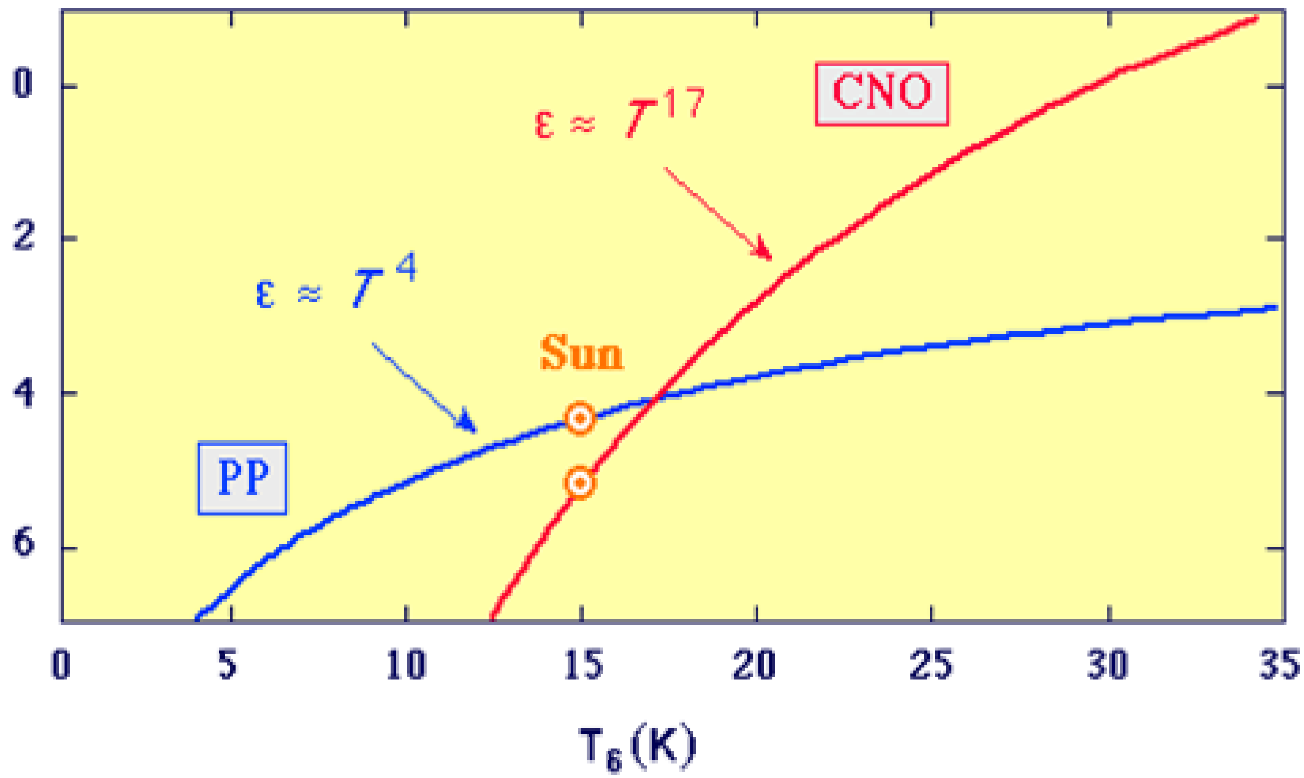
Lecture 4. Evolution of massive stars. Stellar winds. Wolf-Rayet stars and large blue variables.

On the Main Sequence: CNO



Importance of radiation pressure

In regions where the star is supported entirely by radiation pressure and the radiation is diffusing the luminosity is the Eddington luminosity.

The stellar structure equation for the radiative temperature gradient is

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho}{T^3}\frac{L(r)}{4\pi r^2}$$

implies

$$L(r) = \frac{c}{\kappa\rho} 4\pi r^2 \frac{d}{dr}\left(\frac{1}{3}aT^4\right)$$

if the pressure is given by

$$P_{rad} = (1\text{-}\beta)\,\mathrm{P}_{\mathrm{tot}}$$

where $\beta = P_{ideal}/\mathrm{P}_{\mathrm{tot}}$, then

$$L(r) = \frac{4\pi r^2 c}{\kappa\rho}\;\frac{d}{dr}(1-\beta)\,P_{tot}$$

which if β is a constant gives (with hydrostatic equilibrium)

$$L(r) = \frac{4\pi r^2 c}{\kappa\rho}(1-\beta)\frac{GM(r)\rho}{r^2} = (1-\beta)\frac{4\pi GMc}{\kappa}.$$

If β=0, this is the Eddington luminosity

Upper mass limit: Theoretical

Ledoux (1941)	radial pulsation, e- opacity, H	100 $M_\odot$
Schwarzchild & Härm (1959)	radial pulsation, e- opacity, H and He, evolution	65-95 $M_\odot$
Stothers & Simon (1970)	radial pulsation, e- and atomic	80-120 $M_\odot$
Larson & Starrfield (1971)	pressure in HII region	50-60 $M_\odot$
Cox & Tabor (1976)	e- and atomic opacity Los Alamos	80-100 $M_\odot$
Klapp et al. (1987)	e- and atomic opacity Los Alamos	440 $M_\odot$
Stothers (1992)	e- and atomic opacity Rogers-Iglesias	120-150 $M_\odot$

Upper mass limit: Observational

R136	Feitzinger et al. (1980)	250-1000 $M_\odot$
Eta Car	various	120-150 $M_\odot$
R136a1	Massey & Hunter (1998)	136-155 $M_\odot$
Pistol Star	Figer et al. (1998)	140-180 $M_\odot$
Eta Car	Damineli et al. (2000)	~70+? $M_\odot$
LBV 1806-20	Eikenberry et al. (2004)	150-1000 $M_\odot$
LBV 1806-20	Figer et al. (2004)	130 (binary?) $M_\odot$
HDE 269810	Walborn et al. (2004)	150 $M_\odot$
WR20a	Bonanos et al. (2004) Rauw et al. (2004)	82+83 $M_\odot$

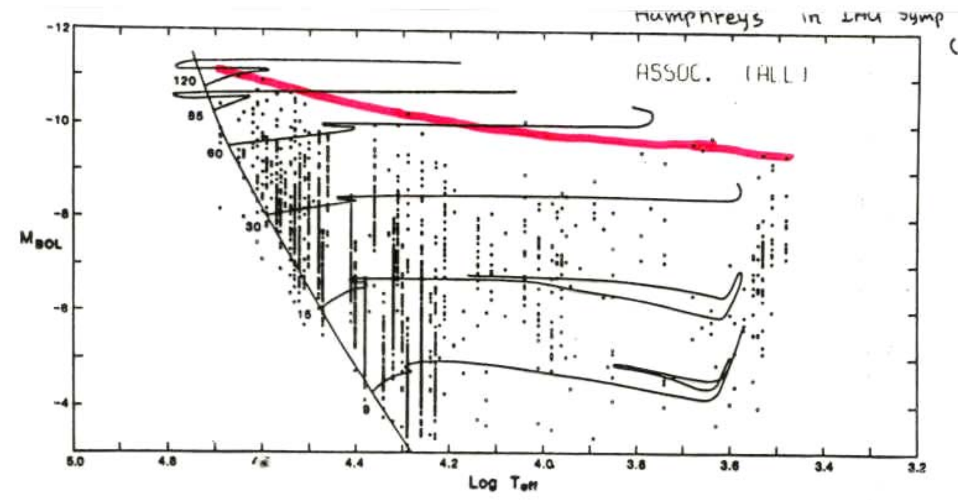
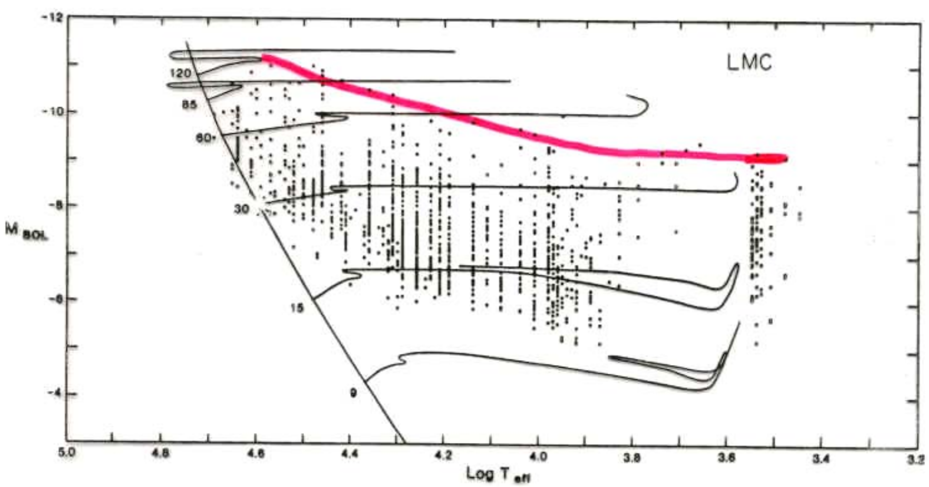
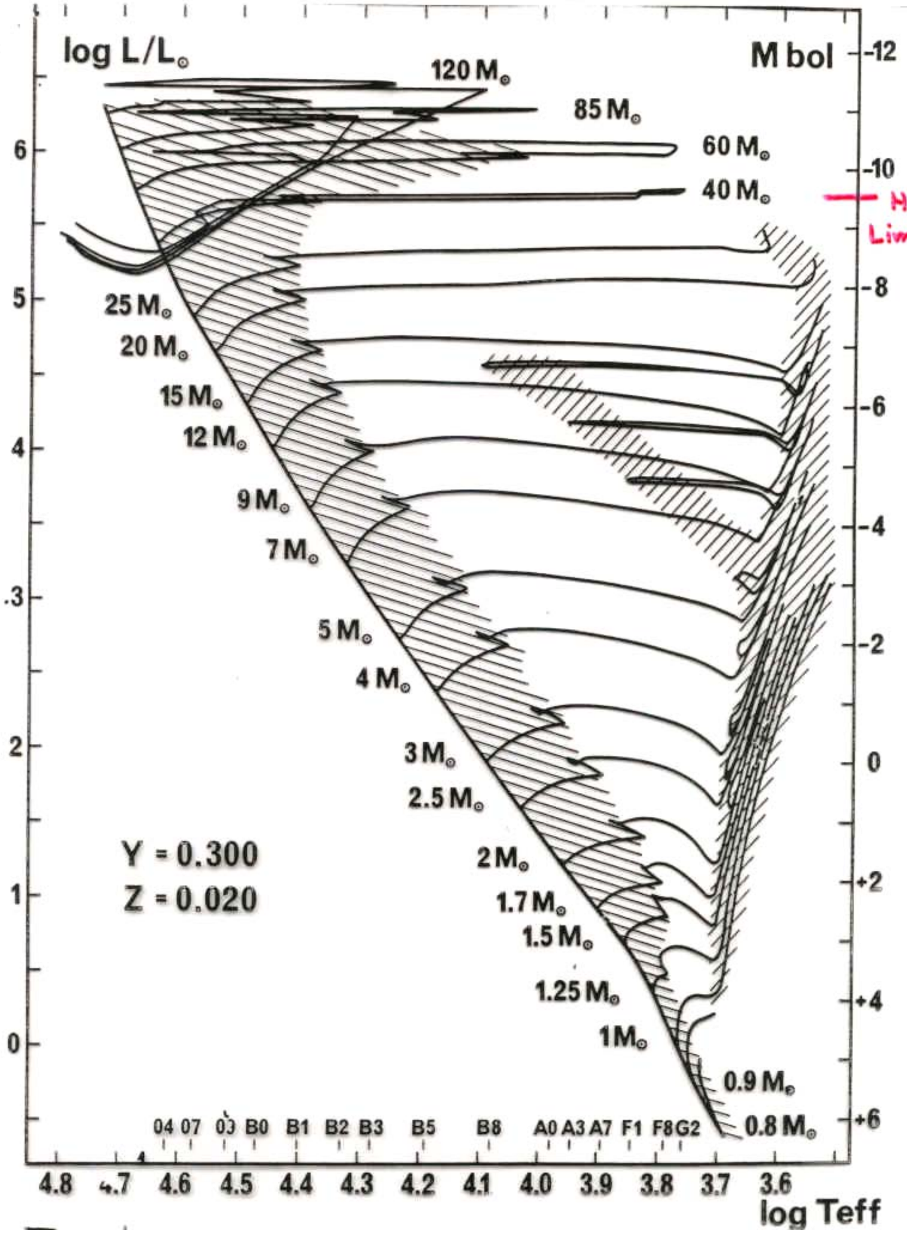
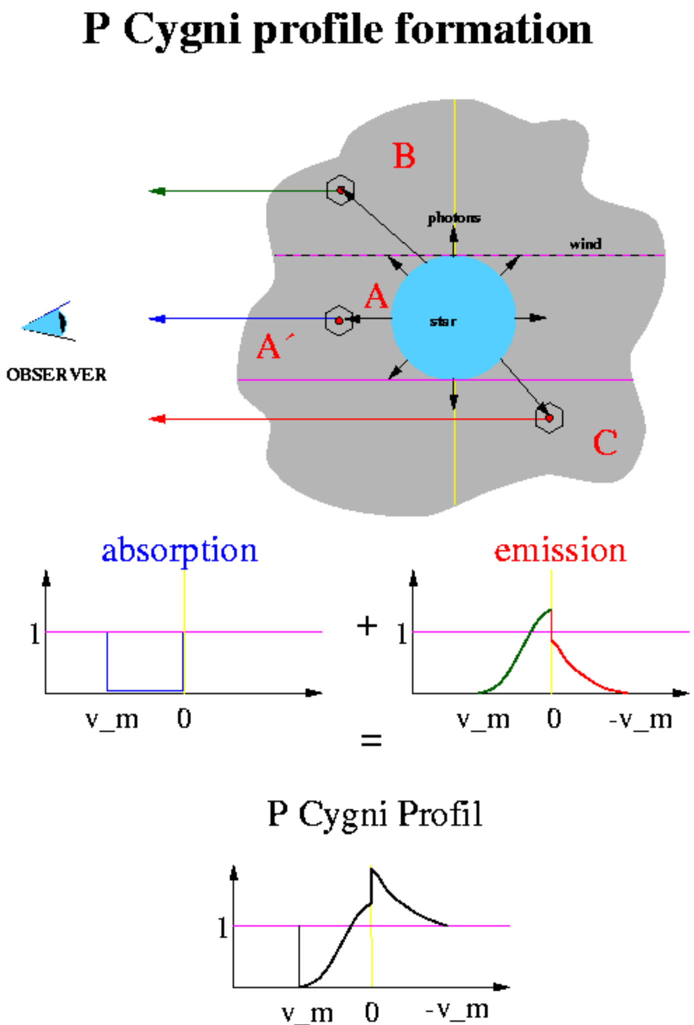


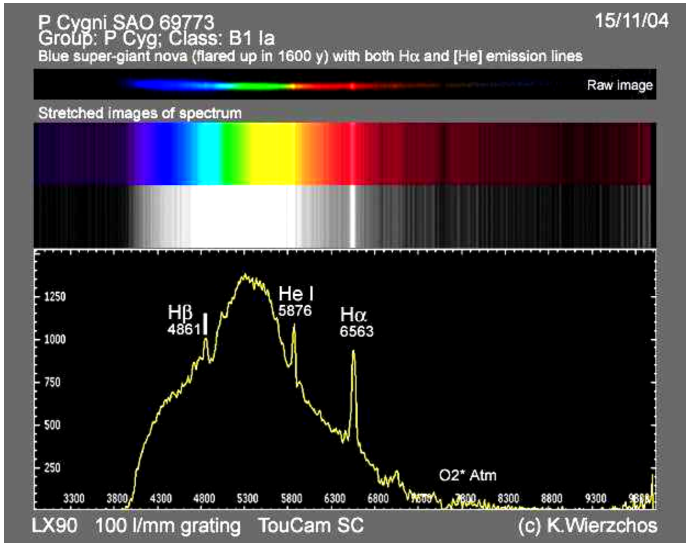
Figure 1 - The HR diagram, M_{Bol} vs. log T_{eff}, for O-type stars, supergiants, and less luminous early-type stars in 91 stellar associations and clusters in the solar region of our Galaxy.

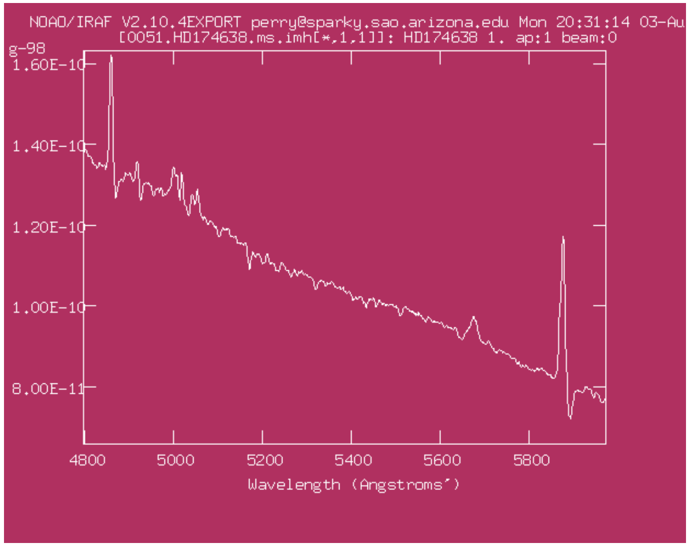




Stellar winds: Observations: PCyg emission line profiles

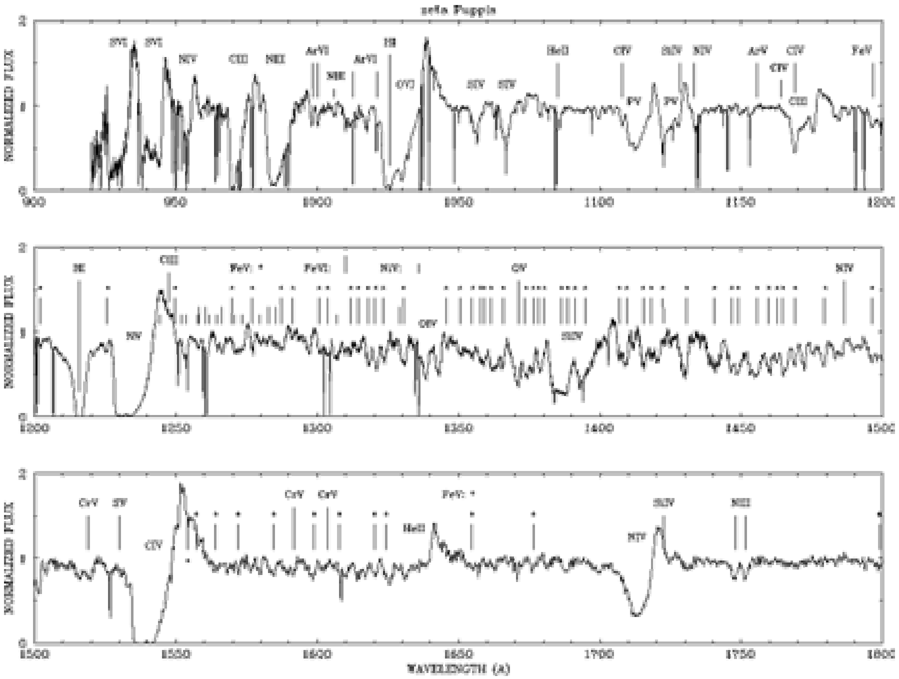




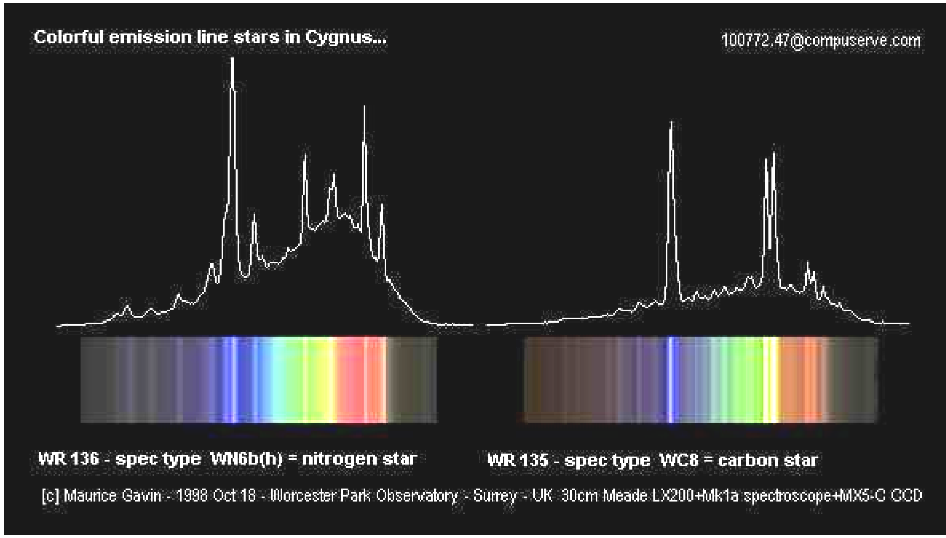


Other bright examples:

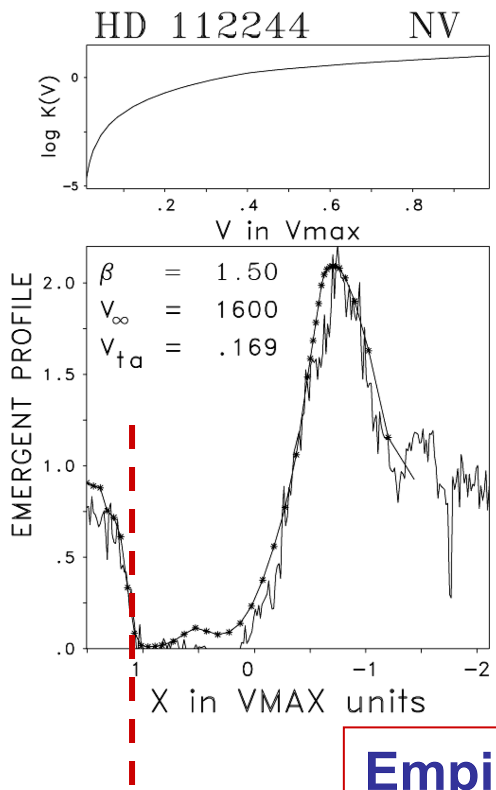
O4 I(f) supergiant zeta Puppis (UV-spectrum by Copernucus)



Wolf-Rayet stars

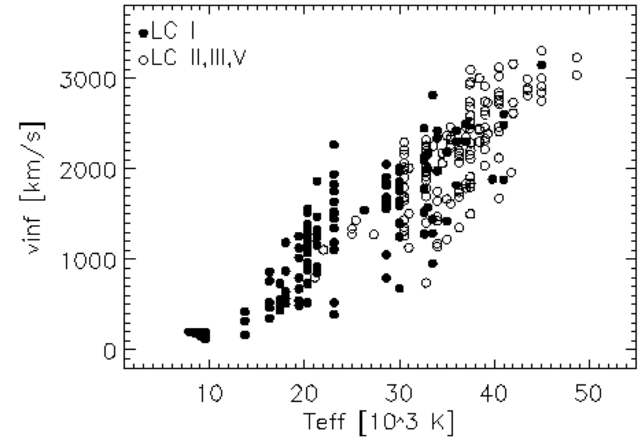


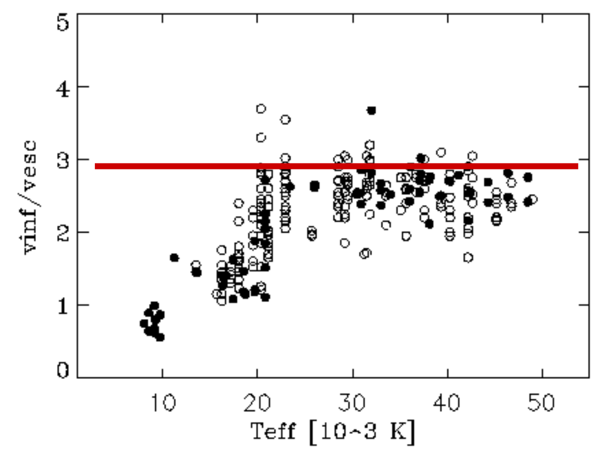
Stellar winds: Measurements: velocities



V_∞

Line profile fitting





Empirical result:
$V_\infty \sim 3V_p = 3(2GM/R)^{1/2}$

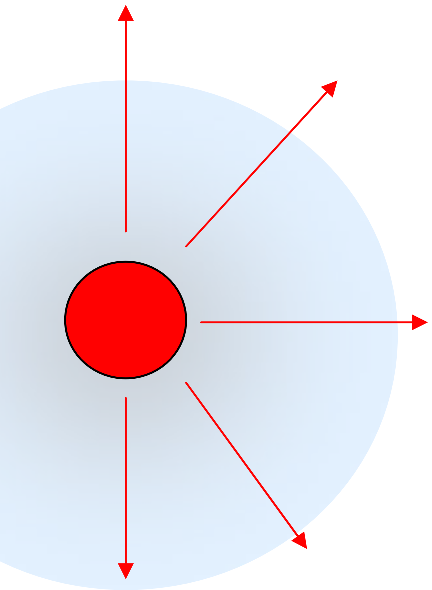
But v(r) is very model dependent!

Stellar winds: Measurements: Mass loss rates

Continuity: $\dot{M} = 4\pi r^2 \rho(r) v(r)$

How to measure density (clumpiness etc.) ??

An elegant way - by IR and radio observations of thermal emission from stellar winds:



$$\alpha_\nu^{ff}(RJ) \simeq \frac{\rho^2}{\nu^2} T^{-3/2}, \ assume\ T(r) = const\ (isothermal\ wind)$$

$$Wind\ \ photosphere: \ \tau^{ff} = \int_{r_{ph}}^{\infty} \alpha_\nu^{ff} dr = 1$$

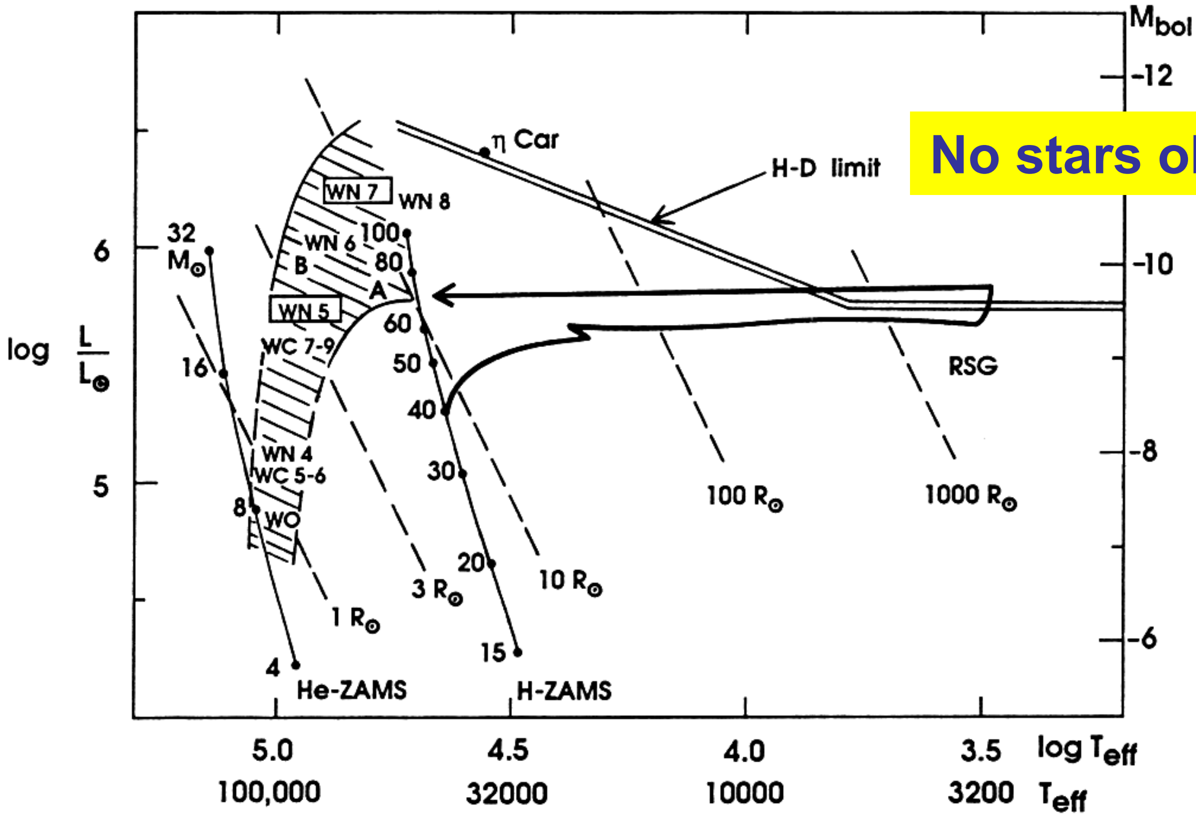
$$+Continuity: \ \rho \sim (\dot{M}/r^2)V \ \Rightarrow \ r_{ph} \sim \dot{M}^{3/2} T^{-1/2} \nu^{-2/3}$$

$$Observed\ \ flux: \ F_\nu \simeq \left(\frac{r_{ph}}{d}\right)^2 B_\nu(T), \ B_\nu^{RJ}(T) = \frac{2\nu^2 k_B T}{c^2}$$

$$\Rightarrow \quad F_\nu \sim \dot{M}^{4/3} \nu^{2/3} / d^2 \quad independent\ \ of\ \ unknown\ \ T!$$

dM/dt for WR and OB supergiants ~ 10^{-4}-10^{-5} $M_\odot$/yr

Wolf-Rayet stars and Large Blue Variables (LBV)



Humphreys-Davidson limit

No stars observed above this limit

$L \sim L_{Edd} = 10^{38}$ erg/s $(M/M_\odot)$

$M \sim 8\text{-}50\ M_\odot$

Classification of Wolf-Rayet Stars

- "*early*" (hot; WxE) and "*late*" (cooler, WxL) types
- WN stars show helium lines (HeI, HeII) and lines of ionized nitrogen (NIII, NIV, NV)
- WC stars show lines of ionized carbon (CIII, CIV) and oxygen (OIV, OV, OVI)
- WC stars where oxygen lines dominate over carbon lines are also called WO stars.
- decreasing levels of ionization are denoted by decreasing arabic numbers
  - WNE = WN2...WN6
  - WNL = WN7...WN10
  - WCE = WC4...WC6
  - WCL = WC7...WC10
- WNE stars are subdivided in stars with strong (WNE-s) and weak (WNE-w) emmision lines. WNE-s stars experience much higher mass loss rates than WNE-w stars. (Schmutz, Hamann, Wessolowski 1989, A&A, 210, 236)
- WNL stars show some (up to 40 %) hydrogen and are in general more luminous

Evolutionary sequences with mass loss – Chiosi and Maeder (1986)

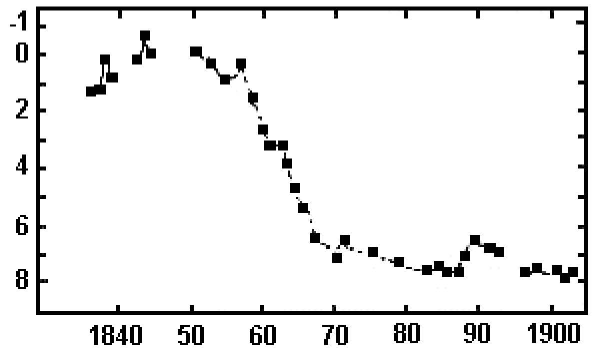
For $M > 60\ M_{\odot}$ Always Blue
O star–Of–BSG and LBV–WN–WC–(WO)–SN

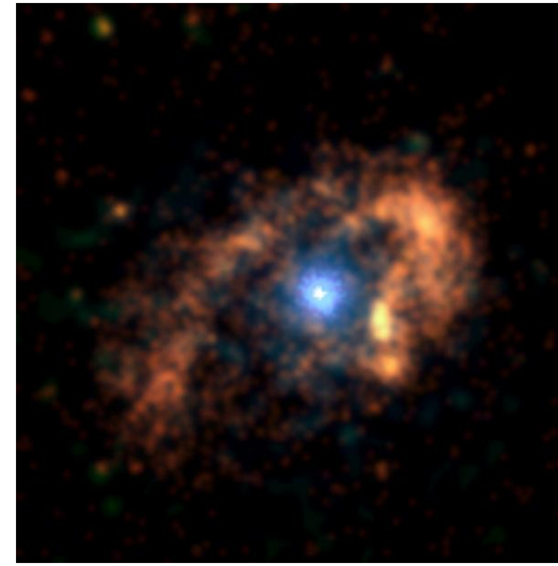
For $25\ M_{\odot} < M < 60\ M_{\odot}$ Blue–Red–Blue
O star–BSG–YSG and RSG–WN–(WC)–SN : High $\dot{M}$
SN : Low $\dot{M}$

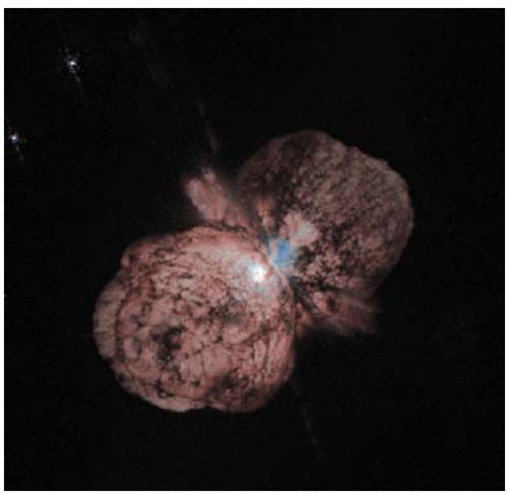
For $M < 25\ M_{\odot}$ Blue–Red
O star–(BSG)–RSG–YSG and Cepheid–RSG–SN

where the abbreviations are as follows: BSG, blue supergiant; YSG, yellow supergiant; RSG, red supergiant; LBV, luminous blue variables; WN, Wolf-Rayet star of the nitrogen sequence; WC, Wolf-Rayet star of the carbon sequence; WO, Wolf-Rayet star of the oxygen sequence; SN, supernova.

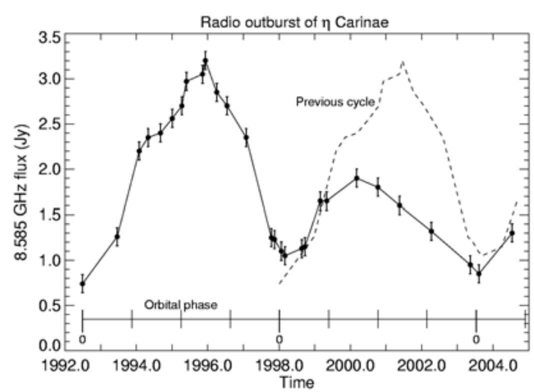
LBV: Eta Carinae in LMC

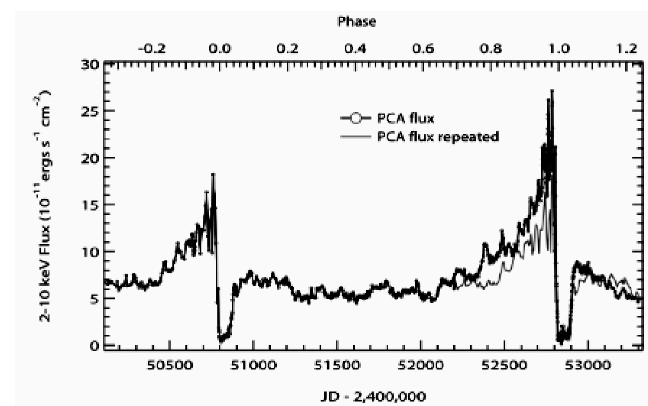






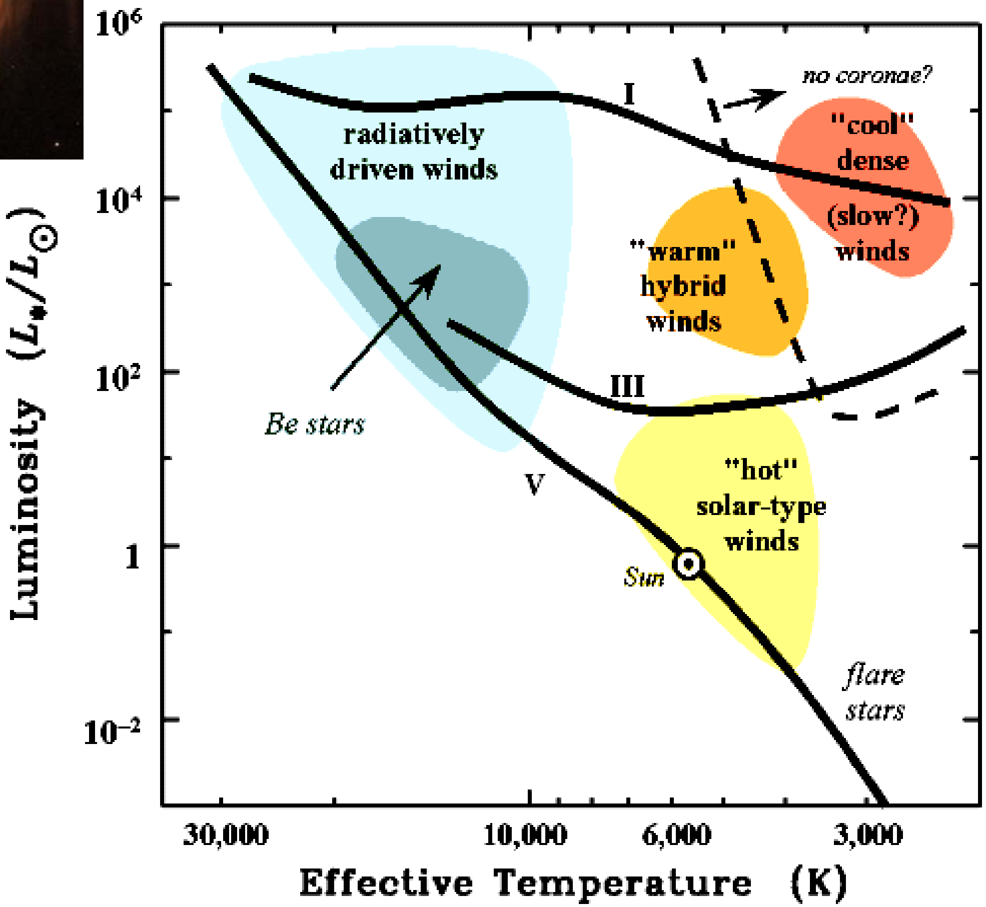
Eruptions and strong variability

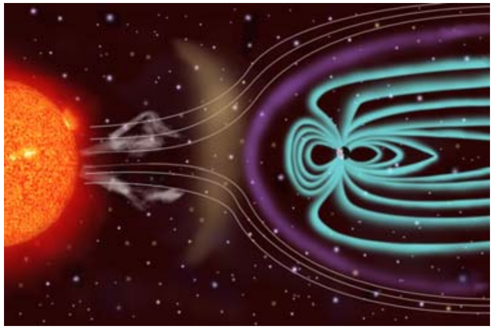


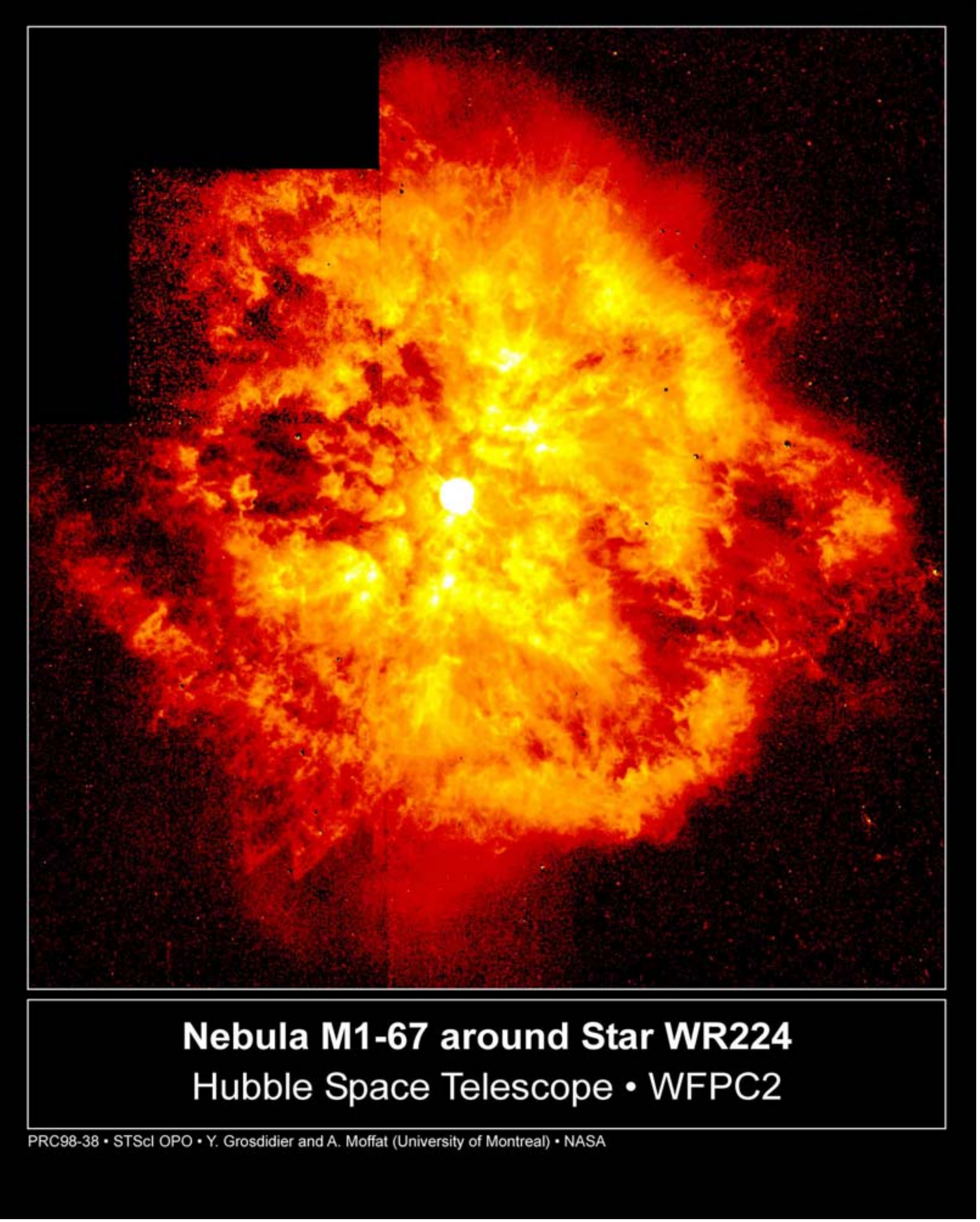


All LBV show bipolar structure! ***Open issue: is it a pre-WR stage?***

Types of stellar winds







The Wolf-Rayet star WR224 is found in the nebula M1-67 which has a diameter of about 1000 AU

The wind is clearly very clumpy and filamentary. Clumpiness decreases mass loss rate derived from line spectroscopy

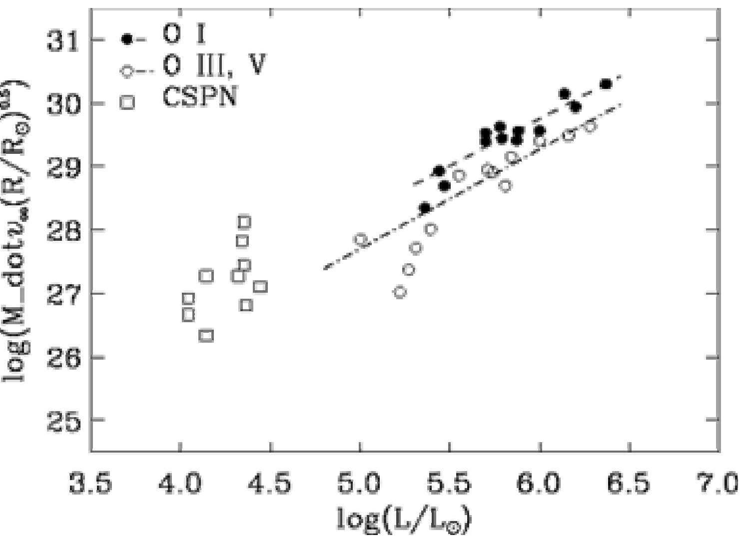
Radiation-driven mass loss

***Physical reason*: radiation pressure due to resonant photon scatterings in resonant (UV) lines: Si V (1394-1403A), CIV (1548-1551A, NV(1240 A) etc.**

$$Theory: \quad \dot{M} \sim (1-(L/L_{Edd}))^{-\mu},\ \mu > 0, \dot{M} \to \infty \ \ as \ \ L \to L_{Edd} \Rightarrow Cause \ \ for \ \ LBVeruptions?$$

$$L_{Edd} = \frac{4\pi GMc}{\kappa},\ \kappa = f(T,\rho)$$

so L_{Edd} can decrease and star turns out super-Eddigton



Radiation line pressure:

dM/dt V_∞~L/c

More precisely:

$$\dot{M}V_\infty\sqrt{R} \sim L^{3/2}$$

Consistent with observations of winds from OB supergiants and central stars of planetary nebulae!

Mass Loss – Implications in Massive Stars

1) May reveal interior abundances as surface is peeled off of the star. E.g., CN processing, s-process, He, etc.

2) Structurally, the helium and heavy element core – once its mass has been determined is insensitive to the presence of the envelope. If the entire envelope is lost however, the star enters a phase of rapid Wolf-Rayet mass loss that does greatly affect everything – the explosion, light curve, nucleosynthesis and remnant properties. A massive hydrogen envelope may also make the star more difficult to explode.

3) Mass loss sets an upper bound to the luminosity of red supergiants. This limit is metallicity dependent. For solar metallicity, the maximum mass star that dies with a hydrogen envelope attached is about 35 solar masses.

4) Mass loss – either in a binary or a strong wind – may be necessary to understand the relatively small mass of Type Ib supernova progenitors. In any case it is necessary to remove the envelope and make them Type I.

5) The nucleosynthesis ejected in the winds of stars can be important – especially WR-star winds.

6) In order to make gamma-ray bursts in the collapsar model for gamma-ray bursts, the final mass of the helium core must be large. Also the mass loss rate inferred from the optical afterglows of GRBs imply a relatively low mass loss rate.

7) The winds of presupernova stars influence the radio luminosity of the supernova

8) Mass loss can influence whether the presupernova star is a red or blue supergiant.

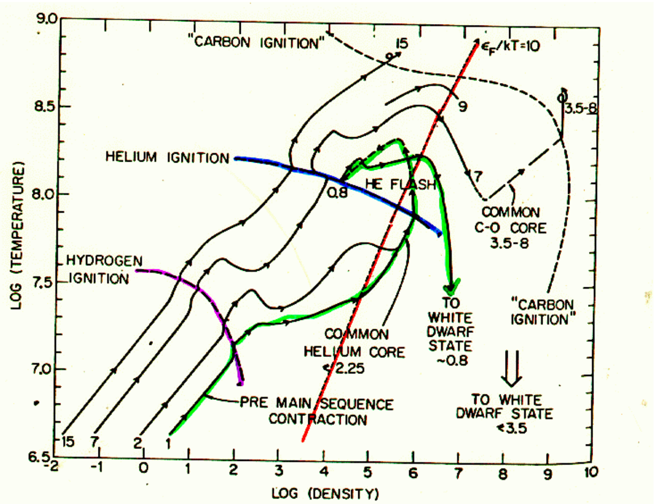
9) The calculation of mass loss rates from theory is an important laboratory test ground for radiation hydrodynamics.

10) The metallicity dependence of mass loss is the chief cause of different evolutionary paths for stars of the same mass at different times in cosmic history.

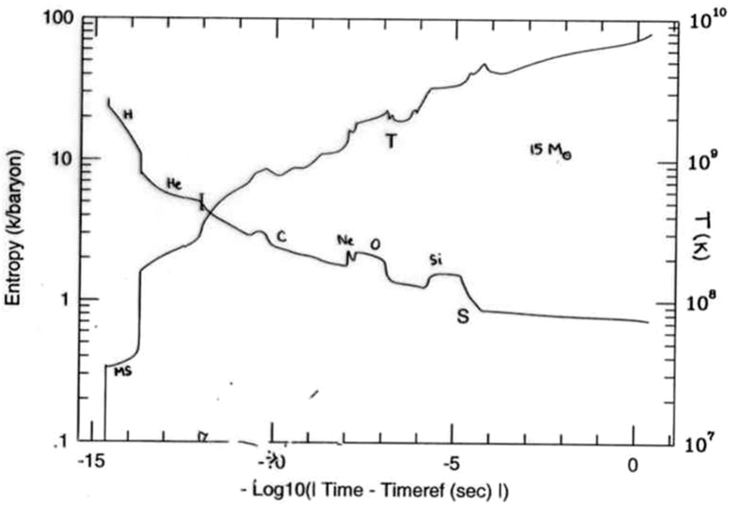
Summary of physical properties governing massive star evolution (after S.Woosley)

$$S = const + \frac{N_A k}{\mu} ln(\frac{T^{3/2}}{\rho}) + \frac{4aT^3}{3\ \rho}.$$

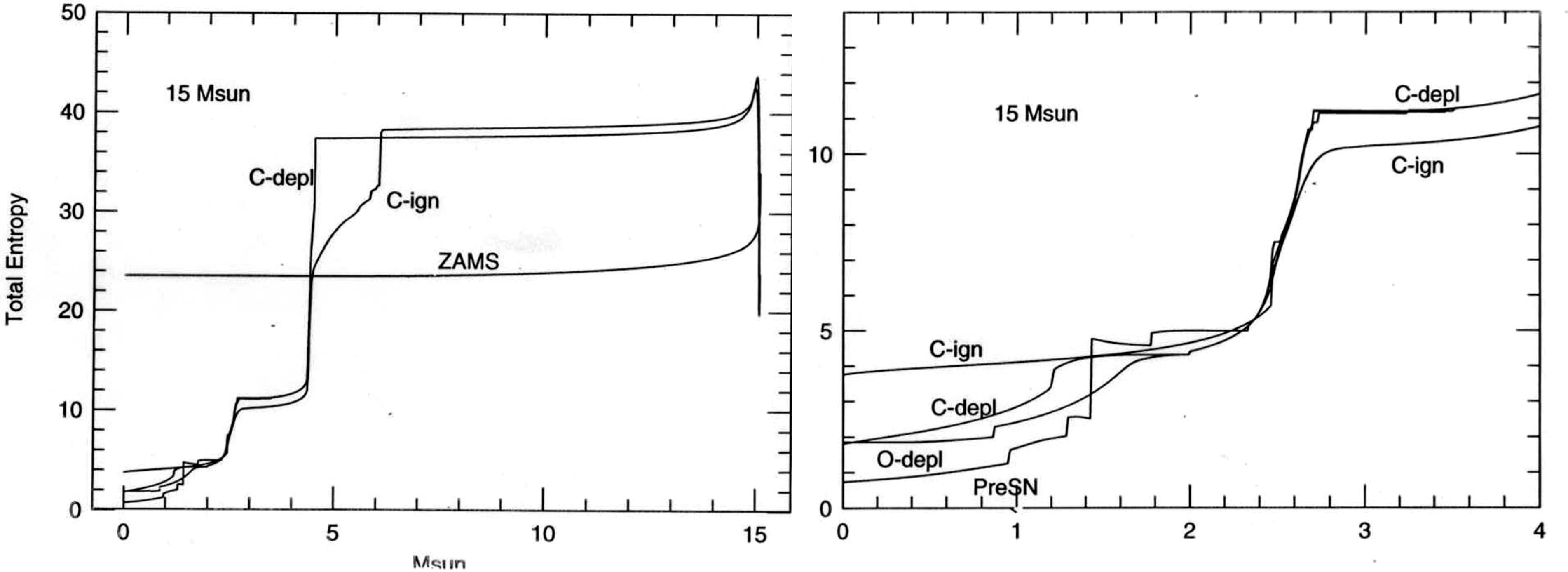
- Stars tend to evolve keeping T^3/ρ in their centers constant unless degeneracy intervenes.
- Bigger stars have bigger T^3/ρ in their center and also larger T_c, lower ρ_c, and higher S_c.
- There exist critical masses for igniting a given fuel. The exact values depend on rotation, overshoot mixing, etc. Typical values are 0.08, 0.45, 8, etc.
- Except for convective regions which have dS/dr very slightly > 0, S increases monotonically with r.
- The central entropy of a massive star decreases as it evolves. This makes degeneracy more important in the later stages and leads to “core convergence”
- But unless degeneracy pressure intervenes, the central temperature always rises, igniting new burning stages from the ashes of the previous ones. Neutrino losses speed the late stages of the evolution. 8 – 11 solar mass stars are complex.



Tracks in the ρ-T plane traced out by the centers of stars of various masses



Example: Entropy in 15 $M_{\odot}$

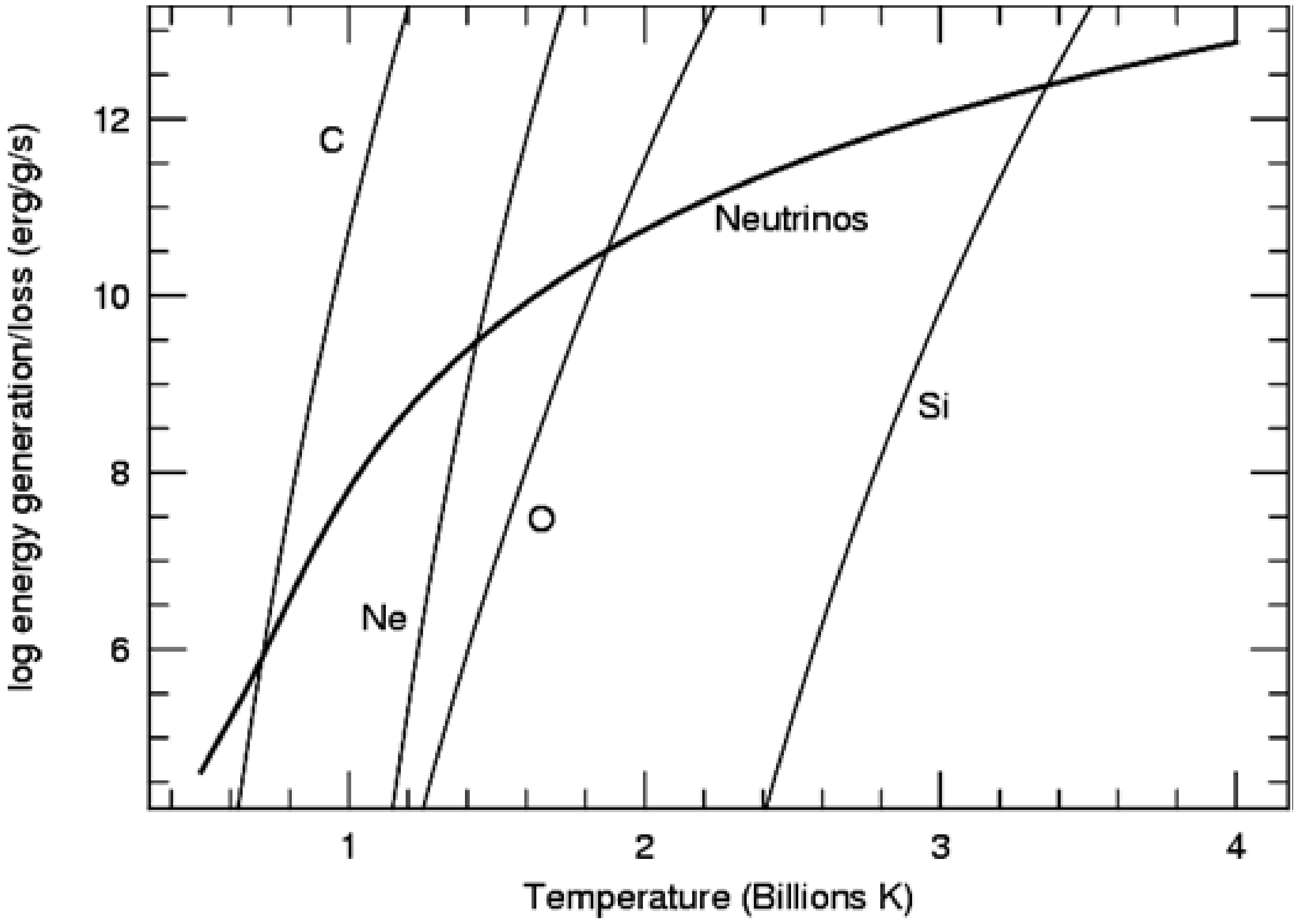


Summary of advanced nuclear burning

Advanced Nuclear Burning Stages
(e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O, ^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

Importance of weak interactions



$\varepsilon_\nu \sim T^6$

$(A,Z)+e^- \rightarrow (A,Z-1)+\nu_e$,

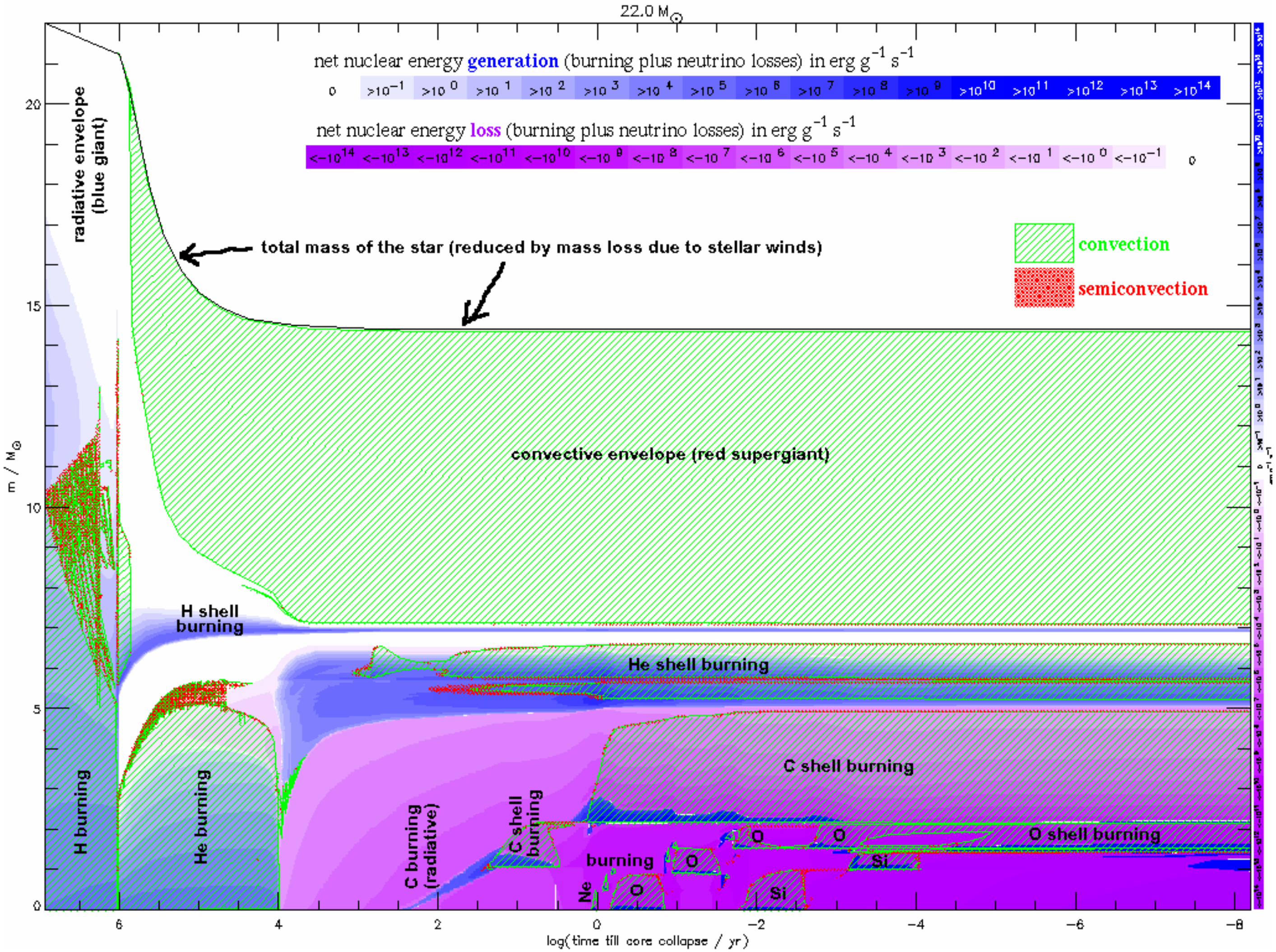
$(A,Z-1) \rightarrow (A,Z)+e^- + \tilde{\nu}_e$

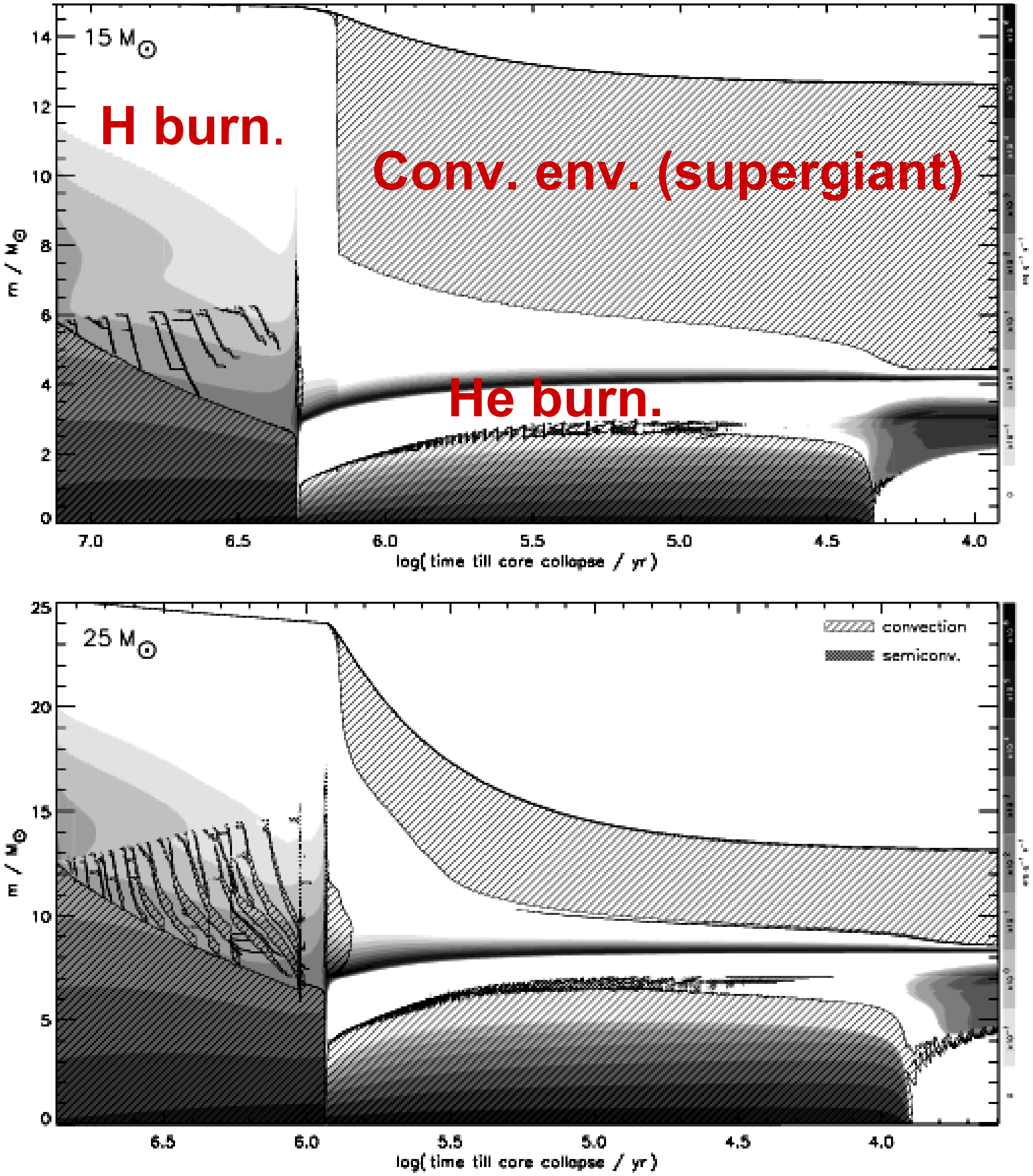
(URCA-processes)

$\varepsilon_\nu \sim T^9$

$(e^+ + e^- \rightarrow \nu_e + \tilde{\nu}_e)$

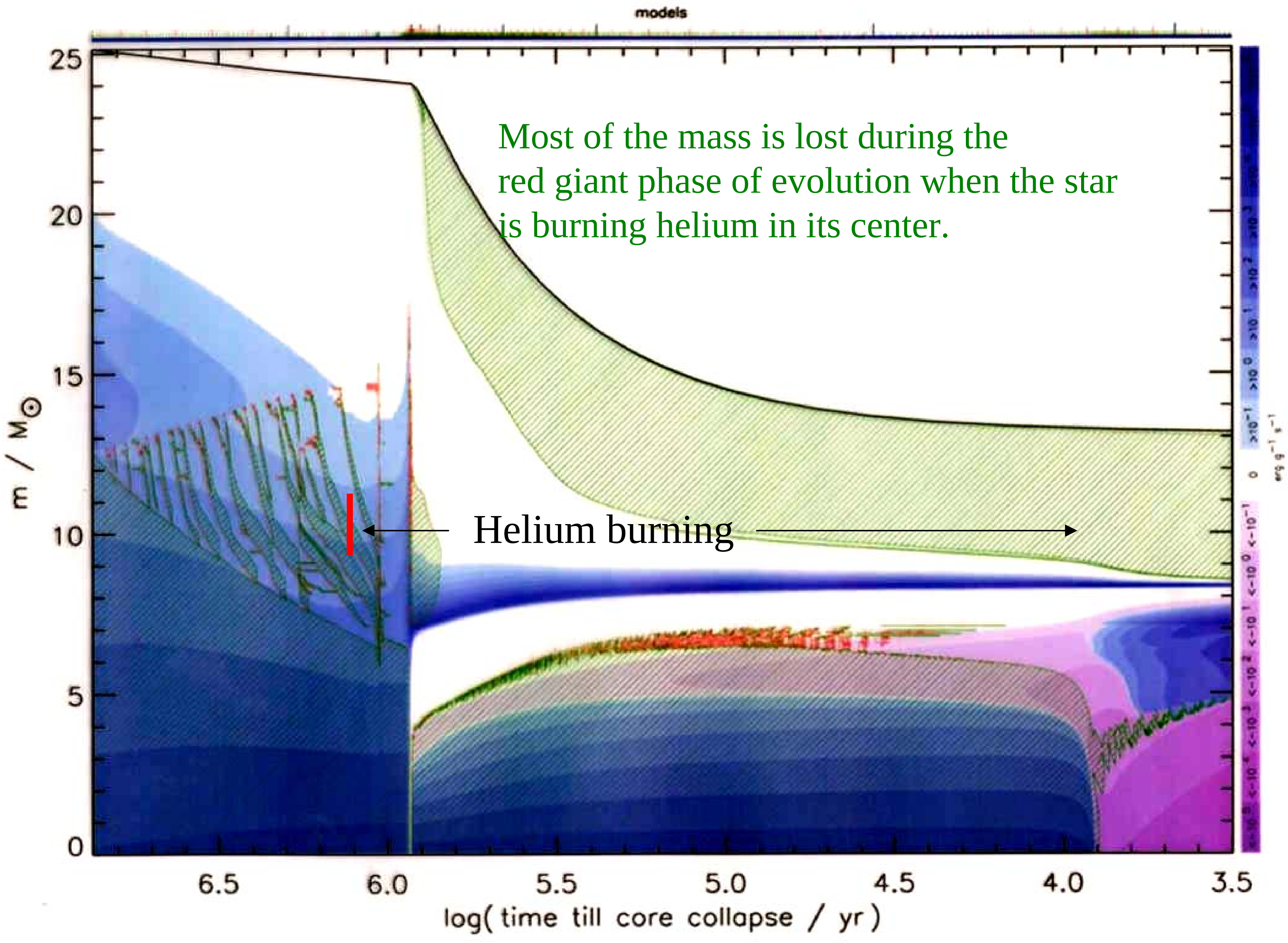
Particular example: Woosley, Heger, Langer models – the "Kepler code" (www.supersci.org)



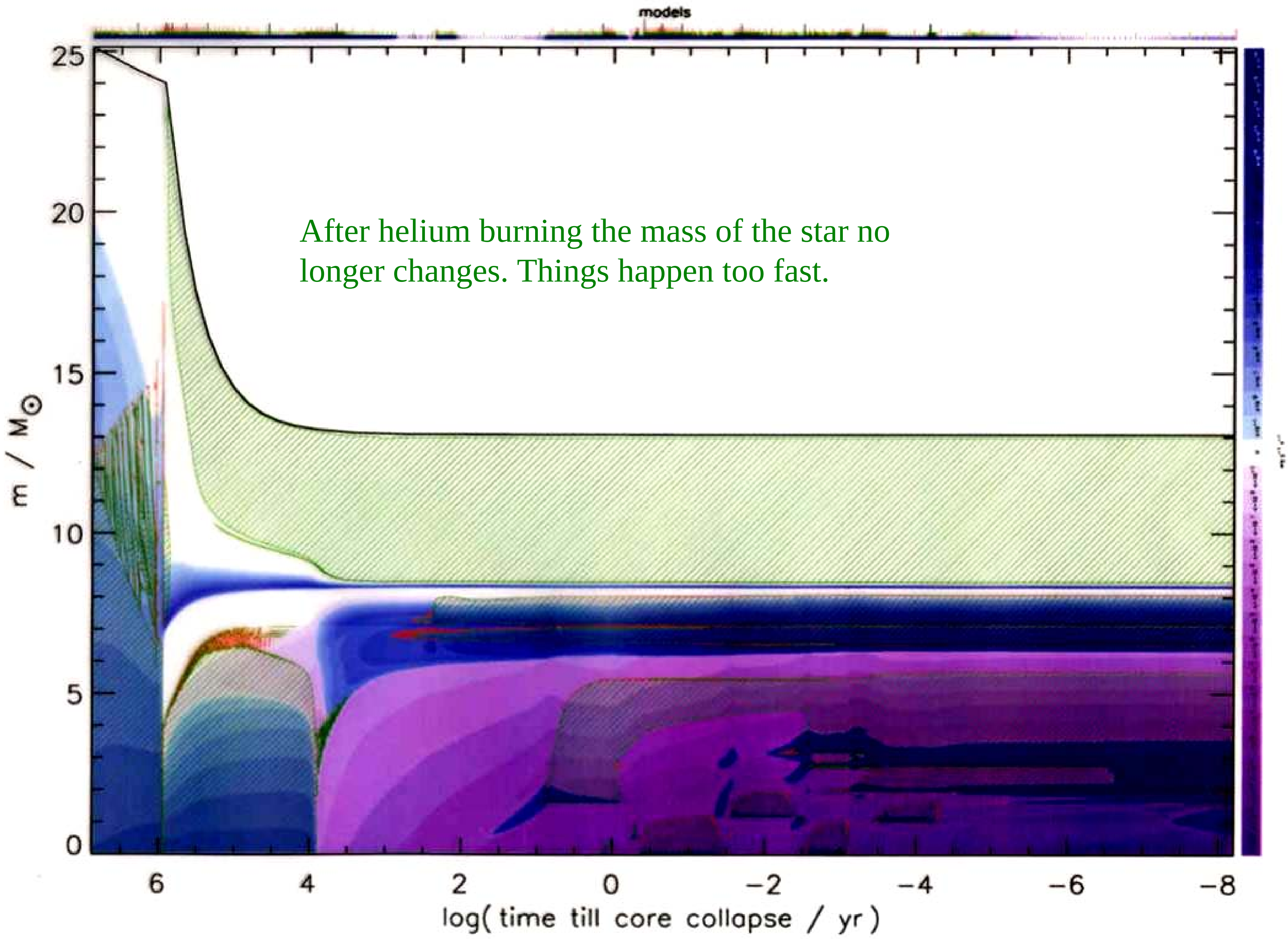


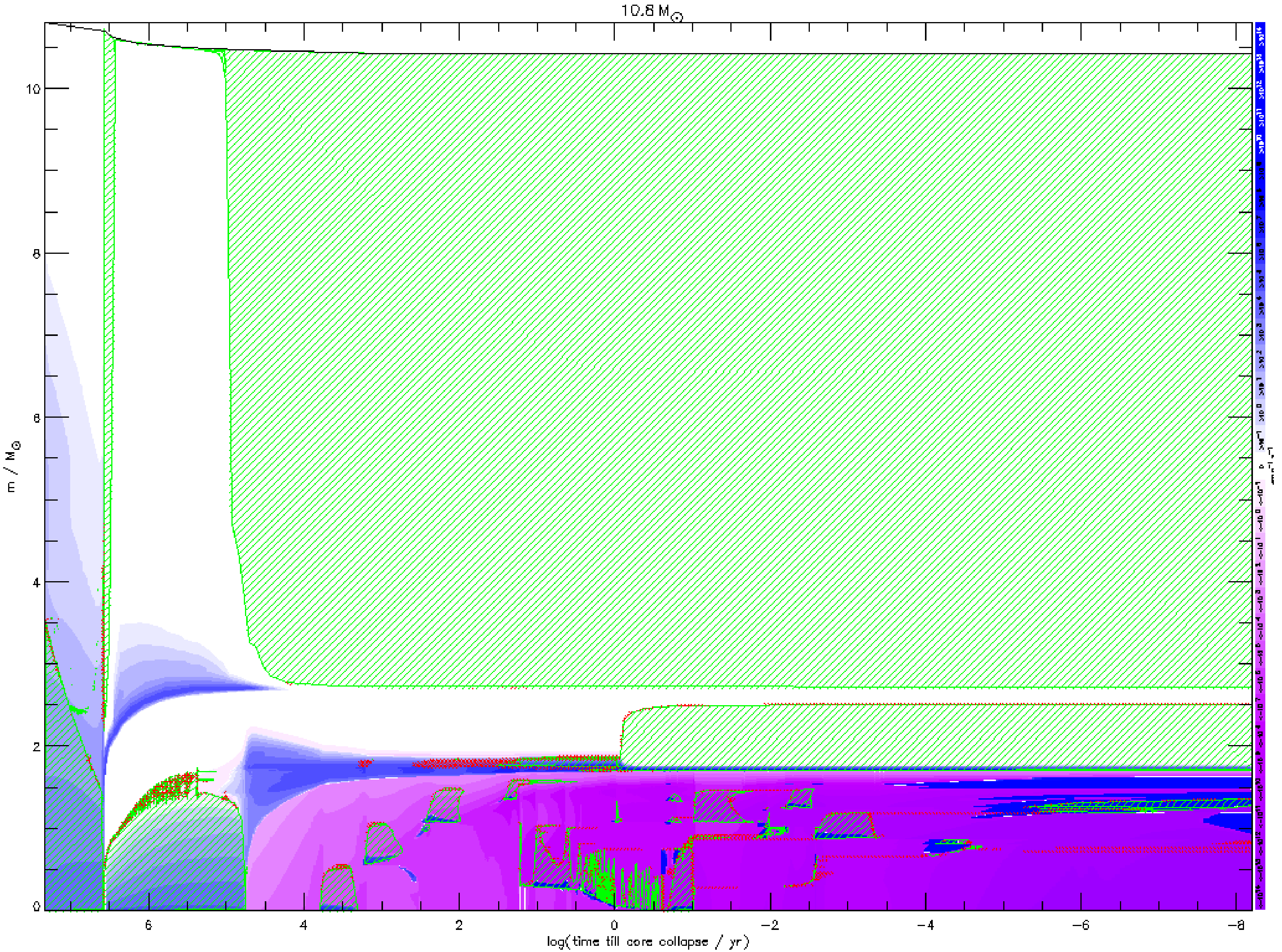
The three greatest uncertainties in modeling the evolution of single massive stars are:

- **Convection and convective boundaries (favored by a large fraction of radiation pressure!)**
- **Rotation (leads to meridional circulation)**
- **Mass loss (especially the metallicity dependence)**



models
Most of the mass is lost during the
red giant phase of evolution when the star
is burning helium in its center.
Helium burning
m / M⊙
25
20
15
10
5
0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
log(time till core collapse / yr)


models
25
20
15
10
5
0
m / $M_\odot$
After helium burning the mass of the star no longer changes. Things happen too fast.
6
4
2
0
−2
−4
−6
−8
log(time till core collapse / yr)


10.8 $M_\odot$
m / $M_\odot$
log(time till core collapse / yr)