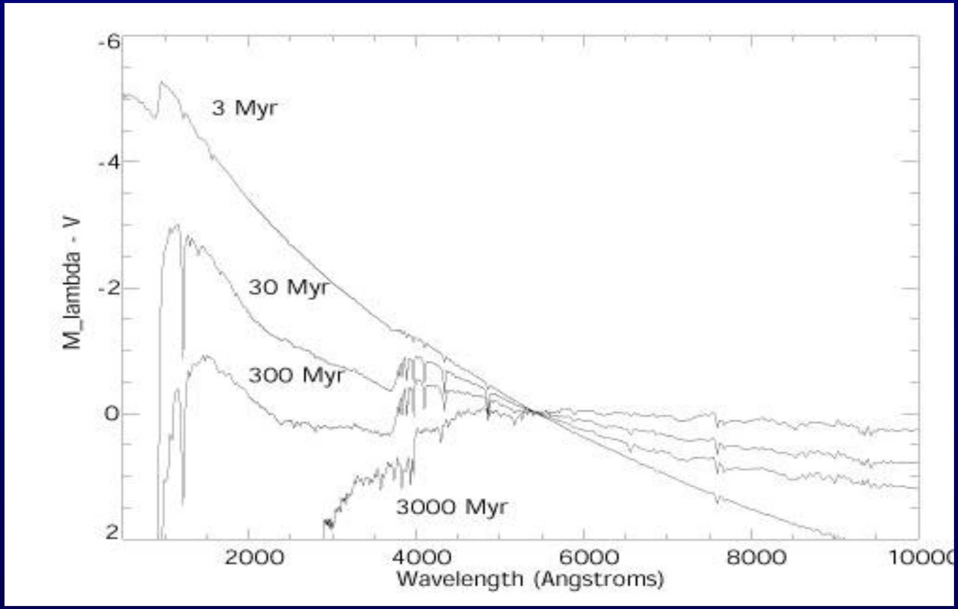
Uncertainties of stellar evolution models
UV emitters



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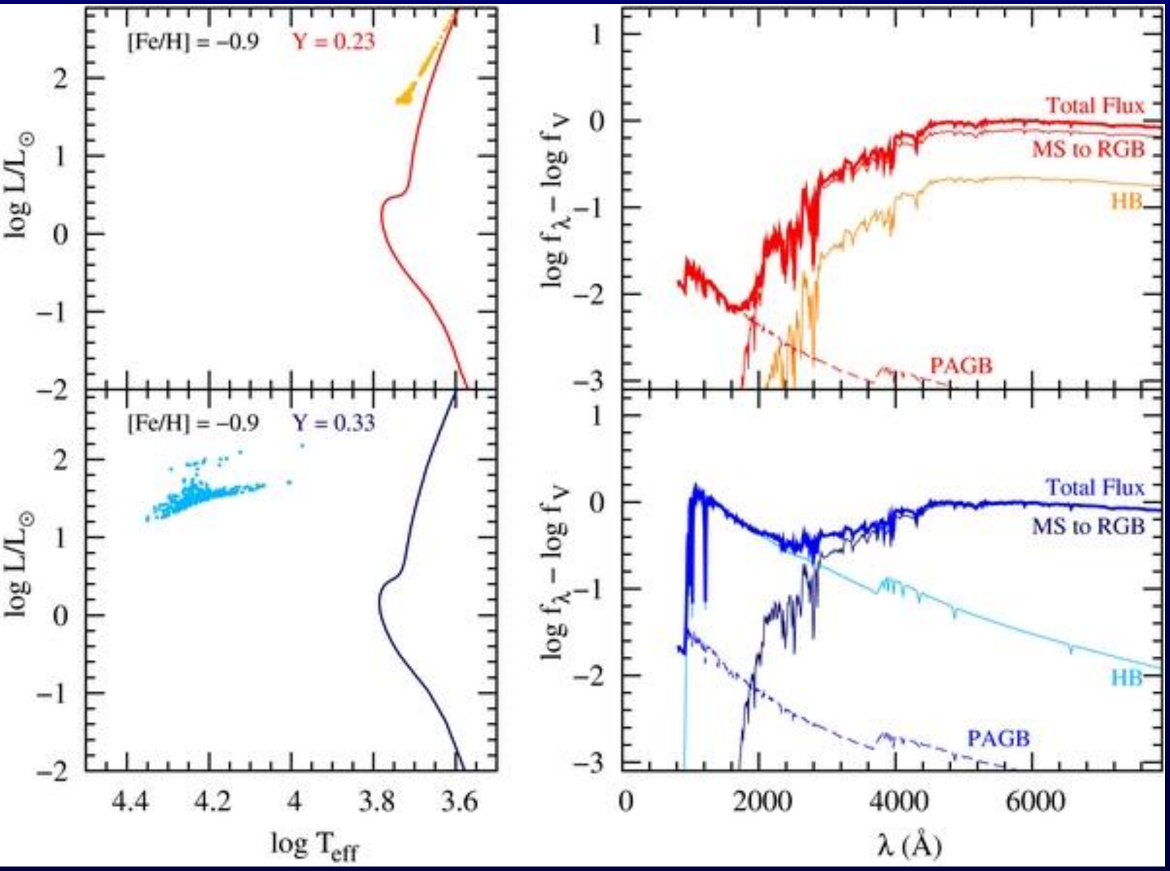
OUTLINE

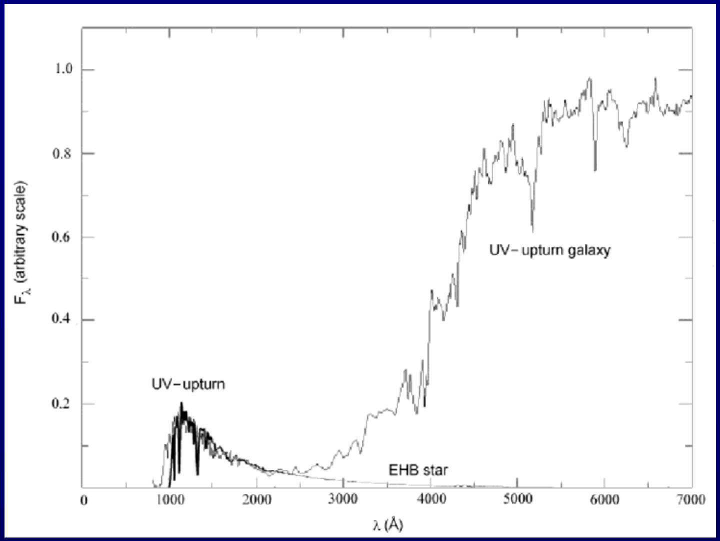
i) UV-emitters in old/intermediate age populations (EHB, hot flashers, post-AGB)

ii) Massive stars in young populations (mixings, rotation and related angular momentum/element transport)

UV emitters in old populations (hot HB stars)

Chung et al. (2011)

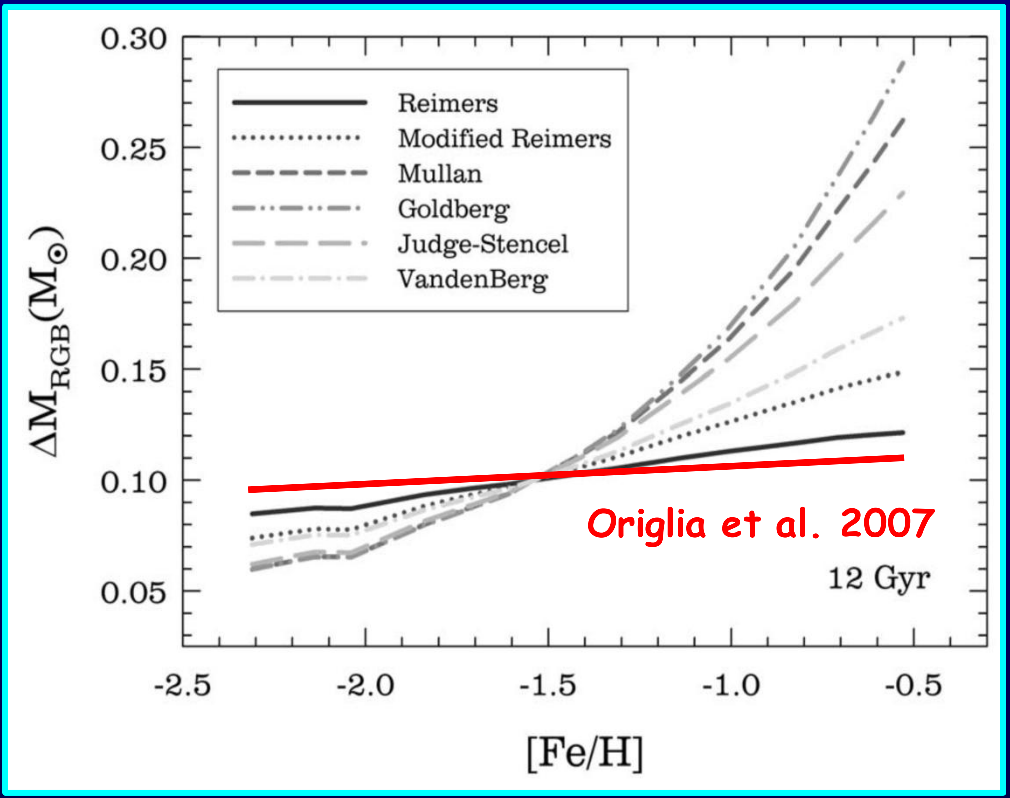


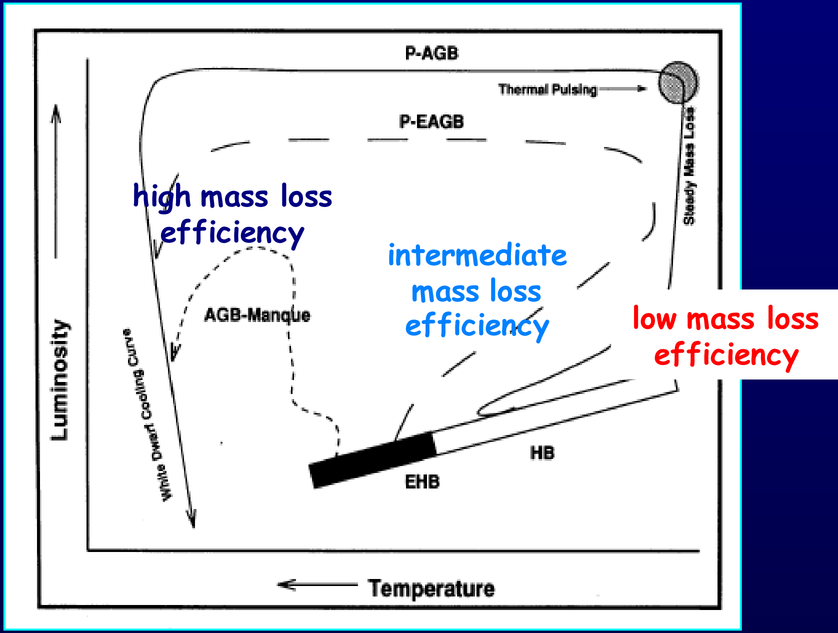


Hot HB stars in ellipticals (?)

Mass loss on the RGB

Different parametrizations → different results





Reimers

Free parameter

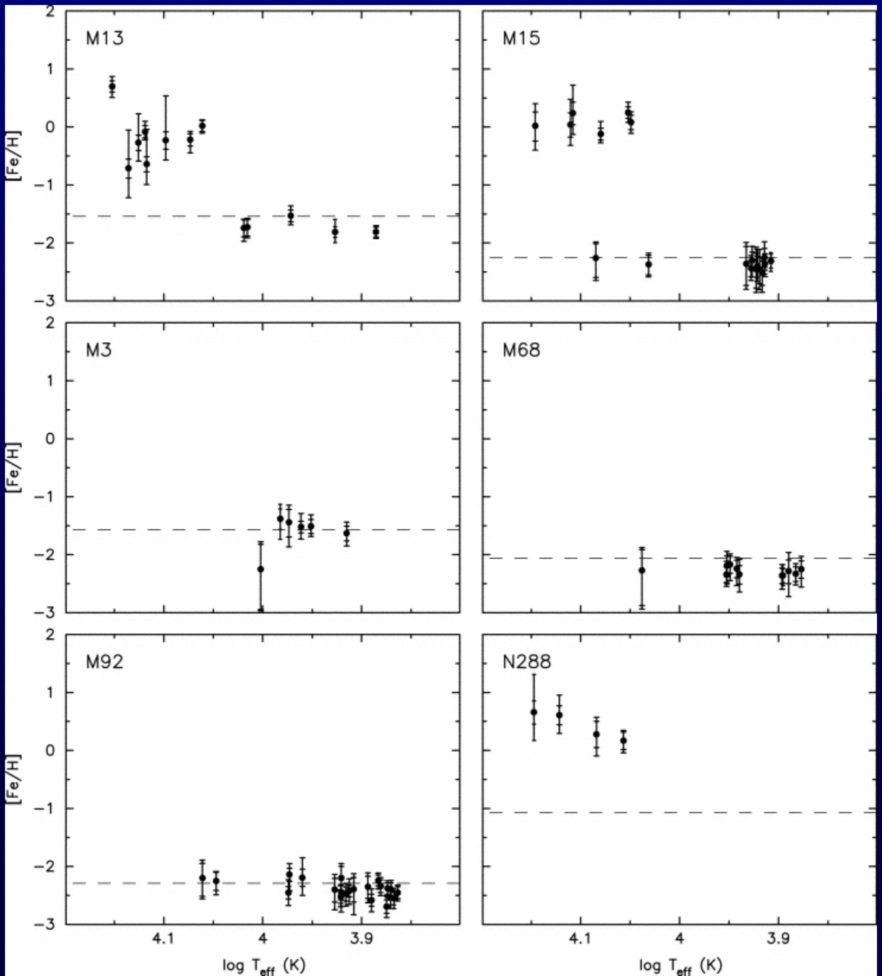
$$\frac{dM_{RGB}}{dt} = -4\times10^{-13}\eta_R\frac{L}{gR}$$

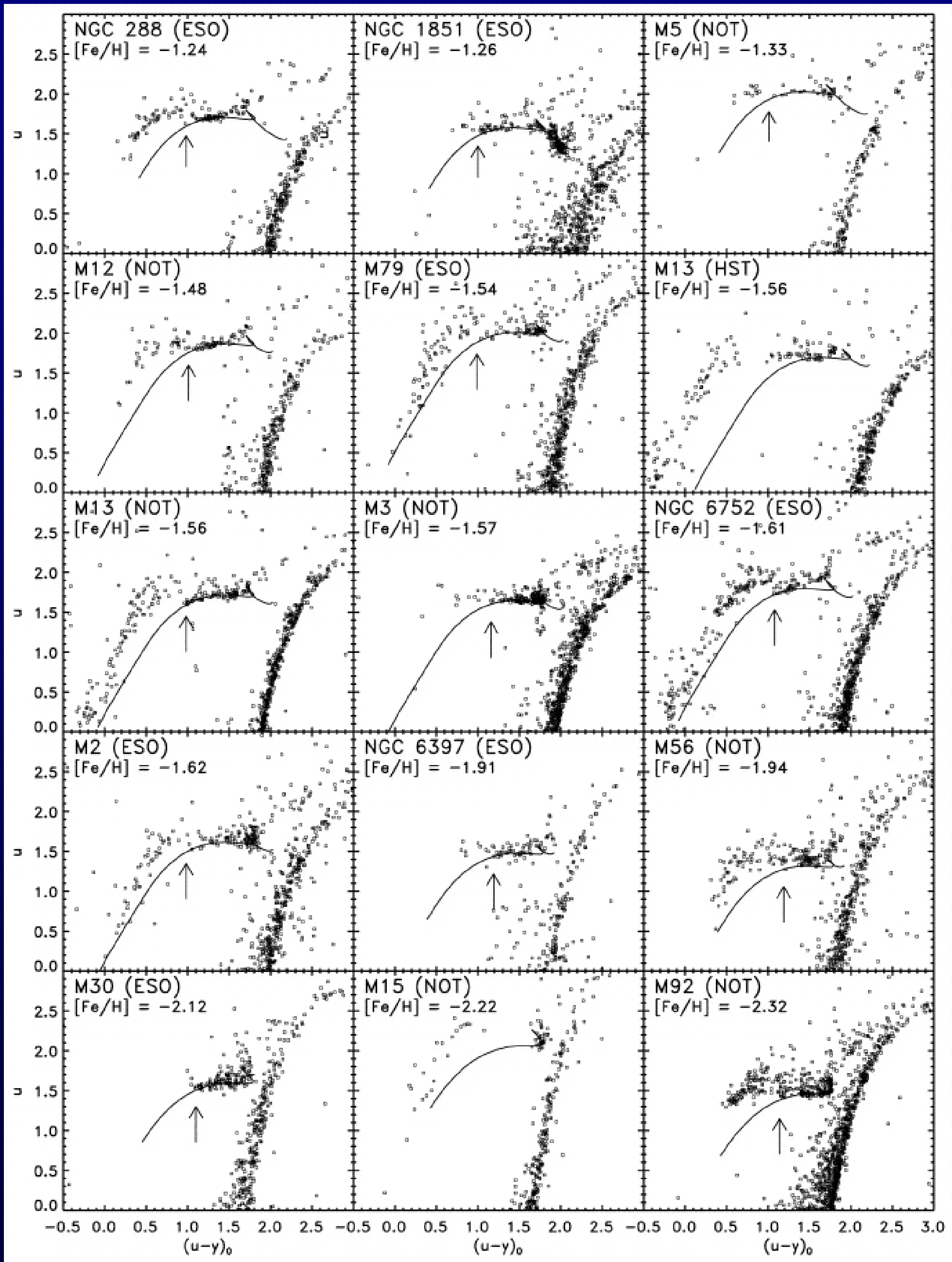
Diffusion + levitation on the hot HB

Grundahl et al. (1999)

Elements like Mg and Si remain nearly invariant all along the HB (with the same RGB abundances) while above 11500 K He is underabundant and Fe, Ti, P, Cr, Mn, Ni are enhanced by factors ≈100.

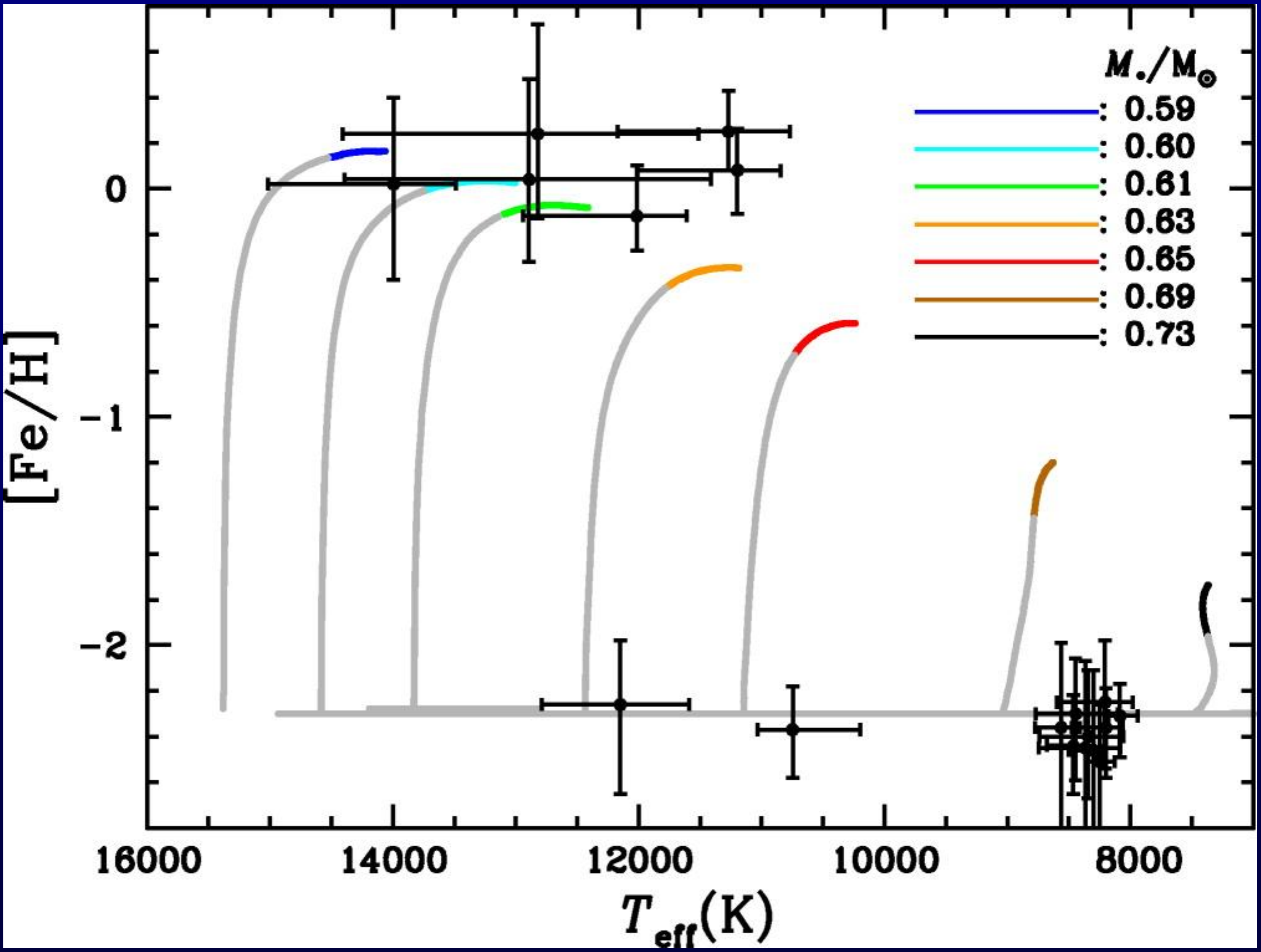
Behr (2003)





Michaud et al. (2008)

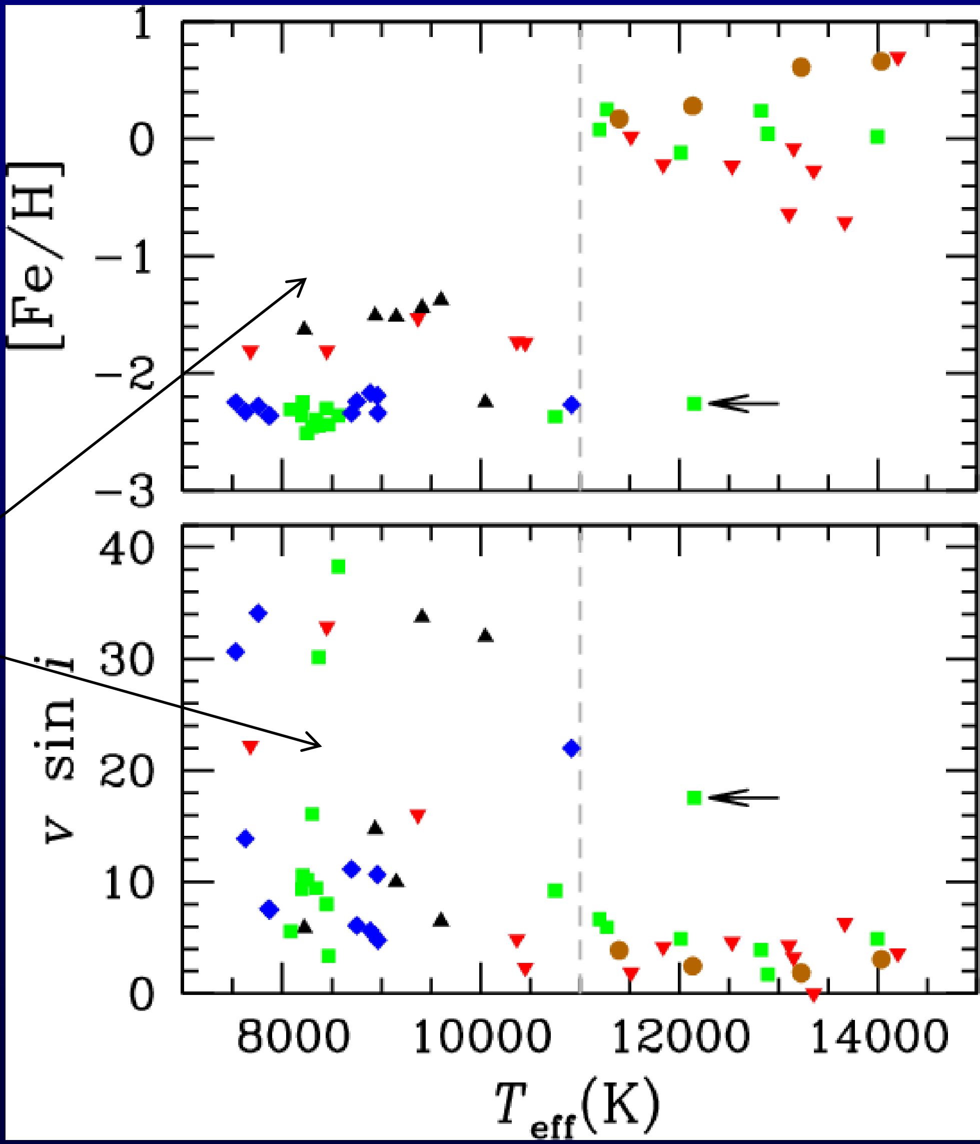
M15



Inhibition of levitation ?

Models (few) that include diffusion+radiative levitation on the HB predict the onset of surface abundance changes at T_{eff} well below 11500 K.
Also, the detailed abundance pattern is not well reproduced (Fe and Mg)
Michaud et al. (2008)

Quievy et al. (2009)
Behr (2003)

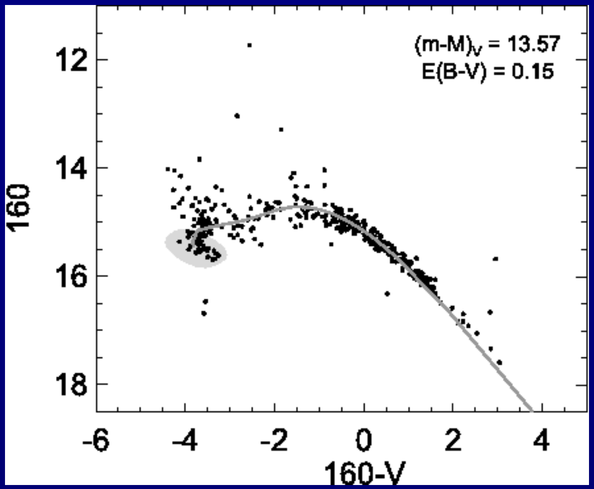


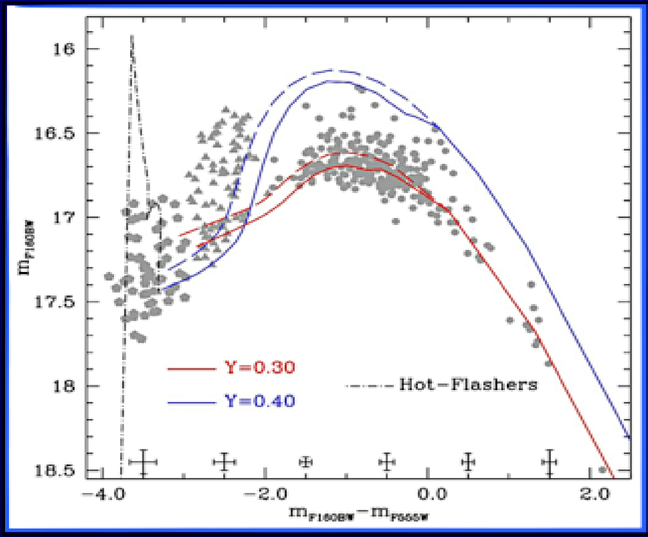
Link between rotationally-induced mixing and the suppression of diffusion+levitation effects?

Why this distribution of HB rotation velocities ?

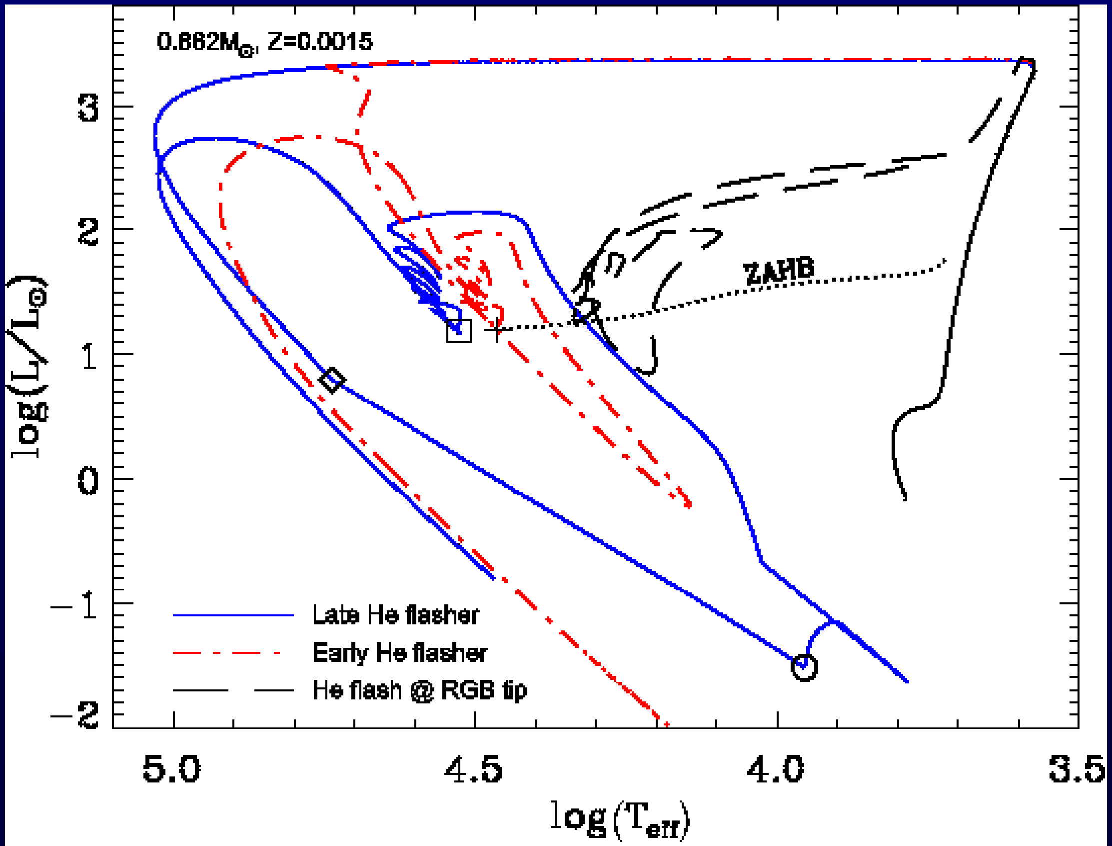
Hot flashers

He-flash during transition to He-core WD or along the bright WD sequence (depends on envelope mass)



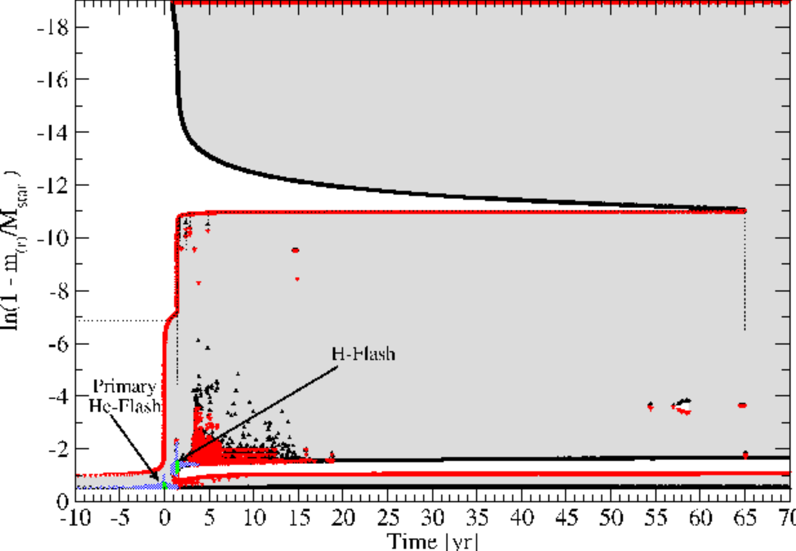


NGC2808
Dalessandro, Salaris et al. (2011)



Cassisi et al. (2003)

Time dependent mixing necessary

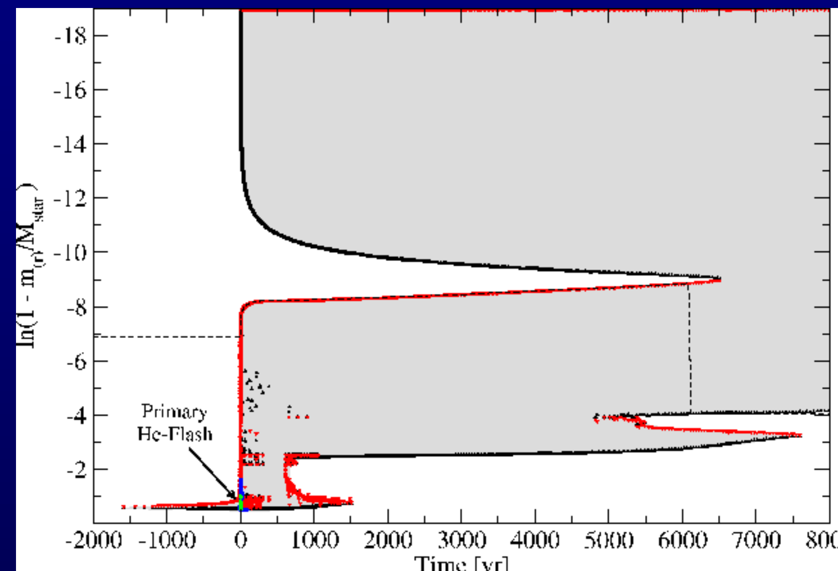


Deep mixing – H↓↓↓↓

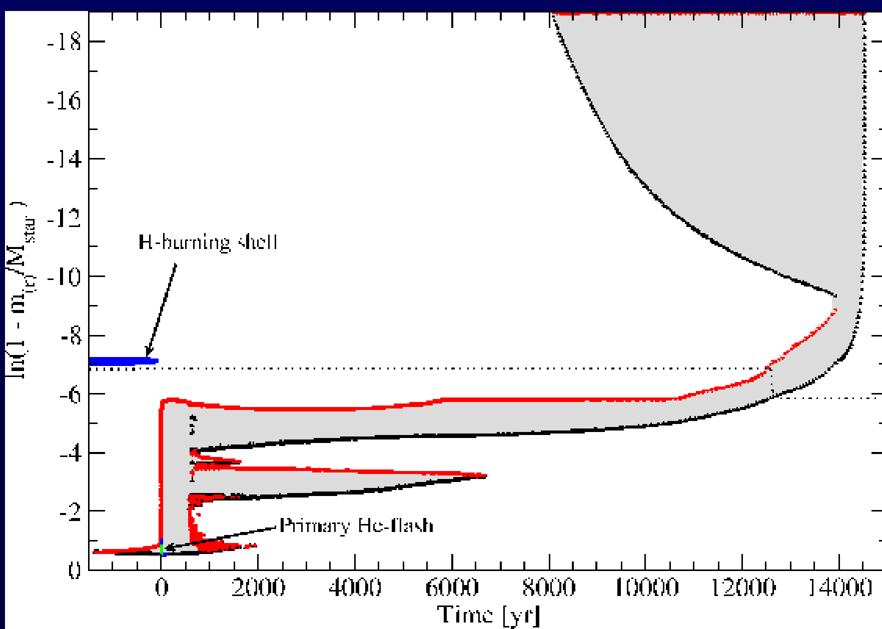
surface X ≈ 10^{-5}

Xc ≈ 0.05

Surface He and C increase



Shallow mixing
(slight CNO burning) – H↓↓
X=0.01-0.001   Xc ≈ 0.01



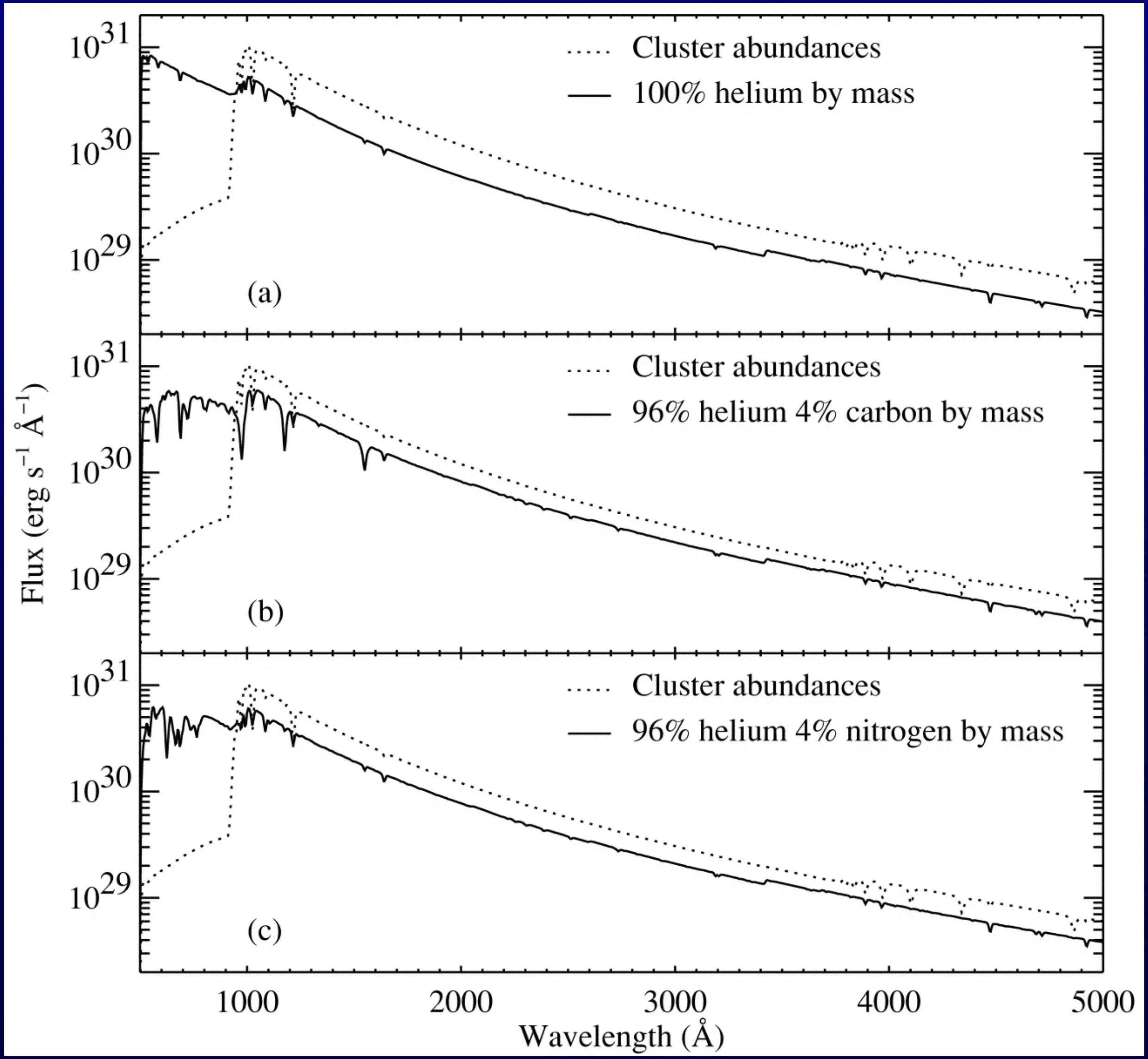
Shallow mixing (no CNO burning)-H↓   X~0.2
Xc ≈ 0.01

Mixing and burning timescales comparable

Miller Bertolami et al. (2008)

Hot flashers spectral energy distribution

Brown
et al.
(2001)



Time dependent mixing: An example

Treatment as a diffusion process

Herwig et al. (1997)

$$\frac{\mathrm{d}X_i}{\mathrm{d}t} = \left(\frac{\partial X_i}{\partial t}\right)_{\mathrm{nuc}} + \frac{\partial}{\partial M_r}\left[\left(4\pi r^2 \rho\right)^2 D \frac{\partial X_i}{\partial M_r}\right] \qquad (1)$$

$D_r = 0$ Radiative region

$D_c = 1/3 v_c l$ Convective region

$$D_{\mathrm{os}} = D_0 \exp\frac{-2z}{H_{\mathrm{v}}}, \quad D_0 = v_0 \cdot H_{\mathrm{p}}, \quad H_{\mathrm{v}} = f \cdot H_{\mathrm{p}}, \qquad (3)$$

Free parameter

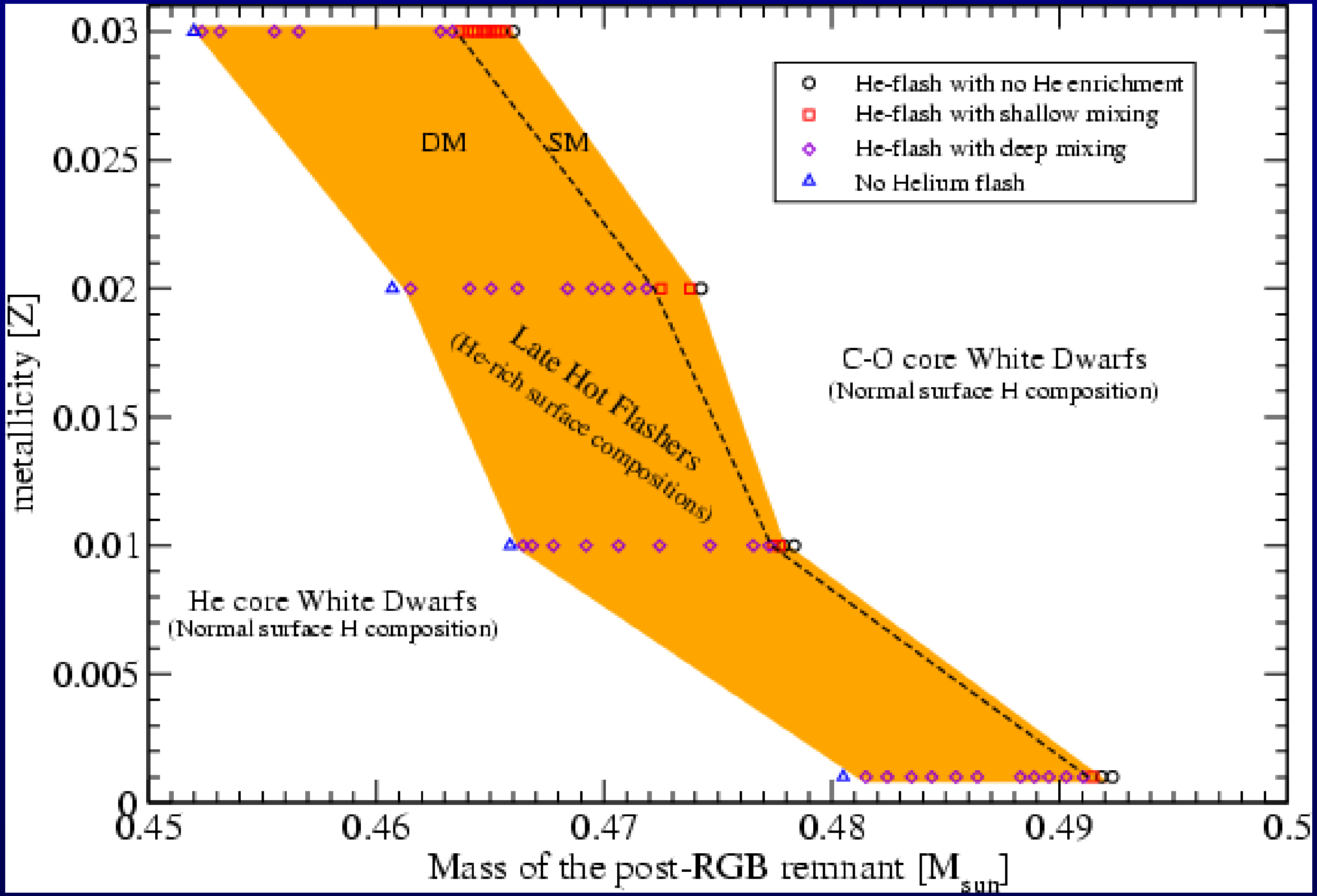
Overshooting

$f=0.02$

v_c , v_o from MLT

Following Freytag et al. (1996) hydro-simulations

Miller Bertolami et al. (2008)



Quantitative predictions depend on

RGB mass loss law

Treatment of convective boundaries

Treatment of time-dependent mixing

Interplay between diffusion/levitation and radiative winds

Typically, models predict too low H compared to observations

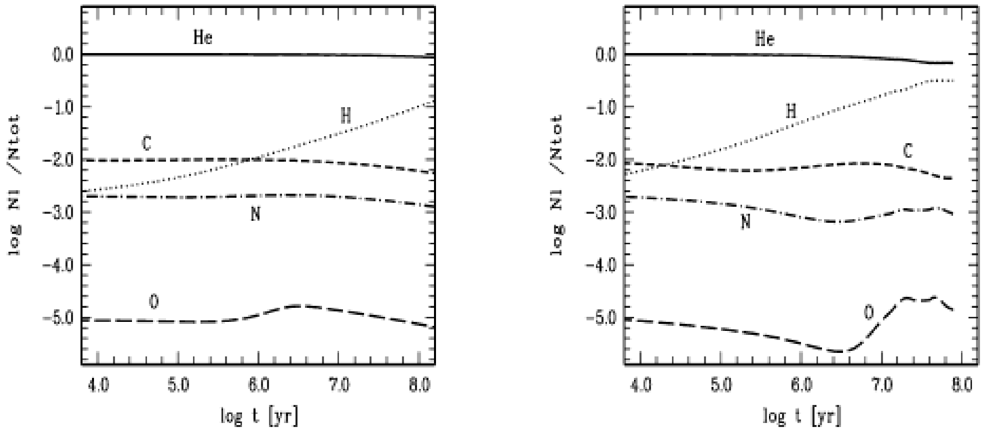


Figure 1. Predicted surface composition (number fractions) as a function of time for $\dot{M} = 10^{-13}\,M_\odot/yr$ (left figure) and $\dot{M} = 10^{-14}\,M_\odot/yr$ (right figure) and the initial composition from the deep mixing scenario.

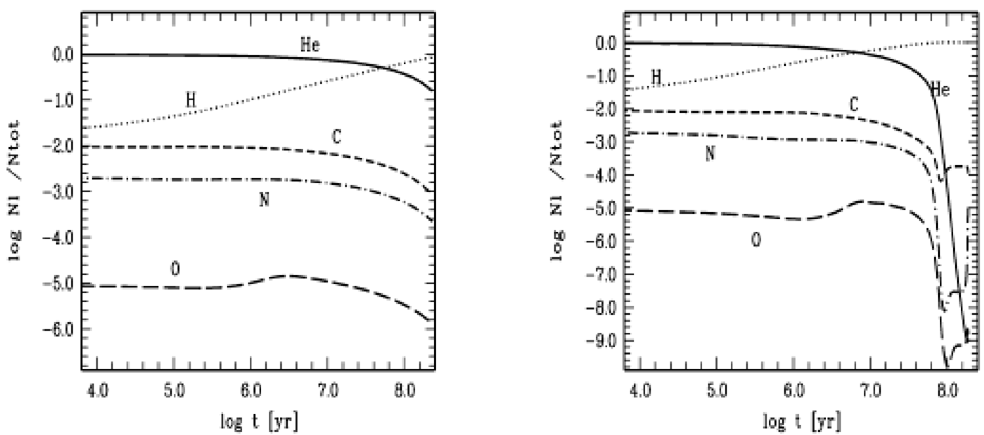


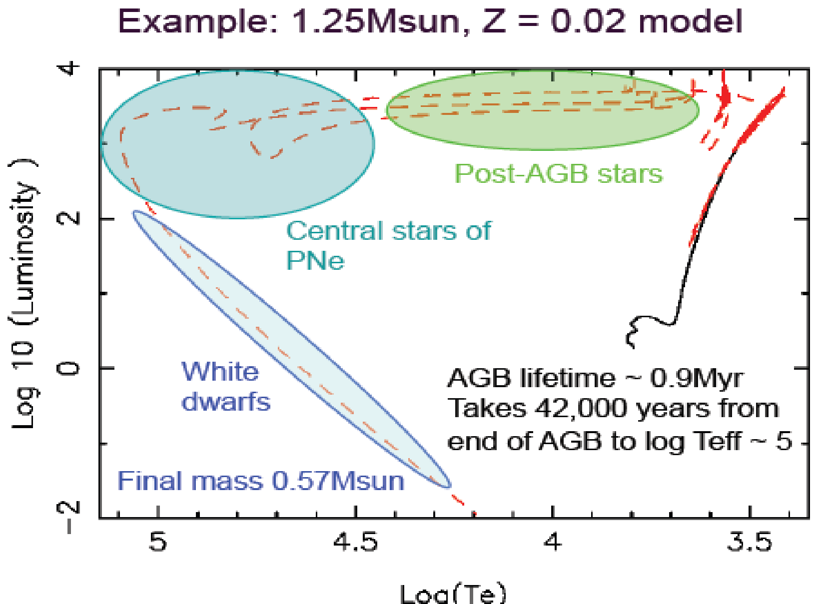
Figure 2. The same as Fig. 1 with an initial ratio of H/He increased by a factor of ten for $\dot{M} = 10^{-13}\,M_\odot/yr$ (left figure) and $\dot{M} = 2.5 \cdot 10^{-14}\,M_\odot/yr$ (right figure).

Teff=35000 K
log(g)=6.0

Unglaub (2005)

Post-AGB stars

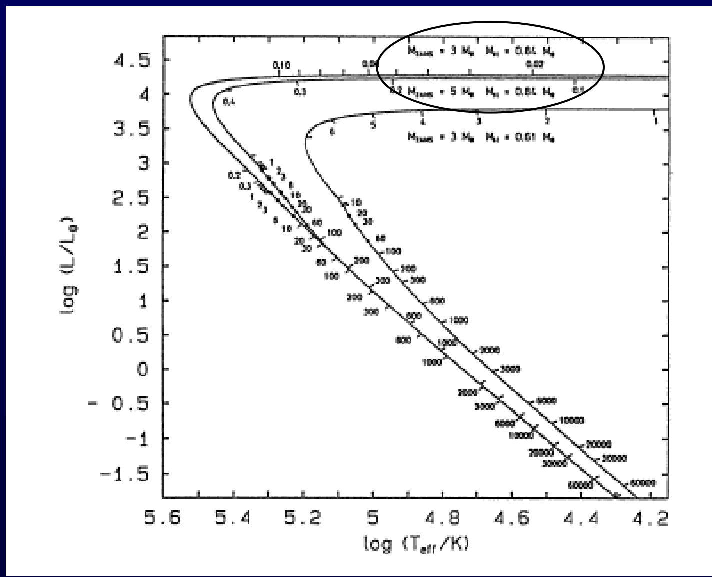
- Once the envelope mass drops below ~0.01Msun, the star leaves the AGB
- Evolves at almost constant luminosity toward hotter Teff
- Transition times very rapid (~100 years) for most massive objects → No PN
- Transition times ~10^4 years for low-mass objects
- Mass loss rates are low (~10^{-8} Msun yr^{-1})



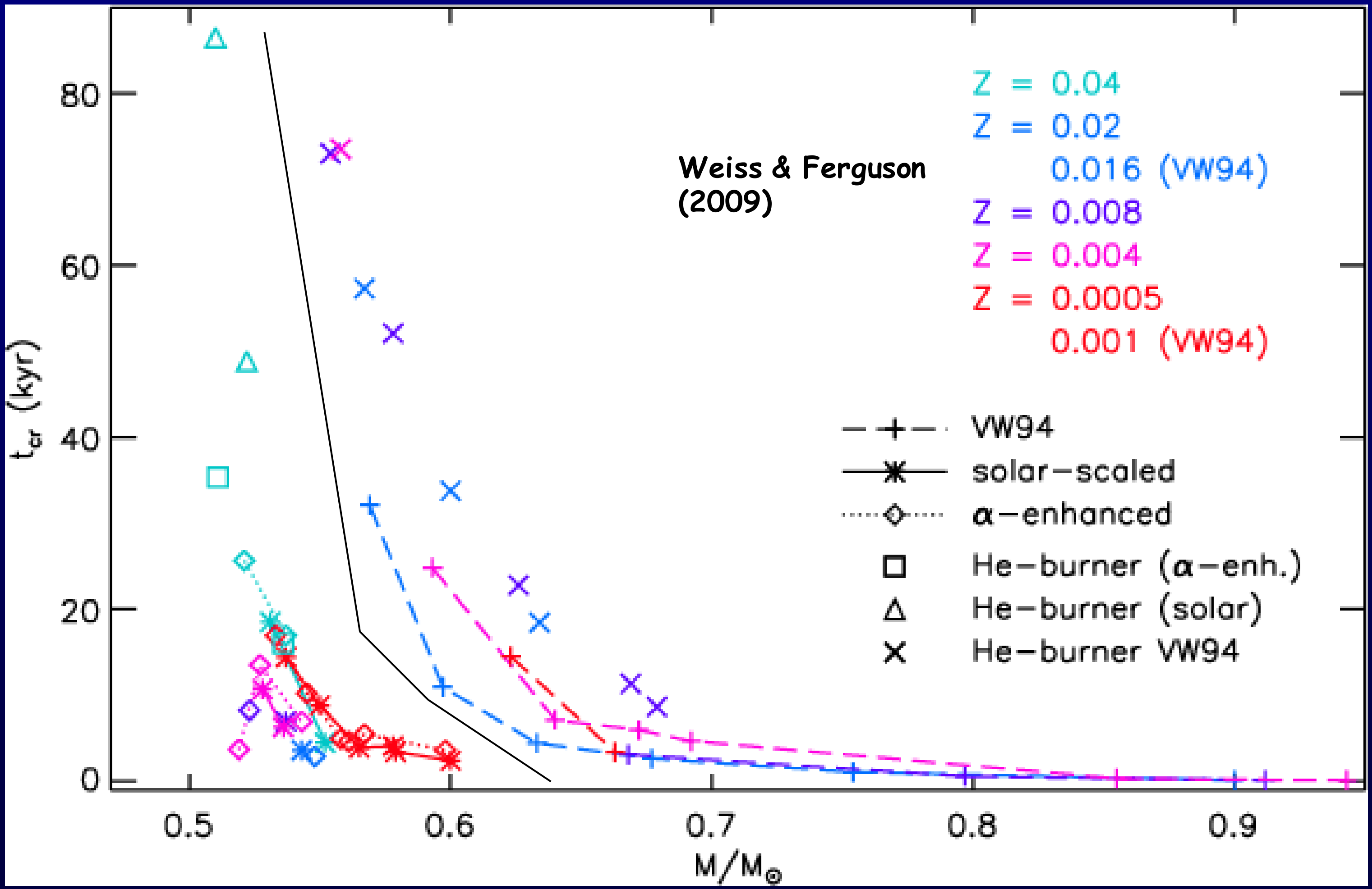
Larger envelope mass → slower evolution

H- or He-burners, depending on the moment they leave the AGB during the TP cycle

Transition times at fixed post-AGB mass depend on progenitor history (Bloecker 1995), because of the different T-P stratification.
Lower mass progenitor, faster transition



Post-AGB crossing time (T_{eff} from 10^4 to 10^5 K)



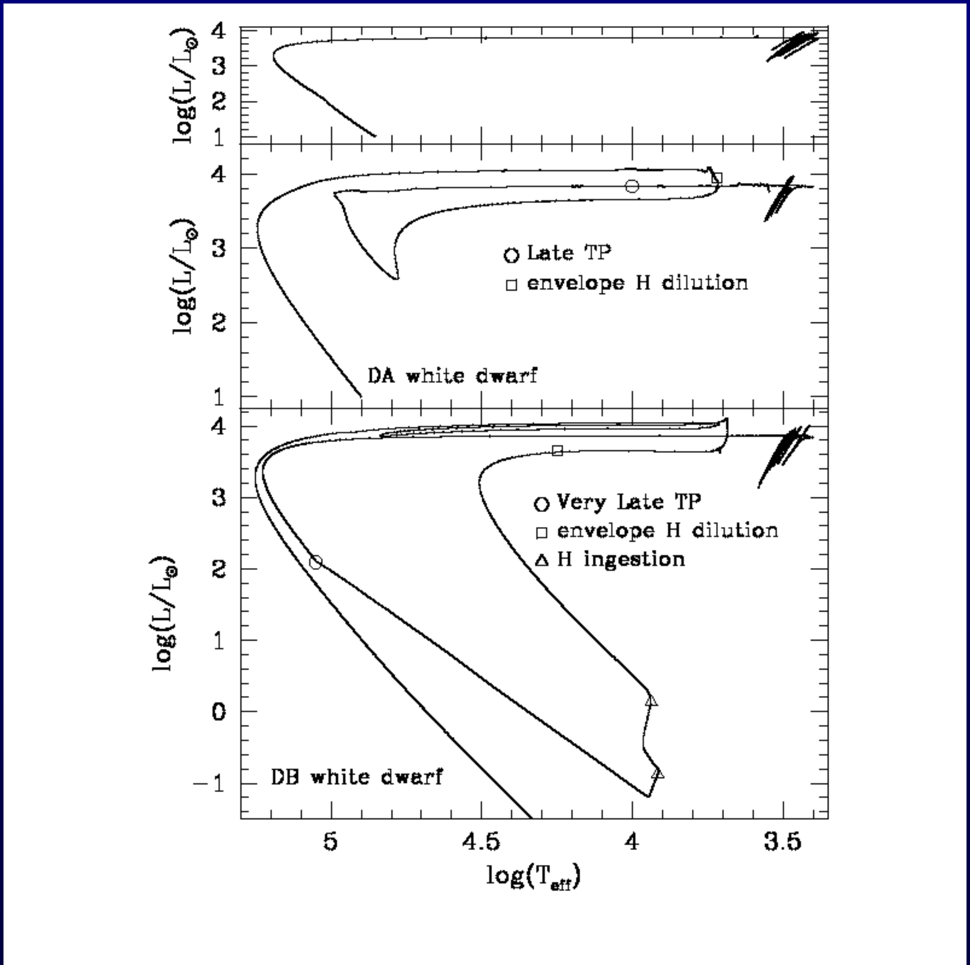
Late Thermal Pulse

Late-TP

No dredge-up expected unless high mass loss and/or some overshooting. At most some dilution of H

Very late TP

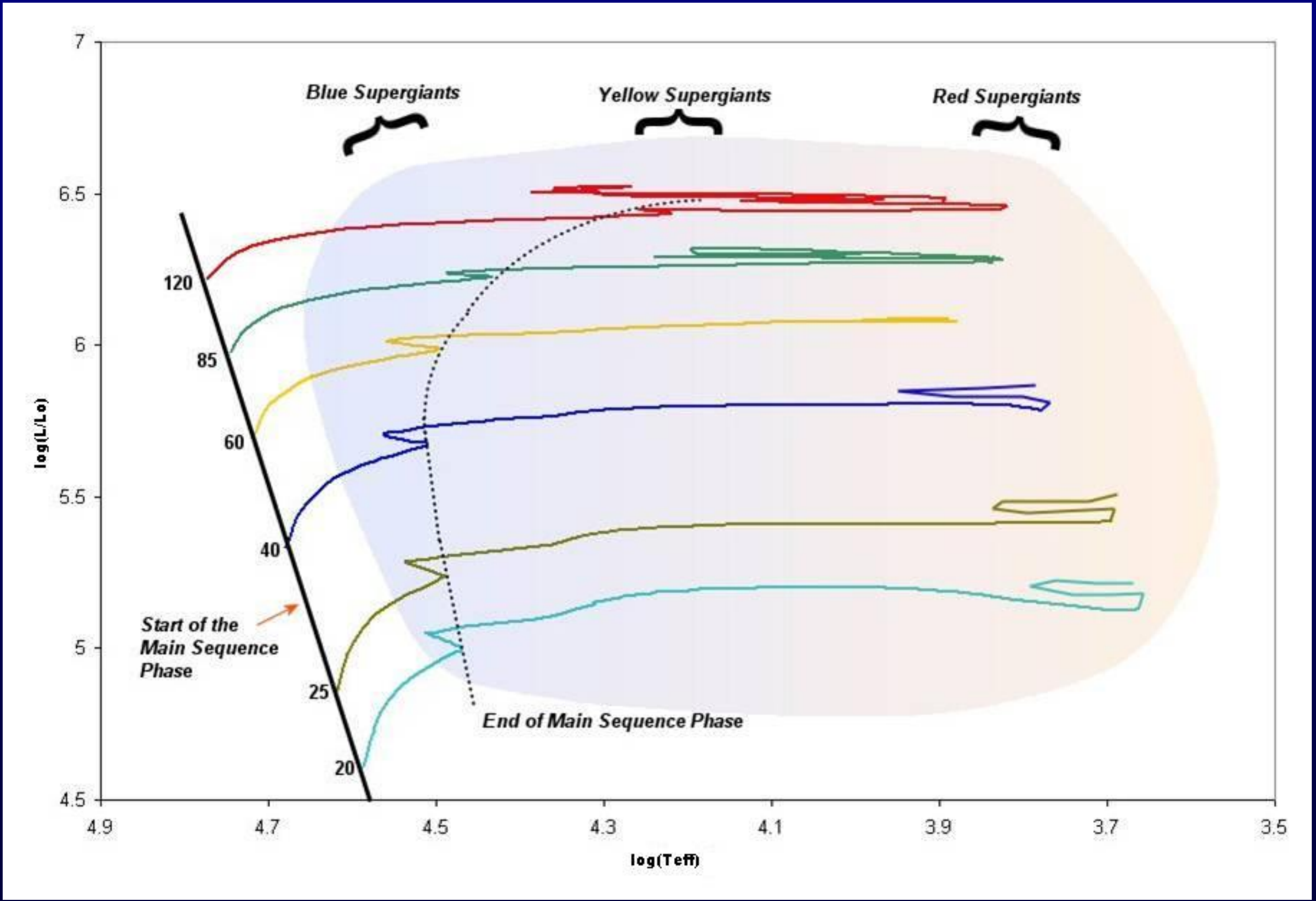
Similar to hot flasher scenario
Surface H depletion,
enrichment of C and O



Timescale of VLTP evolution depend on efficiency of mixing (Herwig 2001)

Cassisi & Salaris (2013)

High mass stars



Semiconvection in massive stars

$$\nabla_{ad} < \nabla_T < \nabla_L$$

Layer stable according to Ledoux criterion but unstable according to Schwarzschild criterion

$$\nabla_L \equiv \nabla_{ad} + B$$

$$B = \frac{\varphi}{\delta}\nabla_\mu$$

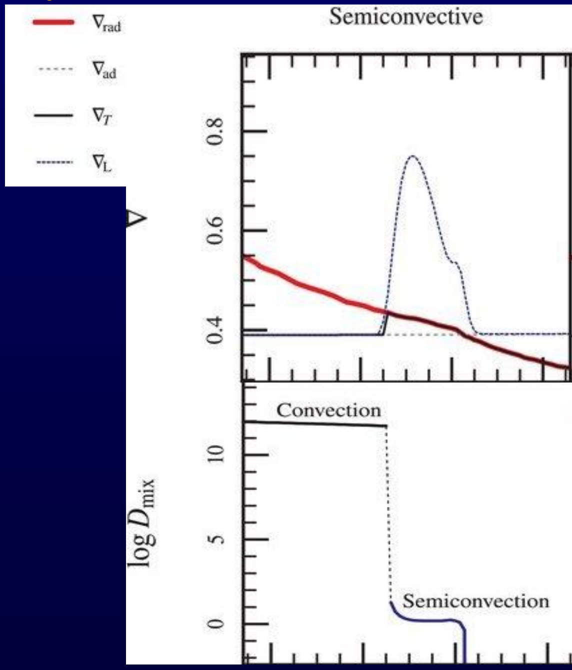
$$\delta := -\left(\frac{\partial \ln \rho}{\partial \ln T}\right)_{\mu,P}, \quad \varphi := \left(\frac{\partial \ln \rho}{\partial \ln \mu}\right)_{P,T}$$

Mixing usually treated as a diffusive process

$$D_{sc} = \alpha_{sc}\left(\frac{K}{6C_P\rho}\right)\frac{\nabla_T - \nabla_{ad}}{\nabla_L - \nabla_T}$$

Free parameter

Diffusion coefficient according to Langer et al. (1983)



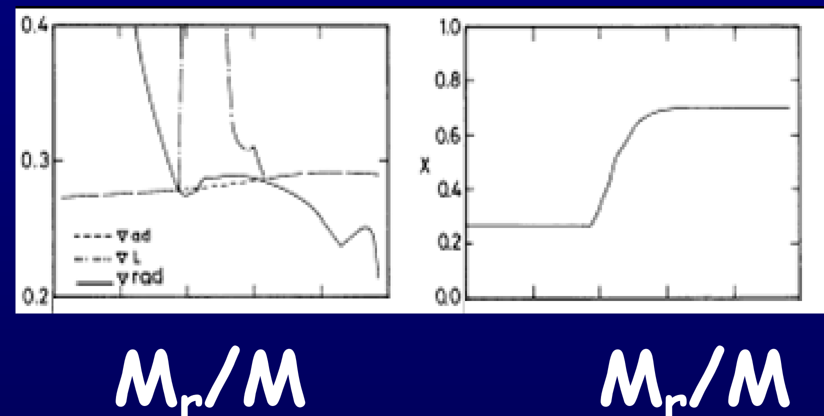
Semiconvection in massive stars

Langer et al. (1983)

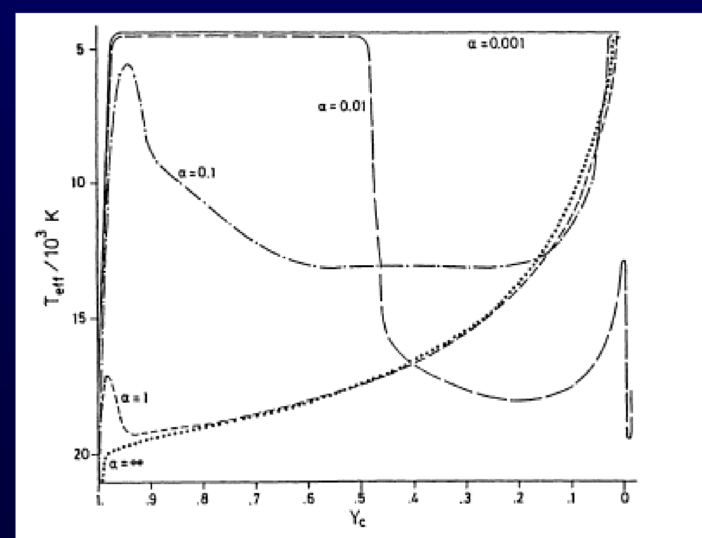
Convective mixing outside the central H-burning core following the end central H-depletion.

30 M_o

$$D_{\rm sc} = \alpha_{\rm sc} \left(\frac{K}{6 C_P \rho} \right) \frac{\nabla_T - \nabla_{\rm ad}}{\nabla_{\rm L} - \nabla_T}$$



$20\, M_\odot \quad Z = 0.25\, Z_\odot$						
α	M_{He}	$M_{C/O}$	C_c	$\%\tau_{He}$ blue	$\%\tau_{He}$ red	$T_{eff,expl.}$
∞	6.71	4.69	0.06	99	1	4500
1.0	6.73	4.67	0.06	99	1	4500
0.1	6.79	3.03	0.05	99	1	4500
0.01	6.27	2.21	0.15	50	50	17000
0.001	6.01	2.00	0.19	0	100	4500



The presence of a fully mixed shell favours a blue He ignition

Decreasing efficiency of mixing → He ignition increasingly to the red

The B/R ratio of supergiants can in principle be used to calibrate the efficiency of mixing in semiconvective regions (Langer & Maeder 1995)

Rotation of massive stars

Shellular rotation	⇒	ω and c.c. constant on an isobar
Roche approximation	⇒	mass centrally concentrated
Equivalent volumes	⇒	Adoption of the radii of the equivalent spheres

Strong horizontal turbulence
(Zahn 1992)

Standard 1D stellar evolution equations with the addition of 'form factors' (Kippenhahn & Thomas 1970).
Radius of the sphere the encloses the same volume as the corresponding isobar
Thermodynamic quantities are mean values over an isobar

$$\rho \frac{\partial X_i}{\partial t}\Big|_{M_r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho r^2 D_{\mathrm{chem}}\frac{\partial X_i}{\partial r}\right)$$

Chemical element transport

advection

$$\rho \frac{\partial}{\partial t}(r^2\bar{\Omega})_{M_r} = \boxed{\frac{1}{5r^2}\frac{\partial}{\partial r}(\rho r^4 \bar{\Omega} U_2(r))} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho D_{\mathrm{ang}} r^4 \frac{\partial\bar{\Omega}}{\partial r}\right)$$

Angular momentum transport

Ω=angular velocity on an isobar

U_2=radial component of the meridional circulation velocity

Meridional circulation

Large scale motion of matter (gravity and T on an equipotential surface vary with latitude) that transports chemicals and angular momentum

Shear (horizontal D_h , vertical D_{shear})

Generated by angular velocity variations with depth in radiative regions

$$D_{chem} = D_{shear} + D_{eff}$$

$$\rho \frac{\partial X_i}{\partial t}\bigg|_{M_r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\, r^2 D_{\mathrm{chem}} \frac{\partial X_i}{\partial r}\right)$$

$$D_{\mathrm{eff}} = \frac{1}{30}\frac{|r\,U(r)|^2}{D_{\mathrm{h}}}.$$

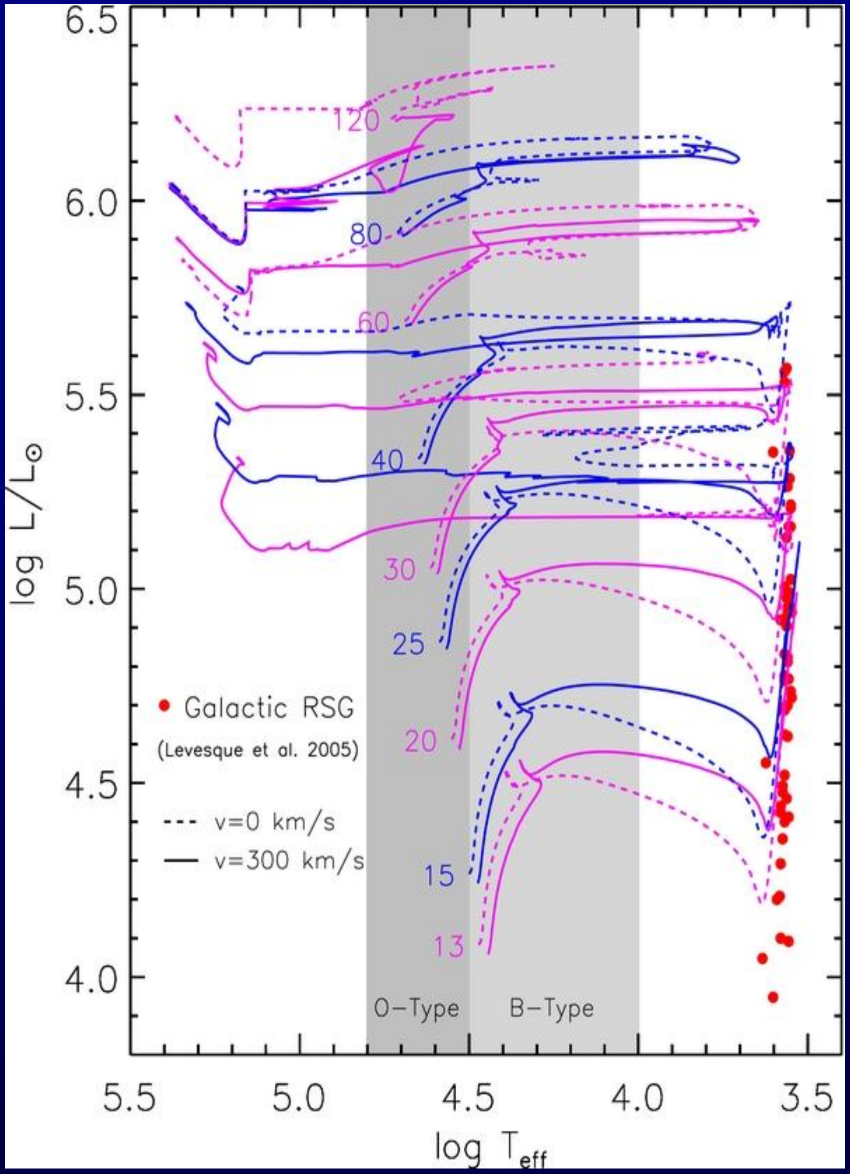
Meridional circulation

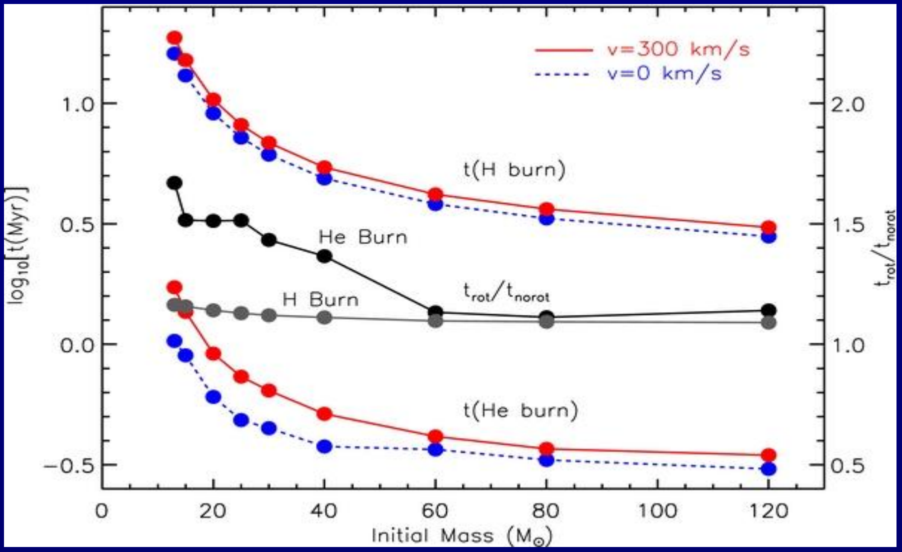
Horizontal diffusion

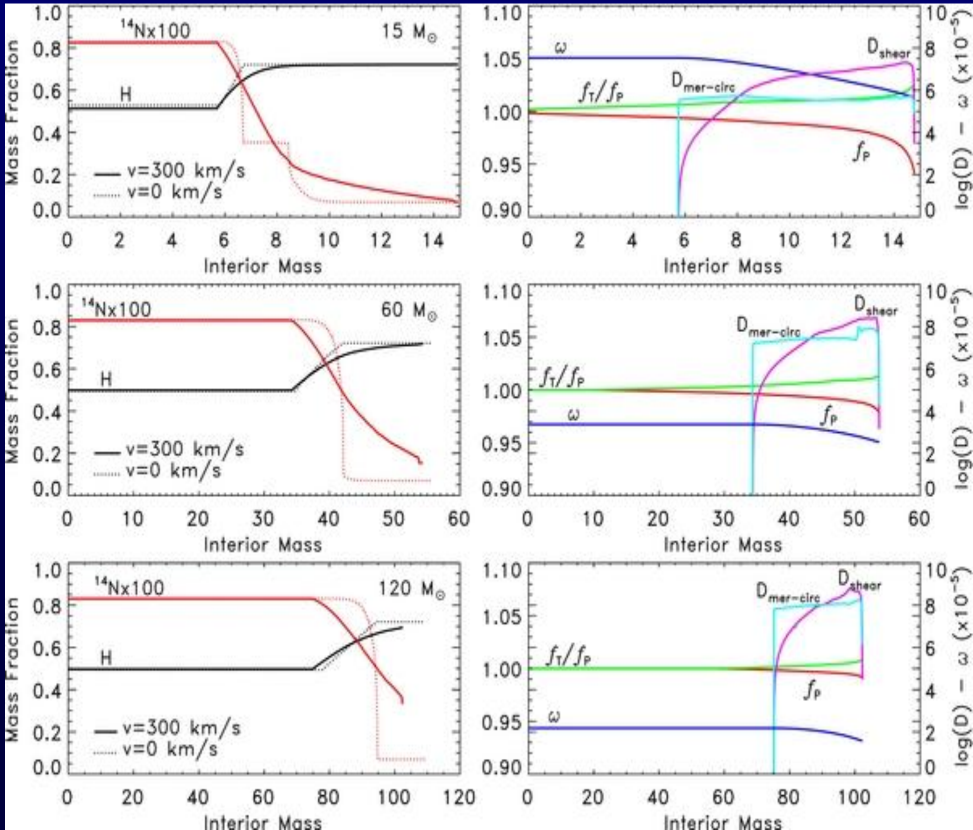
$$\rho \frac{\partial}{\partial t}(r^2\bar{\Omega})_{M_r} = \frac{1}{5r^2}\frac{\partial}{\partial r}(\rho\, r^4 \bar{\Omega}\, U_2(r)) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\, D_{\mathrm{ang}}\, r^4 \frac{\partial \bar{\Omega}}{\partial r}\right)$$

$$D_{ang} = D_{shear}$$

Meridional circulation (radial component)

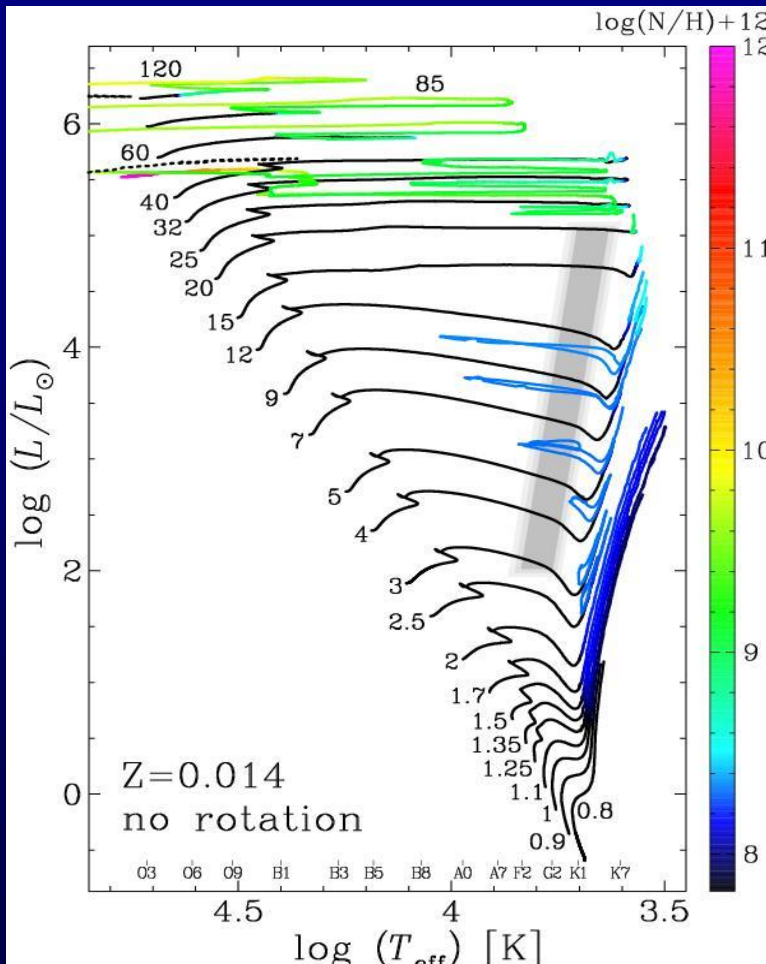




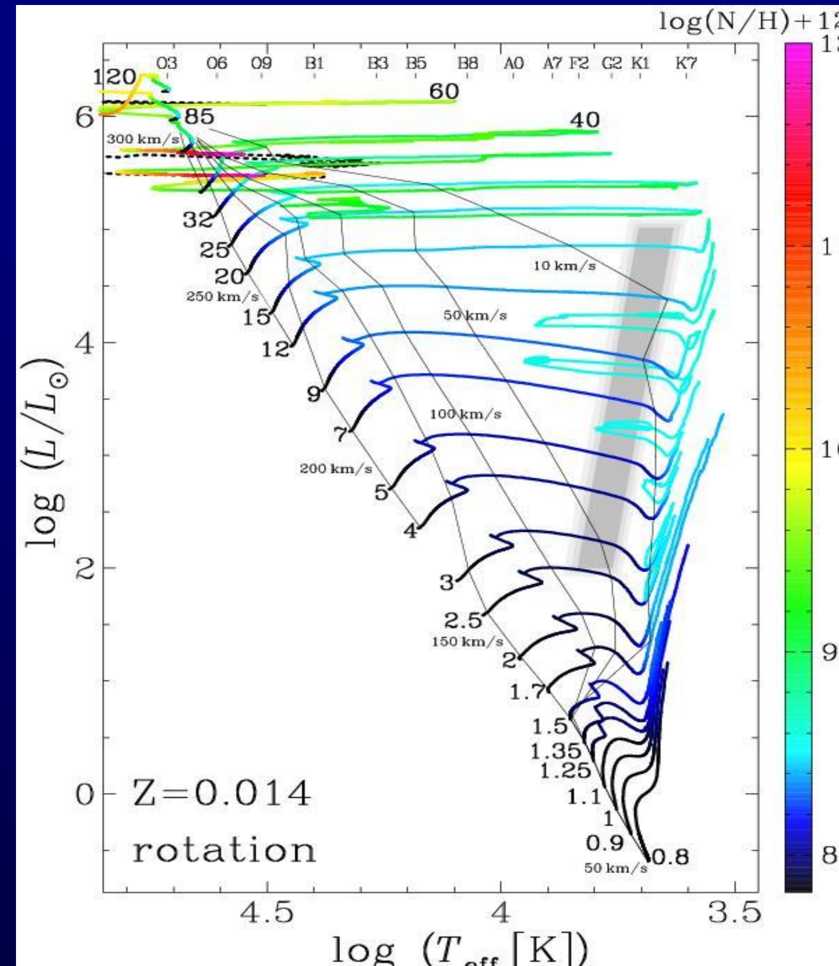


Chieffi & Limongi (2013)

Surface N-enhancement



Mass loss
Dredge up



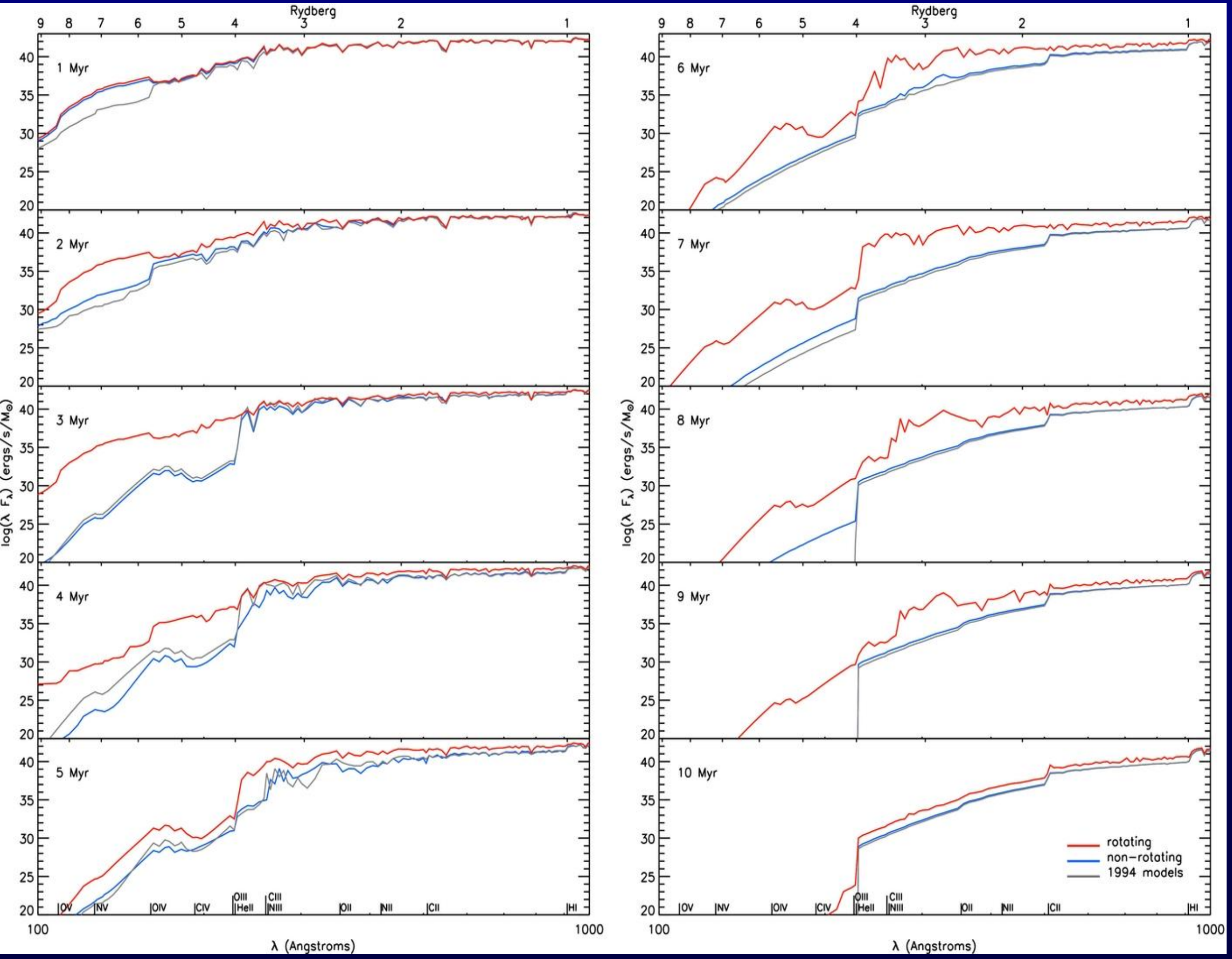
Rotational mixing
Mass loss
Dredge up

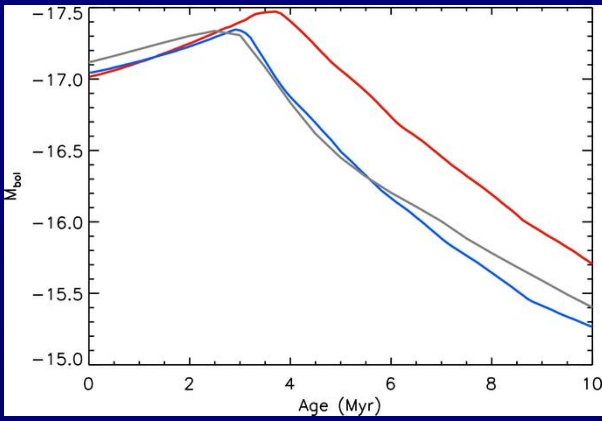
Ekstroem et al. (2012)

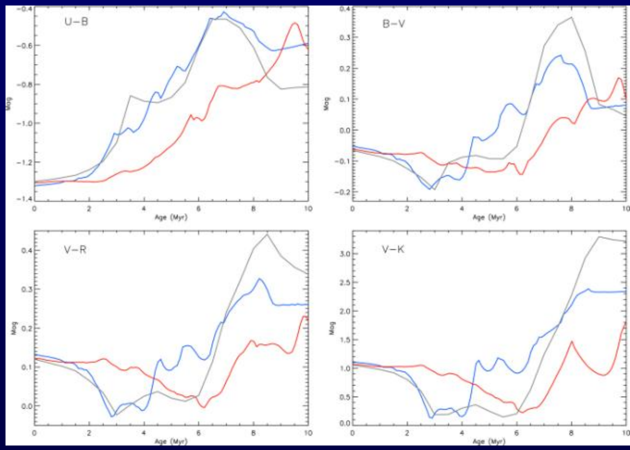
Effect of rotation on far-UV integrated fluxes

V_{ini}=0.4 V_{cr}

Broadband colours and bolometric magnitudes





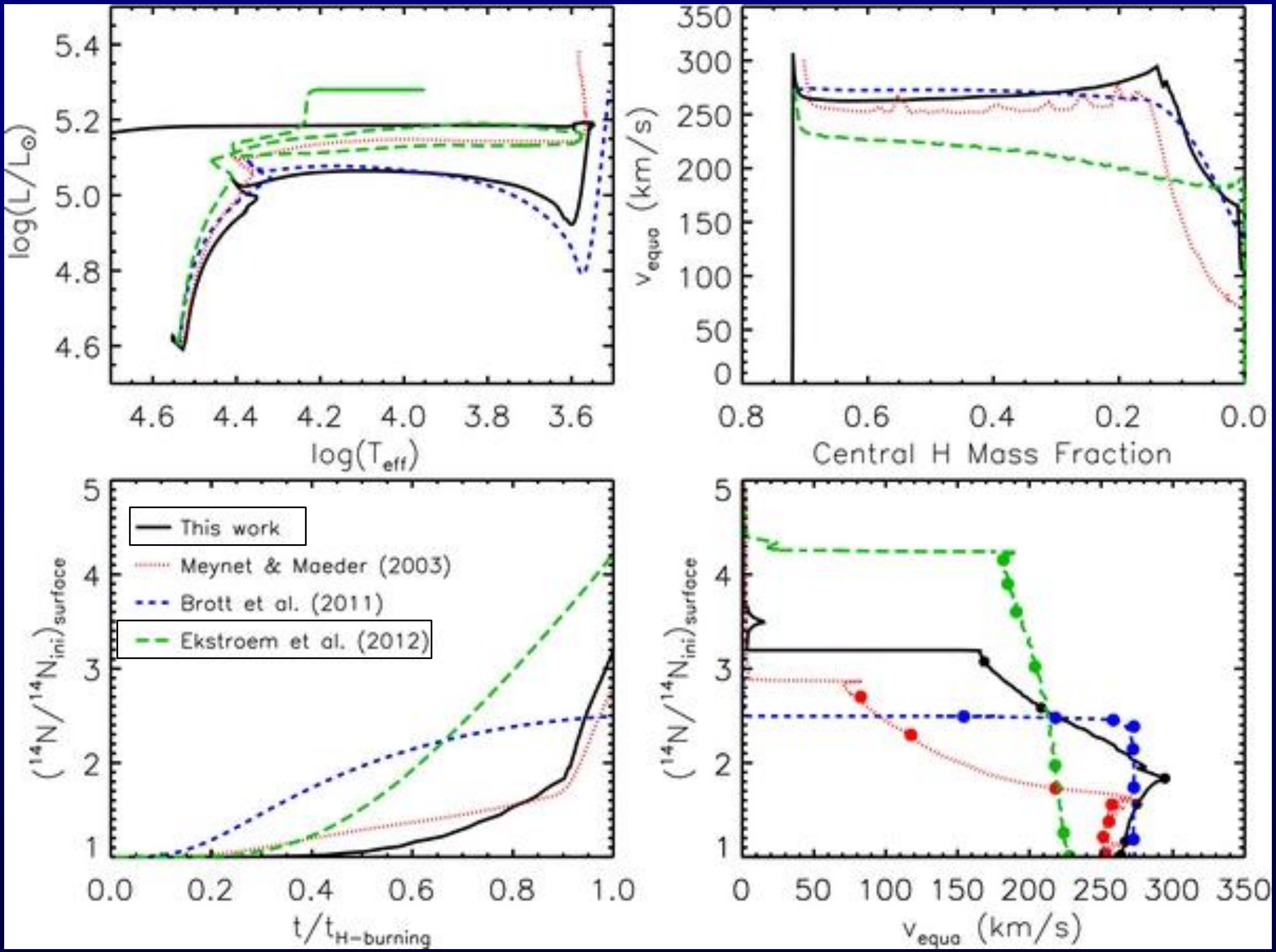


Levesque et al. (2012) based on rotating and non rotating models by Ekstroem et al. (2012)

The spectrum of a rotating star is actually a composite spectrum made up of local atmospheres of varying g and T_{eff}.

Different authors..... different results

Chieffi & Limongi (2013)



$20M_{\odot}$

Effect of different angular momentum and chemical diffusion efficiencies

$$D_{chem} = D_{shear} + D_{eff}$$

$$\rho \frac{\partial X_i}{\partial t}\bigg|_{M_r} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\, r^2 D_{\rm chem}\frac{\partial X_i}{\partial r}\right)$$

$$D_{\rm eff} = \frac{1}{30}\frac{|r\,U(r)|^2}{D_{\rm h}}.$$

Meridional circulation

Horizontal diffusion

$$\rho\frac{\partial}{\partial t}(r^2\bar{\Omega})_{M_r} = \frac{1}{5r^2}\frac{\partial}{\partial r}(\rho\, r^4\bar{\Omega}\,U_2(r)) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(\rho\, D_{\rm ang}\, r^4\frac{\partial\bar{\Omega}}{\partial r}\right)$$

$$D_{ang} = D_{shear}$$

Meridional circulation (radial component)

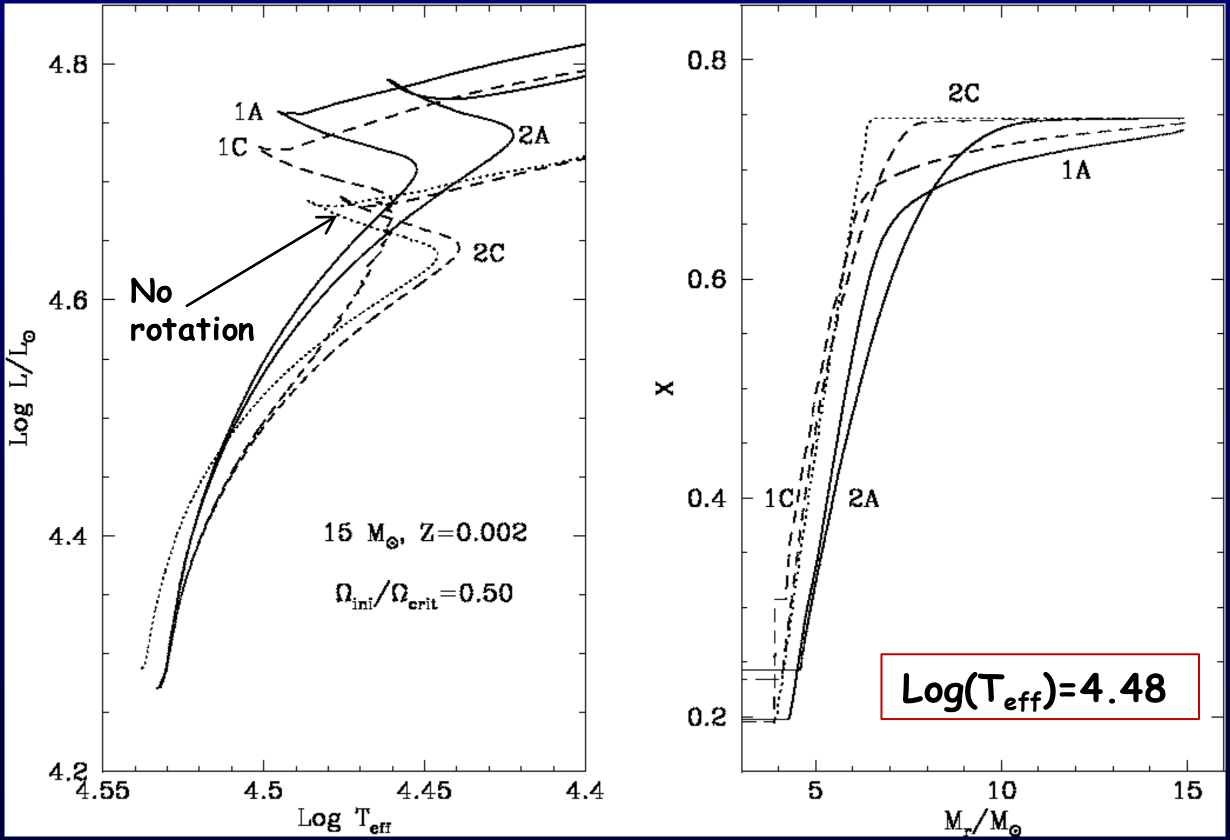
Meynet et al. (2013)

Different combinations of:

i) Two prescriptions for vertical shear diffusion coefficient D_{shear} (1 and 2)
ii) Three prescriptions for horizontal shear diffusion, D_h (A, B, C)

D_h controls the efficiency of mixing in regions with strong μ gradients (e.g. The edge of convective H-core during MS)

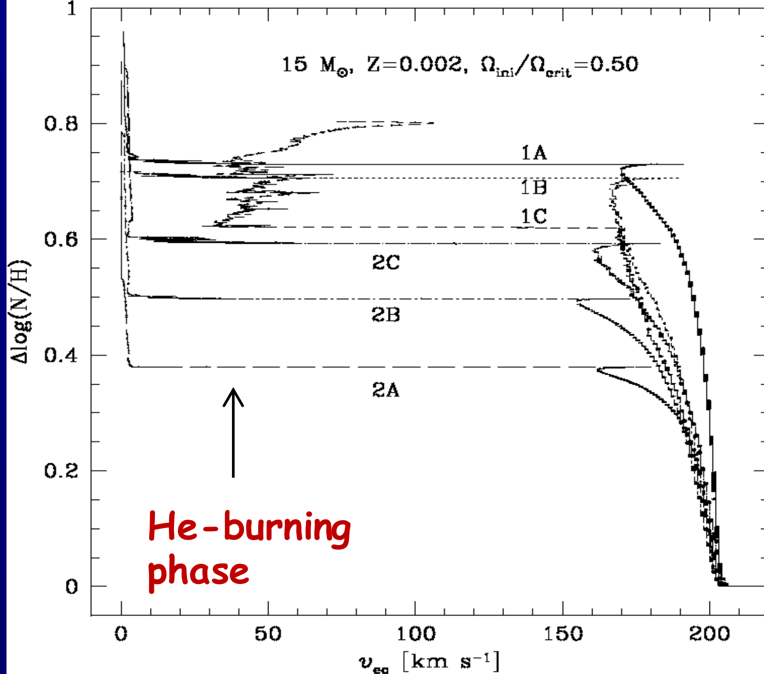
D_{shear} controls the efficiency of mixing in regions with weak or vanishing μ gradients



MS lifetimes vary within ~ 15%, comparable to the effect of neglecting rotation

Meynet et al. (2013)

Evolution of surface N/H ratio

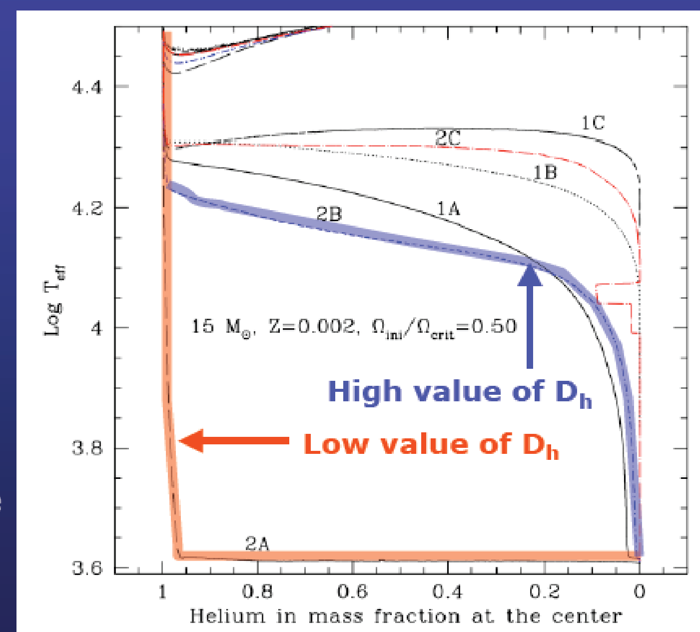


The outputs most affected by these different prescriptions are the shape of evolutionary tracks, blue-to-red evolution, surface enrichments.

The evolution of core angular momentum and surface velocities are marginally affected

- Impact of horizontal turbulence
  - Example: The problem of the B/R ratio
  - Observations: B/R decreases when Z decreases
  - Standard models: B/R increases when Z decreases

B/R ratio is very sensitive to the value of D_h

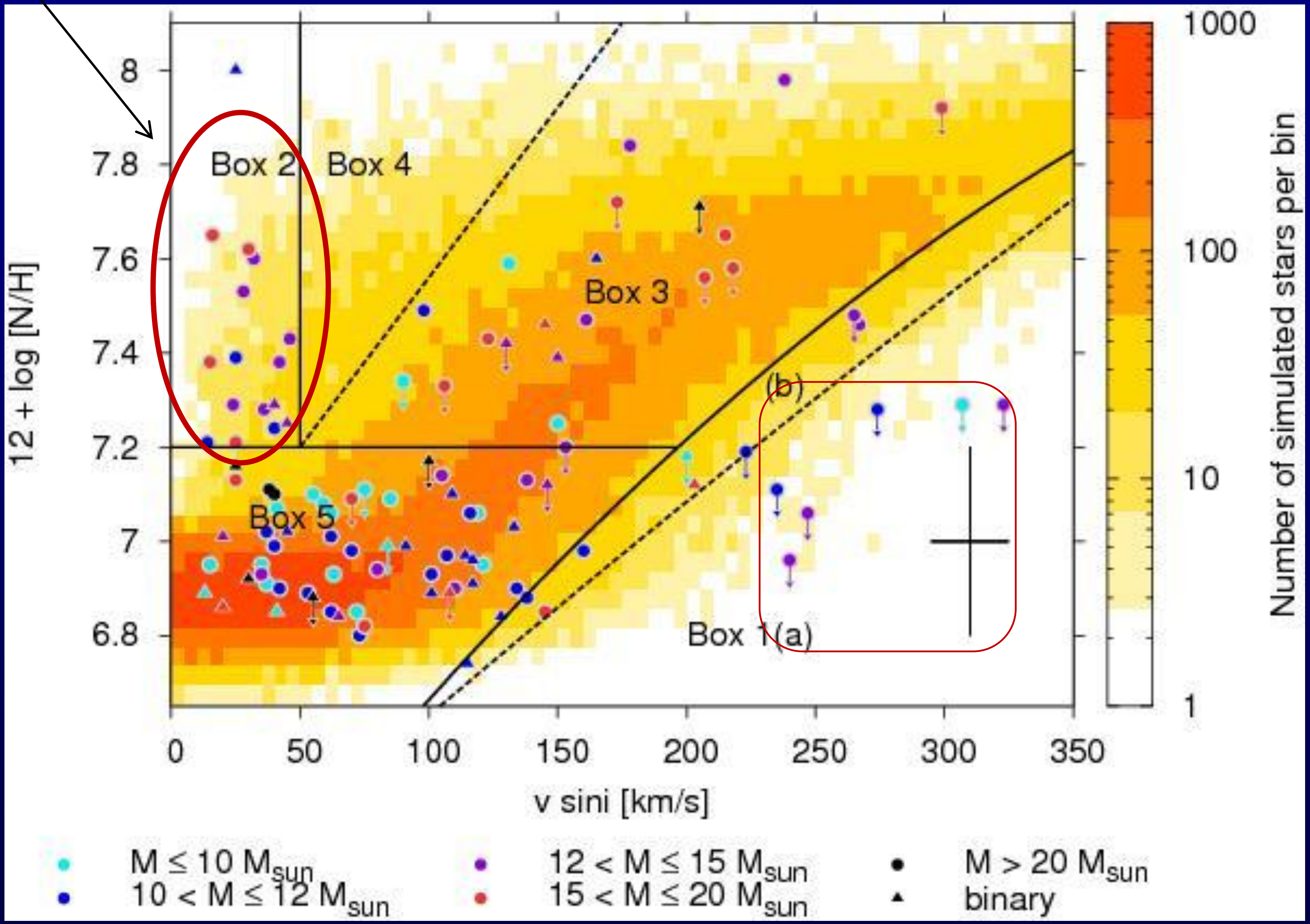


Meynet et al. 2013

Sample of LMC B-stars

(VLT-FLAMES observations – Hunter et al. 2009)

16 objects



About 100 observed stars

Brott et al. (2011)

EPILOGUE

We are still left with the long standing open problems of how to treat hydrodynamical processes in the stellar regime (element and angular momentum transport, efficiency of atomic diffusion+levitation, mass loss)

More accurate observations are needed (as calibrators), but in parallel strong theoretical advances are necessary to boost the 'quantitative' predicting power of the stellar models.

Synergy of:
i) analytical developments based on 'scaling' results from lab-experiments, meteorology, oceanography
ii) numerical simulations of treatable phenomena, restricted to small stellar regions