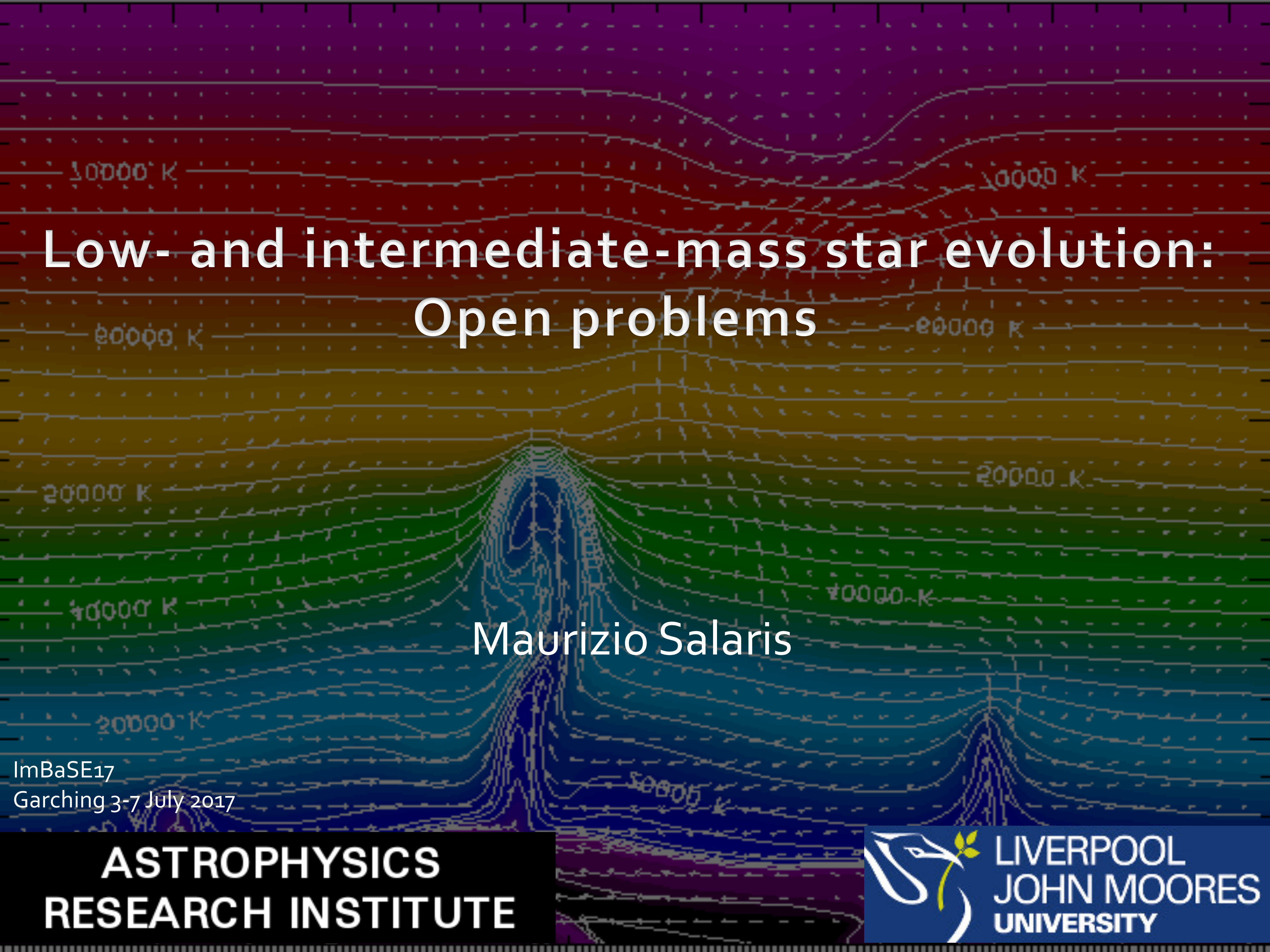

Low- and intermediate-mass star evolution: Open problems

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ImBaSE17
Garching 3-7 July 2017

ASTROPHYSICS RESEARCH INSTITUTE

LIVERPOOL JOHN MOORES UNIVERSITY

How accurately can we predict radii, effective temperatures, chemical stratification (hence surface abundances and evolutionary timescales) of low-intermediate-mass stars?

Convection

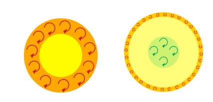
Thermohaline mixing

Element transport in radiative regions

Mass loss

CONVECTION

i) How extended is the mixing region beyond the formal convective border (convective boundary mixing -CBM)?



Instantaneous mixing in this region?
Diffusive mixing (following Freytag et al. 1996)?

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

with

$$D_{\rm ov} = D_{\rm c} \exp\left(-\frac{2z}{f{\rm H_p}}\right)$$

$$D_{\rm c} = (1/3)\alpha_{MLT} v_{\rm c} H_P$$

ii) What is the temperature gradient in this CBM region? Adiabatic (overshooting) or radiative (penetration)?

iii) How do we reduce to zero the extension of the CBM region when convective core masses approach zero?

iv) What is the temperature gradient in surface convective regions?

Choices made affect evolutionary times (star counts), luminosities, T_{eff}, loops in the Colour-Magnitude-Diagrams, predicted populations of variable stars in stellar populations, chemical profiles, asteroseismic properties.

Helium burning core mixing

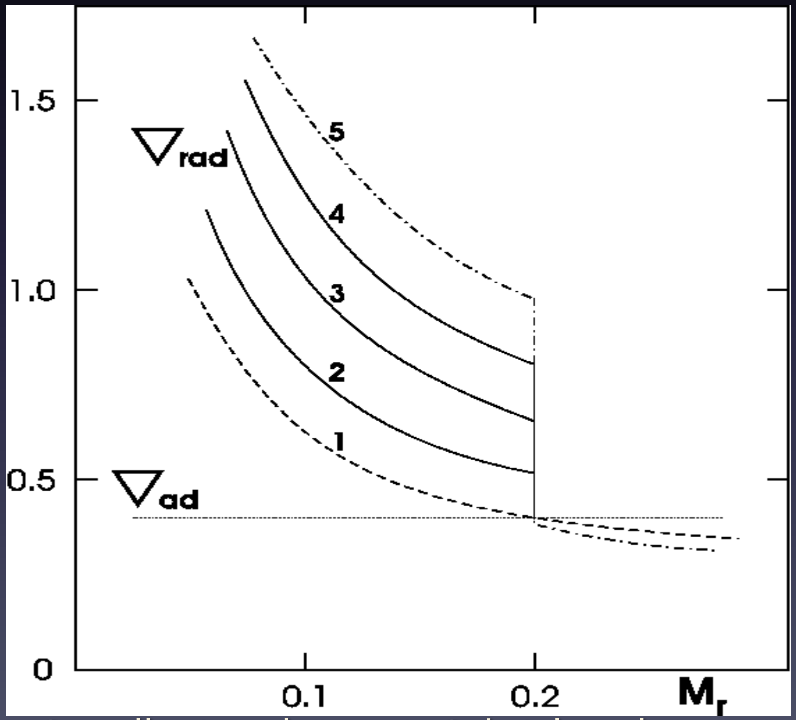
Core Expansion

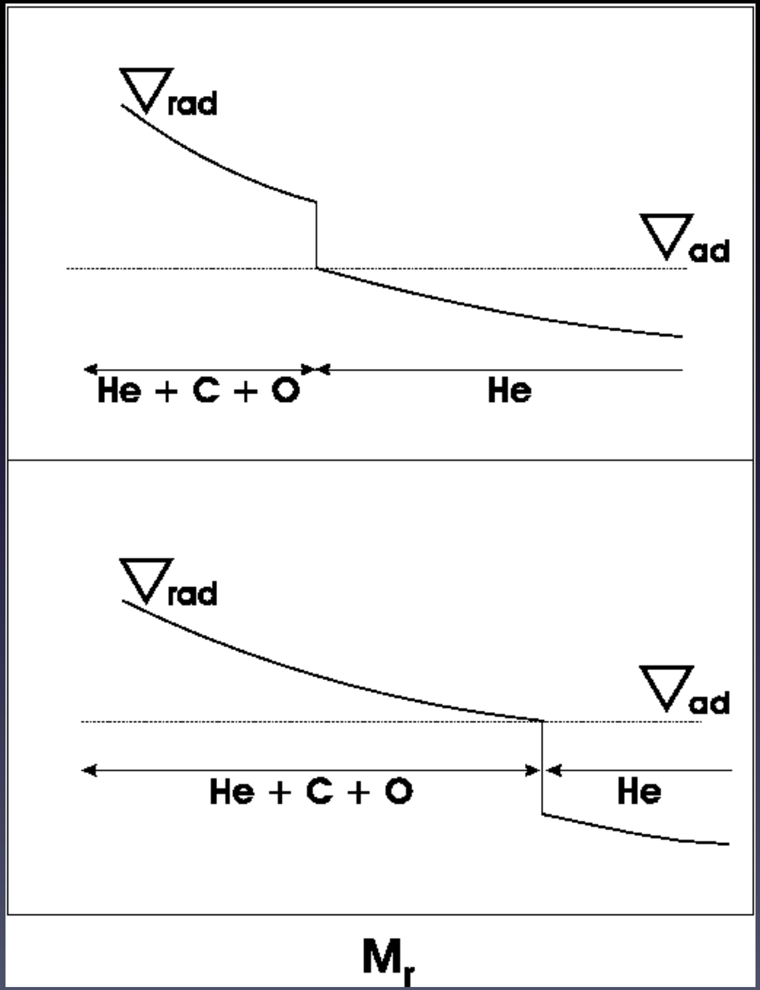
Mass of fully mixed core increases

C produced by He-burning

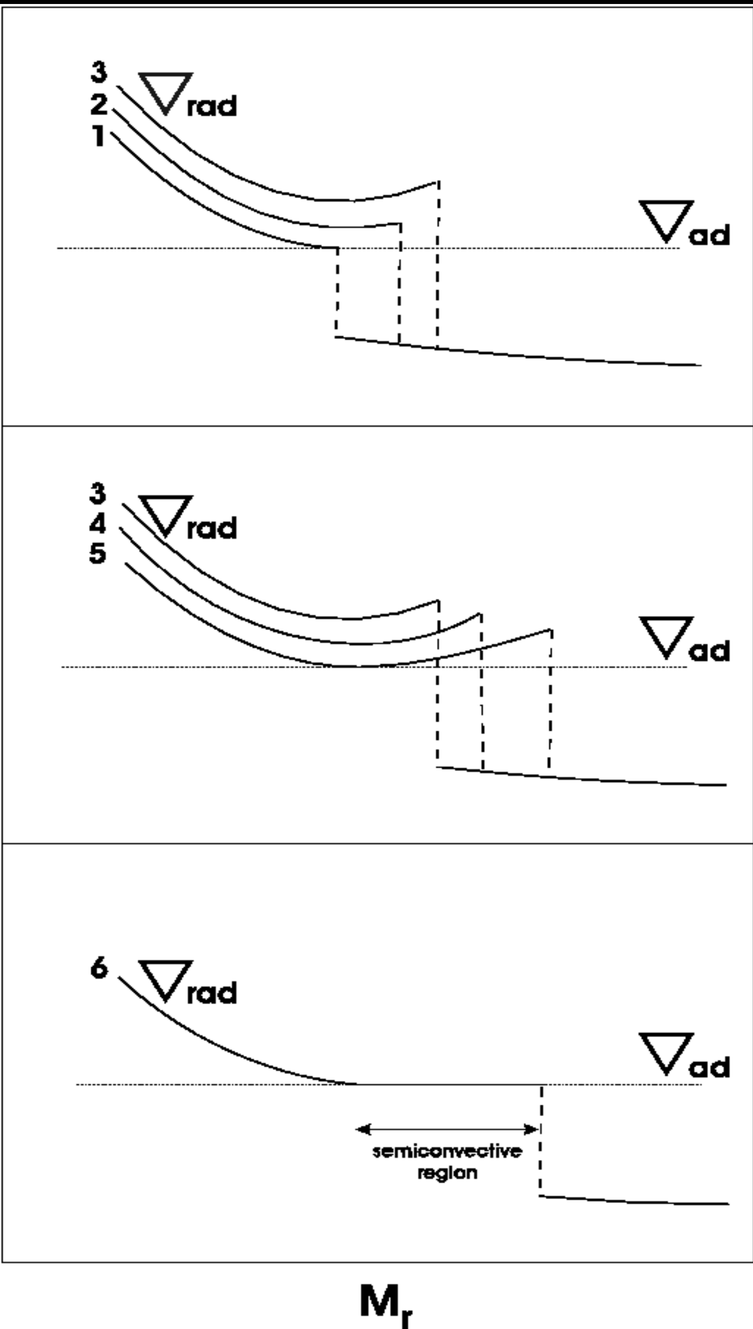
Opacity increases $F_c \approx \nabla_{rad} - \nabla_{ad}$

Radiative gradient discontinuity at the convective core boundary





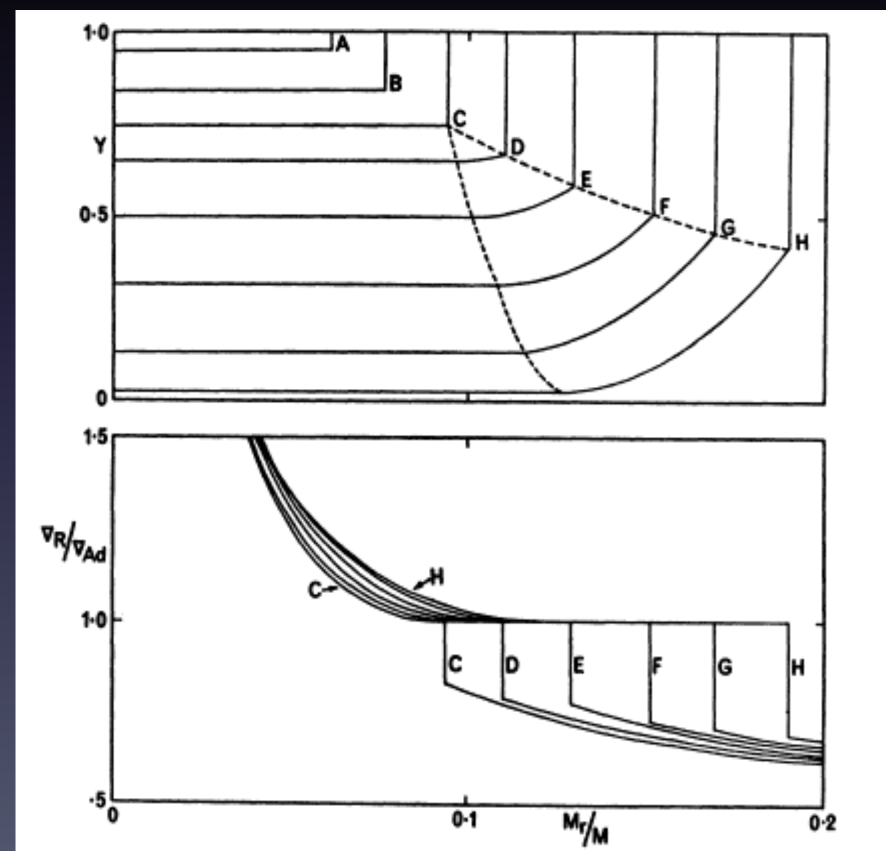
See, e.g. Castellani et al. (1971), Gabriel et al. (2015)



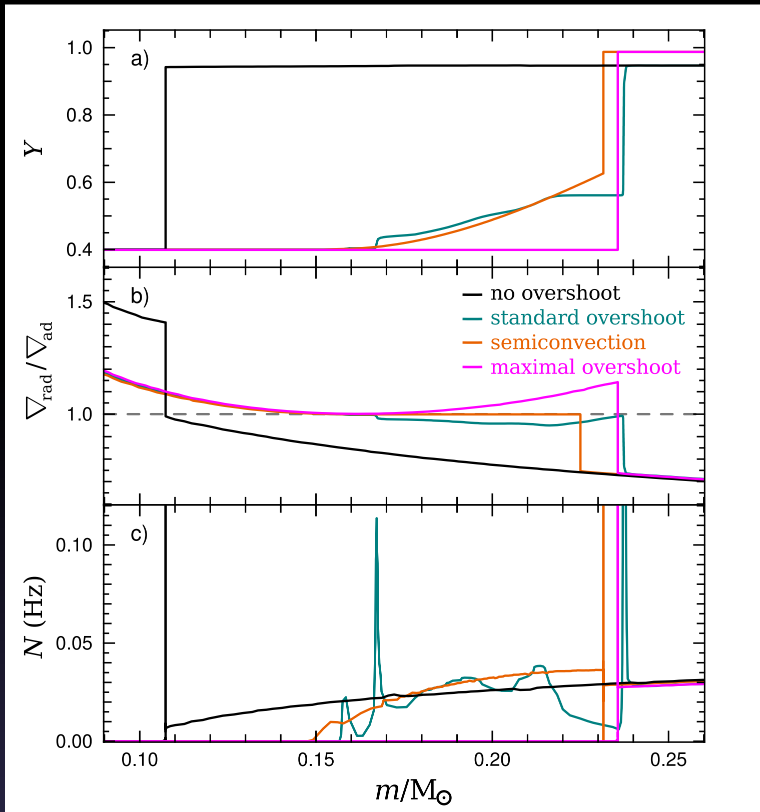
What happens now?

When Y_c decreases below ~0.7, a ‘partial mixing’ may be invoked beyond the boundary of the convective core (called semiconvection).

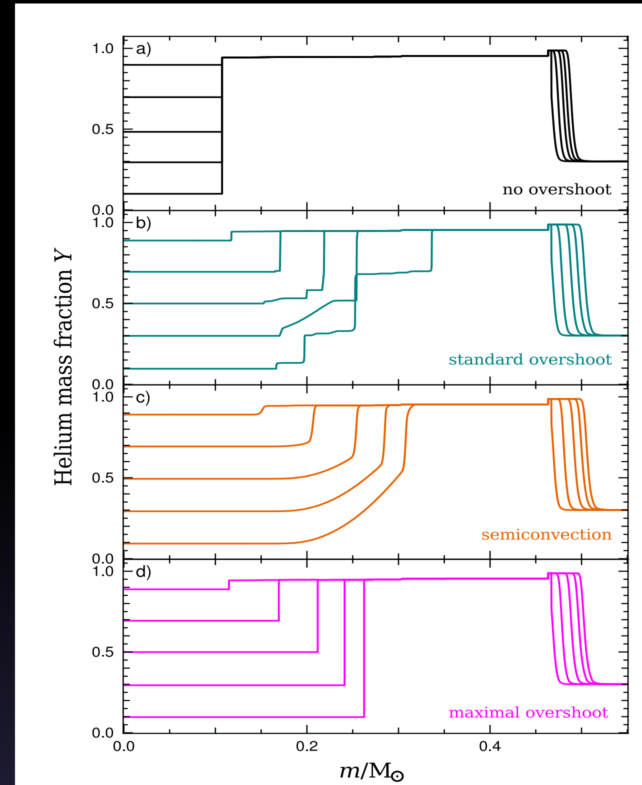
But other options do exist



1 $M_\odot$ solar initial compositon

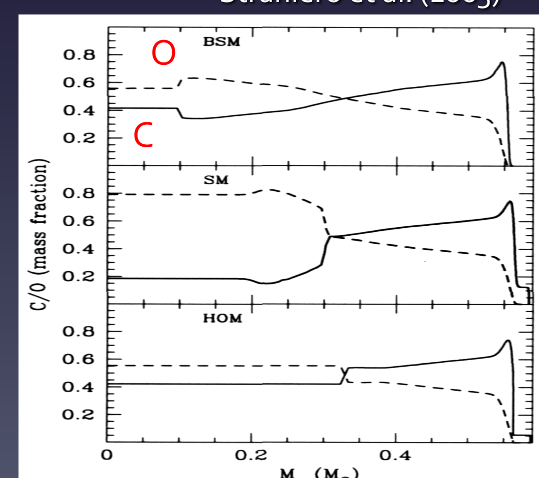


$N^2 \simeq \frac{g^2\rho}{p}(\nabla_{ad} - \nabla + \nabla_\mu)$



Constantino et al. (2015)

Straniero et al. (2003)



Y_c=0.4

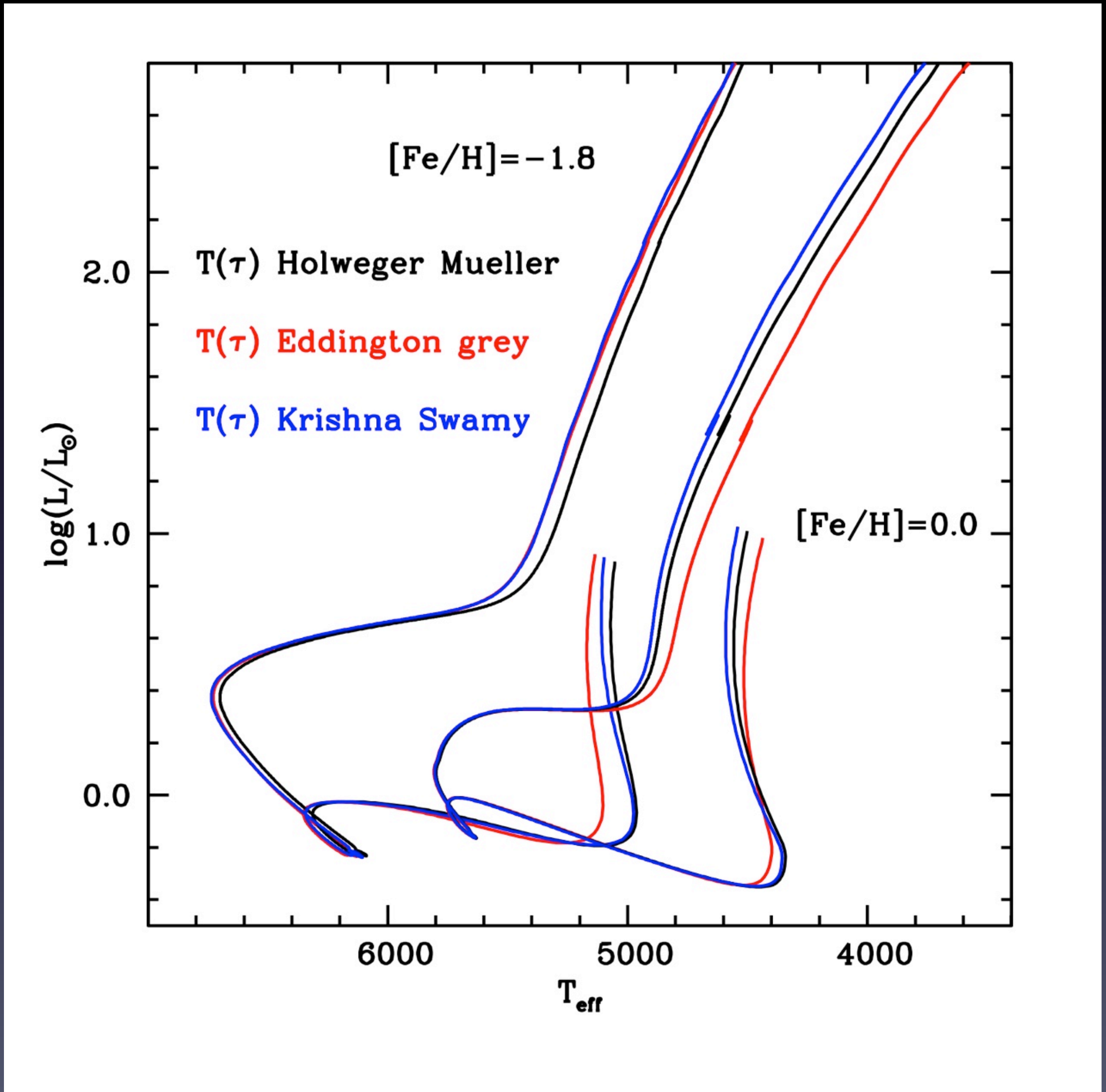
Gravity mode period spacing (same *l* and consecutive *n*) from *Kepler* stars favours the maximal overshoot scenario

Studies also by Bossini et al. (2015, 2017)

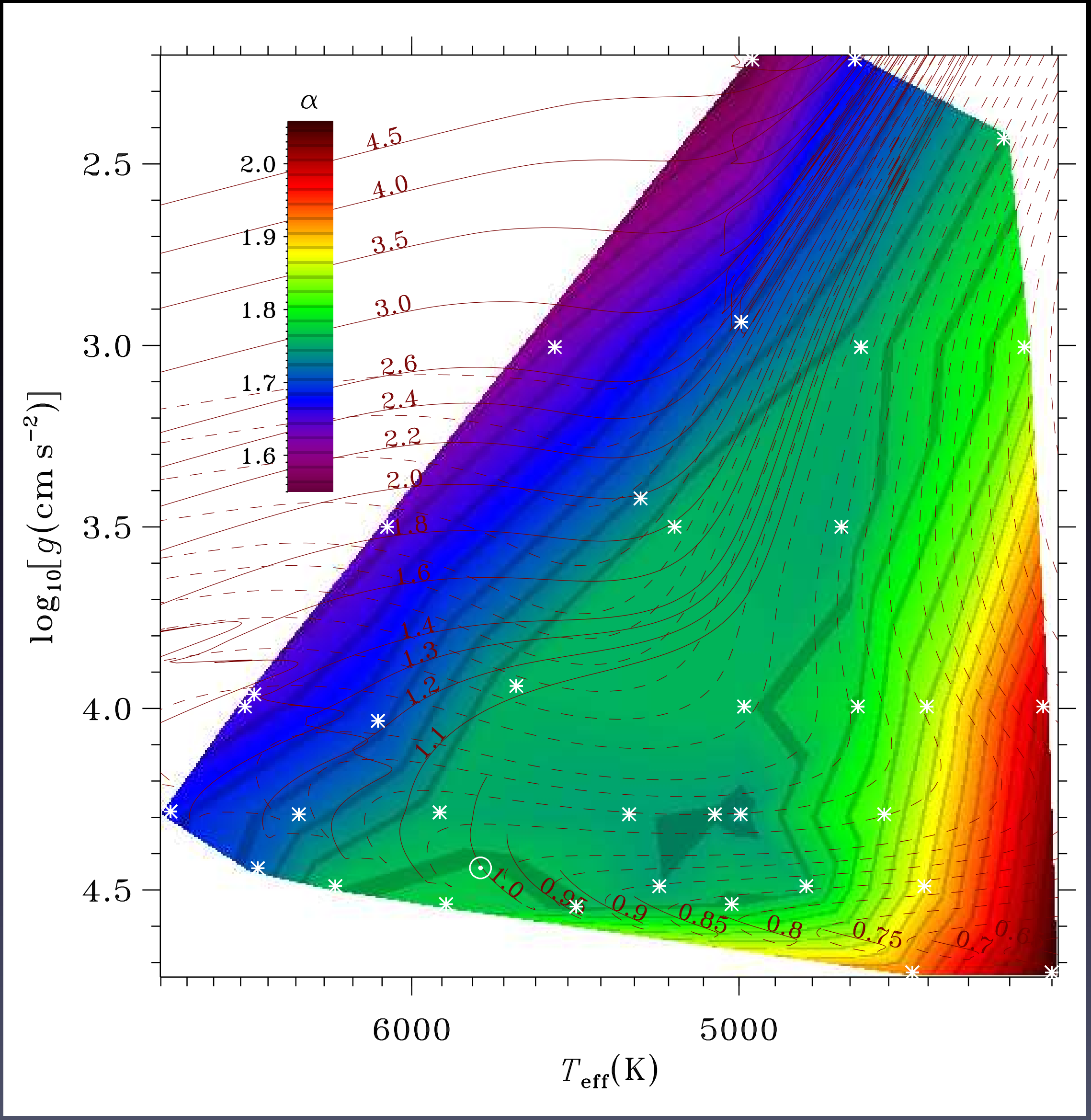
Different mixing schemes, different C/O stratifications

Superadiabatic gradient : MIXING LENGTH THEORY

T_{eff} mismatches/trends between theory and observations might have nothing to do with a variation of the mixing length α_{MLT}



3D radiation hydrodynamics simulations predict a variable mixing length α_{MLT}



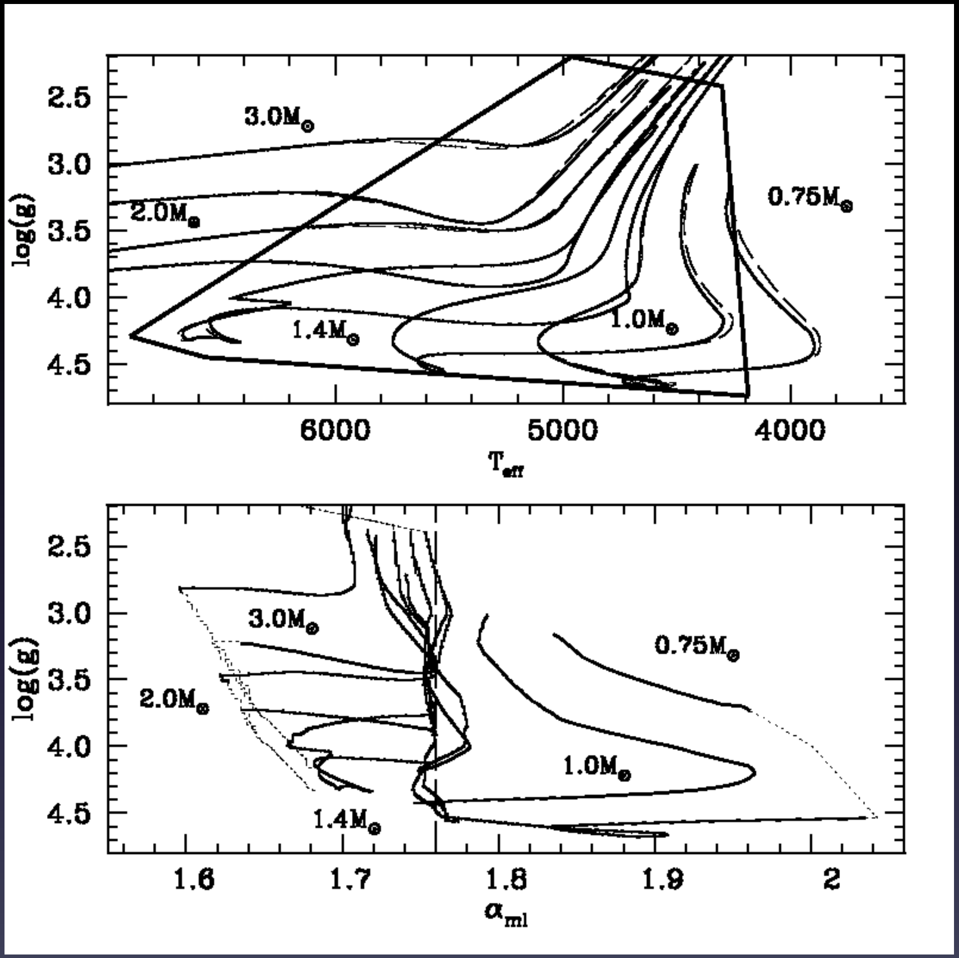
Trampedach et al. (2014)

Are stellar models very affected by the variation of α_{MLT}?

3D radiation hydrodynamics calibration (<u>mixing length and boundary conditions</u>) by Trampedach et al. (2014)

Solar metallicity only

At most just 30-50 K difference between solar and variable α calibration



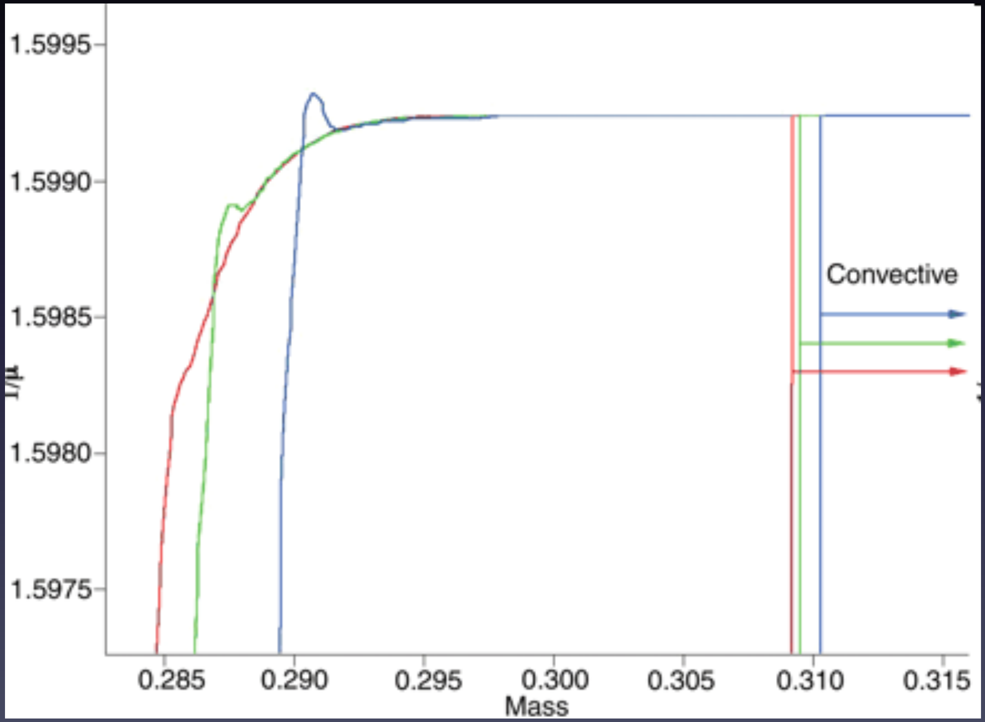
Salaris & Cassisi (2015)

THERMOHALINE MIXING

"The H-burning front moves outward into the stable region, but preceding the H-burning region proper is a narrow region, usually thought unimportant, in which ^{3}He burns.

The main reaction is ^{3}He (^{3}He, 2p)^{4}He: two nuclei become three nuclei, and the mean mass per nucleus decreases from 3 to 2. Because the molecular weight (μ) is the mean mass per nucleus, but including also the much larger abundances of H and ^{4}He that are already there and not taking part in this reaction, this leads to a small inversion in the μ gradient. "

1M$_\odot$ solar composition



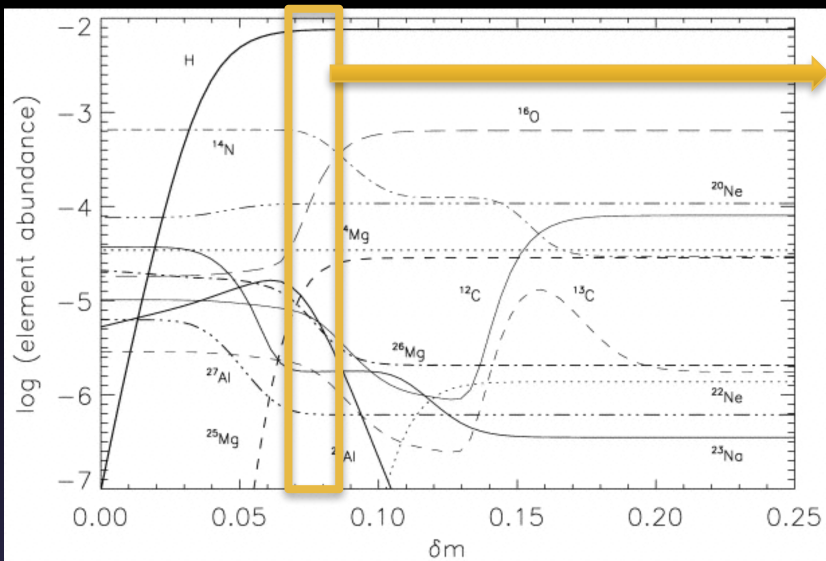
Eggleton et al. (2006)

Field halo stars

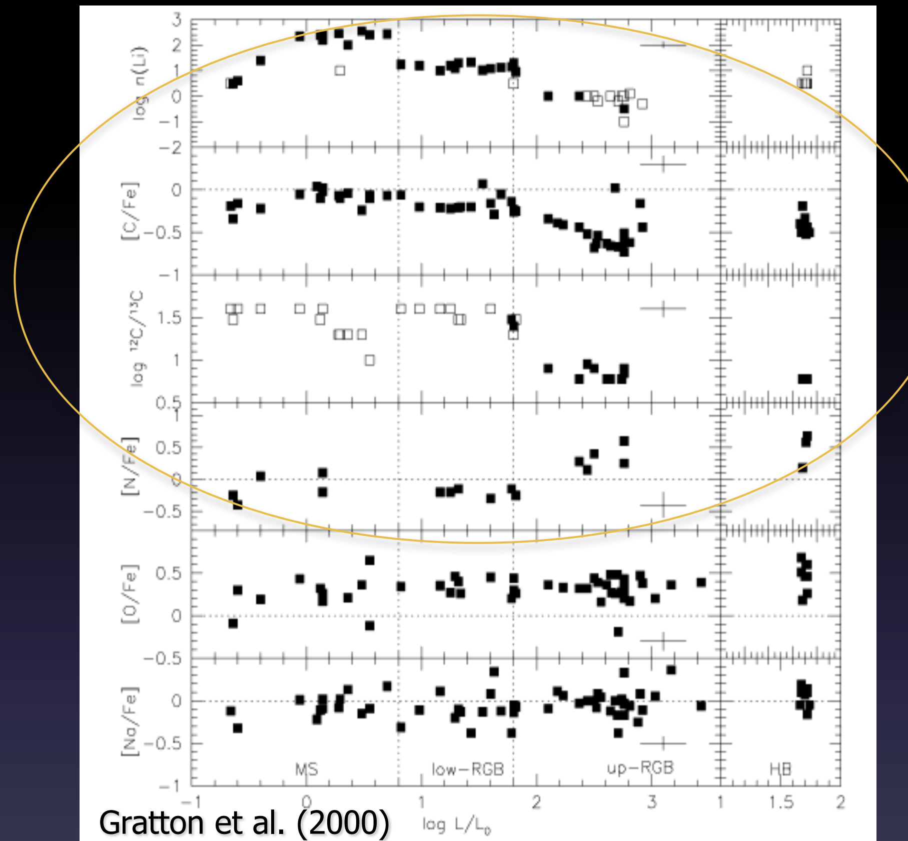
1st dredge up

RGB extra-mixing after first dredge up

0.8 $M_\odot$ metal poor RGB model



Salaris et al. (2002)



Gratton et al. (2000)

Bottom conv. envelope at δm=1
Bottom H-burning shell at δm=0

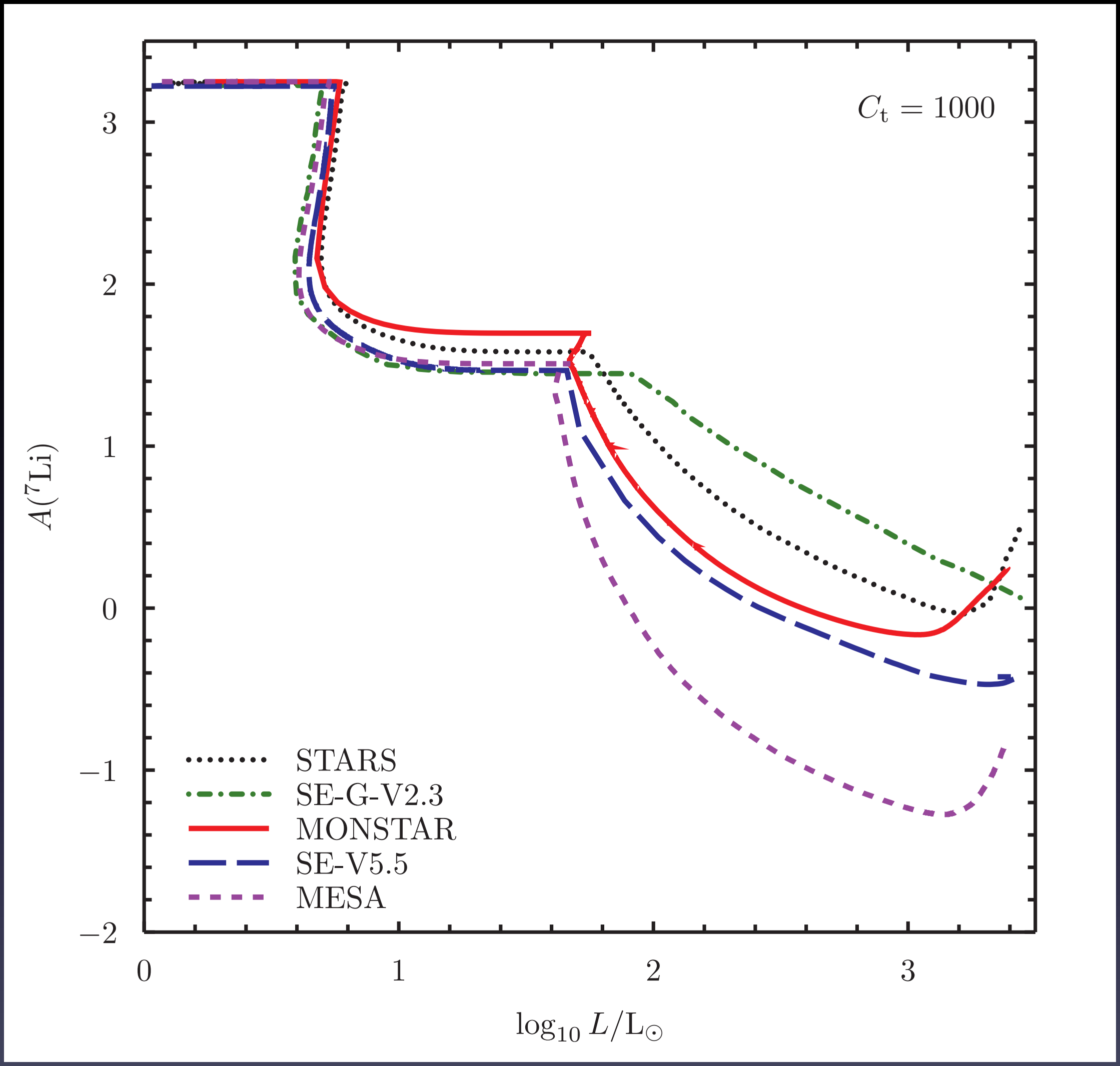
0.8 $M_\odot$ [Fe/H]= −1.58

$$D_{\rm th} = C_{\rm th}\, \frac{K}{c_p \rho} \left(\frac{\phi}{\delta}\right) \frac{\nabla_\mu}{(\nabla_{\rm rad} - \nabla_{\rm ad})}$$

$$C_{\rm th} = (8/3)\pi^2 \alpha^2$$

with α free parameter
(Charbonnel & Zahn 2007)

1.25 $M_\odot$ solar initial composition



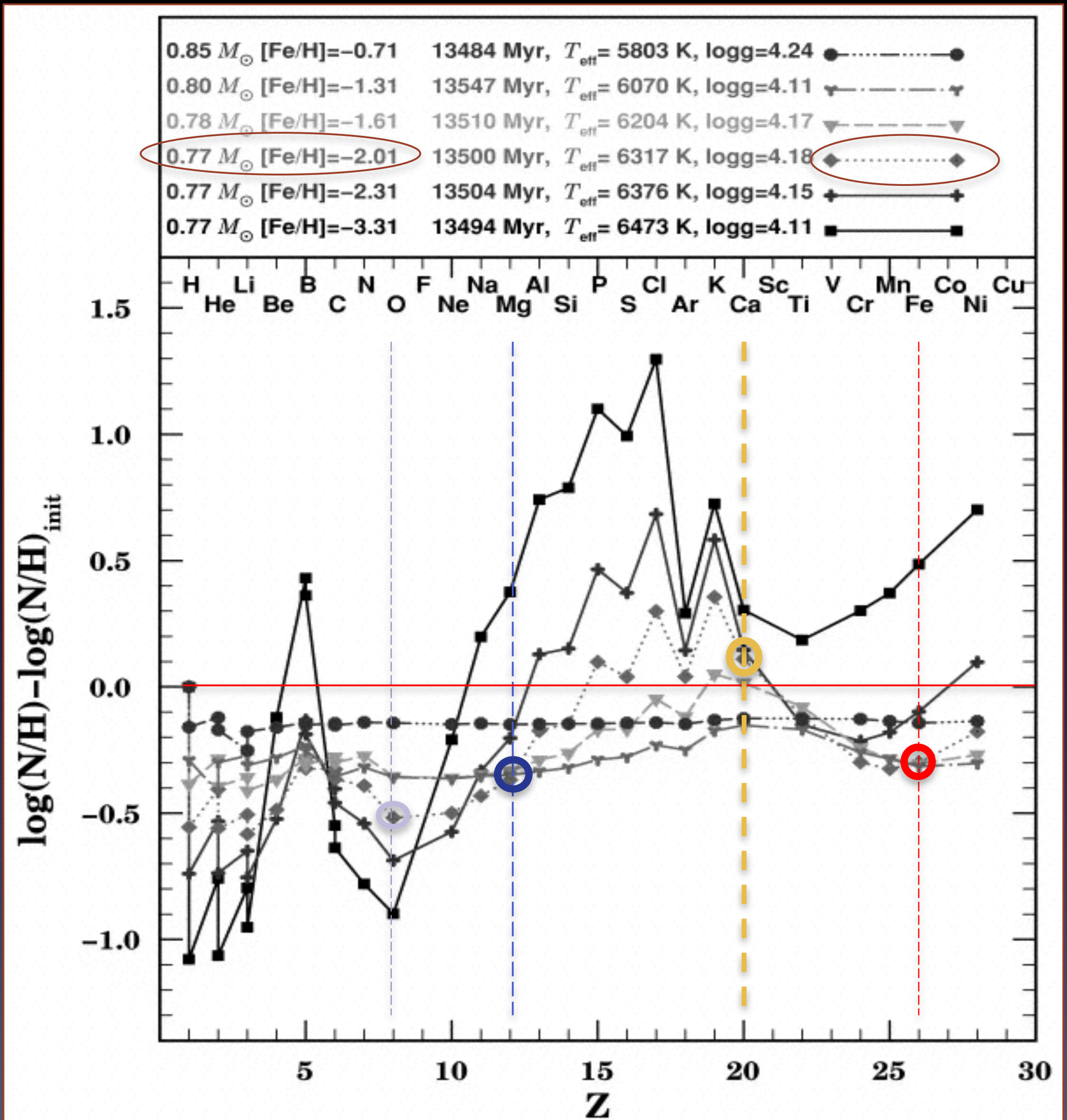
Surface abundances for a given C_t are very sensitive to timestep and mesh resolution adopted in the stellar model calculations

Also, hydro-simulations of this process do not give definitive results, even though they hint that $C_t < 1000$

Lattanzio et al. (2015)

Atomic diffusion on the Main Sequence

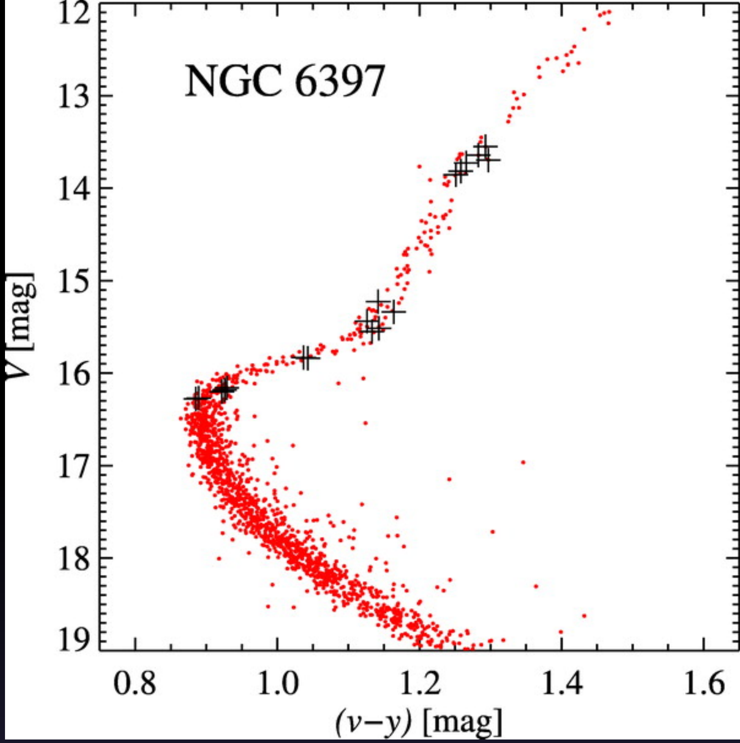
Treatment from first principles

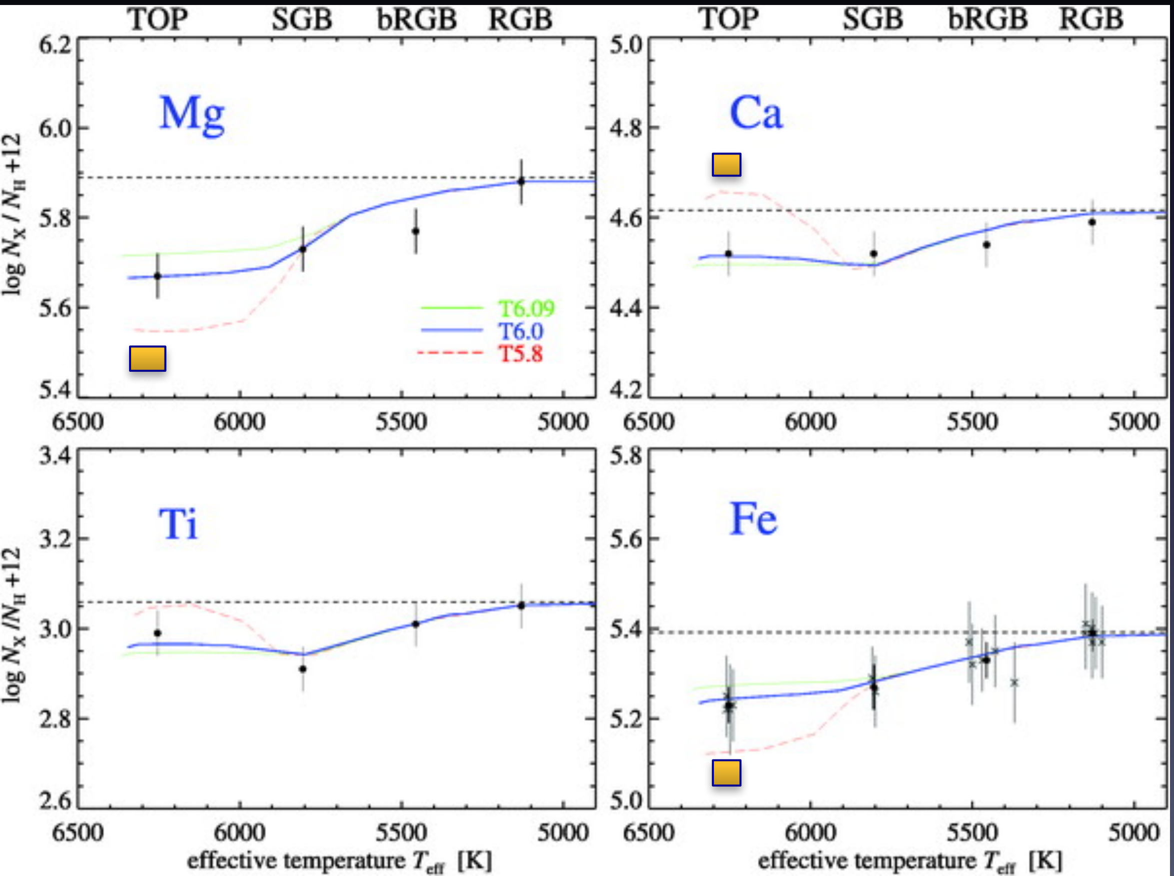


Richard et al. (2002)

Puzzling observations

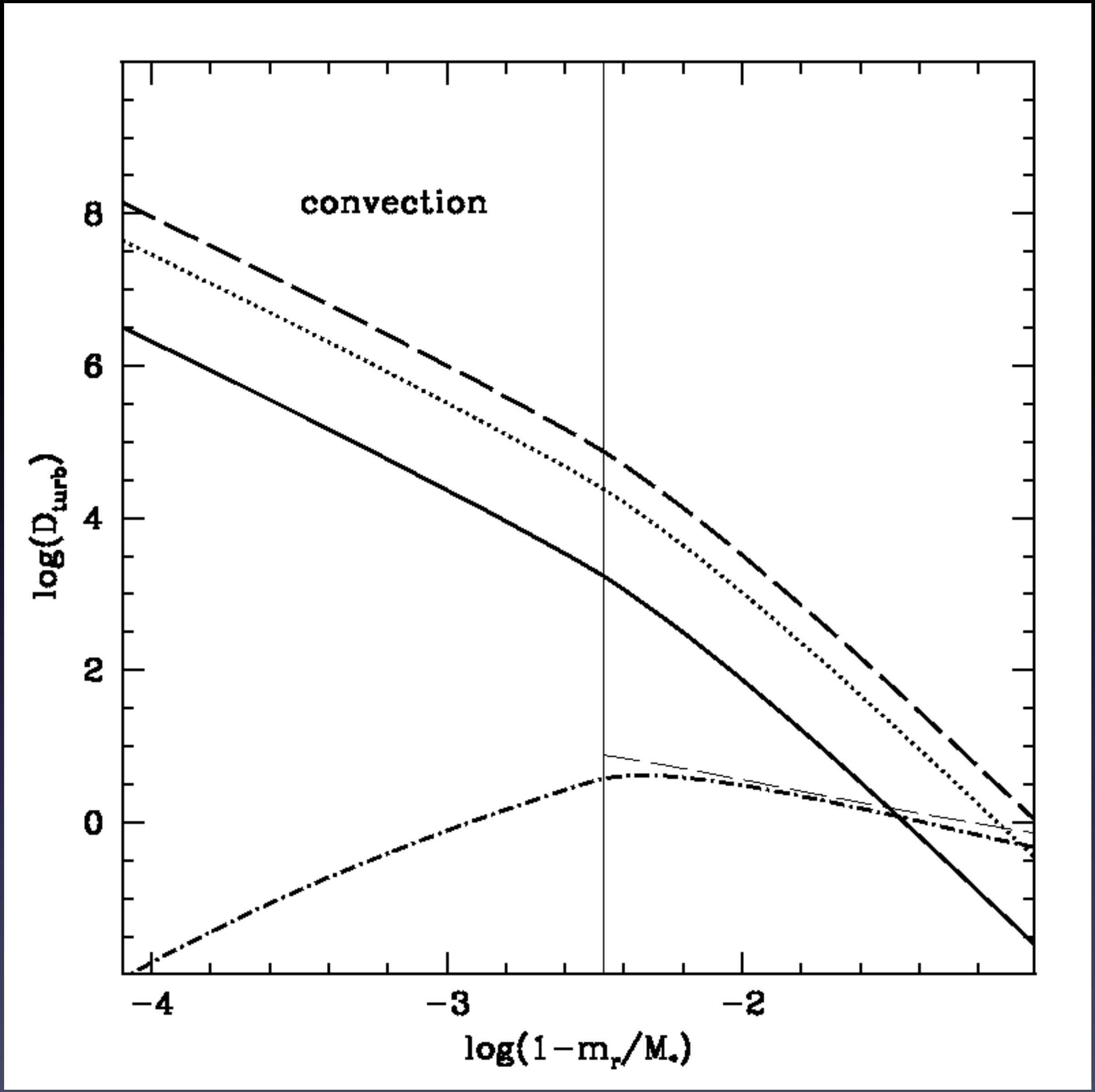
Korn et al. (2007)

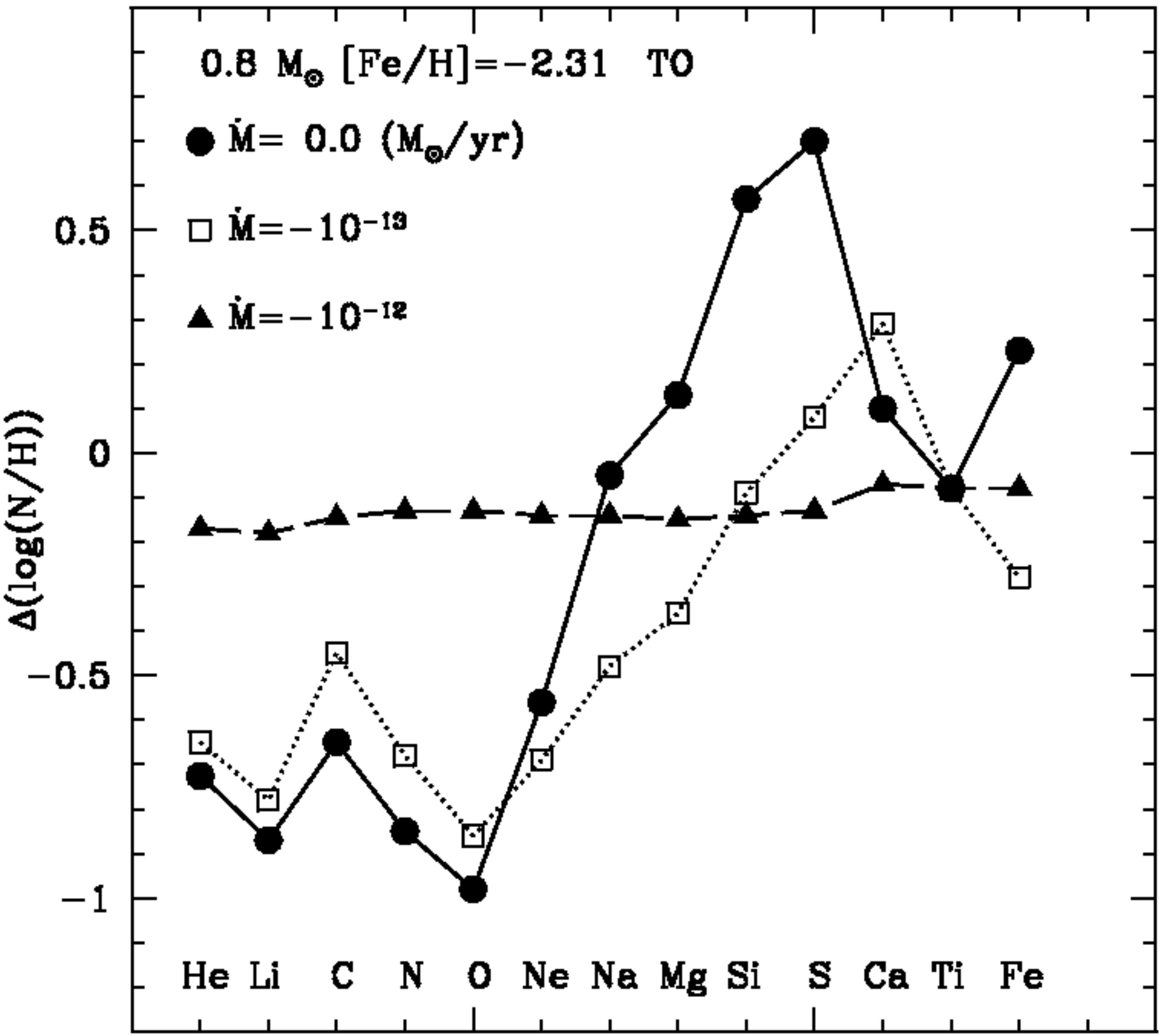




Inhibition of diffusion from/into the convective envelopes with *ad-hoc* counteracting diffusive mixing (called generically *turbulence*)

$0.8M_{\odot}$, [Fe/H]=−1.3 model, in the latter phase of its MS evolution. The vertical thin line marks the bottom of the convective envelope



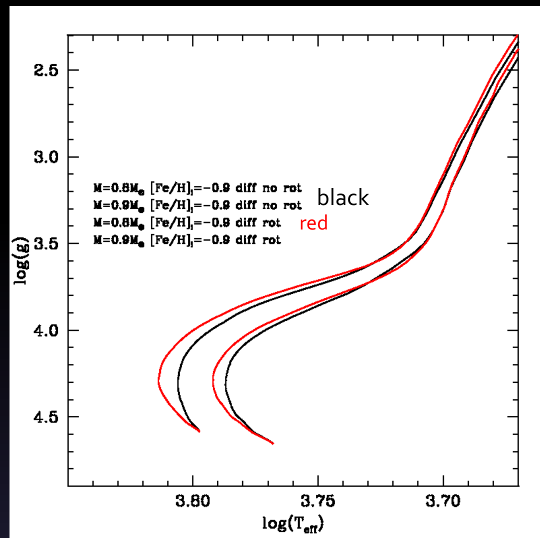


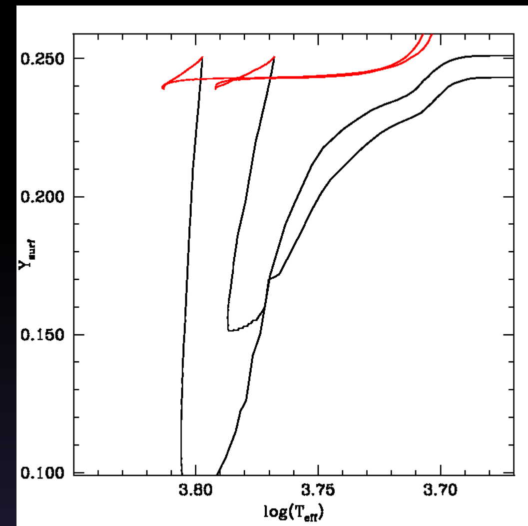
Effect of <u>mass loss</u>

Data from Vick et al. (2013)

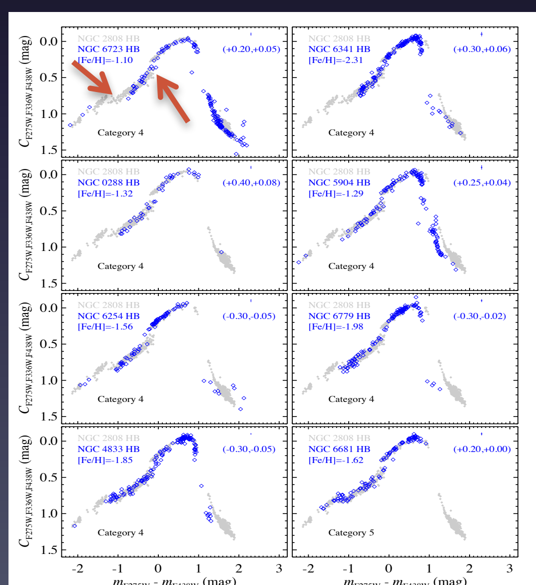
Rotation inhibits atomic diffusion from surface and also increases evolutionary timescales (rotational mixing counteracts the development of chemical gradients)

Georgy et al. (2013)



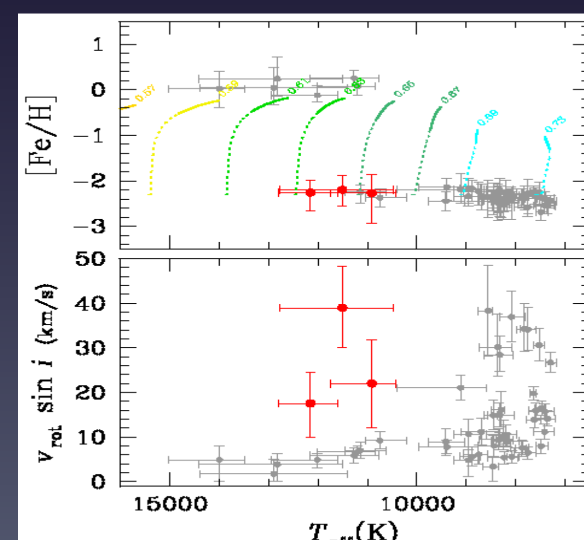


Brown et al. (2016)



Atomic diffusion in HB stars

M15, M68, M92



Michaud et al. (2011)

Also problem matching Abundances of sdB stars

(Hu et al. 2011)

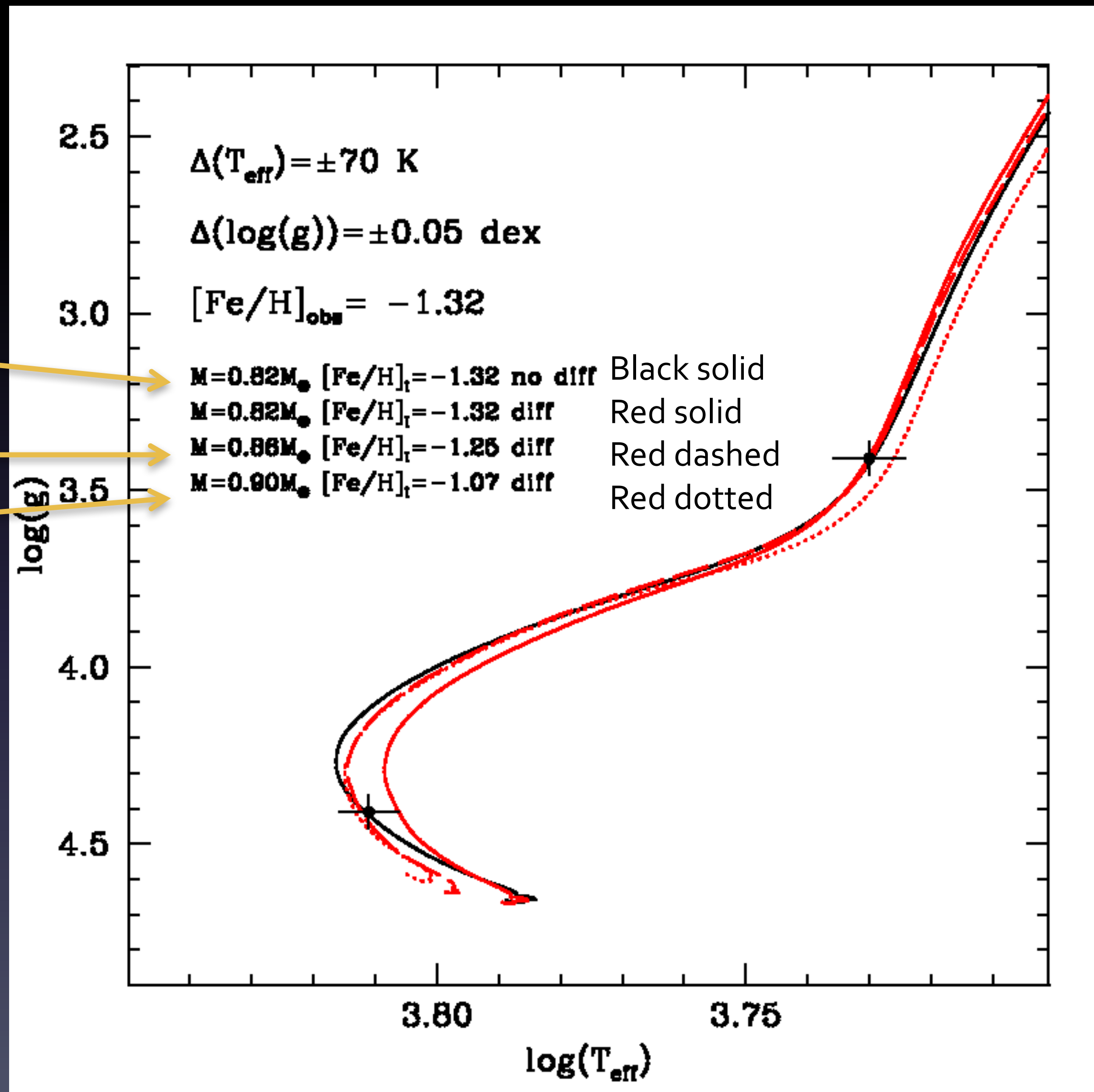
EFFICIENCY OF ATOMIC DIFFUSION AND AGE OF FIELD STARS

MS

≅8.5 Gyr

≅6 Gyr

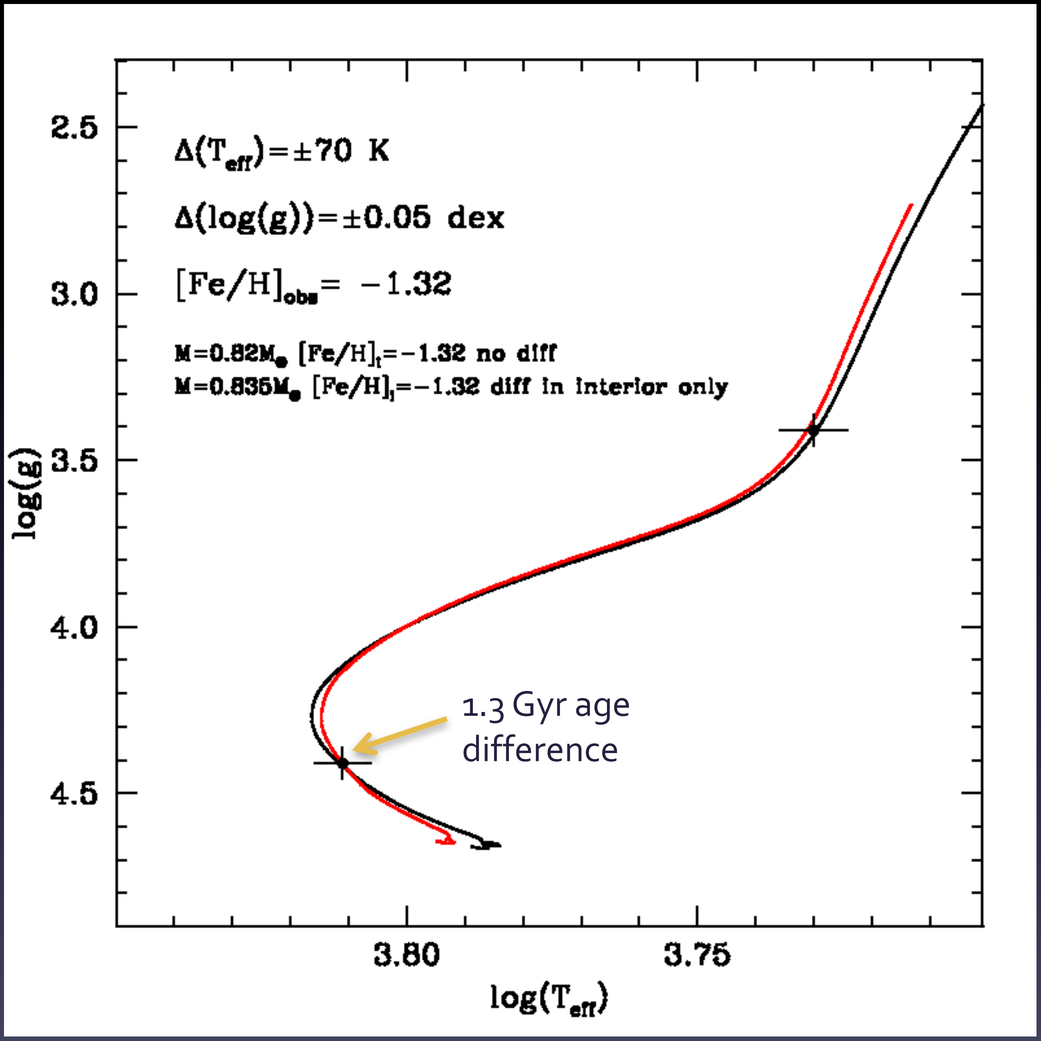
≅5 Gyr



<u>Large age uncertainty if we do not know the stellar mass</u>

Zero-order test with atomic diffusion inhibited from envelopes

Spectroscopy of GCs tells us that gravitational settling-levitation are strongly inhibited (at least) for the convective envelope

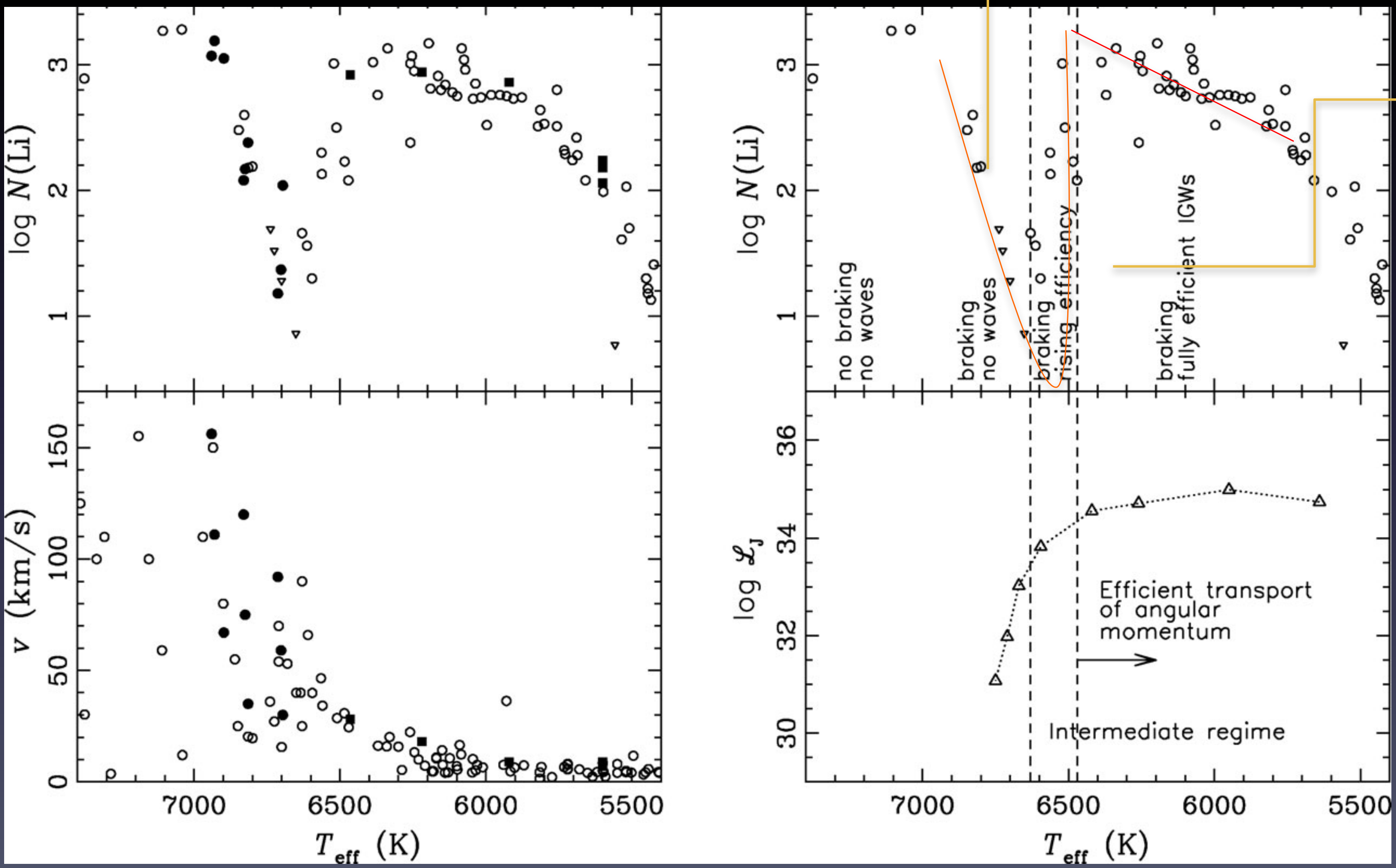


Diffusion and more in open clusters. An example

Surface brakes
Increase diff rot.
More rotational mixing and Li destruction

Hyades (Turn off mass ~ 2.3 $M_\odot$)

Charbonnel & Talon (2009)

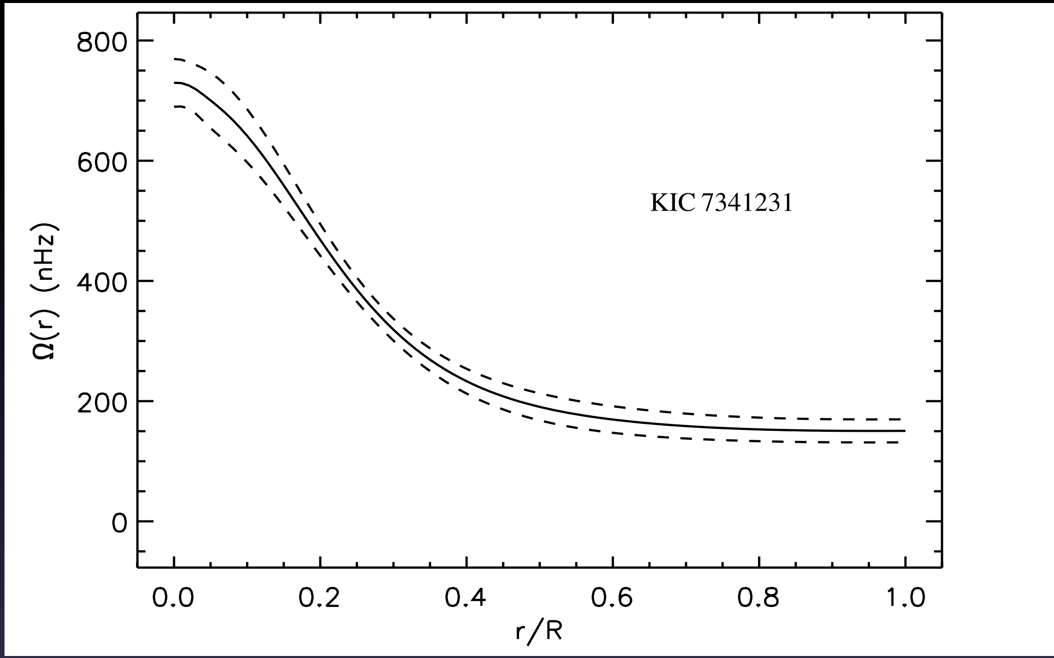


Gravity waves decrease diff. rotation.

Li destruction decreases

Why are we talking about gravity waves?(internal gravity waves - IGWs)

These IGWs are expected to be generated by the injection of kinetic energy from a turbulent region into an adjacent stable region

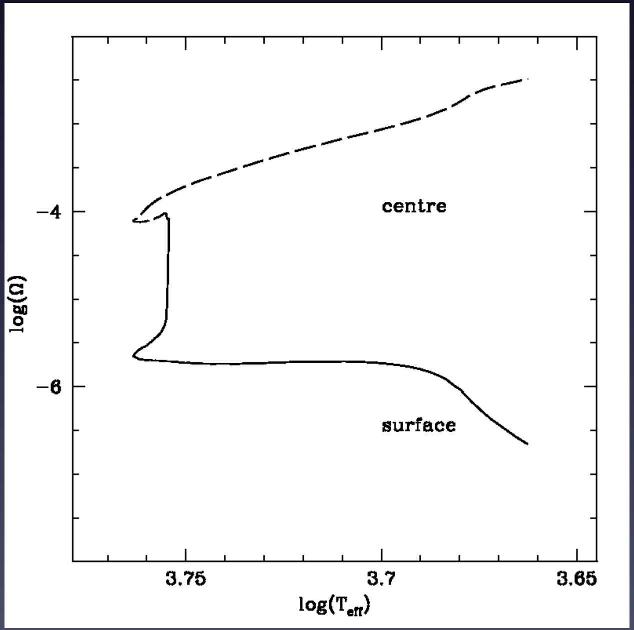


Inferred rotational profile

0.84$M_\odot$ lower RGB star

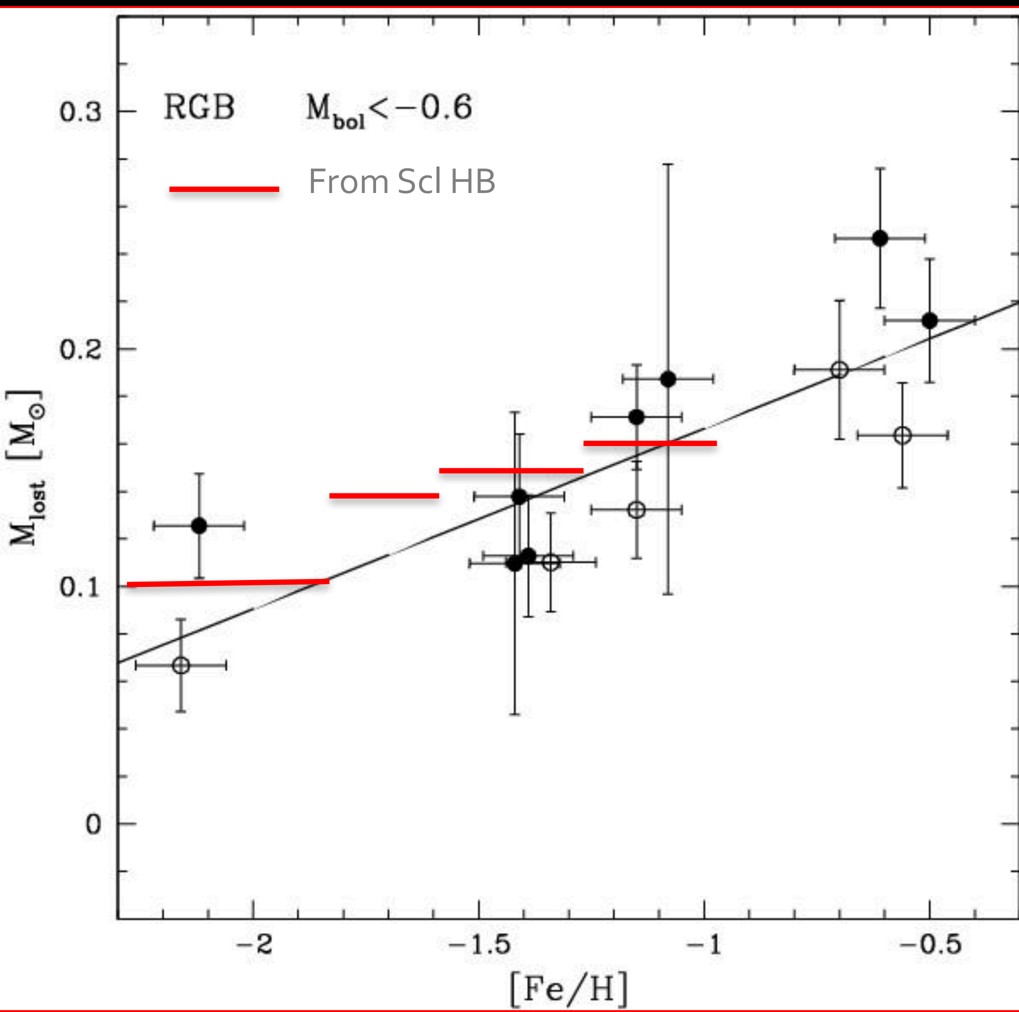
(Deheuvels et al. 2012)

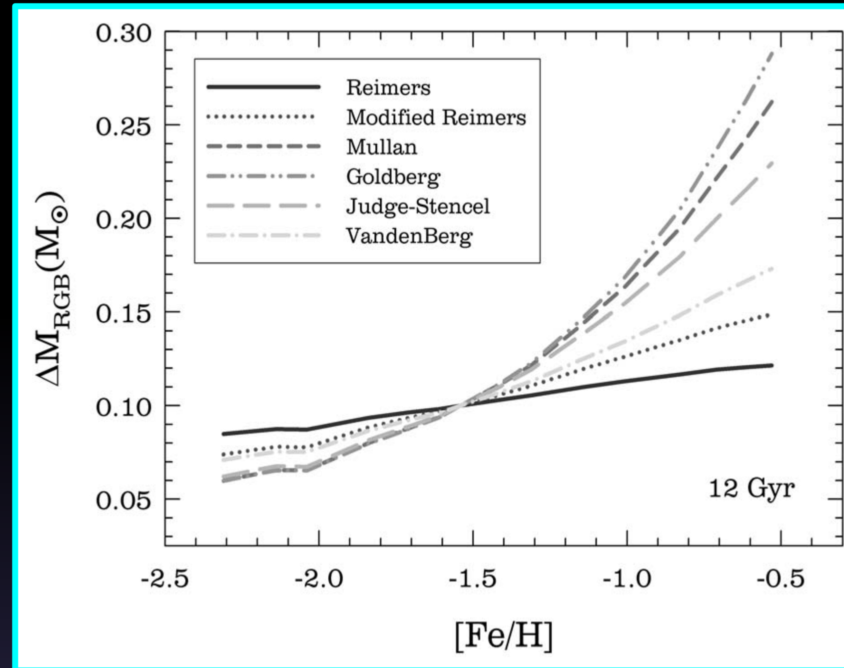
Some extra angular momentum transport needs to be included in the current generation of rotating stellar models, because they predict much larger rotation rates for stellar cores compared to the surface



Model from Ekstroem et al. (2012)

RGB mass loss





Catelan (2009)

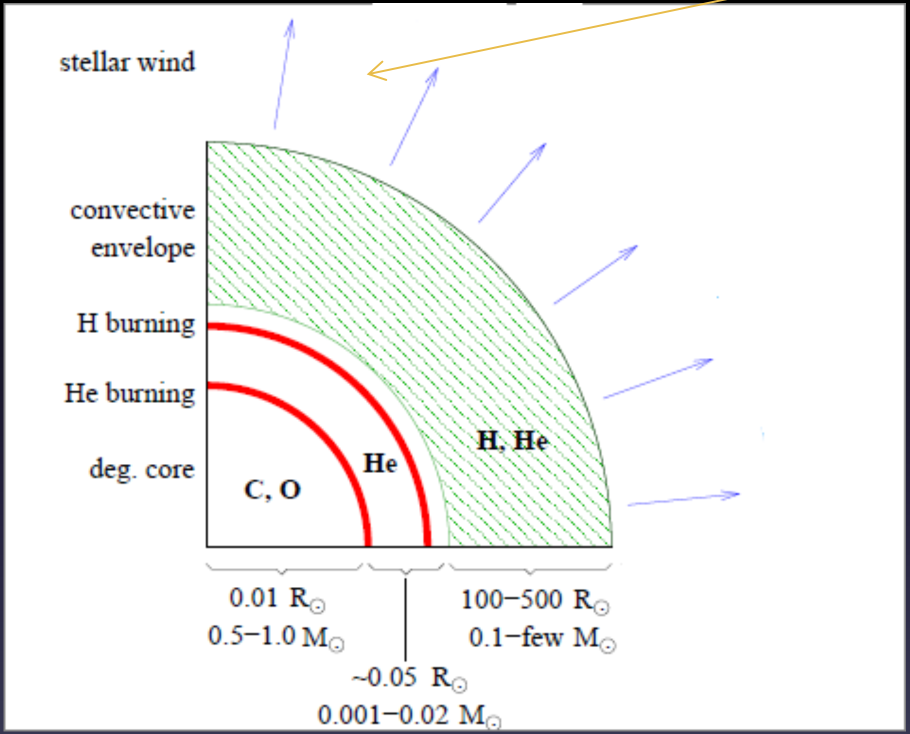
IR excess RGB globular cluster stars (Origlia et al 2014)

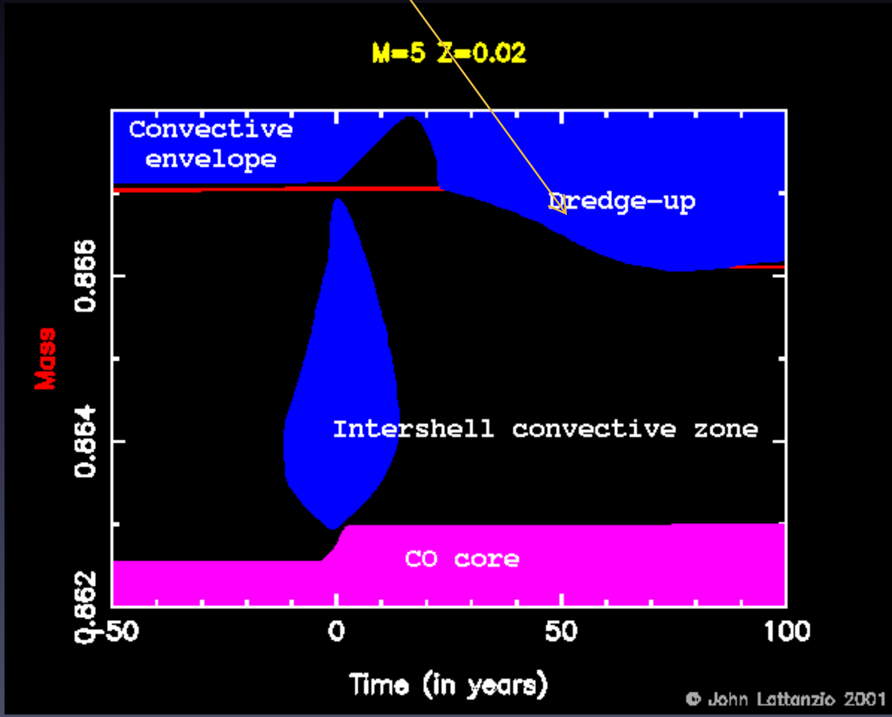
Synthetic HB modelling of Sculptor with known SFH (Salaris et al. 2015)

AGB stars

Mass loss, boundaries of convection

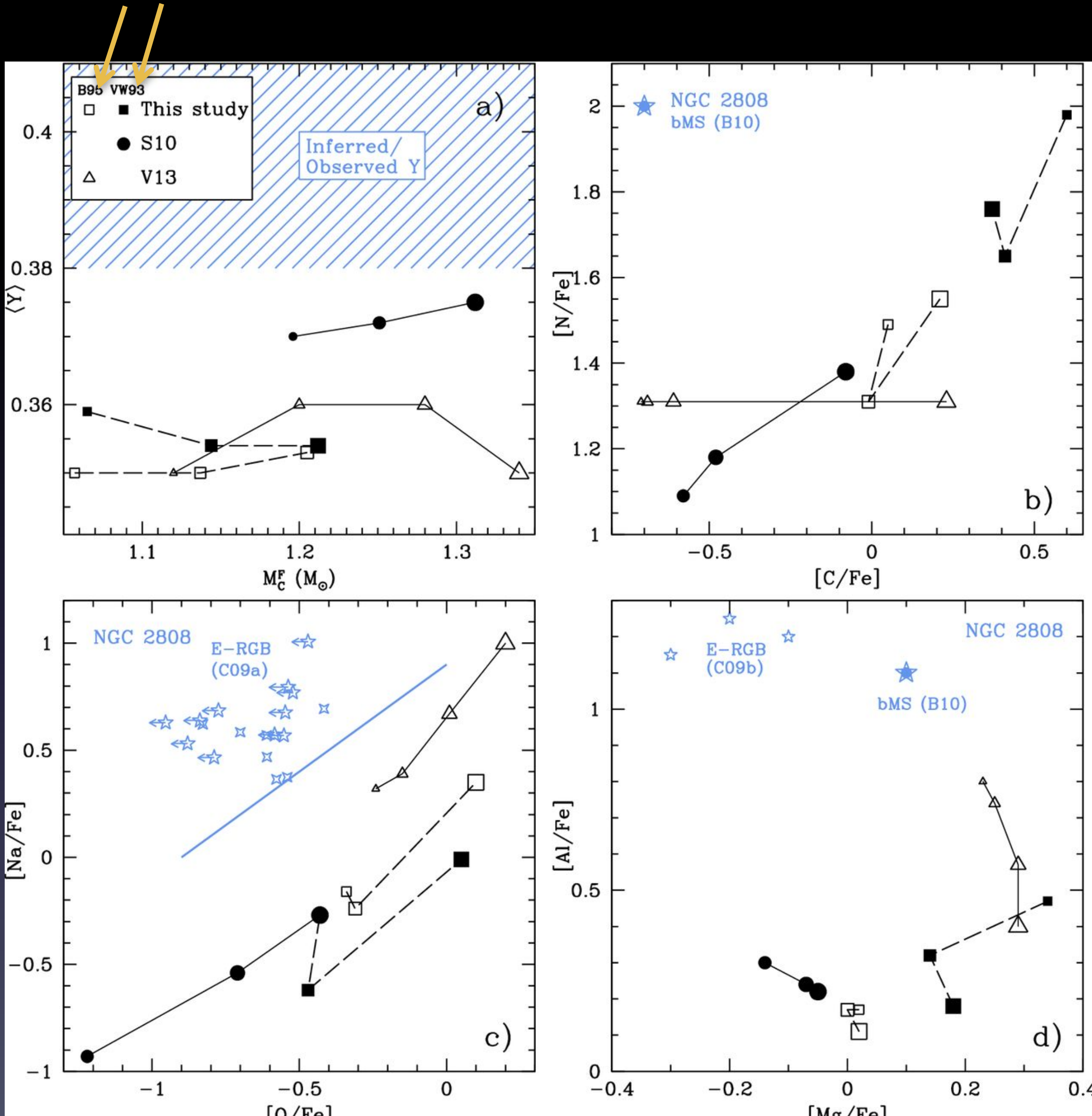
UNCERTAIN !!!!!





Uncertain yields

Different AGB mass loss law



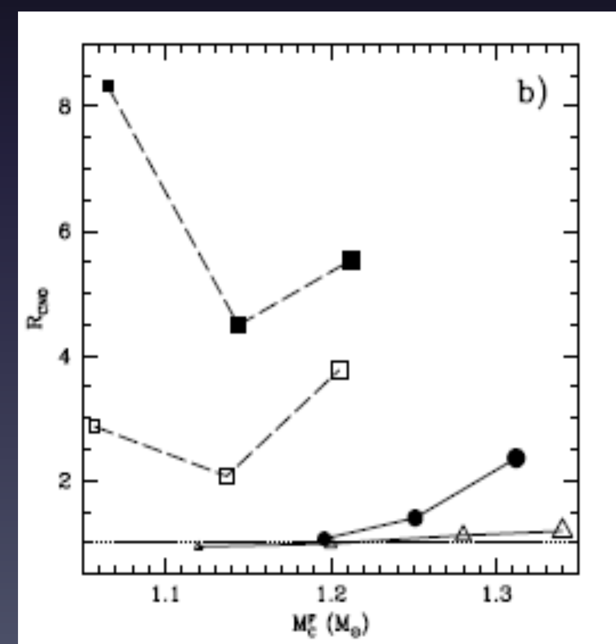
Doherty et al. (2014)

Super-AGB models only

Z=0.001
M=6.5, 7.0, 7.5 $M_\odot$

V13 M=6.0, 6.5 ,7.0, 7.5 $M_\odot$

S10 M= 8.0, 8.5, 9.0 $M_\odot$



HOPES FOR THE FUTURE…….

Convection

- test Magic et al. (2015) 3D-hydro α_{MLT} calibration (covers a large [Fe/H] range) once they provide their boundary conditions
- Asteroseismology to help for boundary mixing and core He-mixing ?
- Hopefully, increasingly more realistic 3D hydro-simulations
- Eclipsing binaries (M-R diagrams)
- Asteroseismology of WDs

Thermohaline mixing

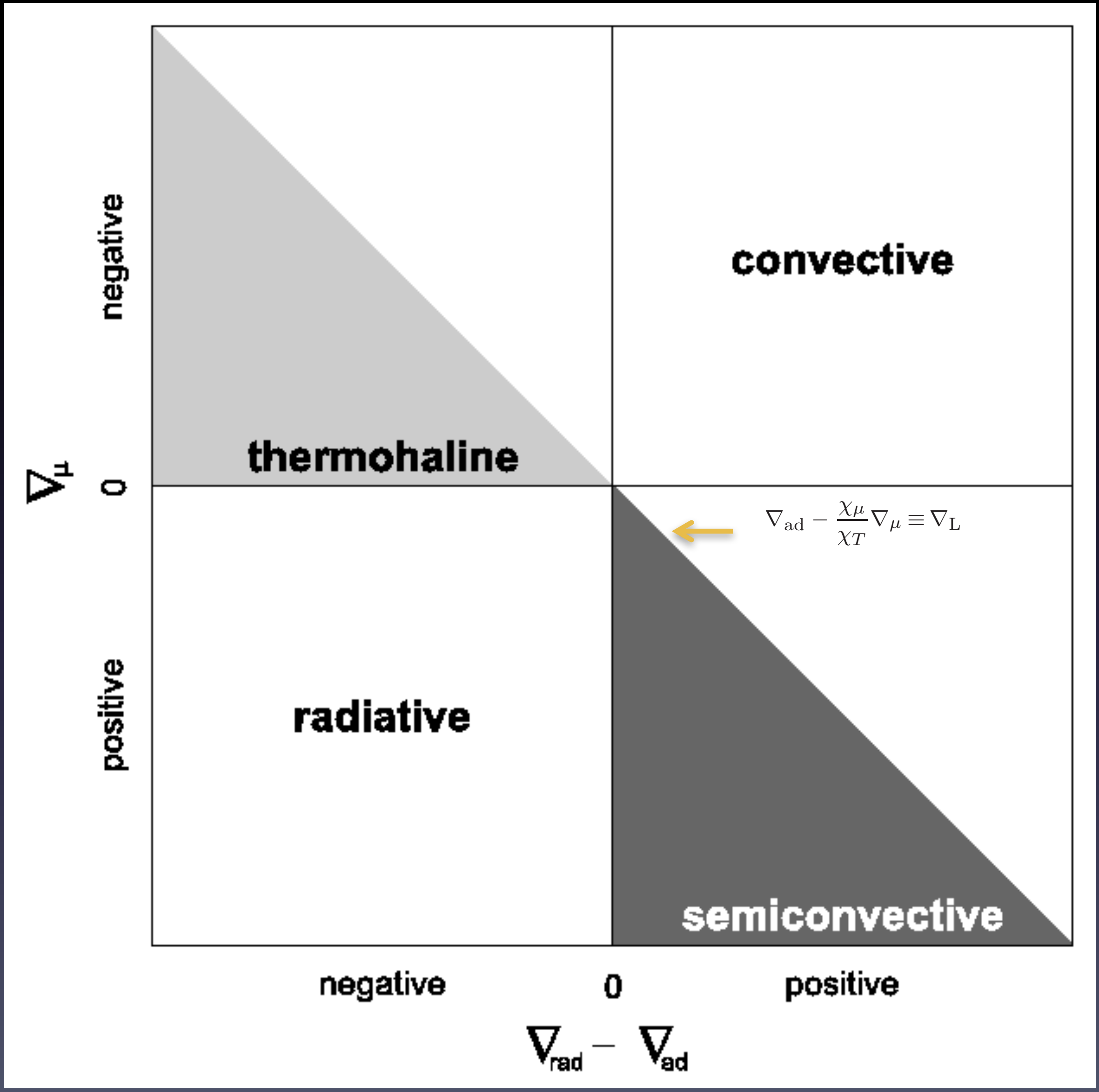
More RGB spectroscopy on clusters of varying age to put stronger observational constraints but also improved hydro simulations and also stellar model calculations following criteria set out by Lattanzio et al. (2015)

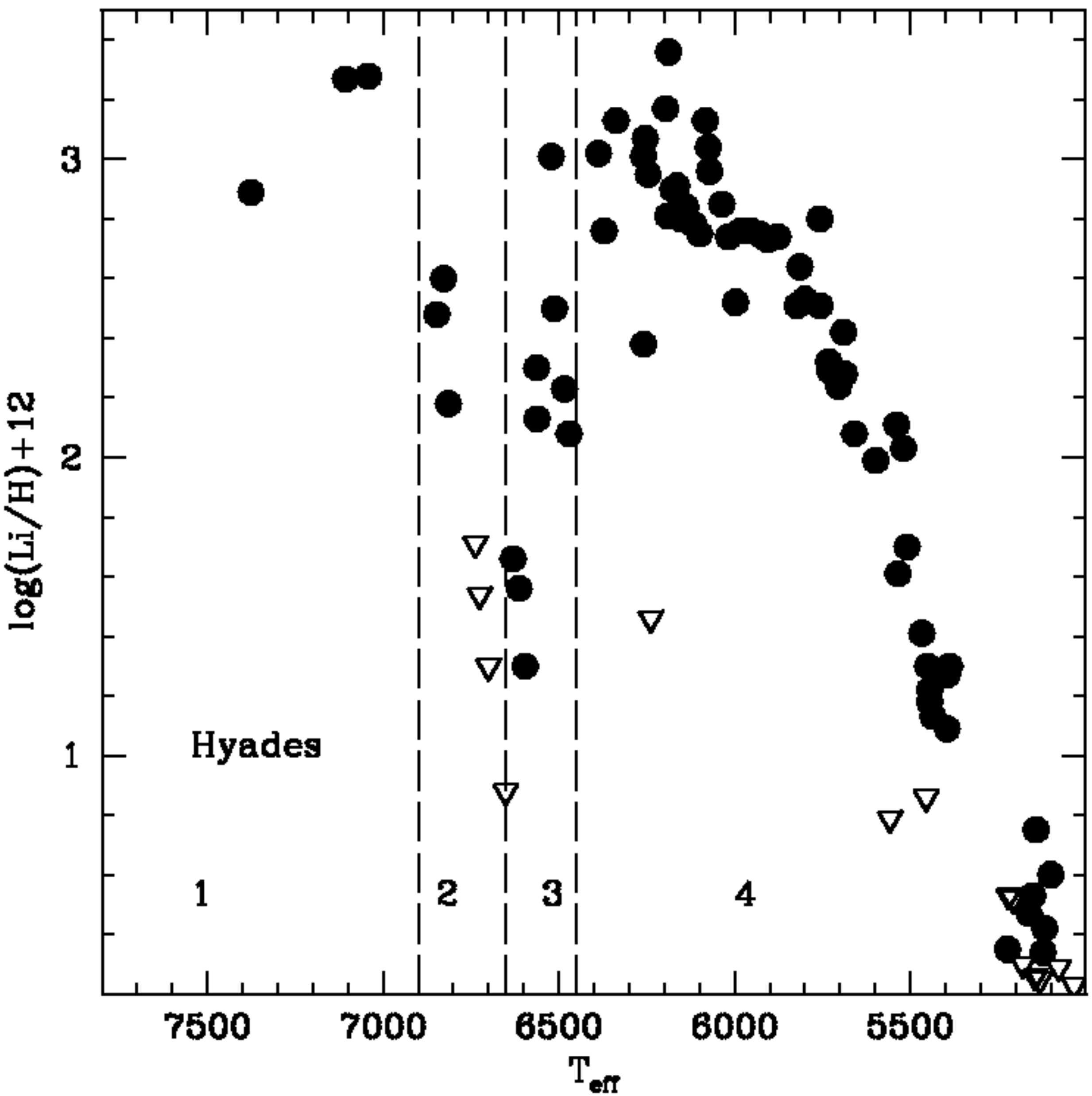
Element transport in radiative regions ??

Mass loss

RGBs …… hopefully more constraints from modelling of HBs in Local Group dwarf galaxies (e.g. Salaris et al. 2015)

Instabilities in non-rotating stars





Hyades
1
2
3
4
log(Li/H)+12
3
2
1
7500
7000
6500
6000
5500
T_{eff}