# Thermohaline mixing and rotation-induced mixing in low- and intermediate-mass stars


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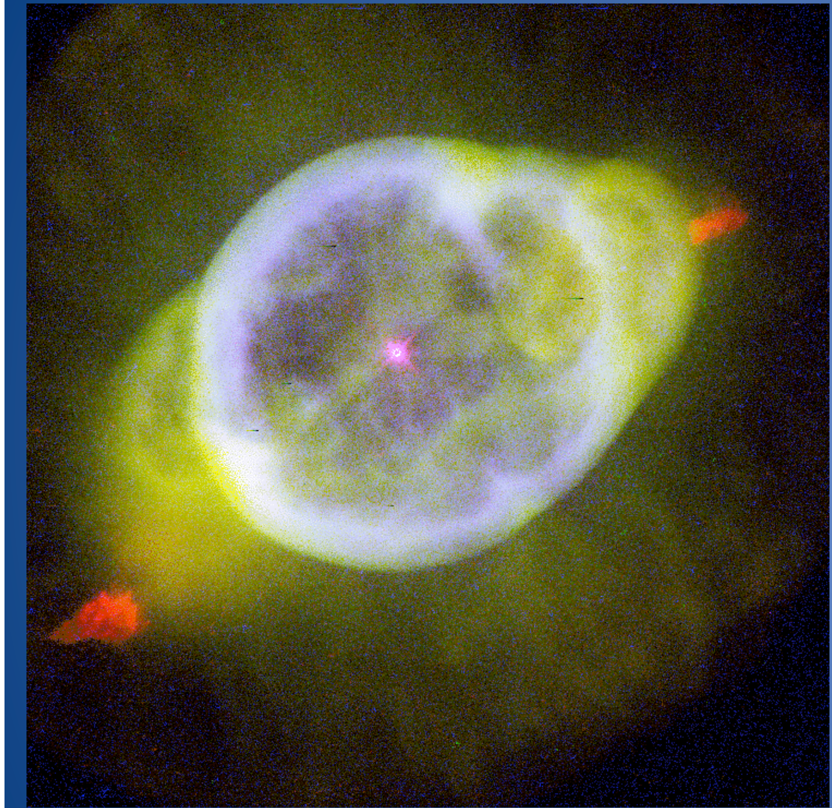
Geneva observatory



OBSERVATOIRE DE GENÈVE FONDÉ EN 1772

1559 2009 450 ans UNIVERSITÉ DE GENÈVE

# Introduction



NGC 3242

- NGC 3242 has an abundance of $^3He$ as predicted by classical models.

- Galactic chemical evolution shows that only ≈10% or less of the low-mass stars were actually releasing $^3He$ as predicted by the classical stellar theory (Tosi 1998, 2000 ; Palla et al. 2000 ; Romano et al. 2003)

- The majority of low-mass stars experiences deep mixing in red giant phase.

I. Classical predictions

II. Observational evidence for 2nd mixing episode on RGB

III. Transport processes :

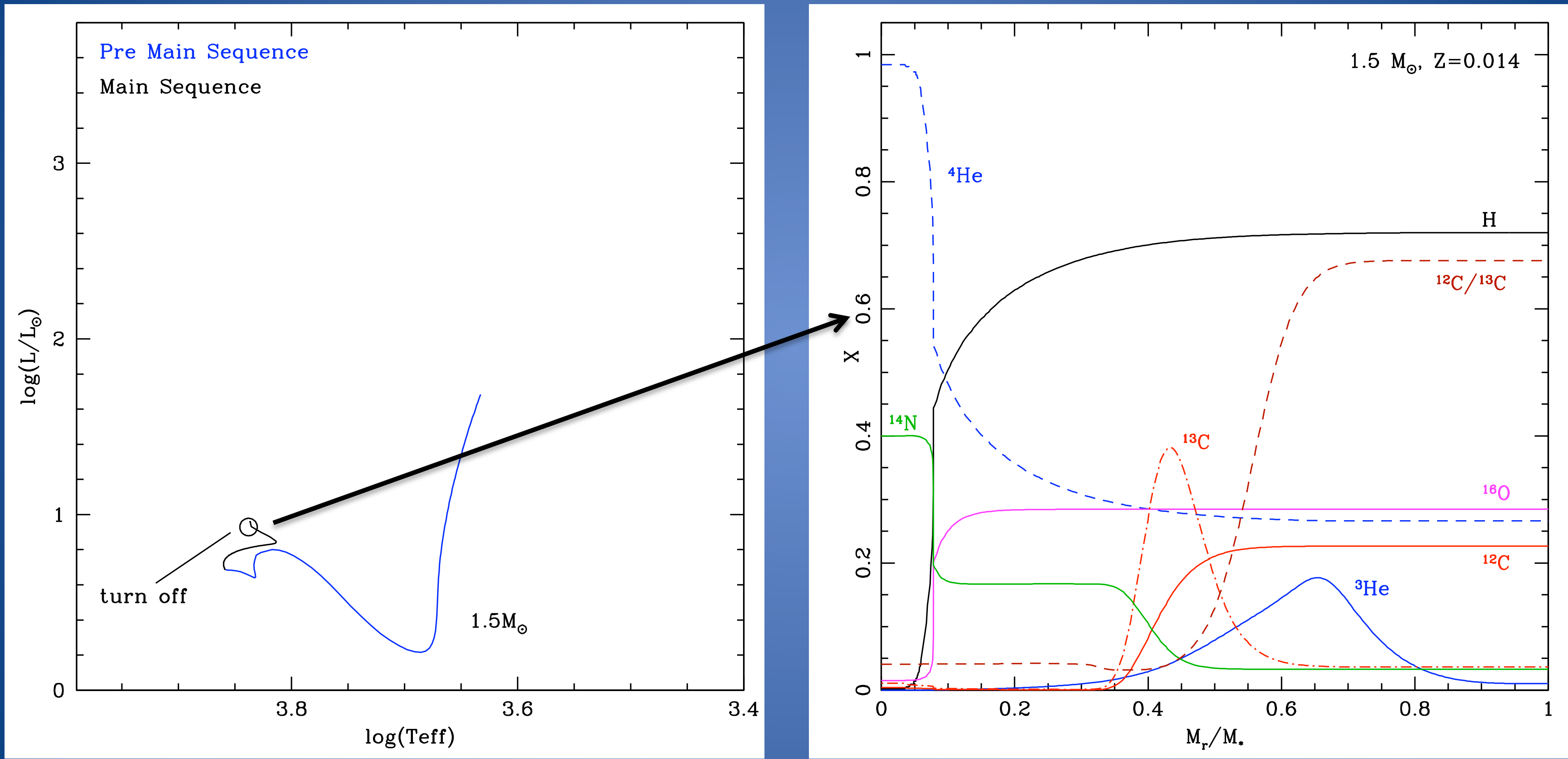
- Rotation-induced mixing
- Thermohaline mixing

IV. Comparison of models predictions with observations

- $^3He$ case

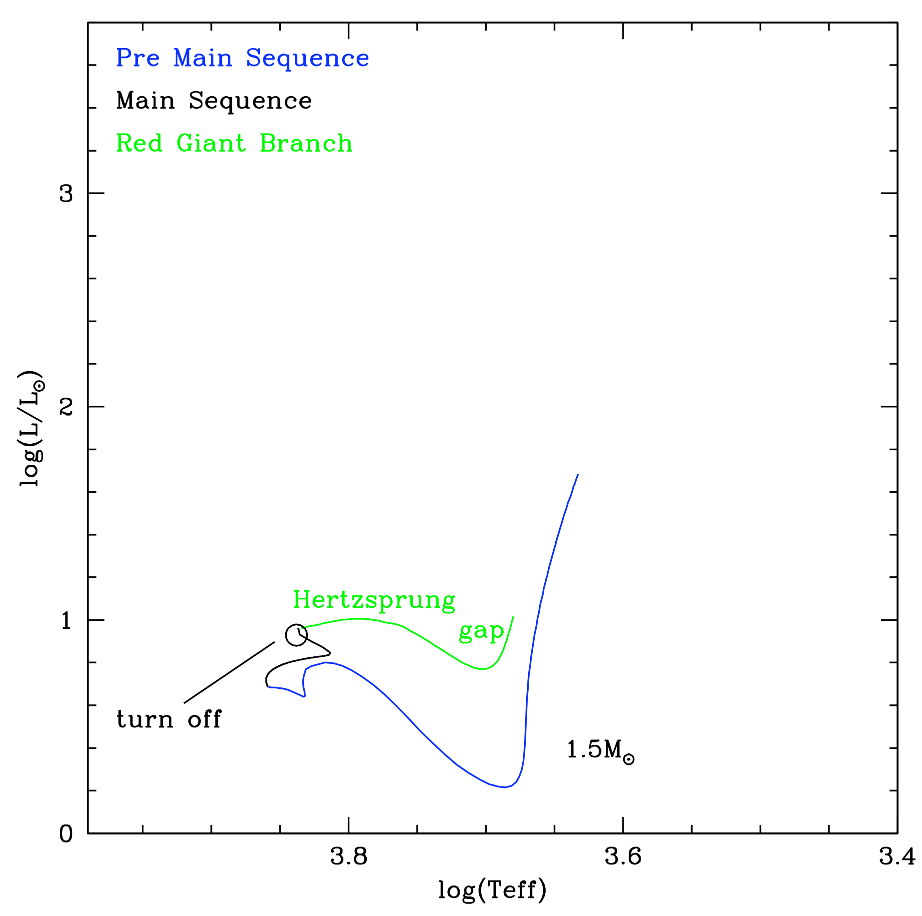
# I- Classical predictions

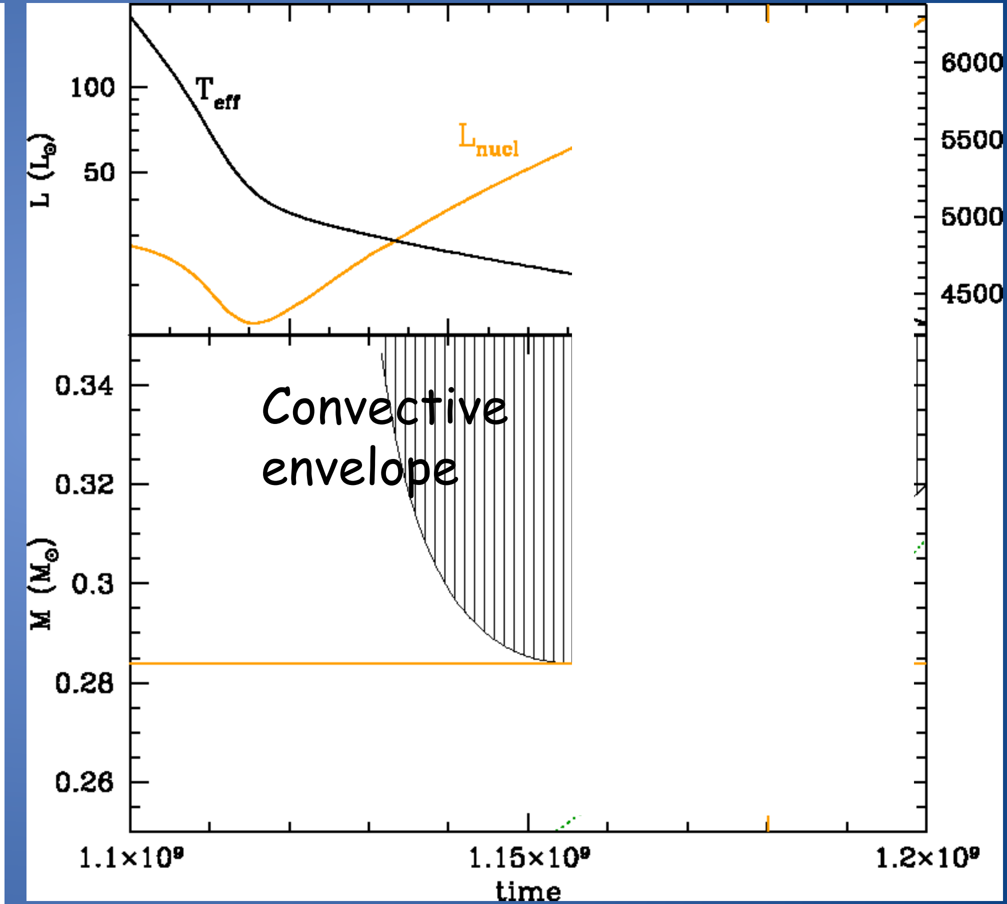
# Classical predictions




Mass fraction
100 x X($^3$He, $^{12}$C)
1000 x X($^{13}$C)
50 x X($^{14}$N, $^{16}$O)

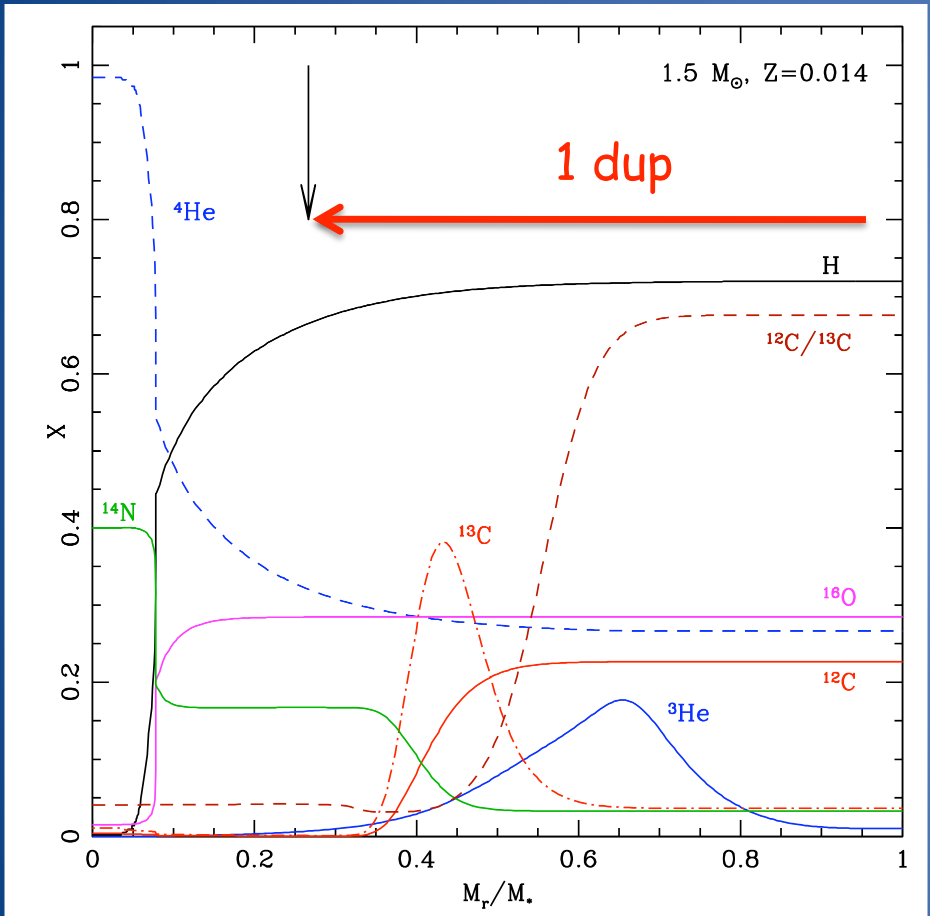
# Classical predictions

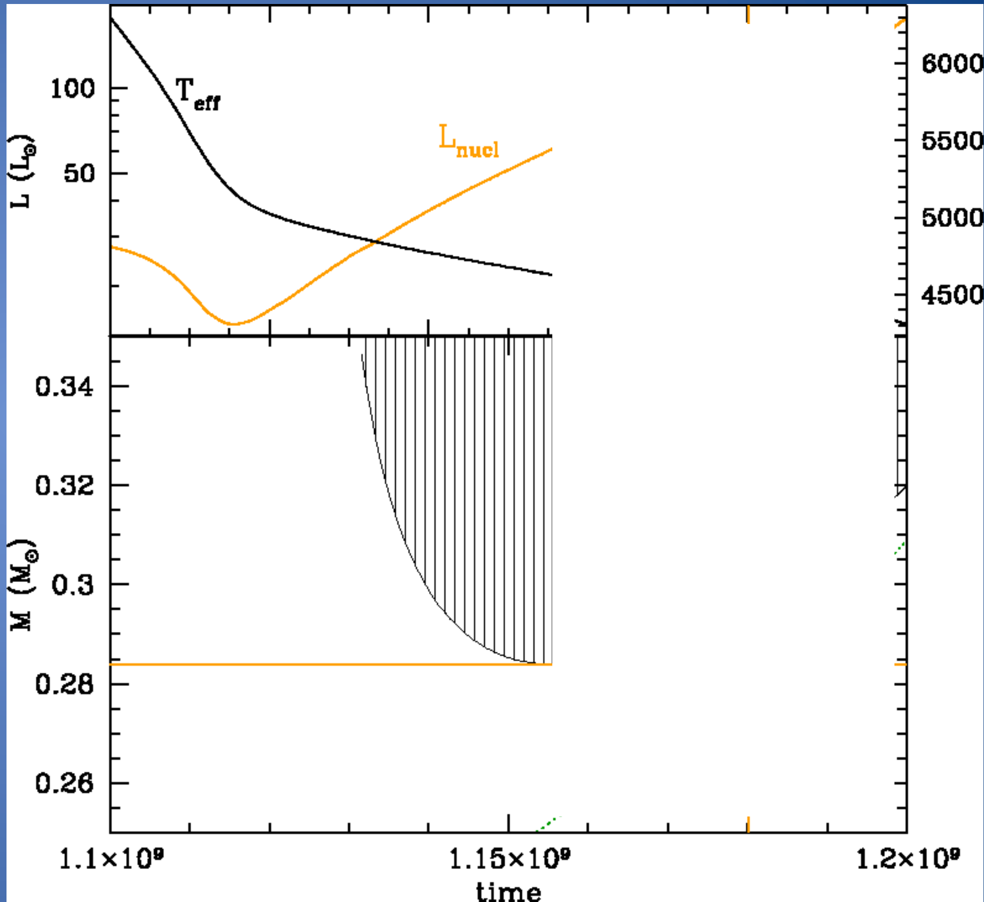


# Classical predictions

Iben (1967)




Mass fraction
100 x X($^3$He, $^{12}$C)
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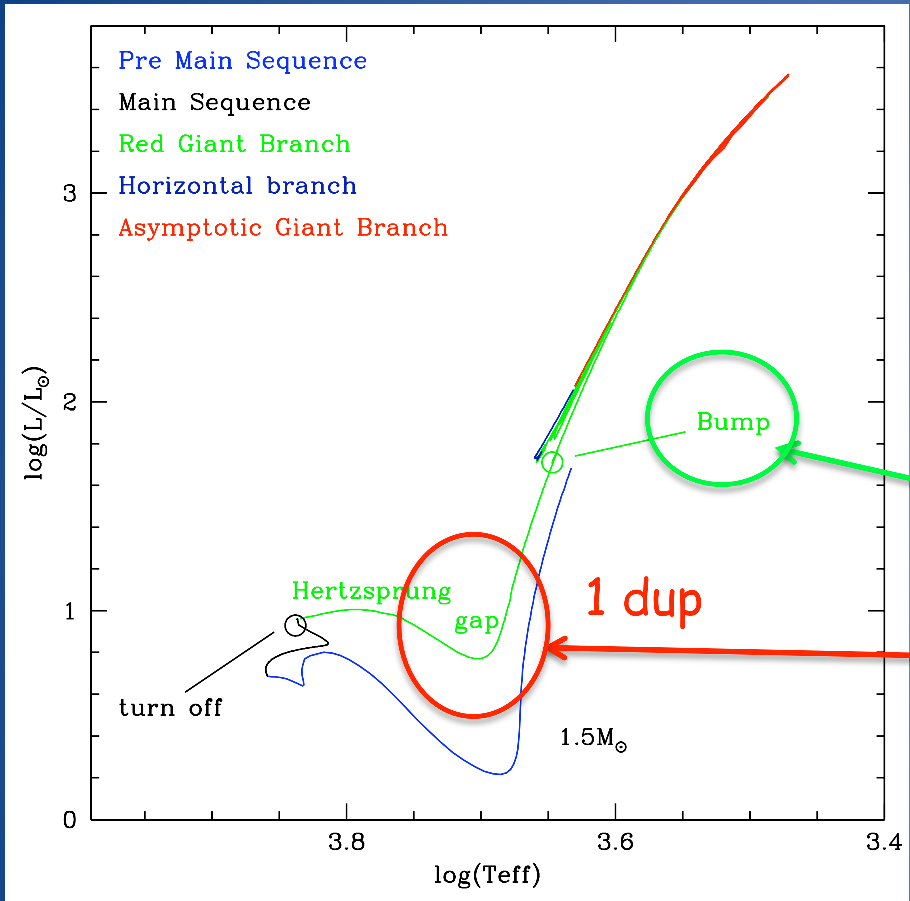
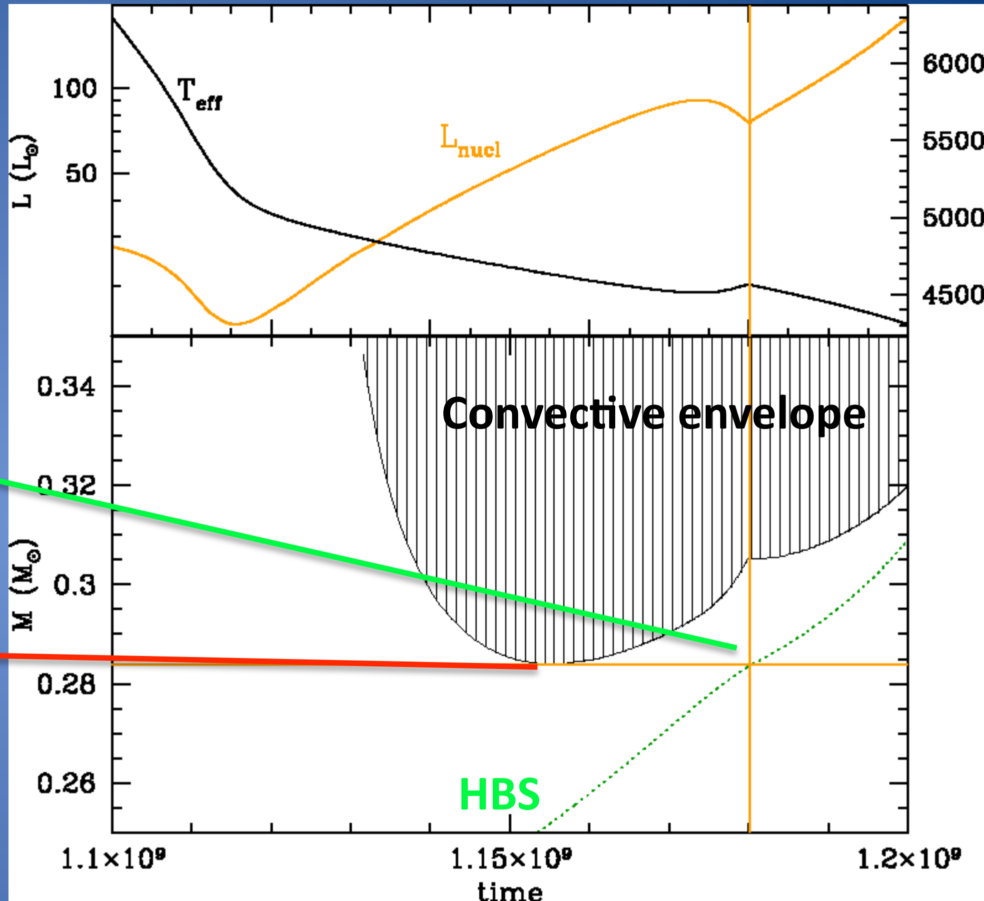
50 x X($^{14}$N, $^{16}$O)

**Predictions at the 1dup :**

$^{12}C/^{13}C$, Li, $^{12}C$ ↘
$^{14}N$, $^3He$, $^{13}C$ ↗
$^{16}O$ and the heavier elements stay constant

# Classical predictions



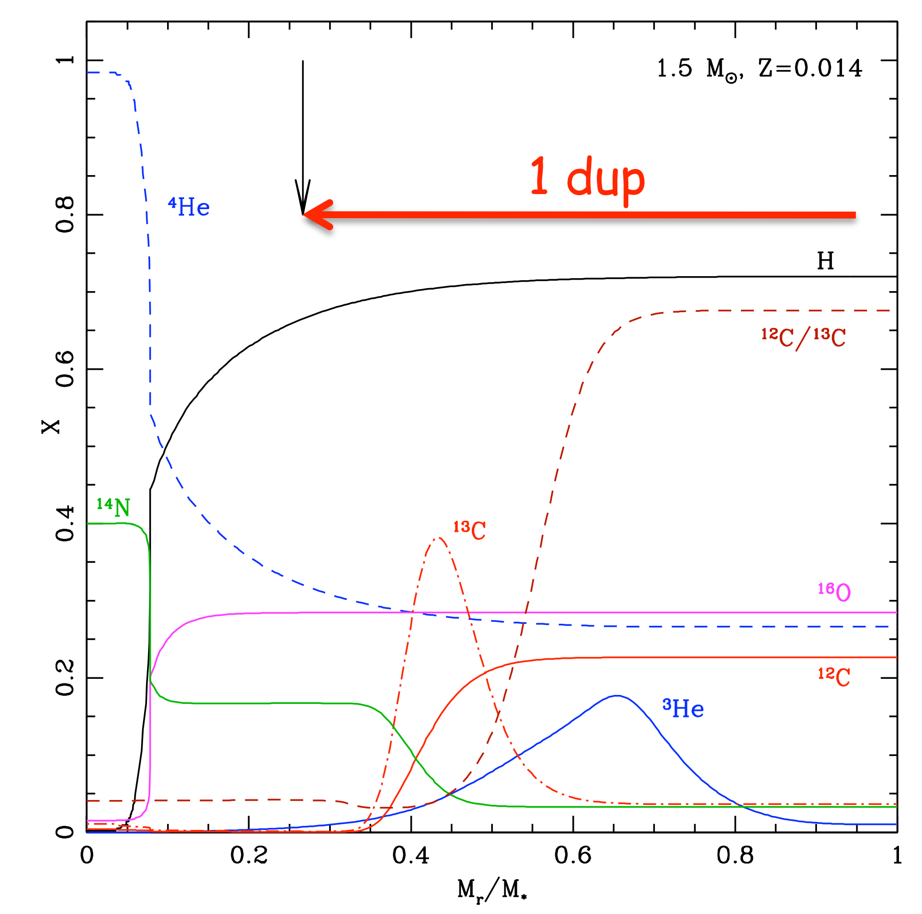



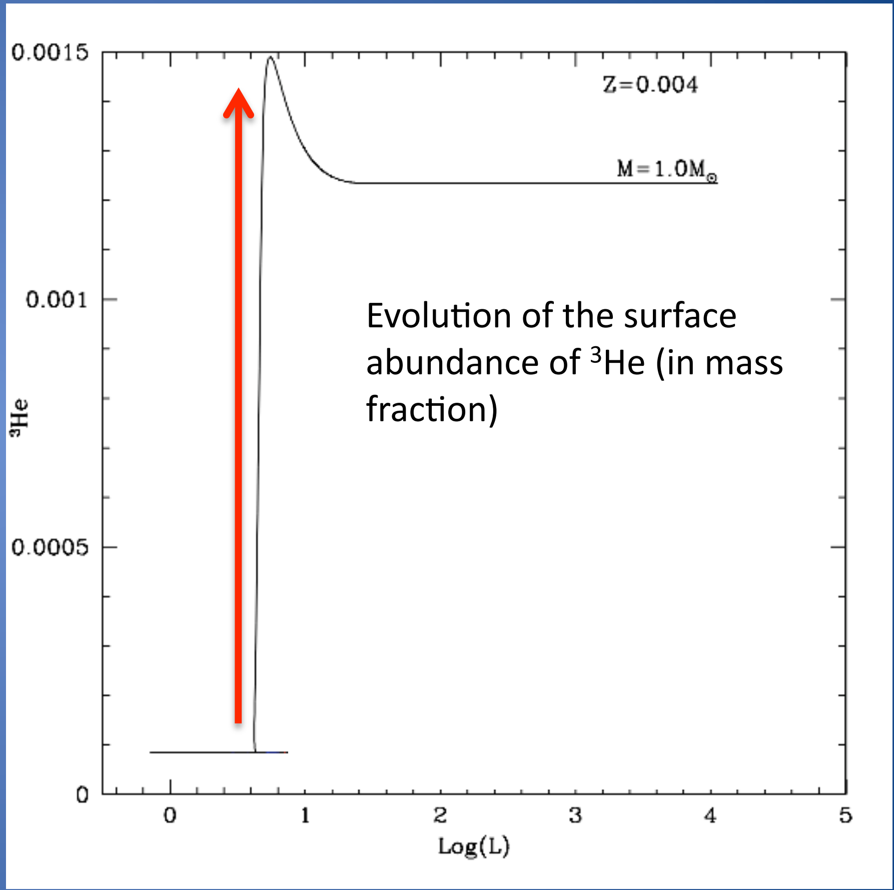

$L_{BUMP}$ = The hydrogen burning shell crosses the discontinuity left behind by the 1DUP.

-> decrease of molecular weight -> luminosity decreases

-> Hydrogen continues to burn in region with constant μ -> Luminosity increases

# Classical predictions : nucleosynthesis

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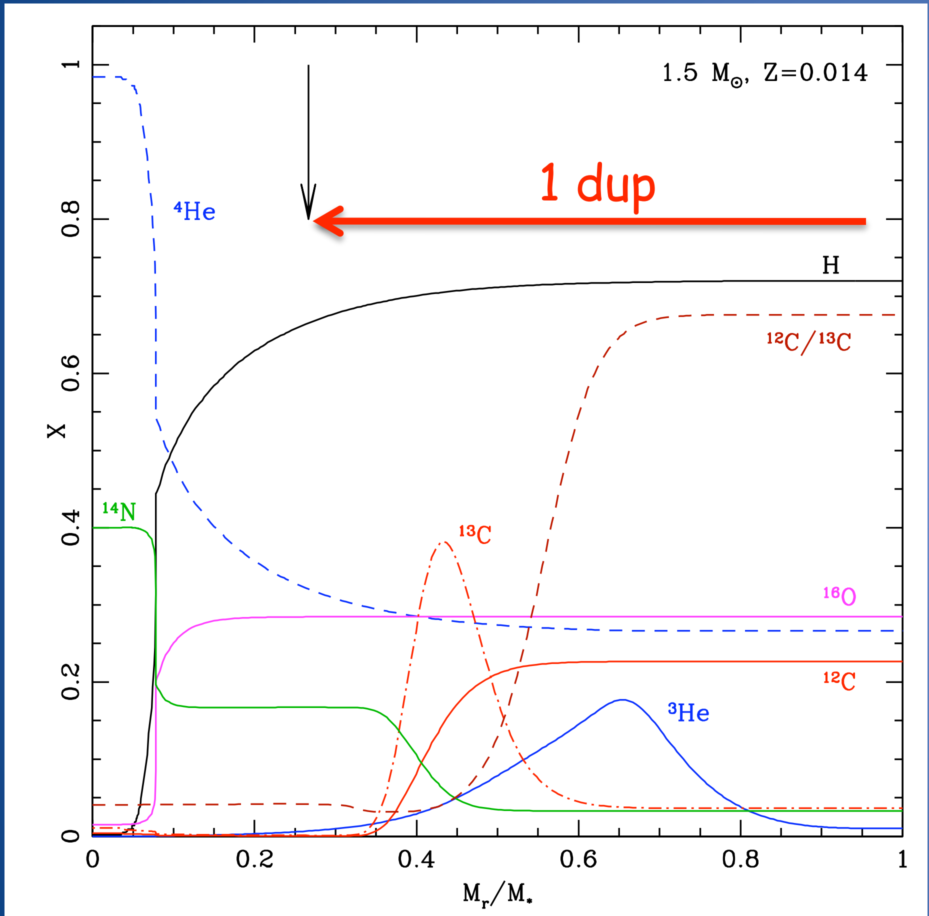
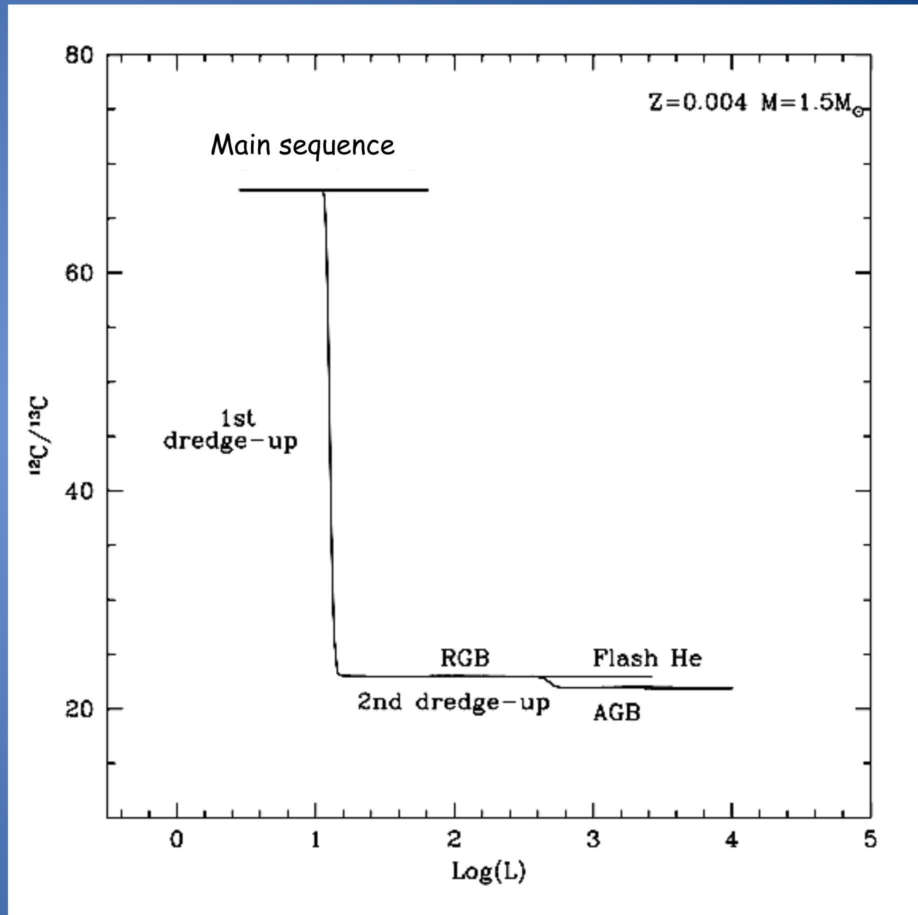
# Connection to abundance anomalies in RGBs

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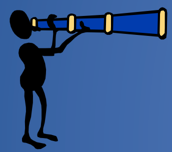
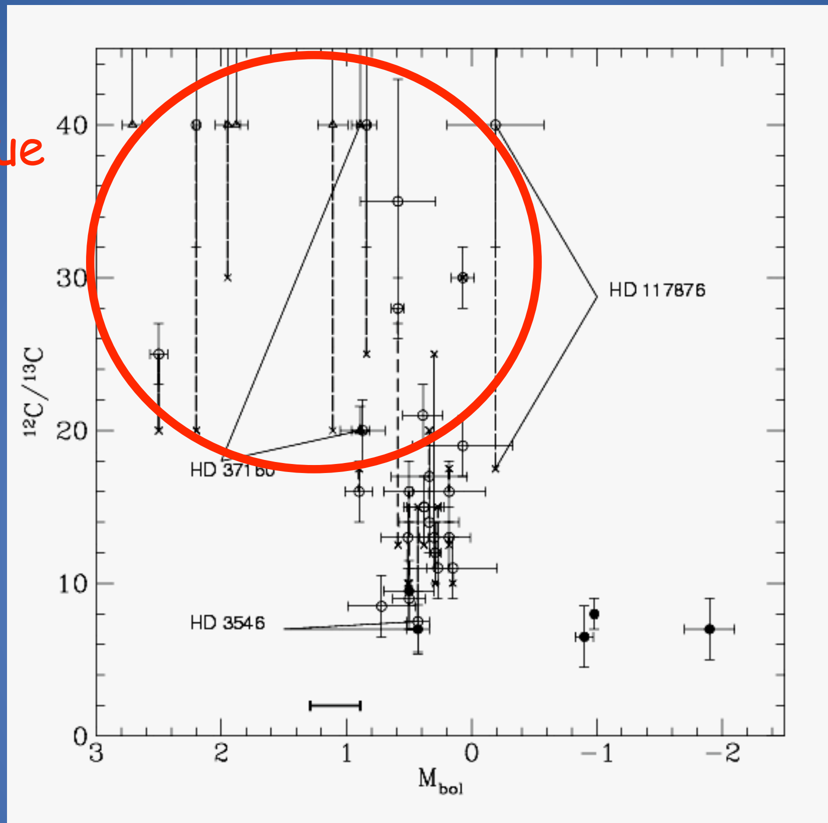


# II- Observational evidence for $2^{nd}$ mixing on RGB

# Classical predictions : 1st dredge-up

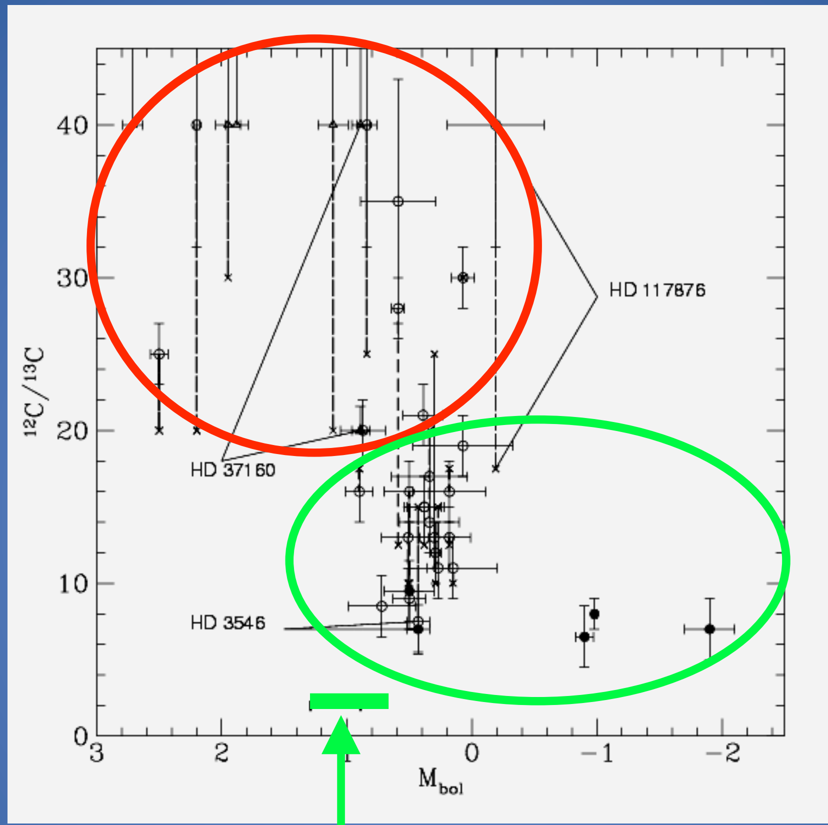
Post dredge-up value




Field stars with Π Hipparcos

Charbonnel, Brown & Wallerstein (98)

# Signature of "extra-mixing" at the L bump

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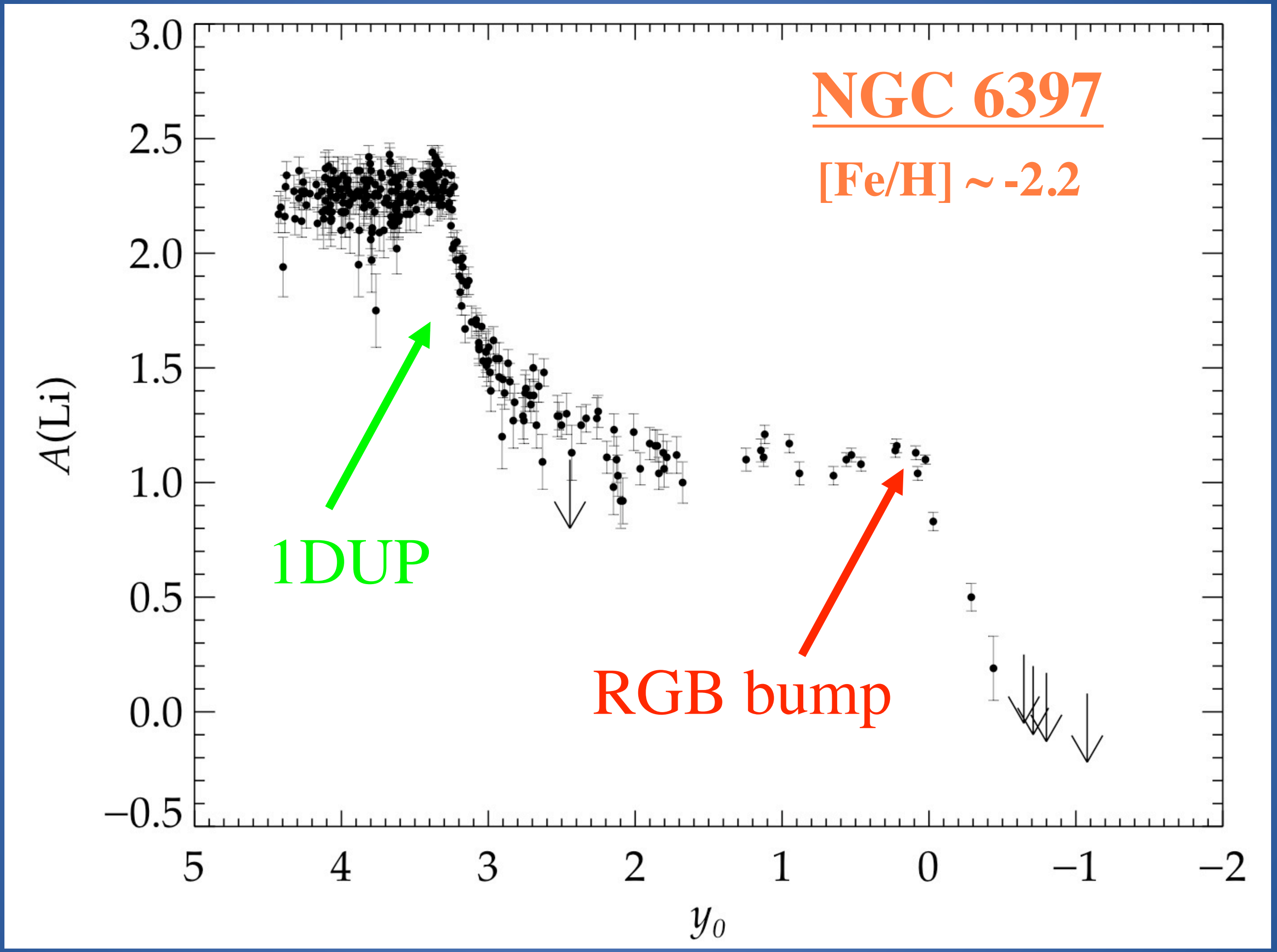
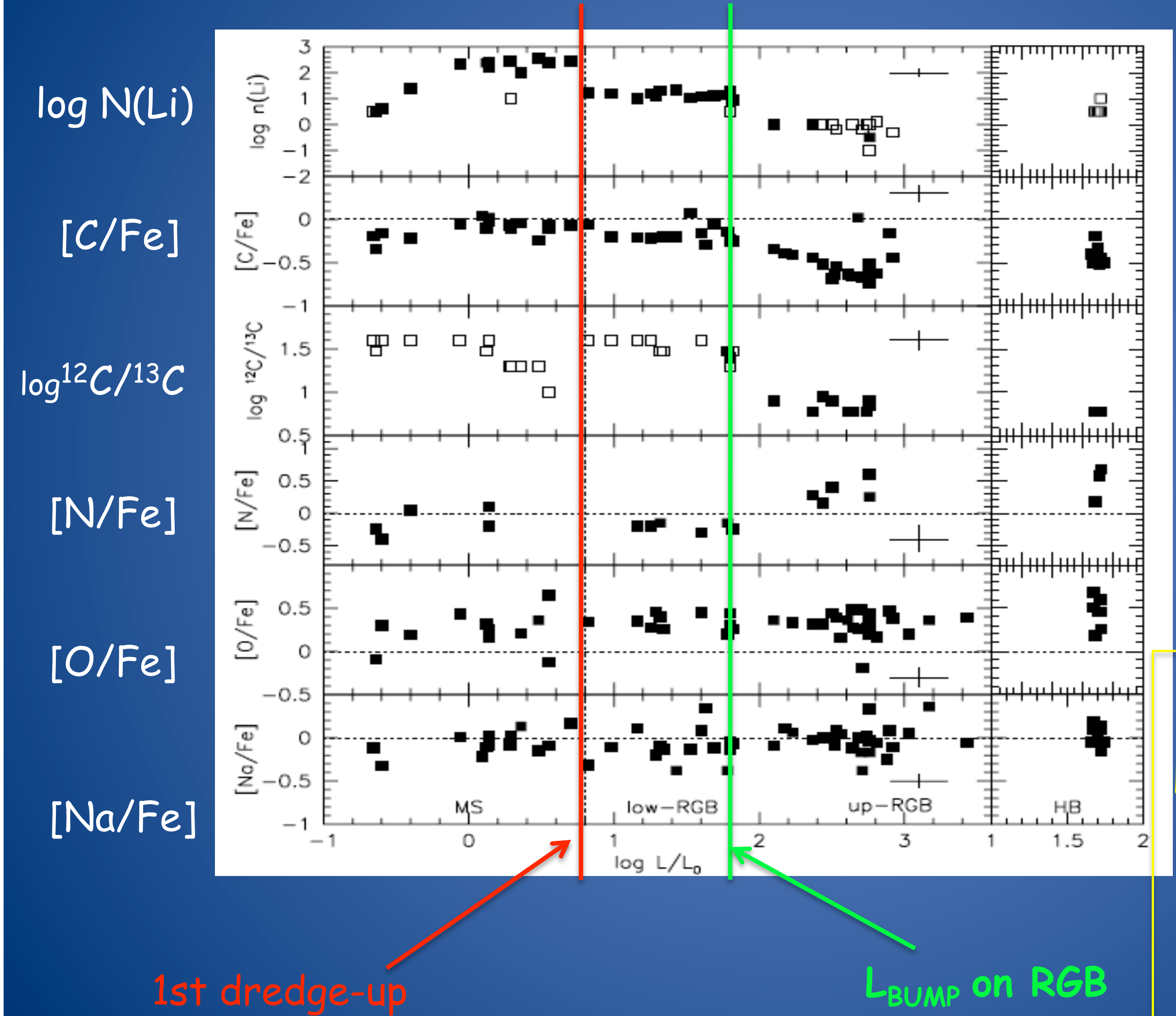



Lind, Primas, Charbonnel, Grundahl, Asplund (2009)

# Observations

Gratton et al. (2000)




At $L_{BUMP}$ :

Li, [C/Fe], $^{12}C/^{13}C$ ↘

[N/Fe] ↗

[O/Fe], [Na/Fe] ≈

# III. Transport processes

# Rotation-induced mixing

Zahn (92) and Maeder & Zahn (98)

Transport of angular momentum (advection and diffusion )

$$\rho \frac{\mathrm{d}\left(r^2\Omega\right)}{\mathrm{d}t} = \frac{1}{5r^2}\frac{\partial}{\partial r}\left(\rho r^4 \Omega U r\right) + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^4 \rho \nu_v \frac{\partial \Omega}{\partial r}\right)$$

Meridional circulation

(Shear) turbulence

Chemical species transport (diffusion)

$$\rho \frac{\mathrm{d}\overline{c_i}}{\mathrm{d}t} = \dot{c}_i + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \rho U_{\mathrm{diff}} \overline{c_i}\right] + \frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2 \rho \left(D_{\mathrm{eff}} + D_v\right) \frac{\partial \overline{c_i}}{\partial r}\right]$$

Nuclear reactions

Atomic diffusion

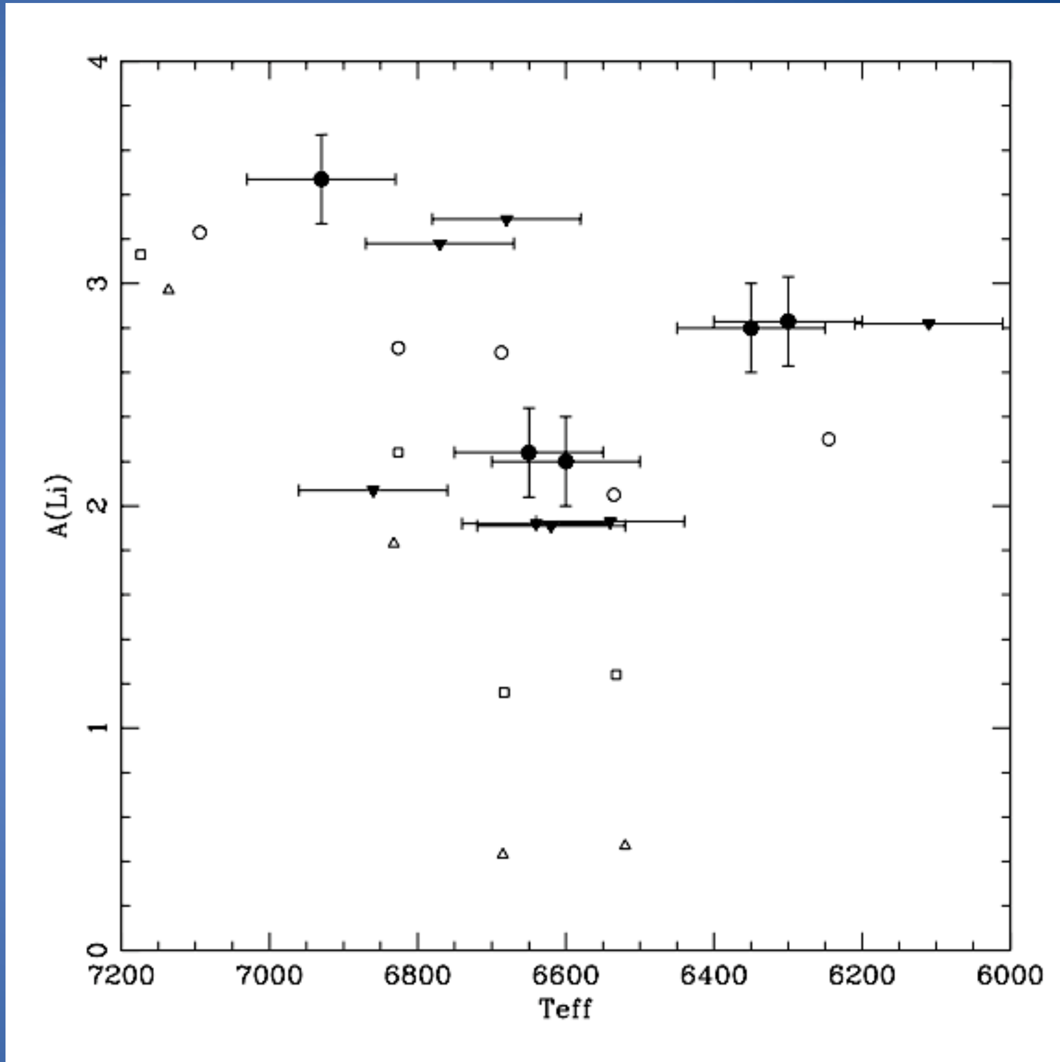
Meridional circulation and shear turbulence

# Open cluster IC 4651 : A(Li) & A(Be)

1. Main sequence stars

Observations :
● = exact values
▼ = higher values

Models :
○ = $V_{ZAMS}$=50km/s
□ = $V_{ZAMS}$=80km/s
△ = $V_{ZAMS}$=110km/s




Smiljanic , R.; Pasquini, L.; Charbonnel, C.; Lagarde, N. (2009)

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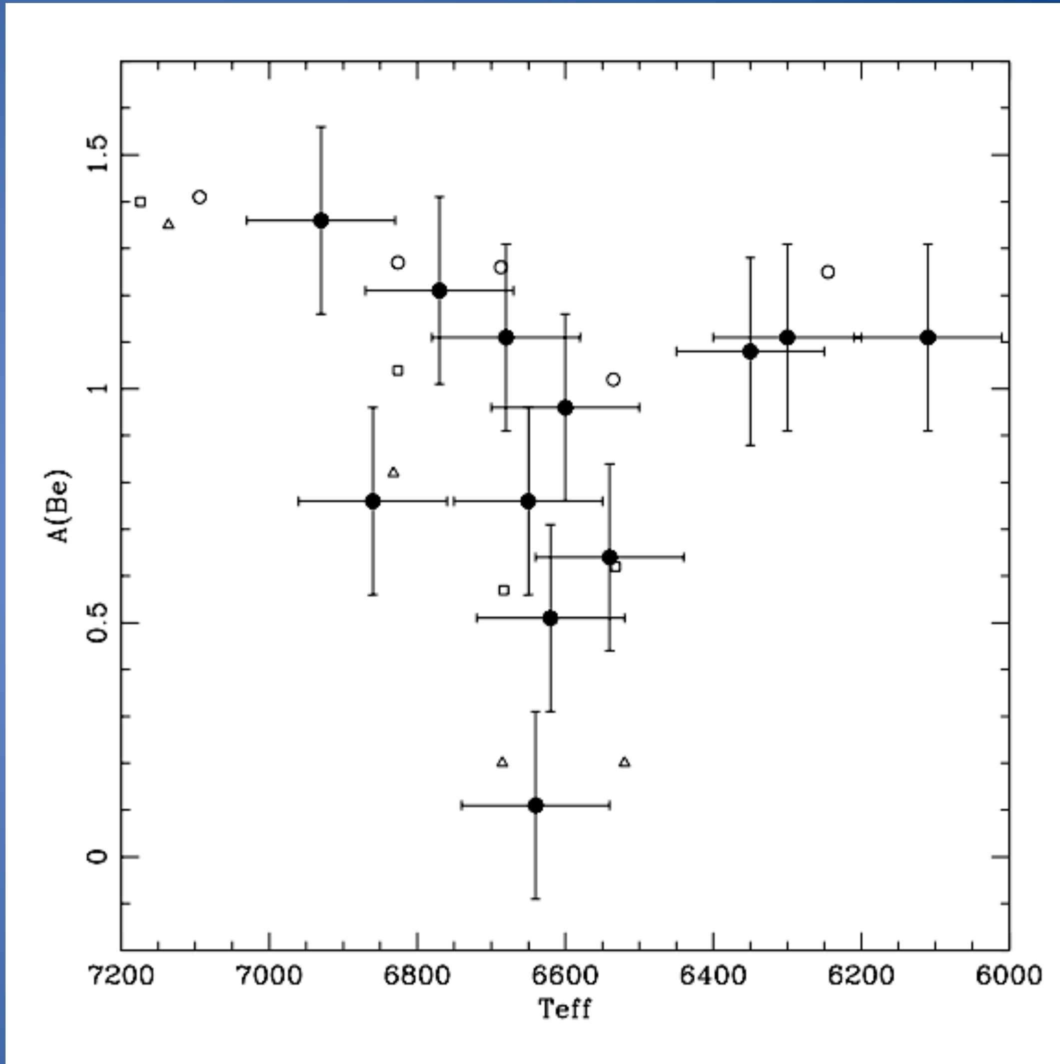
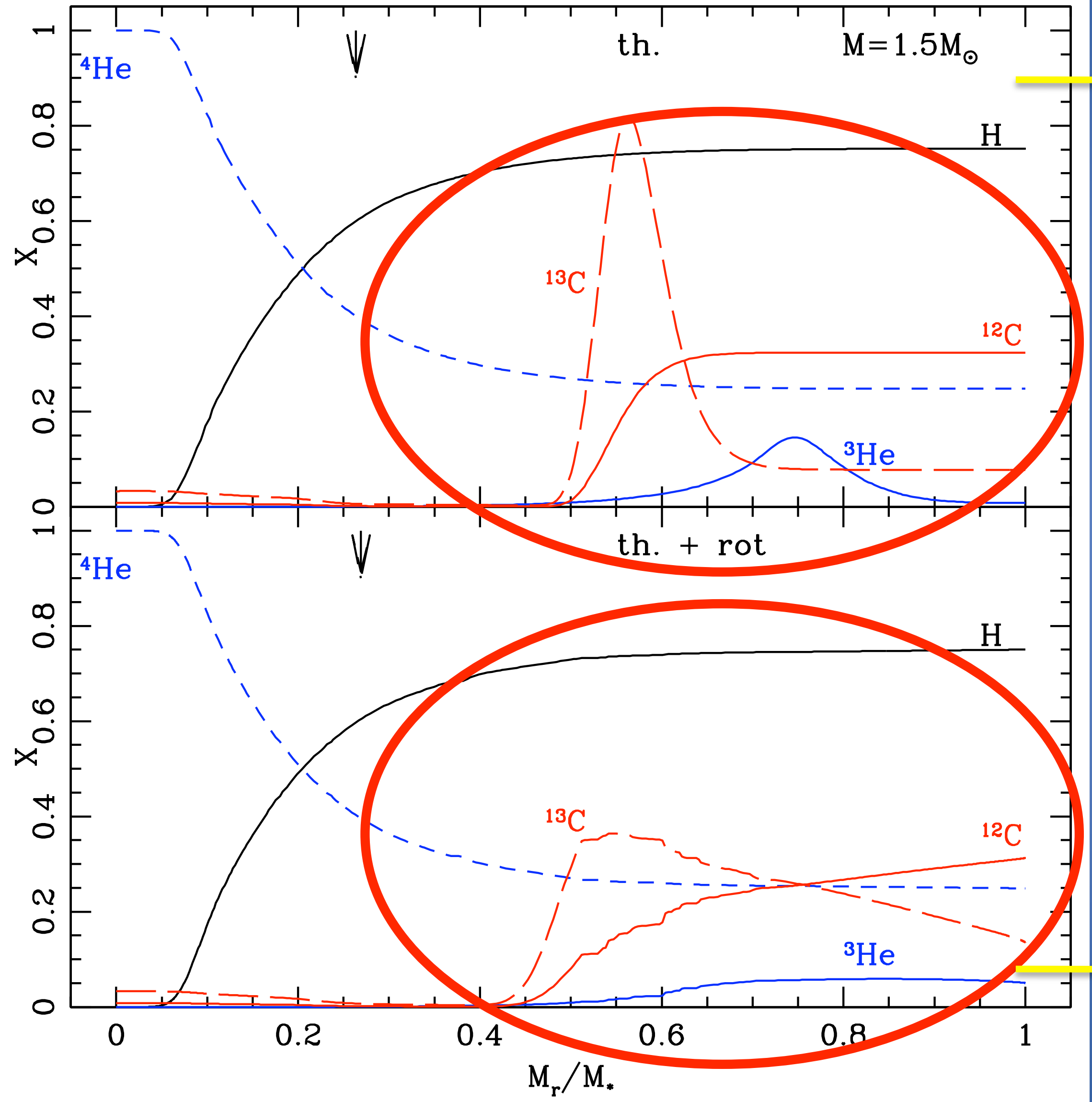



Smiljanic , R.; Pasquini, L.; Charbonnel, C.; Lagarde, N. (2009)

# Rotation-induced mixing




Without rotation

**Rotation :**

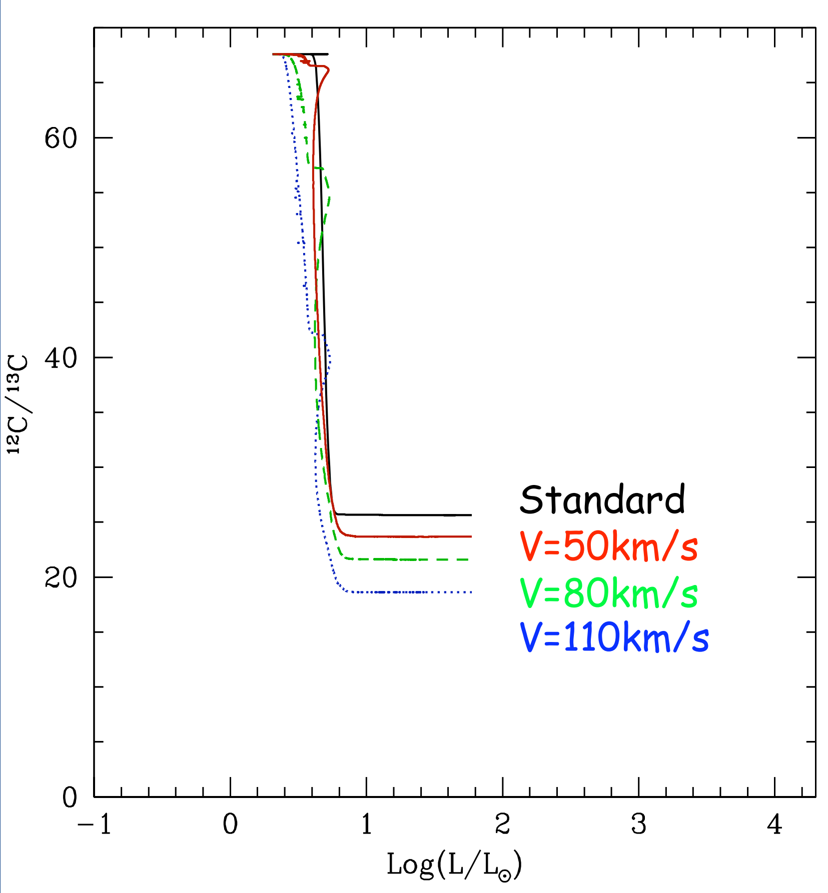
-> $^{3}$He $^{13}$C diffuse outwards
-> $^{12}$C diffuses inwards

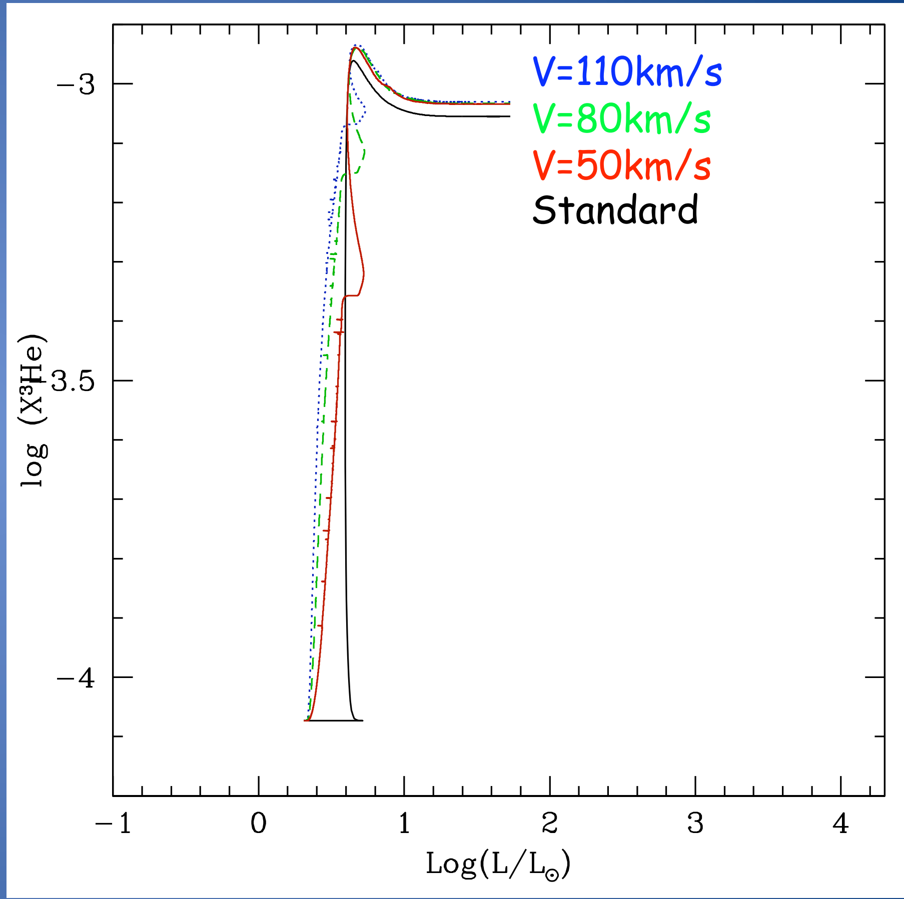
-> Rotation-induced mixing has an impact on the internal abundance profiles during the MS.

With rotation

Abundances profiles at the end of Main sequence.

# Rotation-induced mixing




The post dredge-up $^{12}C/^{13}C$ ratios is lower than in non-rotating case.

More $^{3}He$ is brought into the stellar envelope than in non rotating case.

# Open cluster IC 4651 : A(Li) & A(Be)

2. Subgiant stars

____ Classical models

Models with thermohaline and rotation :

------ $V_{ZAMS}$=80 km/s

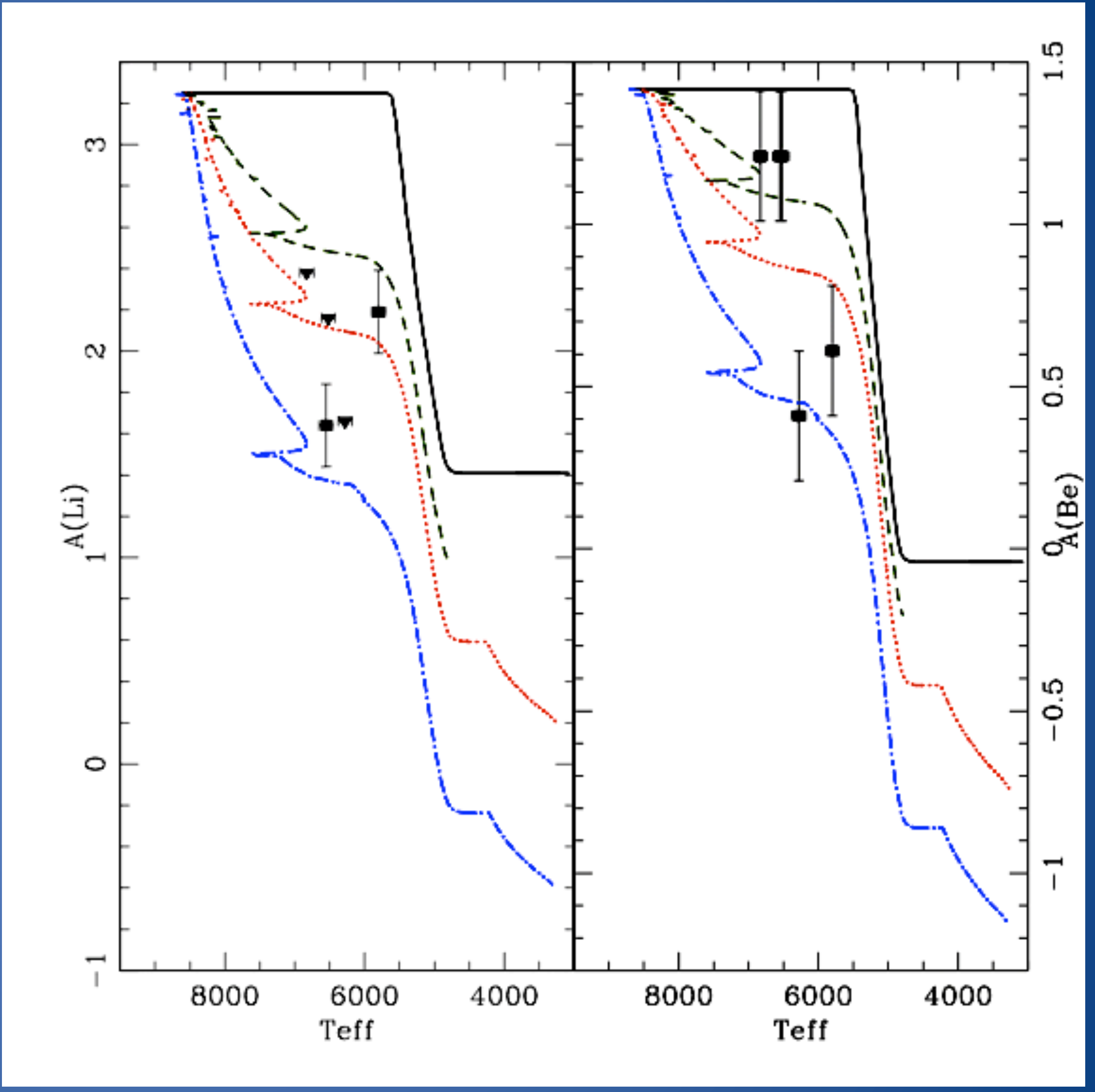
------ $V_{ZAMS}$=110km/s

------ $V_{ZAMS}$=180 km/s

Observations :

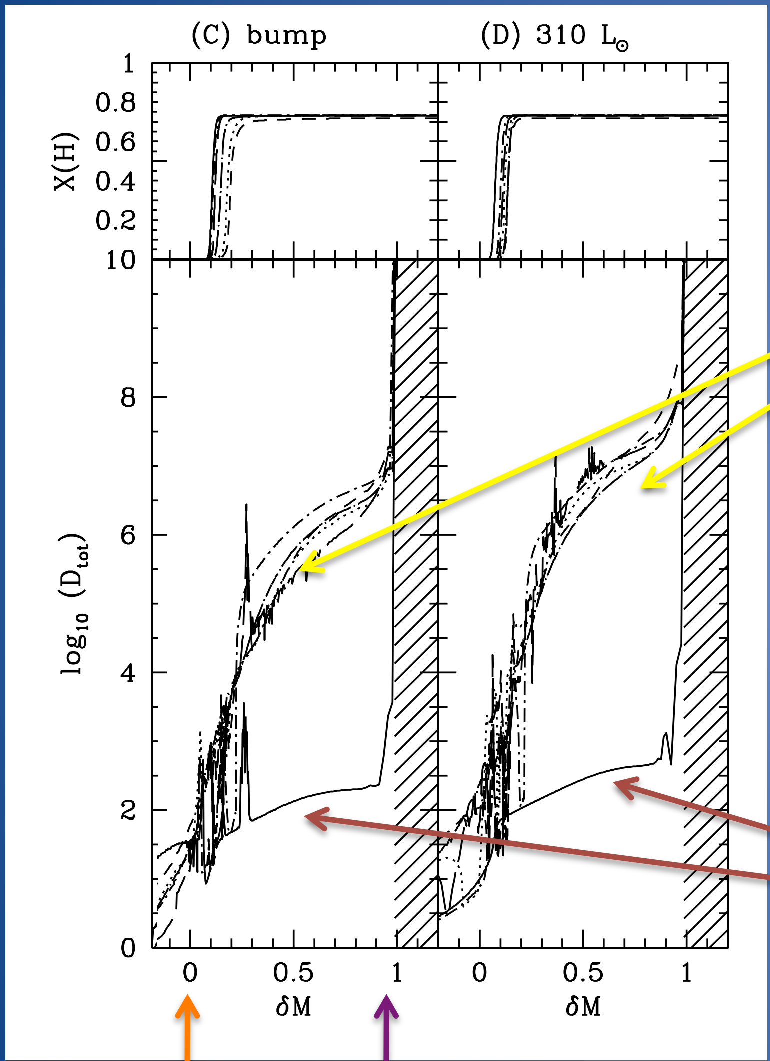
● = exact values

▼ = higher values




Smiljanic , R.; Pasquini, L.; Charbonnel, C.; Lagarde, N. (2009)

# Rotation-induced mixing on RGB




Diffusion coefficient with differential rotation in CE.

Large differential rotation -> Shear flow becomes turbulent

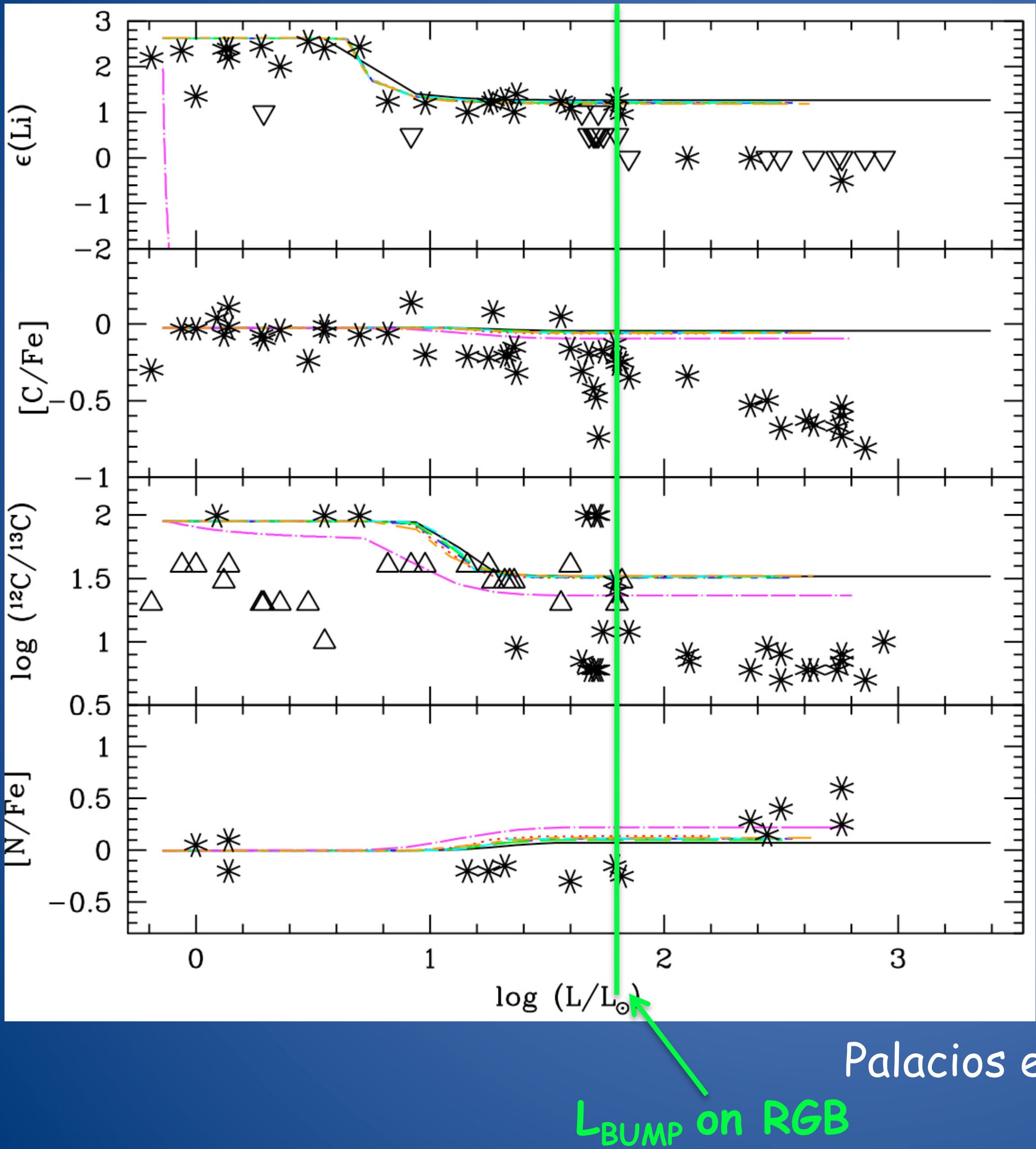
Uniform angular velocity (solid rotation) in CE.
Negligible differential rotation below the CE

Base of HBS
δM=0

Base of CE
δM=1

Palacios et al. 2006

# Effects of rotation on RGB




Rotation-induced mixing is not efficient enough to noticeably change the surface abundance

Palacios et al. 2006

# III.b Thermohaline mixing

# Mean molecular weight (μ) inversion

Reaction $^3He$ $(^3He,2p)$ $^4He$

$$\nabla_\mu = \frac{d\ln\mu}{d\ln P} < 0$$

Eggleton et al. (06),
Kippenhahn (80),
Ulrich (72)

Ulrich (72) : this reaction produces more particles per units mass than it started from

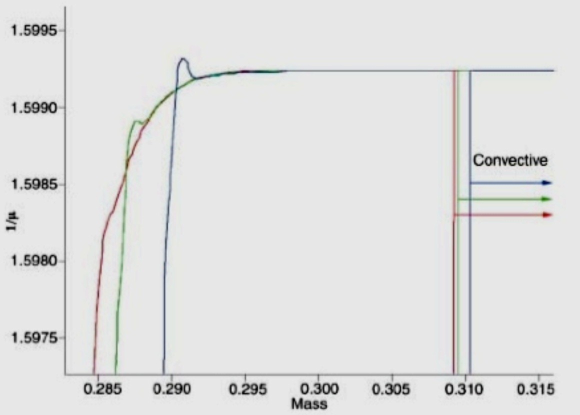



**Fig. 3.** The profile of reciprocal molecular weight (1/μ), as a function of mass in solar units, at three successive times (red, then green 2 million years later, then blue 2 million years later still).

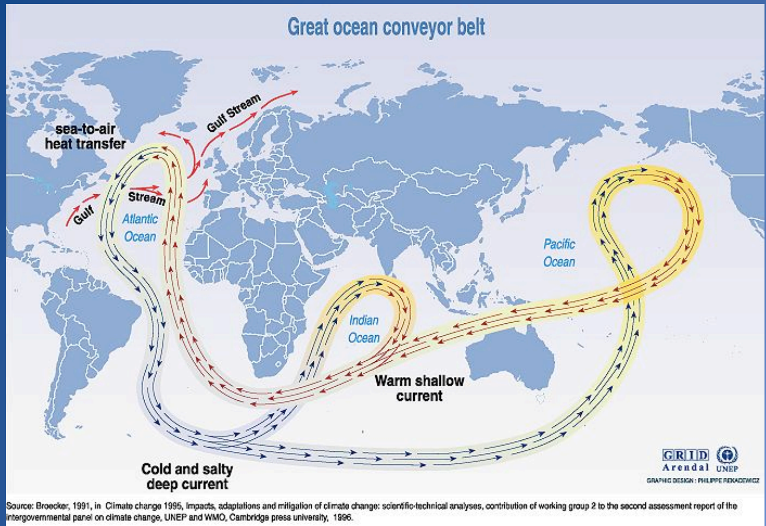
Eggleton et al. : 3D hydrodynamic code to model a low-mass star at the RGB tip

↓

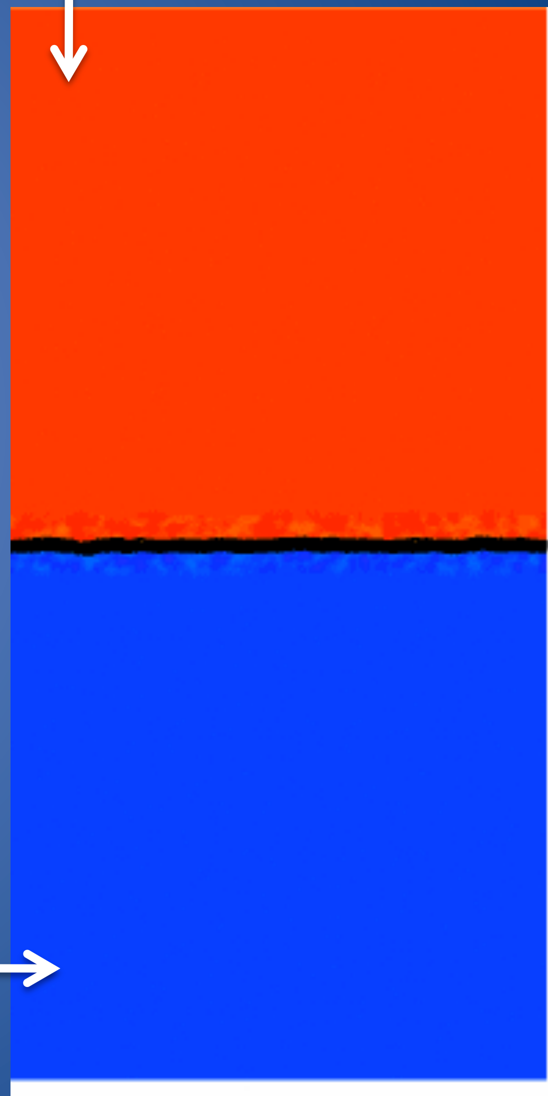
The inverse μ-gradient builds up
Such a μ-profile leads to efficient mixing.

The instability responsible for that mixing is the Rayleigh-Taylor instability
=> convective instability

# Thermohaline circulation




warm salty water



- refers to the part of the large-scale ocean circulation
- The density of ocean water is controlled by temperature (thermo-) and salinity ( - haline), and the circulation driven by density differences is called the thermohaline circulation
- Thermohaline mixing takes a form of salt fingers

cool fresh water

From ICOM - Department of Earth Science and Engineering, Imperial College London.

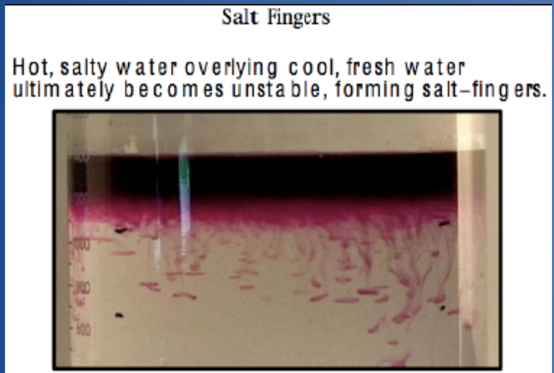
# Thermohaline mixing

Reaction $^{3}He\ (^{3}He, 2p)\ ^{4}He$

$$\nabla_{\mu} = \frac{d\ln\mu}{d\ln P} < 0$$

Eggleton et al. (06), Kippenhahn (80), Ulrich (72)

✧ Thermohaline mixing Charbonnel & Zahn (07)




Krishnamurti (03)

Th. instability differs from the convective instability in that it involves two components, of which one, the stabilizing one (T) diffuses faster than the other (salt) whose stratification is unstable.

$$D_t = C_t K \left(\frac{\varphi}{\delta}\right) \frac{-\nabla_{\mu}}{(\nabla_{ad} - \nabla)}$$

$$\varphi = \left(\frac{d\ln\rho}{d\ln\mu}\right)_{P,T}$$

$$\delta = -\left(\frac{d\ln\rho}{d\ln T}\right)_{P,\mu}$$

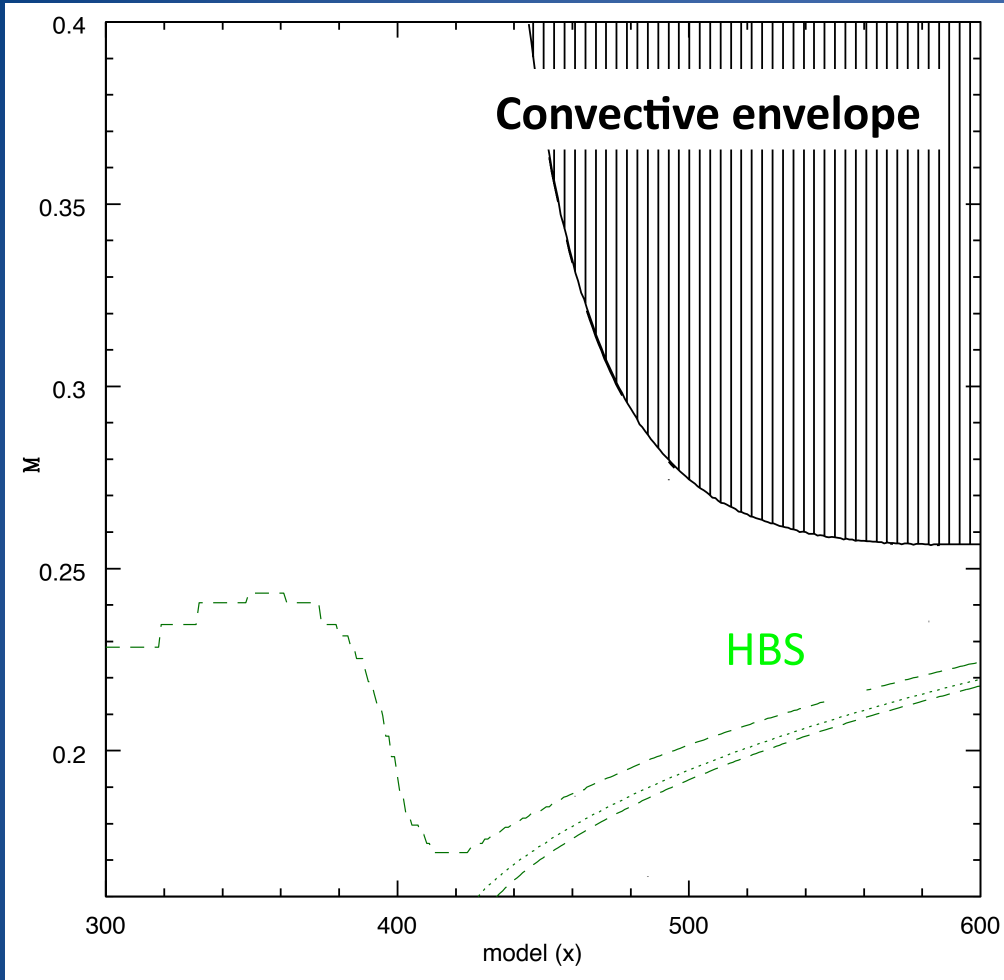
$$C_t = \frac{8}{3}\pi^2\alpha^2$$

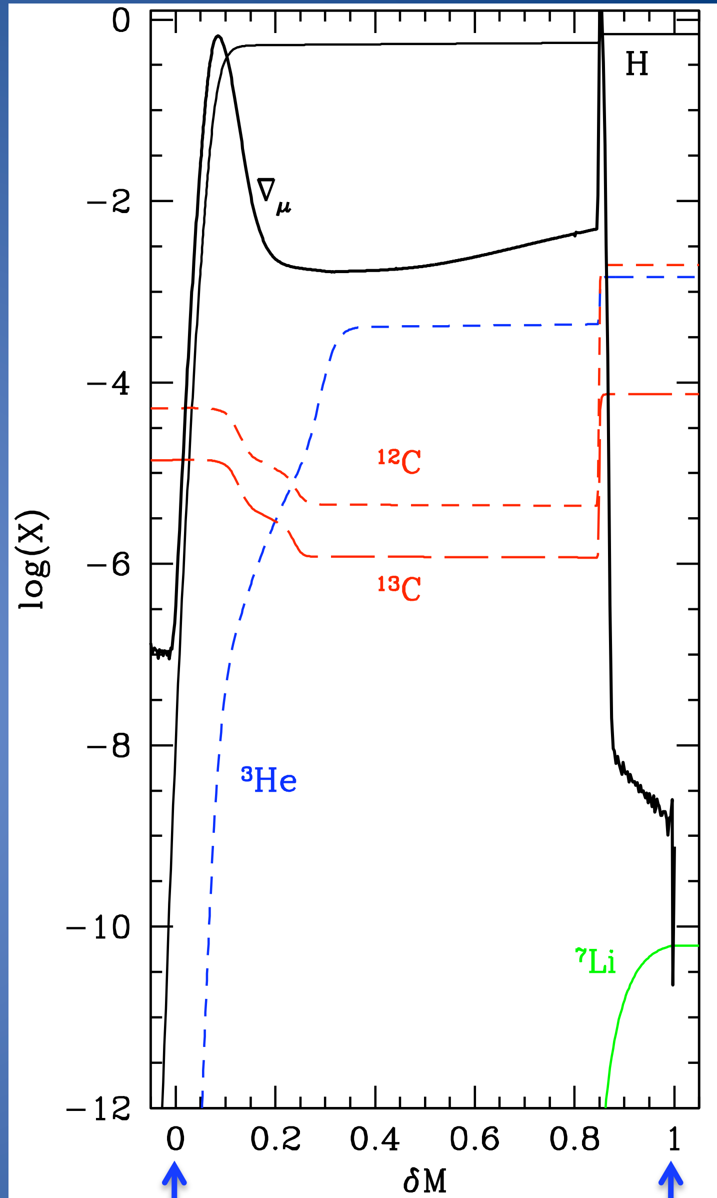
α =aspect ratio (length / width) of the fingers ~ 5

- Stern (60)
- C-rich material deposited at the surface of a star in a mass transferring binary (Stothers & Simon 69; Stancliffe et al. 07)
- Accretion of heavy elements during planet formation (Vauclair 04)
- Iron accumulation in A-F stars (Théado et al. 09)

Where and How this mixing takes place in RGB stars ??

# 1 dredge-up



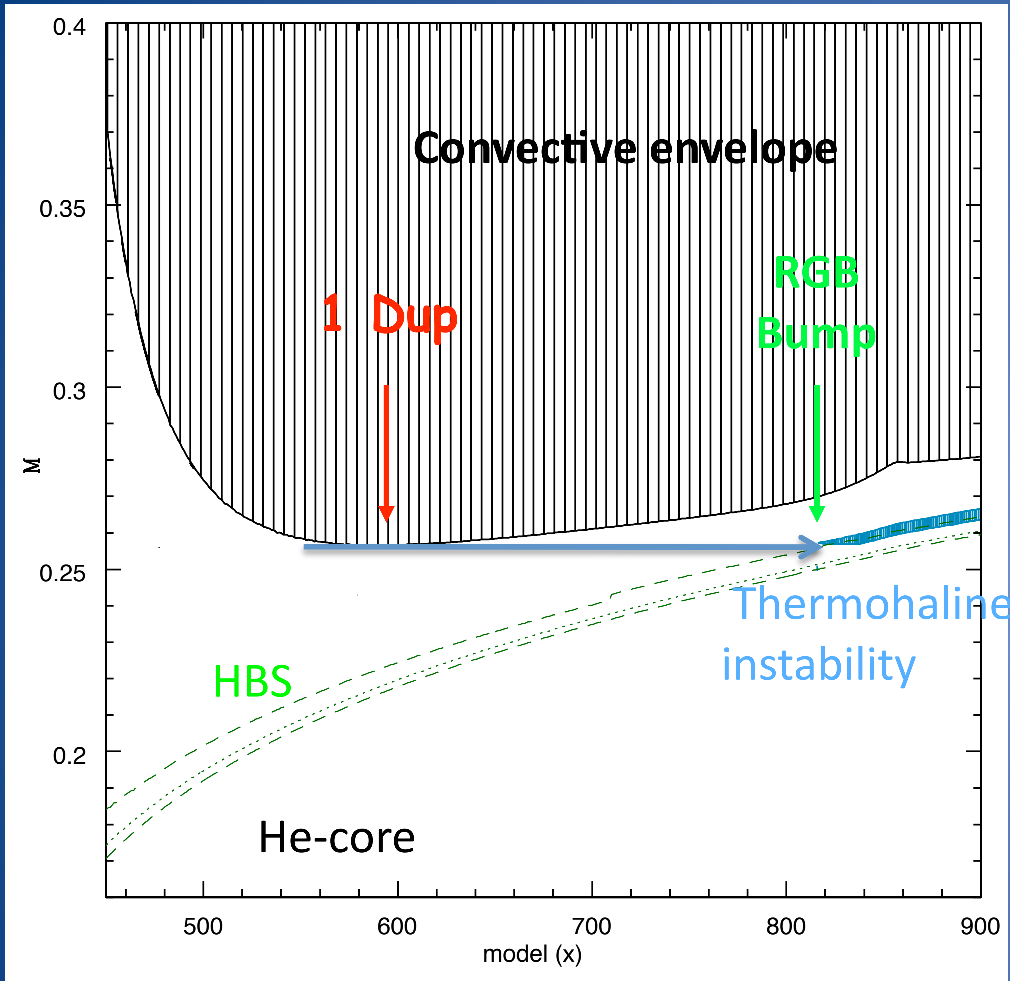




Base of HBS

Base of CE

During 1DUP, convective envelope :
-> homogemises the stars down to very deep regions and builds a very steep gradient of molecular weight
-> dillute chemical species in these regions

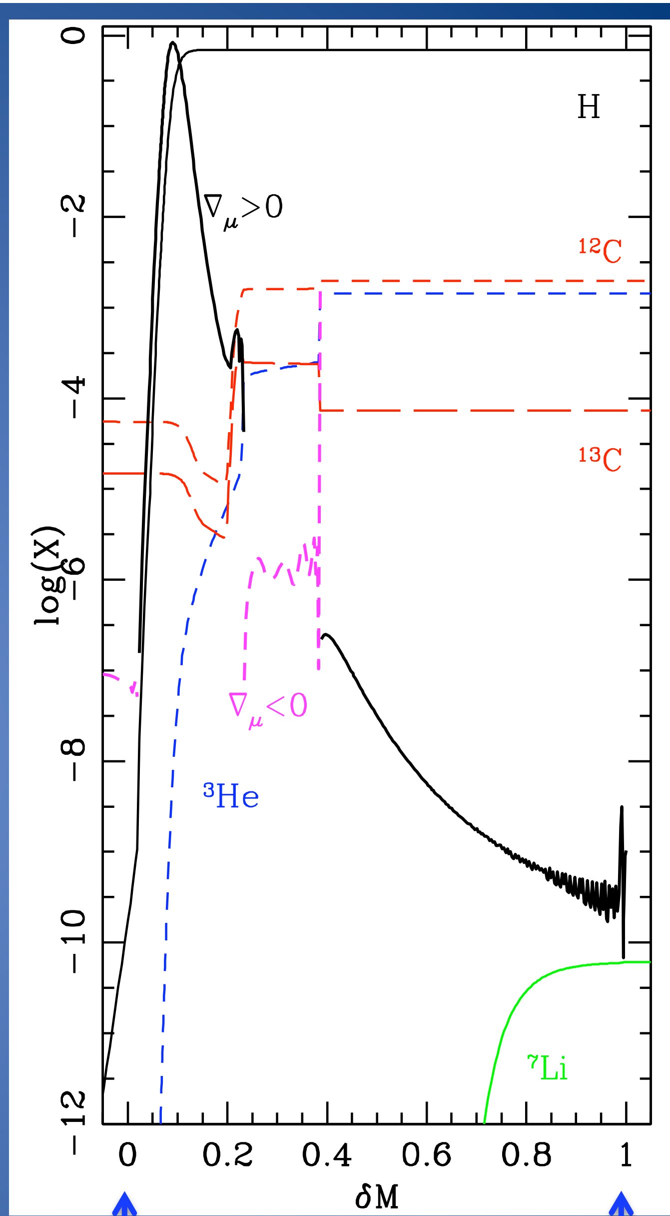
# BUMP




$^3He+^3He \rightarrow ^4He+2p$ decreases the molecular weight

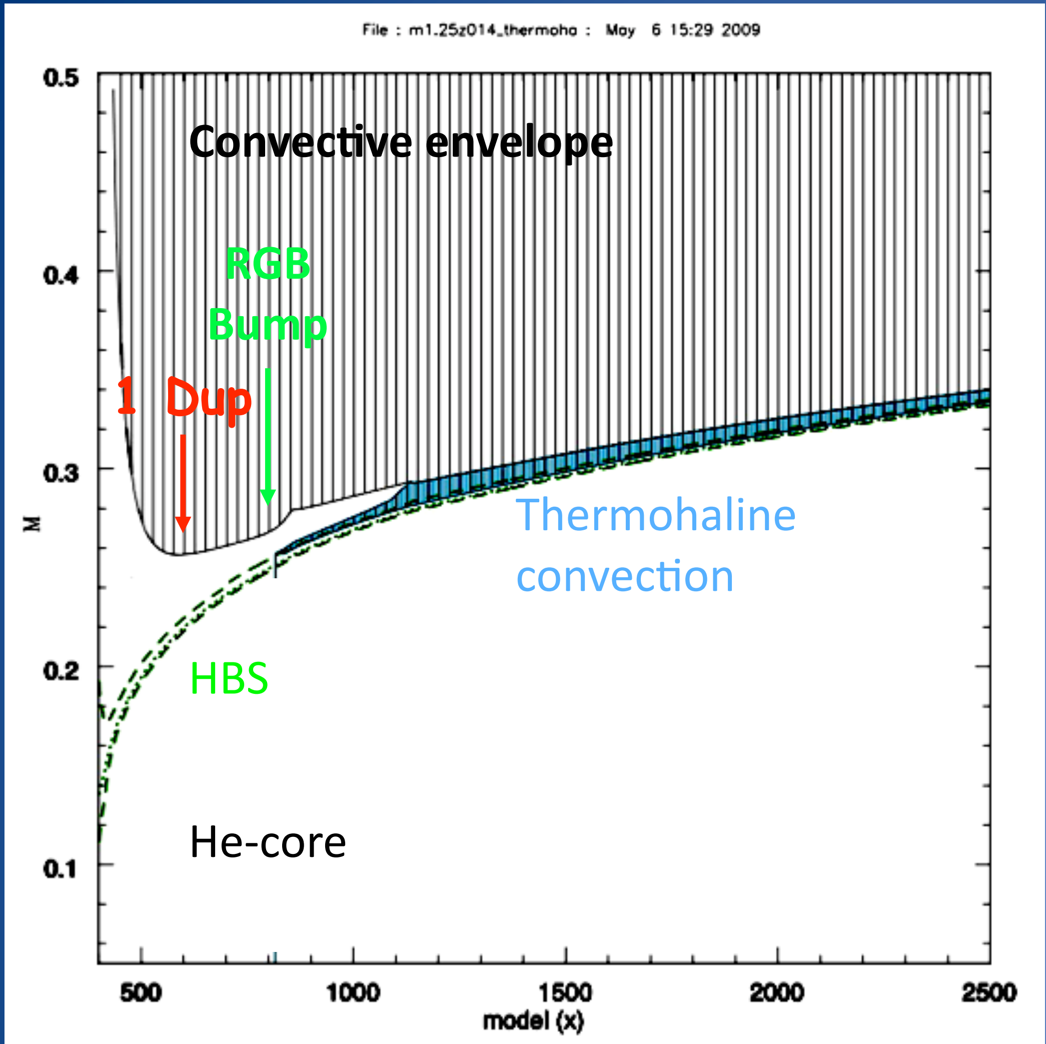
-> gradient of μ becomes negative

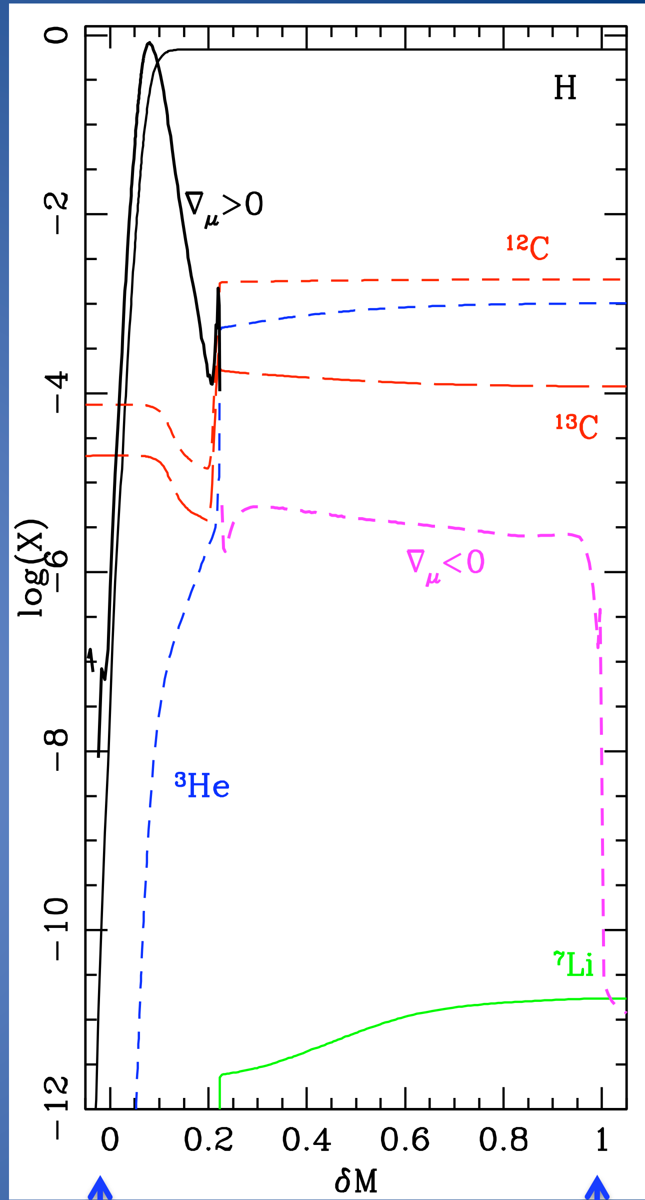
-> thermohaline instability develops between the $^3He$ burning region and CE




Base of HBS

Base of CE



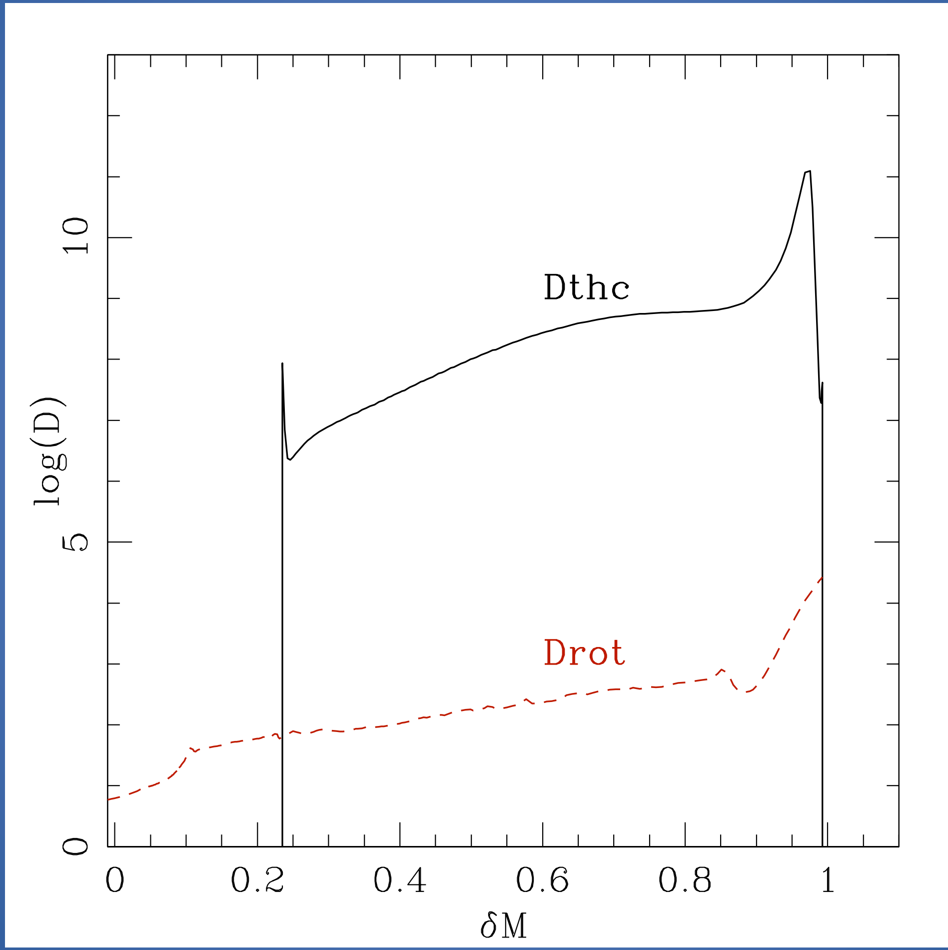

Base of HBS

Base of CE

Thermohaline mixing "connects" HBS and CE

-> changes in the surface abundances

# Diffusion coefficients : Rotation & Thermohaline

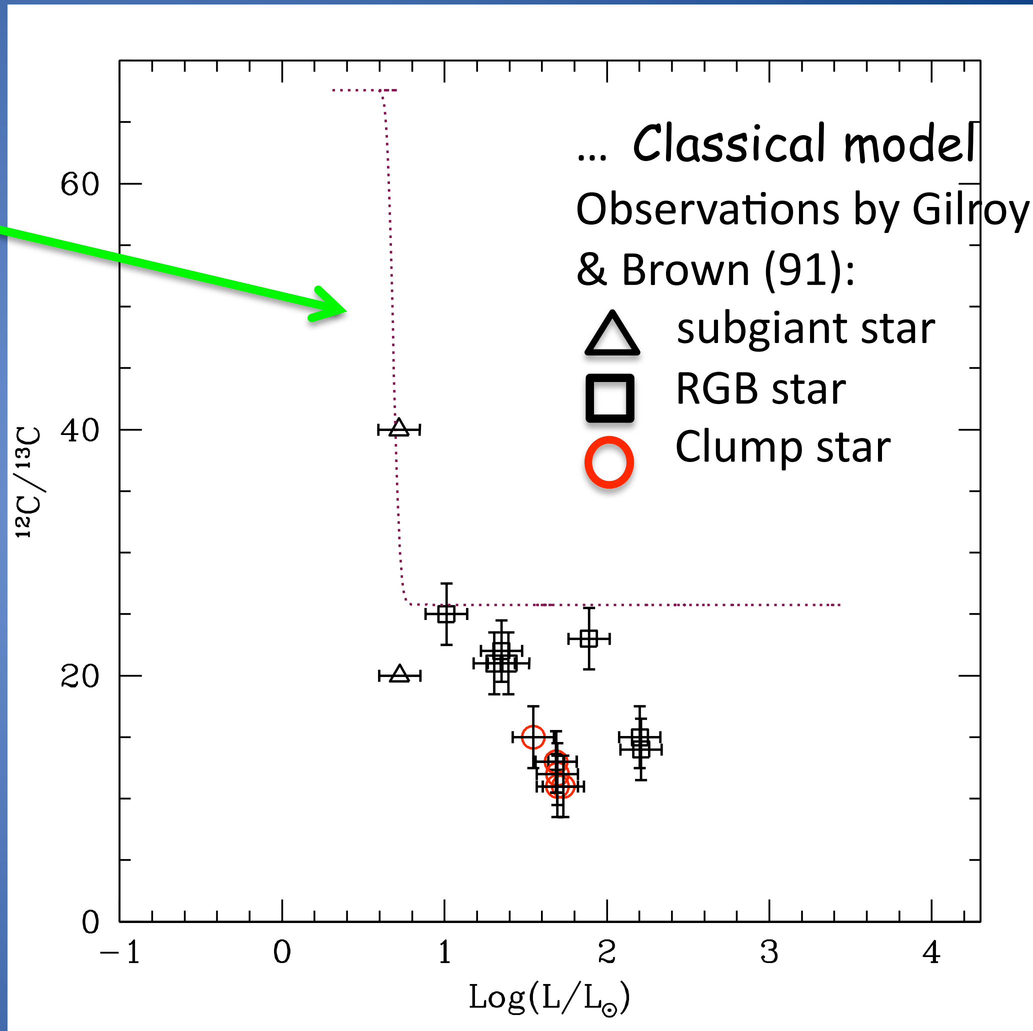



Dthc is 5 to 6 orders of magnitude higher than Drot, and it is independant of the initial rotation velocity on th ZAMS.

# IV. Comparison of models predictions with observations

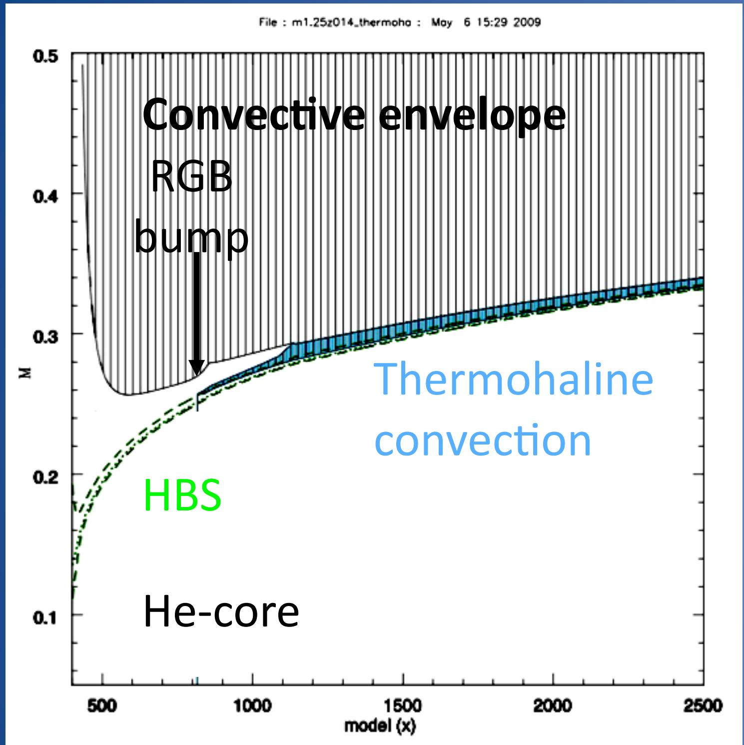
# Standard predictions ($1.25 M_\odot$)/ M67 ($M_{TO}=1.2 M_\odot$)

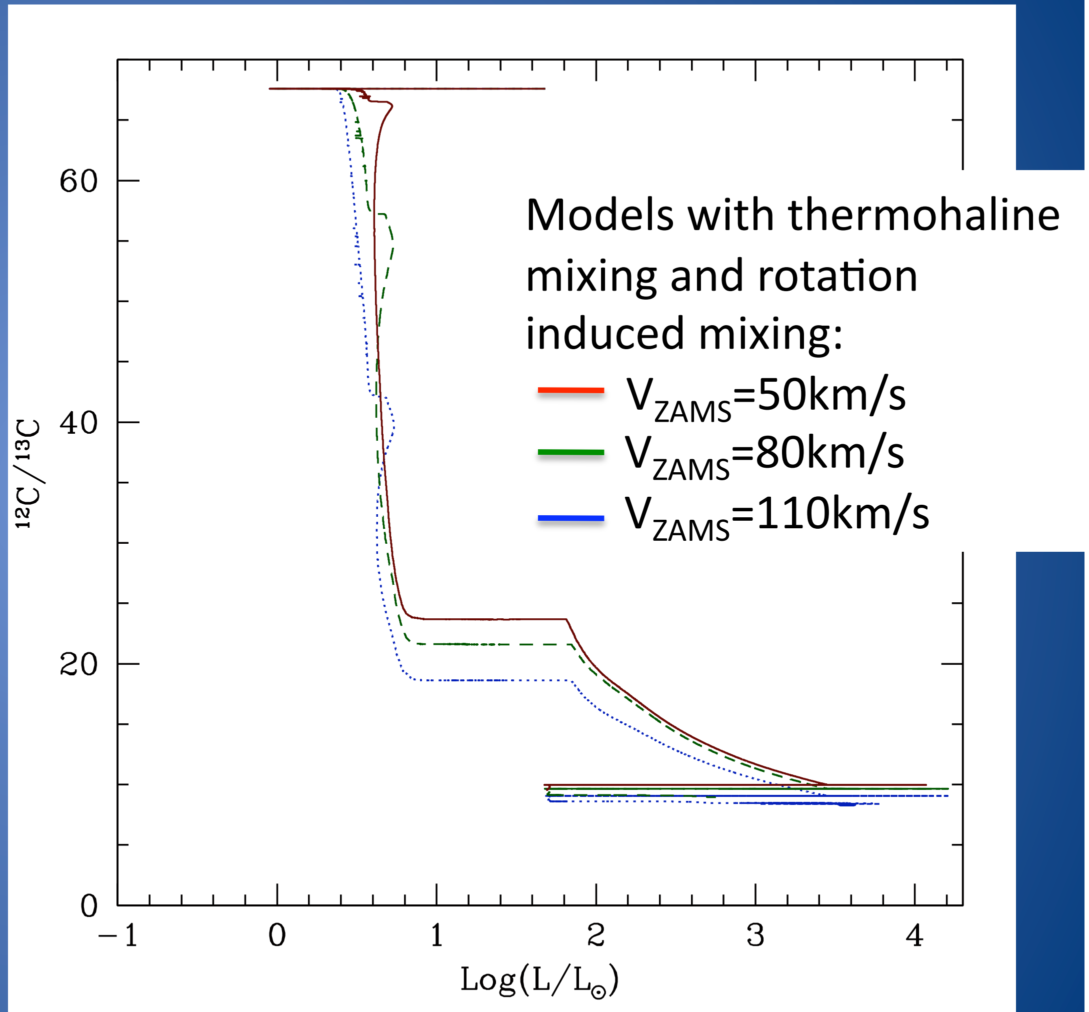
1er dredge-up




Charbonnel & Lagarde (2010)

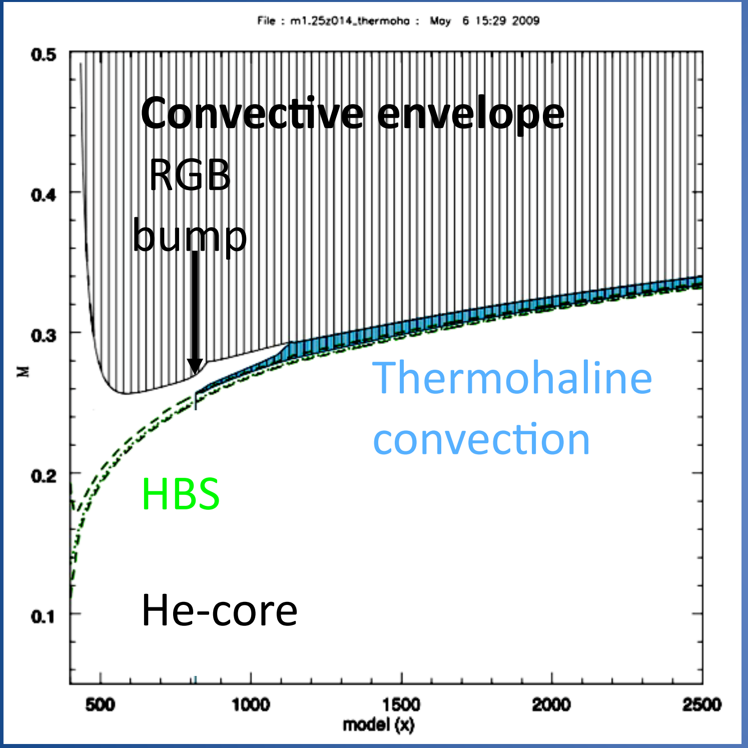
# Models (1.25M$_{\odot}$) at different velocities

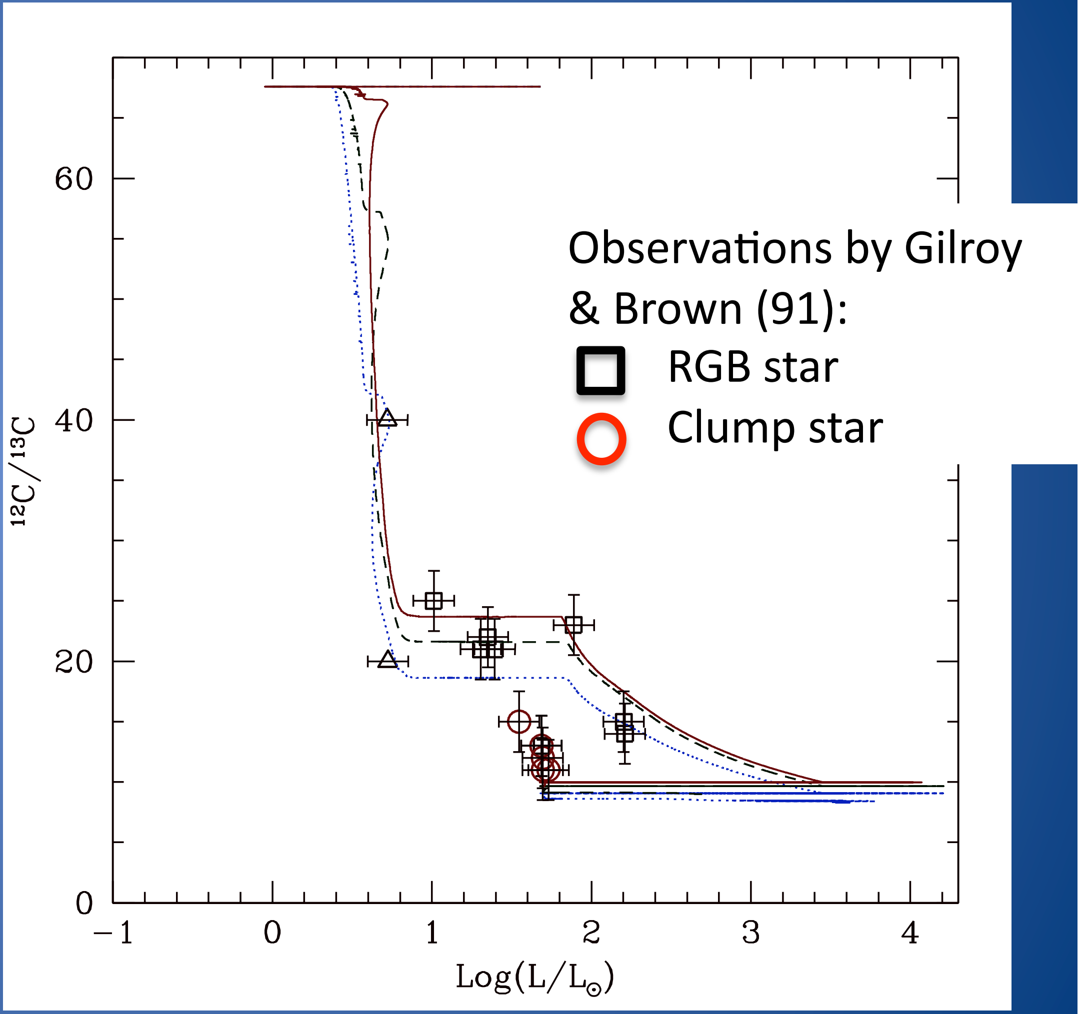



Charbonnel & Lagarde (2010)

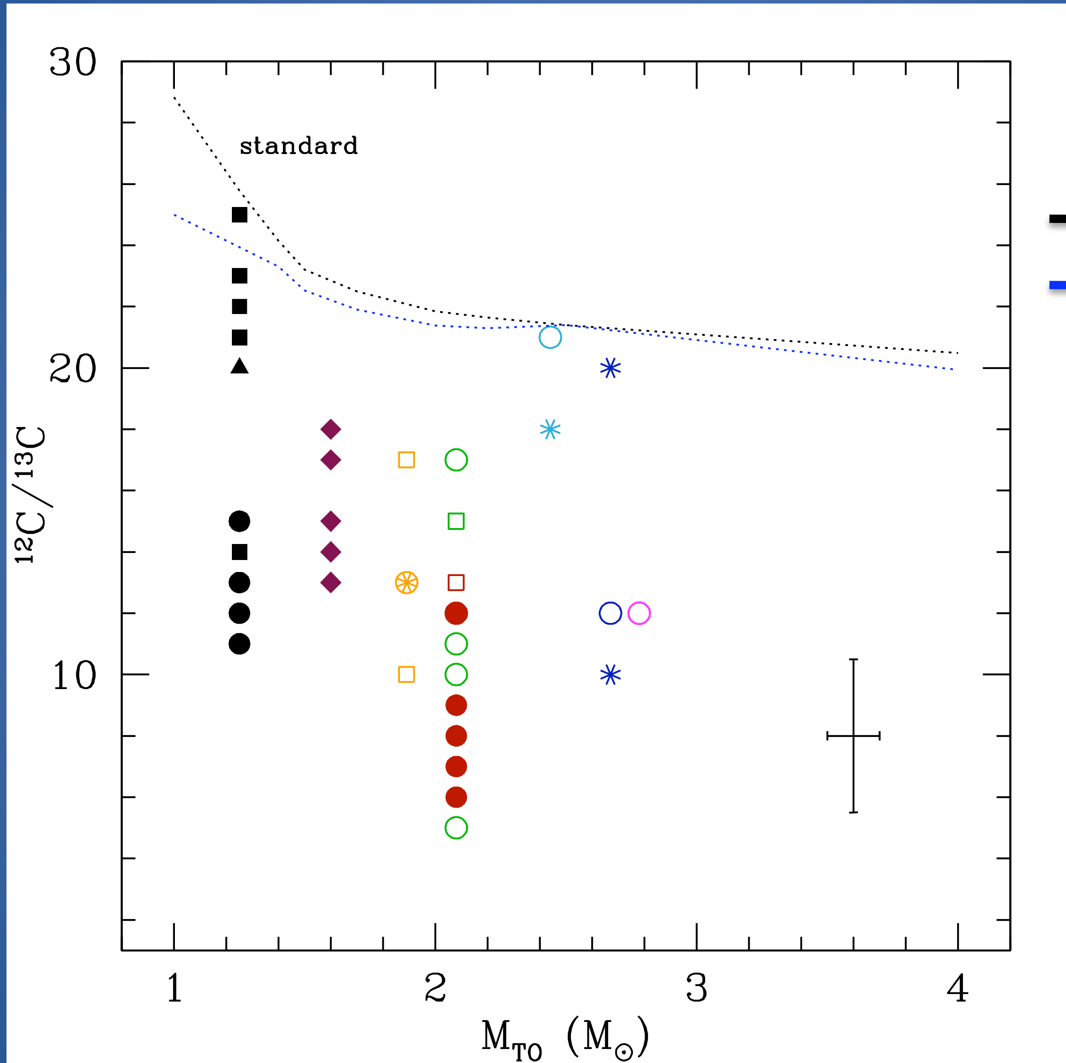
# Open cluster : M67 ($M_{TO}$=1.25$M_\odot$)




Charbonnel & Lagarde (2010)

# $^{12}C/^{13}C$ as a function of $M_{TO}$




Models:
RGB tip
after the 2nd DUP

Observations :
RGB star
Clump star
* early-AGB star
doubtful
evolutionary status

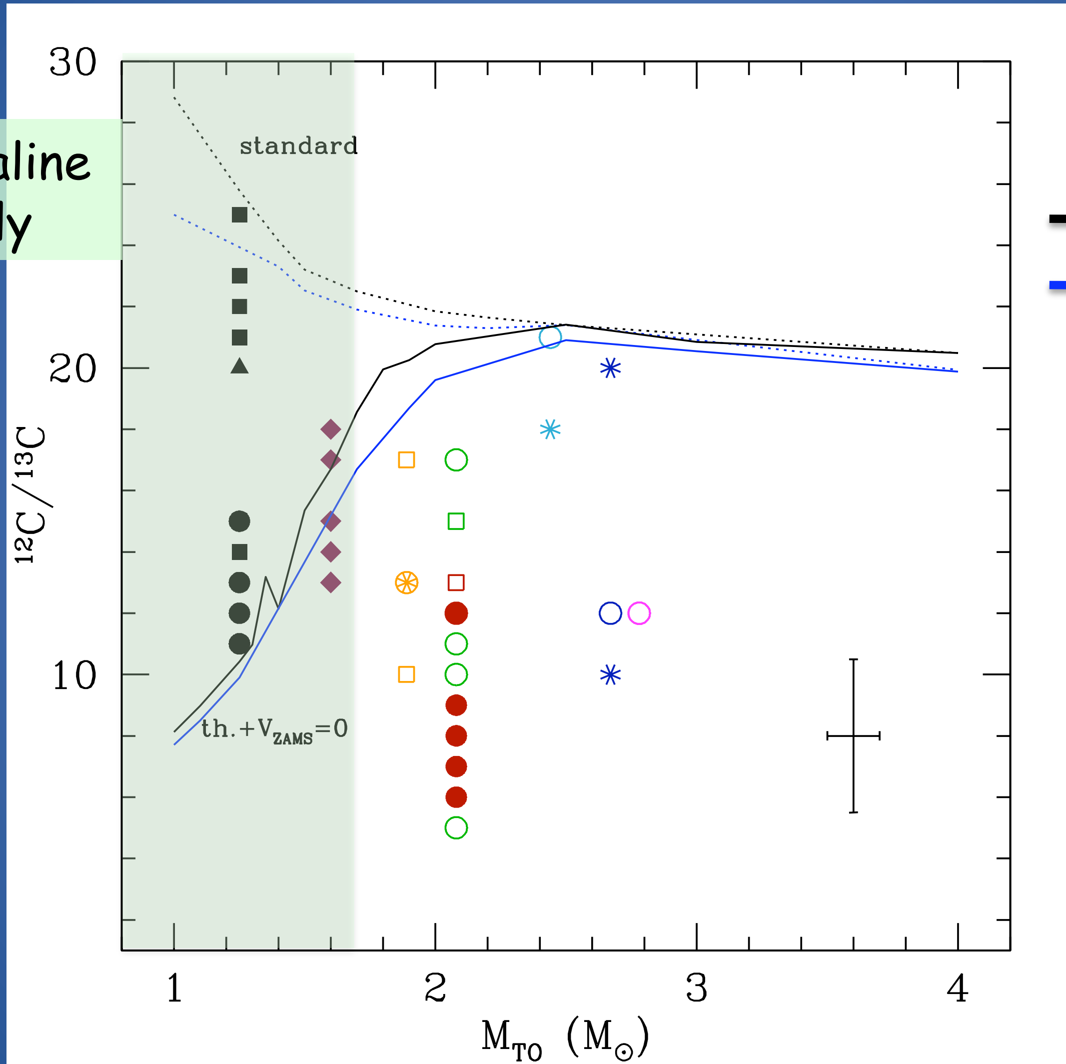
Observations :

Smiljanic et al. (2009); Gilroy (1989) ; Gilroy & Brown (1991) ; Mikolaitis et al. (2010)

Charbonnel & Lagarde (2010)

# $^{12}C/^{13}C$ as a function of $M_{TO}$

Thermohaline mixing only




Models:
- RGB tip
- after the 2nd DUP

Observations :
- RGB star
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Charbonnel & Lagarde (2010)

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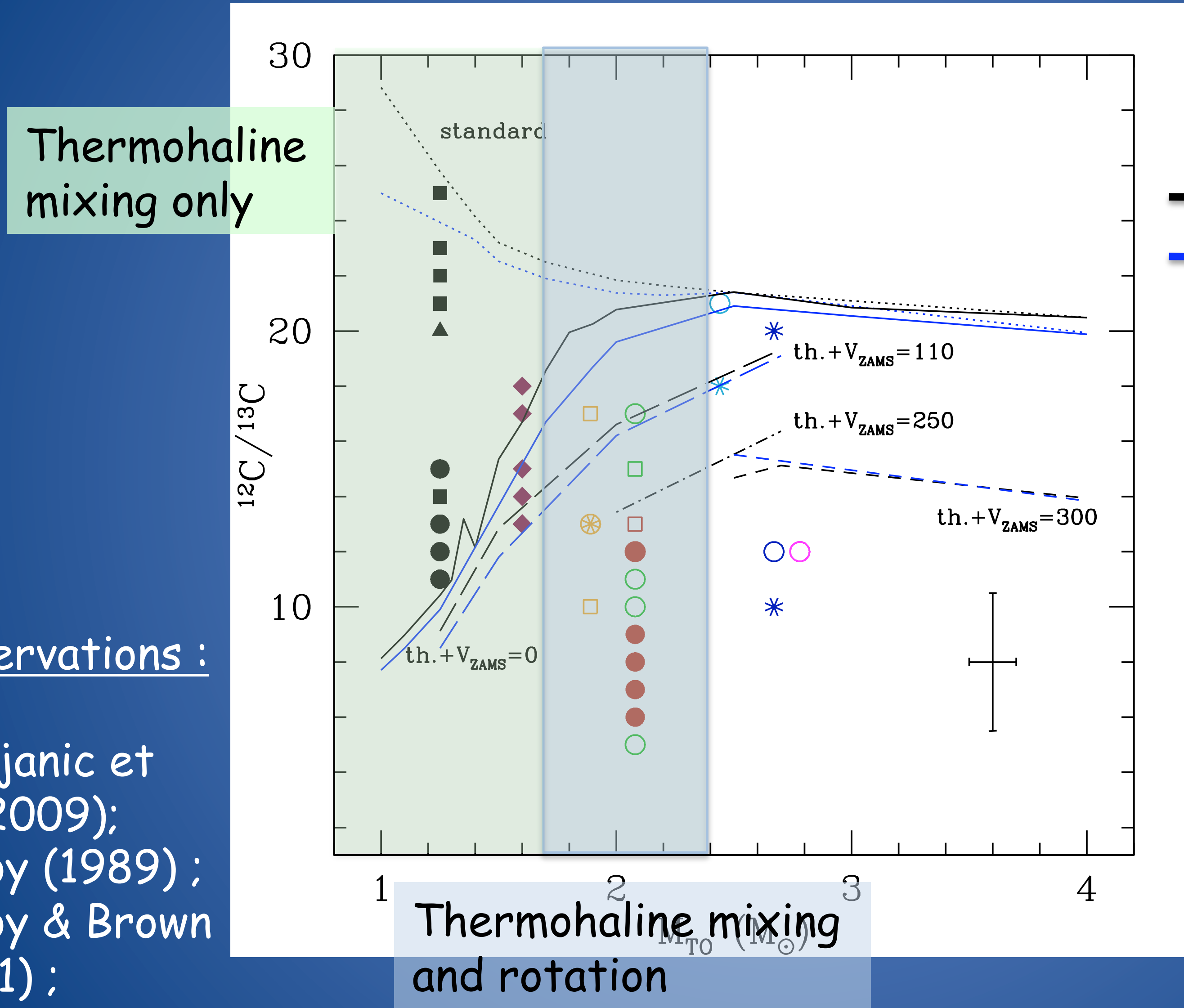


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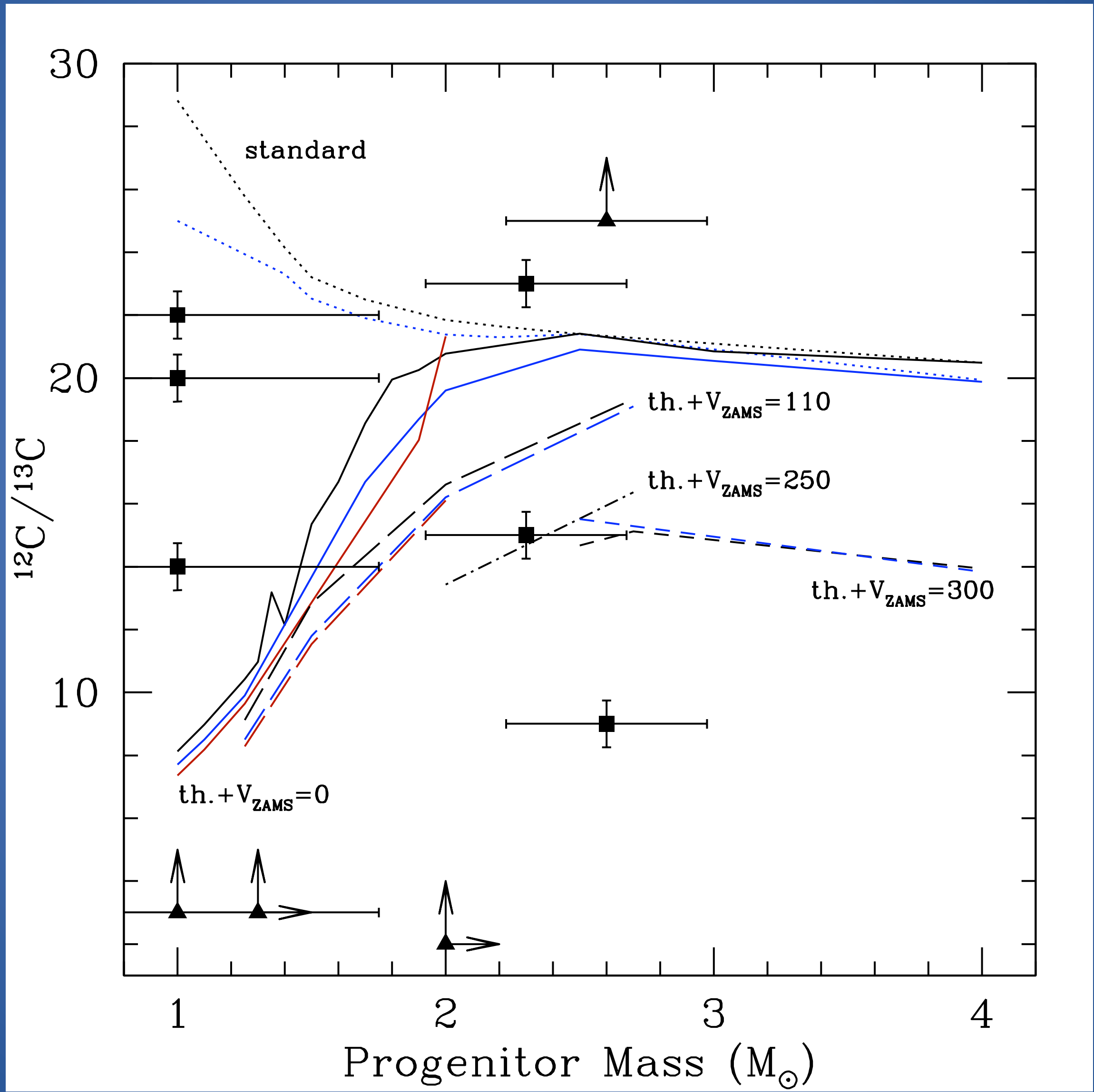
Charbonnel & Lagarde (2010)

# $^{12}C/^{13}C$ in planetary nebulae




Sample of planetary nebulae : Palla et al. 2000

Charbonnel & Lagarde (2010)

# Lithium destruction on RGB

**Observations from Charbonnel et al. (in prep.):**

○ Exact value

▽ Upper limits

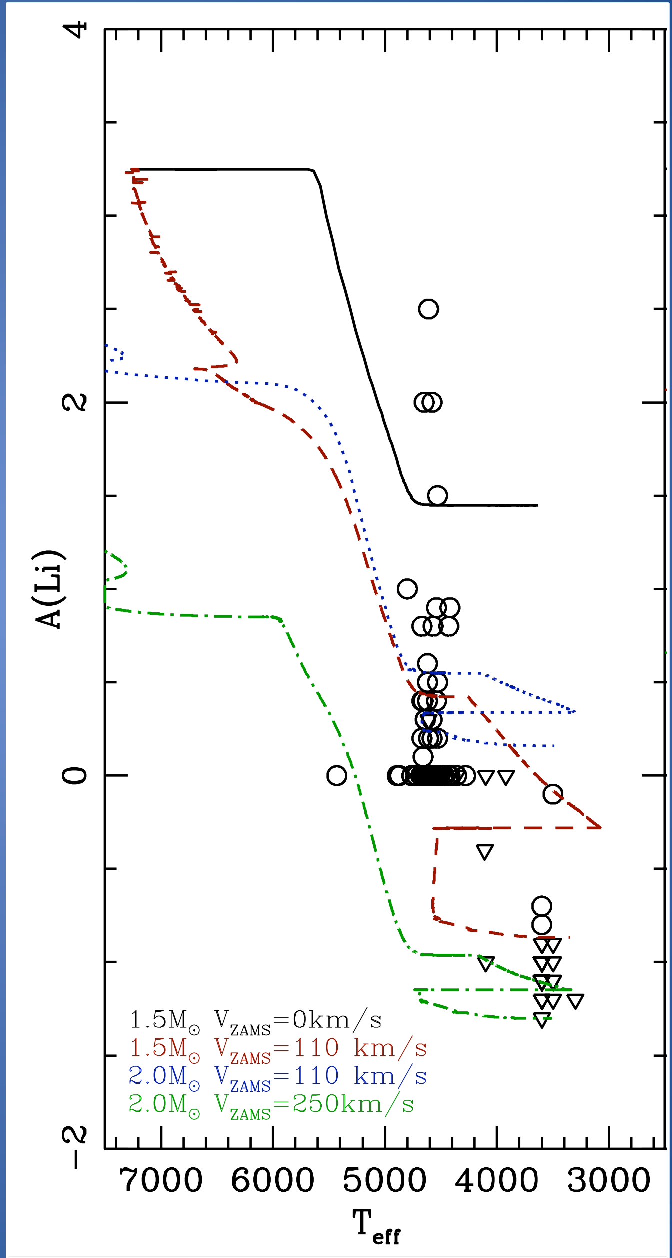
Models :

1.5 $M_\odot$ standard

$V_{ZAMS}$=110 km/s

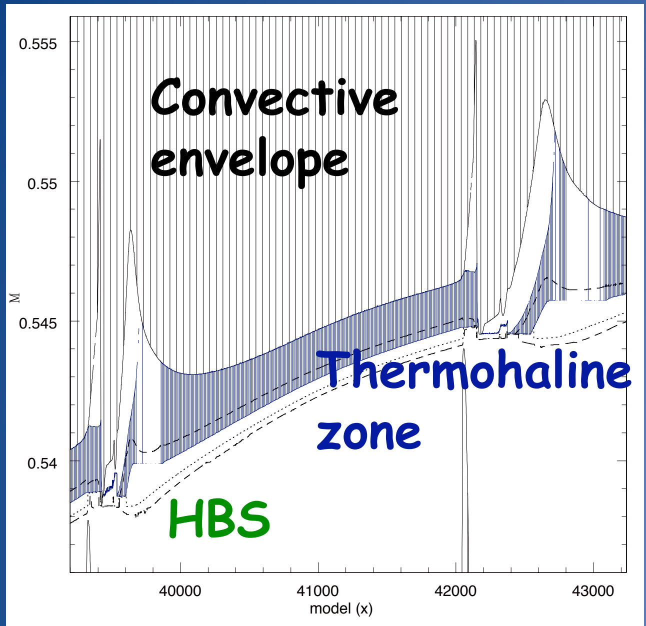
2.0 $M_\odot$ $V_{ZAMS}$=110km/s

$V_{ZAMS}$=250 km/s




Charbonnel & Lagarde (2010)

# Li production during TP-AGB

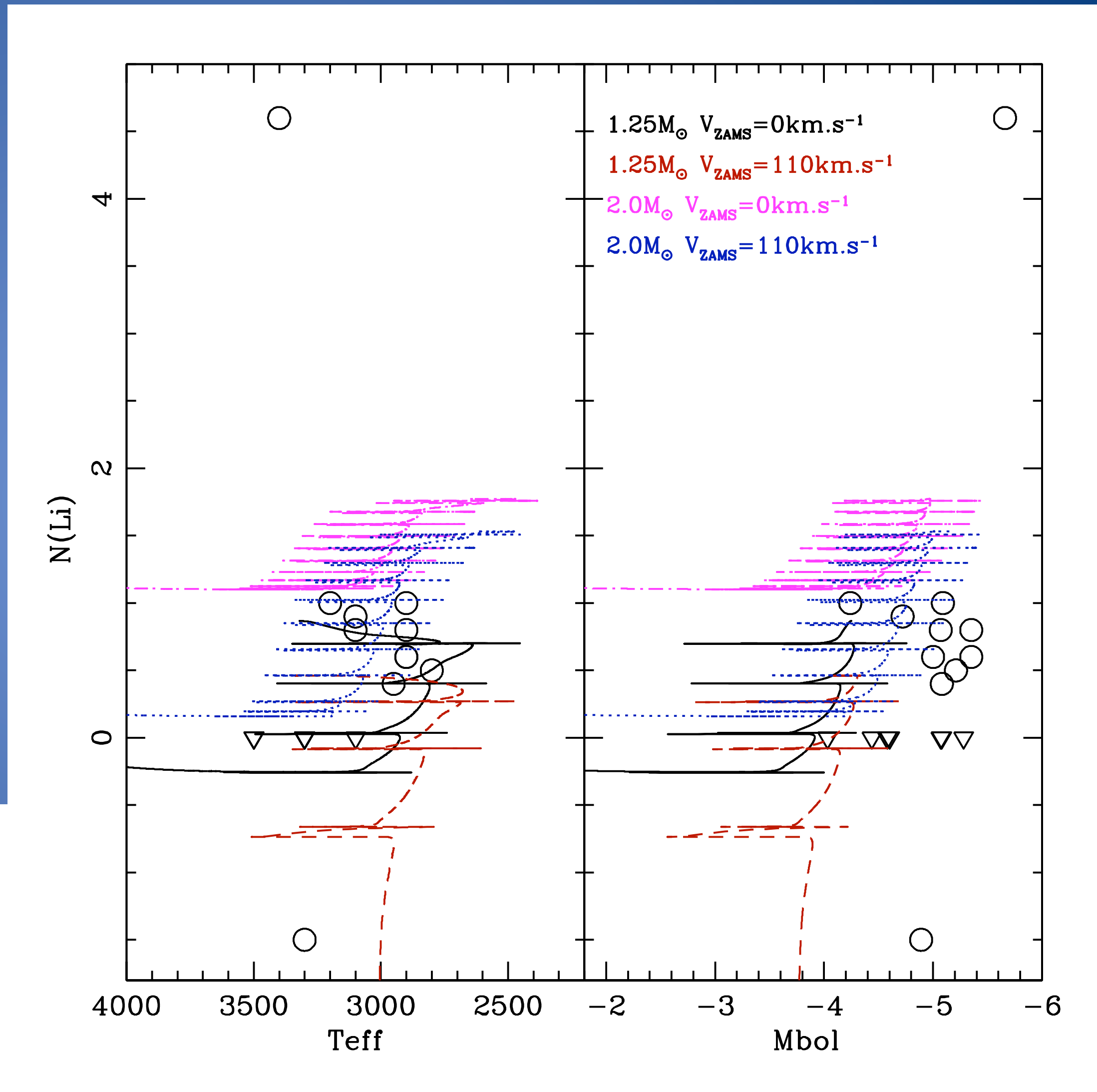



Chaine PP II :

$^{3}He + ^{4}He \rightarrow ^{7}Be + \gamma$

$^{7}Be + e^{-} \rightarrow ^{7}Li + \nu_{e}$

$^{7}Li + H \rightarrow 2\ ^{4}He$



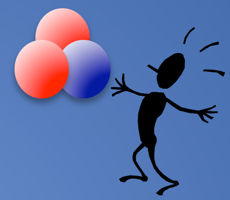

Observations (Uttenthaler & Lebzelter 2010):

○ Exact values

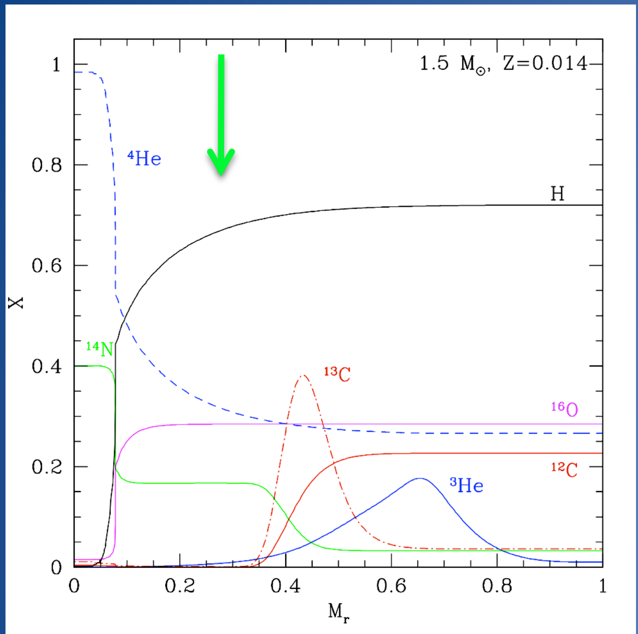
▽ Upper limits

Charbonnel & Lagarde (2010)

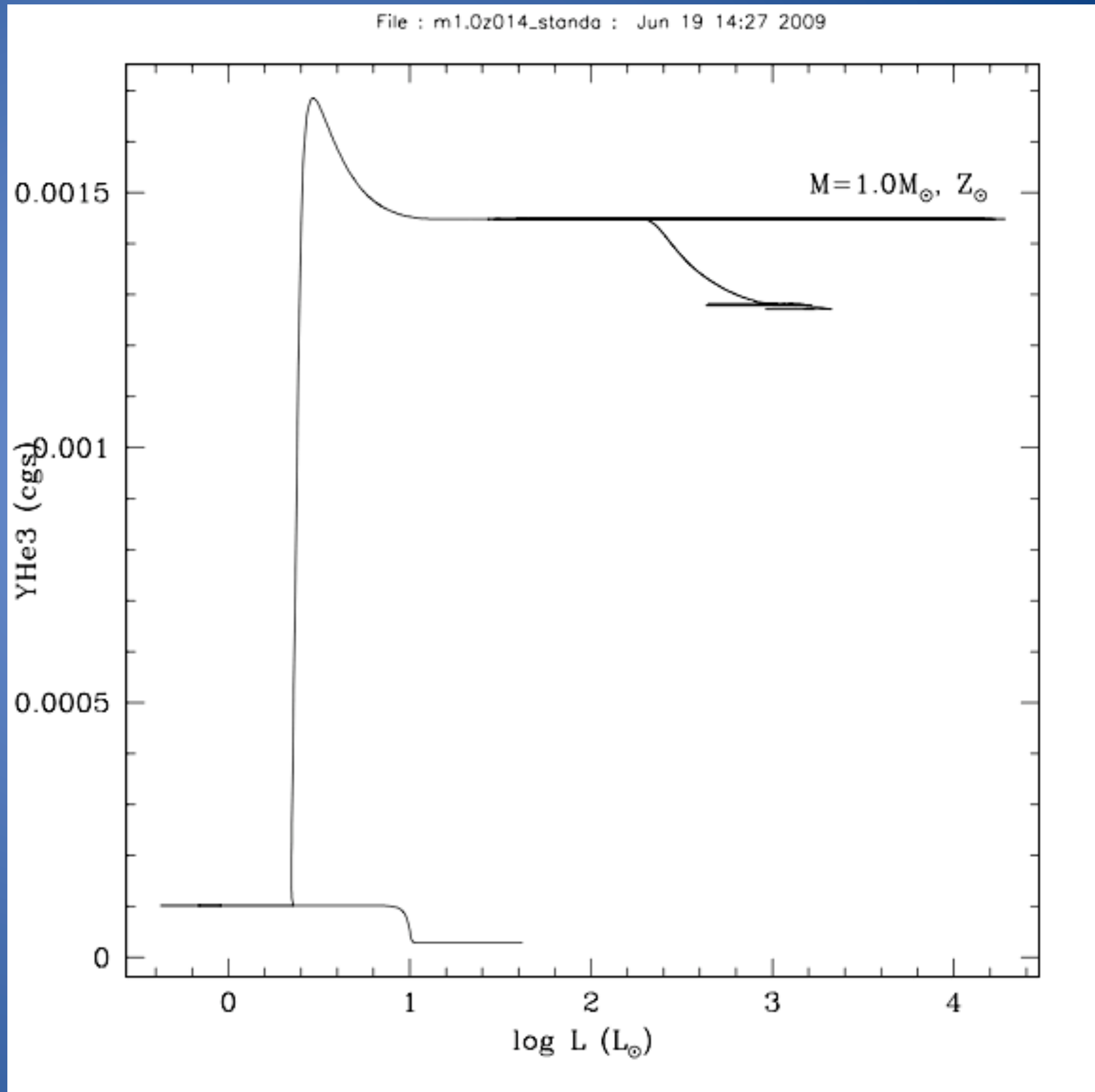
# $^{3}$He case



# Standard evolution of $^3He$

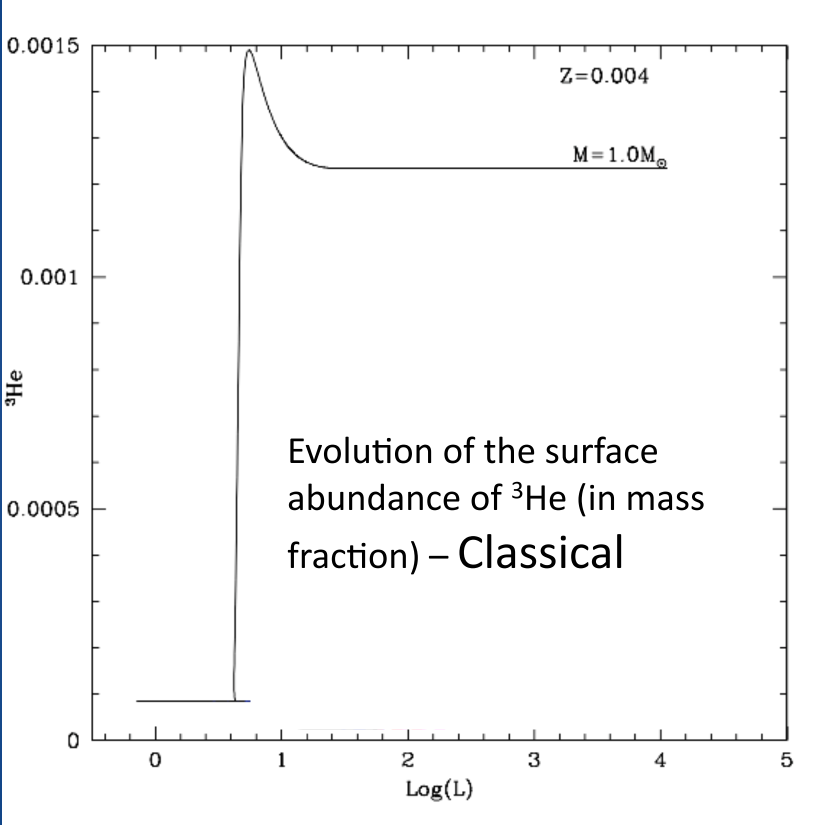


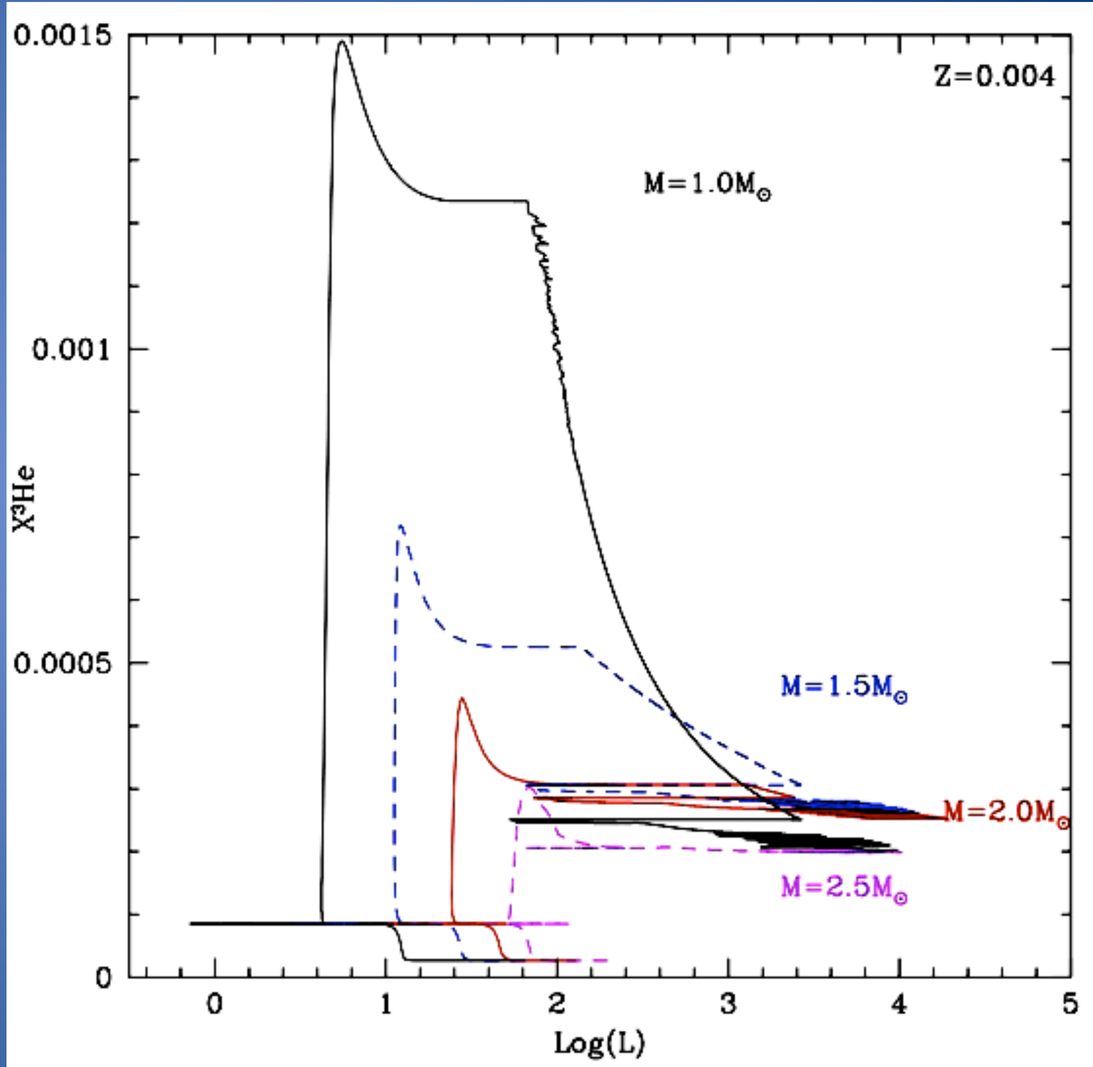

Surface abundance of $^3He$




Lagarde et al. (en prep.)

# $^{3}He$ with thermohaline mixing

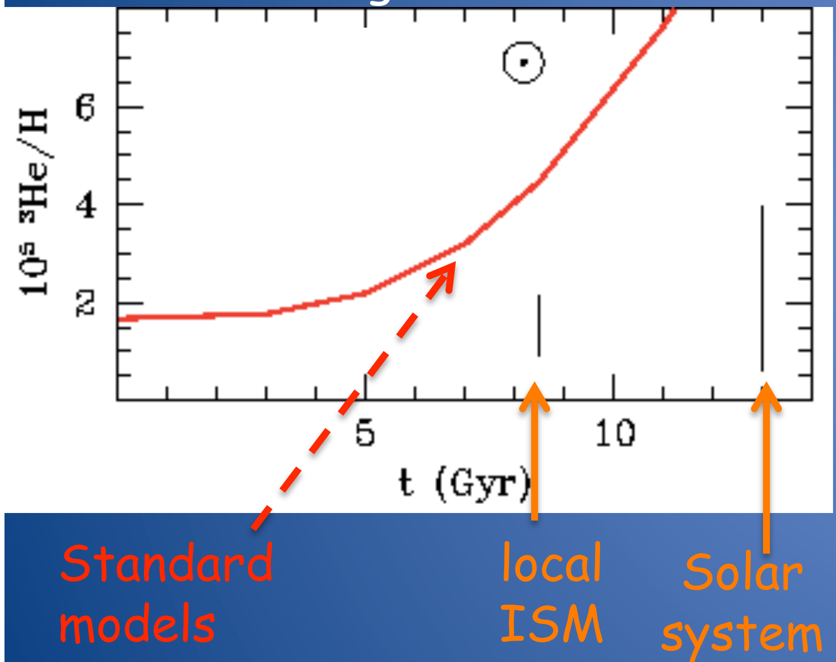



Lagarde et al. (2011, in prep.)

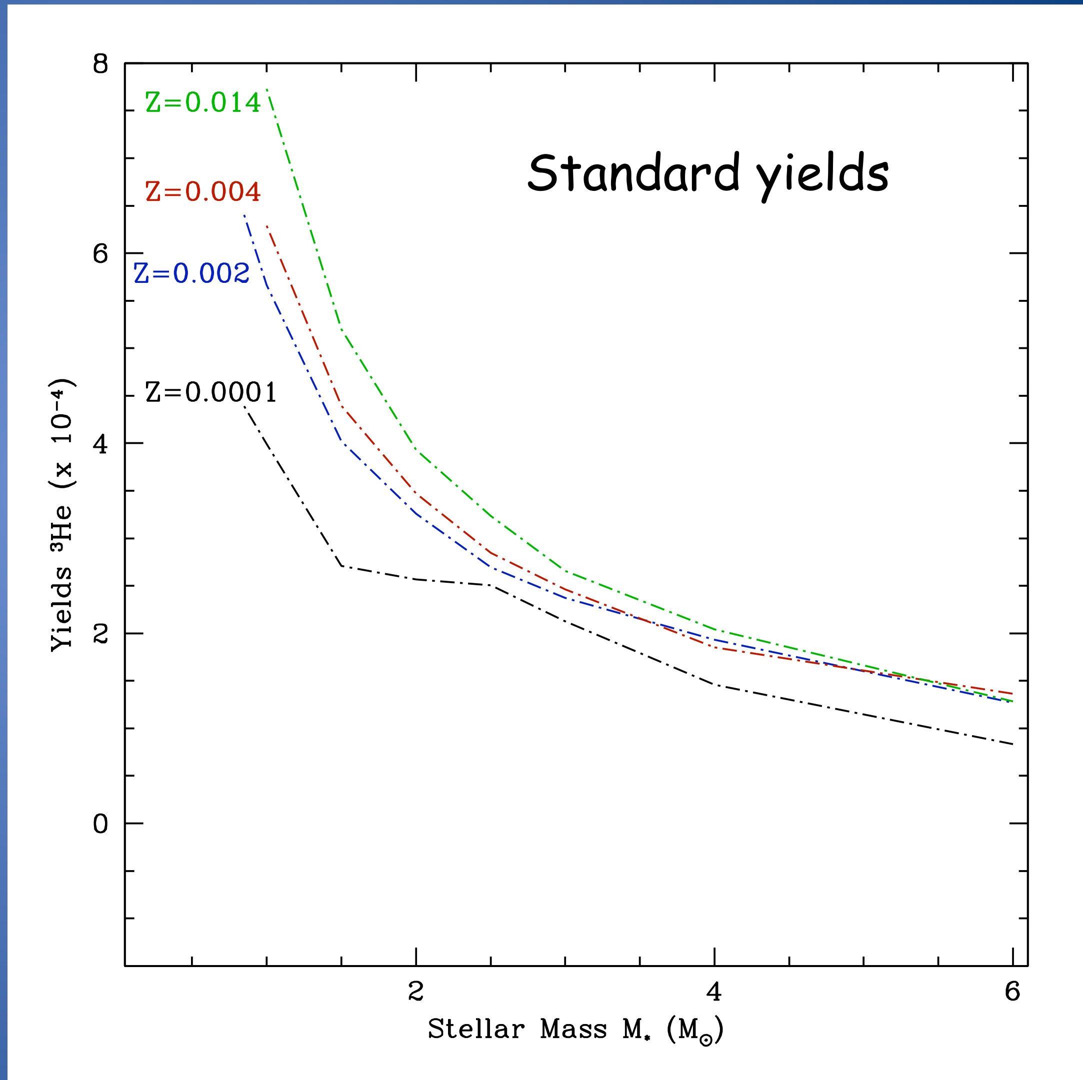
# Standard yields of $^3$He

Galactic chemical evolution of $^3$He in the solar neighbourhood.




Tosi (98)

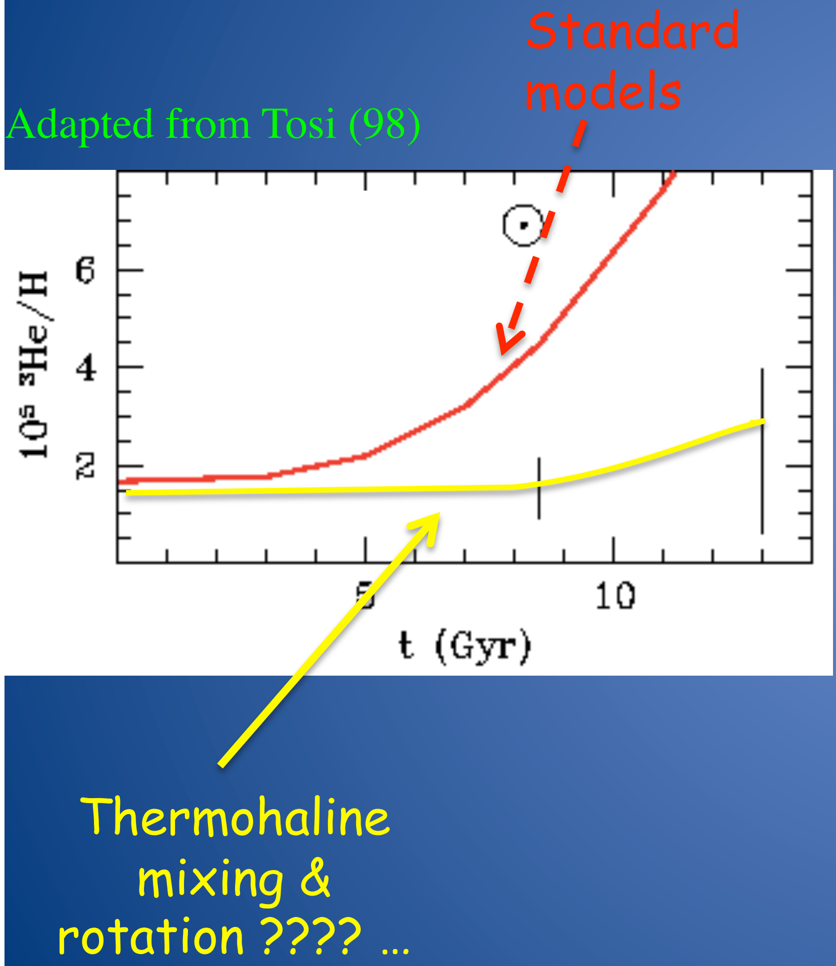
"$^3$He problem"

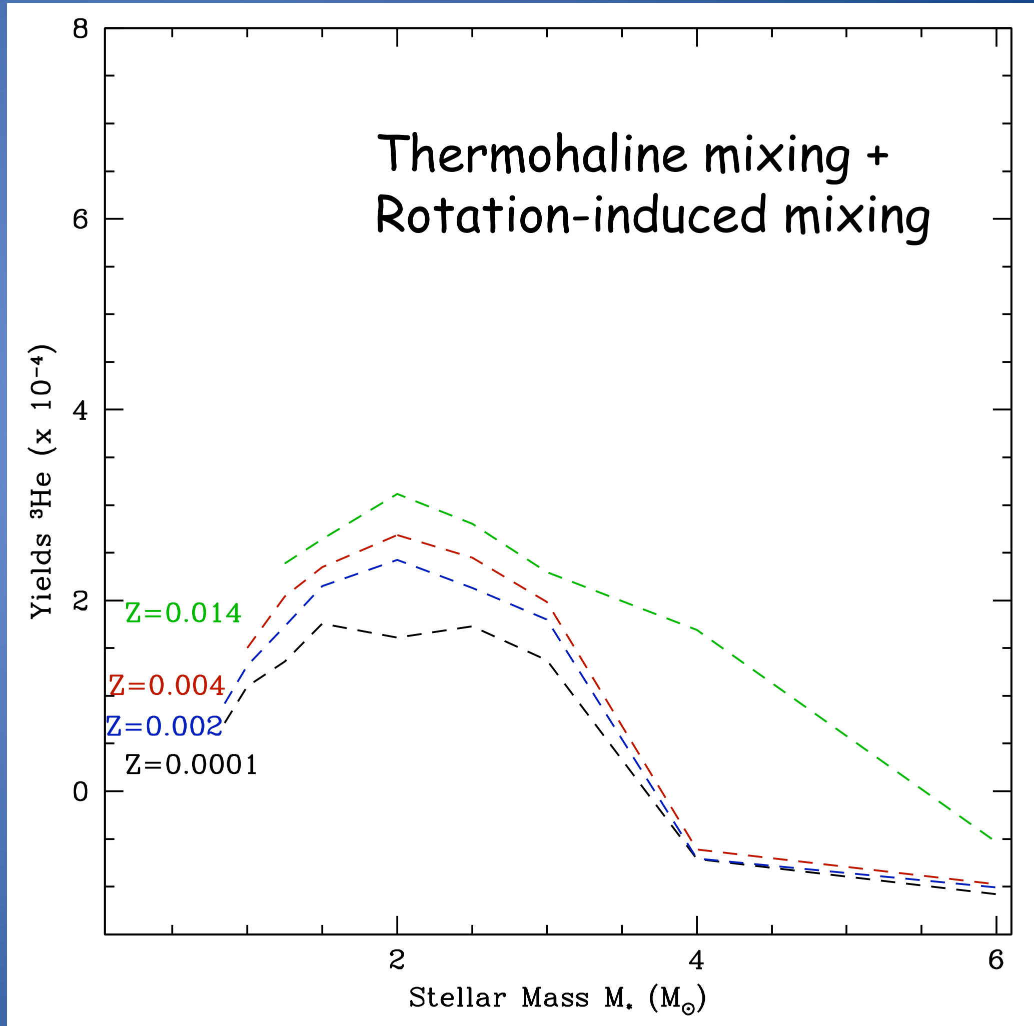



Lagarde et al. (en prep.)

# Yields of $^3$He with thermohaline mixing and rotation-induced mixing

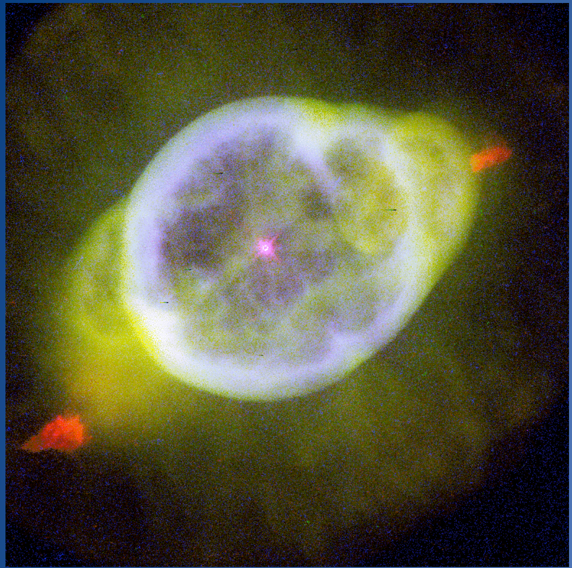
Adapted from Tosi (98)




Lagarde et al. (en prep.)

# *The stubborn PNe NGC 3242 and J 320*



What prevents thermohaline mixing in ~ 5 % of low-mass stars ?

Charbonnel & Zahn (2007b) proposed that thermohaline mixing may be inhibited by a fossil magnetic field in a large fraction of descendants of Ap stars.

Ap stars ~ 5 % of A-type stars

# Conclusions

- Mixing exists on the RGB (at the bump luminosity)

- Li and CN-processing of the envelope material in RGB stars brighter than the L bump

- Thermohaline instability
  - explains the Li, C, N, $^{12}C/^{13}C$ observations in bright RGB low-mass stars
  - and Li during TP-AGB

- … solves the long standing $^{3}He$ problem in the Galaxy ?? (Answer at the end of my stay here)