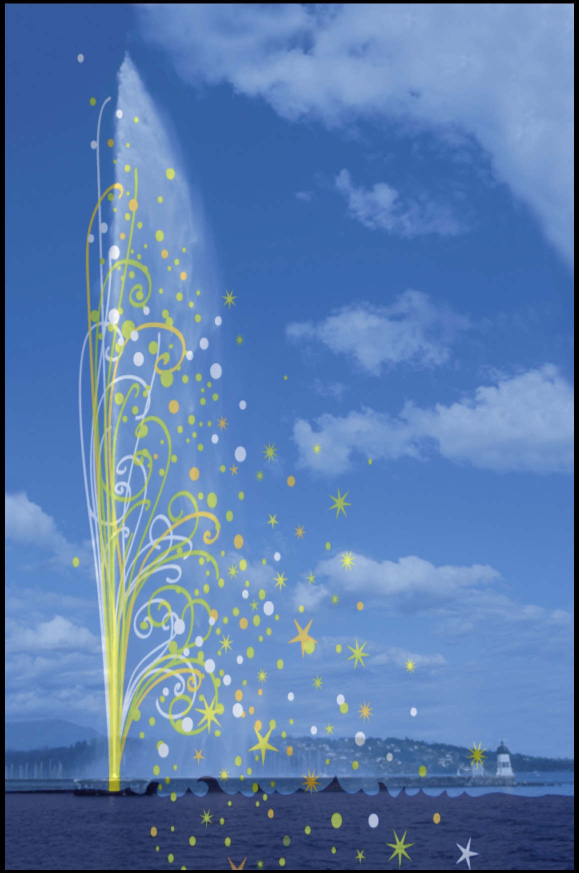
Thermohaline mixing in stars
Solving the long-standing ^{3}He problem



Nadège Lagarde

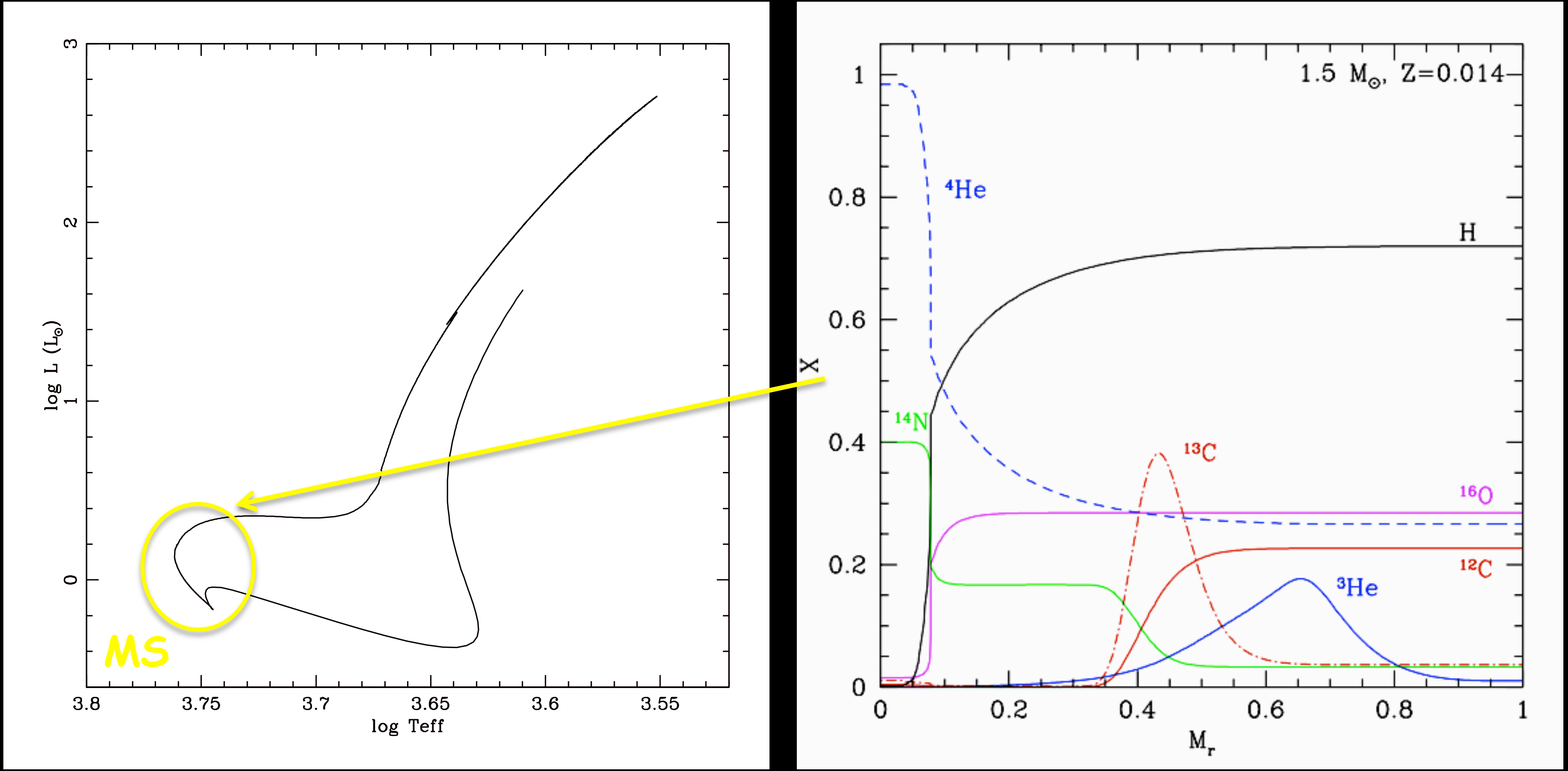
Corinne Charbonnel

Geneva observatory

IAU 268 : Light elements in the Universe

Stellar nucleosynthesis

Iben (1967)



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

Predictions at the 1dup :

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

Lagarde & Charbonnel - IAU 268

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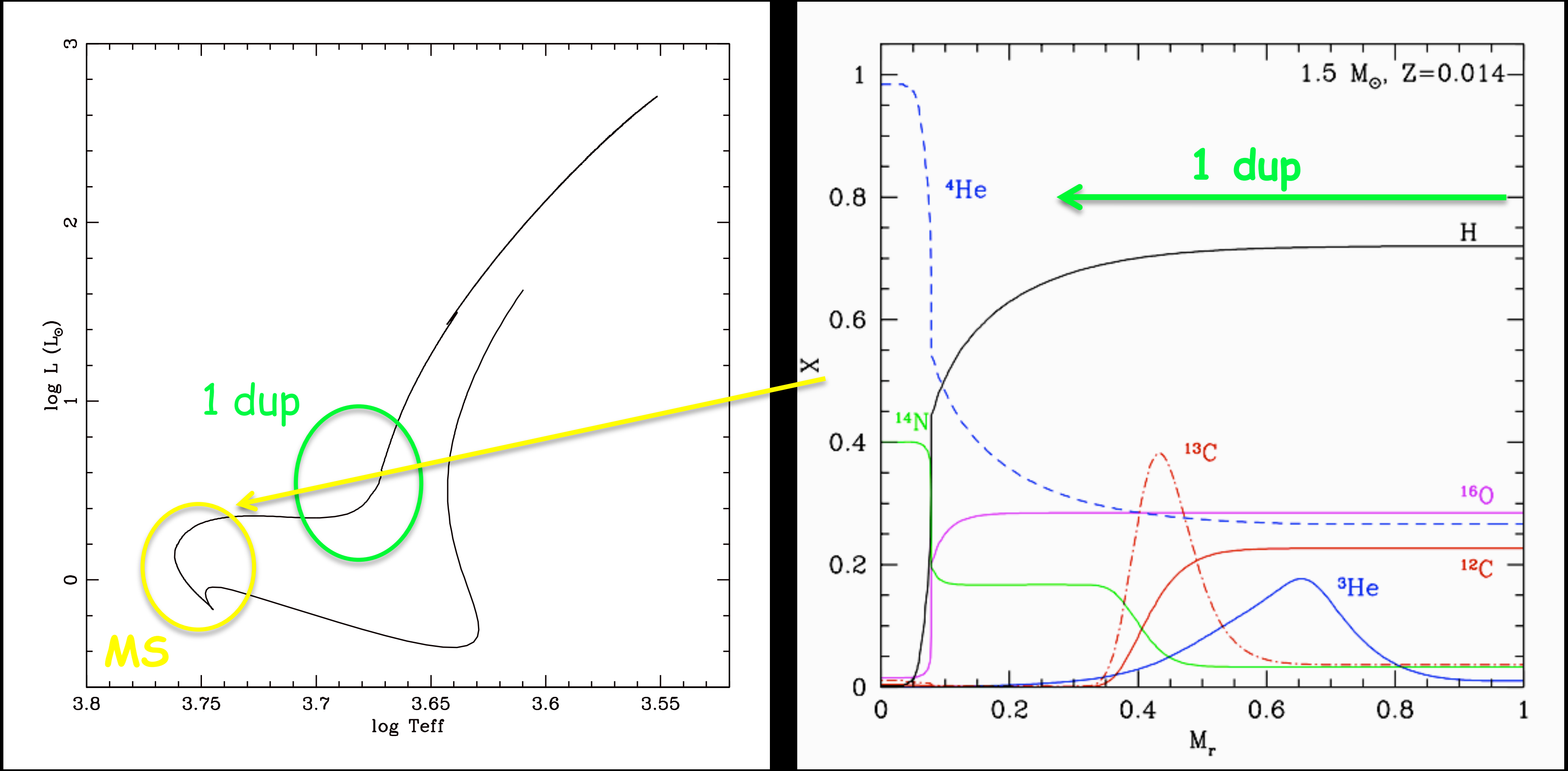

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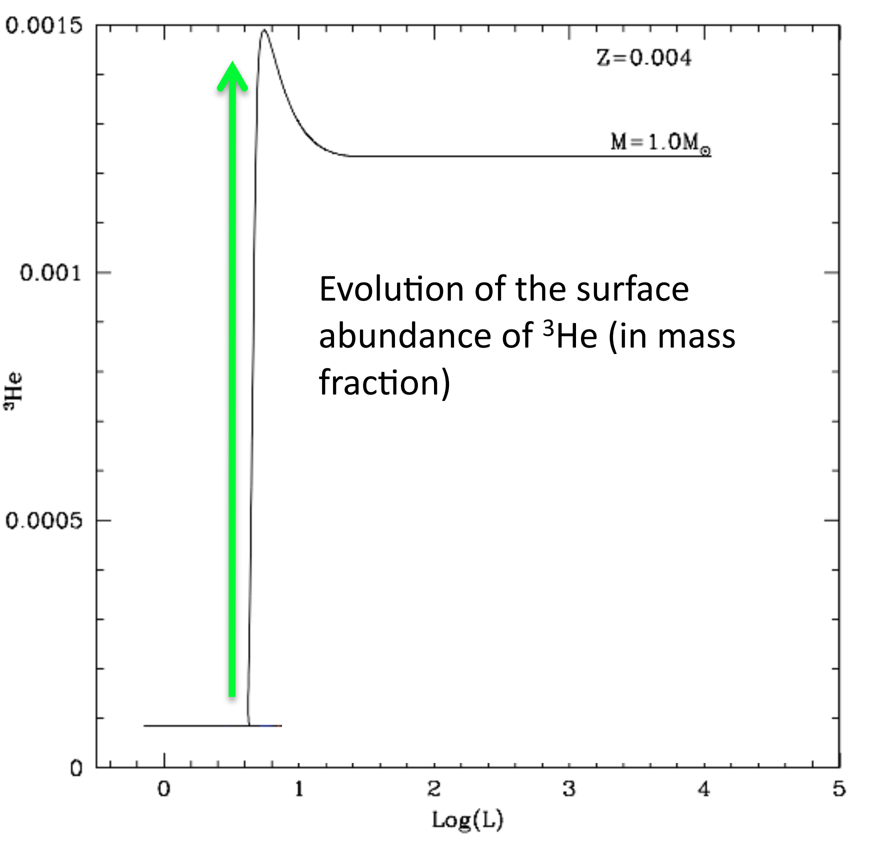
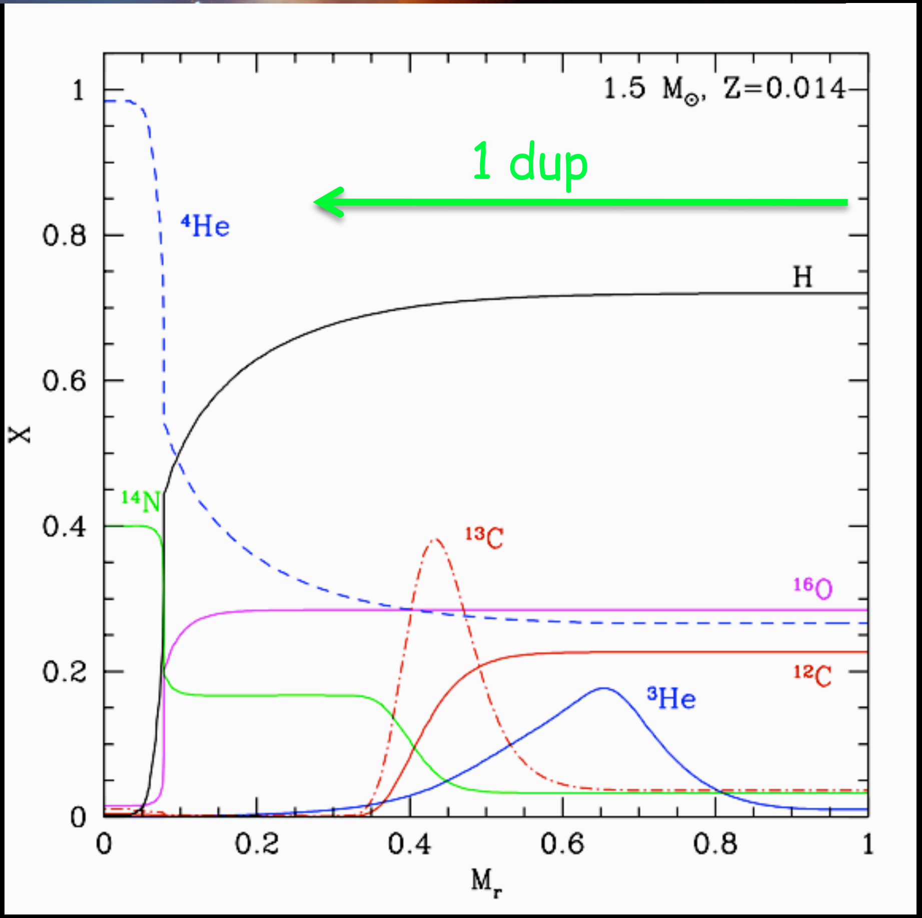
Stellar nucleosynthesis of ^{3}He



Evolution of the surface abundance of ^{3}He (in mass fraction)



Mass fraction
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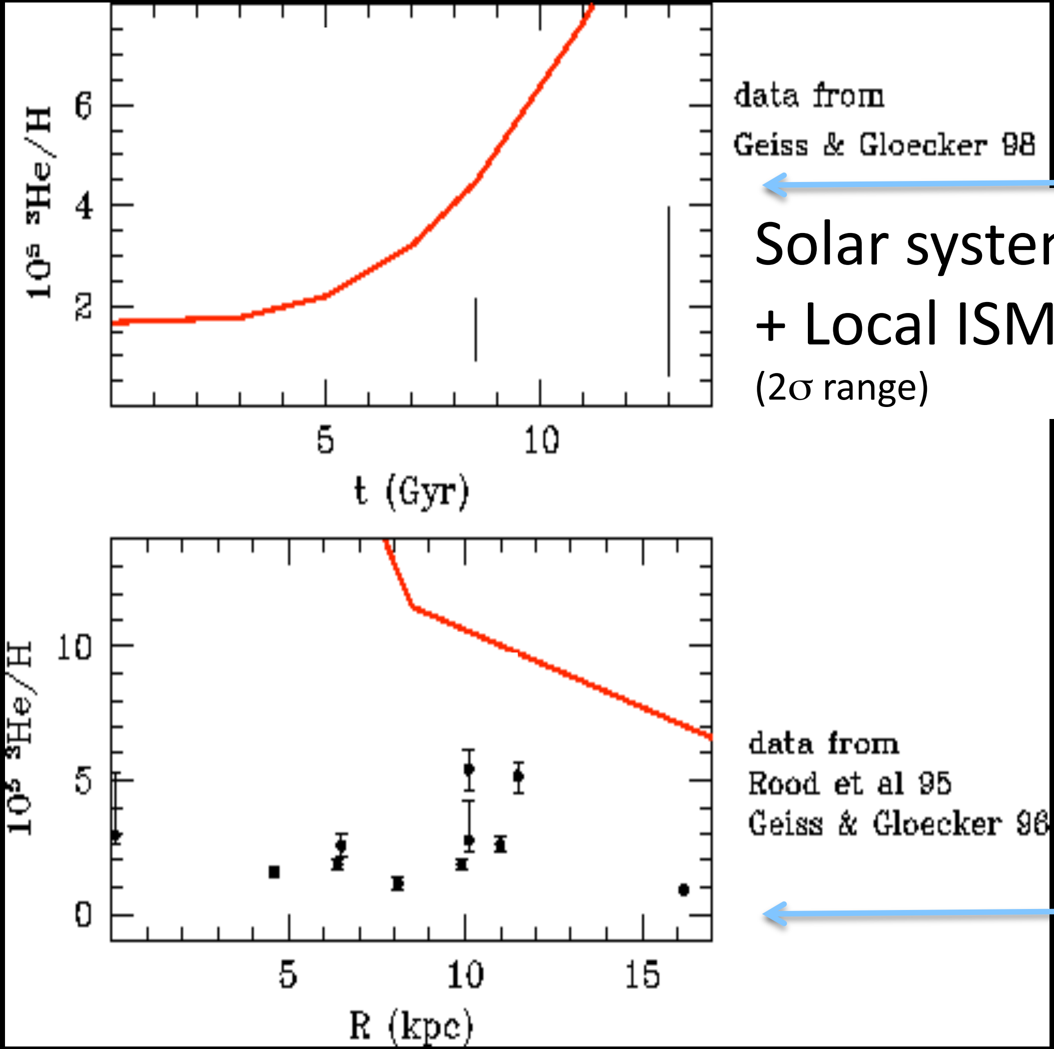
Classical predictions : Helium 3 galactic evolution



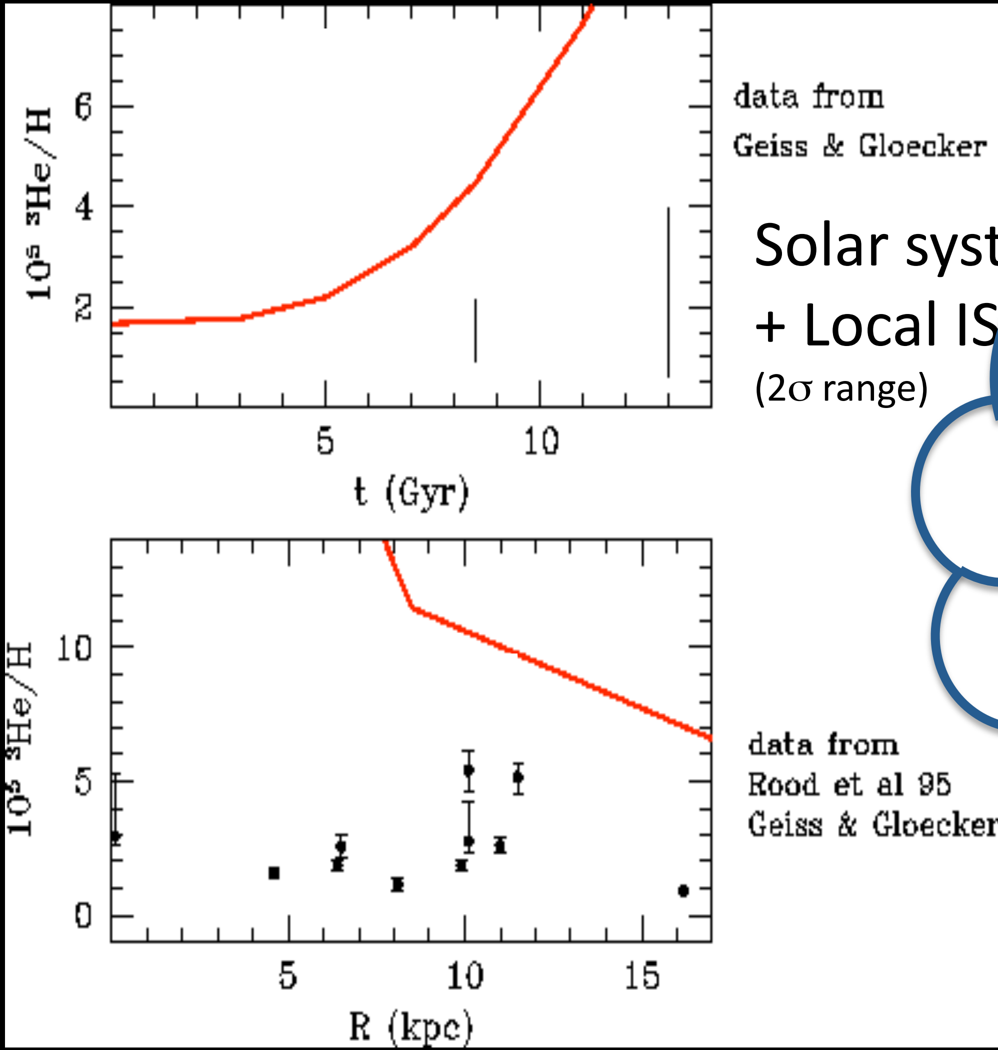
Solar system
+ Local ISM
(2σ range)

The time behaviour in the solar neighbourhood predicted when classical model yields are considered.

The corresponding radial distribution at the present epoch.
Data : HII values derived by Rood et al. in HII regions.

Adapted from Tosi (98)

Classical predictions : Helium 3 galactic evolution



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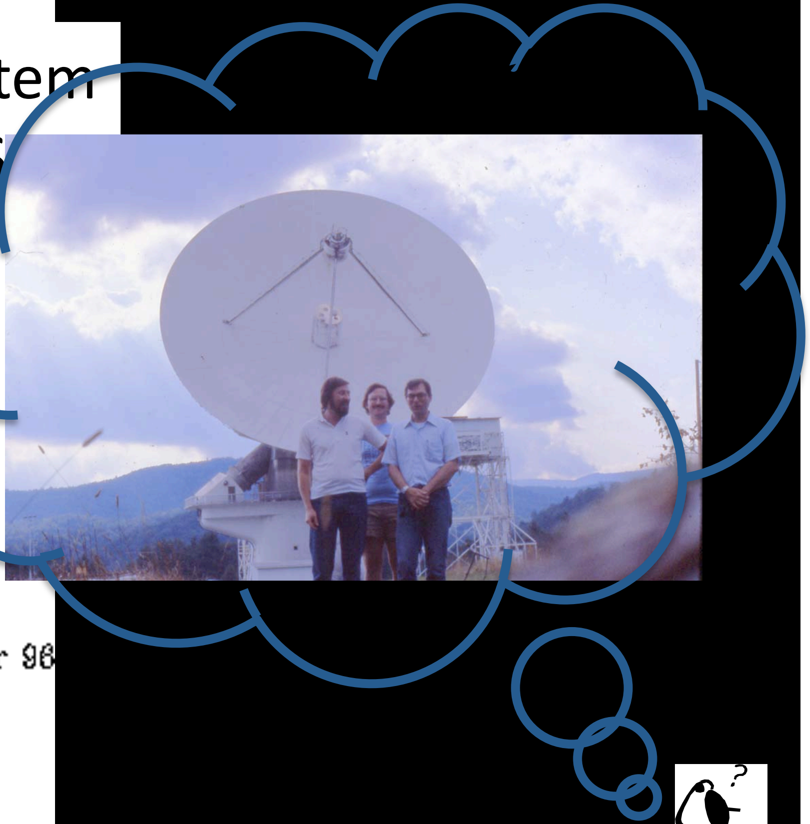
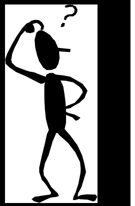
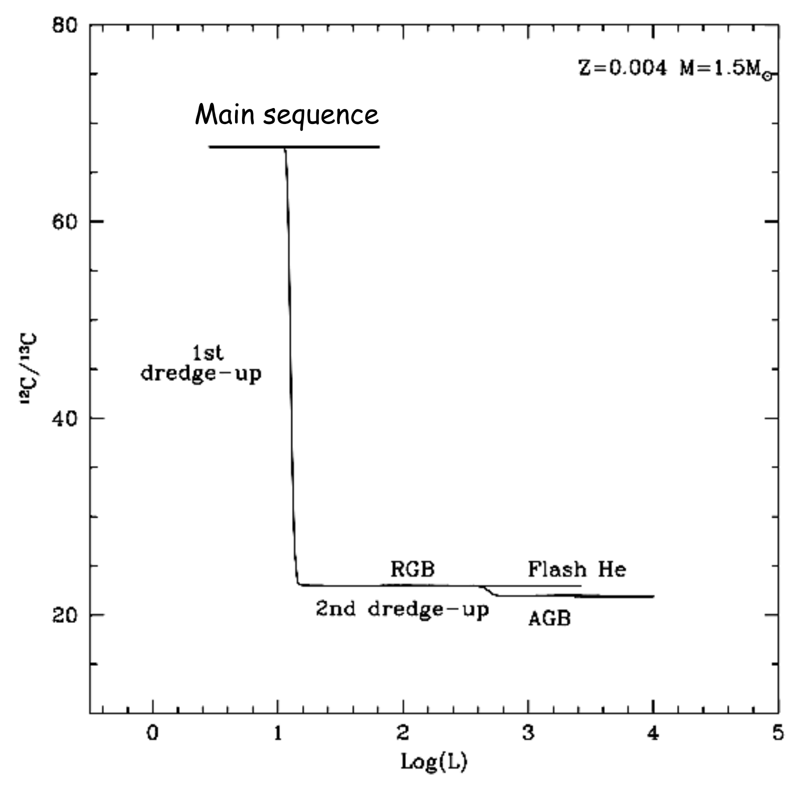
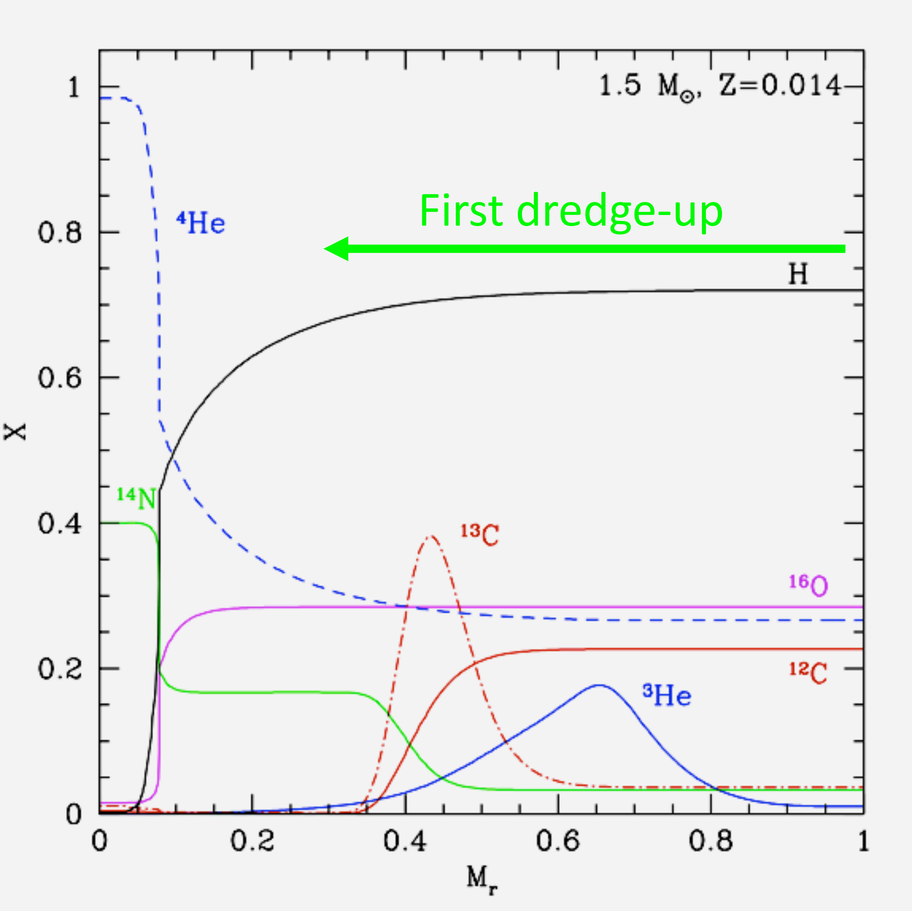




Connection to abundance anomalies in RGBs





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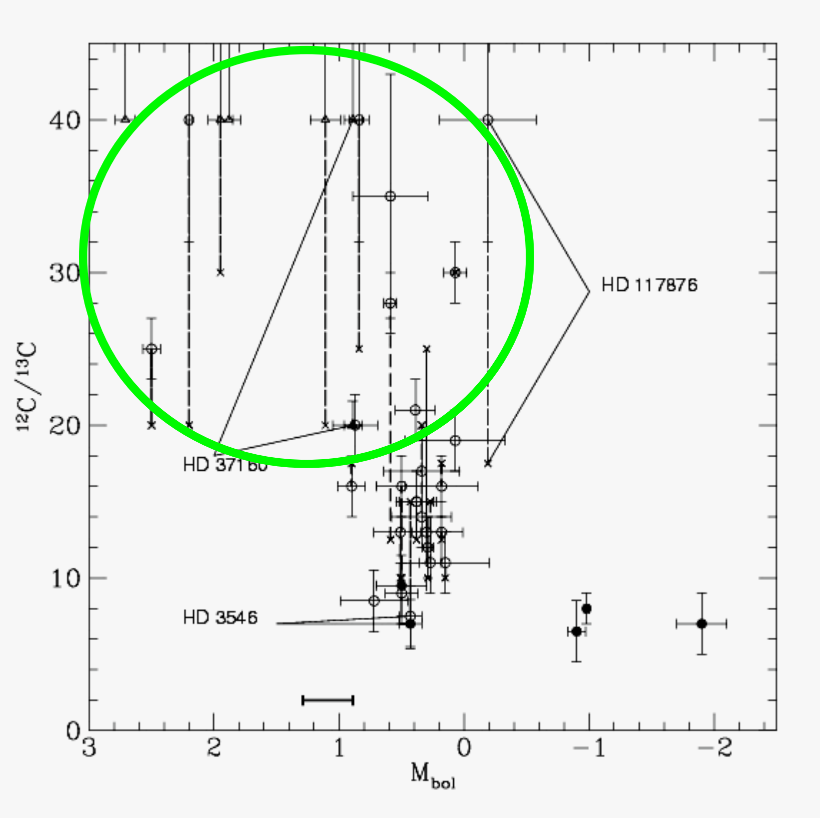
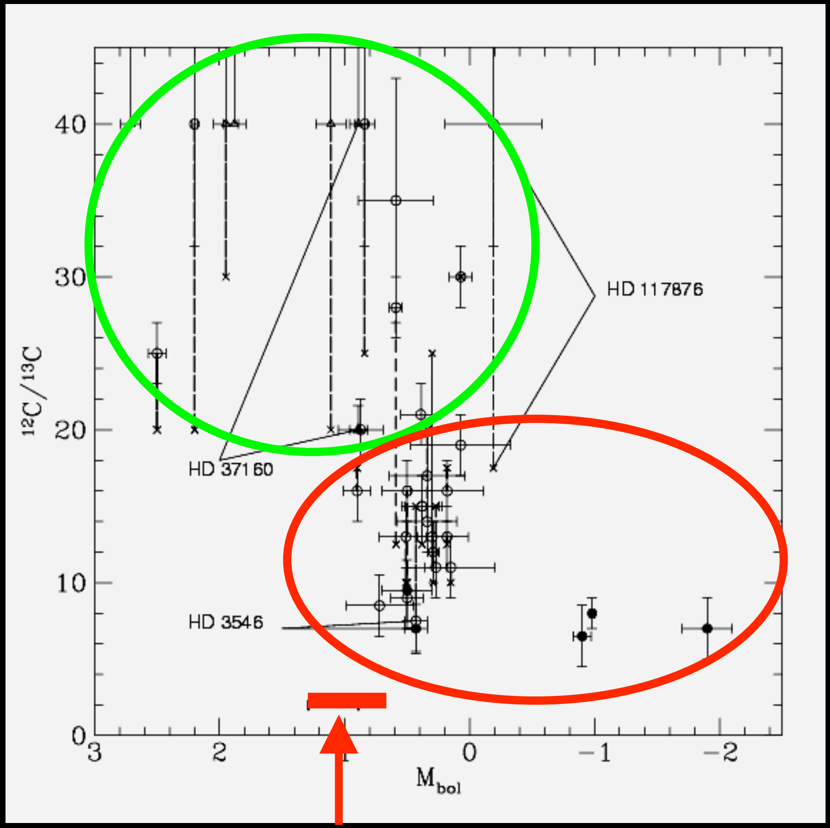
Classical predictions : 1st dredge-up



Field stars with Π Hipparcos

Charbonnel, Brown & Wallerstein (98)

Signature of "extra-mixing" at the L bump



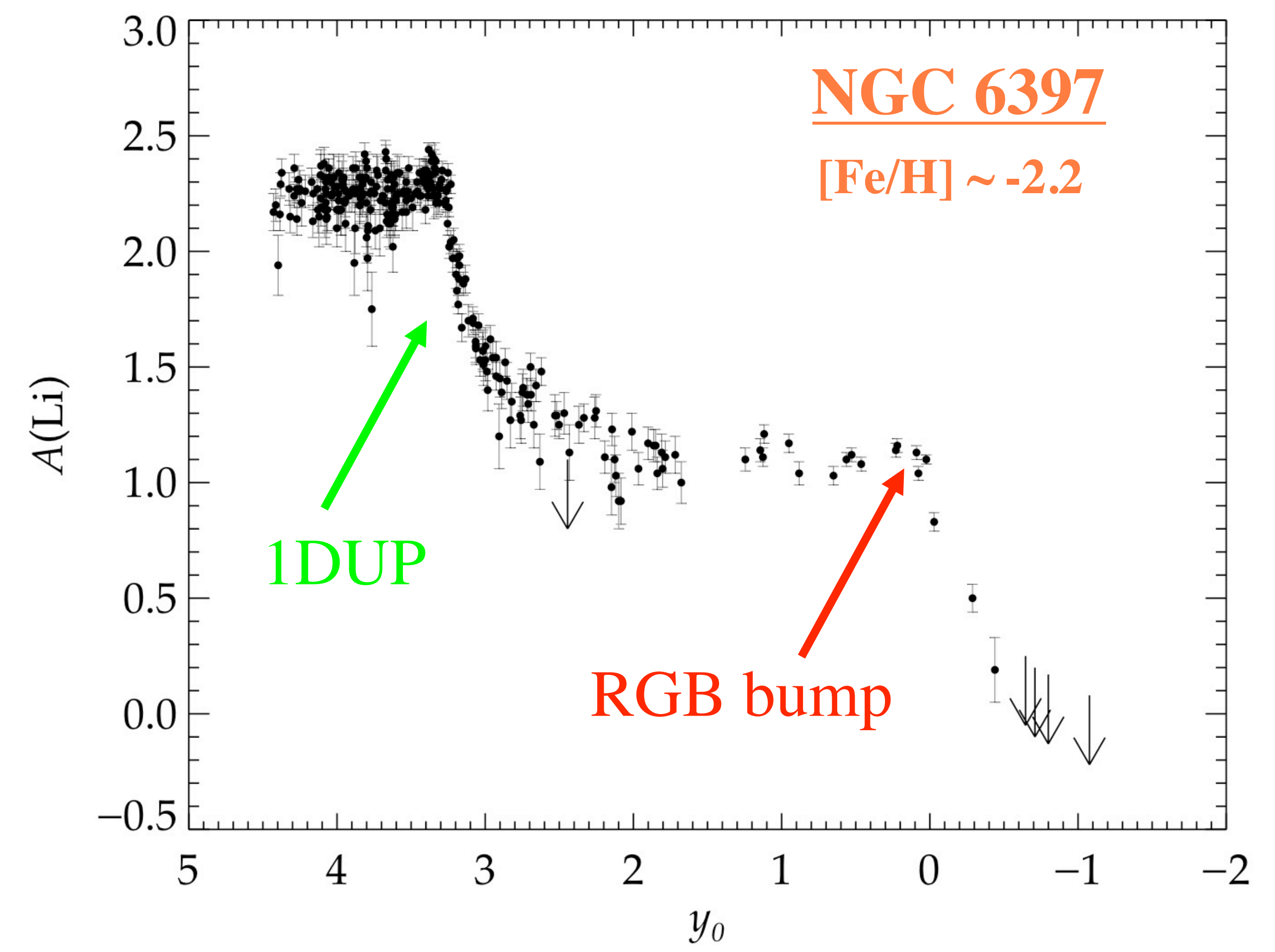
RGB bump

Field stars with Π Hipparcos

Charbonnel, Brown & Wallerstein (98)

CN processing of envelope material at the RGB bump

Signature of "extra-mixing" at the L bump



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

Mean molecular weight (μ) inversion

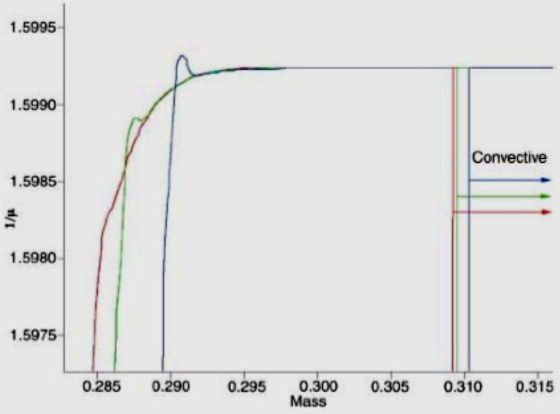
^3He (^3He,2p) ^4He

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

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

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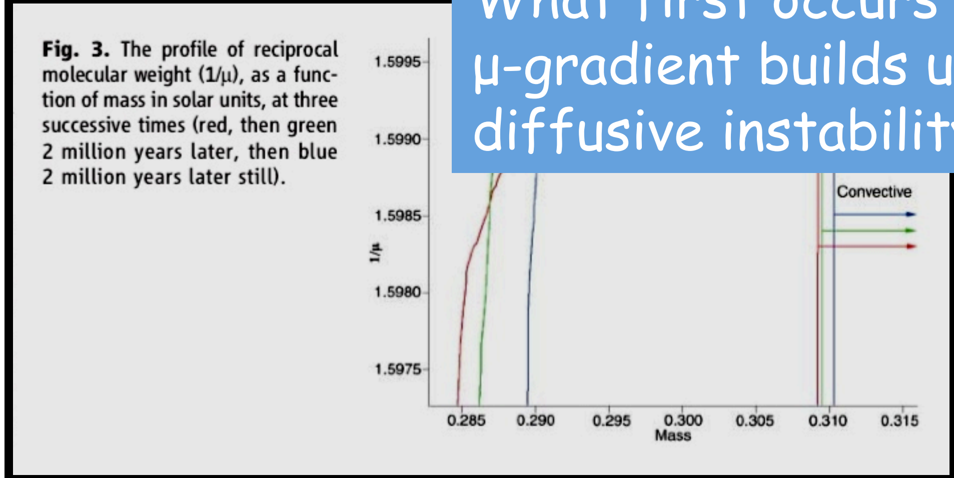

Fig. 3. The profile of reciprocal molecular weight (1/μ), as a function of mass in solar units, at three successive times (red, then green 2 million years later, then blue 2 million years later still).

What first occurs in a star as the inverse μ-gradient builds up, is actually a double diffusive instability.

odynamic code
r at the RGB tip

↓

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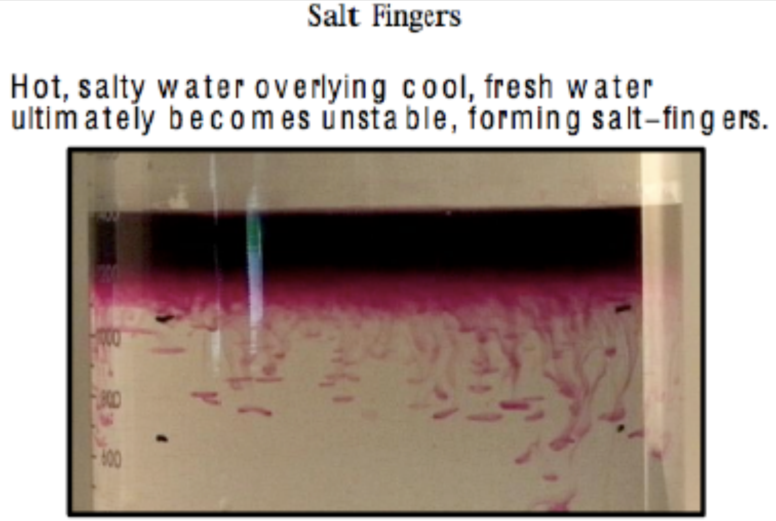
✧ Thermohaline mixing Charbonnel & Zahn (07)

- 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)



Salt Fingers

Hot, salty water overlying cool, fresh water ultimately becomes unstable, forming salt-fingers.

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.

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

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

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

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

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

Description of our models

Stellar evolution model were computed with **the code STAREVOL** (e.g., Palacios et al.03, 06).

They take into account :

(1) **rotation-induced processes** following the formalism by Zahn (92) and Maeder & Zahn (98)

(2) Atomic Diffusion

(3) thermohaline mixing as described by Charbonnel & Zahn (07).

Assumed initial rotation velocities correspond to typical observed values for stars on the zero age main sequence.

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

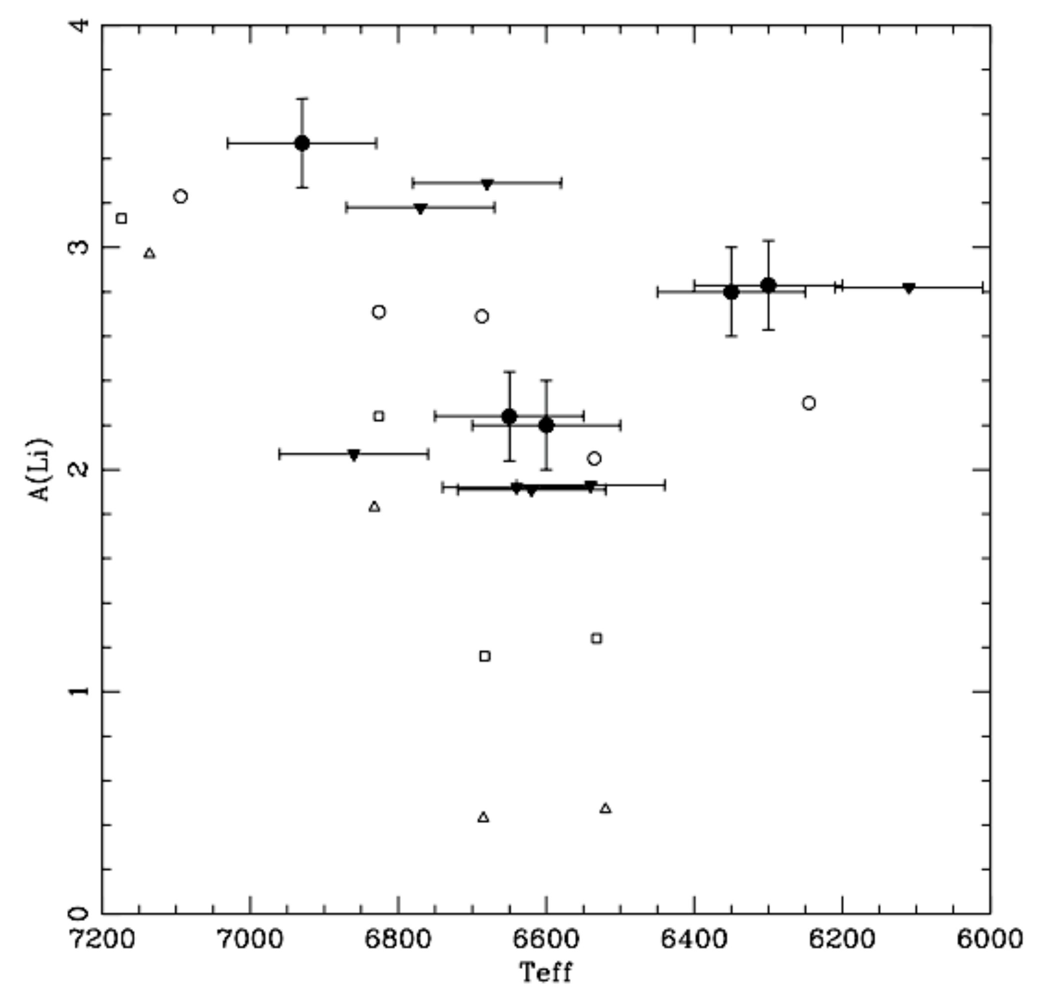
1. Main sequence stars

Observations :
● = exact values
▼ = higher values

Models :
○ = V_{ZAMS}=110km/s

□ = V_{ZAMS}=80km/s

△ = V_{ZAMS}=50km/s



Smiljanic et al. 2009

See poster « **Beryllium abundances along the evolutionary sequence of IC 4651** » by Smiljanic et al.

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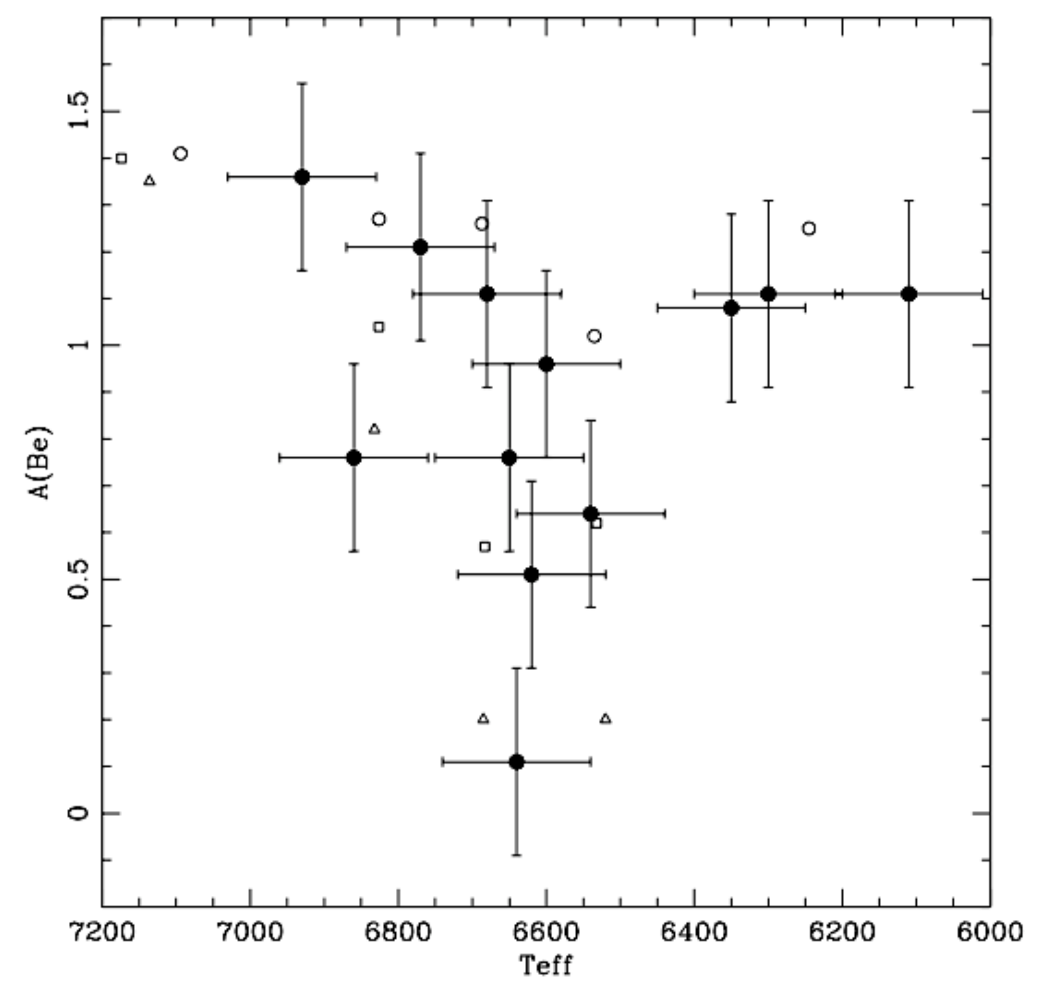


Smiljanic et al. 2009

See poster « **Beryllium abundances along the evolutionary sequence of IC 4651** » by Smiljanic et al.

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

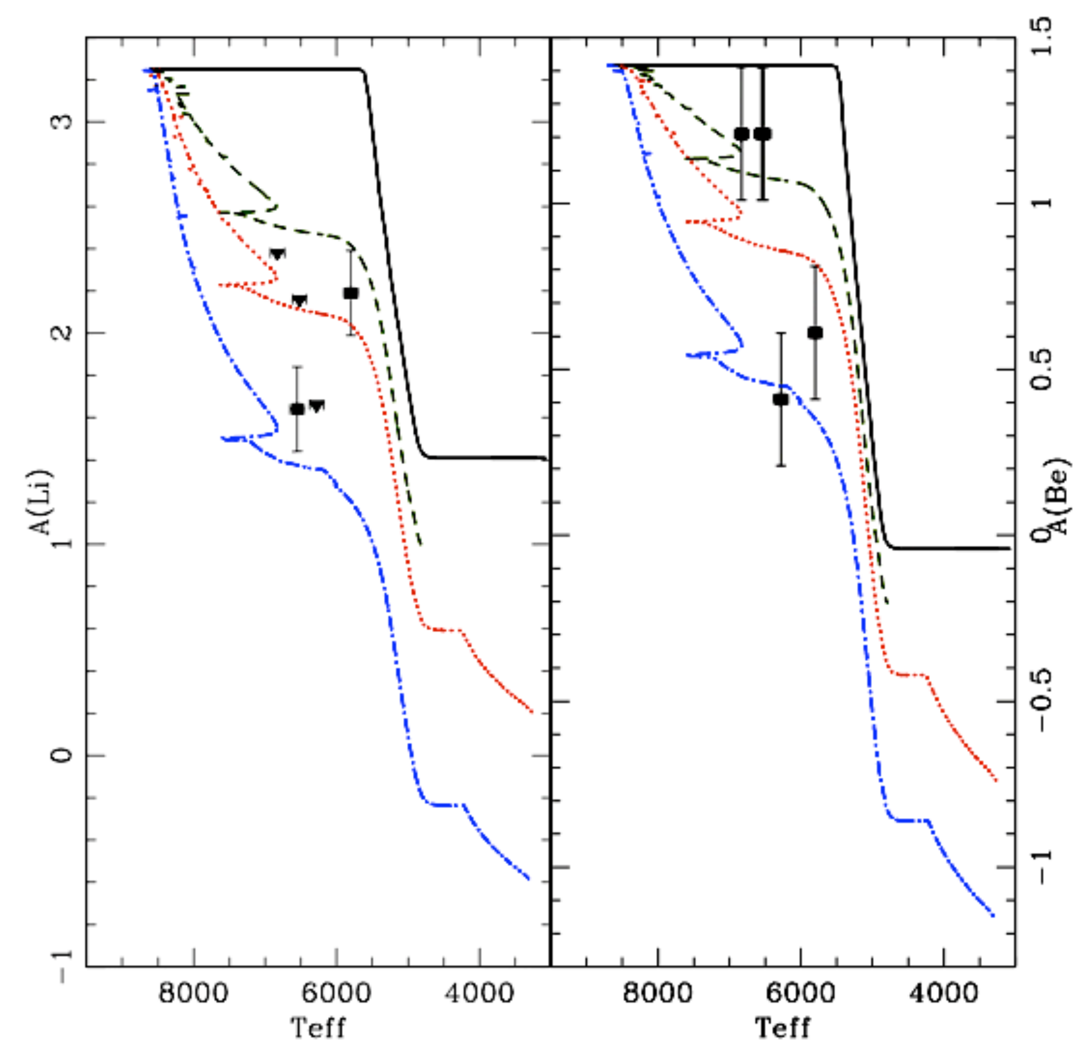
2. Sub-giant stars

______ Classical models

Models with thermohaline and rotation :

------ V_{ZAMS}=80 km/s
------ V_{ZAMS}=110km/s
------ V_{ZAMS}=180 km/s

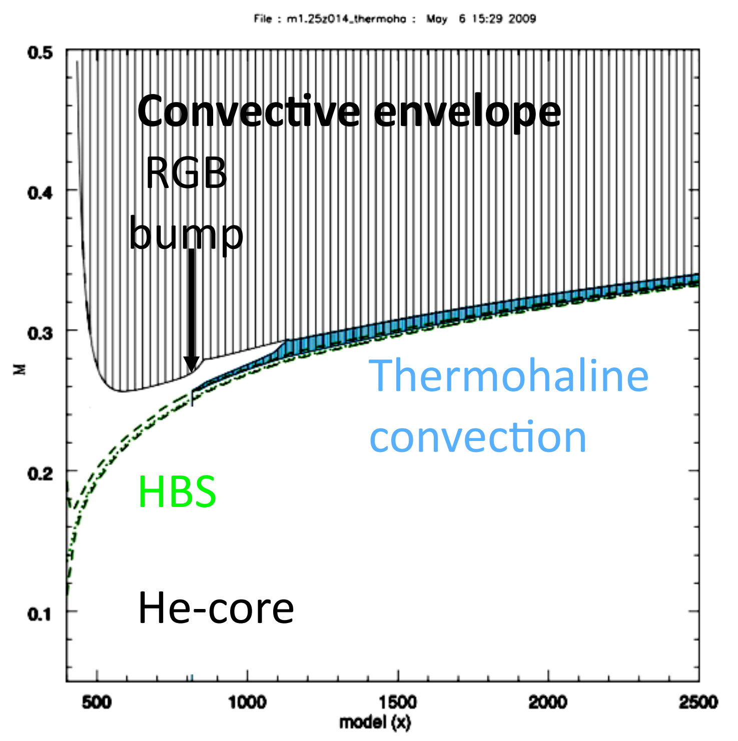
See poster « **Beryllium abundances along the evolutionary sequence of IC 4651** » by Smiljanic et al.

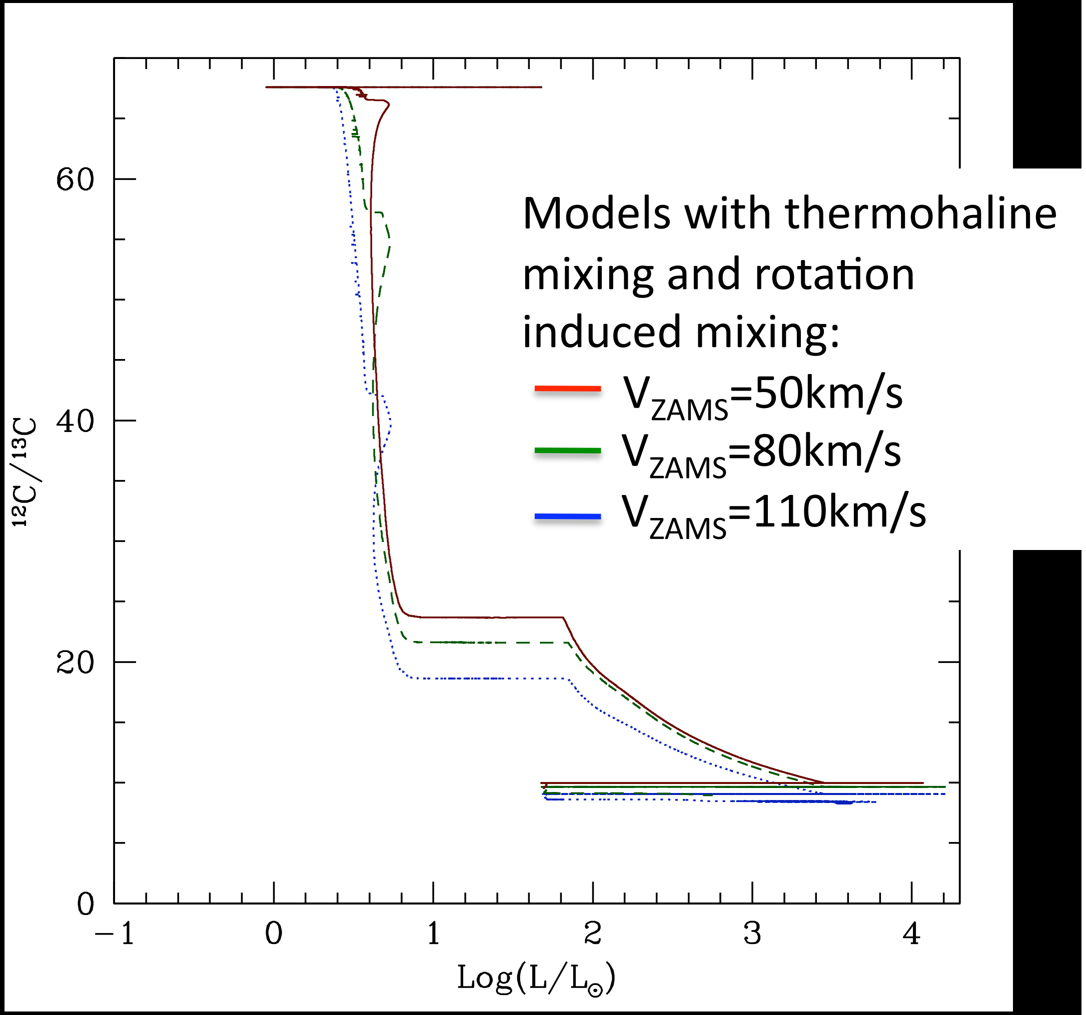


Smiljanic et al. 2009

For field stars : see Poster *"Li survey in giant stars : Probing non-standard stellar physics"* by *Lagarde et al.*

Model for 1.25 $M_\odot$, $Z_\odot$ star



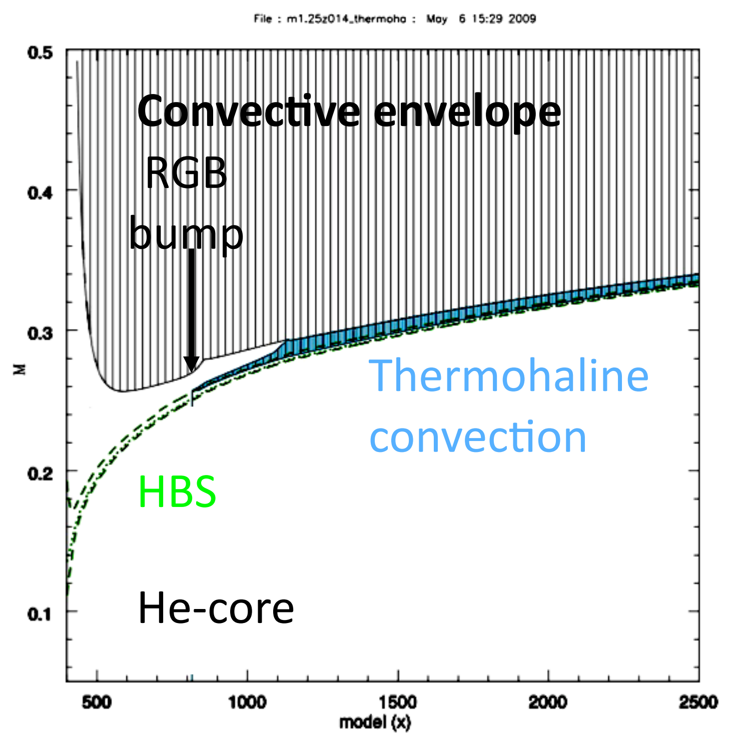


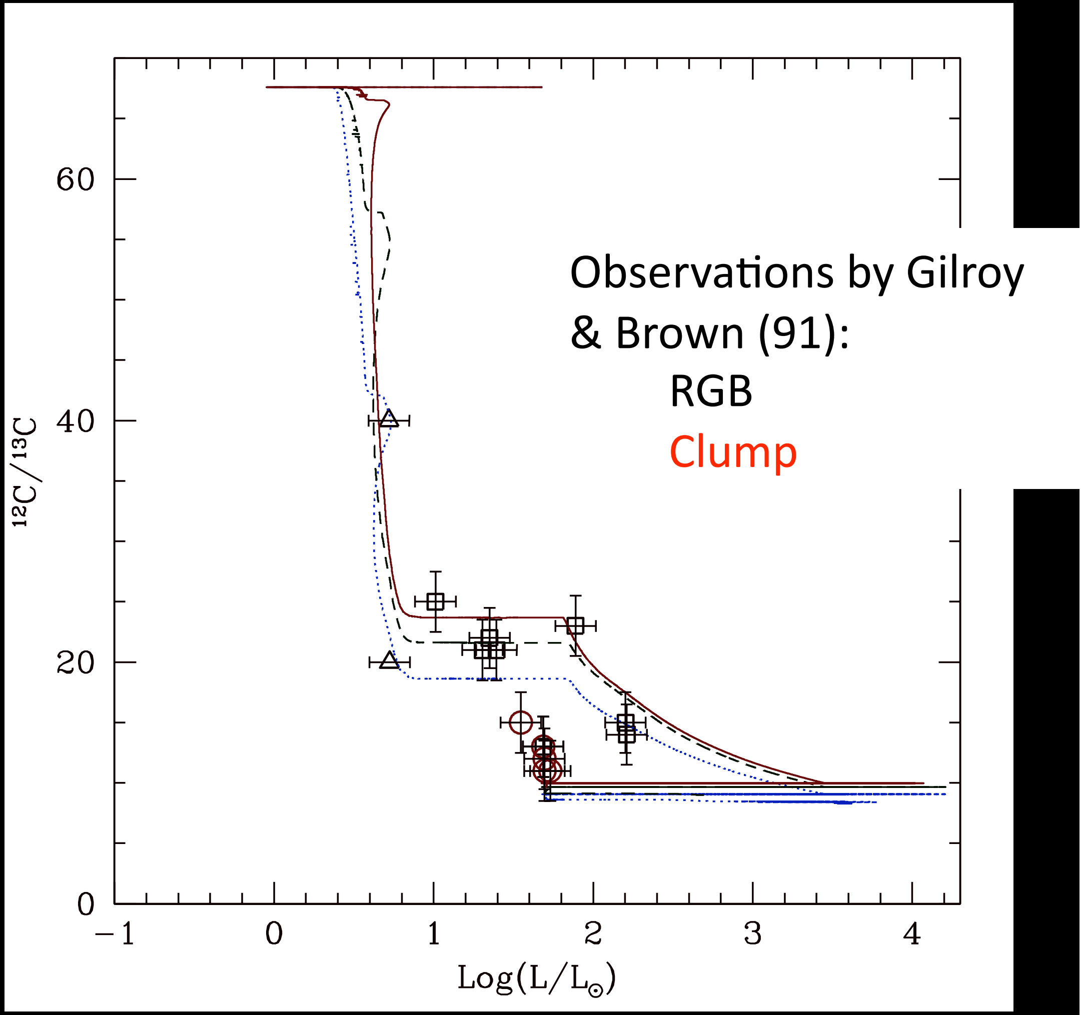
Models with thermohaline mixing and rotation induced mixing:

- V_{ZAMS}=50km/s
- V_{ZAMS}=80km/s
- V_{ZAMS}=110km/s

Lagarde & Charbonnel (in prep.)

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





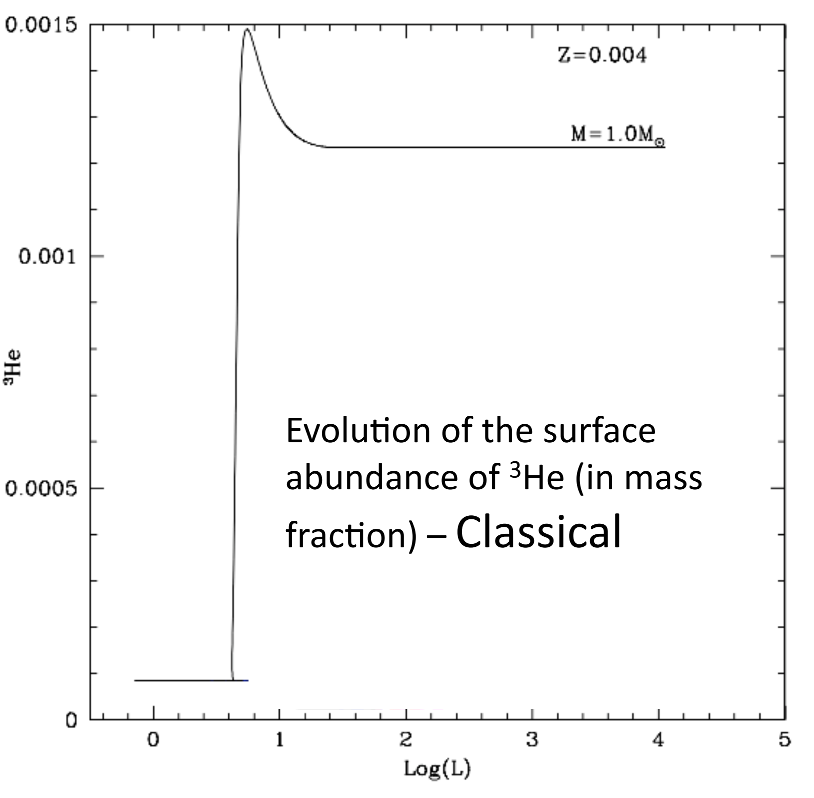
Observations by Gilroy & Brown (91):

RGB

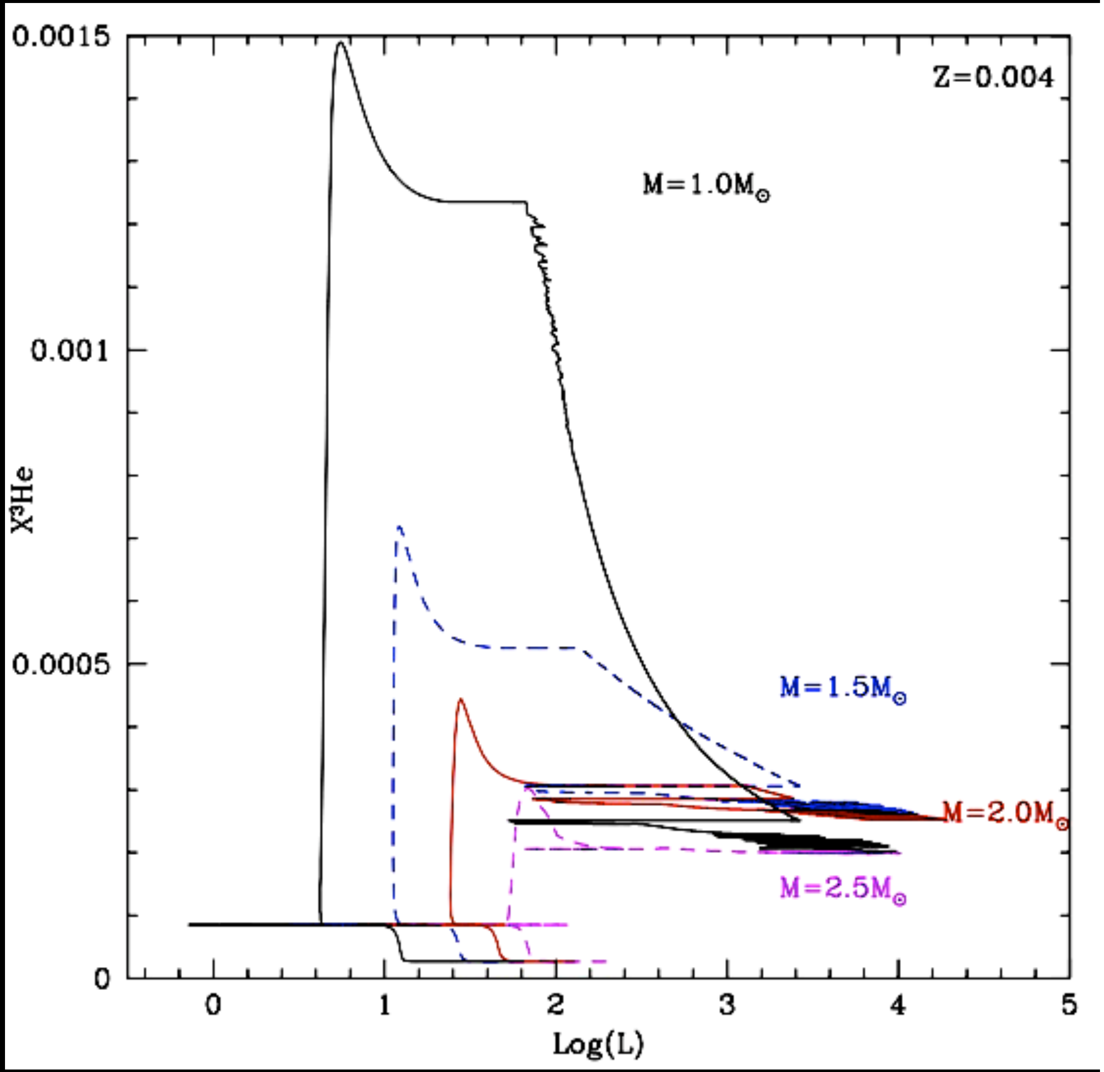
Clump

Lagarde & Charbonnel (in prep.)

^{3}He with thermohaline mixing



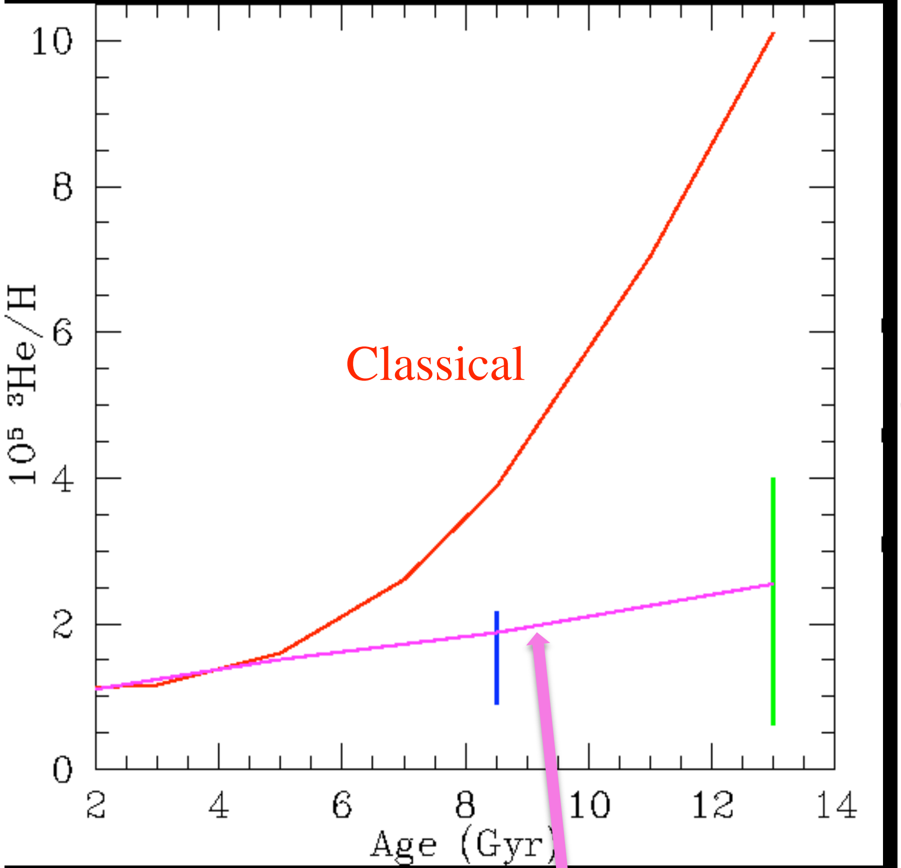
Evolution of the surface abundance of ^{3}He (in mass fraction) – Classical



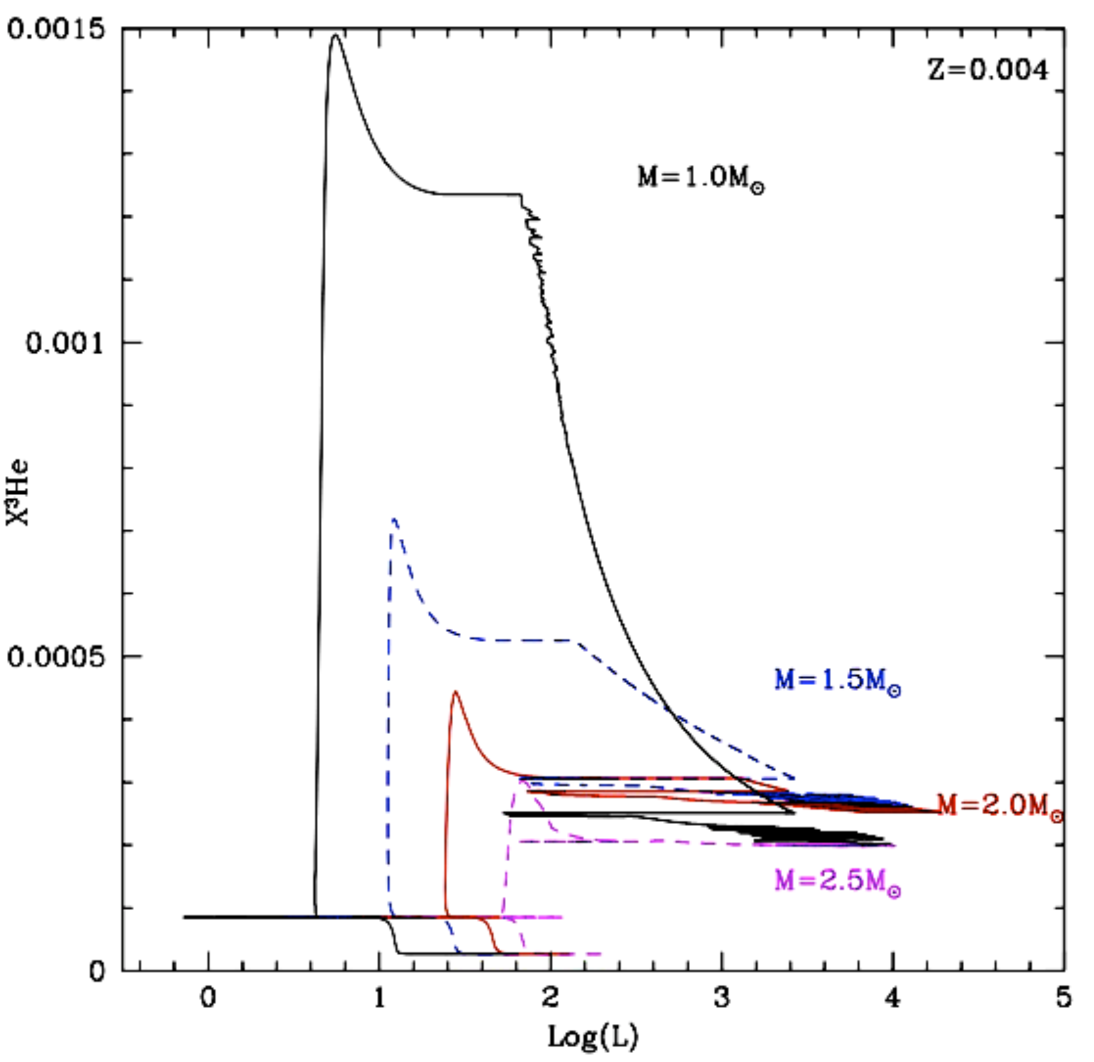
Lagarde & Charbonnel (10)

Lagarde & Charbonnel - IAU 268

^{3}He with thermohaline mixing

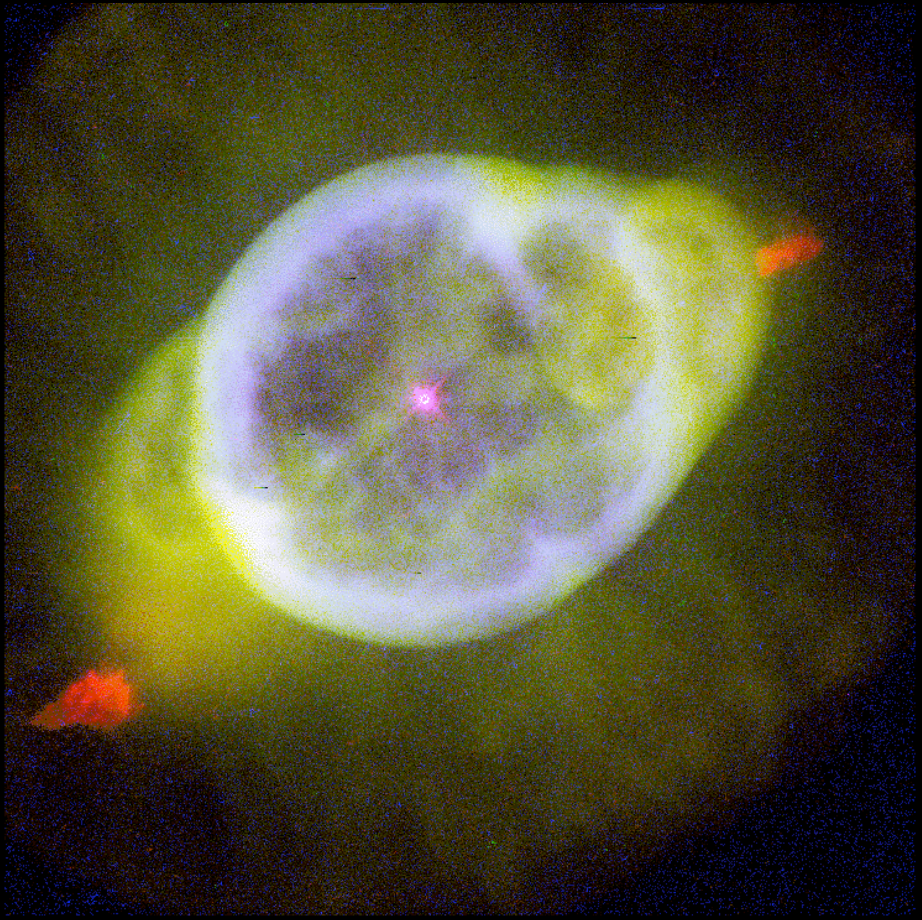


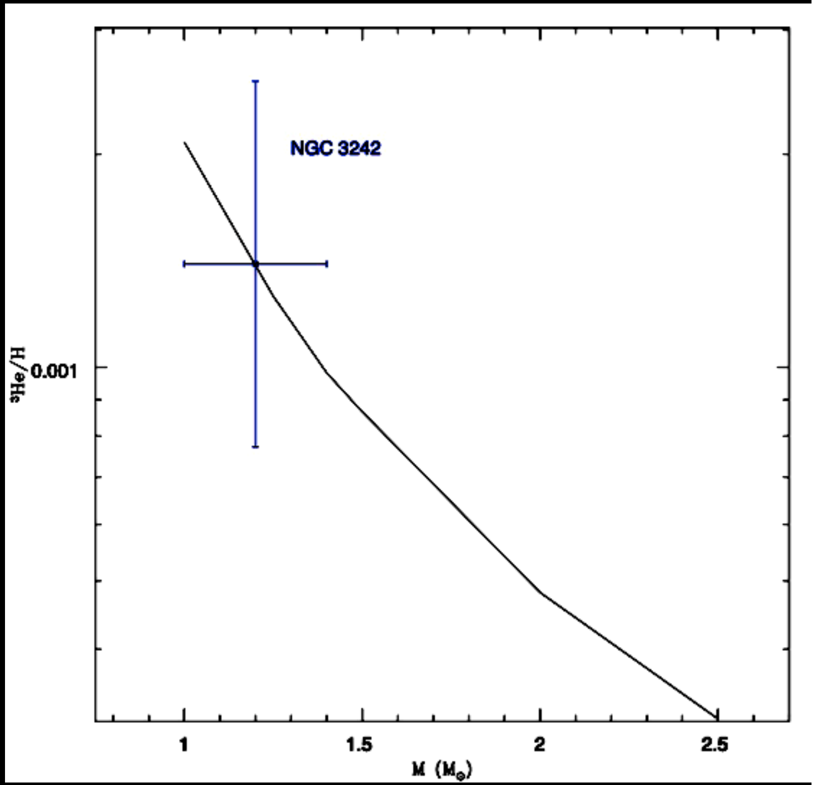
Thermohaline and rotation !?!



Lagarde & Charbonnel (in prep.)

The stubborn PNe NGC 3242 and J 320





Standard prediction (Charbonnel et al. 08)
Observation (Galli et al. 97)
$^{12}C/^{13}C$ is also standard

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

Lagarde & Charbonnel - IAU 268

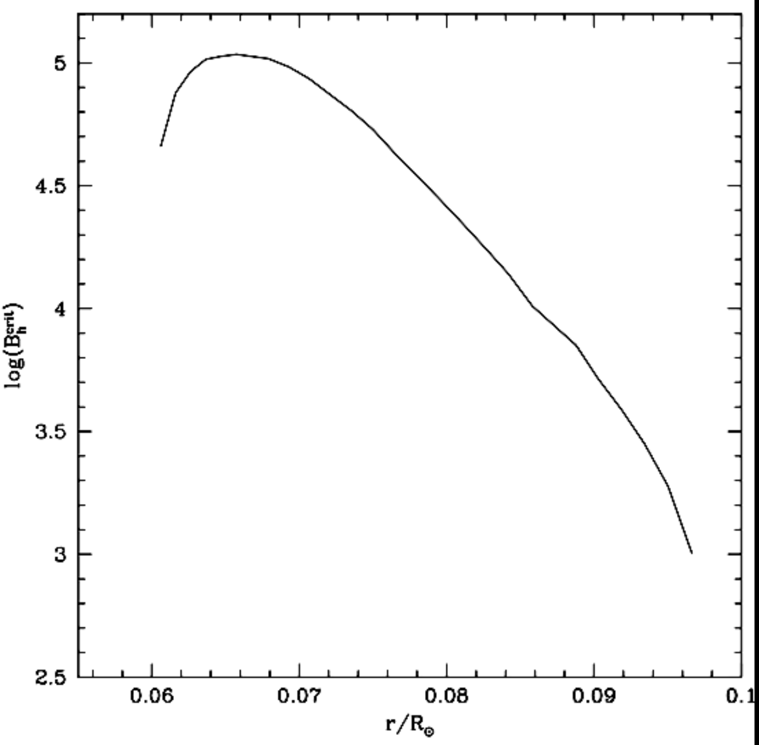
Fossil magnetic field in Ap star descendants

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

Local criteria for a magnetic field that may prevent thermohaline instability in RGB star:

$B_h^2 > \rho \lambda^2 |N_\mu^2| / \pi$
λ : horizontal size of the ^{3}He fingers



Main sequence Ap stars: surface magnetic fields ~ 10^2 - 3×10^4 G
On the RGB, as the central region of the star contracts during the evolution on giant branch, may be enhanced by ~ 2 o.magnitude, due to flux conservation

Charbonnel & Zahn (07b)

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
    - solves the long standing ^{3}He problem in the Galaxy

- ^{3}He and $^{12}C/^{13}C$ "standard" in NGC 3242 and J360
    - fossil magnetic field in Ap star descendants