Thermohaline mixing in low-mass AGB stars

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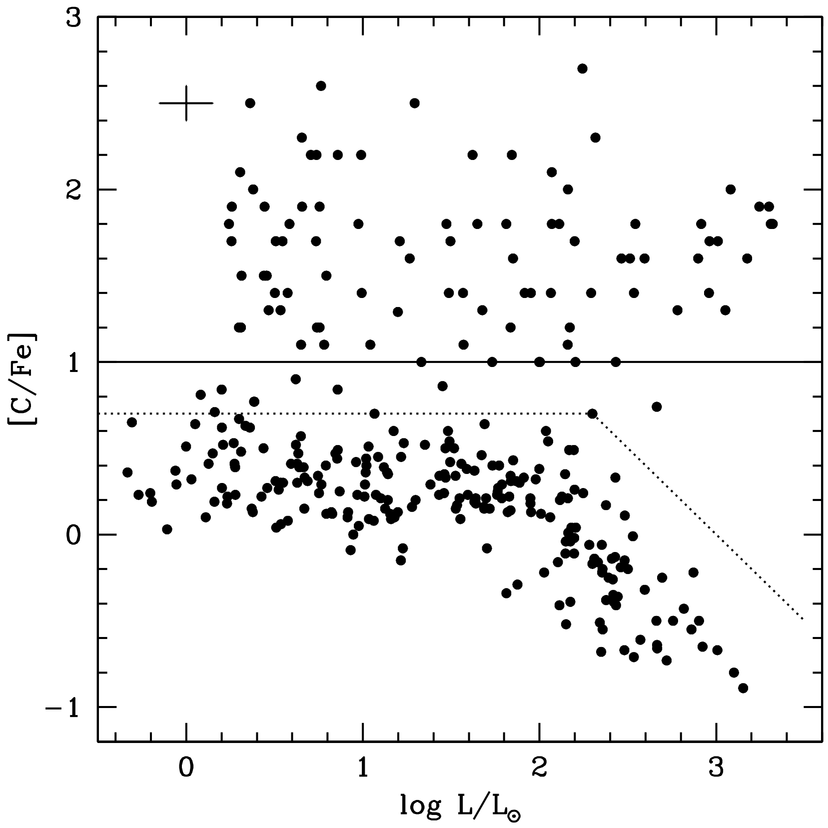
Overview

- Motivation: Li-rich carbon-enhanced metal-poor stars
- What is thermohaline mixing?
- Effects on low-metallicity, low-mass asymptotic giant branch stars

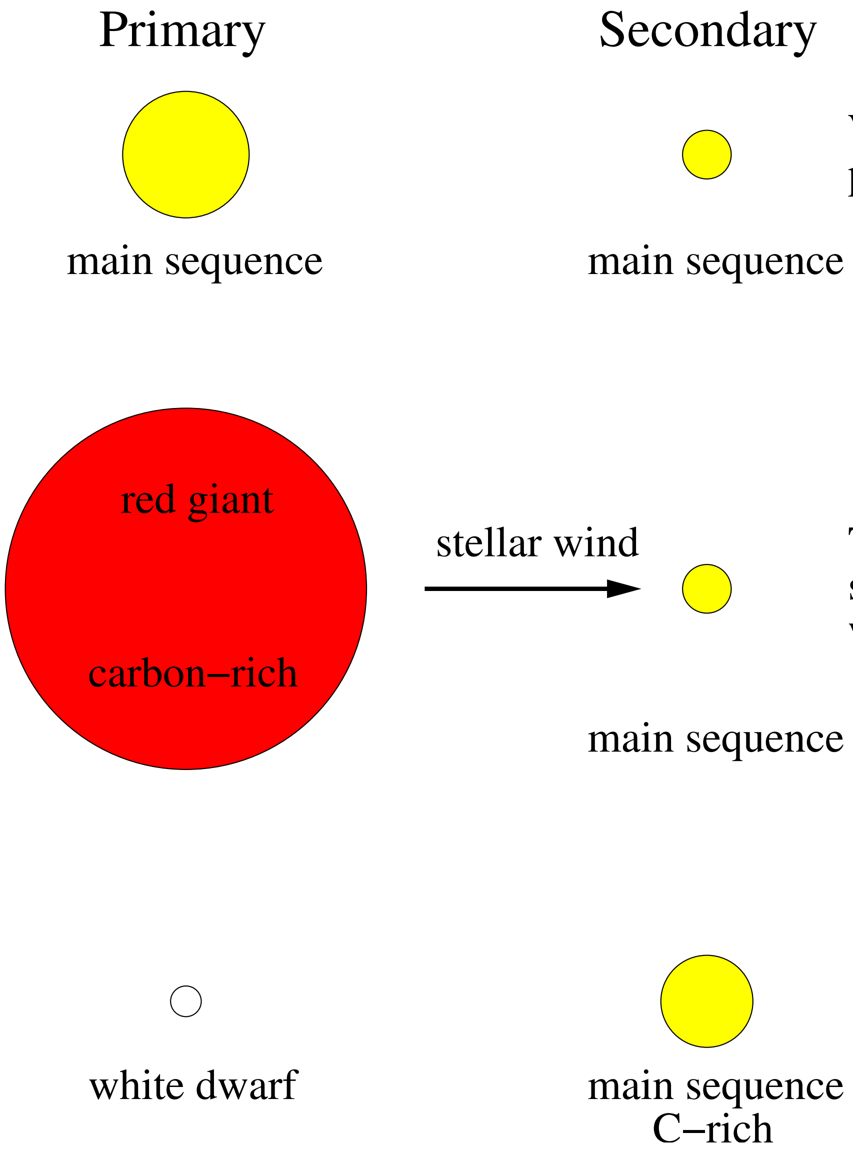
Carbon-enhanced metal-poor stars?

- As many as 20% of metal-poor stars show substantial carbon enhancement
- Enhancement of s-process elements found in about 70% of CEMPs
- Of these, about 70% show radial velocity variation – this suggests binary stars!

Lucatello et al. (2006)



Mass Transfer



Wide binary forms, consisting of a 1−3Msol primary and a lower mass companion.

The primary evolves, becomes an AGB star and produces carbon. Strong stellar winds transfer material to the secondary.

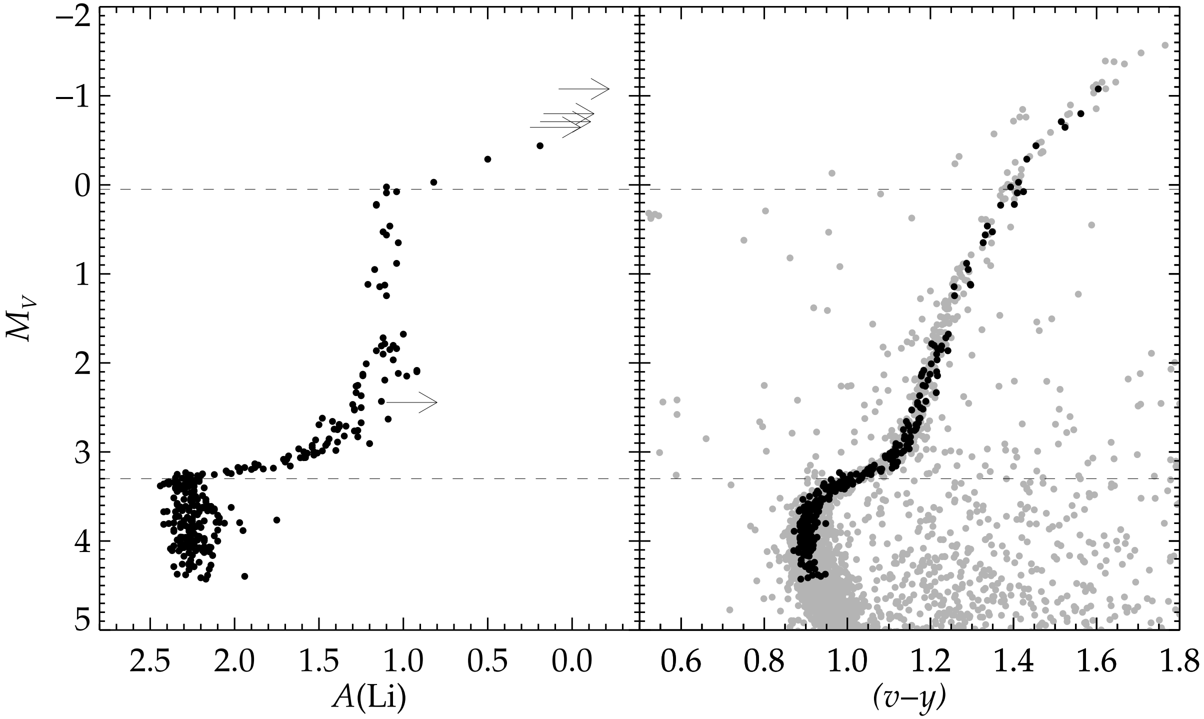
The primary becomes a white dwarf, which fades from view. We observe the secondary as a C−rich star.

CS 22964-161

- Reported by Thompson et al. (2008)
- Double-lined spectroscopic binary
- Both components are CEMPs!
- Unevolved and Li-rich – $\log \epsilon(\mathrm{Li}) = +2.09$
- This is not the only CEMP that is Li-rich!

Low-mass stars destroy lithium

- Lithium is fragile – burns at around 2.5×10^6K
- Li abundances drops at first dredge-up
- Extra-mixing on the giant branch depletes Li further
- We expect low-mass stars to be devoid of Li!



Lind et al. (2009)

Thermohaline Mixing

- Occurs when material of high mean molecular weight lies on top of material of low mean molecular weight
- A double diffusive processes
- Displace a blob of material downward – at thermal equilibrium, it is heavier than its surroundings
- The blob continues to sink and mixing occurs

Helium-3 burning

- How do you get a molecular weight inversion within a star?

$$\boxed{{}^{3}\mathrm{He} + {}^{3}\,\mathrm{He} \rightarrow 2p + {}^{4}\,\mathrm{He}}$$

- Also need the existing mean molecular weight gradient to be erased
- This will happen after episodes of dredge-up – penetration of the convective envelope
- Occurs after first dredge-up on the red giant branch

Thermohaline mixing can explain...

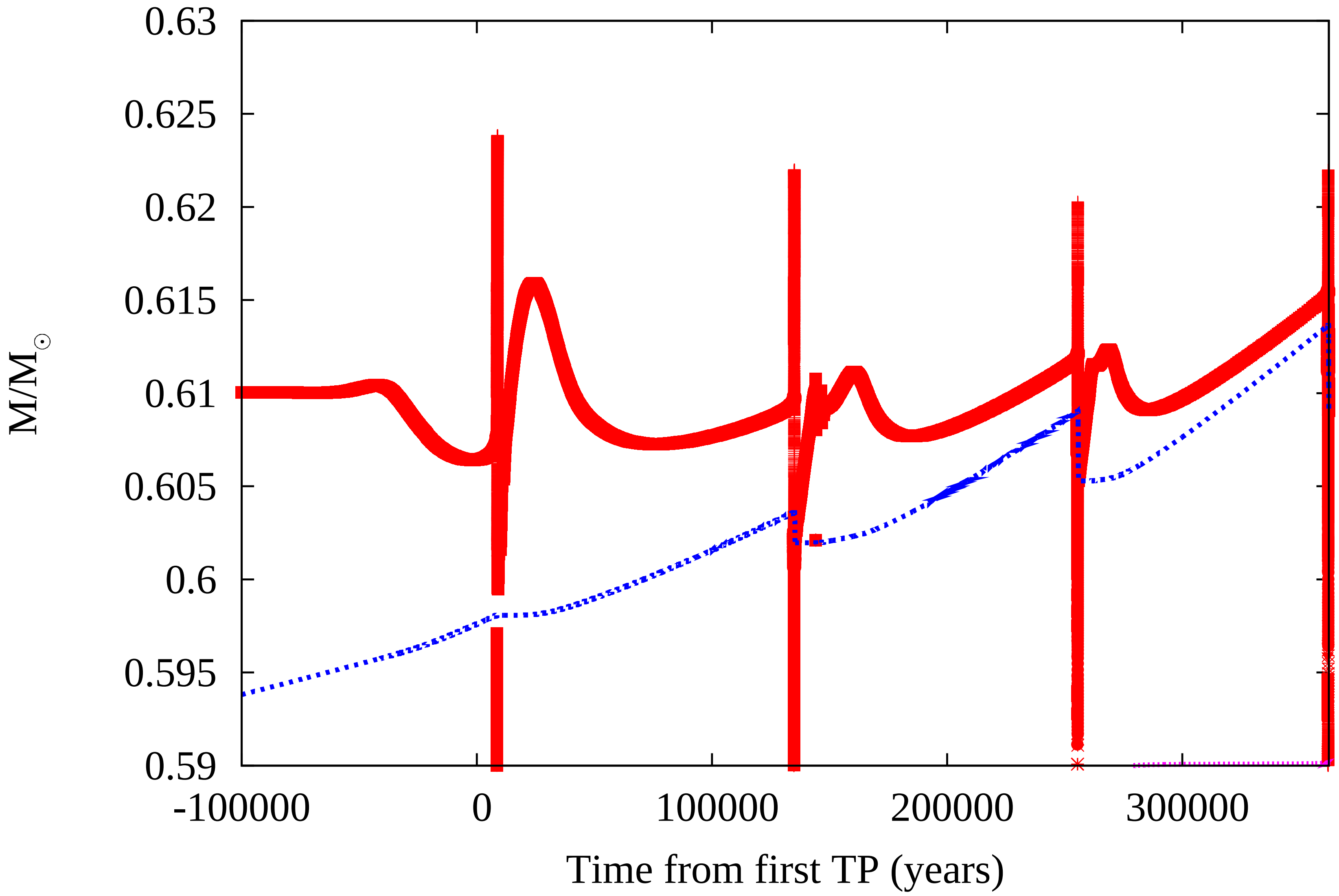
- $^3\mathrm{He}$ destruction in low-mass stars (Eggleton, Dearborn & Lattanzio 2006) – more from Corinne later!
- C, N and Li-variations on the red giant branch (Charbonnel & Zahn 2007, Eggleton, Dearborn & Lattanzio 2008)
- Giant branch mixing in both carbon-normal and carbon-rich metal-poor stars (Stancliffe et al. 2009)

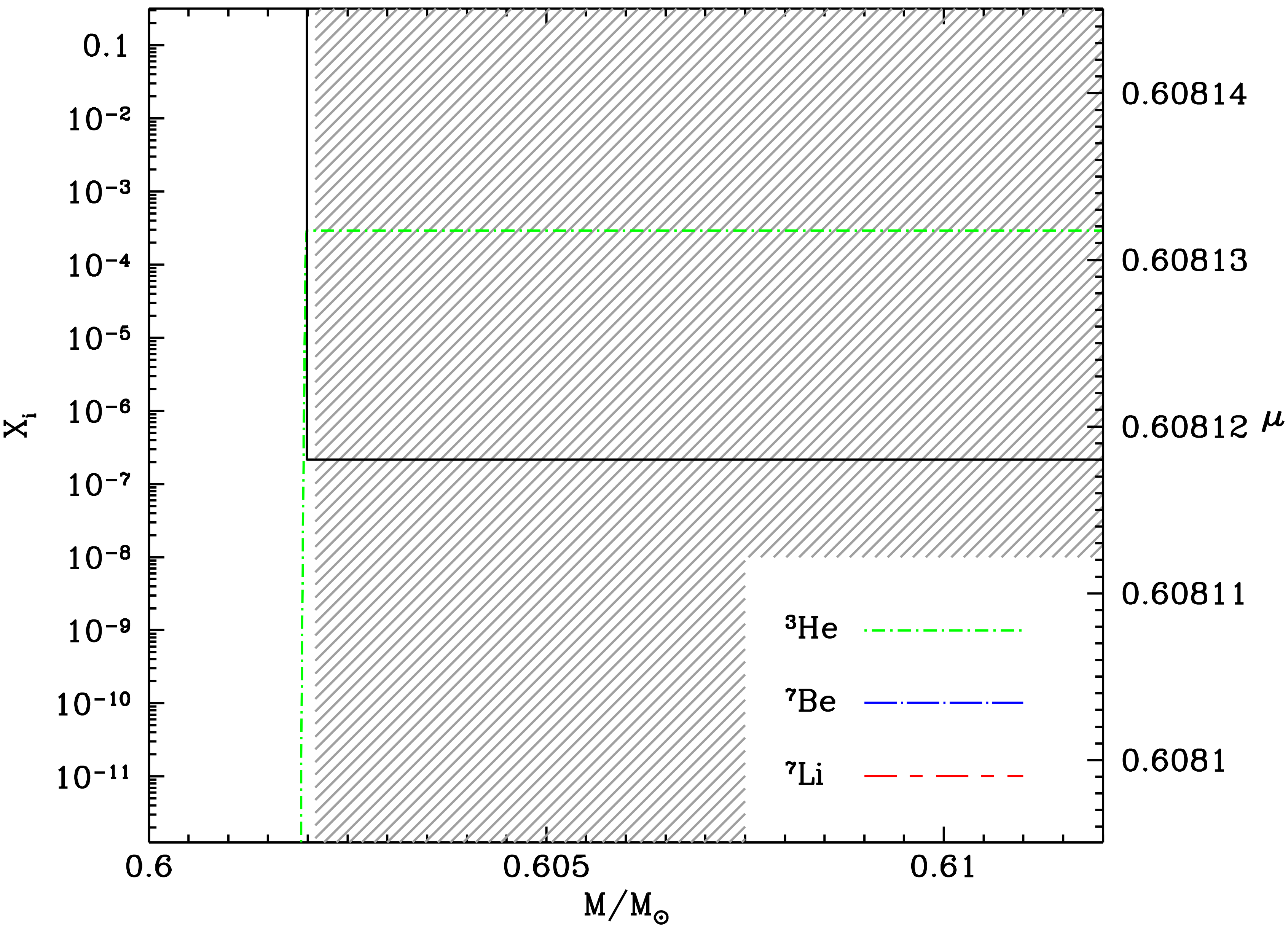
Modelling

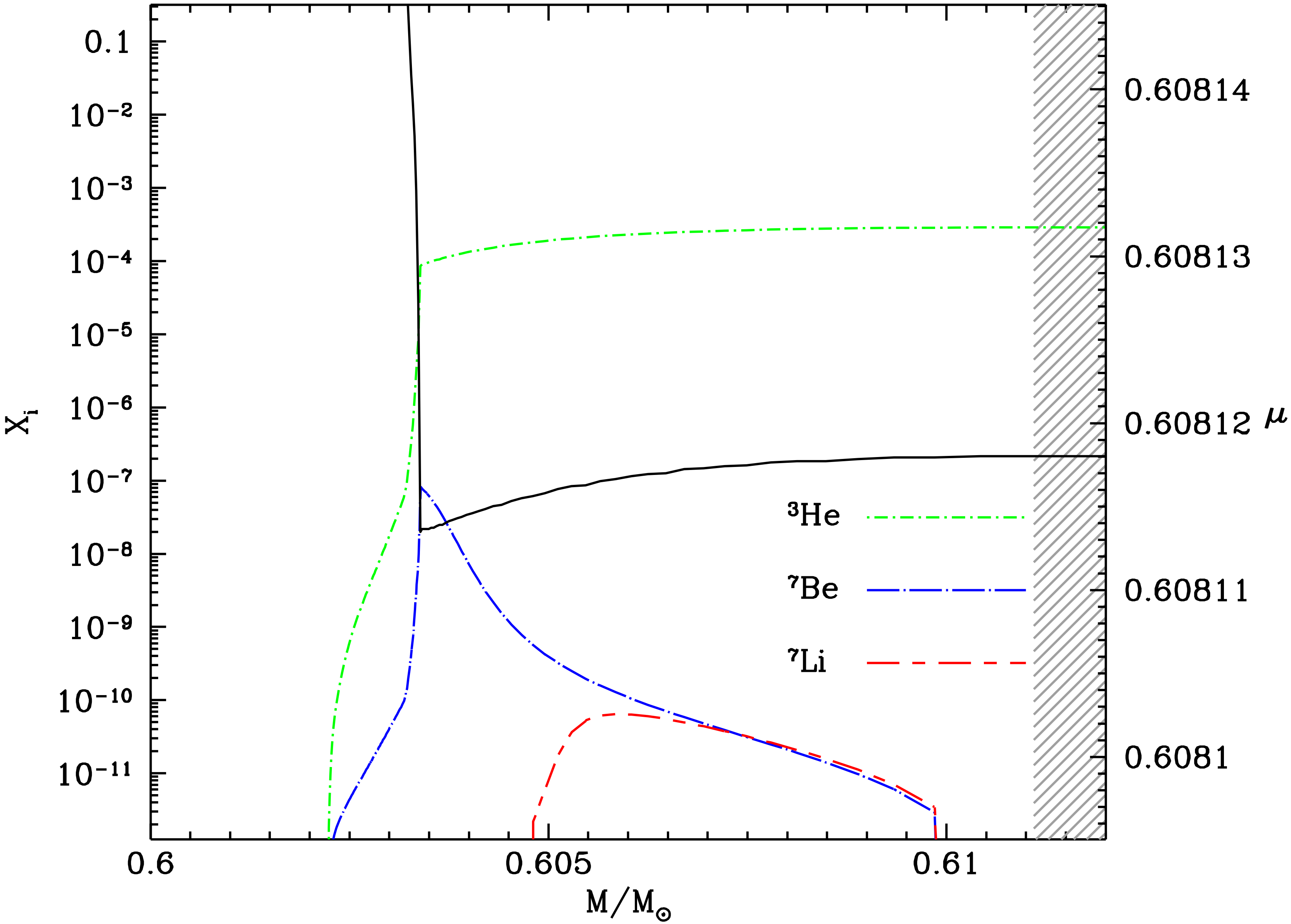
- Models made with the STARS code (Eggleton 1971, Stancliffe & Eldridge 2009)
- $Z = 10^{-4}$ or [Fe/H] = -2.3
- 1, 1.5 and 2 $M_\odot$
- Thermohaline mixing applied throughout the simulations
- Diffusion coefficient tuned to reproduce mixing seen on the giant branch in the C-normal population
- Same diffusion coefficient applied throughout

Can we get AGB thermohaline mixing?

- Some (but not much!) $^3\mathrm{He}$ remains after the first giant branch – around 2×10^{-4} by mass fraction
- Third dredge-up erases the mean molecular weight gradient in the envelope, so...
- ...can we get thermohaline mixing?
- And why does this help us with Li???


0.63
0.625
0.62
0.615
0.61
0.605
0.6
0.595
0.59
$M/M_\odot$
-100000
0
100000
200000
300000
Time from first TP (years)


0.1
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
10⁻⁹
10⁻¹⁰
10⁻¹¹
X_i
0.60814
0.60813
0.60812
0.60811
0.6081
μ
0.6
0.605
0.61
M/M_⊙
³He
⁷Be
⁷Li


0.1
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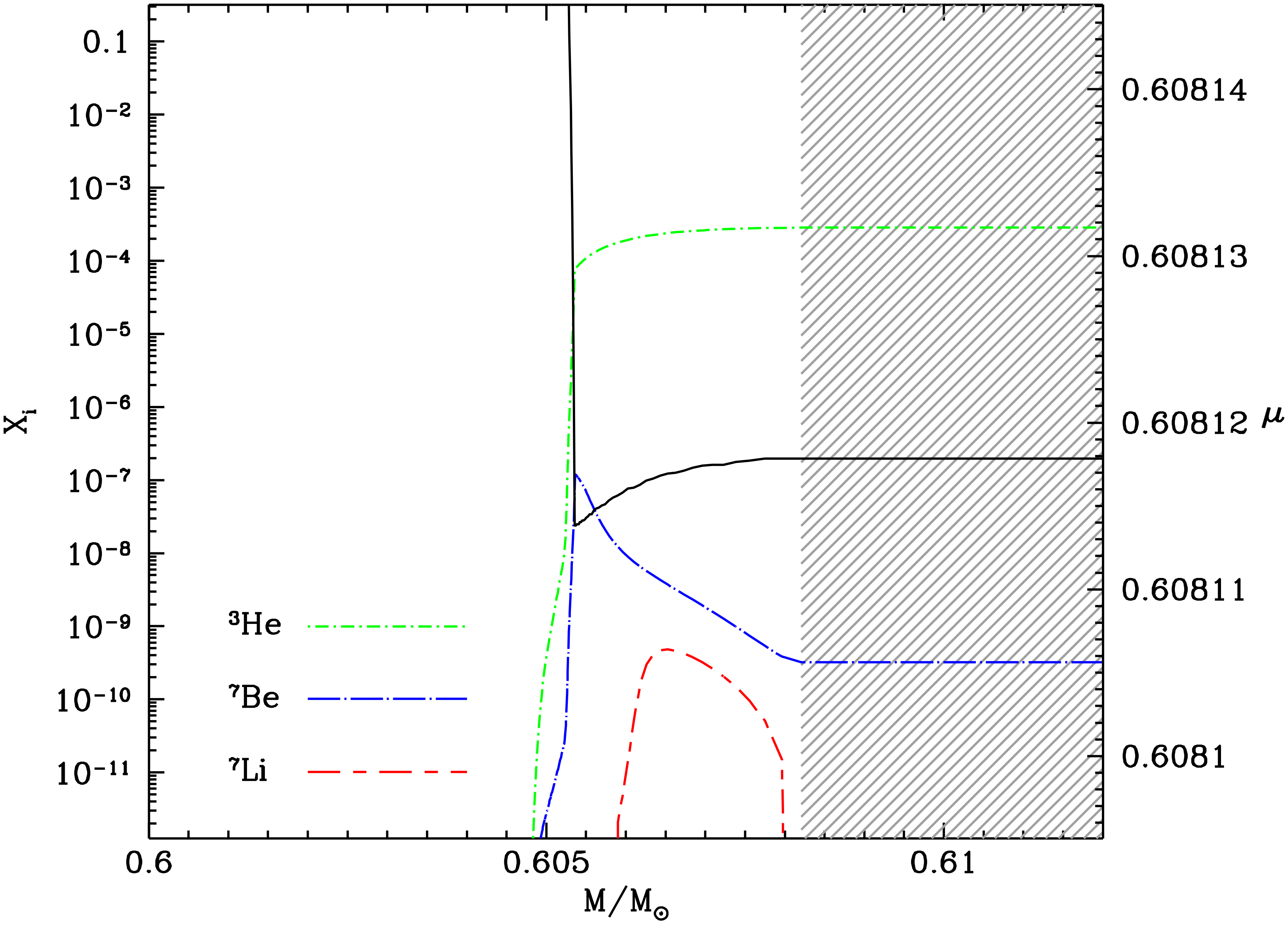
X_i
0.6
0.605
0.61
$M/M_\odot$
0.60814
0.60813
0.60812
0.60811
0.6081
μ
^{3}He
^{7}Be
^{7}Li


0.1
10⁻²
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10⁻⁴
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10⁻¹¹
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0.60814
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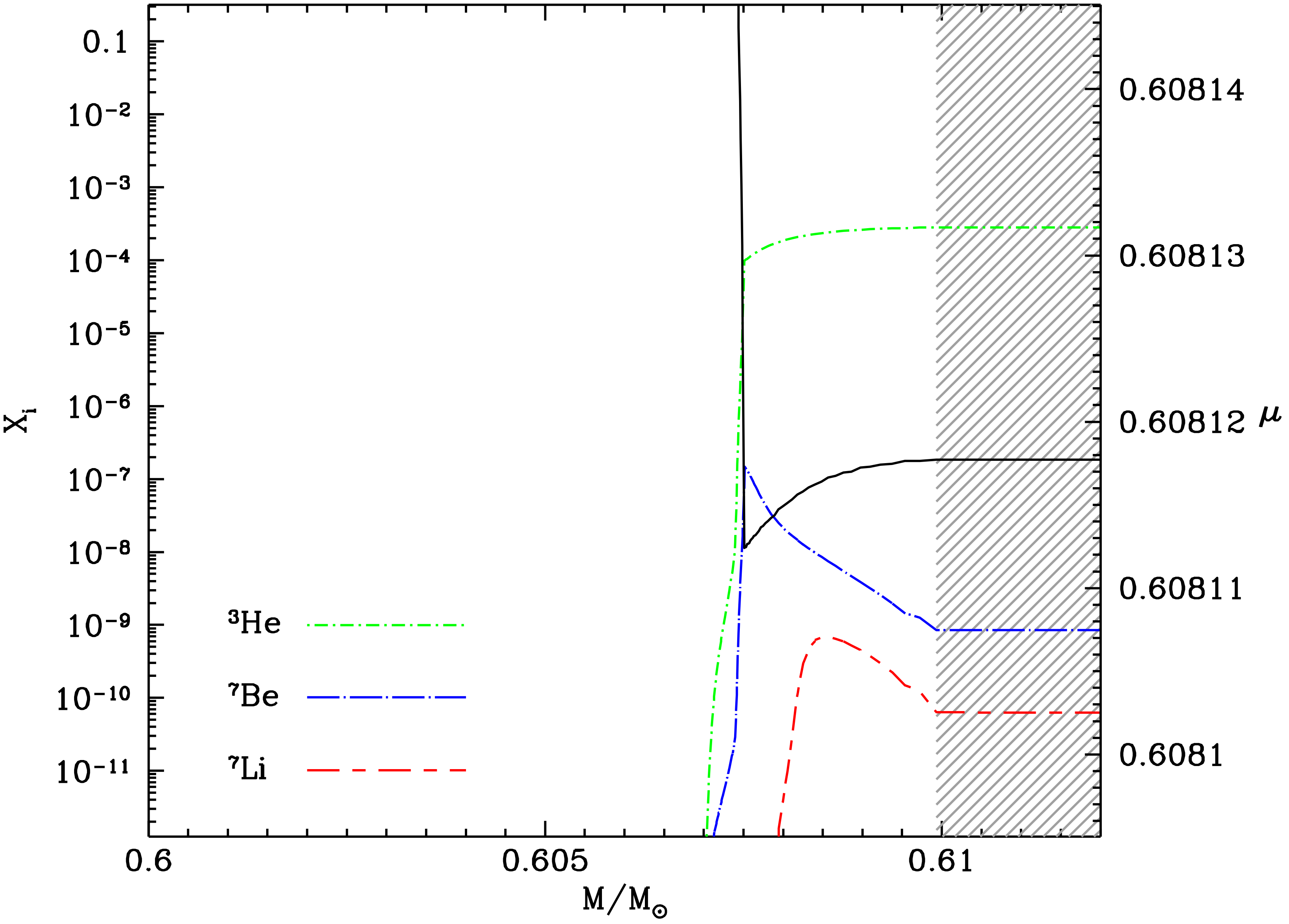
0.60811
0.6081
μ
0.6
0.605
0.61
M/M☉
³He
⁷Be
⁷Li


0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
X_i
^{3}He
^{7}Be
^{7}Li
0.6
0.605
0.61
$M/M_\odot$
0.60814
0.60813
0.60812
0.60811
0.6081
μ

Li-production

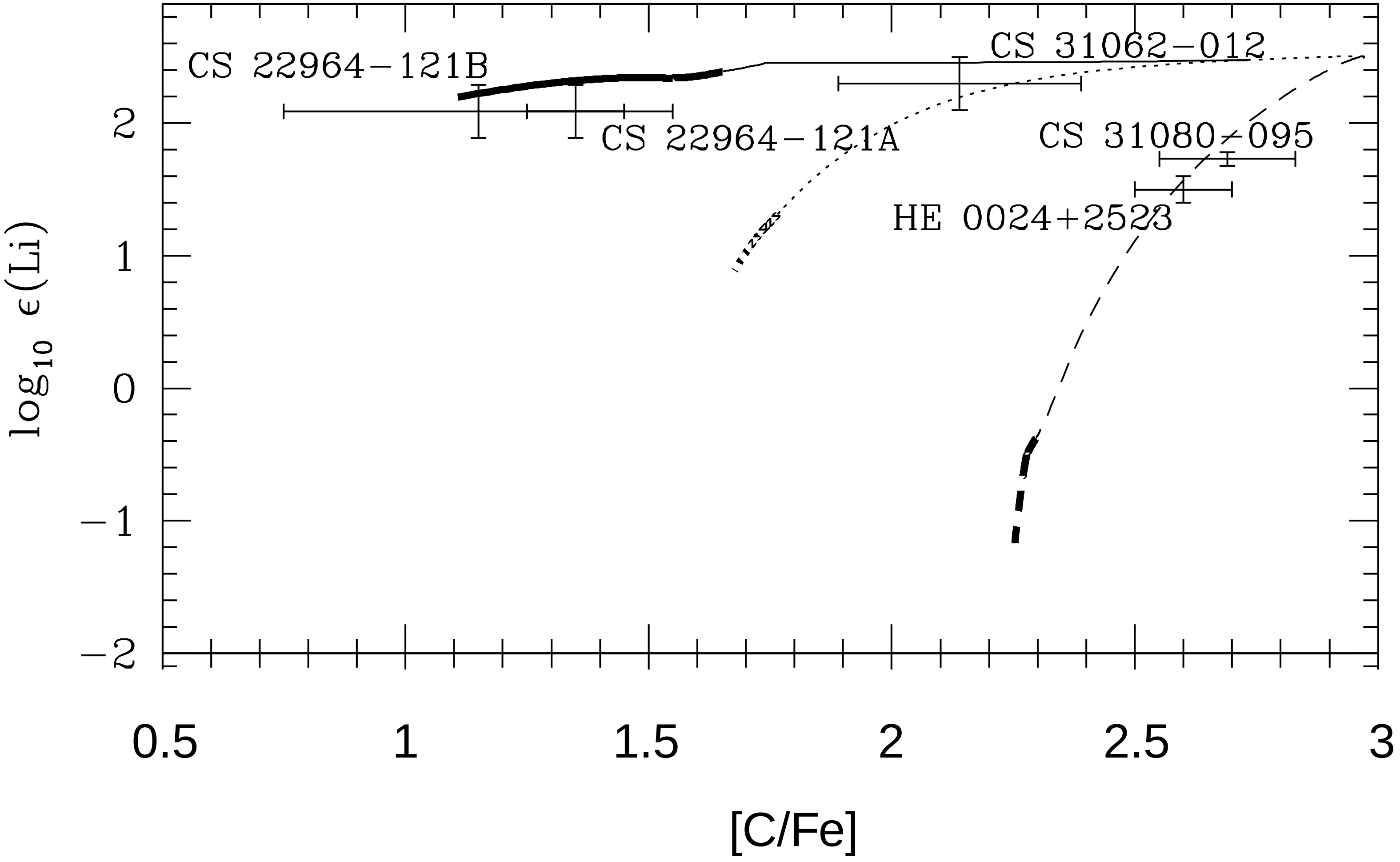
- We can reach $\log\ \epsilon(^7\mathrm{Li}) = 2.5$ in a 1.5 $M_\odot$ star of $Z = 10^{-4}$
- Not so much in a 1 $M_\odot$ star – $\log\ \epsilon(^7\mathrm{Li}) = 1.0$
- Or in a 2 $M_\odot$ star – $\log\ \epsilon(^7\mathrm{Li}) = 1.4$
- We can get Li- and C-enrichment at the same time
- And we do see Li and C-rich metal-poor stars!

Modelling secondaries

- Accrete some of this material on to a secondary
- Evolve the model to the turn-off to see what you get

Non-convective processes included (see Stancliffe & Glebbeek 2008, Stancliffe 2009):

- Thermohaline mixing
- Gravitational settling
- Richard et al. (2005) ad hoc mixing


CS 22964−121B
CS 31062−012
CS 22964−121A
CS 31080−095
HE 0024+2523
$\log_{10}\ \epsilon(\mathrm{Li})$
2
1
0
−1
−2
0.5
1
1.5
2
2.5
3
[C/Fe]

Conclusions

- Thermohaline mixing can occur in low-mass, low-metallicity AGB stars
- It can lead to substantial lithium abundances
- $\log\ \epsilon(^7\mathrm{Li}) = 2.5$ in a 1.5 $M_\odot$ star of $Z = 10^{-4}$
- This is in line with the Li-rich, carbon enhanced metal-poor stars