Lithium abundance in the globular cluster M4:

from the Turn-Off up to the RGB Bump

Mucciarelli et al. 2010, arXiv:1010.3879

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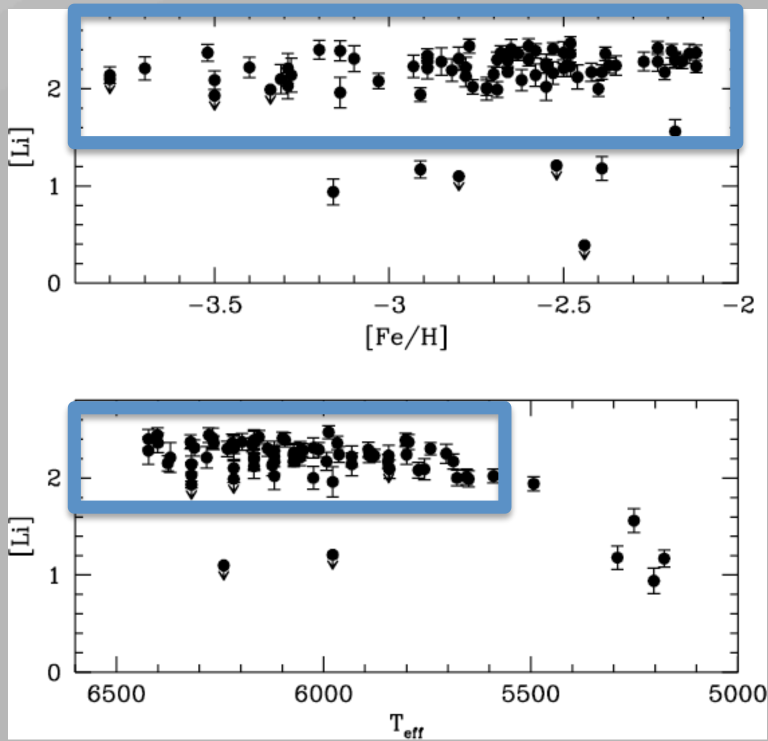
The Lithium discrepancy



From the theory

- Li is produced during the Big Bang nucleosynthesis
- Li burning : $T_{eff} \sim 2.5 \times 10^6$ K

From the observations

- Constant A(Li) (2.2/2.3 dex) in dwarf, Pop II stars regardless of the metallicity and T_{eff} (Spite Plateau)

The Spite Plateau has been interpreted as the signature of the primordial Li abundance, but…

WMAP + Big Bang Nucleosynthesis standard model

A(Li) = 2.72 ± 0.06 (Cyburt et al. 2008)

A factor of 3 to 4 higher than the Spite Plateau

The Lithium discrepancy: possible solutions

✓ Inadequacy of the Big Bang Nucleosynthesis Standard Model
(WMAP A(Li) does not represent the pristine Li abundance)

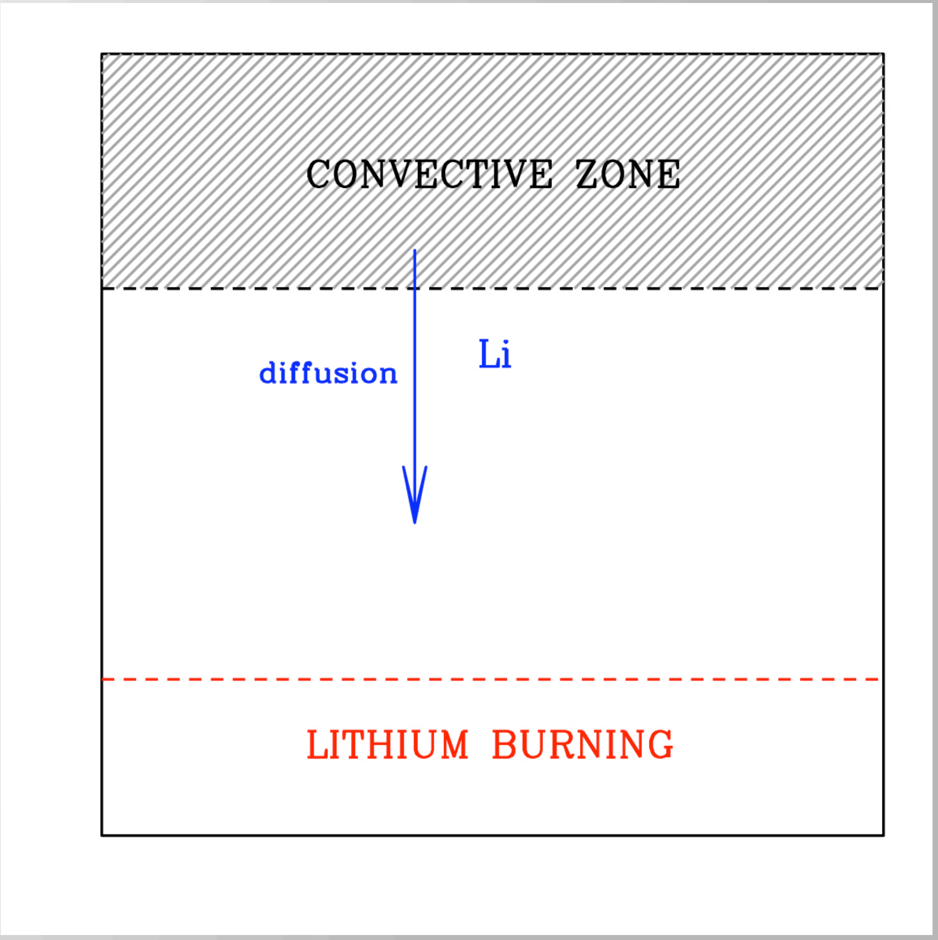
✓ Stellar evolution mechanisms (atomic diffusion) that deplete
the surface Li abundance in the dwarfs stars
(the Spite Plateau does not indicate the primordial A(Li))

✓ Population III stars, able to destroy some of the initial A(Li) (Piau et al. 2007)
(a complex, fine-tuned model that partially reduces the discrepancy)

Atomic diffusion …

Atomic diffusion is a basic element transport mechanism, driven by pressure, temperature and composition gradients.

It is a fundamental ingredient in the standard solar model in order to reproduce the evidences from heliosismology.



Diffusion causes Li (and other elements) to sink below the photosphere

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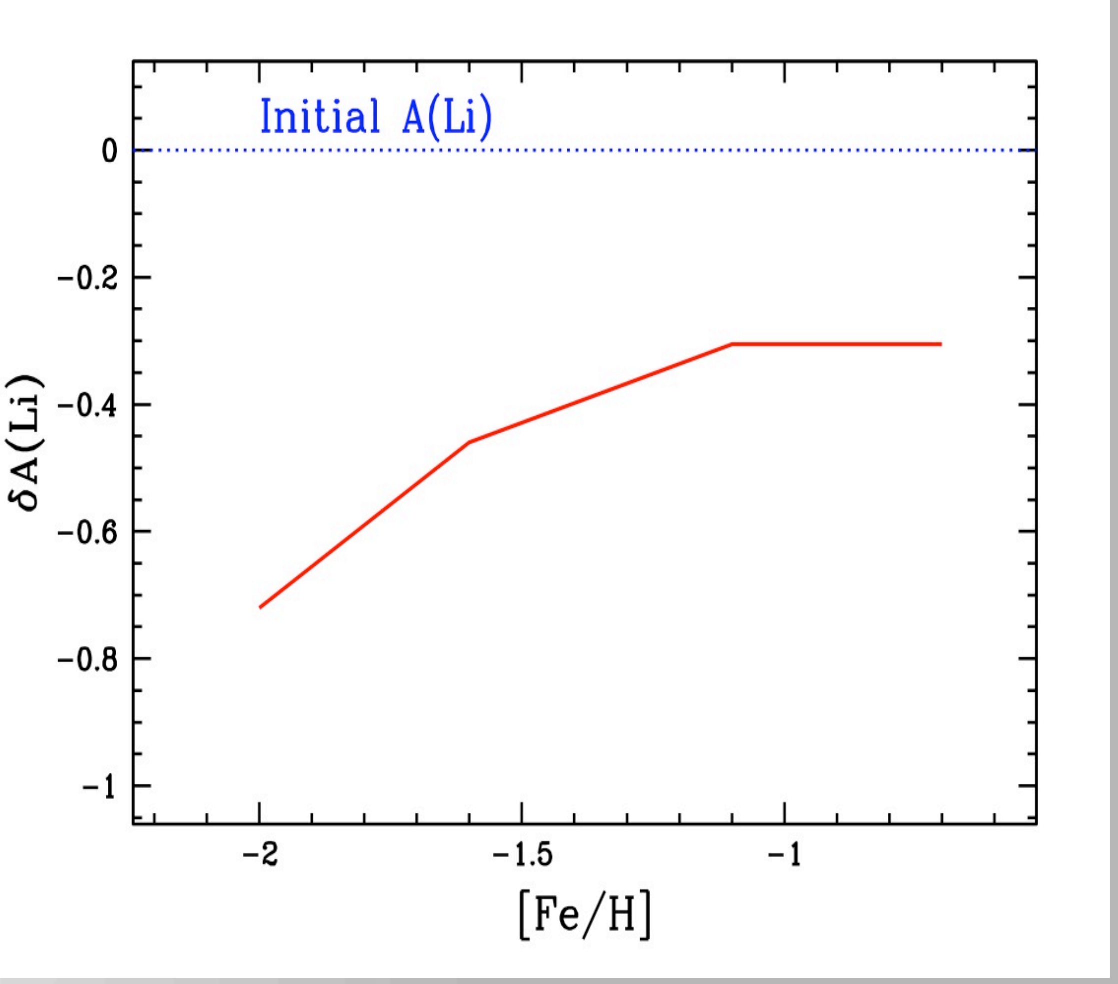


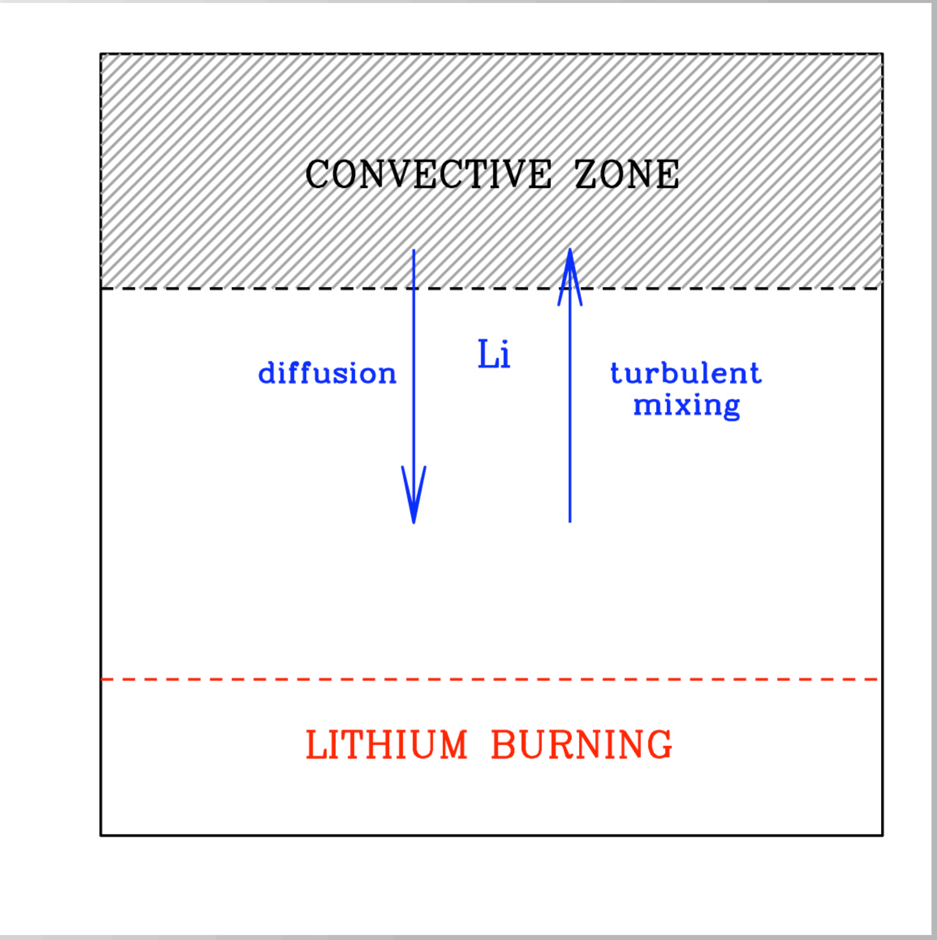
The diffusion is more efficient at low metallicity (shallow convective envelope)

Theory predicts a trend of A(Li) with the metallicity but this is contradicted by the Spite Plateau

Other mechanisms occur …

Atomic diffusion … and turbulent mixing

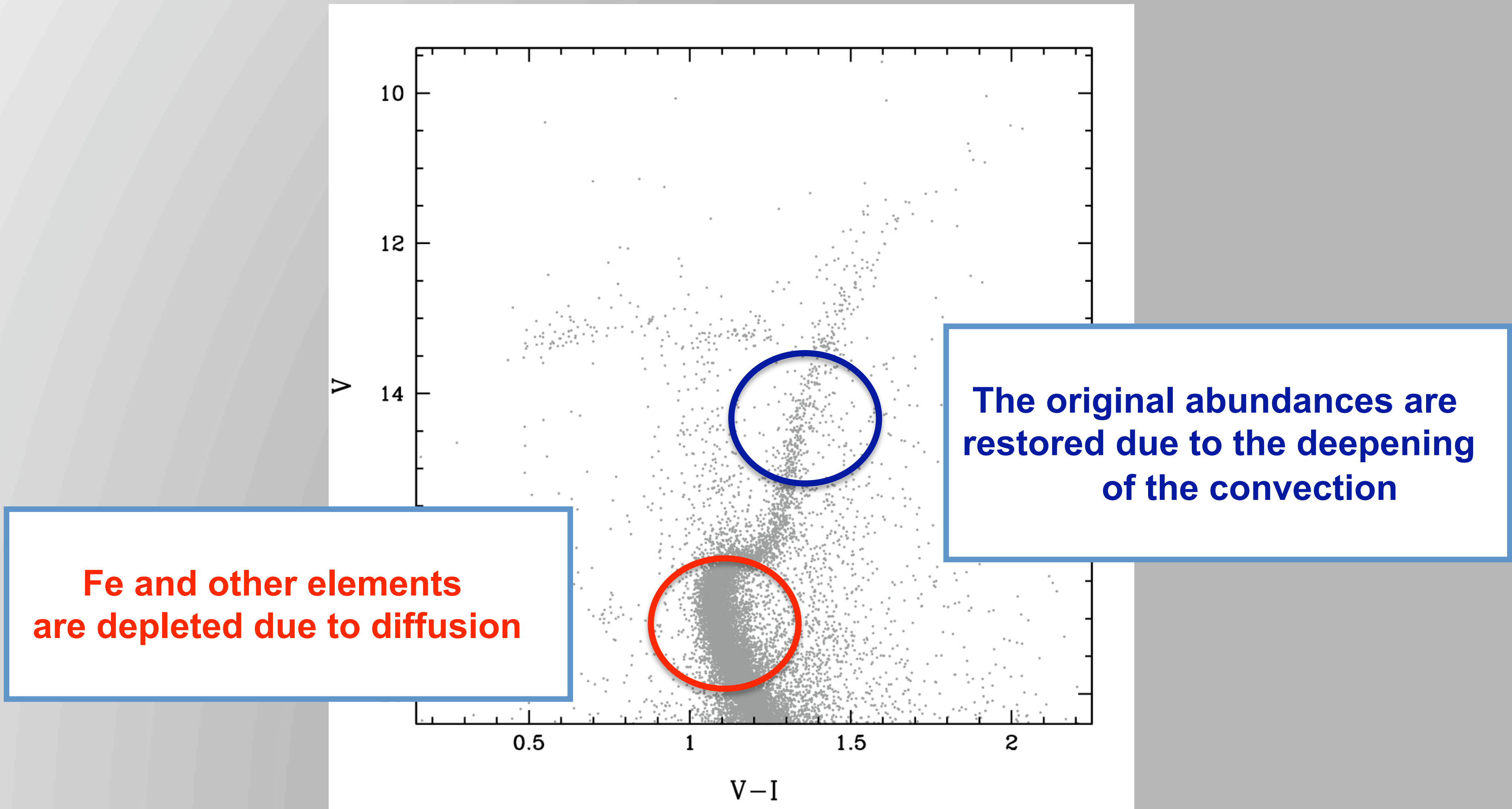
Turbulent mixing is an additional mechanism
introduced to inhibit the diffusion effects
(it is based on a <u>parametrization</u>, not on basic physics !!!)



Part of the diffused Li is
restored in the photosphere

Giants remember what dwarfs forget !!!

Globular clusters provides an ideal tool to identify the signatures of the diffusion, by comparing dwarfs and giants abundances



Li abundances measured in unevolved GC stars

M 92	A(Li) = 2.36	(Bonifacio 2002)
NGC 6397	A(Li) = 2.24	(Korn et al. 2006)
	A(Li) = 2.30	(Gonzalez Hernandez et al. 2009)
NGC 6752	A(Li) = 2.35	(Shen et al. 2010)
47 Tuc	A(Li) = 2.26	(D'Orazi et al. 2010)

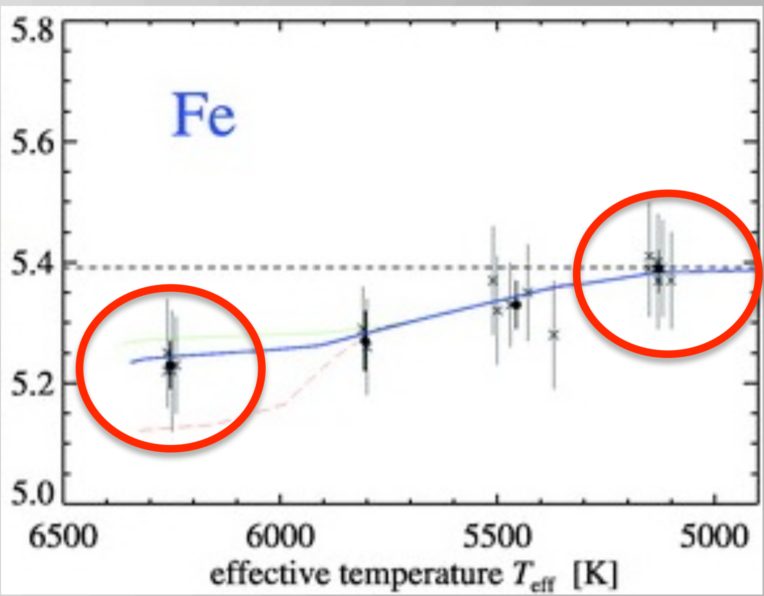
[ω Centauri A(Li) = 2.19 (Monaco et al. 2010)]

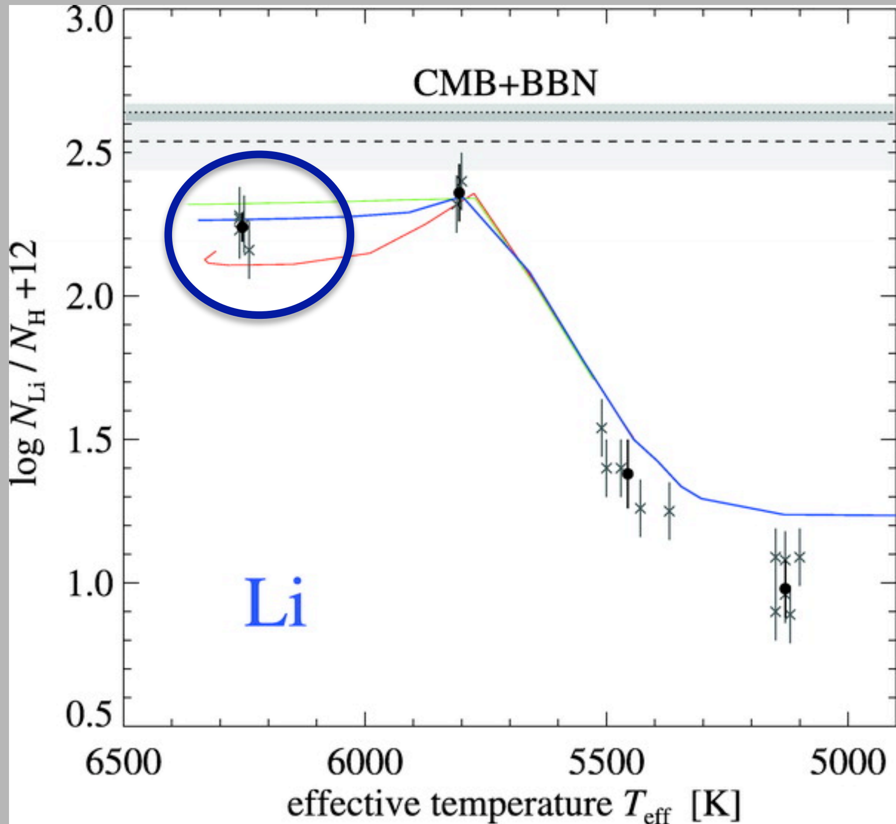
The Lithium discrepancy: the solution by Korn et al. (2006)

The metal-poor ([Fe/H] = -- 2 dex) GC NGC 6397

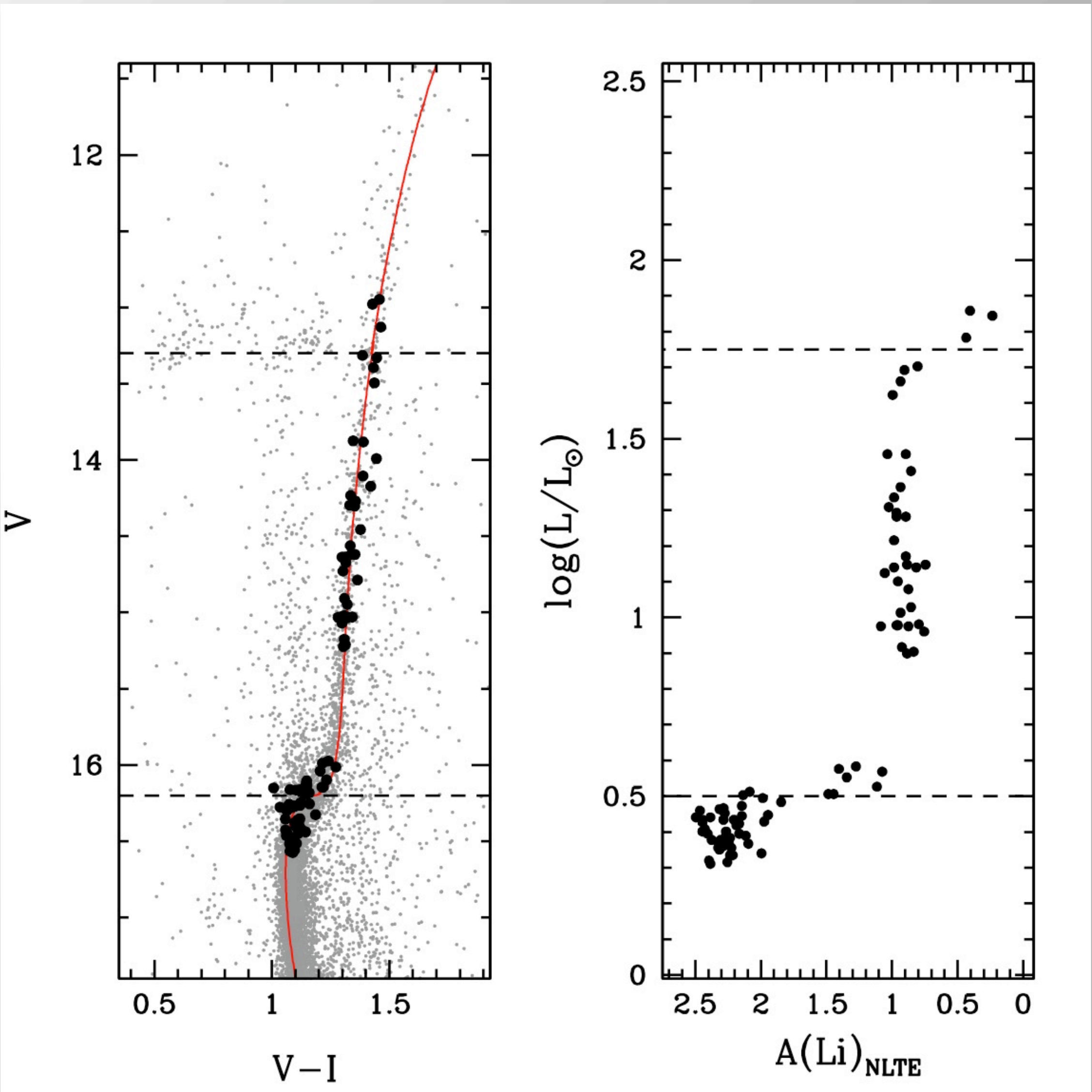
The Li abundance is compatible with the WMAP A(Li)
by considering atomic diffusion + turbulent mixing (models by Richard et al. 2005)

NGC 6397 formed from a gas with a pristine Li abundance higher than that of the Spite Plateau



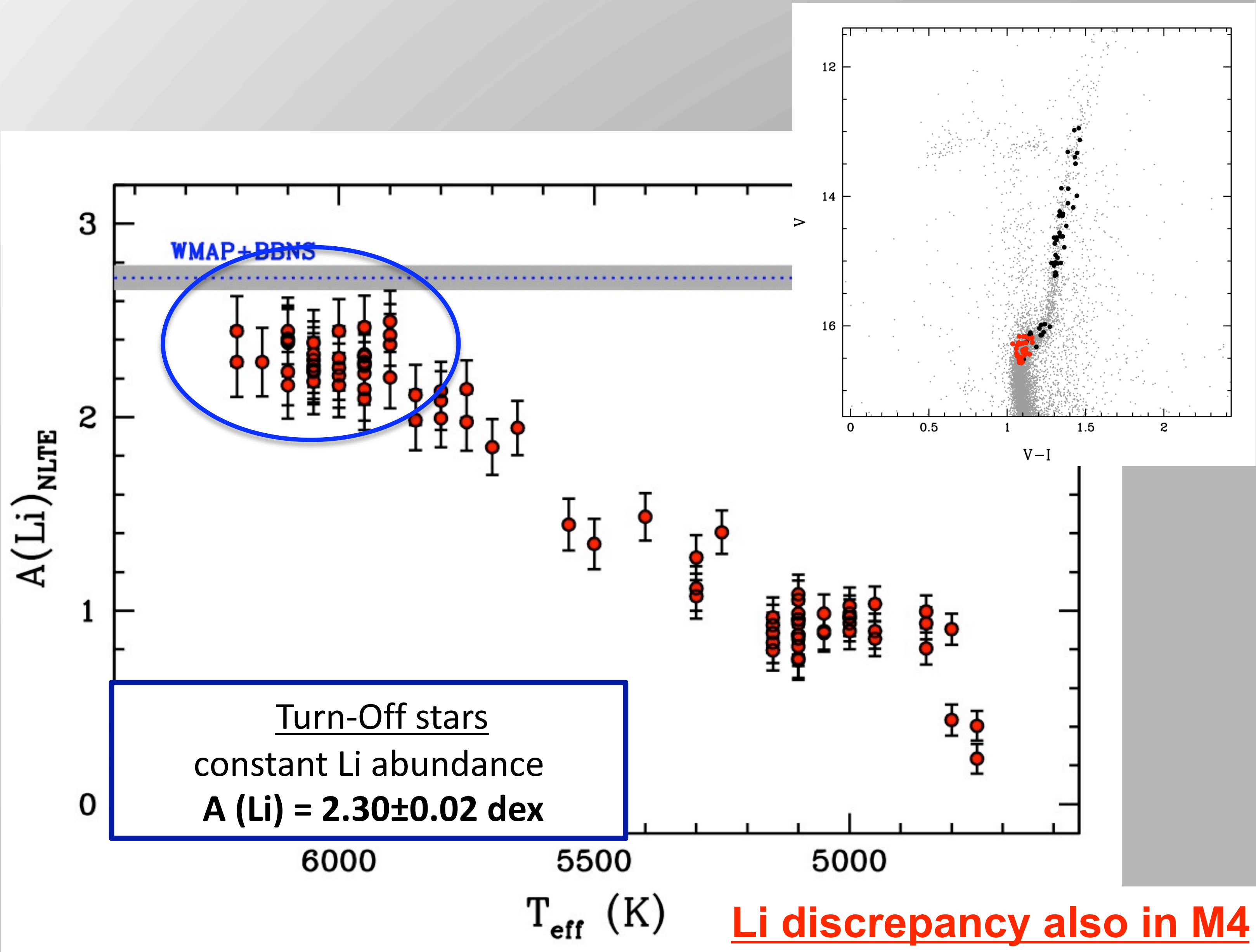


M4: Giraffe spectra of 87 stars

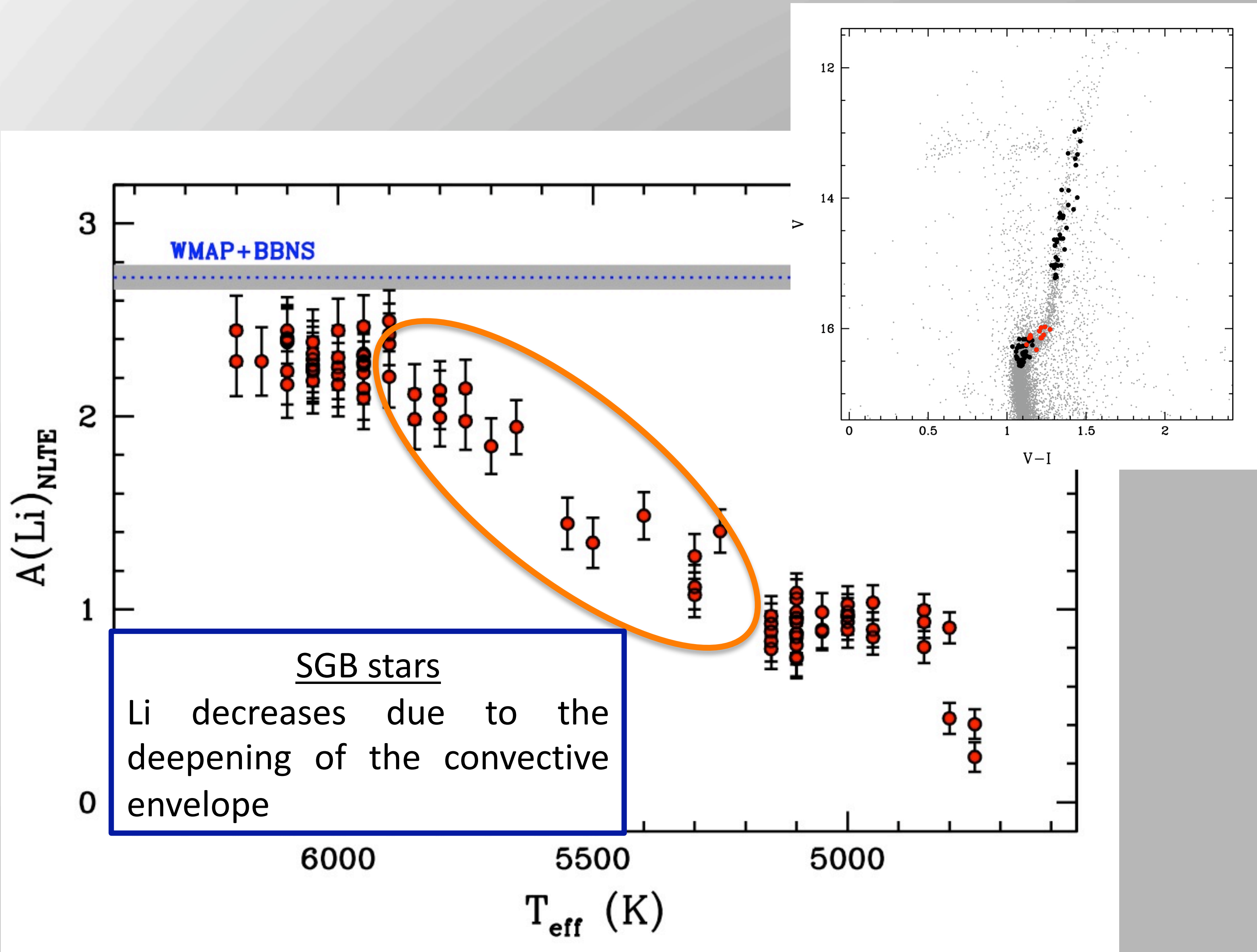


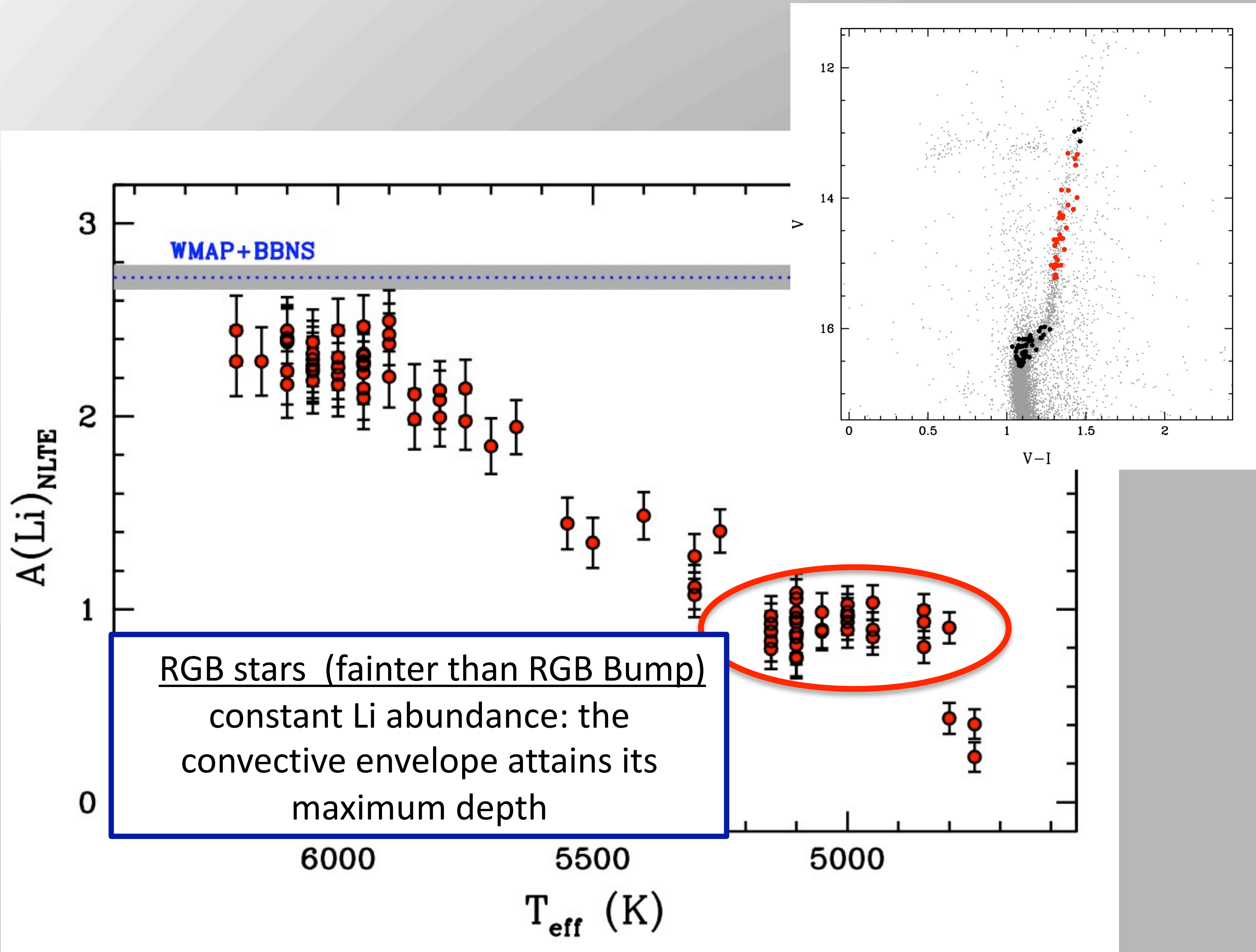
RGB Bump
(extra-mixing episode)

First Dredge-Up
(deepening of the convective envelope)



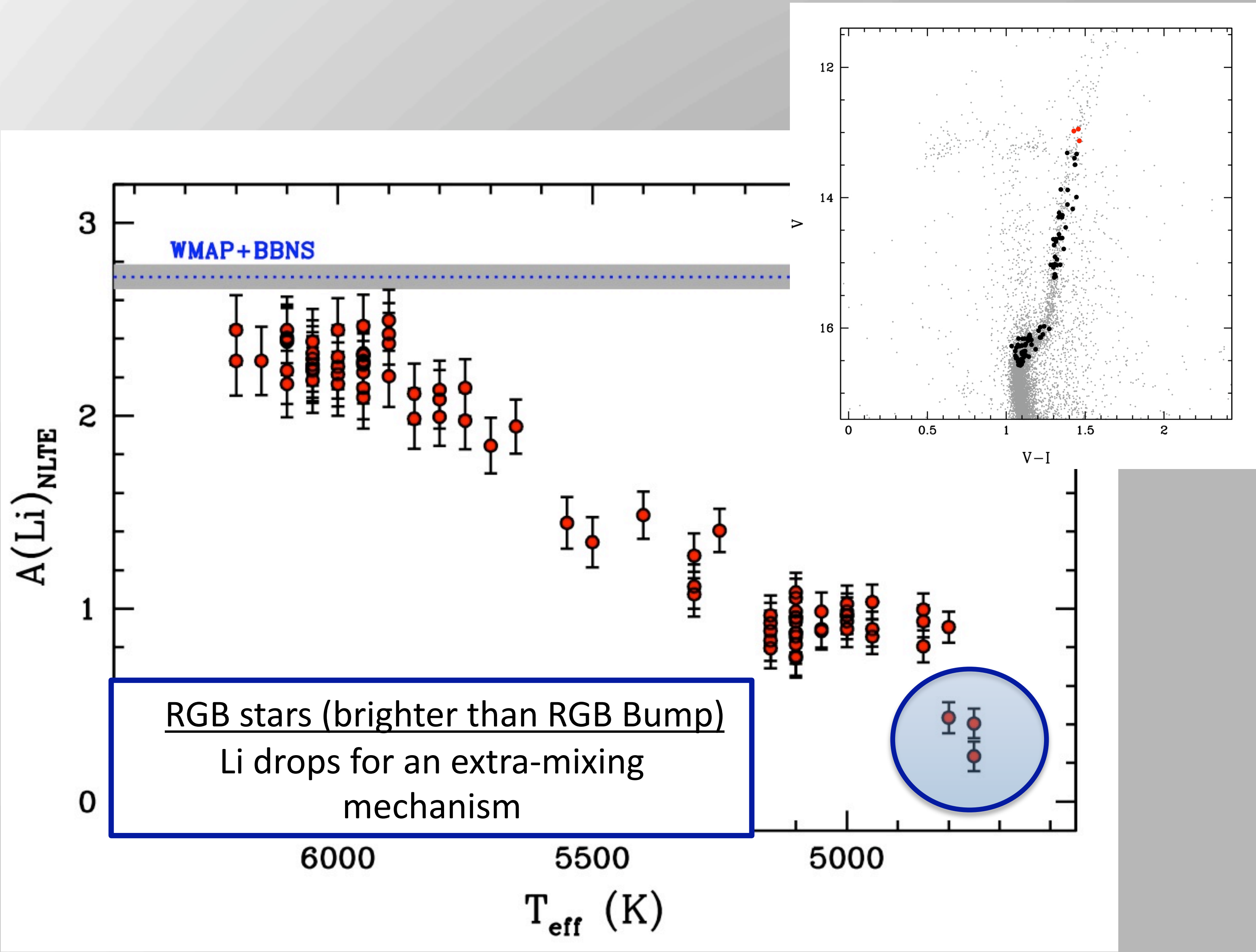
Li discrepancy also in M4


WMAP+BBNS
A(Li)NLTE
Teff (K)
6000
5500
5000
V
V−I
SGB stars
Li decreases due to the deepening of the convective envelope

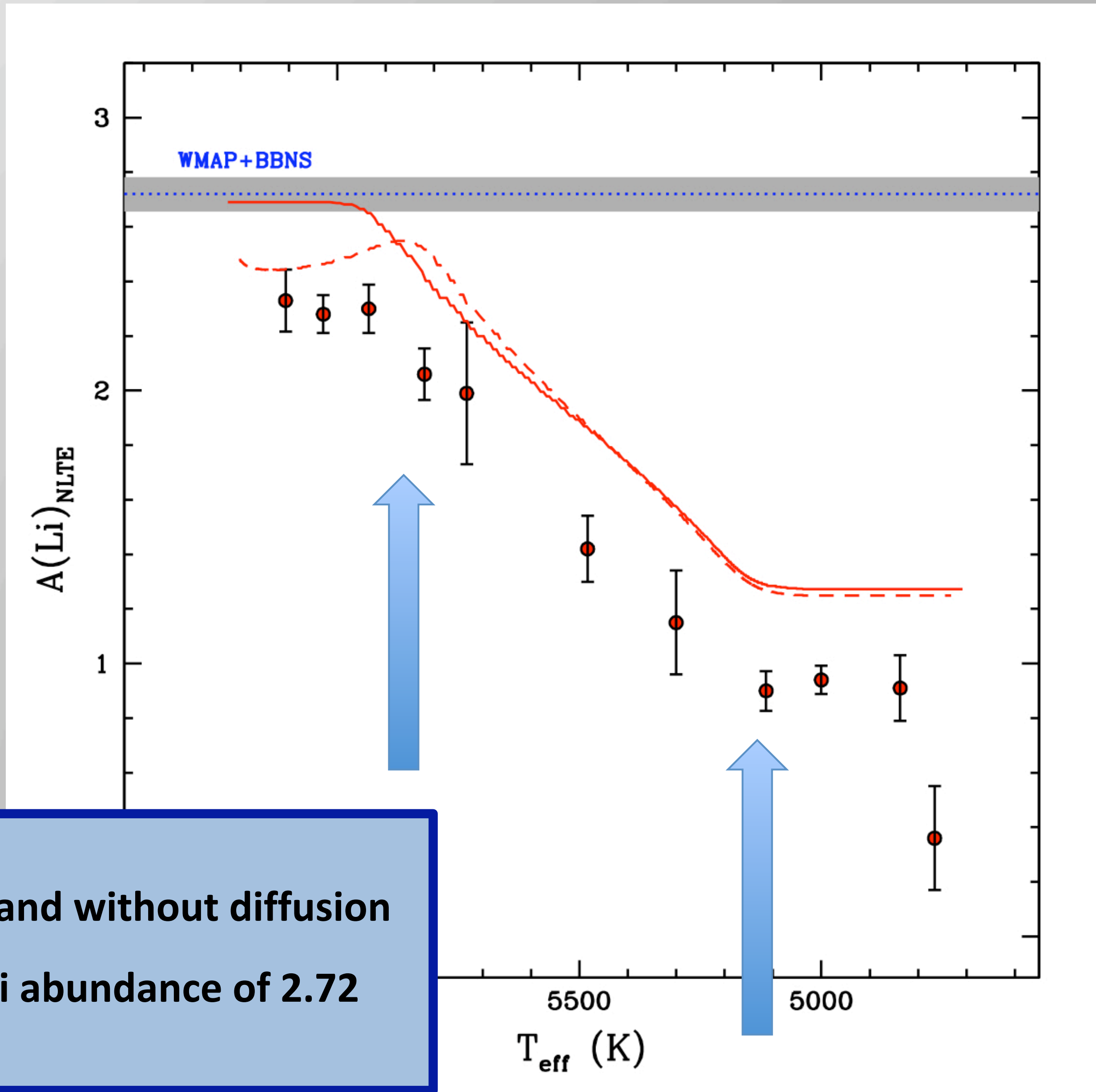


RGB stars (fainter than RGB Bump)

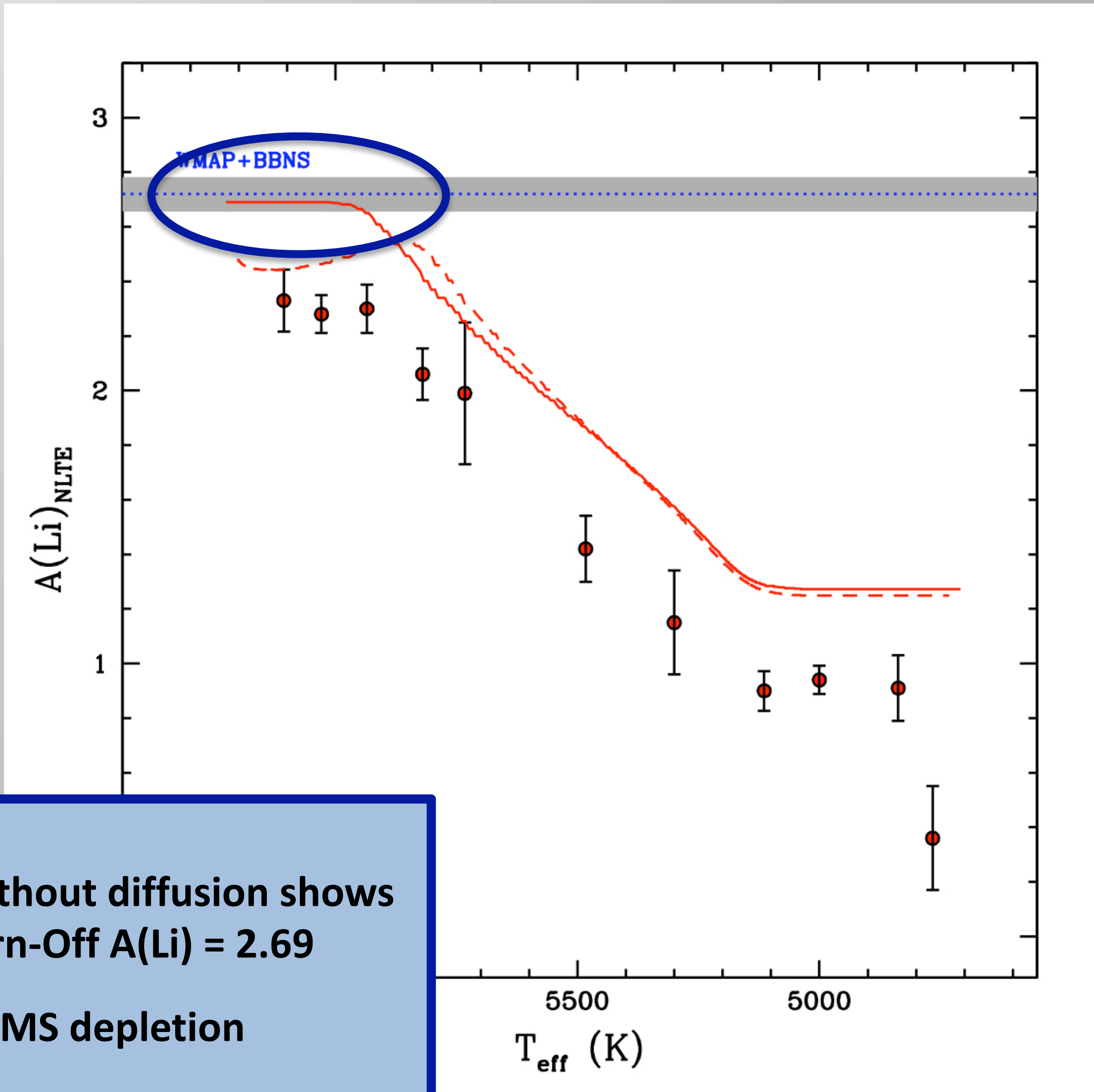
constant Li abundance: the convective envelope attains its maximum depth



WMAP+BBNS
A(Li)NLTE
Teff (K)
6000
5500
5000
3
2
1
0
V
V−I
12
14
16
0
0.5
1
1.5
2
RGB stars (brighter than RGB Bump)
Li drops for an extra-mixing
mechanism

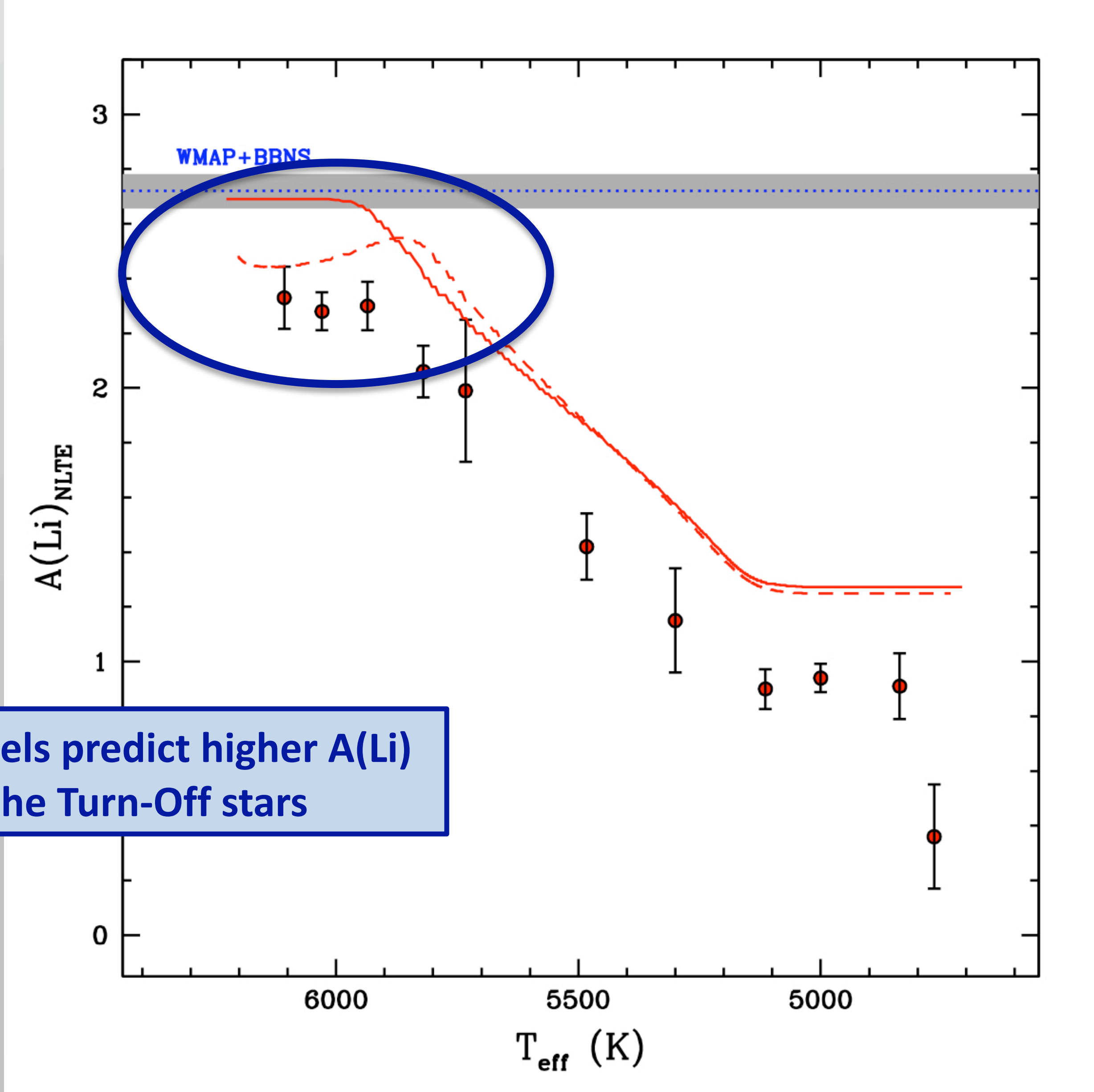


Models with and without diffusion and initial Li abundance of 2.72

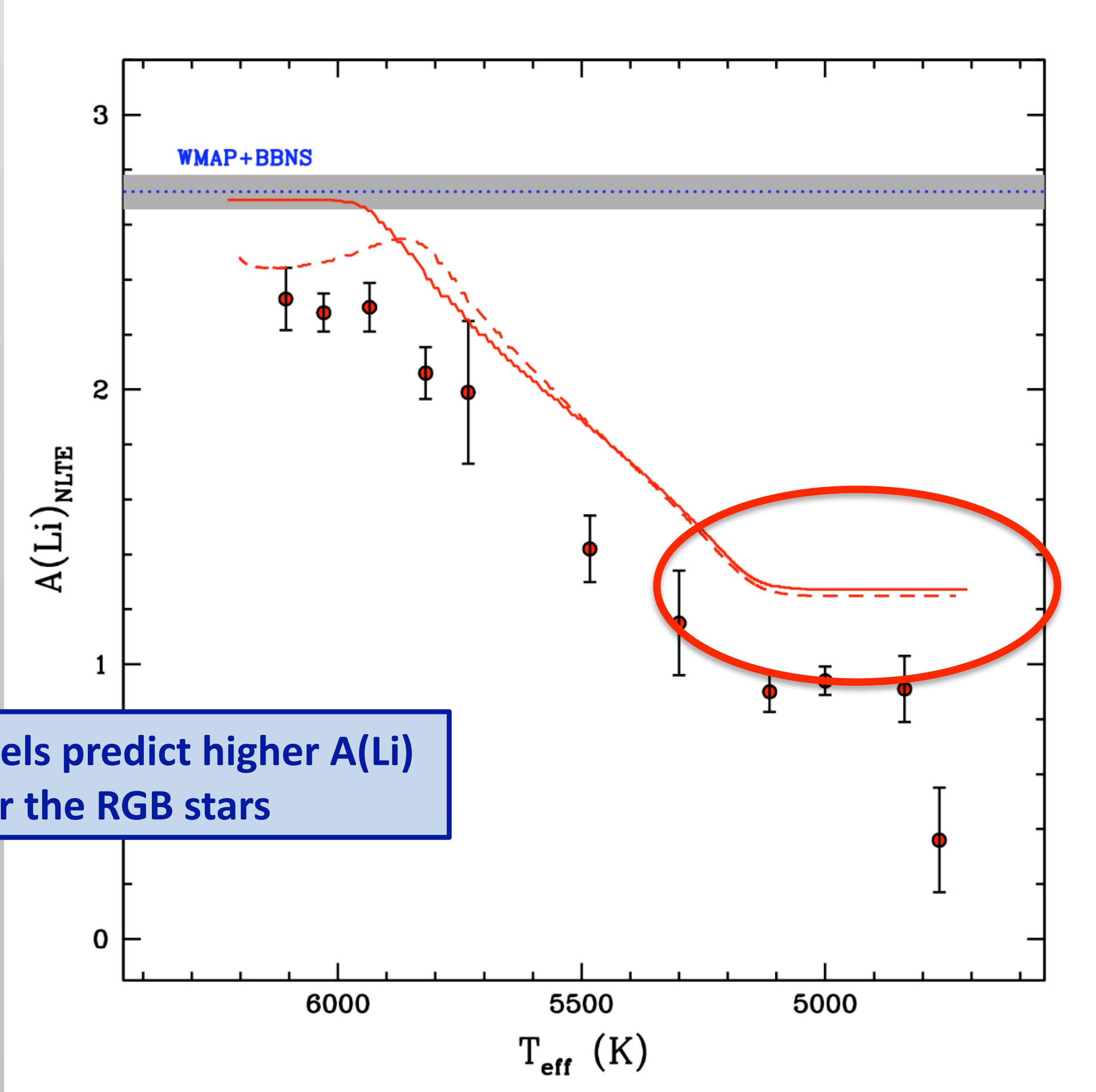


The model without diffusion shows at the Turn-Off A(Li) = 2.69

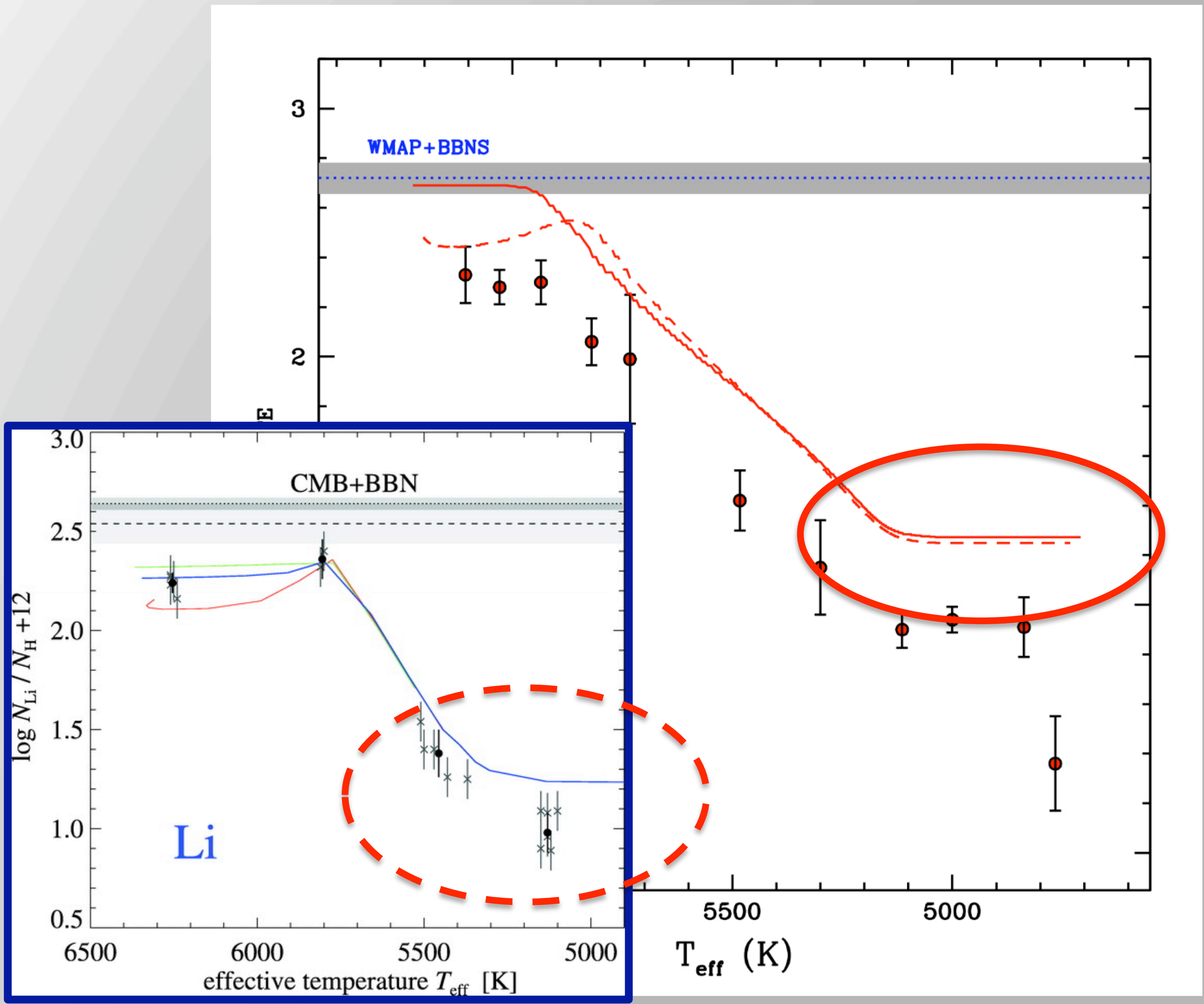
Pre – MS depletion



Both models predict higher A(Li) for the Turn-Off stars



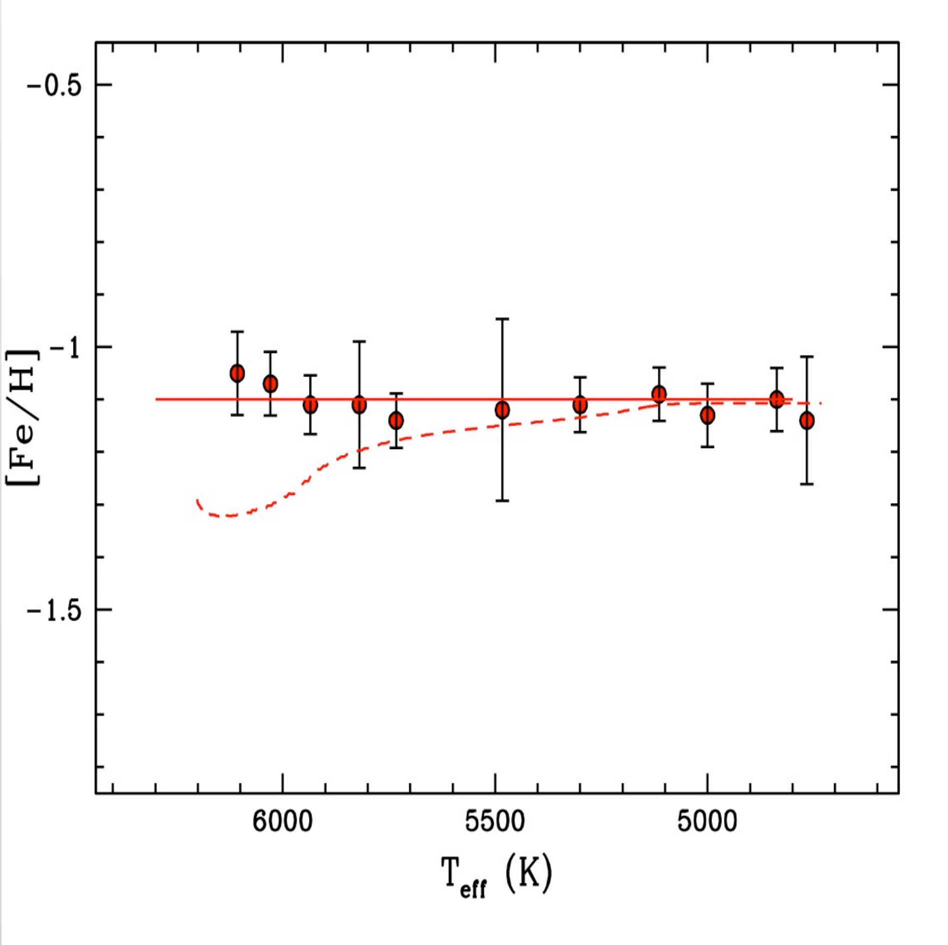
Both models predict higher A(Li) for the RGB stars



WMAP+BBNS
3
2
5500
5000
T_eff (K)
CMB+BBN
3.0
2.5
2.0
1.5
1.0
0.5
log N_Li / N_H +12
Li
6500
6000
5500
5000
effective temperature T_eff [K]

The lesson from the iron

[Fe/H] = -1.10±0.01

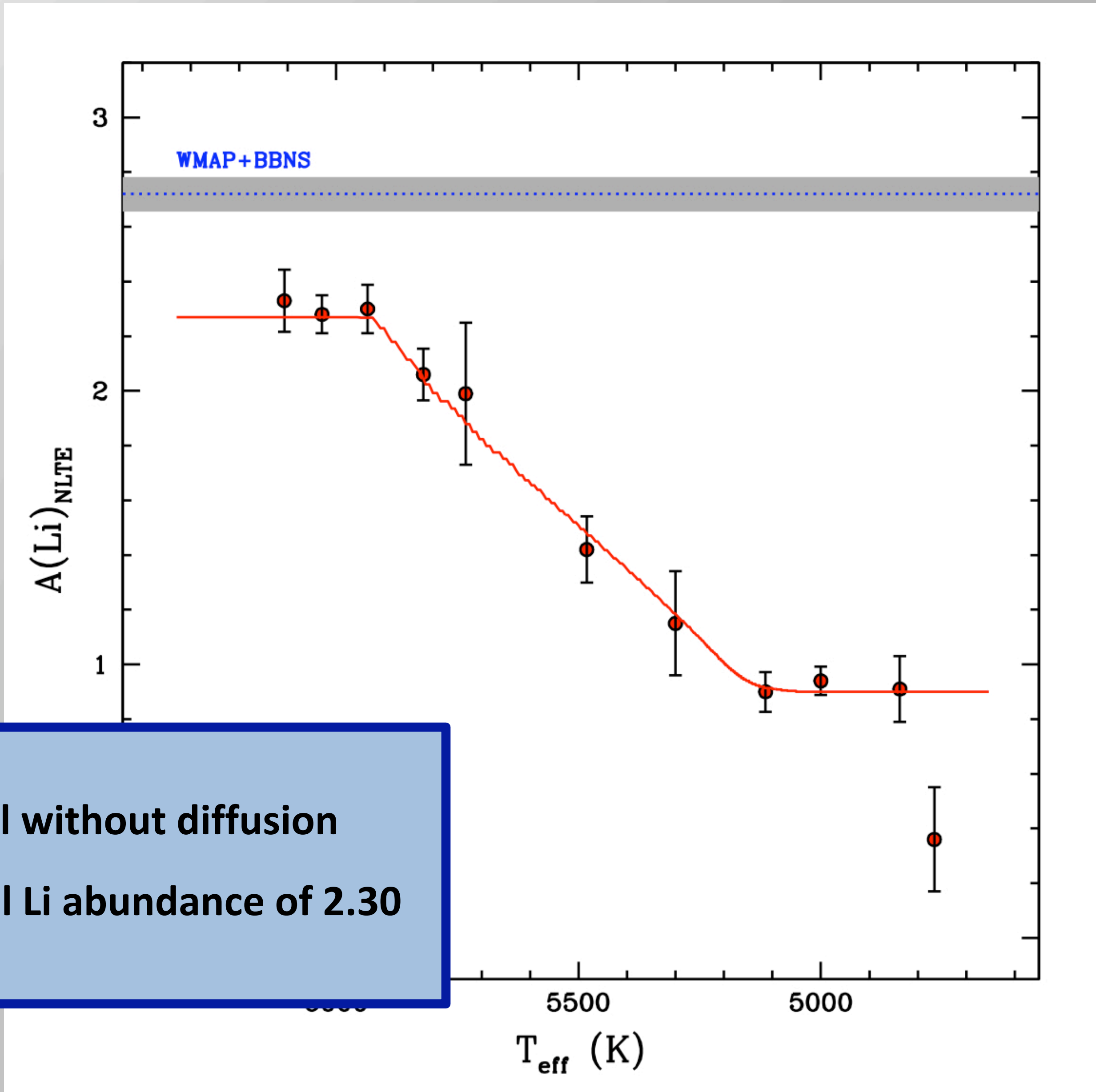


The model with diffusion:

- dwarf stars: the iron is depleted of 0.2 dex (at the metallicity of M4)
- giant stars: convection restores the original iron abundance

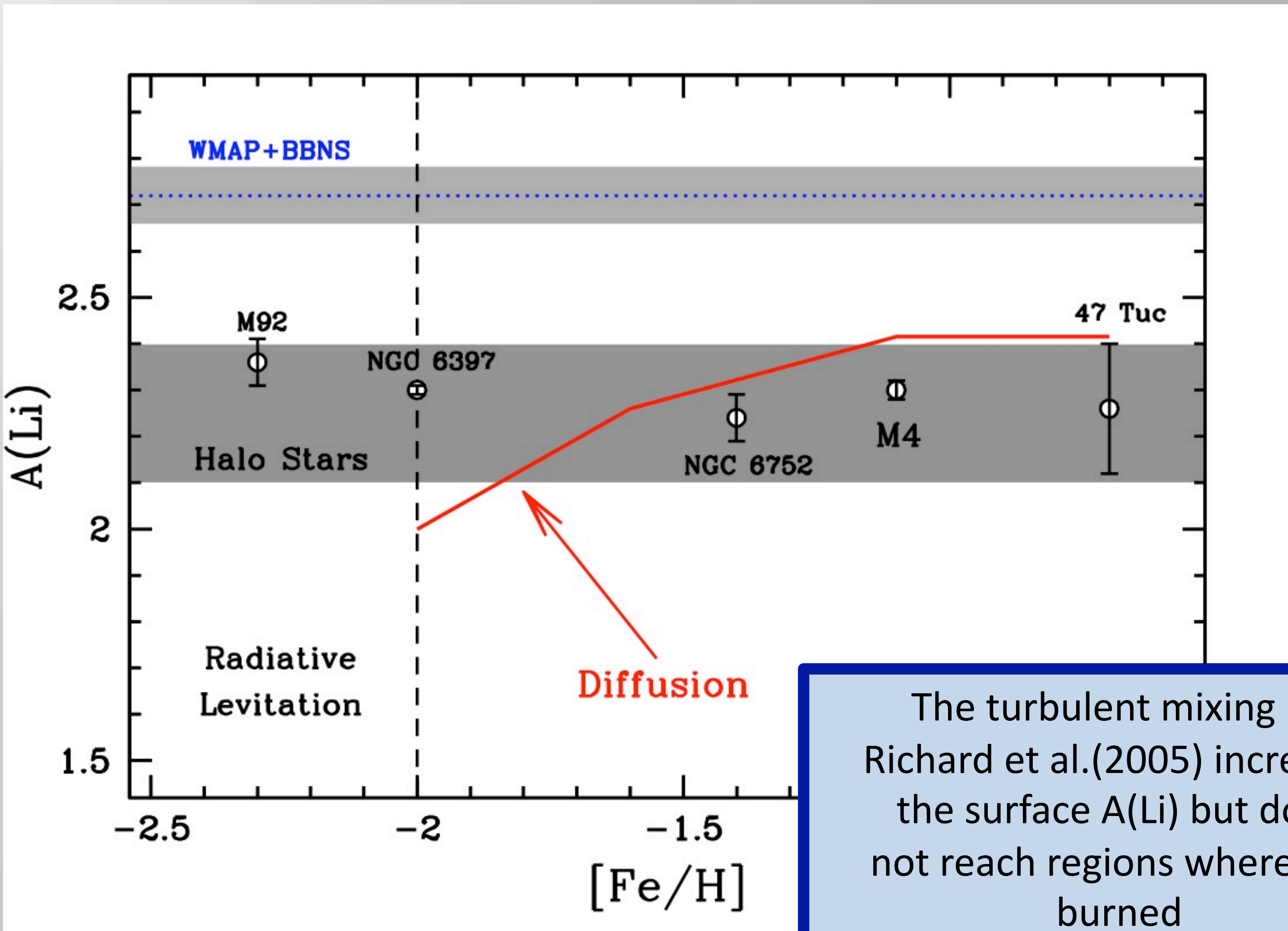
No systematic difference between dwarf and giant stars.

The atomic diffusion is totally inhibited by other effects (turbulent mixing outside the convective zone?)



Model without diffusion

and initial Li abundance of 2.30



The turbulent mixing by Richard et al.(2005) increases the surface A(Li) but does not reach regions where Li is burned

The initial A(Li) of M4 ?

The solution is not unique, depending on the adopted turbulent mixing

✓ **M4 was born with the WMAP A(Li)**

The turbulent mixing by Richard et al. (2005) worsens the discrepancy !

We need to use a more efficient turbulent mixing

The solution claimed by Korn et al.(2006) is not universal !

✓ **M4 was born with initial A(Li) < $A(Li)_{WMAP}$ (extreme case A(Li) ~ 2.3)**

We can use the turbulent mixing by Richard et al.(2005)

The discrepancy between Pop II and WMAP remains !

Conclusions … and open questions

Can we identify univocally the initial A(Li) of M4?

Can we solve the Li discrepancy in M4 with the solution by Korn et al. (2006)?

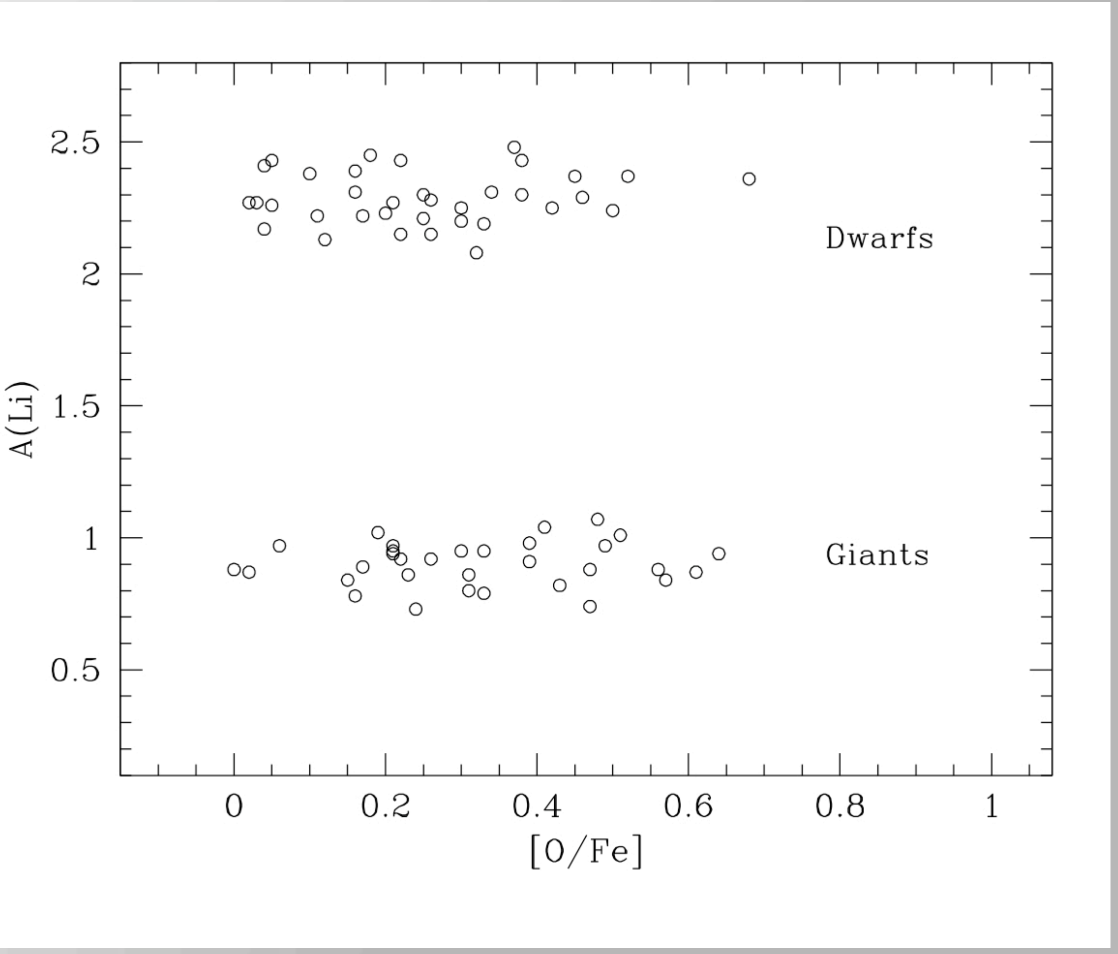
NO !!!

Can we solve the Li discrepancy with the current models including diffusion and turbulent mixing?

The Li problem is far from being solved

There is no cause for alarm,
but there probably will be !

Self-enrichment in GC: hot CNO cycle occurs at $T>5 \times 10^7$ K
Second generation should be Li-free
The observations provide high A(Li) also in the second generation stars and in some cases Li-Na anticorrelations (6752 and maybe 6397)



<u>Production of Li ?</u>
Massive stars are not able to produce Li

AGB stars can produced Li through the Cameron-Fowler mechanism

Li – Na & Li – O in other GCs