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The many ways in which stars modify their surface lithium

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Lithium depletion in stars

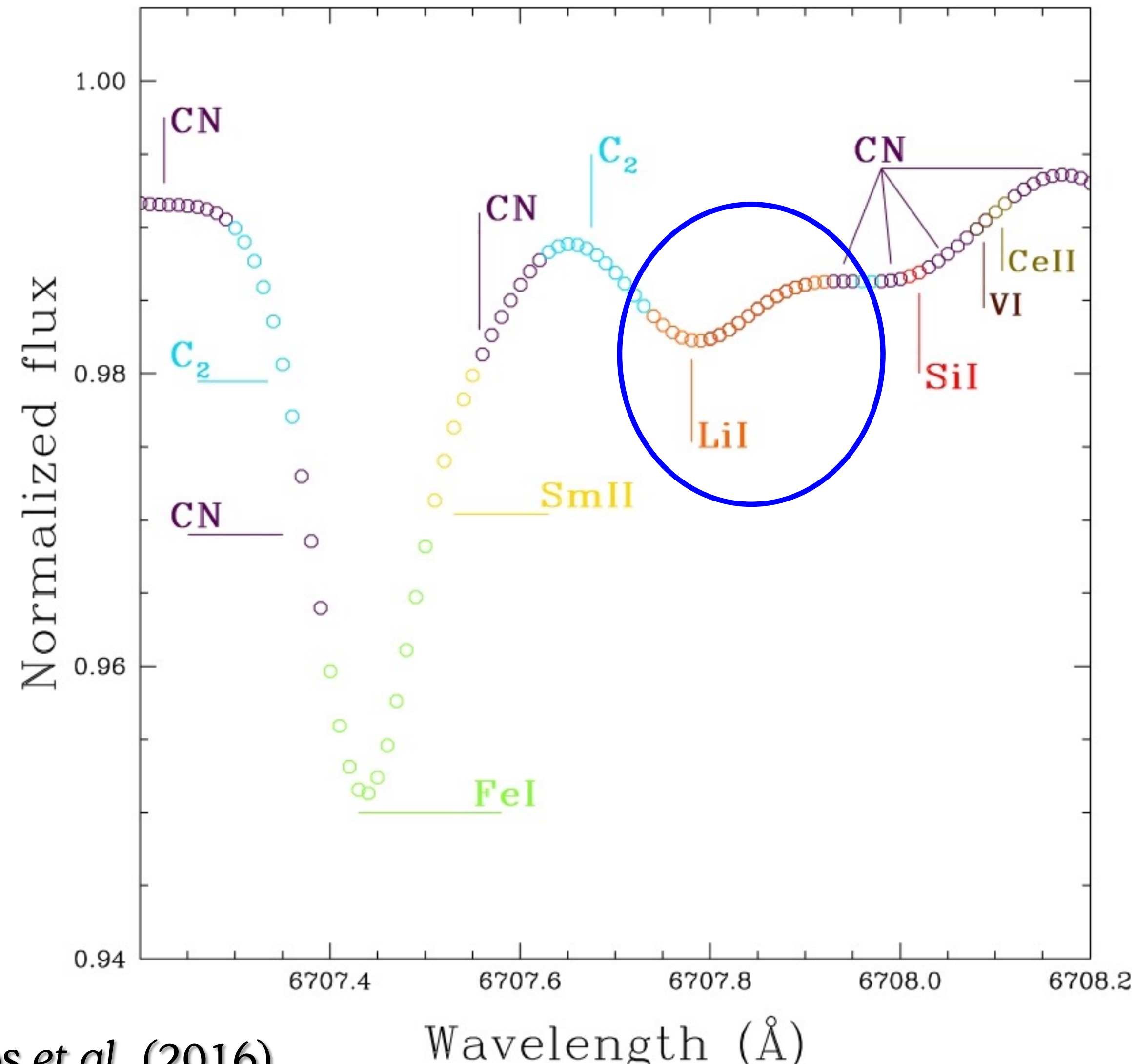
Li is pretty fragile and suffers proton capture at $T \geq 2.5$ MK.

Look no further than the Sun:

$$\log \varepsilon(\mathrm{Li})_{\mathrm{surface}} \sim \mathbf{1} \quad \text{vs.} \quad \log \varepsilon(\mathrm{Li})_{\mathrm{meteorites}} \sim \mathbf{3.3}$$

I.e., the Sun has destroyed 99.5% of its initial lithium. 😵‍💫

The only Li feature in the solar spectrum

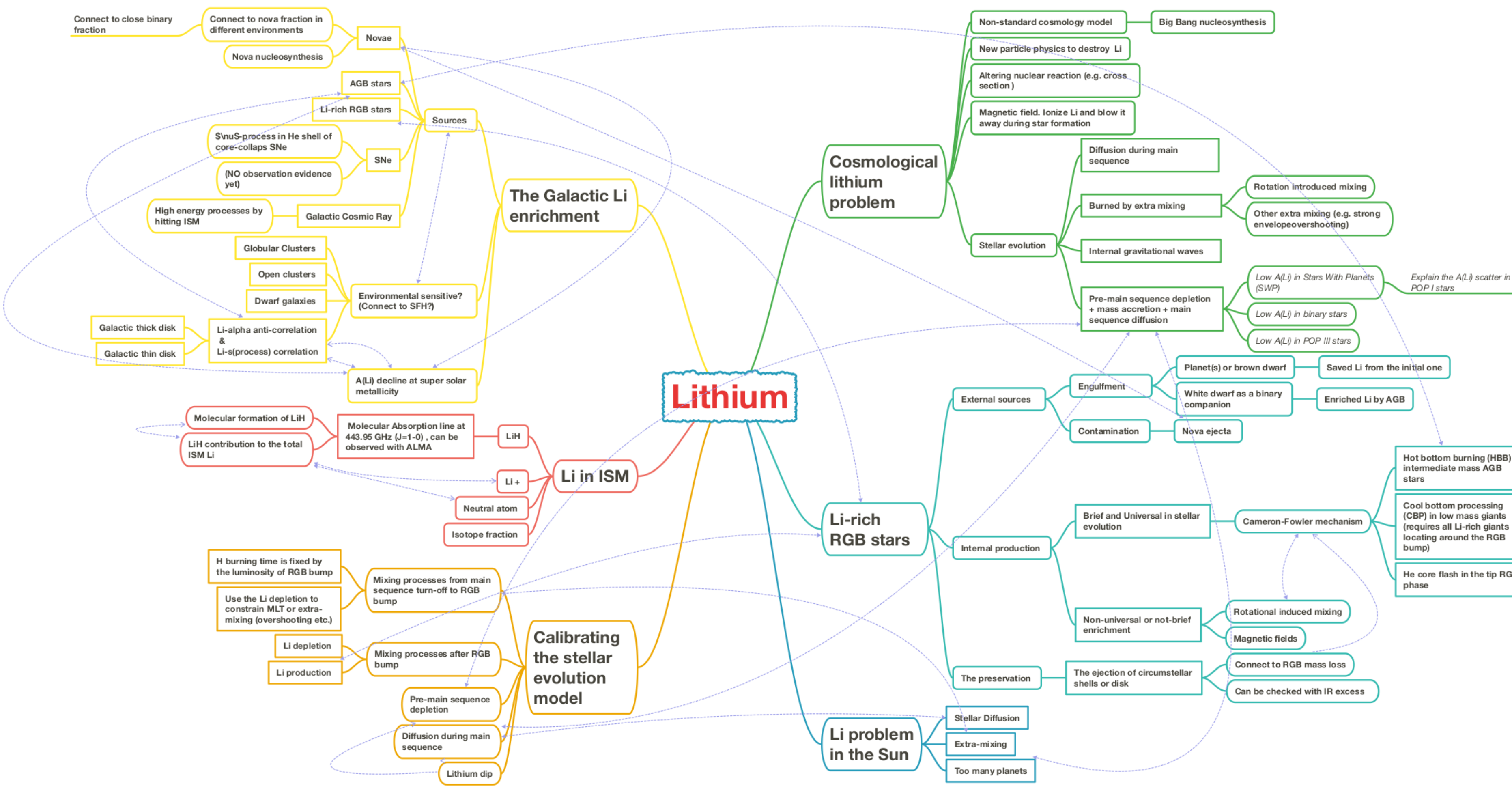


Carlos *et al.* (2016)

Not easy to get an accurate solar Li abundance from the solar flux spectrum! (Better in intensity spectra.)

Is log ε(Li) ~ 1 typical for stars with solar properties? More or less.

Xiaoting Fu's lithium concept map



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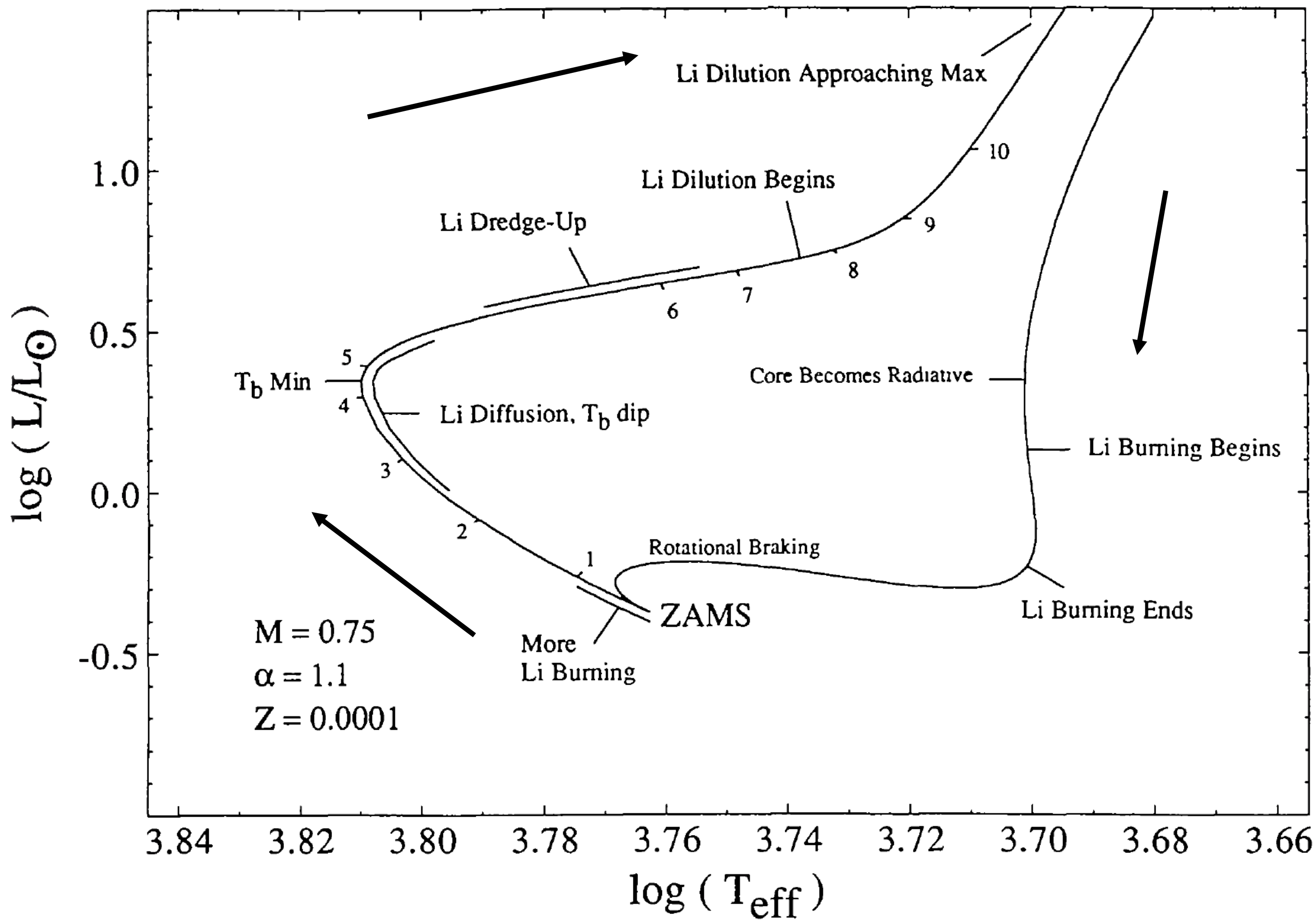
Are halo stars equally negligent about Li?

To survive to the present day, old halo stars must have masses not exceeding 0.8 $M_\odot$. This would make them more convective than the Sun, i.e. more Li destruction!

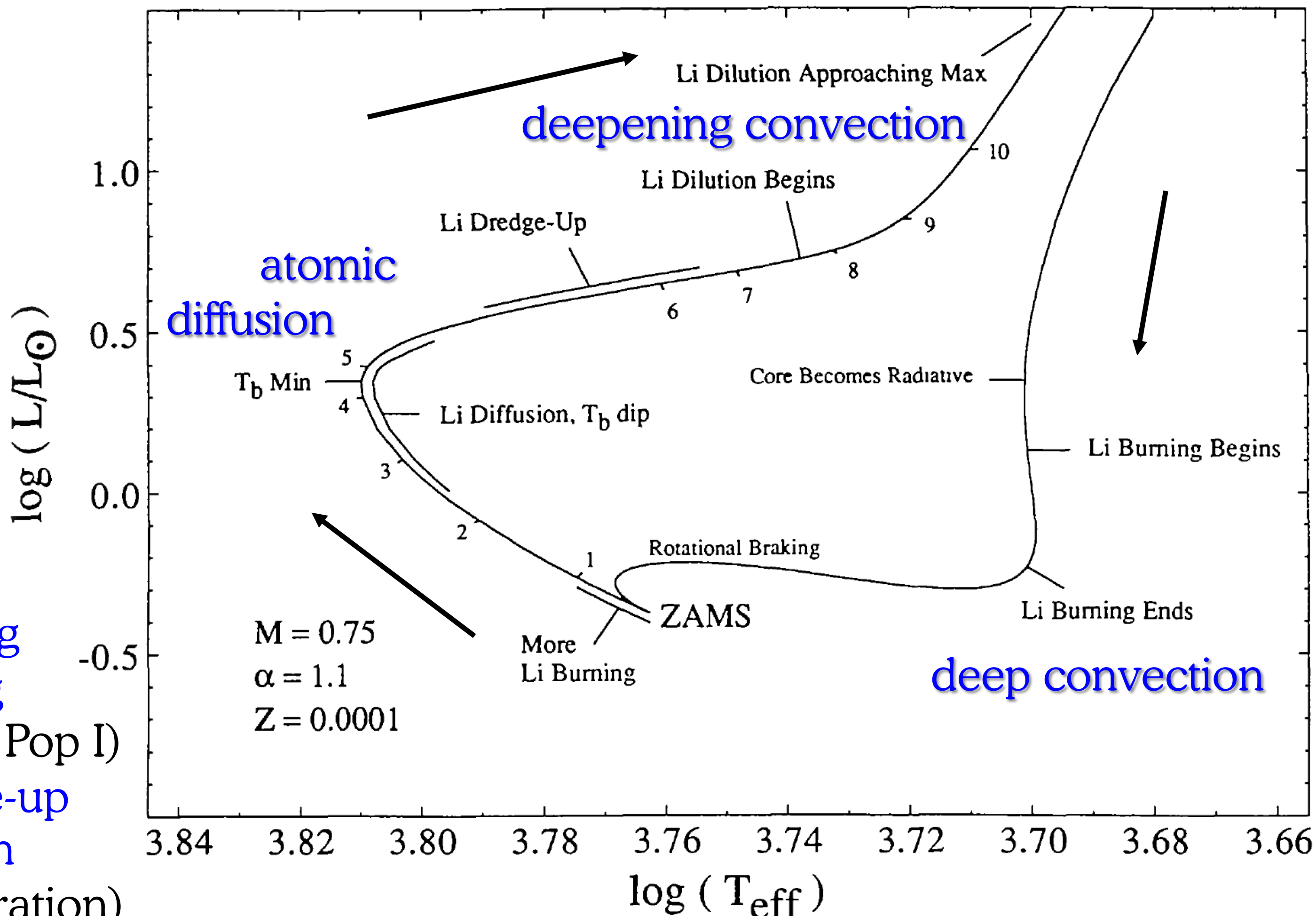
Metallicity to the rescue. The lower opacities make these stars more compact, they evolve at higher T_{eff}.

Expectations from stellar structure & evolution



Deliyannis *et al.* (1990)

Expectations from stellar structure & evolution



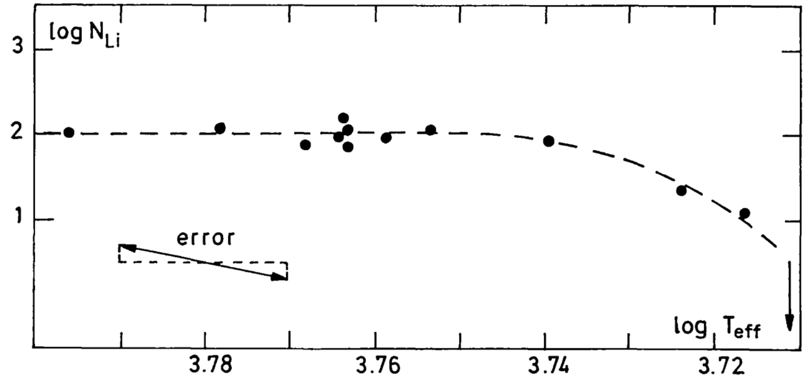
Episodes of

- lithium burning
- lithium settling
- (lithium dip in Pop I)
- lithium dredge-up
- lithium dilution
- (lithium obliteration)
- (lithium production)

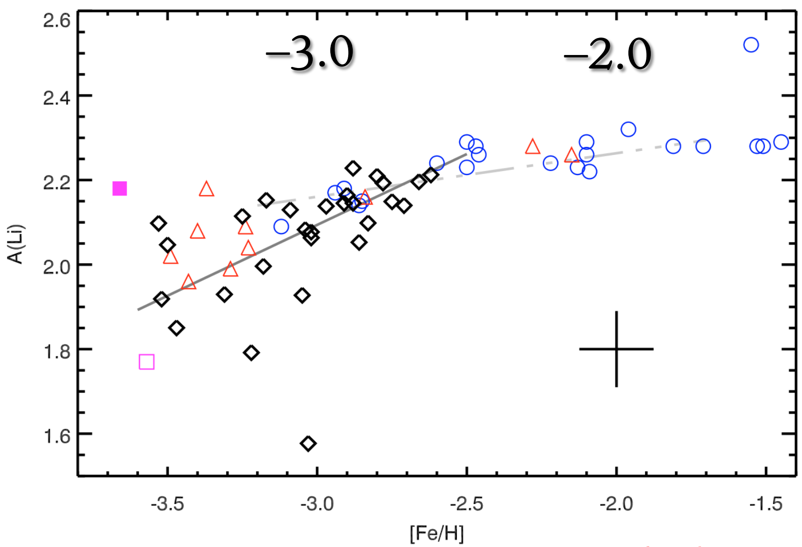
as low-mass stars evolve.

Deliyannis *et al.* (1990)

Li-7 in old stars: homogeneous and flat?

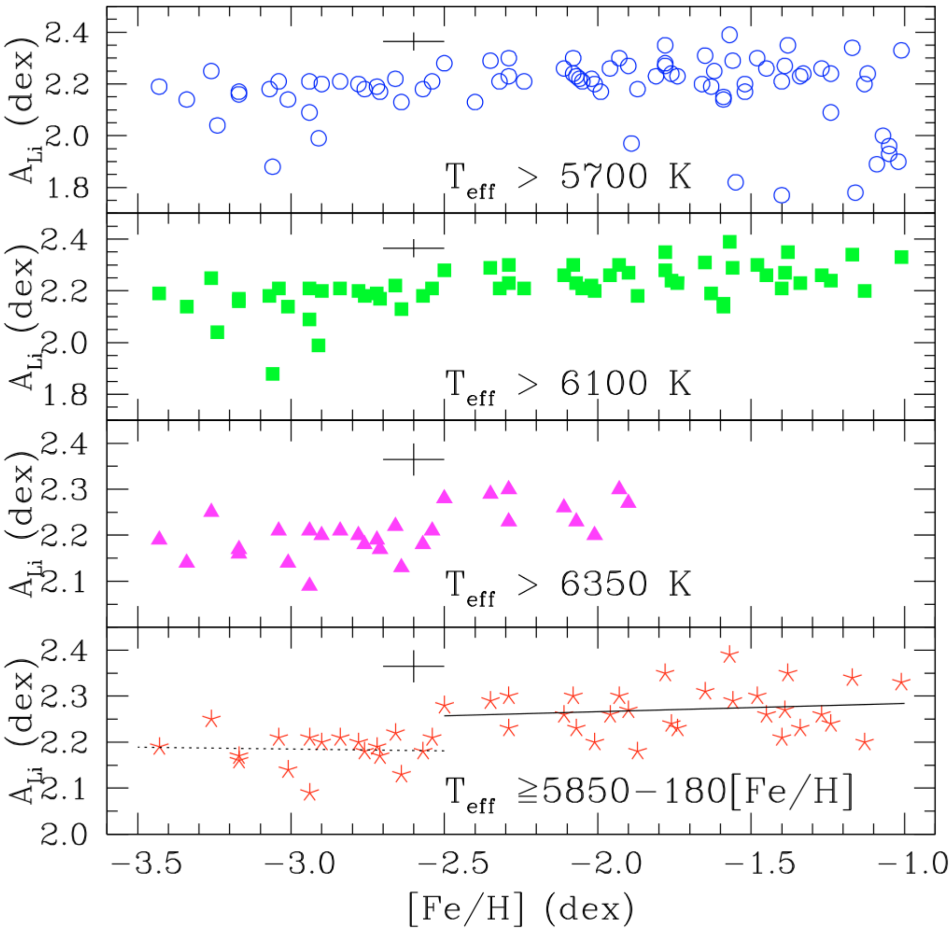


Spite & Spite (1982)



Sbordone *et al.* (2010): **meltdown!**

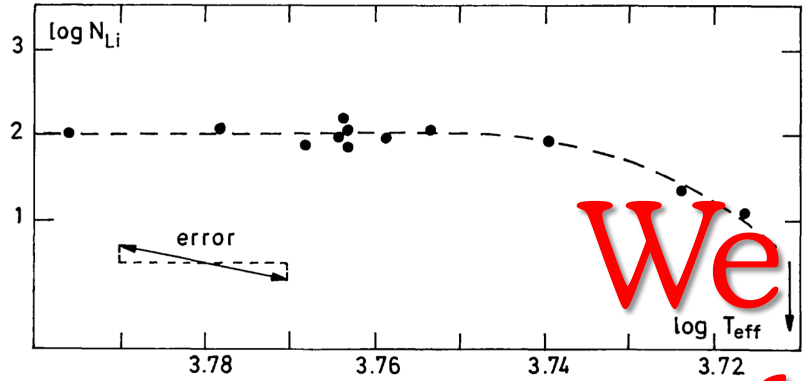
Melendez *et al.* (2010)



It's complicated! **By stellar physics!**

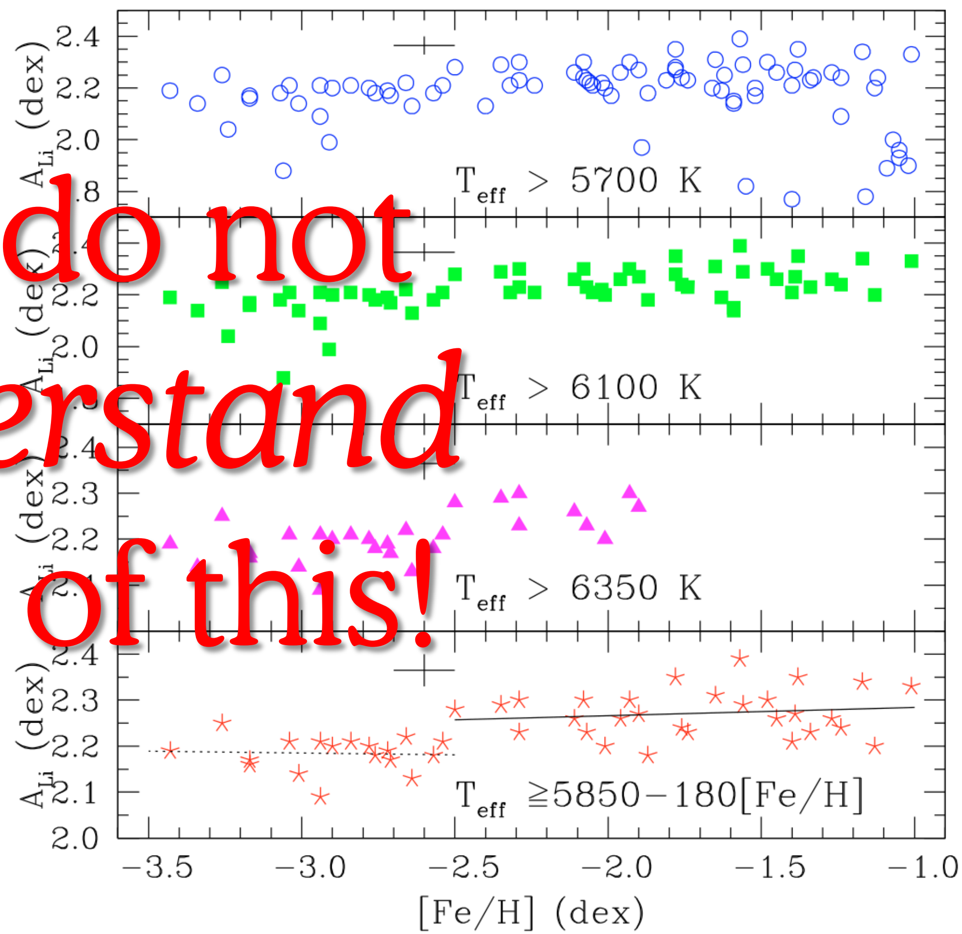
see also Gao *et al.* (2020)

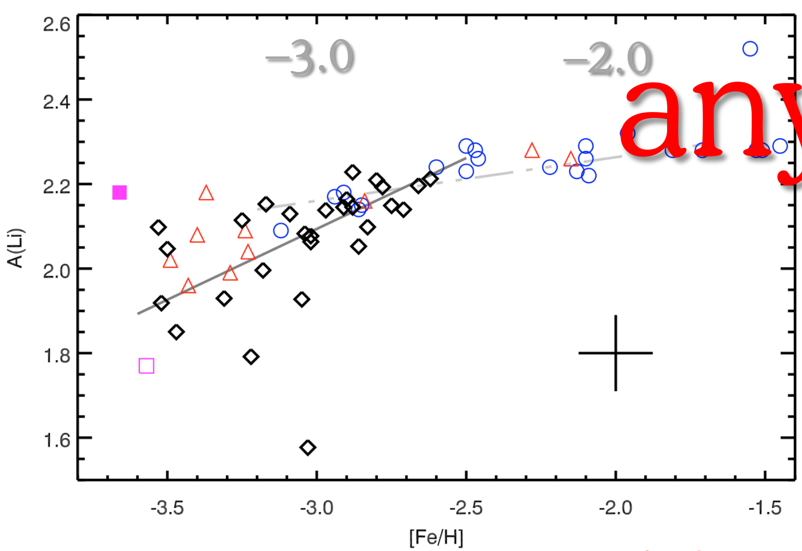
Li-7 in old stars: homogeneous and flat?



Spite & Spite (1982)

Melendez *et al.* (2010)





Sbordone *et al.* (2010):

meltdown!

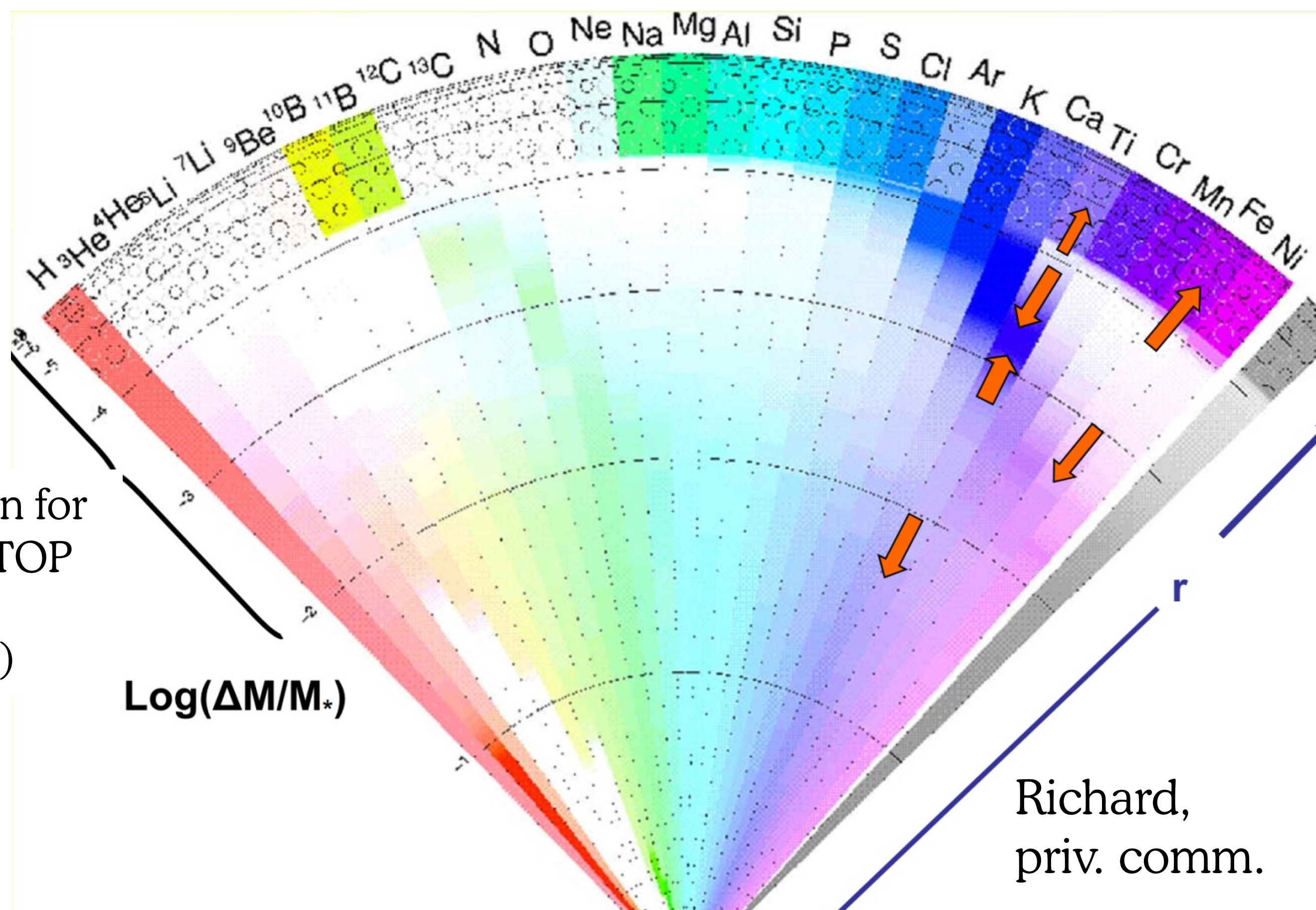
We do not understand any of this!

It's complicated! **By stellar physics!**

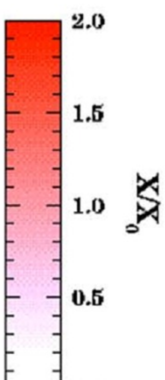
see also Gao *et al.* (2020)

The beautiful mess of atomic diffusion

Elements can move (*diffuse*) throughout stars under the prevailing forces (gradients of pressure, temperature and concentration). E.g. lithium will settle (and burn at $T \geq 2.5$ MK).

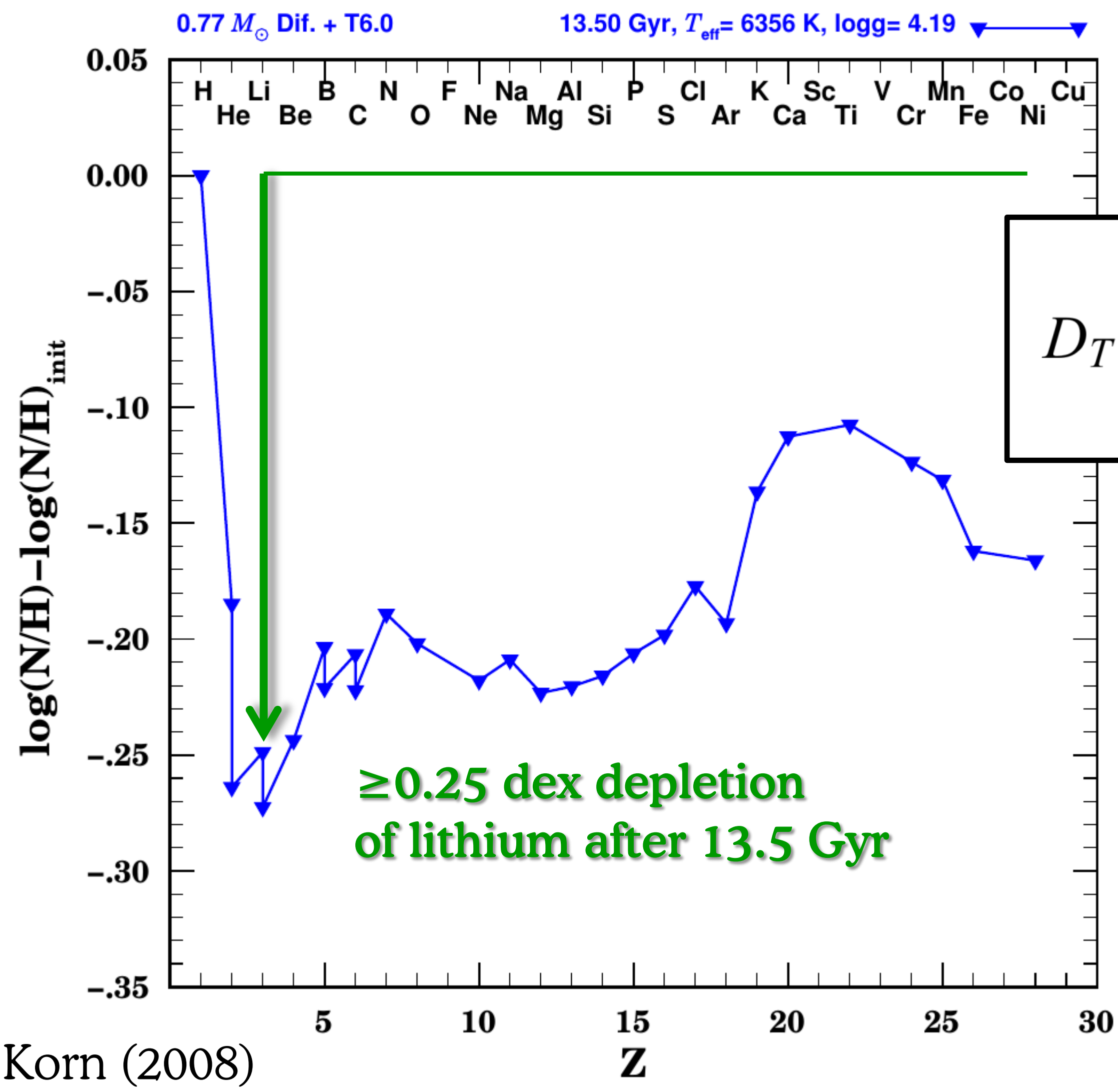


Elemental composition for a 12 Gyr old **0.8 M$_\odot$** TOP star with [Fe/H]$_{init}$=−2 (***uninhibited*** diffusion)



Richard, priv. comm.

Diffusion moderated by *some* mixing



Korn (2008)

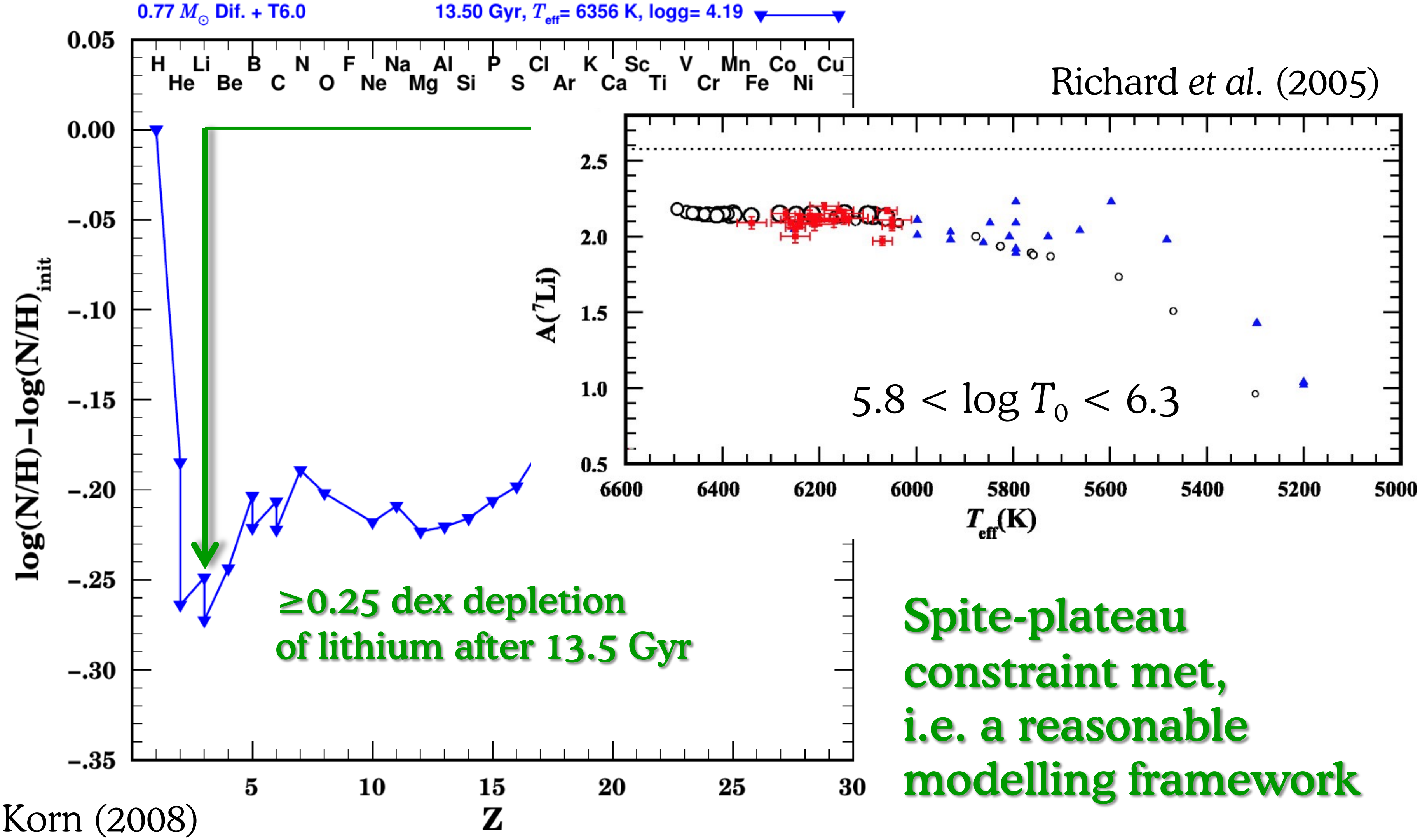
$$D_T = 400\, D_{\rm He}(T_0)\left[\frac{\rho}{\rho(T_0)}\right]^{-3}$$

Proffitt & Michaud (1991)

Atomic diffusion "is always present in stars. It cannot be turned off. It can only be rendered inefficient by sufficient mass motion either due to meridional circulation or turbulence."

Michaud *et al.* (1984)

Diffusion moderated by *some* mixing

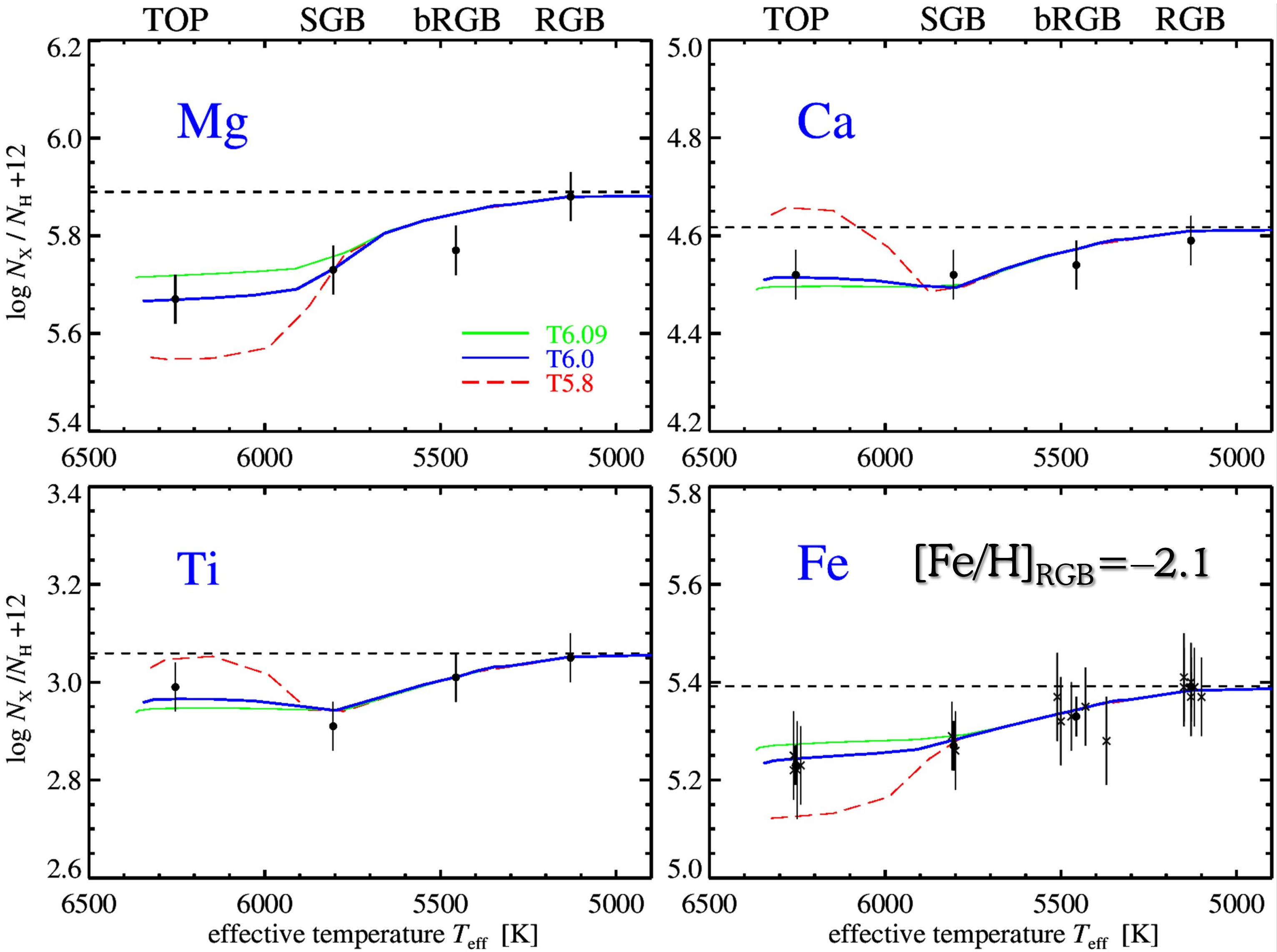


Richard *et al.* (2005)

Korn (2008)

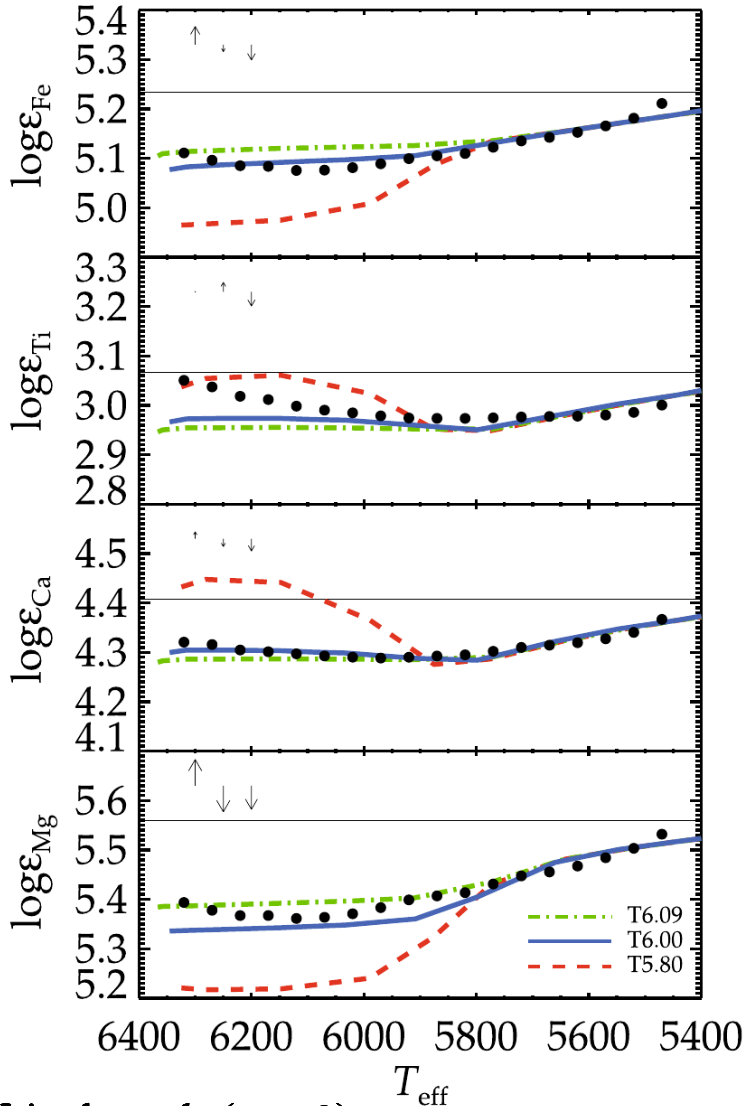
Spite-plateau constraint met, i.e. a reasonable modelling framework

Atomic diffusion in NGC6397 (10s of stars)

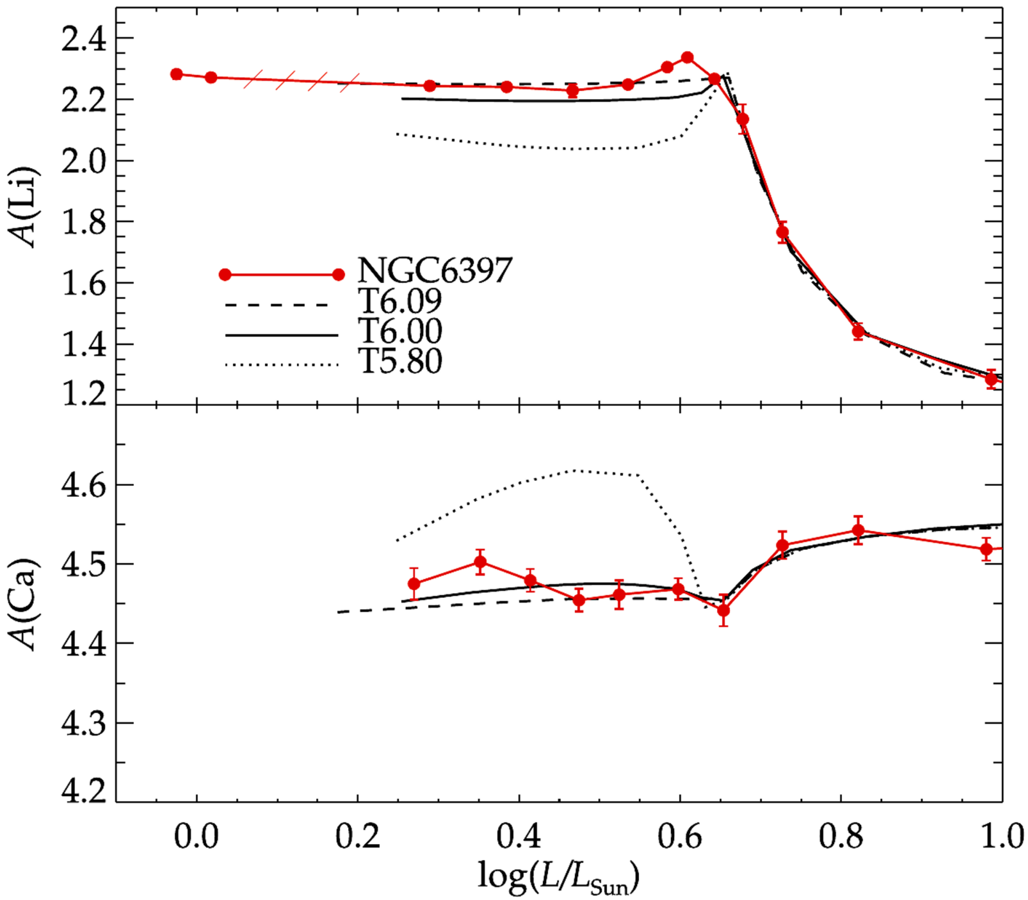


Korn *et al.* (2006, 2007)

Subsequent analyses (100s of stars)

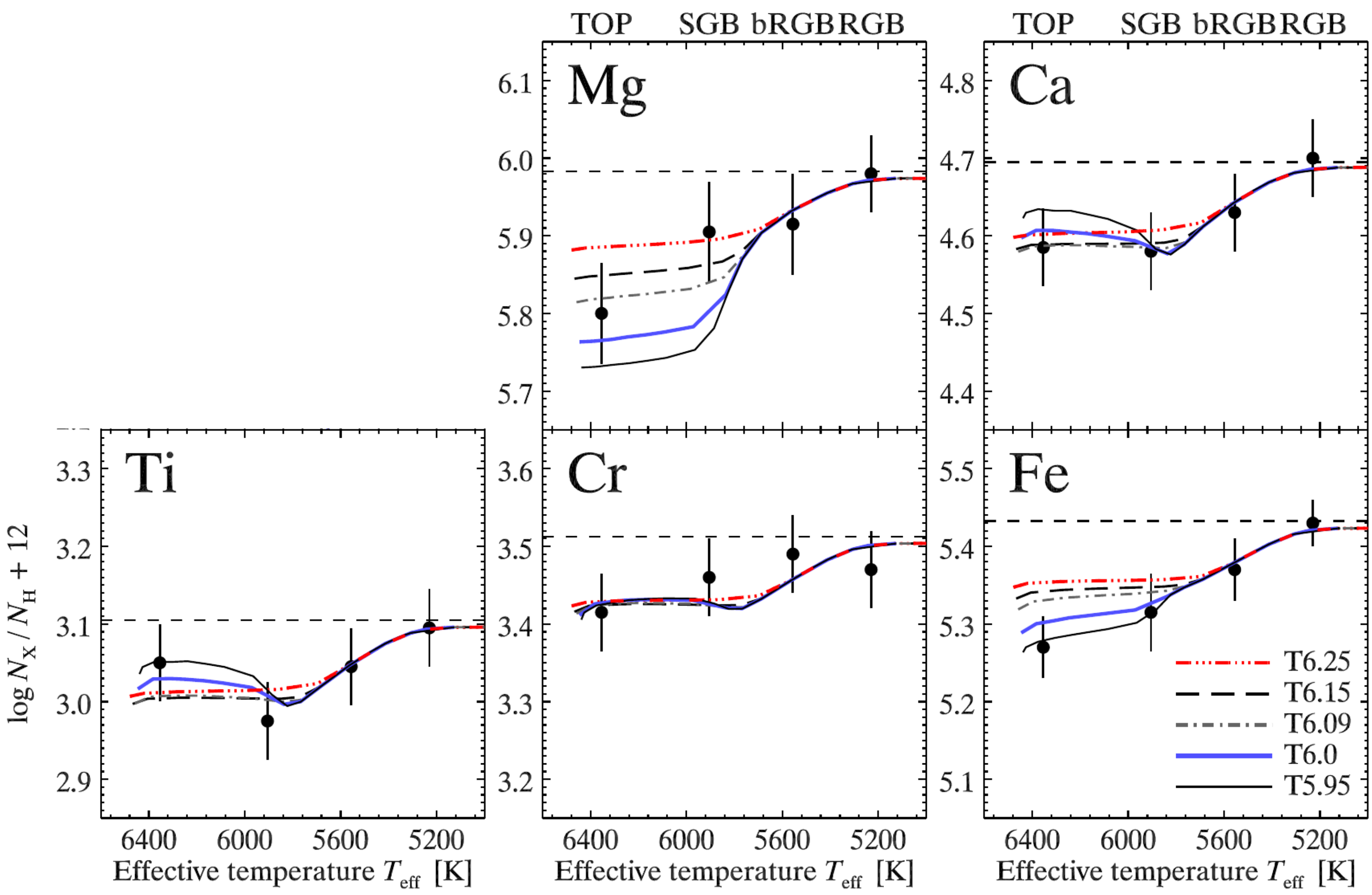


Lind *et al.* (2008)

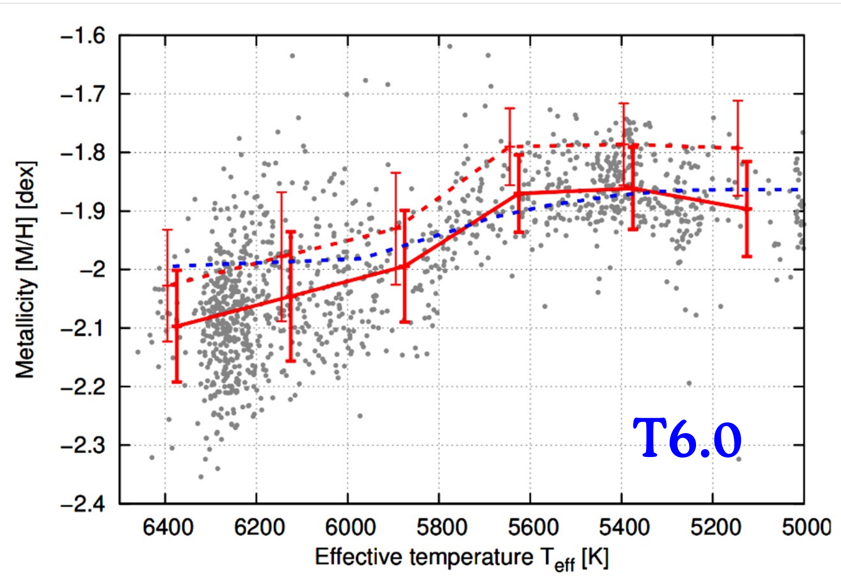


Lind *et al.* (2009),
but see González Hernández *et al.* (2009)

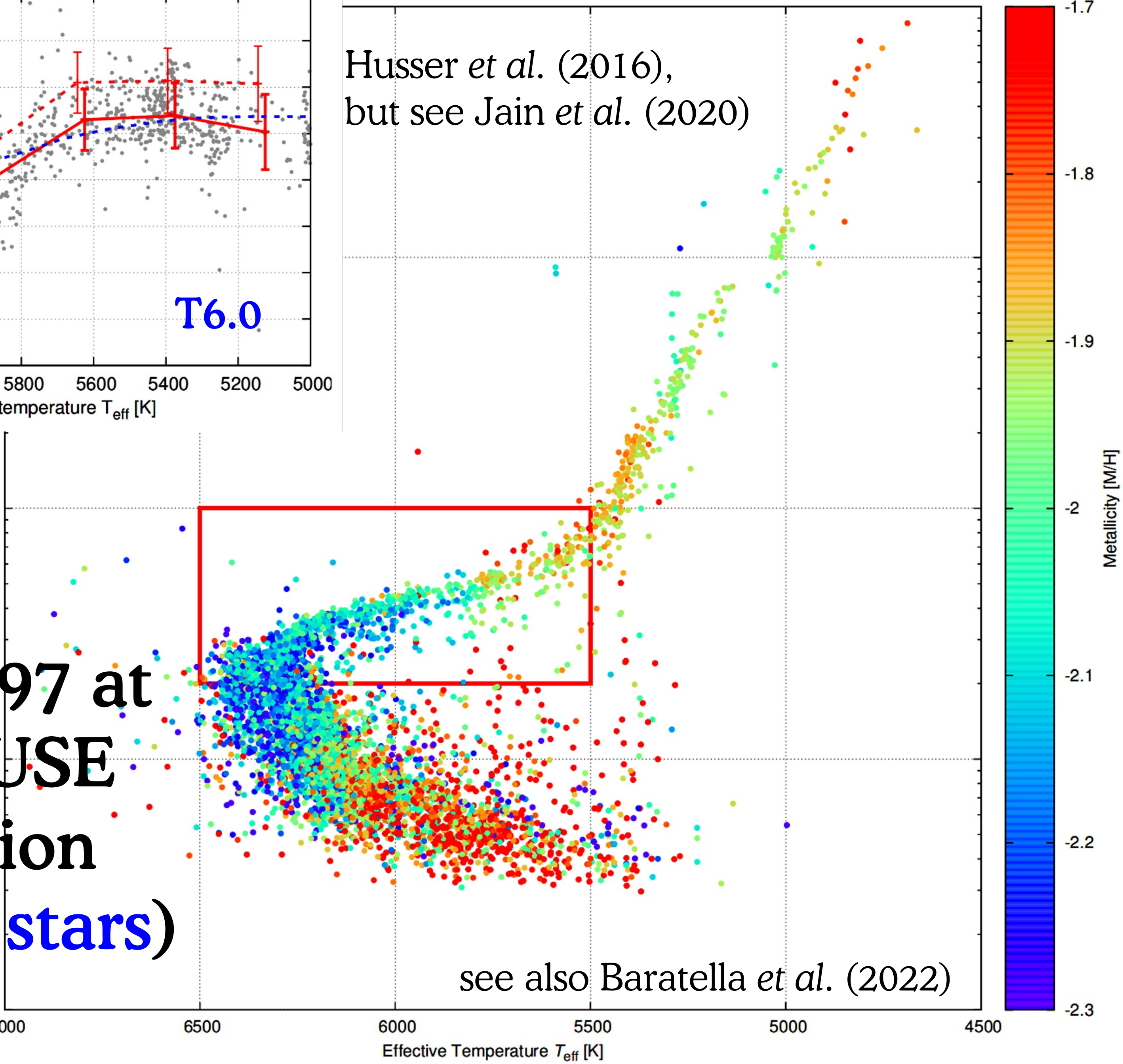
Subsequent analyses (updated T_{eff} scale)



Nordlander *et al.* (2012)



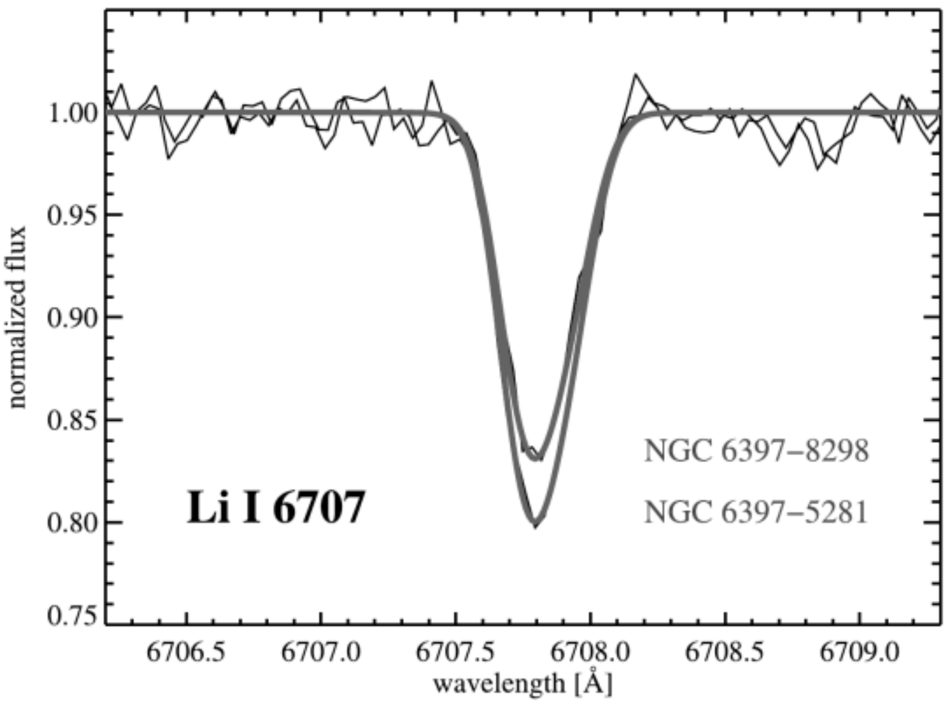
Husser *et al.* (2016),
but see Jain *et al.* (2020)

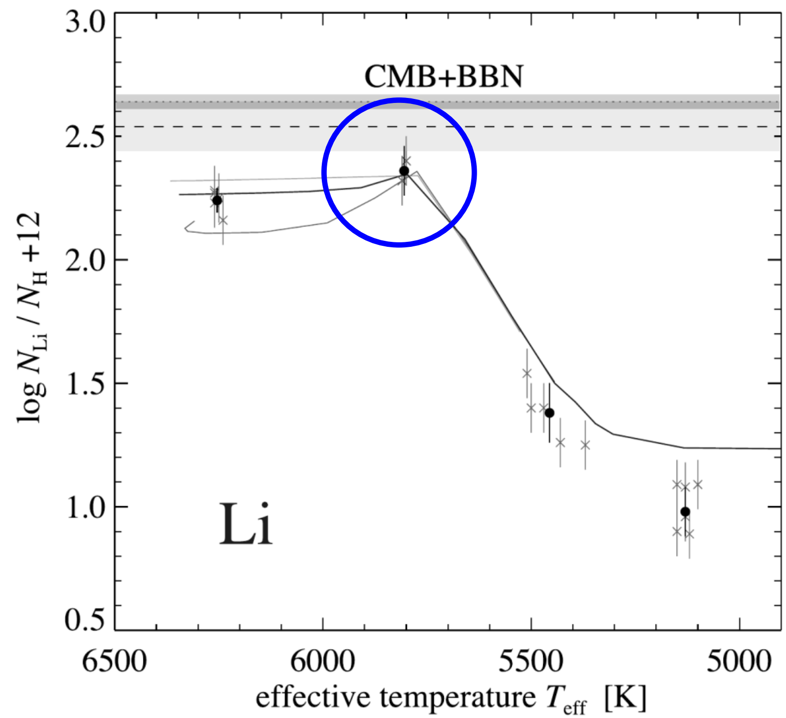


NGC 6397 at VLT/MUSE resolution (1000s of stars)

see also Baratella *et al.* (2022)

Caught in the act: lithium dredge-up





When the stars evolve towards the red-giant branch, a slight (~0.1 dex) **increase in surface lithium abundance** signals the onset of the first dredge-up. (Eventually, surface lithium is reduced by a factor of ~20.)

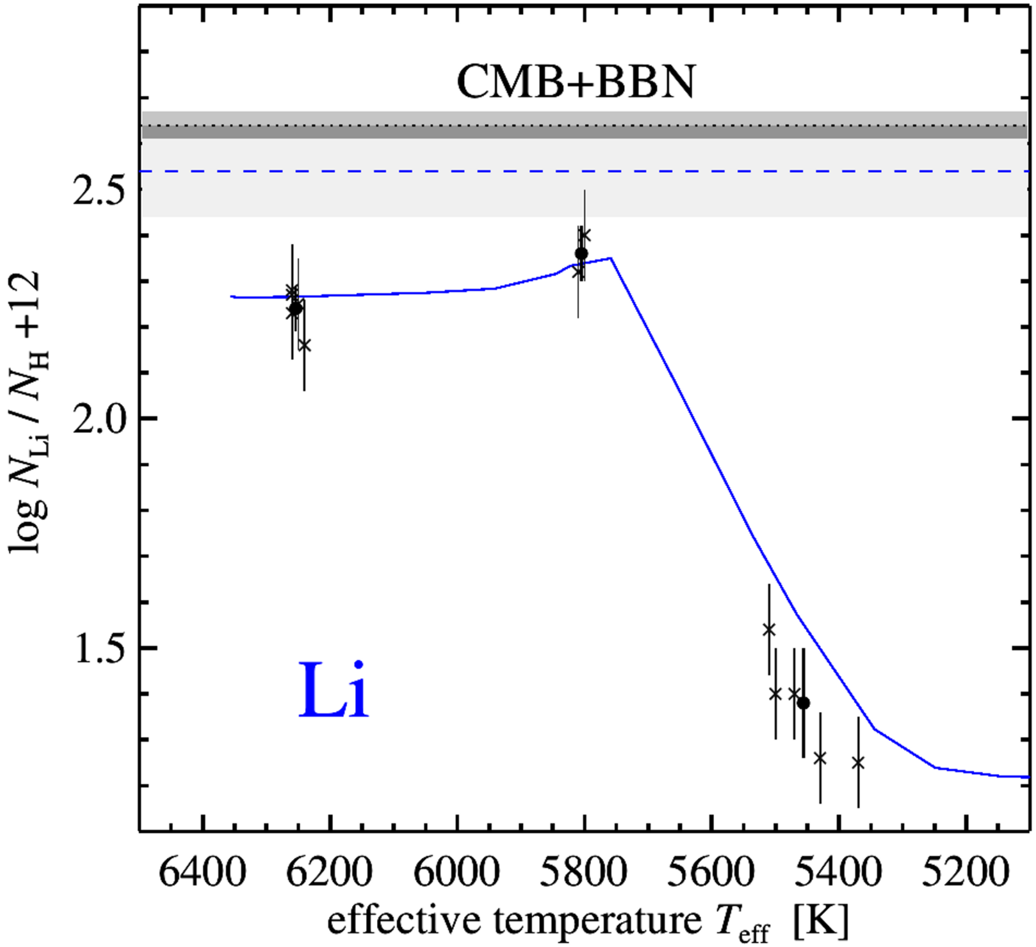
So far, we have only seen this **"Li hump"** in NGC 6397, in accord with the predictions from Richard models.

Inference for lithium in NGC 6397

$\log \varepsilon(\mathrm{Li})_{\text{AD-corr}}$ = **2.54 ± 0.1**

vs.

$\log \varepsilon(\mathrm{Li})_{\mathrm{BBN}}$ = **2.64 ± 0.03**
(WMAP 3-yr results coupled to Standard BBN)
Agreement within 1σ.



Korn *et al.* (2006)

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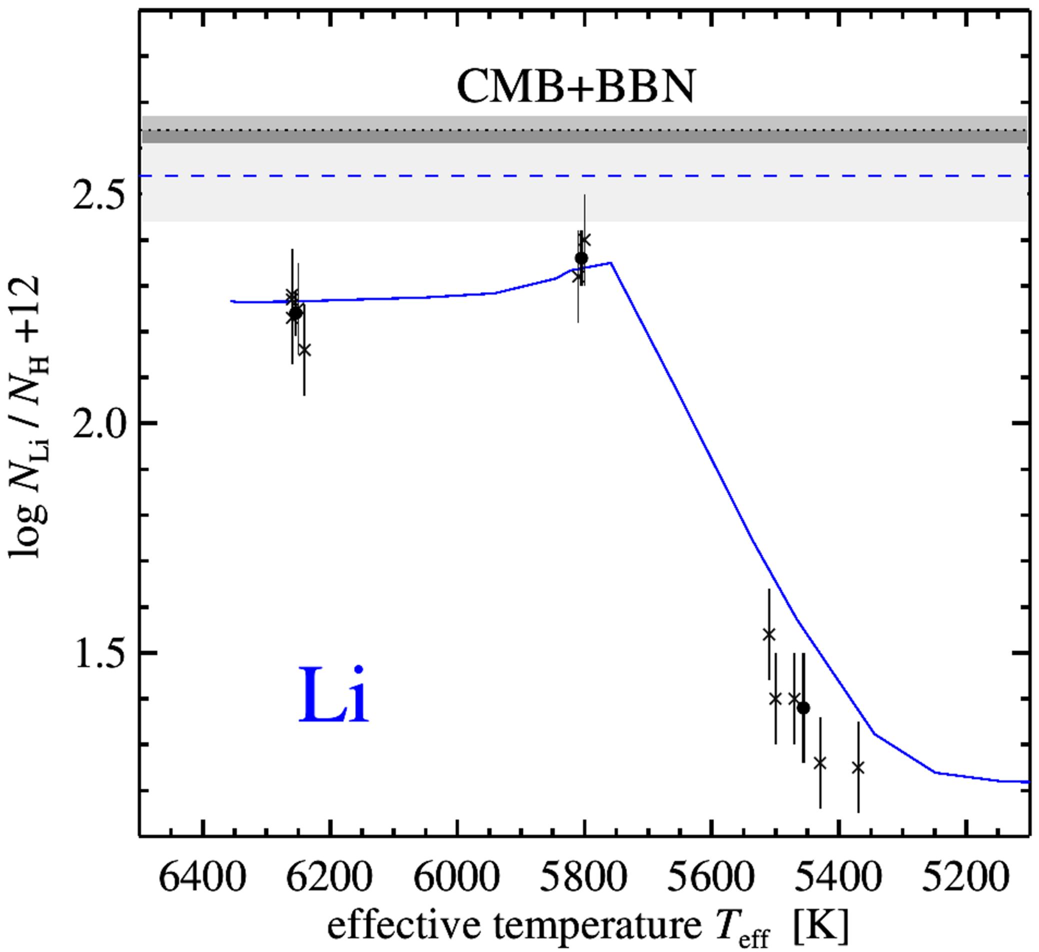
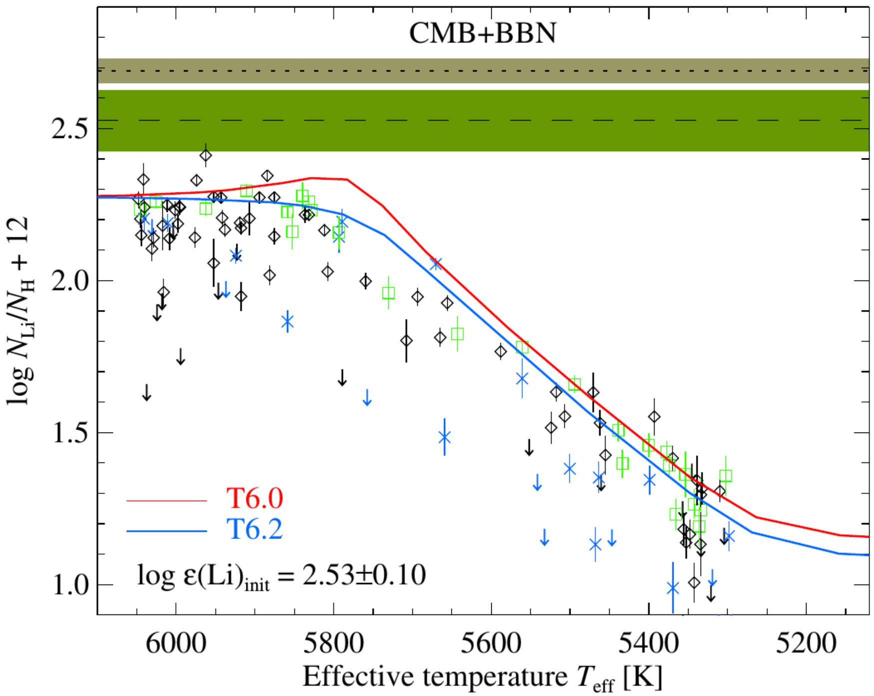
(WMAP 3-yr results coupled to Standard BBN)
Agreement within 1σ.

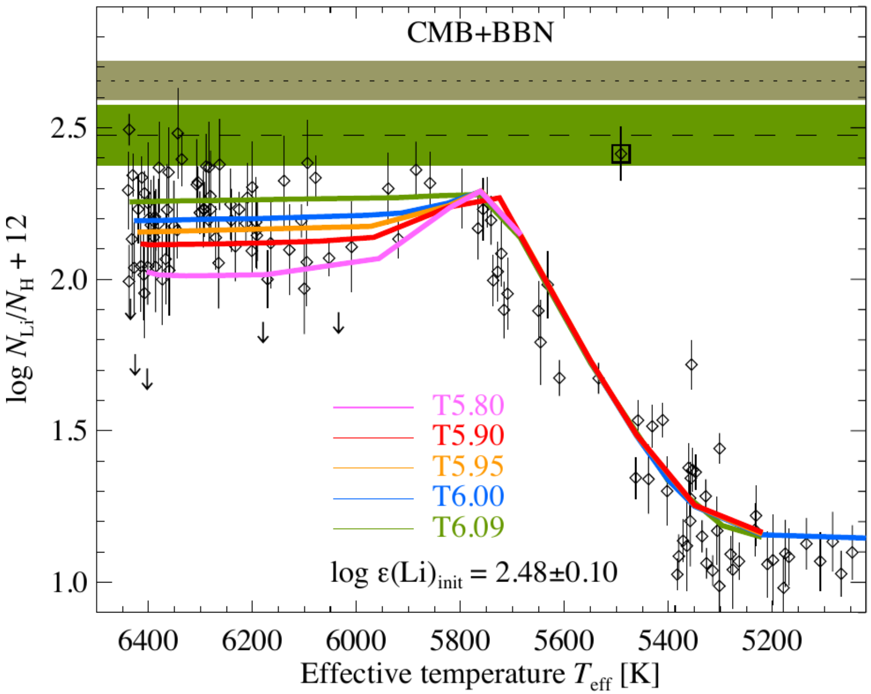
However, the latest BBN estimate is a little higher:
log $\varepsilon(\text{Li})_{\text{BBN}}$ = **2.71 ± 0.02**
(Pizzone *et al.* 2024)



Korn *et al.* (2006)

Lithium in other globular clusters





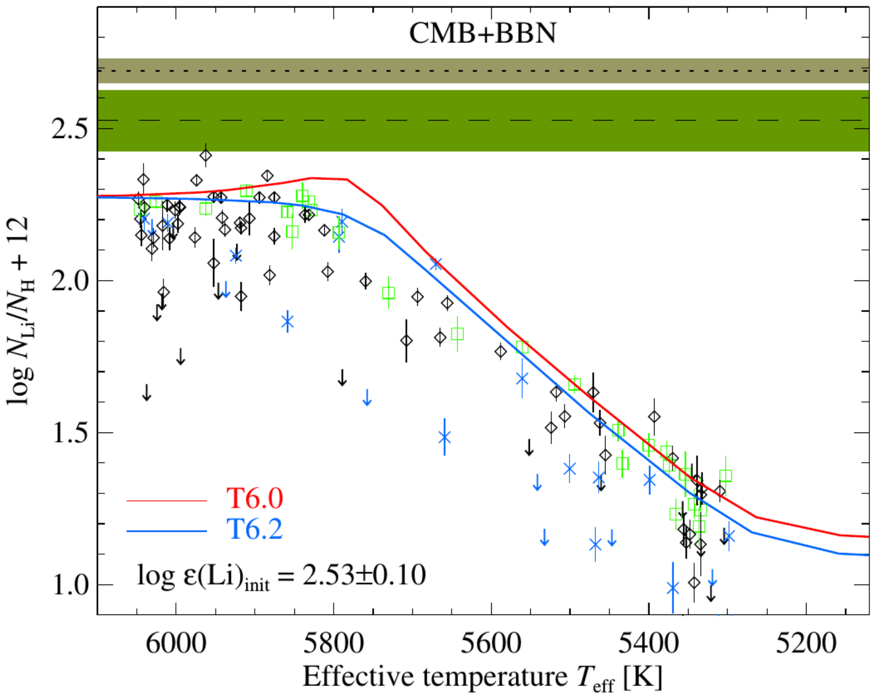
NGC 6752 @ [Fe/H]=–1.5:

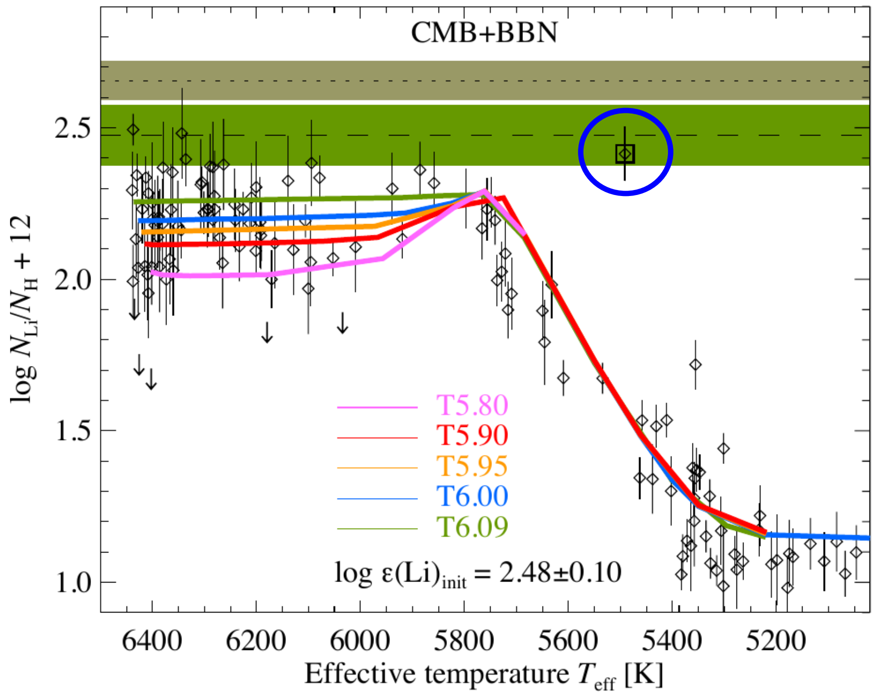
log ε(Li)$_{\text{AD-corr}}$ = **2.52** / **2.58**
vs log ε(Li)$_{\text{BBN}}$ = 2.69 ± 0.04
1.5σ agreement with BBN.
(Gruyters *et al.* 2013, 2014)

Messier 30 @ [Fe/H]=–2.3:

log ε(Li)$_{\text{AD-corr}}$ = **2.48 ± 0.1**
vs log ε(Li)$_{\text{BBN}}$ = 2.66 ± 0.06
BBN agreement *possible*.
(Gruyters *et al.* 2016)

Lithium in other globular clusters





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ADiOS series of papers

The Astrophysical Journal, 671:402–419, 2007 December 10

ATOMIC DIFFUSION AND MIXING IN OLD STARS. I. VERY LARGE TELESCOPE FLAMES-UVES OBSERVATIONS OF STARS IN NGC 6397[1]

A. J. Korn
Department of Astronomy and Space Physics, Uppsala University, 75120 Uppsala, Sweden; akorn@astro.uu.se

A&A 490, 777–786 (2008)
DOI: 10.1051/0004-6361:200810051

Astronomy & Astrophysics

Atomic diffusion and mixing in old stars

II. Observations of stars in the globular cluster NGC 6397 with VLT/FLAMES-GIRAFFE⋆,⋆⋆

K. Lind[1,2], A. J. Korn[1], P. S. Barklem[1], and F. Grundahl[3]

The Astrophysical Journal, 753:48 (9pp), 2012 July 1 doi:1

ATOMIC DIFFUSION AND MIXING IN OLD STARS. III. ANALYSIS OF NGC 6397 STARS UNDER NEW CONSTRAINTS

T. Nordlander[1], A. J. Korn[1], O. Richard[2], and K. Lind[3]

A&A 555, A31 (2013)
DOI: 10.1051/0004-6361/201220821

Astronomy & Astrophysics

Atomic diffusion and mixing in old stars

IV. Weak abundance trends in the globular cluster NGC 6752⋆,⋆⋆

P. Gruyters[1], A. J. Korn[1], O. Richard[3], F. Grundahl[2], R. Collet[5,6], L. I. Mashonkina[4], Y. Osorio[1], and P. S. Barklem[1]

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2 Stellar Astrophysics Centre, Department of Physics and Astronomy, Århus University, Ny Munkegade 120, 8000 Århus C, Denmark
3 LUPM, Université Montpellier II, CNRS, CC072, Place E. Bataillon, 34095 Montpellier Cedex, France
4 Institute of Astronomy, Russian Academy of Science, 119017 Moscow, Russia

A&A 567, A72 (2014)
DOI: 10.1051/0004-6361/201423590

Astronomy & Astrophysics

Atomic diffusion and mixing in old stars

V. A deeper look into the globular cluster NGC 6752⋆,⋆⋆

Pieter Gruyters, Thomas Nordlander, and Andreas J. Korn

A&A 589, A61 (2016)
DOI: 10.1051/0004-6361/201527948

Astronomy & Astrophysics

Atomic diffusion and mixing in old stars

VI. The lithium content of M30⋆,⋆⋆

Pieter Gruyters[1,2], Karin Lind[1], Olivier Richard[3], Frank Grundahl[4], Martin Asplund[5], Luca Casagrande[5], Corinne Charbonnel[6,7], Antonino Milone[5], Francesca Primas[8], and Andreas J. Korn[1]

A&A 652, A75 (2021)
https://doi.org/10.1051/0004-6361/202140770

Astronomy & Astrophysics

Atomic diffusion and mixing in old stars

VII. Abundances of Mg, Ti, and Fe in M 30⋆

Alvin Gavel[1], Pieter Gruyters[1], Ulrike Heiter[1], Andreas J. Korn[1], Thomas Nordlander[2,3],

Monthly Notices of the Royal Astronomical Society
MNRAS 527, 12120–12139 (2024) https://doi.org/10.1093/mnras/stad3973
Advance Access publication 2023 December 23

Atomic diffusion and mixing in old stars – VIII. Chemical abundance variations in the globular cluster M4 (NGC 6121)

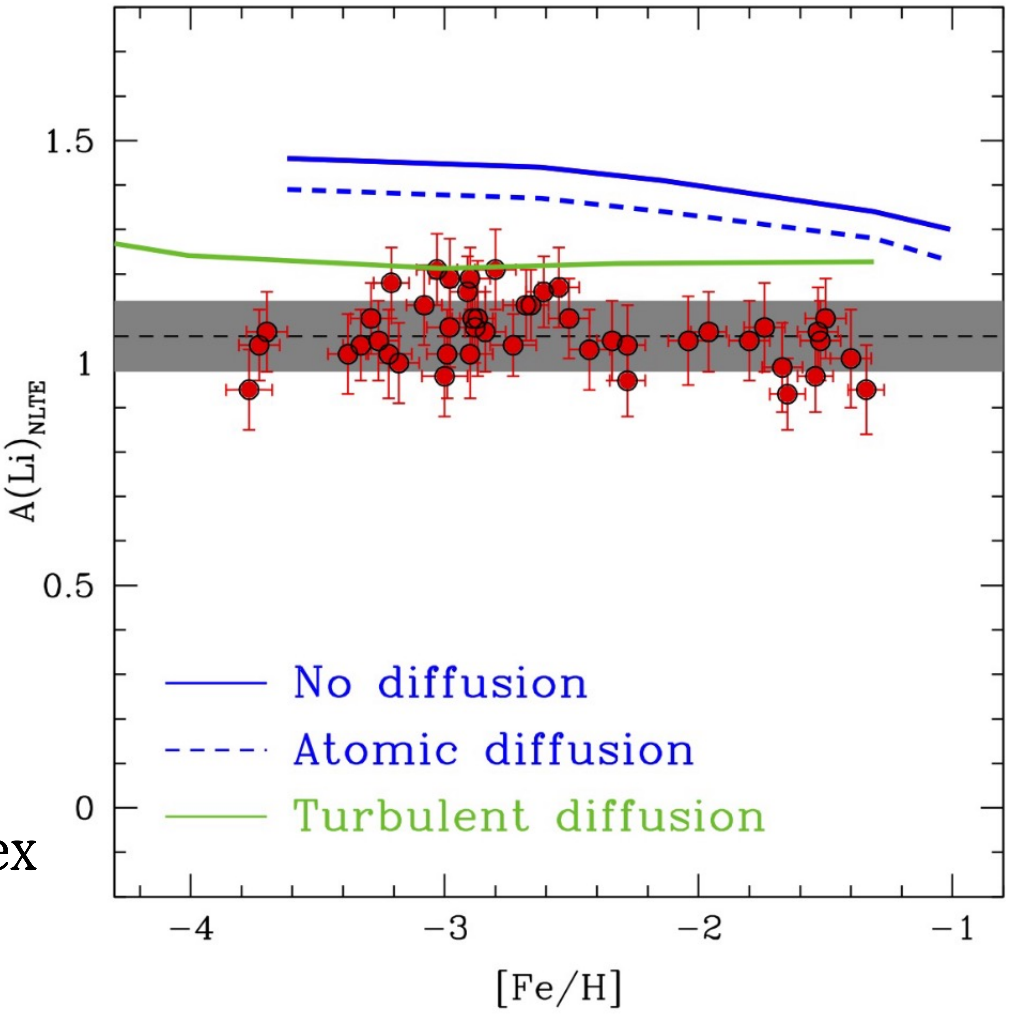
T. Nordlander[1,2,3]⋆† P. Gruyters,[3,4] O. Richard[5] and A. J. Korn[3]
1 Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia
2 ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Australia
3 Division of Astronomy and Space Physics, Department of Physics and Astronomy, Uppsala University, Box 516, SE-75120 Uppsala, Sweden
4 Lund Observatory, Division of Astrophysics, Department of Physics, Lund University, Box 43, SE-221 00 Lund, Sweden
5 Laboratoire Univers et Particules de Montpellier, CNRS, Université de Montpellier, CC072, Place E. Bataillon, F-34095 Montpellier Cedex, France

Another plateau with new properties

Mucciarelli *et al.* (2022) identified a thin and flat plateau of lithium among lower-RGB stars.

This **plateau does not melt down** like the one among dwarfs/subgiants.

Richard models can explain it starting from BBN abundance, modulo 0.15 dex (40% in linear abundance).



The stellar take on lithium

A *purely stellar solution* to the cosmological lithium problem is *still probable*.
(See Fu *et al*. 2015, Piau *et al*. 2006, Takeda 2019 and Deal & Martins 2021 for related/other stellar solutions)

In any case, a significant *stellar alleviation* of the problem is *inevitable*.

We are not done yet: we do not understand Li depletion in the Sun and in very metal-poor stars. Our best models have tuneable parameters.

The stellar take on lithium

A *purely stellar solution* to the cosmological lithium problem is *still probable*.
(See Fu *et al*. 2015, Piau *et al*. 2006, Takeda 2019 and Deal & Martins 2021 for related/other stellar solutions)

In any case, a significant *stellar alleviation* of the problem is *inevitable*.

Nuclear/particle physicists should try to solve the remaining 0.1-0.15 dex / 25-50% problem (?) in lithium abundance.

Let’s do this together!

Thank you for you time and attention!

Li-6 in old stars?

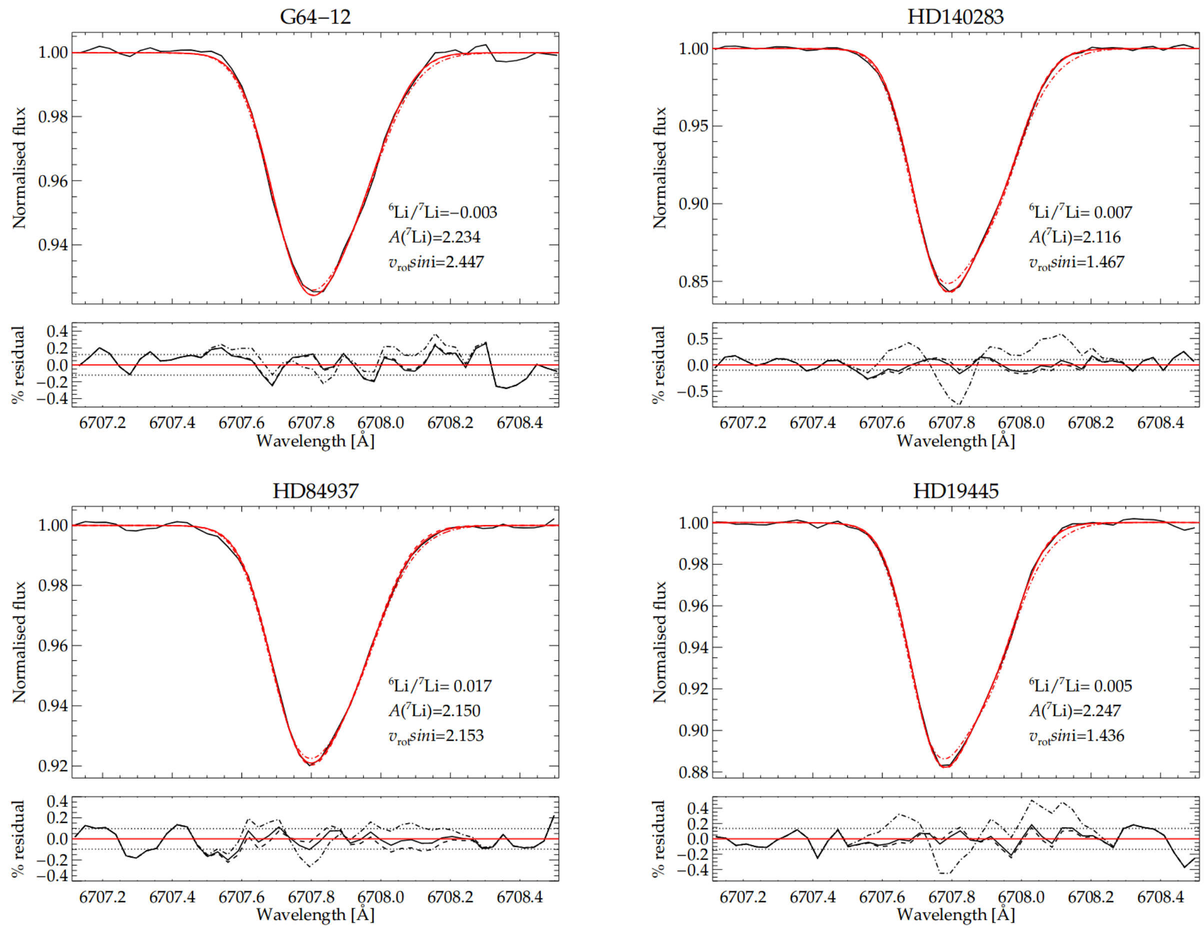
Individual local halo stars seemed to show Li-6 at the level of a few percent of lithium-7 (e.g. Smith *et al*. 1993). However, one swallow does not signal the onset of summer…

In 2006, Asplund *et al*. **claimed** the **existence of a Li-6 plateau**. Highly controversial, as pre-MS destruction would tilt the plateau (requiring an extrapolation to Fe/H=0 and thus rather low Li-6 abundances). Still, this finding really got BBN modellers excited as they now had ***two lithium problems*** **as two potential constraints for modified BBN calculations**.

No significant Li-6, it's all gone!

Using the latest 3D+NLTE modelling techniques, Lind *et al*. (2013) could show that **none of the previous detections** were in fact **real**.

The line asymmetry produced by stellar convection had previously been mistaken for a finite amount of Li-6. Had been feared, but could only be shown after 3D models could be combined with NLTE line formation.



This is a good example of the importance of a high degree of modelling realism in stellar spectroscopy! See also Wang *et al*. (2022).