18th Russbach School on Nuclear Astrophysics, March 13-17, 2023

Solving the Li problem

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Which Li problem?

There are in fact many! Because Li is pretty fragile!

- ~2000 onwards: Li-7 problem

Less lithium in old stars than predicted by CMB-calibrated BBN calculations?

- 2006 onwards: Li-6 problem

More light lithium in old stars than predicted by BBN?

Which Li problem?

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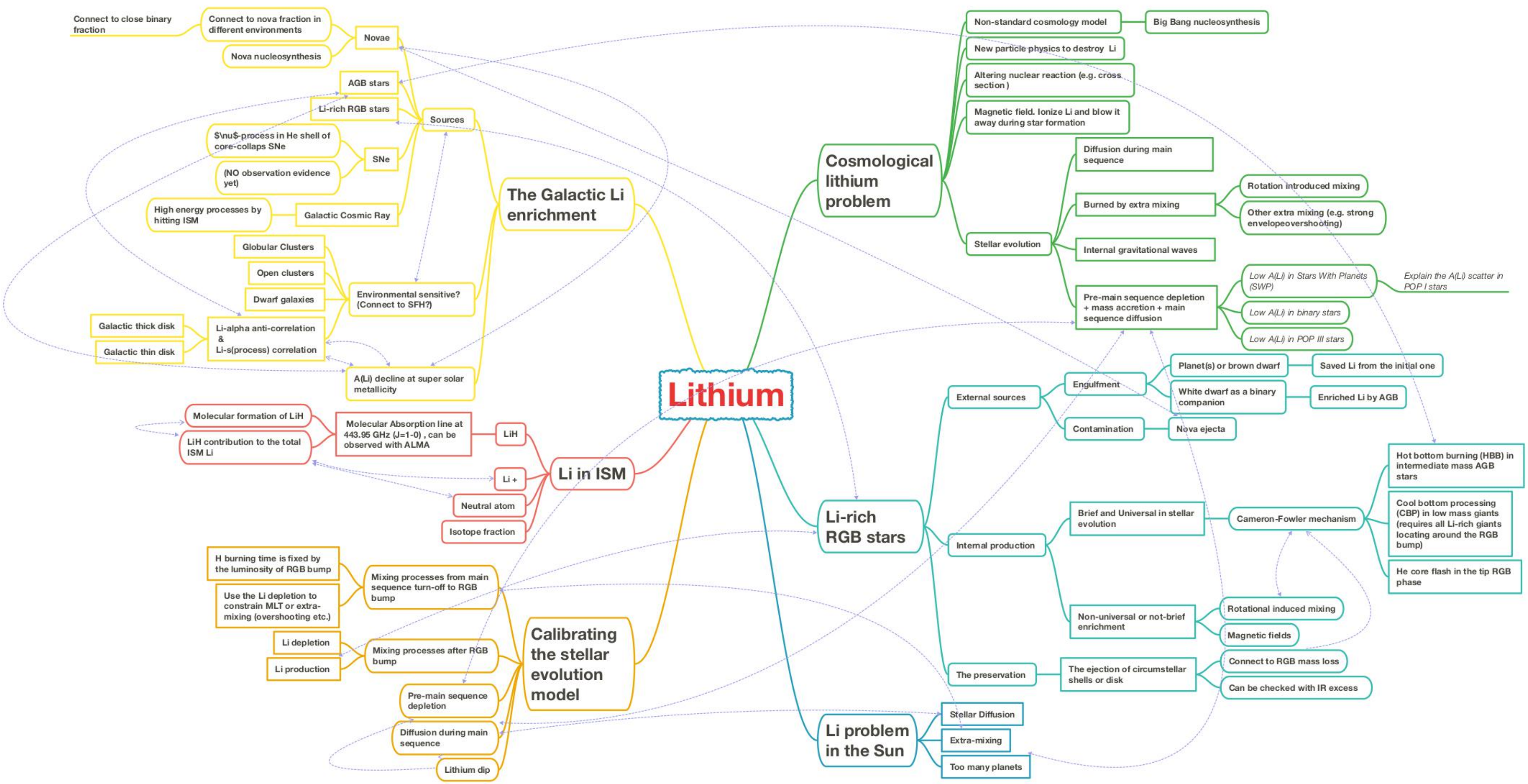
More light lithium in old stars than predicted by BBN?

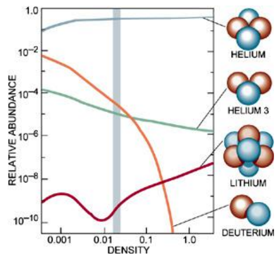
Not discussed here:

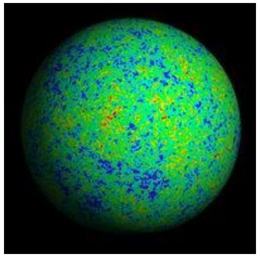
- the solar lithium problem (typical depletion or not?)
- the thin-disc lithium problem (always increasing or not?)

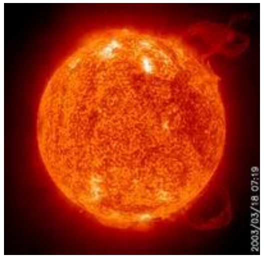
Xiaoting Fu's Li concept map



The evolution of the cosmos





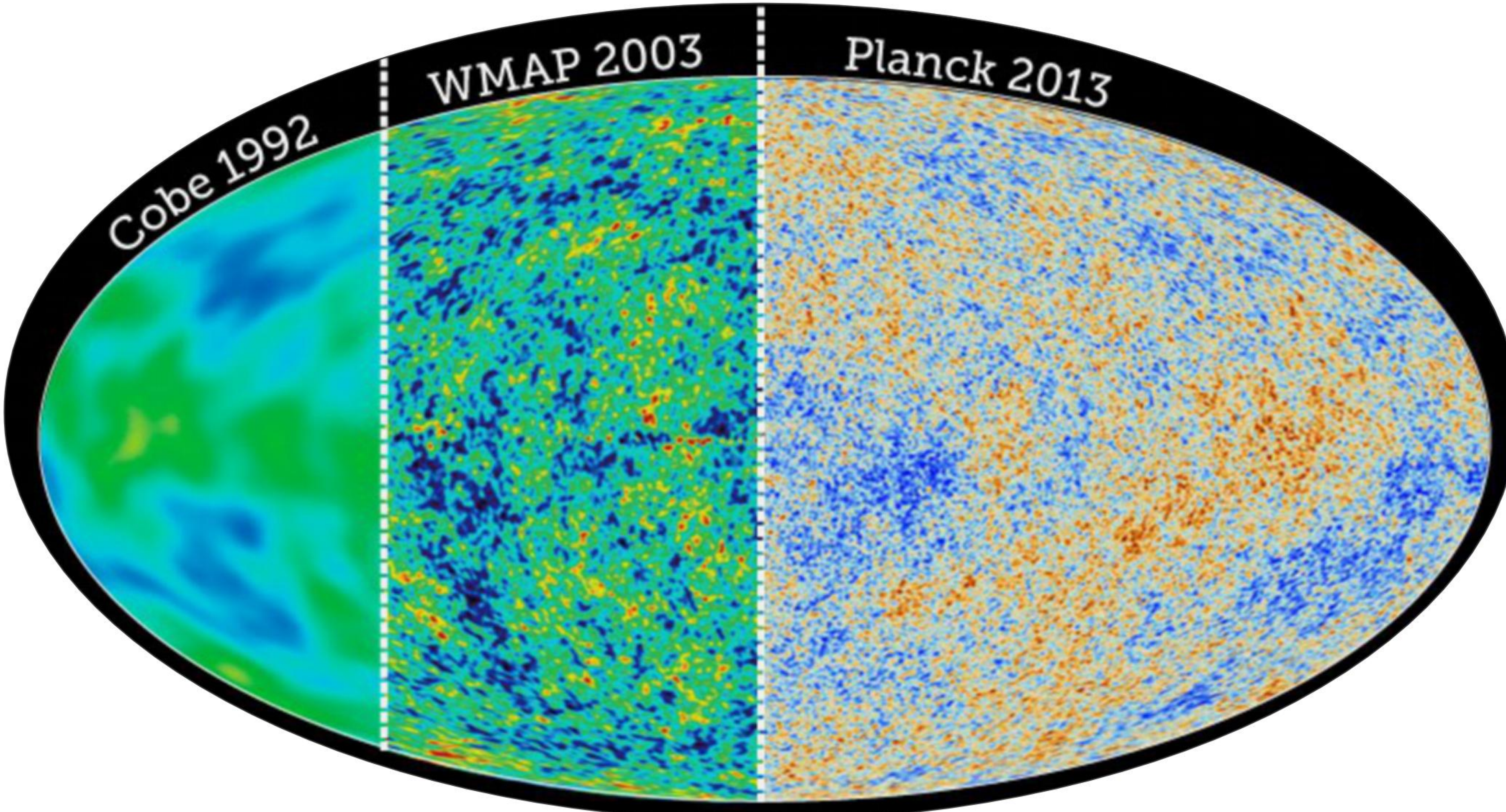


Big Bang	Big-Bang nucleosynthesis	microwave background	formation of galaxies	formation of the sun	astronomers on earth
0	3 min	380 000 yr	200 Myr	9 Gyr	13.7 Gyr

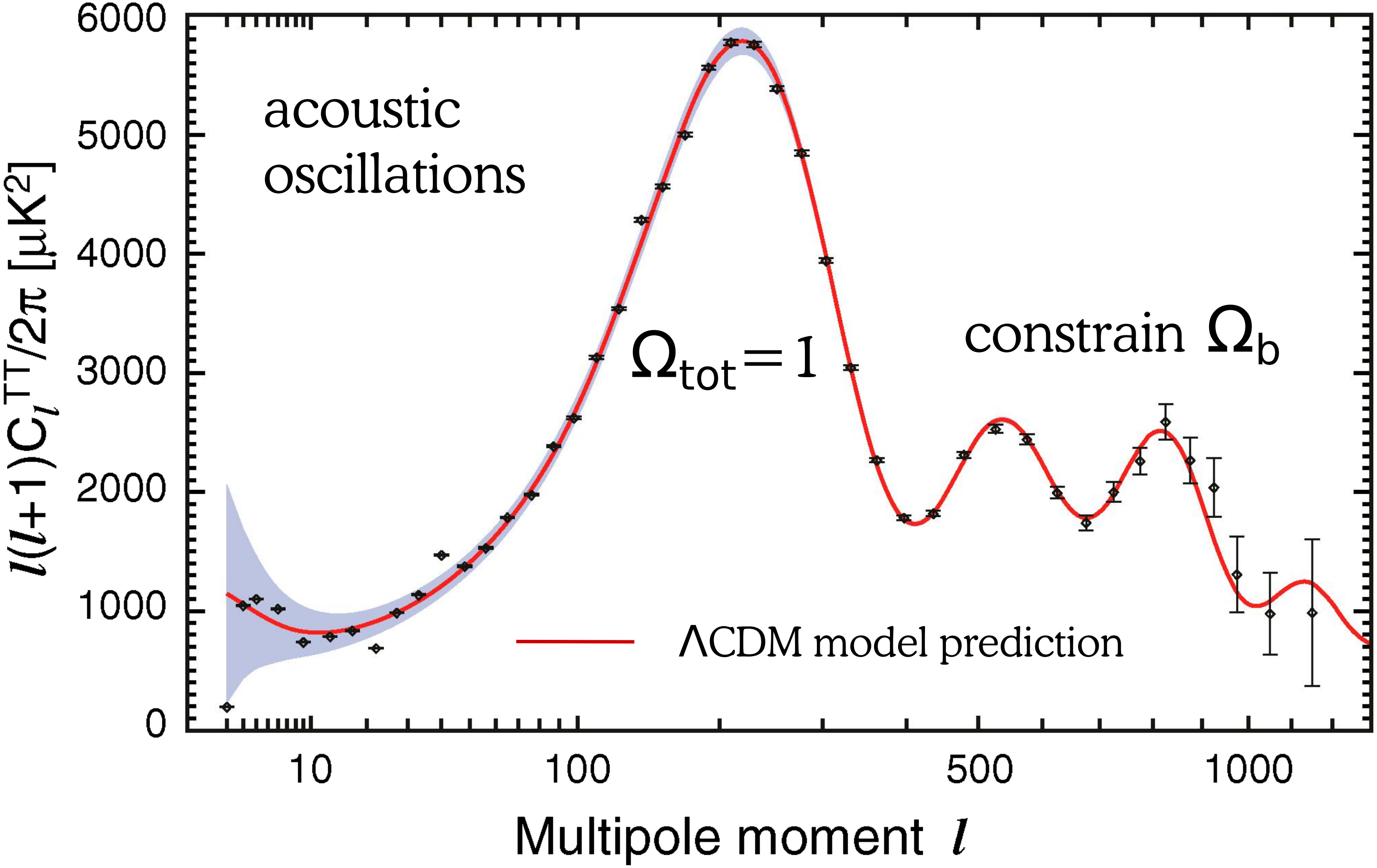
t

Using a variety of techniques, we can, in principle, study *all* phases of cosmic evolution

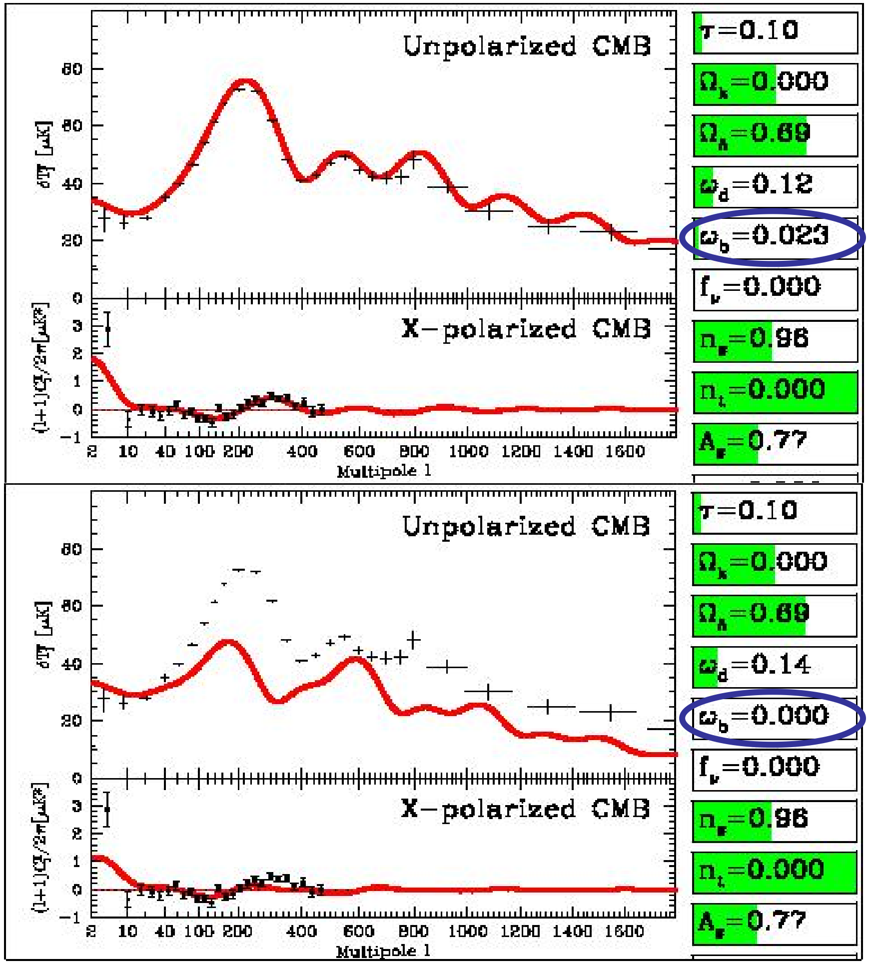
Observing the CMB



CMBology (Era of Precision Cosmology)



Play with the CMB



http://space.mit.edu/home/tegmark/movies.html

(CMB movies)

Fixing the baryonic density of the universe

Six-Parameter ΛCDM Fit [a]

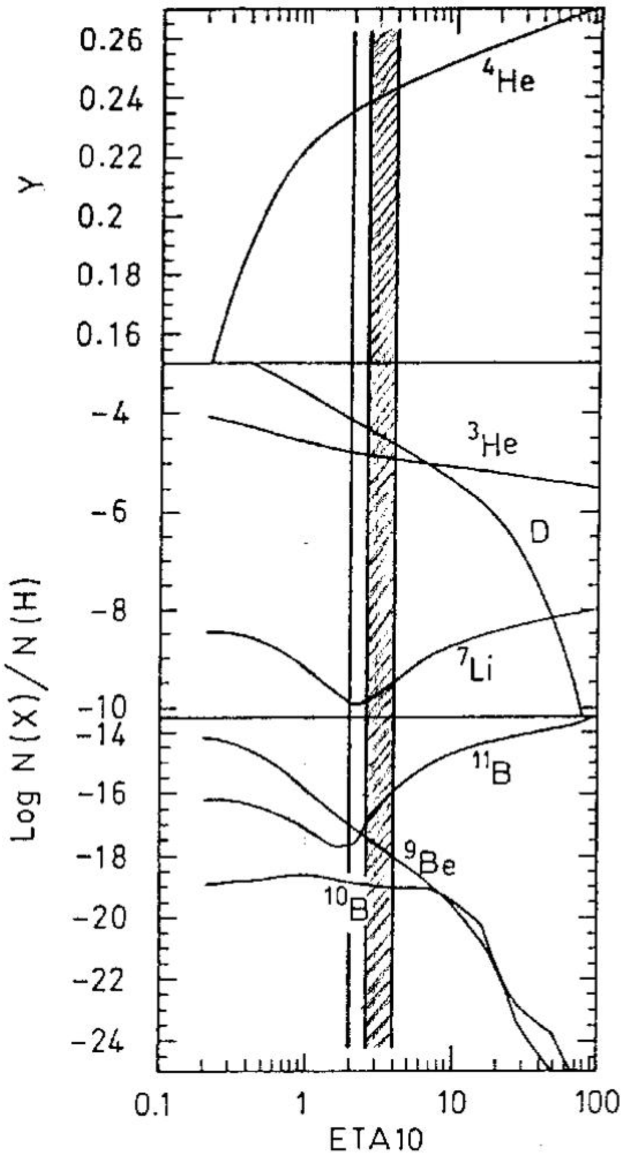
Parameter	7-year Fit	5-year Fit
Fit parameters		
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	2.273 ± 0.062
$\Omega_c h^2$	0.1109 ± 0.0056	0.1099 ± 0.0062
Ω_Λ	0.734 ± 0.029	0.742 ± 0.030
$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.41 \pm 0.11) \times 10^{-9}$
n_s	0.963 ± 0.014	$0.963^{+0.014}_{-0.015}$
τ	0.088 ± 0.015	0.087 ± 0.017
Derived parameters		
t_0	13.75 ± 0.13 Gyr	13.69 ± 0.13 Gyr
H_0	71.0 ± 2.5 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc
σ_8	0.801 ± 0.030	0.796 ± 0.036
Ω_b	$\boxed{0.0449 \pm 0.0028}$	0.0441 ± 0.0030
Ω_c	0.222 ± 0.026	0.214 ± 0.027
$z_{\rm eq}$	3196^{+134}_{-133}	3176^{+151}_{-150}
$z_{\rm reion}$	10.5 ± 1.2	11.0 ± 1.4

[a] Models fit to *WMAP* data only. See Komatsu et al. (2010) for additional constraints.

Larson *et al.* (2010)

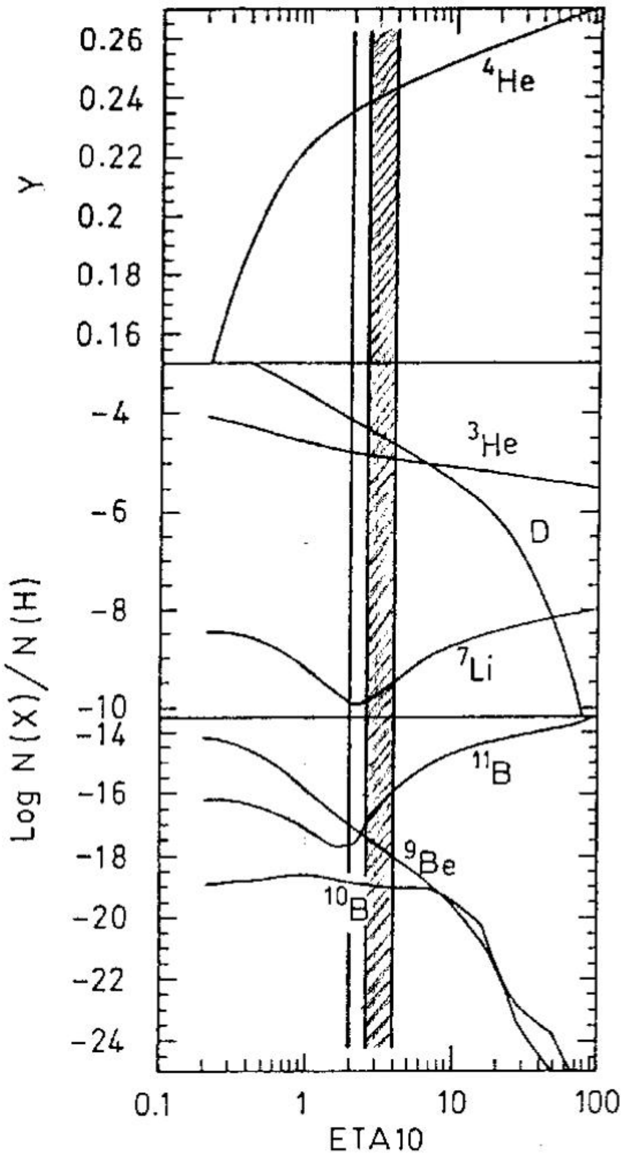
95% of the cosmos in the dark sector!

Pre- vs post-WMAP BBN



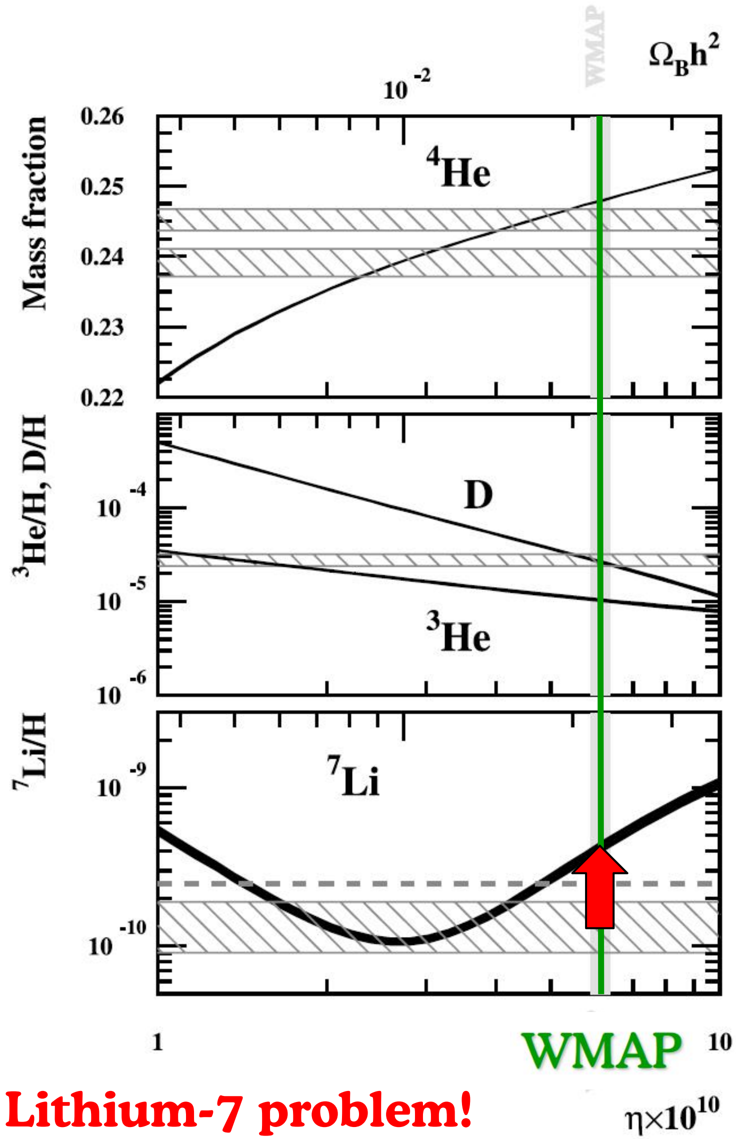
Korn 1996, MSc thesis

Pre- vs post-WMAP BBN



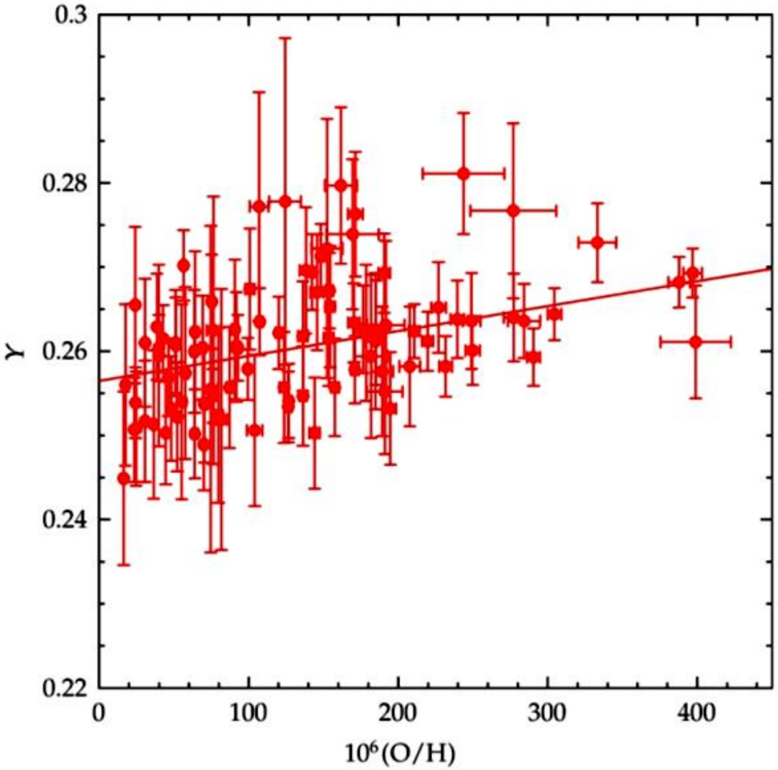
Korn 1996, MSc thesis

Detailed measurements of CMB anisotropies fix the baryon-to-photon ratio (η): **Standard BBN becomes predictive, uniquely predicts primordial abundances!**



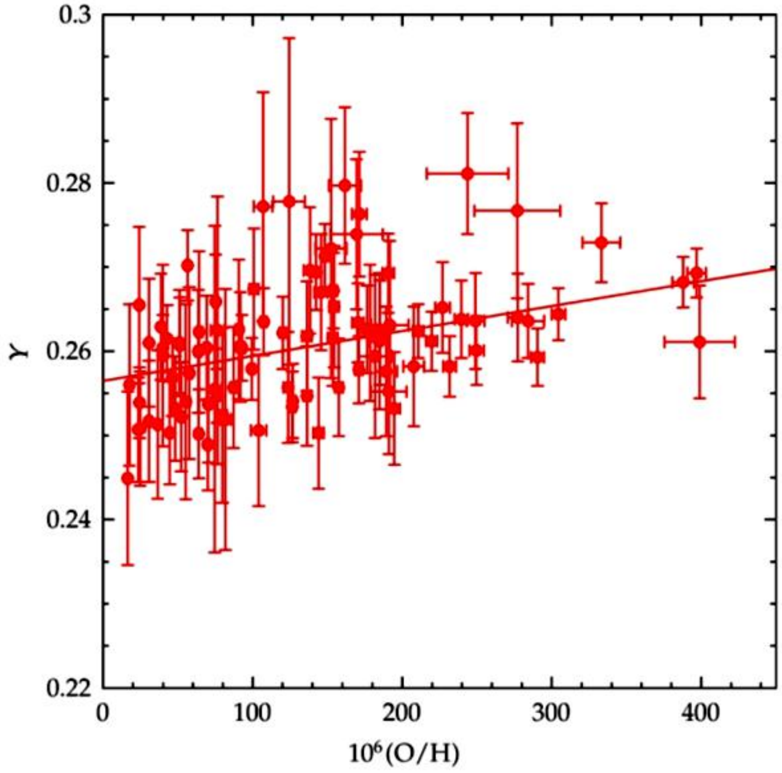
Lithium-7 problem!

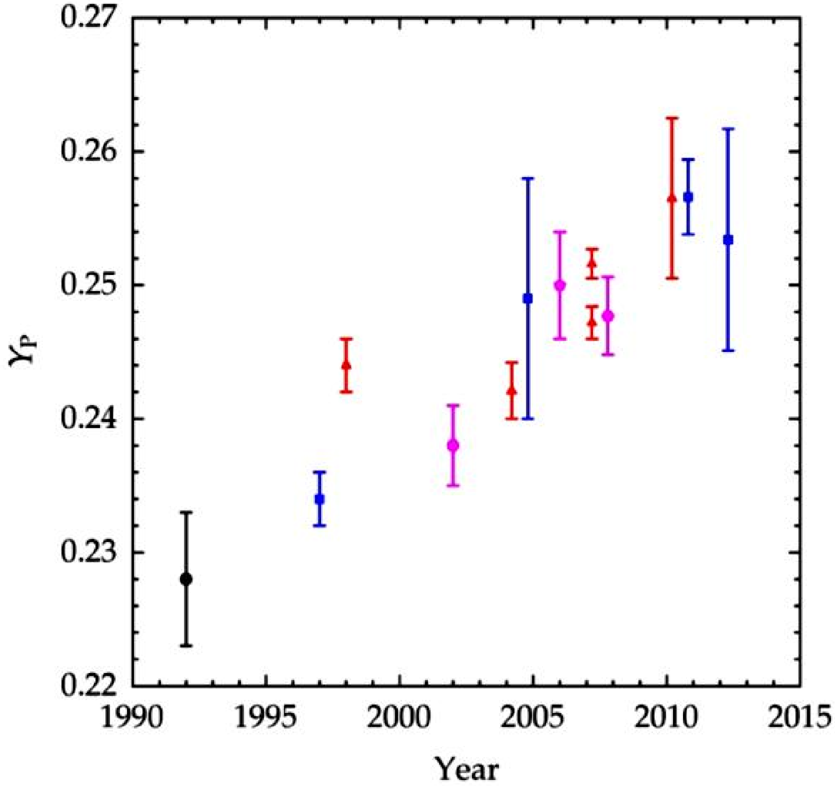
Observating BBN: examples



Helium: observing and modelling emission lines in HII regions as a function of a stellar metal, here O. Systematics and scatter limit the validity of the extrapolation.

Observating BBN: examples



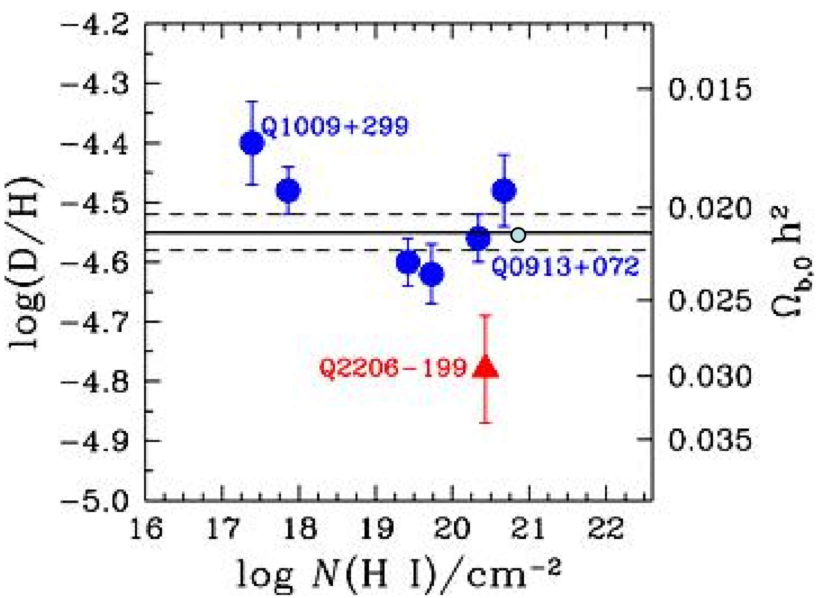


Helium: observing and modelling emission lines in HII regions as a function of a stellar metal, here O. Systematics and scatter limit the validity of the extrapolation.

Y_p a function of human time??
Not flattering, but a scientific reality.

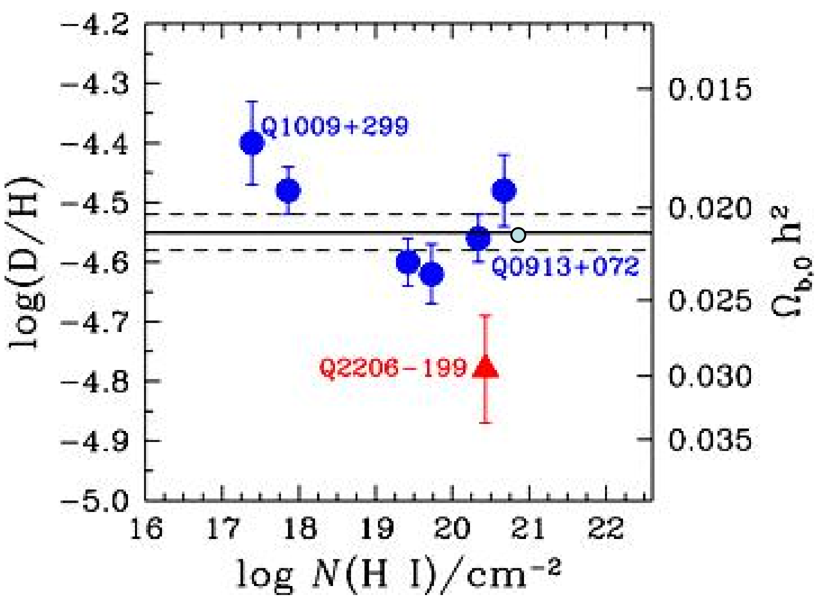
(Not unique in science, by the way.)

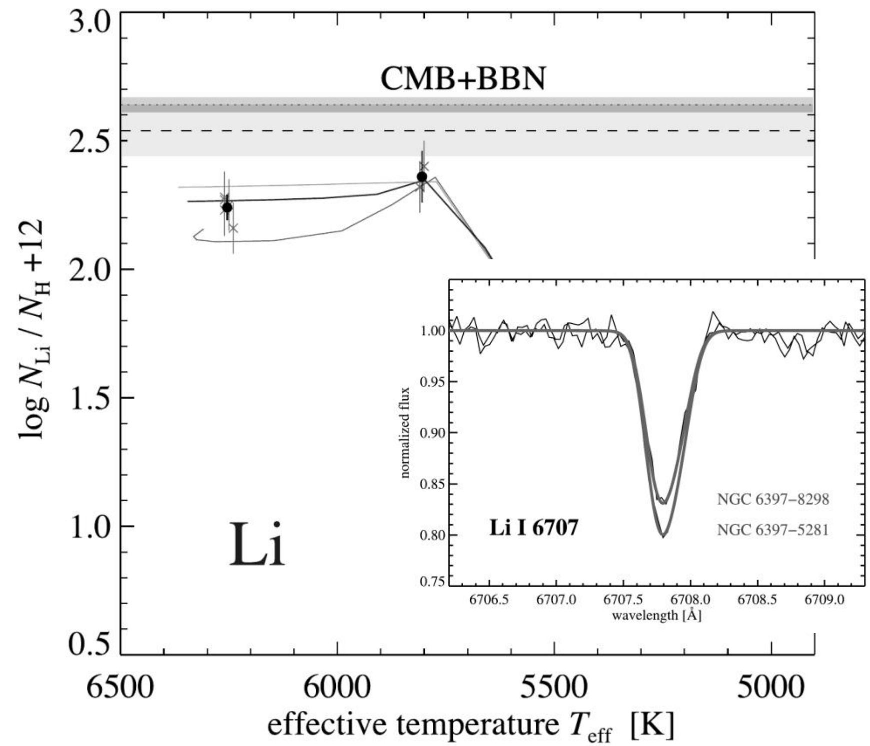
Observing BBN: more examples



Deuterium: observing a 10^{-5} contribution to Lyman-series absorption lines towards high-redshift quasars.
Few data points, some (significant?) scatter.
How to get rid of chance interlopers?

Observating BBN: more examples

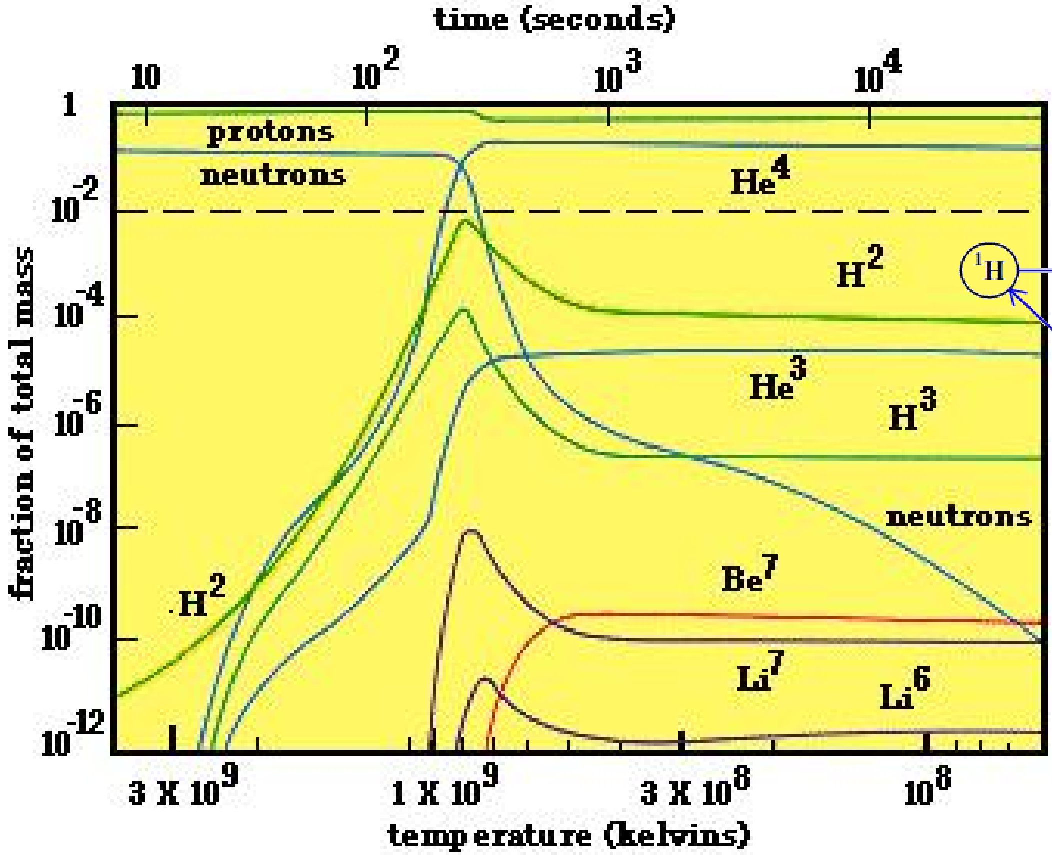


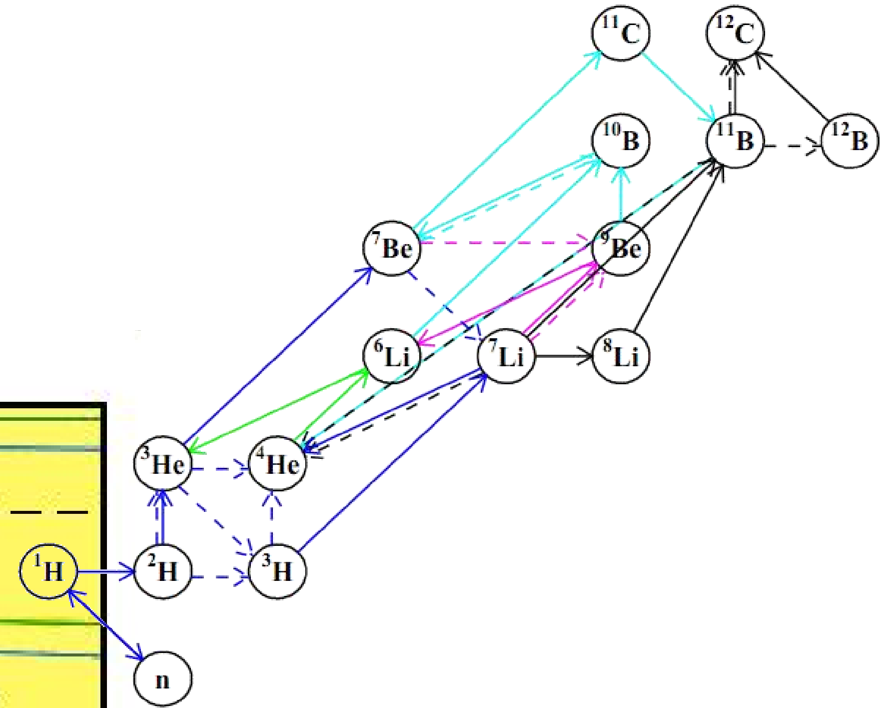


Deuterium: observing a 10^{-5} contribution to Lyman-series absorption lines towards high-redshift quasars.
Few data points, some (significant?) scatter.
How to get rid of chance interlopers?

Lithium: observing and modelling stellar absorption lines of metal-poor stars down to $V = 17$.
Modelling trustworthy (3D+NLTE), but interpretation subject to systematics (atomic diffusion).

Recall from Monday morning





⇦ some Li-6 produced?

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**.

Modifications to BBN

New Physics Lithium Solutions
an Incomplete Survey

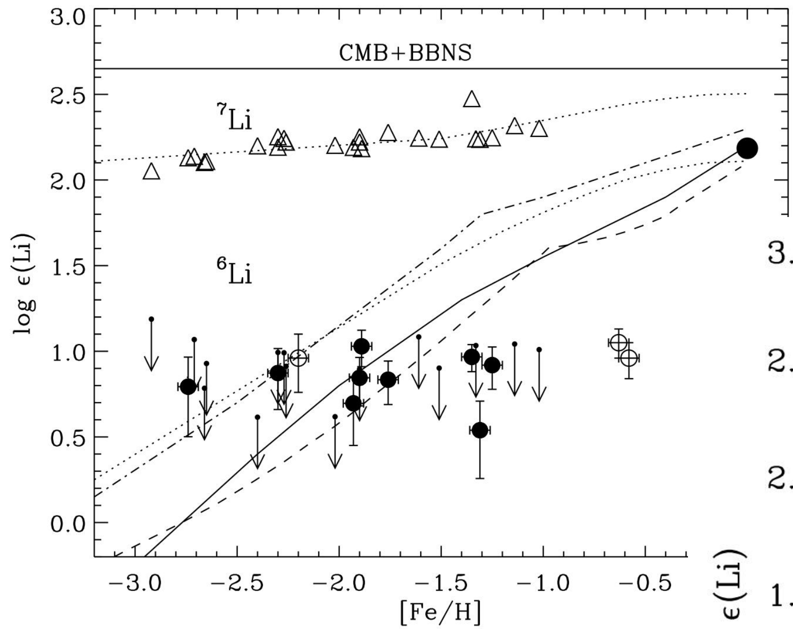
- Particle Physics Beyond the Standard Model
  - decaying particles / Supersymmetry Cyburt+ 2012
  - mirror neutrons Coc+ 2013
  - magnetic fields+decays Yamazaki+ 2014
  - lepton asymmetry (degenerate neutrinos) Makki+ 2019
  - light particles with nucleon interactions Goudelis+ 2016
  - sterile neutrinos Salvati+ 2016
  - axion quark nuggets Flambaum+ 2019
  - Stable ^{8}Be Scherrer+ 2017
  - Non-extensive statistics Hou+ 2017
- Evolving Fundamental Constants
  - change couplings and bindings Martins+ 2021
- Nonstandard Cosmology
  - Lithium diffusion after recombination Pospelov 2012
  - "Hubble bubble" of inhomogeneous abundances Regis+ 2010
  - Cosmic lithium destruction via early stellar processing Piau+ 2006
  - Nonthermal "cosmic rays" during BBN Kang+ 2019

Many (most?) now excluded by precision D observations

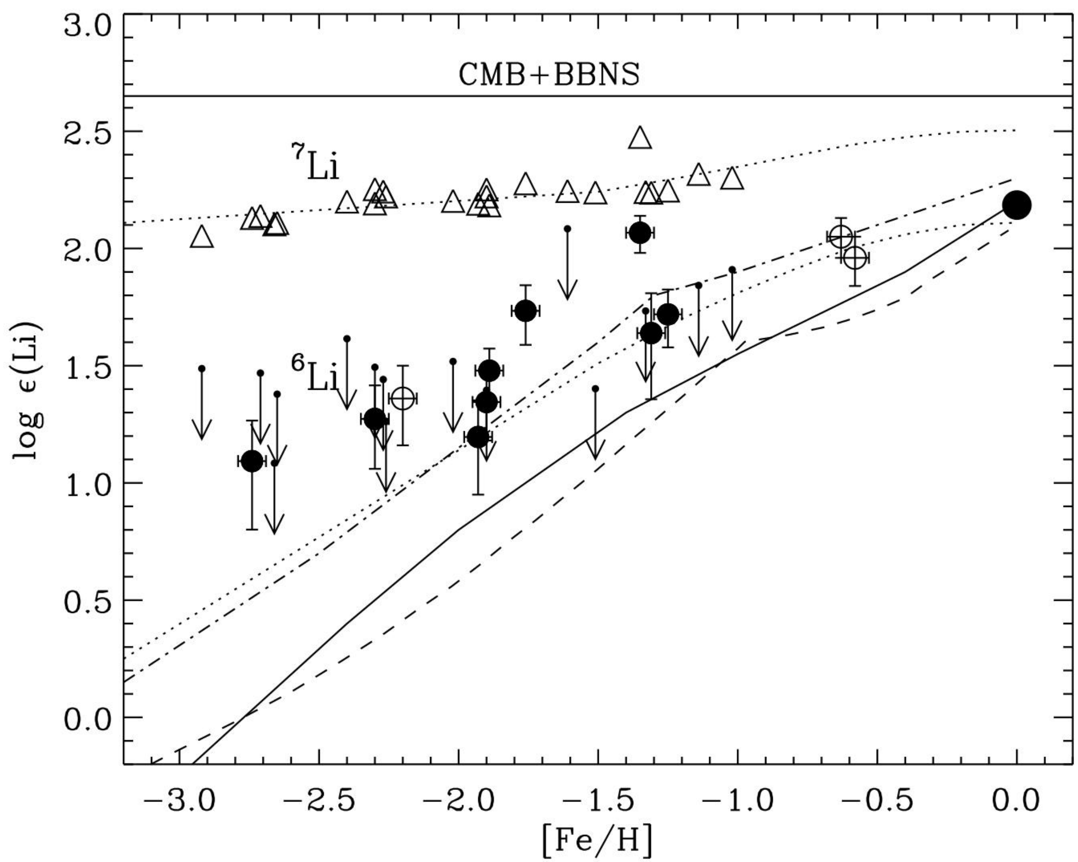
https://www.chetec-infra.eu/snaqs/

See SNAQs talk by Brian Fields (12(2021)

The claimed Li-6 plateau



Asplund *et al.* (2006)

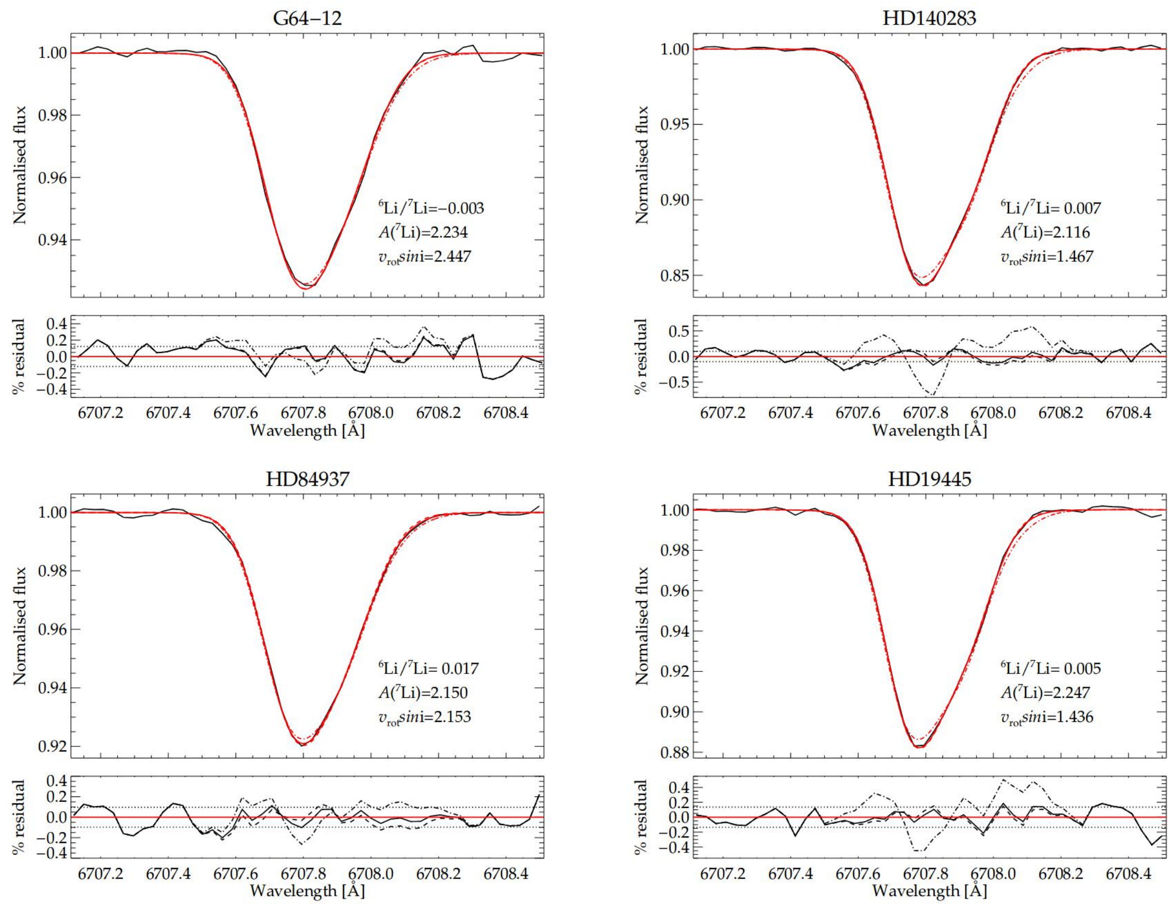


No significant Li-6

see also Wang *et al.* (2022)

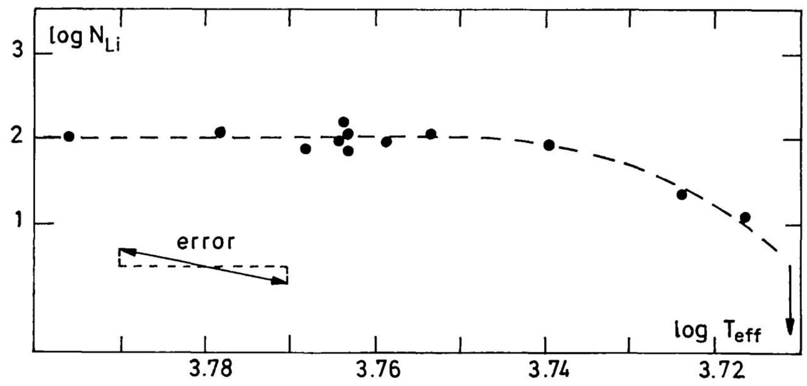
Using the latest 3D+NLTE modelling techniques, Lind *et al.* (2013) could show that **none of the previous detections** were in fact **real**.

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.



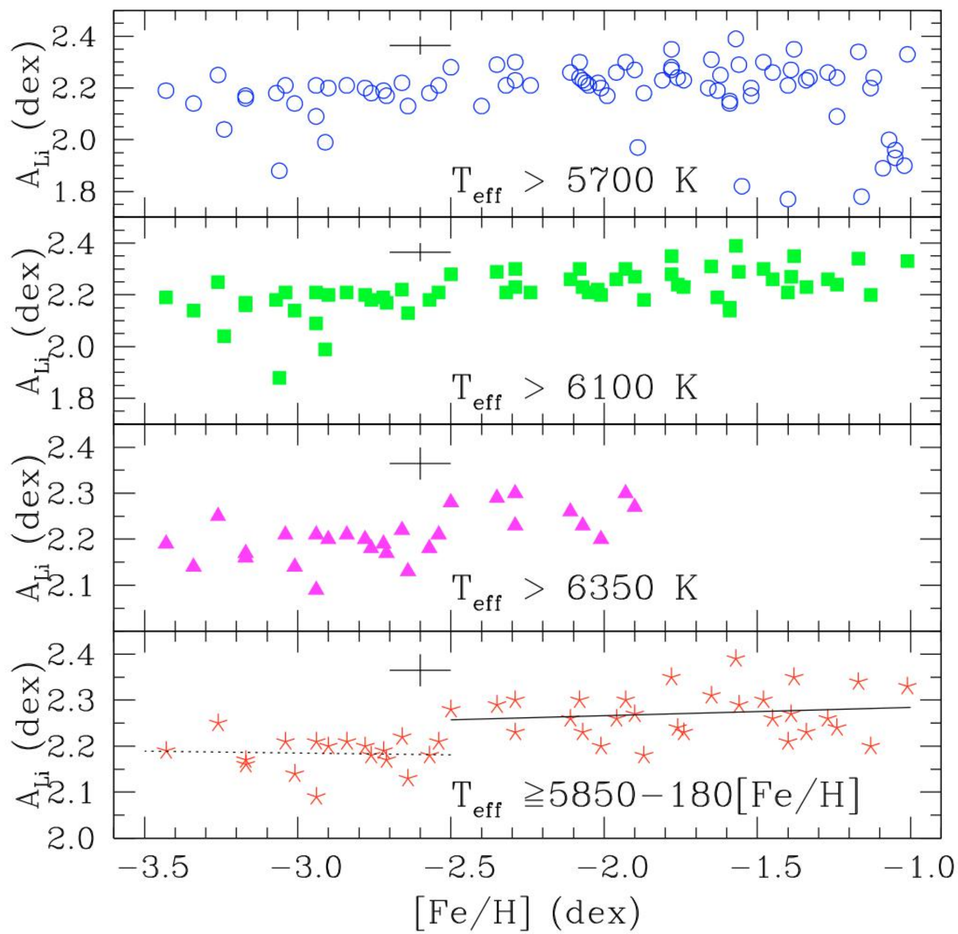
This is a good example of the importance of the need for a high degree of modelling realism!

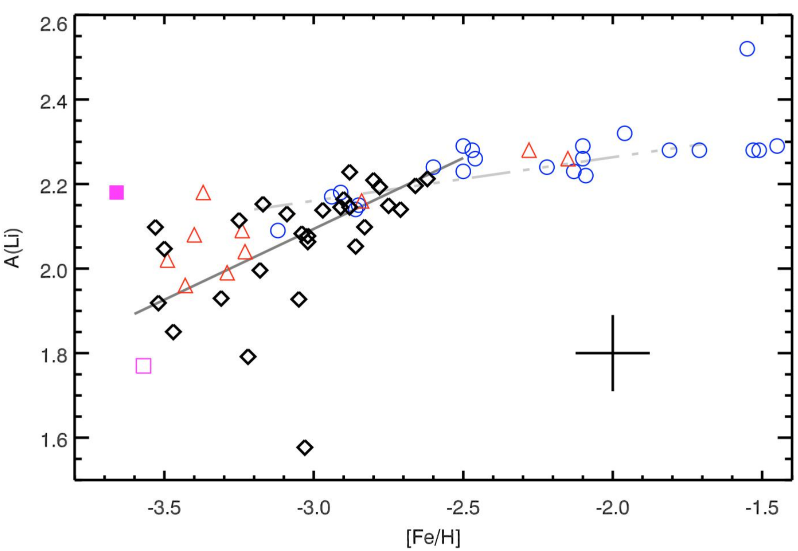
Li-7 in old stars: uniform and primordial?



Spite & Spite (1982)

Melendez *et al.* (2010)





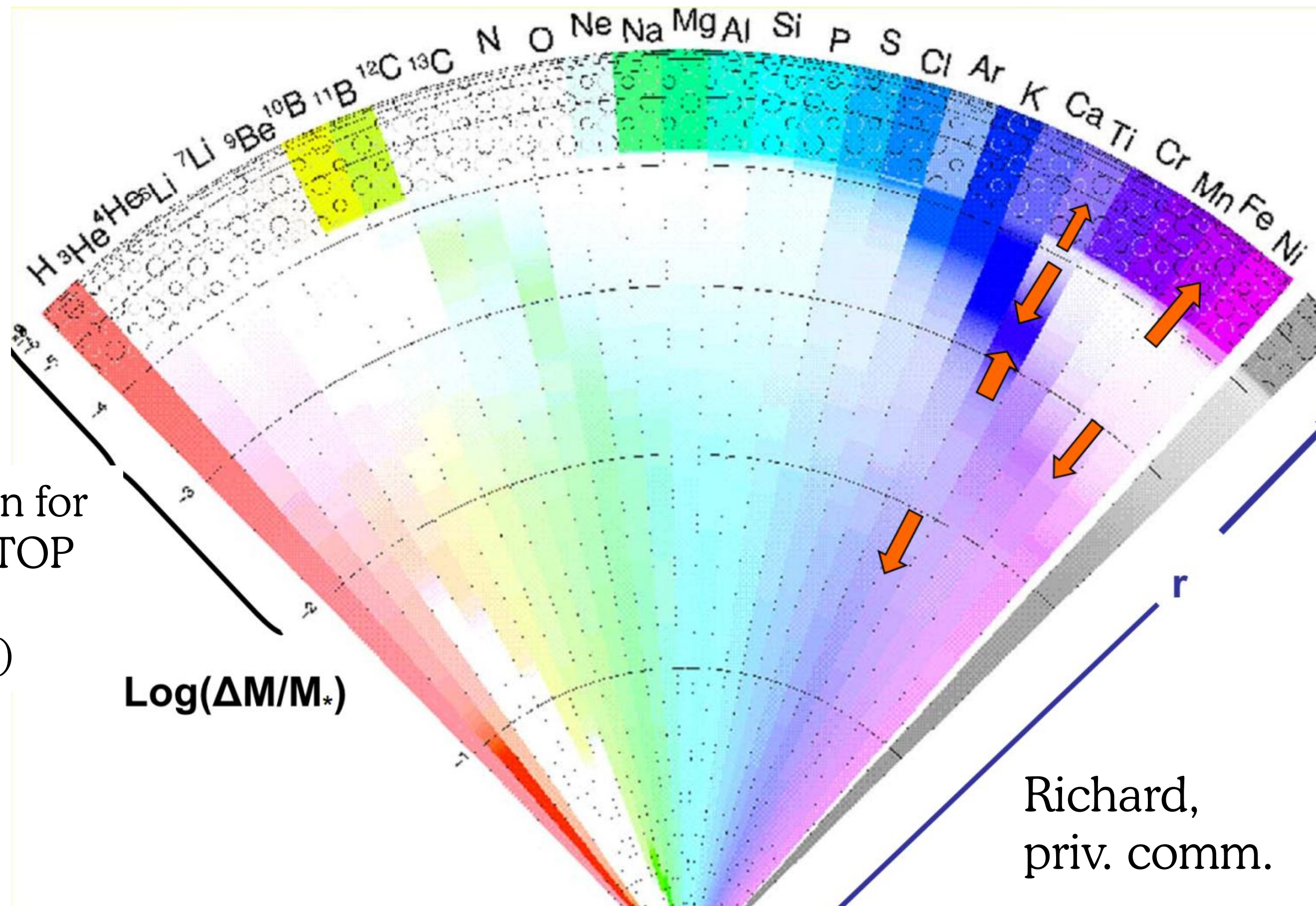
Sbordone *et al.* (2010): **meltdown!**

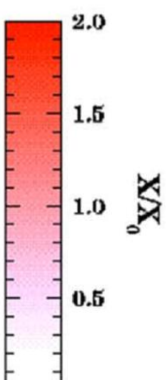
It's complicated! **By stellar physics!**

see also Gao *et al.* (2020)

Atomic diffusion

Elements can move (*diffuse*) throughout stars under the prevailing forces. Lithium e.g. will settle (and burn at T > 2.5 MK).

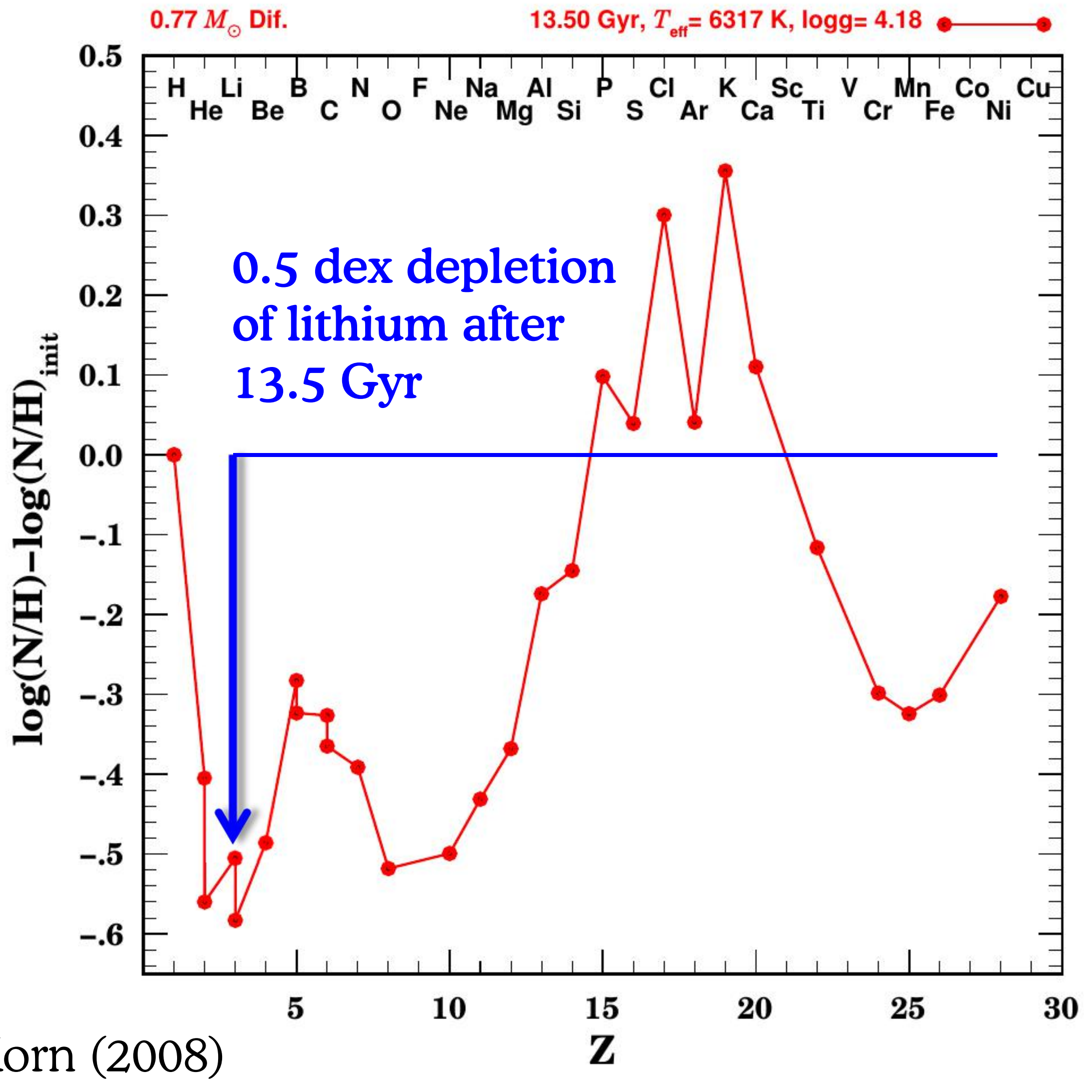




Elemental composition for a 12 Gyr old **0.8 M$_\odot$** TOP star with [Fe/H]$_i$=−2 (***uninhibited*** diffusion)

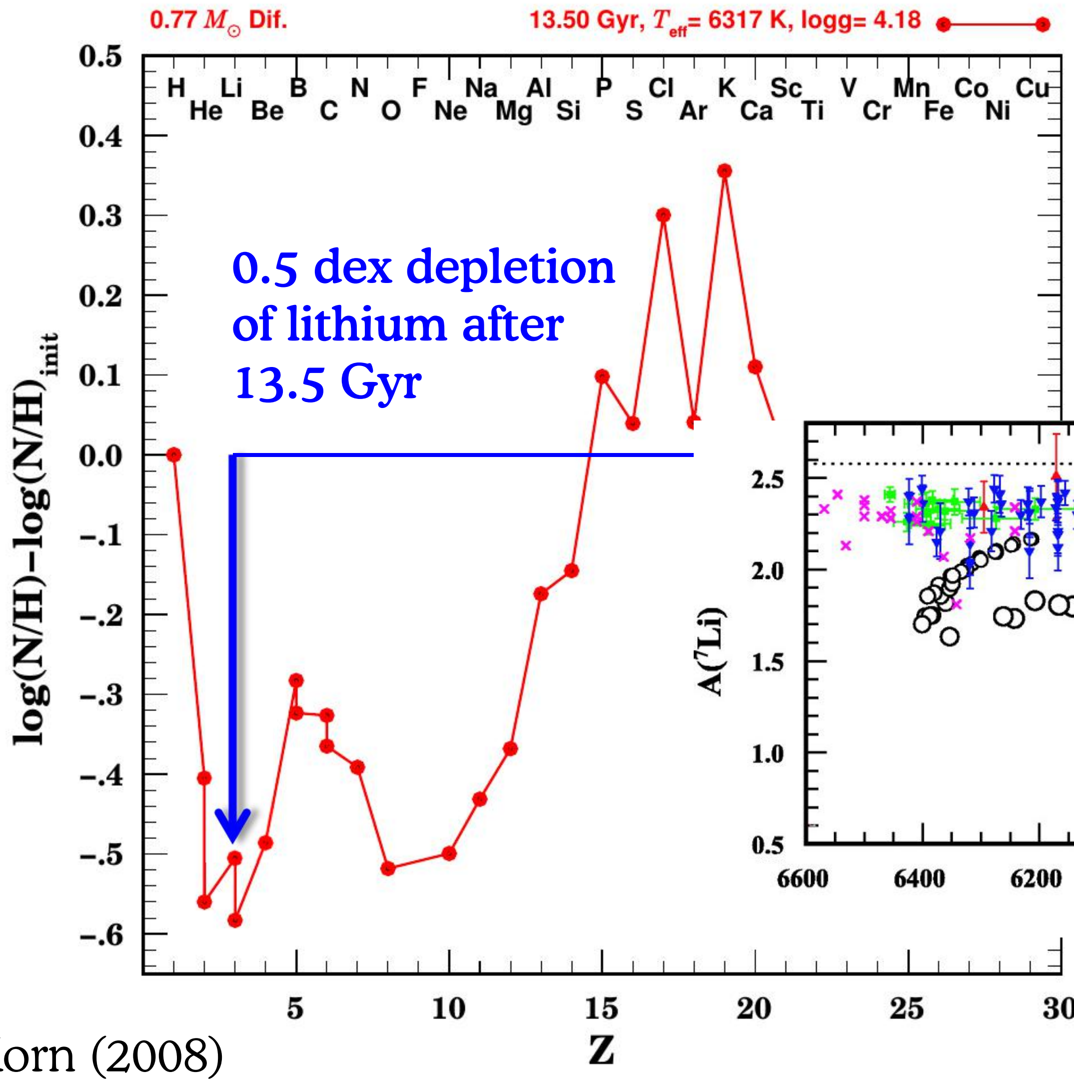
Richard, priv. comm.

Uninhibited diffusion in Pop II stars

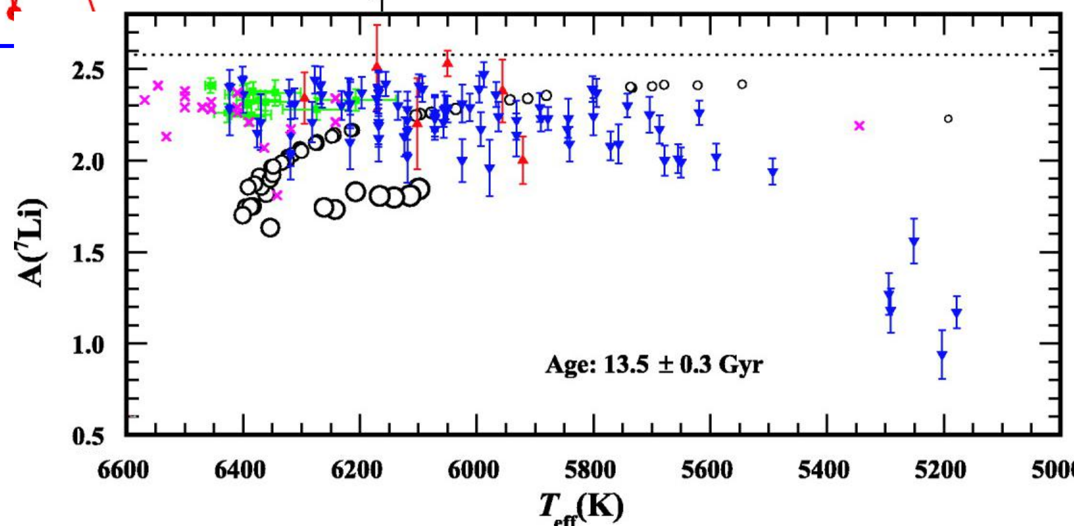


Korn (2008)

Uninhibited diffusion in Pop II stars

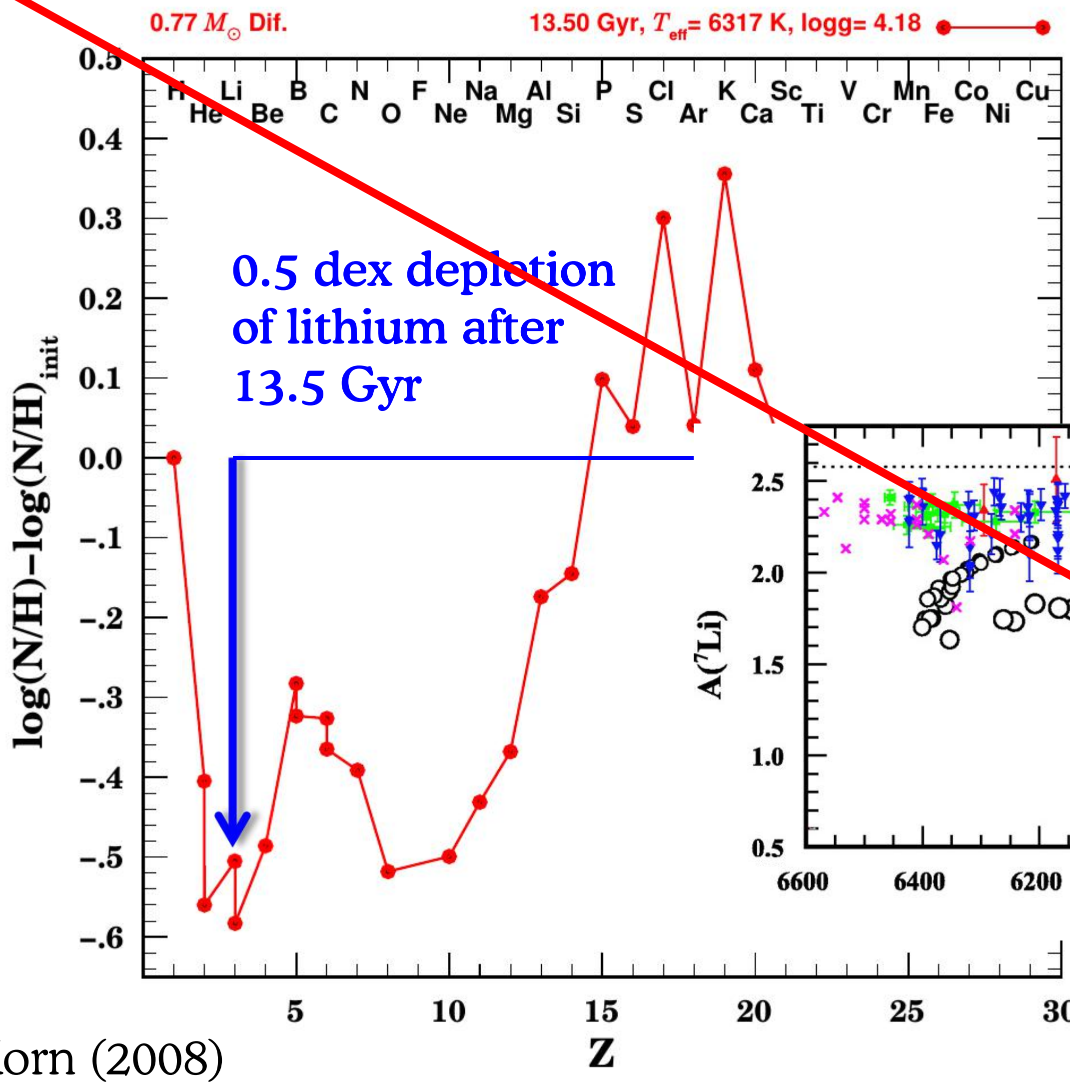


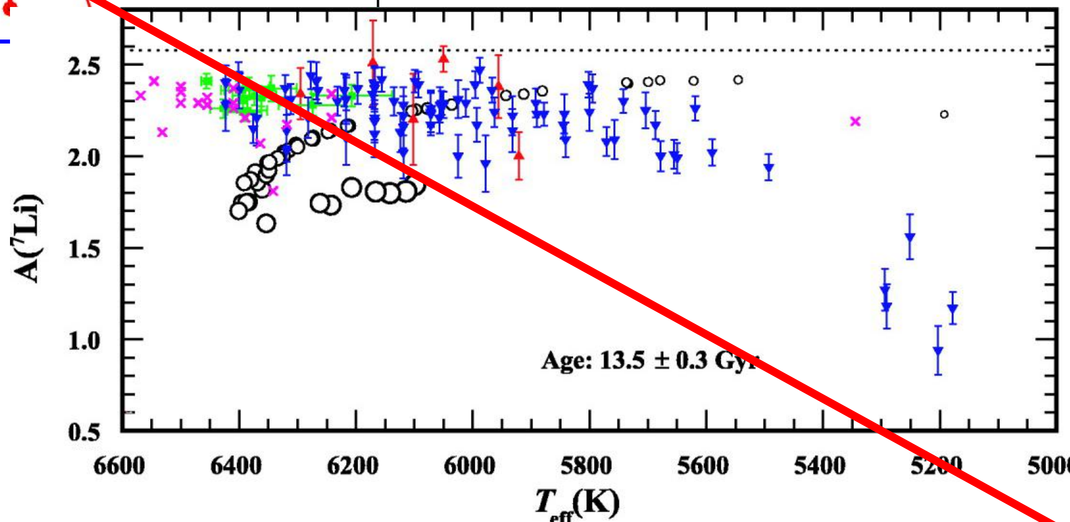
Korn (2008)



Richard *et al.* (2005)

Uninhibited diffusion in Pop II stars



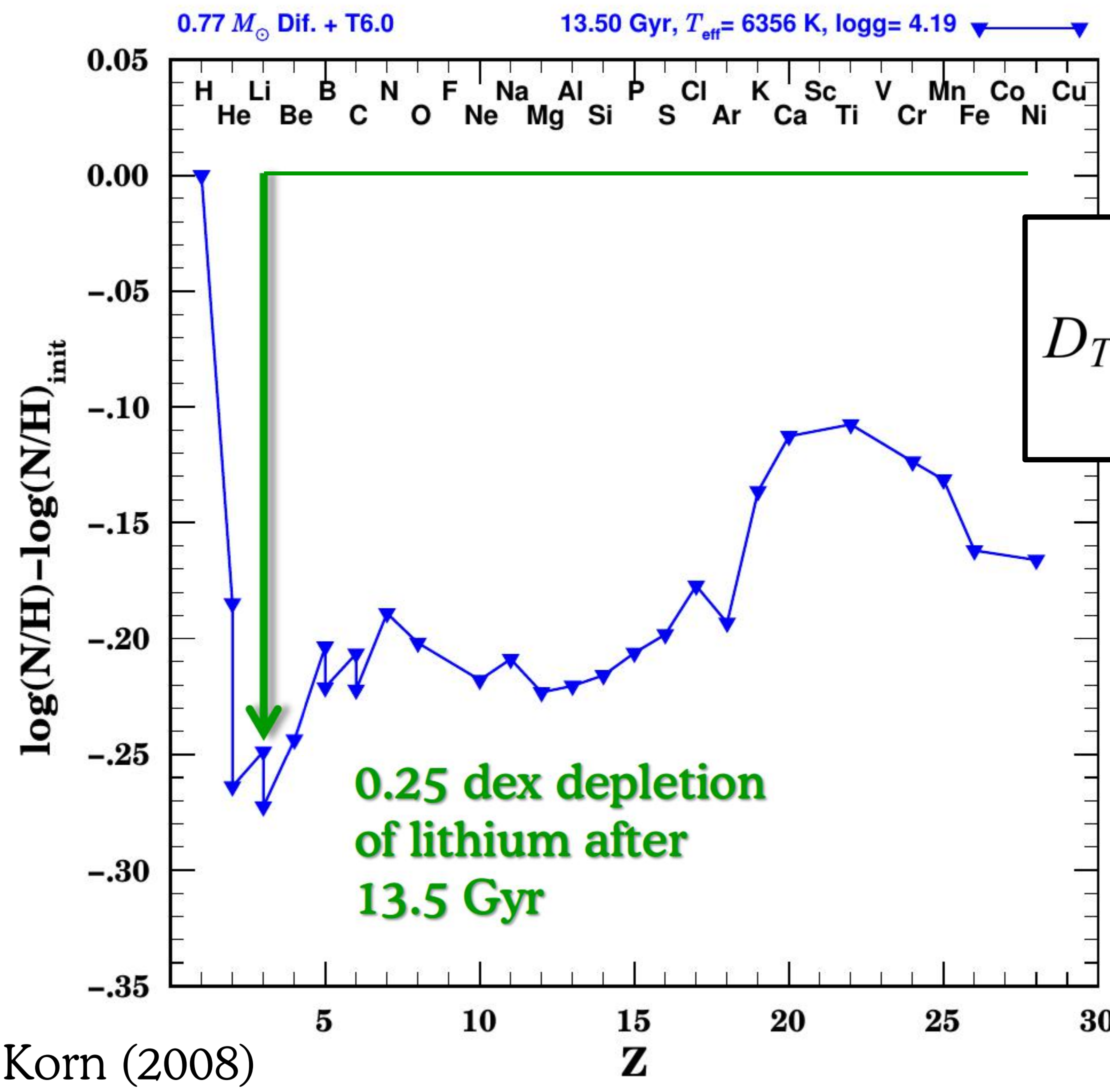


Not realized in Pop II stars!

Richard *et al.* (2005)

Korn (2008)

Diffusion moderated by *some* mixing



Korn (2008)

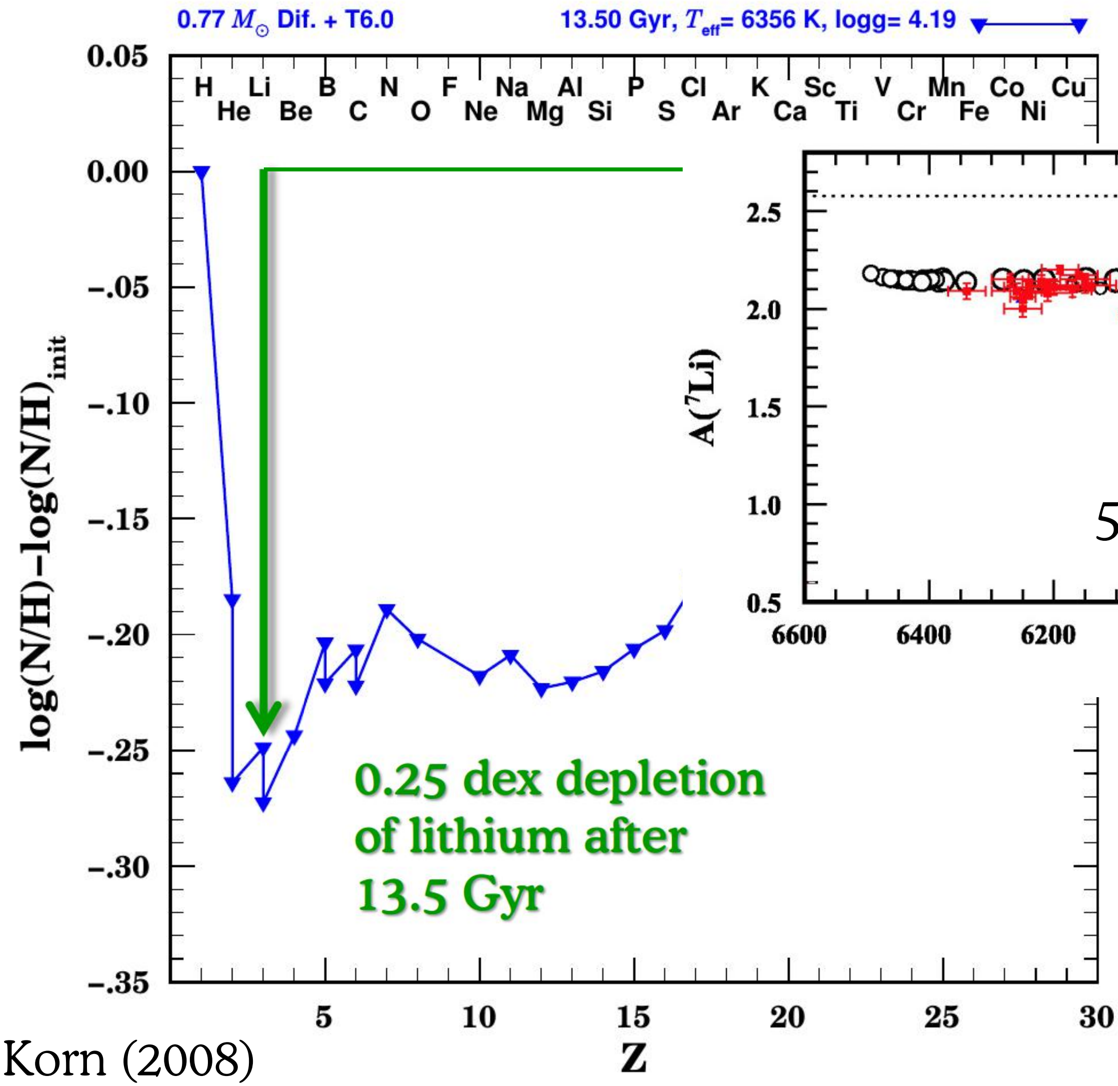
$$D_T = 400\, D_{\rm He}(T_0) \left[\frac{\rho}{\rho(T_0)} \right]^{-3}$$

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)

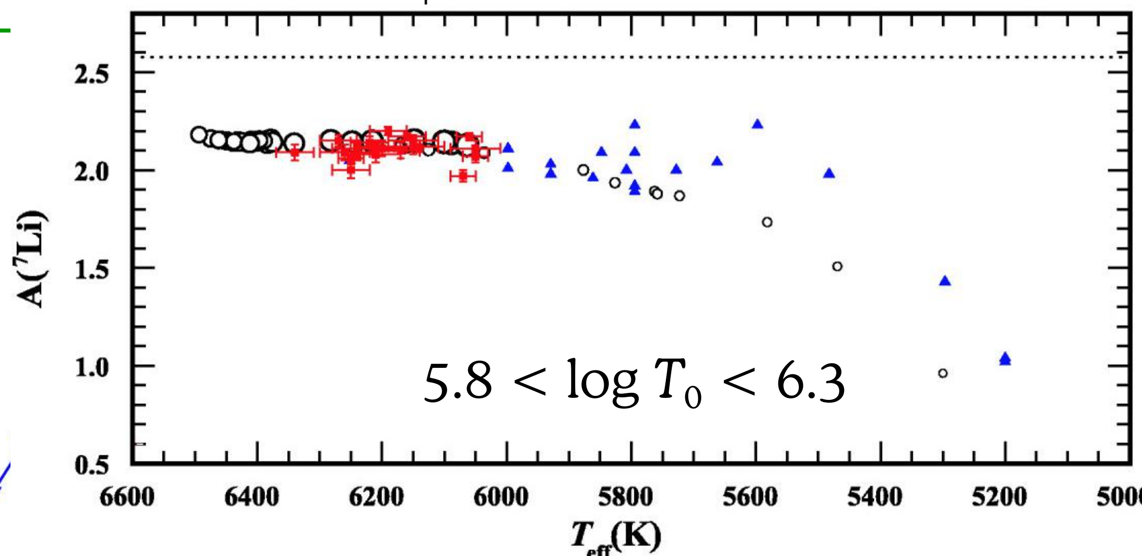
Diffusion moderated by *some* mixing



0.25 dex depletion of lithium after 13.5 Gyr

Korn (2008)

Richard *et al.* (2005)



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

Lithium in globular clusters

A set of lithium abundances with **some crucial advantages**:

- dwarfs *and* giants born together with the same age and composition (not fully realized in nature)
- we know the evolutionary phase of the stars and thus their stellar parameters of the stars very well. Ages constrained by several means.

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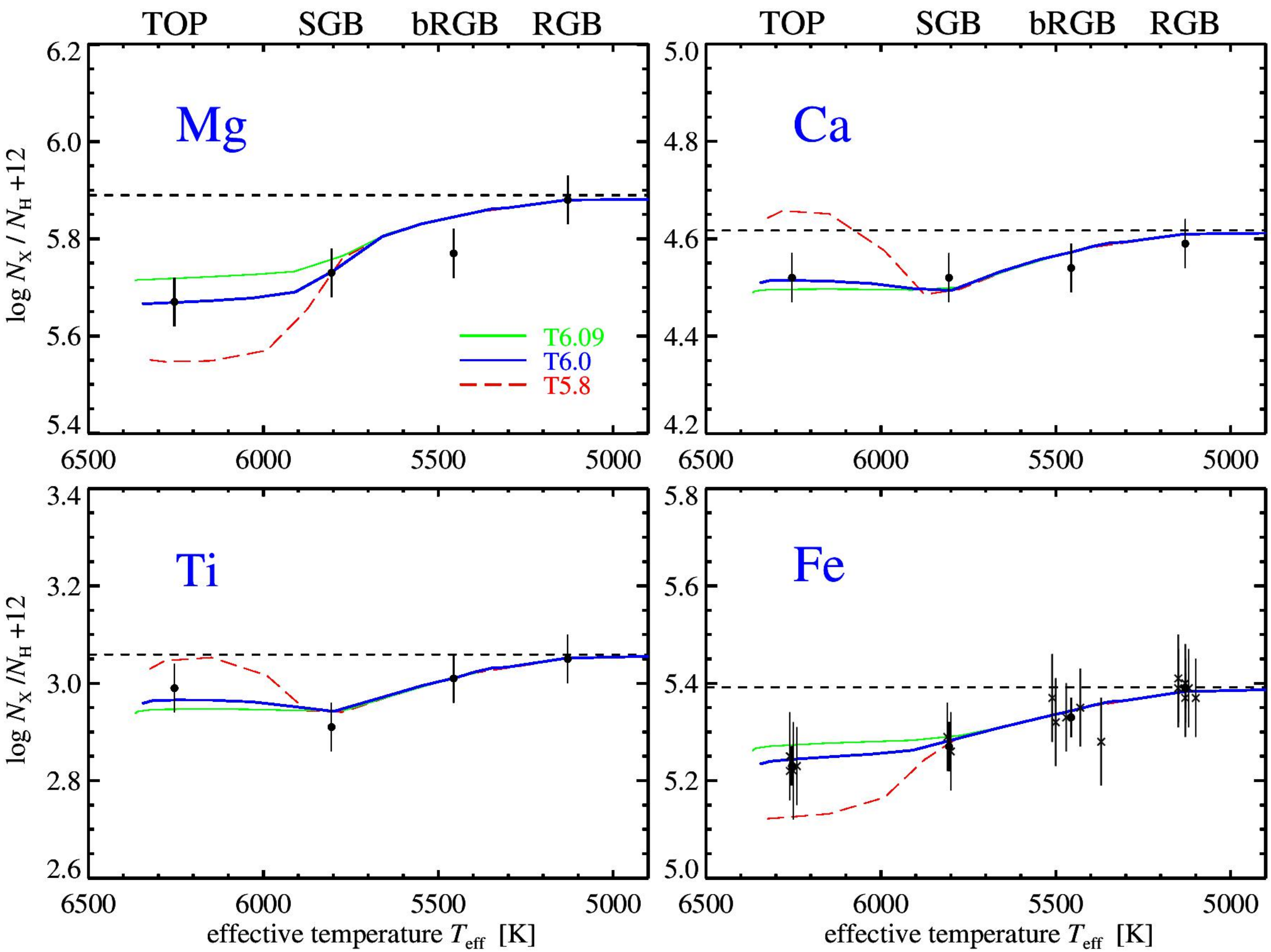
- we know the evolutionary phase of the stars and thus their stellar parameters of the stars very well. Ages constrained by several means.

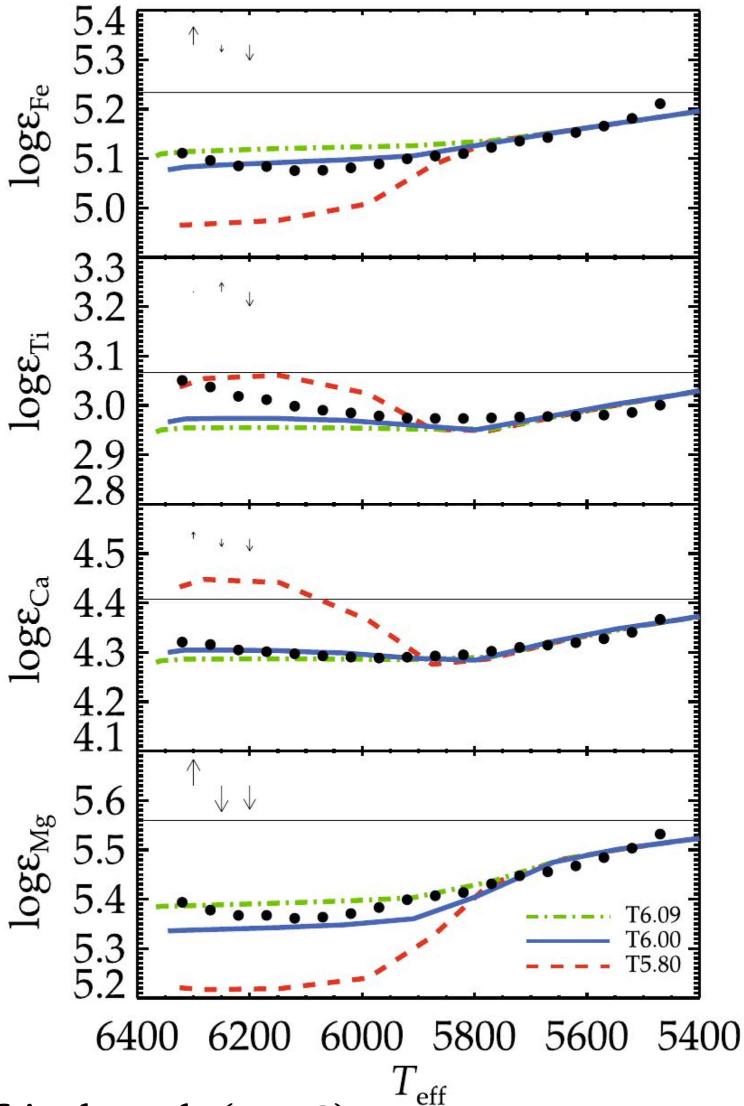
Main disadvantage: the unevolved stars in even the nearest globular clusters are faint ($V > 16.5$) requiring hours of integration at 8m telescopes.

Atomic diffusion in NGC6397 (10s of stars)

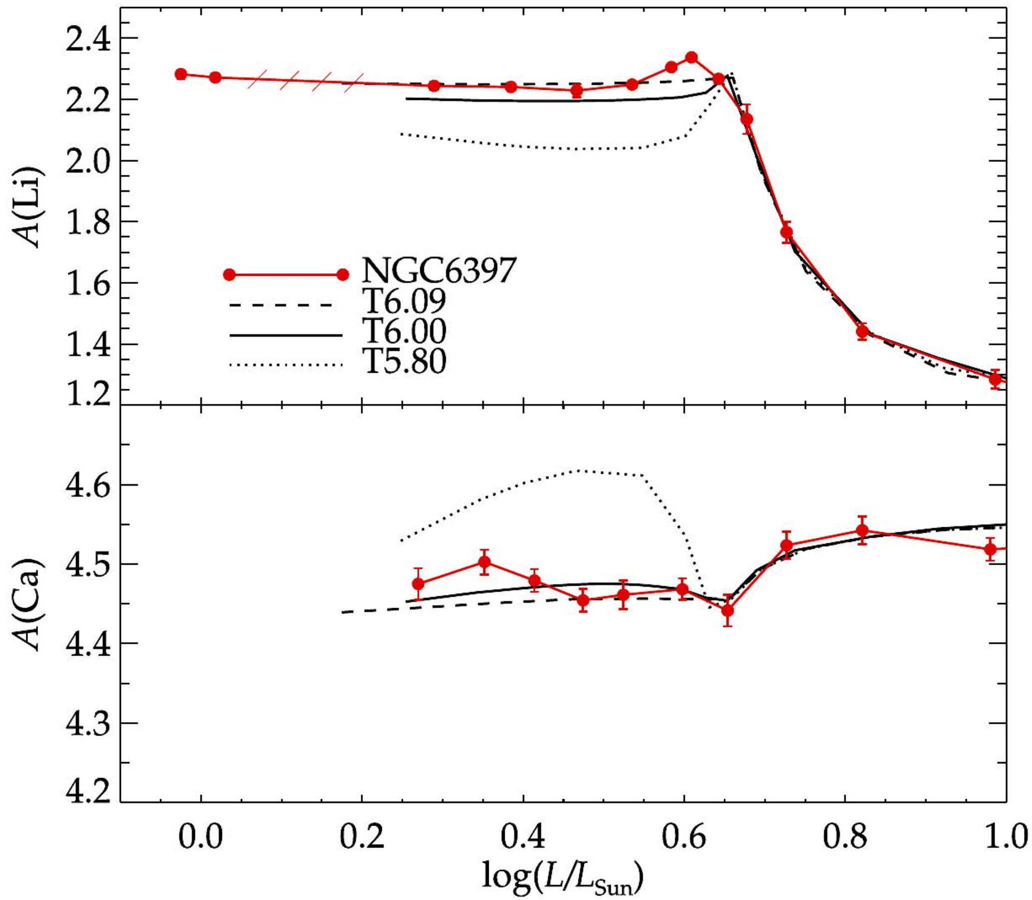


Korn *et al.* (2006, 2007)

Subsequent analyses (100s of stars)

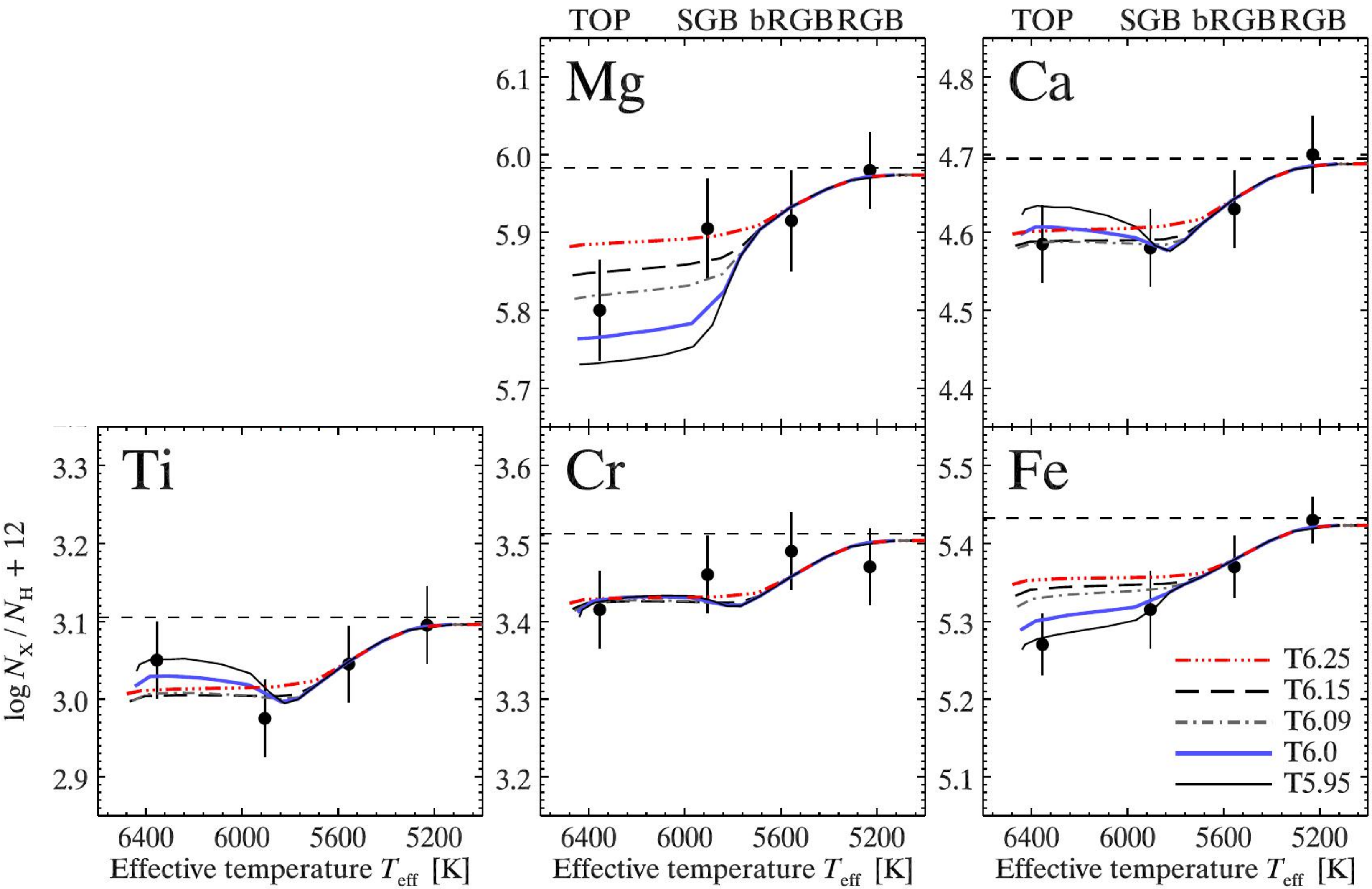


Lind *et al.* (2008)

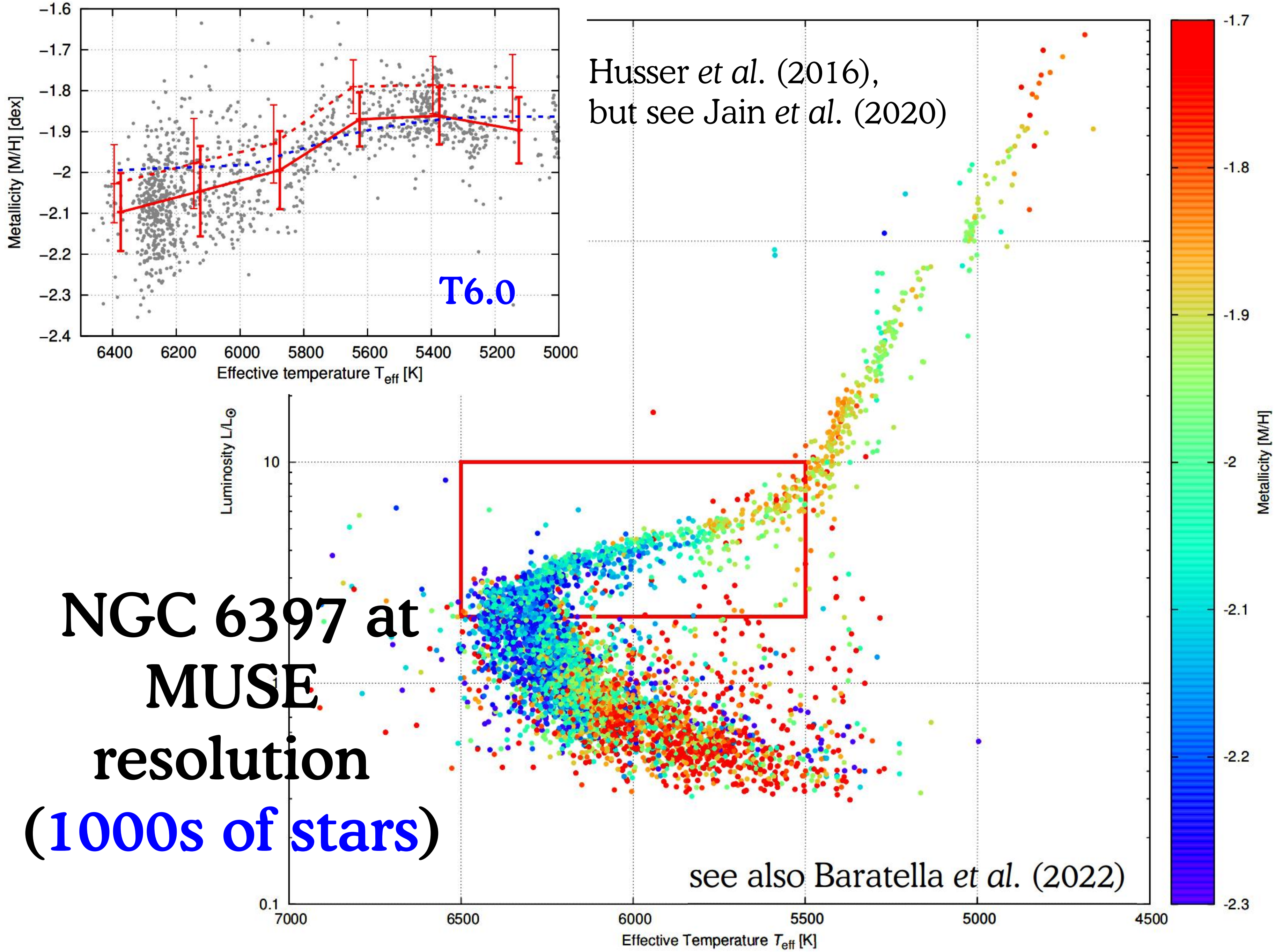


Lind *et al.* (2009),
but see González Hernández *et al.* (2009)

Subsequent analyses (updated T_{eff} scale)



Nordlander *et al.* (2012)



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

NGC 6397 at MUSE resolution (1000s of stars)

see also Baratella *et al.* (2022)

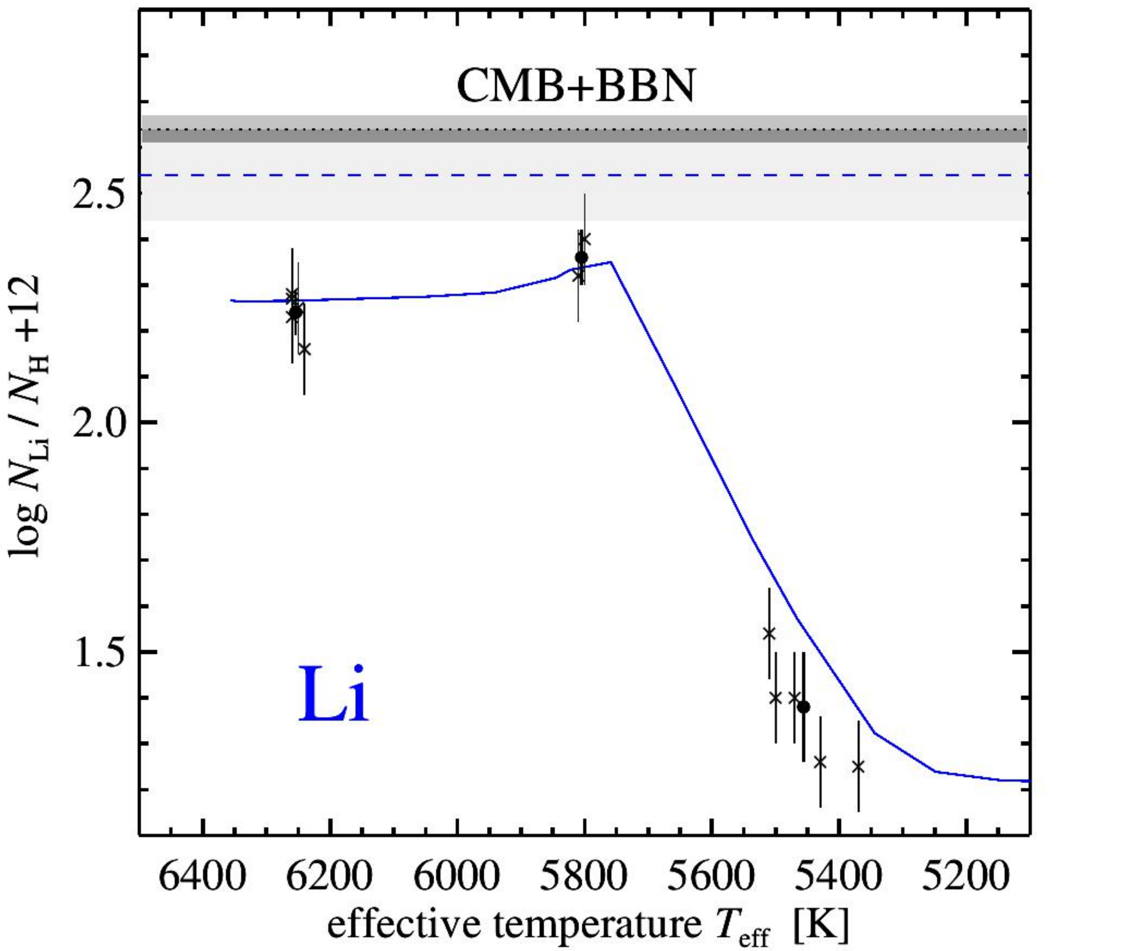
Inference for lithium in NGC 6397

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

vs

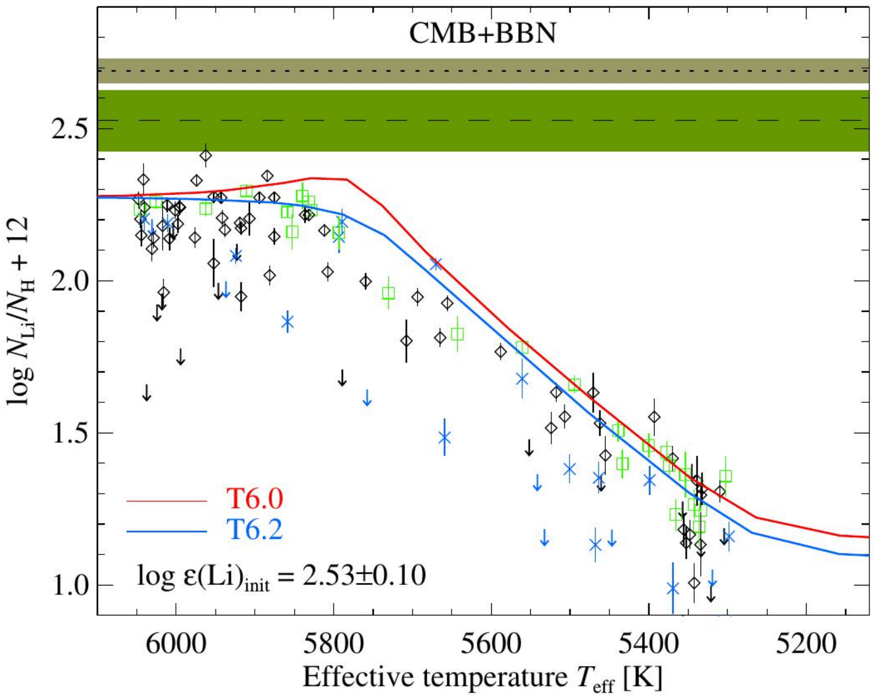
$\log \varepsilon(\text{Li})_{\text{BBN}}$ = 2.64 ± 0.03
(WMAP 3-yr results coupled to Standard BBN)

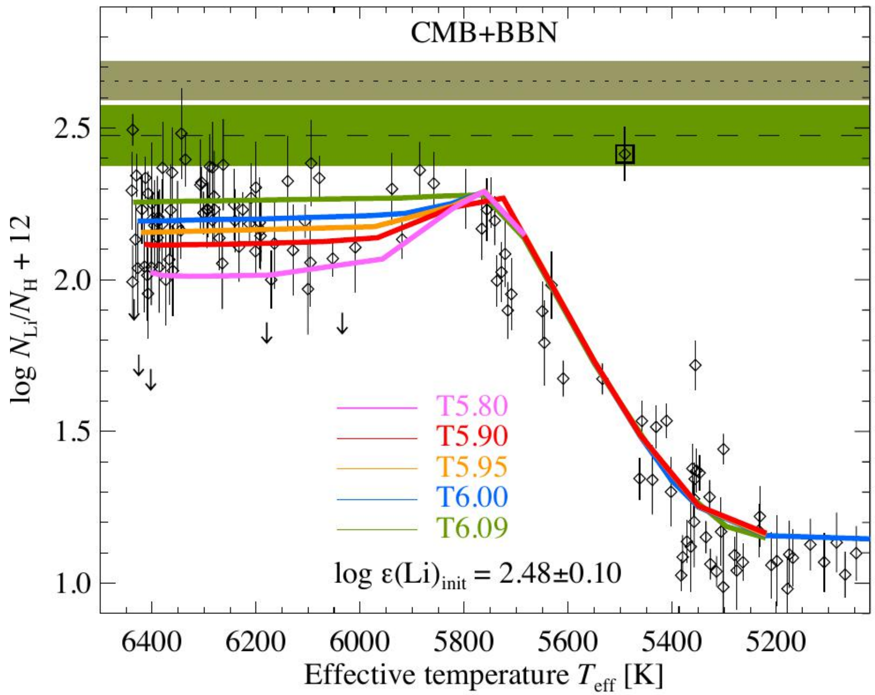
Agreement within 1σ.



Korn *et al.* (2006)

Lithium in other globular clusters





NGC 6752 @ [Fe/H]=−1.5:

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

Messier 30 @ [Fe/H]=−2.3:

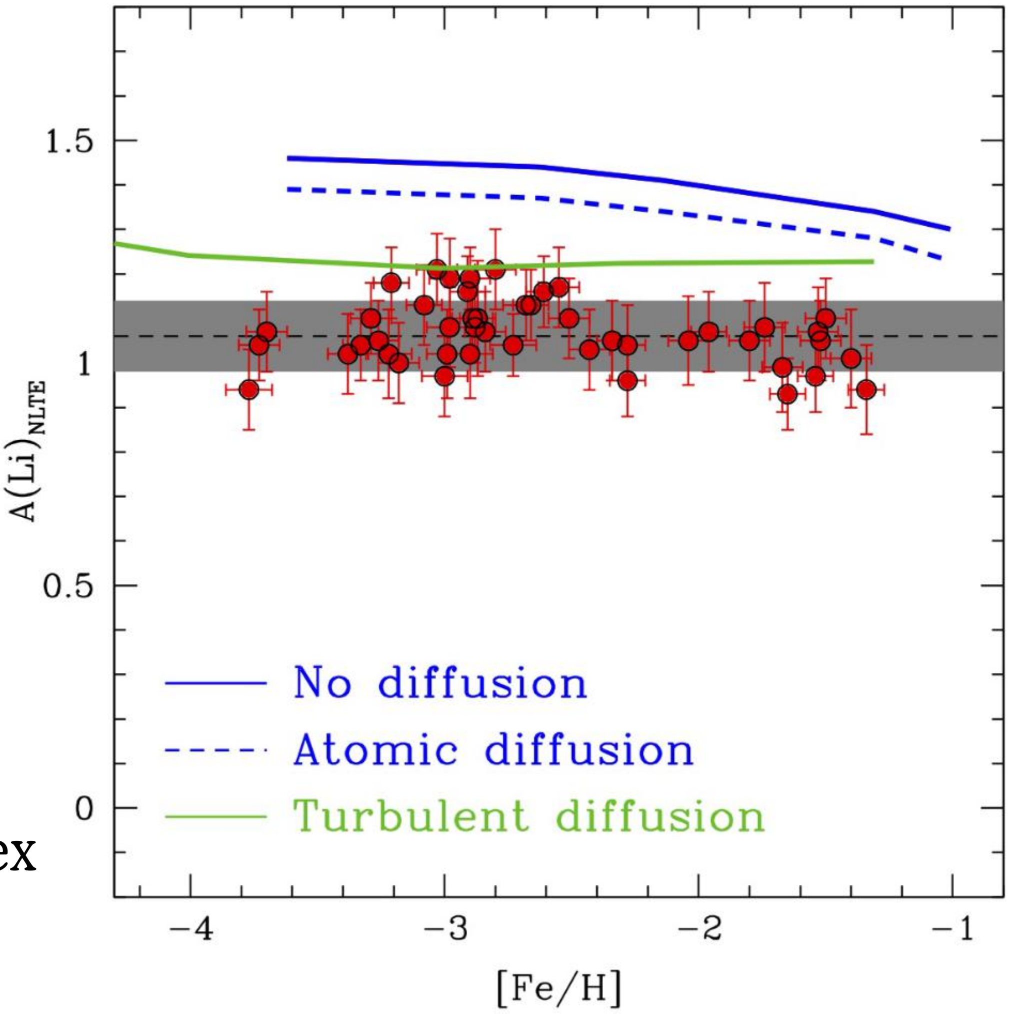
log $\varepsilon(\mathrm{Li})_{\mathrm{AD\text{-}corr}}$ = **2.48 ± 0.1**
vs log $\varepsilon(\mathrm{Li})_{\mathrm{BBN}}$ = 2.66 ± 0.06
BBN agreement *possible*.
(Gruyters *et al*. 2016)

The latest: another plateau

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 bottom line on lithium

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

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

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

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

Nuclear/particle physicists should thus not try to solve a factor of 2-3 problem, but rather a 20-50% problem in lithium abundance.