Observational Evidence for depletion in the Spite plateau:

solving the cosmological Li discrepancy?

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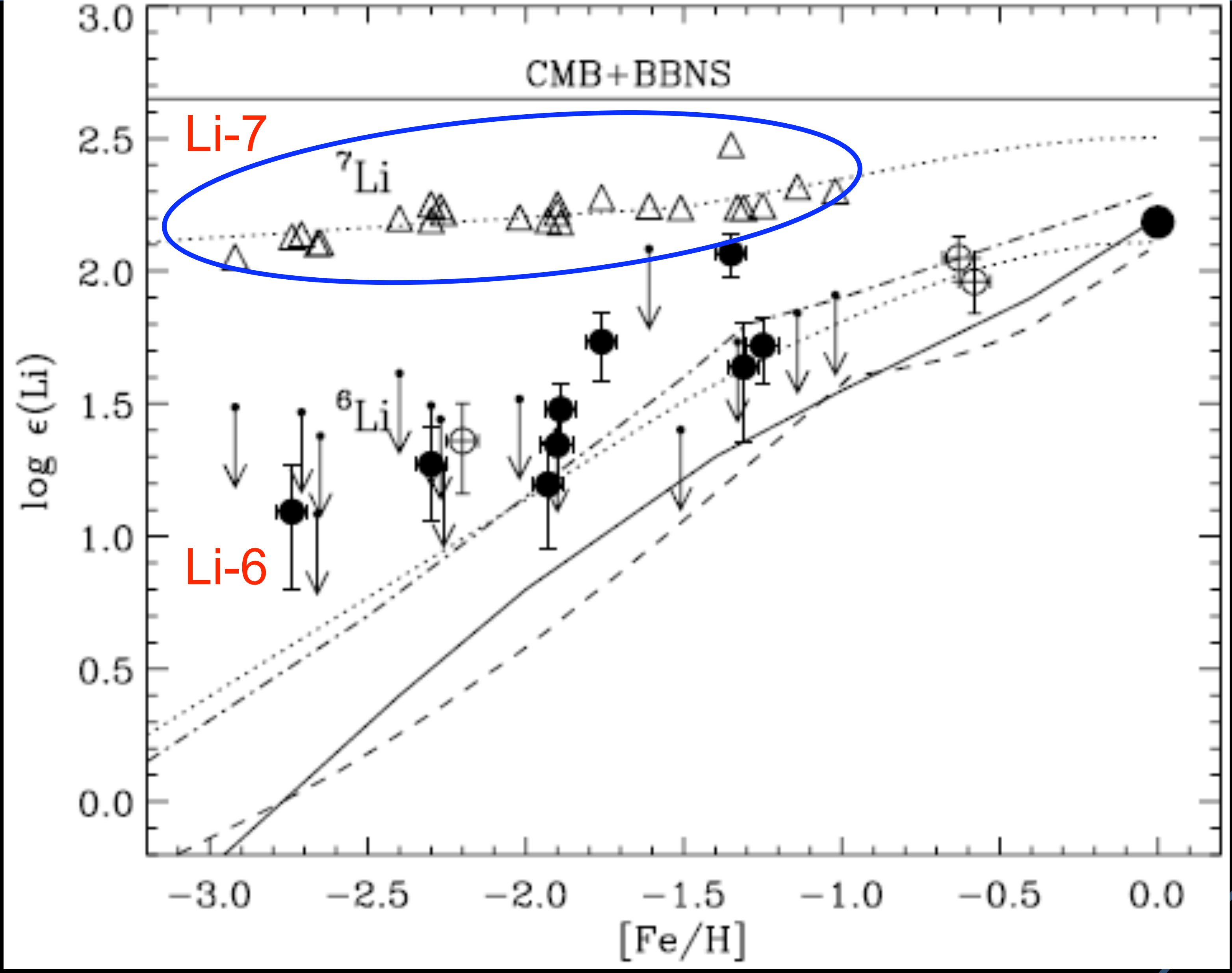
Hawaii, after observing run ...

VLT Li-6 survey (Asplund et al. 2006): too much Li-6, too little Li-7

We will discuss here how to improve the Li-7 abundances to get new insights into the cosmological Li problem.



Asplund et al. (2006)

How to get new insights into the Li-7 problem?: *improving the Li abundances*

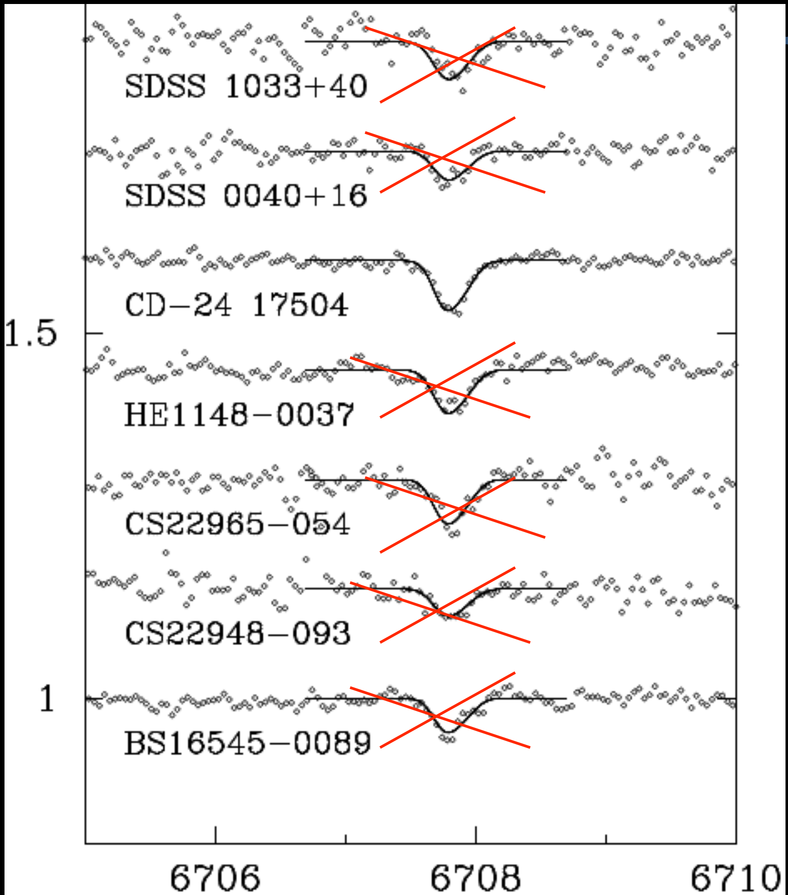
I. Less is more: use the best available data (higher resolution, higher S/N, or average literature EW data)

II. Better handle of reddening: E(B-V) affects the photometric T_{eff}, so precise E(B-V) is needed

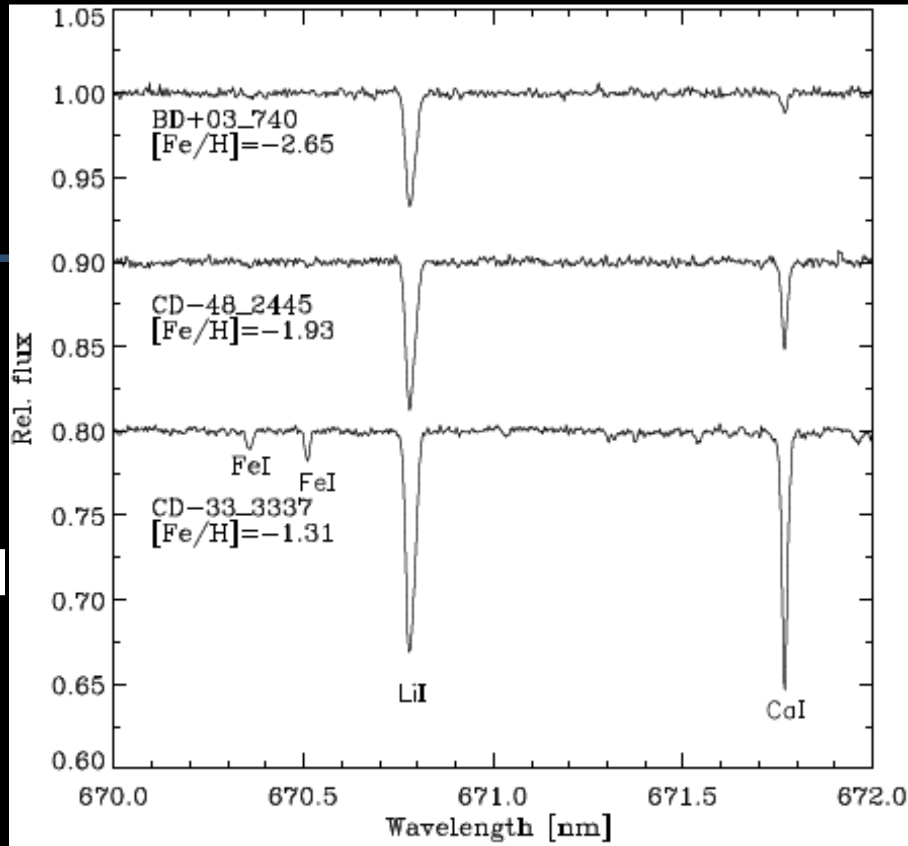
III. Improve the T_{eff} scale: higher T_{eff} ⟹ higher Li

IV. Explore other variables: e.g. lithium vs. mass

I. Best available data



Aoki et al. 2009; Subaru+HDS



Asplund et al 2006; VLT+UVES

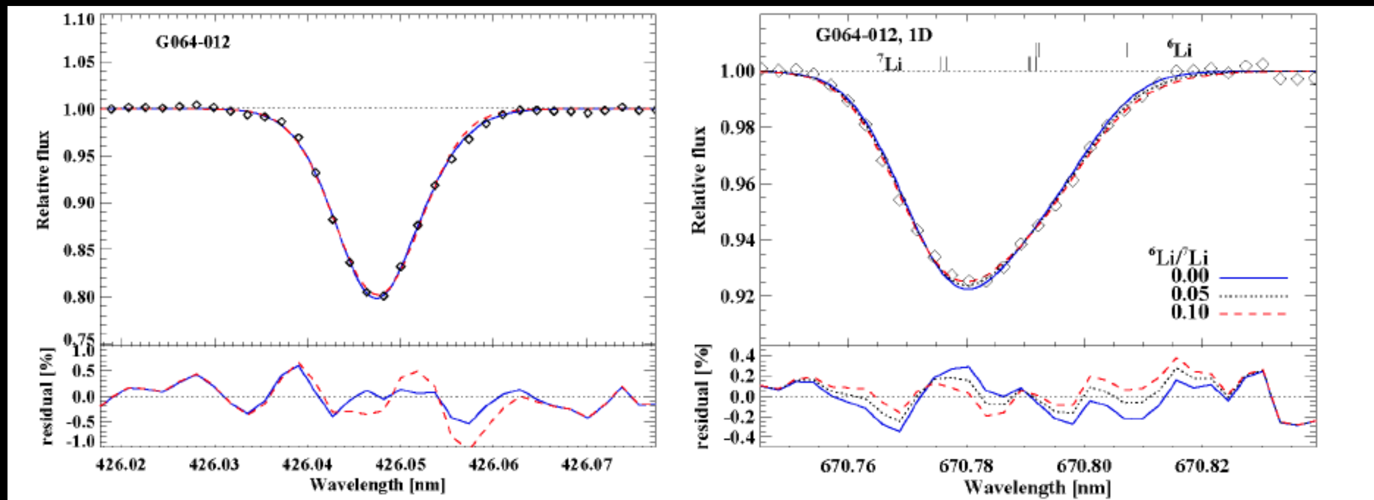


FIGURE 1. *Left panel:* The observed Fe I 426 nm line in G064-012 (rhombs) together with the best-fitting 1D (dashed, red) and 3D (solid, blue) profiles. Notice the much reduced residuals in the 3D case due to the predicted line asymmetry. *Right panel:* The observed and predicted (1D) profiles of the Li I 670.8 nm line for three different $^6Li/^7Li$ ratios. The best-fitting value is $^6Li/^7Li \approx 5\%$.

Asplund & Meléndez 2008; Keck + HIRES

I. Best available data: σ(EW) ~ 3%

- VLT+UVES equivalent widths (Asplund et al. 2006; Bonifacio et al. 2007) and archive spectra.
- Keck + HIRES (Asplund & Meléndez 2008; Meléndez & Barbuy 2009; unpublished & archive spectra)
- Other good EW available in the literature (Meléndez & Ramírez 2004 updated; Boesgaard et al. 2005, etc.)
- The sample has 73 stars with $5250 < T_{eff} < 6600$ K, $3.6 < \log g < 4.8$, $-3.5 < [Fe/H] < -1$, $0.6M_{\odot} < M < 0.9M_{\odot}$

II. Improve the precision of E(B-V)

- A wrong E(B-V) value will introduce errors in T_{eff} and therefore scatter in A(Li)

- E(B-V) can be determined from maps, photometry, interstellar NaD lines, etc.

- Unfortunately maps and photometric methods have relatively large errors (~0.01mag = 47K)

- We use NaD (& maps)

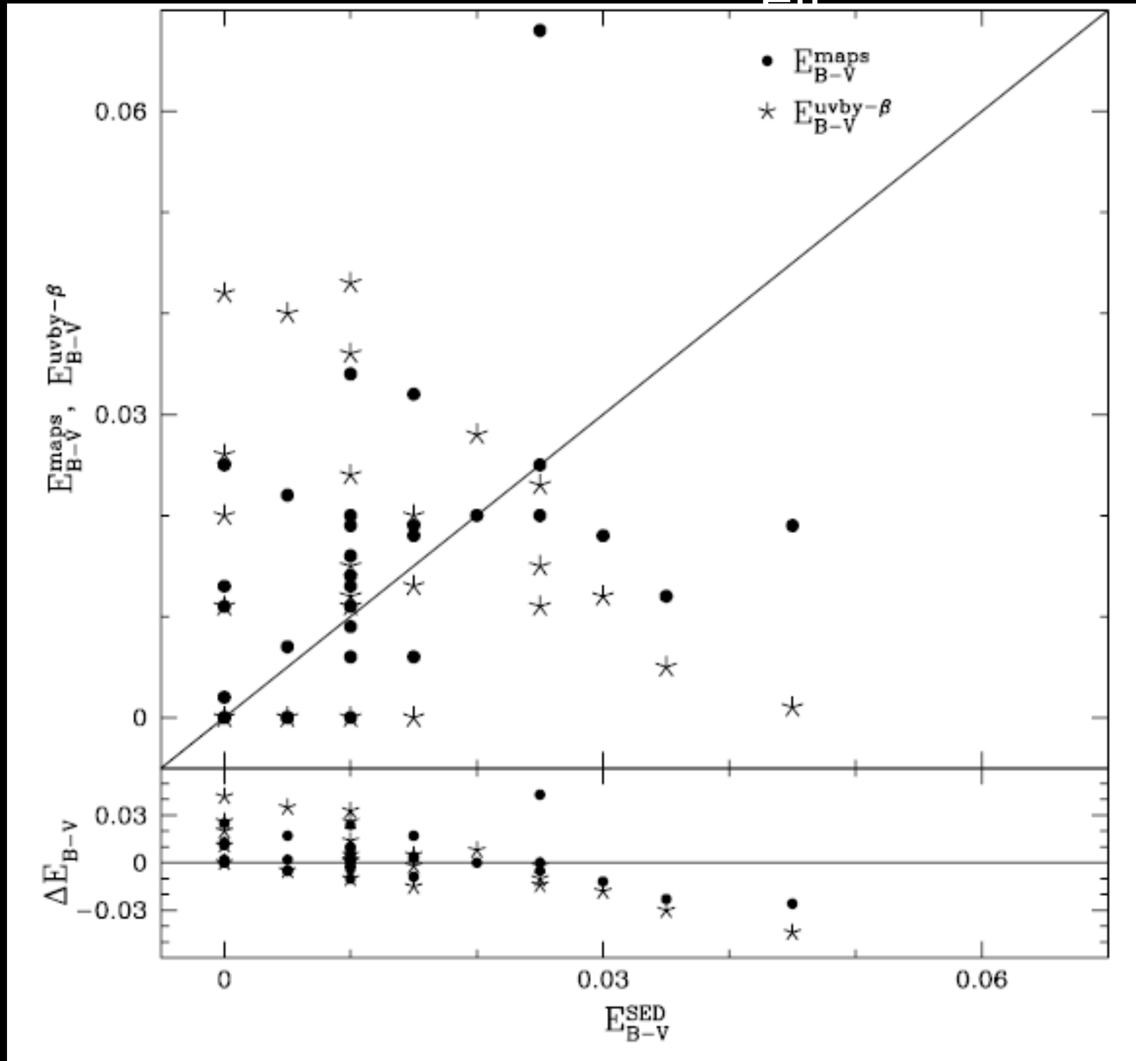
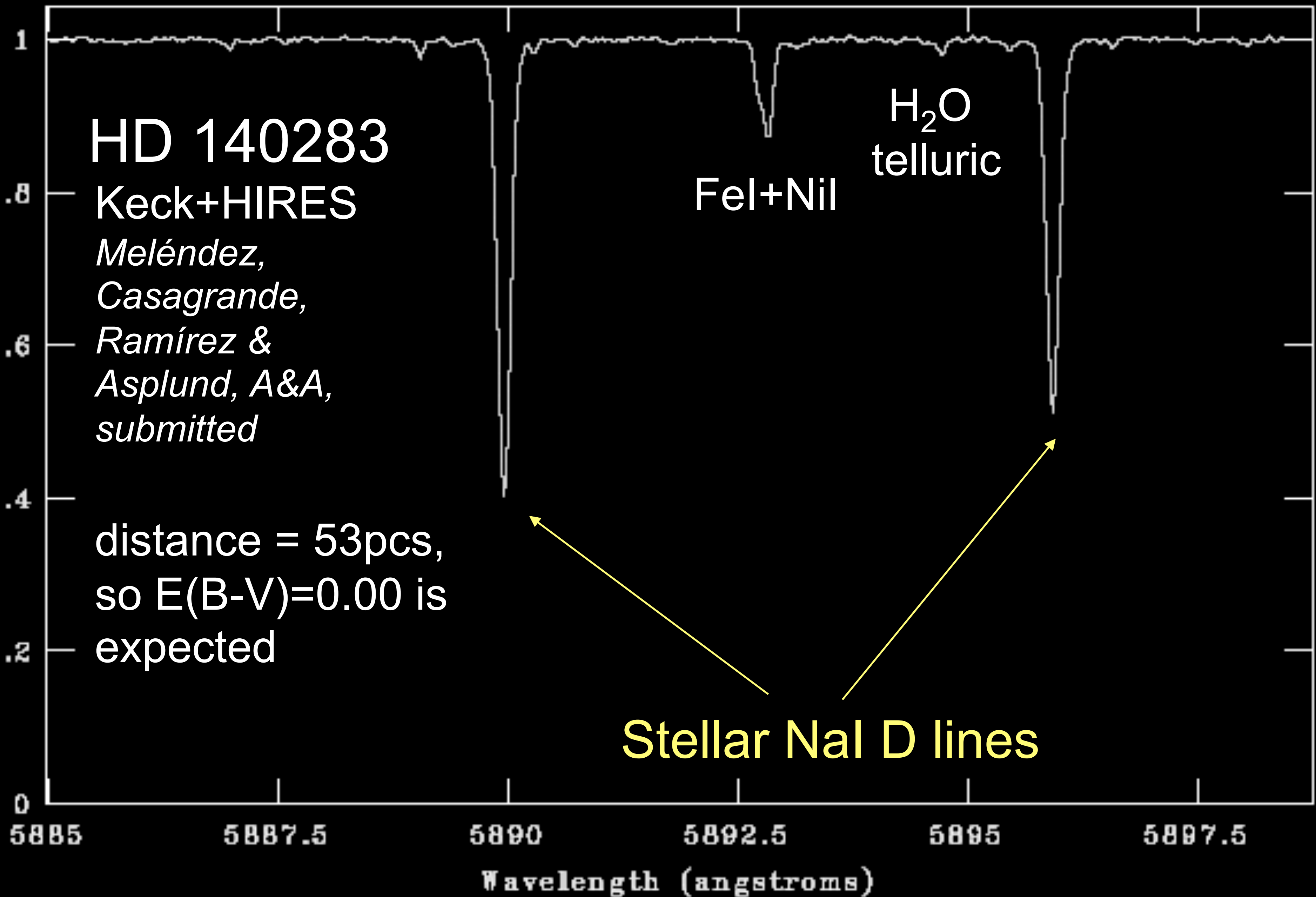


Fig. 2.—Comparison between extinction obtained from maps (E^{maps}_{B-V}), Strömgren photometry ($E^{uvby-\beta}_{B-V}$), and stellar energy distributions (E^{SED}_{B-V}).

Meléndez et al. 2006, ApJ, 642, 1082

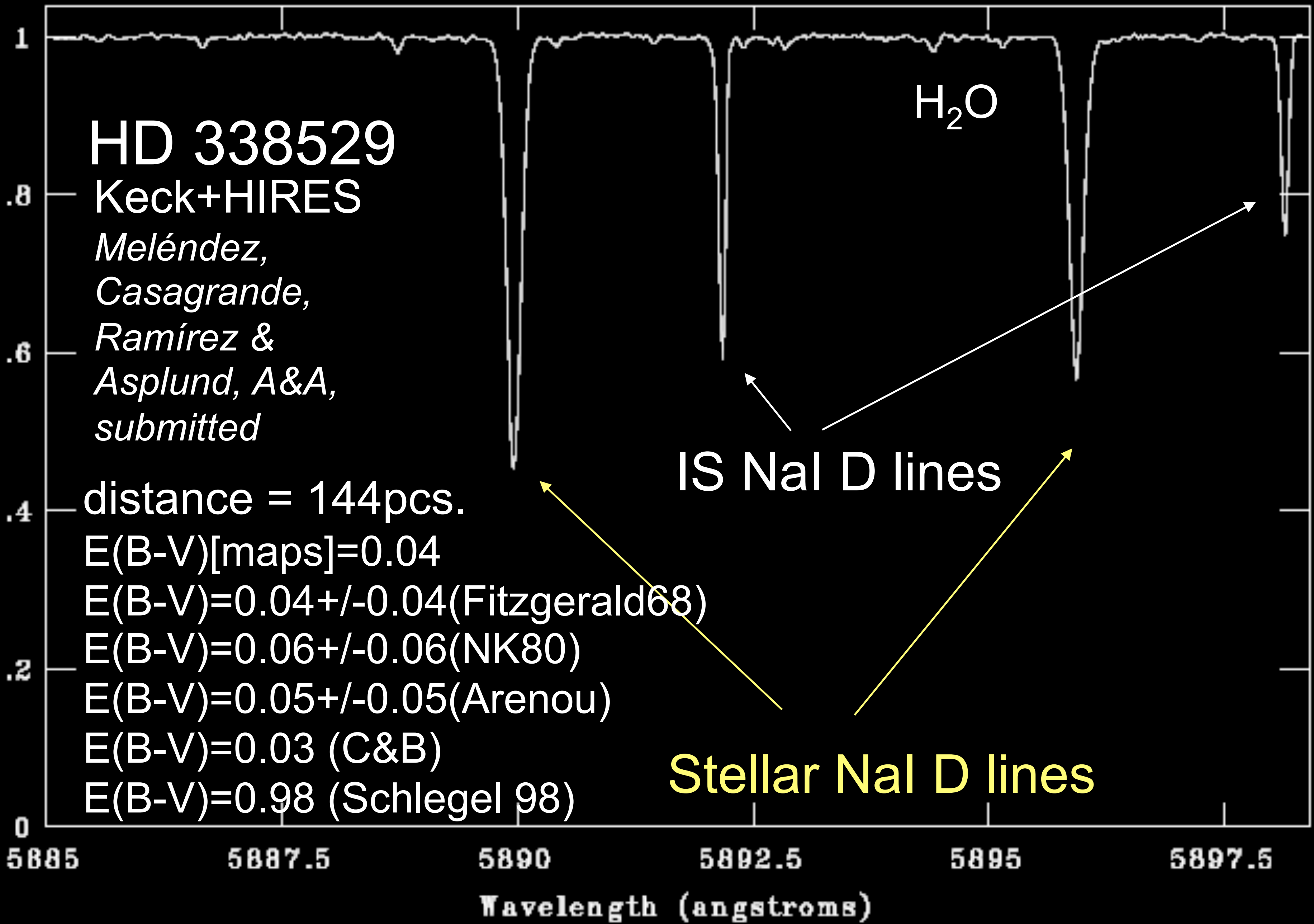
II. Improve E(B-V): using NaD lines

E(B-V) = 0.000 +/- 0.001 mag



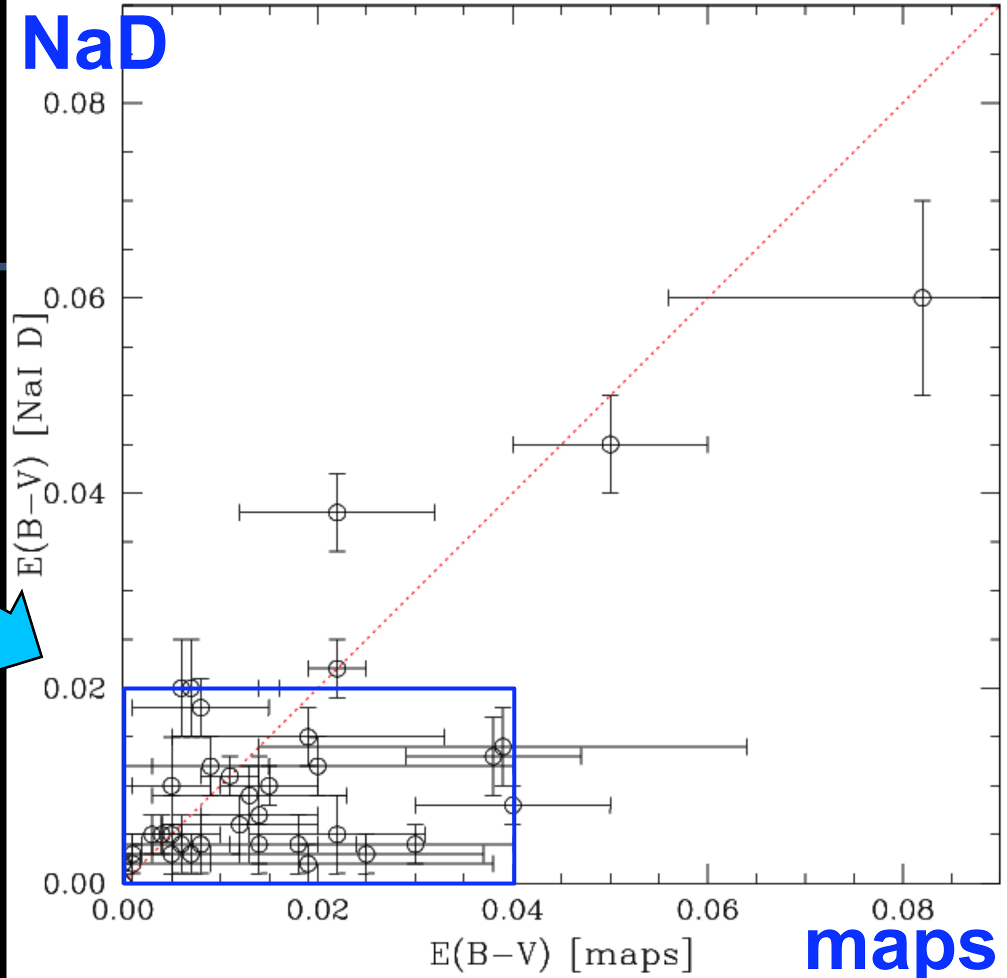
II. Improve E(B-V): using NaD lines

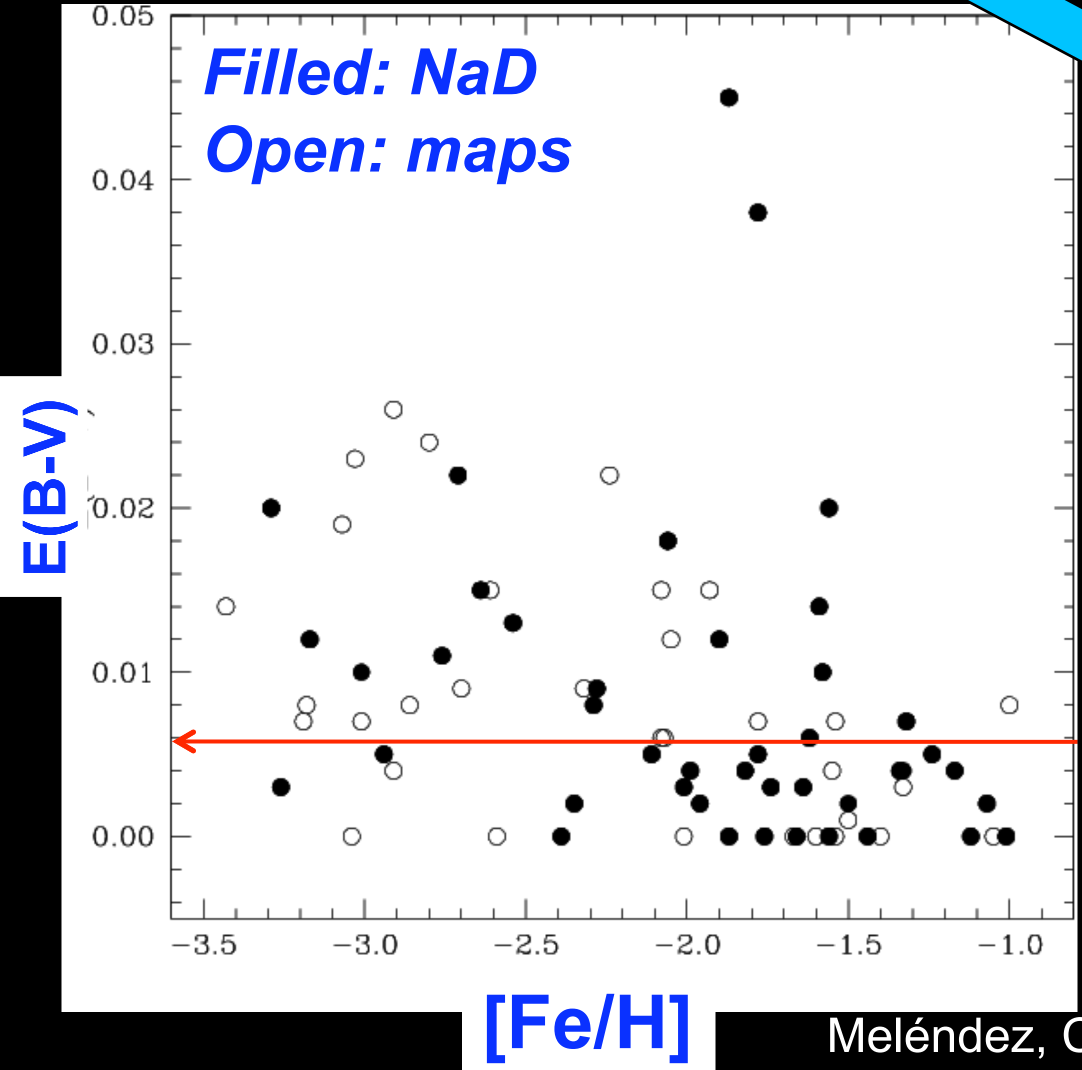
E(B-V) = 0.008 +/- 0.001 mag



II. Improving E(B-V)

- Both methods NaD & maps give similar results, but maps tend to overestimate E(B-V)





E(B-V) from NaD & maps have similar distributions with [Fe/H]. The typical reddening is low, E(B-V)= 0.006(median)

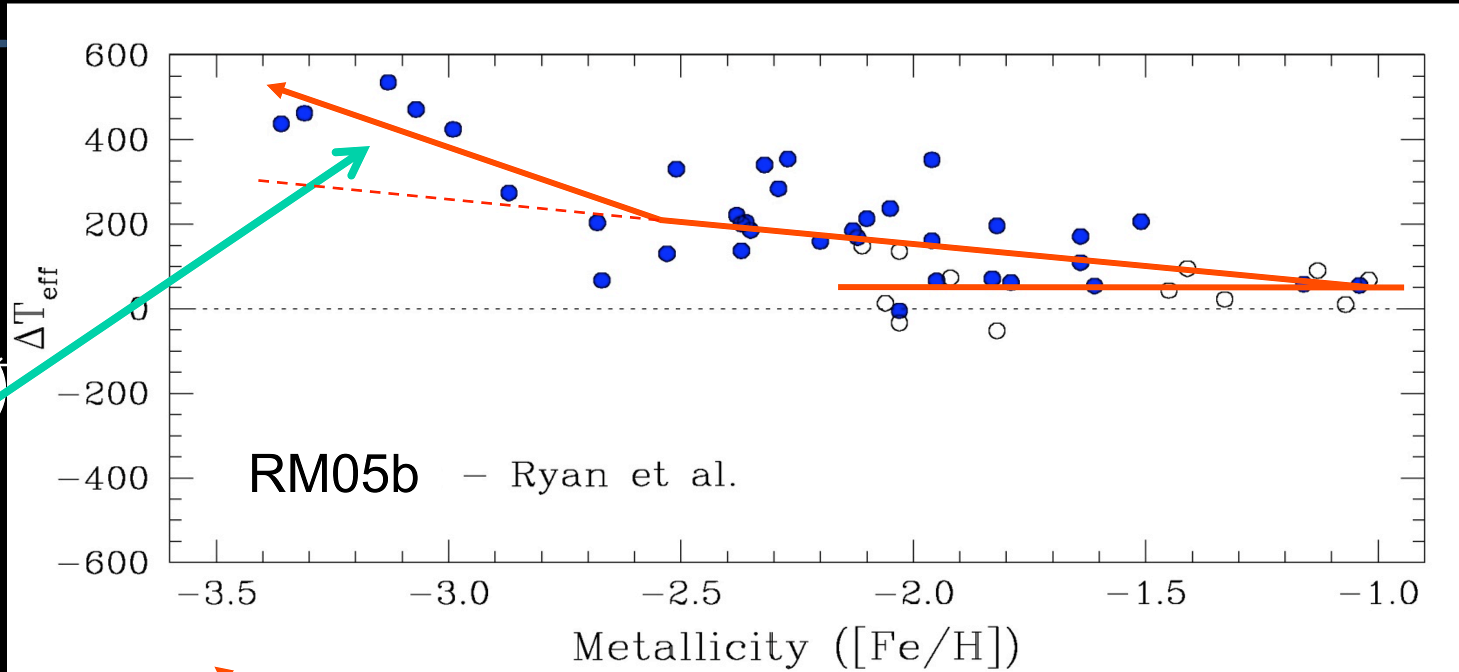
Meléndez, Casagrande, Ramirez & Asplund 2009 submitted

III. Improve the temperature scale

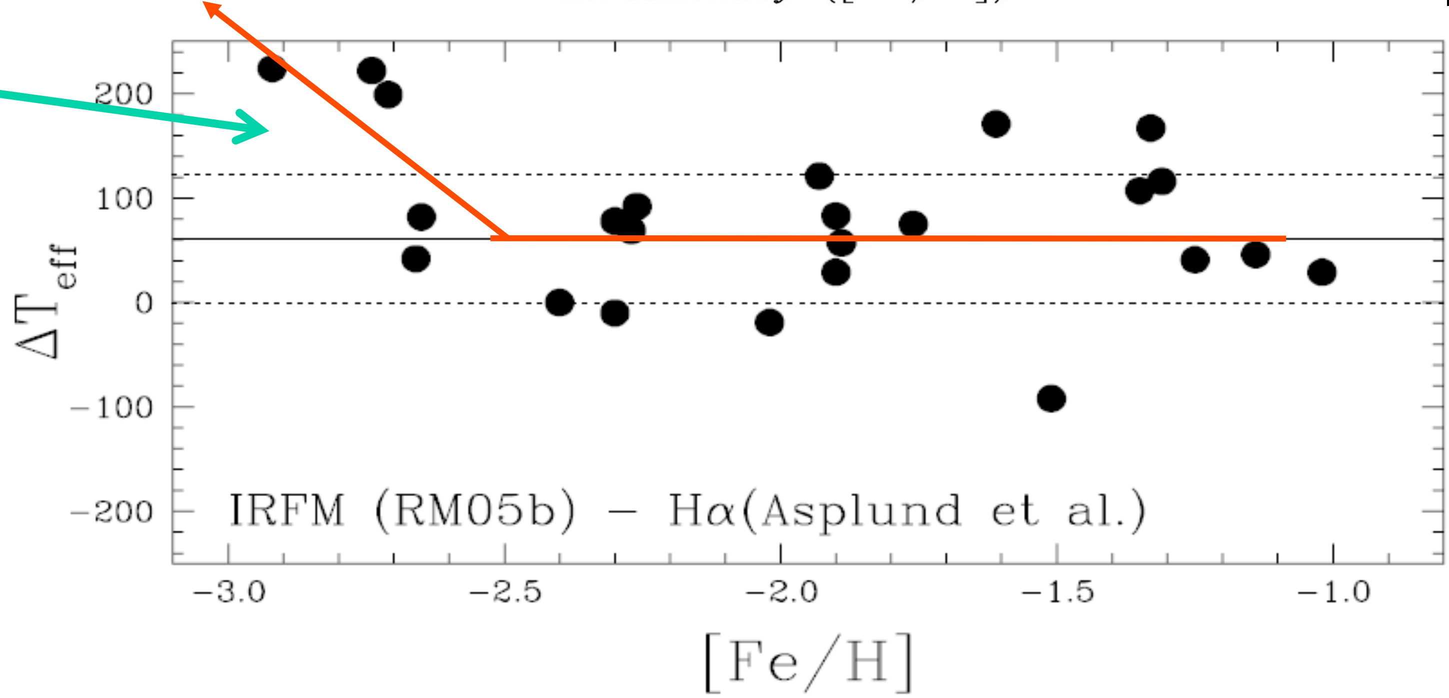
Ramírez & Meléndez 2005 (T_{eff} IRFM)

minus

Ryan et al. (T_{eff} colors)



RM05 T_{effs} for [Fe/H] < -2.5 may be too high due to the use of Alonso et al. BC



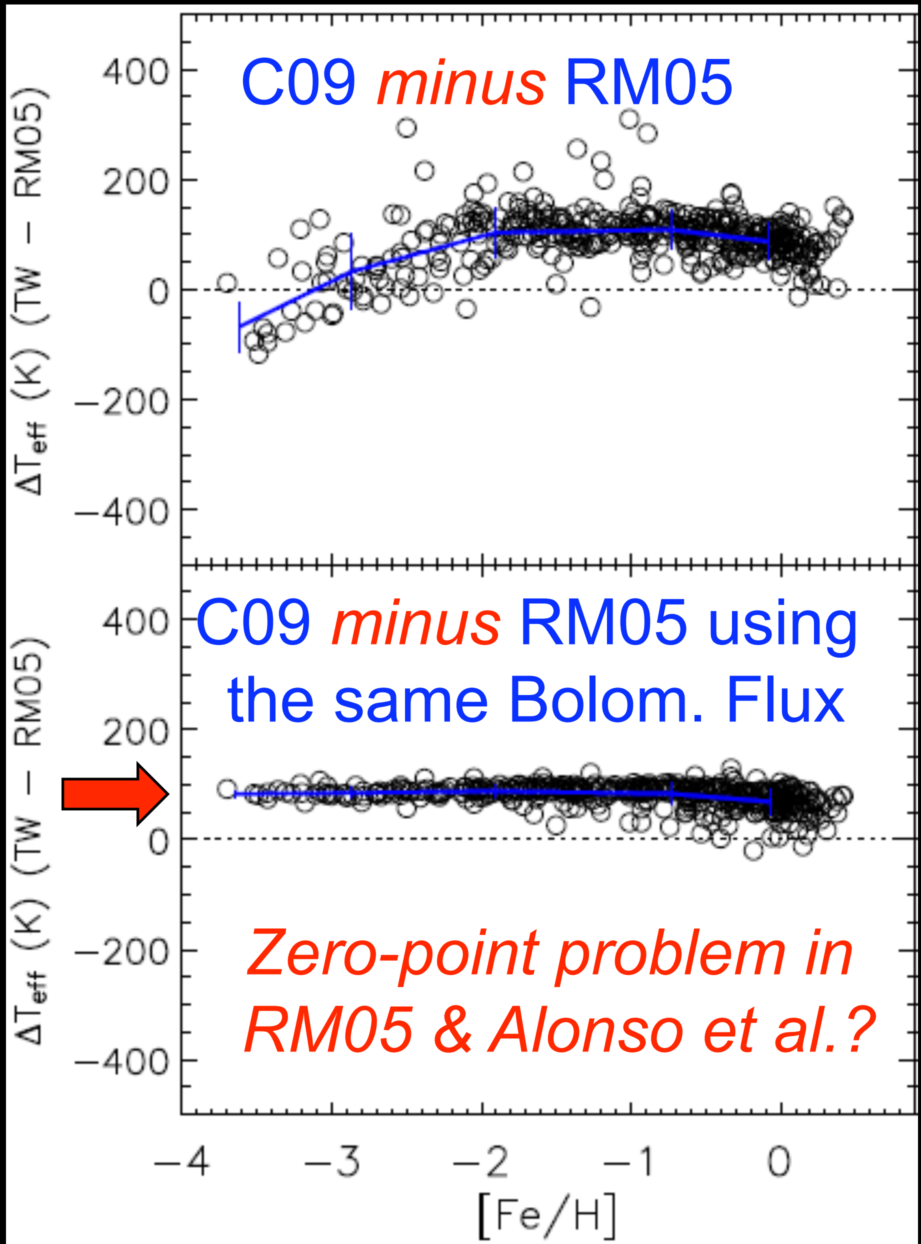
Ramírez & Meléndez 2005 (T_{eff} IRFM)

minus

Asplund et al. (T_{eff} Hα)

III. Improve the T_{eff} scale: Casagrande+

Casagrande, Ramírez, Meléndez, Bessell & Asplund 2009 (A&A, submitted)



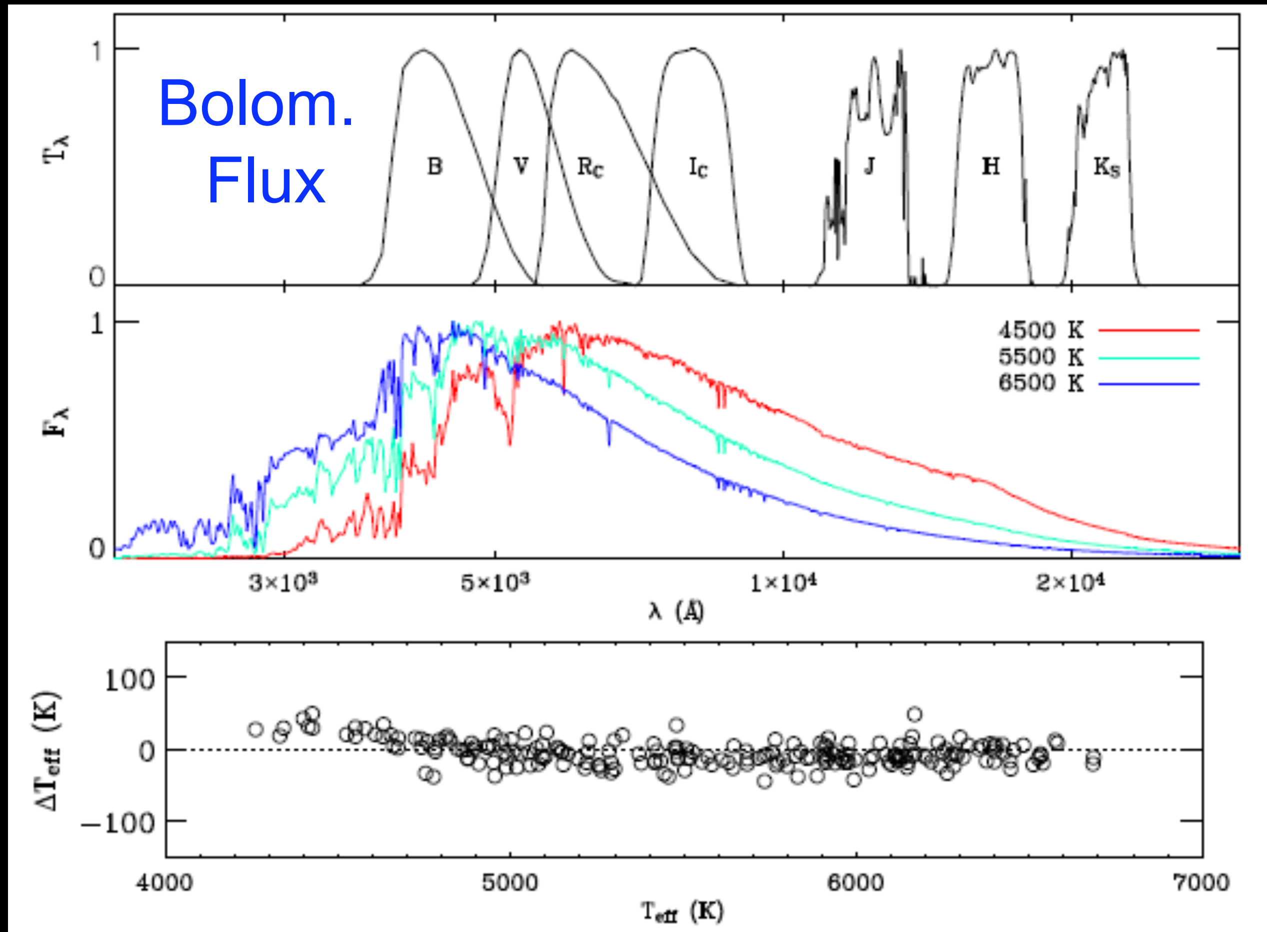


Fig. 1. Top panel: Johnson-Cousins-2MASS filter sets used in this work. Middle panel: synthetic solar metallicity spectra at different T_{eff}. For the sake of comparison all curves have been normalized to unit. Bottom panel: difference in effective temperatures with – without using $(RI)_C$ magnitudes to recover the bolometric flux.

III. Improve the T_{eff} scale: solar twins

The Sun has a very accurate T_{eff}, but inaccurate colors

The zero-point of the temperature scale

is uncertain at the 100 K level !

Solar twins: accurate T_{eff} & accurate colors

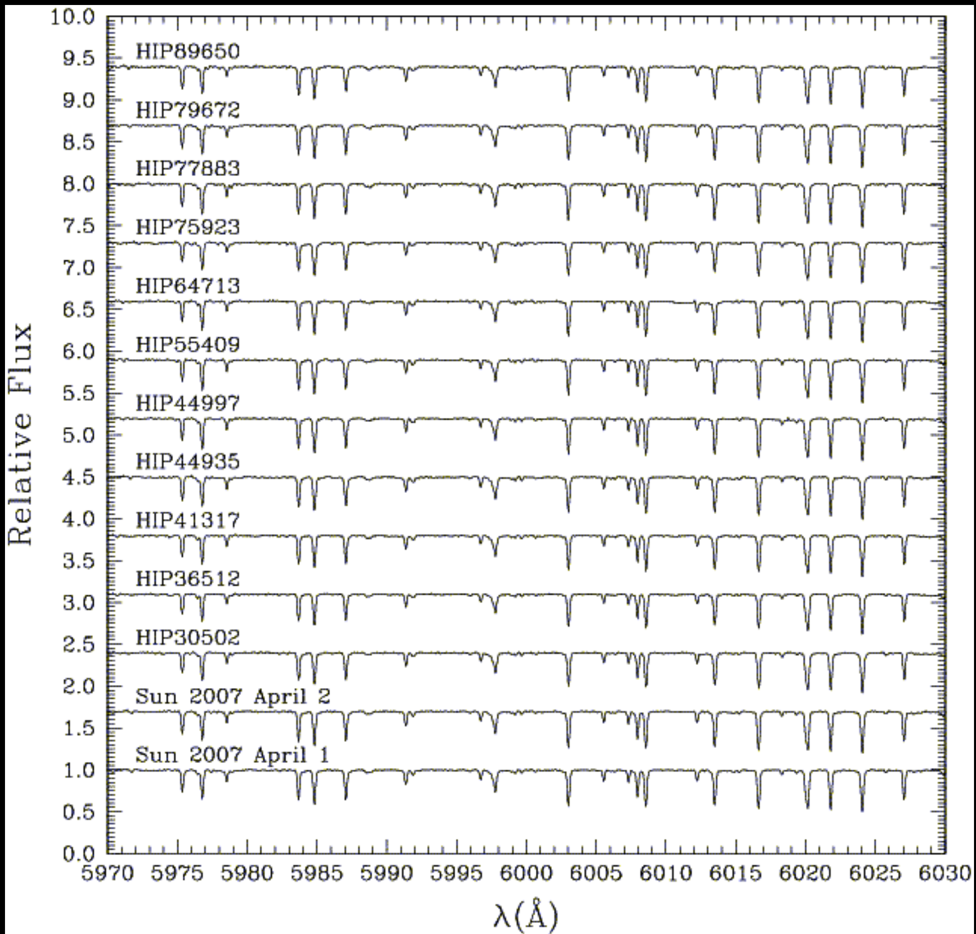
Solar twin survey: North with McDonald 2.7m; South with Magellan 6.5m

Meléndez et al.06; Meléndez & Ramírez07; Meléndez et al.09,Ramírez et al.09

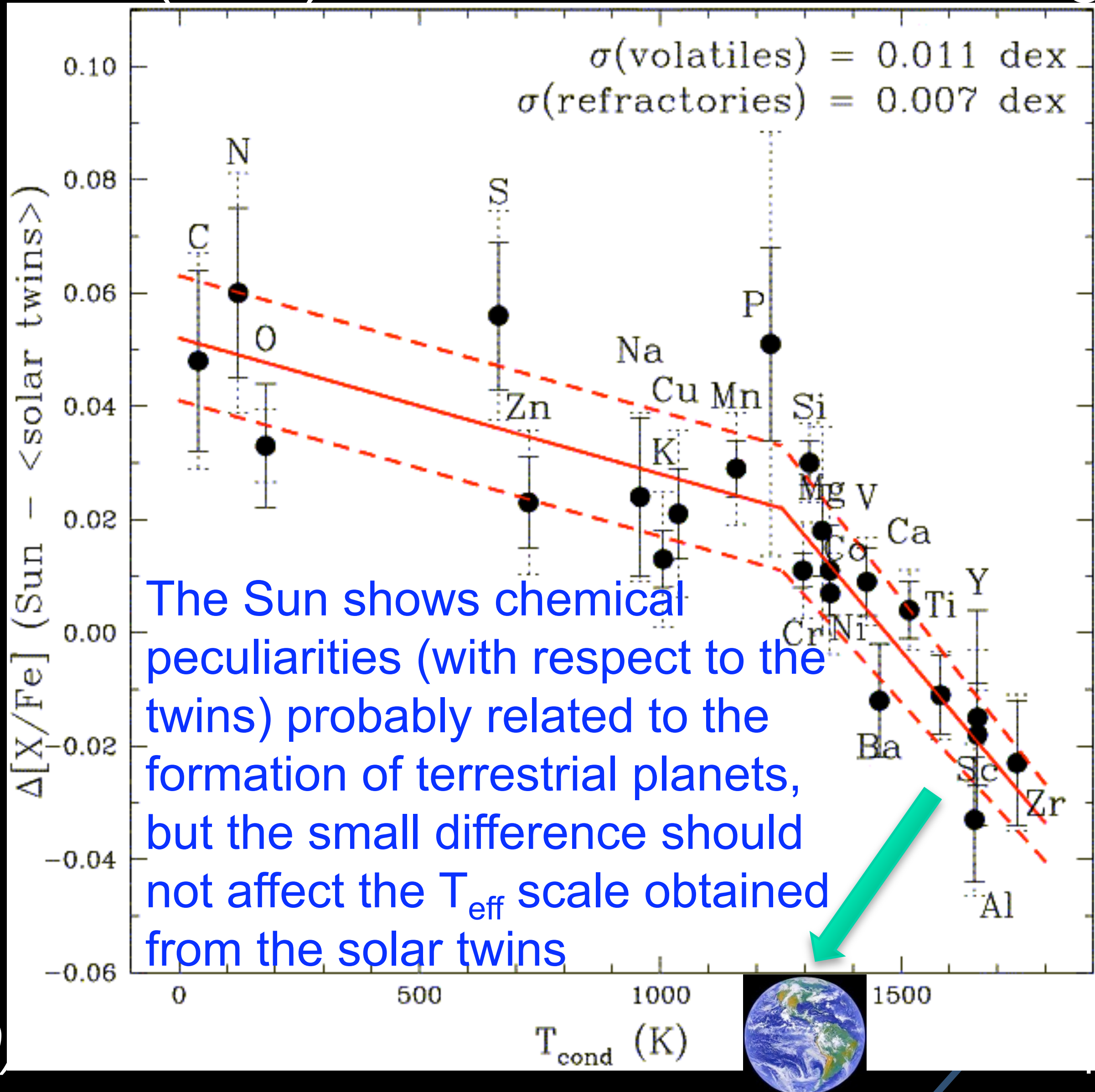
III. Improve the T_{eff} scale: solar twins

Casagrande, Ramírez, Meléndez, Bessell & Asplund 2009 (A&A, submitted)

Zero-point of our new T_{eff} scale (C09) has been checked using solar twins



Southern Solar twins found with Magellan+MIKE (Meléndez et al.09)

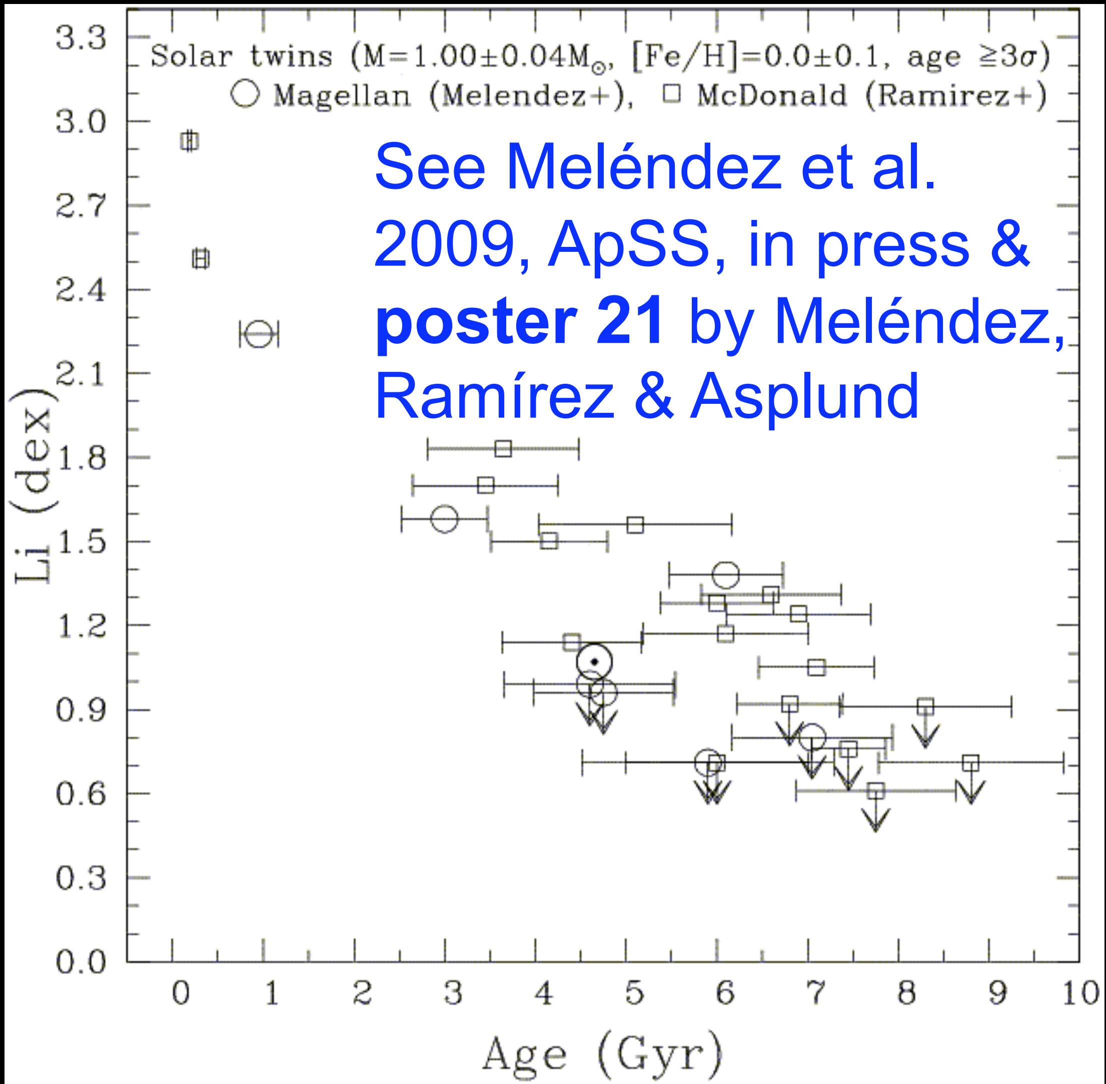


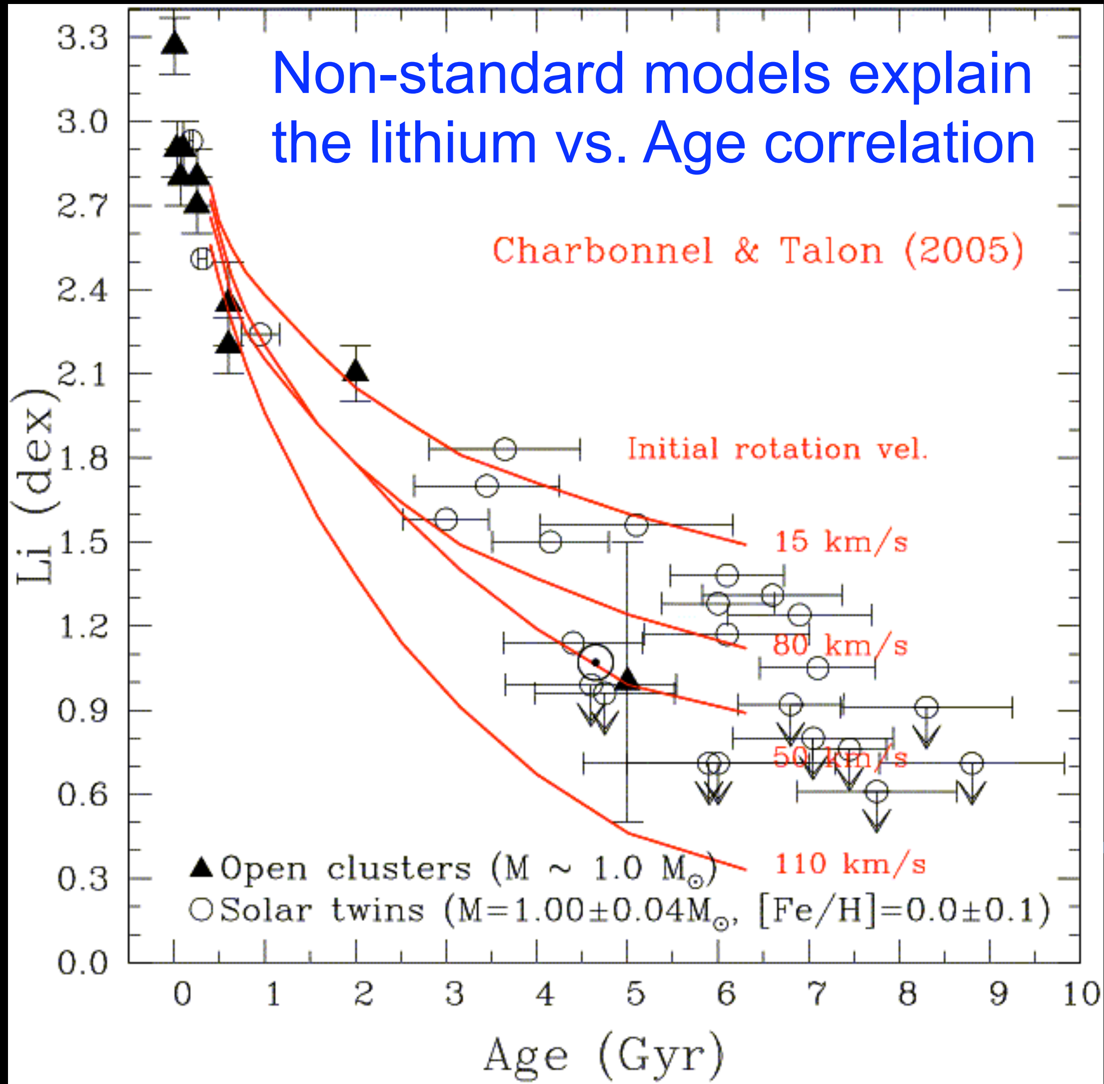
The Sun shows chemical peculiarities (with respect to the twins) probably related to the formation of terrestrial planets, but the small difference should not affect the T_{eff} scale obtained from the solar twins

III. Improve the T_{eff} scale: Solar twins

Casagrande et al. 2009 (A&A, submitted)

The twins have also been useful to show that the Sun is normal in Li for its age & that low Li is not related to the presence of planets





IV. Results: A(Li) vs. Teff

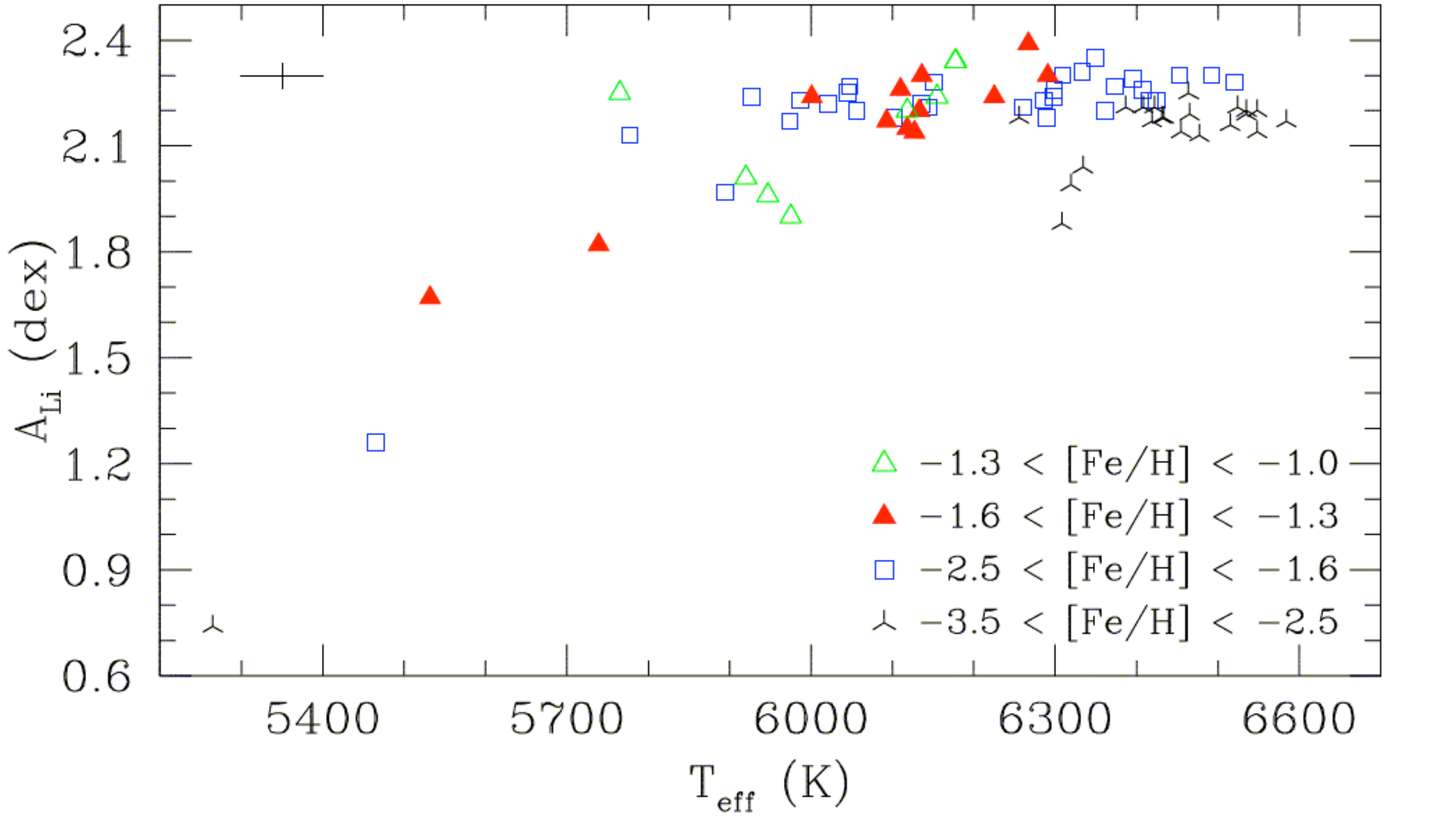


Fig. 1. Li abundances vs. $T_{\rm eff}$ for our sample stars in different metallicity ranges. A typical error bar is shown.

Meléndez, Casagrande, Ramirez & Asplund 2009, A&A, submitted

IV. A(Li) vs. [Fe/H]: depletion signatures

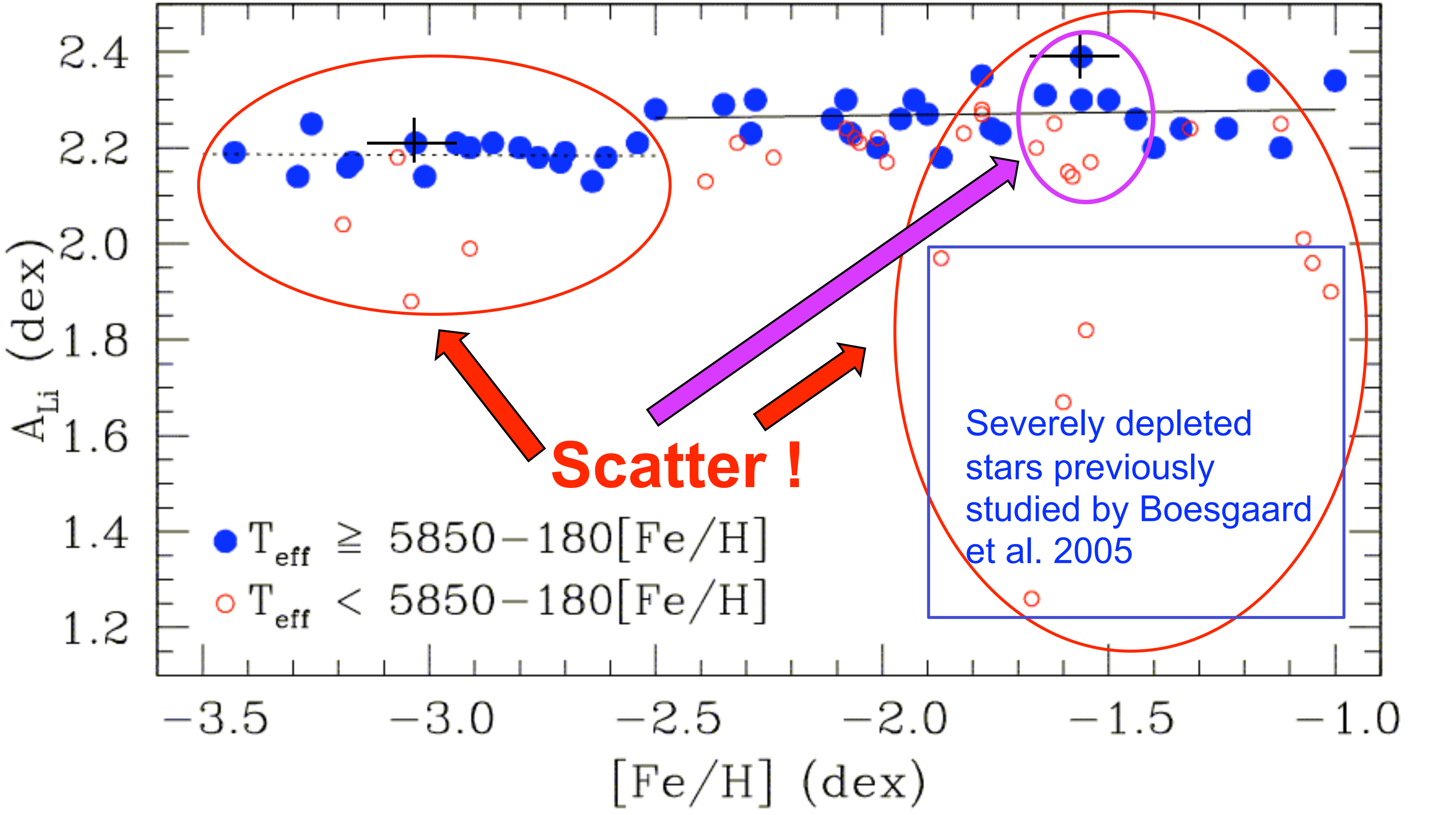
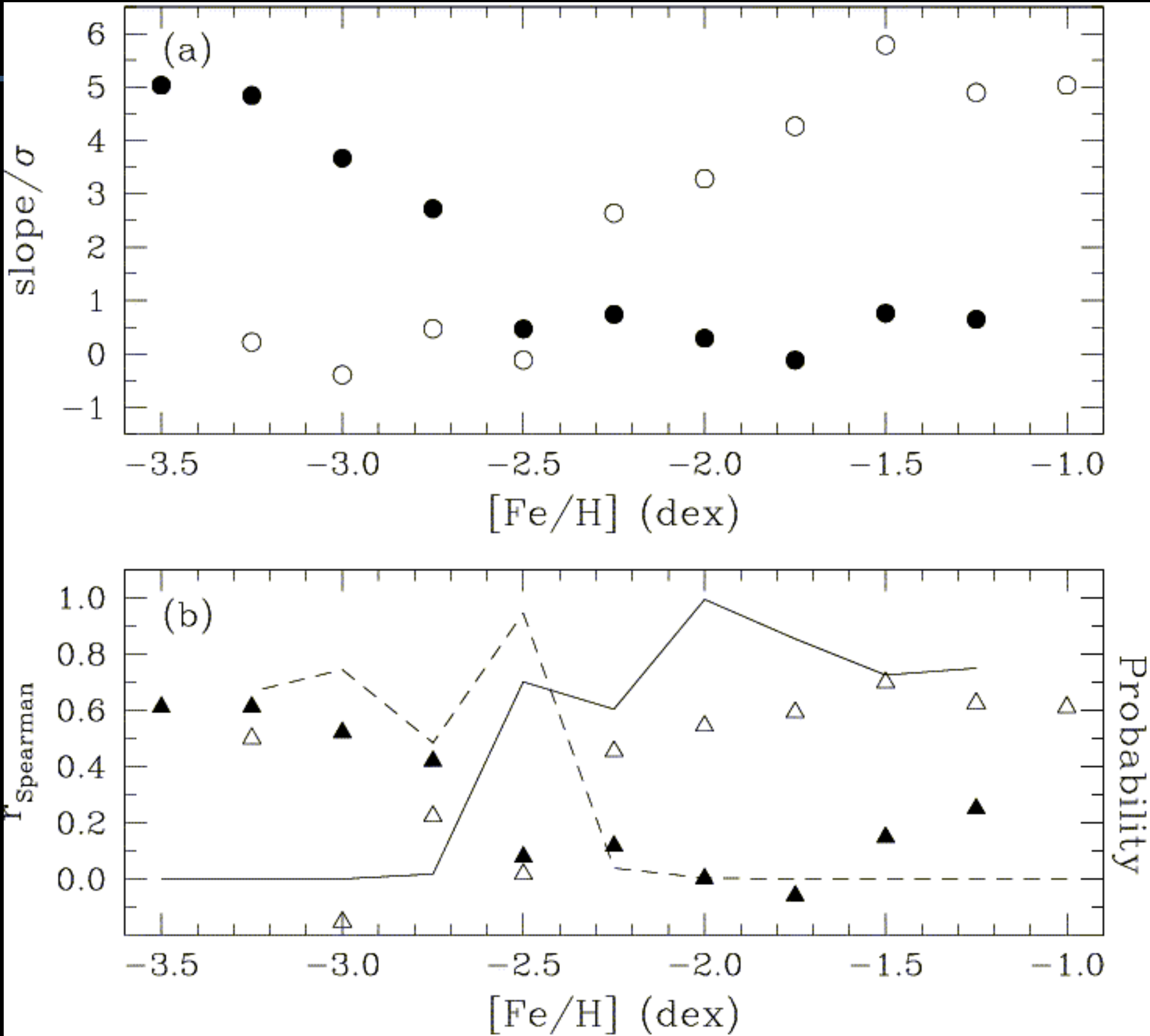


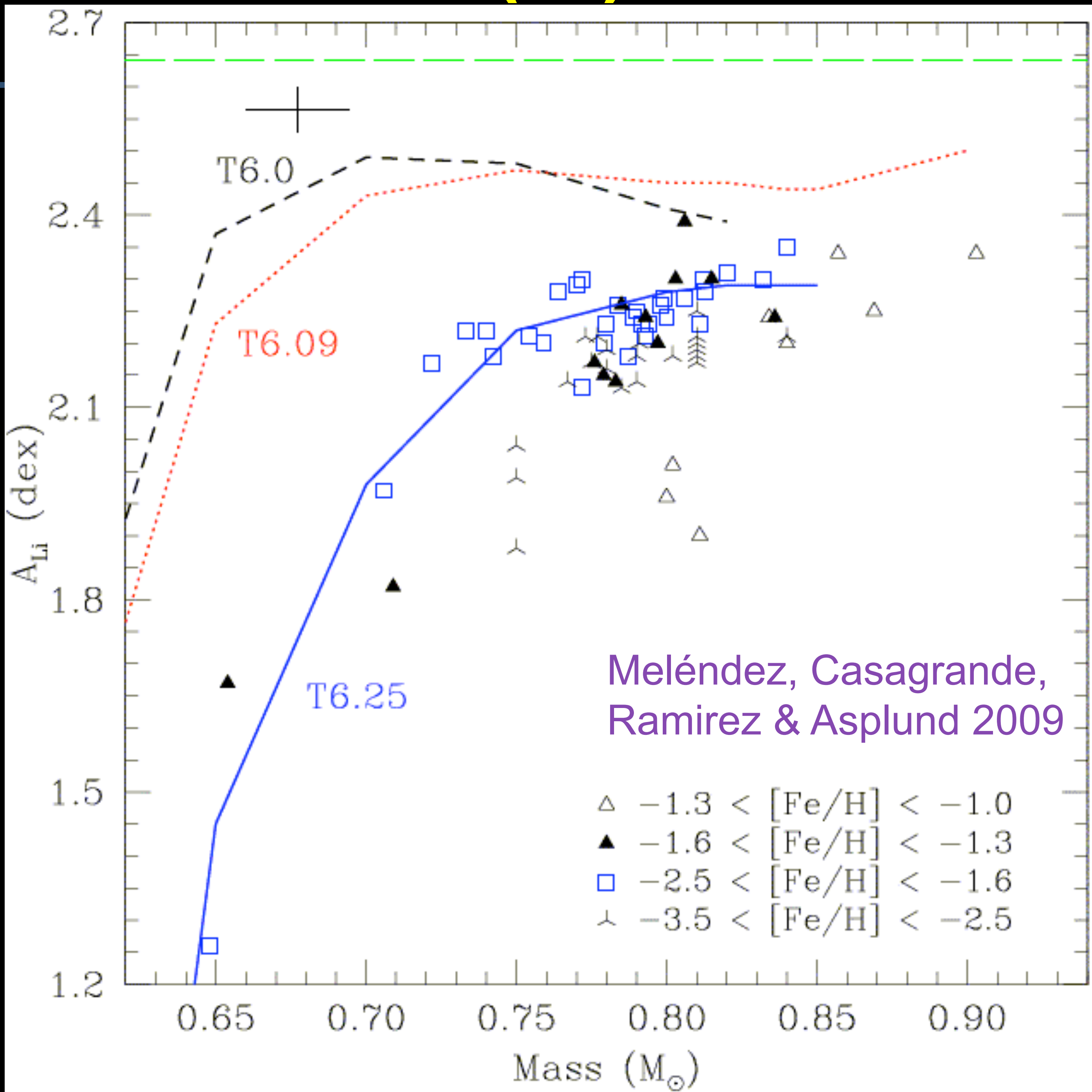
Fig. 2. Li abundances for stars with T_{eff} ≥ (filled circles) and < (open circles) than the cutoff T_{eff} = 5850 - 180×[Fe/H]. The stars above the cutoff in T_{eff} (filled circles) fall in plateaus with σ=0.03 and 0.05 dex for [Fe/H] < −2.5 and ≥ −2.5, respectively. Linear fits are shown by dotted ([Fe/H] < −2.5) and solid ([Fe/H] ≥ −2.5) lines. Meléndez, Casagrande, Ramirez & Asplund 2009, submitted

IV. Results: a break at [Fe/H] = -2.5



Meléndez, Casagrande, Ramirez & Asplund 2009, submitted

IV. Results: A(Li) vs. mass



Comparison with Richard et al. models for [Fe/H] = -2.3 including diffusion, grav. settling & T6.0, 6.09 & 6.25 turb.

The best fit is for the T6.25 models adopting an initial A(Li)=2.64 (MARCS) or 2.72 (Kurucz overshooting)

$$D_T = 400 D_{\rm He}(T_0)\left[\frac{\rho}{\rho(T_0)}\right]^{-3}. \quad (2)$$

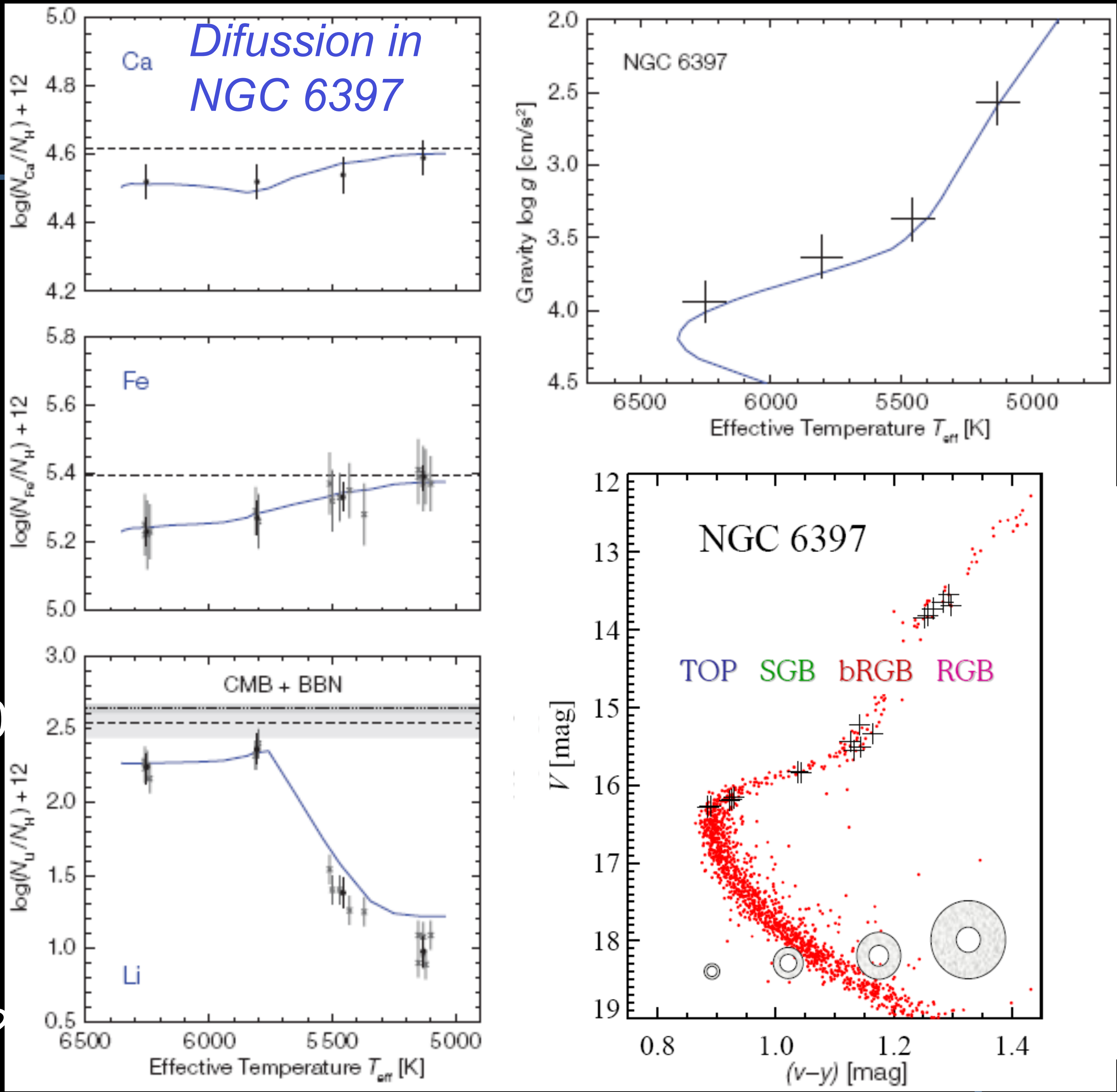
To simplify notation, T6.0 is used instead of T6.0D400-3, since all models discussed in this paper have the D400-3 parameterization. The ρ^{-3} dependence is suggested (see Proffitt & Michaud 1991a) by observations of the Be solar abundance in the present day, which shows that it is hardly smaller than the original Be abundance (see, e.g., Bell et al. 2001). This imposes a rapid decrease of the turbulent transport coefficient as ρ or T increases. Examples of these turbulent diffusion co-

Other evidences of Li depletion

Korn et al. 2006, Nature 442, 657

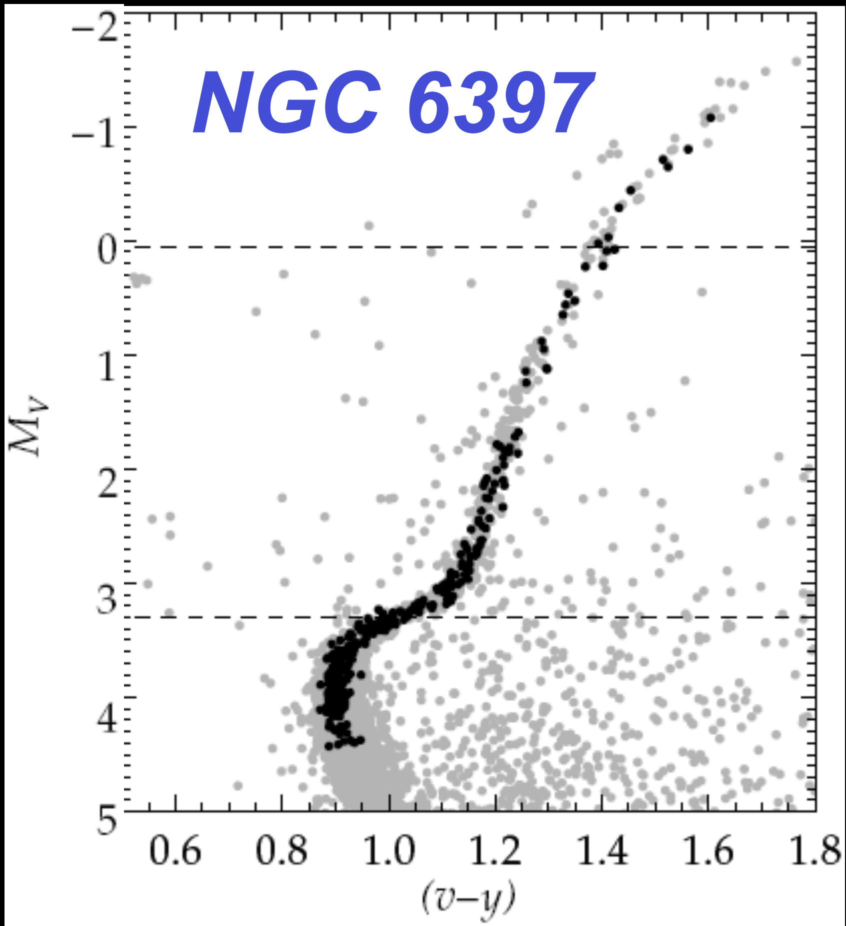
A(Li) = 2.54 +/-0.10 using T6 difussion model (Richard05)

Using our new T_{eff} scale: A(Li) = 2.60?



Other evidences of Li depletion

Lind et al. 2009



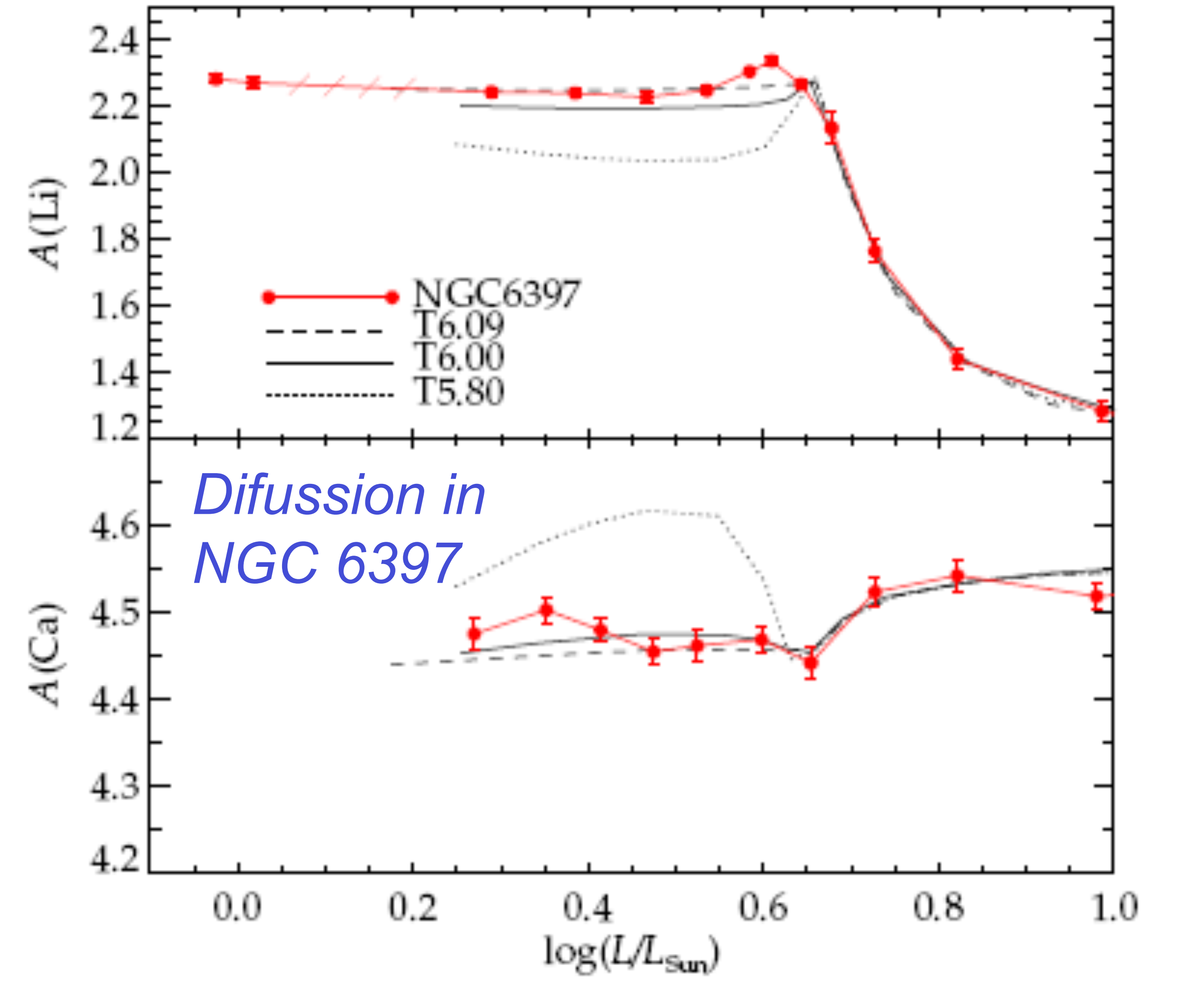


Fig. 10. *Top:* Comparison between bin-averaged Li abundances (red filled circles connected with solid lines) and the predictions from the stellar-structure models of Richard et al. (2005). T5.80 represents the model with lowest efficiency of turbulent transport, T6.00 intermediate efficiency, and T6.09 highest efficiency. The reference scale is logarithmic luminosities in units of solar luminosities. *Bottom:* The same plot for Ca abundances. A

Conclusions

- There is evidence for Li depletion in the Spite plateau
- Our work shows that the depletion depends on both mass and metallicity
- The T6.25 difussion+turbulence model provides the best fit to our NLTE Li abundances, implying a primordial A(Li) = 2.64 (MARCS) and 2.72 (Kurucz overshooting), in good agreement with BBN
- More data is needed to confirm our results and to better constrain the stellar depletion models

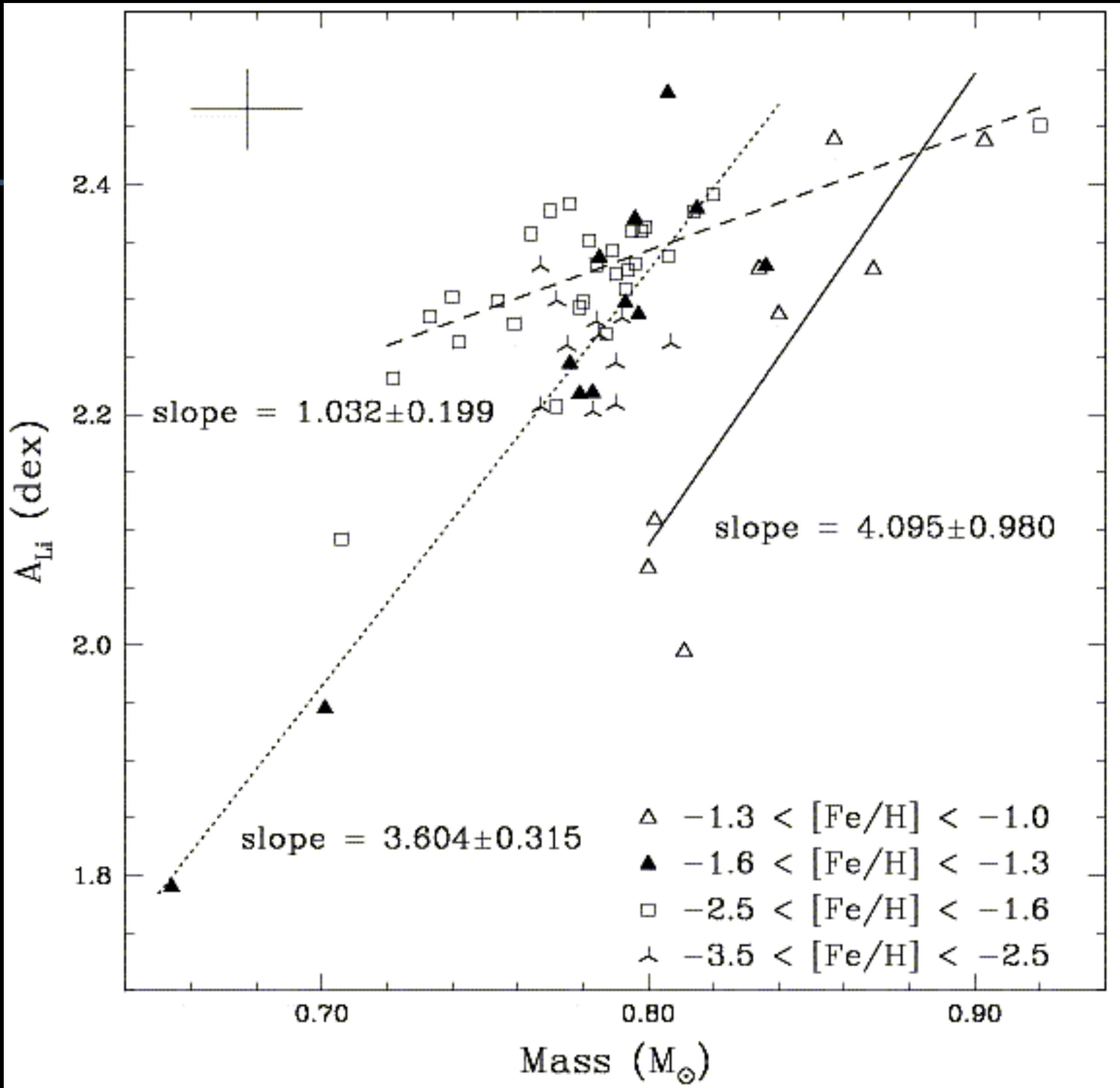
What about Li-7 ?

- New high precision study of ~ 75 stars by Melendez, Casagrande, Ramirez, Asplund (2009)

- Aim: To determine precise masses and Li abundances in order to see depletion signatures (if any) in the Spite plateau

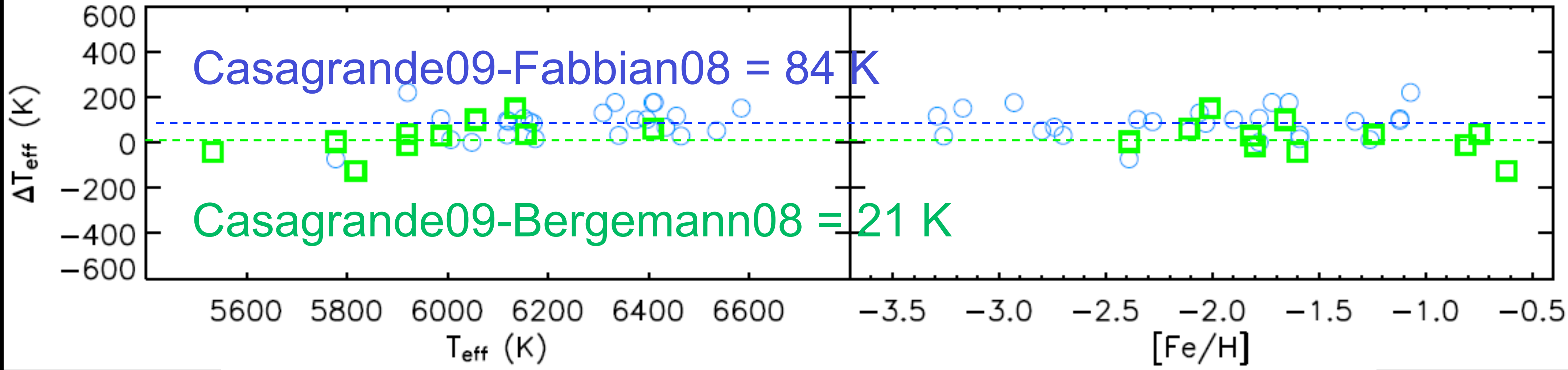
- We use better effective temperatures, minimizing uncertainties in E(B-V) (~ 10 K). Only precise equivalent widths (mostly UVES/HIRES) with errors (mostly) below 3%

Lithium vs. Mass



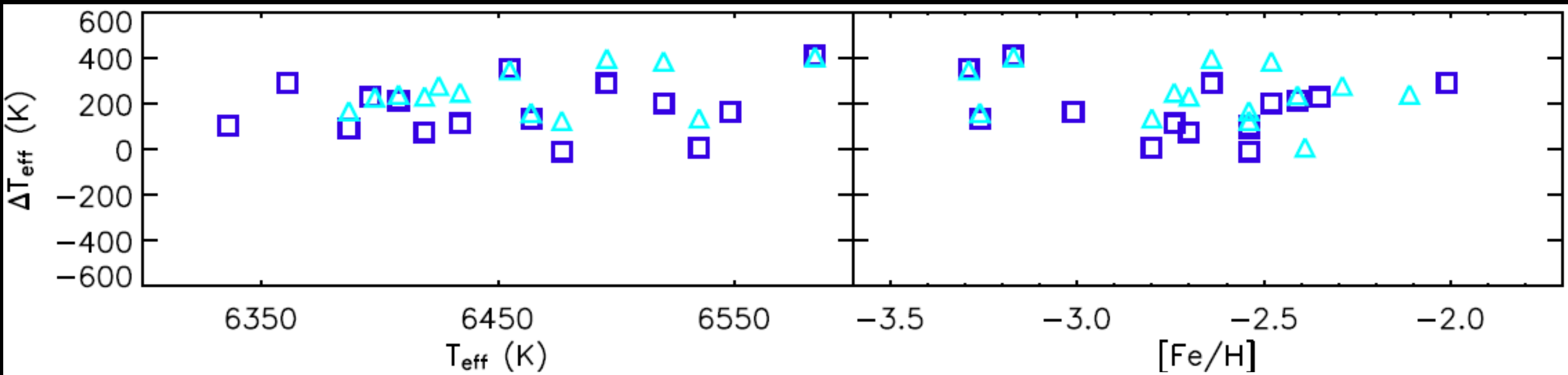
Trends with mass are significant at the 4-11 sigma level

Melendez, Casagrande, Ramirez & Asplund (2009, in prep.)



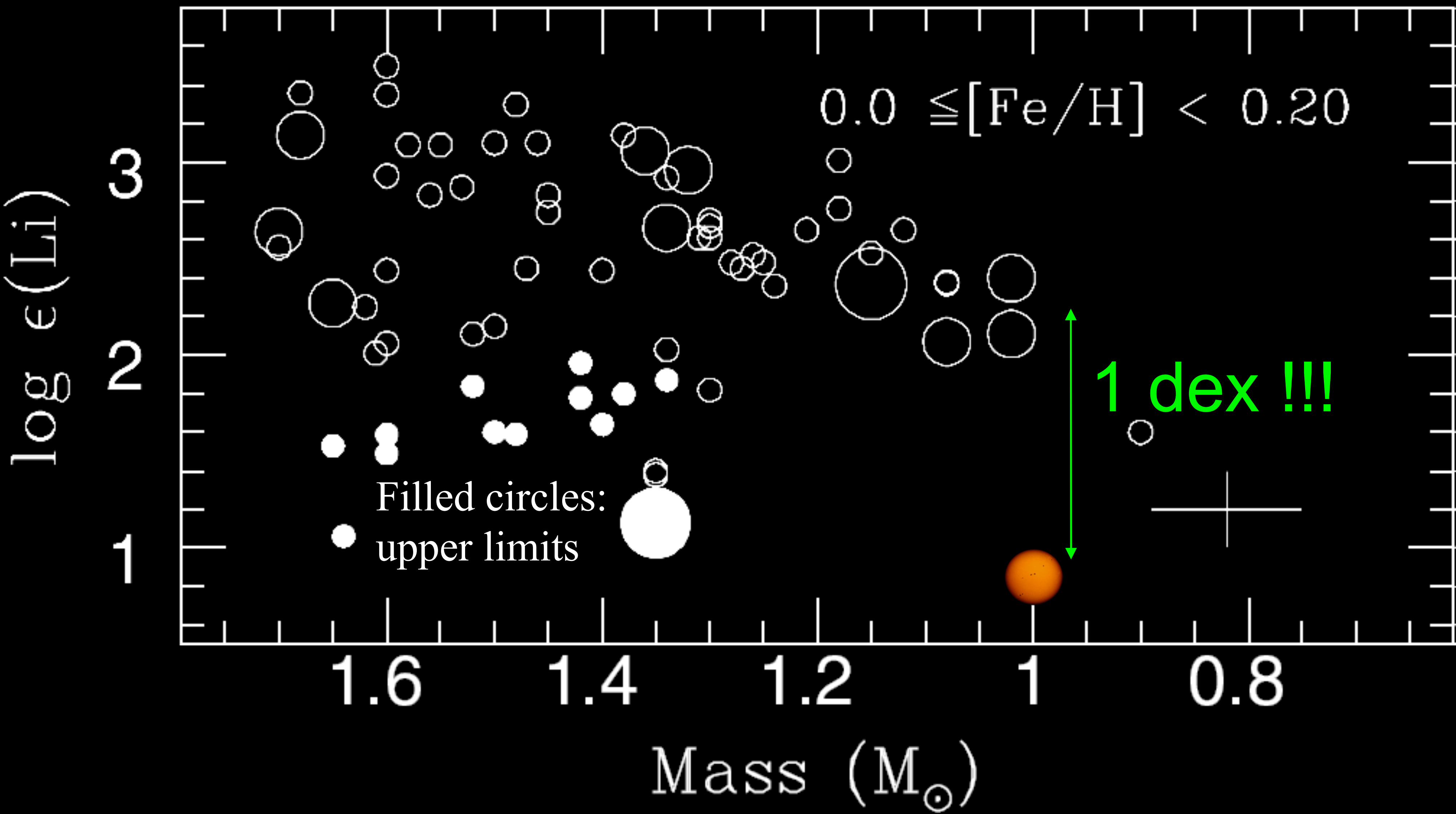
Hα,Hβ

Fig. 10. Upper panels: comparison between the effective temperatures determined in this work and those obtained from the Hβ (Fabbian et al. 2008, circles) and Hα plus Hβ (Bergemann 2008, squares) line pro-



files. Lower panel: comparison with respect to the excitation equilibrium temperatures determined by Hosford et al. (2008). Two sets of data points are shown because Hosford et al. (2008) temperatures are sensitive to the uncertain log g values of metal-poor stars; squares (triangles) represents $T_{\rm eff}$ derived assuming the star to be on the main-sequence (sub-giant branch). $\Delta T_{\rm eff}$ are this − other works in all panels.

Is the Sun Li poor ?



Lambert & Reddy (2004): the Sun may be peculiar and thefore of dubious value for calibrating non-standard models of Li depletion

Is the Sun peculiar ? May be not

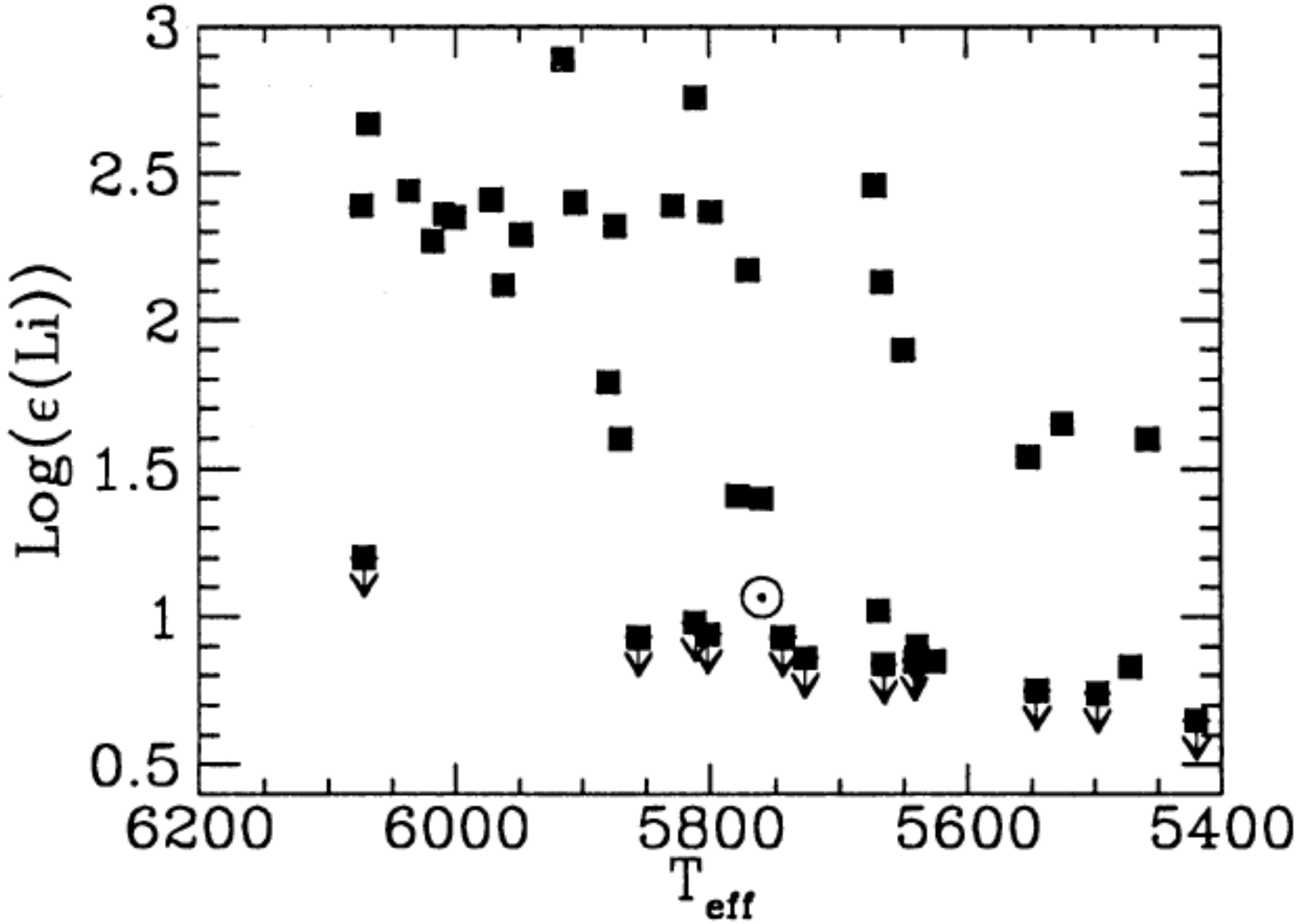
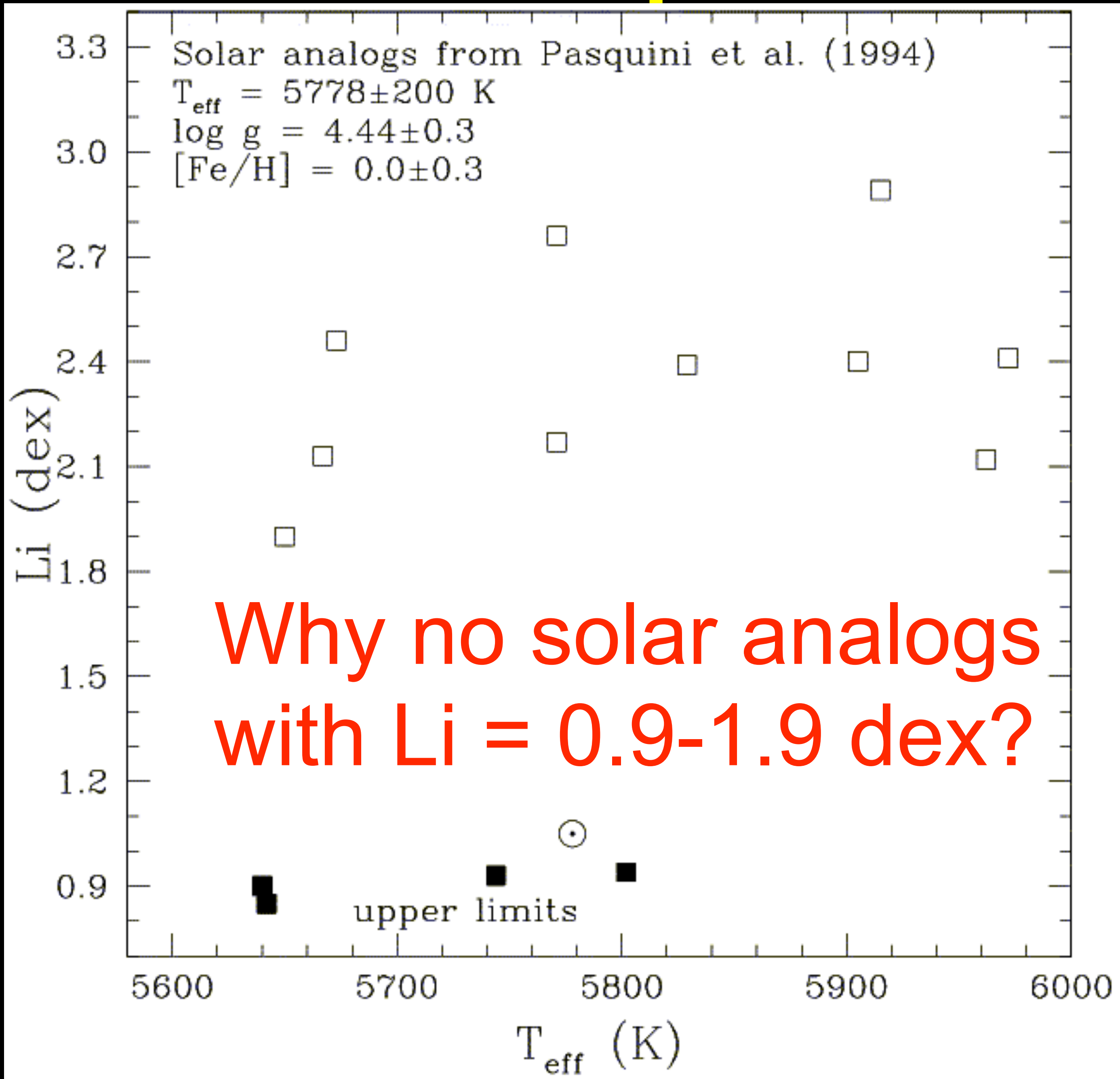


Fig. 3. Li abundance as a function of stellar effective temperature T_{eff}. The position of the Sun is also indicated (⊙)

CAUTION:
Stars in a broad range of stellar parameters
5400 < T_{eff} < 6100 K
3.9 < log g < 4.6
-1.6 < [Fe/H] < +0.2

Pasquini et al. (1994): the Sun seem to be representative of low-lithium solar-like stars (about 50% of the sample)

Is the Sun peculiar ? May be not



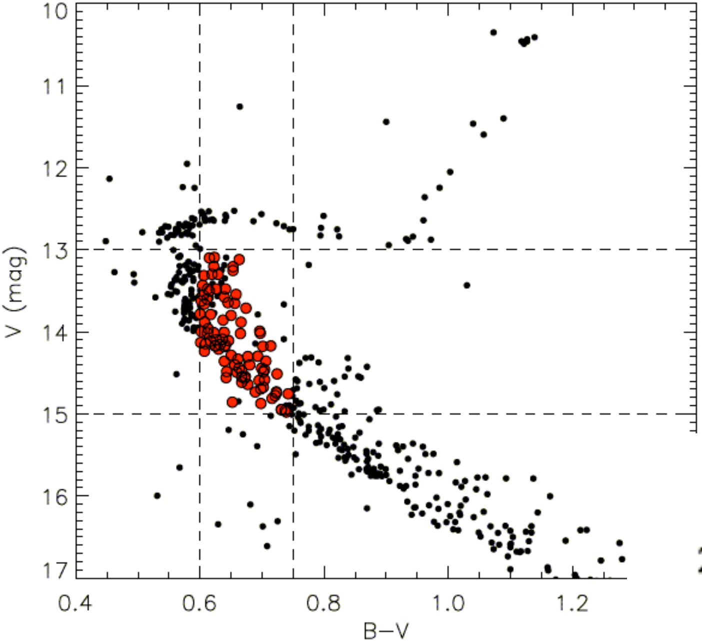
Why no solar analogs with Li = 0.9-1.9 dex?

Solar analogs from Pasquini et al. with T_{eff} = 5778 ± 200 K
log g = 4.44 ± 0.3
[Fe/H] = 0.0 ± 0.3

The Sun indeed doesn't seem to have an unusually low Li-abundance (30% of solar analogs show low lithium).

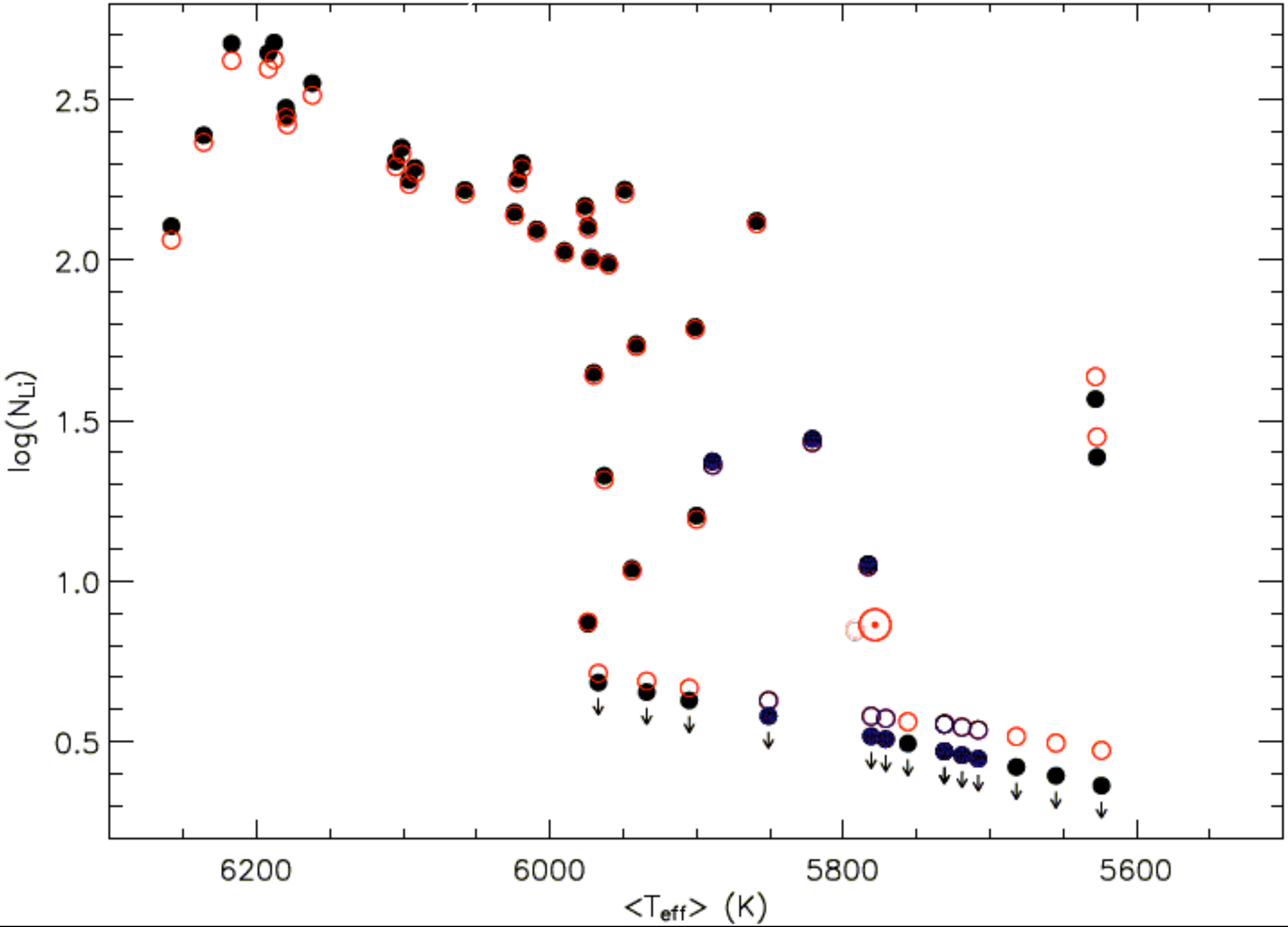
Solar twins in M67
(Pasquini et al. 2008)

Open cluster with solar age (3.5-4.8 Gyr) and slightly higher [Fe/H] = +0.03 (Randich et al. 2006, Pace et al. 2008)



Sun seems normal in Li (or slightly rich) with respect to M67.

Note that upper limits in the M67 Li data may have to be increased (at least by a factor of 2?) R ~ 17k, S/N ~ 80-110



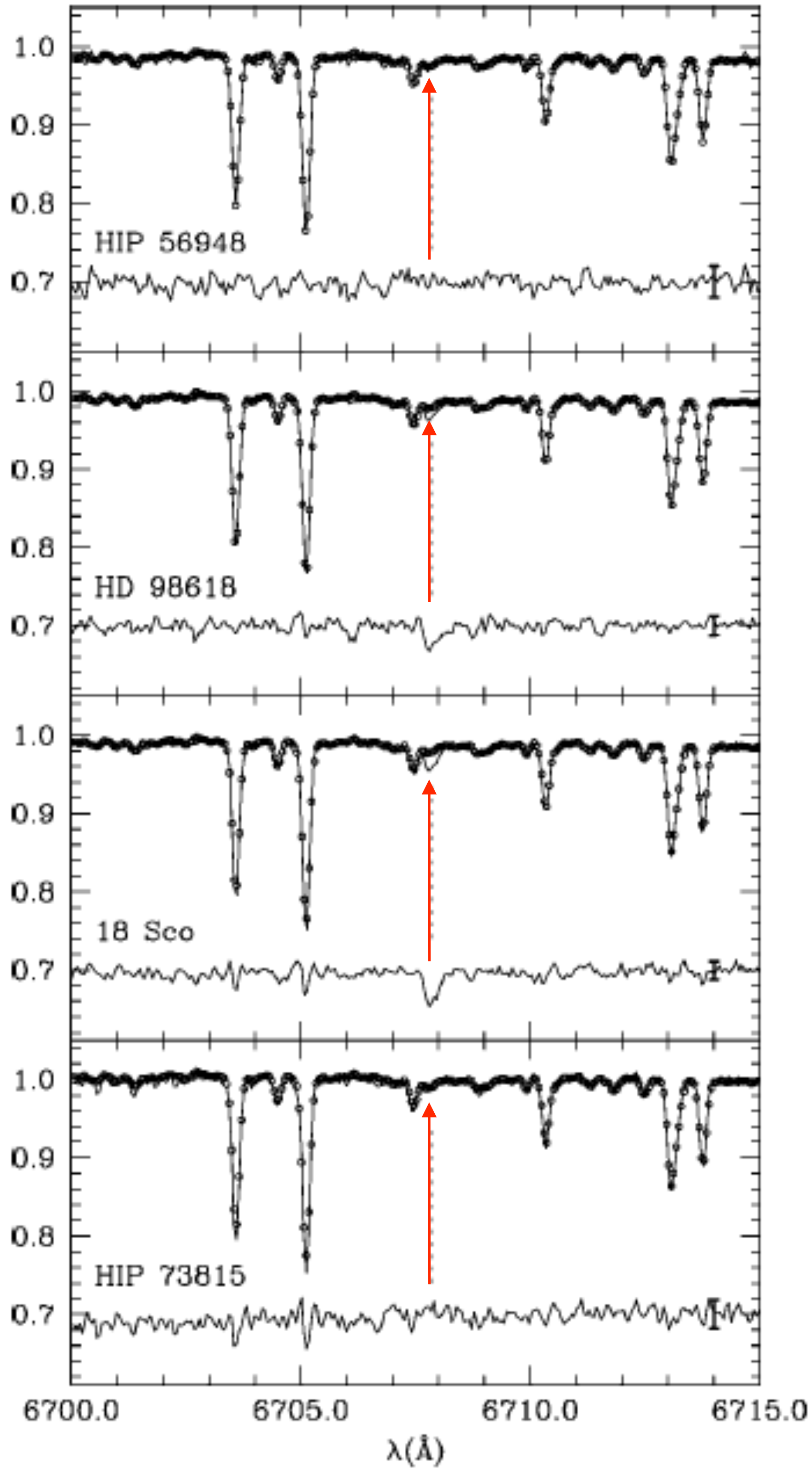
McDonald solar twin survey

New solar twins HIP 56948 &

HIP 73815 have low Li (~1.0)!

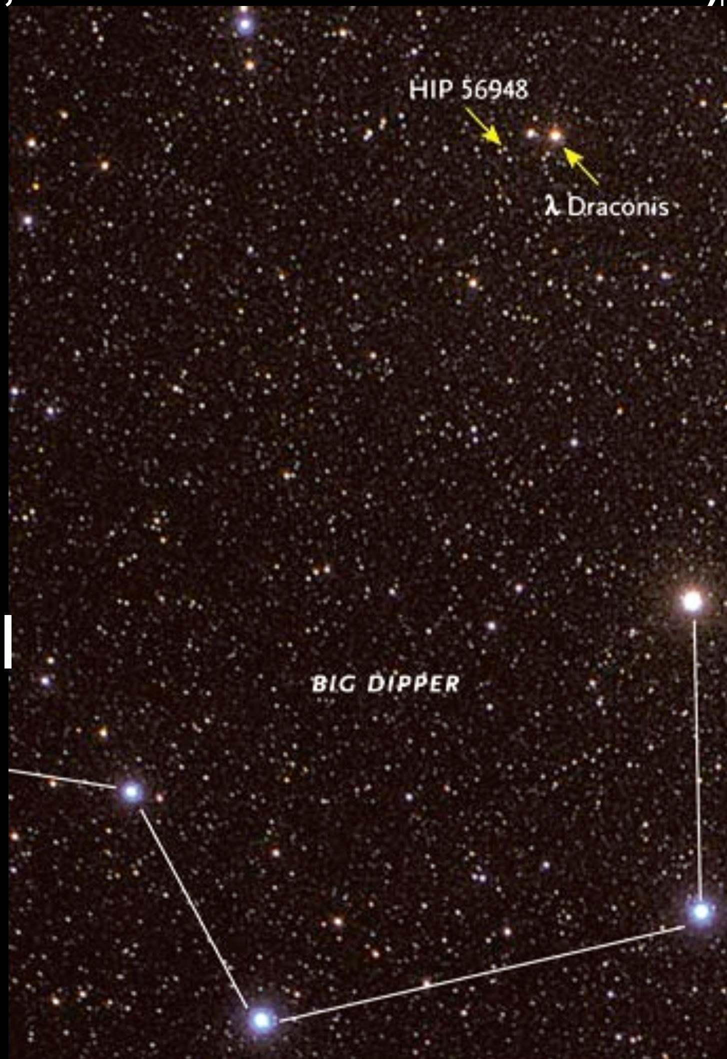
Other 2 have relatively low (Li ~1.5)

(Melendez et al. 2006;Melendez & Ramirez 07)



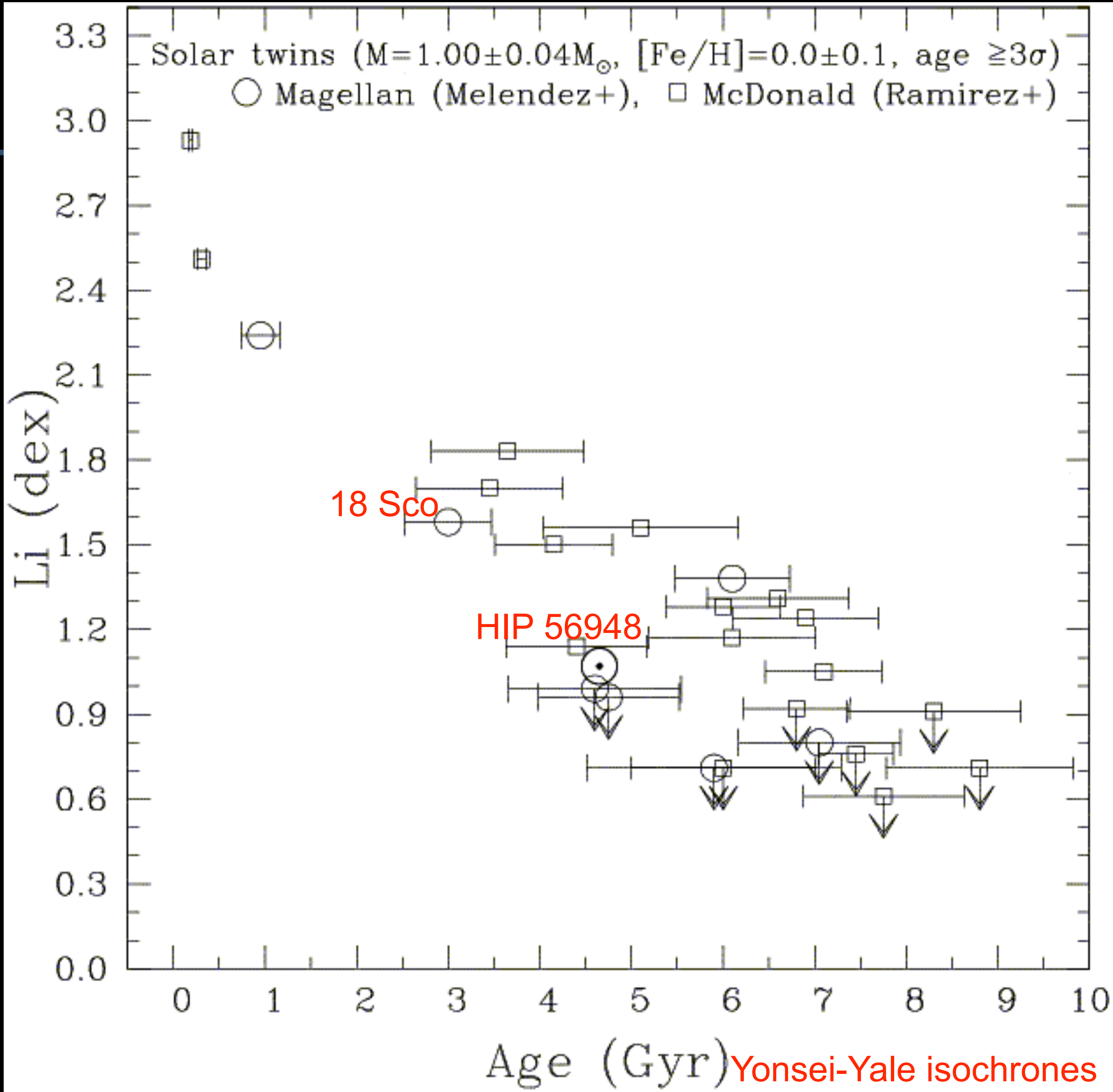
Best solar twin is HIP 56948 (better than 18 Sco)

HIP 56948 is almost an identical Sun. It also has a low lithium abundance

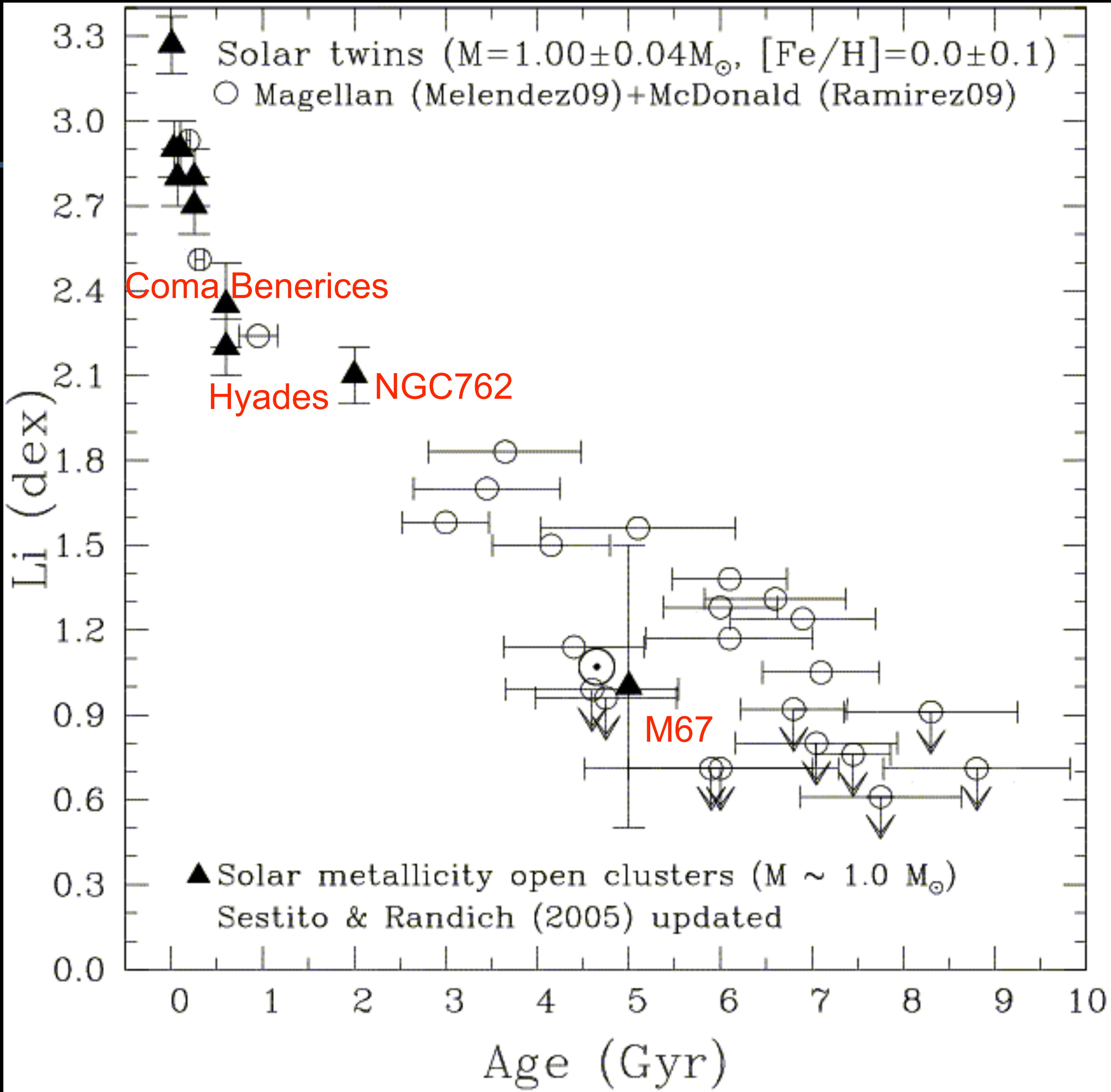


Lithium in solar twins

(Melendez+09, Ramirez+09)

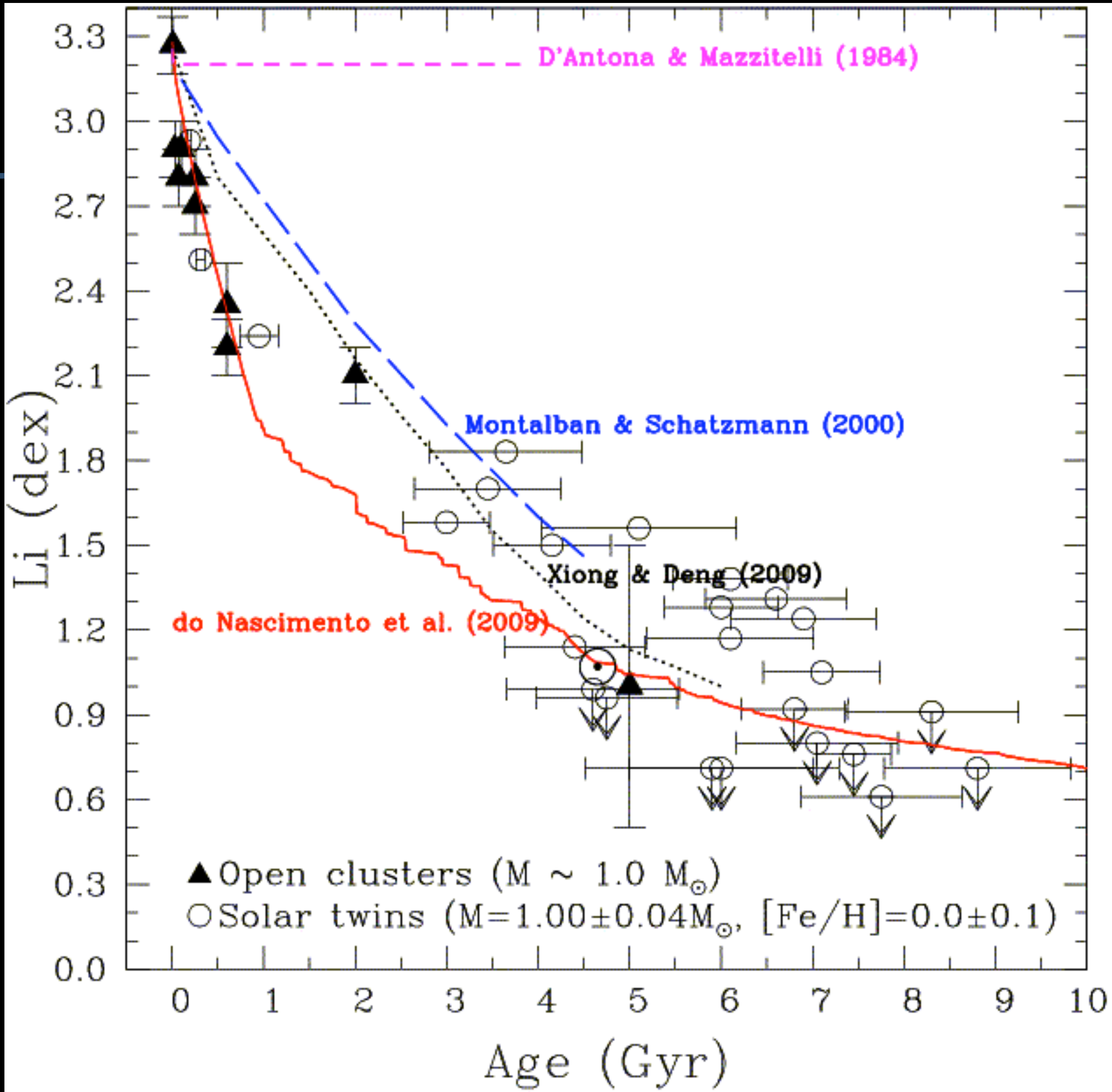


The solar Li is "normal" for a 1-solar-mass of solar metallicity at 4.6 Gyr



Synergies between open cluster and field stars !

The solar Li is normal for a 1-solar-mass star at 4.6 Gyr

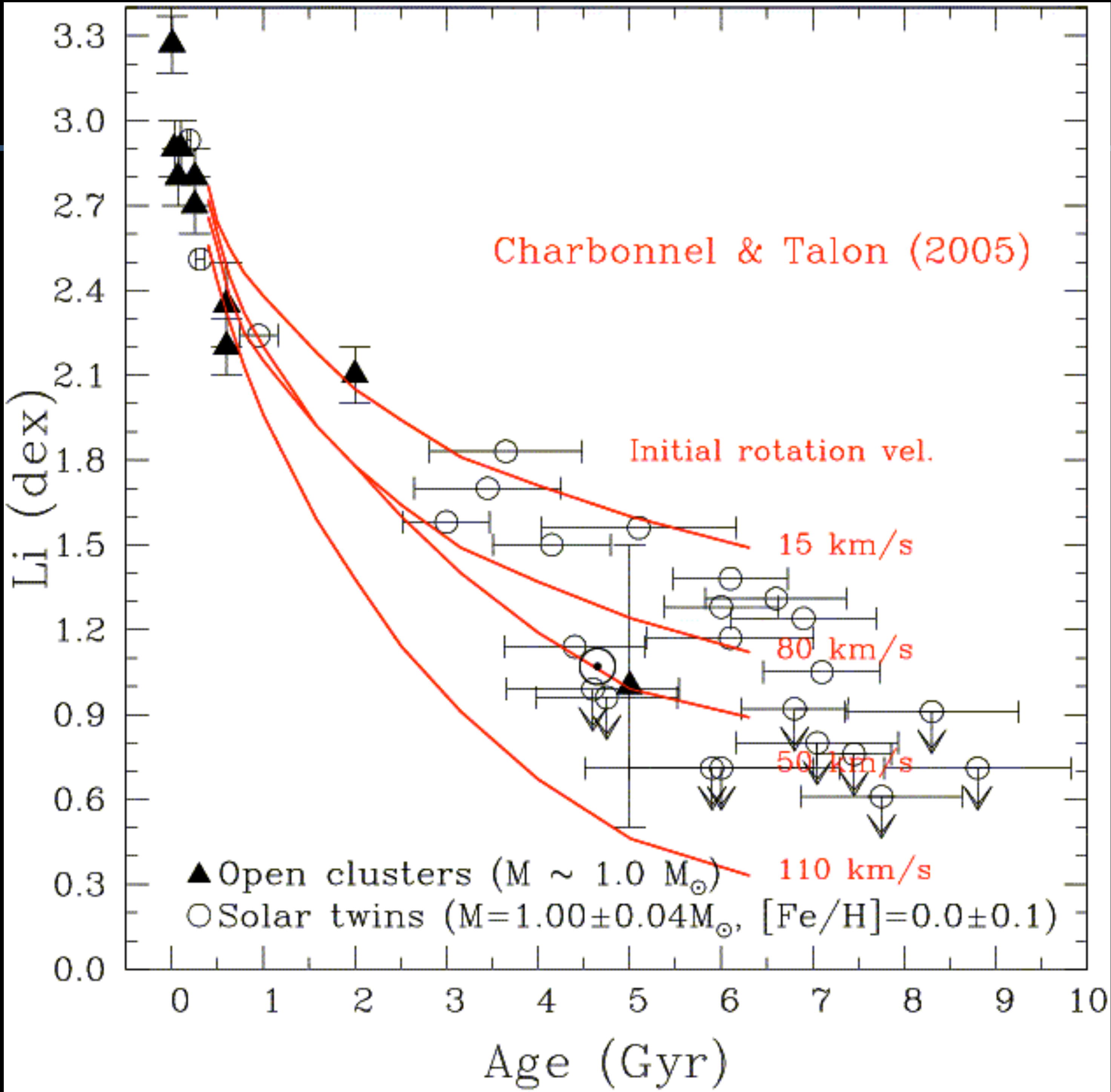


Non-standard solar models roughly fit data

Montalban & Schatzmann: mixing by internal waves

Xiong & Deng: Convective overshooting + gravitational settling

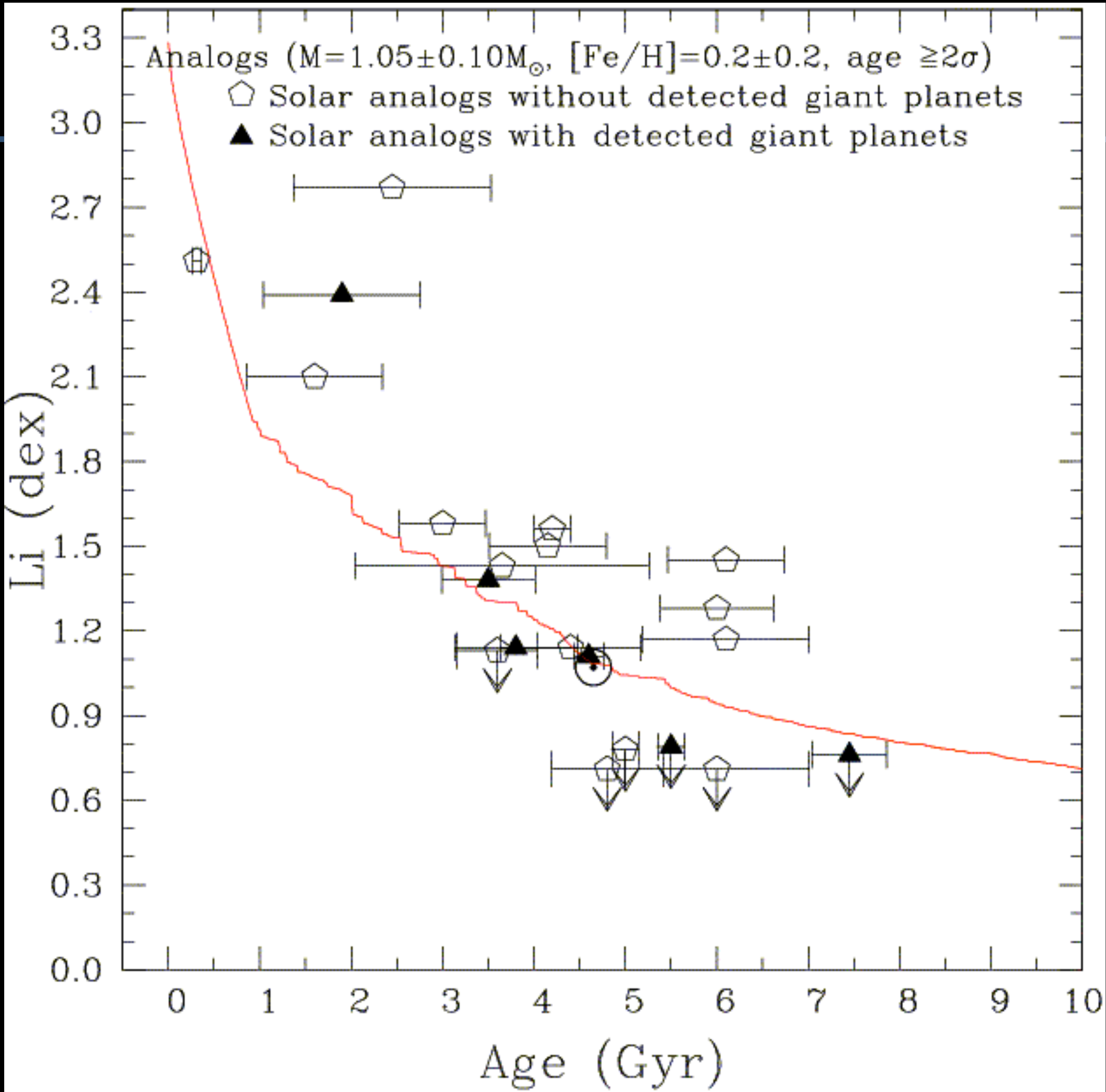
Do Nascimento et al: Difussion + grav settling + rotation-induced mixing



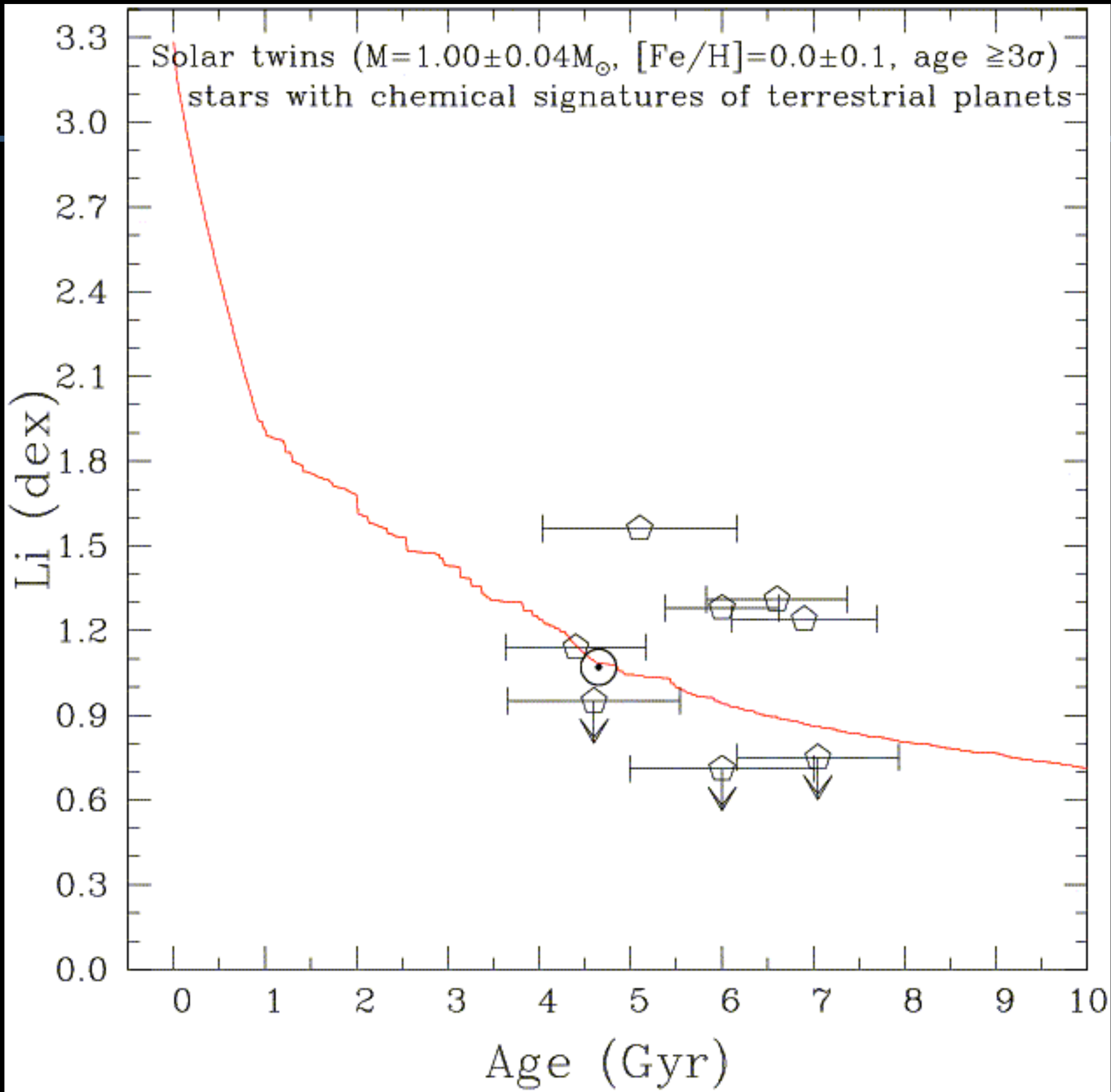
Non-standardss olar models roughly fit data

If Li dispersion is real it may be explained but different initial rotation velocities: more data needed !

Li in stars with and without planets is similar



If Li dispersion is real it may be explained but different initial rotation velocities: more data needed !



Li in stars with and without planets is similar

If Li dispersion is real it may be explained but different initial rotation velocities: more data needed !

Conclusions: the solar Li problem

- The Sun is not unusually depleted among stars of the same mass, age & metallicity
- Both open cluster and field solar twins give a consistent chemical evolution history for Li
- Lithium in the Sun, field & open cluster solar twins could help to refine the solar model
- Better ages & Li abundances should be obtained for young & old solar twins, respectively: help in the way (HARPS: seismic age of 18 Sco; Li: high S/N UVES spectra)


END