Depletion signatures in the Spite plateau
new insights from UVES data

Altiplano
Peruvian high plateau in the Andes

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Iván Ramírez *(Austin)*, **Karin Lind** *(MPA)*

Spread of the Spite plateau: NO

Astron. Astrophys. 307, 172–183 (1996)

Spread of the lithium abundance in halo stars*

M. Spite[1], P. François[2], P.E. Nissen[3], and F. Spite[1]

[1] Observatoire de Paris, Section de Meudon, DASGAL, URA 335 du CNRS, F-92195 Meudon Cedex, France
[2] Observatoire de Paris, DASGAL, URA 335 du CNRS, 61 Av. de l'Observatoire F-75014 Paris, France
[3] Institute of Physics and Astronomy, University of Aarhus, DK

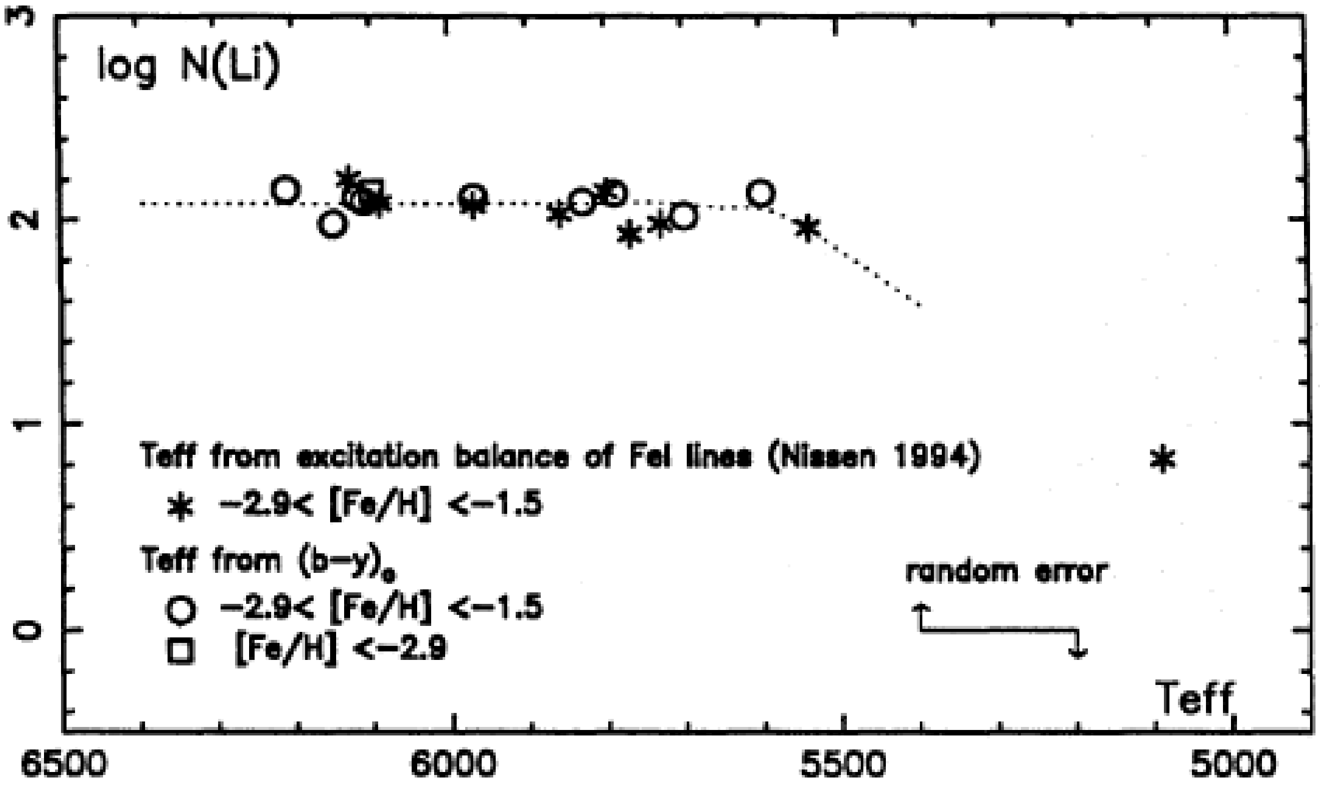


Fig. 5. Lithium abundance versus temperature. When the temperature could not be deduced from the excitation balance of the FeI lines (stars in Nissen et al. 1994) it has been deduced from the $(b-y)_o$ index. The level of the plateau is 2.08 and the rms scatter around the mean 0.07.

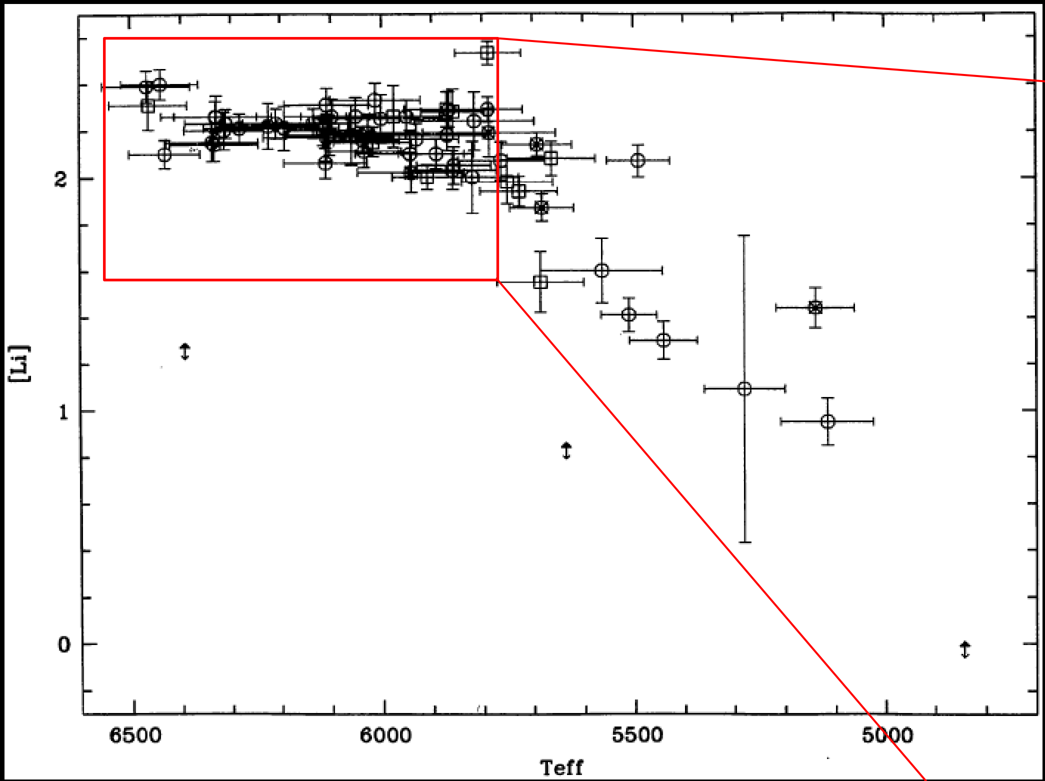
Spread of the Spite plateau: tiny

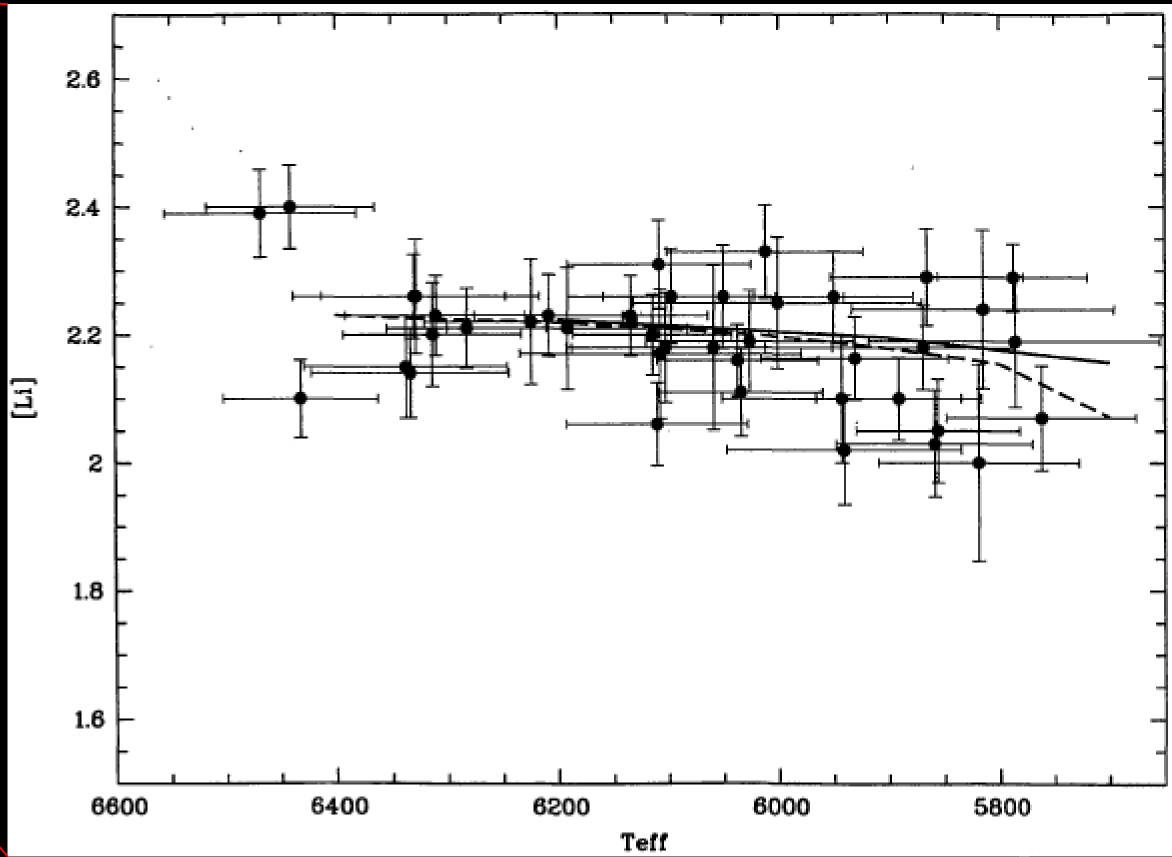
Mon. Not. R. Astron. Soc. **285**, 847–861 (1997)

The primordial lithium abundance

P. Bonifacio and P. Molaro

[Fe/H] ≤ -1.5) we found no evidence for intrinsic dispersion, a tiny trend with T_{eff} and no trend with [Fe/H]. The trend with the T_{eff} is fully consistent with the standard





Spread of the Spite plateau: NO

THE ASTROPHYSICAL JOURNAL, 523:654–677, 1999 October 1

THE SPITE LITHIUM PLATEAU: ULTRATHIN BUT POSTPRIMORDIAL[1]

SEAN G. RYAN
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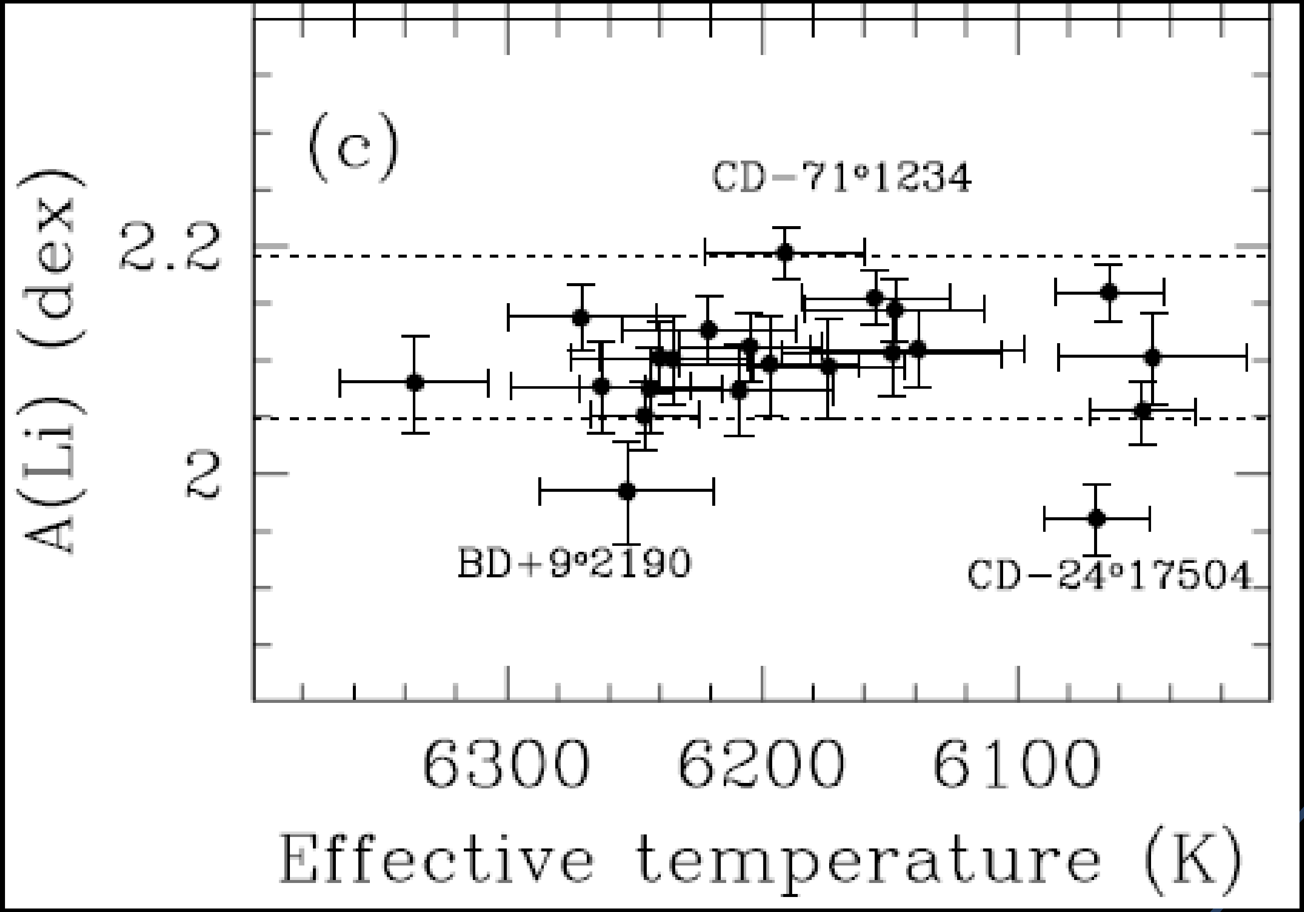
AND

previous studies. Our sample does not exhibit a trend with effective temperature, although the temperature range is limited. However, for $-3.6 < [Fe/H] < -2.3$ we do recover a dependence on metal-



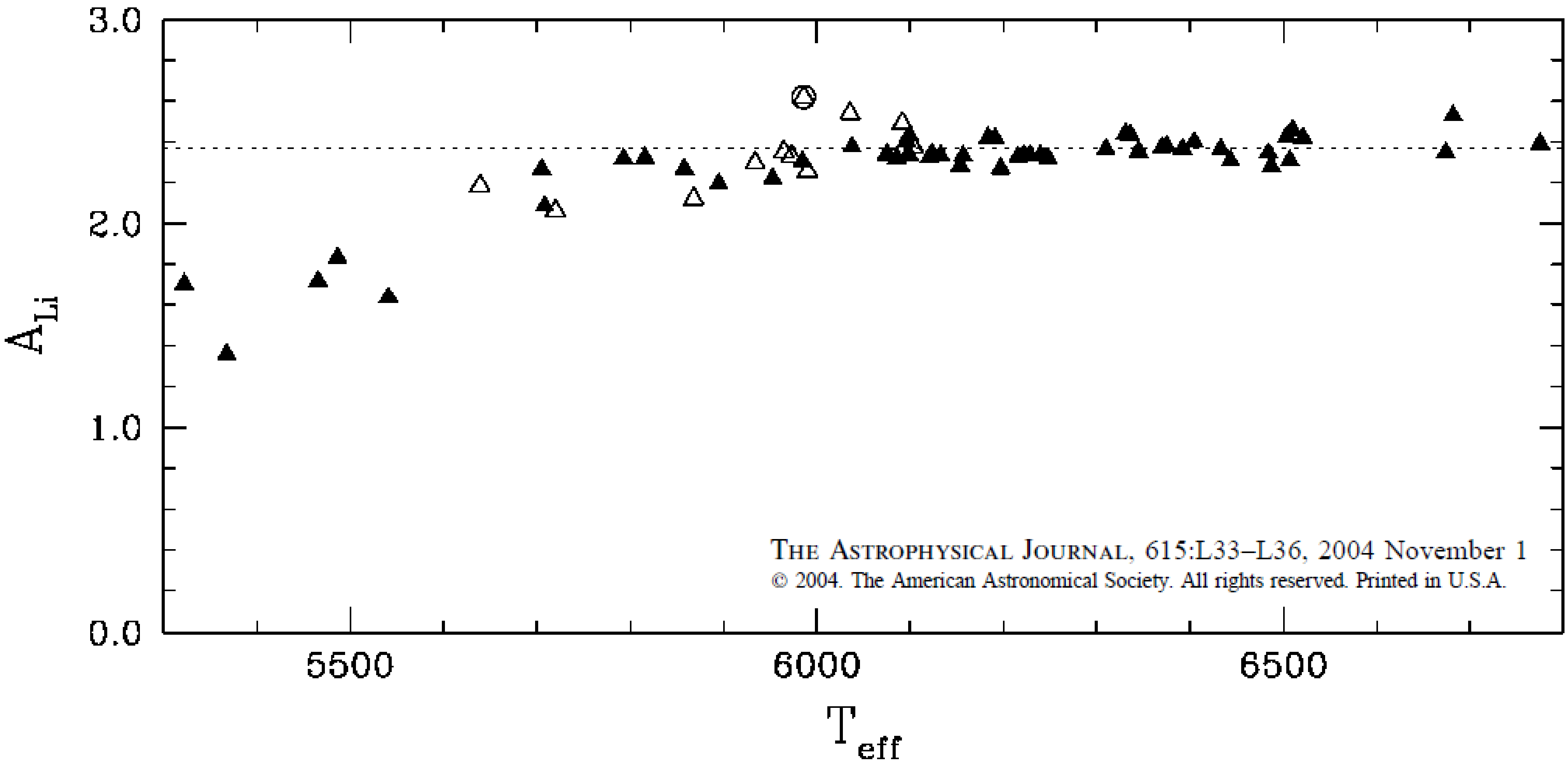
Spread of the Spite plateau: NO

REAPPRAISING THE SPITE LITHIUM PLATEAU: EXTREMELY THIN AND MARGINALLY CONSISTENT WITH *WMAP* DATA

JORGE MELÉNDEZ[1] AND IVÁN RAMÍREZ[2]

Received 2004 July 27; accepted 2004 September 15; published 2004 September 27

and an improved infrared flux method temperature scale. The Li abundance of 41 plateau stars (those with T_{eff} > 6000 K) is found to be independent of temperature and metallicity, with a star-to-star scatter of only 0.06 dex over a broad range of temperatures (6000 K < T_{eff} < 6800 K) and metallicities (−3.4 < [Fe/H] < −1), thus imposing



THE ASTROPHYSICAL JOURNAL, 615:L33–L36, 2004 November 1

Spread of the Spite plateau: perhaps

The lithium content of the Galactic Halo stars★

A&A 442, 961–992 (2005)
DOI: 10.1051/0004-6361:20042491

Charbonnel[1,2] and F. Primas[3,2,★★]

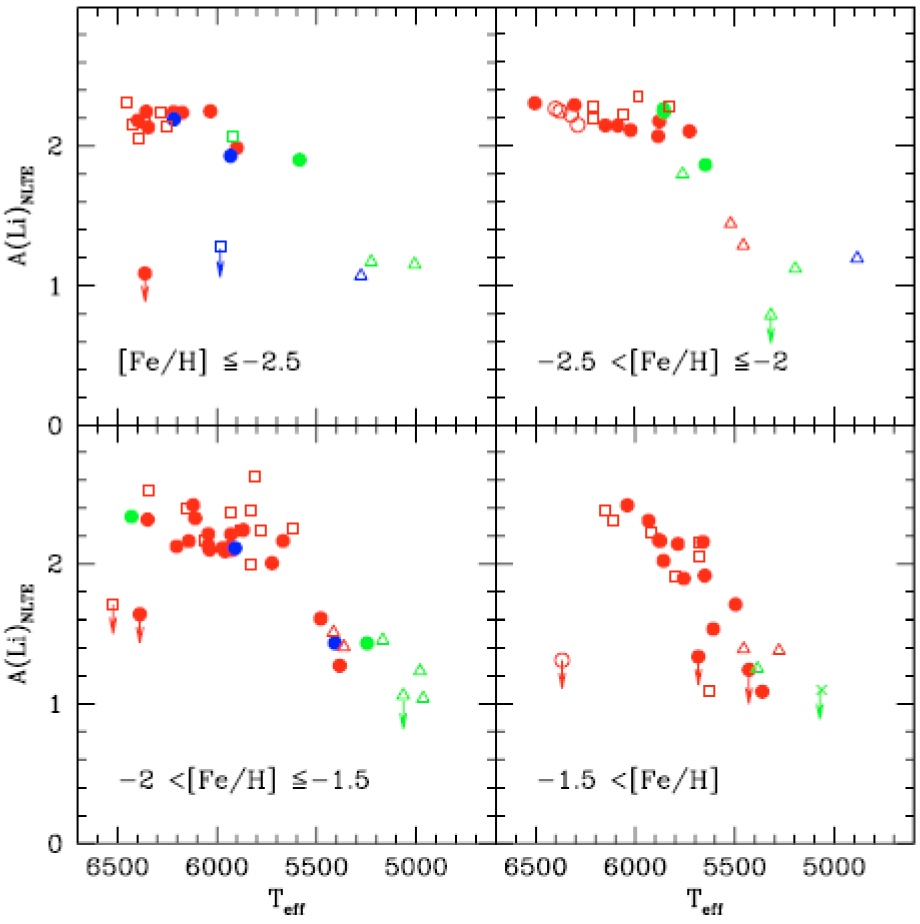


Fig. 17. $A(\mathrm{Li})_{\mathrm{NLTE}}$ versus T_{eff} (2) for our *complete* sample stars, for separate metallicity bins. The different symbols indicate the evolutionary status of the stars. Filled circles: dwarfs. Open circles: turnoff stars. Open squares: subgiants. Open triangles: stars at the base of the RGB. Crosses: RGB stars. The arrows indicate the lithium upper limits.

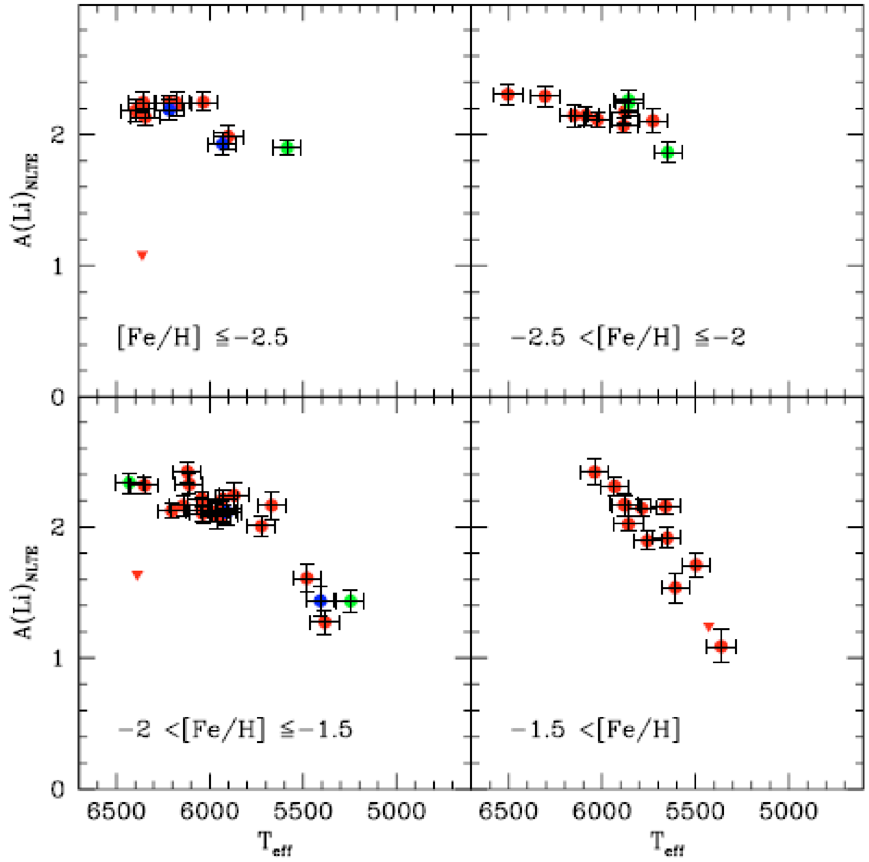


Fig. 18. $A(\mathrm{Li})_{\mathrm{NLTE}}$ versus T_{eff} (2) for the dwarfs of our *complete* sample. Upside-down triangles represent lithium upper limits.

Spread of the Spite plateau: no

A&A 462, 851–864 (2007)

First stars VII - Lithium in extremely metal poor dwarfs★,★★

P. Bonifacio[1,2,3], P. Molaro[2,3], T. Sivarani[4], R. Cayrel[2], M. Spite[2], F. Spite[2], B. Plez[5], J. Andersen[6,7], B. Barbuy[8], T. C. Beers[4], E. Depagne[9], V. Hill[2], P. François[2], B. Nordström[6], and F. Primas[10]

$-3.0 < [Fe/H] < -2.5$. Our best value for the mean level of the plateau is $A(Li) = 2.10 \pm 0.09$. The scatter around the mean is entirely explained by our estimate of the observational error and does not allow for any intrinsic scatter in the Li abundances. In addition, we

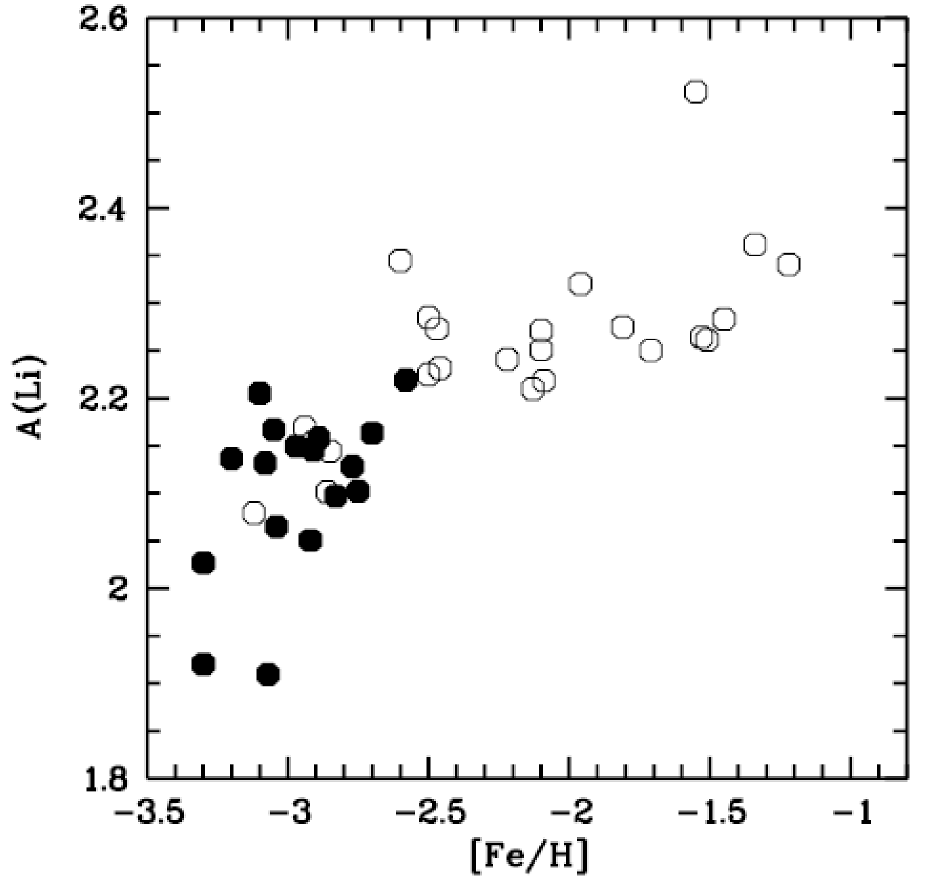


Fig. 7. Comparison of our sample (filled circles), with that of A06 (open circles). The temperature scale of both samples is based on Hα profiles.

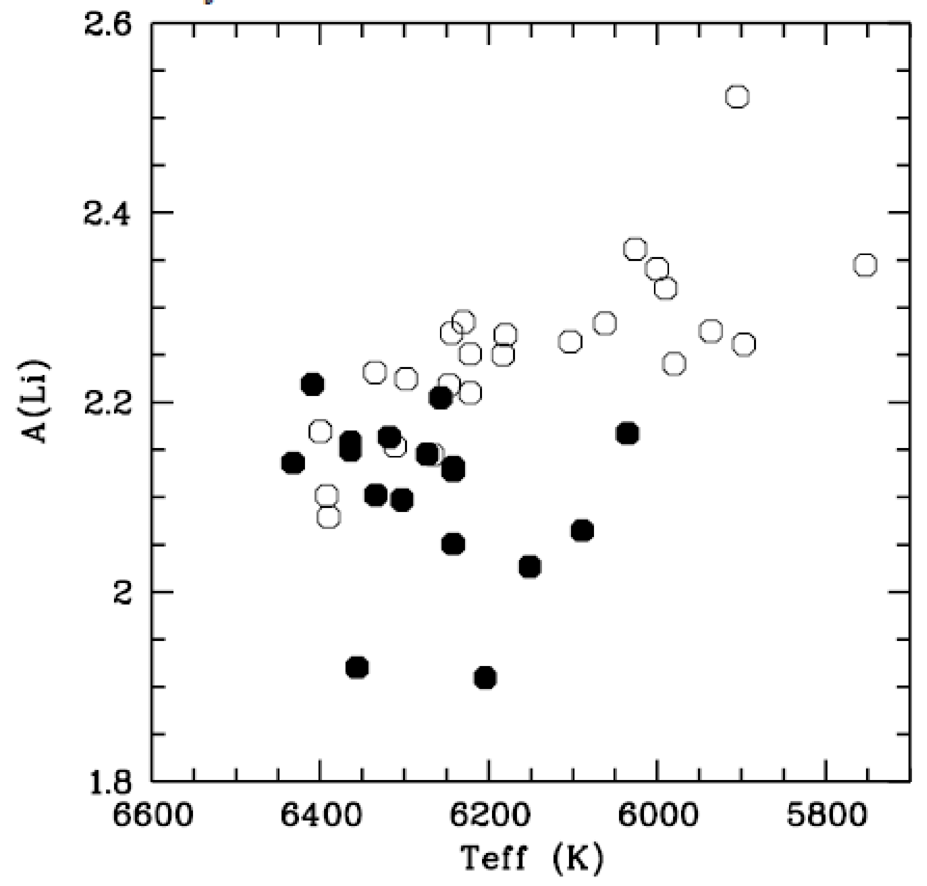


Fig. 9. Comparison of our sample (filled circles), with that of A06 (open circles) in the Li-$T_{\rm eff}$ plane.

Spread of the Spite plateau: at low [Fe/H]

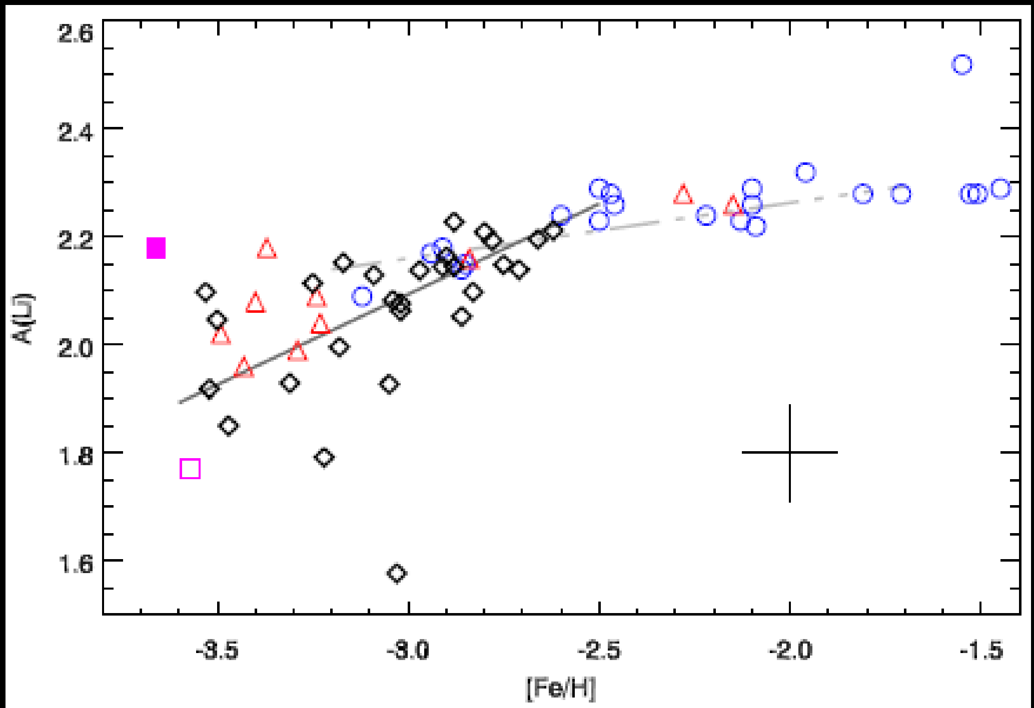
2010A&A...522A..26S

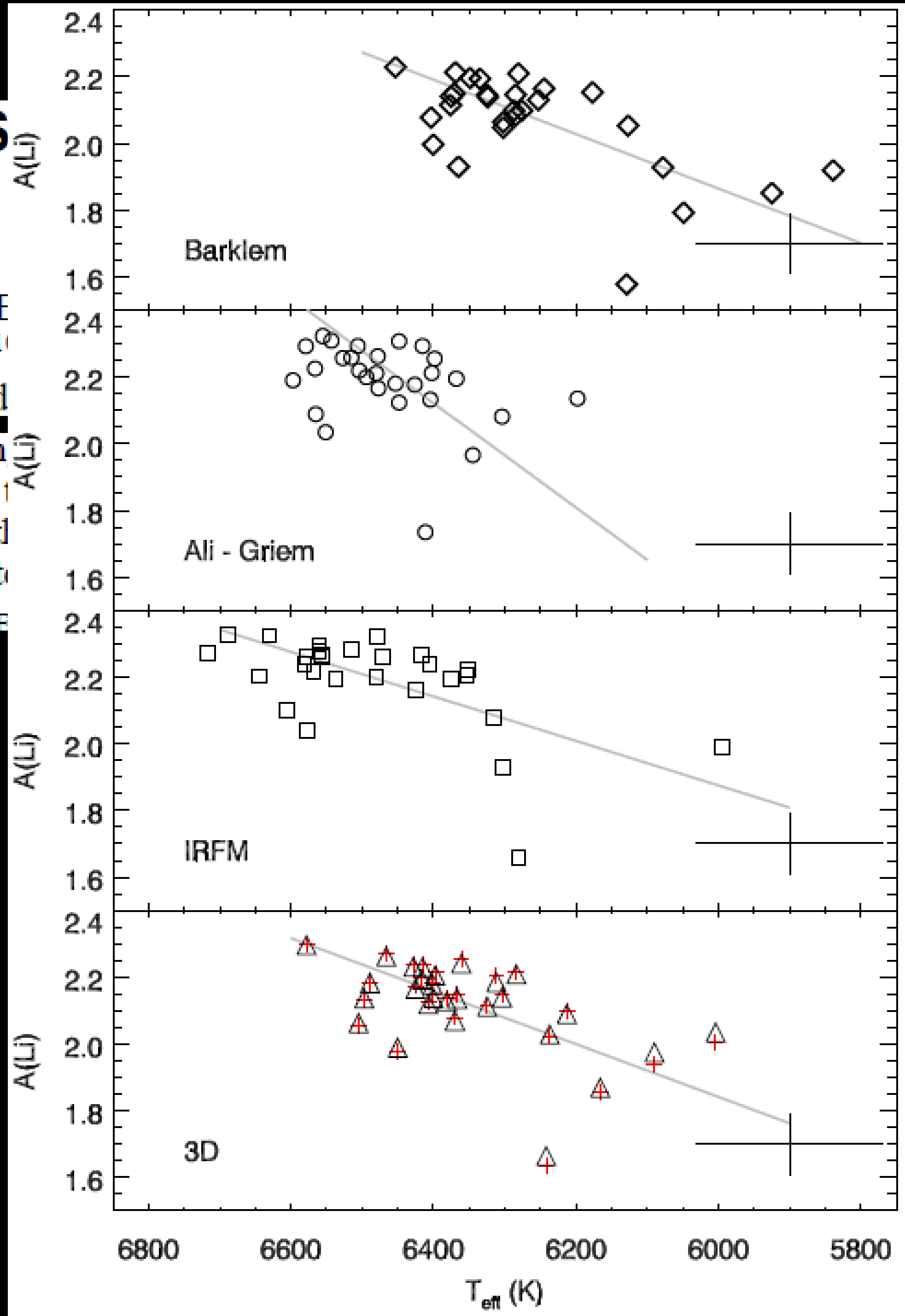
The metal-poor end of the S

I: Stellar parameters, metallicities, and

L. Sbordone[1,2,3], P. Bonifacio[1,2,4], E. Caffau[2], H.-G. Ludwig[1,2,5], N. T. B
Steffen[8], R. Cayrel[2], B. Freytag[9], C. Van't Veer[2], P. Molaro[4], B. Plez[1
Beers[12], N. Christlieb[5], P. François[2], and

dex in [Fe/H], which has a significance of 2-3 σ. The slopes derived usin
significant slope is also detected in the A(Li)–$T_{\rm eff}$ plane, driven mainly by t
to be Li-poor. However, when we remove these stars the slope detected in th
the full sample is considered, the scatter in A(Li) increases by a factor of 2 t
thin above [Fe/H]=−2.8. At this metallicity, the plateau lies at ⟨A(Li)$_{\rm 3D,NLTE}$





Spread of the Spite plateau: YES

A&A 515, L3 (2010)

Observational evidence for a broken Li Spite plateau and mass-dependent Li depletion★,★★

J. Meléndez[1], L. Casagrande[2], I. Ramírez[2], M. Asplund[2], and W. J. Schuster[3]

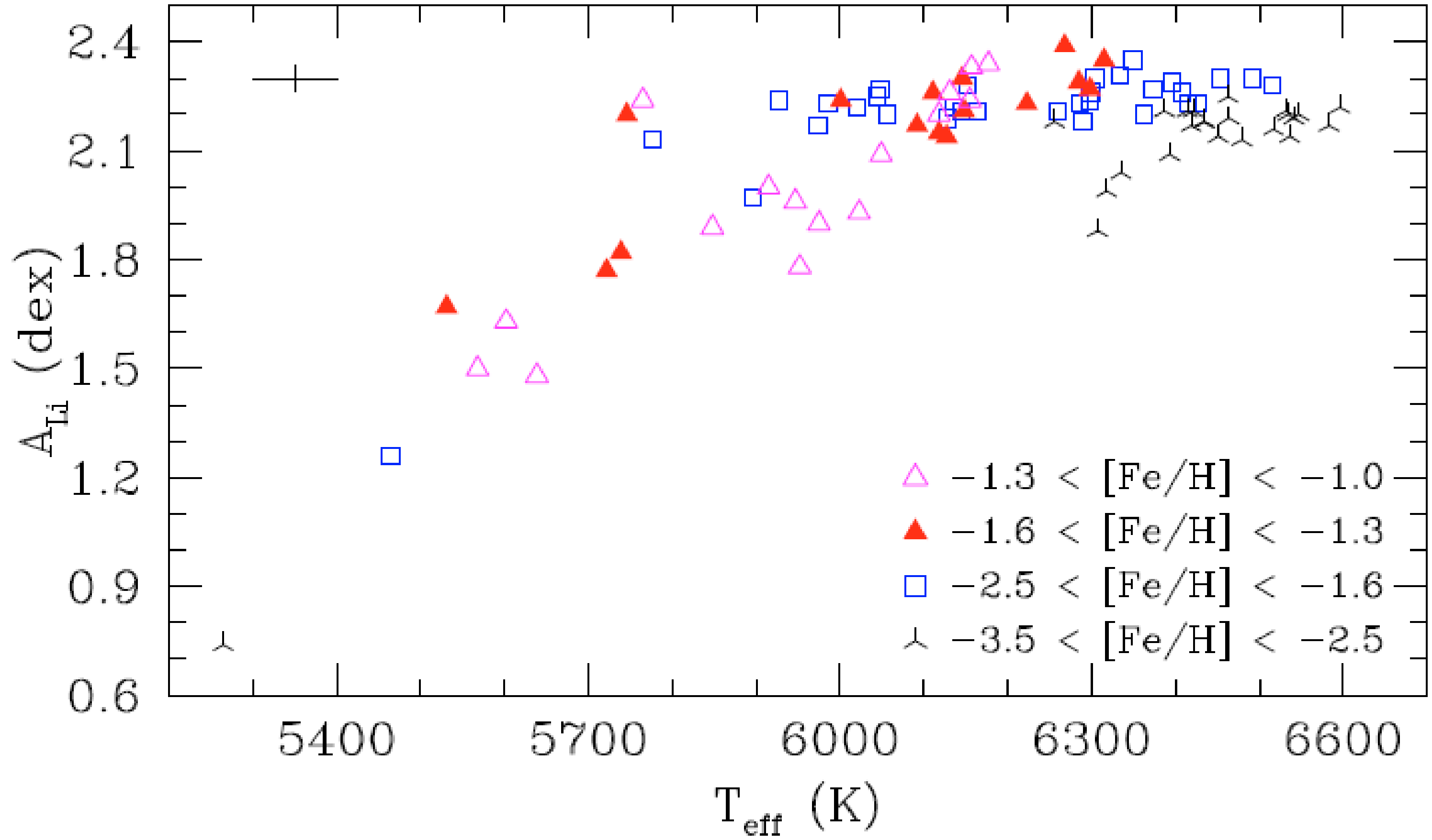


Fig. 2. Li abundances vs. T_{eff} for our sample stars in different metallicity ranges. A typical error bar is shown.

Spread of the Spite plateau: YES

A&A 515, L3 (2010)

Observational evidence for a bi
and mass-dependent Li

J. Meléndez[1], L. Casagrande[2], I. Ramírez[2], M.

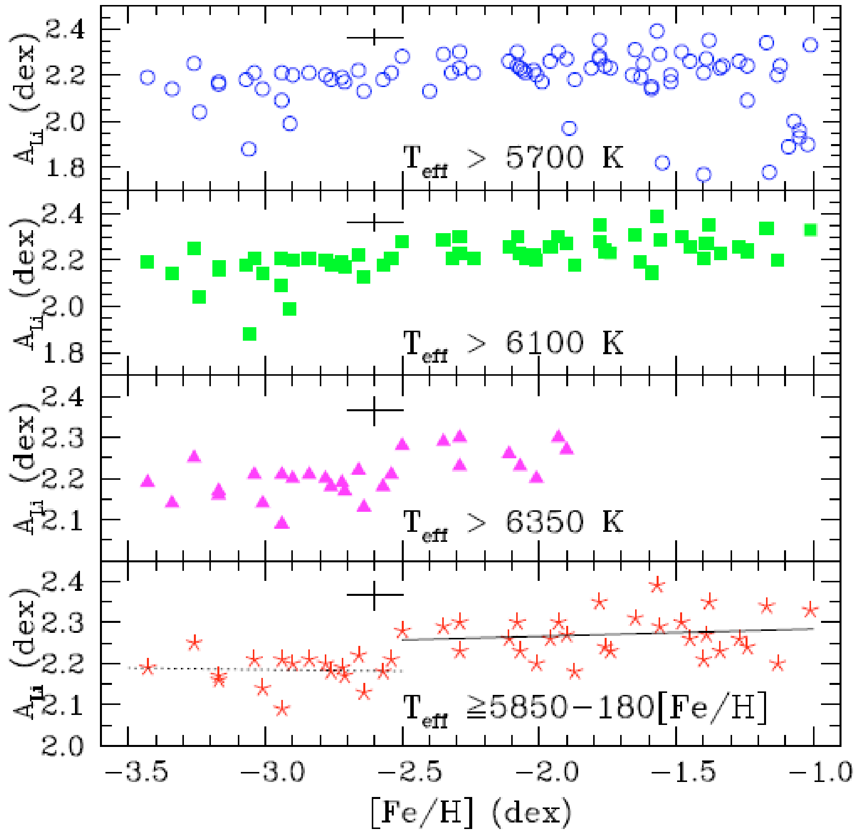


Fig. 3. Li abundances for stars with $T_{eff} > 5700$ K (open circles), >6100 K (filled squares), >6350 K (filled triangles) and ≥5850−180 × [Fe/H] (stars). In *the bottom panel* stars above the cutoff in T_{eff} fall into two flat plateaus with $\sigma = 0.04$ and 0.05 dex for [Fe/H] < −2.5 (dotted line) and [Fe/H] ≥ −2.5 (solid line), respectively.

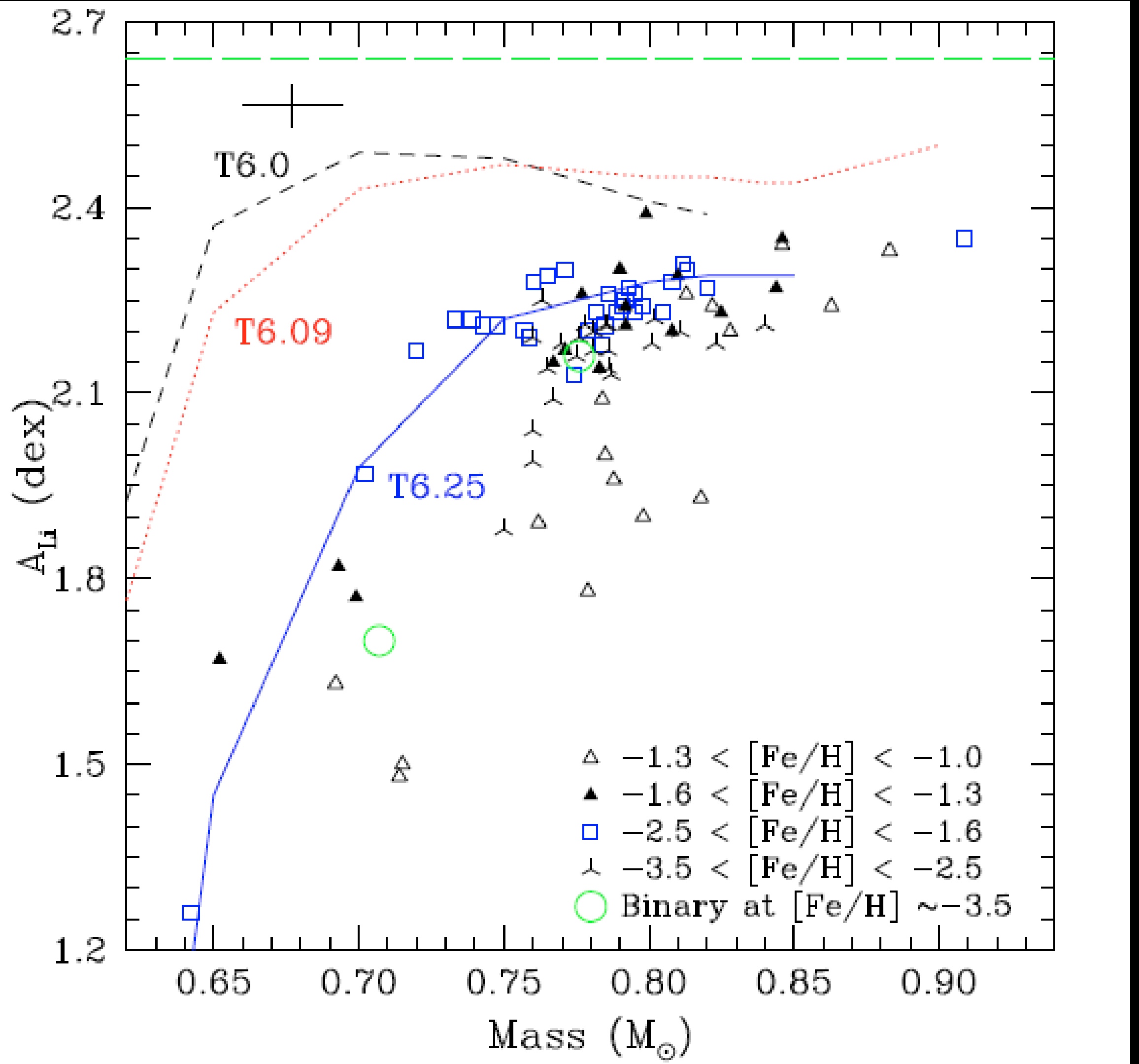


Fig. 5. Li abundances as a function of stellar mass in different metallicity ranges. The metal-poor ([Fe/H] ∼ −3.5) binary BPS CS22876-032 (G08) is represented by open circles, nicely fitting the Li-mass trend. Models at [Fe/H] = −2.3 including diffusion and T6.0 (short dashed line), T6.09 (dotted line) and T6.25 (solid line) turbulence (Richard et al. 2005) are shown. The models were rescaled to an initial A_{Li} = 2.64 (long dashed line) and by $\Delta M = +0.05\ M_\odot$.

Highest precise homogeneous analysis of Li covering a broad range in T_{eff} and metallicity

- 113 stars, mostly based on UVES/VLT data, plus some HIRES/Keck data + Data from the literature
- $-3.5 < [Fe/H] < -1$
- 5400 K < Teff < 6600 K

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

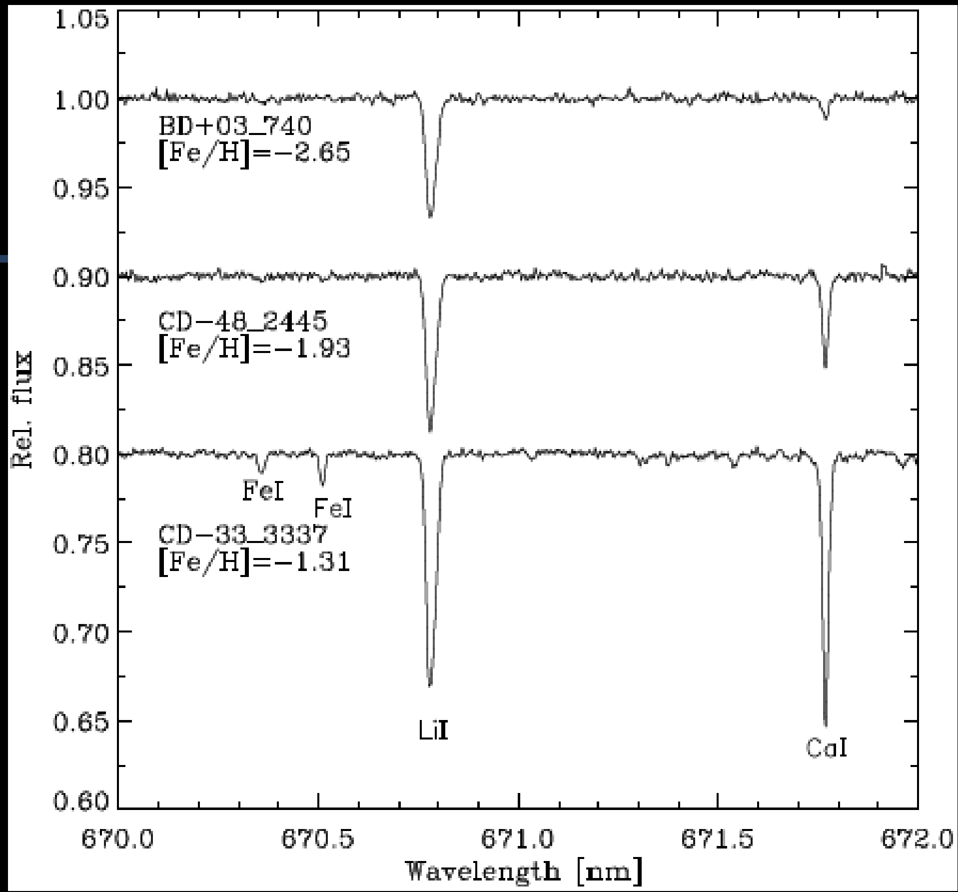
I. Less is more: use the best available data (higher resolution, higher S/N, or average literature EW data)

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. evolutionary stage, different [Fe/H] intervals

I. Best available data



Asplund et al. 2006; VLT+UVES

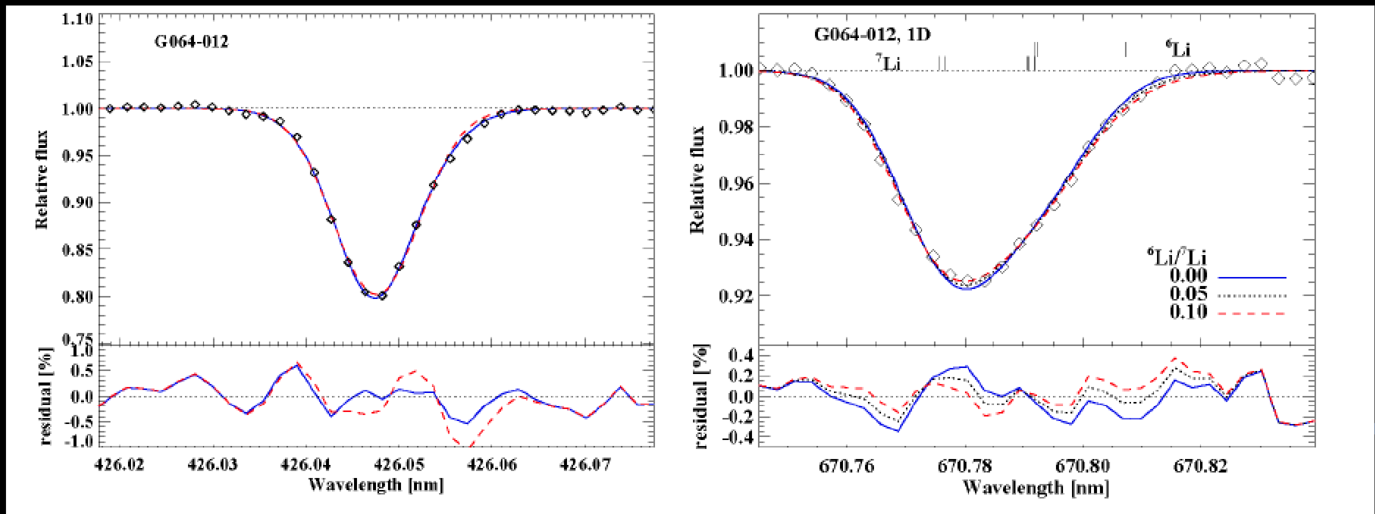


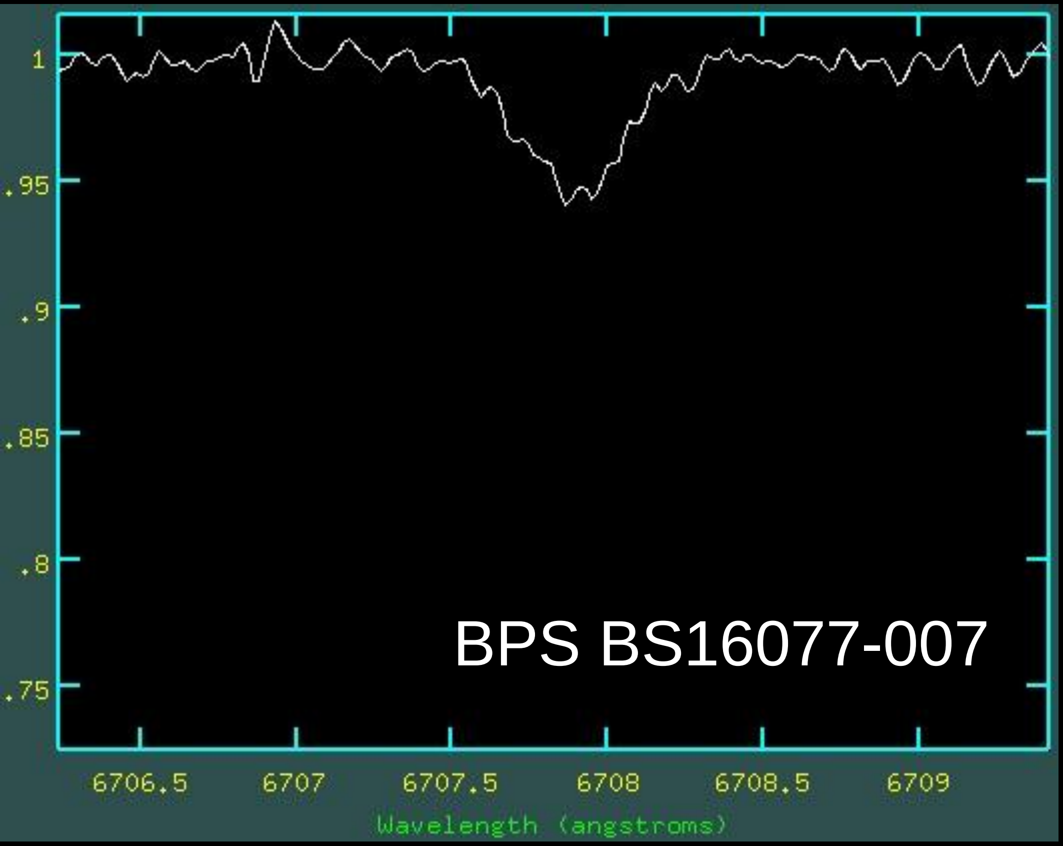
FIGURE 1. *Left panel:* The observed Fe I 426 nm line in G064-012 (rhombs) together with the best-fitting 1D (dashed, red) and 3D (solid, blue) profiles. Notice the much reduced residuals in the 3D case due to the predicted line asymmetry. *Right panel:* The observed and predicted (1D) profiles of the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

Asplund & Meléndez 2008; Keck + HIRES

I. New UVES (+HIRES) data

New UVES program (2010-B).
PI: Meléndez,
co-I: Casagrande, Ramirez, Asplund, Lind

- 23 stars observed for NaD (IS) and Li

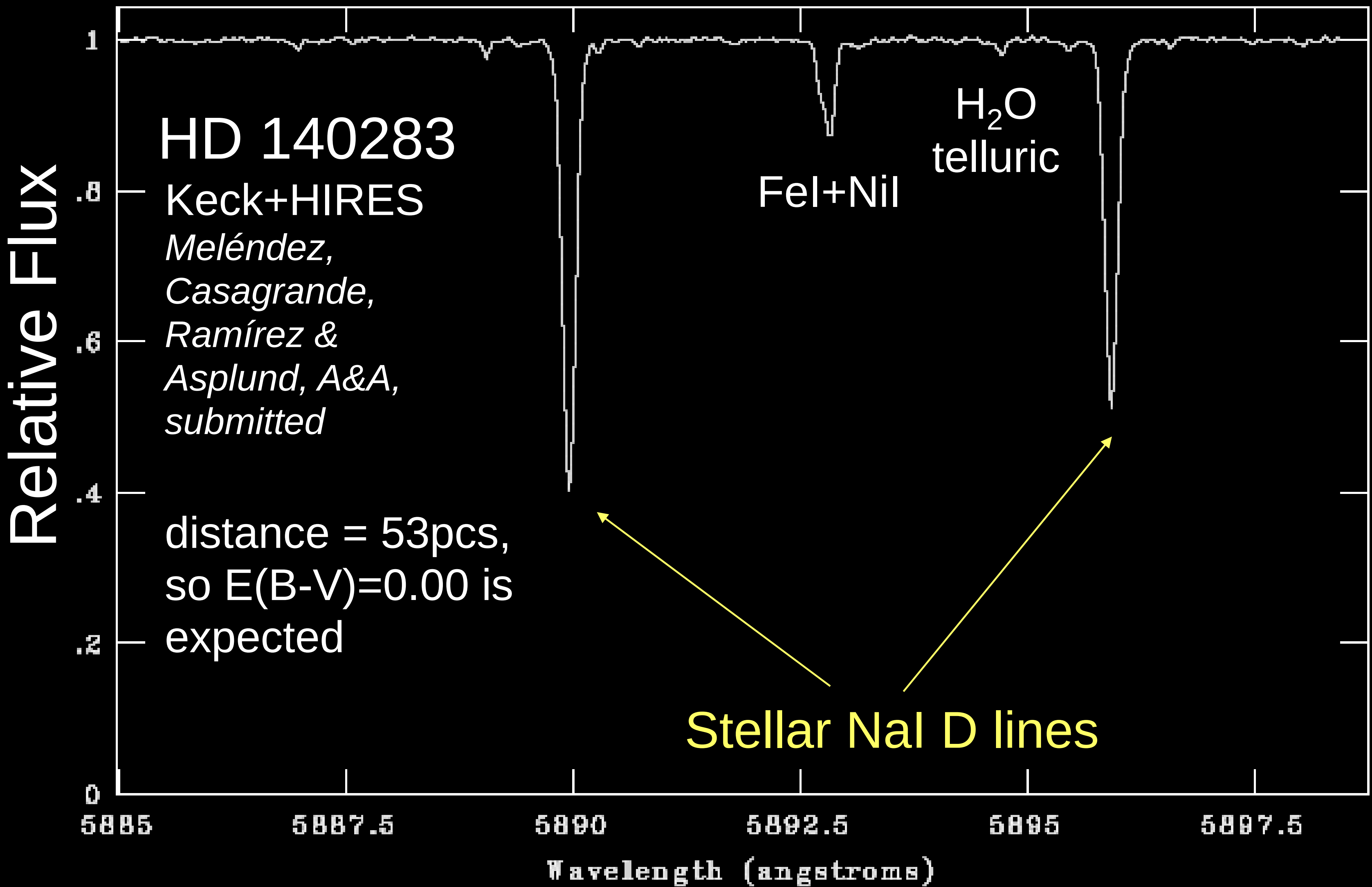


- A few more stars added from the ESO and Keck archives
(Thanks to P. Bonifacio and F.S. team for sharing the NaD region of 11 stars)

- Total sample (Melendez et al. 2010) + new sample =
113 stars in the metallicity range
$-3.5 < [Fe/H] < -1$

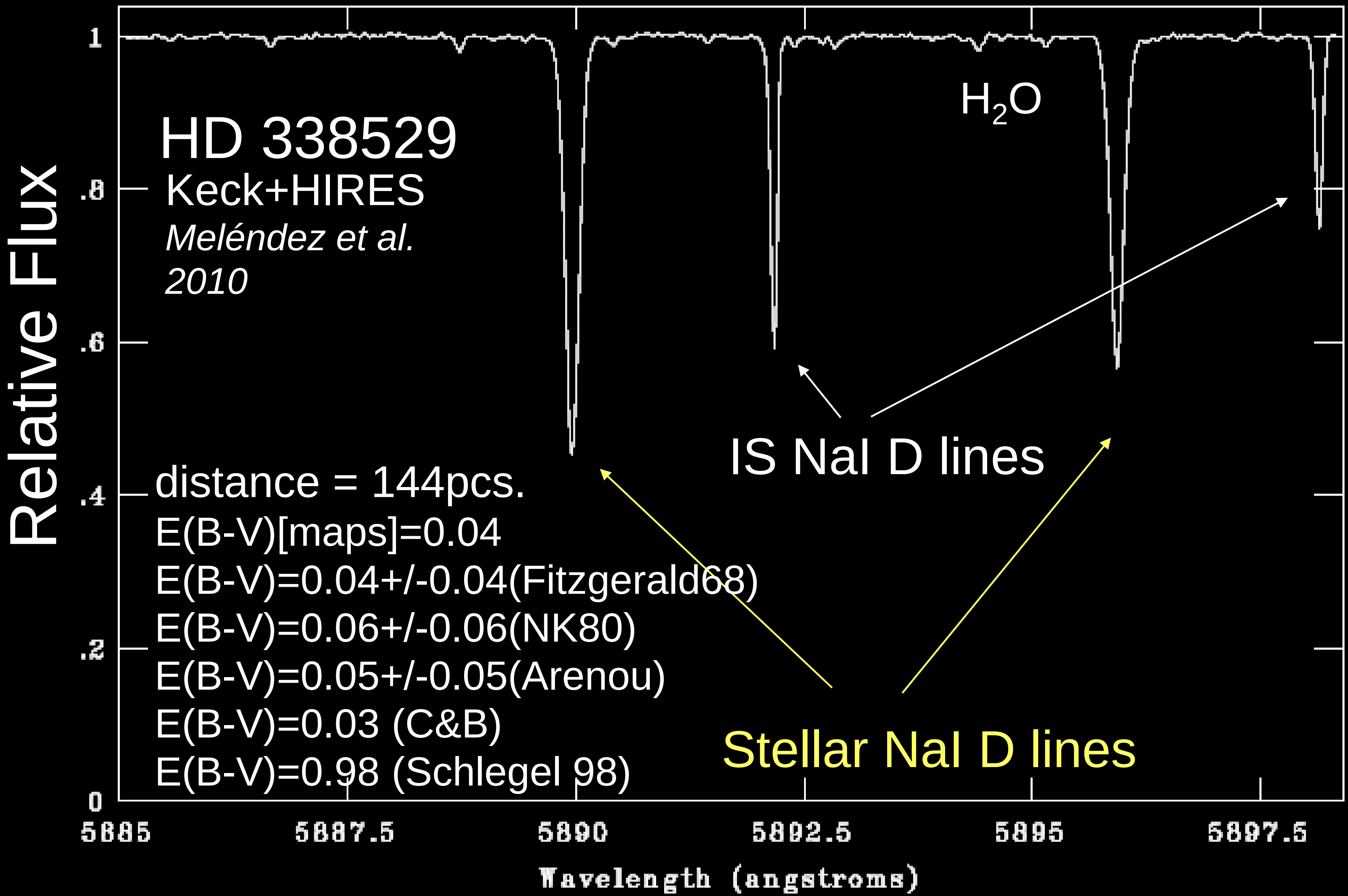
II. Improve E(B-V): using NaD lines

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



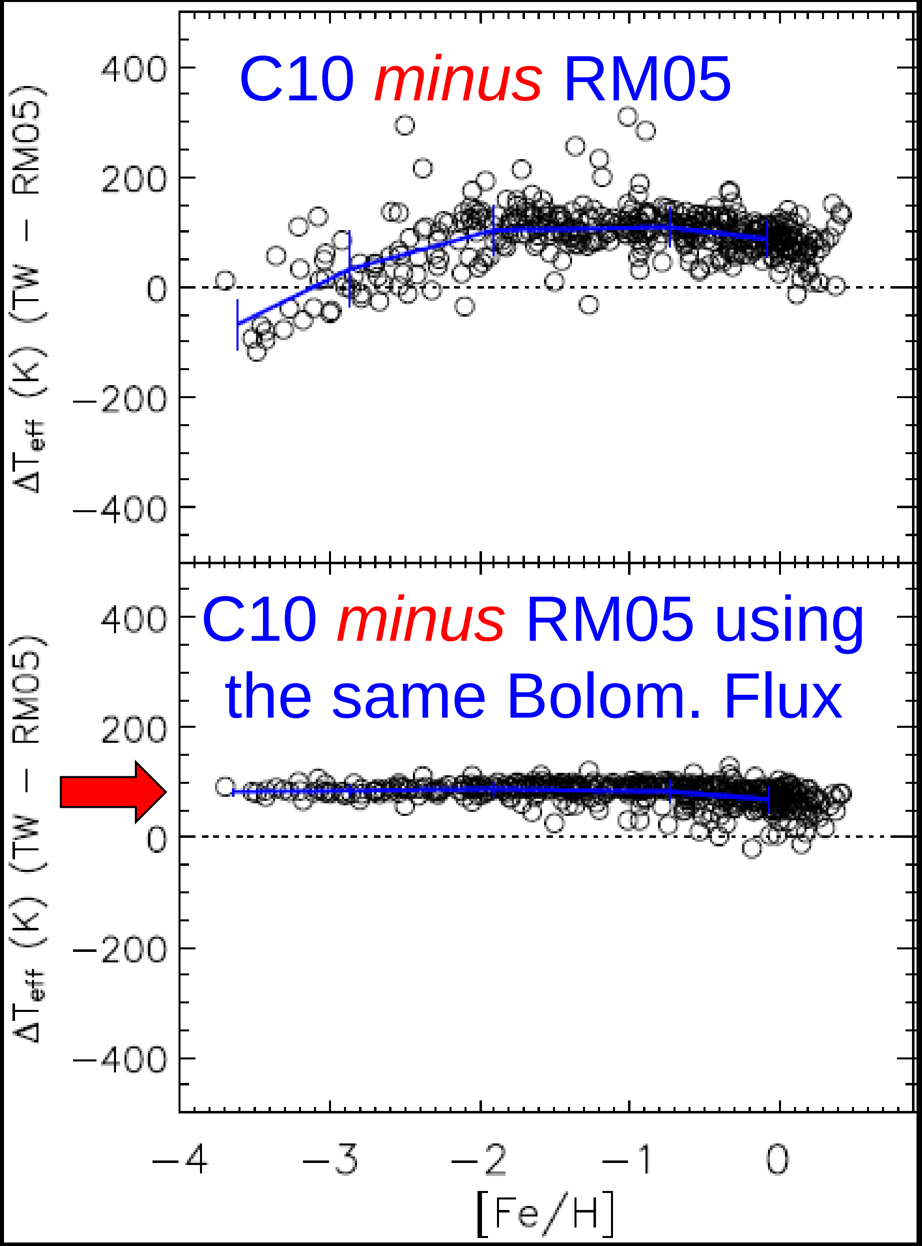
II. Improve E(B-V): using NaD lines

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



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

Casagrande, Ramírez, Meléndez, Bessell & Asplund 2010 (A&A, in press)



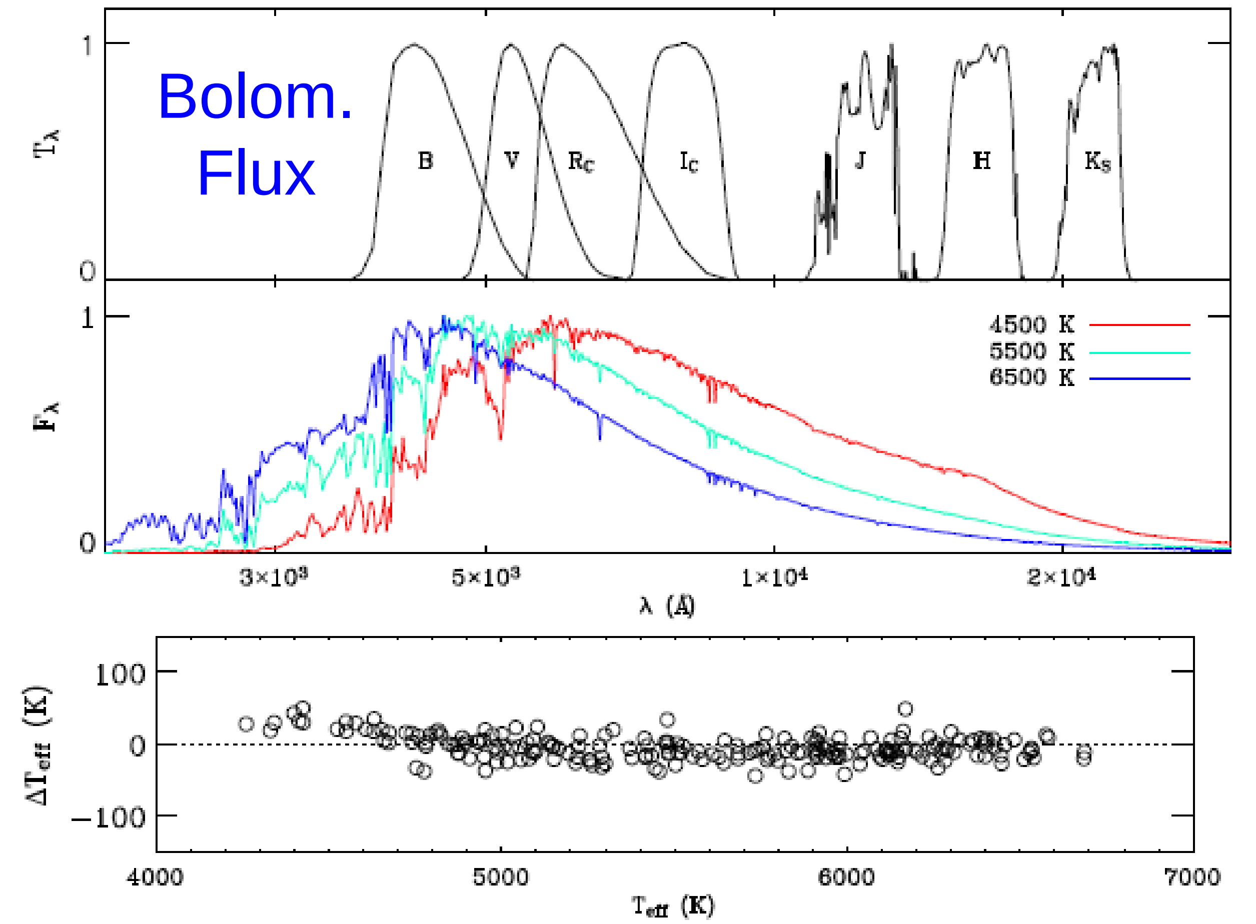
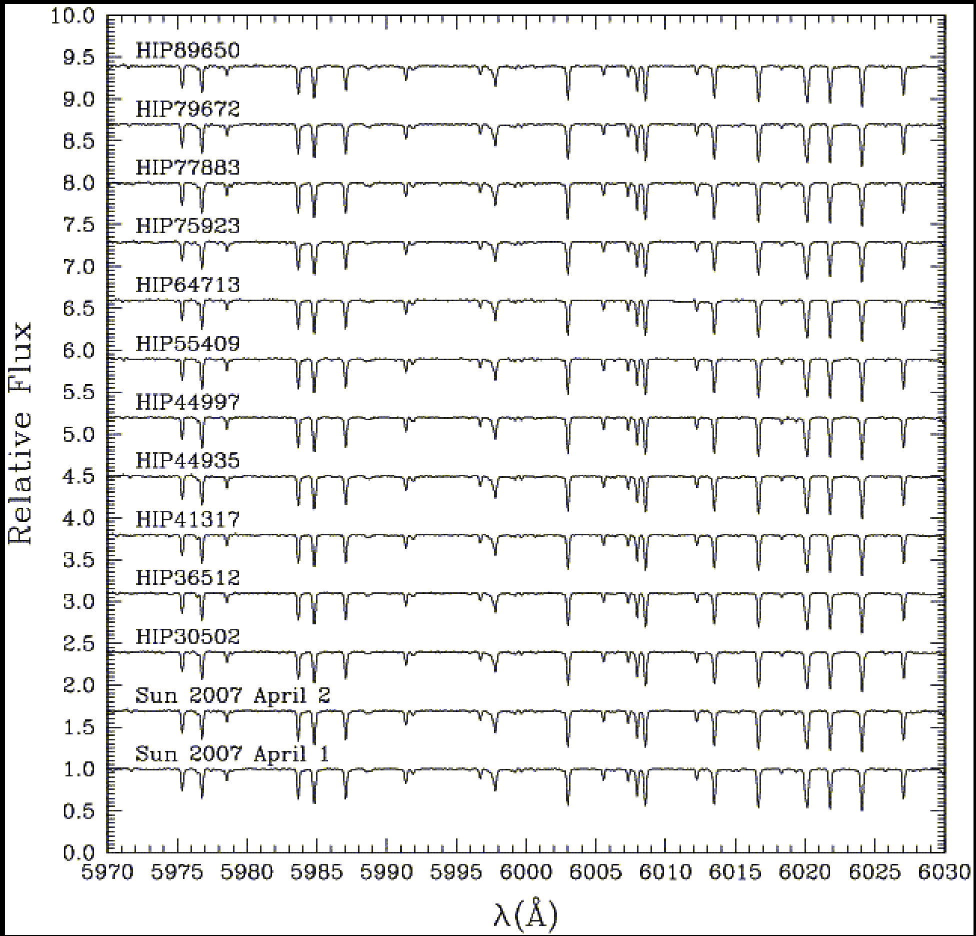


Fig. 1. Top panel: Johnson-Cousins-2MASS filter sets used in this work. Middle panel: synthetic solar metallicity spectra at different $T_{\rm eff}$. For the sake of comparison all curves have been normalized to unit. Bottom panel: difference in effective temperatures with – without using $(RI)_C$ magnitudes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

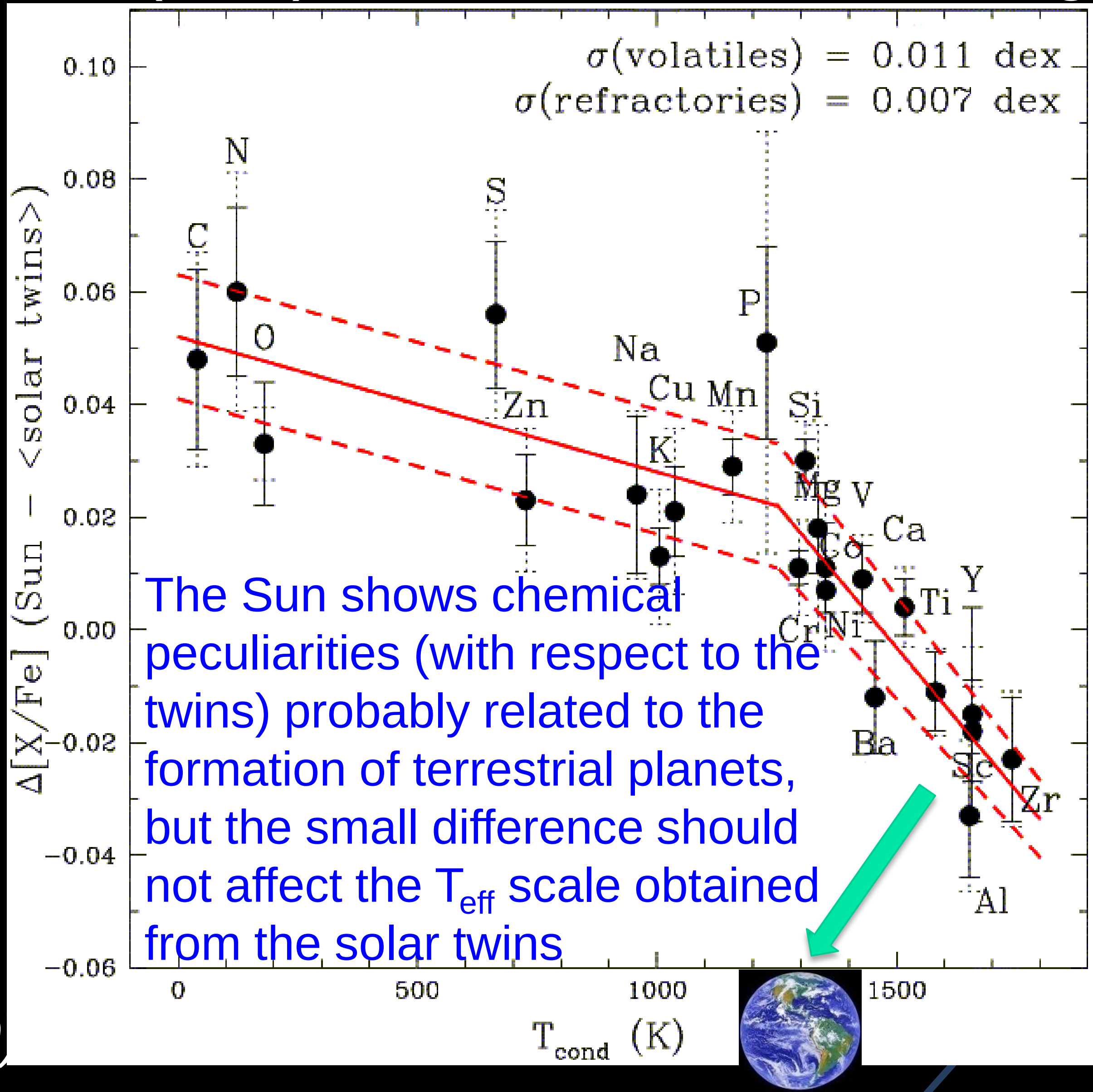
III. Improve the T_{eff} scale: solar twins

Casagrande, Ramírez, Meléndez, Bessell & Asplund 2010, A&A

Zero-point of our new T_{eff} scale (C10) has been checked using solar twins

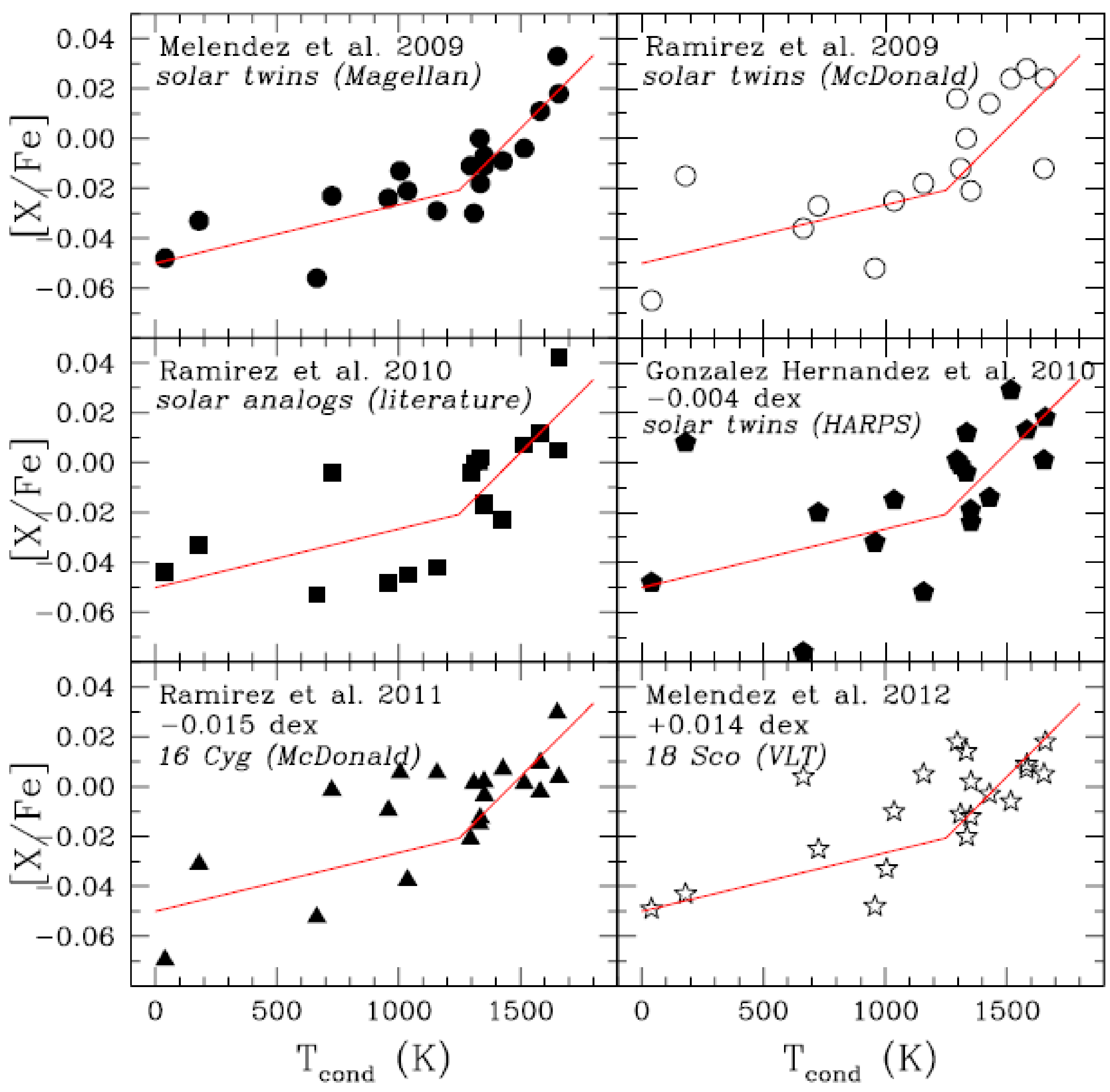


Southern Solar twins found with Magellan+MIKE (Meléndez et al.09)

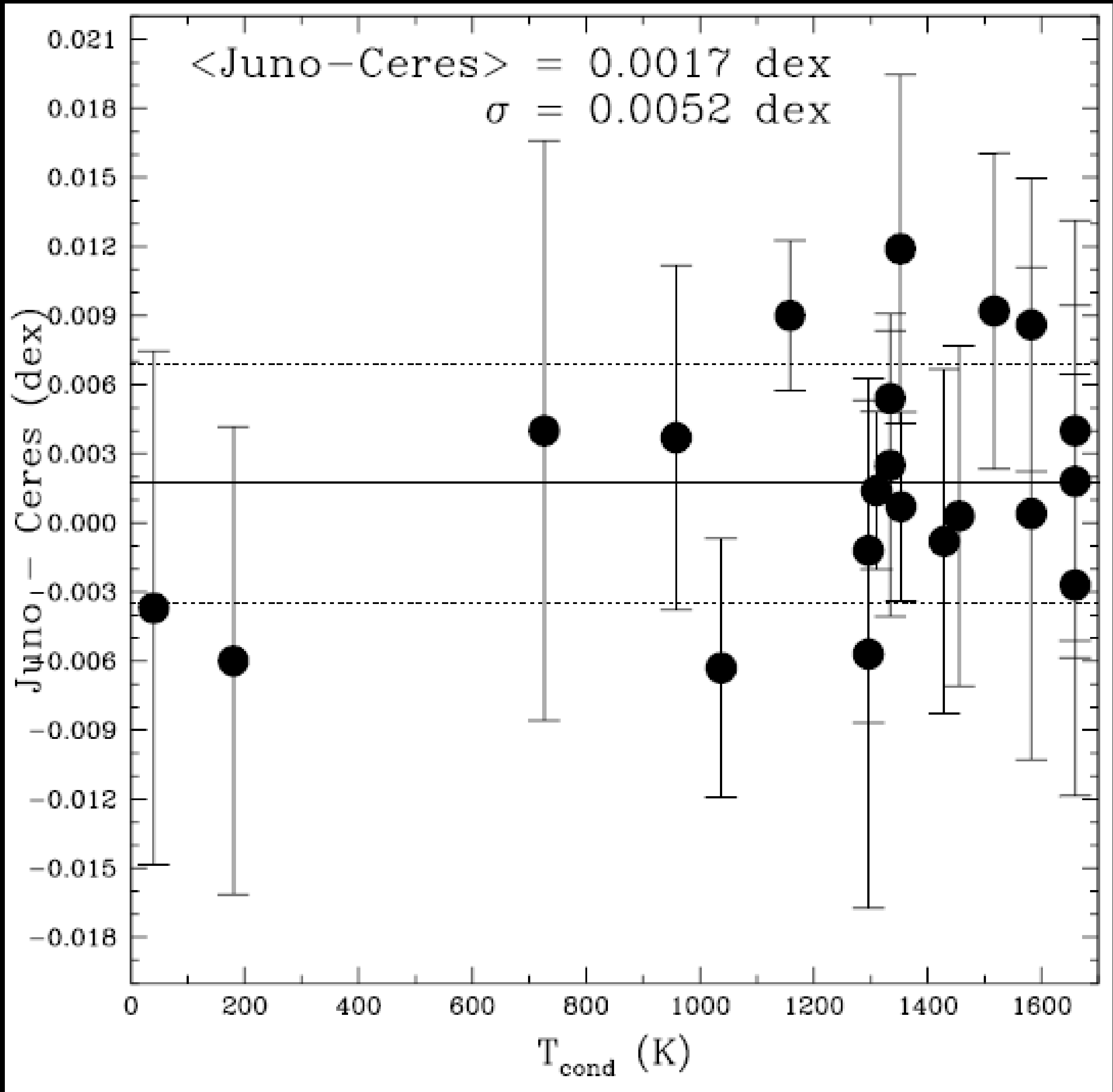


The Sun shows chemical peculiarities (with respect to the twins) probably related to the formation of terrestrial planets, but the small difference should not affect the T_{eff} scale obtained from the solar twins

The Sun has chemical anomalies!

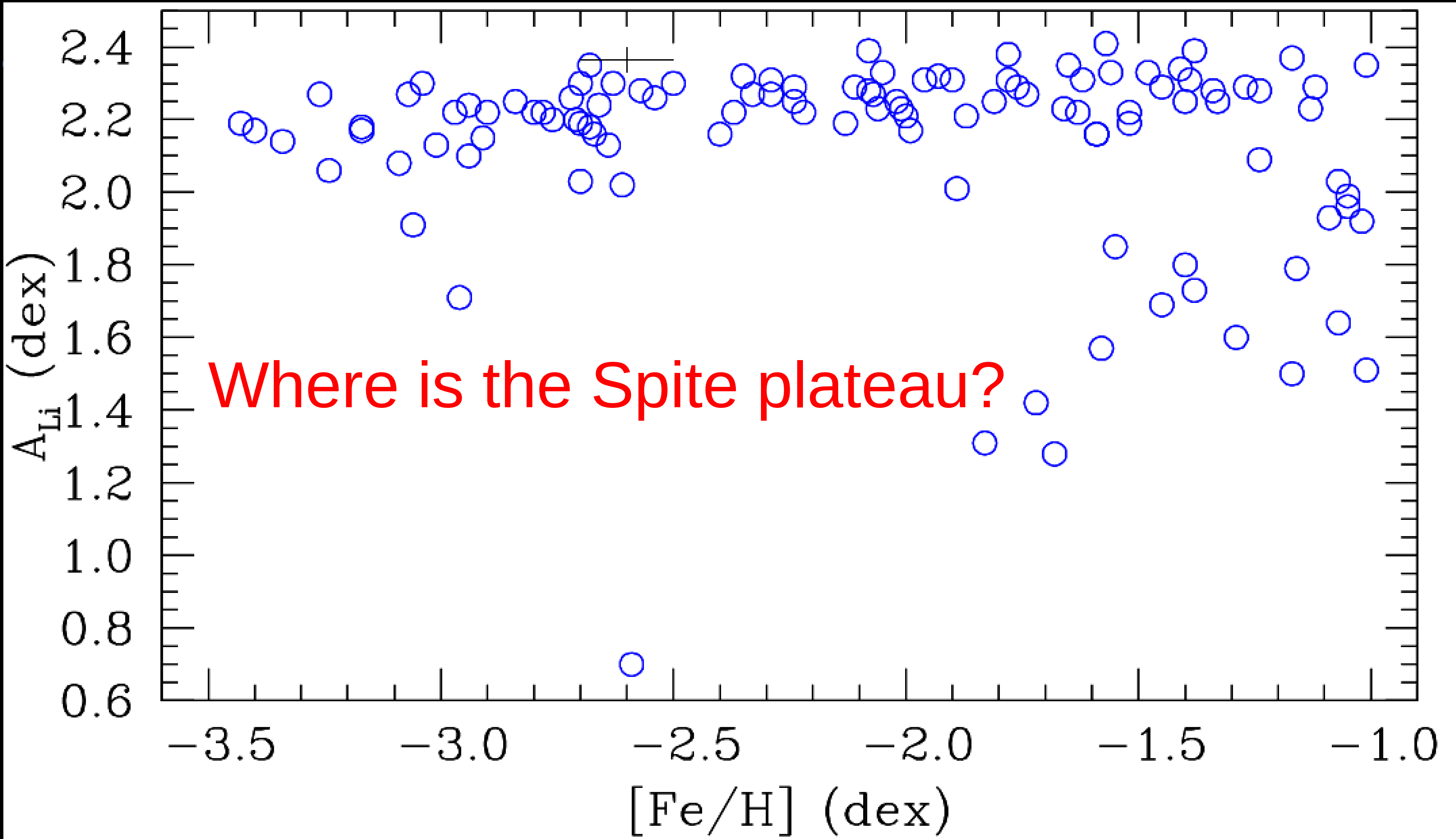


Check of our errors using 2 asteroids (sigma = 0.005 dex !!!)



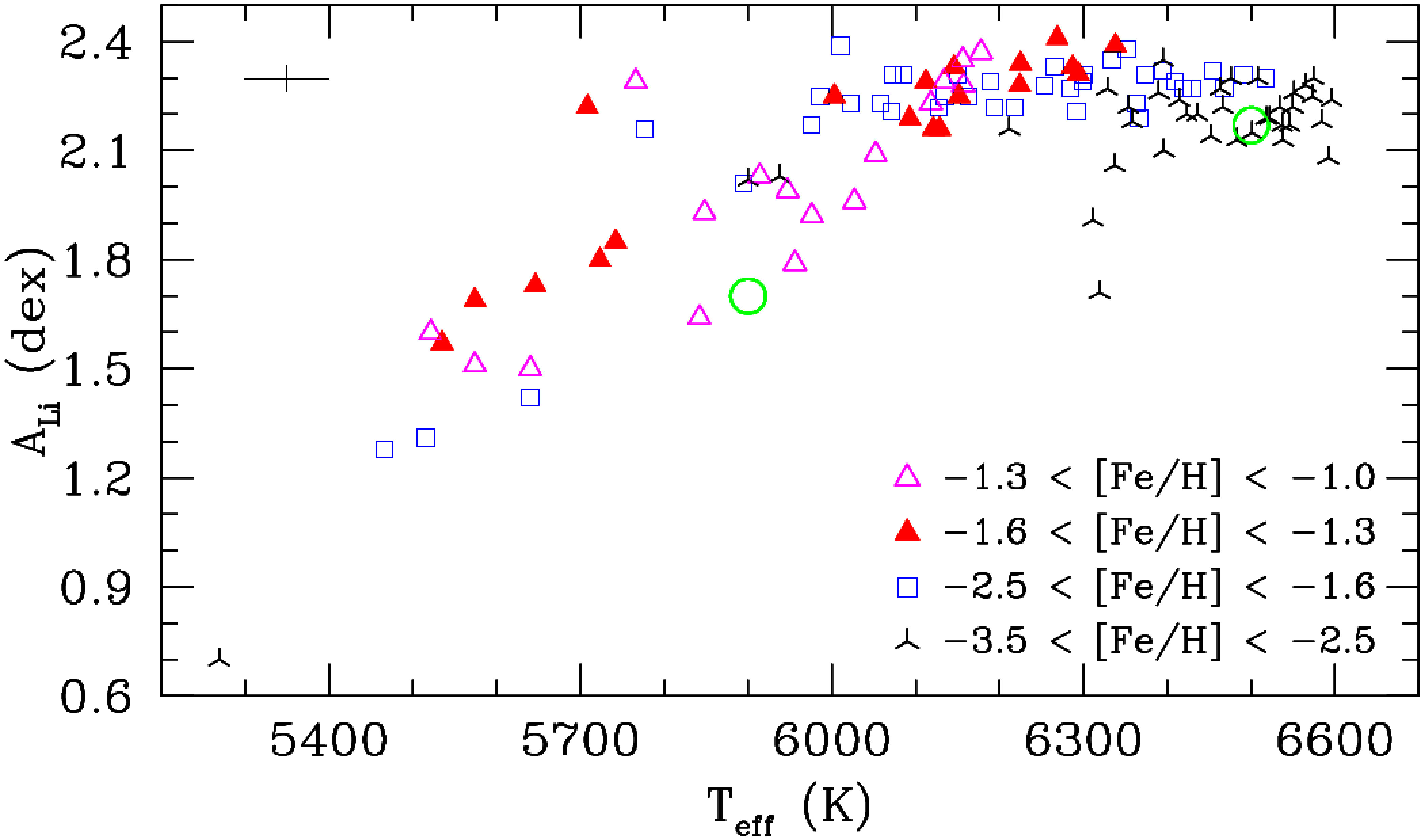
IV. New results on Li in metal-poor stars

IV. New results: A(Li) vs. [Fe/H]



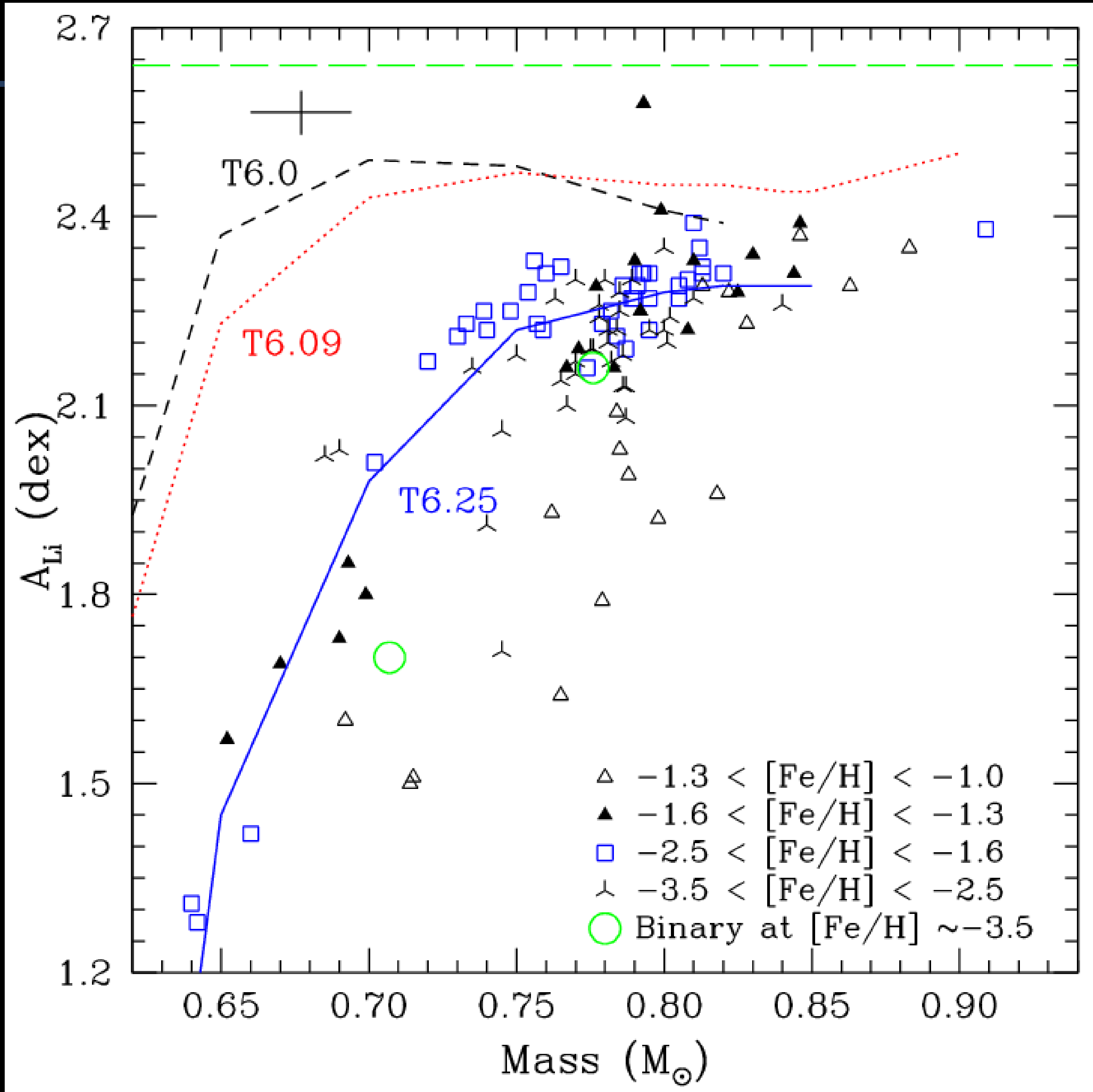
Meléndez et al. 2012, in preparation

IV. New results: A(Li) vs. Teff



Meléndez et al., in preparation

IV. New results: A(Li) vs. mass



Meléndez et al., in preparation

Explore stellar depletion in 6 metallicity bins (113 stars)

- 1.25 < [Fe/H] < -1.00

- 1.50 < [Fe/H] < -1.25

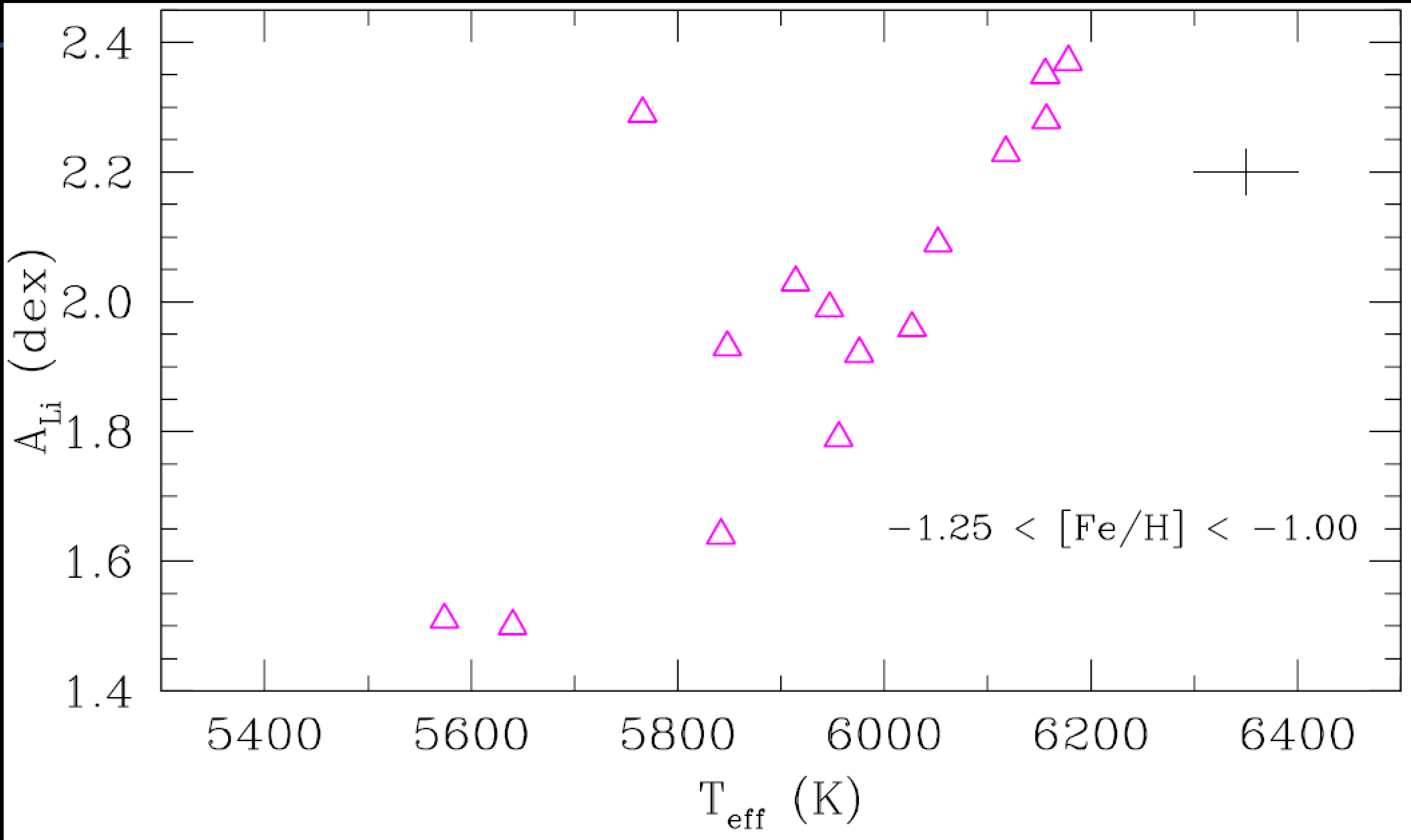
- 2.0 < [Fe/H] < -1.5

- 2.5 < [Fe/H] < -2.0

- 3.0 < [Fe/H] < -2.5

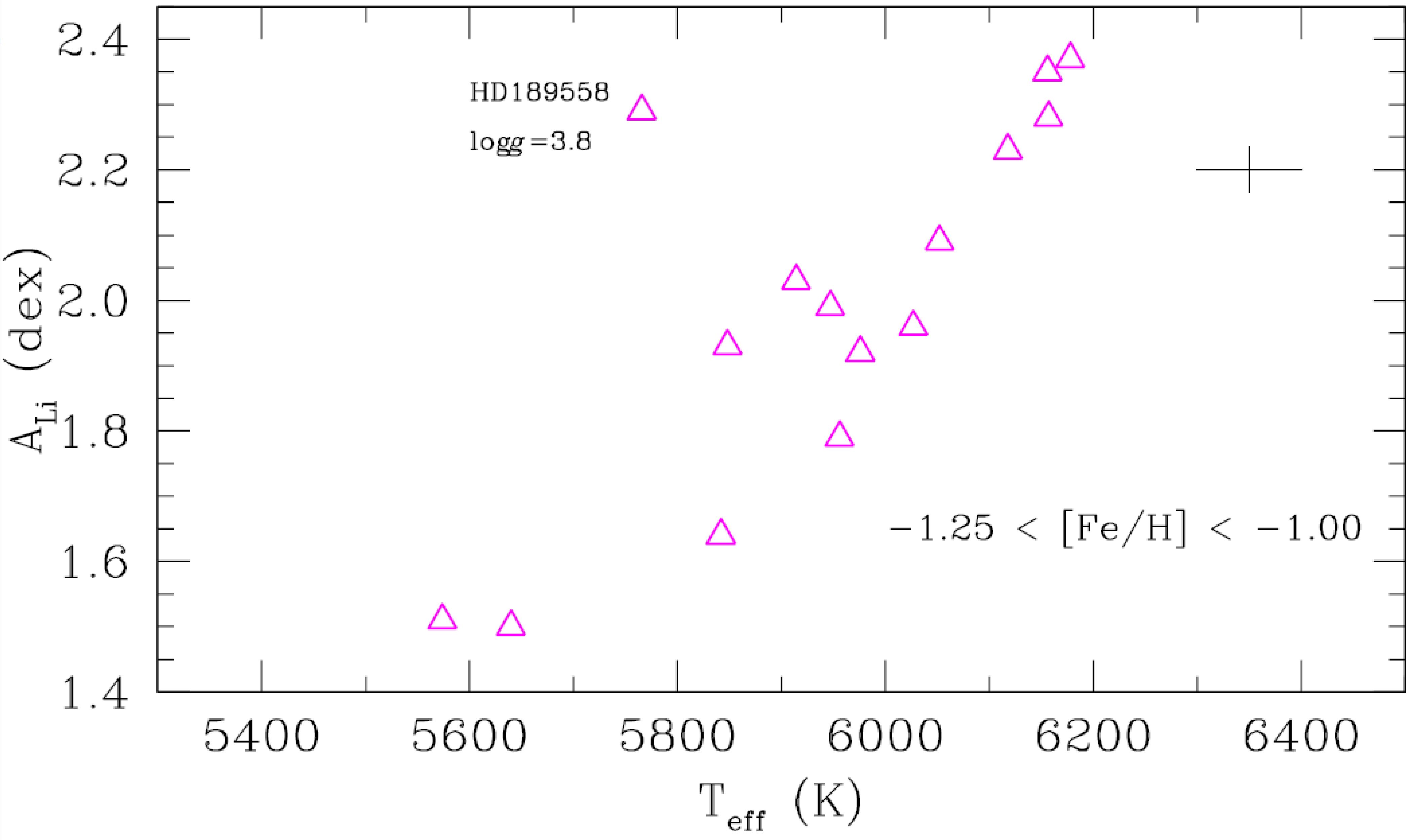
- 3.5 < [Fe/H] < -2.0

- 1.25 < [Fe/H] < -1.00



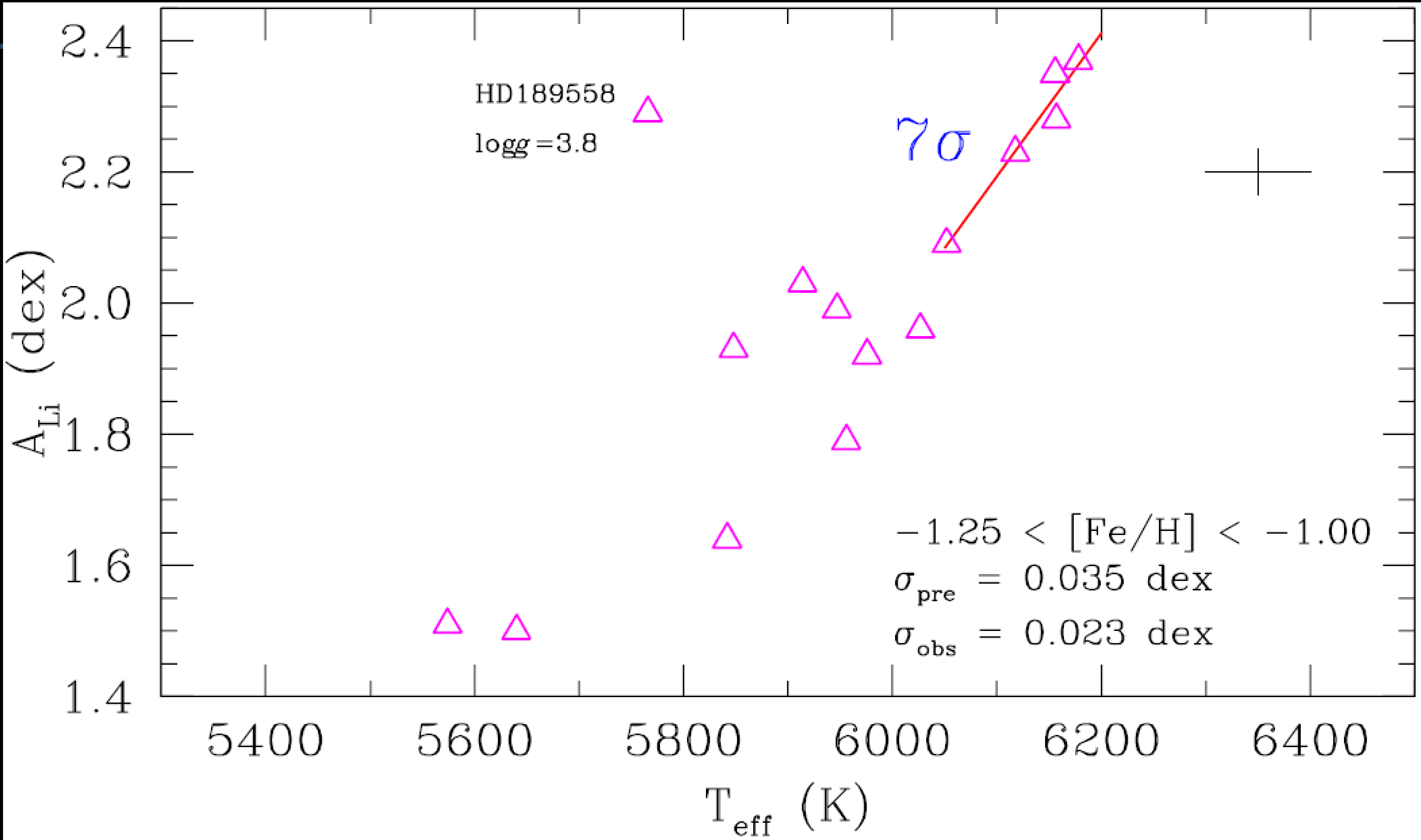
2.4
2.2
2.0
1.8
1.6
1.4
A_{Li} (dex)
5400
5600
5800
6000
6200
6400
T_{eff} (K)
−1.25 < [Fe/H] < −1.00

- 1.25 < [Fe/H] < -1.00



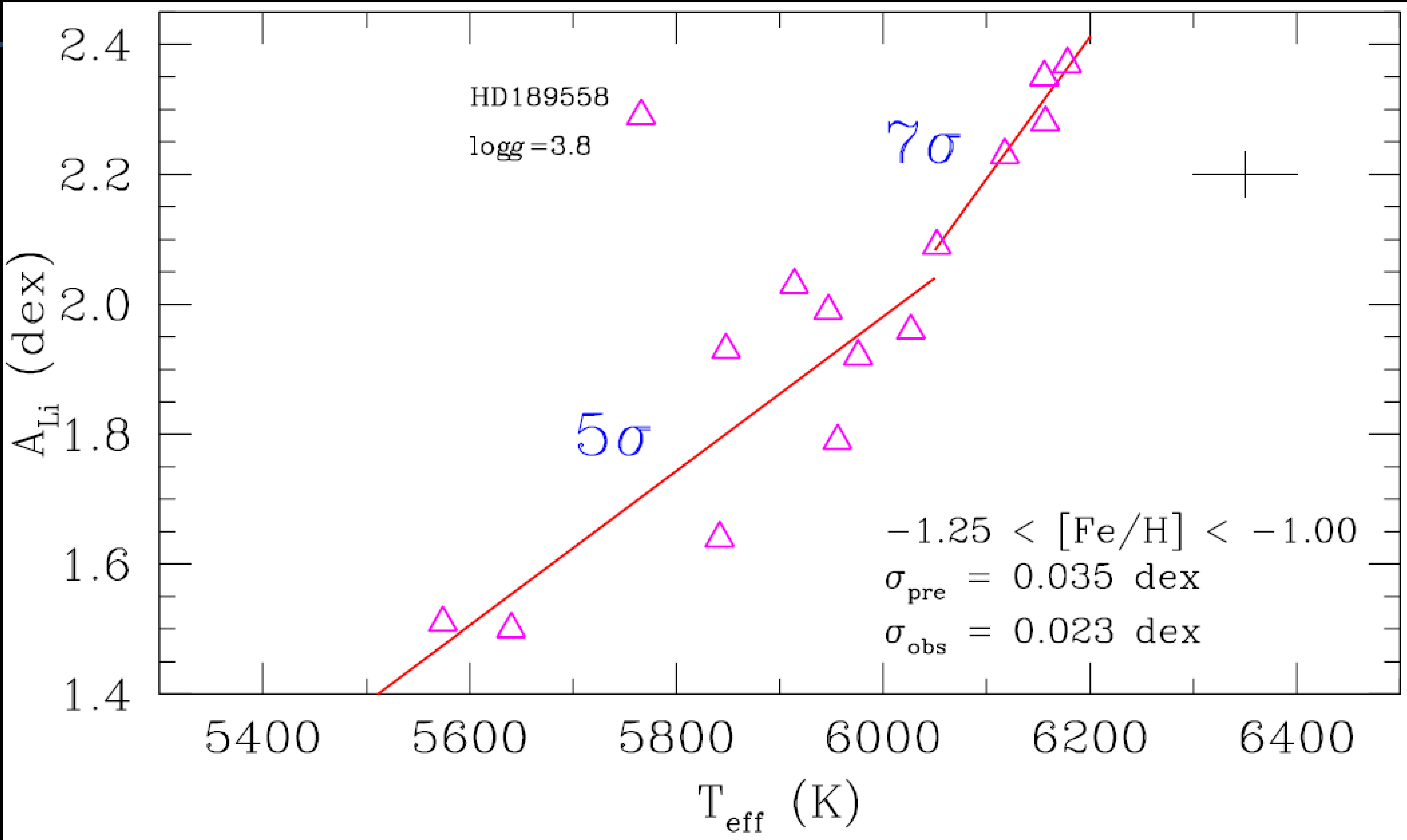
HD189558
logg =3.8
−1.25 < [Fe/H] < −1.00
2.4
2.2
2.0
1.8
1.6
1.4
A_{Li} (dex)
5400
5600
5800
6000
6200
6400
T_{eff} (K)

- 1.25 < [Fe/H] < -1.00



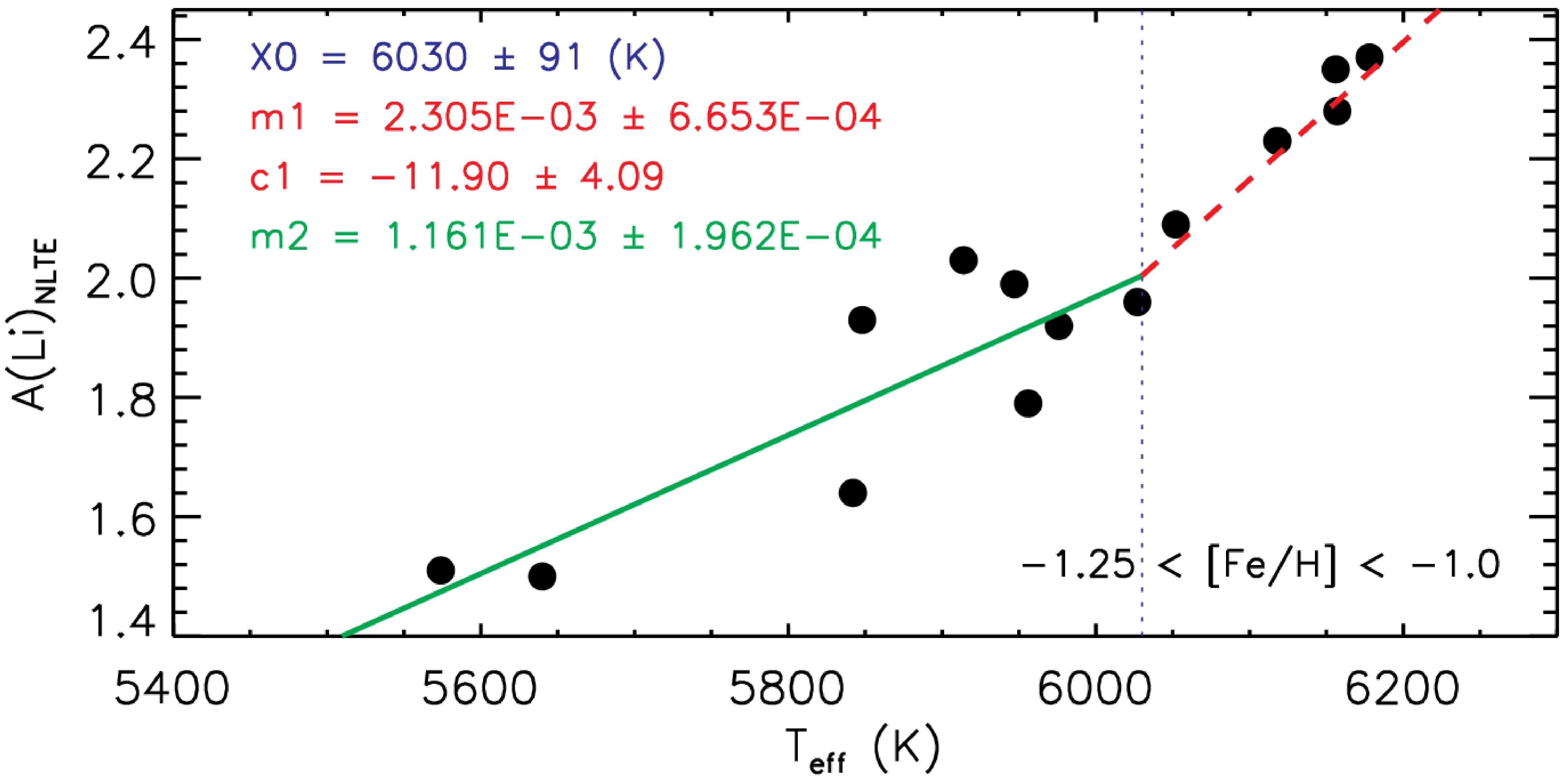
HD189558
logg=3.8
7σ
−1.25 < [Fe/H] < −1.00
σ_pre = 0.035 dex
σ_obs = 0.023 dex
A_Li (dex)
T_eff (K)
2.4
2.2
2.0
1.8
1.6
1.4
5400
5600
5800
6000
6200
6400

- 1.25 < [Fe/H] < -1.00

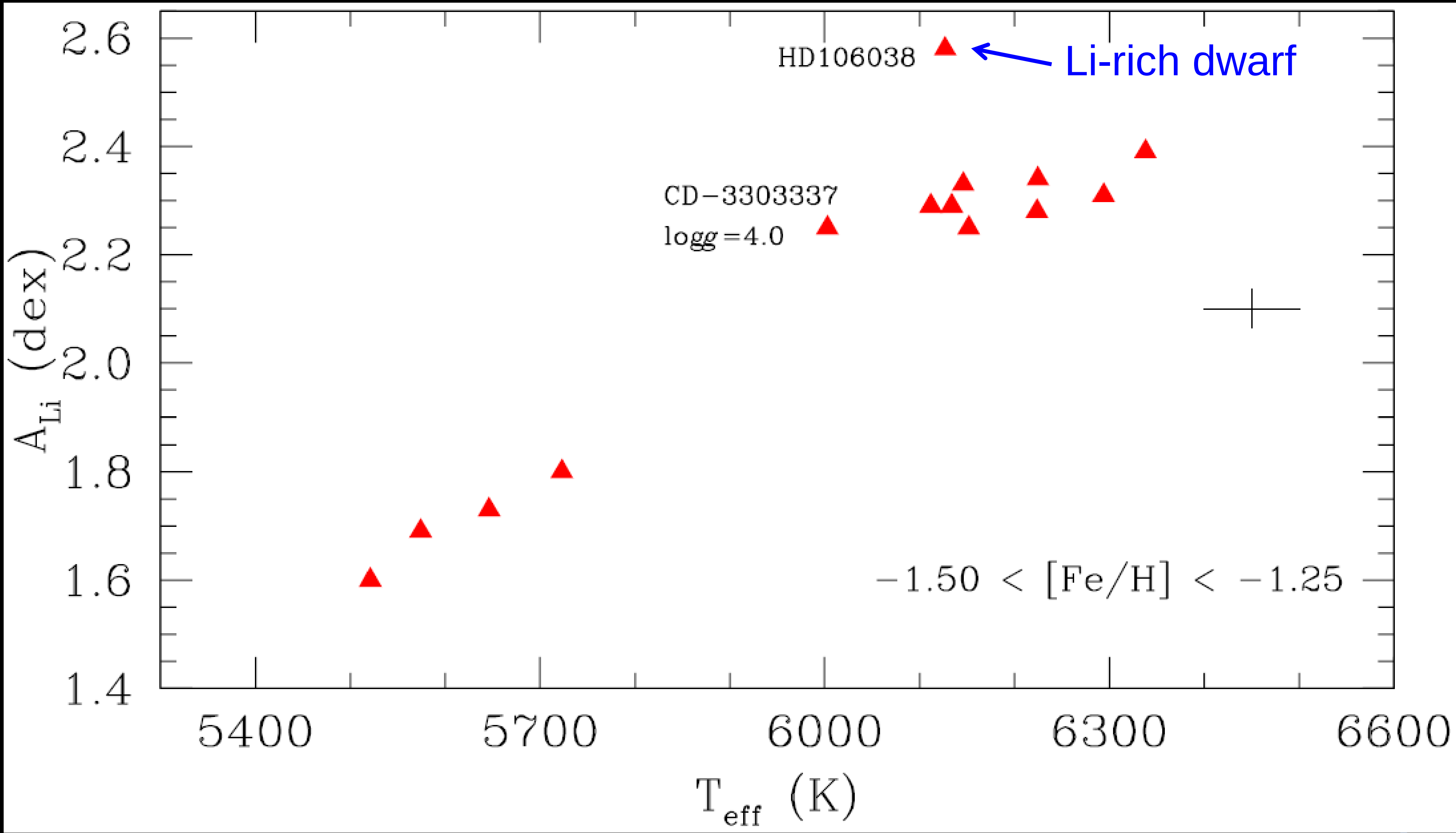


2.4
2.2
2.0
1.8
1.6
1.4
A_Li (dex)
HD189558
logg=3.8
7σ
5σ
−1.25 < [Fe/H] < −1.00
σ_pre = 0.035 dex
σ_obs = 0.023 dex
5400
5600
5800
6000
6200
6400
T_eff (K)

- 1.25 < [Fe/H] < -1.00
Automatic fit of the "break"

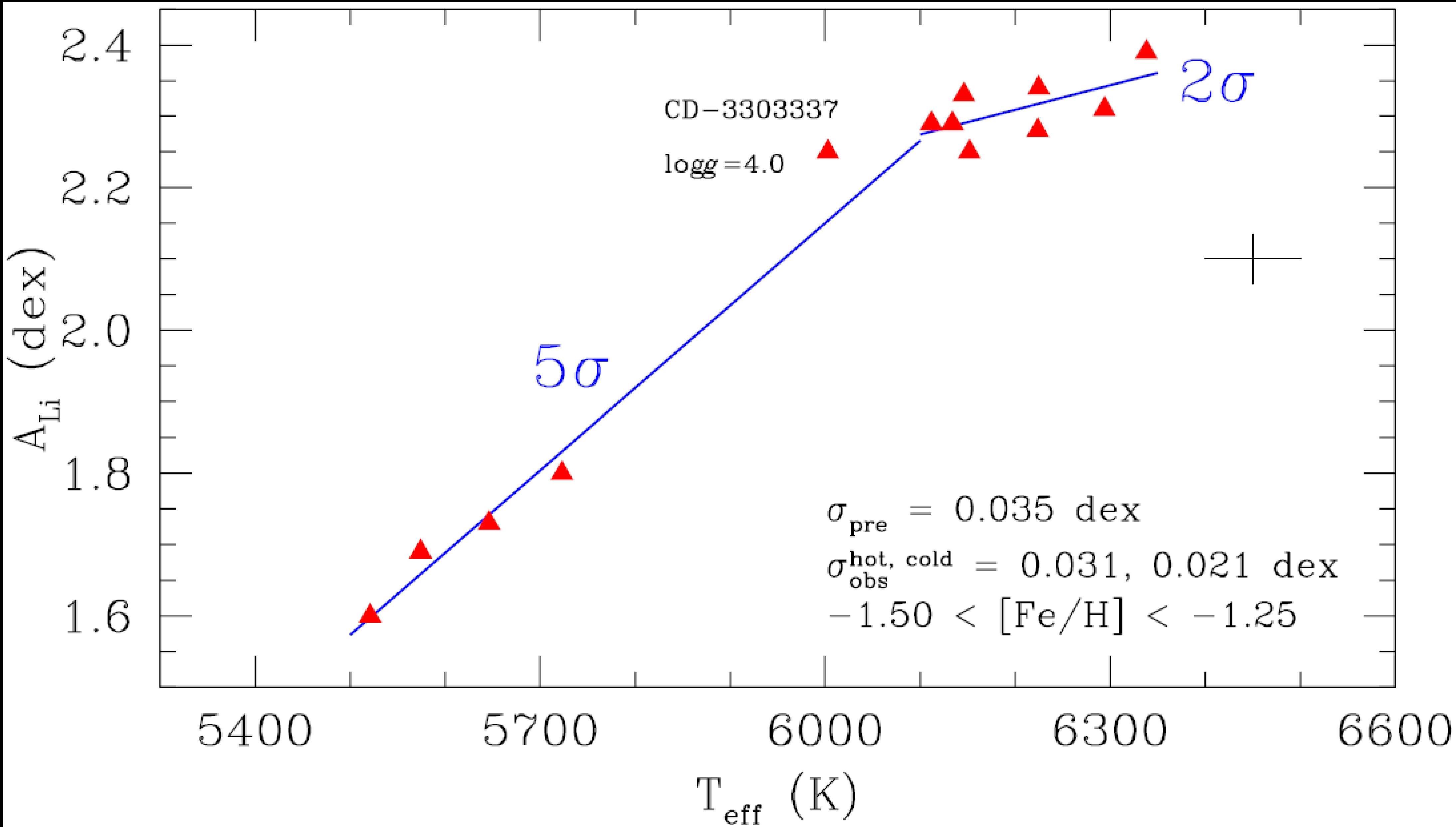


- 1.50 < [Fe/H] < -1.25



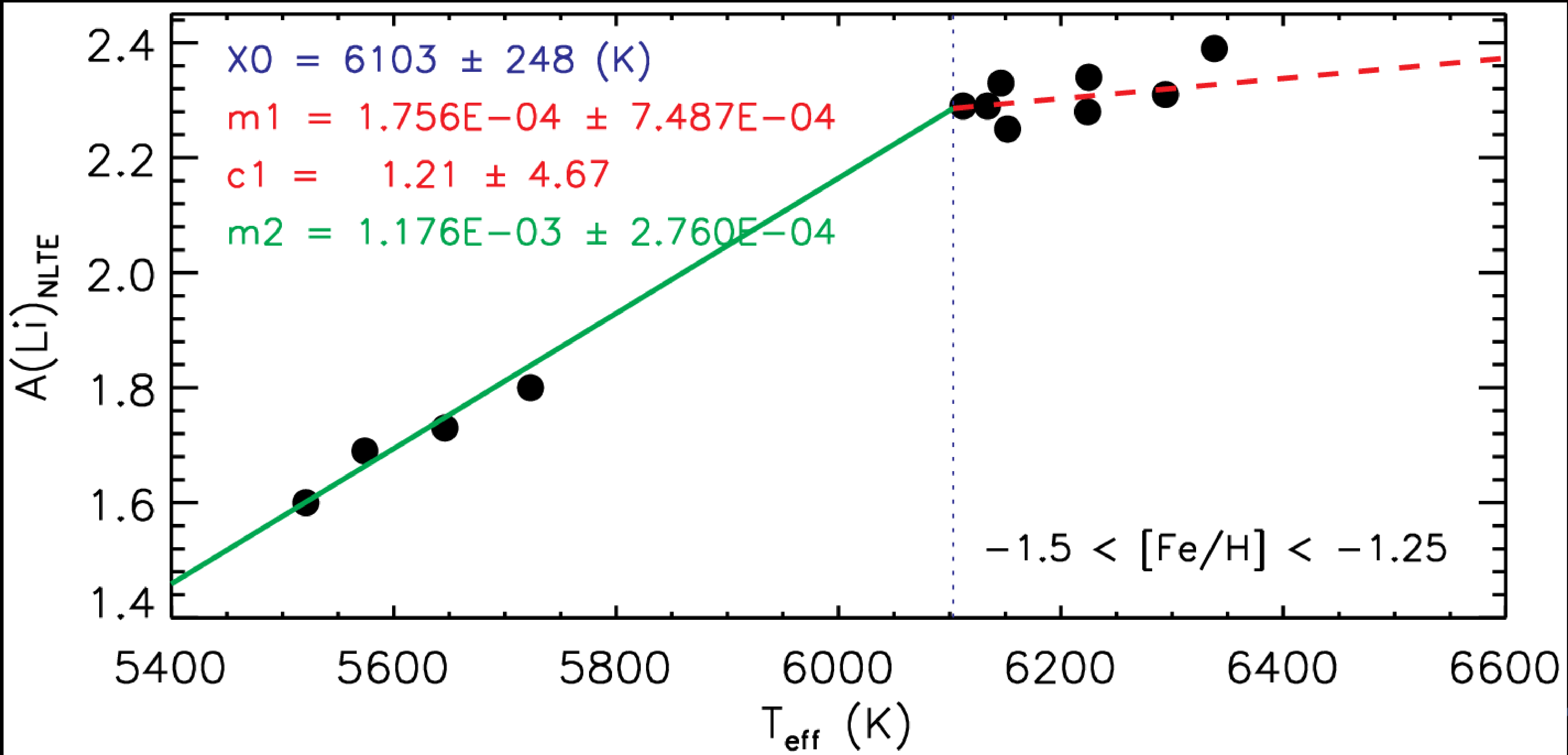
HD106038
Li-rich dwarf
CD−3303337
logg=4.0
−1.50 < [Fe/H] < −1.25
A_{Li} (dex)
T_{eff} (K)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
5400
5700
6000
6300
6600

- 1.50 < [Fe/H] < -1.25

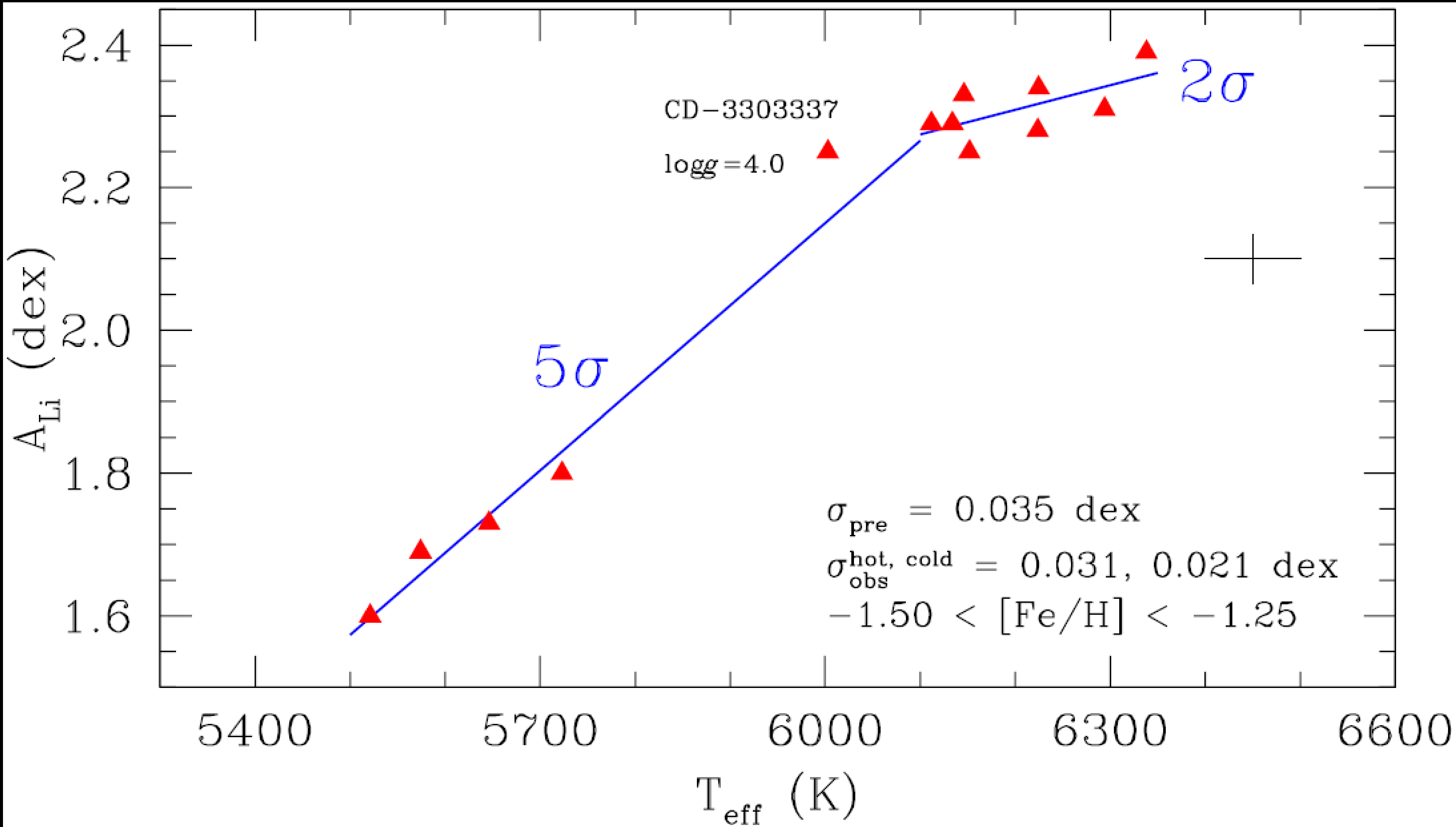


CD−3303337
logg=4.0
2σ
5σ
σ_{pre} = 0.035 dex
$\sigma_{obs}^{hot, cold}$ = 0.031, 0.021 dex
−1.50 < [Fe/H] < −1.25
2.4
2.2
2.0
1.8
1.6
A_{Li} (dex)
5400
5700
6000
6300
6600
T_{eff} (K)

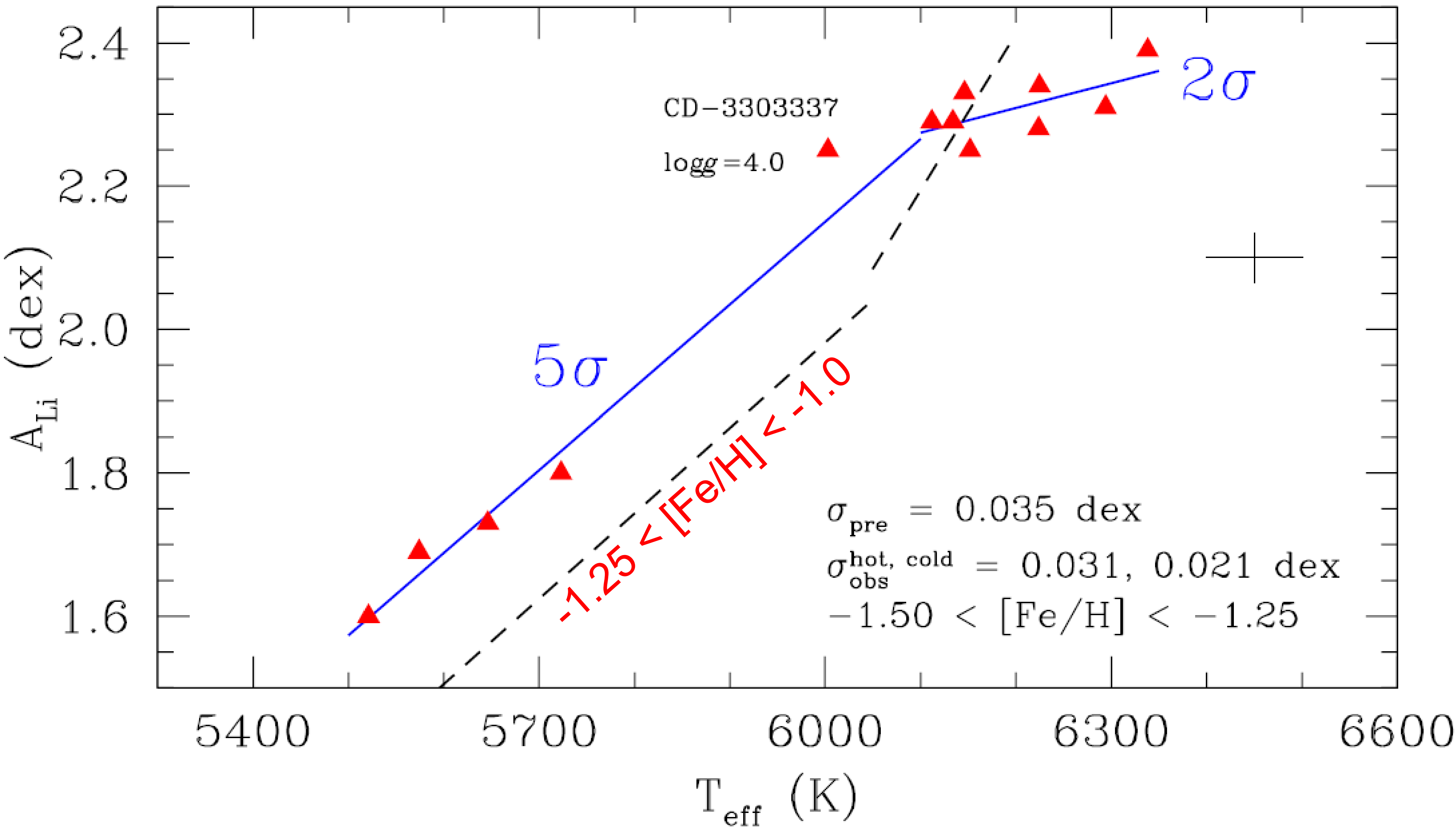
- 1.50 < [Fe/H] < -1.25
Automatic fit of the "break"



- 1.50 < [Fe/H] < -1.25

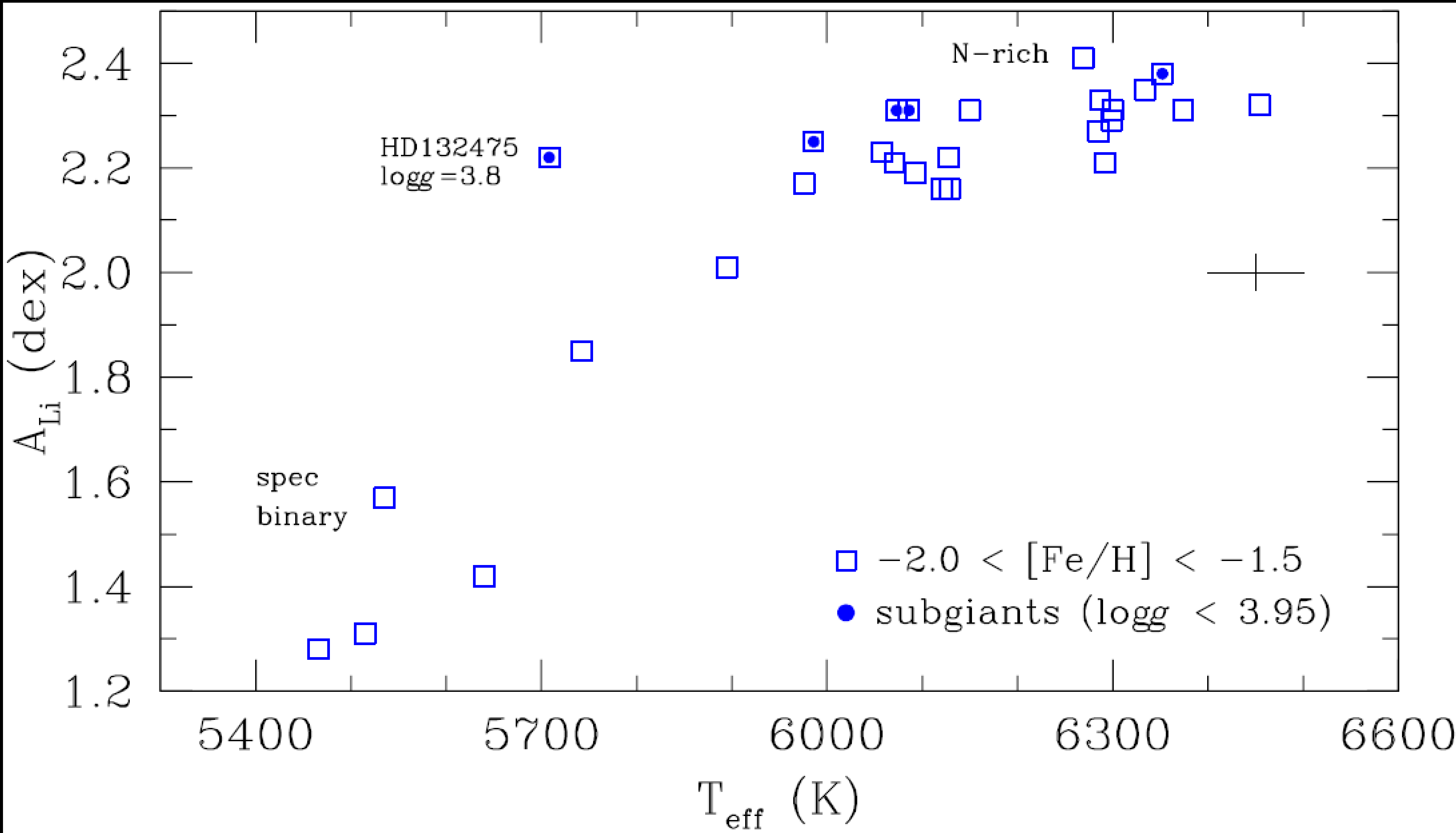

CD−3303337
log g = 4.0
2σ
5σ
σ_pre = 0.035 dex
σ_obs^hot, cold = 0.031, 0.021 dex
−1.50 < [Fe/H] < −1.25
A_Li (dex)
T_eff (K)
2.4
2.2
2.0
1.8
1.6
5400
5700
6000
6300
6600

- 1.50 < [Fe/H] < -1.25



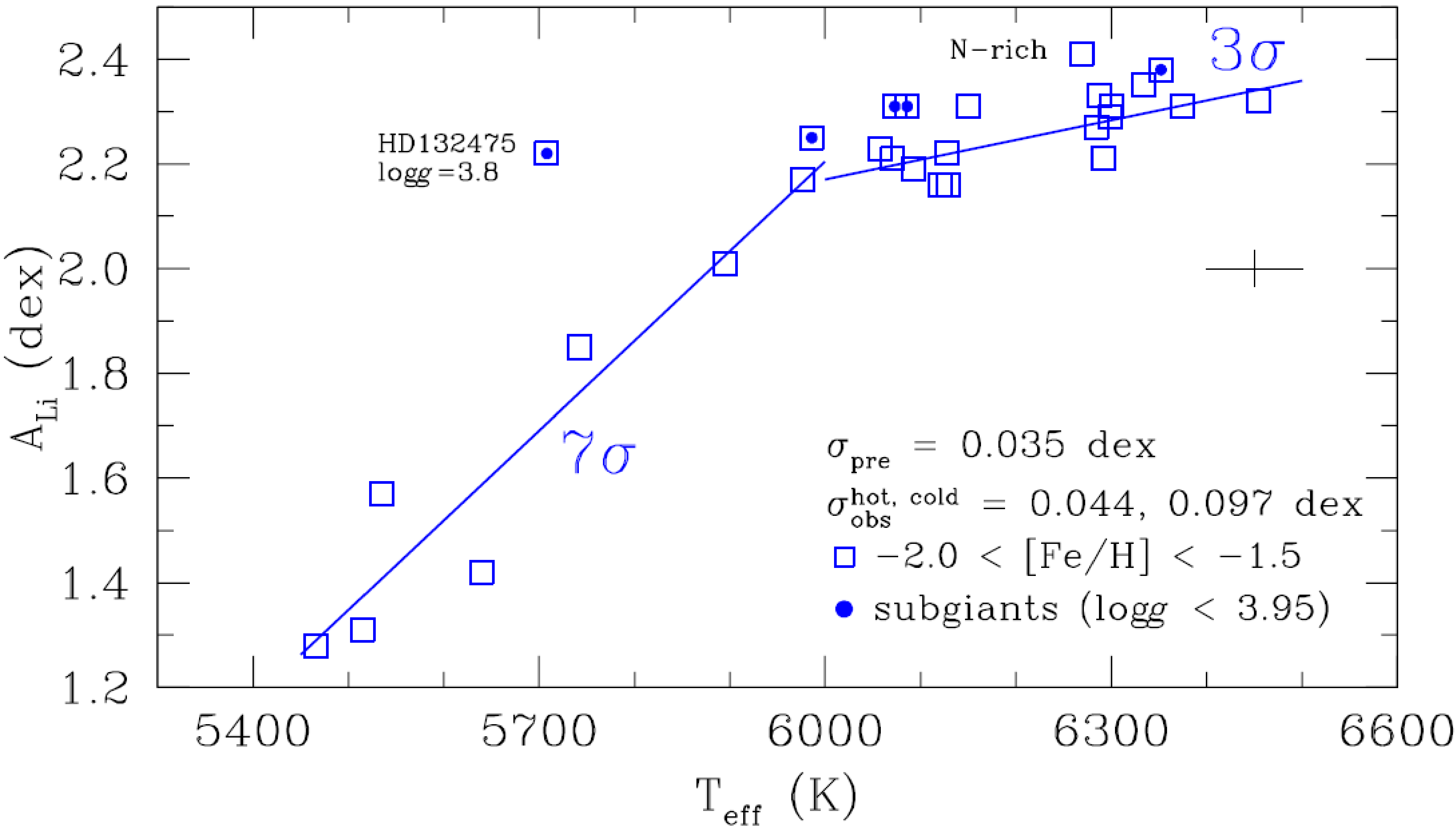
2.4
2.2
2.0
1.8
1.6
A_Li (dex)
CD−3303337
logg = 4.0
2σ
5σ
-1.25 < [Fe/H] < -1.0
σ_pre = 0.035 dex
σ_obs^hot, cold = 0.031, 0.021 dex
−1.50 < [Fe/H] < −1.25
5400
5700
6000
6300
6600
T_eff (K)

- 2.0 < [Fe/H] < -1.5



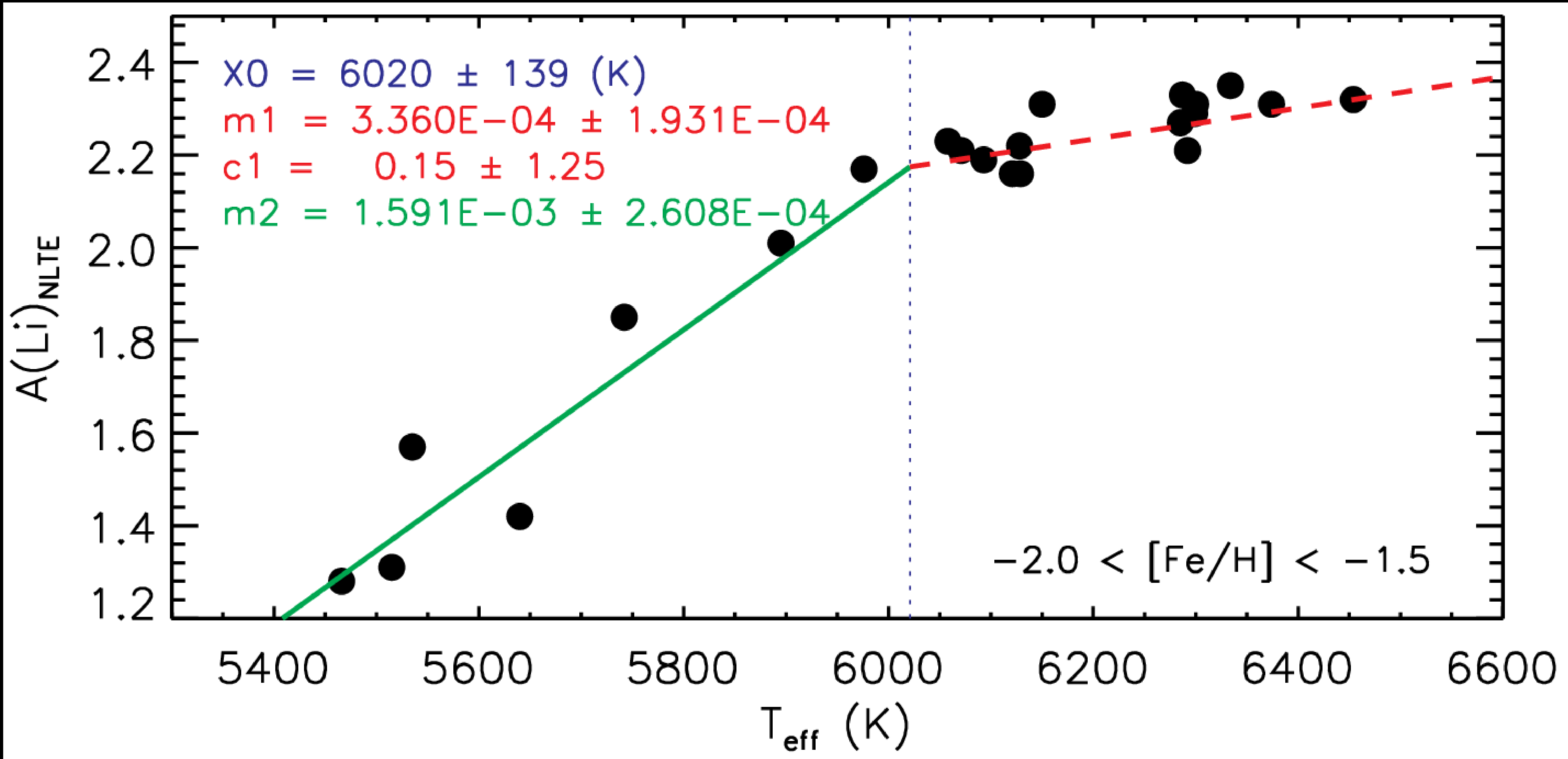
Early subgiants have high Li abundances ! (Chabonnel & Primas 2005)

- 2.0 < [Fe/H] < -1.5

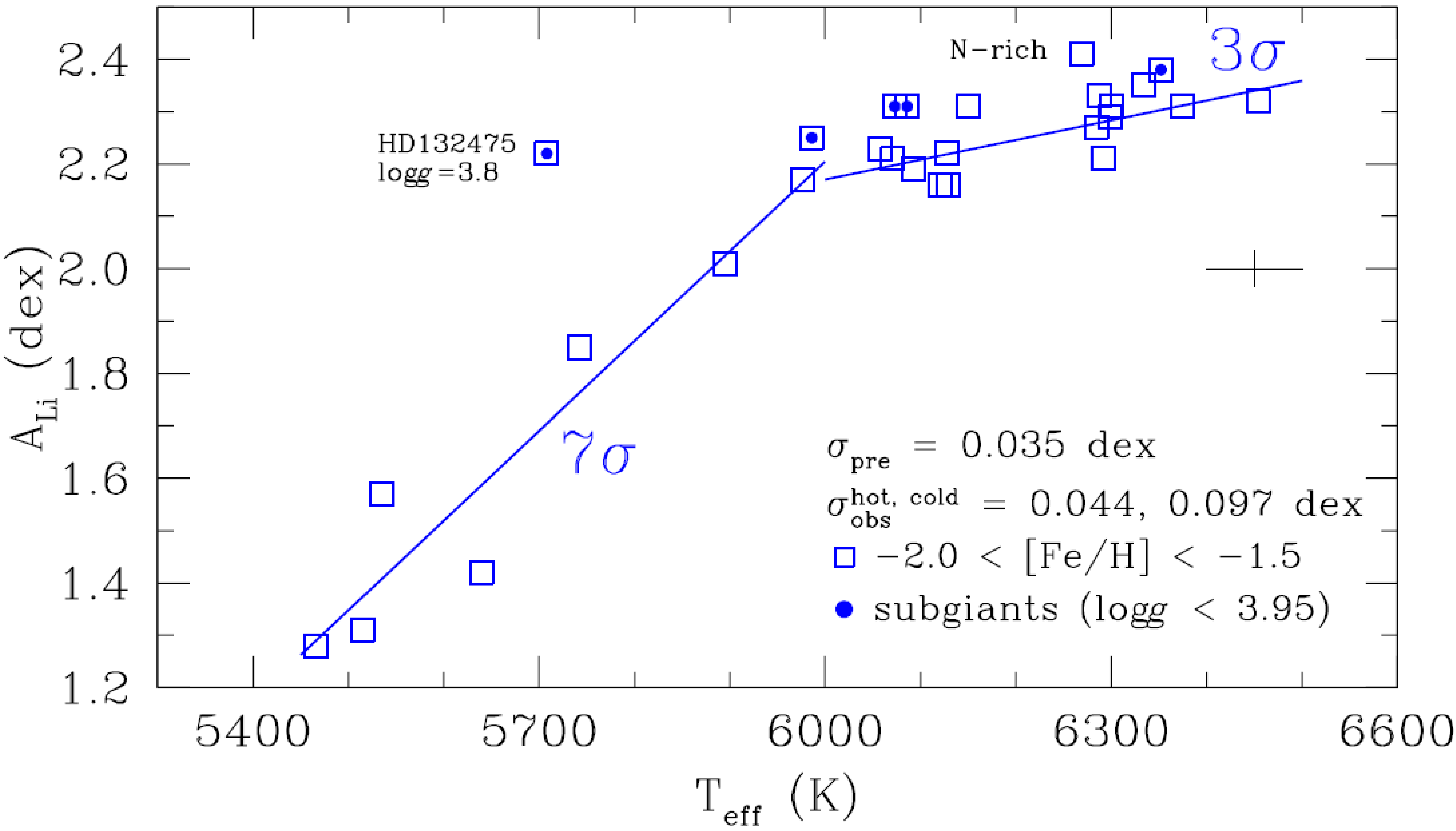


N-rich
3σ
HD132475
logg =3.8
7σ
σ_{pre} = 0.035 dex
$\sigma_{obs}^{hot,\ cold}$ = 0.044, 0.097 dex
−2.0 < [Fe/H] < −1.5
subgiants (logg < 3.95)
A_{Li} (dex)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
5400
5700
6000
6300
6600
T_{eff} (K)

- 2.0 < [Fe/H] < -1.5
Automatic fit of the "break"

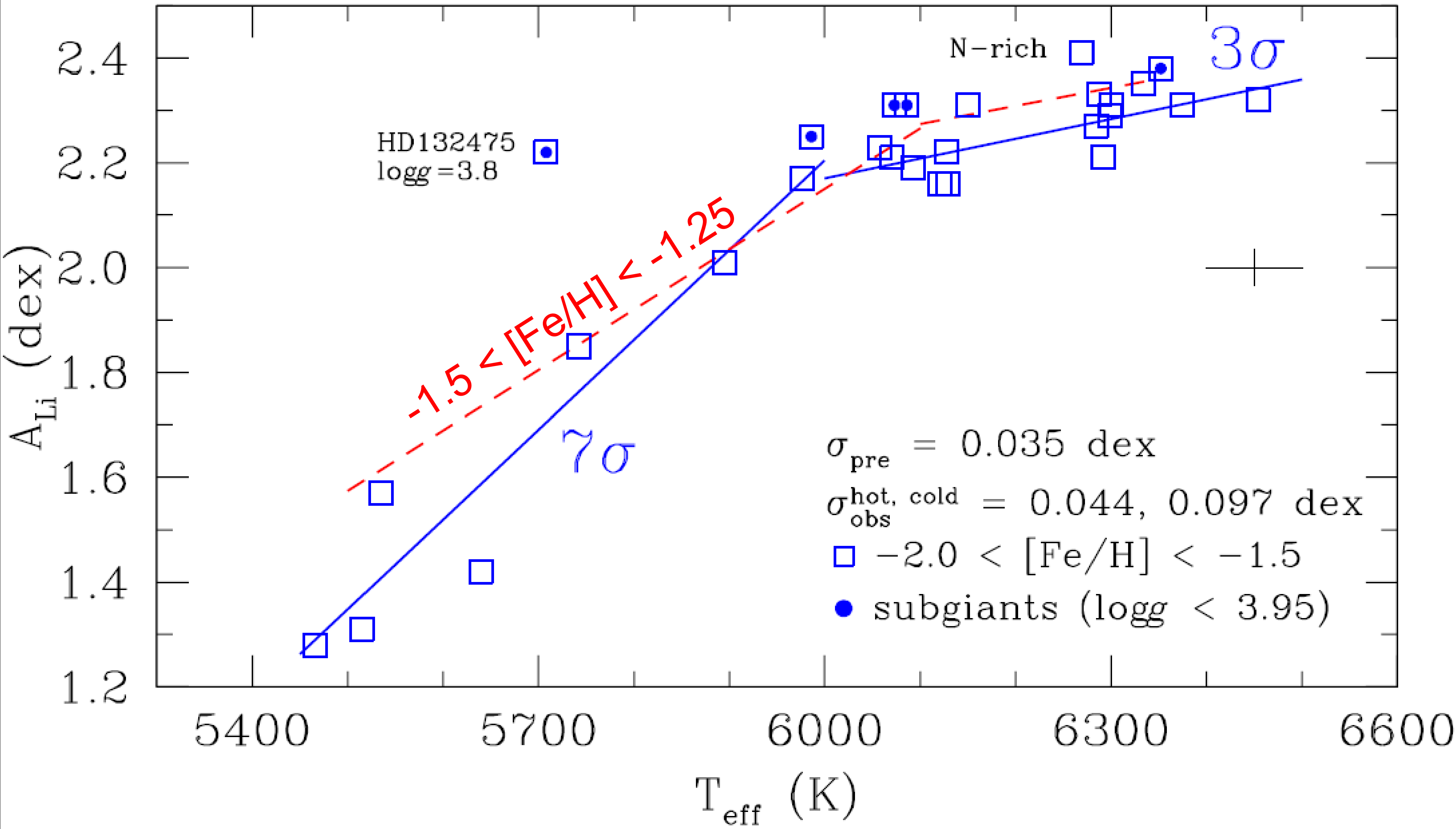


- 2.0 < [Fe/H] < -1.5



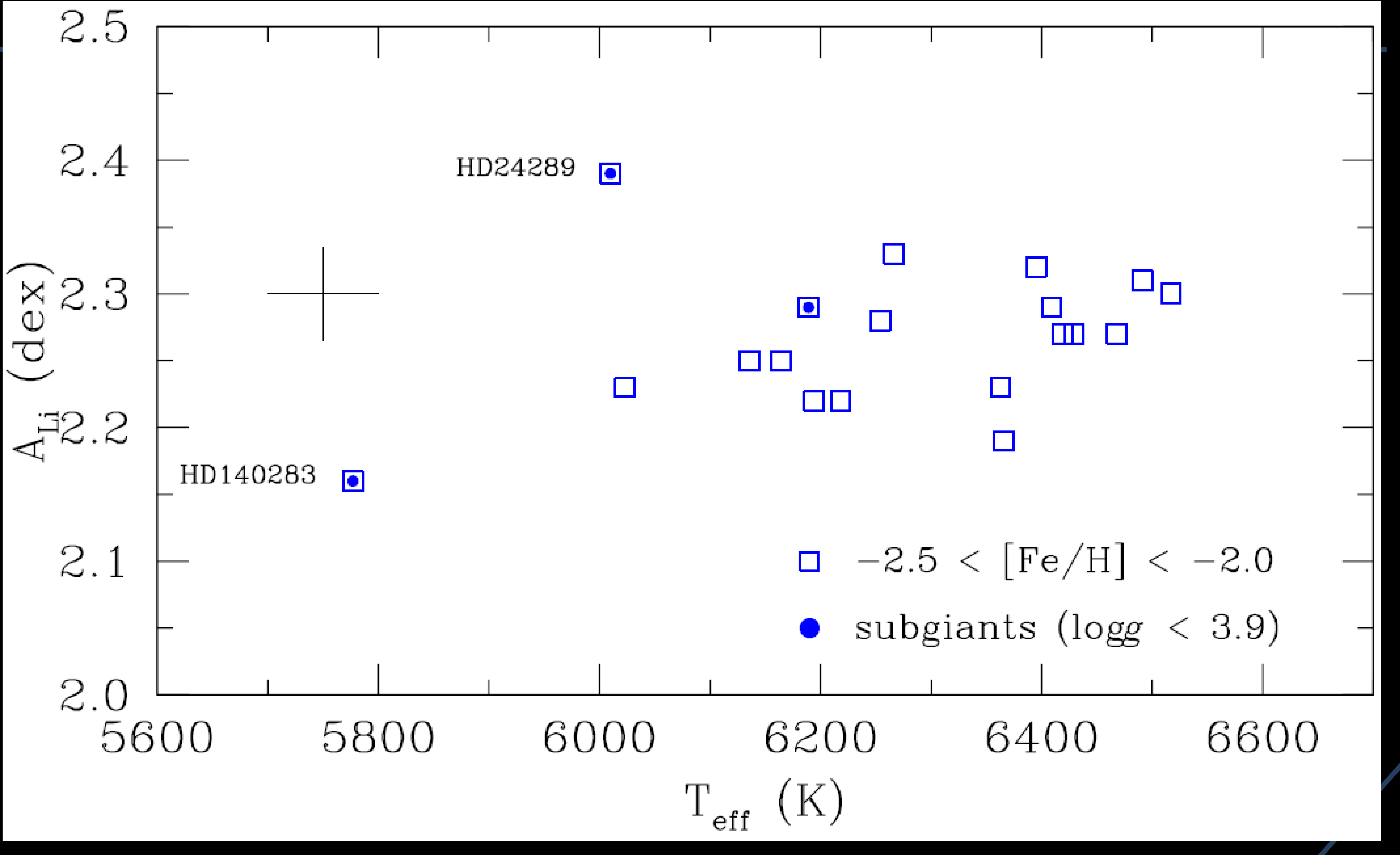
N−rich
HD132475
logg = 3.8
3σ
7σ
σpre = 0.035 dex
σobs hot, cold = 0.044, 0.097 dex
−2.0 < [Fe/H] < −1.5
subgiants (logg < 3.95)
A Li (dex)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
5400
5700
6000
6300
6600
T eff (K)

- 2.0 < [Fe/H] < -1.5



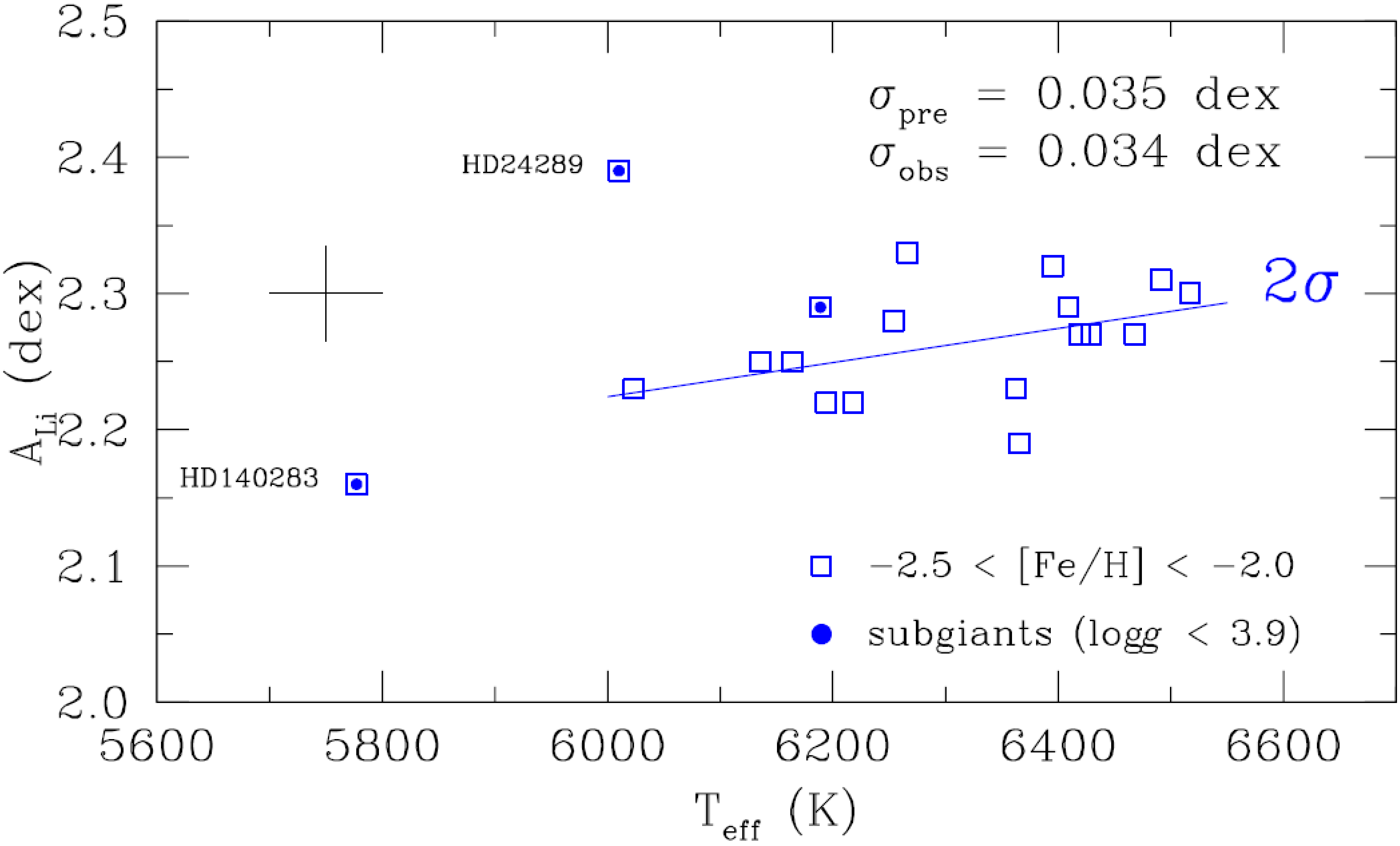
N−rich
3σ
HD132475
logg =3.8
-1.5 < [Fe/H] < -1.25
7σ
σ pre = 0.035 dex
σ obs hot, cold = 0.044, 0.097 dex
−2.0 < [Fe/H] < −1.5
subgiants (logg < 3.95)
A Li (dex)
2.4
2.2
2.0
1.8
1.6
1.4
1.2
5400
5700
6000
6300
6600
T eff (K)

- 2.5 < [Fe/H] < -2.0



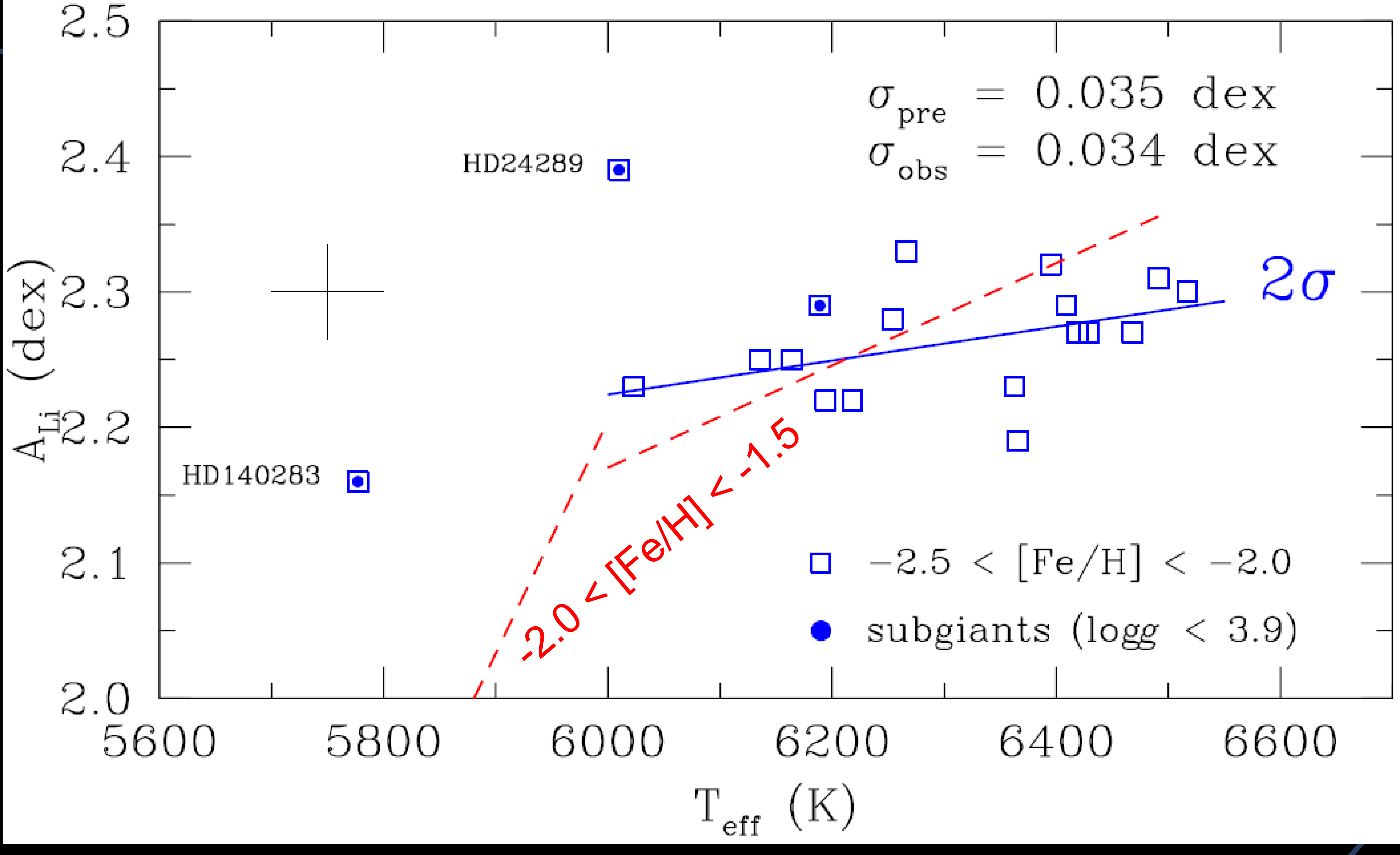
2.5
2.4
2.3
2.2
2.1
2.0
A_Li (dex)
HD24289
HD140283
−2.5 < [Fe/H] < −2.0
subgiants (logg < 3.9)
5600
5800
6000
6200
6400
6600
T_eff (K)

- 2.5 < [Fe/H] < -2.0



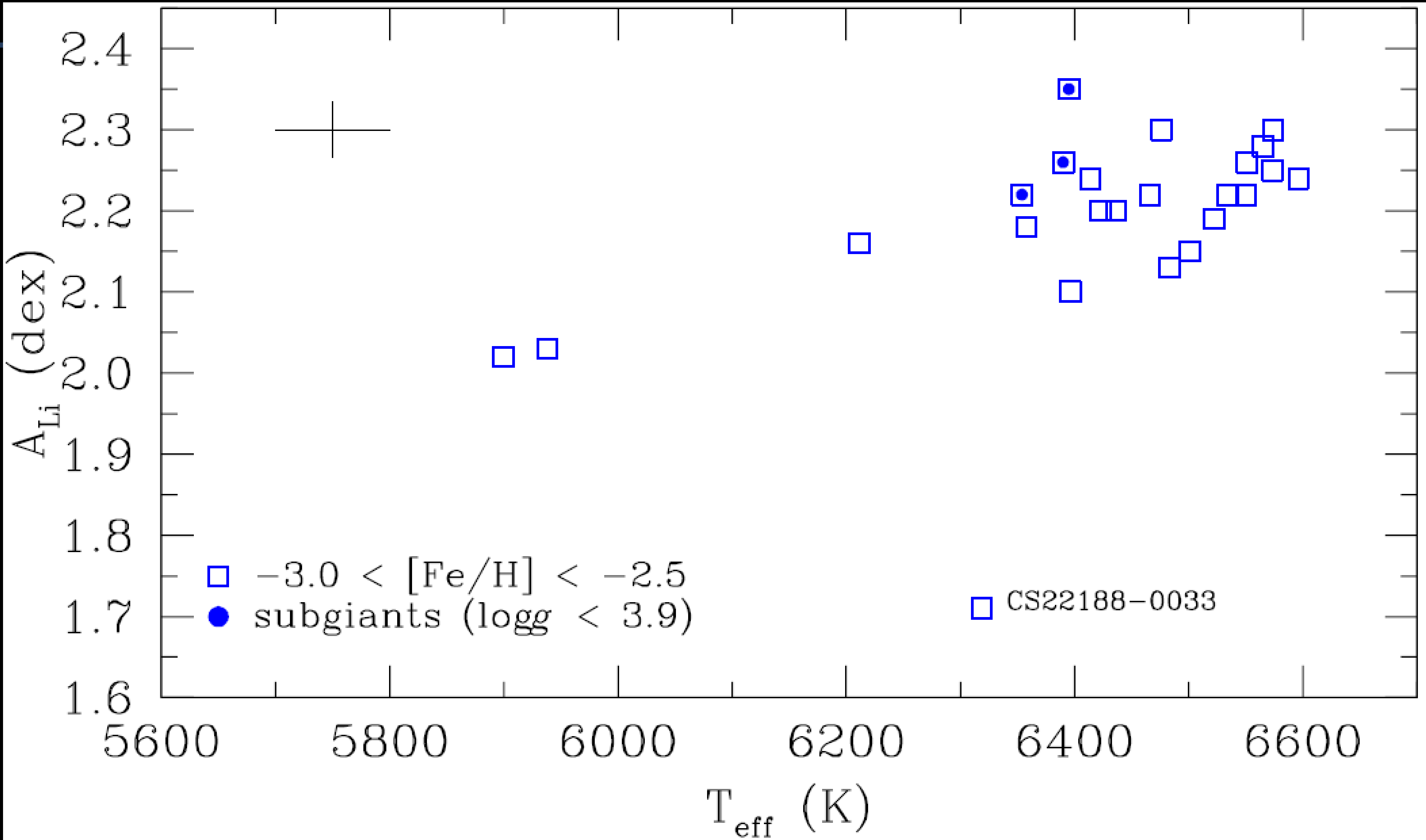
2.5
2.4
2.3
2.2
2.1
2.0
A_{Li} (dex)
5600
5800
6000
6200
6400
6600
T_{eff} (K)
HD24289
HD140283
σ_{pre} = 0.035 dex
σ_{obs} = 0.034 dex
2σ
−2.5 < [Fe/H] < −2.0
subgiants (logg < 3.9)

- 2.5 < [Fe/H] < -2.0



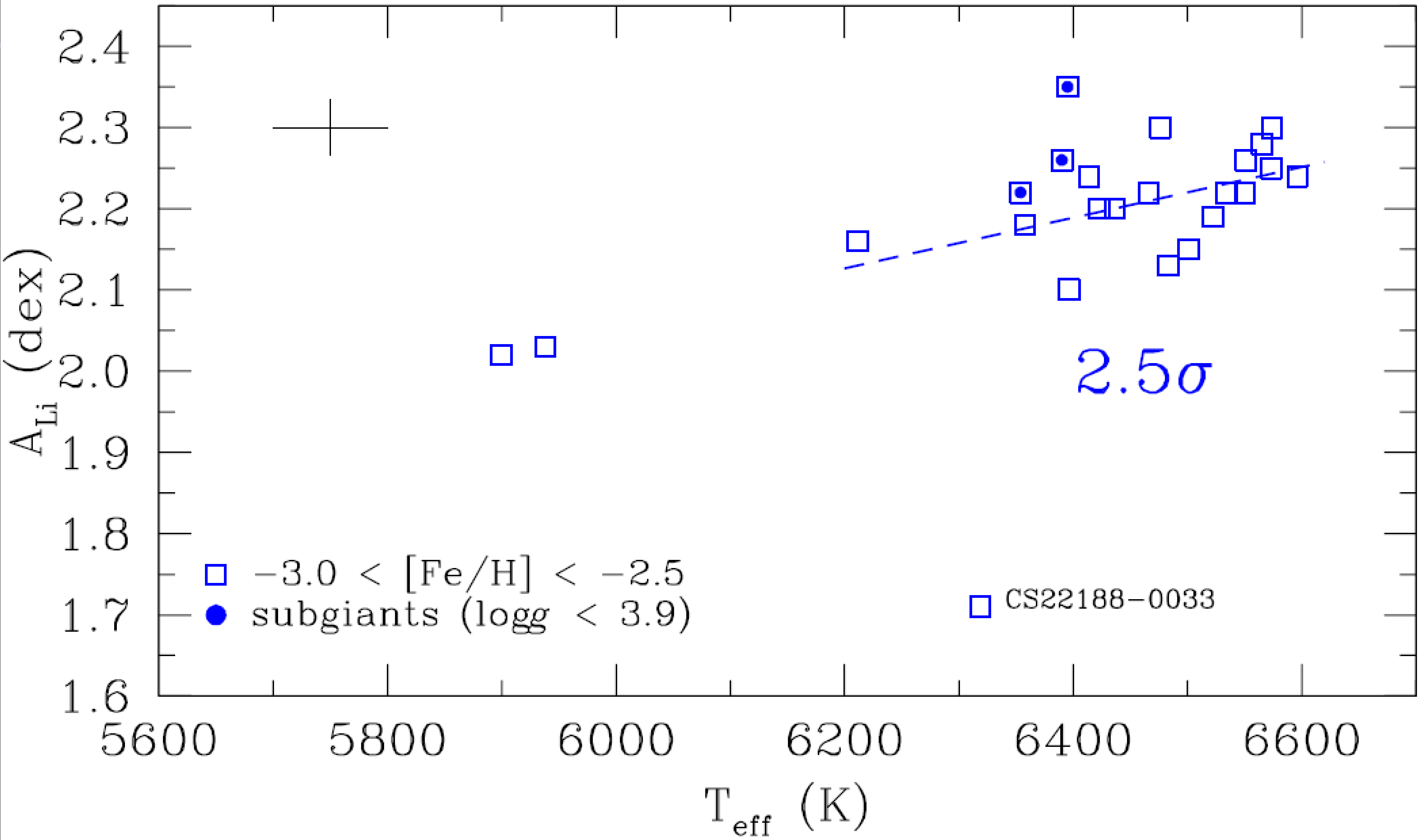
2.5
2.4
2.3
2.2
2.1
2.0
A_{Li} (dex)
5600
5800
6000
6200
6400
6600
T_{eff} (K)
σ_{pre} = 0.035 dex
σ_{obs} = 0.034 dex
HD24289
HD140283
2σ
-2.0 < [Fe/H] < -1.5
−2.5 < [Fe/H] < −2.0
subgiants (log*g* < 3.9)

-3.0 < [Fe/H] < -2.5



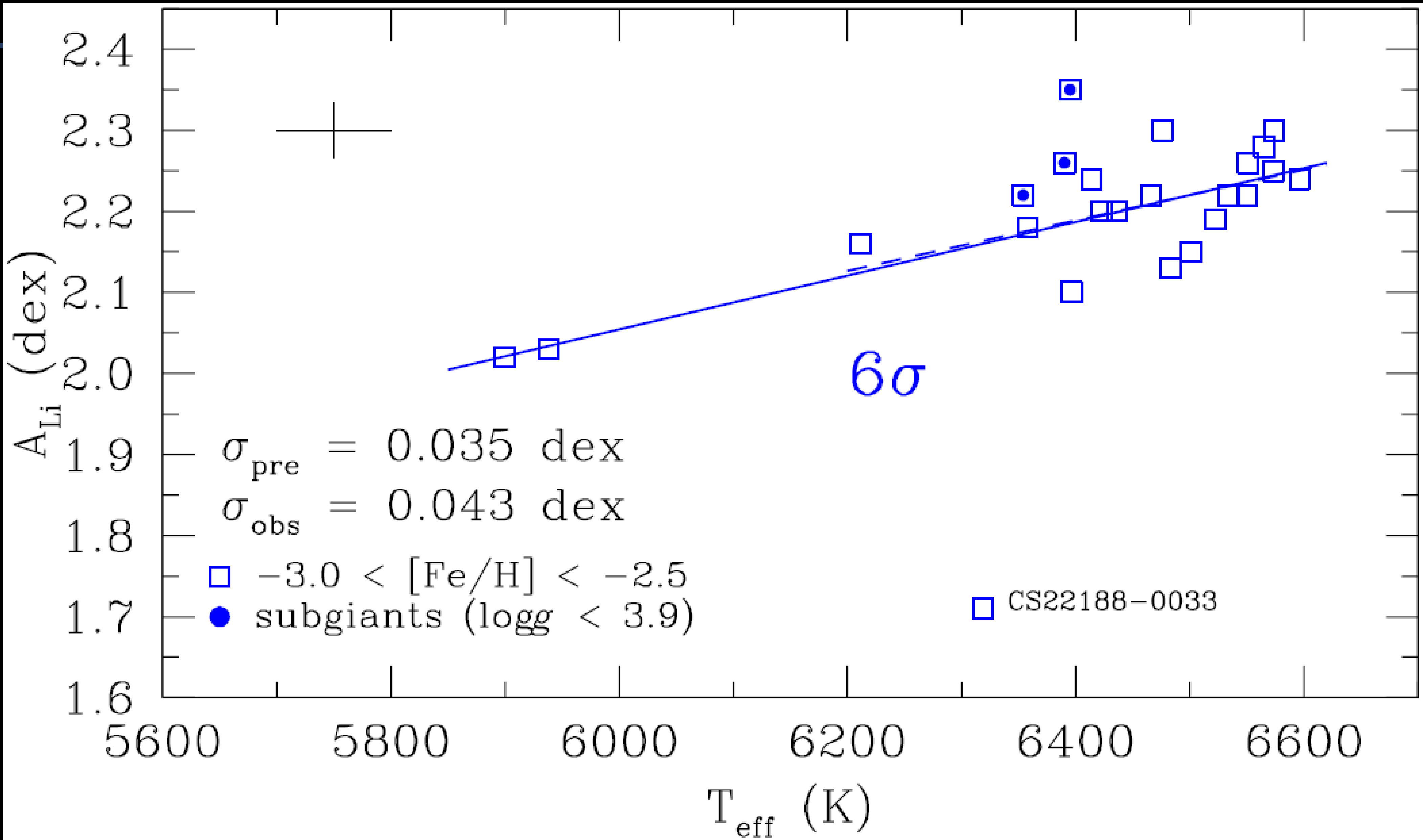
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
A_Li (dex)
5600
5800
6000
6200
6400
6600
T_eff (K)
−3.0 < [Fe/H] < −2.5
subgiants (logg < 3.9)
CS22188−0033

-3.0 < [Fe/H] < -2.5



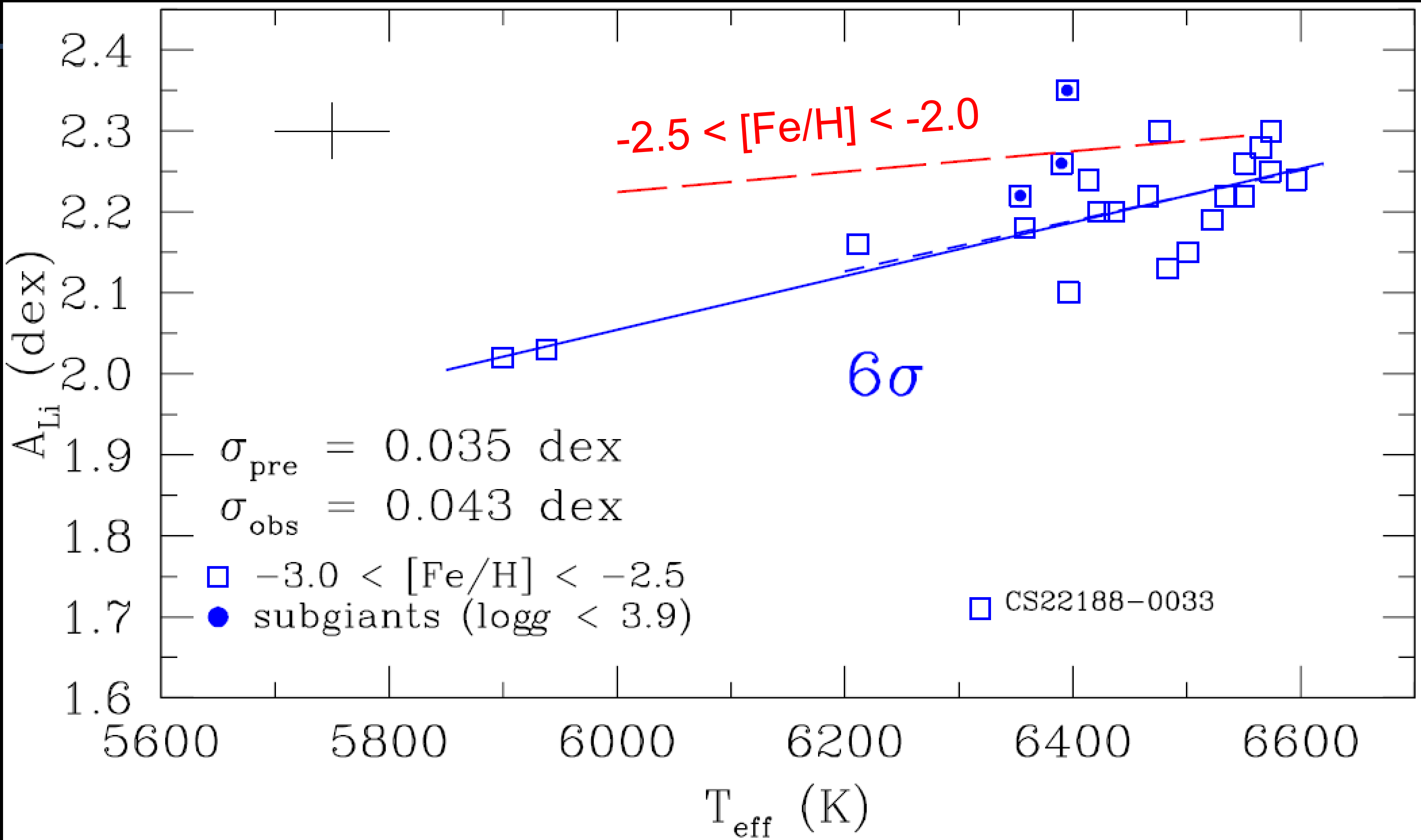
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
A_{Li} (dex)
5600
5800
6000
6200
6400
6600
T_{eff} (K)
2.5σ
−3.0 < [Fe/H] < −2.5
subgiants (logg < 3.9)
CS22188−0033

-3.0 < [Fe/H] < -2.5



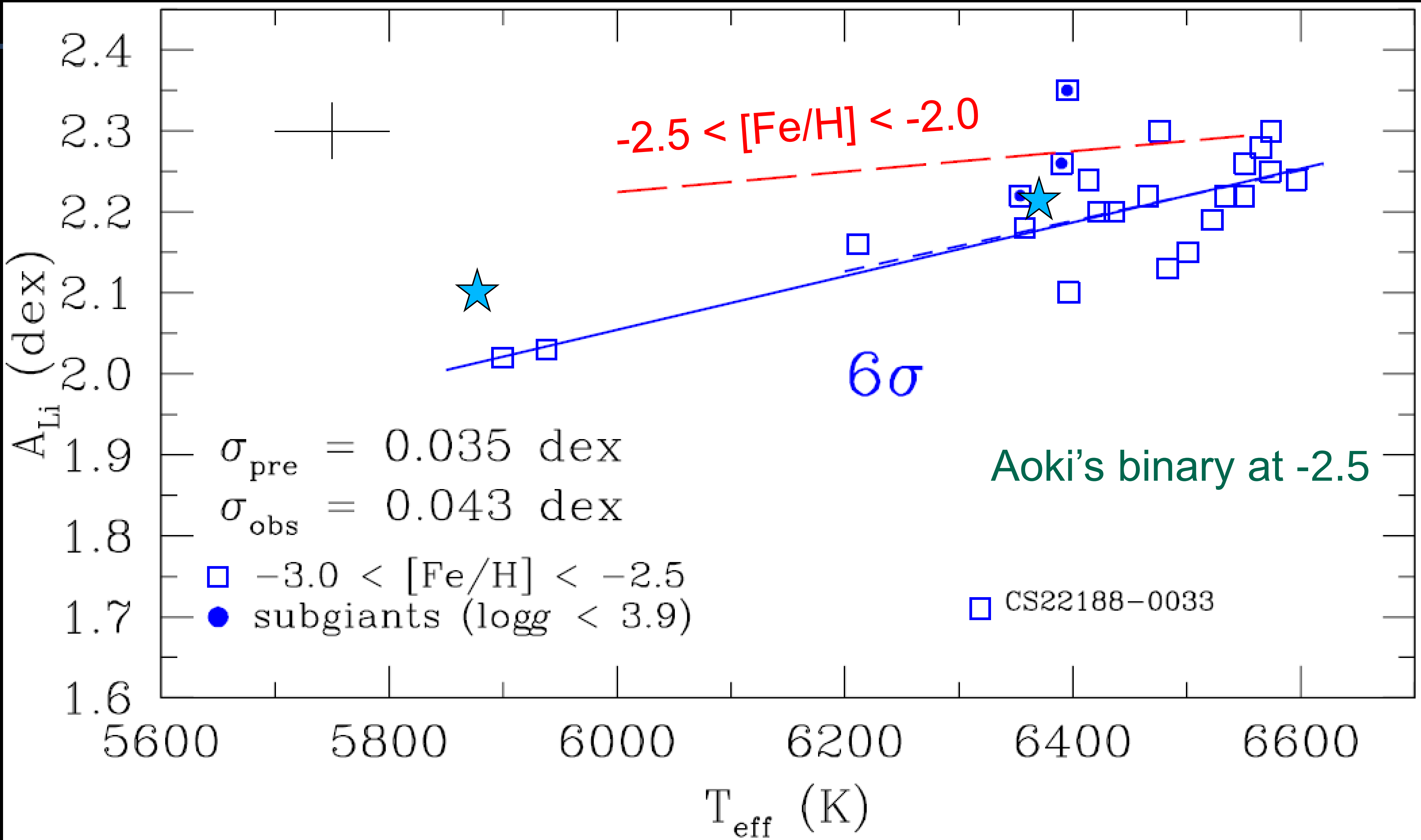
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
A_{Li} (dex)
5600
5800
6000
6200
6400
6600
T_{eff} (K)
6σ
σ_{pre} = 0.035 dex
σ_{obs} = 0.043 dex
−3.0 < [Fe/H] < −2.5
subgiants (logg < 3.9)
CS22188−0033

-3.0 < [Fe/H] < -2.5



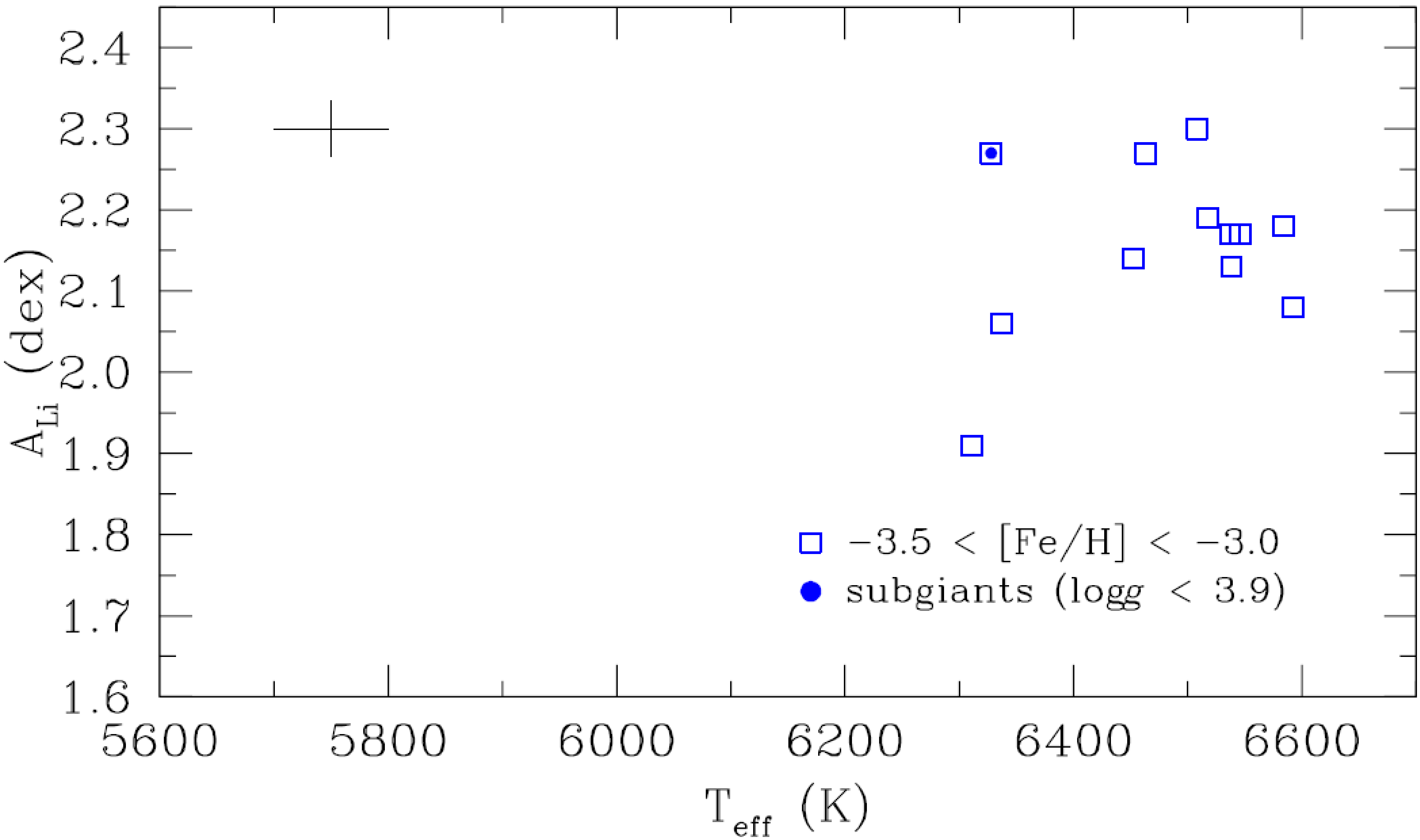
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
A_Li (dex)
-2.5 < [Fe/H] < -2.0
6σ
σ_pre = 0.035 dex
σ_obs = 0.043 dex
−3.0 < [Fe/H] < −2.5
subgiants (logg < 3.9)
CS22188−0033
5600
5800
6000
6200
6400
6600
T_eff (K)

-3.0 < [Fe/H] < -2.5



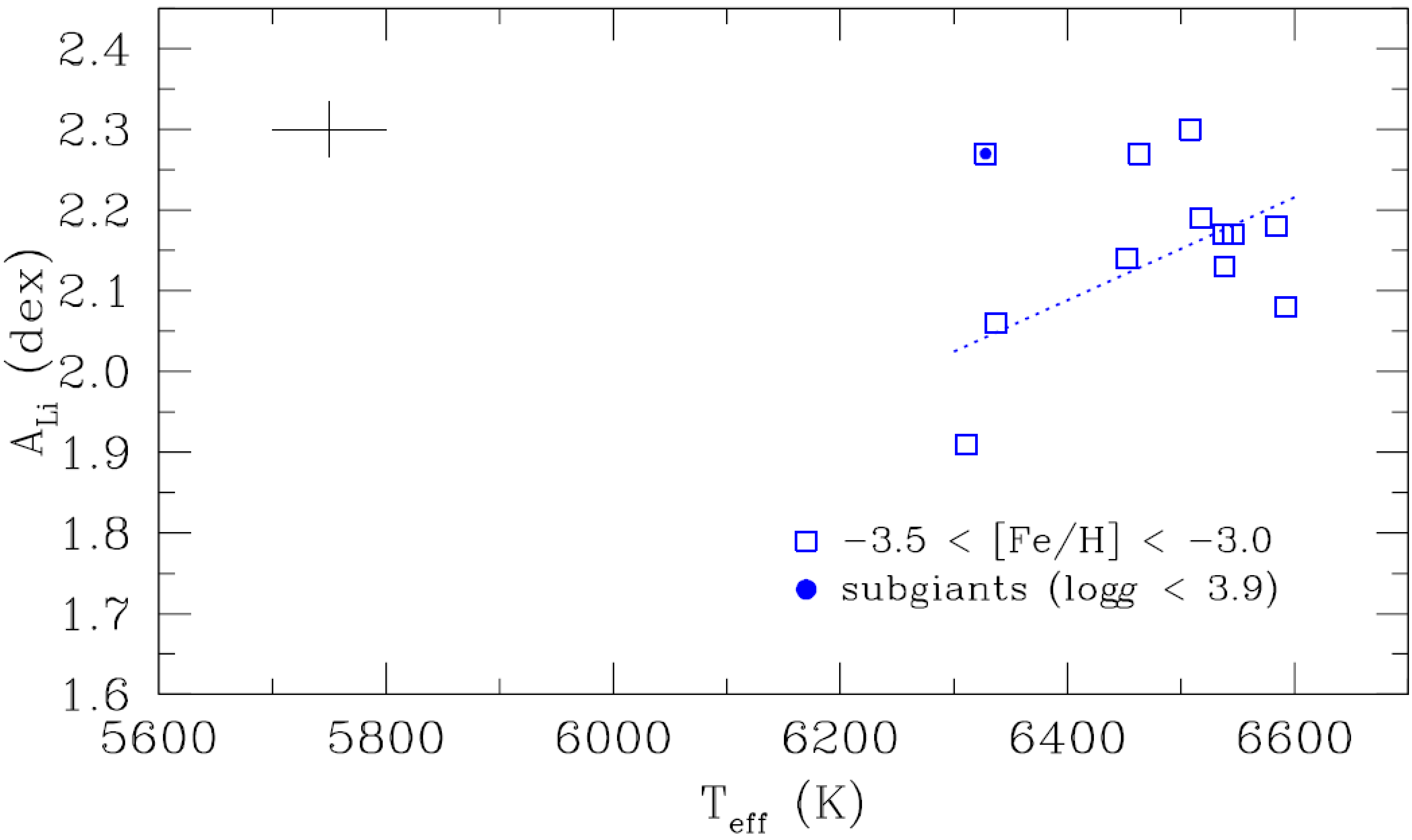
-2.5 < [Fe/H] < -2.0
6σ
σ pre = 0.035 dex
σ obs = 0.043 dex
Aoki's binary at -2.5
−3.0 < [Fe/H] < −2.5
subgiants (logg < 3.9)
CS22188−0033
A Li (dex)
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
5600
5800
6000
6200
6400
6600
T eff (K)

-3.5 < [Fe/H] < -3.0



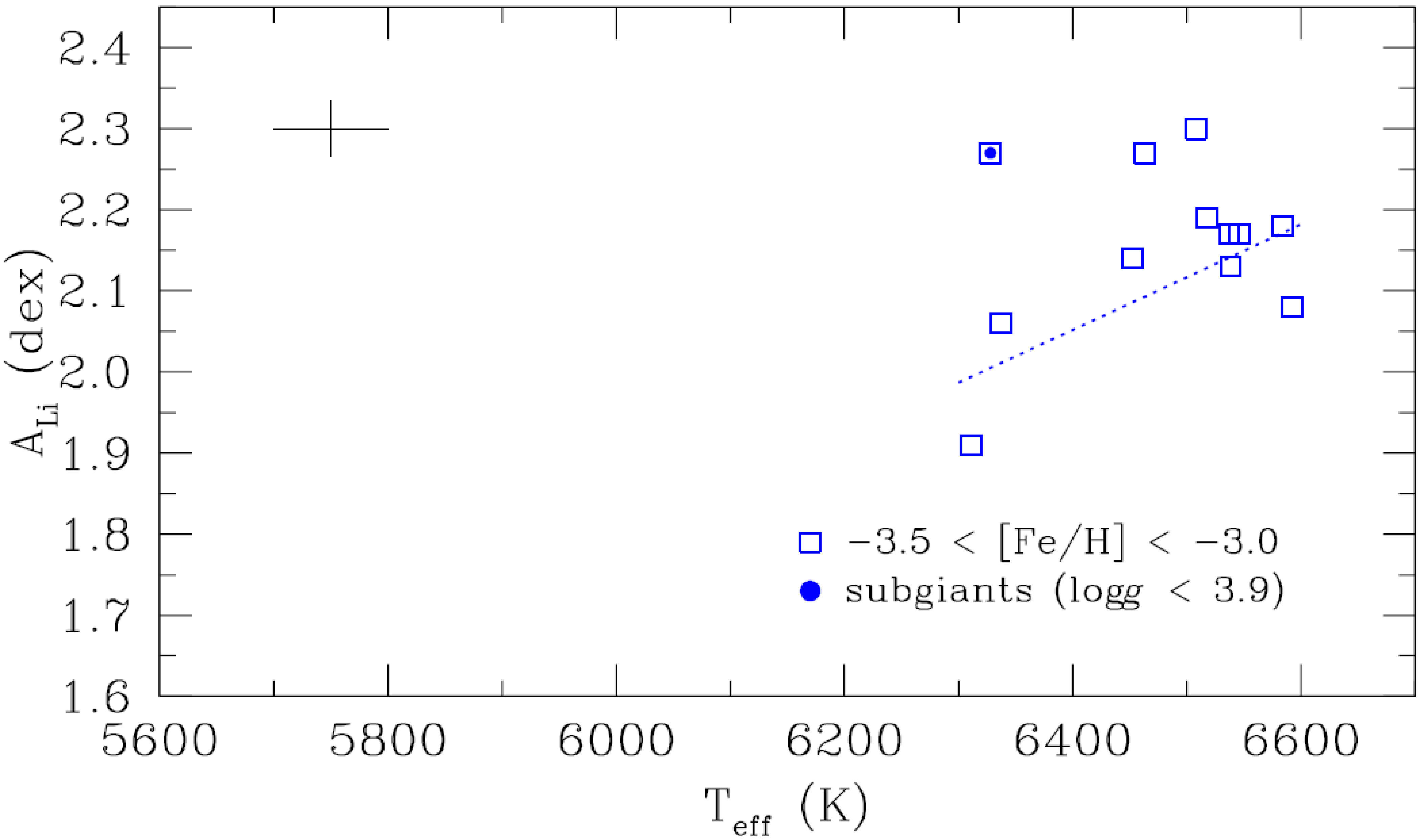
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
A_{Li} (dex)
5600
5800
6000
6200
6400
6600
T_{eff} (K)
−3.5 < [Fe/H] < −3.0
subgiants (logg < 3.9)

-3.5 < [Fe/H] < -3.0



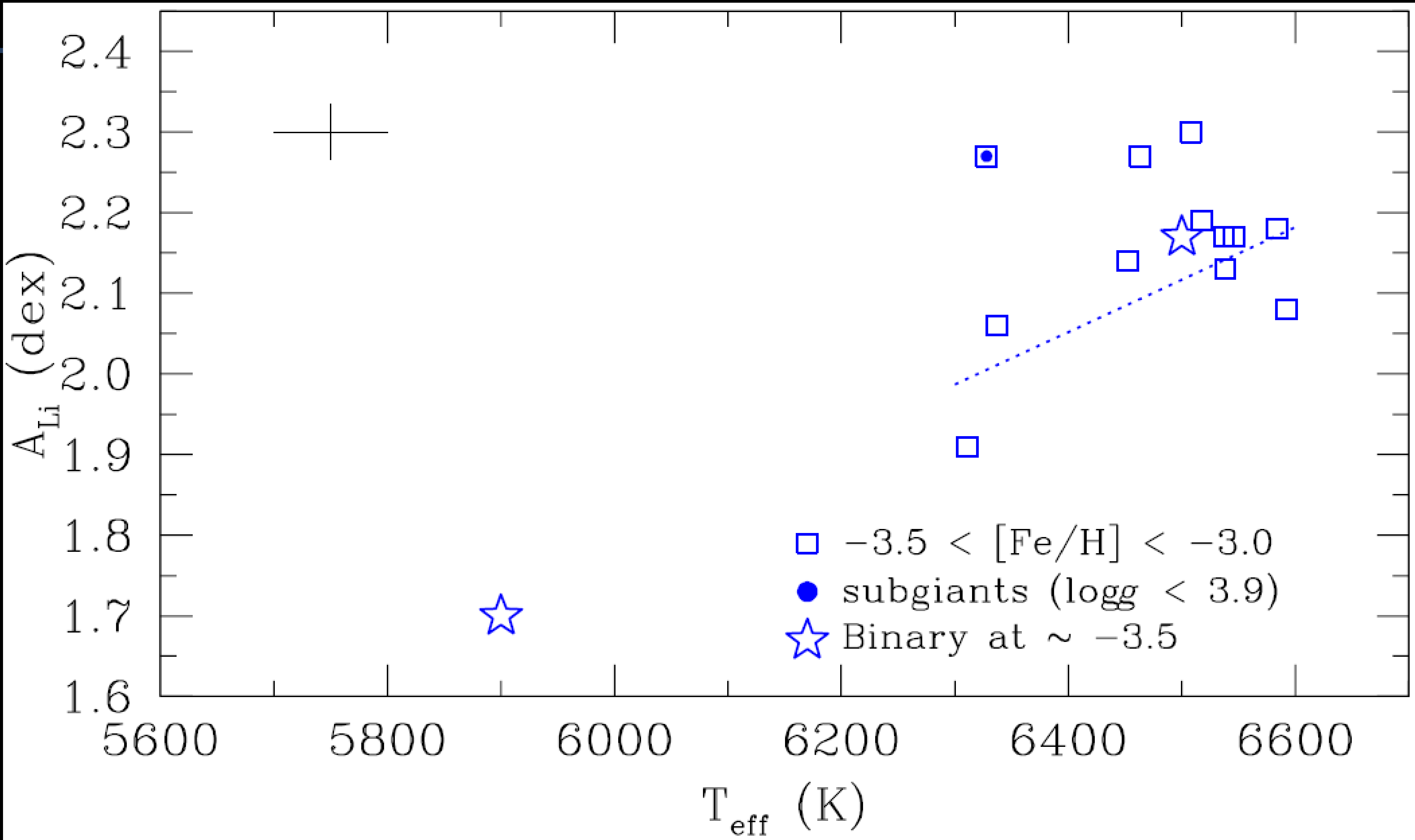
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
5600
5800
6000
6200
6400
6600
T_{eff} (K)
A_{Li} (dex)
−3.5 < [Fe/H] < −3.0
subgiants (logg < 3.9)

-3.5 < [Fe/H] < -3.0



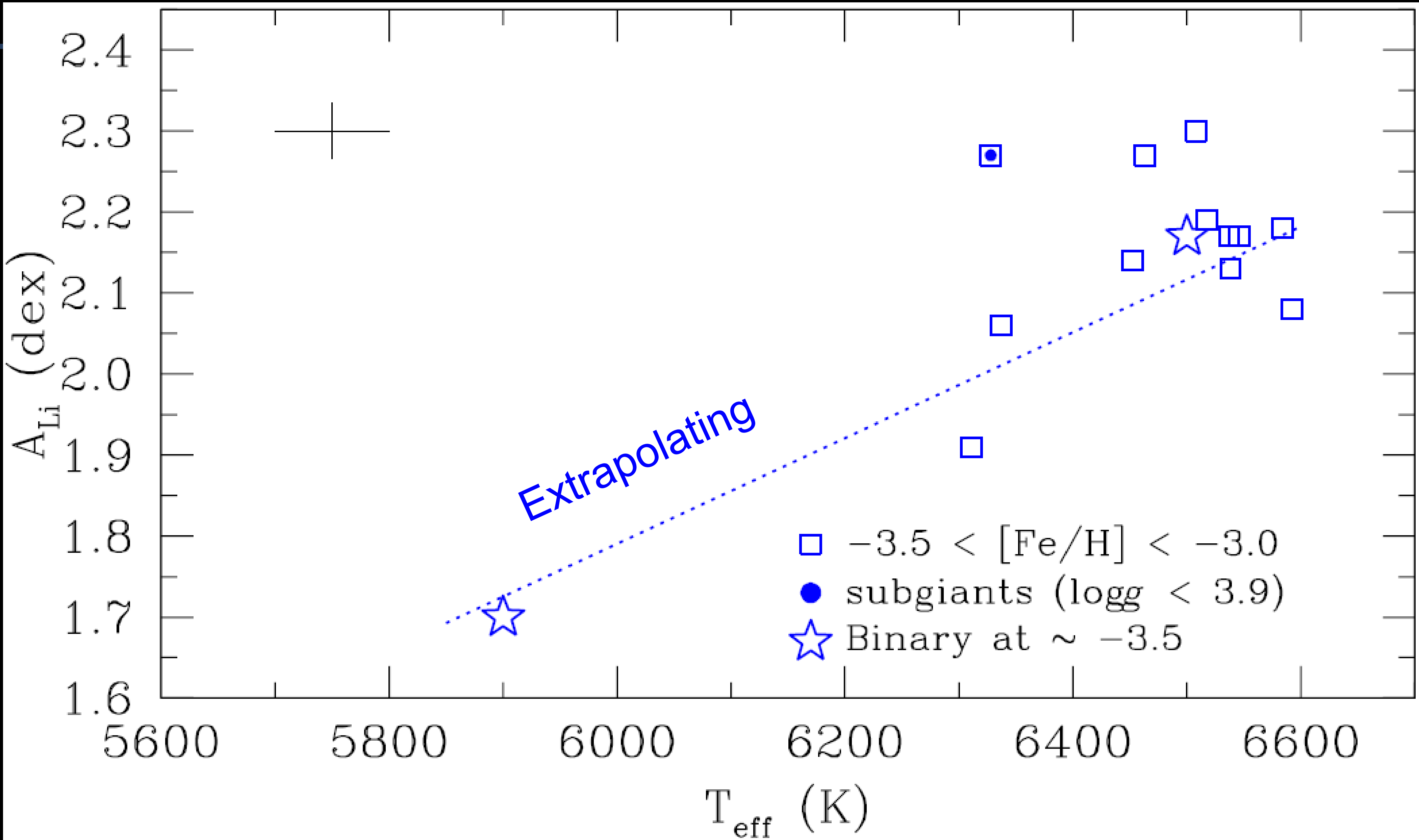
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
A_{Li} (dex)
5600
5800
6000
6200
6400
6600
T_{eff} (K)
−3.5 < [Fe/H] < −3.0
subgiants (logg < 3.9)

-3.5 < [Fe/H] < -3.0



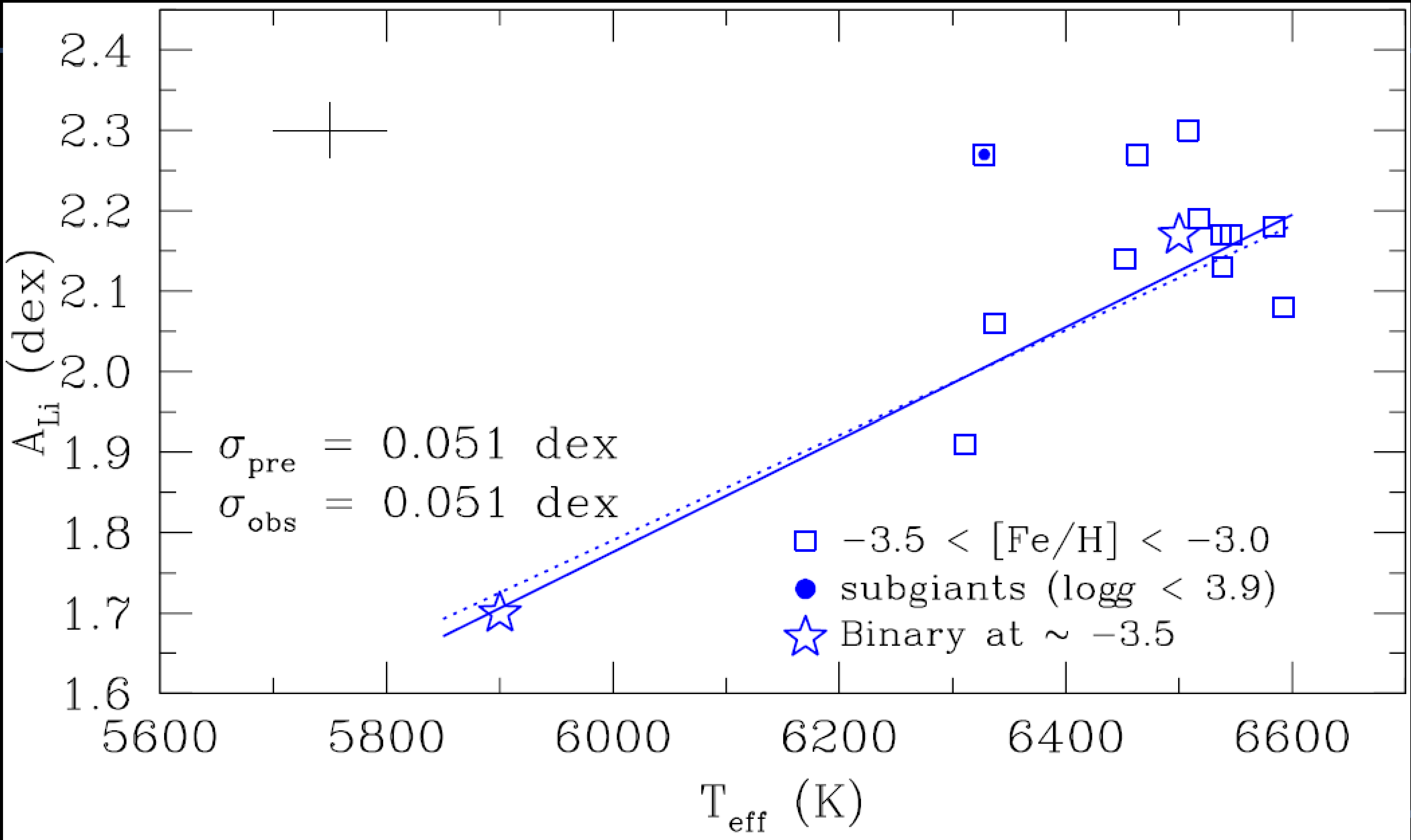
Binary from Gonzalez Hernandez et al.

-3.5 < [Fe/H] < -3.0



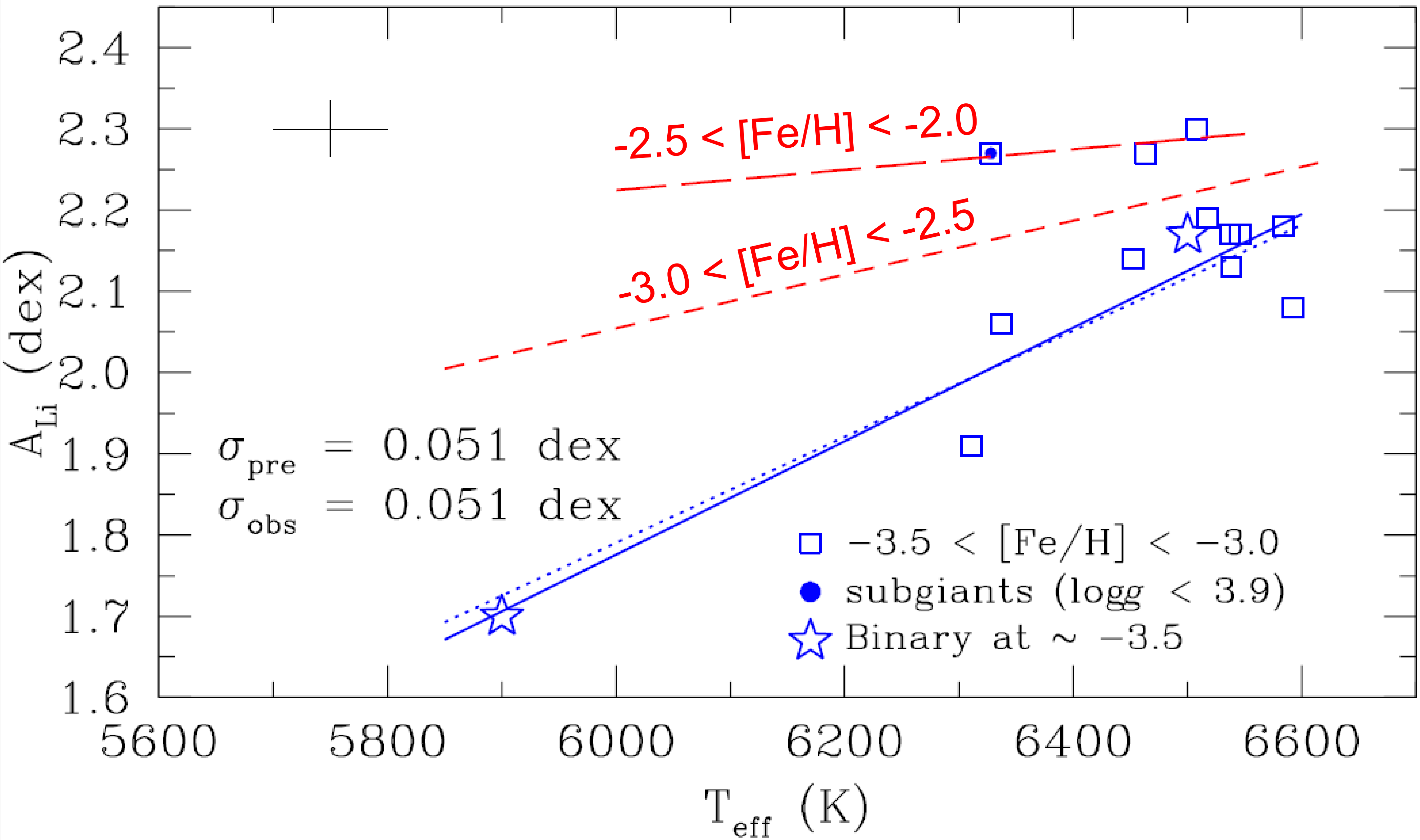
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
A_Li (dex)
5600
5800
6000
6200
6400
6600
T_eff (K)
Extrapolating
−3.5 < [Fe/H] < −3.0
subgiants (logg < 3.9)
Binary at ~ −3.5

-3.5 < [Fe/H] < -3.0



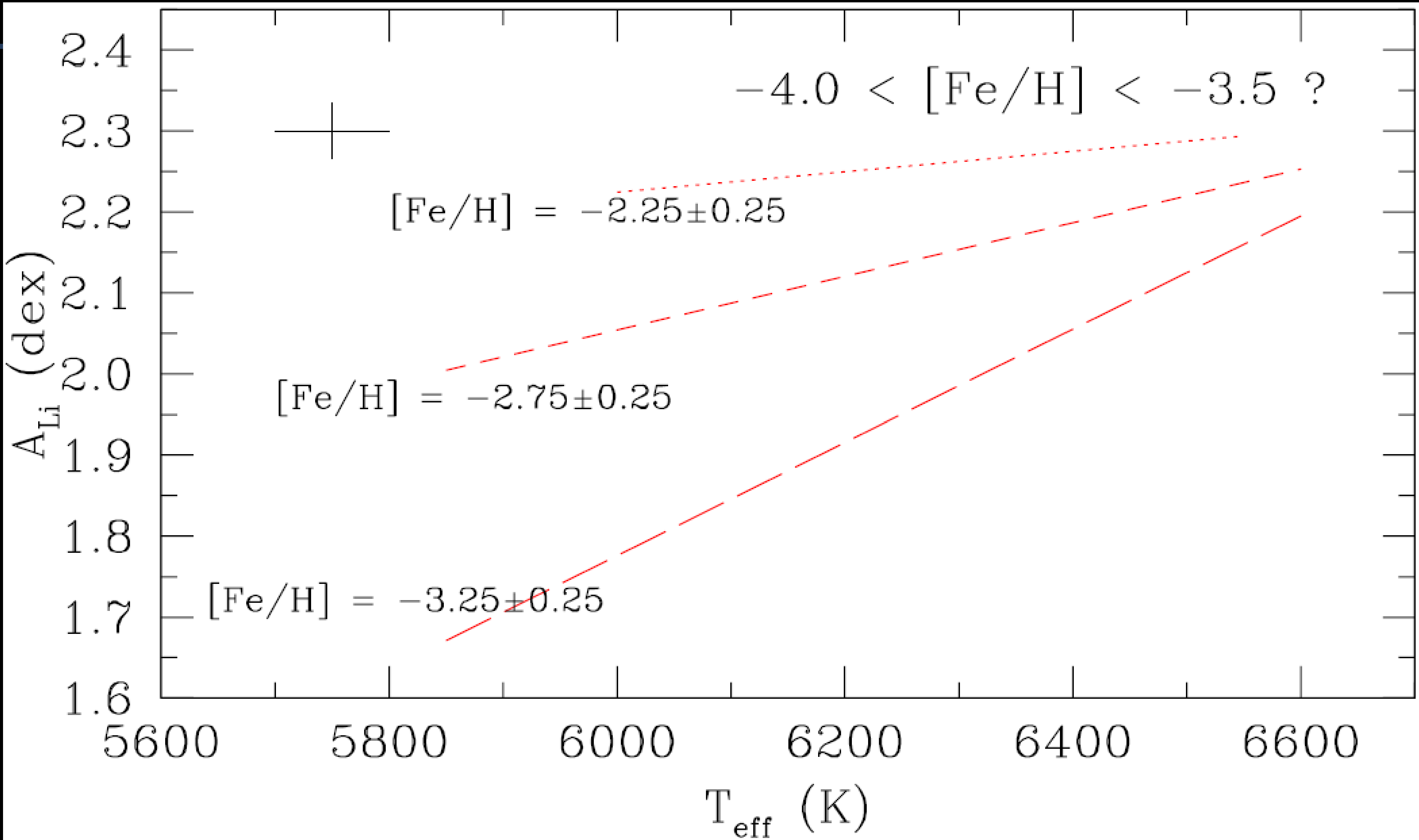
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
A_{Li} (dex)
σ_{pre} = 0.051 dex
σ_{obs} = 0.051 dex
−3.5 < [Fe/H] < −3.0
subgiants (logg < 3.9)
Binary at ~ −3.5
5600
5800
6000
6200
6400
6600
T_{eff} (K)

-3.5 < [Fe/H] < -3.0



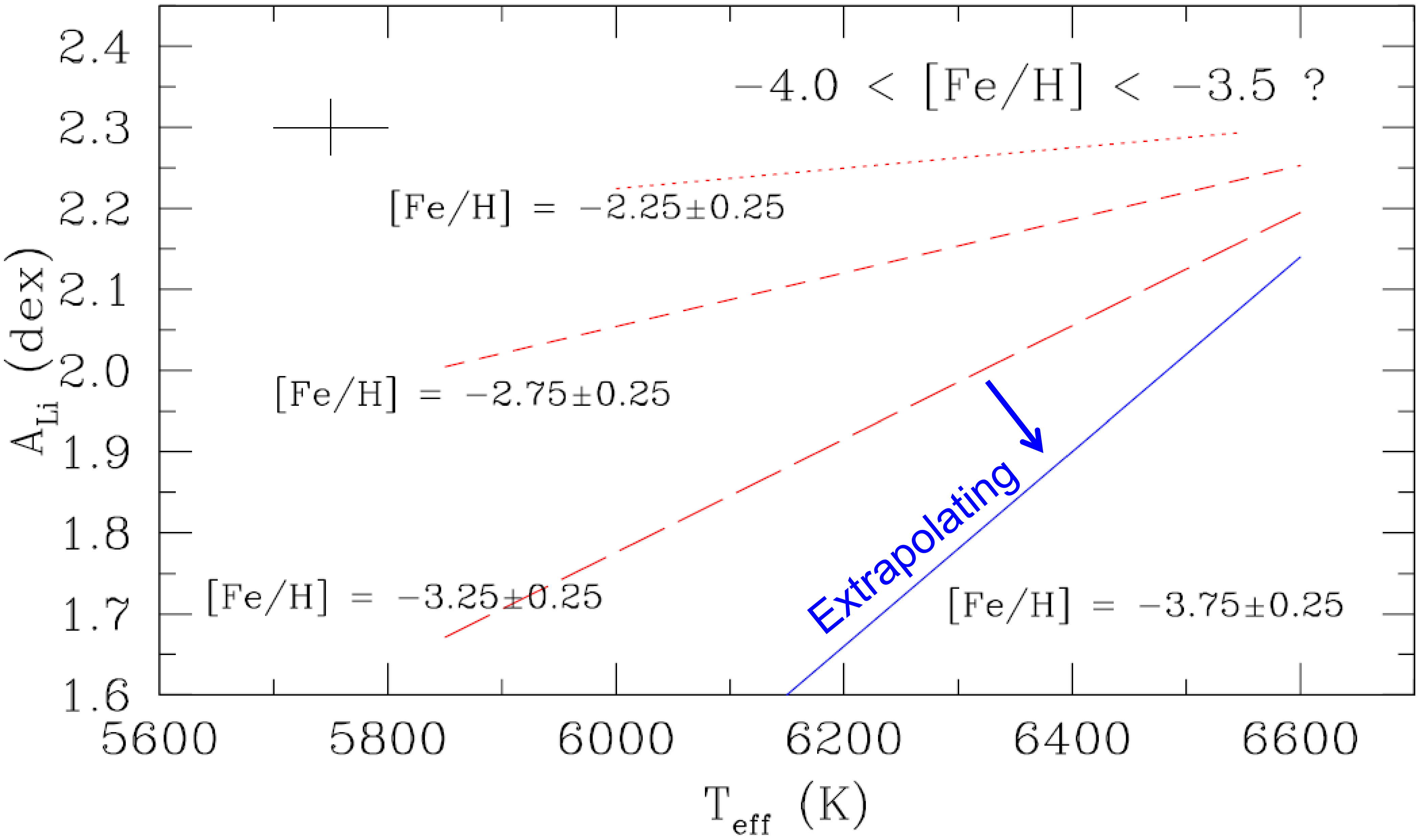
-2.5 < [Fe/H] < -2.0
-3.0 < [Fe/H] < -2.5
σ_{pre} = 0.051 dex
σ_{obs} = 0.051 dex
−3.5 < [Fe/H] < −3.0
subgiants (logg < 3.9)
Binary at ~ −3.5
A_{Li} (dex)
T_{eff} (K)
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
5600
5800
6000
6200
6400
6600

[Fe/H] < -3.5 ...



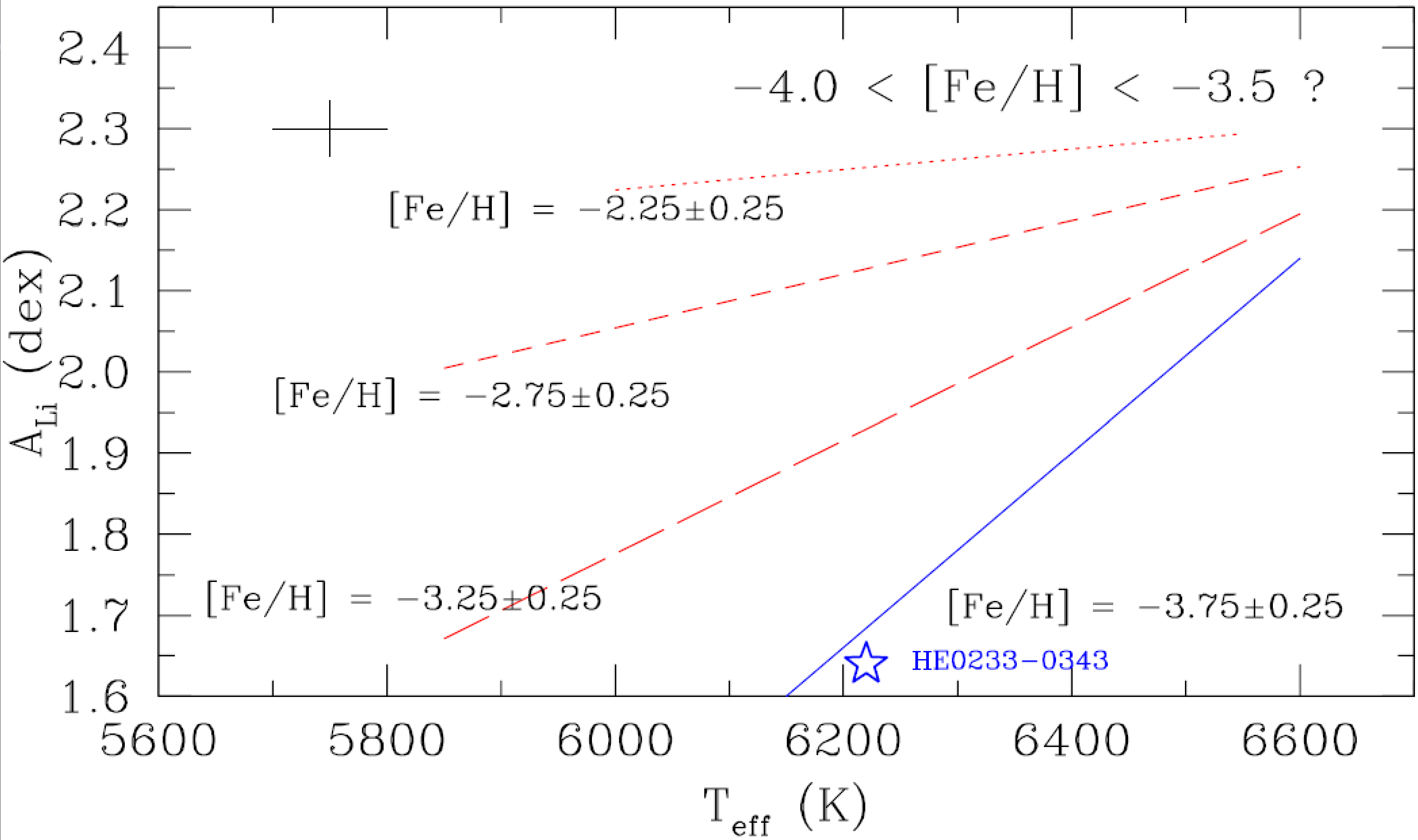
−4.0 < [Fe/H] < −3.5 ?
[Fe/H] = −2.25±0.25
[Fe/H] = −2.75±0.25
[Fe/H] = −3.25±0.25
A_Li (dex)
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
5600
5800
6000
6200
6400
6600
T_eff (K)

[Fe/H] < -3.5 ...



−4.0 < [Fe/H] < −3.5 ?
[Fe/H] = −2.25±0.25
[Fe/H] = −2.75±0.25
[Fe/H] = −3.25±0.25
[Fe/H] = −3.75±0.25
Extrapolating
A_Li (dex)
T_eff (K)
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
5600
5800
6000
6200
6400
6600

[Fe/H] < -3.5 ...



EMP by Garcia Perez et al.

Conclusions

- The (undepleted) Spite plateau is at A(Li) >= 2.3
- There is strong evidence for Li stellar depletion at all metallicities.
- The depletion is metallicity dependent, imposing strong constraints on stellar models of Li depletion
- In extremely metal-poor stars ([Fe/H] < -3.5) the Li abundance will be very low even at high T_{eff}
- We need more data at all metallicities below [Fe/H] < 1