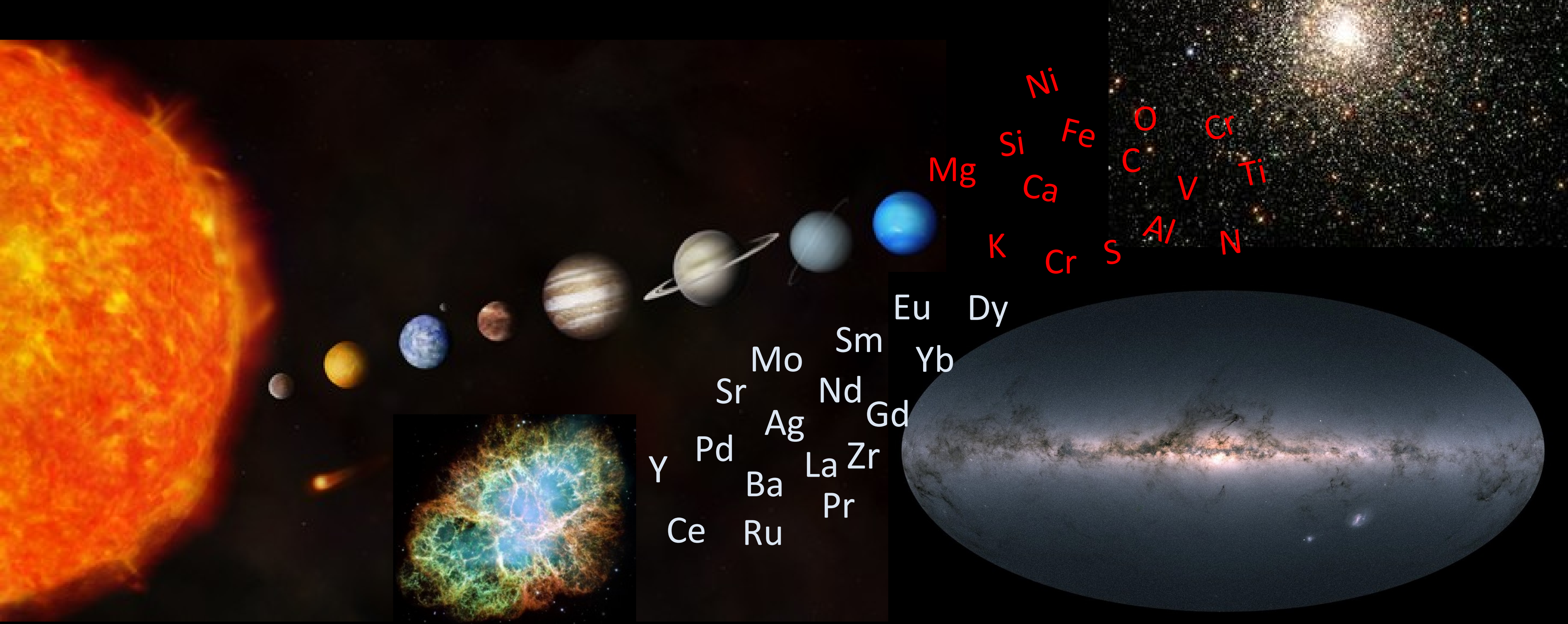
High Precision Differential Spectroscopy: Method & Science Cases



@DrJorgeMelendez

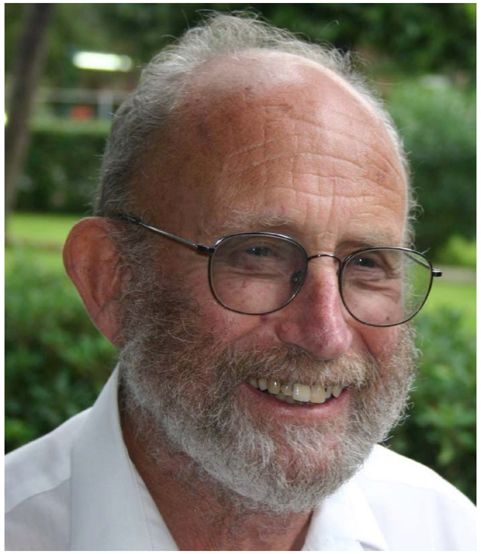
Univ. São Paulo, Brazil

INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS

SAMPA
Stellar Atmospheres, Planets and Abundances

Standing on the shoulders of giants

Cecilia Payne

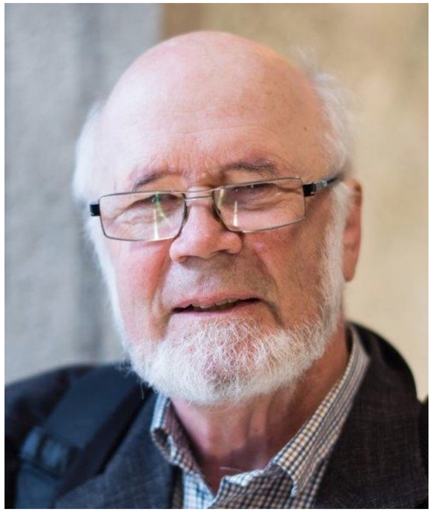


George Wallerstein

Chris Sneden

Beatriz Barbuy

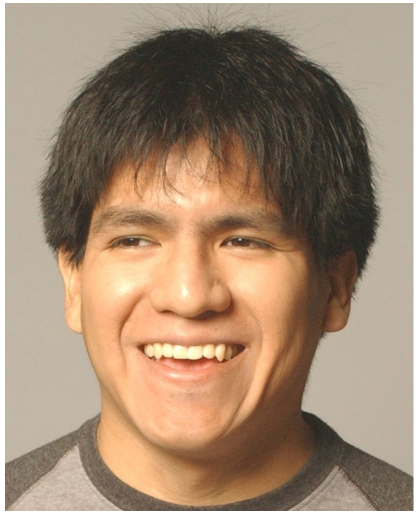
Raffaele Gratton



Bengt Gustafsson

Poul Nissen

Martin Asplund



Iván Ramírez

What is the limit in chemical abundance precision?

From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
Proceedings IAU Symposium No. 228, 2005
V. Hill, P. François & F. Primas, eds.

doi:10.1017/S1743921305005934

Globular cluster and halo field abundances: similarities and a few differences

Christopher Sneden[1]

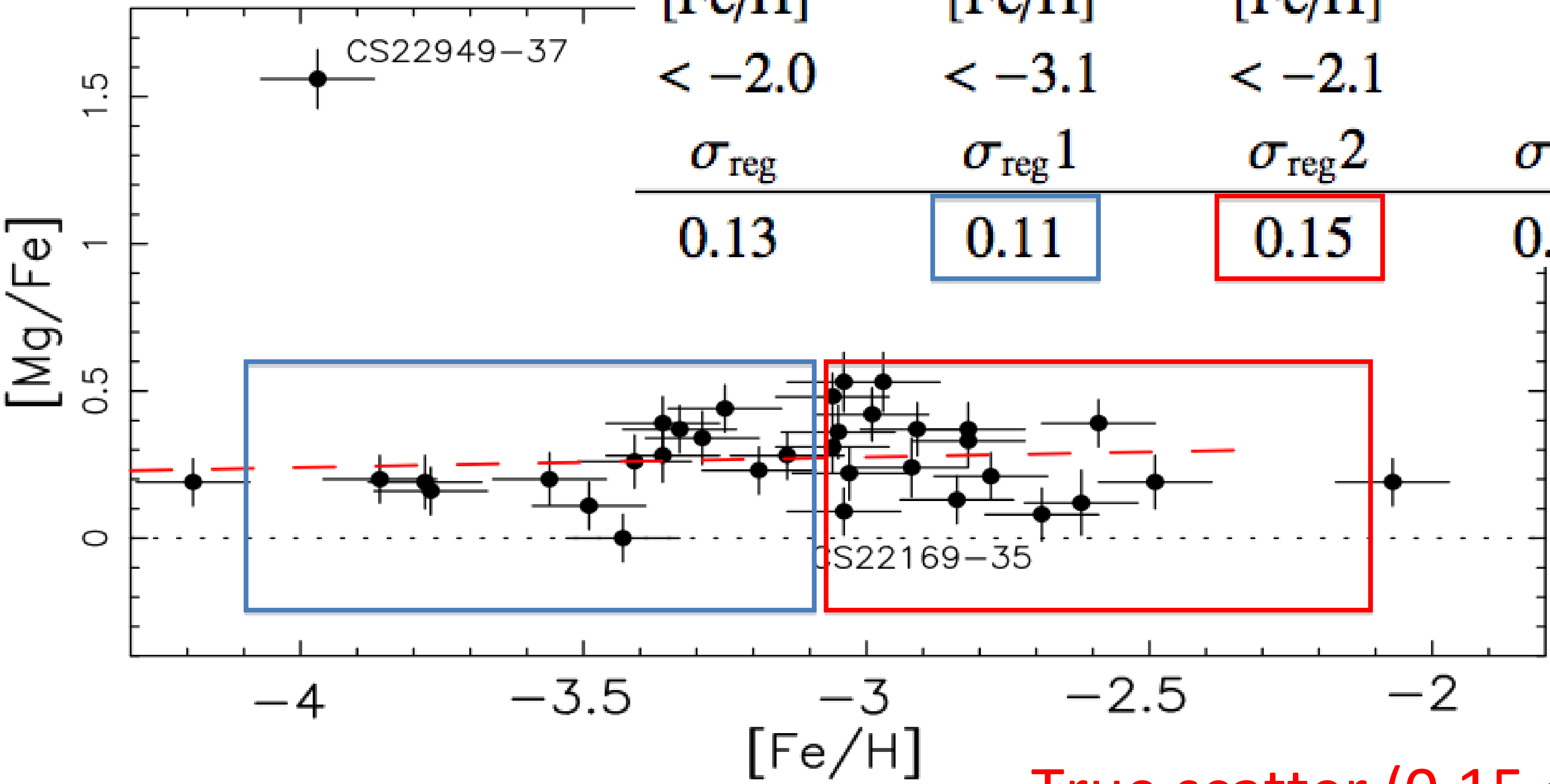
[1]Department of Astronomy, University of Texas, Austin, TX 78712, USA
email: chris@verdi.as.utexas.edu

Sneden suggests a precision ≥0.06 dex and accuracy worse than 0.1 dex: "accuracy better than 0.1 dex in abundance ratios is difficult to achieve at the moment"

What is the limit in abundance precision?

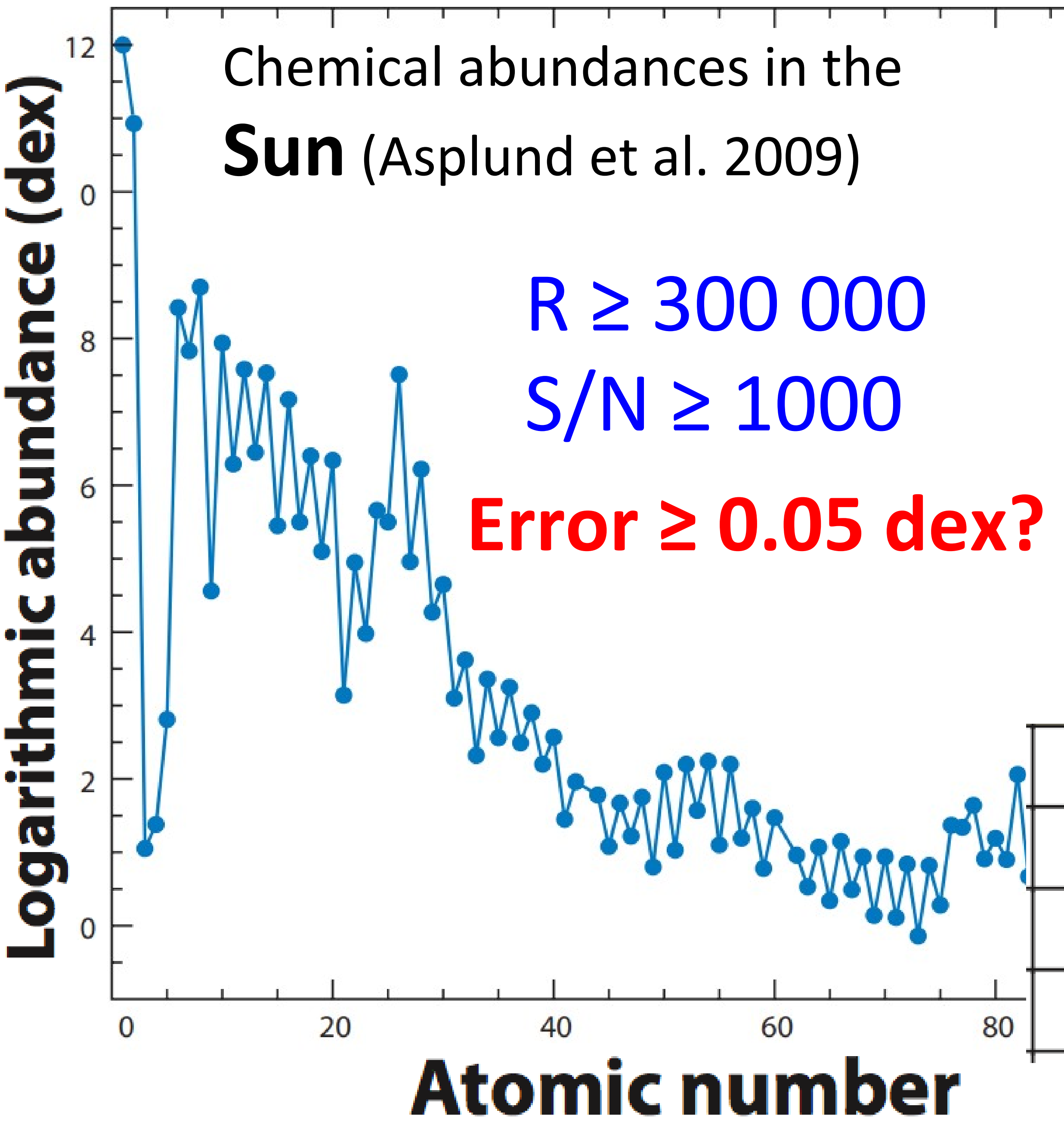
Cayrel et al. 2004

$-4.1 <$ [Fe/H] < -2.0 σ_{reg}	$-4.1 <$ [Fe/H] < -3.1 $\sigma_{reg}1$	$-3.1 <$ [Fe/H] < -2.1 $\sigma_{reg}2$	σ_{mes}
0.13	$\boxed{0.11}$	$\boxed{0.15}$	0.09



True scatter (0.15 dex) or abundance errors?

What is the limit in abundance precision?



Chemical abundances in the **Sun** (Asplund et al. 2009)

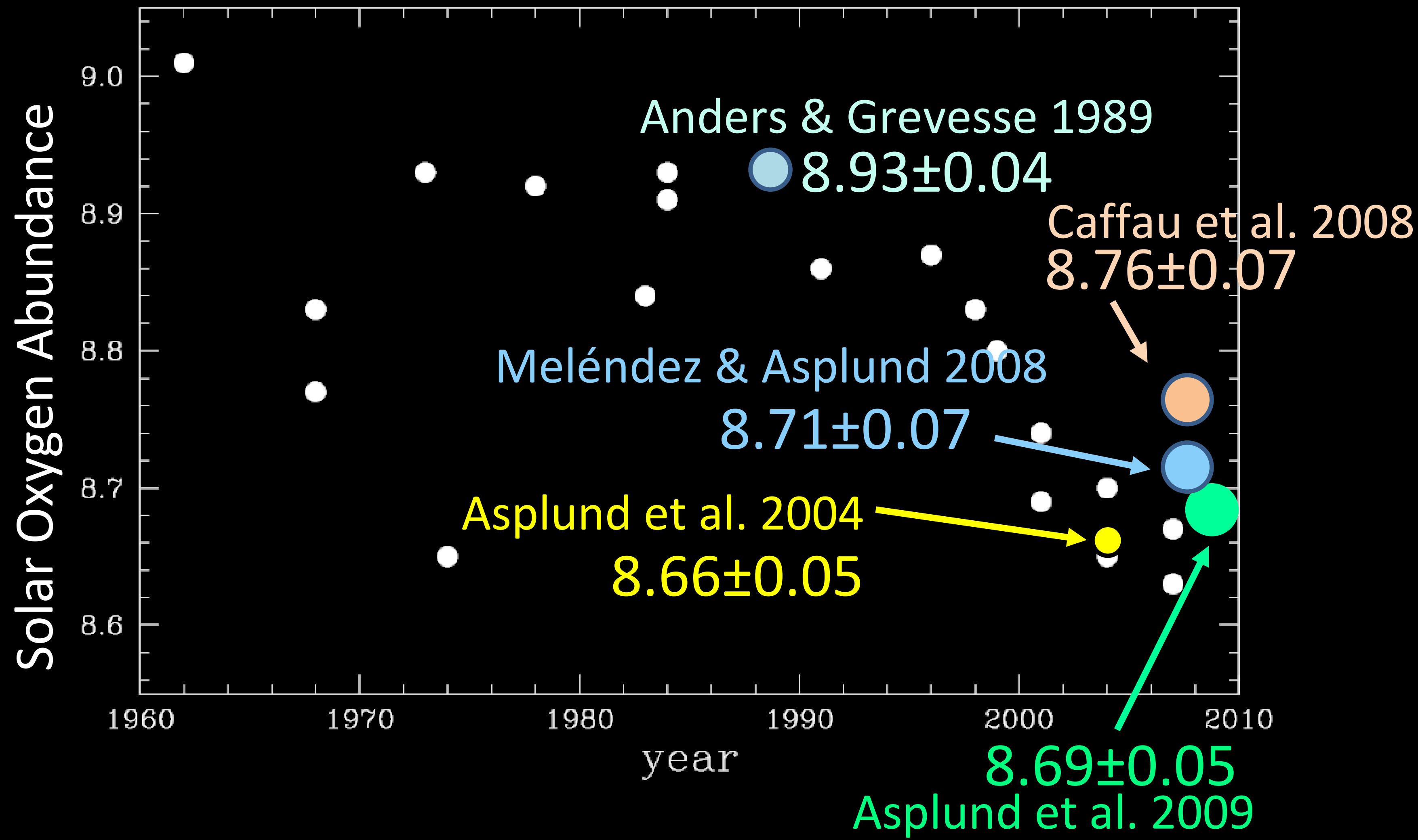
R ≥ 300 000

S/N ≥ 1000

Error ≥ 0.05 dex?

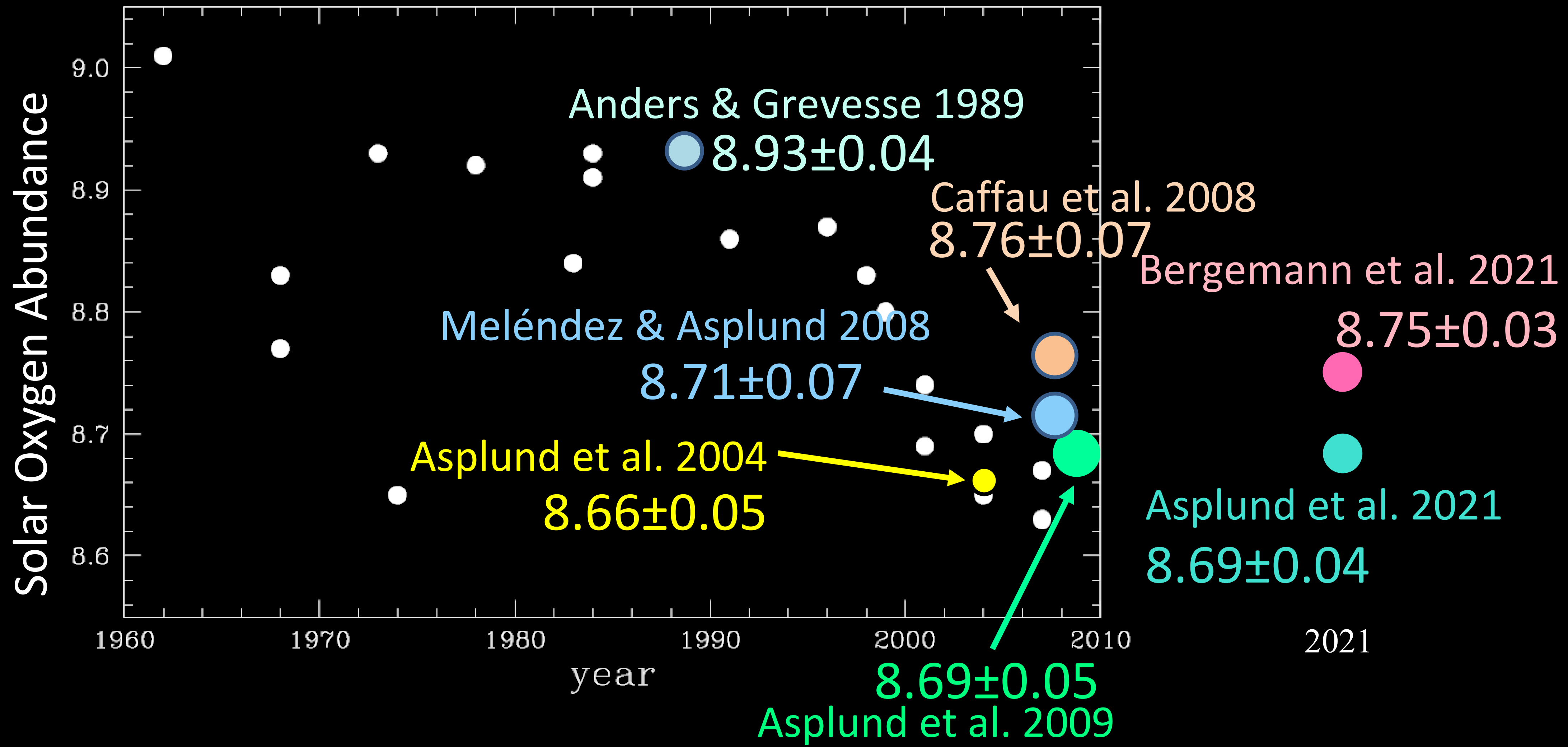
Z	Element	Photosphere
1	H	12.00
2	He	[10.93 ± 0.01]
3	Li	1.05 ± 0.10
4	Be	1.38 ± 0.09
5	B	2.70 ± 0.20
6	C	8.43 ± 0.05
7	N	7.83 ± 0.05
8	O	8.69 ± 0.05
44	Ru	1.75 ± 0.08
45	Rh	0.91 ± 0.10
46	Pd	1.57 ± 0.10
47	Ag	0.94 ± 0.10

What is going on with the solar O abundance?



Discrepancy in modern analyses: ΔO ~ 0.07 dex

What is going on with the solar O abundance?



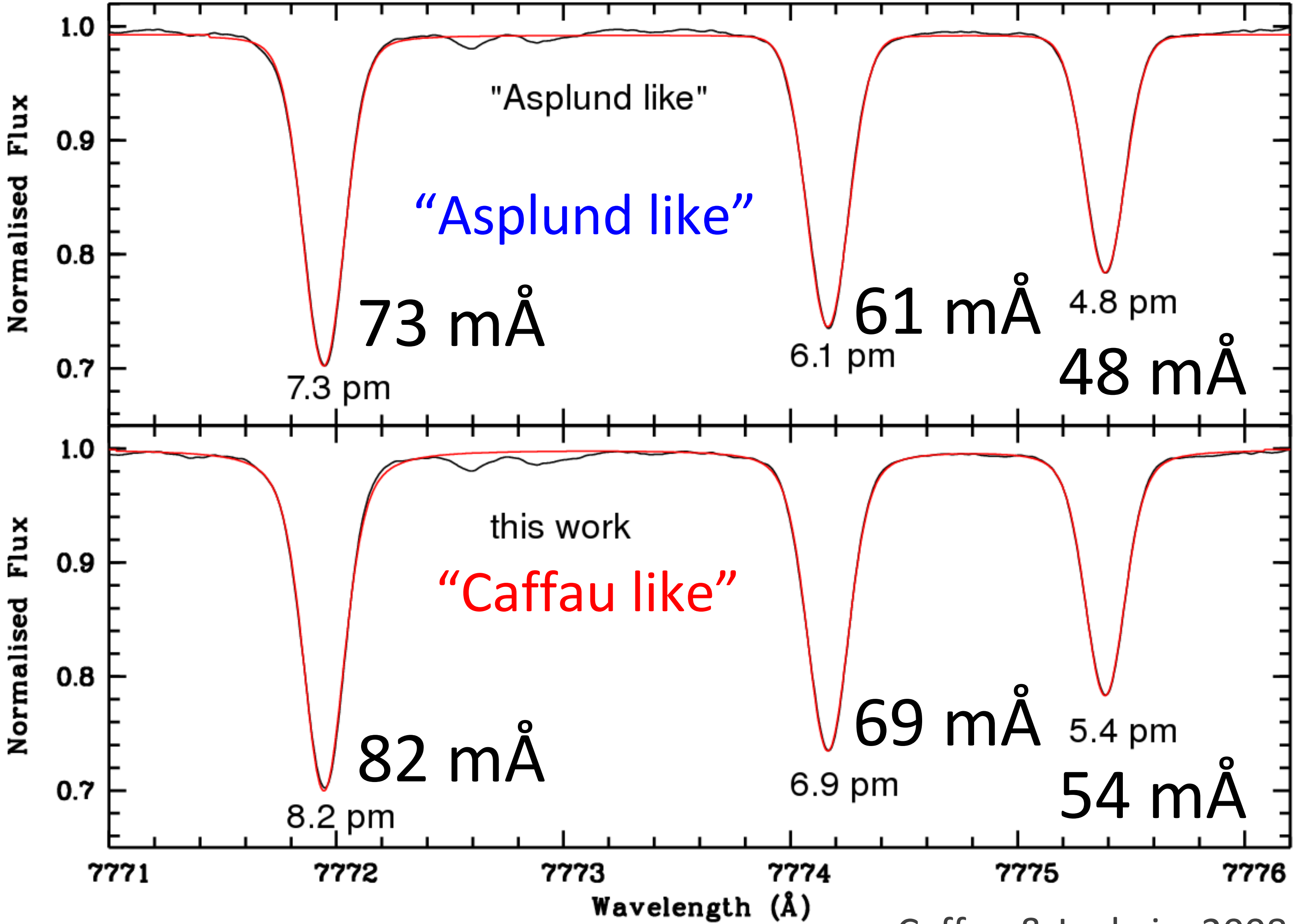
Discrepancy in modern analyses: ΔO ~ 0.07 dex

Caffau et al. vs. Asplund oxygen abundance

Asplund et al.
8.69 ± 0.05

Caffau et al.
8.76 ± 0.07

Main reason for the discrepancy is the different set of EW measurements by both groups



Caffau & Ludwig, 2008

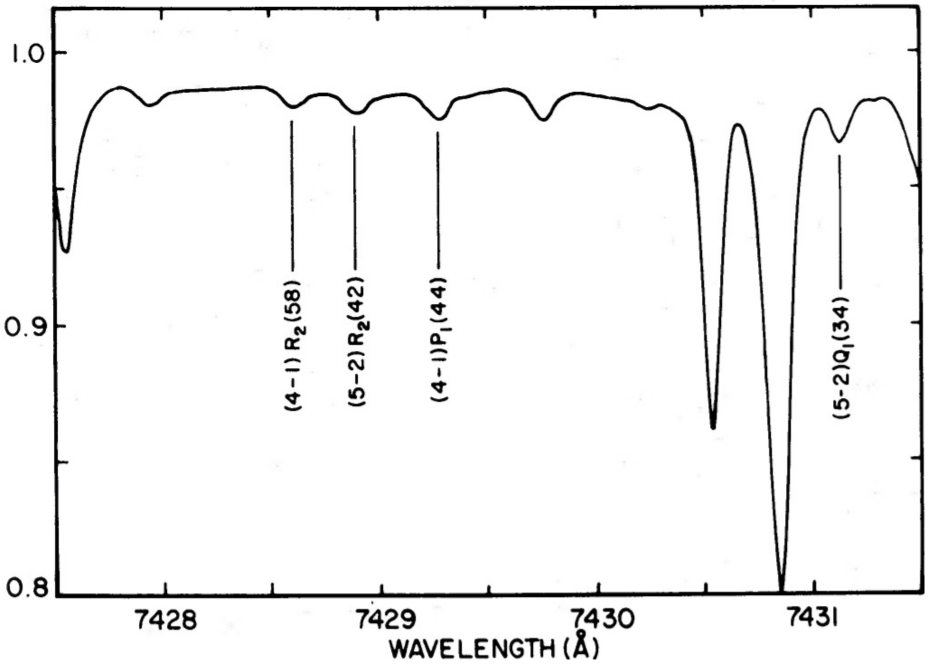
Who is correct?

CN is ubiquitous in the solar spectrum

THE ASTROPHYSICAL JOURNAL, **259**: 381–391, 1982 August 1

THE CN RED SYSTEM IN THE SOLAR SPECTRUM

CHRISTOPHER SNEDEN AND DAVID L. LAMBERT[1]
Department of Astronomy, University of Texas, Austin



CN RED SYSTEM—BAND OSCILLATOR STRENGTHS

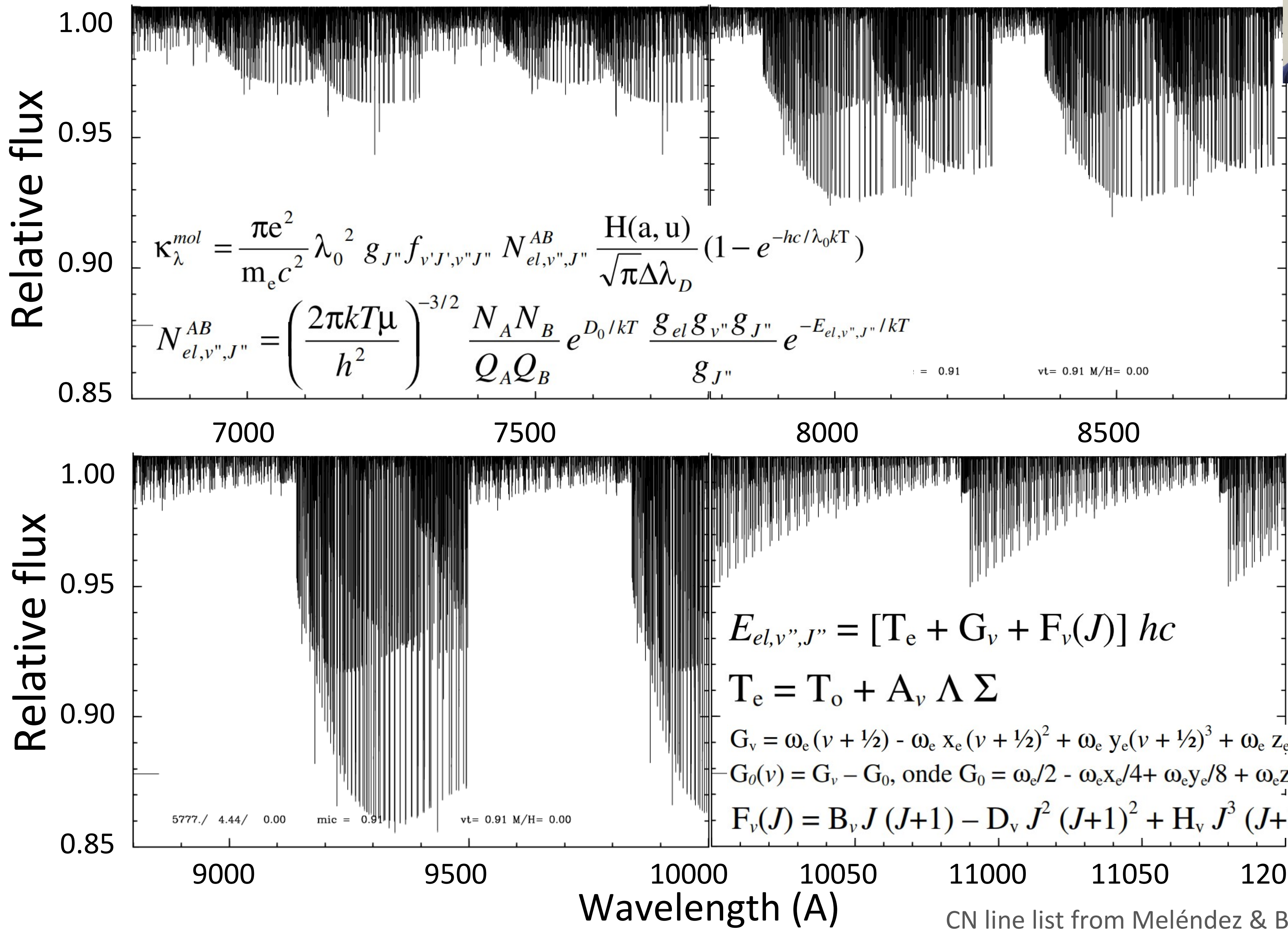
Δv	$v'-v''$	$\lambda_{v'v''}$ (Å)	W_λ[a] (mÅ)	$\bar{r}_{v'v''}$[b] (Å)	$q_{v'v''}$[b]	$R_e^2(\bar{r}_{v'v''})/R_e^2(r_{00})$[c]	Log $f_{v'v''}^{\odot}$	$f_{v'v''}^{\odot}$	$f_{v'v''}^{th}$
−2	0–2	19760	2	1.304	1.13-1	1.07	−3.60 ± 0.12	2.5-4	2.61-4
	1–3	20580	2	1.312	2.24-1	0.93	−3.38 ± 0.08	4.2-4	4.92-4
	2–4	21465	...	1.320	2.88-1	...	...	...	5.96-4
−1	0–1	14130	10	1.252	3.72-1	0.88	−3.02 ± 0.05	9.6-4	1.30-3
	1–2	14600	6.5	1.261	3.48-1	0.95	−3.03 ± 0.06	9.4-4	1.16-3
	2–3	15100	2.5	1.271	2.07-1	0.97	−3.26 ± 0.10	5.5-4	6.57-4
	3–4	15640	...	1.284	8.10-2	...	...	...	2.41-4
0	0–0	10965	20	1.205	4.96-1	1.00	−2.73 ± 0.04	1.9-3	2.36-3
	1–1	11280	1	1.222	4.37-2	1.25	−3.70 ± 0.13	2.0-4	1.95-4
	2–2	11610	...	1.190	1.32-2	...	...	...	6.17-5
+1	1–0	9170	12	1.164	3.21-1	1.00	−2.84 ± 0.06	1.5-3	1.91-3
	2–1	9410	6	1.173	2.39-1	1.15	−2.92 ± 0.06	1.2-3	1.37-3
	3–2	9665	2.5	1.184	9.69-2	1.37	−3.25 ± 0.13	5.7-4	5.32-4
	4–3	9930	...	1.208	1.43-2	...	...	...	7.34-5
+2	2–0	7895	6	1.127	1.27-1	1.26	−3.08 ± 0.04	8.4-4	9.06-4
	3–1	8090	6	1.135	1.95-1	1.24	−2.91 ± 0.05	1.2-3	1.35-3
	4–2	8295	2.5	1.143	1.82-1	1.25	−2.95 ± 0.06	1.1-3	1.21-3
	5–3	8505	1.2	1.152	1.21-1	1.36	−3.10 ± 0.13	8.0-4	7.82-4
	6–4	8730	...	1.164	5.67-2	...	...	...	3.50-4
+3	3–0	6940	2.5	1.094	4.05-2	1.35	−3.49 ± 0.06	3.3-4	3.34-4
	4–1	7105	2.5	1.101	9.56-2	1.19	−3.18 ± 0.06	6.6-4	7.67-4
	5–2	7275	2.5	1.109	1.35-1	1.26	−3.02 ± 0.08	9.6-4	1.05-3
	6–3	7455	1.5	1.116	1.42-1	1.40	−2.96 ± 0.07	1.1-3	1.08-3
	7–4	7645	...	1.124	1.21-1	...	...	...	8.85-4
+4	4–0	6205	1.2	1.064	1.14-2	1.31	−4.00 ± 0.10	1.0-4	1.07-4
	5–1	6345	1.5	1.071	3.67-2	1.49	−3.45 ± 0.07	3.6-4	3.34-4
	6–2	6490	1.2	1.078	6.85-2	1.33	−3.24 ± 0.10	5.8-4	6.08-4
	7–3	6645	1.0	1.085	9.58-2	1.41	−3.08 ± 0.07	8.4-4	8.28-4
	8–4	6805	...	1.092	1.10-2	...	...	...	9.23-4

$$W_\lambda = \epsilon_C \epsilon_N gf_{\rm line} G(\lambda, \chi, D_0{}^0, \text{atmosphere})$$

$$gf_{\rm line} = \left(\frac{2-\delta_{0,\Lambda''}}{2-\delta_{0,\Lambda'+\Lambda''}}\right) f_{v'v''} S_{\rm line} H(v'J'; v''J'')\lambda_{v'v''}/\lambda_{\rm line}$$

CN is ubiquitous in the solar spectrum

Beatriz Barbuy
USP, Brazil



$$\kappa_\lambda^{mol} = \frac{\pi e^2}{m_e c^2}\lambda_0^{\,2}\, g_{J''} f_{v'J',v''J''}\, N^{AB}_{el,v'',J''} \frac{H(a,u)}{\sqrt{\pi}\Delta\lambda_D}\left(1-e^{-hc/\lambda_0 kT}\right)$$

$$N^{AB}_{el,v'',J''} = \left(\frac{2\pi kT\mu}{h^2}\right)^{-3/2}\frac{N_A N_B}{Q_A Q_B}\, e^{D_0/kT}\,\frac{g_{el}\, g_{v''}\, g_{J''}}{g_{J''}}\, e^{-E_{el,v'',J''}/kT}$$

$$E_{el,v'',J''} = [T_e + G_v + F_v(J)]\, hc$$

$$T_e = T_o + A_v\, \Lambda\, \Sigma$$

$$G_v = \omega_e (v + ½) - \omega_e\, x_e (v + ½)^2 + \omega_e\, y_e (v + ½)^3 + \omega_e\, z_e (v + ½)^4 + \ldots$$

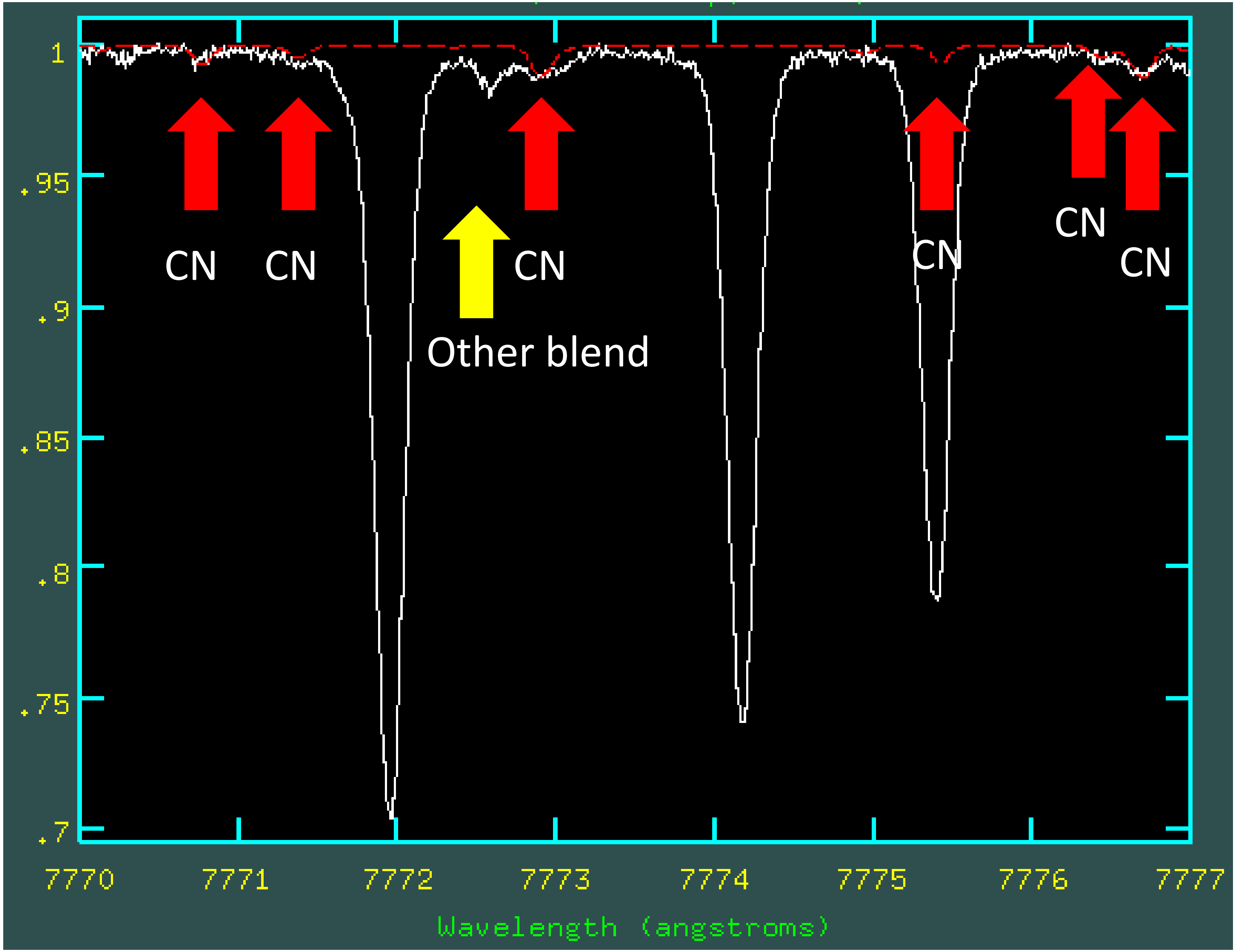
$G_0(v) = G_v - G_0$, onde $G_0 = \omega_e/2 - \omega_e x_e/4 + \omega_e y_e/8 + \omega_e z_e/16$

$$F_v(J) = B_v J (J+1) - D_v J^2 (J+1)^2 + H_v J^3 (J+1)^3 + \ldots,$$

CN line list from Meléndez & Barbuy (1999)

CN blends for O I triplet

CN blends must be taken into account, otherwise the EW may be inaccurate



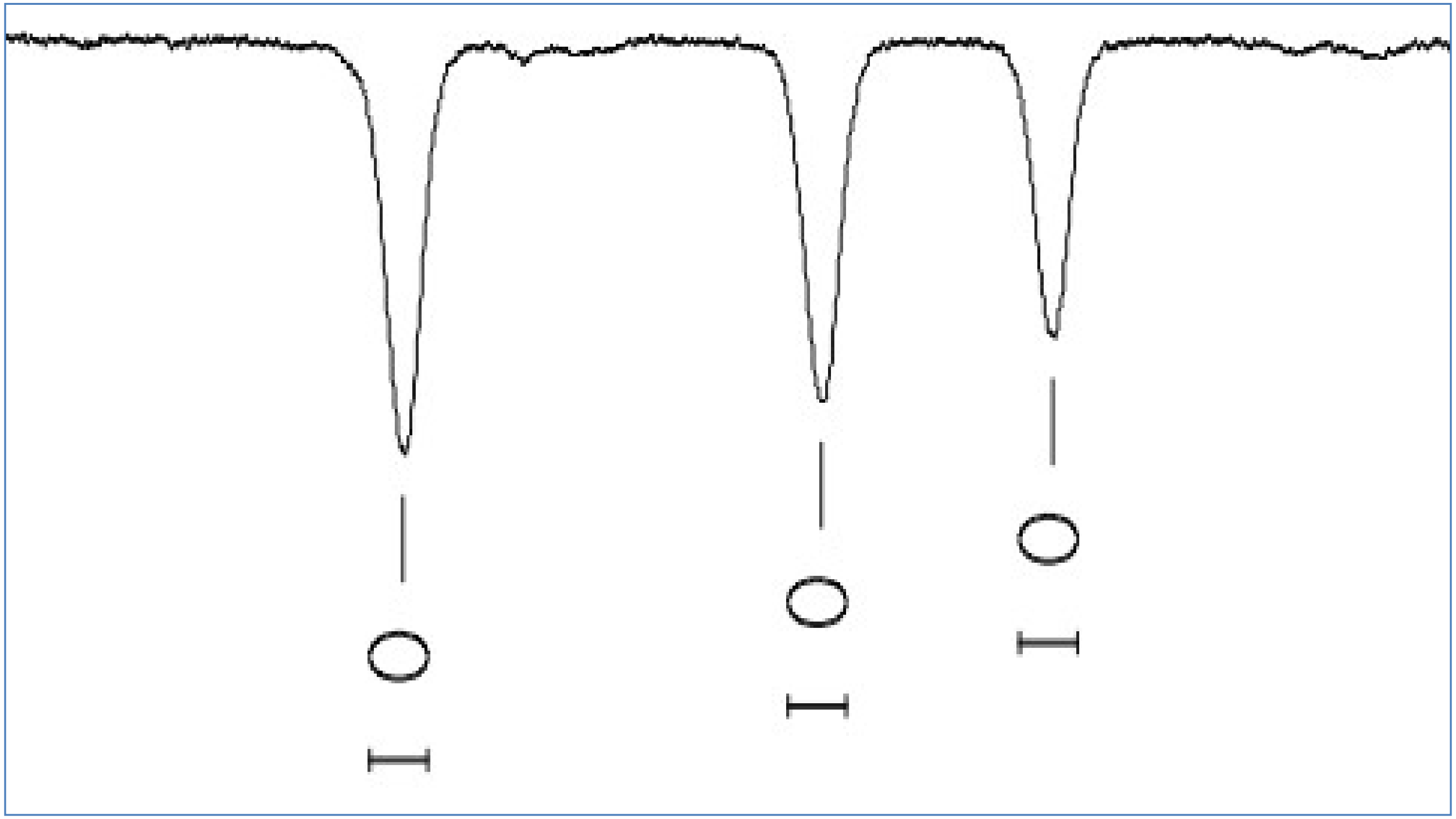
Comparison of equivalent widths for the O I triplet

Line (A)	Asplund E.W. (A)	Caffau E.W. (A)	Melendez E.W. (A)
7771	71.2	81.4	74.3 ± 2.6
7774	61.8	68.6	63.9 ± 0.5
7776	48.8	54.2	50.4 ± 0.5

Asplund et al. EWs may be underestimated by 4%

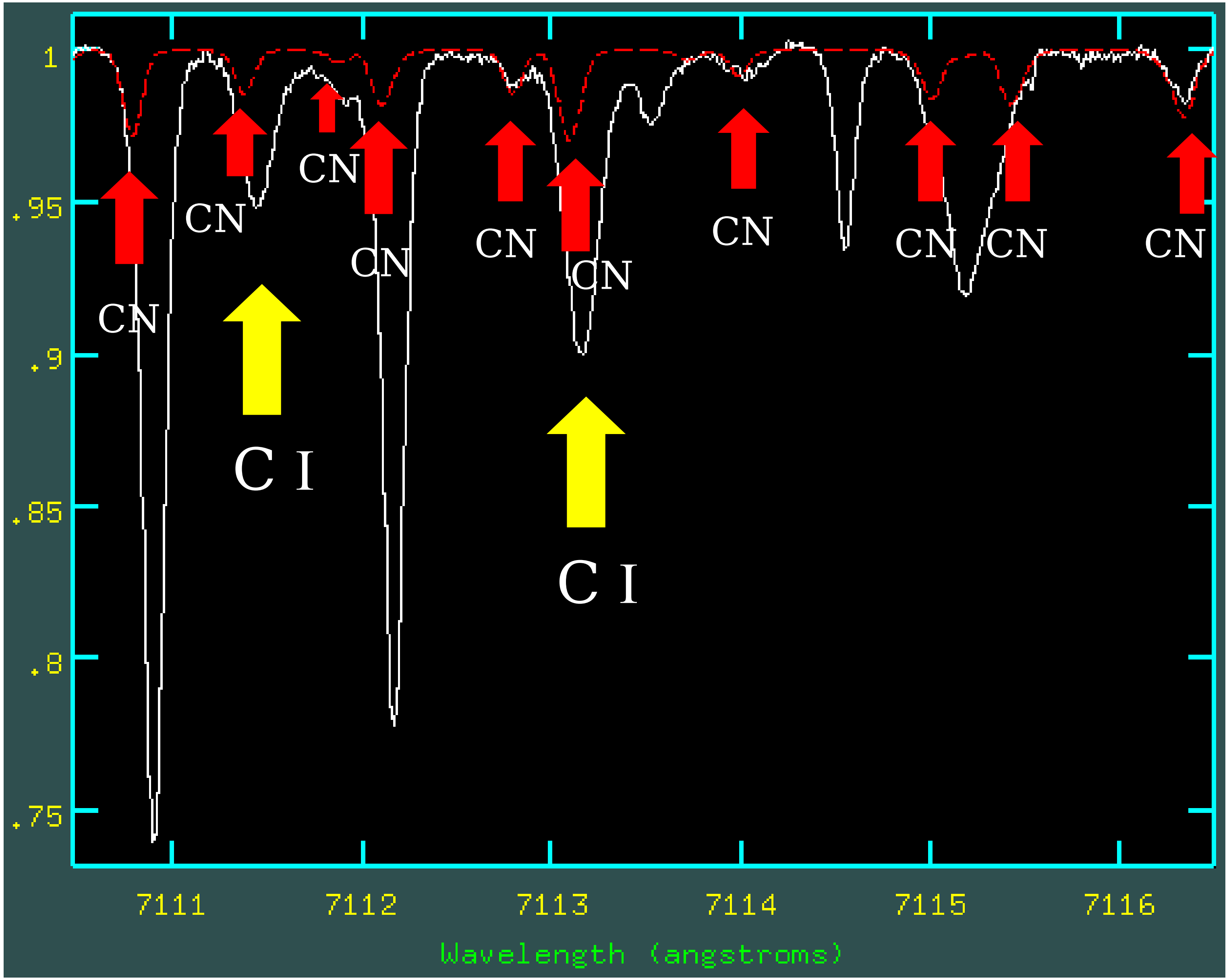
Caffau et al. EWs may be overestimated by 8%

Depending on how we measure the EW, we can have discrepancies at the level of ~0.05 dex, even for relatively clean lines like the OI triplet at 777nm

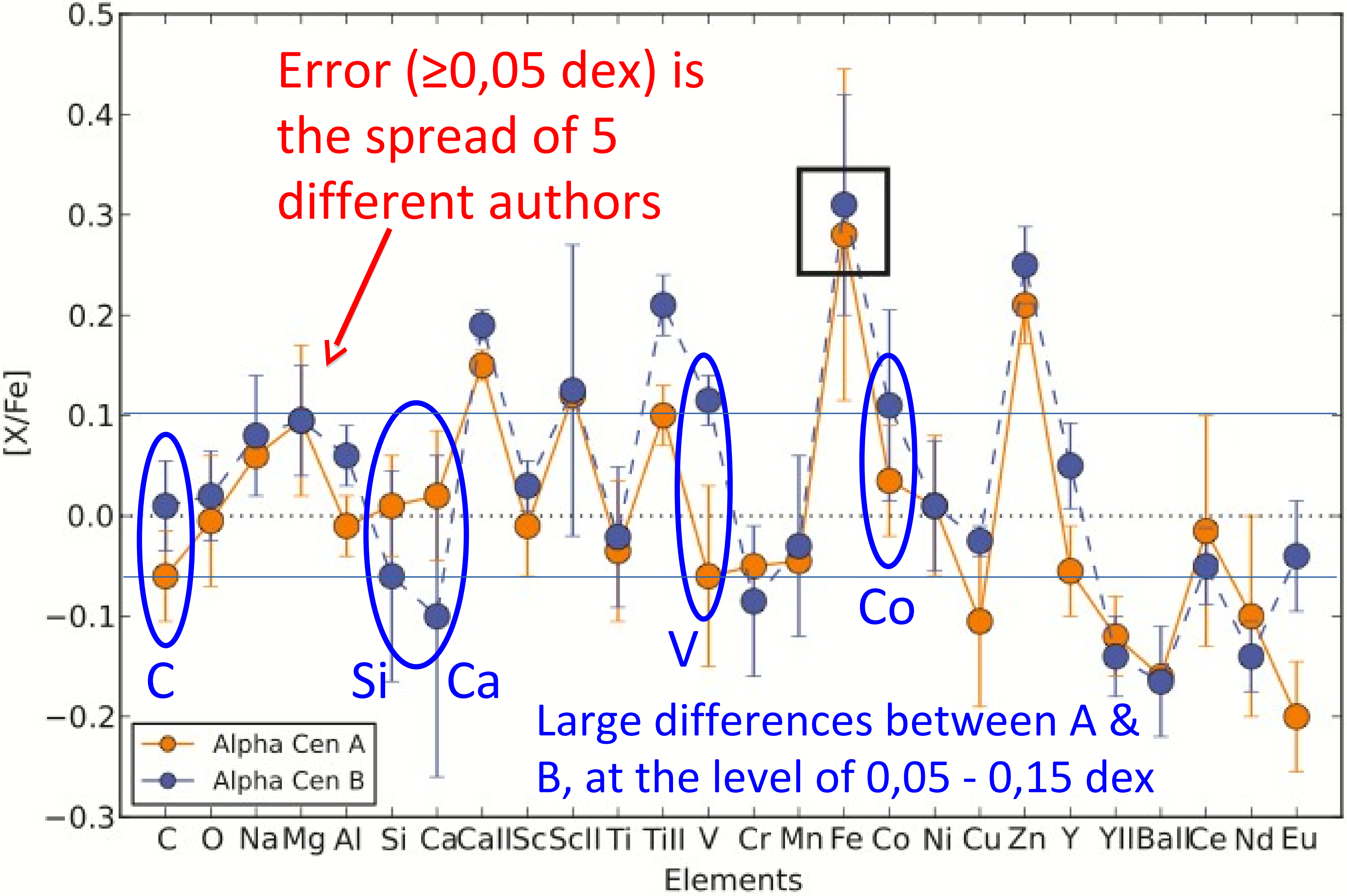


Case study: carbon

Higher absolute abundances from C I lines at 7111,4 & 7113,2 Å



Comparing abundances for α Cen A, α Cen B



Hinkel & Kane 2013

Can we break the 0.05 dex barrier in elemental abundances?

- Very high S/N: *reduces errors in W_λ*
- High spectral resolution: *reduces errors in W_λ*
- Careful selection of lines: *reduces blends*
- Strictly differential line-by-line approach: *eliminates uncertainties in atomic data (gf-values) and reduces model atmosphere errors*

Can we break the 0.05 dex barrier in elemental abundances?

- Very high S/N
- High spectral resolution
- Careful selection of lines
- *Strictly differential approach using stars similar between them (”**stellar twins**”):*

  - precise relative effective temperatures & log g

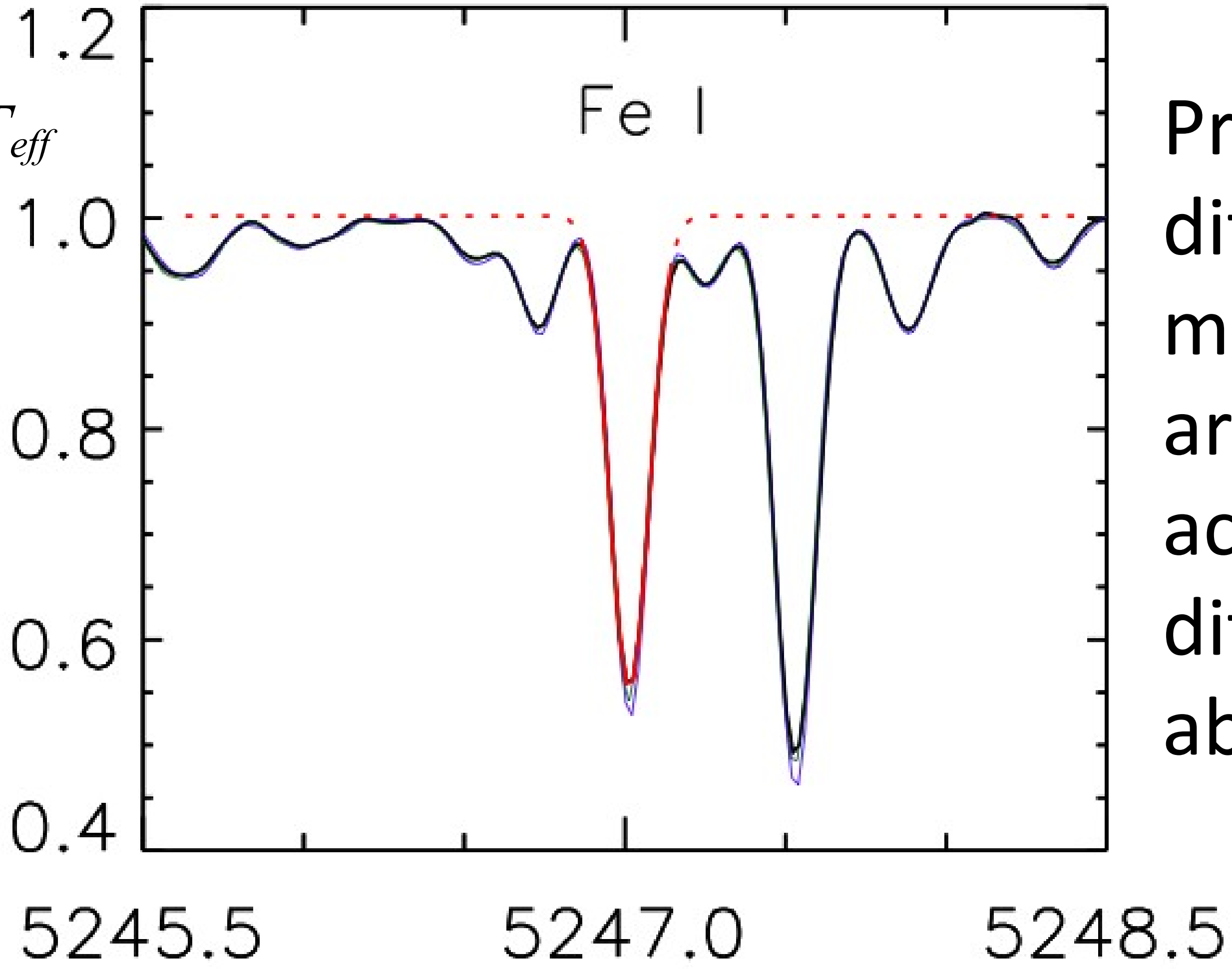
  - line-by-line cancel errors in gf-values

  - very weak dependence on model atmospheres

Differential abundances A_X (element X)

$$\log (W/\lambda) = cte + A_X + \log (g f) + \log \lambda - \theta \chi_{exc} - \log k_{cont,\lambda}$$

$$\theta = 5040/T_{eff}$$



Precise differential EW measurements are key to achieve precise differential abundances

Bedell, Meléndez, Bean et al. 2014

Differential abundances A_X (element X)

$$\log (W/\lambda) = cte + A_X + \cancel{\log (g f) + \log \lambda} - \theta \chi_{exc} - \log k_{cont,\lambda}$$

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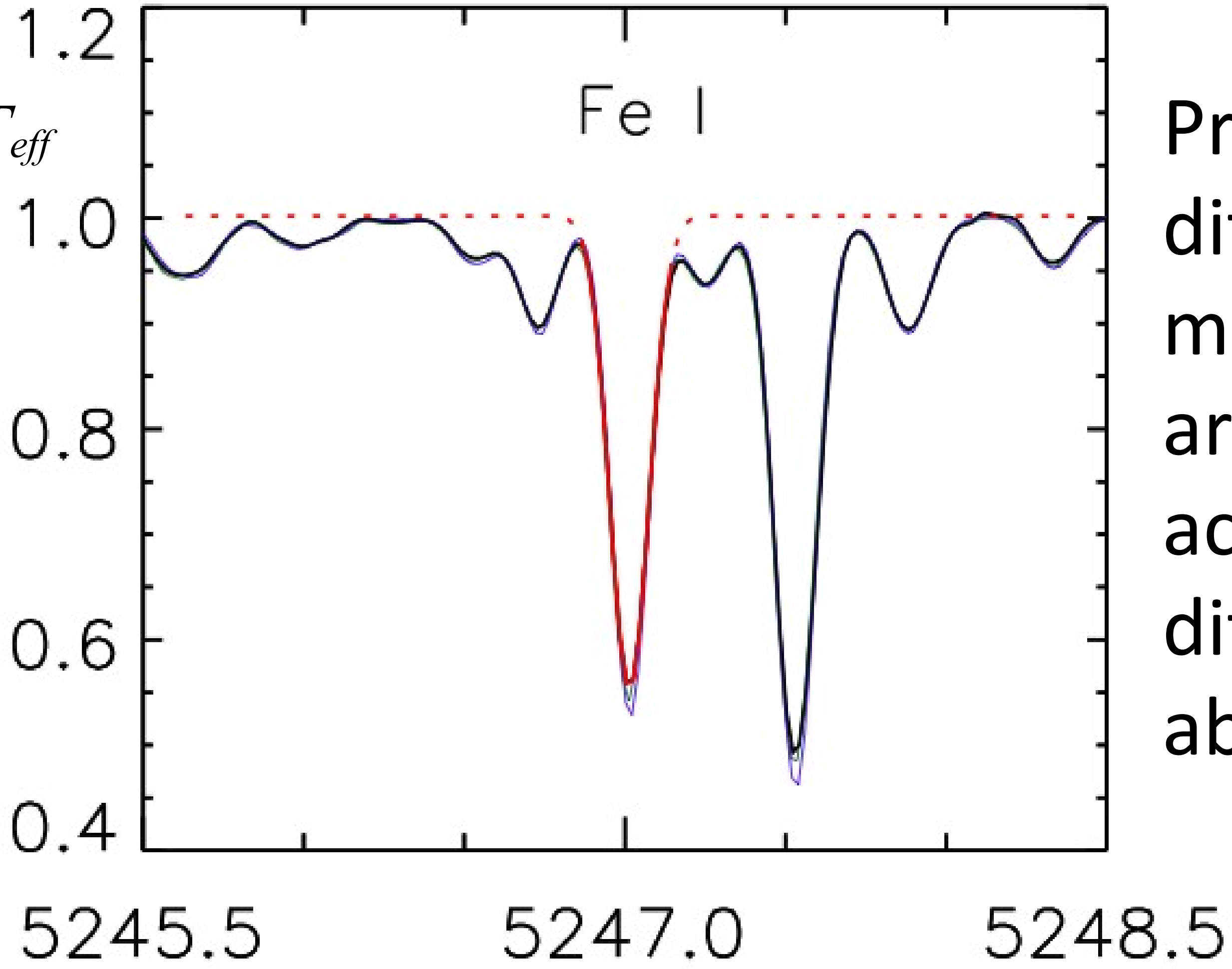

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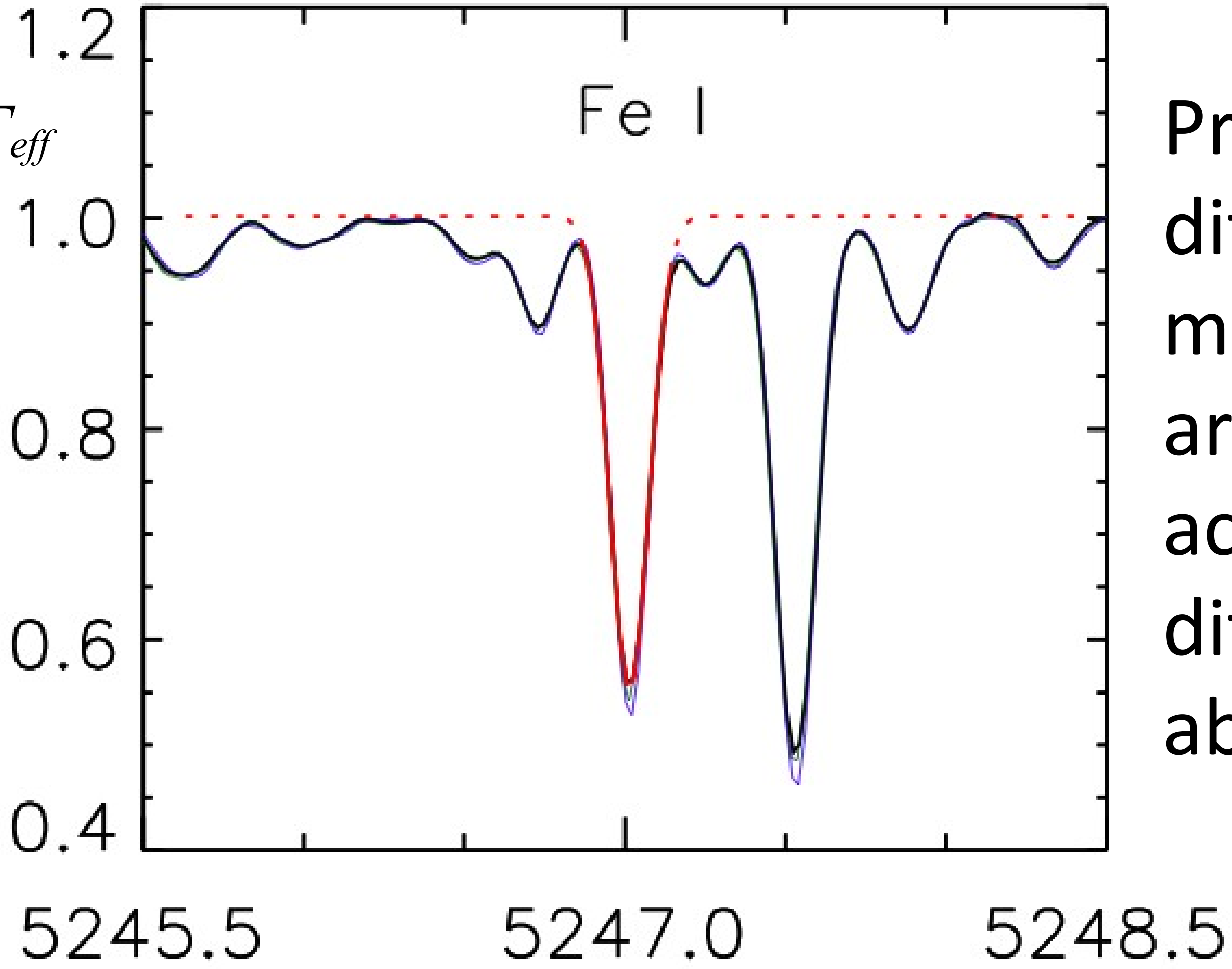
Bedell, Meléndez, Bean et al. 2014

Differential abundances A_X (element X)

$$\log (W/\lambda) = cte + A_X + \log (g f) + \log \lambda \; - \; \theta \chi_{exc} \; - \; \log k_{cont,\lambda}$$

$$\log (W_1/W_2) = A^1{}_X - A^2{}_X \; - (\theta^1 - \theta^2) \; \chi_{exc} \; - \log (k^1{}_{cont}/ k^2{}_{cont})$$

$\theta = 5040/T_{eff}$



Precise differential EW measurements are key to achieve precise differential abundances

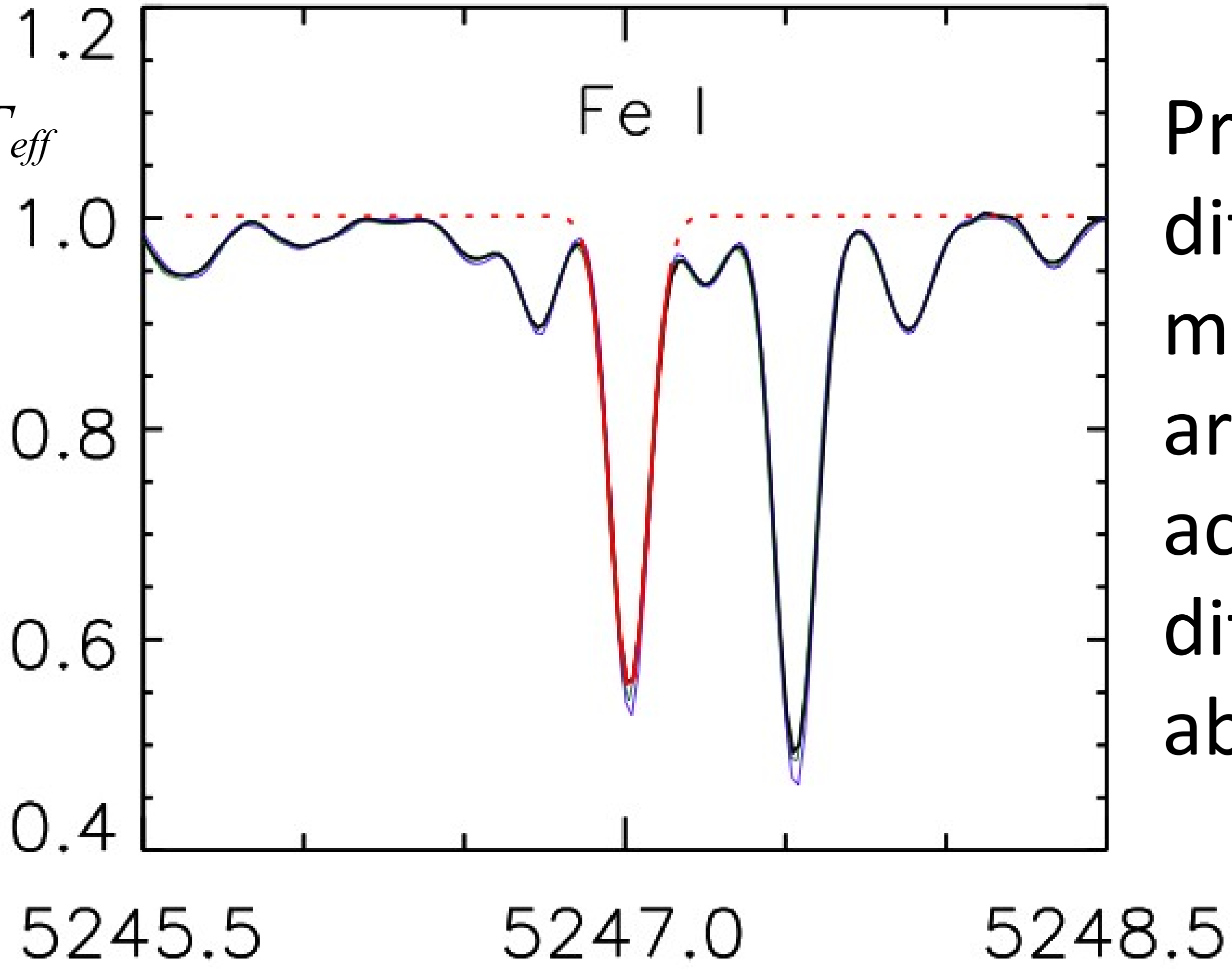
Bedell, Meléndez, Bean et al. 2014

Differential abundances A_X of identical twins

$$\log (W/\lambda) = cte + A_X + \cancel{\log (g f) + \log \lambda} - \theta \chi_{exc} - \log k_{cont,\lambda}$$

$$\log (W_1/W_2) = A^1{}_X - A^2{}_X - \cancel{(\theta^1-\theta^2)\, \chi_{exc}} \cancel{- \log (k^1{}_{cont} / k^2{}_{cont})}$$

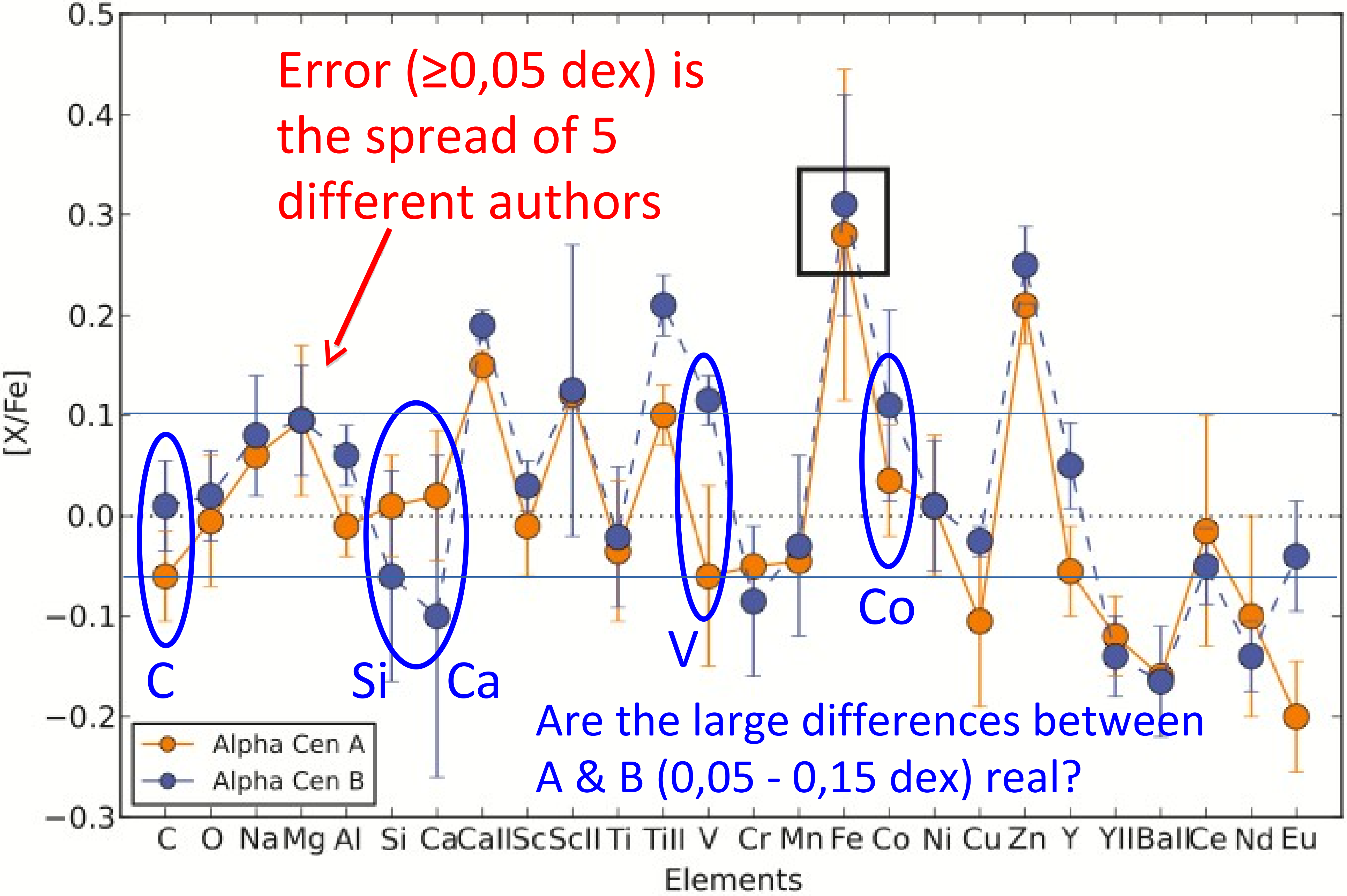
$\theta = 5040/T_{eff}$



Precise differential EW measurements are key to achieve precise differential abundances

Bedell, Meléndez, Bean et al. 2014

Comparing abundances for α Cen A, α Cen B



Hinkel & Kane 2013

A&A 615, A172 (2018)
https://doi.org/10.1051/0004-6361/201833125

Astronomy & Astrophysics

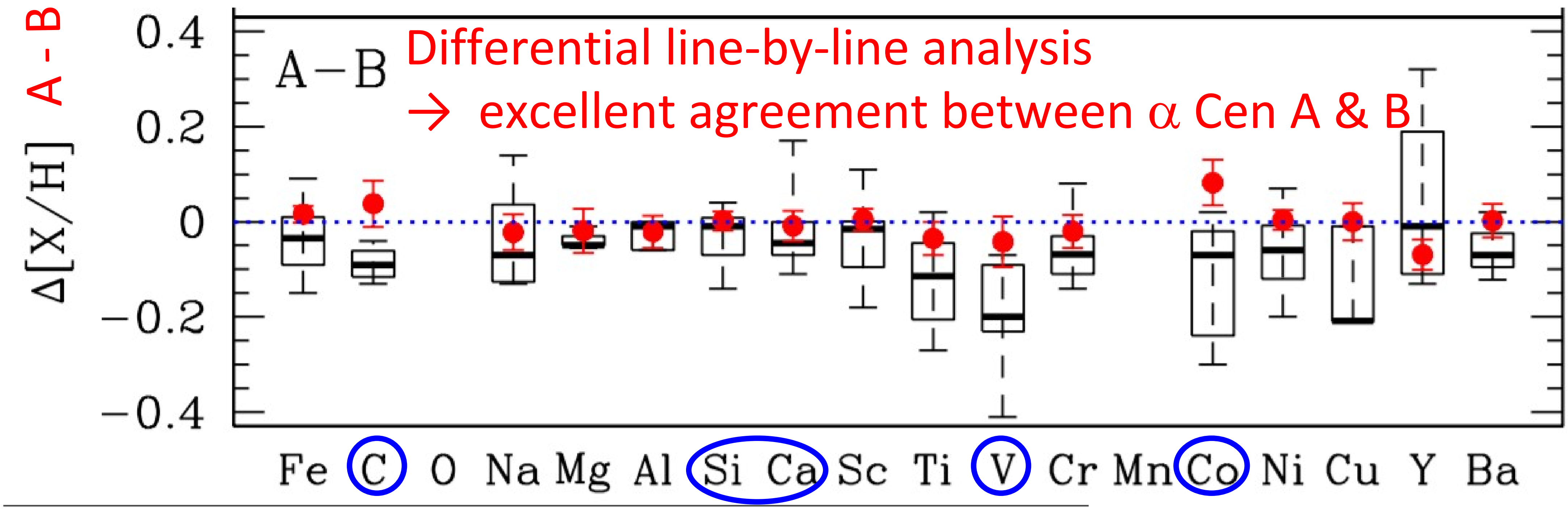
The chemical composition of α Centauri AB revisited★,★★

Thierry Morel

We present a fully self-consistent, line-by-line differential abundance analysis of α Cen AB

Abundances of 21 species with a typical precision of 0.02–0.03 dex are reported.

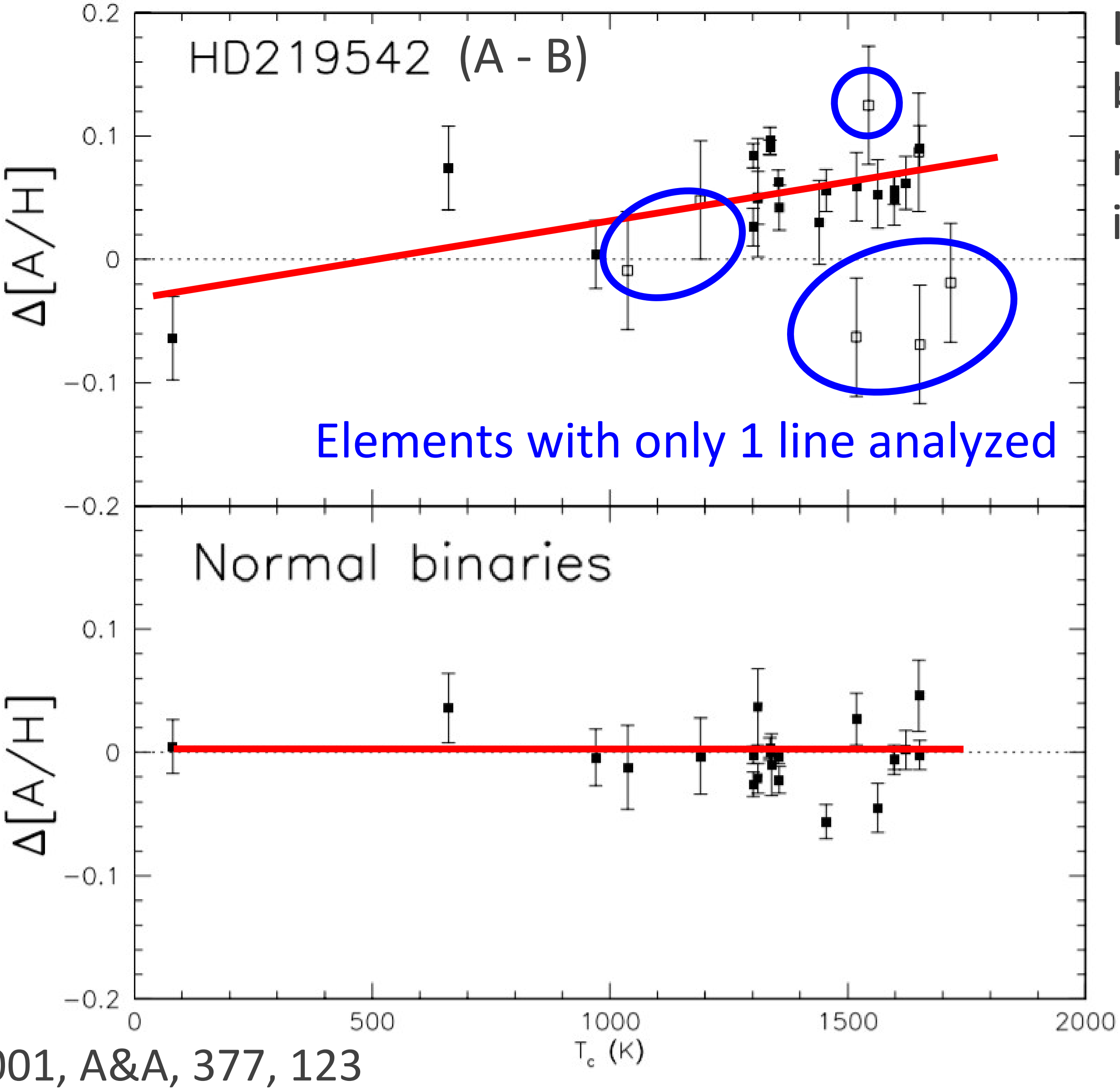
their patterns are strikingly similar, with a mean abundance difference (A – B) with respect to hydrogen of –0.01 ± 0.04 dex.



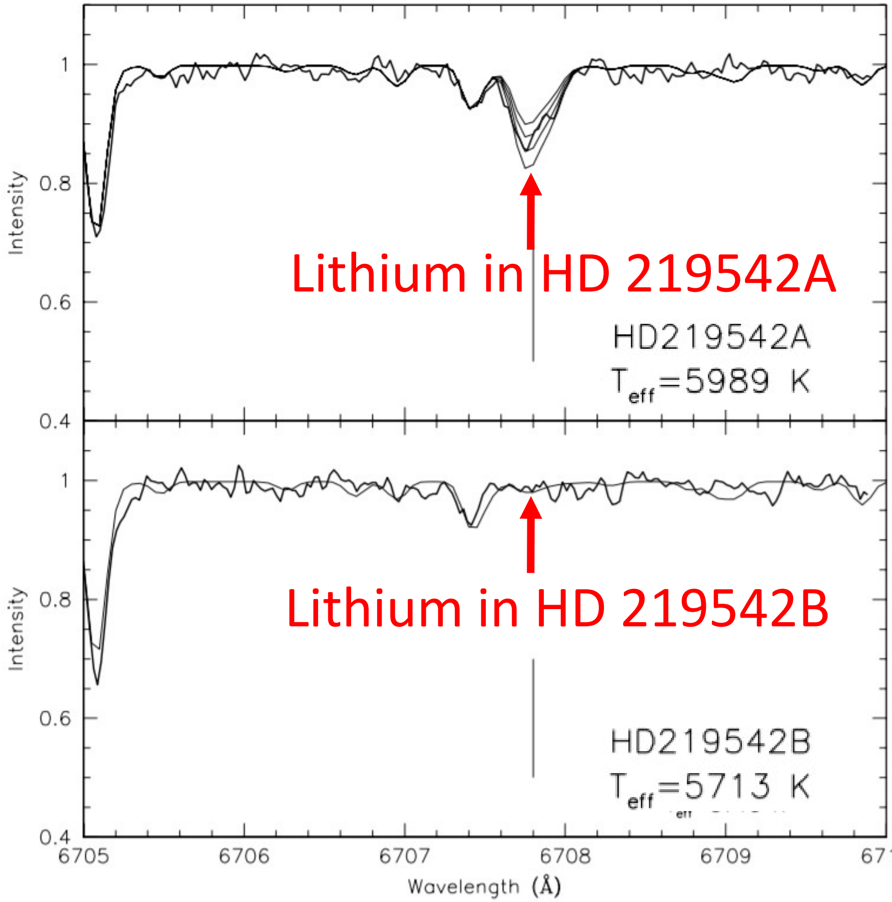
	α Cen A			α Cen B			A – B
	N	Before GCE	After GCE	N	Before GCE	After GCE	
$T_{\rm eff}$ [K]	9	5829 ± 6		9	5189 ± 18		...
log g [cgs]	9	4.35 ± 0.02		9	4.30 ± 0.05		...
ξ [km s^{-1}]	9	1.265 ± 0.012		9	0.950 ± 0.039		...
[Fe/H][a]	9	0.237 ± 0.007	...	9	0.221 ± 0.016	...	0.012 ± 0.018

Non-interacting main-sequence binaries with different chemical compositions: Evidences of infall of rocky material?

R. G. Gratton[1], G. Bonanno[2], R. U. Claudi[1], R. Cosentino[2,3], S. Desidera[1,4], S. Lucatello[1,4], and S. Scuderi[2]



Line-by-line differential analysis in binaries: HD 219542 A is enhanced in rocky-forming elements (**0.06 dex**) & in Li (>1 dex), relative to HD 219542B!



2001, A&A, 377, 123

Some tips for Equivalent Width measurements for Differential Precision Spectroscopy

Hand (manual measurements)

For automatic EW: DAOSPEC, iSpec, ARES ….

Some tips

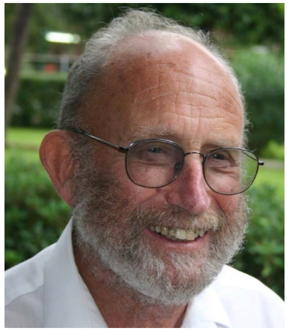
- Try to do consistent observations using the same instrument/configuration. Even better: in the same run!

  (If you're using a stable instrument like HARPS, the data can be taken in different dates)

ABUNDANCES IN G DWARF STARS. I. A COMPARISON OF TWO STARS IN THE HYADES WITH THE SUN*

G. WALLERSTEIN† AND H. L. HELFER‡ 1959, ApJ, 129, 347

To . . . obtain solar equivalent widths with the same equipment, five plates of the asteroid Vesta were obtained on the same nights as the Hyades spectra were photographed. As



Star	$B-V$	$U-B$	Sp. Type
Sun	0.63	. . . .	G2 V
Hyades No. 73 . . . . . . (=HD 28344)	.61	0 13	G2
Hyades No. 63 . . . . . . (=HD 28068)	.63	.17	G1

5777, 4.44, 0.00

5979, 4.47, 0.17

5772, 4.36, 0.12

Because of the similarity between the Hyades stars and the sun, It is to be expected that any differences in atmospheric structure will appear only as second-order effects

Some tips

- Verify your **relative** continuum normalization

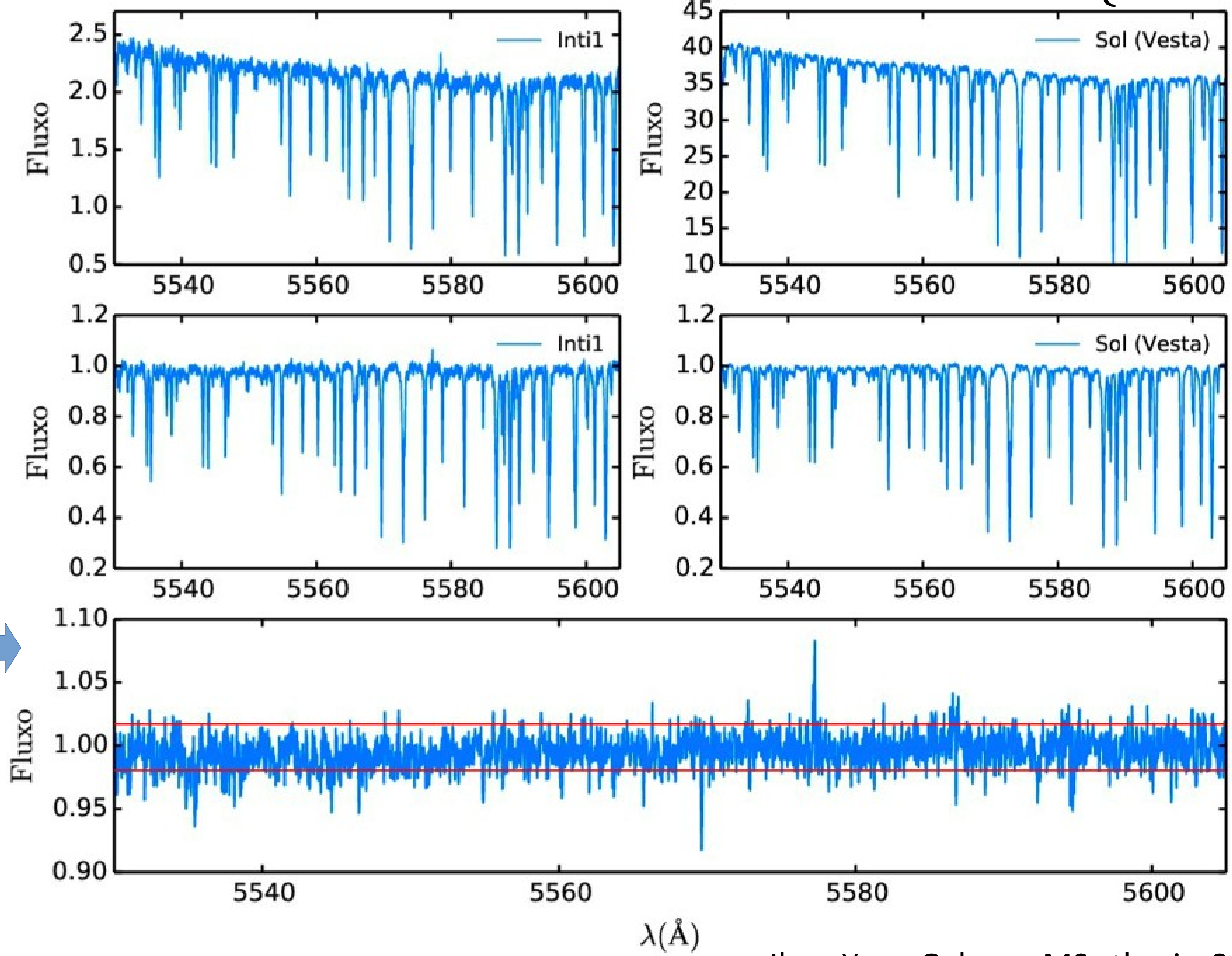
Solar twin star

Reference: Sun (Vesta)

Reduced

Normalized

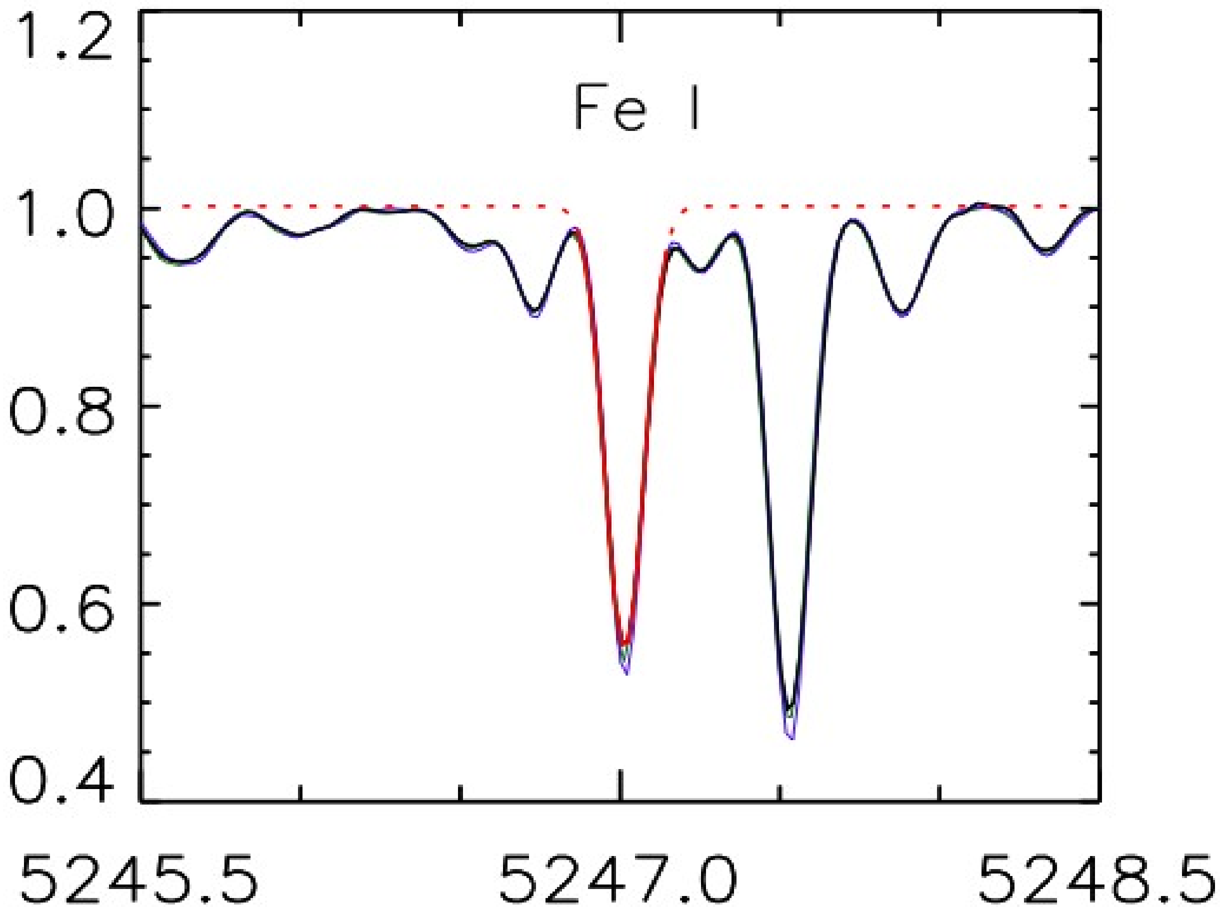
Star/reference should be 1.00 in the continuum



Jhon Yana Galarza, MSc thesis, 2016

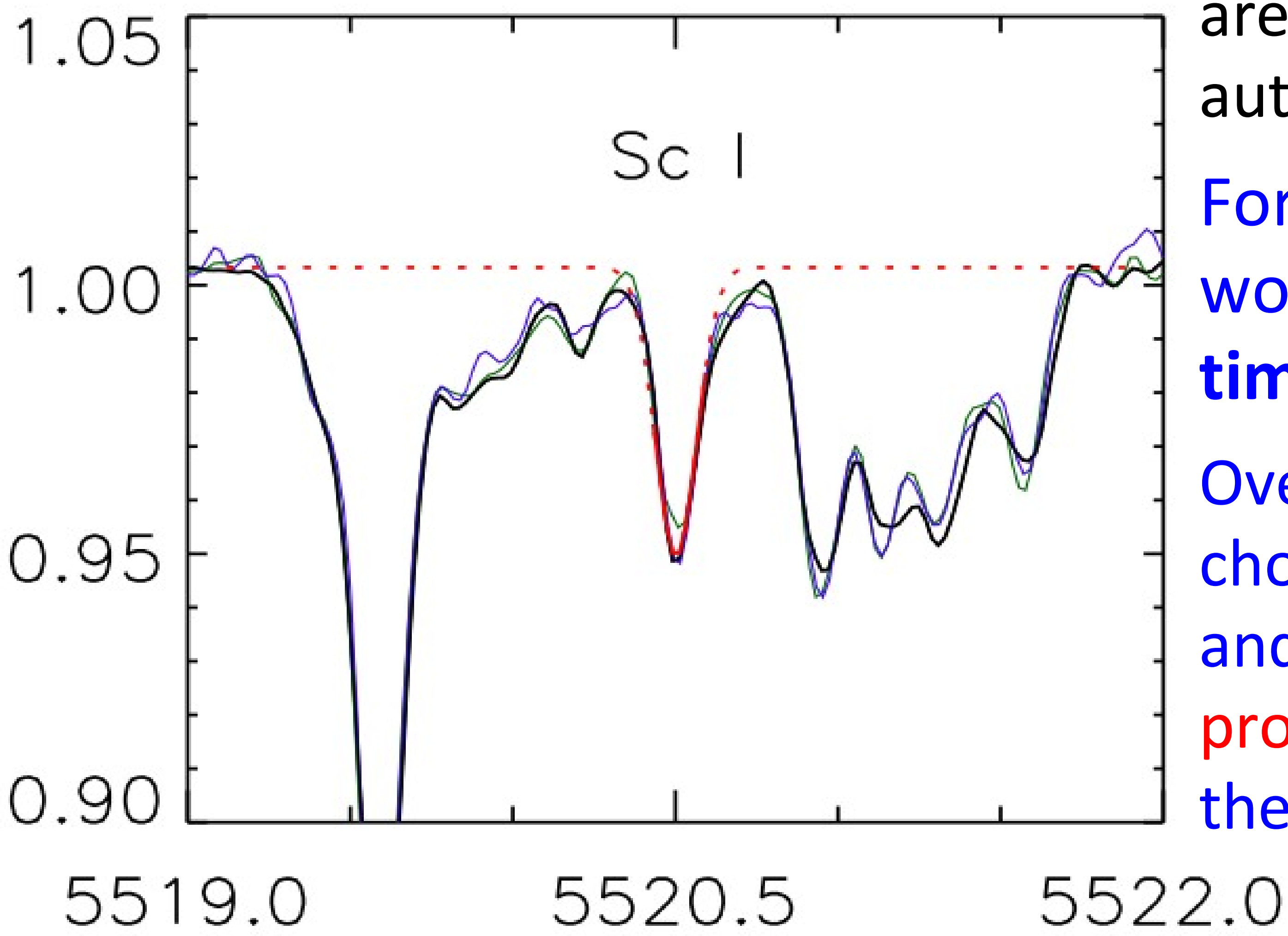
Measuring lines

- Whenever possible choose the cleanest lines
- If the lines are not perfectly clean, try to choose a line close to a continuum region



Bedell et al. 2014, ApJ, 795, 23

Measuring lines



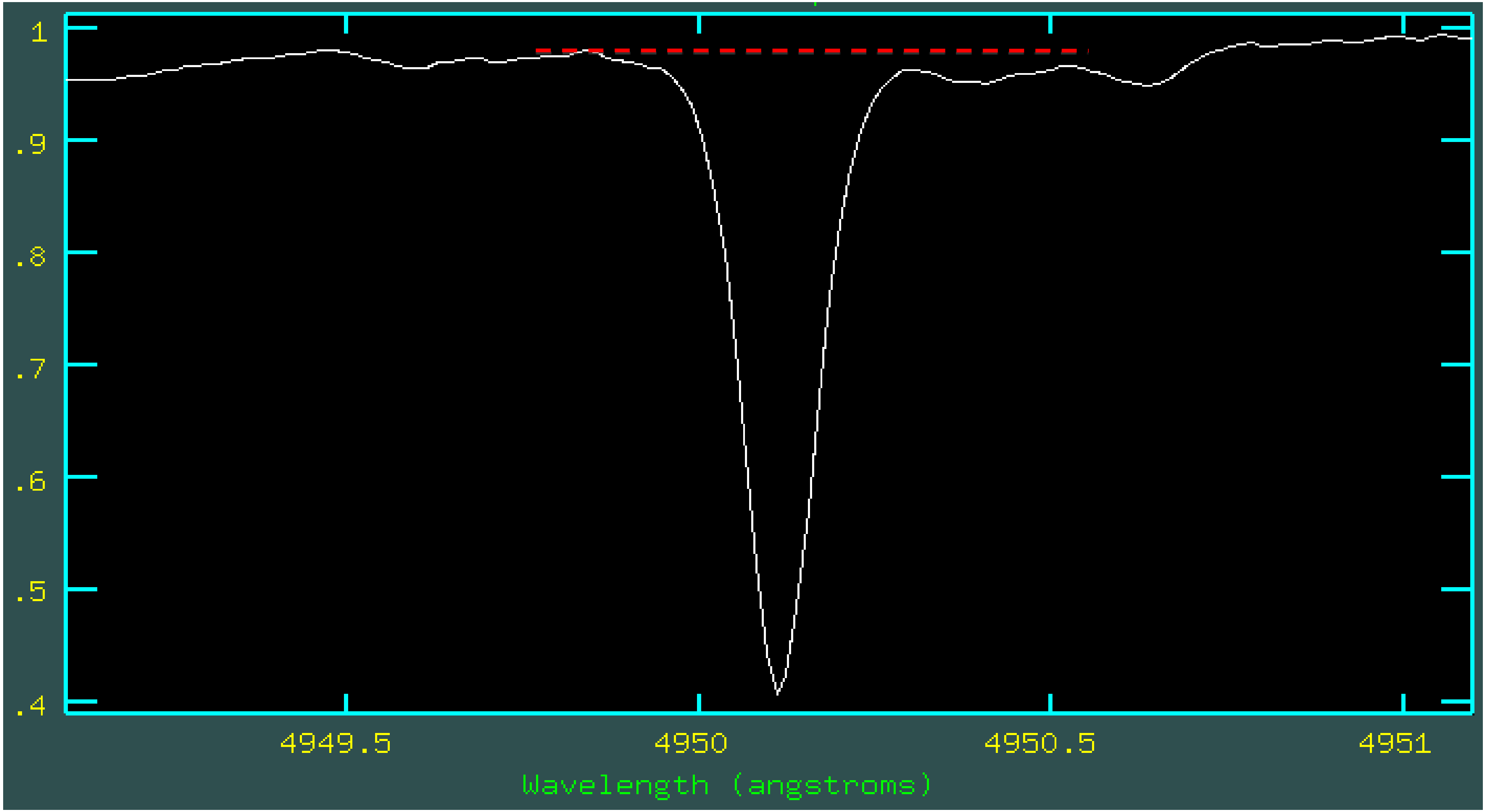
In classical abundance work, all lines in a given star are measured by hand or automatically.

For precision differential work, **measure 1 line at a time in all stars.**

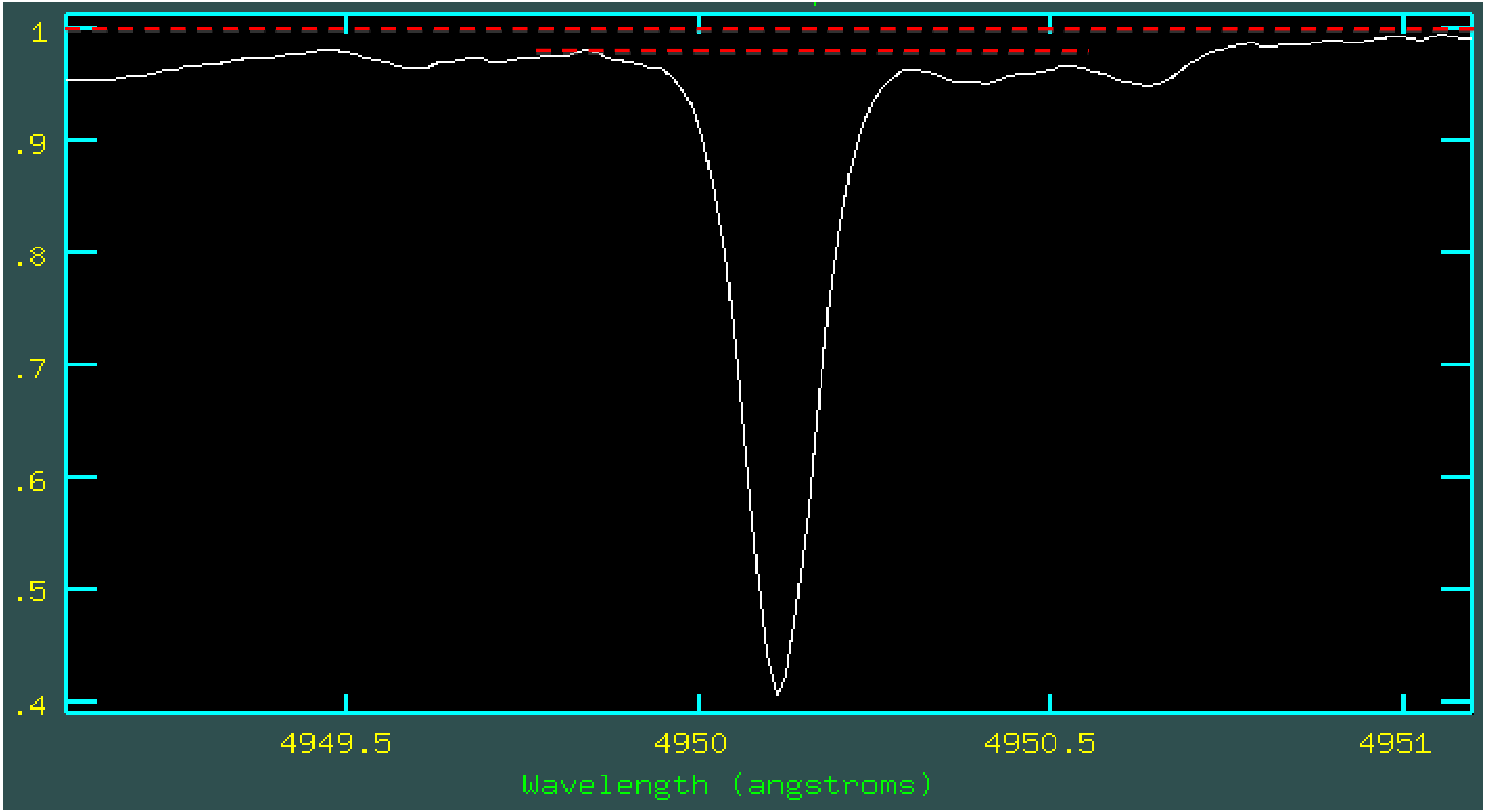
Overplot the spectra and choose both the continuum and the part of the line profile that will be used for the gaussian fit

Bedell et al. 2014, ApJ, 795, 23

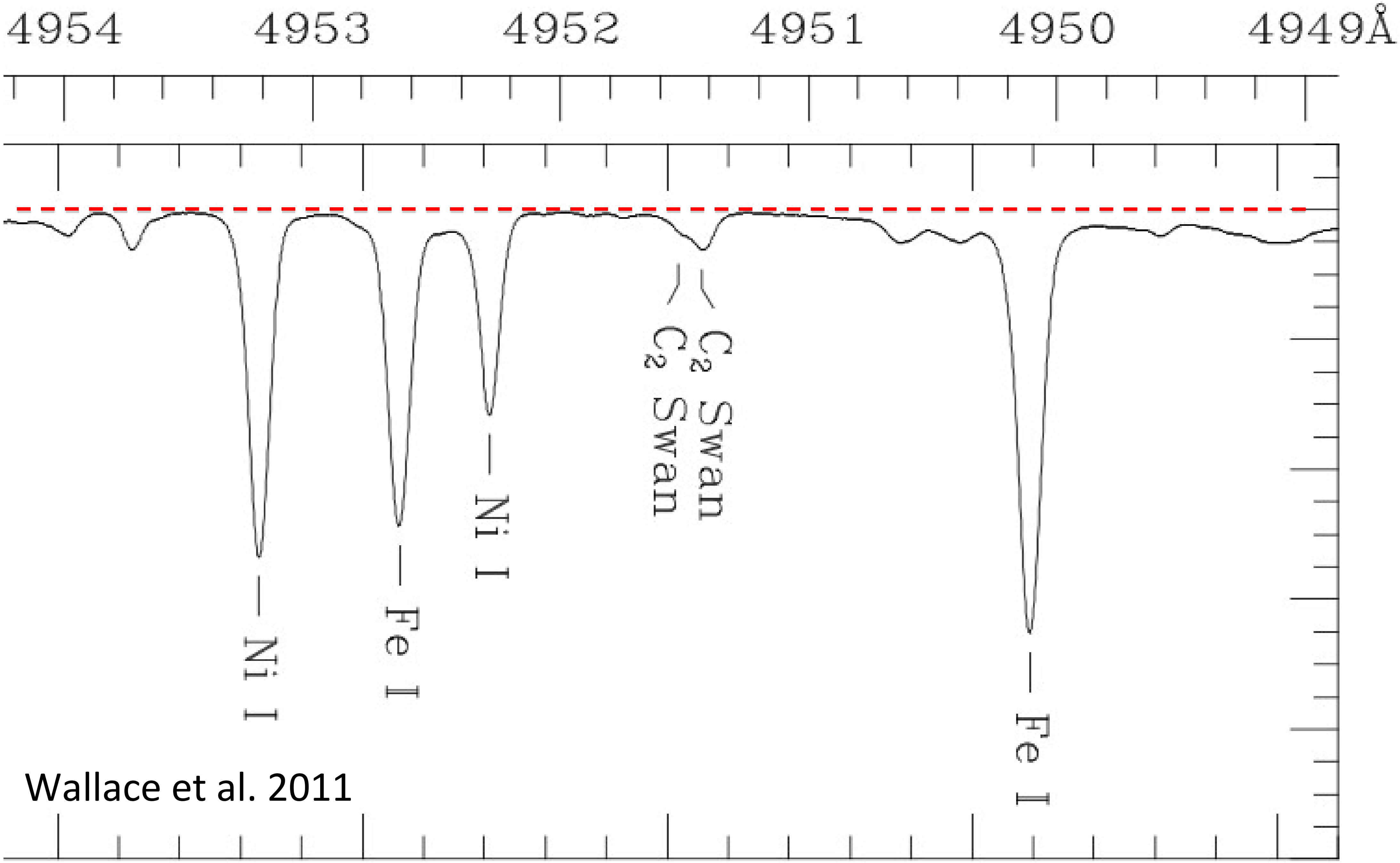
Continuum region too small (±1Å)



Continuum region too small (±1Å)
Better to use ±3Å

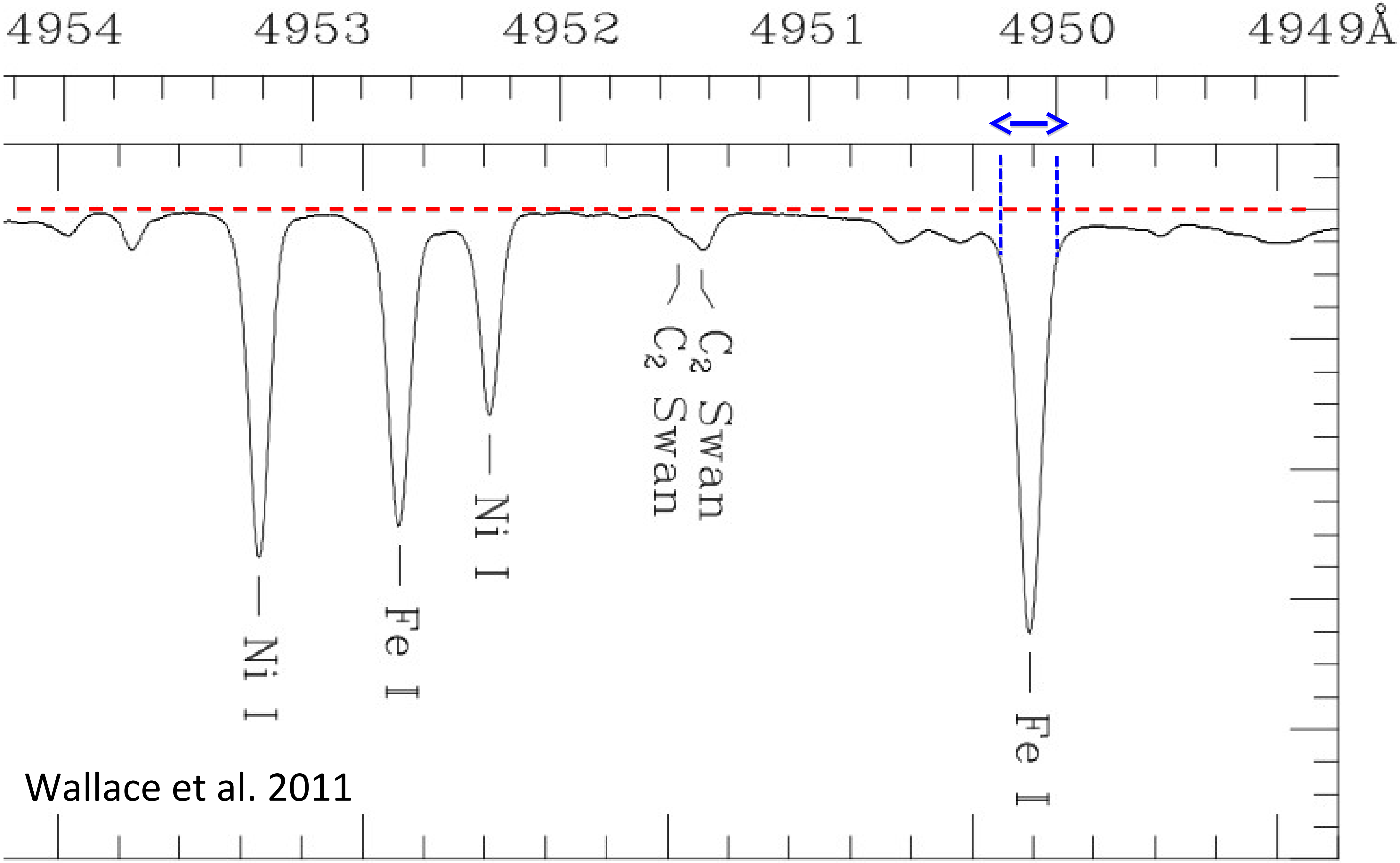


Use a solar atlas to verify the continuum



Wallace et al. 2011

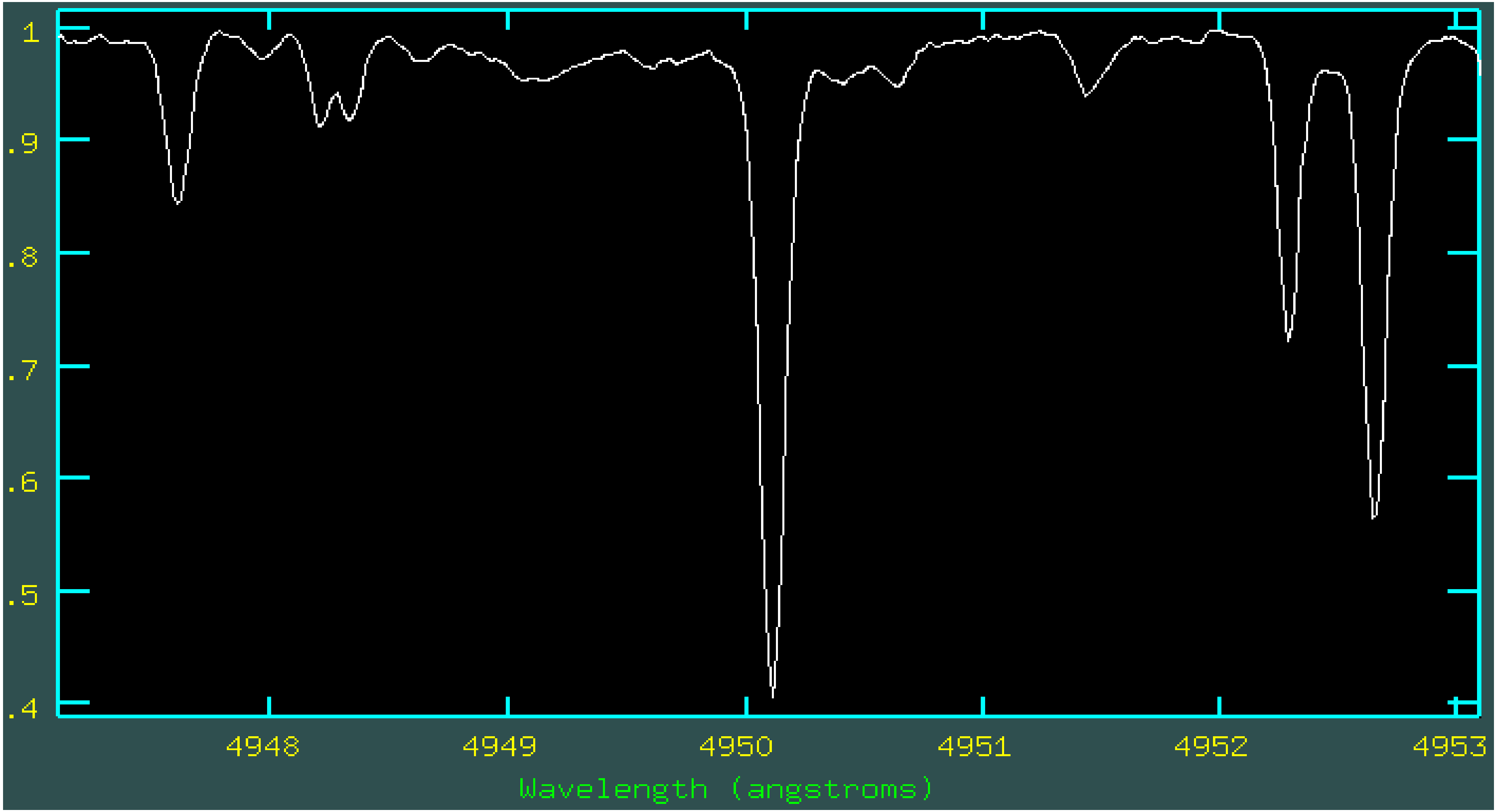
Use solar atlas to verify the continuum & profile fitting limits



Wallace et al. 2011

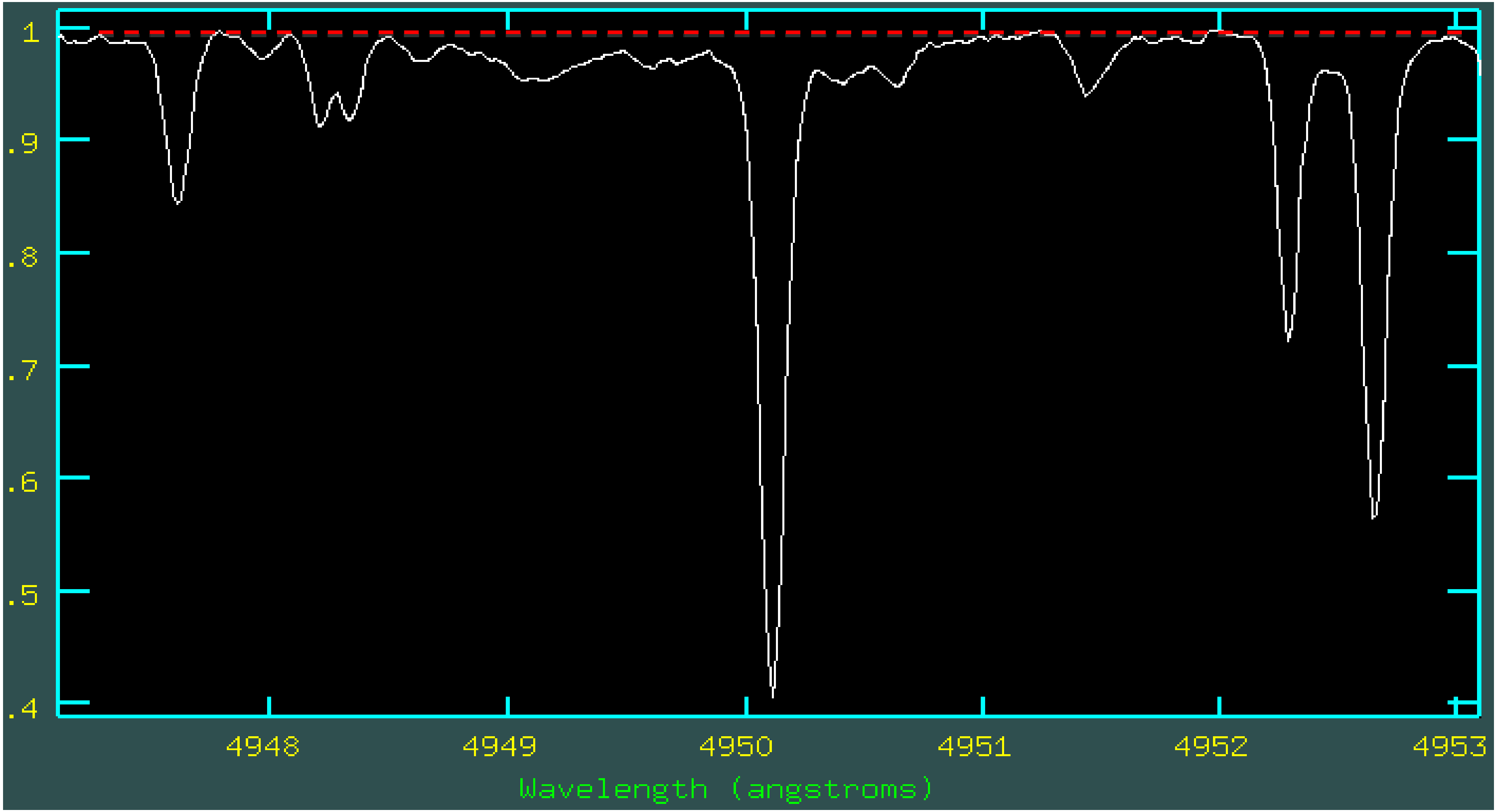
Choose the continuum using ±3 Å around your line

```
onedspec> splot HIP102152 xmin=4947.1 xmax=4953.1
```

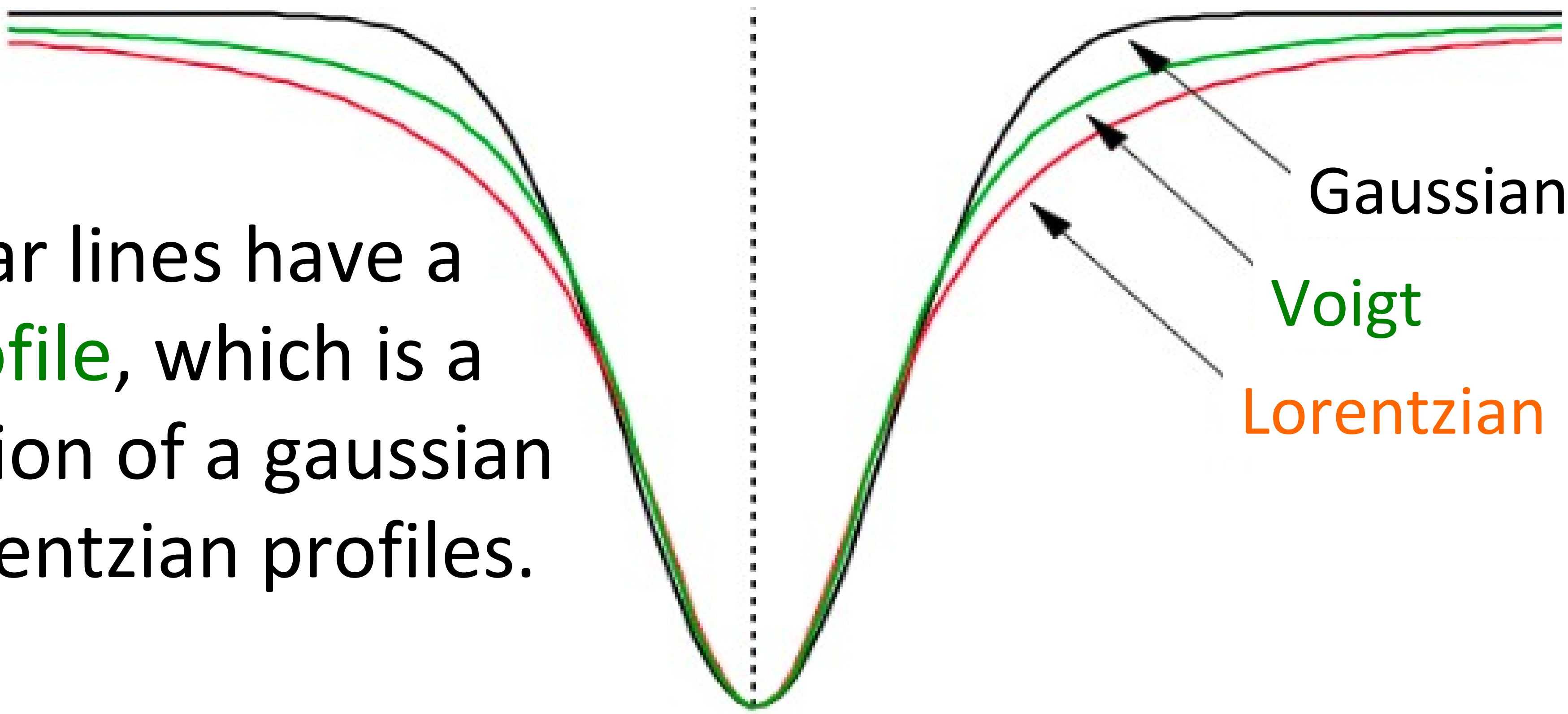


Choose the continuum using ±3 Å around your line

```
onedspec> splot HIP102152 xmin=4947.1 xmax=4953.1
```



Equivalent Width (EW) measurements: not trivial

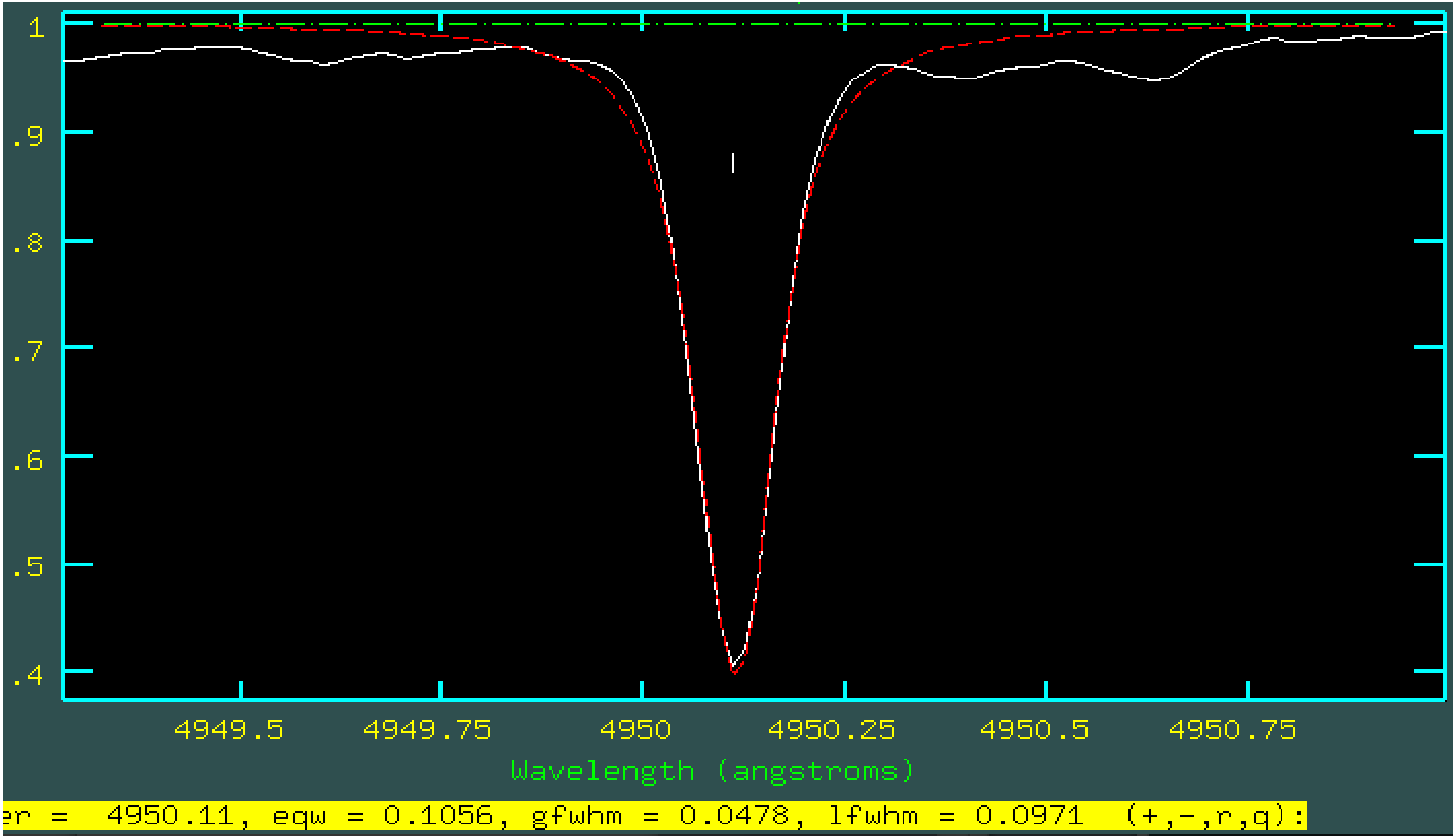


The stellar lines have a Voigt profile, which is a convolution of a gaussian and a lorentzian profiles.

In theory using a Voigt profile is more correct, but in practice a gaussian generally gives you better precision

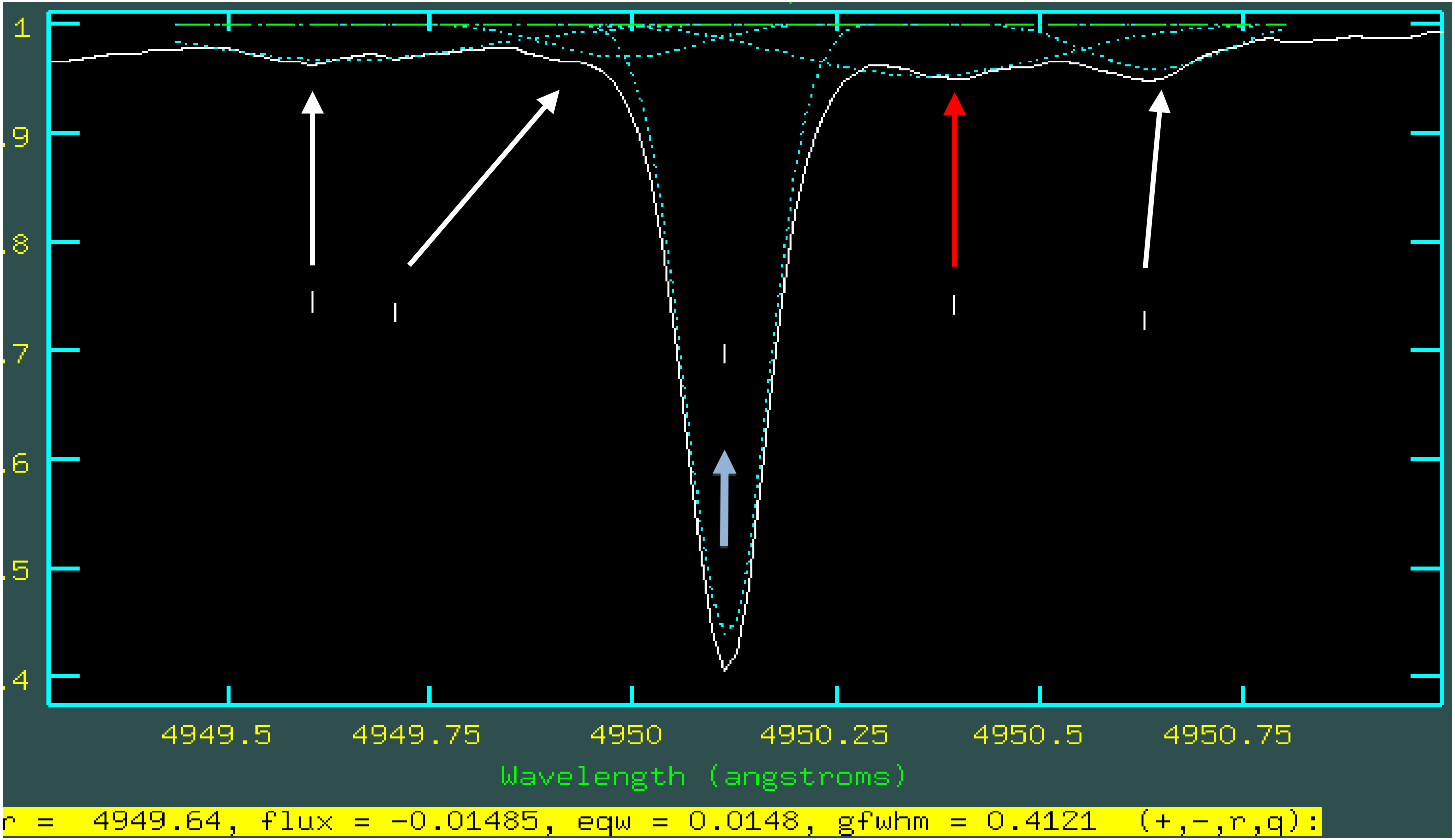
Reason: for the Voigt profile, you have to fit 1 additional parameter and some lines may show weak (or badly blended) lorentzian wings

Fitting a Voigt profile: uncertain wings

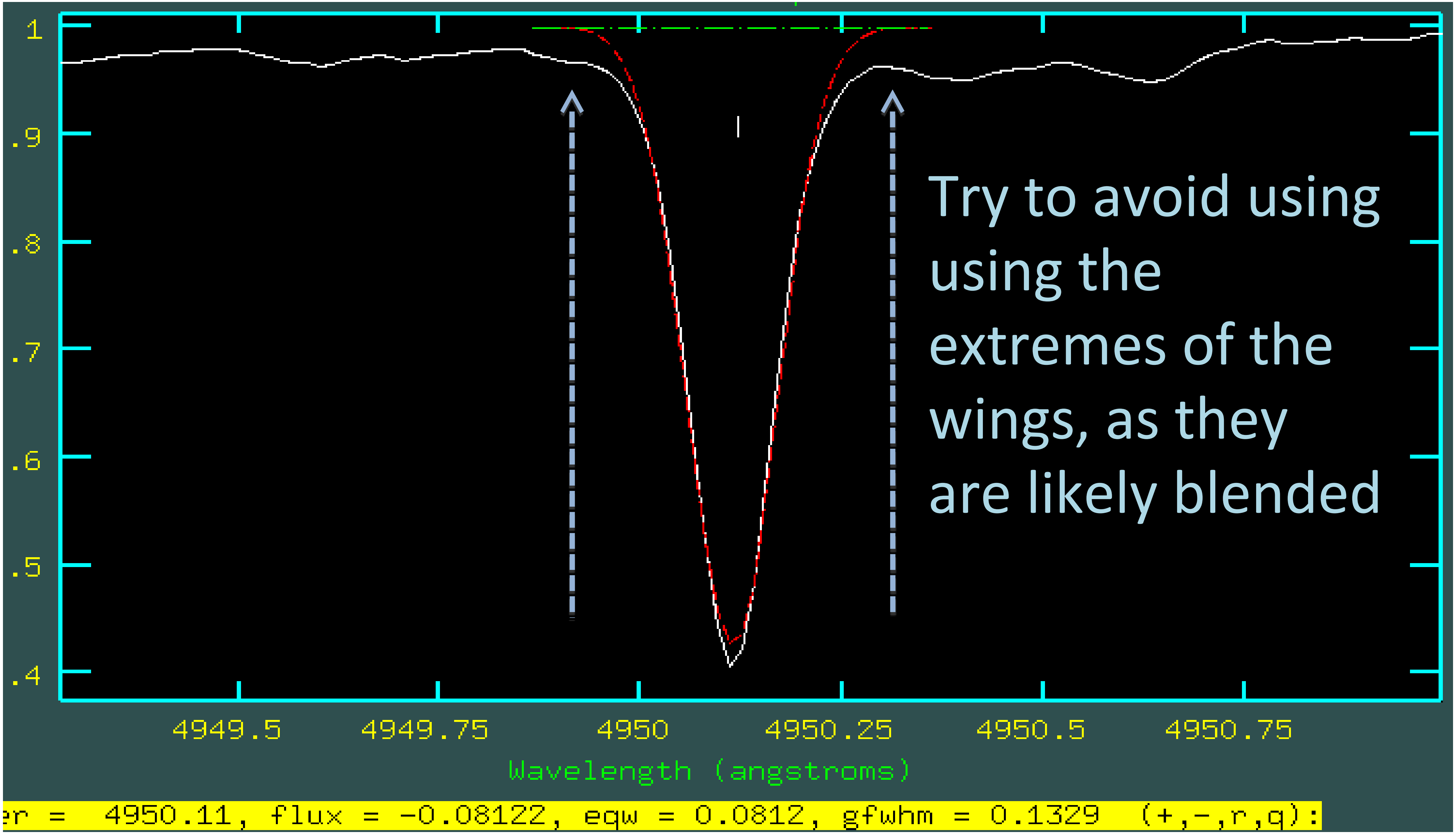


Sometimes deblending may give you worse results:

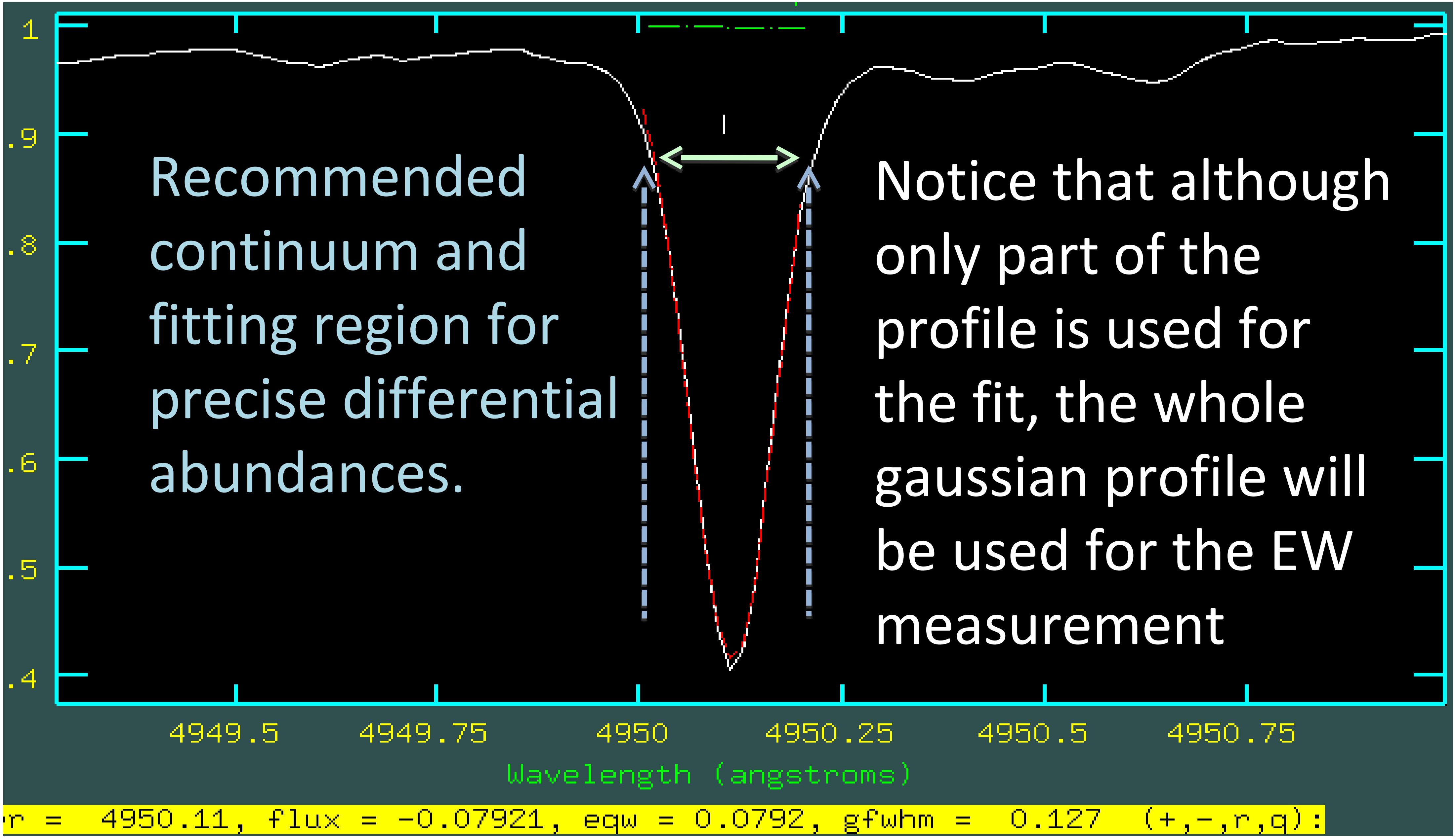
careful about uncertainties from overestimated (or underestimated) contribution of 1 or more components!



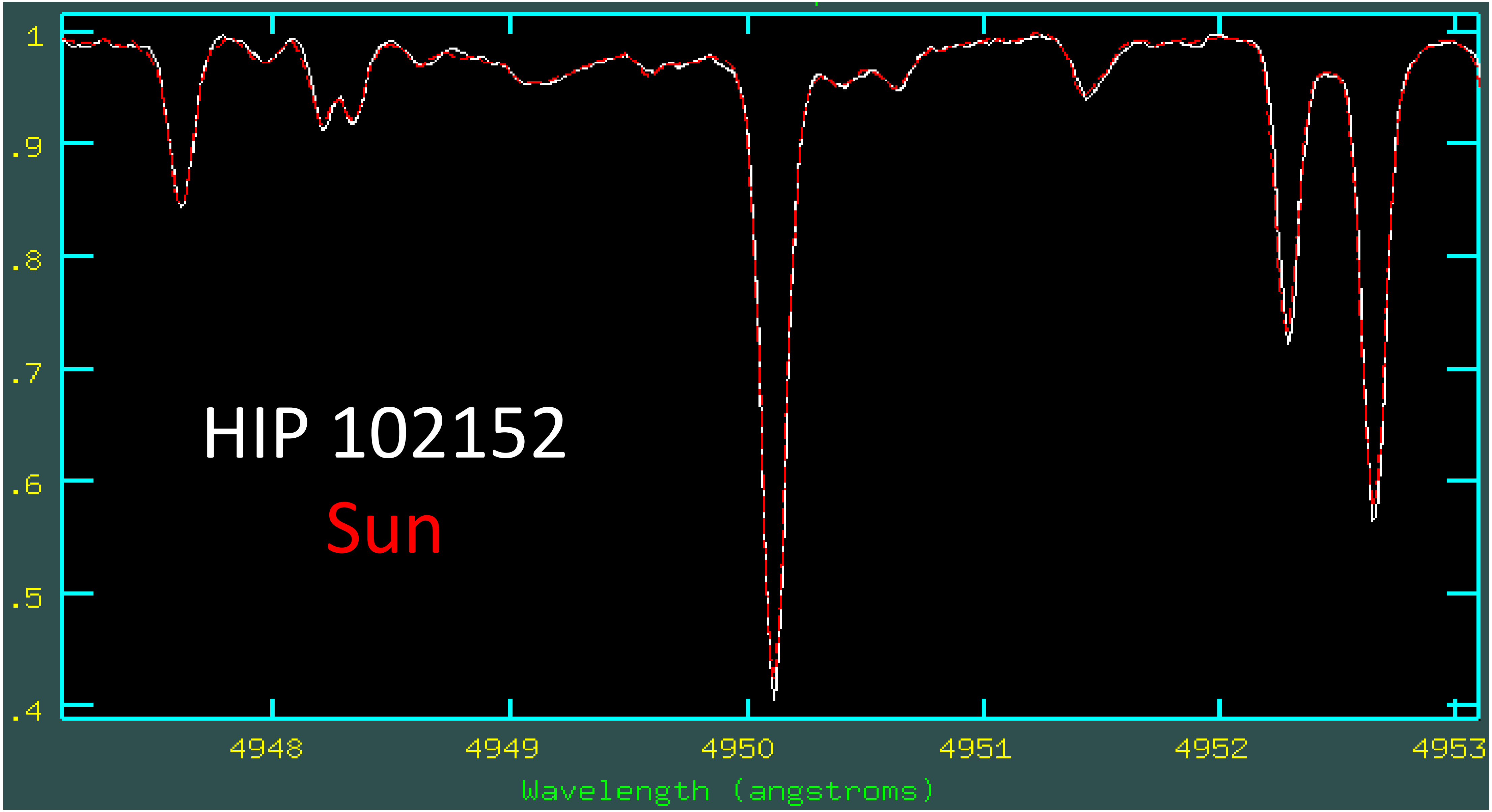
Using a single gaussian: careful about using the ends of the wings (blends may have an important contribution)



Using a single gaussian: careful about using the ends of the wings (blends may have an important contribution)

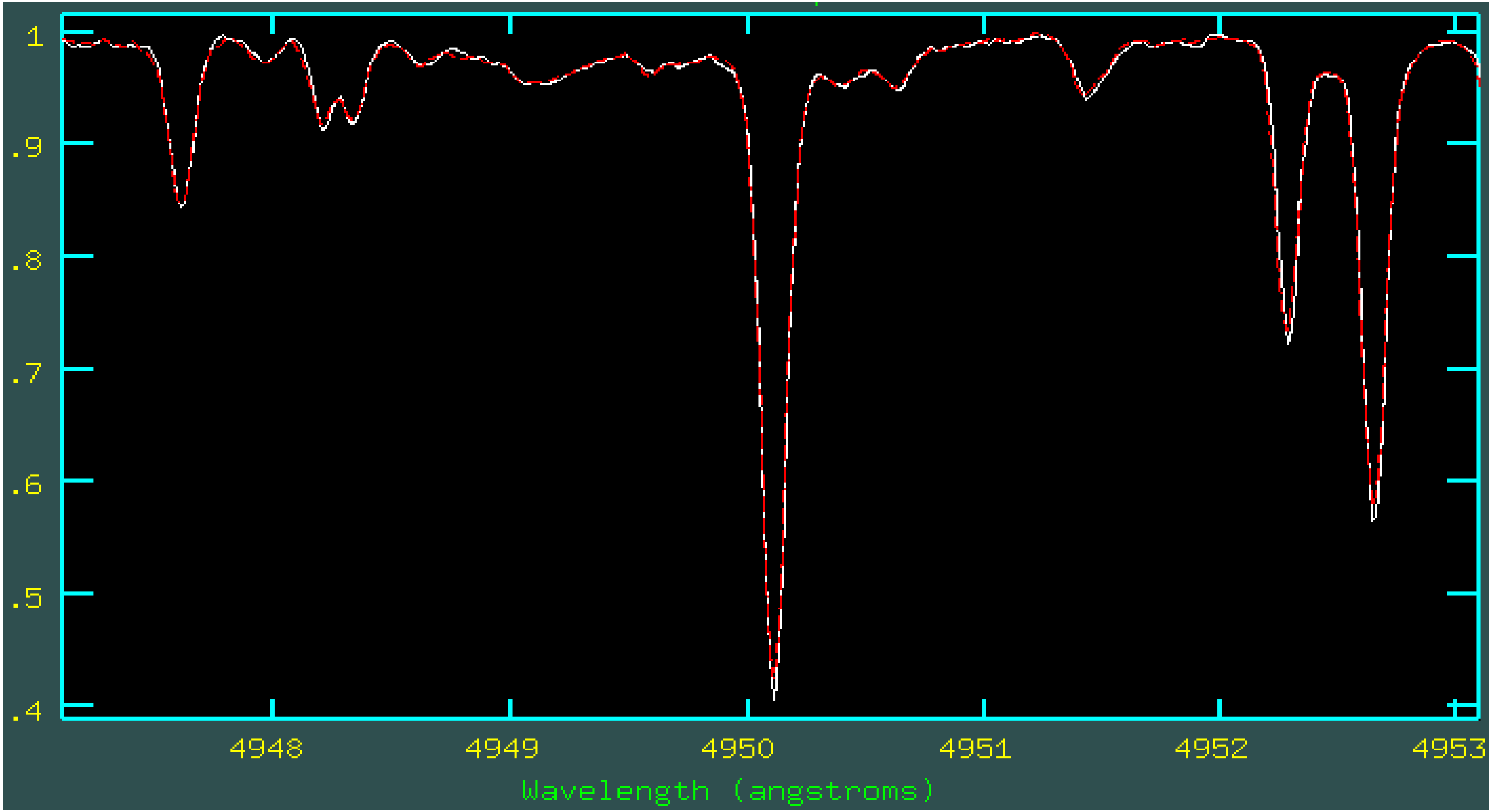


Overplotting the star and the Sun is time consuming, but important to achieve high precision



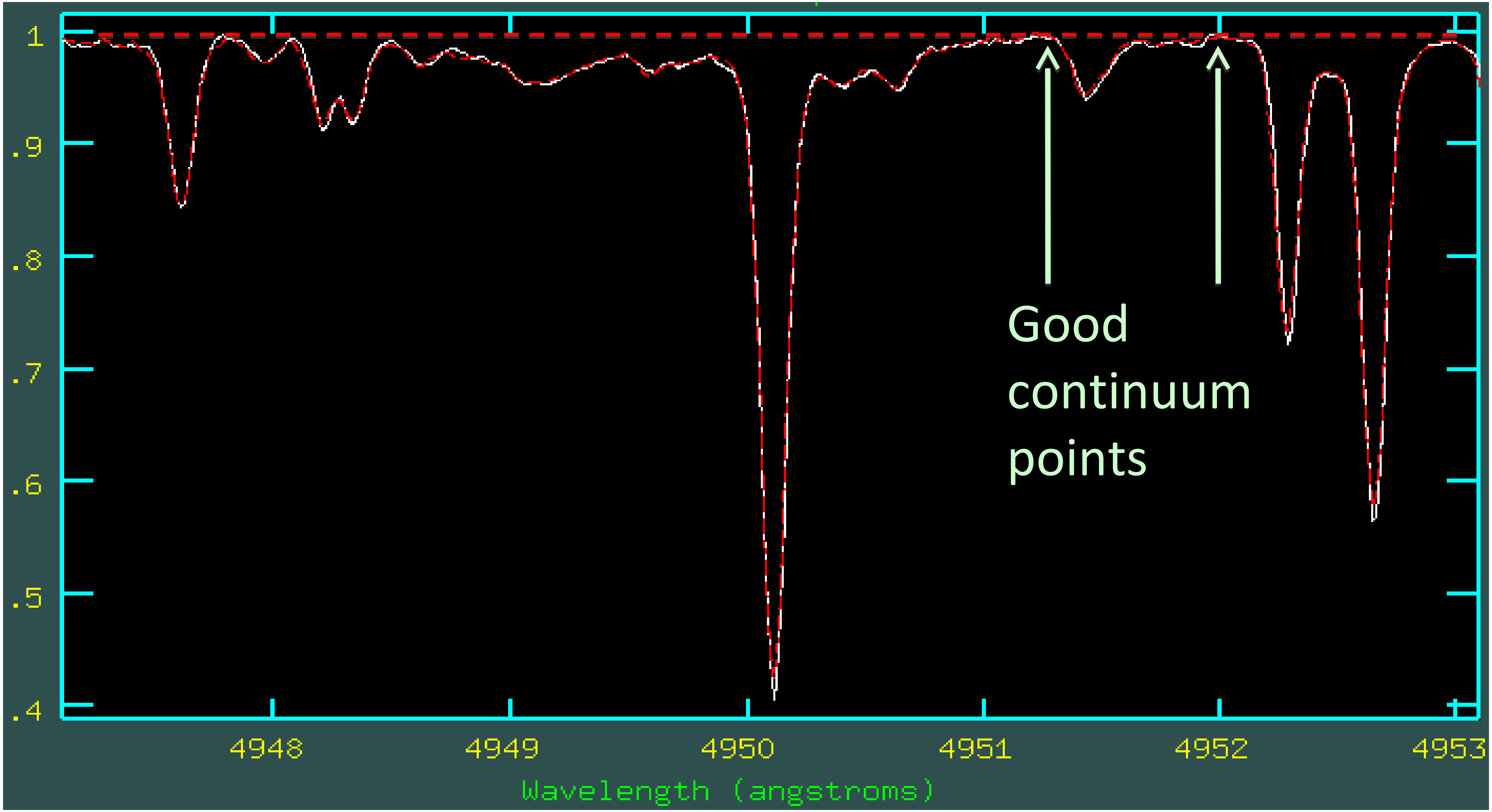
HIP 102152

Overplotting with splot (“o” “g” …) the Sun’s spectrum



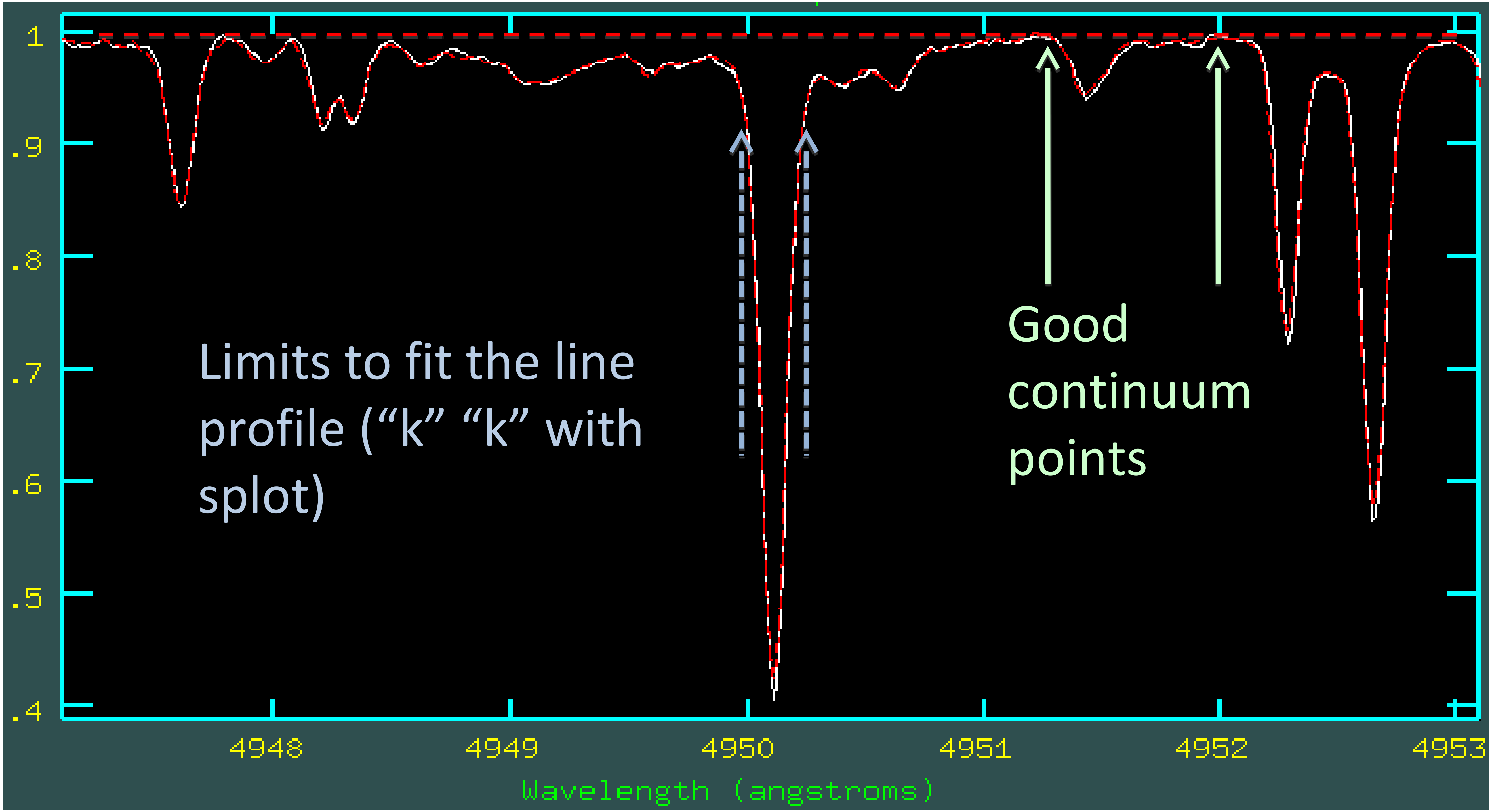
HIP 102152

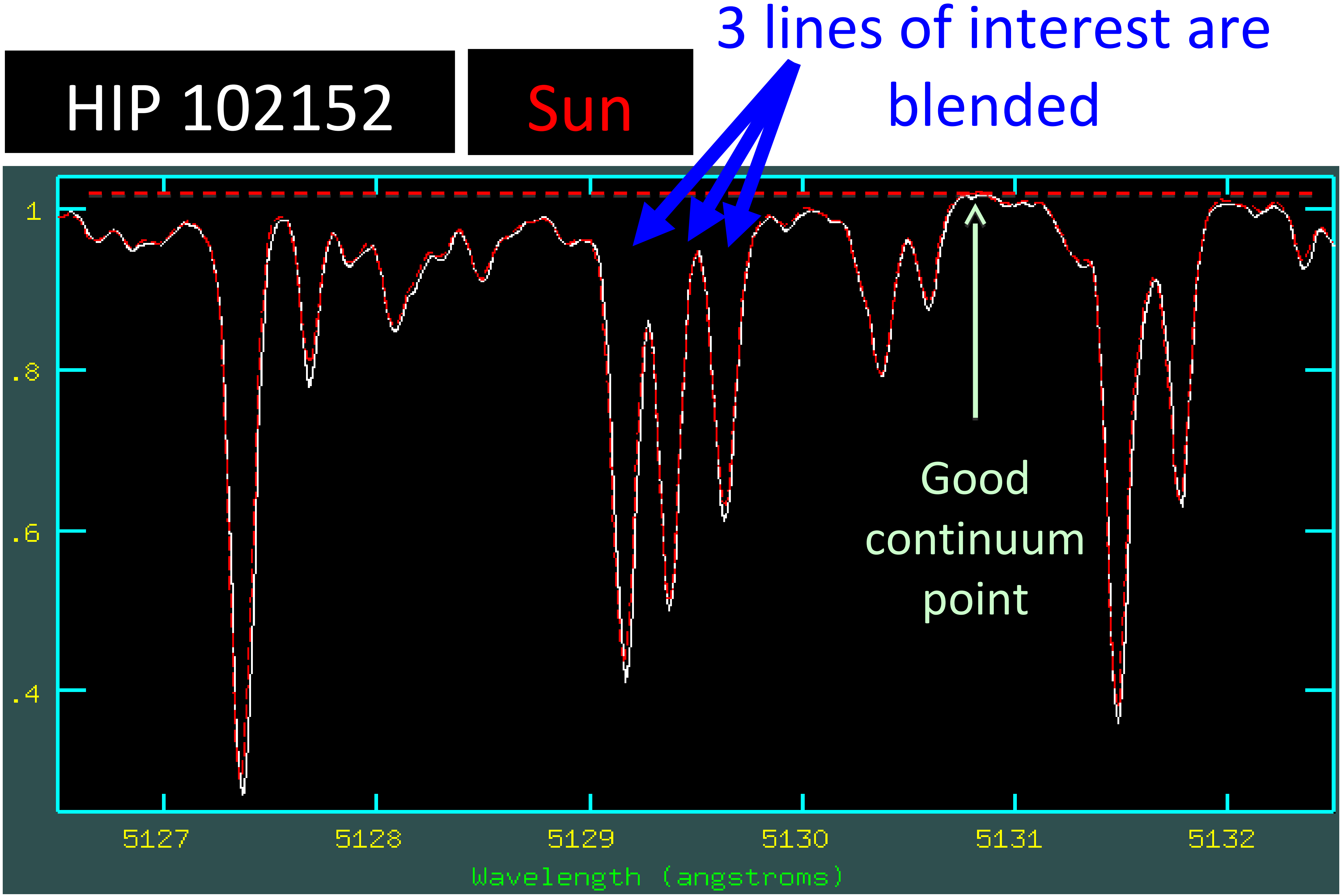
Overplotting with splot (“o” “g” …) the Sun’s spectrum



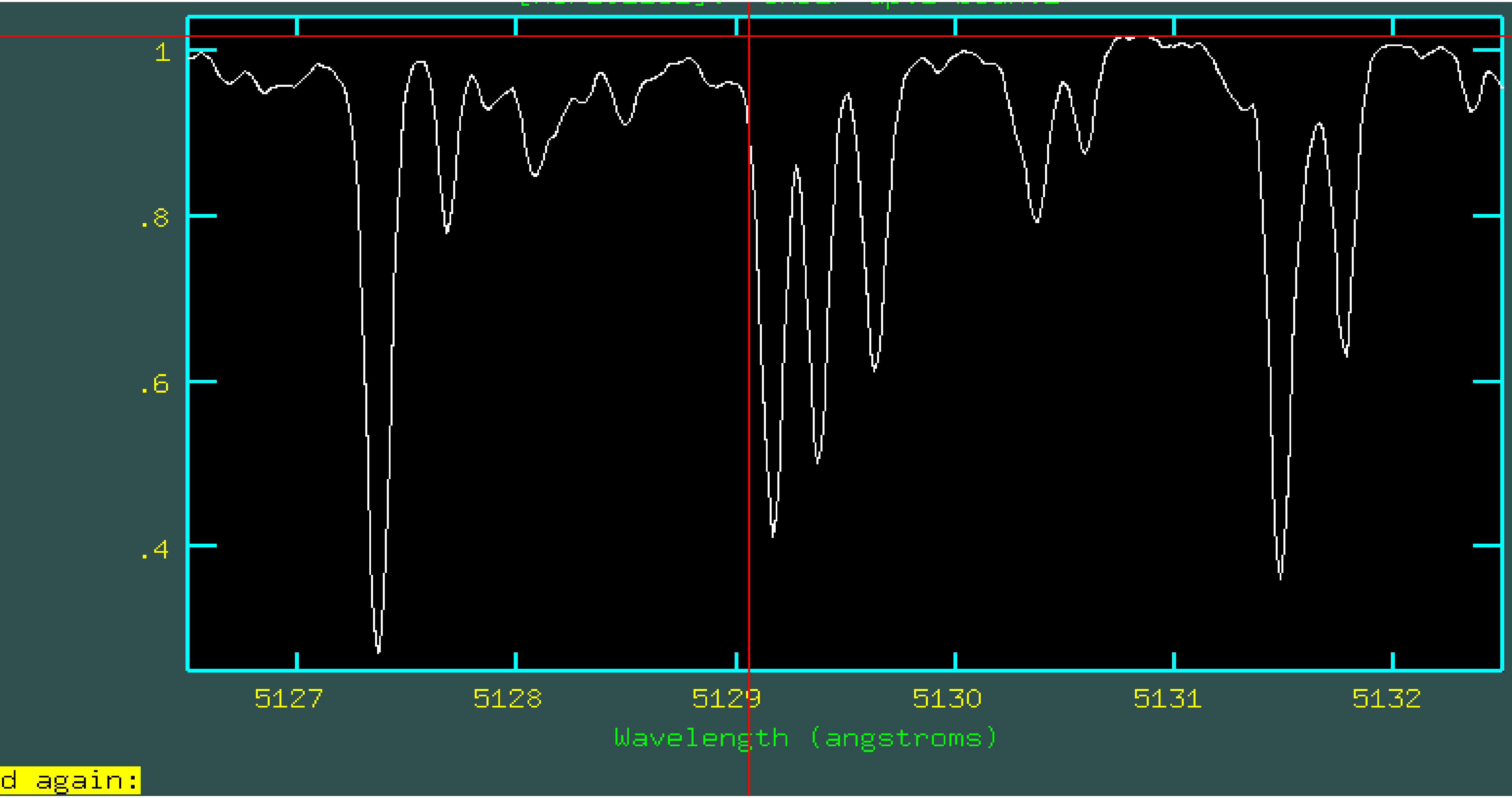
HIP 102152

Overplotting with splot (“o” “g” …) the Sun’s spectrum

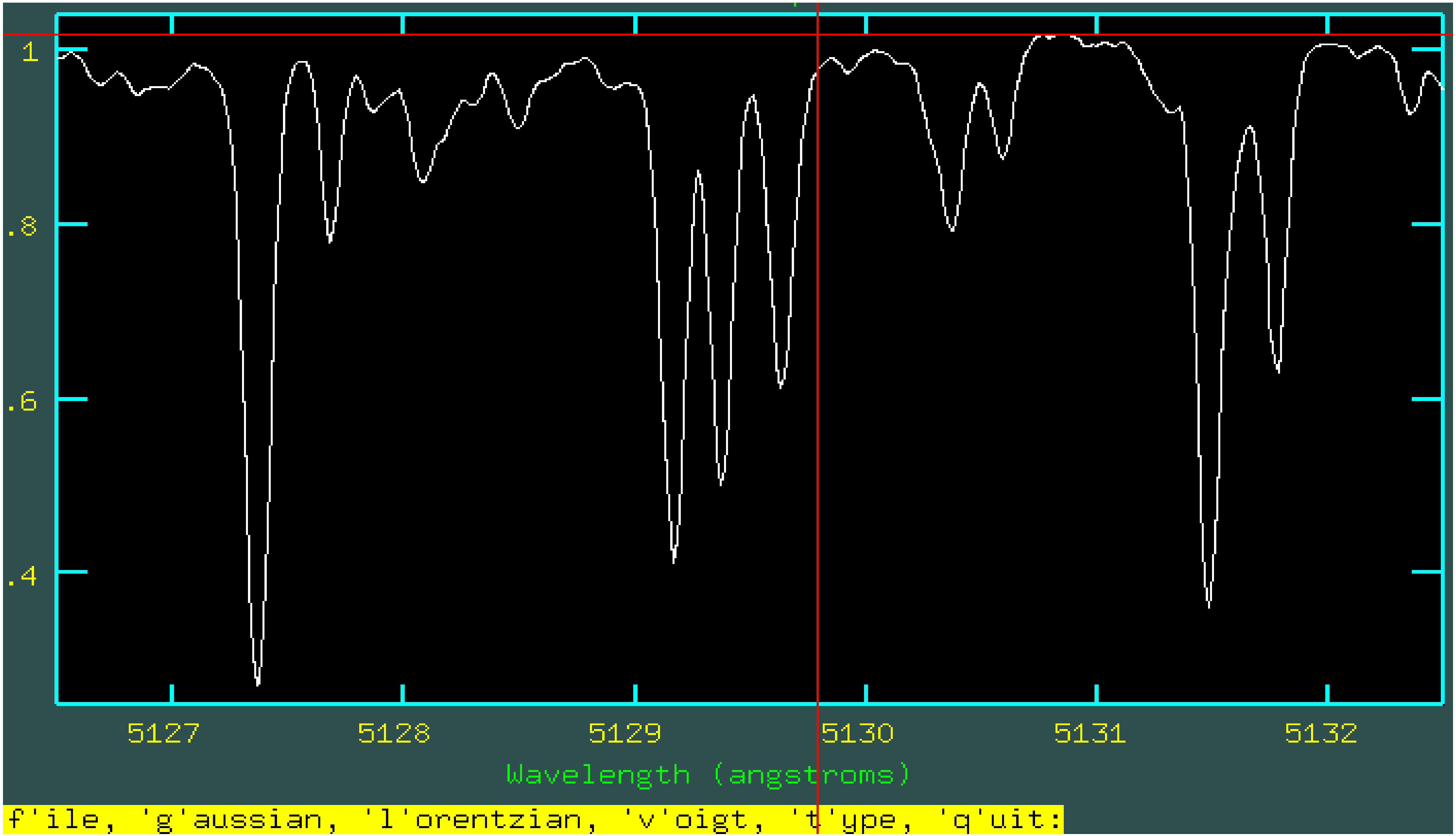



HIP 102152
Sun
3 lines of interest are blended
Good continuum point
1
.8
.6
.4
5127
5128
5129
5130
5131
5132
Wavelength (angstroms)

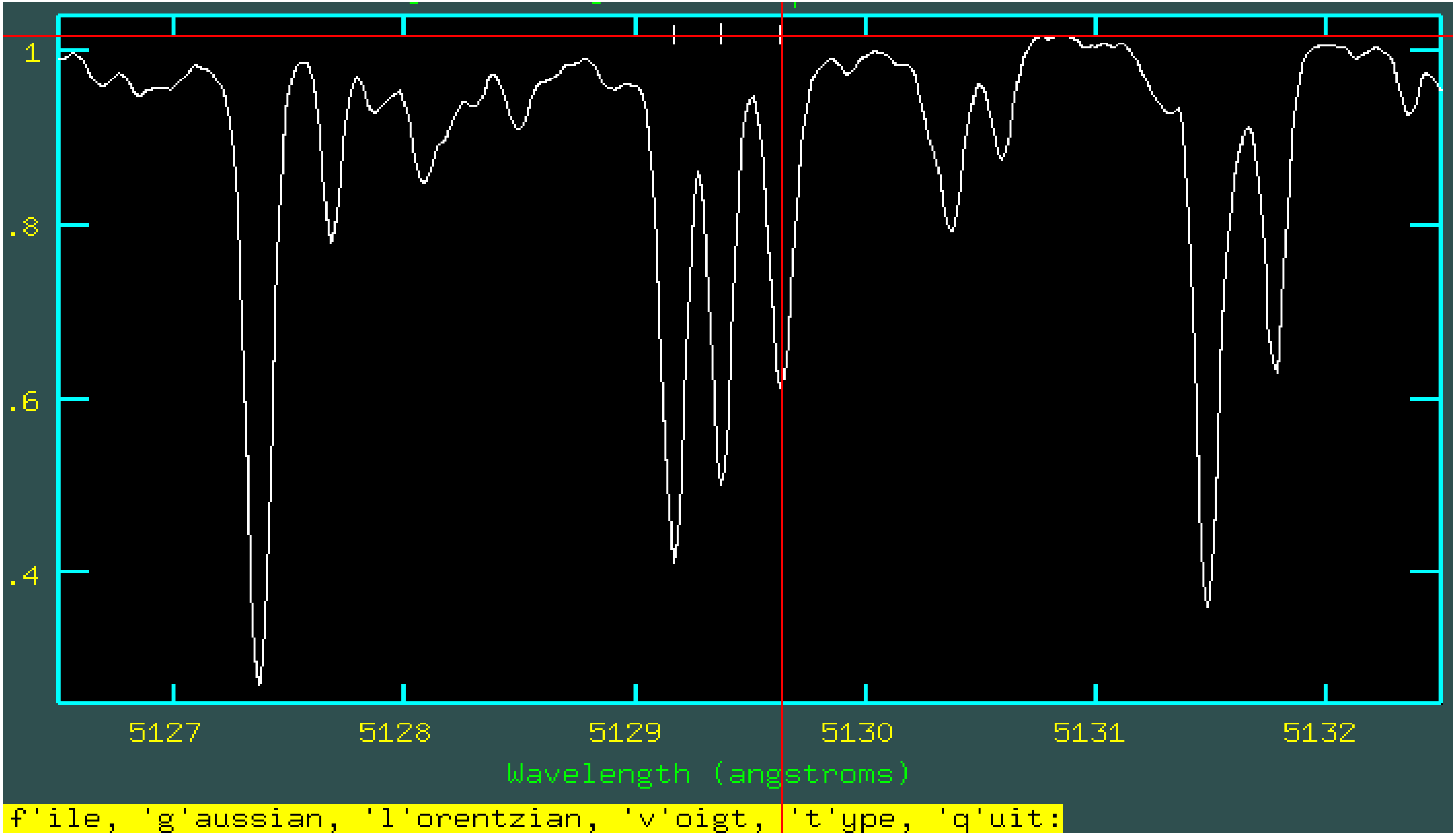
Deblending 3 lines in HIP102152



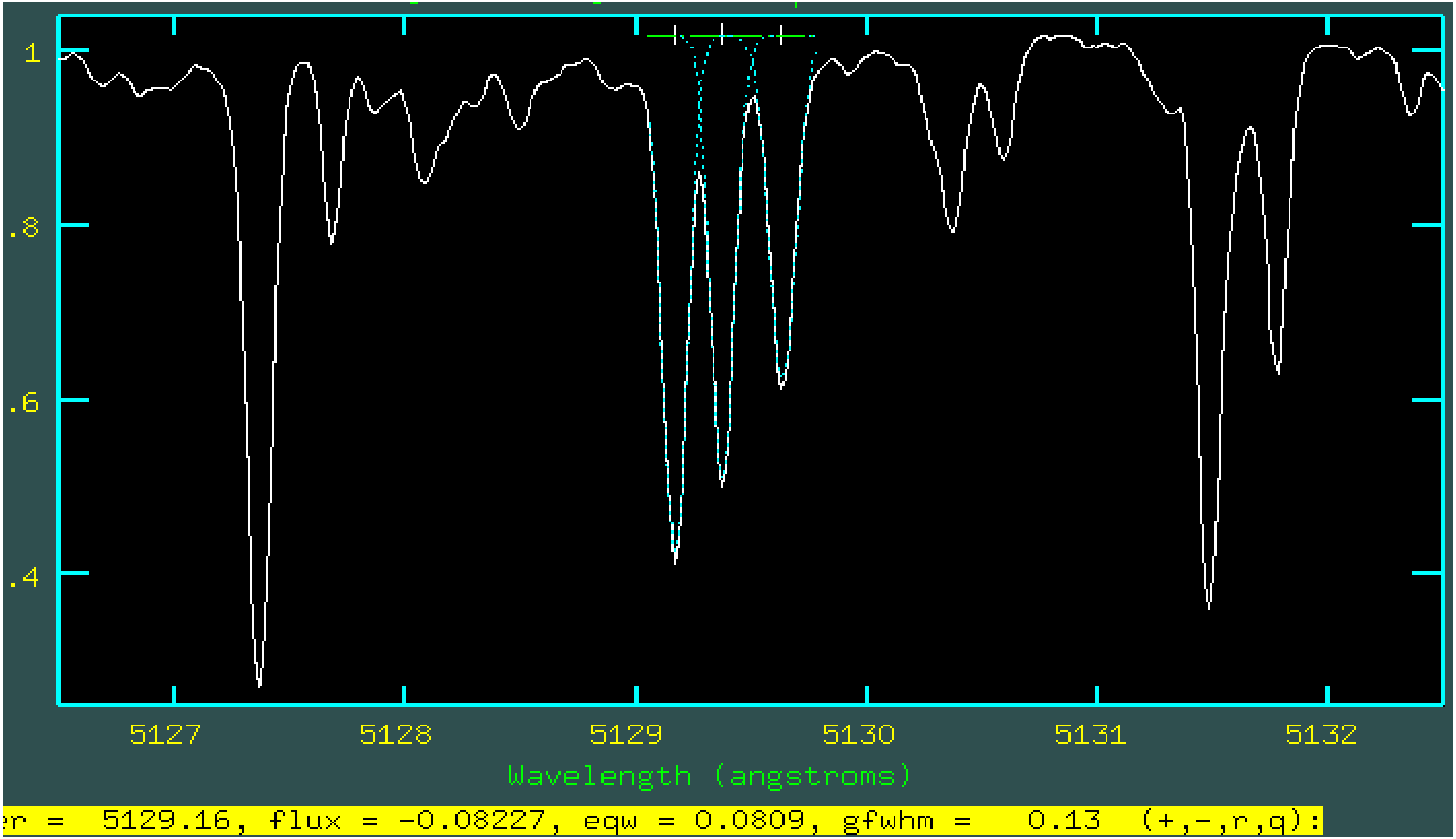
Deblending 3 lines in HIP102152



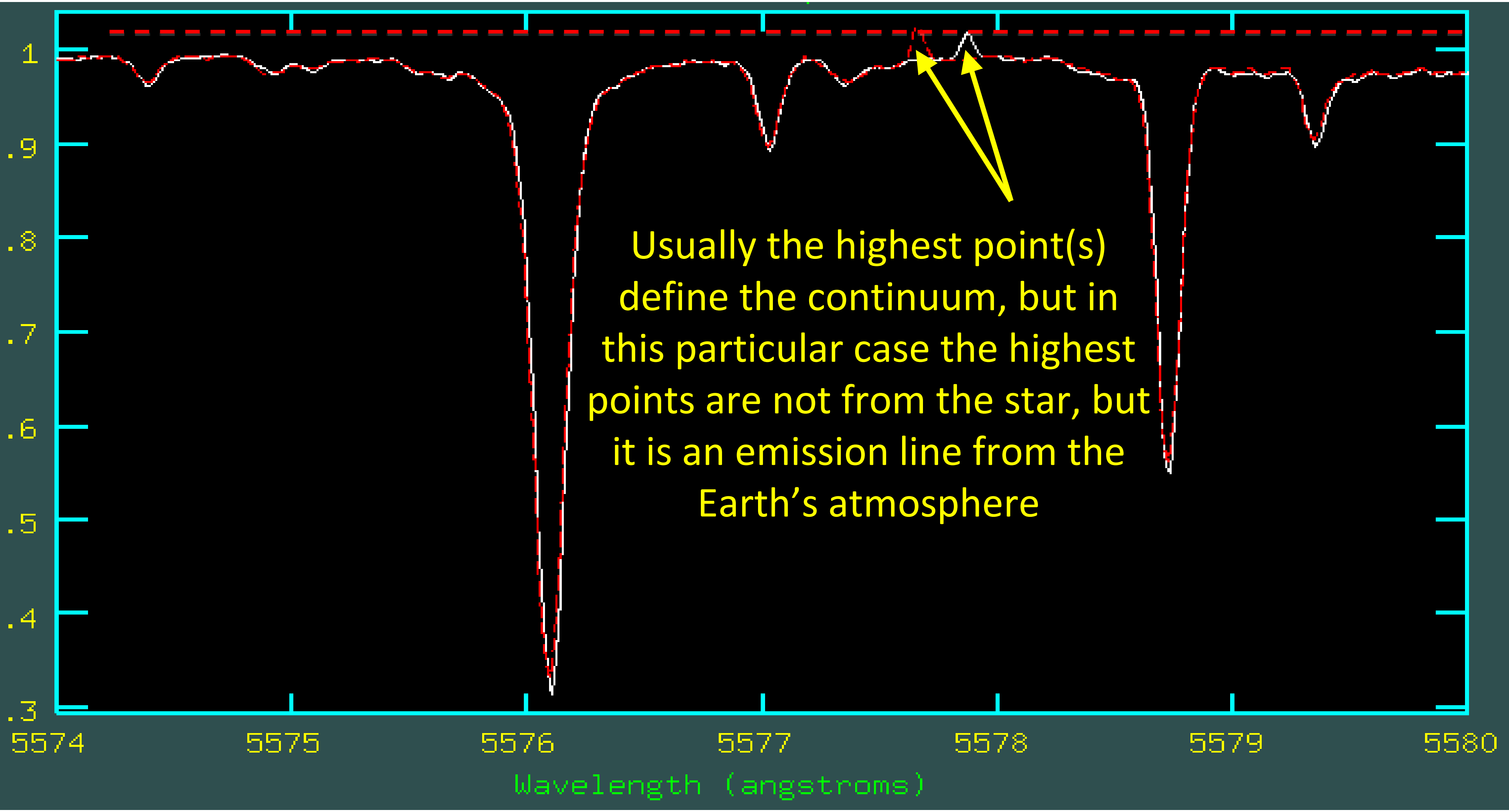
Deblending 3 lines in HIP102152



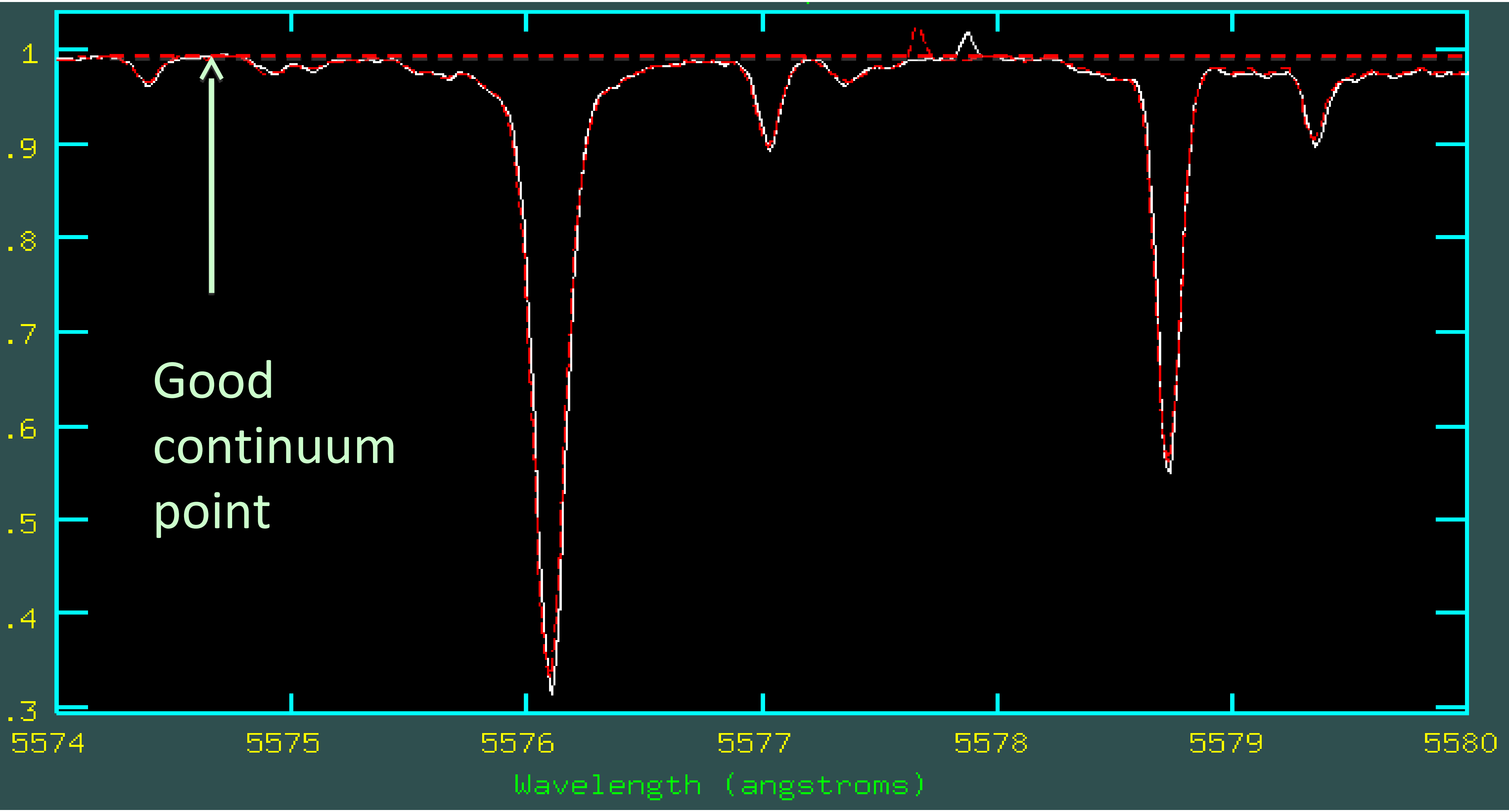
Deblending 3 lines in HIP102152



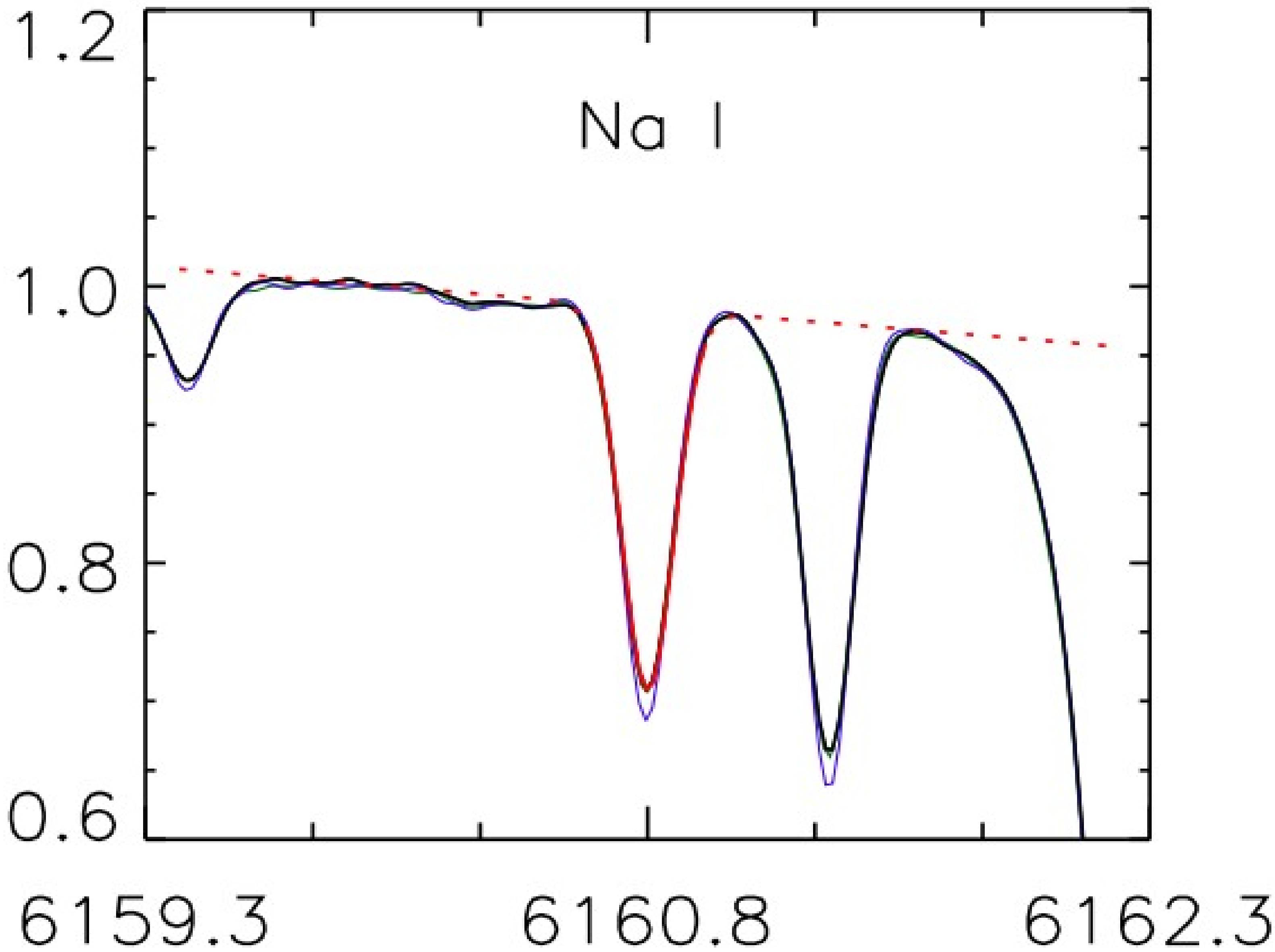
FeI line at 5577 Å



FeI line at 5577 Å

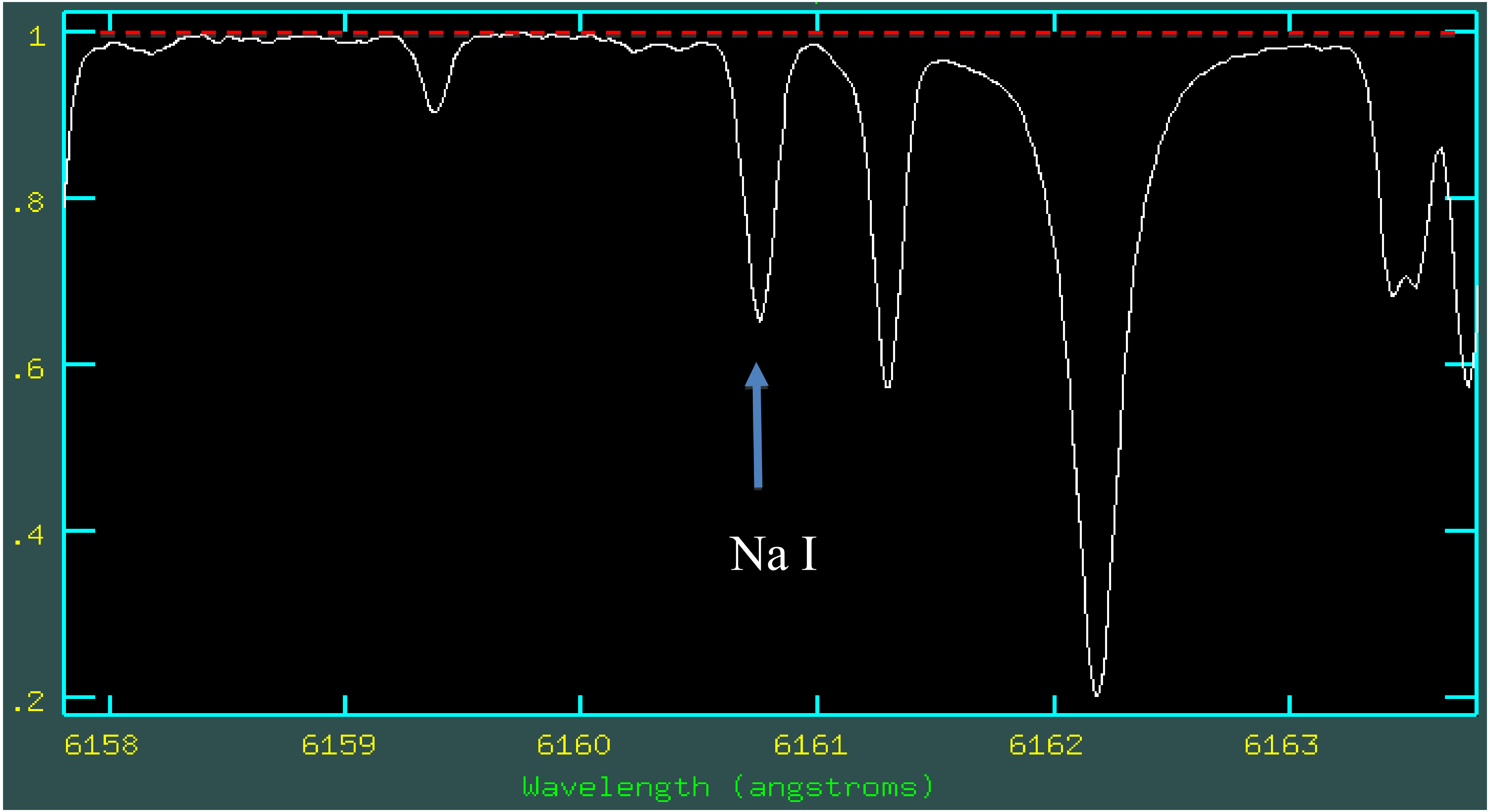


NaI at 6160.8 Å: inclined continuum

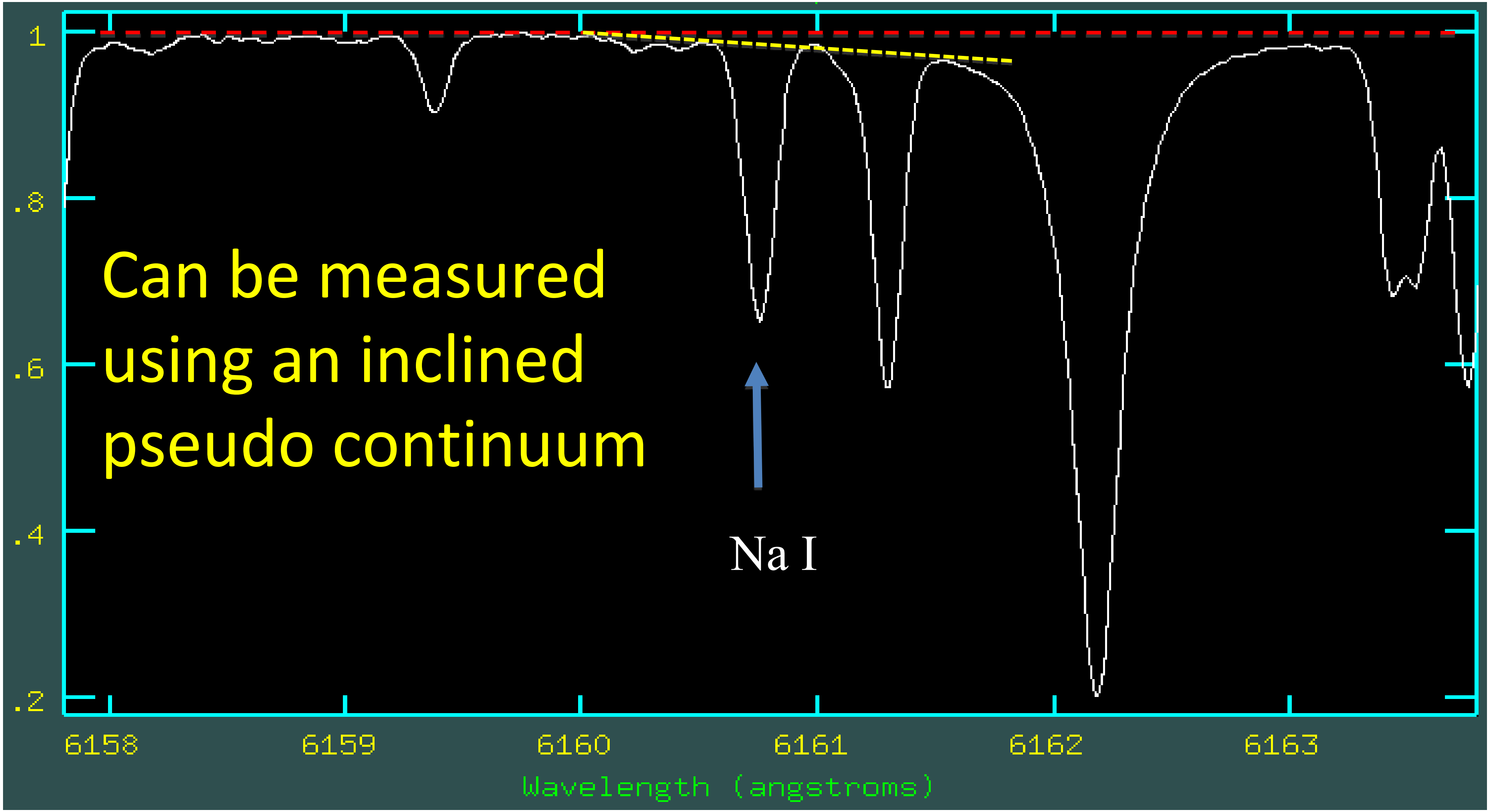


Bedell et al. 2014, ApJ, 795, 23

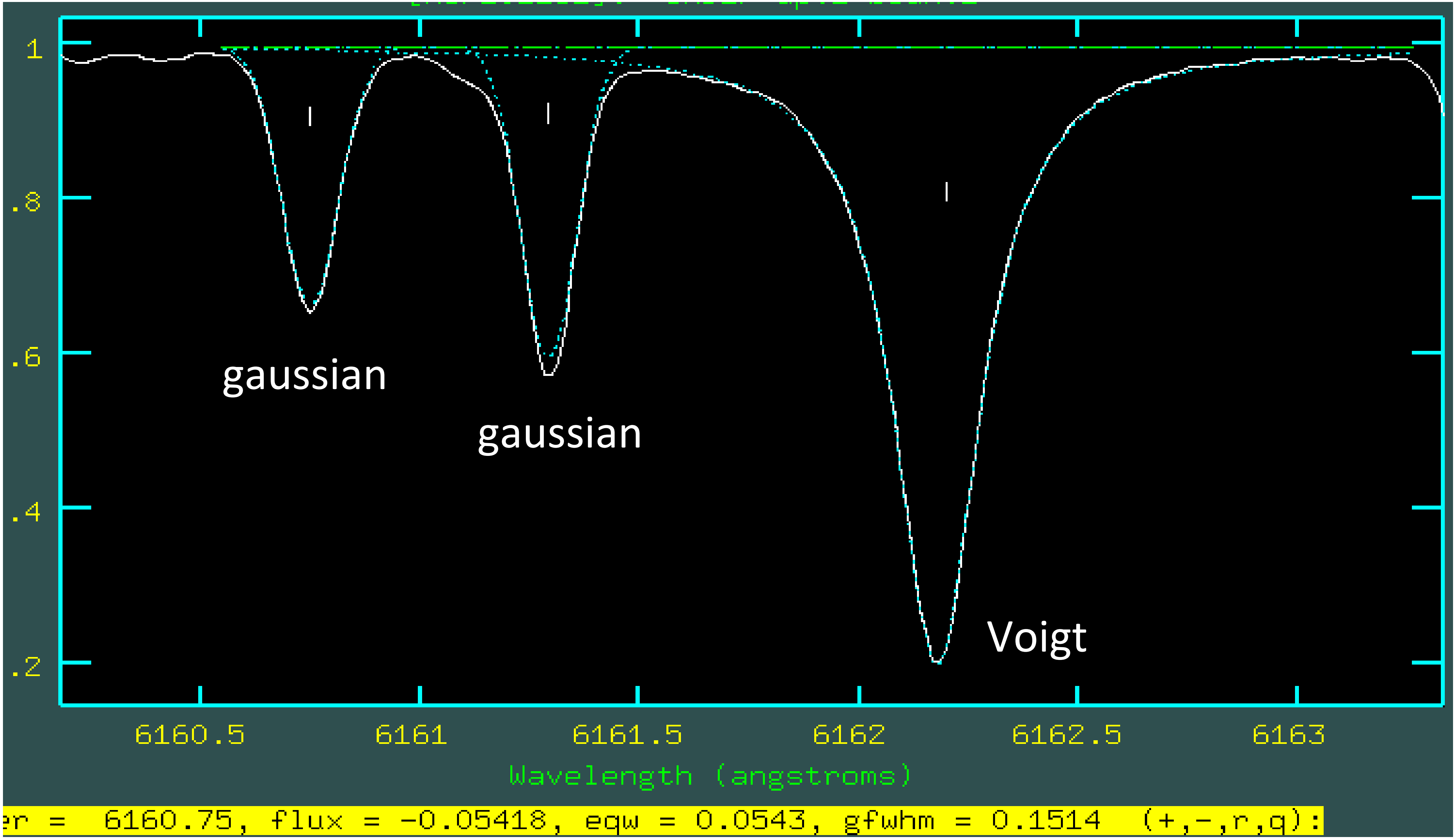
Local pseudo continuum has slope due to (Lorentzian) wing of strong nearby line



Local pseudo continuum has slope due to (Lorentzian) wing of strong nearby line

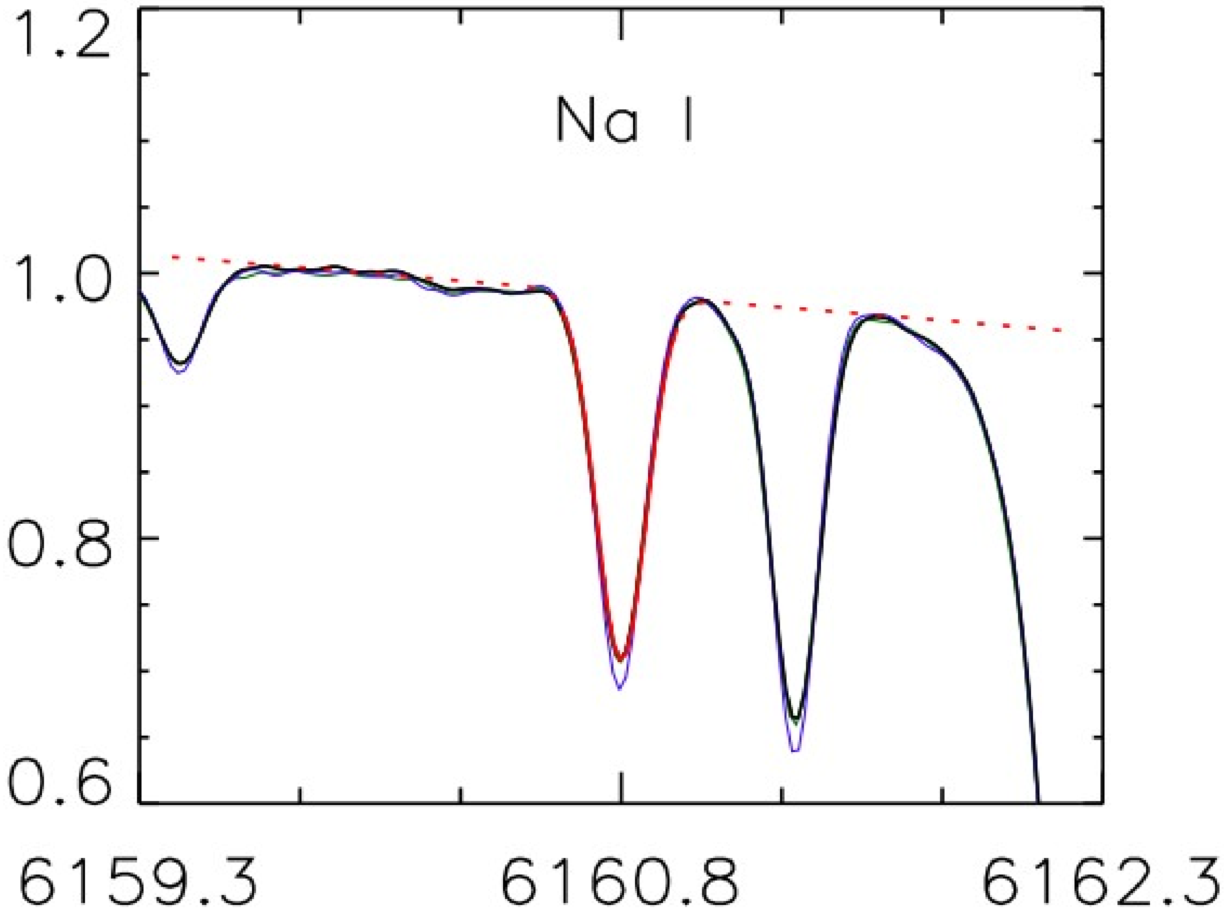


Another option: instead of an inclined pseudo-continuum, it could be deblended adopting a Voigt profile for the strong line



Whatever you do, always try to use the same criteria regarding continuum determination and the region used for fitting a given line profile, for all sample stars

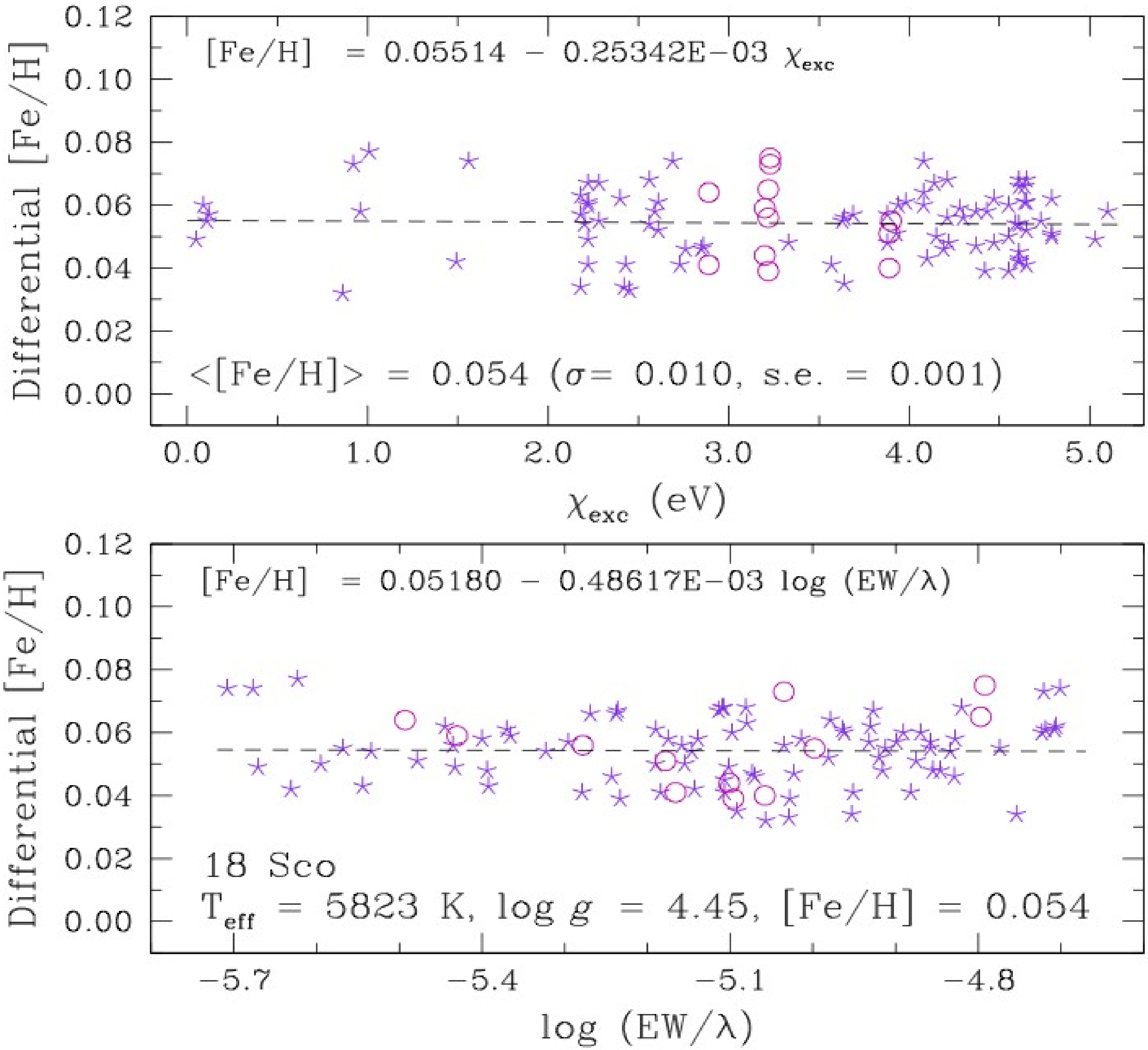
Ideally, specific measurement criteria should be established for each individual line



Final tip:

To minimize the degeneracy in your solutions and to avoid biases, try to include lines of different strengths (from weak to moderate intensity) at a given χ_{exc}.

Also, be careful about having too many lines of a given χ_{exc} or line strength



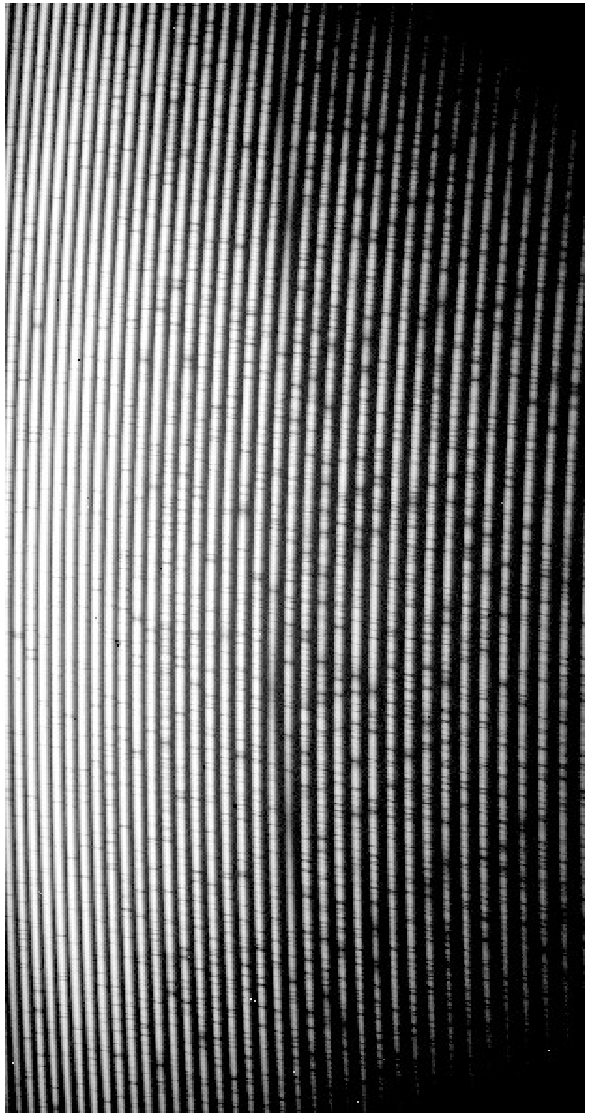
End of the first part

Second part:
some applications of high precision differential spectroscopy

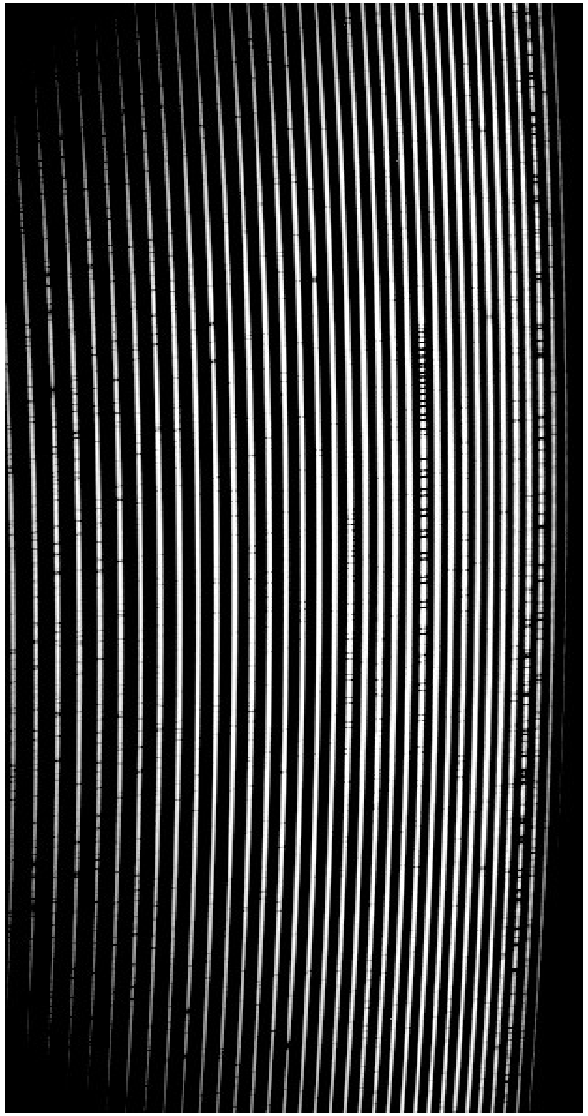
Experiment in 4/2017 using solar twins

- Magellan 6.5m telescope
& MIKE spectrograph
- R = 65,000
- S/N = 450 per pixel
- coverage 340 – 1000 nm
- Solar spectrum: Vesta (same run)
- 3 nights of observations

Echelle observations of the solar twin 18 Sco



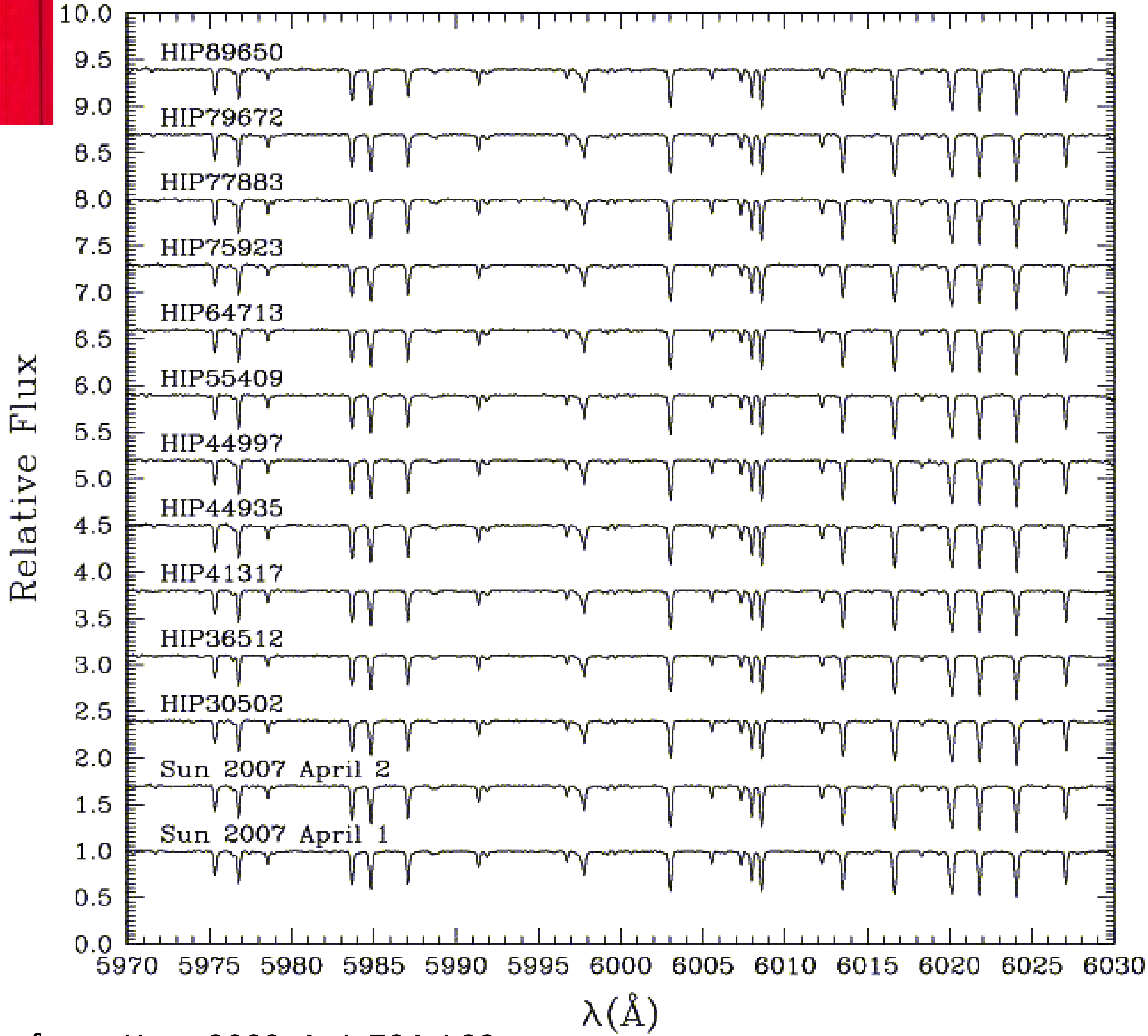
BLUE frame



RED frame

Observations in 2007, analysis finished in 2009:

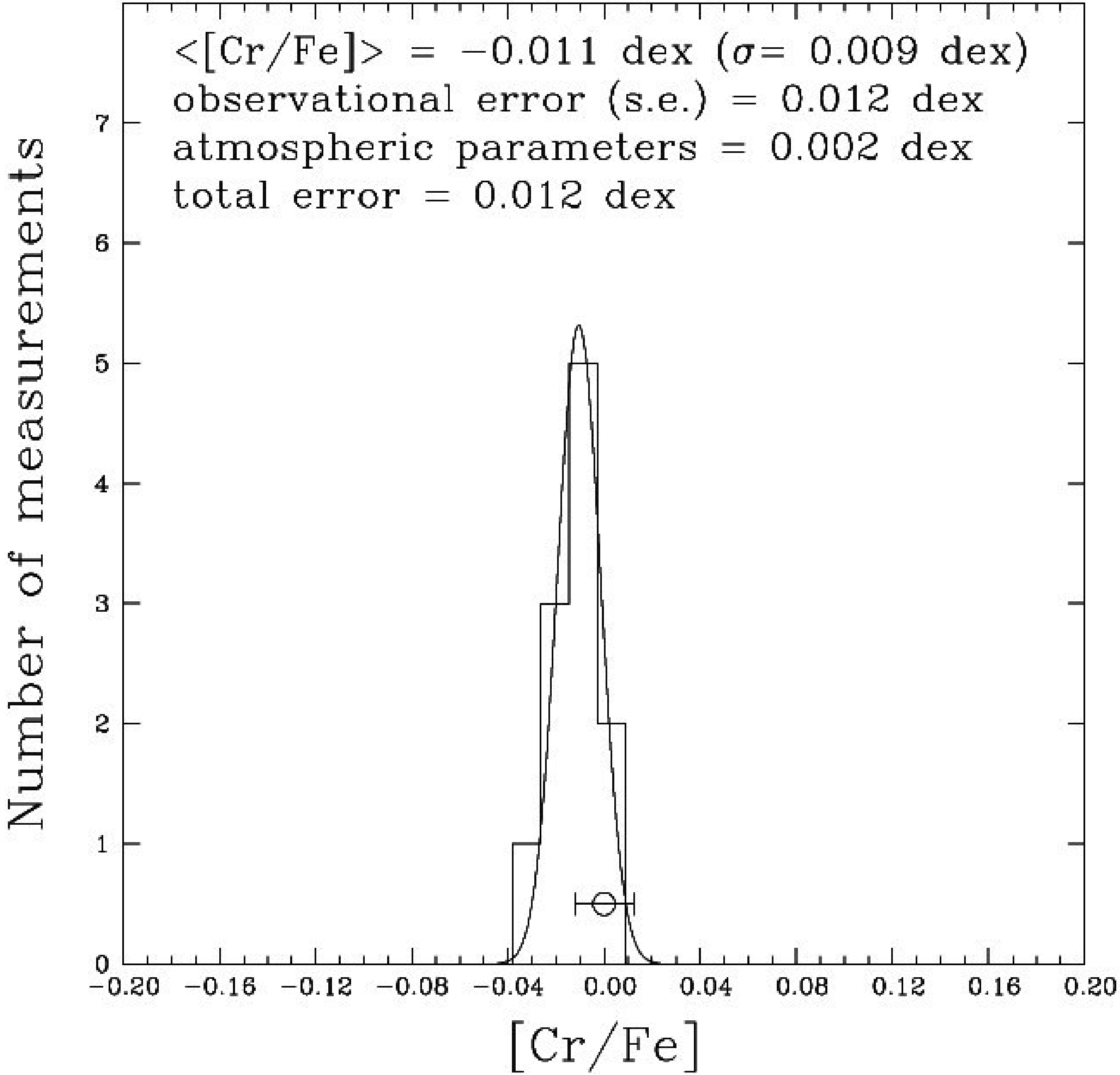
Differential study of the chemical composition of Solar Twins relative to the Sun (observed in the same run)



Meléndez, Asplund, Gustafsson, Yong 2009, ApJ, 704, L66

[Cr/Fe] distribution in 11 solar twins

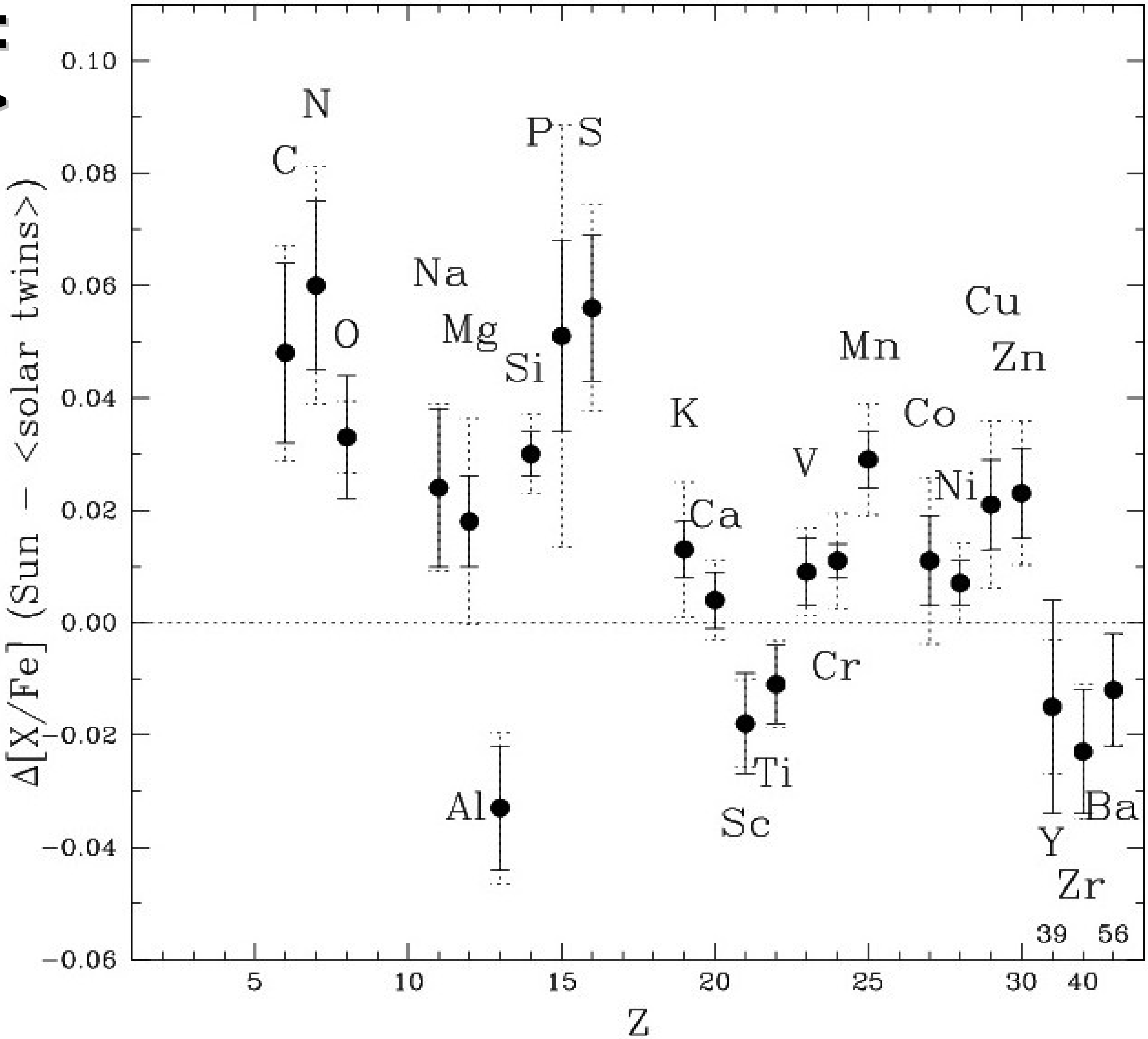
Star-to-star scatter of only **0.009 dex in [C/Fe]**



Δ abundance: Sun - <twins> vs. atomic number Z

Sun typical : Δ = 0

Sun weird : Δ ≠ 0



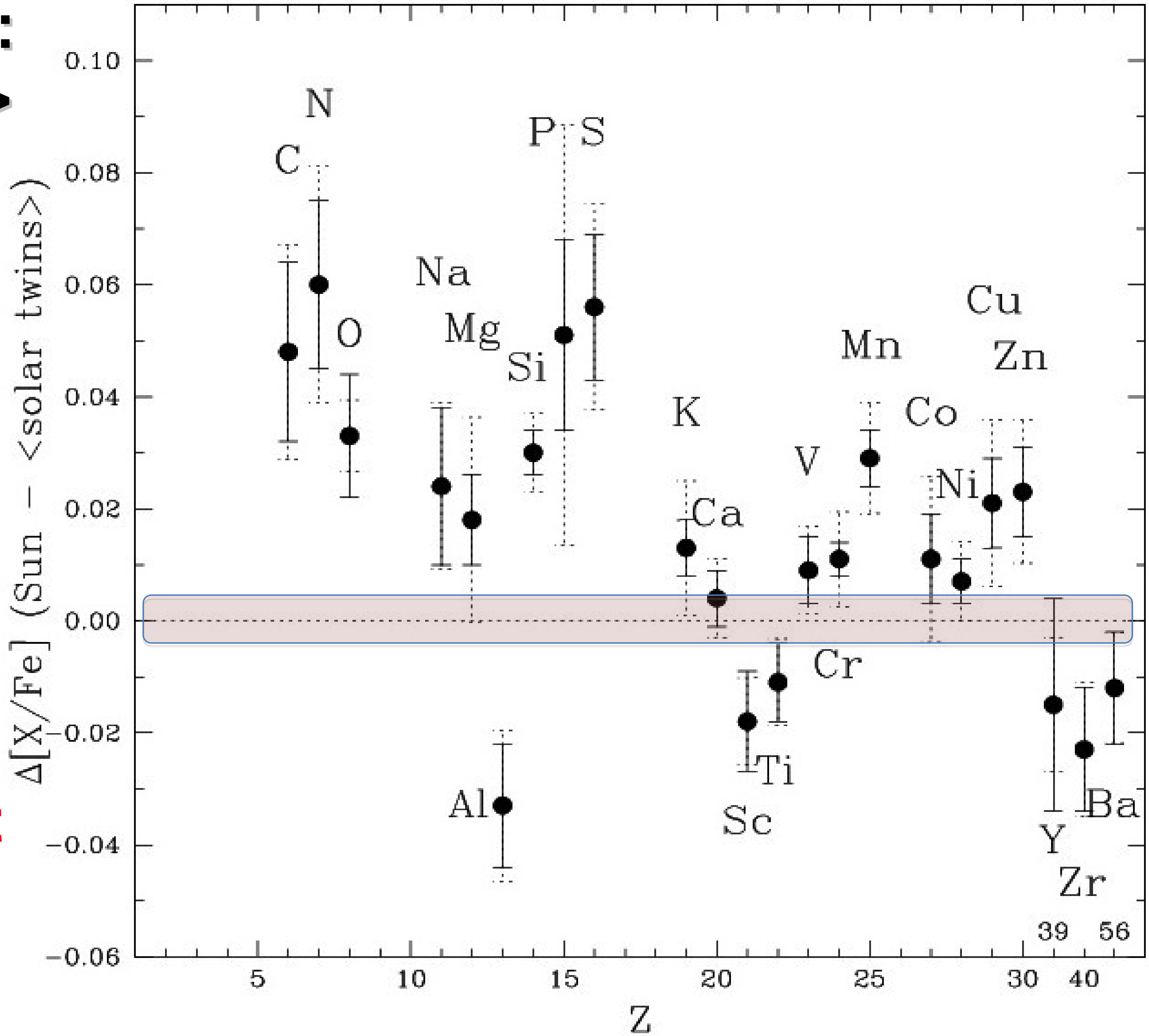
Meléndez, Asplund, Gustafsson, Yong 2009, ApJ, 704, L66

Δ abundance: Sun - <twins> vs. atomic number Z

Sun typical : Δ = 0

Sun weird : Δ ≠ 0

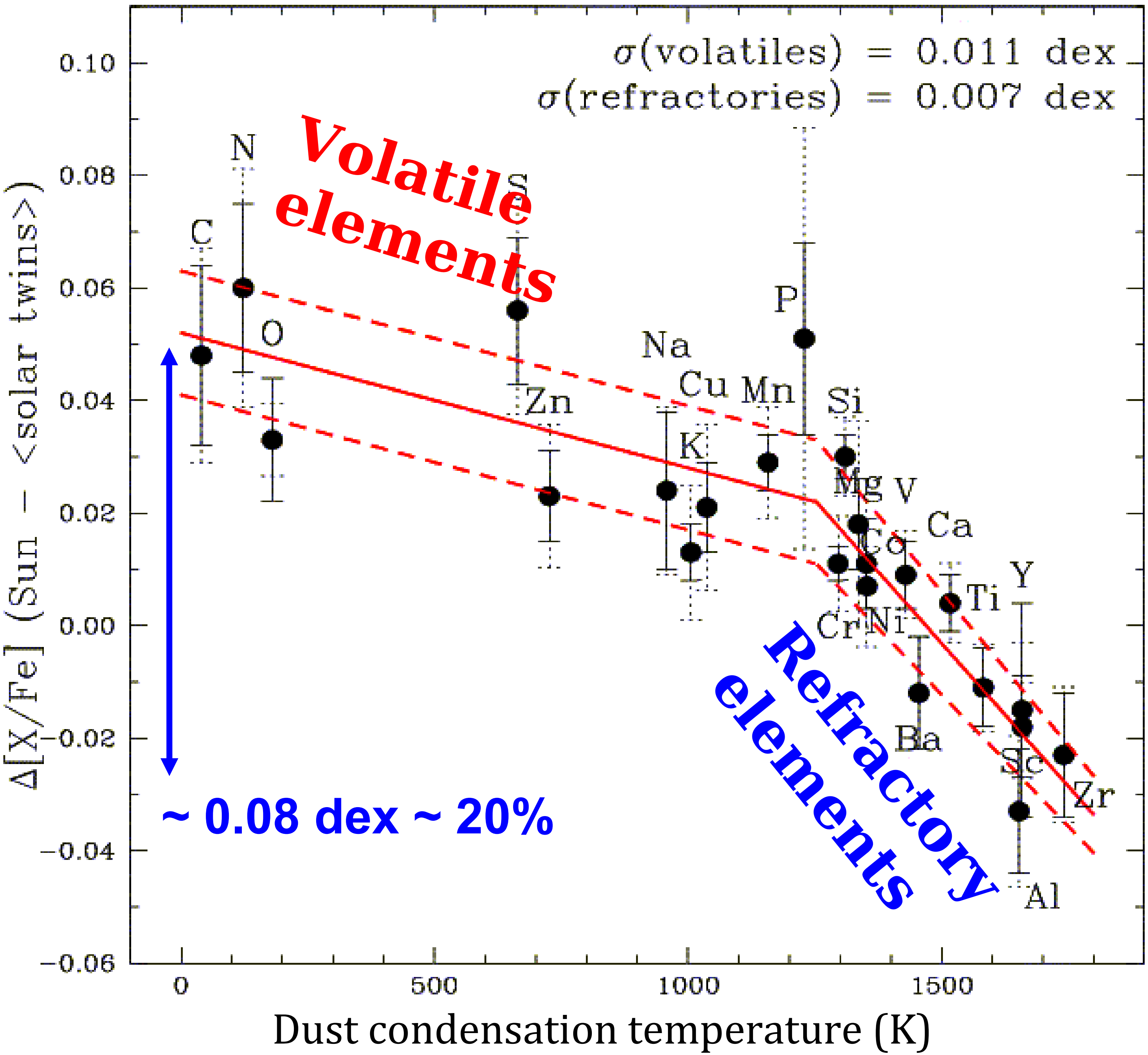
Our solar system is not host by a typical 'Sun'



Meléndez, Asplund, Gustafsson, Yong 2009, ApJ, 704, L66

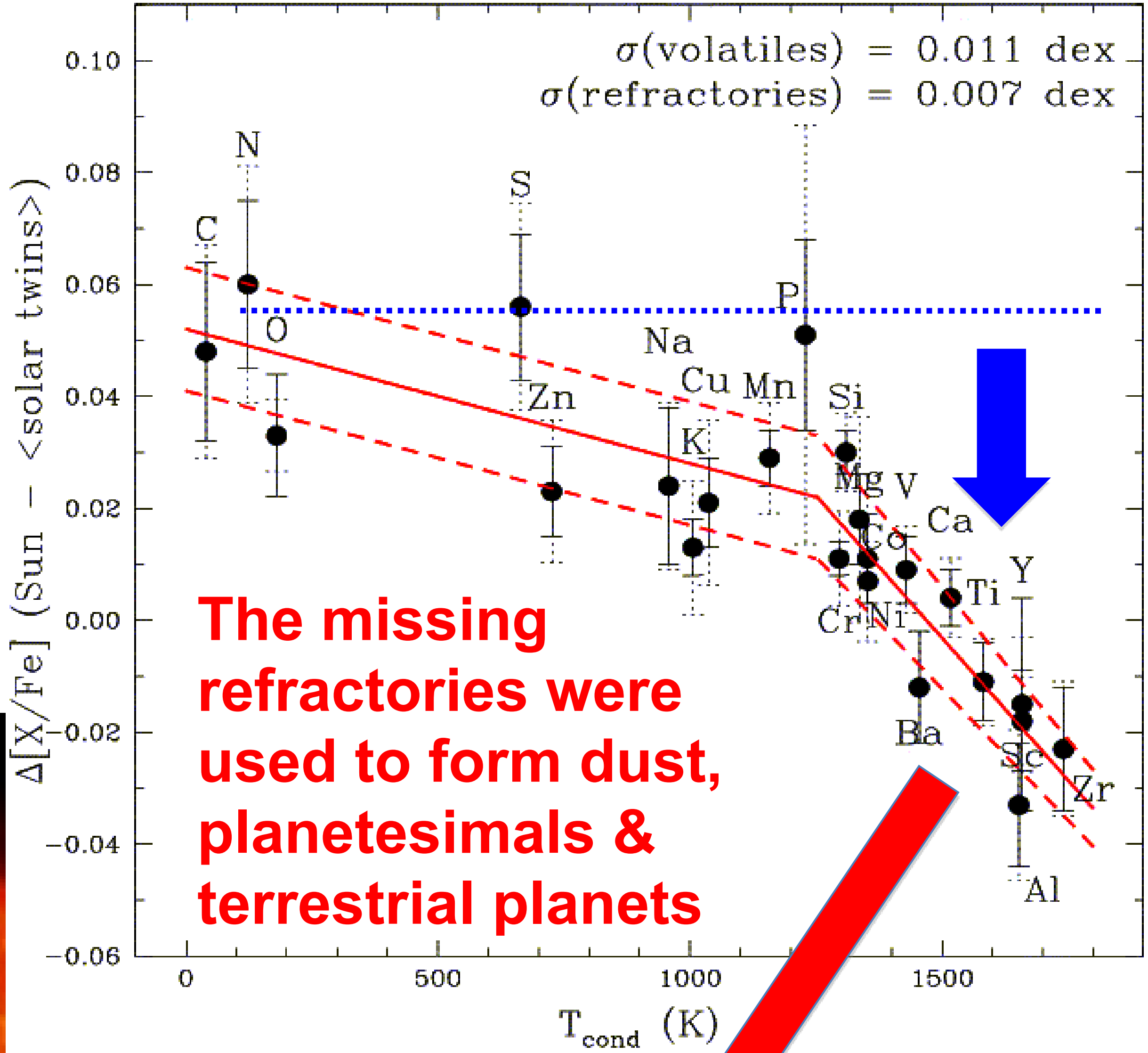
Sun's anomalies are strongly correlated to the dust condensation temperature of the elements!

Correlation is highly significant probability ~**10**$^{-9}$ to happen by chance

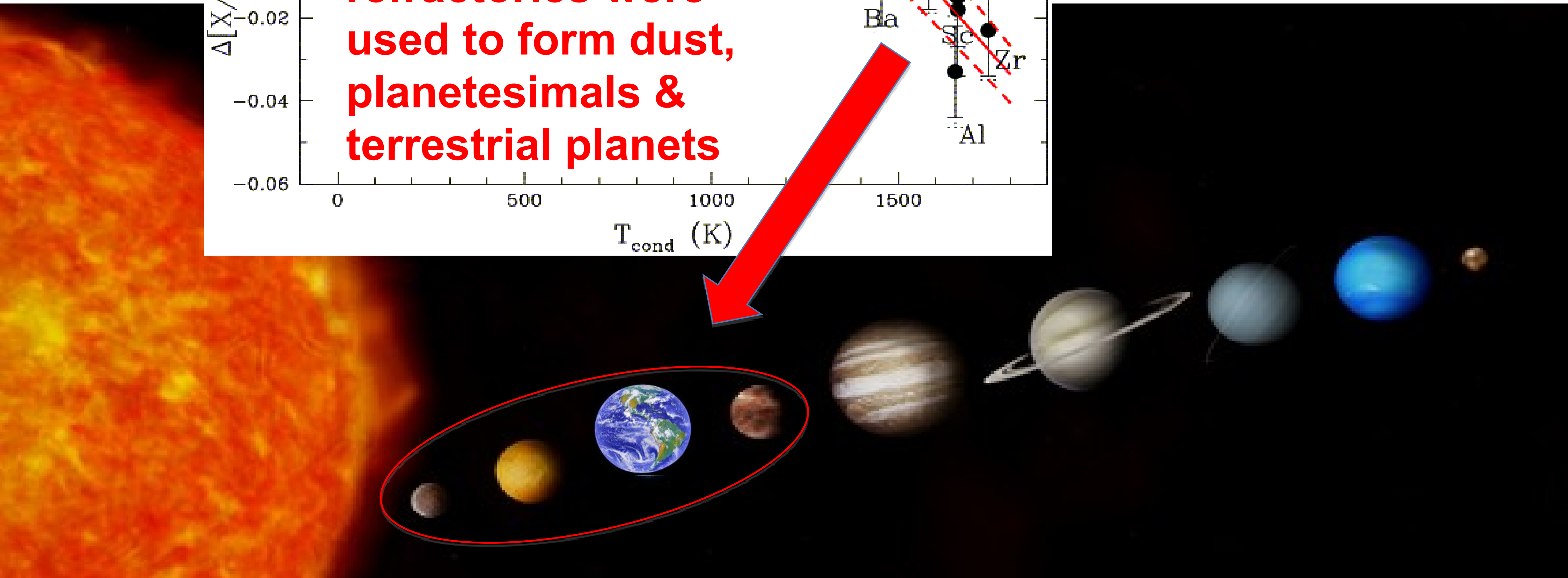


Meléndez, Asplund, Gustafsson, Yong 2009, ApJ, 704, L66

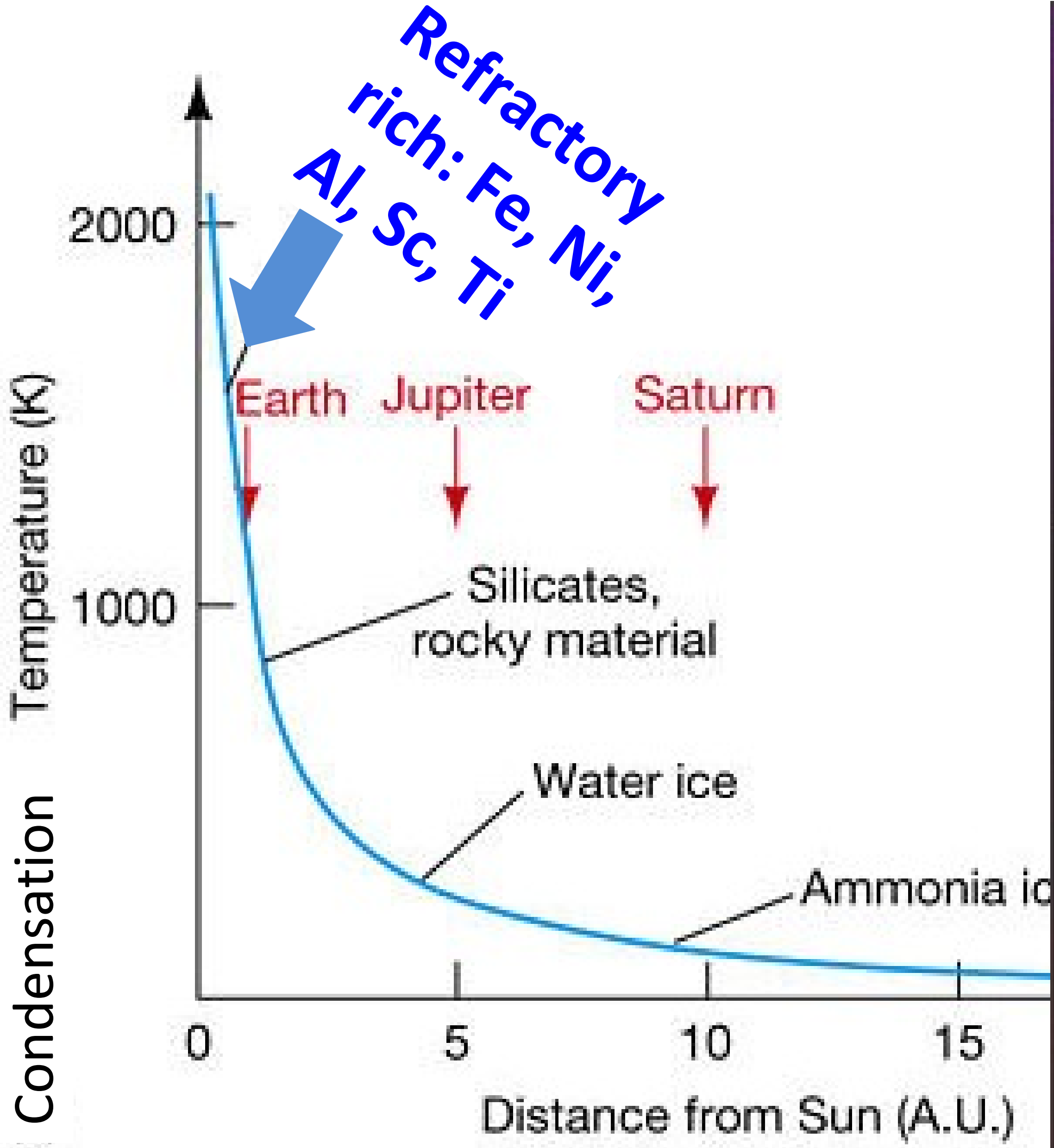
Meléndez et al. 2009



The late accreted gas in the convection zone was deficient in refractories



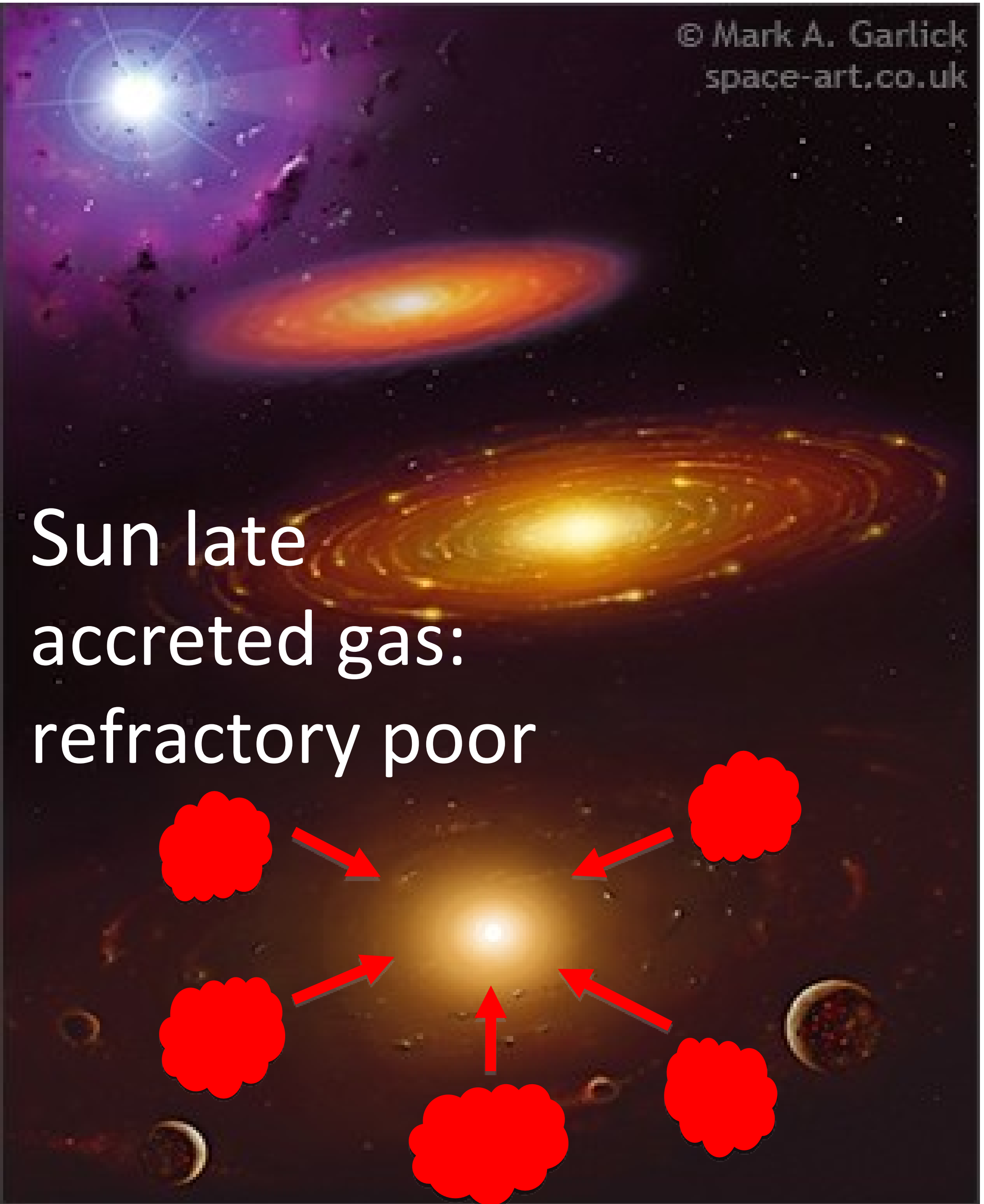
Rocky material: rich in refractory elements (high condensation temperature)



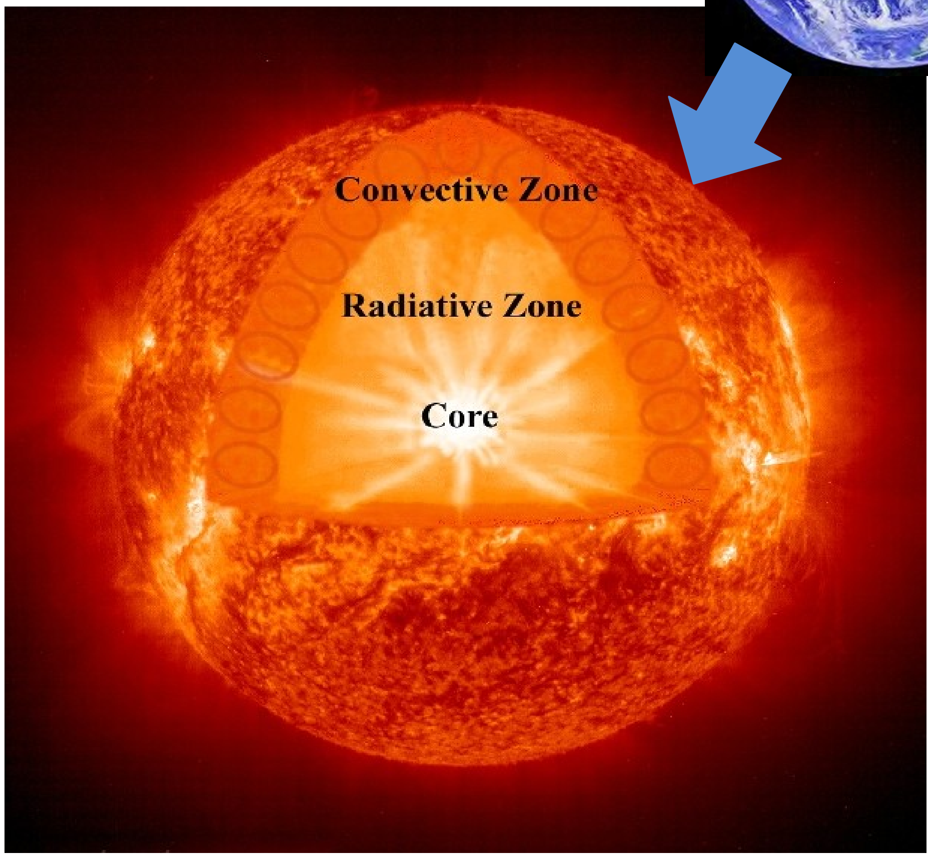
Chemical Signatures of planets

1. Dust removed: refractory poor

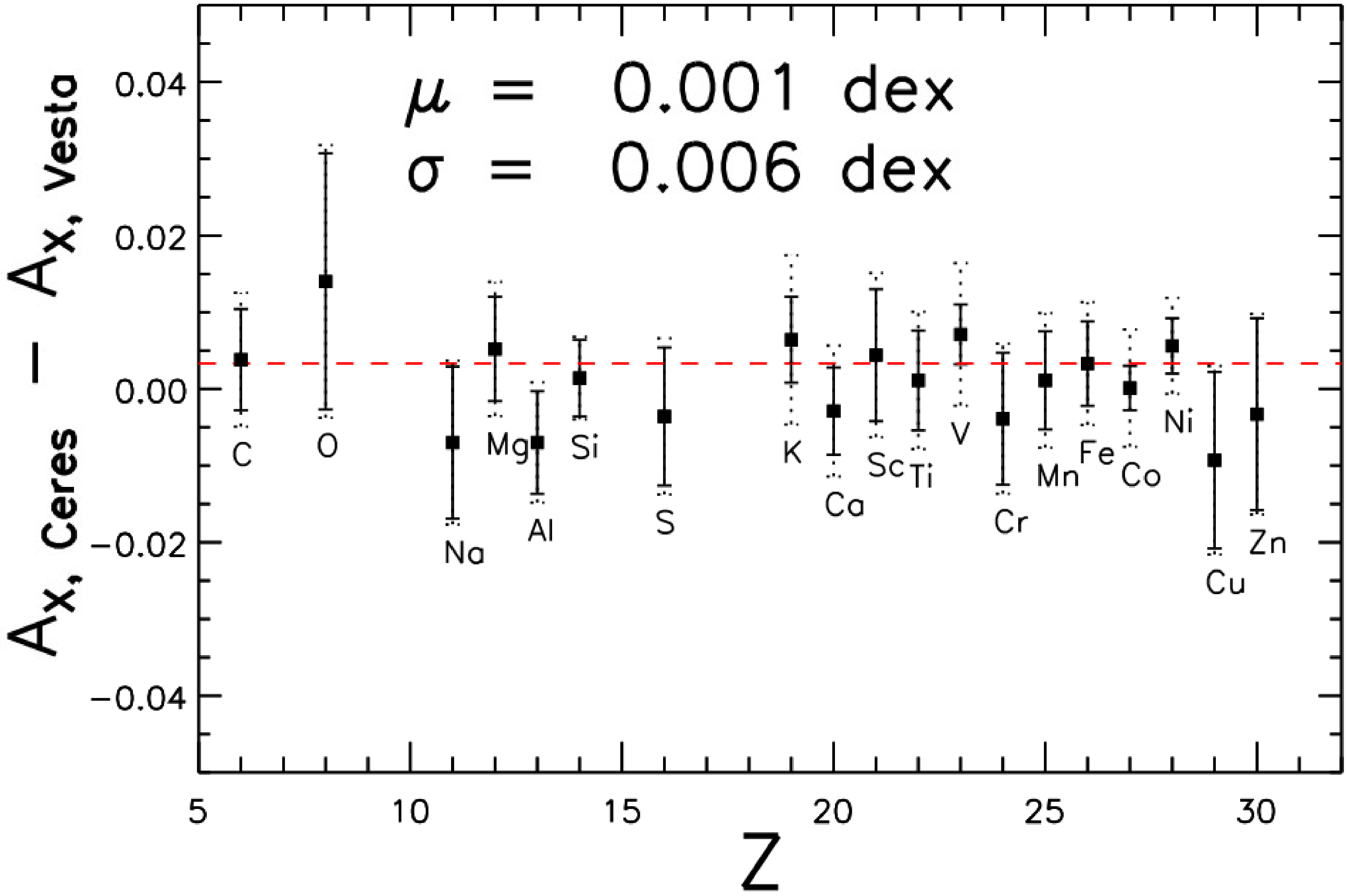
2. Planet accretion: refractory rich



Planet engulfment



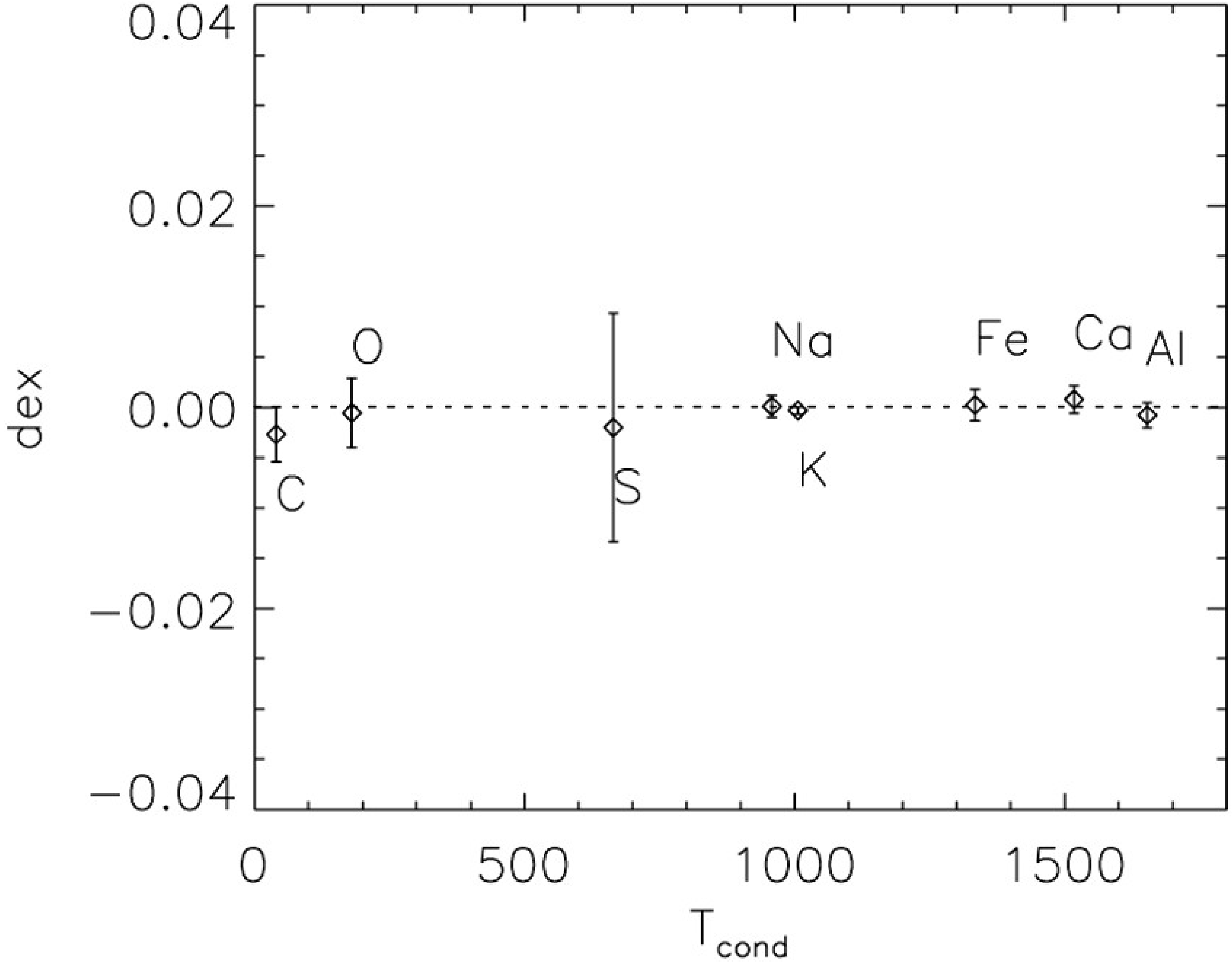
Test of our precision using asteroids: scatter of 0.006 dex



Bedell, Meléndez, Bean, Ramírez, Leite & Asplund 2014

Test: different Sun's spectra: no variations (< 0.003 dex)

There are no changes in the abundances obtained at different latitudes in the Sun for both volatile (to within 0.005 dex) and refractory (to within 0.002 dex) elements.



A&A 535, A14 (2011)

Is the solar spectrum latitude-dependent?

D. Kiselman[1,2], T. M. D. Pereira[3,⋆], B. Gustafsson[4,5], M. Asplund[6,3], J. Meléndez[7], and K. Langhans[1,2,⋆⋆]

Planet effects in binary system with ”twins”

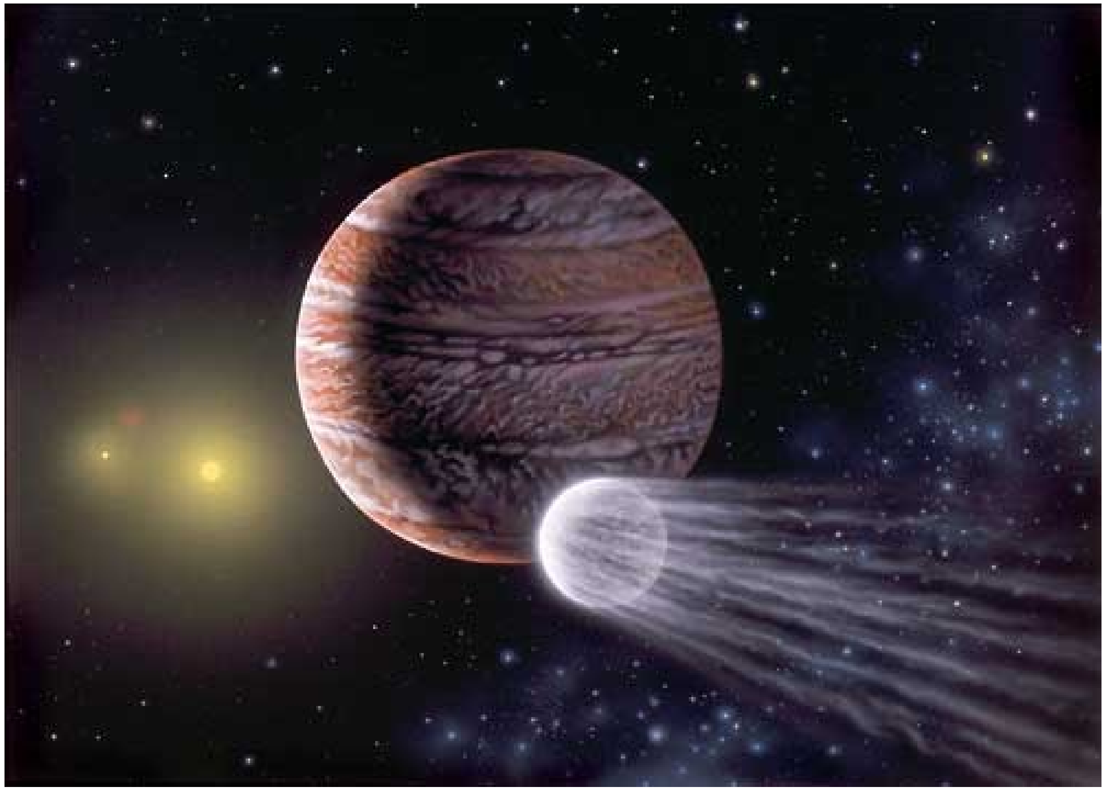
The Astrophysical Journal, 740:76 (15pp), 2011 October 20 doi:10.1088/0004-637X/740/2/76

ELEMENTAL ABUNDANCE DIFFERENCES IN THE 16 CYGNI BINARY SYSTEM: A SIGNATURE OF GAS GIANT PLANET FORMATION?

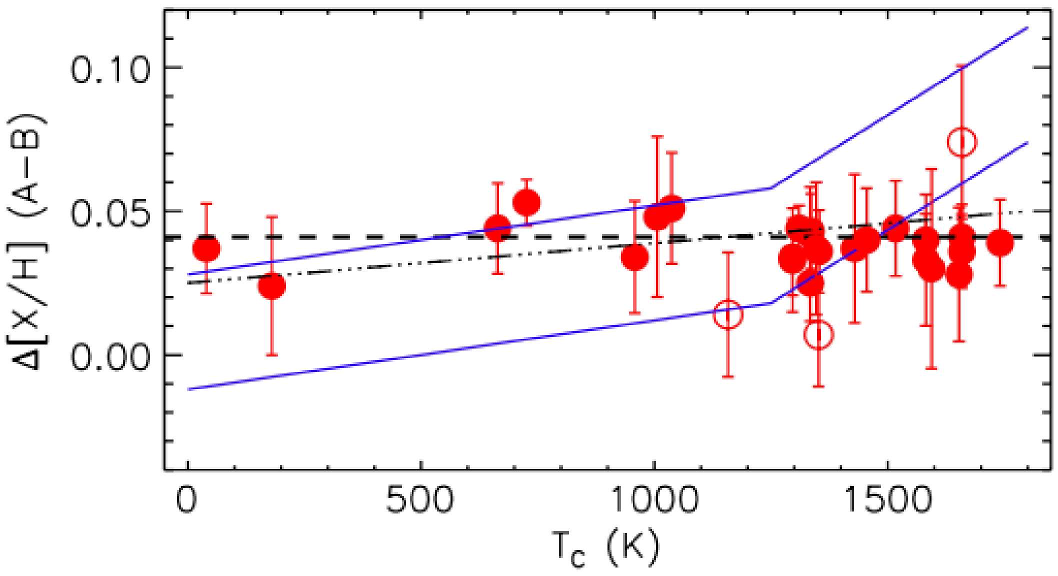
I. Ramírez[1], J. Meléndez[2], D. Cornejo[3], I. U. Roederer[1], and J. R. Fish[1,4]

16 Cyg: widely separated pair of solar twins

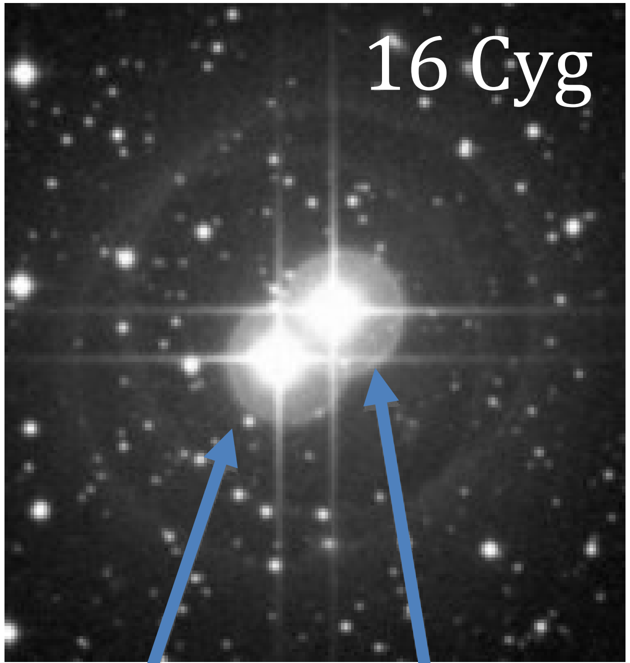
16 Cyg A : no planets, 16 Cyg B : giant planet (~ 2 M_J)



Ramirez et al. 2011: 16 Cyg A is ~0.04 dex more metal-rich than 16 Cyg B

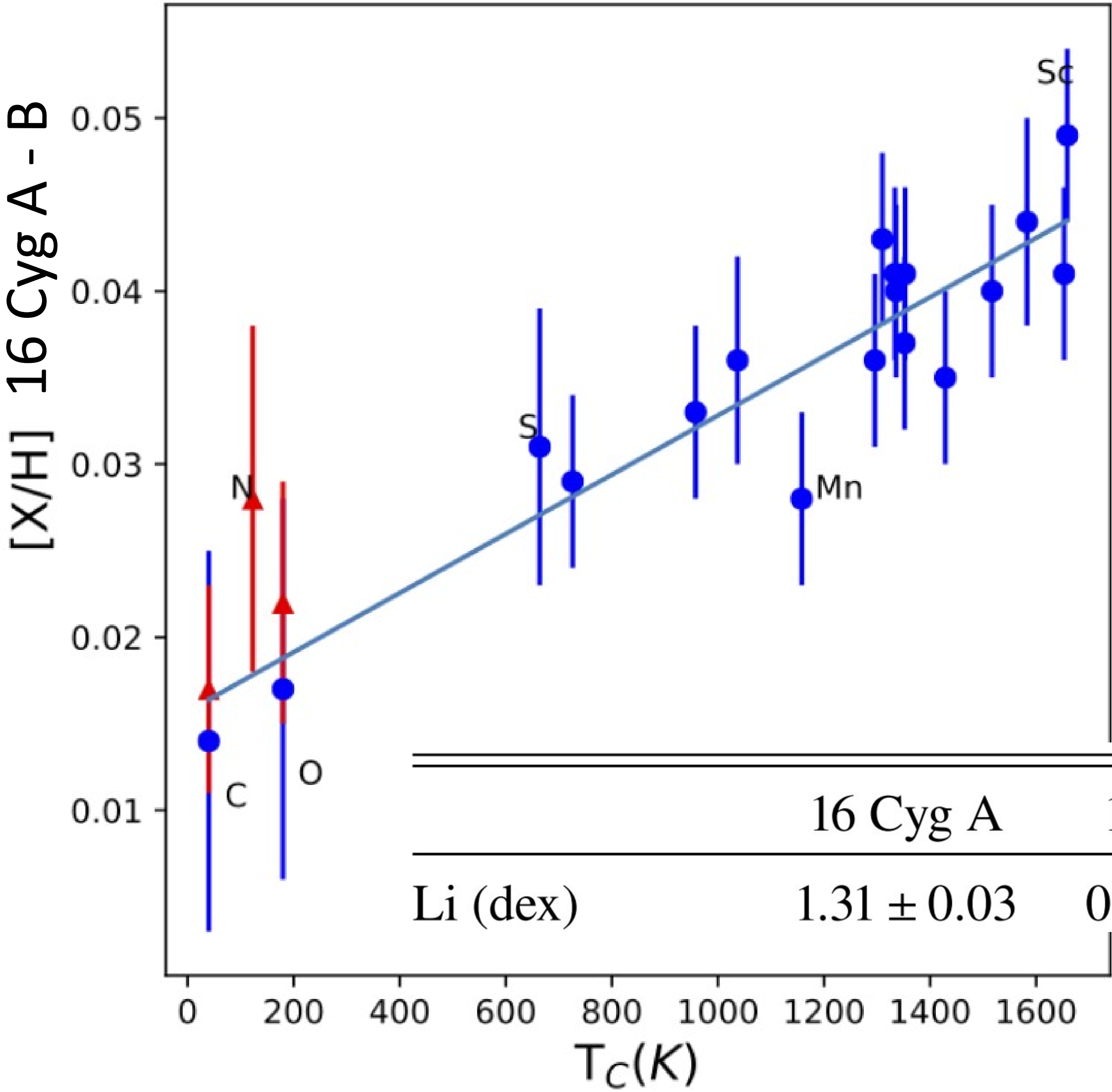


Signatures of planet engulfment in the 16 Cyg binary



A: no planet

B: hosts a giant planet (~ 2 M_J)

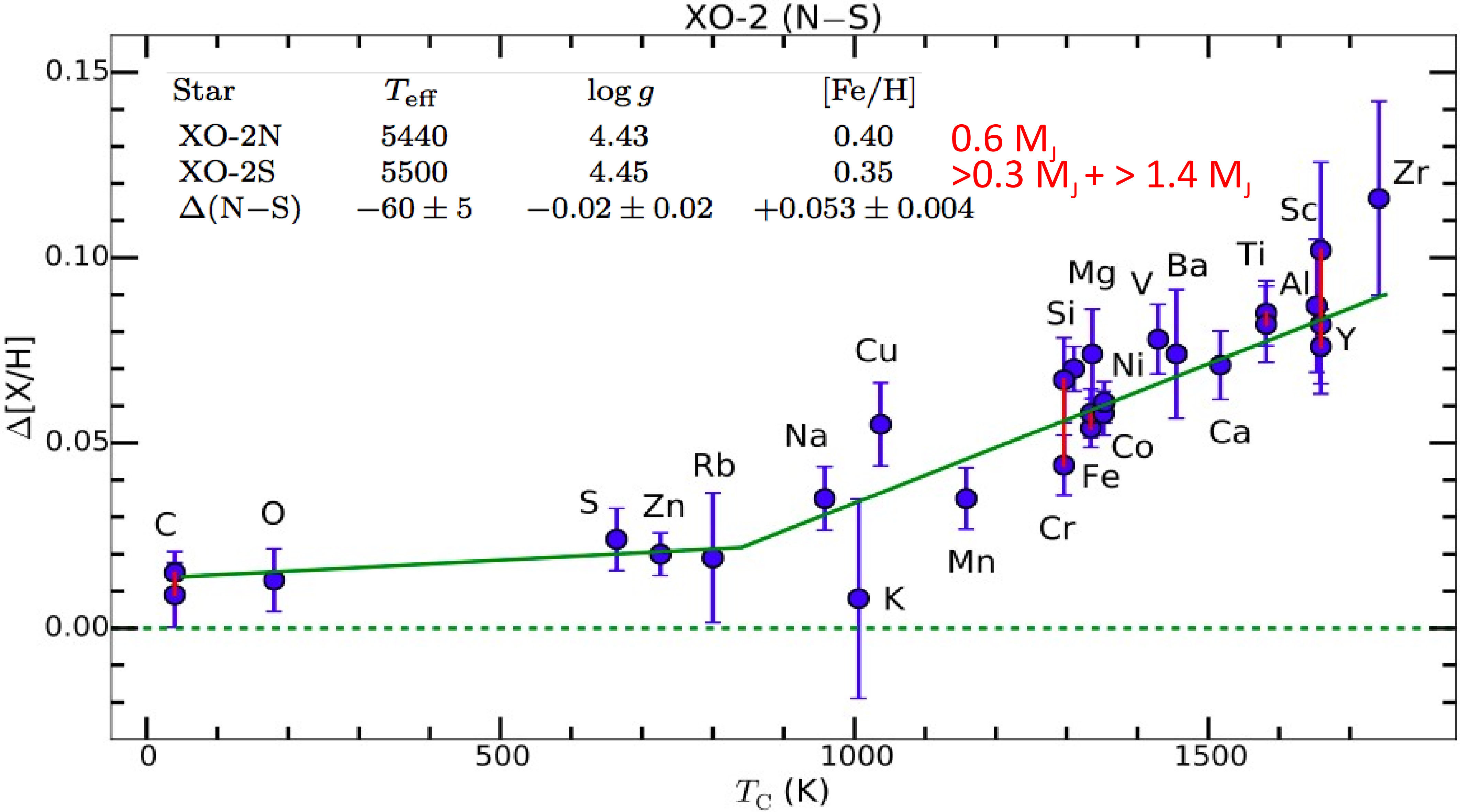


	16 Cyg A	16 Cyg B
Li (dex)	1.31 ± 0.03	0.61 ± 0.03

Subaru telescope + HDS
R = 160 000
S/N = 750

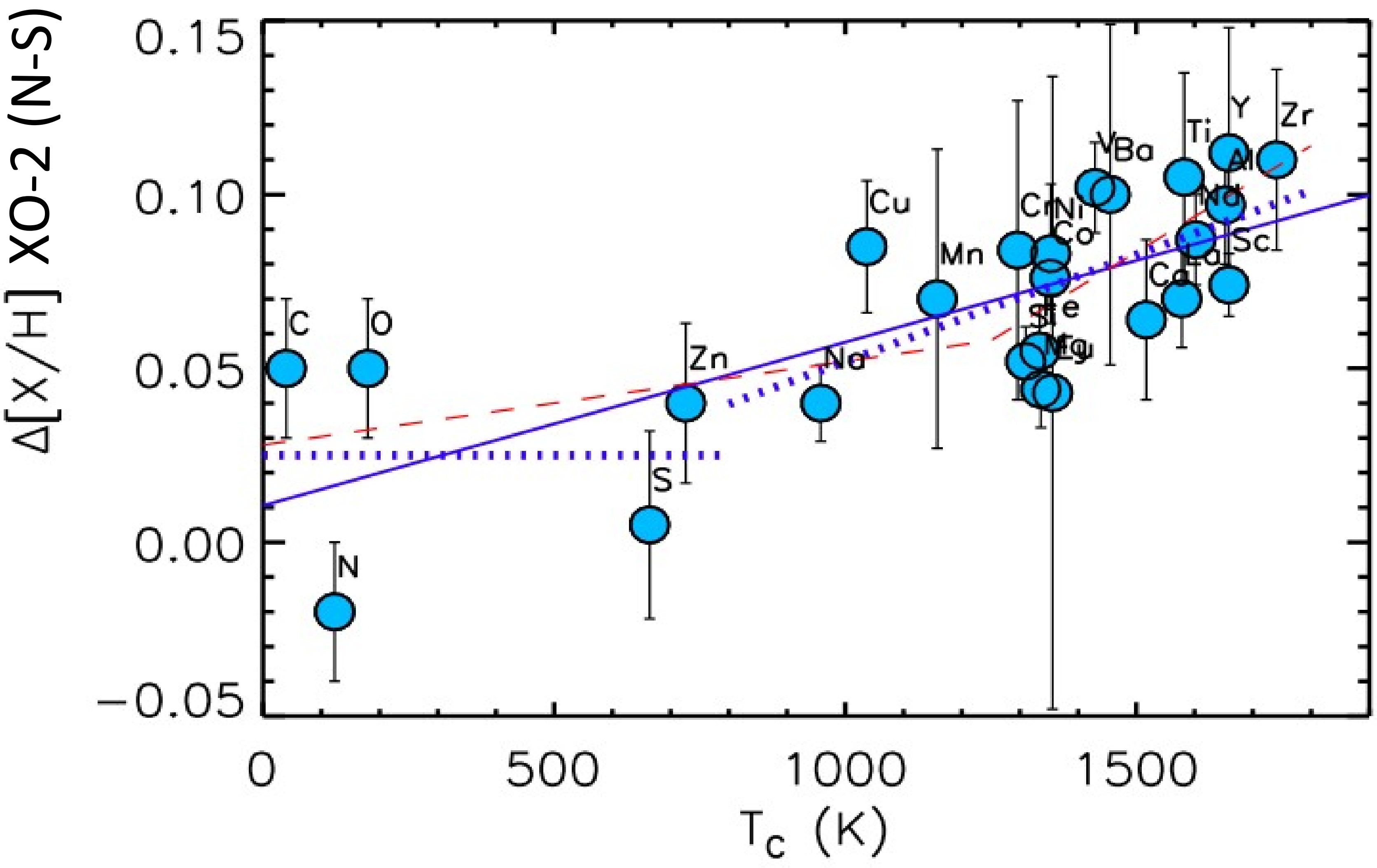
Tucci Maia et al. 2019: 16 Cyg A may have eaten a planet!

Another binary system: XO-2
Both components host planets



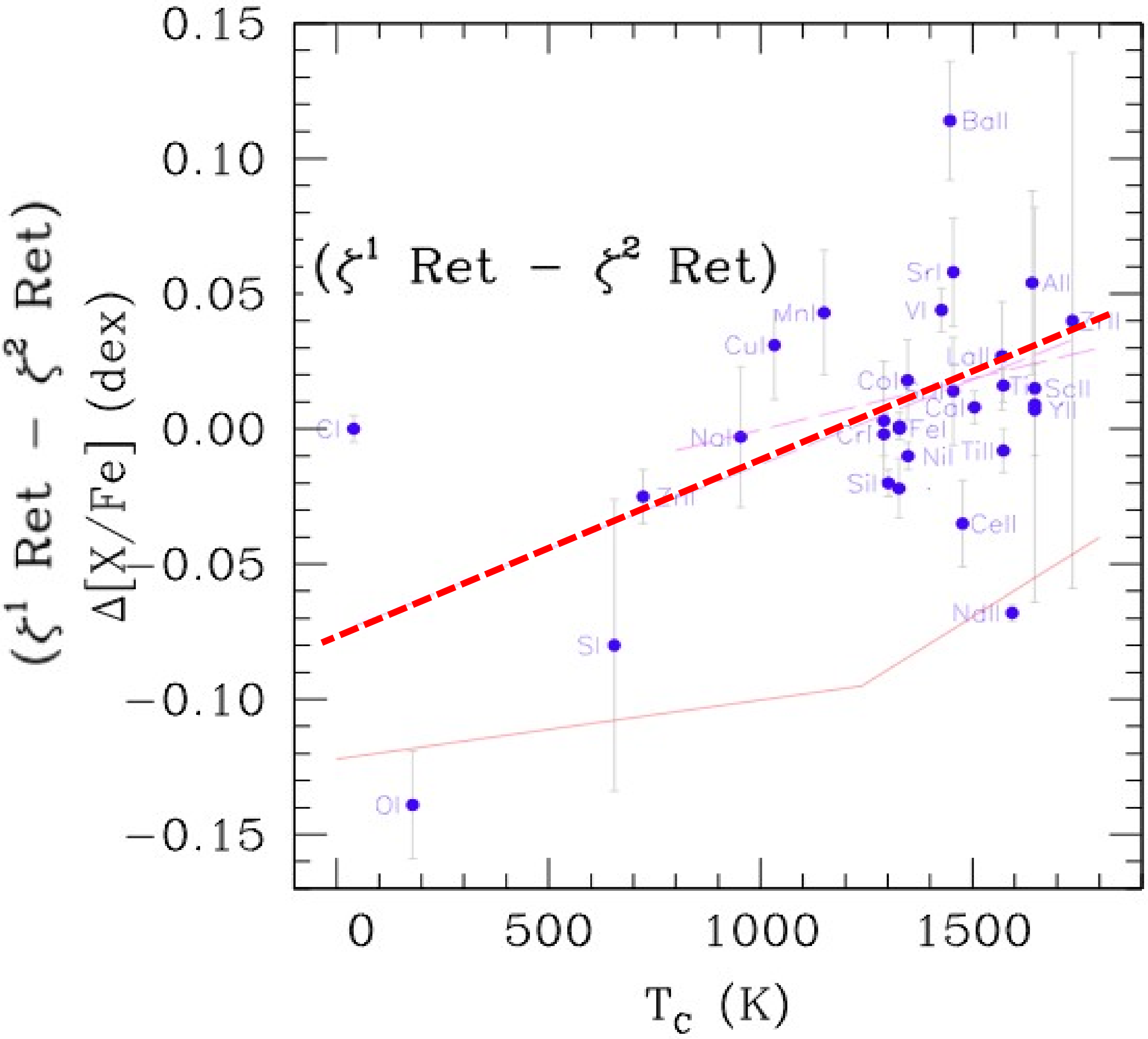
Ramírez et al. 2015. See also Teske et al. 2015; Biazzo et al. 2015

Consistent independent results for binary XO-2 have been obtained by Biazzo et al. (2015)



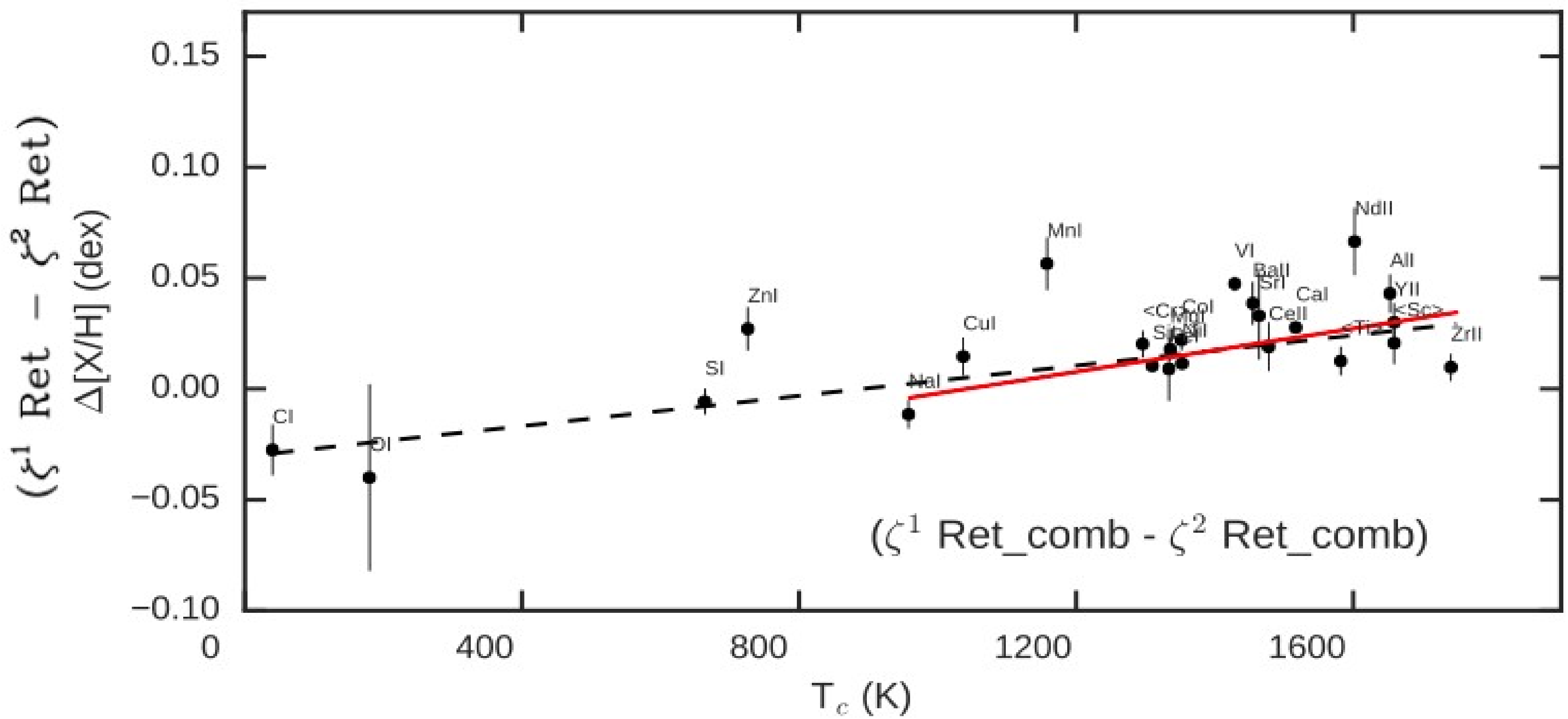
See also Teske et al. 2015

Binary pair ζ *Ret* with debris disk in one component *(ζ^2)*



Chemical signature found by Safe et al. 2016

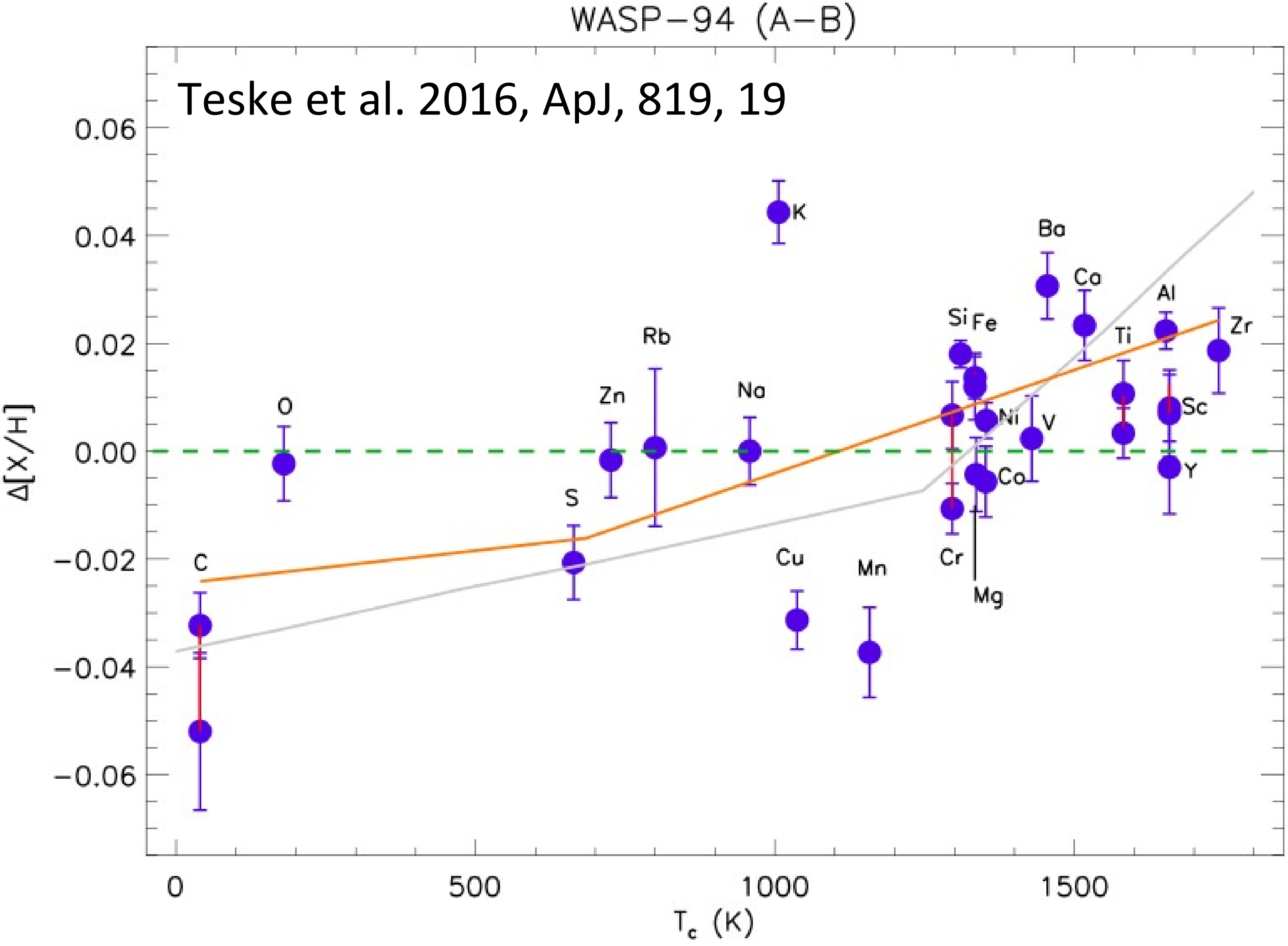
Binary pair ζ *Ret* with debris disk in one component *(ζ^2)*



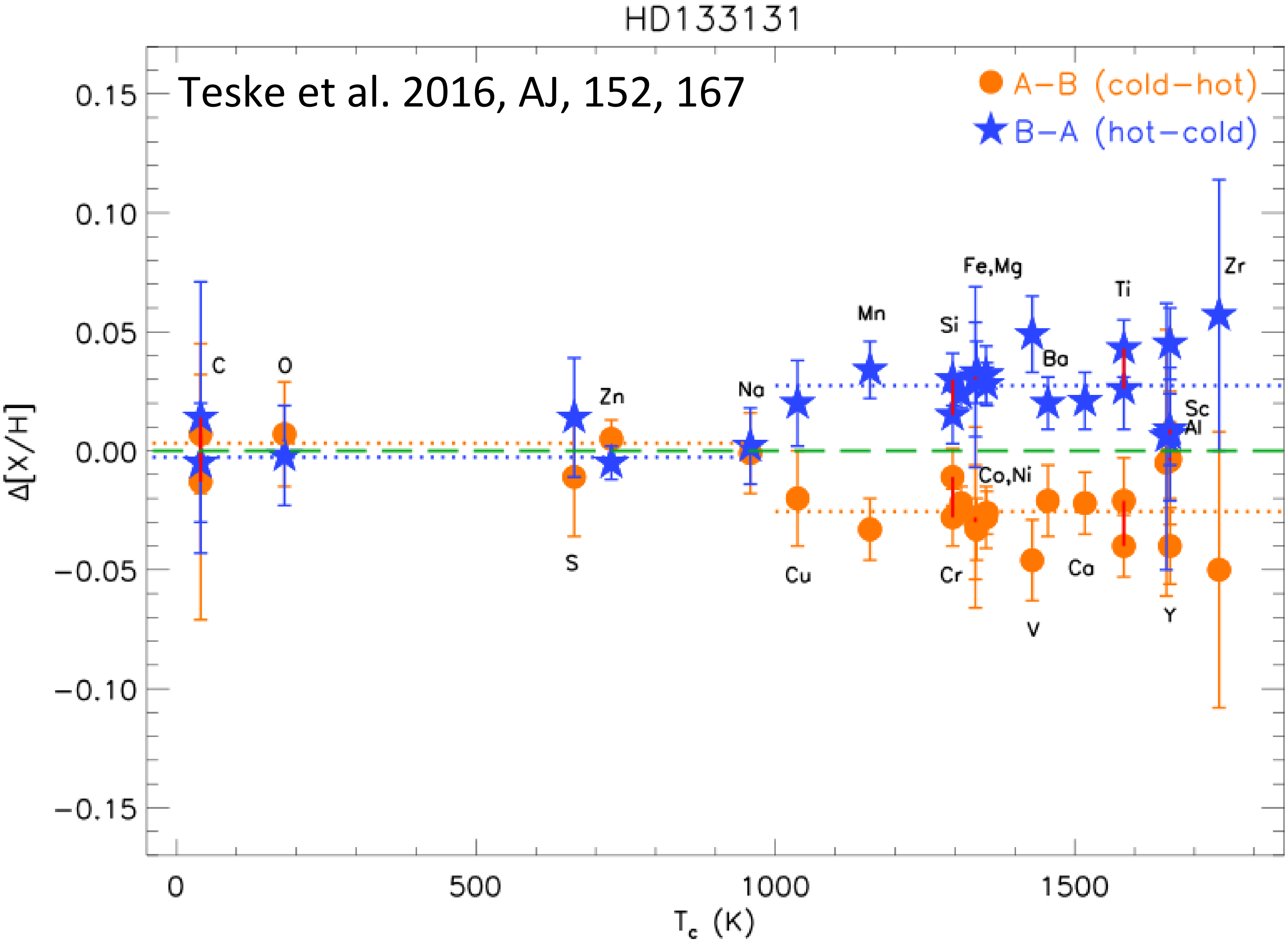
Trend with T_{cond} confirmed by Adibekyan et al. 2016

The Curious Case of Elemental Abundance Differences in the Dual Hot Jupiter Hosts WASP-94AB*

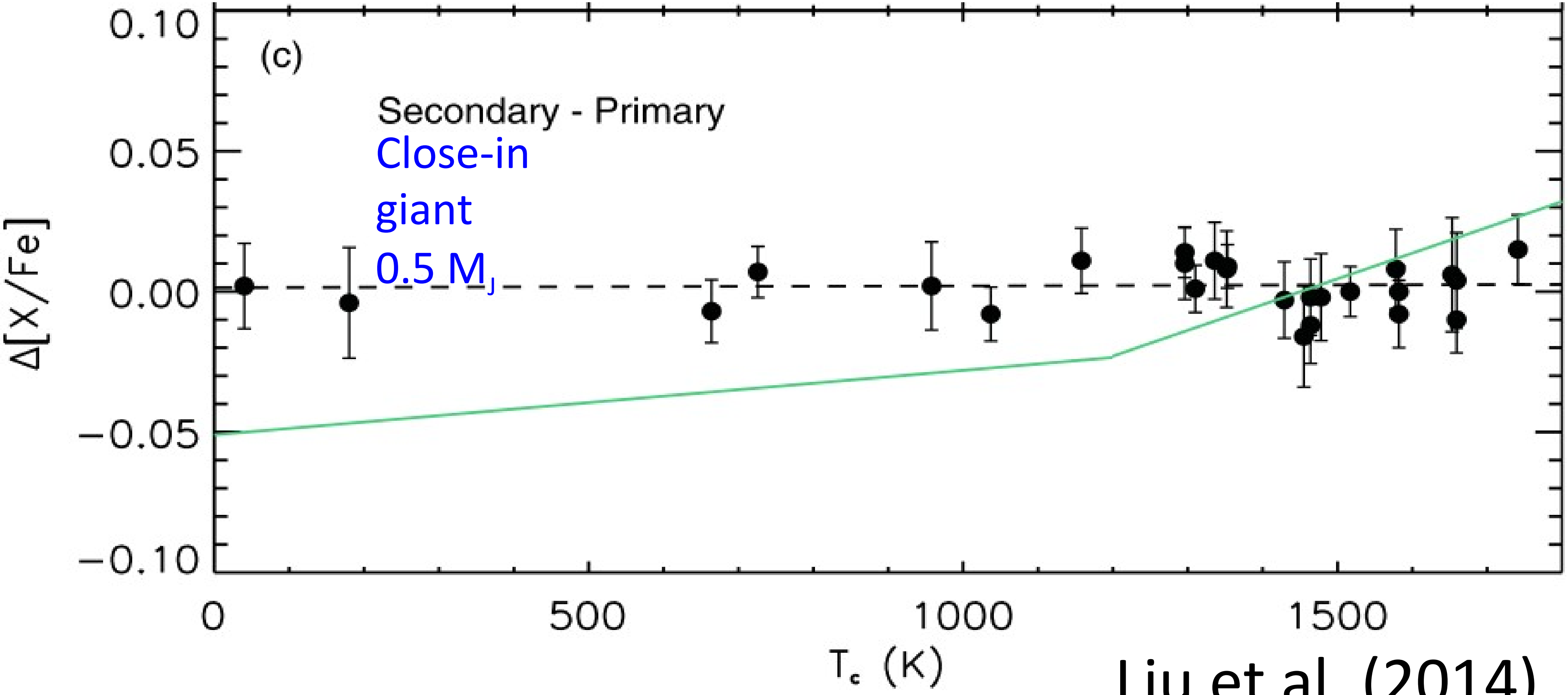
Johanna K. Teske[1,+], Sandhya Khanal[2], Ivan Ramírez[2]



The Magellan PFS Planet Search Program: Radial Velocity and Stellar Abundance Analyses of the 360 AU, Metal-Poor Binary "Twins" HD 133131A & B†



Negative results: HAT P-1 binary



Liu et al. (2014)

Also negative results for **HD80606** + HD80607 (Mack et al. 2016; Safe et al. 2015)

Evidence of rocky planet engulfment in the wide binary system HIP 71726/HIP 71737

Jhon Yana Galarza [1,2] Ricardo López-Valdivia [3] Jorge Meléndez [1] and Diego Lorenzo-Oliveira [1]

arXiv:2109.00679

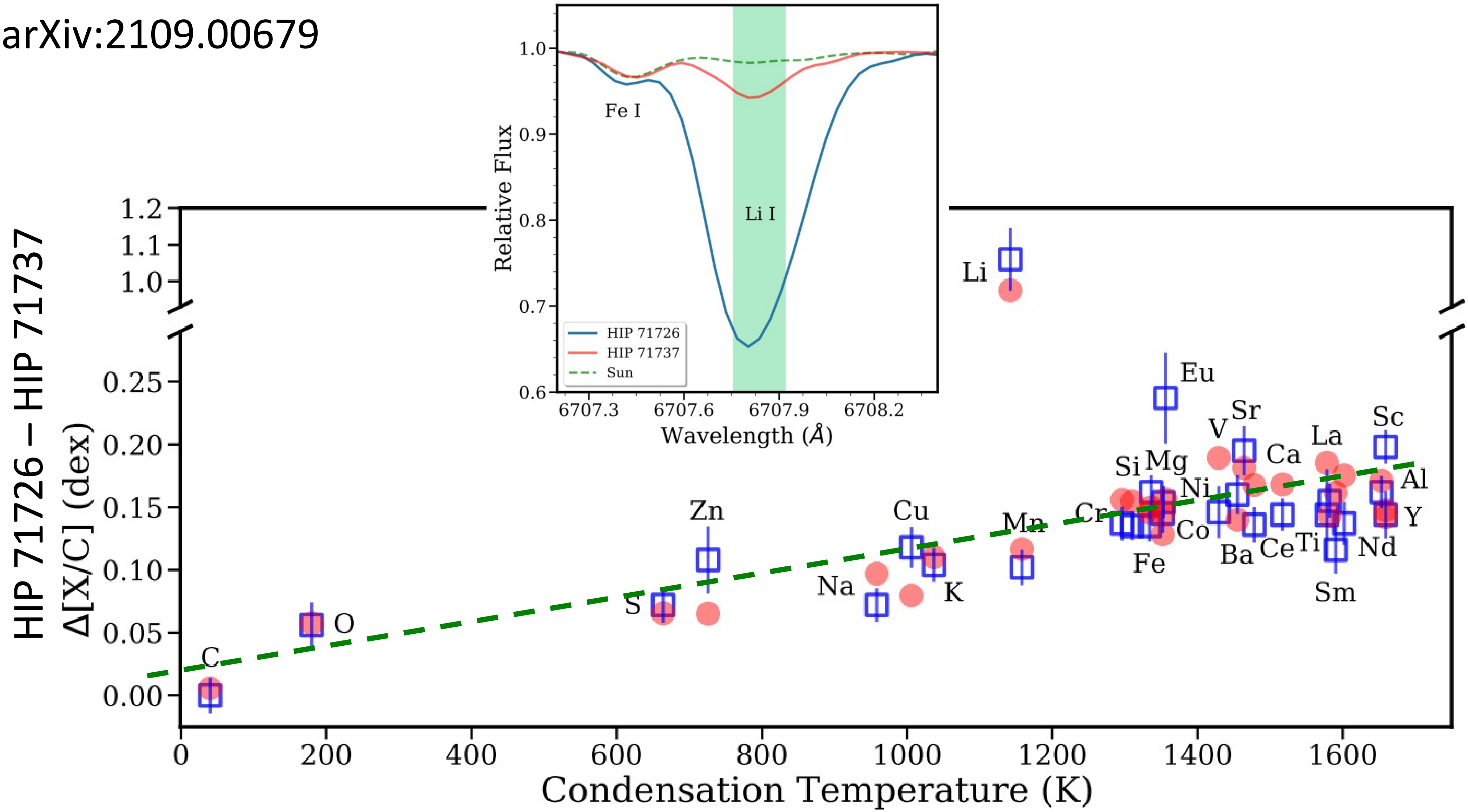


Figure 3. Comparison of the abundances of HIP 71726 relative to HIP 71737 (blue squares) as a function of dust condensation temperature, and the predicted abundances (red circles) estimated from a planetary engulfment of $9.8^{+2.0}_{-1.6}$ $M_{\oplus}$.

Trends between abundances and stellar ages

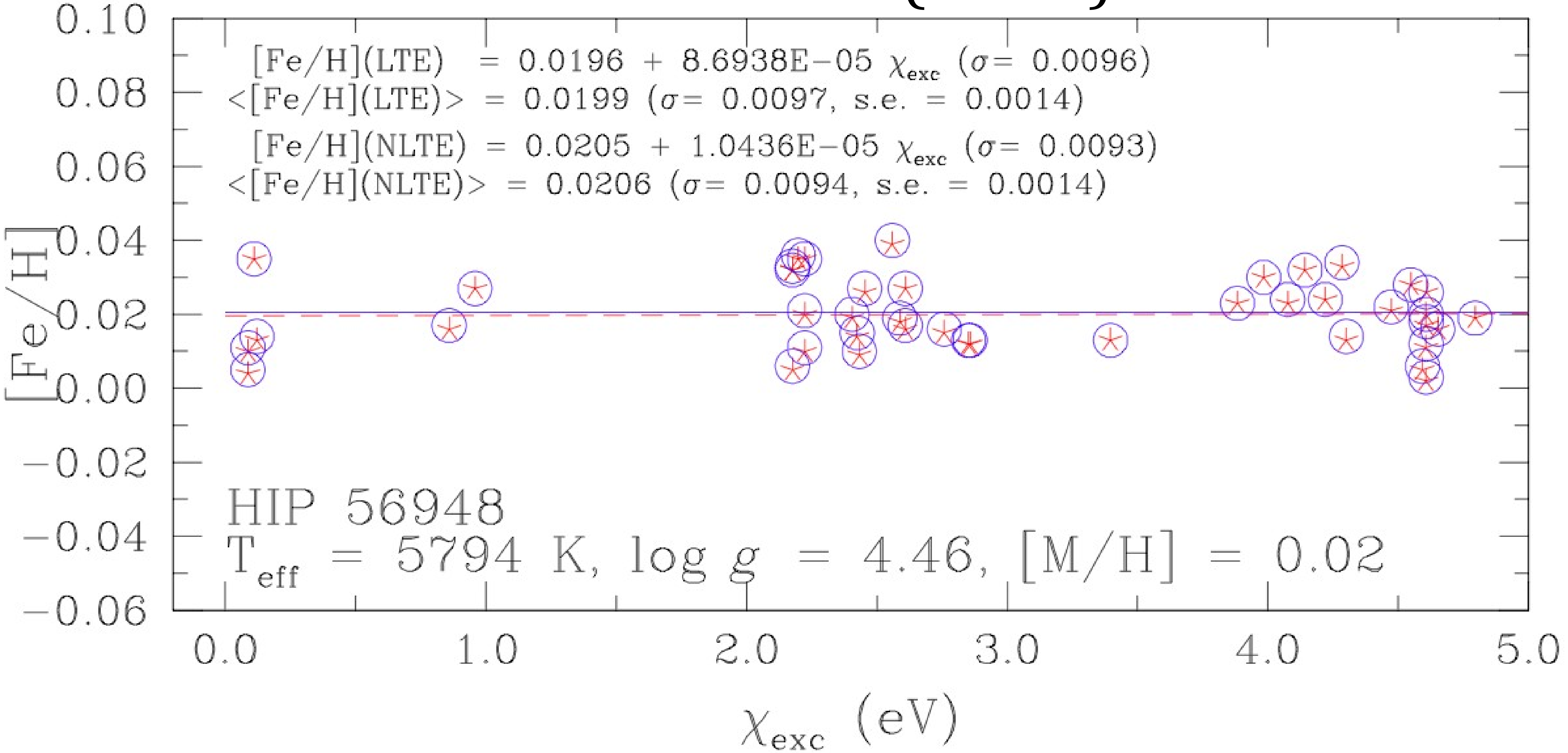
(important for stellar evolution & galactic chemical evolution)

Precise abundances are important to obtain precise stellar parameters

HIP 56948

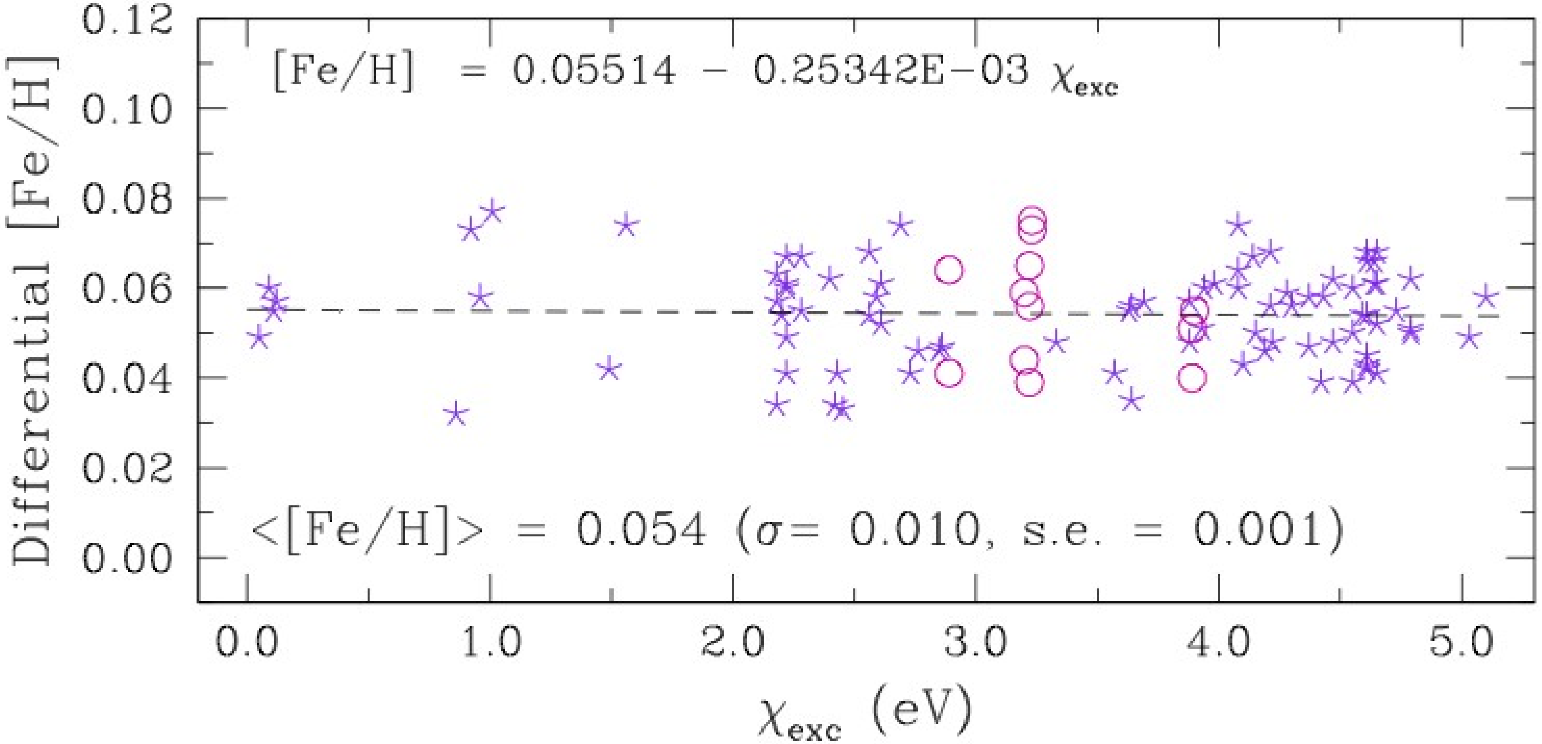
σ (LTE) = 0.0096 dex

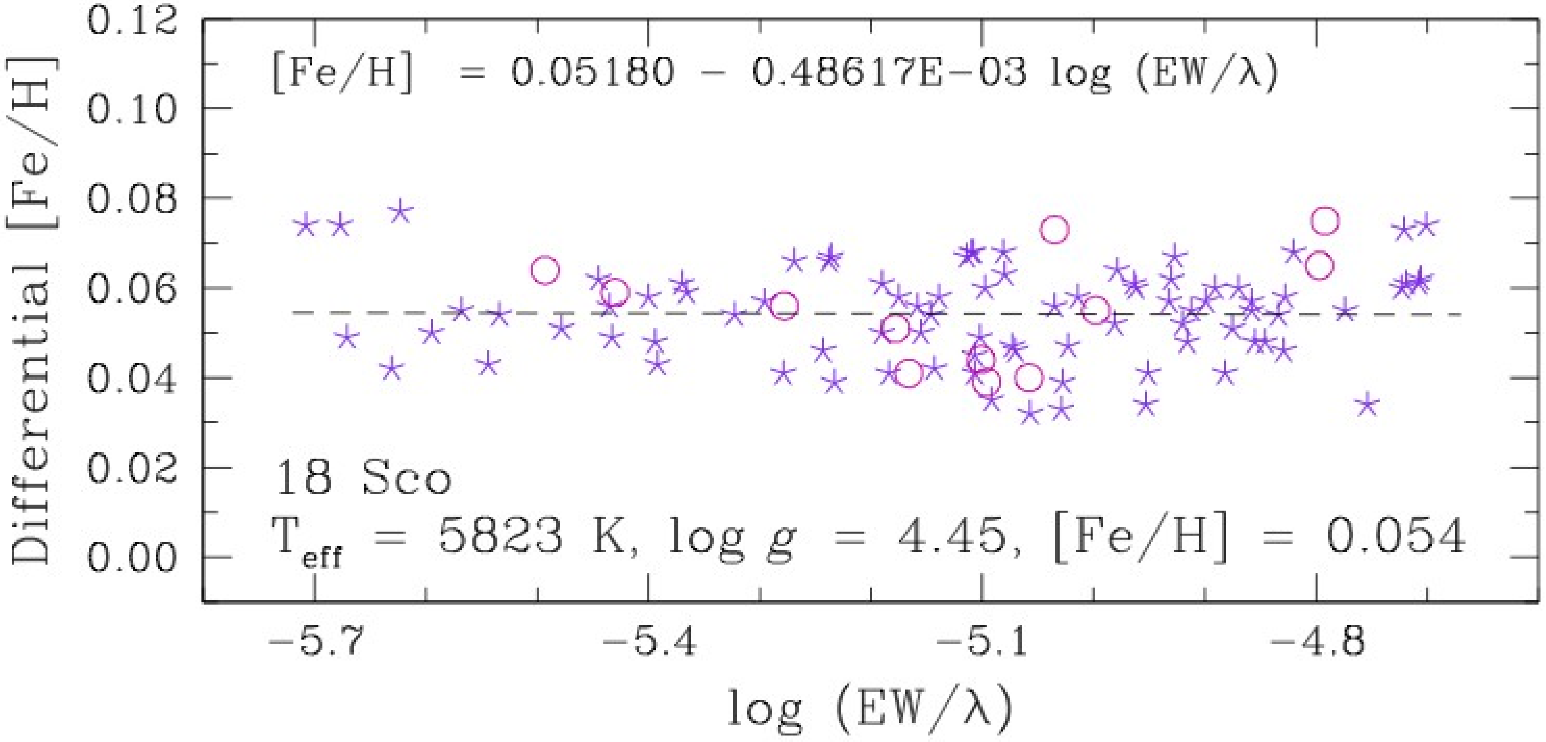
σ (NLTE) = 0.0093 dex



18 Sco
$\sigma = 0.010$ dex

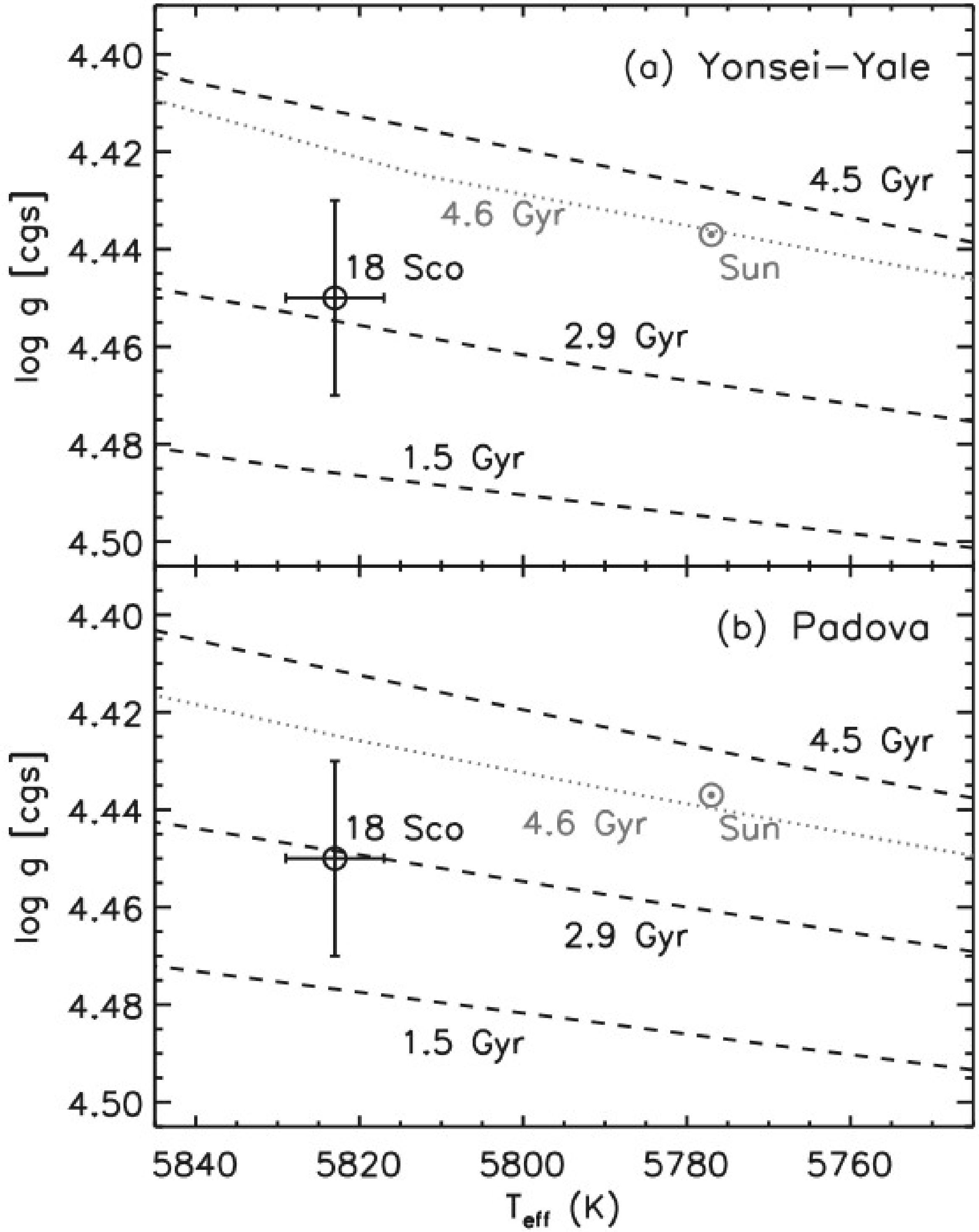
Precise abundances are important to obtain precise stellar parameters



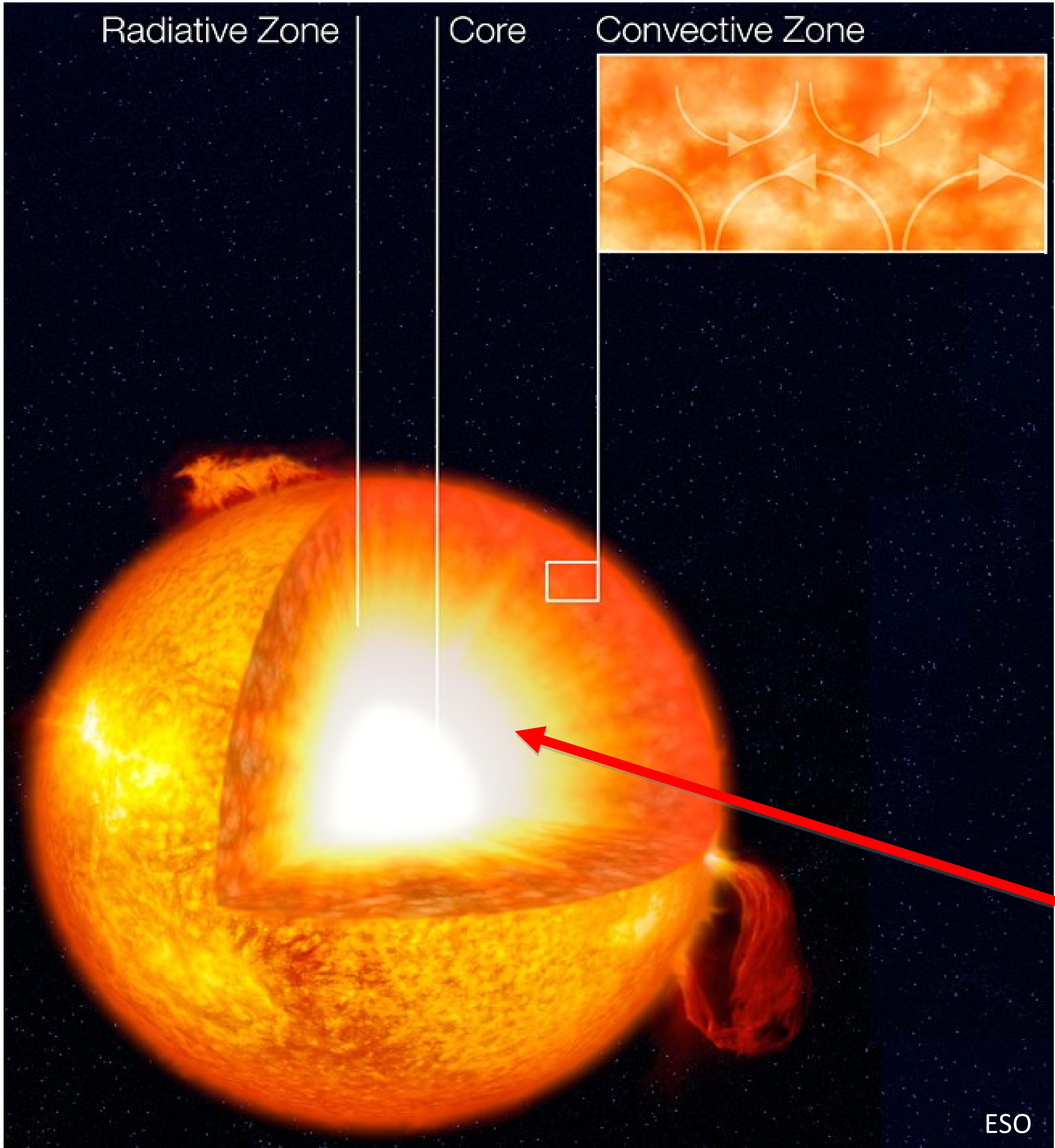


Precise stellar parameters
(**Δ Teff ≤ 10 K, Δ log g ≤ 0.02 dex**)

→ **good stellar masses and ages**

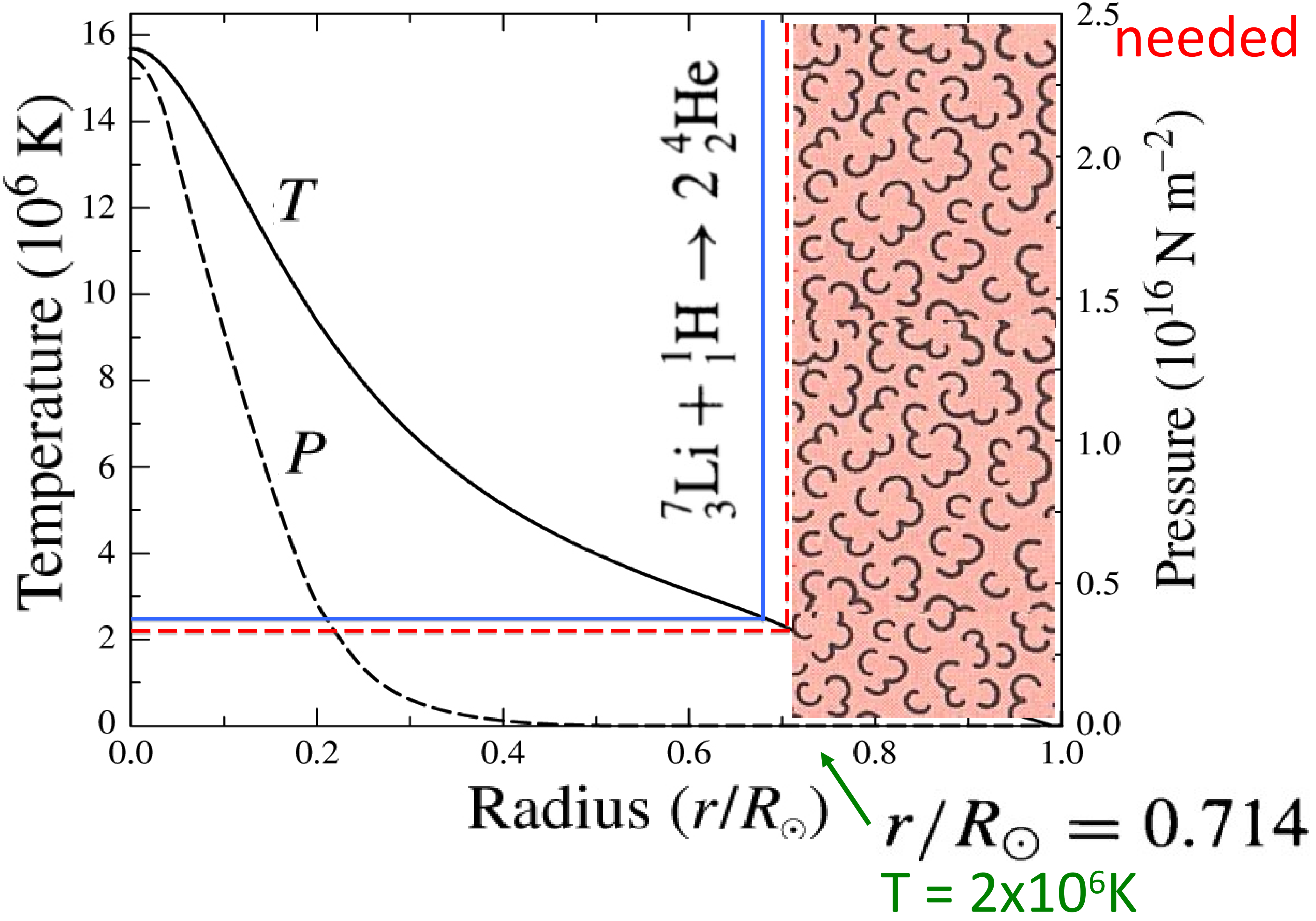


The solar lithium problem



- The solar Li is about 160 times lower than in meteorites.
- *Li burns at 2.5 10^6 K; **below** the convection zone: no depletion in the photosphere!*

Lithium burns at T = 2,5x10⁶K. Extra mixing needed



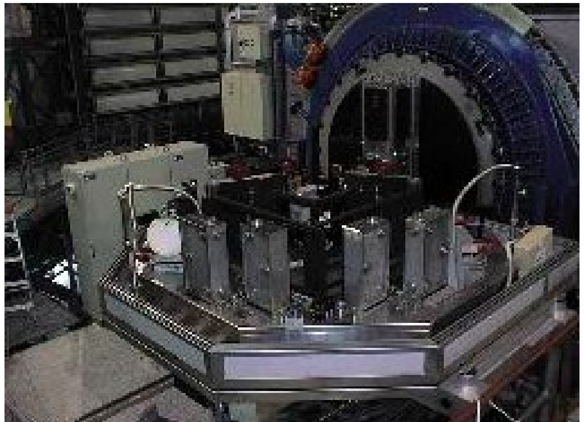
High quality spectra needed to study Li!

VLT + UVES

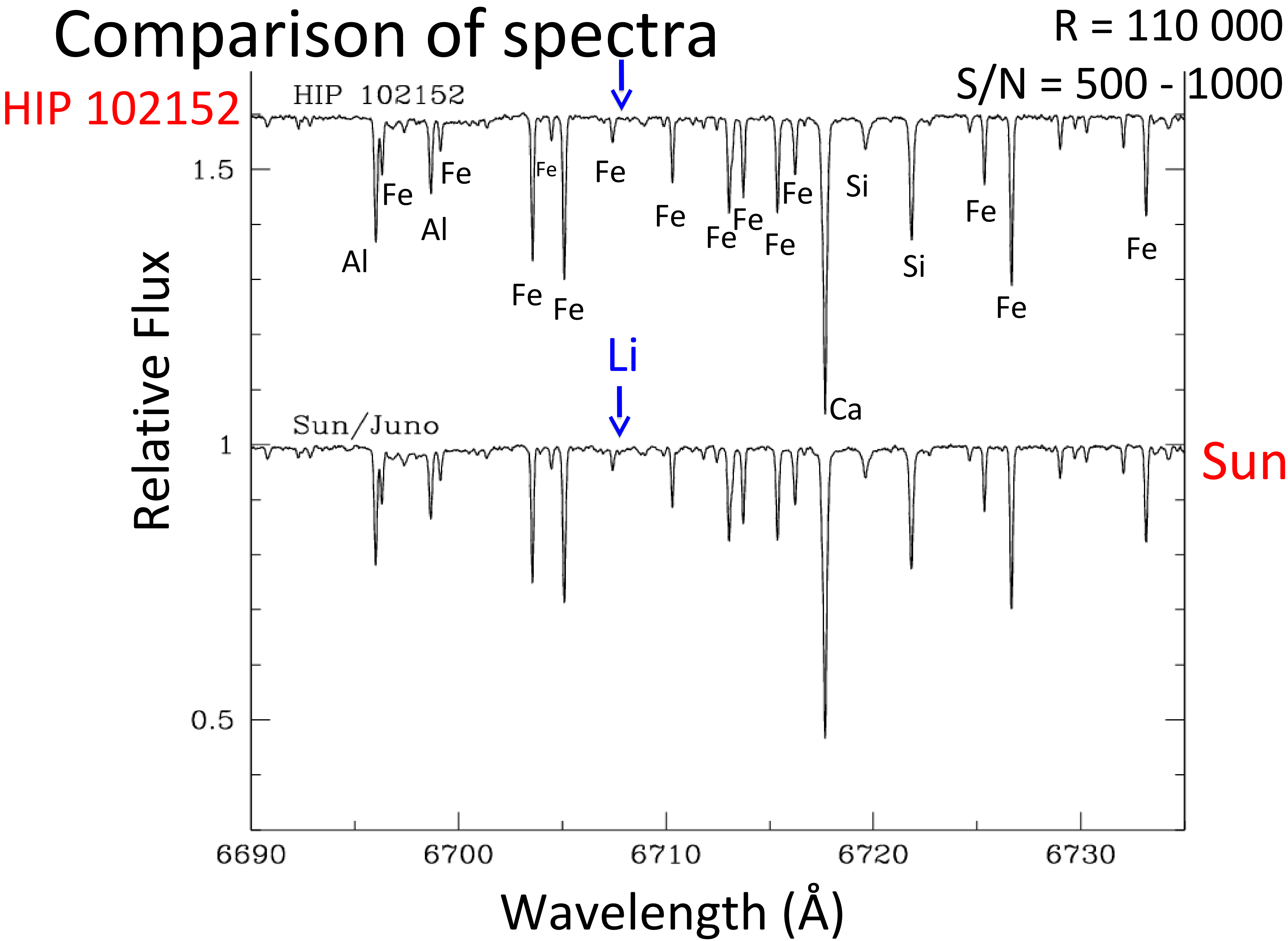
R = 110 000, S/N ~ 500 - 1000 at the Li feature

Very Large Telescope, 8 meters (Paranal)

UVES spectrograph

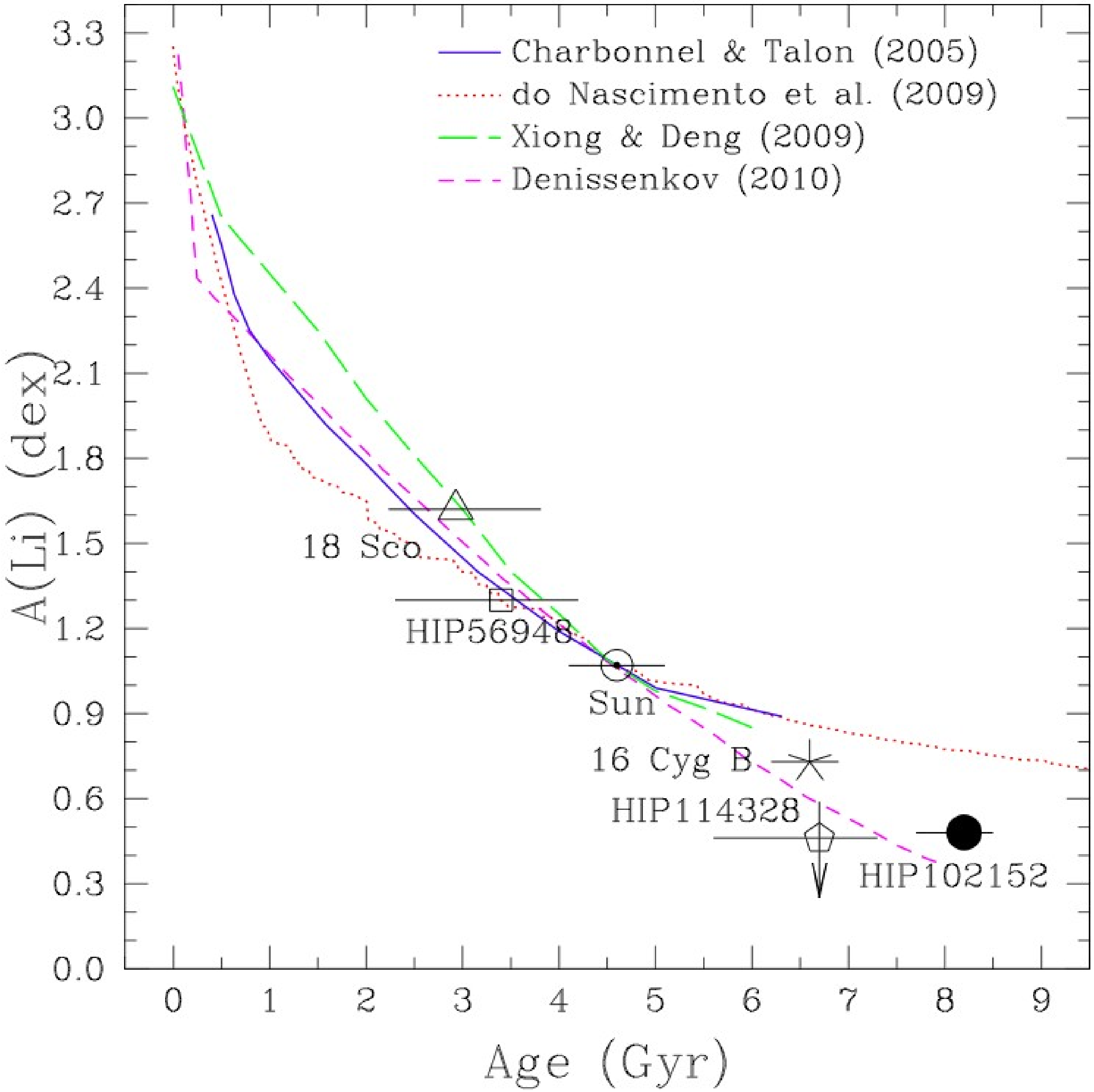


Comparison of spectra



Lithium-age correlation in solar twins.

Li depletion increases with age

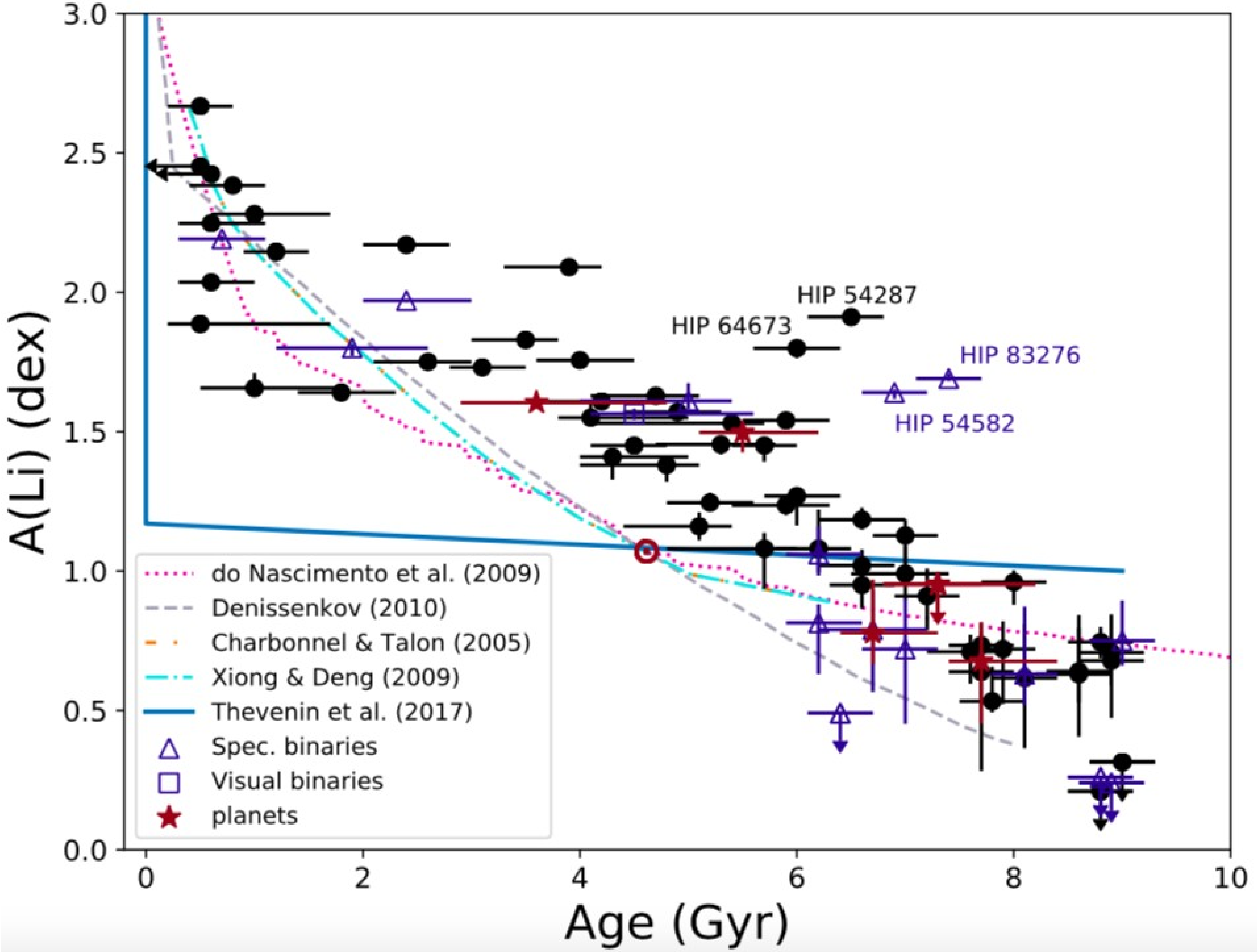


A&A 567, L3 (2014)
DOI: 10.1051/0004-6361/201424172

HIP 114328: a new refractory-poor and Li-poor solar twin*,**

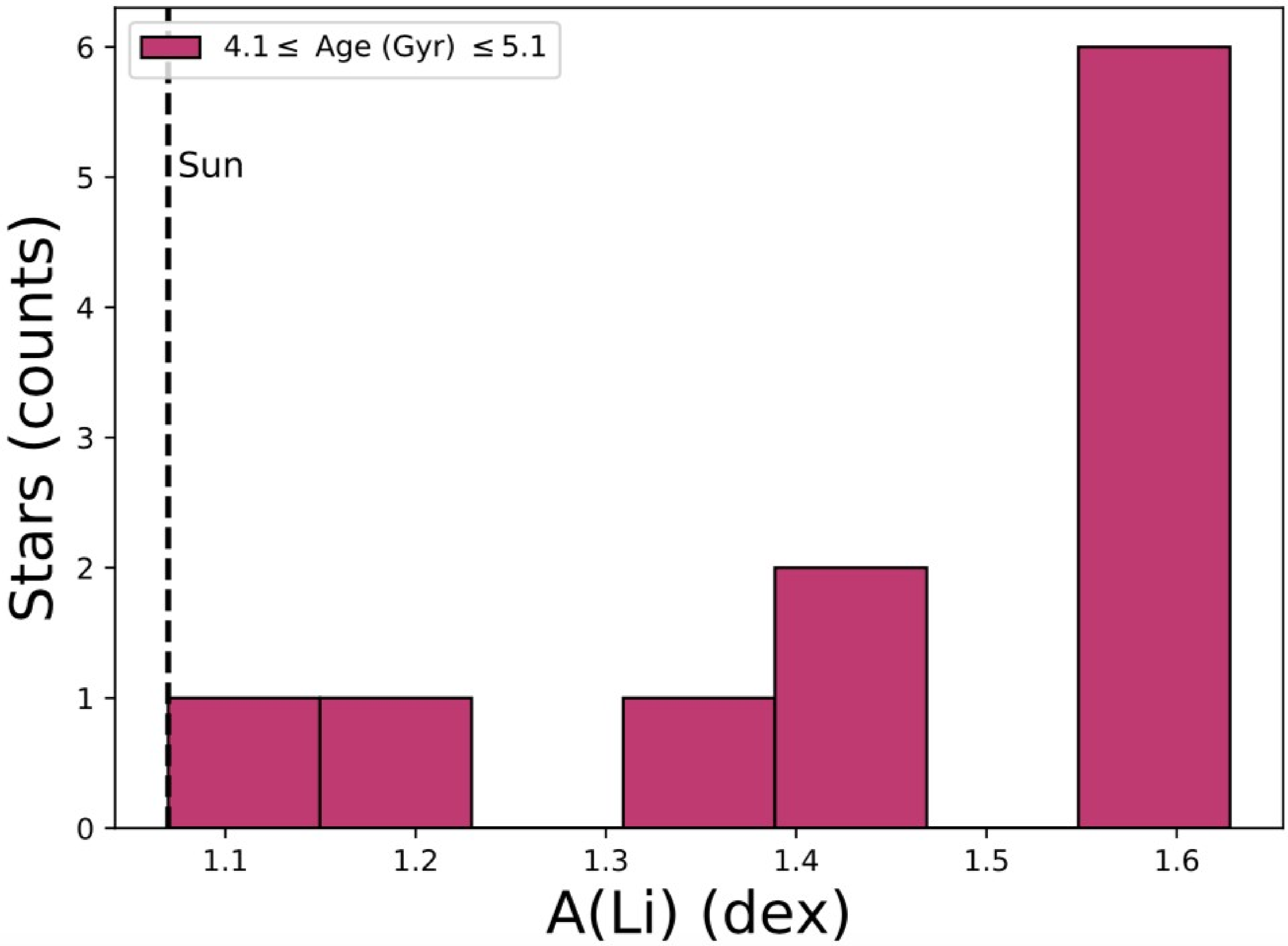
Jorge Meléndez[1], Lucas Schirbel[1], TalaWanda R. Monroe[1], David Yong[2], Iván Ramírez[3], and Martin Asplund[2]

Sun is lithium-poor relative to solar twins!



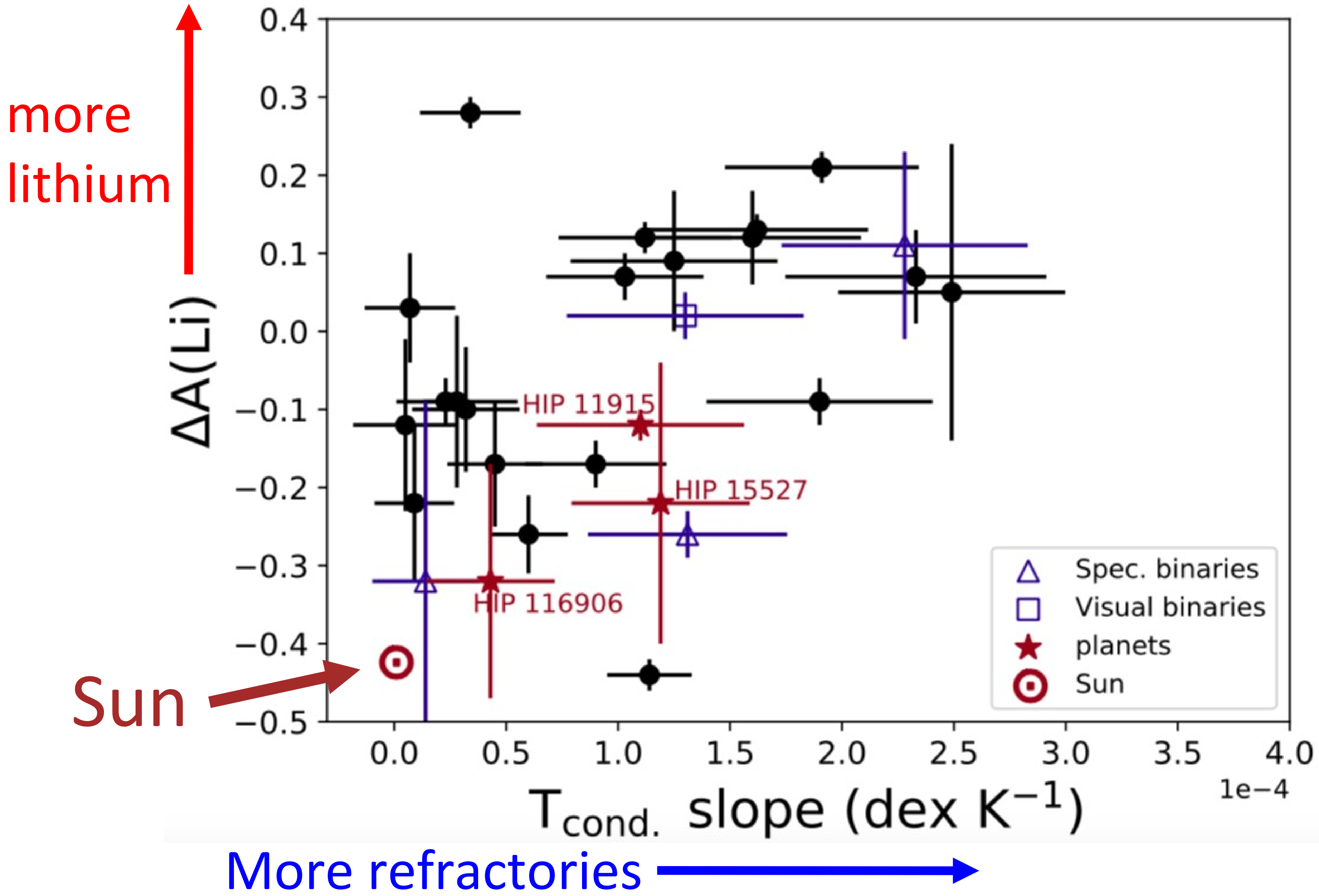
Marília Carlos et al. 2019

The Sun is the star with the lowest lithium among solar twins with solar age (4.6 ± 0.5 Gyr)

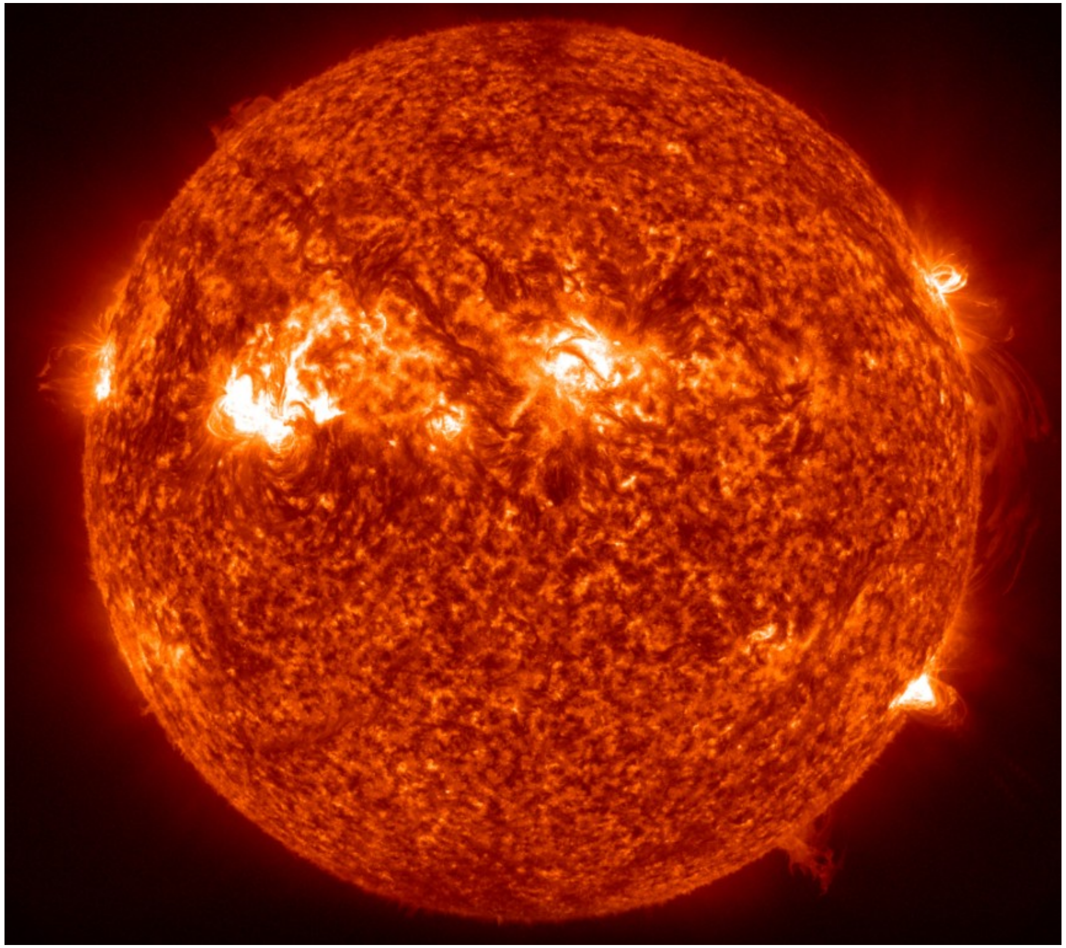


Marília Carlos et al. 2019

Interestingly, stars more depleted in lithium seem less abundant in refractory elements!



The effect of magnetic activity on chemical abundances and stellar parameters



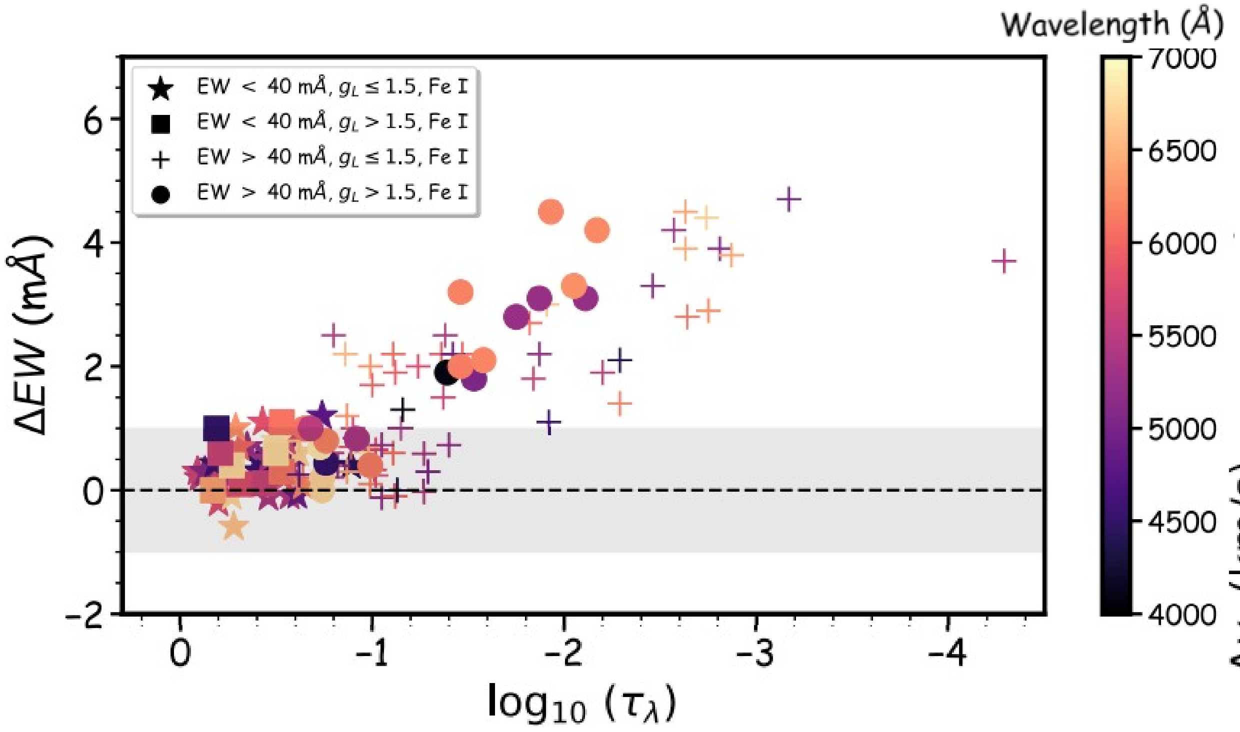
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **490,** L86–L90 (2019) doi:10.1093/mnrasl/slz153

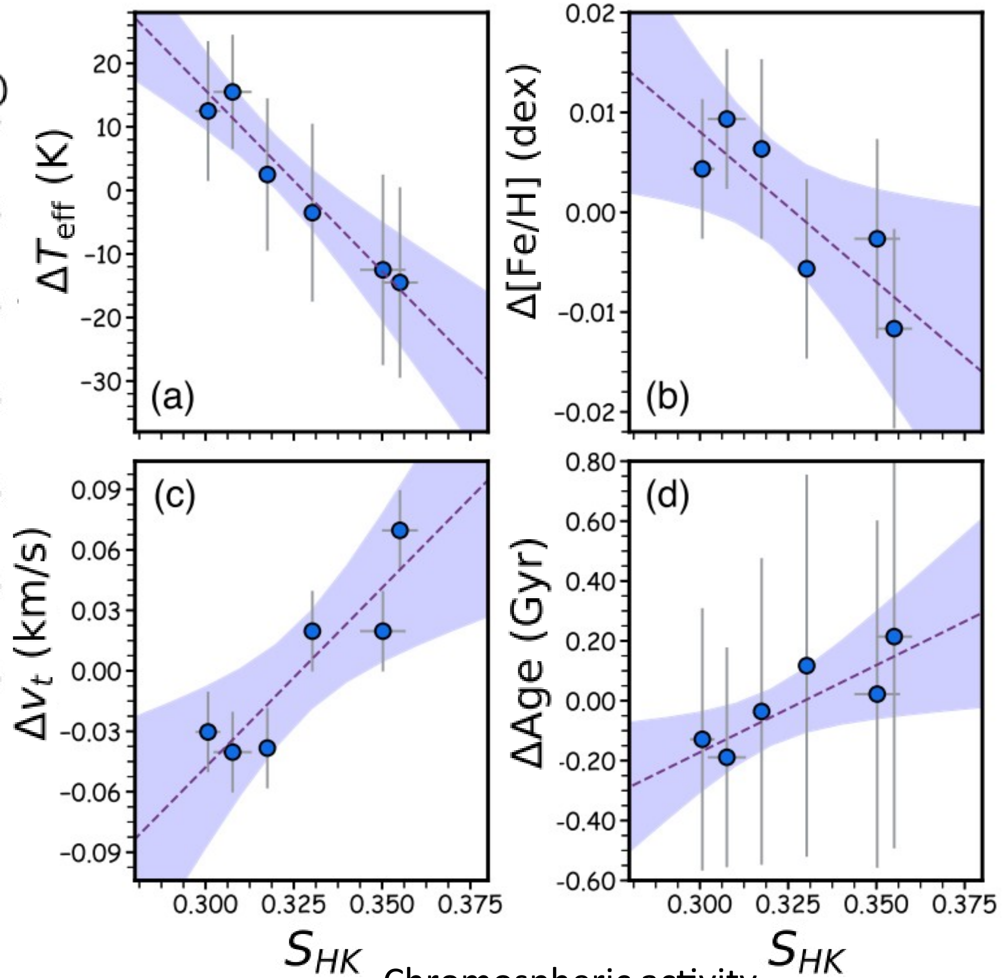
The effect of stellar activity on the spectroscopic stellar parameters of the young solar twin HIP 36515

Data: HARPS spectra at different phases of stellar activity

Jhon Yana Galarza,[1★] Jorge Meléndez,[1★] Diego Lorenzo-Oliveira,[1★] Adriana Valio,[2] Henrique Reggiani,[1] Marília Carlos,[1] Geisa Ponte,[2,3] Lorenzo Spina,[4] Raphaëlle D. Haywood[5†] and Davide Gandolfi[6]



Optical depth of line formation in the atmosphere for Fe I lines

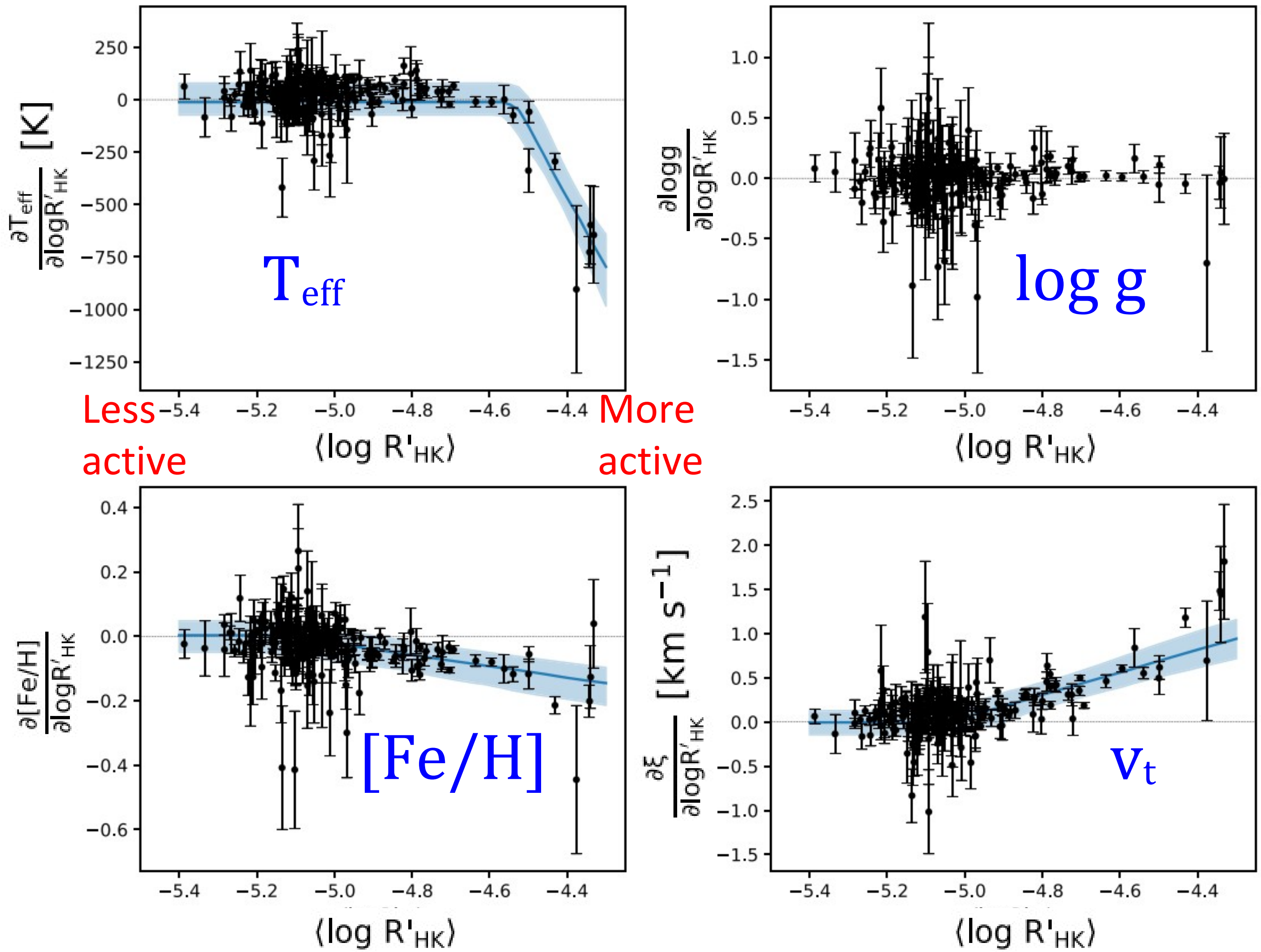


Chromospheric activity

The Astrophysical Journal, 895:52 (14pp), 2020 May 20 https://doi.org/10.3847/1538-4357/ab8bd7

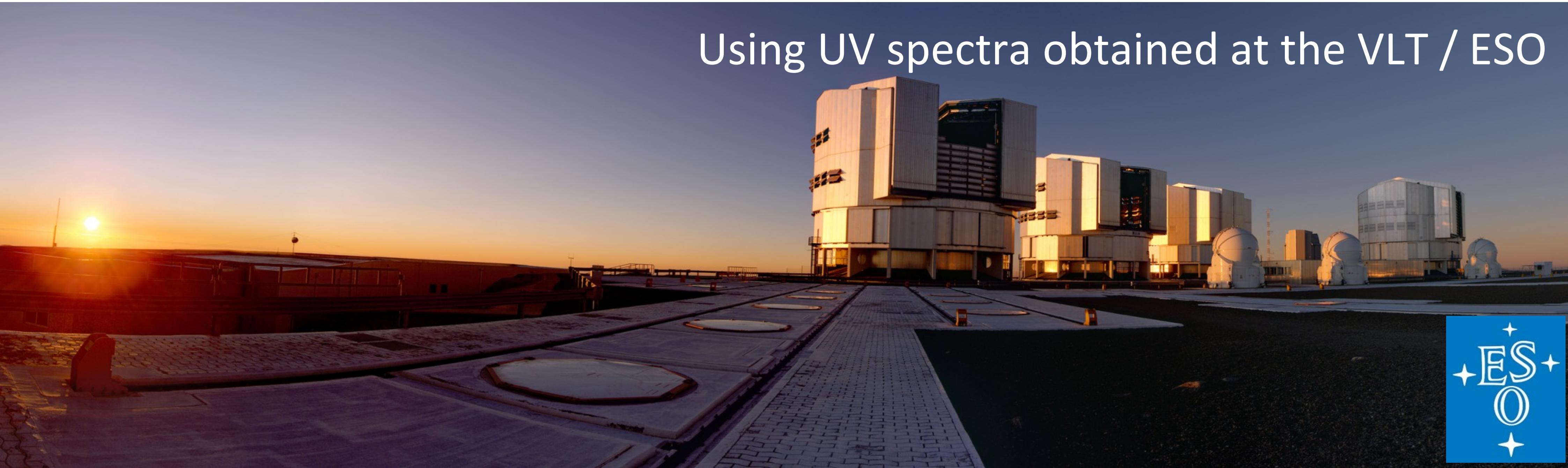
How Magnetic Activity Alters What We Learn from Stellar Spectra

Lorenzo Spina[1,2], Thomas Nordlander[2,3], Andrew R. Casey[1,2], Megan Bedell[4], Valentina D'Orazi[5], Jorge Meléndez[6], Amanda I. Karakas[1,2], Silvano Desidera[5], Martina Baratella[5,7], Jhon J. Yana Galarza[6], and Giada Casali[1,8,9]

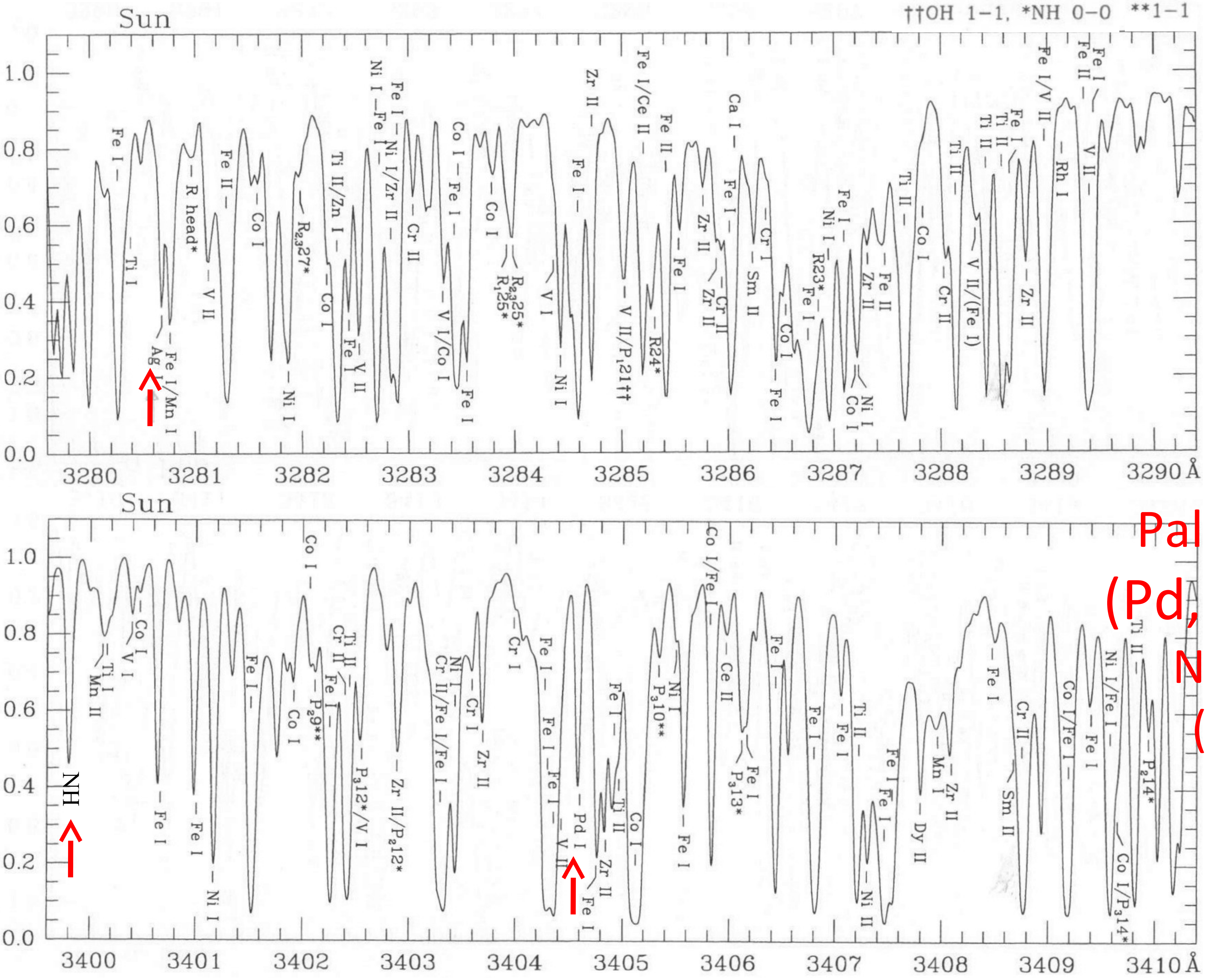


Galactic Chemical Evolution

High precision abundances in 18 Sco:
a solar twin rich in refractories and neutron-capture elements



UV Atlas of the Arcturus (and Solar) Spectrum 1150-3800 A, Hinkle et al. 2005



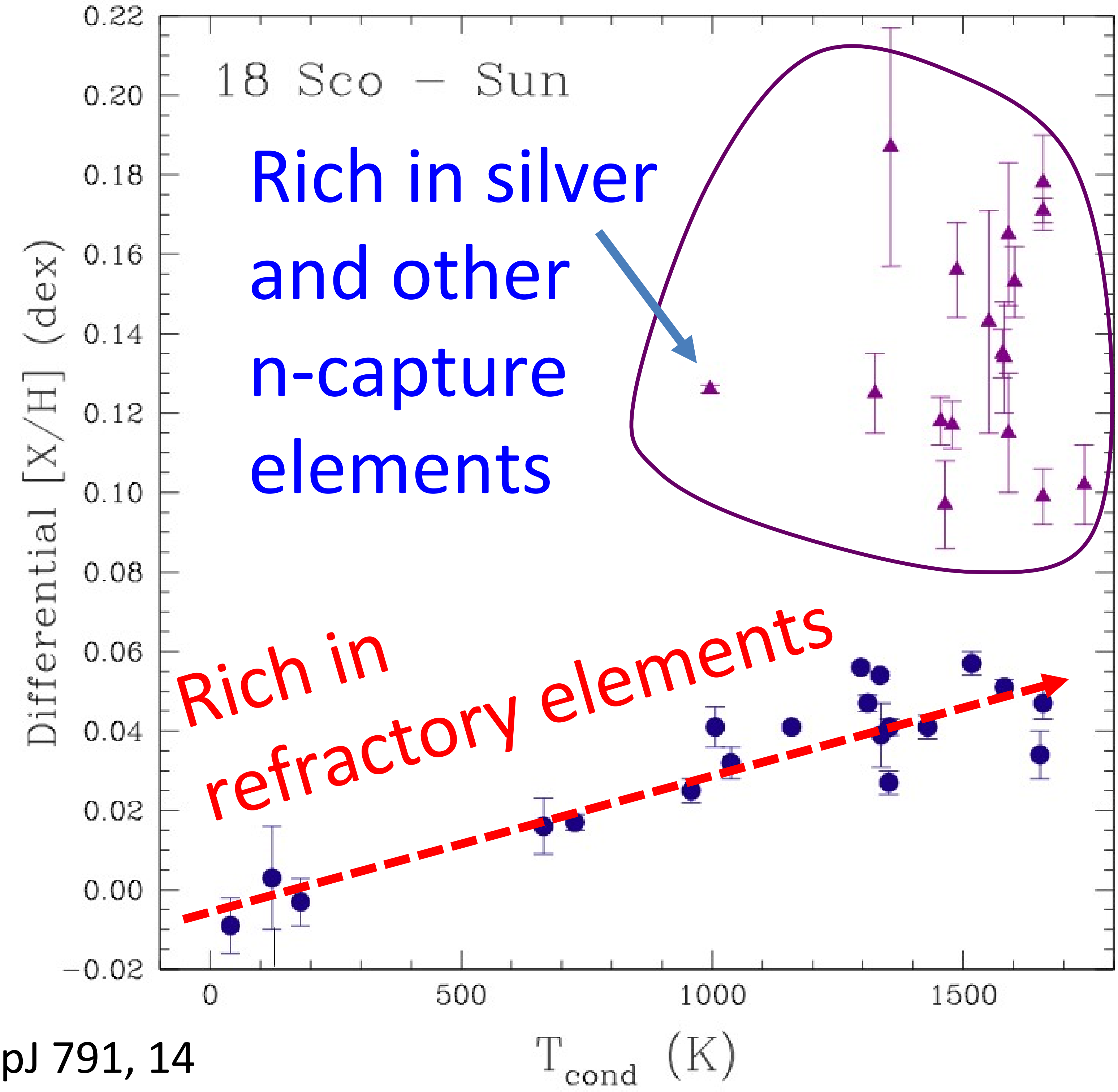
Silver (Ag, Z=47) in the Sun

Palladium (Pd, Z=46)

Nitrogen (N, Z=7)

18 Sco

(brightest solar twin, V = 5.5)
UVES+VLT
R = 110 000 (red)
R = 65 000 (blue)



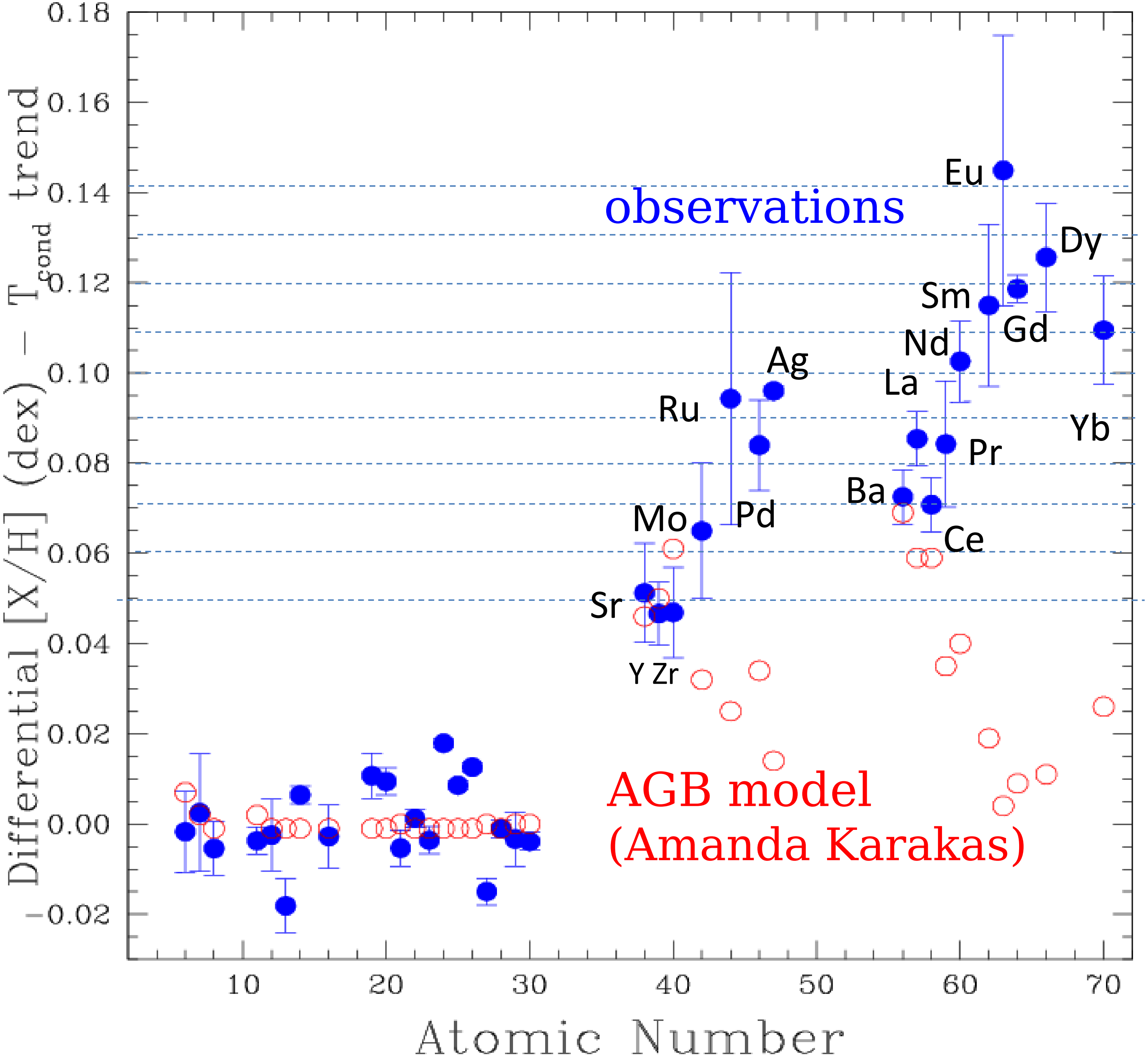
Age ~ 3 Gyr

Meléndez et al. 2014, ApJ 791, 14

18 Sco

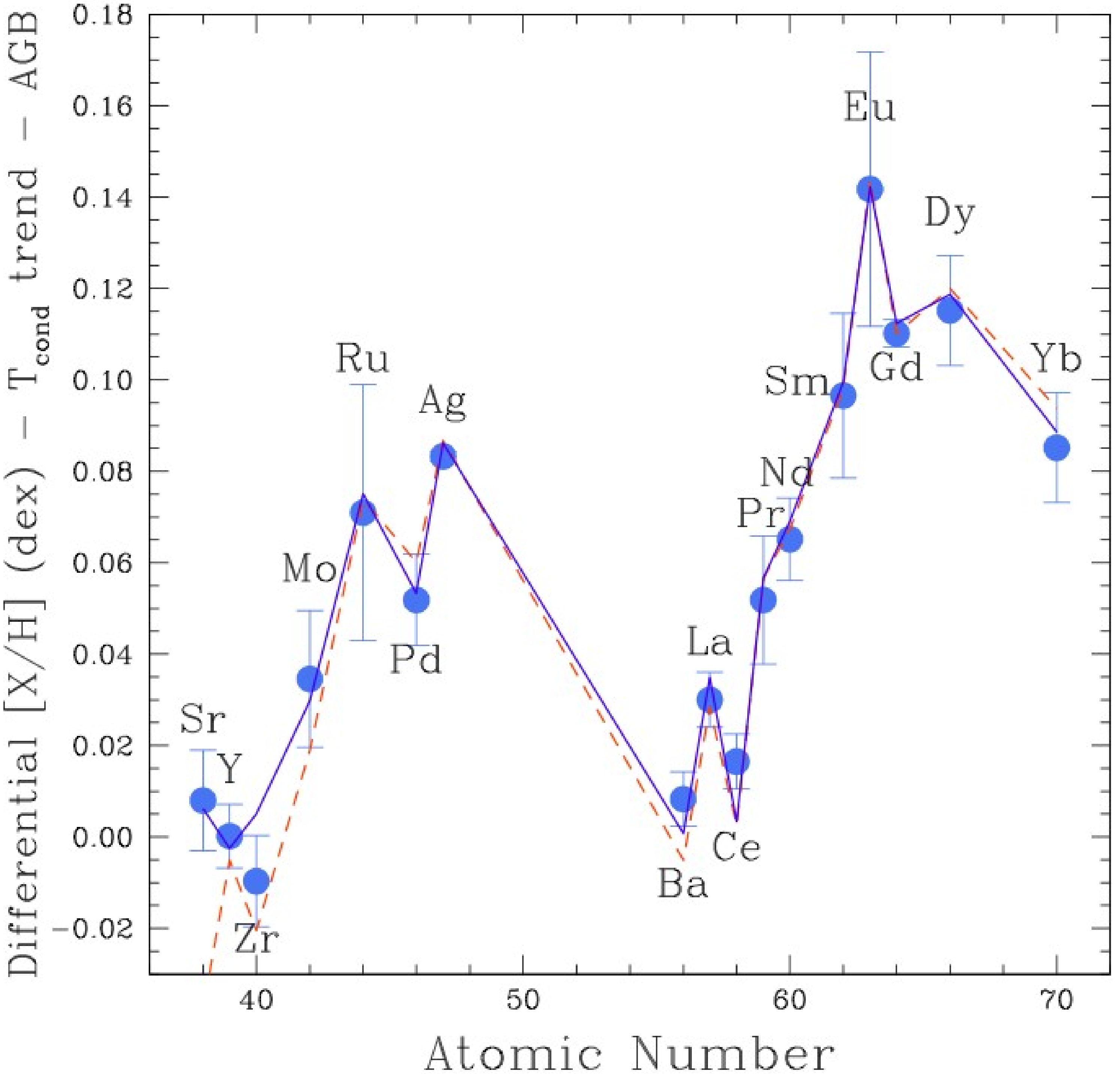
(brightest solar twin, V = 5.5)
UVES+VLT
R = 110 000
S/N = 800

Subtracting T_{cond} trend



Meléndez et al. 2014, ApJ

Perfect agreement between residual abundances and predictions from the SS r-process fractions

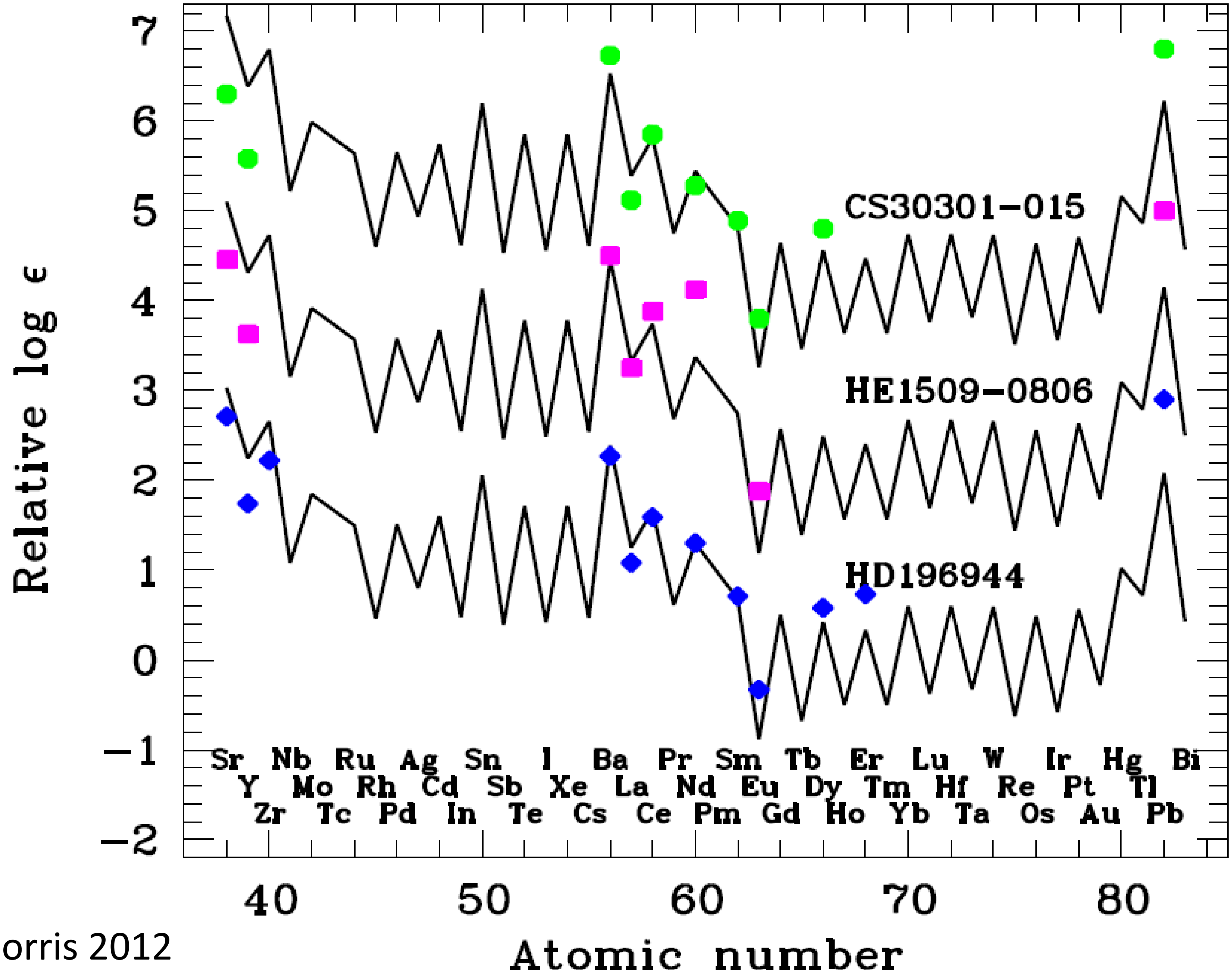


Meléndez et al. 2014, ApJ

Figure 10. Filled circles represent the [X/H] ratios in 18 Sco after they have been subtracted from the condensation temperature trend (Figure 8) and from the AGB contribution (Figure 9). The residual enhancement, $[X/H]_r$ (filled circles), is in extraordinary agreement with the predicted *r*-process enhancement based on the solar system *r*-process fractions by Simmerer et al. (2004) and Bisterzo et al. (2011, 2013), represented by dashed and solid lines, respectively.

r-processs in metal-poor stars is “easy” (~ 0.5 – 1.0 dex)

Differential r-process in solar twin 18 Sco: ~ 0.015-0.02 dex



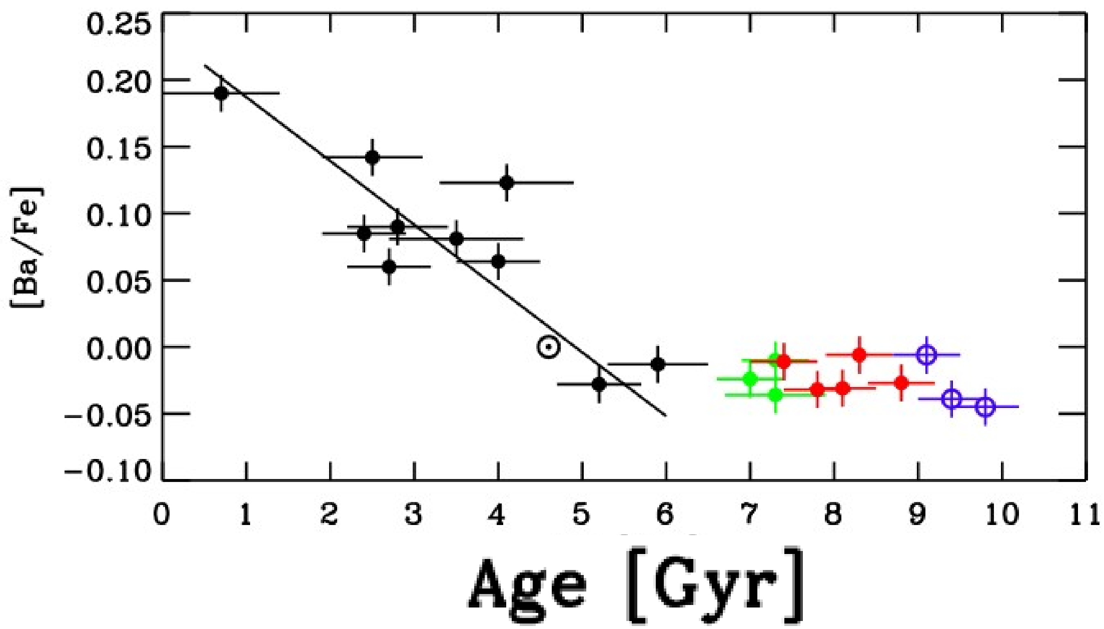
Frebel & Norris 2012

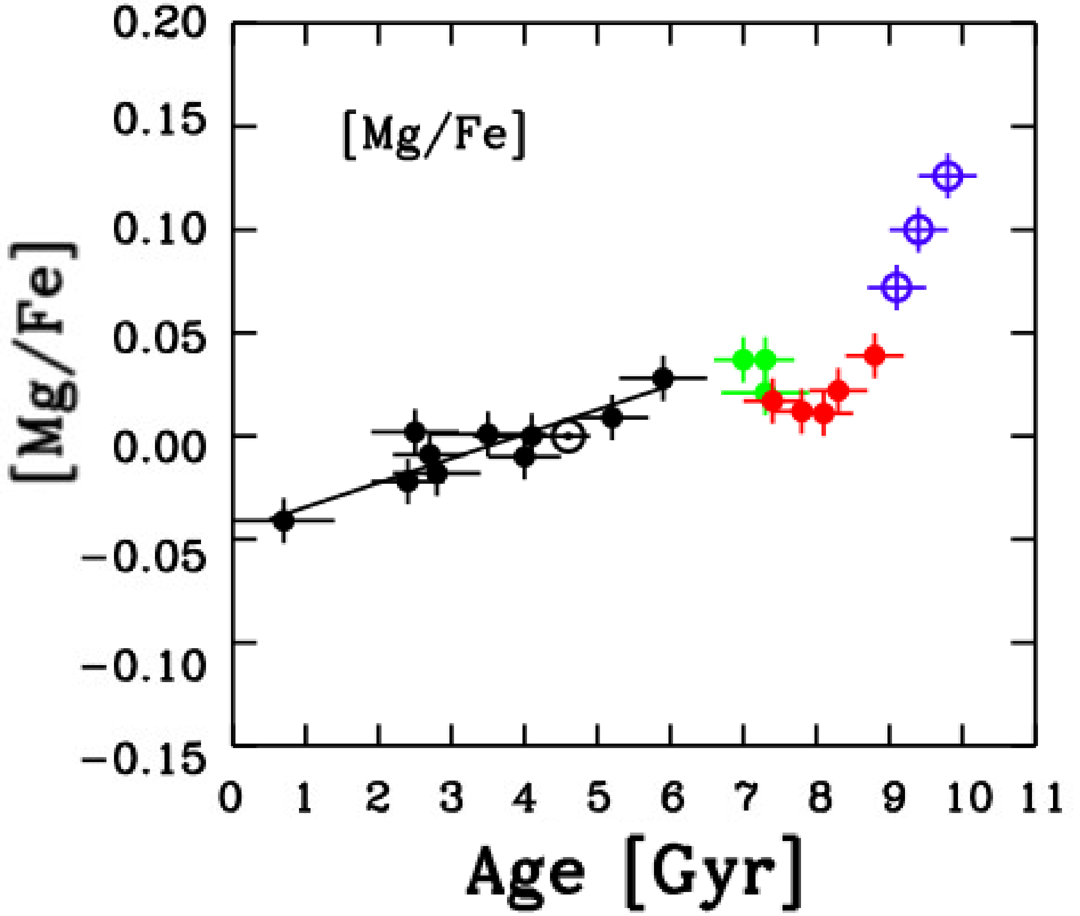
Abundance ratios as a function of age

High-precision abundances of Sc, Mn, Cu, and Ba in solar twins

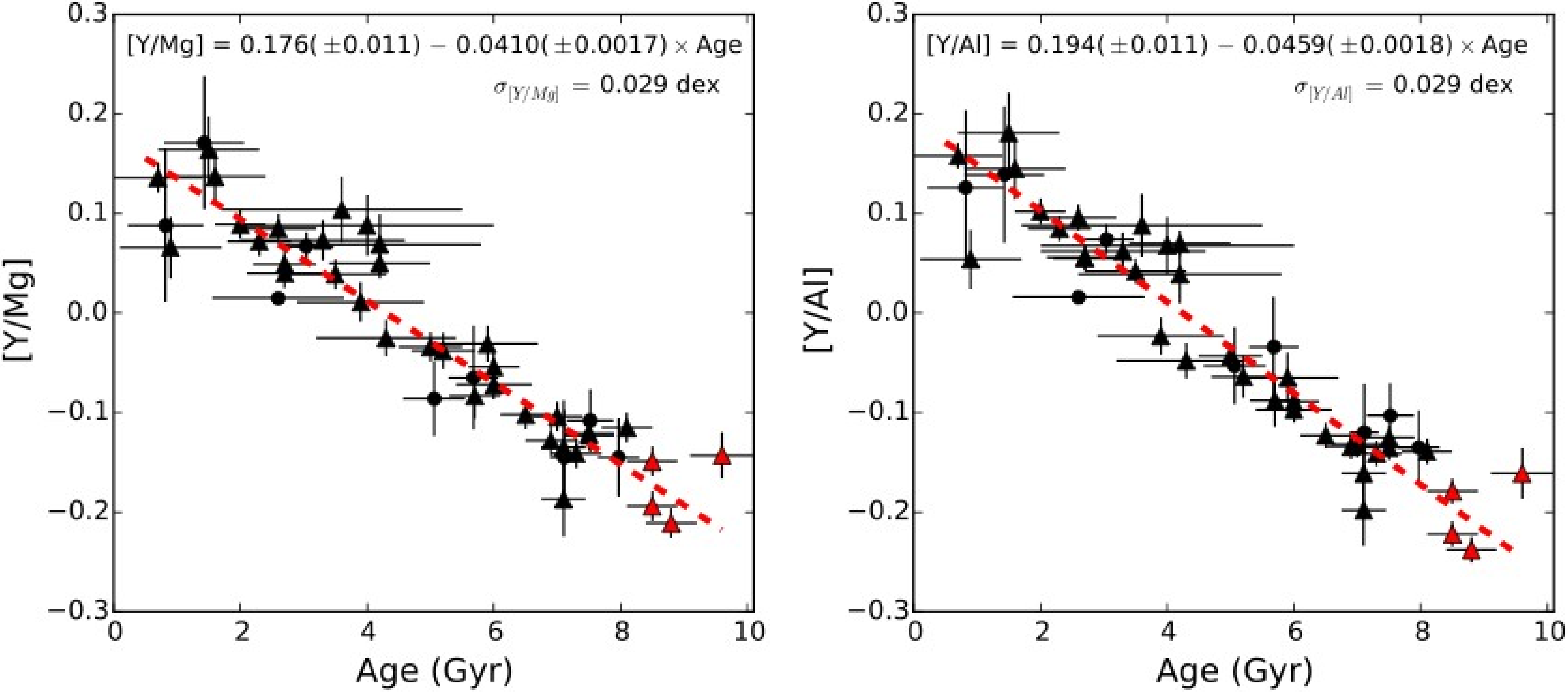
Trends of element ratios with stellar age ⋆

P. E. Nissen



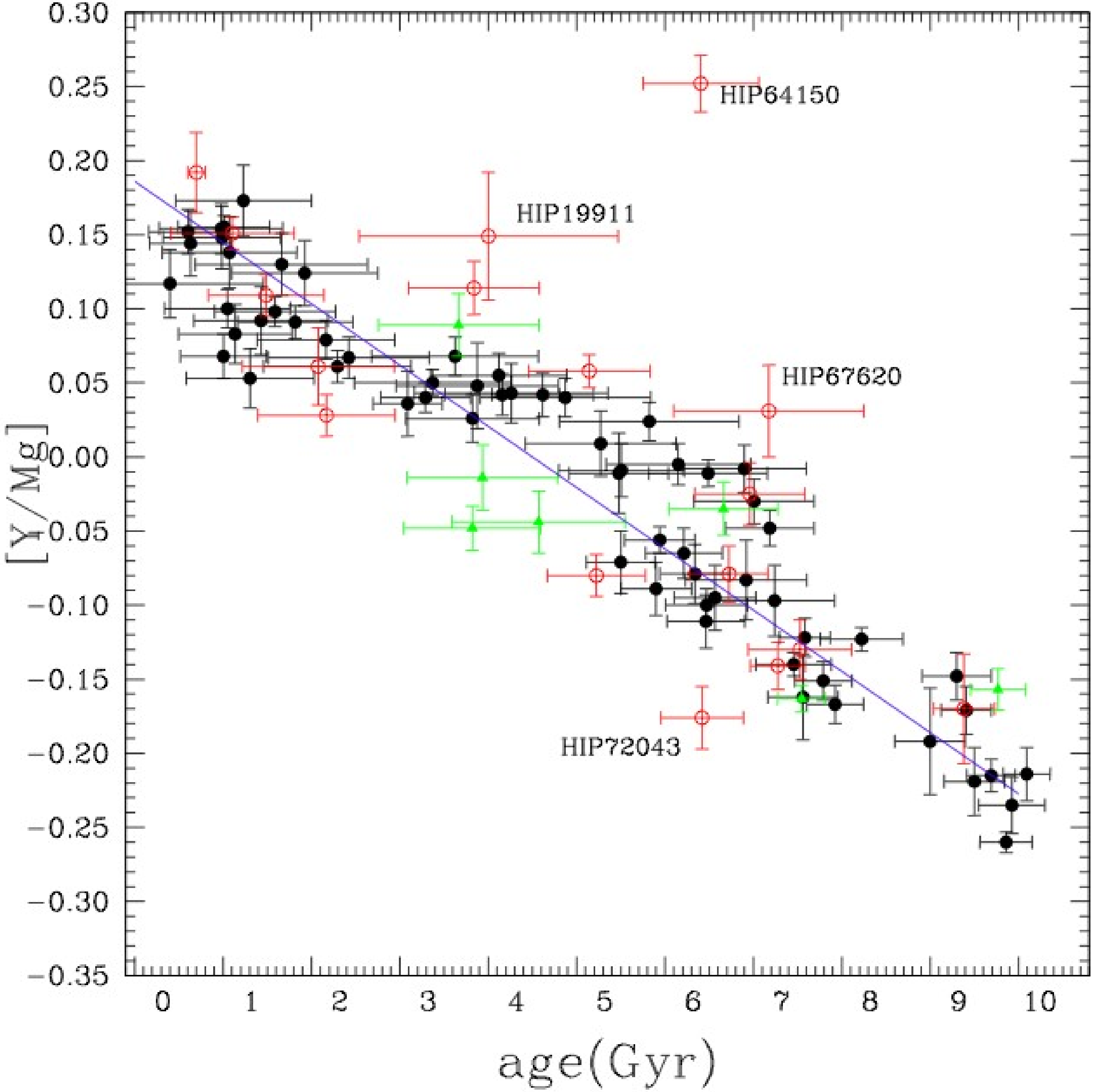


Spina et al. (2016): chemical clocks



Tucci-Maia et al. 2016

[Y/Mg] can also tell us about mass transfer in binaries



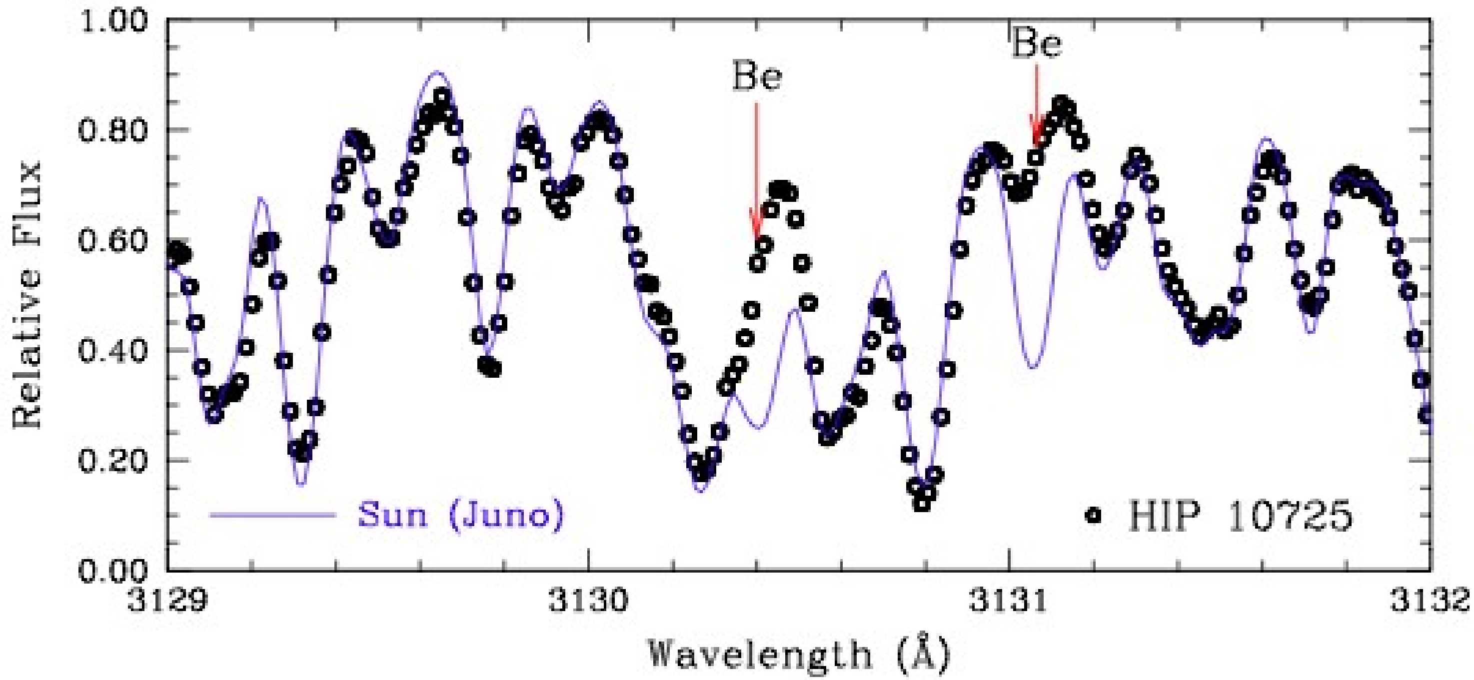
A&A 584, A116 (2015)
DOI: 10.1051/0004-6361/201527303

Astronomy & Astrophysics

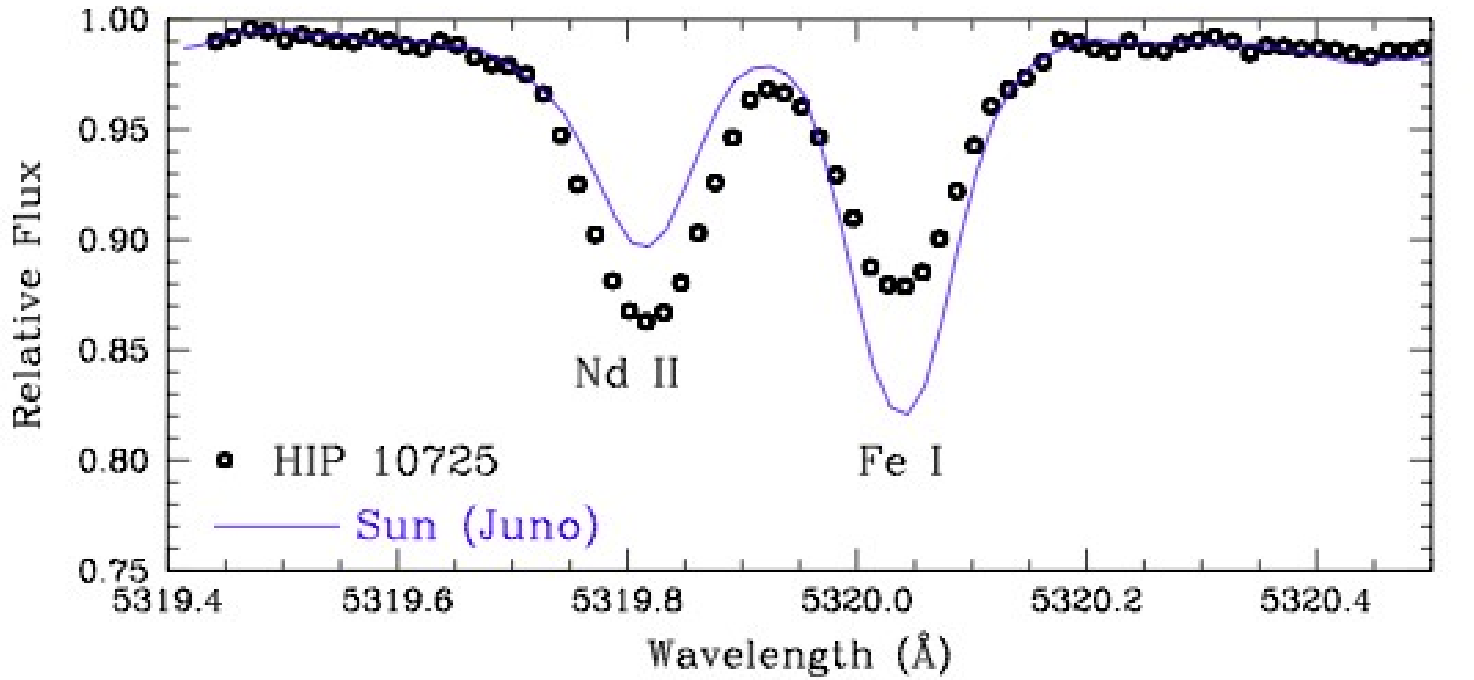
HIP 10725: The first solar twin/analogue field blue straggler⋆,⋆⋆

Lucas Schirbel[1], Jorge Meléndez[1], Amanda I. Karakas[2], Iván Ramírez[3], Matthieu Castro[4], Marcos A. Faria[5], Maria Lugaro[6], Martin Asplund[2], Marcelo Tucci Maia[1], David Yong[2], Louise Howes[2], and José D. do Nascimento Jr.[4,7]

The vast majority of solar twins have roughly solar Be abundances, but HIP 10725 is heavily depleted in Be

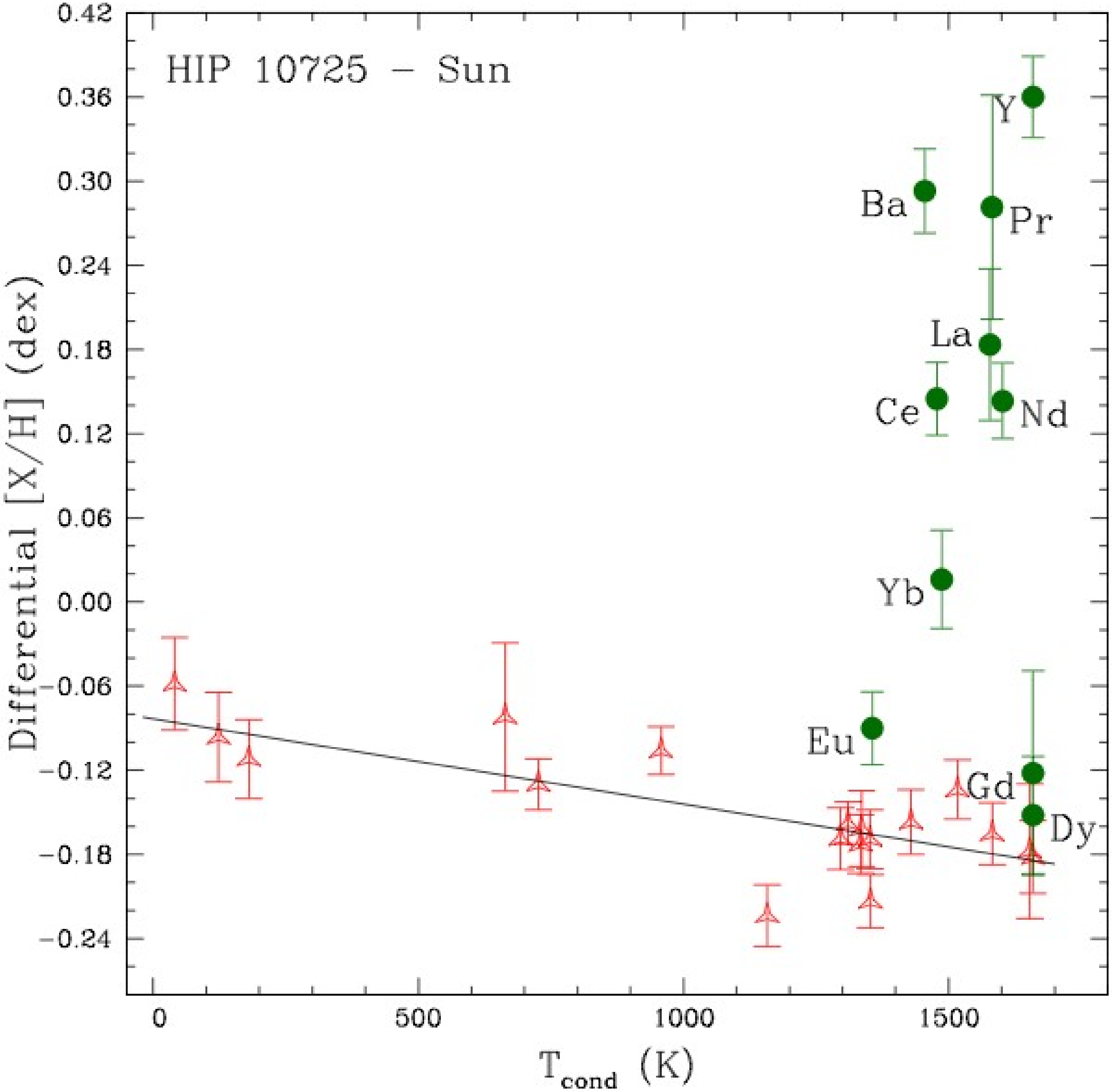


HIP 10725 is somewhat deficient in iron relative to the Sun, but enhanced in s-process elements



Schirbel et al. 2015

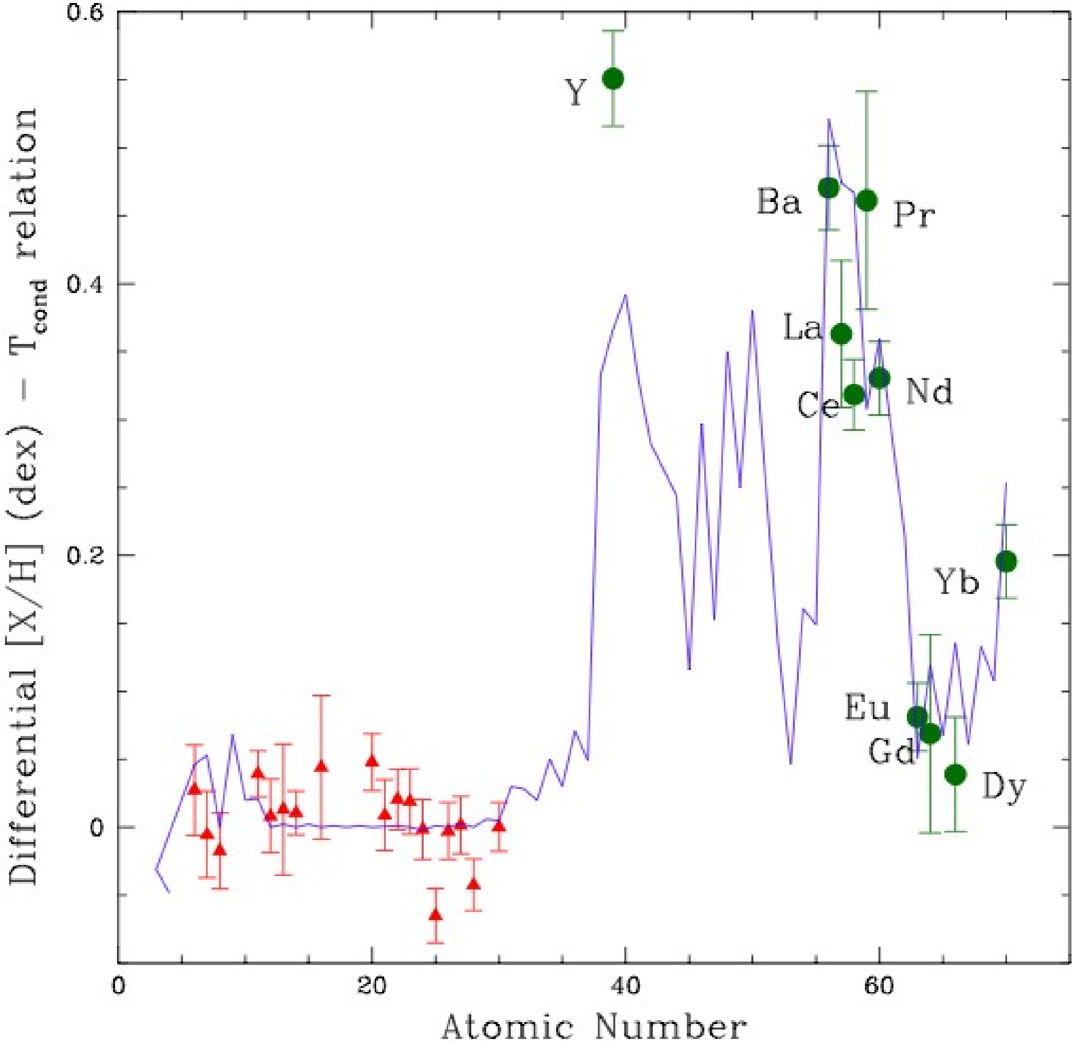
HIP 10725 is somewhat deficient in refractory elements, but enhanced in s-process elements



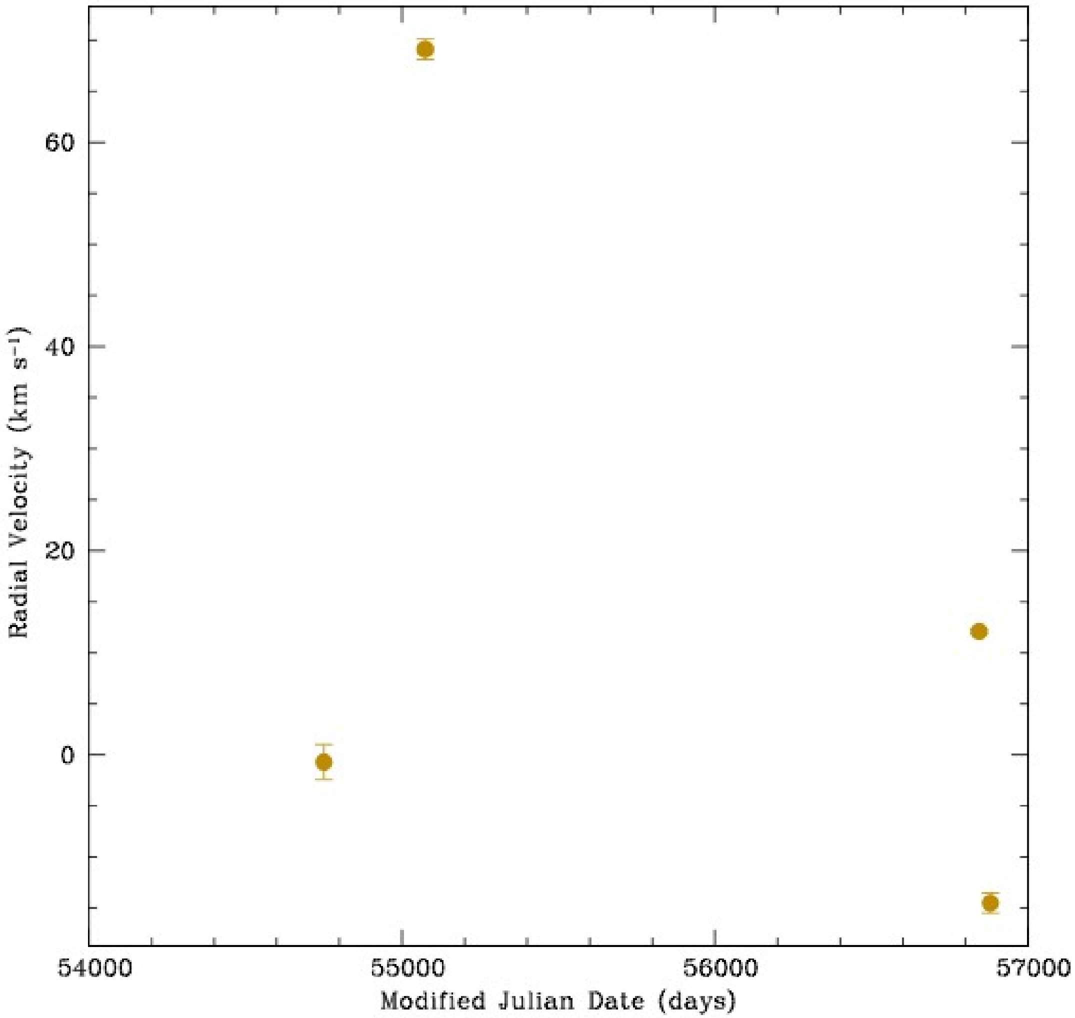
Schirbel et al. 2015

Signatures of former AGB star companion

Pollution by AGB star matches well the observed abundances



RV variations observed, likely due to white dwarf companion

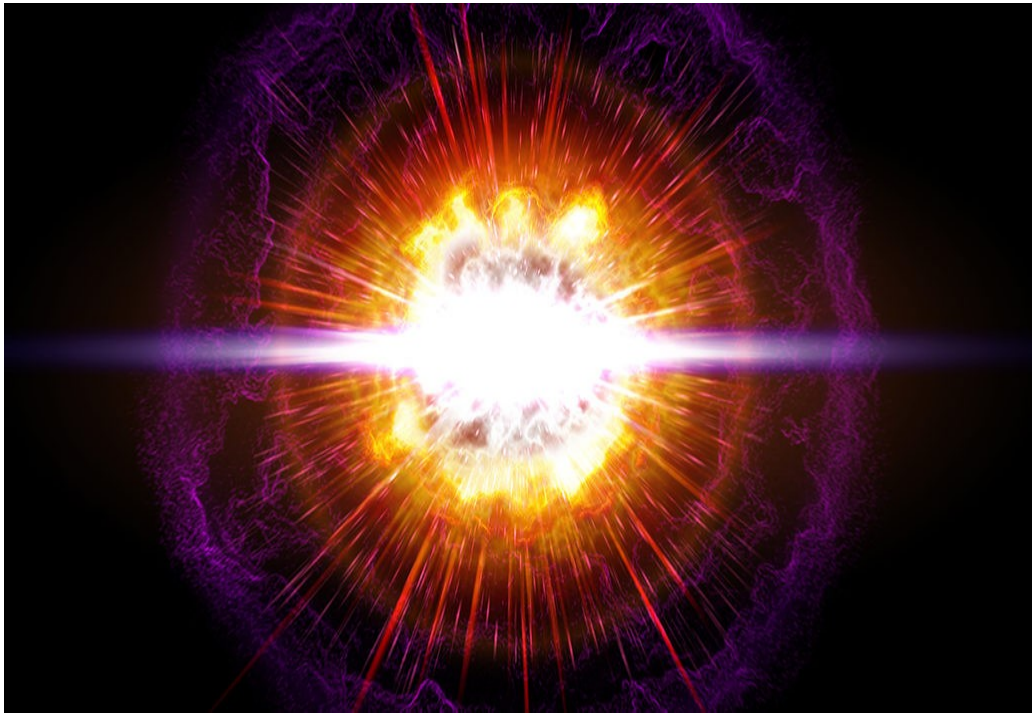


Schirbel et al. 2015

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **502,** L104–L109 (2021) doi:10.1093/mnrasl/slab010
Advance Access publication 2021 January 29

Explosive nucleosynthesis of a metal-deficient star as the source of a distinct odd-even effect in the solar twin HIP 11915

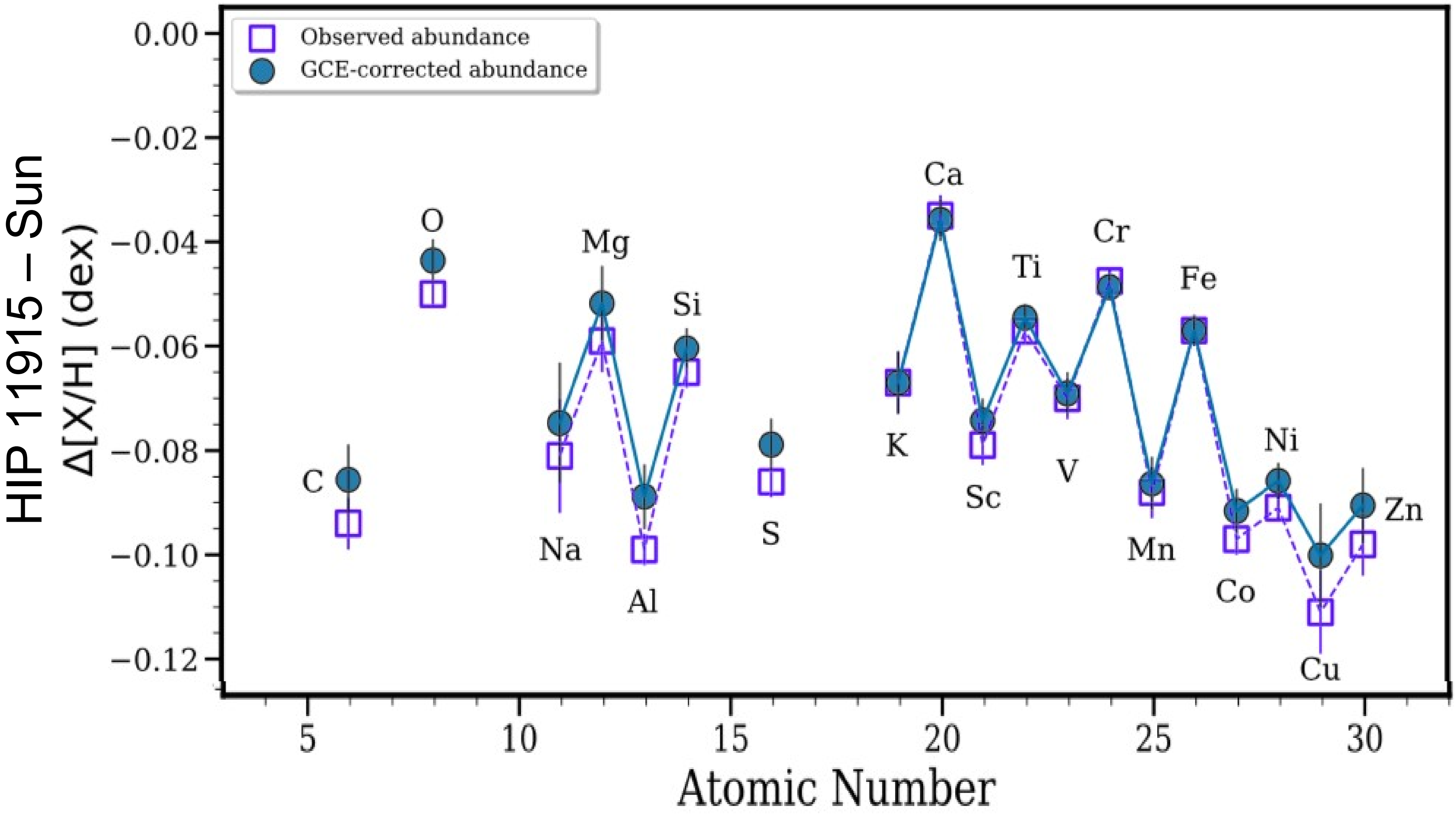
Jhon Yana Galarza [1]★ Jorge Meléndez [1]★ Amanda I. Karakas [2,3]★ Martin Asplund[4] and Diego Lorenzo-Oliveira [1]
[1] Universidade de São Paulo, Departamento de Astronomia do IAG/USP, Rua do Matão 1226, Cidade Universitária, 05508-900 São Paulo, SP, Brazil
[2] Monash Centre for Astrophysics, School of Physics and Astronomy, Monash University, Victoria 3800, Australia
[3] ARC Centre of Excellence for All Sky Astrophysics in 3 Dimensions (ASTRO 3D), Monash University, Victoria 3800, Australia
[4] Max Planck Institute for Astrophysics, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany



ESPRESSO/VLT
R = 140 000
S/N ~ 400

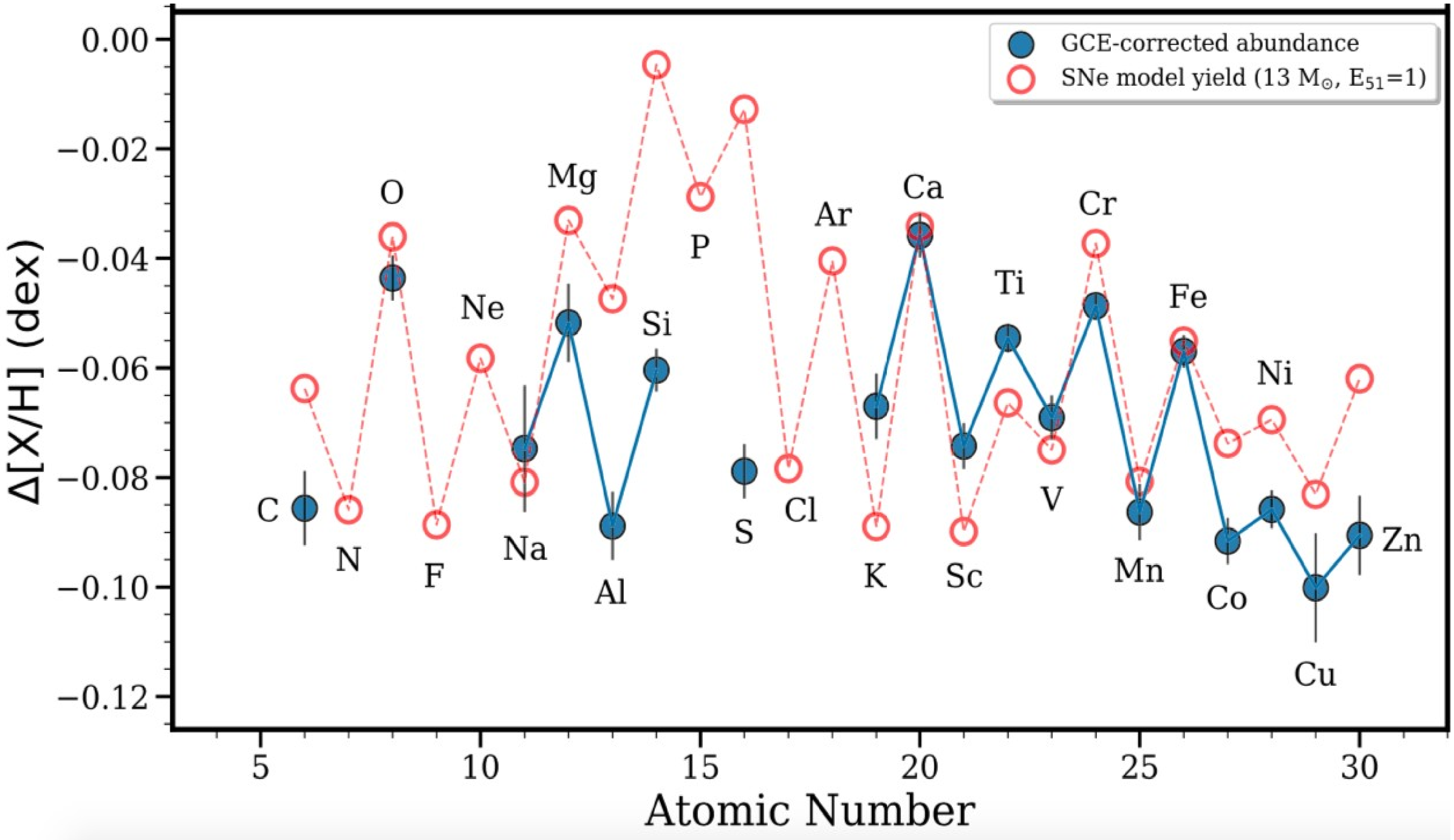
→ differential chemical abundances ~0.01 dex

Solar twin HIP 11915 has an odd-even abundance pattern stronger than the Sun!



Yana Galarza et al. 2021

The abundance pattern could be due to a supernova from a star of initial mass of 13 solar masses with sub-solar metallicity

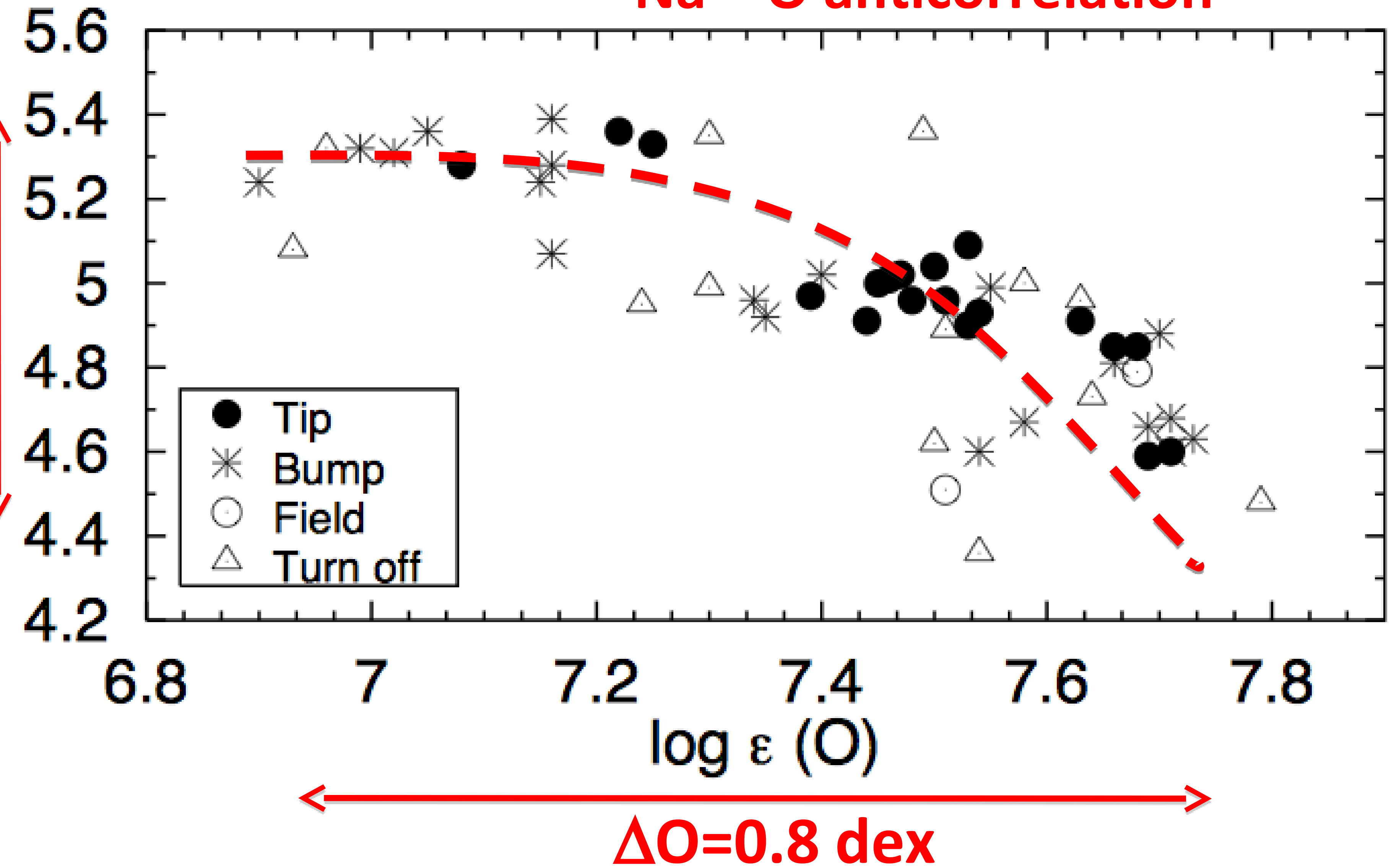


Yana Galarza et al. 2021

Precision Spectroscopy in Globular Clusters

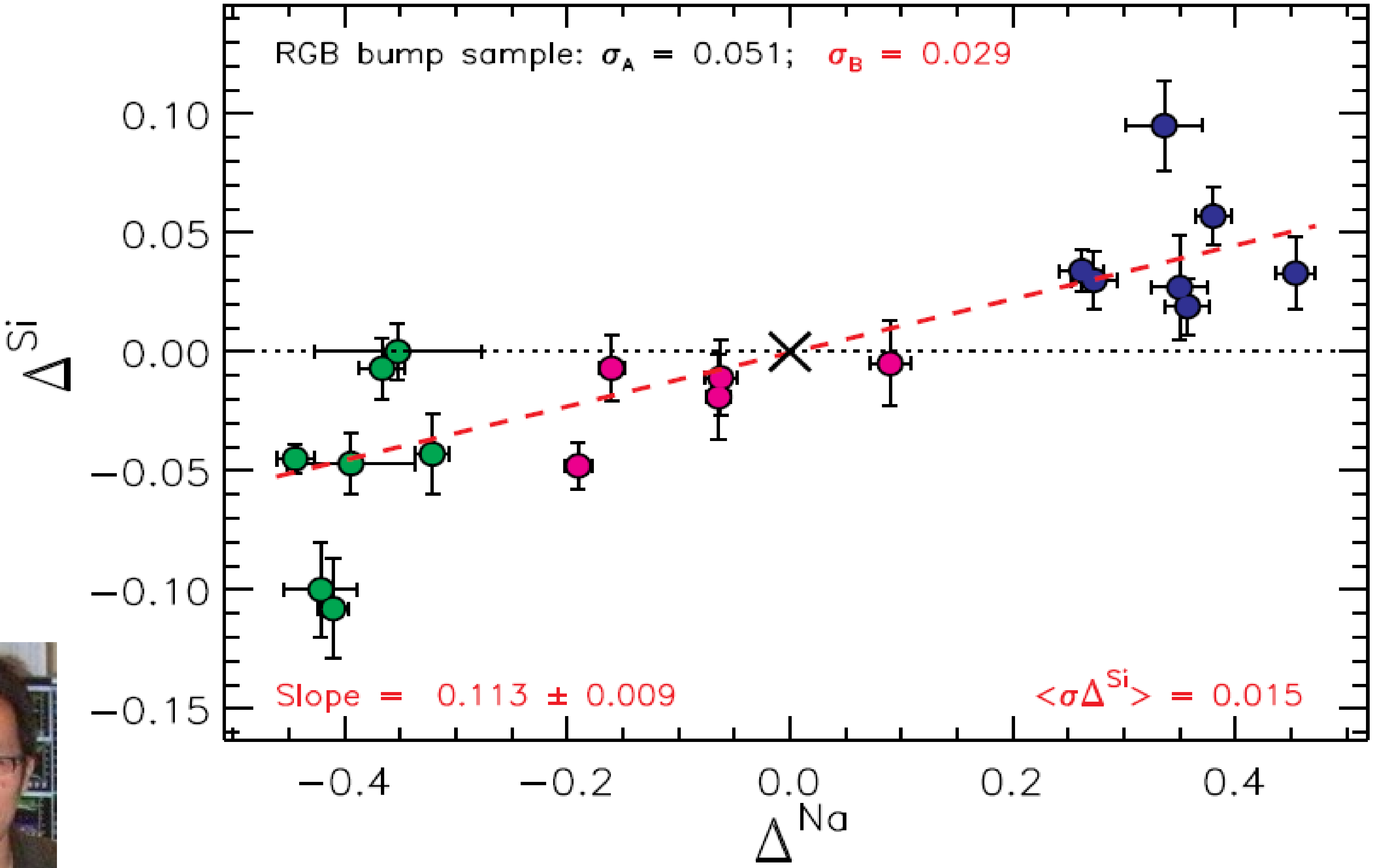
Yong et al. 2003, A&A 402, 985

Globular Cluster NGC 6752, Na – O anticorrelation



Are there hidden abundance variations at 0.01 dex level?

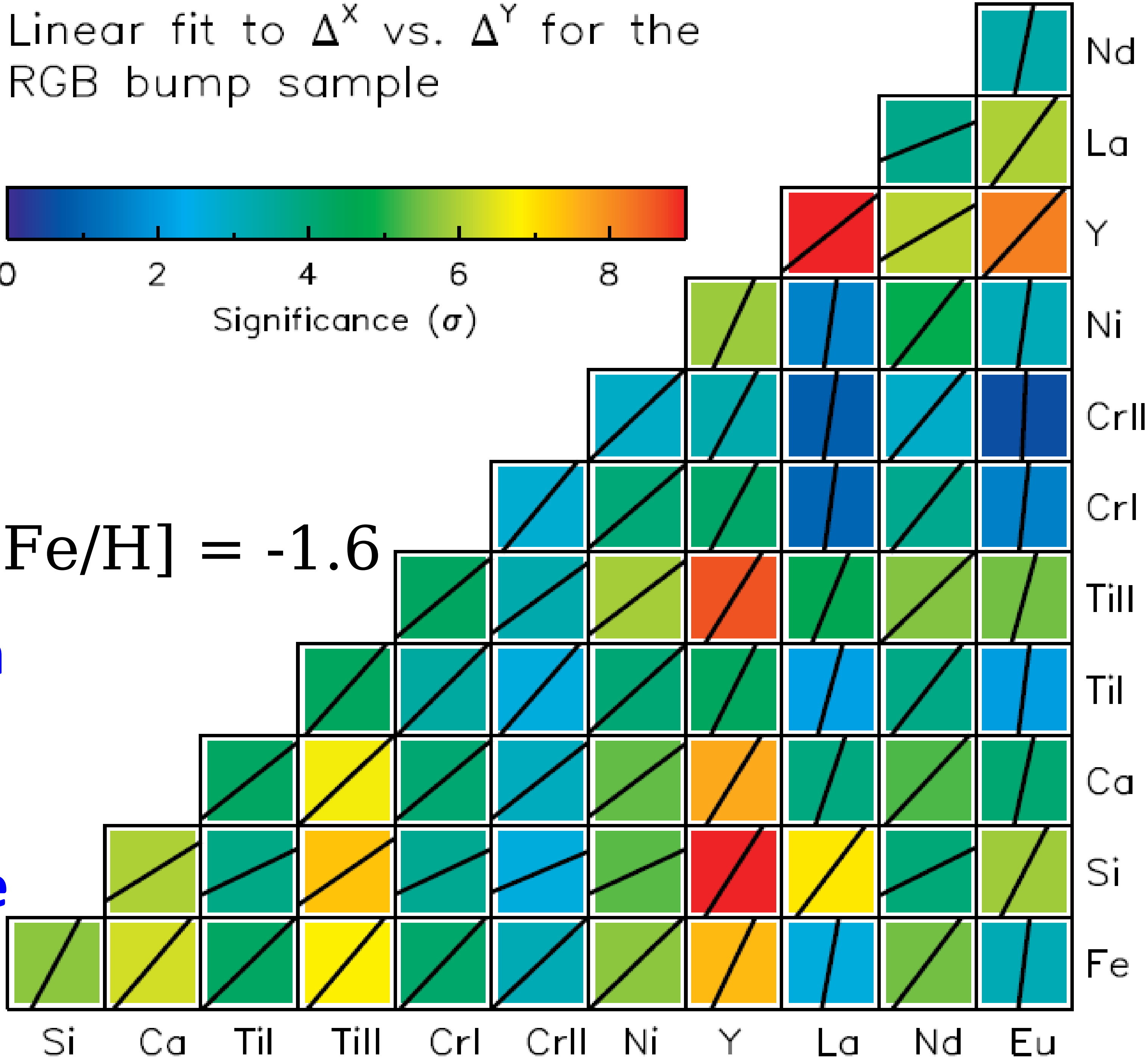
Differential techniques applied to **cool metal-poor giants** in globular cluster NGC 6752 ([Fe/H] = -1.6)



David Yong, Jorge Meléndez, Frank Grundahl, F., et al. 2013

Differential techniques applied to **cool metal-poor giants** in NGC 6752 [Fe/H] = -1.6

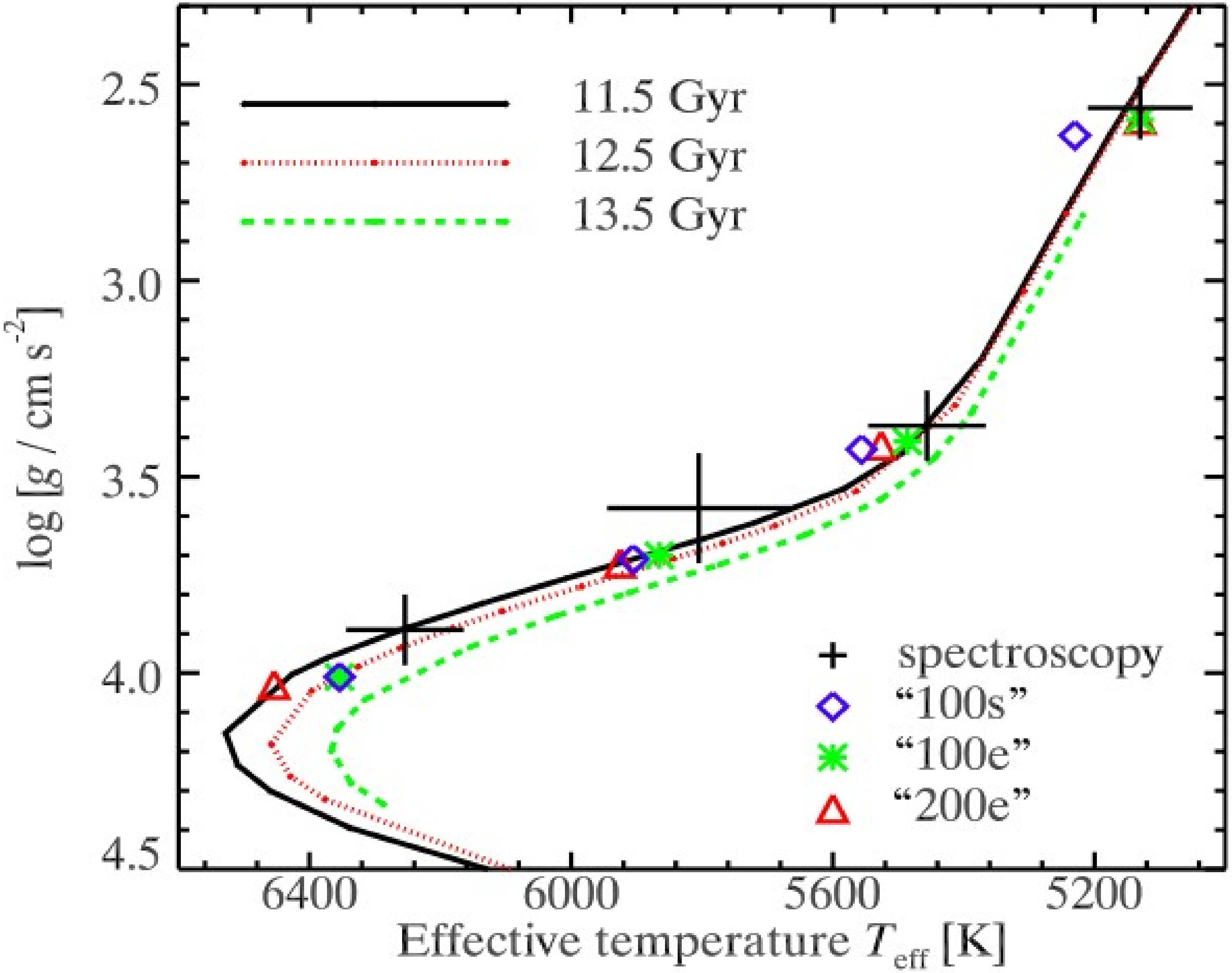
At high precision (0.01-0.02 dex) all elements show abundance variations



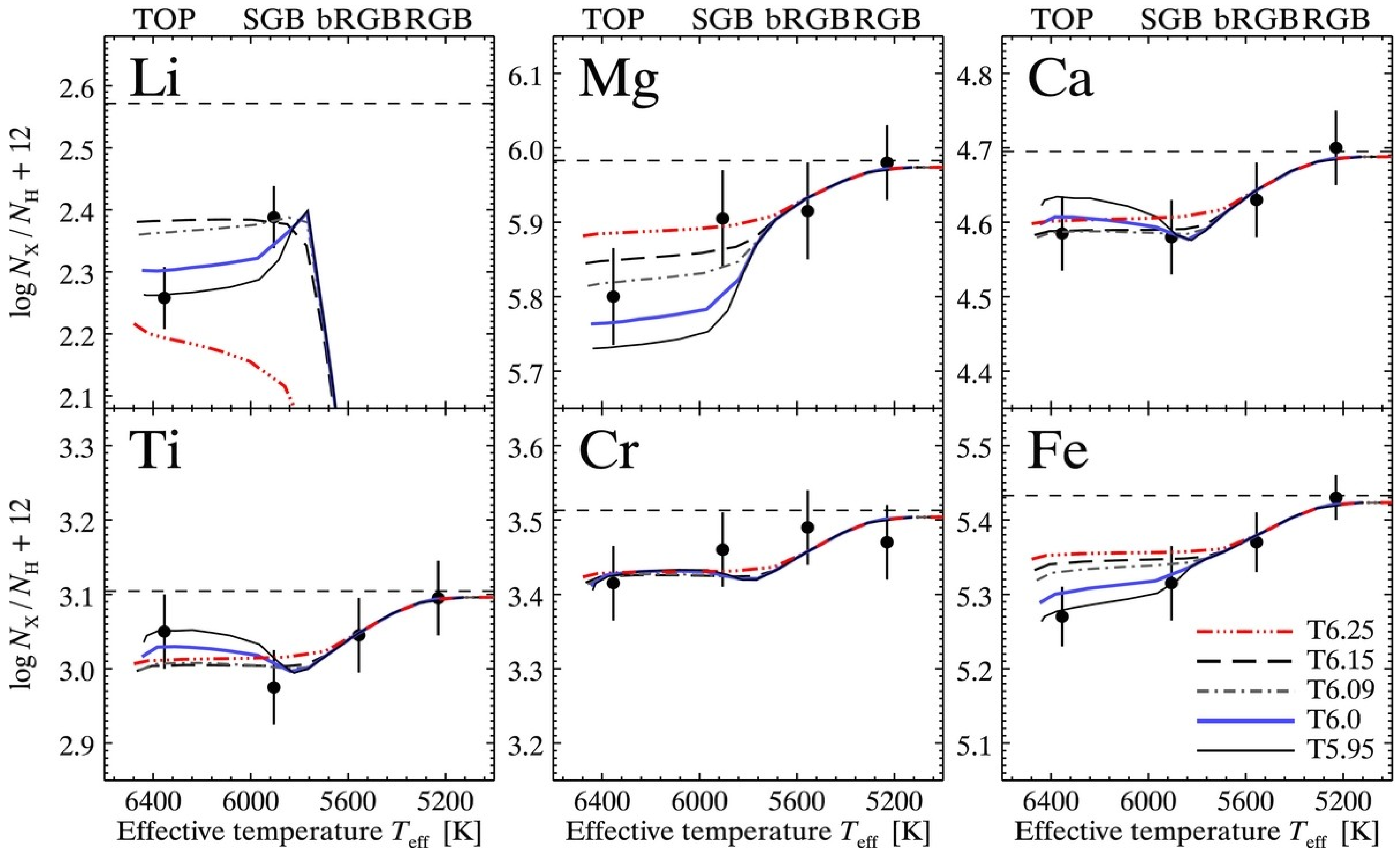
David Yong, Jorge Meléndez, Frank Grundahl, F., et al. 2013

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] ApJ 2012



Signatures of atomic diffusion in the globular cluster NGC 6397



Nordlander et al. 2012

High precision abundances in field metal-rich halo stars

A&A 511, L10 (2010)
DOI: 10.1051/0004-6361/200913877

Astronomy & Astrophysics

Letter to the Editor

Two distinct halo populations in the solar neighborhood★,★★,★★★

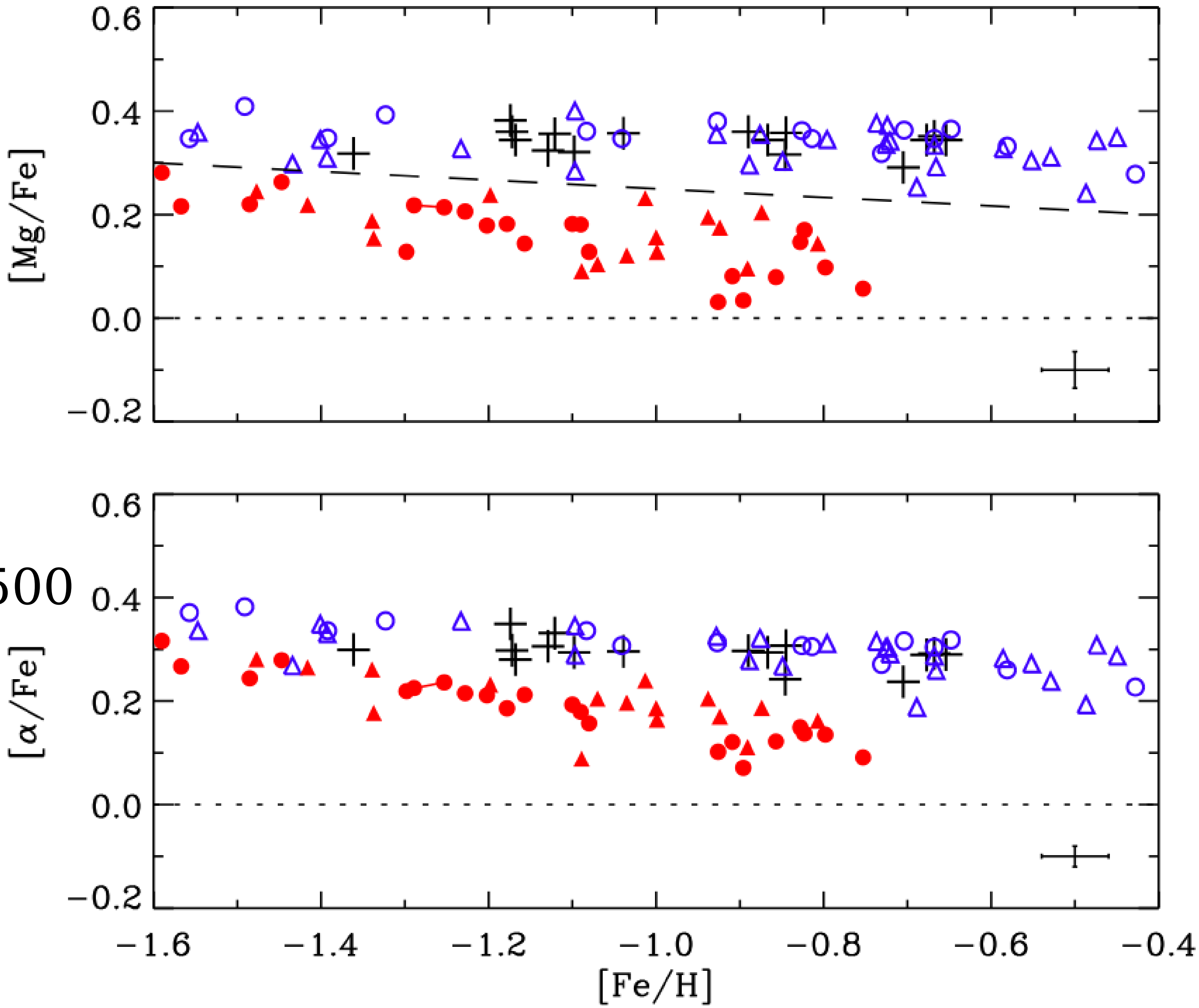
Evidence from stellar abundance ratios and kinematics

P. E. Nissen[1] and W. J. Schuster[2]

UVES@VLT
FIES@NOT

R ~ 50 000
S/N ~ 200 - 500

Nissen & Schuster 2010



The Astrophysical Journal, 757:164 (13pp), 2012 October 1 doi:10.1088/0004-637X/75

OXYGEN ABUNDANCES IN LOW- AND HIGH-α FIELD HALO STARS AND THE DISCOVERY OF TWO FIELD STARS BORN IN GLOBULAR CLUSTERS

I. Ramírez[1], J. Meléndez[2], and J. Chanamé[3]

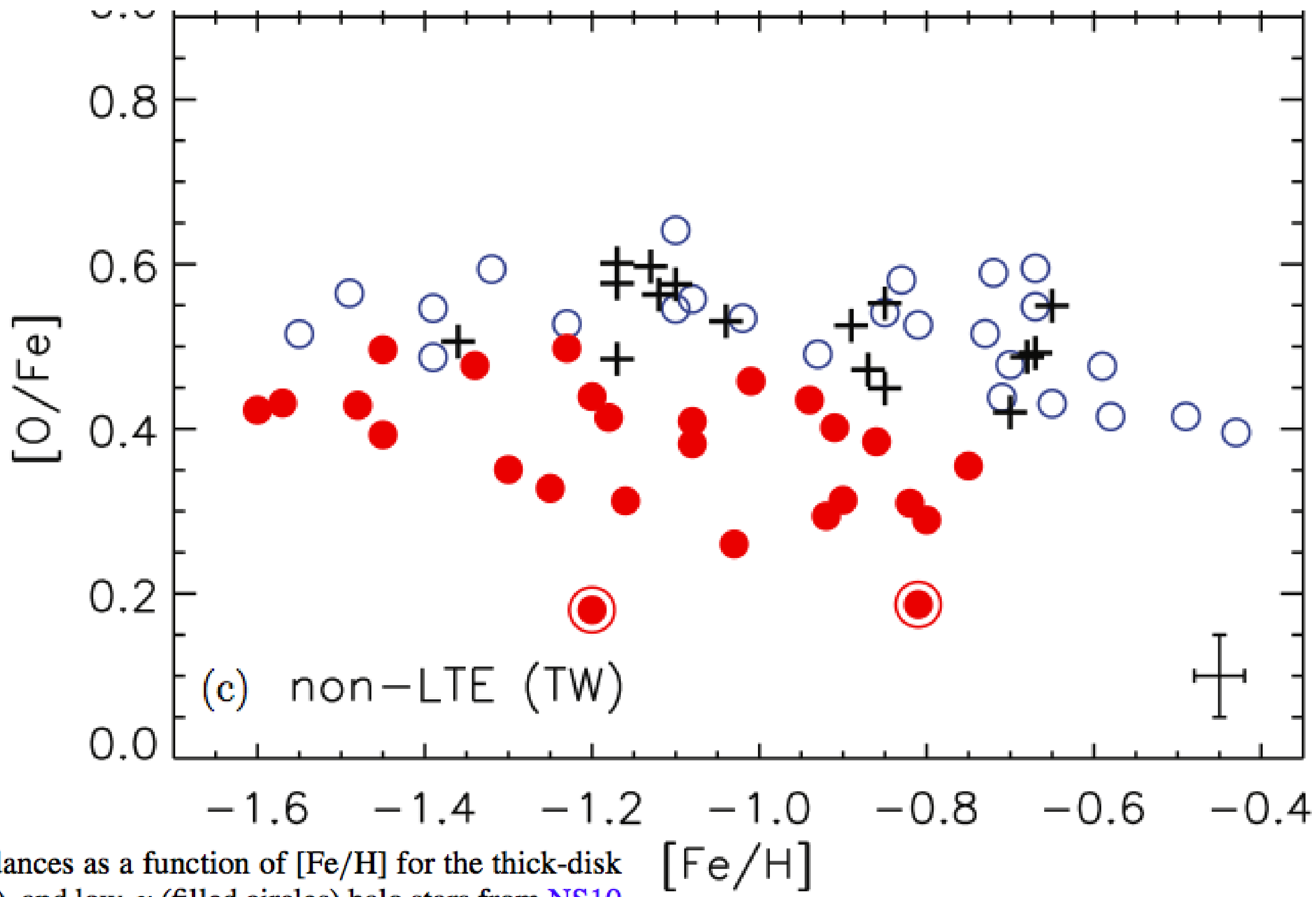
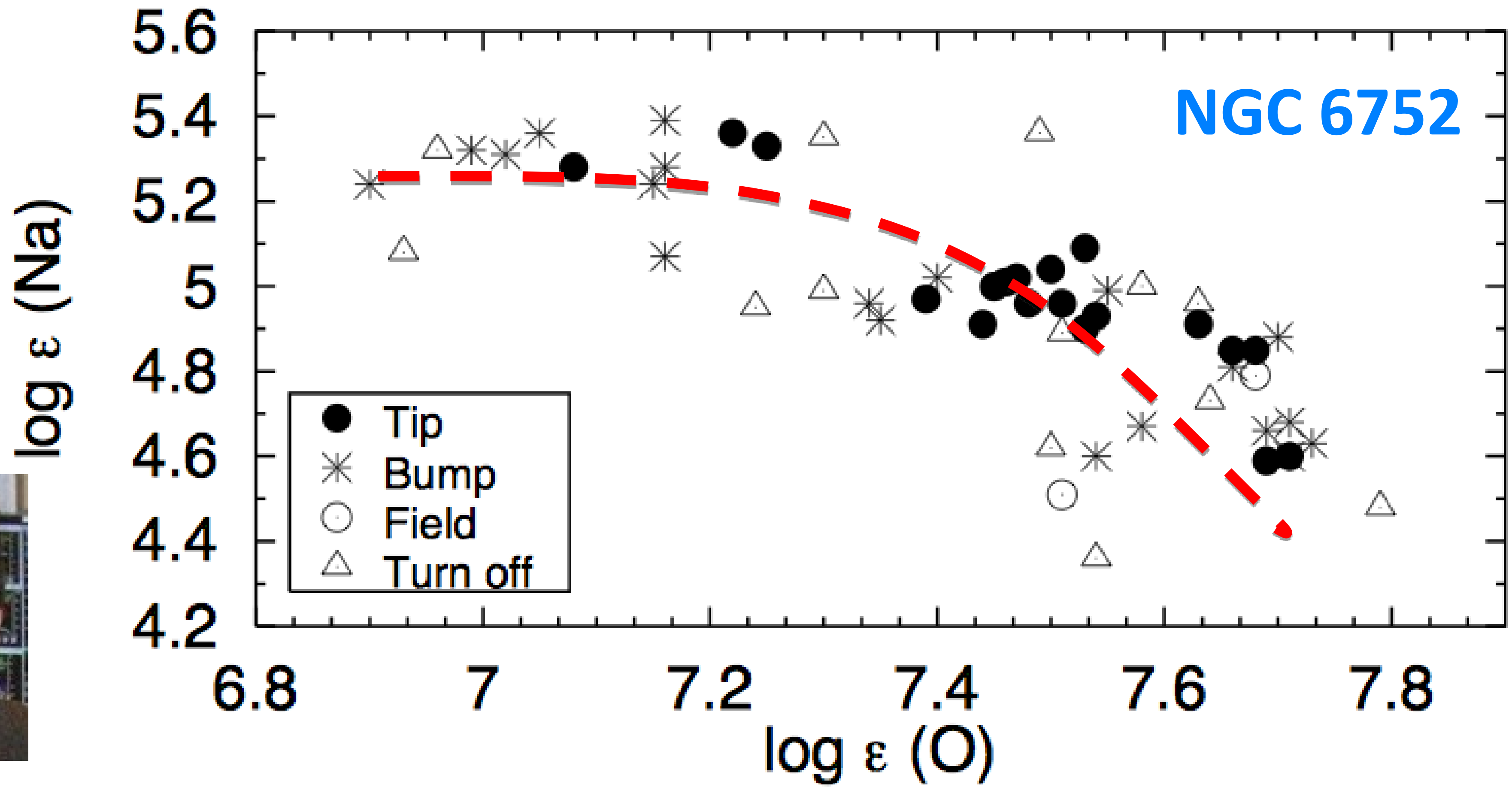


Figure 1. (a) α-element abundances as a function of [Fe/H] for the thick-disk (crosses), high-α (open circles), and low-α (filled circles) halo stars from NS10 included in this work. The two low-α stars with large open circles surrounding them are G53-41 ([Fe/H] = −1.20) and G150-40 ([Fe/H] = −0.81). (b) LTE oxygen abundances as a function of [Fe/H] for the stars plotted in panel (a). (c) Non-LTE corrected oxygen abundances. The α-element abundances are those derived by NS10; the oxygen abundances are those derived in this work (TW). Typical error bars are shown at the bottom right side of each panel.

Tagging field stars born in Globular Clusters



Yong et al. 2003, A&A 402, 985

The Astrophysical Journal, 757:164 (13pp), 2012 October 1 doi:10.1088/0004-637X/75

OXYGEN ABUNDANCES IN LOW- AND HIGH-α FIELD HALO STARS AND THE DISCOVERY OF TWO FIELD STARS BORN IN GLOBULAR CLUSTERS

I. Ramírez[1], J. Meléndez[2], and J. Chanamé[3]

Field stars born in a globular cluster

2 in a sample of 67 field stars (3 ± 2%)

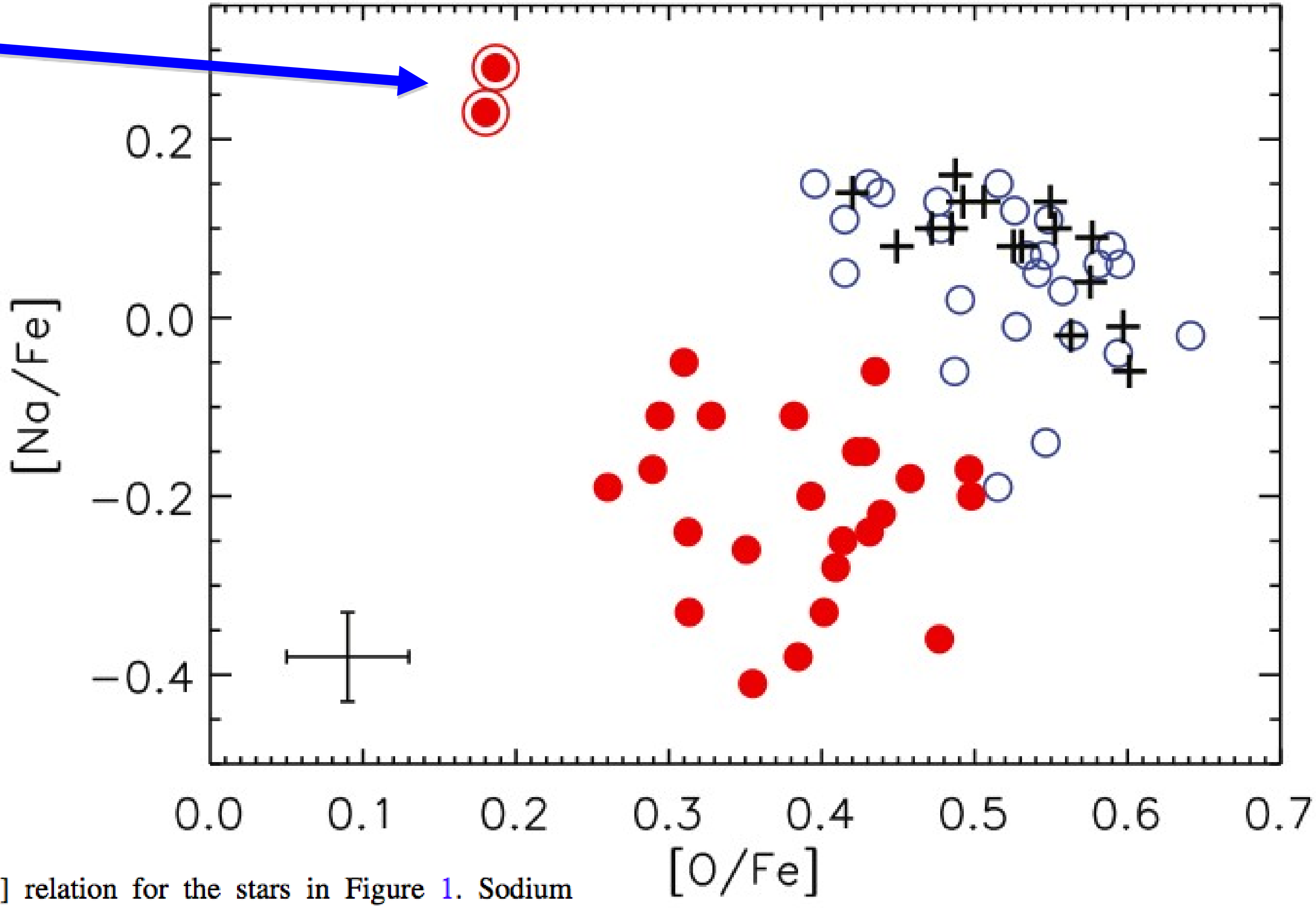
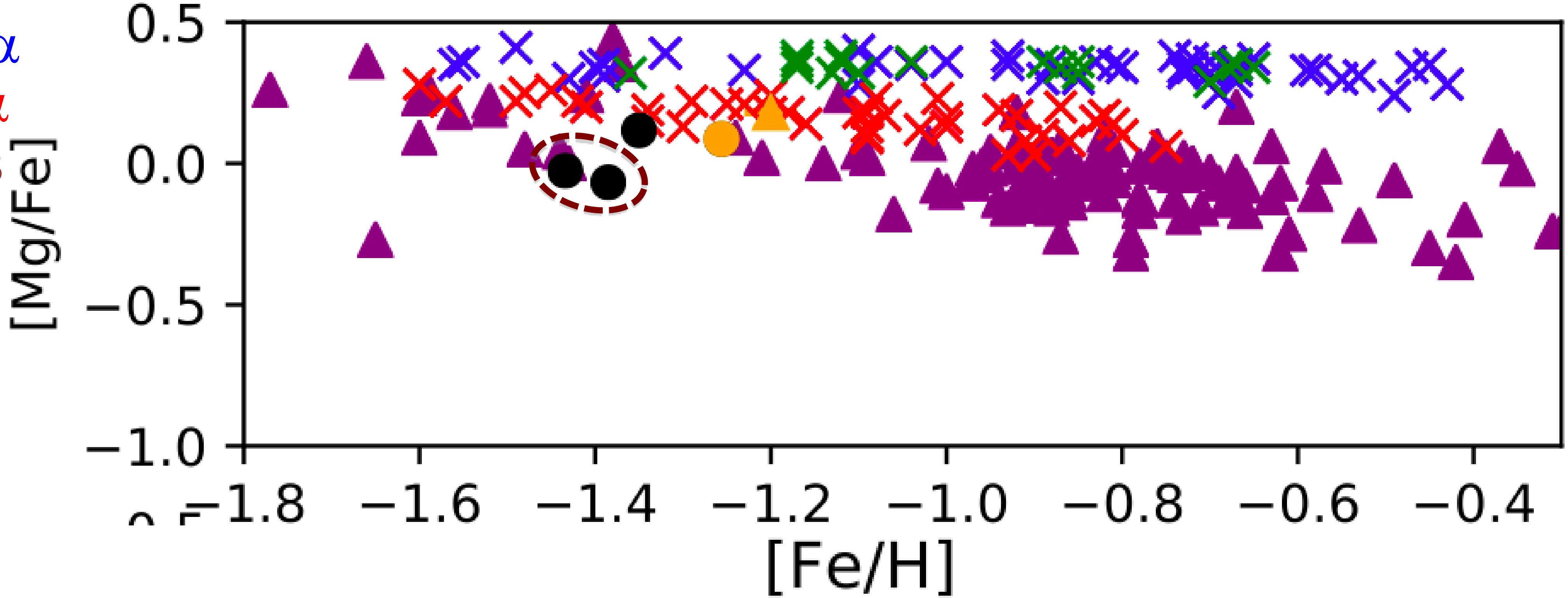


Figure 7. [Na/Fe] vs. [O/Fe] relation for the stars in Figure 1. Sodium abundances are from Nissen & Schuster (2010). Typical error bars are shown at the bottom left corner.

Chemical tagging in field stars accreted from Dwarf Spheroidals

Field halo stars accreted from Dwarf Spheroidals

High-α
Low-α
dSphs



Reggiani & Meléndez 2018

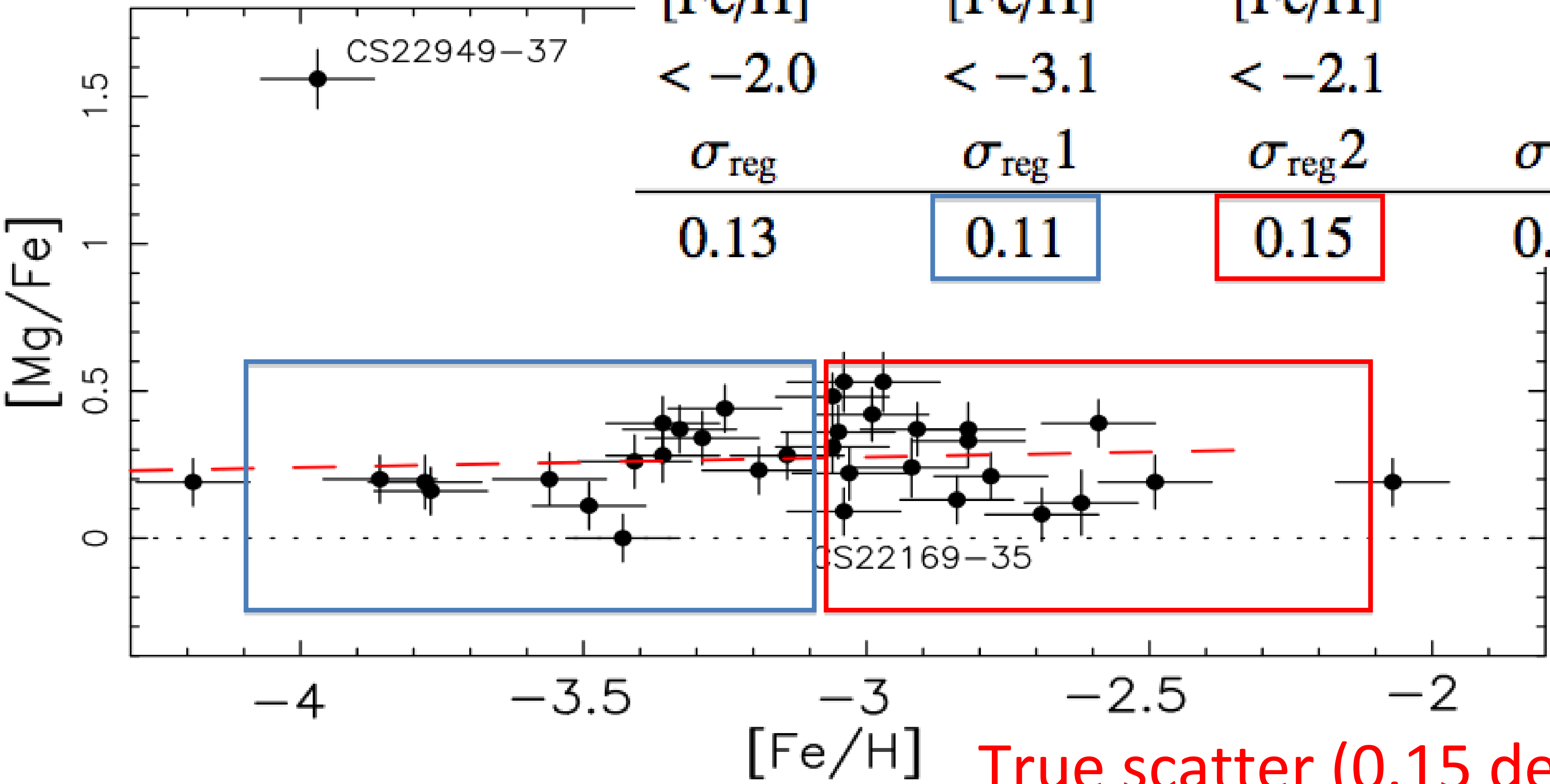
High-α	Nissen & Schuster
Low-α	(2010)
dSphs	Literature

High precision abundances in field extremely metal-poor halo stars ([Fe/H] < -3)

Cosmic scatter in metal-poor stars?

Cayrel et al. 2004

$-4.1 <$ [Fe/H] < -2.0	$-4.1 <$ [Fe/H] < -3.1	$-3.1 <$ [Fe/H] < -2.1	
$\sigma_{\rm reg}$	$\sigma_{\rm reg}1$	$\sigma_{\rm reg}2$	$\sigma_{\rm mes}$
0.13	$\boxed{0.11}$	$\boxed{0.15}$	0.09



True scatter (0.15 dex)?

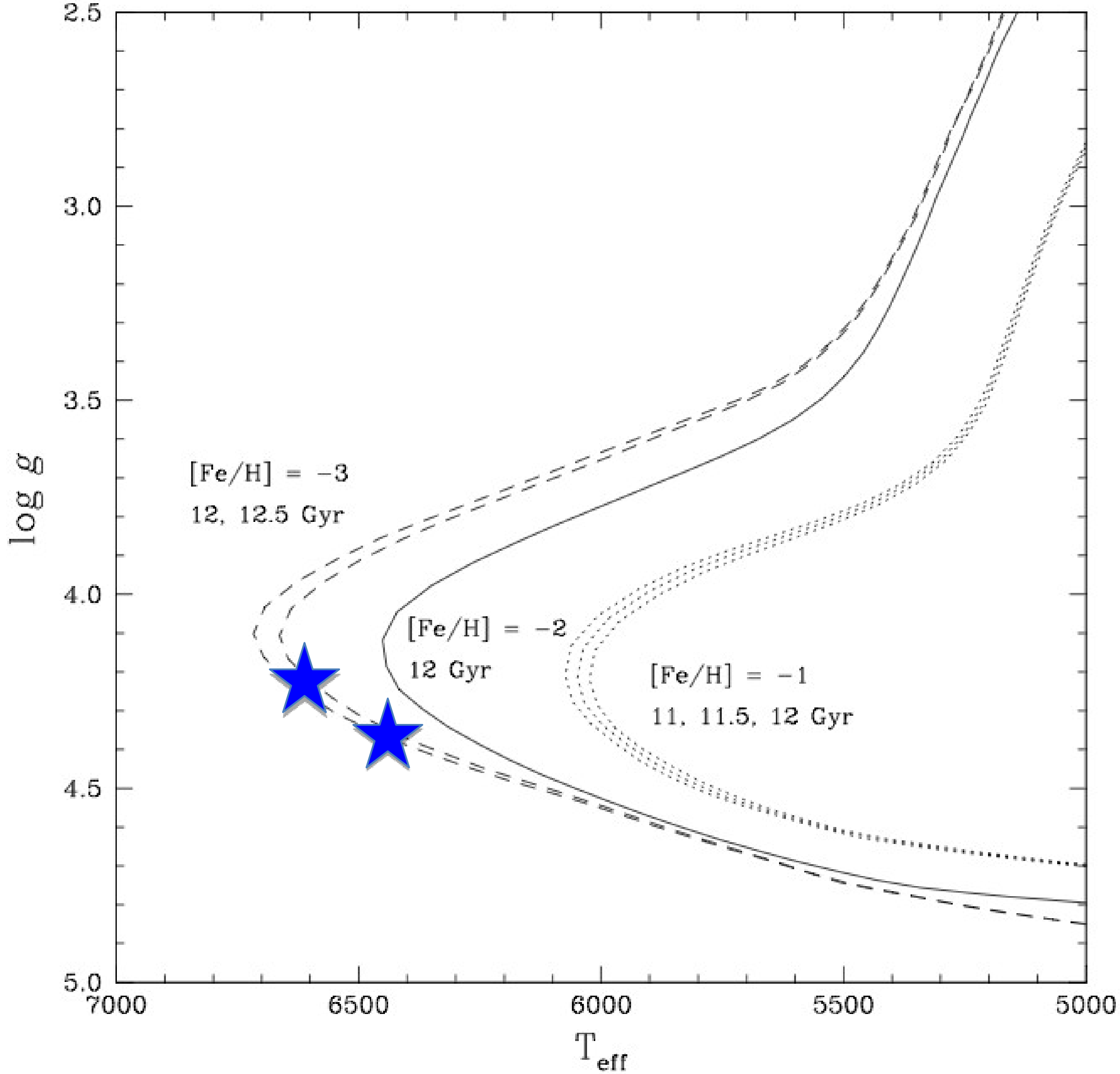
First high precision analysis of extremely metal-poor stars ([Fe/H] < -3)

Henrique Reggiani et al. (2016, A&A 586, A67)

G 64-12, G64-37: Extremely metal-poor "twins"

6463 K, 6570 K;
log g = 4.26, 4.40;
[Fe/H] = -3.2, -3.0

HIRES @ Keck, R ~ 95 000
S/N ~ 700

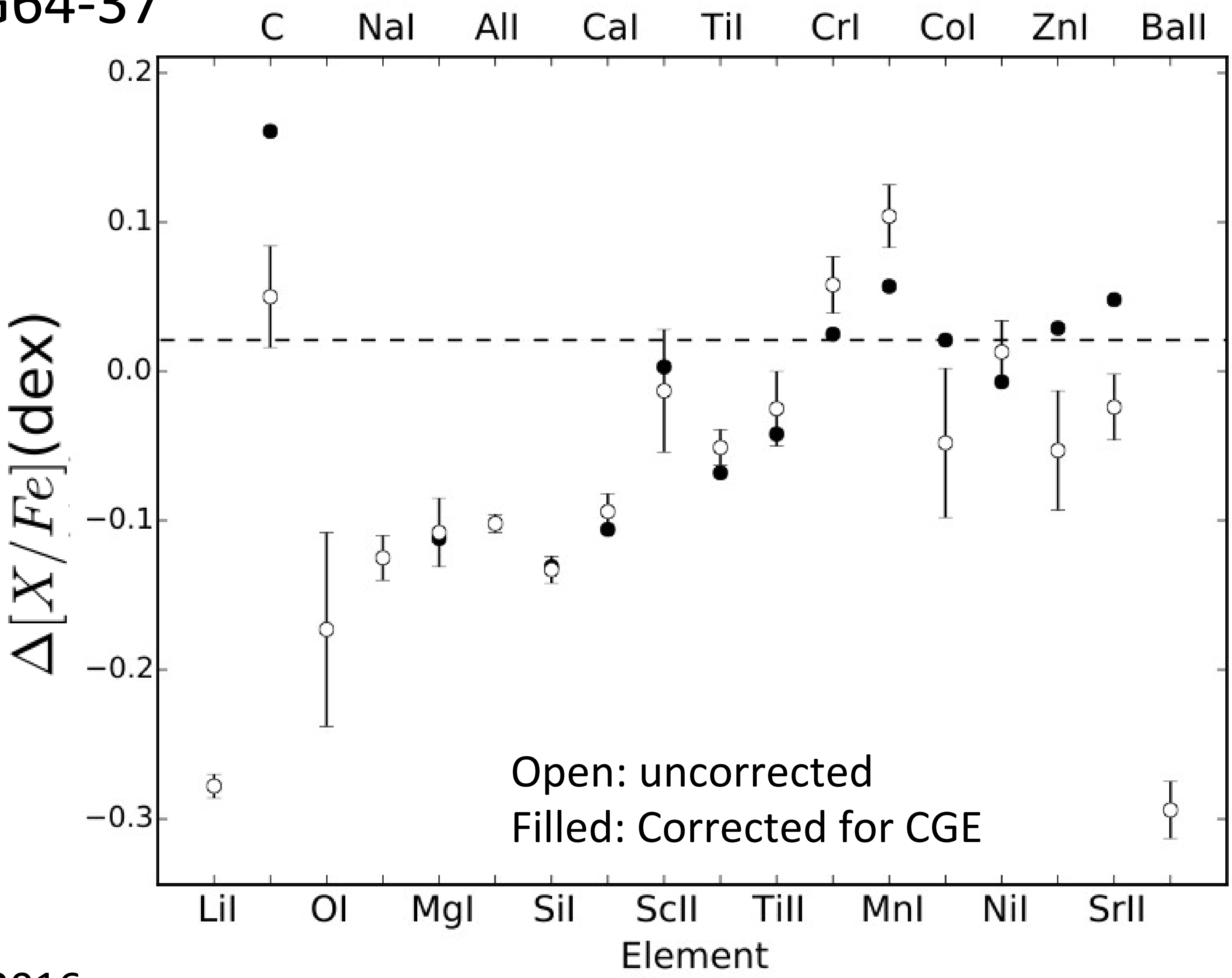


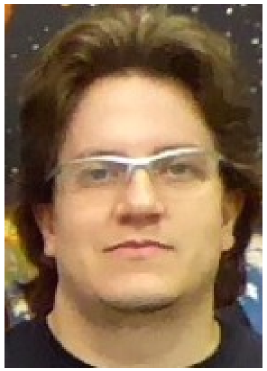
Distinct abundances in extremely metal-poor "twins"

G64-12 & G64-37

EMP stars

[Fe/H] < -3

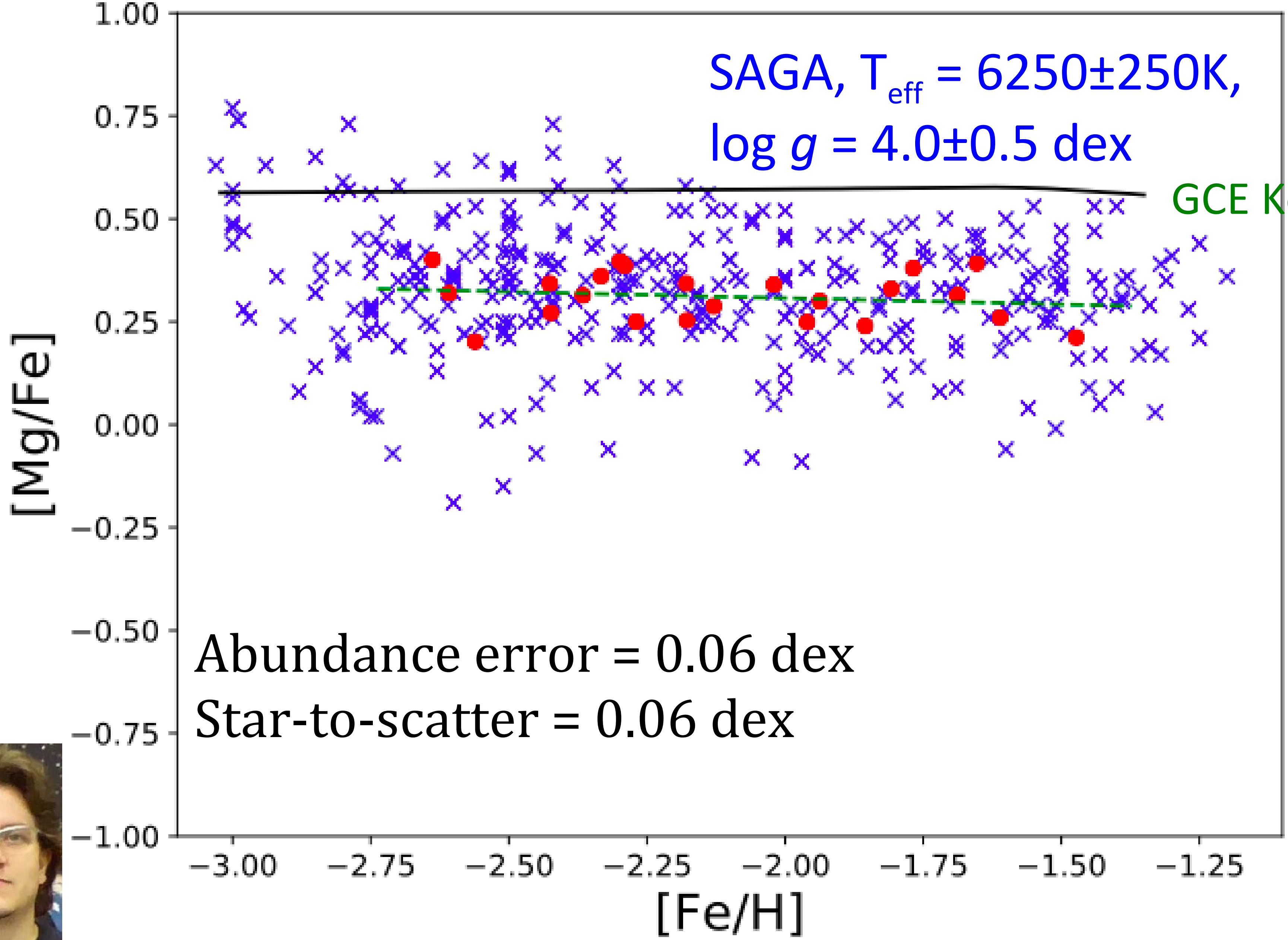




Reggiani et al. 2016

High precision abundances in field very metal-poor halo stars ([Fe/H] ~ -2)

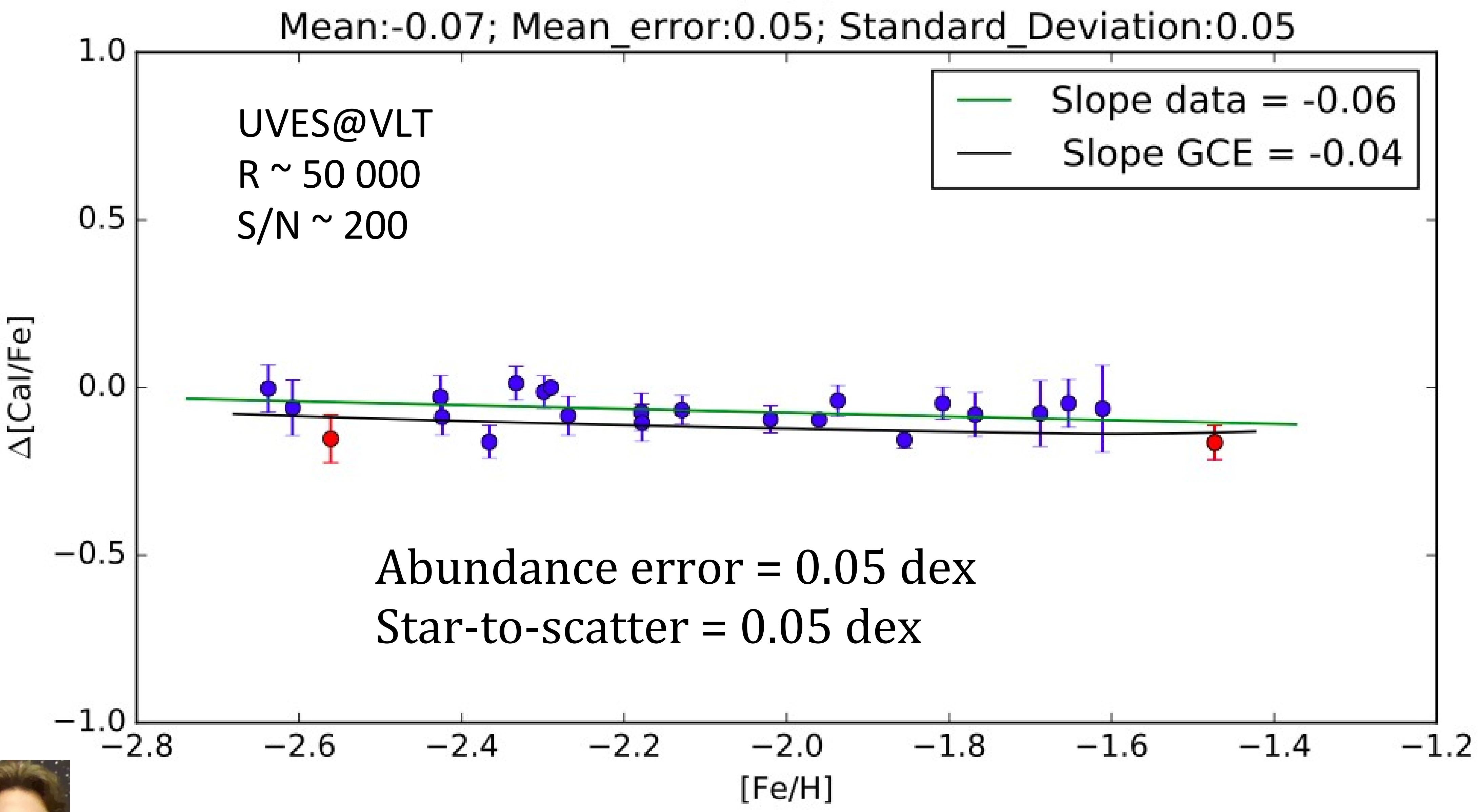
High Precision in Very Metal-Poor Stars



UVES@VLT
R ~ 50 000
S/N ~ 250

Henrique Reggiani et al. 2017

Precise abundances in Very Metal-Poor Stars are important constraints on GCE models



Henrique Reggiani et al. 2017

Testing chemical homogeneity using open cluster stars

Chemical homogeneity in open clusters: 0.03 dex

THE CHEMICAL HOMOGENEITY OF OPEN CLUSTERS

Bovy 2016

JO BOVY
Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON, M5S 3H4, Canada;

Determining the level of chemical homogeneity in open clusters is of fundamental importance in the study of the evolution of star-forming clouds and that of the Galactic disk. Yet limiting the initial abundance spread in clusters has been hampered by difficulties in obtaining consistent spectroscopic abundances for different stellar types. Without reference to any specific model of stellar photospheres, a model for a homogeneous cluster is that it forms a one-dimensional sequence, with any differences between members due to variations in stellar mass and observational uncertainties. I present a novel method for investigating the abundance spread in open clusters that tests this one-dimensional hypothesis at the level of observed stellar spectra, rather than constraining homogeneity using derived abundances as traditionally done. Using high-resolution APOGEE spectra for 49 giants in M67, NGC 6819, and NGC 2420 I demonstrate that these spectra form one-dimensional sequences for each cluster. With detailed forward modeling of the spectra and Approximate Bayesian Computation, I derive strong limits on the initial abundance spread of 15 elements: $< 0.01\,(0.02)$ dex for C and Fe, $\lesssim 0.015\,(0.03)$ dex for N, O, Mg, Si, and Ni, $\lesssim 0.02\,(0.03)$ dex for Al, Ca, and Mn, and $\lesssim 0.03\,(0.05)$ dex for Na, S, K, Ti, and V (at 68 % and 95 % confidence, respectively). The strong limits on C and O imply that no pollution by massive core-collapse supernovae occurred during star formation in open clusters, which, thus, need to form within $\lesssim 6$ Myr. Further development of this and related techniques will bring the power of differential abundances to stars other than solar twins in large spectroscopic surveys and will help unravel the history of star formation and chemical enrichment in the Milky Way through chemical tagging.

Ness et al. 2017

GALACTIC DOPPELGANGER: THE CHEMICAL SIMILARITY AMONG FIELD STARS AND AMONG STARS WITH A COMMON BIRTH ORIGIN

M. NESS[1], H-W. RIX[1], DAVID W. HOGG[1,2,3,4], A.R. CASEY[5], J. HOLTZMAN[6], M. FOUESNEAU[1], G. ZASOWSKI[7,8], D. GEISLER[9], M. SHETRONE[10], D. MINNITI[11,12,13] PETER M. FRINCHABOY[14], ALEXANDRE ROMAN-LOPES[15]

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ROYAL ASTRONOMICAL SOCIETY

MNRAS **457**, 3934–3948 (2016)
Advance Access publication 2016 January 29

The Hyades open cluster is chemically inhomogeneous

F. Liu,[1★] D. Yong,[1] M. Asplund,[1] I. Ramírez[2] and J. Meléndez[3]

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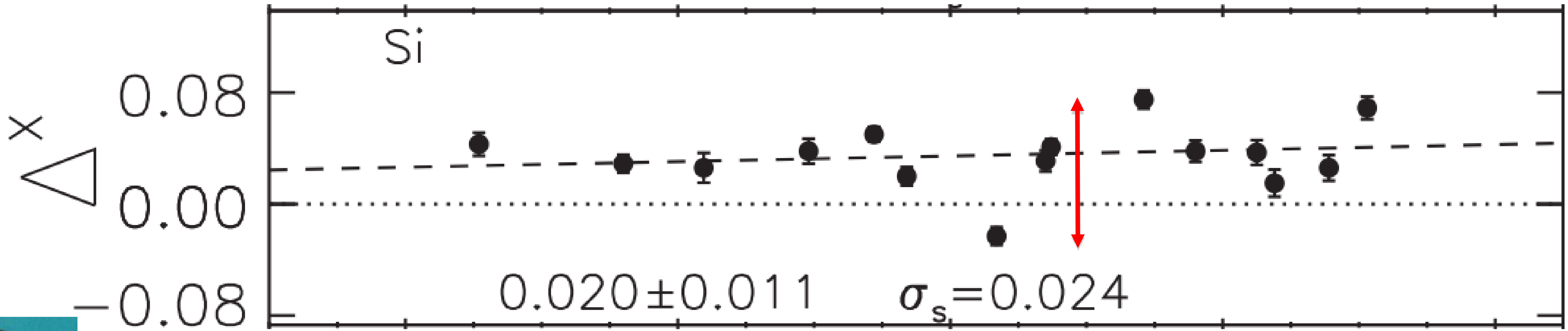


Spread 0.08 dex

Fan Liu

Chemical inhomogeneity in open clusters: solar twins in M67 have different abundances

Fan Liu

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **463,** 696–704 (2016) doi:10.1093/r
Advance Access publication 2016 August 15

The chemical compositions of solar twins in the open cluster M67

F. Liu,[1,2★] M. Asplund,[1] D. Yong,[1] J. Meléndez,[3] I. Ramírez,[4] A. I. Karakas,[1,5] M. Carlos[3] and A. F. Marino[1]

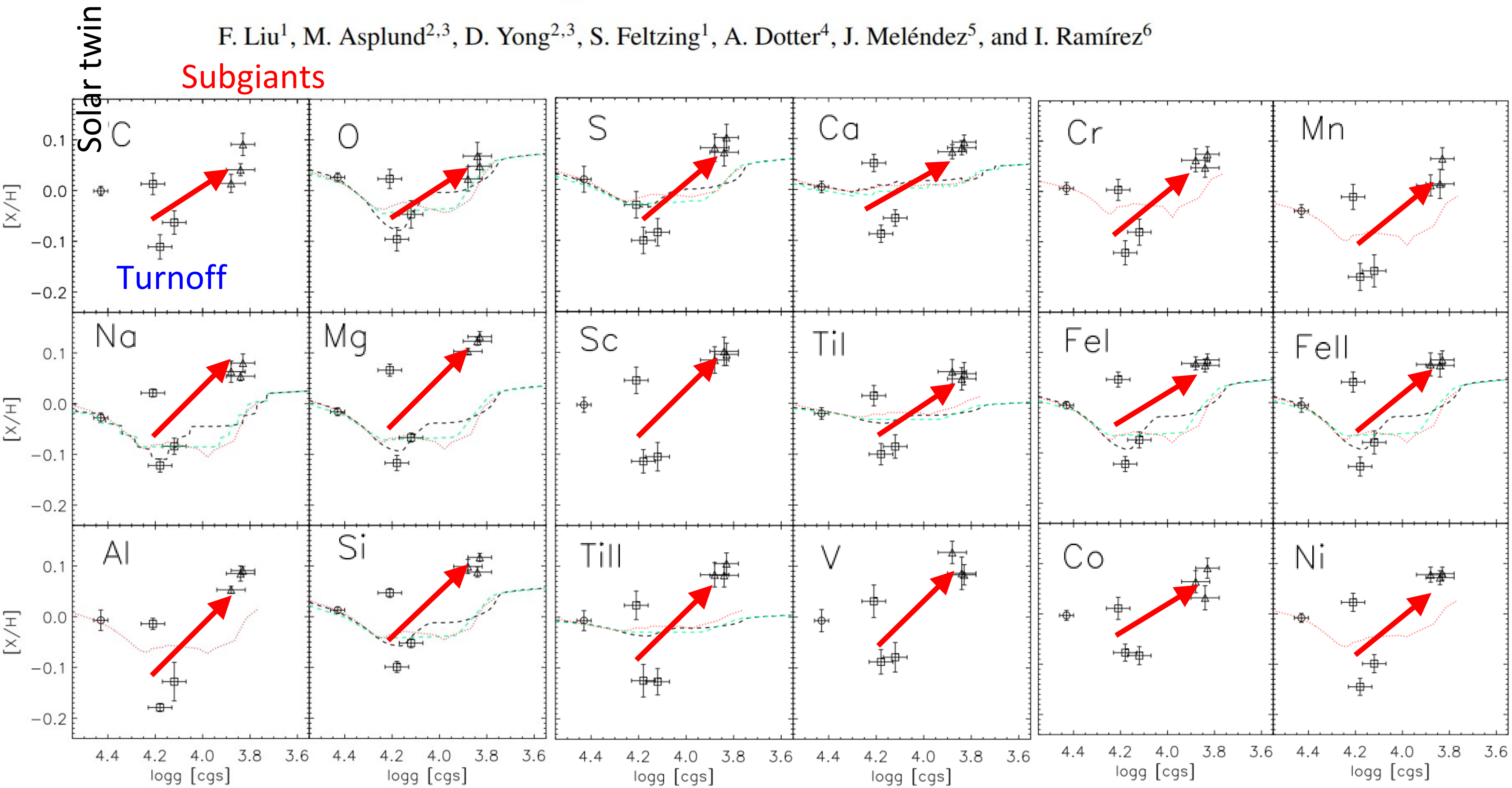
Object	$T_{\rm eff}$ (K)	$\log g$ [$\rm cm\,s^{-2}$]	ξ_t ($\rm km\,s^{-1}$)	[Fe/H]
Hebe (Sun)	5777	4.44	1.00	0.00
M67-1194	5786±13	4.46±0.02	1.04±0.02	−0.005±0.010
M67-1315	5933±23	4.47±0.05	1.05±0.04	−0.061±0.014

A&A 627, A117 (2019)
https://doi.org/10.1051/0004-6361/201935306

Astronomy & Astrophysics

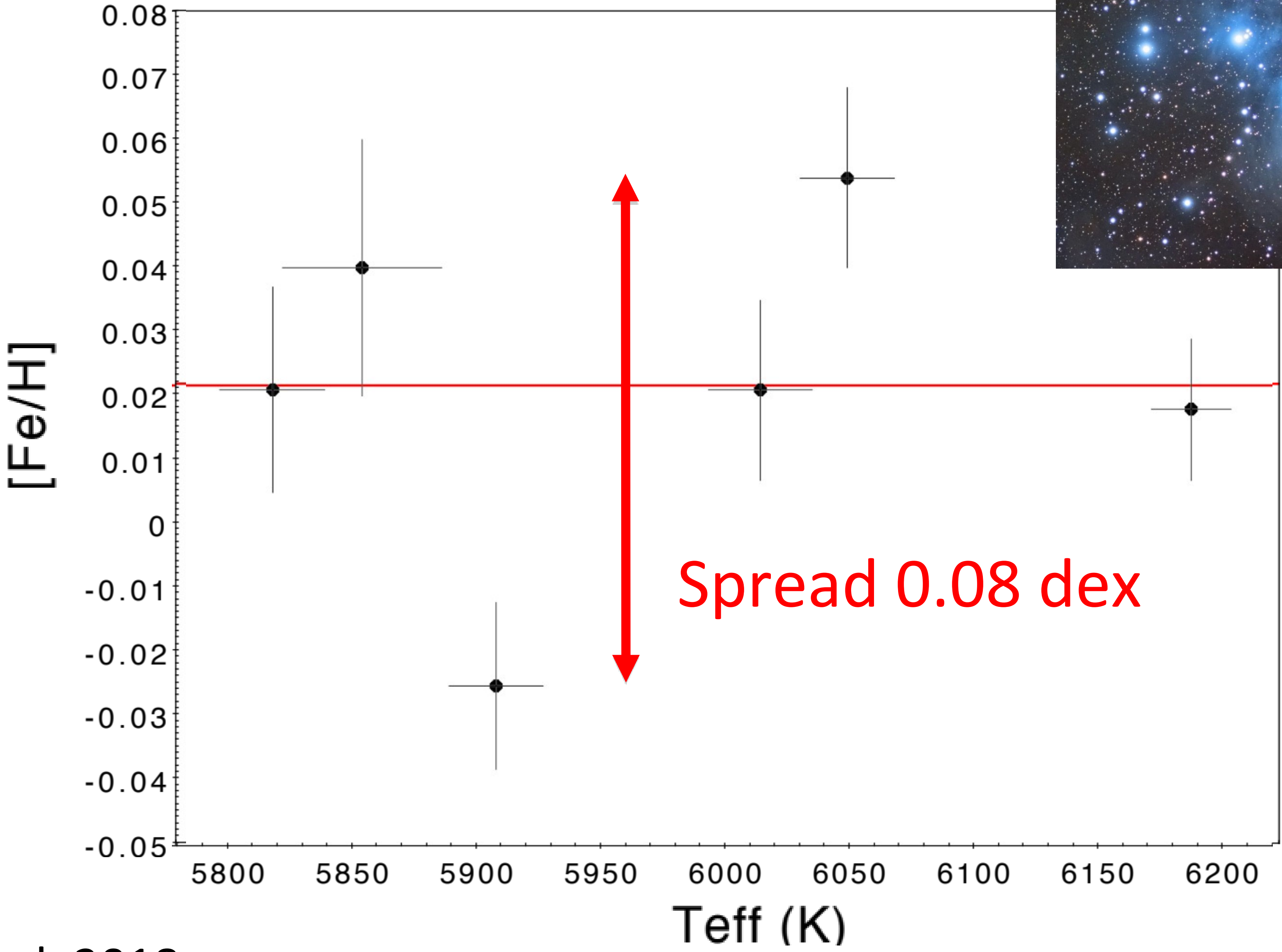
Chemical (in)homogeneity and atomic diffusion in the open cluster M 67★,★★

F. Liu[1], M. Asplund[2,3], D. Yong[2,3], S. Feltzing[1], A. Dotter[4], J. Meléndez[5], and I. Ramírez[6]



1. Inhomogeneity in turnoff stars
2. Subgiants have higher abundances than turnoff stars

Chemical inhomogeneity in open clusters: solar analogs in the Pleiades



Spina et al. 2018

Final remarks

Precision Spectroscopy (0.01 – 0.02 dex) of stellar twins in field stars, binaries, open clusters and globular clusters, is a powerful tool for studies related to planets, stellar evolution, stellar populations and galactic chemical evolution

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INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS

SAMPA

Stellar Atmospheres, Planets and Abundances