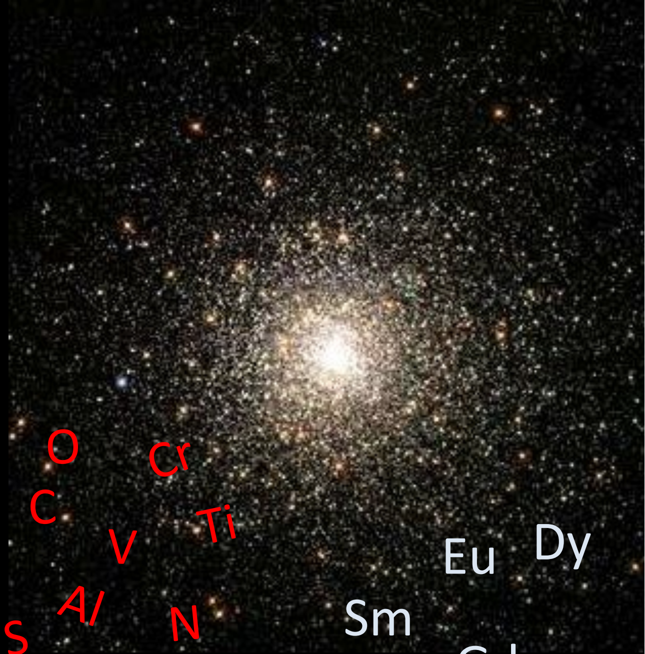
High Precision Chemical Abundances



@DrJorgeMelendez

Univ. São Paulo, Brazil

SAMPA

Stellar Atmospheres, Planets and Abundances

@DrJorgeMelendez

@DrJorgeMelendez

@DrJorgeMelendez

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]

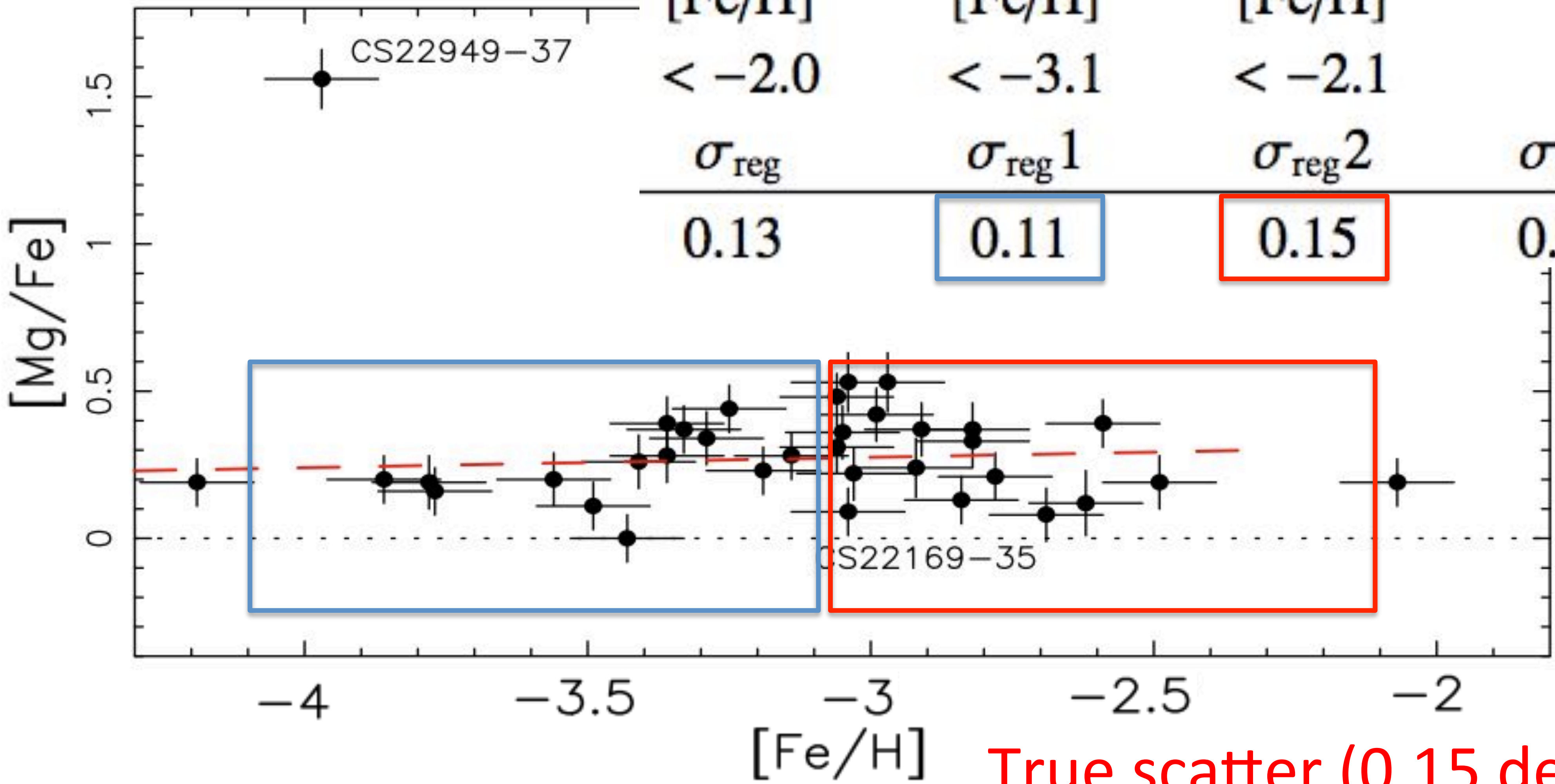
[1]Department of Astronomy, University of Texas, Austin, TX 78712, USA
email: chris@verdi.as.utexas.edu

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?

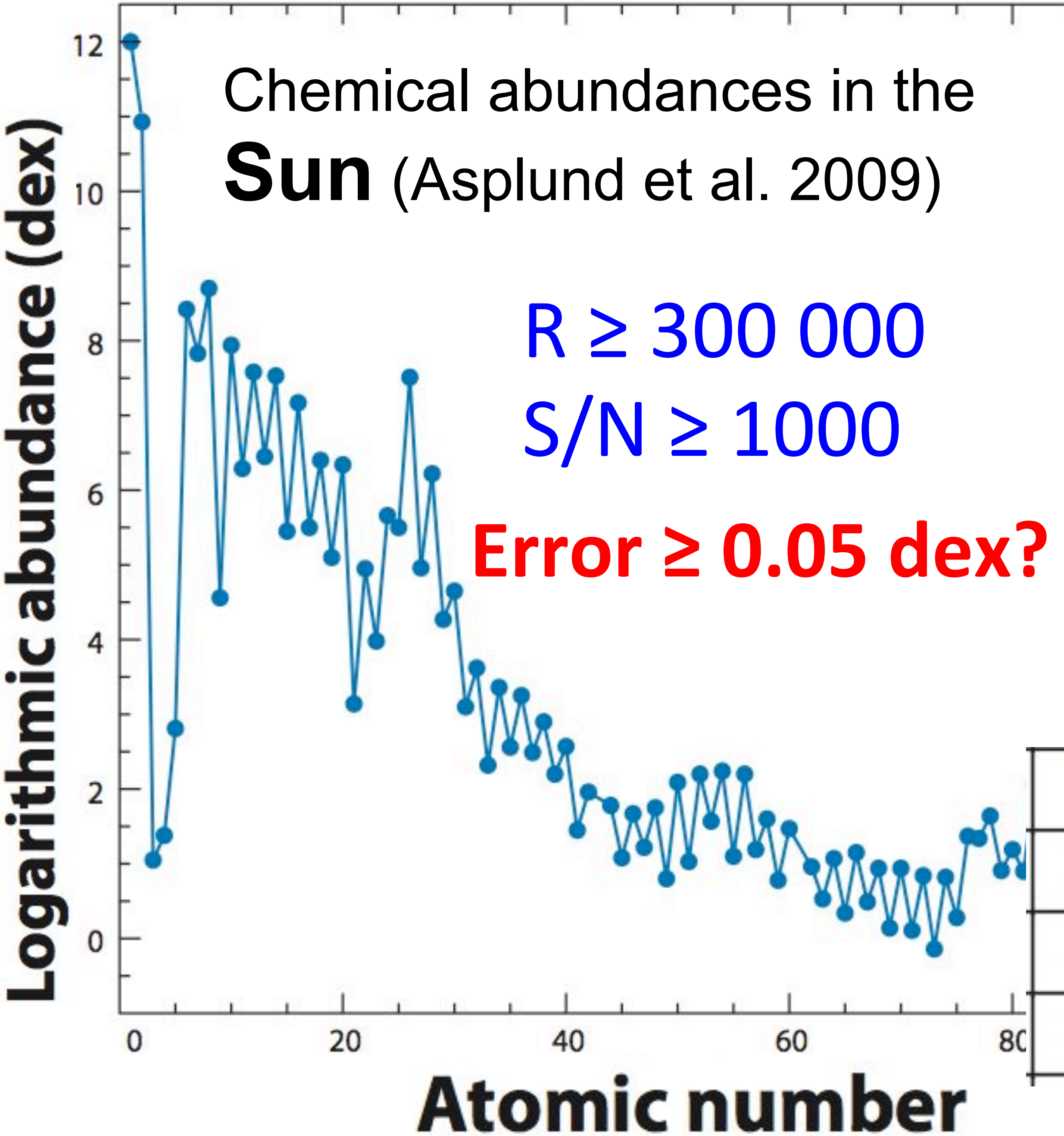
Cayrel et al. 2004

$-4.1 <$ [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	0.11	0.15	0.09



True scatter (0.15 dex)?

What is the limit in abundance precision?



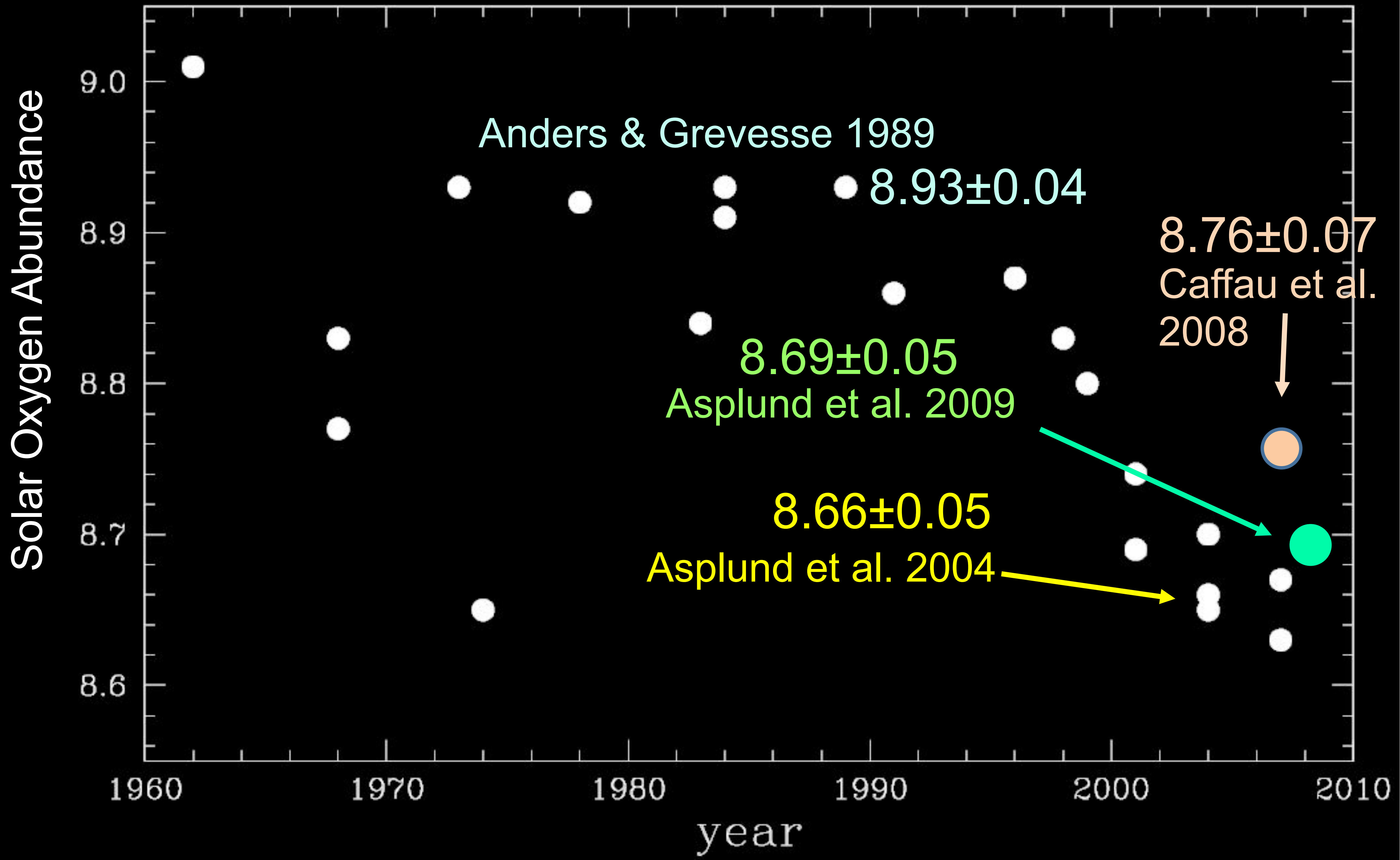
Chemical abundances in the **Sun** (Asplund et al. 2009)

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?

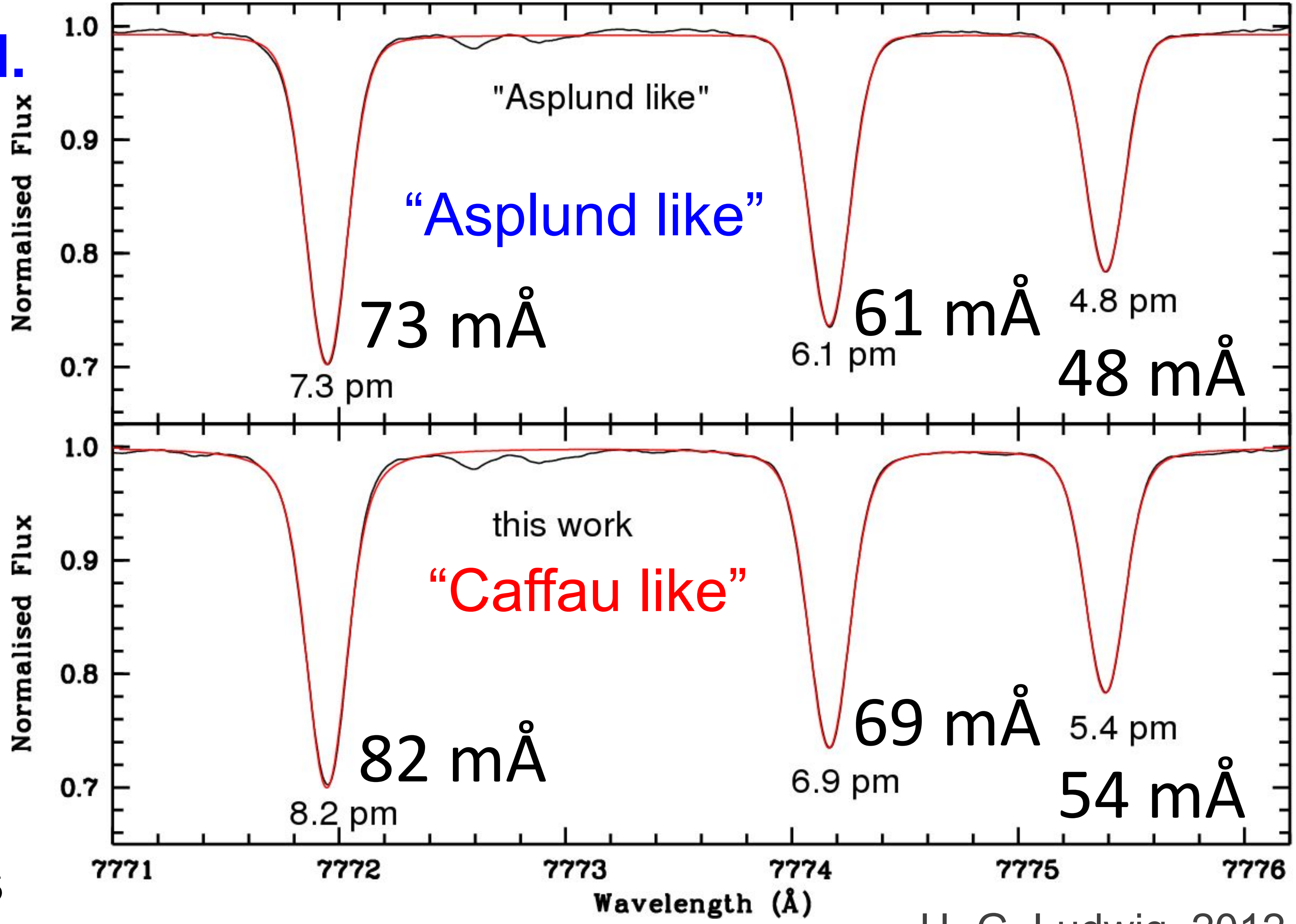


Caffau et al. vs. Asplund oxygen abundance

Asplund et al.
8.69 ± 0.05

Caffau et al.
8.76 ± 0.07

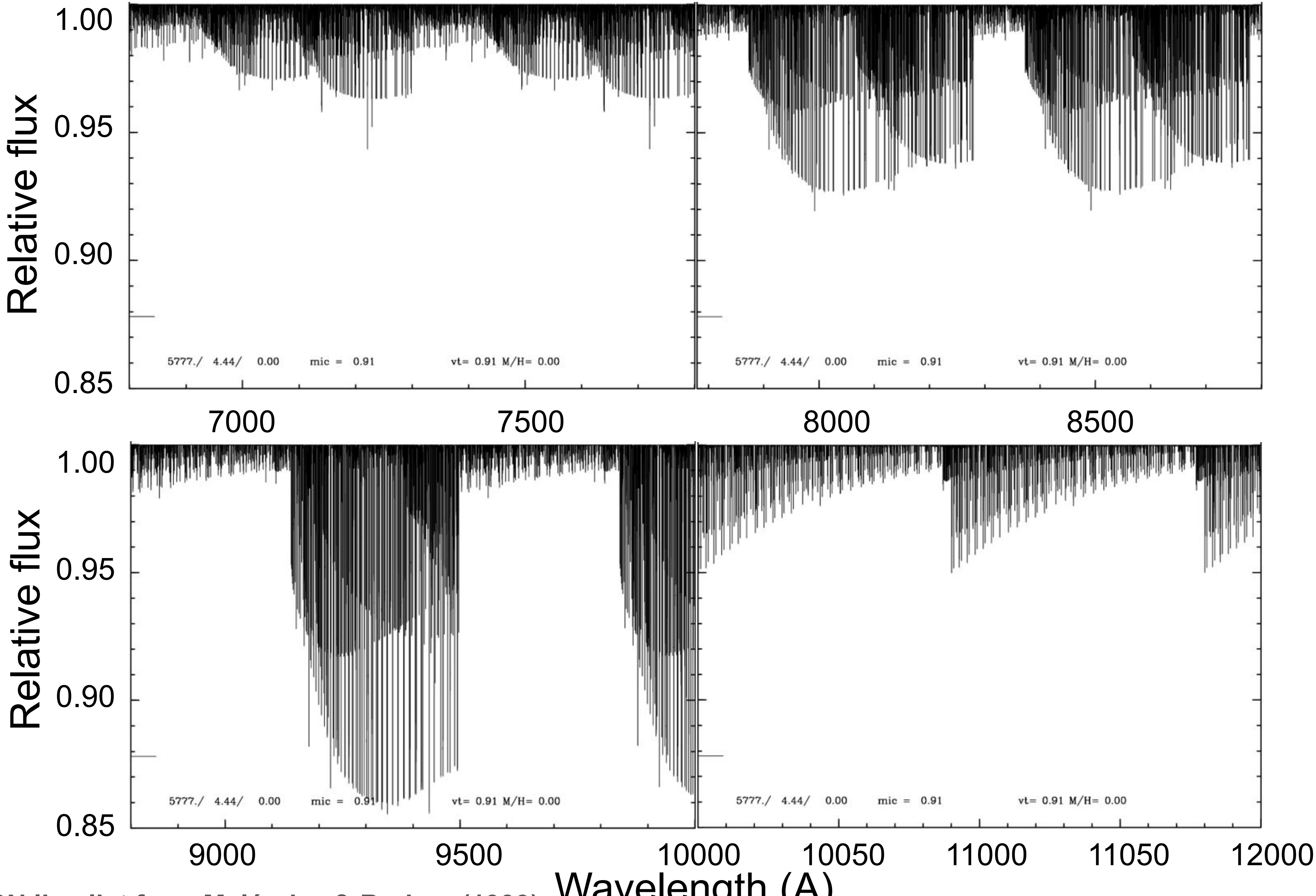
Main reason for discrepancy is the different set of EW measurements by both groups



H.-G. Ludwig, 2012

Who is correct?

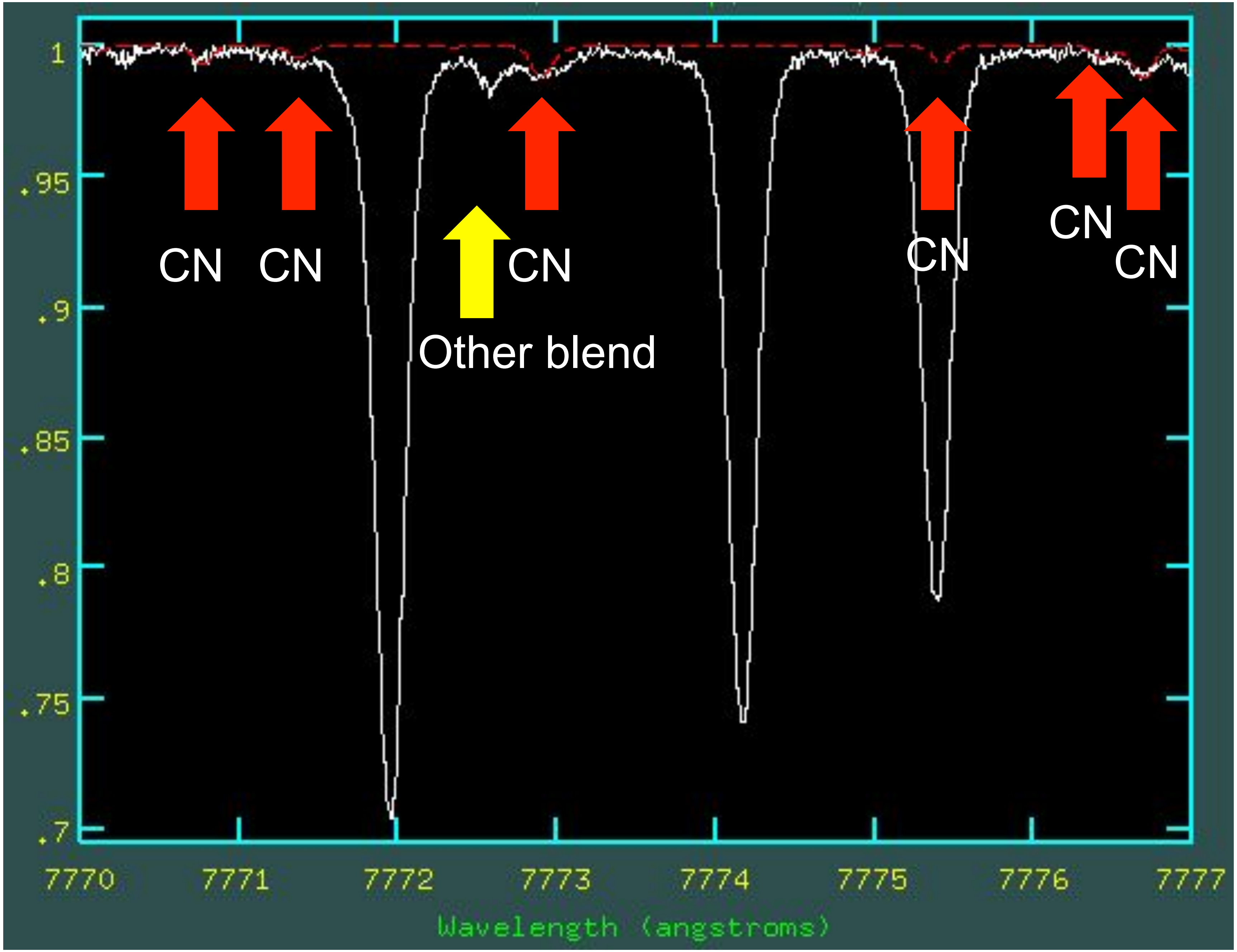
CN is ubiquitous in the solar spectrum



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



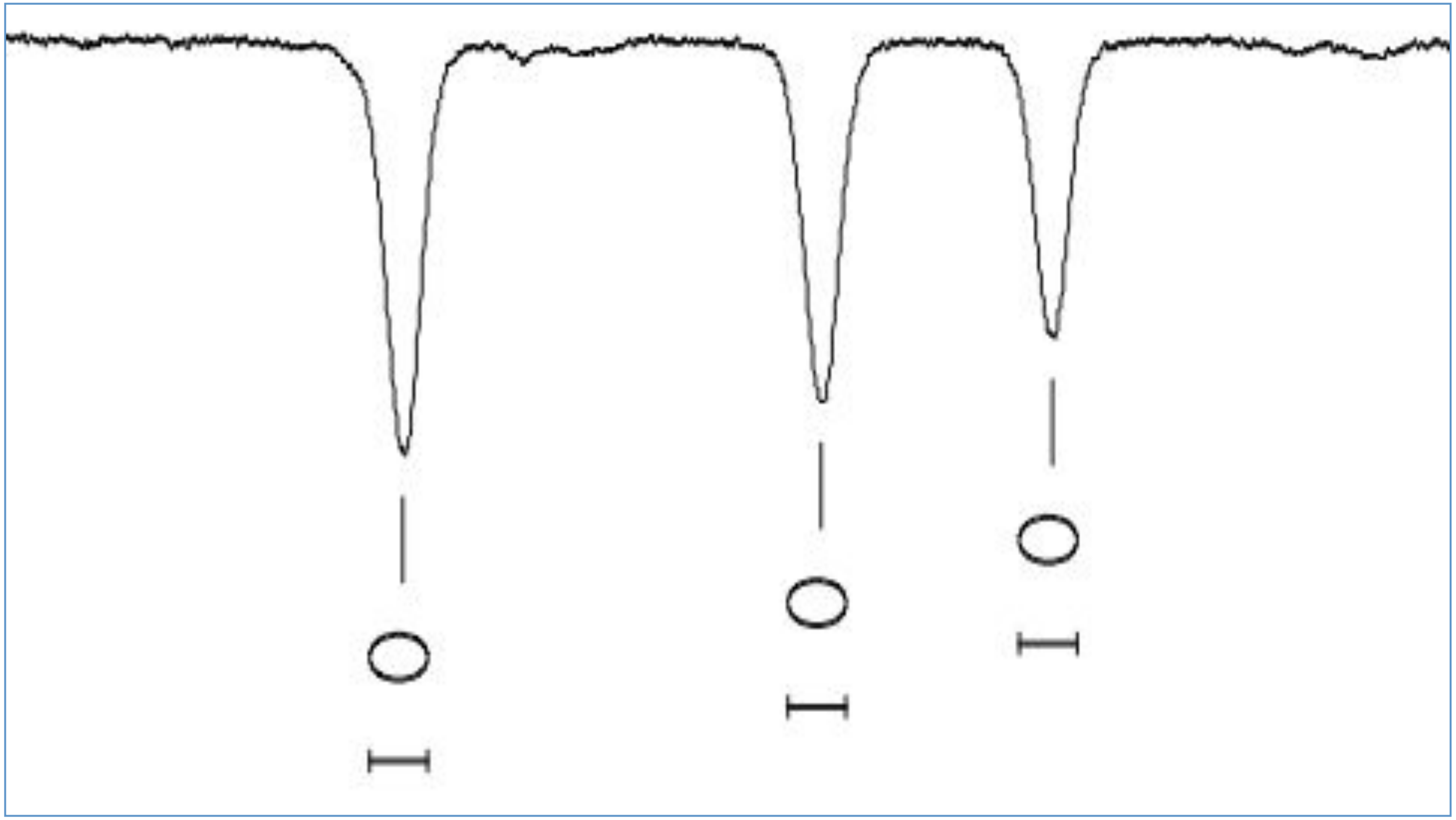
Comparison of equivalent widths for O I triplet

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

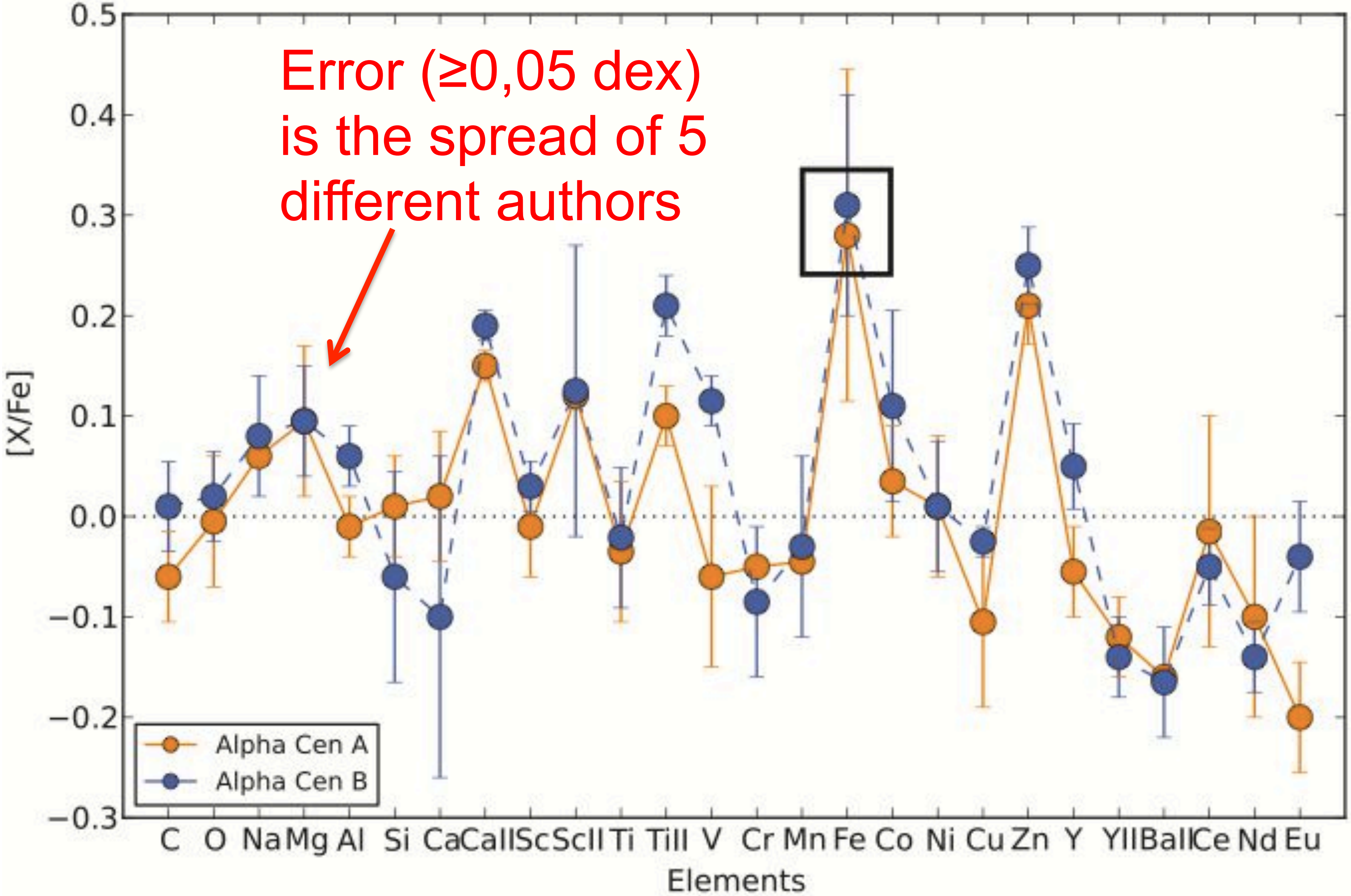
Asplund et al. E.W. may be underestimated by 3,5%

Caffau et al. EW may be overestimated by 8,2%

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



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 approach: *reduces model 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 efective temperartures

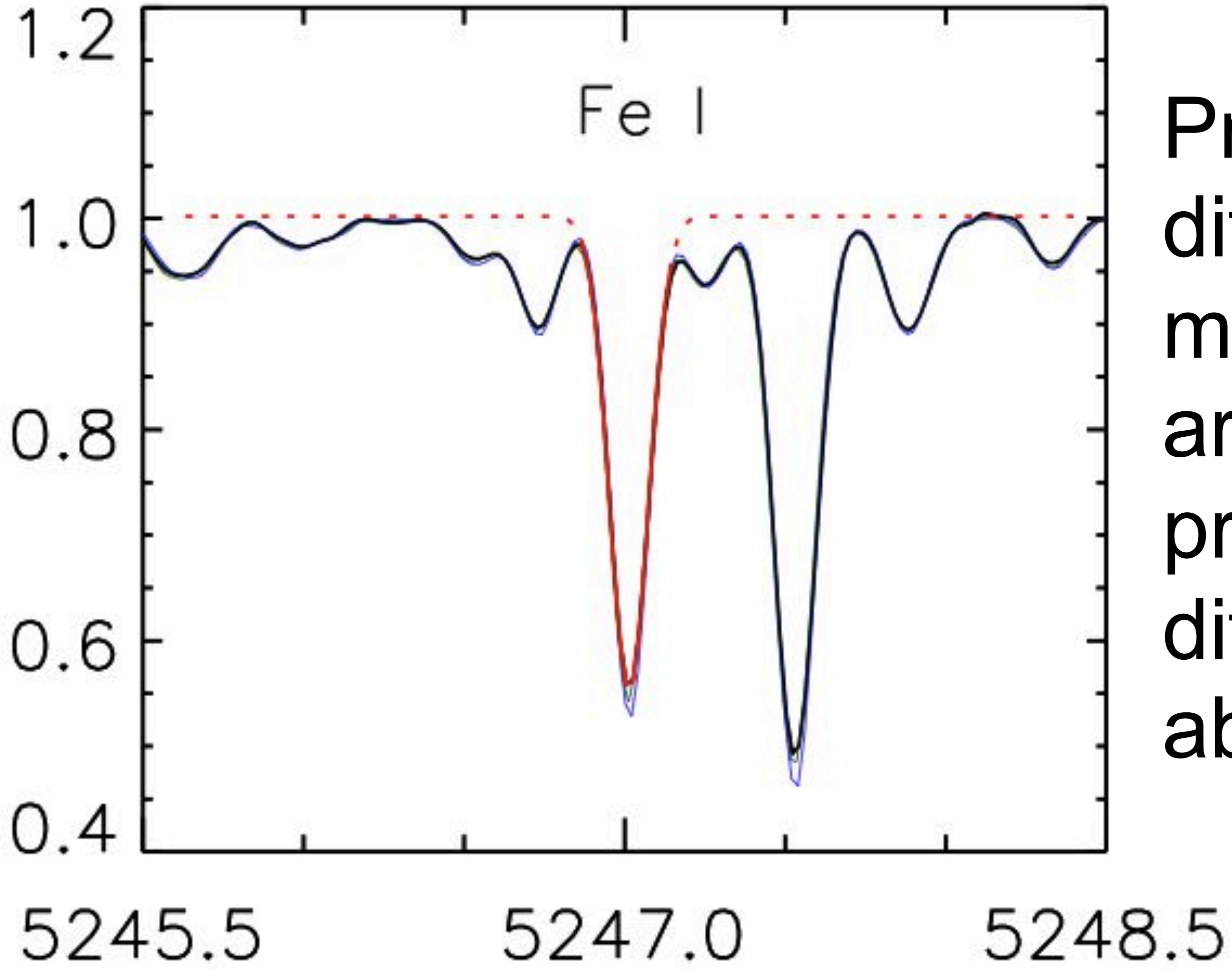
  - line-by-line cancel errors in gf-values

  - weak dependence on model atmospheres

Differential abundances A_X (element X)

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

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

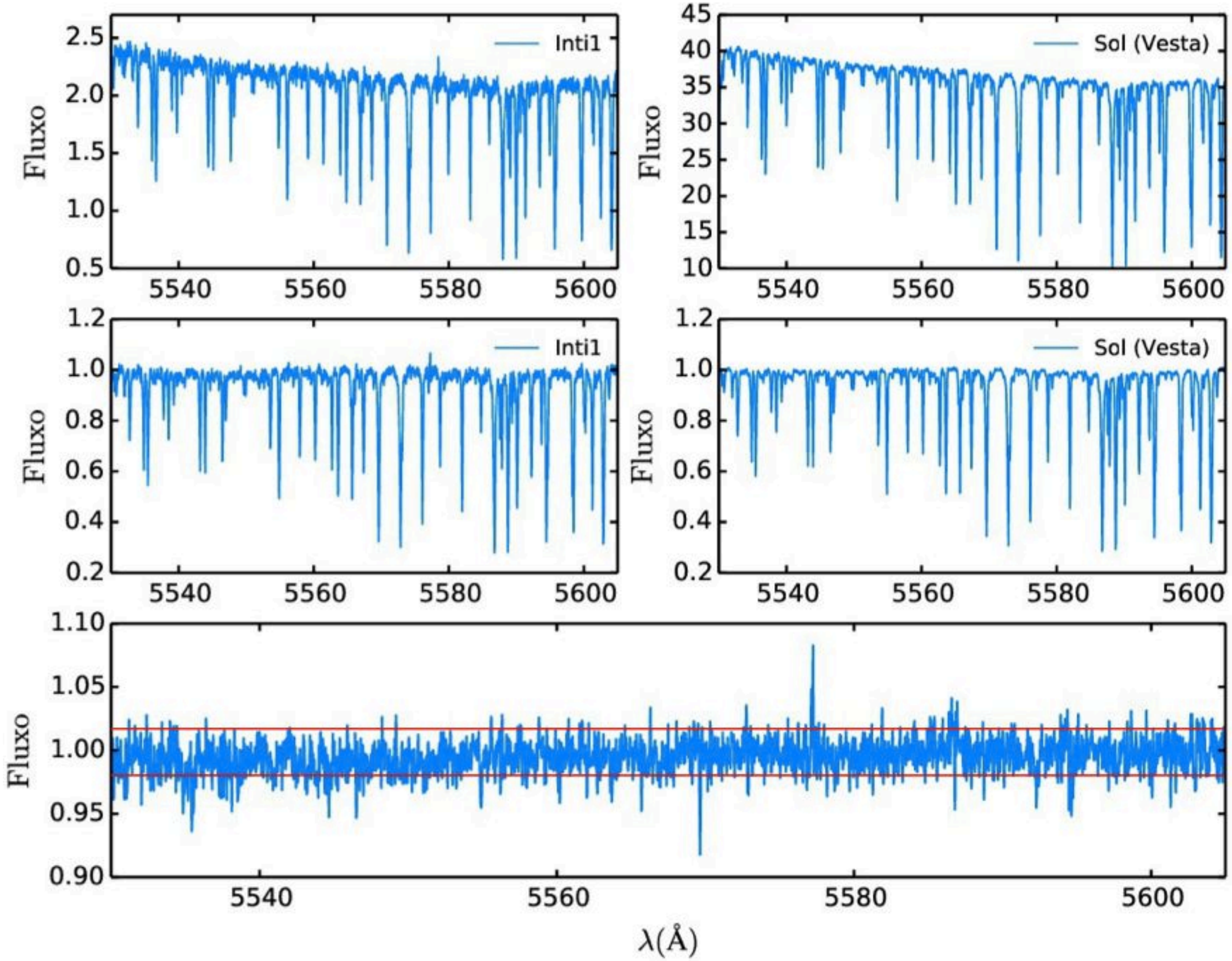


Precise differential EW measurements are key to precise differential abundances

Bedell, Meléndez, Bean et al. 2014

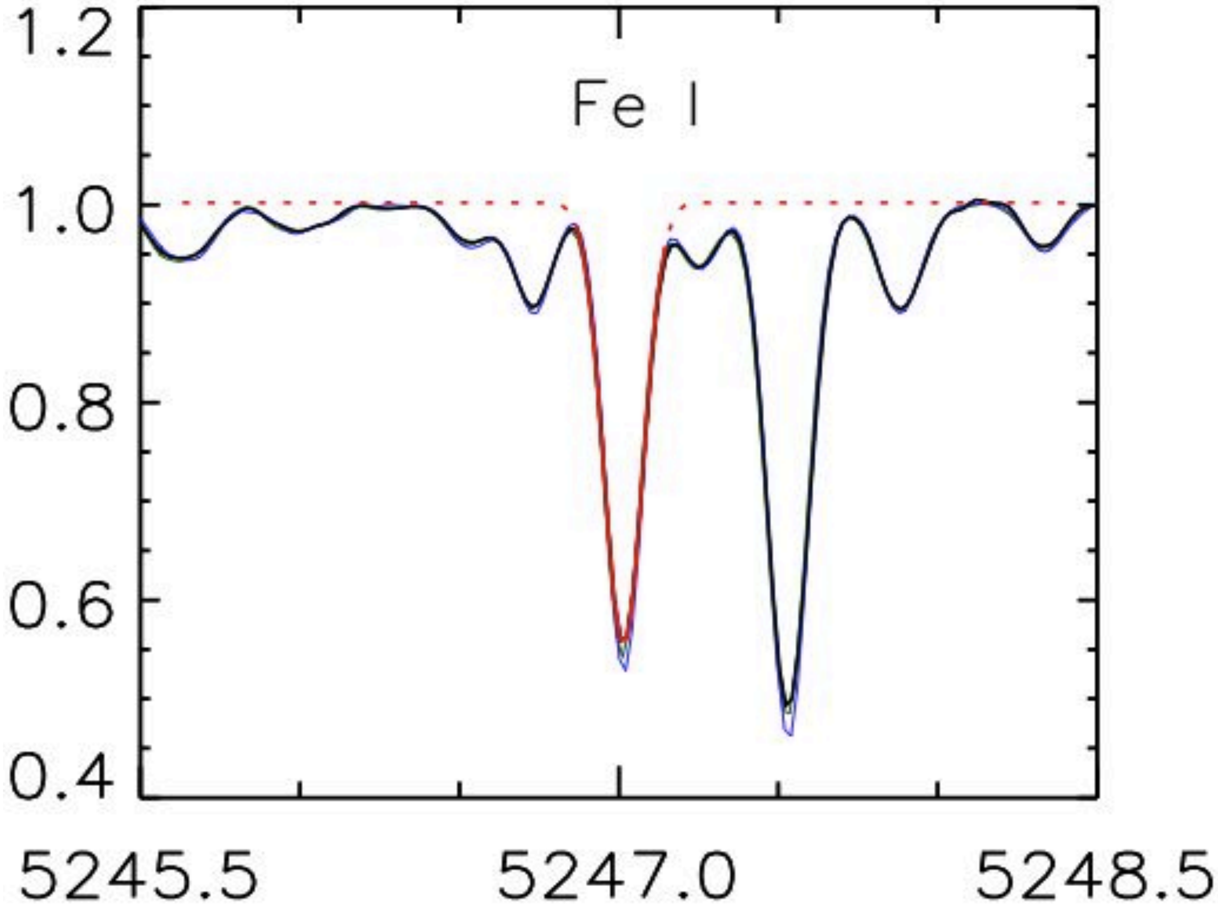
Some tips

- Try to do consistent observations using the same instrument/configuration
- Verify your relative continuum normalization



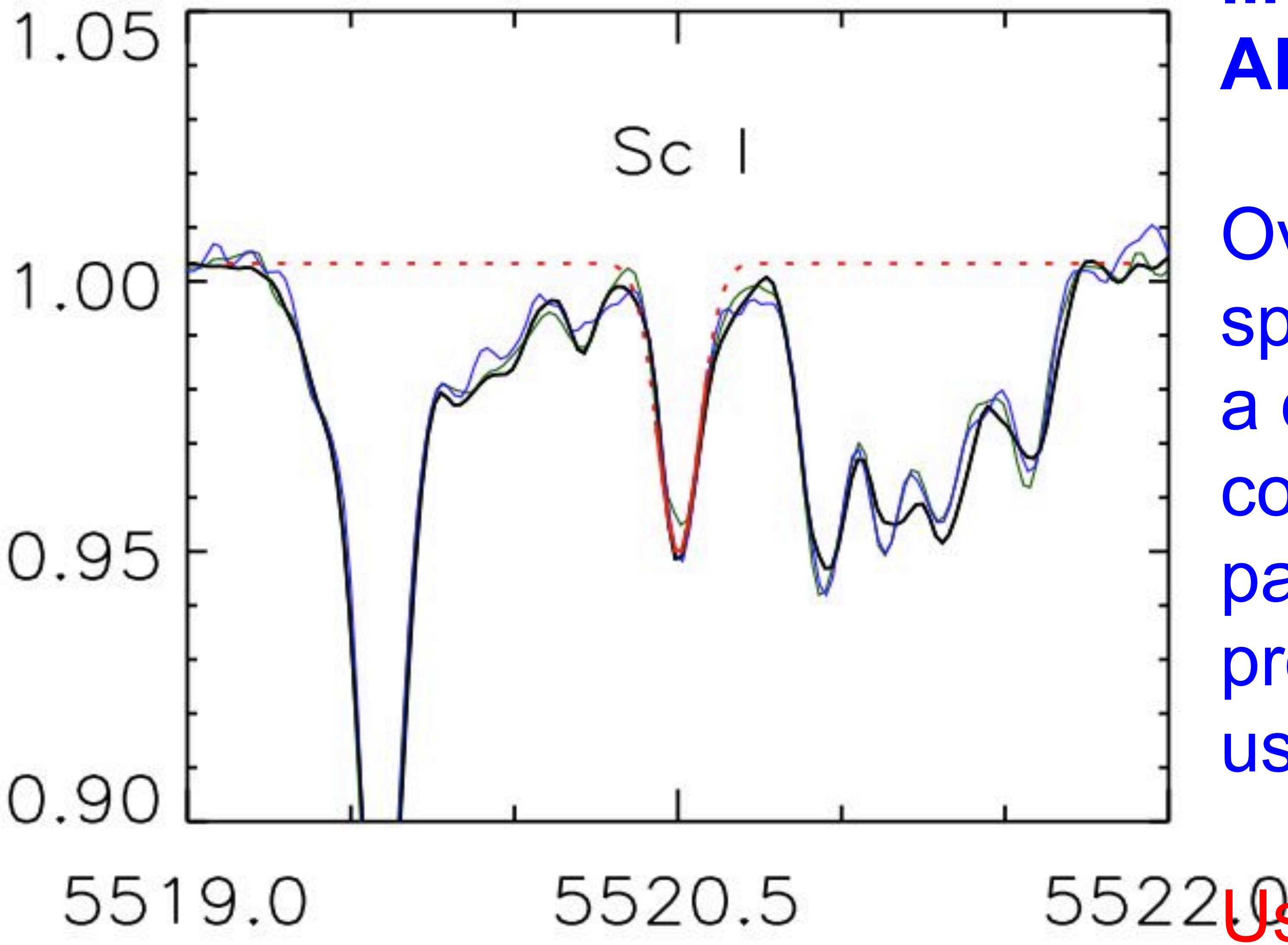
Measuring lines

- 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



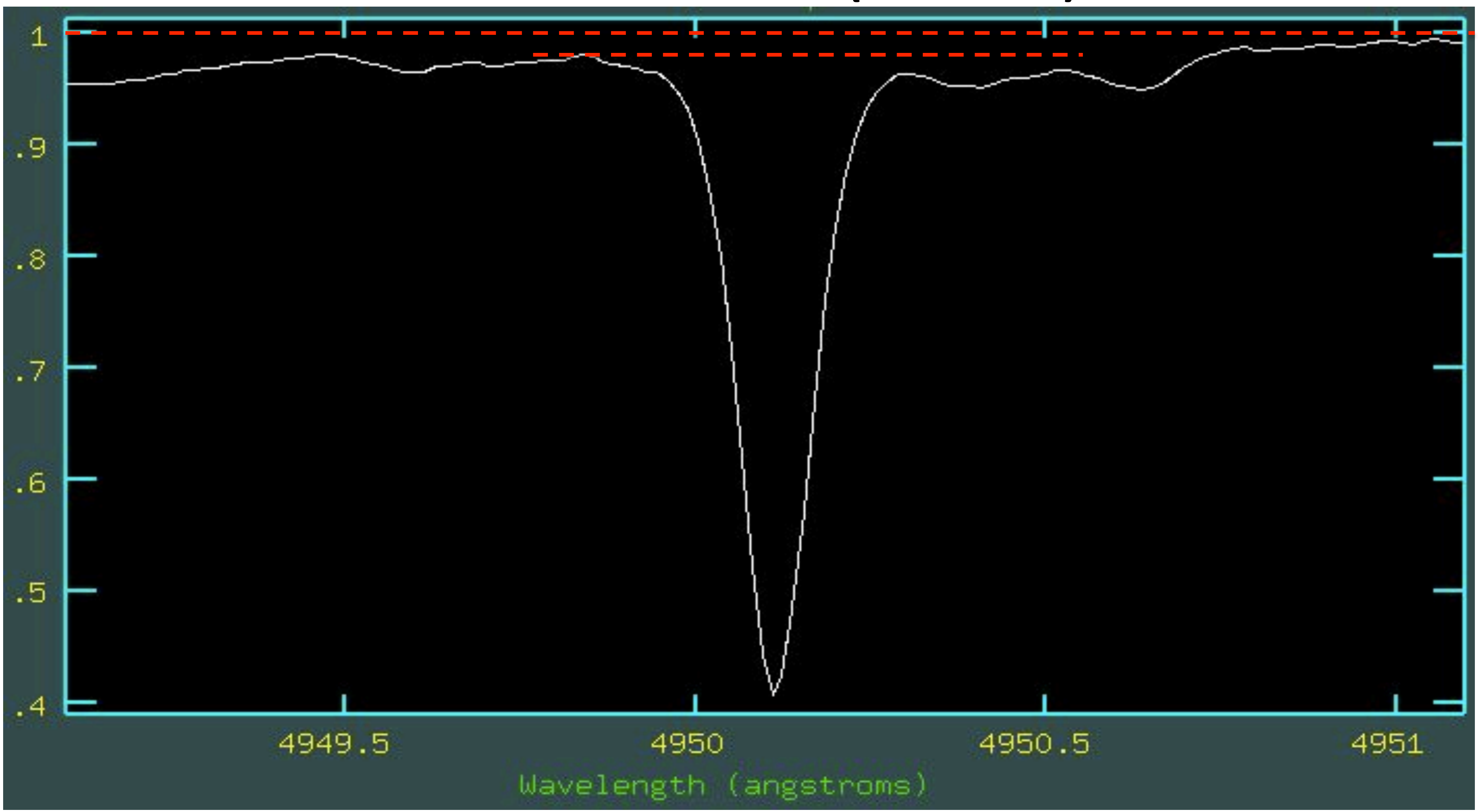
Bedell et al. 2014, ApJ, 795, 23

Measure one line at a time in ALL STARS.

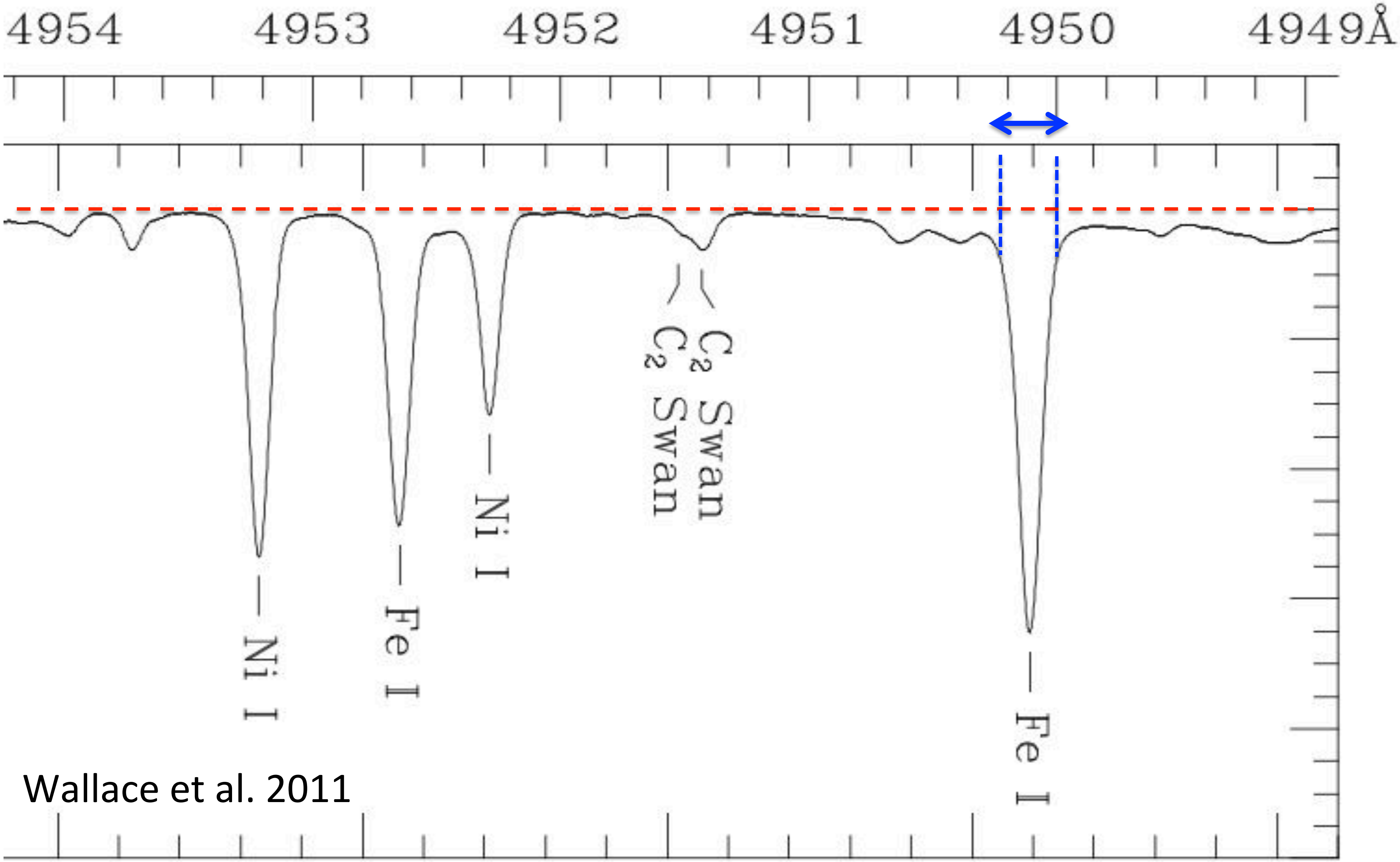
Overplot the spectra and make a decision about continuum and part of the line profile that will be used

Usual approach is to measure ALL LINES in one star

Continuum region too small (±1Å)
Better to use (±2,5Å)



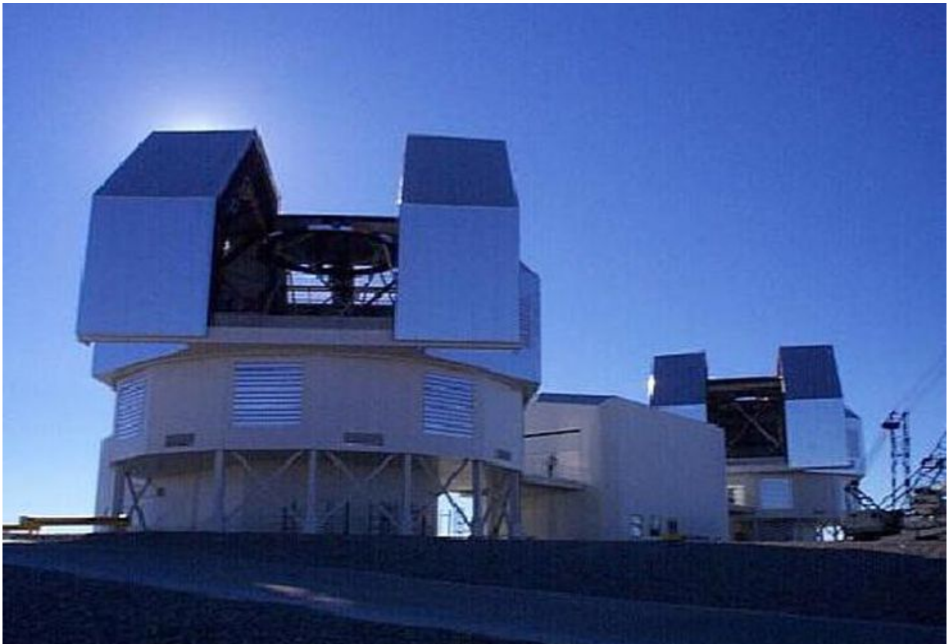
Verifying continuum & profile limits with solar atlas



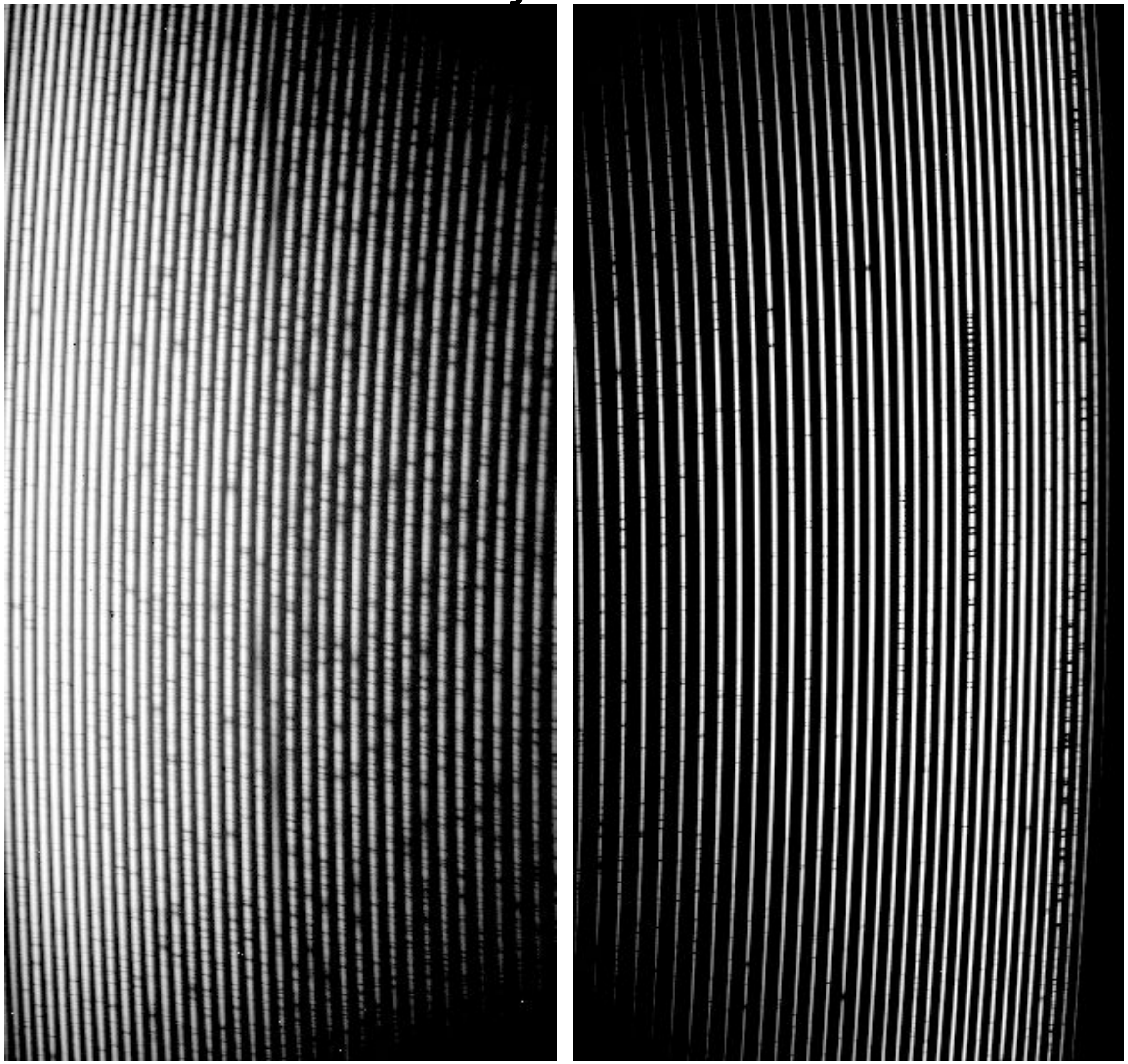
Wallace et al. 2011

Experiment using solar twins

- Magellan 6.5m Telescope & Mike spectrometer
- R = 65,000
- S/N = 450 per pixel
- coverage 340 – 1000 nm
- Solar spectrum: Vesta
- 3 nights of observations

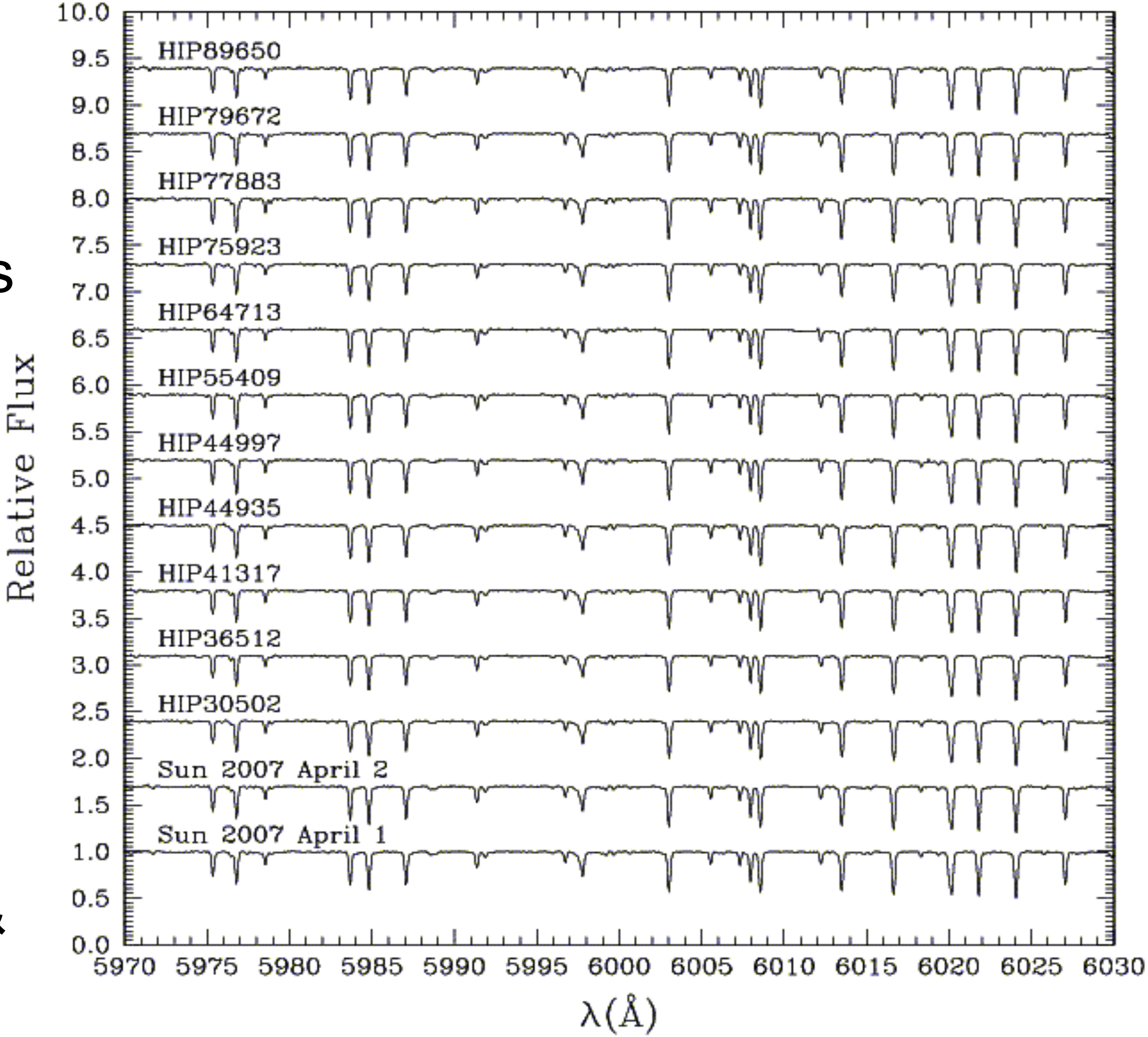


Observations of the solar twin 18 Sco



BLUE frame **RED frame**

Example of Magellan spectra of 11 solar twins and the Sun *(total spectral coverage 3350 A -1μm)*

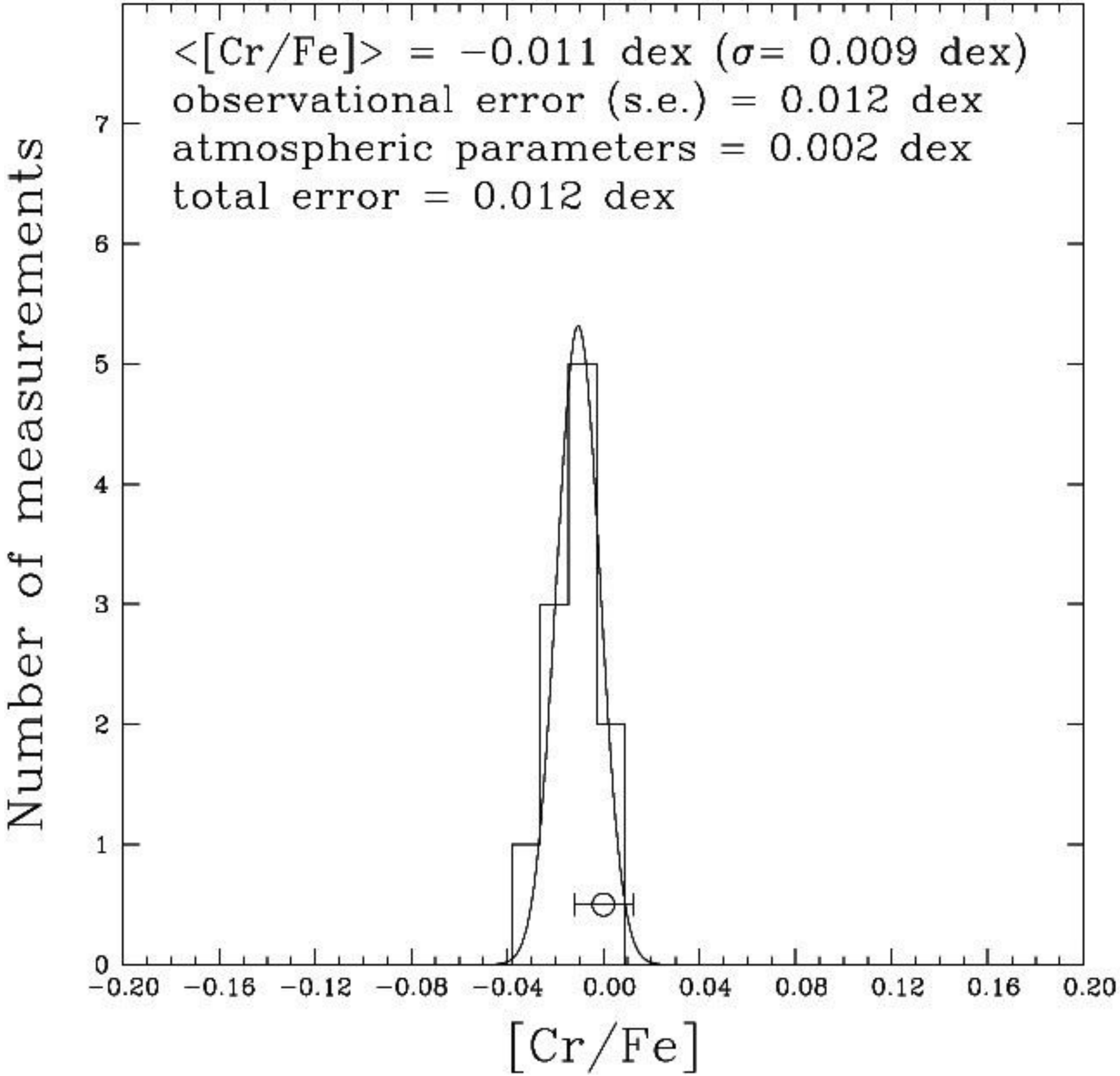


Small part (597-603nm) of solar twin & Sun's spectra

Meléndez et al. 2009, ApJ, 704, L66

[Cr/Fe] distribution in 11 solar twins

Star-to-star scatter of only **0.009 dex**

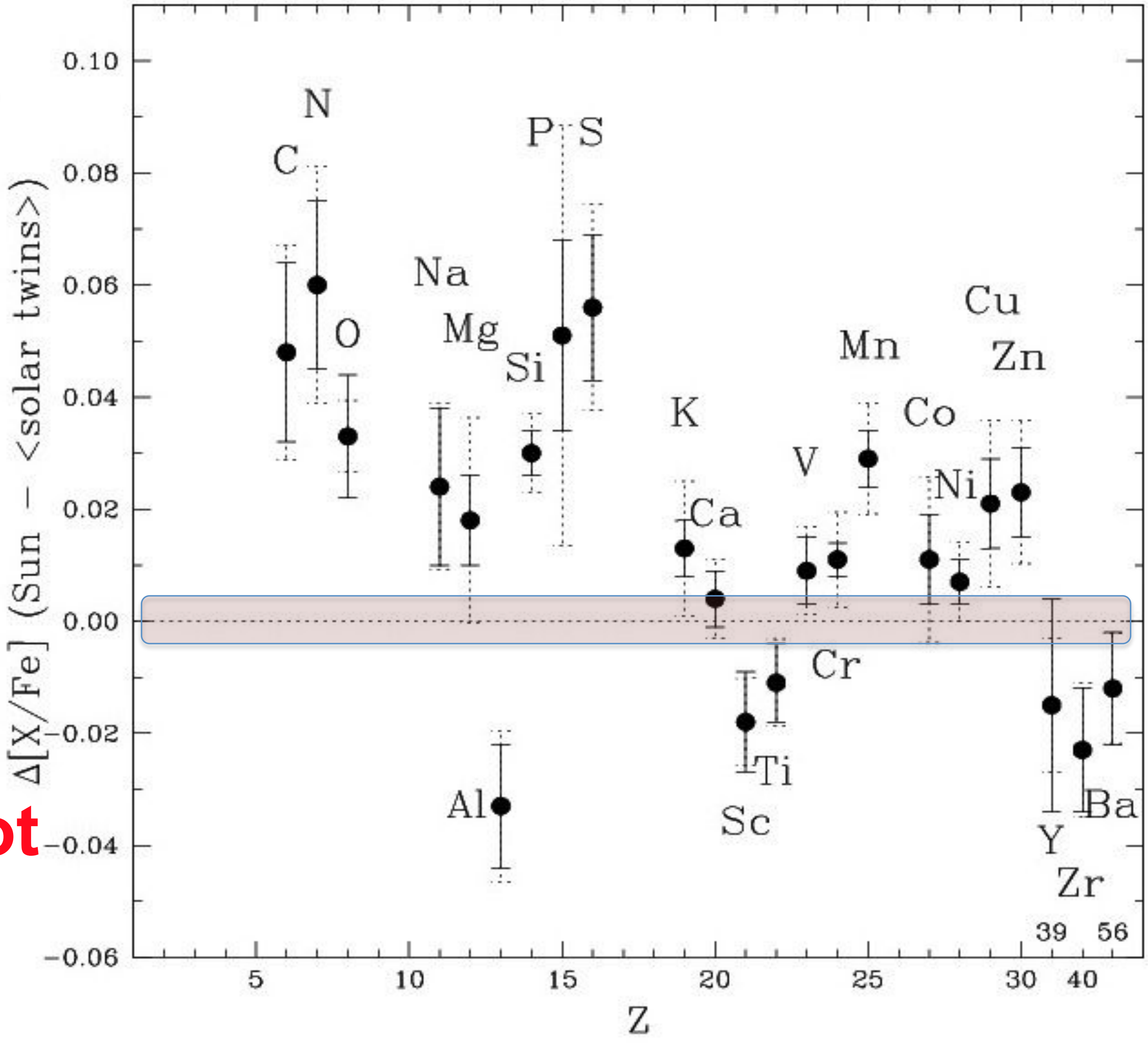


Δ abundance:
Sun - <twins>
vs. atomic
number Z

Sun typical :
Δ = 0

Sun weird :
Δ ≠ 0

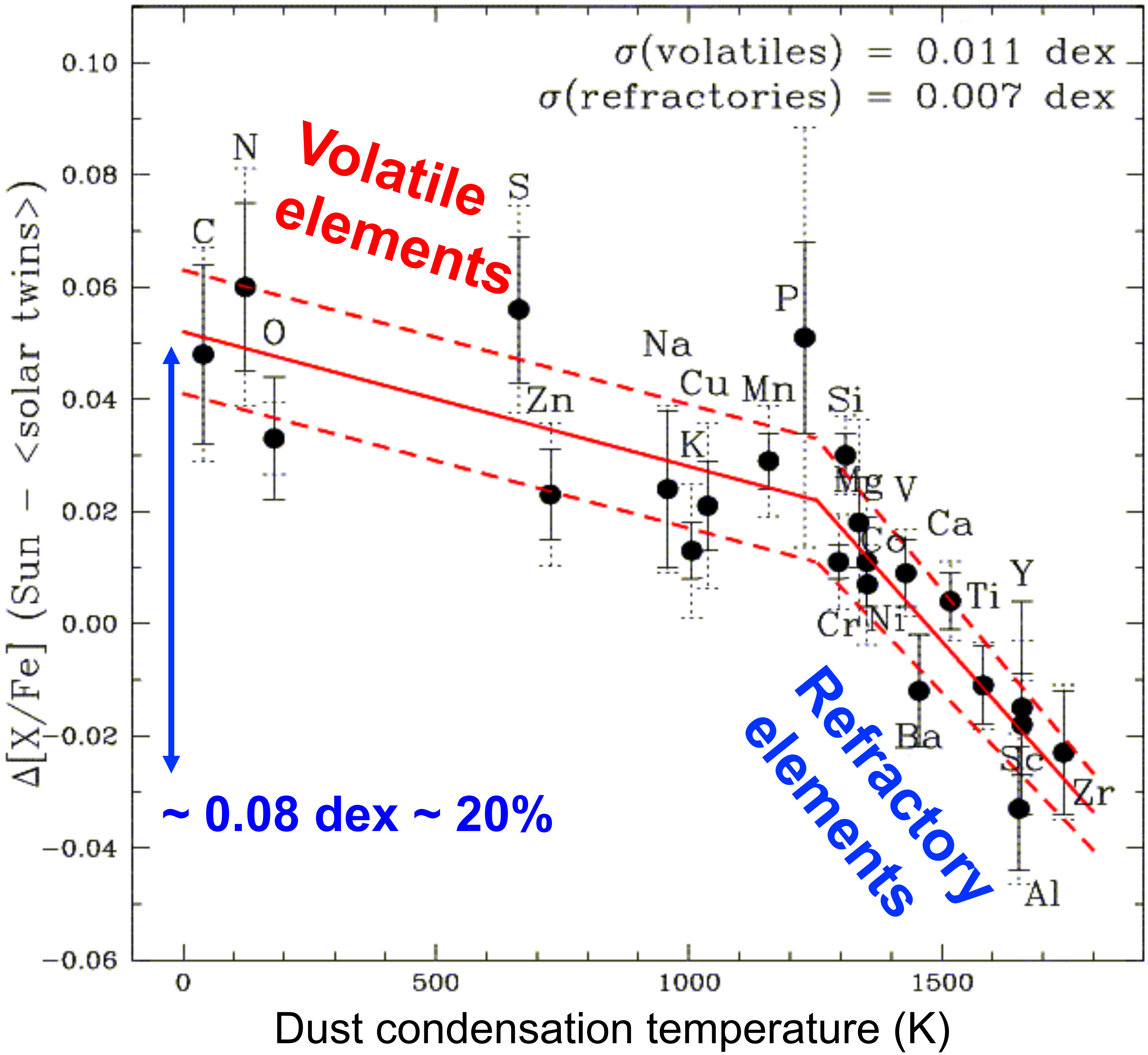
Our solar system is not host by a typical 'Sun'



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

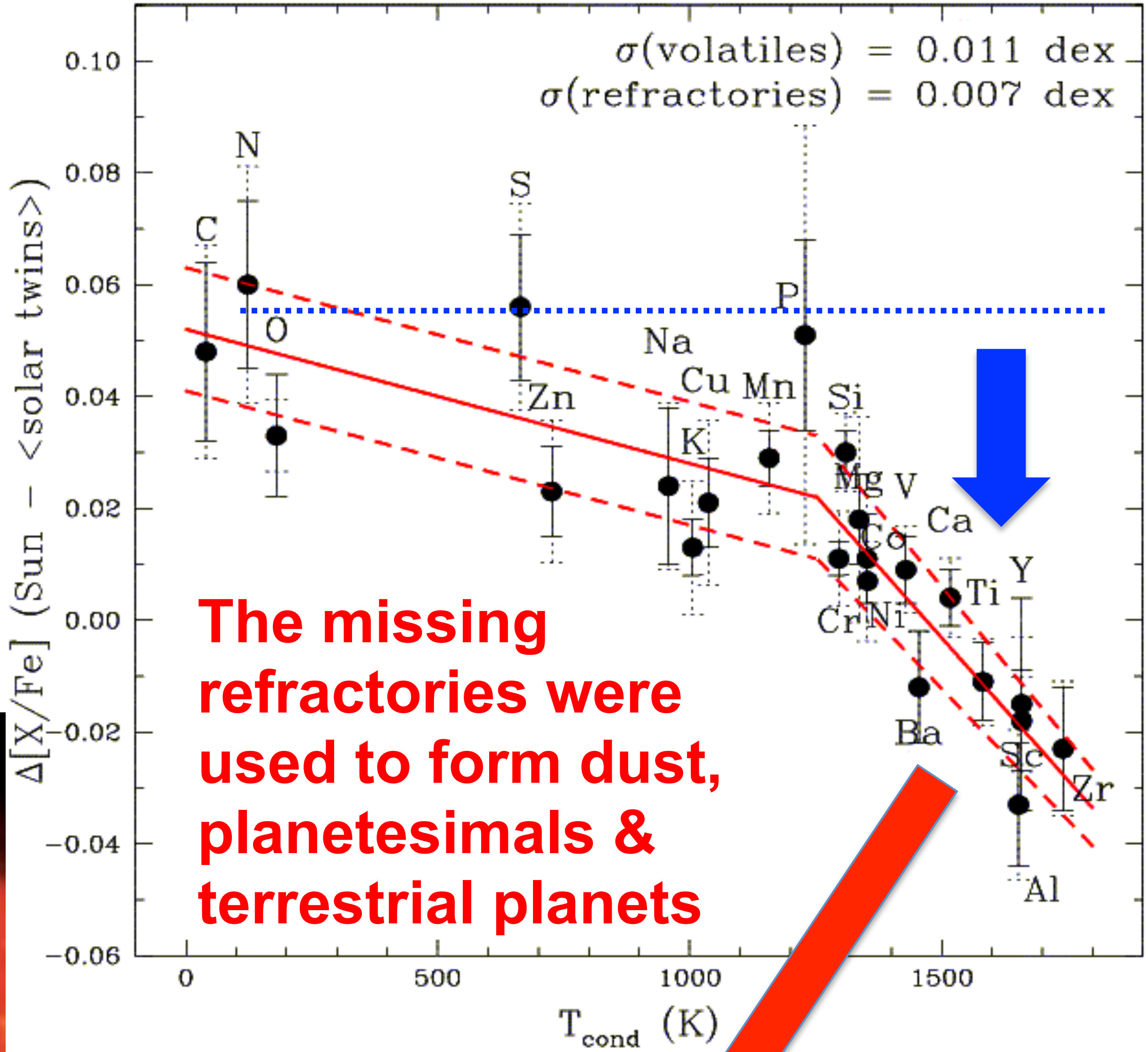
Correlation is highly significant probability ~**10^{-9}** to happen by chance

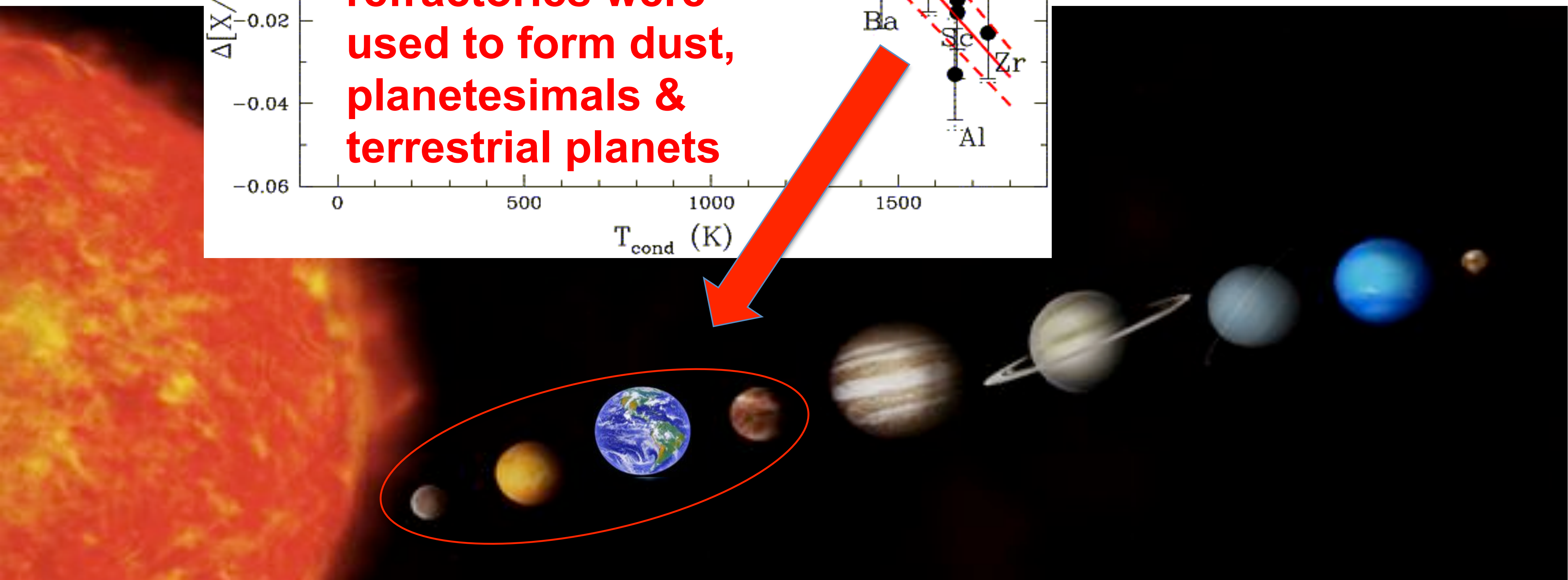
It's most likely to win the lottery



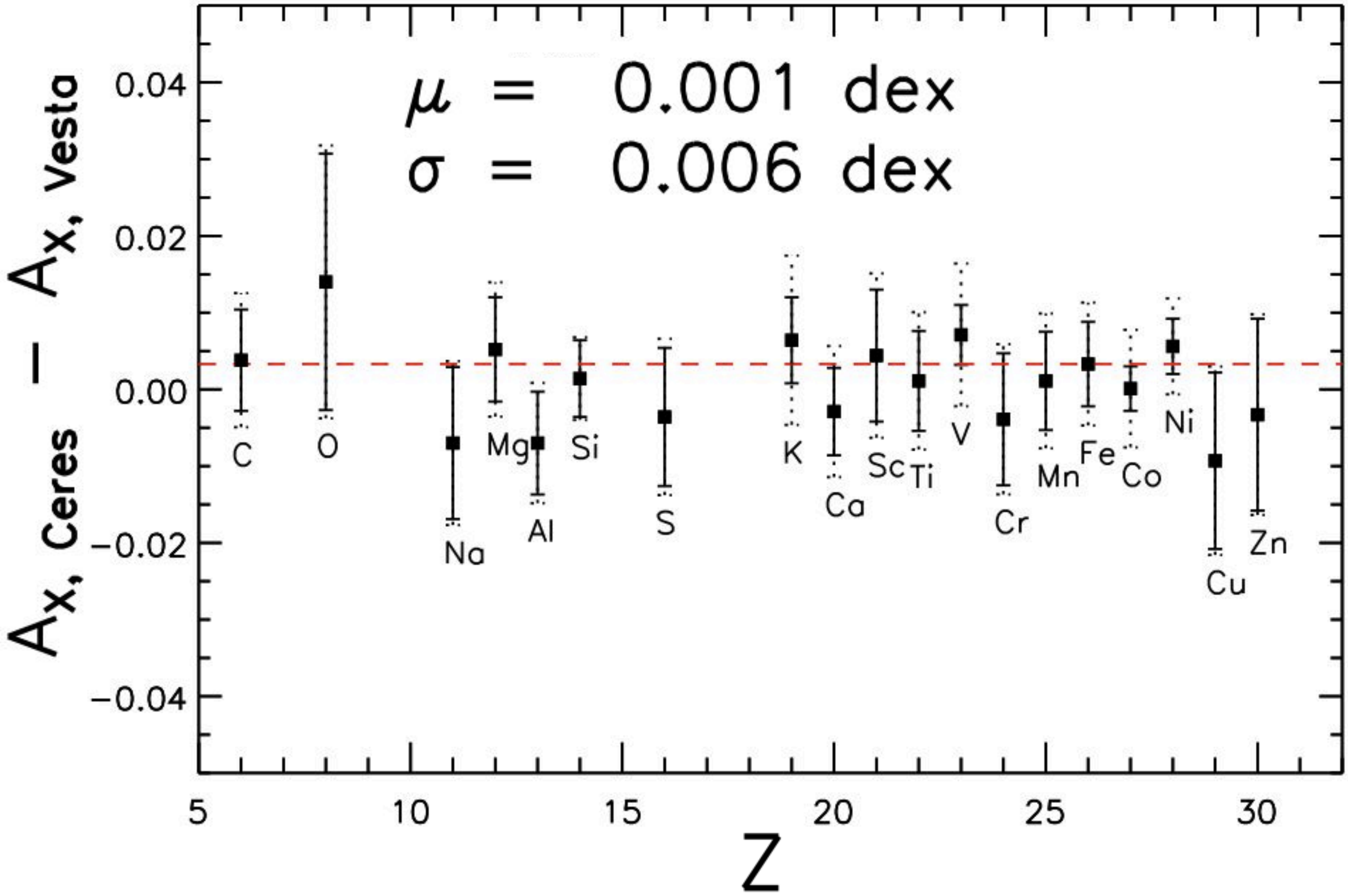
Meléndez, Asplund, Gustafsson, Yong 2009, ApJ Letters

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



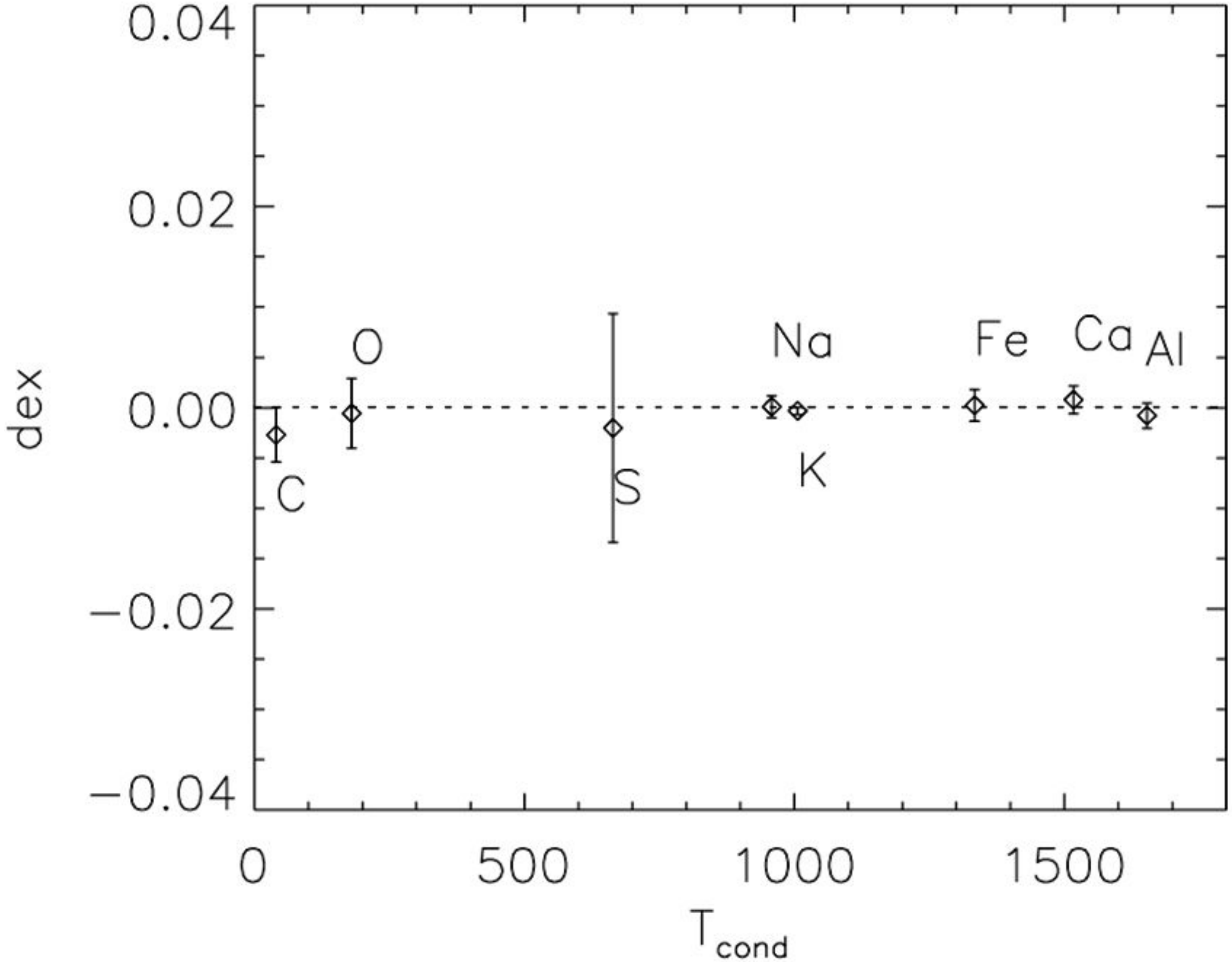


Test using asteroids: scatter of 0.006 dex



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

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



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,⋆⋆]

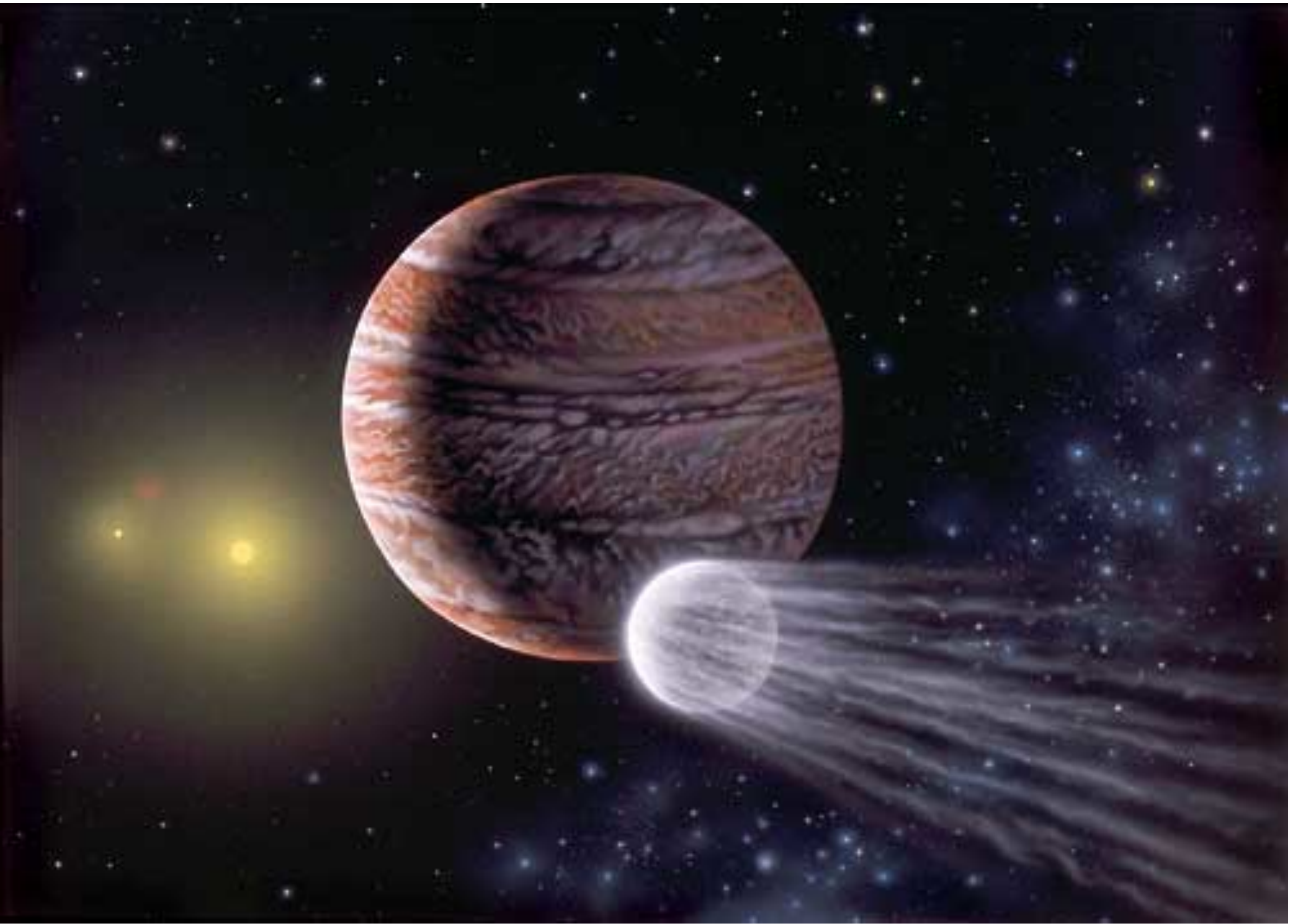
Planet effects in binary system with "twins"

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]

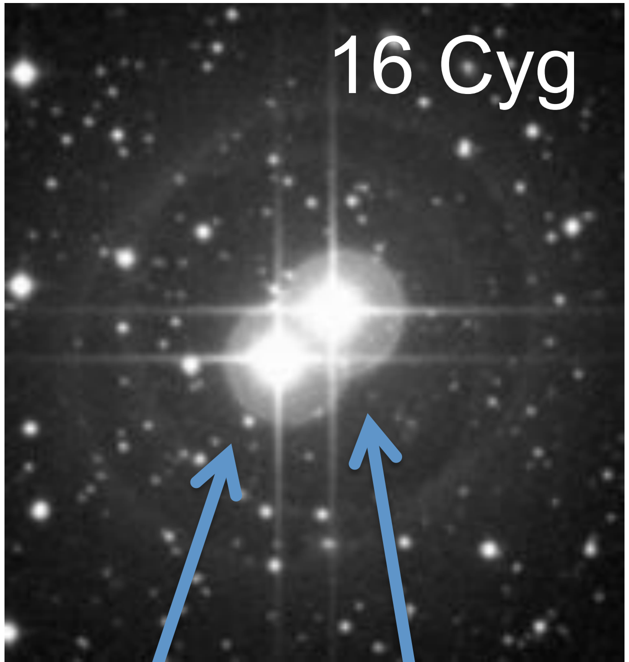
16 Cyg: widely separated pair of solar analogs



16 Cyg A : no planets

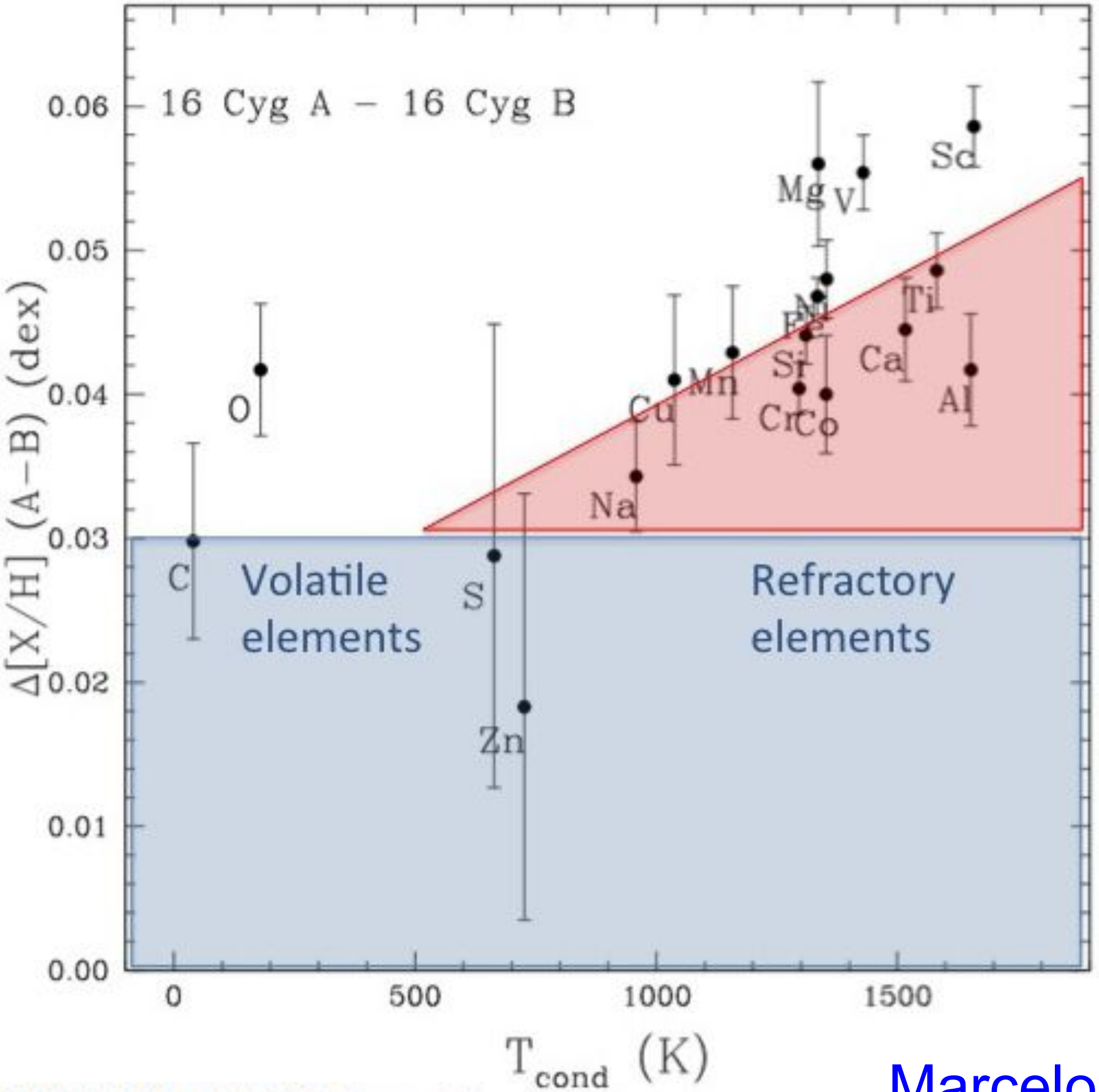
16 Cyg B : giant planet
(~ 2 M_J)

Signatures of giant planet formation: 16 Cyg binary



A: no planet

B: hosts a giant planet



Rocky accretion core

Giant planet's envelope

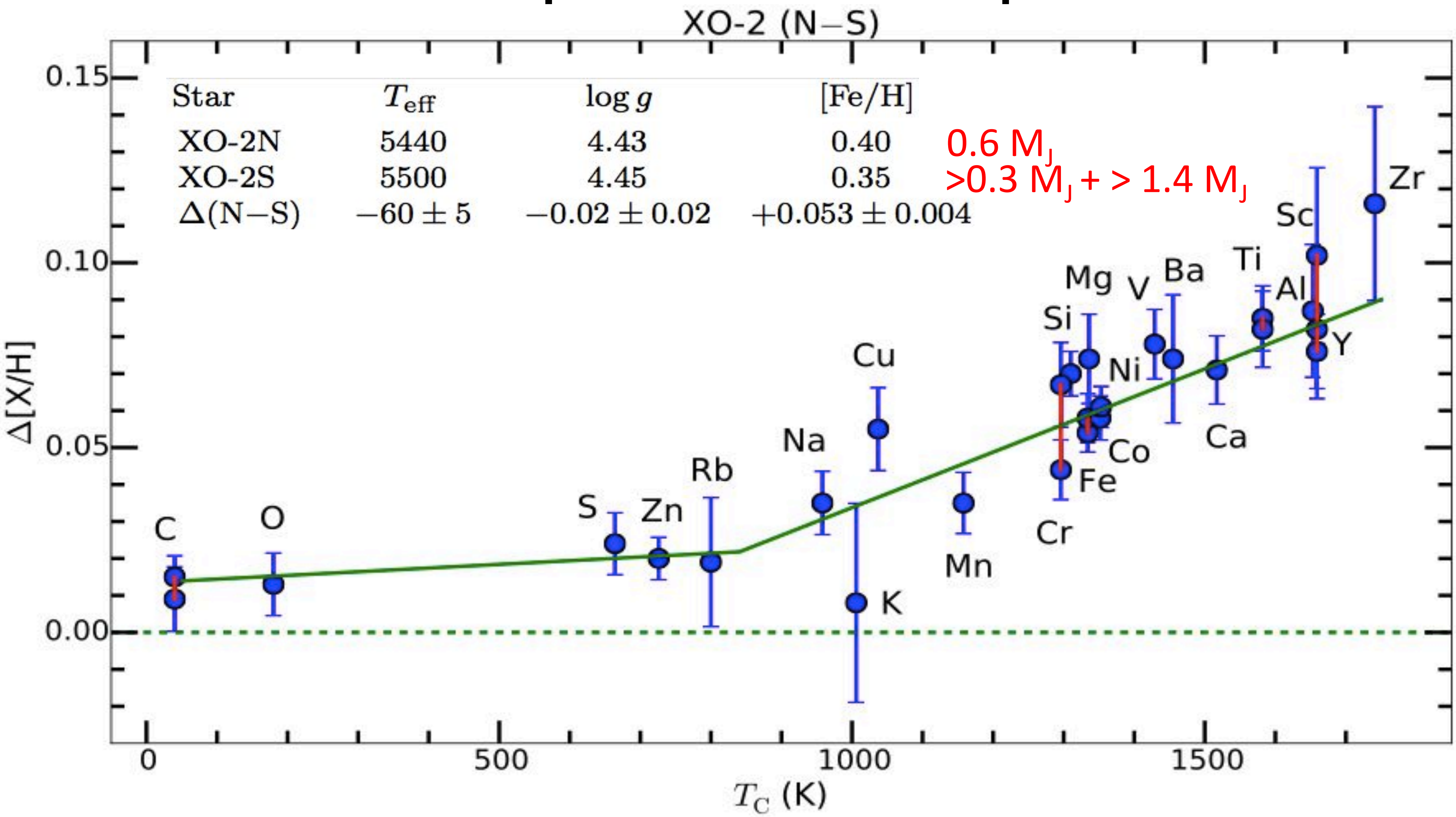
Marcelo Tucci Maia's talk 16:30 estrelas

The Astrophysical Journal Letters, 790:L25 (5pp), 2014 August 1

HIGH PRECISION ABUNDANCES IN THE 16 Cyg BINARY SYSTEM: A SIGNATURE OF THE ROCKY CORE IN THE GIANT PLANET*

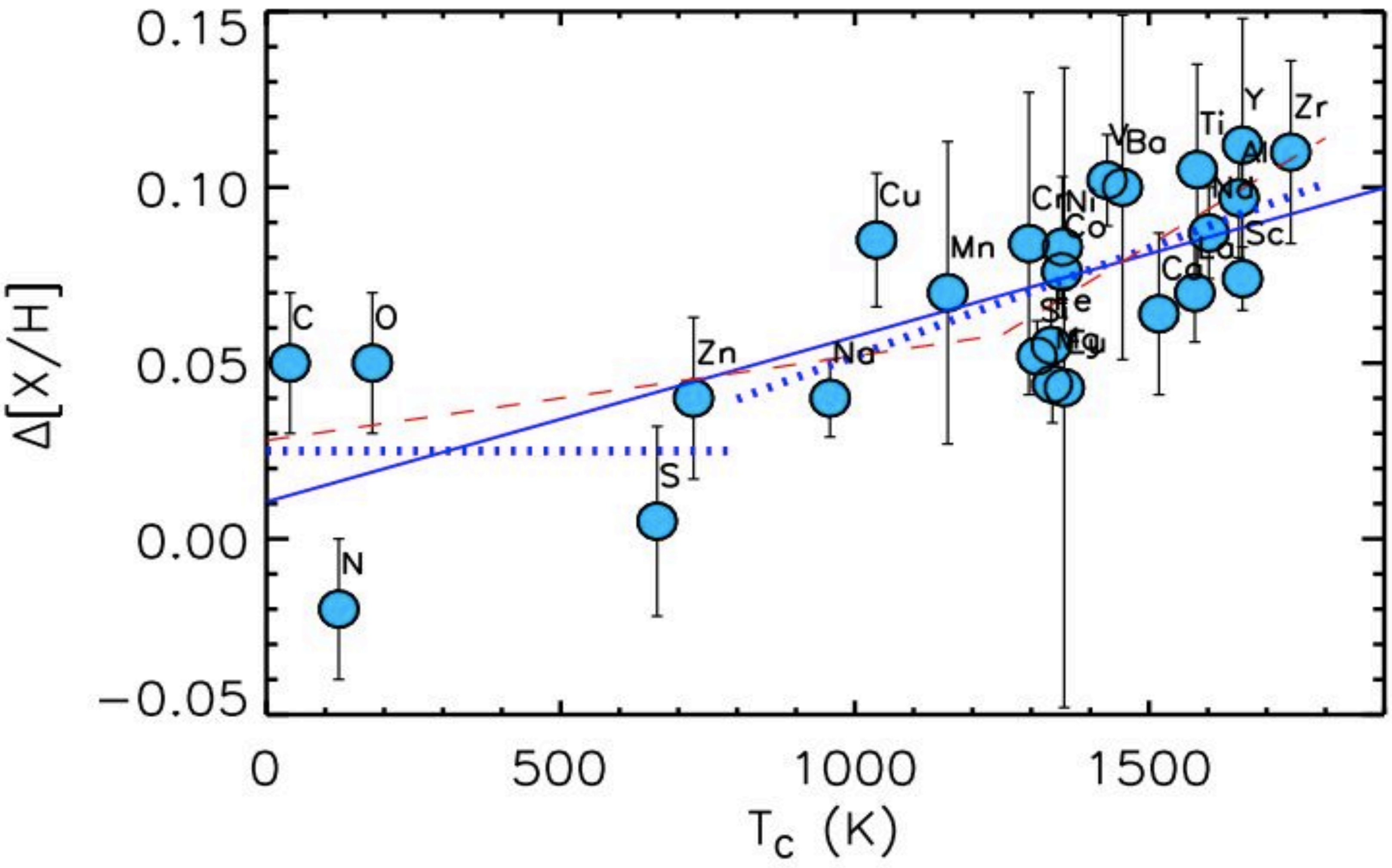
Marcelo Tucci Maia[1], Jorge Meléndez[1], and Iván Ramírez[2]

Another binary system: XO-2
Both components host planets



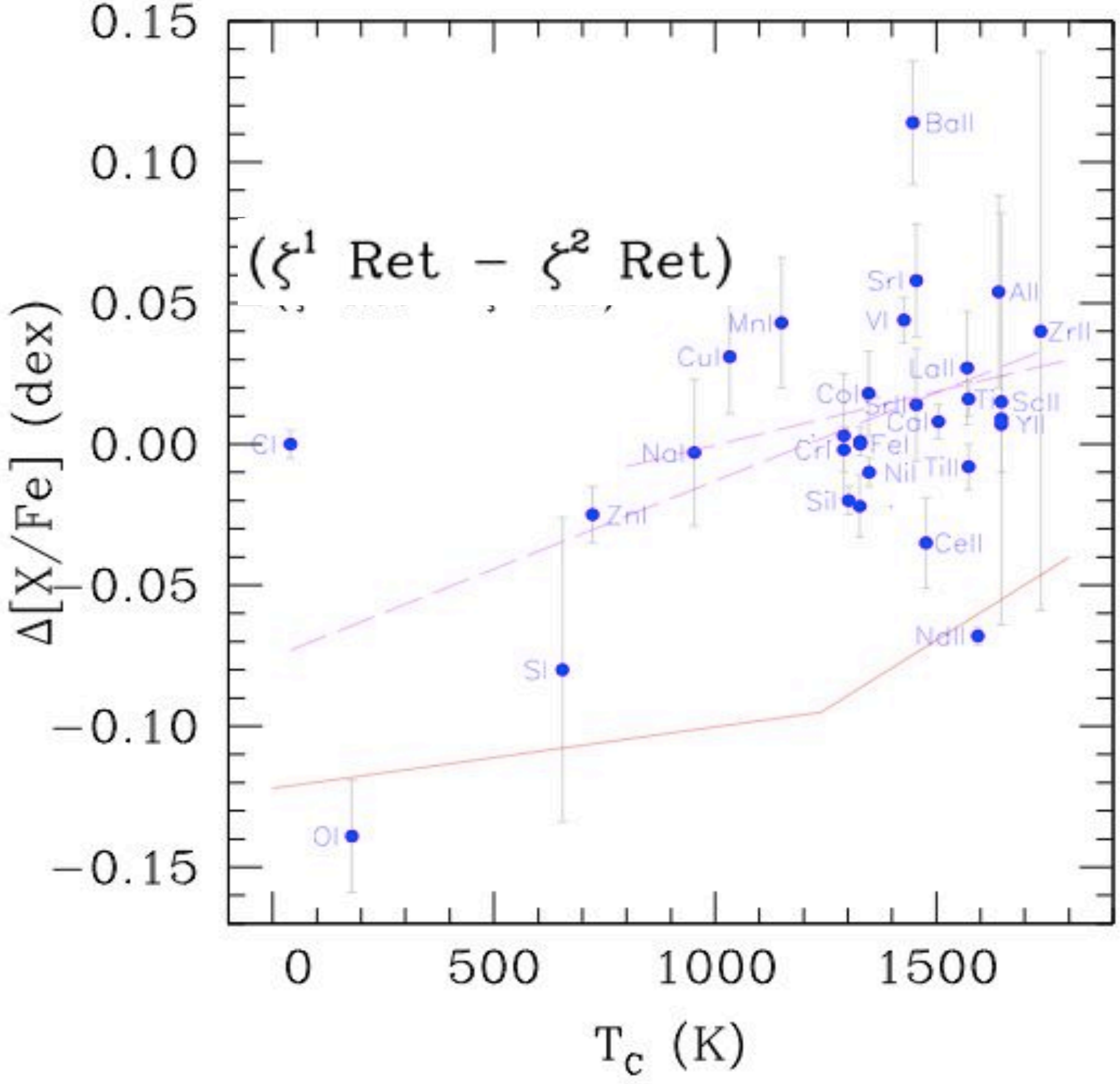
Ramírez et al. 2015. See also Teske et al. 2015; Biazzo et al. 2015

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



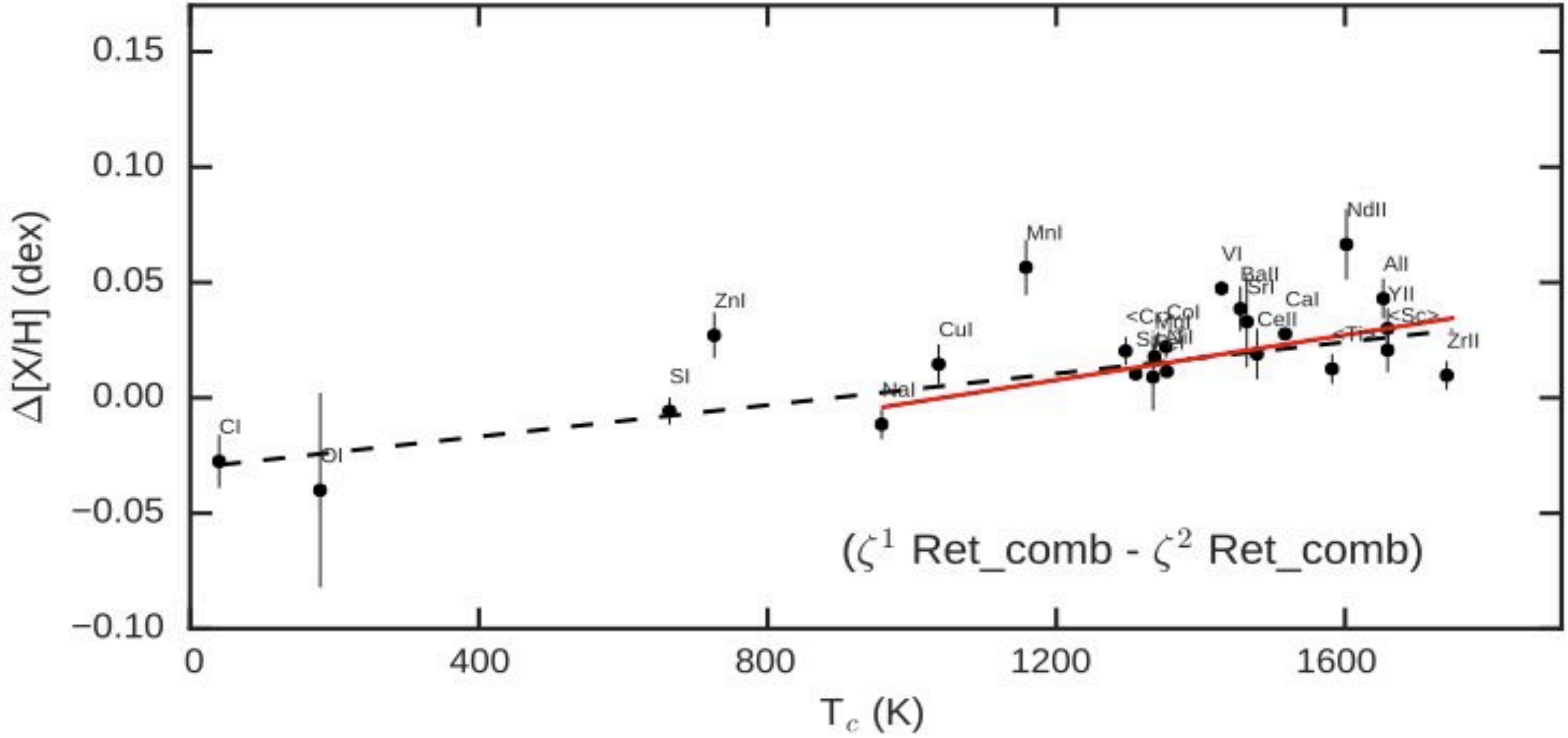
See also Teske et al. 2015

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



Chemical signature found by
Safe et al. 2016

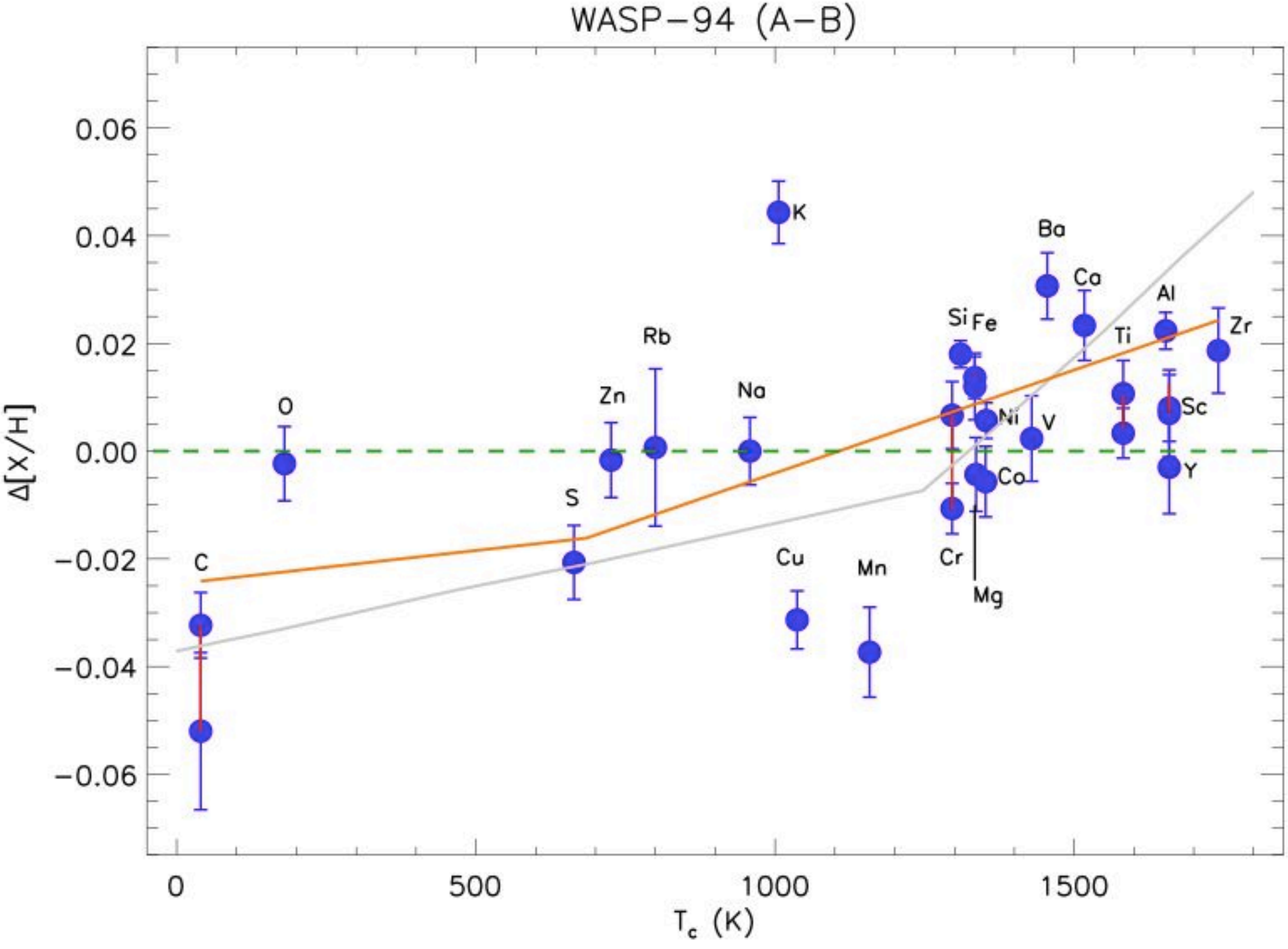
Binary pair ζ *Ret* with debris disk in one component *(ζ^2)*



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

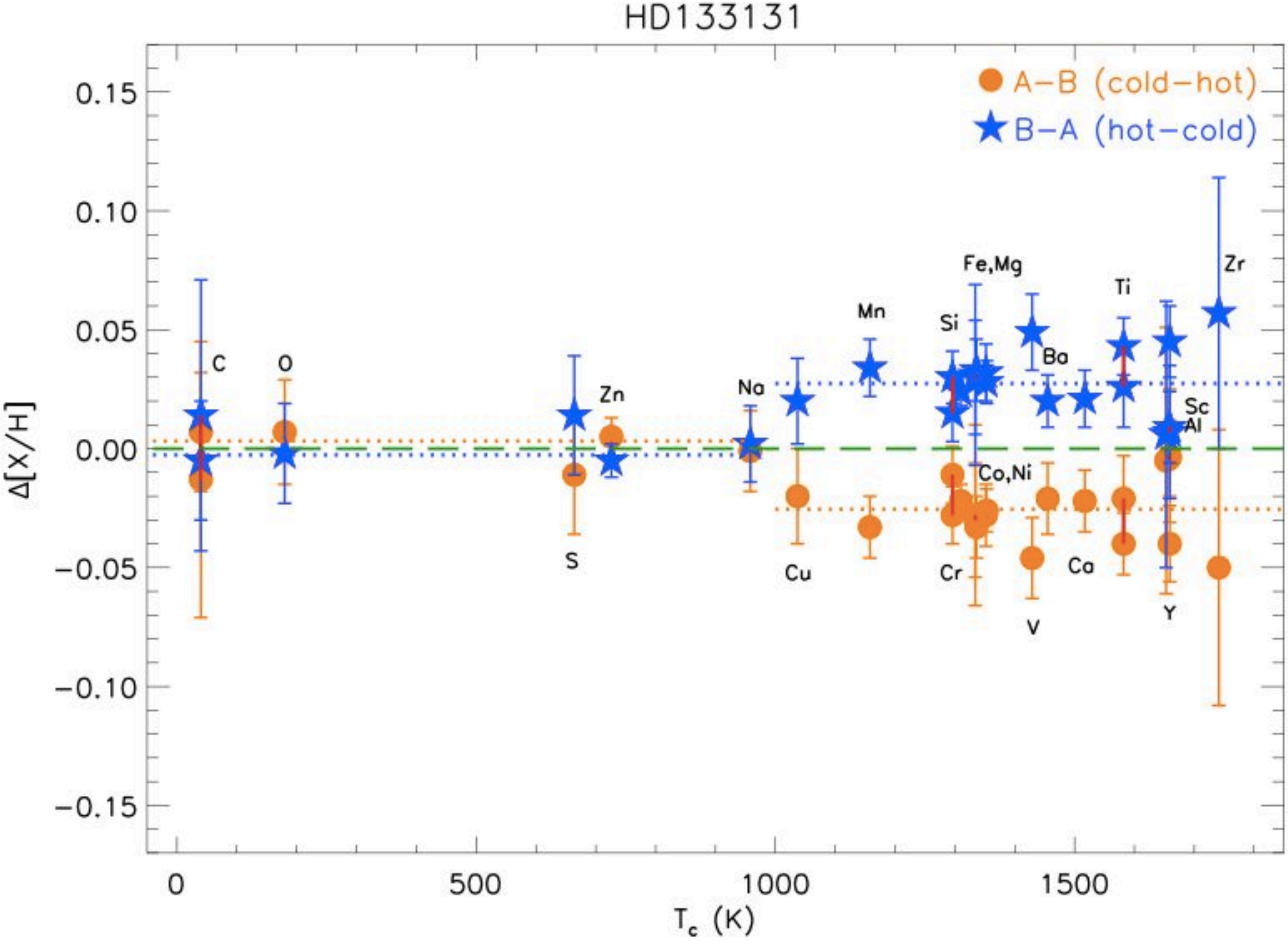
The Curious Case of Elemental Abundance Differences in the Dual Hot Jupiter Hosts WASP-94AB*

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

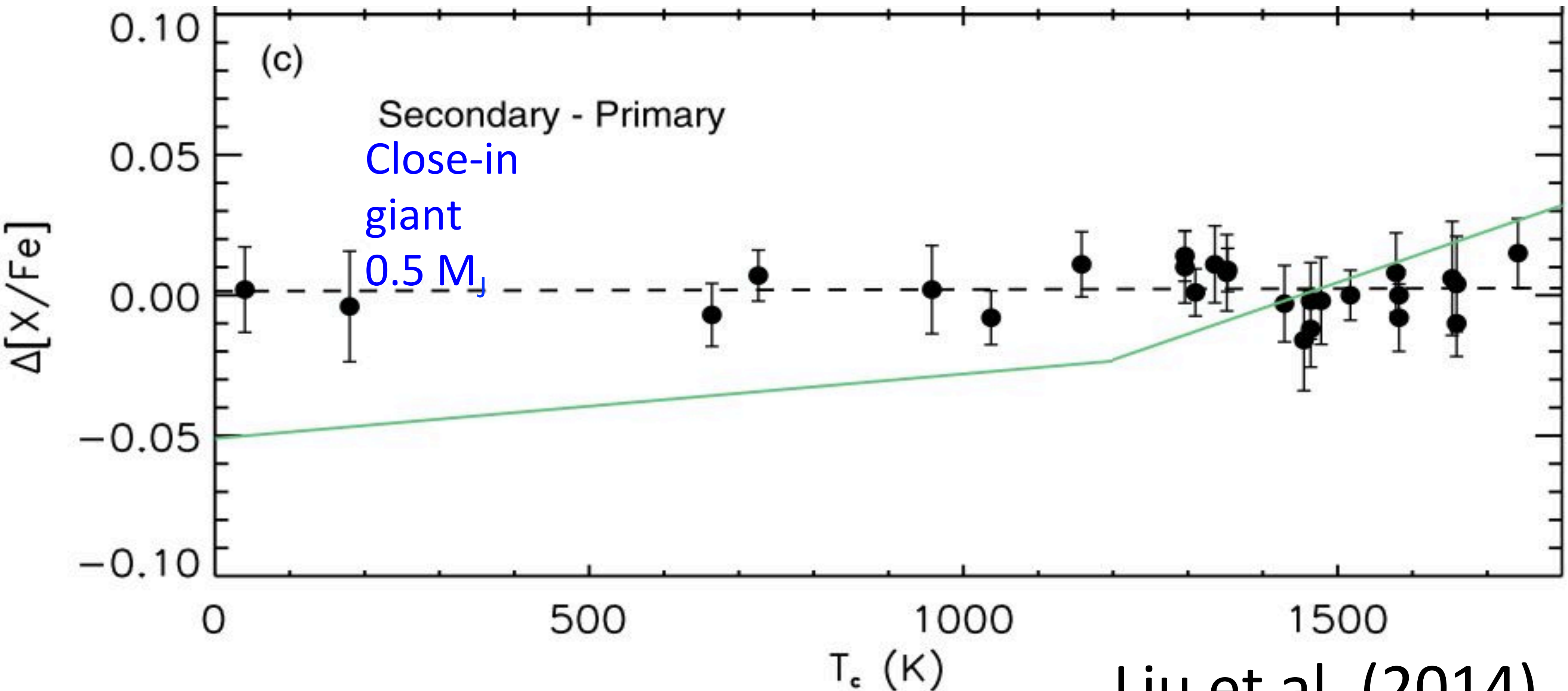


The Magellan PFS Planet Search Program: Radial Velocity and Stellar Abundance Analyses of the 360 AU, Metal-Poor Binary "Twins" HD 133131A & B†

Teske et al. 2016, in press



Negative results: HAT P-1 binary



Liu et al. (2014)

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

Planet Search at La Silla: 88 nights

International project lead by USP (Prof. Jorge Melendez).

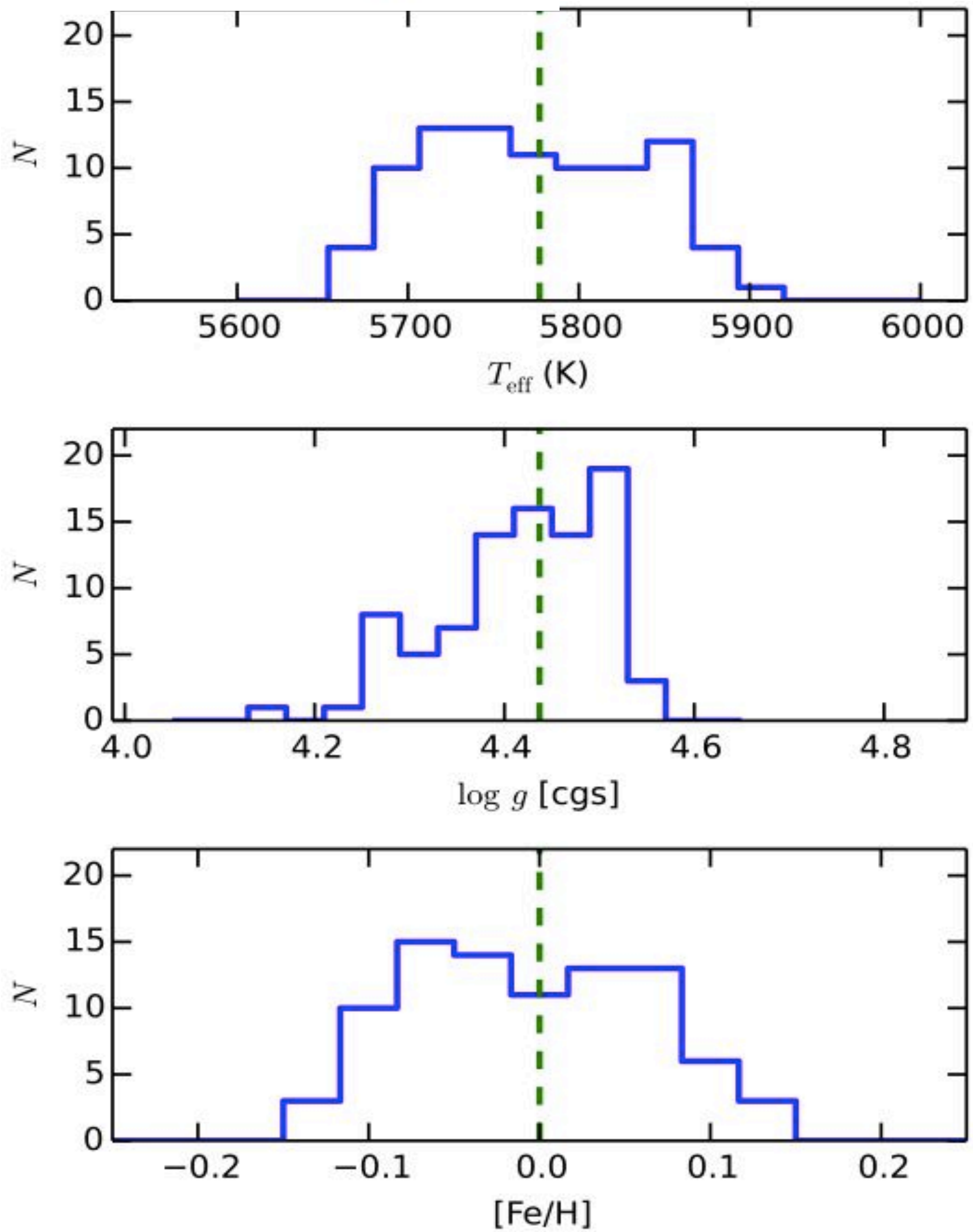
Brazil, USA, Germany, Australia

HARPS at the 3,6m telescope has a precision of 1m/s

The Solar Twin Planet Search

I. Fundamental parameters of the stellar sample★

Ramírez et al. 2014
MIKE spectra
R = 65 000
S/N = 400



A&A 581, A34 (2015)
DOI: 10.1051/0004-6361/201525748

Astronomy & Astrophysics

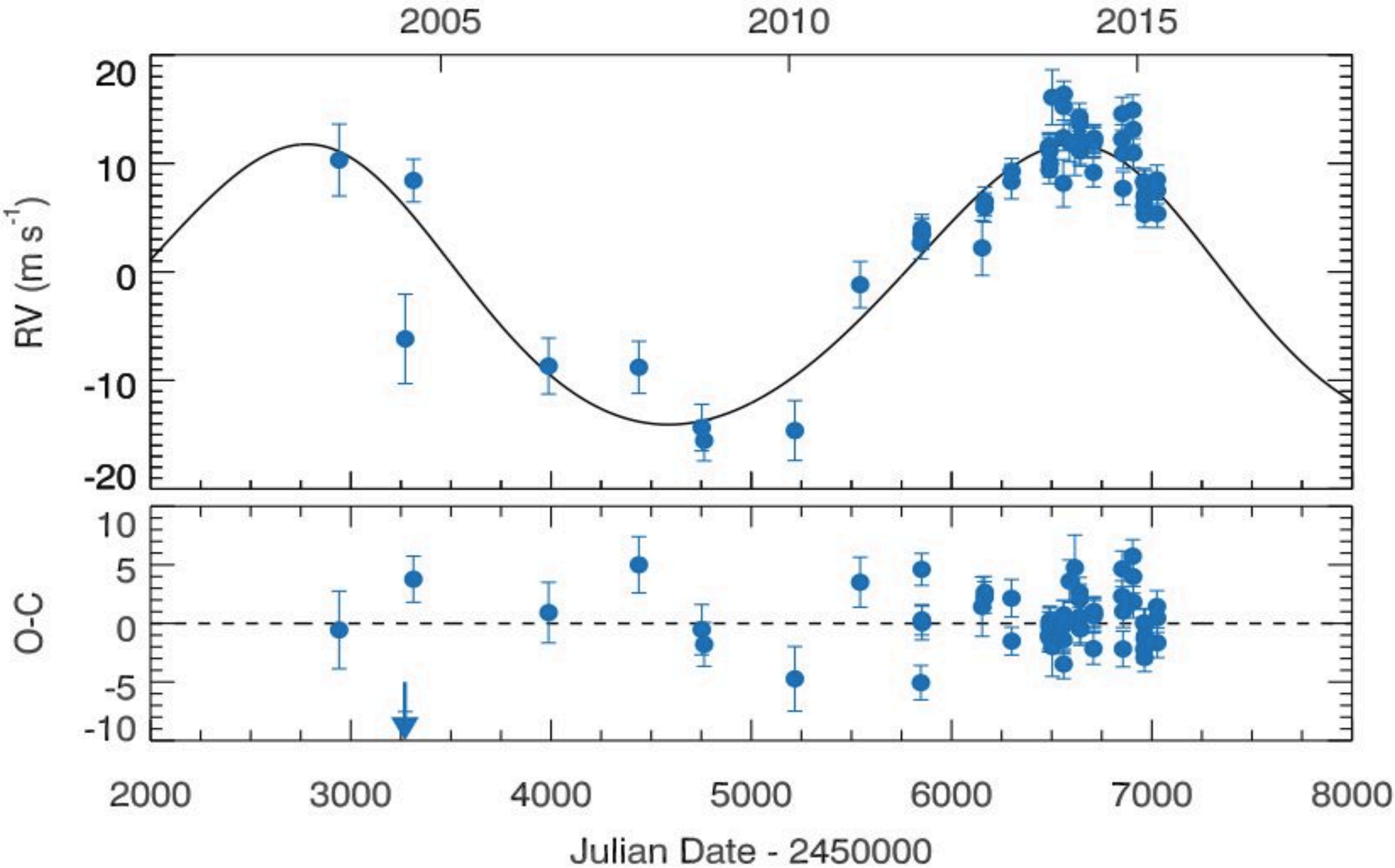
The Solar Twin Planet Search

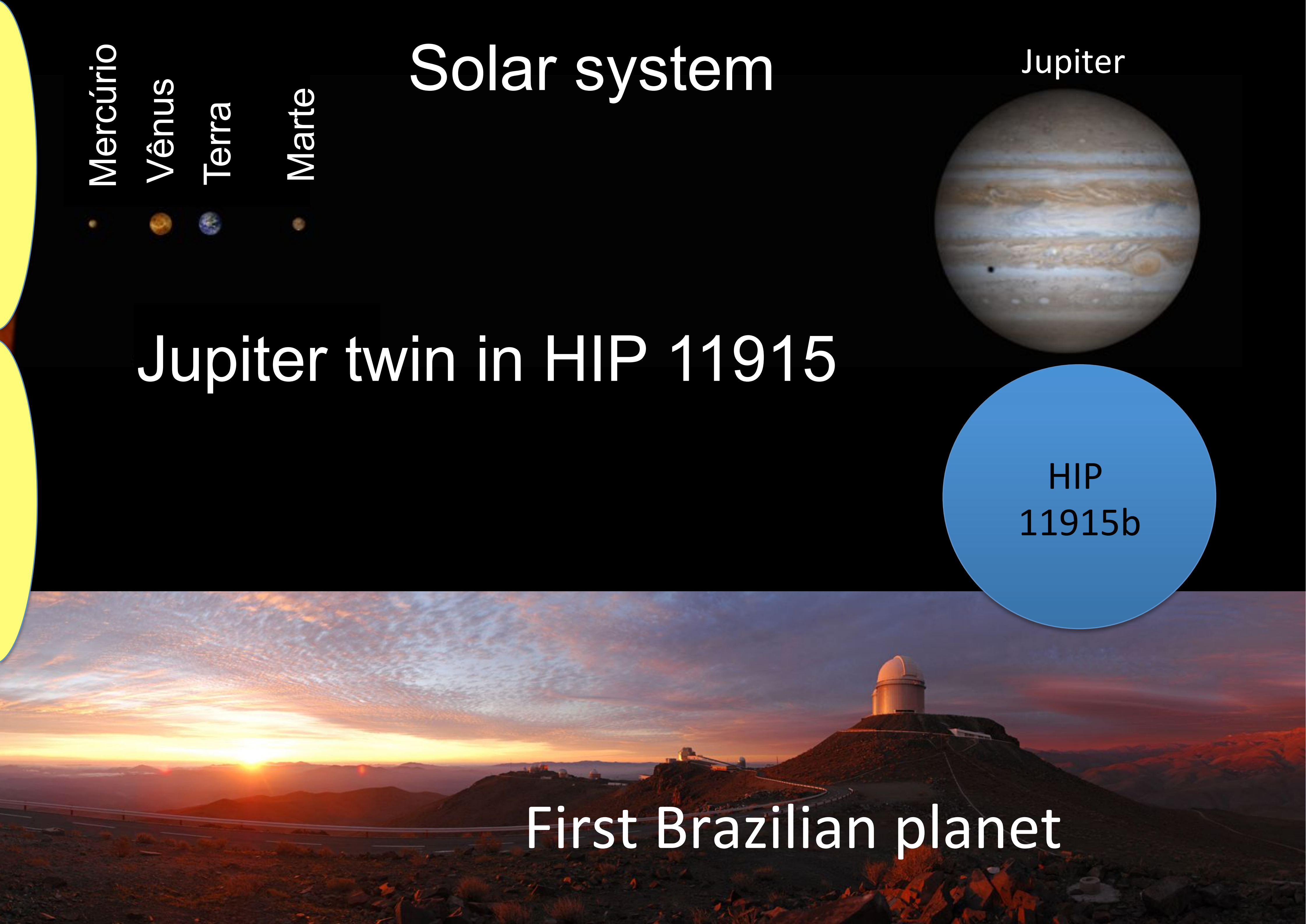
II. A Jupiter twin around a solar twin★

M. Bedell[1,★★], J. Meléndez[2], J. L. Bean[1], I. Ramírez[3], M. Asplund[4], A. Alves-Brito[5], L. Casagrande[4], S. Dreizler[6], T. Monroe[2], L. Spina[2], and M. Tucci Maia[2]

[1] Department of Astronomy and Astrophysics, University of Chicago, 5640 S. Ellis Ave, Chicago, IL 60637, USA
e-mail: mbedell@oddjob.uchicago.edu
[2] Departamento de Astronomia do IAG/USP, Universidade de São Paulo, Rua do Matão 1226, Cidade Universitária, 05508-900 São Paulo, SP, Brazil
[3] McDonald Observatory and Department of Astronomy, University of Texas at Austin, USA
[4] Research School of Astronomy and Astrophysics, The Australian National University, Cotter Road, Weston, ACT 2611, Australia
[5] Instituto de Fisica, Universidade Federal do Rio Grande do Sul, Av. Bento Goncalves 9500, Porto Alegre, RS, Brazil
[6] Institut für Astrophysik, University of Göttingen, Germany

Received 26 January 2015 / Accepted 27 June 2015


2005
2010
2015
20
10
0
-10
-20
RV (m s^{-1})
10
5
0
-5
-10
O-C
2000
3000
4000
5000
6000
7000
8000
Julian Date - 2450000

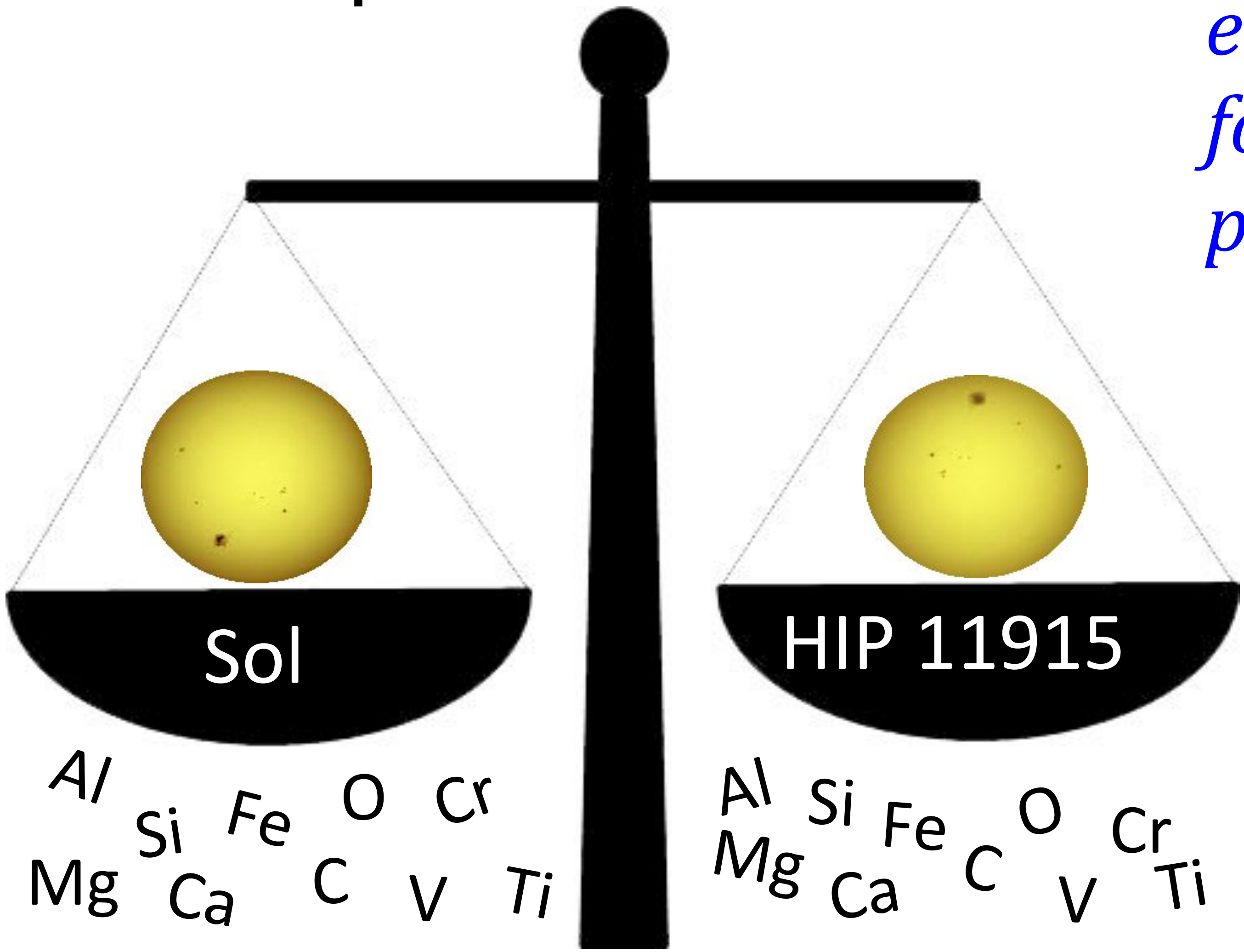


Solar system
Mercúrio
Vênus
Terra
Marte
Jupiter
Jupiter twin in HIP 11915
HIP 11915b
First Brazilian planet

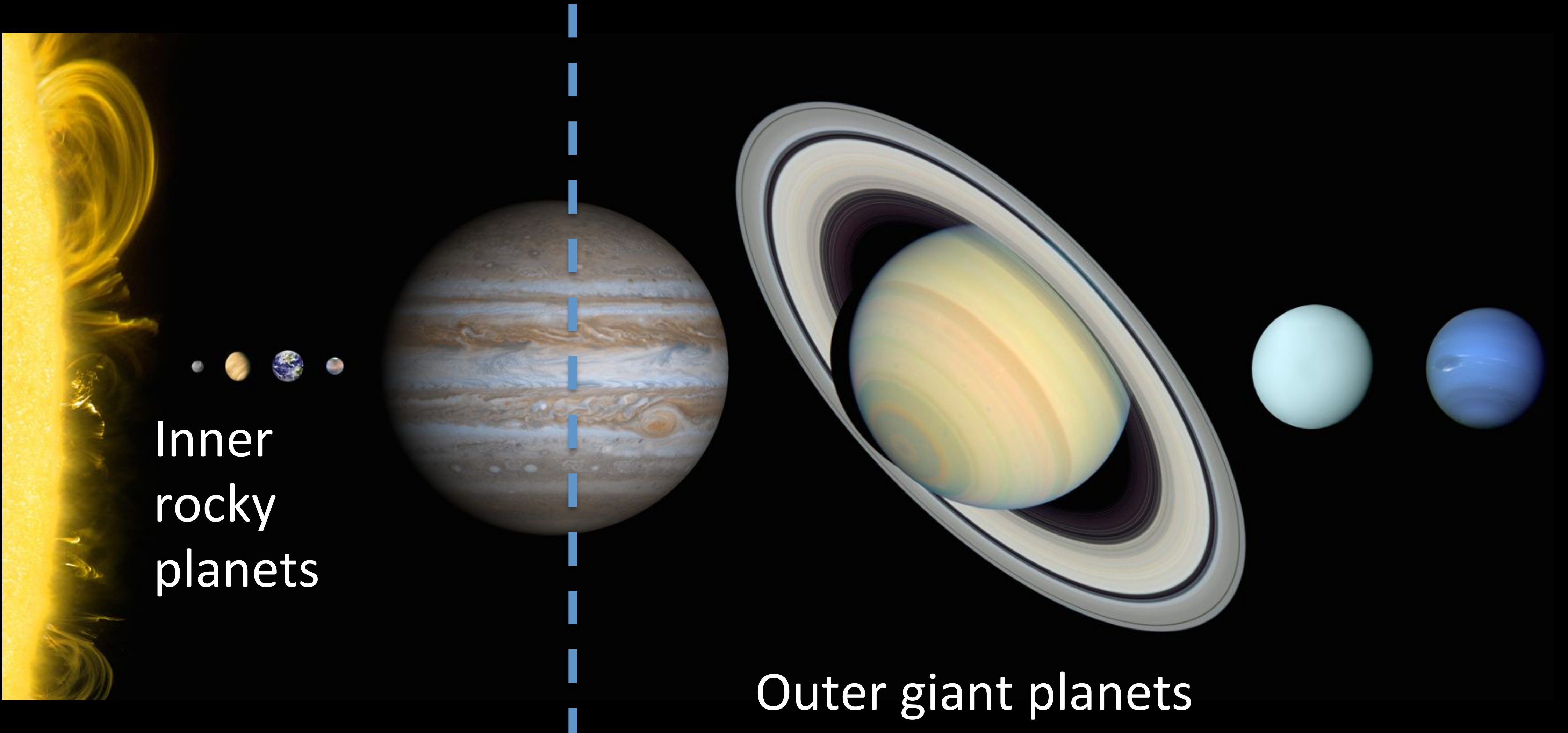
HIP 11915

Chemical composition like the Sun

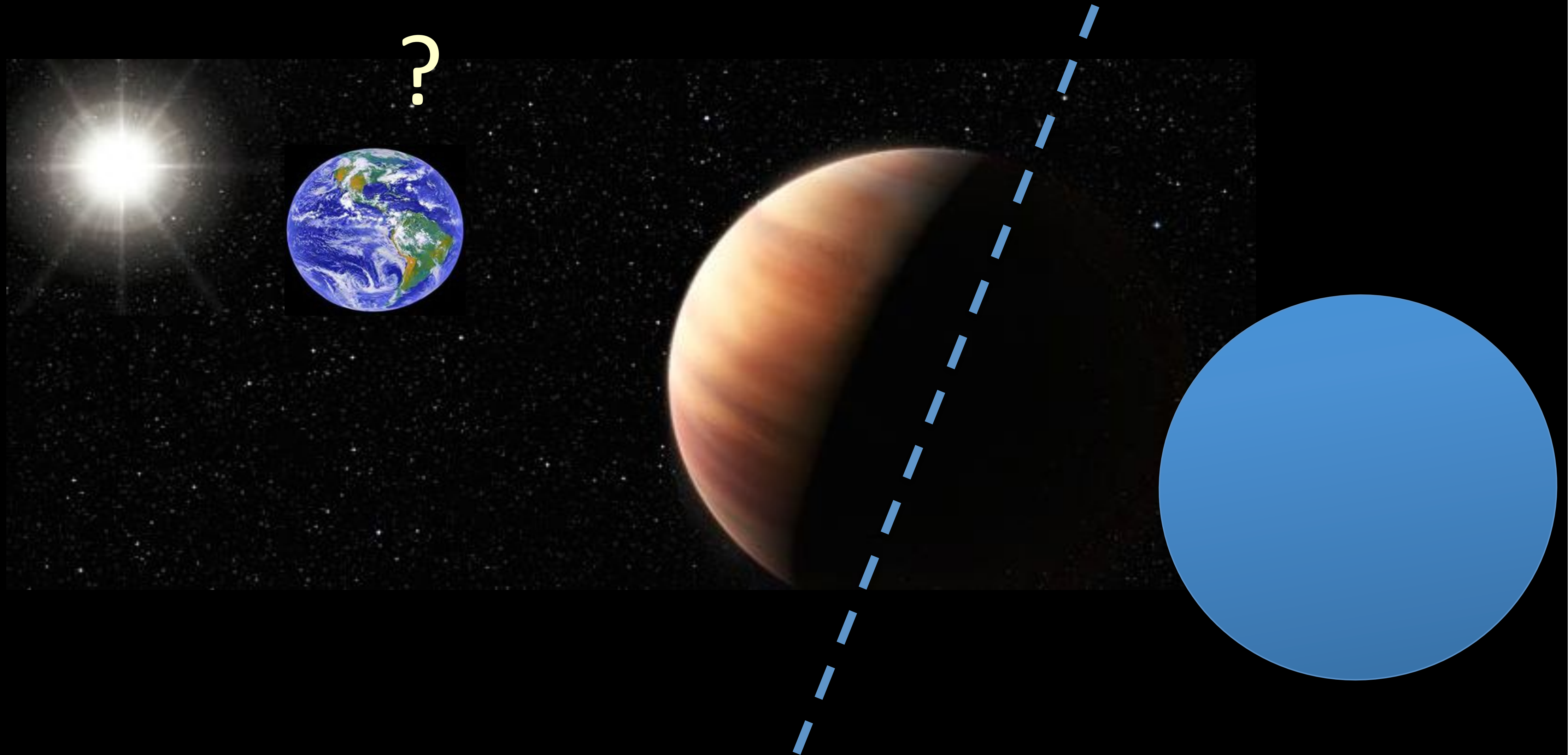
HIP 11915 is equipped to form rocky planets!



Jupiter is fundamental to keep the Solar System architecture



HIP 11915: solar system twin candidate?



HIP 11915: solar system twin candidate?

Life in hypothetical planet?

Age only 10% smaller than the Sun: perhaps enough to develop intelligent life

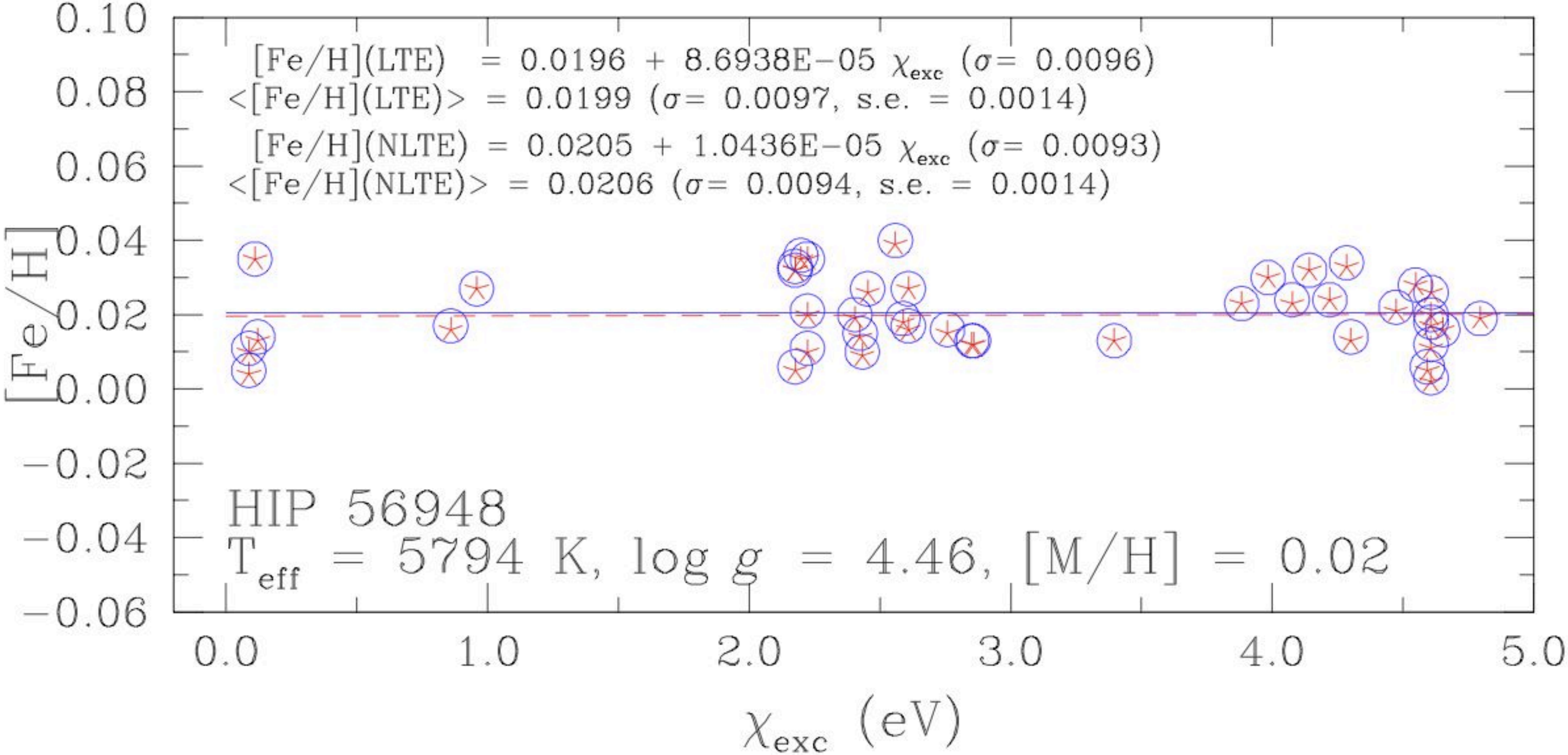
Trends between abundances and stellar ages

(important for stellar evolution & galactic chemical evolution)

HIP 56948

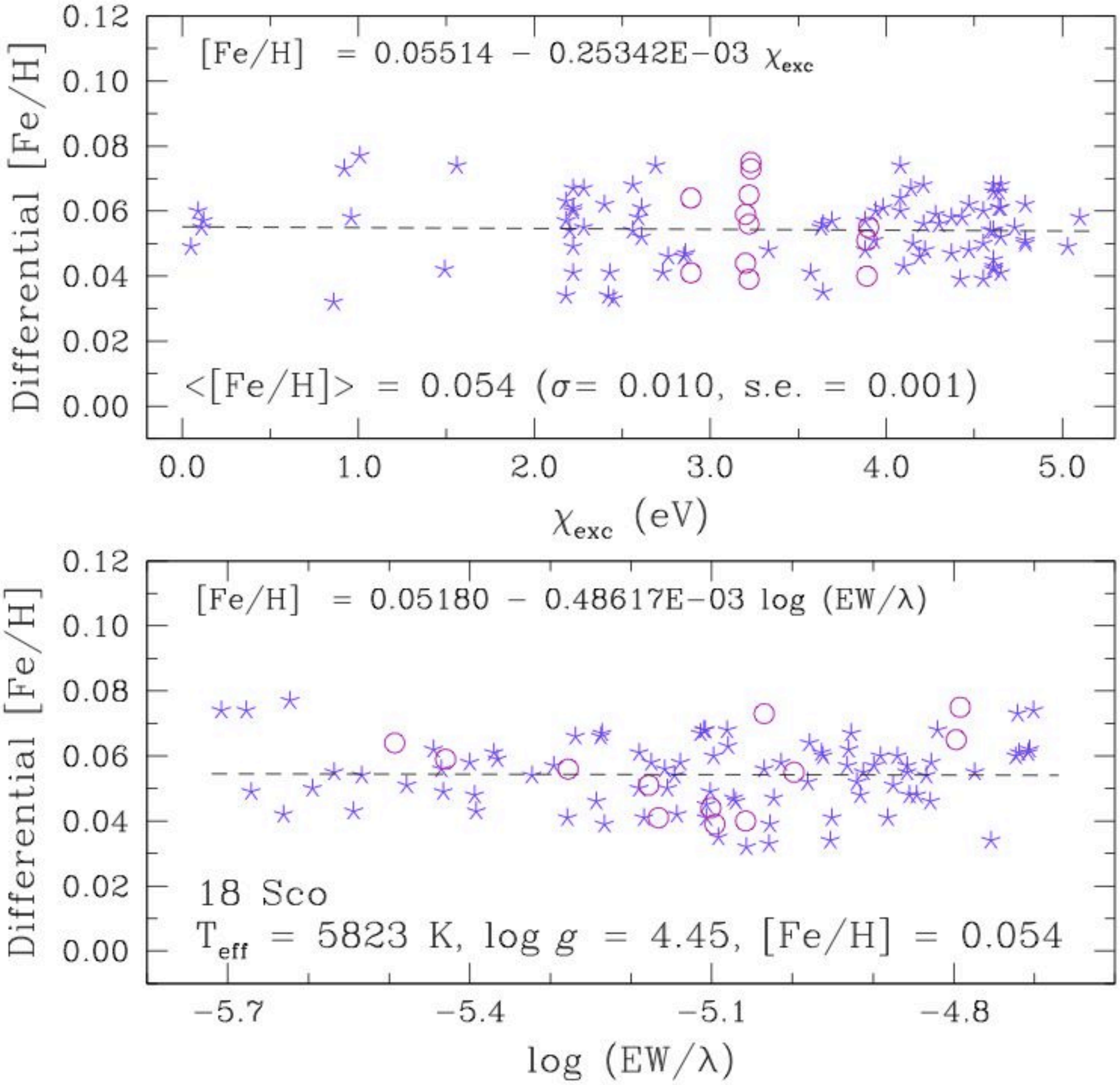
σ (LTE) = 0.0096 dex

σ (NLTE) = 0.0093 dex



σ = 0.010 dex

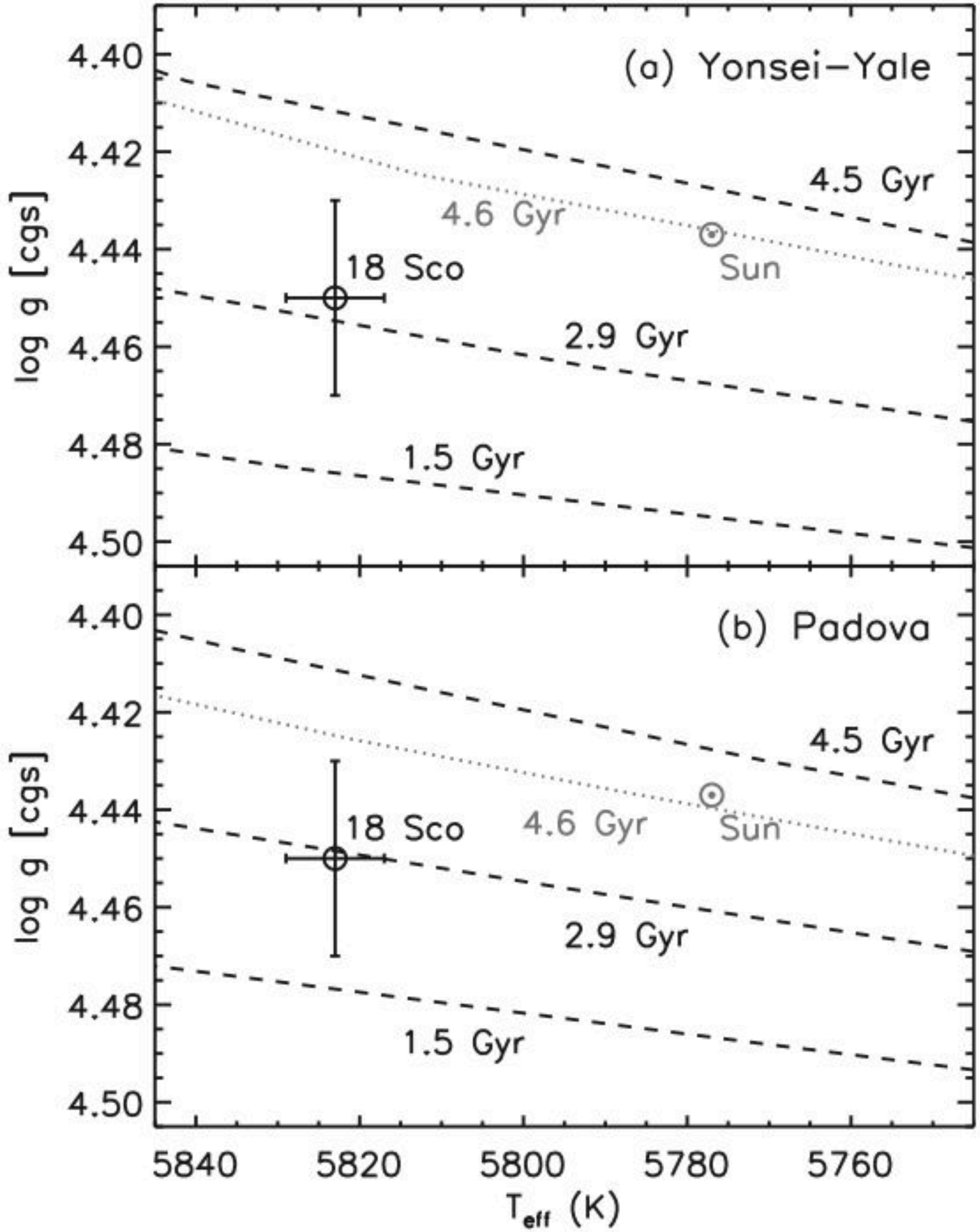
18 Sco



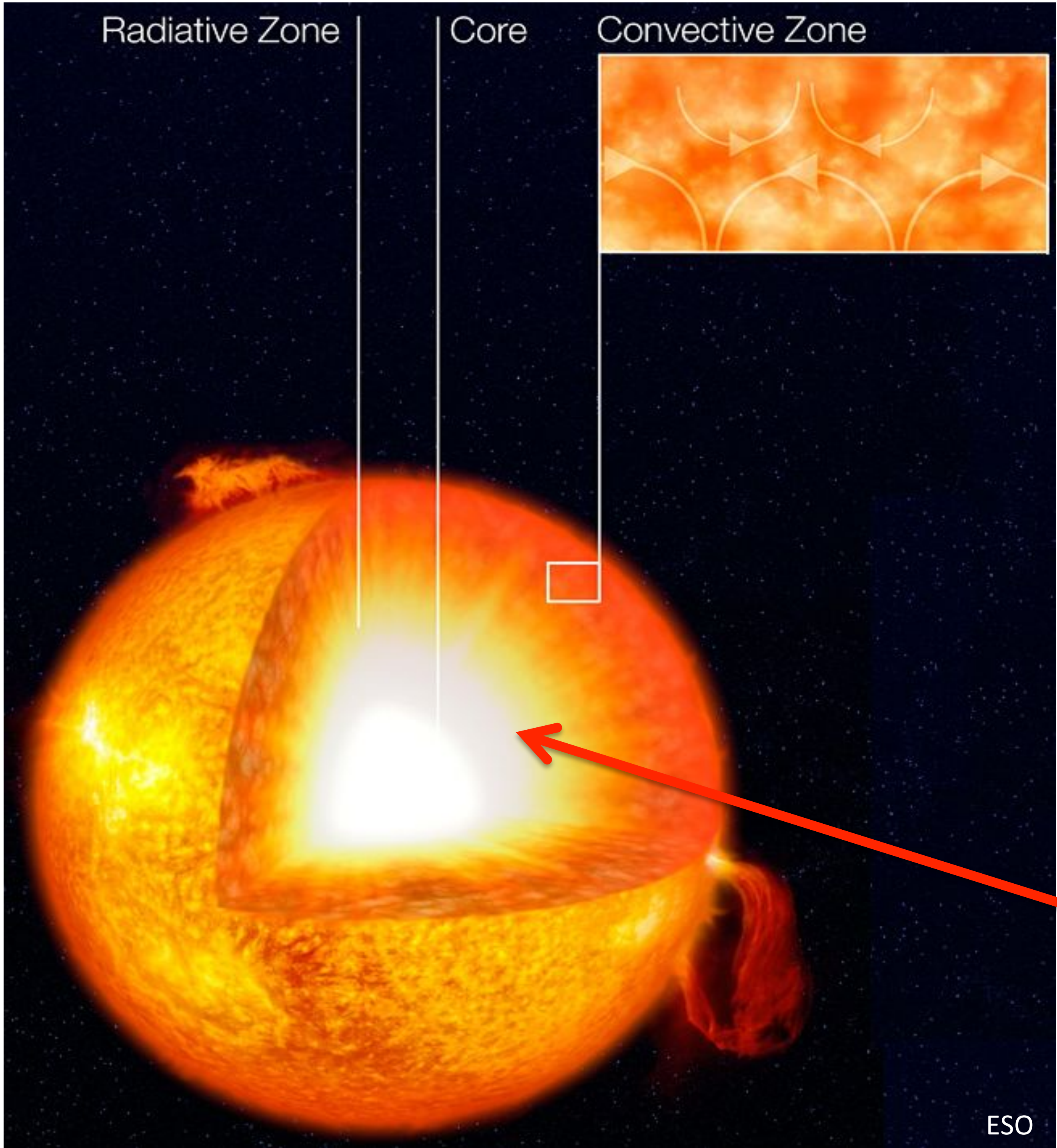
Differential method is also useful to obtain high precision stellar parameters

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

→ **good stellar masses and ages**



The solar lithium problem



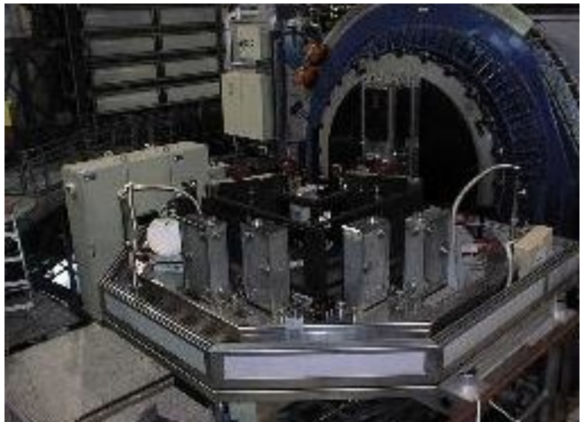
- The solar Li is about 160 times lower than in meteorites.
- *Li burns at 2.5 10^6 K; **below** the convection zone: no depletion in the photosphere!*

High quality spectra needed to study Li!

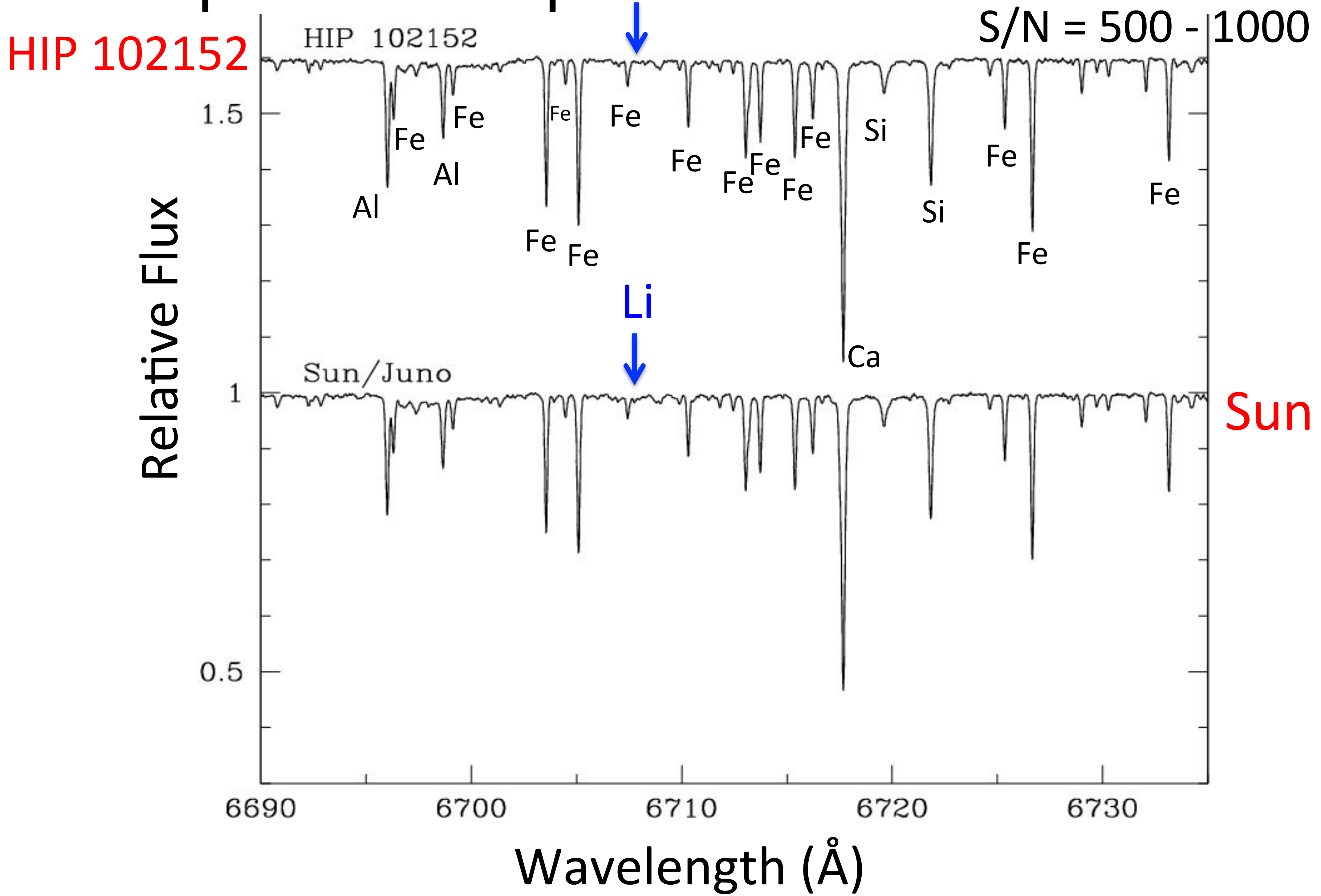
VLT + UVES

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

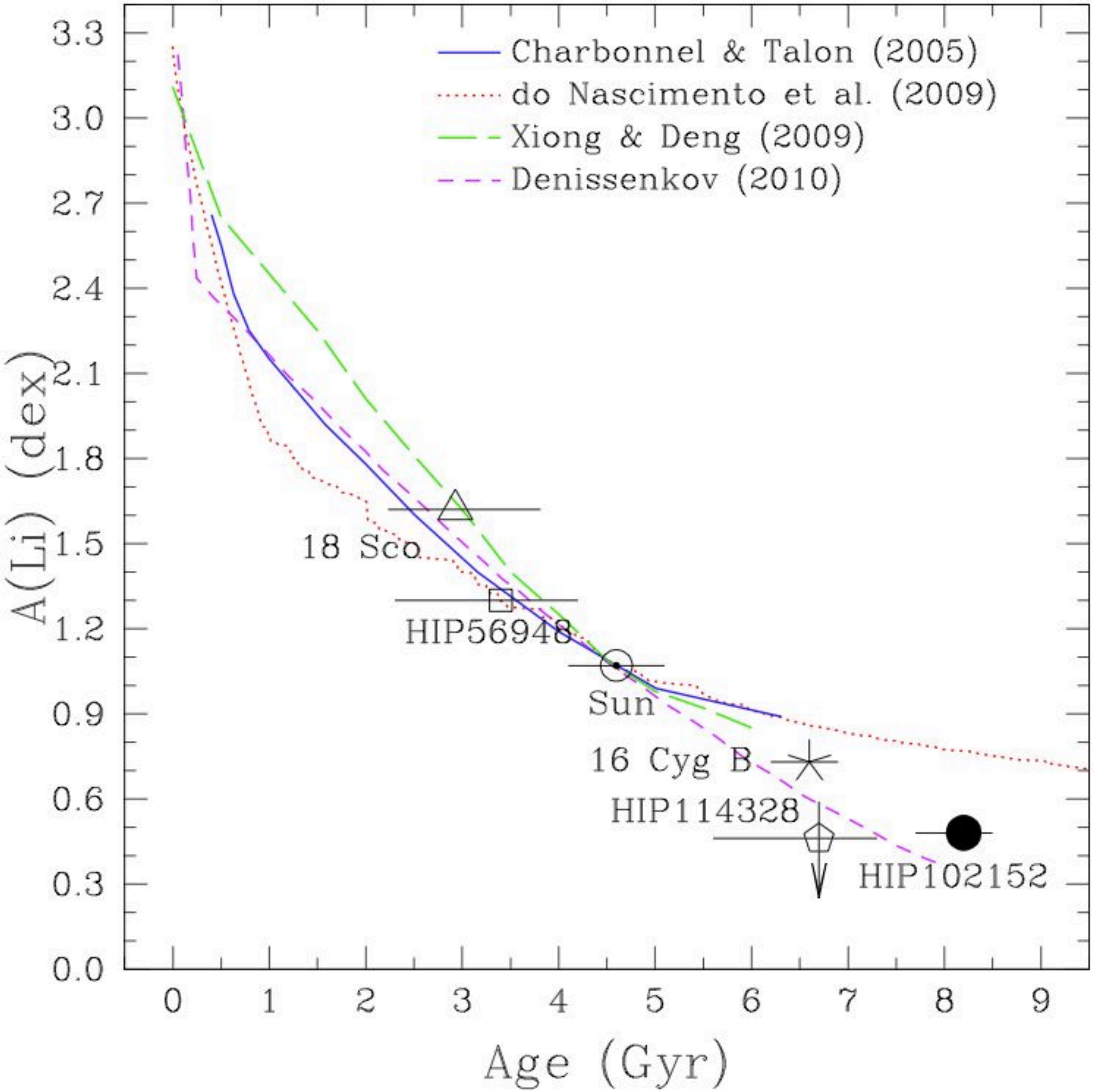
UVES spectrograph



Comparison of spectra



HIP 114328 and HIP102152: old Li-poor solar twins



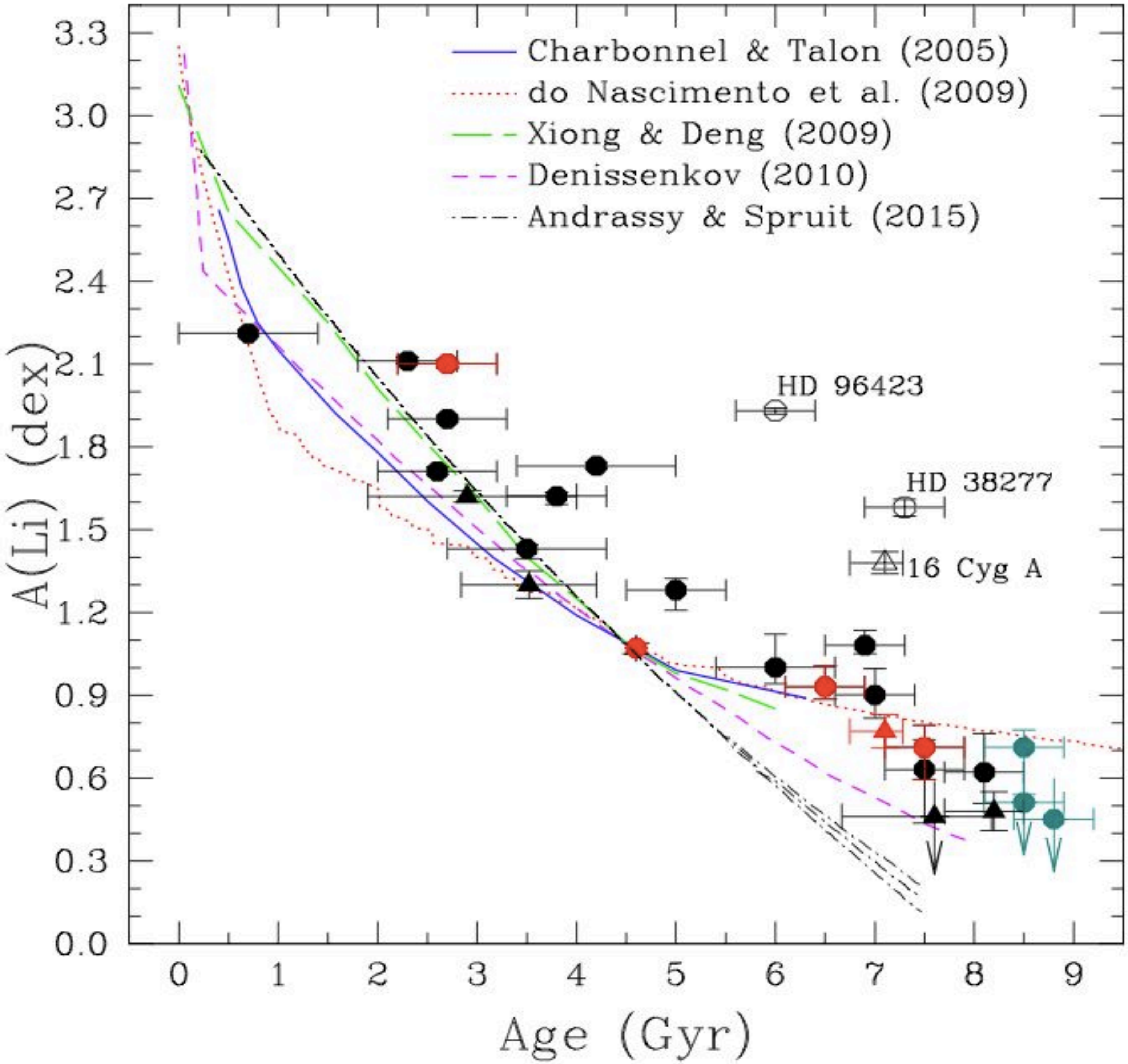
A&A 567, L3 (2014)
DOI: 10.1051/0004-6361/201424172

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]

Most stars follow a lithium – age correlation, including stars with planets

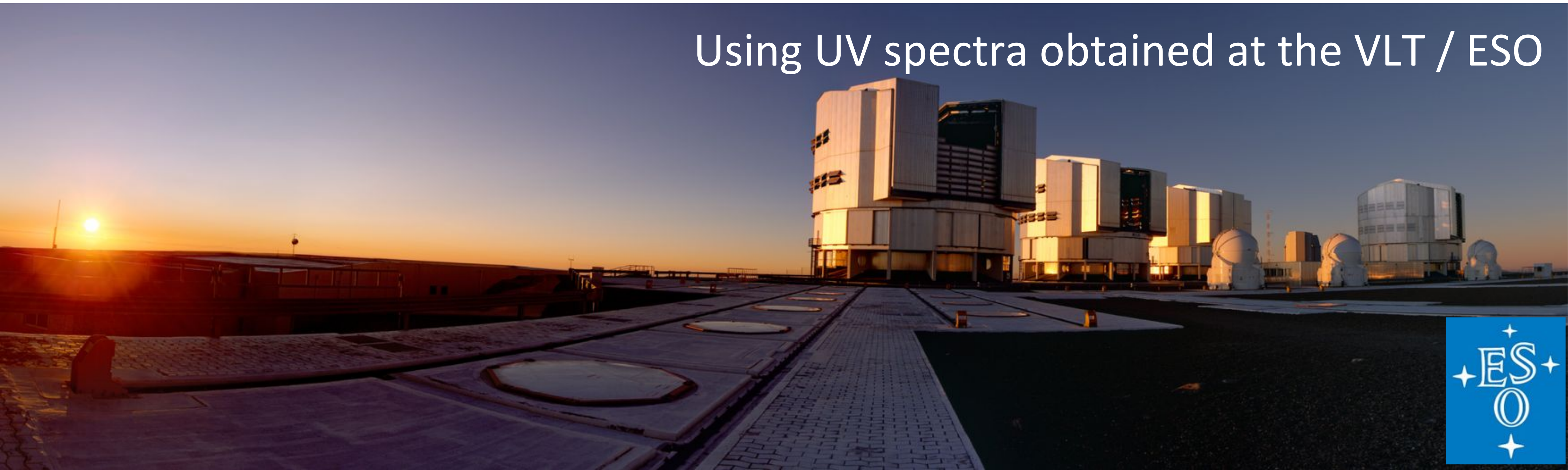
16 Cyg B (planet host) is normal in Li. Perhaps 16 Cyg A accreted a planet (also rich in refractories)



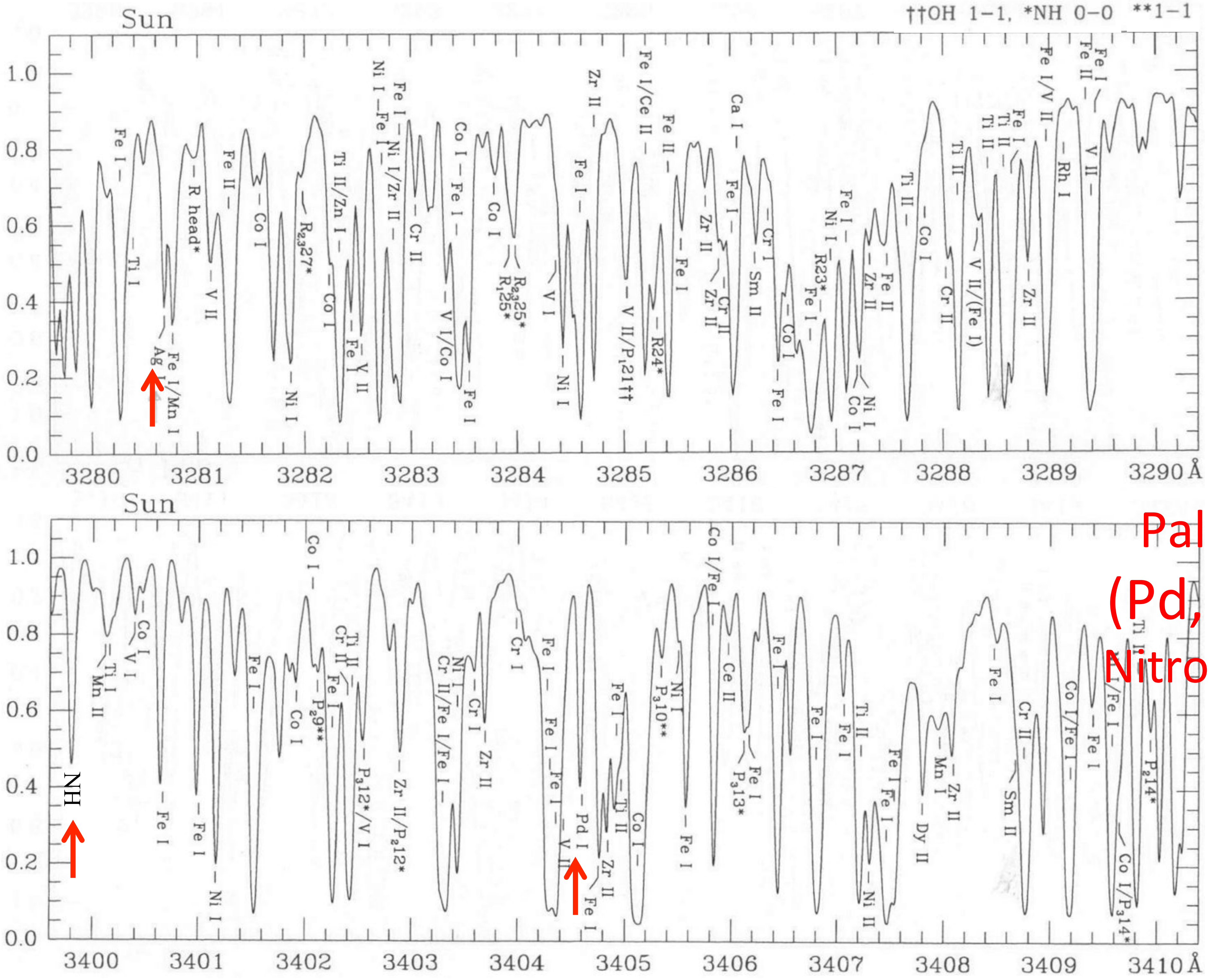
Carlos, Nissen & Melendez (2016)

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

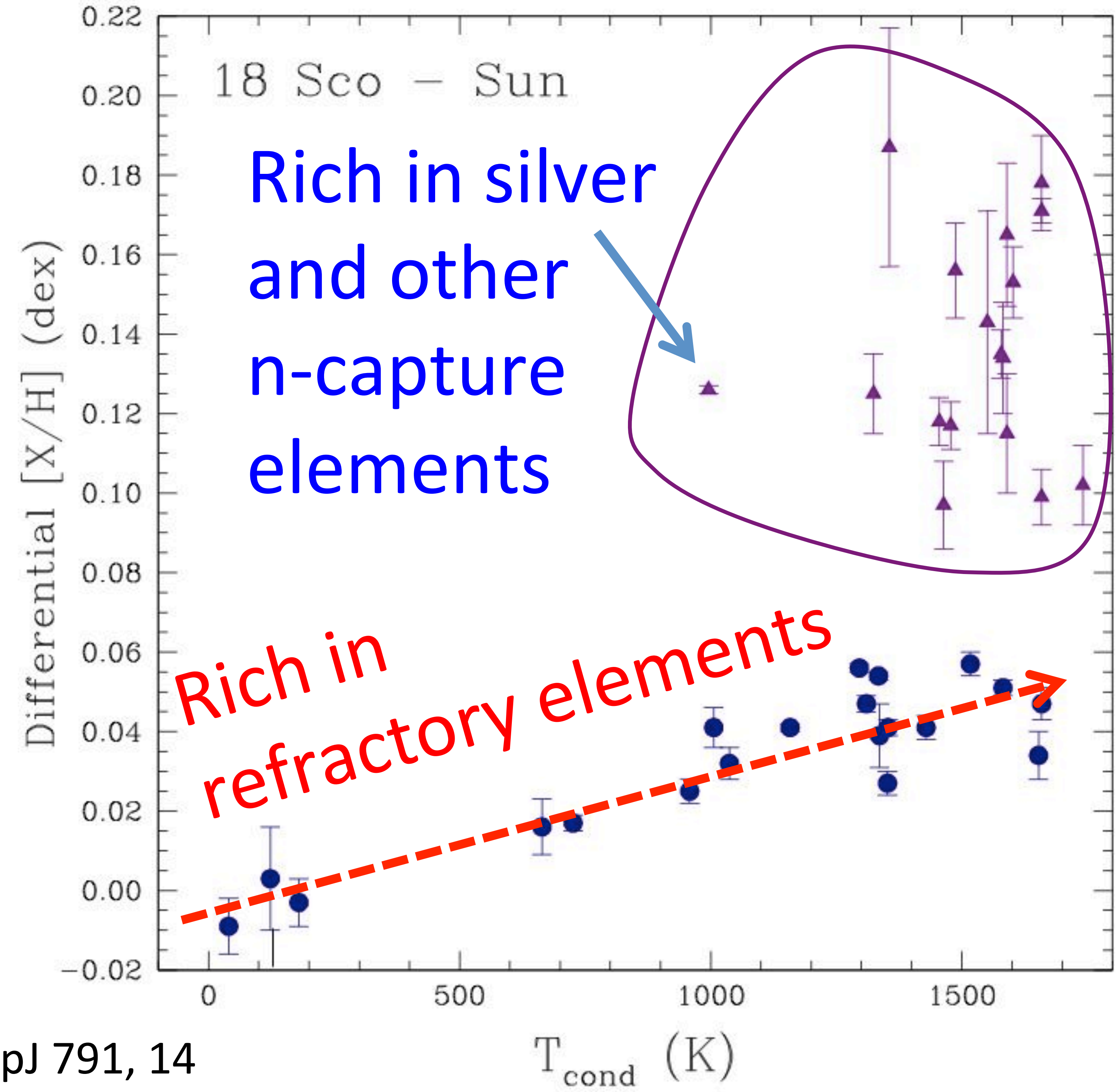
(brightest solar twin, V = 5.5)

UVES+VLT

R = 110 000 (red)

R = 65 000 (blue)

Age = 2.9 Gyr



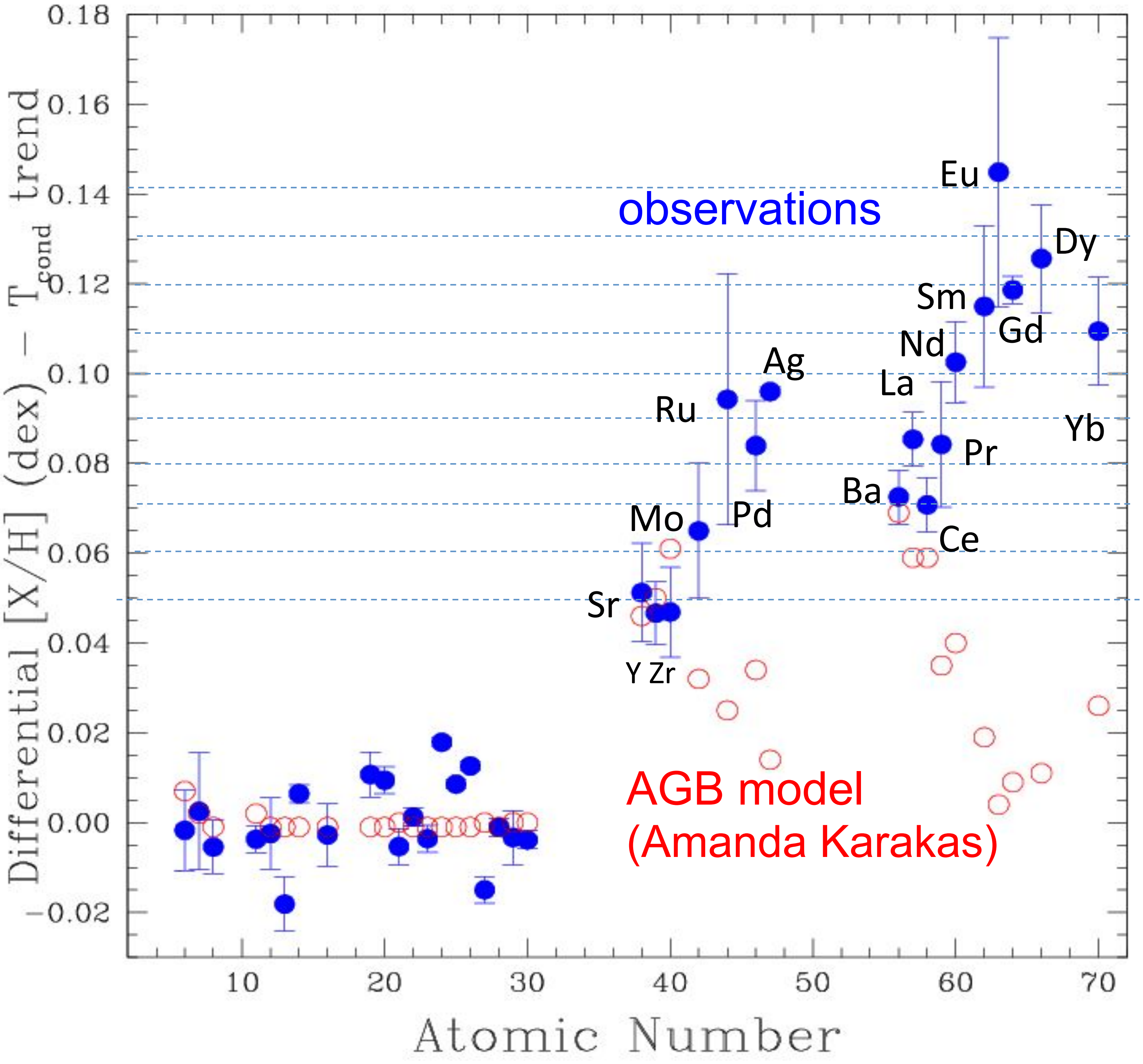
Meléndez et al. 2014, ApJ 791, 14

August 10, 2014

18 Sco

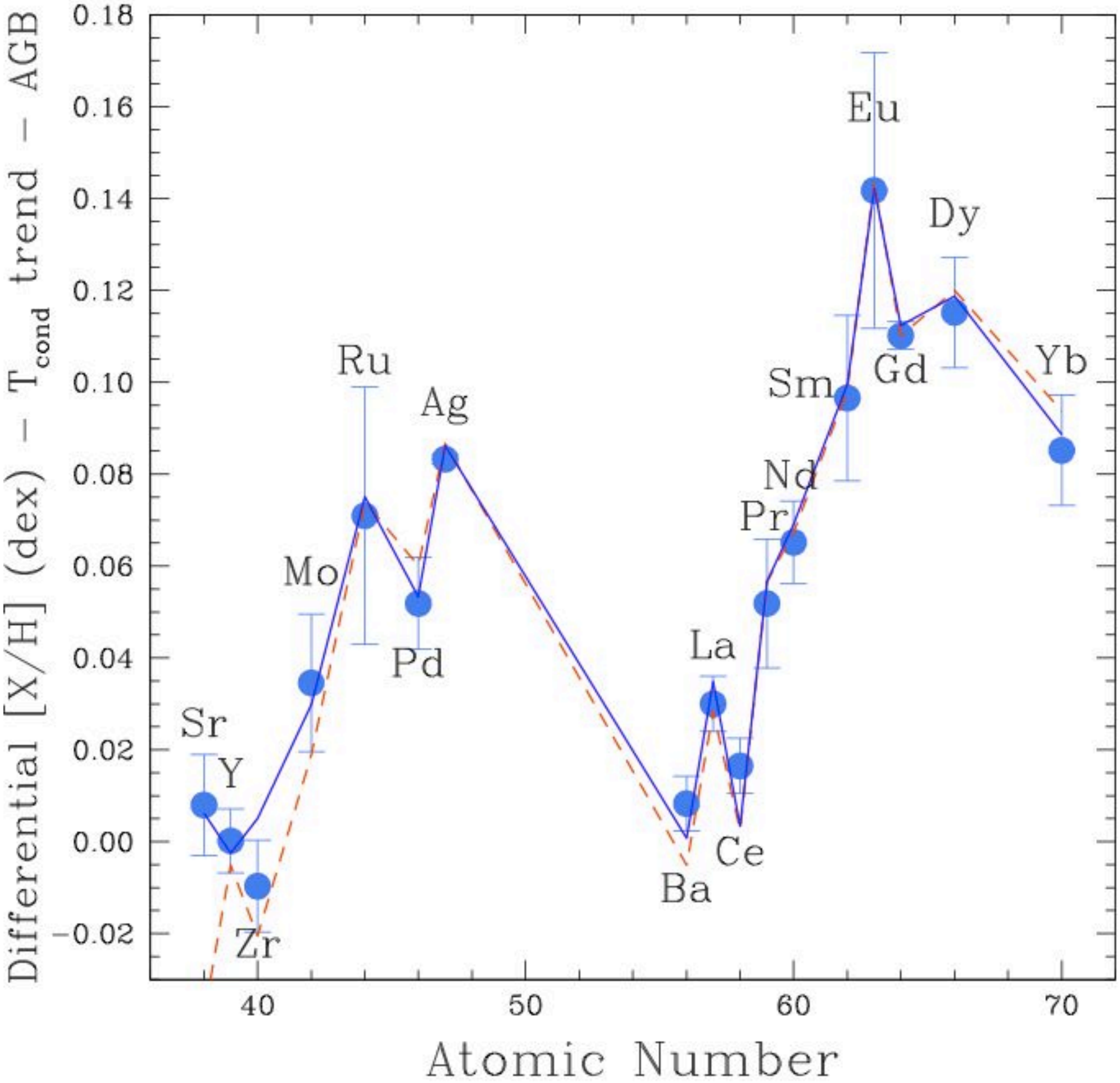
(brightest solar twin, V = 5.5)
UVES+VLT
R = 110 000
S/N = 800

Subtracting T_{cond} trend



Meléndez et al. 2014, ApJ

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

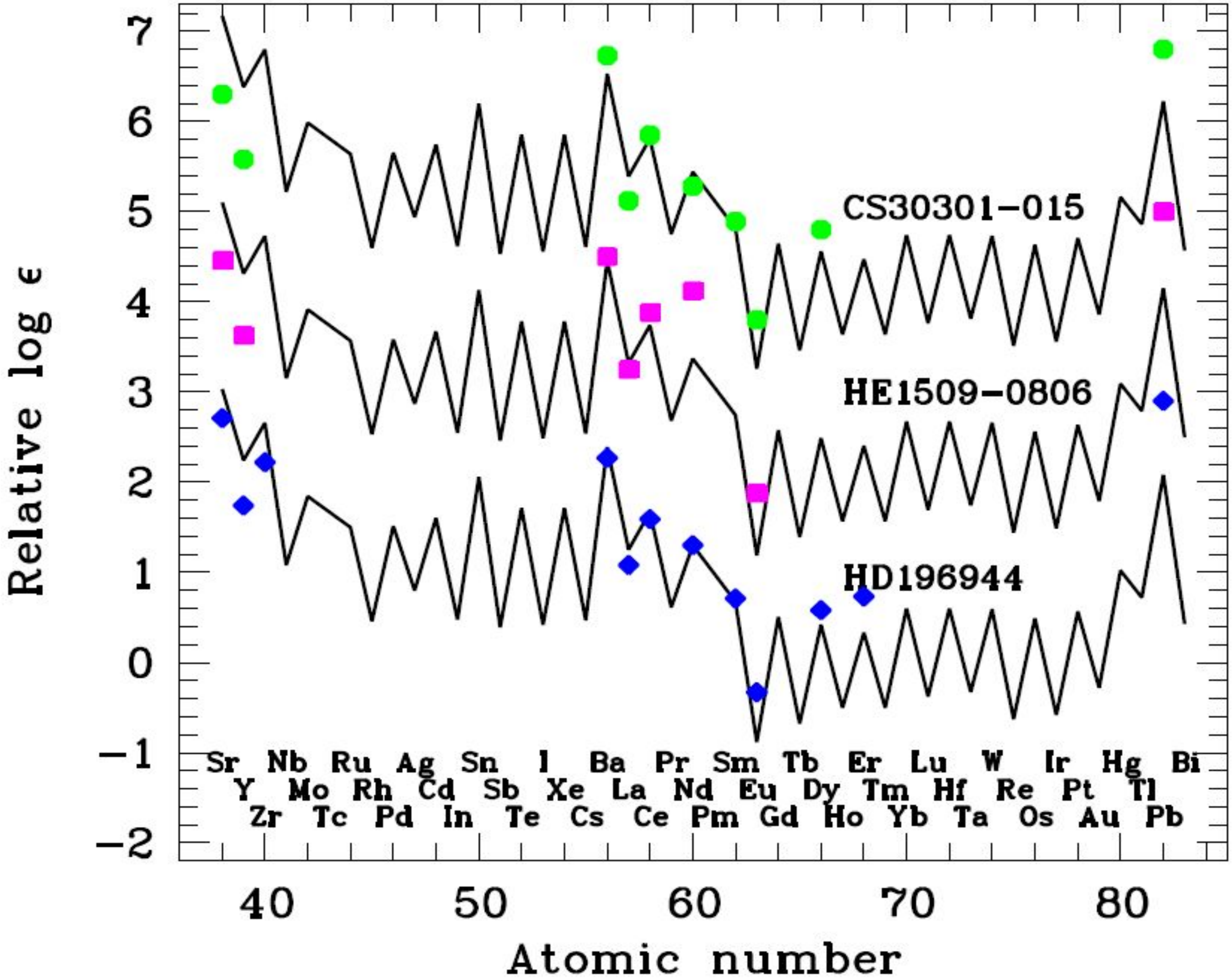


Meléndez et al. 2014, ApJ

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)

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



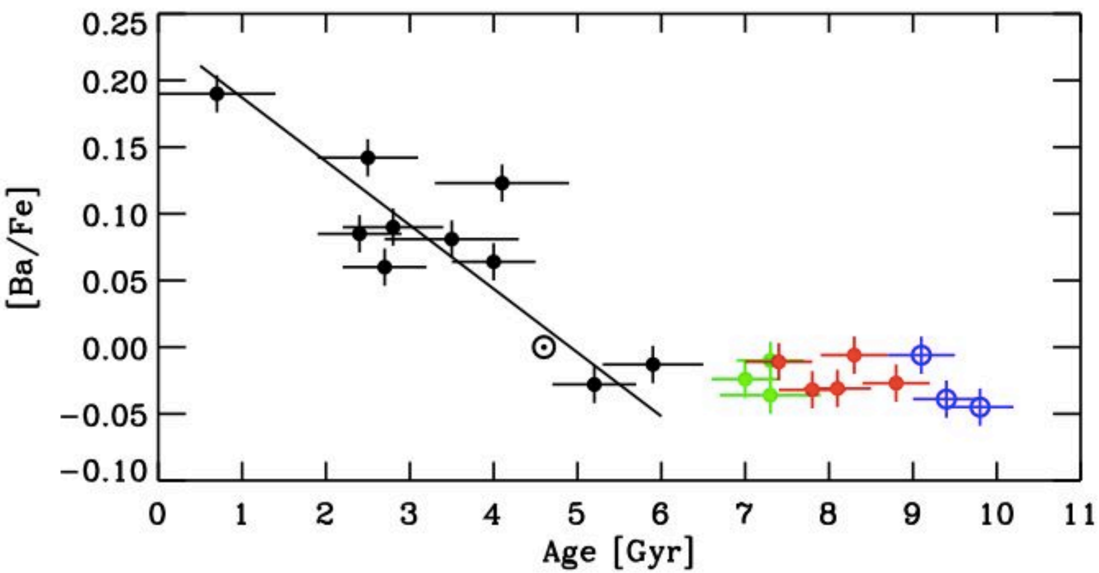
Frebel & Norris 2012

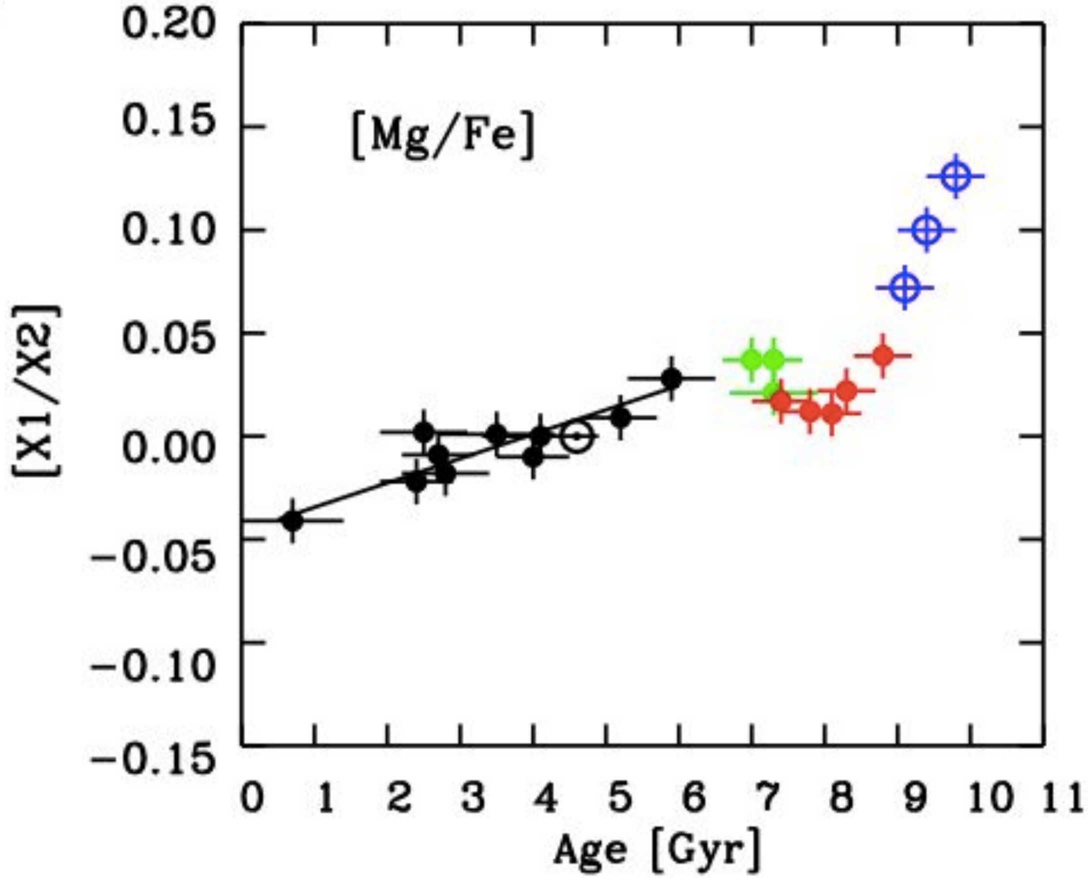
Abundance ratios as a function of age

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

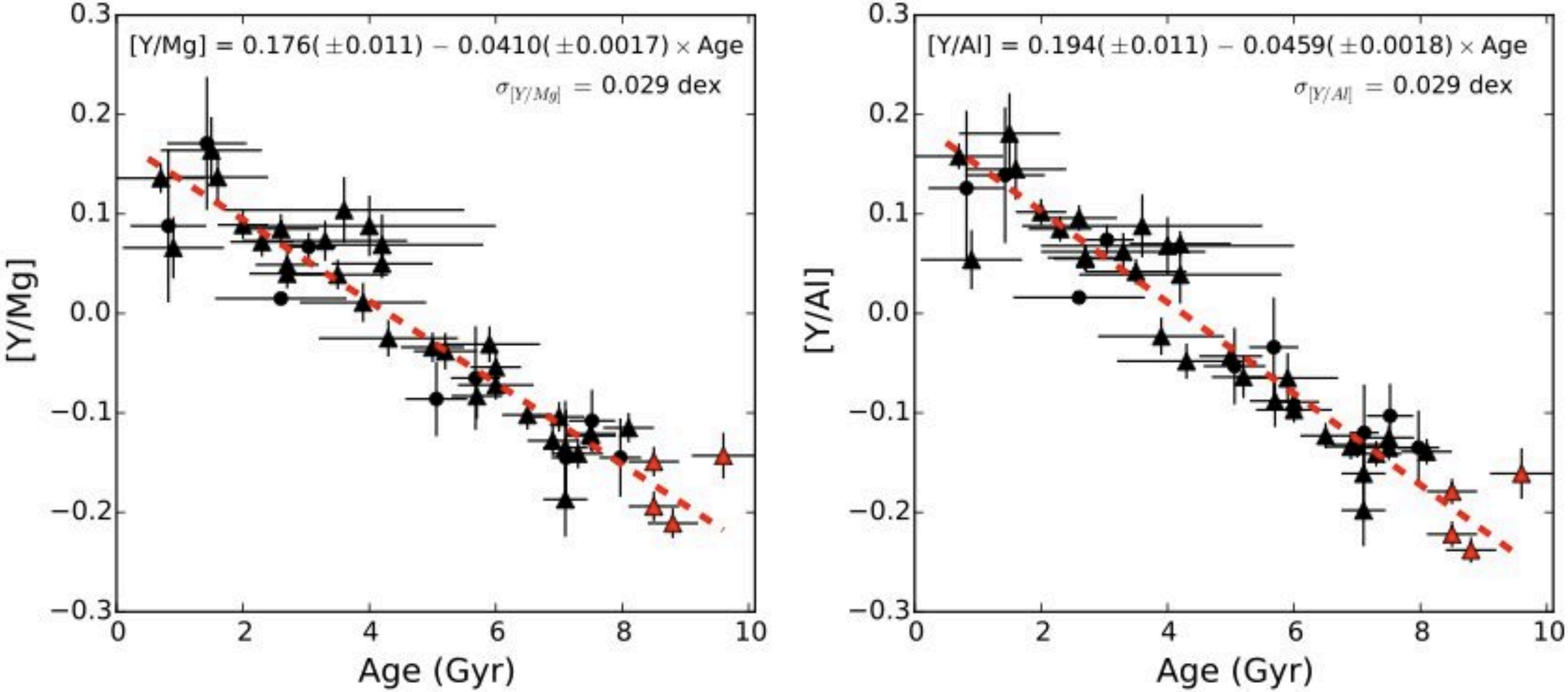
Trends of element ratios with stellar age ⋆

P. E. Nissen



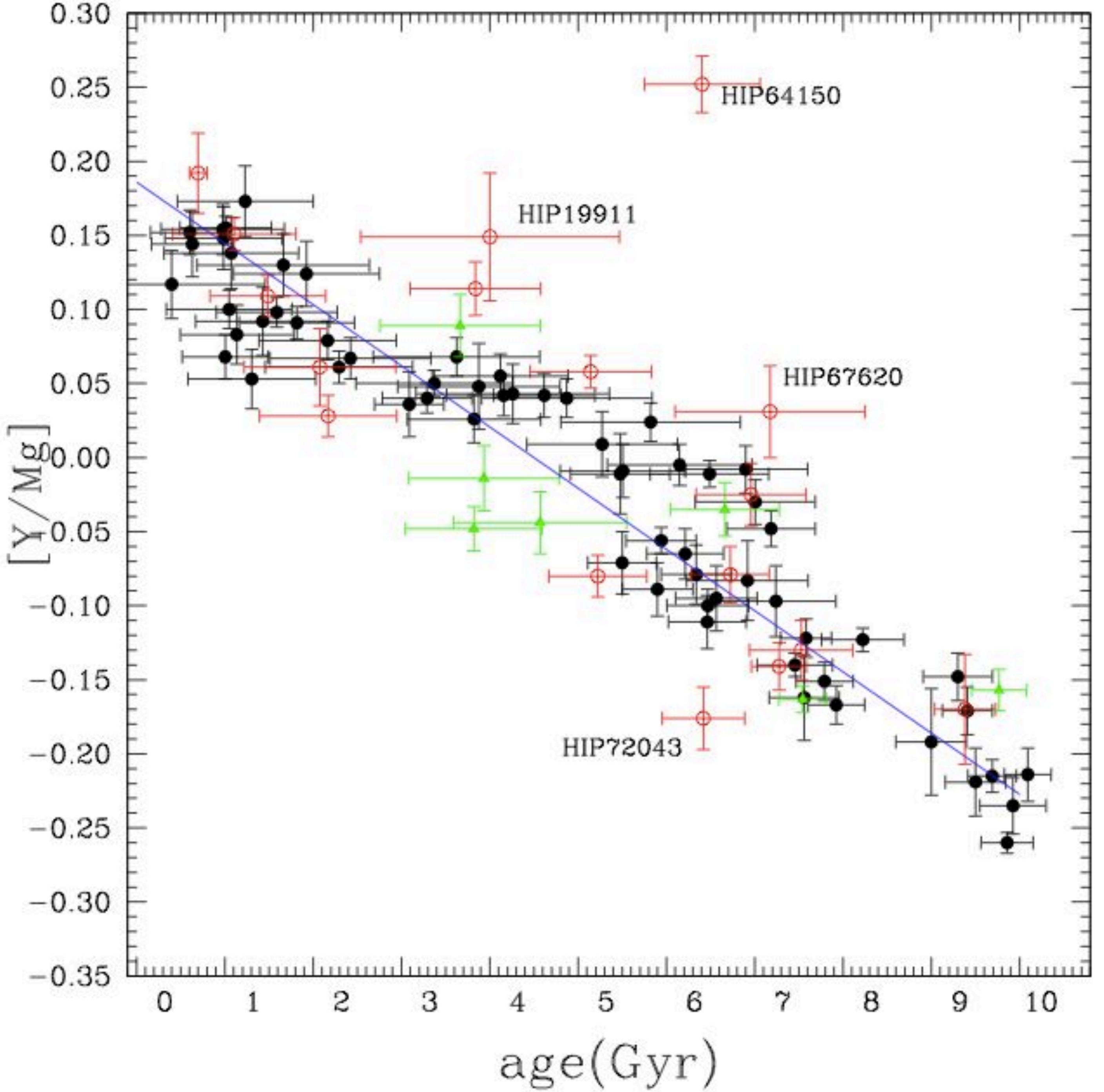


Spina et al. (2016): chemical clocks



Tucci-Maia et al. 2016

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

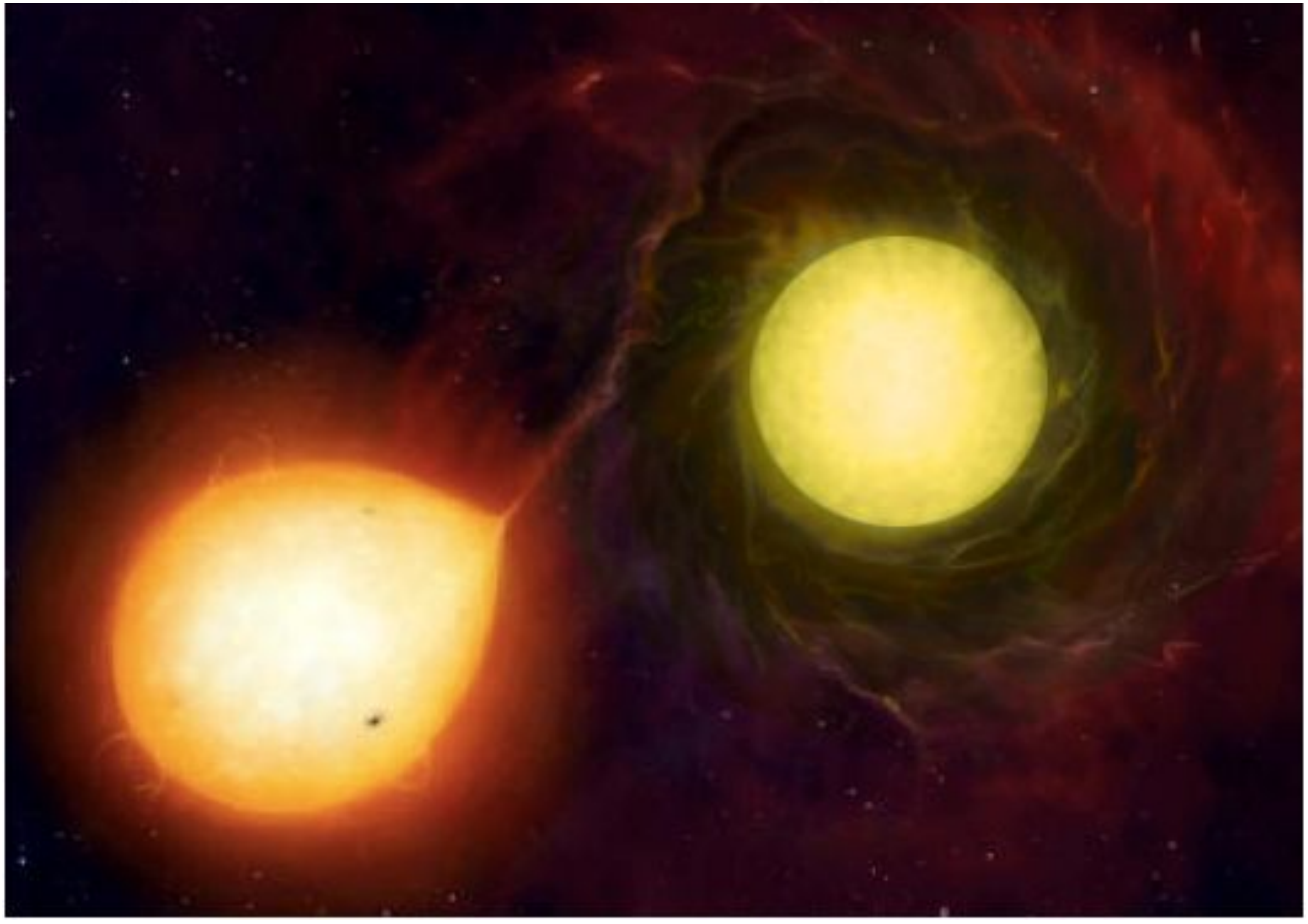


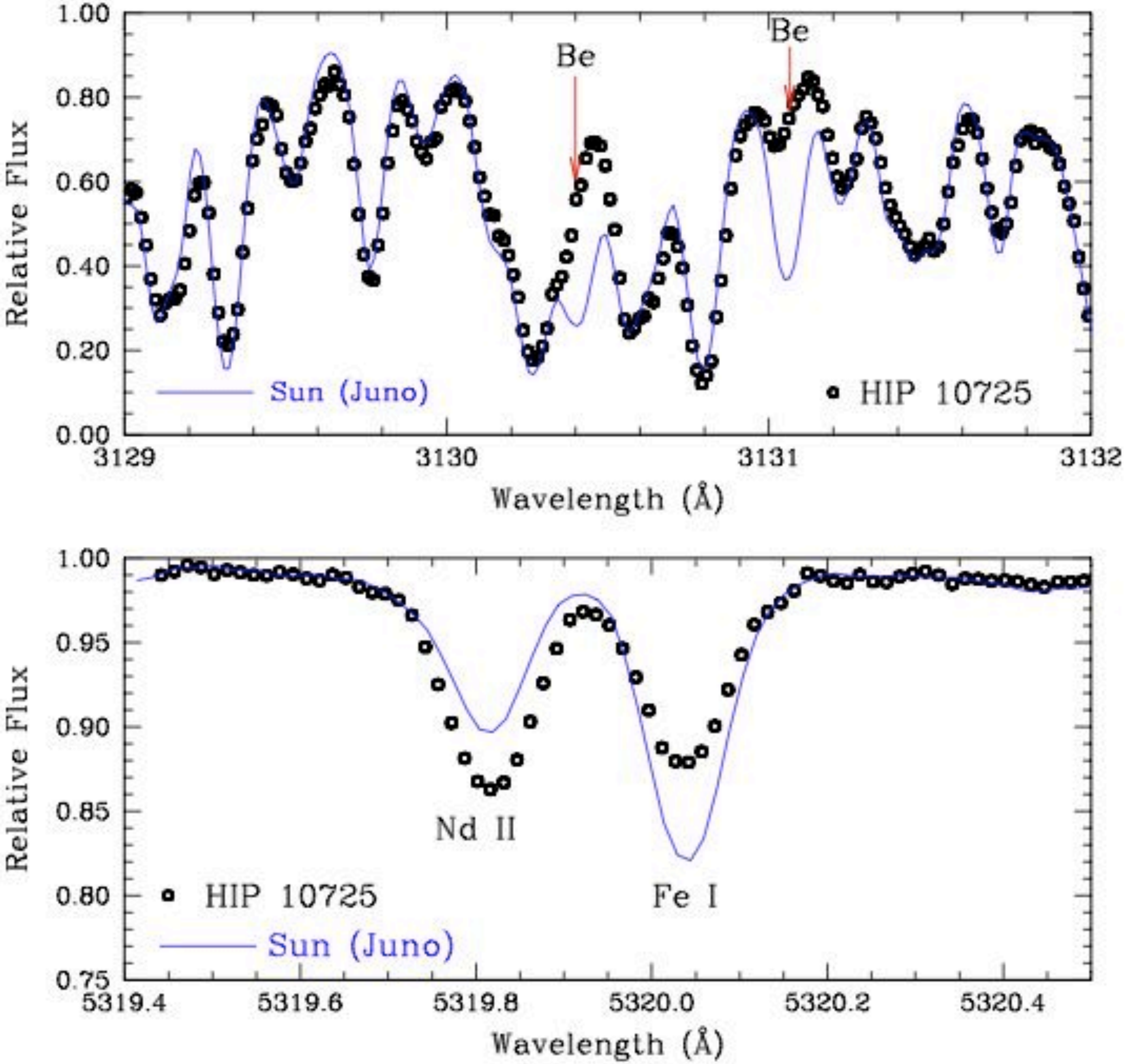
A&A 584, A116 (2015)
DOI: 10.1051/0004-6361/201527303

Astronomy & Astrophysics

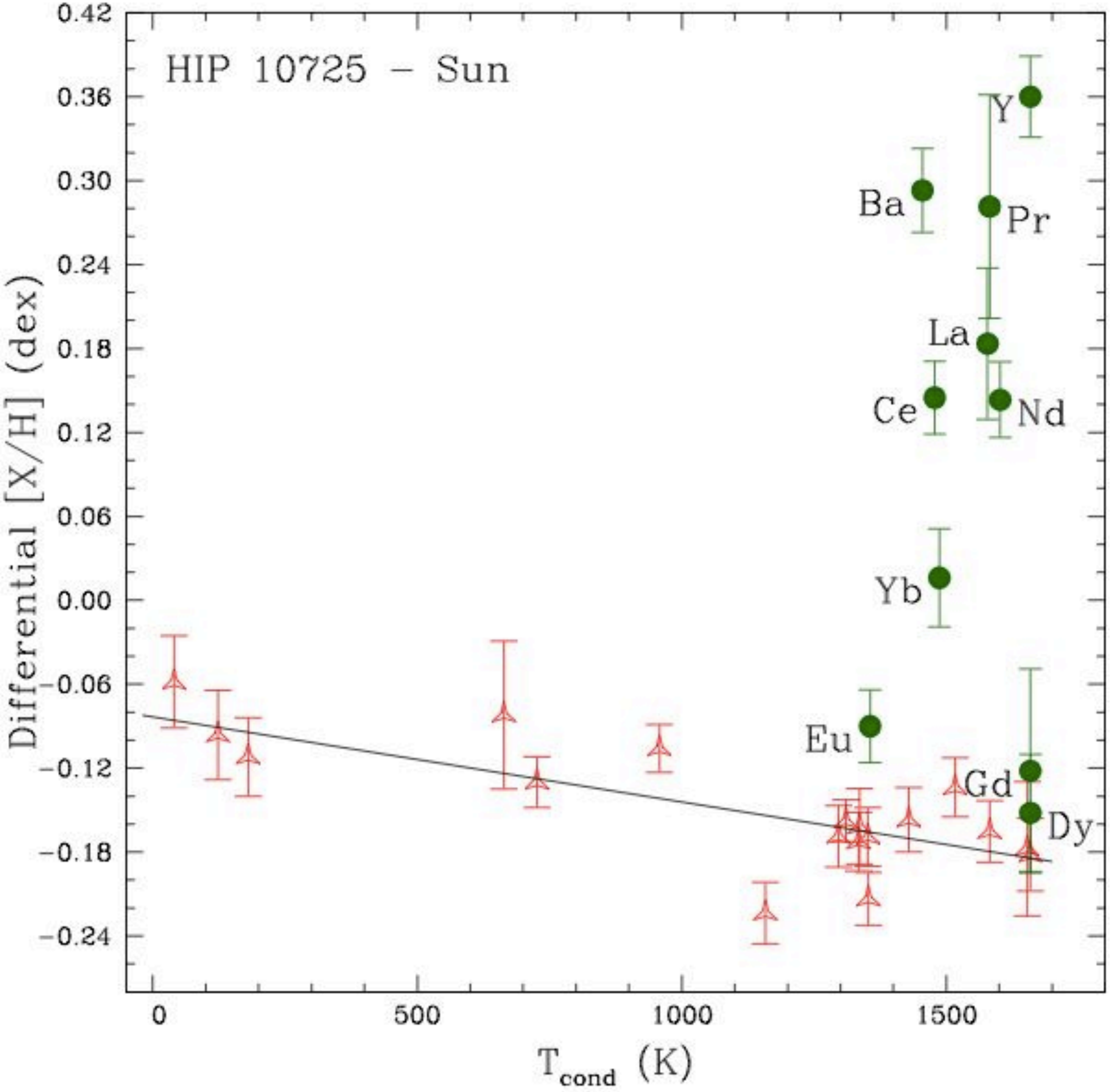
HIP 10725: The first solar twin/analogue field blue straggler⋆,⋆⋆

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]



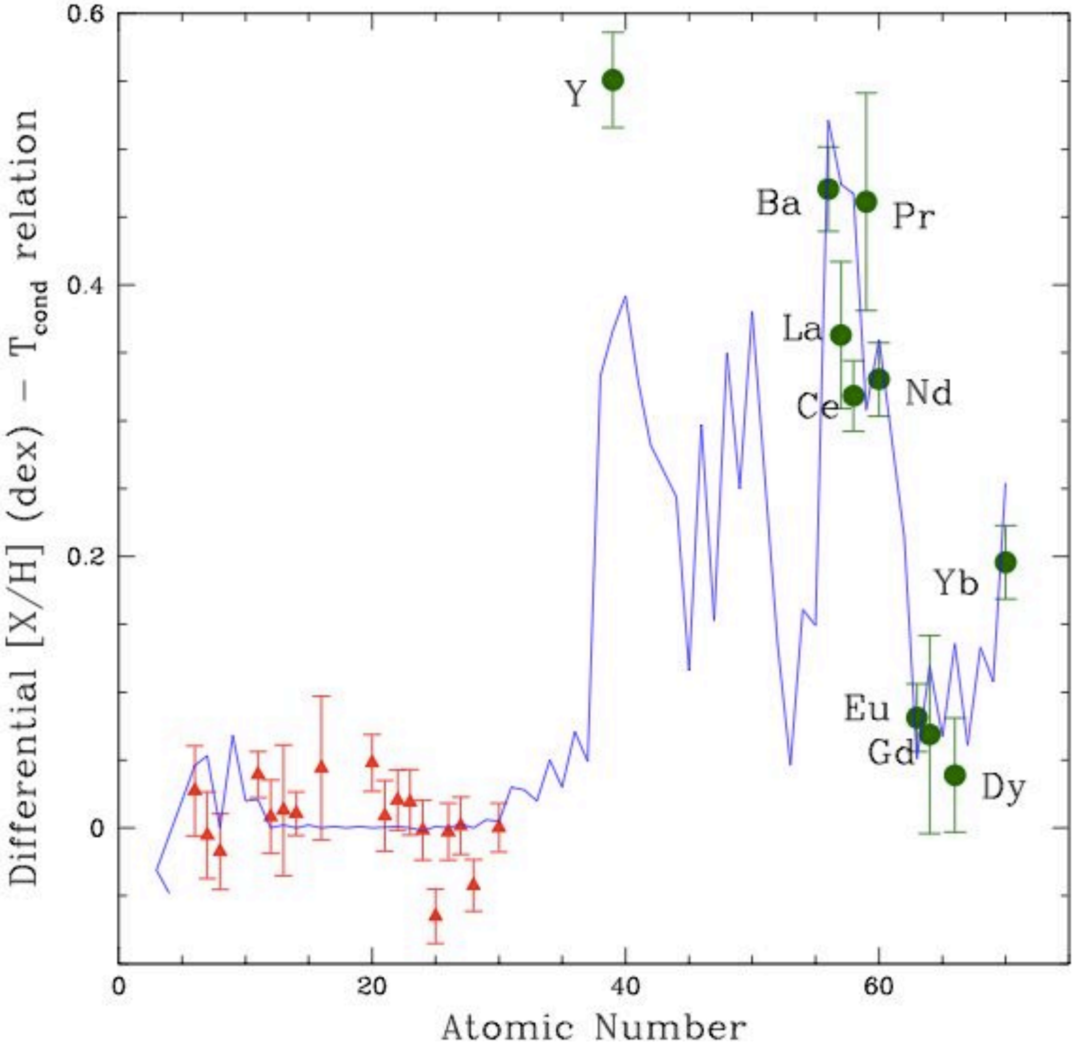


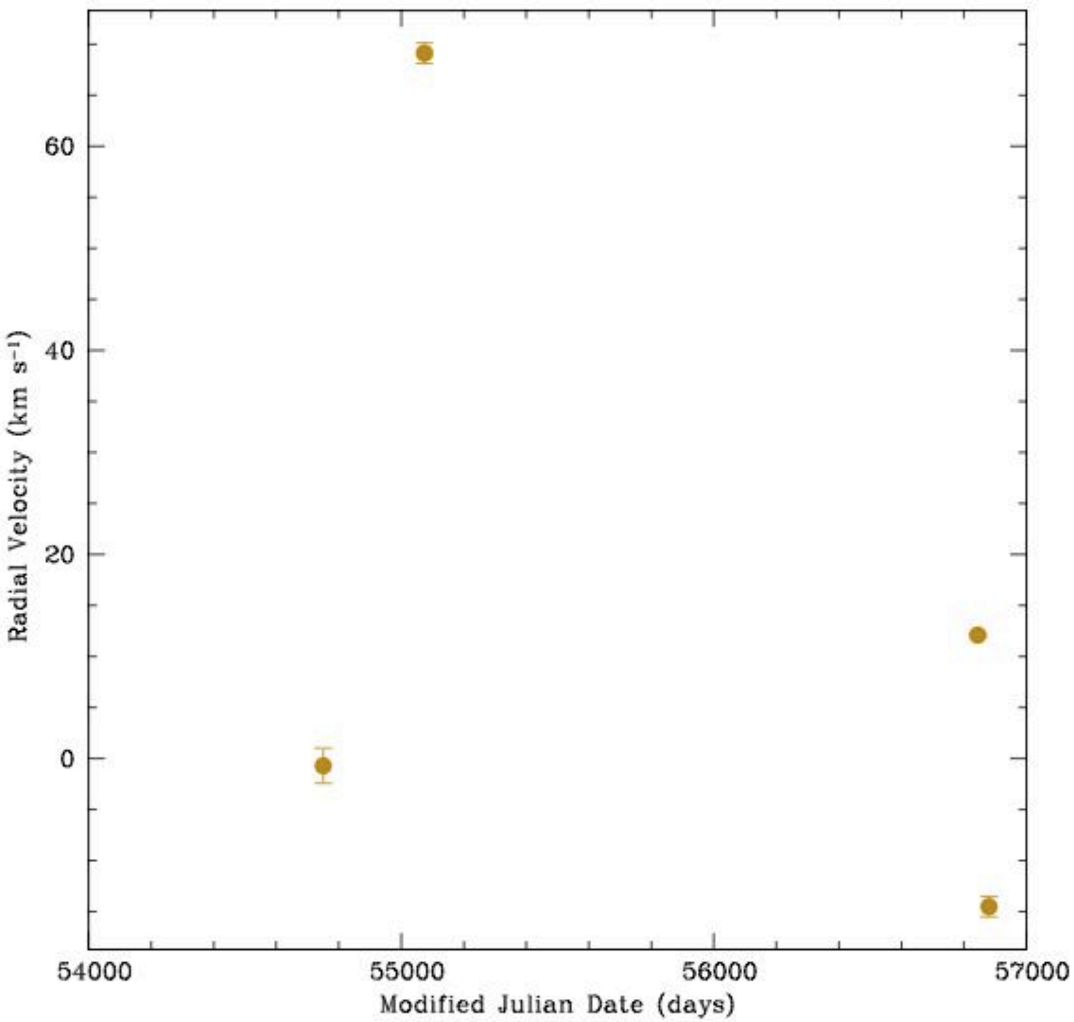
Be
Be
Sun (Juno)
HIP 10725
Relative Flux
Wavelength (Å)
1.00
0.80
0.60
0.40
0.20
0.00
3129
3130
3131
3132
Nd II
Fe I
HIP 10725
Sun (Juno)
Relative Flux
Wavelength (Å)
1.00
0.95
0.90
0.85
0.80
0.75
5319.4
5319.6
5319.8
5320.0
5320.2
5320.4



HIP 10725 – Sun
Y
Ba
Pr
La
Ce
Nd
Yb
Eu
Gd
Dy
Differential [X/H] (dex)
0.42
0.36
0.30
0.24
0.18
0.12
0.06
0.00
−0.06
−0.12
−0.18
−0.24
0
500
1000
1500
T_{cond} (K)

Signatures of former AGB star





Conclusion

Precision Spectroscopy (0.01 dex) of solar twins (and stellar twins) is a powerful tool for studies related to planets, stellar evolution and galactic chemical evolution

SAMPA

Stellar Atmospheres, Planets and Abundances