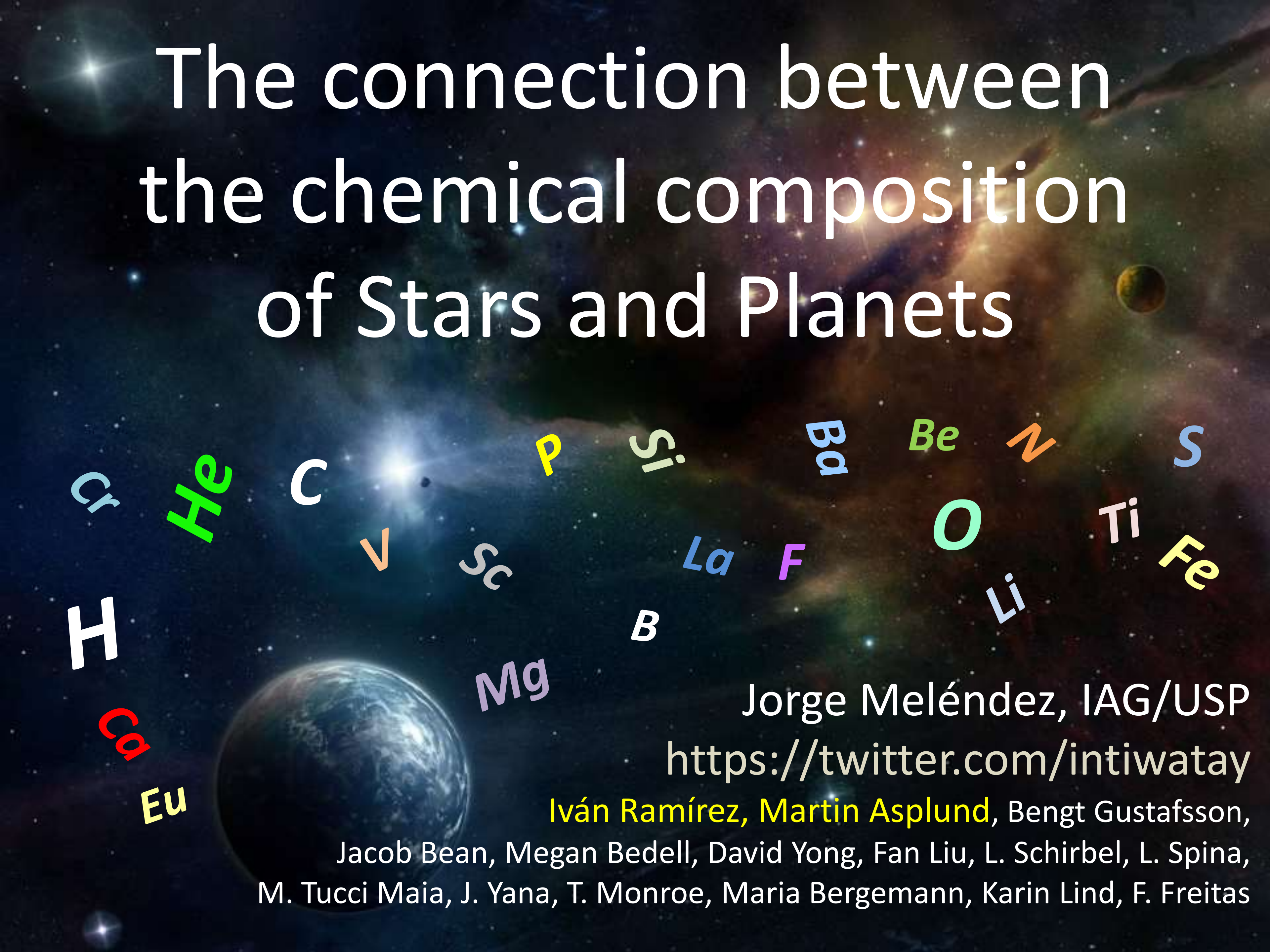
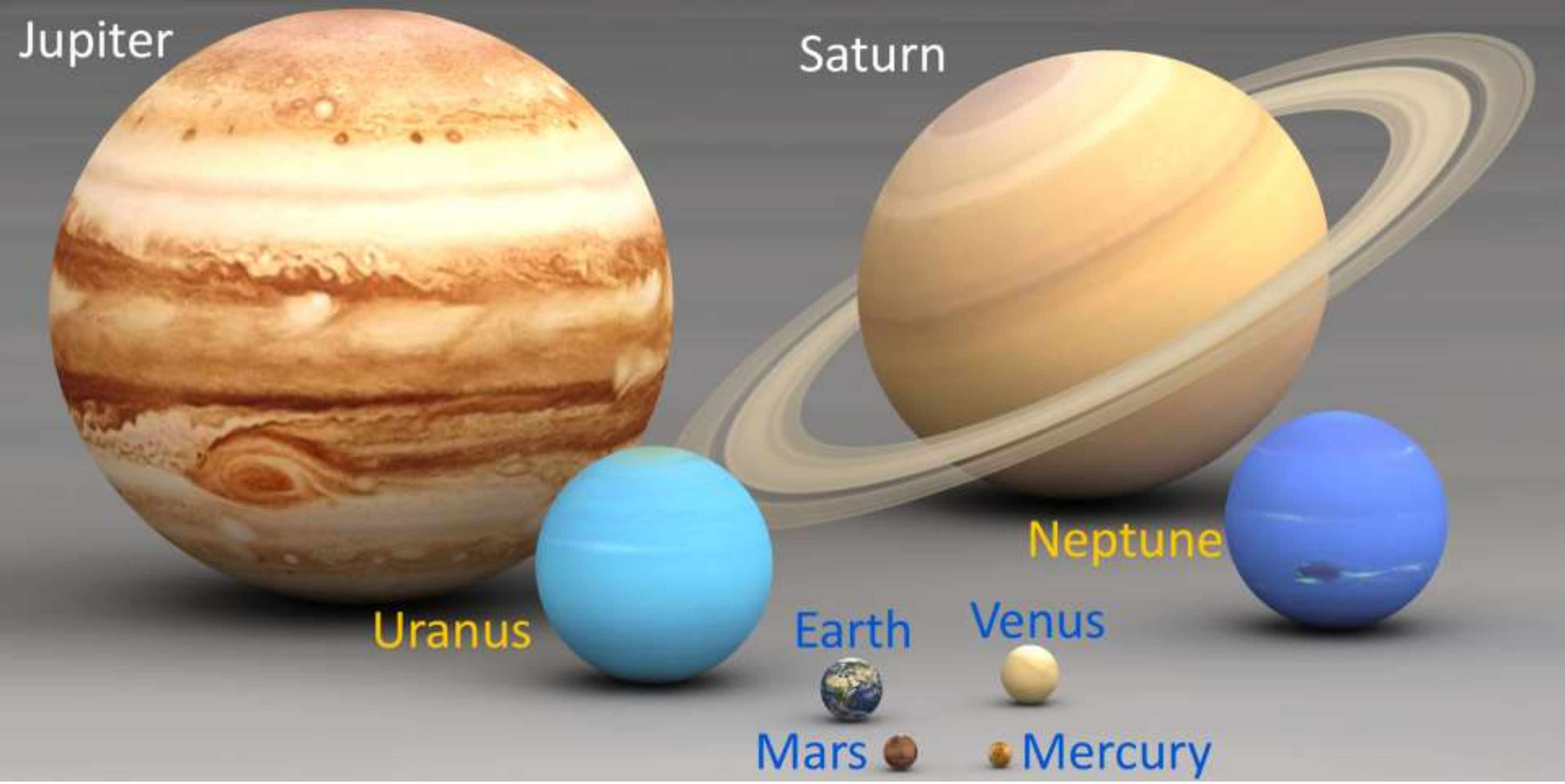
The connection between the chemical composition of Stars and Planets



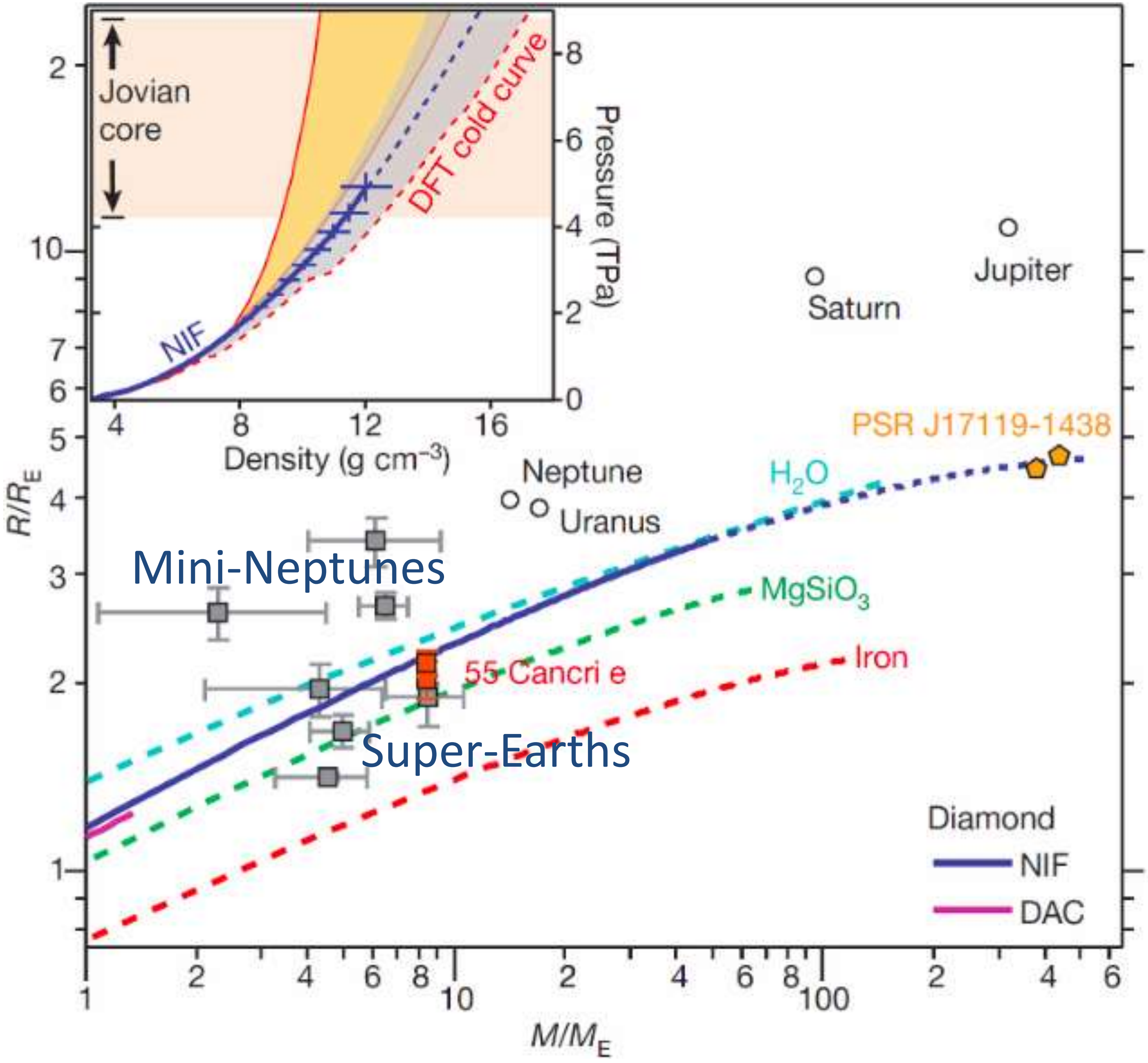
Jorge Meléndez, IAG/USP
https://twitter.com/intiwatay
Iván Ramírez, Martin Asplund, Bengt Gustafsson,
Jacob Bean, Megan Bedell, David Yong, Fan Liu, L. Schirbel, L. Spina,
M. Tucci Maia, J. Yana, T. Monroe, Maria Bergemann, Karin Lind, F. Freitas



Solar system:
- Jupiters
- Neptunes
- Earths

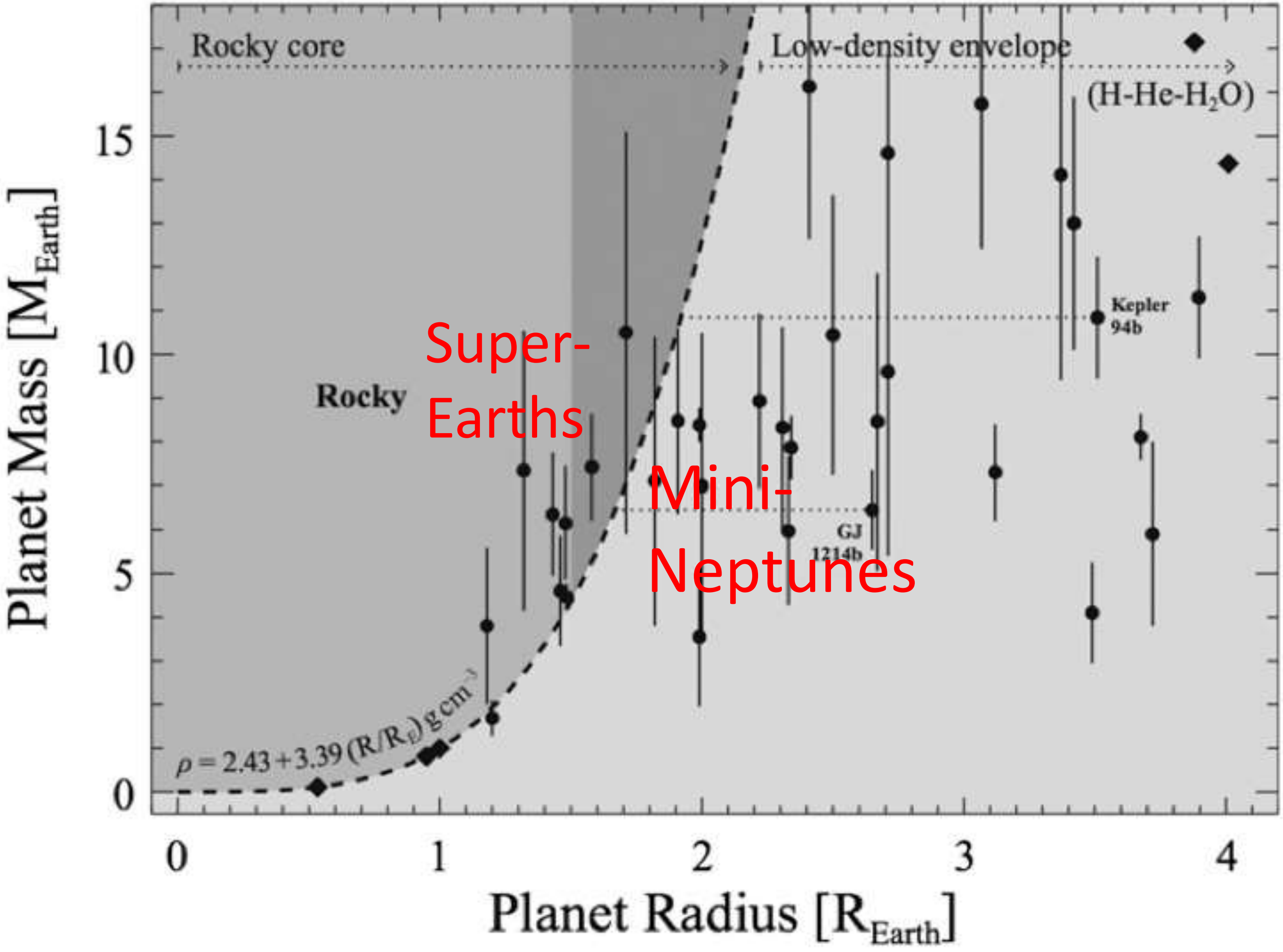
Other systems may host:
- Hot-Jupiters
- Mini-Neptunes
- Super-Earths

http://www.lesud.com/lesud-astronomy_pageid81.html



Mini-Neptunes

Super-Earths



Marcy et al. 2014 PNAS

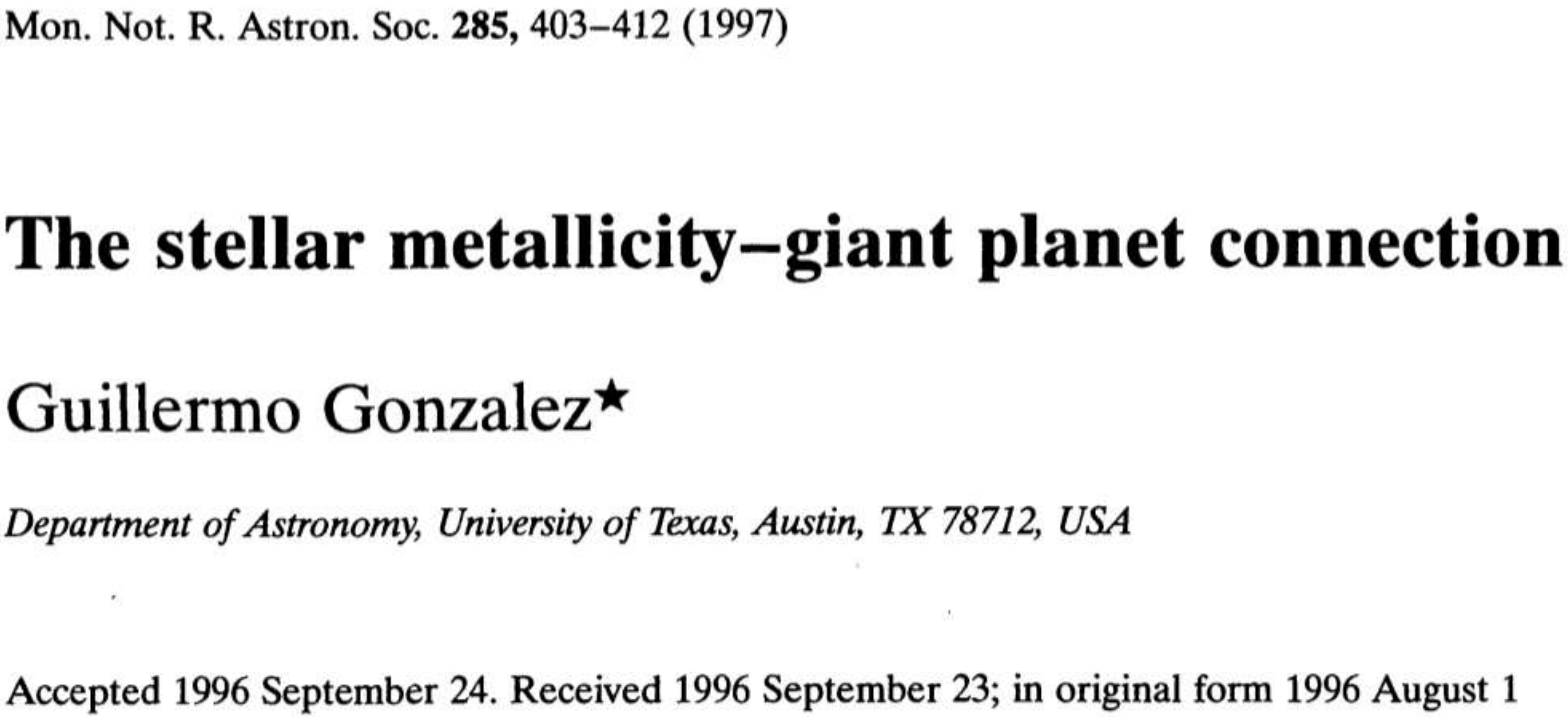
Notation

- A abundância química A_X de um elemento X é: $A_X = \log (N_X/N_H) + 12$ → hidrogênio: $A_H = 12$

- $[X/H] = A_X^{star} – A_X^{Sun}$
  - [Fe/H] = 0: same iron abundance as the Sun
  - [Fe/H] = -1.0 is 1/10 solar

- [X/Fe] = [X/H] – [Fe/H]
  - [Ca/Fe] = +0.3 means twice the number of Ca atoms per Fe atoms, relative to the Sun

Metallicity – close-in giant planet connection



Mon. Not. R. Astron. Soc. **285,** 403–412 (1997)

The stellar metallicity–giant planet connection

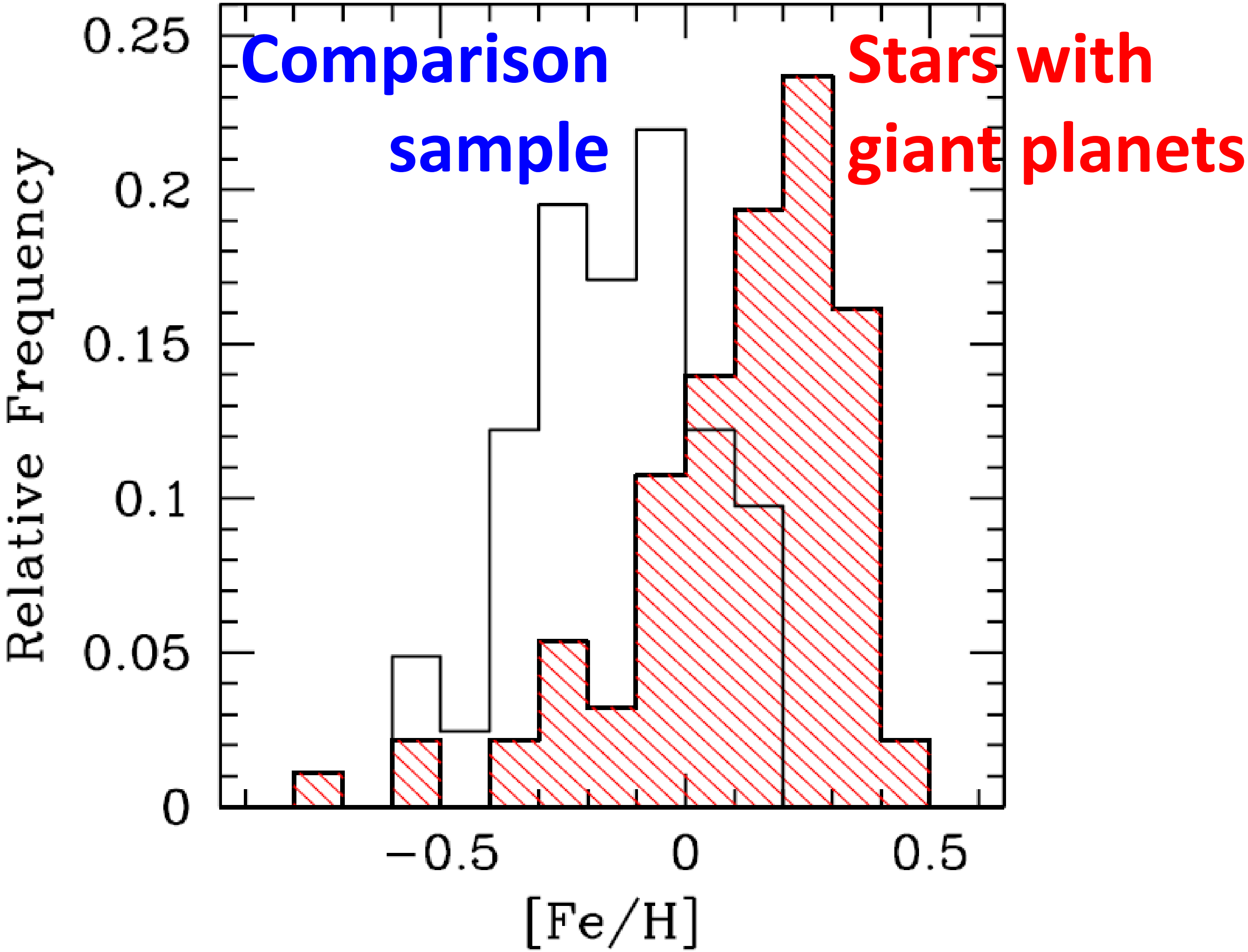
Guillermo Gonzalez★

Department of Astronomy, University of Texas, Austin, TX 78712, USA

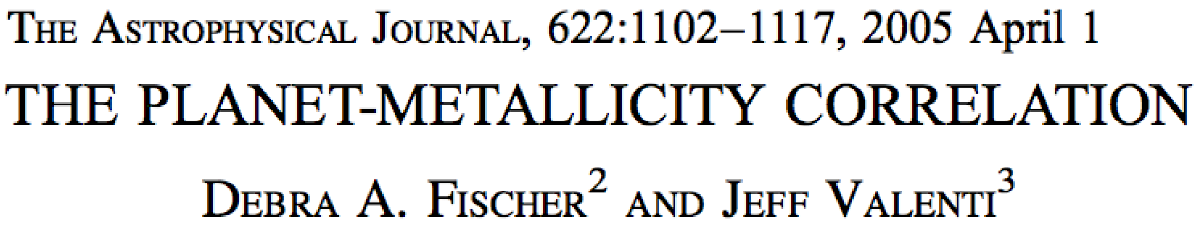
Accepted 1996 September 24. Received 1996 September 23; in original form 1996 August 1

Metallicity – close-in giant planet connection

N. C. Santos[1,2], G. Israelian[3], and M. Mayor[2]
A&A 415, 1153–1166 (2004)



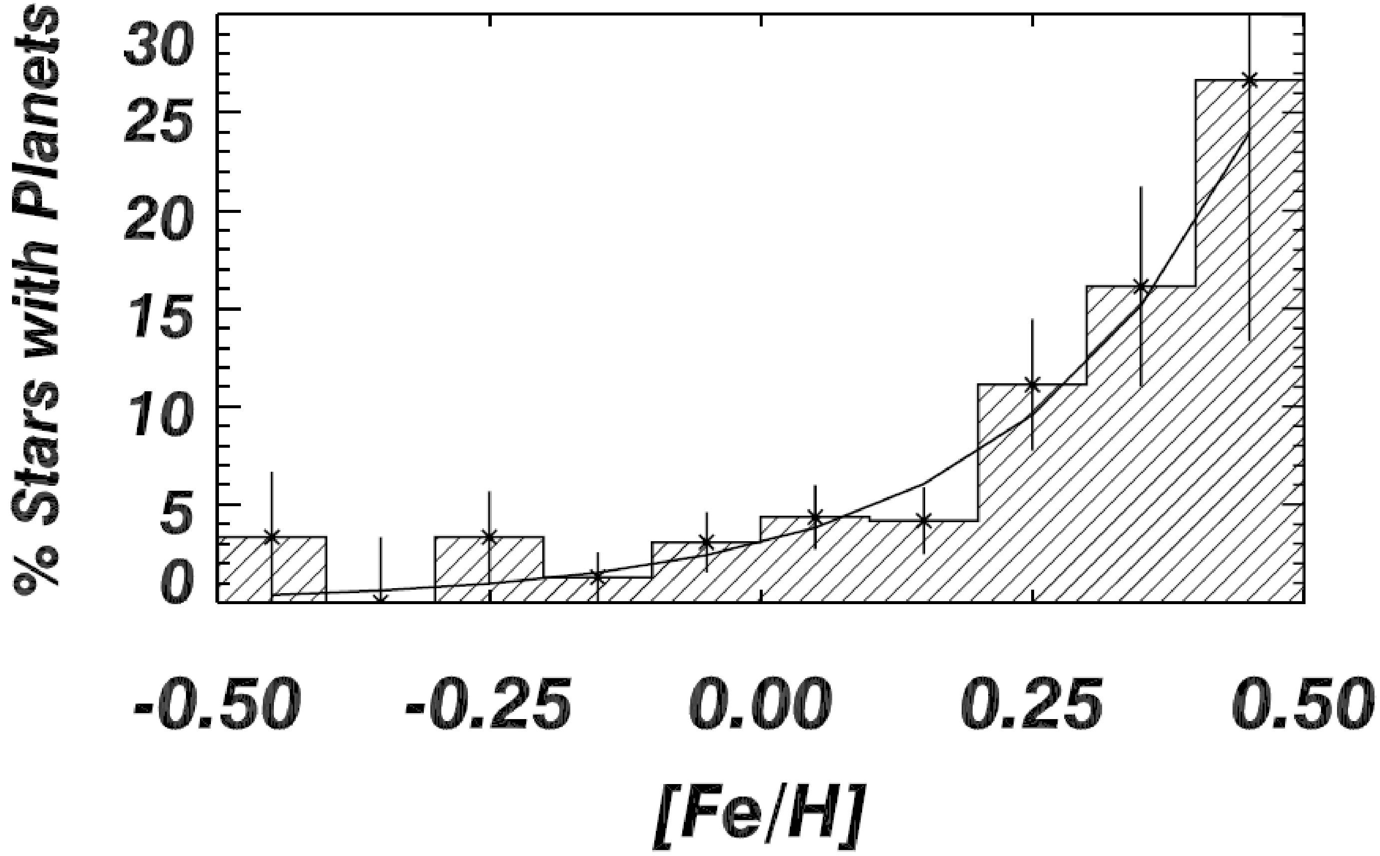
Metallicity – close-in giant planet connection



THE ASTROPHYSICAL JOURNAL, 622:1102–1117, 2005 April 1

THE PLANET-METALLICITY CORRELATION

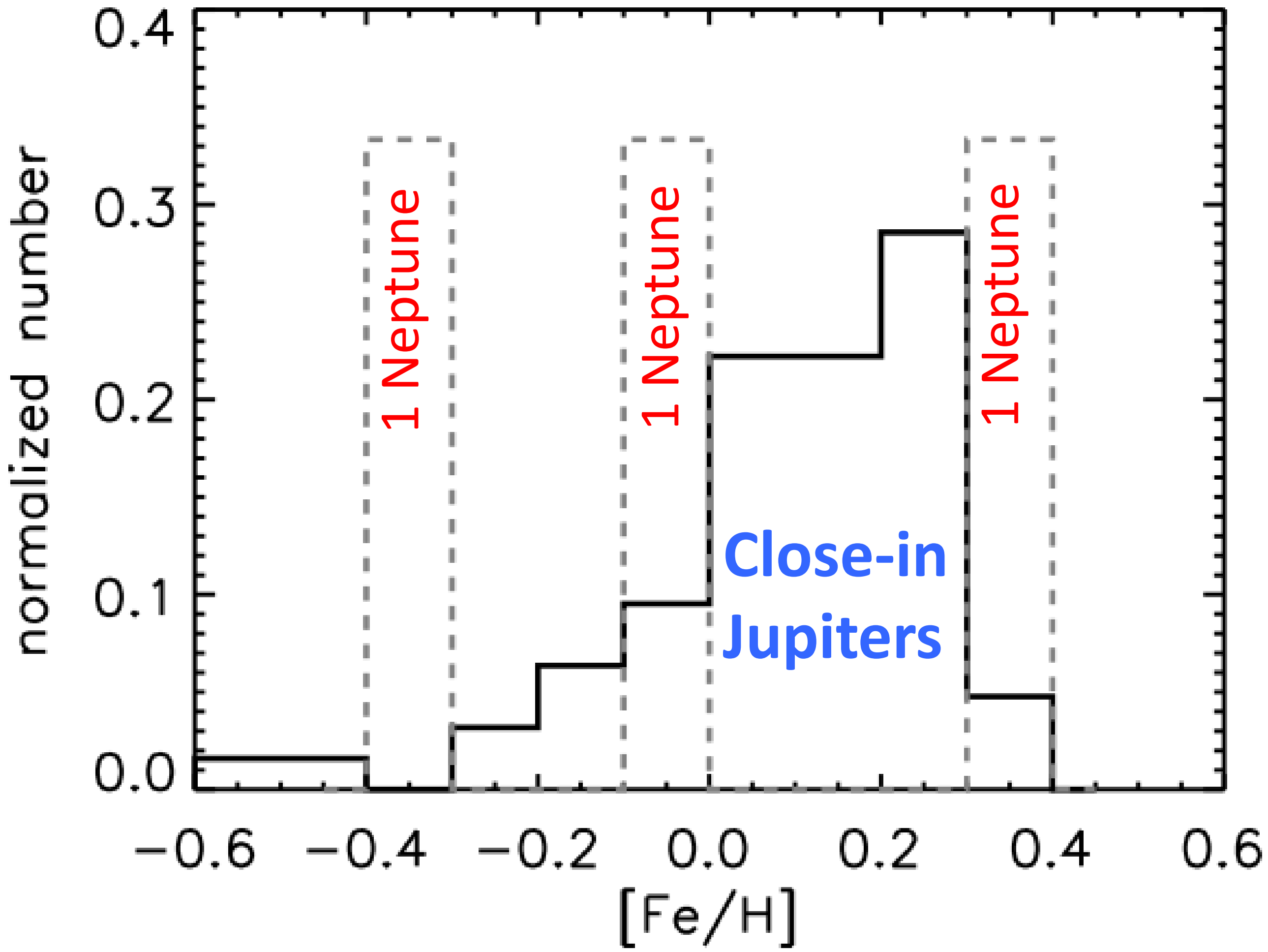
DEBRA A. FISCHER[2] AND JEFF VALENTI[3]



1040 FGK-type stars

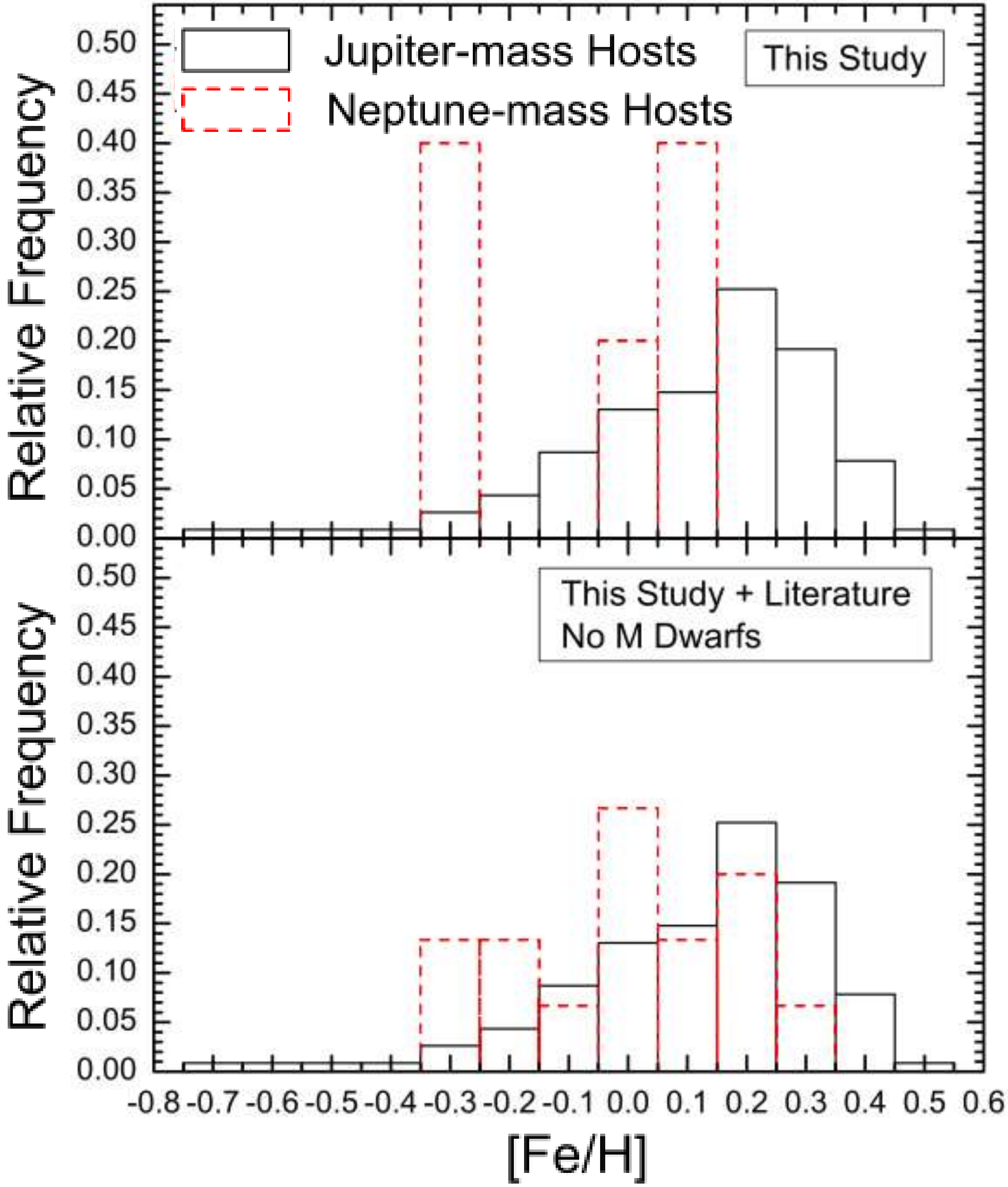
Metallicity – planet connection: **Neptunes can be formed at any metallicity**

Sousa et al. 2008, A&A 487, 373



Metallicity – planet connection:

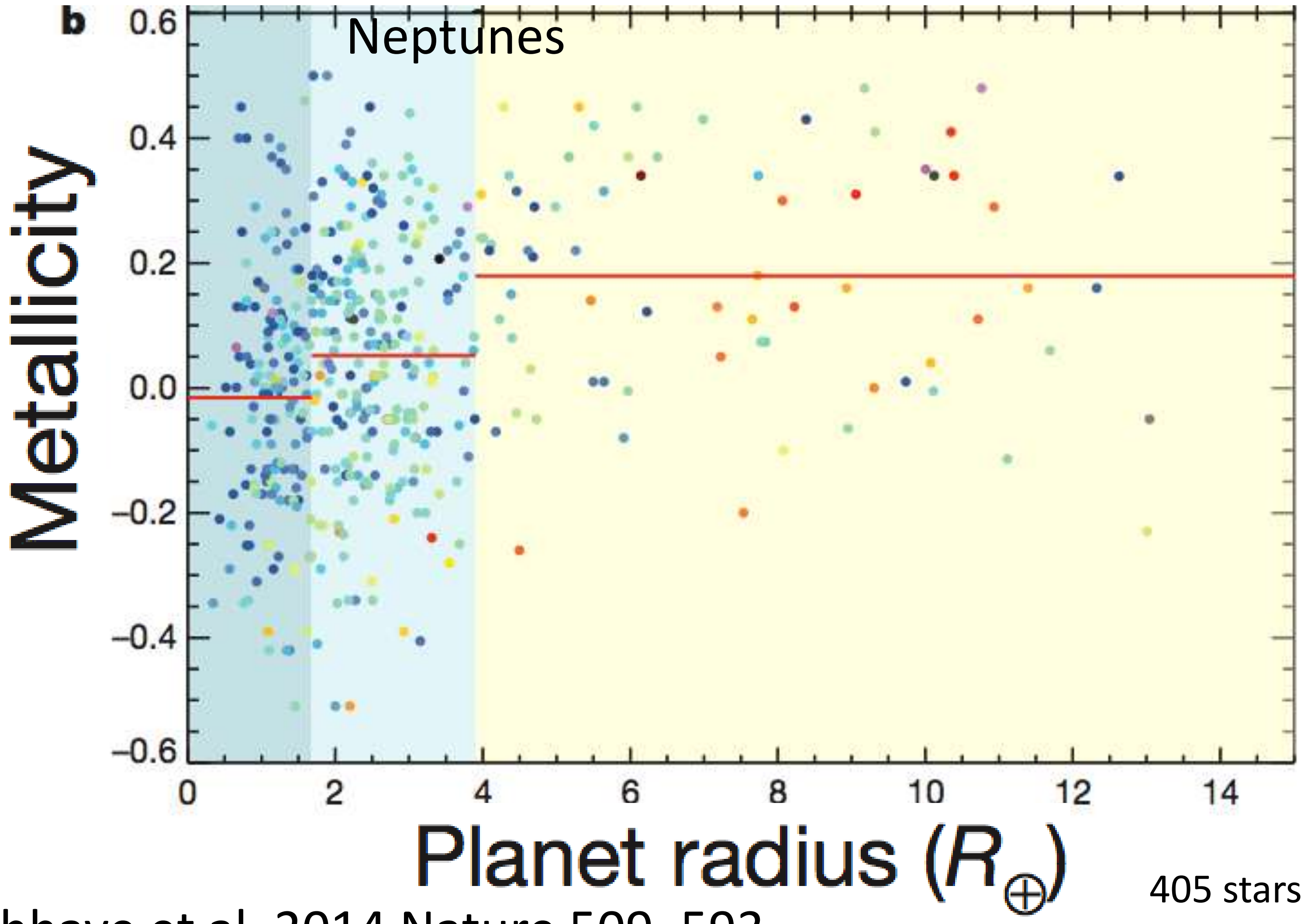
Neptunes can be formed at any metallicity



Ghezzi et al. 2010
ApJ 720, 1290

Metallicity – planet connection in FGK stars:

Rocky planets can be formed at any [Fe/H]



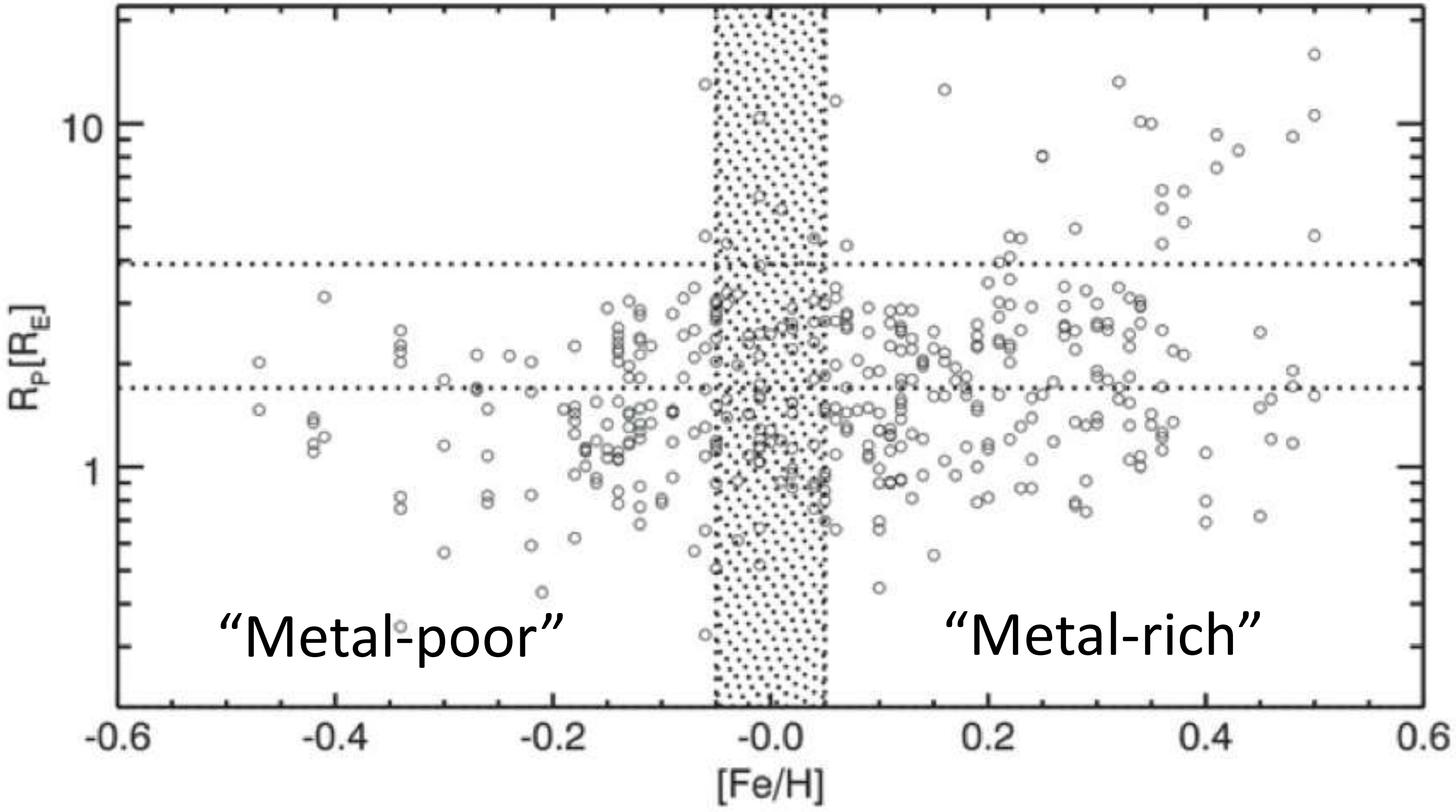
Rocky Mini-Neptunes Ice/gas giants

Buchhave et al. 2014 Nature 509, 593

405 stars with 600 exoplanet candidates

“Universal” metallicity – planet connection:

Rocky & giant planets occur more frequently in metal-rich stars

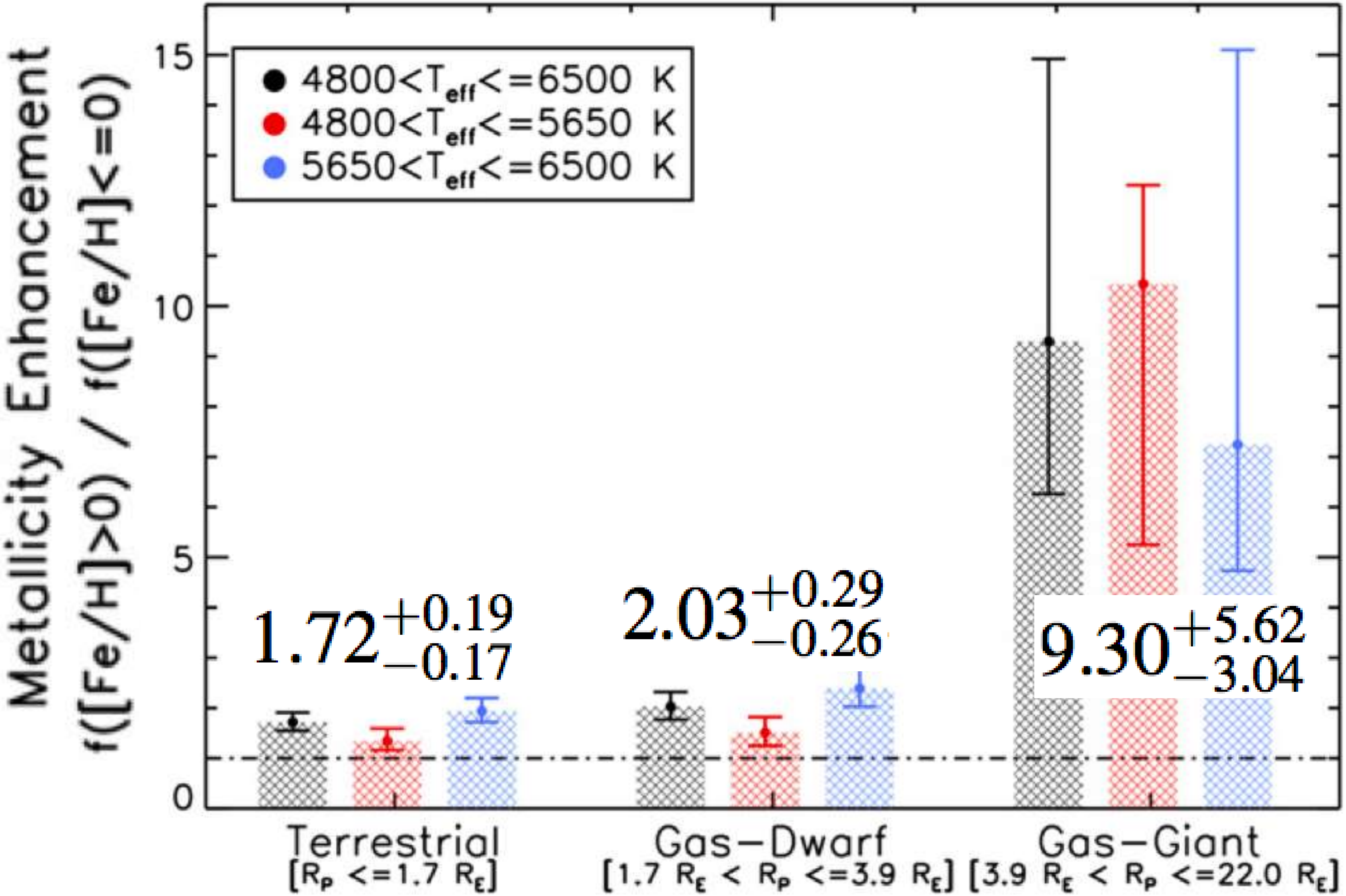


Wang & Fischer 2015 ApJ 149, 14

406 KOI

"Universal" metallicity – planet correlation:

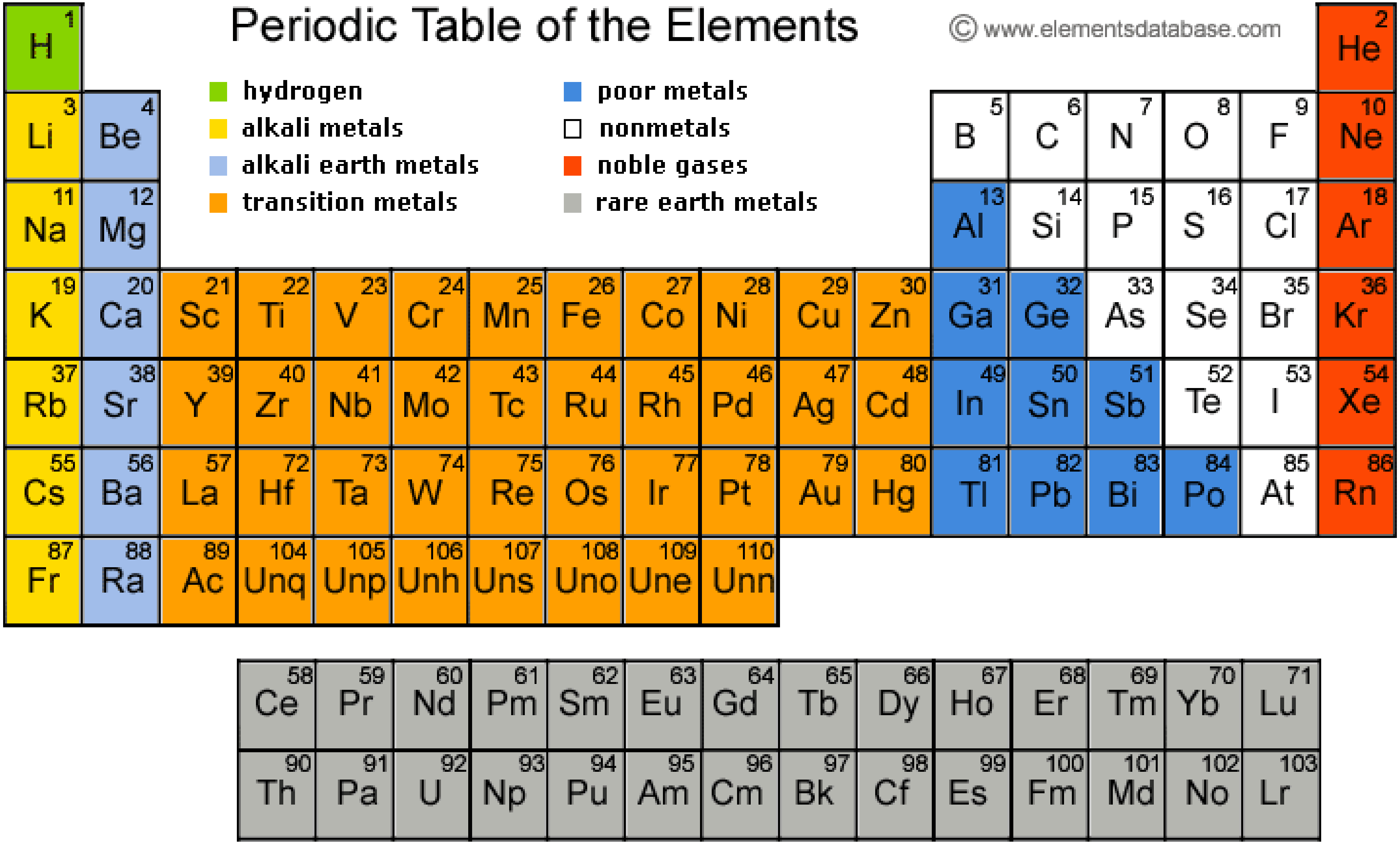
but giant planets depend much more on [Fe/H]



Wang & Fischer 2015 ApJ 149, 14

~100 000 stars; ~250 planet hosts

What about other elements besides iron?



Periodic Table of the Elements

© www.elementsdatabase.com

🟩 hydrogen
🟨 alkali metals
▨ alkali earth metals
🟧 transition metals
🟦 poor metals
☐ nonmetals
🟥 noble gases
▩ rare earth metals

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

nature Vol 462 | 12 November 2009 LETTERS

Enhanced lithium depletion in Sun-like stars with orbiting planets

Garik Israelian[1,2], Elisa Delgado Mena[1,2], Nuno C. Santos[3,4], Sergio G. Sousa[1,3], Michel Mayor[4], Stephane Udry[4], Carolina Domínguez Cerdeña[1,2], Rafael Rebolo[1,2,5] & Sofia Randich[6]

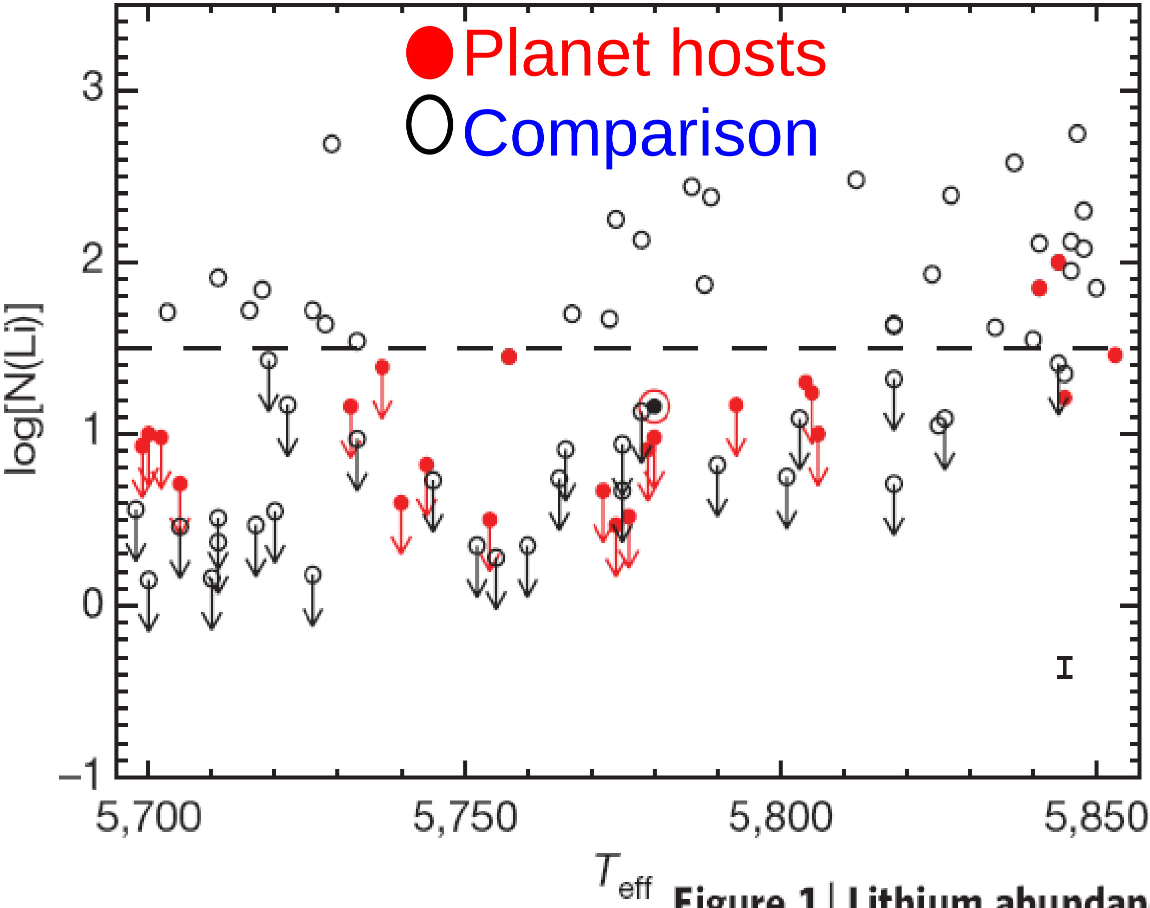


Figure 1 | Lithium abundance plotted against effective temperature in solar-analogue stars with and without detected planets. The planet-

Lithium

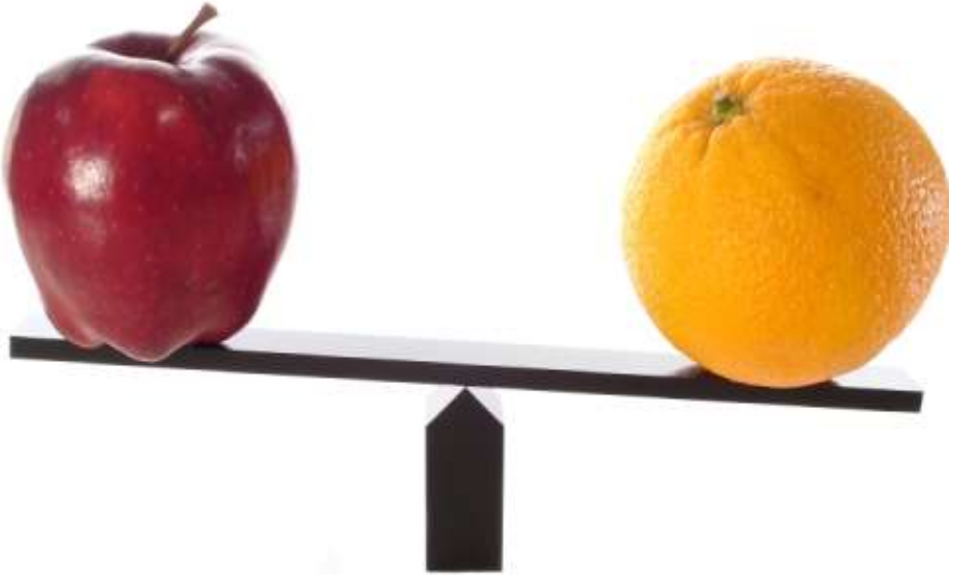
Planet-host stars around ***solar*** $\boldsymbol{T_{eff}}$ *seem depleted in lithium*

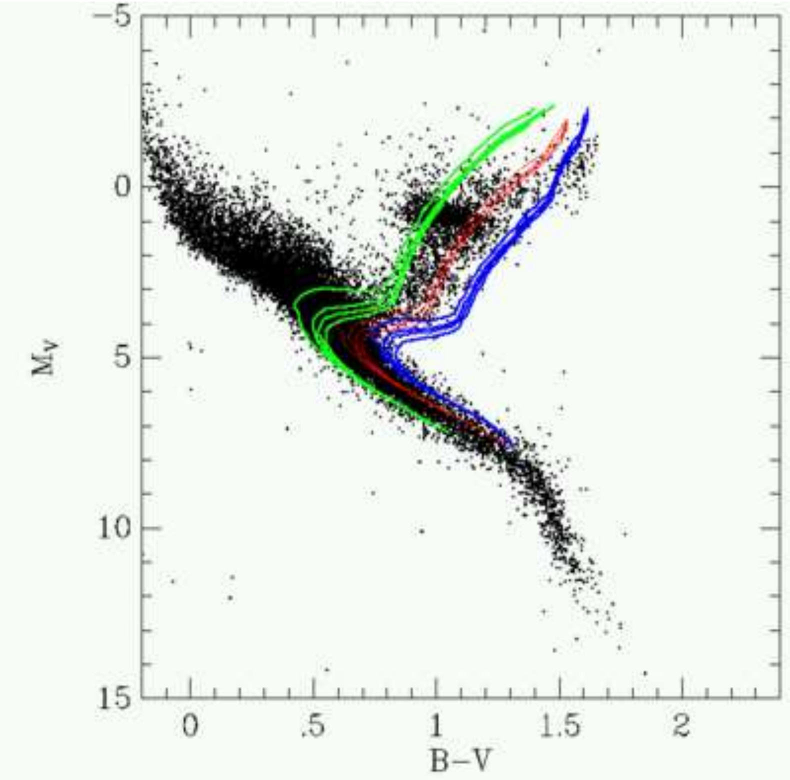
You cannot compare apples and oranges …

comparer des pommes avec des oranges

comparer des pommes et des poires

comparar peras con manzanas

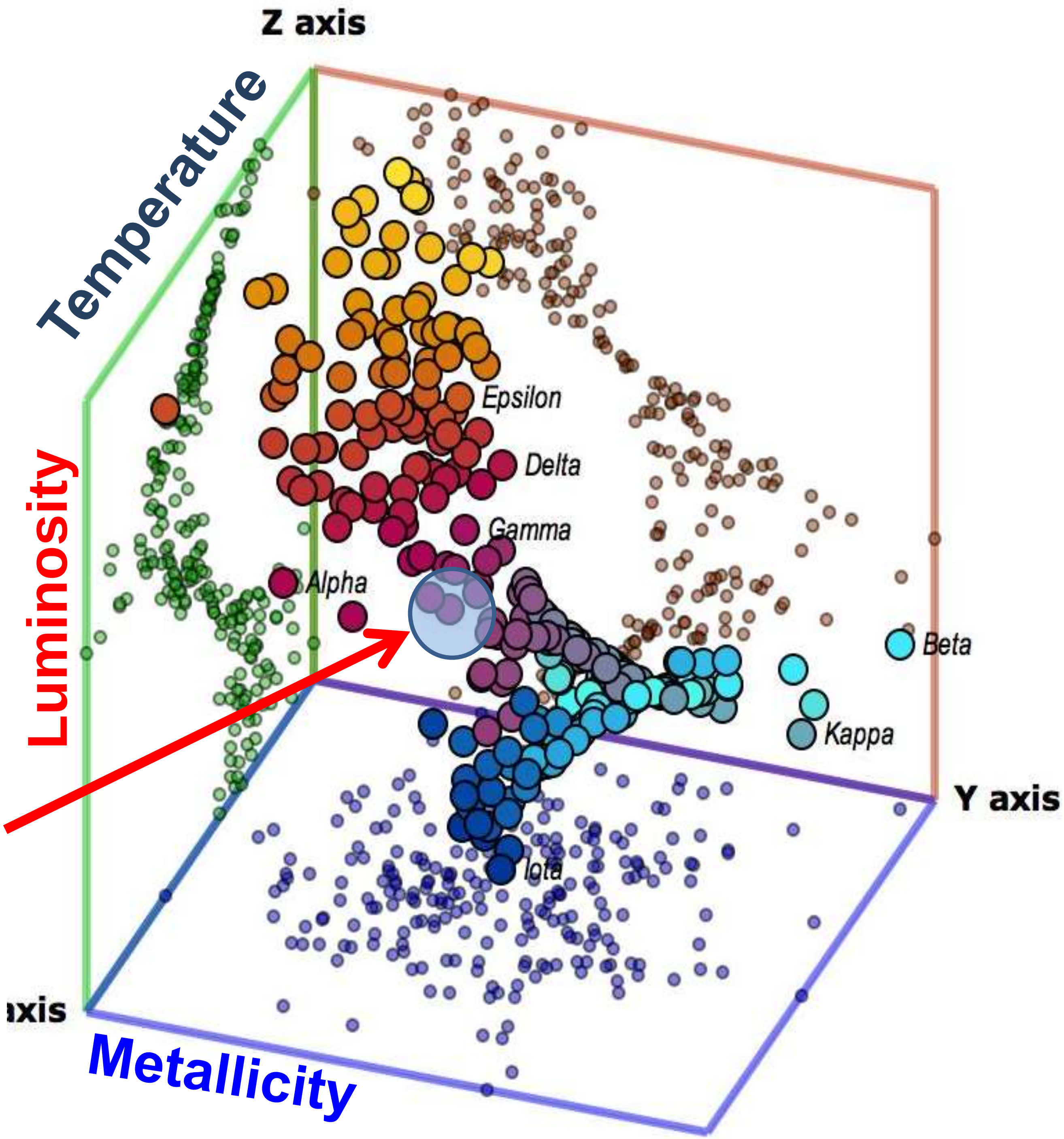




You cannot add pears and apples …

No puedes sumar peras con manzanas

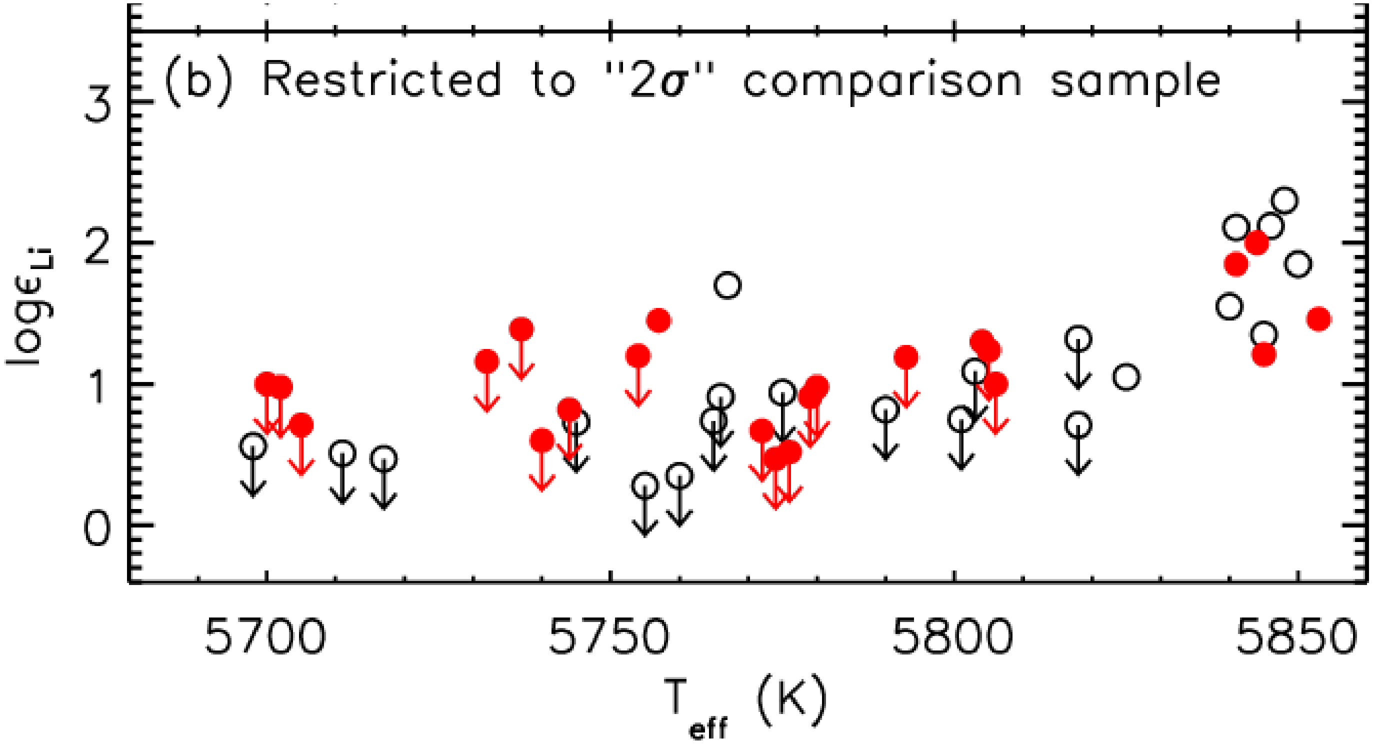
Comparing apples & apples in a 3D parameter space



Li depletion is not enhanced in planet hosts !

Comparing apples & apples

(only stars with similar stellar parameters within 2-sigma)

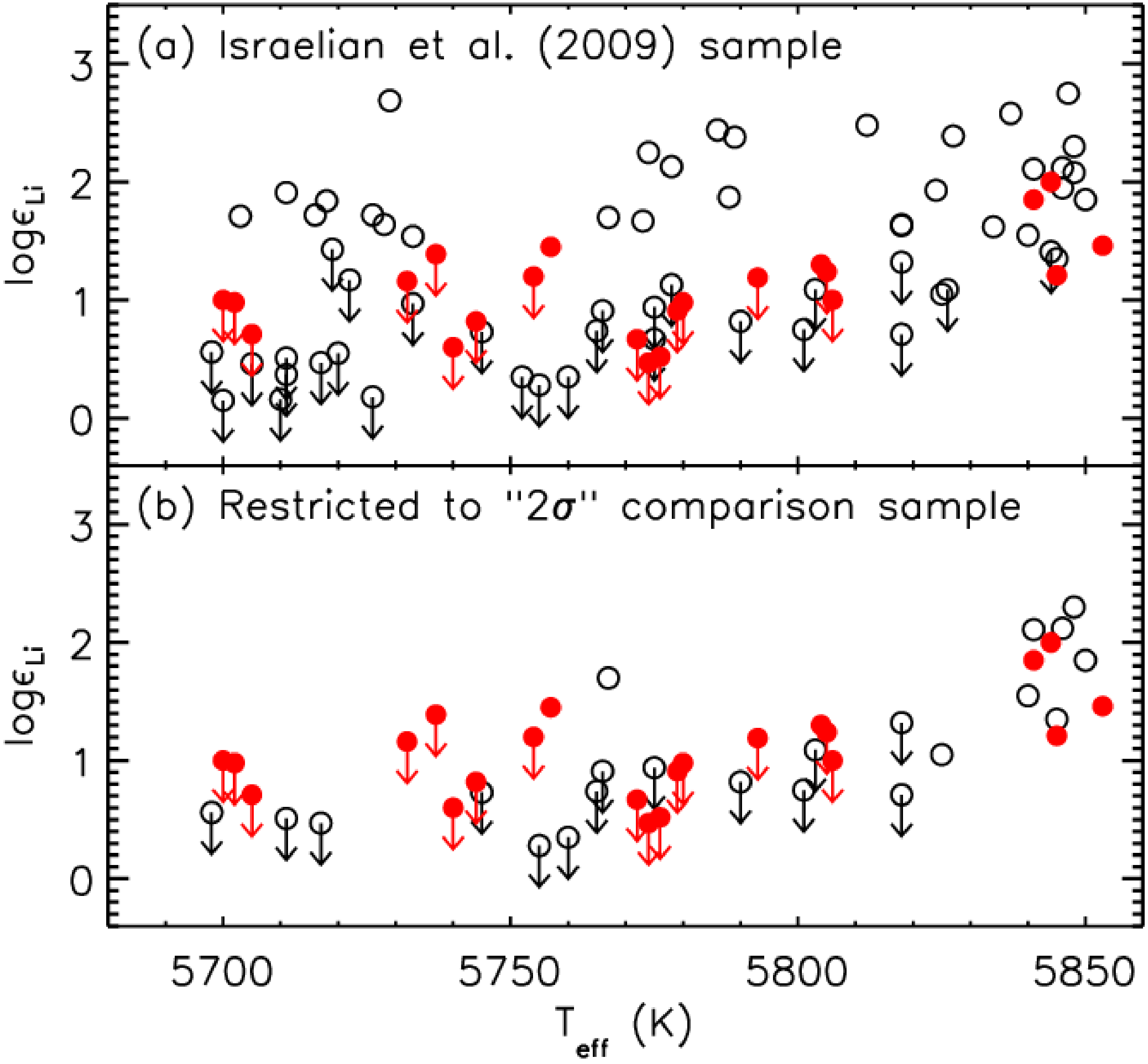


● Planet hosts

○ Comparison

Baumann, Ramírez, Meléndez & Asplund 2010, A&A, 519, A87

Li depletion is not enhanced in planet hosts !



Apples & oranges

Israelian et al. 2009, Nature

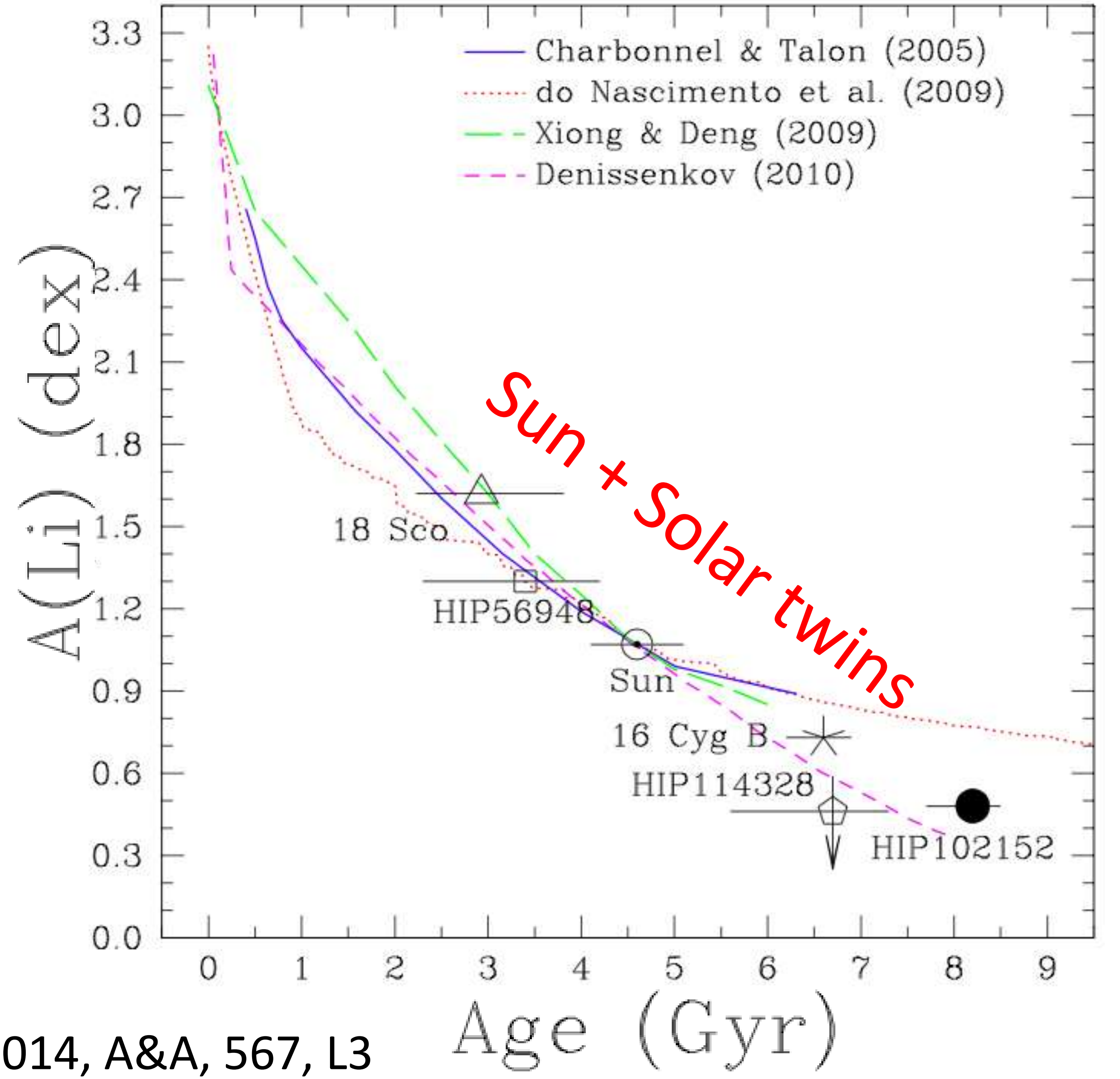
● Planet hosts

○ Comparison

Apples & apples

Baumann et al. 2010, A&A, 519, A87

Lithium seems correlated with age



Melendez et al. 2014, A&A, 567, L3

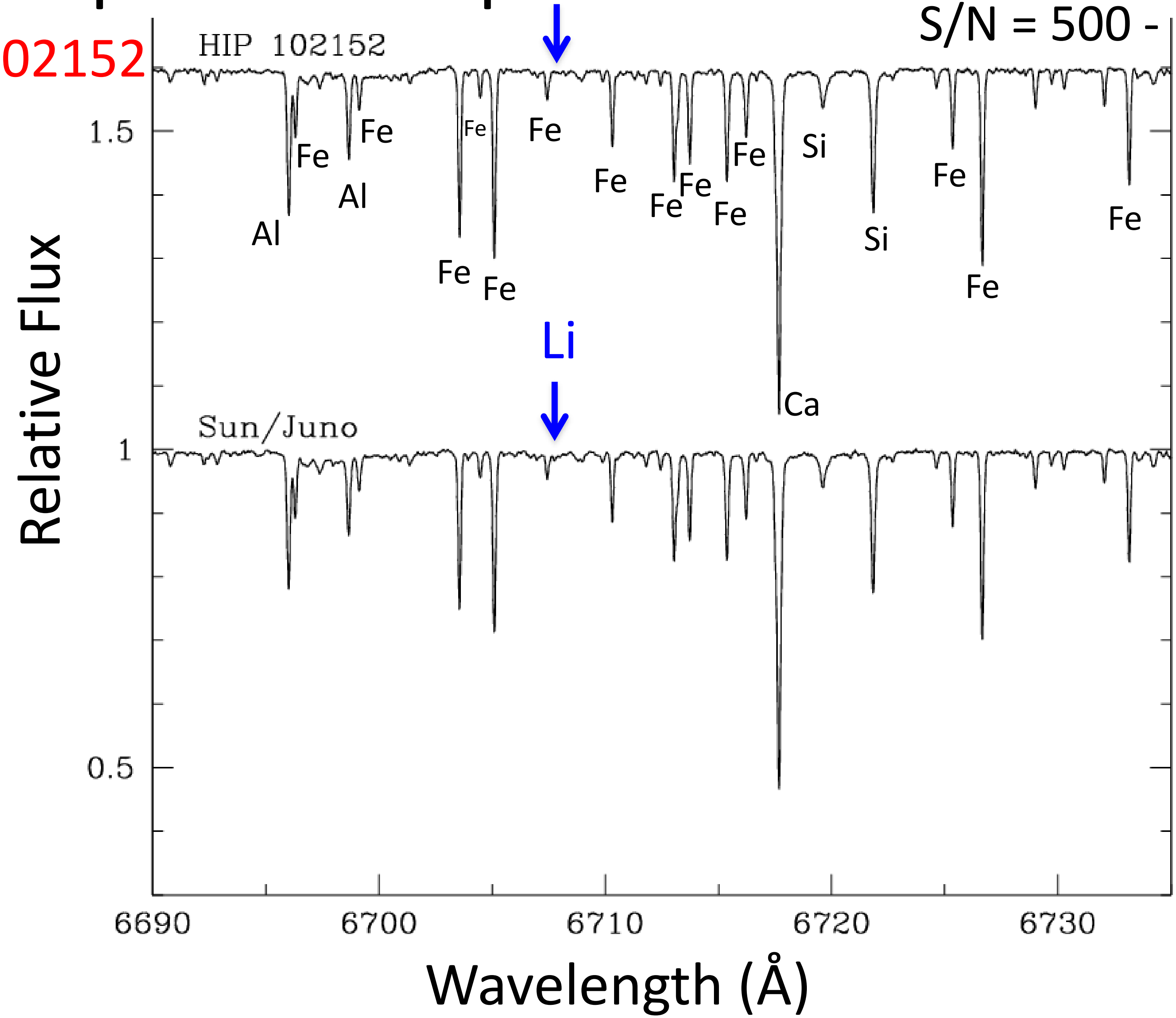
See also Monroe et al. 2013, Baumann et al. 2010

Comparison of spectra

R = 110 000

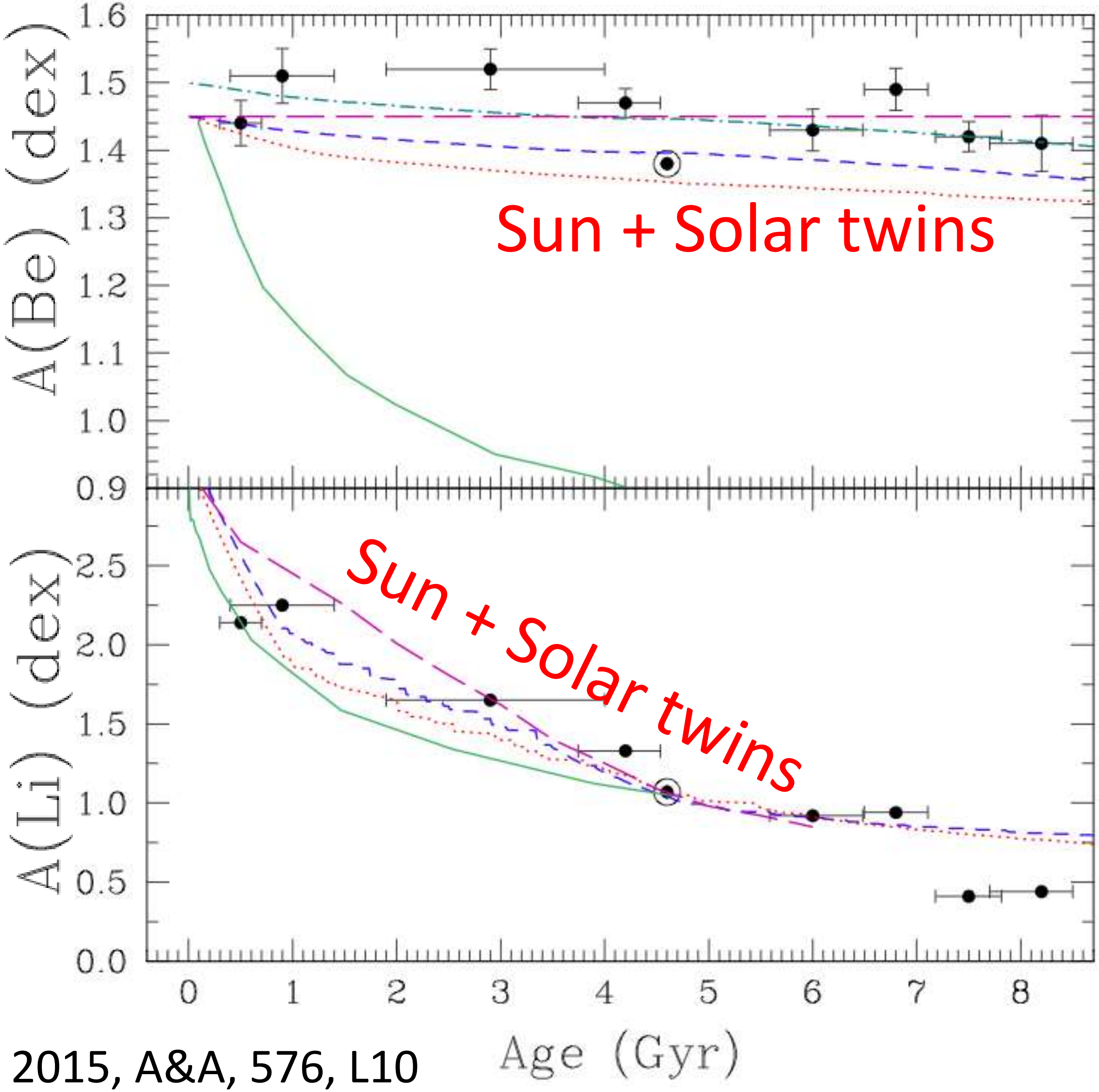
S/N = 500 - 1000

HIP 102152



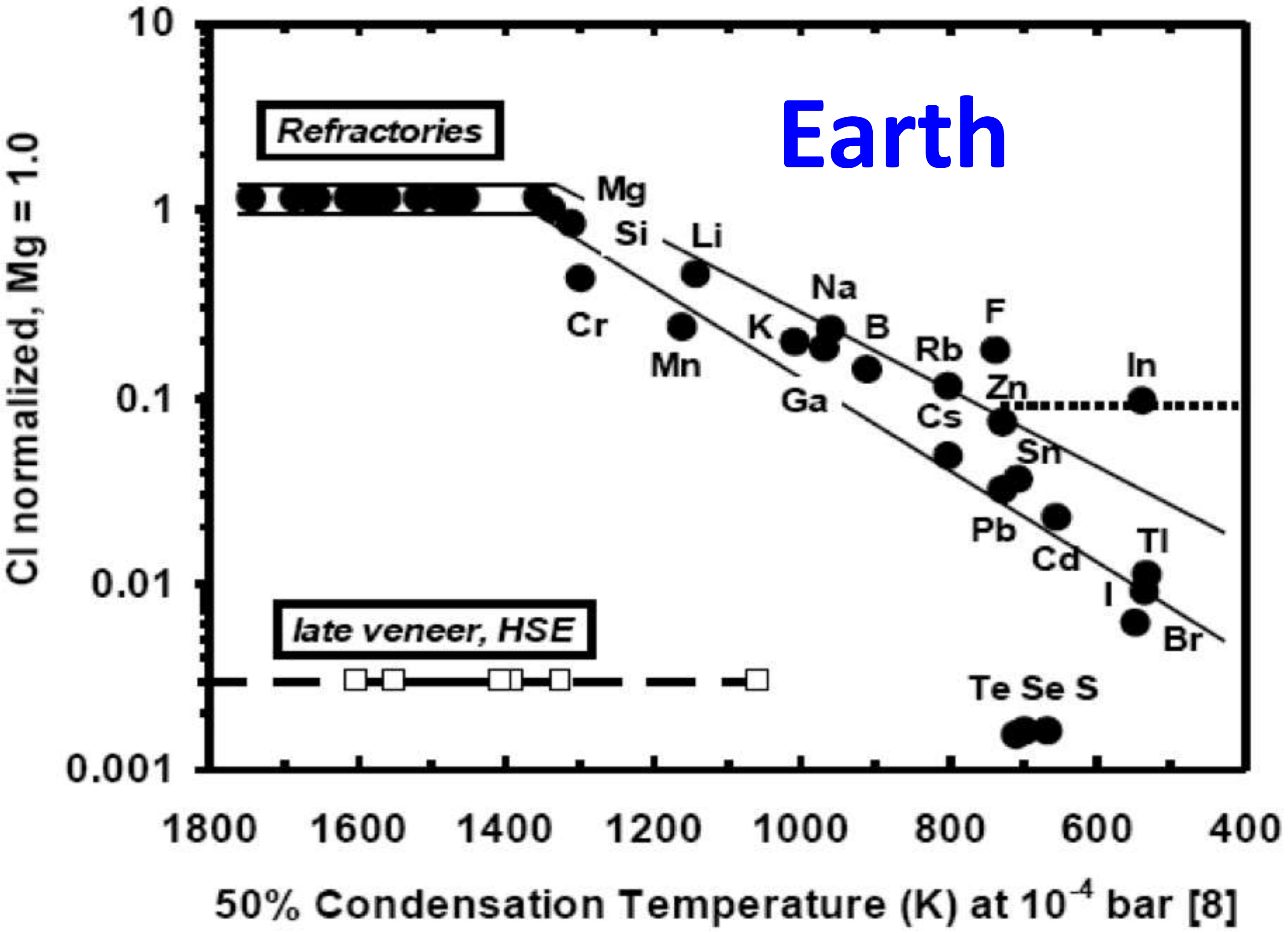
Sun

Lithium & beryllium as probes of stellar interiors



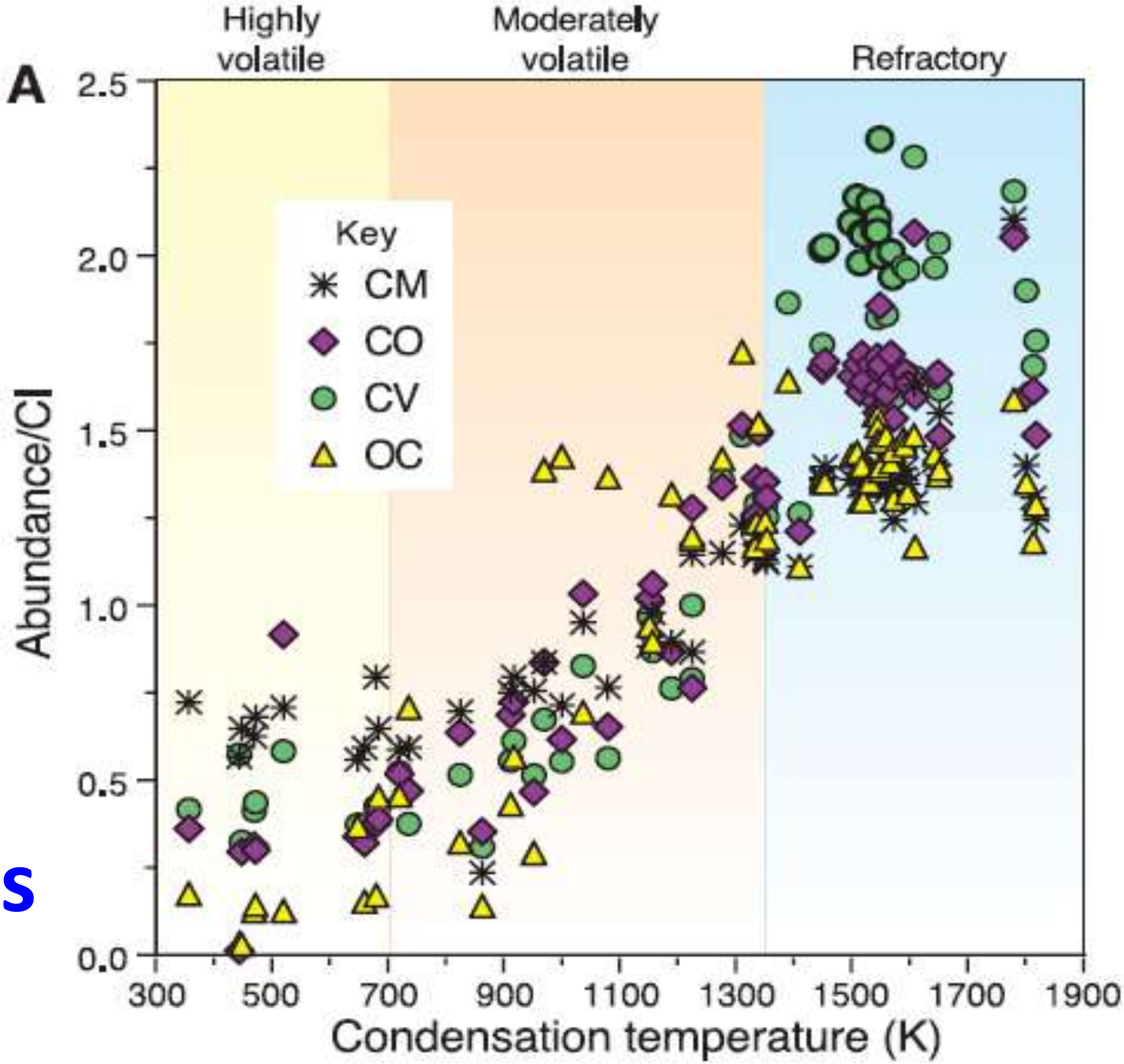
Tucci Maia et al. 2015, A&A, 576, L10

What about other elements? Refractories



Depletion trend of volatiles in Earth's mantle probably reflects primary nebular depletion in the Earth making material (Witt-Eickschen et al.2007).

What about the refractory elements?

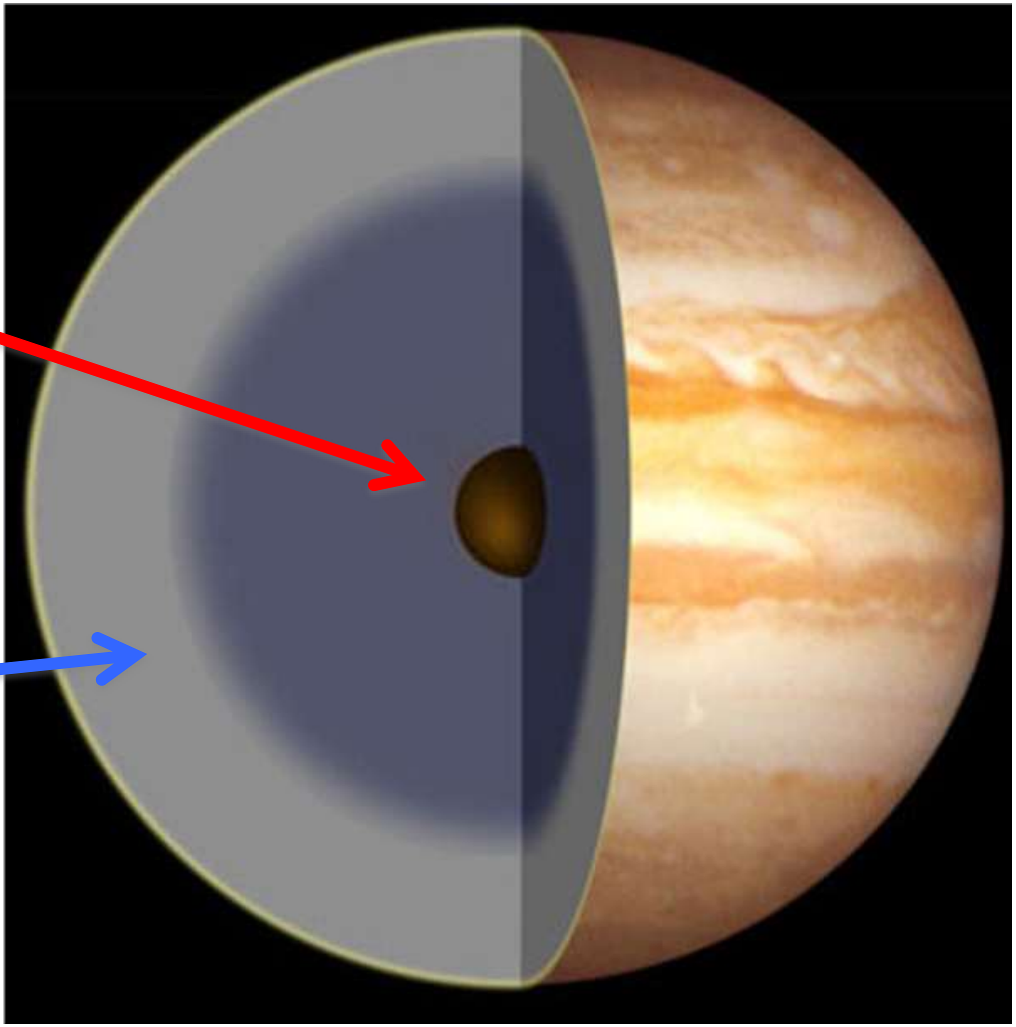


Alexander et al. (2001)

Meteorites

What about the refractory elements?

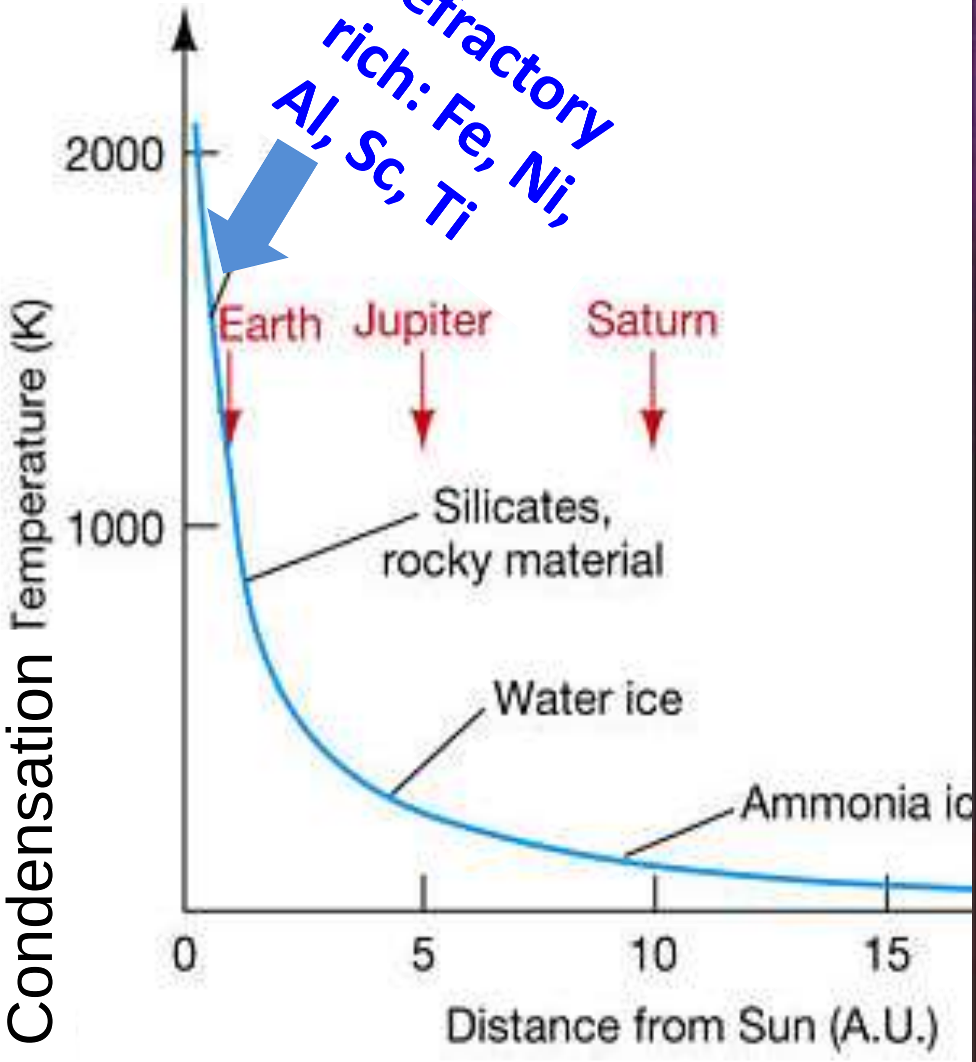
Jupiter



Rocky core rich in refractories

Envelope rich in volatiles

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

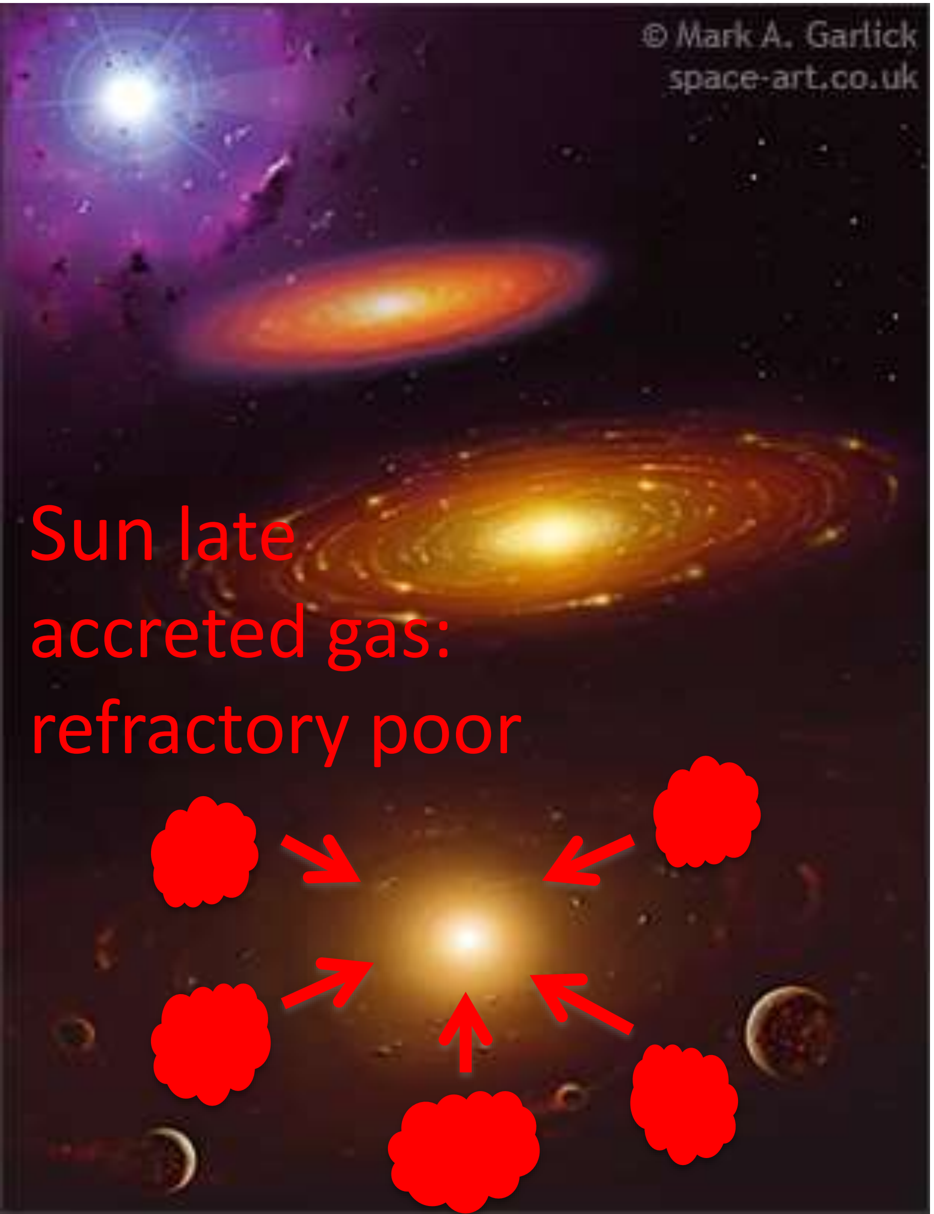


Refractory rich: Fe, Ni, Al, Sc, Ti

© Mark A. Garlick
space-art.co.uk

Signatures of planets

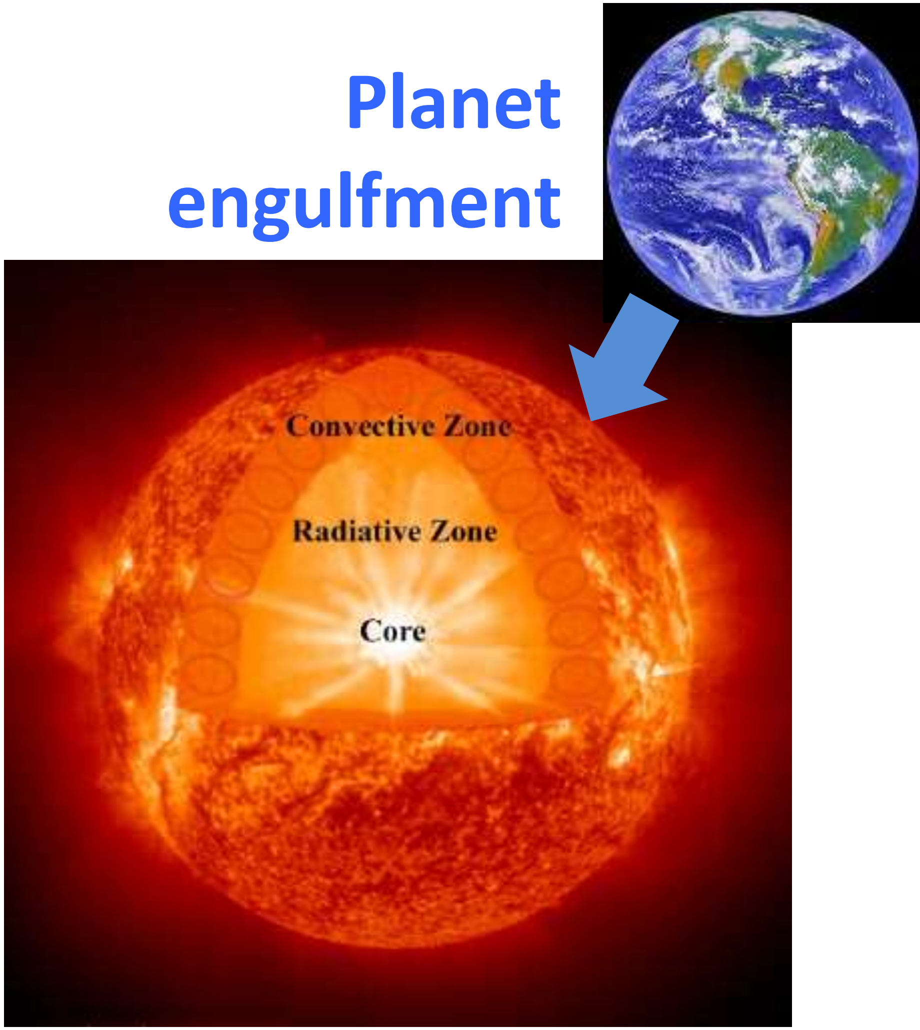
1. Dust removed: refractory poor



Sun late
accreted gas:
refractory poor

2. Planet accretion:
refractory rich

**Planet
engulfment**



Chemical signatures of rocks in White Dwarfs

THE ASTROPHYSICAL JOURNAL, 584:L91–L94, 2003 February 20

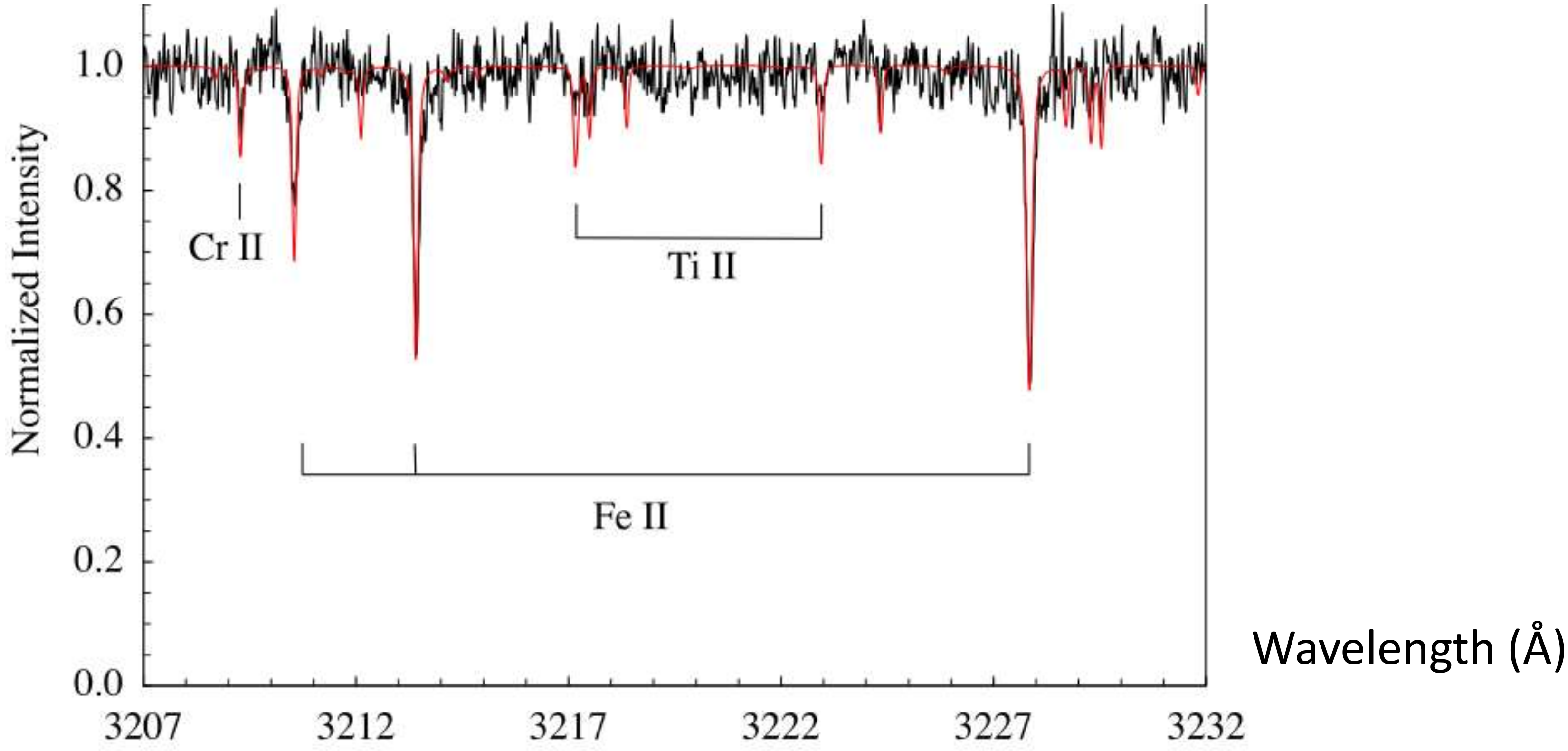
A TIDALLY DISRUPTED ASTEROID AROUND THE WHITE DWARF G29-38

M. JURA

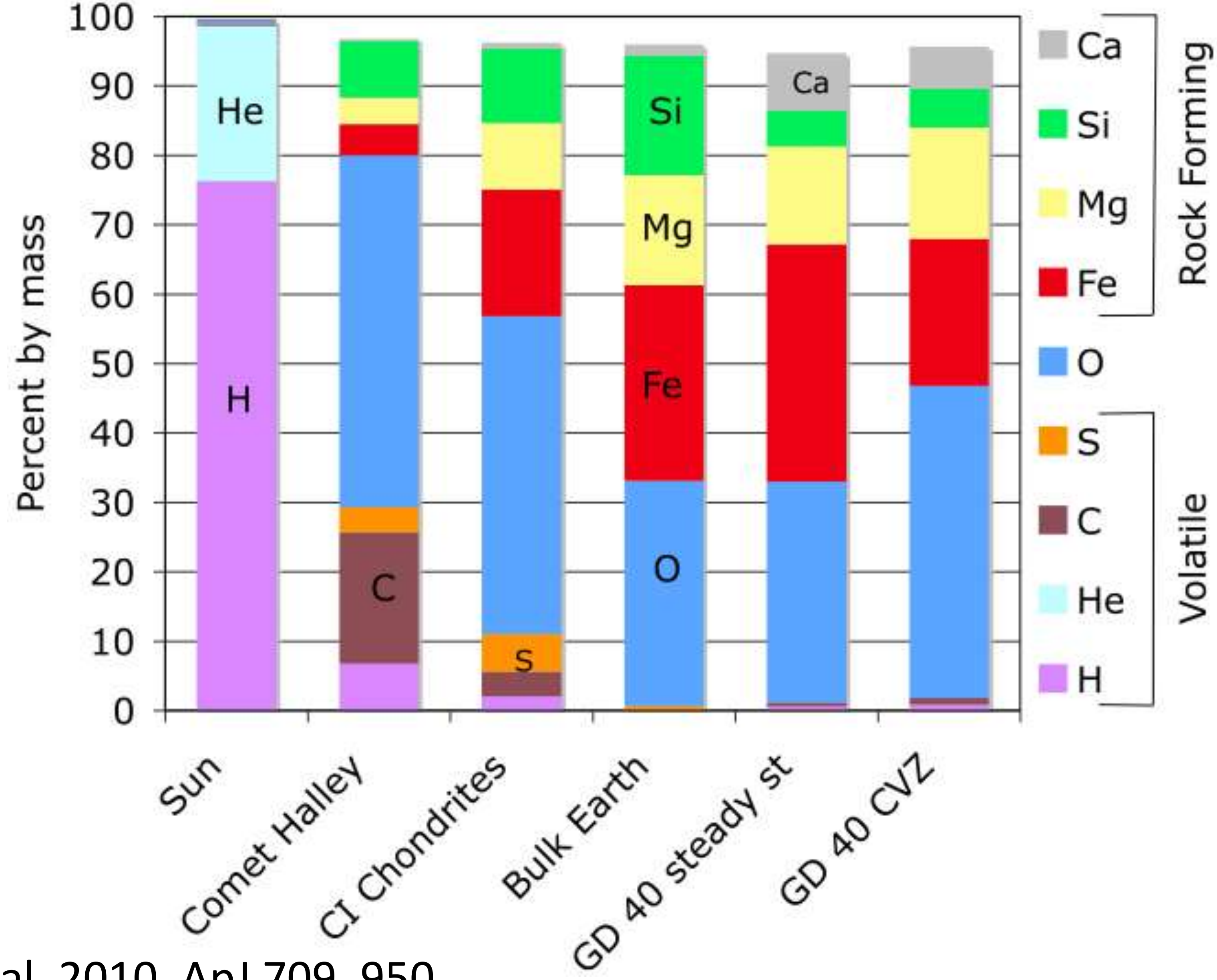
THE ASTROPHYSICAL JOURNAL, 709:950–962, 2010 February 1

CHEMICAL ABUNDANCES IN THE EXTERNALLY POLLUTED WHITE DWARF GD 40: EVIDENCE OF A ROCKY EXTRASOLAR MINOR PLANET

B. KLEIN[1], M. JURA[1], D. KOESTER[2], B. ZUCKERMAN[1], AND C. MELIS[1,3]

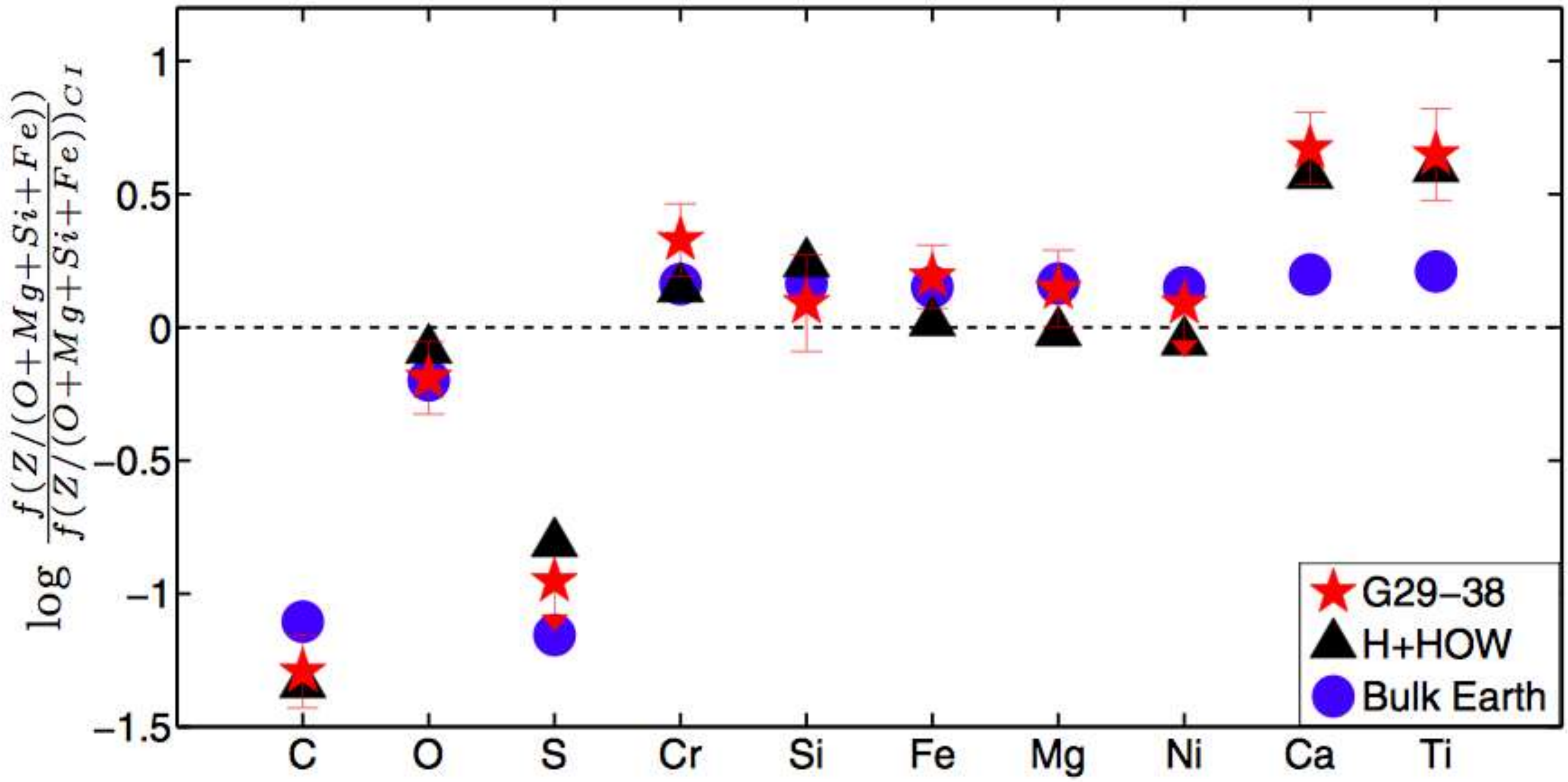


Chemical signatures of rocky material in White Dwarfs



Klein et al. 2010, ApJ 709, 950

Chemical signatures of rocky material in White Dwarfs

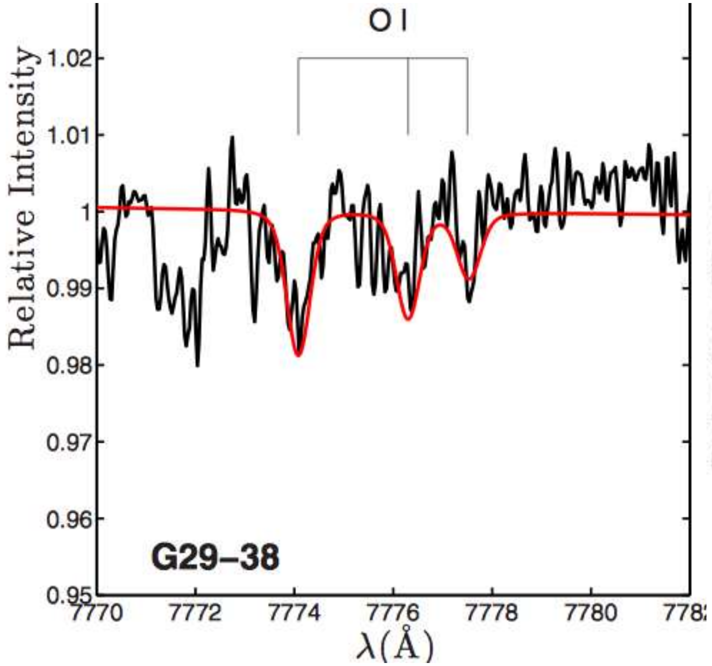


Xu et al. 2014, ApJ 783, 79

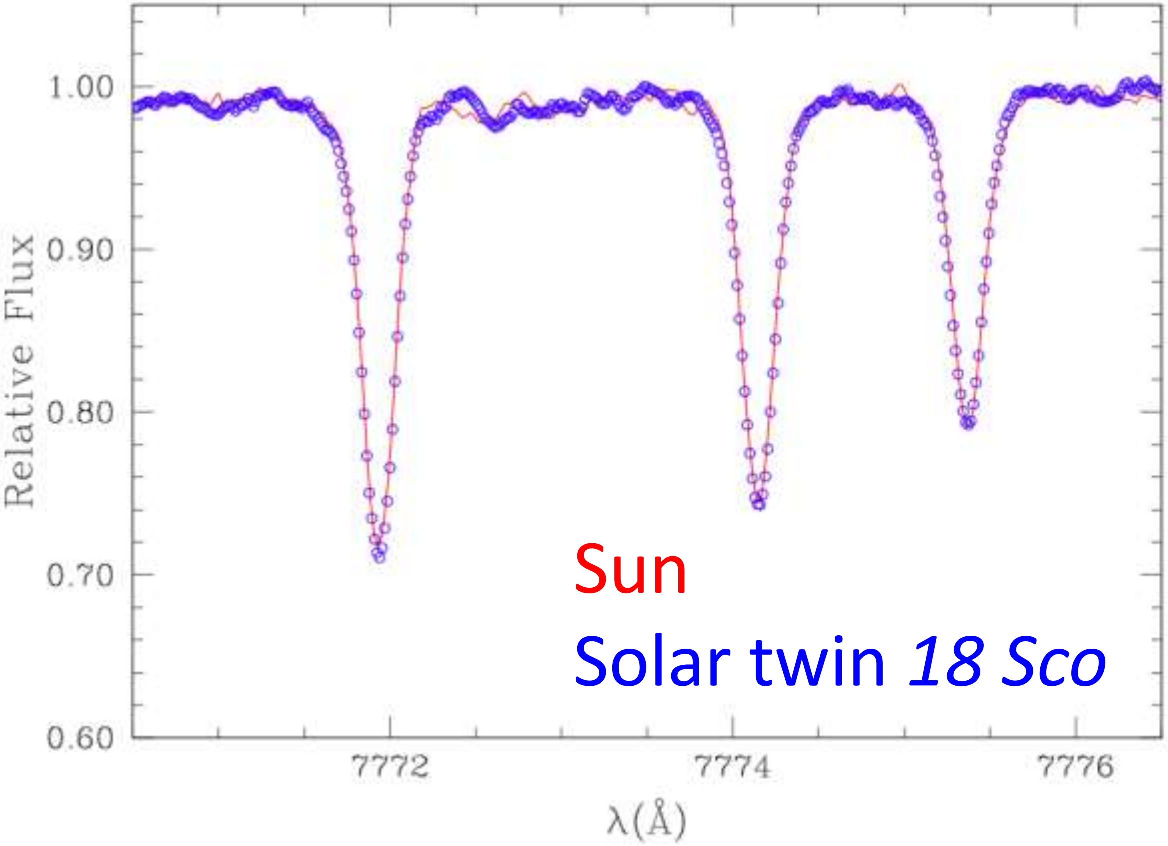
Oxygen triplet in White Dwarf and Sun/Solar Twin

White Dwarf G29-38

model



Xu et al. 2014, ApJ 783, 79

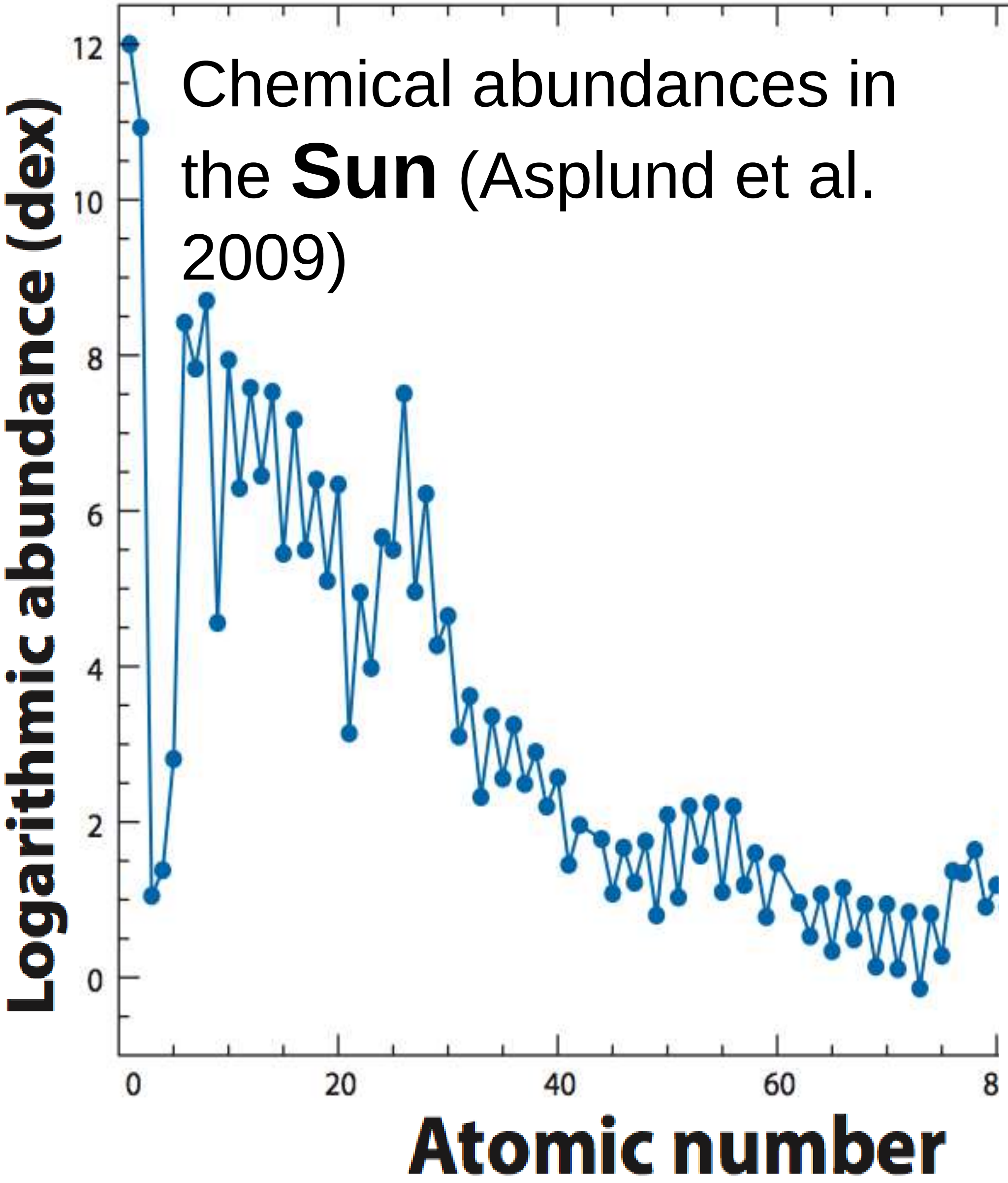


Sun

Solar twin *18 Sco*

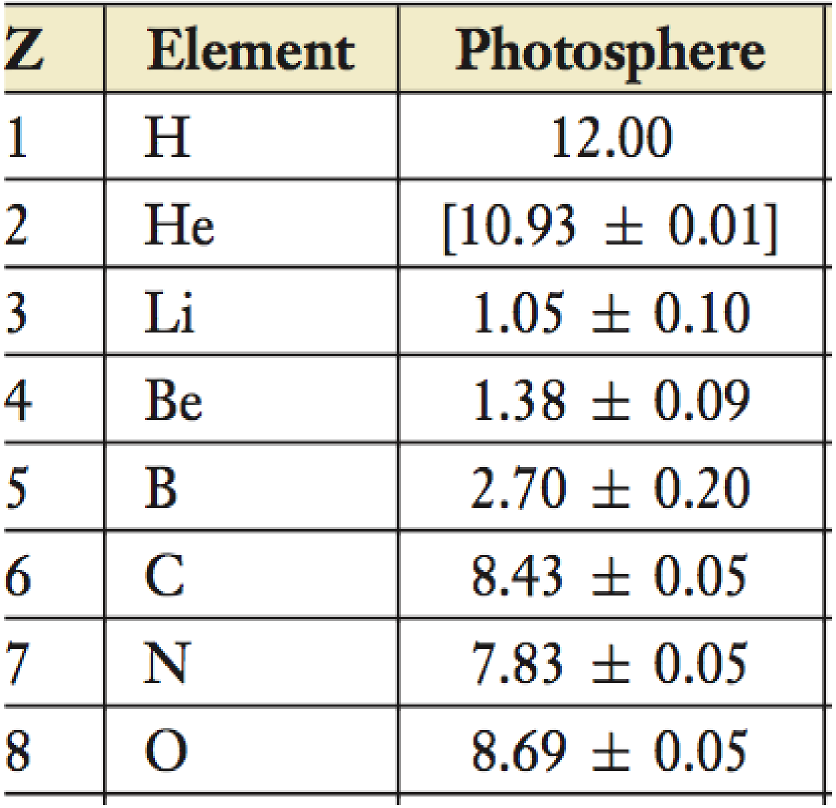
Jorge Melendez, from UVES spectra

Predicted Sun’s depletion due to rocks **~ 0.04 dex (about 10% effect)**



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

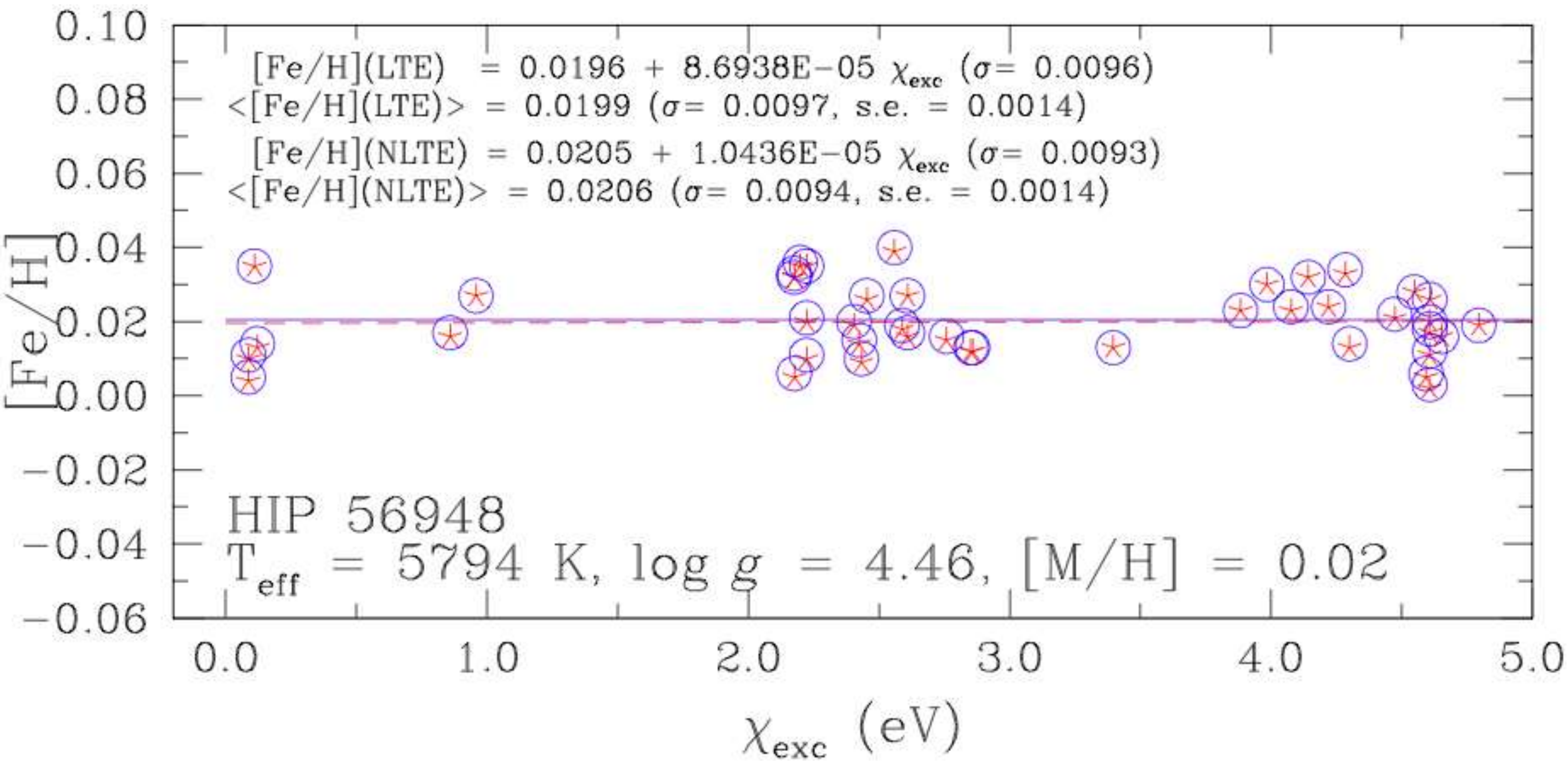
Typical errors in chemical abundance analyses is ≥ 0.05 dex!



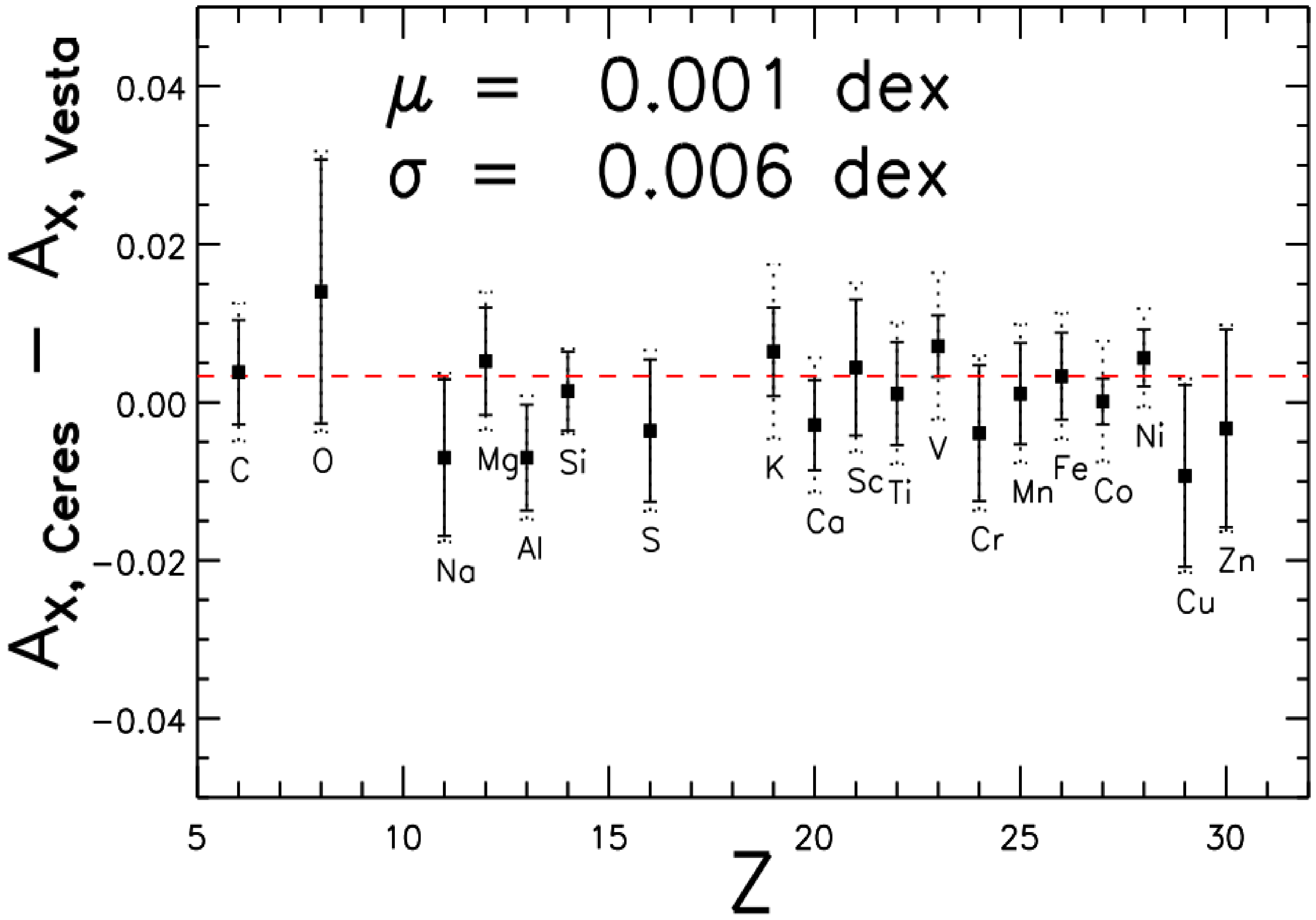
Z	Element	Photosphere
1	H	12.00
2	He	[10.93 ± 0.01]
3	Li	1.05 ± 0.10
4	Be	1.38 ± 0.09
5	B	2.70 ± 0.20
6	C	8.43 ± 0.05
7	N	7.83 ± 0.05
8	O	8.69 ± 0.05

Reaching a precision of **0.01 dex** in chemical abundances using **stellar twins**

- High S/N (> 300), High resolution (R > 60 000)
- Careful selection of lines
- *Strictly differential approach using "**solar twins**"*



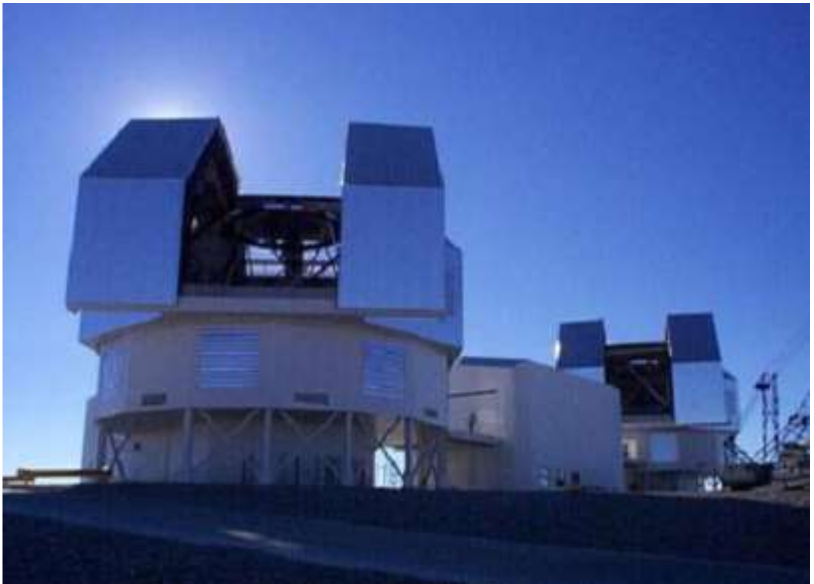
Test using Sun's reflected light by asteroids: scatter of 0.006 dex



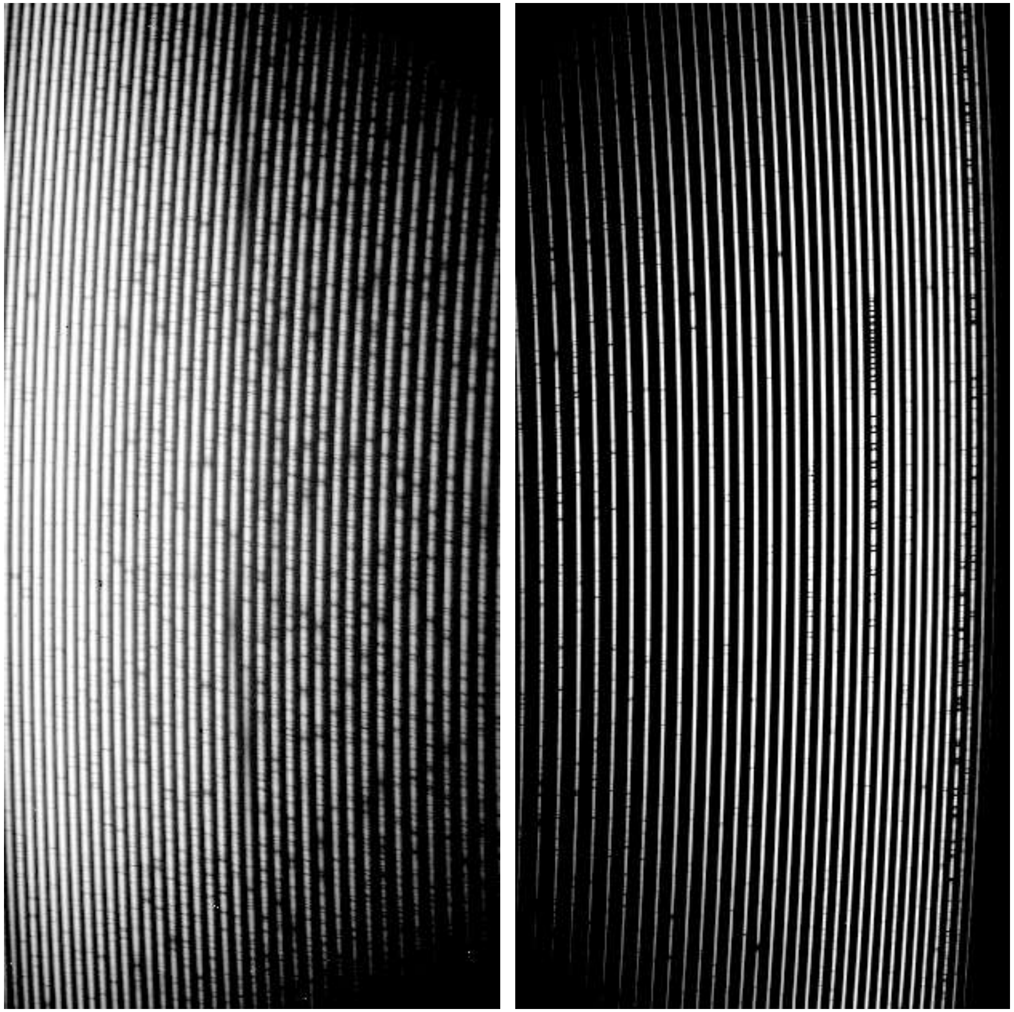
Bedell, Meléndez, Bean, Ramírez, Leite & Asplund 2014, ApJ 795, 23

Experiment using solar twins

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

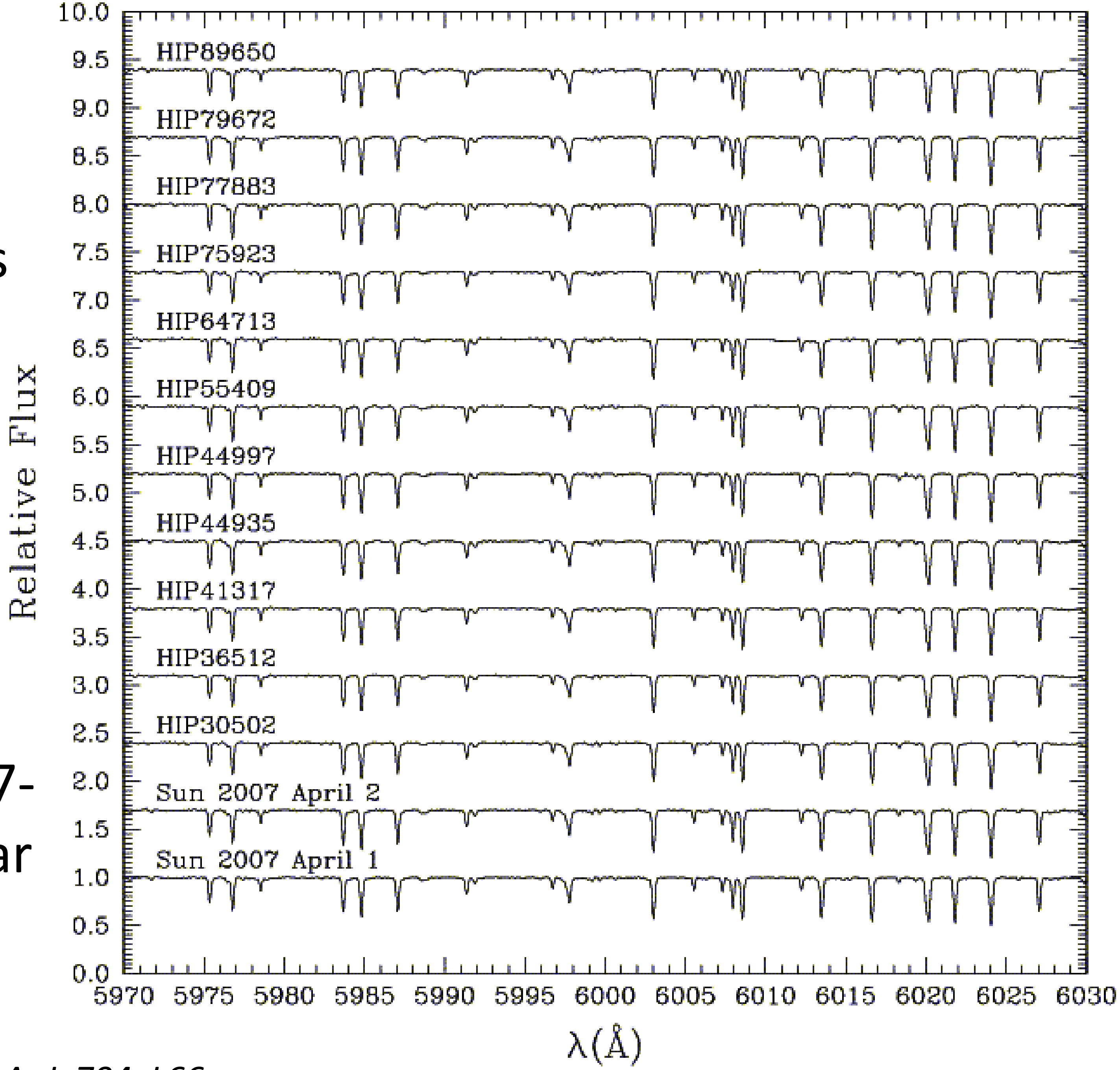


Observations of the solar twin 18 Sco



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

Δ abundance:

Sun - <twins>

vs. atomic number Z

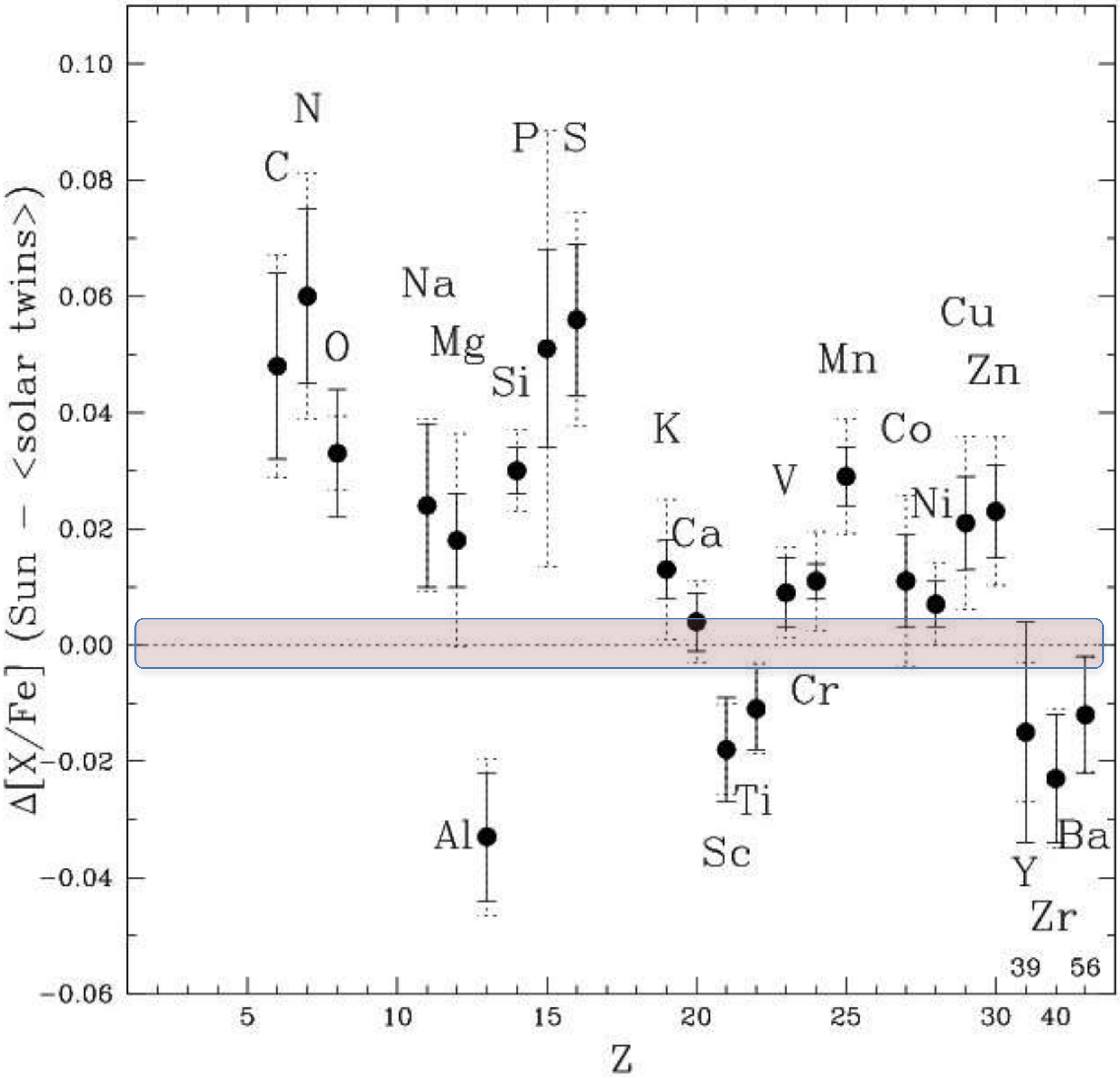
Sun typical :

Δ = 0

Sun weird :

Δ ≠ 0

Our solar system is not host by a typical ‘Sun’



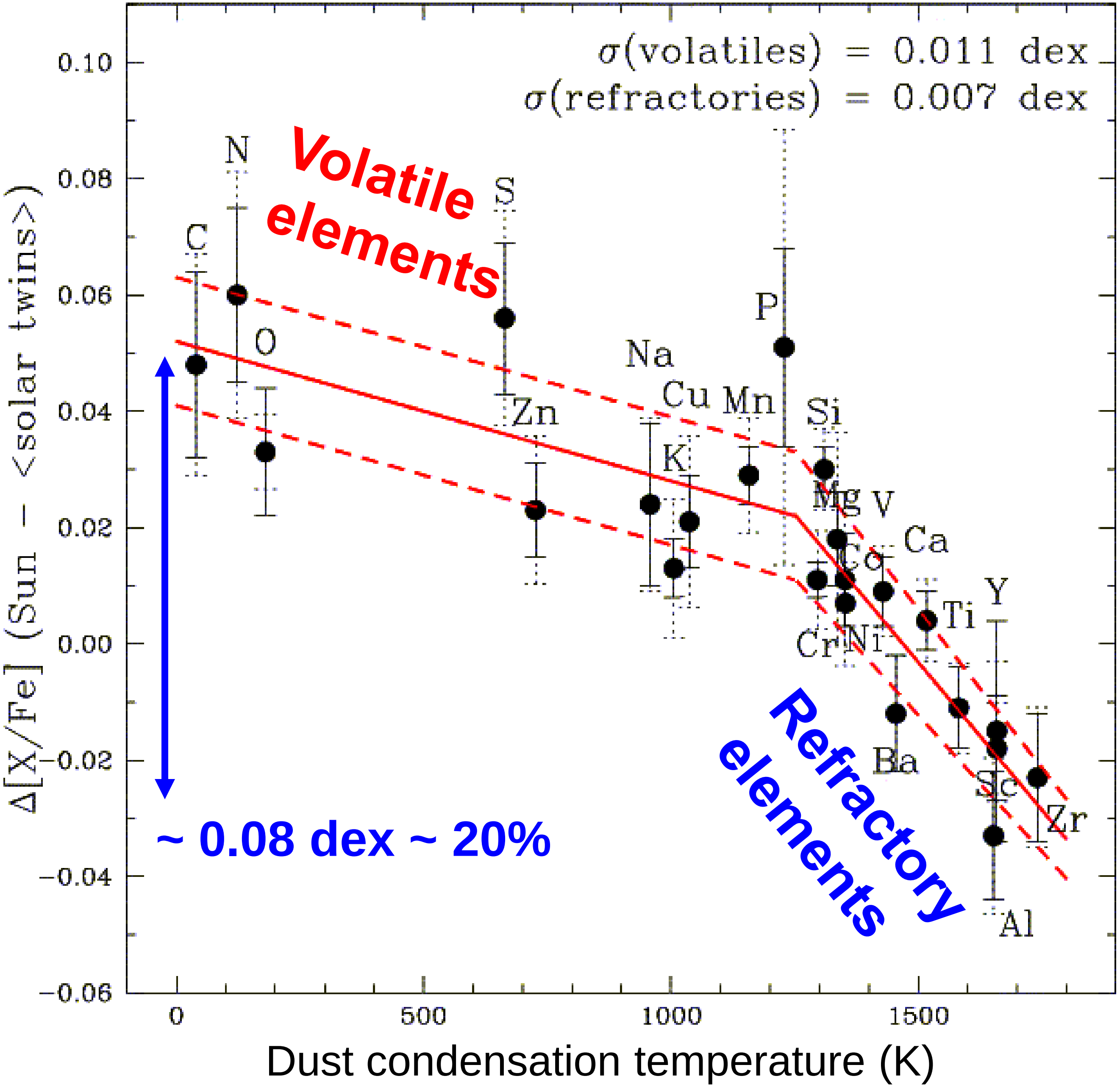
Meléndez et al. 2009

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

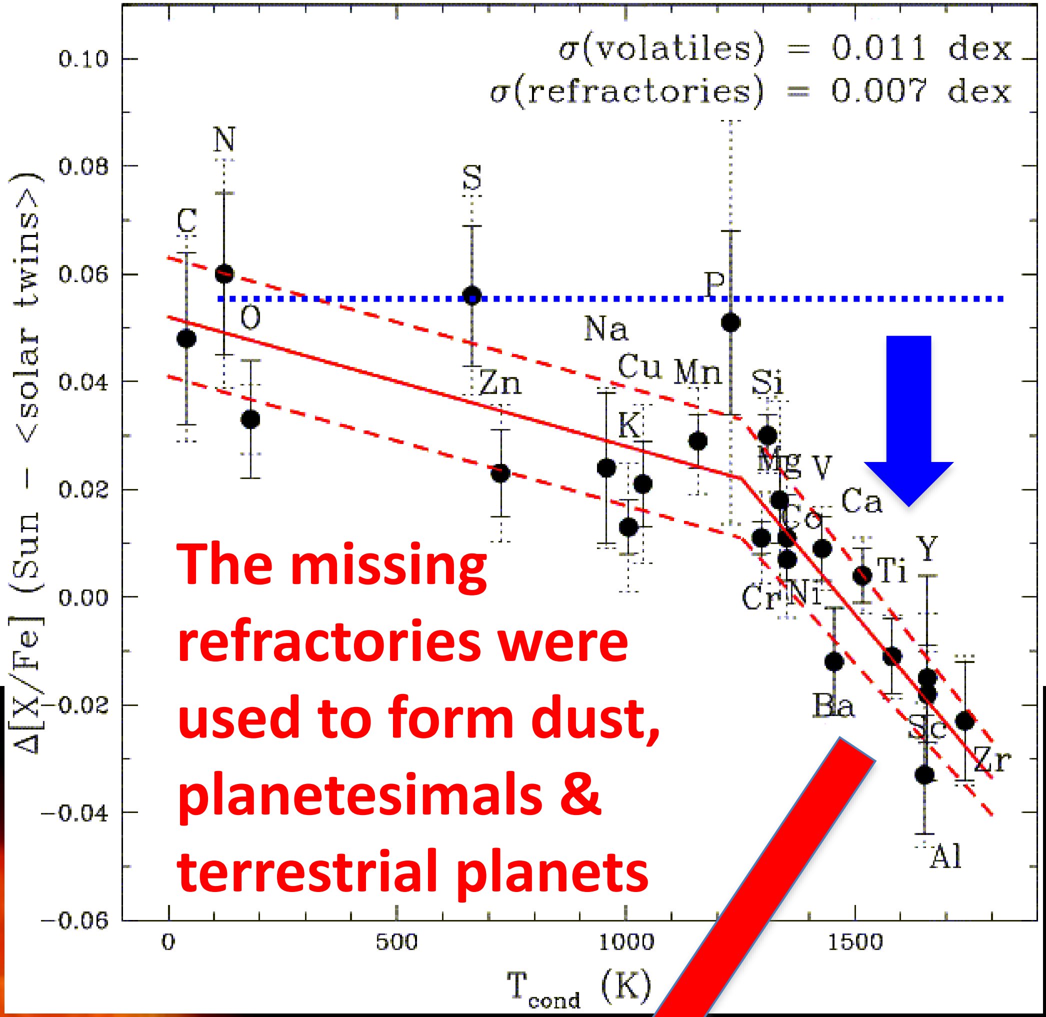
It’s most likely to win the lottery



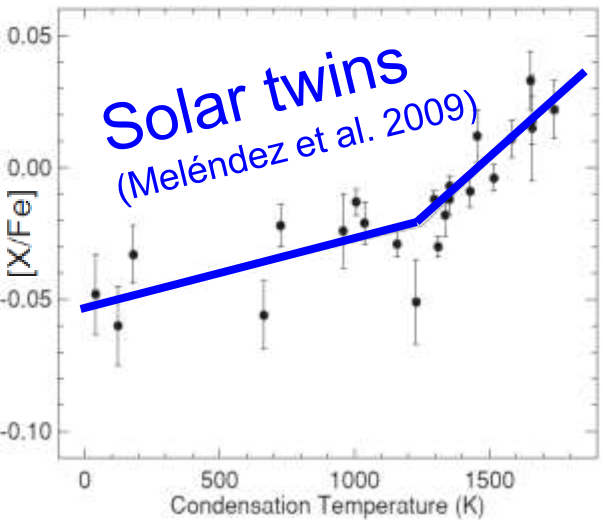
Meléndez, Asplund, Gustafsson, Yong 2009, ApJ Letters

Meléndez et al. 2009

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



The missing refractories were used to form dust, planetesimals & terrestrial planets



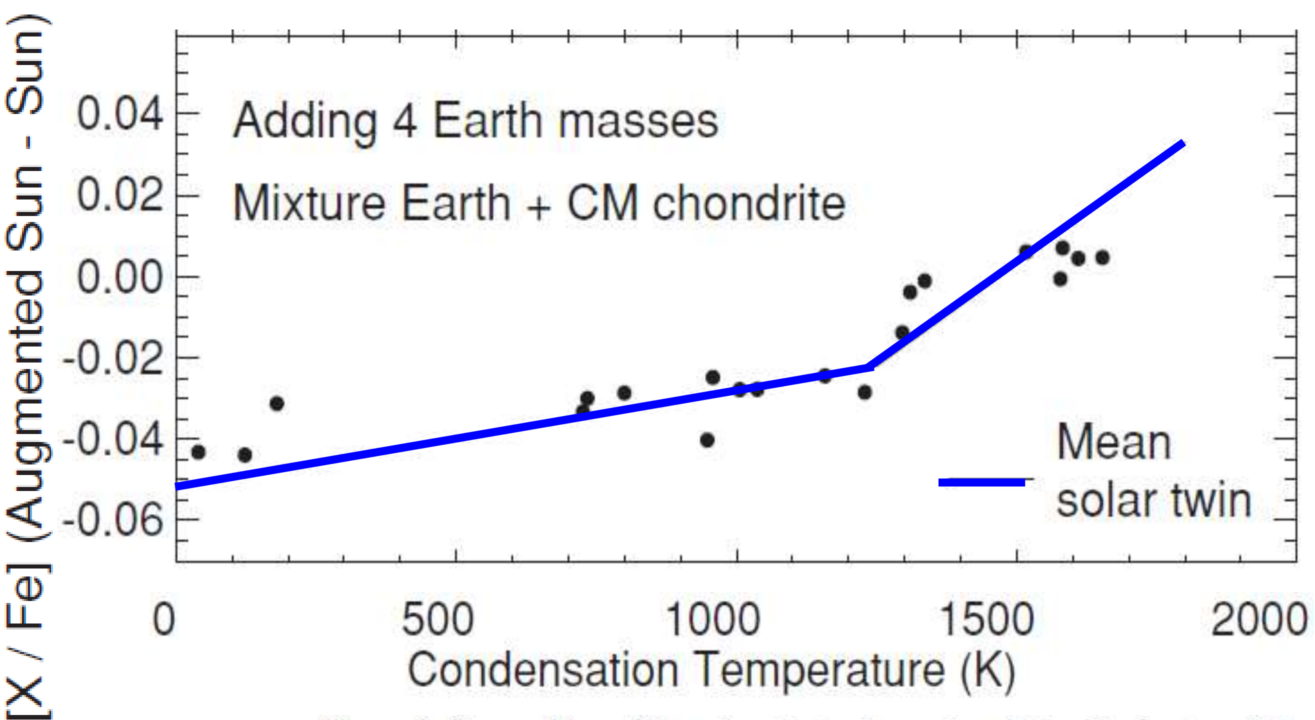
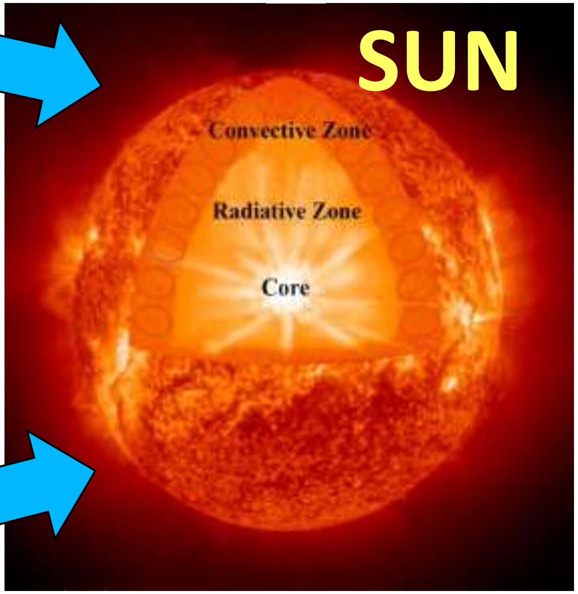


Figure 2. Composition of the solar photosphere when 4 $M_\oplus$ of refractory-rich material is added to the solar convection zone, compared to the unmodified Sun. Abundances are normalized with respect to Fe. The line segments show rms fits to the mean abundance pattern for 11 solar twins found by Meléndez et al. (2009).

Earth-like material



Meteorite-like material

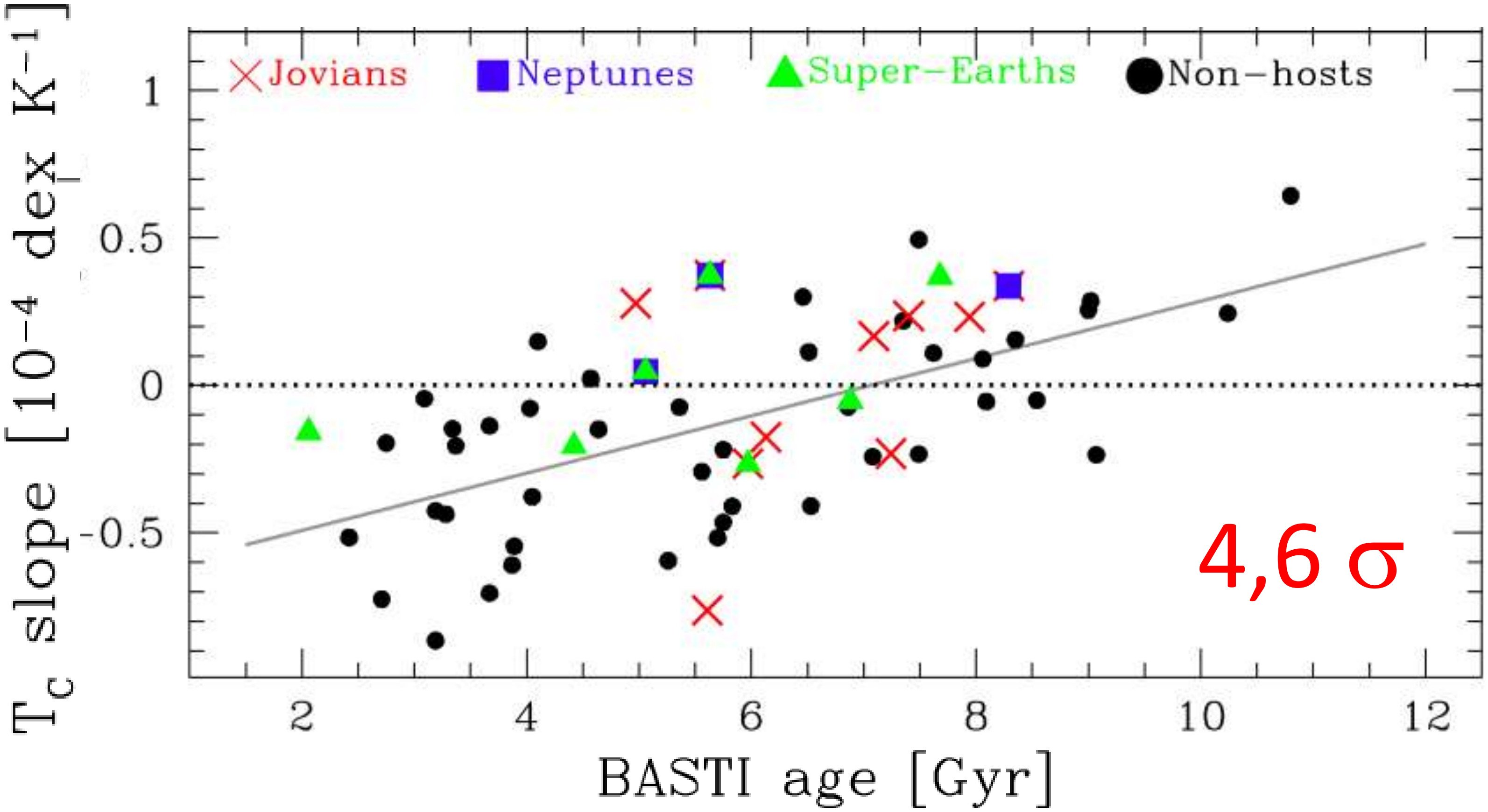
The Astrophysical Journal, 724:92–97, 2010 November 20

J. E. Chambers

STELLAR ELEMENTAL ABUNDANCE PATTERNS: IMPLICATIONS FOR PLANET FORMATION

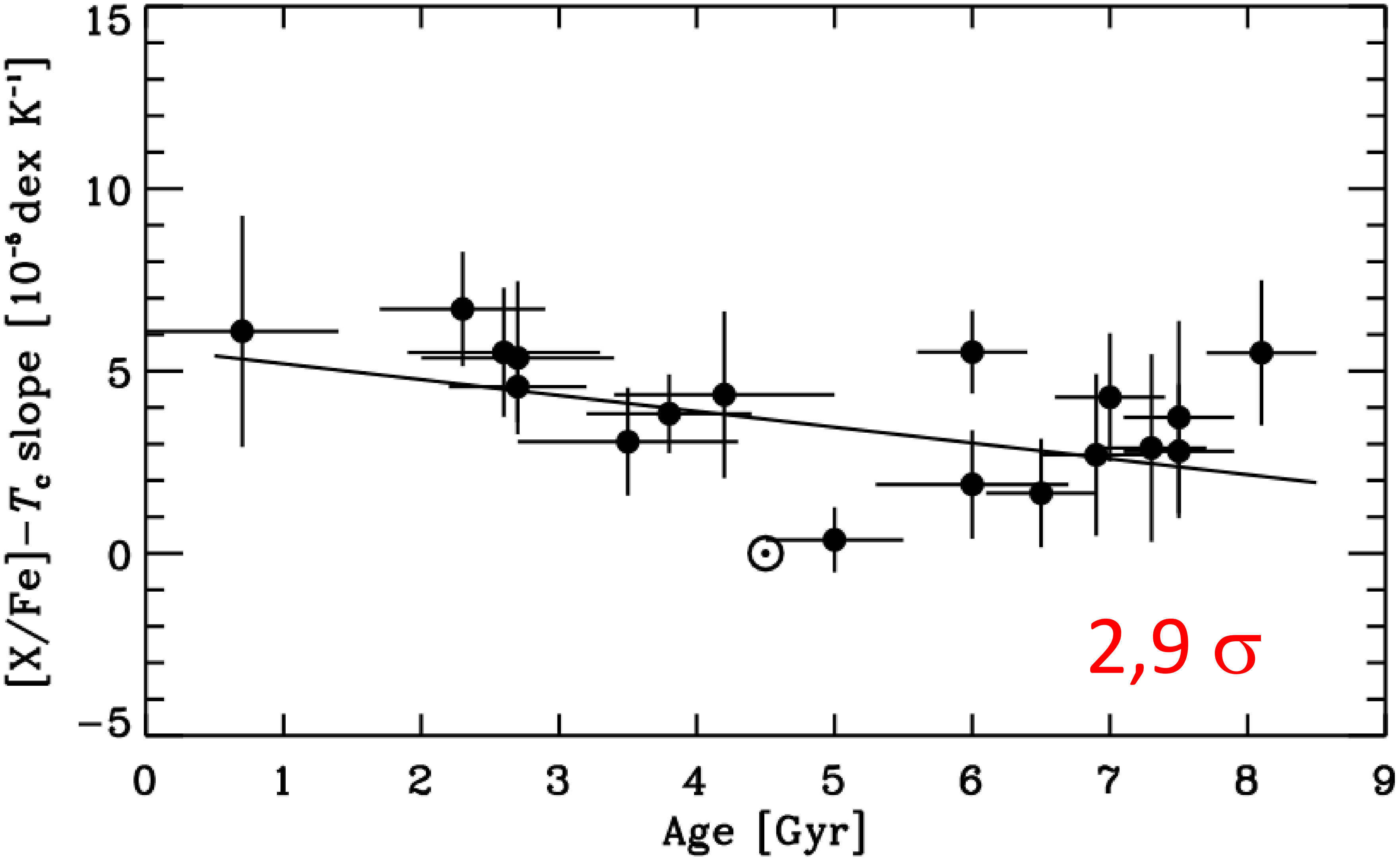
Other possible interpretations

- Sun born in a massive cluster? (A. Korn talk)
- Inclination effects? NO: Kiselman et al. 2011
- Age effect? Adibekyan et al. 2014 A&A 564 L15



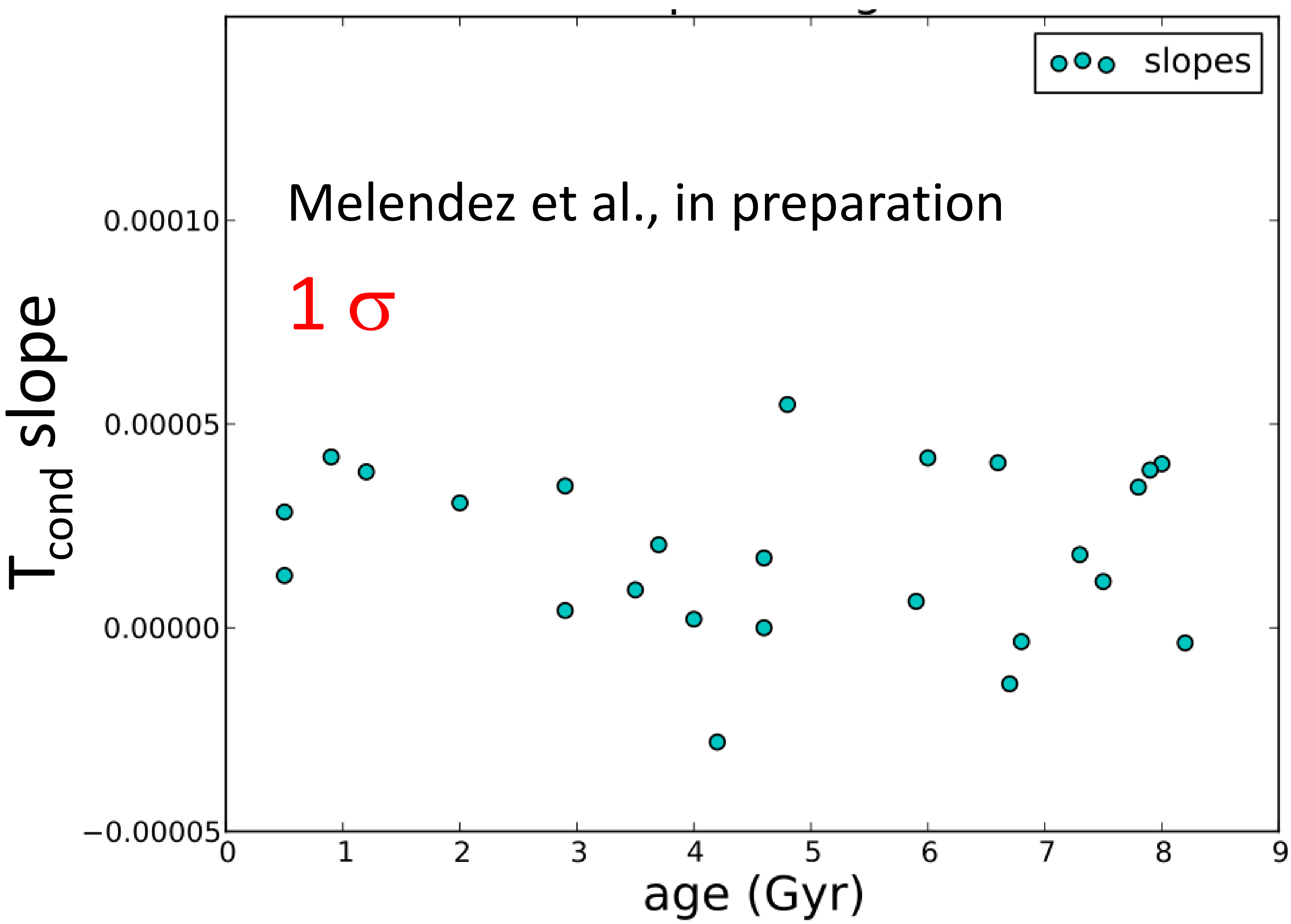
4,6 σ

Other possible interpretations: age effect?



Nissen 2015 A&A in press, arXiv:1504.07598

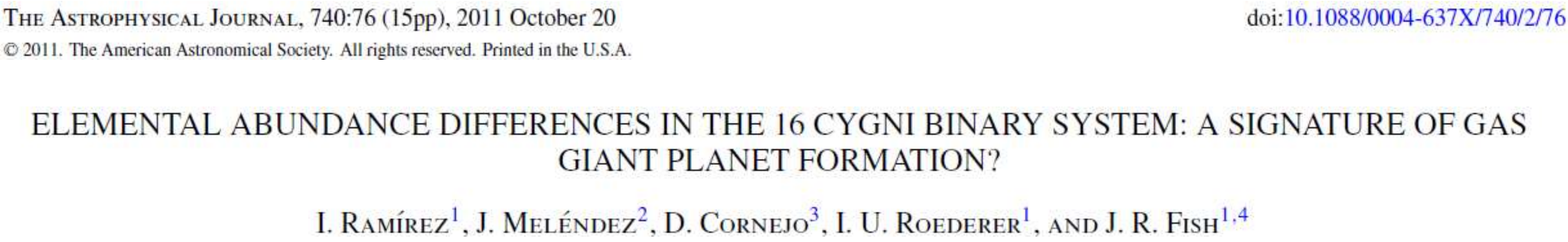
No significant age effect?



Melendez et al., in preparation

1 σ

Planet effects in binary system with "twins"



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

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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]

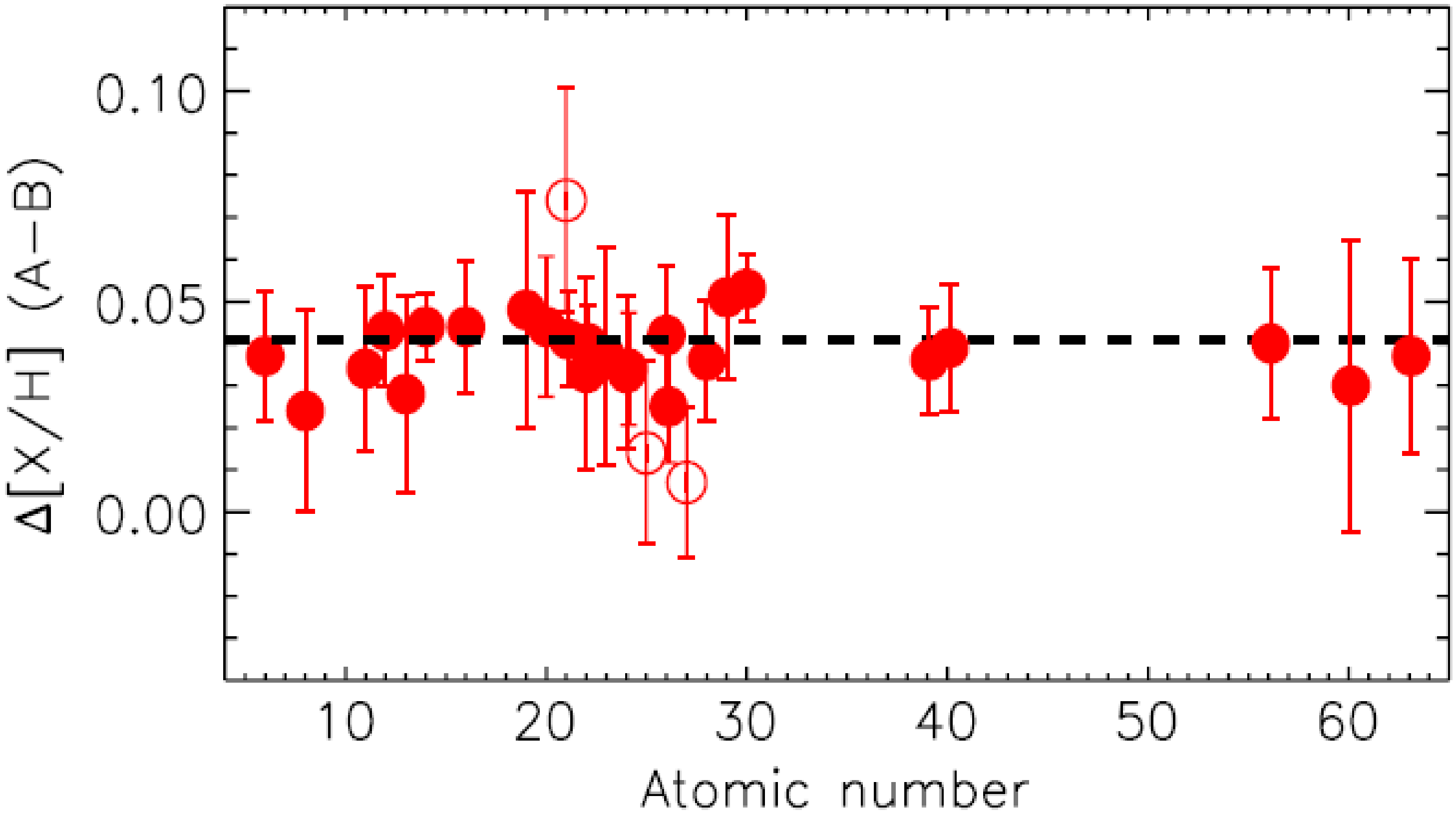
16 Cyg: widely separated pair of solar analogs

16 Cyg A : no planets

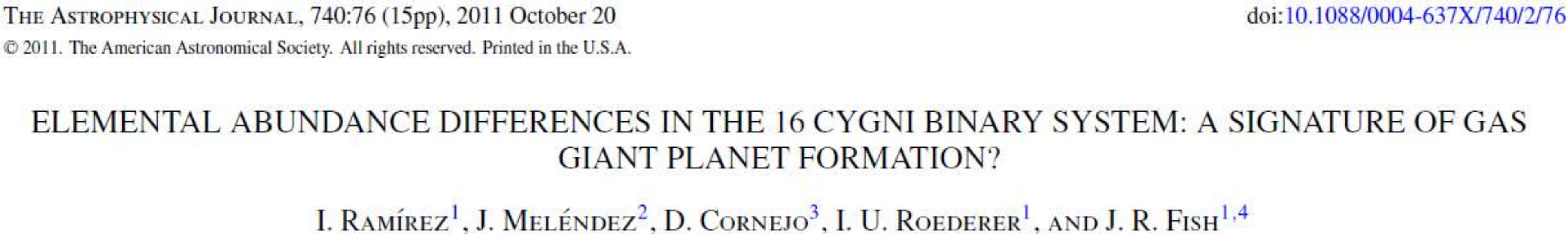
16 Cyg B : giant planet
(~ 2 M_J)

Analysis using McDonald spectra with **R = 60 000**

16 Cyg B (planet-host) is 0,04 dex more metal-poor in all elements (photospheric abundances)!



The missing material in 16 Cyg B may have been used to form its giant planet 16CygBb


THE ASTROPHYSICAL JOURNAL, 740:76 (15pp), 2011 October 20 doi:10.1088/0004-637X/740/2/76

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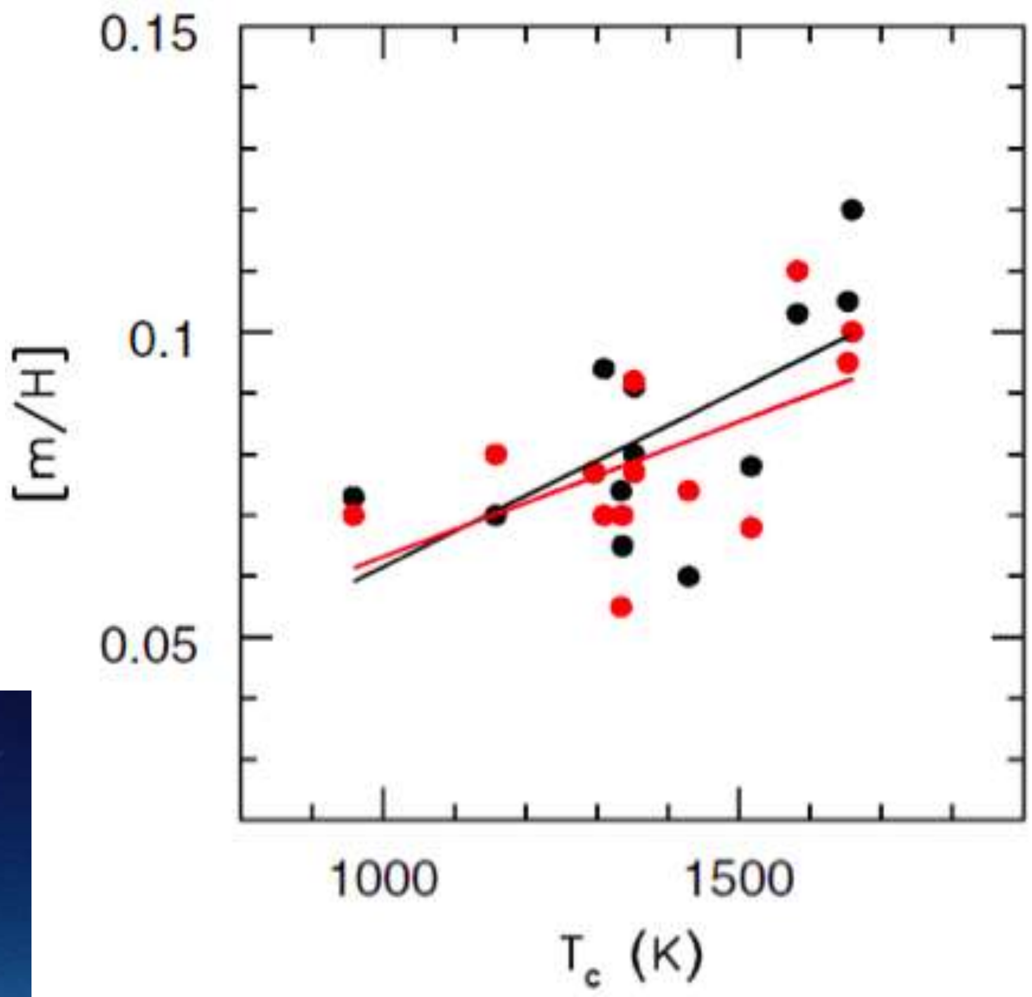
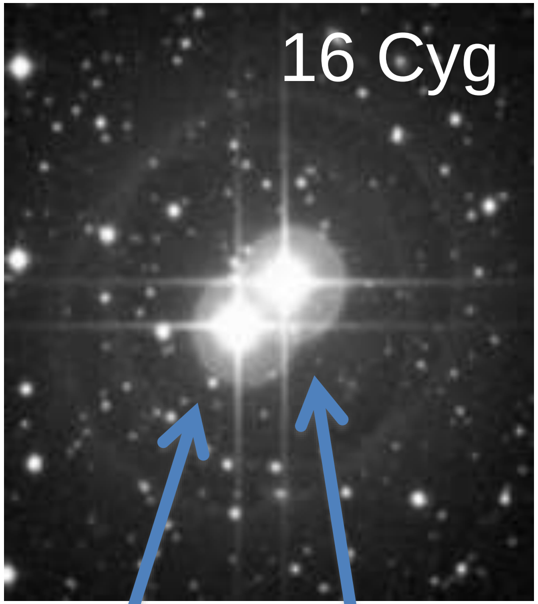
Another work published at about the same time (with lower resolution, **R= 45000**) didn't find a difference between 16 Cyg A & B (Schuler et al. 2011 ApJ 737 L32)



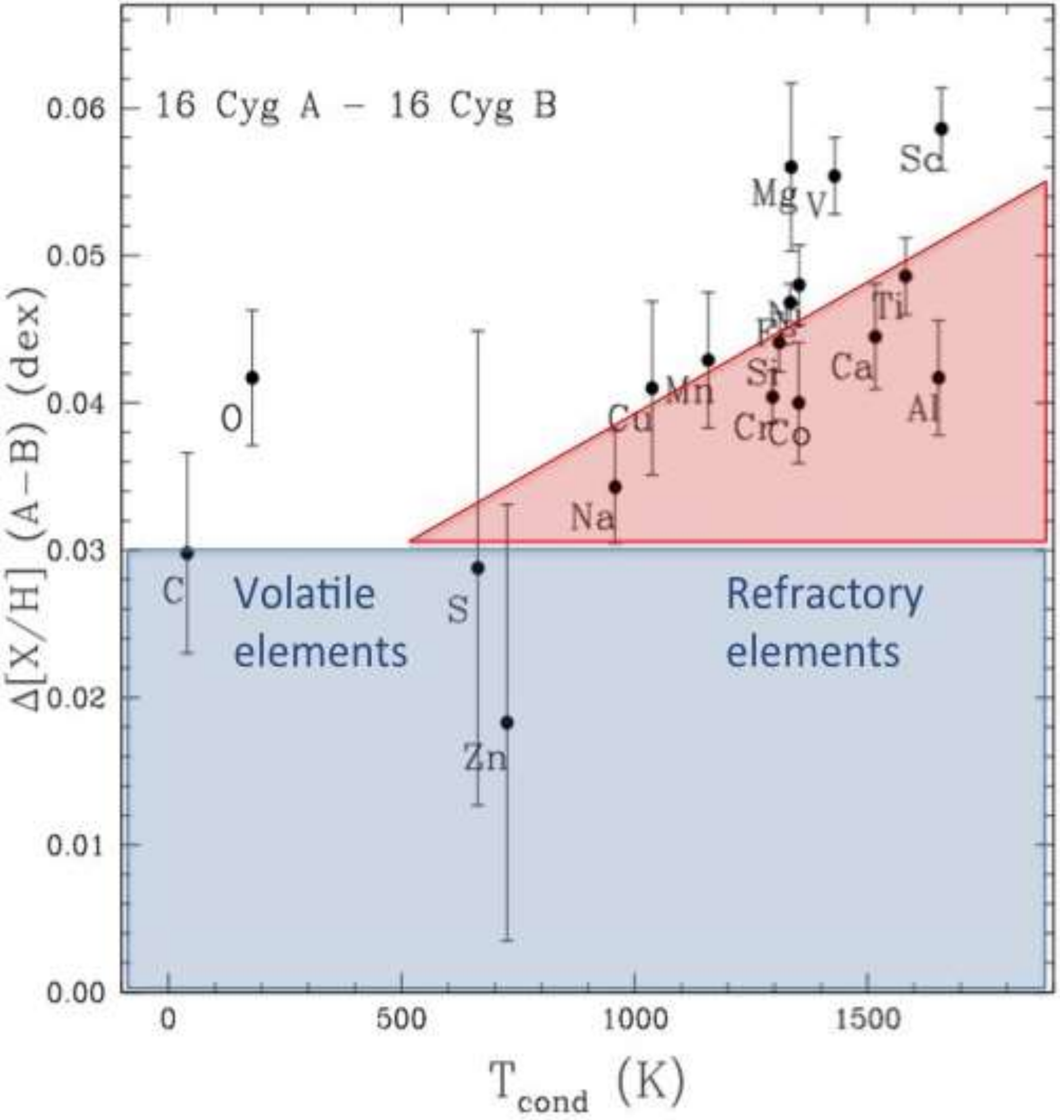
To clarify the situation, we acquired new better spectra at the CFHT, using **R = 81 000, S/N = 700**

Signatures of giant planet formation: 16 Cyg binary



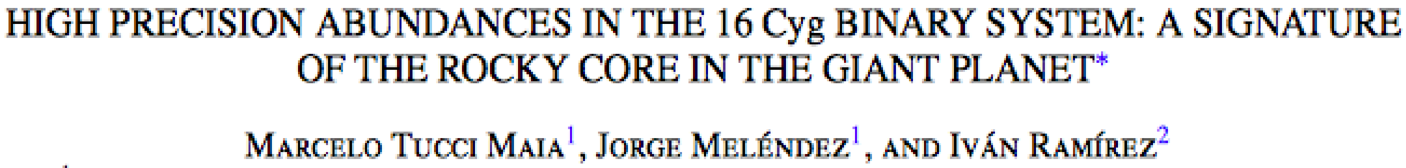
A: no planets

B: hosts a giant planet ~2 M_J



Rocky accretion core

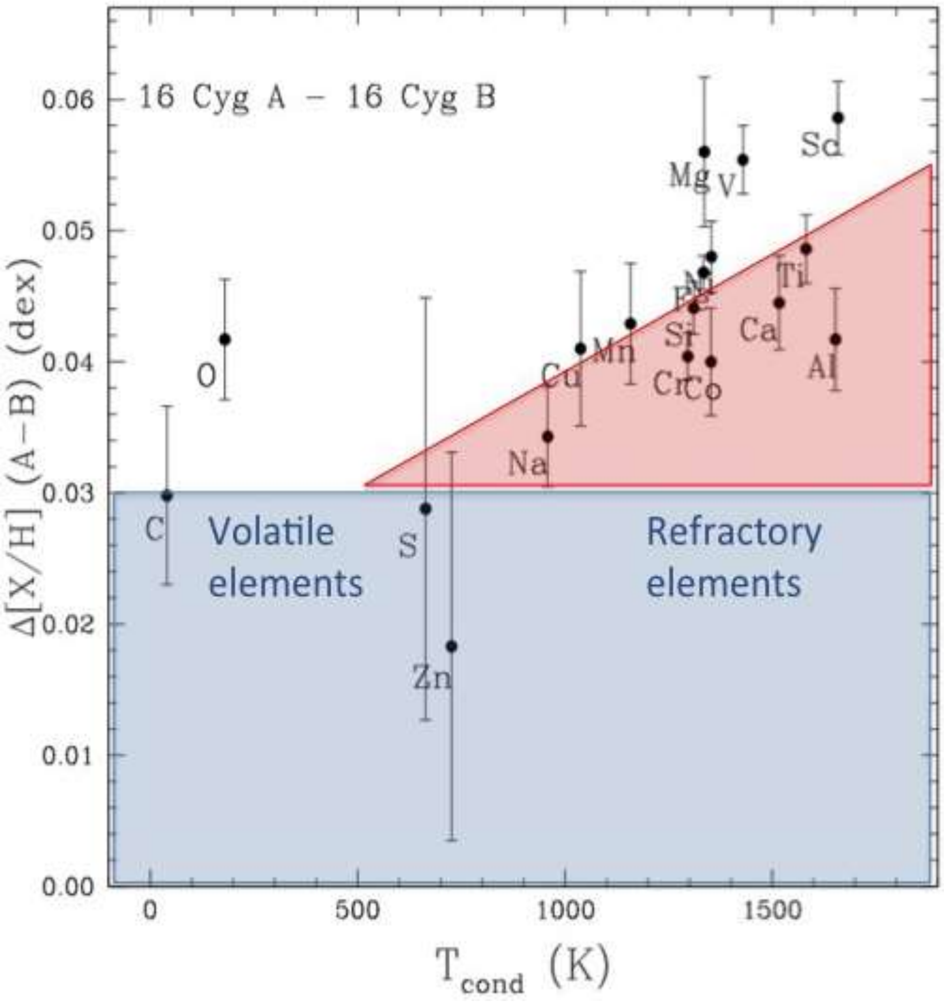
Giant planet's envelope

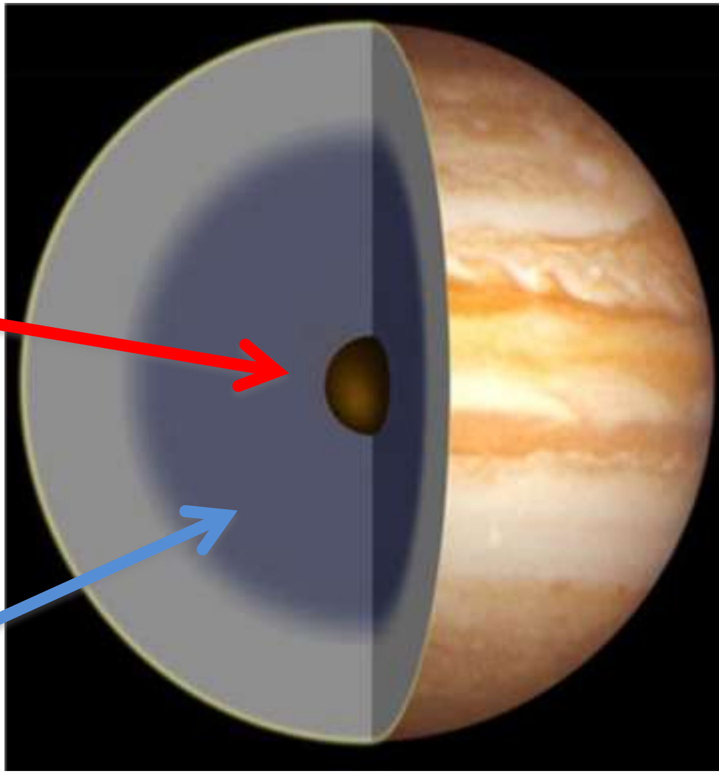


HIGH PRECISION ABUNDANCES IN THE 16 Cyg BINARY SYSTEM: A SIGNATURE OF THE ROCKY CORE IN THE GIANT PLANET*

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

Signatures of giant planet formation: 16 Cyg binary

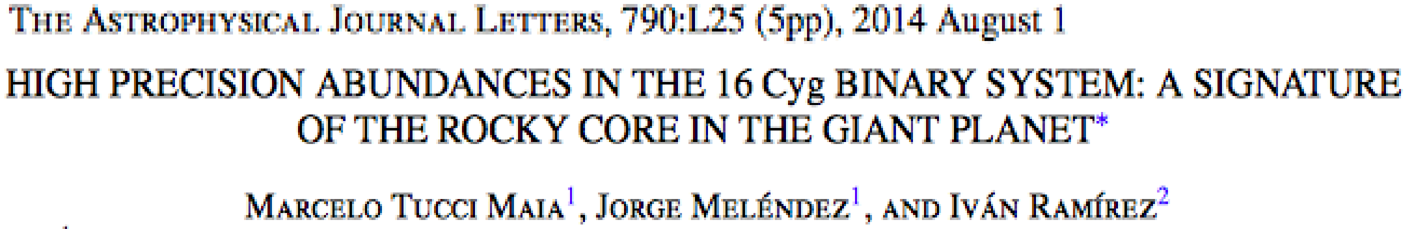




Rocky accretion core

Giant planet's envelope

~ 2 M_J

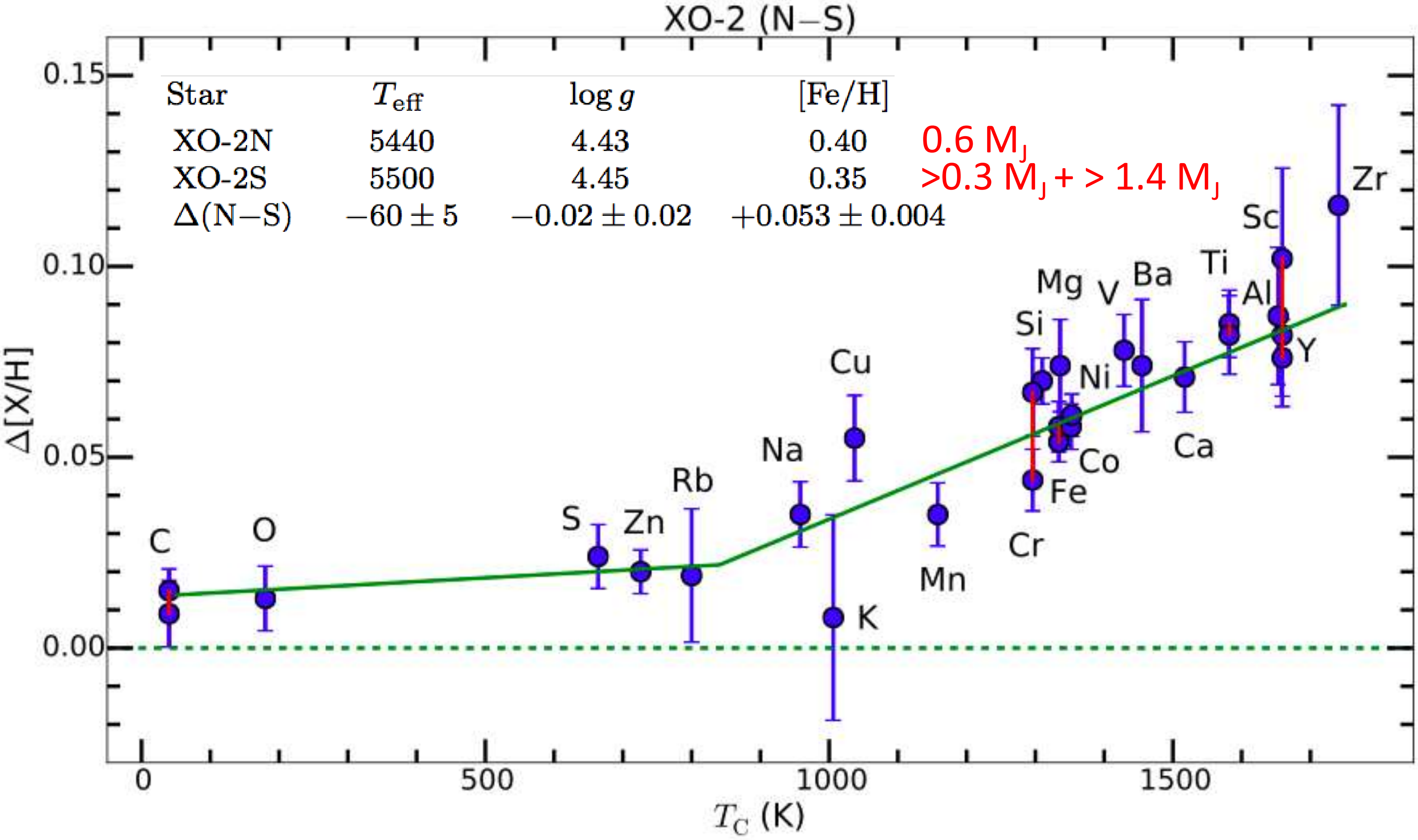


THE ASTROPHYSICAL JOURNAL LETTERS, 790:L25 (5pp), 2014 August 1

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



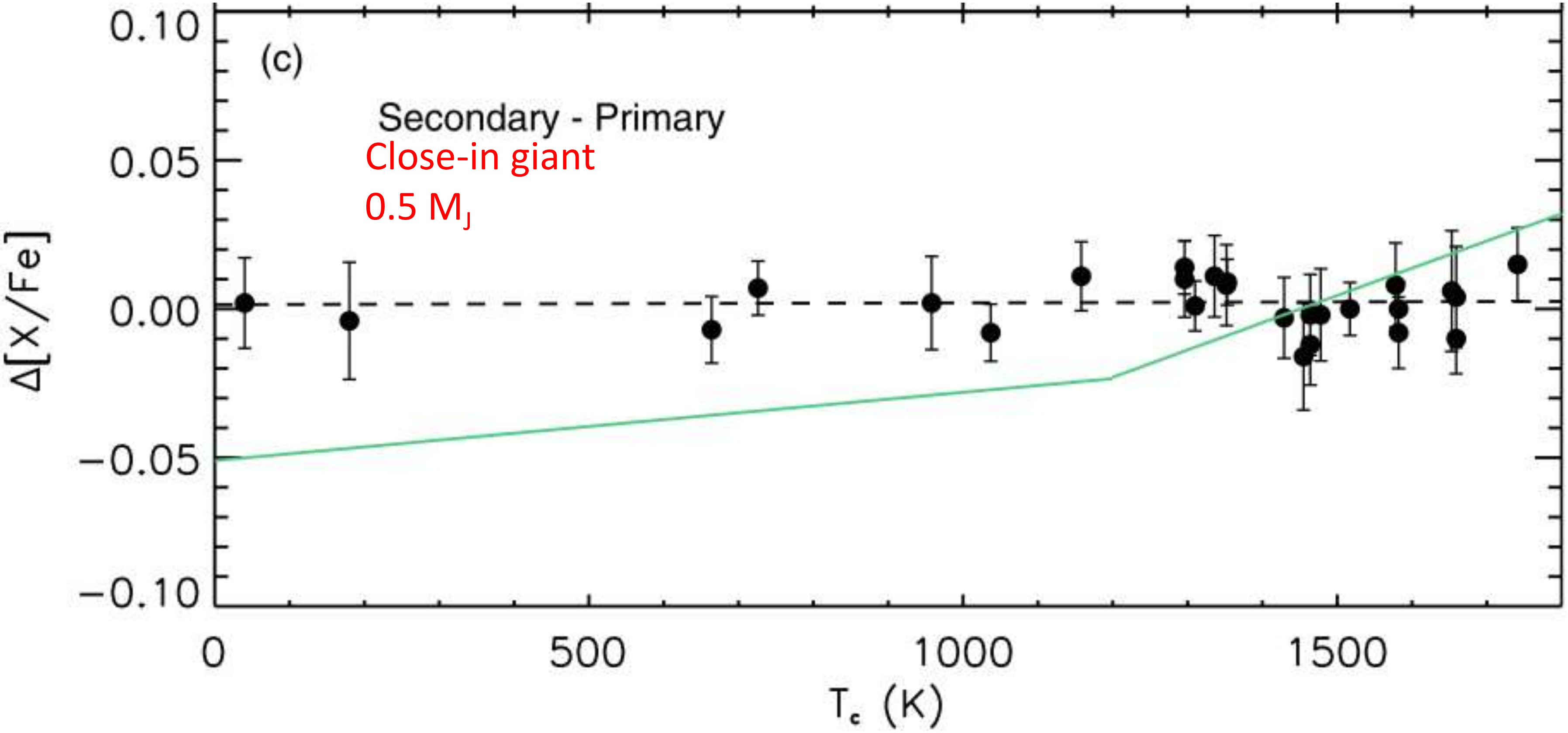
Star	$T_{\rm eff}$	$\log g$	[Fe/H]
XO-2N	5440	4.43	0.40
XO-2S	5500	4.45	0.35
Δ(N−S)	−60 ± 5	−0.02 ± 0.02	+0.053 ± 0.004

0.6 M_J

>0.3 M_J + > 1.4 M_J

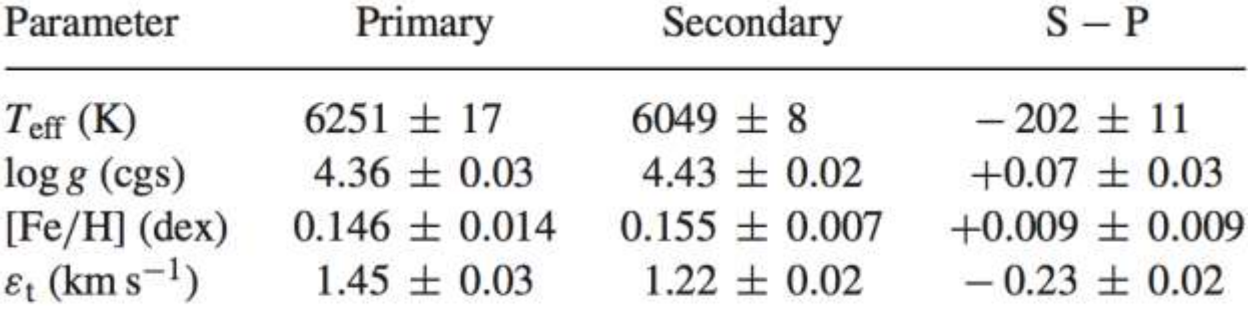
Ramírez et al. 2015, ApJ in press. See also Teske et al. 2015 ApJ 801, L10

No abundance differences: HAT-P-1



Close-in giant

0.5 M_J



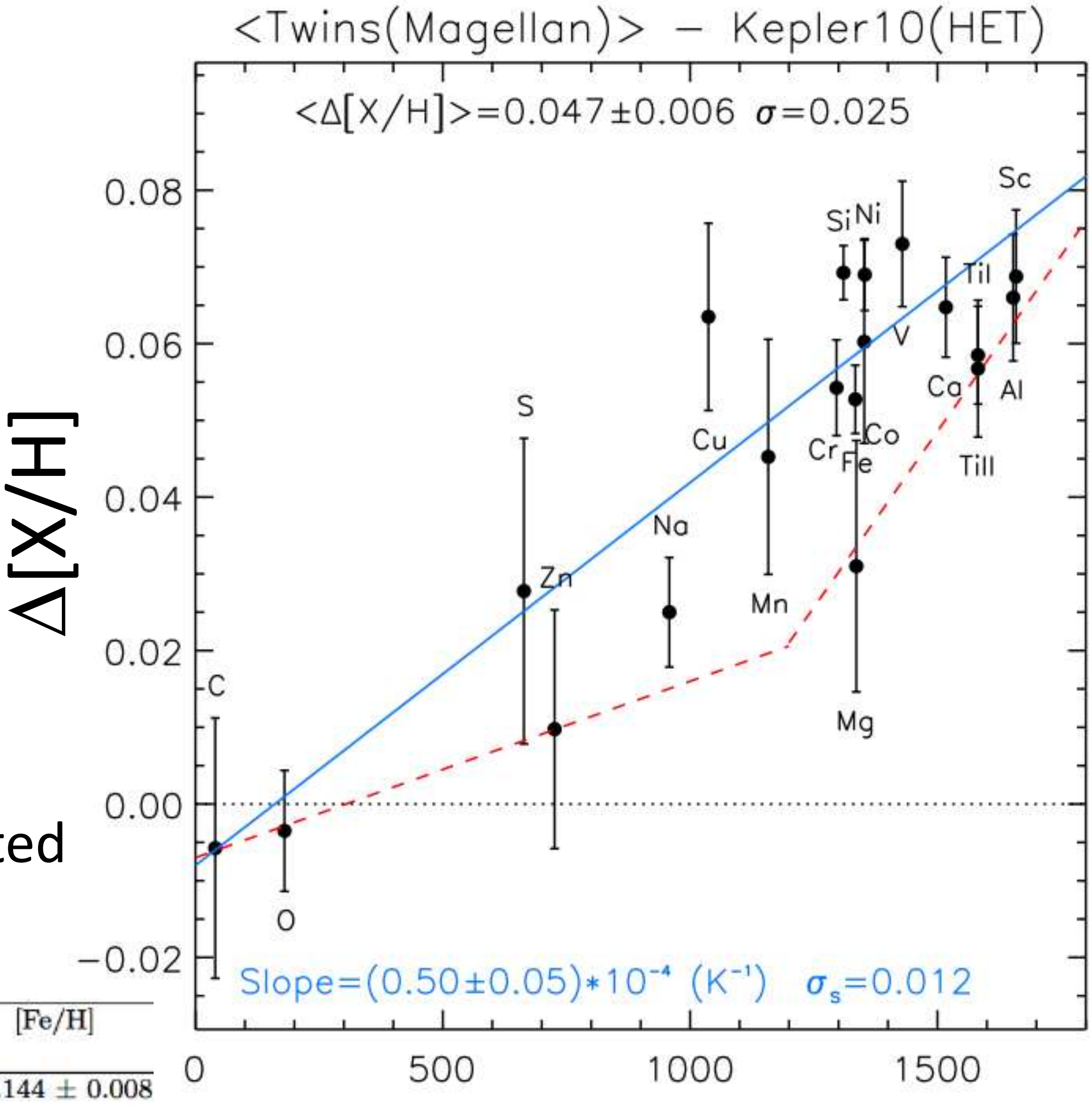
Parameter	Primary	Secondary	S − P
$T_{\rm eff}$ (K)	6251 ± 17	6049 ± 8	−202 ± 11
log g (cgs)	4.36 ± 0.03	4.43 ± 0.02	+0.07 ± 0.03
[Fe/H] (dex)	0.146 ± 0.014	0.155 ± 0.007	+0.009 ± 0.009
ε_t (km s^{-1})	1.45 ± 0.03	1.22 ± 0.02	−0.23 ± 0.02

Liu et al. 2014, MNRAS 442, L51

Kepler-10: host of rocky planets

Kepler-10b: 3 $M_{\oplus}$
Kepler-10c: 17 $M_{\oplus}$
Density ~ Earth

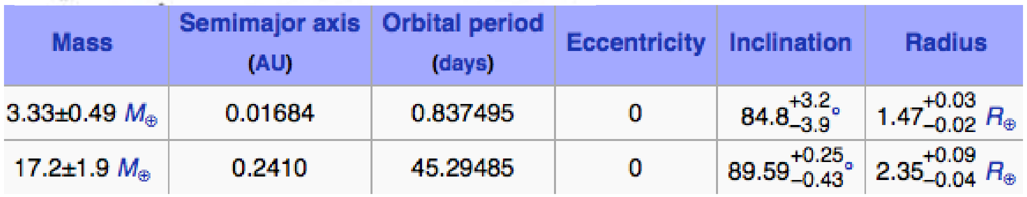
Liu et al. 2015, submitted



T_{cond} (K)

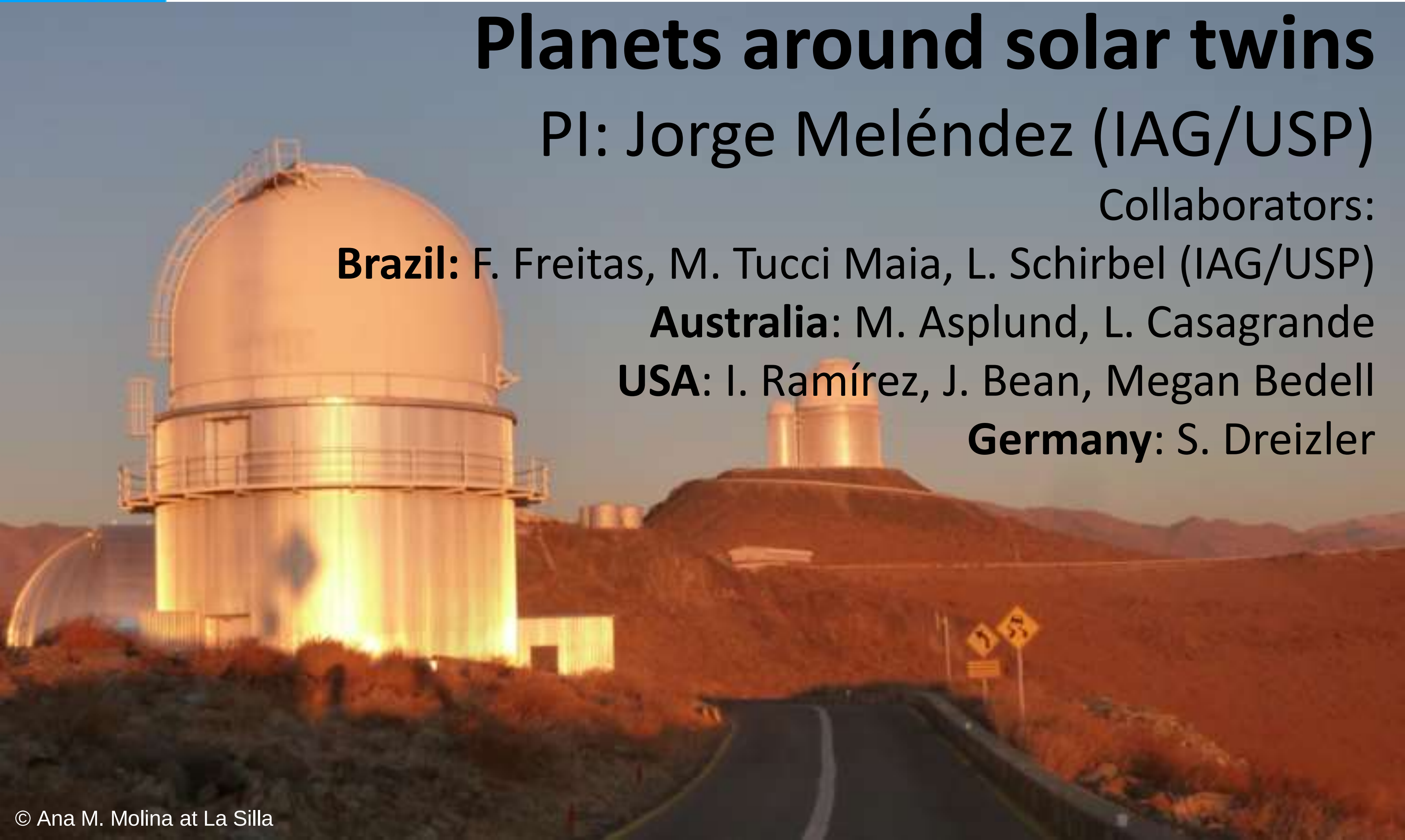
Thick disk

Object	$T_{\rm eff}$ (K)	log g [cgs]	[Fe/H]
Kepler-10[a]	5700 ± 8	4.40 ± 0.02	−0.144 ± 0.008



Mass	Semimajor axis (AU)	Orbital period (days)	Eccentricity	Inclination	Radius
3.33±0.49 $M_{\oplus}$	0.01684	0.837495	0	$84.8^{+3.2}_{-3.9}$°	$1.47^{+0.03}_{-0.02}$ $R_{\oplus}$
17.2±1.9 $M_{\oplus}$	0.2410	45.29485	0	$89.59^{+0.25}_{-0.43}$°	$2.35^{+0.09}_{-0.04}$ $R_{\oplus}$

Large Programme: **88 nights at La Silla**
3.6m telescope + HARPS spectrograph



Planets around solar twins

PI: Jorge Meléndez (IAG/USP)

Collaborators:

Brazil: F. Freitas, M. Tucci Maia, L. Schirbel (IAG/USP)

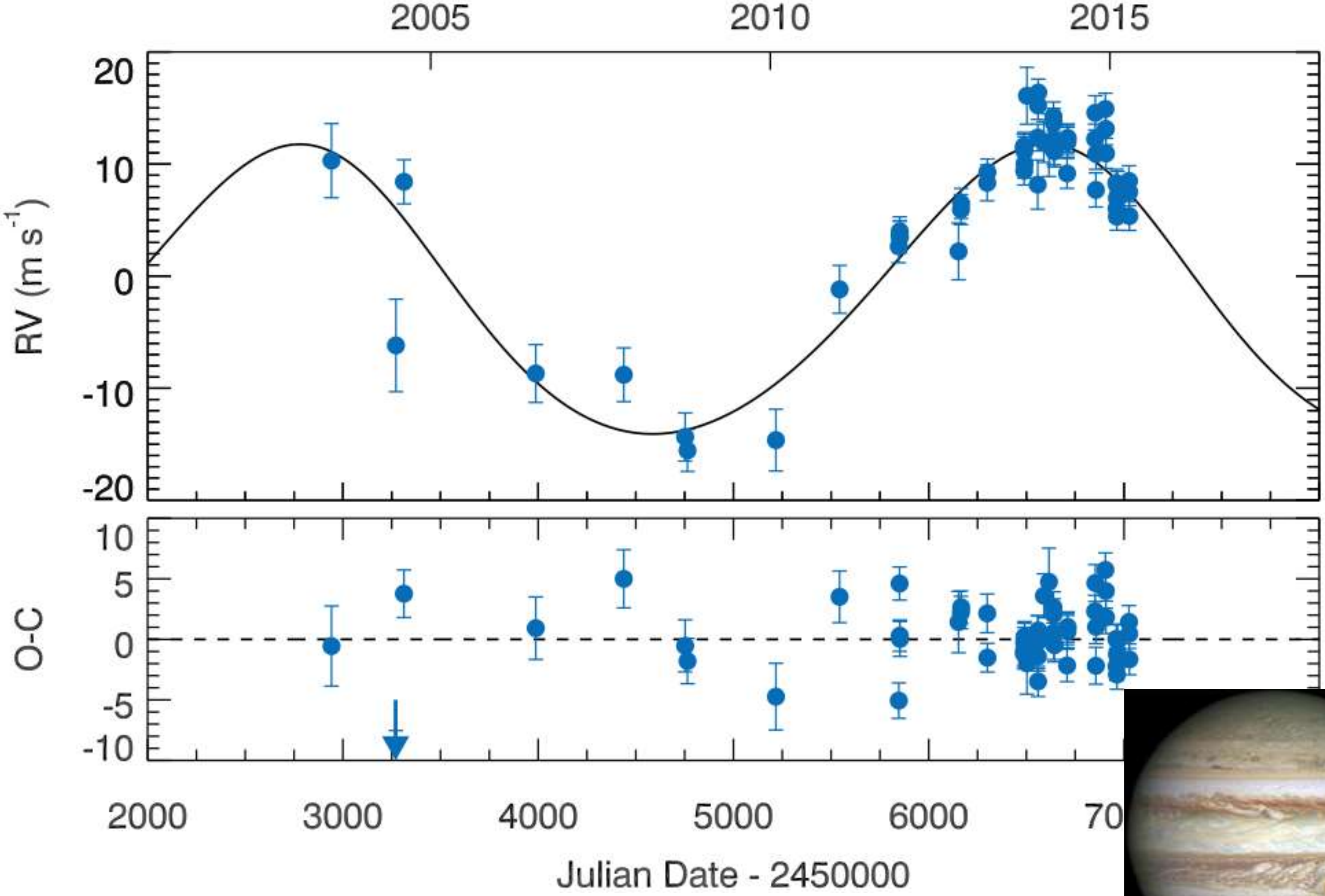
Australia: M. Asplund, L. Casagrande

USA: I. Ramírez, J. Bean, Megan Bedell

Germany: S. Dreizler

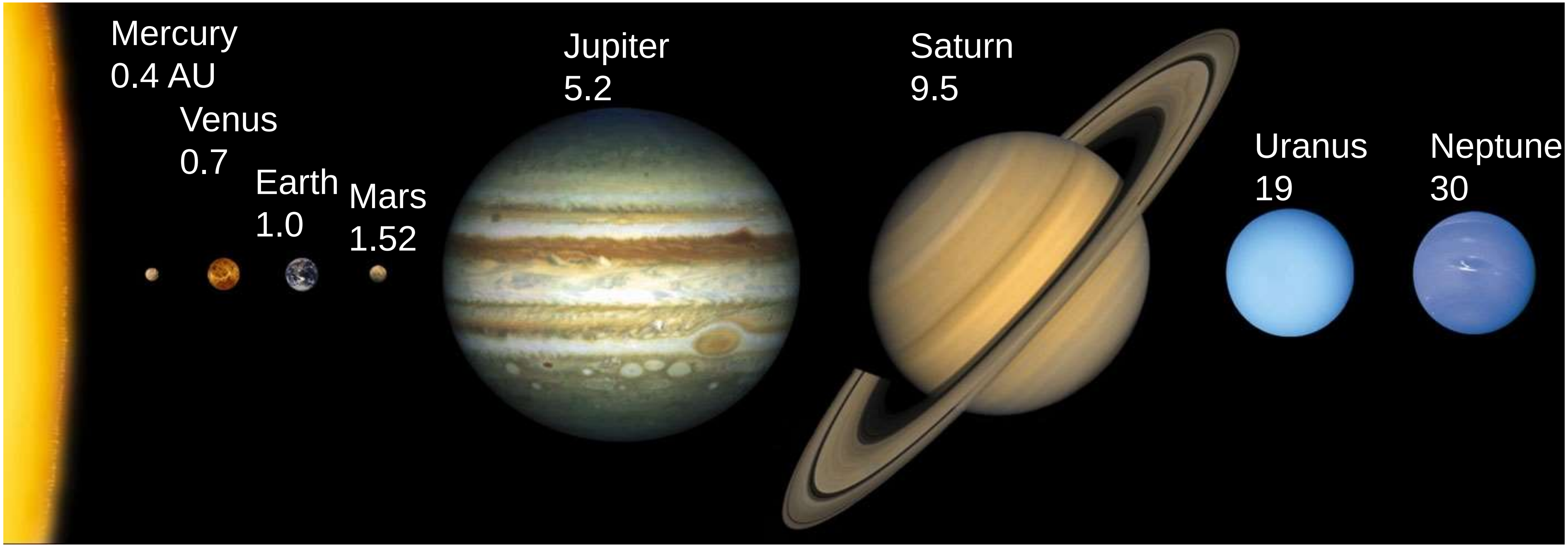
© Ana M. Molina at La Silla

A Jupiter twin around a solar twin!



Bedell et al. 2015, A&A, submitted

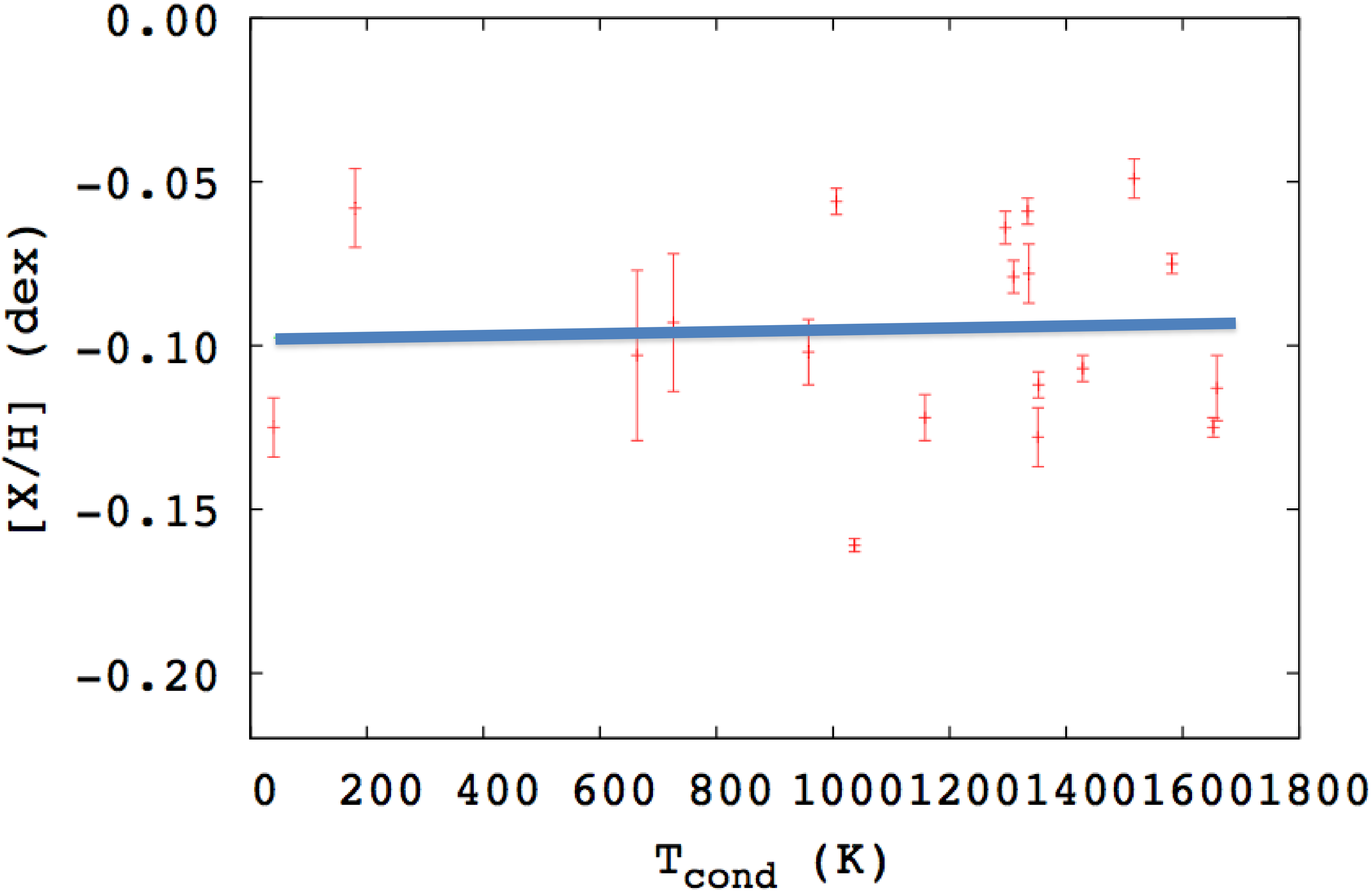
Solar System: no Super-Earths, no mini-Neptunes



Batygin & Laughlin 2015: inward migration of Jupiter cleared the SS from super-Earths, then outward migration

Izidoro et al 2015: Jupiter prevented Uranus & Neptune (and perhaps Saturn's core from becoming super-Earths)

Solar system twin? Jupiter + rocky planets?



Conclusions

- Metallicity can enhance planet formation, but its effect is mainly seen in close-in giants. Neptunes and Earths seem to form around stars in a broad metallicity range.
- Planets can imprint signatures in the chemical composition of their host stars, either by sequestering refractories (& volatiles) or by planet engulfment.
- Planet signatures are small (a few 0.01 dex), hence high precision is mandatory.