Connecting Stellar Abundances and Planet Habitability
Schedule (SatMeet8) for 13-14 July, Pathways15

~~~~~~~MONDAY 13 JULY SCHEDULE~~~~~~~

Lecture Room 206

Opening Remarks – Goals of the Satellite Meeting
Mon 14:00-14:10

Title: Determining stellar atmospheric parameters and chemical abundances of FGK stars with iSpec
Speaker: Sergi Blanco-Cuaresma
Mon 14:10-14:30

Based on the widely known SPECTRUM code by R. O. Gray, we developed an integrated spectroscopic software framework suitable for the determination of atmospheric parameters (i.e., effective temperature, surface gravity, metallicity) and individual chemical abundances. The code, named iSpec and freely distributed, is written mainly in Python and can be used on different platforms: http://www.blancocuaresma.com/s/

iSpec can derive atmospheric parameters by using the synthetic spectral fitting technique and the equivalent width method. We validated the performance of both approaches by developing two different pipelines and analyzing the Gaia FGK benchmark stars spectral library. The analysis was complemented with several tests designed to assess other aspects, such as the interpolation of model atmospheres and the performance with lower quality spectra.

Title: A Study of Stellar Elemental Abundance Techniques
Speaker: Natalie R. Hinkel
Mon 14:30-14:50

Understanding stellar abundances is fundamental to learning about the star, its formation and evolution, as well as the chemical interplay with orbiting planets – when applicable. To adapt to the ever increasing demand for finer abundance precision and accuracy, the stellar abundance community has developed a multitude of techniques, taking advantage of the most up-to-date atmospheric models, line lists, statistics, and solar abundance scales. Unfortunately, the variations introduced by these methods create systematic and stochastic differences between data sets, even when examining the same elements within the same stars. I will discuss results from an international collaboration involving six groups who analyzed the same high-resolution spectra using a variety of techniques. We analyze the results of the autonomous methods in addition to the effect of standardizing the stellar parameters, line list, and their combination. Our conclusions suggest that standardization on any level minimizes the discrepancy between different stellar abundance techniques, although the manner and extent may vary per element and spectral type.

Title: Behavior of elements from Lithium to Europium in stars with [Fe/H] > –0.2
Speaker: Tamara Mishenina
Mon 14:50-15:10

Analysis of the distribution of elements from Lithium to Europium in the dwarfs in the solar neighborhood (∼ 20 pc) with the temperatures in the range of 5500 - 6200 K and metallicity [Fe/H] more than -0.2 (that is one of the signs of the planet host stars) was made. Determination of atmospheric parameters and chemical composition are taken from our previous work (Mishenina et al. 2008, 2012, 2013). Estimation of errors in abundance determination that is an important part in the study and further interpretation of obtained chemical composition was presented. It is discussed whether there is a difference in the behavior of other elements (lithium, oxygen, etc.) in stars with an excess of metal that is not associated with belonging to the various galactic components.

Title: Barium abundances as diagnostics of stellar youth
Speaker: Valentina D'Orazi
Mon 15:10-15:30

High-resolution spectroscopic studies focussing on abundance determination for slow n-capture process elements in open cluster stars, moving groups and young associations have revealed the presence of an anti-correlation between the barium abundance and the stellar/cluster age. The younger the cluster, the higher the Ba content. The reason of such a peculiar trend is yet to be understood and several aspects need to be deeply investigate; for instance we cannot ascertain whether the Ba enhancement is accompanied by a similar behaviour in the other slow n-capture elements (e.g., Y, Zr, La), that might imply a revision of the input physics in stellar evolution models. Regardless of the origin of this phenomenon, we can take advantage of the increasing trend in Ba abundance to provide an independent information on the star's youthfulness and on its (possible) membership to stellar clusters and associations.

The age determination is particularly critical for planet-host stars because it severely affects the calibration of the age-luminosity relationship for sub-stellar objects and is crucial to our understanding of how planets have formed (see e.g., the well known case of HR 8799). We present in this contribution our results for barium abundance determination in open clusters, young associations as well as isolated, field stars known to host planetary companions and discuss the scientific implications.

Title: Abundances of Planet Hosting Red Giant Stars: a Key for Understanding Pollution and Planet Engulfment
Speaker: Joleen Carlberg
Mon 15:30-15:50

Red giant stars (RGs) have the potential to be a crucial link for understanding the pollution of stellar hosts by planet formation processes and the bulk composition of exoplanets. Because of their massive atmospheres, RGs can uncover pollution effects that occur on the main sequence (MS) when the stellar convection zones (CZs) are thin. Such pollution will be erased when the CZ deepens during the RG phase. Furthermore, some light elements are heavily depleted in stellar interiors, making replenishment of those particular elements by later planet engulfment relatively easy to detect.

However, studies of the abundances of RG planet hosts have lagged far behind similar studies of MS stars. Until recently, most studies have focused solely on Fe, and there is still no consensus on whether RG planet hosts show the same trend of increased planet frequency with metallicity that MS hosts show. One of the difficulties for abundance studies is that field RGs have poorly constrained masses, making it more difficult to find appropriate control samples of non-planet hosts for comparative studies.

In this talk, I will summarize the latest results on the metallicity of RG planet hosts, ways to identify candidate planet engulfment stars, and the remaining challenges of using RGs to better understand the connection between stellar metallicity and planet composition and habitability.

Title: The nature of very accurate abundance trends in solar analogs
Speaker: Jonay I. González Hernández
Mon 15:50-16:10

The exhaustive search for extrasolar planets over the past decade has provided as a byproduct a significant collection of high-quality spectroscopic data of solar-type stars in the solar neighbourhood. In particular, the HARPS spectrograph (R 115,000) already accumulates thousands of hours distributed over hundreds of FGKM-type stars. A subsample of about 100 solar analogs have already very high-quality spectra that allow abundance determinations at internal precisions even below 0.01 dex. This opens the interesting possibility to seek for small chemical signatures of the presence of terrestrial planets on anomalies in the refractory-to-volatile abundance ratios. However, other effects concerning stellar age and chemical evolution of the Galaxy may be responsible for the different refractory-to-volatile abundance ratios found in these stars. In this talk I will give an overview of the current status of this field and I will show the most recent results on a subsample of solar analogs with high-accuracy abundance ratios [X/Fe] derived using very high-quality HARPS spectra.

Title: Chemical abundance studies of Kepler-10 relative to solar twins
Speaker: Fan Liu
Mon 16:10-16:30

Chemical abundance studies of the Sun and solar twins demonstrate that the solar composition of refractory elements is depleted when compared to volatile elements, and this could be due to the formation of terrestrial planets. In order to further examine this scenario, we conducted a line-by-line differential chemical abundance analysis of the terrestrial planet host Kepler-10 and eight of its stellar twins. Stellar parameters and elemental abundances of Kepler-10, relative to the stellar twins, were obtained with extremely high precision. When compared to the four thick disc stellar twins, the refractory elements are depleted by $\sim$0.06 dex relative to the volatile elements in Kepler-10. The abundance pattern corresponds to $\sim$14 Earth masses of rocky material, while the two planets in Kepler-10 system have a combined $\sim$20 Earth masses. This result adds further support to the hypothesis that the process of rocky planet formation may result in a depletion of refractory elements relative to volatile elements in the host star.

~~~~~~~TUESDAY 14 JULY SCHEDULE~~~~~~~

Meeting Room 105

Title: Abundances of CNO in planet harbouring stars
Speaker: Lucia Suarez Andres
Tues 14:00-14:20

CNO elements possible play the most important role in the formation and evolution of planets and their atmospheres. Surface CNO abundances of planet hosts stars are used by planet formation models as input parameters to study the evolution of these elements in planetary interiors and atmospheres. Obviously formation of organic life in the Universe is related to this issue in a most direct way. Nevertheless, we are still not able to obtain precise abundance measurements of these elements in the atmospheres of sun-like stars. There are serious concerns about the validity of several absorption lines of CNO as abundance indicators. The problem is not new. It has been outlined and studied in metal poor stars since 1980s. Today we know that this issue is unsolved in solar type metal rich stars as well. Our group has undertaken a vigorous program to make a uniform and homogenous study of CNO in a large sample solar type stars with and without known planets using all available CNO abundance indicators between 3100 and 9000 Å. We study atomic lines and molecular bands using standard 1D LTE models of atmospheres. Recently we obtained precise N abundances from the near UV NH band 3360 Å for a sample of 90 solar-type stars, from which 50 are known to harbour extrasolar planets . We are also studying abundance of C from the CH band at 4300 Å and several atomic lines. We will present our latest results and will outline a future work undertaken by our group.

Title: Detecting planets through detailed stellar abundances: constraints from Messier 67
Speaker: Andreas Korn
Tues 14:20-14:40

One of the possible explanations of the departing chemical profile of the Sun with respect to solar twins in the solar neighborhood is that planet formation locks up certain (refractory) elements (Melendez et al. 2009). I will review our recent work on the chemical profiles of stars in the solar-age, solar-metallicity cluster Messier 67, including the first solar twin in a cluster. While work is still on-going, we can already draw some interesting conclusion about stellar signatures of planetary formation.

Title: Searching for signatures of planet formation in stars with circumstellar debris discs
Speaker: Jesus Maldonado
Tues 14:40-15:00

Twenty years after the first exoplanet discoveries our understanding of what stellar properties influence (on how) planet formation is far to be complete. Excluding the well-established correlation between stellar metallicity and the probability that the star hosts a gas-giant planet, any other claim of a chemical trend in planet-hosting stars has been so far disputed. In the last years, detailed chemical abundance studies have reported different trends between samples of planet and non-planet hosts. In parallel, tentative correlations between the presence of dusty debris discs and low-mass planets have been presented. In this contribution we present the results of a homogeneous spectroscopy study of

251 stars including stars with known debris discs, with debris discs and planets, and only with planets. The [Fe/H] and <[X/Fe]>-Tc trends are discussed and set into the context of planet formation. The possible correlations between the <[X/Fe]>-Tc slopes and stellar properties such as metallicity or age are also discussed.

Title: The metallicities of stars with and without transiting planets
Speaker: Lars A. Buchhave
Tues 15:00-15:20

Abstract: Host star metallicities have been used to infer observational constraints on planet formation throughout the history of the exoplanet field. The giant planet metallicity correlation has now been widely accepted, but questions remain as to whether the metallicity correlation extends to the small terrestrial-sized planets. Here, we report metallicities for a sample of 518 stars in the Kepler field that have no detected transiting planets and compare their metallicity distribution to a sample of stars that hosts small planets ($\mathrm{Rp} < 1.7\ \mathrm{R}_{Earth}$). Importantly, both samples have been analyzed in a homogeneous manner using the same set of tools (Stellar Parameters Classification tool; SPC). I will discuss the average metallicities of the two samples and whether the two samples are drawn from the same parent population and conclude whether or not the homogeneous analysis of the data supports the hypothesis that stars hosting small planets have a metallicity similar to stars with no known transiting planets in the same area of the sky.

Title: Conditioning interior structure of rocky exoplanets to abundance constraints of their host stars
Speaker: Caroline Dorn
Tues 15:20-15:40

Conditioning interior structure of rocky exoplanets to abundance constraints of their host stars Characterizing the interior structure of exoplanets is key to understand planet formation and to estimate the probability of the existence of habitable planets outside our solar system. Determining interior structure of rocky exoplanets from measurements of mass and radius is highly degenerate. We show that the degeneracy can be significantly reduced by using relative abundances of the host stars photosphere as proxies for the planetary bulk abundances. For refractory elements (i.e., Fe, Si, Mg), these proxies are valid for the terrestrial Solar System planets, and also planet formation models show an abundance-correlation between host star and rocky planets.

In our study, we determine the degeneracy of interior structure of predominantly rocky Super-Earths. Our assumptions are the following: (1) only rocky silicate exoplanets are considered with small gaseous envelopes, i.e. no oceans; (2) bulk exoplanet composition is derived from stellar photospheric abundance measurements (=CI-chondrites in the case of the Sun); (3) exoplanet cores are assumed to be made of pure iron. We perform a full probabilistic inverse analysis (Markov chain Monte Carlo), in order to rigorously estimate the degeneracy of the physico-chemical structure of a planet while formally accounting for data and model uncertain- ties. This enables us to characterize how the variability of core size and mantle composition depends on the available data and associated uncertainties. Our main conclusions are (1) observations of mass and radius are sufficient to constrain core size; (2)

the photospheric host star abundances (Fe, Si, Mg) used as proxies for planetary bulk abundances can significantly reduce the degeneracy in interior structure models; (3) the degree to which model parameters can be constrained depends not only on the uncertainties of mass, radius, and stellar element abundances but also on the absolute values of mass and radius.

We provide a general methodology of analyzing interior structures of exoplanets that may help to understand how observable planetary and stellar properties can be used to determine the possibility of habitability. The methodology we propose is sufficiently general to allow its future extension to more complex internal structures including volatile-rich exoplanets including oceans and ice.

Title: Composition of rocky planets based on the host star chemistry:
What observations are telling us?
Speaker: Vardan Adibekyan
Tues 15:40-16:00

Abstract: It is well known that stellar metallicity plays an important role on the formation and evolution of different type of planets. Interestingly, individual stellar elemental abundances (and their ratios) will also determine the composition and type of the planets that forms. We explored the possibility that the stellar abundances of different species can be used to constraint the core and mantle abundances in known transiting rocky planets as recently suggested by Dorn et al. (2015). We derived stellar parameters and chemical abundances from high resolution spectra for Fe, Si, Mg, O, and C in three stars hosting low mass, rocky planets. These abundances, together with a simple stoichometric model, were used to estimate the iron mass fraction in each planet, assuming stellar composition. Our observational results suggest that stellar abundances can be used to put strong constraints on the chemical composition of orbiting rocky planets.

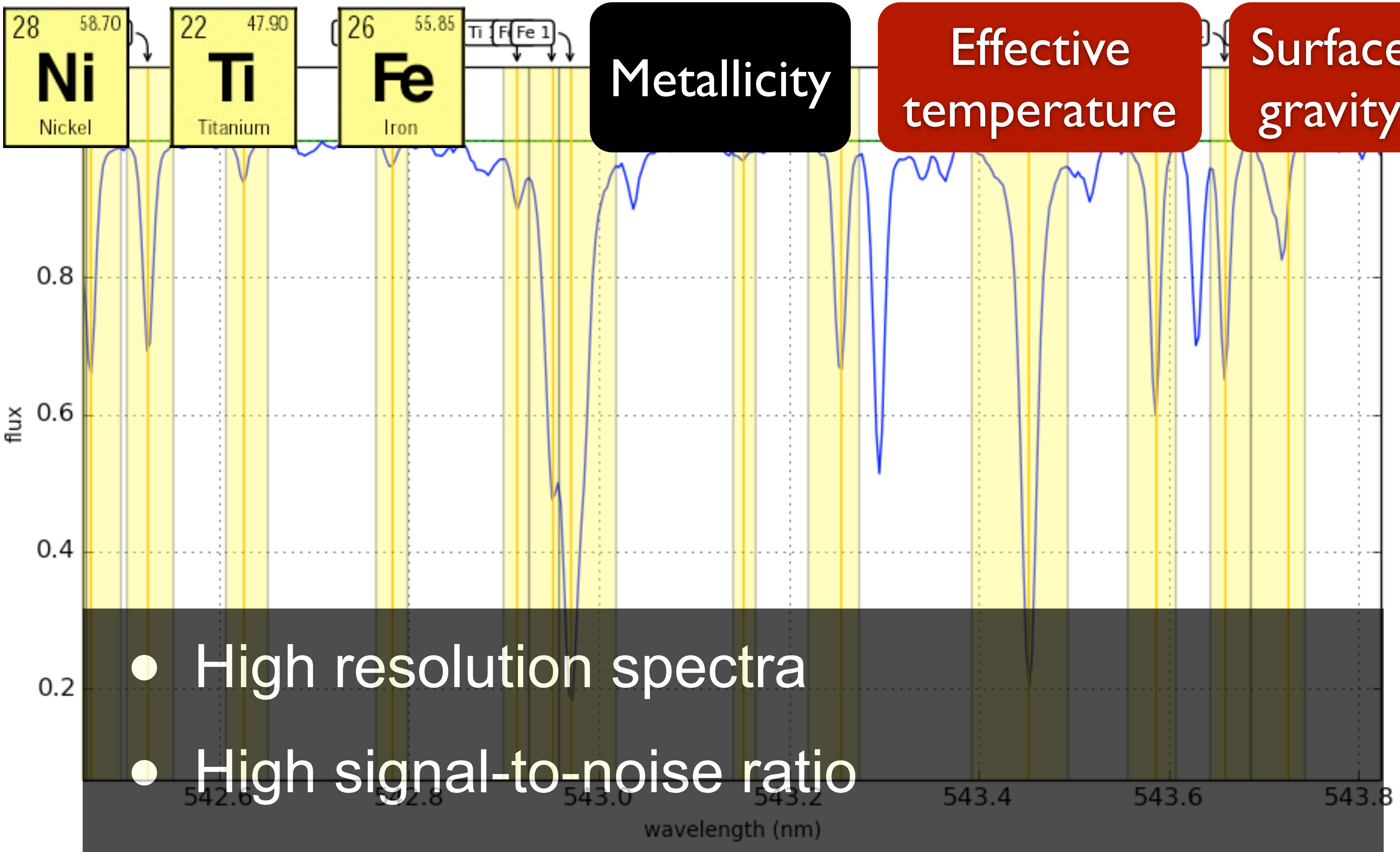
Round-Table Discussion of Results and Conclusions from Presented Talks
Speaker: All workshop participants and attendees
Tues 16:00-16:30

Stellar parameters and abundances with iSpec

Sergi Blanco-Cuaresma
University of Geneva

Abundances

Atmospheric parameters



Metallicity

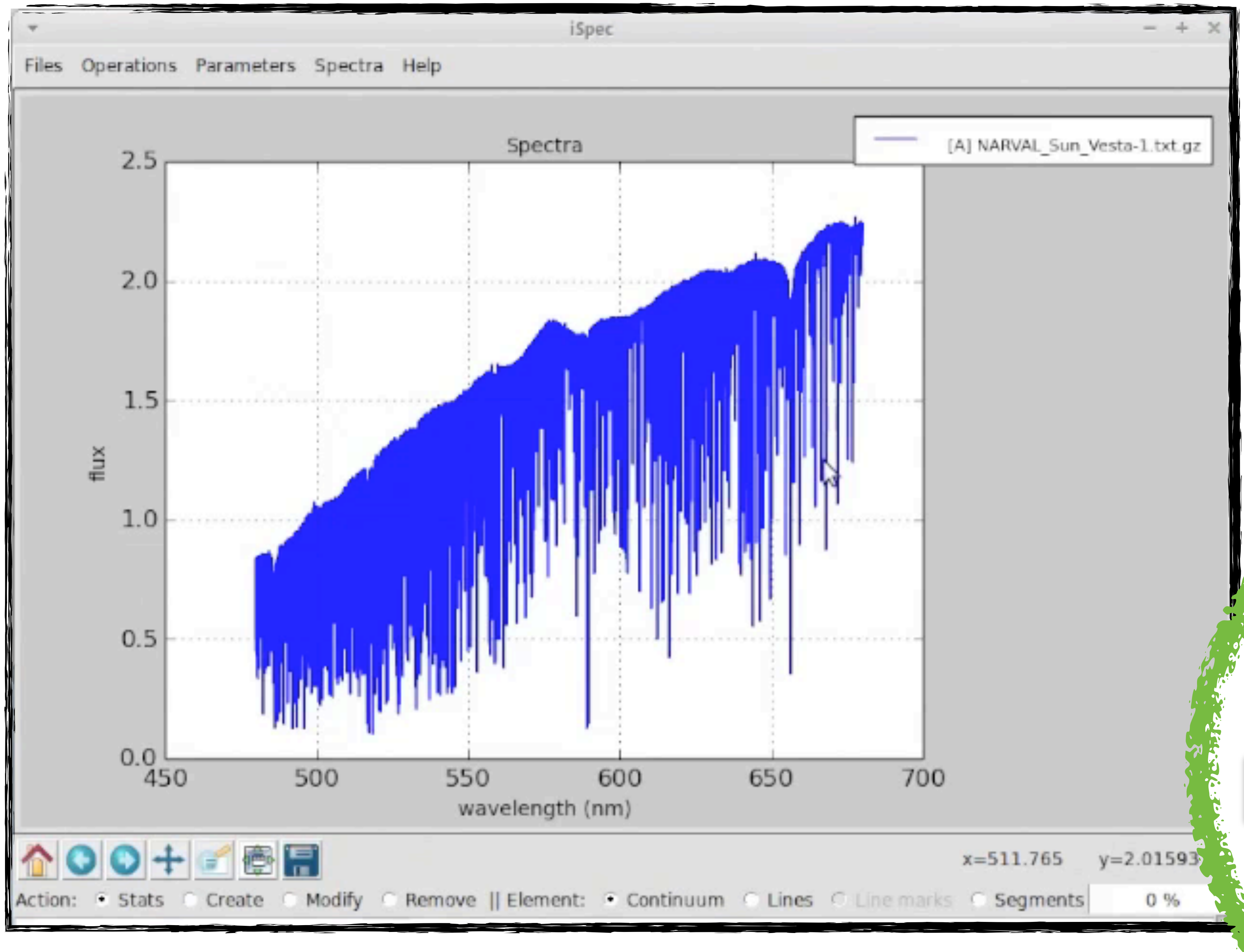
Effective temperature

Surface gravity

- High resolution spectra
- High signal-to-noise ratio
- Optical range (480 - 670 nm)

iSpec

Visual interface + Python



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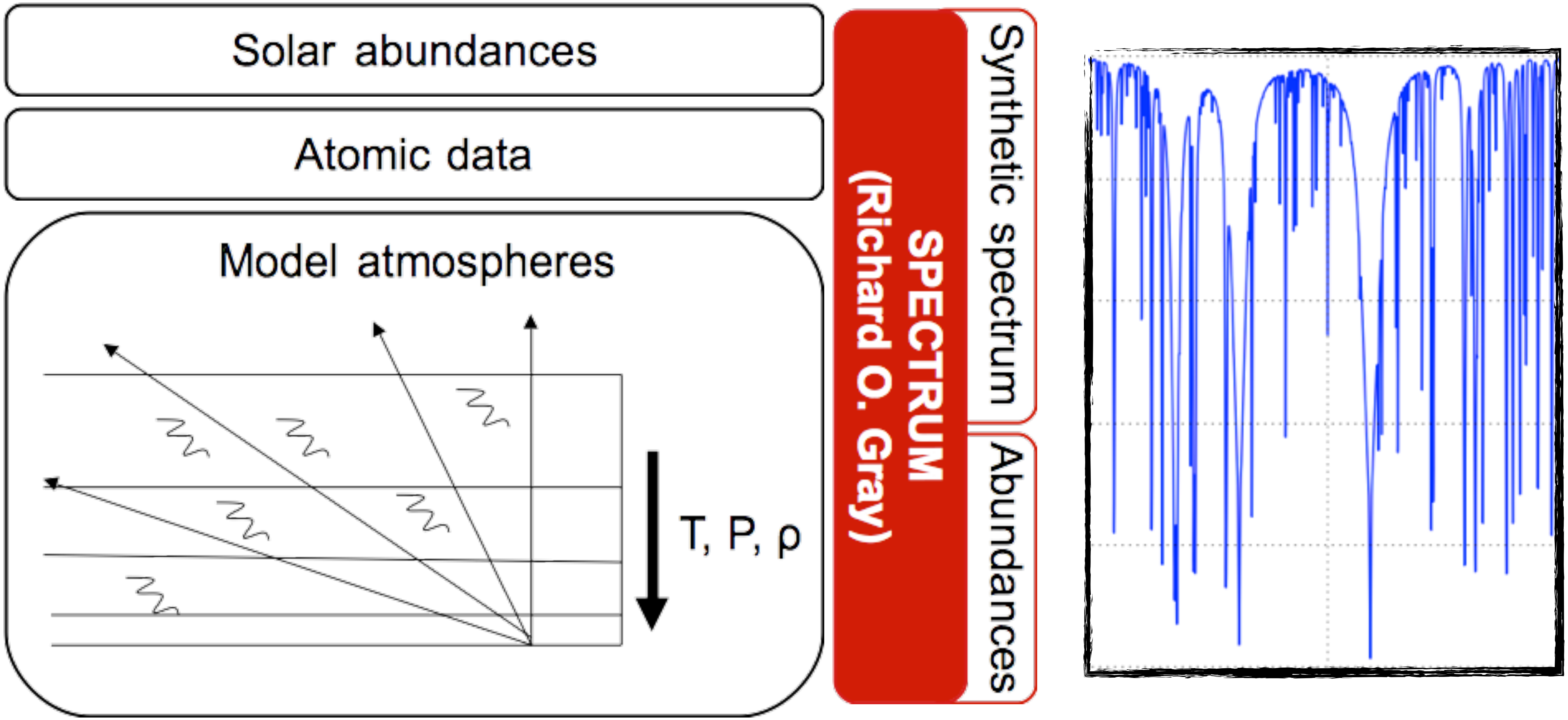
Determining stellar atmospheric
parameters and chemical
abundances of FGK stars with
iSpec (Blanco-Cuaresma et al. 2014a)

+20,000
lines of code

www.blancocuaresma.com/s/

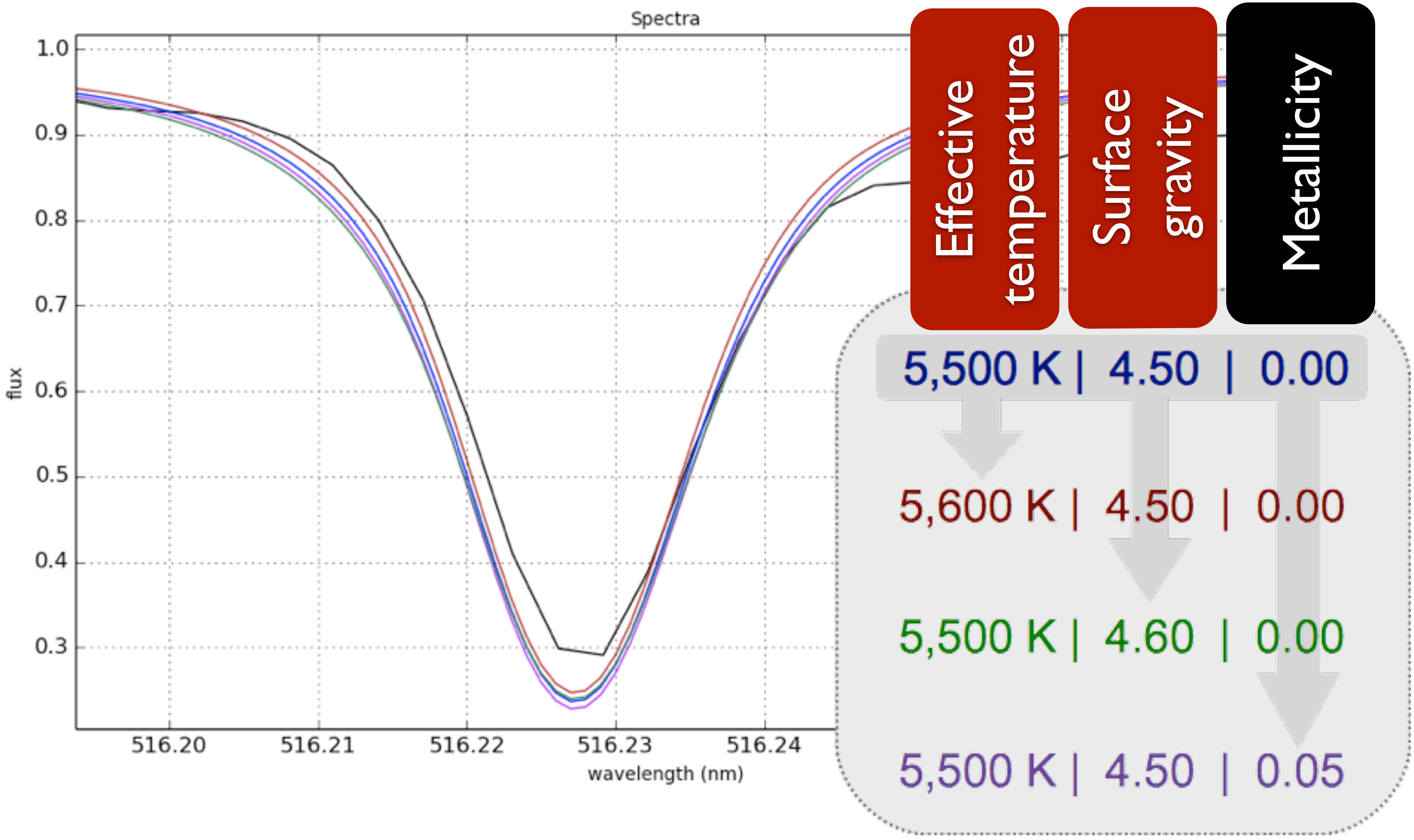
Spectral synthesis



iSpec

Atmospheric parameters and individual abundances

Difference minimization | Least square algorithm



Effective temperature | **Surface gravity** | **Metallicity**

5,500 K | 4.50 | 0.00

5,600 K | 4.50 | 0.00

5,500 K | 4.60 | 0.00

5,500 K | 4.50 | 0.05

Gaia

FGK Benchmark Stars

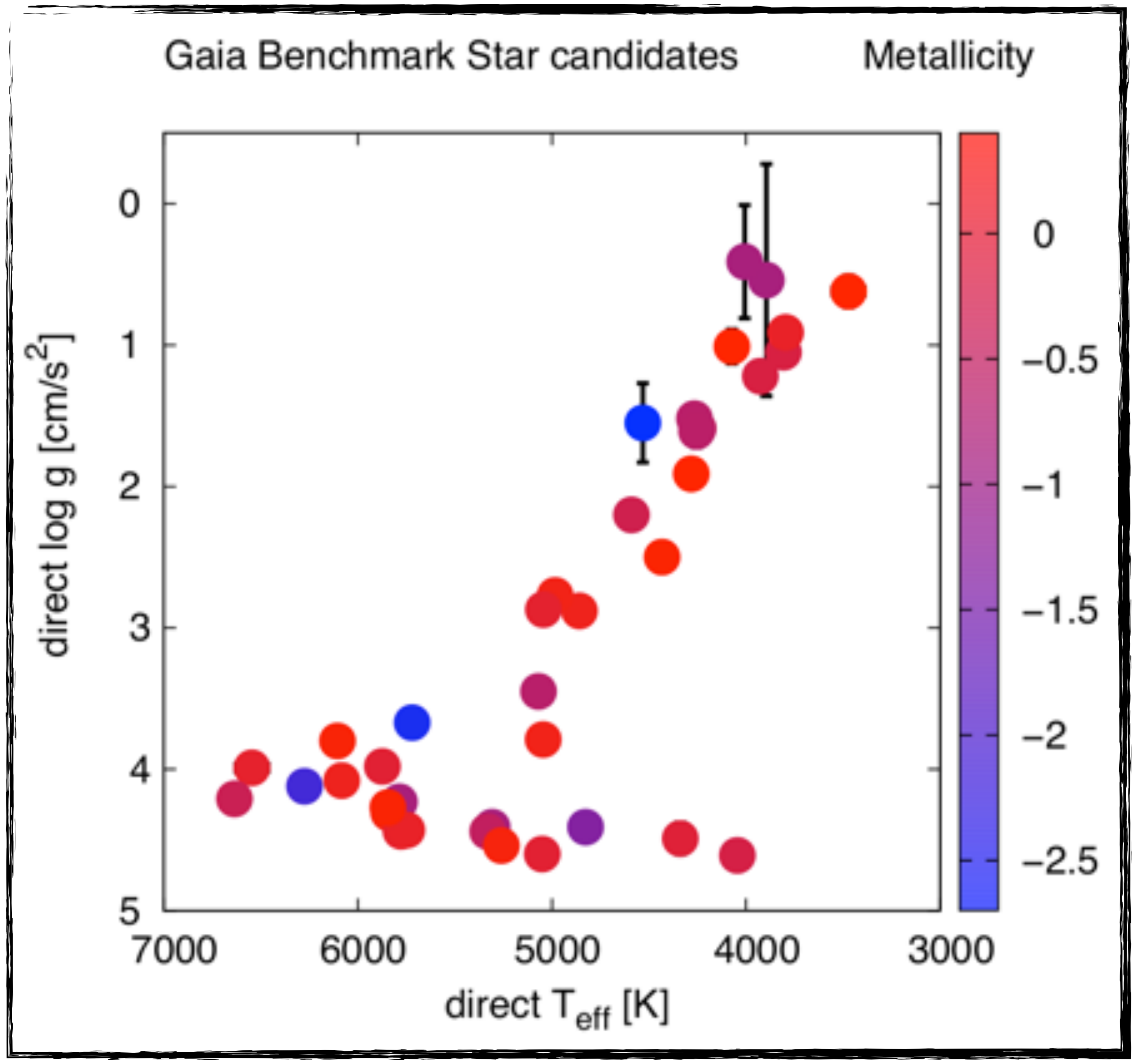
Reference parameters

34

very well-known FGK stars

Calibration and assessment

- Gaia mission
- Gaia ESO Survey



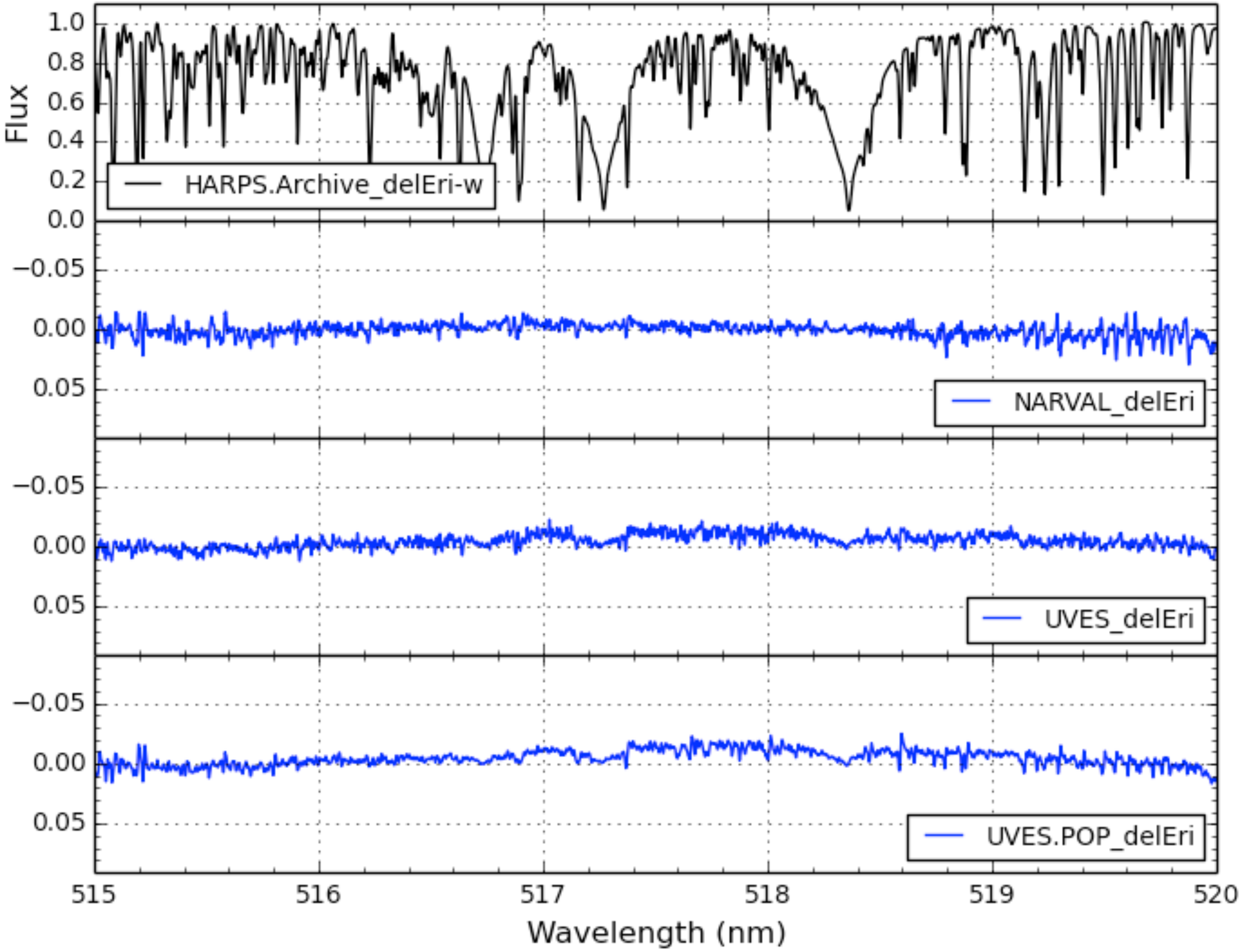
Astrophysical parameters: Heiter et al. 2015
Metallicities: Jofré et al. 2014

Gaia

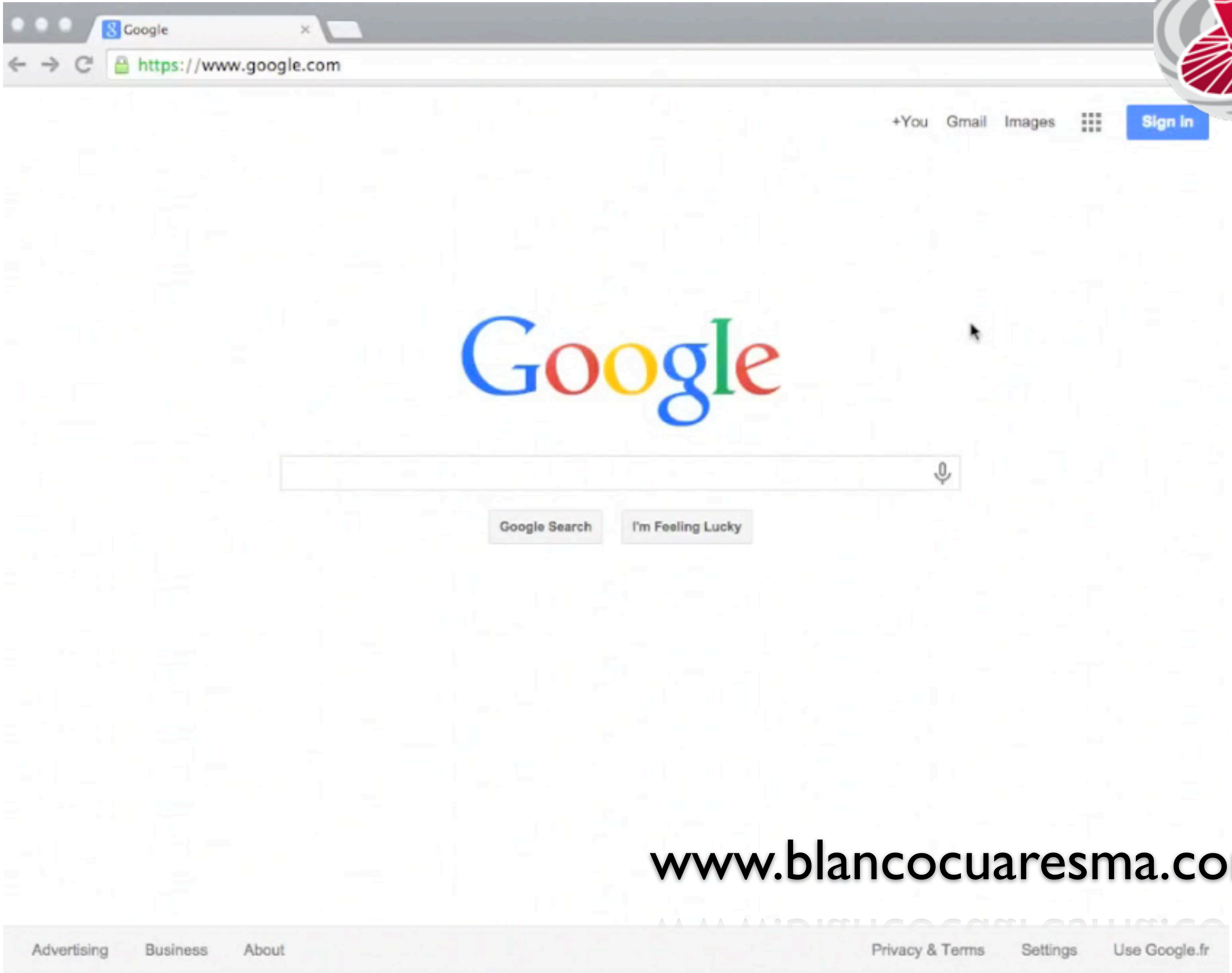
FGK Benchmark Stars

Spectral compilation:

- NARVAL
- ESPaDOnS
- HARPS
- UVES

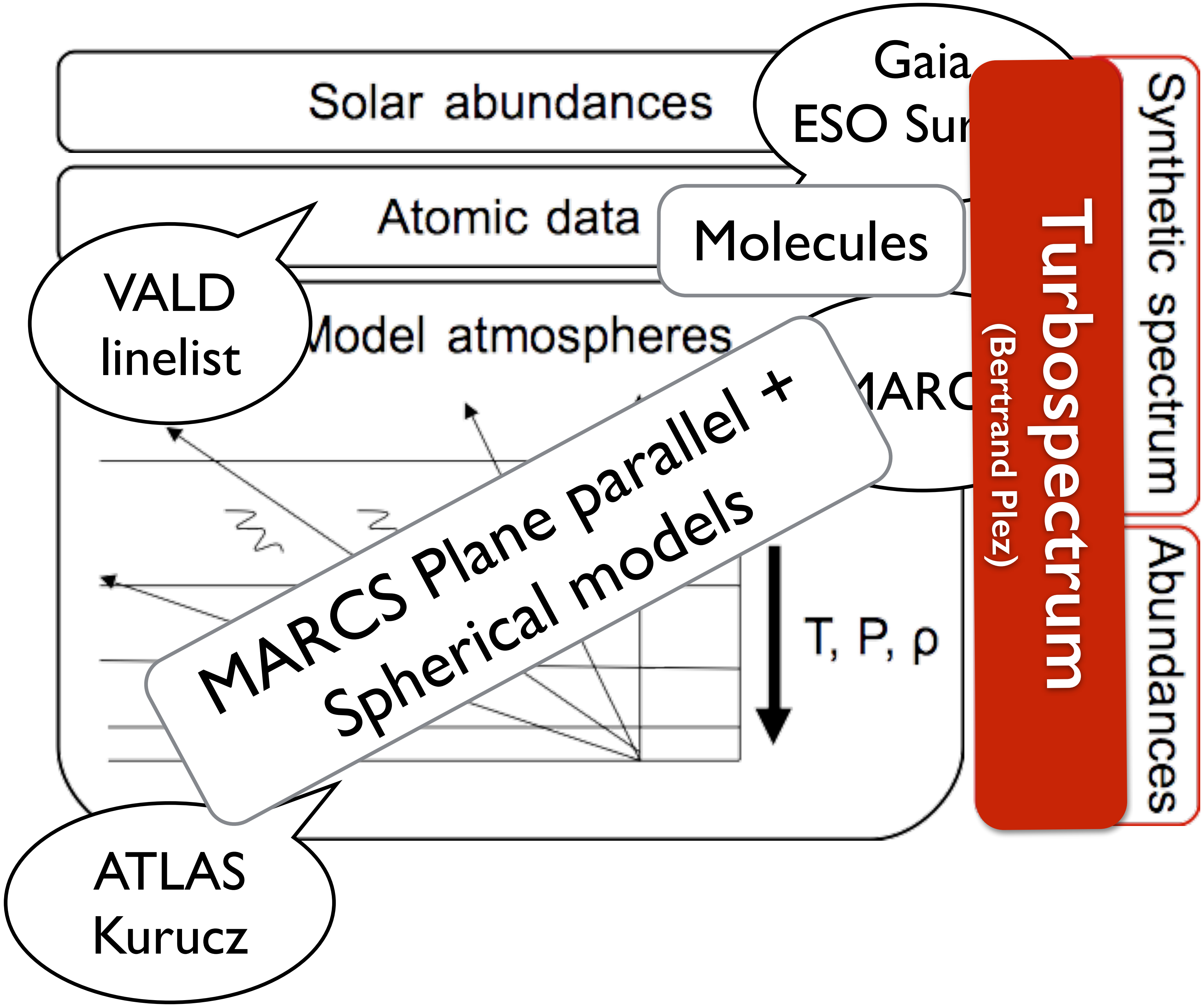


The Gaia FGK benchmark stars.
High resolution spectral library.
(Blanco-Cuaresma et al. 2014b)



www.blancocuaresma.com/s/

Spectral synthesis



Solar abundances

Gaia
ESO Sur

Atomic data

Molecules

VALD
linelist

Model atmospheres

MARC

MARCS Plane parallel +
Spherical models

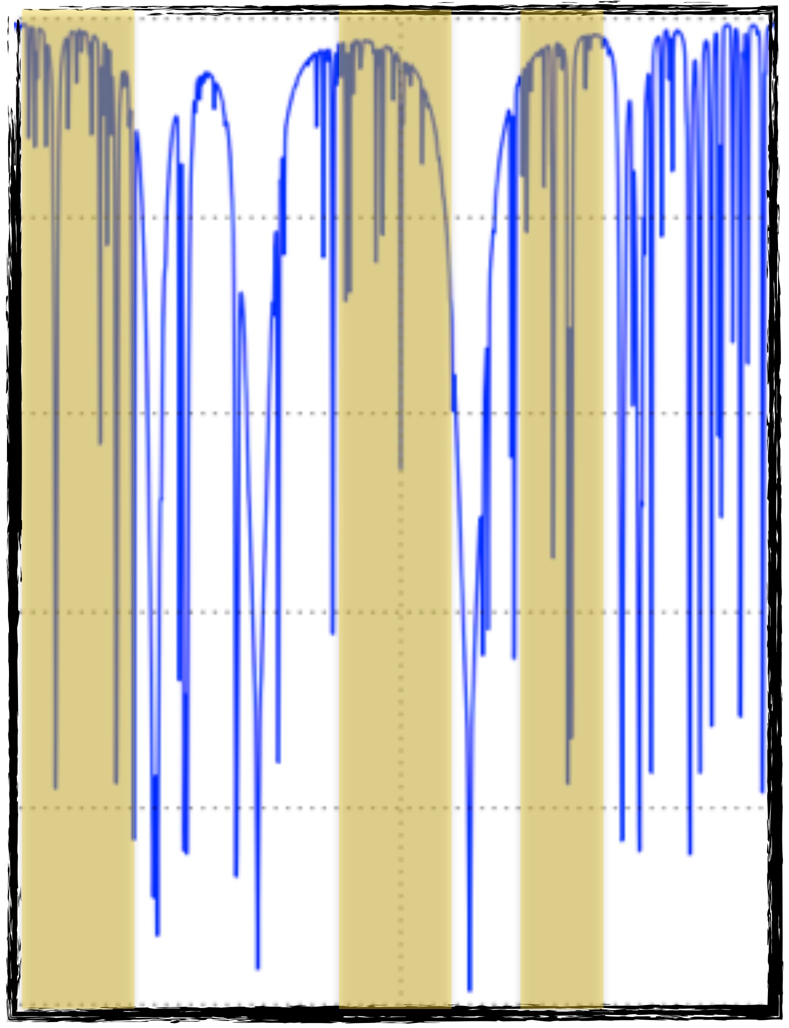
T, P, ρ

ATLAS
Kurucz

Turbospectrum
(Bertrand Plez)

Synthetic spectrum

Abundances

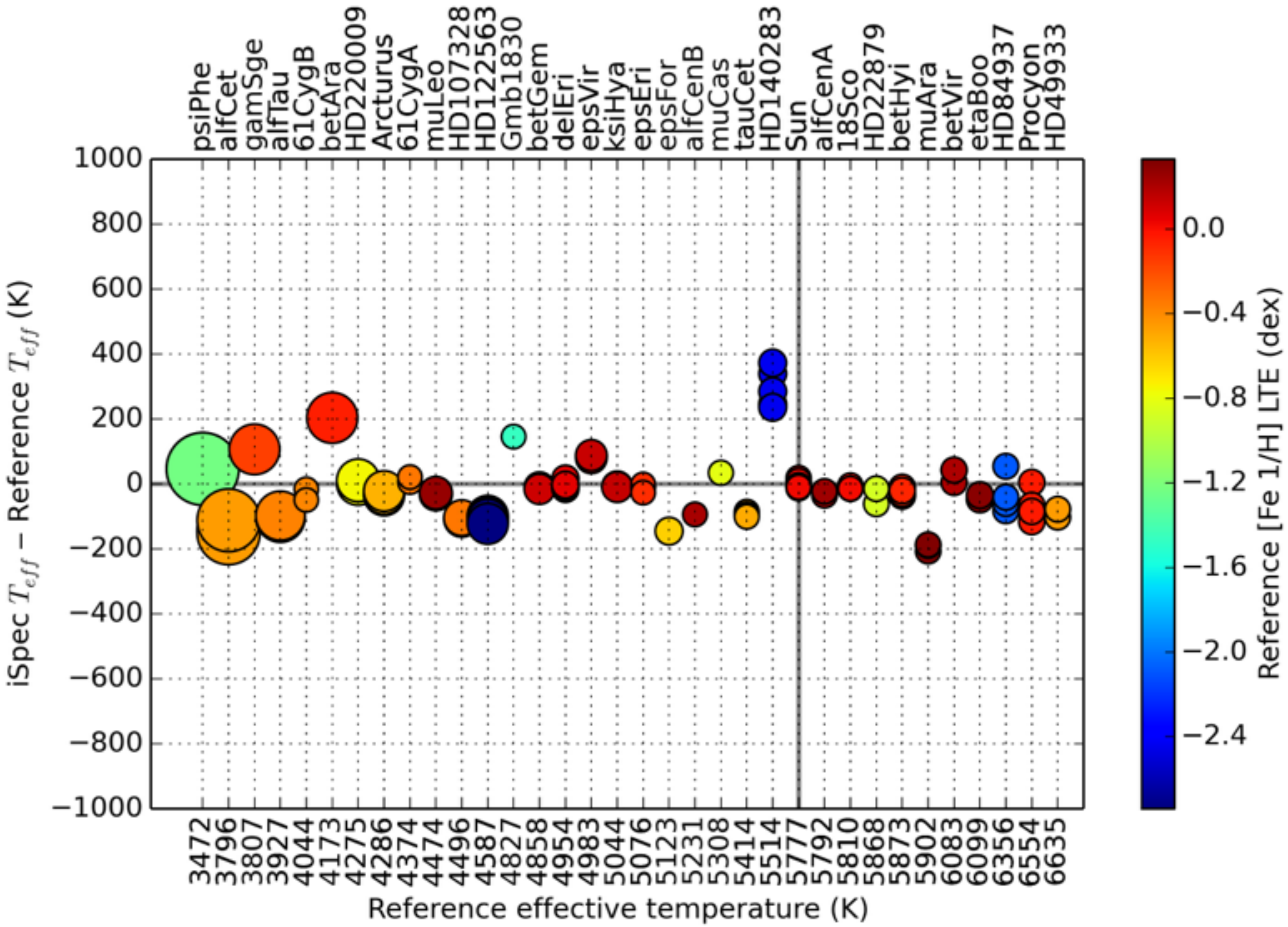


Determining stellar atmospheric parameters and chemical abundances of FGK stars with iSpec (Blanco-Cuaresma et al. 2014a)

Gaia

FGK Benchmark Stars

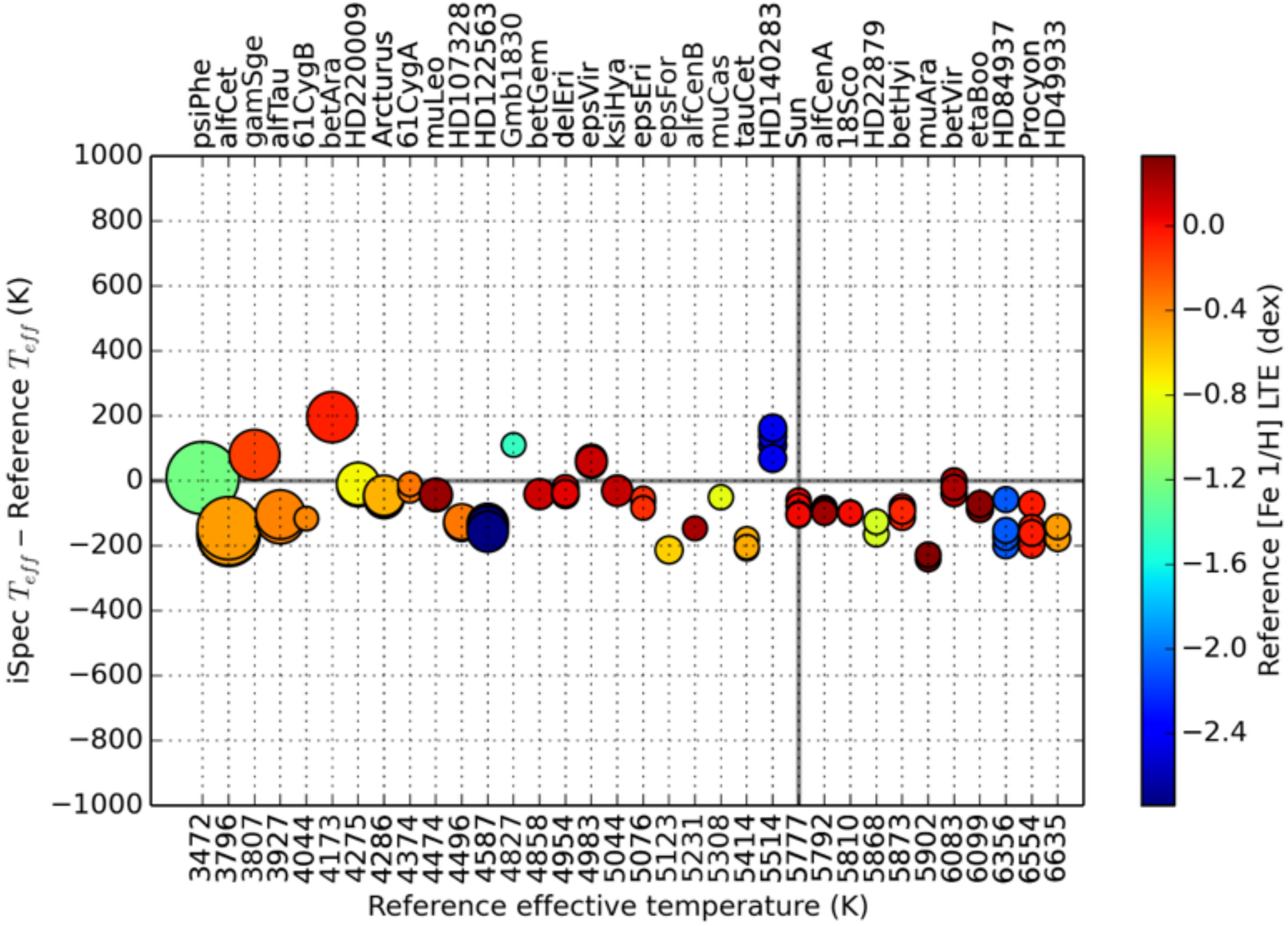
SPECTRUM



Gaia

FGK Benchmark Stars

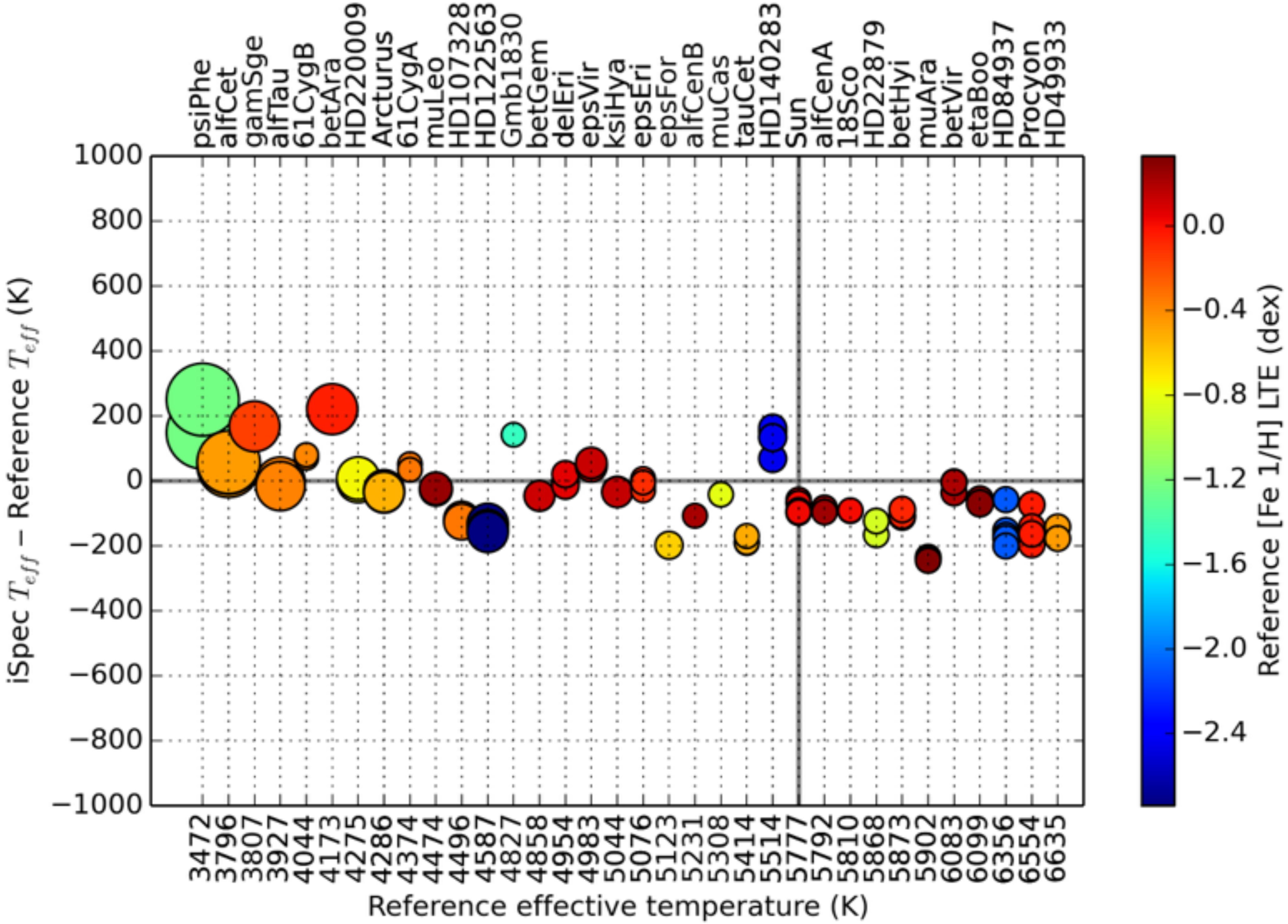
Turbospectrum



Gaia

FGK Benchmark Stars

Turbospectrum + molecules



Gaia FGK Benchmark Stars

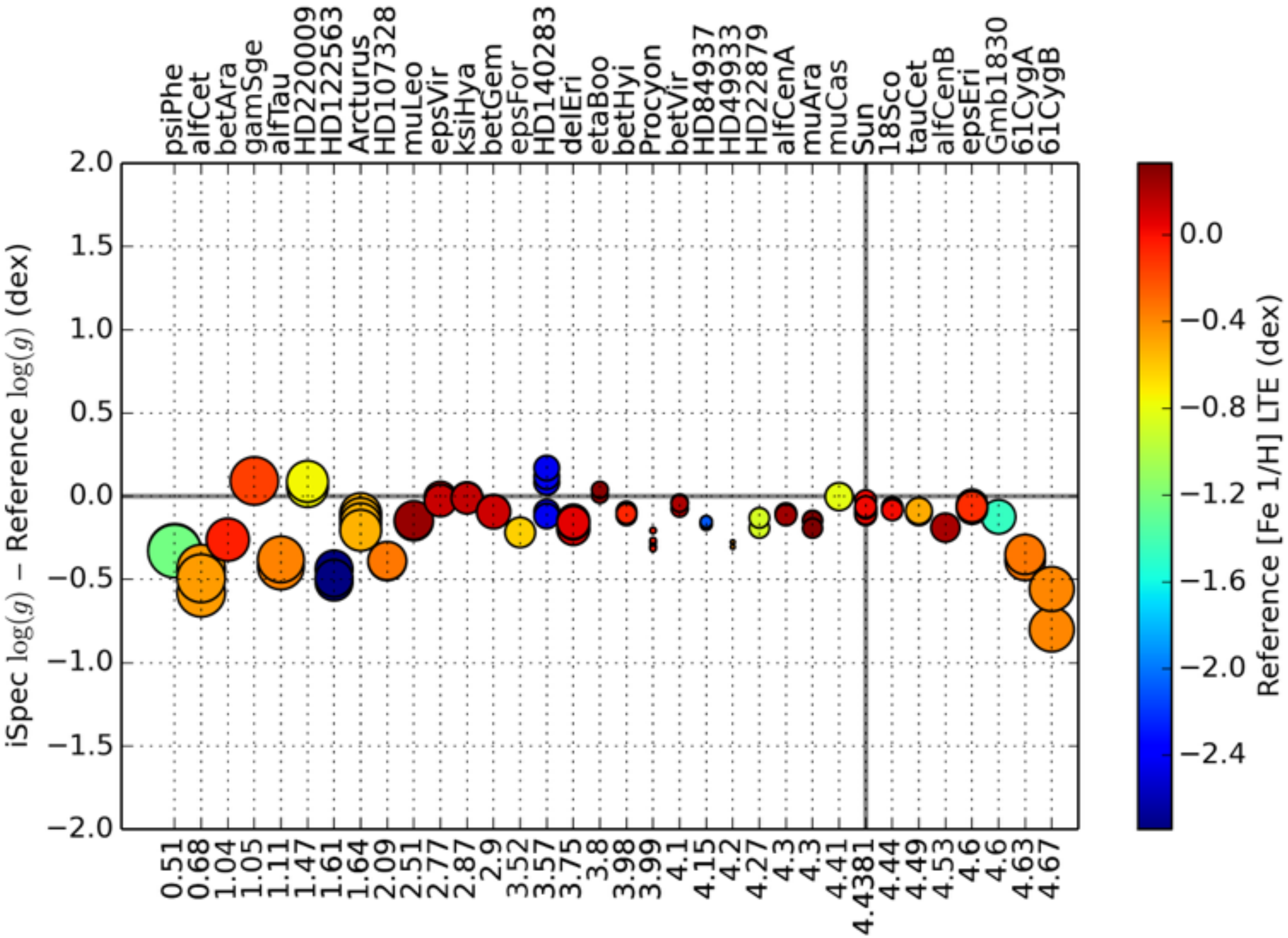
iSpec assessment

	SPECTRUM	Turbospectrum	Turbospectrum + molecules
Teff	-27 ± 68 K	-85 ± 76 K	-38 ± 90 K
log(g)			
[Fe I/H]			

Gaia

FGK Benchmark Stars

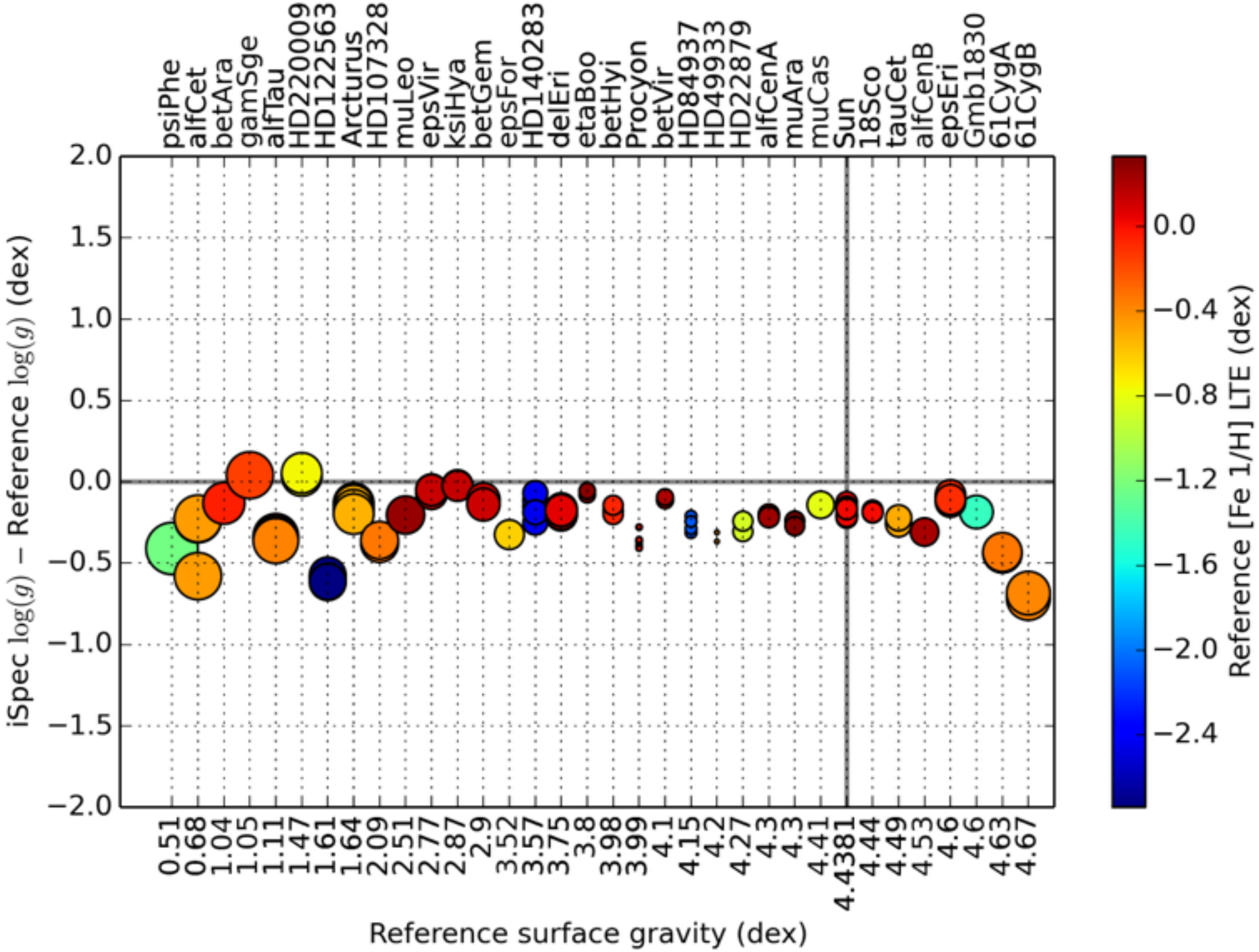
SPECTRUM



Gaia

FGK Benchmark Stars

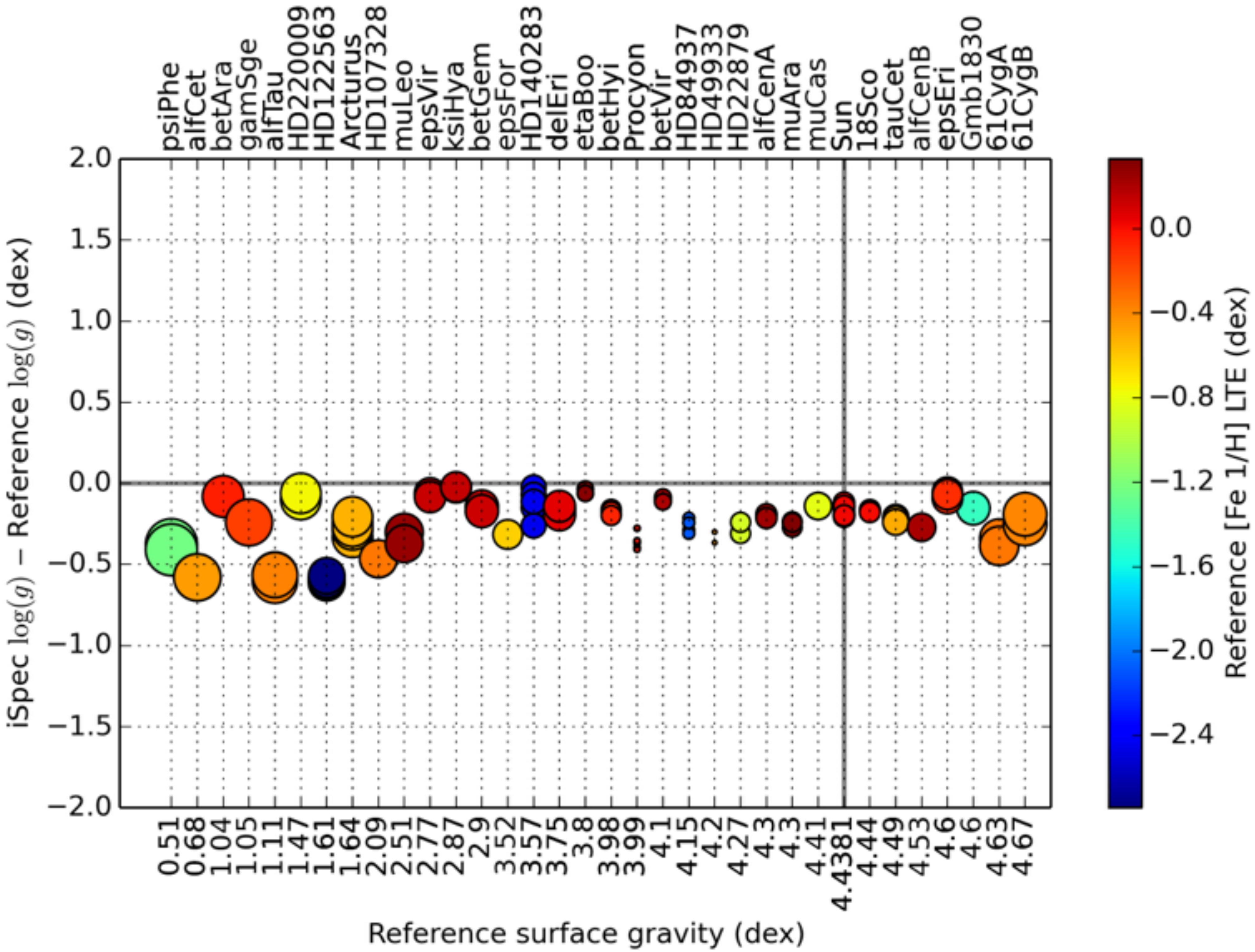
Turbospectrum



Gaia

FGK Benchmark Stars

Turbospectrum + molecules



Gaia FGK Benchmark Stars

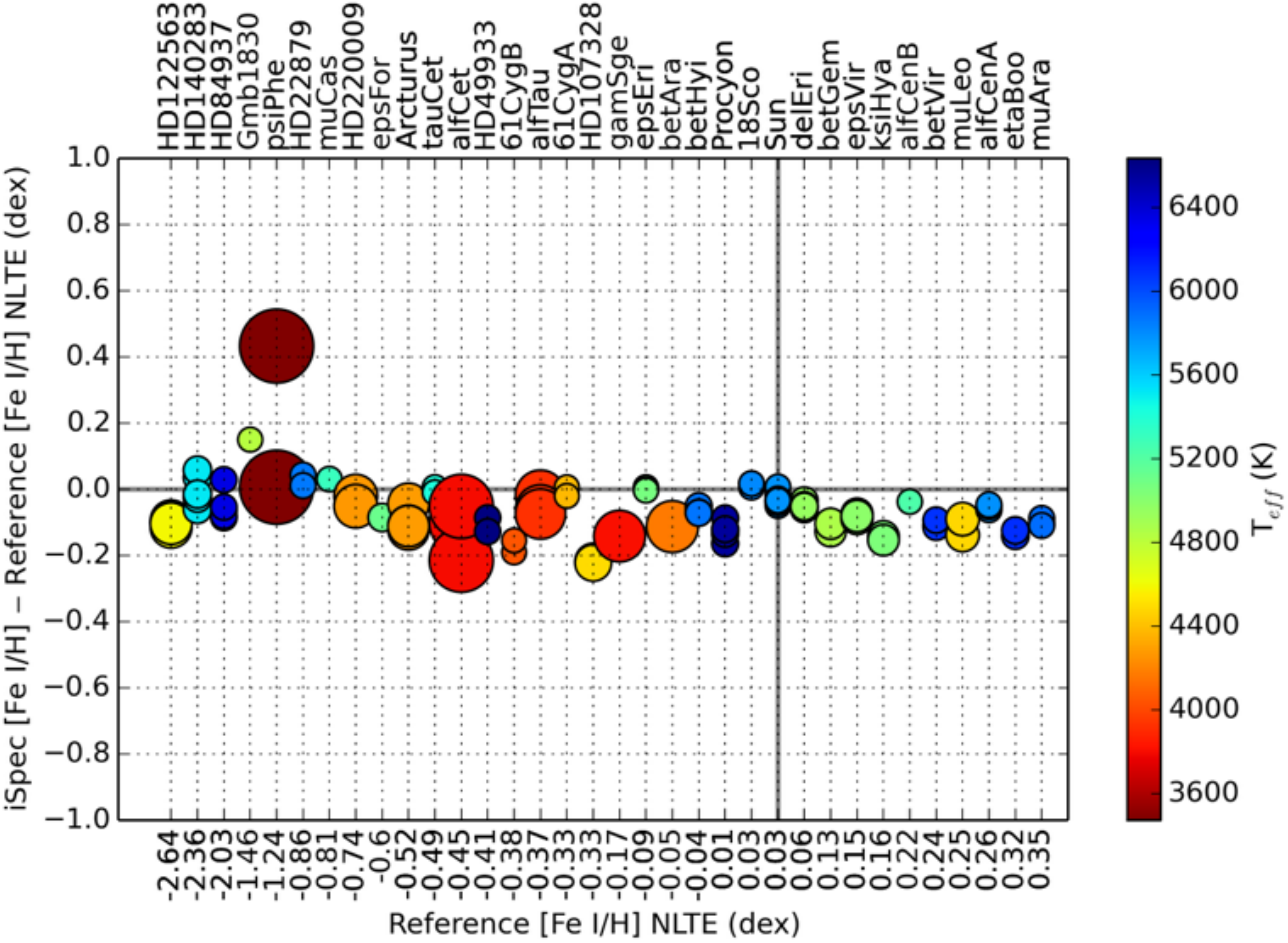
iSpec assessment

	SPECTRUM	Turbospectrum	Turbospectrum + molecules
Teff	-27 ± 68 K	-85 ± 76 K	-38 ± 90 K
log(g)	**-0.15 ± 0.14**	**-0.20 ± 0.12**	**-0.22 ± 0.12**
[Fe I/H]			

Gaia

FGK Benchmark Stars

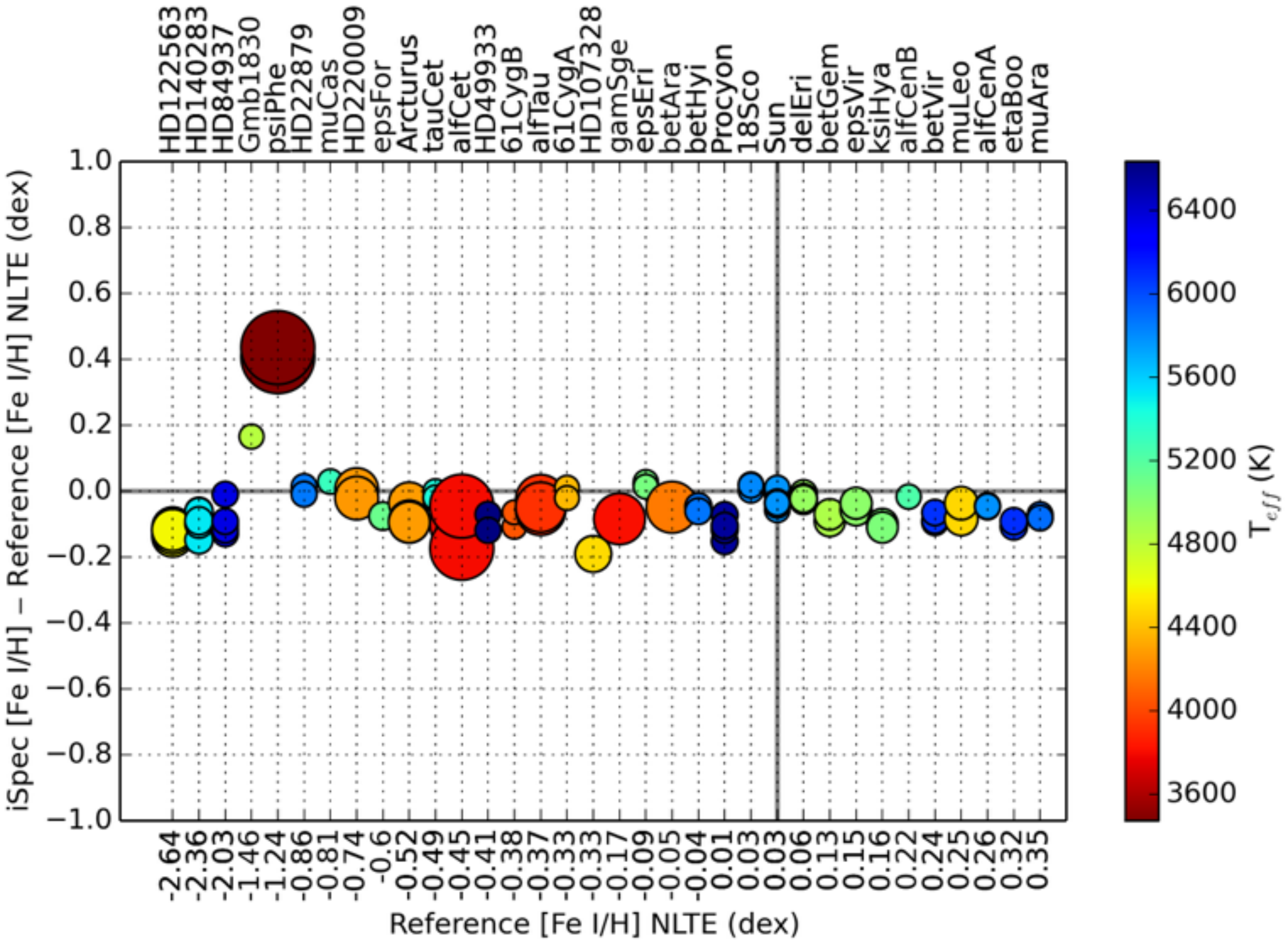
SPECTRUM



Gaia

FGK Benchmark Stars

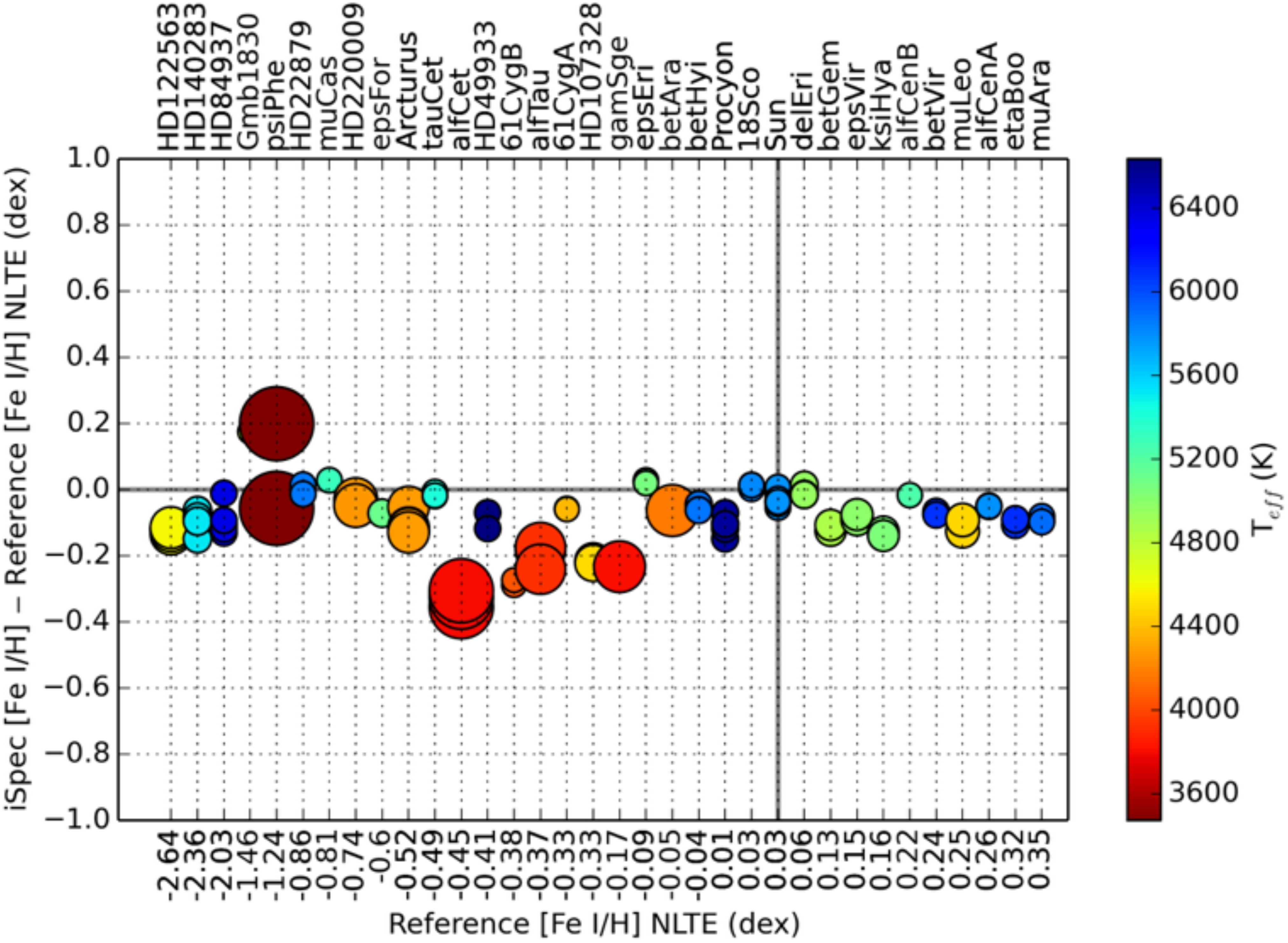
Turbospectrum



Gaia

FGK Benchmark Stars

Turbospectrum + molecules



iSpec assessment

	SPECTRUM	Turbospectrum	Turbospectrum + molecules
Teff	-27 ± 68 K	-85 ± 76 K	-38 ± 90 K
log(g)	-0.15 ± 0.14	-0.20 ± 0.12	-0.22 ± 0.12
[Fe I/H]	**-0.06 ± 0.05**	**-0.06 ± 0.05**	**-0.07 ± 0.06**

Conclusions

1. The Gaia FGK Benchmark stars spectral library is a powerful tool
2. iSpec is an easy-to-use tool for spectroscopy
3. Sometimes it is difficult to predict the impact of better physics, but…
    - NLTE effects
    - <3D> model atmospheres (plane-parallel/spherical geometr

WE ARE
MADE OF
STAR
STUFF

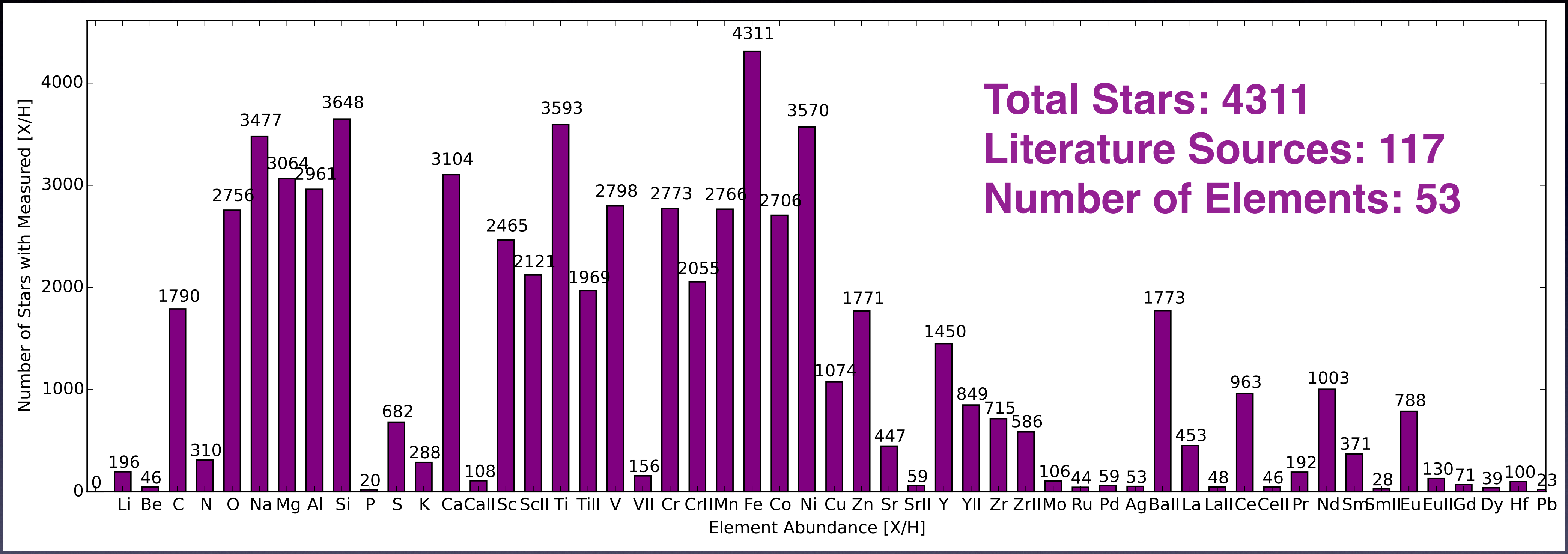
–CARL SAGAN

A Study of Stellar Elemental Abundance Techniques

Natalie Hinkel
Arizona State University

Pathways Towards Habitable Planets
Connecting Stellar Abundances & Planet Habitability
Bern, Switzerland 13-17 July 2015

The Hypatia Catalog



Total Stars: 4311

Literature Sources: 117

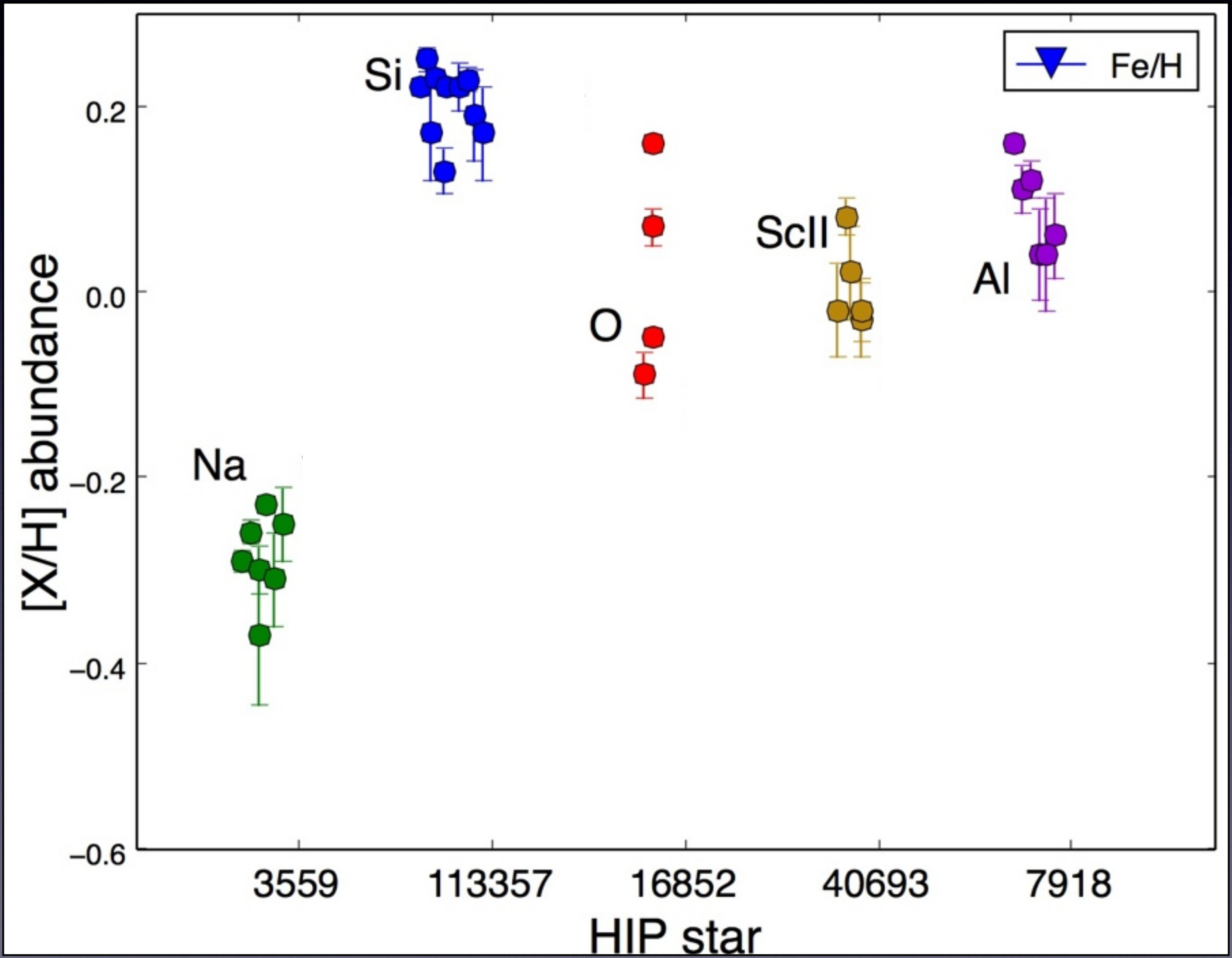
Number of Elements: 53

Compiled spectroscopic abundance determinations for stars in the solar neighborhood from published literature sources (Hinkel et al. 2014, 148, 54, Hinkel et al. 2015 in prep.).

But there are many different methods…

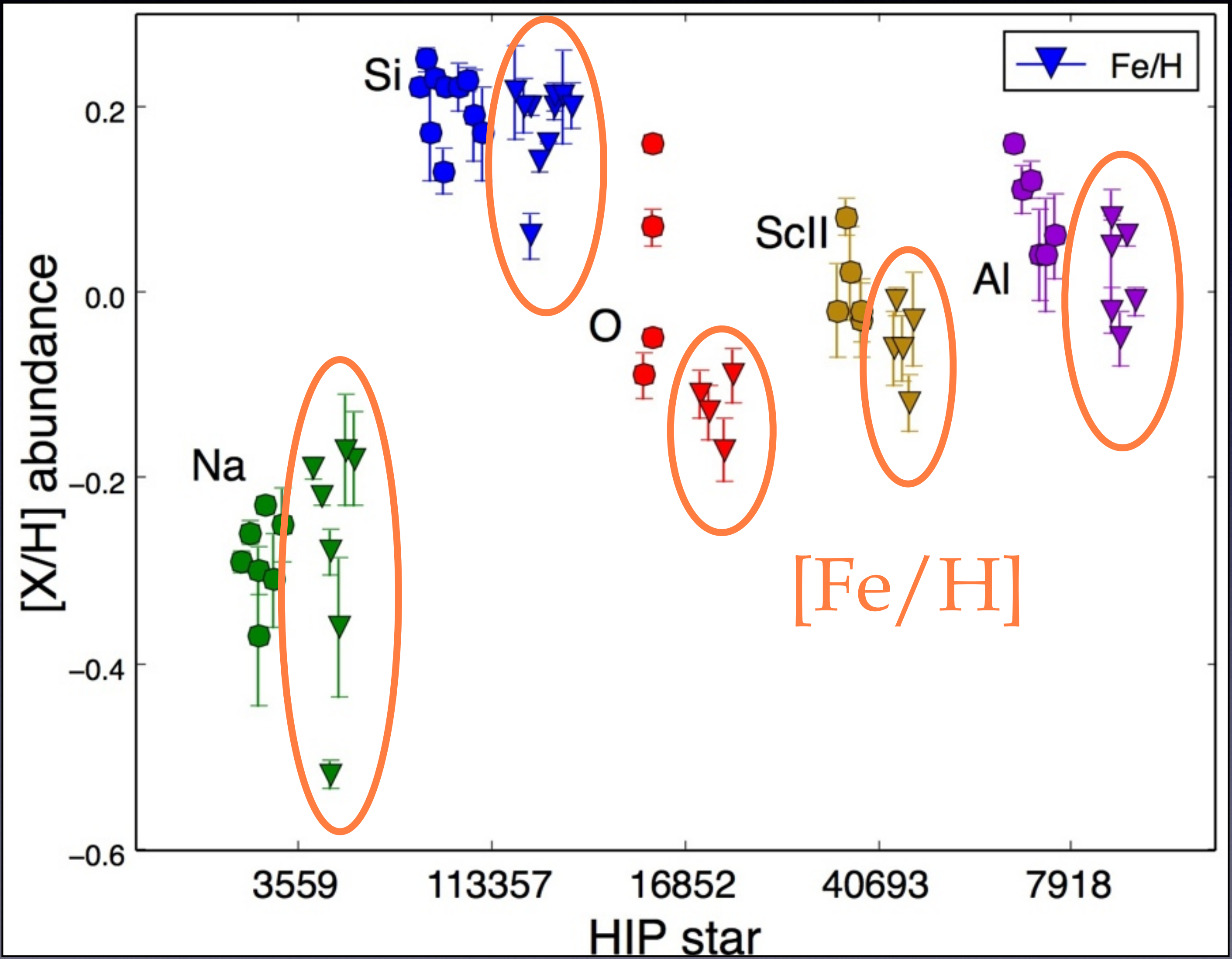
N. Hinkel

The Spread



Fe/H
Si
O
ScII
Al
Na
0.2
0.0
−0.2
−0.4
−0.6
[X/H] abundance
3559
113357
16852
40693
7918
HIP star

The Spread


Fe/H
Si
O
ScII
Al
Na
[Fe/H]
0.2
0.0
−0.2
−0.4
−0.6
[X/H] abundance
3559
113357
16852
40693
7918
HIP star

International Collaboration

ASU held a “Stellar Stoichiometry” Workshop where five groups were given the same spectra to analyze for 4 stars in order to understand how the methods, stellar parameters, & line lists affected the element abundance determinations. Similar to Smiljanic et al (2014), we sought to understand important systematic differences between models (Hinkel et al. in prep).

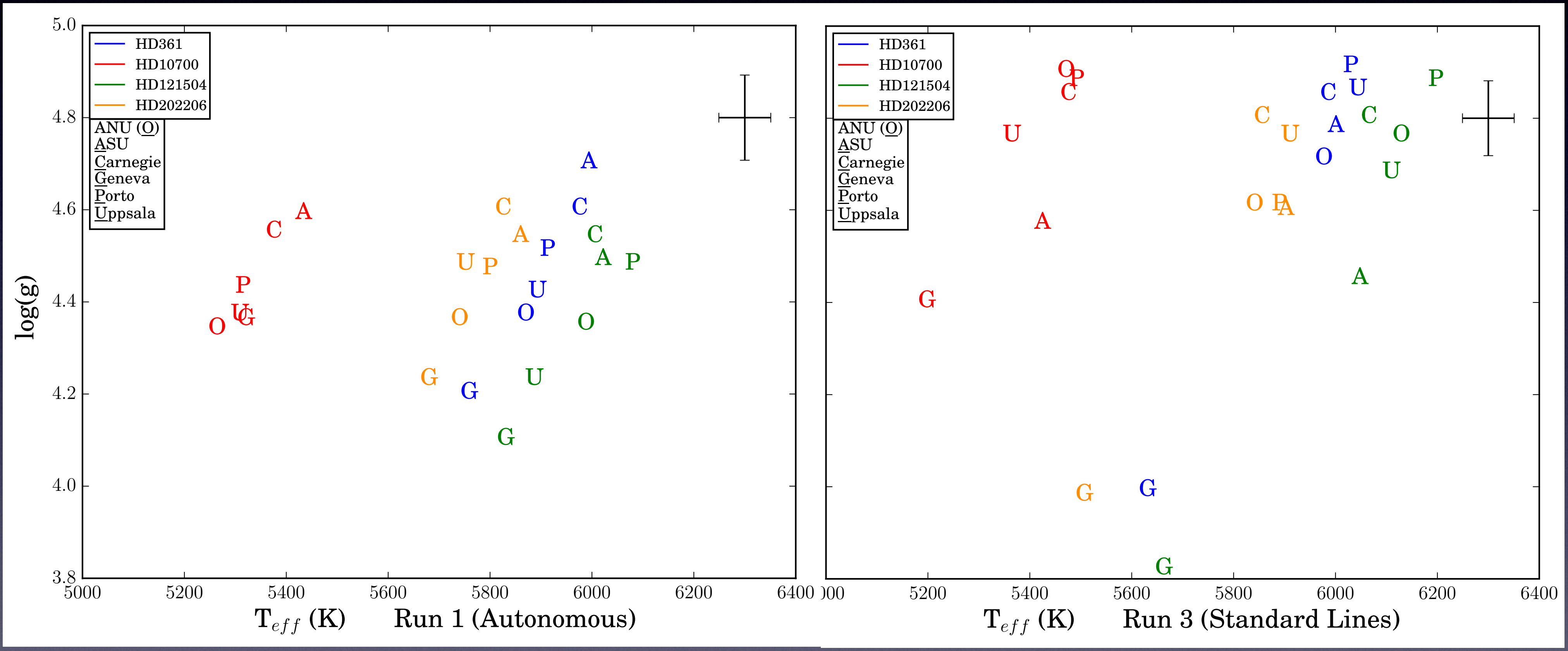
Specifically chose iron-rich to iron-poor stars:
HD 202206, HD 121504, HD 361, HD 10700

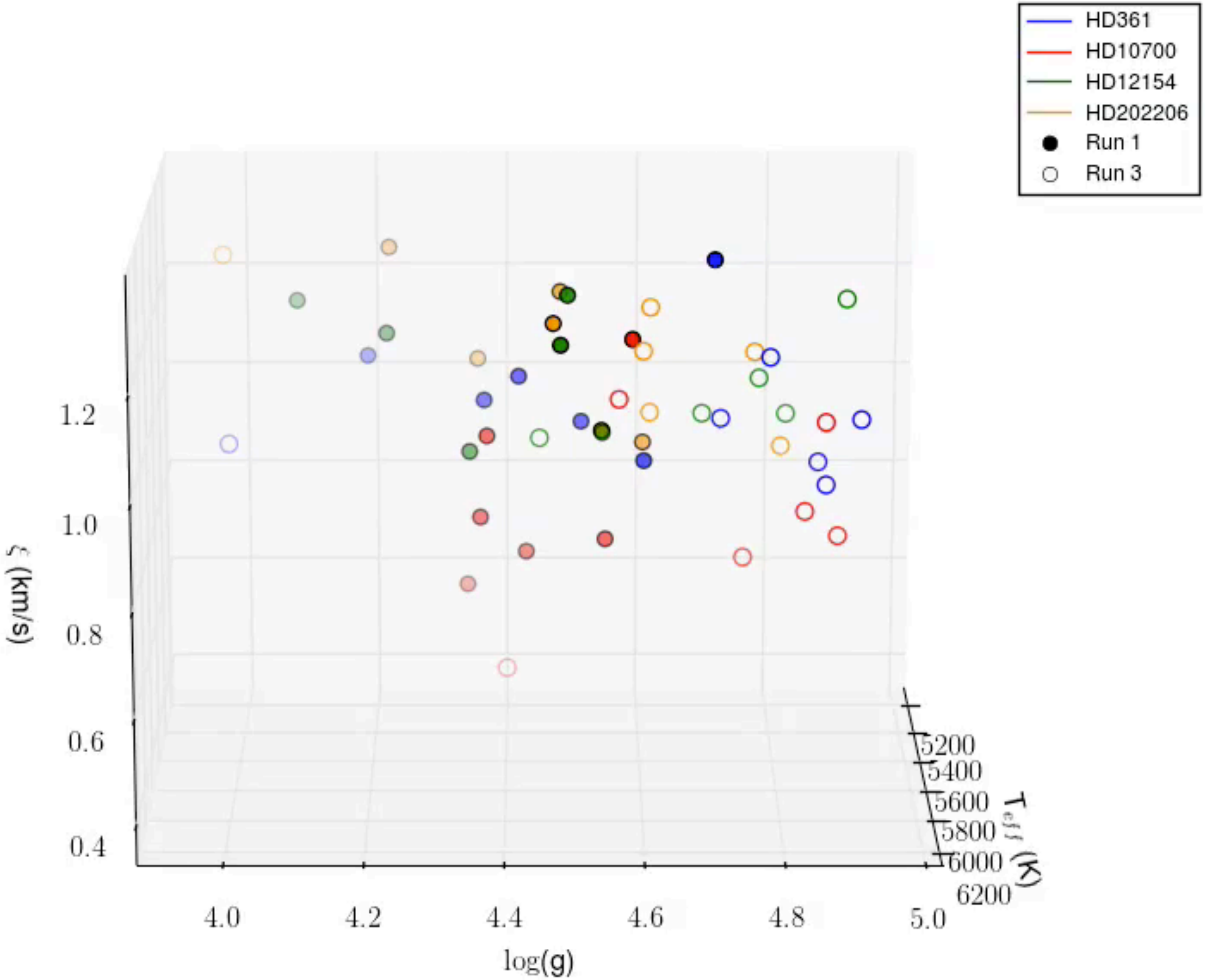
Planet hosts

Models for the Homework

Name	**Stellar Atmo**	**EQ Width**	**CoG/Spec Fit**
ANU	ATLAS9	ARES	MOOG
ASU	ATLAS9	ARES/IRAF	MOOG
Carnegie	MARCS	ARES/IRAF	MOOG
Geneva	MARCS	SPECTRUM	SF via SPECTRUM
Porto	ATLAS9	ARES/IRAF	MOOG
Uppsala	MARCS	SME	SF via SME

Stellar Parameters

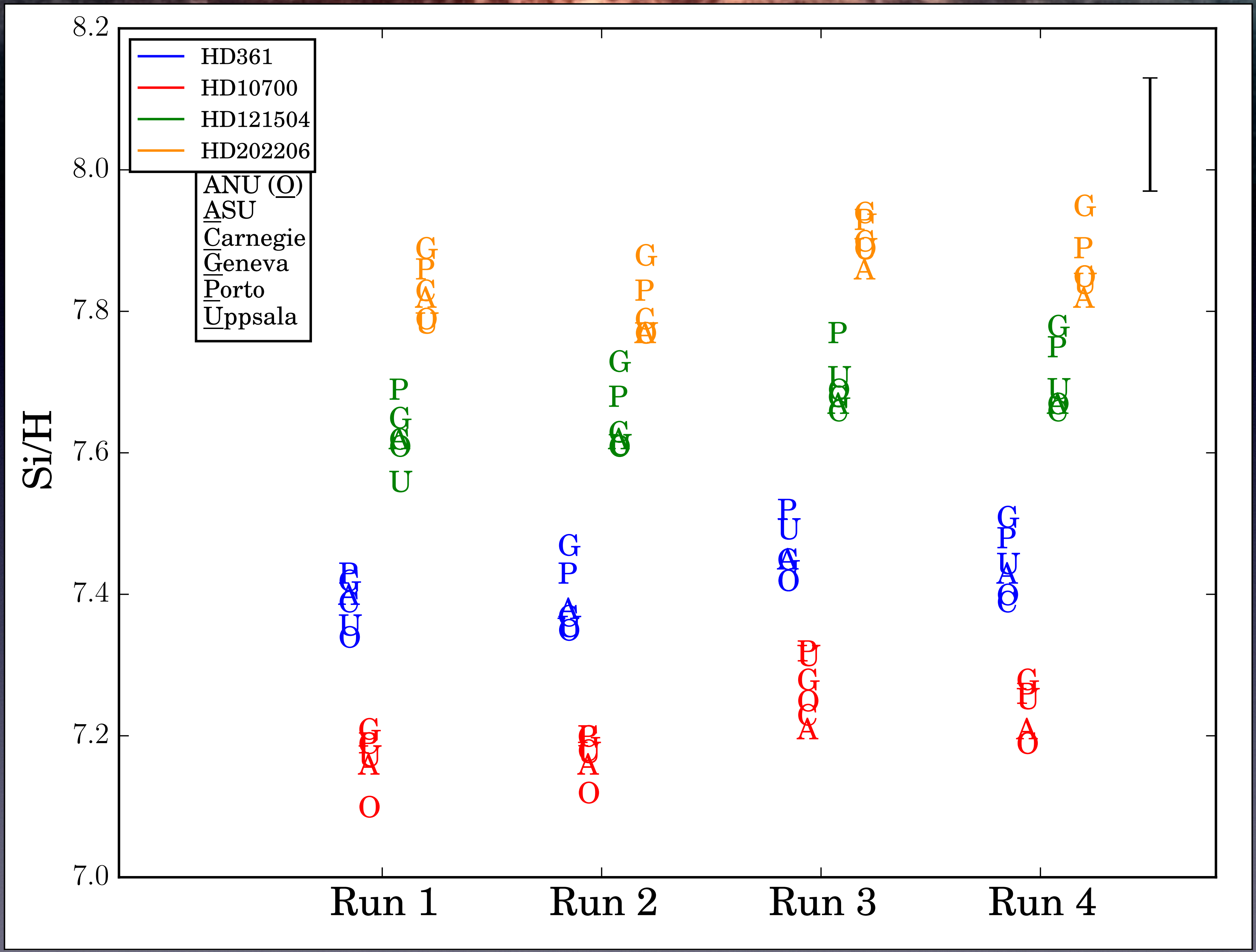



HD361
HD10700
HD12154
HD202206
Run 1
Run 3
ξ (km/s)
1.2
1.0
0.8
0.6
0.4
4.0
4.2
4.4
4.6
4.8
5.0
log(g)
5200
5400
5600
5800
6000
6200
T_{eff} (K)

Parameters Overview

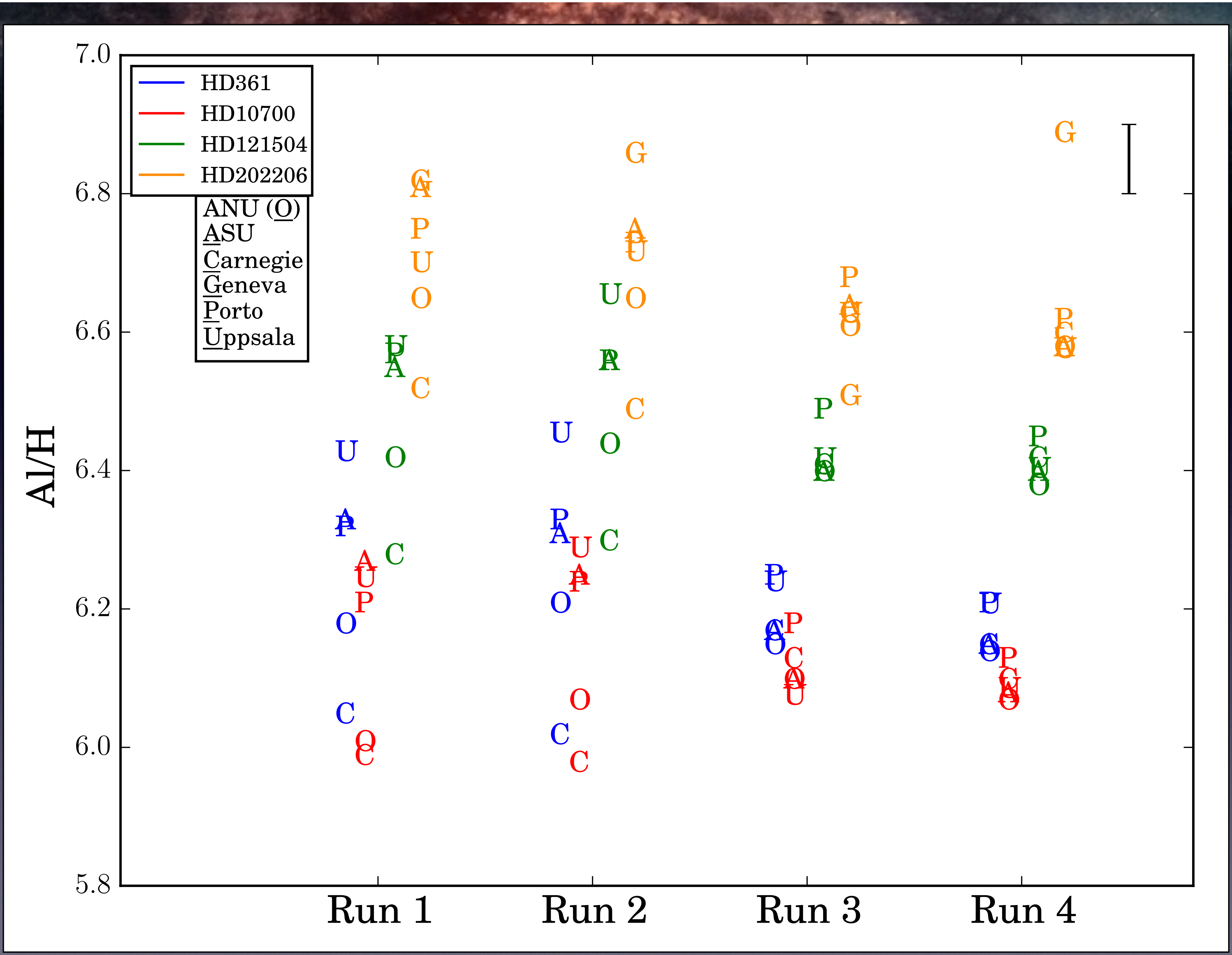
- Both Teff and log(g) varied quite dramatically between Runs 1 and 3. But after outliers were removed, Run 3 has the smallest ranges for all stars.
- There was no noticeable change in ξ between Runs.
- We conclude that the standard line list had a polarizing effect on the methods analyzed in this study – making some calculations more similar and others vastly different.

But what about the abundances…



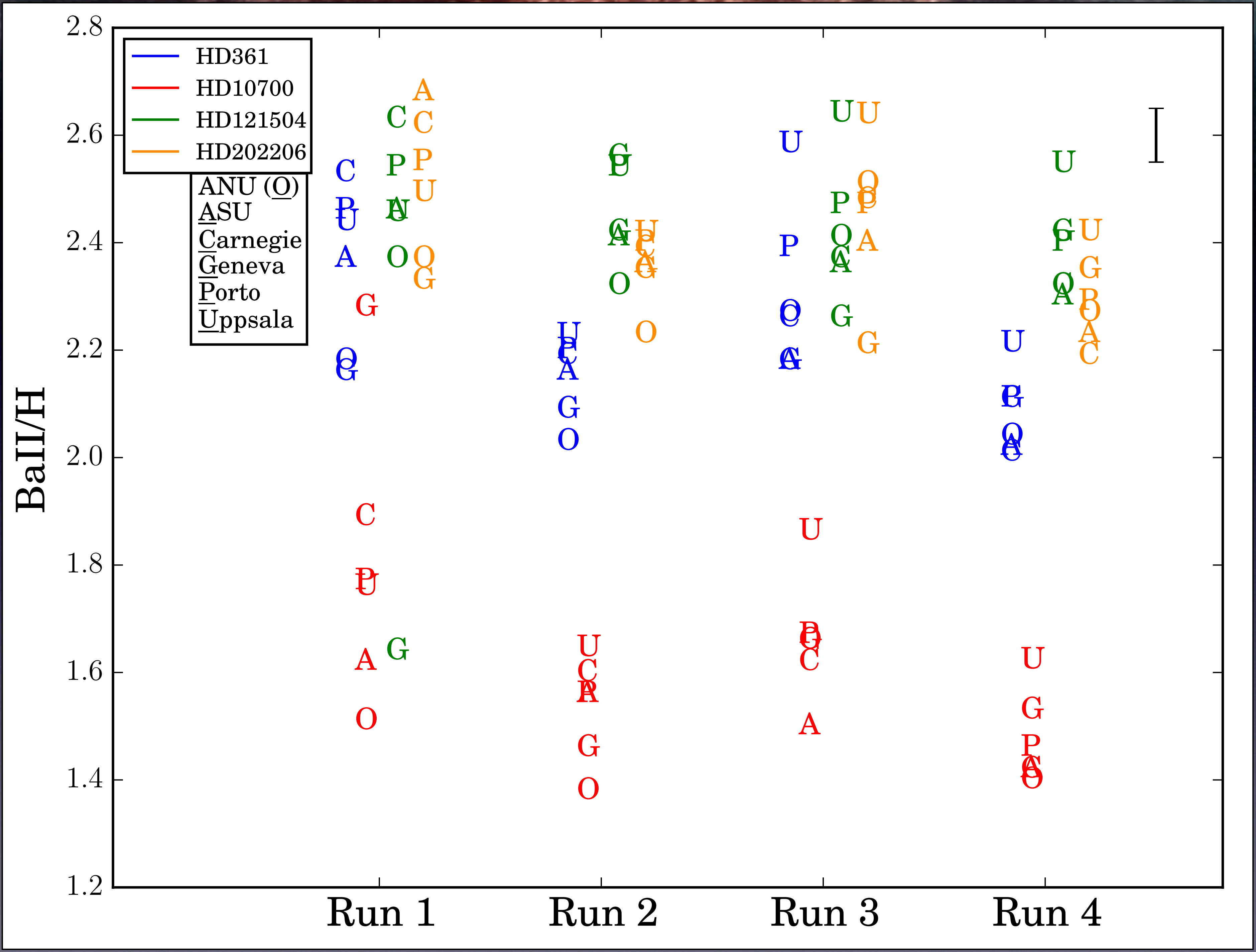
Autonomous Std. Params Std. Lines Std. Params/Lines

N. Hinkel



Autonomous Std. Params Std. Lines Std. Params/Lines

N. Hinkel



Autonomous Std. Params Std. Lines Std. Params/Lines

Elements Overview

α-elements (C, O, Mg, Si) respond very well to the standardized line list.

Odd-Z elements (Na, Al) also showed the most improvement when using the line list.

Iron-Peak (Ni, Fe) had almost no change during the different runs (although both had ranges > error).

Neutron-Capture (BaII, EuII) had unusual dispersion and requires special attention.

In general, any standardization helps!

Summary

Stellar abundances are complicated, by definition. But there are significant issues between datasets due to different techniques, which have not been addressed -- so we see a *spread* in the data. Our measurement techniques need to be more transparent if we are to understand the effects of planets on stellar compositions.

Partial solution: In conjunction with benchmark stars, create a database of EWs measured per star so obvious outlier lines can be identified.

Pathways 2015:Pathways towards habitable planets

13-17 July 2015
Bern, Switzerland

Behaviour of Elements from Lithium to Europium in Stars with [Fe/H] > -0.5

Tamara Mishenina

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Shevchenko Park, 65014, Odessa, Ukraine

Aims

Independent assessment of correlation between the presence of planets and chemical composition of stars.

- Database: about 500 dwarfs and giants to study of chemical and dynamical evolution of the Galaxy (Mishenina et al. 2004, 2006, 2008, 2012, 2013) with collaboration of Caroline Soubiran (Observatoire de Bordeaux, France).

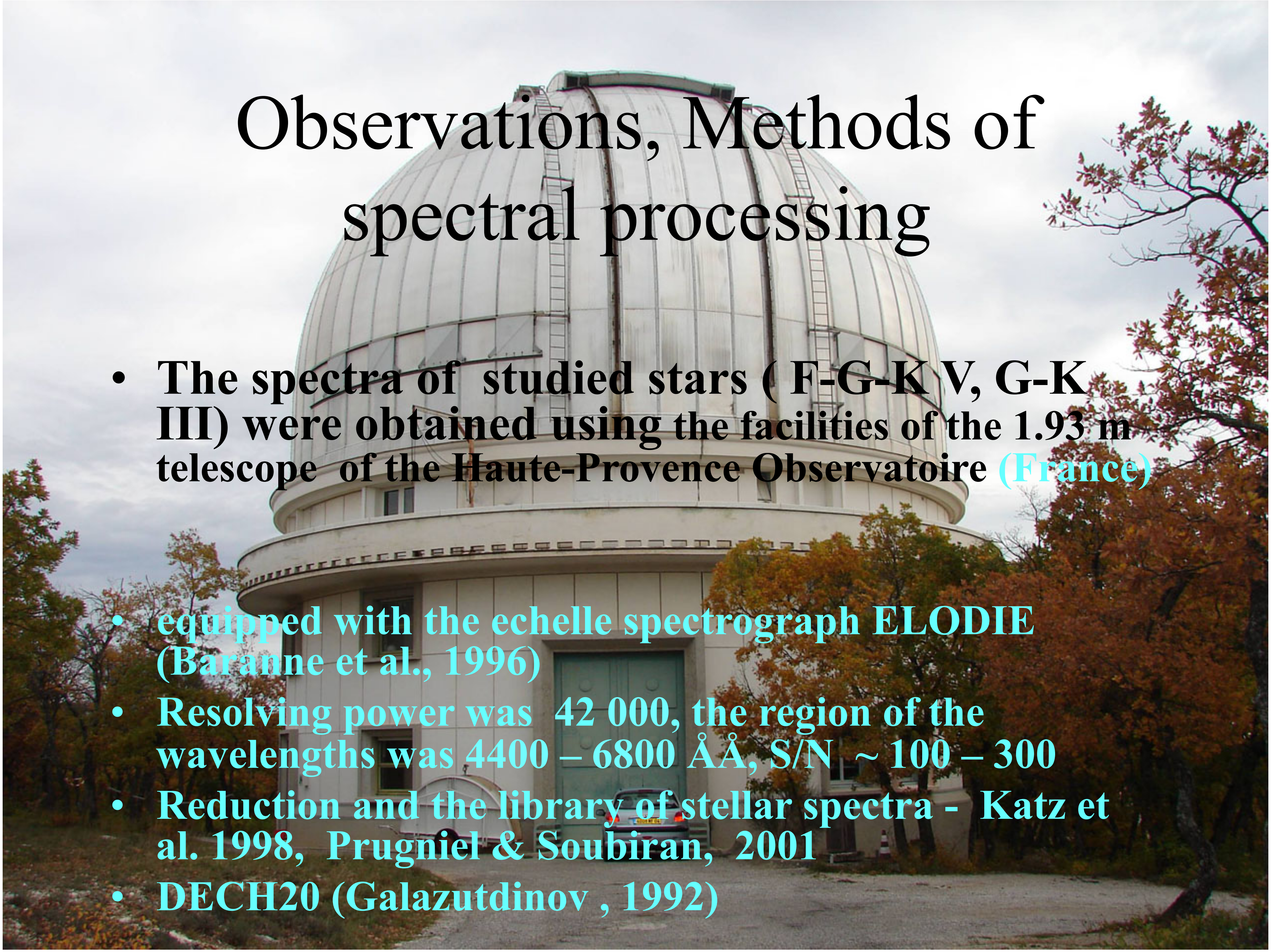
Selected:

- the dwarfs with Teff in the range of 5500 – 6200 K and [Fe/H] from -0.5 dex from our database;

- planet-hosting stars from Catalog - Schneider et al. (2011).

HD	Teff	log g	[Fe/H]	Planet	Mass (Mjup)
3651	5277	4,5	0,15	HD 3651 b	0,2
7924	5165	4,4	-0,22	HD 7924 d	0,0203
				HD 7924 c	0,0247
				HD 7924 b	0,0273
9826	6074	4	0,1	ups And c	1,8
				ups And d	10,19
				ups And b	0,62
38858	5776	4,3	-0,23	HD 38858 b	0,0961
87883	5015	4,4	0	HD 87883 b	12,1
95128	5887	4,3	0,01	47 Uma d	1,64
				47 Uma c	0,54
97658	5136	4,5	-0,32	HD 97658 b	0,02375
128311	4960	4,4	0,03	HD 128311 c	3,21
145675	5406	4,5	0,32	14 Her b	4,64
154345	5503	4,3	-0,21	HD 154345 b	1
156668	4850	4,2	-0,07	HD 156668 b	0,0131
186427	5752	4,2	0,02	16 Cyg B b	1,68
189733	5818	4,3	-0,03	HD 189733 b	1,138
217014	5778	4,2	0,14	51 Peg b	0,46

Observations, Methods of spectral processing



- **The spectra of studied stars (F-G-K V, G-K III) were obtained using the facilities of the 1.93 m telescope of the Haute-Provence Observatoire (France)**

- **equipped with the echelle spectrograph ELODIE (Baranne et al., 1996)**
- **Resolving power was 42 000, the region of the wavelengths was 4400 – 6800 ÅÅ, S/N ~ 100 – 300**
- **Reduction and the library of stellar spectra - Katz et al. 1998, Prugniel & Soubiran, 2001**
- **DECH20 (Galazutdinov , 1992)**

Parameter determination

- T_{eff} were estimated by the line depth ratio R_1/R_2 method (Kovtyukh V.V.),
- dT_{eff} = ~± 10 K for dwarfs

- **[Fe/H]** – iron abundance determined from Fe I lines

NLTE corrections do not exceed 0.1 dex (Mashonkina et al. 2011)

- **log g** for dwarfs:two methods (iron ionisation balance and using parallaxes)
  $\langle \log g_{IE} - \log g_P \rangle = -0.06 \pm 0.16$ (T_{eff} > 5000 K, 80 stars)
- ($\log g_P$ - Allende Prieto et al., 1999)
- **V_t** – independence of log A(Fe) from EW for Fe I lines
-

Error parameter determination

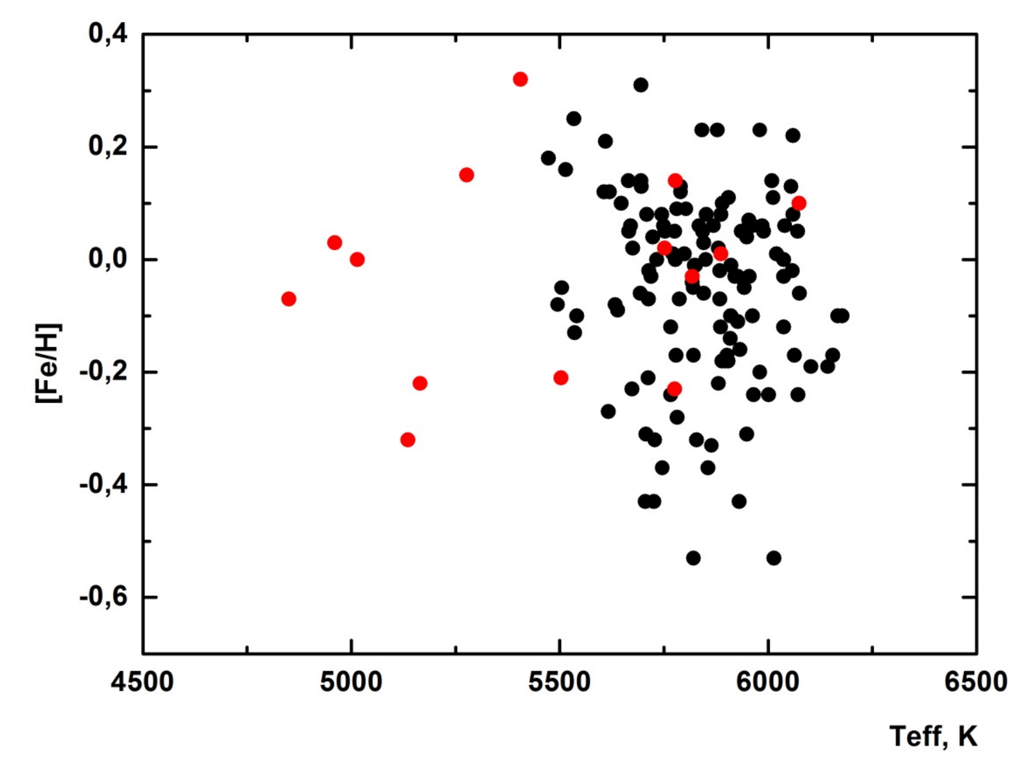
ΔT_{eff} = ±100 K; Δlog g = ±0.2 dex;
ΔV_t = ±0.2 km/s; Δ [Fe/H]= ±0.25 and
an uncertainty of ±2 mA in the EW
an uncertainty of 0.02 dex in fitting of profiles

Abundance determination

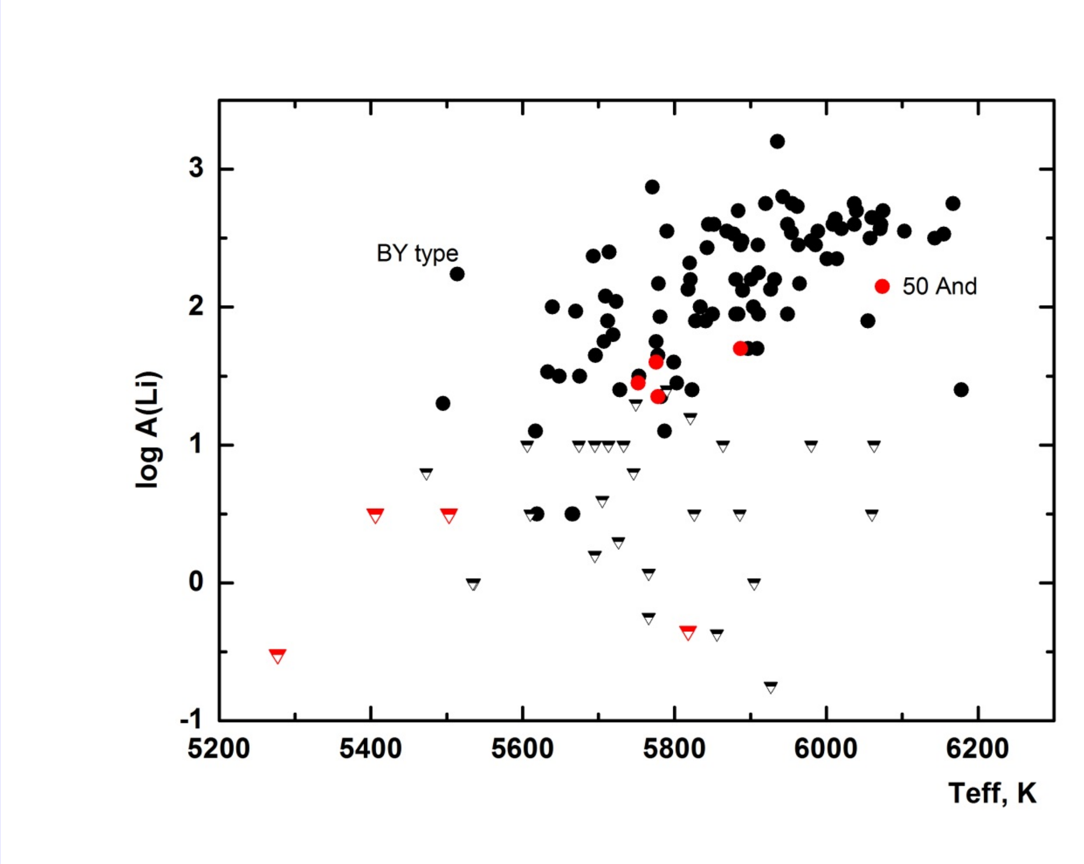
- **Kurucz's models (LTE);**
- **WIDTH9, LTE (Kurucz R.) – Si, Ca, Ni, Fe, Zn, Y, Zr, La, Ce, Pr, Nd, Sm;**
- **STARSP, LTE (new version) (Tsymbal V. , 1996) – Li, O, S, Eu (HFS);**
- **Modified MULTI, NLTE (Carlsson M., Korotin S.) – Na, Al, Mg, and Ba.**
- Differential approach: the spectra of Moon and asteroids obtained with ELODIE as solar spectrum.
- The total uncertainty due to parameter and EW errors for Fe I, Fe II is 0.10, 0.12, respectively.
- The sulfur abundances in all investigated stars, as well as the lithium abundances in some of them, were specially determined for this report. The determination accuracy varies from 0.1 to 0.2 dex.

Our target stars in [Fe/H] vs. Teff

(red — with planets, black — without detected planets)



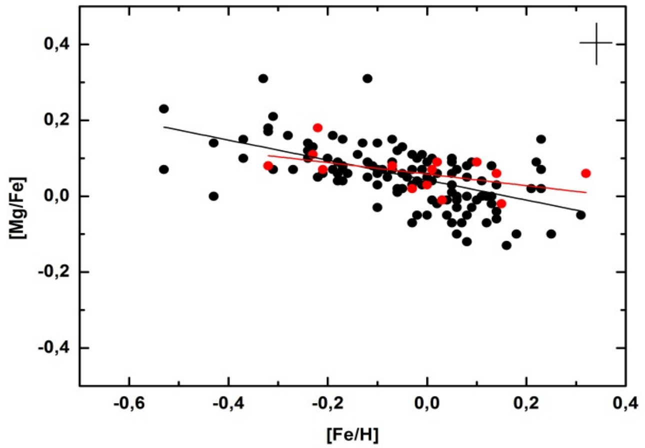
Lithium

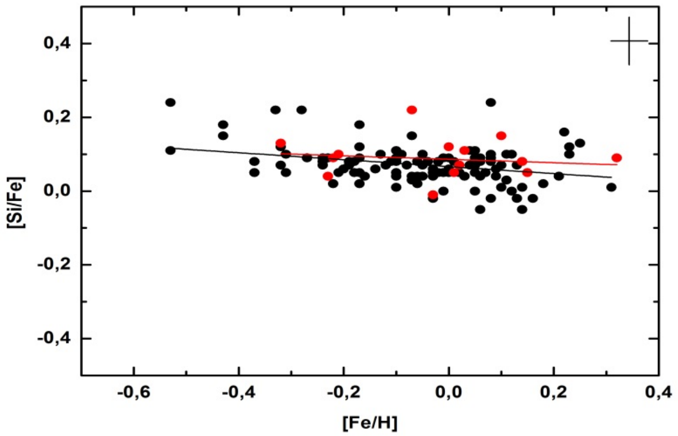


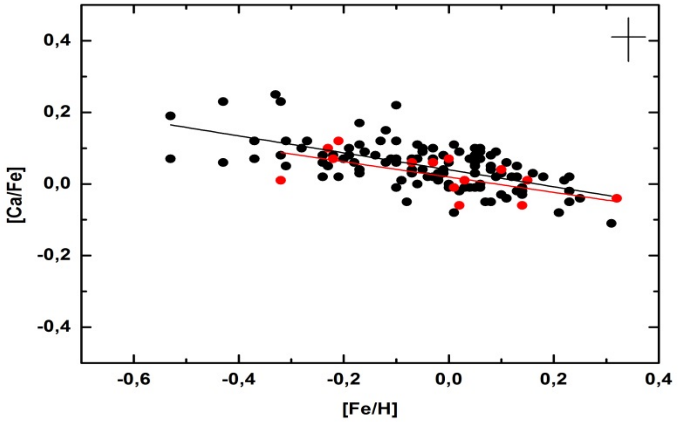
Underabundance of Li was associated with the presence of planets: Gonzalez & Laws (2000), Gonzales et al. (2008, 2010), Israelian et al. (2004, 2009), Delgado Mena et al.(2013), Figueira et al.(2014) etc. **Error in Li abundance**: Figueira et al. (2014).

Li in the planet-hosting stars is lower than in other dwarfs.

α-elements

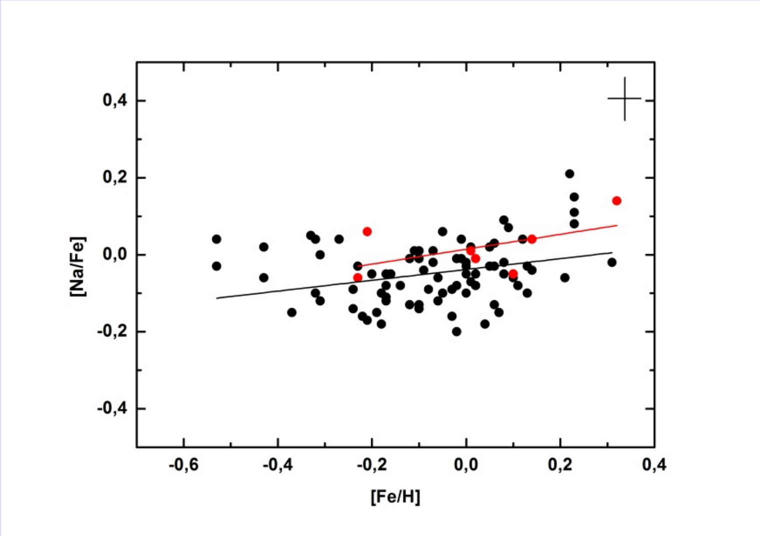


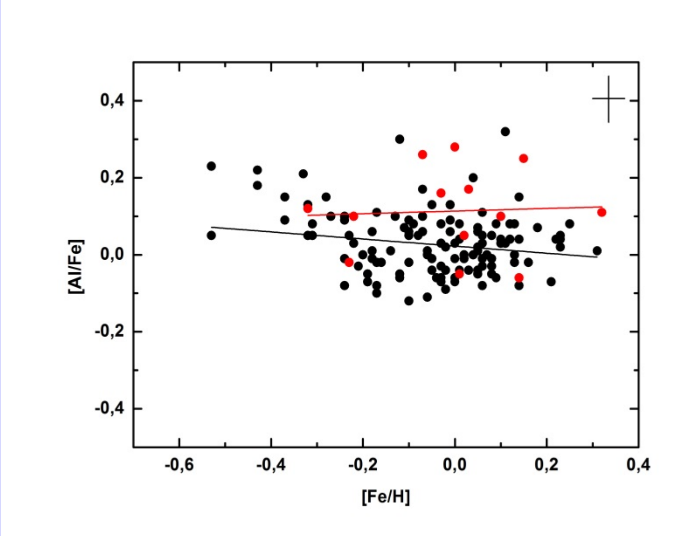




There are no significant differences between α-element abundances in stars with and without planets.

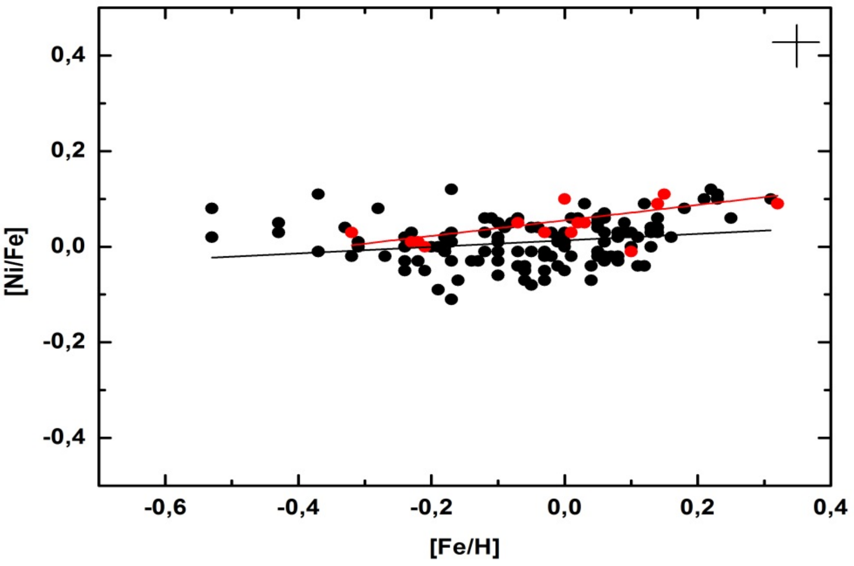
Na, Al





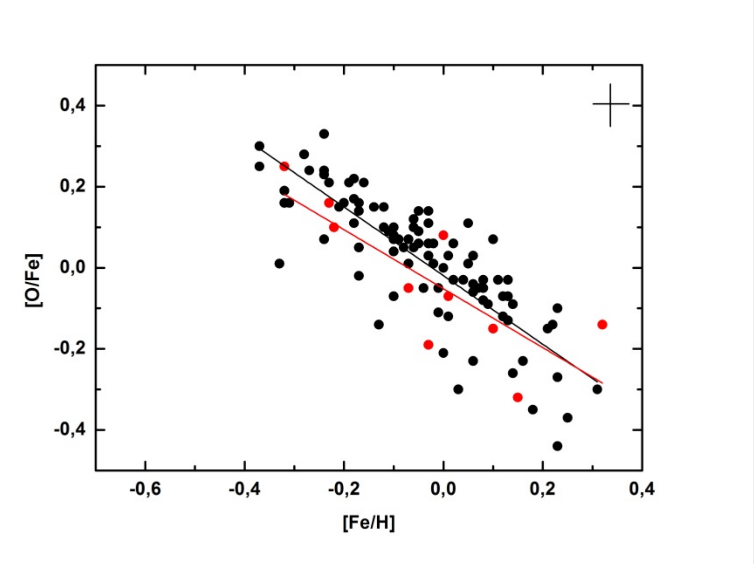
We observed some difference between abundances in stars with planets and without them, that is in the limits of determination errors.

Iron peak element Ni

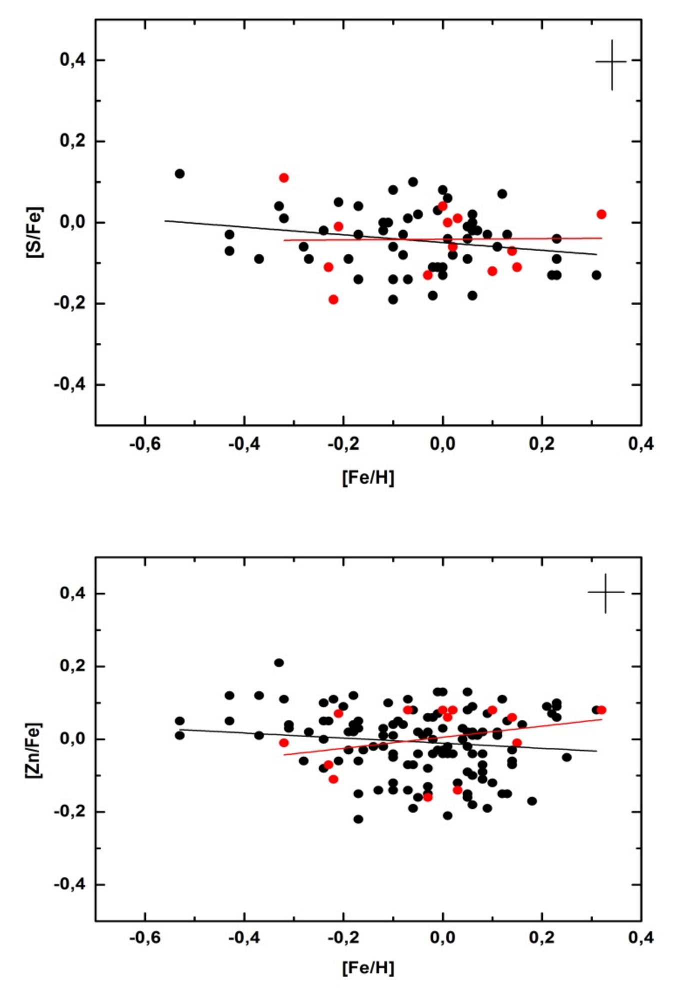


We see no significant difference either.

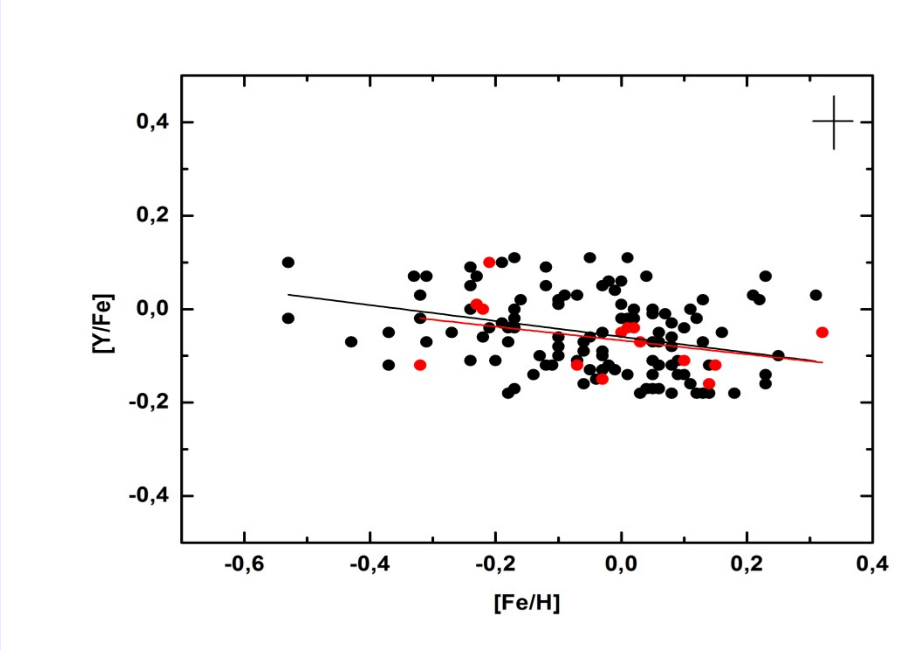
O, S, Zn



We cannot confidently support the hypothesis of their underabundance in the stars with planets.

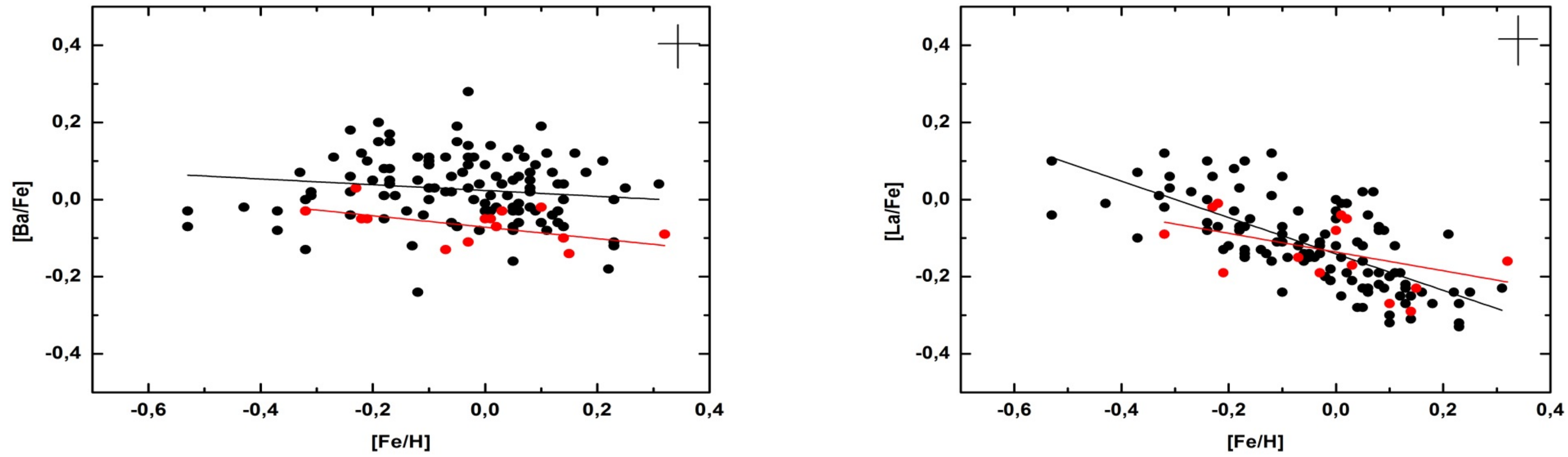


n-capture elements



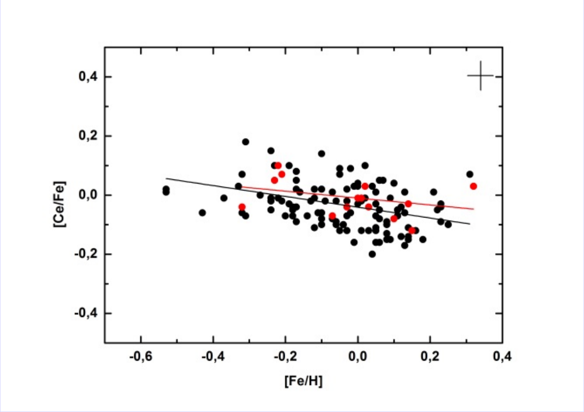
- [Y/Fe] do not show a different trends with [Fe/H] for stars with and without planets.

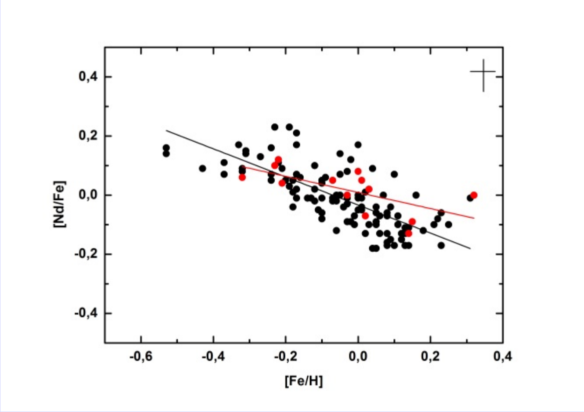
n-capture elements



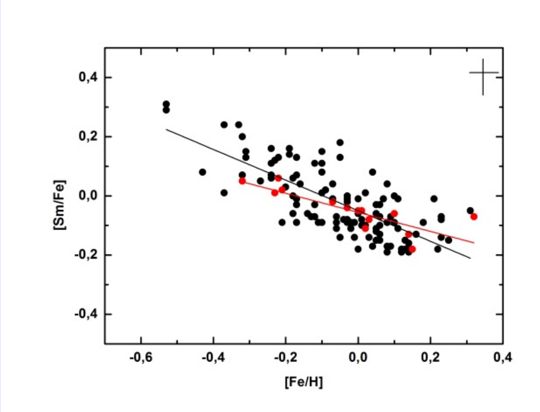
Barium shows a different behaviour in the stars with and without planets.
It requires further verification.

n-capture elements

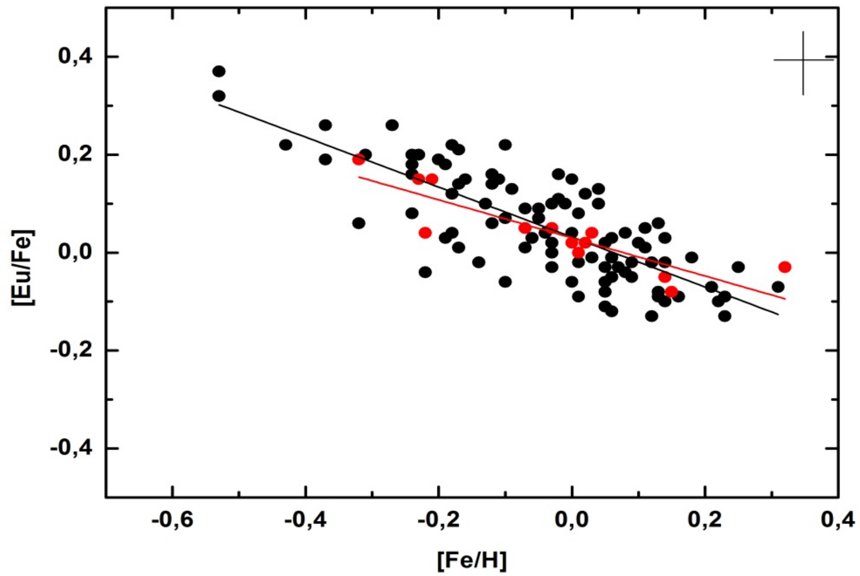




The neutron-capture elements show no significant differences in trends which are within the determination errors.



Abundance of r-process element Eu vs. [Fe/H]



Europium, the element
med predominantly
-process (80 – 90 %
olar abundance),
ws a marked trend
h [Fe/H] and no
ference for stars with
without planets.

Connection with chemical enrichment of different galactic substructures

– 14 selected planet-hosting stars are **thin disk stars;**

– All comparisons were made for the stars of **the thin disk;**

– Belonging of stars to the galactic substructures (thin and thick disks and halo) was made by kinematic criteria;

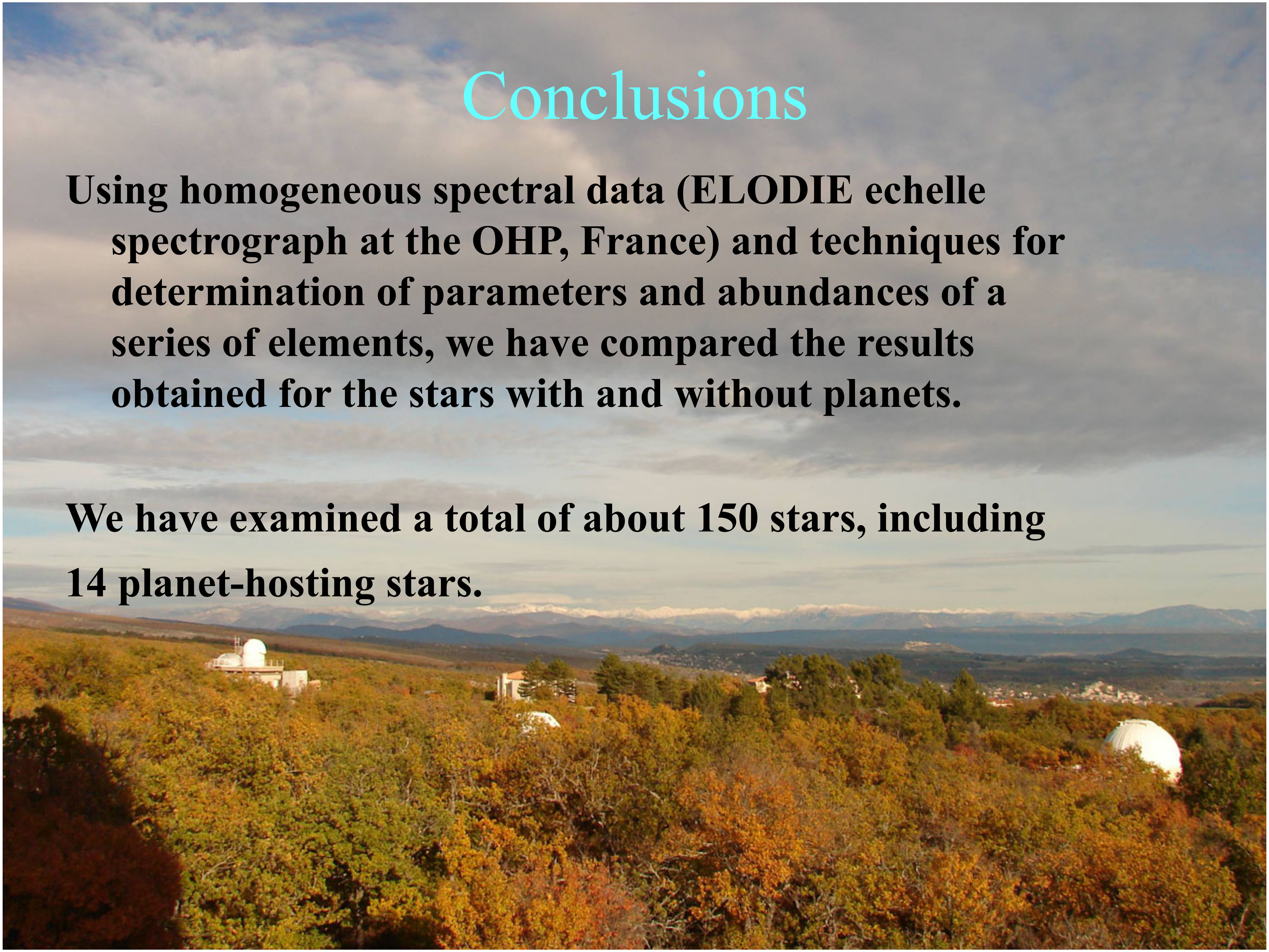
– The difference in the behaviour of Ba in stars with and without planets could be interpreted as a consequence of the Ba abundance depending on the age in the galactic disk (e.g. Bensby et al.2007). But:

contra - no clear relationship of barium abundances on the age in the thin disc (Mishenina et al. 2013), it is due to the dispersion of [Fe/H] in the thin disc;

per - 5 planet-hosting stars we were able to determine the age, they are not the young stars, their ages are from 5 to 9 Gyr;

contra – only 5 planet-hosting stars;

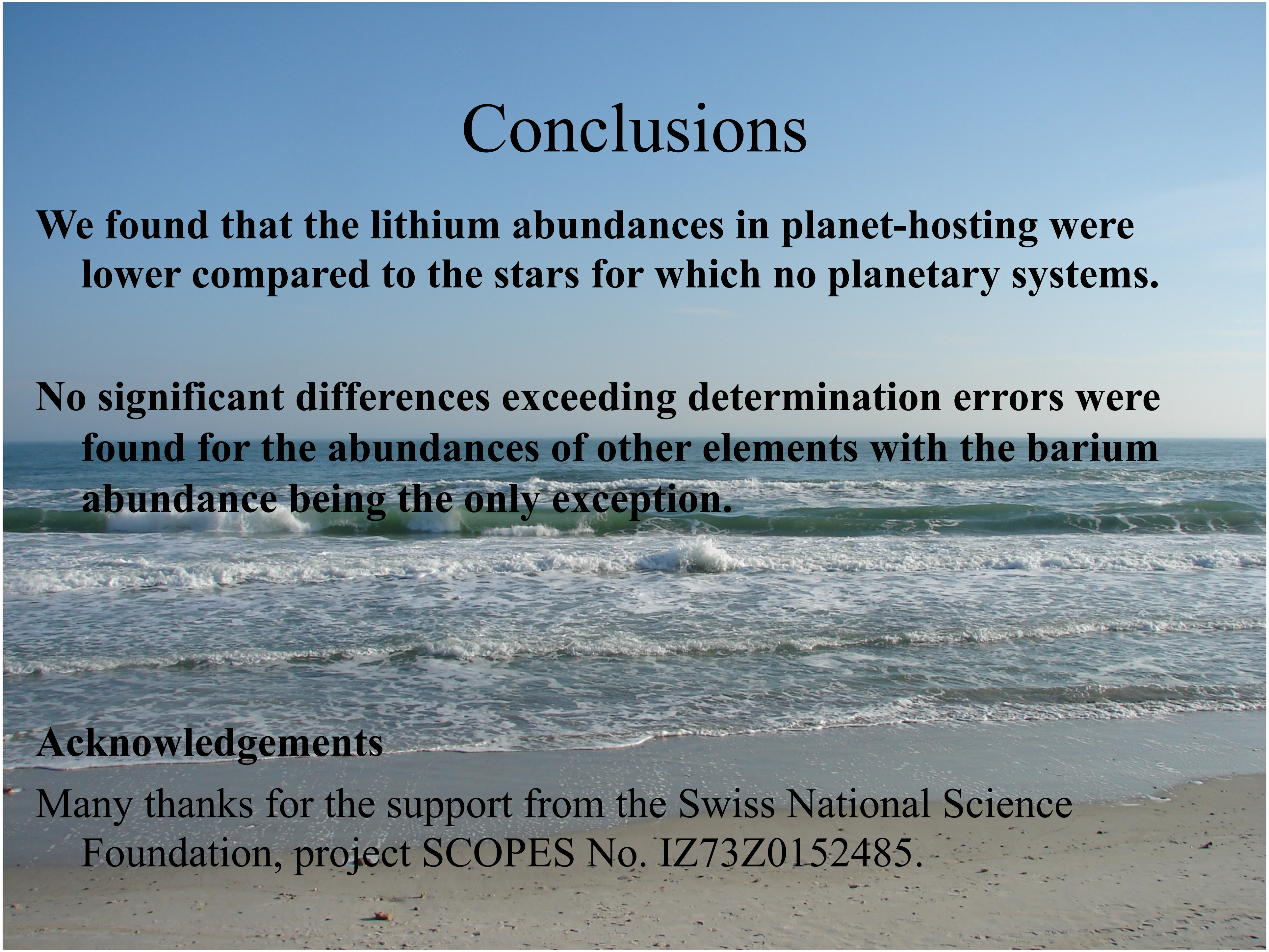
per – Ba abundances in OC stars show the trend with age and significant spread .



Conclusions

Using homogeneous spectral data (ELODIE echelle spectrograph at the OHP, France) and techniques for determination of parameters and abundances of a series of elements, we have compared the results obtained for the stars with and without planets.

We have examined a total of about 150 stars, including 14 planet-hosting stars.



Conclusions

We found that the lithium abundances in planet-hosting were lower compared to the stars for which no planetary systems.

No significant differences exceeding determination errors were found for the abundances of other elements with the barium abundance being the only exception.

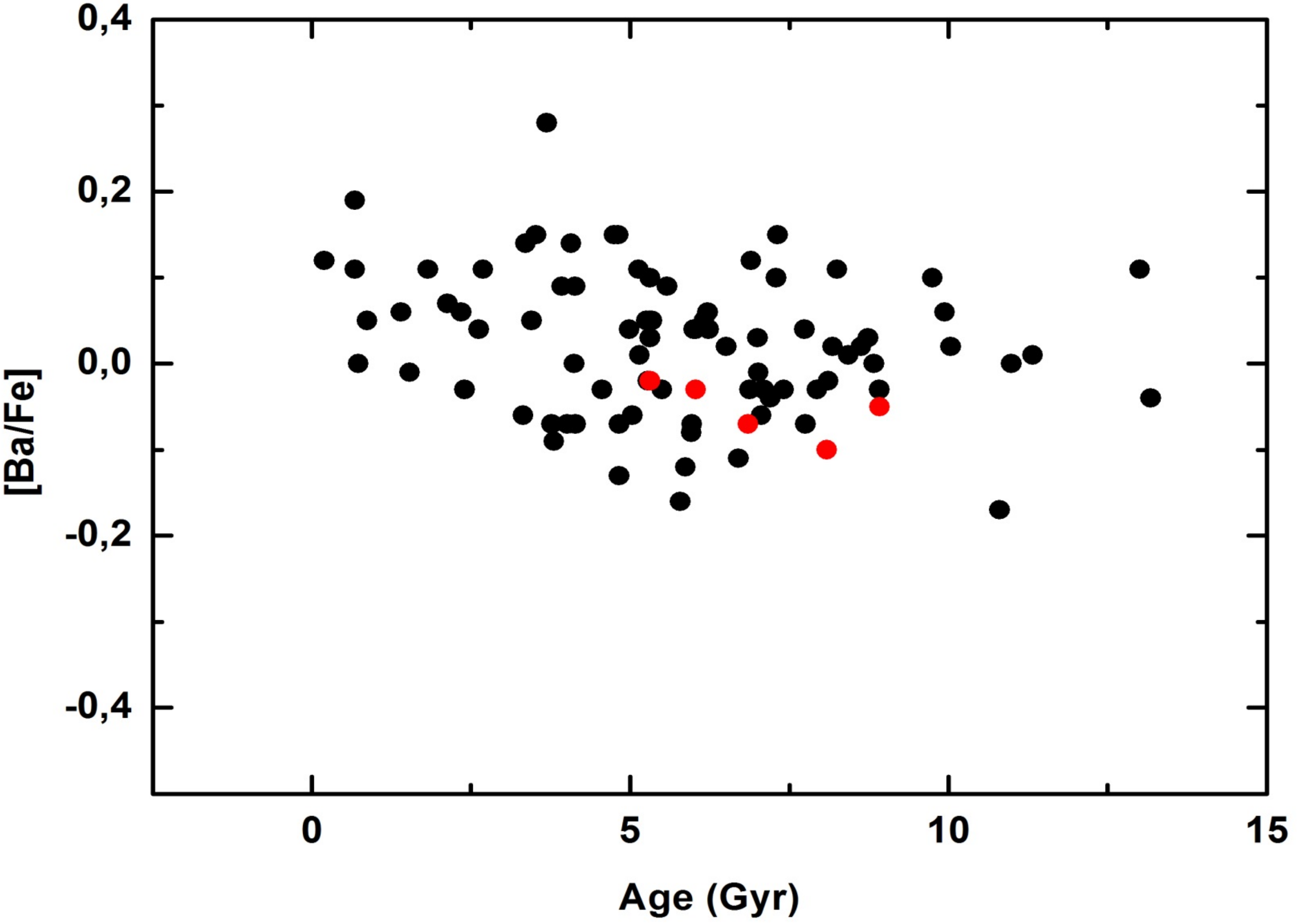
Acknowledgements

Many thanks for the support from the Swiss National Science Foundation, project SCOPES No. IZ73Z0152485.

Co-authors:

- **Basak N.Yu., Belik S.I., Bieneyme O., Gorbaneva T.I., Kovtyukh V.V., Korotin S.A., Paramonova O., Pignatari M., Soubiran C., Usenko I.A.**

- **Thank for you attention!**


0,4
0,2
0,0
-0,2
-0,4
[Ba/Fe]
0
5
10
15
Age (Gyr)

Barium abundances as diagnostics of stellar youth

Valentina D'Orazi

INAF Padova
Macquarie University
Monash Centre for Astrophysics

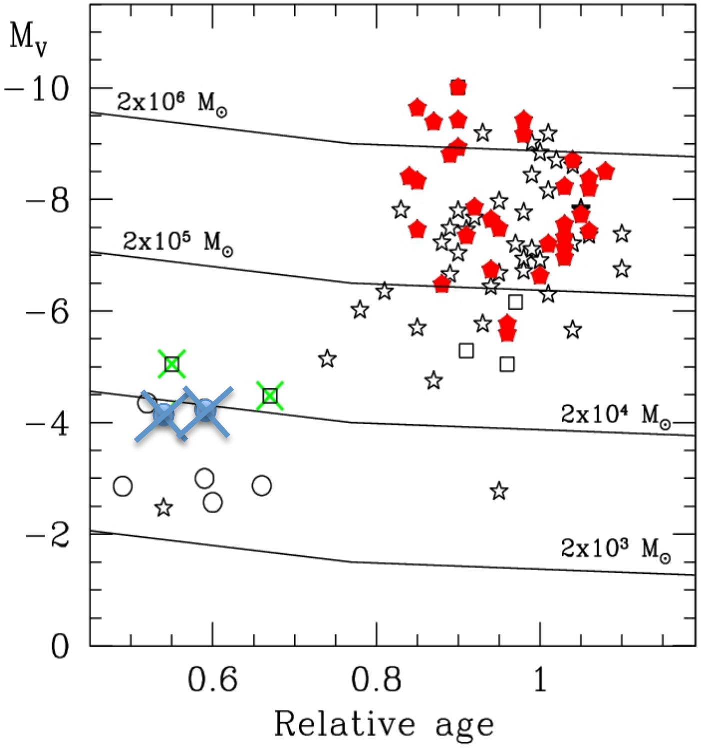
Colls: S. Desidera, R. Gratton, S. Andrievsky, G. de Silva, C. Melo, M. Lugaro, A. Vigan and many more….

Pathways2015 - Connecting Stellar Abundances and Planet Habitability
Bern, 13th July 2015

Simple Stellar Populations: OPEN CLUSTERS

Open clusters *DO NOT* exhibit an age-metallicity relation → old, super-solar metallicity open clusters + young sub-solar metallicity clusters → the birthplace is more important than when the OC formed in terms of disk chemical evolution imprinted on these stars (RADIAL METALLICITY GRADIENT)

Other elements (α-, light, and Fe-peak elements) follow the iron very well, with OCs having [X/Fe] ratios independent on cluster age and galactocentric radius



Open Clusters are known NOT to exhibit the proton-capture element variations
(e.g., De Silva et al. 2009)

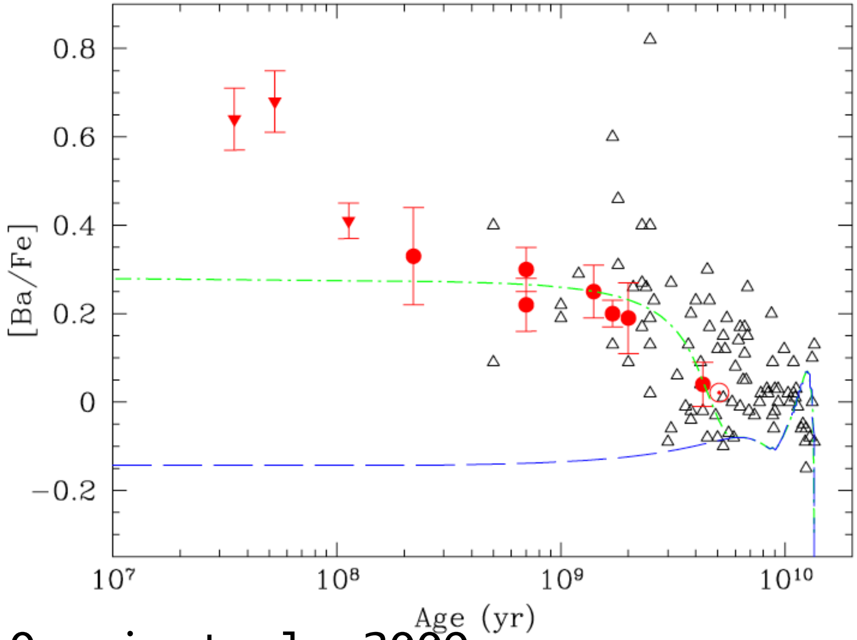
GCs with Na-O anticorrelation

Terzan 7 and Palomar 12

The Open clusters Berkeley 39 and NGC 6791 (Bragaglia et al. 2012, 2014)

However exciting results from the *n*-capture elements

Trend of increasing [Ba/Fe] with decreasing open cluster's age



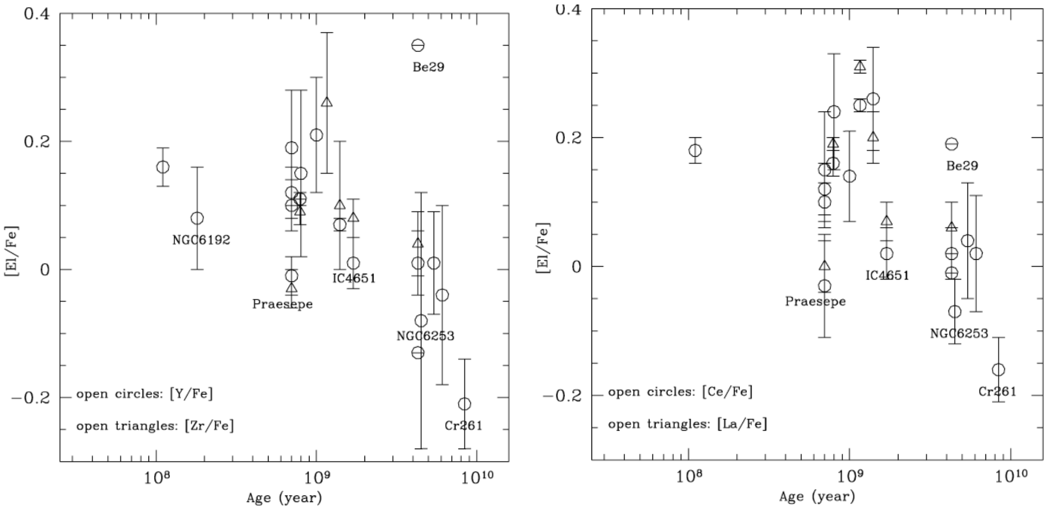
D'Orazi et al. 2009

Galactic chemical evolution model only assuming a higher Ba yield from low-mass AGB stars (i.e. ~1-1.5 $M_{\odot}$) than that previously predicted

While a chemical evolution model with enhanced Ba production can account for the observed raising trend up to ~500 Myr, it dramatically fails in reproducing the young stellar clusters (possible NLTE due to chromospheric activity, D'Orazi et al. 2012)

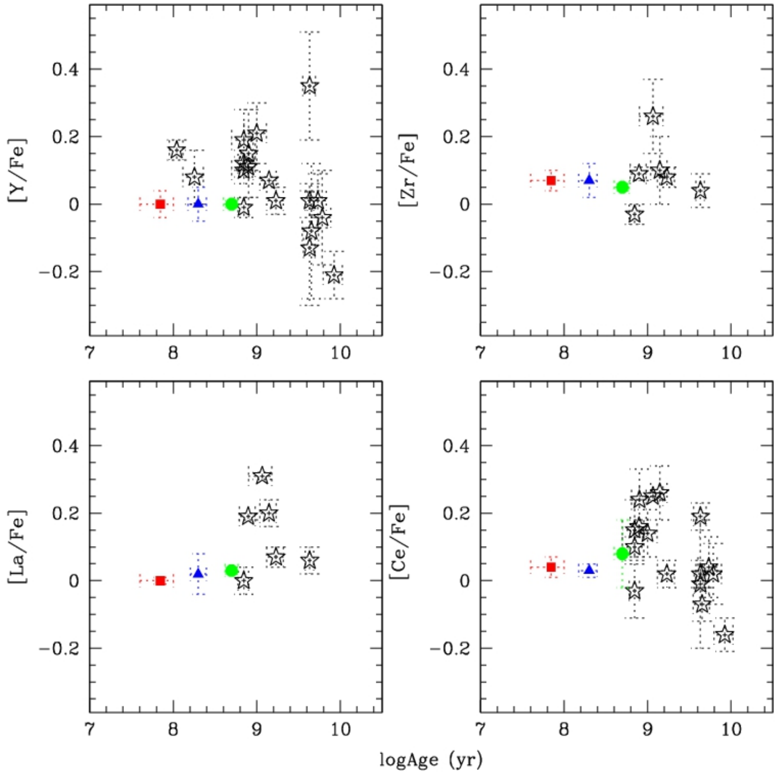
Do the other *s*-process elements follow the enhancement in Ba?

Maiorca et al. (2011):
Y, Ce, Zr, La analogous trend

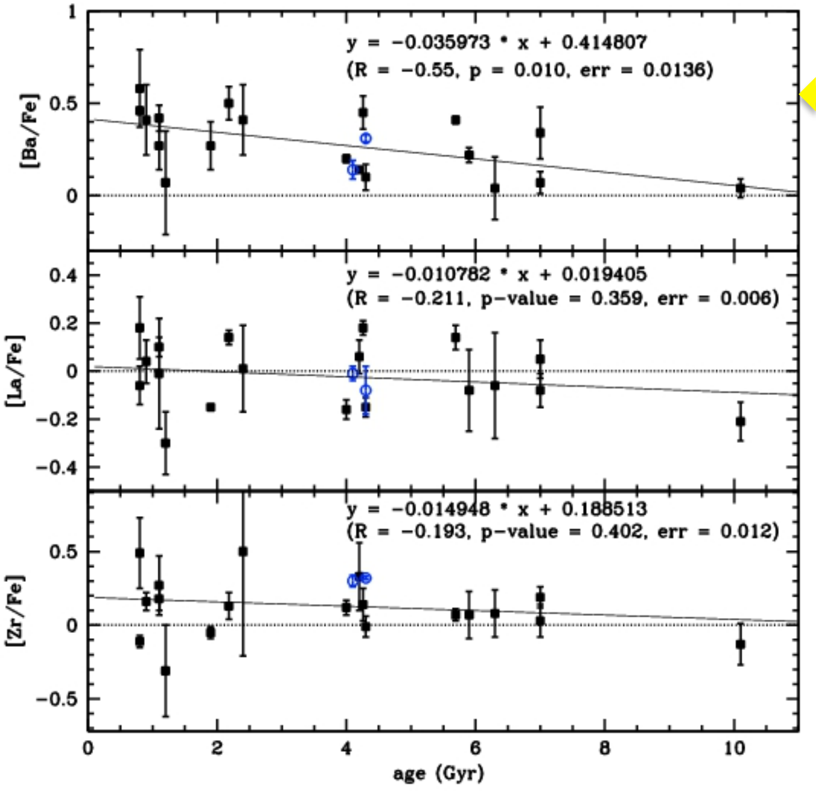


D’Orazi et al. (2012):
NO trends for Y, Zr, La and Ce

Yong et al. (2012) from 11 OCs confirmed trend for Ba (and perhaps Zr), but no for Ce and/or La (even opposite than Maiorca’s results)



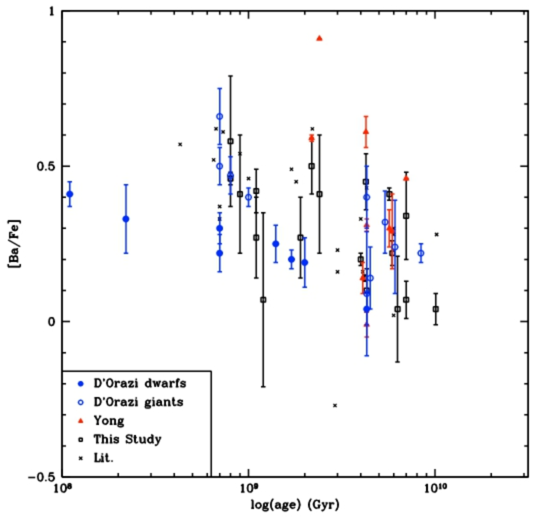
s-process element trends with OC ages



Data show a statistically significant trend of increasing [Ba/Fe] with decreasing age as in D’Orazi+(2009) (and then found by Yong+12)

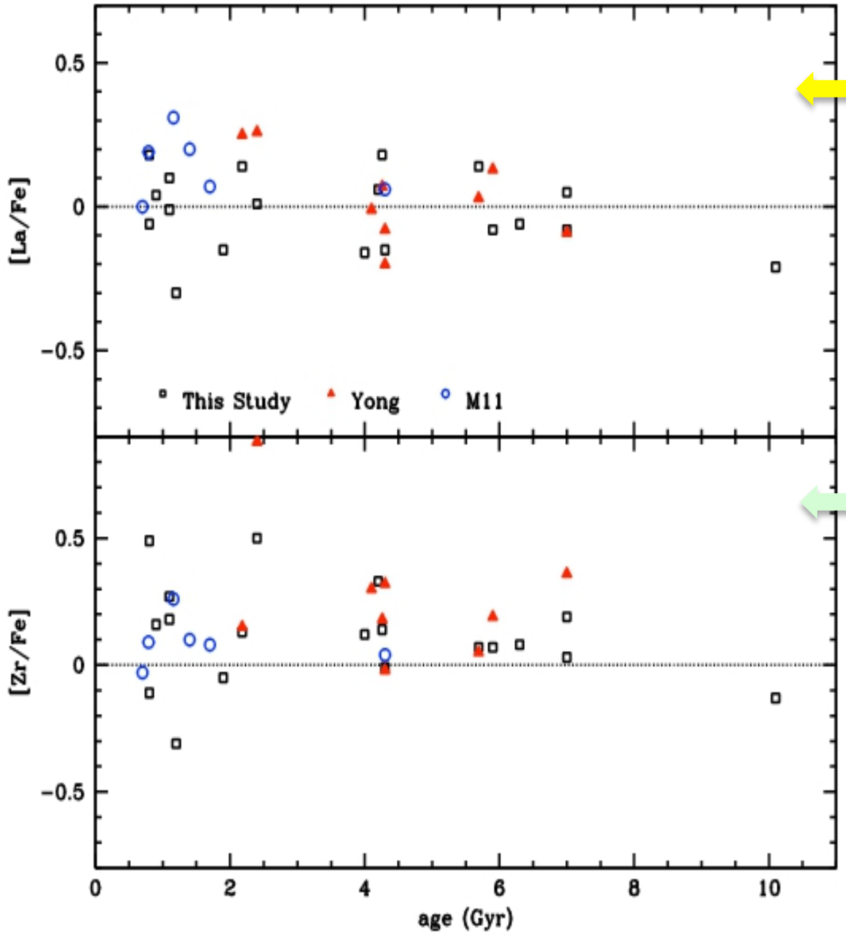
The total sample contains 50 stars in 19 OCs (age ranges from ~700 Myr to 10 Gyr), with a maximum of FOUR stars per cluster

Jacobson & Friel 2013



NO trends of La with age contrary to Maiorca+11

Yong+ (2012) found a POSITIVE correlation of La with age based on their 10 OCs + 6 OCs from literature: HOWEVER →



When adjusted to this abundance scale, taking into account the systematic offset of ~0.3 dex, the trend disappears.

No trend in [Zr/Fe] ratios vs age as for [La/Fe]

Except for Barium, all the other s-process elements DO NOT SHOW any increasing trend with age

Reddy et al. (2015)

Species	NGC 1342	NGC 1662	NGC 1912	NGC 2354	NGC 2447
[Na I/Fe]	+0.28 ± 0.04	+0.22 ± 0.04	+0.33 ± 0.04	+0.12 ± 0.04	+0.12 ± 0.04
[Mg I/Fe]	0.00 ± 0.04	−0.06 ± 0.03	+0.03 ± 0.02	−0.17 ± 0.04	−0.02 ± 0.04
[Al I/Fe]	−0.05 ± 0.02	−0.03 ± 0.03	+0.06 ± 0.02	−0.11 ± 0.03	−0.14 ± 0.03
[Si I/Fe]	+0.11 ± 0.02	+0.16 ± 0.03	+0.23 ± 0.02	+0.16 ± 0.03	+0.11 ± 0.03
[Ca I/Fe]	+0.07 ± 0.05	+0.11 ± 0.06	+0.14 ± 0.03	−0.07 ± 0.06	+0.02 ± 0.05
[Sc I/Fe]	+0.04 ± 0.05	+0.02 ± 0.10	...	...	+0.04 ± 0.09
[Sc II/Fe]	...	+0.11 ± 0.08	**+0.10**	+0.05 ± 0.10	+0.10 ± 0.05
[Ti I/Fe]	+0.02 ± 0.05	+0.06 ± 0.05	−0.07 ± 0.03	+0.01 ± 0.07	−0.04 ± 0.05
[Ti II/Fe]	−0.04 ± 0.05	+0.05 ± 0.07	+0.03 ± 0.06	−0.06 ± 0.06	−0.05 ± 0.06
[V I/Fe]	+0.01 ± 0.06	+0.03 ± 0.06	−0.07 ± 0.04	+0.04 ± 0.06	−0.02 ± 0.06
[Cr I/Fe]	+0.01 ± 0.06	0.00 ± 0.04	+0.01 ± 0.06	−0.03 ± 0.05	−0.04 ± 0.04
[Cr II/Fe]	+0.03 ± 0.06	+0.07 ± 0.07	+0.05 ± 0.05	−0.03 ± 0.06	+0.02 ± 0.07
[Mn I/Fe]	**−0.12**	**−0.05**	**−0.12**	**−0.05**	**−0.07**
[Fe I/H]	−0.14 ± 0.05	−0.10 ± 0.06	−0.11 ± 0.05	−0.19 ± 0.04	−0.13 ± 0.05
[Fe II/H]	−0.13 ± 0.06	−0.11 ± 0.07	−0.09 ± 0.06	−0.16 ± 0.08	−0.11 ± 0.08
[Co I/Fe]	−0.03 ± 0.04	0.00 ± 0.04	−0.10 ± 0.02	+0.07 ± 0.04	−0.04 ± 0.04
[Ni I/Fe]	−0.06 ± 0.04	−0.02 ± 0.04	−0.02 ± 0.05	0.00 ± 0.06	−0.07 ± 0.04
[Cu I/Fe]	**−0.29**	**−0.24**	**−0.30**	**−0.12**	**−0.28**
[Zn I/Fe]	**−0.29**	**−0.13**	**+0.10**	**−0.31**	**−0.38**
[Rb I/Fe]	**−0.04**	**−0.14**	**−0.30**	**−0.17**	**−0.18**
[Y II/Fe]	+0.12 ± 0.05	+0.15 ± 0.05	+0.06 ± 0.04	+0.14 ± 0.05	+0.03 ± 0.06
[Zr I/Fe]	+0.18 ± 0.06	+0.25 ± 0.07	+0.10 ± 0.04	+0.13 ± 0.08	+0.13 ± 0.07
[Zr II/Fe]	+0.25 ± 0.04	+0.31 ± 0.03	...	...	+0.16 ± 0.05
[Ba II/Fe]	**+0.32**	**+0.54**	**+0.70**	**+0.17**	**+0.23**
[La II/Fe]	+0.16 ± 0.05	+0.22 ± 0.05	+0.14 ± 0.04	+0.23 ± 0.08	+0.13 ± 0.05
[Ce II/Fe]	+0.36 ± 0.05	+0.37 ± 0.06	+0.23 ± 0.04	+0.38 ± 0.05	+0.32 ± 0.06
[Nd II/Fe]	+0.29 ± 0.04	+0.26 ± 0.05	+0.13 ± 0.04	+0.33 ± 0.05	+0.22 ± 0.05
[Sm II/Fe]	+0.24 ± 0.05	+0.22 ± 0.05	+0.04 ± 0.04	+0.24 ± 0.05	+0.19 ± 0.05
[Eu II/Fe]	**+0.22**	**+0.20**	**+0.07**	**+0.16**	**+0.22**

None of the current models can account for such a trend in Ba, without bearing similar enhancement in other *s*-process elements

(D'Orazi et al. 2012)

Microturbulence values? No consensus whether young, active stars are characterized by higher microturbulence values due to the presence of strong magnetic fields (see Steenbock & Holweger 1981; James et al. 2006; Santos et al. 2008; D'Orazi & Randich 2009; Biazzo et al. 2011).
WE DEMONSTRATED THAT IT CANNOT BE THE EXPLANATION

Chromospheric effects????

(i) CaII H&K chromospheric emission, (logR_HK)
(ii)coronal emission (X-ray luminosity)
(iii) rotational velocity (vsini)

NLTE effects of the 5853 Å line

Over-ionisation

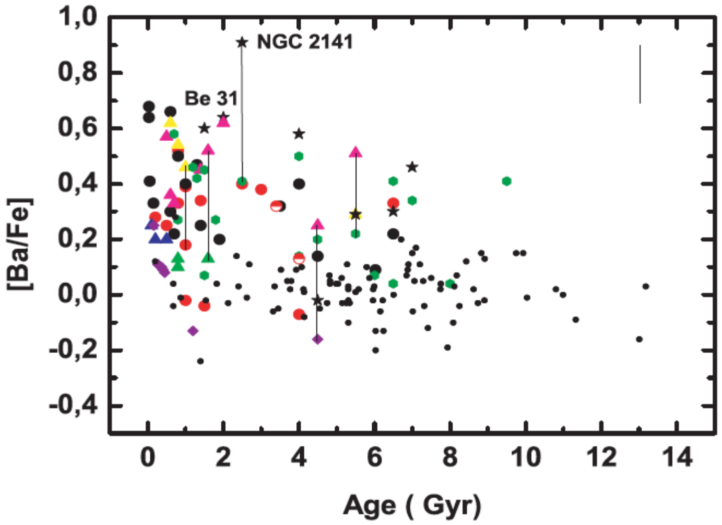
Mishenina et al. (2015)

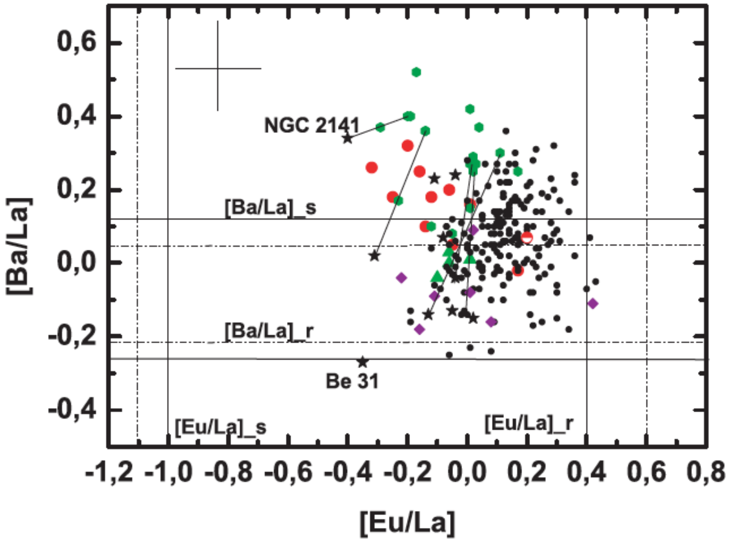
Five intermediate-age OCs: Cr 110, Cr 261, NGC 2477, NGC 2506 and NGC 5822

Confirm the trend of Ba overabundance in OCs, and show its large dispersion for clusters younger than ~ 4 Gyr

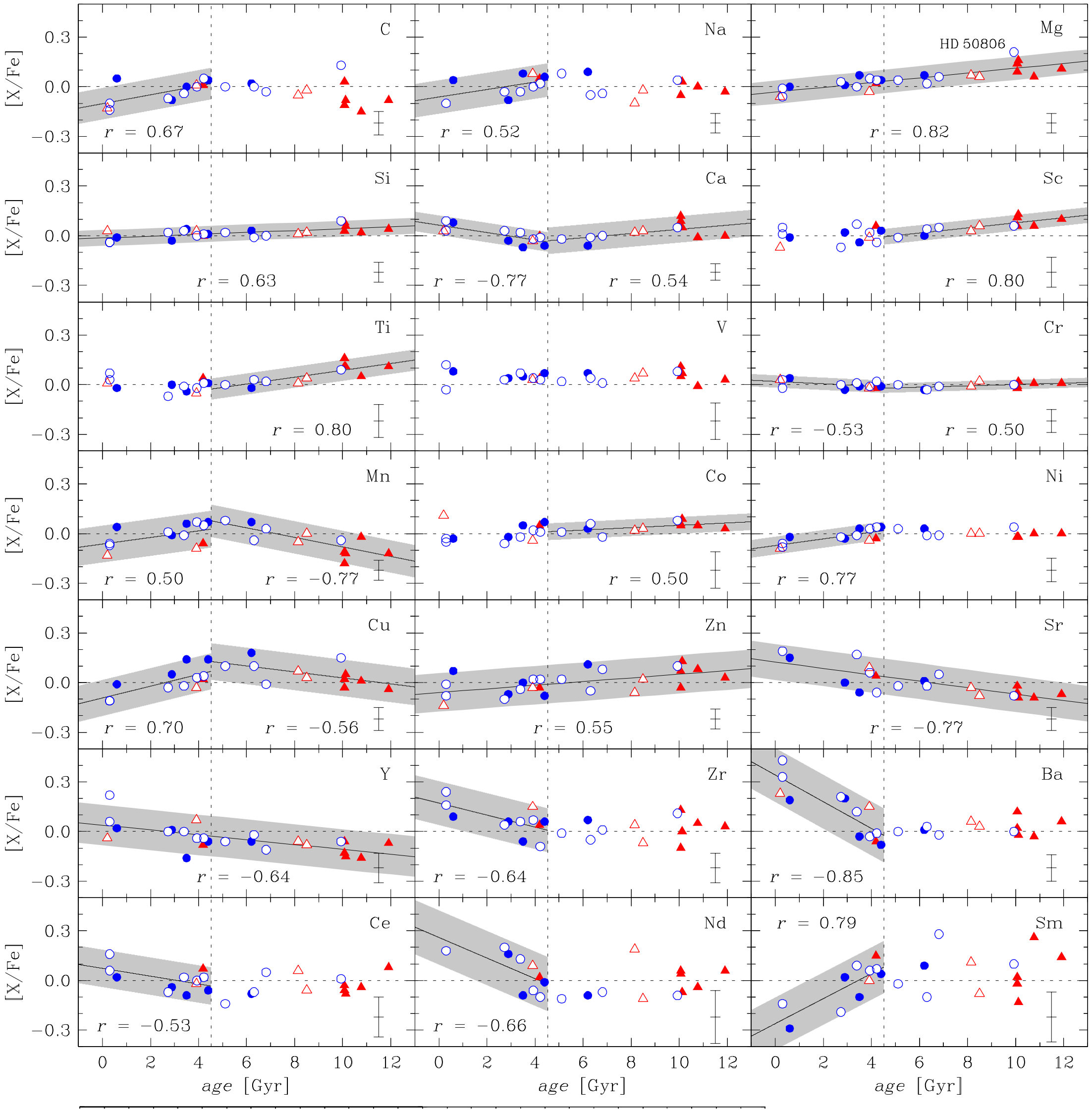
The Ba enrichment compared to other neutron-capture elements in OCs cannot be explained by the contributions from the s process (and the rapid neutron-capture process).

→ An additional contribution by the intermediate neutron-capture process. (the i process)





What about field stars?



da Silva, R. et al. (2012)
solar-type stars in
the solar vicinity
(within 50 pc)
show similar
trends of [*s*/Fe] –for
stars younger than the Sun
(especially Ba and Zr)

Whatever is the nature of this Ba enhancement, we can exploit it as an indication of youth and/or membership..

Age is critical for planet-host stars

In particular for field stars present the common drawback of having significant uncertainties in their ages, which translates themselves into a corresponding uncertainty in planetary masses: this severely affects the calibration of the age-luminosity relationship for sub-stellar objects and is crucial to our understanding of how planets have formed.

For instance, in the case of HR 8799 Moya et al. (2010) claimed an age of approximately 1 Gyr, according to asteroseismology data, whereas kinematics properties suggest a possible link to the Columba association (hence an age of roughly 30 Myr, Zuckerman et al. 2011,), implying a downward revision of the masses for its planetary companions.

The case of HD 61005

A nearby young solar type star that shows a large infrared excess due to a debris disk and indication of planetary companion(s). ???

The interpretation of the direct imaging results in terms of planetary mass limits (Buenzli et al. 2010) and of possible future planetary detections heavily relies on the derived stellar age.

→ Hines et al. (2007) estimated the age of HD61005 to be 90 +/- 40 Myr, while Weise et al. (2010) and Roccatagliata et al. (2009) report 30 and 135 Myr, respectively

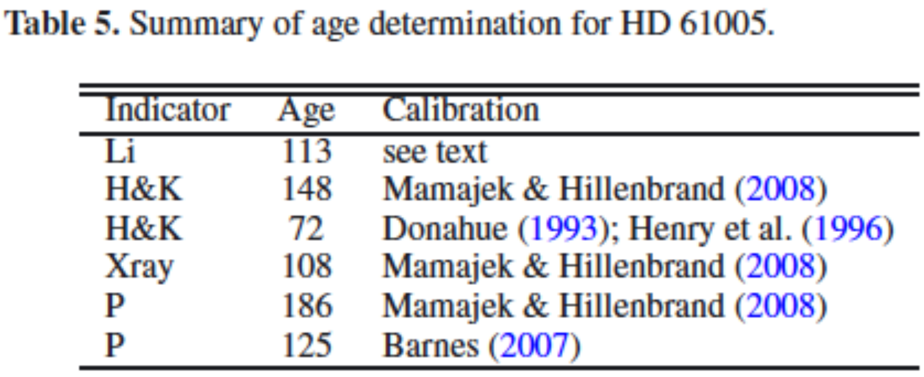


Table 5. Summary of age determination for HD 61005.

Indicator	Age	Calibration
Li	113	see text
H&K	148	Mamajek & Hillenbrand (2008)
H&K	72	Donahue (1993); Henry et al. (1996)
Xray	108	Mamajek & Hillenbrand (2008)
P	186	Mamajek & Hillenbrand (2008)
P	125	Barnes (2007)

However the kinematic properties strongly support its membership in the younger (40 Myr) Argus association, which also includes the IC 2391 open cluster

We found that when applying the standard age calibrations to the values of several age indicators (lithium, chromospheric and coronal emissions, rotation period) HD61005 results of age comparable to that of the Pleiades (120 Myr).

However, the kinematic parameters strongly indicate membership in the Argus association,which is significantly younger (40 Myr; Torres et al. 2008).

We then compared the properties of HD61005 to those of Argus association members, including the open cluster IC 2391.

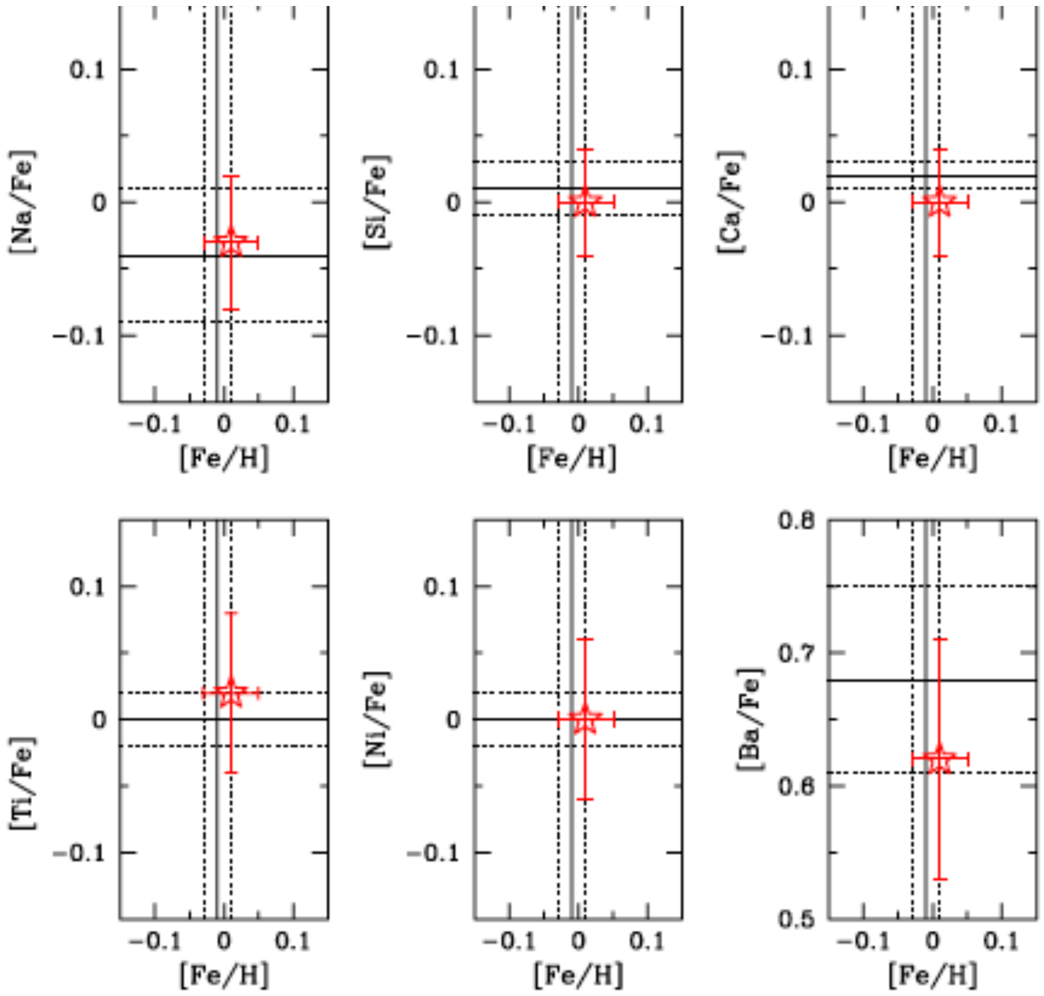
We found that HD61005 parameters are on the edges but not outside the distribution of IC2391 members. The lithium content and coronal emission are similar to those of members of IC 2391 of comparable rotational period. HD61005 also has a similar chemical composition to IC 2391. HD61005, therefore, can have the same age as the slowly rotating, less active, and (relatively) Li-poor stars in IC 2391.

The kinematic parameters strongly indicate that this is indeed the case→

Table 4. Metallicity and [X/Fe] ratios for HD 61005, where errors represent uncertainties due to *EW*s.

Name	[Fe/H]	[Na/Fe]	[Si/Fe]	[Ca/Fe]	[Ti/Fe]	[Ni/Fe]	[Ba/Fe]
HD 61005	0.01 ± 0.04	−0.03 ± 0.05	0.00 ± 0.04	0.00 ± 0.04	0.02 ± 0.06	0.00 ± 0.06	0.63 ± 0.06
IC 2391[a]	−0.01 ± 0.02	−0.04 ± 0.05	0.01 ± 0.02	0.02 ± 0.01	0.00 ± 0.02	0.00 ± 0.02	0.68 ± 0.07

Notes. (a) Average abundances (with standard deviations from the mean) for IC 2391 by D'Orazi & Randich (2009) and D'Orazi et al. (2009a), for comparison.



Desidera et al. (2011)

The younger age for HD61005 than currently assumed (90Myr, Hines et al. 2007) has a significant impact on the detection limits of planetary companions in direct imaging programs.

Buenzli et al. (2010) derive limits of about 3 and 5 M_J at 50 and 15 AU, respectively, assuming a 90 Myr age.

These limits become significantly smaller when taking the revised age into account.

Therefore, only less massive planets may perturb the disk and be a likely cause for the peculiar features (and why they are not detectable)

GJ 758

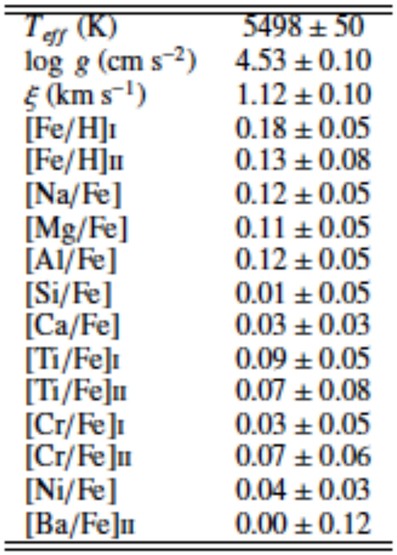
GJ 758B is a brown dwarf companion to a nearby (15.76 pc) solar-type, metal-rich ([M/H] = +0.2 dex) main-sequence star (G9V).

Vigan et al. (2015, submitted)

A reassessment of stellar parameters of GJ 758 is warranted considering their relevance in the derivation of the properties of its sub-stellar companion

GJ 758 is classified as an old star (age 0.7–8.7 Gyr; Janson et al. 2011)

Table 5: Spectroscopic stellar parameters and abundances for GJ 758.



T_{eff} (K)	5498 ± 50
log g (cm s^{-2})	4.53 ± 0.10
ξ (km s^{-1})	1.12 ± 0.10
[Fe/H]ɪ	0.18 ± 0.05
[Fe/H]ɪɪ	0.13 ± 0.08
[Na/Fe]	0.12 ± 0.05
[Mg/Fe]	0.11 ± 0.05
[Al/Fe]	0.12 ± 0.05
[Si/Fe]	0.01 ± 0.05
[Ca/Fe]	0.03 ± 0.03
[Ti/Fe]ɪ	0.09 ± 0.05
[Ti/Fe]ɪɪ	0.07 ± 0.08
[Cr/Fe]ɪ	0.03 ± 0.05
[Cr/Fe]ɪɪ	0.07 ± 0.06
[Ni/Fe]	0.04 ± 0.03
[Ba/Fe]ɪɪ	0.00 ± 0.12

Adopting the trigonometric parallax and proper motion by van Leeuwen (2007) and the absolute radial velocity by Nidever+ (2002), space velocities U,V,W = 21.1; -14. 1; -3.0 km/ s are obtained.

These are very similar to those of the Argus association. Gagné et al. 2014 found a membership probability of 97.8%. BUT IT IS MUCH YOUNGER! (~40 Myr)

(Other) Age indicators

GJ 758 is known to have a low activity level as resulting from several measurements in the literature: log R_{HK} =-4. 94 (Wright et al. 2004), -5.015 (Isaacson & Fischer 2010); -5.060 (Duncan et al. 1991 ; Mamajek & Hillenbrand 2008).

The calibration by Mamajek & Hillenbrand (2008) yields values of 5.5-7.7 Gyr for these activity values.

The X-ray non-detection in the ROSAT All Sky Survey (Voges et al. 1999 , 2000), the small projected rotational velocity (0–2 km/s) and the small photometric variability (0.008 mag from Hipparcos) further support the low activity level of GJ 758, as expected for a few-Gyr old star.

Lithium is another highly-sensitive age indicator for young stars: the Li 6708Å resonance line is not detected, confirming the null result by Takeda & Kawanomoto (2005). For stars with GJ 758 colors, detectable amounts of lithium vanish at about the age of the Hyades.

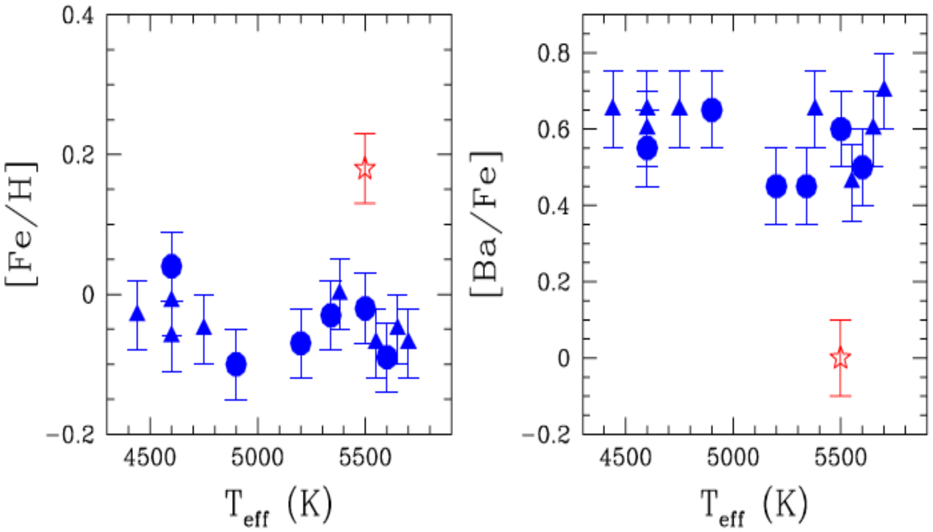
→ the lack of lithium allows us to infer a stellar age older than ~600 Myr.

The chemical composition and comparison with Argus/IC 2391

[Ba/Fe] = 0.53±0.03 (rms=0.08 dex) for the Argus association

[Ba/Fe] = 0.62±0.02 (rms=0.07) for IC 2391.

GJ758: [Ba/Fe] = 0.00±0.12 for our star, which implies a difference in the Ba content more than a factor of 3.5.



Thus, in terms of chemical composition, Ba provides us with the strongest observational constraint: GJ 758 cannot be born from the same molecular cloud as Argus.

Although the kinematic analysis yields a high probability for GJ 758 to be a member of Argus, all other age indicators firmly exclude such young ages.

Chemical tagging derived from an homogeneous comparison of abundances of several elements with those of confirmed members of Argus association and IC 2391 open cluster also rules out a link between GJ 758 and Argus, with Barium abundance suggesting an age similar to the Sun.

Therefore, we conclude that the kinematic parameters of GJ 758 are similar to those of Argus association just by chance, confirming the statistical nature of kinematic ages and the need for independent youth indications to conclusively infer membership in young moving groups.

The young-disk kinematics decrease the probability of a star significantly older than the Sun. The age of the system is likely within 1 to 6 Gyr, and the most probable value ~3 Gyr, with isochrone fitting yielding younger values than chromospheric activity

What's next ?

Determination of Ba abundances in sample stars from the VLT/NACO Large program (Desidera et al. 2015)

The survey is designed to search for planets and brown dwarfs in wide orbits around 86 stars (the mean distance and age is 64 pc and 100 Myr, median mass =1.01 $M_{\odot}$)

A large fraction of the targets observed with NaCo were poorly investigated in the literature. We performed a study to characterize the fundamental properties (age, distance, mass) of the stars in our sample.

We measured spectroscopic parameters and age diagnostics using dedicated observations acquired with FEROS and CORALIE

In preparation for SPHERE observations (!)

Abundances of Planet Hosting Red Giant Stars:

A Key for Understanding Pollution and Planet Engulfment

Joleen Carlberg
NPP Postdoctoral Fellow, NASA GSFC
July 13, 2015

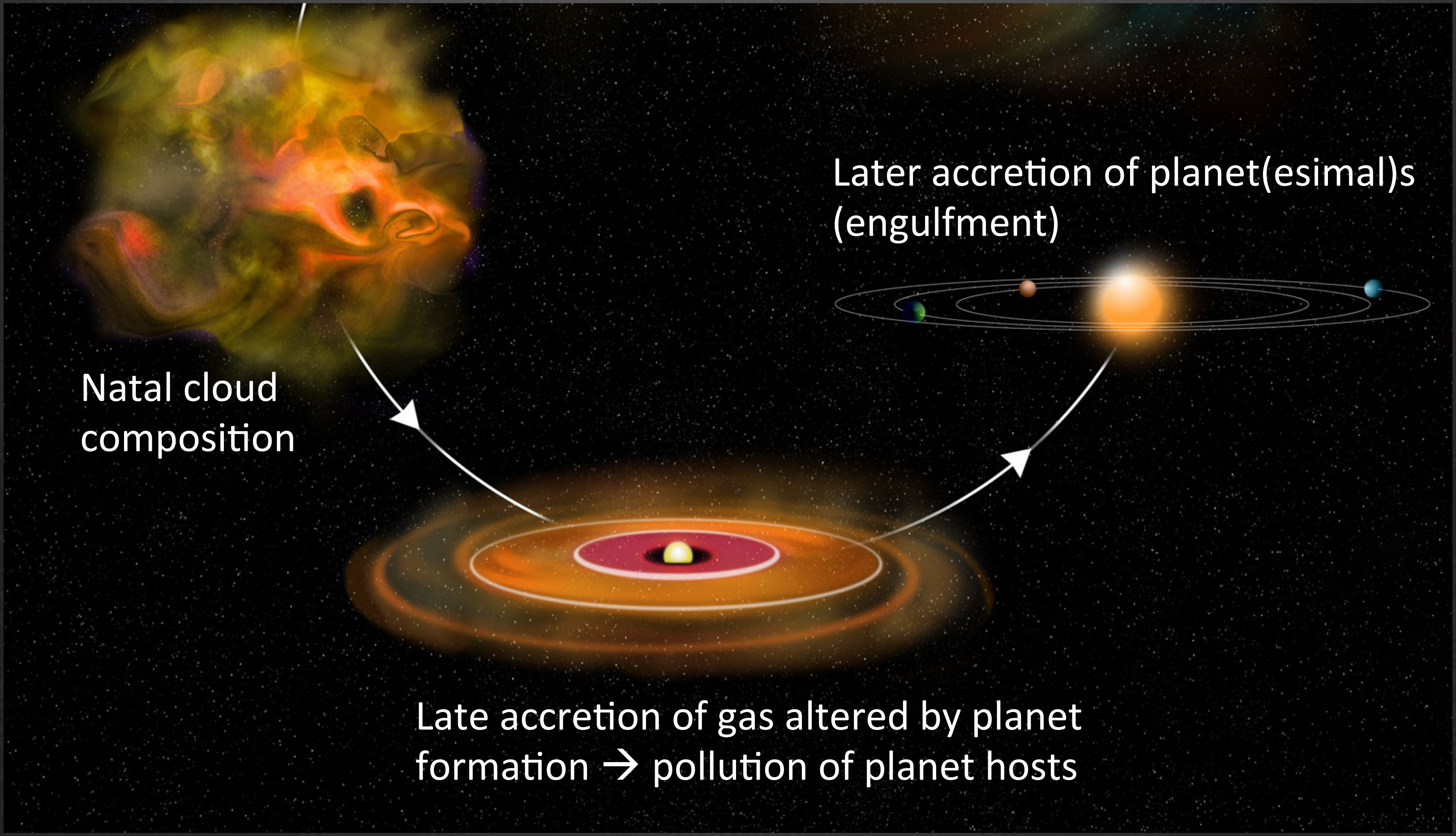
Outline

- **Stellar abundances are windows to BULK planet composition (via planet engulfment)**
  - Habitability of planets depend in part their composition

- **Unique contributions of red giants:**
  - Test cause of abundance trends in main sequence stars: pollution vs intrinsic
  - Engulfment is happening! → identifying likely engulfment candidates

- **Future work:** know your star, know your (engulfed) planet

What stellar abundances encode

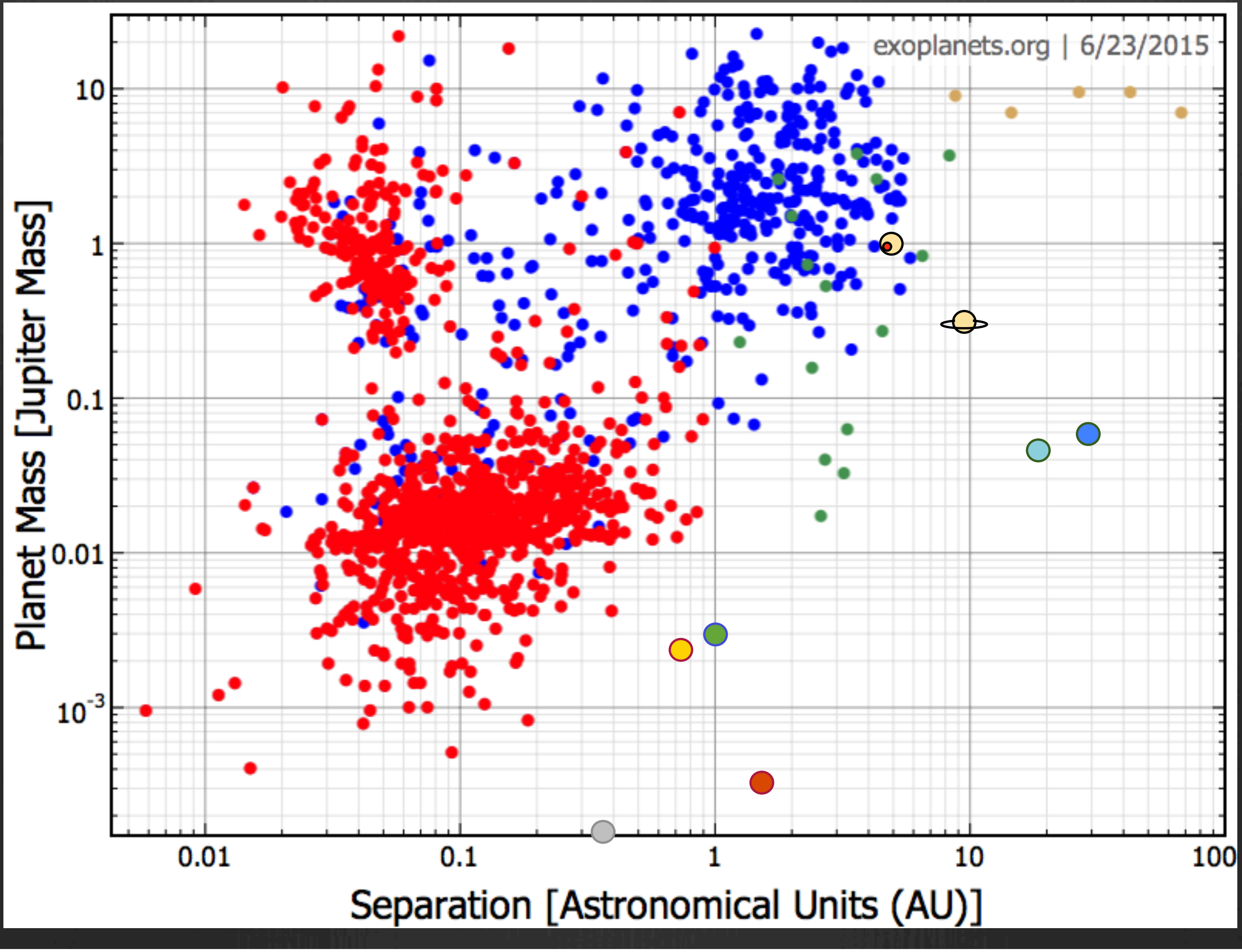


Later accretion of planet(esimal)s (engulfment)

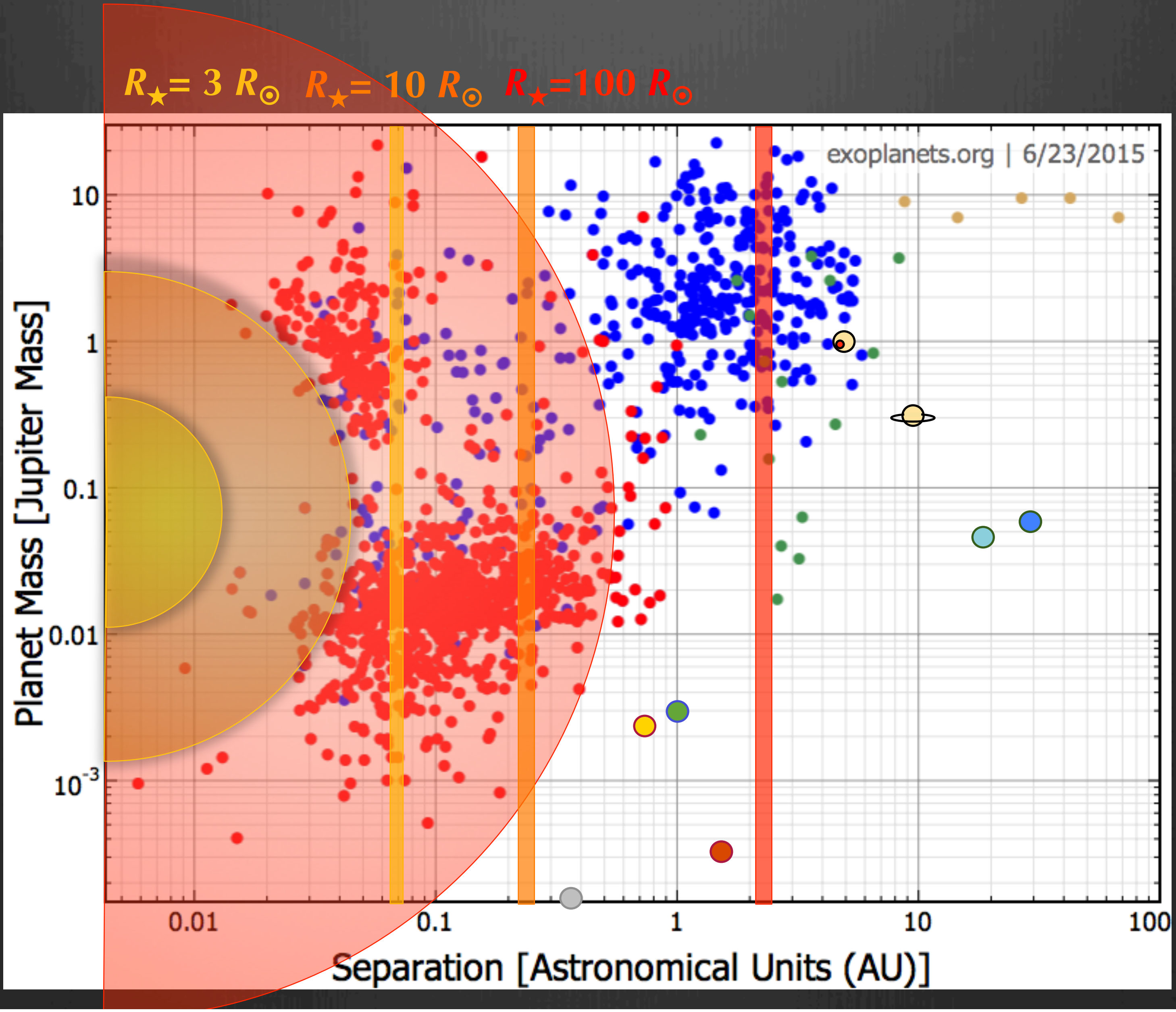
Natal cloud composition

Late accretion of gas altered by planet formation → pollution of planet hosts

Why Red Giants: Planet Engulfment



Generally, a RG star can engulf approximately 5x its current radius

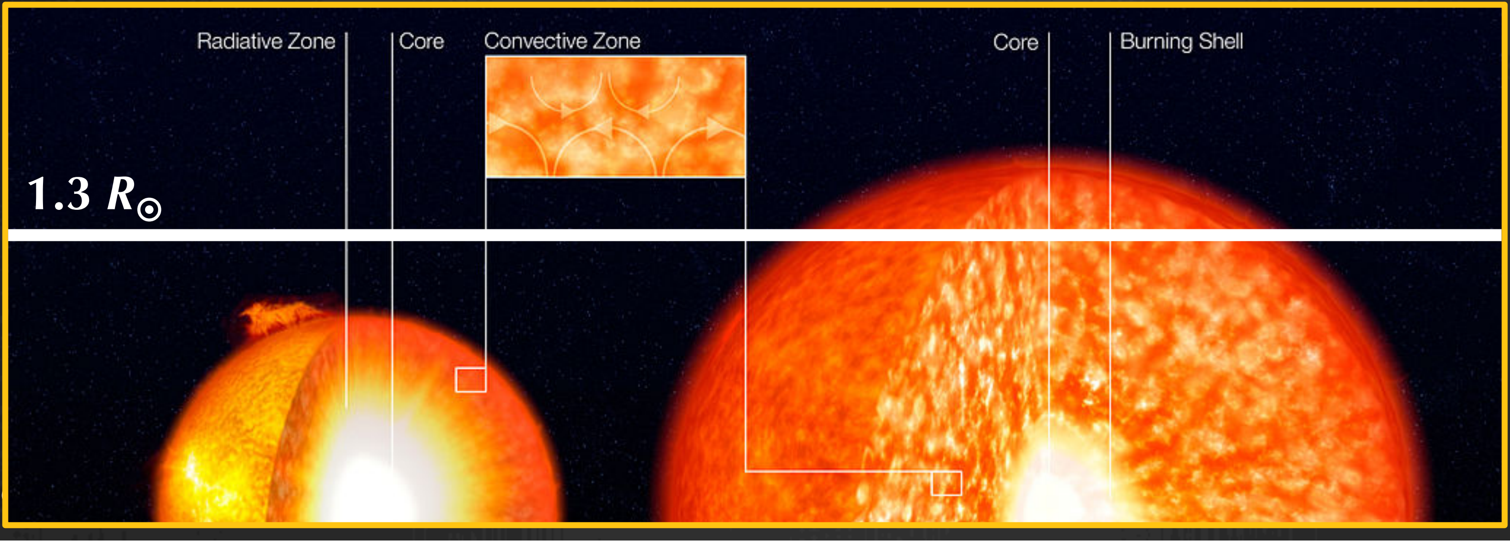


Why Red Giants?

PRO	CON
They have large, massive convective zones	They have large, massive convective zones

Engulfing Planets by Expanding Stars

- Roche lobe overflow & tidal destruction of planet more likely to occur *inside* RG star. E.g, for a Jupiter around a Sun $a_{\mathrm{shred}} = 1.3\ R_{\odot}$ (Nordhaus et al. 2010)
- Heavy element enrichment:
  - For Jupiter/Saturn: $\Delta[\mathrm{C/H}]_{\star}$ = 0.03-0.11 dex (MS) vs. 0.001-0.03 dex (RG)
  - Super-Earth/Mini-Neptune: larger enhancements in key elements
- Main sequence abundance trends: erased if caused by pollution



13 July 2015

Why Red Giants?

PRO

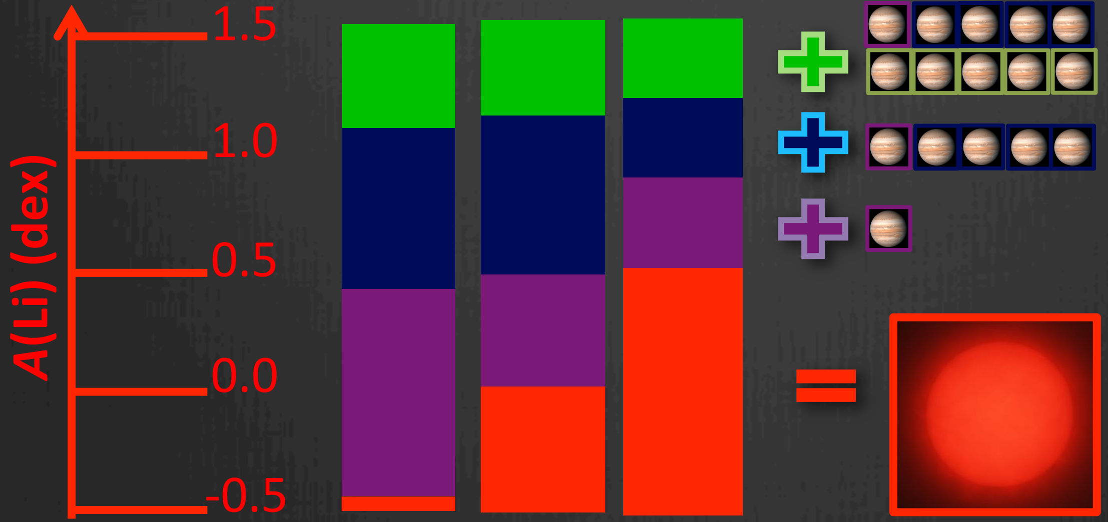
- They have large, massive convective zones
- They are cool, slow rotators for wide range of masses
- Have unique chemical signatures that are distinct from planets

CON

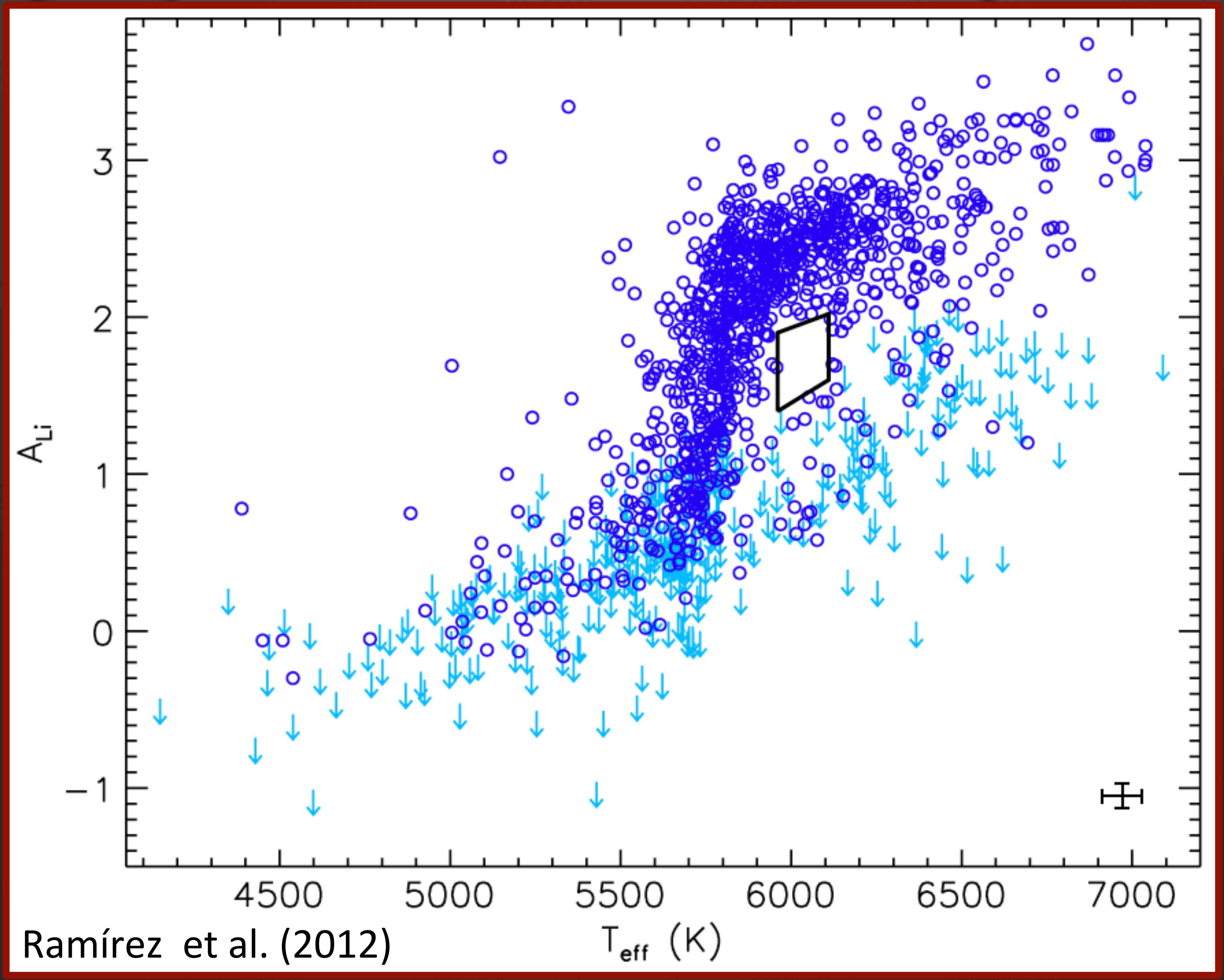
- They have large, massive convective zones
- Masses are very hard to pin down
- Unique signatures show wide dispersion --- what is normal?

Identifying Engulfment Candidates

- Red giants are generally VERY slow rotators
  - Thus, moderately fast rotation = planet engulfment candidate
  - Known exoplanets have sufficient angular momentum for spin-up (Carlberg et al 2009)
- Light elements (Li, Be, B) are depleted in red giants
  - Thus, replenished Li, Be, B = planet engulfment candidate



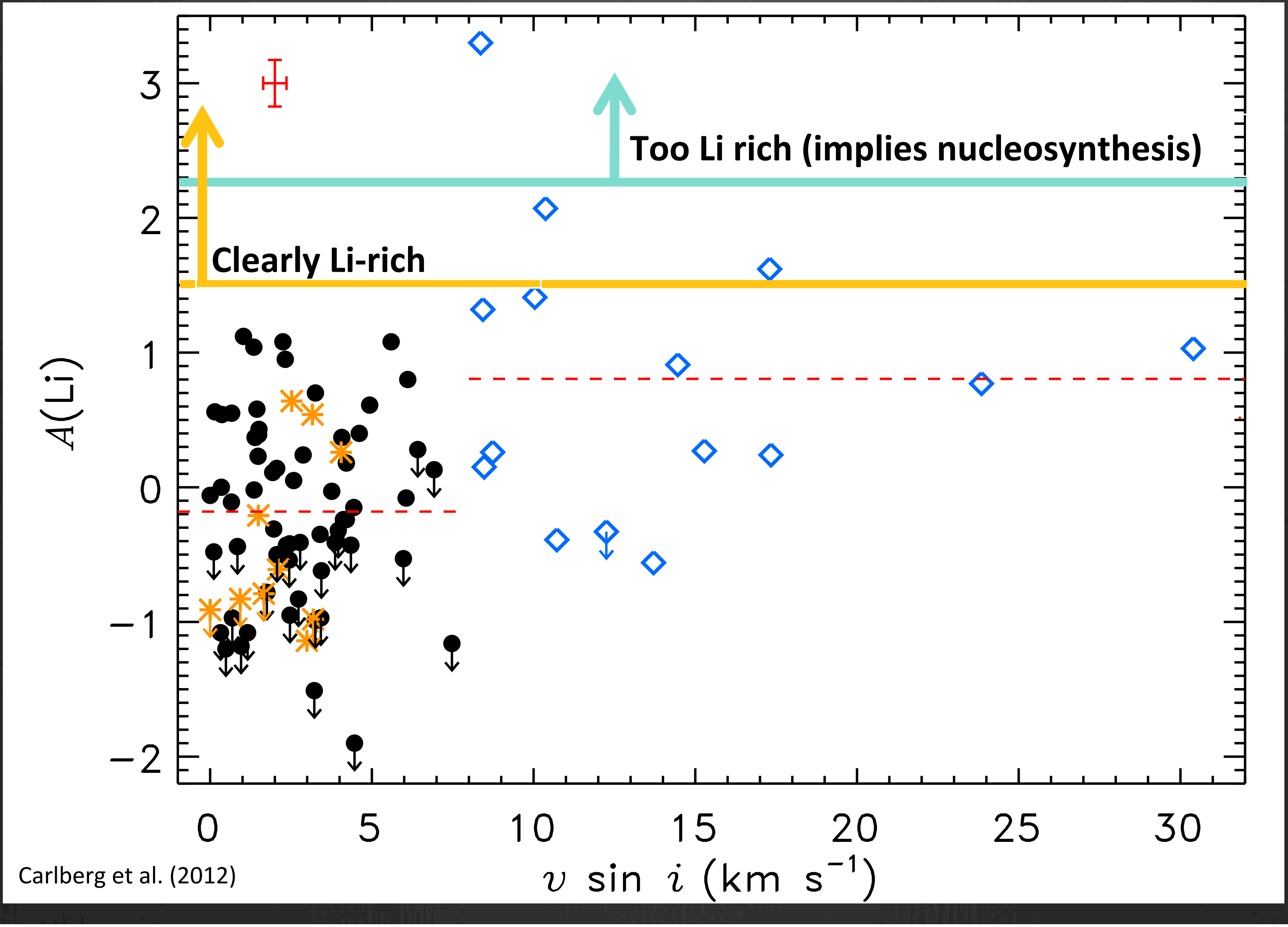
A(Li) on the main sequence



Ramírez et al. (2012)

Stellar mass →

Li in red giants: replenishment?



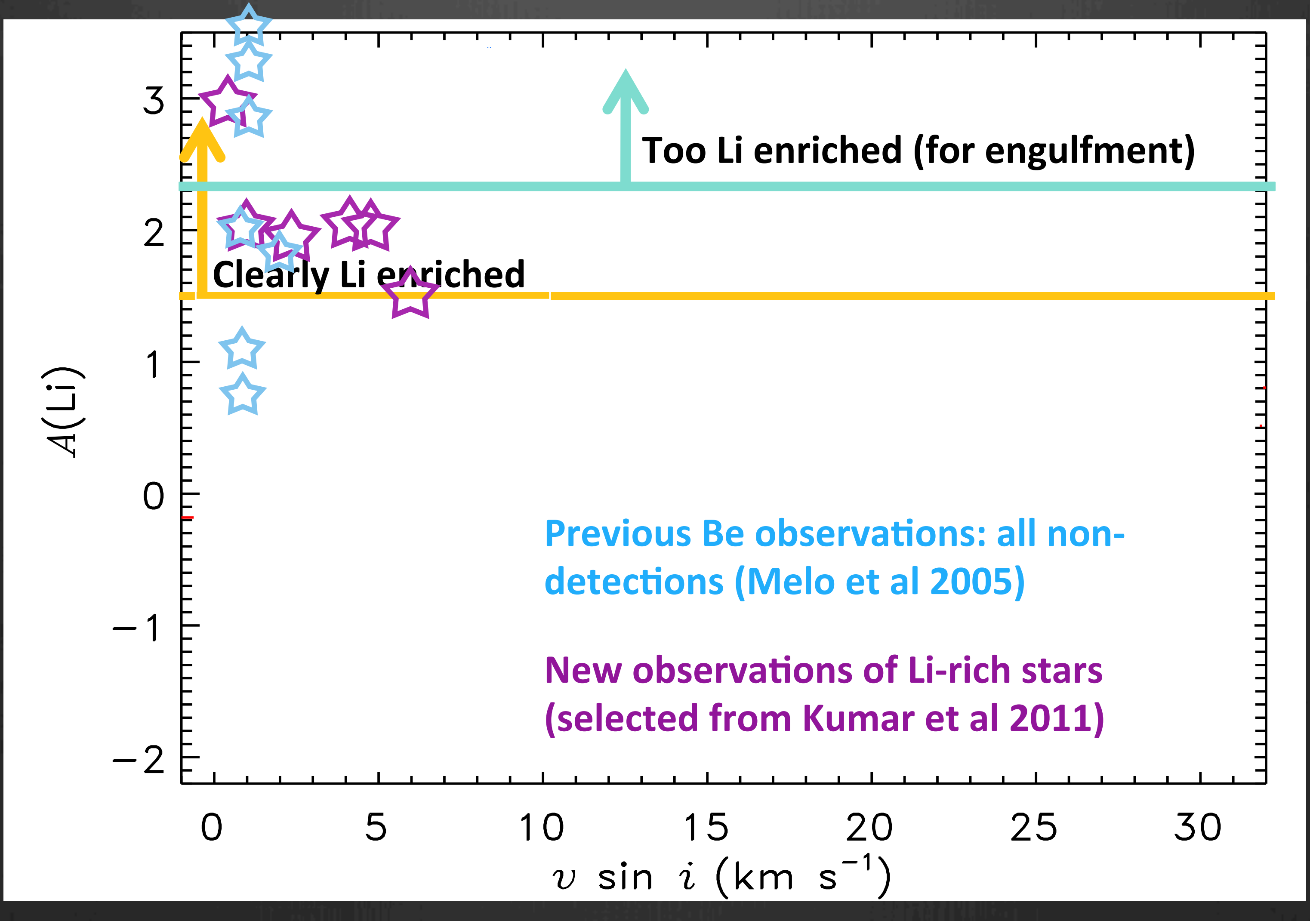
Carlberg et al. (2012)

Testing with Be abundances

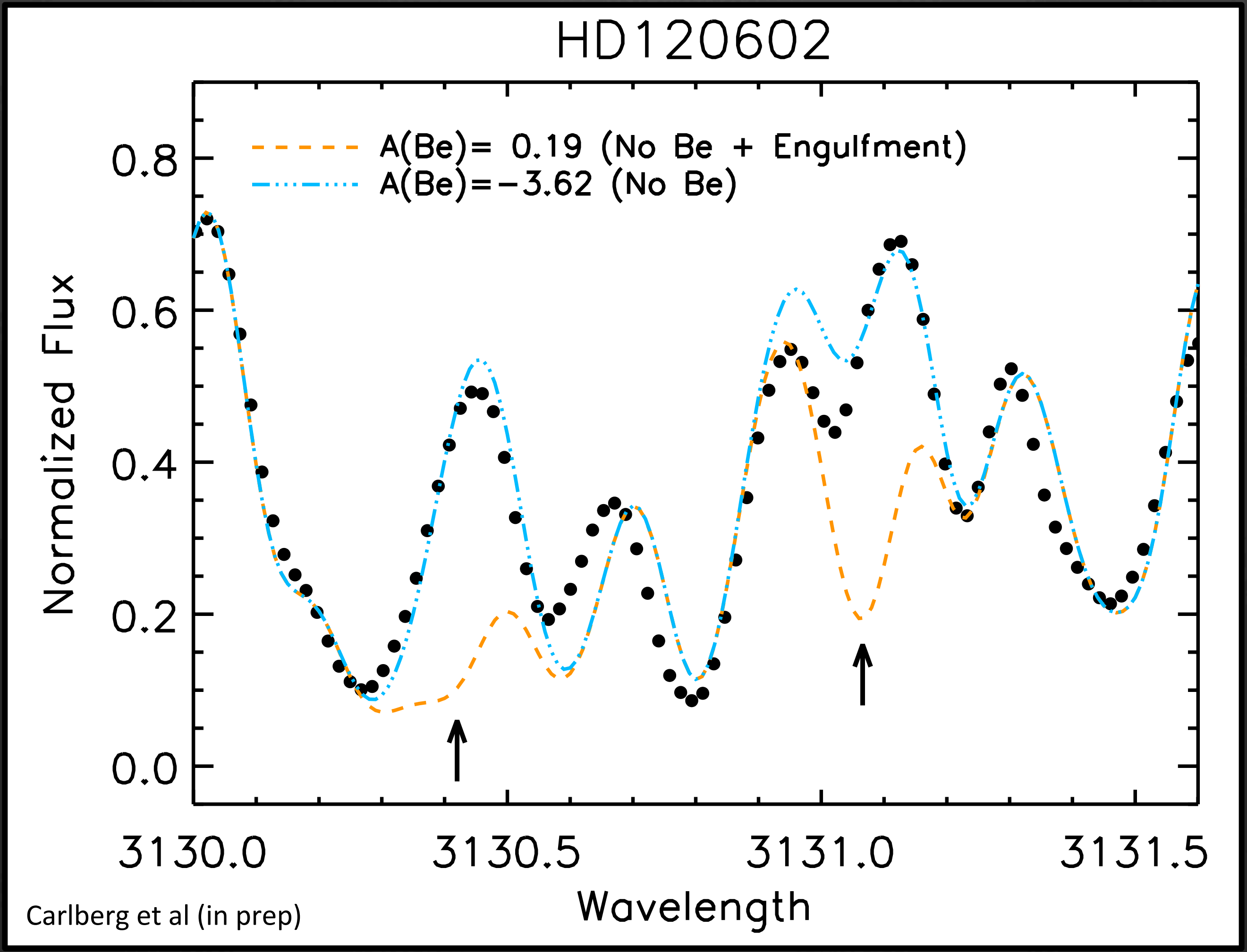
- Li-rich due to nucleosynthesis: No beryllium enhancement (or more Be depletion, Sackmann & Boothroyd 1999)
- Li-rich due to engulfment: Beryllium enhancement

Testing with Be abundances

- Requires VERY bright targets



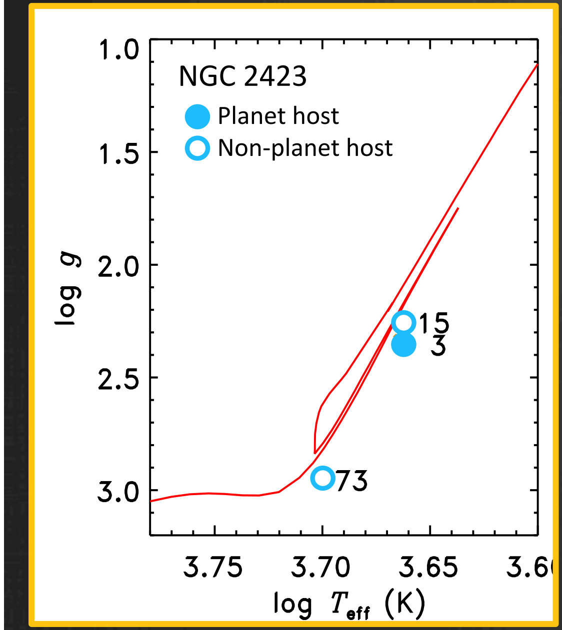
Preliminary results:

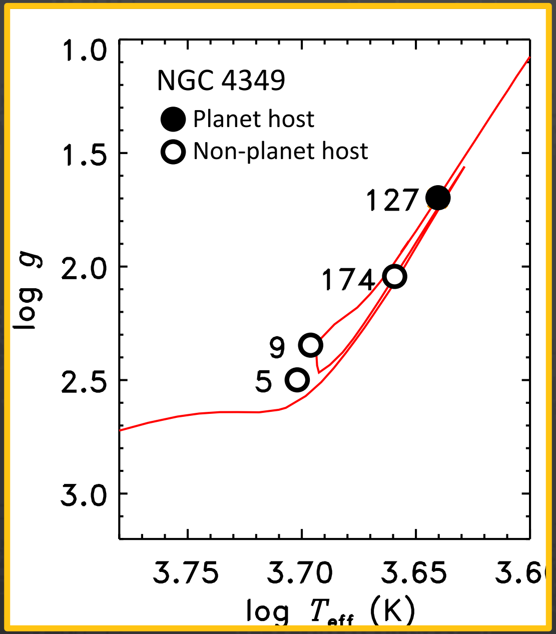


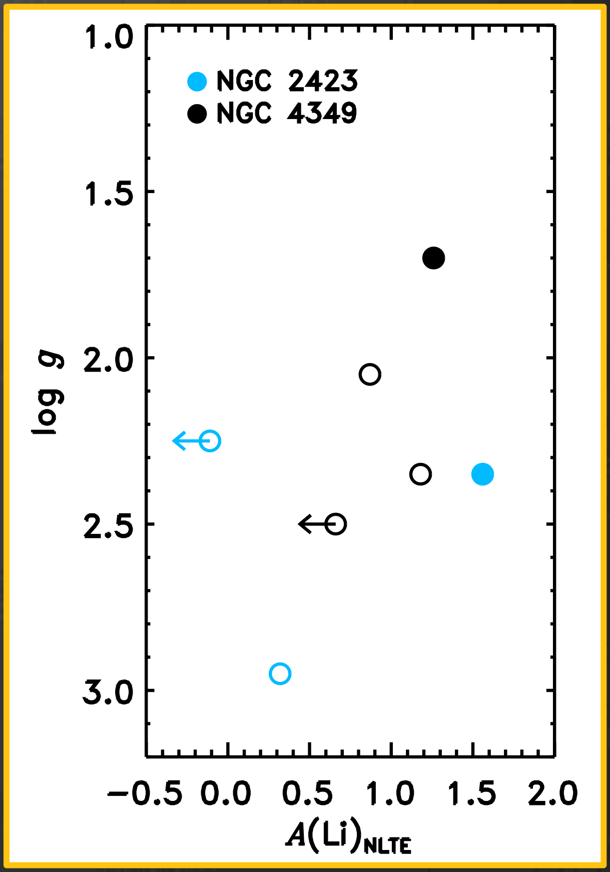
Carlberg et al (in prep)

Testing with open clusters?

- Coeval population of stars at same metallicity
- Comparison stars of nearly identical mass/evolutionary stage







Carlberg et al (in prep)

The Way Forward…

- Using RGs to distinguish between primordial and pollution origins of stellar abundance signatures in planet hosts
- RG stars' abundance changes provide means of ID'ing engulfment candidates, but…
  - we must understand all relevant stellar astrophysics
  - we need more bright, fast rotating, Li-rich stars!
- Coeval populations (clusters, binaries) can help bridge our knowledge gap
- Once engulfment candidates ID'd, can potentially learn about bulk composition of massive, "non-solar" planets (sub-Neptunes and super-Earths!)

THE NATURE OF VERY ACCURATE ABUNDANCE TRENDS IN SOLAR ANALOGS

Jonay I. González Hernández

Instituto de Astrofísica de Canarias

Pathways 2015: **Pathways towards habitable exoplanets**

SM8: Connecting Stellar Abundances and Planet Habitability

Bern, Switzerland, 13th July 2015

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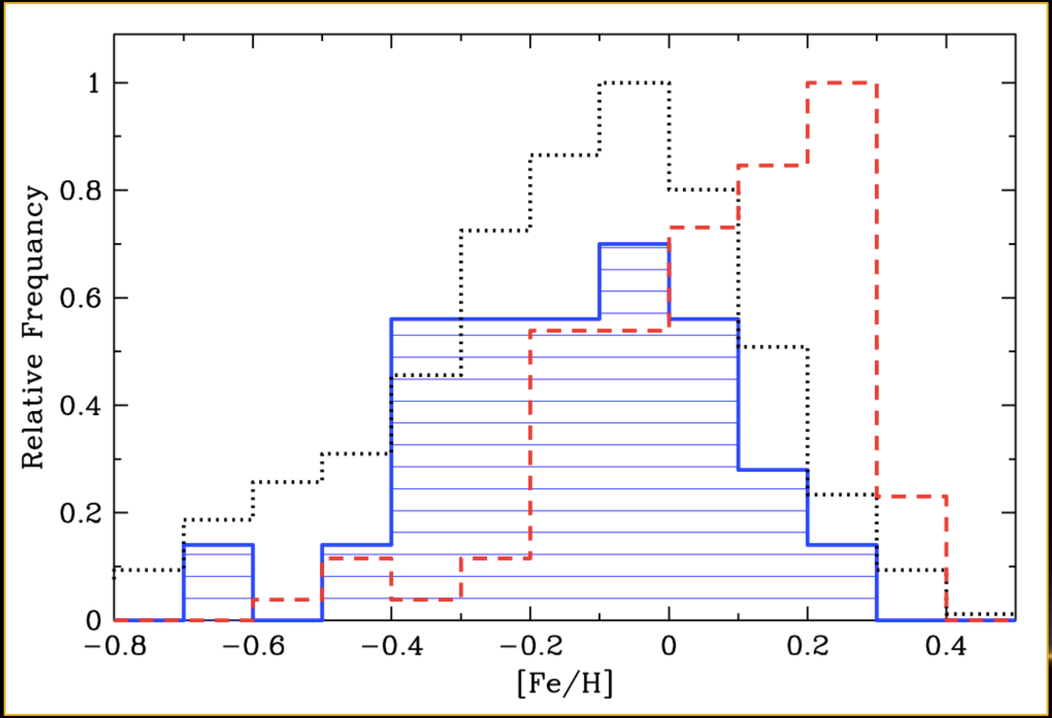
METALLICITIES OF PLANET HOSTS

- Santos et al. (2001; 2004) : giant planet hosts tend to be metal rich
- Sousa et al. (2008); Neves et al. (2009) : Neptune planet hosts do not need high-metallicity enviroments
- Adibekyan et al. (2012a) : Neptune and super-Earth planet hosts show distributions similar to single stars, for all elements

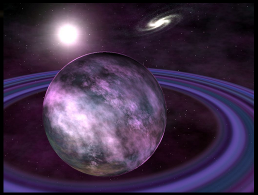


Single stars

Jovian hosts

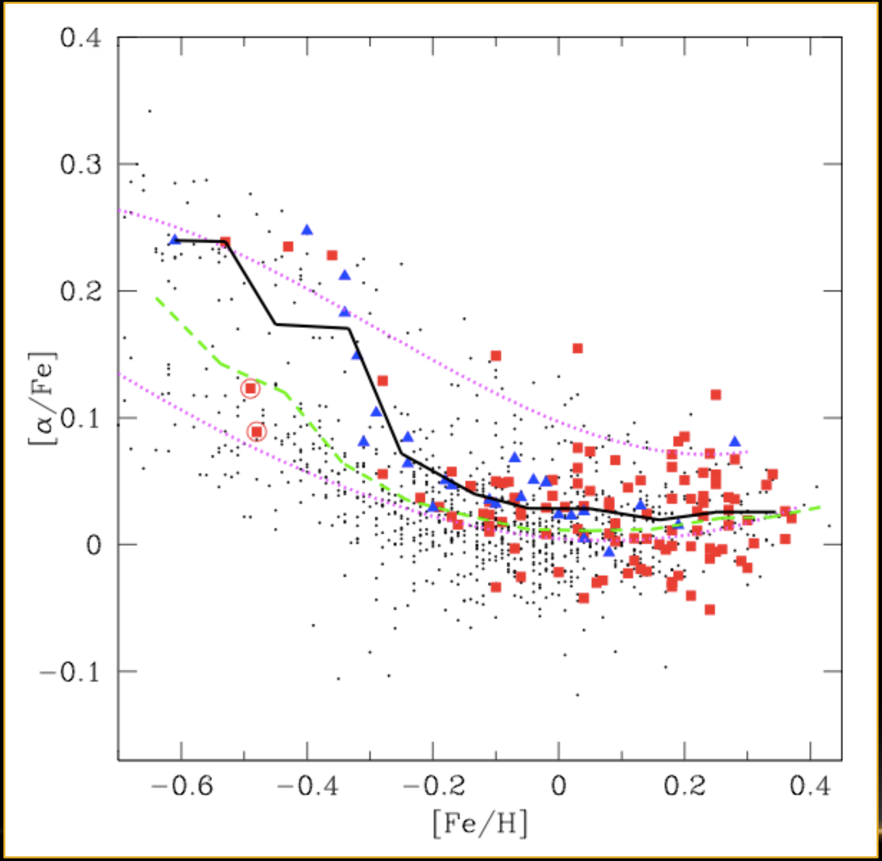
Neptune/super-Earth hosts

Adibekyan et al. (2012a, A&A)



PLANET HOSTS: α-ELEMENTS

- Adibekyan et al. (2012b) : stars at low metallicity with planets tend to be α-enhanced, and thus chemically belong to the thick disc



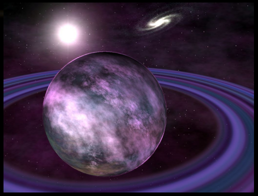
Single stars

Jovian hosts

Neptune/super-Earth host

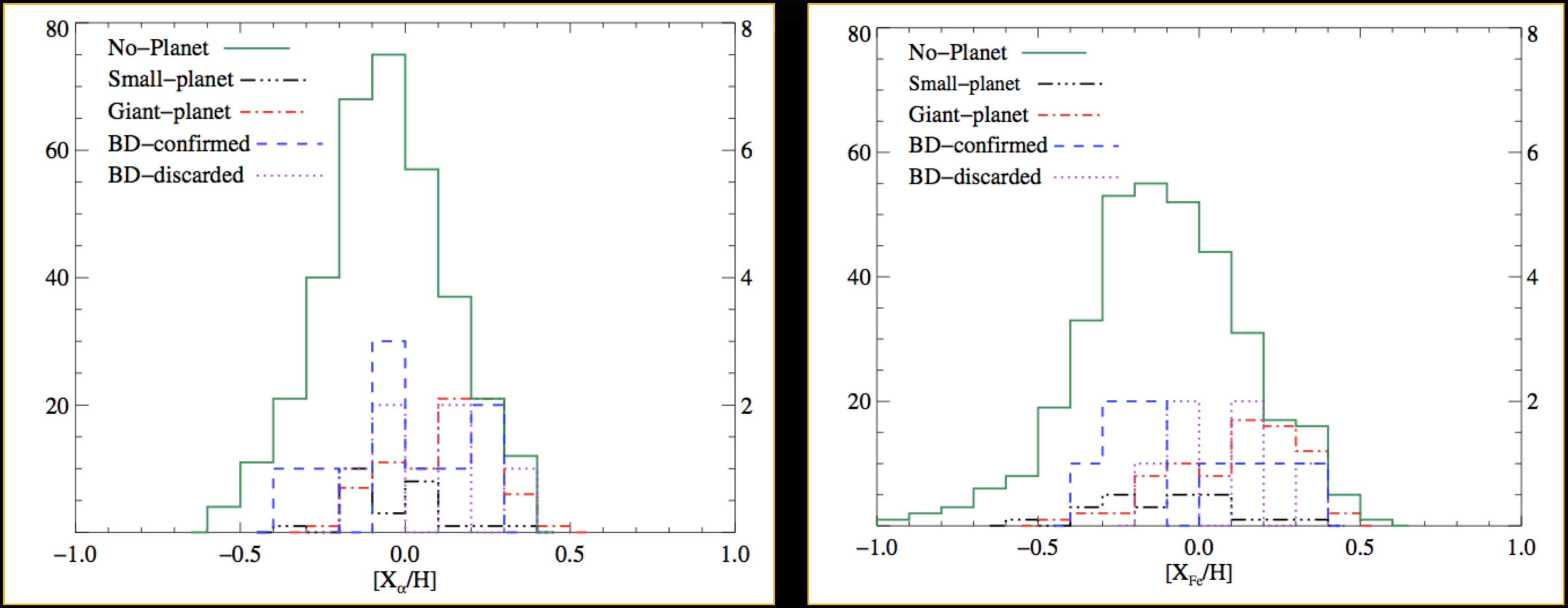
α-low and α-high fits

Adibekyan et al. (2012b, A&A)

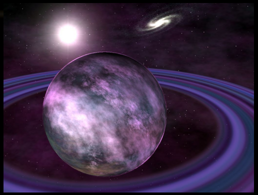


Brown Dwarfs: α-elements and Fe-peak elements

- Mata Sánchez et al. (2014) : stars with BDs show distributions in a-elements and Fe-peak elements similar to single stars

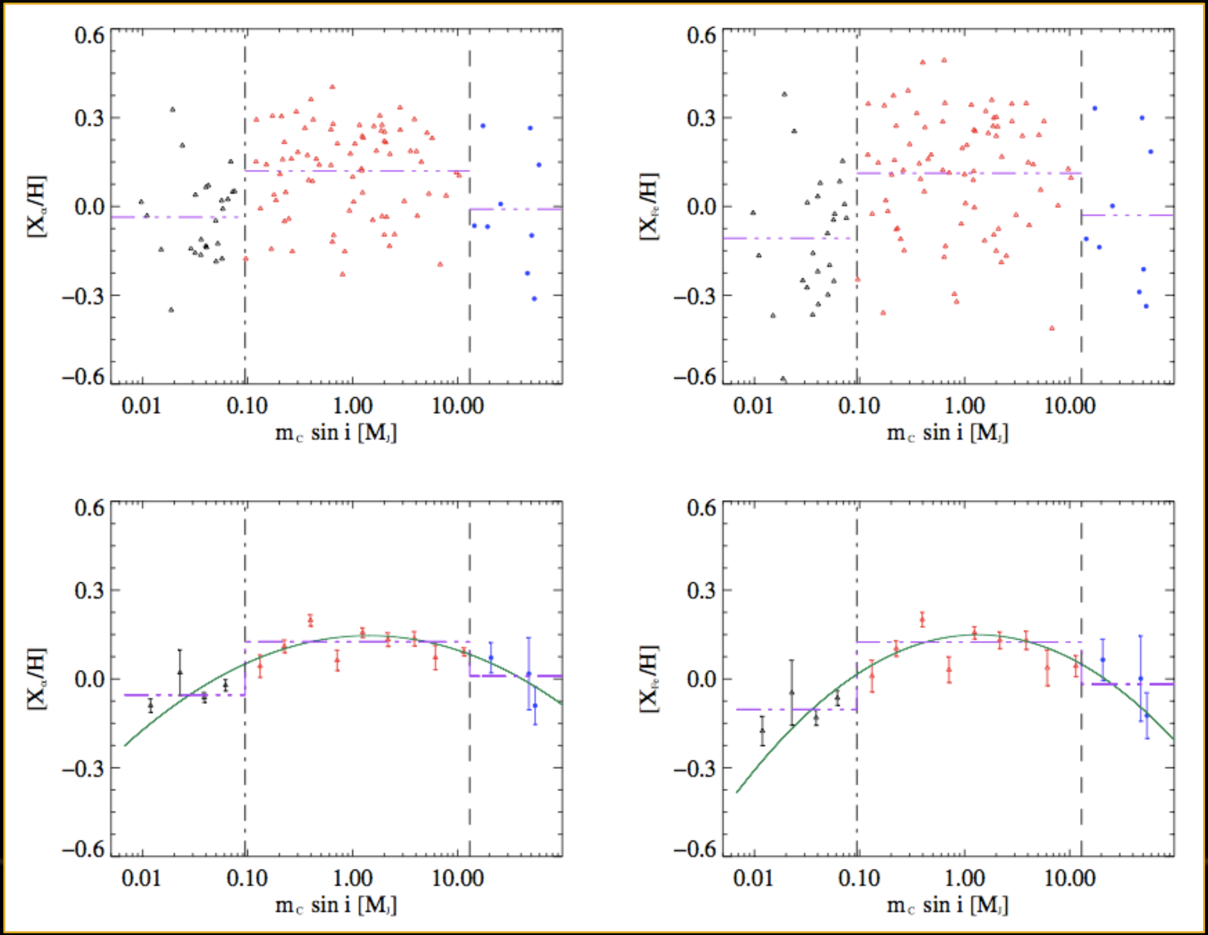


Mata Sánchez et al. (2014, A&A)

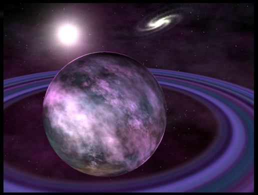


BROWN DWARFS: α-ELEMENTS AND FE-PEAK ELEMENTS

- Mata Sánchez et al. (2014) : stars with less massive BDs show different behaviour to more massive BDs, pointing to different BD formation mechanisms



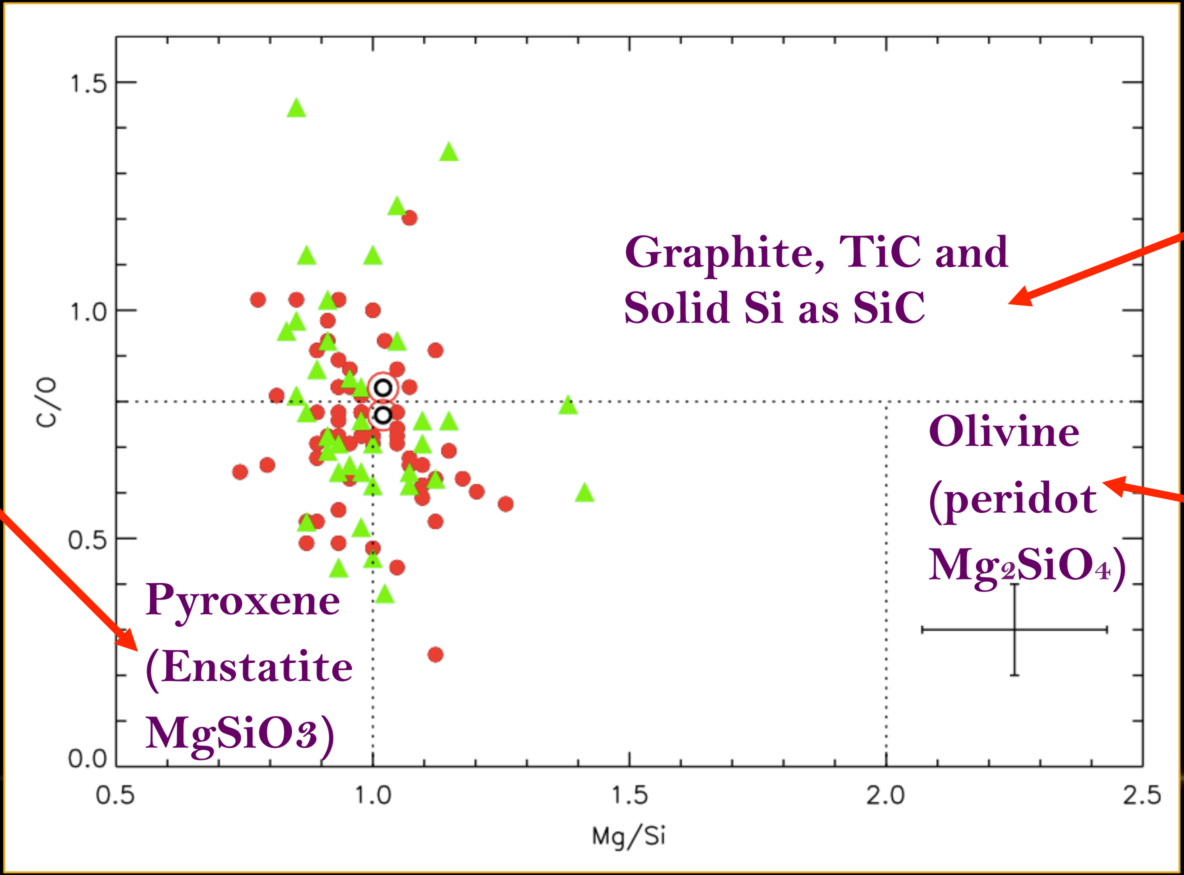
Mata Sánchez et al. (2014, A&A)



C/O versus Mg/Si

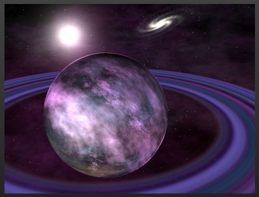
See talks by Elisa Delgado Mena and Lucía Suárez Andrés

- Most of the stars show ratios Mg/Si < 1: form complex molecules as pyroxene ($MgSiO_3$)
- Implications on atmostpheric compositions, plate tectonics and volcanism of terrestrial planets different from the Earth

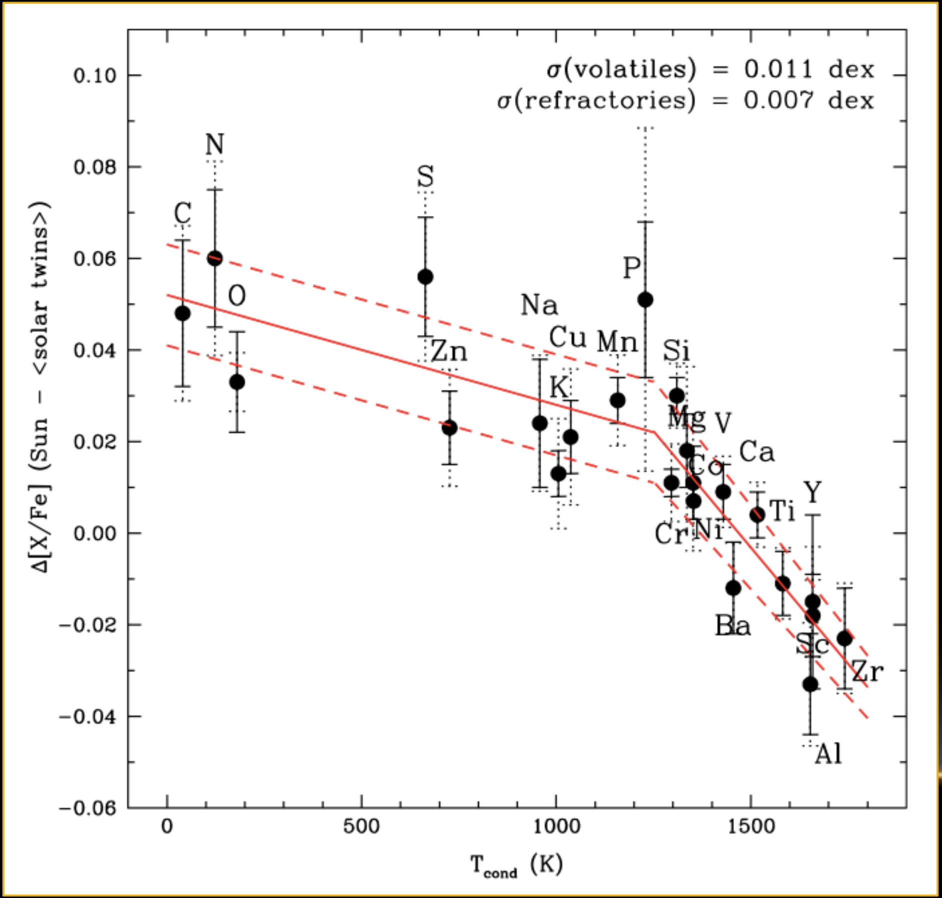


Delgado Mena et al. (2010, ApJ); Carter-Bond et al. (2012, ApJ letters)

VOLATILE AND REFRACTORY ELEMENTS



- Mélendez et al. (2009) : 11 solar twins show
  - refractory elements ($T_C > 1250$K) : $\Delta[X/Fe]_{SUN-STARS} < 0$
  - volatile elements ($T_C < 1250$K) : $\Delta[X/Fe]_{SUN-STARS} > 0$



High quality spectra
S/N ~ 450
R~65,000

However, there is a time-scale problem:
- Proto-planetary disks < 10Myr

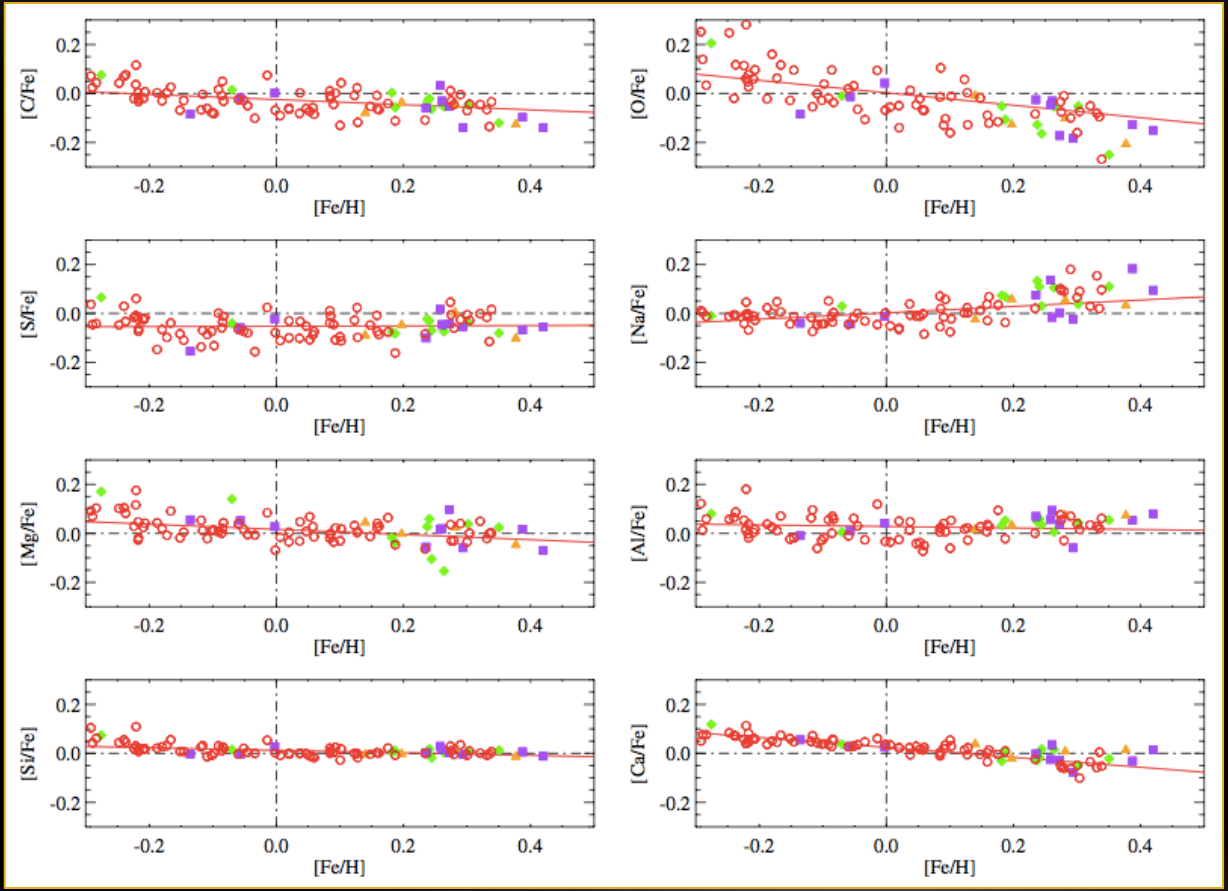
M_{CZ} ~38% at τ ~ 10Myr and 2% at τ > 30 Myr

Negative slopes mean higher refractory-to-volatile abundance ratios than in the Sun

Meléndez et al. (2009, ApJ letters)

VOLATILE AND REFRACTORY ELEMENTS

- González Hernández et al. (2010) : solar twins and solar analogs



High quality spectra
S/N > 350
R~115,000

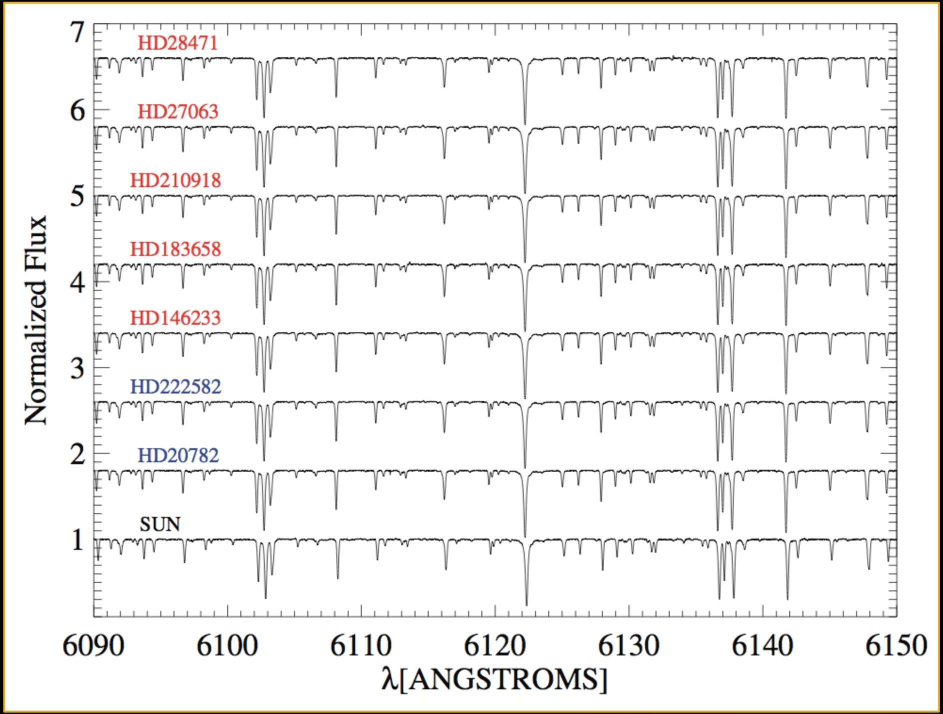
Fully differential chemical analysis
Very Accurate abundances

62 "single" stars and 33 stars with planets

González Hernández et al. (2010, ApJ)

SOLAR TWINS: HARPS DATA

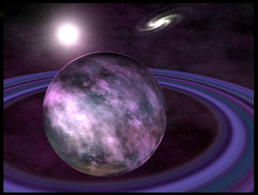
- González Hernández et al. (2010) : solar twins (7 stars in HARPS)
  - No so clear trend versus T_C



High quality spectra
S/N > 370
R~115,000

- $\mathrm{Teff}_{\mathrm{TWINS\text{-}SUN}} < 77\mathrm{K}$
- $\mathrm{Logg}_{\mathrm{TWINS\text{-}SUN}} < 0.1\mathrm{dex}$
- $[\mathrm{Fe/H}]_{\mathrm{TWINS\text{-}SUN}} < 0.07\mathrm{dex}$
- S/N > 370

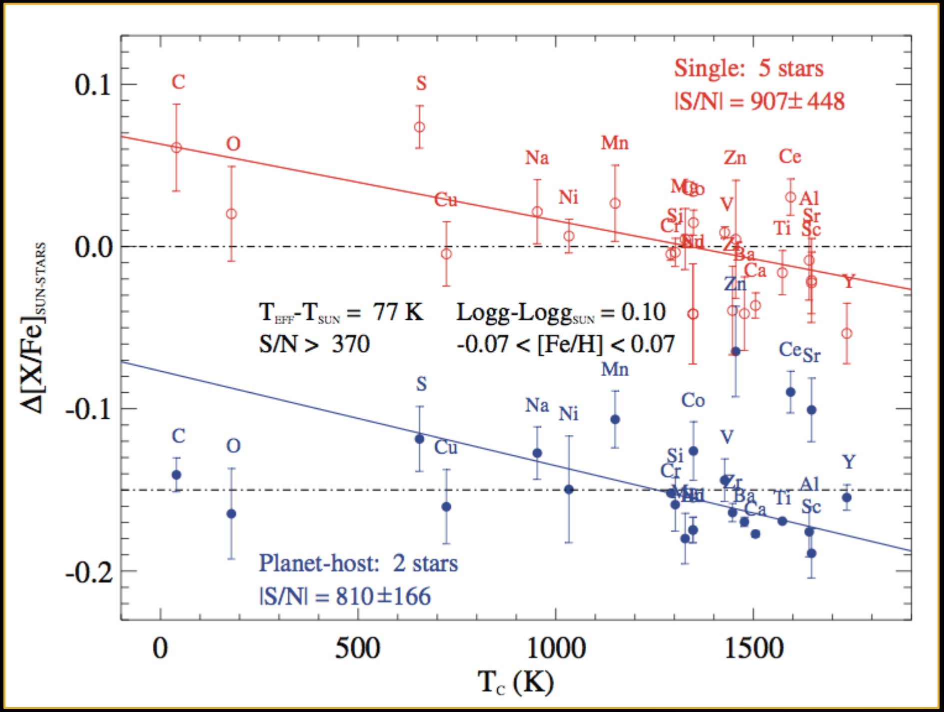
González Hernández et al. (2010, ApJ)



VOLATILE AND REFRACTORY ELEMENTS: SOLAR TWINS

- González Hernández et al. (2010) : solar twins (7 stars in HARPS)

  - No so clear trend versus T_C

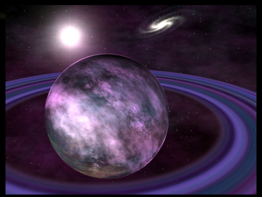


González Hernández et al. (2010, ApJ; 2011, CS16 ASP)

High quality spectra
S/N > 370
R~115,000

- $Teff_{TWINS-SUN} < 77K$
- $Logg_{TWINS-SUN} < 0.1dex$
- $[Fe/H]_{TWINS-SUN} < 0.07dex$
- S/N > 370

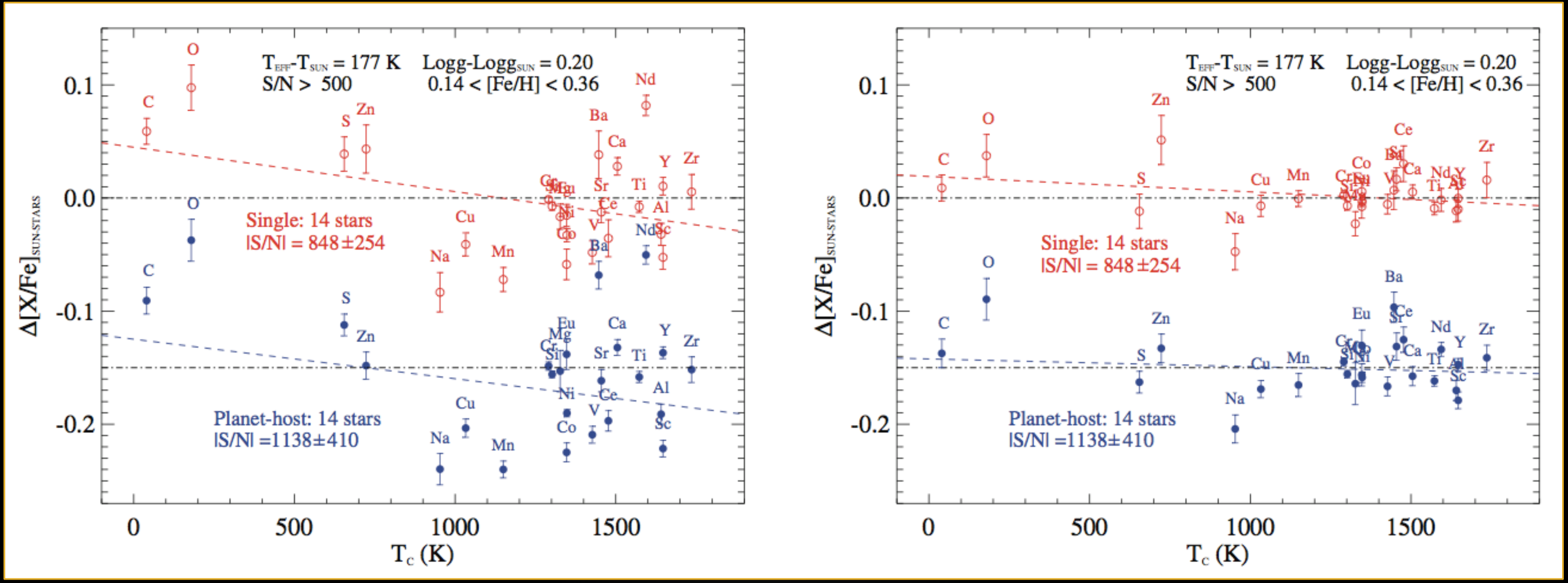
- 5 planet hosts and 2 single stars
- Negative slopes -> no terrestrial planets (according to Meléndez et al.)



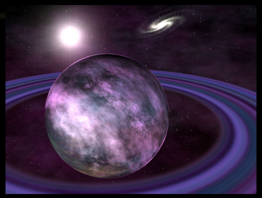
METAL RICH SOLAR ANALOGS

- González Hernández et al. (2011) : solar analogs

- No trend versus T_C for metal-rich solar analogs after subtracting the chemical galactic trends



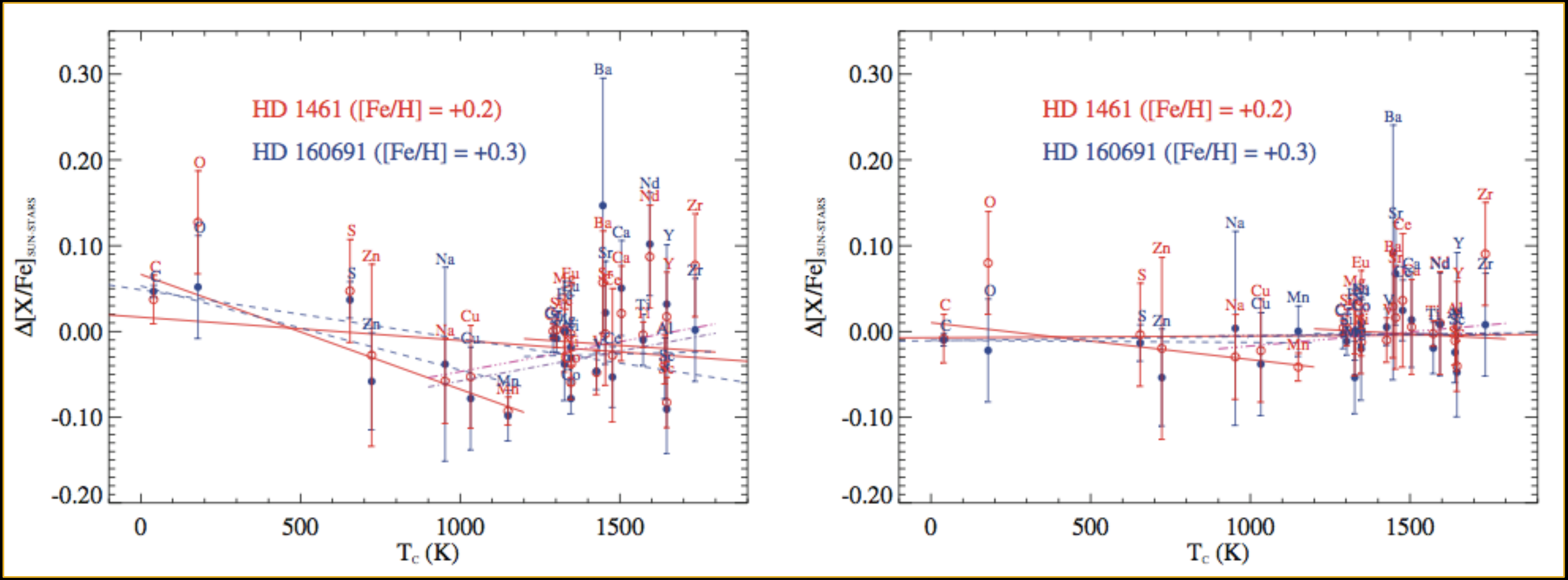
González Hernández et al. (2010, ApJ, 2011, CS16 ASP)



METAL RICH SOLAR ANALOGS WITH SUPER-EARTHS

- González Hernández et al. (2011) : solar analogs

- No trend versus T_C for metal-rich solar analogs with super-Earth like planets after subtracting the chemical galactic trends

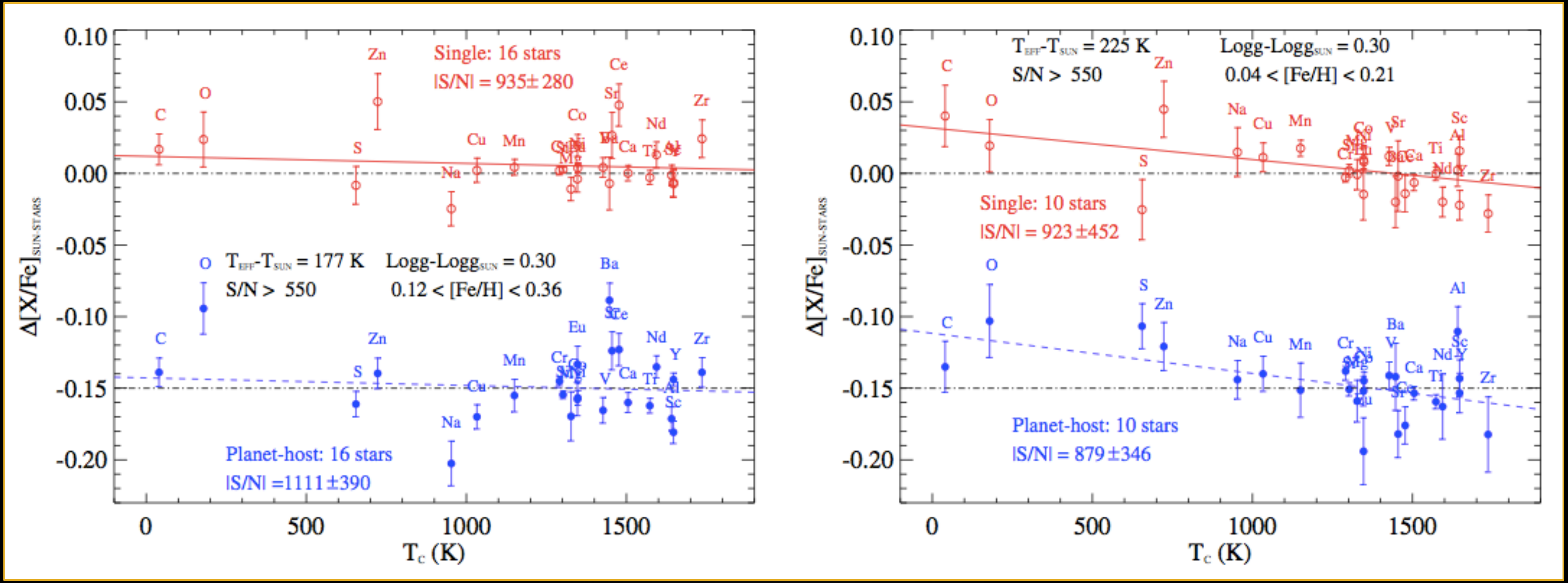


González Hernández et al. (2010, ApJ, 2011, CS16 ASP)

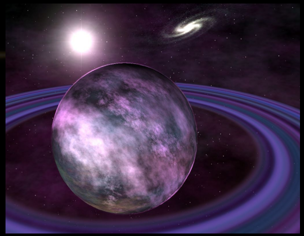
Metal Rich Solar Analogs and “hot” Analogs

- González Hernández et al. (2010; 2013) : solar and “hot” analogs

- No trend versus T_C for metal-rich solar analogs with super-Earth like planets after subtracting the chemical galactic trends



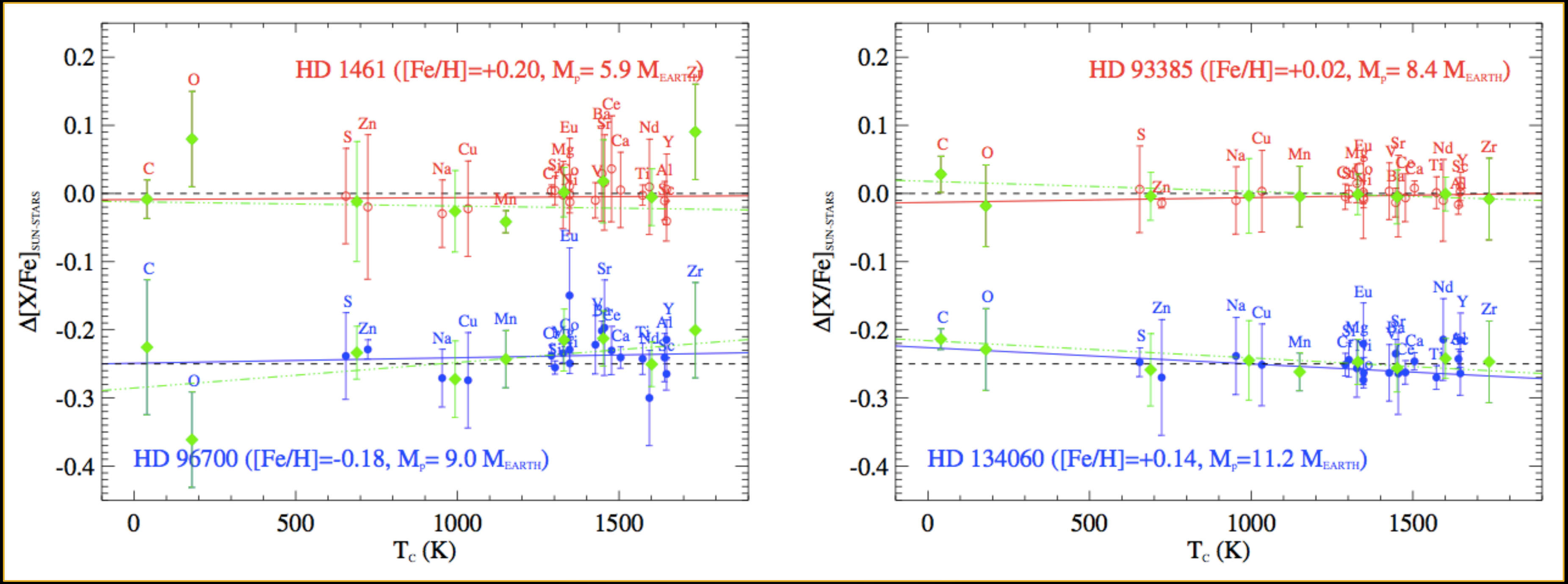
González Hernández et al. (2010, ApJ; 2013, A&A; 2013, AN)



Solar Analogs and “hot” Analogs with super-Earths

- González Hernández et al. (2010; 2013) : solar and “hot” analogs

- Stars with super-Earth like planets showing positive, negative and flat trends after subtracting the chemical galactic trends

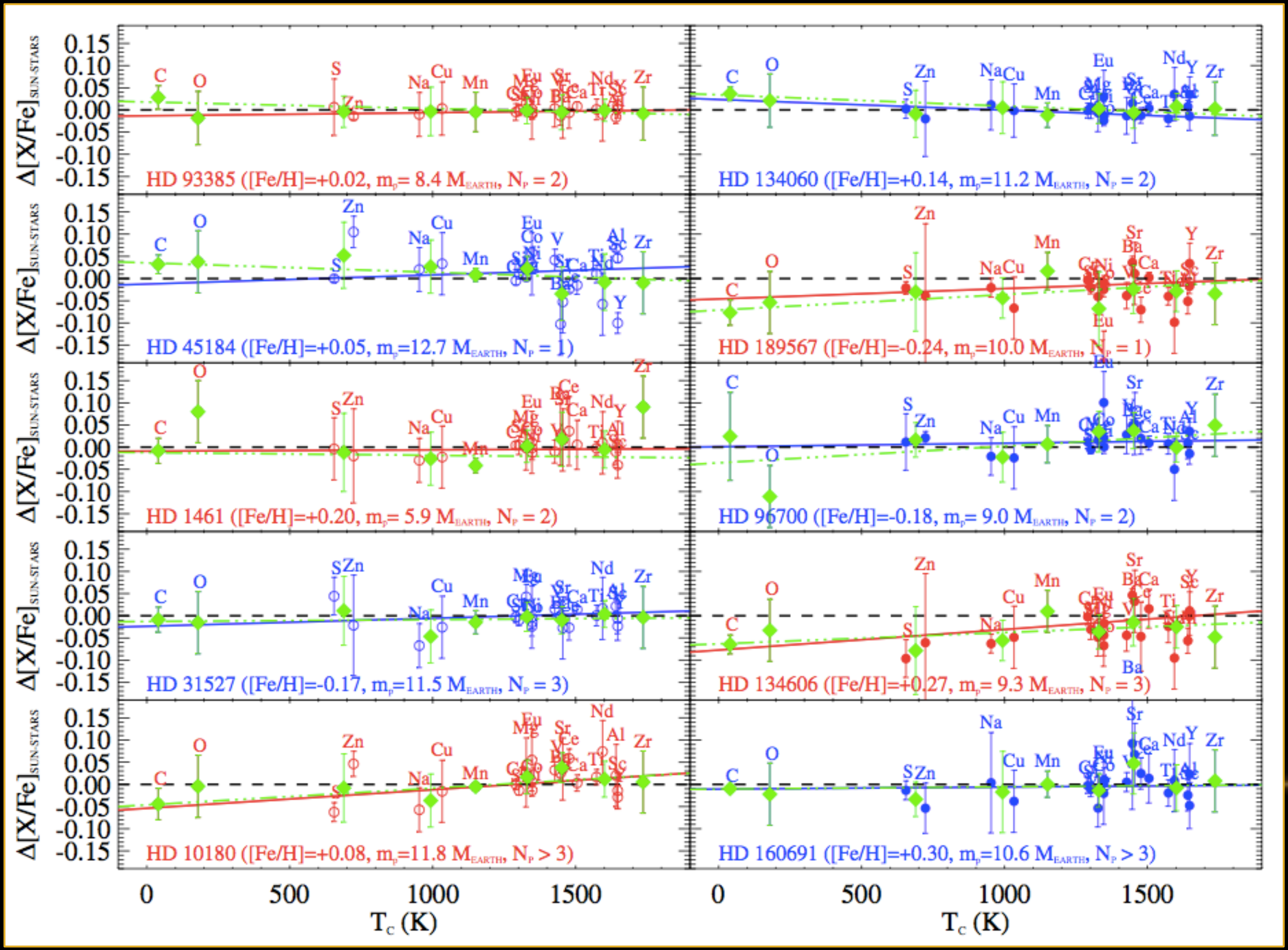


González Hernández et al. (2010, ApJ; 2013, A&A; 2013, AN)

SOLAR ANALOGS AND "HOT" ANALOGS WITH SUPER-EARTHS

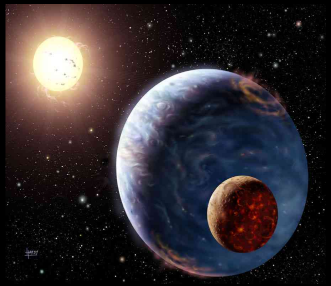
- González Hernández et al. (2010; 2013) : solar and "hot" analogs

  - Stars with super-Earth like planets showing positive, negative and flat trends after subtracting the chemical galactic trends



8 solar analogs and 2 "hot" analogs with super-Earth like planets

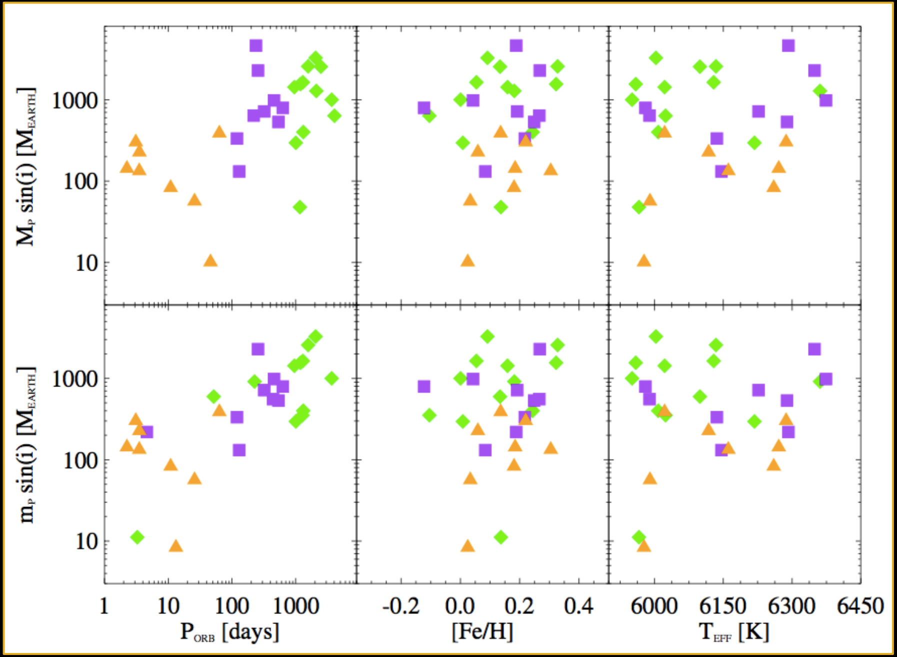
González Hernández et al. (2013, A&A)



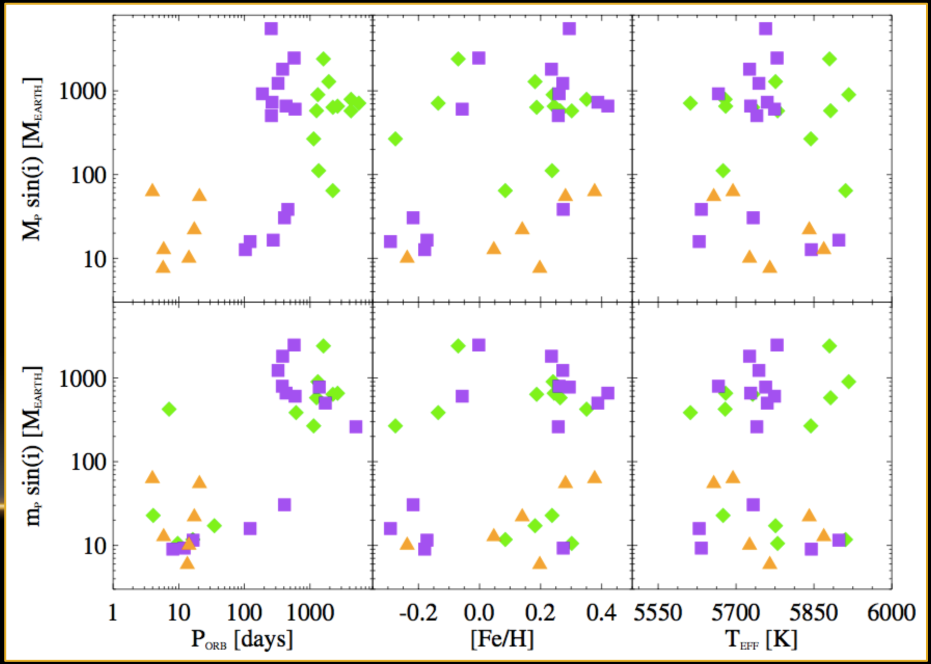
Solar and Hot Analogs With Planets: Parameters

- González Hernández et al. (2013) : solar and hot analogs with planets

  Very diverse planetary systems, covering a wide range of planet masses and orbital periods at differente Teff and [Fe/H]

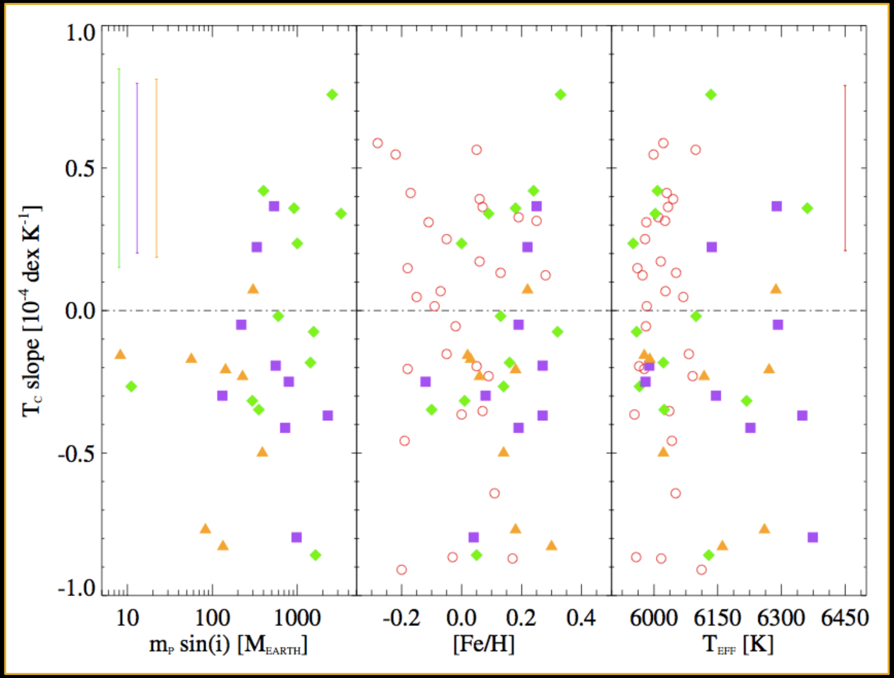


González Hernández et al. (2013, A&A)



Solar and Hot Analogs With Planets: Slopes

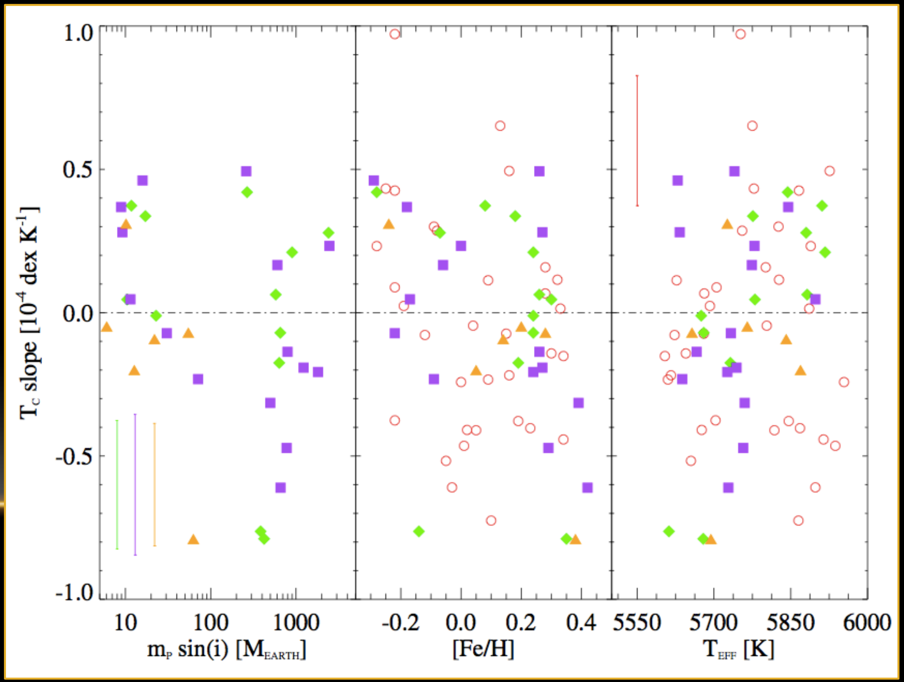
- González Hernández et al. (2013) : positive and negative slopes for solar and hot analogs with planets at different planet masses



Sample 148 stars with high-quality HARPS data:

- solar analogs (95 stars: 62 “single” stars and 33 planet hosts)
- “hot” analogs (61 stars: 32 “single” stars and 29 planet hosts)

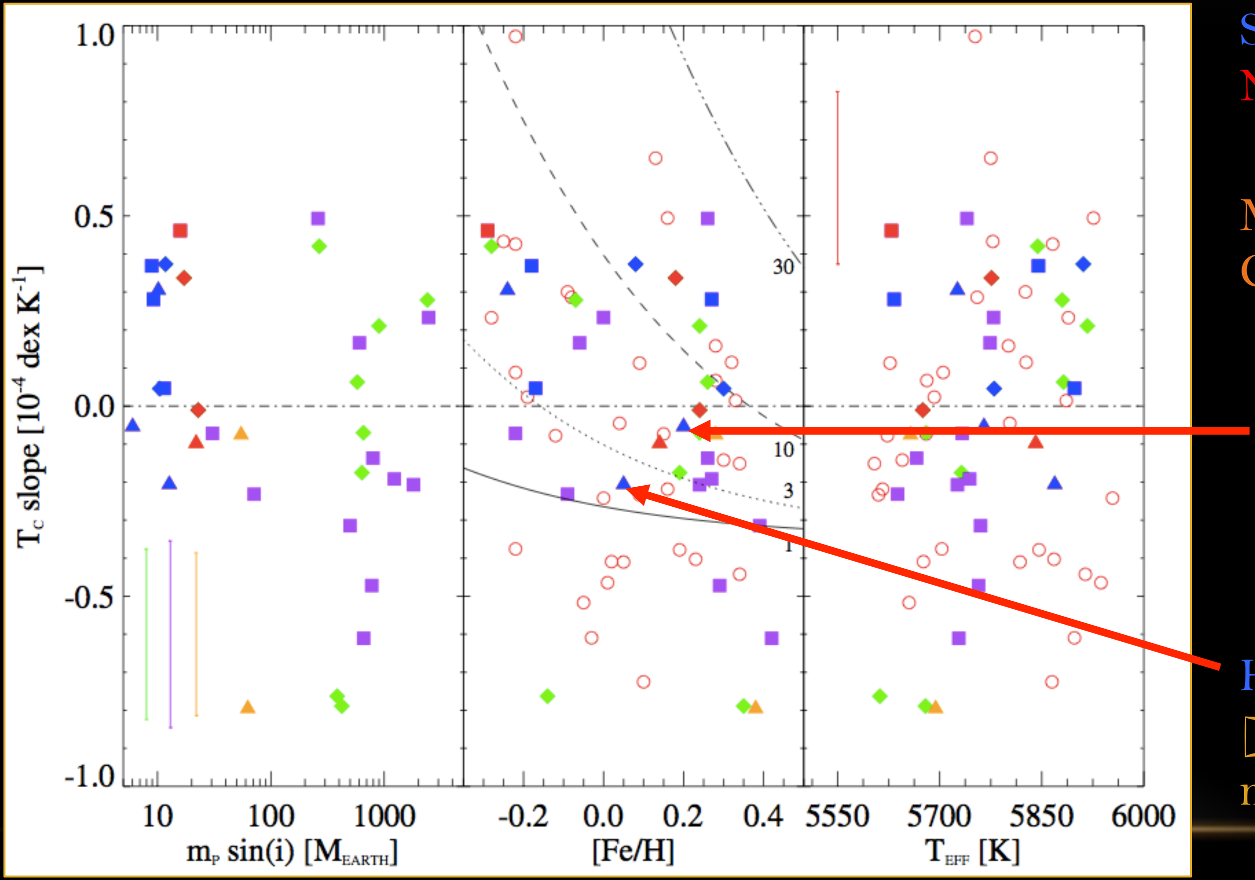
González Hernández et al. (2013, A&A)



Positive slopes means lower refractory-to-volatile abundance ratios than in the Sun

SOLAR ANALOGS WITH PLANETS: SLOPES

- González Hernández et al. (2013) : positive and negative slopes for solar analogs with planets at different planet masses



Super-Earths

Neptunes

Model from Chambers (2010)

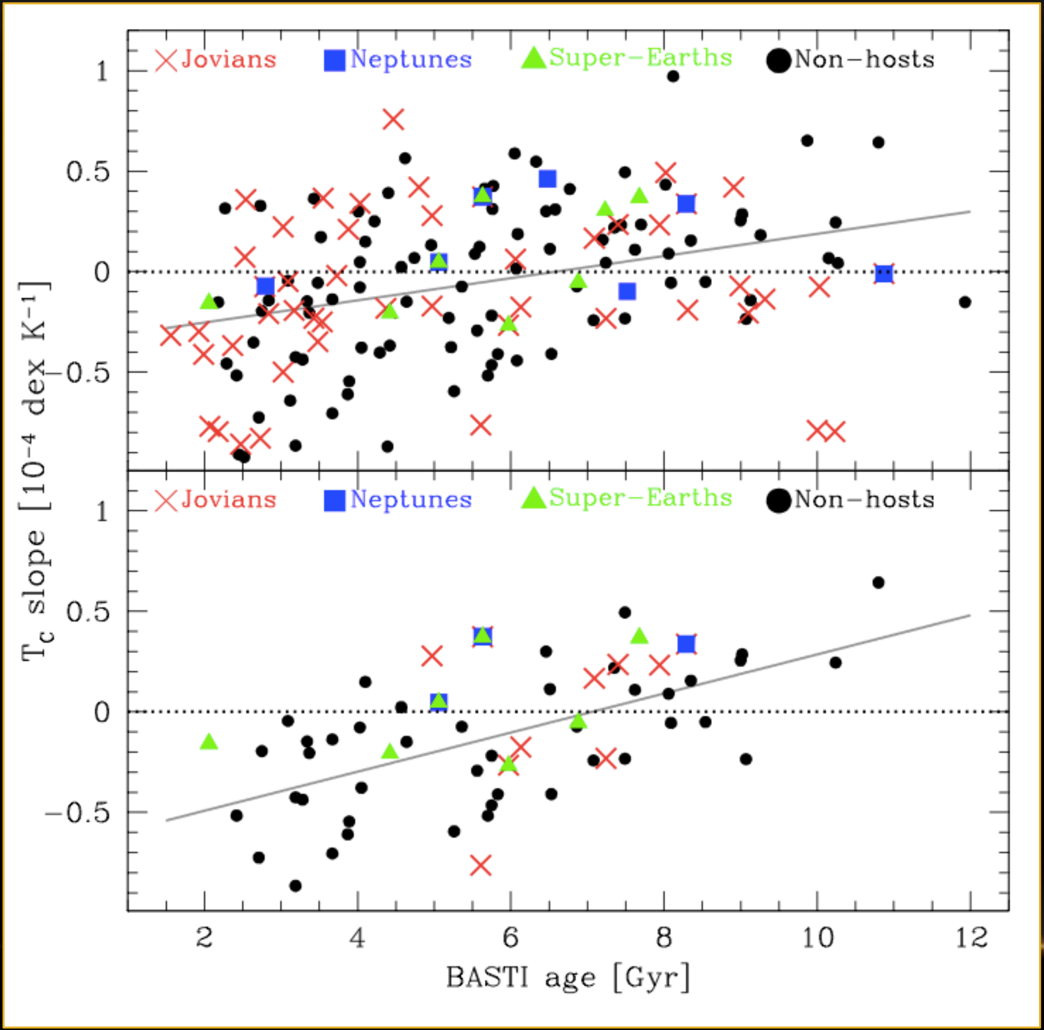
HD 1461:
[Fe/H]~+0.20,
$m_p$sini~5.9 M⊕
$m_p$sini~7.2 M⊕

HD 45184:
[Fe/H]~+0.05,
$m_p$sini~13M⊕

González Hernández et al. (2013, A&A)

SOLAR AND HOT ANALOGS WITH PLANETS: AGES

- Adibekyan et al. (2014) : strong correlation T_c slopes with age



Adibekyan et al. (2014, A&A letters)

Super-Earths
Neptunes
Jovian
Single stars

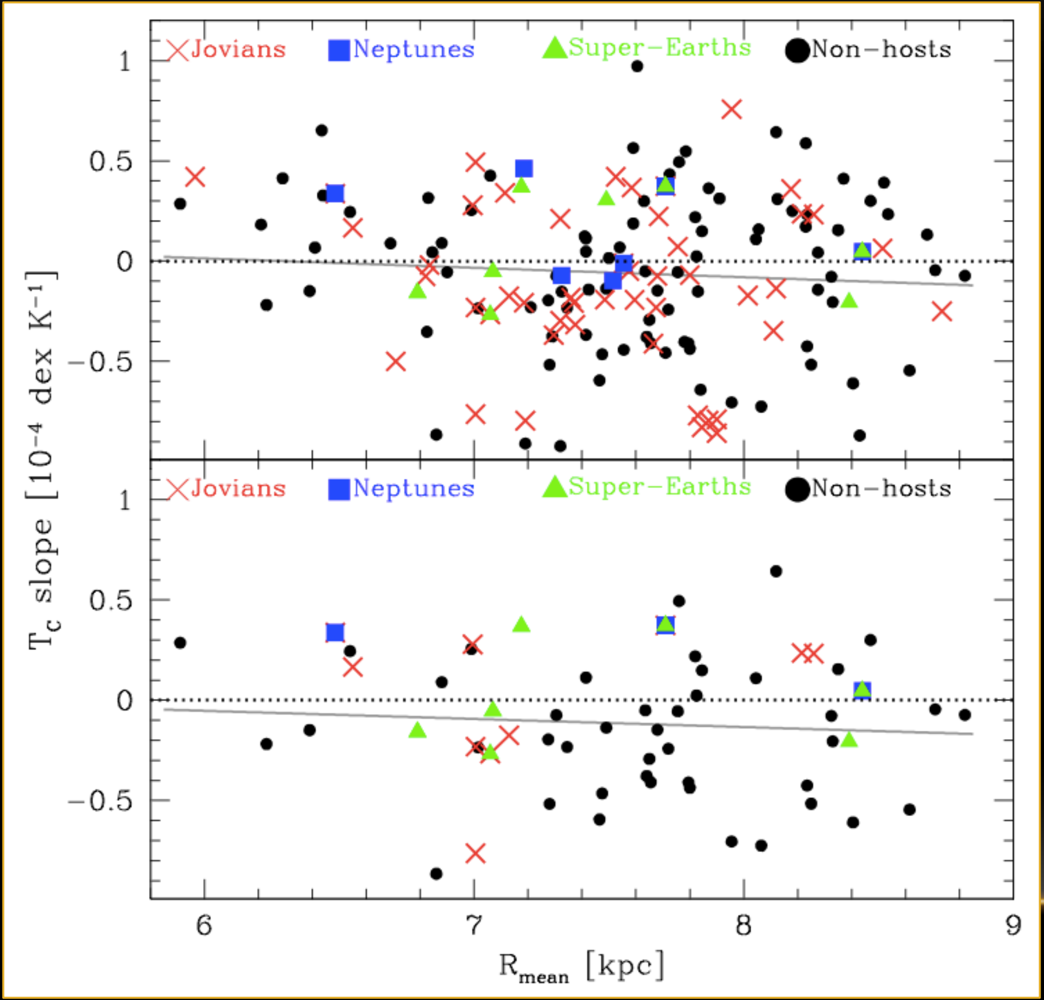
T_C slopes from González Hernández et al. (2010, 2013)

Sample 148 stars:
95 SA and 61 HA stars

Old stars more depleted in refractories (lower refractory- to-volatile ratios) than their younger counterparts

SOLAR AND HOT ANALOGS WITH PLANETS: RMEAN

- Adibekyan et al. (2014) : weaker correlation T_c slopes with R_{mean} (mean of the apo- and pericentric distances of galactocentric orbits



Adibekyan et al. (2014, A&A letters)

Super-Earths
Neptunes
Jovian
Single stars

Stars at low R_{mean} have positive average *Tc* slopes (≈0.071 ± 0.065) than the average of the stars with R_{mean} = 8 ± 1 kpc (*Tc* ≈ −0.086 ± 0.035).

Stars with positive *Tc* slopes (lower refractory-to-volatile ratios) probably have originated in the inner Galaxy.

The chemical composition of the "birth place" may partially responsible for the *Tc* trends

THE NATURE OF VERY ACCURATE ABUNDANCE TRENDS IN SOLAR ANALOGS

Jonay I. González Hernández

Instituto de Astrofísica de Canarias

Pathways 2015: **Pathways towards habitable exoplanets**

SM8: Connecting Stellar Abundances and Planet Habitability

Bern, Switzerland, 13th July 2015

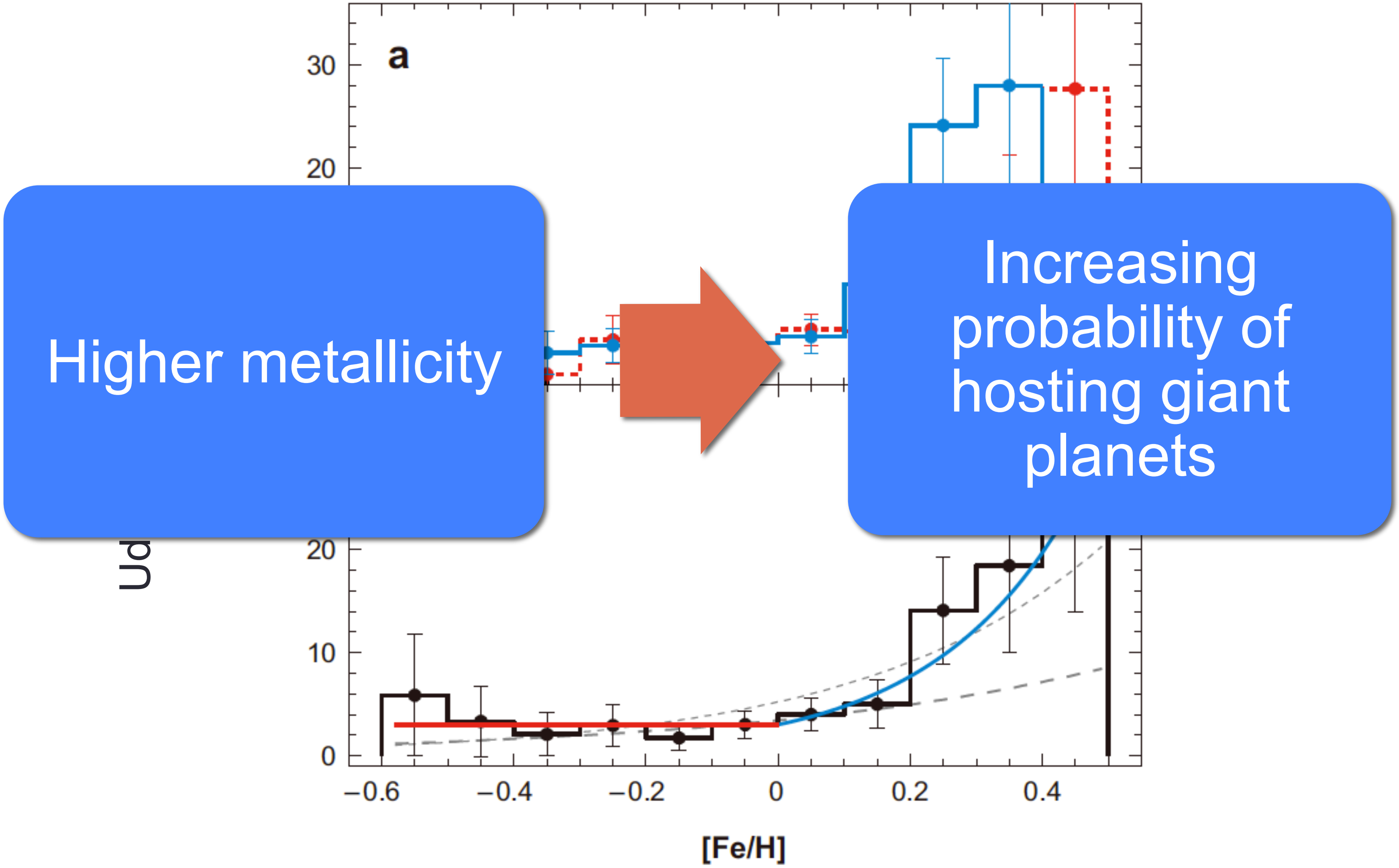
THE CHEMICAL COMPOSITION OF KEPLER-10

A possible signature of terrestrial planet formation?

Fan Liu
D. Yong, I. Ramirez, J. Melendez
M. Asplund, B. Gustafsson, L. Howes
D. Lambert, T. Bensby

Australian
National
University

Metallicity of planet hosts

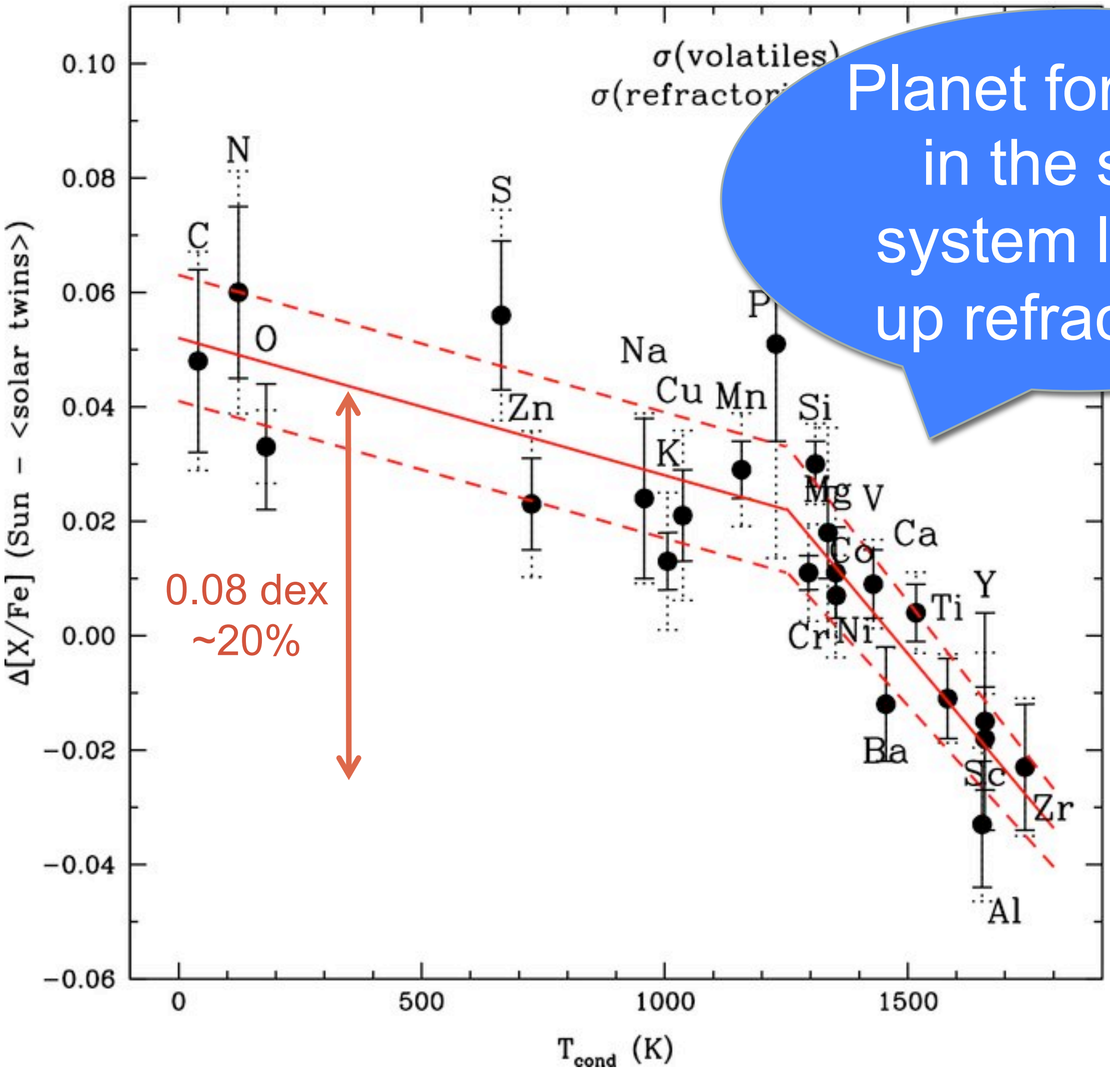


Higher metallicity

Increasing probability of hosting giant planets

Signatures of terrestrial planet formation?

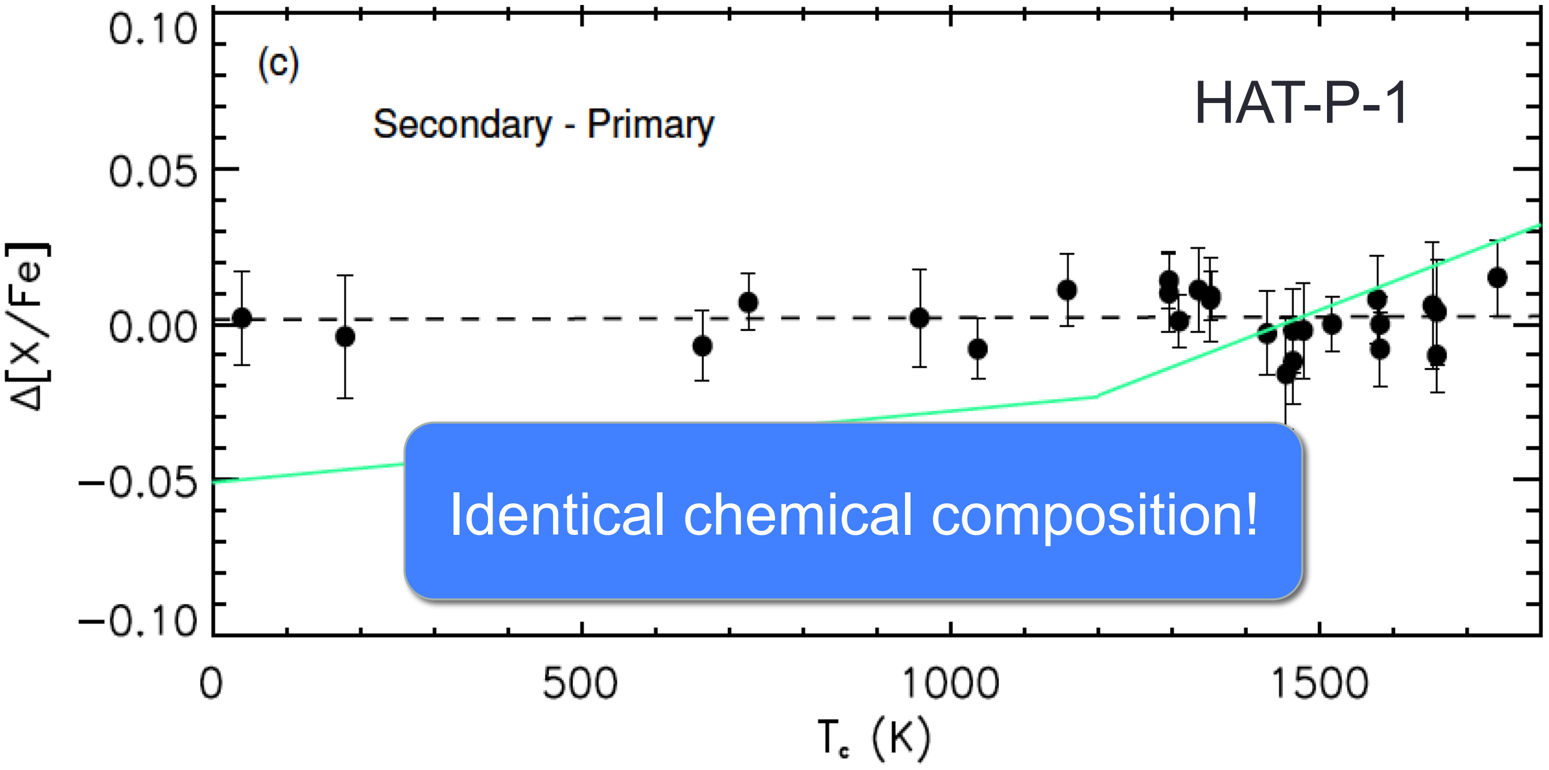
Melendez et al. 2009



Planet formation in the solar system locked up refractories

Condensation temperature

No obvious signature of giant planet formation?

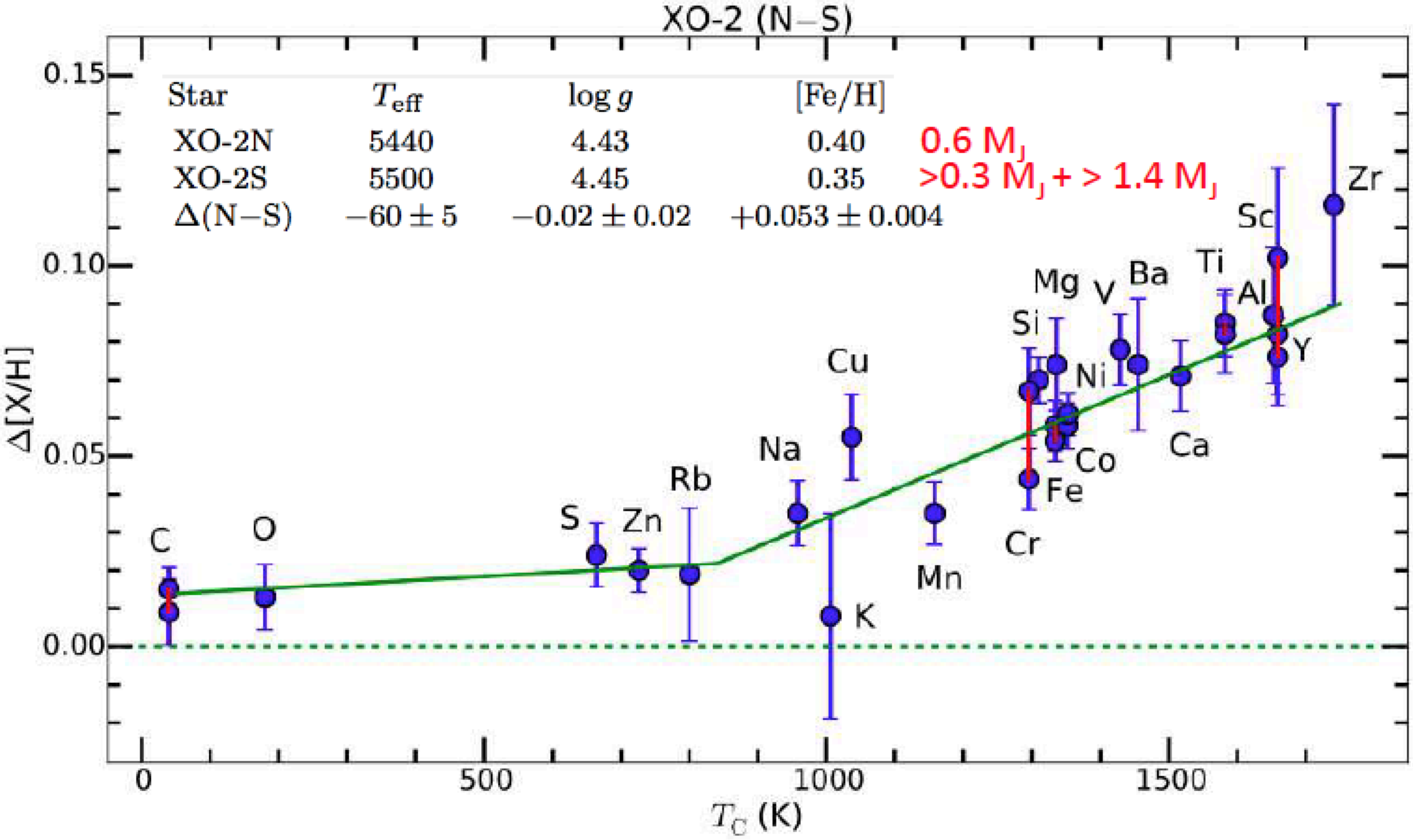


Liu et al. 2014

Identical chemical composition!

Presence of giant planets does not imprint chemical differences of their hosts?

Another binary system: XO-2

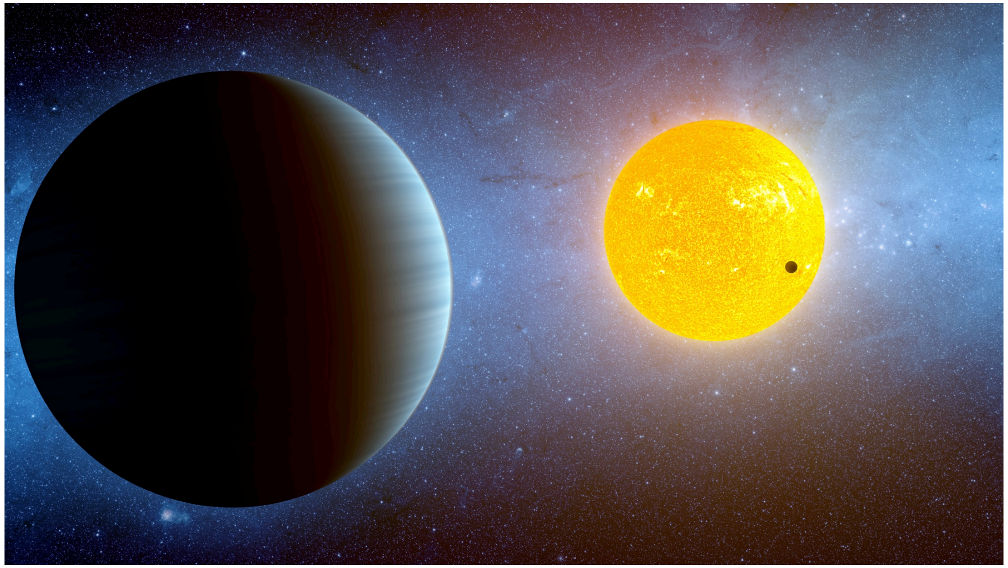


Ramirez…Liu…et al. 2015, ApJ in press. See also Teske et al. 2015

Kepler-10

- Two rocky planets (Kepler-10b ~ 3.3 M_E, Kepler-10c ~ 17.2 M_E, Dumusque et al. 2014)

- Ideal target to test the possible chemical signatures of rocky planet formation

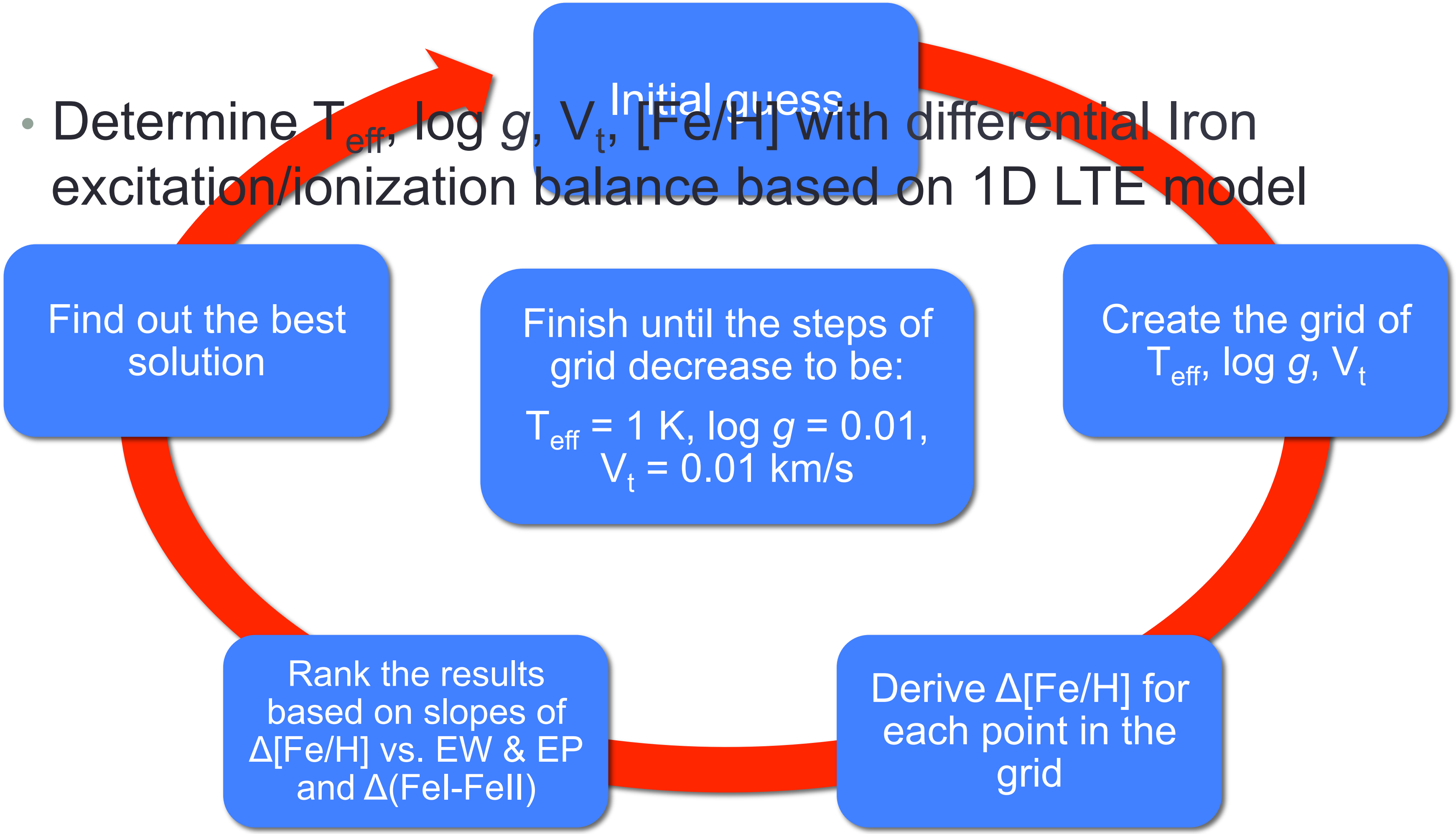


Observations

Target	Telescope/ Instrument	Resolution	S/N (per pixel)
Kepler-10	HET-HRS	60,000	> 350
Kepler-10	CFHT-ESPaDOnS	68,000	~ 300
Kepler-10's stellar twins	Magellan-MIKE	65,000 (red) 83,000 (blue)	> 300

Methodology

- Determine T_{eff}, log g, V_t, [Fe/H] with differential Iron excitation/ionization balance based on 1D LTE model



Initial guess

Create the grid of T_{eff}, log g, V_t

Derive Δ[Fe/H] for each point in the grid

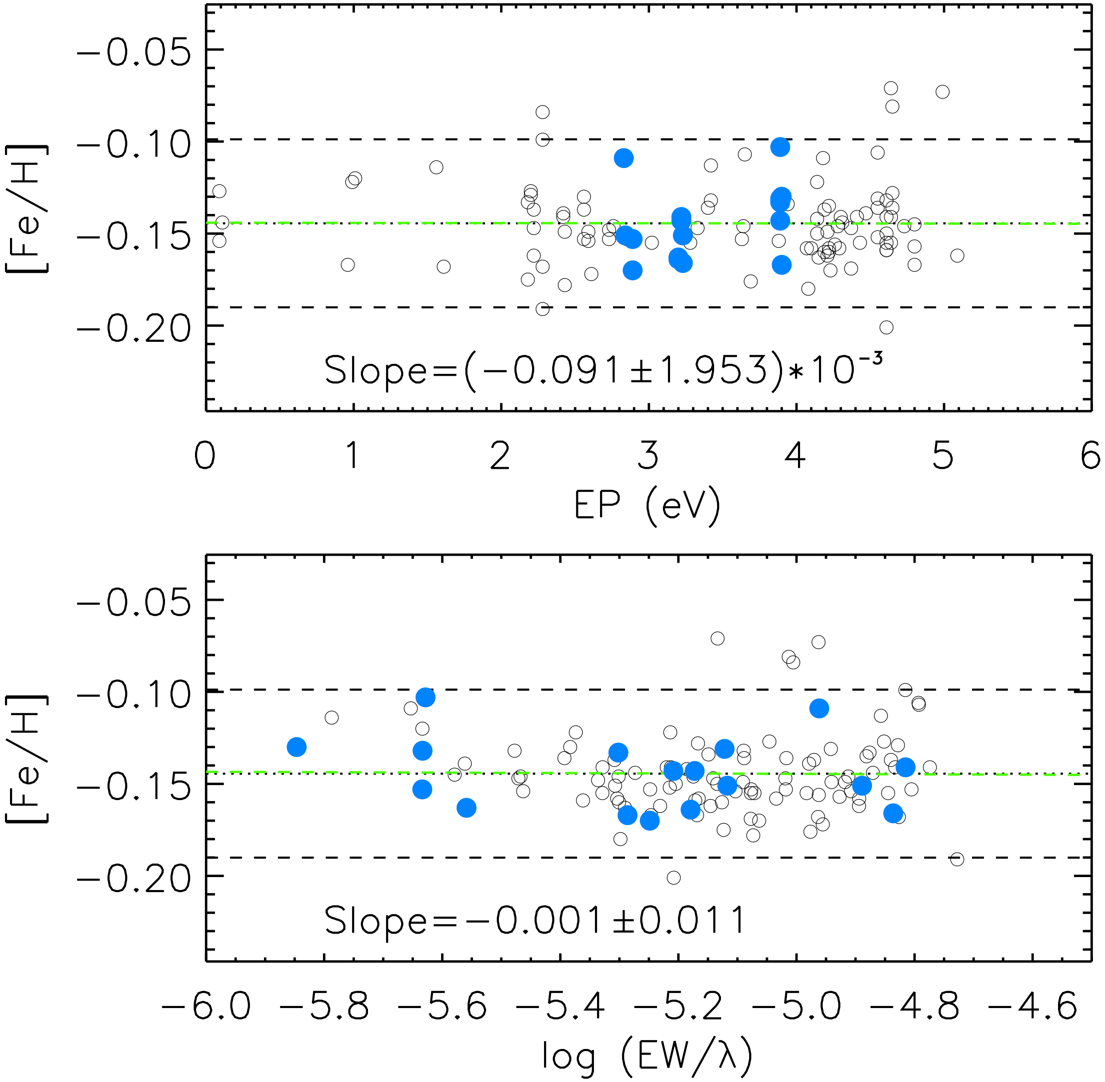
Rank the results based on slopes of Δ[Fe/H] vs. EW & EP and Δ(FeI-FeII)

Find out the best solution

Finish until the steps of grid decrease to be:

T_{eff} = 1 K, log g = 0.01, V_t = 0.01 km/s

Example of balancing plot



Stellar parameters

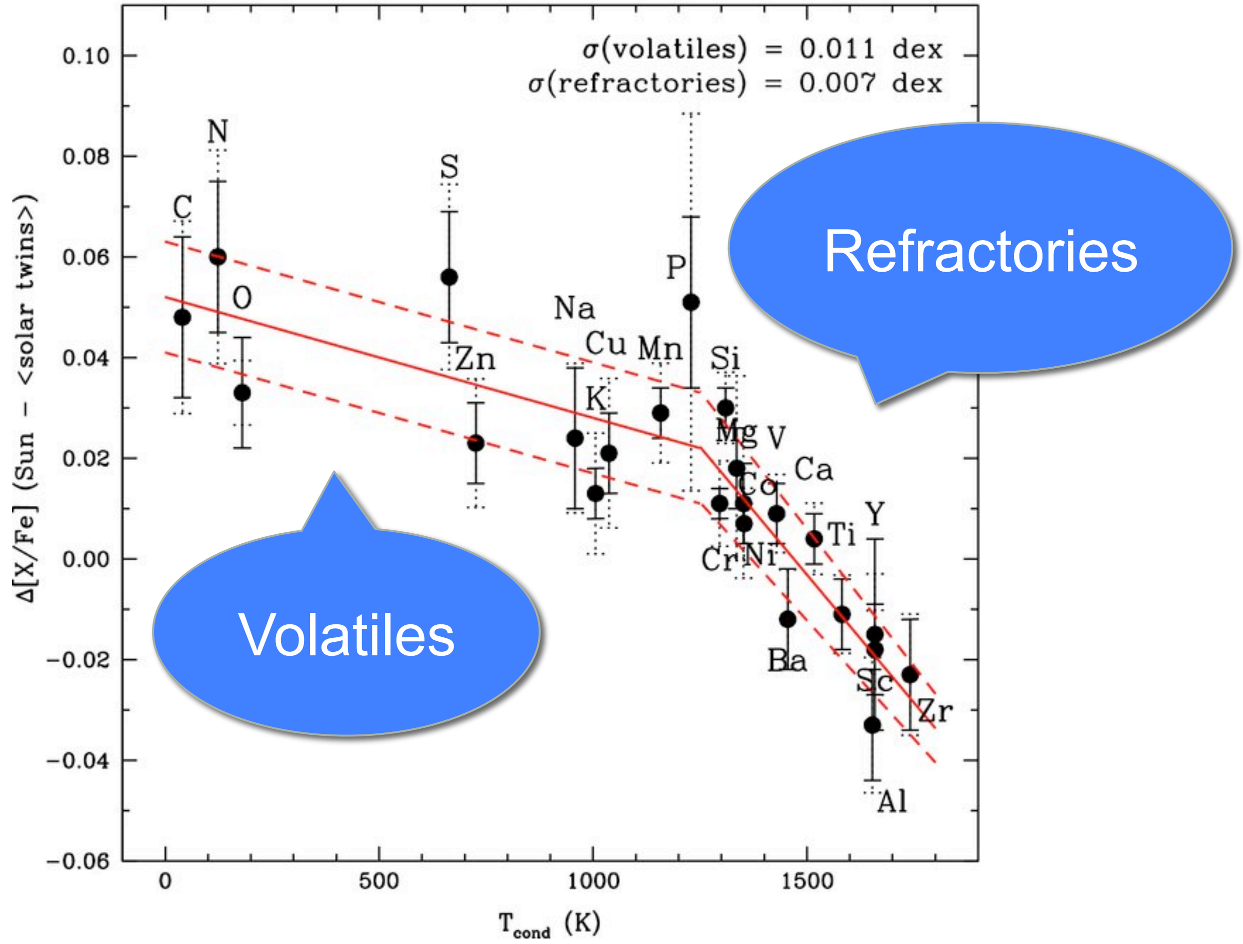
Target	T_{eff} (K)	log *g* [cgs]	[Fe/H]	Age (Gyr)
Kepler-10	5700 ± **12**	4.39 ± 0.03	-0.145 ± **0.011**	9.3 ± 0.9
HD 87320	5669 ± **10**	4.39 ± 0.03	-0.145 ± **0.010**	8.8 ± 0.8
HD 106210	5703 ± **12**	4.39 ± 0.03	-0.126 ± **0.013**	8.2 ± 0.9
HD 115231	5719 ± **14**	4.43 ± 0.04	-0.087 ± **0.015**	7.0 ± 1.2
HD 117126	5788 ± **15**	4.24 ± 0.04	-0.031 ± **0.014**	8.6 ± 0.3

- Kepler-10 is an old, thick disk star
- Four stellar twins are similar to Kepler-10

Differential abundance analysis

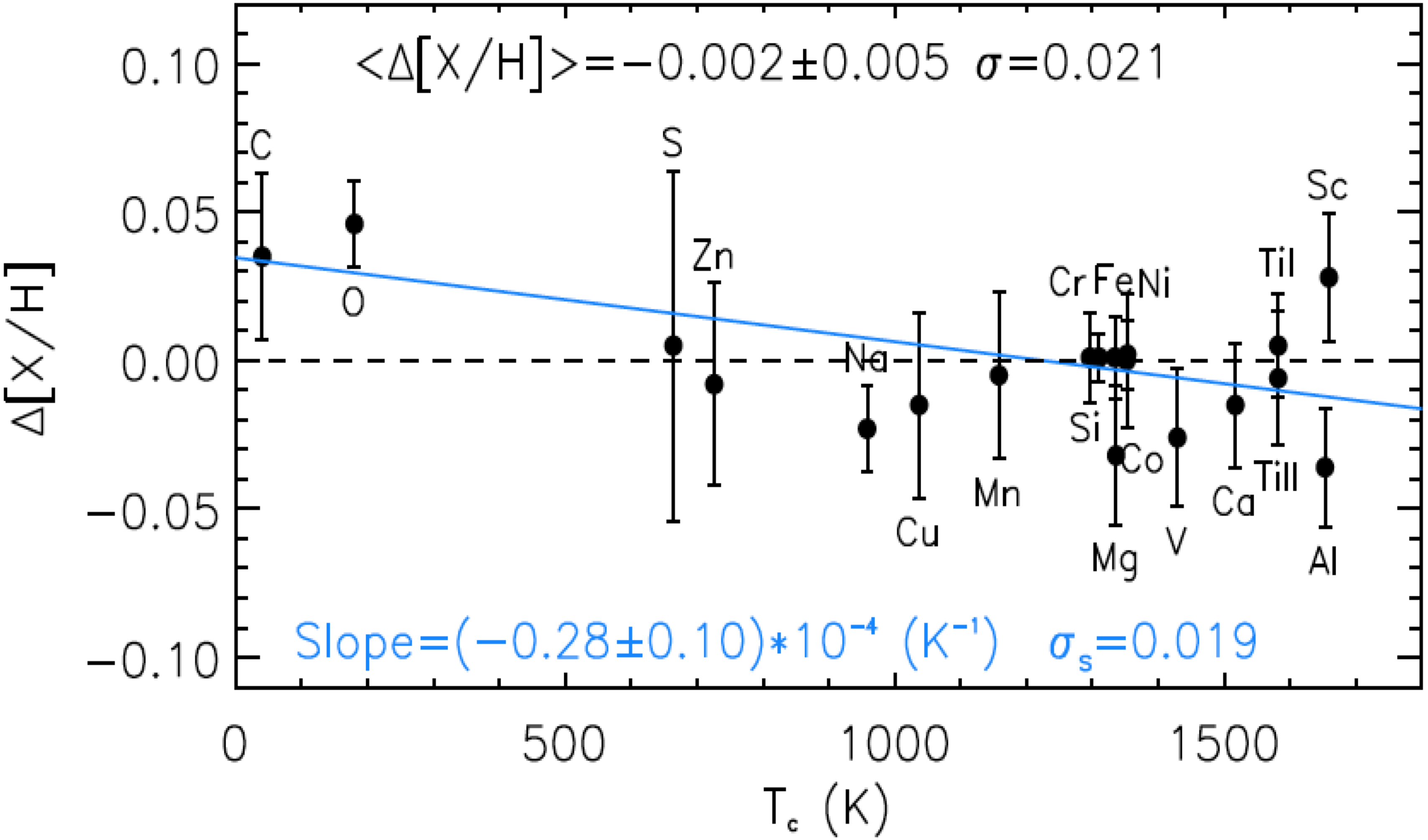
- 18 elements: volatiles (C, O, S etc.) and refractories (Mg, Si, Ca, Fe-peak etc.)

Melendez et al. 2009

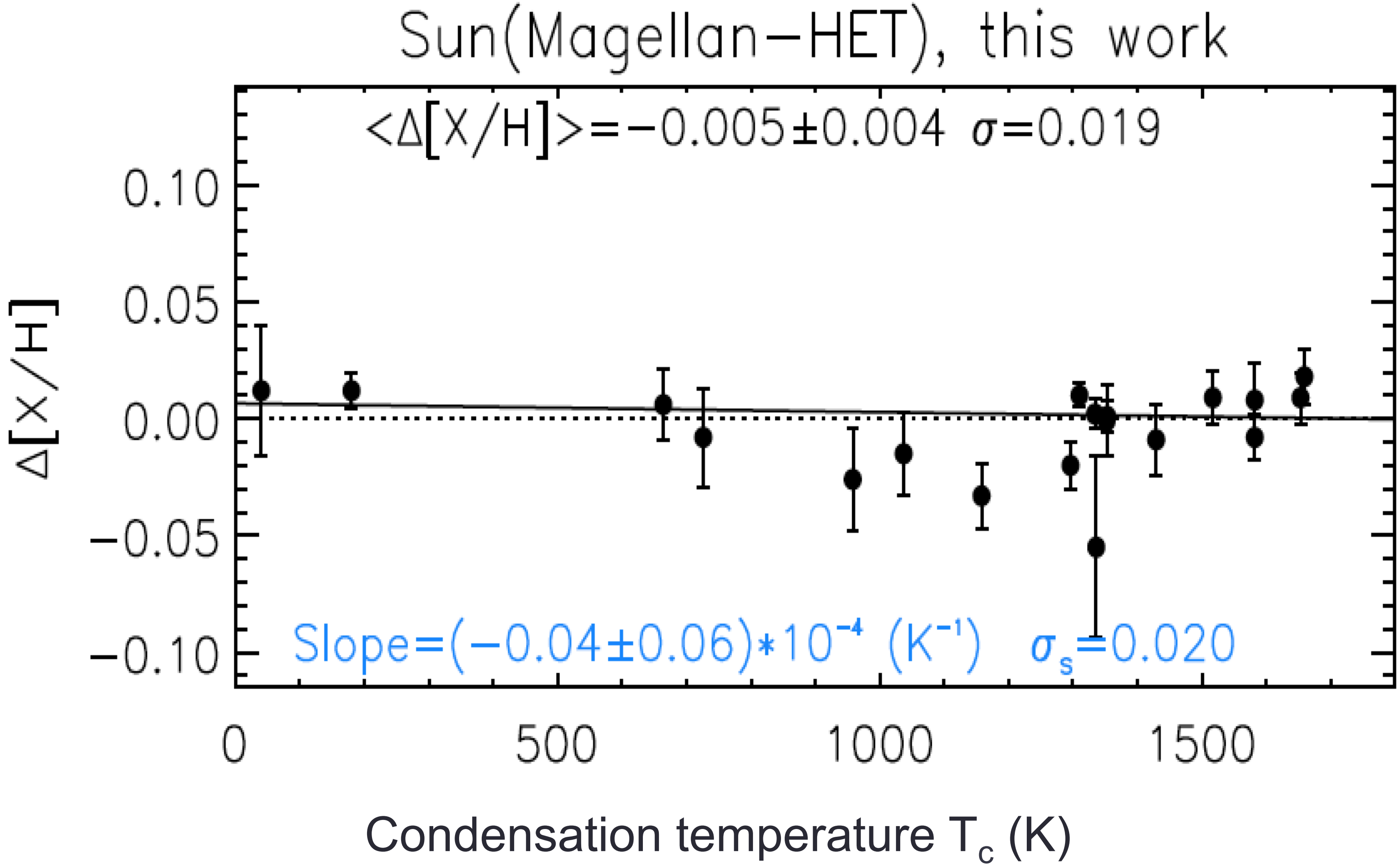


Difference between instruments

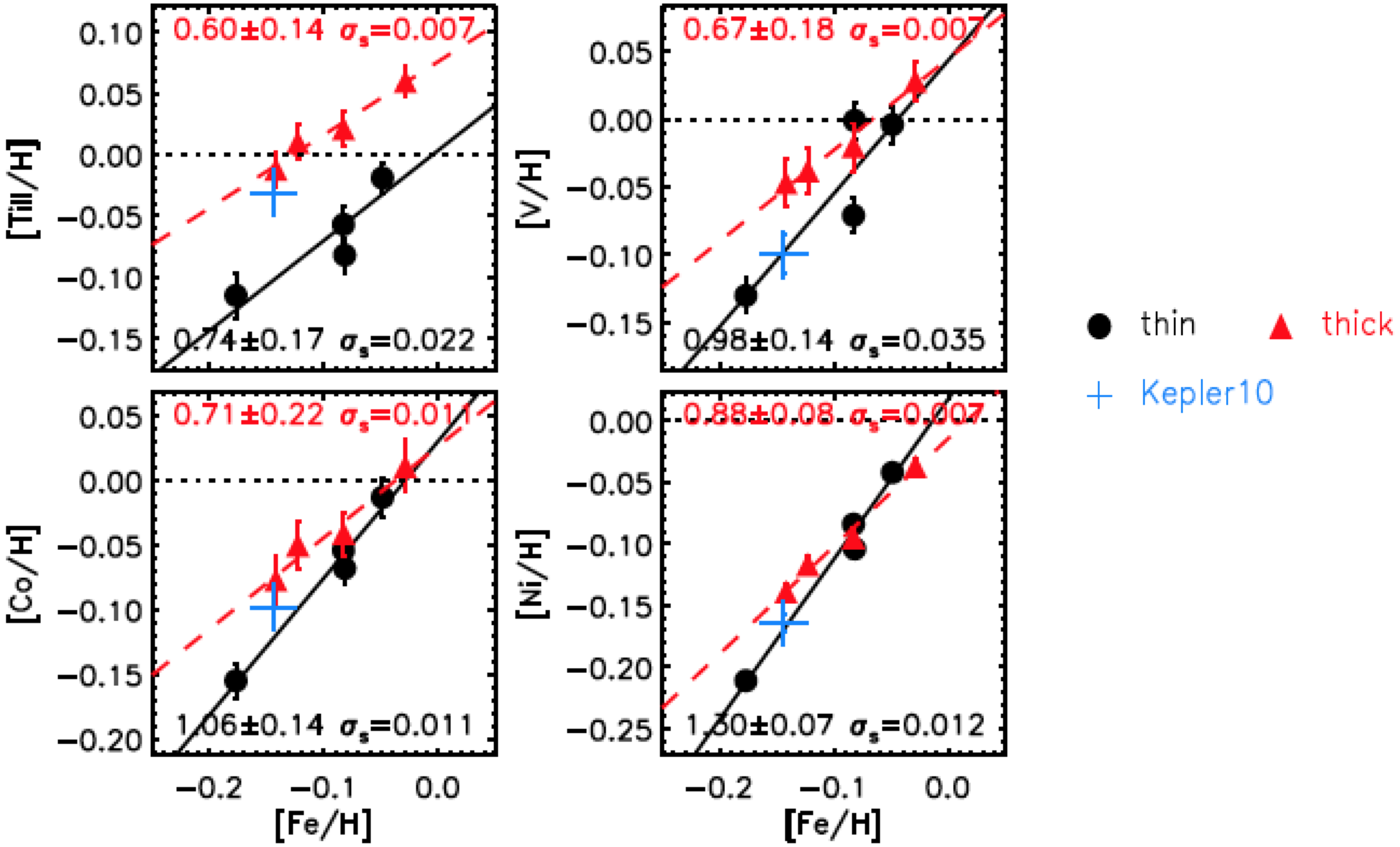
Kepler-10 (HET – CFHT)



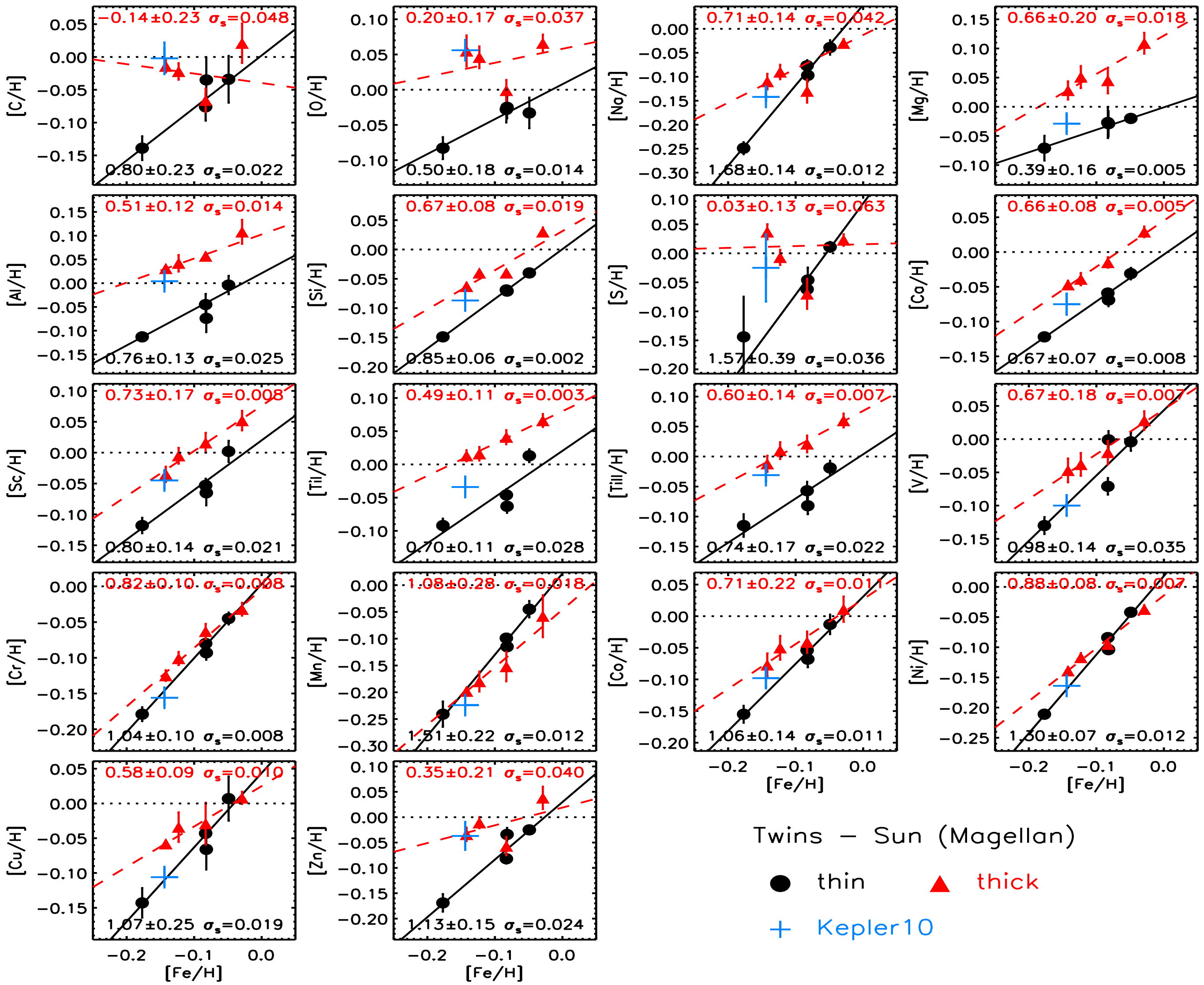
Other systematics?



Subset of elemental abundances

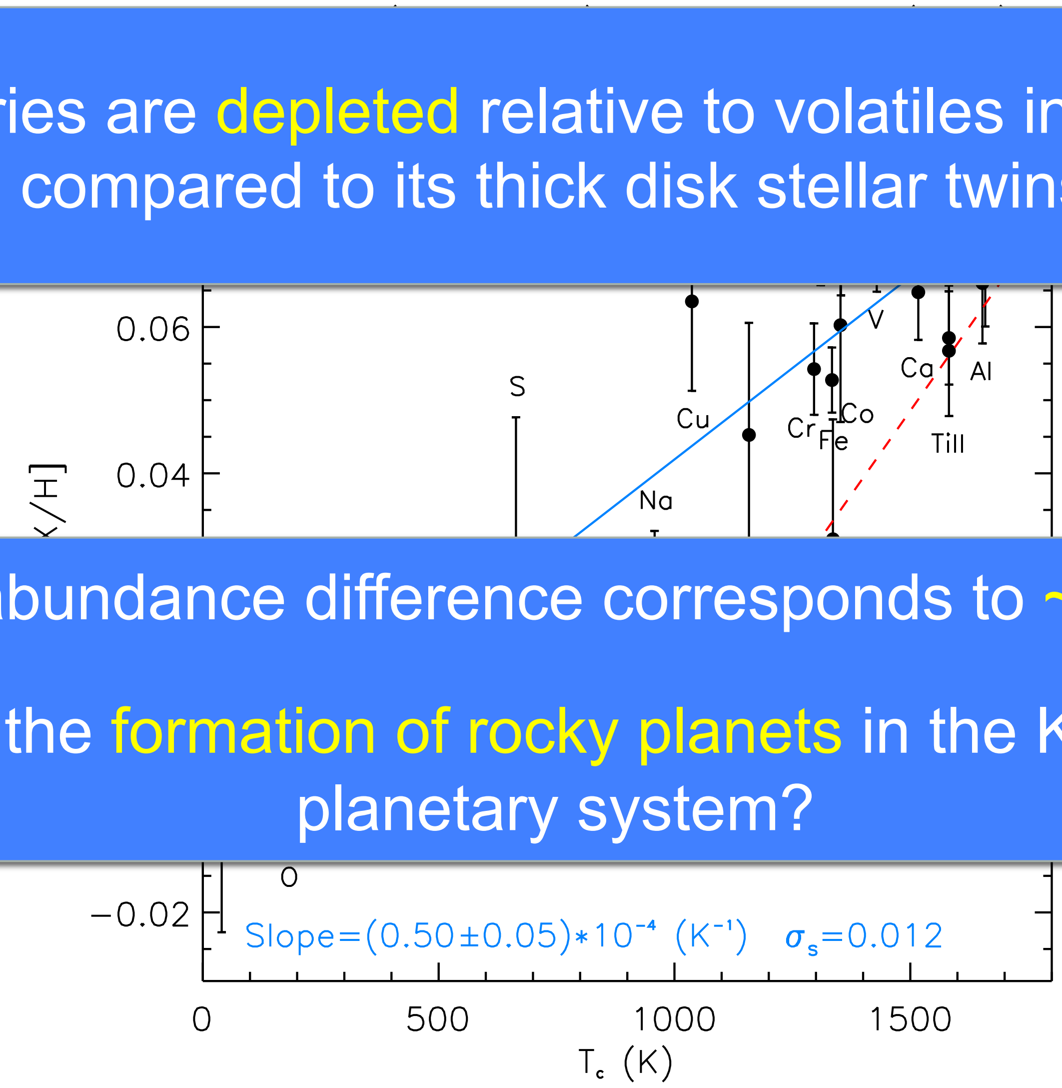


Elemental abundances



Signatures of rocky planet formation?

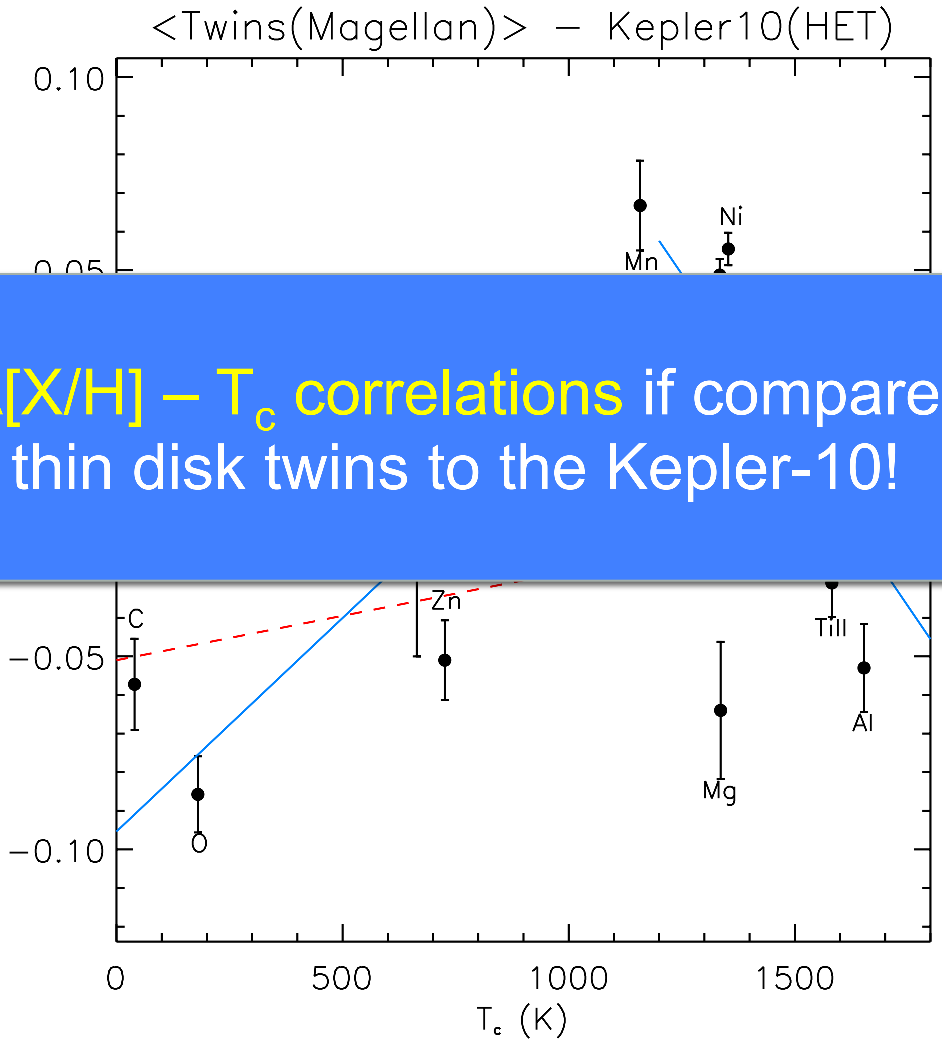
Refractories are depleted relative to volatiles in Kepler-10 compared to its thick disk stellar twins



The abundance difference corresponds to ~ 14 M_E

Due to the formation of rocky planets in the Kepler-10 planetary system?

Comparison to the thin disk twins?

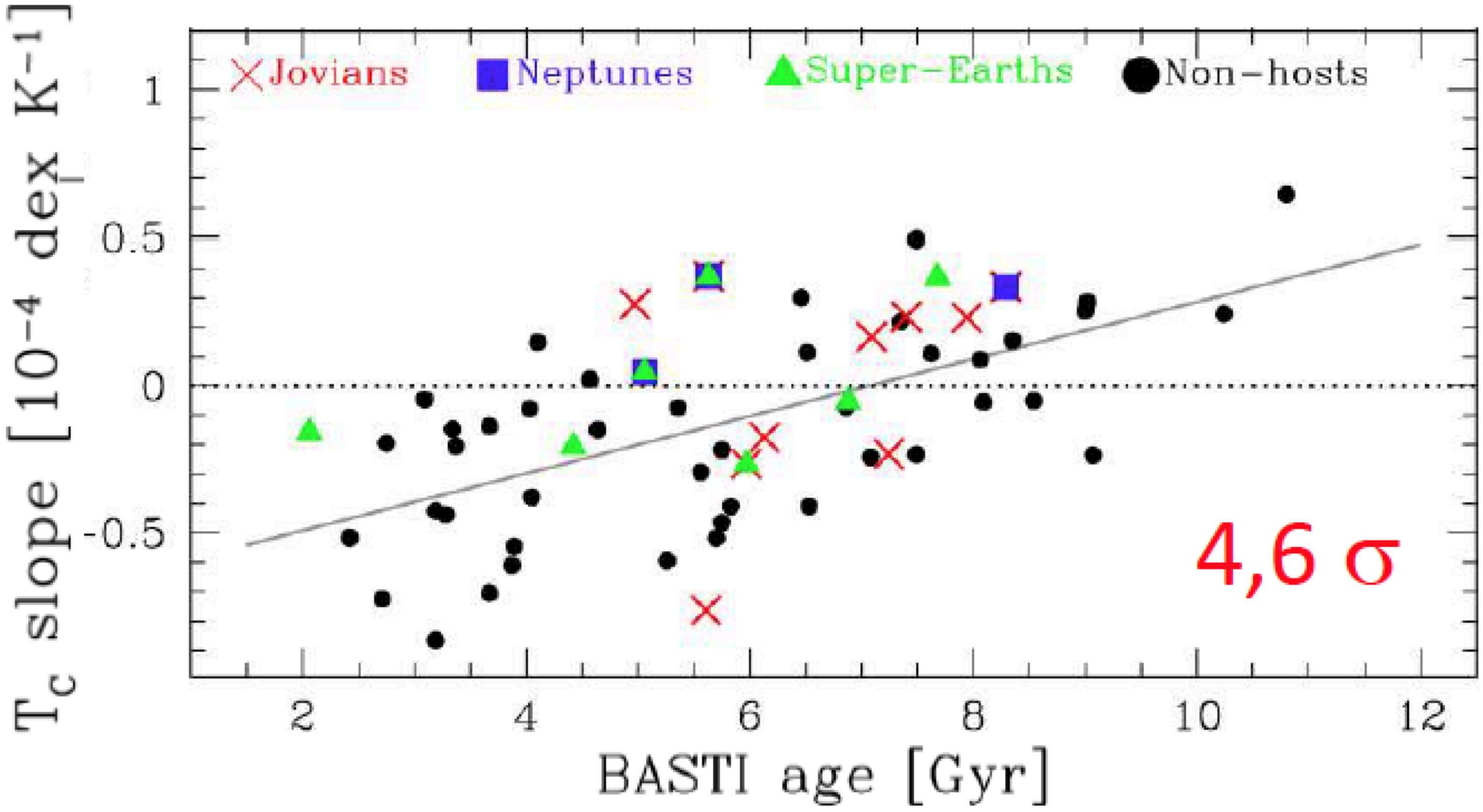

<Twins(Magellan)> – Kepler10(HET)

No Δ[X/H] – T_c correlations if compare the thin disk twins to the Kepler-10!

Other possible interpretations

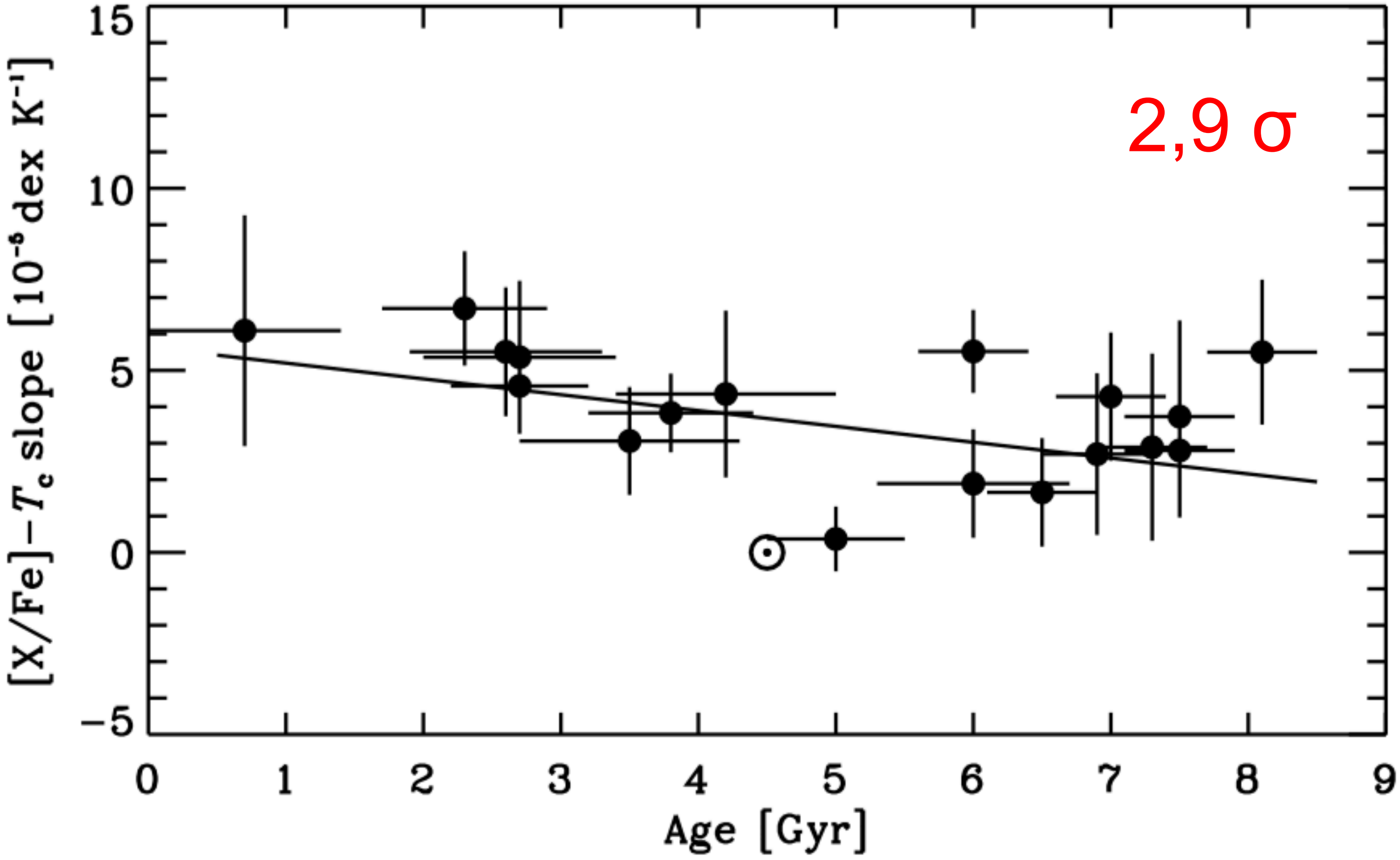
- Sun born in a dense environment? (A. Korn's talk)
- Age effect?

Adibekyan et al. 2014



4,6 σ

Nissen 2015



Summary

- Kepler-10 hosts two rocky planets
- The refractories are depleted relative to volatiles in Kepler-10, when compared to its thick disk stellar twins
- Possibly due to the formation of rocky planets in the Kepler-10 system?

Future plan (open clusters)

- Hyades, no apparent chemical signatures of planet formation found, chemical inhomogeneity detected!

- M67, Keck/HIRES

- Ruprecht 147, VLT/UVES

- Coma Berenices & Praesepe, HET/HRS

- More open clusters (K2 mission)

CNO behaviour in planet-harbouring stars

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Pathways 2015

July 14, 2015

Collaborators

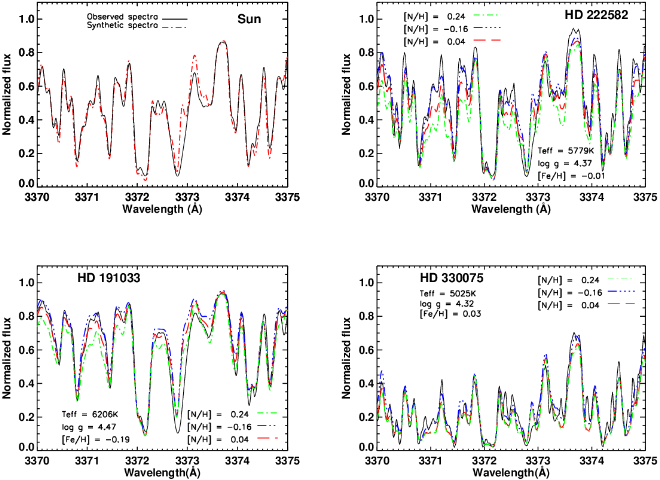
- G. Israelian (IAC, Spain)
- J.I. González Hernández (IAC, Spain)
- V. Adibekyan (CAUP, Portugal)
- E. Delgado Mena (CAUP, Portugal)
- N.C. Santos (CAUP, Portugal)
- S.G. Sousa (CAUP, Portugal)

Background.

- The aim of this work is to understand the formation and the evolution of exoplanetary systems using chemical elements as tracers.
- We made an uniform comparison between stars with and without planetary mass companions in a limited sample in order to study the behaviour of light elements in both samples.
- We studied two light elements, C and N, using molecular bands.

NH Band

- The NH band is the strongest feature in the range of 3345-3375Å



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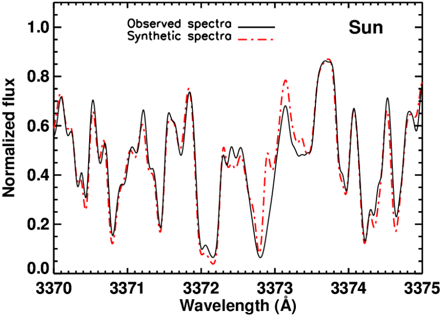
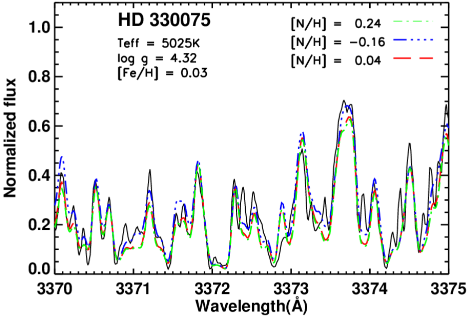




Sample description

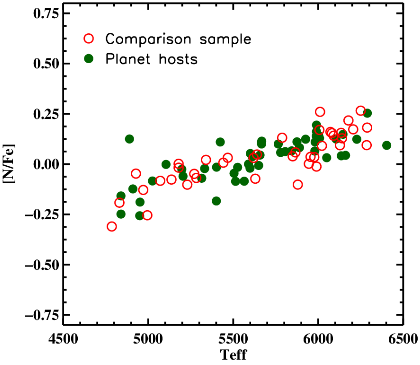
- High resolution spectra taken with UVES@VLT (UT2 Kueyen Telescope)
- 90 stars were observed, 50 of them with known planetary companion.
- Stellar parameters were taken from Santos et al. (2004), Sousa et al. (2011a,b)
- Chemical abundances of other elements were taken from Adibekyan et al. (2012) and Bodaghee et al. (2003)

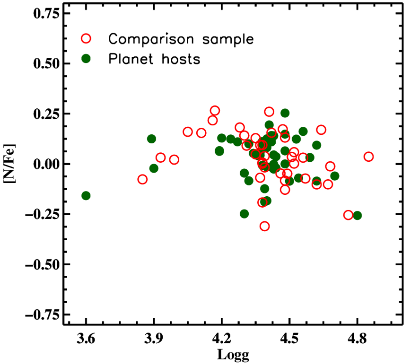
Analysis

- Abundances were determined using LTE analysis with synthesis code MOOG (2013 version) and a grid of Kurucz (1993) ATLAS9 atmospheres models.
- FITTING code (González Hernández et al. 2011) was used to obtain bestfit abundances.
- Bestfit was obtained using a χ^2 minimization procedure.

Results

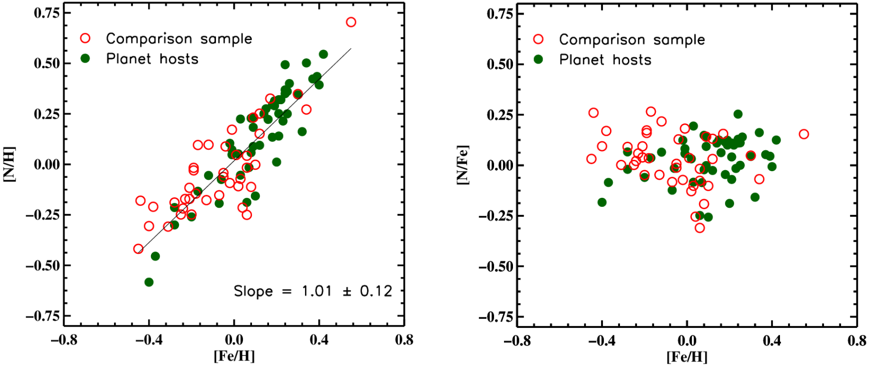
- Nitrogen increases with $\mathrm{T_{eff}}$.
- No relation between [N/Fe] and log$g$.
- Both samples, planet hosts and comparison stars, show the same behaviour.





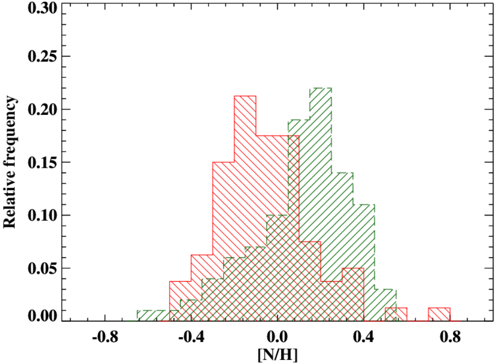
Results

- Results suggest a 1:1 relation between [N/H] and [Fe/H]
- Both samples, planet hosts and comparison stars, show the same behaviour.



Results

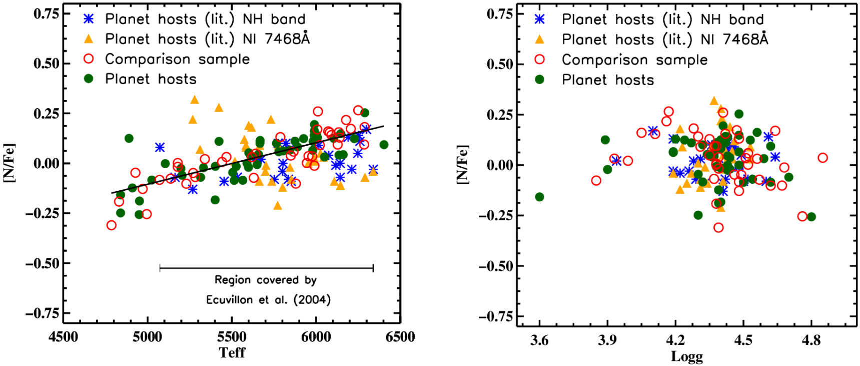
- Planet hosts, green, are more frequent at higher [N/H].
- Consequence of more metallic stars being preferred as planet hosts.



Results: Comparison with literature

A few studies can be found using the NH band in solar type stars.
Reference: Ecuvillon et al. 2004

- Comparison with previous studies confirm our results.
- Mismatch with NI at 7418Å.



Results: Comparison with literature

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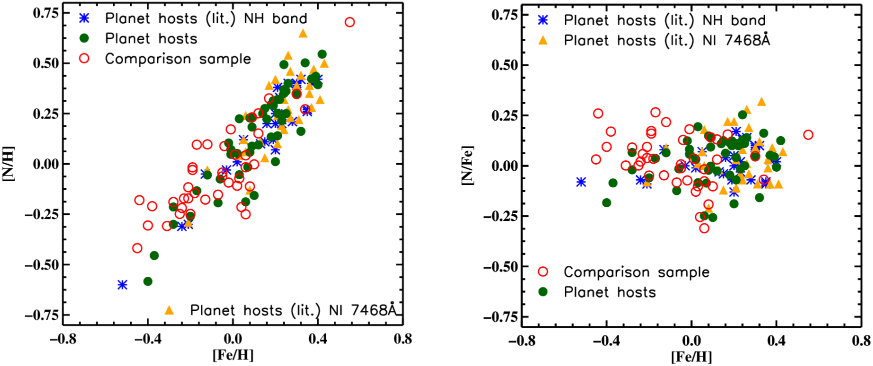
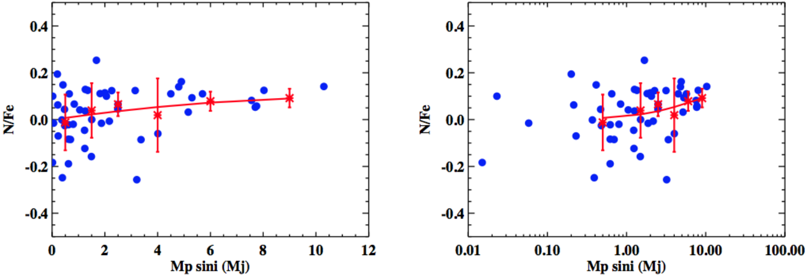
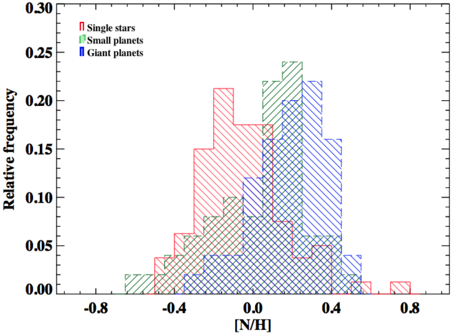


And what about the planets?



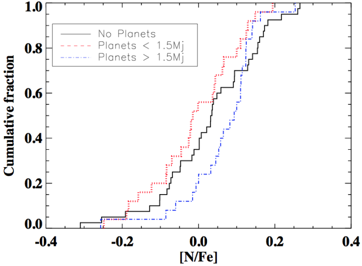
- We made a separation between small planets ($< 1.5 M_J$) and giant planets ($> 1.5\ M_J$).
- Out of 50 stars with planets, 25 have small planets and 25 giant planets.

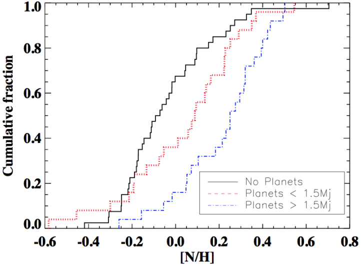
And what about the planets?



- We made a separation between small planets ($< 1.5 M_J$) and giant planets ($> 1.5\ M_J$).
- Out of 50 stars with planets, 25 have small planets and 25 giant planets.

Kuiper test: some statistics





	No Planets
Small Planets (SP)	0.72
Giant Planets (GP)	0.03
SP-GP	0.08

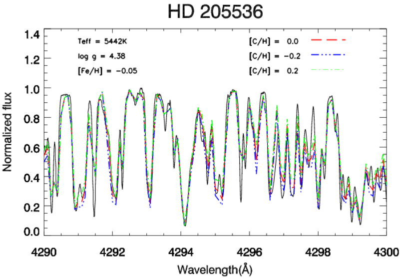
Table : Kuiper test for [N/Fe]

	No Planets
Small Planets (SP)	0.07
Giant Planets (GP)	0.00
SP-GP	0.18

Table : Kuiper test for [N/H]

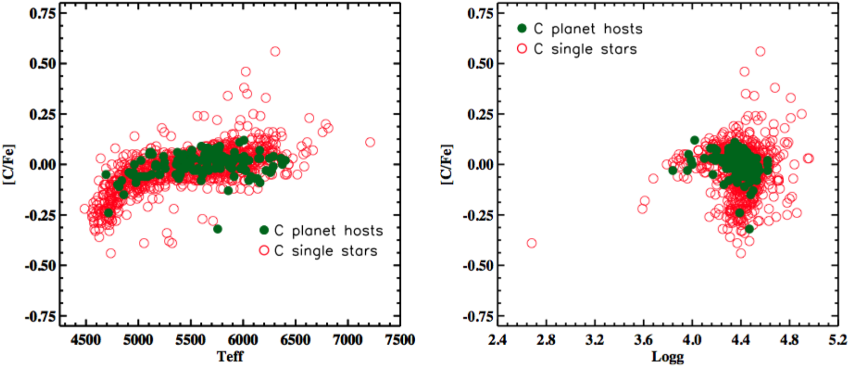
Ongoing work: Carbon

- The CH band is a sensitive region to study carbon abundance located at 4300Å.
- We are studying a sample of 1111 solar-type stars from HARPS planet search program.
- Stellar parameteres were obtained from Santos et al. 2004, Sousa et al, 2011a,b.
- Chemical abundances from Adibekyan et al. 2012.



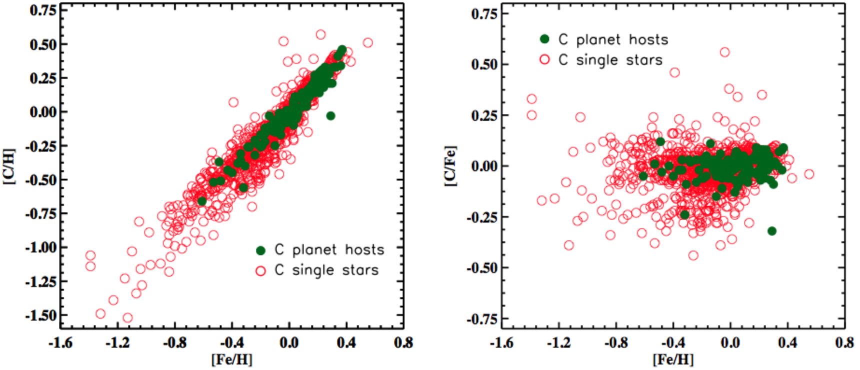
Carbon: Preliminary results

- Carbon increases with T_{eff}.
- Both samples, planet hosts and comparison stars, show the same behaviour.



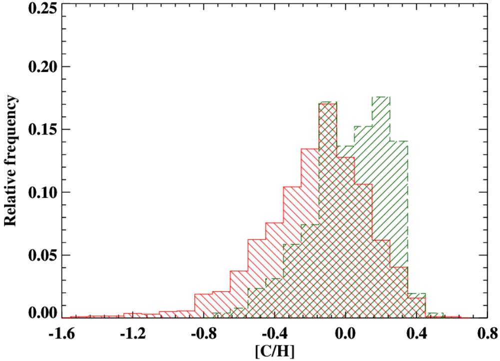
Carbon: Preliminary results

- Results suggest a 1:1 relation between [C/H] and [Fe/H]
- Both samples, planet hosts and comparison stars, show the same behaviour.



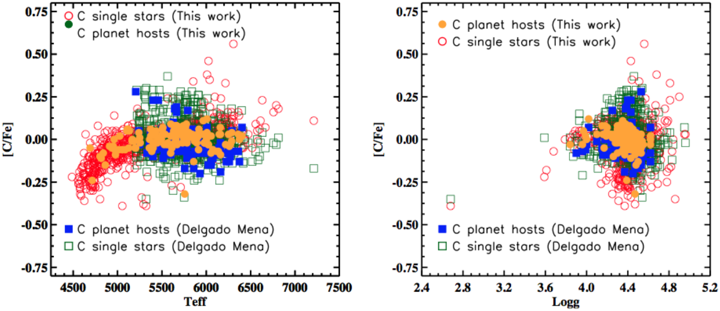
Results

- Planet hosts, green, are more frequent at higher [C/H].
- Consequence of more metallic stars being preferred as planet hosts.



Results: Comparison with literature

We compared our results with those obtained by Delgado Mena. (presented yesterday at main conference)



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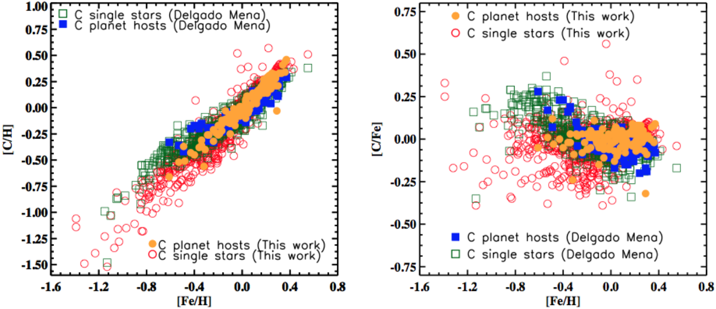
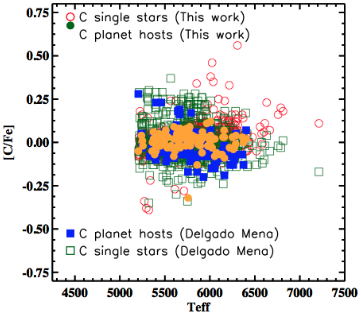
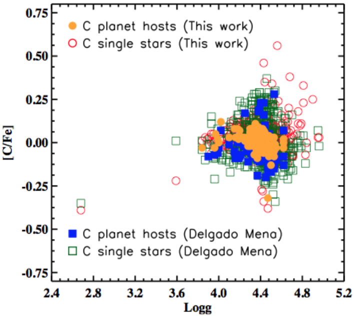


Results: Comparison with literature

We compared our results with those obtained by Delgado Mena. (presented yesterday at main conference)

- Better agreement at $T_{eff} > 5200K$.

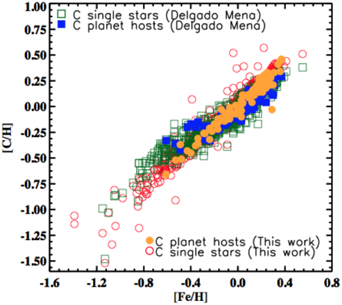




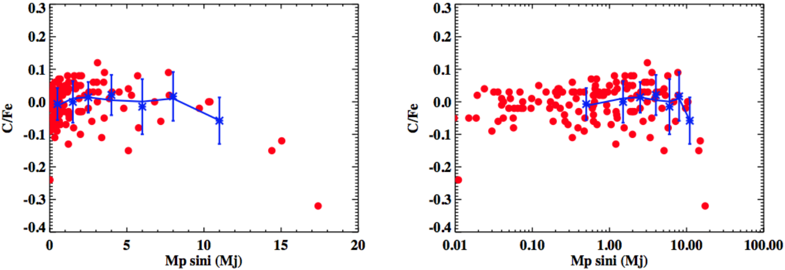
Results: Comparison with literature

We compared our results with those obtained by Delgado Mena. (presented yesterday at main conference)

- Comparison with previous studies confirm our results.
- Better agreement at $T_{eff} > 5200K$.

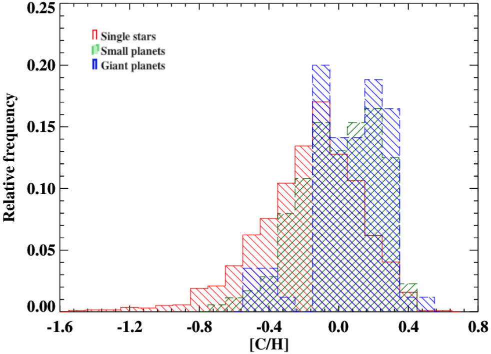


And what about the planets?



- We made a separation between small planets ($< 1.5 M_J$) and giant planets ($> 1.5\ M_J$).
- Out of 128 stars with planets, 88 have small planets and 40 giant planets.

And what about the planets?



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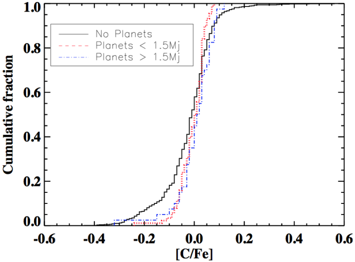
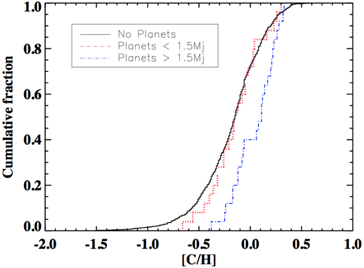




	No Planets
Small Planets (SP)	0.00
Giant Planets (GP)	0.09
SP - GP	0.33

Table : Kuiper test for [C/Fe]

	No Planets
Small Planets (SP)	0.91
Giant Planets (GP)	0.02
SP - GP	0.18

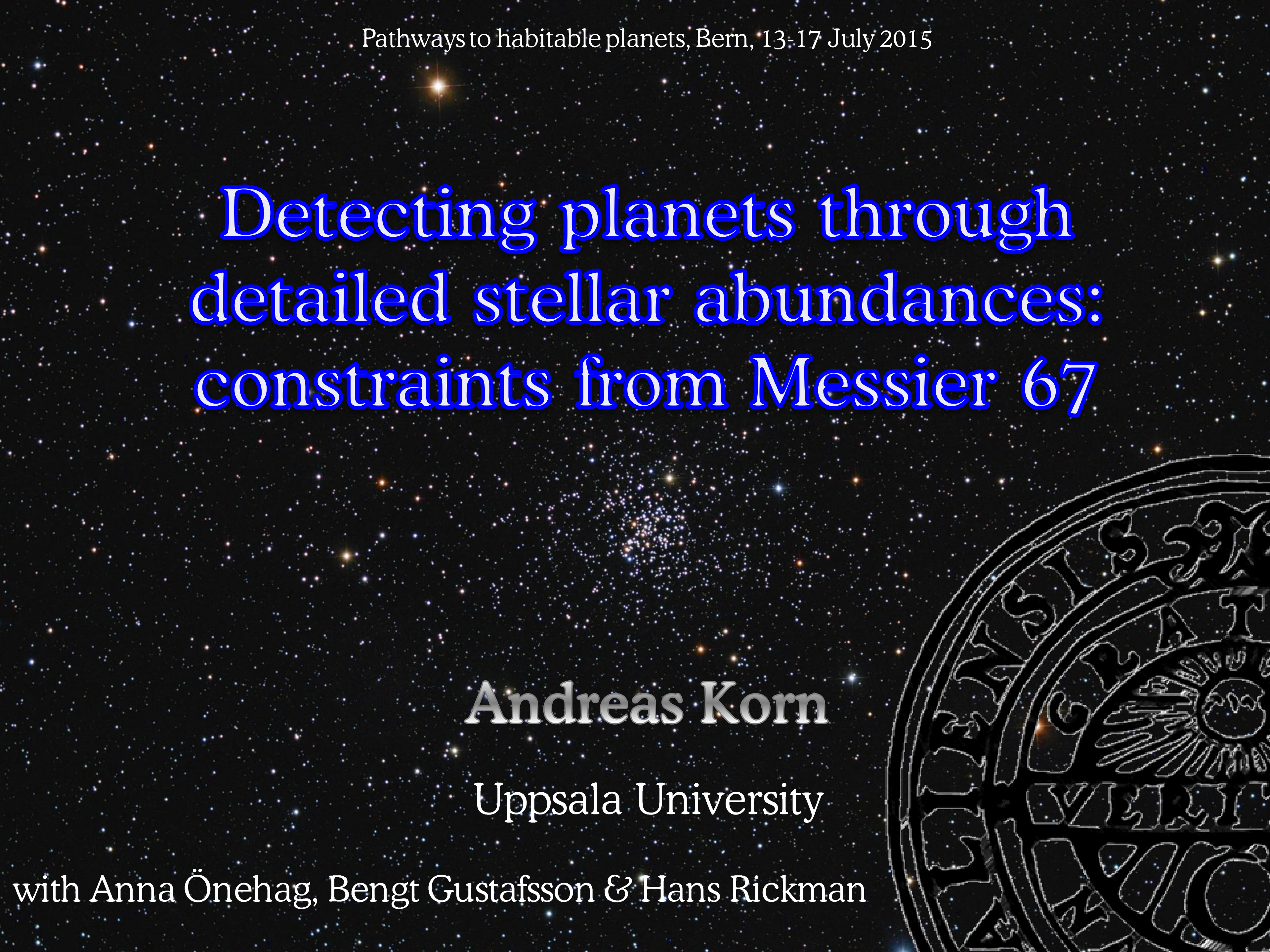
Table : Kuiper test for [C/H]

Conclusions

- We studied the NH and CH band to study nitrogen and carbon using molecular bands
- For nitrogen, we studied a sample of 90 solar-type stars, with 50 of them to known to harbour planets.
- For carbon, we studied a sample of 1111 solar-type stars, 128 of them to known to harbour planets.
- Both nitrogen and carbon have a 1:1 relation with iron.
- Both nitrogen and carbon increase with $\mathrm{T}_{\mathrm{eff}}$.
- No relation between nitrogen and log$g$ or between carbon and log$g$.
- No different behaviour can be inferred from nitrogen or carbon abundances for both samples.
- Results agree with other works (Ecuvillon et al. 2004; Delgado Mena et al., in preparation)
- Stars with small planets ($M_P < 1.5 M_J$) behave more like single stars than like giant-planets ($M_P > 1.5 M_J$) (For both carbon and nitrogen)

Thank you

- PS. You can see the pictures with more detail on poster hall, 2nd floor left.



Pathways to habitable planets, Bern, 13-17 July 2015

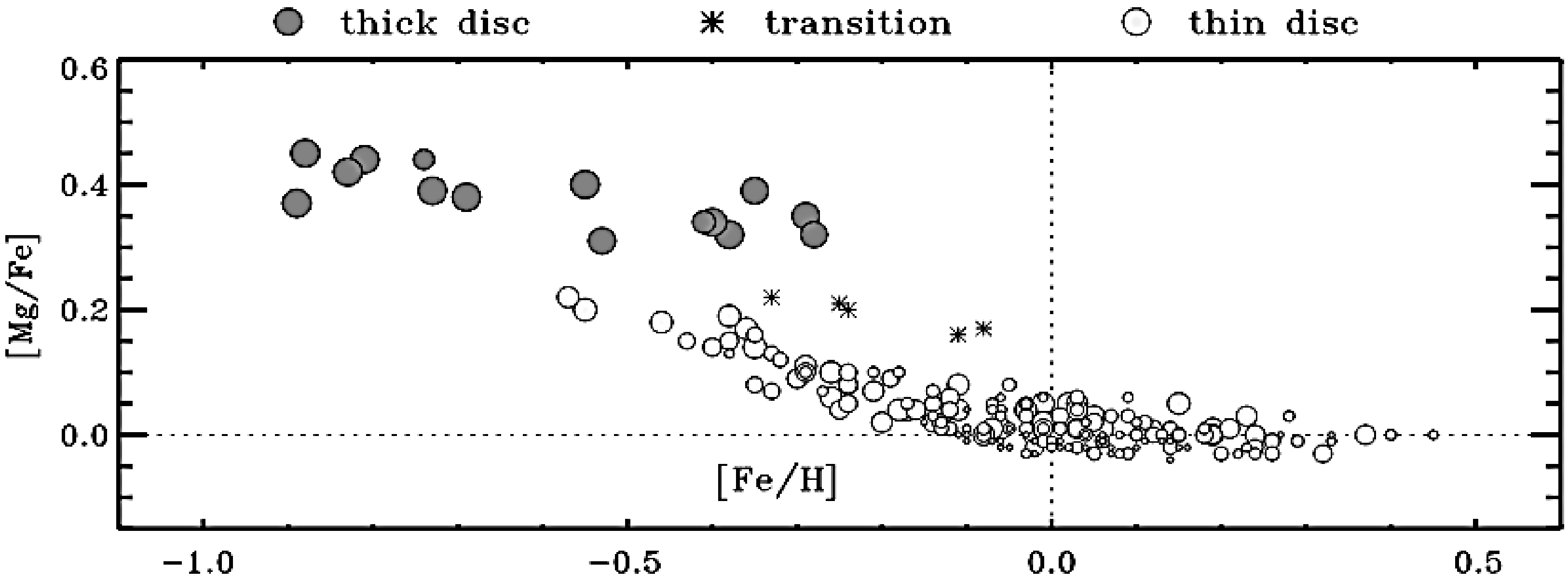
Detecting planets through detailed stellar abundances: constraints from Messier 67

Andreas Korn

Uppsala University

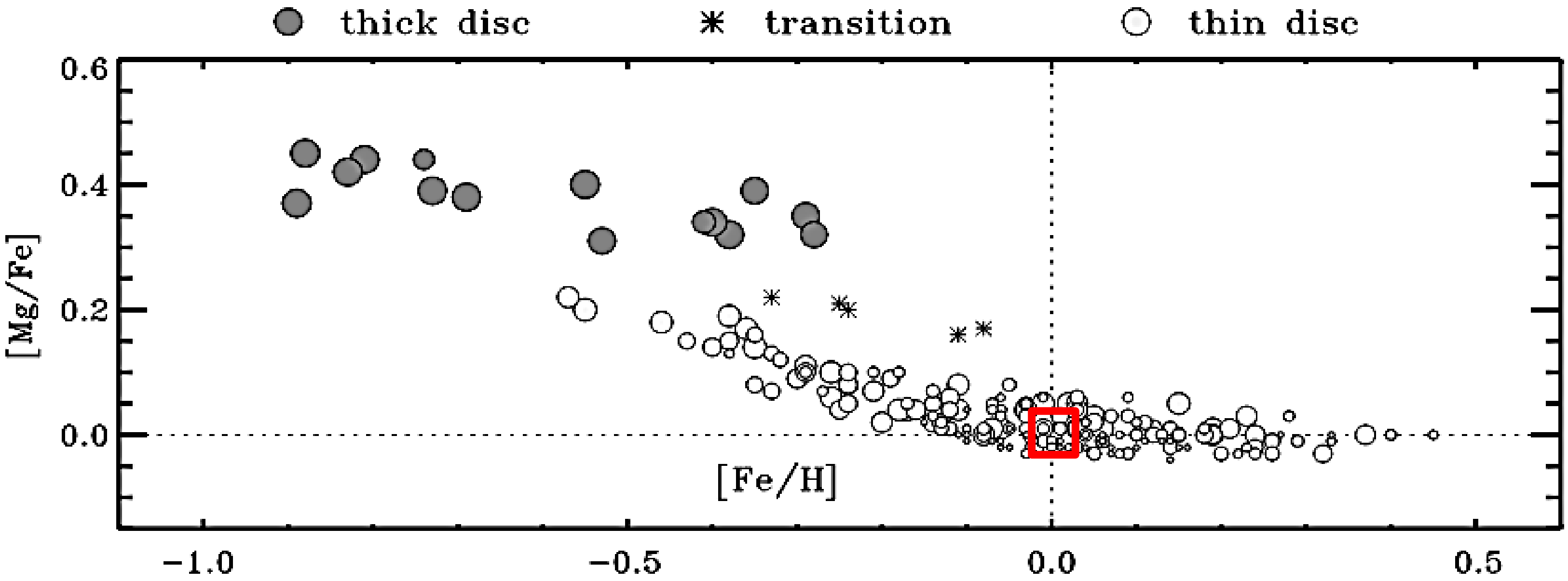
with Anna Önehag, Bengt Gustafsson & Hans Rickman

The Sun, an ordinary thin-disk star



The Sun is a perfectly normal, albeit fairly high-mass, thin-disk star. There are many stars like the Sun…

The Sun, an ordinary thin-disk star



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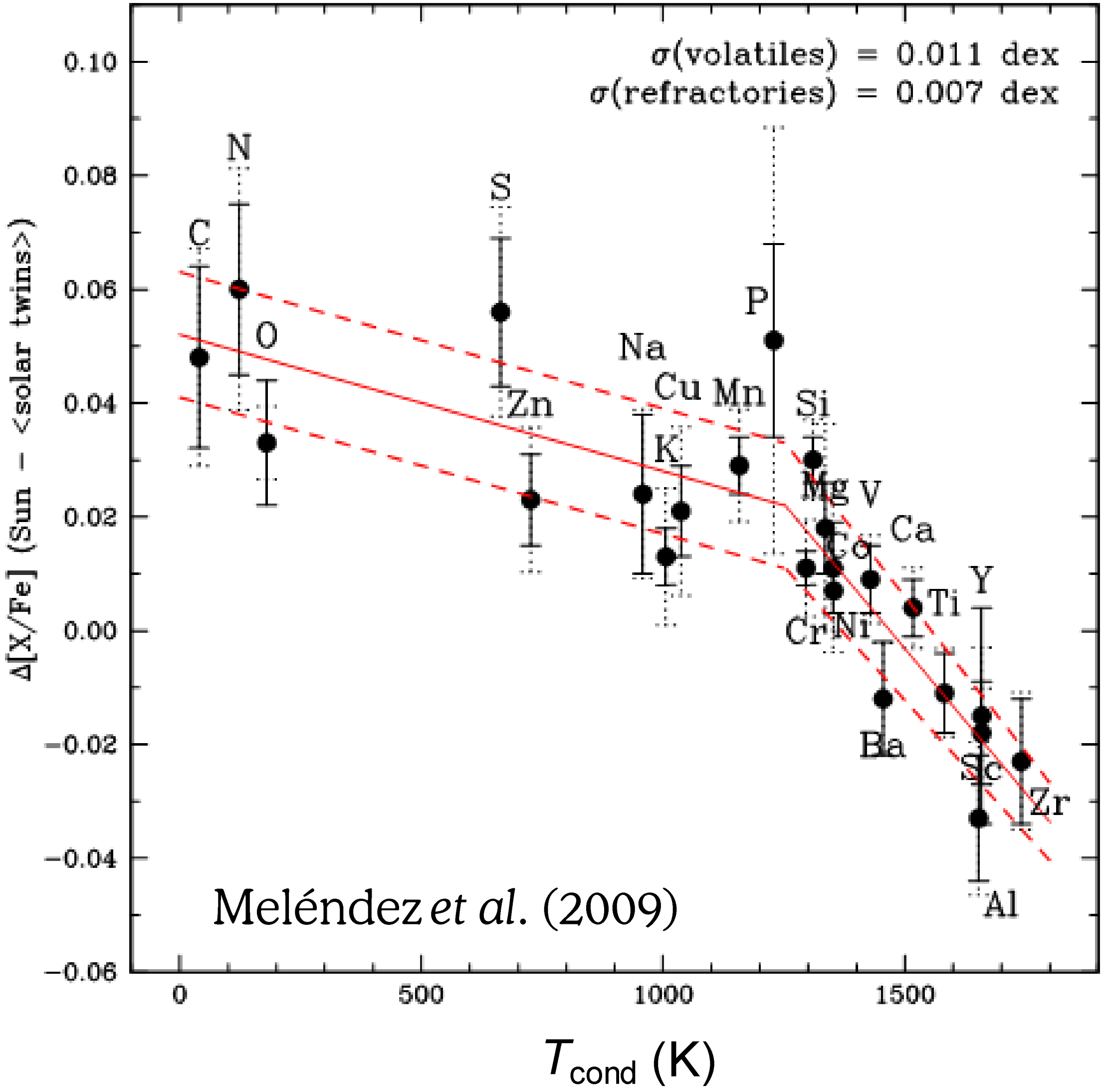
However, Sun vs. Solar twins…



Relative to solar twins in the field, the Sun is rich in volatile elements and poor in high-T_{cond} refractories

A *tell-tale* sign of terrestrial planets?

Or the imprint of the stellar birth environment?

The birth cluster of the Sun

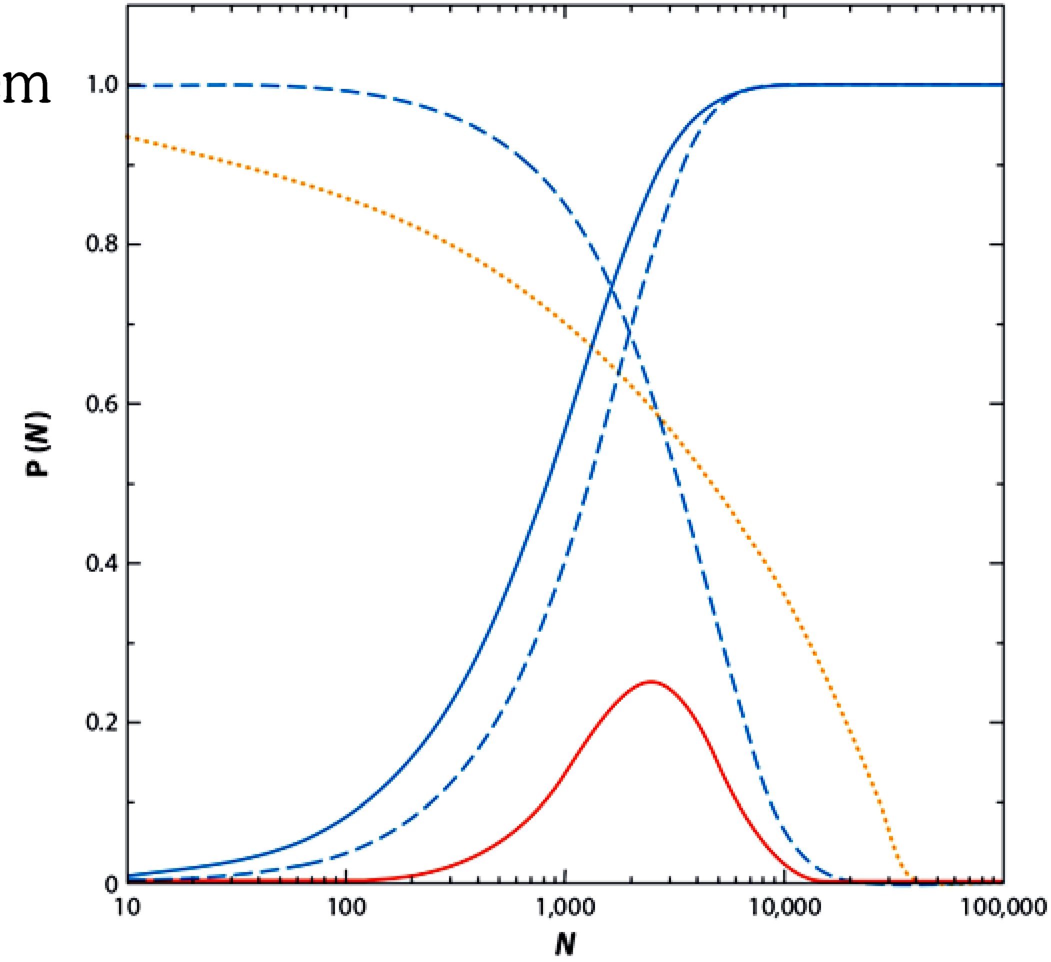
Constraints from solar-system properties

- short-lived nuclei (Al-26, Fe-60 etc.)
- extraction of Sedna
- stability of planetary orbits
- limited photo-evaporation of the solar nebula

lead to

$\langle N \rangle = 4300 \pm 2800$.

Adams, ARAA (2010)



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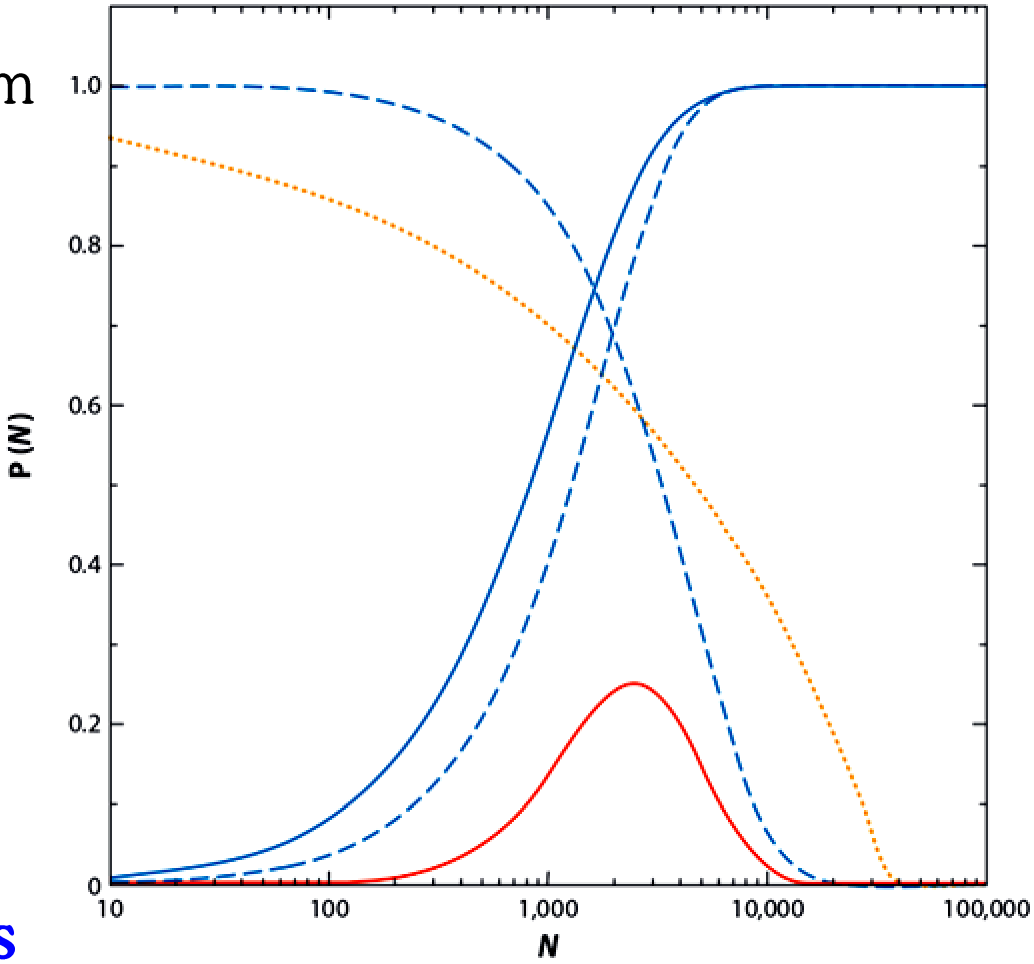
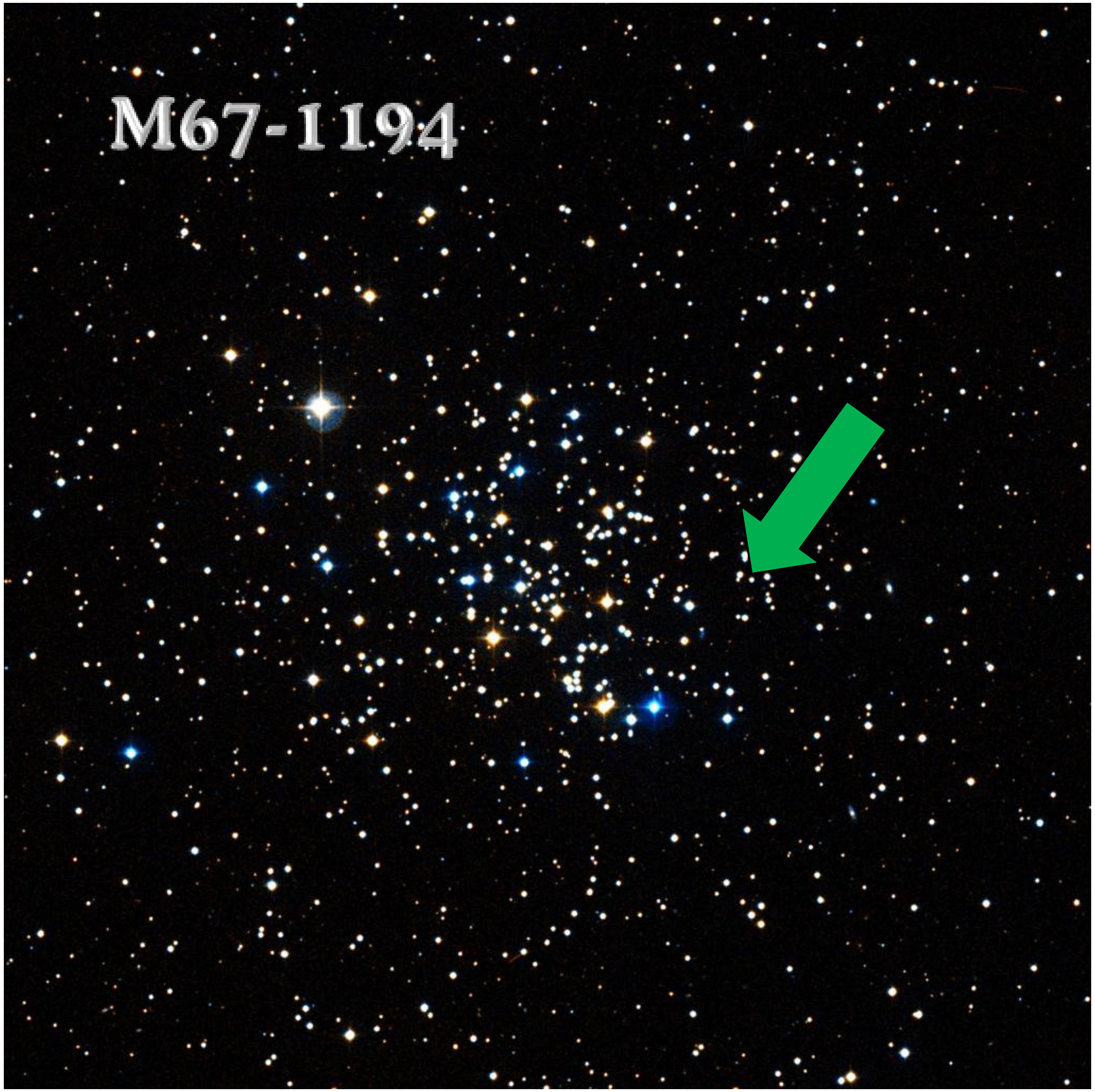
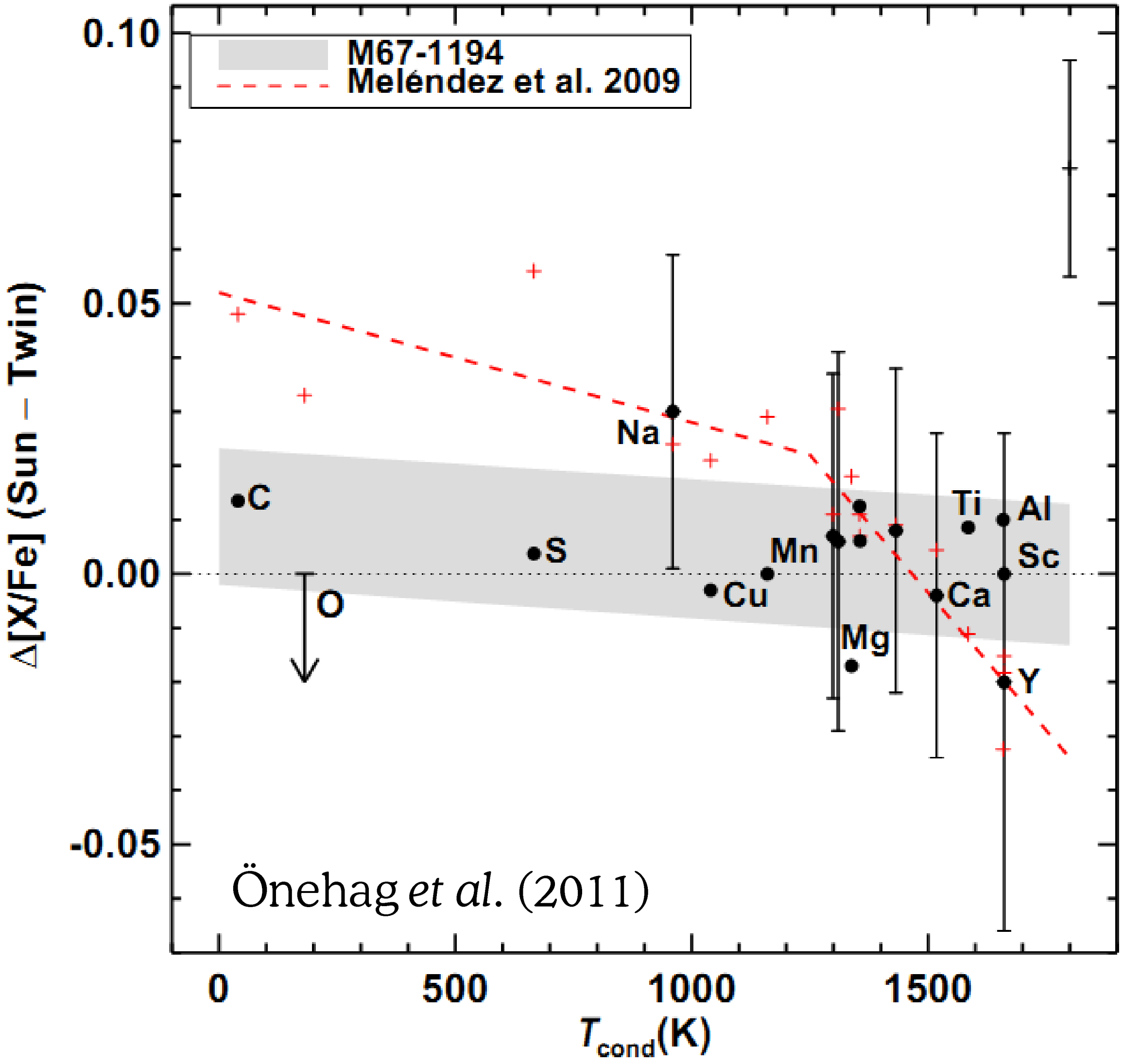


Only 1 in a few 100 stars originates from such a rich stellar environment!

The first Solar twin in a cluster



Detailed Sun vs. 1194 composition

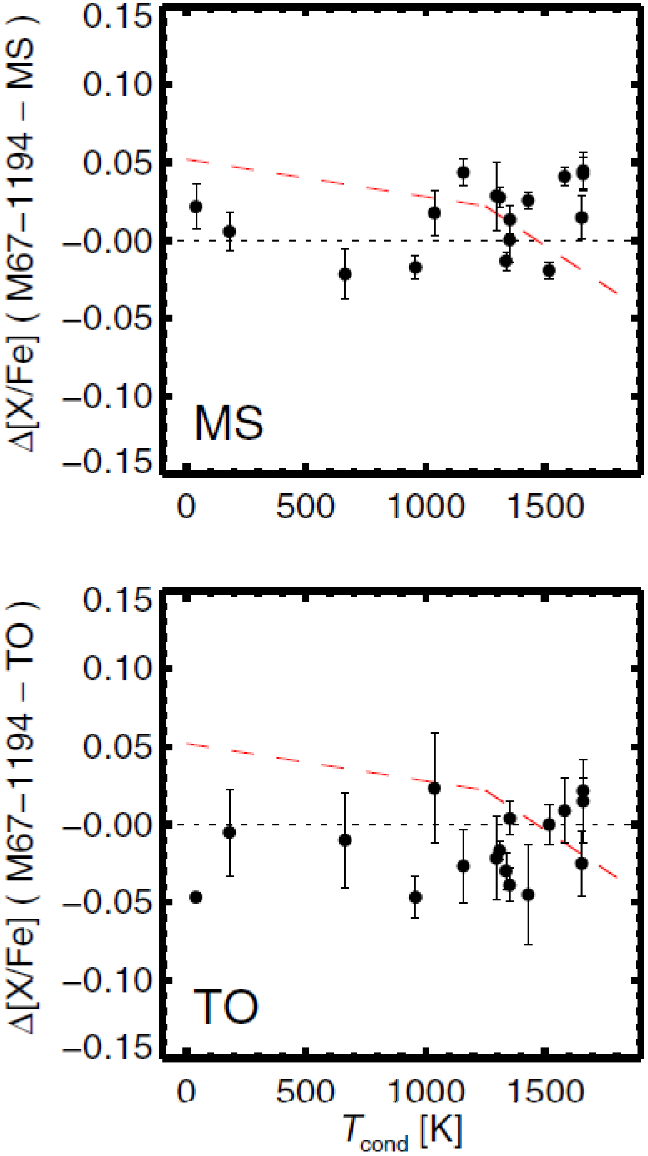


Önehag *et al.* (2011)

Relative to solar twins in the field, the Sun is rich in volatile elements and poor in high-$T_{\rm cond}$ refractories

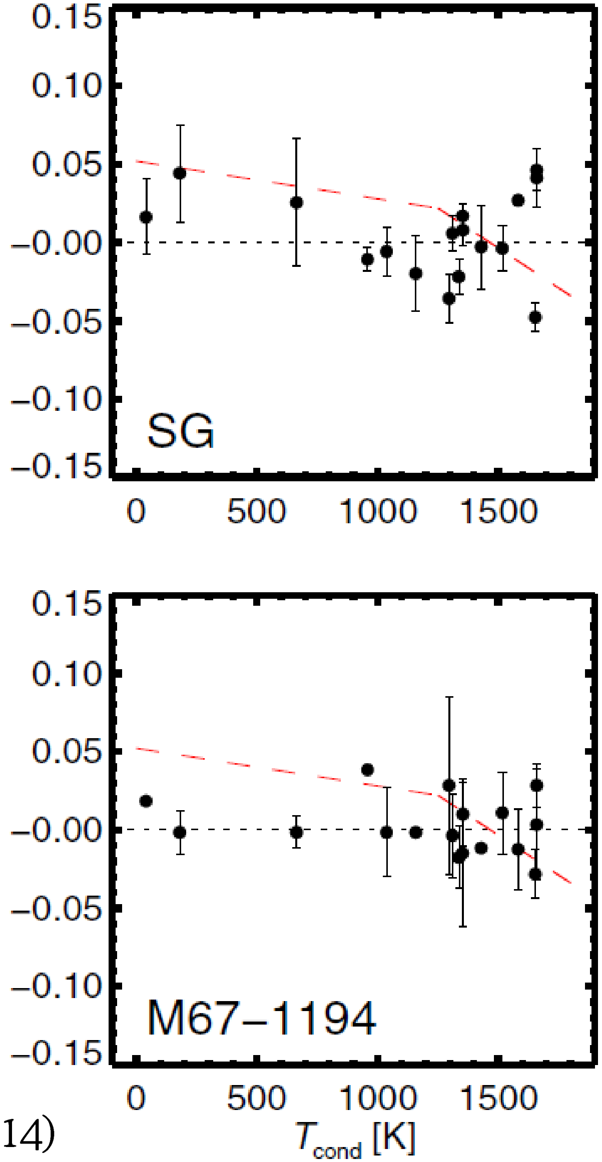
Chemically, M67-1194 resembles the Sun!

Limited to 1194? No!



5 MS, 3 TO and 2 SG stars in M67 support the solar-like chemical profile,
3 SG do not (unambiguously).

More ST & SG stars observed in P94, analysis pending.



Önehag *et al.* (2014)

The hot Jupiter around 1194

A&A 561, L9 (2014)
DOI: 10.1051/0004-6361/201322584

Astronomy
&
Astrophysics

LETTER TO THE EDITOR

Three planetary companions around M 67 stars[⋆,⋆⋆]

A. Brucalassi[1,2], L. Pasquini[3], R. Saglia[1,2], M. T. Ruiz[4], P. Bonifacio[5], L. R. Bedin[6], K. Biazzo[7], C. Melo[8], C. Lovis[9], and S. Randich[10]

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e-mail: `abrucala@mpe.mpg.de`
[2] University Observatory Munich, Ludwig Maximillian Universitaet, Scheinerstrasse 1, 81679 Munich, Germany
[3] ESO – European Southern Observatory, Karl-Schwarzschild-Strasse 2, 85748 Garching bei München, Germany
[4] Astronomy Department, Universidad de Chile, 36-D Casilla, Santiago, Chile
[5] GEPI, Observatoire de Paris, CNRS, Univ. Paris Diderot, Place Jules Janssen, 92190 Meudon, France
[6] Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Padova, 35122 Padova, Italy
[7] Istituto Nazionale di Astrofisica, Osservatorio Astronomico di Catania, 95123 Catania, Italy
[8] ESO – European Southern Observatory, 19001 Santiago, Chile
[9] Observatoire de Genève, 1290 Sauverny, Switzerland
[10] Istituto Nazionale di Astrofisica, Osservatorio Astrofisico di Arcetri, Firenze, Italy

The planetary system around 1194 does not resemble the *present* make-up of our PS!

Putting together the pieces…

- The Sun is a perfectly normal G-type star of the Galactic thin disk. Unlike most stars, however, the Sun was born in a rich stellar environment.

- Most Solar twins show a non-Solar V/R abundance ratio.

- M67-1194 (and most of the other M67 stars) show a Solar V/R abundance ratio.

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- The Sun is a perfectly normal G-type star of the Galactic thin disk. Unlike most stars, however, the Sun was born in a rich stellar environment.

- Most Solar twins show a non-Solar V/R abundance ratio.

- M67-1194 (and most of the other M67 stars) show a Solar V/R abundance ratio.

$\Longrightarrow$ **The most straightforward explanation is that a Solar V/R ratio is a chemical reflection of a rich *stellar* birth environment (like that of M67).**

Caveats/open questions

- With M67 alone, we cannot probe the *t* parameter, i.e. Galactic chemical evolution (see Adibekyan *et al*. 2014; Nissen 2015). Seems to play a role!
  Study more clusters!

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- This scenario cannot explain binaries with differing volatile-to-refractory ratios (XO-2: Ramirez *et al*. 2015; Kepler-10: Liu *et al*. 2015; but HAT-P-1: Liu *et al*. 2014; do we understand this range of results?)

- Why is the dust cleansing homogeneous throughout the cluster and limited to ≈20%?

Conclusions

- The Sun is one of relatively few stars to originate from a rich stellar environment, similar to M67. There are many arguments for this, we add the remarkable chemical similarity between M67 stars and the Sun. Spectroscopic work on other rich clusters is needed.
- This finding may explain the dissimilarity between the Sun and the Solar-neighbourhood Solar twins.
- The idea that a solar-like chemical profile is solely and predominantly related to the existence of terrestrial planets is not supported in this analysis.

Age determination for M67

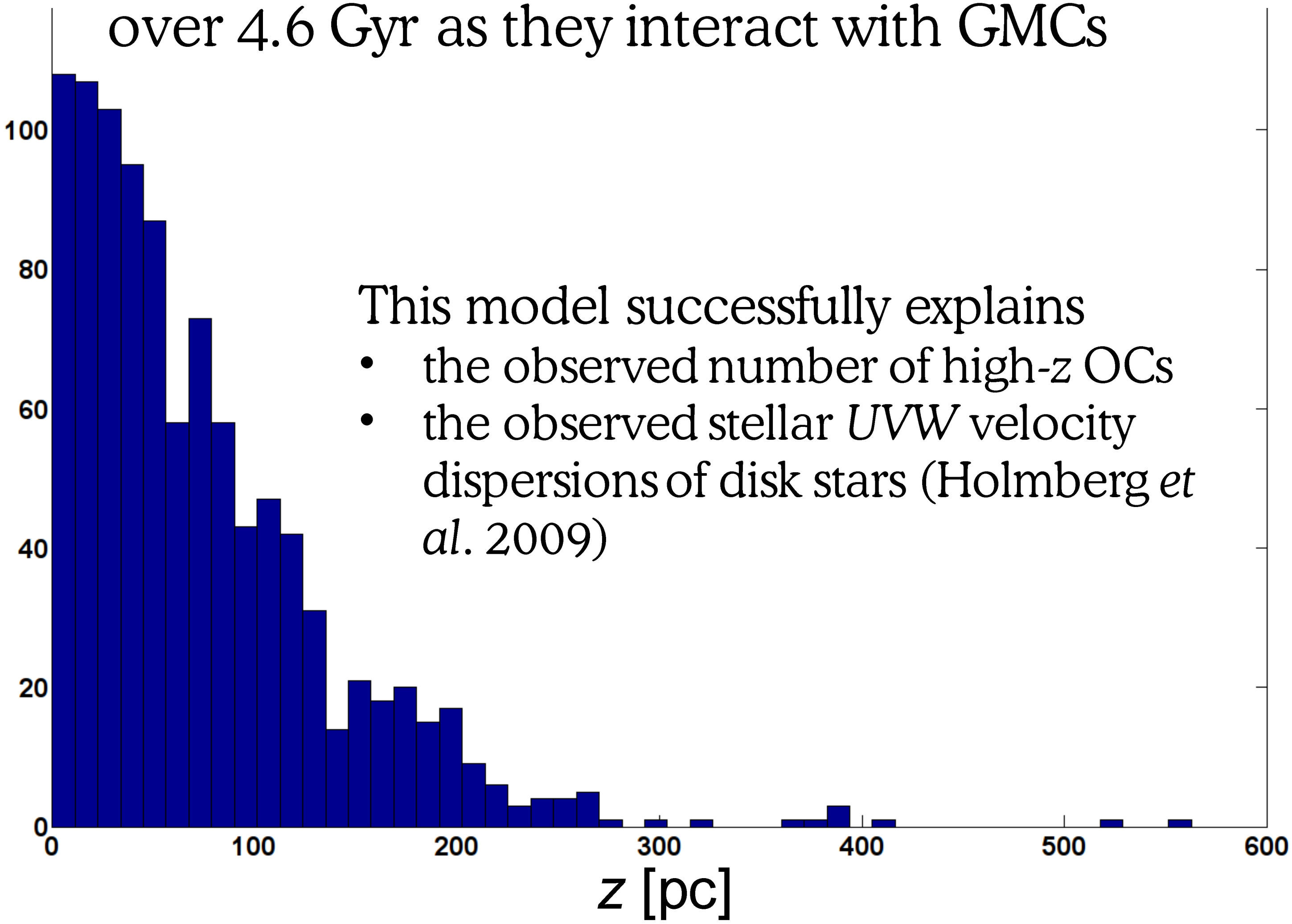
- Most age determinations in the literature scatter around 4 Gyr, both from fitting of the turnoff region and the white dwarf cooling sequence (e.g. Magic *et al*. 2010; Bellini *et al*. 2010)
- M67-1194 allows us to age-date M67 with a reduced sensitivity to systematic biases: $t = 4.2 \pm 1.6\,\mathrm{Gyr}$; compatible with the solar age (Önehag *et al*. 2010)
- Using the methods of Baumann *et al*. (2010), we would derive $t = 4.67 \pm^{1.0}_{1.8}\,\mathrm{Gyr}$
- Applying the method of Nissen (2015), based on the [Y/Mg] abundance ratio, yields an age of 4.45 Gyr.

Scenario for Sun $\in$ M67

- M67, including the Sun, forms in the Galactic disk The UV radiation of nearby stars shapes the chemical composition of the proto-solar nebula, e.g. via dust cleansing.
- The Sun leaves M67 after $<$ 1 Gyr with M67 still in the disk.
- M67 experiences a close encounter with a GMC and is diverted into its present-day orbit.
- M67, the *Ultimate Survivor* (Croswell 2004), is still there after 4.6 Gyr as it spends most of its orbit outside the disk. The Sun is a field star.

Explaining OCs at high latitudes

Following the evolution of 1000 test clusters over 4.6 Gyr as they interact with GMCs



This model successfully explains

- the observed number of high-z OCs
- the observed stellar *UVW* velocity dispersions of disk stars (Holmberg *et al*. 2009)

Searching for signatures of planet formation in stars with circumstellar debris discs

Jesús Maldonado

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Connecting Stellar Abundances and Planet Habitability @ Pathways II

Collaborators:

- **C. Eiroa** (Universidad Autónoma de Madrid)
- **E. Villaver** (Universidad Autónoma de Madrid)
- **B. Montesinos** (Department of Astrophysics, Centro de Astrobiología (CAB, CSIC-INTA))
- **A. Mora** (ESA-ESAC Gaia SOC)

Outline

Outline

Correlated phenomena?

Planetesimals are the "building blocks" of planets ⇒ Do their host stars have similar properties?

Discs

- Incidence no higher around planet-host stars
- No correlation with stellar properties

(e.g. Bryden et al. 2009, Kóspál et al. 2009)

Planets

- Trend of ⇑ [Fe/H] of stars hosting gas-giant planets
- Low-mass planets $\mathrm{M_p} < 30\ \mathrm{M}_{\oplus}$ do not follow this trend
- Puzzling results in evolved stars hosting planets **(e.g. Maldonado et al. 2013)**

Low-mass planets: a major challenge

- $\sim$ 55% more SWDPs w.r.t. previous works
- Debris discs and low-mass planets: "Good neighbours?"
  (e.g. Maldonado et al. 2012, Wyatt et al. 2012, Marshall et al. 2014)
- "Fingerprints" of terrestrial planet formation in the stellar photospheric abundances? **(e.g. Meléndez et al. 2009; Ramírez et al. 2009, 2010, 2014)**

Outline

In this study:

Chemical abundances of four samples of solar-like stars

1. **Stars with known debris discs (SWDs)**
   IRAS, ISO, Spitzer, Herschel data (68 stars)
2. **Stars with known debris discs and planets (SWDPs)**
   $\sim$ 55% more SWDPs w.r.t. previous works (31 stars)
3. **Stars with known planets (SWPs)**
   Stars hosting gas-giant/low-mass planets (32 stars)
4. **Comparison sample (SWODs)**

   No IR-excess found at Spitzer/Herschel's λs (119)

Spectroscopic Analysis

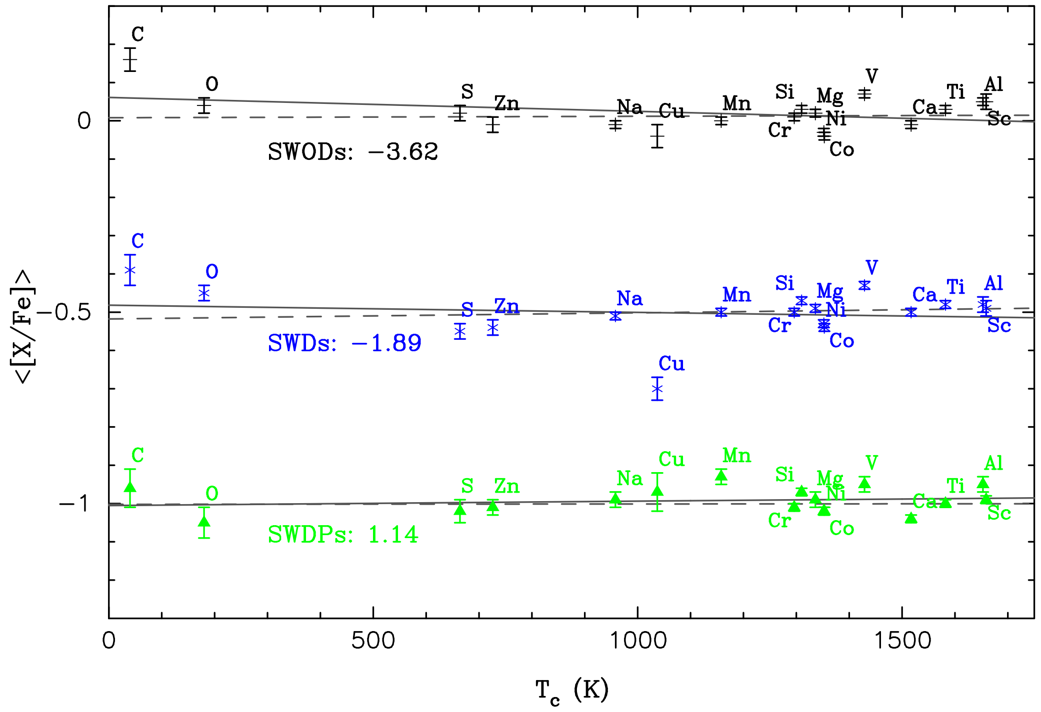
- **Stellar parameters, code TGVIT (Takeda et al. 2005)**
  Iron ionisation and excitation conditions, match of the curve of growth
- **MOOG code (Sneden 1973) + ATLAS9 models**
  C, O, Na, Mg, Al, Si, S, Ca, Sc, Ti I, Ti II, V, Cr I, Cr II, Mn, Co, Ni, Cu, Zn

Outline

1. Introduction
2. Observations and analysis
3. **Abundance trends**
4. Discussion
5. Summary

Different behaviour <[X/Fe]>-T_{C} slope in SWDPs

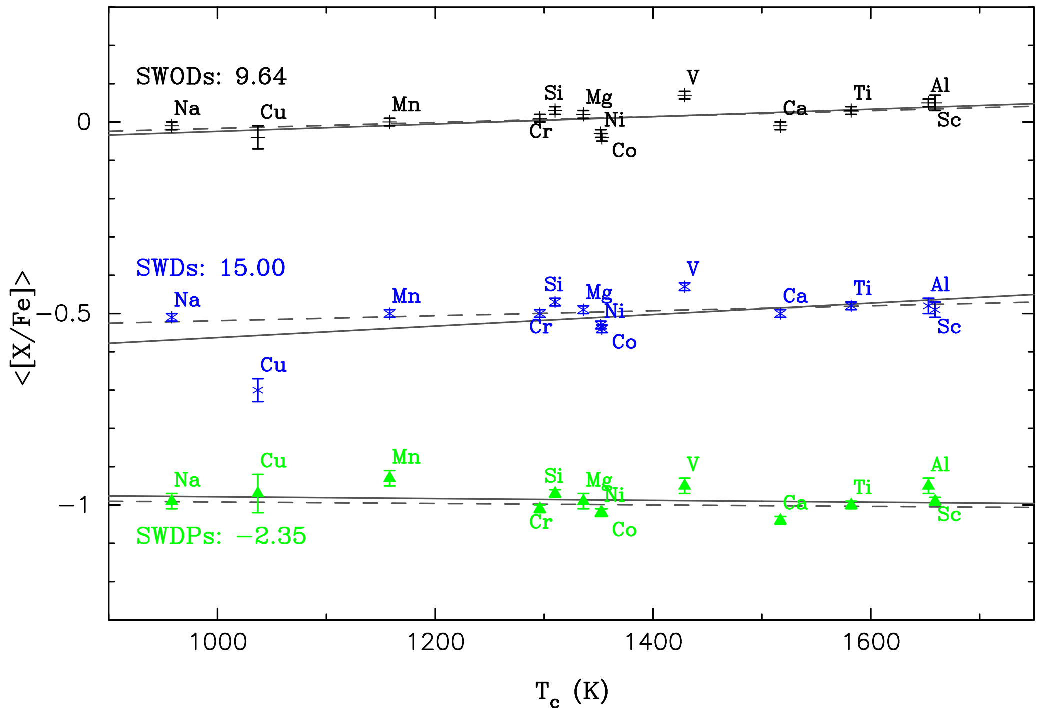
All elements



- SWDs/SWODs $<$ slopes; SWDPs $>$ slopes

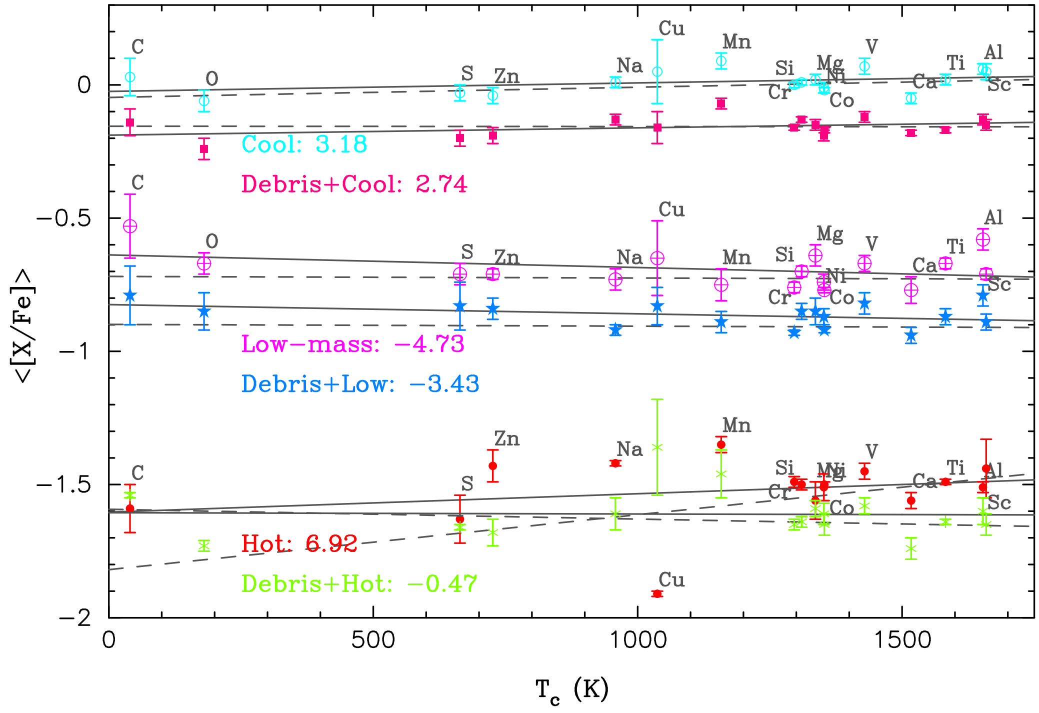
Abundances of volatiles not as reliable as refractories' ones

Only $T_C > 900$ K



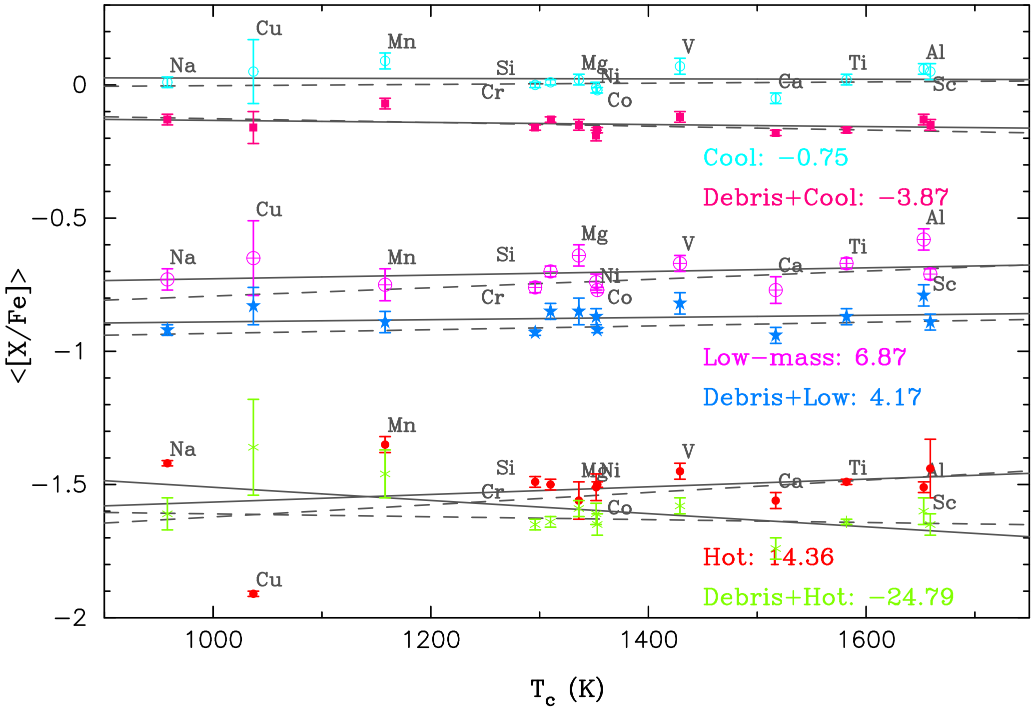
- Slope change their signs, but still there is a difference in **SWDPs** wrt **SWDs**/SWODs

Comparison with planet hots (all elements)



- **SWDPs behave as stars with planets**
- **Differences between stars with cool and low-mass planets**

Comparison with planet hots (only refractories)



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Previous analysis:

- **Meléndez et al. 2009:** Deficit of refractory in the Sun wrt other solar twins.
  Related to the formation of low-mass planets
- **González Hernández et al. 2012, 2013; Adibekyan et al. 2014:**
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In this work:

1. **Similar behaviour SWDs/SWODs**
2. **Similar behaviour SWDPs/SWPs**
3. **No differences in stars with low-mass planets (wrt SWODs/SWDs)**
4. **Different behaviour in stars with cool-Jupiters**
5. **Positive slopes in stars with hot-Jupiters**

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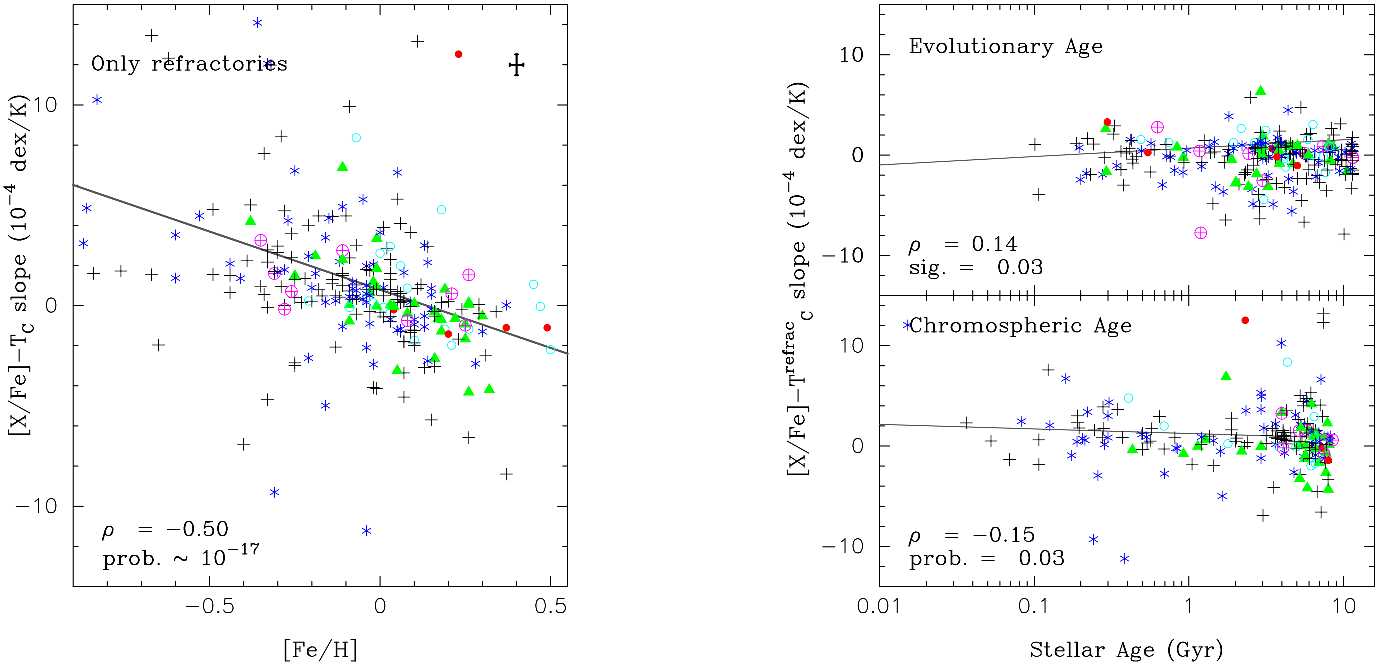
Key questions:

1. Might the <[X/Fe]>-T_C trends be influenced by GCE effects?
2. Do the <[X/Fe]>-T_C trends fit in the ME09 hypothesis?

Might the <[X/Fe]>-T_C trends be influenced by GCE effects?

Abundance patterns may be affected by GCE effects

T_C slope vs. [Fe/H], age, and R_{mean}



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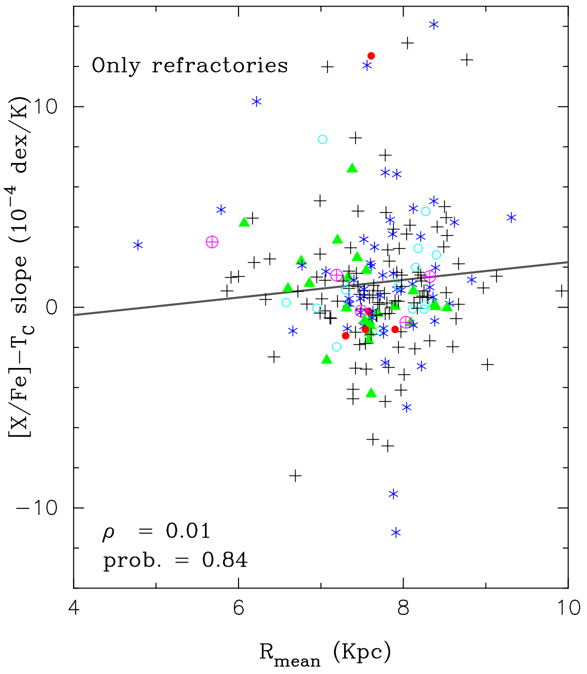

[Fe/H]	Moderate, significant
Age	Weak, but significant
R_{mean}	Not clear correlation

GCE corrections

[X/H] vs. [Fe/H] linear fits

○ Still correlations with the chromospheric age and the stellar radius remain

○ Might this correction “delete” possible chemical depletions?

Do the <[X/Fe]>-T_C trends fit in the ME09 hypothesis?

1. **Similar behaviour SWDs/SWODs**
2. **Similar behaviour SWDPs/SWPs**
3. **No differences in stars with low-mass planets (wrt SWODs/SWDs)**

Do the <[X/Fe]>-T_C trends fit in the ME09 hypothesis?

1. **Similar behaviour SWDs/SWODs**
2. **Similar behaviour SWDPs/SWPs**
3. **No differences in stars with low-mass planets (wrt SWODs/SWDs)**

- **Planet: key factor in revealing the chemical behaviour of the star**
  Consistent with core-accretion model of planet formation.
- **Correlation between dust and low-mass planets?**
  Significant fraction of low-mass hosts among the SWDPs.
  In agreement with recent results **(e.g. Wyatt et al. 2012, Marshall et al. 2014)**

Do the <[X/Fe]>-T_C trends fit in the ME09 hypothesis?

3. **No differences in stars with low-mass planets (wrt SWODs/SWDs)**
4. **Different behaviour in stars with cool-Jupiters**

Do the <[X/Fe]>-T_C trends fit in the ME09 hypothesis?

3. **No differences in stars with low-mass planets (wrt SWODs/SWDs)**
4. **Different behaviour in stars with cool-Jupiters**

- **Not in agreement with ME09**
  Low-mass planet hosts: only $<$ slopes for all elements, but similar to SWDs/SWODs
  Cool-Jupiter hosts: differences in T_C^{all} and T_C^{ref}; $<$ slopes in T_C^{ref} analysis

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5. **Positive slopes in stars with hot-Jupiters**

Do the <[X/Fe]>-T_C trends fit in the ME09 hypothesis?

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  Cool-Jupiter hosts: differences in T_C^{all} and T_C^{ref}; $<$ slopes in T_C^{ref} analysis

5. **Positive slopes in stars with hot-Jupiters**

- **Caution, small sample size!**
  Also SWDs/SWODs show $>$ slopes in T_C^{ref}
  Indication of non low-mass planets?

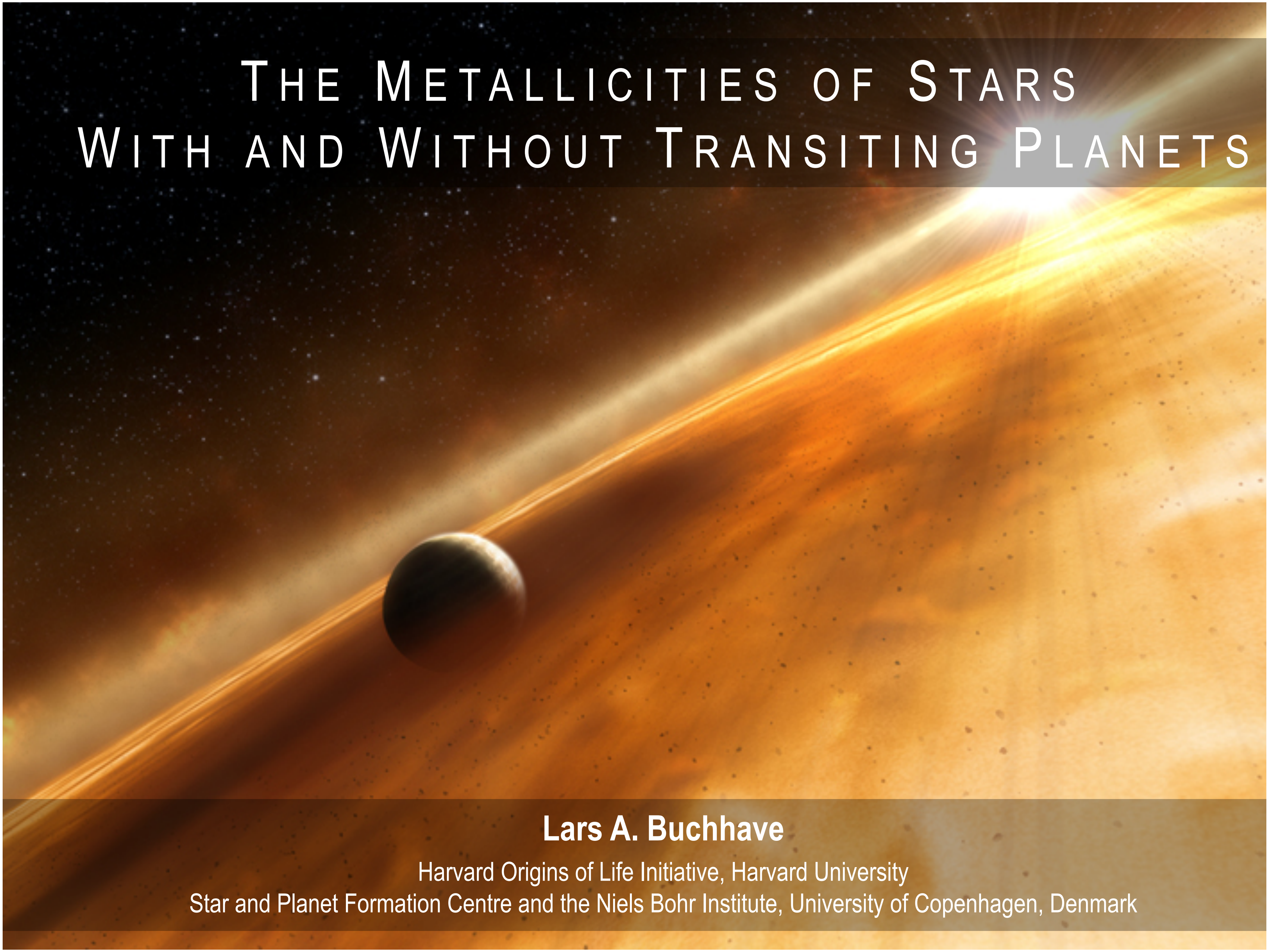
Outline

Ref: Maldonado et al. 2015, A&A, 579, A20

Summary

Detailed chemical analysis of SWDs and SWDPs

- **No differences SWDs/SWODs**
- **SWDPs driven by the type of planet**
    - In agreement with core-accretion models
    - Correlation debris disc/low-mass planets?
    - Lack correlation debris discs/giant planets?
- **Tentative [X/Fe]-T_C trends in SWPs**
    - Different behaviour in stars with cool-planets
    - Similar behaviour low-mass planets hosts / non-planets samples
    - Stars with hot Jupiters: higher [Fe/H], positive slopes?
- **Chemical depletions/Planet formation?**
    - Low statistical significances
    - Correlation T_C-[Fe/H]
    - After GCE corrections: still correlations with age, radius



The Metallicities of Stars With and Without Transiting Planets

Lars A. Buchhave

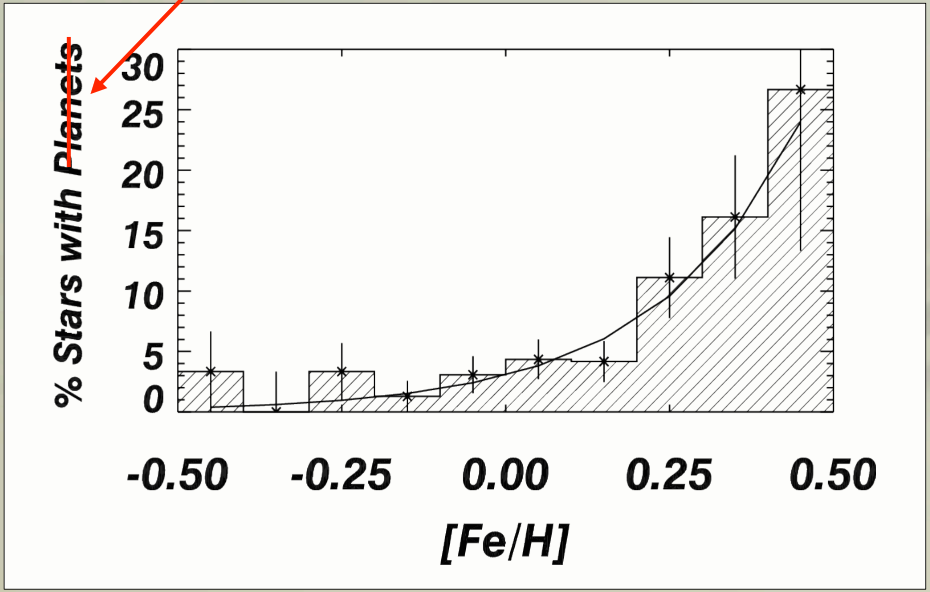
Harvard Origins of Life Initiative, Harvard University
Star and Planet Formation Centre and the Niels Bohr Institute, University of Copenhagen, Denmark

THE PLANET-METALLICITY CORRELATION

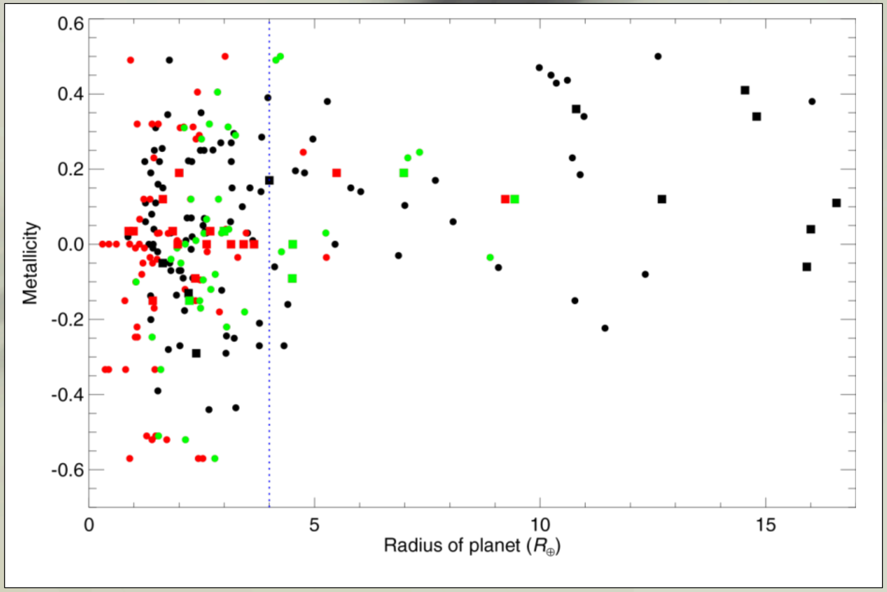
- Metal-rich stars tend to host hot Jupiter exoplanets
- Small planets form at a wide range of metallicities

close-in hot Jupiter planets

Fischer & Valenti 2005



Buchhave el al. 2012



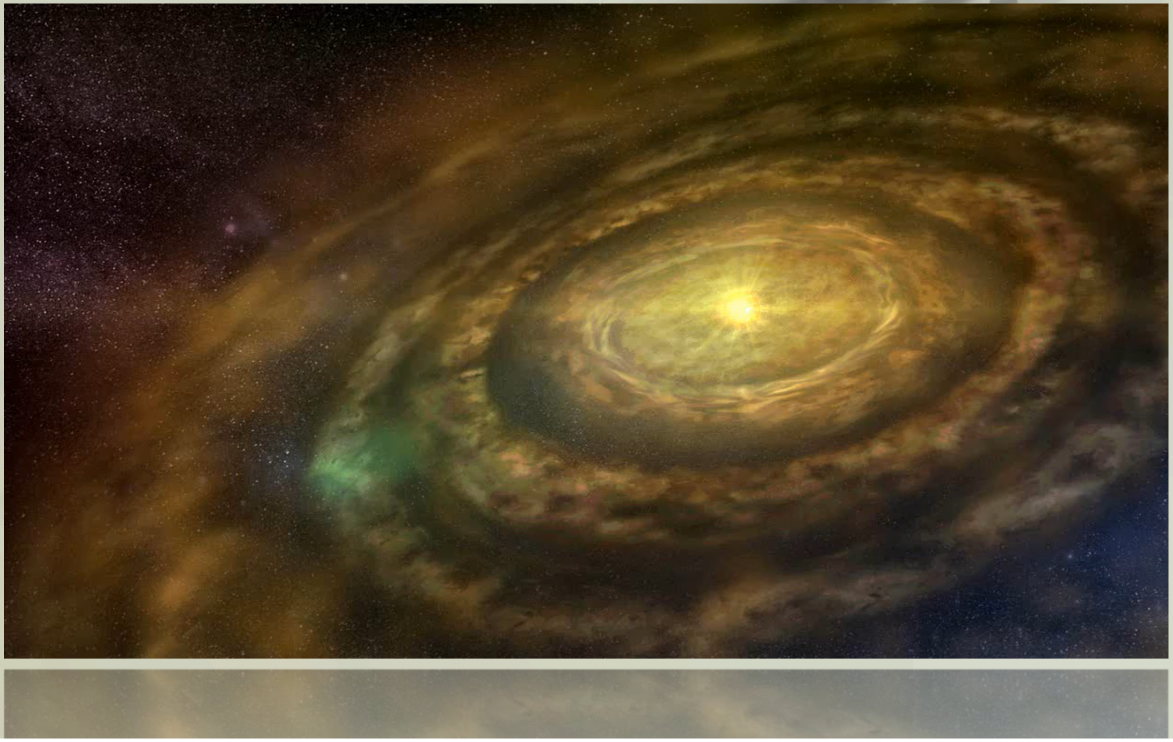
KEPLER HOST STAR METALLICITIES

- Metallicities
  - 600 Kepler exoplanets candidates
  - 405 unique host stars
  - Over 2000 high-resolution spectra from four different instruments

- The metallicity of the host stars reflects the metallicity of the initial protoplanetary disc

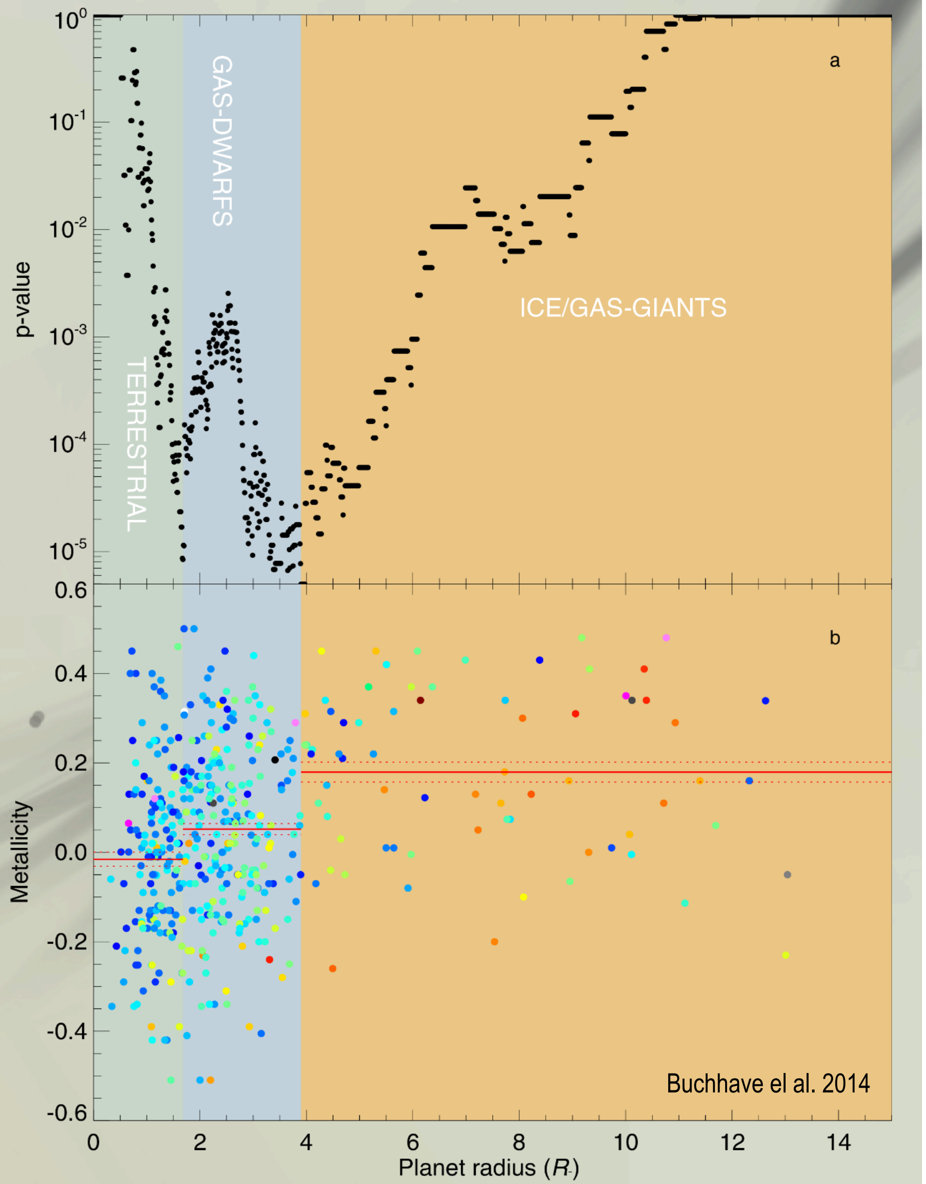
- Homogeneously derived metallicities using SPC

- Many small exoplanets



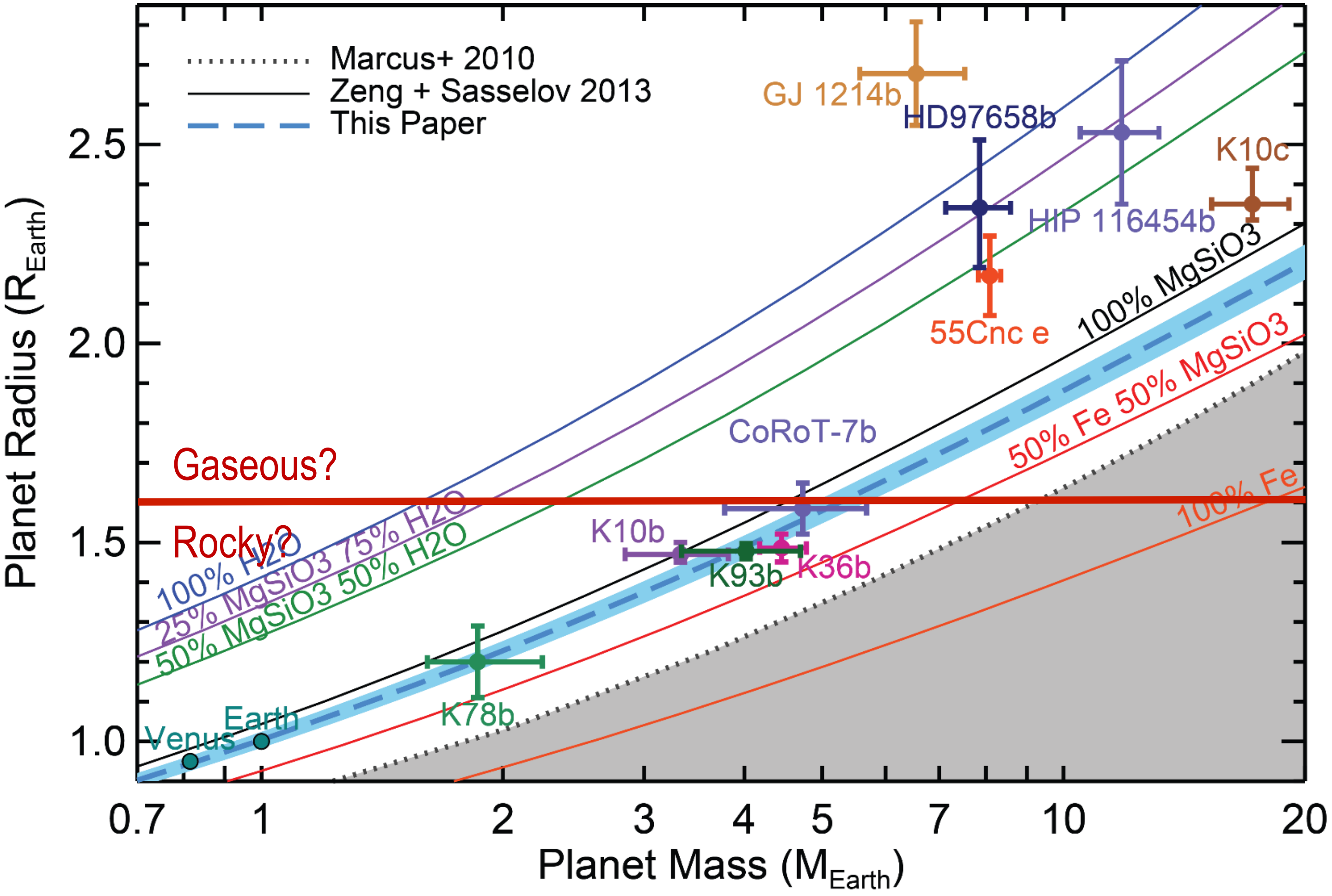
THREE REGIMES OF EXOPLANETS INFERRED FROM HOST STAR METALLICITIES

- Two features in K-S test diagram
    - $R_P = 1.7\ R_\oplus$ (4.5σ)
    - $R_P = 3.9\ R_\oplus$ (4.6σ)
- Monte Carlo simulation
    - $R_P = 1.55_{-0.04}^{+0.88}\ R_\oplus$ ($4.2_{-0.4}^{+0.5}\ \sigma$)
    - $R_P = 3.52_{-0.28}^{+0.74}\ R_\oplus$ ($4.7_{-0.4}^{+0.6}\ \sigma$)
- Interpretation:
    - Three regimes of exoplanets inferred from host star metallicities
        - Ice/gas-giants
        - Gas-dwarfs
        - Terrestrial planets
- Removing highly irradiated planets increased the significance of feature at 1.7 $R_\oplus$ from 3.5σ to 4.5σ
- Transition from rocky to gaseous planets



Buchhave el al. 2014

TRANSITION FROM ROCKY TO GASEOUS PLANETS?

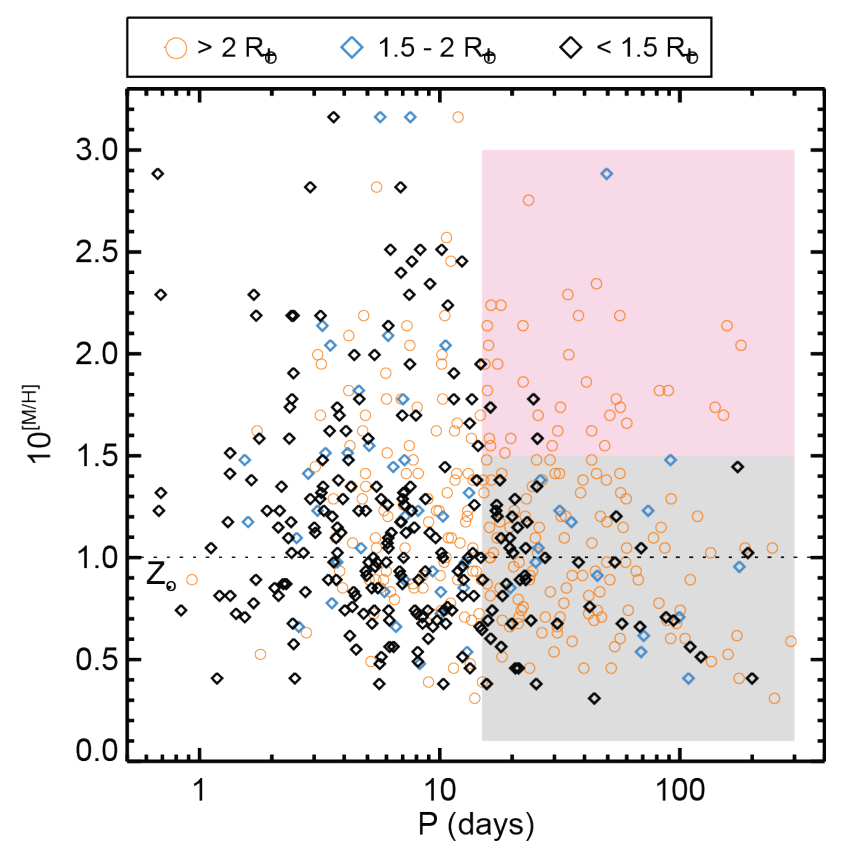


Dressing el al. 2014

A METALLICITY RECIPE FOR ROCKY PLANETS

Dawson el al. 2015

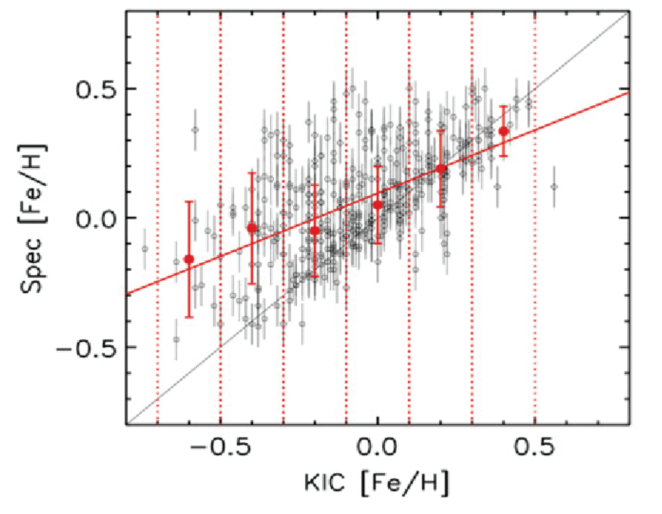
- Dawson et al. 2015 confirms trend from Buchhave el al. 2014, but dividing in metallicity rather than planetary radius
- At *P* > 15 days, metallicity can distinguish between metal-rich stars with predominantly gas-enveloped planets (pink box) from metal-poor stars with a combination of gas-enveloped and purely rocky planets (gray box).
- Higher metallicity stars are accompanied by disks with higher solid surface densities, which in turn spawn > 2 $M_\oplus$ cores faster, within the gas disk lifetime of ~1 Myr; these planets more readily acquire atmospheres and inflate their radii to > 2 $R_\oplus$ (orange).

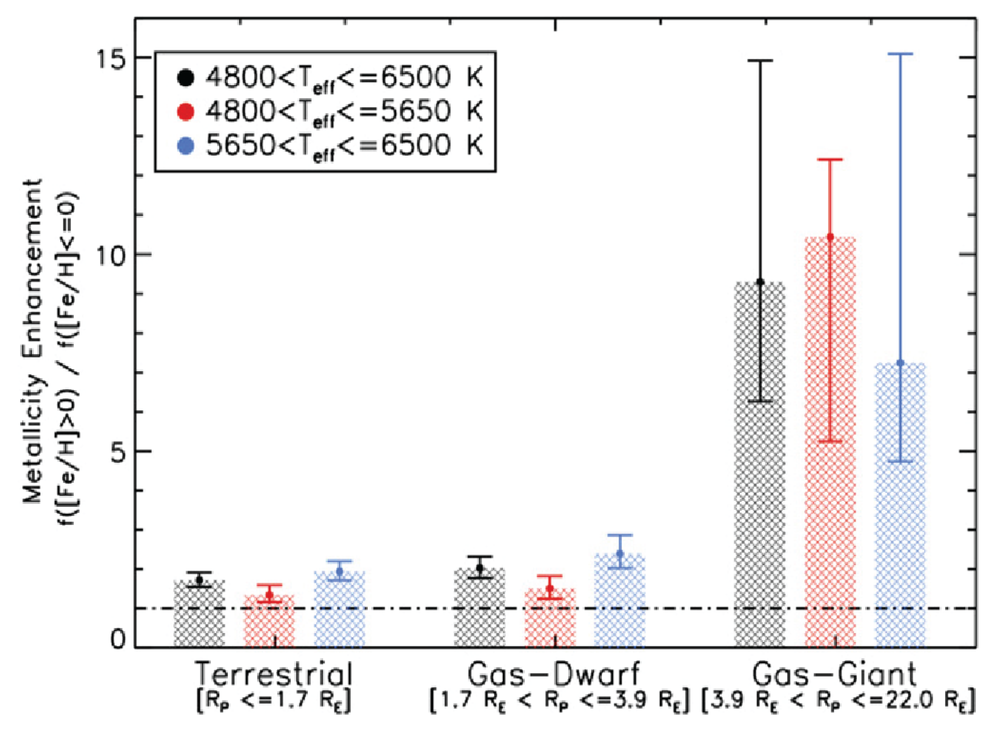


Dawson el al. 2015

UNIVERSAL PLANET-METALLICITY RELATION?

- Wang & Fisher 2015 claim a universal metallicity relation by comparing metallicities from Buchhave el al. 2014 to KIC metallicities
- States "metallicity enhancement" of $1.72↓−0.19↑+.017$ for terrestrial planets





Wang & Fischer 2015

- Adjustment of KIC metallicities to SPC metallicities. Difficult to do when looking for subtle metallicity differences!
- The KIC metallicities are intrinsically poorly determined.

THE "GOLD STANDARD" SAMPLE

- The Kepler Follow-up Program (KFOP) observed a large sample of KIC stars with asteroseismicsally determined stellar parameters to provide a well-characterized set of stars to the stellar properties working group tasked with deriving stellar parameters for the entire Kepler sample

- We derived stellar parameters for 518 stars using SPC. These stars have no detected transiting planets
  - But most stars in the sample most probably *do* host planets, since the occurrence rates are so high
  - Burke et al. 2015 derive an occurrence rate of 0.77 planets per star for $50 < P < 300$ days and $0.75 < R_P < 2.5\ R_\oplus$

- We compare the metallicities of these stars with no detected transiting planets (SNTP) to the host stars with small planets (STP)
  - Both sets of metallicities have been derived in a homogeneous way with the same tool (SPC)

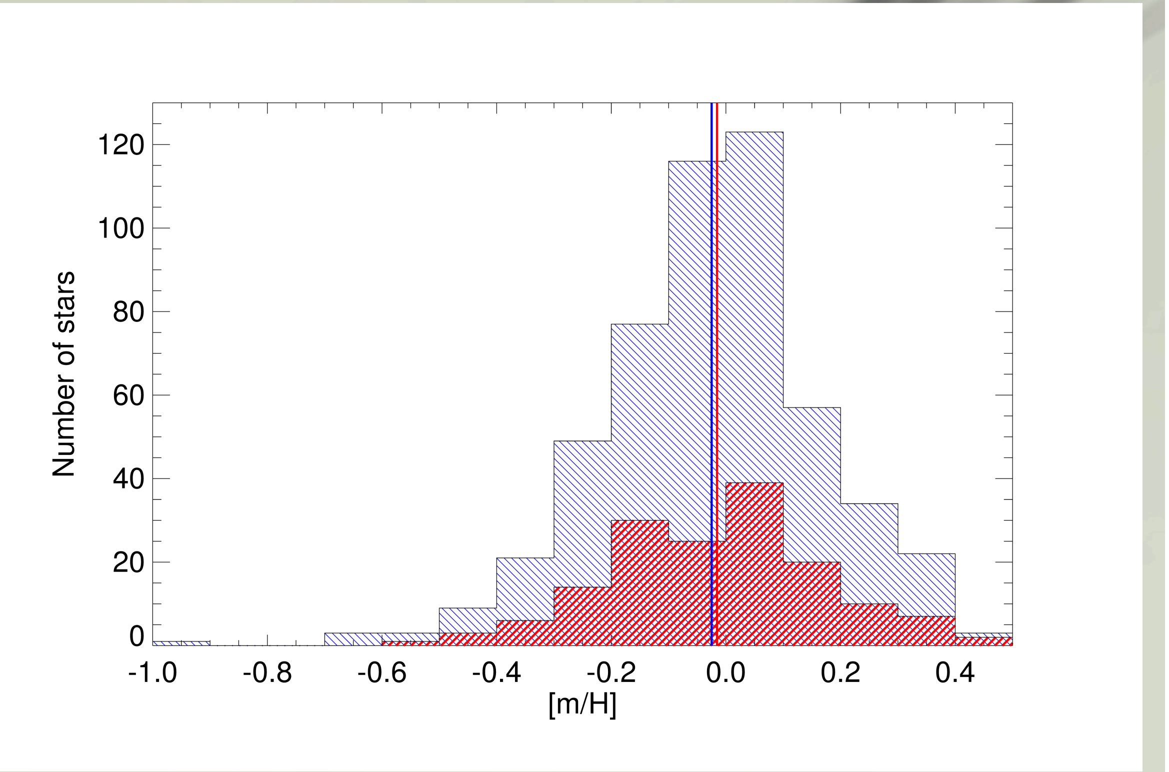
THE METALLICITIES OF STARS WITH AND WITHOUT TRANSITING PLANETS

- Metallicity of stars with transiting planets smaller than $R_P < 1.7\ R_\oplus$

  $[m/H]_{STP} = -0.02 \pm 0.02$ dex
- Metallicity of stars without detected transiting planets

  $[m/H]_{SNTP} = -0.02 \pm 0.01$ dex

- K-S test p-value of 0.50 (0.67 σ)
  - *Indicates the K-S test fails to reject the null hypnosis that the two samples are drawn randomly from the same parent population*



Buchhave & Latham 2015

THE METALLICITIES OF STARS WITH AND WITHOUT TRANSITING PLANETS

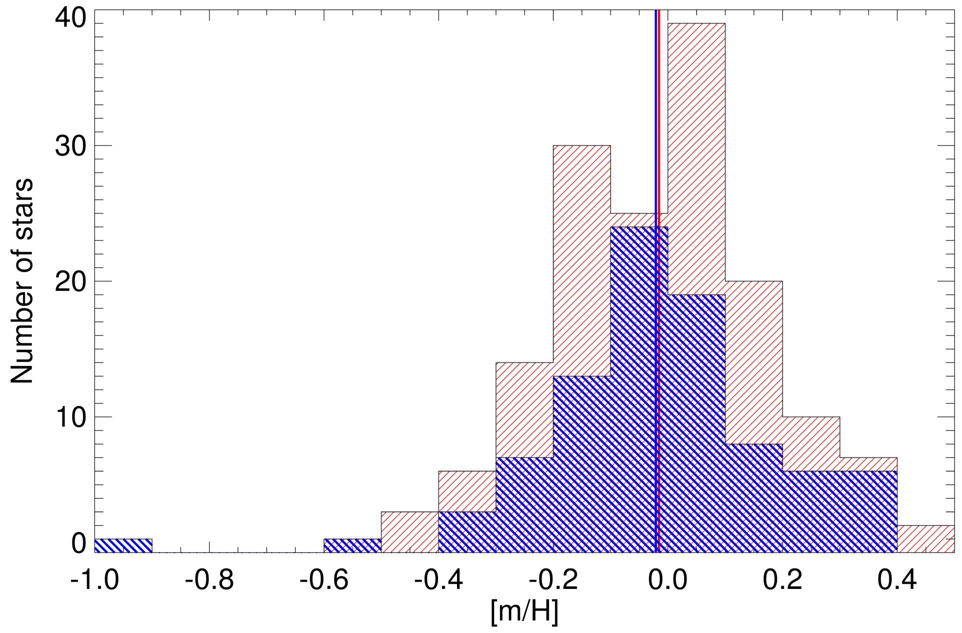
- Metallicity of stars with transiting planets smaller than $R_P < 1.7\ R_\oplus$

  $[m/H]_{STP} = -0.02 \pm 0.02$ dex

- Metallicity of stars without detected transiting planets (only dwarfs)

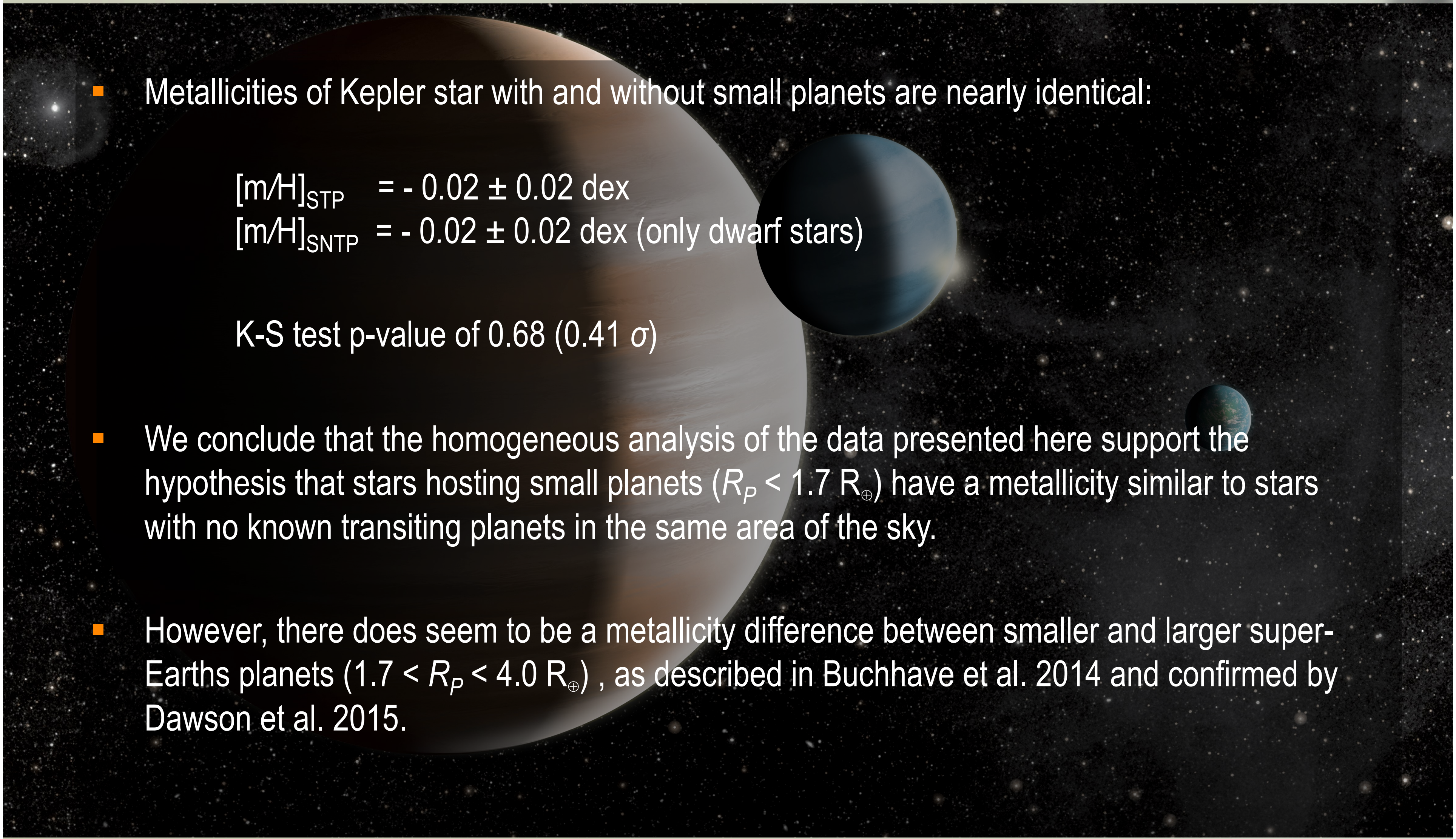
  $[m/H]_{SNTP} = -0.02 \pm 0.02$ dex

- K-S test p-value of 0.68 (0.41 σ)



Buchhave & Latham 2015

CONCLUSIONS



- Metallicities of Kepler star with and without small planets are nearly identical:

  $[m/H]_{STP}$ = - 0.02 ± 0.02 dex
  $[m/H]_{SNTP}$ = - 0.02 ± 0.02 dex (only dwarf stars)

  K-S test p-value of 0.68 (0.41 σ)

- We conclude that the homogeneous analysis of the data presented here support the hypothesis that stars hosting small planets ($R_P < 1.7\ R_\oplus$) have a metallicity similar to stars with no known transiting planets in the same area of the sky.

- However, there does seem to be a metallicity difference between smaller and larger super-Earths planets ($1.7 < R_P < 4.0\ R_\oplus$) , as described in Buchhave et al. 2014 and confirmed by Dawson et al. 2015.

Conditioning interiors of low-mass rocky exoplanets to abundances of their host stars

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Pathways conference Bern - 2015

b
UNIVERSITÄT
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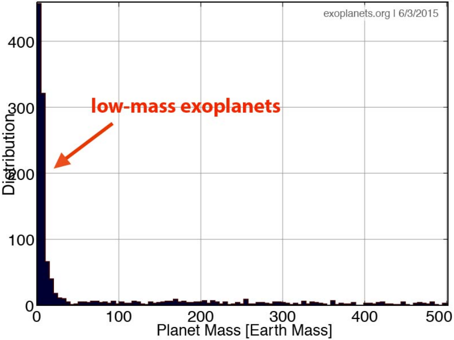
PlanetS
National Centre of Competence in Research

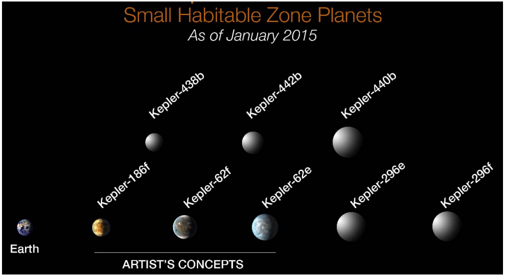
FNSNF
Swiss National Science Foundation

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

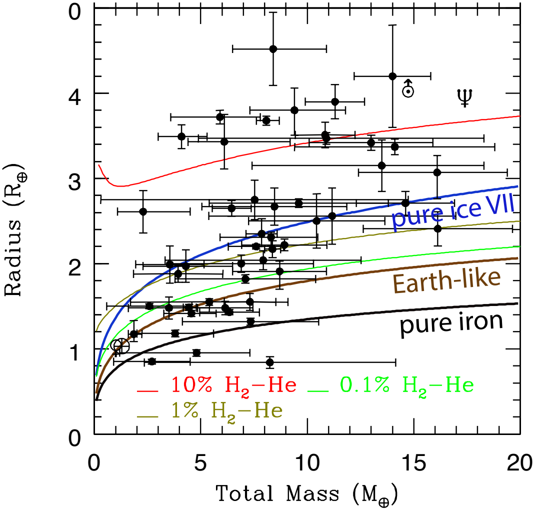
Why bother about low-mass exoplanets?

- they are **numerous**
- targets of **habitablility studies**
- one representative is most detailed studied planet: **Earth**
- explore bulk composition of Super-Earths and Mini-Neptunes (e.g., Gliese 1214b)





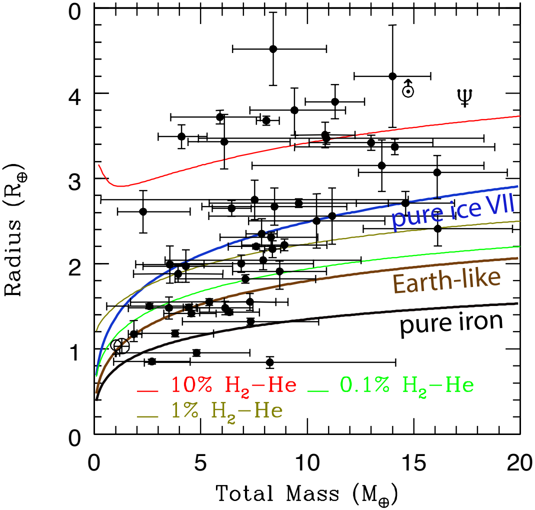
low-mass exoplanets



Howe et al. (2014)

- significant uncertainties on mass and radius

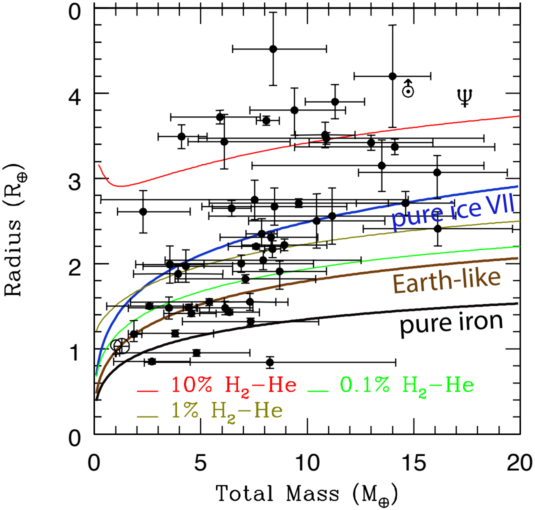
low-mass exoplanets



Howe et al. (2014)

- significant uncertainties on mass and radius
- model uncertainty: the equations of state

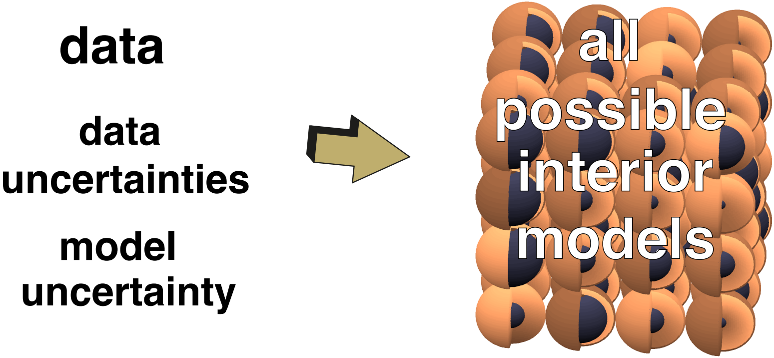
low-mass exoplanets



- significant uncertainties on mass and radius
- model uncertainty: the equations of state
- degeneracy: different interior models can have identical mass and radius

Howe et al. (2014)

Inverse approach



data

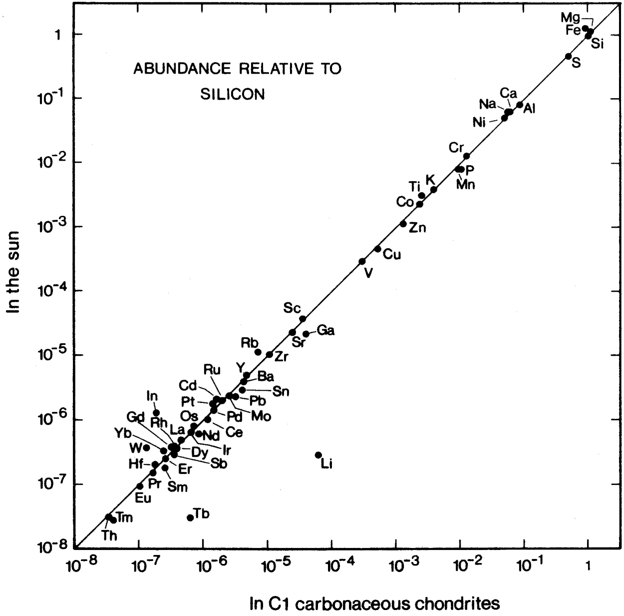
data uncertainties

model uncertainty

all possible interior models

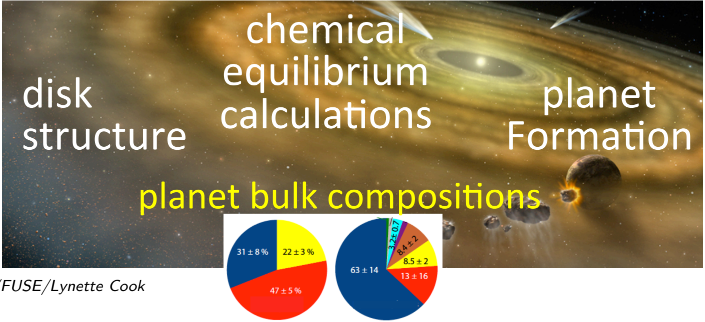
data are mass and radius and... ?

correlation of star & planet compositions



high similarity between relative abundances of refractory atoms in solar atmosphere, chondrites and terrestrial planets

correlation of star & planet compositions



chemical equilibrium calculations

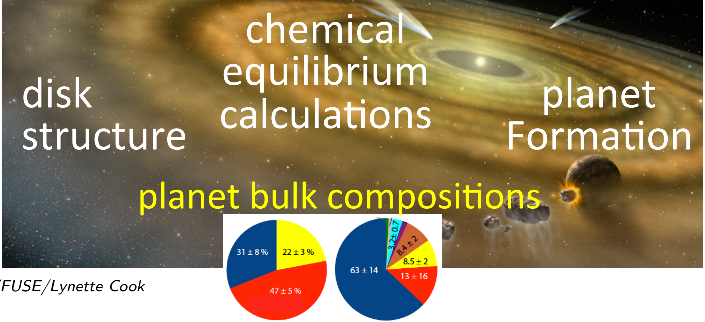
disk structure

planet Formation

planet bulk compositions

source *NASA/FUSE/Lynette Cook*

correlation of star & planet compositions



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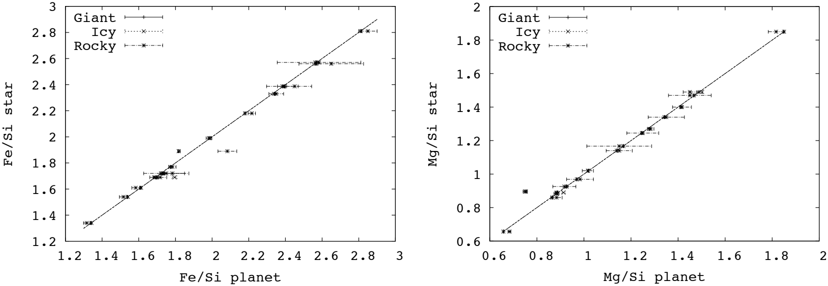
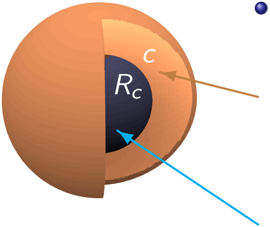


adapted from *Thiabaud et al. 2015*

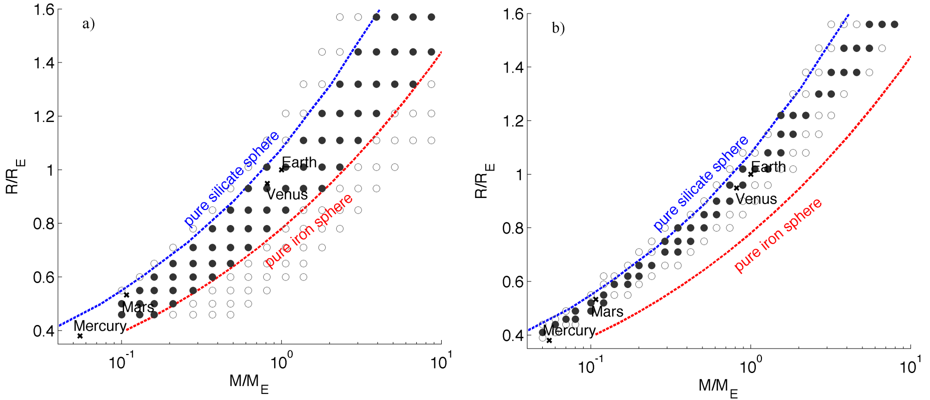
Model I - pure rocky exoplanets



- Rocky composition
  (no water, no atmosphere!)
- **Mantle**: system comprising the oxides
  Na_2O-CaO-FeO-MgO-Al_2O_3-SiO_2
  adiabatic temperature profile
  Fe/Si_{mantle}
  m: Mg/Si_{mantle}
  mantle Si-content
- **Core**: pure iron
  adiabatic temperature profile
  m: R_c core radius

Method testing

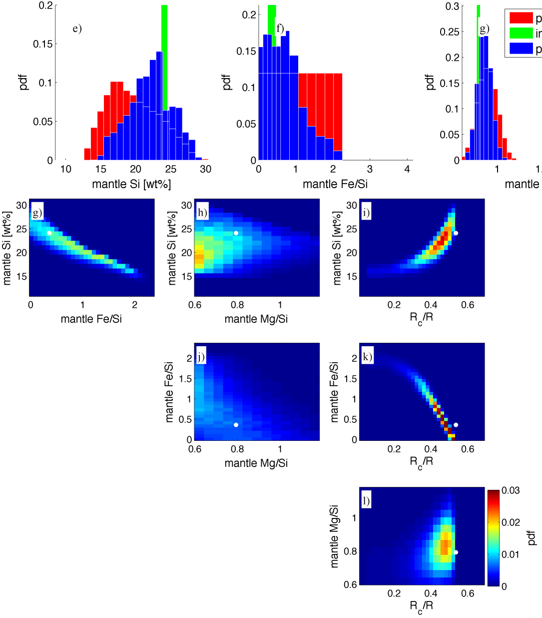
What data can be explained by the model?



NO abundance constraints

assuming solar Fe/Mg/Si abundances

Method testing: Earth case



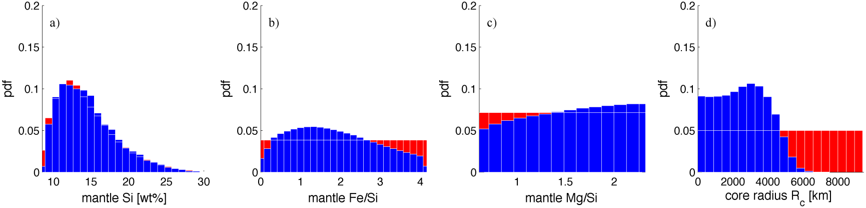
core size is constrained by mass and radius.

underestimation of core size:

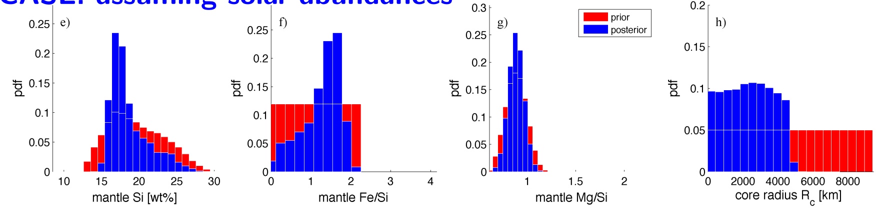
independent model includes light elements in core.

Application to confirmed exoplanets

CASE: NO abundance constraints



CASE: assuming solar abundances



Kepler-36b

mean bulk density $= 7.48\ g/cm^3$

radius $R/R_E = 1.486 \pm 0.035$

mass $M/M_E = 4.45^{+0.33}_{-0.27}$

Ability to constrain core size R_c vs Data uncertainty

Kepler-36b

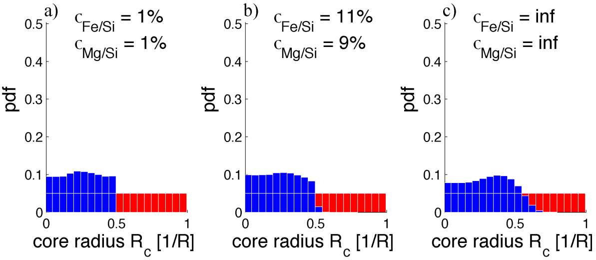
$\rho_{\text{bulk}} = 7.48\ g/cm^3$

$R/R_E = 1.486$

$M/M_E = 4.45$

$\sigma_M = 7\%$

$\sigma_R = 2\%$



Earth

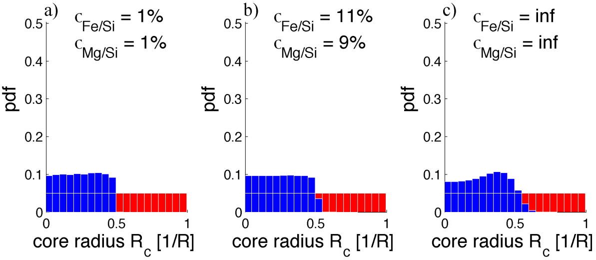
$\rho_{\text{bulk}} = 5.5\ g/cm^3$

$R/R_E = 1$

$M/M_E = 1$

$\sigma_M = 7\%$

$\sigma_R = 2\%$



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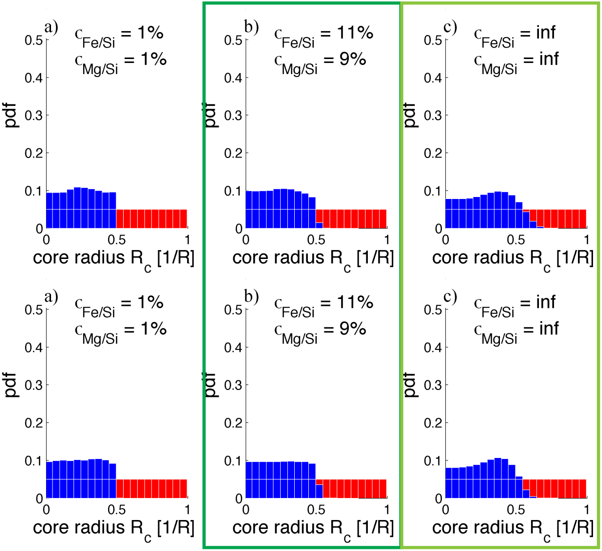

solar uncertainty **no constraints**

Ability to constrain core size R_c vs Data uncertainty

Kepler-36b

$\rho_{\rm bulk} = 7.48\ g/cm^3$

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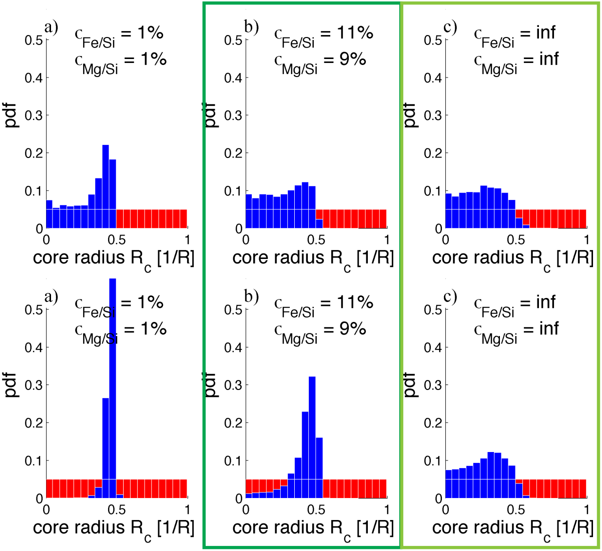


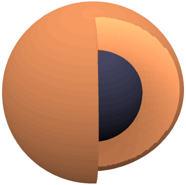
solar uncertainty **no constraints**

Conclusions

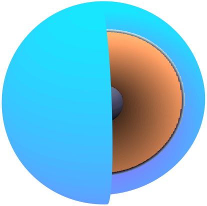
- with the sparse data (M, R, $\mathrm{Fe/Si}_{\mathrm{star}}$, $\mathrm{Mg/Si}_{\mathrm{star}}$) we can constrain the interior structure of exoplanets
- stellar abundances $\mathrm{Fe/Si}_{\mathrm{star}}$, $\mathrm{Mg/Si}_{\mathrm{star}}$ are key parameters to constrain rocky interiors
- how well interiors can be constrained depends on data itself and their uncertainties

Outlook

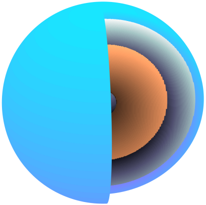
rock



rock + gas



rock + water/ice + gas



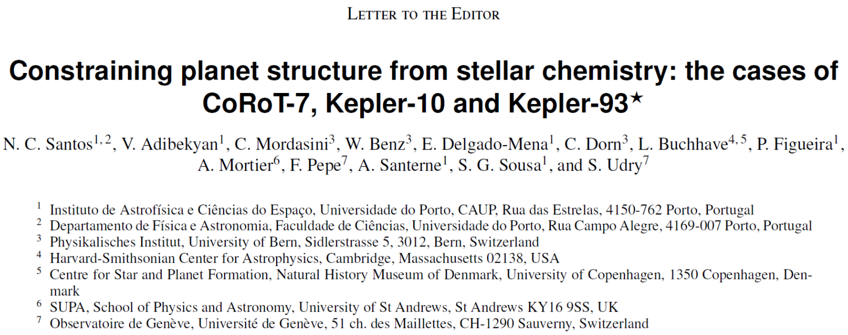
interior structure → dynamics → habitability

Composition of rocky planets based on the host star chemistry

What observations are telling us?

Vardan Adibekyan
Institute of Astrophysics and Space Sciences

14 July 2015
Bern, Switzerland



LETTER TO THE EDITOR

Constraining planet structure from stellar chemistry: the cases of CoRoT-7, Kepler-10 and Kepler-93⋆

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[4] Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138, USA
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[6] SUPA, School of Physics and Astronomy, University of St Andrews, St Andrews KY16 9SS, UK
[7] Observatoire de Genève, Université de Genève, 51 ch. des Maillettes, CH-1290 Sauverny, Switzerland

Are stars with planets chemically different?

Previous studies yielded contradictory results

- Most studies found no systematic difference in abundances (Takeda 2007; Bond et al. 2008; Neves et al. 2009; Delgado Mena et al. 2010)
- Possible enrichment in some species (Bodaghee et al. 2003; Robinson et al. 2006; Brugamyer et al. 2011; Kang et al. 2011)

Refractory elements

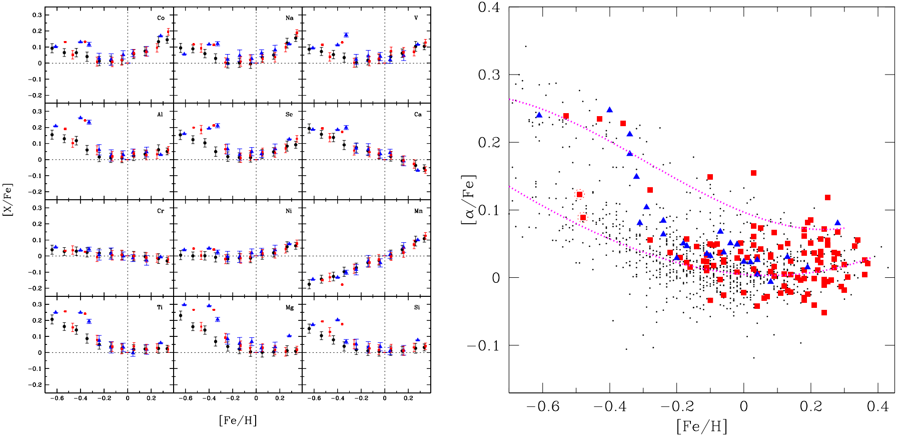


Figure: [X/Fe] vs. [Fe/H] for HARPS sample. Adibekyan et al. 2012a.

Element enhancement of planet hosts

Mg,Ti, Si, Sc, and Al at [Fe/H] $\lesssim$ -0.2 dex

α-elements

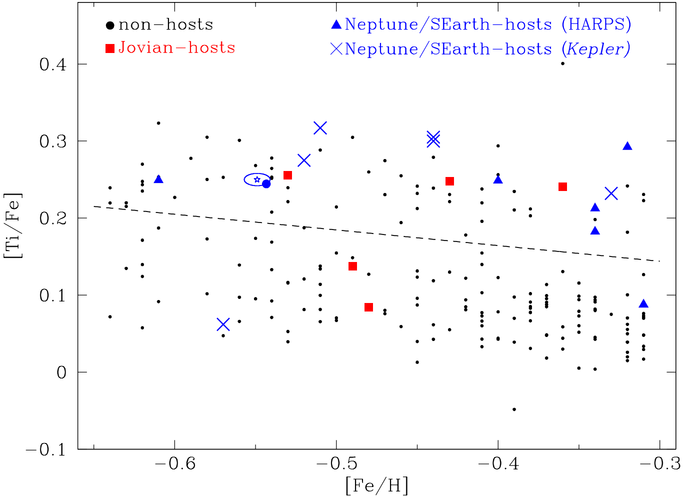
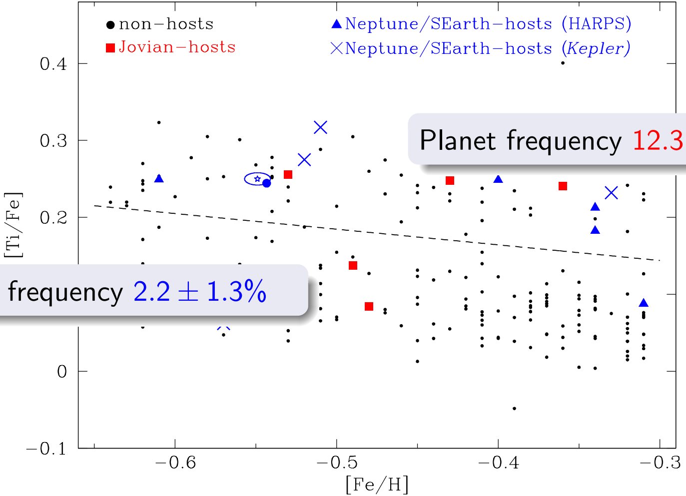


Figure: HARPS + Kepler samples. Adibekyan et al. 2012b.

α-elements



Planet frequency 12.3 ± 4.1%

Planet frequency 2.2 ± 1.3%

Figure: HARPS + Kepler samples. Adibekyan et al. 2012b.

Interior structure of planets and chemical elements

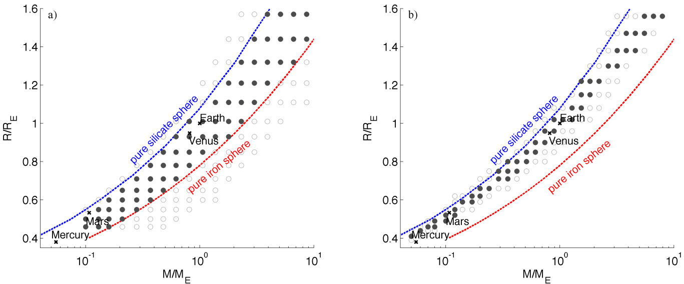


Figure: Dorn et al. 2015.

- Observations of mass and radius are sufficient to constrain core size
- Stellar elemental abundances (Fe, Si, Mg) are principal constraints to reduce degeneracy in interior structure models and to constrain mantle composition

The composition of terrestrial planets

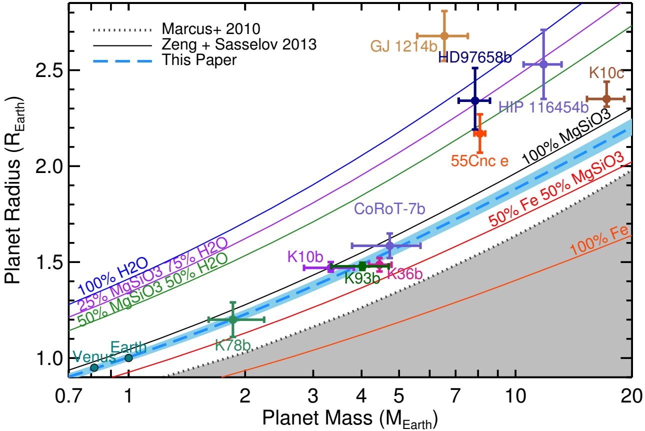


Figure: Dressing et al. 2015.

- Planets with $R < 1.6 R_\oplus$ show similar composition (as the Earth and Venus) - 17% Fe and 83% $MgSiO_3$
- Planets with higher masses have lower densities.

The composition of rocky planet hosts: the cases of CoRoT-7, Kepler-10 and Kepler-93

The data

- Kepler-10: HARPS-N, SOPHIE
- Kepler-93: SOPHIE
- CoRoT-7: HARPS

The goal

Relative abundances of Fe, Mg, and Si are similar in the Sun, Earth, Mars, Venus, and meteorites!

Do rocky exoplanets following a mass-radius relation (similar composition?) have similar composition of their host stars?

The composition of rocky planet hosts: the cases of CoRoT-7, Kepler-10 and Kepler-93

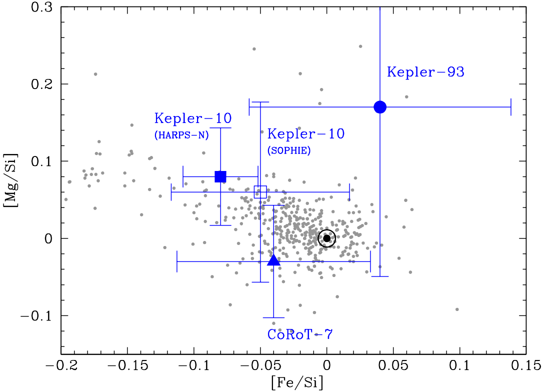


Figure: Santos et al. 2015.

- Kepler-10 is (significantly) depleted in Fe relative to Mg and Si.

The composition of rocky planet: the cases of CoRoT-7, Kepler-10 and Kepler-93

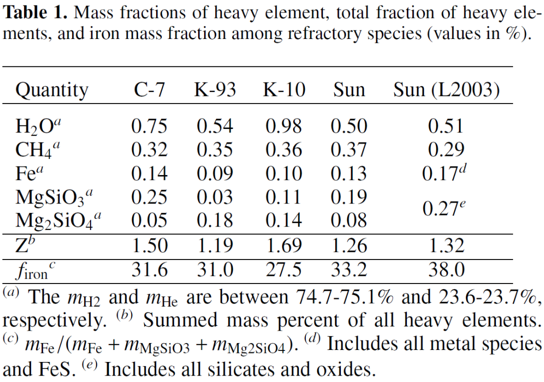


Table 1. Mass fractions of heavy element, total fraction of heavy elements, and iron mass fraction among refractory species (values in %).

Quantity	C-7	K-93	K-10	Sun	Sun (L2003)
H_2O^a	0.75	0.54	0.98	0.50	0.51
$CH_4{}^a$	0.32	0.35	0.36	0.37	0.29
Fe^a	0.14	0.09	0.10	0.13	0.17^d
$MgSiO_3{}^a$	0.25	0.03	0.11	0.19	0.27^e
$Mg_2SiO_4{}^a$	0.05	0.18	0.14	0.08	
Z^b	1.50	1.19	1.69	1.26	1.32
$f_{\text{iron}}{}^c$	31.6	31.0	27.5	33.2	38.0

$^{(a)}$ The m_{H2} and m_{He} are between 74.7-75.1% and 23.6-23.7%, respectively. $^{(b)}$ Summed mass percent of all heavy elements. $^{(c)}$ $m_{\text{Fe}}/(m_{\text{Fe}}+m_{\text{MgSiO3}}+m_{\text{Mg2SiO4}})$. $^{(d)}$ Includes all metal species and FeS. $^{(e)}$ Includes all silicates and oxides.

- CoRoT-7 and Kepler-93 have iron fraction similar to the Sun
- The iron fraction for Kepler-10 is slightly lower.

Conclusion


model
error
Kepler-93
SOPHIE
Fe/Si
ratios
results
significantly
metallicity
allowed
trends
plane
planets
stars
given
Mg/Si
expected
strong
Delgado-Mena-2010
hosting
respectively
also
nominal
constraints
firm
Adibekyan-2012b
situation
transiting
mass
average
changes
mantle
CoRoT-7
forbidden
HARPS-N
rocky
Fe/H
partially
differences
measure
may
quality
sim
expect
Dorn
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allow
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Conclusion

Metallicity and planet formation and evolution

Metallicity is an important factor for planet formation and evolution

- Elements other than iron are also important for planet formation
  Are all the elements equally important?
- Even low-mass/small-size planets need metals to form
  Which metals do they need?
- Chemical composition of the hosts can be used to put constraints on the composition of rocky planets.
  Need more and very accurate data!


THANK
YOU
GRACIAS
ARIGATO
SHUKURIA
BİYAN
SHUKRIA
TINGKI
DANKSCHEEN
TASHAKKUR ATU
YAQHANYELAY
SUKSAMA
EKHMET
MEHRBANI
GRAZIE
MAAKE
KOMAPSUMNIDA
PALDIES
BOLZÏN
MERCI
GOZAIMASHITA
EFCHARISTO
JUSPAXAR
SPASSIBO
SNACHALHUYA
NUHUN
CHALTU
WABEEJA
MAITEKA
YUSPAGARATAM
HUI
GUI
HATUR
UNALCHEESH
SPASIBO
DENKAUJA
NENACHALHYA
MERSI
ATTO
DHANYABAAD
ANIHA
SANCO
MERASTAWHY
GAEJTHO
AGUYJE
FAKAAUE
LAH
TAVTAPUCH
MEDAWAGSE
BAIKA
EKOJU
SIKOMO
MAKETAI
MINMONCHAR