Characterization of Exoplanet-Host Stars

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Why not Sergio?

It was a real war with casualties...


Before going to hospital
he flew 1.5 km in less than 1 min

Main characteristics of stars

Luminosity | Radius | Mass | Age | Rotation | ...

Effective temperature | Surface gravity | Chemical composition

Why is the *precise* characterization of stars important for exoplanet sciences?

Why is the precise characterization of stars important for exoplanet sciences?

Characterization of the planets depends on the characterization of the host stars:

$M_p \sim M_*^{2/3}$

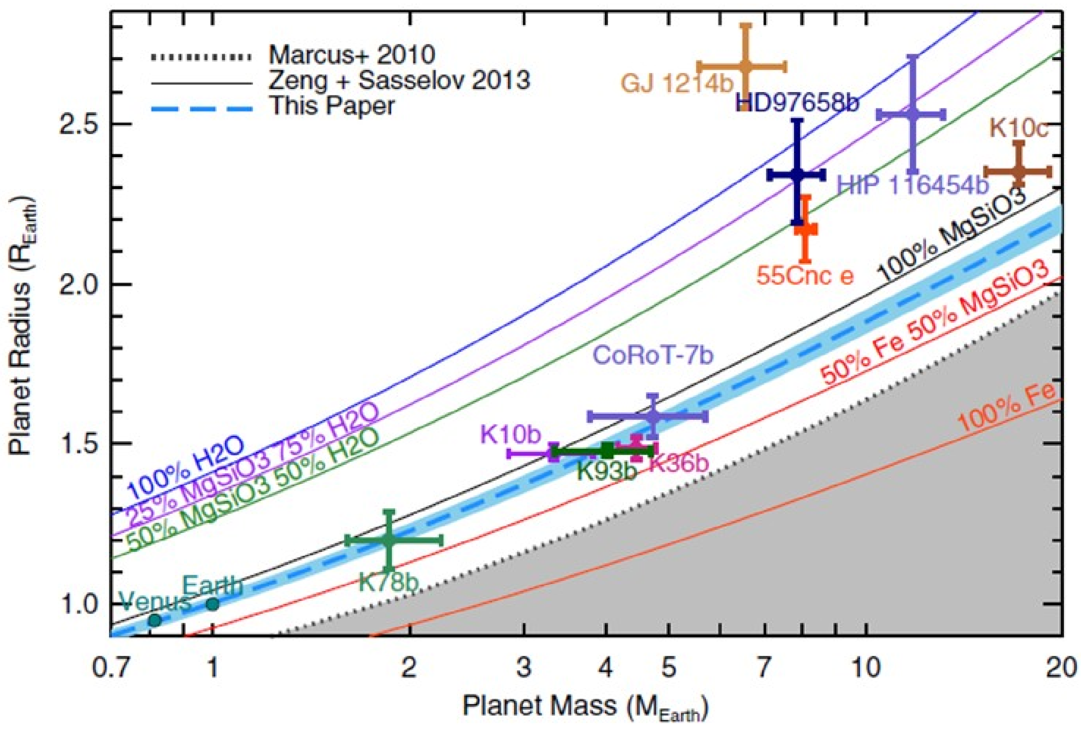
$R_p \sim R_*$

$Age_p \approx Age_*$

….

Why is the precise characterization of stars important for exoplanet sciences?

Precise characterization of the planets depends on the precise characterization of the host stars.

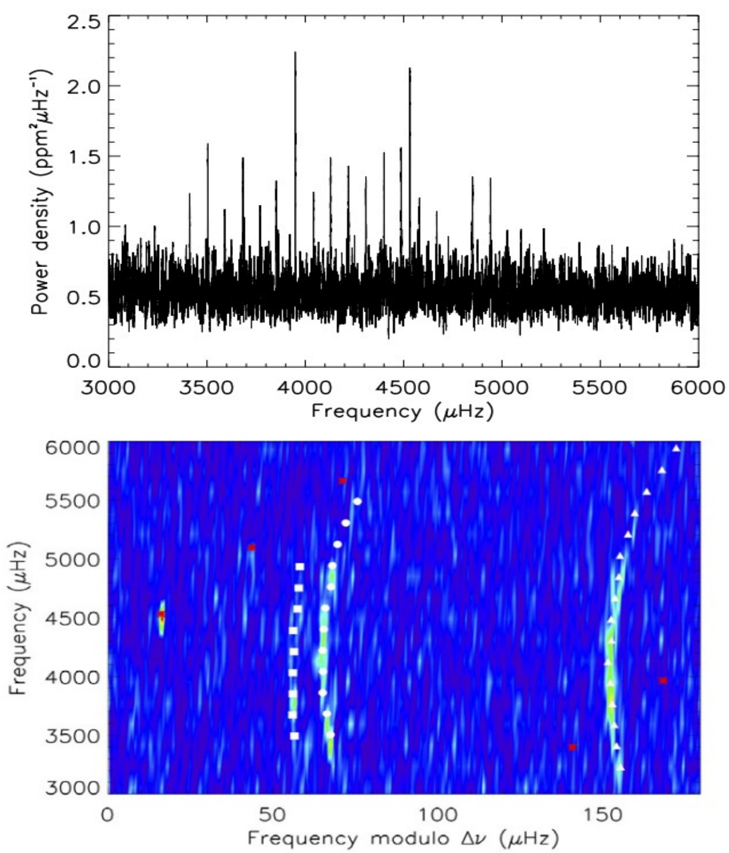


Dressing et al. 2015

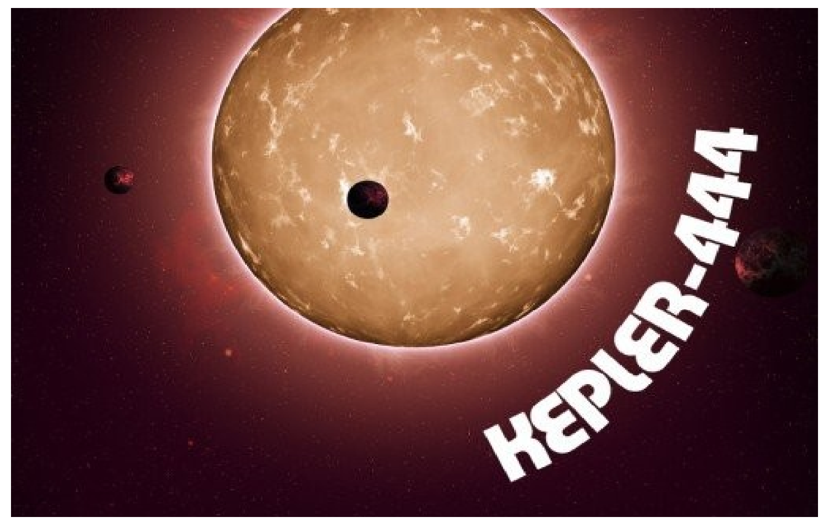
100% water or 100% iron, or ... ?

Why is the precise characterization of stars important for exoplanet sciences?

Precise characterization of the planets depends on the precise characterization of the host stars.



Campante et al. 2015

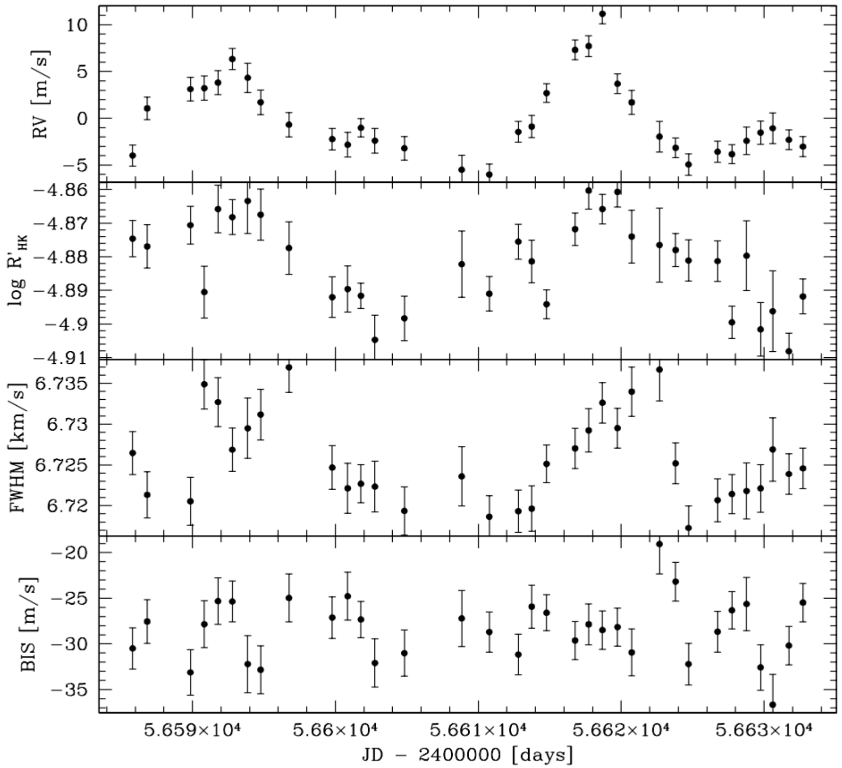


Sub-Earth size planets could be formed in the ancient Galaxy!
Age = 11.2±1 Gyr
Uncertainties in radius of planets ~100 km

Why is the precise characterization of stars important for exoplanet sciences?

Knowledge of stellar properties helps to detect/reject planets.

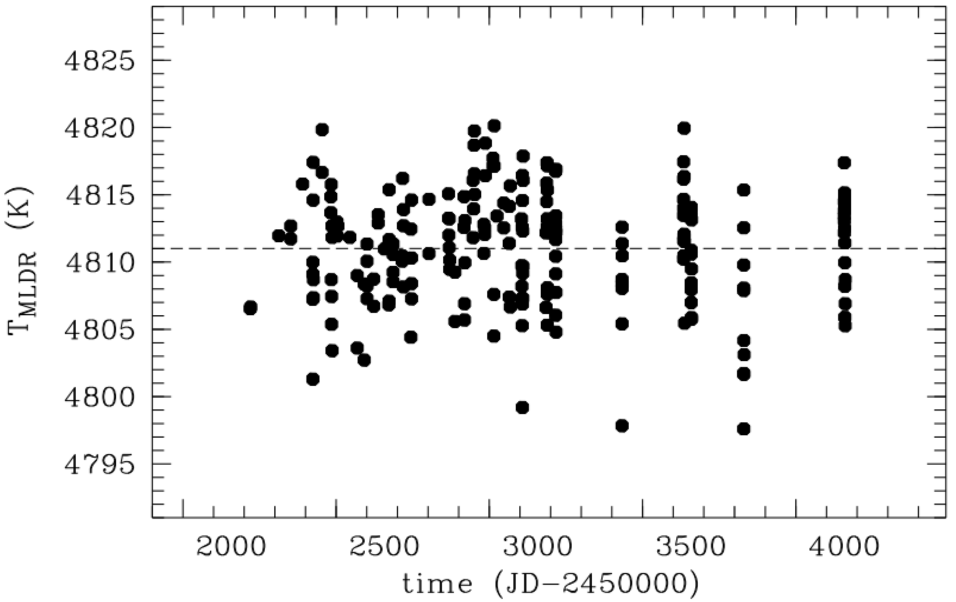
HD 41248: Stellar activity, no planets?



Santos et al. 2014

ν Octantis: A planet, not an activity?

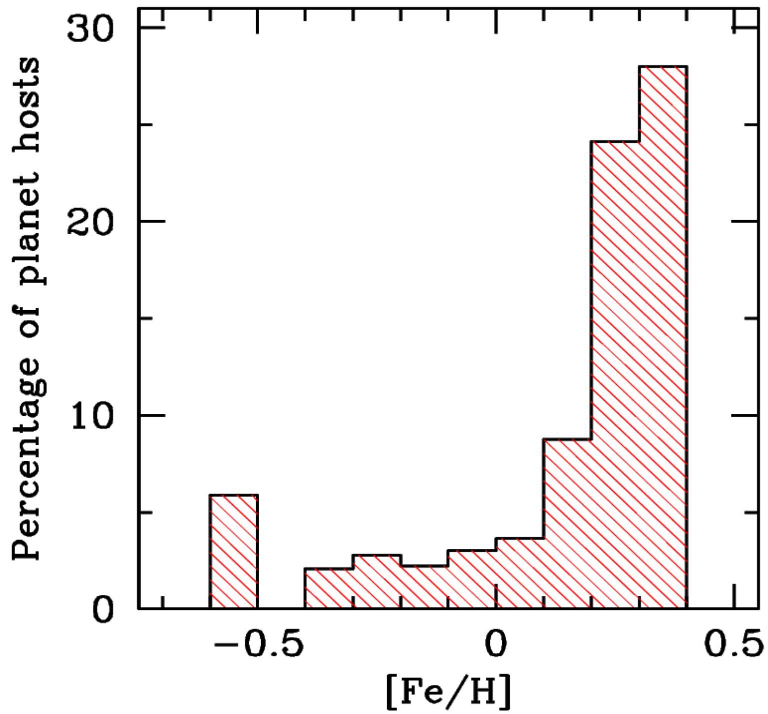
Precise T_{eff} estimation with a σ~4K



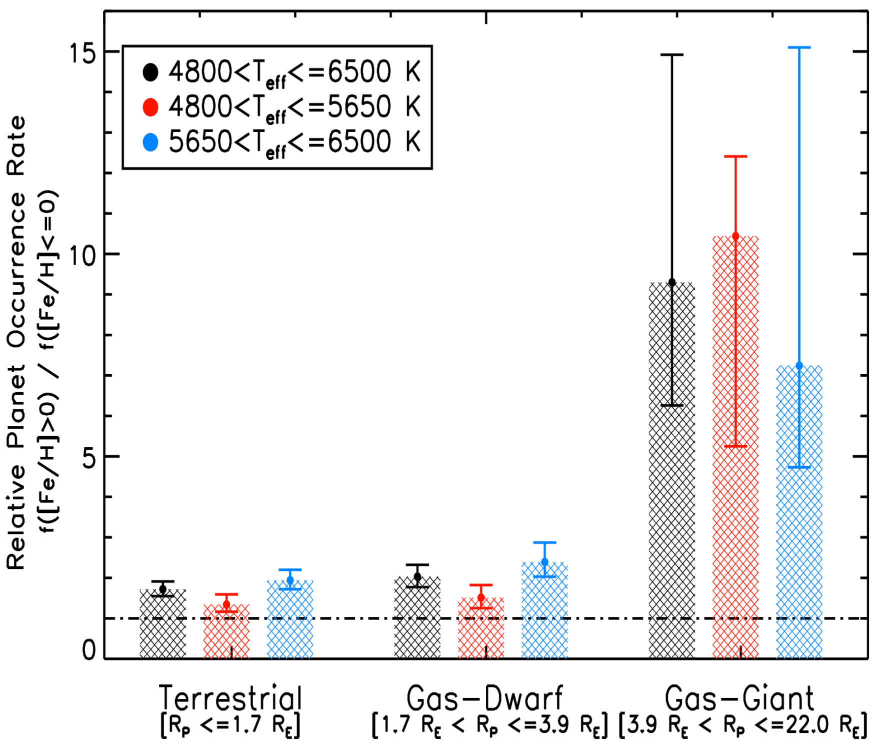
Ramm 2016

Why is the precise characterization of stars important for exoplanet sciences?

Correlations between the properties of planets and their hosts help to understand the formation and evolution of planets.



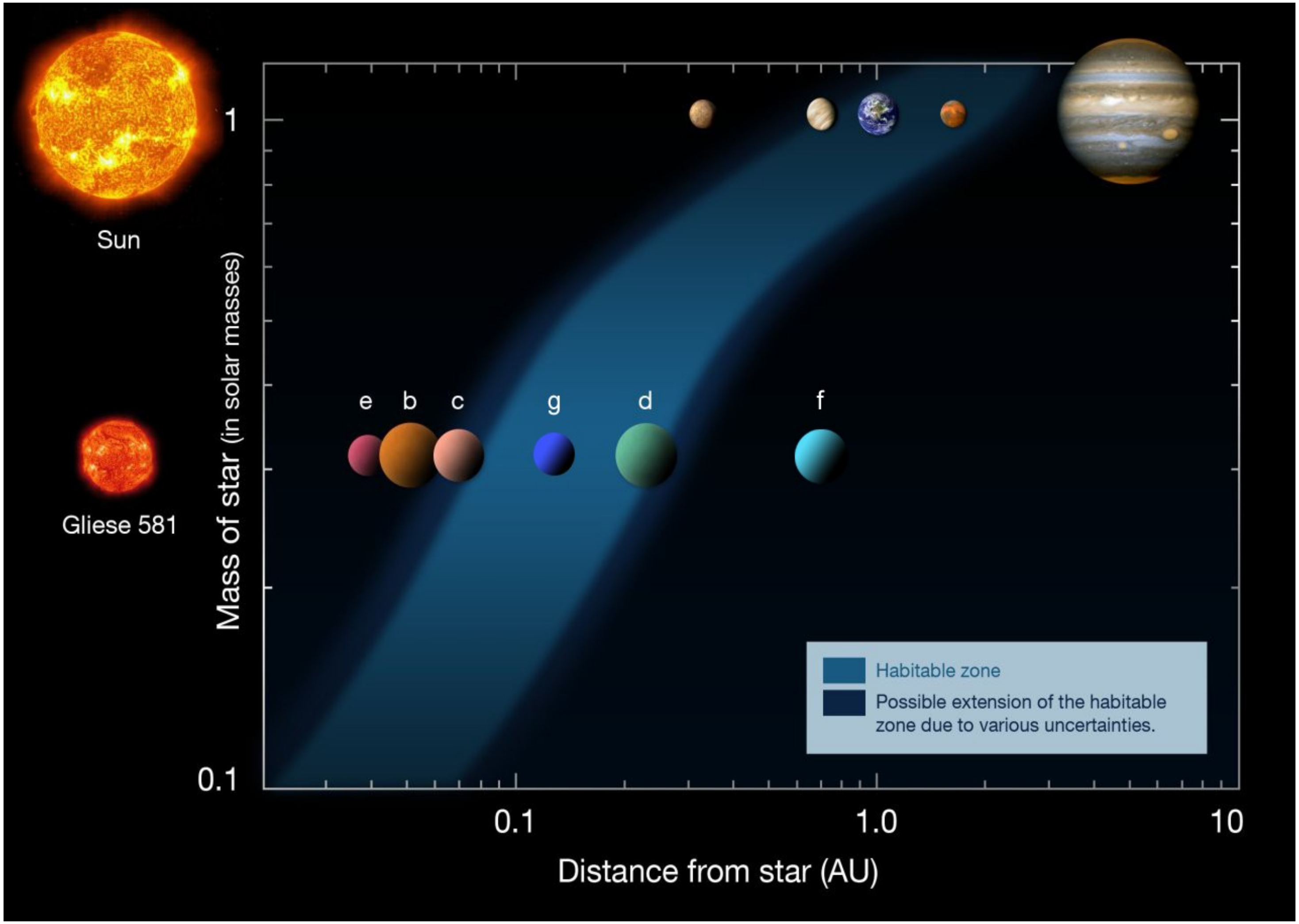
Santos et al. 2004



Wang & Fischer 2015

Why is the precise characterization of stars important for exoplanet sciences?

Need to know the host to know if the planet is 'habitable'



How to derive stellar parameters directly?

Luminosity | Radius | Mass | Age | Rotation | ...

Effective temperature | Surface gravity | Chemical composition

Stellar parameters with direct methods

Effective temperature

$$\sigma T_{eff}^4 \equiv \int_0^{\infty} F_\nu \, d\nu = F_\star = \frac{L}{4\pi R^2}$$

Temperature of a black body that gives the same total power per unit area as the star.

$$F_\star = \frac{\theta^2}{4} f_\oplus$$

angular diameter, that can be directly measured with interferometry

total flux at Earth (UV, visible, IR)

Stellar parameters with direct methods

Surface gravity

$$g = g_{\odot} M / R^2, \rho = \rho_{\odot} M / R^3 \qquad g = R\rho = M^{1/3} \rho^{2/3}$$

Surface gravity can be directly obtained if the stellar mass, radius and/or density are known:

- Eclipsing binary stars: **M** and **R**

Stellar parameters with direct methods

Stellar metallicity and chemical abundances

Not measurable directly!

$$Z = \frac{\text{Mass of all elements heavier than He}}{\text{Total mass in unit volume}}$$

$$\left[\frac{Fe}{H}\right] = \log\left[\frac{N(Fe)}{N(H)}\right]_{star} - \log\left[\frac{N(Fe)}{N(H)}\right]_{sun}$$

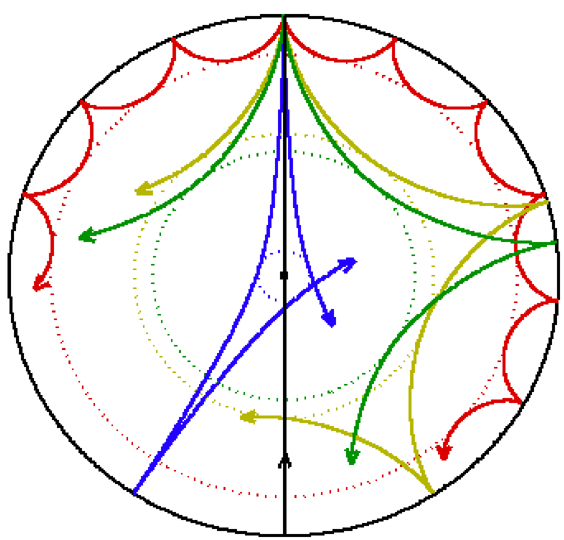
Stellar parameters with direct methods

Direct determination of stellar properties is impossible for most of the stars: Indirect methods are needed

How to characterize the stars with asteroseismology?

Luminosity | Radius | Mass | Age | Rotation | ...

Effective temperature | Surface gravity | Chemical composition

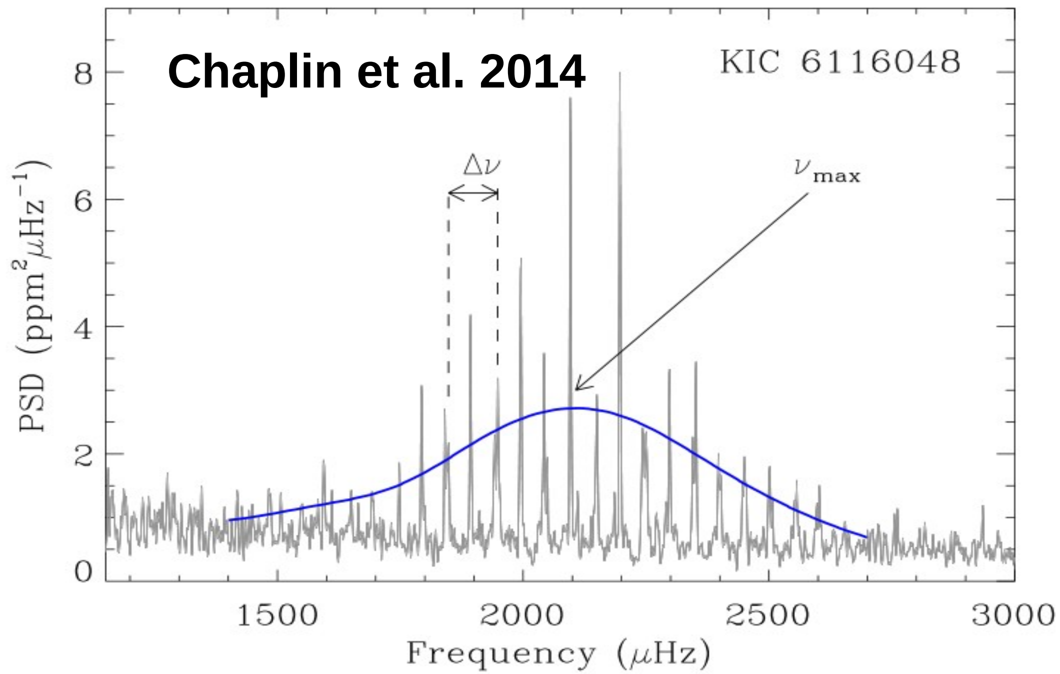


What does asteroseismology give us?

Scaling relations

$$M_\star = \left(\frac{\nu_{\max}}{\nu_{\max,\odot}}\right)^3 \left(\frac{\Delta\nu_\odot}{\Delta\nu}\right)^4 \left(\frac{T_{\rm eff}}{T_{\rm eff,\odot}}\right)^{3/2}$$

$$R_\star = \frac{\nu_{\max}}{\nu_{\max,\odot}} \left(\frac{\Delta\nu_\odot}{\Delta\nu}\right)^2 \sqrt{\frac{T_{\rm eff}}{T_{\rm eff,\odot}}}.$$



Derive M, R, assuming you know Teff

What does asteroseismology give us?

Forward modeling approach

Observations
(**Teff, [M/H]**, Δν, ν_{max},...)

Models
(M, L, α_{ML}, Age, Overshooting...)

Results
(M, R, Age...)

What does asteroseismology give us?

Forward modeling approach

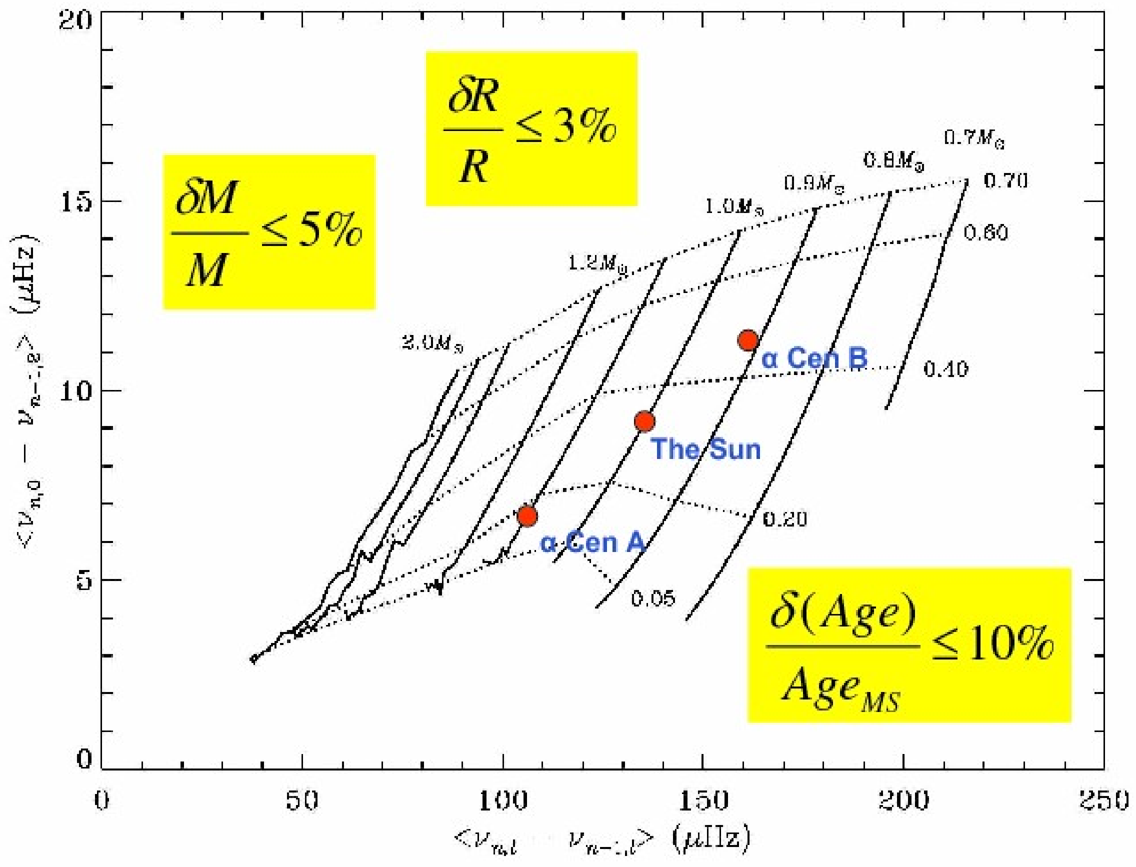
Observations
(**Teff, [M/H]**, $\Delta\nu$, ν_{max},...)

Models
(M, L, α_{ML}, Age, Overshooting...)

Results
(M, R, Age...)

Derive M, R, and age, assuming we know seismic parameters BUT also (at least) the Teff and [M/H]

What does asteroseismology give us and with what precision?



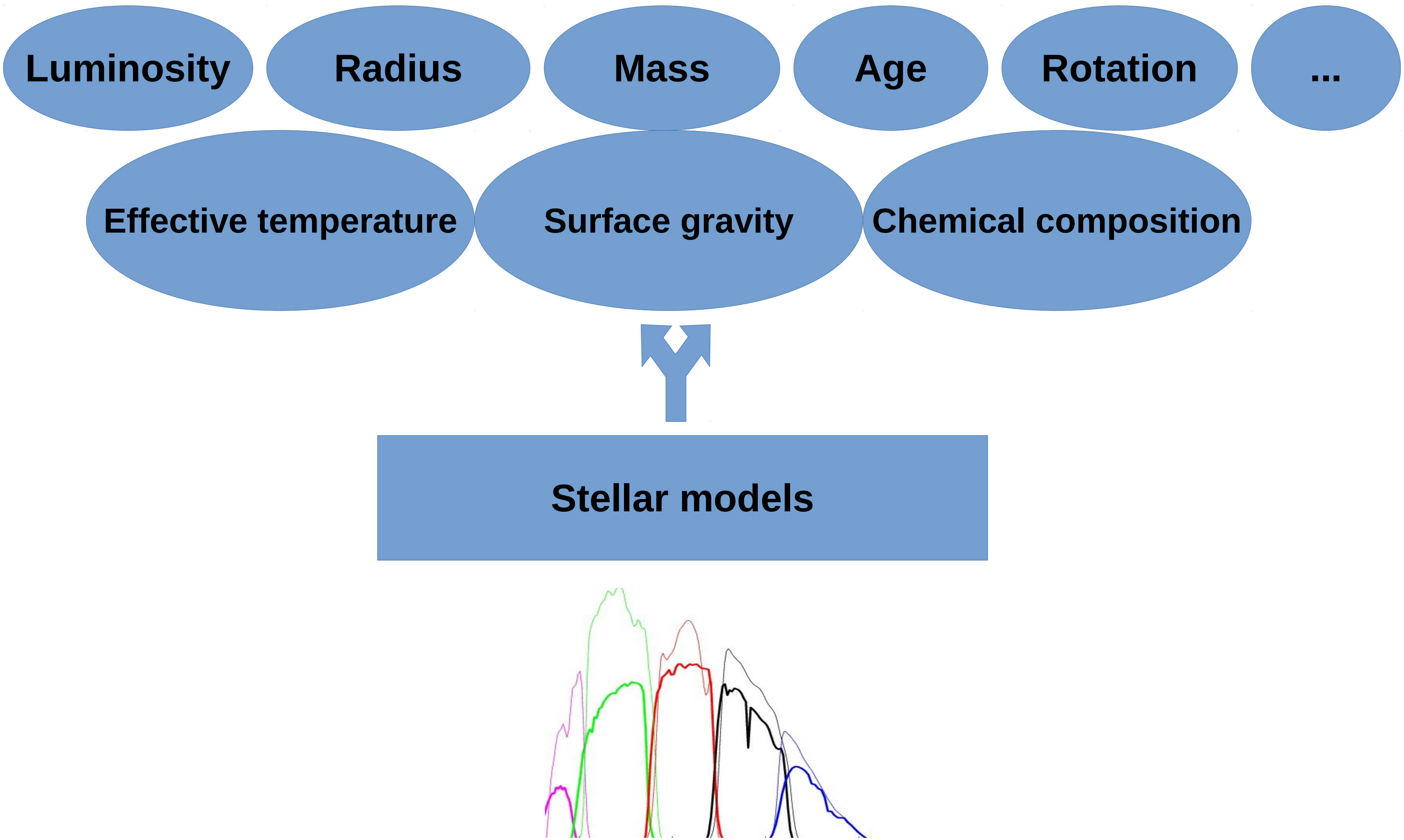
Kjeldsen, Bedding & Christensen-Dalsgaard 2009

What does(not) asteroseismology give us?

- **F- and G-type dwarfs**
  - Asteroseismology provides precise physical properties (if precise Teff and [M/H] is available)

- **K- and M-type dwarfs**
  - Asteroseismology does not help much
  - Need to derive atmospheric parameters

How to derive stellar parameters from photometry?



Stellar parameters from photometry

Infrared Flux Method and Teff-colour relations

$$\frac{F_{\rm bol}}{F(\lambda_{\rm IR})} = \frac{\sigma T_{\rm eff}^4}{F_{\rm mod}(\lambda_{\rm IR}, T_{\rm eff}, [{\rm Fe/H}], \log g)}$$

IRFM provides 'realistic', close to 'fundamental' temperatures

$$\theta_{\rm eff} = b_0 + b_1 X + b_2 X^2 + b_3 X[{\rm Fe/H}] + b_4[{\rm Fe/H}] + b_5[{\rm Fe/H}]^2$$

where $\theta_{\rm eff} = 5040/T_{\rm eff}$, X represents the colour, and b_i ($i = 0, ..., 5$) are the coefficients of the fit.

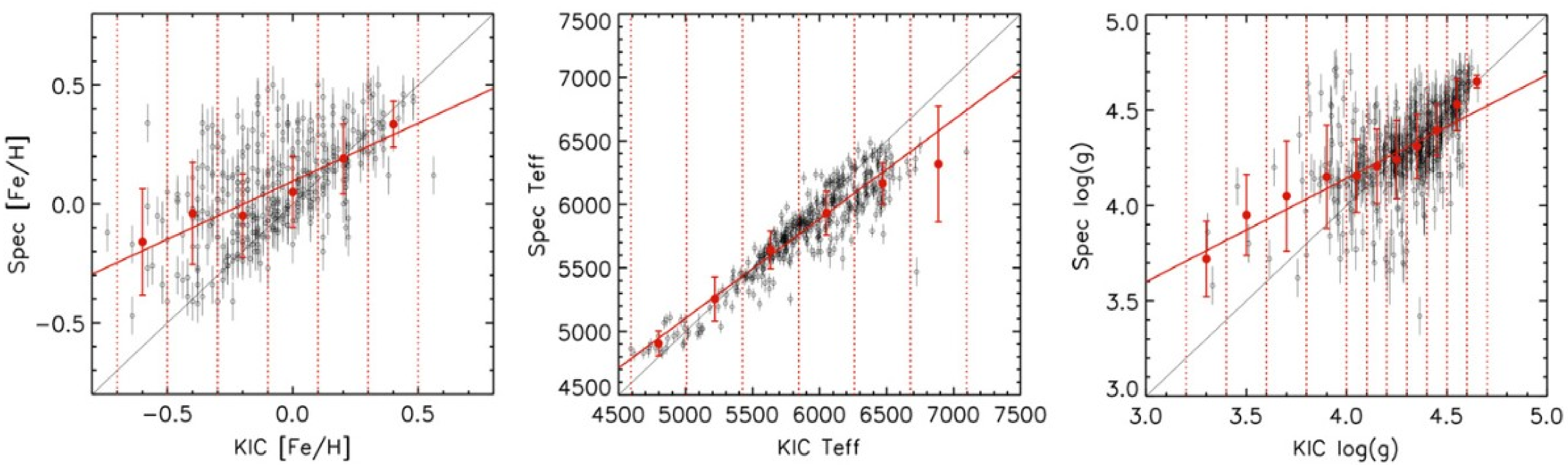
Casagrande et al. 2006, 2010
Gonzalez Hernandez & Bonifacio 2009

Stellar parameters from photometry

Other photometric systems and callibrations

- KIC photometry (e.g. Brown et al. 2011)

ΔTeff ~ 300 K, Δlog g ~ 0.5 dex, Δ[M/H] ~ 0.3 dex?



Wang & Fischer 2015

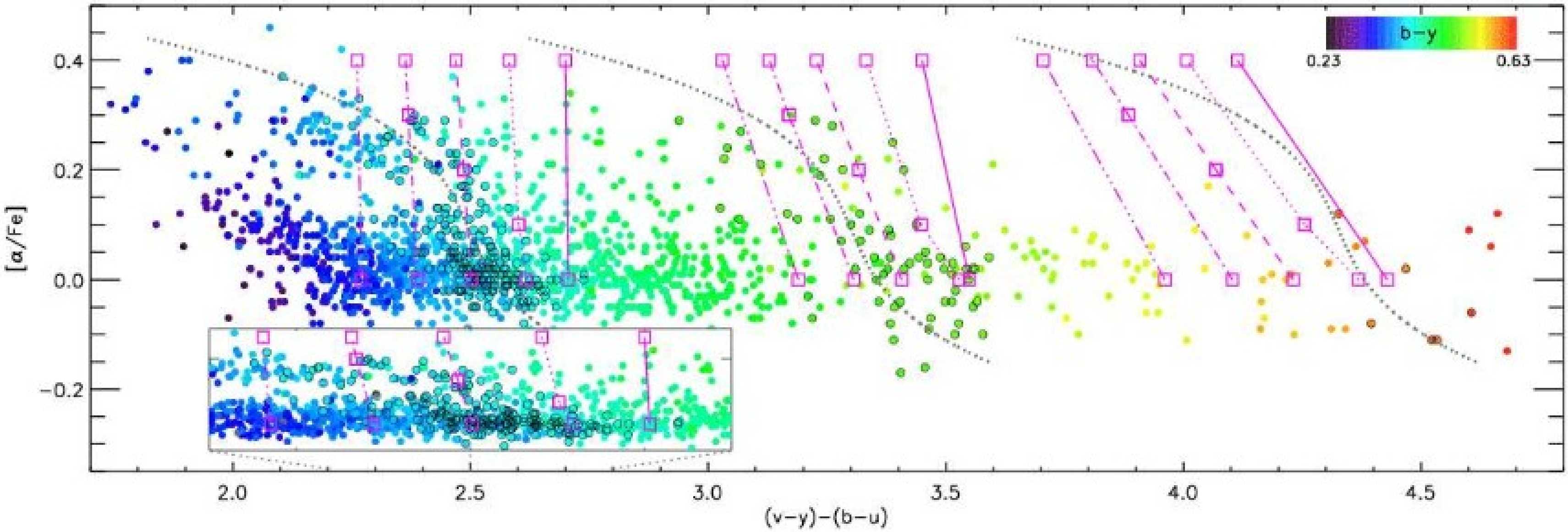
Stellar parameters from photometry

Other photometric systems and callibrations

- Stromgren uvby (Stromgren 1963)

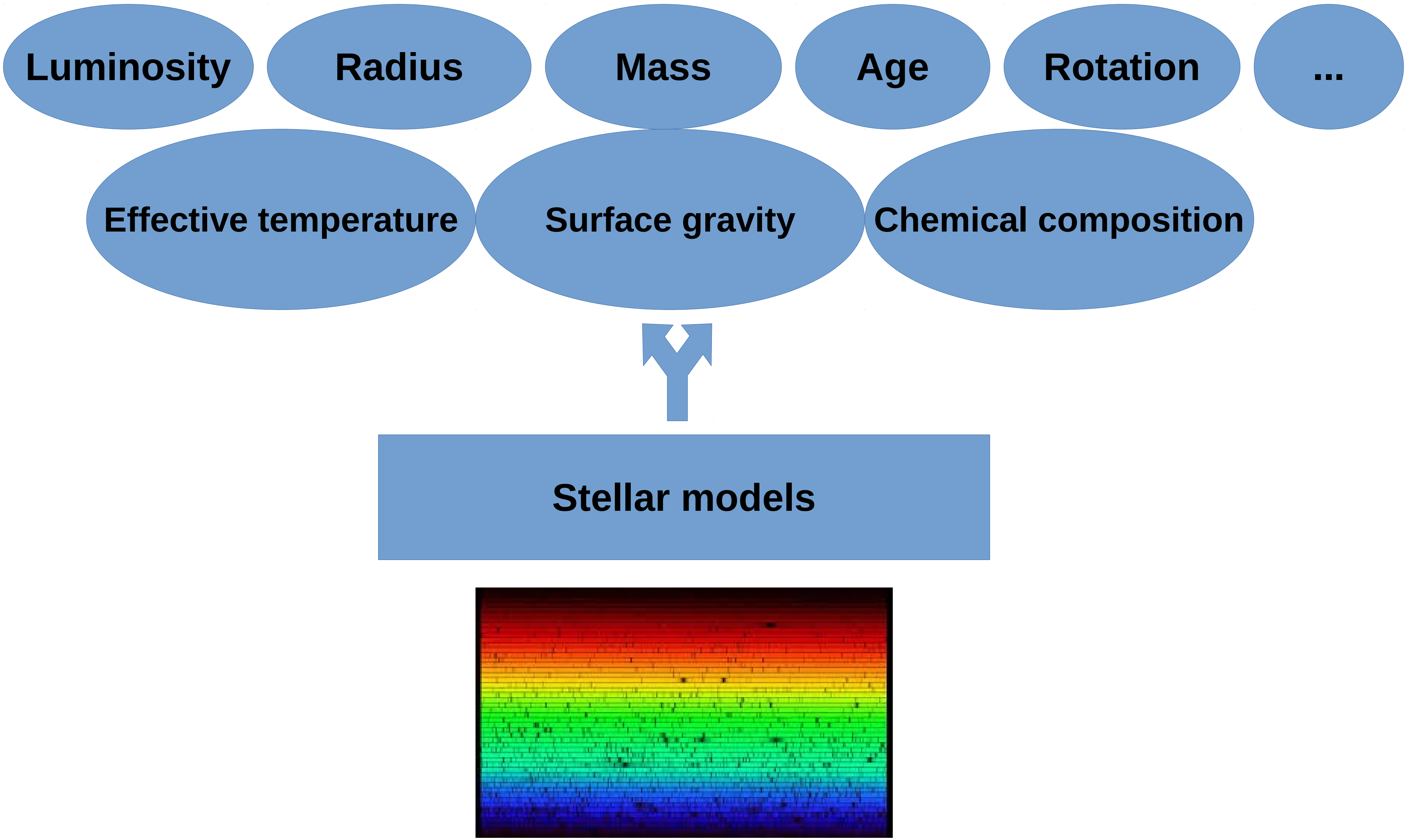
  ΔTeff ~ 100 K, Δ[Fe/H] ~ 0.1 dex

  Allows even to derive [α/Fe]



GCSIII - Casagrande et al. 2011

How to derive stellar parameters from spectra?



Stellar parameters from spectroscopy

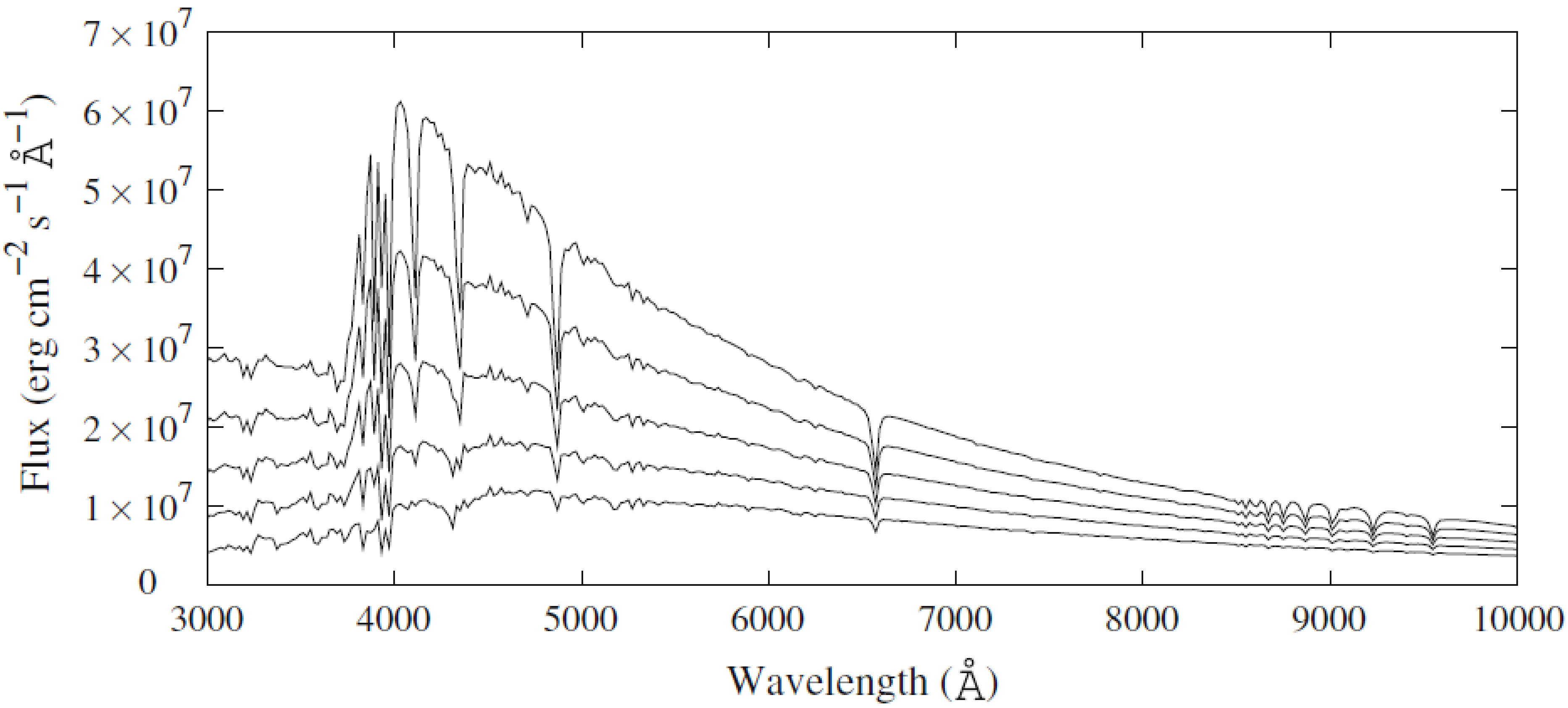
EW method

Spectral synthesis

Other techniques

Stellar parameters: Other techniques

Effective temperature - The Paschen Continuum

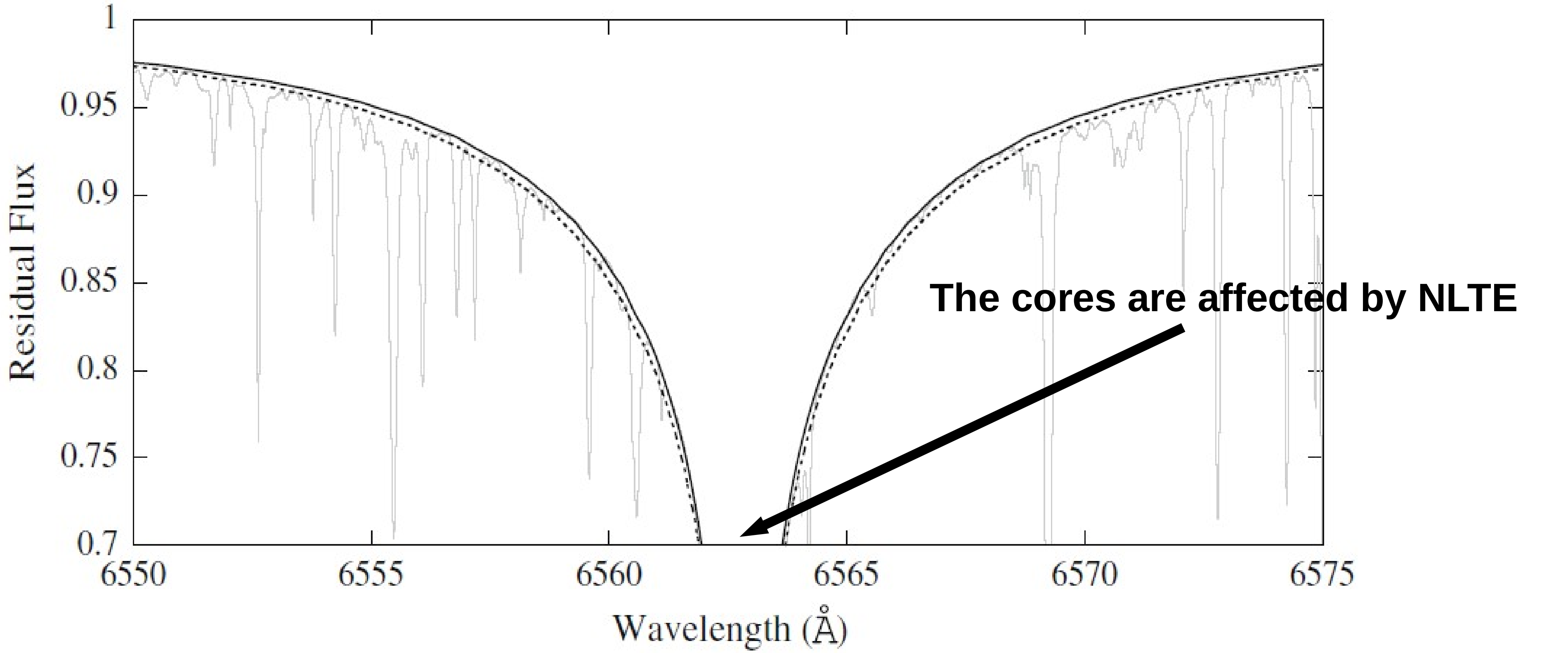


The variation of stellar flux with T_{eff}, ranging from 6,000 K (*bottom*) to 8,000 K (*top*) in steps of 500 K

B. Smalley, 2014

Stellar parameters: Other techniques

Effective temperature - Balemer line profiles (Teff < 8000K)

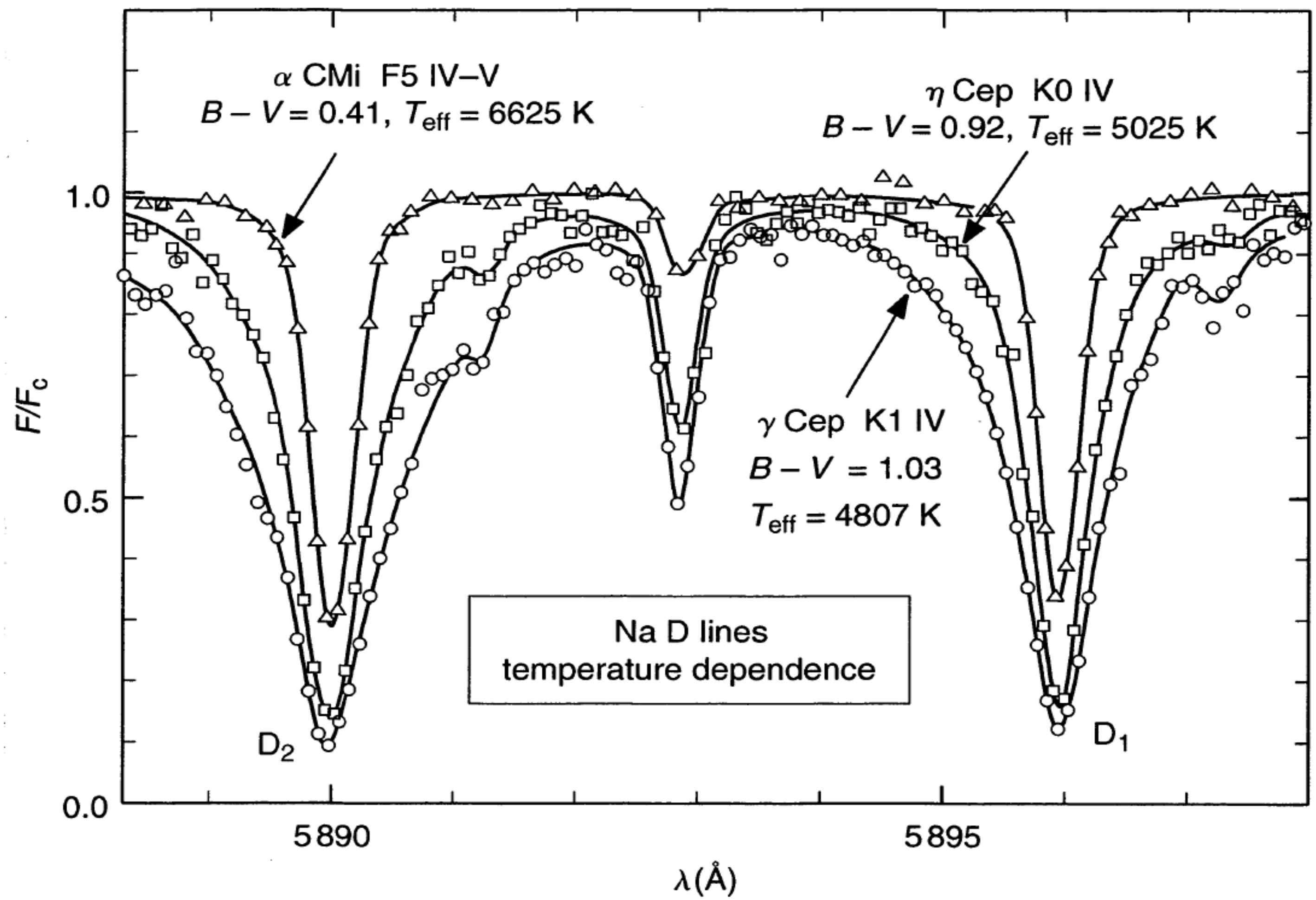


The KPNO Solar Atlas Hα profile (*grey line*). The *dotted-line* is the fit using the parameters for the Sun ($T_{\rm eff}$ = 5,777 K and log g = 4.44), while the *black line* is the 'best-fitting' profile with $T_{\rm eff}$ = 5,720 K

B. Smalley, 2014

Stellar parameters: Other techniques

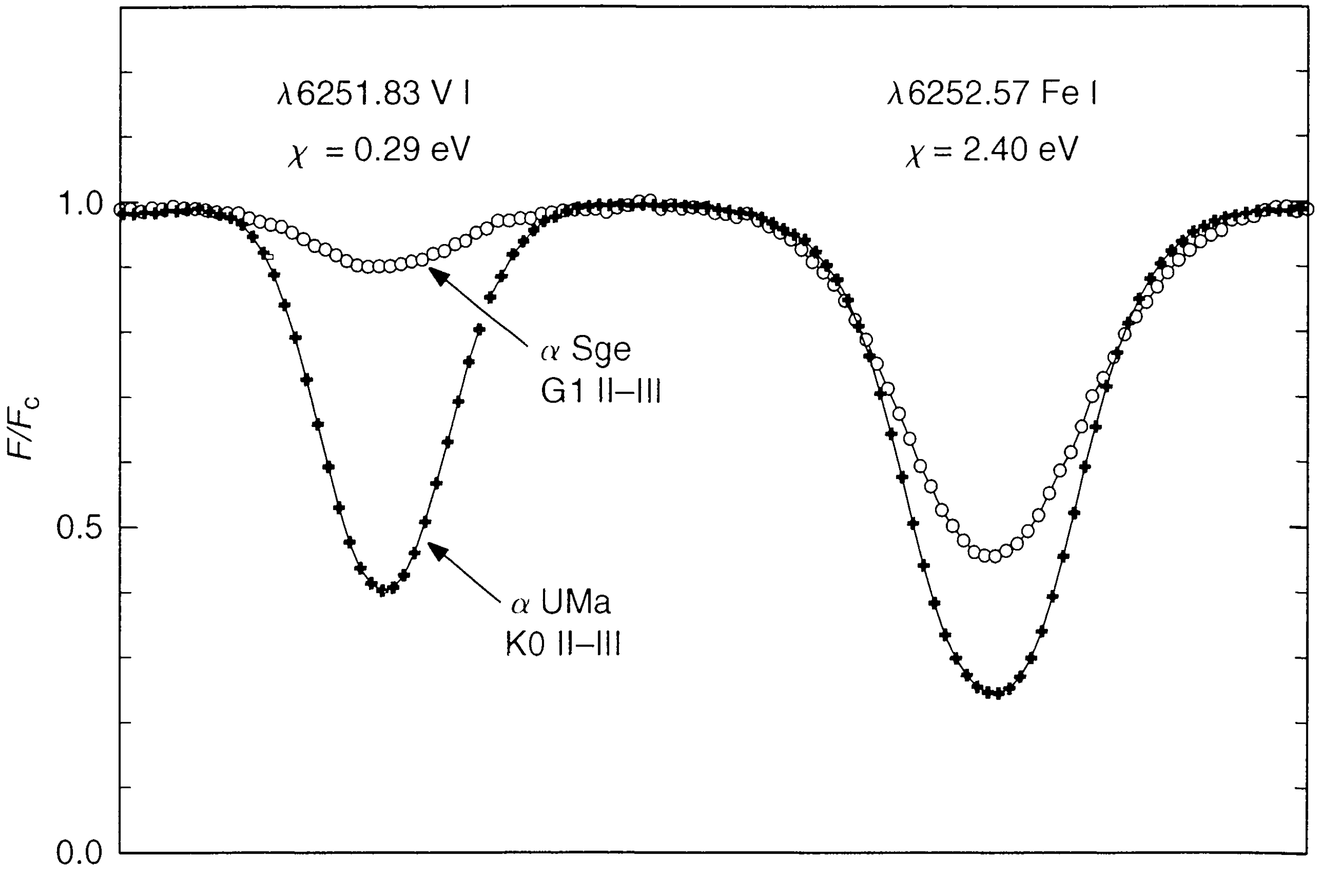
Effective temperature - Sodium D lines



D. Gray 2005

Stellar parameters: Other techniques

Effective temperature - Line depth ratio



$$\delta T = C_0 \frac{\delta r}{r}$$

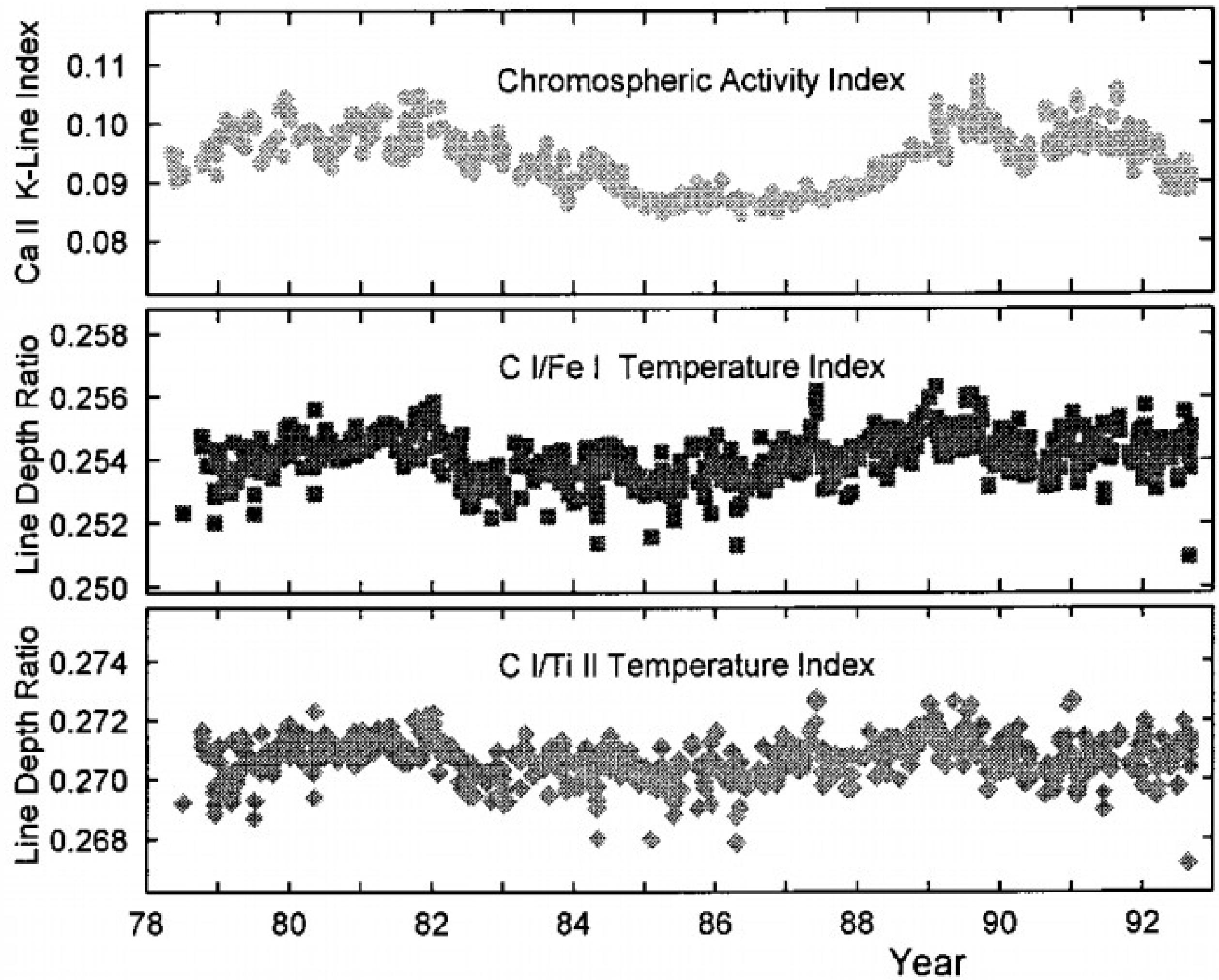
δr change in line depth ratio

δT change in Teff

D. Gray 2005

Stellar parameters: Other techniques

Effective temperature - Line depth ratio



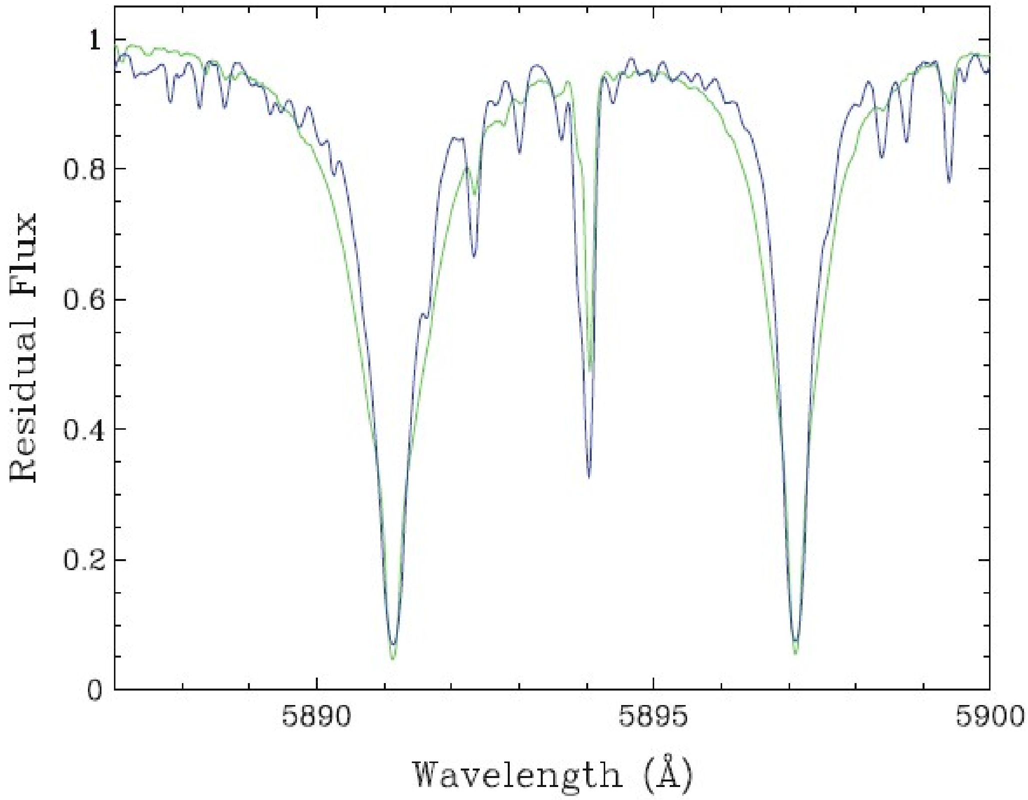
Teff variation of 1.5±0.2 K

Very high precision!
Not so high accuracy!

Gray & Livingstone 1997

Stellar parameters: Other techniques

Surface gravity - Wings of strong lines

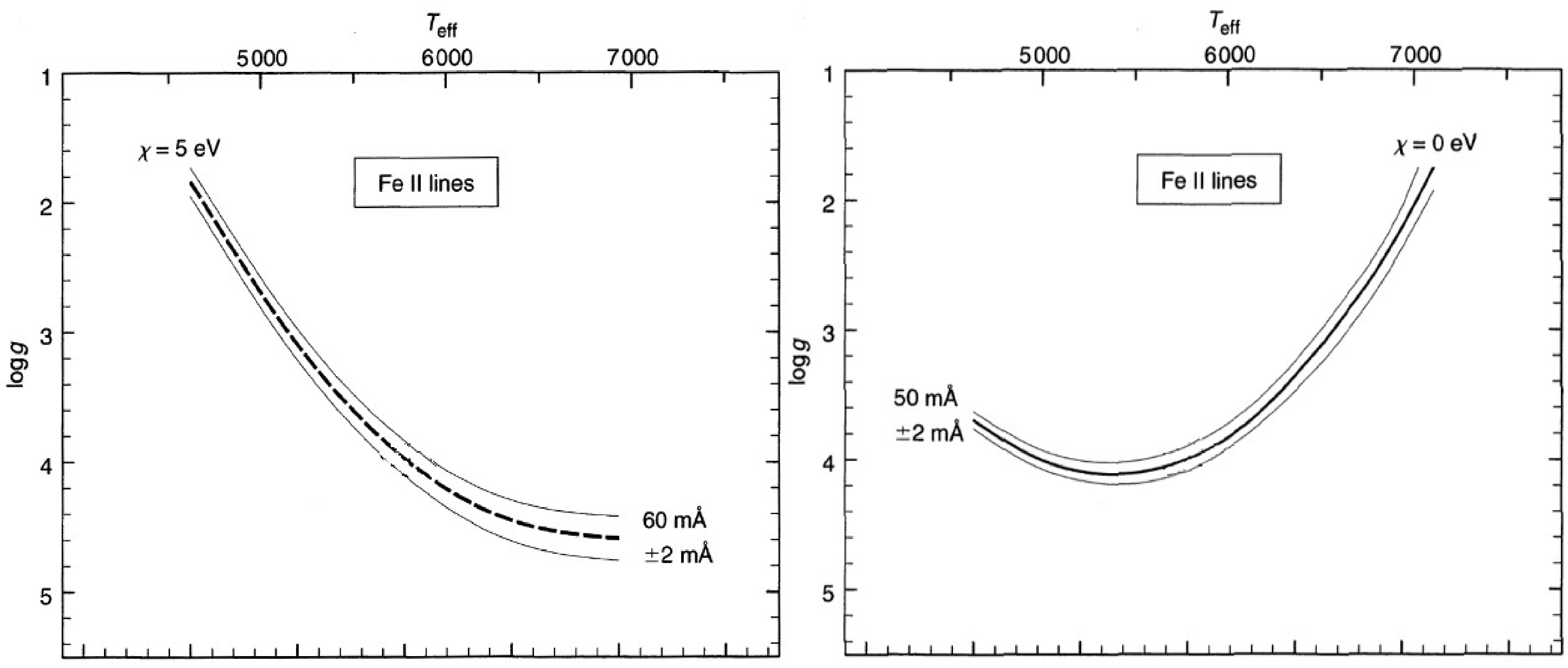


Profiles of the Na D lines of HD 100623 (K0 V, *green*) and HD 99322 (K0 III, *blue*) taken from the UVES-POP database (Bagnulo et al. 2003). The effect of different gravity can clearly be seen, the lines of the giant are narrower than the lines of the dwarf

G. Catanzaro, 2014

Stellar parameters: Other techniques

Log g - Teff diagram

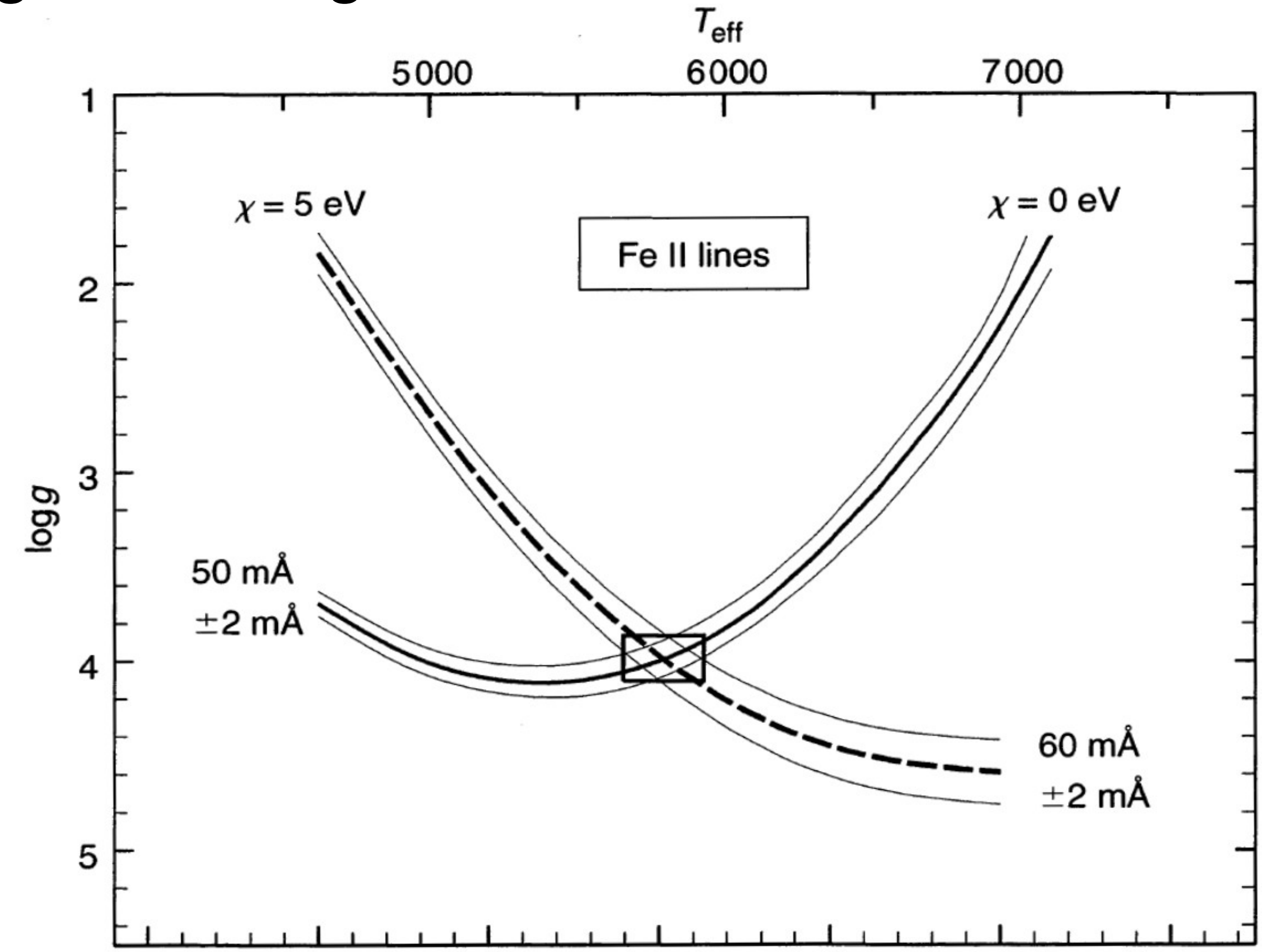


What is the correct Teff and logg of the star?

D. Gray 2005

Stellar parameters: Other techniques

Log g - Teff diagram



The solution is where the lines cross!

D. Gray 2005

Stellar parameters from spectroscopy

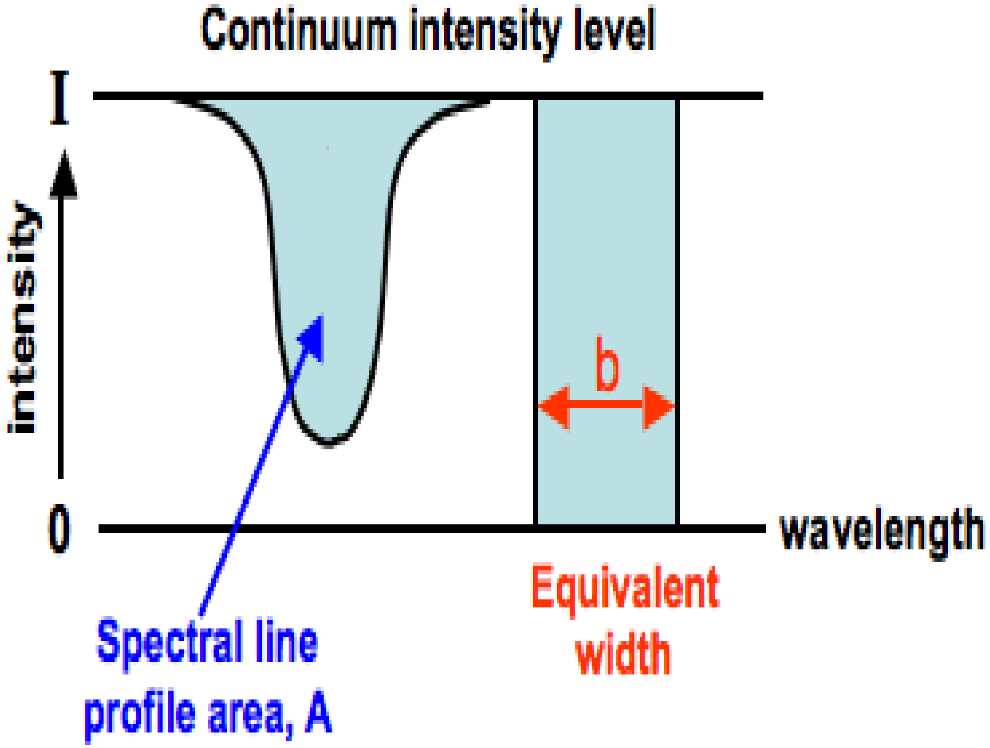
EW method

Equivalent Width

$$W_\lambda = \int (1 - F_\lambda / F_0) d\lambda$$

EW is a measure of number of absorbers

- Does not give information about the shape of profile



LTE (Local Thermodynamical Equilibrium)

LTE assumption can be justified if there is enough interaction between atoms, electrons and photons

$$\frac{N_b}{N_a} = \frac{g_b}{g_a} e^{\frac{-(E_b - E_a)}{kT}}$$

Boltzmann Equation (Excitation temperature)

$$\frac{N_{i+1} P_e}{N_i} = \frac{2kTZ_{i+1}}{Z_i} \left(\frac{2\pi m_e kT}{h^2} \right)^{\frac{3}{2}} e^{\frac{-\chi_i}{kT}}$$

Saha Equation (Ionization Temperature)

$$p(v)dv = \left(\frac{m}{2\pi kT} \right)^{\frac{3}{2}} e^{\frac{-mv^2}{2kT}} 4\pi v^2 dv$$

Maxwell-Boltzmann law (Kinetic temperature)

In LTE, all these temperature are the same = Teff

If we have the right Teff and log g, we can predict the populations of atoms in each level and ionisation stage

NLTE (Non Local Thermodynamical Equilibrium)

In NLTE, atomic level populations are determined by statistical equilibrium equations instead of Saha/Boltzmann distributions

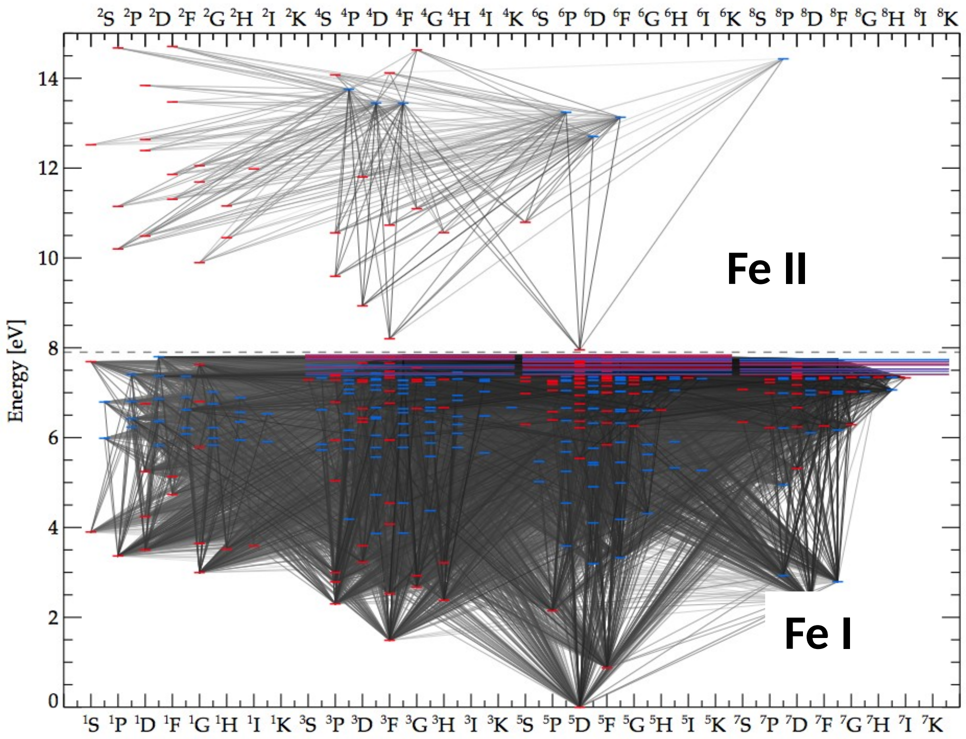
$$\sum_{j \neq i} n_j P_{ji} - \sum_{j \neq i} n_i P_{ij} = 0$$

$$P_{ij} = R_{ij} + C_{ij}$$

Radiative rates

Collisional rates

Model Atom



Credit K. Lind

Curve of Growth

The **curve of growth** shows the dependence of EW of an absorption line on the number of atoms producing the line.

Weak lines are in the linear part of the curve of growth: **best for abundance derivation.**

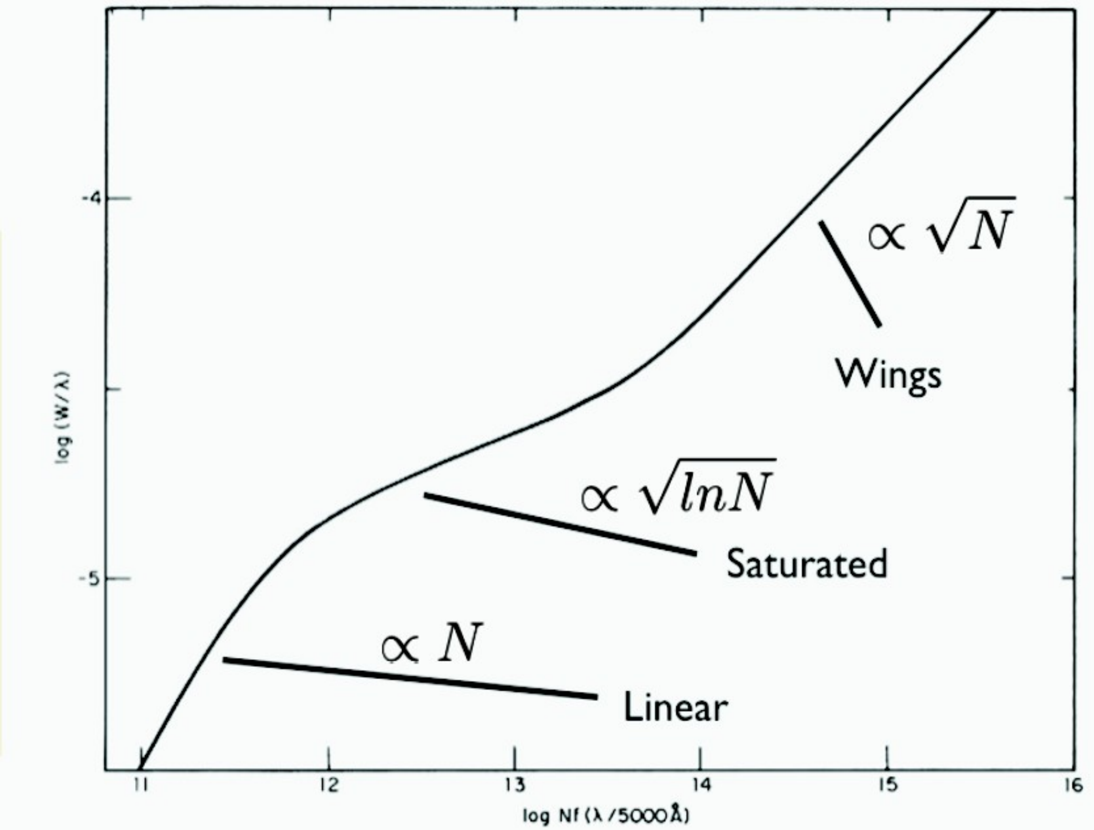


Figure 9.22 A general curve of growth for the Sun. (Figure from Aller, *Atoms, Stars, and Nebulae*, Revised Edition, Harvard University Press, Cambridge, MA, 1971.)

$$\log\left(\frac{W_\lambda}{\lambda}\right) = \log\left(\frac{\pi e^2}{m_e c^2}\frac{N_i/N}{\mathcal{U}(T)}N_{\rm H}\right) + \log A + \log(gf\,\lambda) - \frac{5040}{T}\chi - \log(\kappa_\nu)$$

The effect of temperature

Teff most strongly controls the line strength!

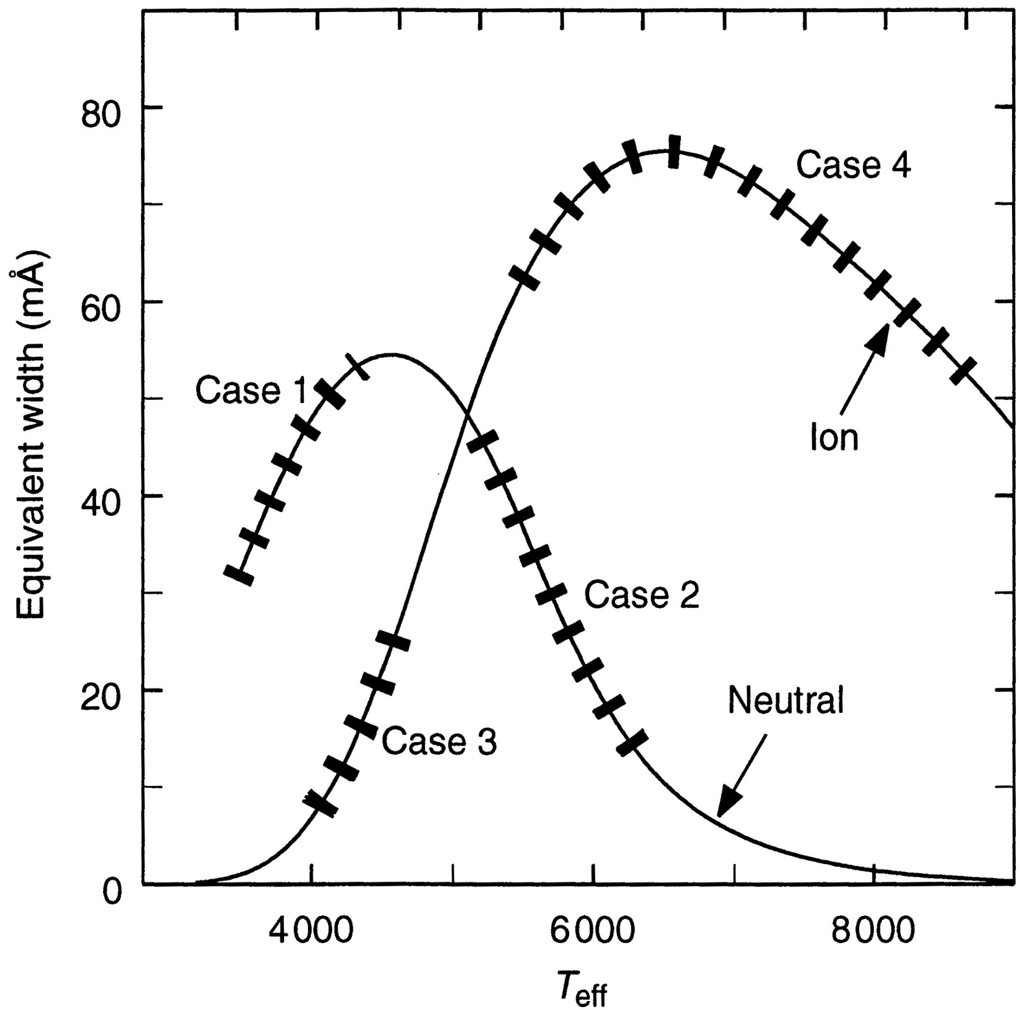
In the case of Sun like stars (case 2 in Fig.), the EW of neutral species decreases with Teff due to ionization of absorbing species.

Case 1. weak lines from a neutral species of mostly neutral element

Case 2: weak lines from a neutral species of mostly ionized element (e.g. FeI in the Sun).

Case 3: weak lines from an ion of a mostly neutral element.

Case 4: weak lines from an ion of a mostly ionized element (e.g. FeII in the Sun).



D. Gray 2005

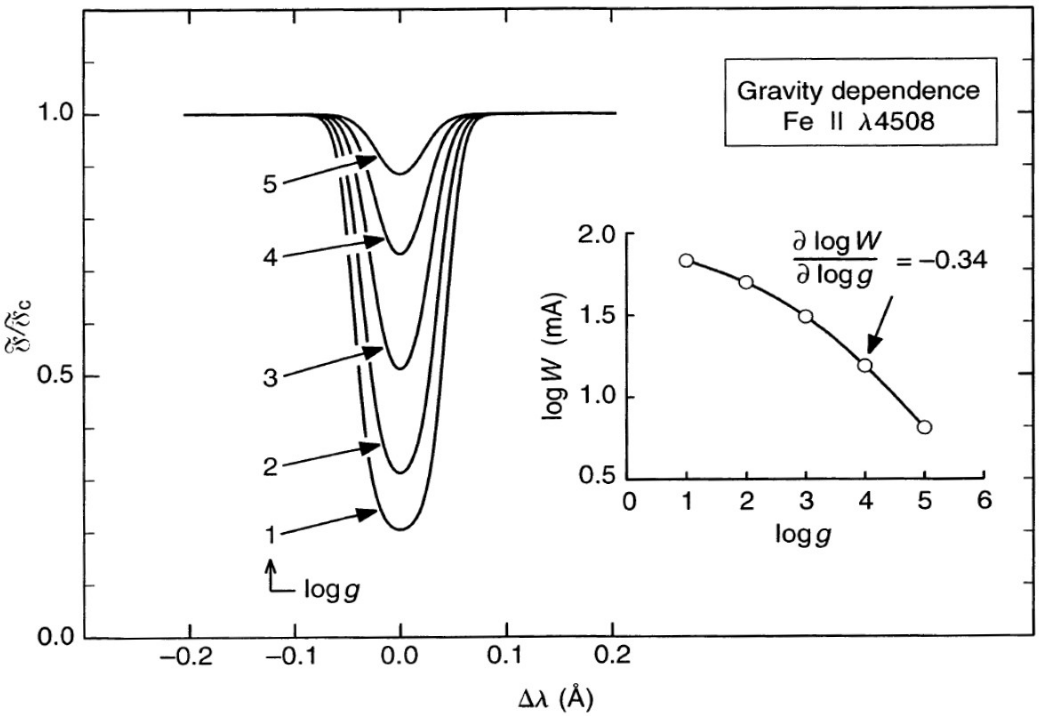
The effect of pressure (surface gravity)

Sensitivity of lines to logg depends on the ionization stage of the element!

In the case of solar temperature stars, the EW decreases with pressure (logg).

Weak line formed by any ion or atom where most of the element is in the **next** higher ionization stage: **gravity insensitive. FeI in the Sun.**

Weak line formed by any ion or atom where most of the element is in the **same** ionization stage: **gravity sensitive. FeII in the Sun.**



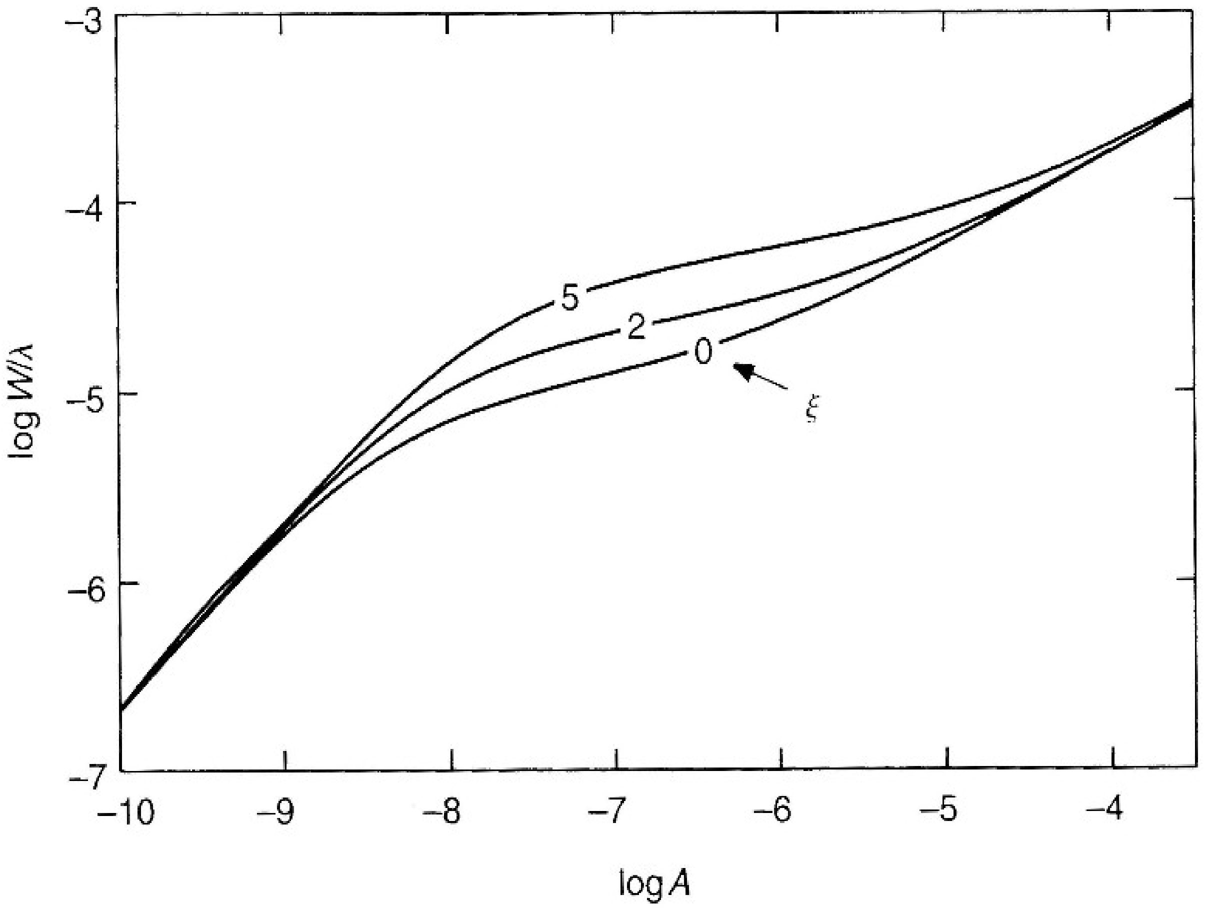
D. Gray 2005

The effect of microturbulence

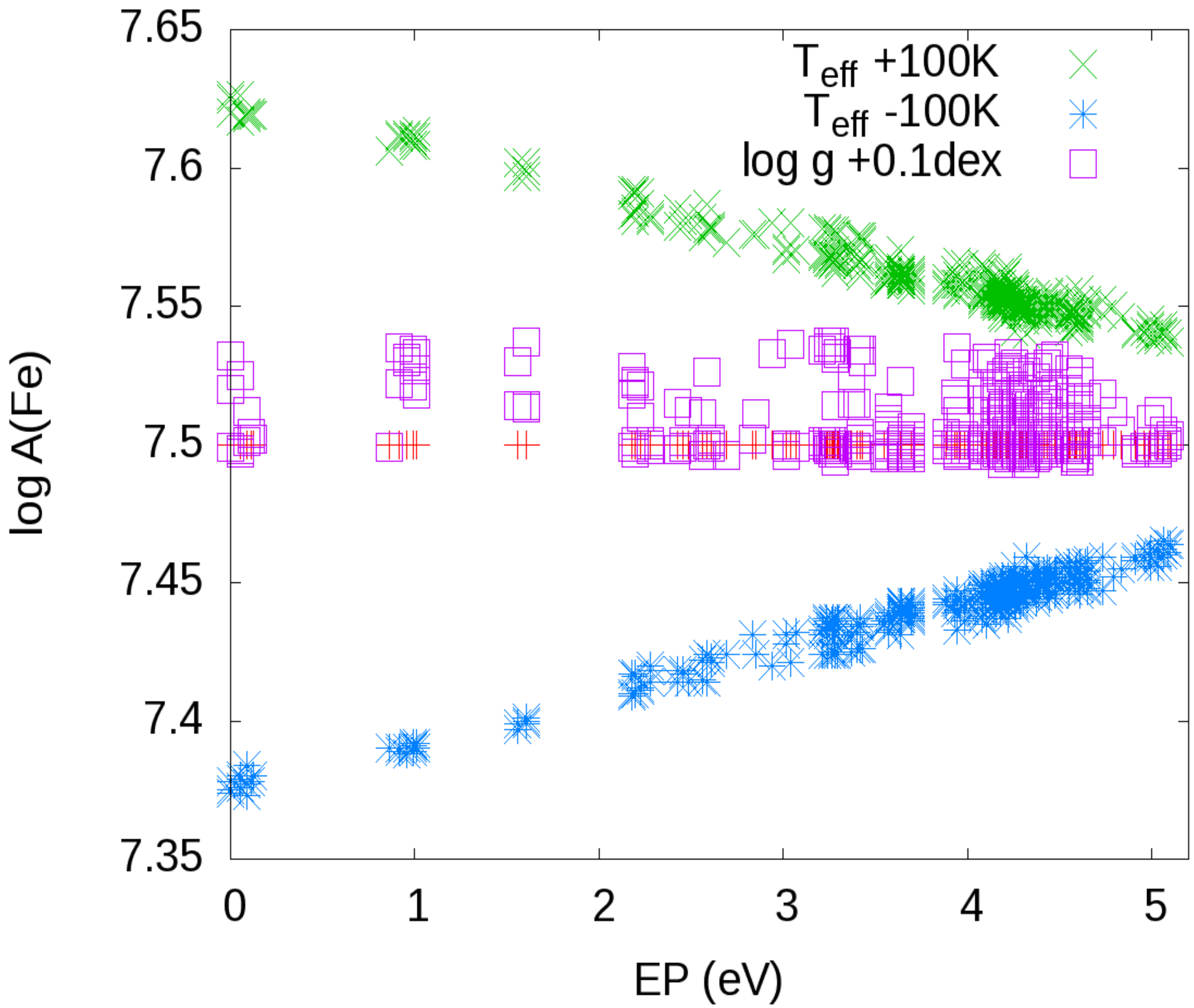
The observed equivalent widths of saturated lines are greater than predicted by models using just thermal and damping broadening.

Microturbulence (a free parameter) was introduced to ensure that abundances from weak and strong lines agree.

No need for Vt in 3D simulations



Effect of changing parameters



Simulation based on

Teff = 6000 K
Logg = 4.5 dex
Log A(Fe) = 7.5 dex

B. Smalley, 2014

Metal Line Diagnostics

• log A versus Excitation Potential => **Teff**
– Abundances from the same element should agree for all excitation potentials, i.e. no trend

● log A versus EW => **Vmicro**
– Adjust ... until no trend with EW

● Ionization Balance i.e. log (AI) = log (AII) => **Logg**
– Average log A obtained from differing ionization stages of the same element must agree

EW + MOOG method

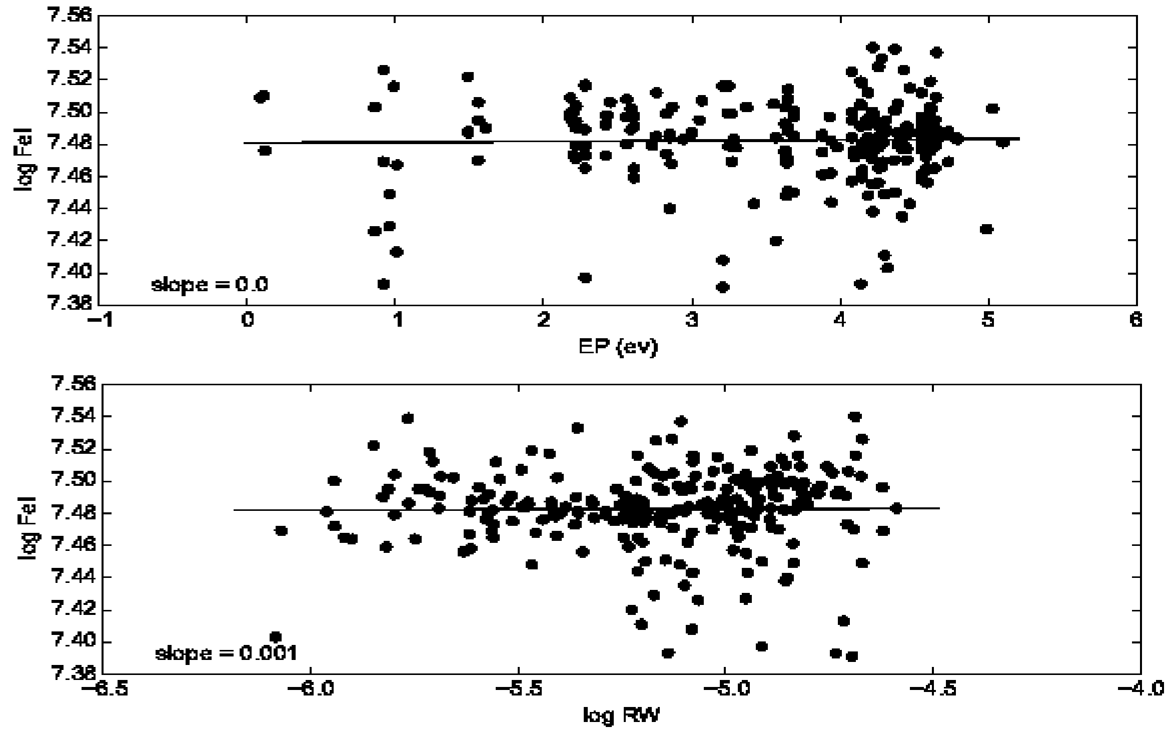
- Assuming LTE
  - Excitation balance
  - Ionization balance

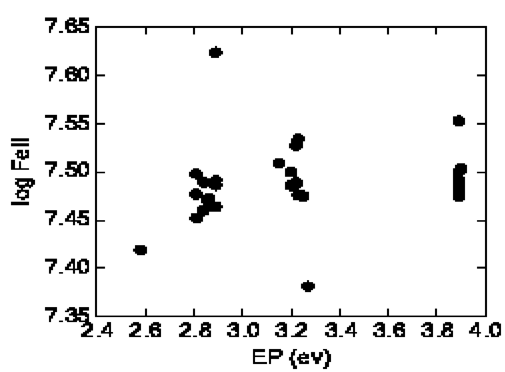
- Carefully selecting lines

- Using radiation transfer code (e.g. Moog – Sneden 1973)

- Using model atmospheres (e.g. Kurucz 1995)

EW + MOOG method





FeI = 7.483± 0.025

FeII = 7.488± 0.041

FeI - FeII = -0.005

T_eff = 5777.0± 10.911

log(g) = 4.43± 0.023

v_t = 0.95± 0.016

[Fe/H] = 0.02± 0.008

Stellar parameters from spectroscopy

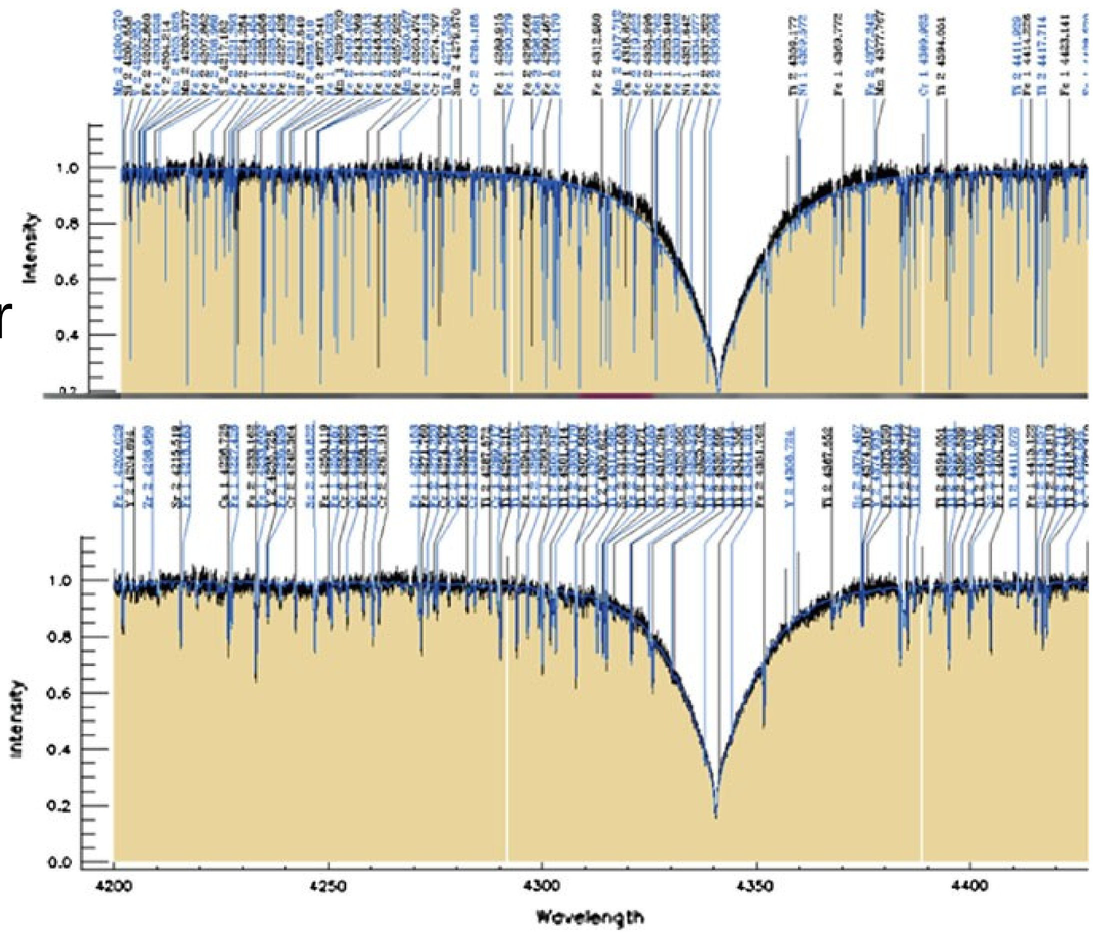
Spectral synthesis

Spectral synthesis

EW method is not always practical – need to do synthesis!

- Vary input parameters, calculate synthetic spectra
- Fit the observed spectrum (or part of it).

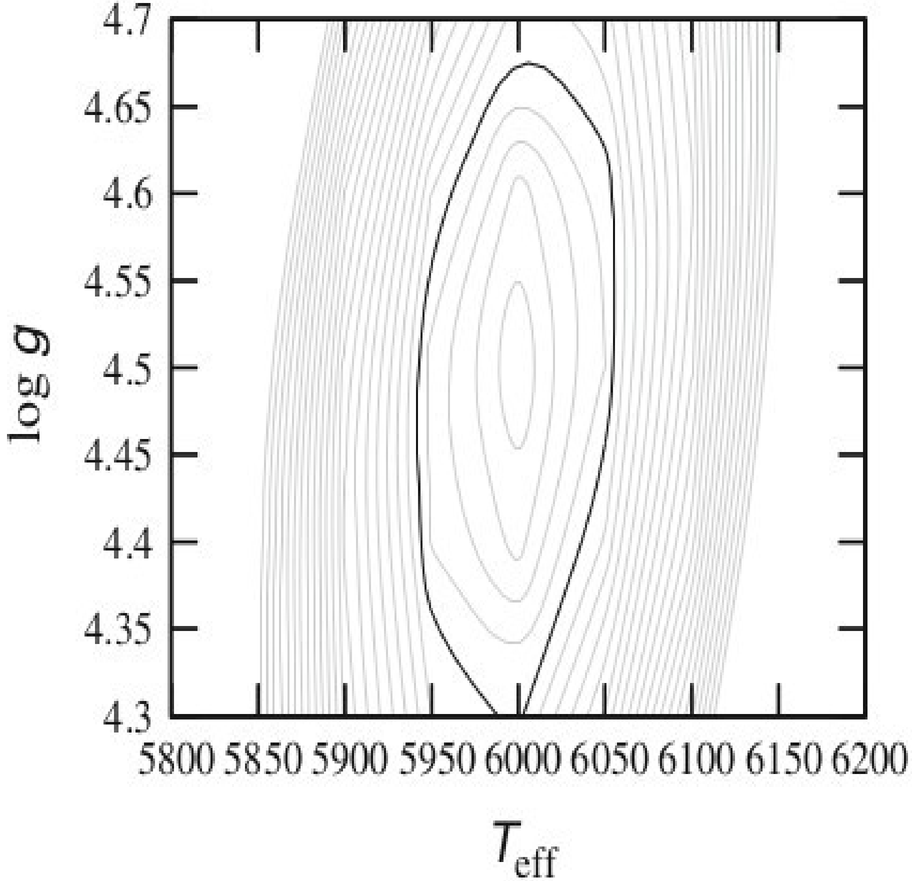
Strongly depends on the line-list and line data!

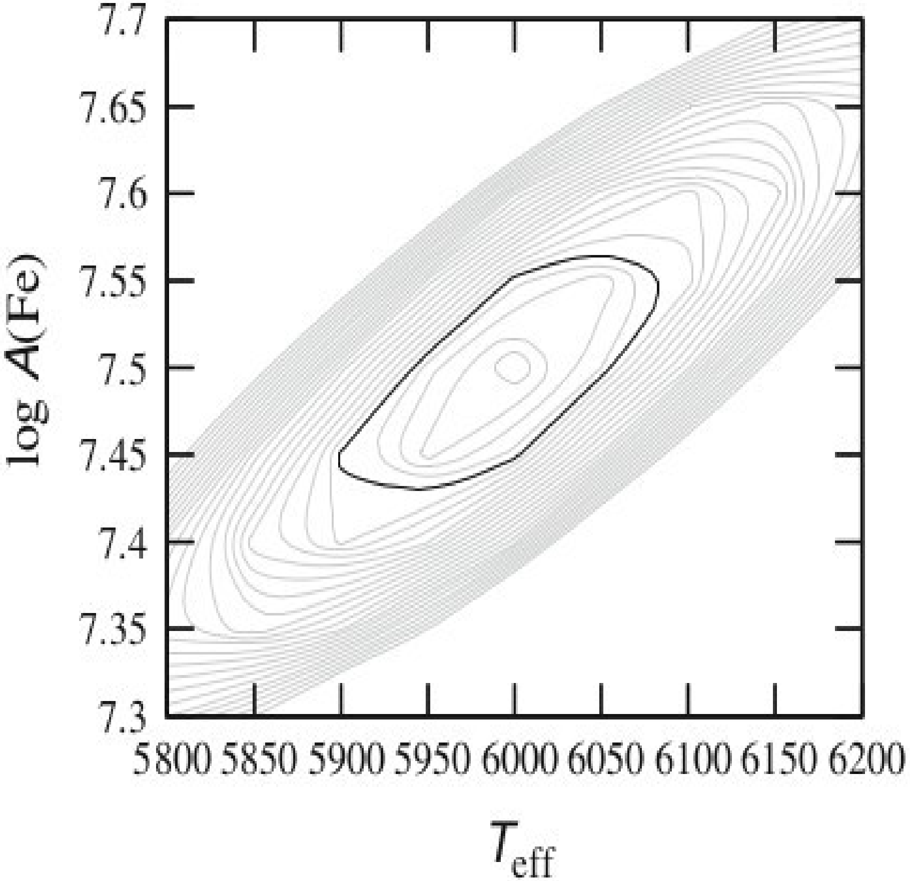


SME, credit Piskunov 2014

Spectral synthesis: χ² Correlations

- The sensitivity to logg is weak!
- Metallicity and Teff correlate





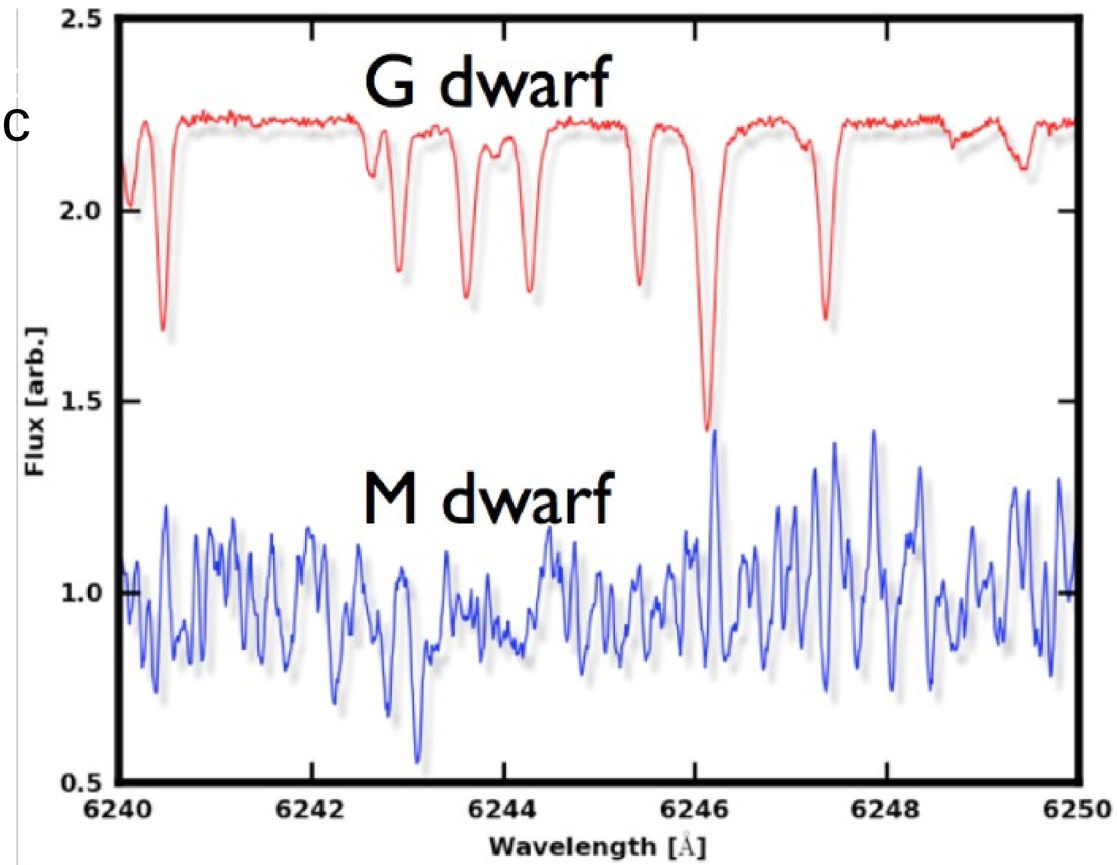
B. Smalley 2014

M dwarfs

- [FeH] and Teff (usually) from spectroscopic and photometric calibration using indices..

Bonfils et al. (2005), Johnson et al. (2012), Rojas-Ayala et al. (2012), Neves et al. (2012), Onehag et al. (2012), Mann et al. (2013)...

NIR is the future!

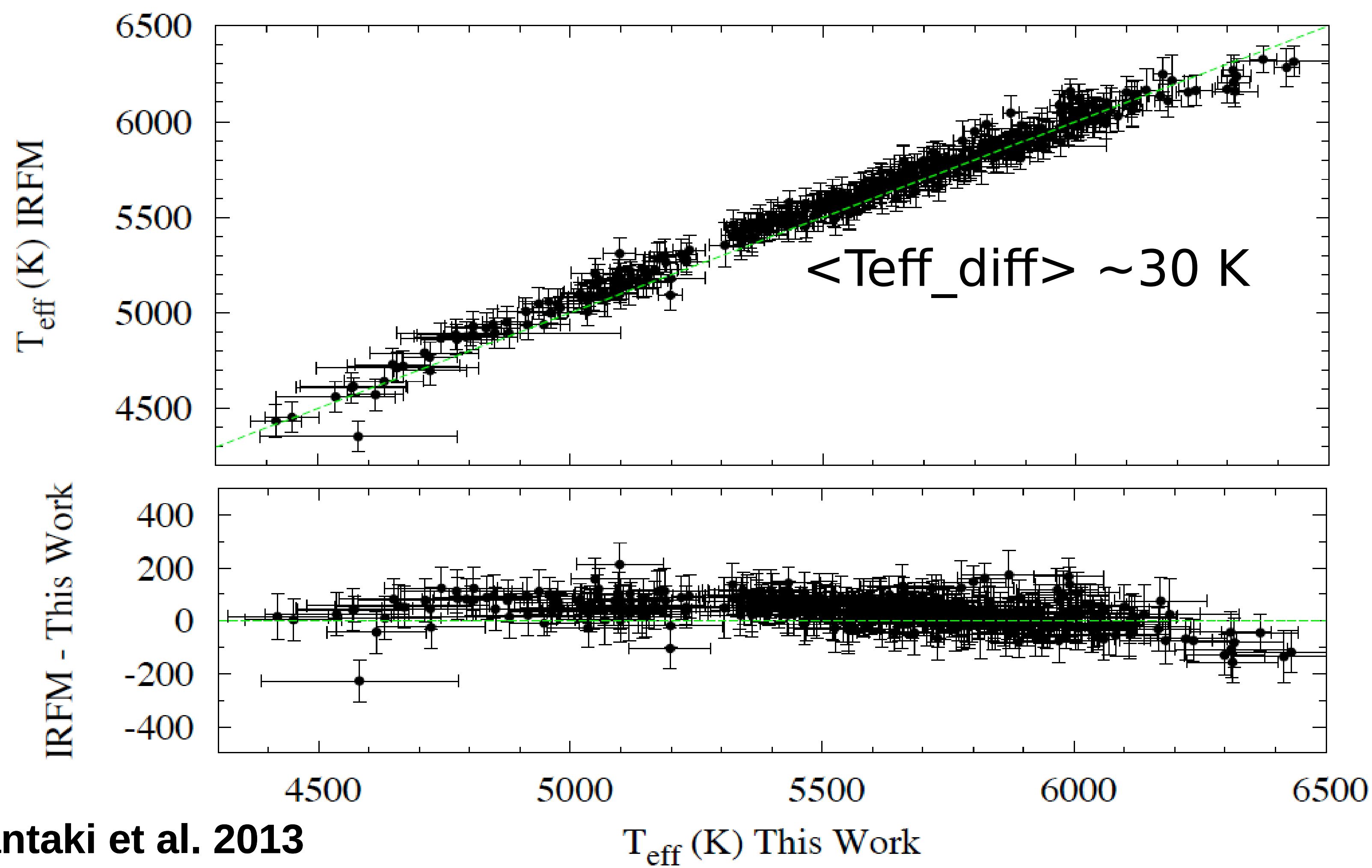


Bonfils 2012

Whats is the precision and accuracy in stellar parameters?

Effective temperature: precision for FGK stars

Used very carefully selected sub-list of lines from Sousa et al. (2008).
Worked better for cooler stars!

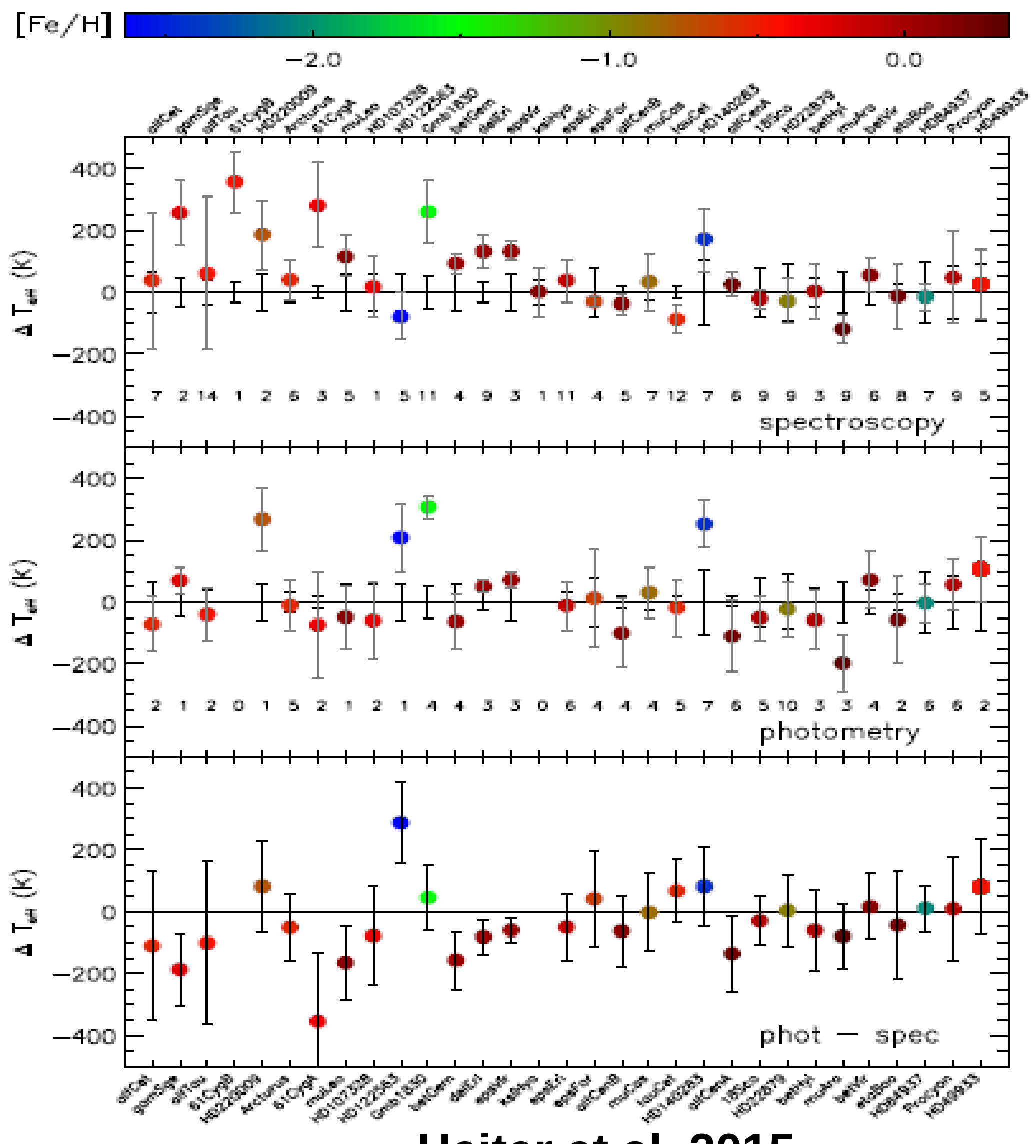


Tsantaki et al. 2013

What about the accuracy?

Comparing the literature data with the 'fundamental' values for benchmark stars.

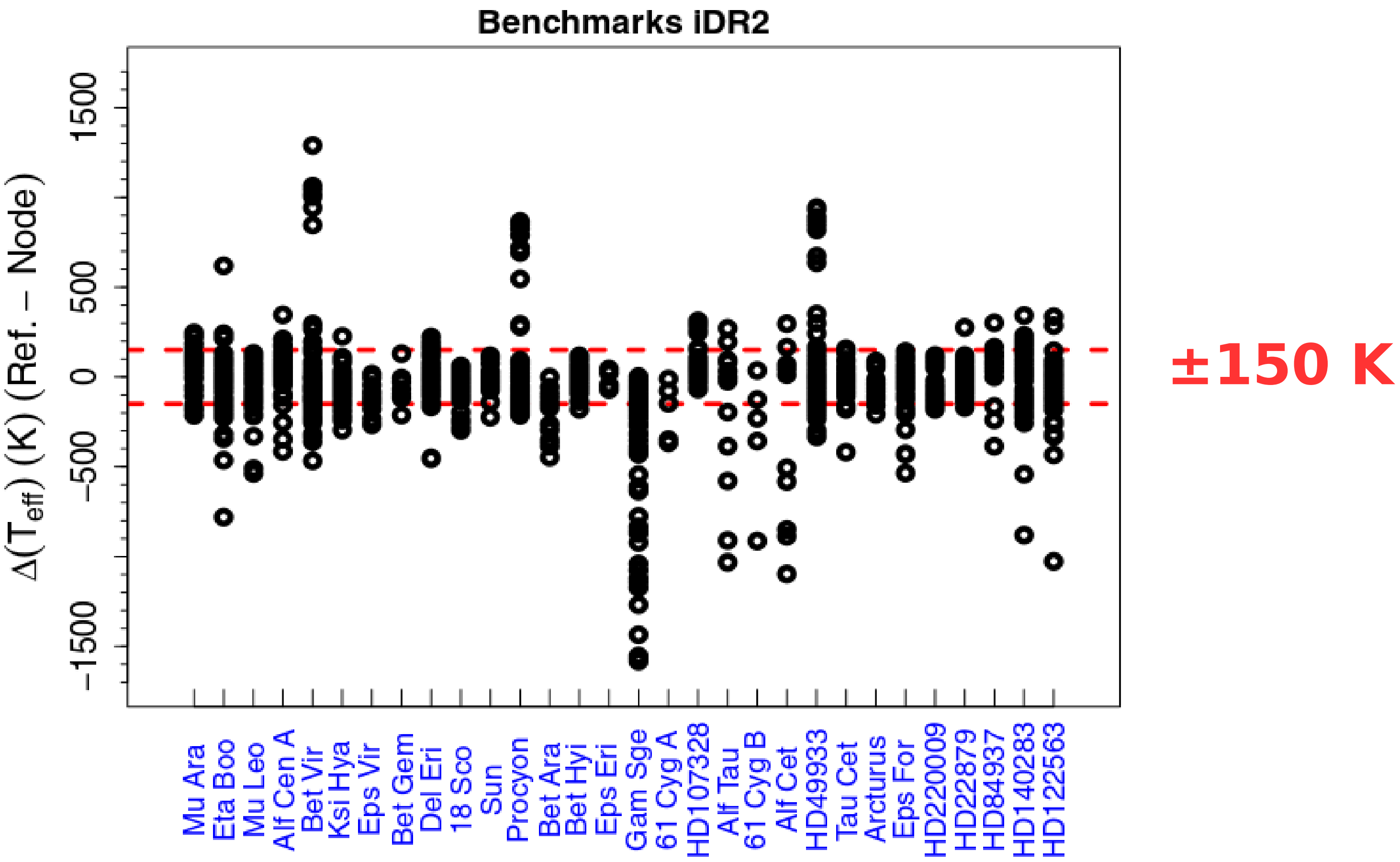
Up to 200-300 K difference!



Heiter et al. 2015

What about the accuracy?

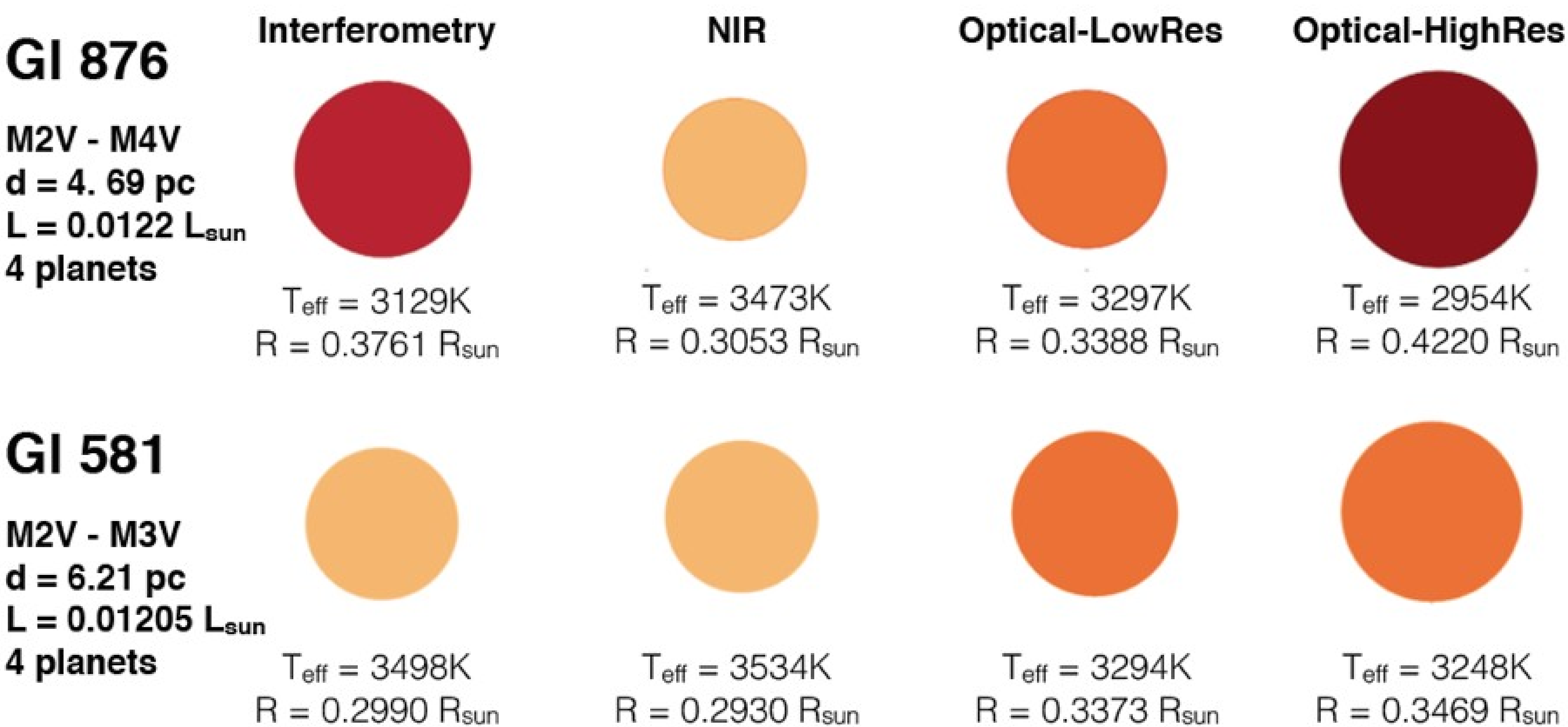
Different group obtain different Teff values for the Gaia-ESO Benchmark stars, including the Sun.



Smiljanic et al. 2014

What about the accuracy?

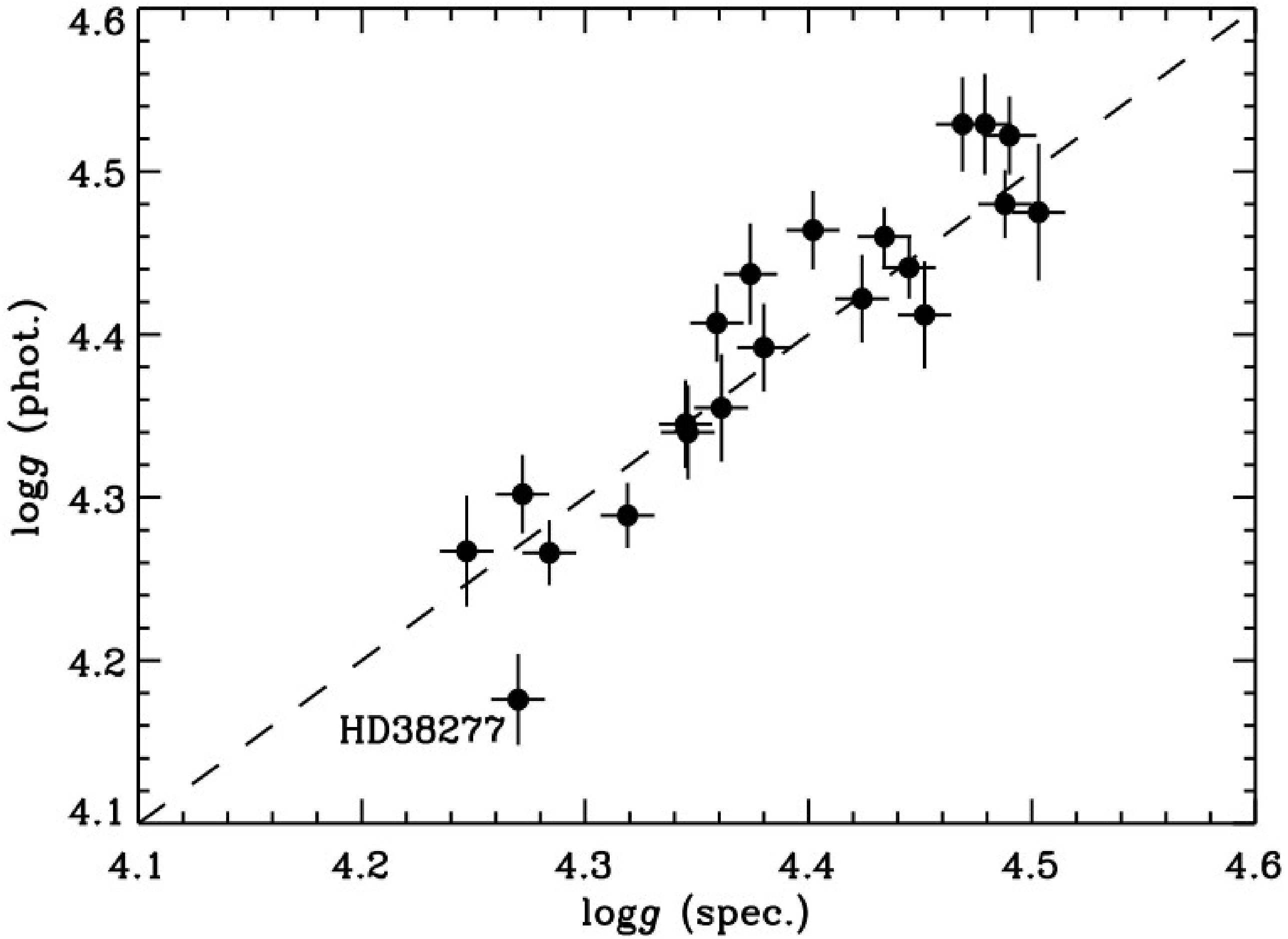
The spread is higher for M dwarfs



Credit B. Rojas-Ayala

Surface gravity: precision and accuracy

For solar twins a precision of much less than 0.01 dex is reported.

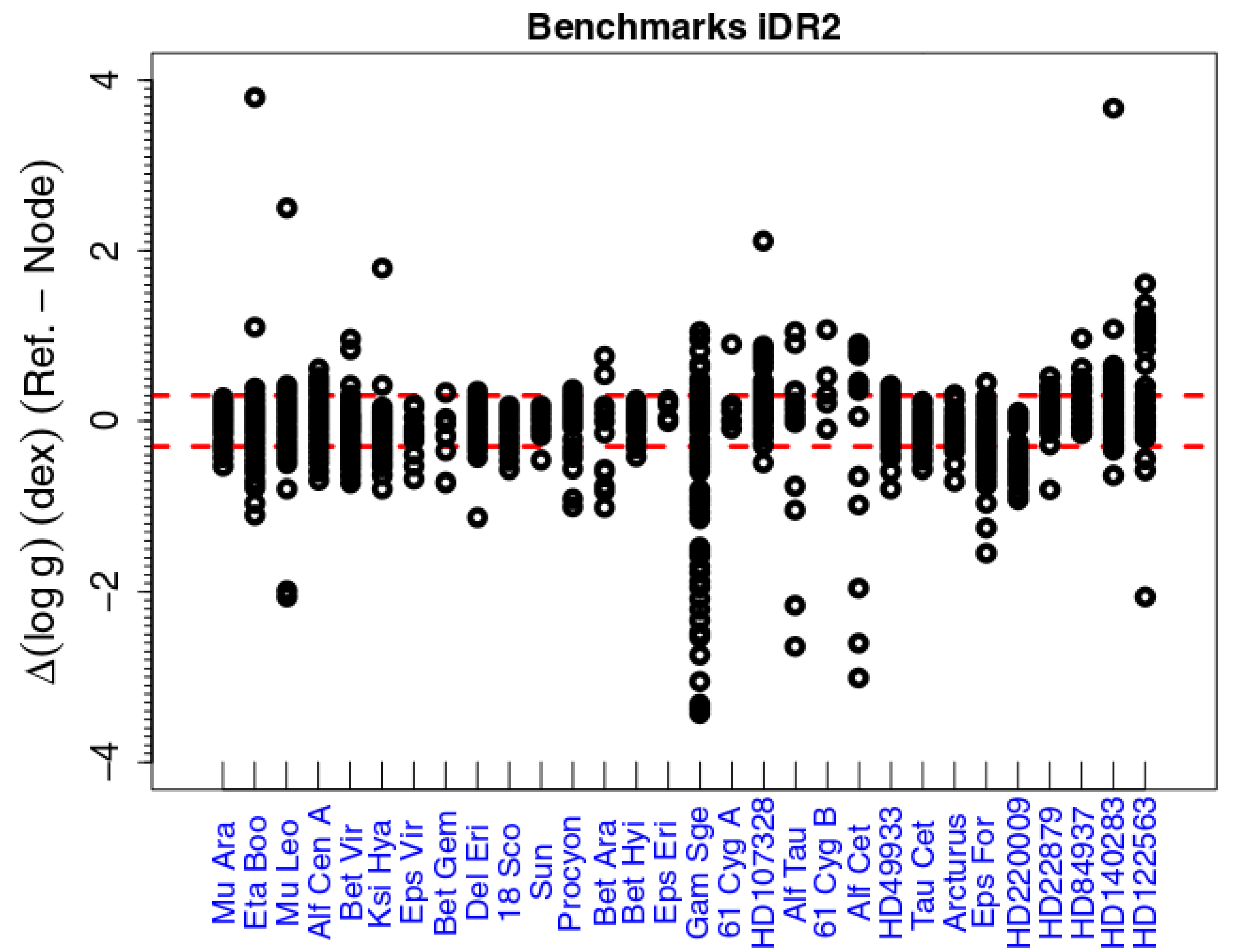


Nissen 2015

Surface gravity: accuracy and other issues

As for Teff, different group obtain different logg values for the Gaia-ESO Benchmark stars, including the Sun.

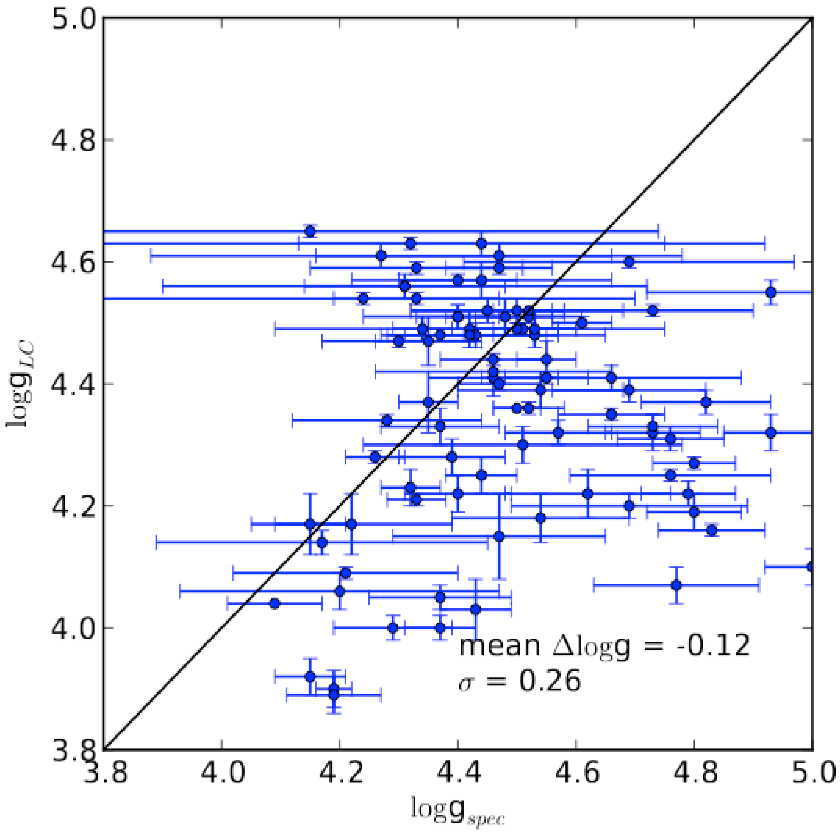
±0.3 dex



Smiljanich et al. 2014

Surface gravity: comparing with 'transit' method

90 transit hosts analysed



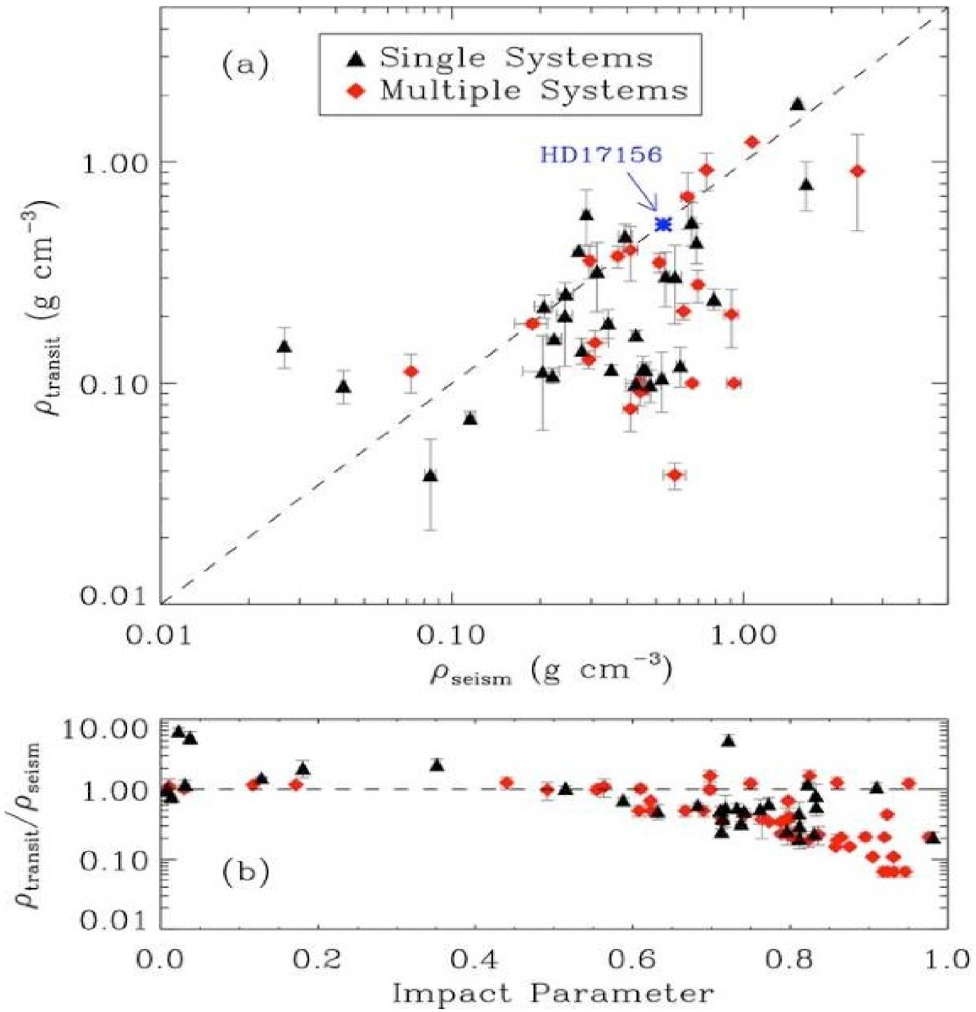
$$\rho_* + k^3 \rho_p = \frac{3\pi}{GP^2} \left(\frac{a}{R_*} \right)^3$$

Spectroscopic surface gravity not well constrained.
Transit light curve surface gravity more precise and accurate

Mortier et al. 2014

Surface gravity: comparing different methods

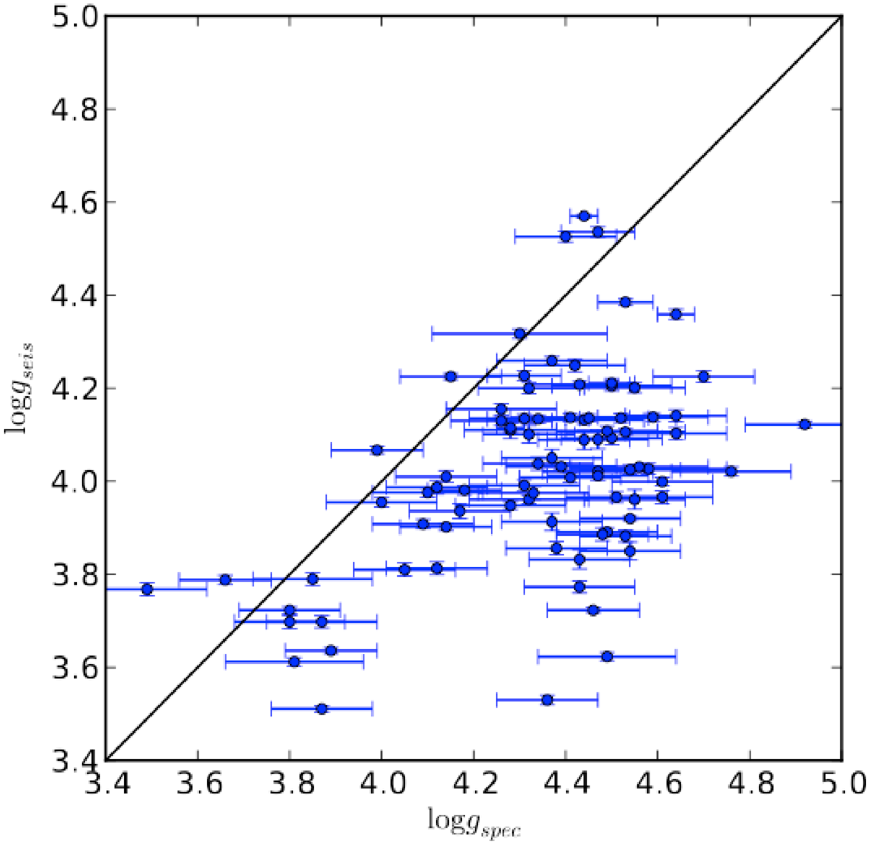
“transit” log g values may also be inaccurate!



Huber et al. 2013

Surface gravity: comparing with 'seismic' method

86 FGK stars analysed



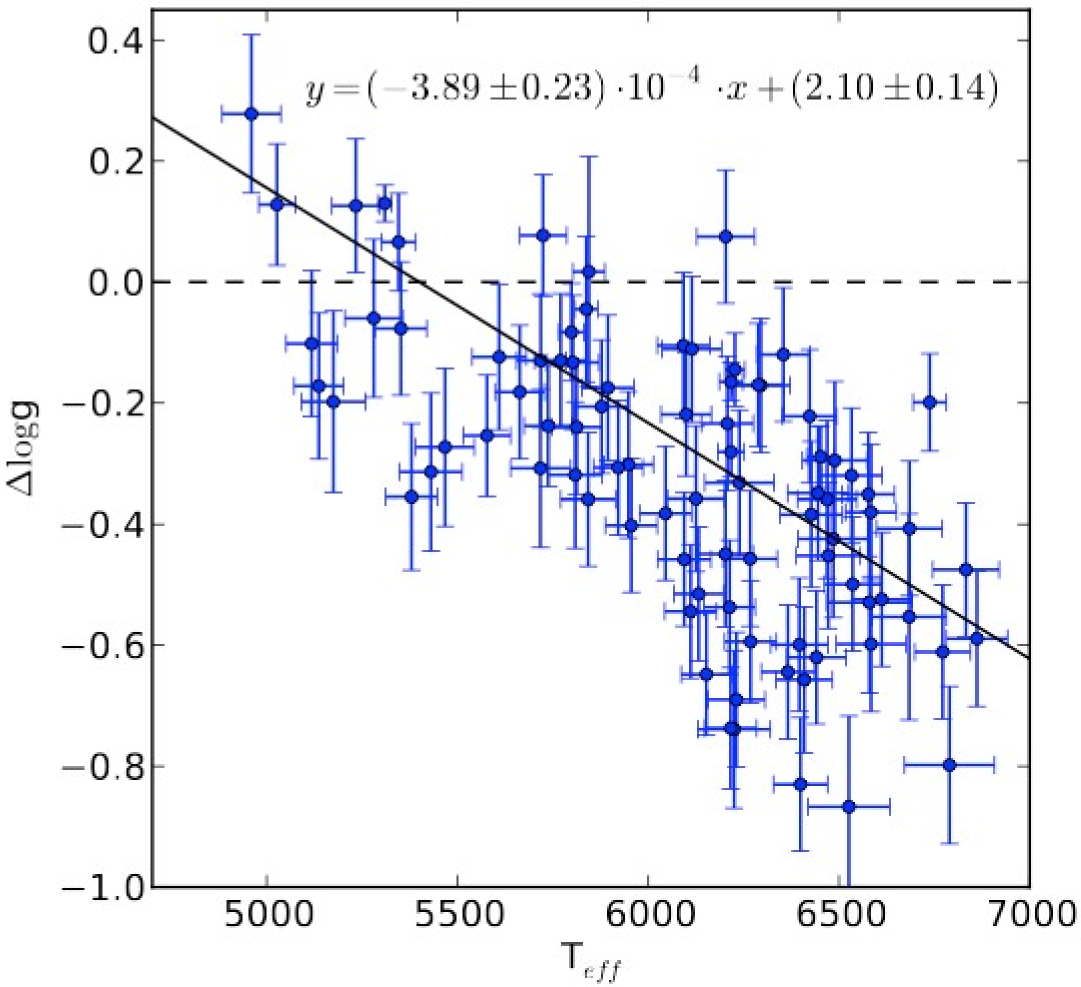
Use large separation $\Delta\nu$, maximum frequency ν_{max}, effective temperature T_{eff}, metallicity [Fe/H], and PARSEC isochrones

Asteroseismic surface gravity more precise and accurate

Mortier et al. 2014

Surface gravity: can be corrected

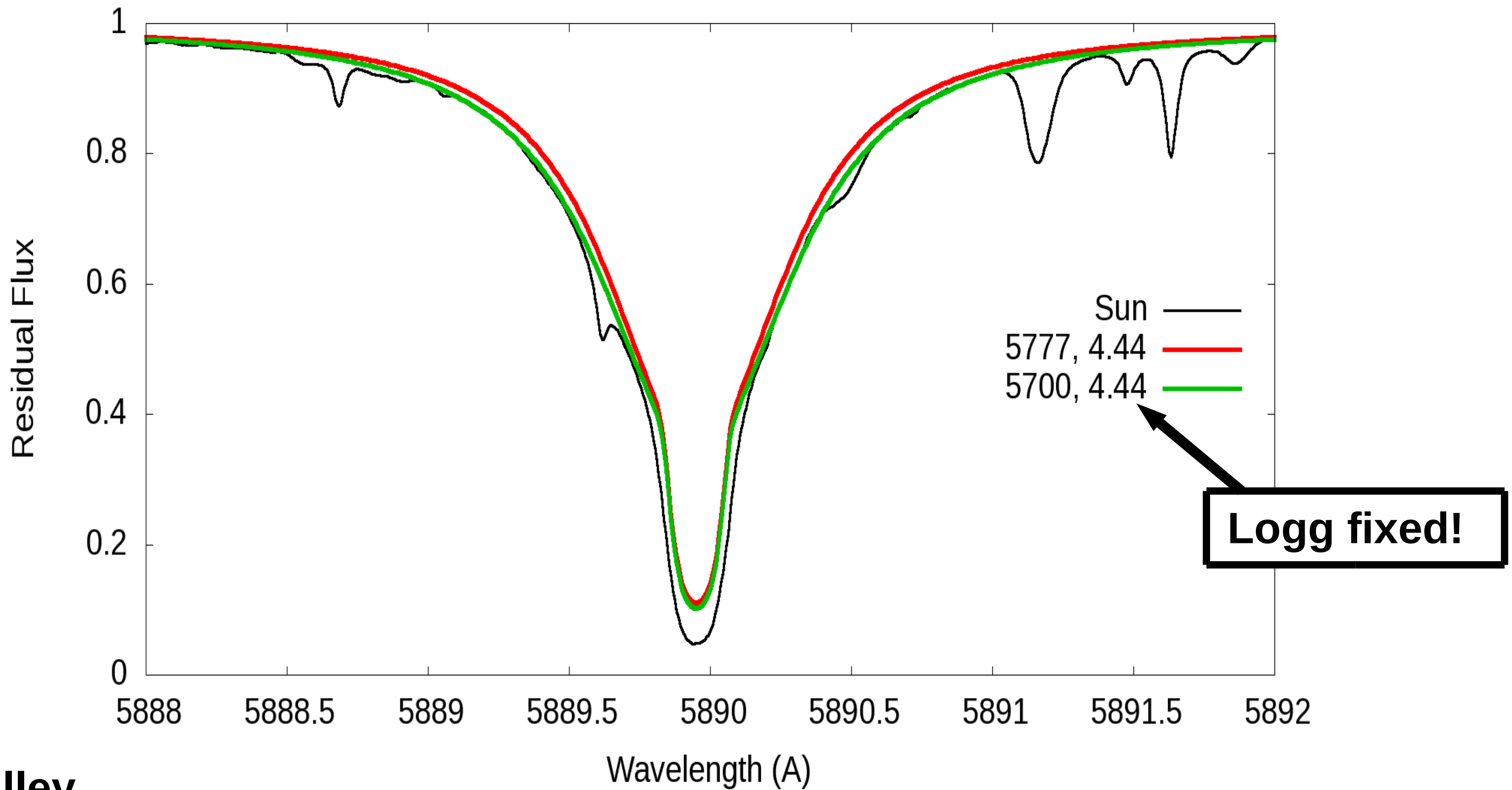
Comparing log g from spectroscopy and asteroseismology



Mortier et al. 2014

Surface gravity: the effect on other parameters

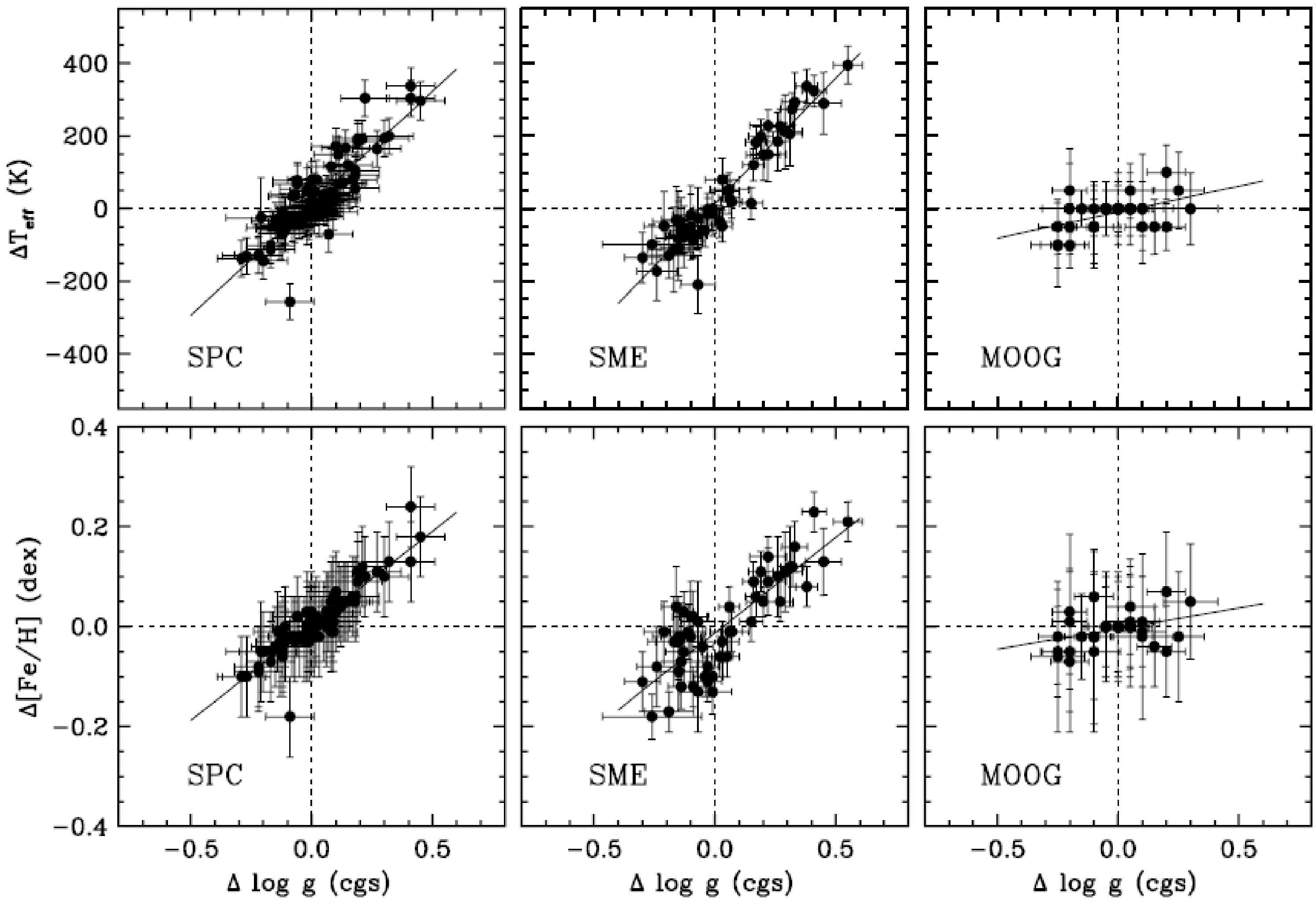
It is not always useful to fix surface gravity and derive other atmospheric parameters.



Credit B. Smalley

Surface gravity: the effect on other parameters

Spectral synthesis methods show strong correlation between [Fe/H], Teff and logg!



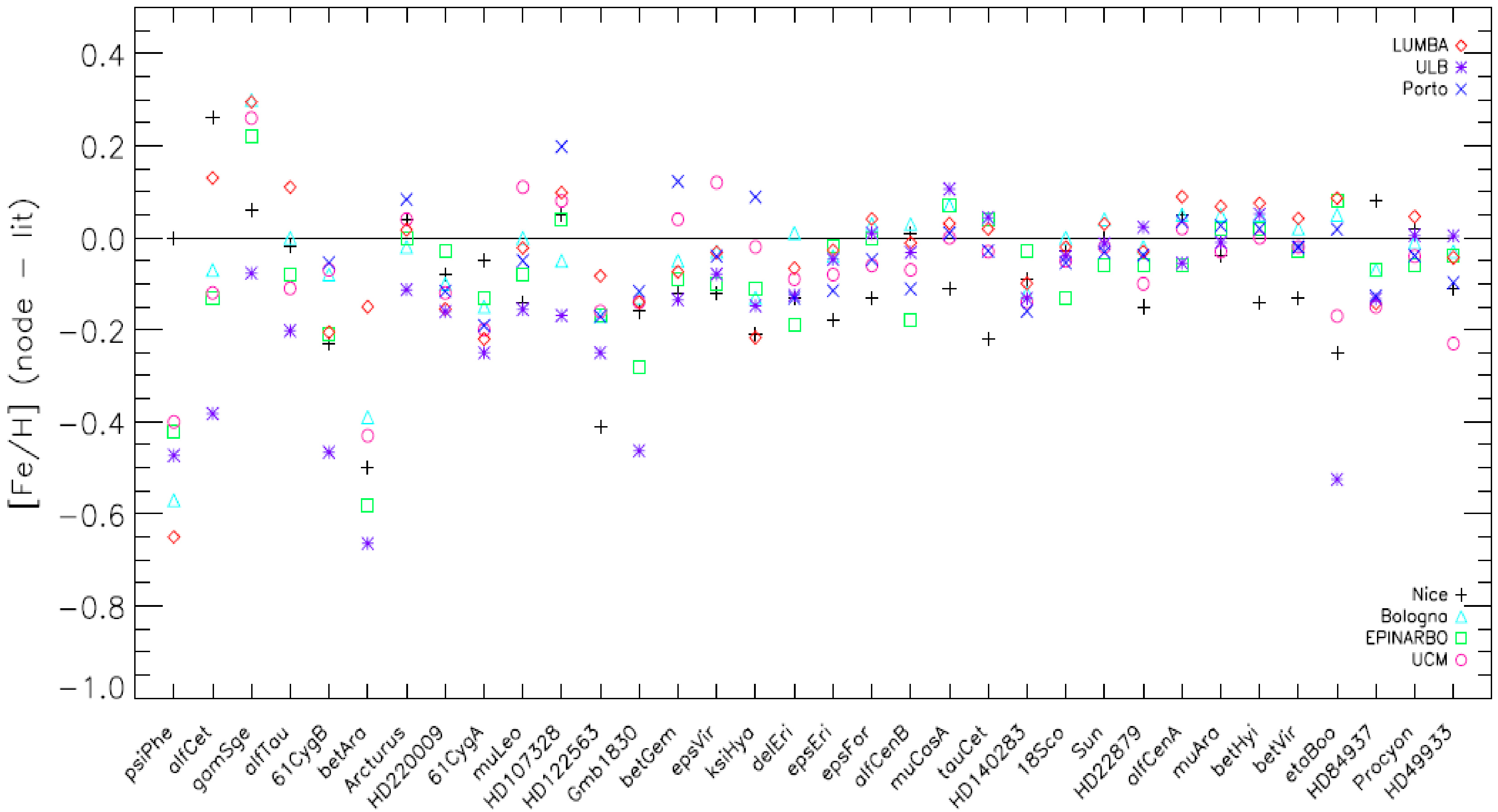
Torres et al. 2012

Surface gravity:

It is not always useful to fix surface gravity and derive other atmospheric parameters.

Metallicity: precision and accuracy

A precision of < 0.01 dex can be obtained (line-by-line analysis)!
Accuracy might be a problem!



Gaia-ESO benchmark stars: Jofre et al. 2014

Metallicity: precision and accuracy

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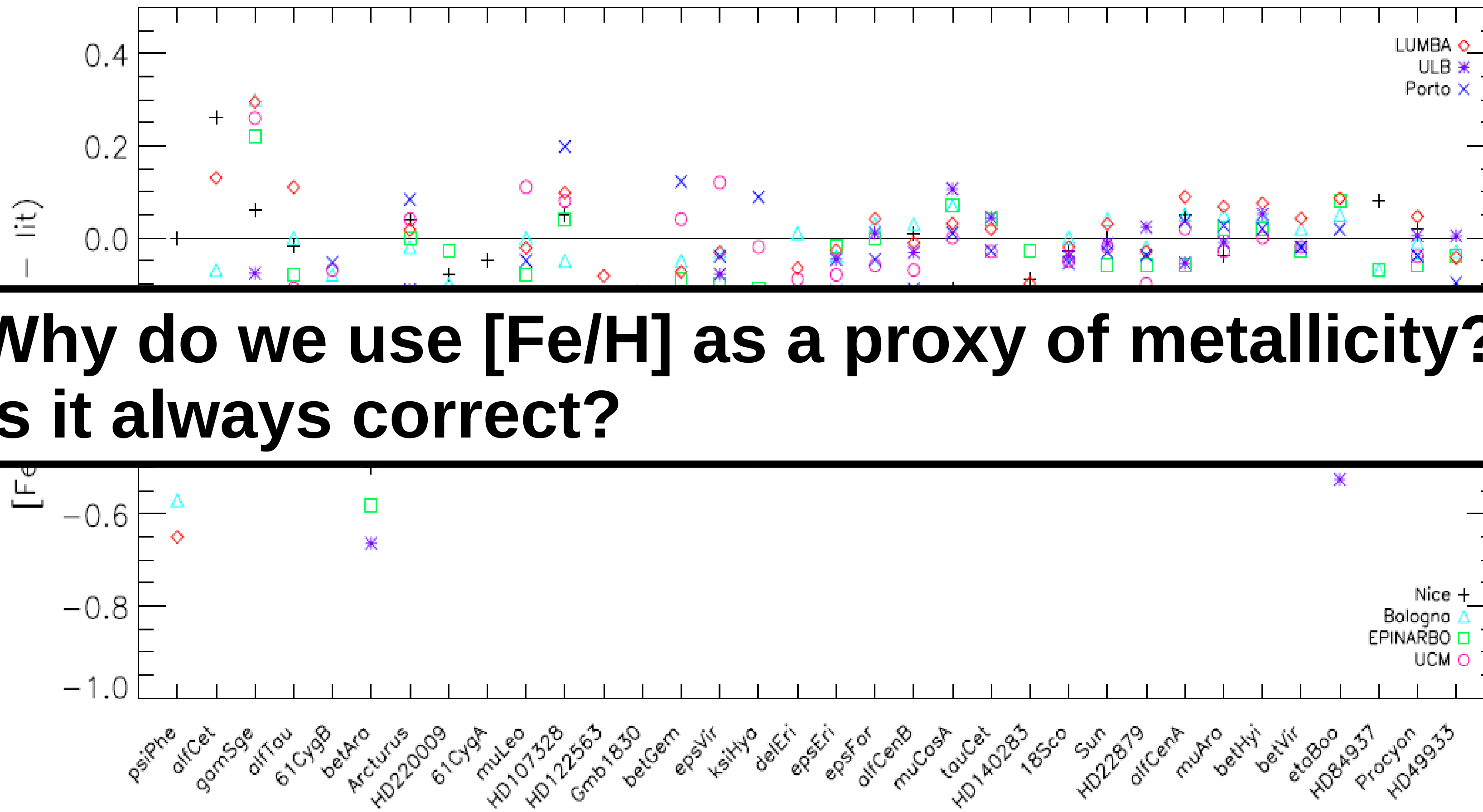
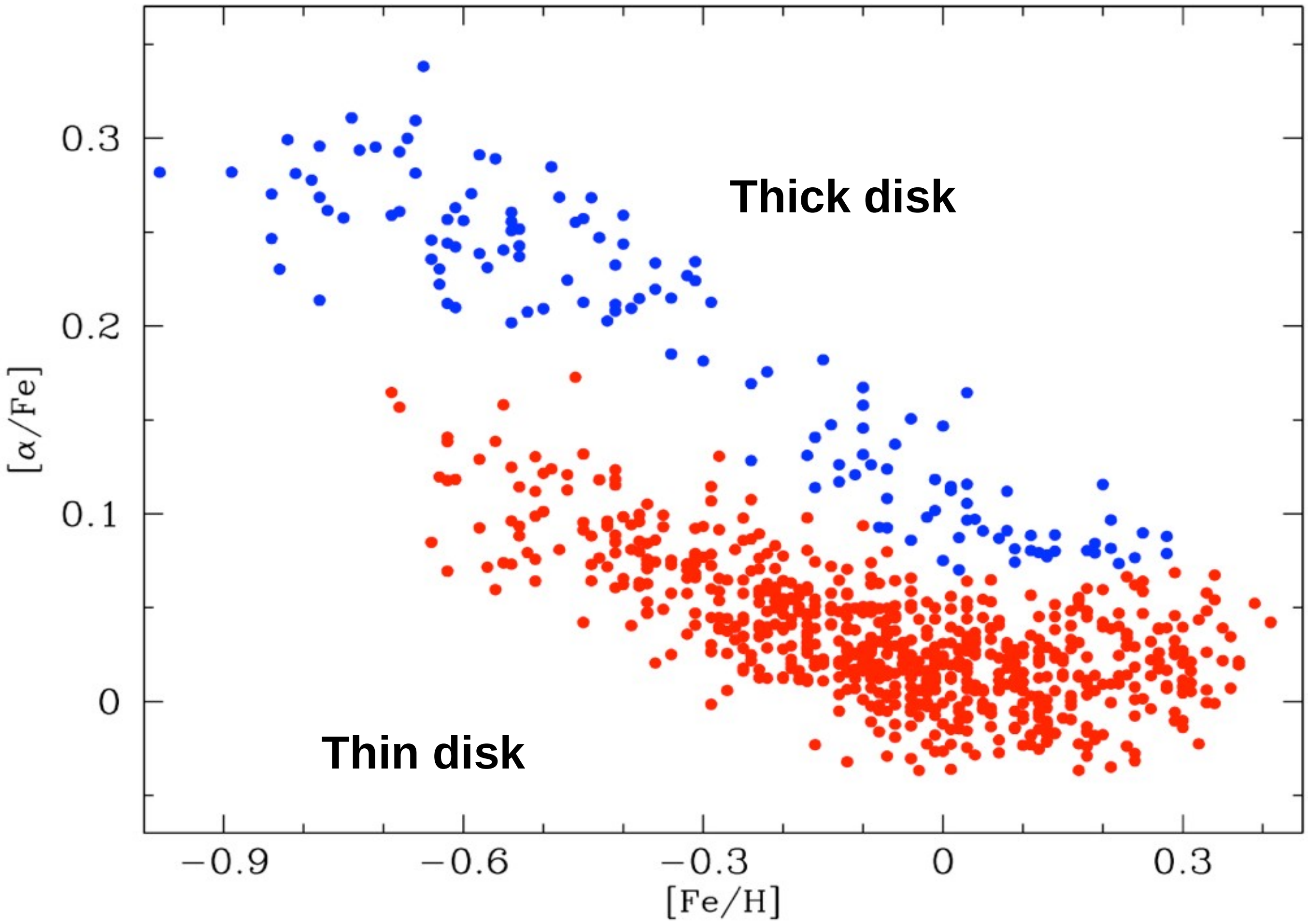


Why do we use [Fe/H] as a proxy of metallicity?
Is it always correct?

Gaia-ESO benchmark stars: Jofre et al. 2014

Abundances of different elements

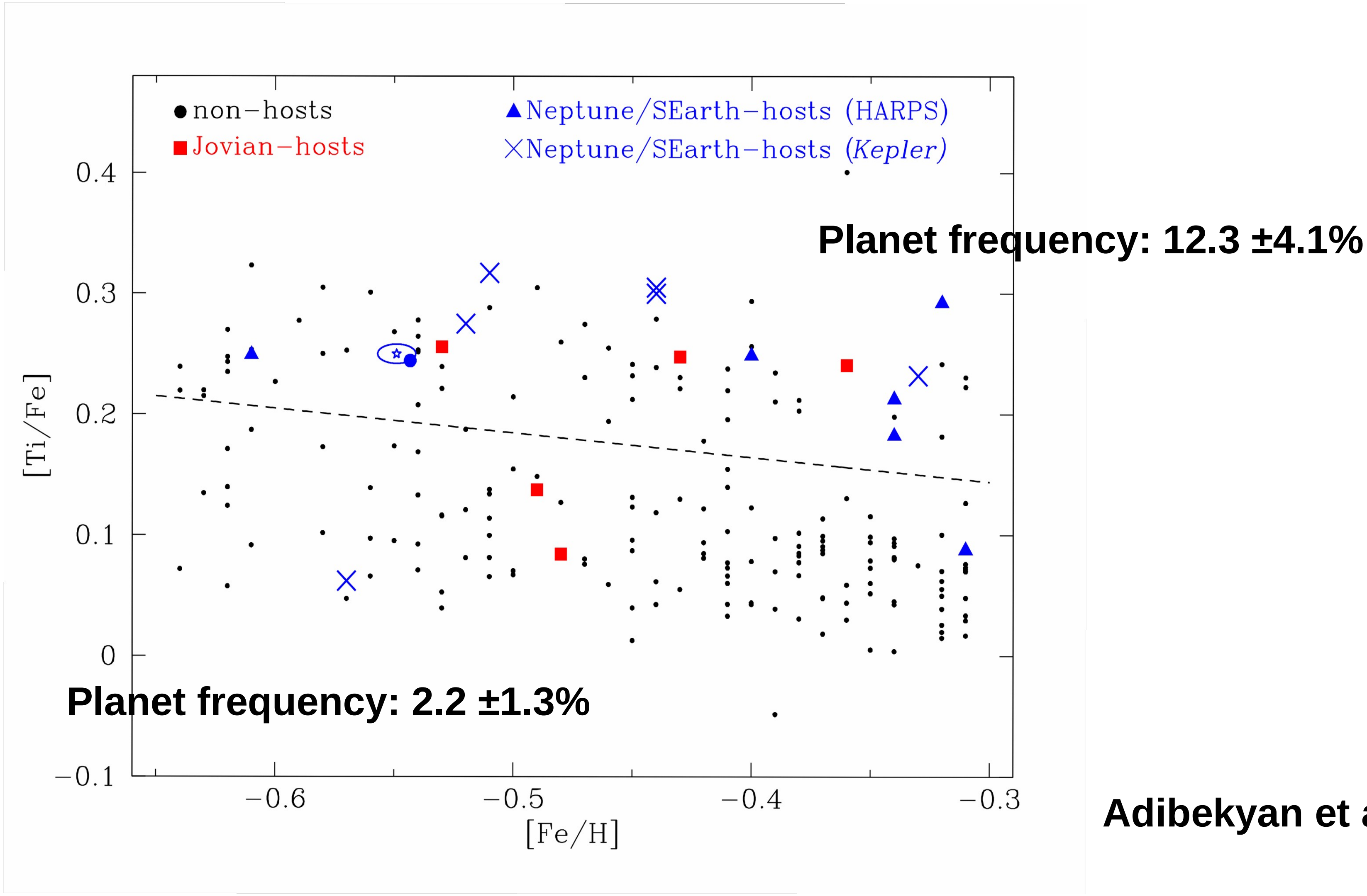
Different stars have different abundances, and abundance ratios.



Adibekyan et al. 2012

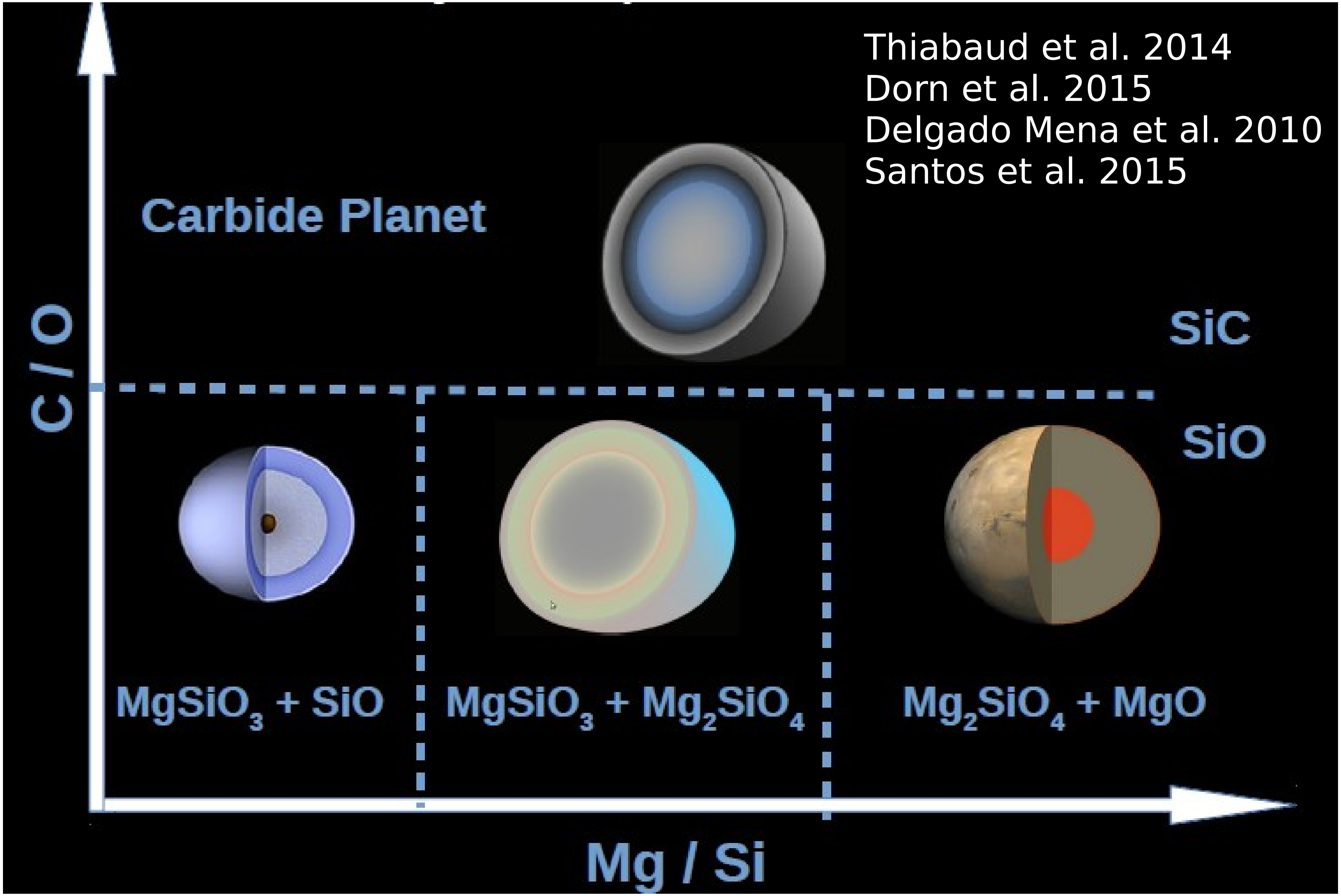
Abundances: why they are important?

Iron-poor planet hosts are enhanced in alpha-elements

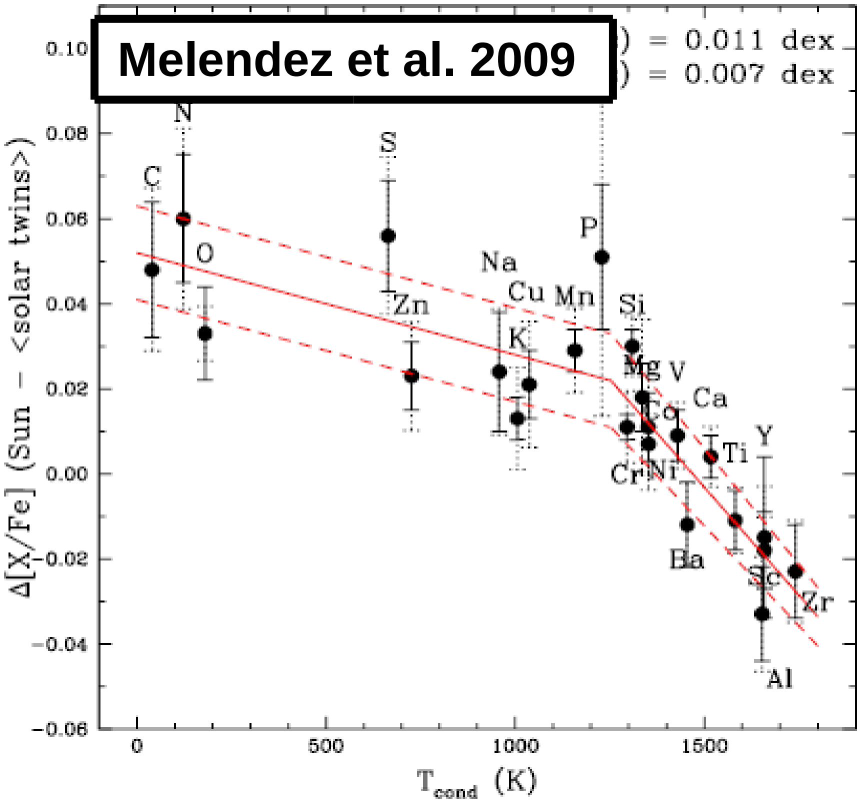


Adibekyan et al. 2012b

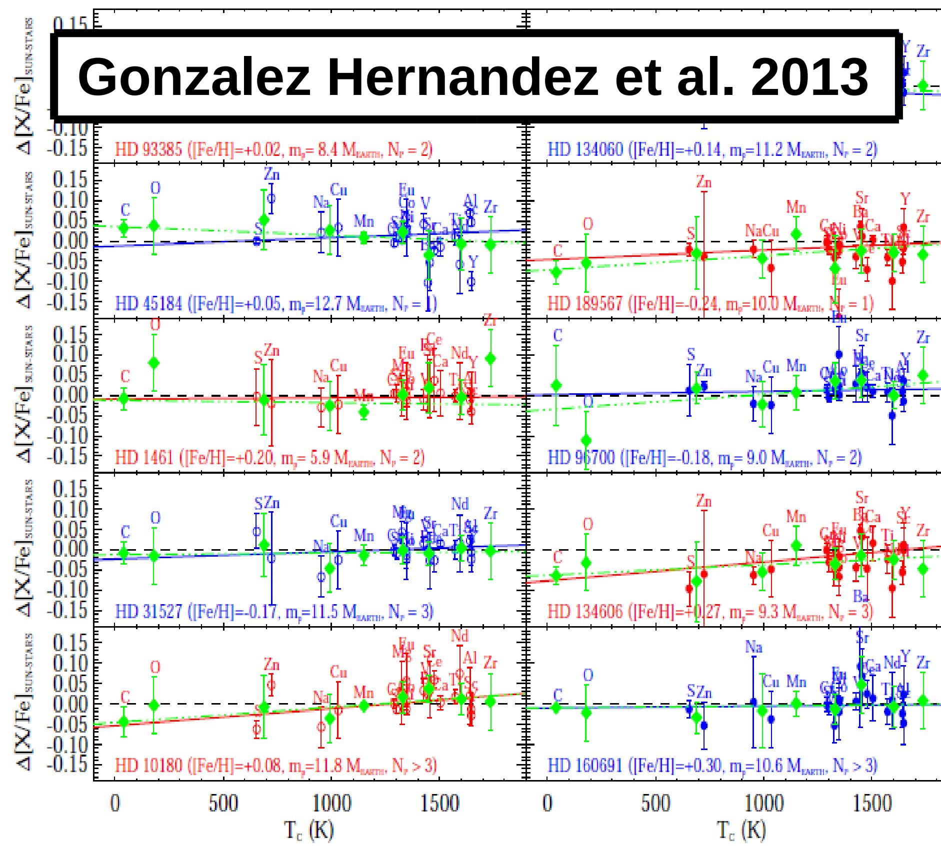
Abundances: why they are important?



Abundances: why they are important?

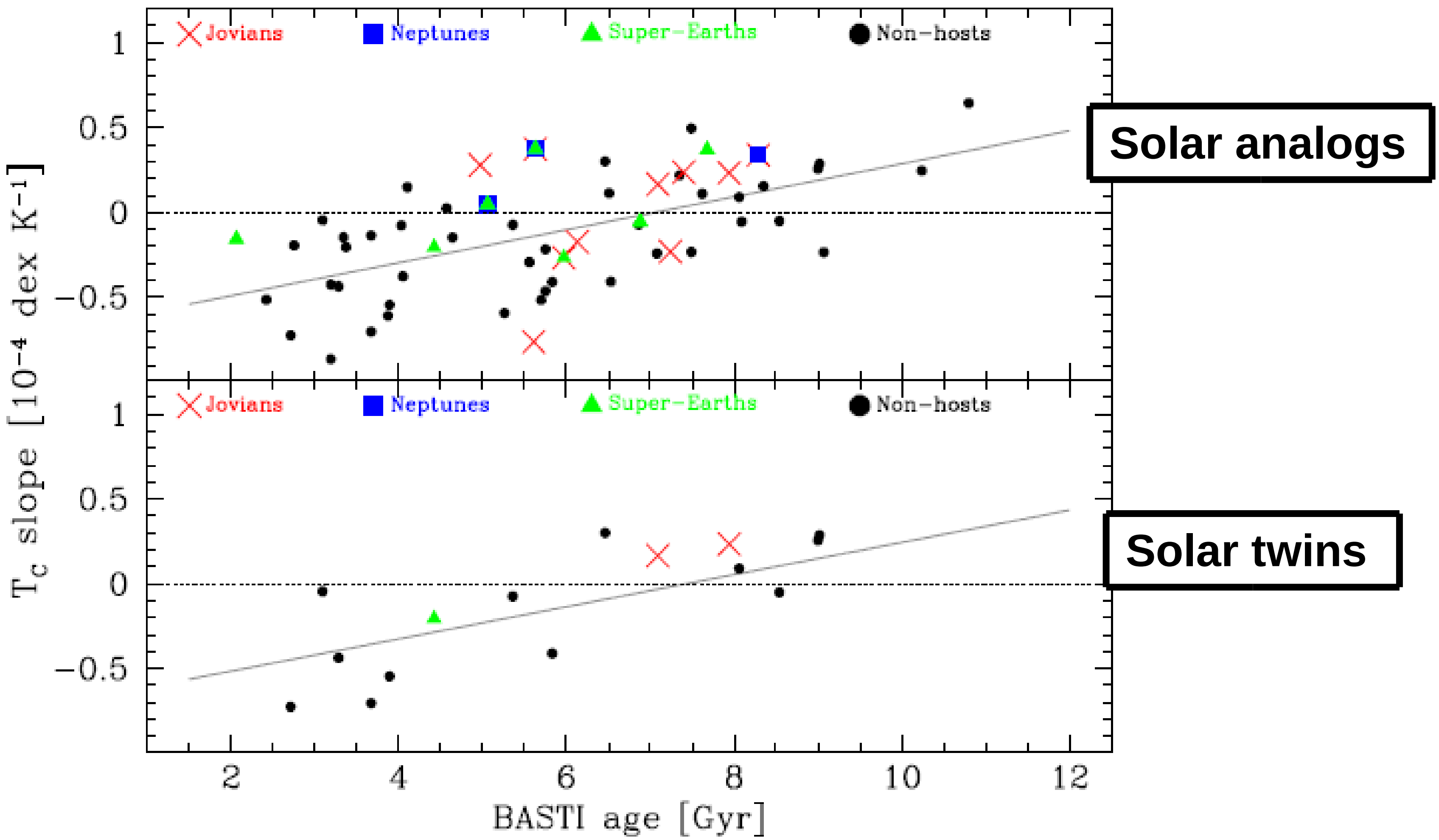


No (significant) evidence for peculiar abundance ratio (Gonzalez Hernandez et al. 2010,2013).



Anomalous volatile-to-refractory ratio of the Sun when compared to solar twins. Refractories remained in rocky planets (Ramirez et al. 2009,2010**).**

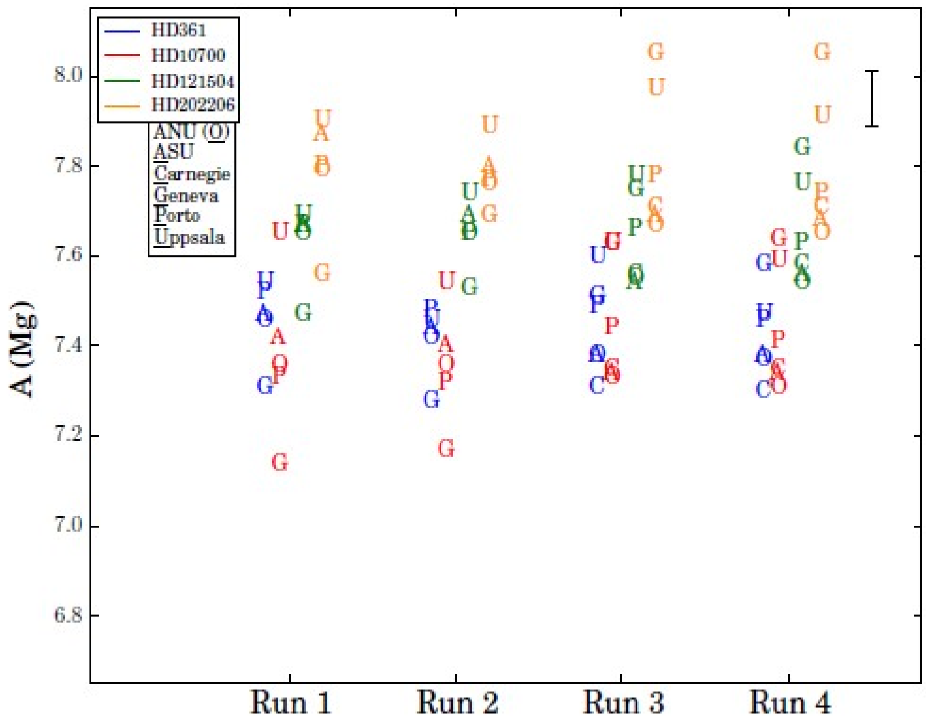
Abundances: why they are important?

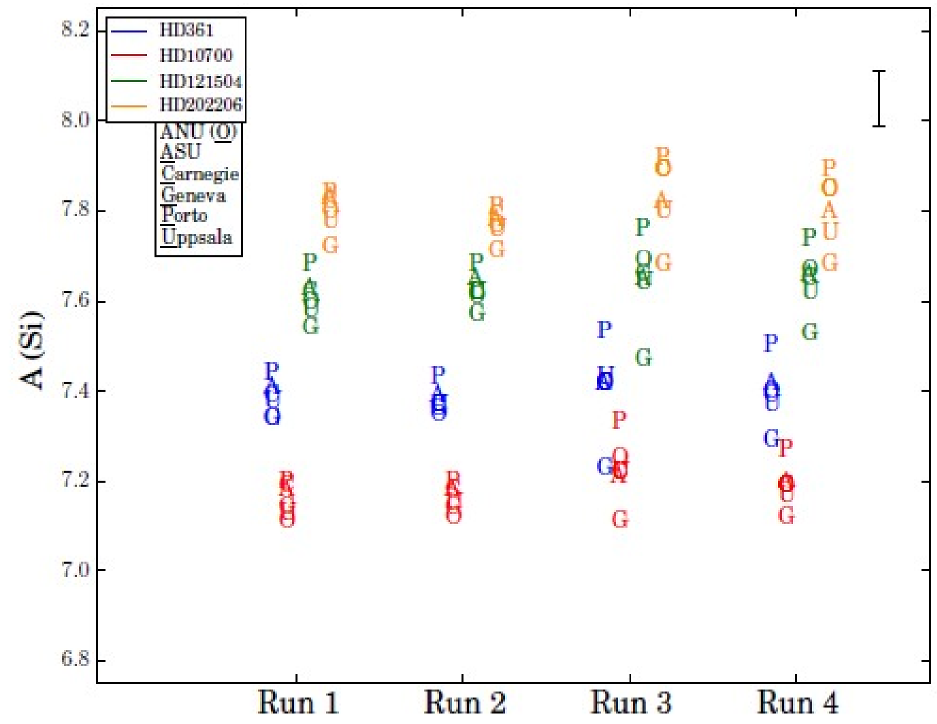


Tc slope strongly correlates with the stellar age.
Older stars show lower refractory-to-volatile ratio independently of the presence of planets. Adibekyan et al. 2014.

Chemical abundances: the accuracy

Very high precision, but not that high accuracy!

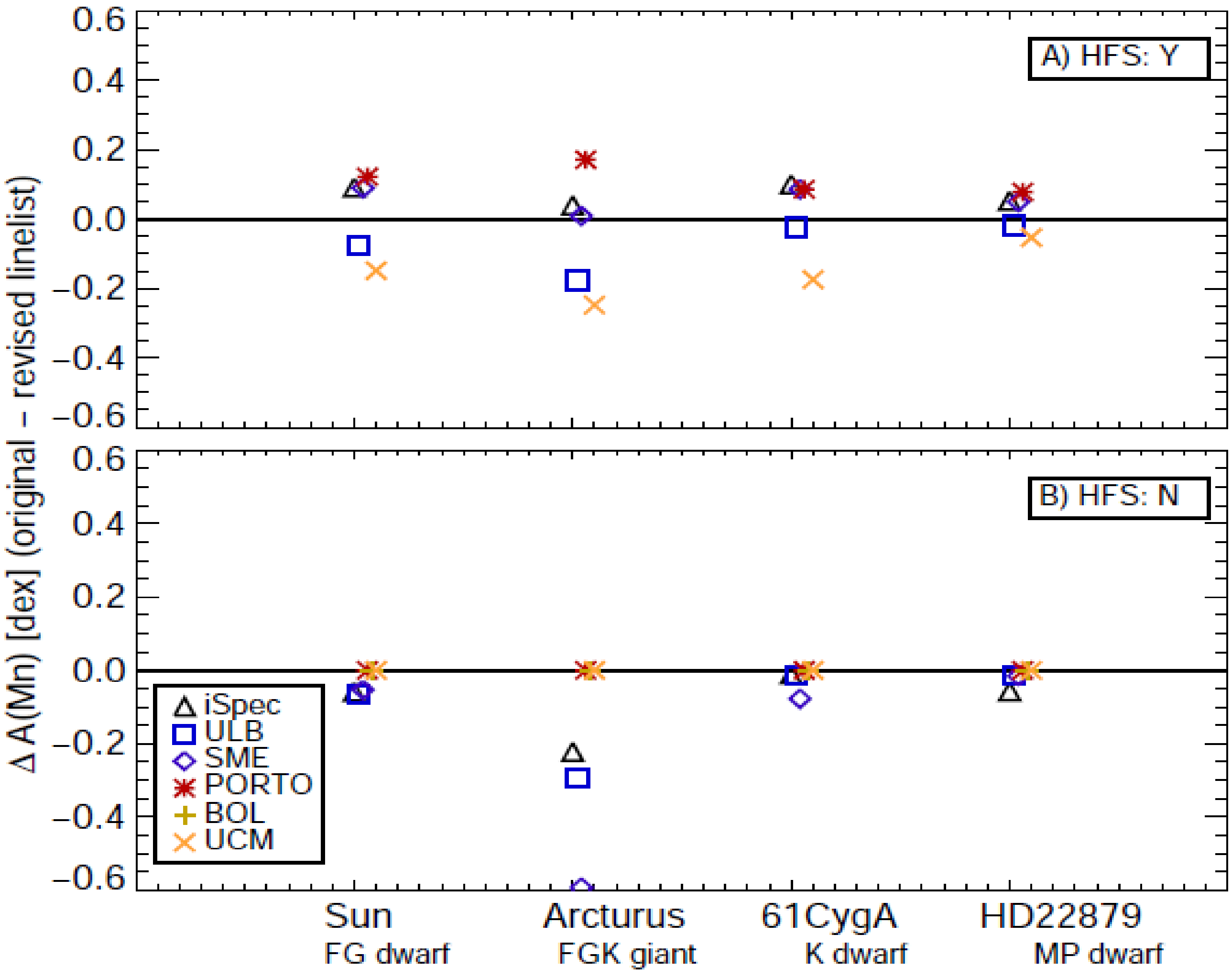




Hinkel et al. 2016

Chemical abundances: the difficulties

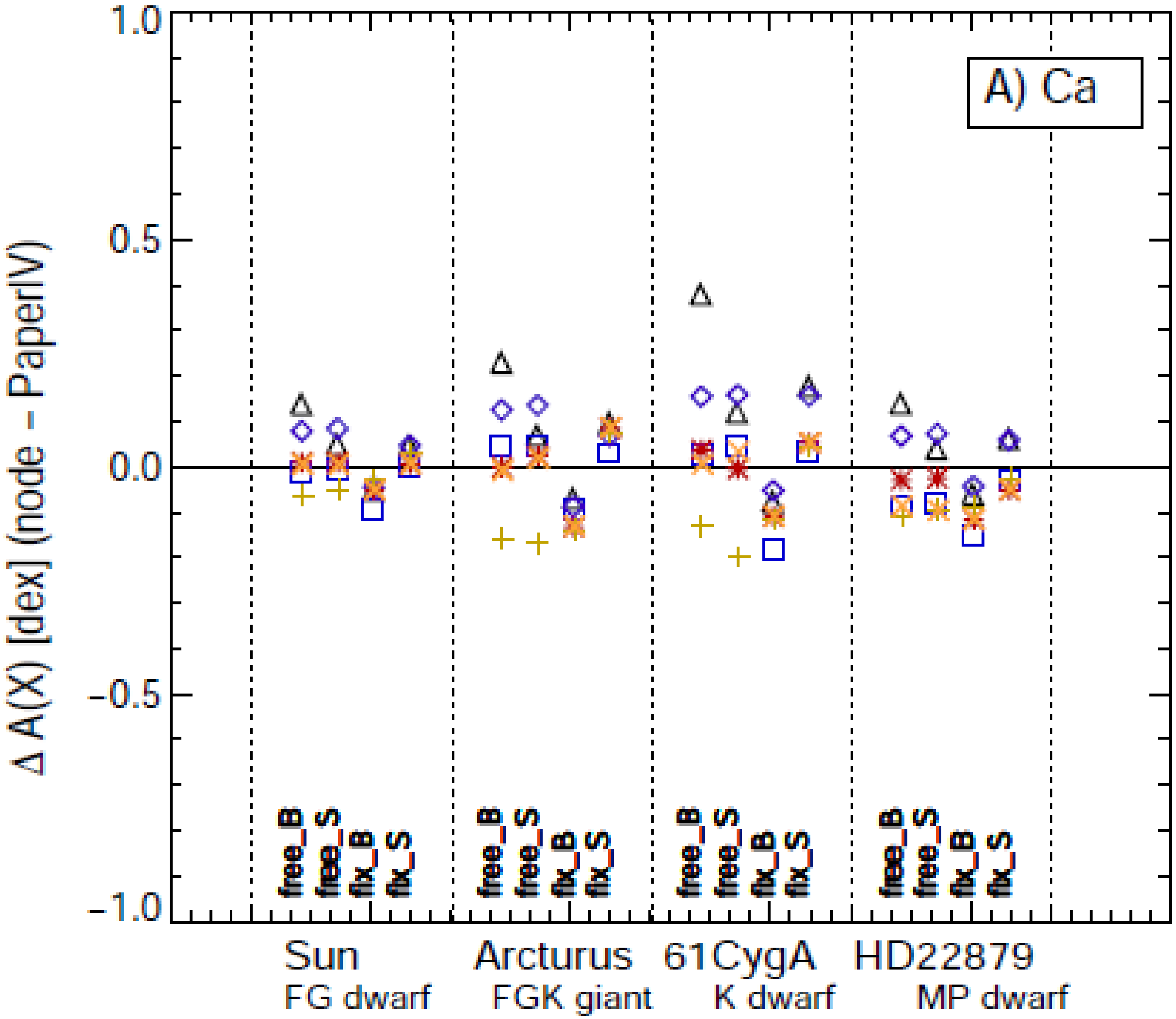
Line-list and atomic data



Jofre et al. 2016, in prep

Chemical abundances: the difficulties

Continuum normalization

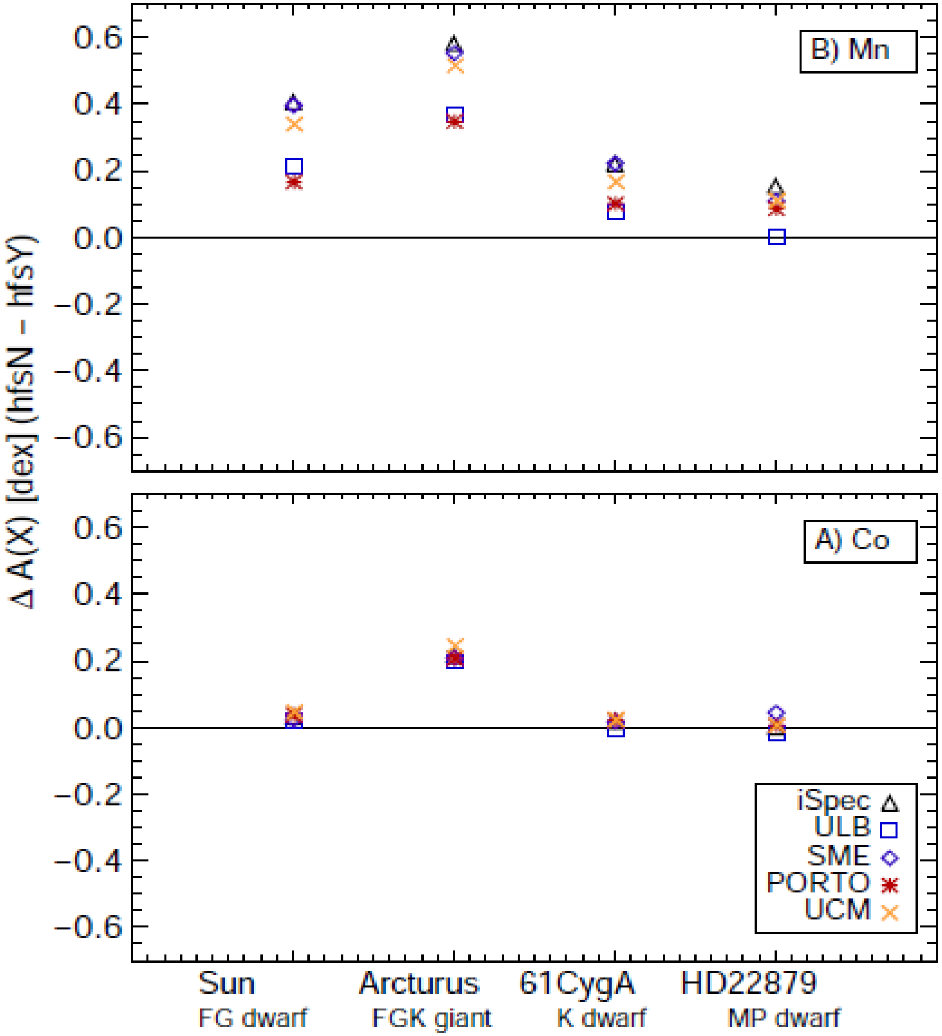


Jofre et al. 2016, in prep

Chemical abundances: the difficulties

Hyper-fine splitting

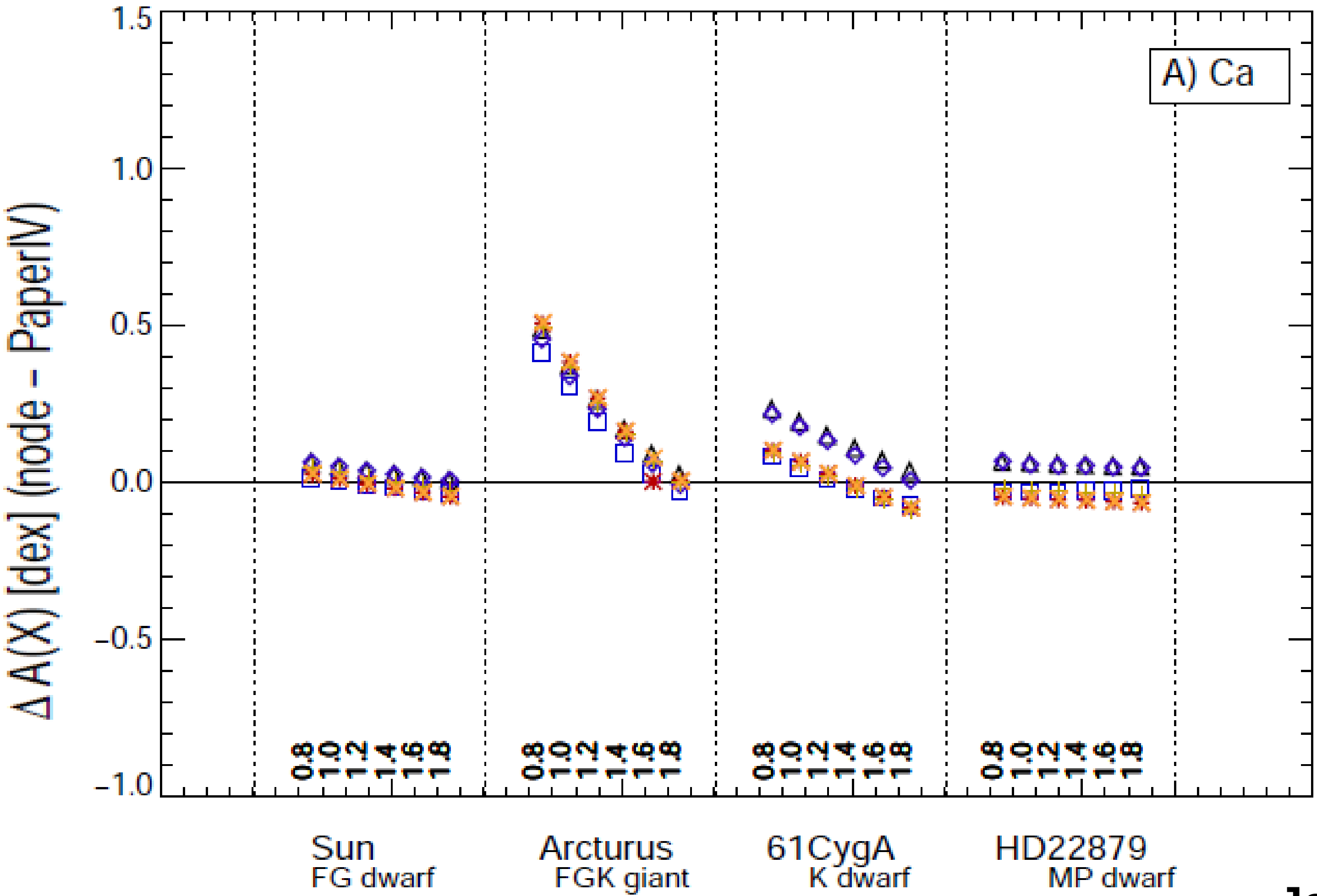
Caused by interaction between electron spin and nucleus spin



Jofre et al. 2016, in prep

Chemical abundances: the difficulties

Microturbulence



Jofre et al. 2016, in prep

Concluding remarks

There are many ways to derive stellar parameters. When combining these methods, precise and even accurate parameters can be obtained!

- Stellar parameters (Teff, [M/H]) fundamental to derive R, M, age, ...
  - Fine for FGK dwarfs, but care is needed (e.g. logg problem)
  - More difficult for M's... (work ongoing)

- Precise abundances of different elements needed
  - Relevant for planet modeling
  - For study of star-planet connection

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Extra Slide: Where to get the best parameters for planet host stars?

SWEET-Cat: a catalog of stellar parameters for stars with planets

SWEET-Cat: a catalog of stellar parameters for stars with planets

SWEET-Cat is a catalogue of stellar parameters for stars with planets listed in the Extrasolar Planets Encyclopaedia. It compiles sets of atmospheric parameters previously published in the literature (including Teff, logg, and [Fe/H]) and, whenever possible, derived using the same uniform methodology (see e.g. Santos et al. 2004; Sousa et al. 2008).

The catalog is described in Santos et al. 2013. However, it is continuously being updated as new planets are announced and new stellar parameters derived. If major changes occur concerning the structure of the catalog they will be described here or in a subsequent paper.

SWEET-Cat is built from literature data, either published or to be published soon. Although we do not encourage, we understand that for simplicity the user may wish to cite only the catalog presentation paper if using it in a statistical way. However, we strongly encourage the user to give the propper credit to the original source of stellar parameters.

(click on any specific header to sort, a detailed description of each field can be found here)

Download Data

Name	HD number	RA	Dec	Vmag	σ(Vmag)	π	σ(π)	Source of π	Teff	σ(Teff)	logg	σ(logg)	LC logg	σ(LC logg)	Vt	σ(Vt)	[Fe/H]	σ([Fe/H])	Mass	σ(Mass)	Reference	Homogeneity flag	Last Update	Comments
11Com	107383	12 20 43.02	+17 47 34.33	4.74	0.02	11.25	0.22	Simbad	4830	79	2.61	0.13	-	-	1.70	0.30	-0.34	0.06	2.80	0.28	Mortier et al. 2013b	1	2013-09-01	-
11UMi	136726	15 17 05.88	+71 49 26.04	5.02	-	8.19	0.19	Simbad	4340	70	1.60	0.15	-	-	1.80	0.00	0.04	0.04	1.80	0.25	Dollinger et al. 2009	0	2013-02-26	-
42Dra	170693	18 25 59.13	+65 33 48.52	4.83	-	10.36	0.20	Simbad	4532	100	2.31	0.10	-	-	1.59	0.30	-0.39	0.12	1.74	-	Luck & Heiter 2007	0	2013-02-26	-
47Uma	95128	10 59 27.97	+40 25 48.92	5.04	0.05	71.11	0.25	Simbad	5954	25	4.44	0.10	-	-	1.30	0.04	0.06	0.03	1.04	0.08	Santos et al. 2004	1	2013-02-26	-
51Peg	217014	22 57 27.98	+20 46 07.79	5.46	0.05	64.07	0.39	Simbad	5804	36	4.42	0.07	-	-	1.20	0.05	0.20	0.05	1.04	0.08	Santos et al. 2004	1	2013-02-26	-
55Cnc	75732	08 52 35.81	+28 19 50.95	5.95	0.05	81.03	0.75	Simbad	5279	62	4.37	0.18	-	-	0.98	0.07	0.33	0.07	0.93	0.09	Santos et al. 2004	1	2013-02-26	-
6Lyn	45410	06 30 47.10	+58 09 45.48	5.88	-	17.92	0.47	Simbad	4978	18	3.16	0.05	-	-	1.10	0.07	-0.13	0.02	1.70	0.20	Sato et al. 2008	0	2013-02-26	-
61Vir	115617	13 18 24.31	-18 18 40.30	4.74	0.01	99.89	0.22	Simbad	5577	33	4.51	0.11	-	-	1.07	0.04	0.01	0.05	0.91	0.08	Santos et al. 2005	1	2013-02-26	-

Homogeneous stellar parameters. Santos et al. 2013

- Over 65% of all planet host stars known
- More than 90% of all stars with RV-detected planets