INTRIGOSS

A new Library of High Resolution Synthetic Spectra

M. Franchini, C. Morossi, P. Di Marcantonio
INAF-Osservatorio Astronomico Trieste, Italy

M. Chavez
INAOE, Mexico

and …

GES Builders

Outline

1. ***General introduction***
2. **INTRIGOSS*: Library of HiRes synthetic spectra for F,G,K stars***
   a) **Atmospheric models**
   b) **HiRes synthetic spectra**
      - Atomic and Molecular line list
      - Astrophysical log ***gf***
3. ***Comparison with other spectral libraries***
   a) **AMBRE**
   b) **GES_Grid**
   c) **PHOENIX**
   d) **Coelho 2014**
   e) **Brahm 2017**
4. ***Conclusions***

Stellar libraries

Stellar libraries have been extensively applied in a number of astrophysical topics

- Automatic analysis of data in stellar surveys to derive atmospheric parameters
- Detection of exoplanets via cross-correlation with spectra templates
- Spectroscopic classification
- Study of star formation history of galaxies by using synthetic and observed photometric indices and/or SED
- Stellar library is the heart of stellar population studies and should provide:
  - Complete coverage of the HR diagram
  - Accurate atmospheric parameters: $T_{\rm eff}$, log$g$, [Fe/H], [Mg/H], etc
  - **Empirical libraries:** limited coverage of HR and carrying on the imprints of the local properties of the solar neighborhood cannot easily reproduce any kind of integrated spectra
  - **Synthetic libraries:** have been increasingly used to overcome limitations of empirical libraries

Stellar libraries

Several theoretical libraries computed to complement the empirical ones

- Coelho+2005, Coelho 2014 (C14)
- Husser+2013 (PHOENIX)
- ….

- de Laverney+ 2012 (AMBRE)
- Brahm+ 2017 (B17)

➢ **Different Atmosphere Model CODES:**
- Atlas9: Castelli & Kurucz 2003
- Atlas12: Kurucz 2005
- MARCS: Gustafsoon+ 2008
- PHOENIX: Hauschildt & Baron 1999
- …

➢ **Different spectral synthesis codes:**
- DFSYNTHE: Castelli 2005, Kurucz 2005
- SPECTRUM: Gray & Corbally 1994
- PHOENIX: Hauschildt & Baron 1999
- MOOG: www.as.utexas.edu/~chris/moog.html
- …

➢ **Different adopted Solar Chemical Mixture, atomic and molecular line lists**

➢ **Not all libraries provides both normalized HiRes spectra and SEDs**

INTRIGOSS: INaf TRIeste Grid Of Synthetic Spectra for F,G,K stars

15600 HiRes spectra

computed with **SPECTRUM** code from the atmosphere models (**ATLAS12**)

atomic and molecular line list containing *bona fide* Predicted Lines built by tuning log*gf* to reproduce HiRes reference spectra

Normalized SPectra (NSP) and surface Flux SPectra (FSP)

λλ4800-5400Å

Δλ=0.01Å

INTRIGOSS: Model Atmospheres

Atlas12 can generates an atmospheric model for:

- ***Any desired individual element abundance***
- ***Microturbence ξ***

based on the Opacity Sampling (OS) Technique

In particular we used:

- **Reference Solar Abundances:** Grevesse 2007
- **starting ATLAS9 atmosphere models** calculated for the APOGEE survey (www.iac.es/proyecto/ATLAS-APOGEE)

  $T_{\rm eff}$: 3750 - 7000 K at step of 250 K

  log g: 0.5 - 5.0 dex at step of 0.5 dex

  [Fe/H]=-1.0 - +0.5 at step of 0.25 dex

  [α/Fe]=-0.25 - +0.5 at step of 0.25 dex (**α-el**: **O, Ne, Mg, Si, S,Ar, Ca,Ti)**

- **Microturbulence** ξ=1 and 2 km s^{-1}

INTRIGOSS: Spectral Synthesis Code

Spectrum v2.76e stellar spectral synthesis code to compute:

- ***Emergent Flux SPectrum (FSP) and Normalized SPectrum (NSP)***
- ***Local Termodynamic Equilibrium approximation (LTE)***

It requires:

- **Line list of atomic and molecular transitions**
- Wavelength range and sampling
- Microturbulence ξ

INTRIGOSS: log *gf* optimization

Reliable atomic and molecular data:

➢ **Several online databases:**

- NIST, VALD, NORAD, Kuruz's website, etc.

  log *gf* values may be determined in the laboratory or derived from theoretical calculations →**accuracy** may vary widely from line to line (1% or better or to be off by orders of mag)

➢ **Possible way to reduce these uncertainties:**

- ***to compare high SNR spectra of stars with their synthetic spectra:***
  - ✓ stars with well known **atmospheric parameters** (T_{eff}, **log*g*, [Fe/H], ξ**) and **abundances**
  - ✓ ***gf***-values may be checked (if needed adapted **iteratively**) by looking for the best agreement in the depths of computed and observed lines → **astrophysical** log ***gf***
  - ✓ Line depths depend both on stellar characteristics and on ***gf***-values:

    risk → wrongly compensate with modified ***gf***-values the potential inaccuracies in **atmospheric parameters** and **abundances**.

    solution → check the modified ***gf***-values in spectra of as many (and as different) as possible stars in order to decouple **astrophysical *gf***-values from the assumed T_{eff}, **log*g*, [Fe/H], ξ** and **abundances**

INTRIGOSS: log *gf* optimization

Lobel 2011 (LO11) used Sun (5777,4.438), Procyon (6550,4.0) and ε Eri (5050,4.5):

- Solar composition assumed for Procyon and ε Eri
- Solar spectrum observed in 1981 with the NSO/KPNO FTS, degraded to R=80,000
- For Procyon and ε Eri several optical spectra with Hermes spectrometer on the 1.2m Mercator telescope at La Palma Observatory, R=80,000
- Updated the ***gf*** values of 911 neutral lines in 4000÷6000Å
- SCANSPEC synthetic spectra

Main causes of uncertainties:

- Problems of deriving the solar intensity (averaged over the solar disk) from NSO/KPNO FTS observations
- Solar composition for Procyon and ε Eri
- The use of only relatively **high temperature** (T_{eff}>5000K) **Main Sequence stars** which does not allow to check ***gf***-values of those atomic and molecular lines that are mainly prominent in spectra of **giants** and/or **cooler stars**

INTRIGOSS: log *gf* optimization

We complement the LO11 work by using the same kind of analysis but

➢ **An *ad hoc* high SNR Solar spectrum:**
- average of 59 integrated sunlight spectra as reflected by the Moon
- HARPS at 3.6m La Silla ESO telescope
- The out-of-transit sub-sample of spectra taken to detect the Rossiter-McLaughlin effect in the Sun due to the Venus transit of 2012 June 6 (Molaro+2017)
- **SNR~4000**
- Degraded at R=80,000 (as Hermes spectra)

➢ ***Normalized synthetic* Solar spectrum:**
- $T_{\rm eff}$=5777K, **log*g***=4.4377 dex, ξ =1.0 km s^{-1} and solar abundance by Grevesse 2007
- Convolved with geometric mean of solar ***vsini*** and macroturbulence (2.5 km s^{-1})
- Degraded to R=80,000 (as Hermes spectra)

Used to ***normalize observed spectrum*** by searching for continuum flux reference points in the solar spectrum and using a polynomial fitting to derive the continuum shape

➢ **Spectra of 5 giants:**
- **UVES,** 580nm setup, Gaia-ESO Survey (GES)
- **SNR** > 100
- 4500 $\leq T_{\rm eff} \leq$ 5000 K
- 2.0 $\leq$ **log*g*** $\leq$ 3.2 dex
- 1.0 $\leq \xi \leq$ 1.5 km s^{-1}
- Elem. abundances in GESiDR4 catalogue

➢ ***Normalized synthetic* spectra of 5 giants:**
- $T_{\rm eff}$, **log*g***, **[Fe/H]**, ξ, ***vsini*,** element abundances derived by GES Consortium and reported in the GESiDR4 catalogue

Used to ***normalize observed spectra*** as for the Solar Spectrum

INTRIGOSS : log *gf* optimization

Input log *gf* 's are a merge of:

- ✓ **Cool5.iso.lst** (Gray 2011 private communication)
- ✓ **Molecular lines** from Kurucz 's website
- ✓ **Atomic and molecular Predicted Lines (PL)** from Kurucz 's website

log *gf* optimization

- At first we compared our observed and synthetic solar spectrum to obtain astrophysical values
- At the same time we double-checked the LO11 values and confirmed their validity for all but ~100 lines that required slight modification of their ***gf*** values and/or central wavelengths

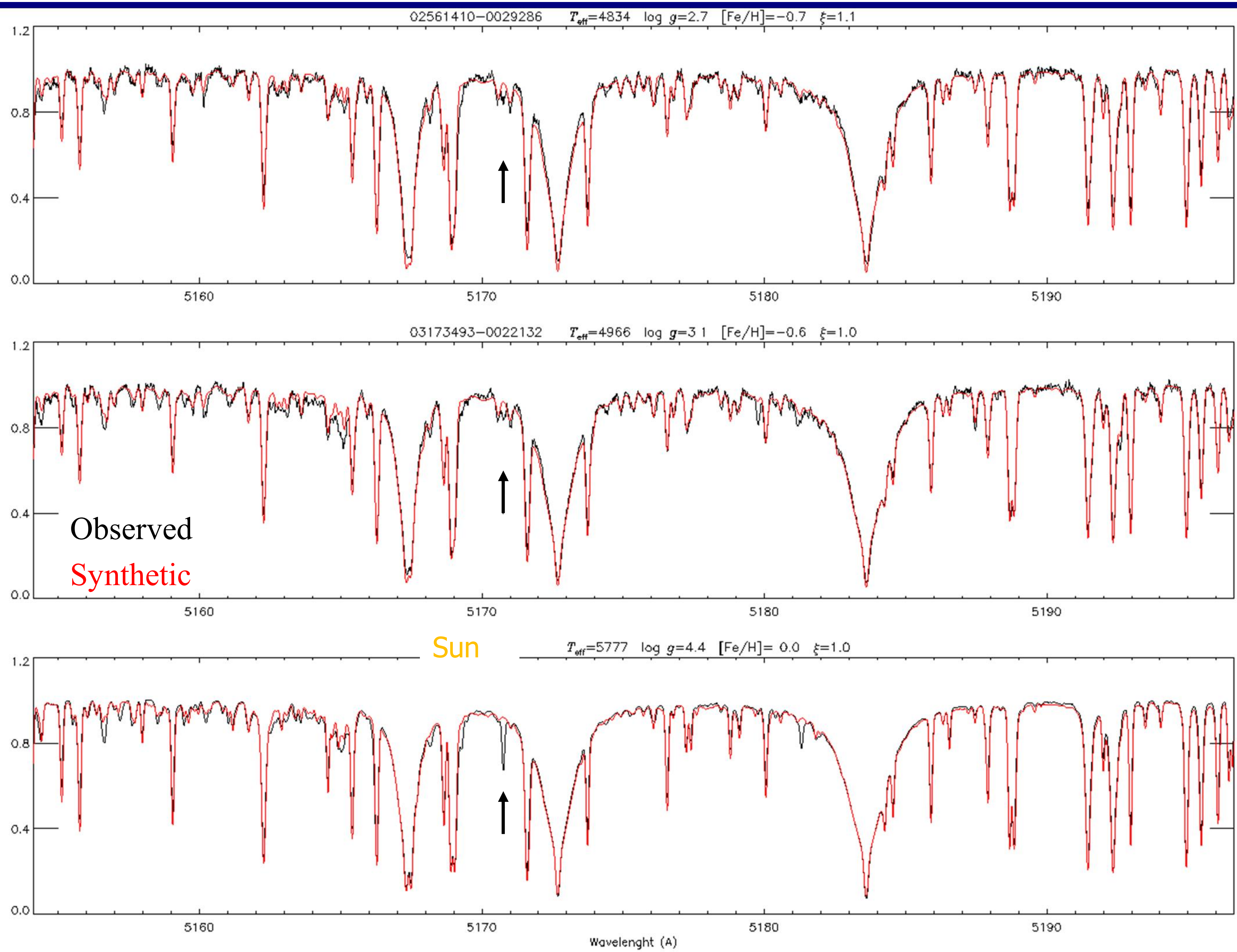
  (These corrections are mainly due to the higher SNR of our solar spectrum and to the inclusion in the synthetic spectra of predicted lines not present in the LO11 SCANSPEC ones.)
- Then we checked those atomic and molecular lines which mainly appear in stars at log*g* and $T_{\rm eff}$ lower than the Sun by using the UVES-U580 spectra of the 5 giants

INTRIGOSS: log *gf* optimization

We derived **astrophysical *gf*** values for
1551 atomic lines + **77** molecular lines
+
1231 Predicted Lines

The latter allow us to minimize

- The unavoidable underestimation of blanketing in synthetic spectra if PLs ignored
- the risk of worsening the match of synthetic spectrum with observed spectrum if PLs with incorrect intensity are used



02561410−0029286 T_{eff}=4834 log g=2.7 [Fe/H]=−0.7 ξ=1.1
03173493−0022132 T_{eff}=4966 log g=3.1 [Fe/H]=−0.6 ξ=1.0
Observed
Synthetic
Sun
T_{eff}=5777 log g=4.4 [Fe/H]= 0.0 ξ=1.0
1.2
0.8
0.4
0.0
5160
5170
5180
5190
Wavelenght (A)

INTRIGOSS: Validity of our line list for F, G, K stars

- **Gaia-ESO iDR4 release that contains**:
  Stacked spectra
  ***T*$_{eff}$, log*g*, [Fe/H],** ξ, Radial and rotational velocities
  Individual element abundance [X/Fe]

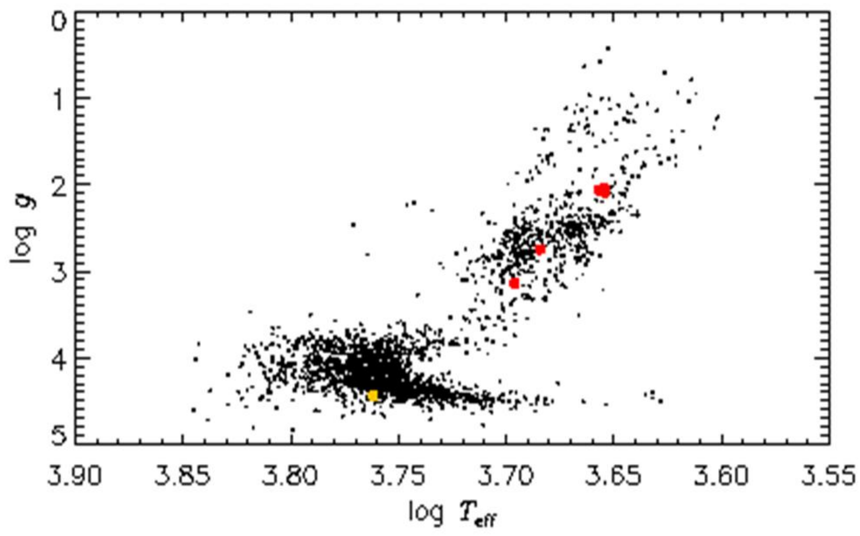
  - **SQL search to download parameters and spectra with the following criteria for FGK stars:**
    $3500 \leq T_{eff} \leq 7000$K and $0.25 \leq \log g \leq 5.25$dex
    UVES-U580 setup centered at 580 nm (476.8-580.1 and 582.2-683.0 nm ***R***~47000)
    SNR > 10

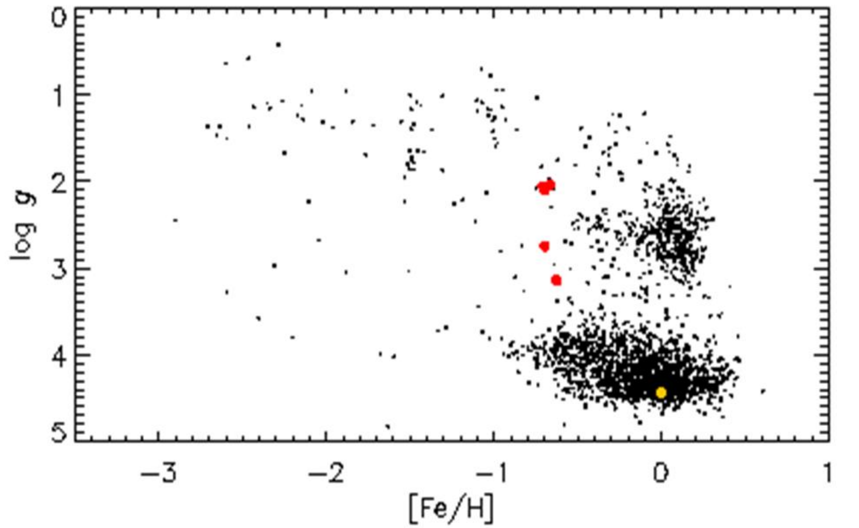
    2616 stars (UVES-U580 sample)

  - **Removed stars with some peculiar flag and/or lack of error estimates of stellar parameters, etc**

    2311 stars

INTRIGOSS: Validity of our line list for F, G, K stars





INTRIGOSS: Validity of our line list for F, G, K stars

For each i-th star

- **Appropriate normalized synthetic spectrum** (**S_i**) running ATLAS12 and SPECTRUM with GES T_{eff}, log$g$, [Fe/H], ξ, $v$sin$i$, and [X/Fe], and our line list
- **S_i** is used to obtain from the corresponding **observed** UVES-U580 spectrum a **normalized one** (**O_i**) with the same technique used for normalizing the solar spectrum

In few cases **S_i** significantly ≠ **O_i** in particular **$\lambda < 5167$Å**

region including C2 bands of the Swan system and in particular the one used to define the C2U index (Gonneau+2016)

→ ***differences in estimated and actual C content?***

[C/Fe] values derived by GES are in general less accurate than other [el/Fe]:

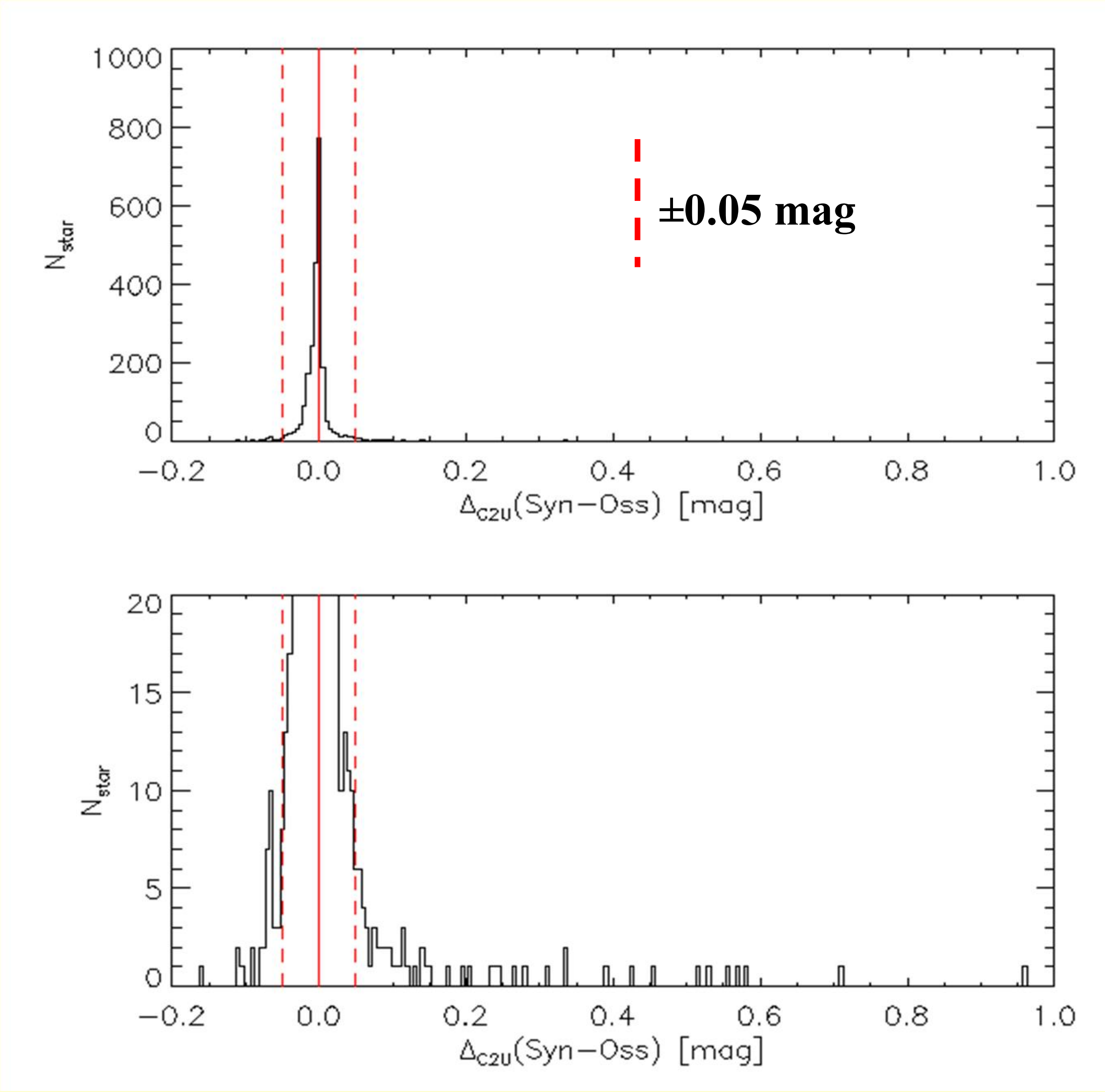
254 stars without estimated value

1572 stars on the bases of only 2 lines

478 stars on the bases of only 1 line

2212 final UVES-U580 sample

INTRIGOSS: Validity of our line list for F, G, K stars

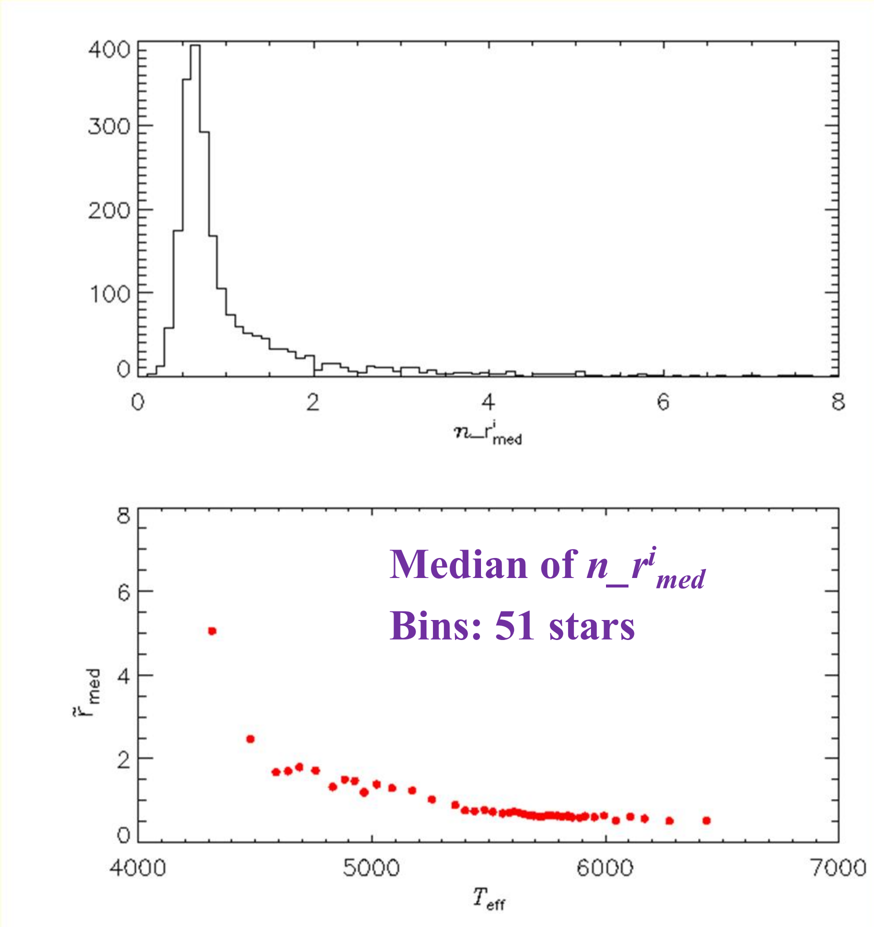


INTRIGOSS: Validity of our line list for F, G, K stars

For each i-th star

- **A figure of merit to quantitatively estimate the agreement between S_i and O_i**

$$n\_r^{i}_{med} = median\left[\left(\frac{O_i(\lambda) - S_i(\lambda)}{\Delta O_i(\lambda)}\right)^2\right]$$



$\lambda\lambda = 4800 \div 5400$ $\Delta\lambda$=0.01Å

ξ= 1 and 2 km s^{-1}

INTRIGOSS library

7840 Normalized synthetic SPectra (NSPs)

7840 surface Flux synthetic SPectra (FSPs)

T_{eff} : 3750 ÷ 7000 K at step of 250 K

log *g*: 0.5 ÷ 5.0 dex at step of 0.5 dex

[Fe/H]: -1.0 ÷ +0.5 dex at step of 0.25 dex

[α/Fe]: -0.25 ÷ +0.5 dex at step of 0.25 dex (α-el: O, Ne, Mg, Si, S,Ar, Ca,Ti)

Comparison with other Spectral Libraries

One of main application of stellar libraries is the automatic analysis of spectra in stellar surveys to derive atmospheric parameters

- Several **examples** in literature by using **different spectral libraries and codes**
- **Accuracy of atmosphere parameters depends on:**
  Reliability of the input stellar libraries
  Algorithms implemented in the numerical codes used to derive them

- It is necessary to remove the effect of the different parameter estimates codes if we want to compare only the spectral libraries

⬇

2212 UVES-U580 stars as reference stars
and assume
their GES atmosphere parameter values as reliable estimates
of the "true" stellar ones

Comparison with other Spectral Libraries

INTRIGOSS

vs

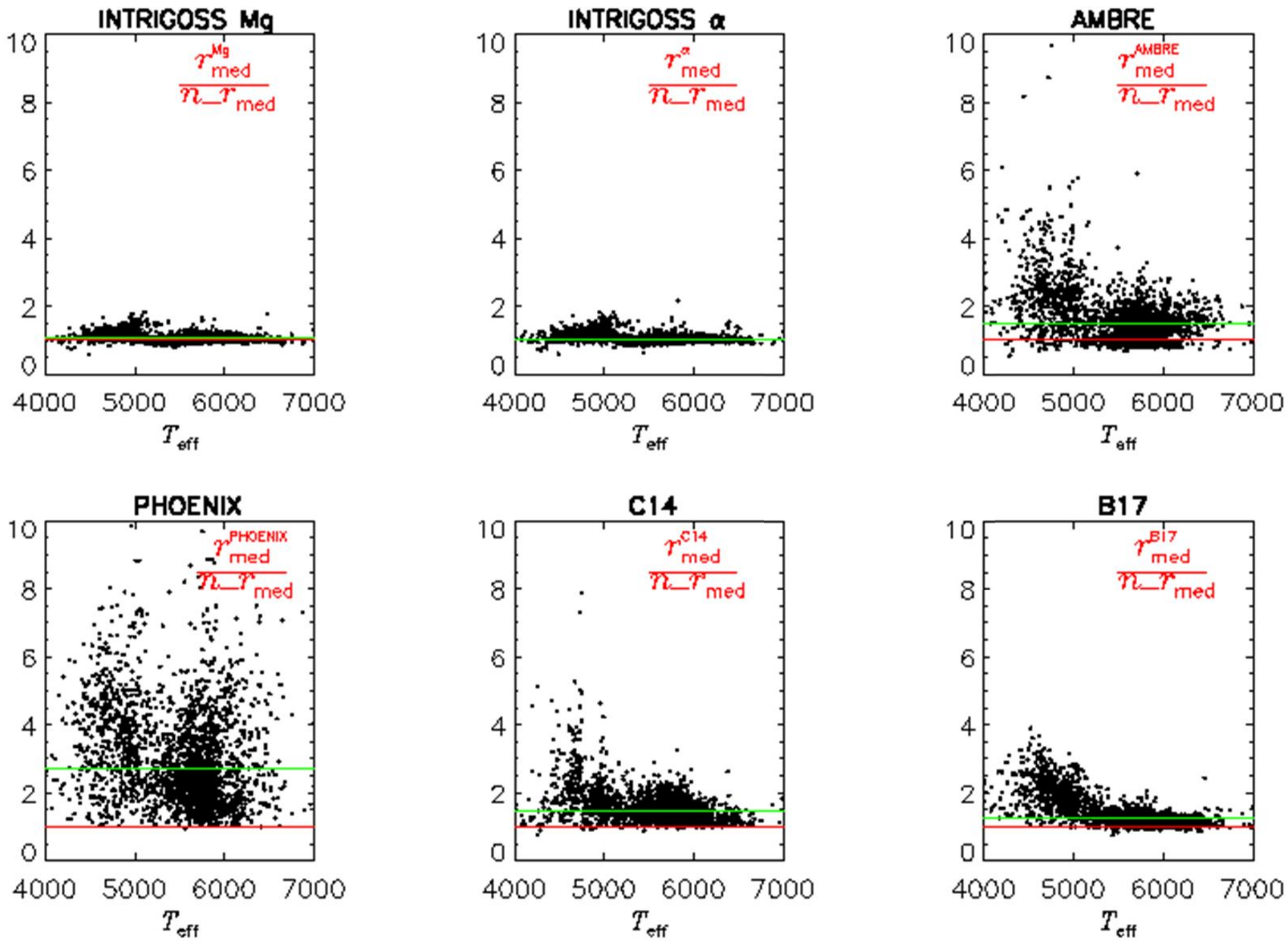
AMBRE – GES_Grid – PHOENIX – Coelho14 (C14) – Brahm+2017 (B17)

For each star we derived the corresponding synthetic spectrum

by interpolating at their atmospheric parameter values within the 6 libraries

$$\textbf{Normalized figure of merit} = \frac{r_{med}}{n\_r_{med}}$$

Comparison with other Spectral Libraries



Level=1

Median

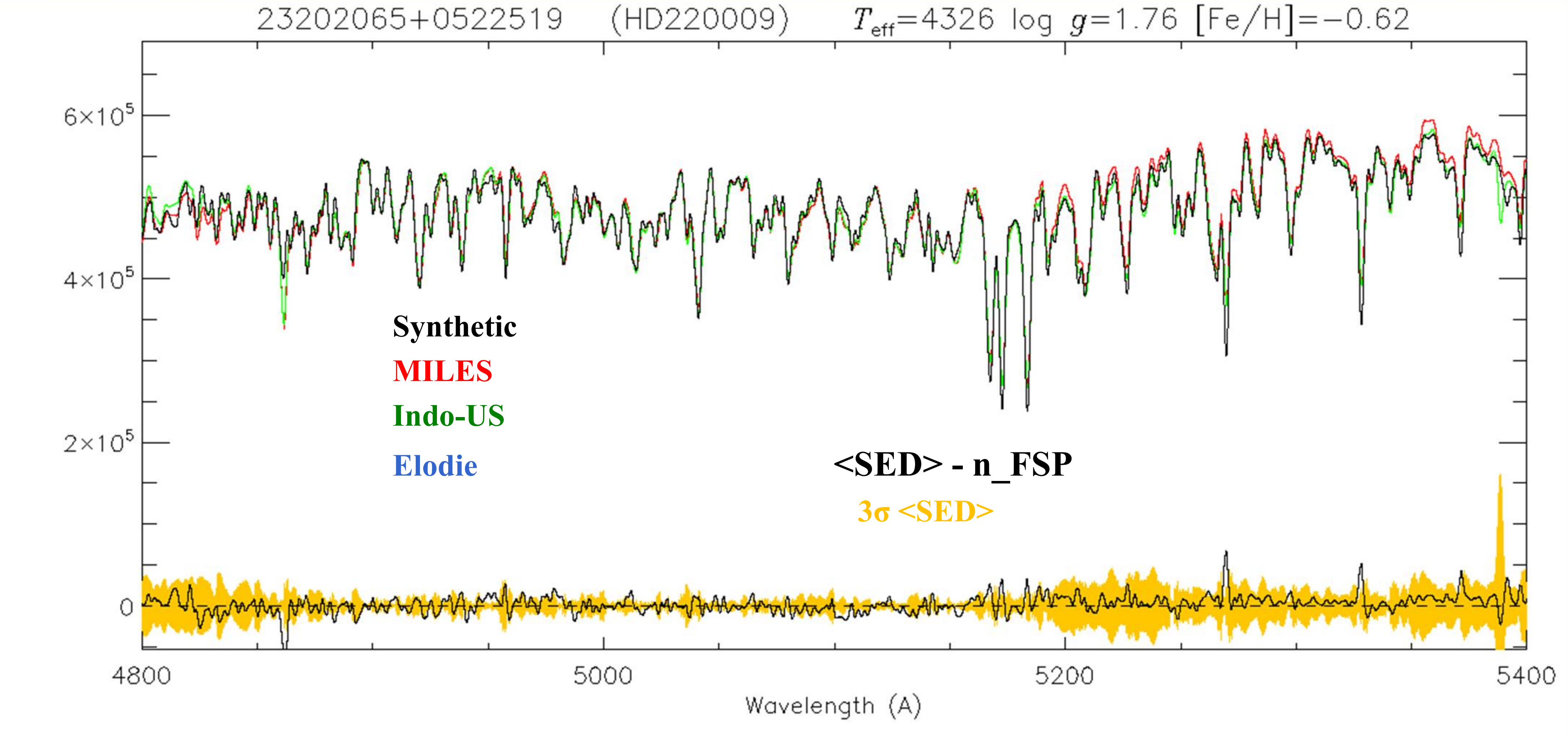
$INTRIGOSS_{Mg}$	**1.05**
$INTRIGOSS_{\alpha}$	**1.03**
AMBRE	**1.49**
GES_Grid	**1.38**
PHOENIX	**2.70**
C14	**1.47**
B17	**1.25**

INTRIGOSS: surface Flux SPectra - FSPs

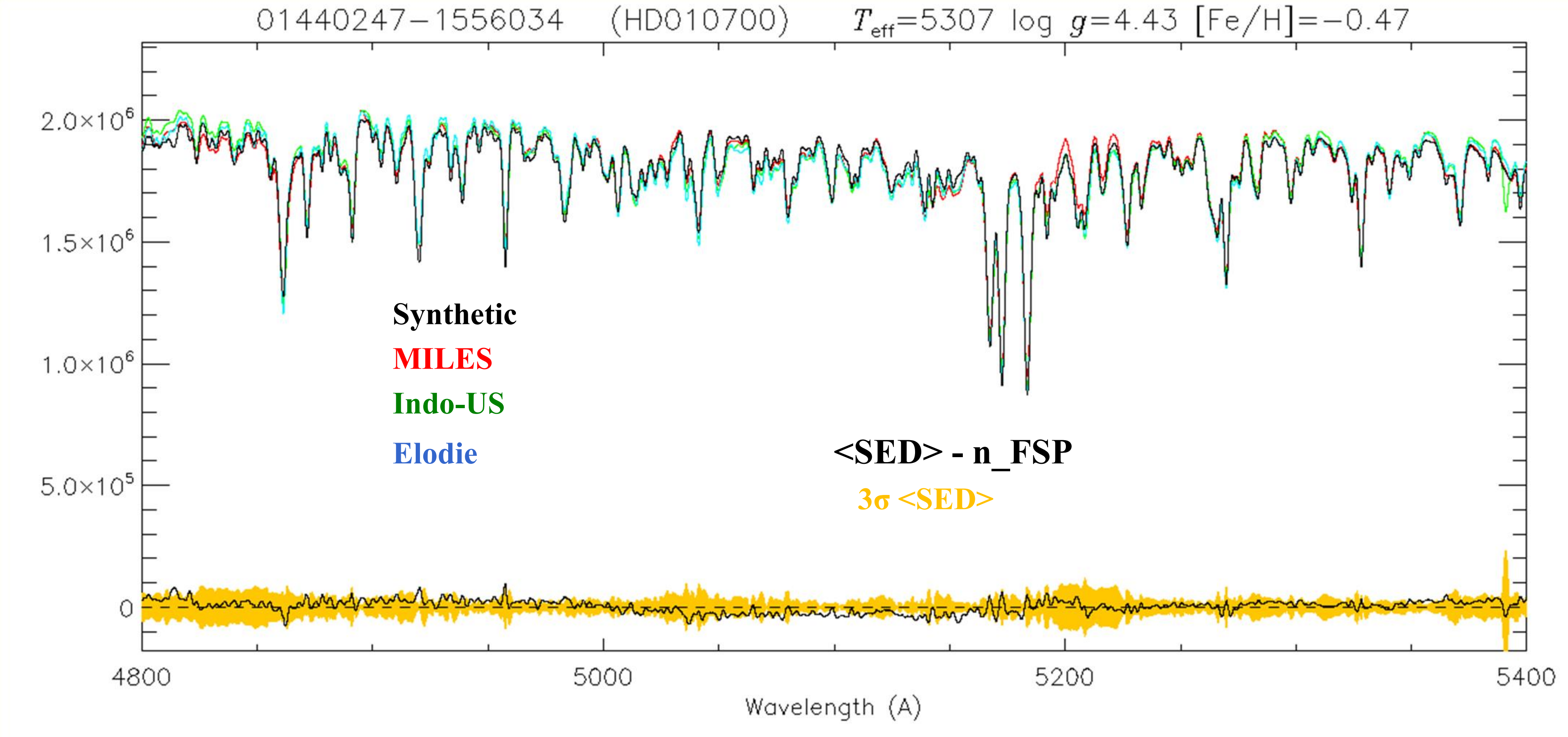
Comparison of FSPs vs observed SEDs:

Observed Flux Calibrated Spectra within ELODIE, INDO-US, MILES

About 20 stars in common with our UVES-U580 sample



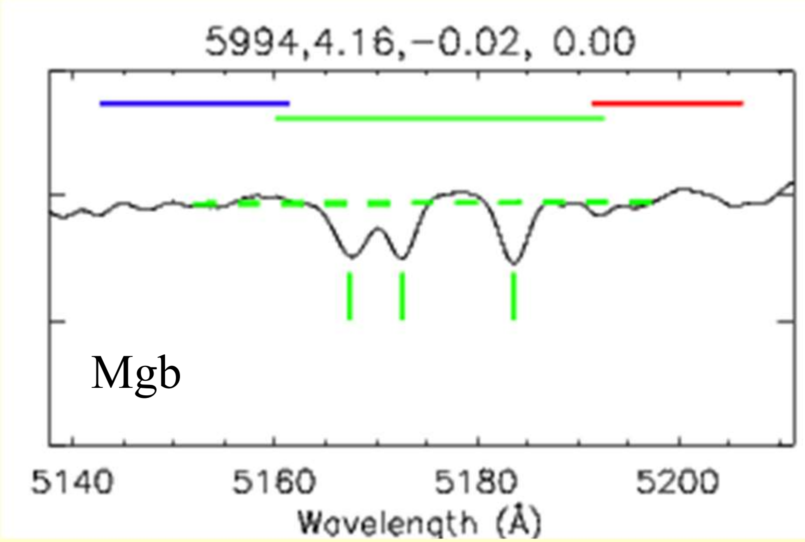
INTRIGOSS: surface Flux SPectra - FSPs



INTRIGOSS: FSPs and Spectral Indices

Different approach to check FSPs
over whole atmosphere parameter space covered INTRIGOSS
Spectral feature indices: Mg_1, Mg_2, Mgb

- **Lick/SDSS system of indices (Franchini+2010)**
  - **Lick/IDS system of indices (Gorgas+ 1993, Worthey+ 1994, etc.)**
  - ***flux calibrated Spectra***
  - **R~1800** like current surveys as SDSS or LAMOST
  - Computed by integrating the spectrum in **central passband** covering prominent features after normalization to a **pseudo-continuum** defined via two bracketing **blue** and **red side bands**
  - The three bandpasses cover in same cases, relatively large wavelength range and therefore indices are sensitive not only to the main absorption feature but also to the overall line blanketing present in the spectra.



We can use spectral indices to check *accuracy* and *completeness* of the Atomic Molecular and Predicted lines used to compute the FSPs

INTRIGOSS: FSPs and Spectral Indices

Observed UVES-U580 indices:

For each of **2212 stars** we computed **Mg_1, Mg_2, Mgb** from the observed spectrum after removing the instrumental signature by means of the corresponding *nominal* n_FSP and degrading the spectrum to R=1800

Synthetic UVES-U580 indices:

***n*_FSP** from the **nominal n_FSPs**

From the synthetic spectra obtained by interpolating the different synthetic libraries at the GES atmospheric parameters:

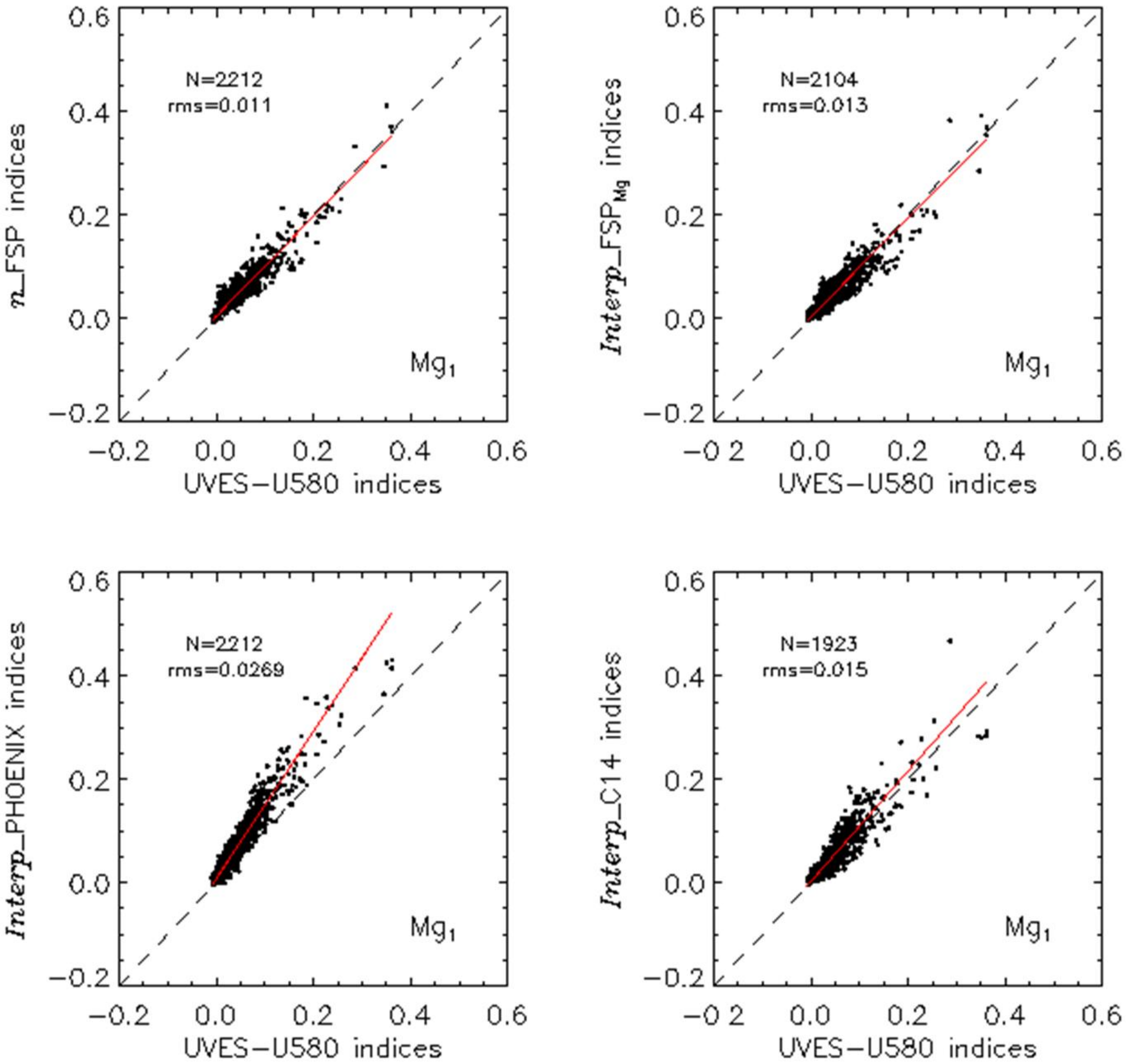
***Interp*_FSP_α** from **INTRIGOSS** FSPs when used stellar [α/Fe]

***Interp*_FSP_{Mg}** from **INTRIGOSS** FSPs when used stellar [Mg/Fe]

***Interp*_PHOENIX** from **PHOENIX** spectra

***Interp*_C14** from **C14** spectra

Synthetic vs UVES-U580 indices

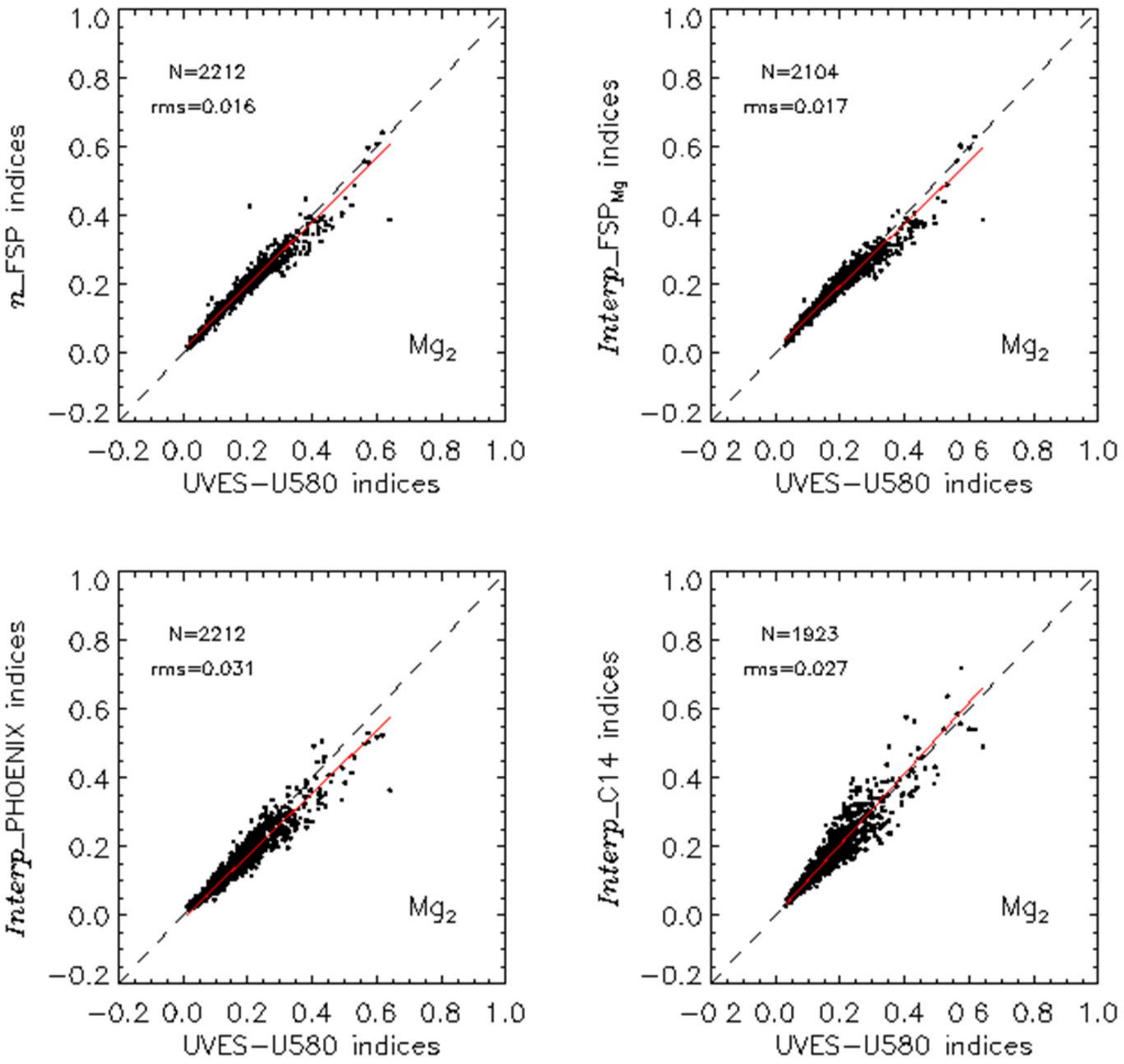


N= number of stars

rms of the deviatons from 45° line

regression lines

Synthetic vs UVES-U580 indices

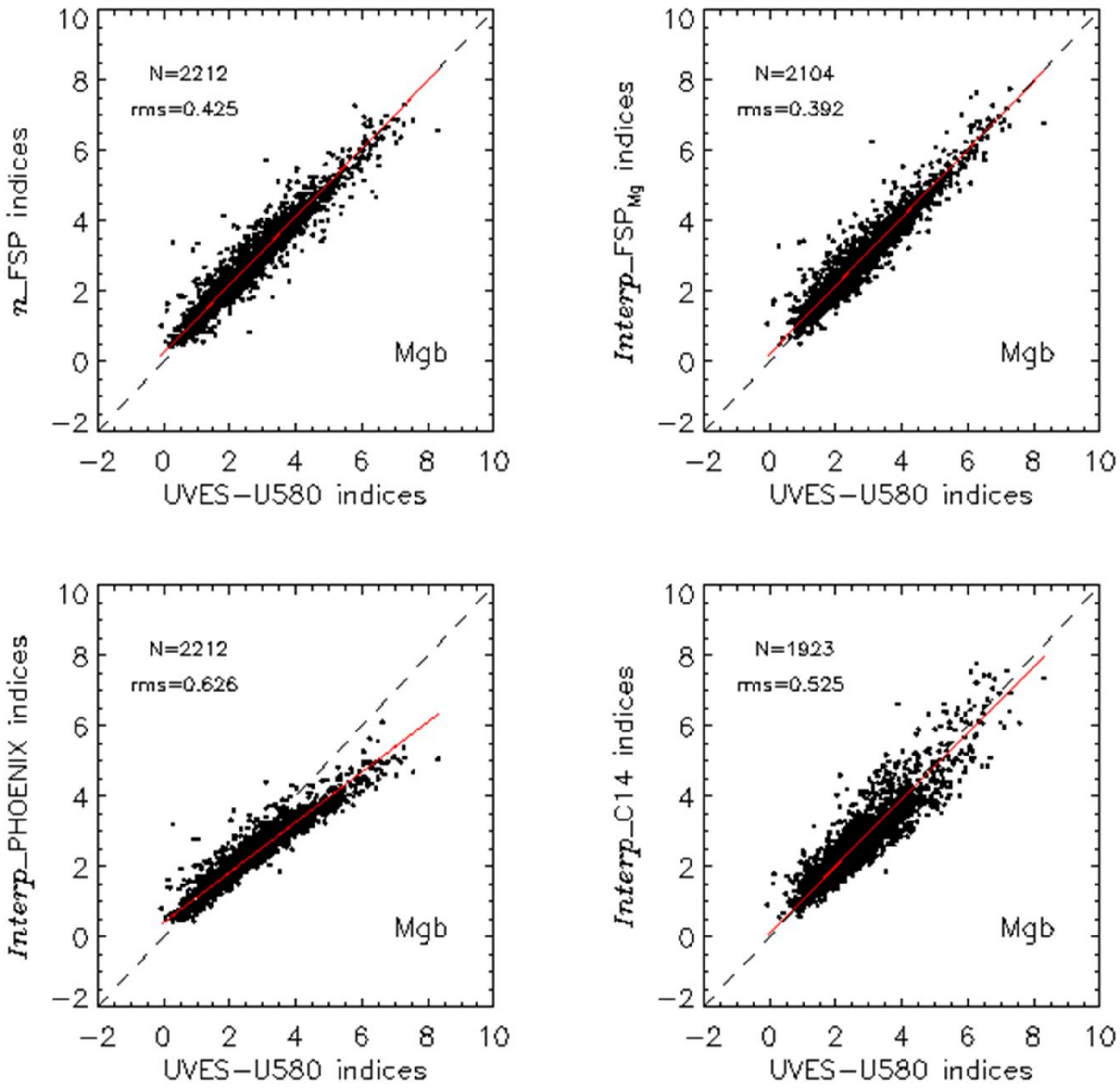


N= number of stars

rms of the deviatons from 45^{o} line

regression lines

Synthetic vs UVES-U580 indices



N= number of stars

rms of the deviatons from 45^{o} line

regression lines

Conclusions

- **INTRIGOSS** is a new HiRes spectra library covering the parameter space range of FGK stars
- ***Atmosphere*** models computed with Atlas12 in order to be able to specify the abundance of each individual element
- ***Spectra*** computed by means of SPECTRUM using the detailed *solar composition by Grevesse 2007* and different [α/Fe] ratios.
- **N**ormalized **SP**ectra (**NSP**s) and surface **F**lux **SP**ectra (**FSP**s)
- Reliable ***astrophysical gf*-values** derived by comparing synthetic prediction with very high S/N Solar Spectrum and good S/N UVES-U580 spectra of cool giants assessed by using more than 2000 stars with homogenous and accurate atmosphere parameters and detailed chemical composition
- *The validity* and greater accuracy of INTRIGOSS NSPs and FSPs with respect to other available spectral libraries was showed.
- The comparison between observational and synthetic **Mg1, Mg2, Mgb Lick/SDSS** indices indicates that the INTRIGOSS FSPs predict well the observed blanketing
- INTRIGOSS will be available on the web and will be a valuable tool for both stellar atmospheric parameters and stellar population studies

Thank you