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Gaia-ESO survey: Empirical and Synthetic Lick/SDSS indices for stellar population studies

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Outline

1. *General introduction*
2. *Spectral indices:*
 - a) Lick/IDS system
 - b) Lick-like system: Lick/SDSS
3. *Empirical Lick/SDSS library: **ELickSDSSv1***
 - a) EIM sample
 - b) FEROS sample
4. *Synthetic Lick/SDSS library: **SLickSDSSv1***
5. *New Empirical Lick/SDSS library: **ELickSDSSv2***
 - a) Gaia-ESO sample
6. *Work in progress: **SLickSDSSv2***

Stellar population study

- Stellar population study is a fundamental tool for the understanding of the physical processes involved in the formation and evolutions of galaxies
- FGK stars, due to their long lifetimes, provide information on the environment chemical enrichment at different star formation episodes
- Abundance patterns like α -enhancement give insight into the role of SNI and SNIa in the chemical enrichment of galaxies
- Out of several approaches to get information about abundance patterns in stellar populations the use of broad and narrow **spectral features or indices** is one of the most widely used
- Study of integrated spectra of stellar system requires both:
 - **Empirical libraries:** carrying on the imprints of the local properties of the solar neighbourhood cannot easily reproduce any kind of integrated spectra
 - **Synthetic libraries:** mandatory to complement empirical libraries to study systems with star formation histories different from that one of the solar neighbourhood

Spectral indices

- **Lick/IDS system** (Gorgas+ 1993, Worthey+ 1994):
 - twenty-one + 4 optical absorption features (18 particularly relevant for G type stars)
 - designed to predict index strengths in the integrated light of stellar populations of different ages and metallicities
 - till now one of the most applied and valuable for stellar studies in the Galaxy as well
 - IDS spectra not flux calibrated – $\lambda\lambda$ 4000÷6000
 - *$R\sim 630$ original Lick/IDS system* (variable with λ)
 - several uncertainties in IDS response and wave calibration
- More recently new **Lick-like system** of indices (e.g. Kim+2016) to avoid:
 - *loss information due to low resolution*
 - *possible uncertainties due to response curve*
- In particular **Lick/SDSS system** of indices (Franchini+2010)
 - $R\sim 1800$ like current surveys as SDSS or LAMOST*
 - Spectra flux calibrated*

Spectral indices

Lick/IDS spectral bands (Worthey & Ottaviani 1997)

Name	Feature Bandpass	Pseudocontinua	Units	IDS Error	Measures
01 CN 1	4142.125-4177.125	4000.125-4117.625 4244.125-4284.125	mag	0.021	CN, FeI
02 CN 2	4142.125-4177.125	4083.875-4096.375 4244.125-4284.125	mag	0.023	CN, FeI
03 Ca4227	4222.250-4234.750	4211.000-4219.750 4241.000-4251.000	Ang	0.27	CaI, FeI, FeII
04 G4300	4281.375-4316.375	4266.375-4282.625 4318.875-4335.125	Ang	0.39	CH, FeI
05 Fe4383	4369.125-4420.375	4359.125-4370.375 4442.875-4455.375	Ang	0.53	FeI, TiIII
06 Ca4455	4452.125-4474.625	4445.875-4454.625 4477.125-4492.125	Ang	0.25	CaI, FeI, NiI, TiIII, MnI, VI
07 Fe4531	4514.250-4559.250	4504.250-4514.250 4560.500-4579.250	Ang	0.42	FeI, TiI, FeII, TiIII
08 H beta	4847.875-4876.625	4827.875-4847.875 4876.625-4891.625	Ang	0.22	H, FeI
09 Fe5015	4977.750-5054.000	4946.500-4977.750 5054.000-5065.250	Ang	0.46	FeI, NiI, TiI
10 Mg 1	5069.125-5134.125	4895.125-4957.625 5301.125-5366.125	mag	0.007	MgH, FeI, NiI
11 Mg 2	5154.125-5196.625	4895.125-4957.625 5301.125-5366.125	mag	0.008	MgH, MgI, FeI
12 Mg b	5160.125-5192.625	5142.625-5161.375 5191.375-5206.375	Ang	0.23	MgI
13 Fe5270	5245.650-5285.650	5233.150-5248.150 5285.650-5318.150	Ang	0.28	FeI, CaI
14 Fe5335	5312.125-5352.125	5304.625-5315.875 5353.375-5363.375	Ang	0.26	FeI
15 Fe5406	5387.500-5415.000	5376.250-5387.500 5415.000-5425.000	Ang	0.20	FeI, CrI
16 Fe5709	5696.625- 720.375	5672.875-5696.625 5722.875-5736.625	Ang	0.18	FeI, NiI, MgI, CrI, VI
17 Fe5782	5776.625-5796.625	5765.375-5775.375 5797.875-5811.625	Ang	0.20	FeI, CrI, CuI, MgI
18 Na D	5876.875-5909.375	5862.375-5877.375 5922.125-5948.125	Ang	0.24	NaI

Lick/SDSS spectral bands (Franchini+ 2010)

Name	Feature Bandpass	Pseudocontinua	Units	IDS Error	Measures
01 Cahk	3900.000-4000.000*	3837.000-3877.000 4040.000-4080.000	Ang	0.64	CaII
02 CN 1	4142.125-4177.125	4000.125-4117.625 4244.125-4284.125	mag	0.021	CN, FeI
03 CN 2	4142.125-4177.125	4083.875-4096.375 4244.125-4284.125	mag	0.023	CN, FeI
04 Ca4227	4222.250-4234.750	4211.000-4219.750 4241.000-4251.000	Ang	0.27	CaI, FeI, FeII
05 G4300	4281.375-4316.375	4266.375-4282.625 4318.875-4335.125	Ang	0.39	CH, FeI
06 Fe4383	4369.125-4420.375	4359.125-4370.375 4442.875-4455.375	Ang	0.53	FeI, TiII
07 Ca4455	4452.125-4474.625	4445.875-4454.625 4477.125-4492.125	Ang	0.25	CaI, FeI, NiI, TiII, MnI, VI
08 Fe4531	4514.250-4559.250	4504.250-4514.250 4560.500-4579.250	Ang	0.42	FeI, TiI, FeII, TiII
9 H beta	4847.875-4876.625	4827.875-4847.875 4876.625-4891.625	Ang	0.22	H, FeI
10 Fe5015	4977.750-5054.000	4946.500-4977.750 5054.000-5065.250	Ang	0.46	FeI, NiI, TiI
11 Mg 1	5069.125-5134.125	4895.125-4957.625 5301.125-5366.125	mag	0.007	MgH, FeI, NiI
12 Mg 2	5154.125-5196.625	4895.125-4957.625 5301.125-5366.125	mag	0.008	MgH, MgI, FeI
13 Mg b	5160.125-5192.625	5142.625-5161.375 5191.375-5206.375	Ang	0.23	MgI
14 Fe5270	5245.650-5285.650	5233.150-5248.150 5285.650-5318.150	Ang	0.28	FeI, CaI
15 Fe5335	5312.125-5352.125	5304.625-5315.875 5353.375-5363.375	Ang	0.26	FeI
16 Fe5406	5387.500-5415.000	5376.250-5387.500 5415.000-5425.000	Ang	0.20	FeI, CrI
17 Fe5709	5696.625- 720.375	5672.875-5696.625 5722.875-5736.625	Ang	0.18	FeI, NiI, MgI, CrI, VI
18 Fe5782	5776.625-5796.625	5765.375-5775.375 5797.875-5811.625	Ang	0.20	FeI, CrI, CuI, MgI
19 Na D	5876.875-5909.375	5862.375-5877.375 5922.125-5948.125	Ang	0.24	NaI

[α /Fe]

sensitive group

intermediate group

quasi-independent group .

Worthey+ 1994

ELickSDSSv1: in Franchini+2010 we used spectra from the following libraries:

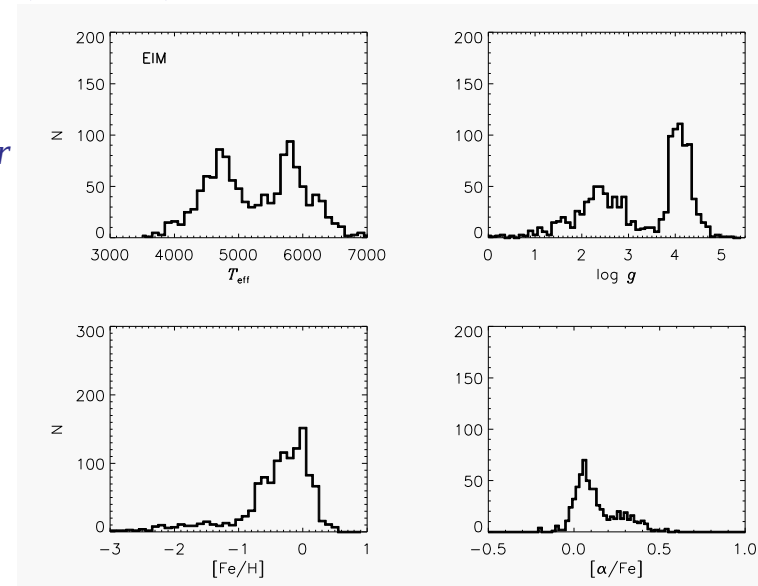
- **•ELODIE** library (Moultaka+ 2004) (4000-6800Å) $R=10000$
- **•INDO-U.S.** library (Valdes+2004) (3525-7500Å) $1\text{\AA}$ (FWHM)
- **•MILES** library (Cenarro+2007) (3525-7500Å) $2.3\text{\AA}$ (FWHM)

- We excluded:
 - Variable stars*
 - Carbon stars*
 - Spectroscopic binaries*
 - Eclipsing binaries*
 - double or*

- We obtained a **final sample of 1232 (EIM sample)**

- **Atmospheric parametes** T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, $[\alpha/\text{Fe}]$, V_r

- Lick/SDSS indices were computed from the 1232 spectra after *radial velocity correction* and *degradation* at the resolution $R=1800$



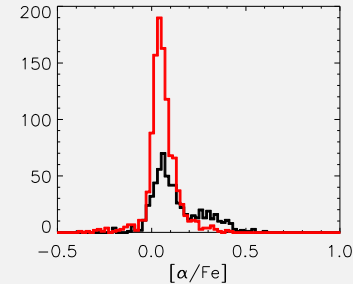
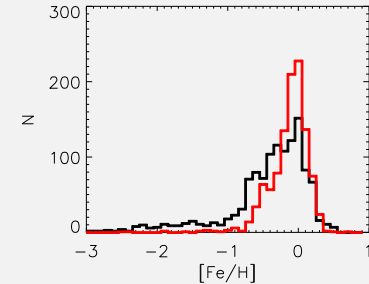
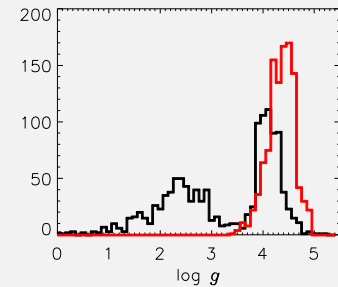
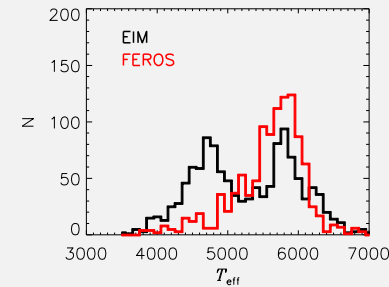
In Franchini+2014 we produced empirical library of 1085 non-supergiant FGK stars from FEROS spectra

a) **FEROS** library (Kaufer+ 1999)

$R=48000$ $\lambda\lambda$ range=360÷920nm

b) **AMBRE** project (Worley+2012): T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$

- Through the FEROS/HARPS processed data Query the **AMBRE atmospheric parameters** in the following ranges:
 $3800 < T_{\text{eff}} < 7500$ $\log g > 3.5$ $[\text{Fe}/\text{H}] > -0.5$
- 2511 spectra were corrected for V_r and degraded at 4000 km/s
- Indices were averaged in the case of multiple observations
- FEROS spectra are **not flux calibrated** → FEROS indices were used to **transform FEROS indices into the Lick/SDSS indices**

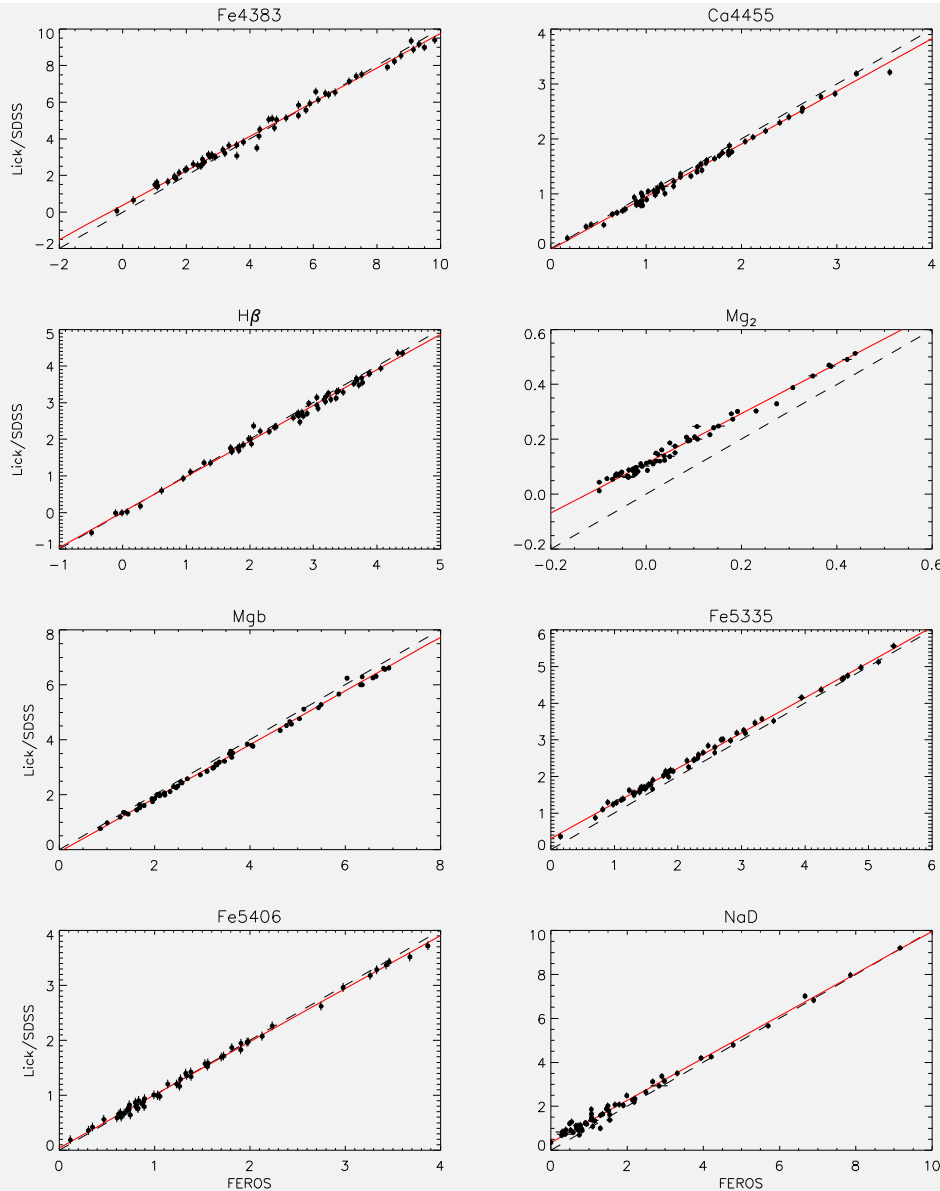


Final FEROS Lick/SDSS library: 1085 non-supergiant FGK stars

Table 1. Table of observational Lick/SDSS indices of 1085 FGK FEROS stars. The atmospheric parameters T_{eff} , $\log g$, $[M/\text{H}]$, and $[\alpha/\text{Fe}]$, and index values are averaged values in the case of more than one spectrum (see text). All the 19 Lick/SDSS indices are available in the online version.

Name	N_{sp}	T_{eff} (K)	$\sigma_{T_{\text{eff}}}$ (K)	$\log g$	$\sigma_{\log g}$ (dex)	$[M/\text{H}]$	$\sigma_{[M/\text{H}]}$ (dex)	$[\alpha/\text{Fe}]$	$\sigma_{[\alpha/\text{Fe}]}$ (dex)	CaHK (Å)	σ_{CaHK} (Å)	CN ₁ (mag)	σ_{CN_1} (mag)
HD 224725	1	6319	38	4.98	0.16	-0.38	0.08	0.07	0.05	8.901	—	-0.044	—
HD 224810	1	5738	12	4.30	0.10	0.06	0.04	0.02	0.02	2.919	—	-0.027	—
HD 224828	1	5598	12	4.45	0.04	-0.47	0.02	0.16	0.01	7.591	—	-0.084	—
HIP 112	3	3970	7	4.84	0.01	0.27	0.03	-0.30	0.01	13.000	3.693	—	—

ELickSDSSv1 -- Empirical Lick/SDSS library



Trasformazione di FEROS indices in the Lick/SDSS system

By merging Lick/SDSS spectral indices of
EIM sample + **FEROS** sample
we have obtained
ELickSDSSv1 library (2165 FGK stars)

SLickSDSSv1: A synthetic library computed starting from HiRes absolute flux-calibrated synthetic spectra degraded at R=1800 (like SDSS)

- **Two grids** of HiRes synthetic spectra:
 - $[\alpha / \text{Fe}] = 0.0$ (**Solar Scaled, SSA**) and $[\alpha / \text{Fe}] = +0.4$ (**No Solar Scaled, NSSA**)
- starting from Kurucz atmosphere models (ATLAS9) computed with **solar and α -enhanced ODF's** by Castelli (2003)
- using SPECTRUM V.2.75 (Gray and Corbally 1994)

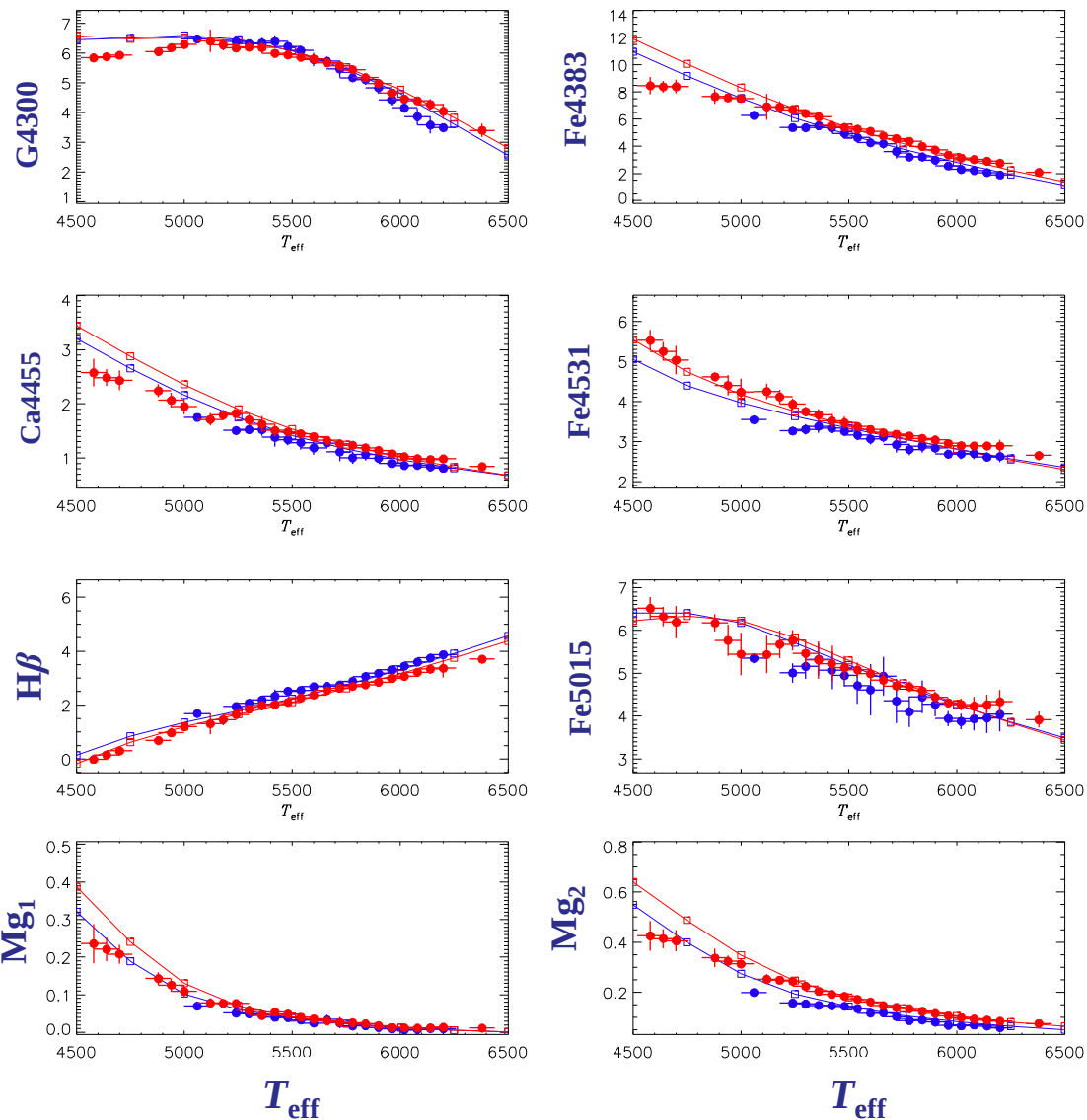
T_{eff} : 3500-7000 K (250 K step)

$\log g$: 0.5- 5.0 dex (0.5 dex step)

$[\text{Fe}/\text{H}] = -2.5, -2.0, -1.5, -1.0, -0.5, 0.0, +0.2, +0.5$ (**NSSA**)

$[\text{Fe}/\text{H}] = -2.5, -2.0, -1.5, -1.0, -0.5, 0.0, +0.2, +0.5$ (**SSA**)

Comparison of observations with SLickSDSSv1 library



FEROS Lick/SDSS indices (points)

rebinned (120 K)

$-0.2 < [\text{Fe}/\text{H}] < 0.2$ $-0.2 < [\alpha/\text{Fe}] < 0.2$

Dwarfs $\log g \sim 4.5$

Subgiants $\log g \sim 4.0$

Synthetic Lick/SDSS indices (lines) :

$[\text{Fe}/\text{H}] = 0$ $[\alpha/\text{Fe}] = 0$

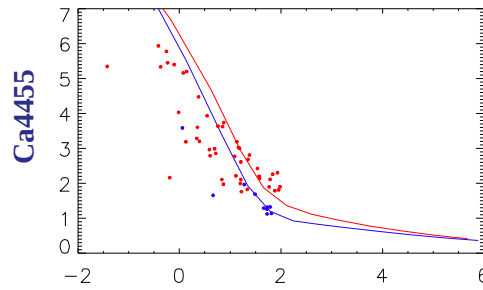
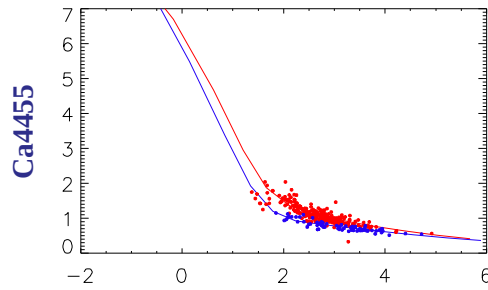
$\log g = 4.5$ —

$\log g = 4.0$ —

In general predictions agree very well with observations

but for $T_{\text{eff}} \leq 5250 \text{ K}$

Comparison of observation with SLickSDSSv1 library



FEROS Lick/SDSS indices (points)

rebinned (120 K)

$-0.2 < [\text{Fe}/\text{H}] < 0.2$ $-0.2 < [\alpha/\text{Fe}] < 0.2$

Dwarfs $\log g \sim 4.5$

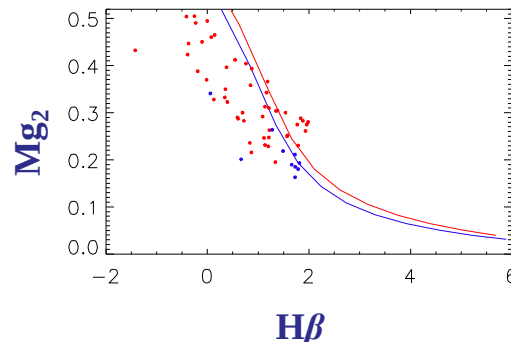
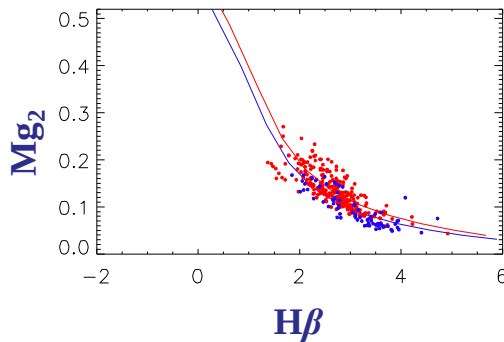
Subgiants $\log g \sim 4.0$

Synthetic Lick/SDSS indices (lines) :

$[\text{Fe}/\text{H}] = 0$ $[\alpha/\text{Fe}] = 0$

$\log g = 4.5$ —

$\log g = 4.0$ —



$T_{\text{eff}} > 5250$

$T_{\text{eff}} < 5250$

*Inadequacies or incorrect assumptions in the model and/or synthetic spectra to derive **SLickSDSSv1** library for cool dwarfs ($T_{\text{eff}} < 5250$ K)*

ELickSDSSv2: Empirical library of Lick/SDSS spectral indices built with: ELickSDSSv1 + 2313 FGK stars from the Gaia-ESO Spectroscopic survey (GES)

Gaia-ESO survey: with FLAMES $\sim 10^5$ stars in MW in the field and in clusters

- **iDR4 most recent release contains:**
 - Teff,logg, [Fe/H],microturbulence,
 - Individual element abundance [X/Fe]
 - Radial and rotational velocities
 - Stacked spectra
- **SQL search to download parameters and spectra with the following criteria for FGK stars:**
 - $3500 \leq T_{\text{eff}} \leq 7000\text{K}$
 - $0.25 \leq \log g \leq 5.25\text{dex}$
 - UVES-U580 setup centered at 580 nm (476.8-580.1 and 582.2-683.0 nm $R \sim 47000$)
 - SNR > 3
 - > 2618 stars
- Removed stars with some peculiar flag and/or lack of error estimates of stellar parameters
 - > **2313 stars Final Sample**

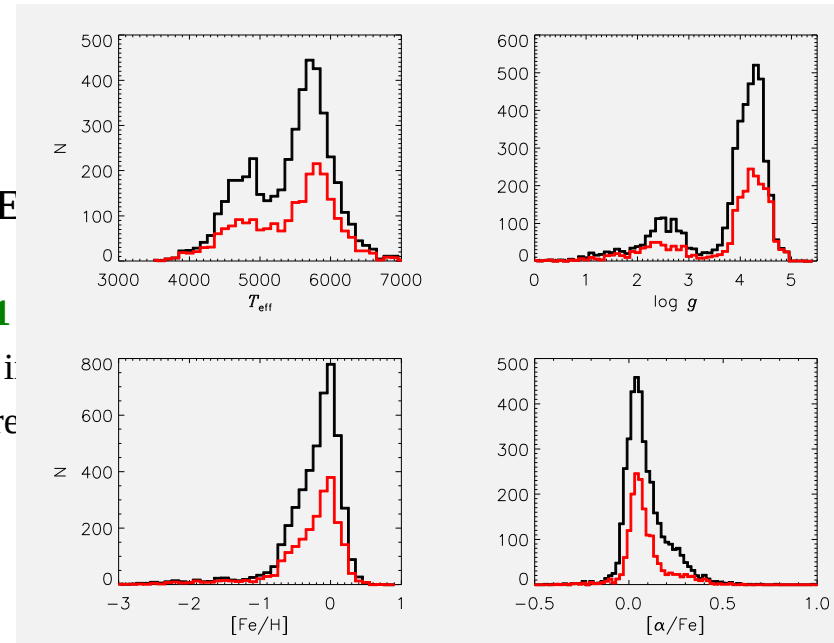
- Due to U580 the wavelength range, we could compute only the following **Lick/SDSS** indices: $H\beta$, $Fe5015$, Mg_1 , Mg_2 , Mg_b , $Fe5270$, $Fe5406$, $Fe5709$, NaD

- Before computing spectral indices the 2313 GES spectra were:
 - corrected for the iDR4 radial velocities
 - degraded to the resolution $R=1800$

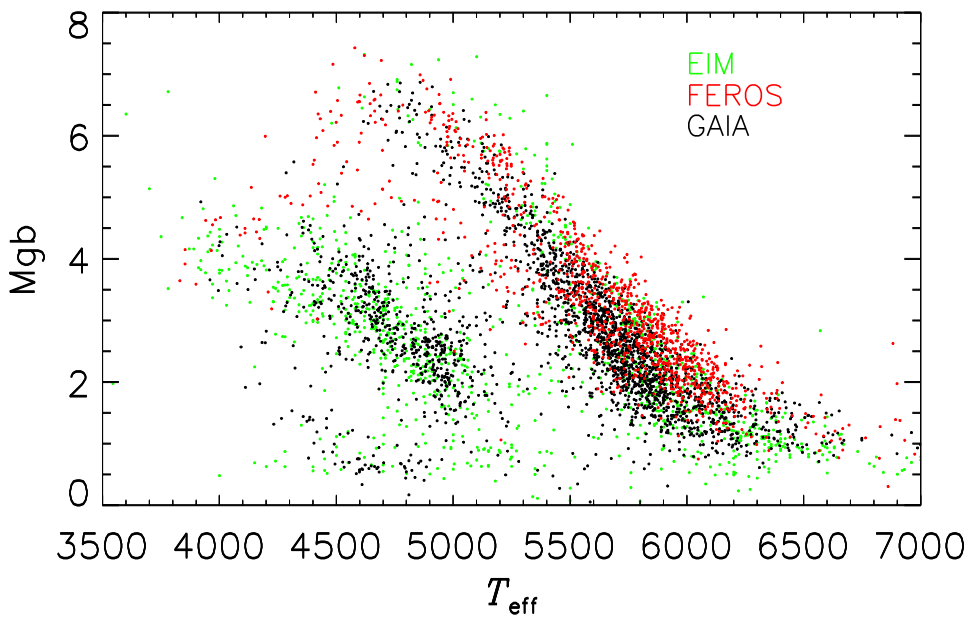
- GES spectra are not flux calibrated so the obtained GE indices are not reliable. To include them into the Lick/SDSS system:

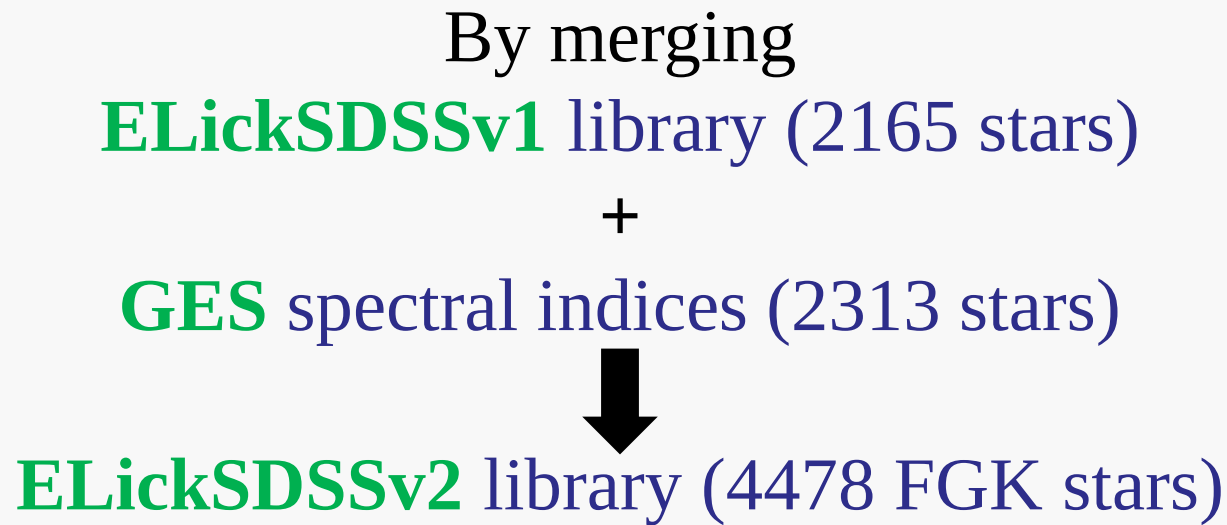
- select stars in common between GES and **ELickSDSSv1**
 - compare uncalibrated GES indices with the index values in the Lick/SDSS system
 - compute transformation coefficients assuming linear regression

- Improvement in Stellar parameter coverage with respect to **ELickSDSSv1**



ELickSDSSv2 library





➤ 12 lookup tables in the parameter ranges for which **ELickSDSSv2** contains enough entries:

- We divide indices in two groups:

- a) A group containing *indices almost independent* of $[\alpha/\text{Fe}]$:

H β , Fe5015, Fe5270, Fe5406, Fe5709

→ One lookup table for each index

- b) A group containing *indices dependent* on $[\alpha/\text{Fe}]$:

Mg₁, Mg₂, Mgb

→ two lookup tables for each index to differentiate

Solar Scaled ($[\alpha/\text{Fe}] \leq 0.05$) and α -enhanced stars ($[\alpha/\text{Fe}] \geq 0.15$)

- Each lookup table contains:

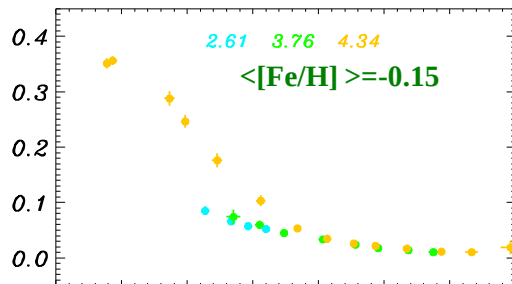
$\langle [\text{Fe}/\text{H}] \rangle$ $\sigma_{[\text{Fe}/\text{H}]}$ $\langle \log g \rangle$ $\sigma_{\log g}$ $\langle T_{\text{eff}} \rangle$ $\sigma_{T_{\text{eff}}}$ $\langle \text{index} \rangle$ σ_{index} Np

Table 1. Lookup table of $H\beta$ ELickSDSSv2 index. The $\langle [Fe/H] \rangle$, $\langle \log g \rangle$, $\langle T_{\text{eff}} \rangle$, and $\langle H\beta \rangle$ columns contain the mean values of the N_p points in each bin (see text). All the lookup tables are available in the on-line version of the paper.

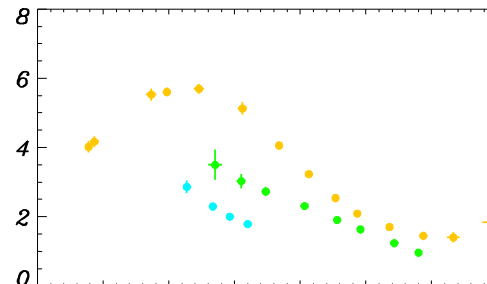
$\langle [Fe/H] \rangle$ dex	$\sigma_{[Fe/H]}$ dex	$\langle \log g \rangle$ dex	$\sigma_{\log g}$ dex	$\langle T_{\text{eff}} \rangle$ K	$\sigma_{T_{\text{eff}}}$ K	$\langle H\beta \rangle$	$\sigma_{H\beta}$	N_p
-0.657	0.006	1.459	0.032	4339	20	1.034	0.030	4
				4412	28	1.008	0.070	9
				4506	30	0.977	0.092	7
				4652	44	1.196	0.167	4
				4438	34	1.028	0.091	7
				4524	27	1.110	0.041	8
				4660	30	1.288	0.077	7
				4786	32	1.452	0.074	8
		1.999	0.027	4893	36	1.551	0.058	5
				4404	14	1.037	0.065	5
				4486	46	1.165	0.084	5
				4690	28	1.178	0.050	8
				4786	23	1.274	0.054	12
				4900	25	1.441	0.047	10
				5035	30	1.574	0.072	7
		2.447	0.028	5055	26	1.542	0.075	6
				5101	26	1.662	0.096	5
				5319	59	1.925	0.158	4
				5419	26	2.034	0.162	6
				5513	33	2.288	0.196	5
				5652	52	2.650	0.106	4
				5794	40	2.973	0.091	5
				5881	34	3.178	0.054	5
		3.570	0.027	5142	15	1.384	0.163	4
				5327	19	1.893	0.142	10
				5430	16	2.043	0.070	24
		4.024	0.008					

ELickSDSSv2 library

Mg1



Mgb



Mean index values vs T_{eff} for different bins in $\log g$:
indices $[\alpha/\text{Fe}]$ dependent

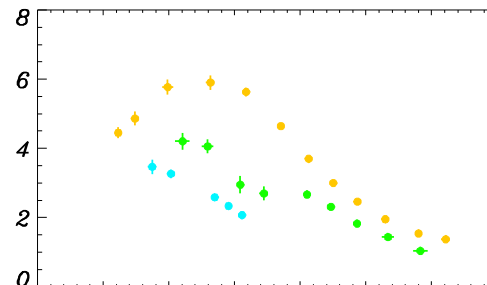
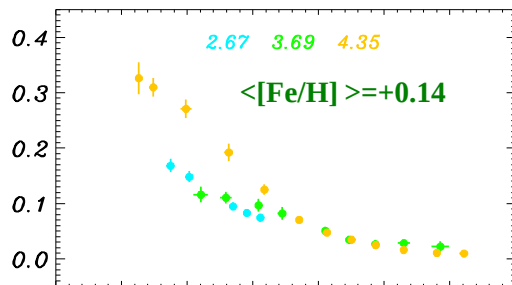
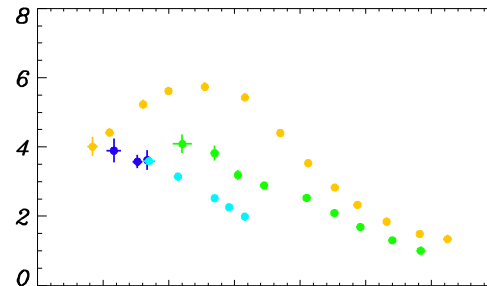
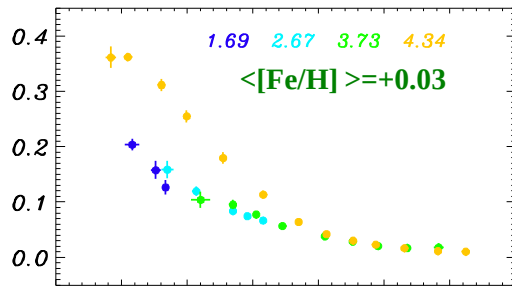
α -low group $[\alpha/\text{Fe}] \leq 0.05$ 1742 stars

Bins

$[\text{Fe}/\text{H}]$ 0.5 dex centered every 0.25 dex

$\log g$ 1.0 dex

T_{eff} 250 K centered every 125 K



3500 T_{eff}

7000

T_{eff}

7000

ELickSDSSv2 library

Mean index values vs T_{eff} for different bins in $\log g$:
indices $[\alpha/\text{Fe}]$ dependent

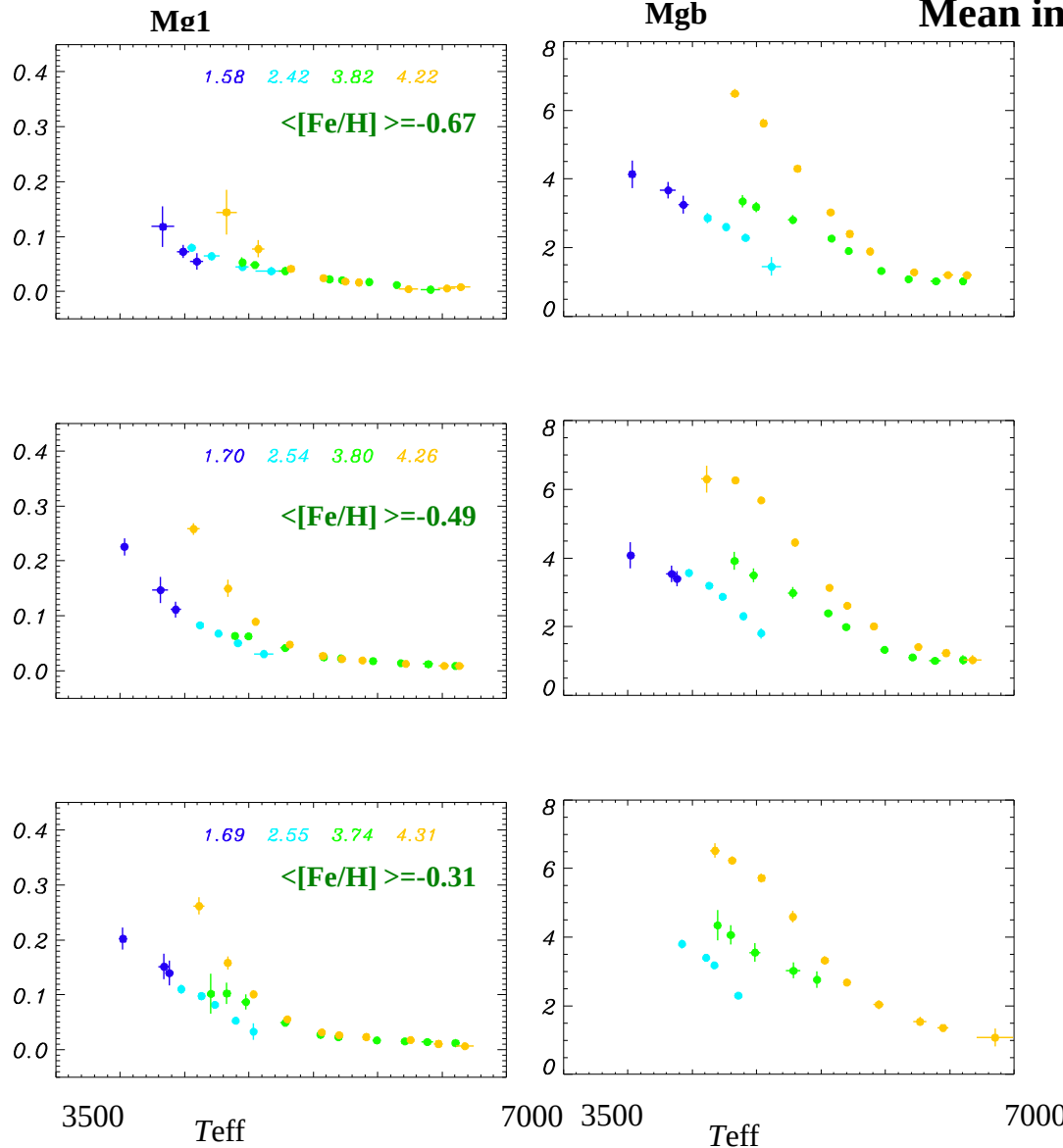
α -high group $[\alpha/\text{Fe}] \geq 0.15$ 939 stars

Bins

$[\text{Fe}/\text{H}]$ 0.5 dex centered every 0.25 dex

$\log g$ 1.0 dex

T_{eff} 250 K centered every 125 K



Synthetic Lick/SDSS library v2.0

New synthetic Lick/SDSS library to complement **ELickSDSSv2**

- Kurucz atmosphere models computed with **ATLAS12**

New molecular opacities and in particular new release of H₂O line list (Kurucz from Partridge & Schwenke)

several chemical compositions:

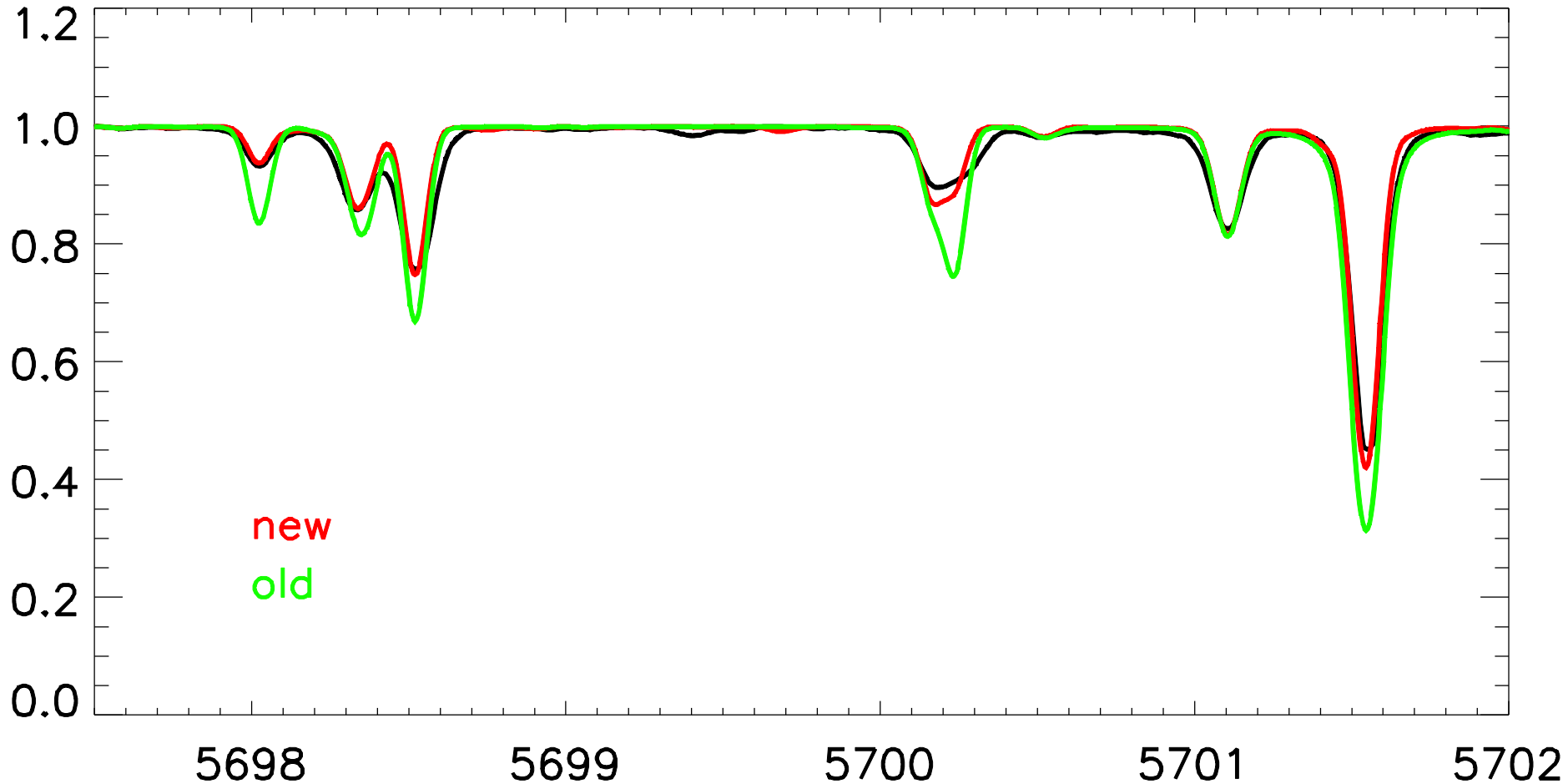
- [Fe/H] from +0.5 to -3.0 with $\Delta[\text{Fe}/\text{H}]=0.25$
- [α /Fe] from +1.0 to -0.5 with $\Delta[\alpha/\text{Fe}]=0.25$
- **Individual α -element abundances** (i.e. $[\text{Mg}/\text{Fe}] \neq [\text{Si}/\text{Fe}] \neq [\text{Ca}/\text{Fe}] \neq [\text{Ti}/\text{Fe}] \neq \dots$)

- HiRes synthetic spectra computed with **SPECTRUM V.2.76e**

- **Refined and more complete atomic and molecular line list** characterized by the use of **empirical log *g_f*** values for the strongest lines derived from comparison between the solar synthetic and observed HiRes spectra

SLickSDSSv2: Preliminary results

HD 175607 HARPS R=115,000

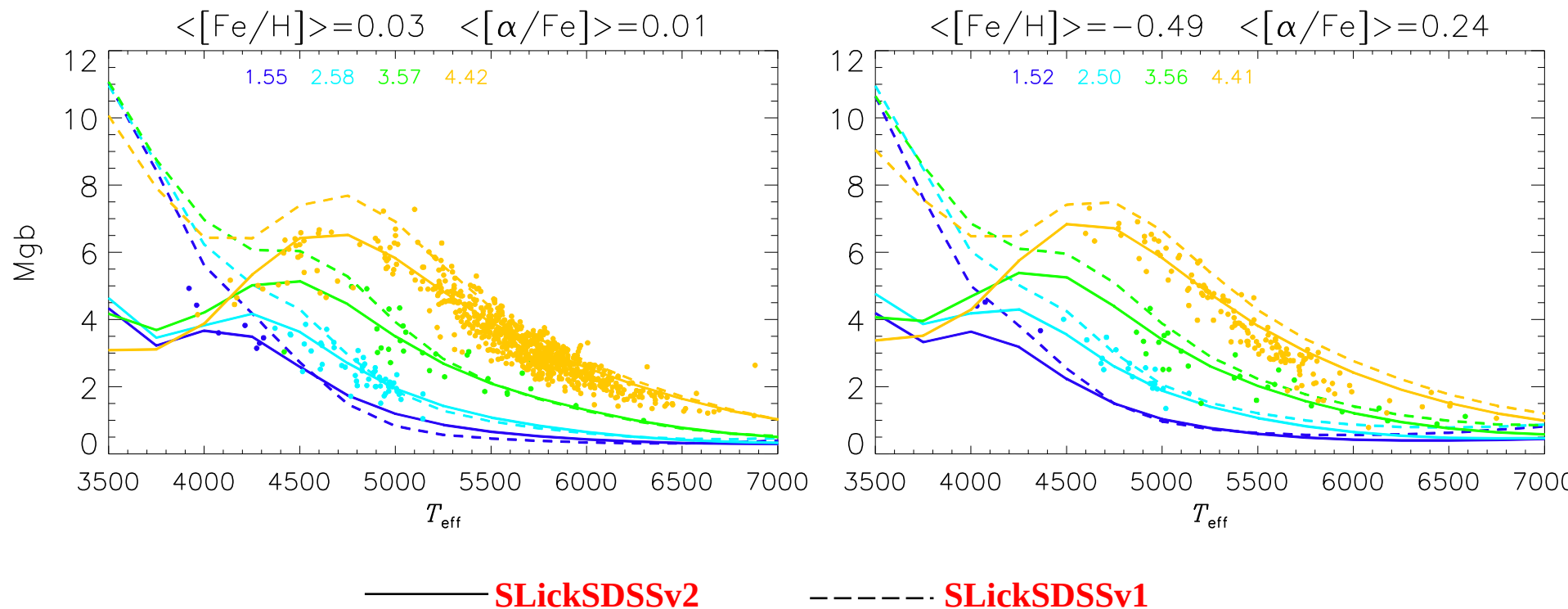


SLickSDSSv2: Preliminary results

Comparison between observations and predictions of new Synthetic Lick/SDSS library

α -low group $[\alpha/\text{Fe}] \leq 0.05$

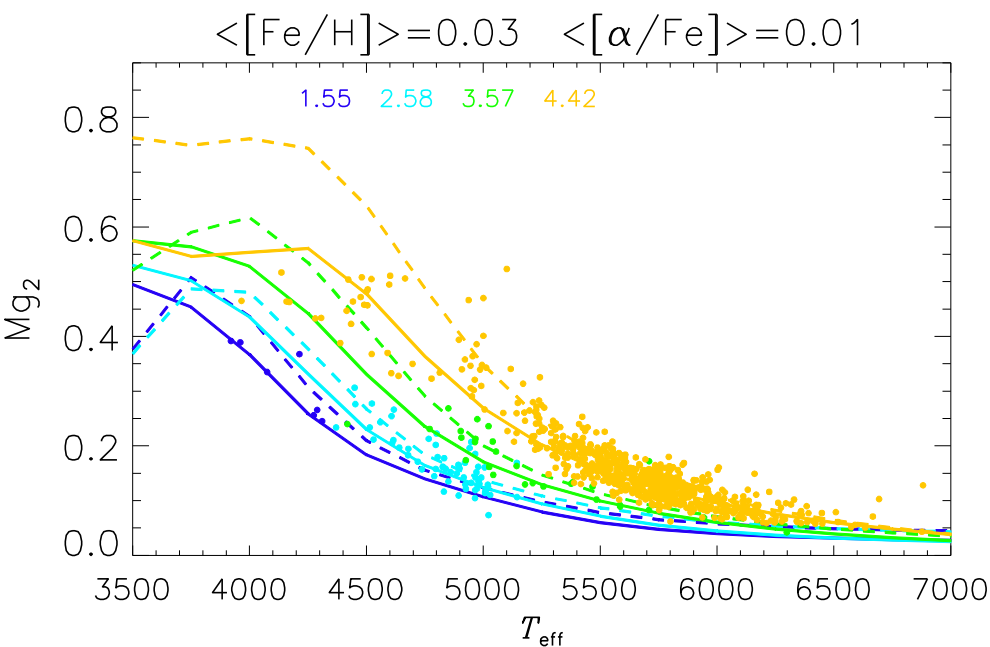
α -high group $[\alpha/\text{Fe}] \geq 0.15$



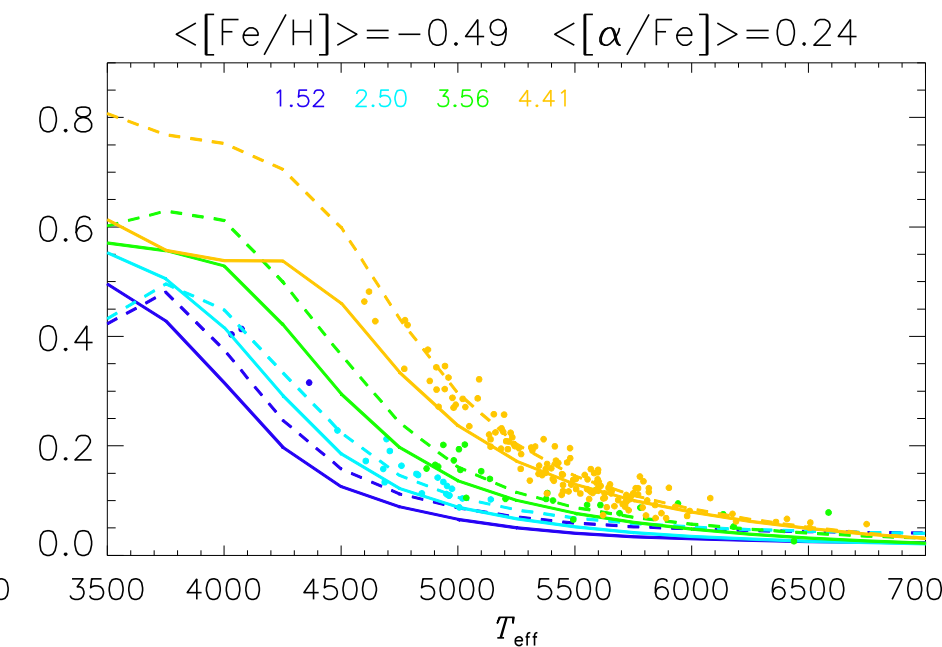
SLickSDSSv2: Preliminary results

Comparison between observations and predictions of new Synthetic Lick/SDSS library

α -low group $[\alpha/\text{Fe}] \leq 0.05$



α -high group $[\alpha/\text{Fe}] \geq 0.15$



— SLickSDSSv2

- - - SLickSDSSv1

Conclusions and work in progress

- We have computed **ELickSDSSv2**, a new empirical Lick/SDSS library, by adding 2313 FGK GES stars to **ELickSDSSv1**

It consists of:

- Lick/SDSS indices: $H\beta$, Fe5015, Mg_1 , Mg_2 , Mgb, Fe5270, Fe5406, Fe5709, NaD of 4478 stars
 - 12 lookup tables containing mean and standard deviations of index values and the corresponding mean and standard deviation of $[Fe/H]$, $\log g$, and T_{eff} , to be used in computing integrated-light characteristics of stellar systems
- We are working on **SLickSDSSv2**, a new theoretical Lick/SDSS library to complement **ELickSDSSv2**:
 - $[Fe/H]$ from +0.5 to -3.0 with $\Delta[Fe/H]=0.25$
 - $[\alpha/Fe]$ from +1.0 to -0.5 with $\Delta[\alpha/Fe]=0.25$
 - Individual α -element abundances (i.e. $[Mg/Fe] \neq [Si/Fe] \neq [Ca/Fe] \neq [Ti/Fe] \neq \dots$)
- Preliminary results shows that **SLickSDSSv2** predictions reproduce well the observed indices of cool dwarfs also at low temperatures where the previous version, **SLickSDSSv1**, failed.
 - It will be a useful tool to study stellar system with star formation histories different from the solar neighbourhood

Thank you