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<b>Authors</b>	FRANCHINI, Mariagrazia, MOROSSI, Carlo, DI MARCANTONIO, Paolo, Chavez, M., GES Builders
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# *Gaia-ESO survey: Empirical and Synthetic Lick/SDSS indices for stellar population studies*

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

M. Chavez  
INAOE, Mexico

and ...

GES Builders

# 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  $\alpha$ -enhancement give insight into the role of SnI and SnII 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~630 original Lick/IDS system* (variable with  $\lambda$ )
  - 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~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, TiII
06 Ca4455	4452.125-4474.625	4445.875-4454.625 4477.125-4492.125	Ang	0.25	CaI, FeI, NiI, TiII, MnI, VI
07 Fe4531	4514.250-4559.250	4504.250-4514.250 4560.500-4579.250	Ang	0.42	FeI, TiI, FeII, TiII
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

[ $\alpha$ /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*

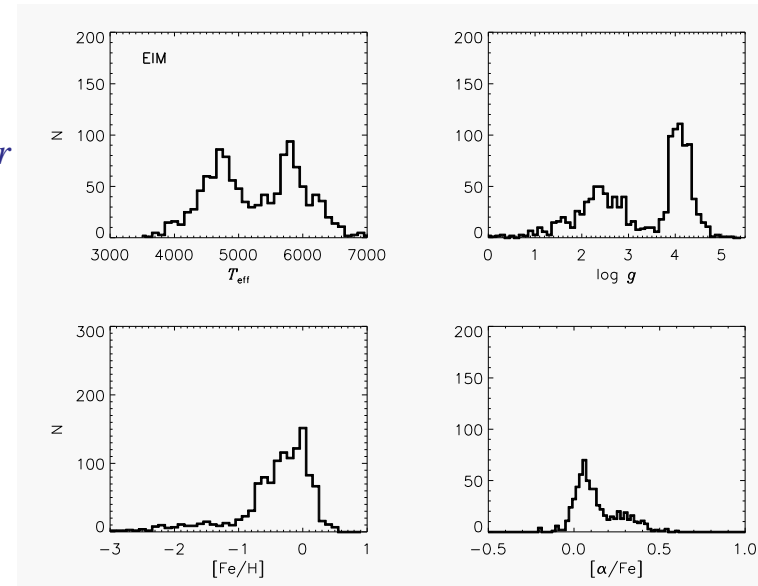
*Spectroscopic binaries*  
*Eclipsing binaries*

*double or*

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

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

- 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): $T_{\text{eff}}$ , $\log g$ , $[\text{Fe}/\text{H}]$

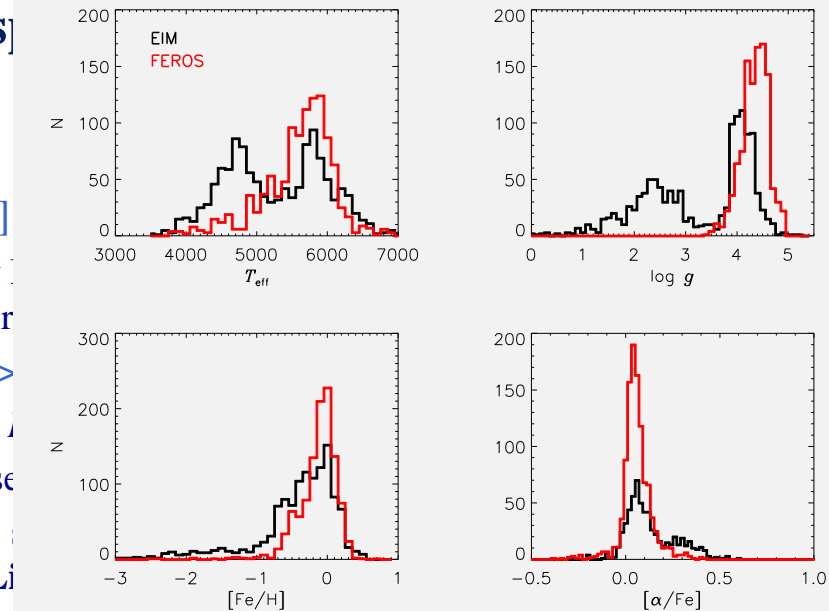
- Through the FEROS/HARPS processed data Query AMBRE *atmospheric parameters* in the following range

$3800 < T_{\text{eff}} < 7500$   $\log g > 3.5$   $[\text{Fe}/\text{H}] >$

- 2511 spectra were corrected for  $V_r$  and degraded at  $0.5 \text{ \AA}$

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**

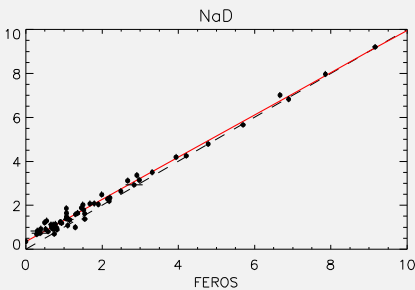
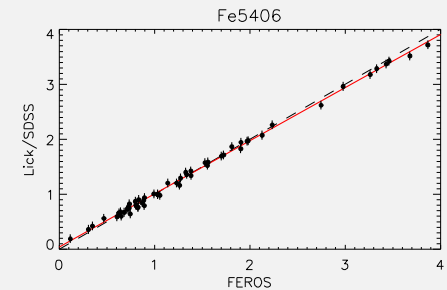
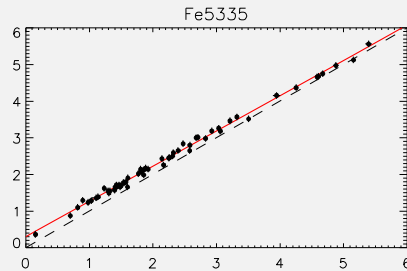
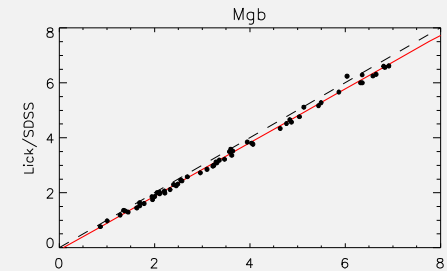
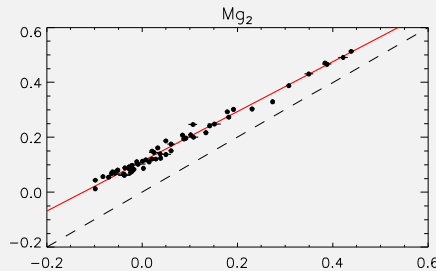
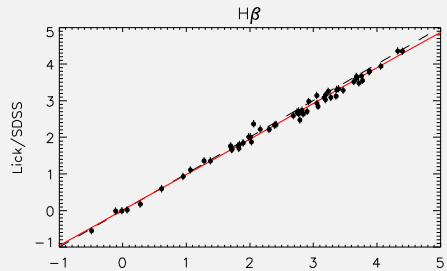
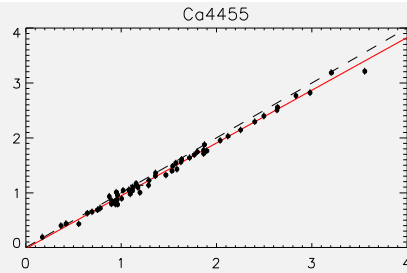
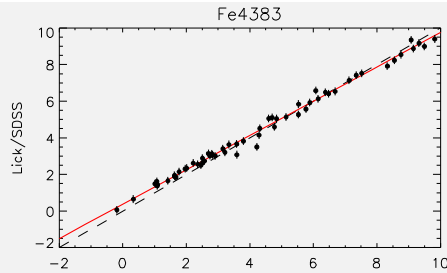


## Final FEROS Lick/SDSS library: 1085 non-supergiant FGK stars

**Table 1.** Table of observational Lick/SDSS indices of 1085 FGK FEROS stars. The atmospheric parameters  $T_{\text{eff}}$ ,  $\log g$ ,  $[M/H]$ , 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	$N_{\text{sp}}$	$T_{\text{eff}}$ (K)	$\sigma_{T_{\text{eff}}}$ (K)	$\log g$	$\sigma_{\log g}$ (dex)	$[M/H]$	$\sigma_{[M/H]}$ (dex)	$[\alpha/\text{Fe}]$	$\sigma_{[\alpha/\text{Fe}]}$ (dex)	CaHK (Å)	$\sigma_{\text{CaHK}}$ (Å)	CN <sub>1</sub> (mag)	$\sigma_{\text{CN}_1}$ (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 indici 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  $\alpha$ -enhanced ODF's** by Castelli (2003)
- using SPECTRUM V.2.75 (Gray and Corbally 1994)

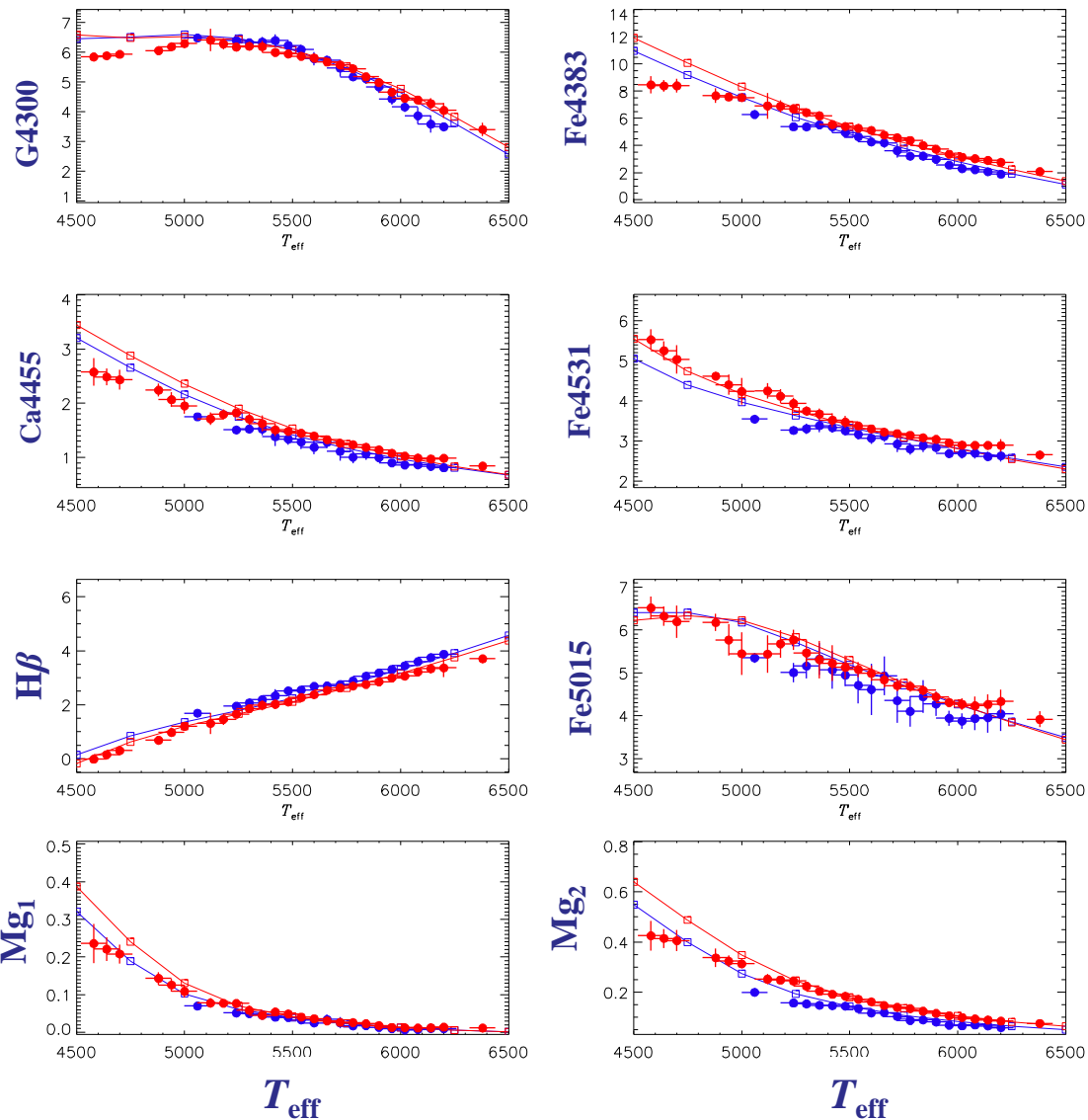
$T_{\text{eff}}$  : 3500-7000 K (250 K step)

$\log g$ : 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) :**

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

**$\log g = 4.5$  —**

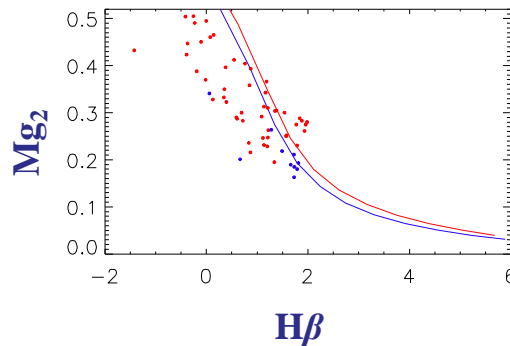
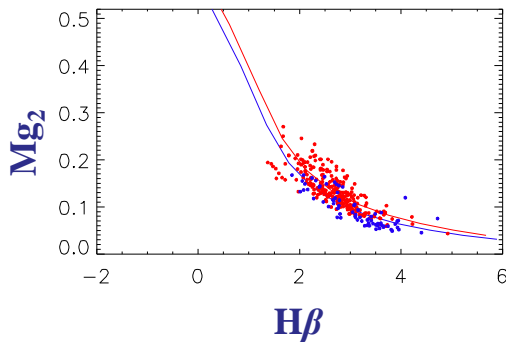
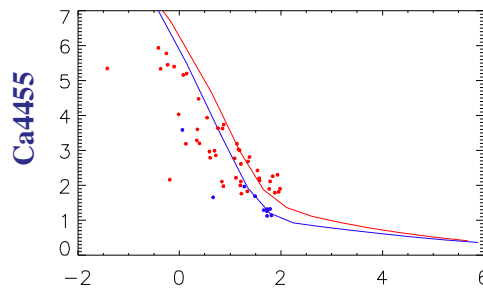
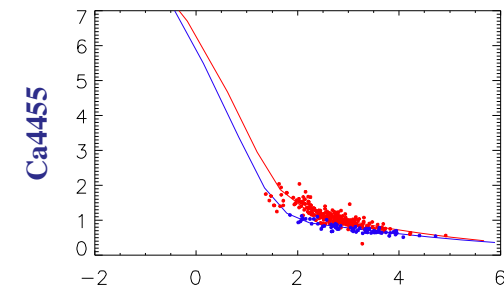
**$\log g = 4.0$  —**

**In general predictions agree very well with observations**

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



# Comparison of observation with SLickSDSSv1 library



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

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

**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) :**

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

**$\log g = 4.5$  —**

**$\log g = 4.0$  —**

*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:**
  - $3500 \leq T_{\text{eff}} \leq 7000\text{K}$
  - $0.25 \leq \text{logg} \leq 5.25\text{dex}$
  - 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*

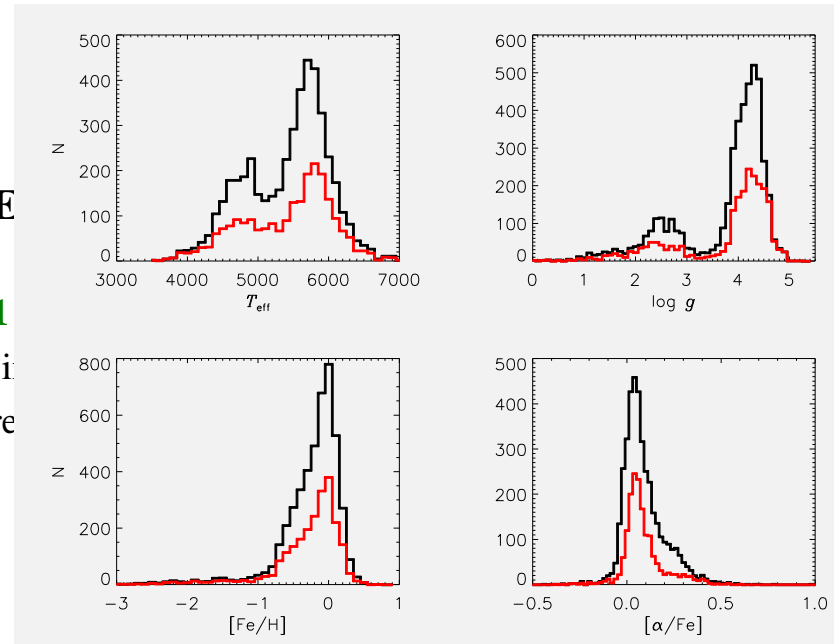
- Due to U580 the wavelength range, we could compute only the following **Lick/SDSS** indices: **H $\beta$** , **Fe5015**, **Mg $_1$** , **Mg $_2$** , **Mgb**, **Fe5270**, **Fe5406**, **Fe5709**, **NaD**

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

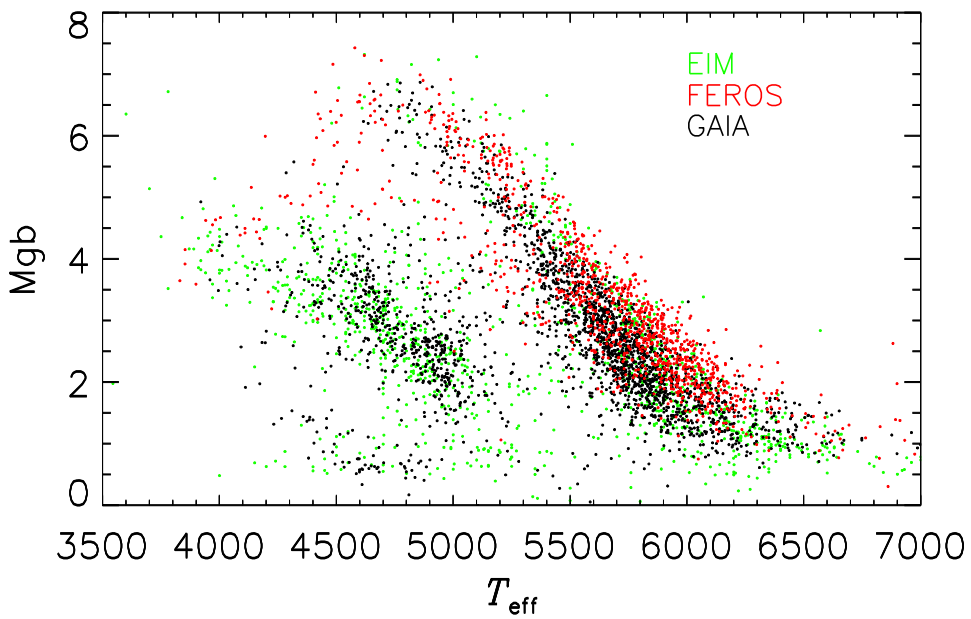
- GES spectra are not flux calibrated so the obtained GE indices are not comparable with the Lick/SDSS system:

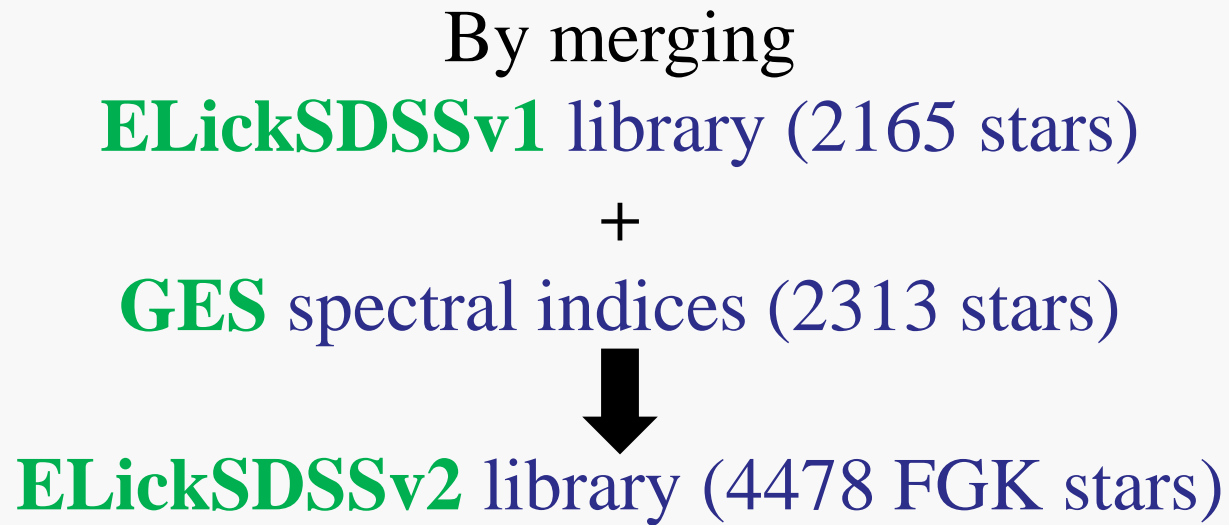
select stars in common between GES and **ELickSDSSv1**  
compare uncalibrated GES indices with the index values in the Lick/SDSS system  
compute transformation coefficients assuming linear regression

- 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 $\beta$ , Fe5015, Fe5270, Fe5406, Fe5709**

→ One lookup table for each index

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

**Mg<sub>1</sub>, Mg<sub>2</sub>, Mgb**

→ two lookup tables for each index to differentiate

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

- Each lookup table contains:

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

# ELickSDSSv2 library

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

$\langle [\text{Fe}/\text{H}] \rangle$ dex	$\sigma_{[\text{Fe}/\text{H}]}$ dex	$\langle \log g \rangle$ dex	$\sigma_{\log g}$ dex	$\langle T_{\text{eff}} \rangle$ K	$\sigma_{T_{\text{eff}}}$ K	$\langle \text{H}\beta \rangle$	$\sigma_{\text{H}\beta}$	Np			
-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	0.027	4893	36	1.551	0.058	5		
					2.447	0.028	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	
					3.570		0.027	0.027	5055	26	1.542
		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		
		4.024	0.008	0.008	5142	15	1.384	0.163	4		
5327	19				1.893	0.142	10				
5430	16				2.043	0.070	24				

# ELickSDSSv2 library

Mean index values vs  $T_{\text{eff}}$  for different bins in  $\log g$ :

*indices*  $[\alpha/\text{Fe}]$  dependent

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

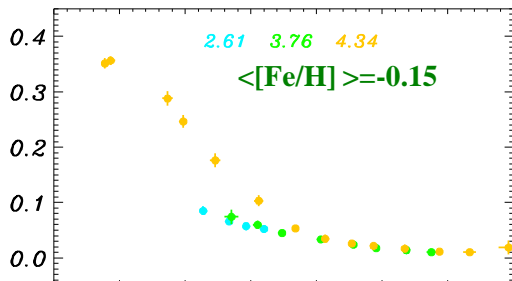
**Bins**

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

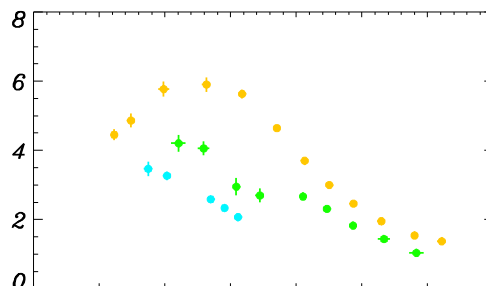
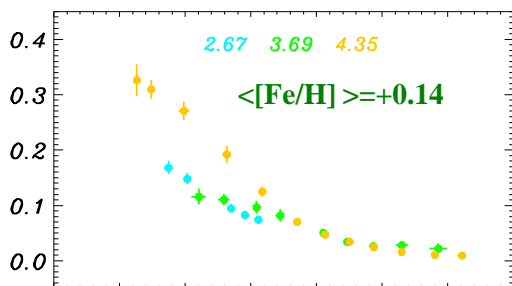
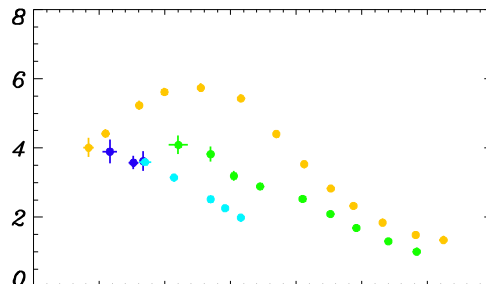
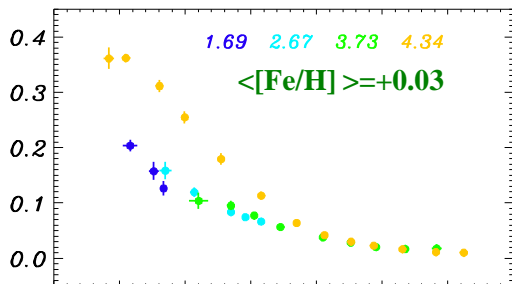
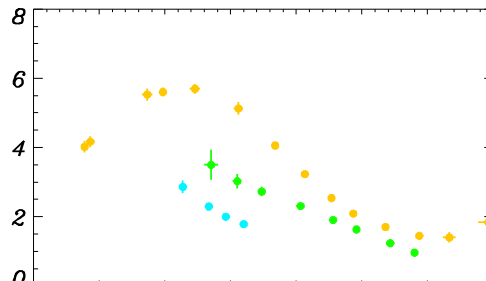
$\log g$  1.0 dex

$T_{\text{eff}}$  250 K centered every 125 K

**Mg1**



**Mgb**



3500  $T_{\text{eff}}$  7000

3500  $T_{\text{eff}}$  7000



# ELickSDSSv2 library

Mean index values vs  $T_{\text{eff}}$  for different bins in  $\log g$ :

*indices*  $[\alpha/\text{Fe}]$  dependent

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

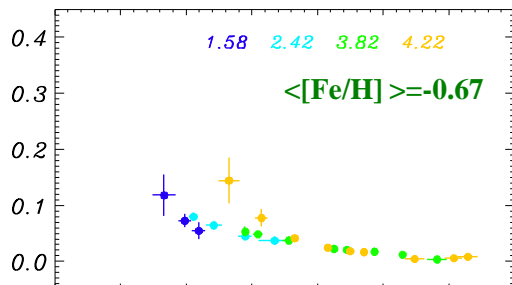
Bins

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

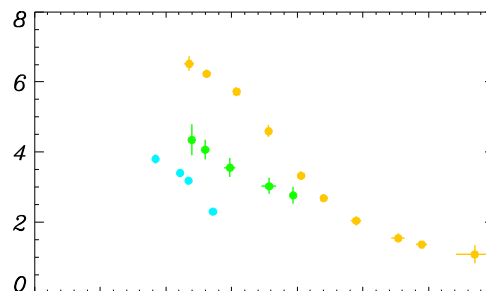
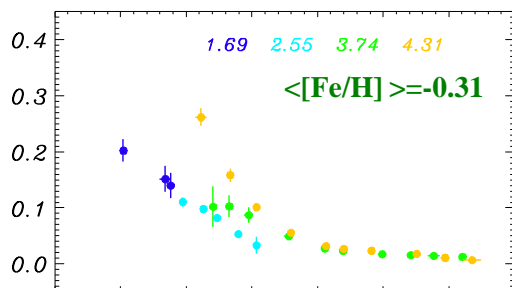
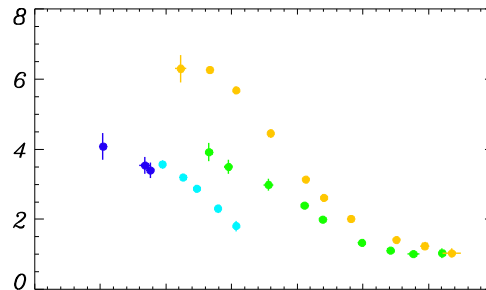
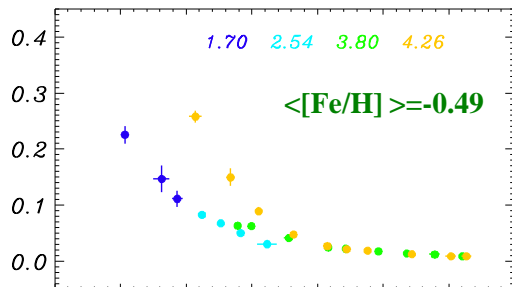
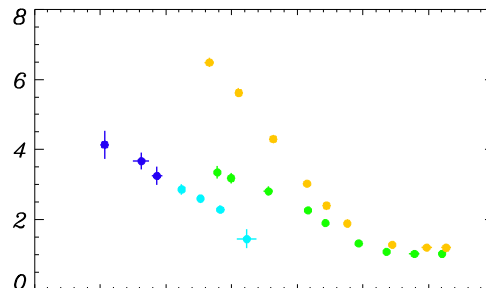
$\log g$  1.0 dex

$T_{\text{eff}}$  250 K centered every 125 K

Mg1



Mgb



3500  $T_{\text{eff}}$  7000

3500  $T_{\text{eff}}$  7000



# 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 H<sub>2</sub>O line list (Kurucz from Partridge & Schwenke)

*several chemical compositions:*

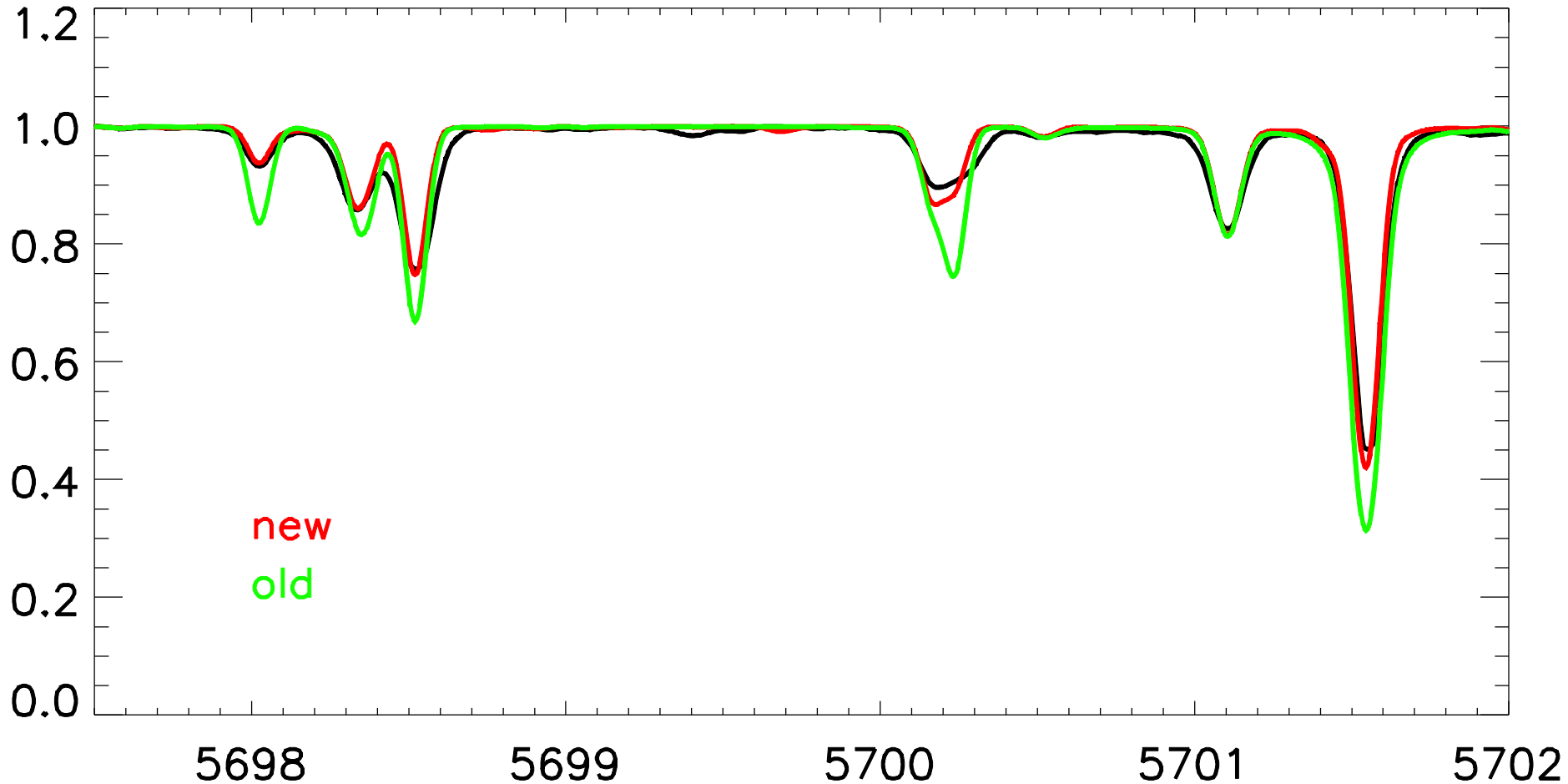
- [Fe/H] from +0.5 to -3.0 with  $\Delta[\text{Fe}/\text{H}]=0.25$
- [ $\alpha$ /Fe] from +1.0 to -0.5 with  $\Delta[\alpha/\text{Fe}]=0.25$
- **Individual  $\alpha$ -element abundances** (i.e.  $[\text{Mg}/\text{Fe}] \neq [\text{Si}/\text{Fe}] \neq [\text{Ca}/\text{Fe}] \neq [\text{Ti}/\text{Fe}] \neq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

- **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

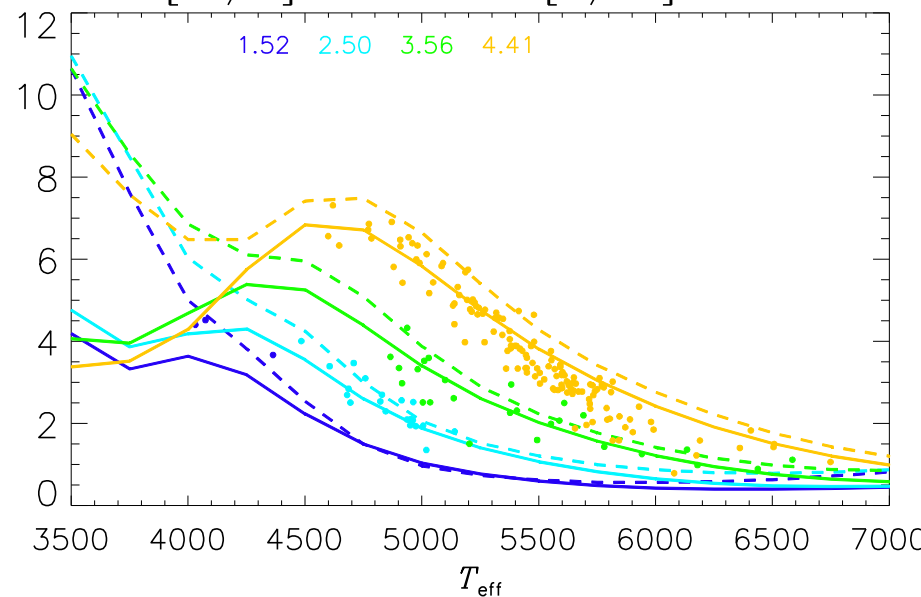
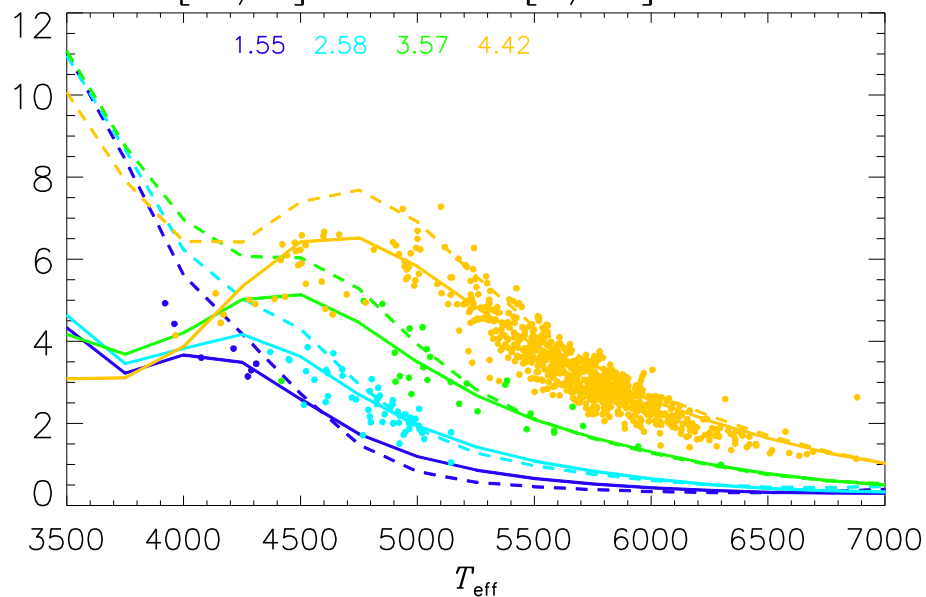
Comparison between observations and predictions of new Synthetic Lick/SDSS library

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

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

$\langle [\text{Fe}/\text{H}] \rangle = 0.03$   $\langle [\alpha/\text{Fe}] \rangle = 0.01$

$\langle [\text{Fe}/\text{H}] \rangle = -0.49$   $\langle [\alpha/\text{Fe}] \rangle = 0.24$



— SLickSDSSv2

- - - SLickSDSSv1

# SLickSDSSv2: Preliminary results

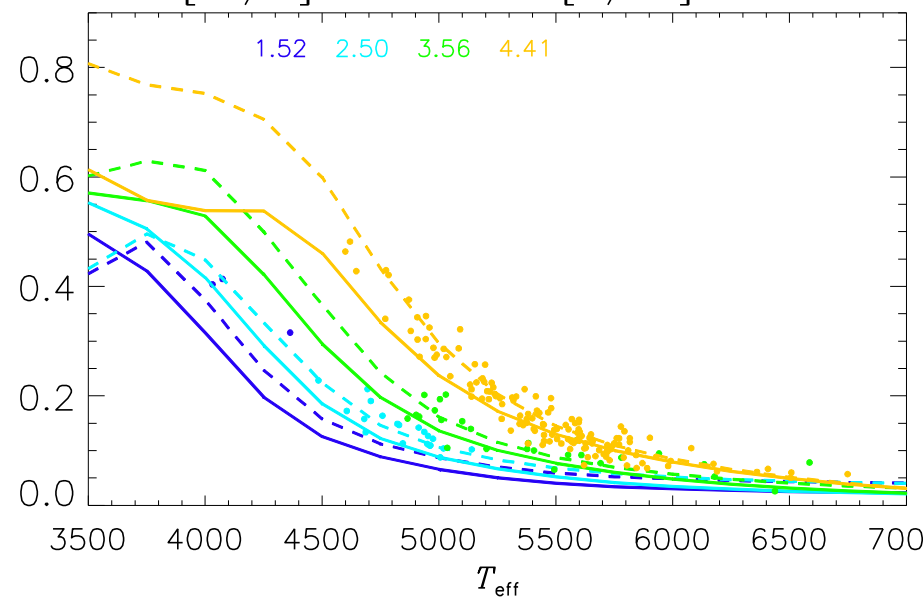
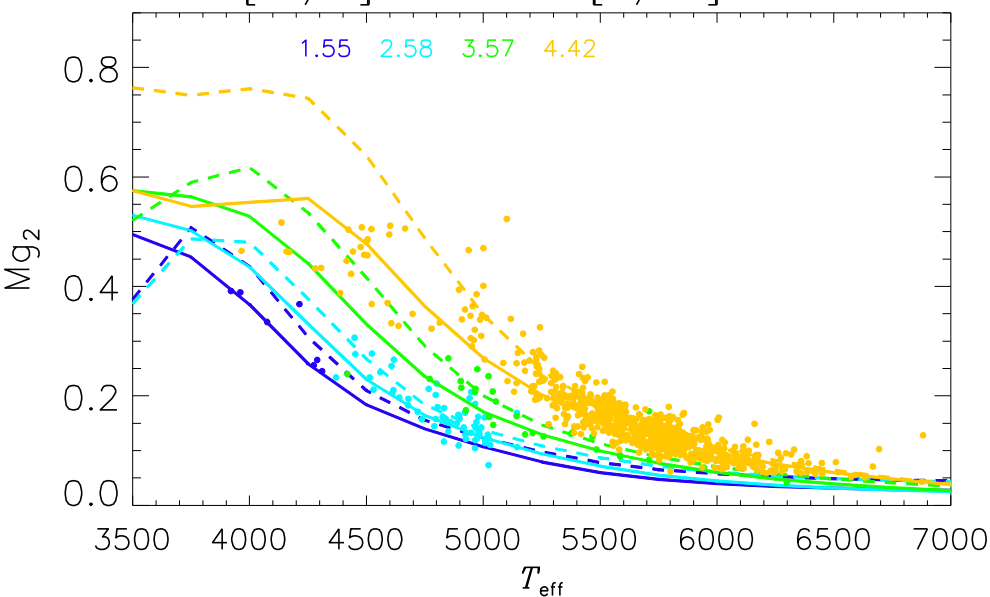
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$\langle [\text{Fe}/\text{H}] \rangle = -0.49$   $\langle [\alpha/\text{Fe}] \rangle = 0.24$



— 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  $T_{\text{eff}}$ , 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  $\alpha$ -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