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

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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 α-enhancement give insight into the role of SnI and SneII 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 – λλ 4000÷6000
  - ***R~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~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

[α/Fe]

sensitive group

intermediate group

quasi-indipendent group .

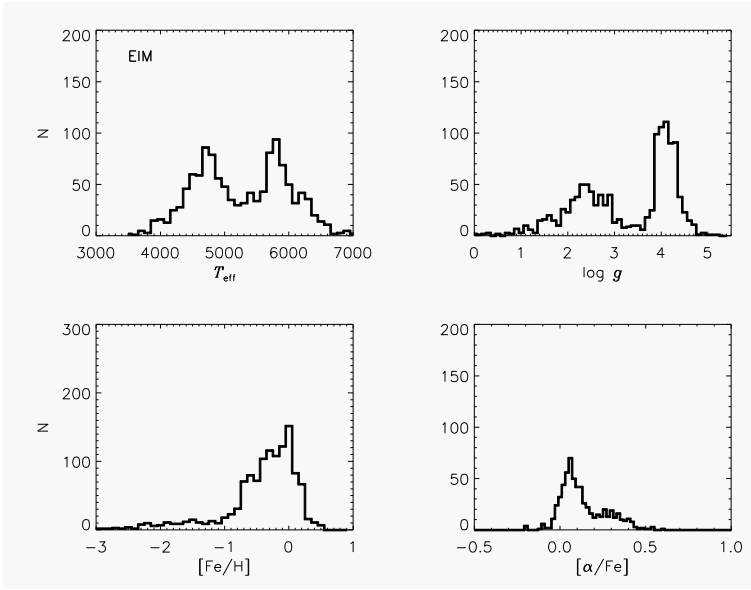
Worthey+ 1994

ELickSDSSv1 -- Empirical Lick/SDSS library

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) 1Å (FWHM)
- **MILES** library (Cenarro+2007) (3525-7500Å) 2.3Å (FWHM)

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



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

- **Atmospheric parametes** $T_{\rm eff,}$ logg, [Fe/H],[α/Fe], *Vr*

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

ELickSDSSv1 -- Empirical Lick/SDSS library

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

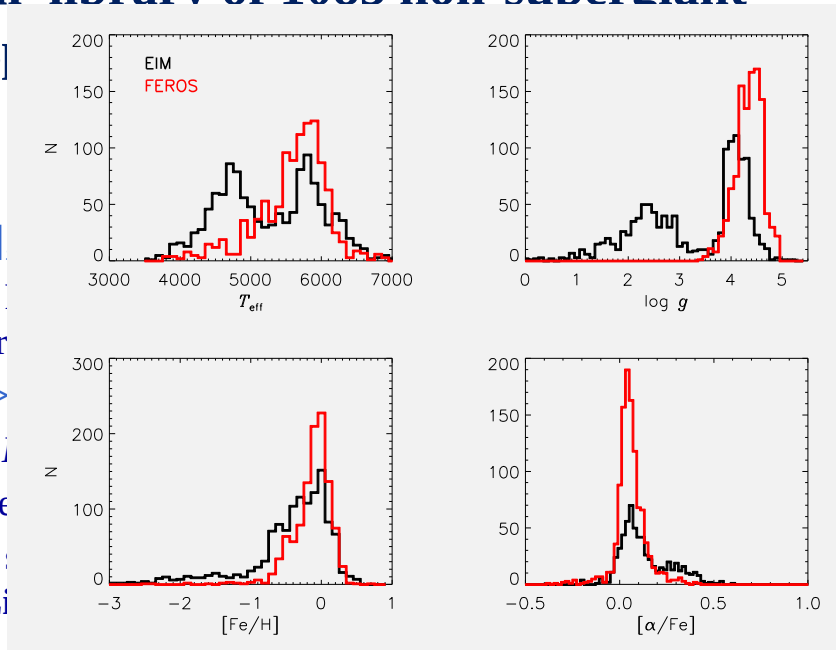
a) **FEROS** library (Kaufer+ 1999)

R=48000 λλ range=360÷920nm

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

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

  **3800<*T*eff<7500 log*g* > 3.5 [Fe/H]>
- 2511 spectra were corrected for V_r and degraded at
  Indices were averaged in the case of multiple obse
- FEROS spectra are **not flux calibrated** → FEROS
  were used to **transform FEROS indices into the Li**

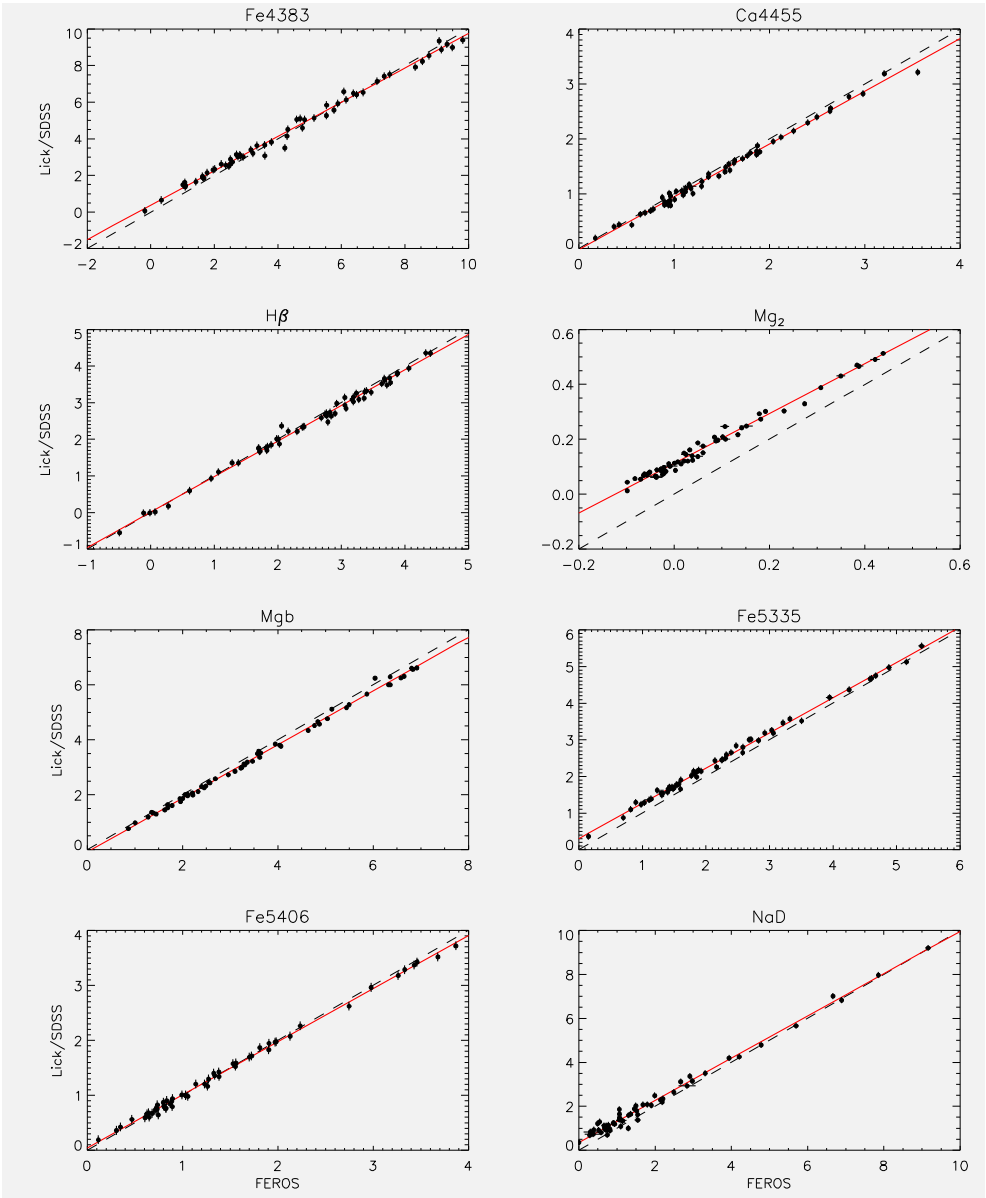


Final **FEROS Lick/SDSS library:** 1085 non-supergiant FGK stars

Table 1. Table of observational Lick/SDSS indices of 1085 FGK FEROS stars. The atmospheric parameters T_{eff}, log g, [M/H], and [α/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)	$\sigma_{T_{eff}}$ (K)	log g	$\sigma_{\log g}$ (dex)	[M/H]	$\sigma_{[M/H]}$ (dex)	[α/Fe]	$\sigma_{[\alpha/Fe]}$ (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



Trasformation of 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:

  [α /Fe] = 0.0 (Solar Scaled, SSA) and [α /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)

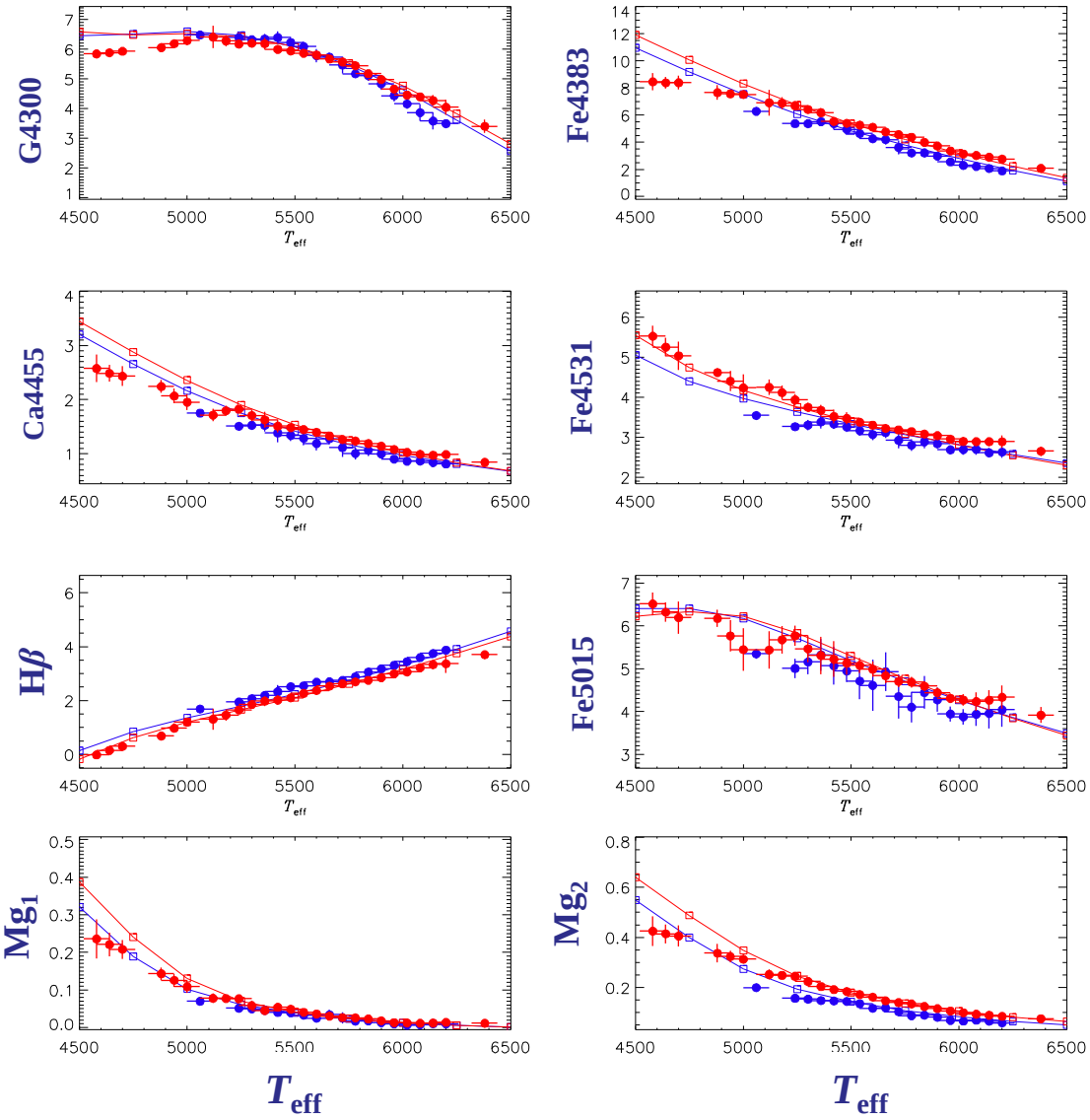
$T_{\rm eff}$: 3500-7000 K (250 K step)

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

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

[Fe/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<[Fe/H]<0.2 -0.2<[α/Fe]<0.2

Dwarfs log*g*~4.5

Subgiants log*g*~4.0

Synthetic Lick/SDSS indices (lines) :

[Fe/H]=0 [α/Fe]=0

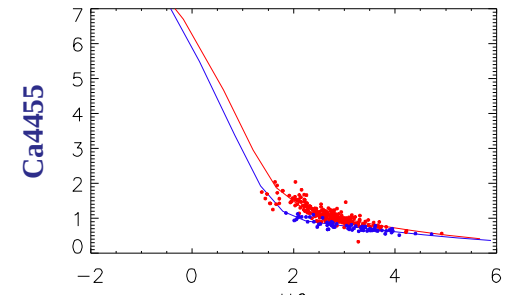
log*g*=4.5 ——

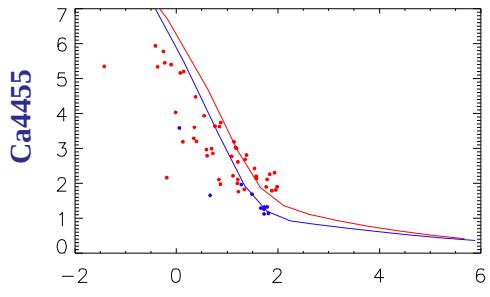
log*g*=4.0 ——

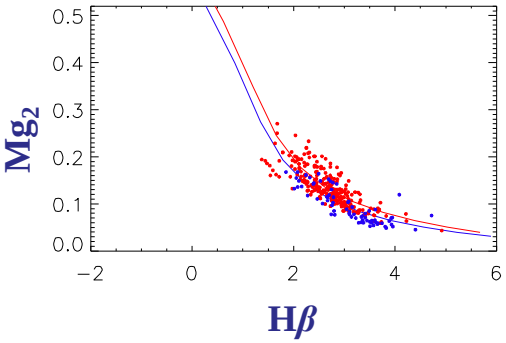
In general predictions agree very well with observations

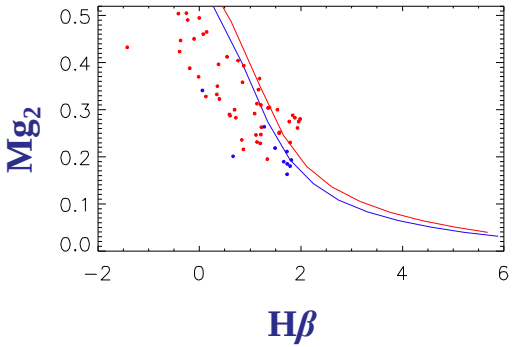
but for T_{eff}≤5250K

Comparison of observation with SLickSDSSv1 library









$T_{eff} > 5250$

$T_{eff} < 5250$

FEROS Lick/SDSS indices (points)

rebinned (120 K)

-0.2<[Fe/H]<0.2 -0.2<[α/Fe]<0.2

Dwarfs log*g*~4.5

Subgiants log*g*~4.0

Synthetic Lick/SDSS indices (lines) :

[Fe/H]=0 [α/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 (Teff<5250 K)

ELickSDSSv2 library

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 ~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:**

  $3500 \leq T_{\rm eff} \leq 7000$K

  $0.25 \leq \log g \leq 5.25$dex

  UVES-U580 setup centered at 580 nm (476.8-580.1 and 582.2-683.0 nm ***R***~47000)

  SNR > 3

  ⟶ 2618 stars

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

  ⟶ **2313 stars** ***Final Sample***

ELickSDSSv2 library

- **Due to U580 the wavelength range, we could compute only the following Lick/SDSS indices:**

  Hβ, 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

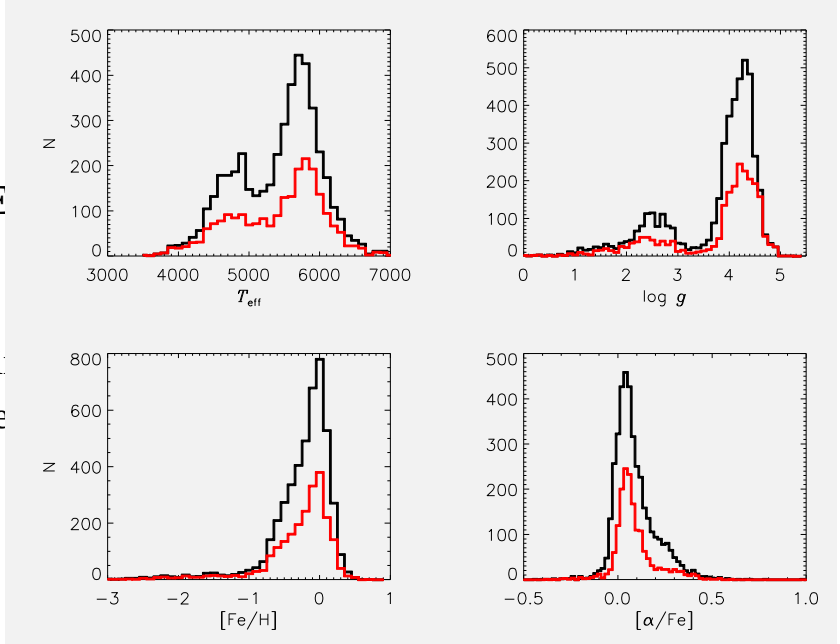
- **GES spectra are not flux calibrated so the obtained GE**
  them into the Lick/SDSS system:

  select stars in common between GES and **ELickSDSSv1**

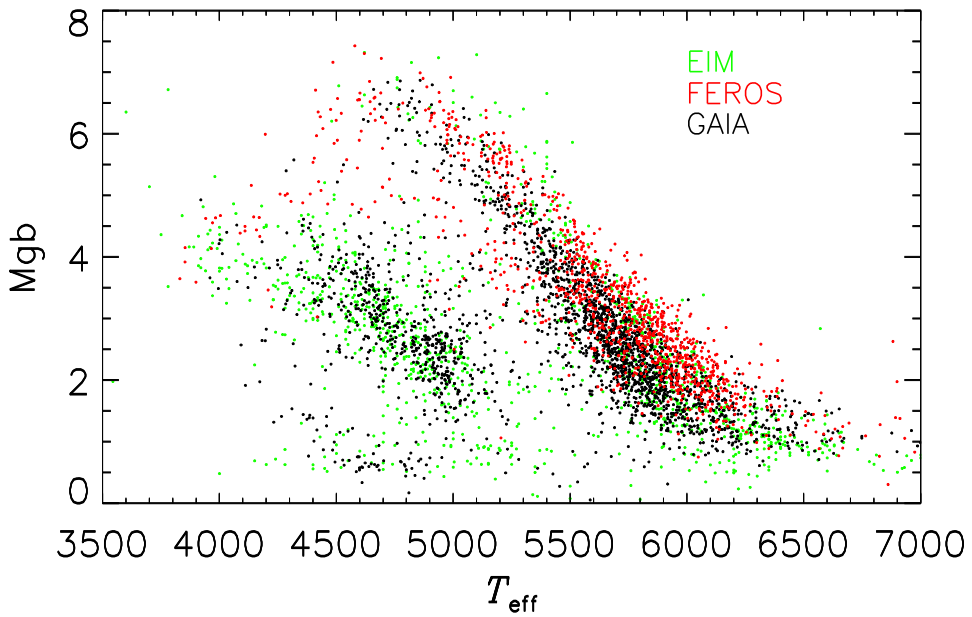
  compare uncalibrated GES indices with the index values i

  compute transformation coefficients assuming linear regre

- **Improvement in Stellar parameter coverage with respect to ElickSDSSv1**



ELickSDSSv2 library



By merging

ELickSDSSv1 library (2165 stars)

+

GES spectral indices (2313 stars)

⬇

ELickSDSSv2 library (4478 FGK stars)

➢ **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 **[α/Fe]:**

Hβ, Fe5015, Fe5270, Fe5406, Fe5709

⟶ One lookup table for each index

b) A group containing ***indices dipendent*** on **[α/Fe]:**

Mg_1, Mg_2, Mgb

⟶ two lookup tables for each index to differentiate

Solar Scaled ([α/Fe]≤0.05) and **α-enhanced** stars **([α/Fe]≥0.15)**

- Each lookup table contains:

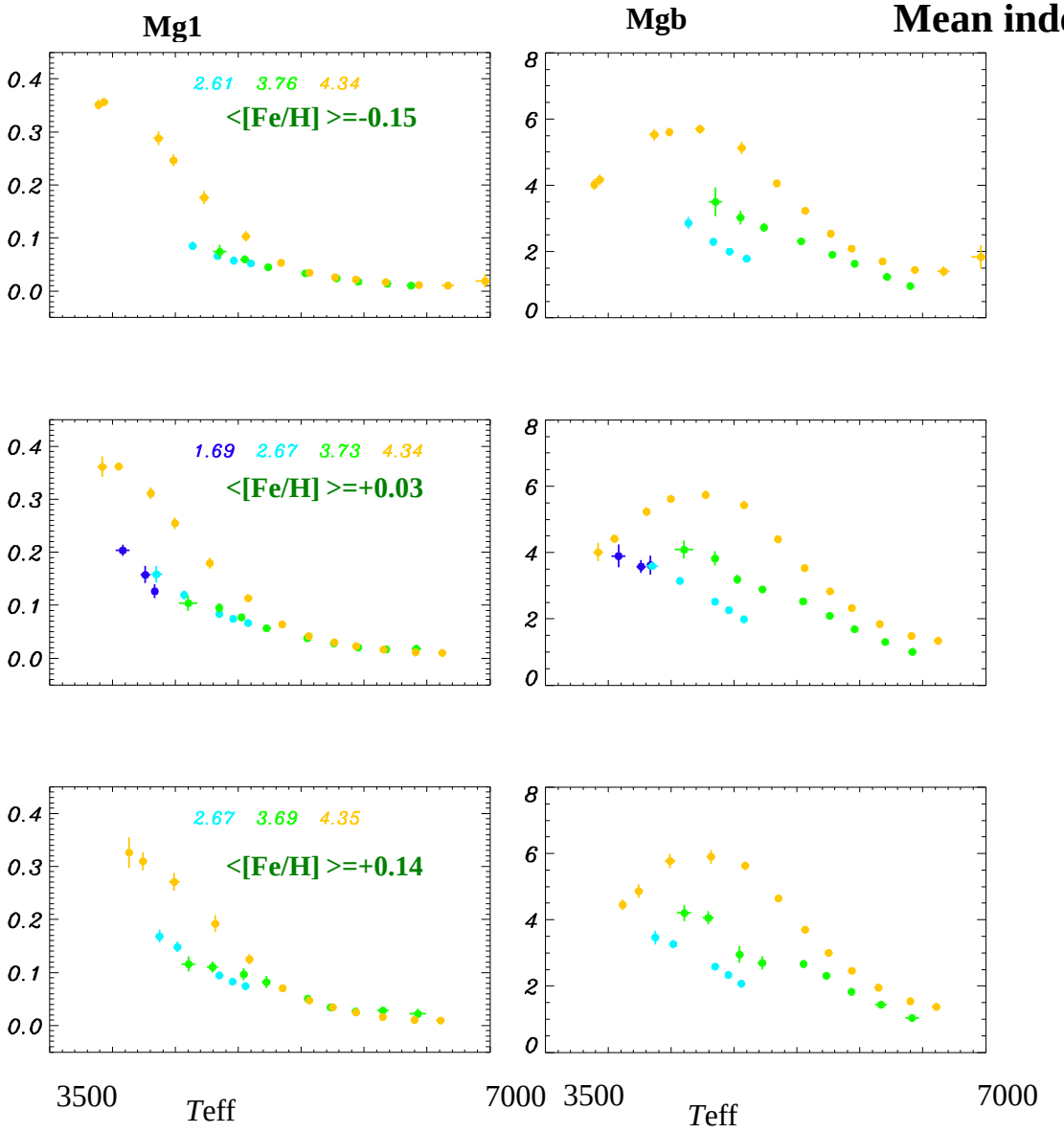
<[Fe/H]> $\sigma_{[Fe/H]}$ **<log*g*>** σ_{logg} $<T_{eff}>$ σ_{Teff} **<index>** σ_{index} **Np**

ELickSDSSv2 library

Table 1. Lookup table of Hβ ELickSDSSv2 index. The <[Fe/H]>, <log g >, < $T_{\rm eff}$ >, and <Hβ > 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.

<[Fe/H]> dex	$\sigma_{\rm [Fe/H]}$ dex	<log g > dex	$\sigma_{\log g}$ dex	< $T_{\rm eff}$ > K	$\sigma_{T_{\rm eff}}$ K	<Hβ >	$\sigma_{\rm H\beta}$	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
		1.999	0.027	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
				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	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
		4.024	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_{eff} for different bins in logg:

indices **[α/Fe] dependent**

α-low group [α/Fe] ≤0.05 1742 stars

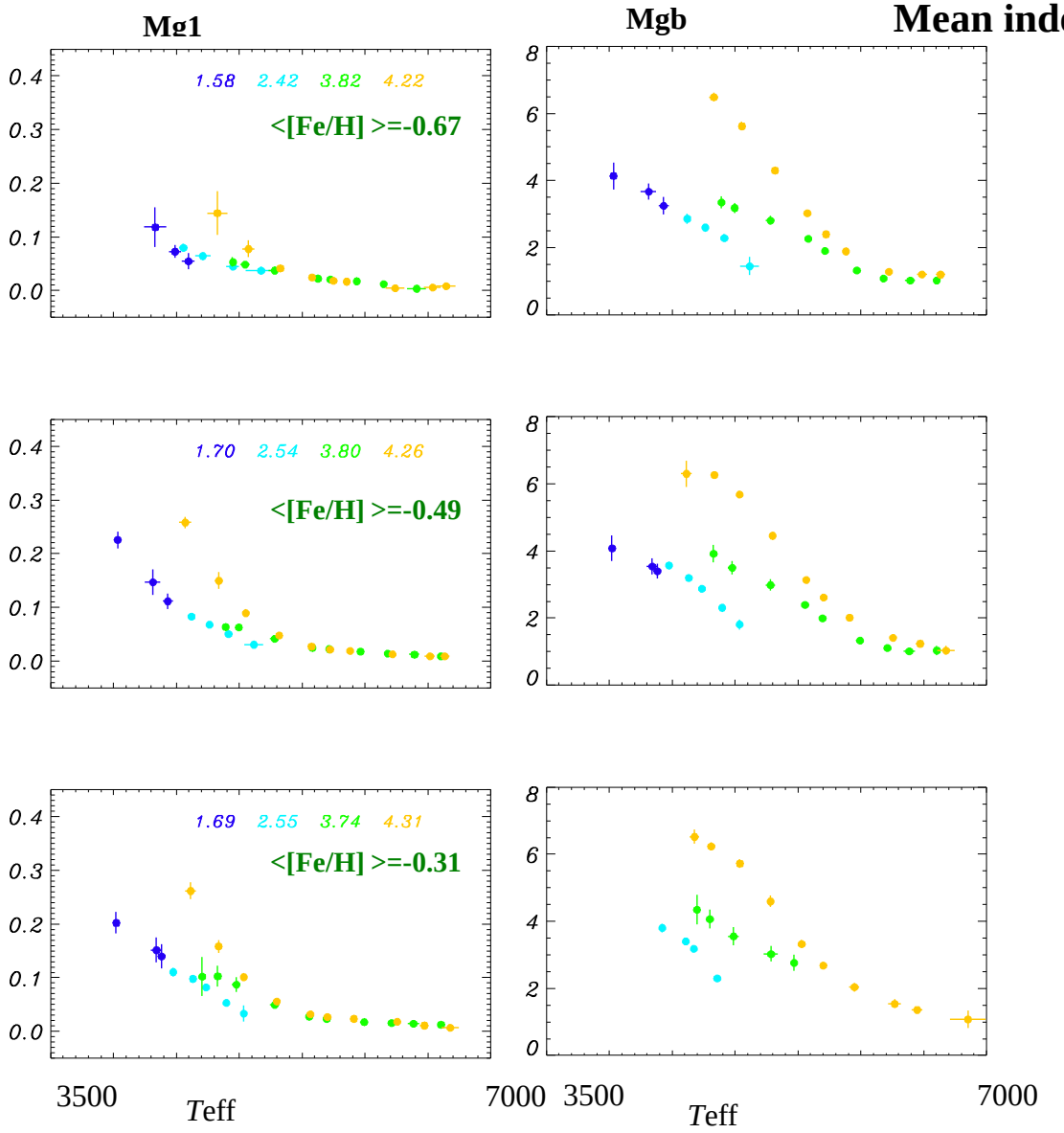
Bins

[Fe/H] 0.5 dex centered every 0.25 dex

logg 1.0 dex

T_{eff} 250 K centered every 125 K

ELickSDSSv2 library



Mean index values vs T_{eff} for different bins in logg:

indices **[α/Fe] dependent**

α-high group [α/Fe] ≥0.15 939 stars

Bins

[Fe/H] **0.5 dex centered every 0.25 dex**

logg **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 Partrige & Schwenke)

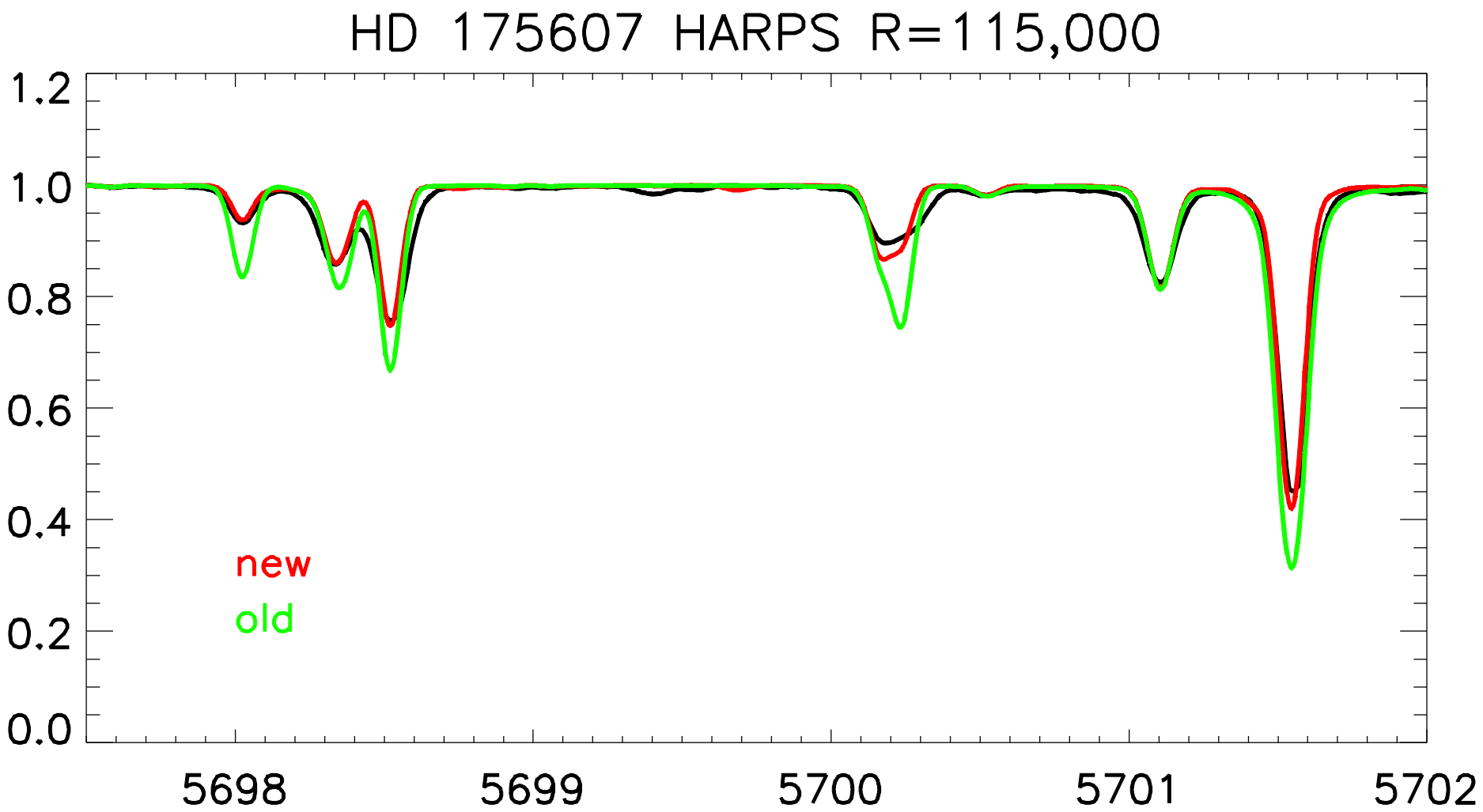
  several chemical compositions:

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

- **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 *gf*** values for the strongest lines derived from comparison between the solar synthetic and observed HiRes spectra

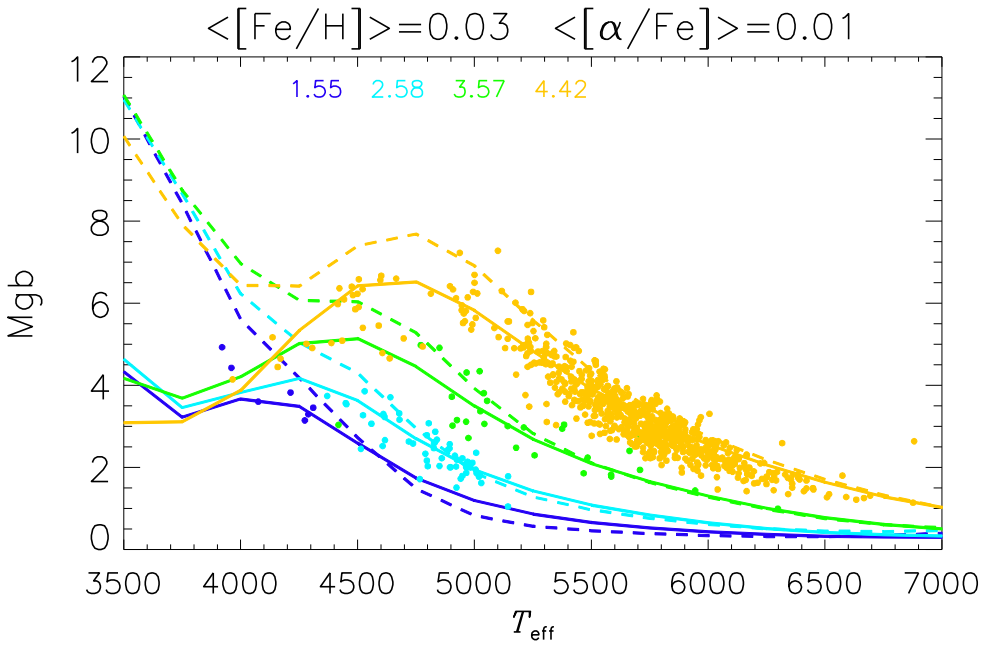
SLickSDSSv2: Preliminary results



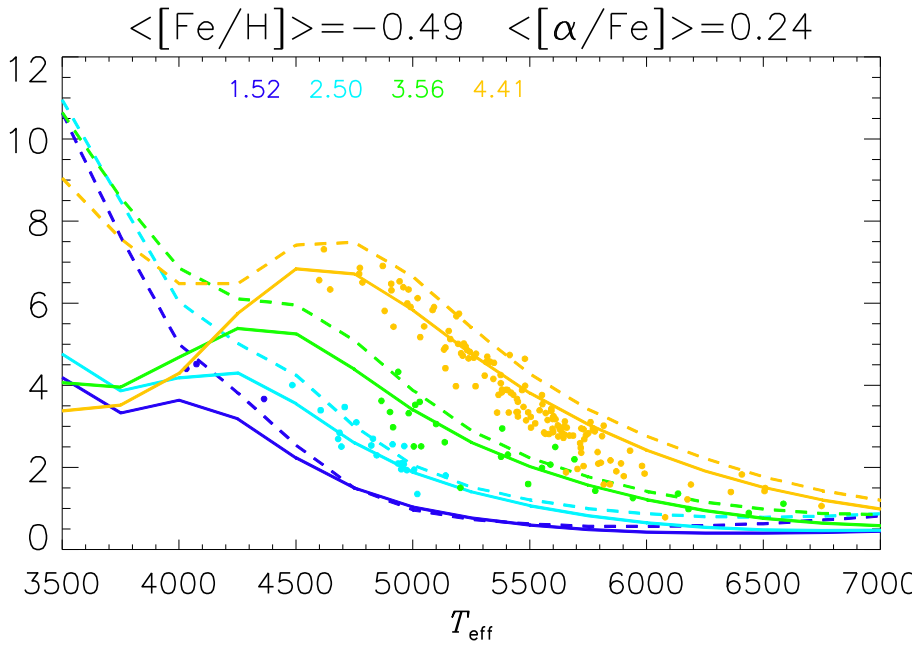
SLickSDSSv2: Preliminary results

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

α-low group [α/Fe] ≤0.05



α-high group [α/Fe] ≥0.15

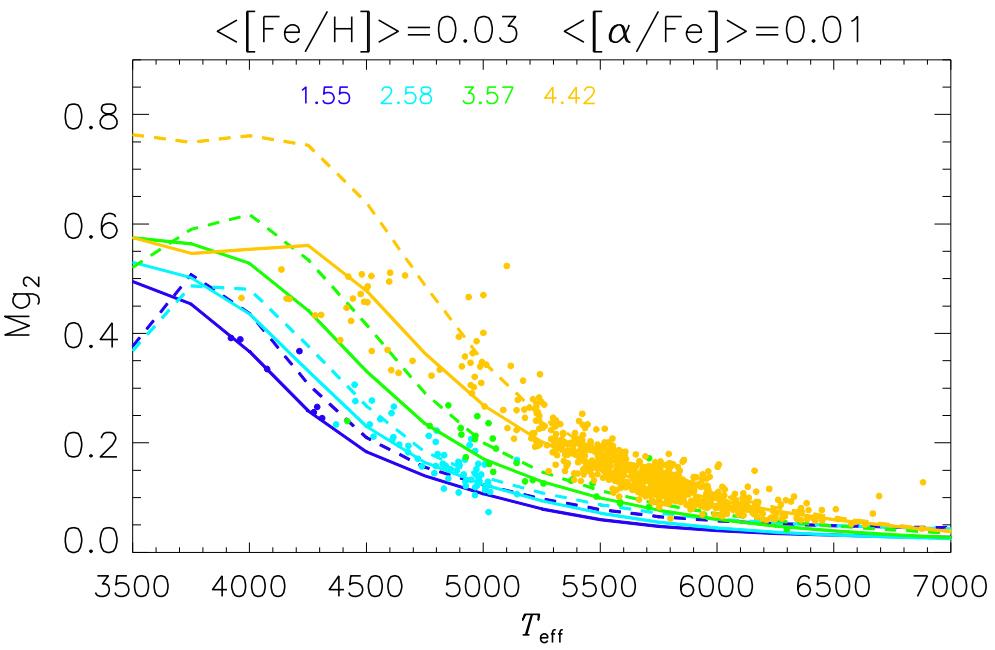


——— **SLickSDSSv2** – – – – – **SLickSDSSv1**

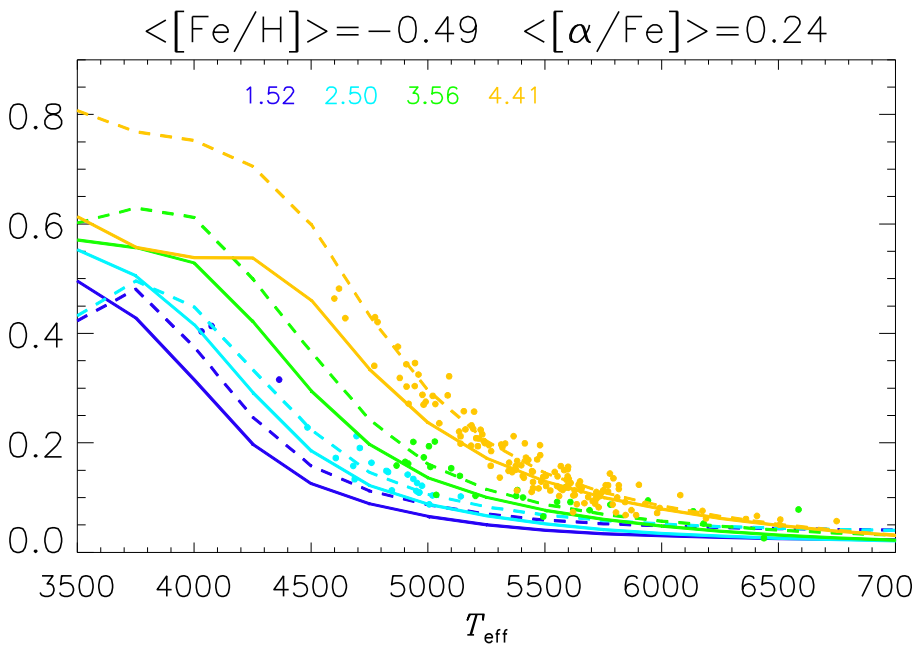
SLickSDSSv2: Preliminary results

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

α-low group [α/Fe] ≤0.05



α-high group [α/Fe] ≥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: Hβ, 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 Δ[Fe/H]=0.25
  - [α /Fe] from +1.0 to -0.5 with Δ[α/Fe]=0.25
  - **Individual α-element abundances** (i.e. [Mg/Fe] ≠ [Si/Fe] ≠ [Ca/Fe] ≠ [Ti/Fe] ≠ …)

- **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