Towards accurate descriptions of stellar population abundance patterns from integrated light spectra

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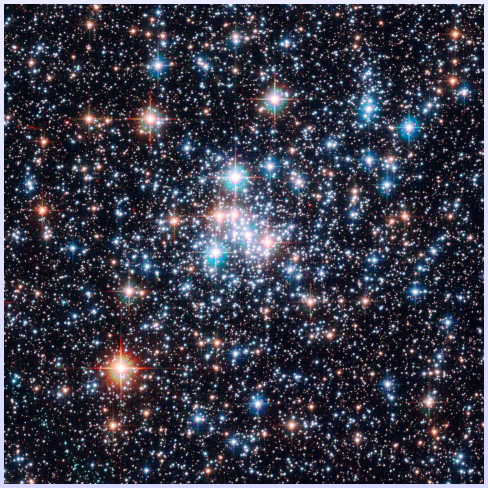
Collaborators: MILES consortium *miles.iac.es*



Overview:

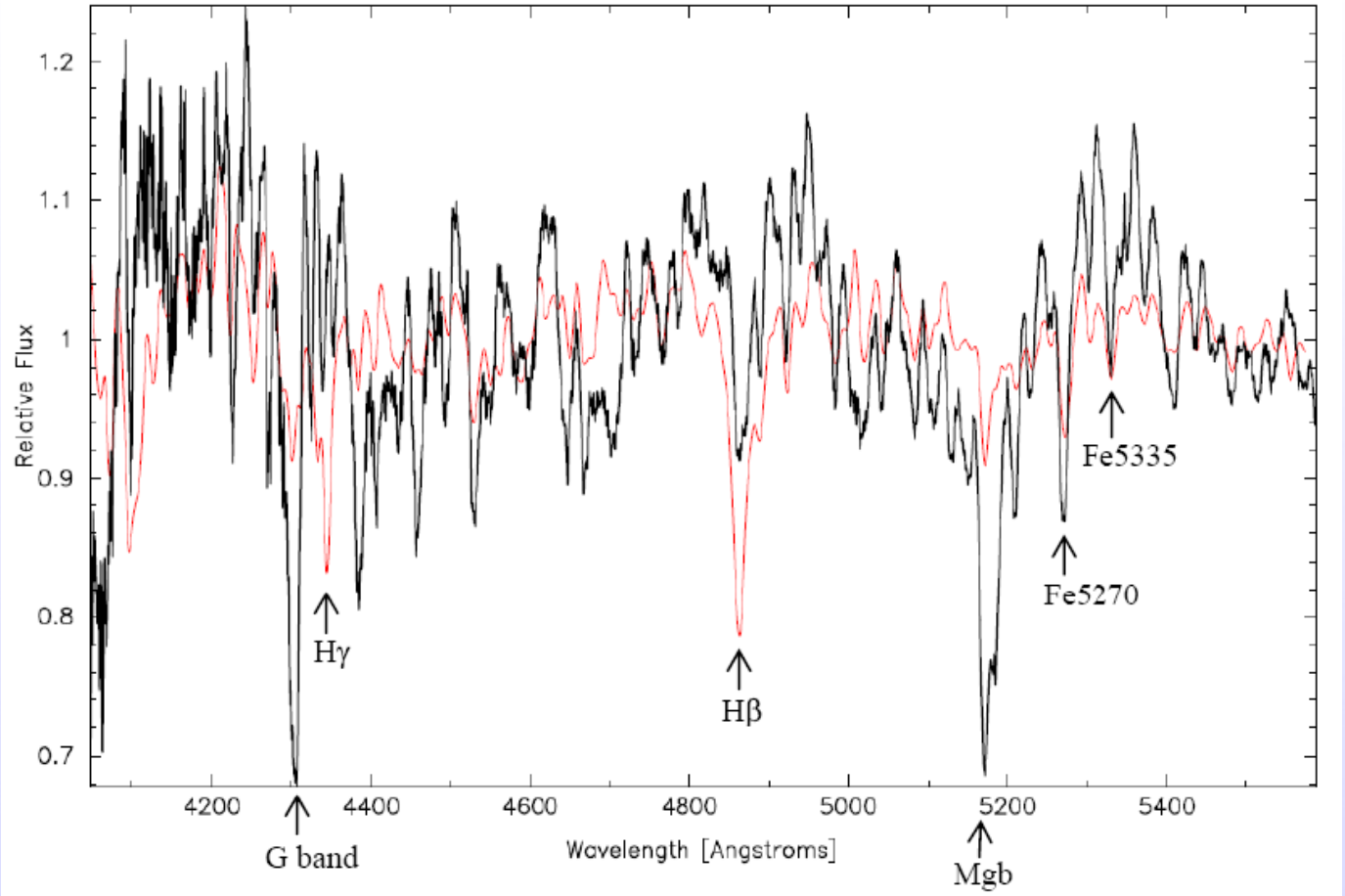
- Past examples
- Methods
- Test theoretical spectra
- Future

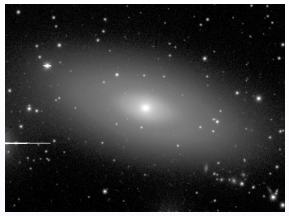
Information in integrated spectra:-

- **Stars summed to give simple stellar populations (SSPs).**
- **SSPs used to interpret star cluster & galaxy spectra:**
  - **age, chemistry, IMF, duration of SF (SNII/SNIa), SFH etc.**
- **[α/Fe] ratios used as a *clock* for SF timescales and extents:-**
  - **SNII provide rapid enrichment (α, Fe, rare elements) ($10^8 > t > 3\times10^6$ *yrs*)**
  - **SNIa provide extended enrichment over time (mainly Fe) (prompt+delayed, $t>10^8$ *yrs*?)**
  - **IMS provide C,N,O enrichment ($t>10^8$ *yrs*)**

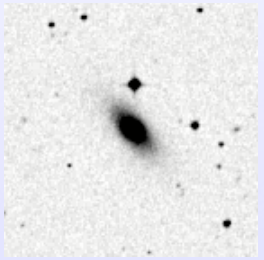
Need to *accurately measure* element ratios [X/Fe] in stars and stellar populations .

Example integrated spectra of high and low luminosity ETGs *(Sansom & Northeast 2008)*





NGC 2784
Luminous S0
High [Fe/H],[α/Fe]
Old (7Gyr)

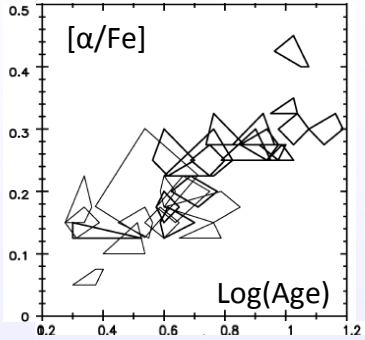


ESO 157-30
Low Luminosity E
Low [Fe/H],[α/Fe]
Young (3Gyr)

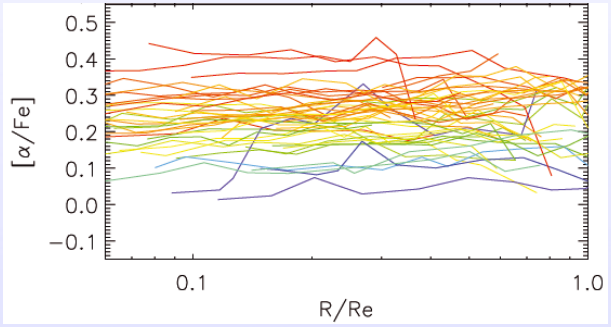
Elliptical & Lenticular galaxies

- ***Davies, Sadler & Peletier (1993)***
  Long-slit spectra - Lick indices across early-type galaxies **(ETGs)**
  Excess [Mg/Fe]

- ***Proctor & Sansom (2002)***
  Long-slit spectra – Lick indices in a range of types
  Aundance pattern advantage -
  Error contours - Non-degen. [α/Fe] v. Log(Age)

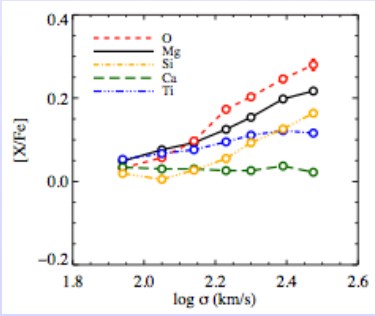


- ***Kuntschner et al. (2010)***
  Used *Schiavon 2007*;
  Element Responses R of *Korn et al. (2005)*
  IFU (SAURON) maps of age, Z and [α/Fe]
  In 48 ETGs - **2-d structure**



- ***Scott et al. (2013)***
  ATLAS^{3D} obs. + models **Mgb trends with V_{esc}**

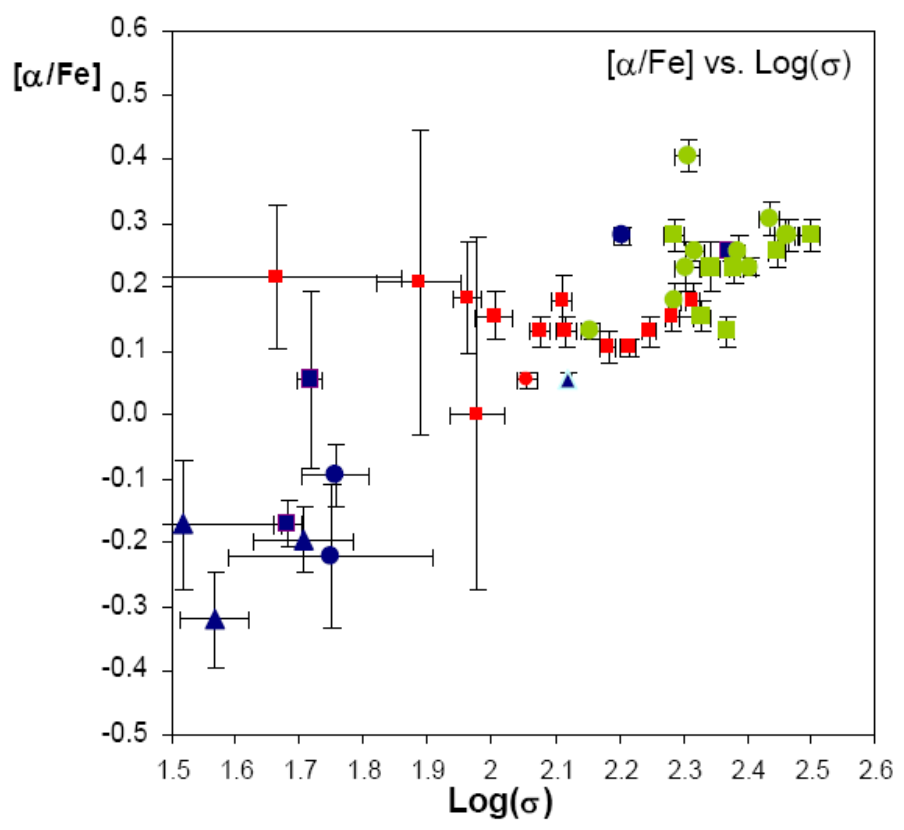
- ***Conroy, Graves & van Dokkum (2014)***
  ETG obs. + models - **Abundances**

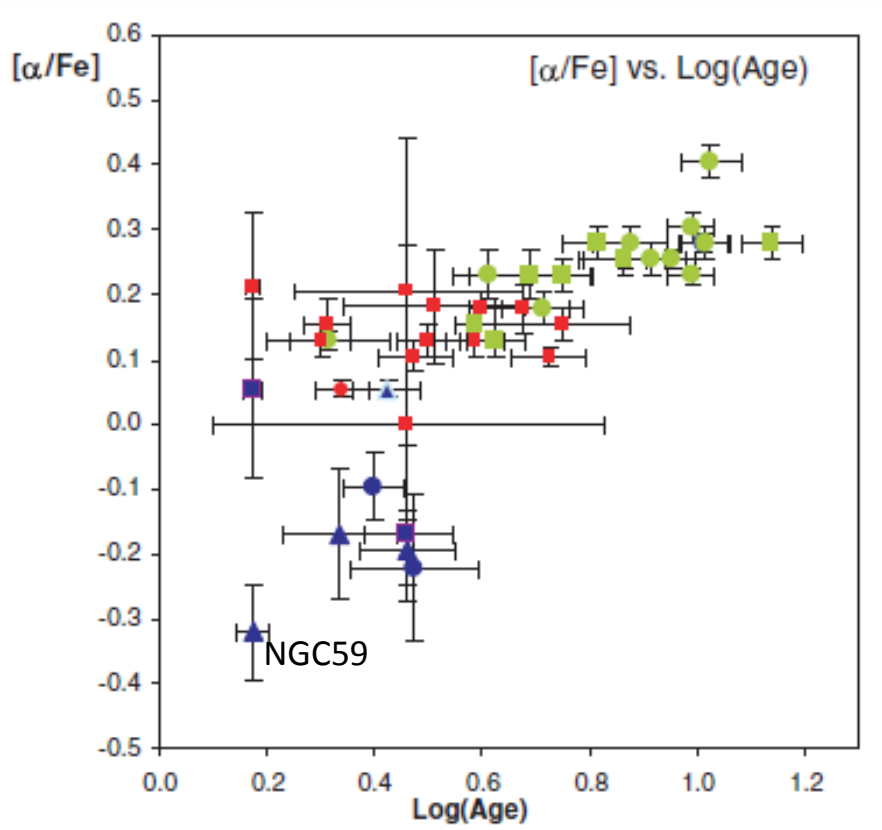


Comparison between spheroids

Green=E,S0 Red=S bulges Blue=LLE,E

*(Sansom & Northeast 2008 – Used **R**s of TB95)*





Trends of abundance patterns with galaxy σ and age.

Methods

Element Responses (*R*):

- Tabulated changes in line indices versus element changes, for star models.
- ***R***s available:
  - Tripicco & Bell 1995 **(TB95)** 3 stars, base Solar Z, 10el+[Z/H] response, 21 indices
  - Houdashelt et al. 2002 **(H02)** Same 3 stars, +Hγ,δ
  - Korn et al. 2005 **(K05)** 21 stars, different base Zs, 25 indices
  - Tantalo et al. 2007 **(T07)** Many stars, [α/Fe] response only
  - Lee et al. 2009 **(L09)** 350 stars (unpublished), SSP responses published

Full spectra:

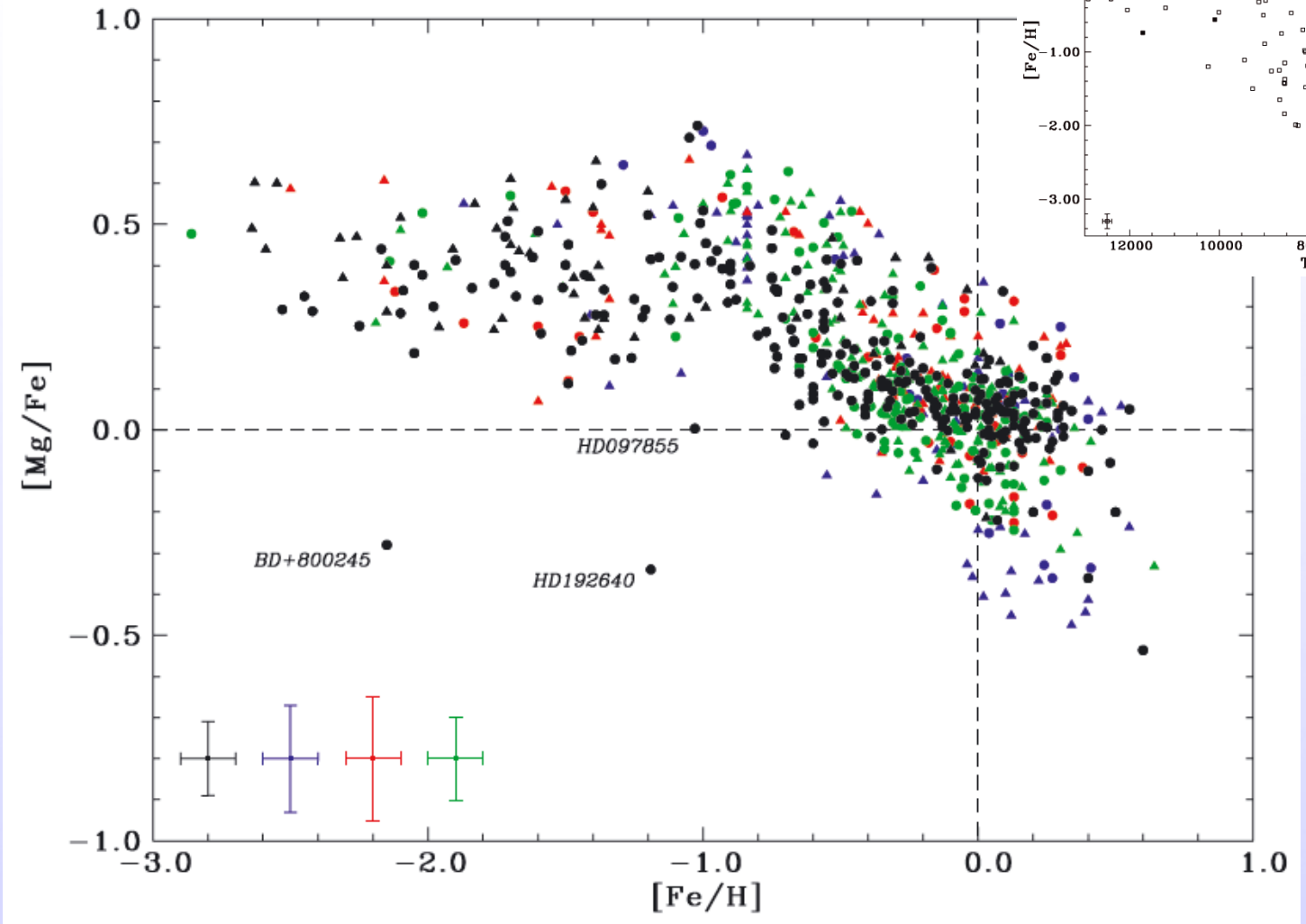
- Theoretical star spectra with different [α/Fe] values (***Coelho et al '05, '14***)
- Needs more testing against real stars with different abundance patterns

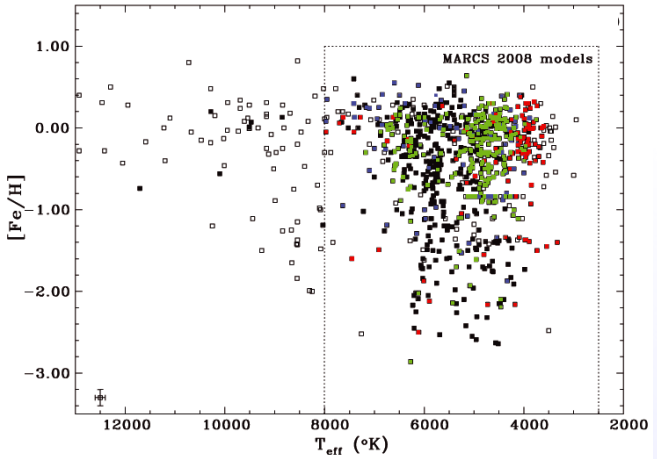
APPLICATION:

- Base SSPs (empirical or theoretical spectra) E.g. MILES
  - Line indices or spectra versus Age & [Fe/H]
- Abundance pattern (theoretical spectra of stars)
  - Weighted sum of stars for SSP effects
  - *Differential* corrections to Line indices or spectra.

[Mg/Fe] versus [Fe/FH] for stars in MILES

(*Milone et al. 2011:* [Mg/Fe] catalogue)





Using element response functions

- Base star model (e.g. solar abundances)
  - Spectral line strengths indices (*I*)
- New abundance pattern (theoretical spectra of stars)
  - Differential corrections. Approximate $Ln(I) \propto [X_i]$ (weak lines)
  - $$I_{new} = I_0 \prod_{i=1}^{n} \exp\left(R_{0.3}(i)\right)^{(\Delta[X_i]/0.3)}$$ *R*=Response fn ($X_i \rightarrow 2X_i$) X_i=element *I* *(Thomas et al. 2003, eq 7)*
  - Correct via fluxes for weak or negative indices (*K05, eq 3*):
  - $$F_{new} = F_0 \prod_{i=1}^{n} \exp\left(\frac{\delta F}{F_0}(i)\right)^{(\Delta[X_i]/0.3)}$$ δF=Flux change for ($X_i \rightarrow 2X_i$)
  - **Correct** from base star (I_0) to new star **[Fe/H]**, then **[α/Fe]**, at a given T_{eff} & Log(g).

Using element response functions - General technique

- Base **star** model (e.g. solar abundances)
  - Spectral line strengths indices (I_0)

- New abundance pattern (theoretical star spectra)
  - Differential corrections – for I *(Thomas et al. 2003, eq 7)*

    R=Response fn ($X_i \rightarrow 2X_i$) X_i=element i
  - Correct via fluxes for weak or negative indices (*K05, eq 3*)

- **Correct** from base star (I_0) to new star **abundances** at a given T_{eff} & Log(g) $\rightarrow$ (I_{new})

Testing element response functions

(Sansom et al. 2013)

- For stars matched in T_{eff}, Log(g), evaluate:
  - **ratios** of **new/base indices** (absorption features)
  - **differences** of **new-base indices** (molecular and - features)

E.g. MILES has 7 CD stars with $T_{eff} \approx 4575$ K, Log(g)≈4.6
HD032147 has [Fe/H]≈[Mg/Fe]≈0 = **CD base star obs.**
K05 Table 12 has ***R*** for this **model:**

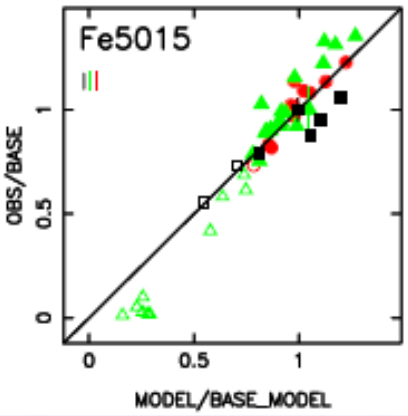
Index	I_0	Error	C	N	O	Mg	Fe	Ca	Na	Si	Cr	Ti	[Z/H]	C0.15	C+O0.3
CN_1	−0.019	0.021	0.123	0.037	−0.033	−0.004	−0.007	−0.007	0.000	0.010	−0.017	0.002	0.014	0.038	0.009
CN_2	0.043	0.023	0.130	0.039	−0.034	−0.009	−0.008	−0.010	−0.002	0.017	−0.018	0.004	0.022	0.040	0.010
Ca4227	3.763	0.270	−0.669	−0.148	0.202	−0.087	−0.069	1.118	−0.028	−0.058	−0.175	−0.007	0.653	−0.212	−0.039
.....															

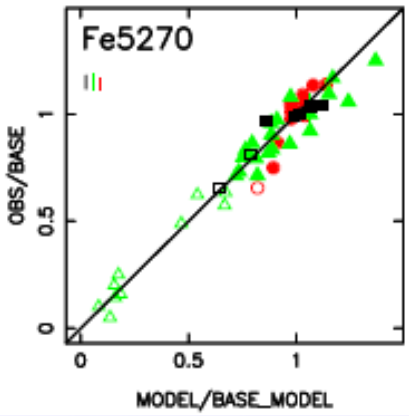
- **Correct** from base star (I_0) to new star **[Z/H]=[Fe/H],** then **[α/Fe].**

- **Plot** normalised **observed** versus **model** indices
  Tests *R* from *K05*: **7 CD stars**
  31 TO stars
  12 CG stars
  } **MILES stars**

Testing K05 Response functions

Fe-sensitive Indices:





Obs. versus models

Key:

= 1:1 line (agreement)

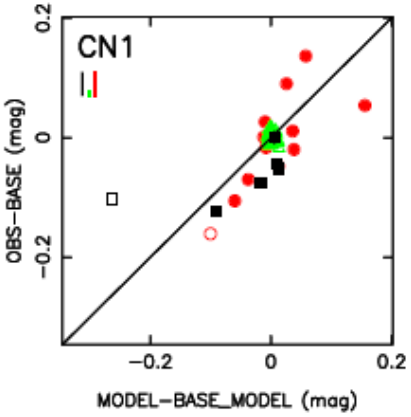
= Cool dwarf stars (CD)

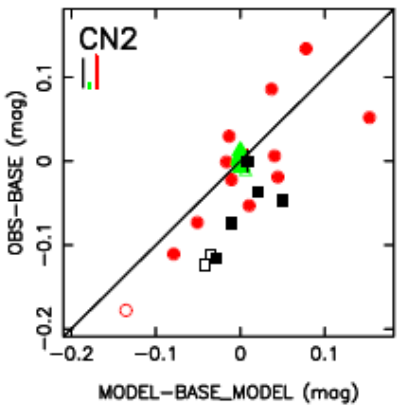
= Turnoff stars (TO)

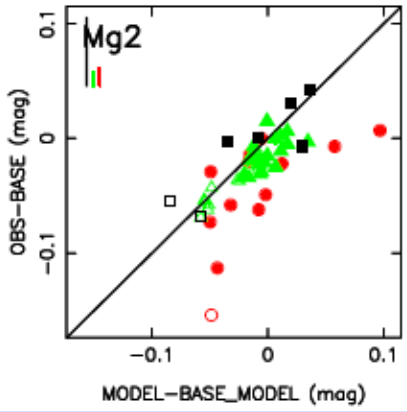
= Cool giant stars (CG)

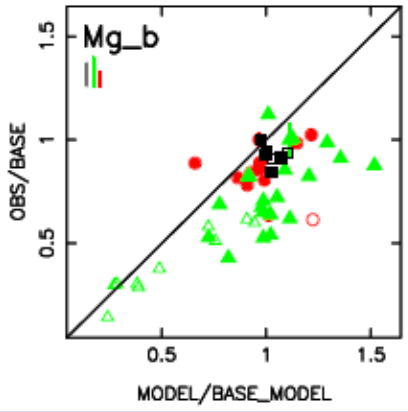
Open symbols = low [Fe/H] <-0.4

Other element indices:



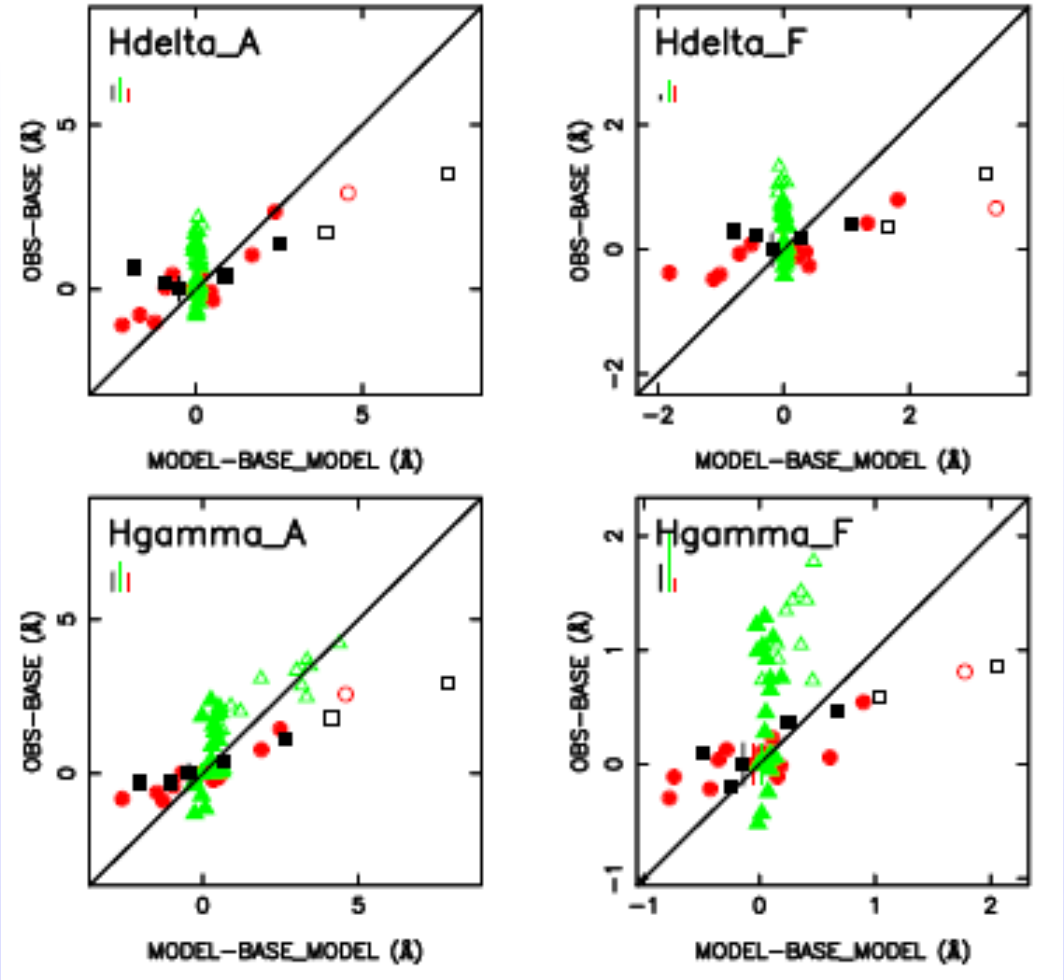






Testing K05 Response functions: H-Balmer indices

Observations versus models



Key:

= 1:1 line (agreement)

■ = Cool dwarf stars (CD)

▲ = Turnoff stars (TO)

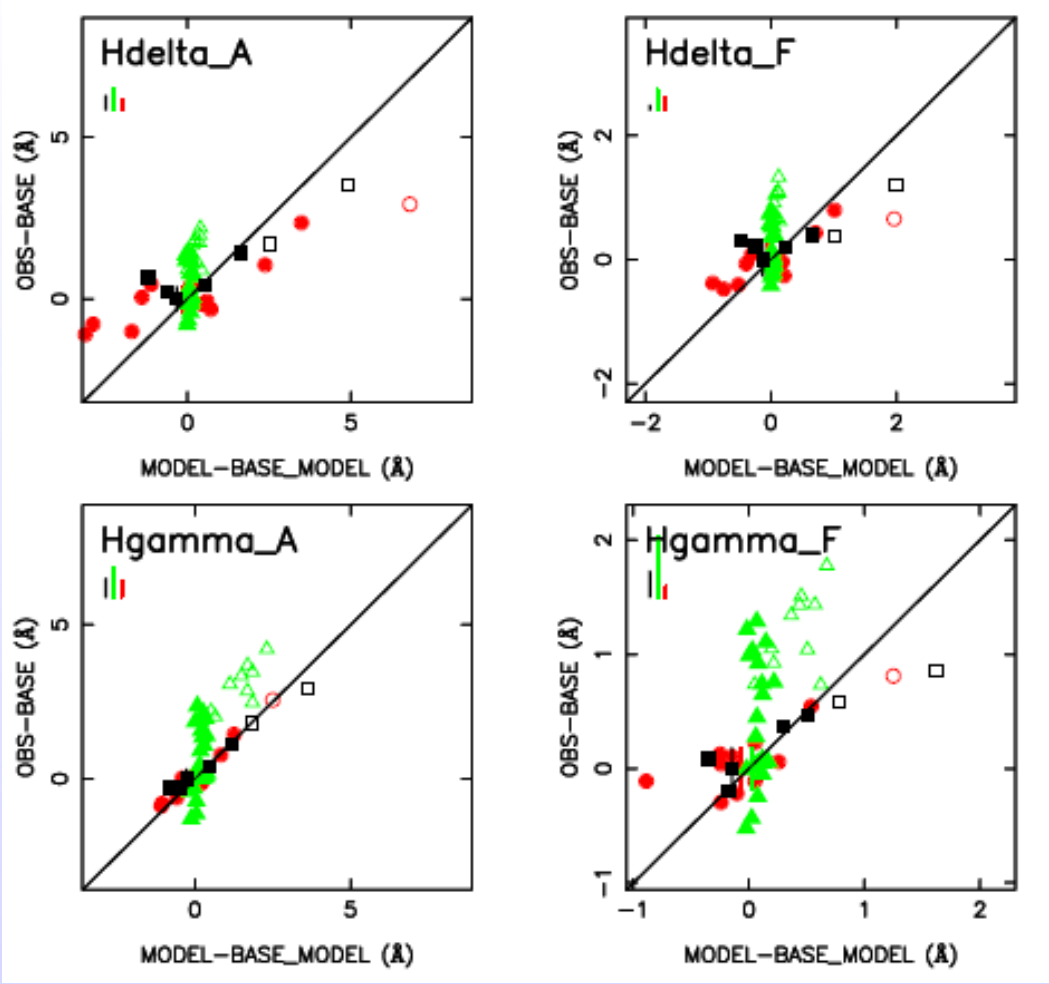
● = Cool giant stars (CG)

Open symbols = low [Fe/H] <-0.4

Other Response Functions

*Houdashelt et al. 2002 (**H02**)* – Update of *TB95. (*Only 3 stars)

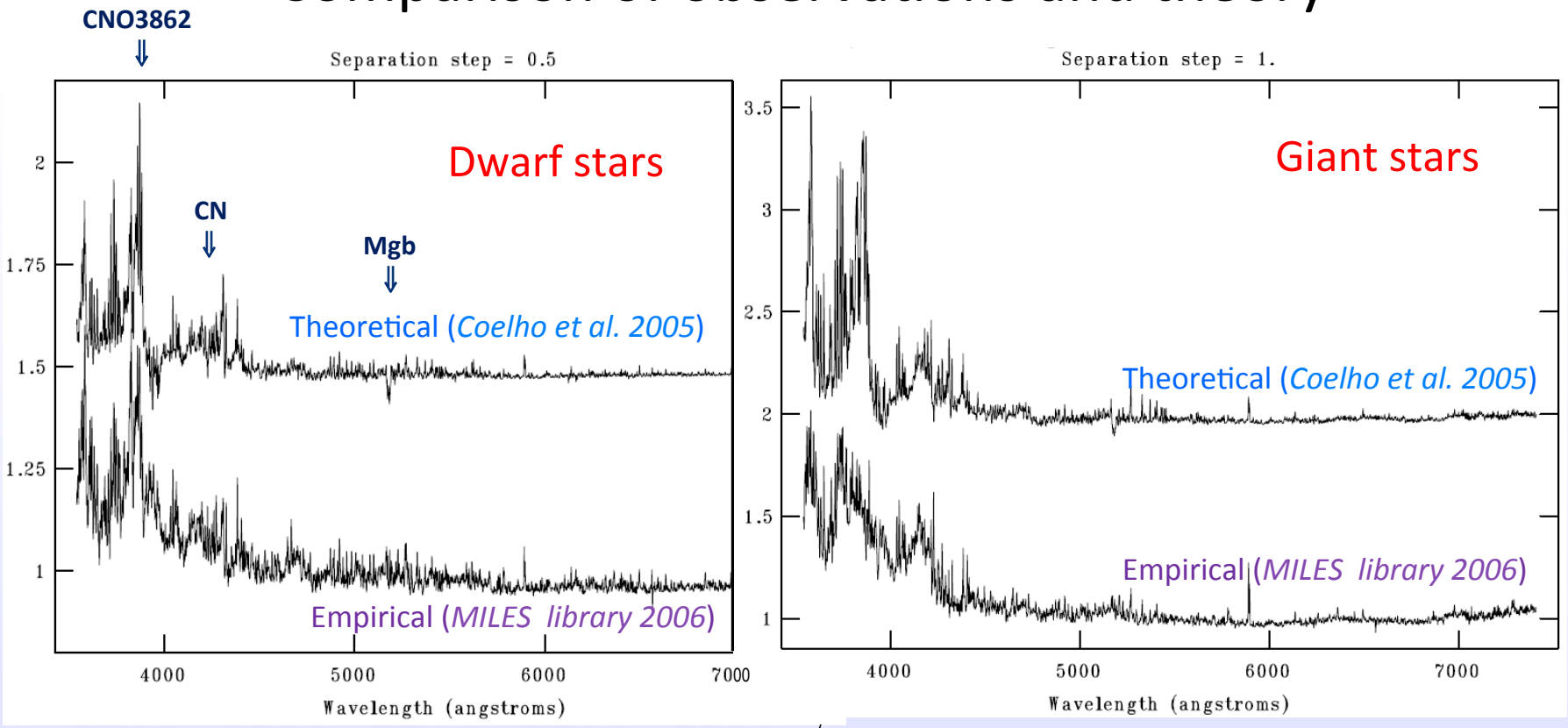
– Results similar to *K05*, but with **improved Hγ responses**.



H02

Ratios of **enhanced /solar** spectra

Comparison of observations and theory

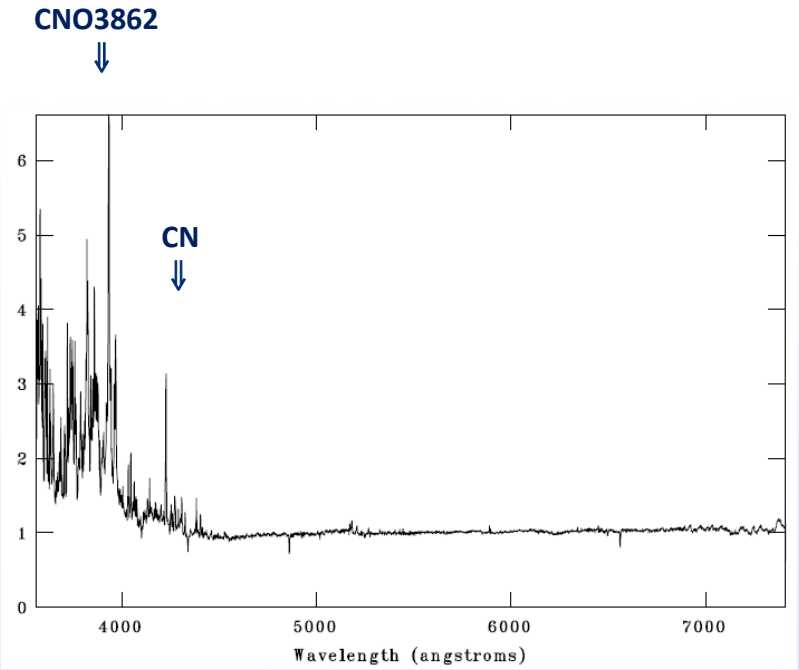


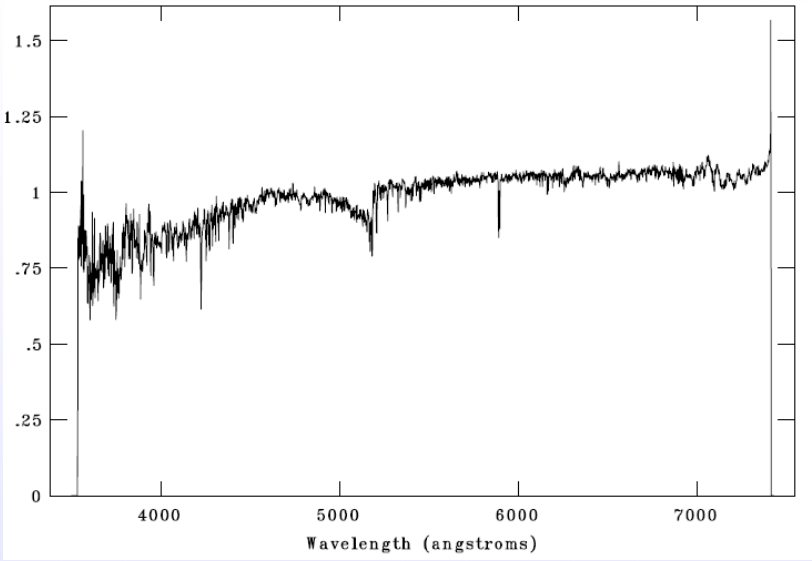
$$\text{Ratio} = \left[\frac{\alpha}{Fe}\right] = +0.4 \Big/ \left[\frac{\alpha}{Fe}\right] = 0.0$$

Dwarf stars: (T_{eff}=5500K, Log(g)=4.0, [Z/H]=0.0) Giant stars: (T_{eff}=4500K, Log(g)=2.0, [Z/H]=0.0)

Find: Excess flux in blue region of enhanced spectra. Differences between obs. & theory.
E.g. CaHK, Mg3835, CNO3862 (*Serven et al. 2005*).

Ratios of MILES giant star spectra



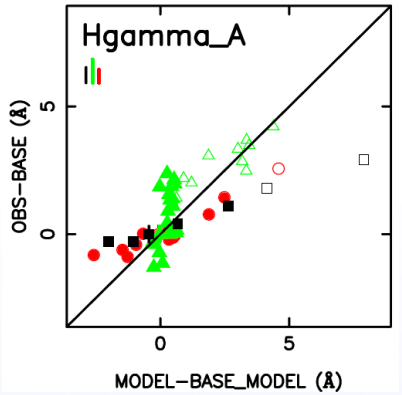


Same [Z/H], different [Mg/Fe],[Fe/H]

Same [Fe/H], different [Mg/Fe],[Z/H]

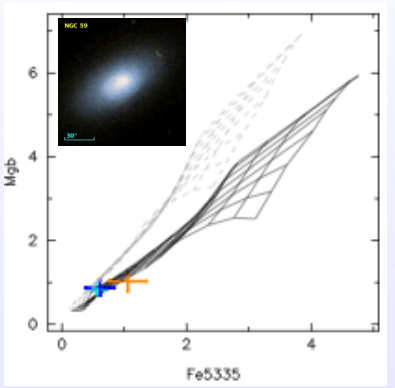
Differences in blue may be dominated by [Fe/H] changes.
With smaller effects due to [Mg/Fe] changes, plus CNO effects.

Summary



Element response functions R:-

- Fe indices – work well (*S13*)
- Hγ, Hδ – systematics *K05* – need revisiting – ***H02* better**
- Mg, Ca, CN indices – large scatter but expected trends
  – comparisons limited by Δobs.



Empirical stellar libraries:-

- Vital for testing spectral dependence on ***abundance patterns***
- MILES library has [Mg/Fe] measurements (*M11*), others needed
- Will improve α-element measurements in ***populations***
- UV/Blue sensitive to abundance variations, mainly Fe, C, N

Future:-

- ❑ H-Balmer indices – testing other theoretical models (e.g. *Coelho14; ?*)
- ❑ New features in the blue and model lower [α/Fe] (for dwarf galaxies)
- ❑ Effects of other elements (e.g. Ca, C, N) – *(Accuracy?)*
- ❑ Test against real stars
- ❑ Way forward – Empirical base SSPs + model abundance pattern
  but – needs a wide library of well tested theoretical star spectra