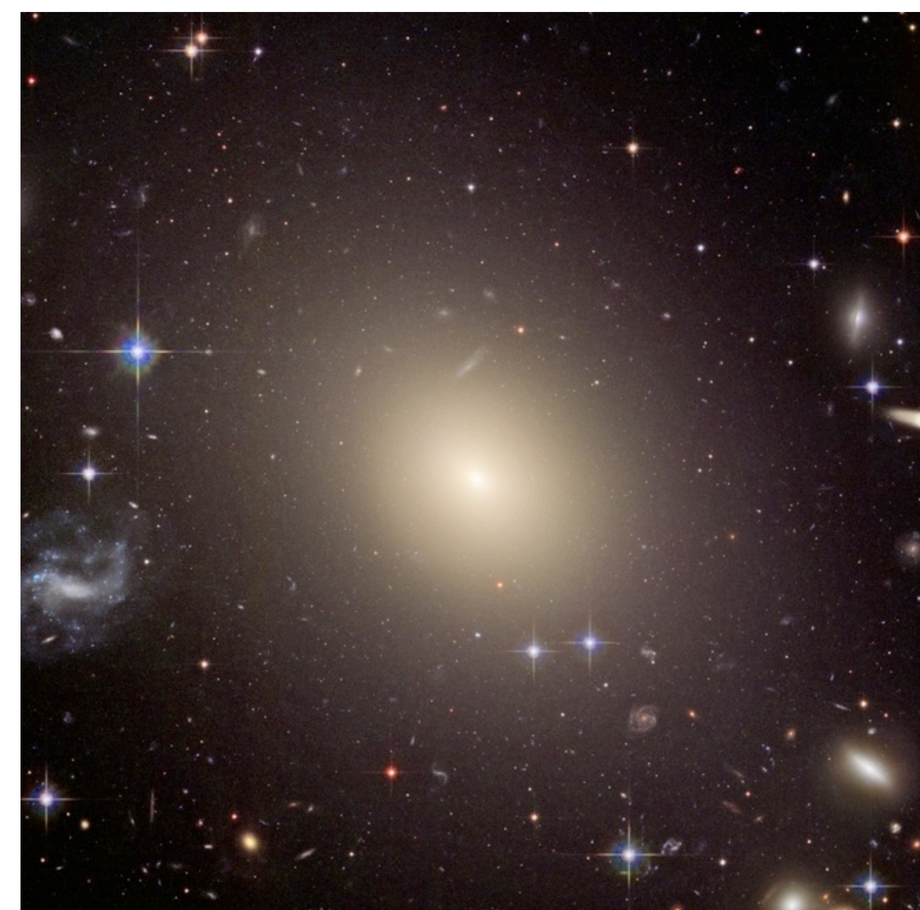
Stellar Populations - Lecture III



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Course outline

1. Introduction

- Phases of stellar evolution

- Simple Stellar Populations

2. Resolved Stellar Populations

- Cluster CMDs

- SSP fitting: age, metallicity, IMF

- Complex populations: SFH, MDF

- Exotica

- Limitations

3. Population synthesis

- Principles and caveats

- Temperature, metallicity and gravity effects on stellar spectra.

- Flux contribtions

- Colours

  Optical age-metallicity degeneracy

  Beyond the optical

- Spectral synthesis

  Empirical and theoretical stellar libraries

  Spectroscopic age/ metallicity indicators.

  IMF indicators

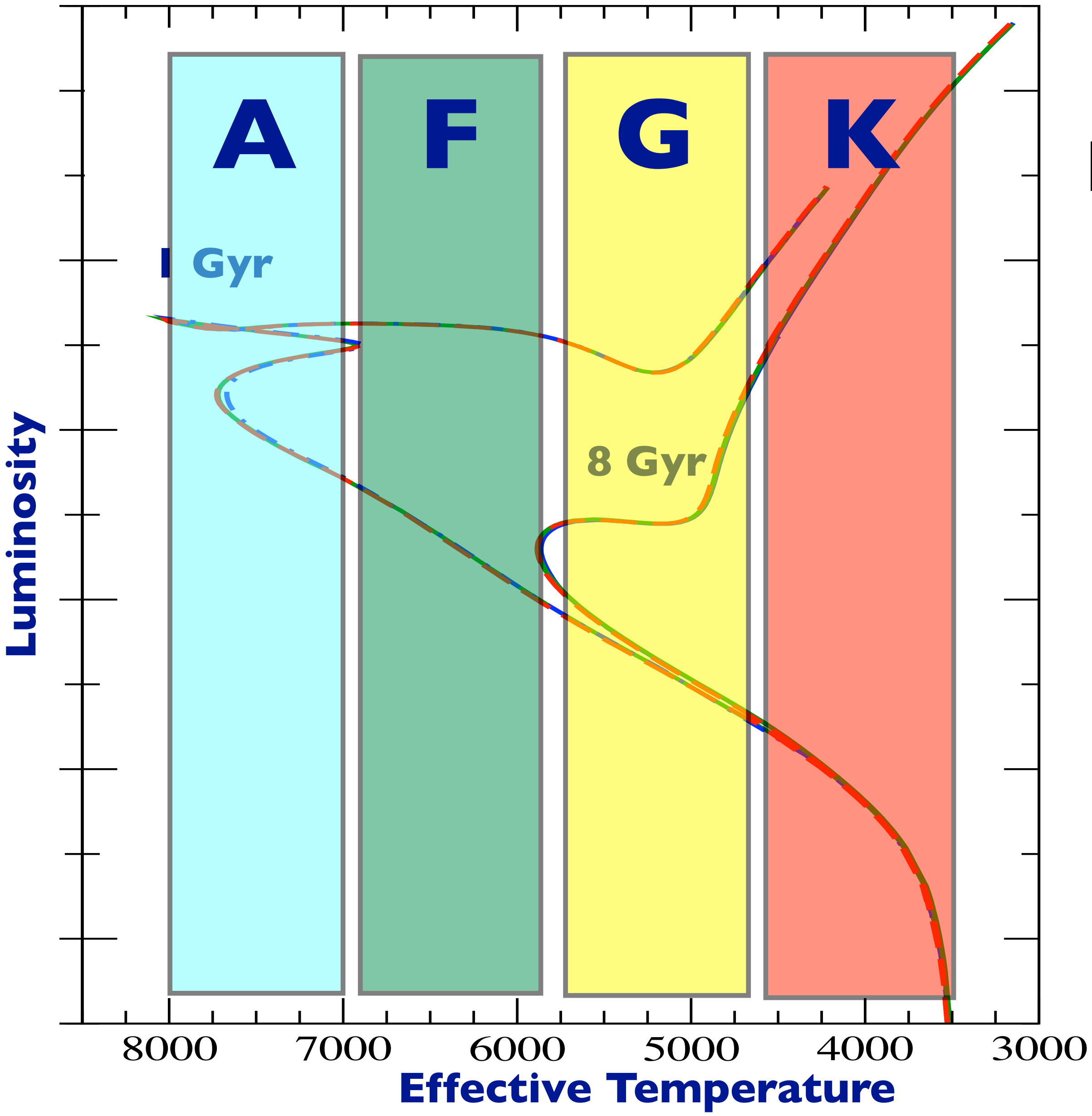
4. Applications

- Chemical evolution.

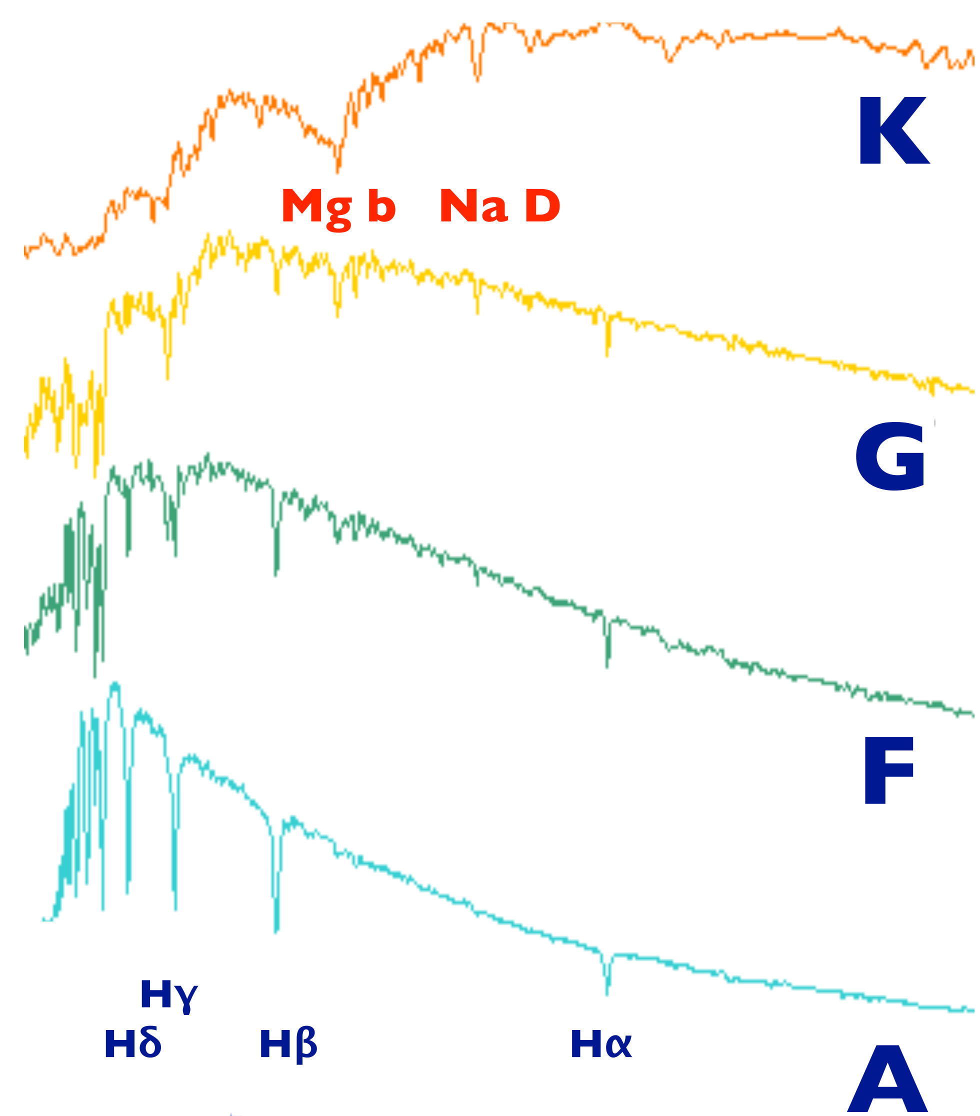
- Star-formation histories

- Stellar masses & photometric redshifts

Spectral synthesis



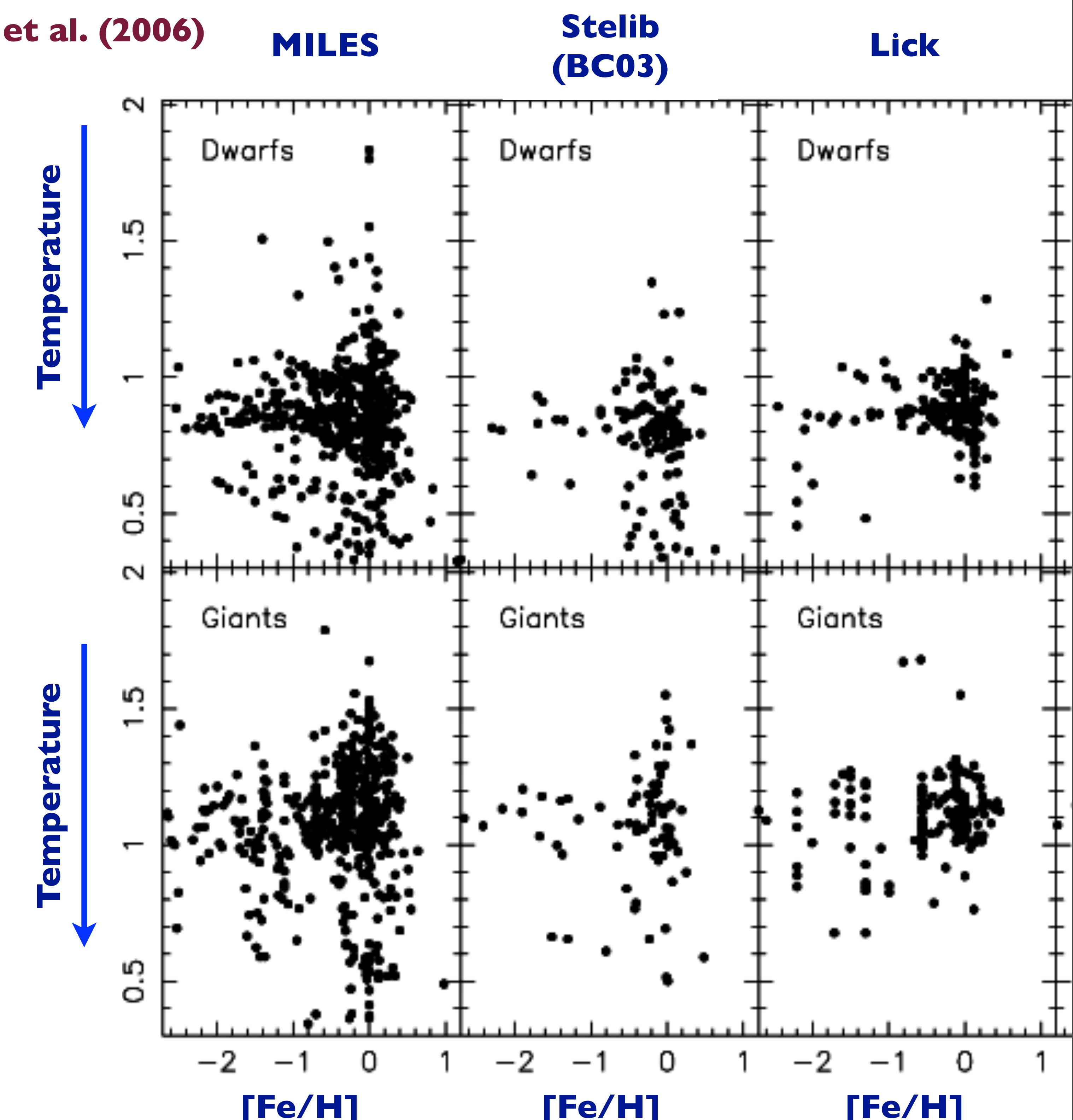
$$F_\lambda(t, Z) = \int_{M_{lo}}^{M_{up}(t)} S_\lambda(T_{eff}(M), g(M) \mid t, Z) \, . \, N(M) \, dM$$



Where do we get the stars?

Empirical spectral libraries

Sanchez-Blazquez et al. (2006)



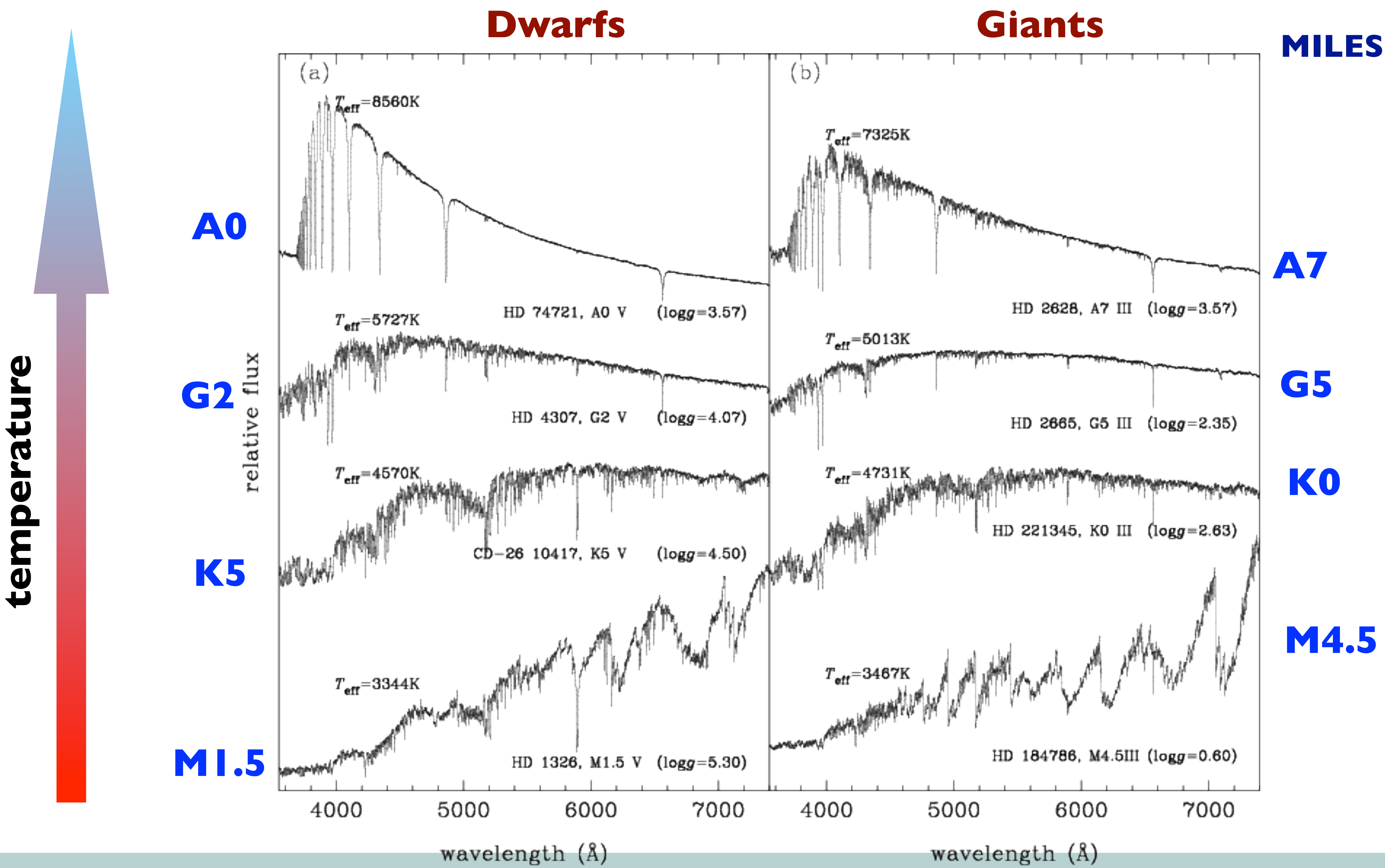
<u>OBSERVED</u> SPECTRA OF STARS

Need to cover large range in T_{eff}, log g (="gravity" i.e. dwarf vs giant) and Fe/H.

And to <u>know</u> the atmospheric parameters of the stars.

The spectra need to be "good": i.e. very high S/N, carefully flux-calibrated, corrected for atmospheric absorption etc.

Empirical spectral libraries

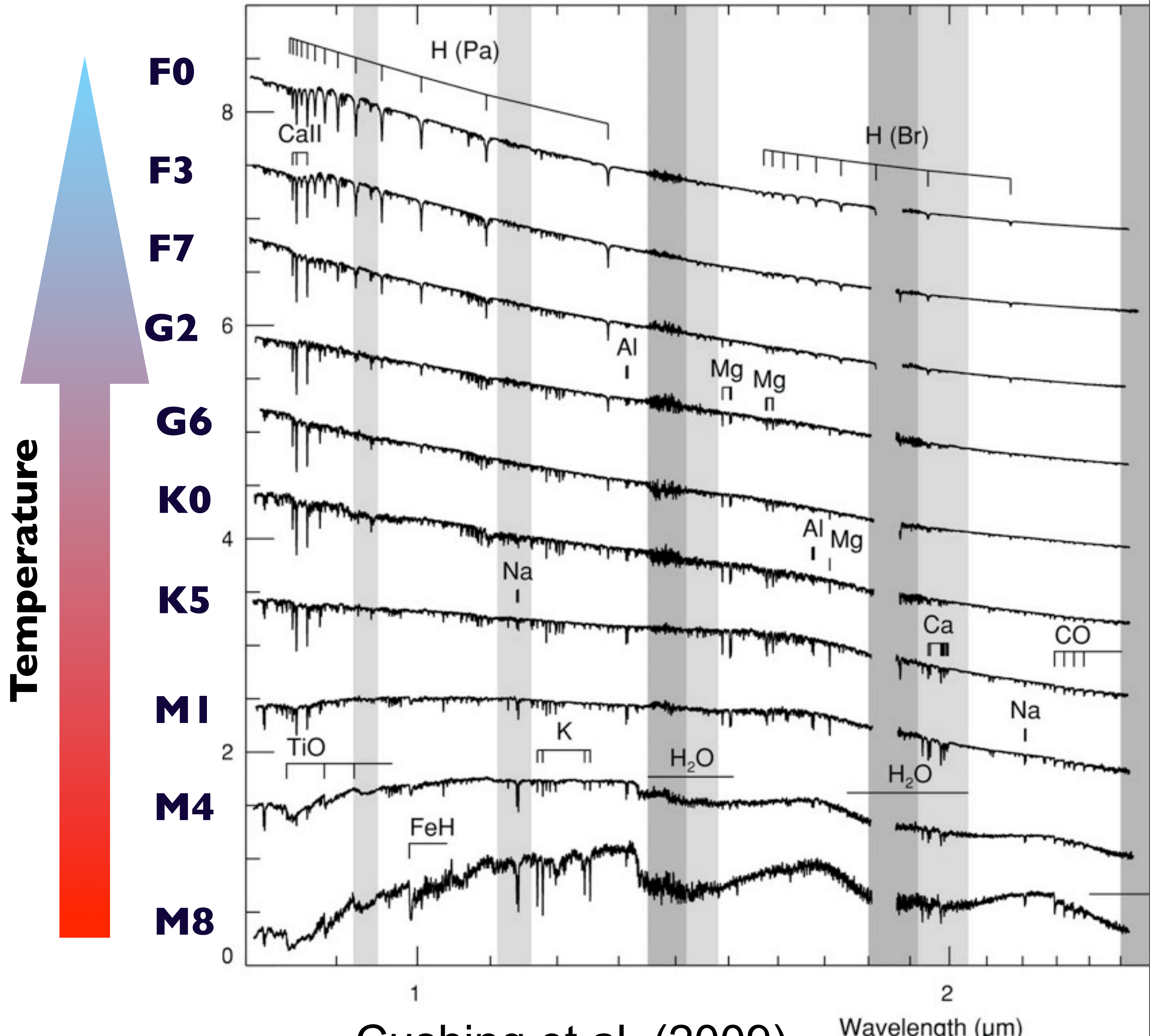


Empirical spectral libraries

IRTF library is state-of-the-art in the IR.

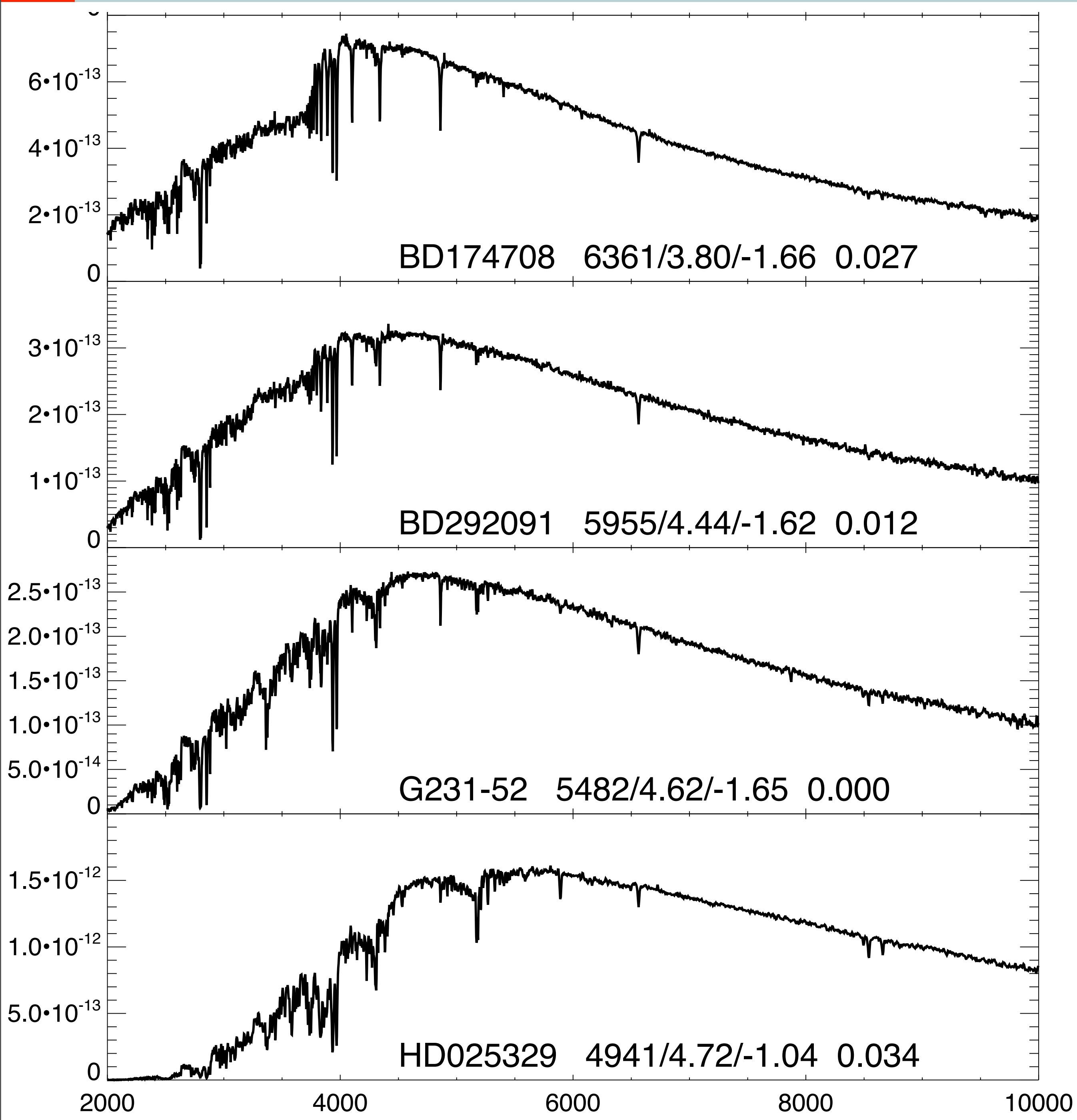
Much smaller than MILES (210 cool stars).

Restricted to near-solar metallicity.



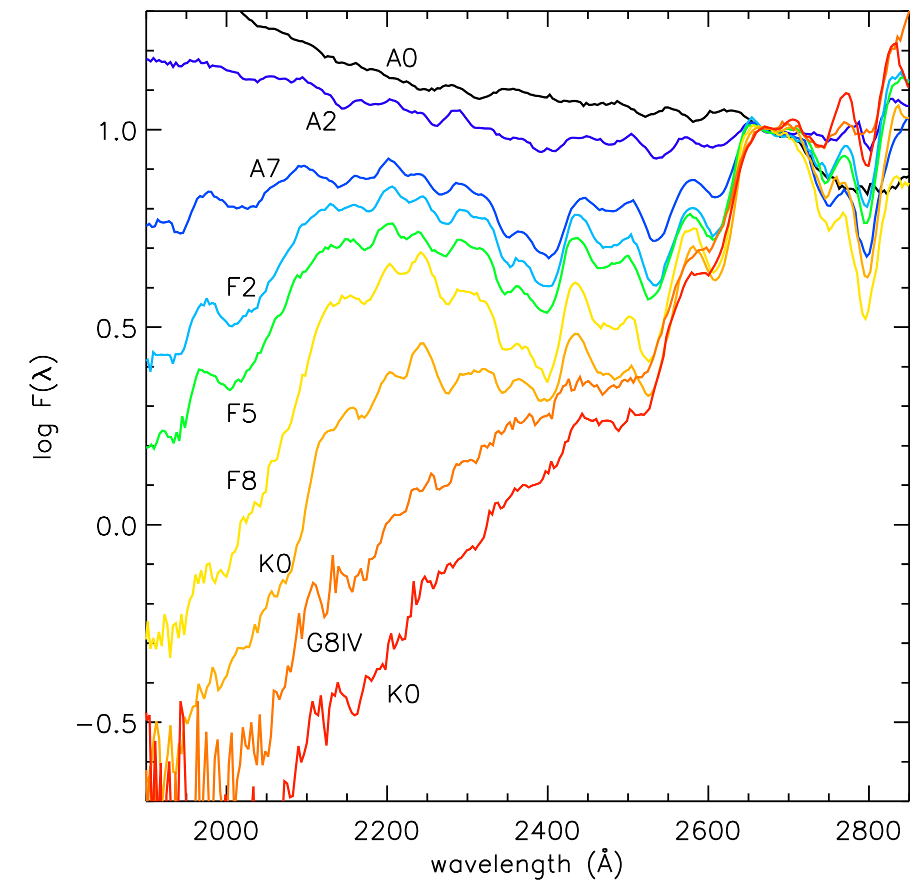
Cushing et al. (2009)

Empirical spectral libraries



Space observations necessary to build empirical library in the <u>rest-frame</u> UV.

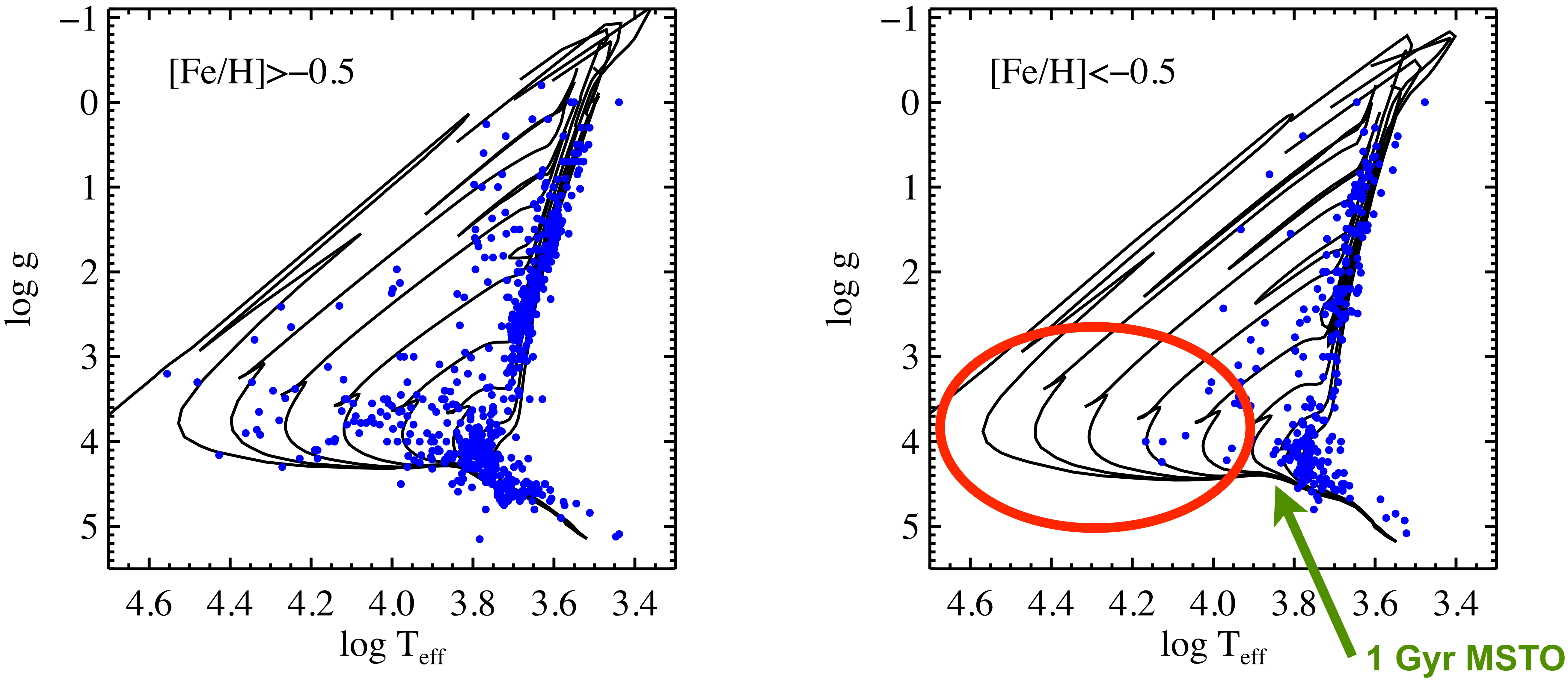
(Recall we might want such a library to interpret observed optical spectra of higher-redshift galaxies.)



HST NGSL : UV-optical spectral library with 374 stars.

Nascent GALEX library? Bertone & Chavez (2011)

Empirical spectral libraries

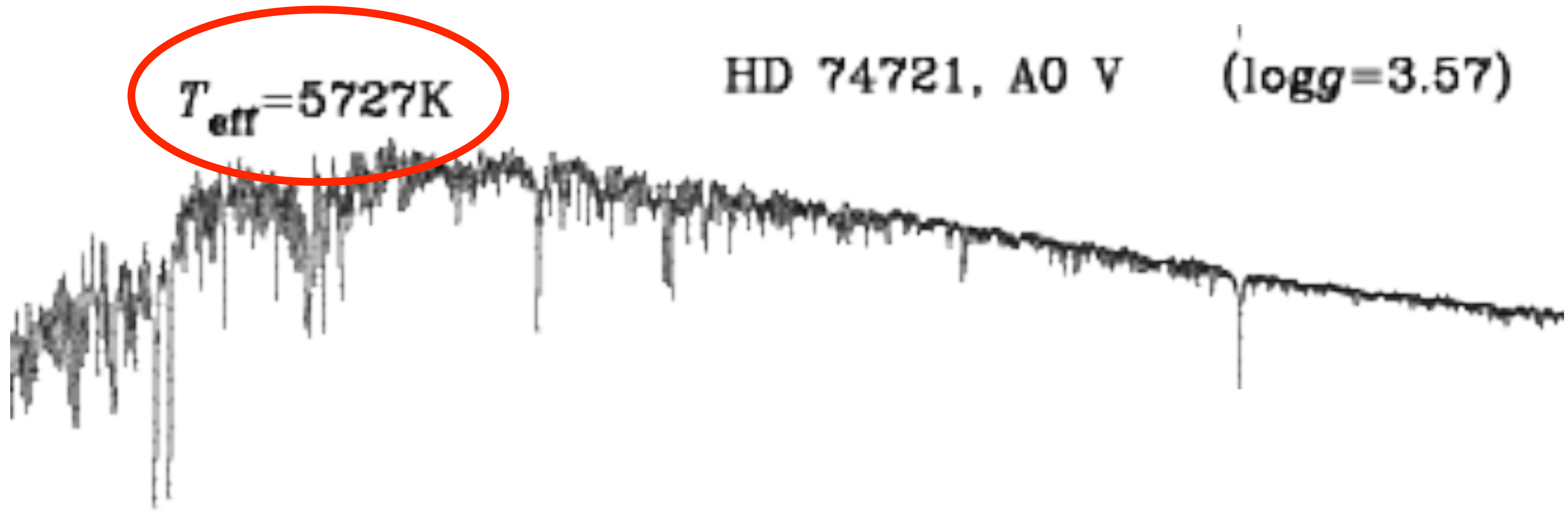


MILES coverage - currently the <u>best</u> published optical library.

Missing low-metallicity dwarfs at T_{eff} > 8000 K, required to synthesise ages <1 Gyr.

Unavoidable: young stars in solar neighbourhood are all metal-rich!

Empirical spectral libraries



Need to *know* the temperatures to match spectrum to correct point on the HRD. And to know the metallicities, to attach to correct isochrone.

Fundamentally, the temperature scale is derived from interferometric measurements of stellar radius, via $L_{bol} = (4\pi R^2)\,\sigma T_{eff}^4$

Metallicities from comparison of library spectra to stellar model spectra, or through high-resolution spectra to measure invididual lines. Difficult for cool stars.

Theoretical spectral libraries

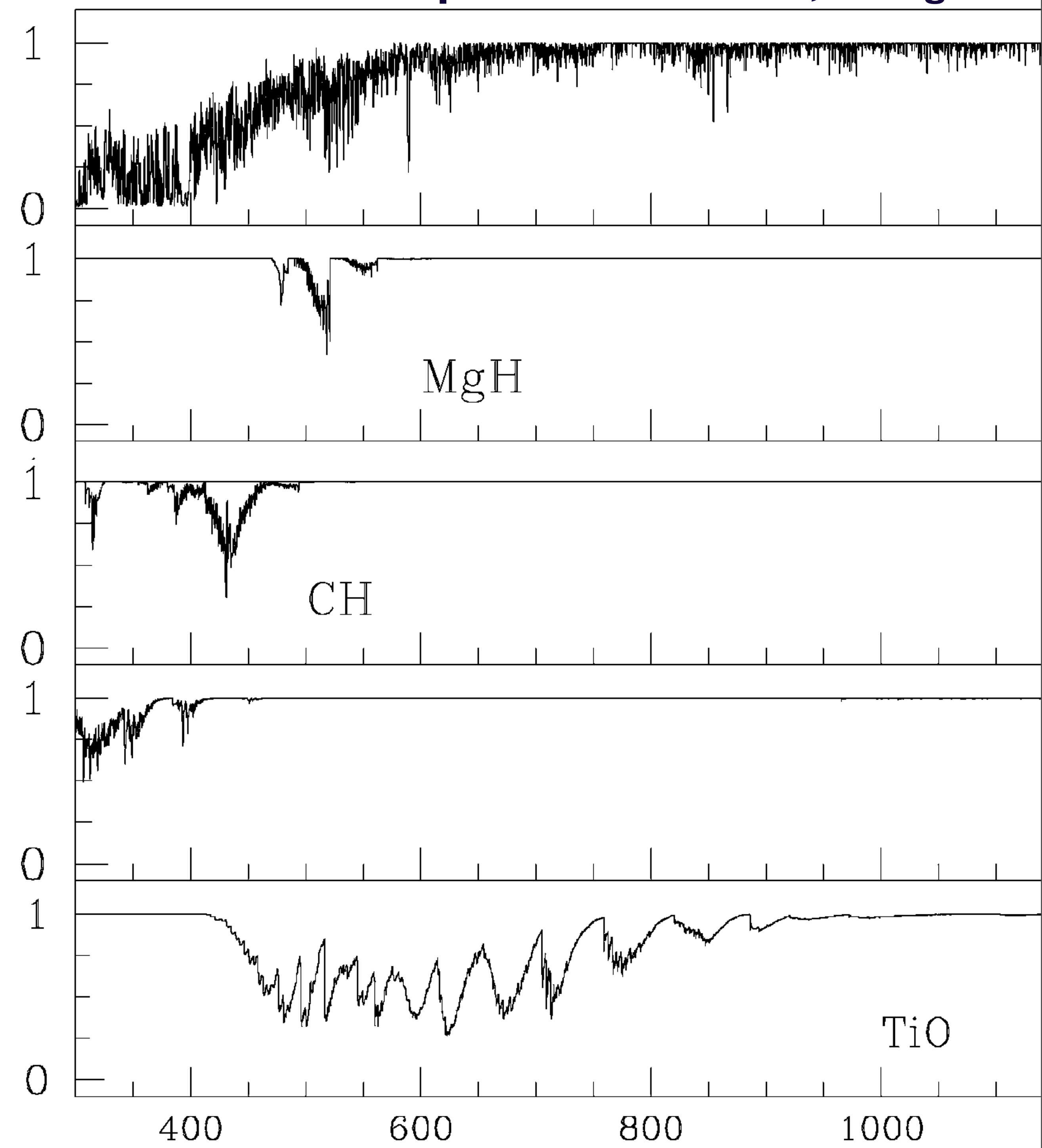
Fundamental limitation of empirical libraries is poor coverage of stellar parameter space by local-neighbourhood stars in the MW.

<u>Alternative possibility: build stars from scratch in a computer.</u>

Model the absorption by all the possible spectral lines of all the species (atoms, ions, molecules) present, and compute expected spectrum.

Advantages obvious: can compute for arbitrary set of atmospheric parameters, and densely sample the parameter space.

Absorption contributions, cool giant



Coelho et al. (2005)

Theoretical spectral libraries

<u>But:</u> in detail, the theoretical spectra do not match perfectly...

Problem is that there are literally millions of atomic/molecular lines to include.

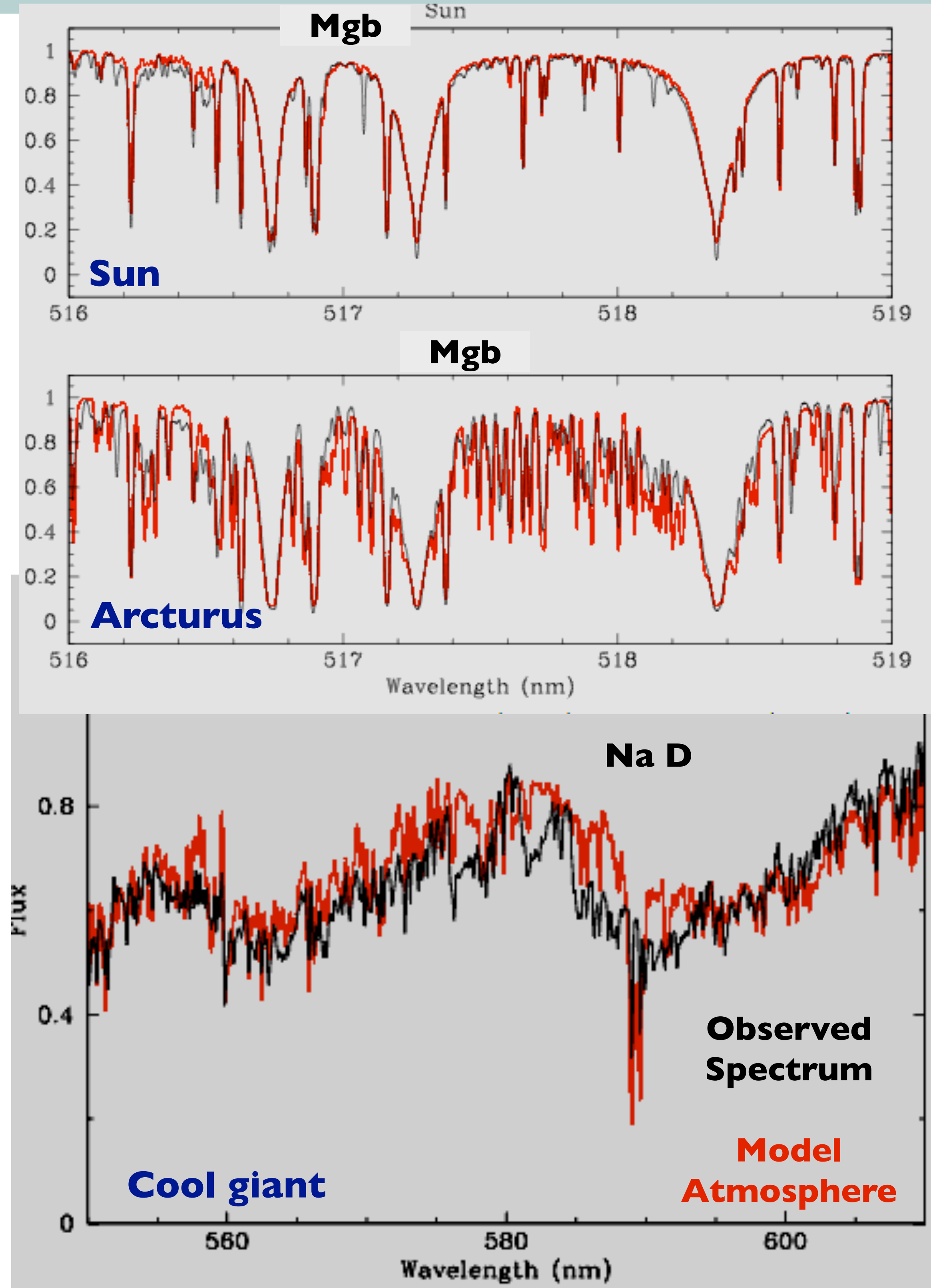
E.g. Current Kurucz line-lists include >37M lines for TiO alone.

Many lines are not measured in the lab, but are predicted by QM.

QM predictions for wavelengths and oscillator strengths have large uncertainties.

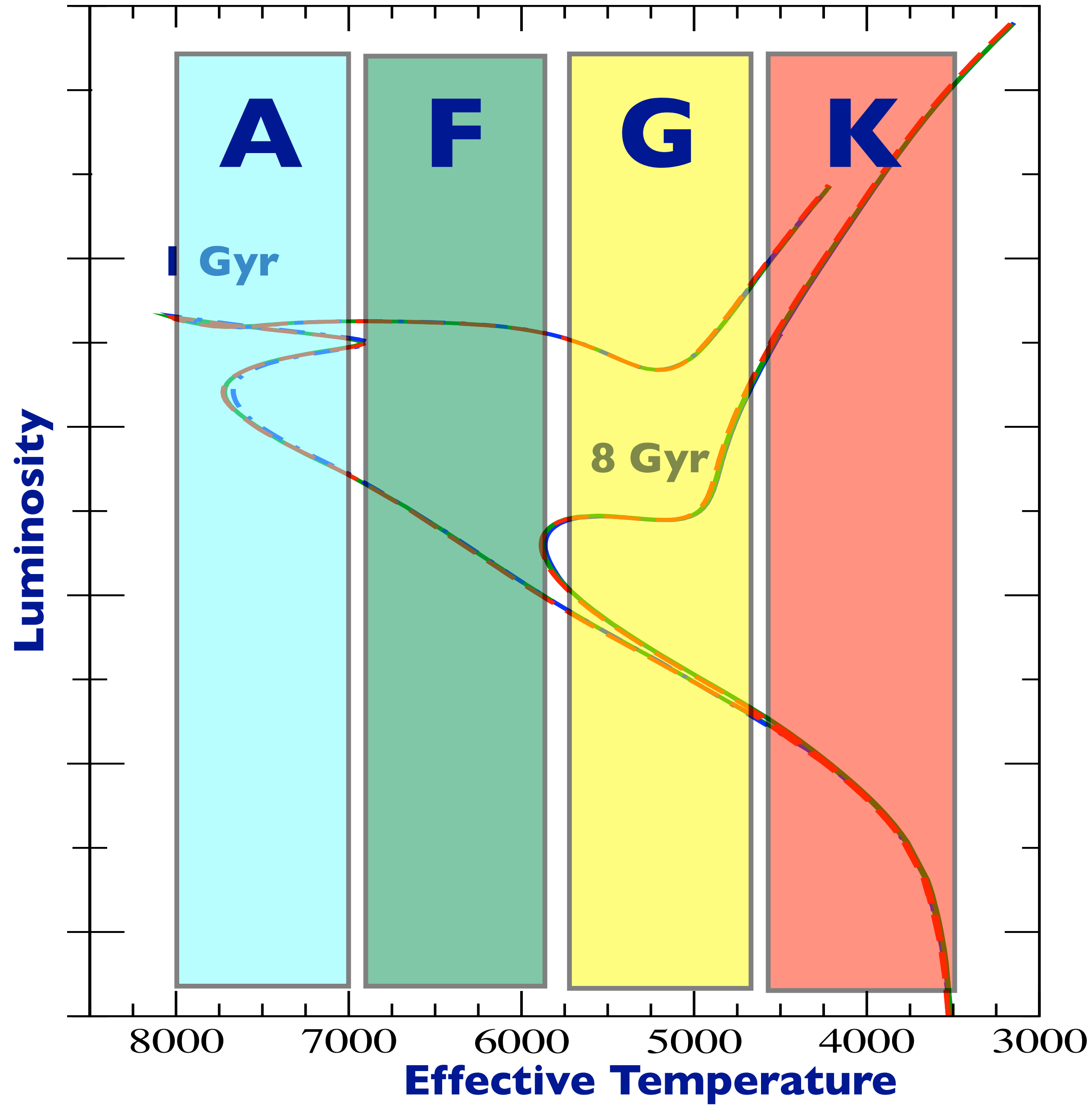
A “good” model for high-resolution stellar analysis is not a good model for broad-band fluxes.

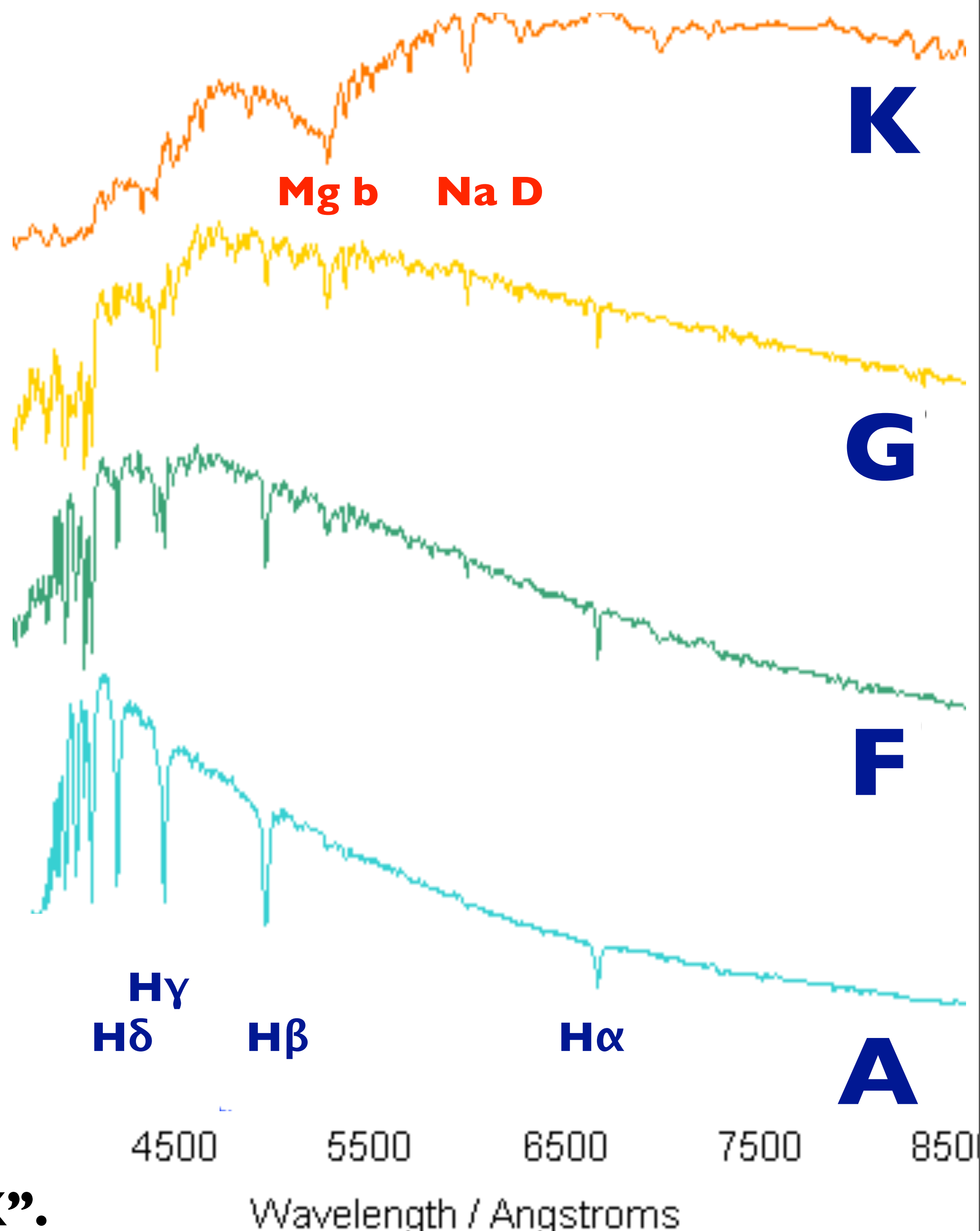
Problems are worst in the blue (atomic line blanketing) and at low temperatures (molecular line lists).



Coelho et al. (2005)

Spectral synthesis





Expect:

8-Gyr population to be "somewhere between G and K".

1-Gyr population to show strong H-lines from A stars.

Galaxy spectra

RESOLUTION LIMITATIONS

Internal motions of stars within a galaxy cause Doppler broadening.

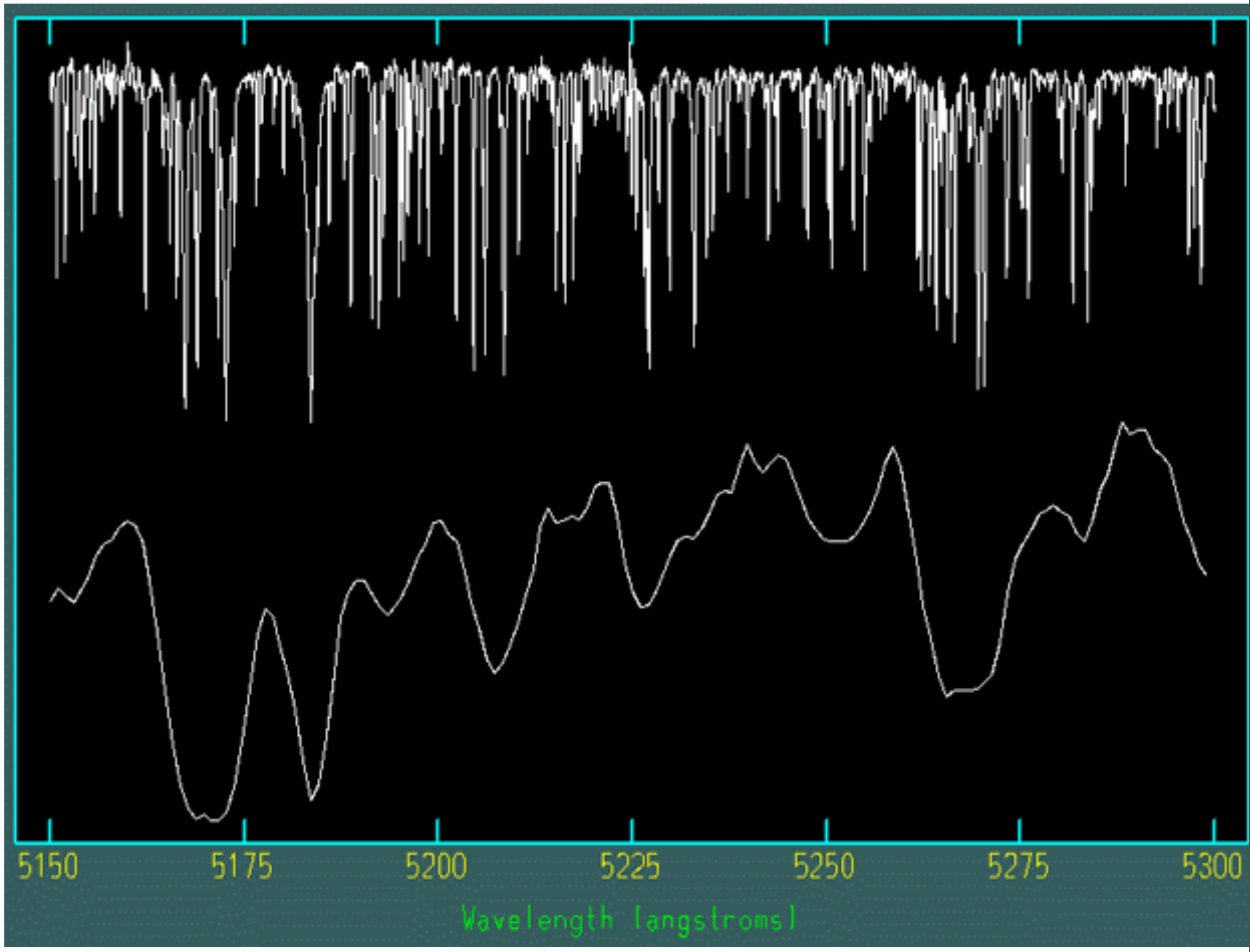
For large elliptical galaxy v>200 km/s.

Cannot reach resolution higher than R= Δλ/λ ~ 1000... no matter how powerful the spectrograph

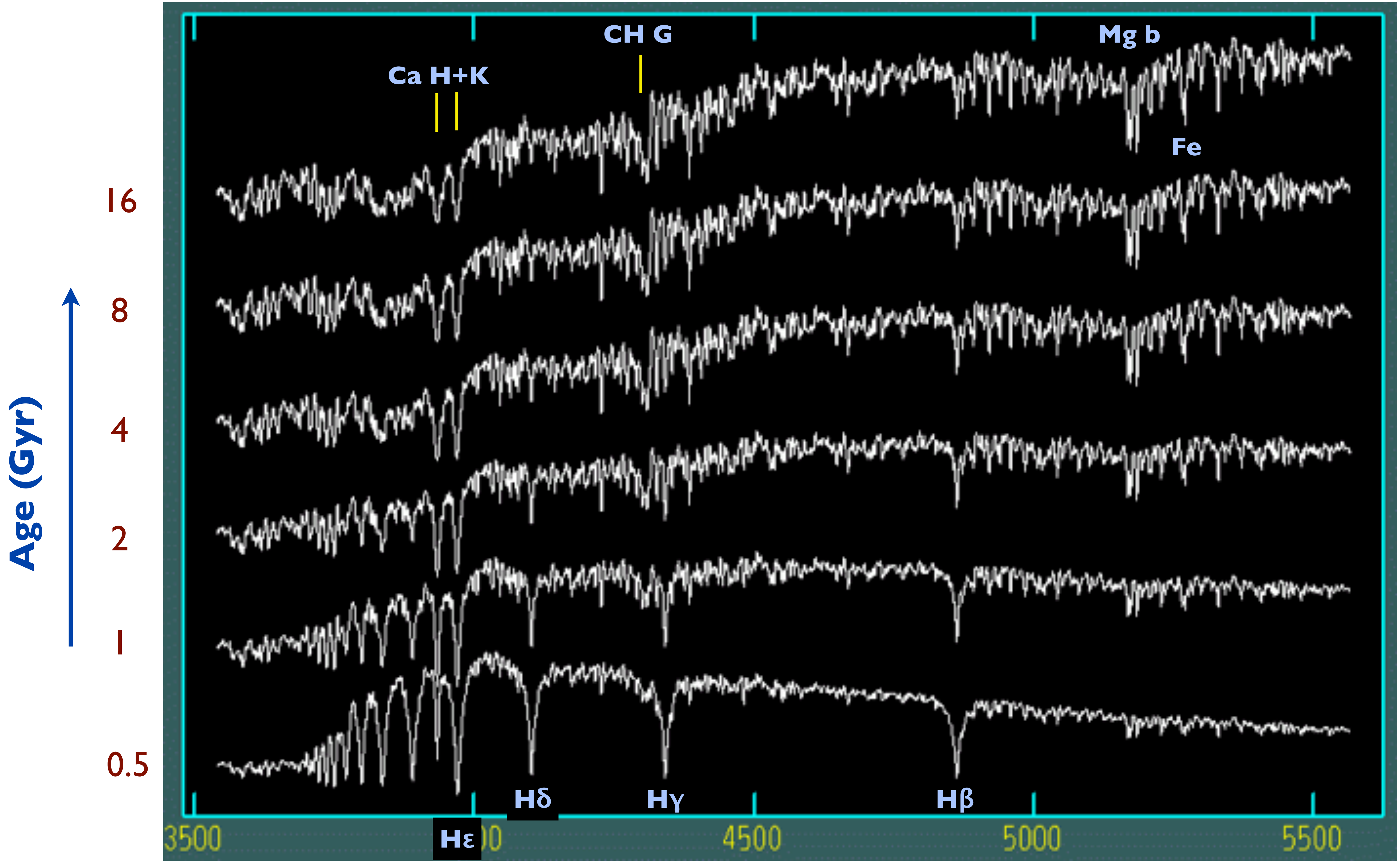
All the features in the galaxy spectrum are blends of many lines.

Continuum is no longer well-defined.

Hence we cannot isolate individual lines.

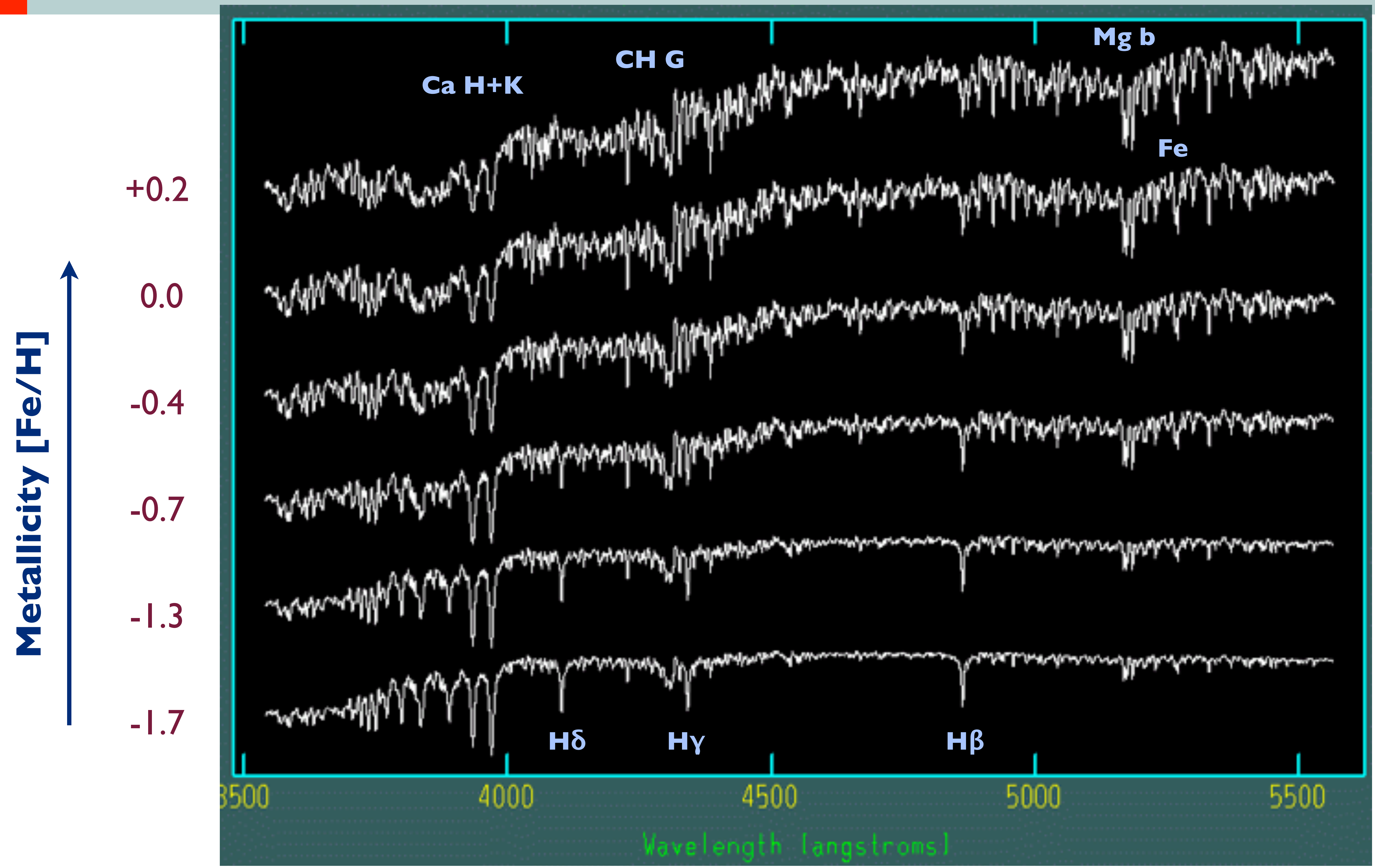


SSP spectra: age sequence



Vazdekis et al. (2007) models at solar Fe/H from MILES library.

SSP spectra: metallicity sequence



Vazdekis et al. (2007) models at age 10 Gyr from MILES library

Disentangling age and metallicity

BREAKING THE DEGENERACY WITH SPECTRA

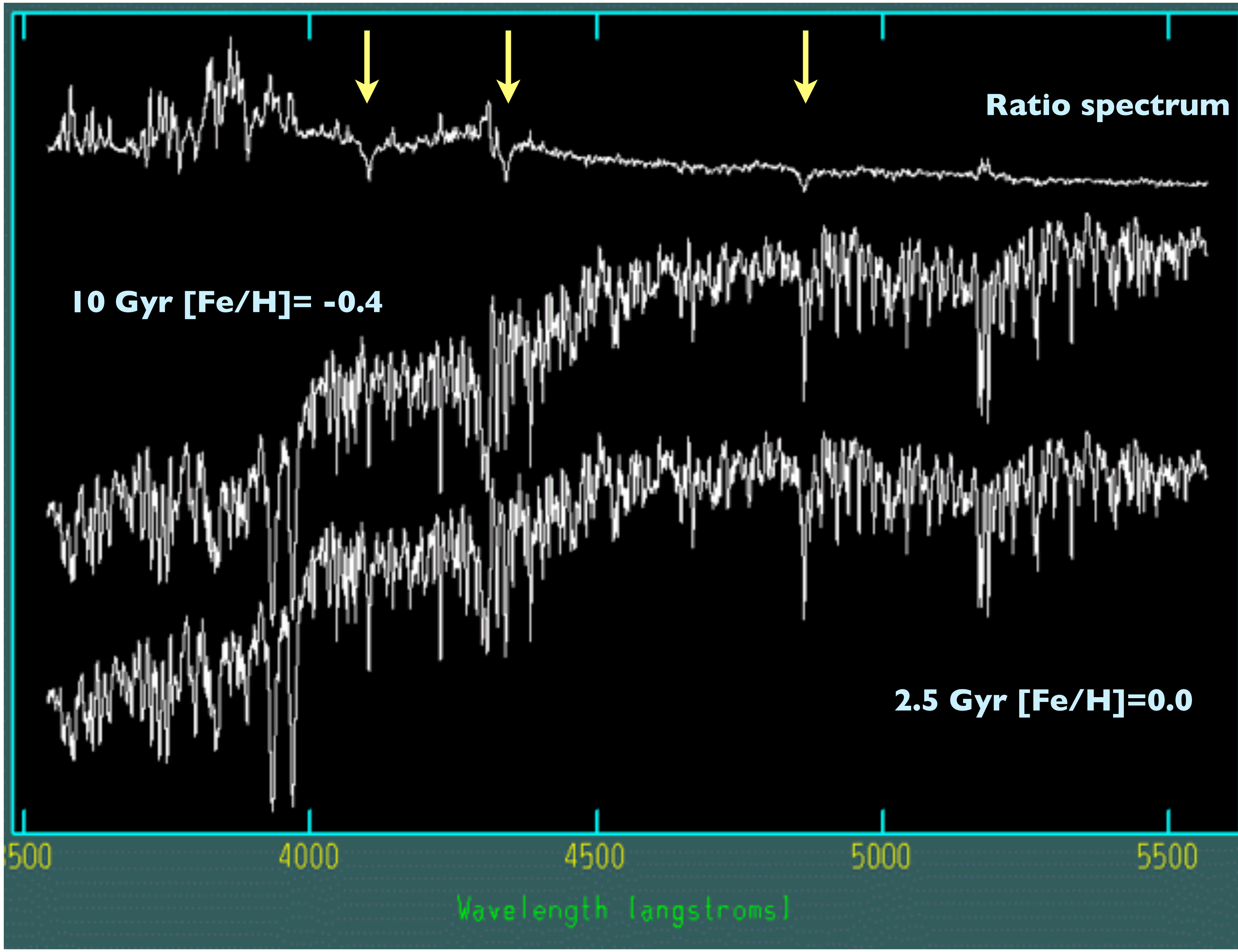
Two spectra with age and metallicity chosen to produce same broad-band colours.

Similar spectra, but differences in detail at the Balmer lines. Also differences at λ<4000Å.

We can exploit this localized spectral information to beat the age-metallicity degeneracy.

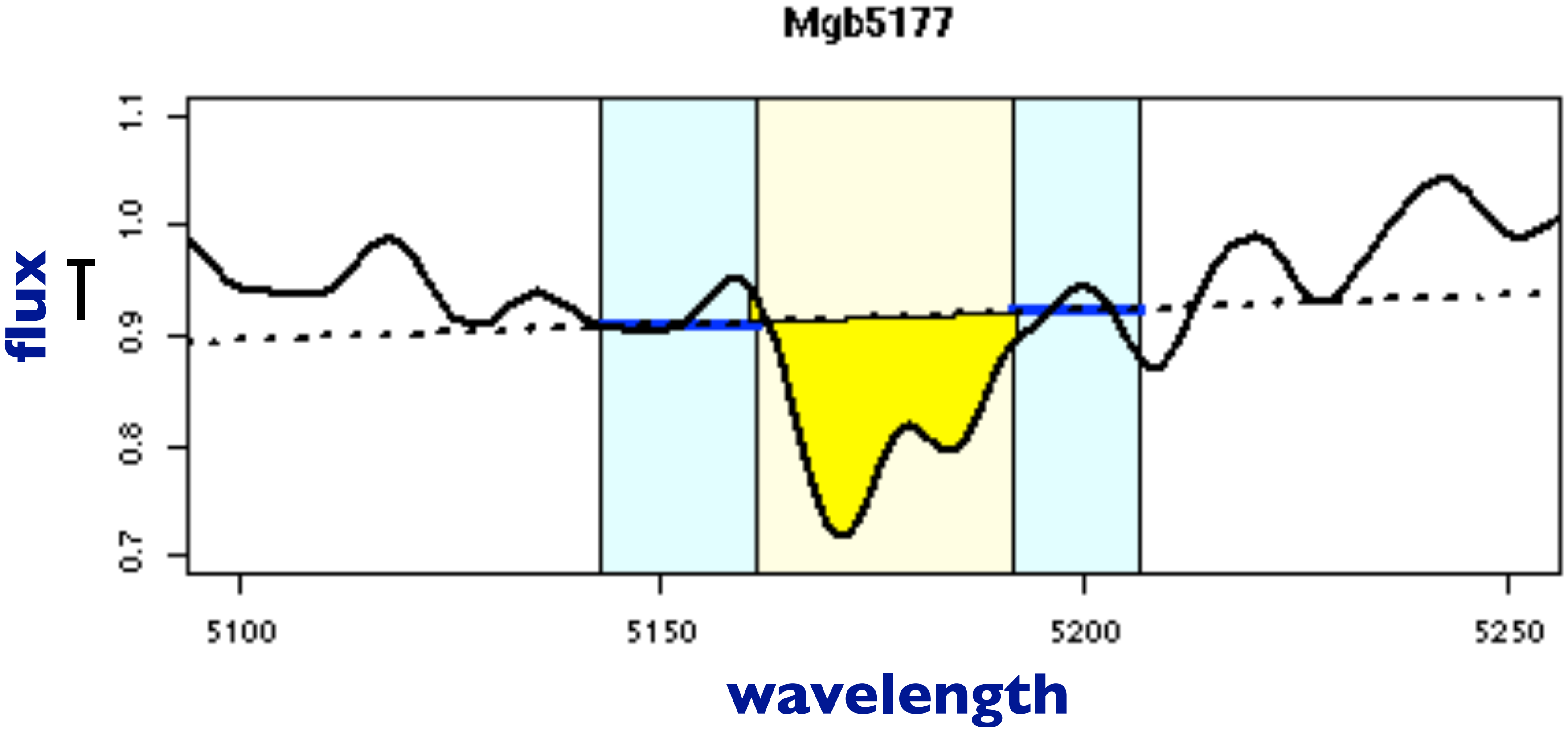
<u>But how?</u>

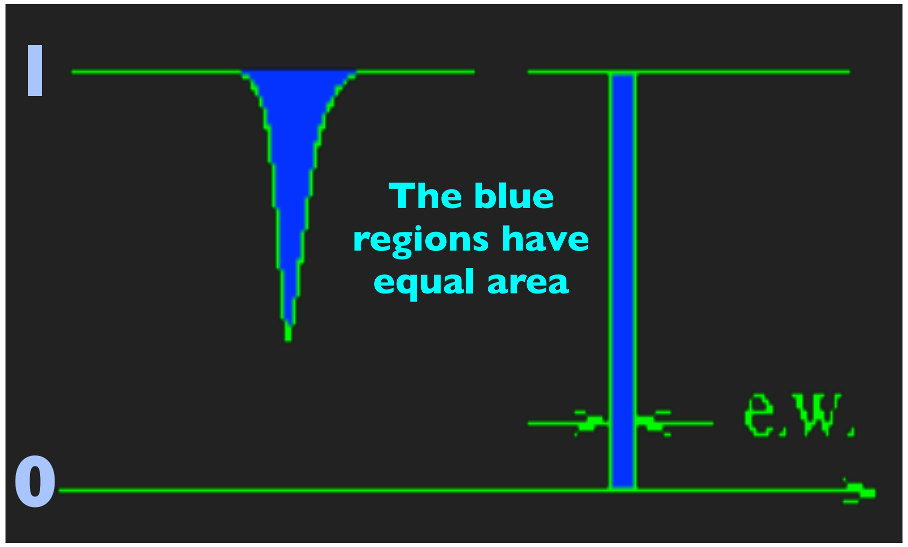
Indices vs full spectral fitting.



Vazdekis et al. (2007) models from MILES library

Absorption indices





EW is the width of a square, completely-absorbed segment of the spectrum with same integrated absorption as the line itself.

Degeneracy-breaking power of spectra is largely localised to particular features.

So define "indices" which isolate these features and so carry much of the information in the spectra.

Cannot see "true" continuum. Use neighbouring region to define "pseudo-continua".

Express absorbed flux as an equivalent width.

Calibrate by measuring same features on models exactly as for the observed spectra.

NB: more modern methods model the full spectrum, but the index-based approach is still useful for illustrative purposes.

Line indices

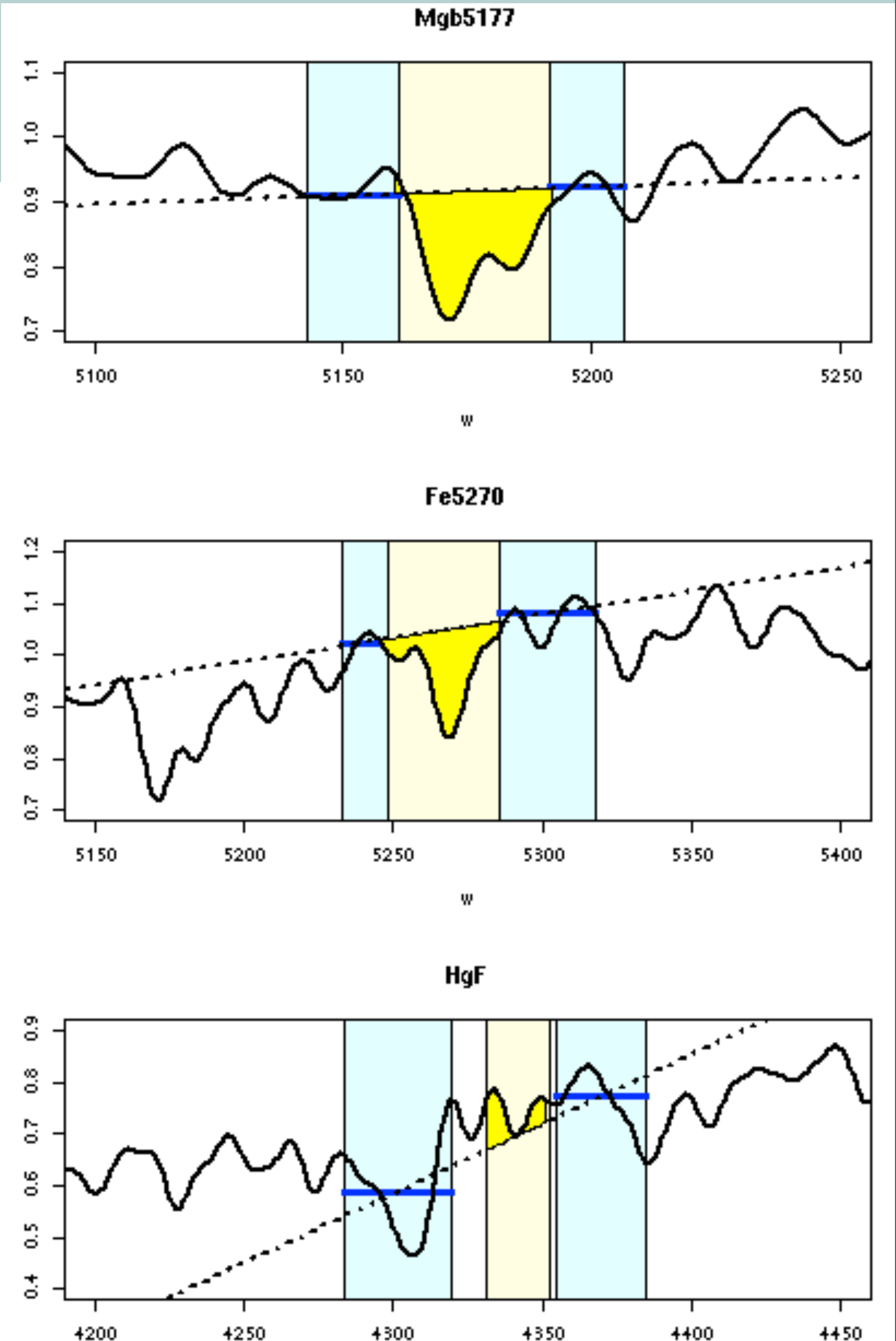
Pseudo-continua and index band defined to be ~10 Angstroms wide to match typical velocity dispersions in galaxies.

An index may be negative even though the feature it measures is still in absorption.

Historically important indices based on the Lick Observatory Stellar Library (Worthey et al. 1994).

Lick Library had low spectral resolution 9 Ang FWHM (okay for giant galaxies, but throwing away information for objects with lower velocity dispersions).

New indices often defined in similar way, e.g. narrow Hγ indices, Ca triplet indices in the red.

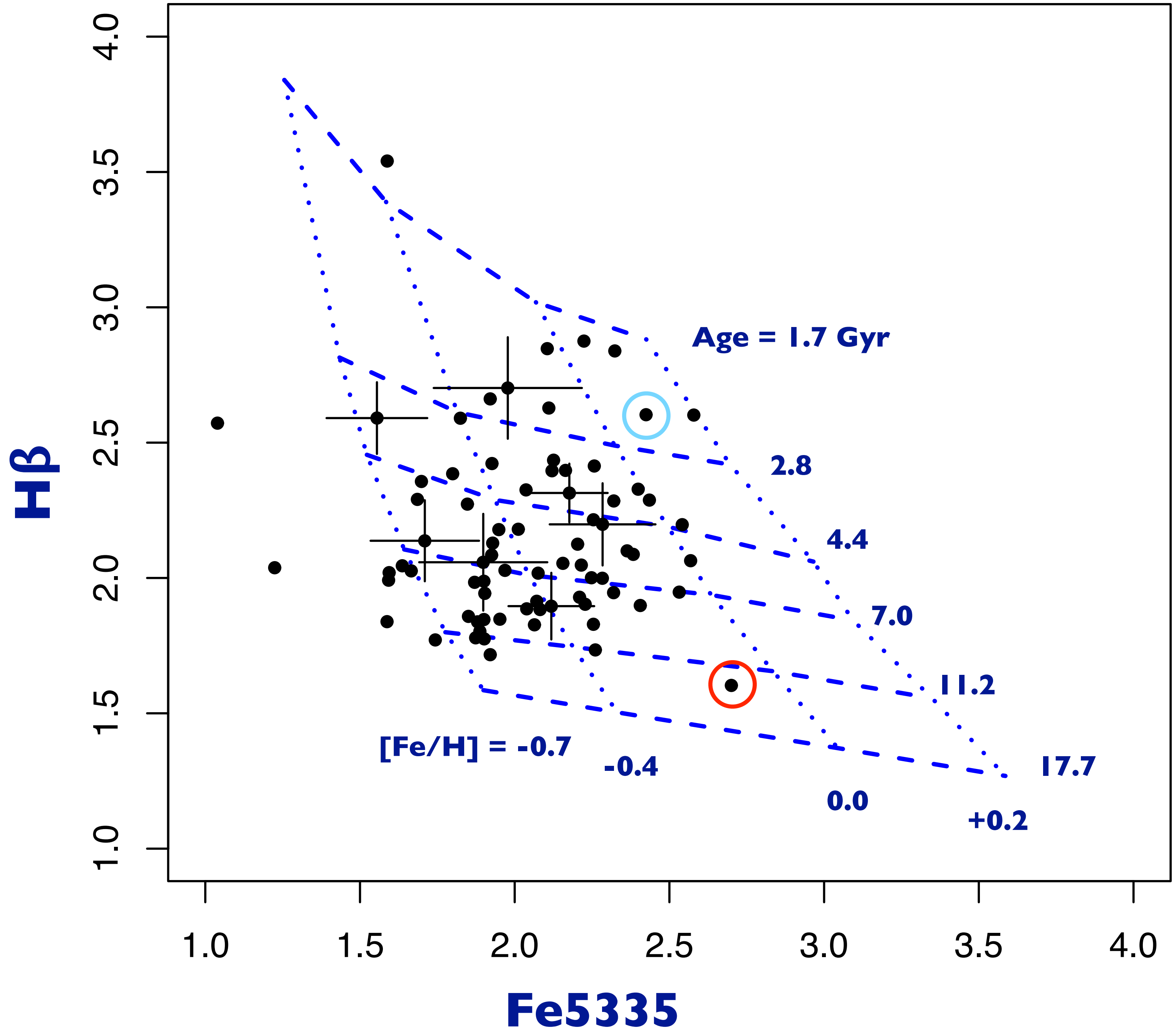


Age-metallicity grids

Either: Sum library spectra along isochrone and measure indices on the synthetic spectra(e.g. Vazdekis, Coelho, Percival).

Or: Measure indices on the library stars and compute luminosity-weighted average index along the isochrone (e.g. Worthey, Schiavon)

Result: Balmer-vs-metallic grids widely separate the constant-age and constant-metallicity tracks. So we can “read off” the results for an observed galaxy.



Grids: Schiavon et al. (2007).
Data for Coma cluster dEs from RJS et al. (2008)

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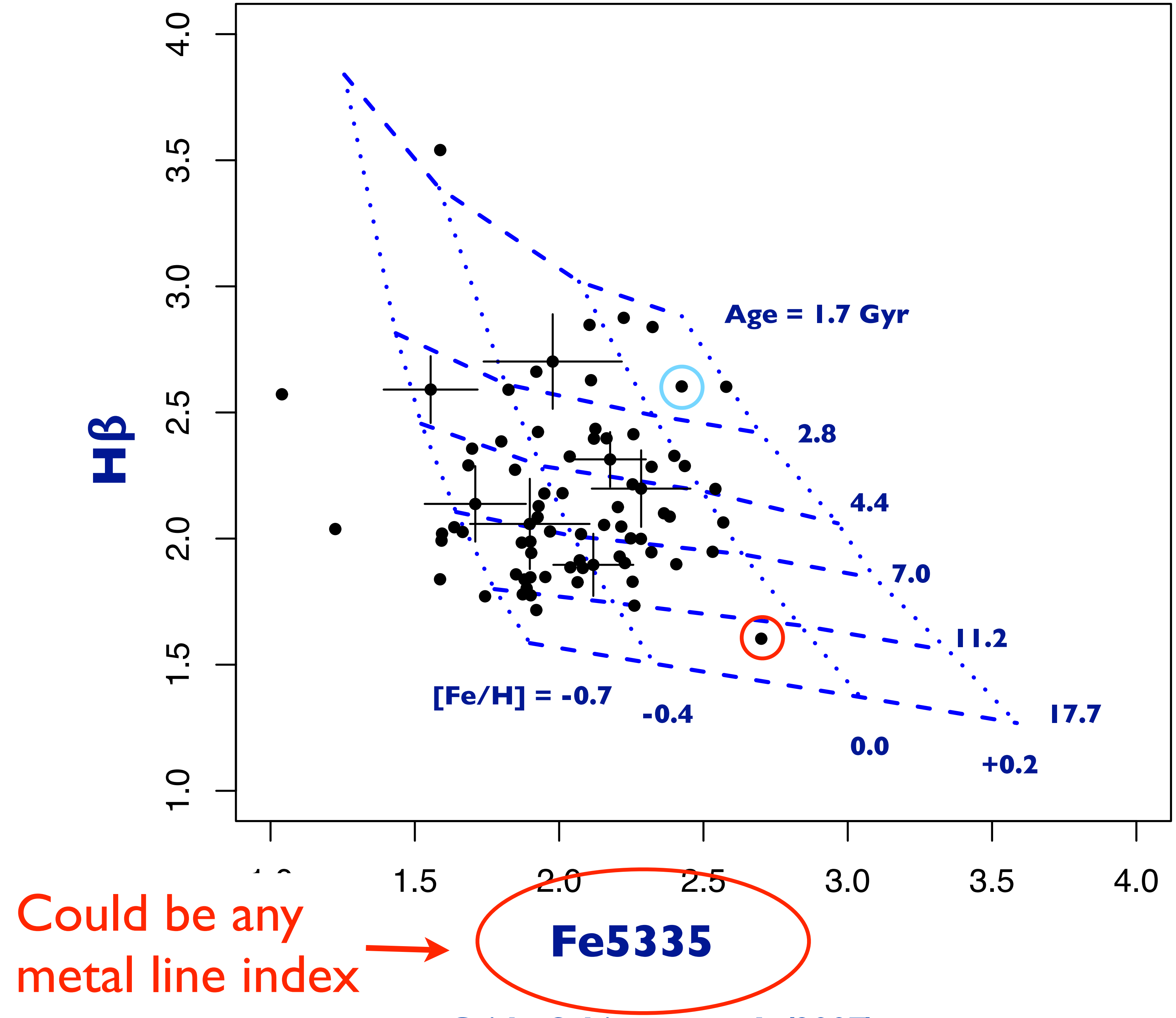

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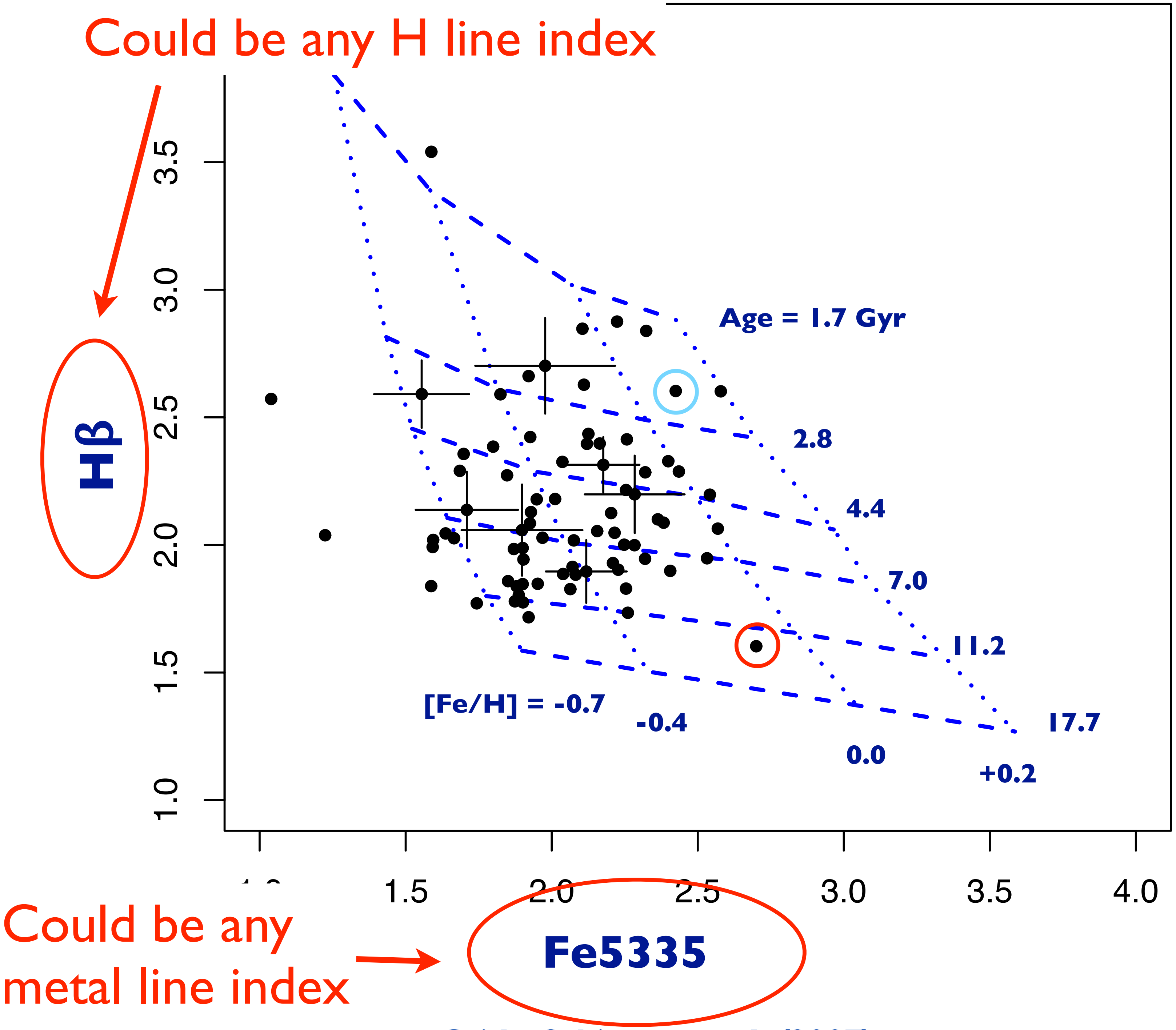

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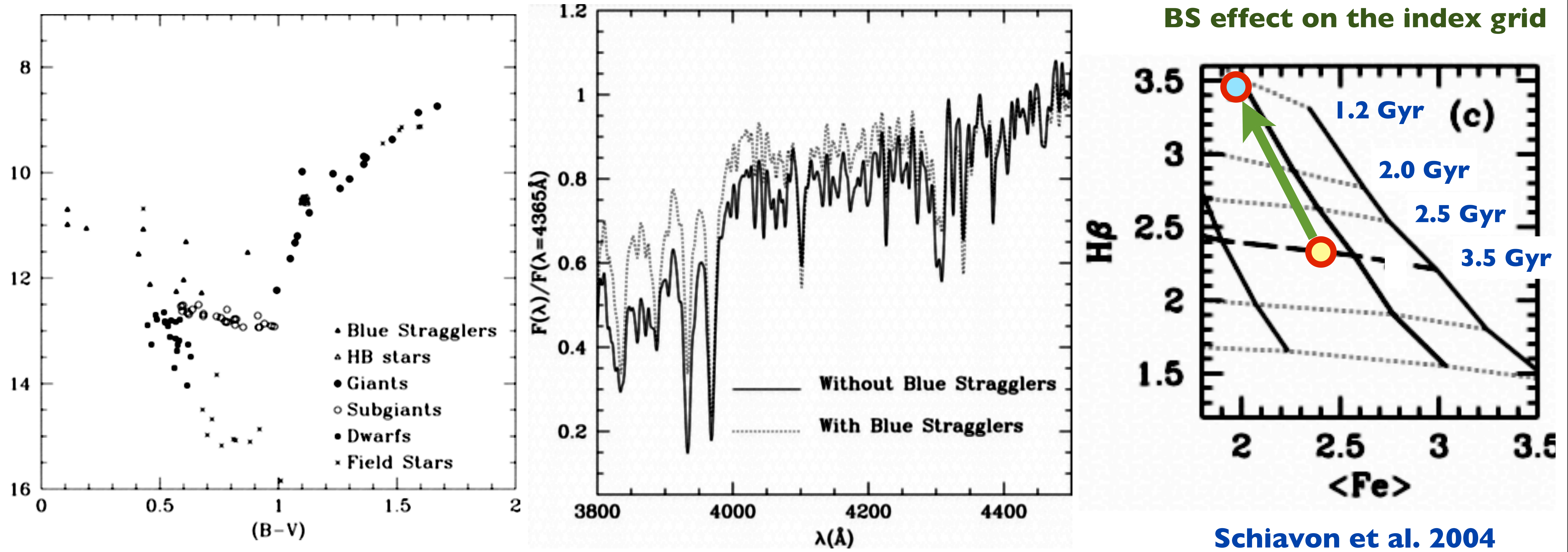
Are we including all the relevant stars?



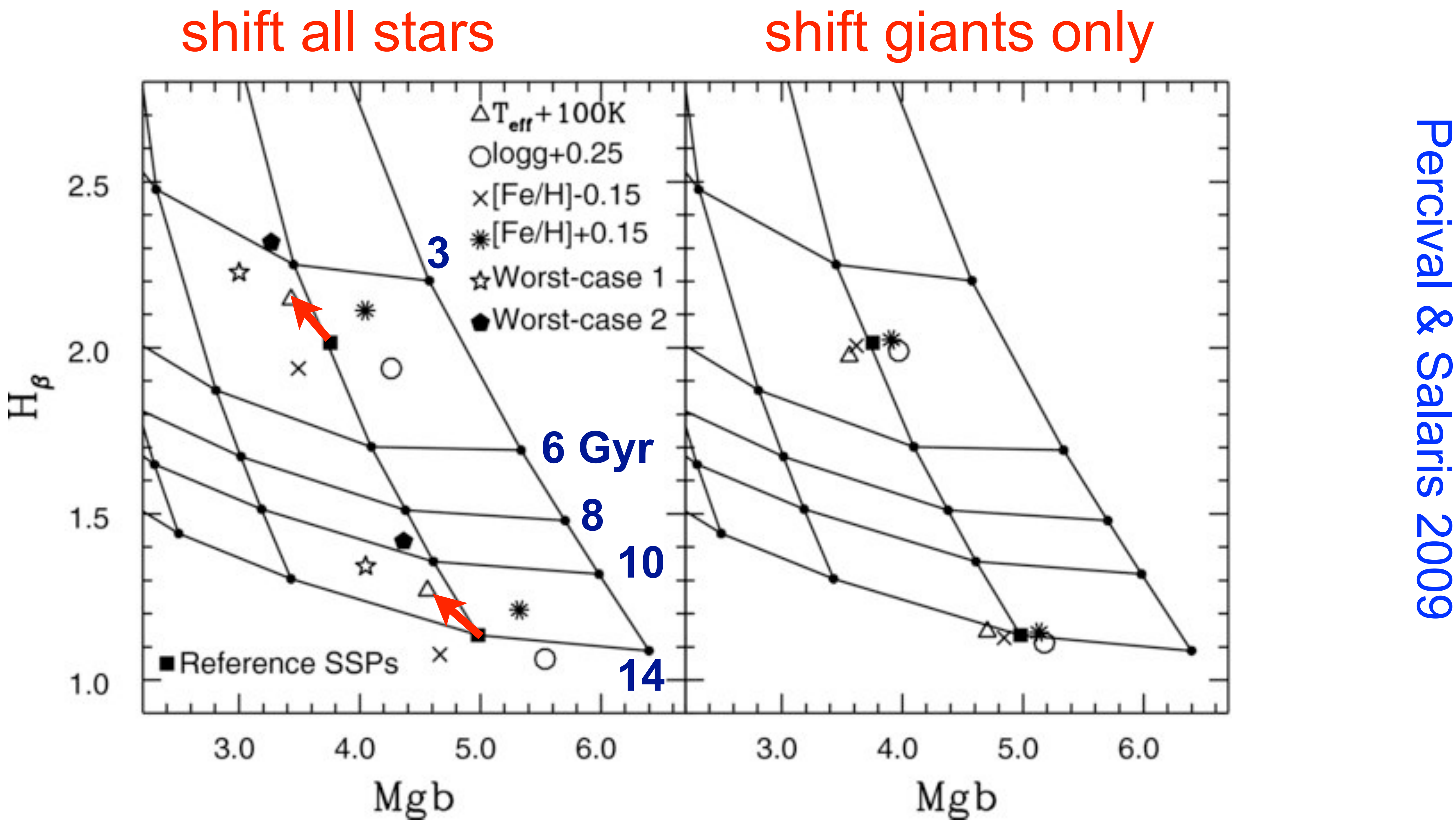
Synthesising the "integrated" spectrum of M67 by adding together spectra for its stars. (Recall, M67 has unusually large population of BSs).

Indices match the CMD-derived age & spectroscopic metallicity if the blue stragglers are not included.

Including the BSs makes a big difference to the indices. BS are essentially A stars, so mimic a young population (BHBs would do same).

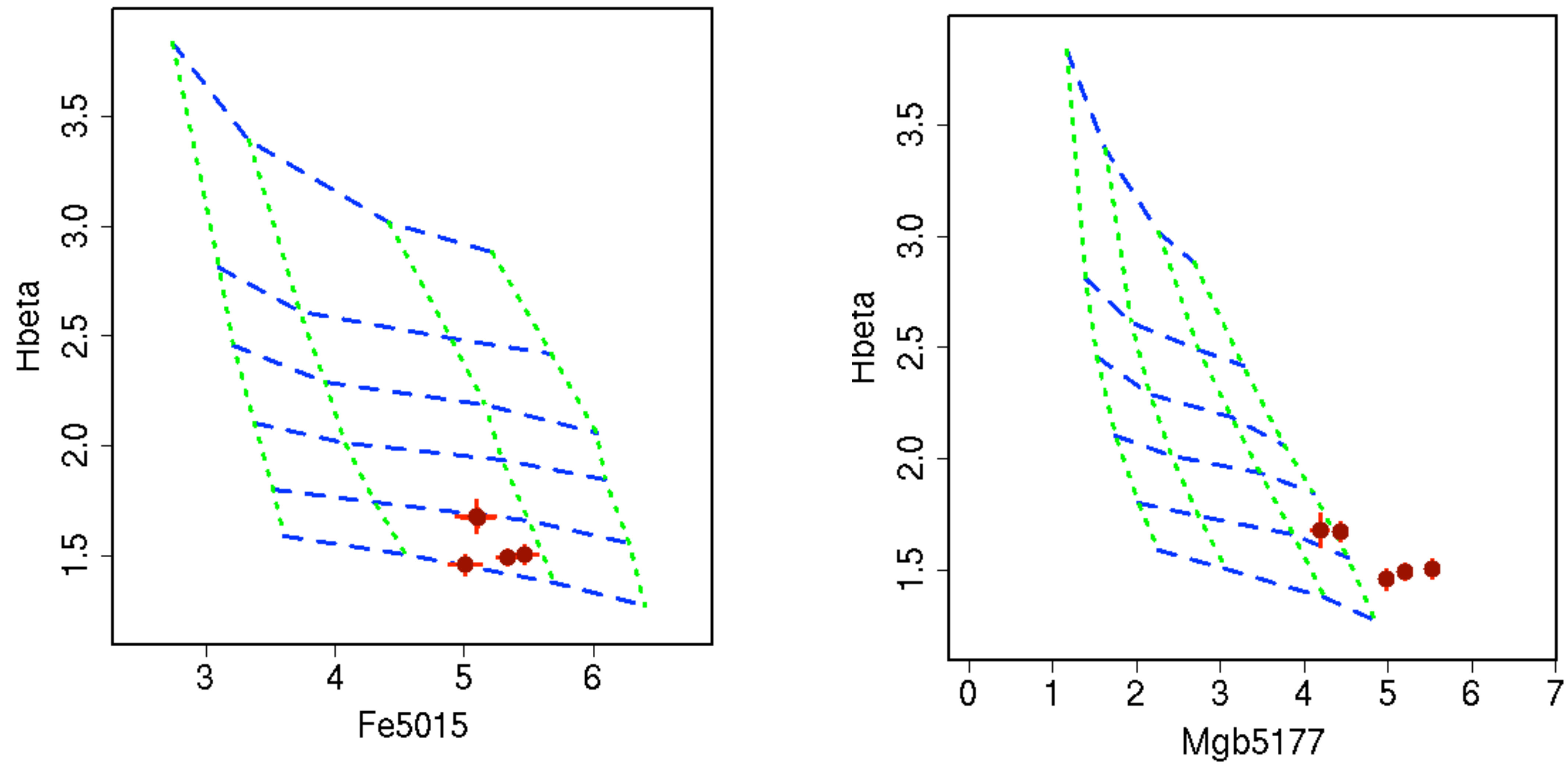
Predicted spectrum is only as good as the isochrones etc. used to build it!

And fundamental systematics?



Effect of shifting T_{eff} scale, metallicity scale, etc.

Consistency between grids?



Same galaxies in each panel (giant ellipticals in Shapley supercluster).

Same grids in age & metallicity, but different indices on x-axis: Fe5015 and Mgb5177

Bad: Fe5015 index gives [Fe/H] ~ -0.1, but with Mgb5177, we get [Fe/H] > +0.2

Worse: with Mgb5177, the data spill beyond the extent of the models!

Consistency between grids?

We seem to have derived metallicities 2x higher measured with Mgb5177 than with Fe5015.

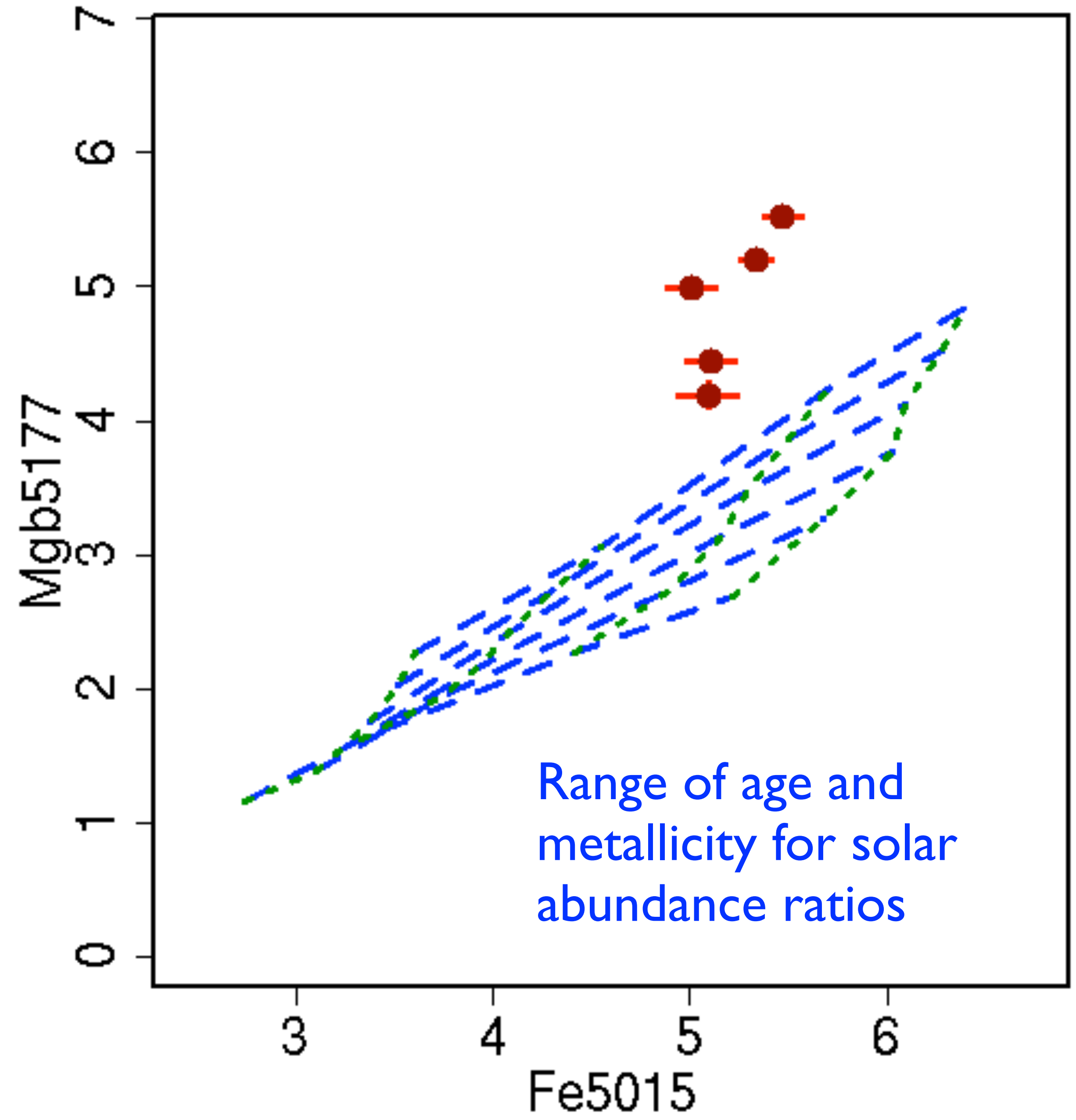
Mgb5177 really measures mostly Mg abundance. Fe5015 really measures mostly Fe abundance.

Conclude that in giant ellipticals there is more Mg per unit Fe than in the library stars from which the models were built.

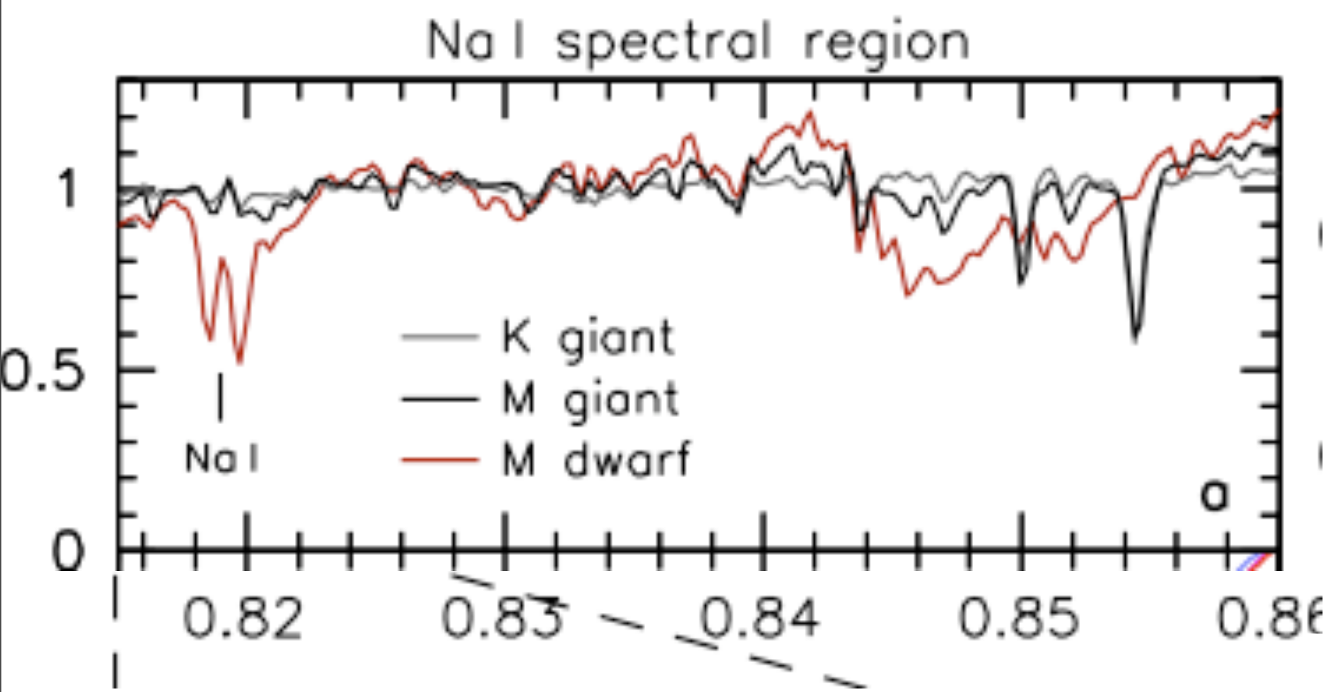
Express this "Mg enhancement" as [Mg/Fe]>0

(we might guess [Mg/Fe] $\approx$ +0.3, based on that factor-of-two discrepancy).

Our models are based on stars with solar Mg/Fe. How do we generalise beyond this? And what is the Mg enhancement telling us anyway?



IMF indicators



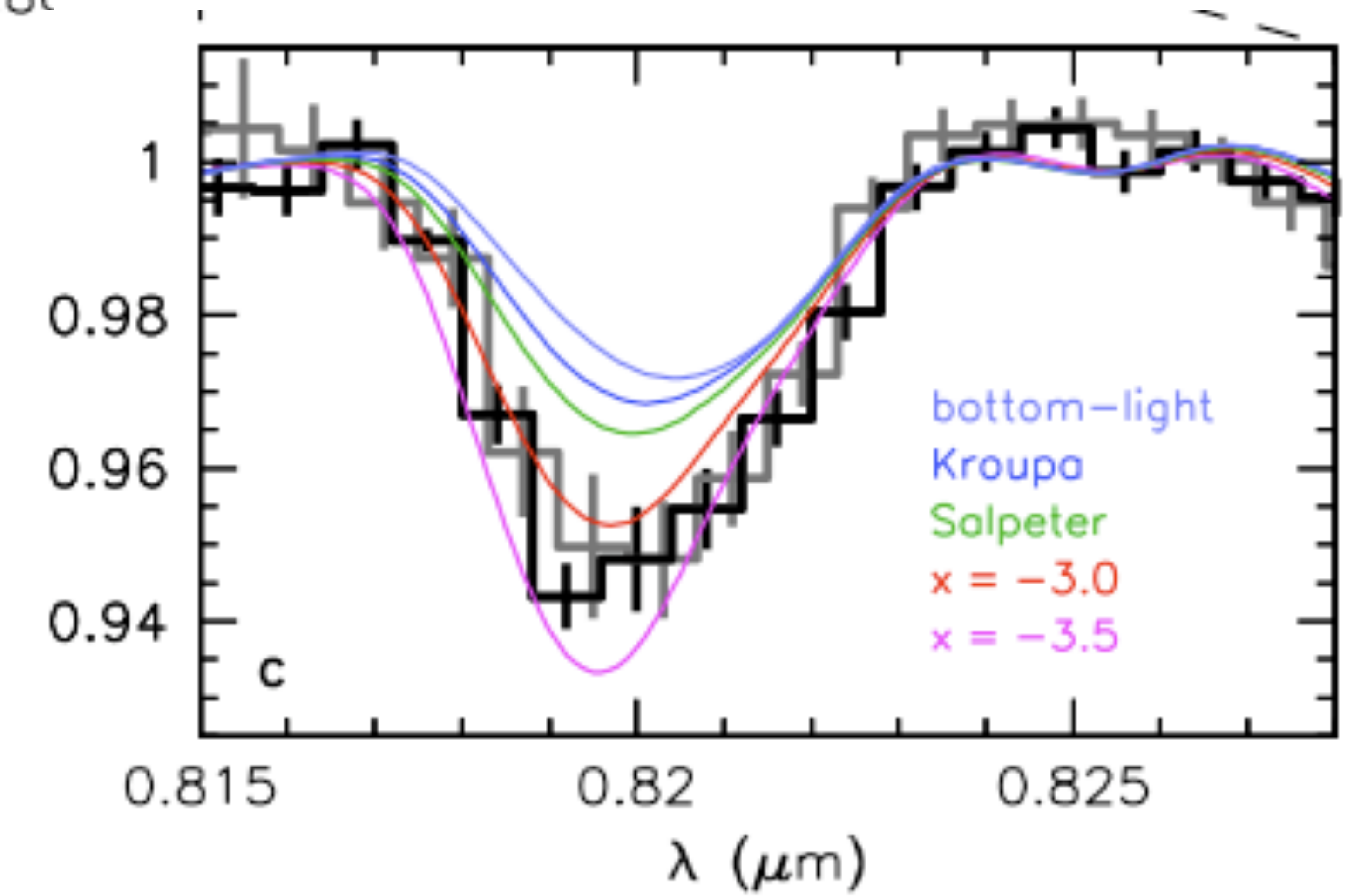
e.g. van Dokkum & Conroy (2010)

In stars, the Na I feature is strong in cool dwarfs but absent in cool giants.

So in galaxy spectra, the strength of the line depends on total contribution of dwarfs vs giants, hence on the IMF.

As observed in giant elliptical galaxies, Na I is too strong to match models with MW-like (e.g. Kroupa/Chabrier) IMFs.

Steeper than Salpeter slopes required (implications for M/L!)



Summary

We seem to be getting there:

The different behaviour of Balmer and metal lines leads to grids that clearly distinguish age differences from metallicity differences. Other features open the way to constraining abundance ratios (Mg/Fe, etc) and the IMF.

Spectra sufficient to measure these lines are available in huge numbers from SDSS for luminous galaxies.

But some worries remain:

Are we including all the relevant stars, e.g. are Blue HB and BS stars treated well enough?

Even if we are including them in the synthesis, are the library stars good enough, e.g. for cool giants?

How do Mg/Fe variations change the stellar evolution and stellar atmospheres? Can we include varying Mg/Fe in a consistent way?