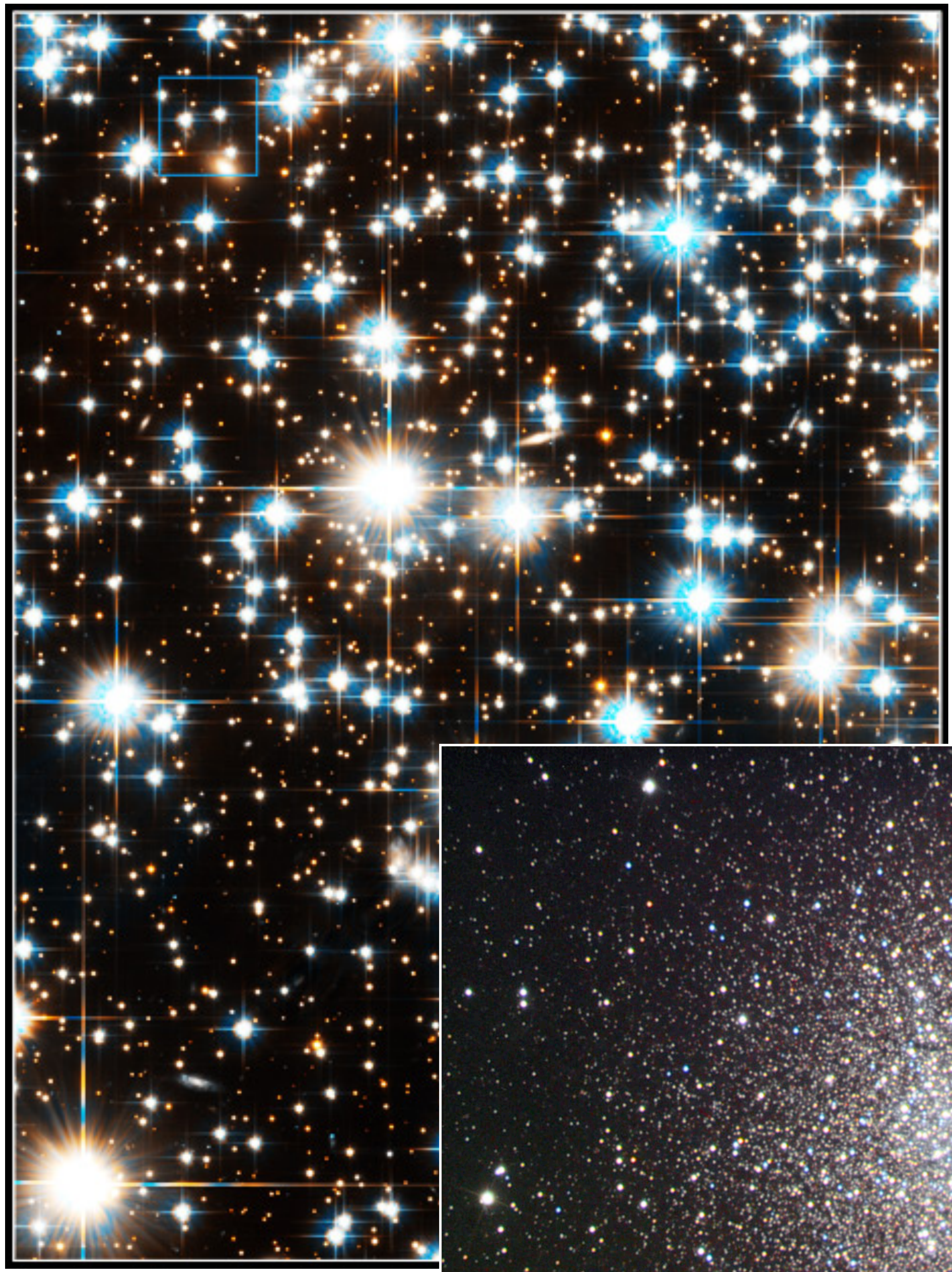
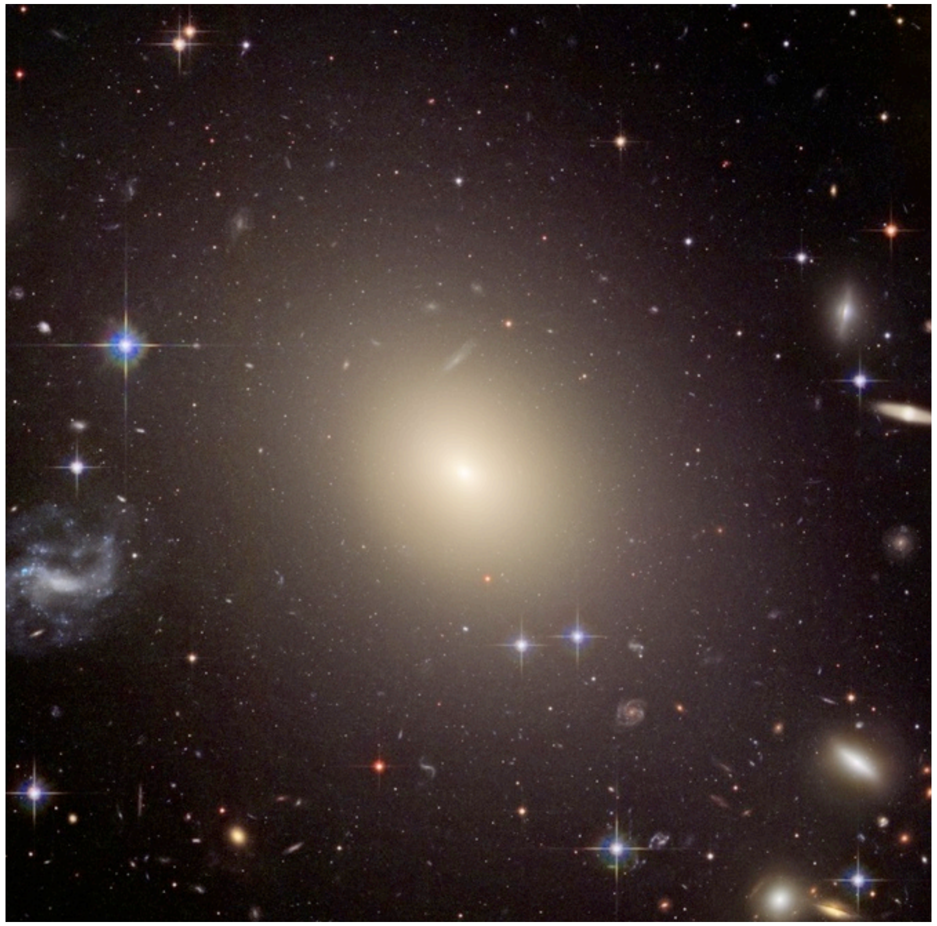
Stellar Populations - Lecture III





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Course Outline

I. *** Resolved stellar populations**

Ingredients of population models: tracks, isochrones and the initial mass function. Effects of age and metallicity. Star cluster colour-magnitude diagrams.

II. *** Colours of unresolved populations**

Population synthesis. Simple stellar populations. The age/metallicity degeneracy. Beyond the optical. Surface brightness fluctuations.

III. *** Spectra of unresolved populations**

Spectral Synthesis. Empirical and theoretical stellar libraries. Line indices. Element abundance ratios.

IV. *** Additional topics: chemical evolution and stellar masses**

Abundance ratios, nucleosynthesis and chemical evolution. Stellar mass estimation: methods, uncertainties and limitations.

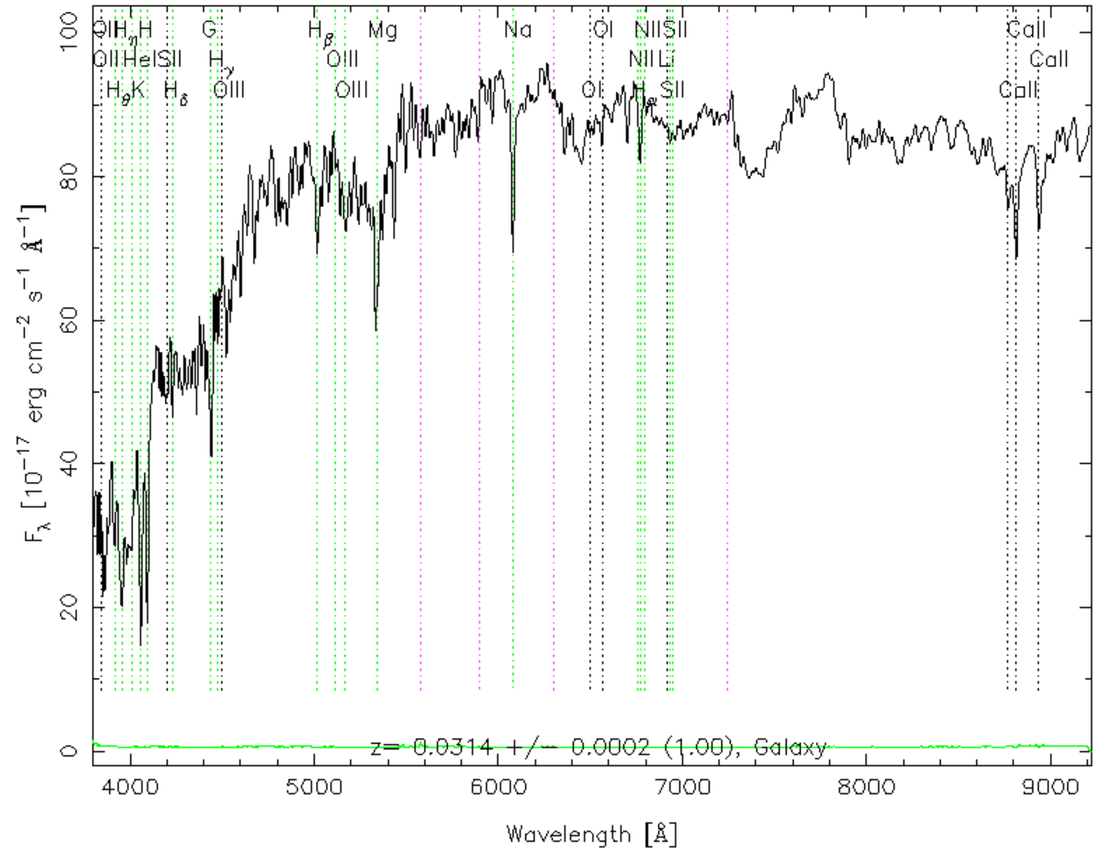
Spectra of Unresolved Populations

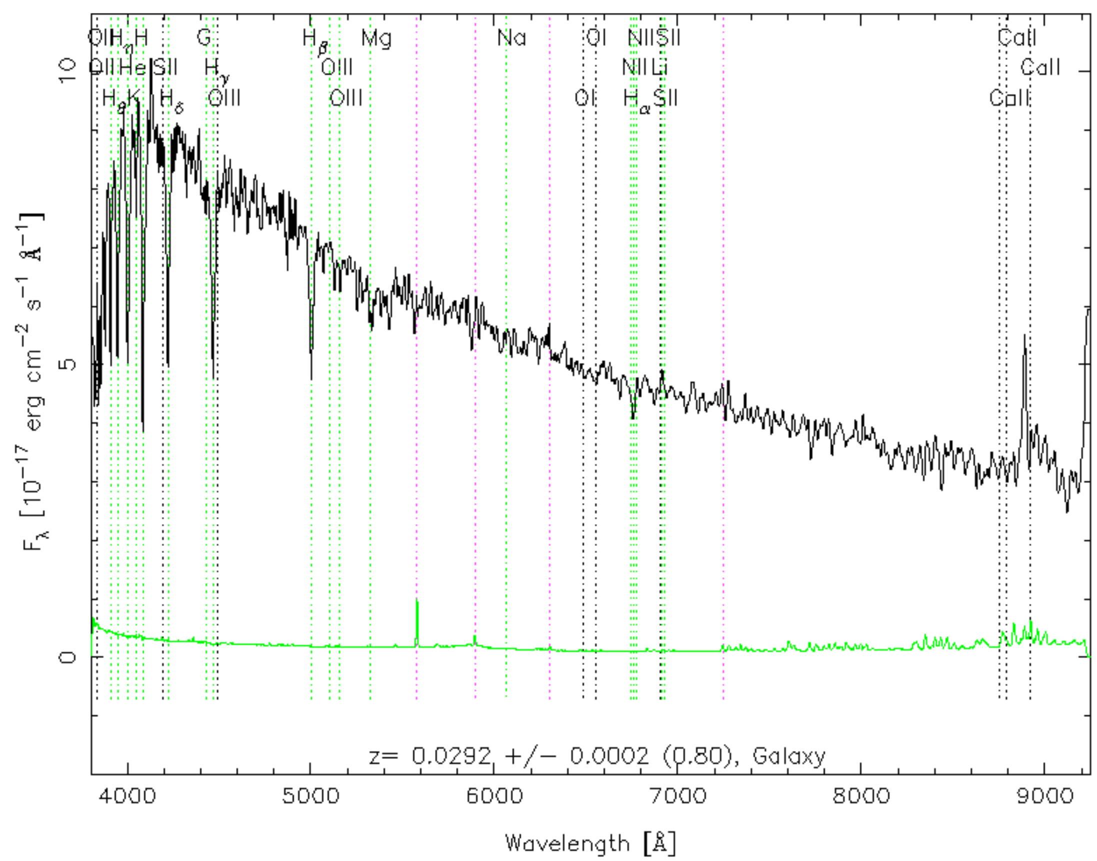
We saw that (optical) colours of unresolved populations cannot be used to infer ages of galaxies because metallicity effects and ages effects redden the integrated population in indistinguishable ways.

With spectroscopy we can isolate narrow regions of the spectrum that can be traced to stellar temperature effects (i.e. population age) or to element abundances (metallicity).

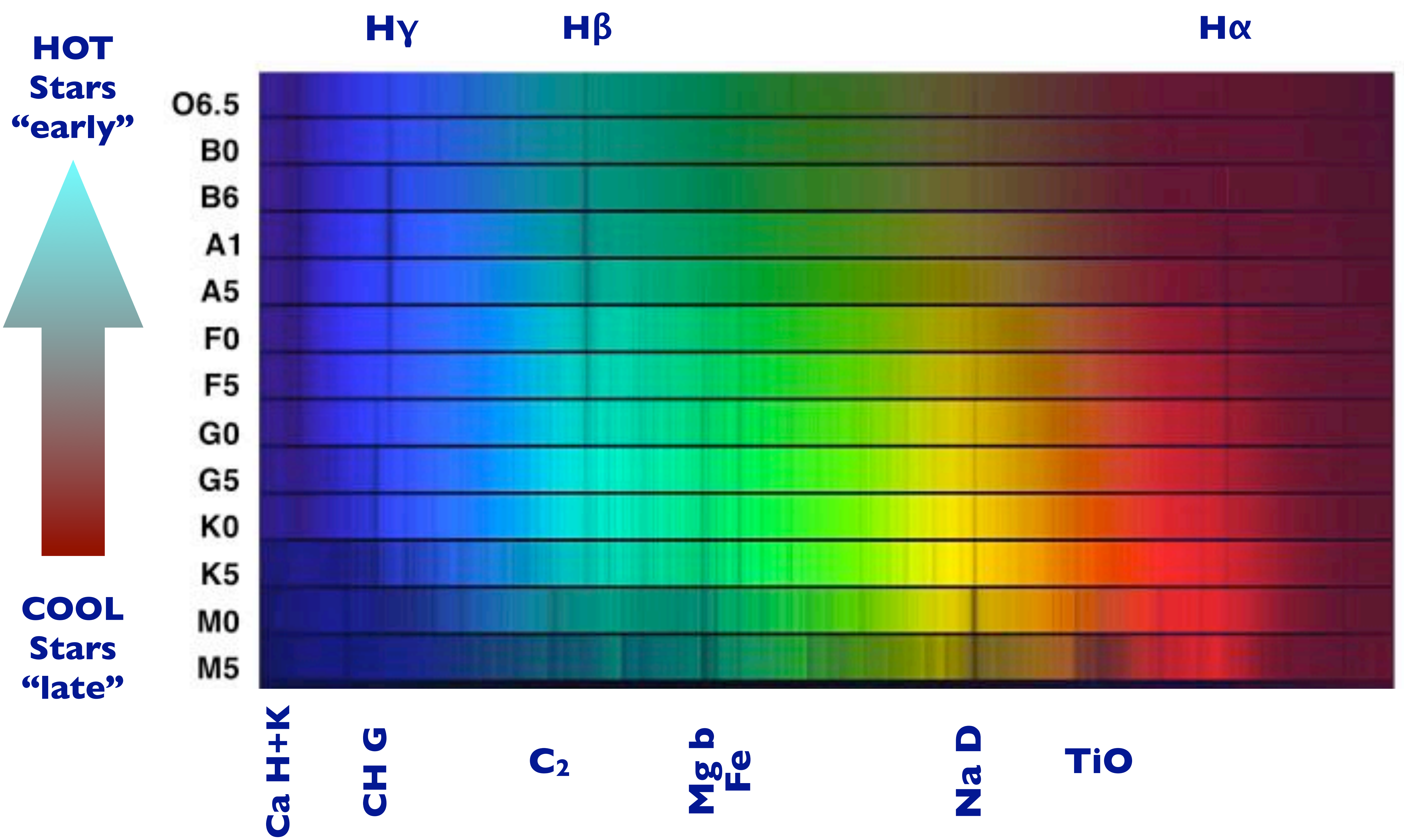
Needs more observation time than colours, but we now have surveys with ~100,000s of galaxy spectra.

As before, start with stars and build up to make predicted spectra for SSPs. Ultimately build complex star-formation histories by summing over SSPs.

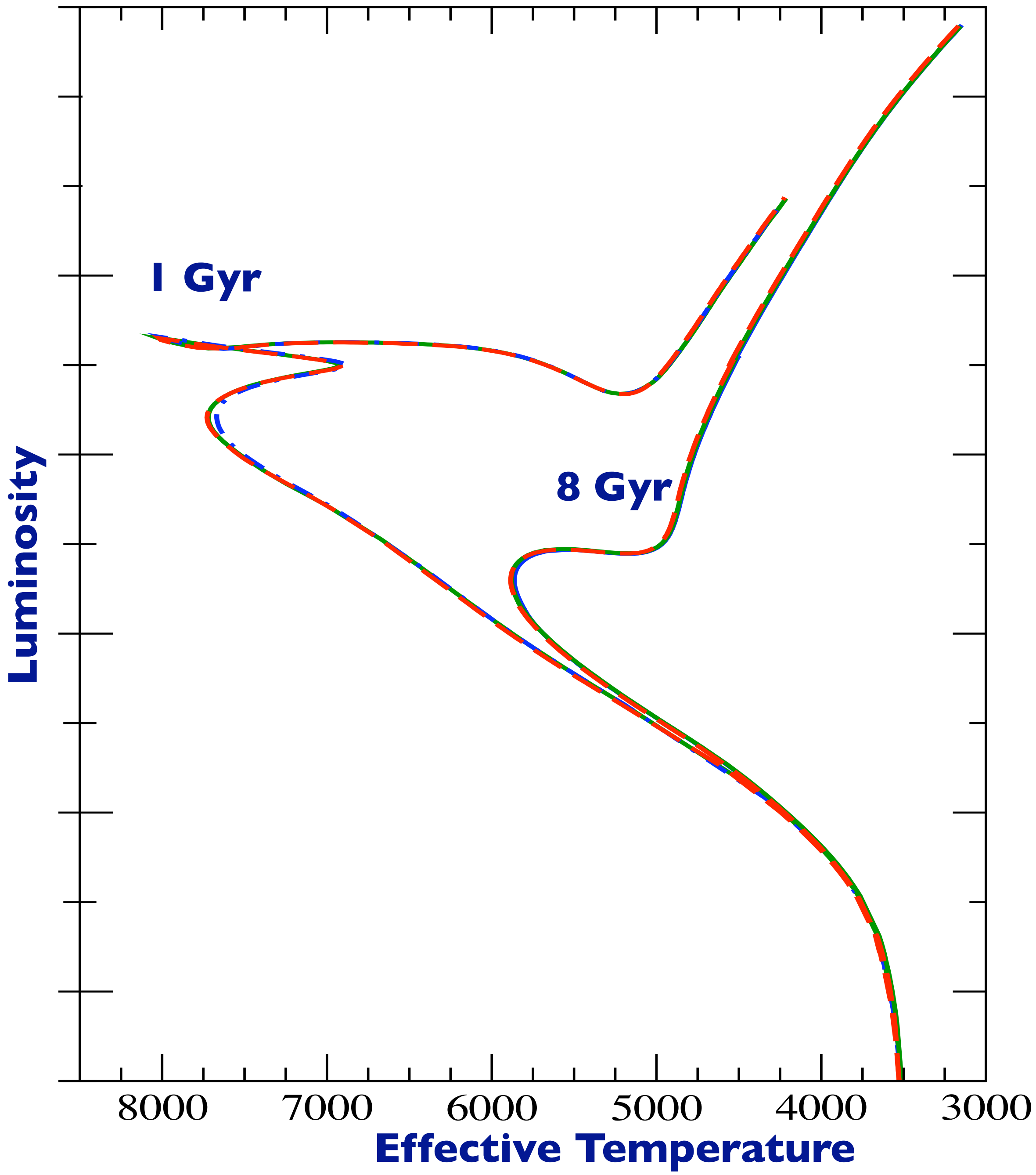


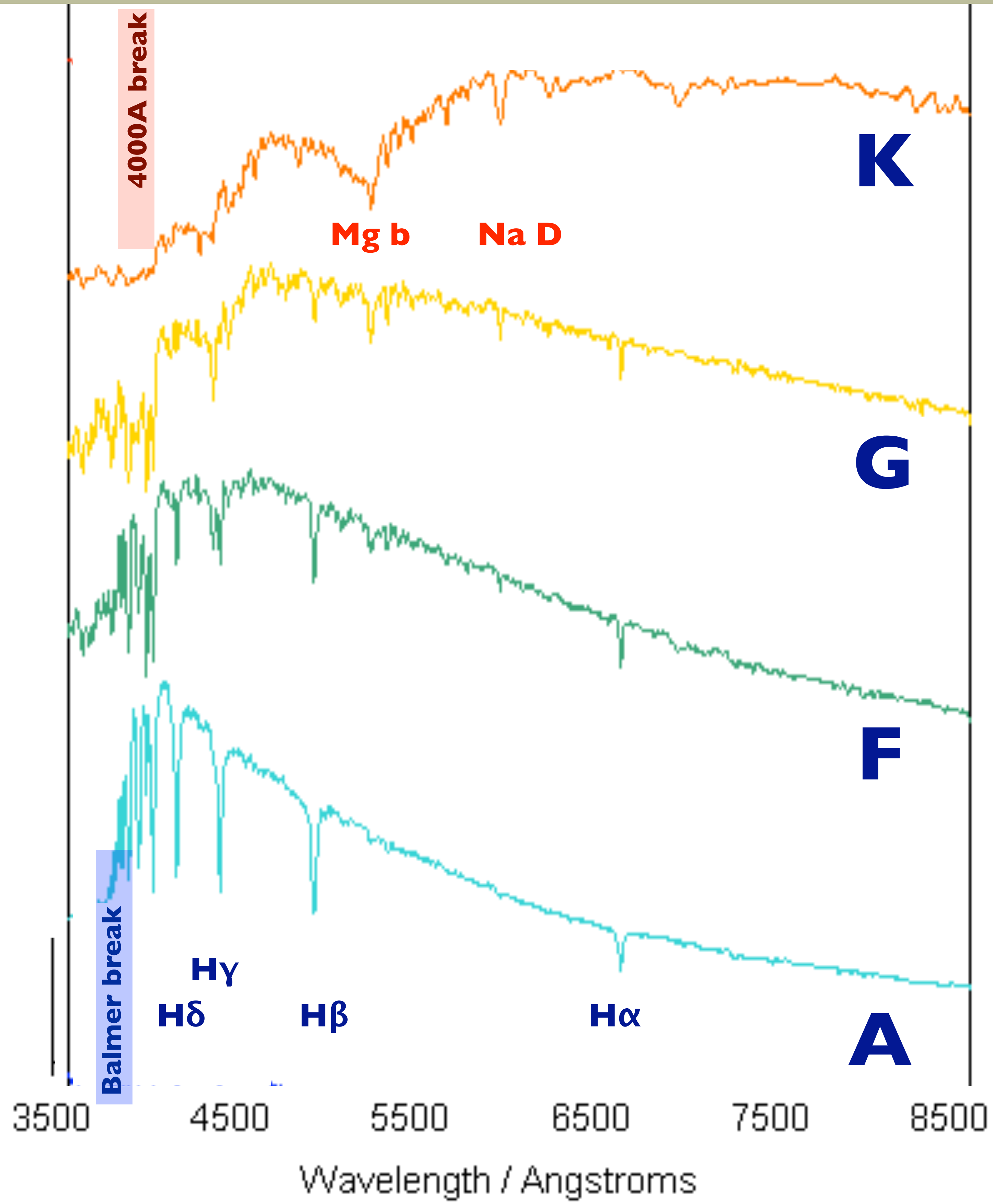


Stellar Spectra



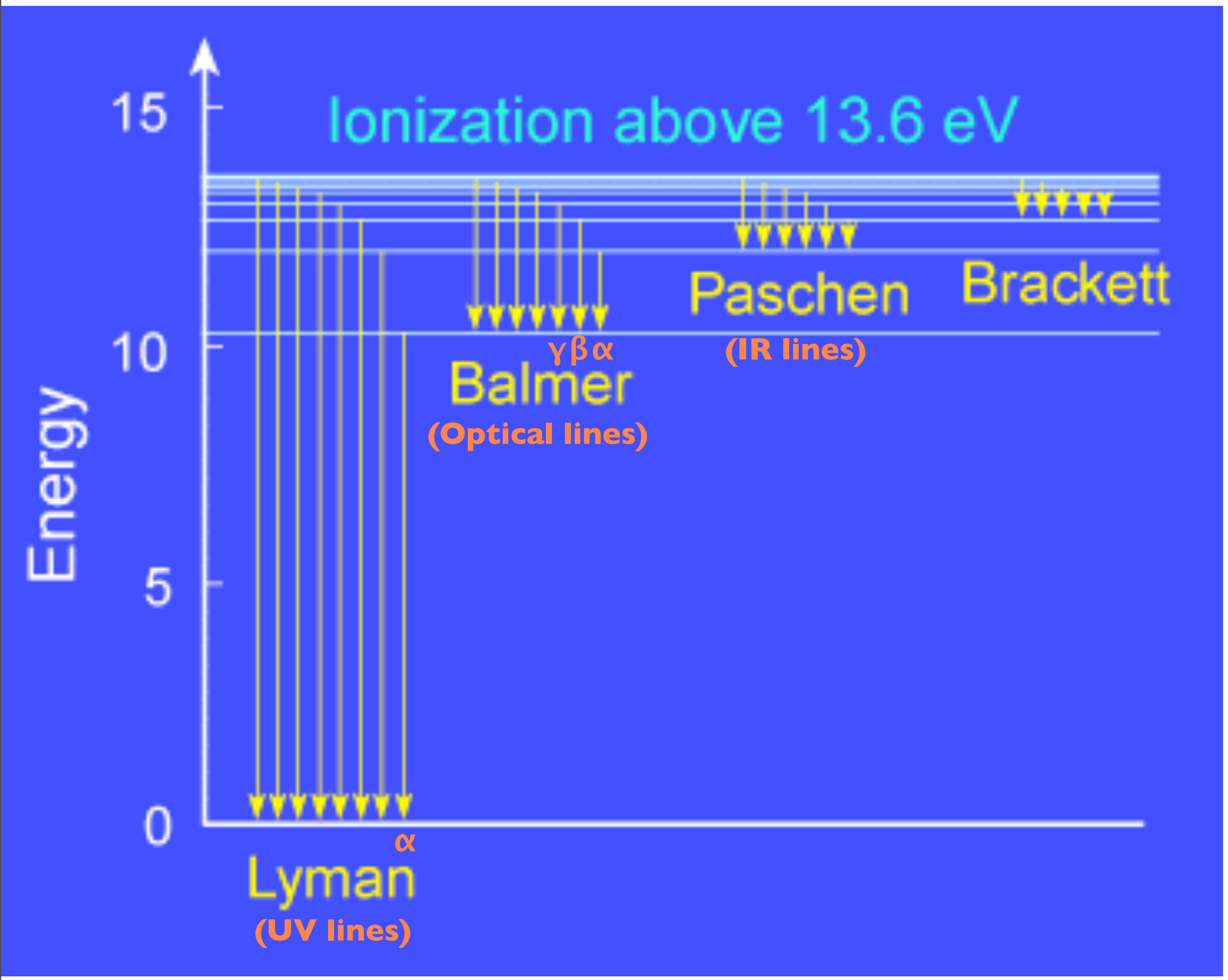
Spectral Synthesis

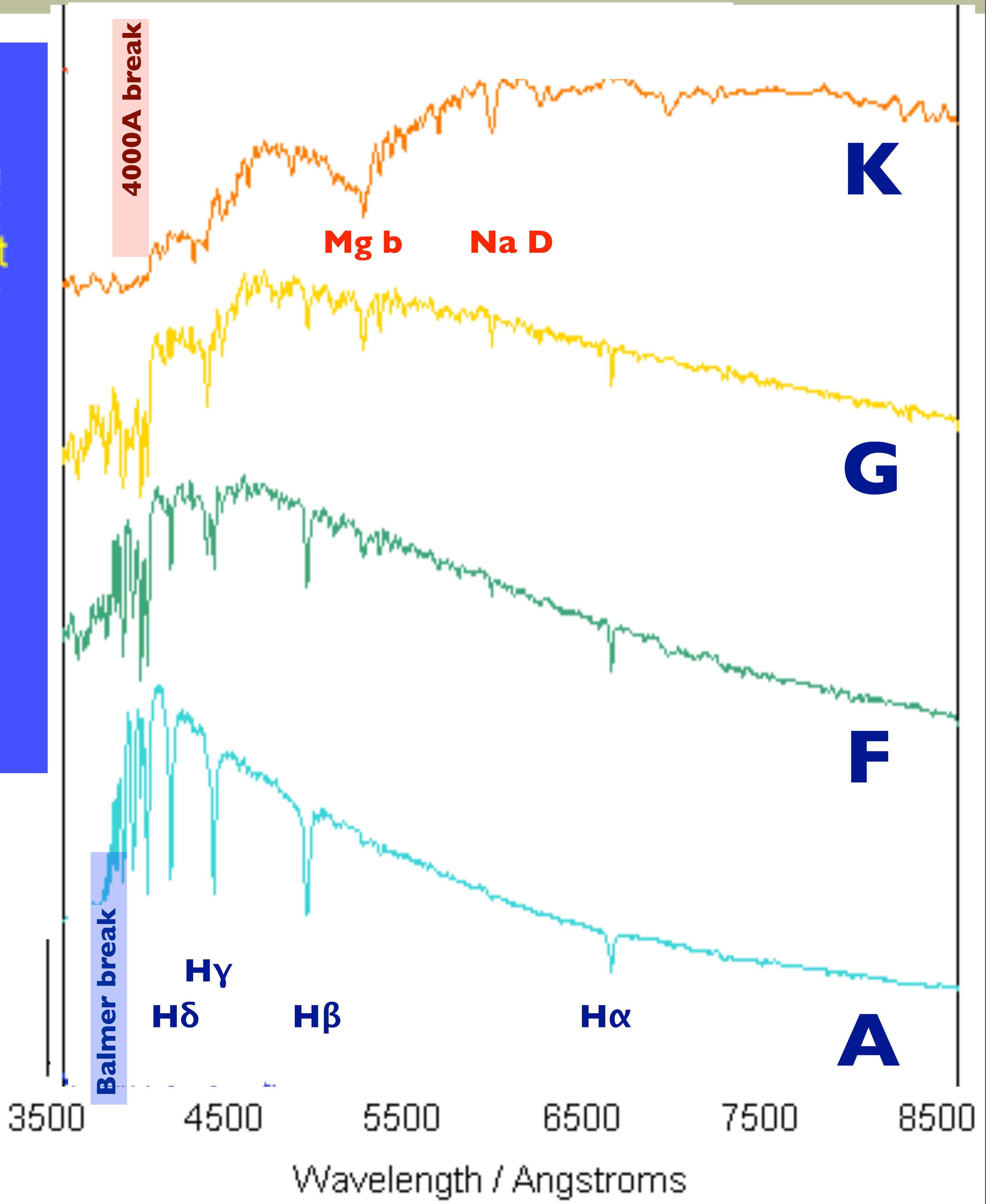




Different spectral types (T_{eff}) populate different parts of the HRD. And have characteristic narrow spectral features.

Spectral Synthesis

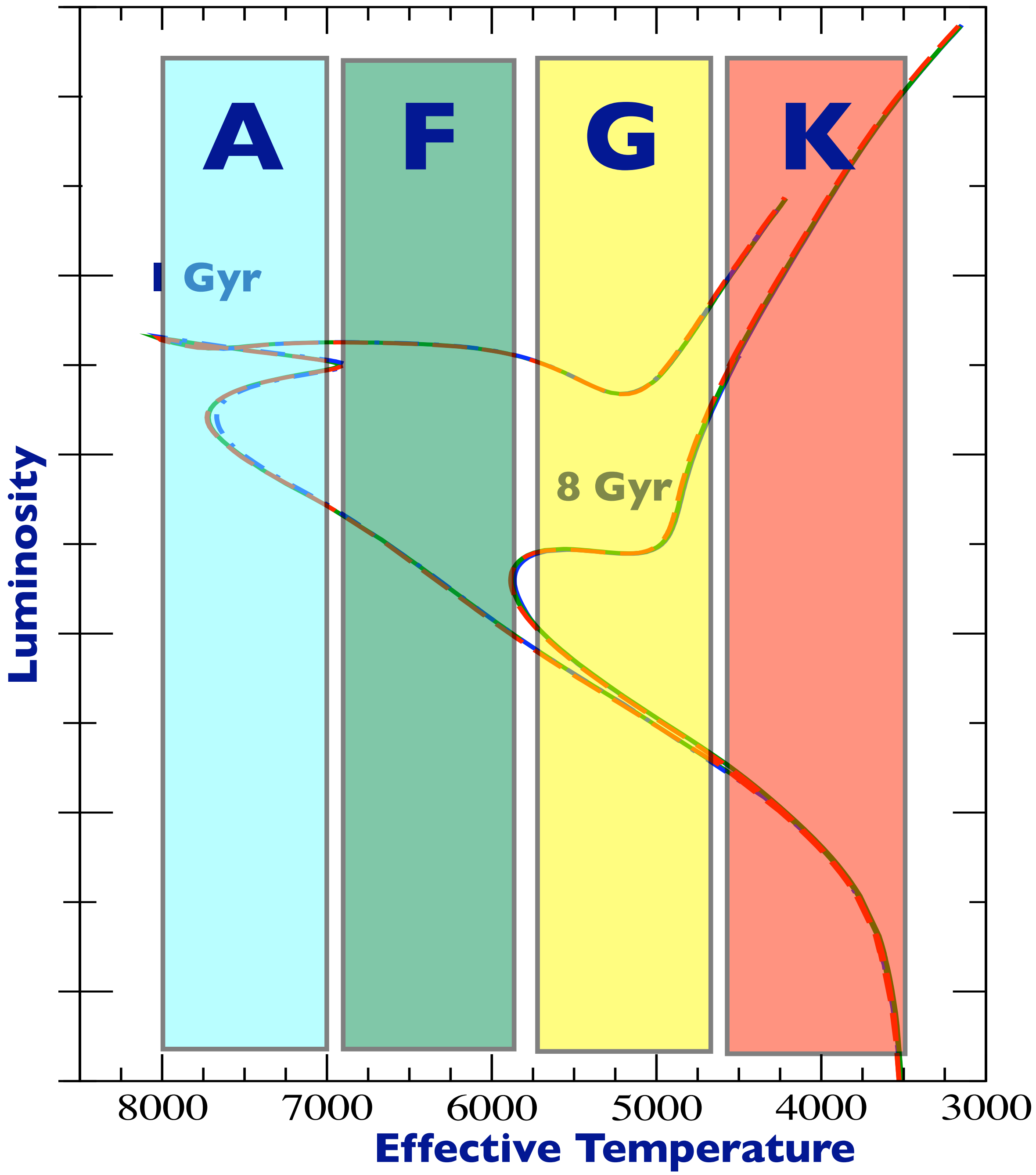


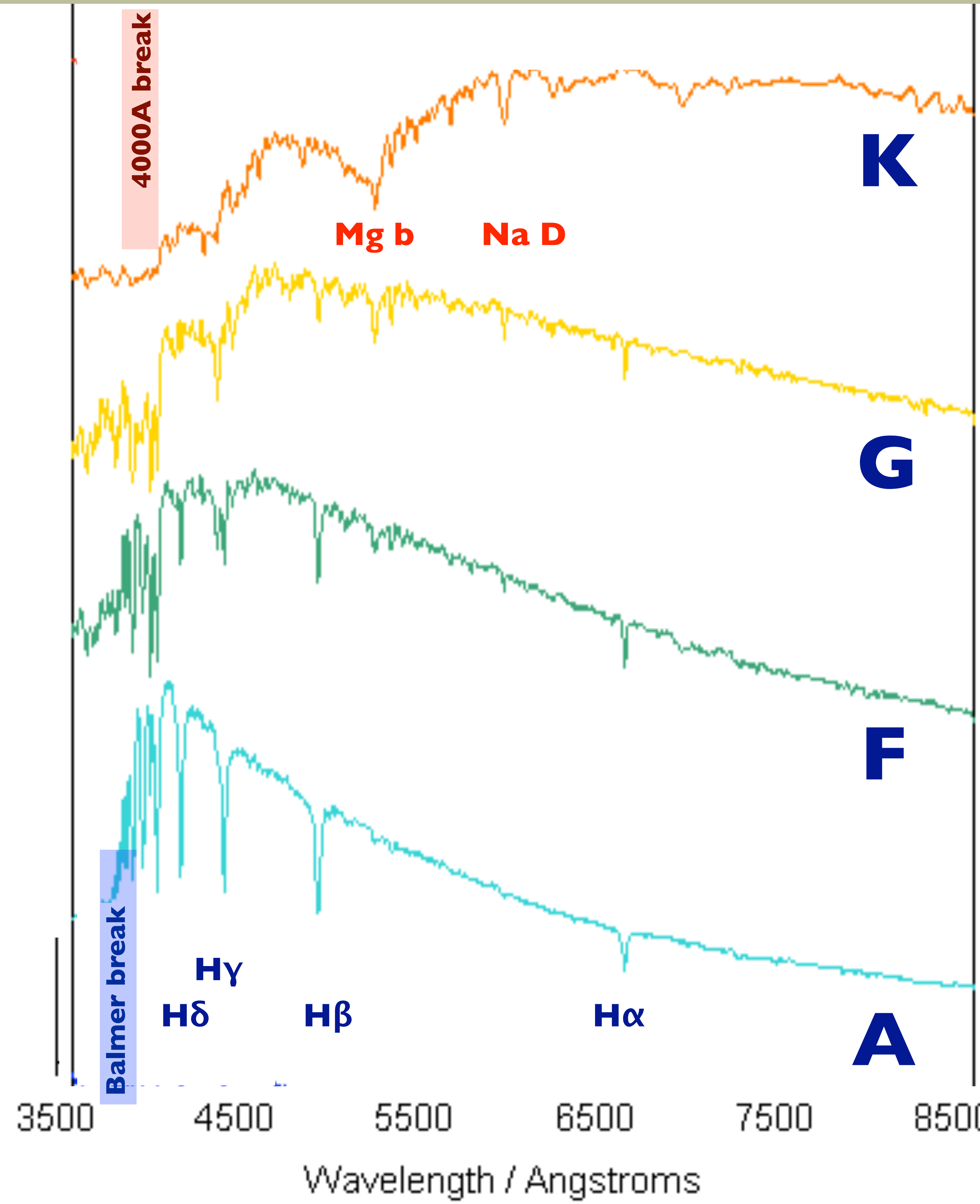


In particular note the increasing strength of Hydrogen lines (Balmer series) in the hotter stars.

These are strongest at spectral type A... which is why they were called "A"!

Spectral Synthesis





Different spectral types (T_{eff}) populate different parts of the HRD. And have characteristic narrow spectral features.

Spectral Synthesis

BASIC IDEA

Simple extension of the synthetic colours for SSPs that we saw earlier.

Now instead of adding <u>luminosities</u>, we add the <u>spectra</u> of stars at different points along the isochrone, to predict the "total" spectrum of the galaxy.

KEY QUESTION

Where do we get the spectra that we will add together?

Empirical or theoretical libraries?

Do the libraries have all the types of star that matter?

ASIDE: WHY NOT....

Try to fit galaxy spectra directly by summing star spectra of different type:

Spectrum = a_1*A + a_2*F + a_3*G + a_4*K + a_5*M, maximizing the weights a_n to get the best match to the galaxy...?

Empirical Spectral Libraries

OBSERVED SPECTRA OF STARS

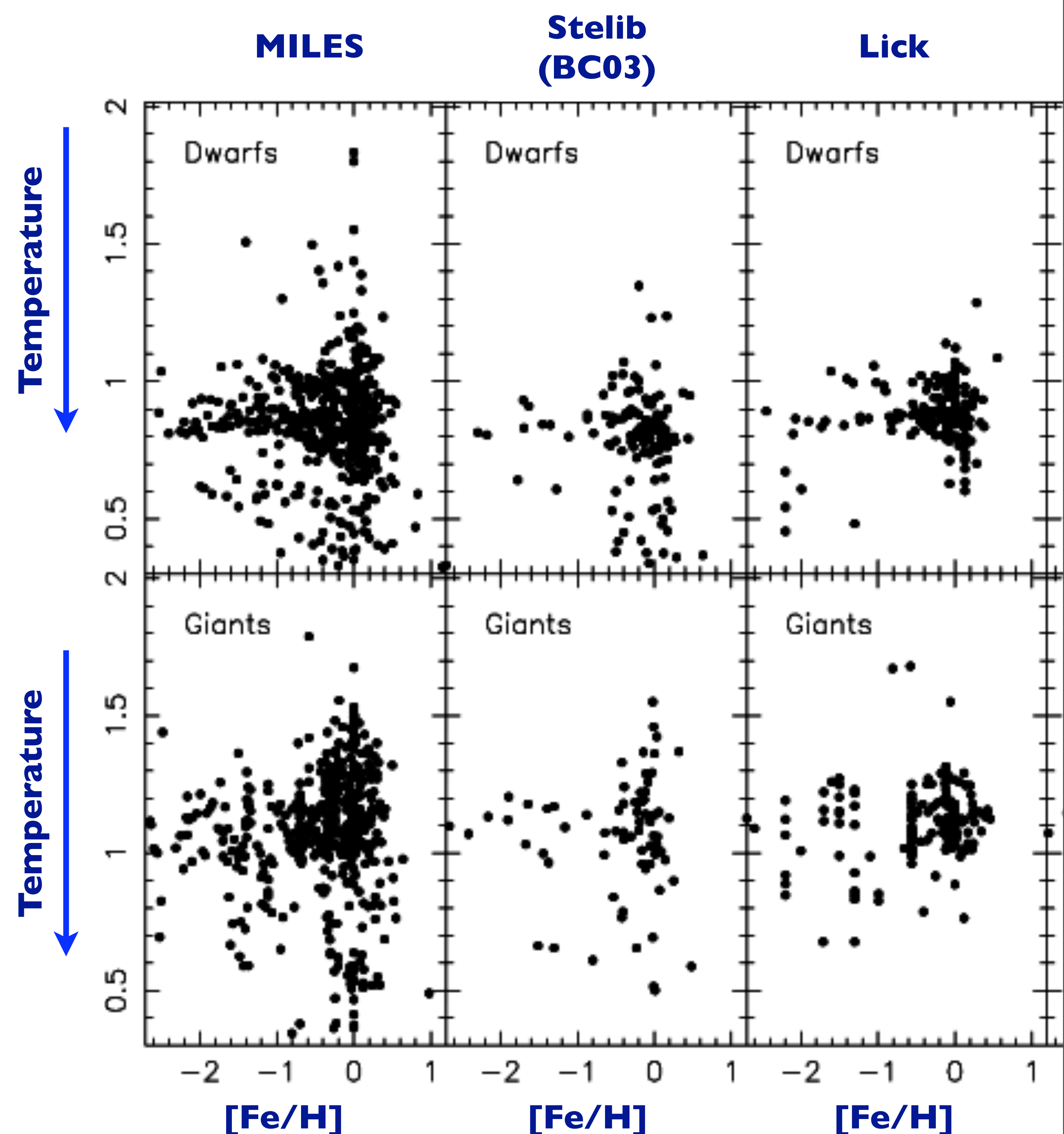
Desirable to cover large range in T_{eff}, log g (="gravity" i.e. dwarf vs giant) and Fe/H.

And to know the atmospheric parameters of the stars (difficult for the coolest stars.)

PROBLEMS

All the stars in empirical libraries are in our galaxy, which limits parameter coverage.

Valid application of the models implicitly restricted to systems with stars "like" those in our galaxy.



Sanchez-Blazquez et al. (2006)

Theoretical Spectral Libraries

THEORETICAL LIBRARIES

Based on stellar atmosphere models, e.g. ATLAS9 (Castelli & Kurucz 2003) MARCS (Gustafsson et al. 2003)

ADVANTAGES

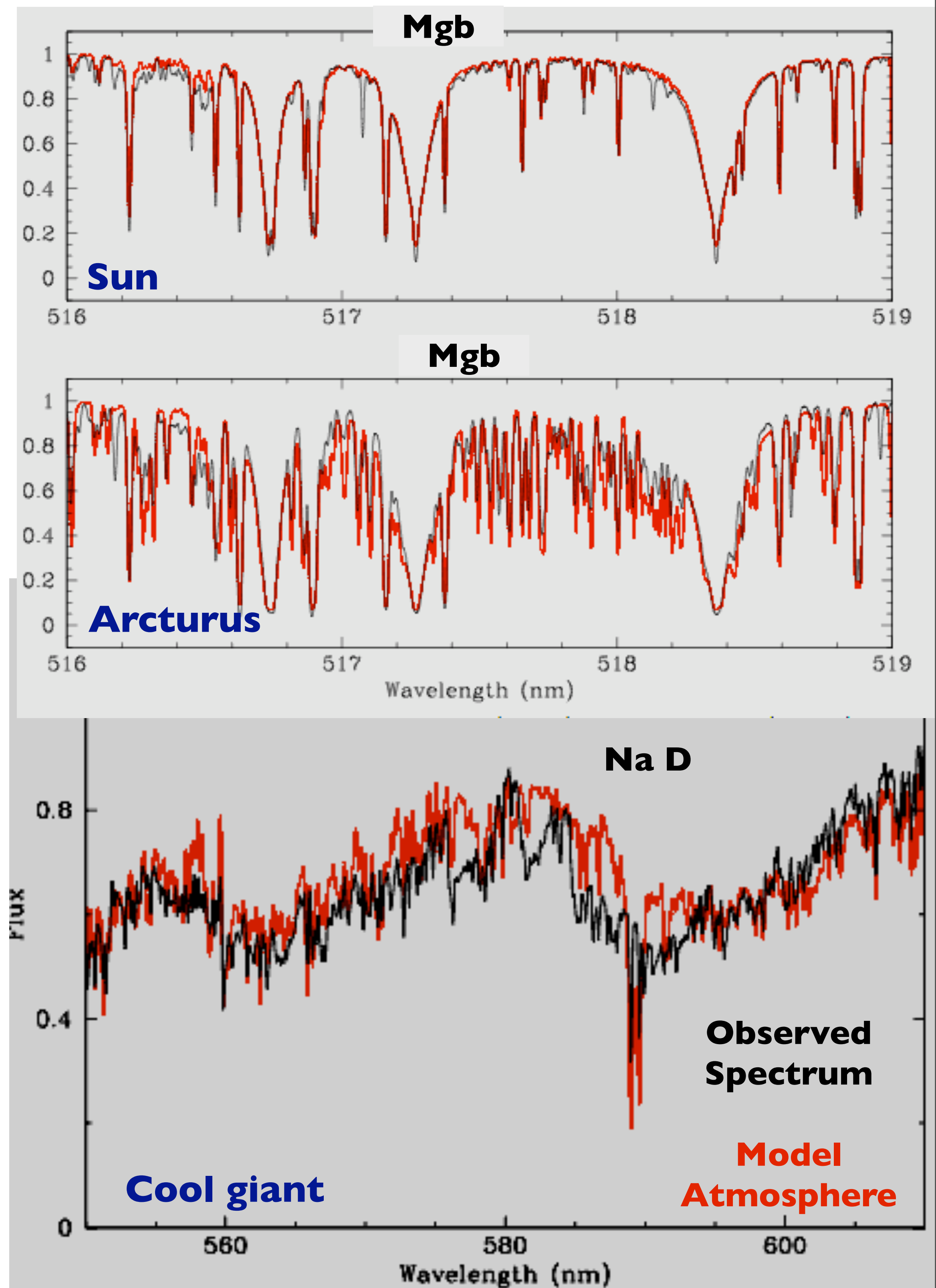
Much more flexible than empirical libraries: In principle can obtain spectra for any value of Teff, log g and Fe/H (and any chemical mixture).

CHALLENGES

Complex atmosphere physics (especially for hottest and coolest stars) may not be adequately modelled.

Empirical atomic and (especially) molecular line-lists may not be complete enough.

Include QM-predicted lines not verified in lab? These can be badly wrong in detail, but needed for accurate colours (Coelho et al.)



Coelho et al. (2007)

Spectral libraries beyond the optical

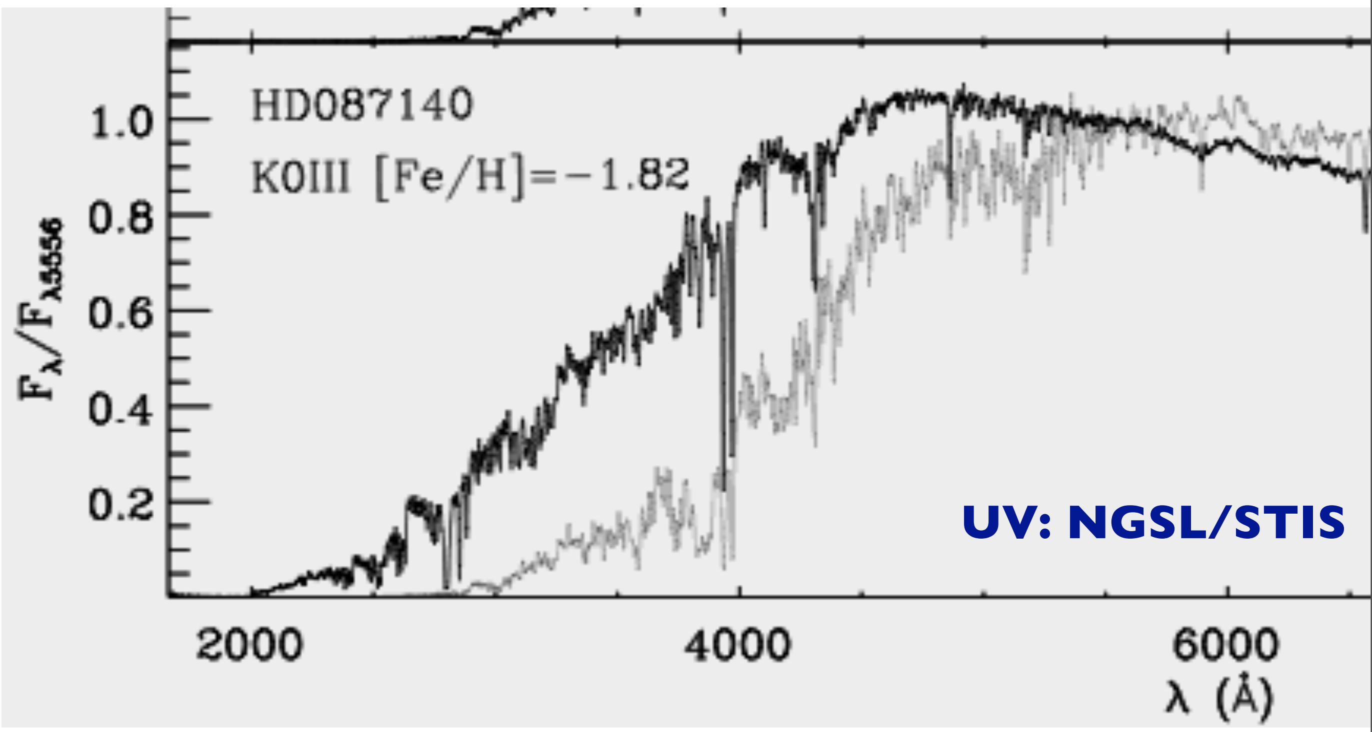
IR and UV spectral libraries typically lag behind the optical.

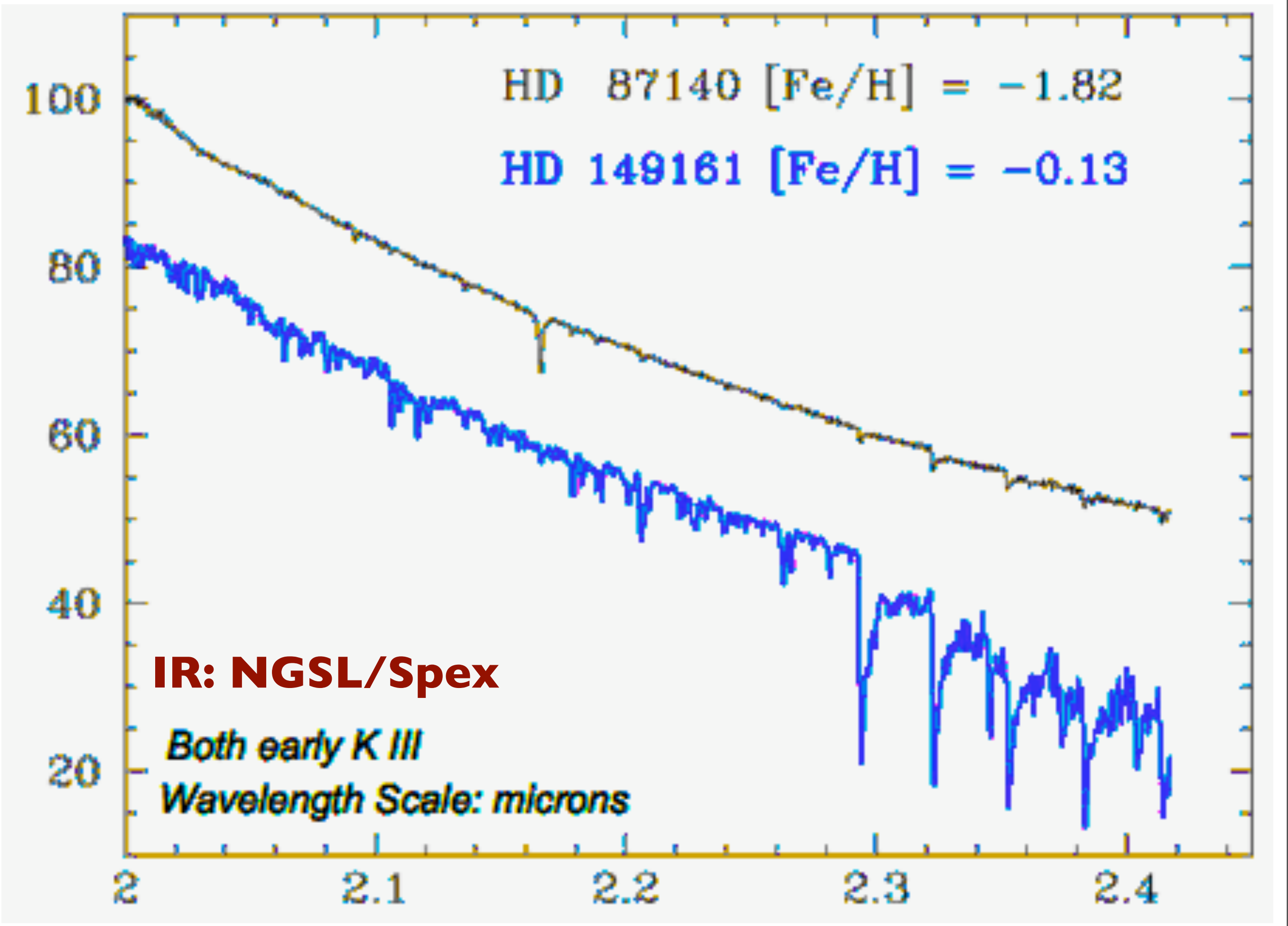
In UV, need space observations, e.g. NGSL/STIS with HST.

In IR, has been a focus on the K-band, in particular CO 2.3um bandhead. (e.g. Marmol-Queralto et al.)

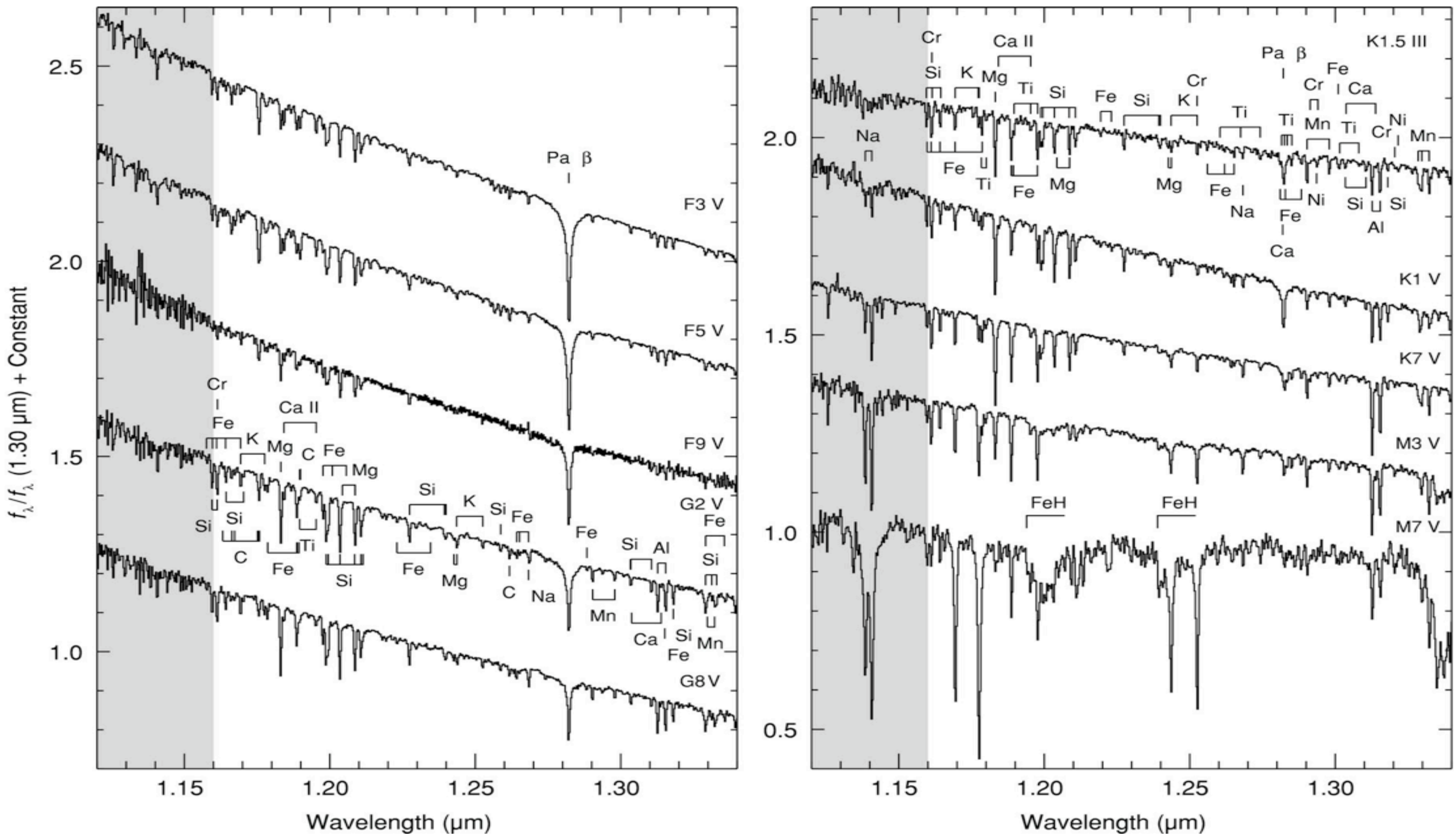
(But this shifts out of ground-based K-window for even very low redshifts...)

Excellent new IR library from Rayner et al. 2009 covers much wider range in wavelength.





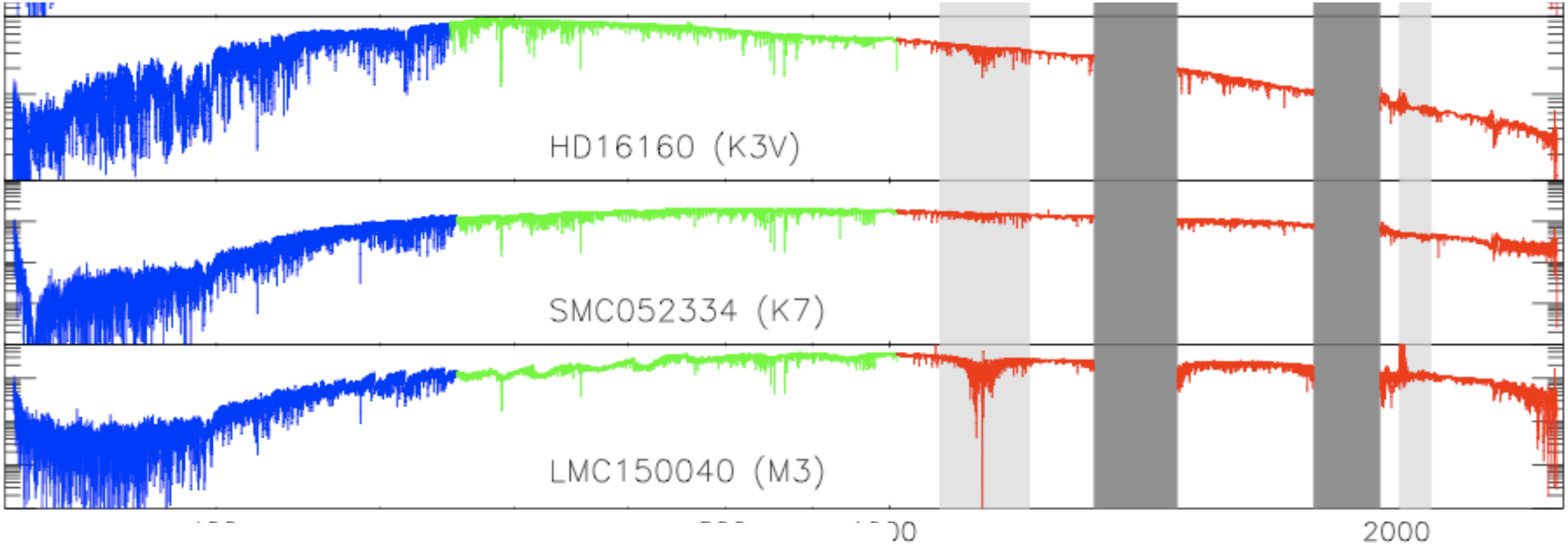
IRTF library in infra-red



Rayner et al. (2009)

IRTF Library of cool (FGKM) stars in the near-IR (0.8-5.0 micron)

X-Shooter Spectral Library



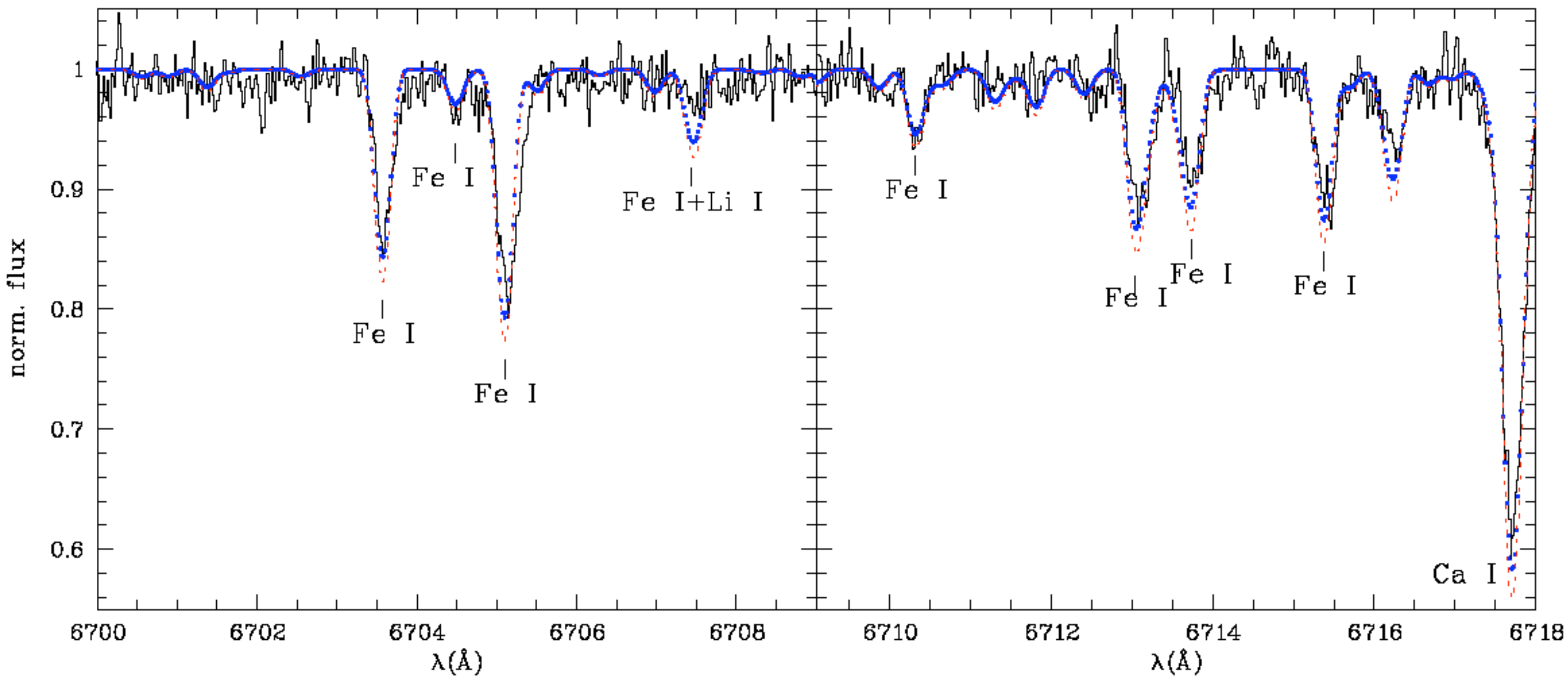
Library	Resolution $R=\lambda/\Delta\lambda$	Spectral range (nm)	Number of stars	Reference
STELIB	2000	320-930	249	[14]
ELODIE	10000	390-680	1300	[15, 16, 17]
INDO-US	5000	346-946	1237	[18]
MILES	2000	352-750	985	[19]
IRTF-SpeX	2000	800-2500	210	[20]
NGSL	1000	167-1025	374	[21]
UVES-POP	80000	307-1030	300	[22]
LW2000	1100	500-2500	100	[23]

XSL 10,000 320-2500 ~600 ~600 Chen et al. 2011

Reminder...

ABUNDANCES FROM HIGH-RESOLUTION SPECTROSCOPY

With high-resolution spectra of individual stars, we can measure equivalent widths of absorption lines from individual atomic transitions.

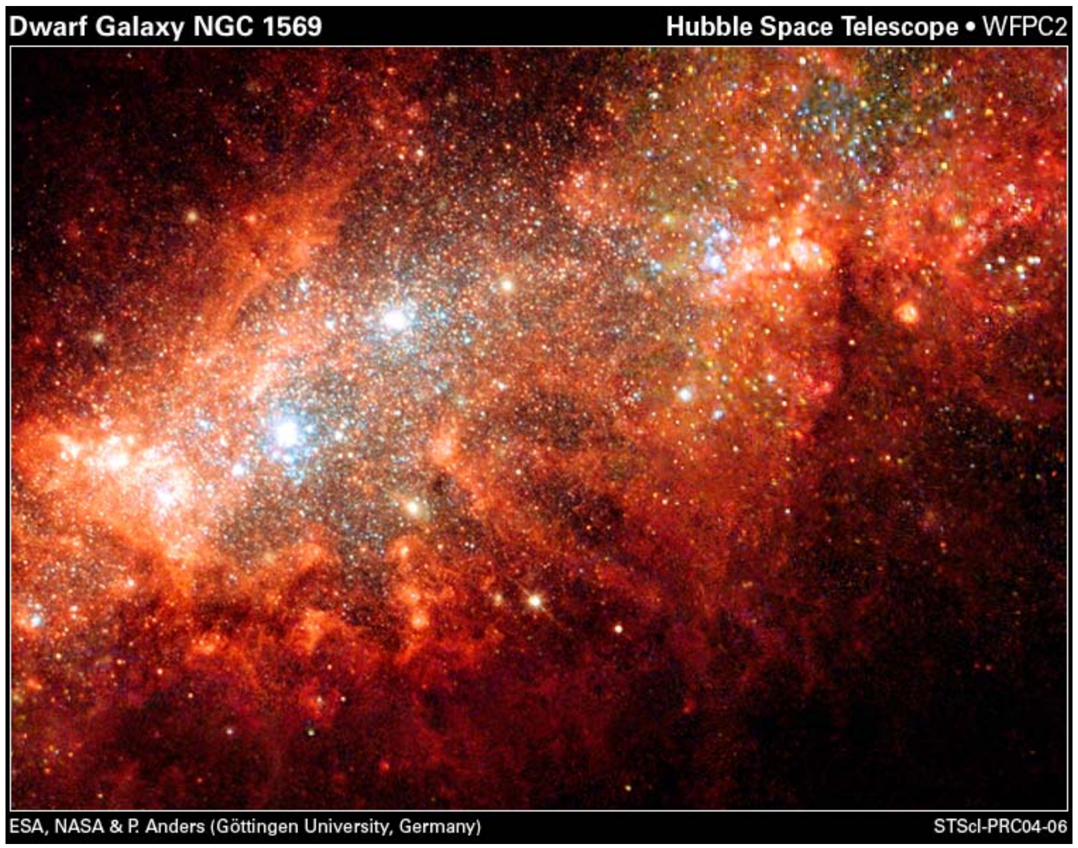


Measure abundances by comparison to "model stellar atmospheres": Model of absorption line formation in outer layers of star.

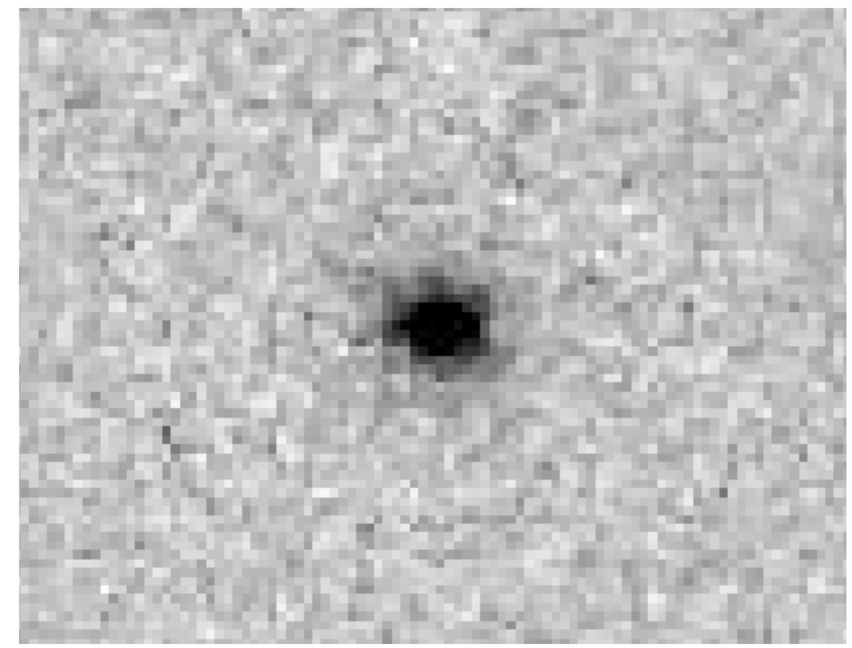
(Inputs to these models are composition, temperature and surface gravity. Outputs are synthetic spectra for comparison to observed)

Can we do this for galaxies?

The Problem - I



“What you’d like to get”



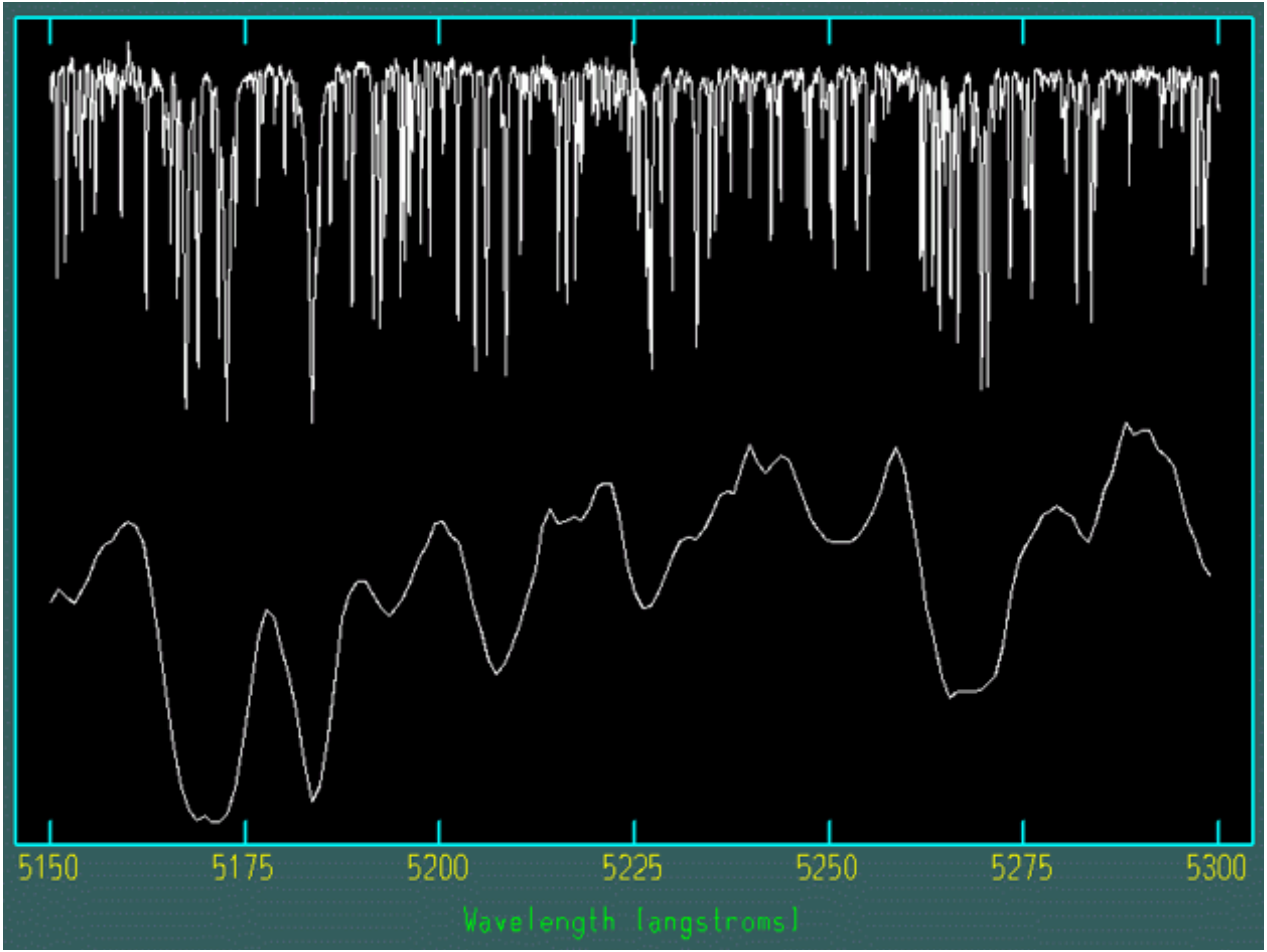
“What you get”

(George Hau)

The Problem - II

What you'd like to get

What you get



Galaxy Spectra

INTRINSIC LIMITATIONS

Internal motions of stars within a galaxy cause Doppler broadening.

For large elliptical galaxy, v>150 km/s.

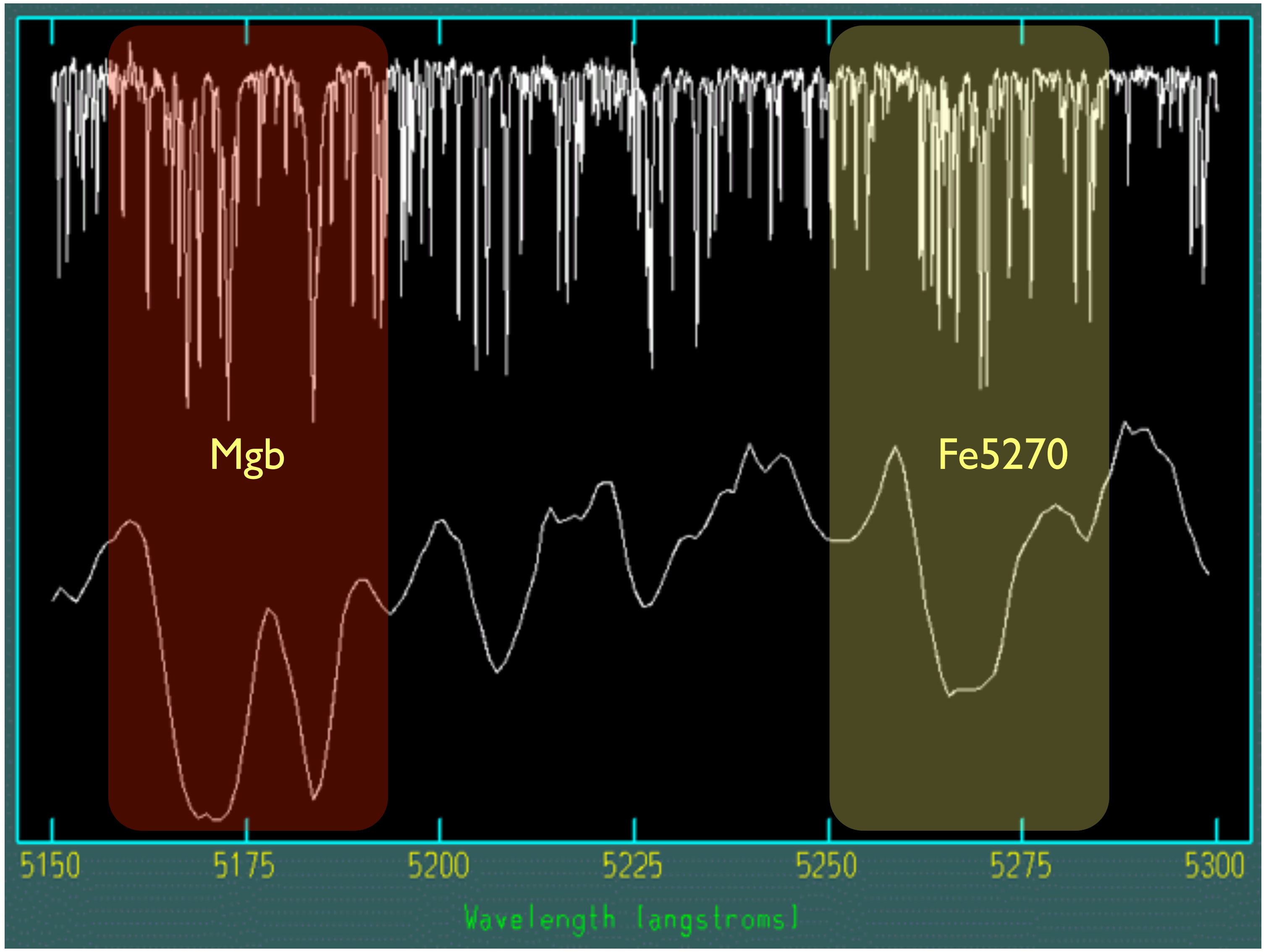
Cannot reach resolution higher than R= Δλ/λ ~ 1000... no matter how powerful the spectrograph

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

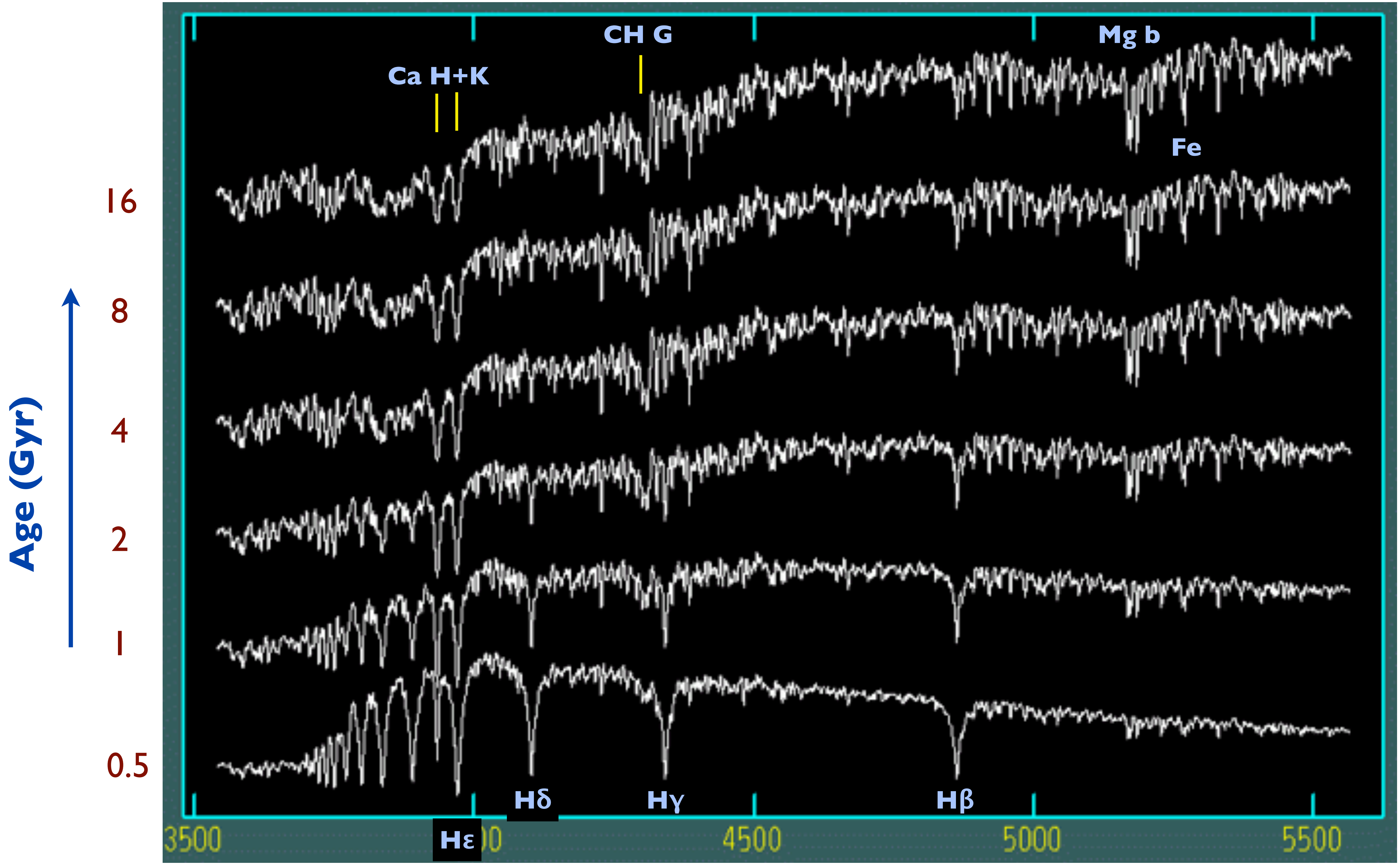
Can no longer isolate individual lines.

Continuum is no longer well-defined.

How can we measure strengths of lines?

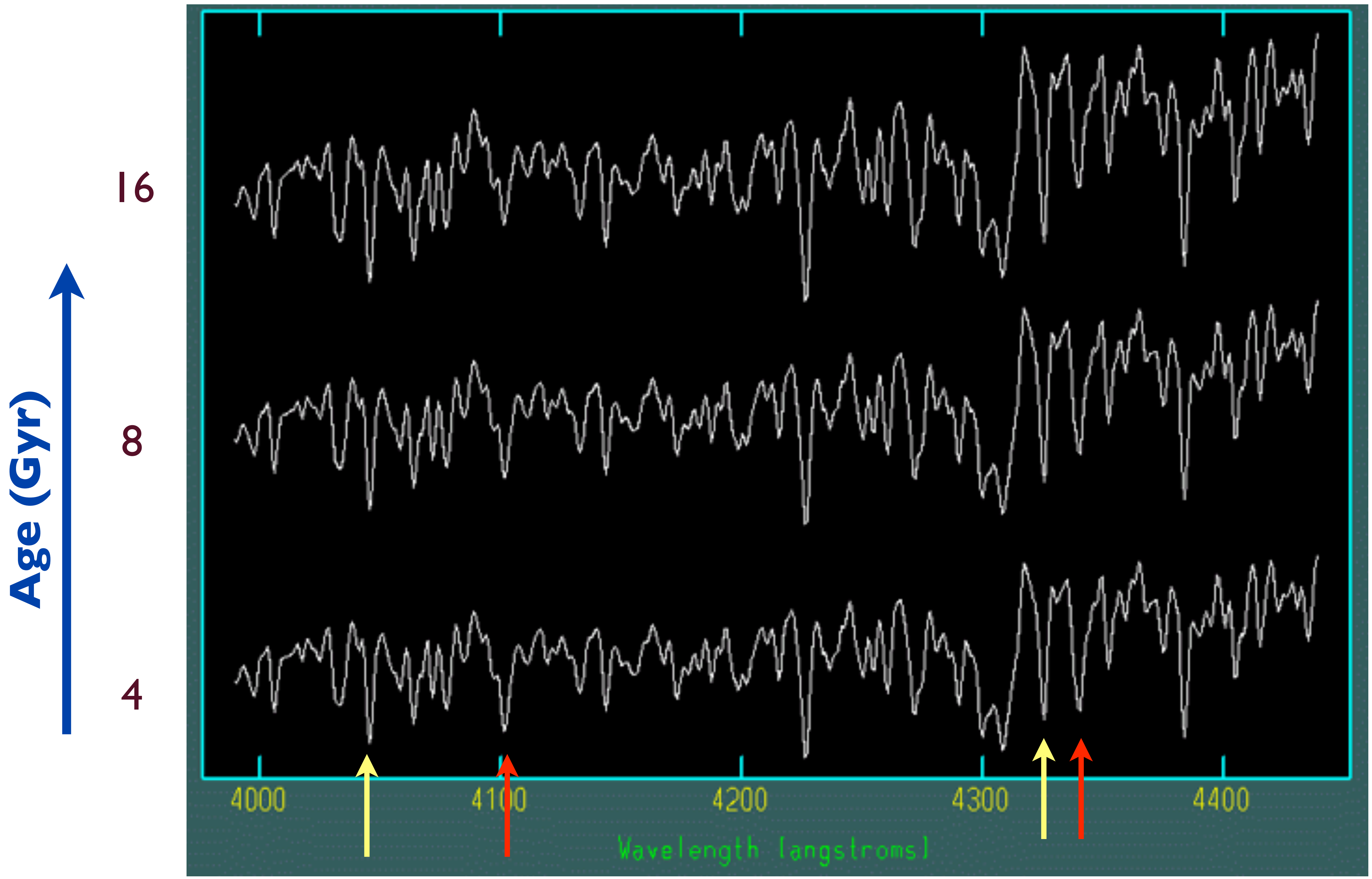


SSP Spectra: Variation with Age



Vazdekis et al. (2010) models at solar Fe/H from MILES library.

SSP Spectra: Variation with Age

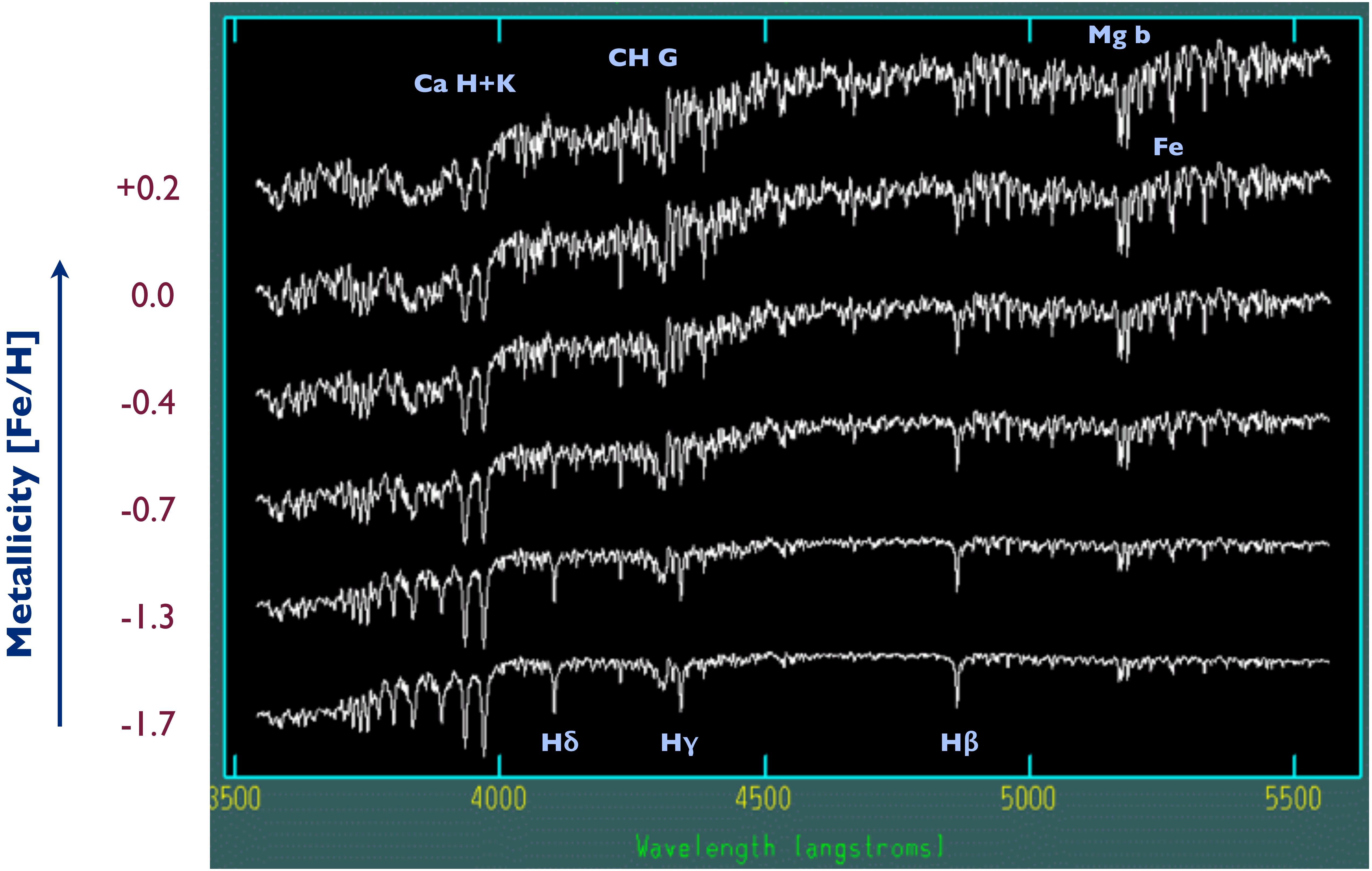


Vazdekis et al. (2010) models at solar Fe/H from MILES library.

Changes in the spectrum are still quite subtle for older ages!

And quite "linear": old + young looks very similar to a middle-age SSP

SSP Spectra: Variation with metallicity



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

Disentangling age and metallicity

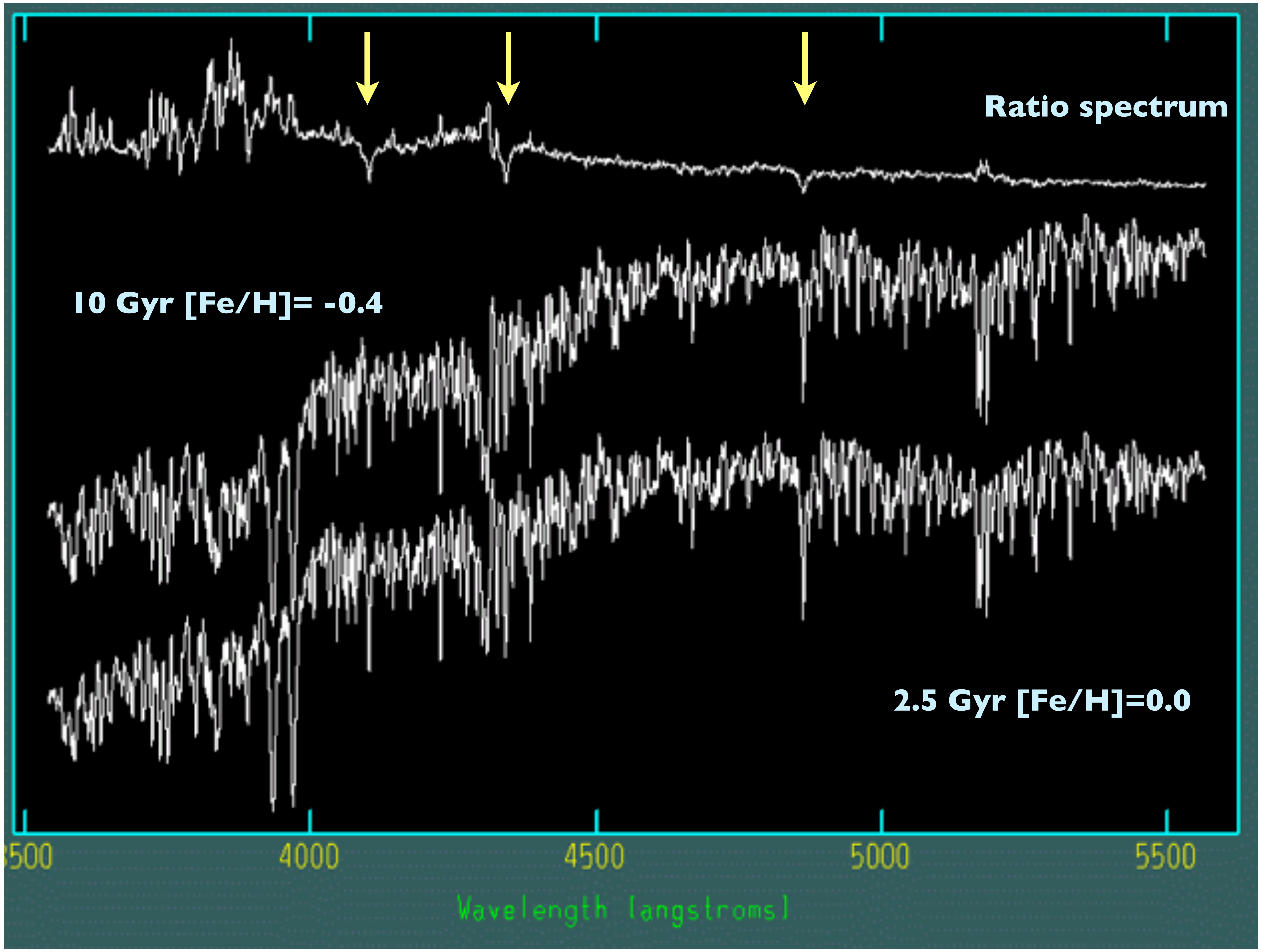
BREAKING THE DEGENERACY WITH SPECTRA

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.

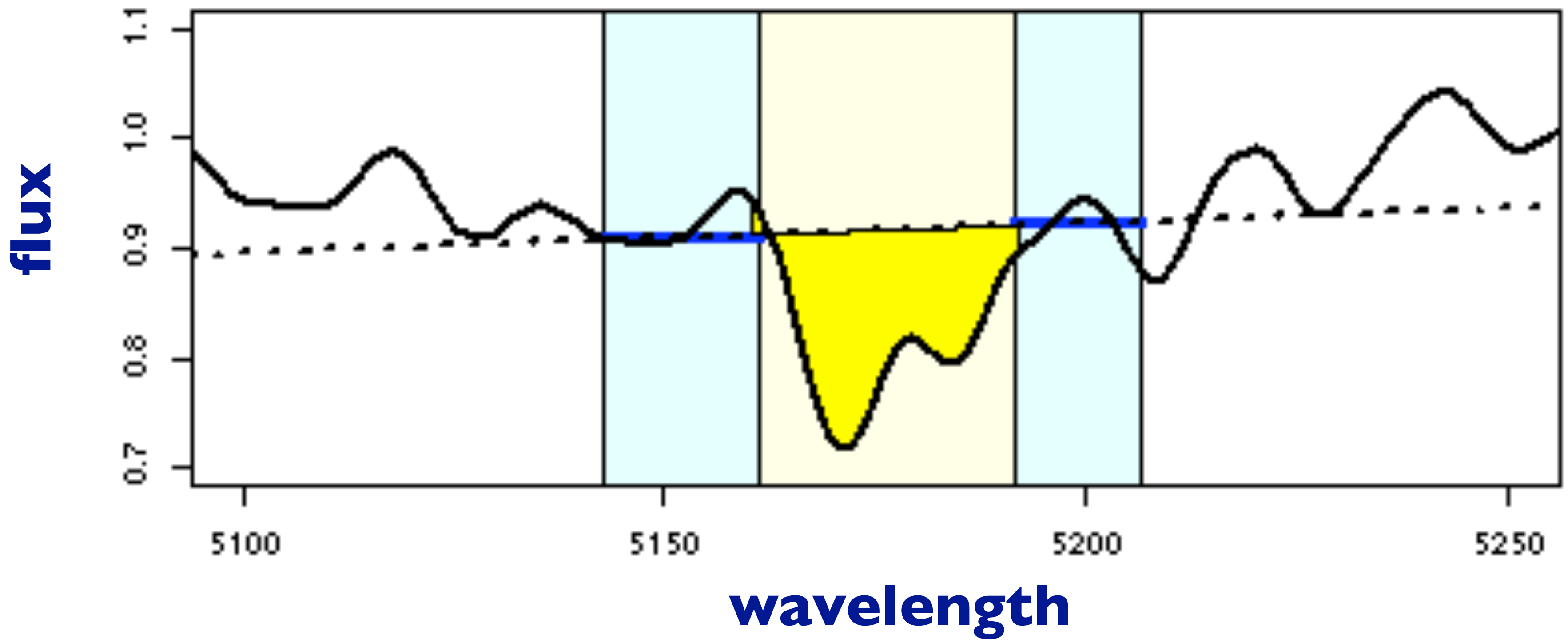
We can exploit this localized spectral information to beat the age-metallicity degeneracy.

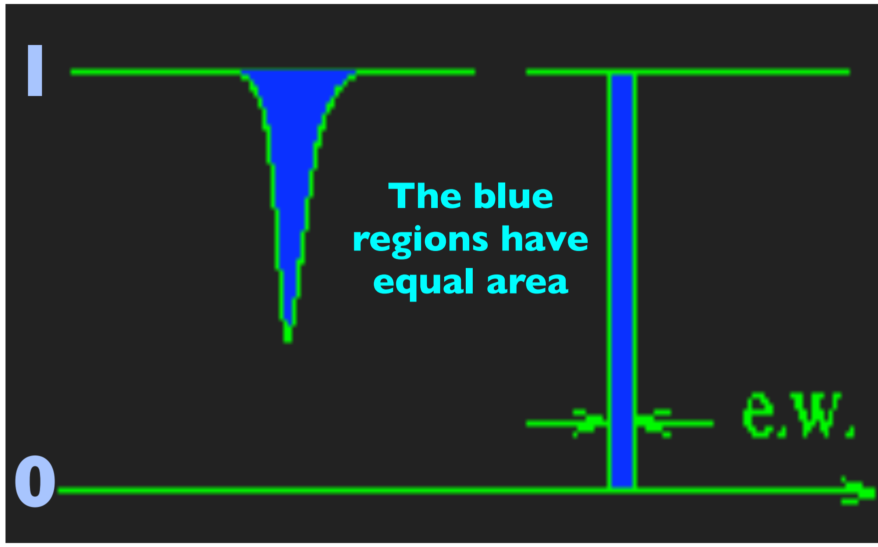
<u>But how?</u>



Vazdekis et al. (2007) models from MILES library

Line indices (e.g. “Lick” indices)





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

We have seen that the degeneracy-breaking power of spectra is localised to particular features.

So define “indices” which isolate these features and so carry most of the information in the spectra.

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

Express absorbed flux as an equivalent width.

Line Indices

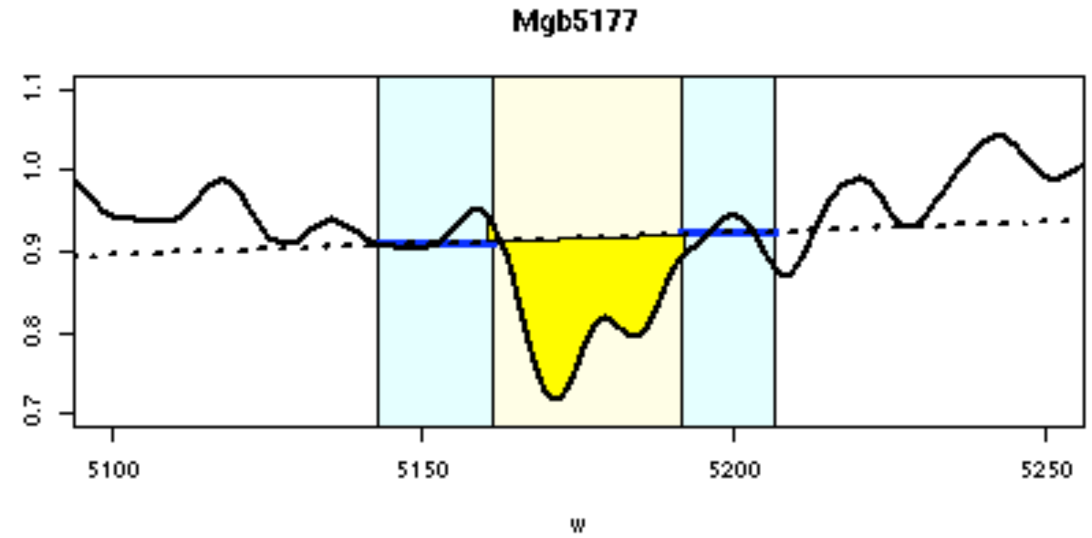
Pseudo-continua and index band defined to be ~10 Angstroms wide to match typical velocity dispersions in galaxies.

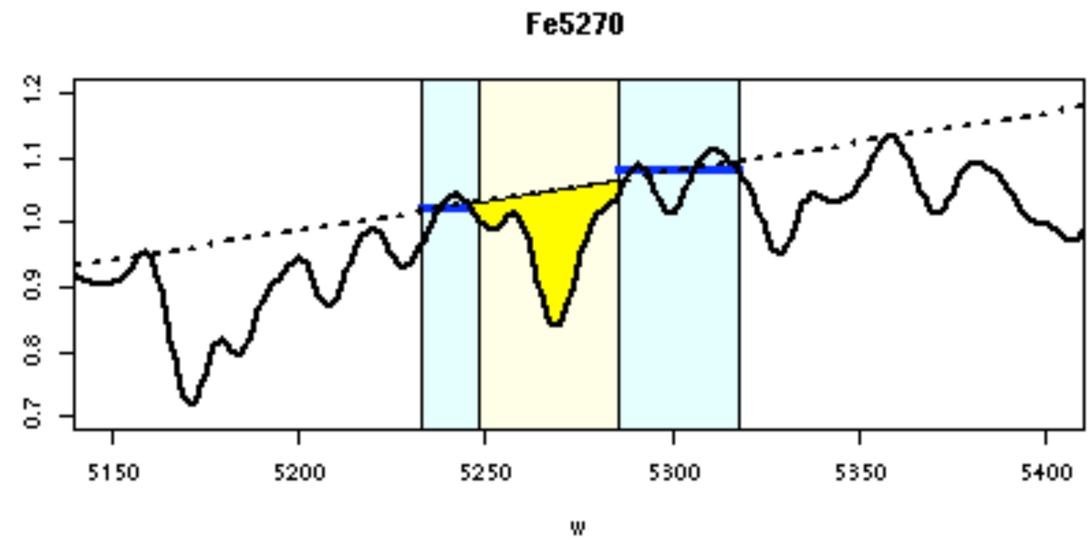
An index may be negative even though the feature it measures is still in absorption.

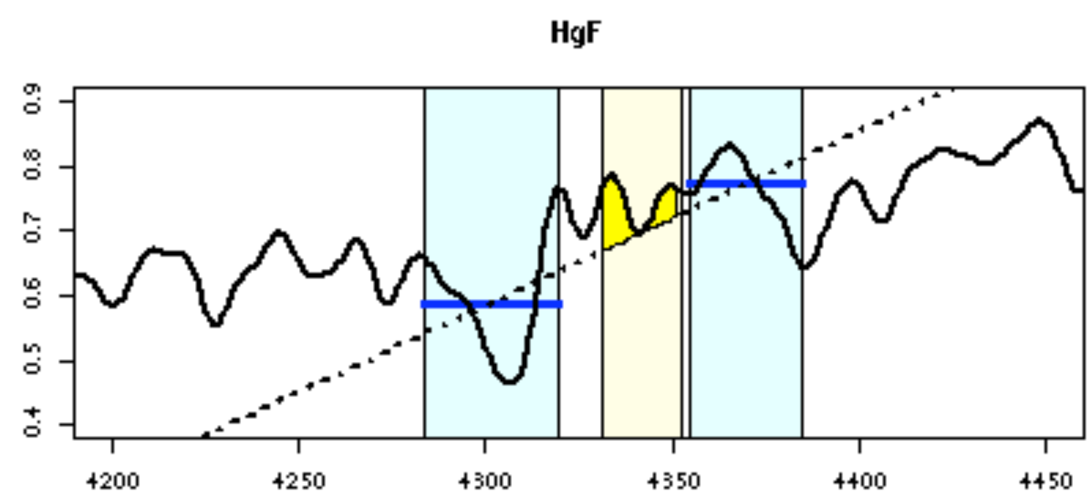
Historically important indices based on the Lick Observatory Stellar Library (Worthey et al. 1994).

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.







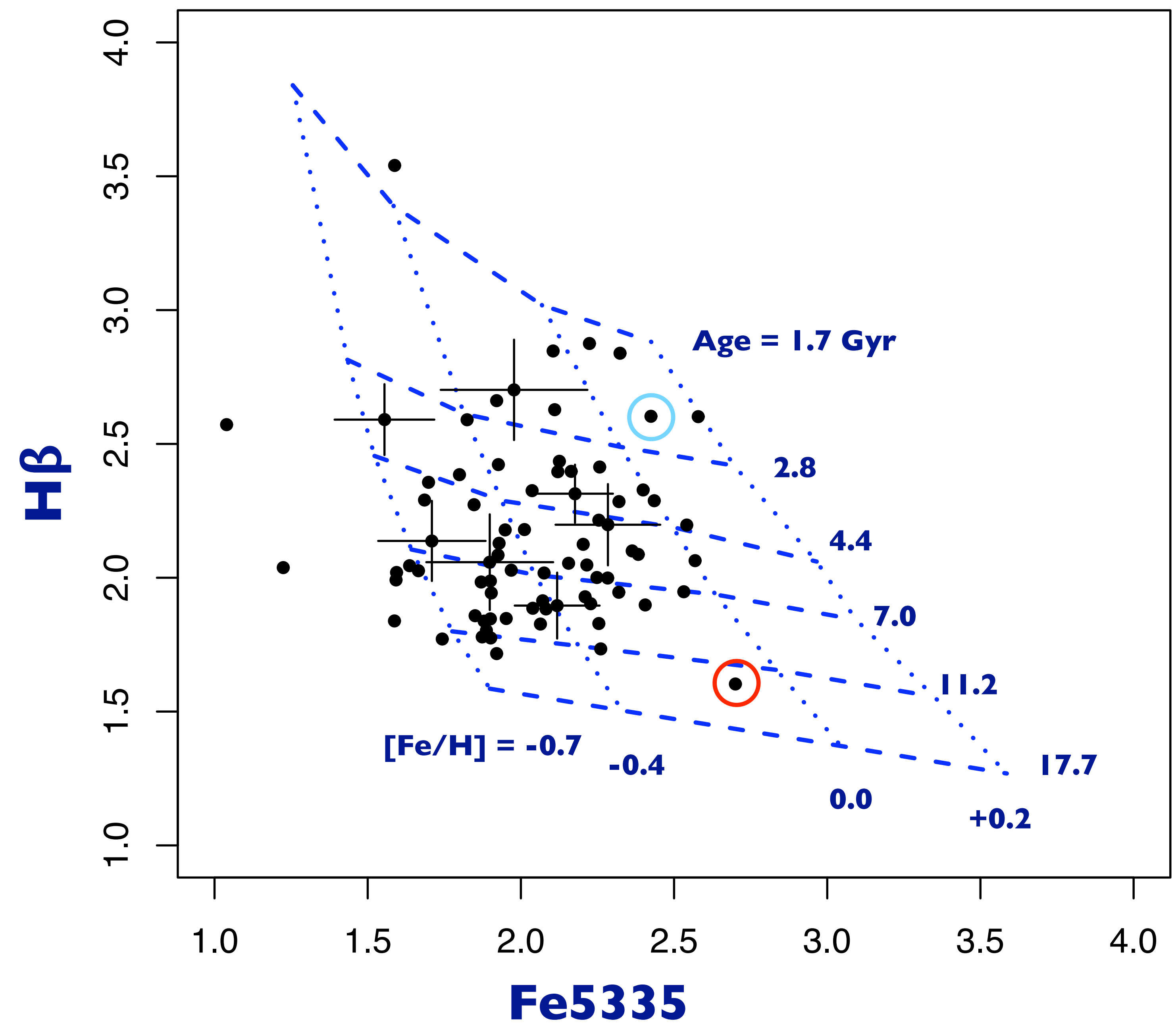
Predicting Indices

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)

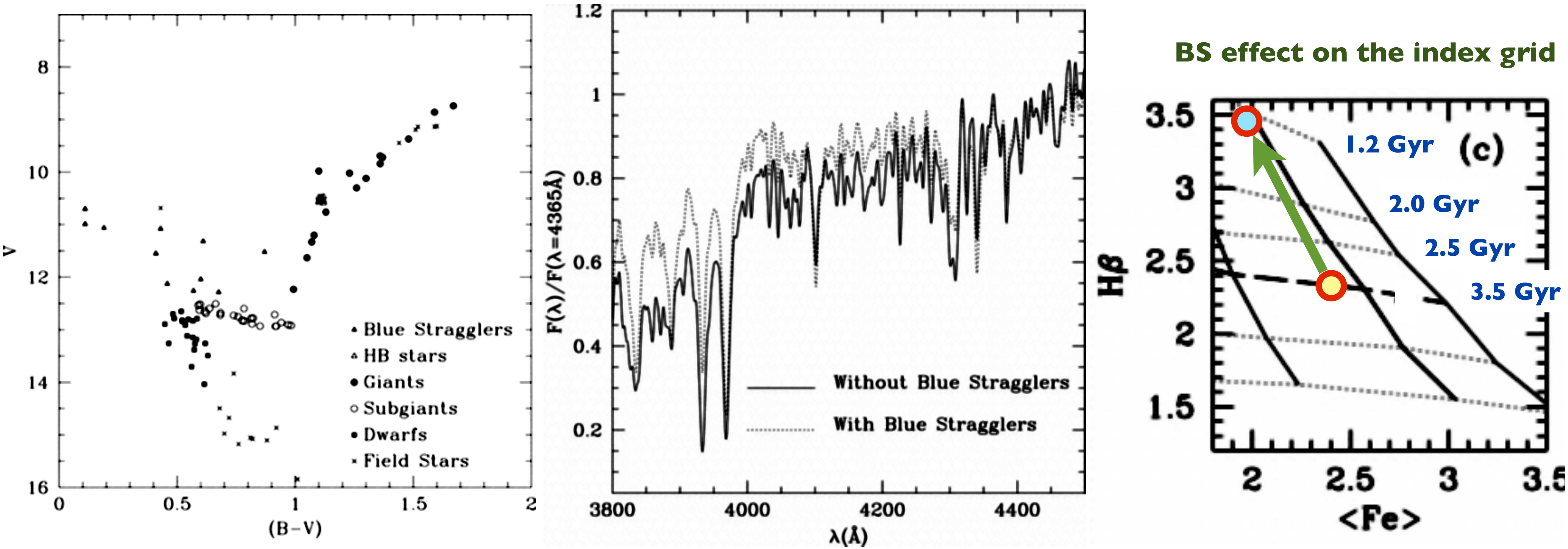
Result: Balmer-vs-metallic grids widely separate the constant-age and constant-metallicity tracks. So we can "read off" the results for an observed galaxy.

Many pairs of indices could be chosen: do they all give the same results for a given galaxy?



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

But are we including all relevant stars?



Schiavon et al. 2004

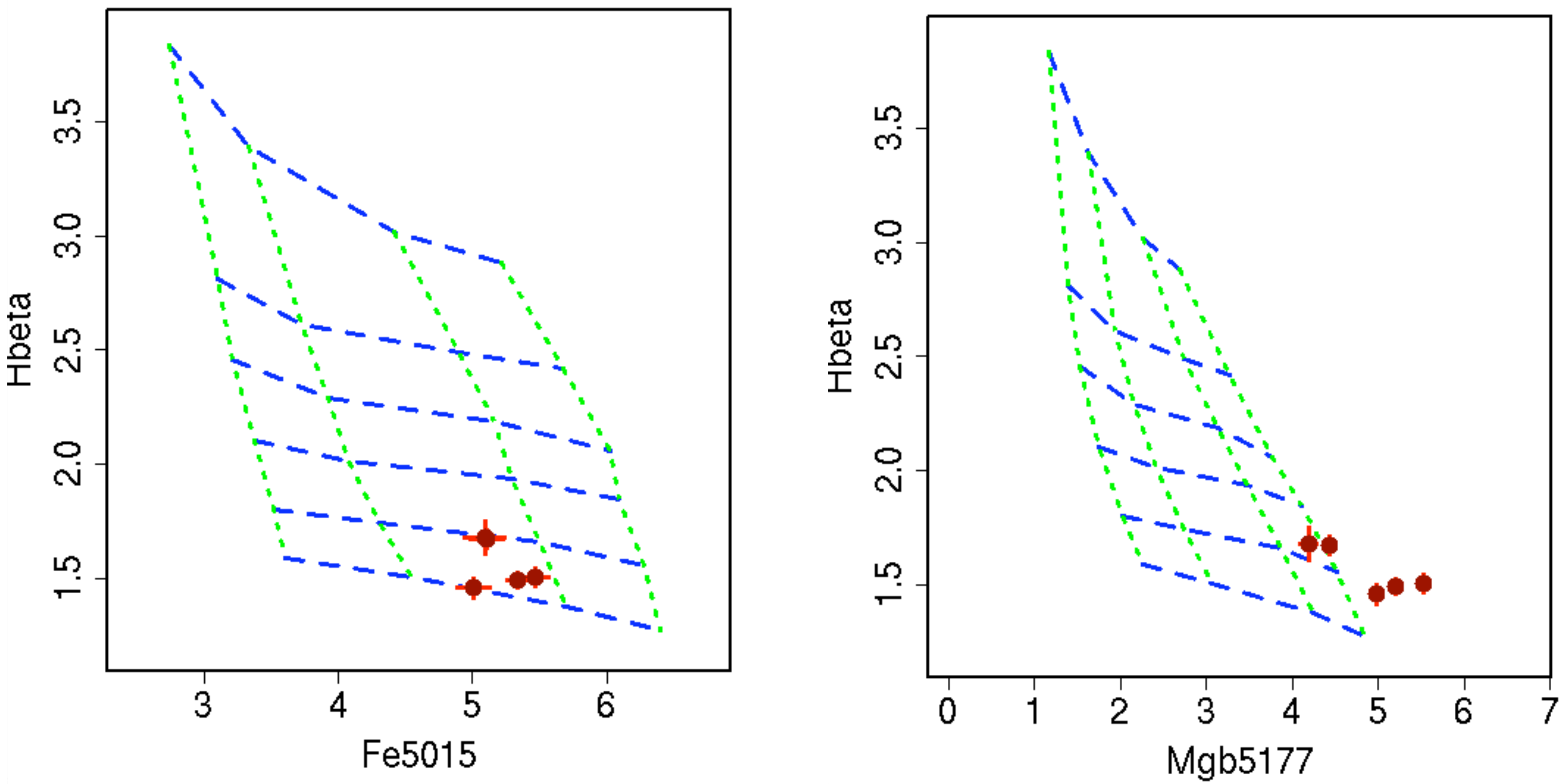
Synthesising the "integrated" spectrum of M67 by adding together spectra for its stars.

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

Including the BSs makes a big difference to the indices (hot stars so strong Balmer lines). (Recall, M67 has unusually large population of BSs).

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

Consistency among 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!

Magnesium Enhancement

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.

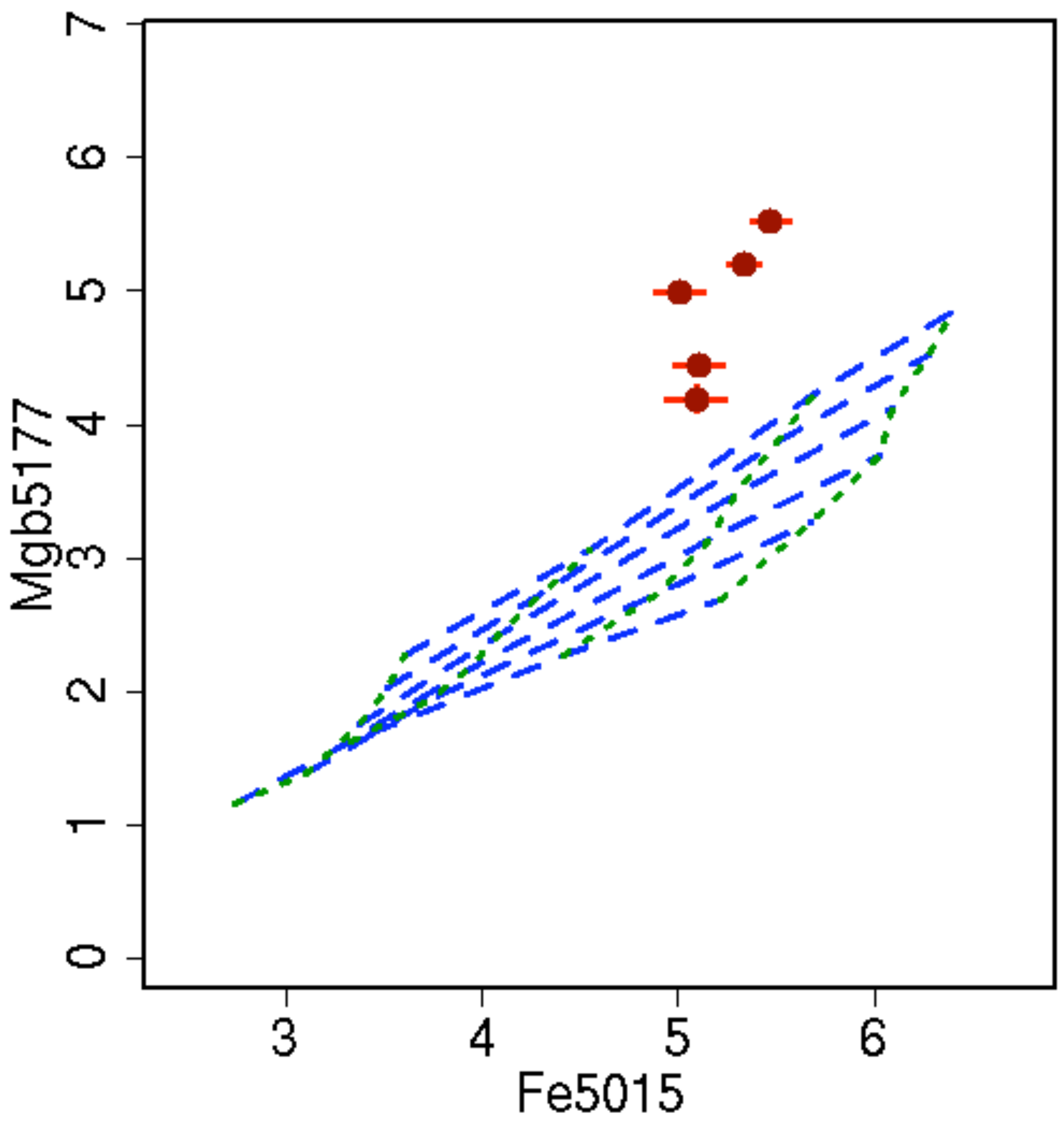
Express this "Mg enhancement" as [Mg/Fe] > 0

(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?



Spectra of unresolved pops: summary

We have come a long way:

The different behaviour of Balmer and metal indices leads to grids that clearly distinguish age differences from metallicity differences.

Spectra sufficient to measure these indices are or will be available in huge numbers from SDSS/GAMA/etc for luminous galaxies.

The difference in abundance of Mg and Fe might provide a crucial window into galaxy evolution.

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. synthetic spectra for cool stars?

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

END OF LECTURE III