# Stellar Populations - Lecture IV

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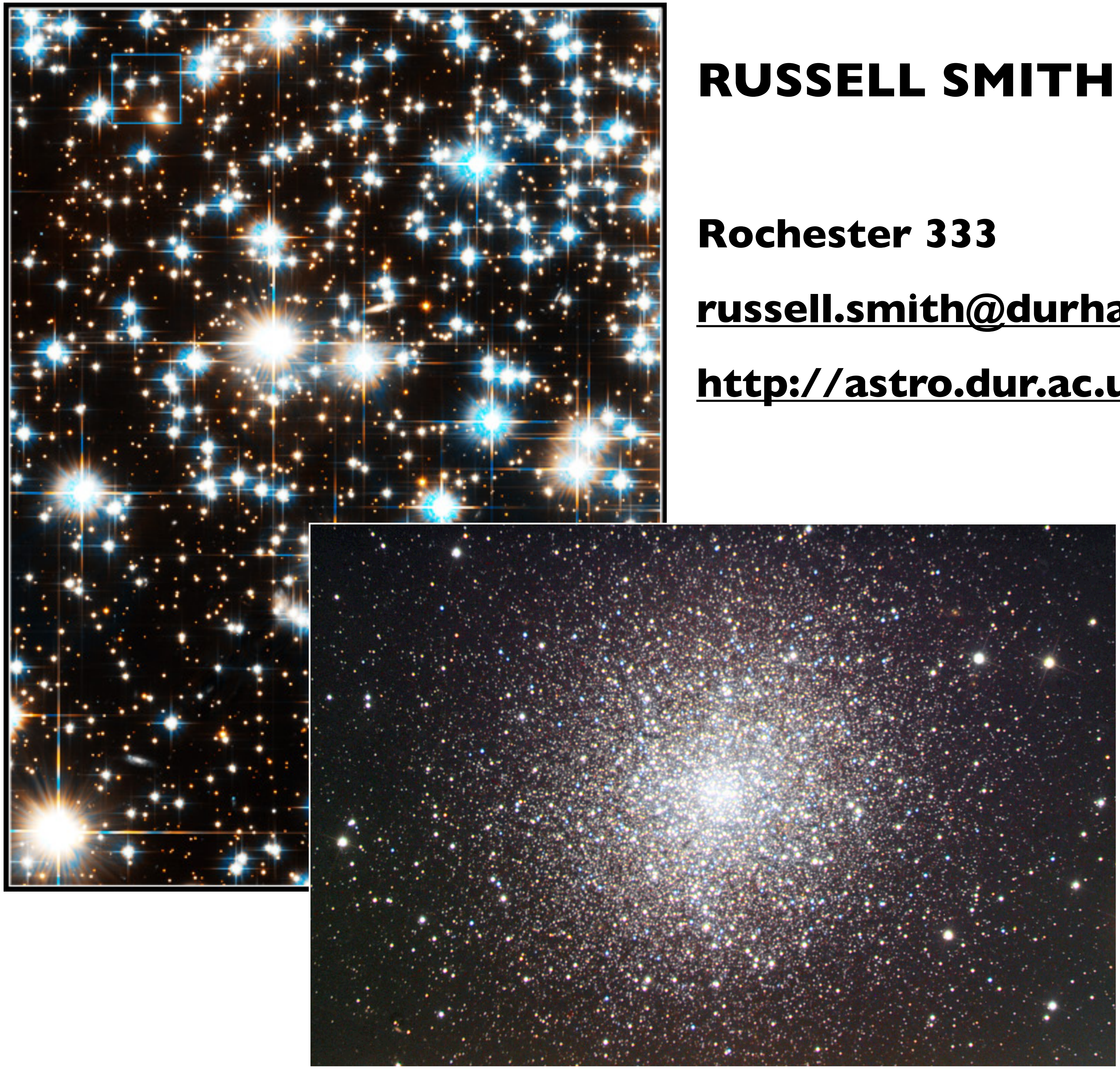
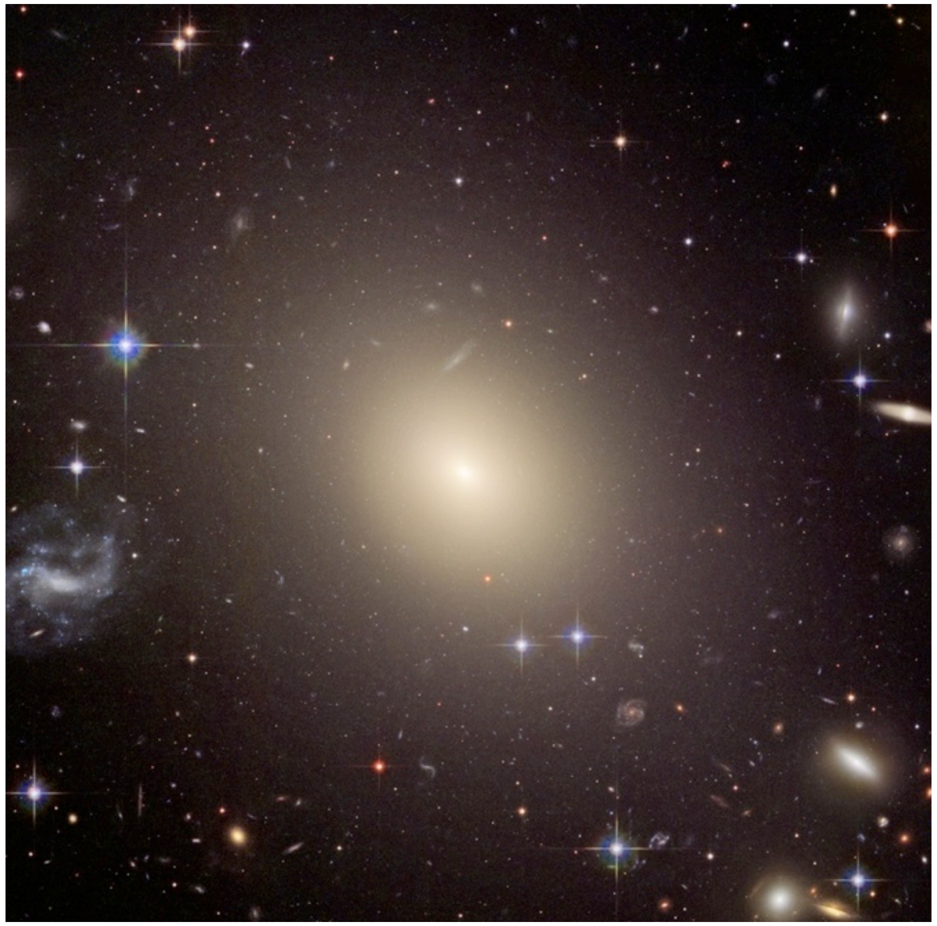
**http://astro.dur.ac.uk/~rjsmith/stellarpops.html**





# Homework problem...

1.) Assume a galaxy forms its stars in a single rapid burst, with a Salpeter initial mass function extending from 0.1 to 100 Msun.

After 10 Gyrs have passed, divide the surviving stars into three groups: lower main-sequence upper main sequence (MS stars with mass > 0.75 Msun), lower main sequence (MS stars with mass < 0.75 Msun), and red giants.

Calculate the fractional contribution of each group to the
a) total *number* of surviving stars.
b) total *mass* in surviving stars.
c) total *luminosity* of the galaxy.

MS lifetime-mass relationship: $T_{MS} \sim 10$ Gyr x $(M/M_{sun})^{-2.5}$

➔ Main-sequence turn-off mass at age 10 Gyr is $M_{TO} = 1\ M_{sun}$

Stars with mass ~1-2 $M_{sun}$ have RGB lifetimes ~1 Gyr

➔ Most massive surviving star must have had MS lifetime ~9Gyr

➔ Corresponds to a mass of $M_{up} = 1.043\ M_{sun}$

# Homework problem...

Calculate the fractional contribution of each group to the
a) total *number* of surviving stars.
b) total *mass* in surviving stars.
c) total *luminosity* of the galaxy.

Fractional contribution of lower-MS to total ***number*** of surviving stars:

$$F_{LMS} = \frac{\int_{M_{lo}}^{M_{cut}} N(m)\, dm}{\int_{M_{lo}}^{M_{up}} N(m)\, dm}$$

Where:

$N(m) = N_0 \, m^{-2.35}$ (Salpeter IMF)

$M_{lo} = 0.1 \, M_{sun}$

$M_{cut} = 0.75 \, M_{sun}$

$M_{up} = 1.043 \, M_{sun}$

→ $F_{LMS} = 0.975.$ Change limits to get $F_{UMS} = 0.022$; $F_{RGB} = 0.0025$

Lower MS dominate the total number of stars

# Homework problem...

Calculate the fractional contribution of each group to the
a) total *number* of surviving stars.
b) total *mass* in surviving stars.
c) total *luminosity* of the galaxy.

Fractional contribution of lower-MS to total ***mass*** of surviving stars:

$$F_{LMS} = \frac{\int_{M_{lo}}^{M_{cut}} N(m)\, m\, dm}{\int_{M_{lo}}^{M_{up}} N(m)\, m\, dm}$$

Where:

$N(m) = N_0\, m^{-2.35}$ (Salpeter IMF)

$M_{lo} = 0.1\ M_{sun}$

$M_{cut} = 0.75\ M_{sun}$

$M_{up} = 1.043\ M_{sun}$

➔ $F_{LMS} = 0.904$. Change limits to get $F_{UMS} = 0.085$; $F_{RGB} = 0.012$

Lower MS also dominate the total mass of stars

# Homework problem...

Calculate the fractional contribution of each group to the
a) total *number* of surviving stars.
b) total *mass* in surviving stars.
c) total *luminosity* of the galaxy.

Fractional contribution of lower-MS to total ***luminosity*** of surviving stars:

$$F_{LMS} = \frac{\int_{M_{lo}}^{M_{cut}} N(m)\, L_{MS}(m)\, dm}{\int_{M_{lo}}^{M_{TO}} N(m)\, L_{MS}(m)\, dm + \int_{M_{TO}}^{M_{up}} N(m)\, L_{RGB}\, dm}$$

Where:

$L_{MS}(m) = L_{sun}\,(M/M_{sun})^{3.5}$ (luminosity-mass relation for MS)

$L_{RGB} = 100\, L_{TO} = 100\, L_{sun}$

→ $F_{LMS} = 0.054$. Change limits to get $F_{UMS} = 0.047$; $F_{RGB} = 0.899$

RGB dominates the total light output.

# Homework problem...

2.) It has sometimes been proposed that elliptical galaxies have a "bottom-heavy" initial mass function, e.g. a power-law with slope -3.5 instead of the Salpeter -2.35. Calculate the total luminosity contributions for the same three mass ranges for the bottom-heavy case.

Repeat the integrals using the new IMF slope $N(m) \sim m^{-3.5}$.

# Homework problem...

Compare the fractions for the two IMFs:

| **Salpeter** | LMS | UMS | RGB |
|---|---|---|---|
| Number | 97.5% | 2.2% | 0.3% |
| Mass | 90.4% | 8.5% | 1.1% |
| Light | 5.4% | 4.7% | 89.9% |

| **x=3.5** | LMS | UMS | RGB |
|---|---|---|---|
| Number | 99.6% | 0.3% | 0.1% |
| Mass | 98.0% | 1.8% | 0.2% |
| Light | 13.3% | 5.1% | 81.6% |

# Homework problem...

3.) Some absorption lines in the spectra of stars depend explicitly on the mass of the star, as well as on temperature and metallicity.

Assume that for one of these features, we define a Lick-like line-index with a "feature band" 25 Angstroms in width. In stars, this feature has an equivalent width of ~5 Angstroms for all stars of mass below 0.75 Msun, but is essentially absent from all stars of higher mass.

We want to exploit this feature to constrain the dwarf-star content of a distant galaxy, from the integrated spectrum. Qualitatively, how will the measured index depend on the slope of the initial mass function?

What signal-to-noise ratio (per angstrom) is required in the spectrum to distinguish between the Salpeter and bottom-heavy scenarios at 3-sigma significance?

For the bottom-heavy IMF 13% of the light comes from stars which have this absorption feature. For the Sapeter IMF, only 5% of the light does.

➔ we expect the feature to be stronger in the integrated spectrum for the bottom-heavy case.

(More generally, increasing strength of this feature implies an IMF with more low-mass stars, relative to ~1$M_{sun}$ stars).

# Homework problem...

What signal-to-noise ratio (per angstrom) is required in the spectrum to distinguish between the Salpeter and bottom-heavy scenarios at 3-sigma significance?

For the bottom-heavy IMF 13% of the light comes from stars which have this absorption feature.

➔ Equivalent width will be diluted from 5 Ang to 0.13 x 5 = 0.65 Ang

For the Salpeter IMF 5% of the light comes from stars which have this absorption feature.

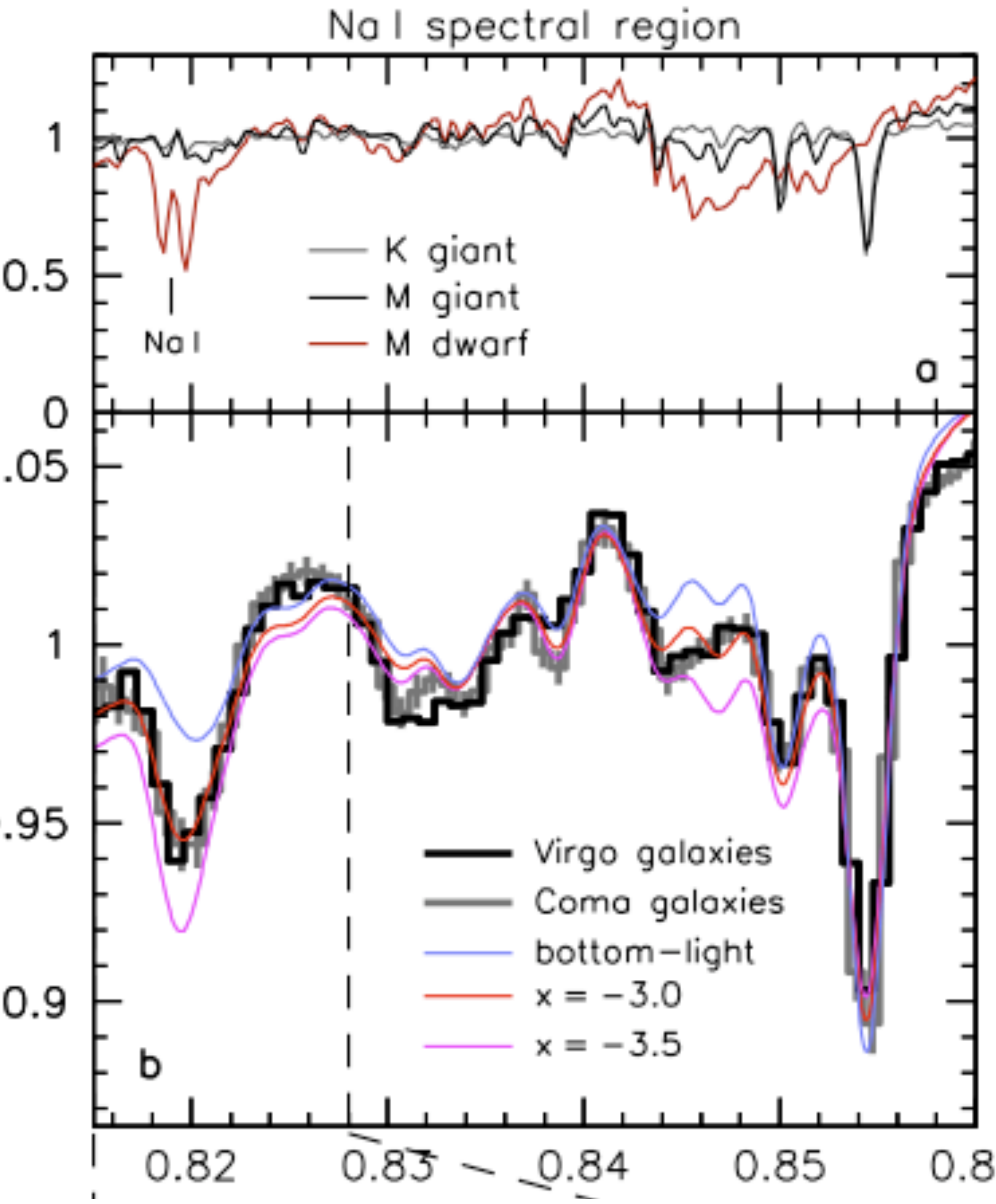
➔ Equivalent width will be diluted from 5 Ang to 0.05 x 5 = 0.25 Ang

To distinguish between these cases at the $3\sigma$ level means we measure the total flux inside the 25-Ang feature window with error less than (0.65-0.25)/3 i.e. error must be < 0.13 Angstrom.

So we need **total** S/N = 25 / 0.13 = 190 over the 25-Ang window.

Required S/N per angstrom is then 190 / sqrt(25) = 38.

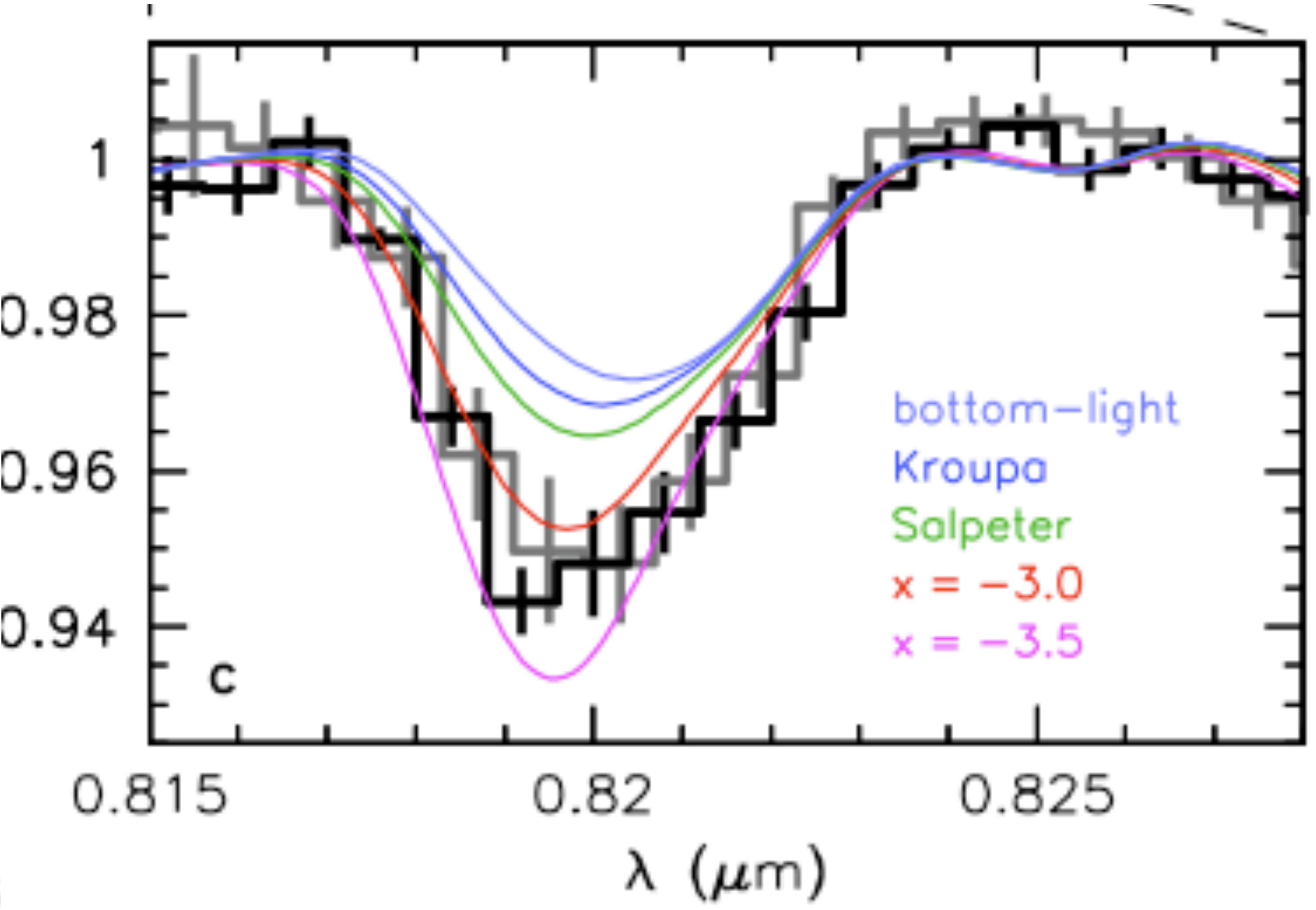
# A dwarf-dominated IMF in ellipticals?



van Dokkum & Conroy (2010)

Na I feature strong in cool dwarf stars but absent in giants.

Observed feature in elliptical galaxies is too strong to match models with MW-like (e.g. Kroupa/Chabrier) IMFs



# 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.

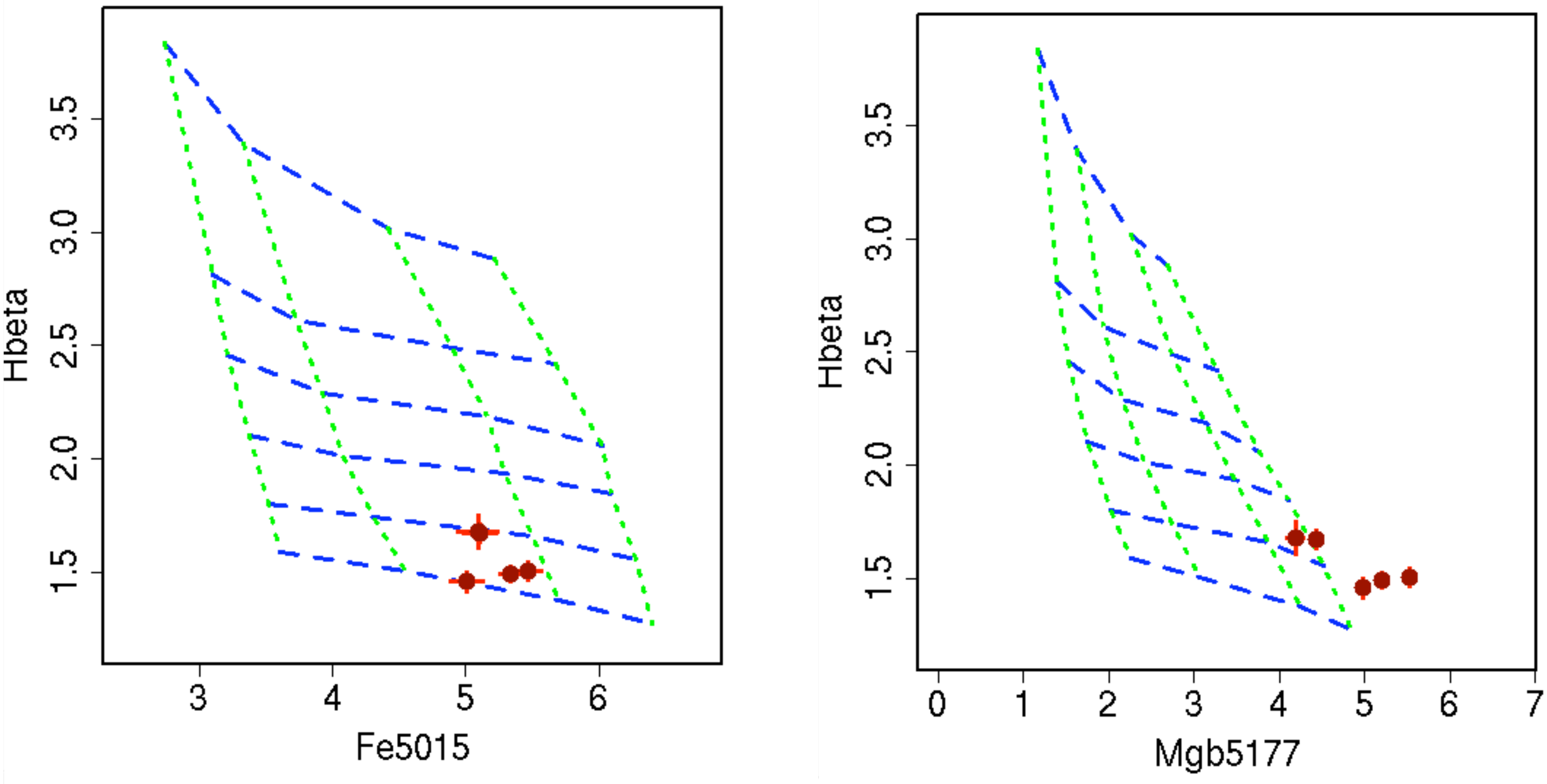
**III.** *** Spectra of unresolved populations**

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.

# Magnesium Enhancement



Discrepancy in metallicity measured using Fe-dominated and Mg-dominated indices.

Seems to indicate these galaxies (massive ellipticals) have Mg enhanced over Fe, relative to solar mixture: [Mg/Fe] > 0.

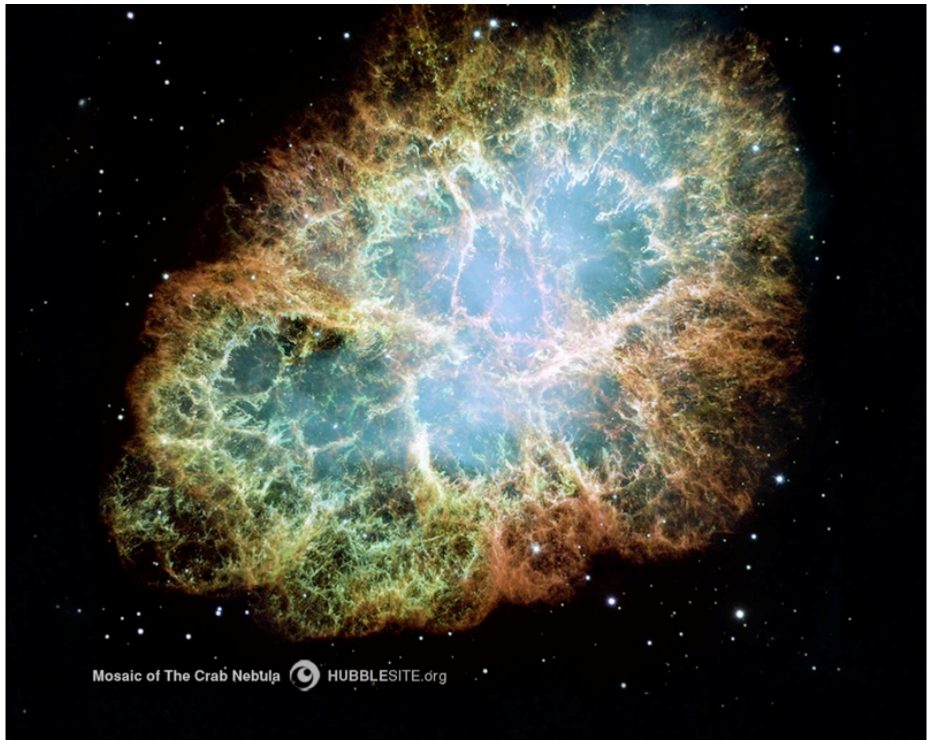
# Where does all this stuff come from?

Big Bang nucleosynthesis only able to create $^4$He (25% by mass), plus traces of D, $^3$He, $^3$Be, $^7$Li, $^6$Li

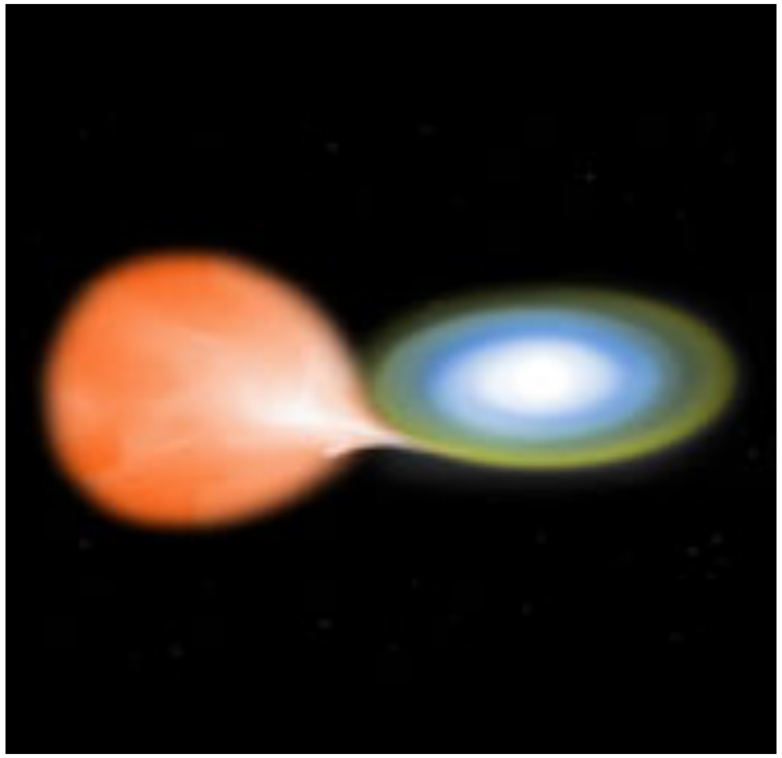
All the interesting stuff in the Universe (C,N,O,Na,Mg,Fe,etc) has been cooked up in stars and recycled in galaxies.

Production/release of different elements by different routes:

**AGB**



**SNII**



**SNIa**

# Low-mass: AGB / planetary nebulae

Stars of mass 1-8 $M_{sol}$

Outer layers of star, enriched in C, N, O from AGB (shell He-burning) phase, ejected into interstellar medium.

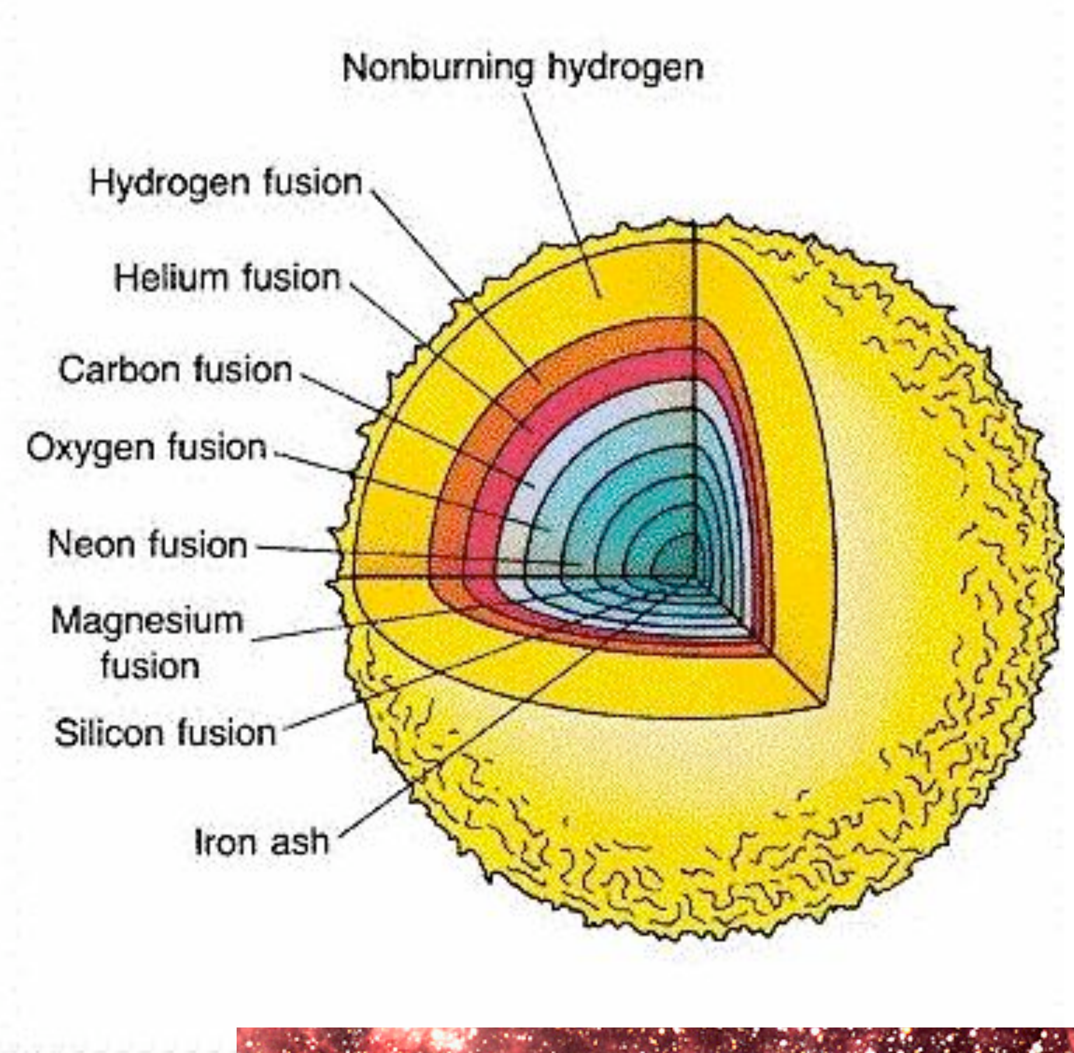
Exposed C-O core remains as a "post-AGB star" which eventually cools to become a white dwarf.

Outer layers become ionised by the p-AGB central star, and shine as a planetary nebula.

Progenitor masses 1-8 $M_{sol}$, lifetime up to $>10^9$ years.

**Major producers of C, N**

# High-mass: Type-II supernova



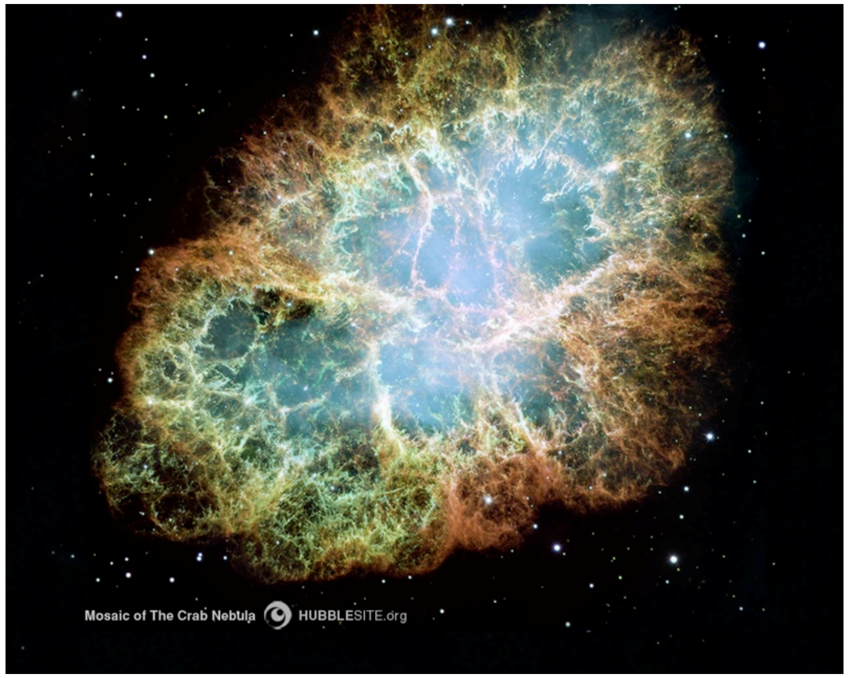
Final collapse of Fe core in evolved massive stars. Formation of neutron star halts the collapse, shockwave ejects the outer layers into the interstellar medium (ISM).

Inner Fe core becomes the NS, outer shells (C, O, Ne, Mg, etc from AGB phase) get ejected.

Progenitor initial mass > 8 $M_{sol}$, lifetime < $10^7$ yr.

**Major producers of O, Mg ( "α-elements" )**

(also of elements heavier than Fe synthesised in the explosion itself.)



# Binary-stars: Type Ia supernova

ESO/M. Kornmesser

Accretion from companion star pushes WD over the Chandrasekhar limiting mass.

WD composed initially of C+O undergoes nuclear fusion all the way to Fe group and ejected into ISM. (Alternatively could be caused by mergers of two WD: we don't know!)

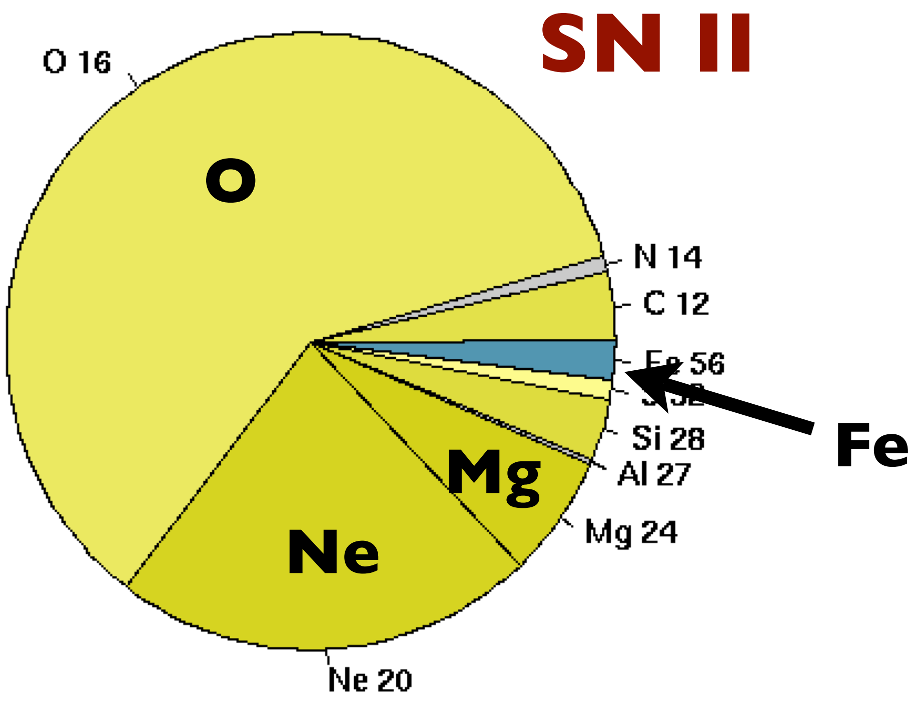
All SNIa explosions at similar mass so similar physics -> standard candle for cosmology.

Progenitor initial mass ~1 $M_{sol}$ (secondary) lifetimes ~ $10^9$ years (broad distribution)

**Major producers of Fe, Ni**

# Supernova Yields

**Yields** = mass of metals released into ISM at star death.



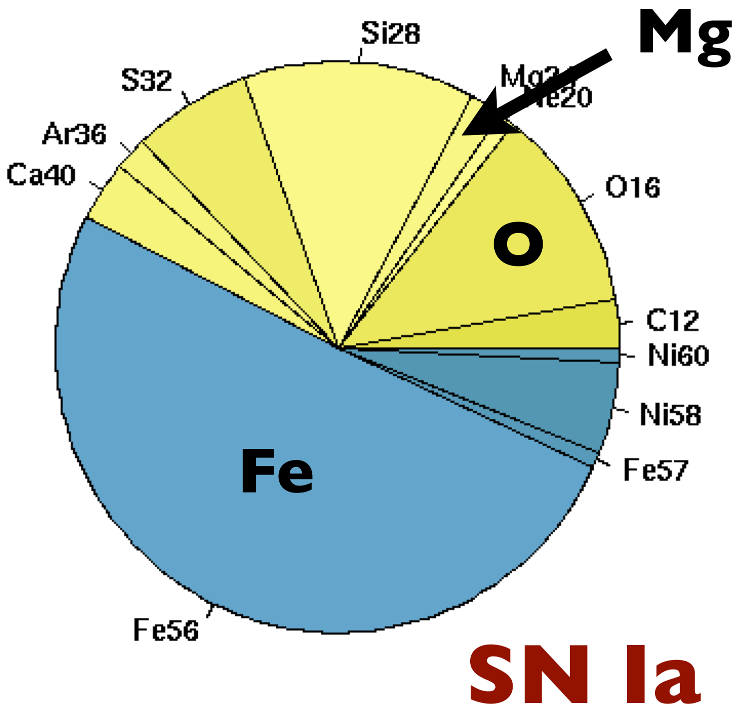
**SNe II** products dominated by O, Ne, Mg (Details depend on progenitor mass)

These nuclei are multiples of He nuclei, i.e. α-particles, produced in post-MS triple-α burning: "α-elements"

Very little Fe ejected.

**SNe Ia** products dominated by Fe (~50% of total heavy elements).

A lesser amount of α-elements (O, Mg, Ne, etc).



**Suggests:** Enhanced Mg/Fe will be seen in stars formed from material with more SNII-enrichment, less SNIa-enrichment, relative to the sun.

# Chemical Evolution

Recycling of enriched material between subsequent generations of stars.

Requires gravitational potentials, i.e. galaxies, to retain stellar ejecta (especially from SNe).

For detailed modelling of "chemical" evolution we need prescriptions for:

- Star-Formation History
- Initial Mass Function (ratio of AGB/SNIa/SNII)
- Element yields for AGB/SNIa/SNII
- Gas inflows and outflows

# Star-Formation duration from Mg/Fe

Consider SN rates from short-duration burst of star formation.

SN II rate is proportional to the star-formation rate!

SNe Ia follow after delay ~$10^{8\text{-}9}$ yr (broad distribution of precursor lifetimes)

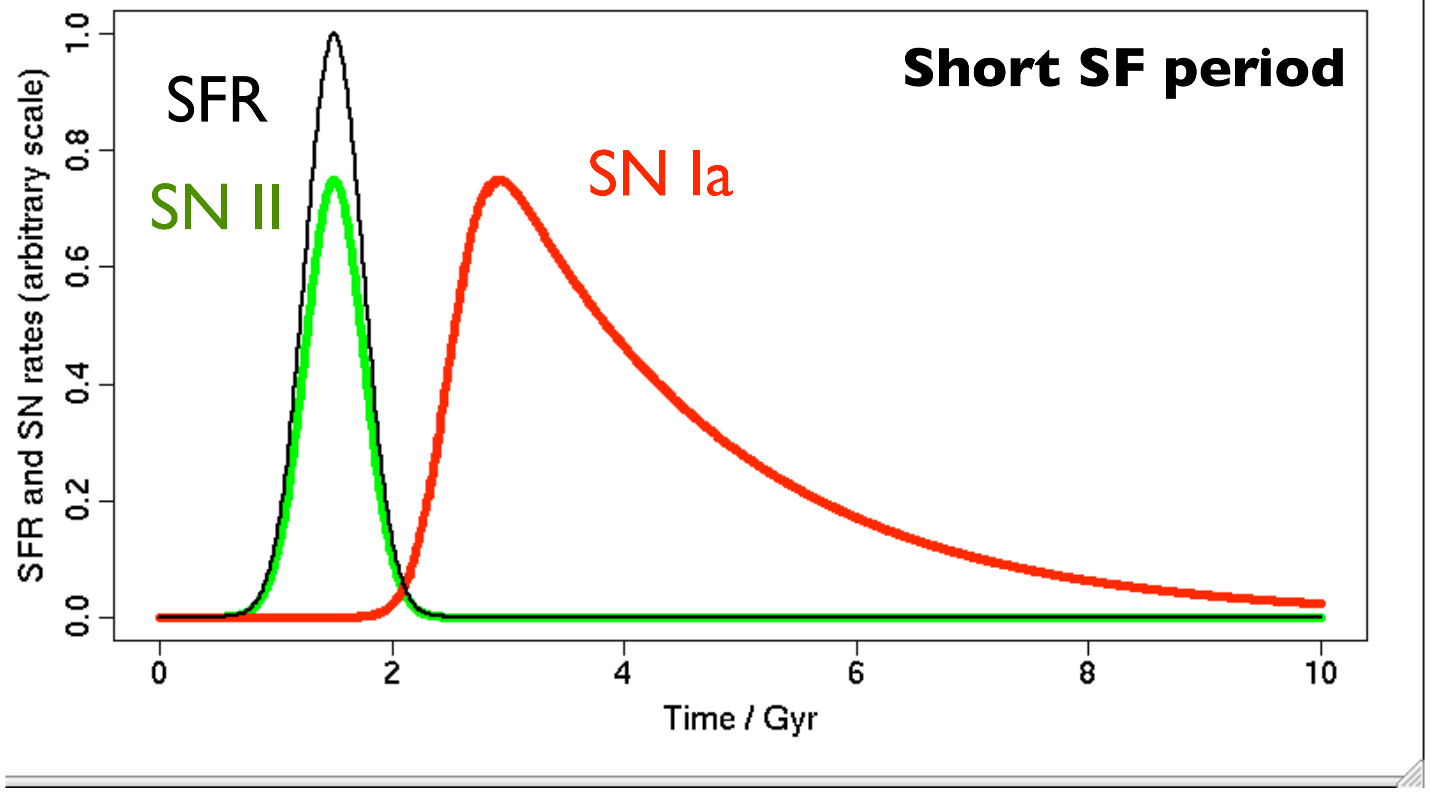
If burst is short, only Mg-rich SNII products incorporated into the stars. (SNIa ejecta just escape from galaxy). Higher Mg/Fe.

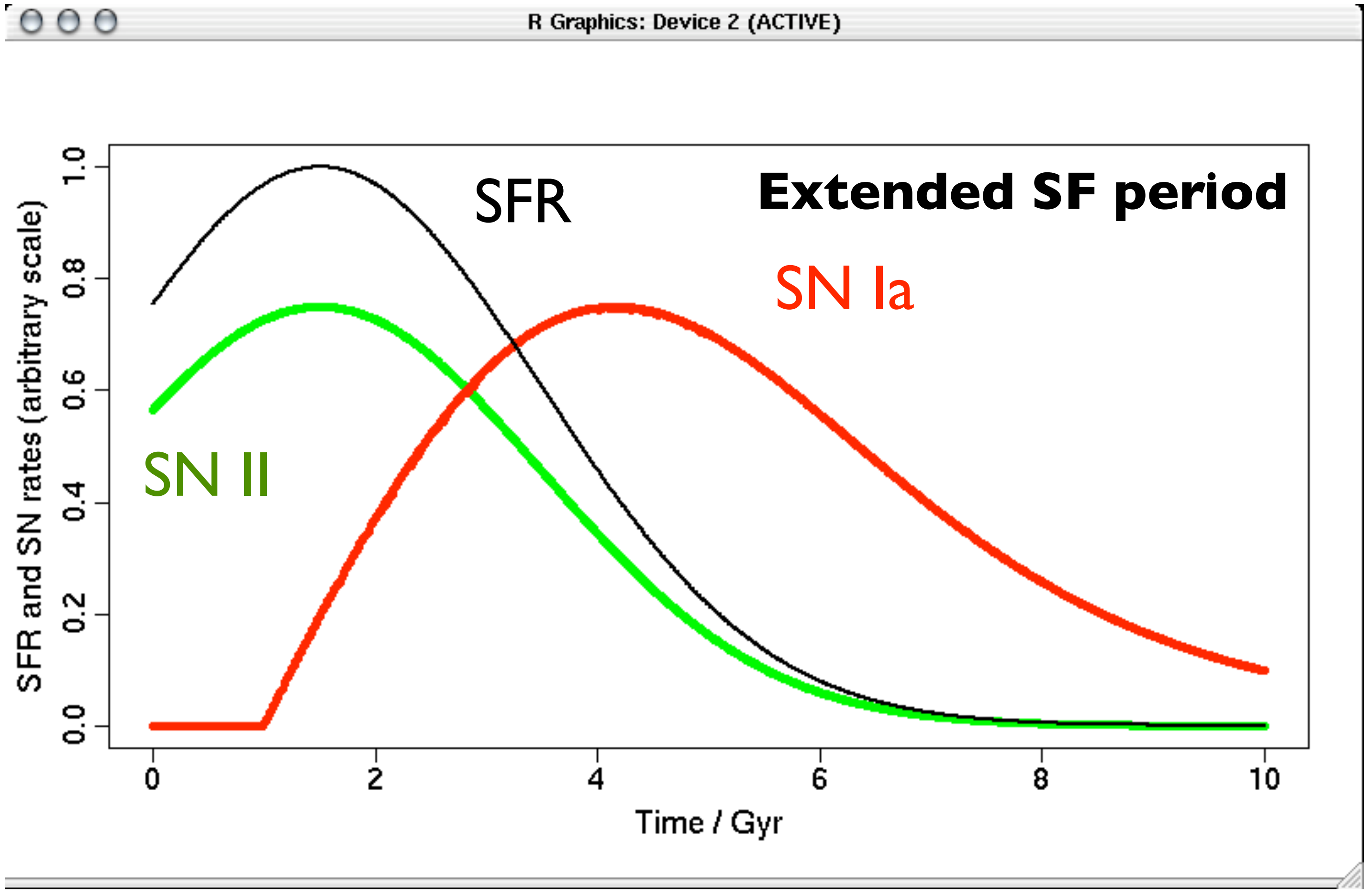
Longer bursts allow incorporation of some of the Fe-rich SNIa ejecta: Lower Mg/Fe.

From "closed-box" chemical evolution models, Thomas et al. (2005) suggest:

$$[\mathrm{Mg/Fe}] = (1/5) - (1/6) \log(\Delta t)$$

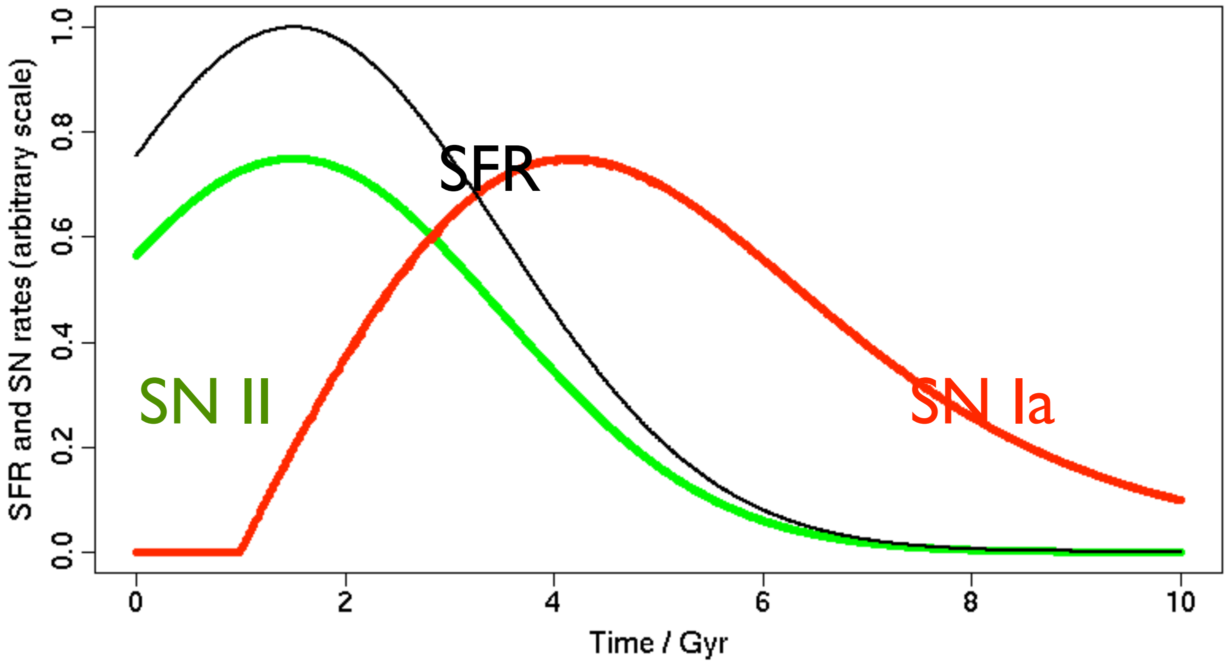
with $\Delta t$ the FWHM of the burst.





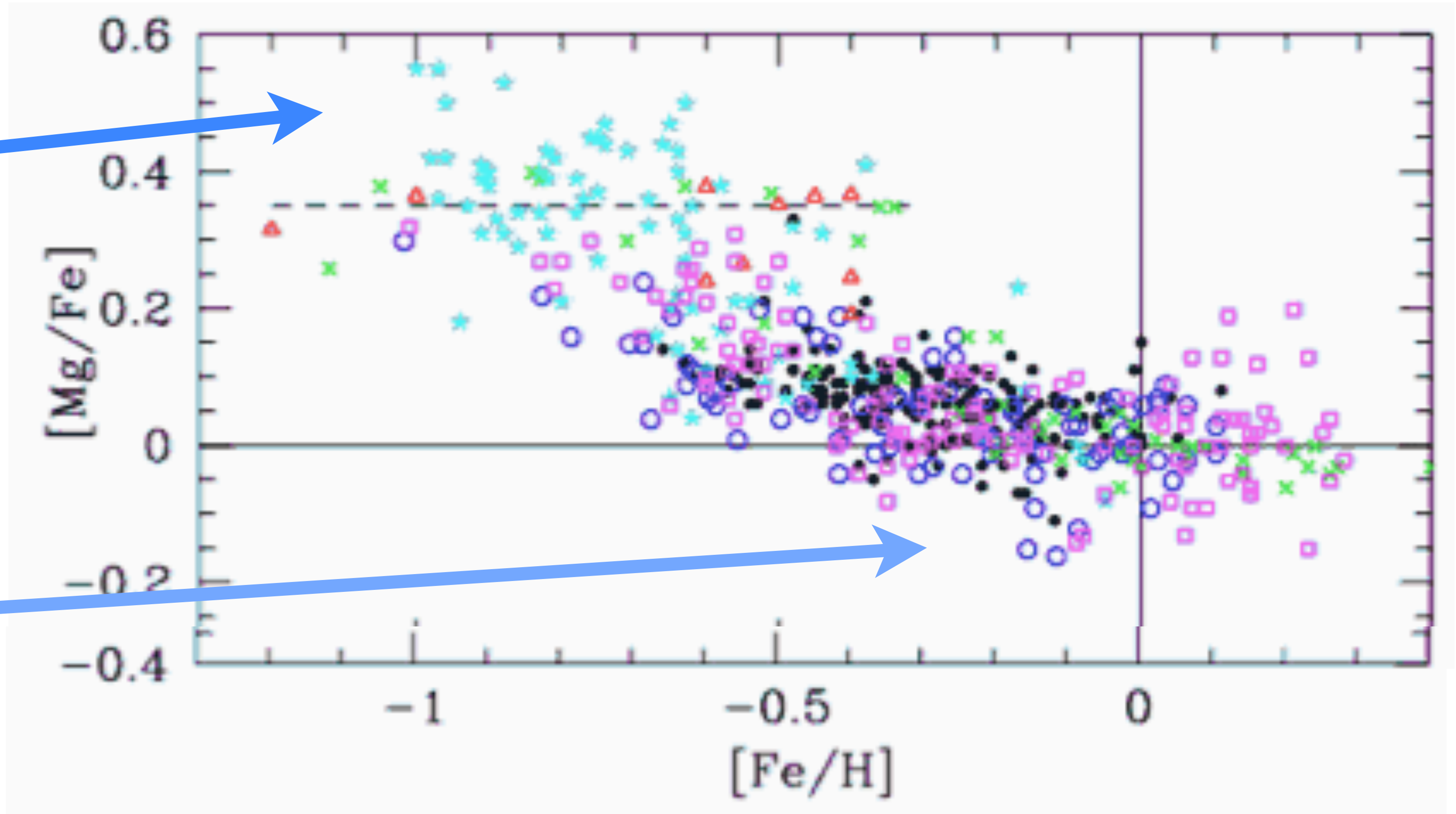
# Mg/Fe in the galactic disk

In the Milky Way disk, we're in the "slow formation" regime.



Earlier stars, with lower overall metallicity, form mostly from SN II material, so high Mg/Fe.

Iron "pollution" by SN Ia ejecta seen in the later, higher metallicity stars: low Mg/Fe



**Individual stars in MW disk (Reddy et al. 2003)**

# Aside: metal-poor stars

Metallicity in the galaxy expected to rise with time, i.e. can use [Fe/H] as a clock to measure early phases of chemical evolution.

First stars must have formed without <u>any</u> metals: "Population III".

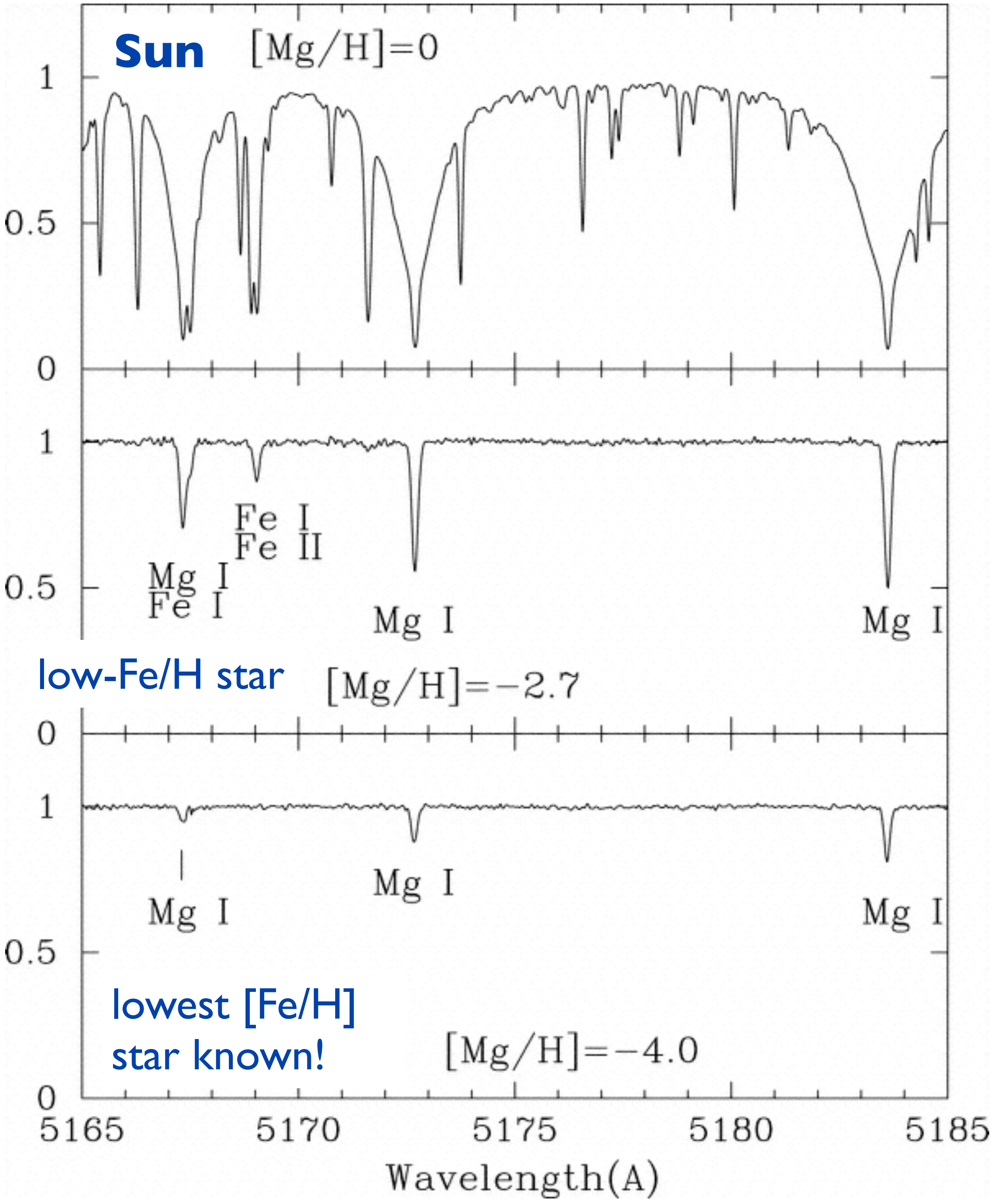
Lowest-metallicity stars known do still have measurable Fe: Current record holder has [Fe/H] = -5.4. ( ~1/250,000 solar)

Is it a Pop III star polluted by accretion from the ISM? Or an extreme Pop II star, formed from Pop-III enriched material?

Pop III stars probably have unusual properties, masses, different SN yields.

Many very-metal-poor stars seem to have strange abundance patterns, e.g. [C/Fe]≈4 which must tell us something about unobserved Pop III.

Frebel et al. (2006)



(Mg triplet region)

# Abundance ratio effects

To measure [Mg/Fe] (or [α/Fe]) we need to extend models to allow for variable abundances.

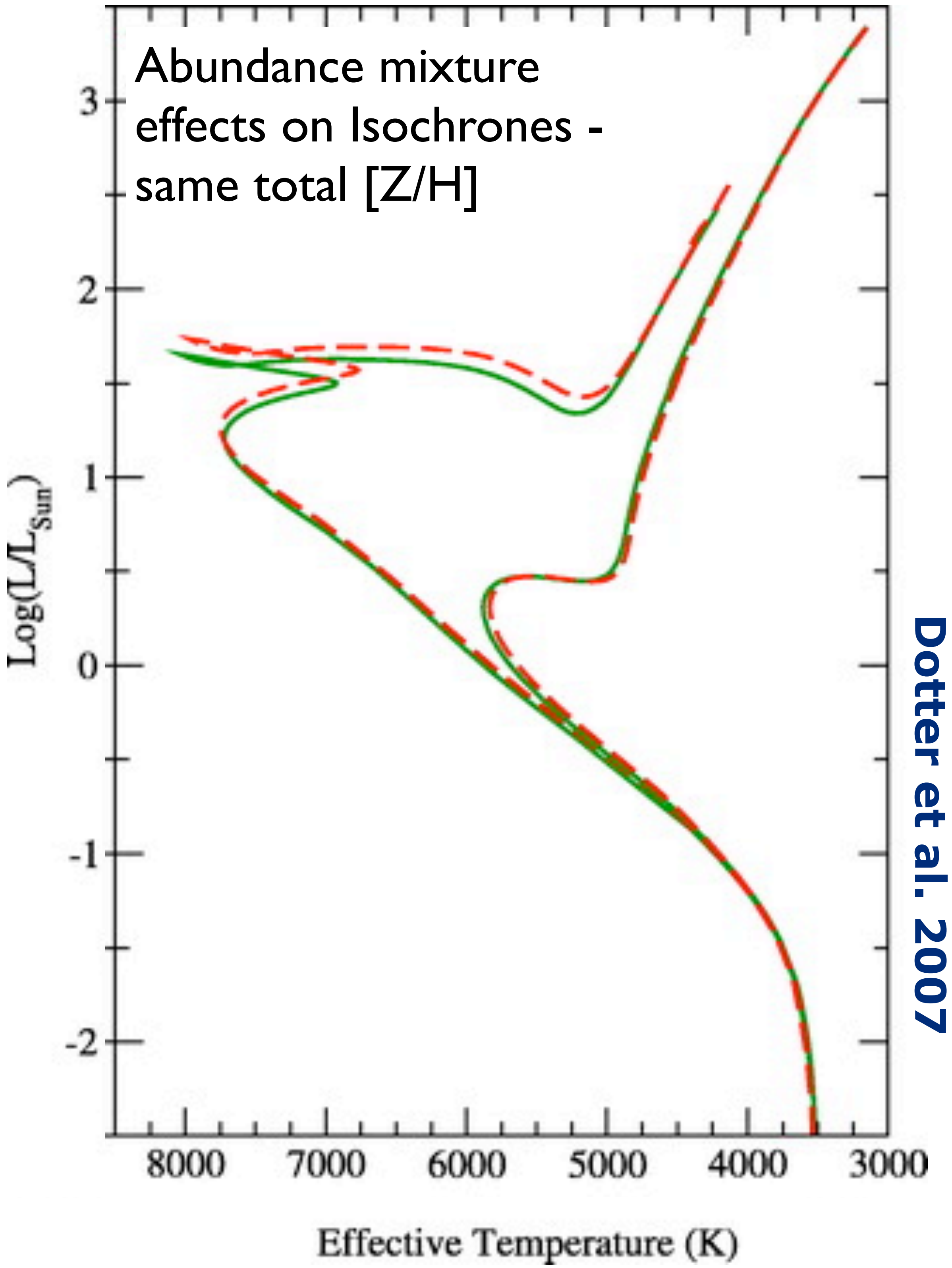
Two influences of [Mg/Fe] on spectra:

(1) stellar evolution effects, via different opacities in the interiors.

(2) stellar atmosphere effects, changing spectral line formation.

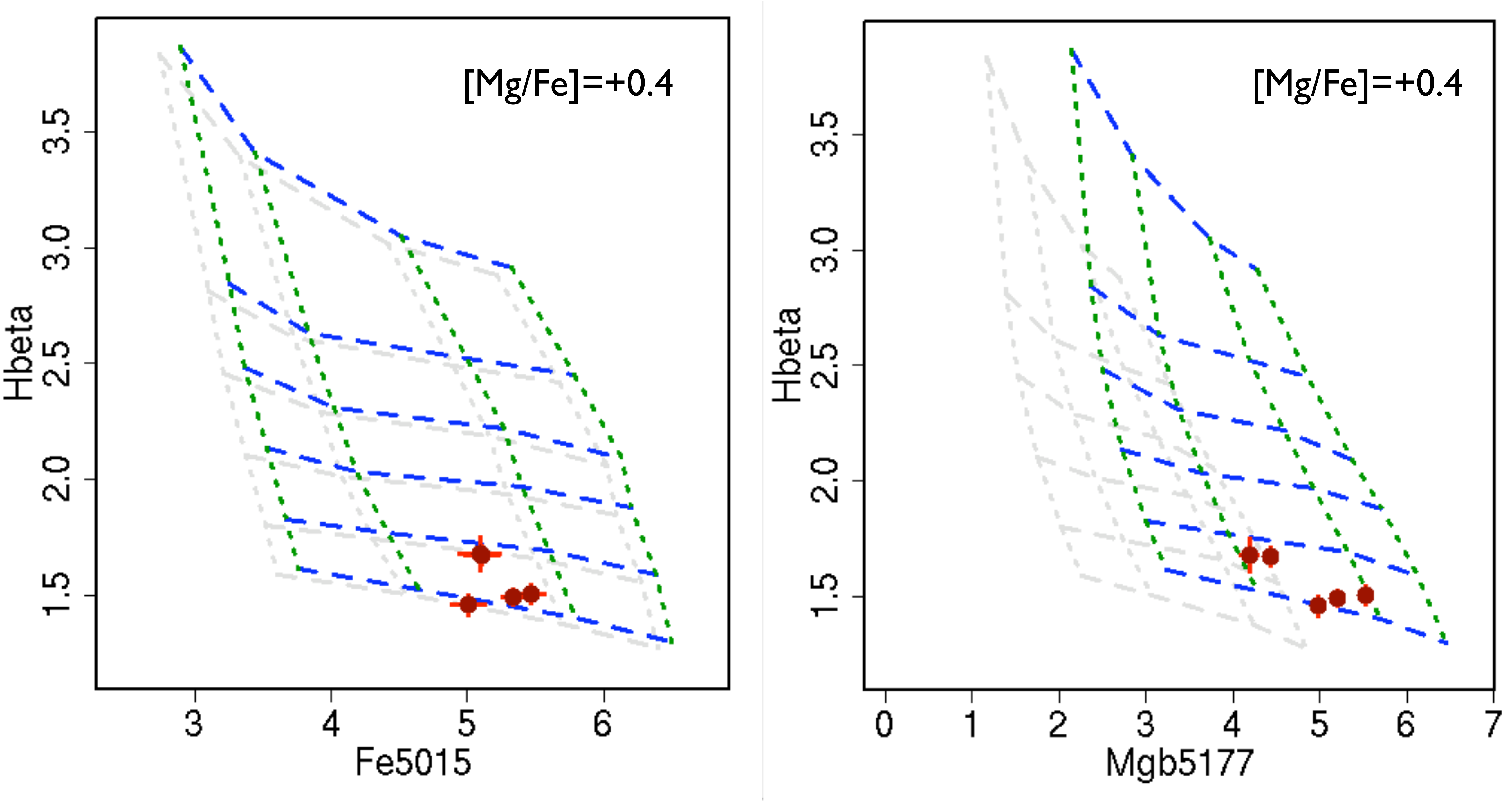
Widely-used models by Thomas et al. (2003) and Schiavon (2007) account only for the second of these!

Recent work on evolution effects by Coelho et al. (2007), Percival et al. (2008), Dotter et al. (2007). Generally suggest these effects are small for indices but important for colours.



**Dotter et al. 2007**

# Consistency among grids?



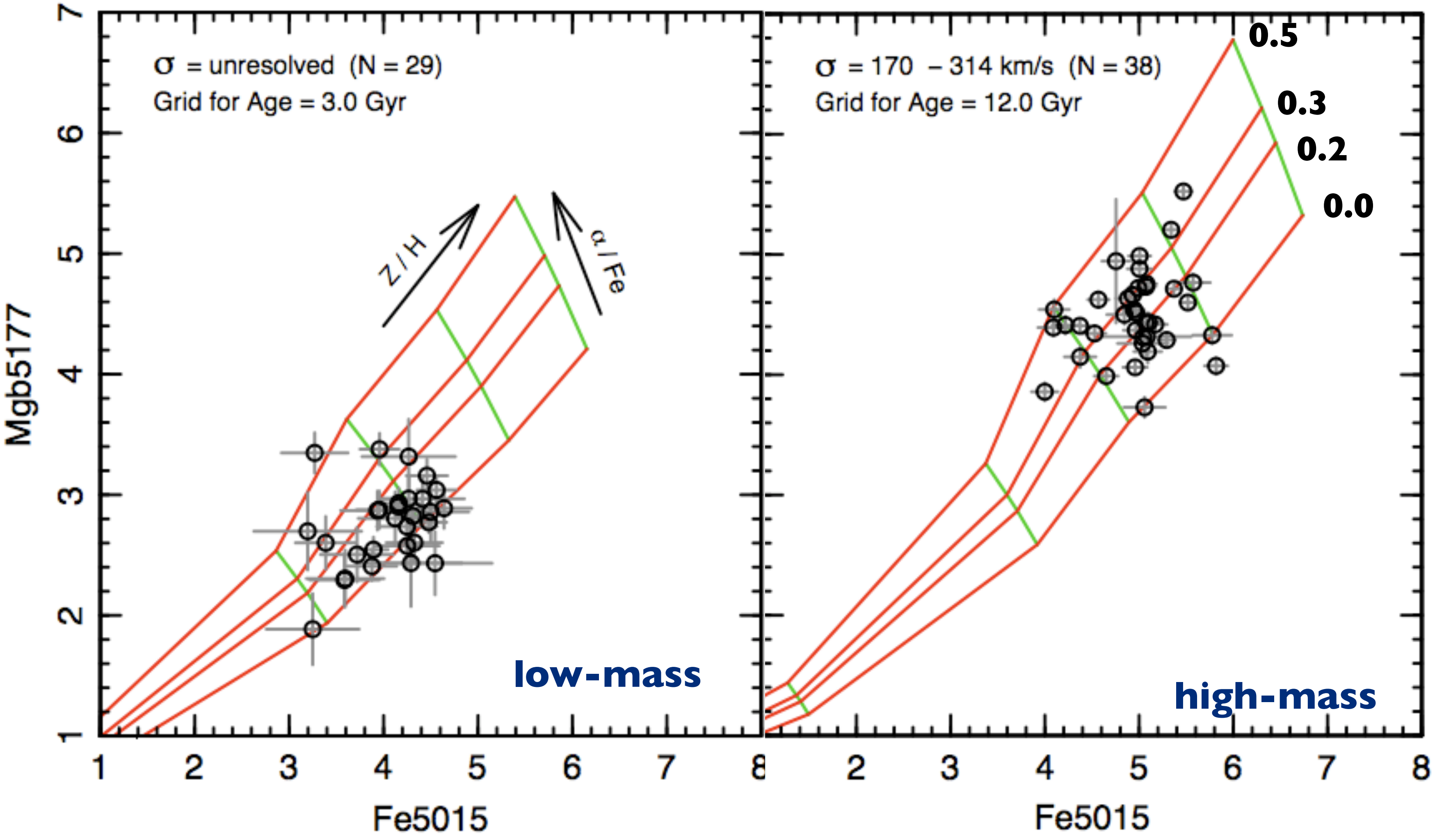
Schiavon (2007) models

Increasing Mg relative to Fe brings two diagrams into better consistency.

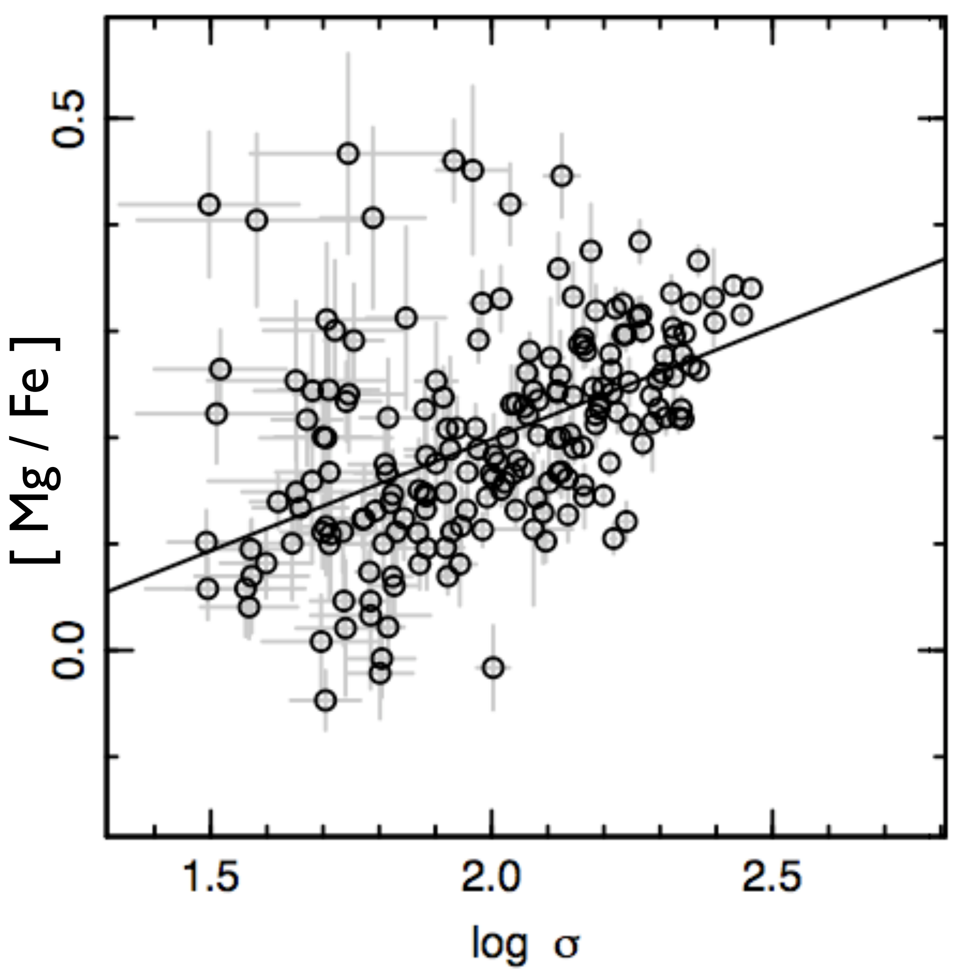
Requiring consistency among grids can be basis for measuring [Mg/Fe] from indices (e.g. EZ-ages method of Graves & Schiavon 2008).

# Mg/Fe versus mass in galaxies

**Smith et al. 2009**



**“galaxy mass”**

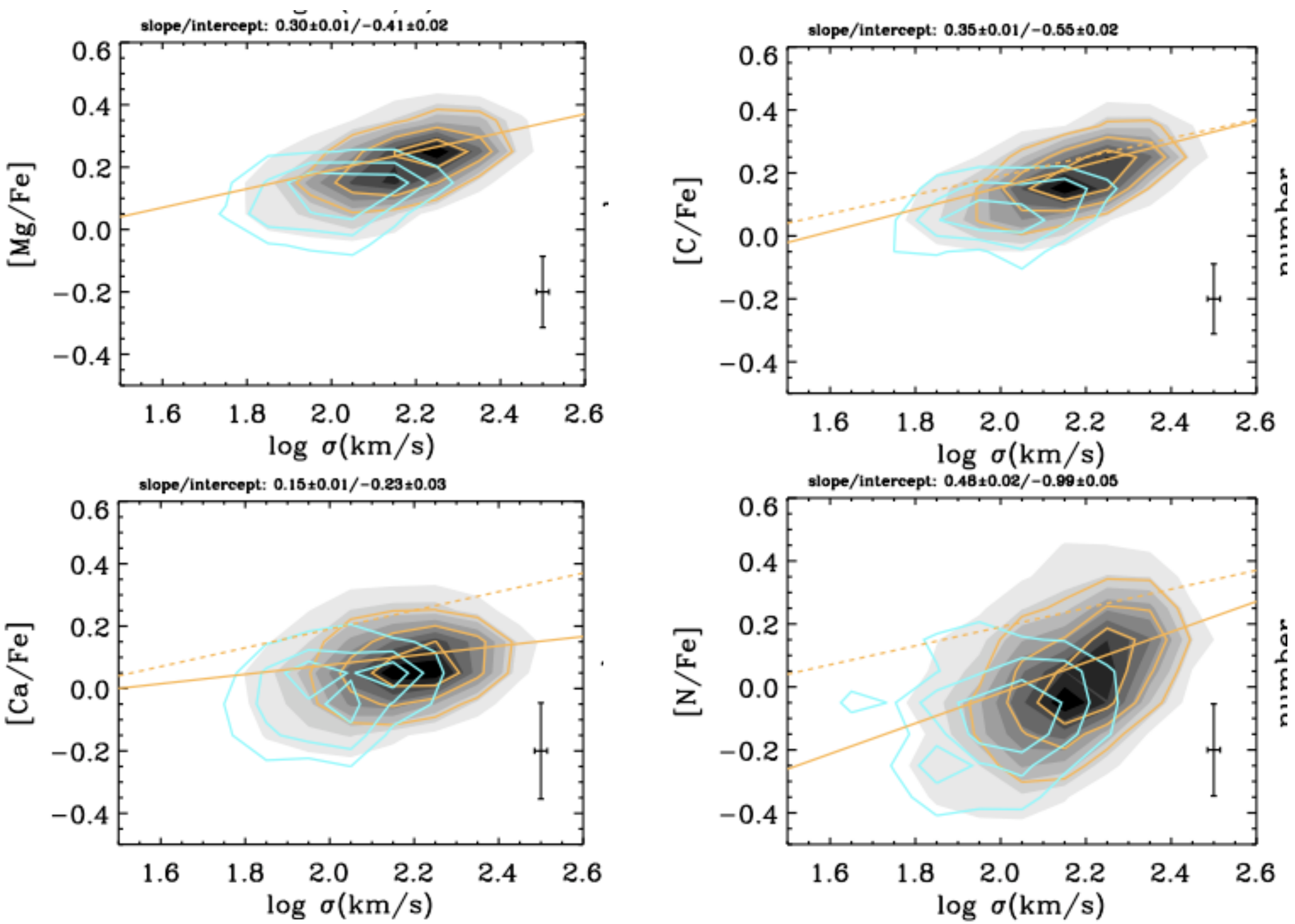


Lots of work show that among red/passive galaxies, more massive ones have higher Mg/Fe while low-mass galaxies have closer to solar abundance ratios. (e.g. Trager et al. 2000; Kuntschner et al. 2001; Nelan et al. 2005; Thomas et al. 2005 etc)

<u>Why?</u> Orthodox answer: more rapid star-formation in high-mass galaxies. Exciting as a route beyond the SSP approximation!

But this might not be the whole story... (IMF, SNIa rates etc).

# Other elements



Johansson, Thomas & Maraston (2012): C,N rise with slope similar to Mg; Ca is flatter.

# Stellar Masses of Galaxies

## Stellar Mass vs Luminosity

Given a galaxy of luminosity $10^{10}\ L_{sol}$ (in some band), is it:

a) an old giant galaxy or

b) a puny dwarf galaxy that just happens to be forming lots of stars right now.

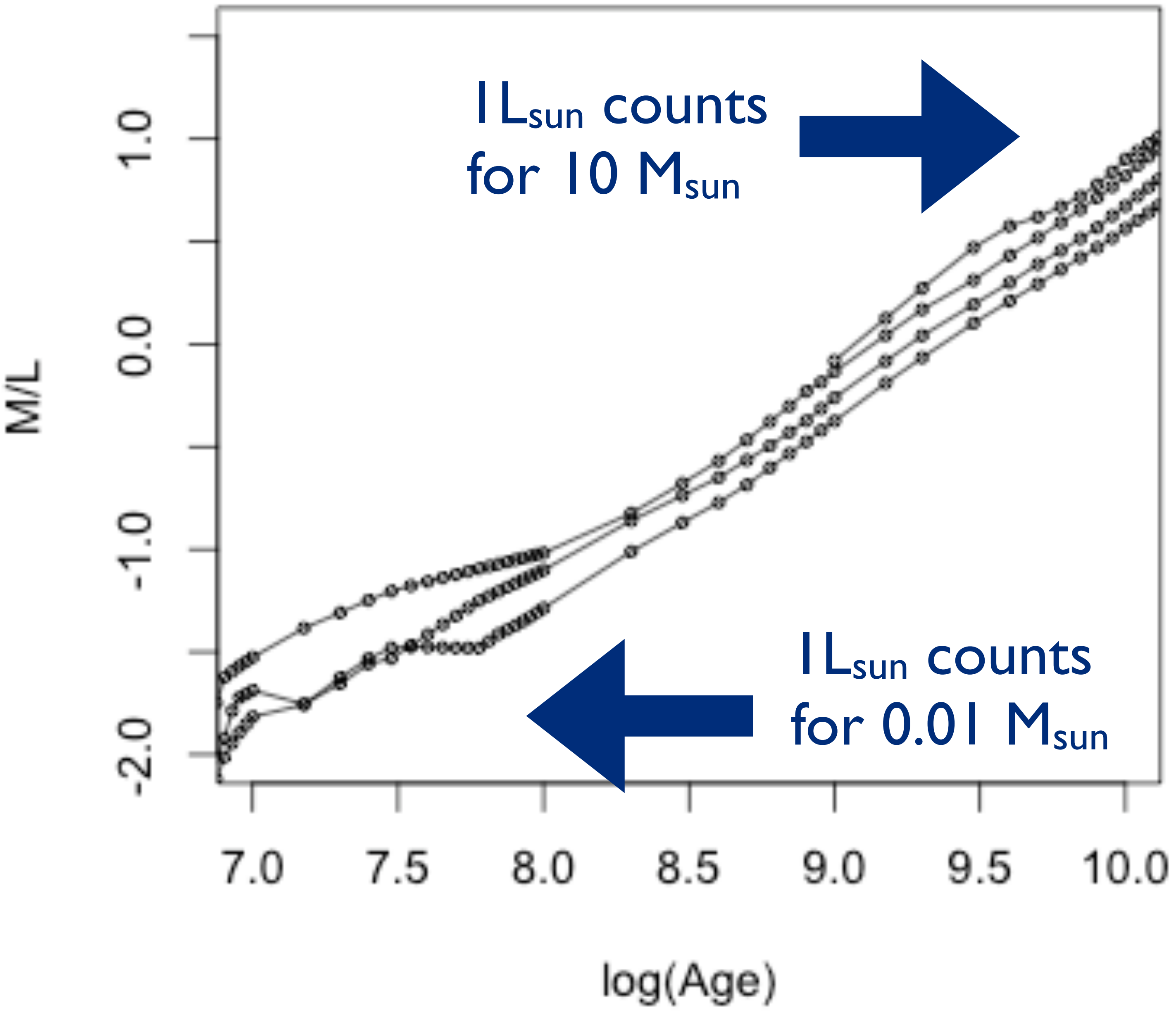
Total "stellar mass" is clearly more <u>fundamental</u> than luminosity!

The conversion between mass and luminosity is the mass-to-light ratio M/L

For an SSP, the M/L depends on age and (to lesser extent) metallicity. For complex populations, M/L depends on the full SFH.

B-band

**Maraston 2005 SSP models**



$1\ L_{sun}$ counts for $10\ M_{sun}$

$1\ L_{sun}$ counts for $0.01\ M_{sun}$

**NB:** in this section we will be considering a much larger range in "age" than previously, even ongoing star-formation.

# Colour-vs-M/L relation

In general we don't know the age/SFH and metallicity for a galaxy.

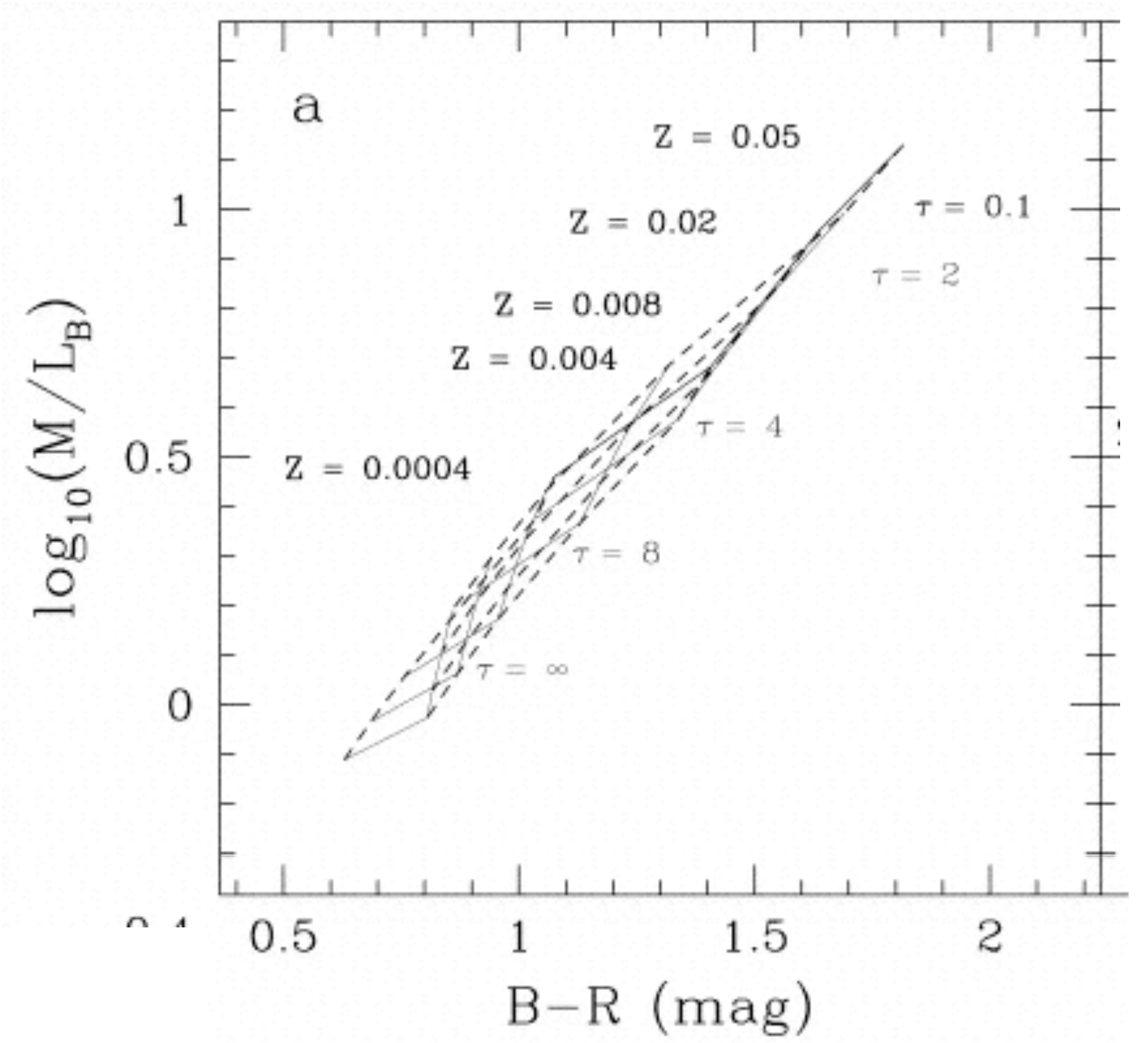
But recall : colours also depend of age and metallicity and we do have those.

Bell & de Jong 2001: For exponential star-formation histories, B-R is a good predictor of $M/L_B$, i.e. compensation between similar degeneracies in colour and M/L.

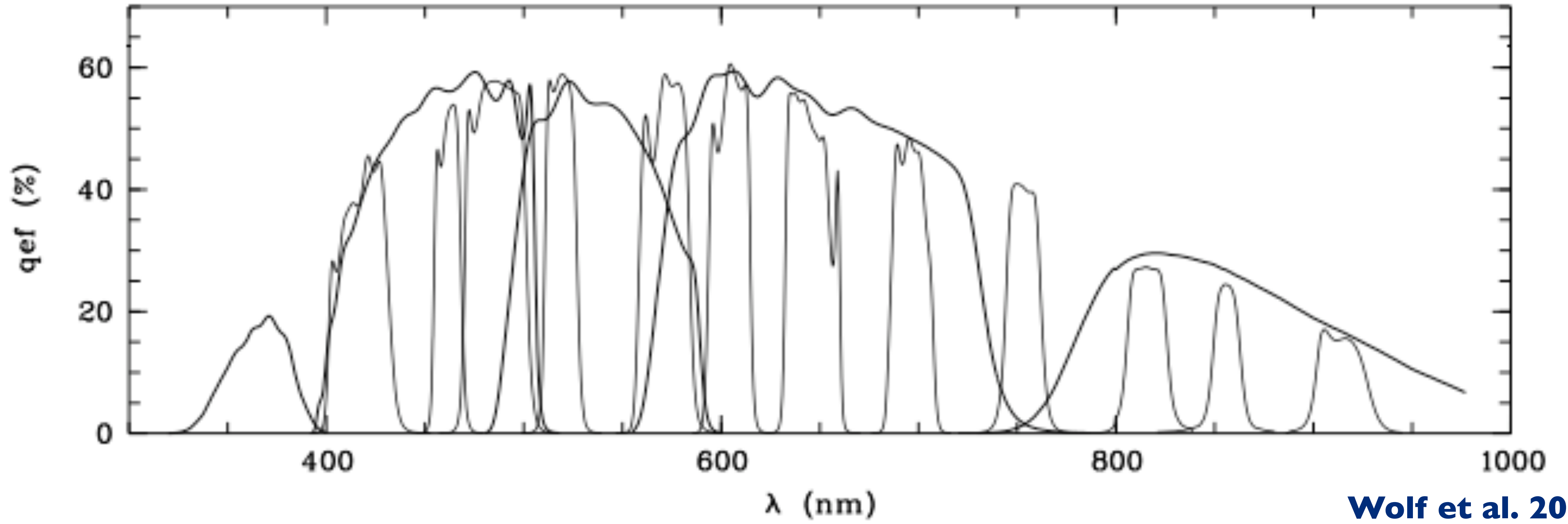
Dust in galaxies tends to lower the luminosity but also redden the population. So with dust, we recover a higher M/L and compensate the reduced luminosity.

Good news: we can estimate stellar mass-to-light ratio better than we can estimate ages!

**Bell & de Jong 2001**



# Multi-colour stellar masses



**Wolf et al. 2002**

Can do even better by fitting photometry in several bands: "SED fitting".

Bell et al. (2003) used SDSS *ugriz* + 2MASS *K*.

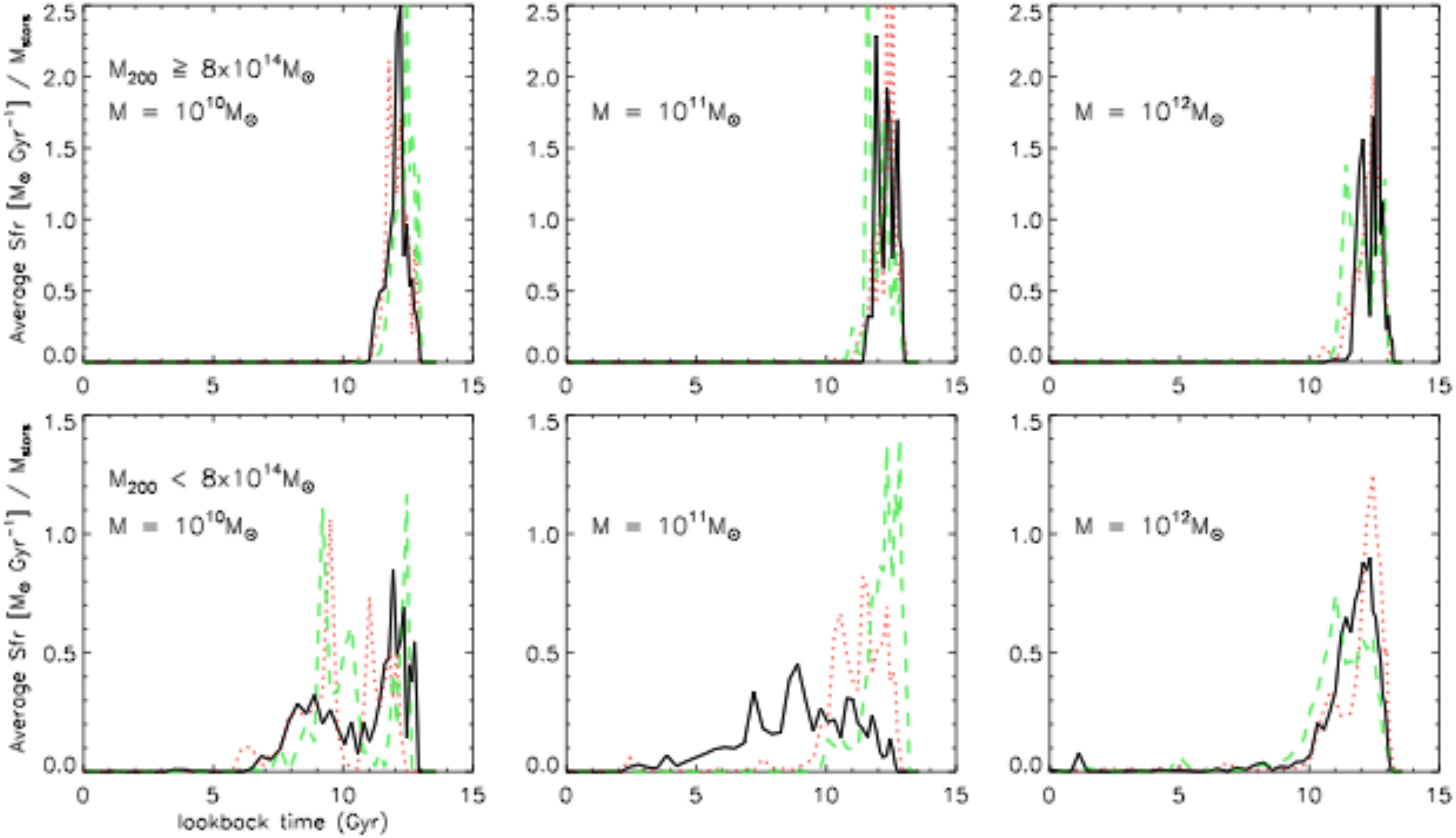
COMBO-17 (Wolf et al. 2002) used 13 medium band + 4 broad band filters.

Find best fitting star-formation history from a library of models, using $\chi^2$ between model and observed magnitude in the set of bands.

Often do this simultaneously with estimating "photometric" redshift. (But sometimes the redshift is known more securely from spectroscopy.)

Assign M/L of the best-fitting SFH model [or the distribution of Prob(M/L | data) ]

# The model SFH library



**De Lucia et al. (2006)**

Unfortunately, the star-formation histories (SFH) of real galaxies probably don’t respect our SSP (or exponential) parametrizations!

(Not that theorists’ models necessarily get it right either...)

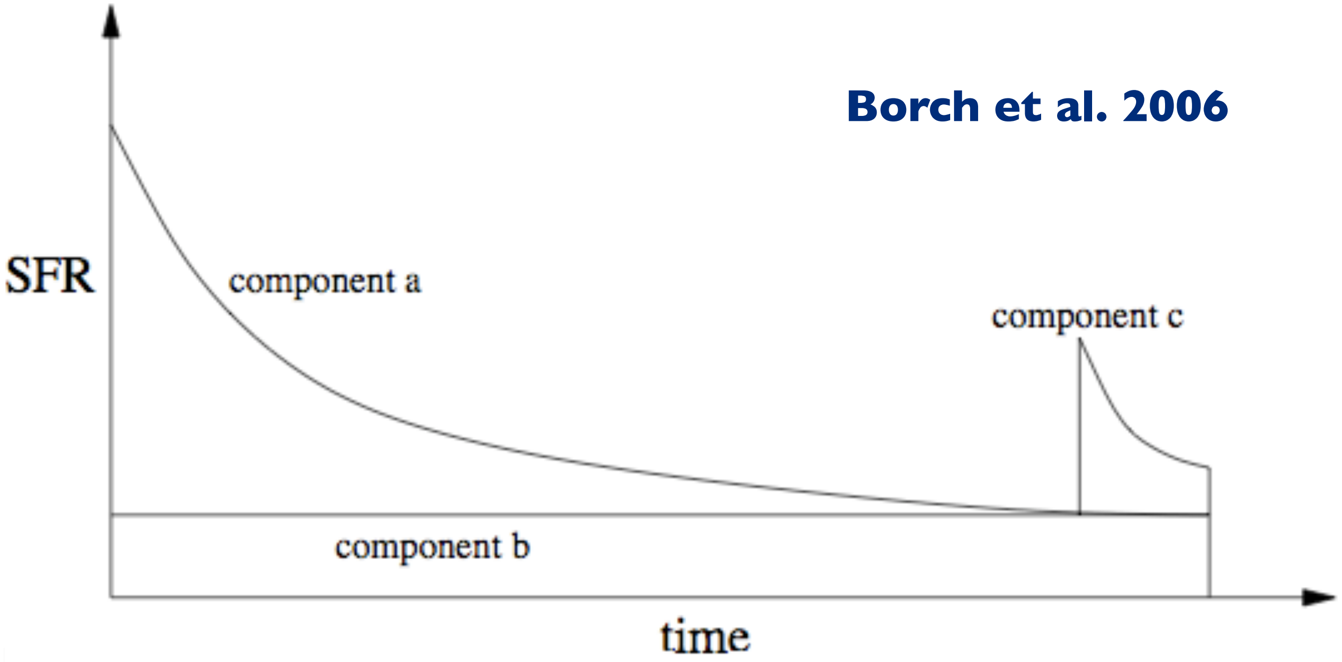
# The model SFH library

Stellar mass determination requires a library of model SFHs.

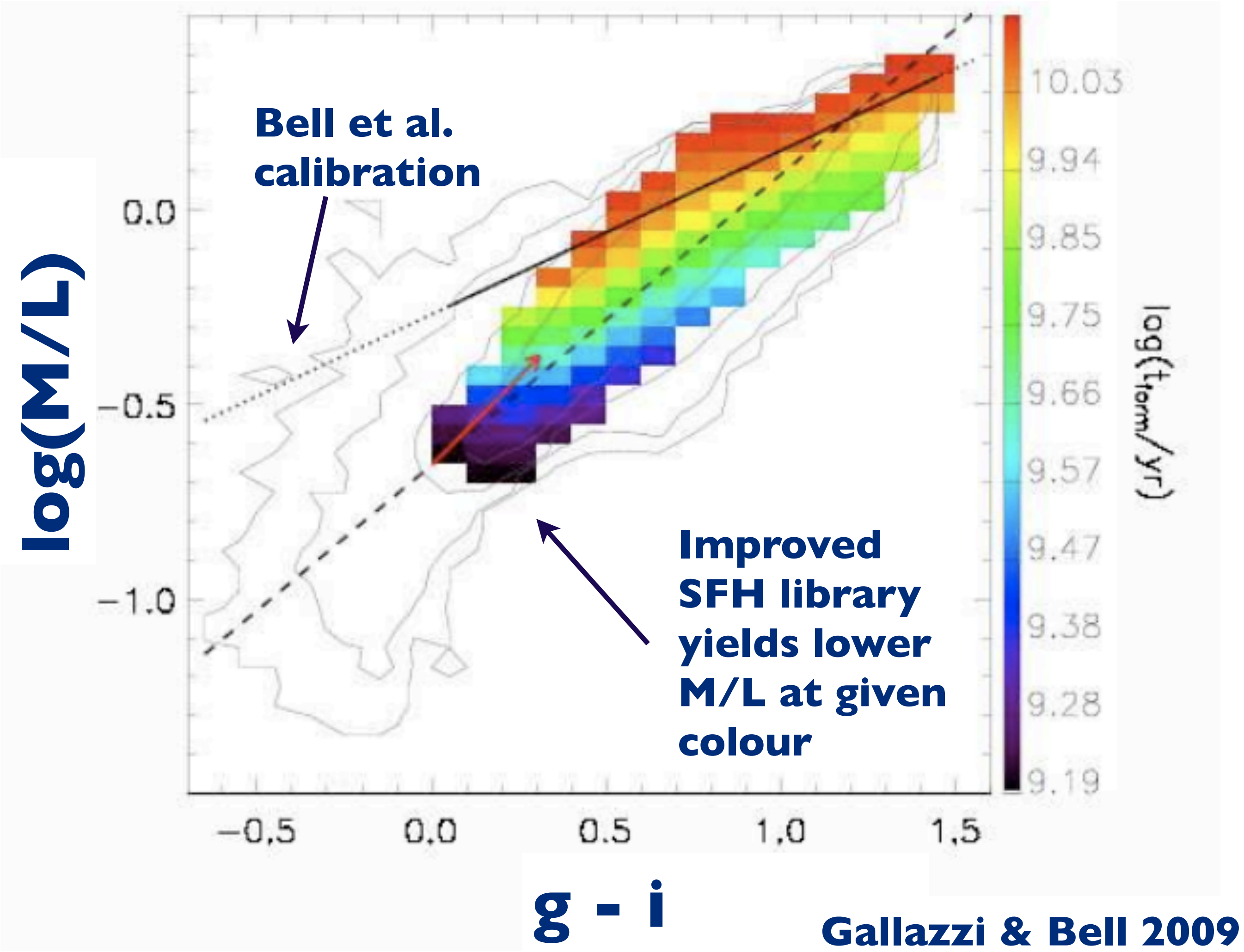
SFH models can be simple (e.g. Bell et al. 2003 exponential decline/rise with constant start time)...

... or more complicated (different start-times, added late bursts etc, e.g. Kauffmann et al. 2003; Borch et al. 2006; Gallazzi & Bell 2009).

More flexible SFH library allows better match to range of true SFHs.



**Borch et al. 2006**



**Bell et al. calibration**

**Improved SFH library yields lower M/L at given colour**

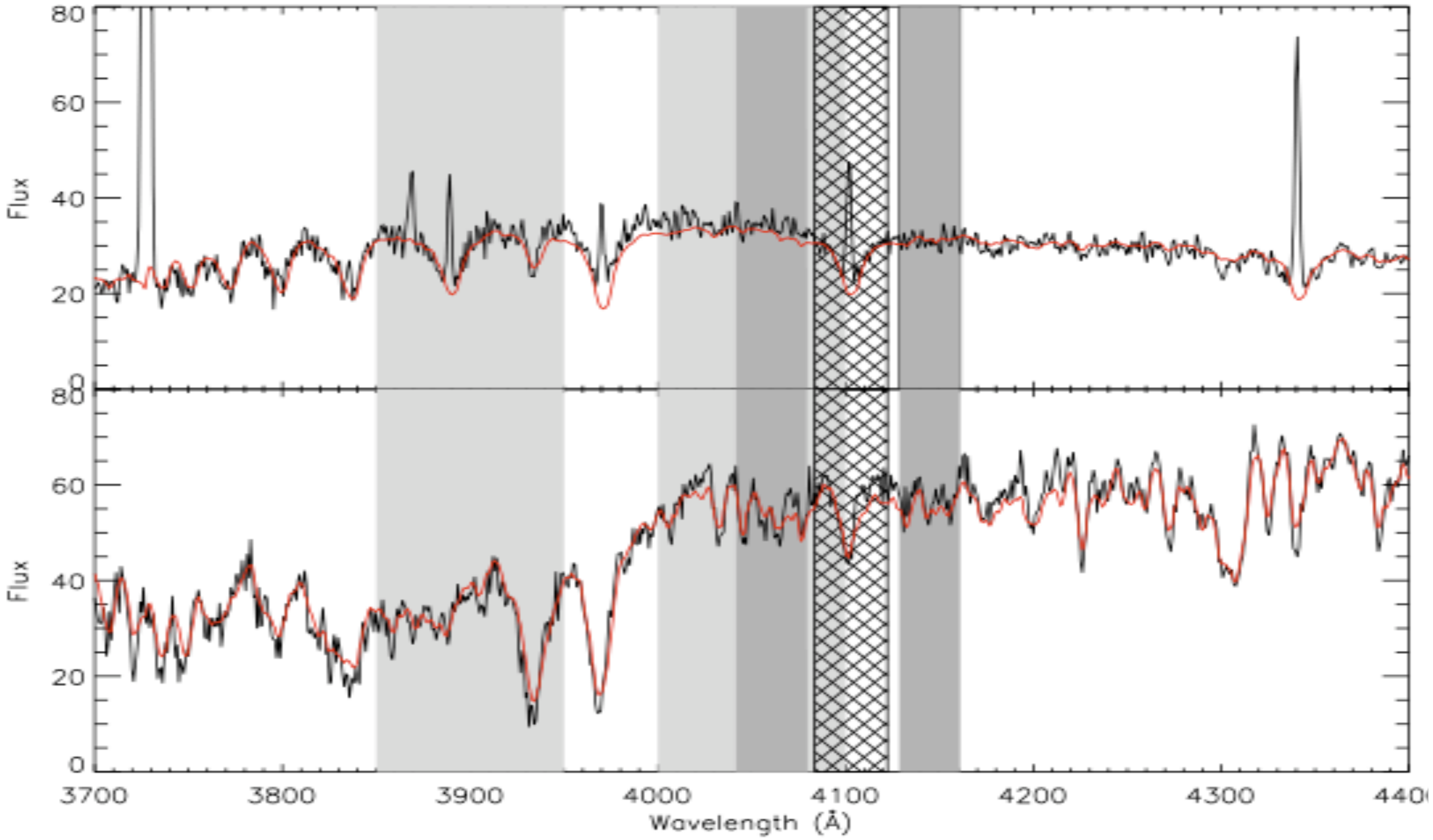
**Gallazzi & Bell 2009**

# Spectroscopic Stellar Masses

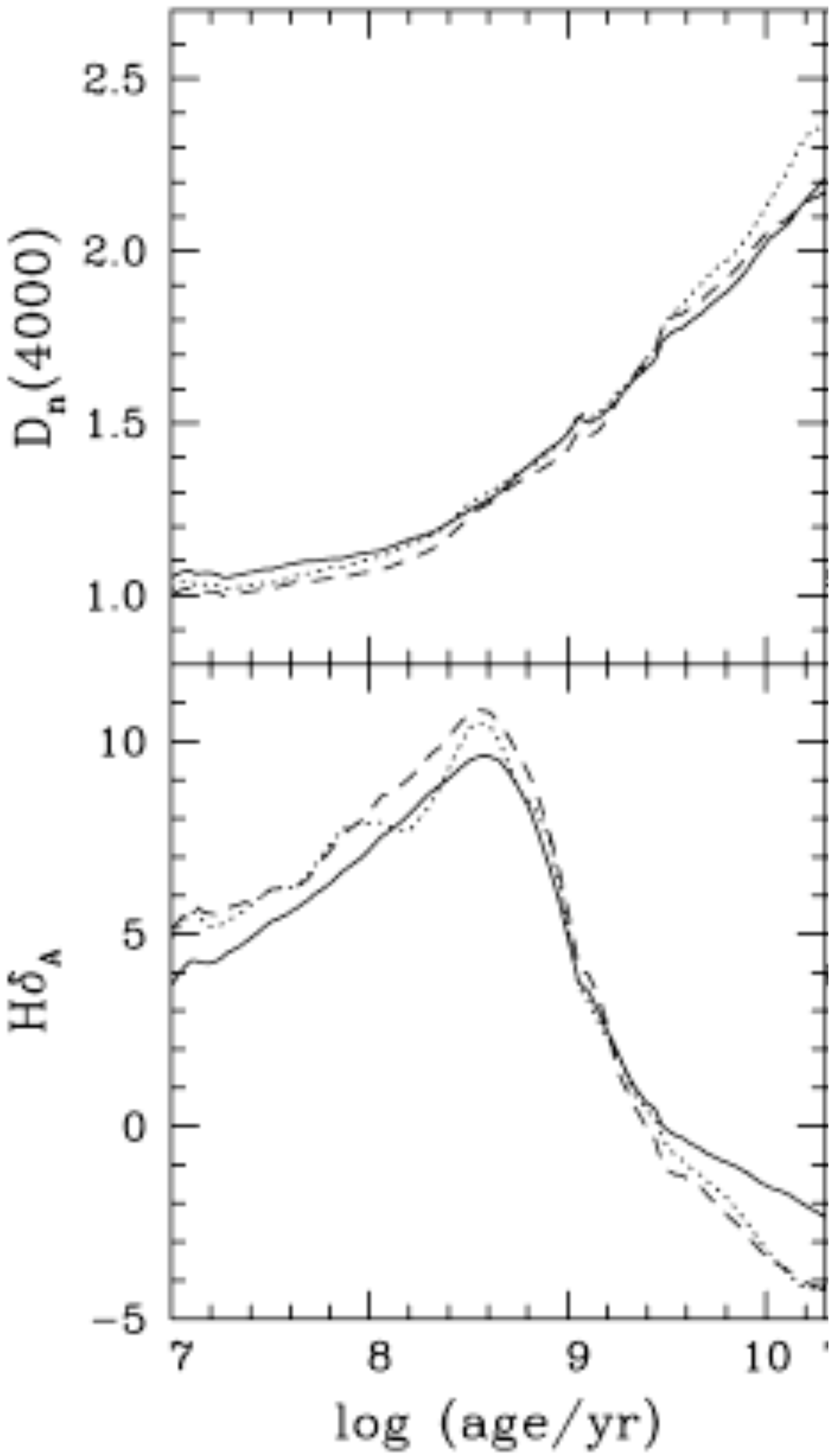
Kauffmann et al. 2003

Similar approach but fit spectroscopic quantities instead of colours.

Focus on D4000 (strength of the 4000 angstrom break ~ age) and Hδ (Balmer line ~ star-formation within the past 1Gyr)

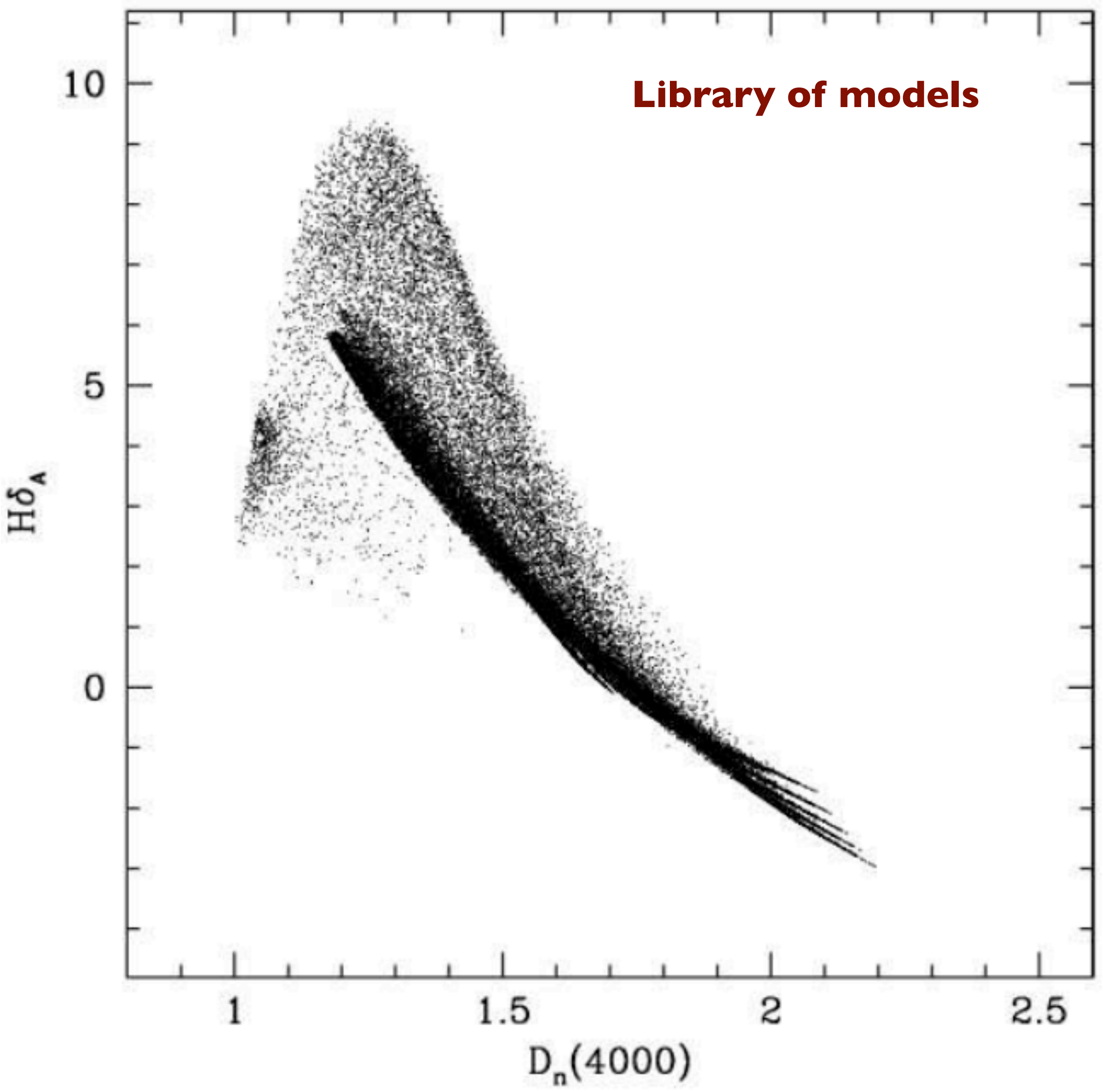


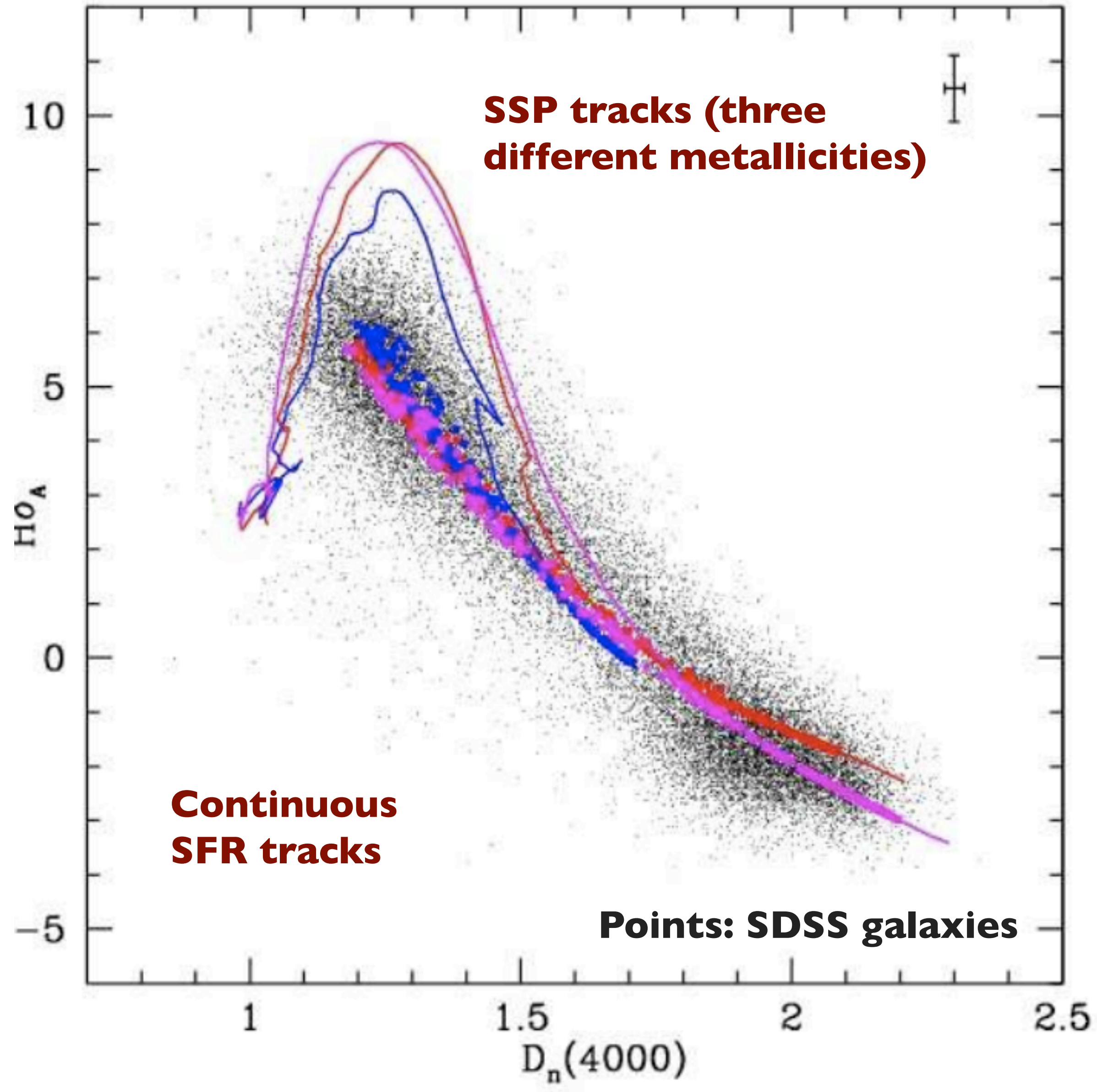
**Kauffmann et al. 2003**



# Spectroscopic Stellar Masses

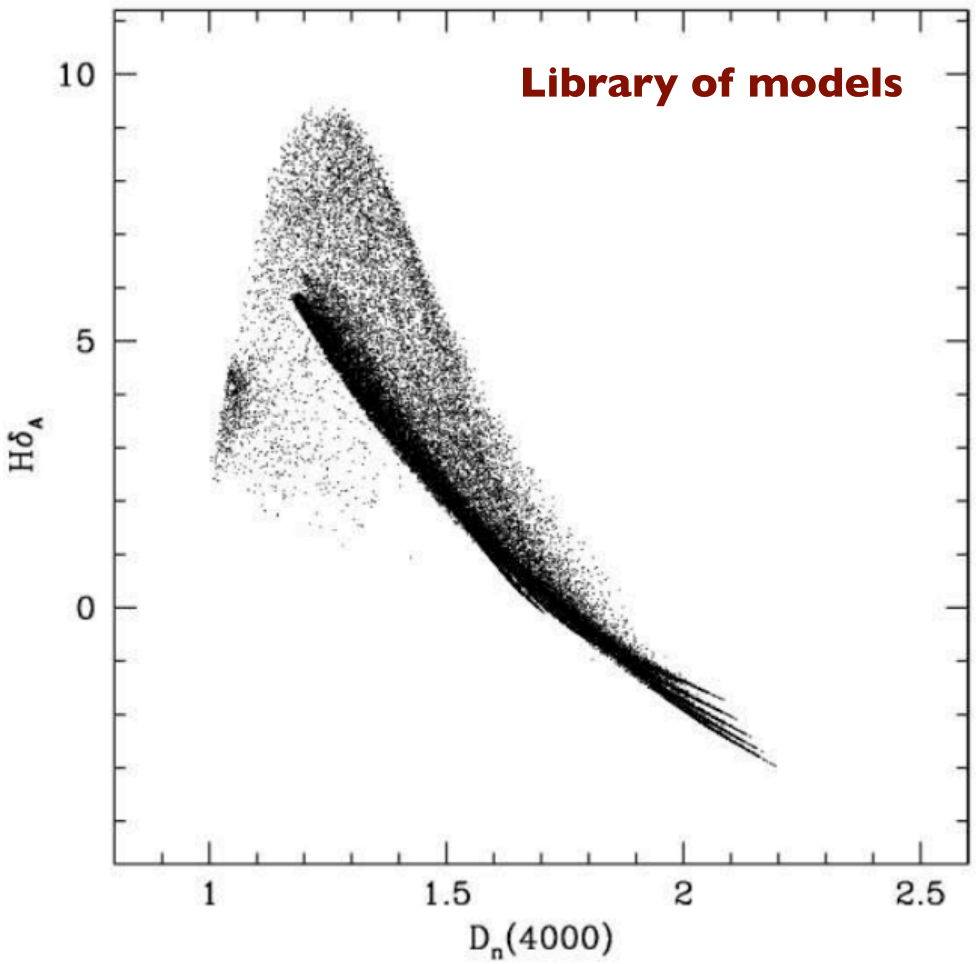
Kauffmann et al. 2003

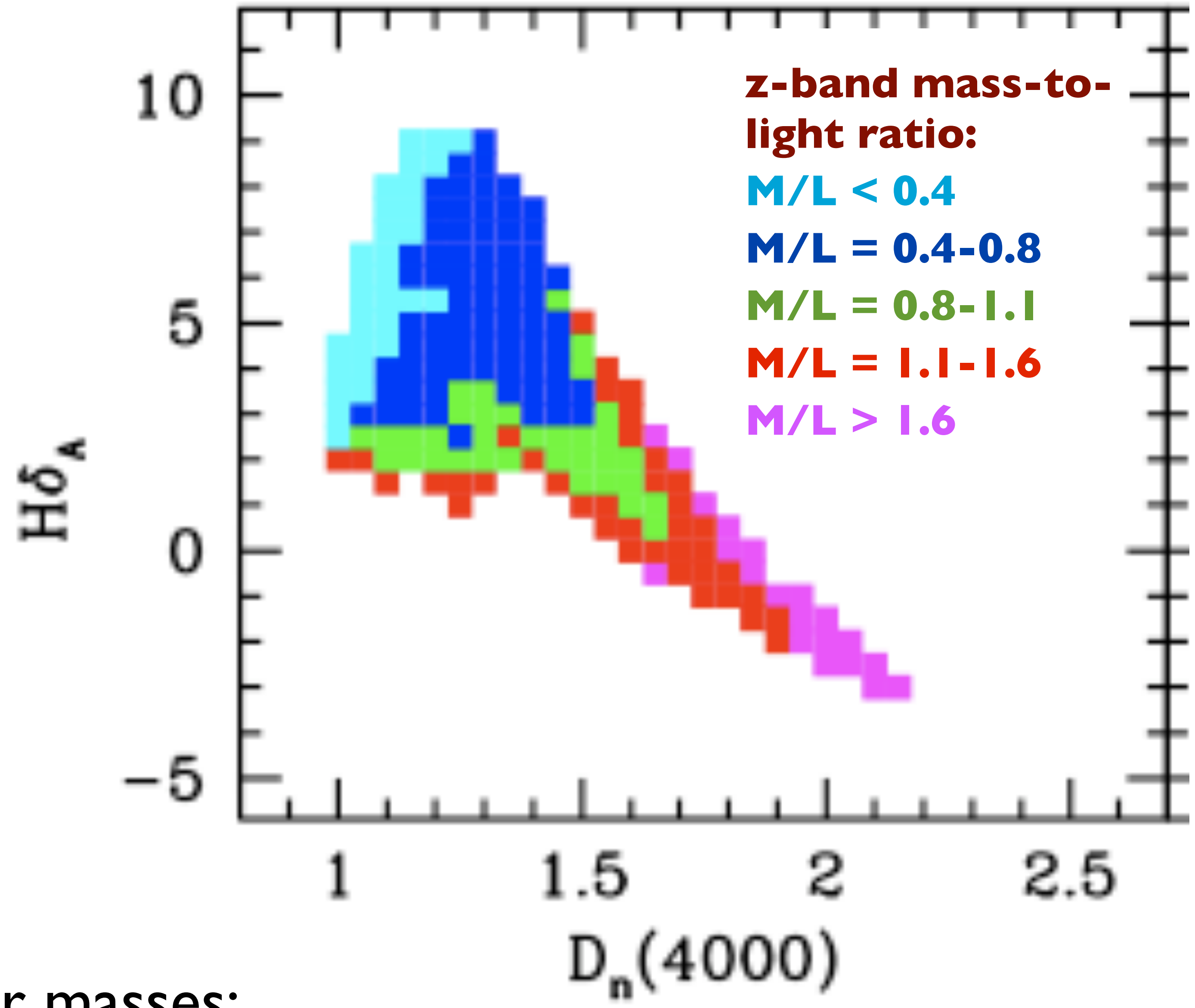




Kauffmann et al. 2003. Library of star-formation histories: exponential decline with varying start-times, some models have added “bursts”.

# Spectroscopic Stellar Masses





**Kauffmann et al. 2003**

A concern about spectroscopic stellar masses:

Do the spectra sample the whole galaxy?

Sometimes only the central part of the galaxy is covered by the spectrograph aperture, which may be unrepresentative of the whole.

# Stellar Masses: How good can they be?

**Gallazzi & Bell (2009) conclude that:**

Important that the library cover a wide range in SFH.

M/L from spectra are better than M/L from colours for old galaxies with smooth SFH. Can reach precision of 10-25%. Better if more indices are used to constrain fit.

For smooth SFH and young ages, colour-based M/L can be almost as good as spectroscopic M/L.

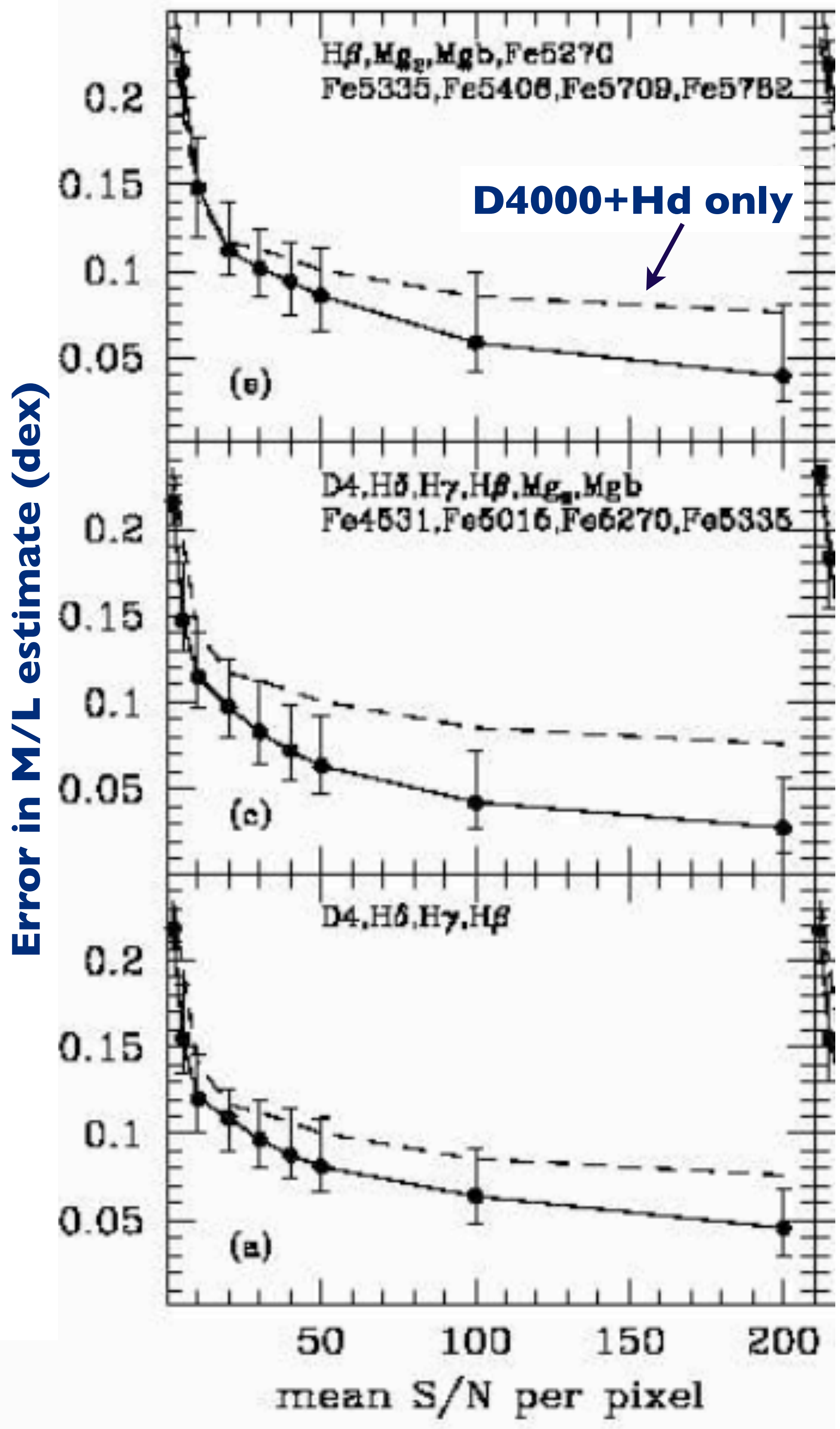
For SFH with recent bursts, spectroscopic M/L are less biased, but errors still larger ~40%.

**More generally:**

As always, need to worry about poorly-understood parts of stellar evolution (e.g. TP-AGB, BS, BHB).

IMF change imposes only a <u>constant</u> rescaling of M/L.

Gallazzi & Bell 2009



# Closing reflections

Theory of stellar evolution underpins almost everything we can learn about galaxy evolution. We need to be aware of its limitations to avoid misinterpreting extra-galactic observations.

Probably the broad-brush methods used in galaxy evolution work are not too crazy. When we apply the models at more detailed level, we need to be much more circumspect, but maybe have the chance to learn much more.

Resolving stellar populations towards the MSTO in external ellipticals will be a huge milestone for E-ELT etc.

Advances in pedestrian-sounding areas (like building more complete stellar libraries) still make a huge impact in understanding galaxy evolution.

Our incomplete understanding of binarity among stars is worrying, especially given their relevance to chemical evolution (SNIa).

In some cases, confronting galaxy observations with models may tell us more about the properties of stars than it does about galaxy evolution. If so, we should try not to be disappointed!

# END OF LECTURE IV