Stellar Populations - Lecture IV

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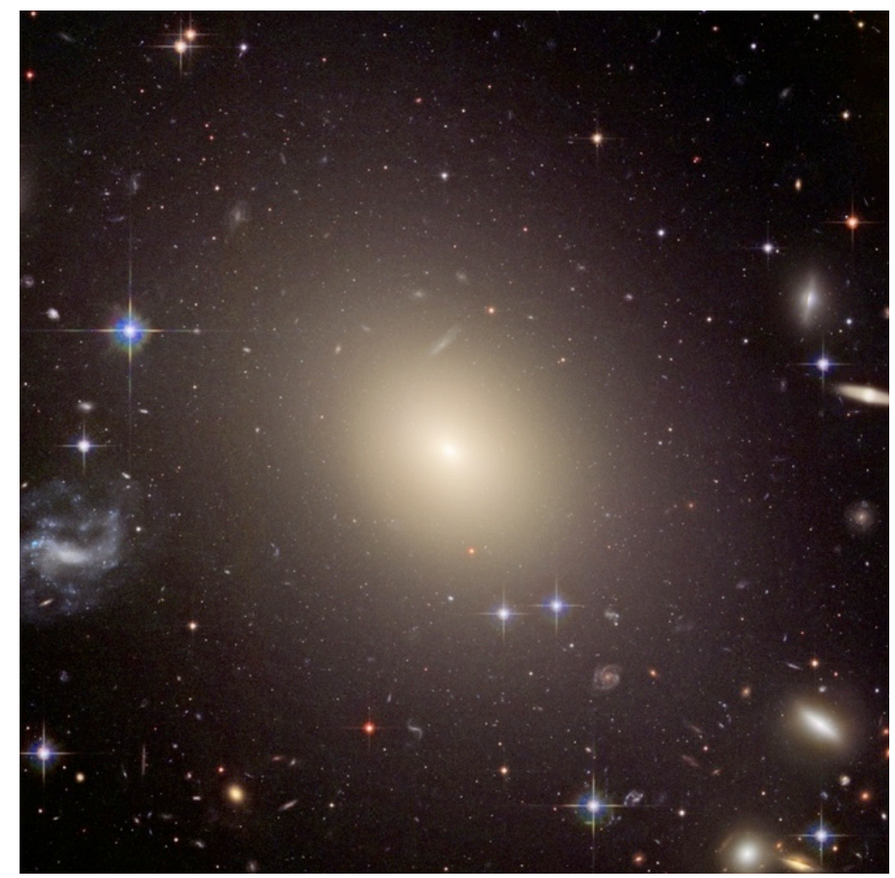
http://astro.dur.ac.uk/~rjsmith/stellarpops.html



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

- Abundance ratios and chemical evolution.
- Star-formation histories and stellar masses.

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- Abundance ratios and chemical evolution.
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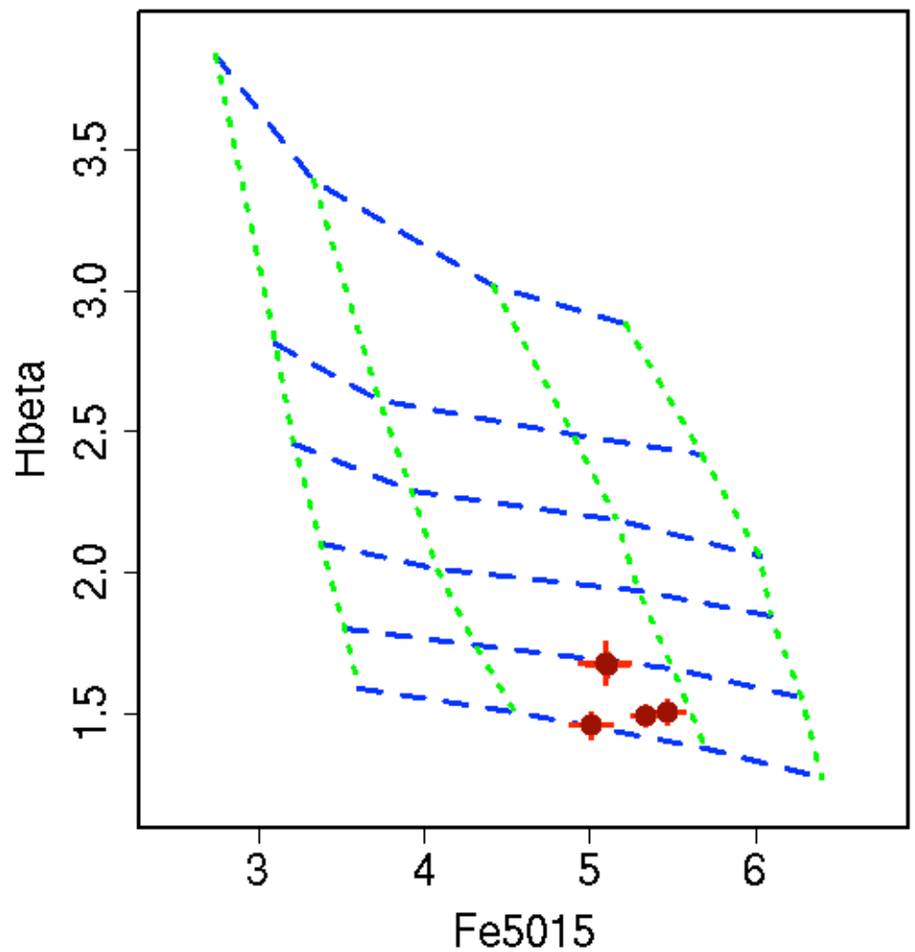
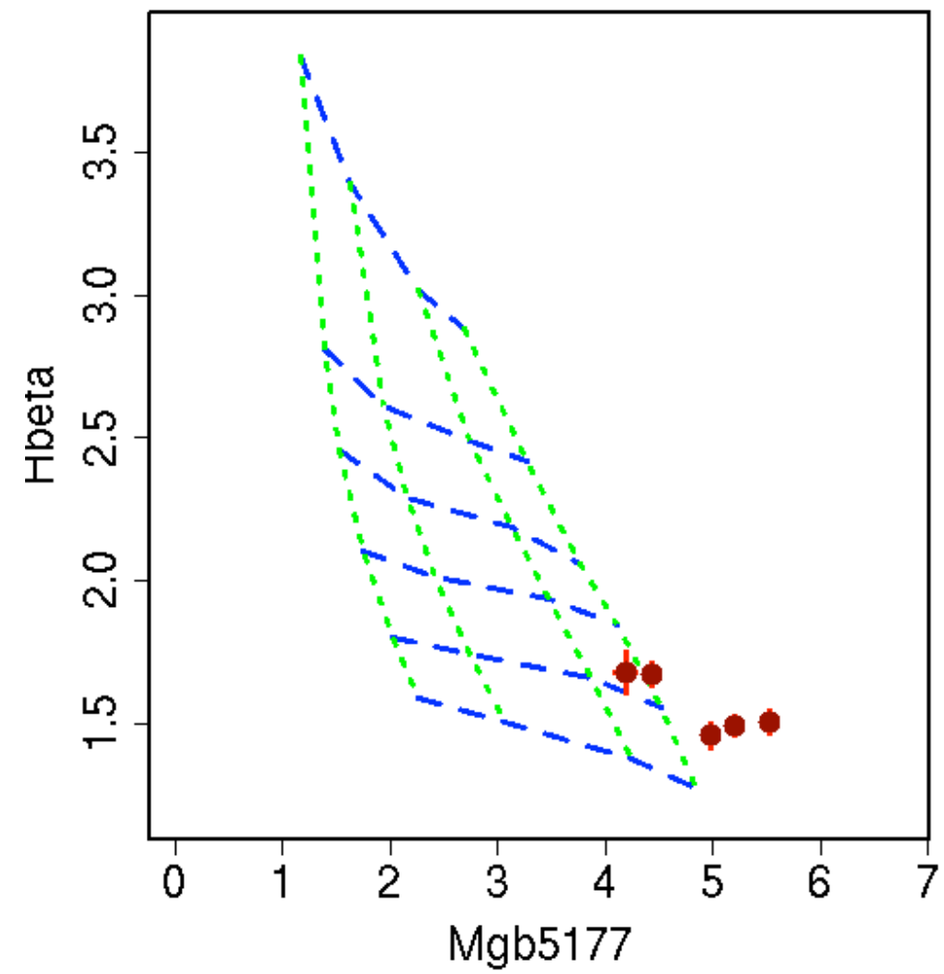
Homework problem: By email this morning. Deadline 2nd Dec

Previously, on “Stellar Populations”...

Good news: can decouple age and metallicity effects using Balmer/metal index grids.





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!

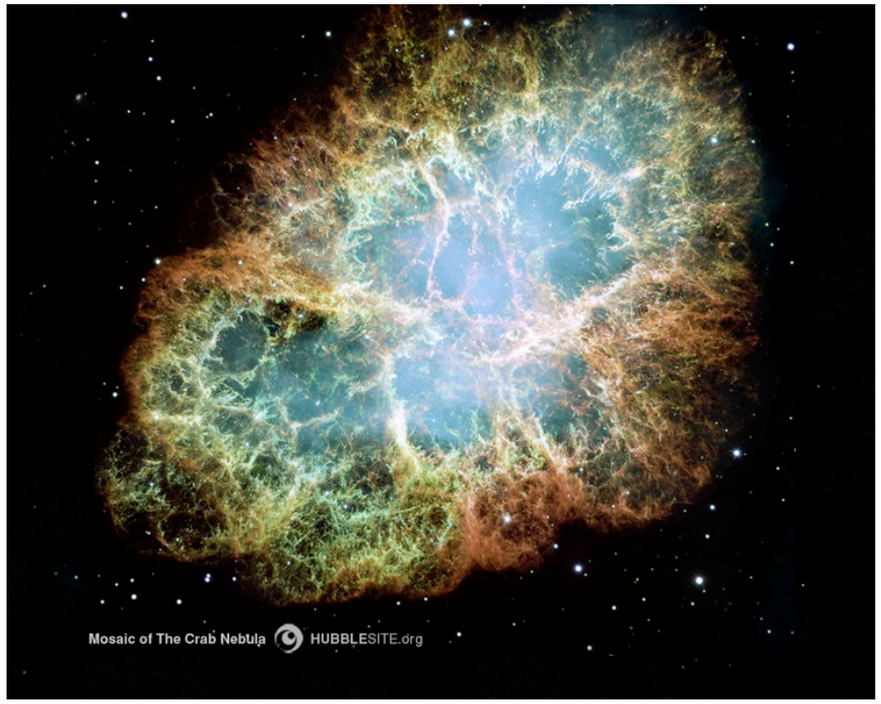
Where does all this stuff come from?

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

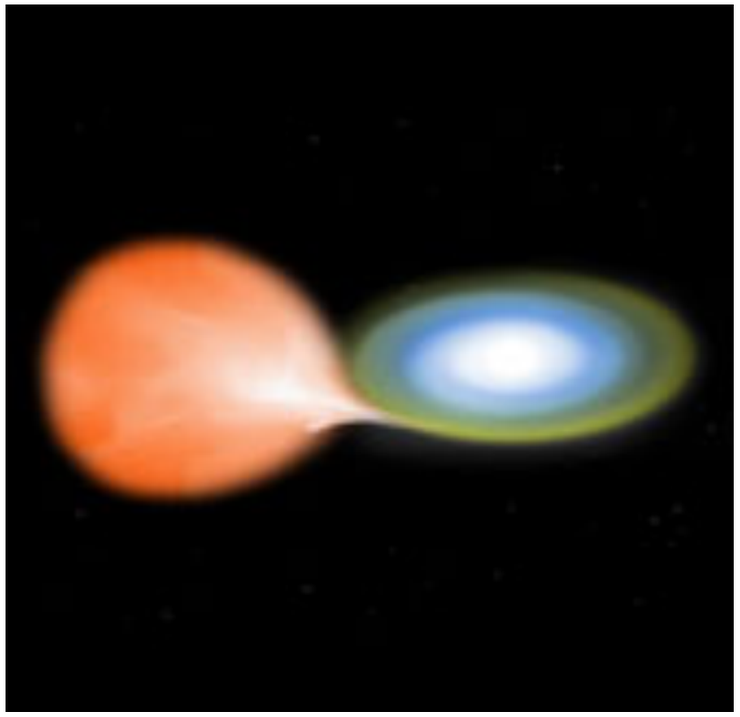
All the <u>interesting</u> stuff in the Universe (C,N,O,Na,Mg,Fe,etc) has been cooked up in <u>stars</u> and recycled in <u>galaxies</u>.

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.

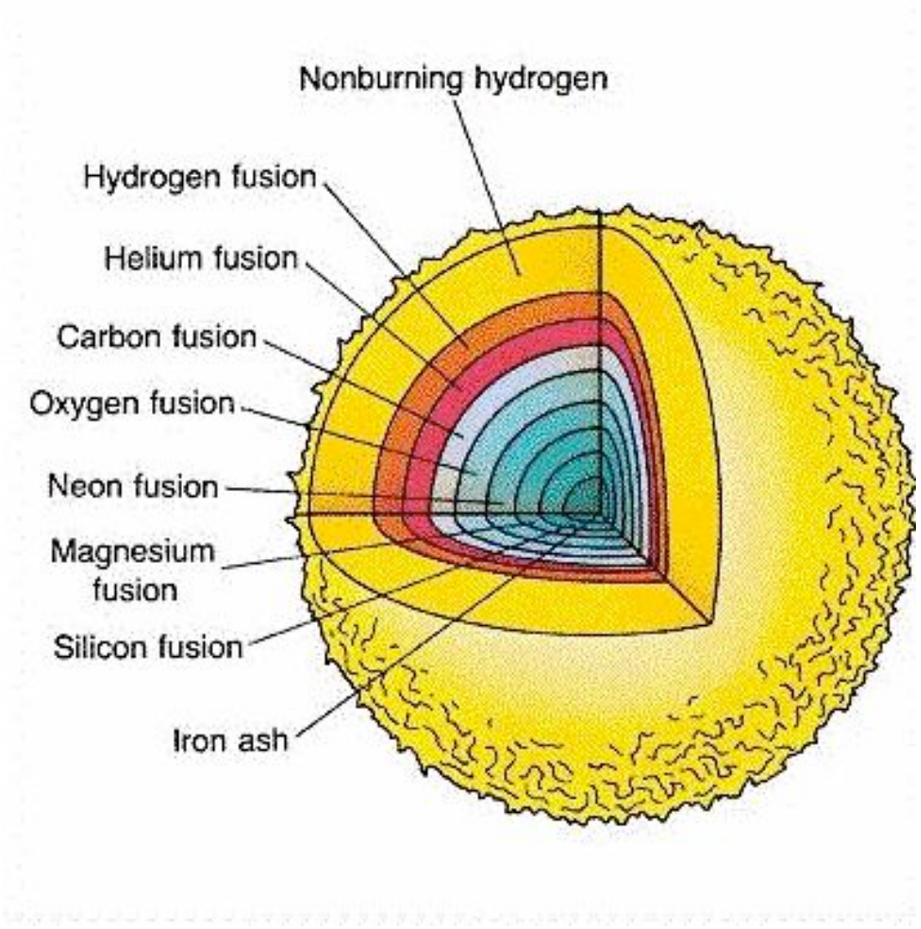
Exposed C-O core remains as a "post-AGB star" which eventually cools to become a white dwarf.

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 supernovae



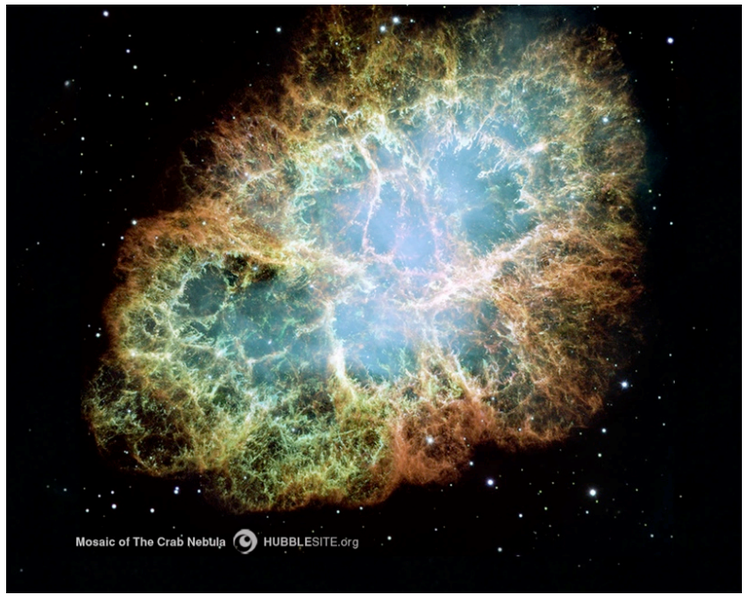
Final collapse of Fe core in evolved massive stars. Formation of neutron star halts the collapse, shockwave ejects the outer layers into the interstellar medium (ISM).

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 supernovae

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!)

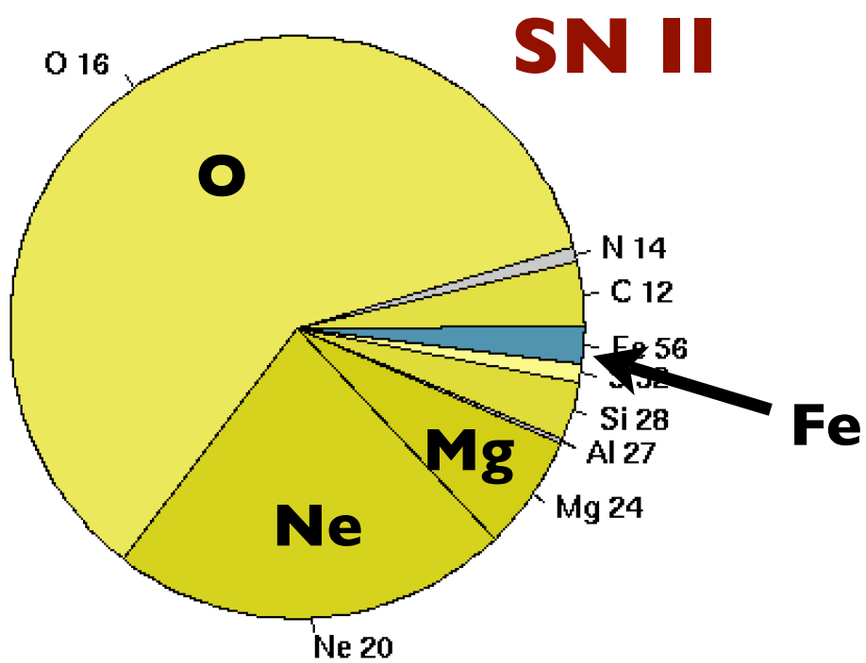
All SNIa explosions at similar mass so similar physics -> standard candle for cosmology.

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.



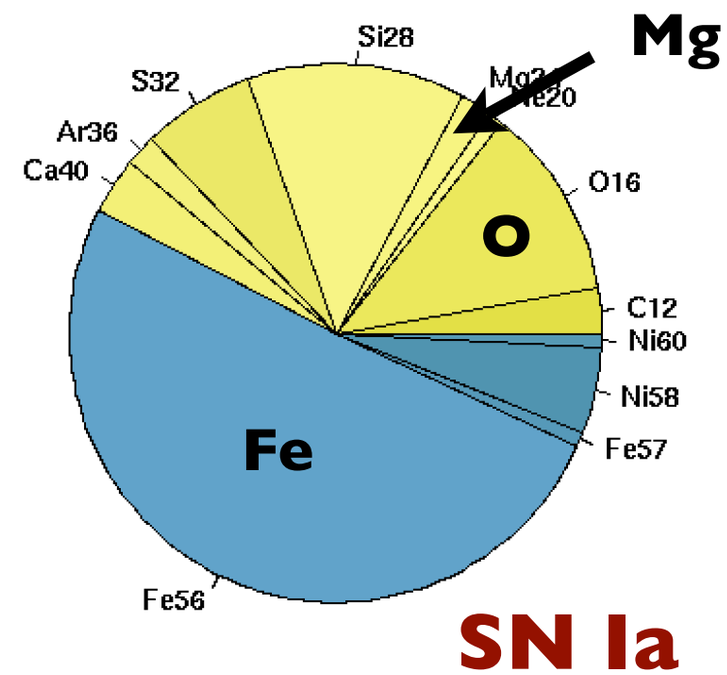
SNe II products dominated by O, Ne, Mg (Details depend on progenitor mass)

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.

Gravitational potentials required to retain stellar ejecta (especially from SNe).

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

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

Star-formation 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)

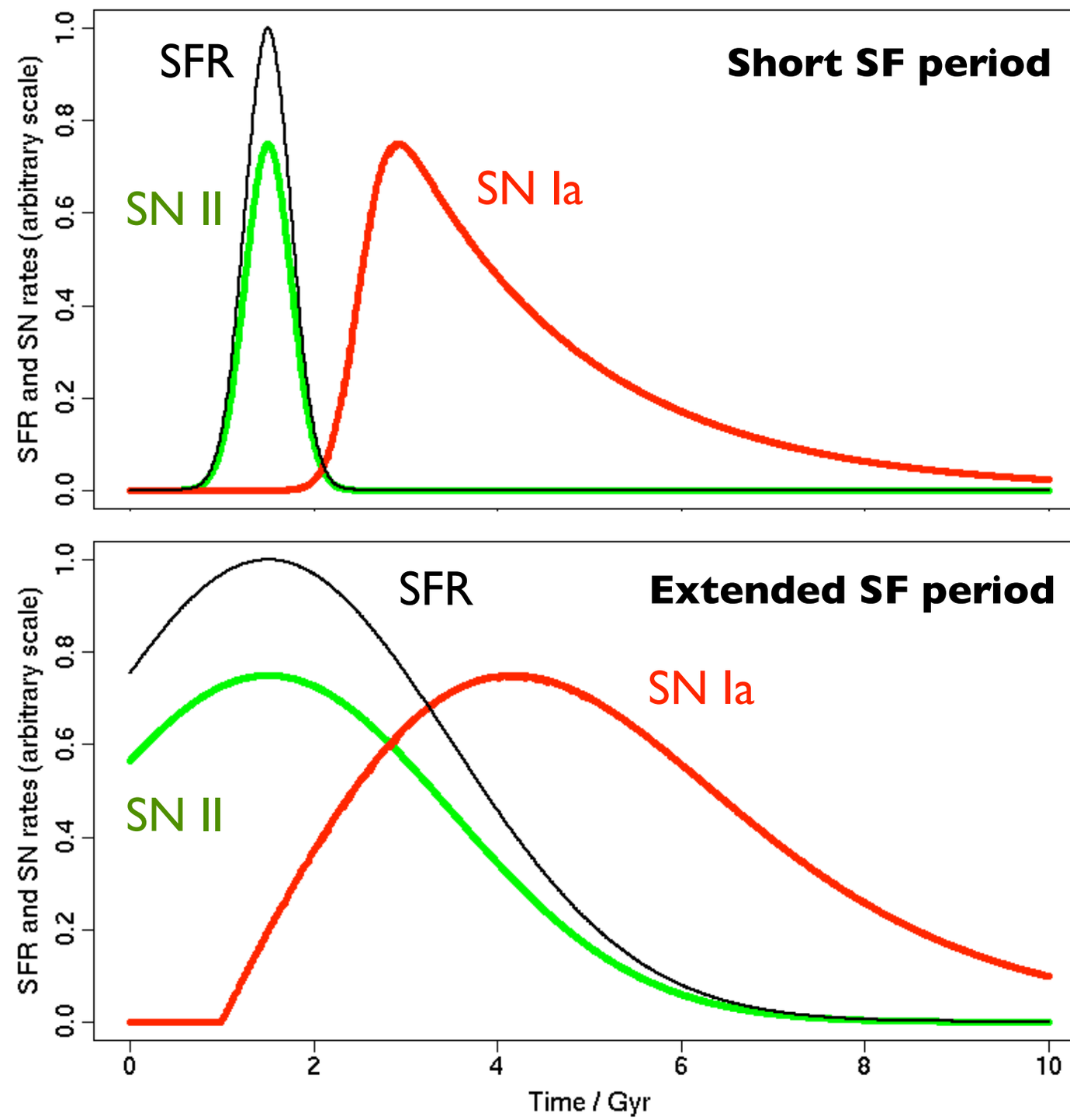
If burst is short, only Mg-rich SNII products incorporated into the stars. (SNIa ejecta just escape from galaxy). Higher Mg/Fe.

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) derive:

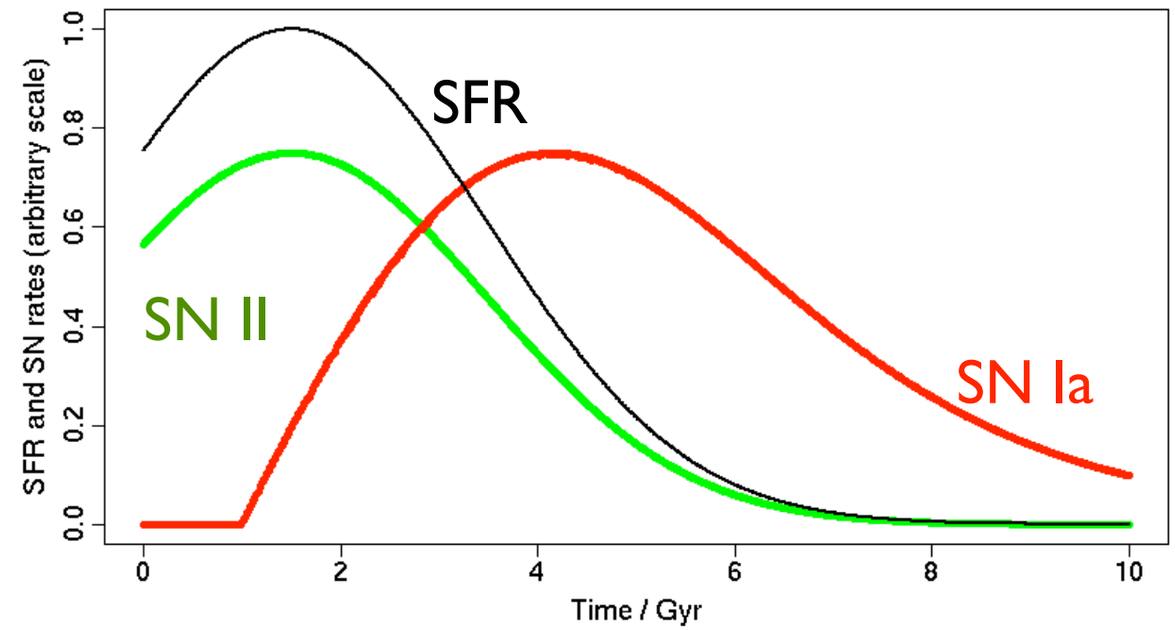
$$[Mg/Fe] = (1/5) - (1/6)\log(\Delta t)$$

with Δt the FWHM of the burst.



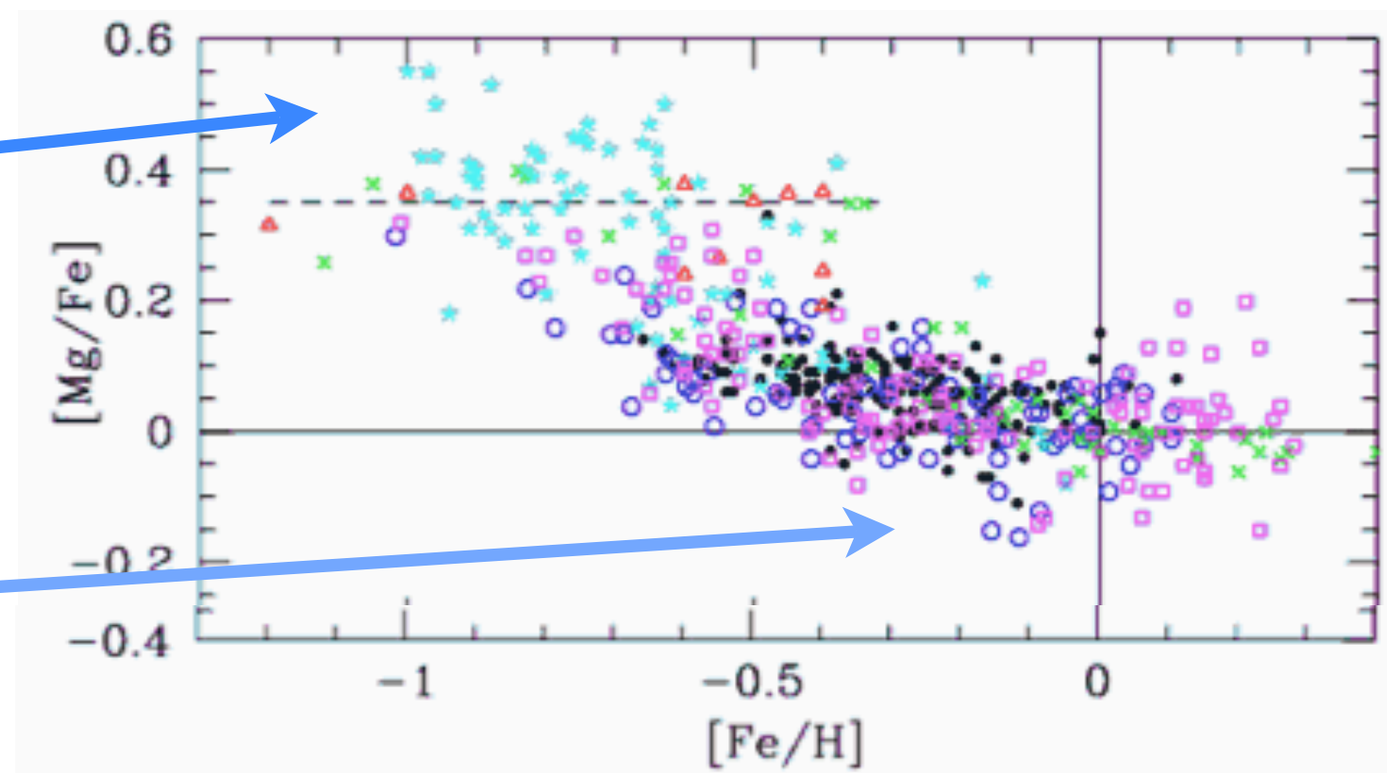
Mg/Fe in the galactic disk

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)

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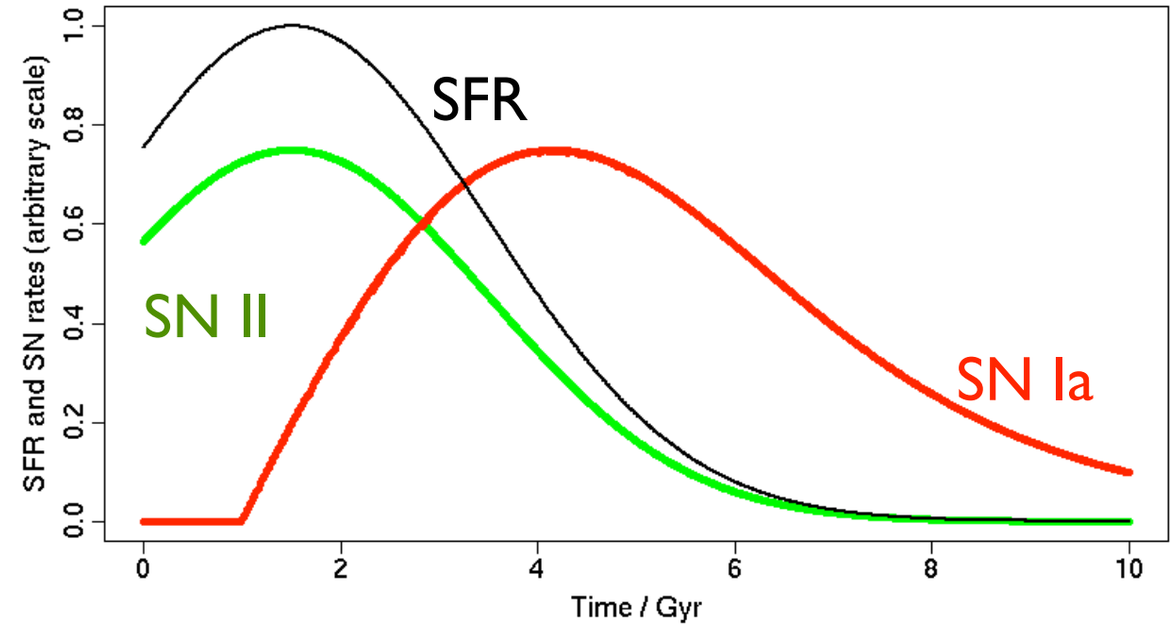

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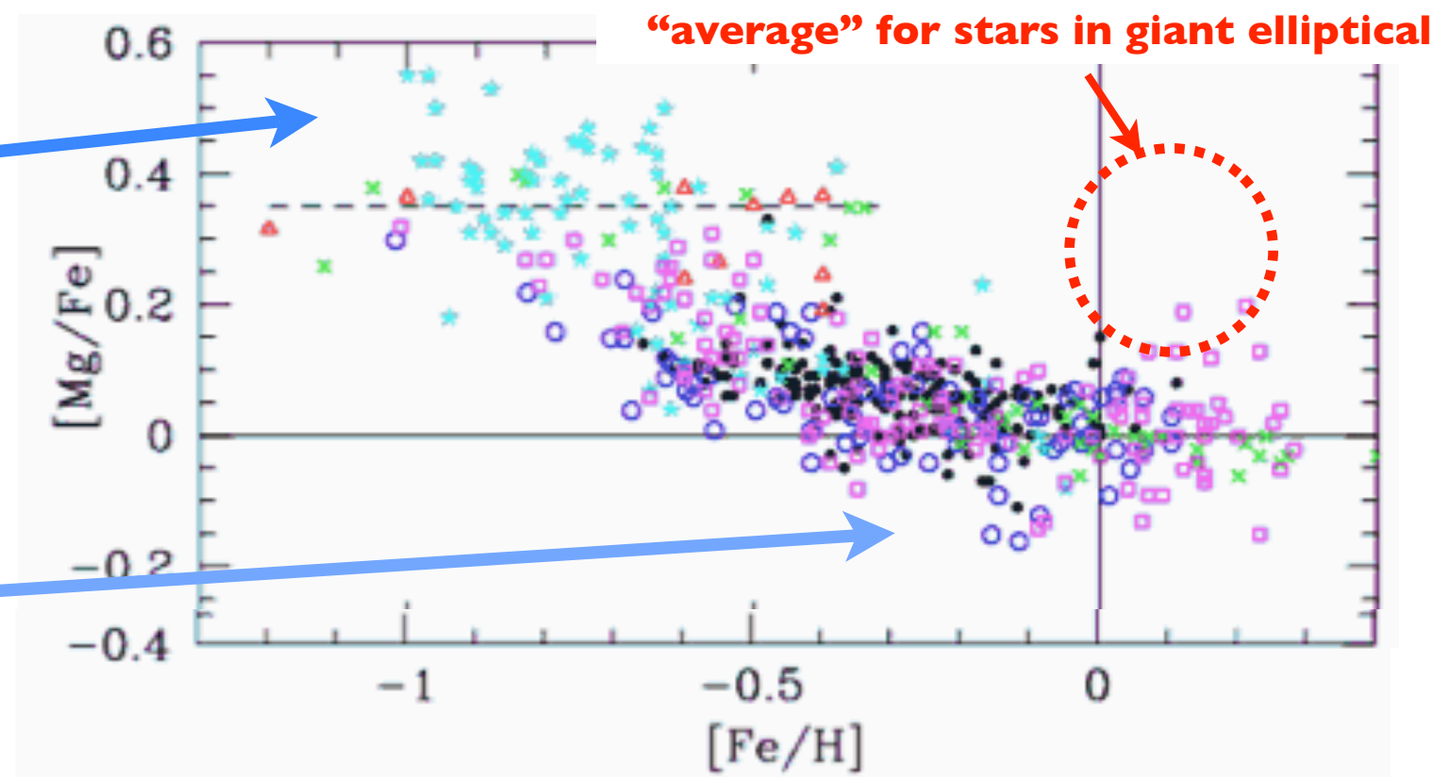


Individual stars in MW disk (Reddy et al. 2003)

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".

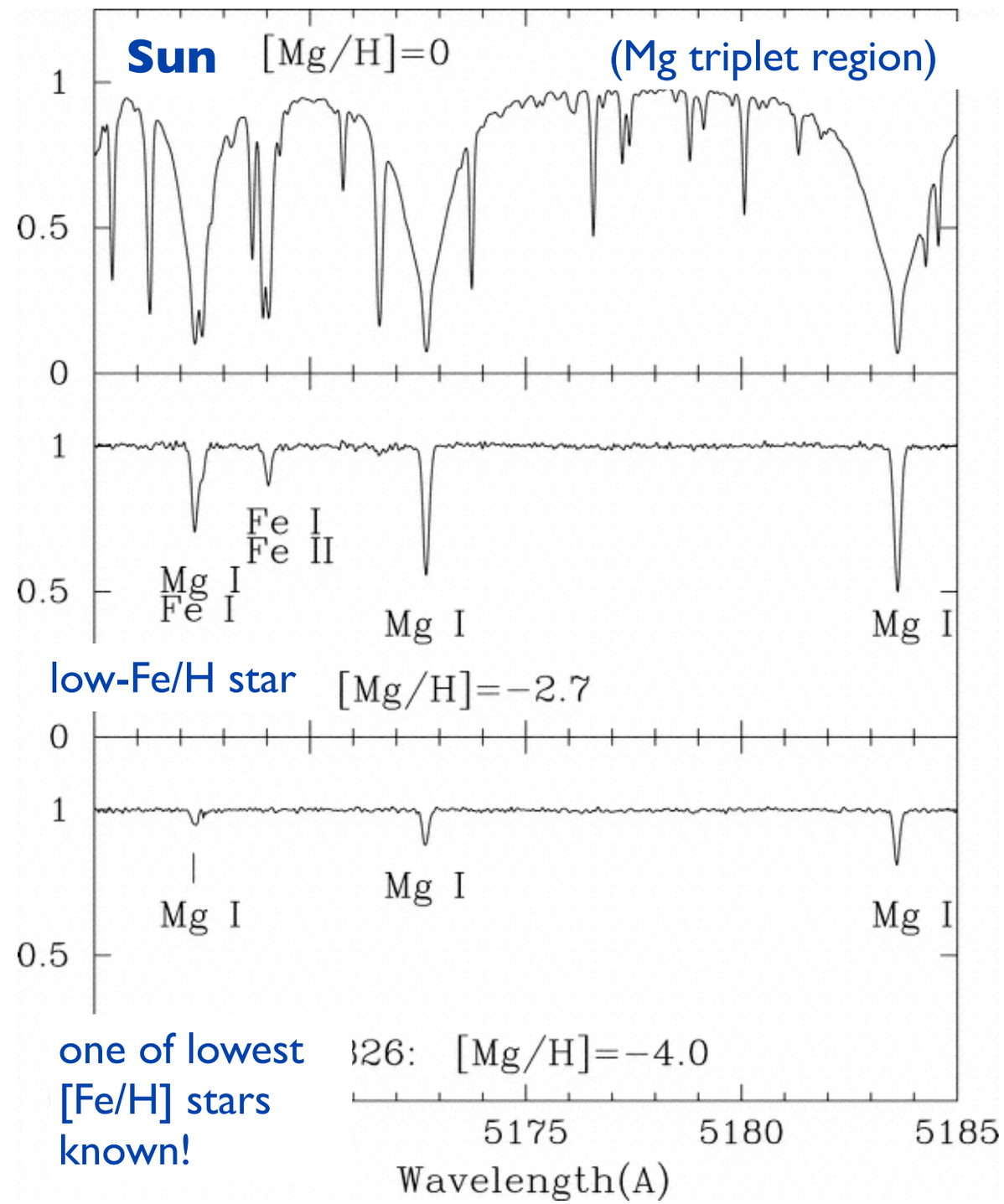
Lowest-metallicity stars known do still have measurable Fe, e.g. [Fe/H] ≈ -5.

Are these Pop III stars polluted by accretion from the ISM? Or extreme Pop II stars, 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)



Abundance ratio effects

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

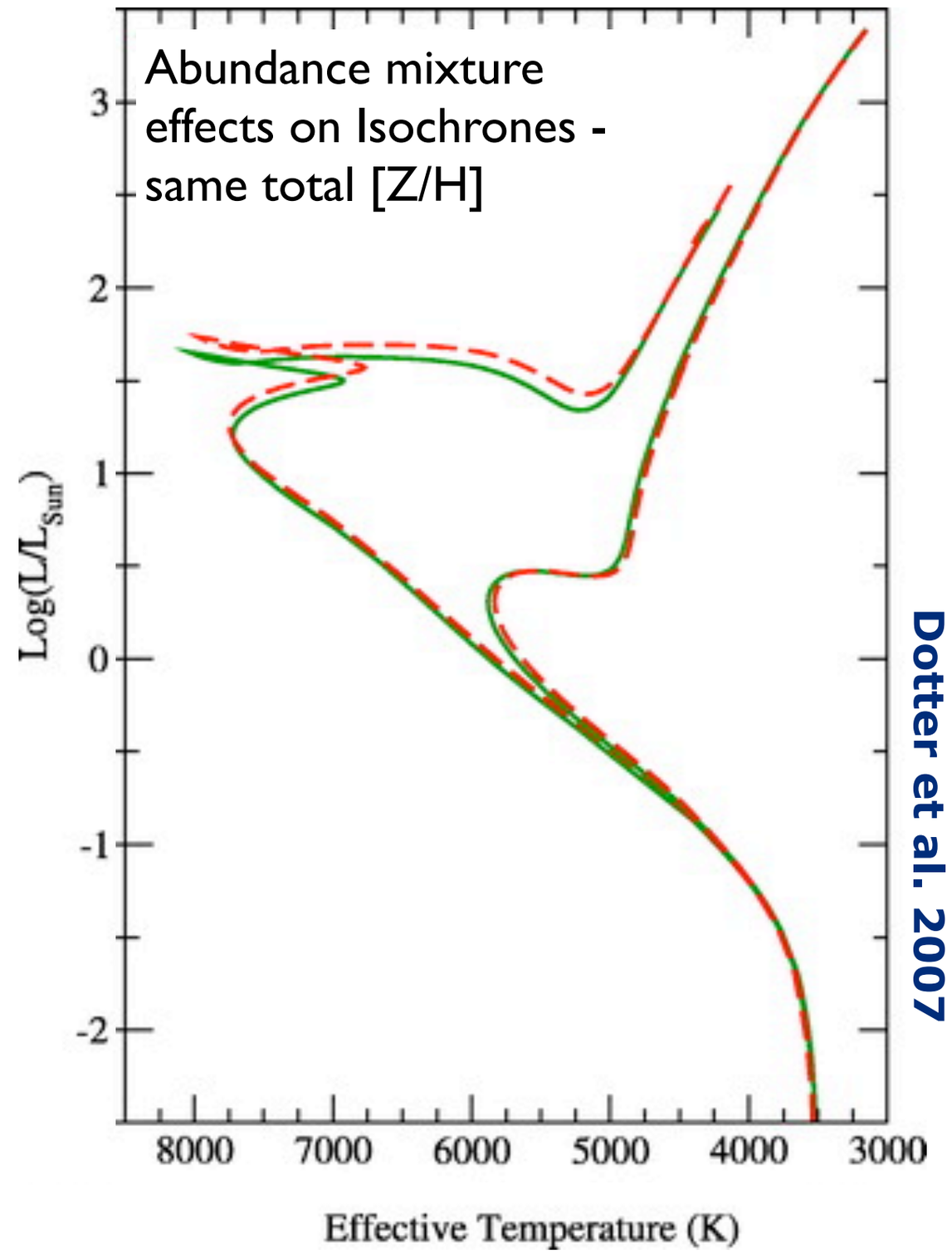
Two influences of [Mg/Fe] on spectra:

(1) stellar evolution effects - temperatures, lifetimes, etc, via different opacities in the interiors.

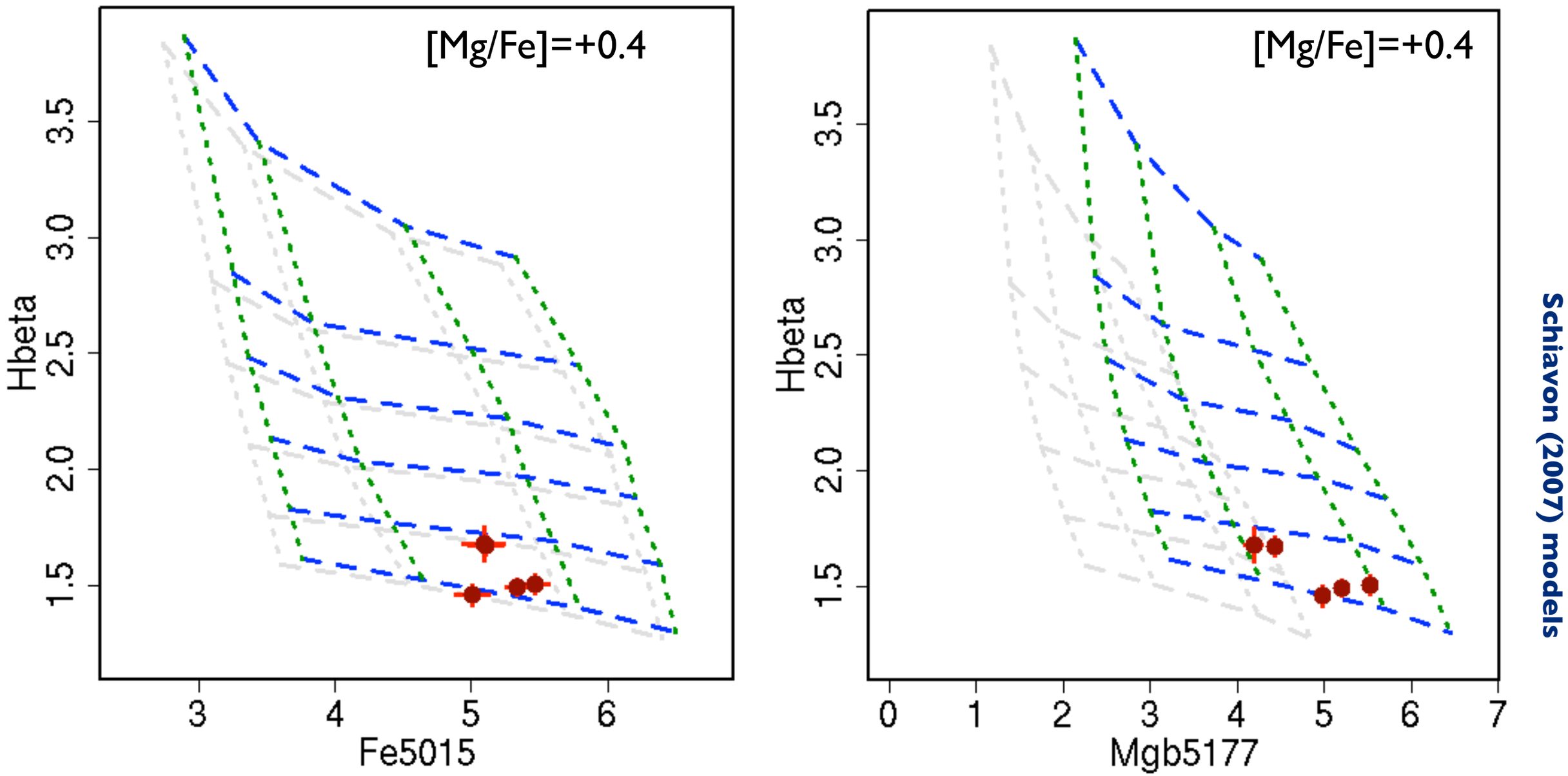
(2) stellar atmosphere effects, changing spectral line formation.

Widely-used models by Thomas et al. (2003) 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 evolution effects are small for indices but important for colours.



Consistency among grids?



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).

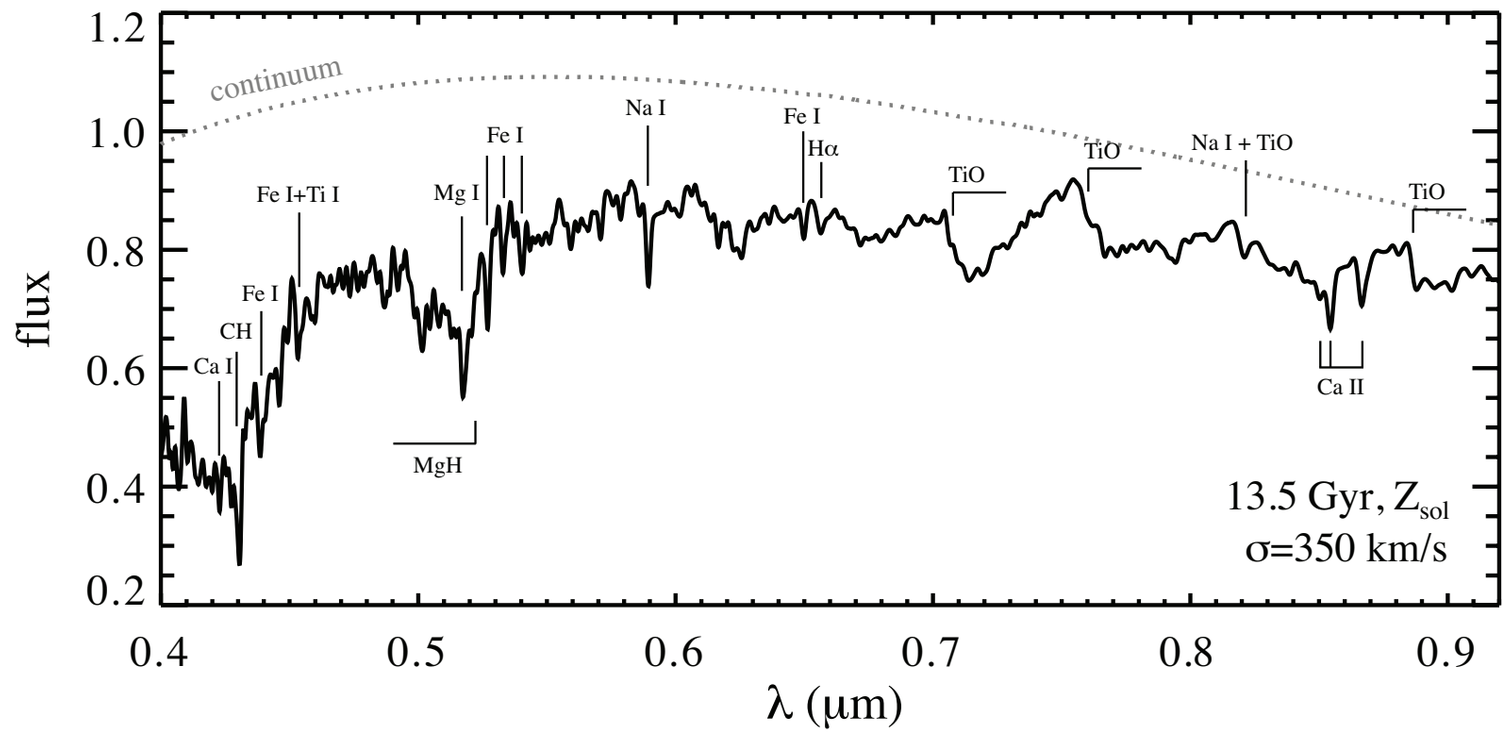
Full-spectrum fitting

Conroy, Graves & van Dokkum 2013

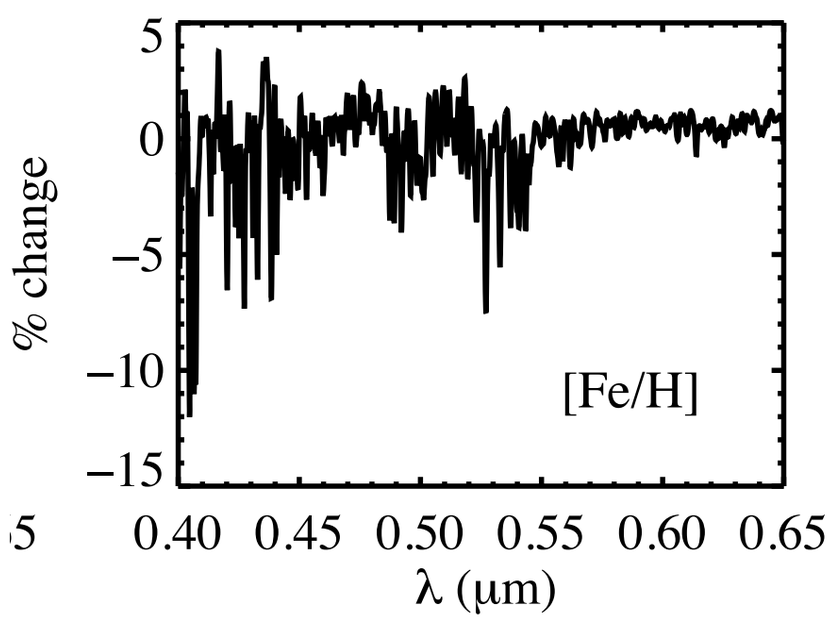
Previously we focussed on age/ metallicity sensitive features by defining “indices”.

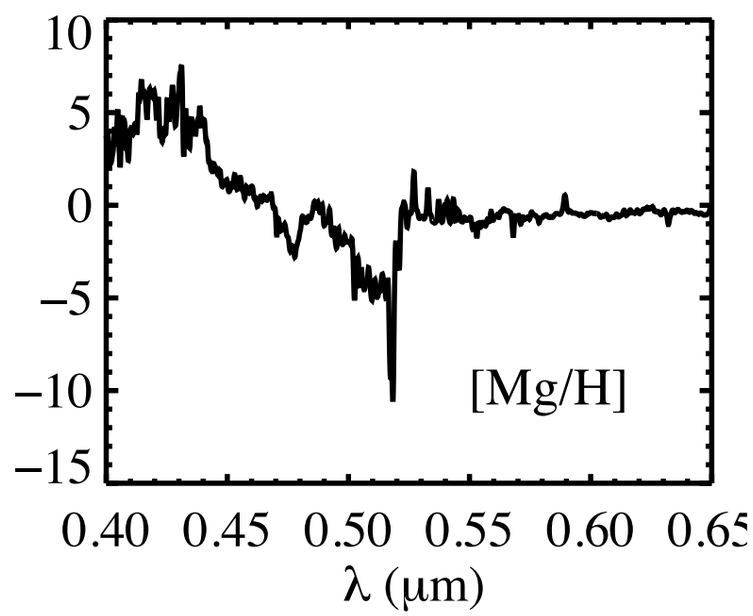
To measure potentially-complex abundance pattern [X/H], need to exploit information content of full spectrum.

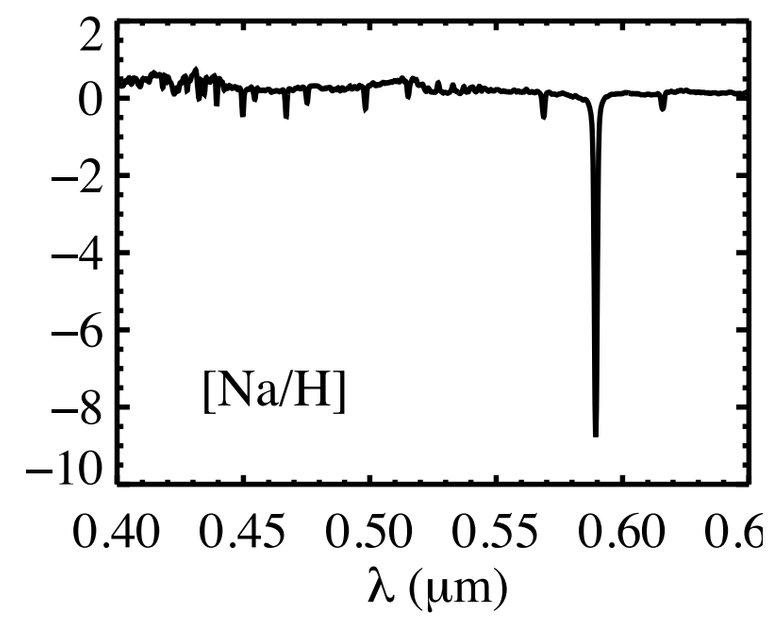
Have to resort to synthetic spectral library, since MW spans limited range in X/Fe.



Response of spectrum to 2x increase in given element (from synthetic atmosphere models)

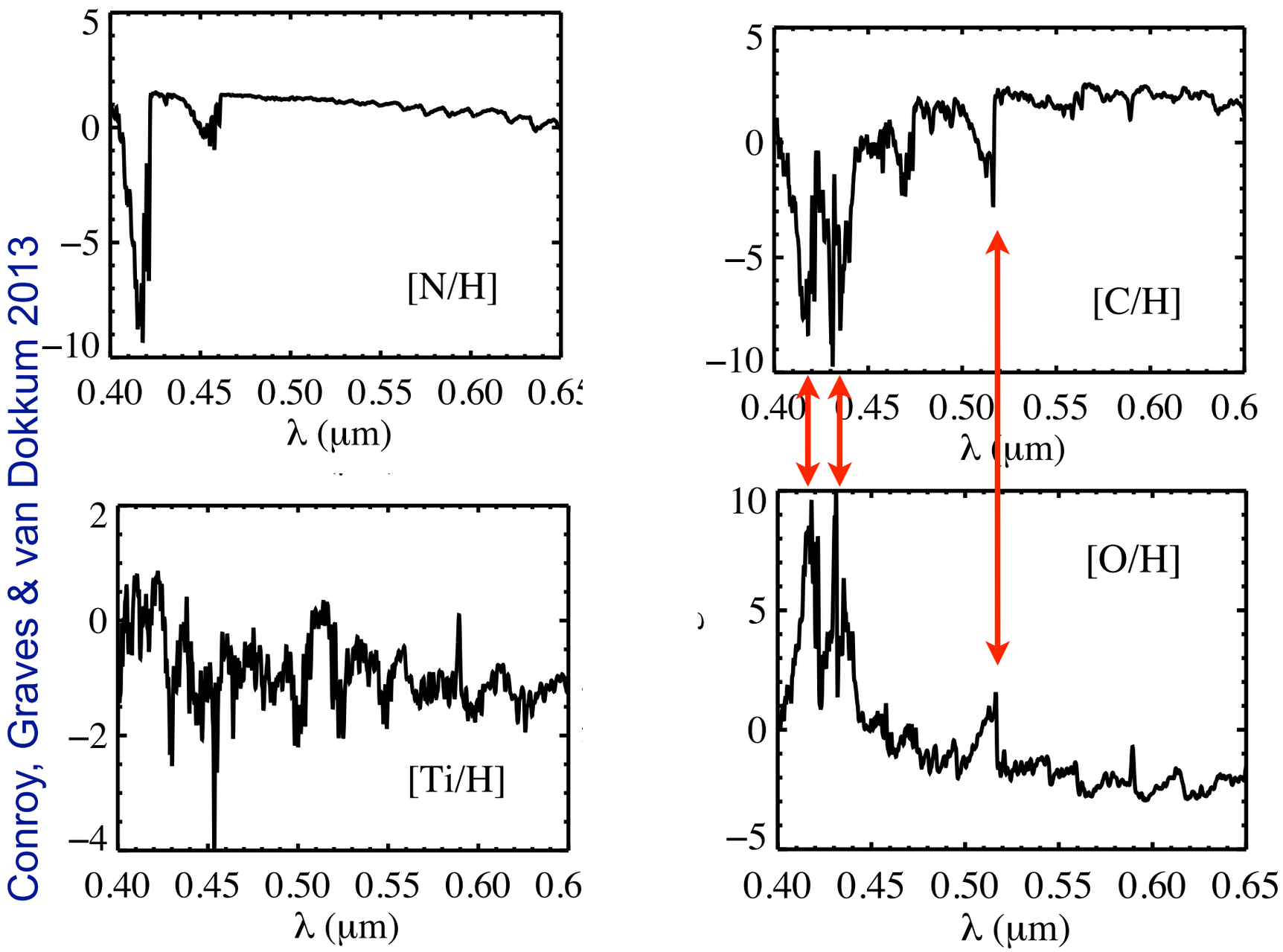






Full-spectrum fitting

More element "response" spectra...



Note "mirror" appearance of [C/H] and [O/H] due to molecular balance.

Adding oxygen forms more CO molecules (which have no strong bands in optical), reducing the carbon available to form other molecules like CN, CH.

Hence oxygen affects optical spectra much like "anti-carbon".

Full-spectrum fitting

Conroy, Graves & van Dokkum 2013

Method implemented by CGvD13:

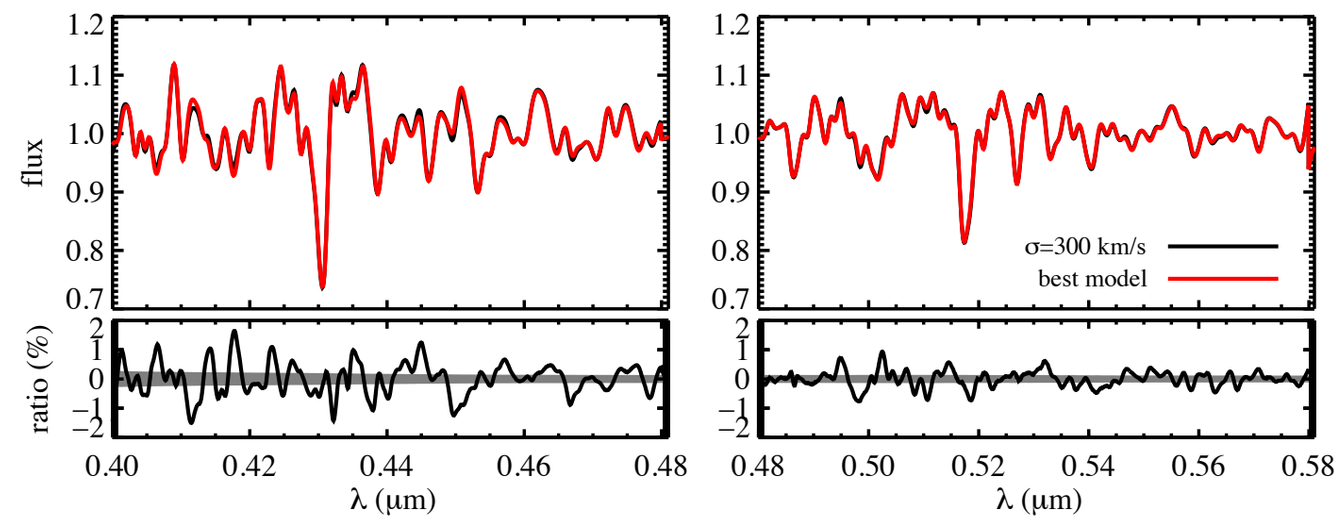
(1) Use best empirical spectral library (MILES) to build SSP spectrum for solar abundances ([Fe/H]=[X/H]=0).

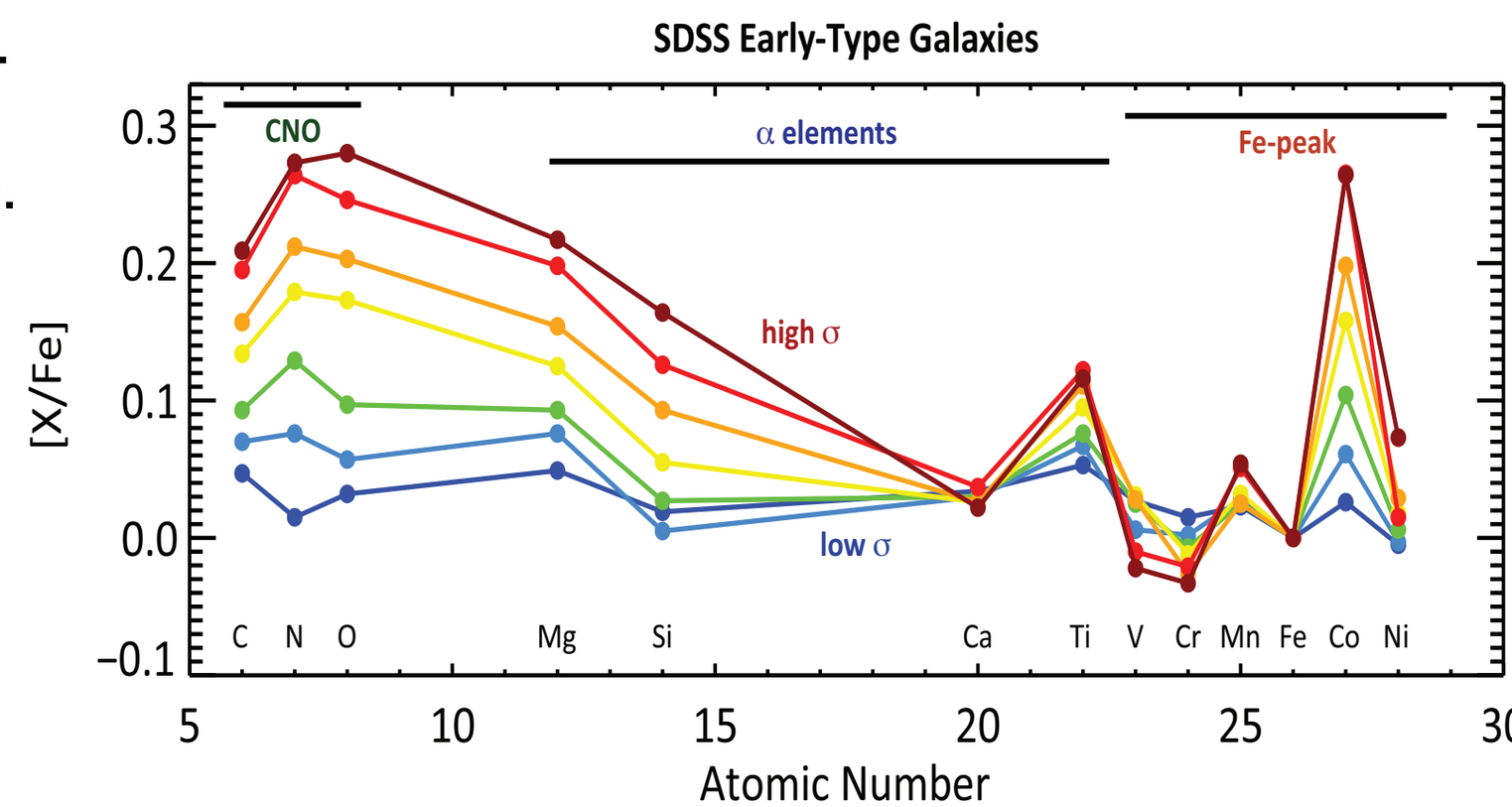
(2) Modify this base spectrum using element response functions derived from synthetic atmosphere calculations.

(3) Add some bells and whistles, e.g. additional younger stellar component, RGB temperature fudge.

Adjust all parameters of the model (40 in total!) to obtain best match to spectrum.

Requires very high S/N - so apply to stacks of SDSS spectra (hundred of galaxies per stack).





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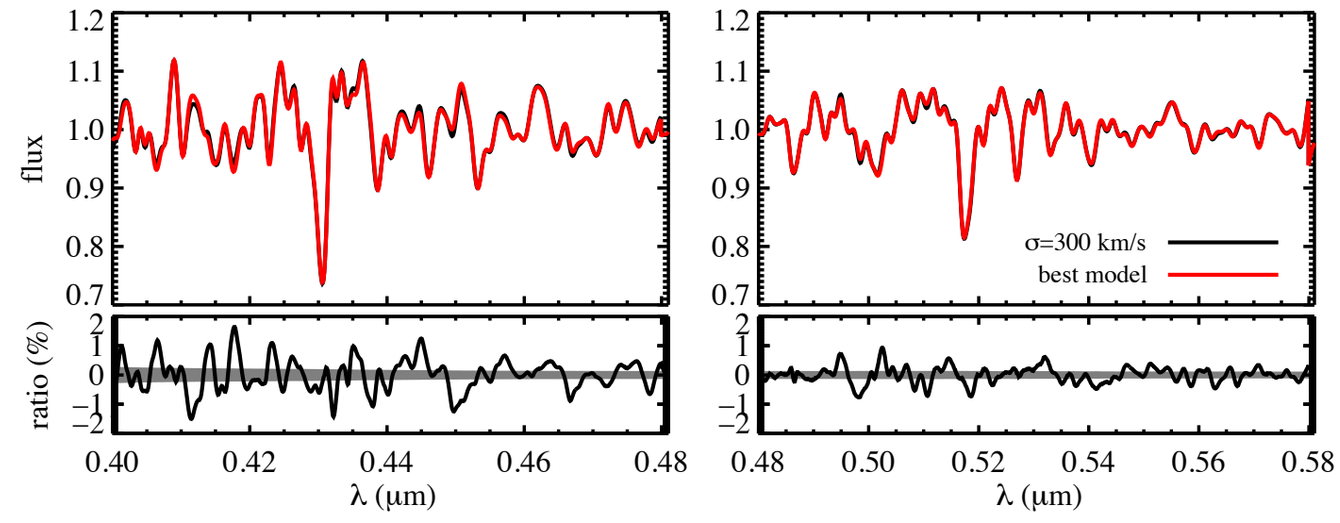
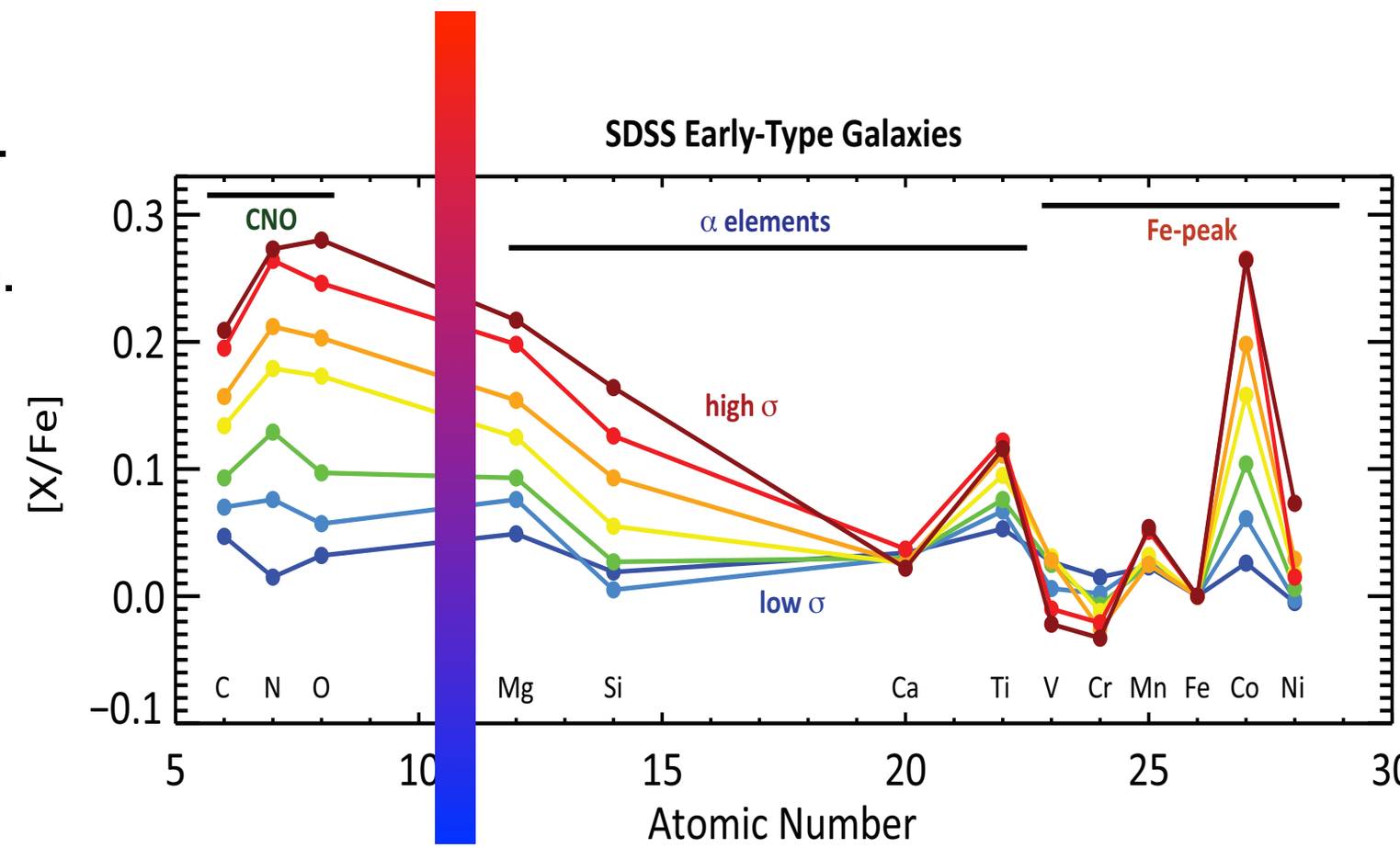
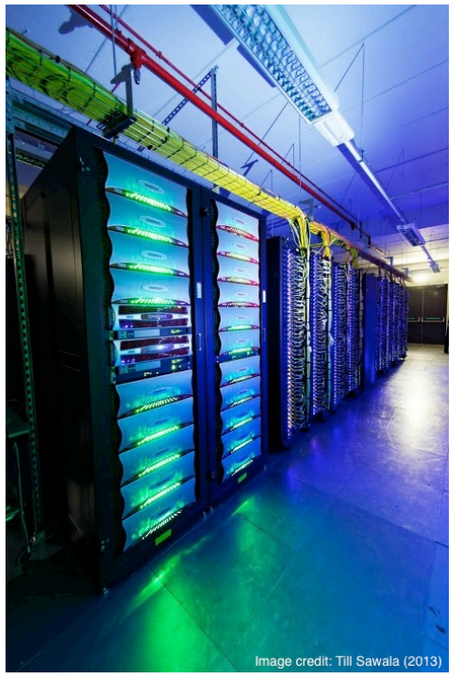
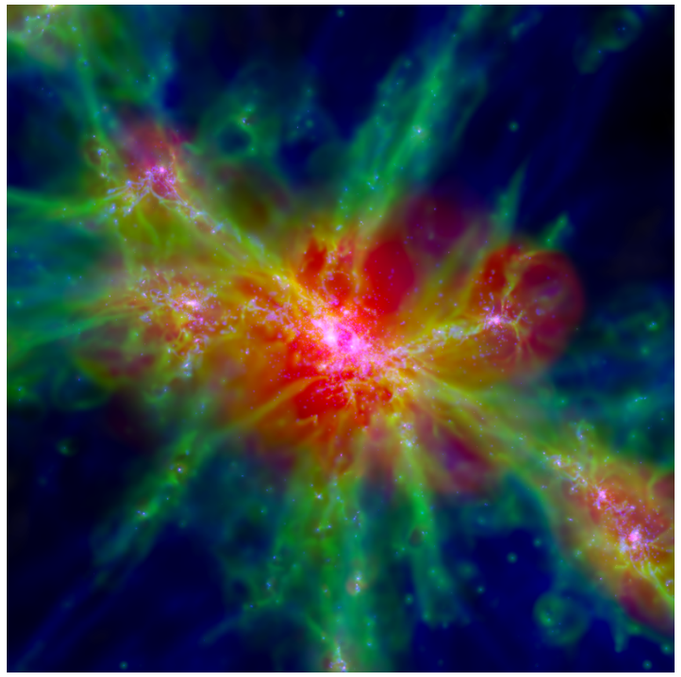




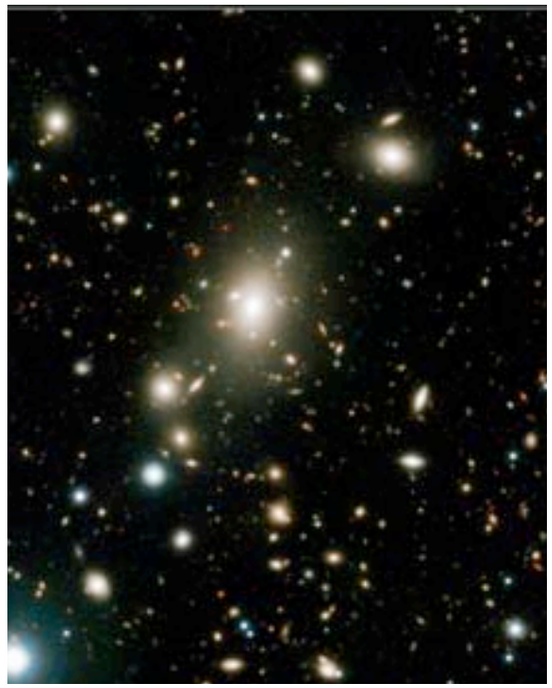
Na

Stellar mass estimation



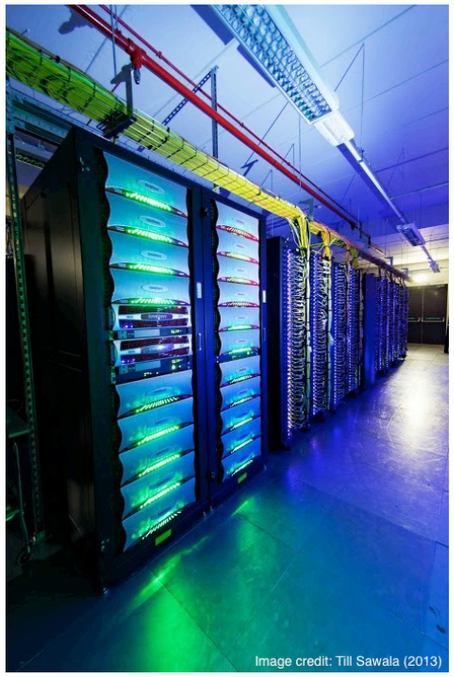


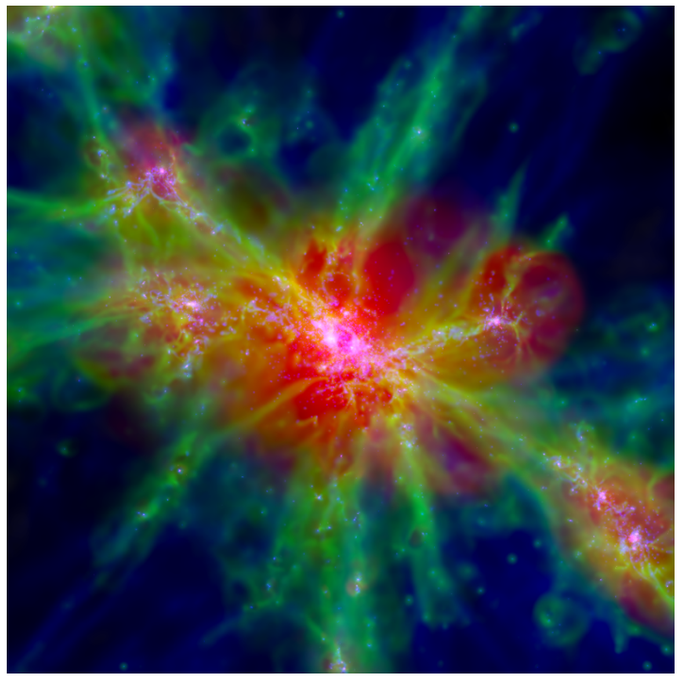
Galaxy formation models predict mass locked into stars in galaxies.



Galaxy surveys measure luminosity of galaxies.

Stellar mass estimation





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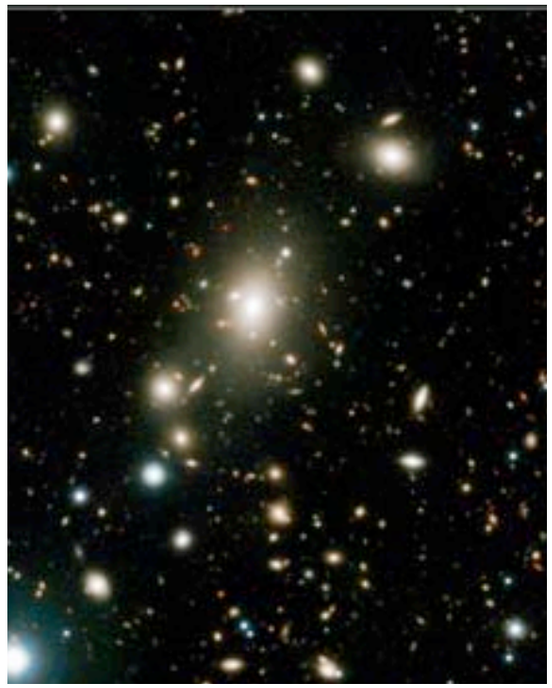

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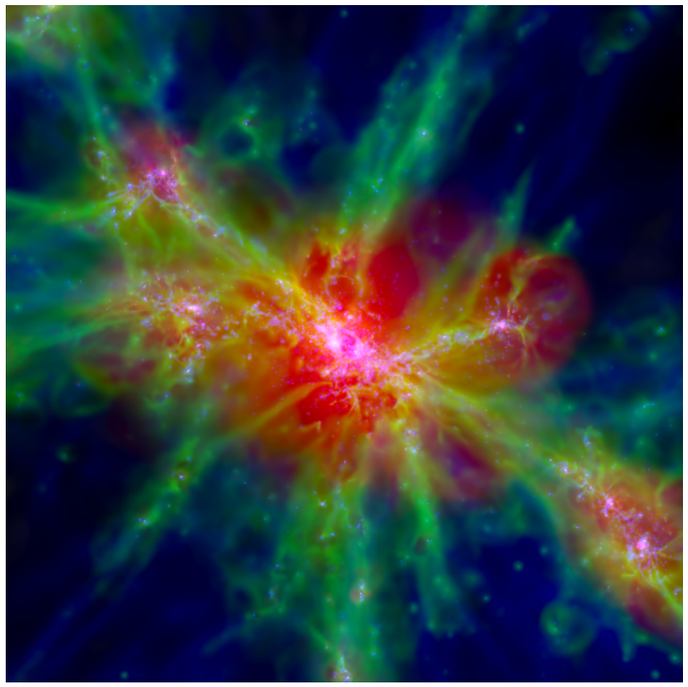
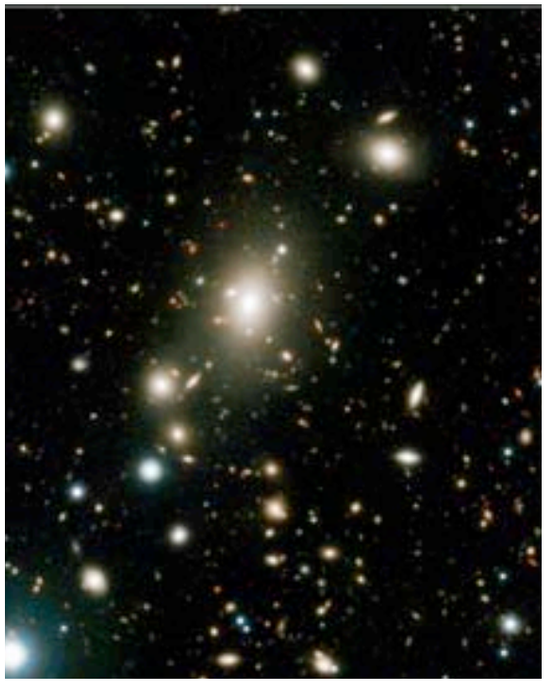
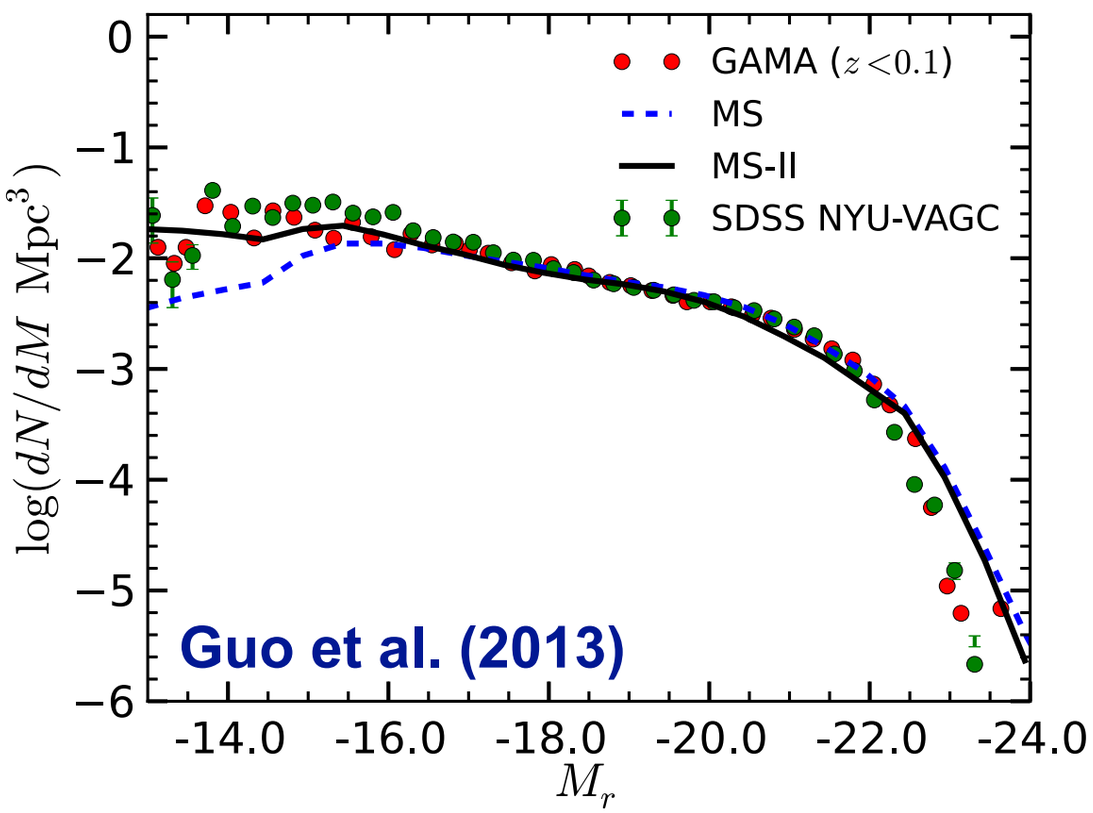






One option is to convert simulation/model stellar mass into luminosities.

Should be “easy”, just tag each star-particle in simulation with an SSP spectrum of corresponding age and metallicity. (Or equivalent process in semi-analytic models.)

Okay for some purposes, e.g. comparing reproduction of luminosity function.

But sometimes we want to go in the opposite direction, e.g. to select a stellar-mass-limited sample of galaxies for spectroscopic follow-up.

Stellar masses of galaxies

Stellar Mass vs Luminosity

Given a galaxy of luminosity 10^{10} L_{sun}, is it:

a) an old giant galaxy or

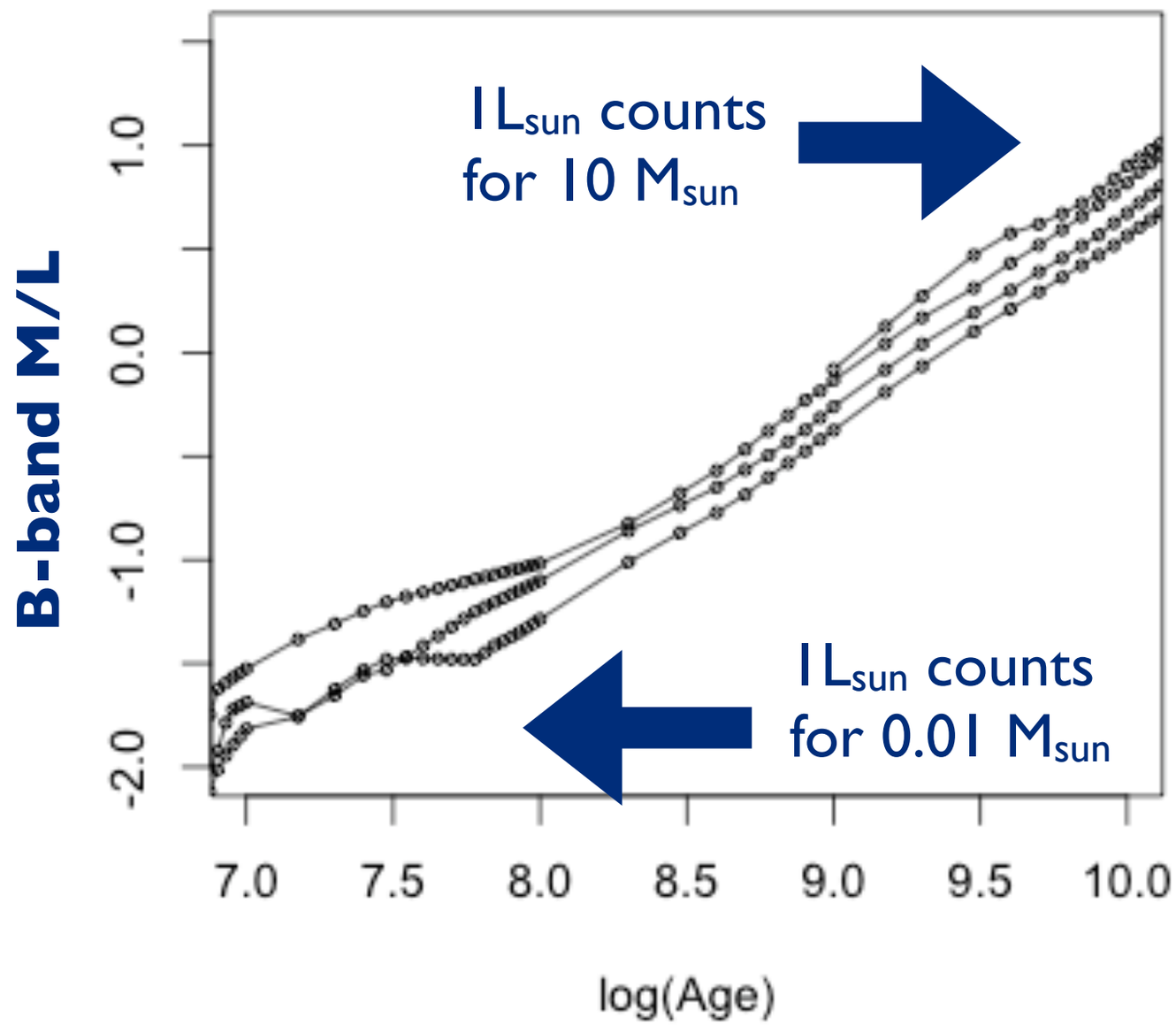
b) a puny dwarf galaxy that just happens to be forming lots of stars right now??

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

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

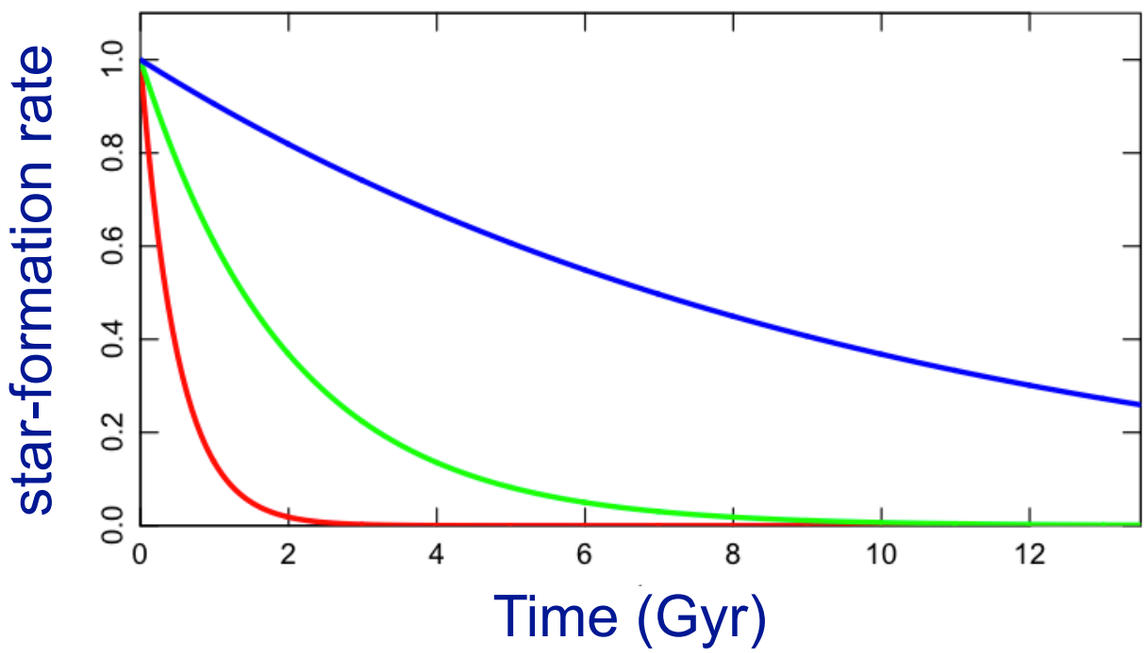
For an SSP, the M/L depends on IMF, age and metallicity. For complex populations, M/L depends on the full star-formation history (SFH).

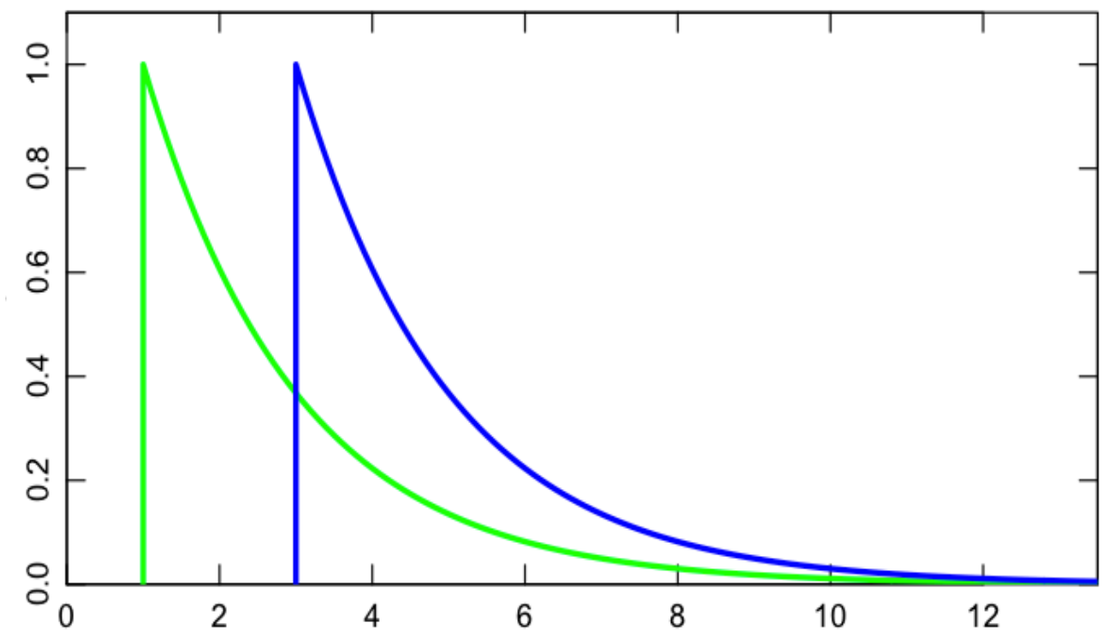
Maraston 2005 SSP models

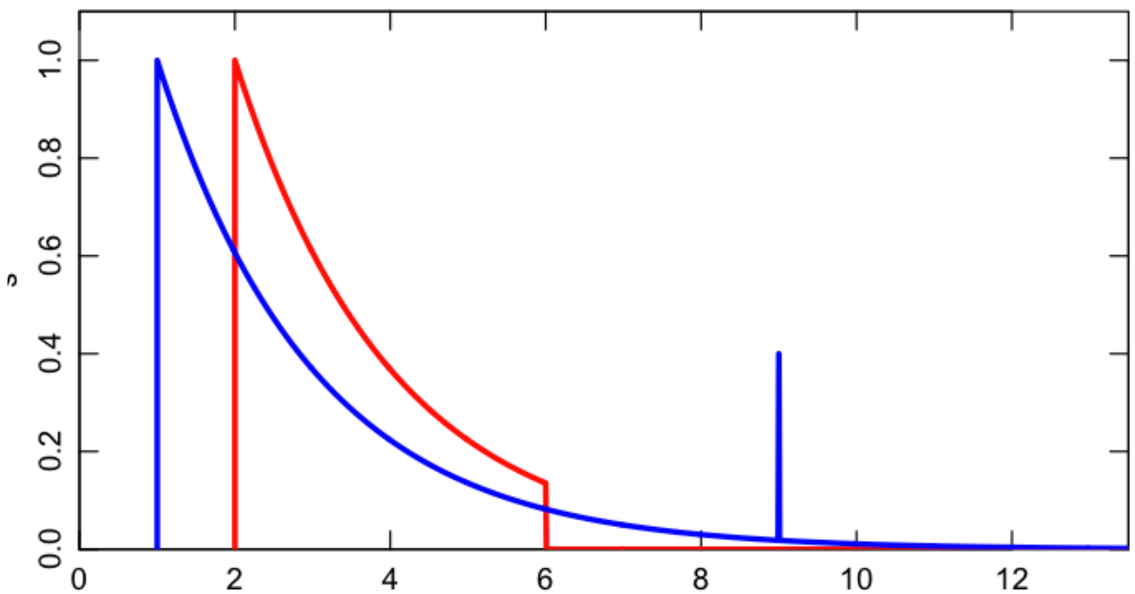


NB: in this section we will be considering a much larger range in "age" than previously, even ongoing star-formation.

Parametrized Star-Formation Histories







Previously, we assumed simple stellar populations (one age, one metallicity).

Possibly okay for clusters and maybe for giant ellipticals. But to fit all types of galaxy, need to allow for extended SFHs.

Commonly parametrized as exponential declining SF, $\sim e^{-t/\tau}$. (Motivated by closed-box chemical evolution models).

Can be modified with initial delays, late truncation, late bursts, etc.

Cheap stellar masses

M/L depends on age/SFH and metallicity for a galaxy.

Colours also depend on age and metallicity.

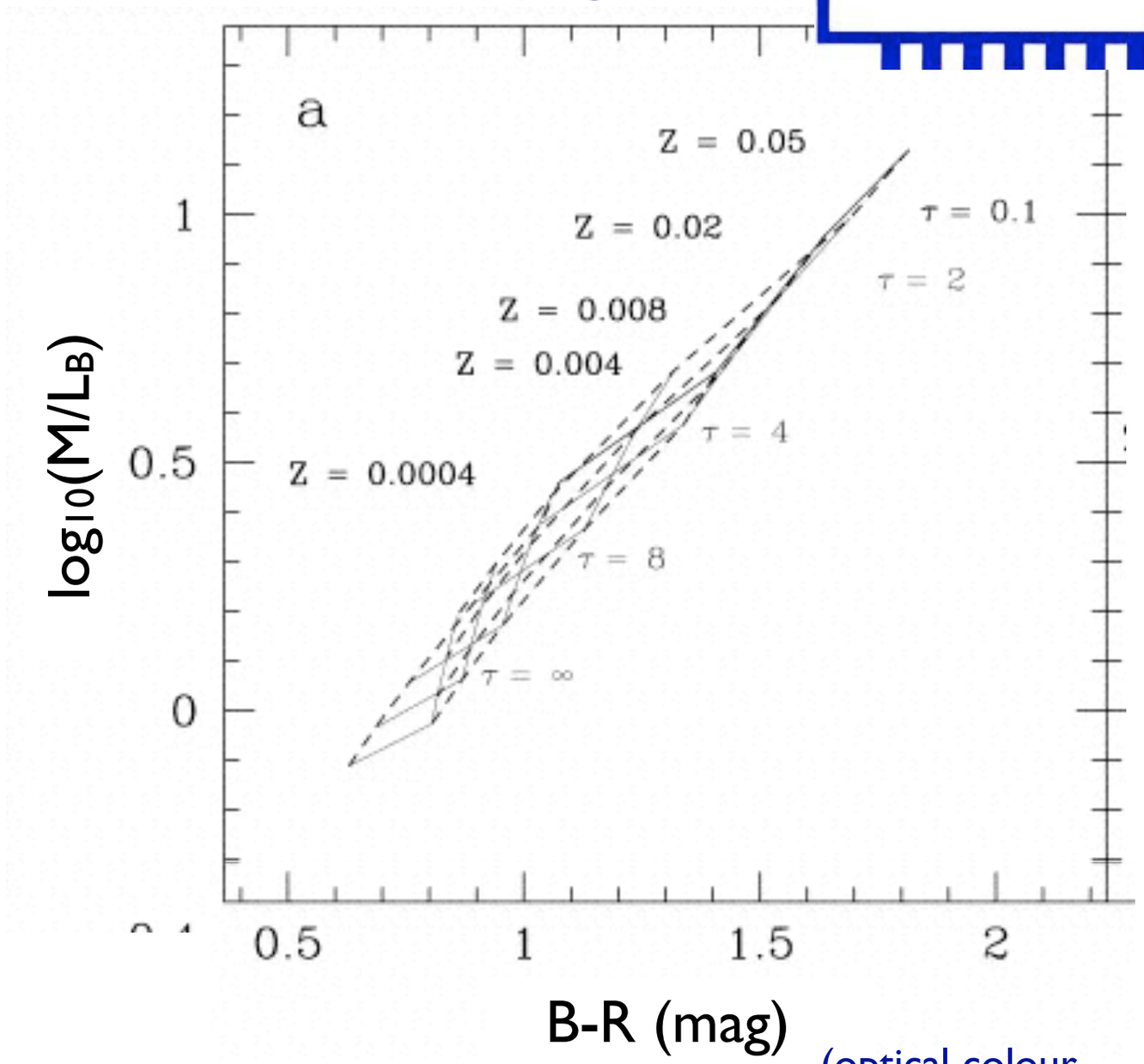
Bell & de Jong 2001: For <u>exponential star-formation histories</u> (with a fixed IMF) B-R is a good predictor of M/L_B, i.e. compensation between similar degeneracies in colour and M/L.

Internal dust reddens the galaxy, but also makes it fainter: approximately preserves colour-M/L relation.

<u>M/L can be determined even though age and metallicity taken separately can not.</u>

Scatter only ~0.1 dex for exponential SFH family. More if late bursts allowed.

Bell & de Jong 2001



(optical colour works best)

(For once - degeneracy is good!)

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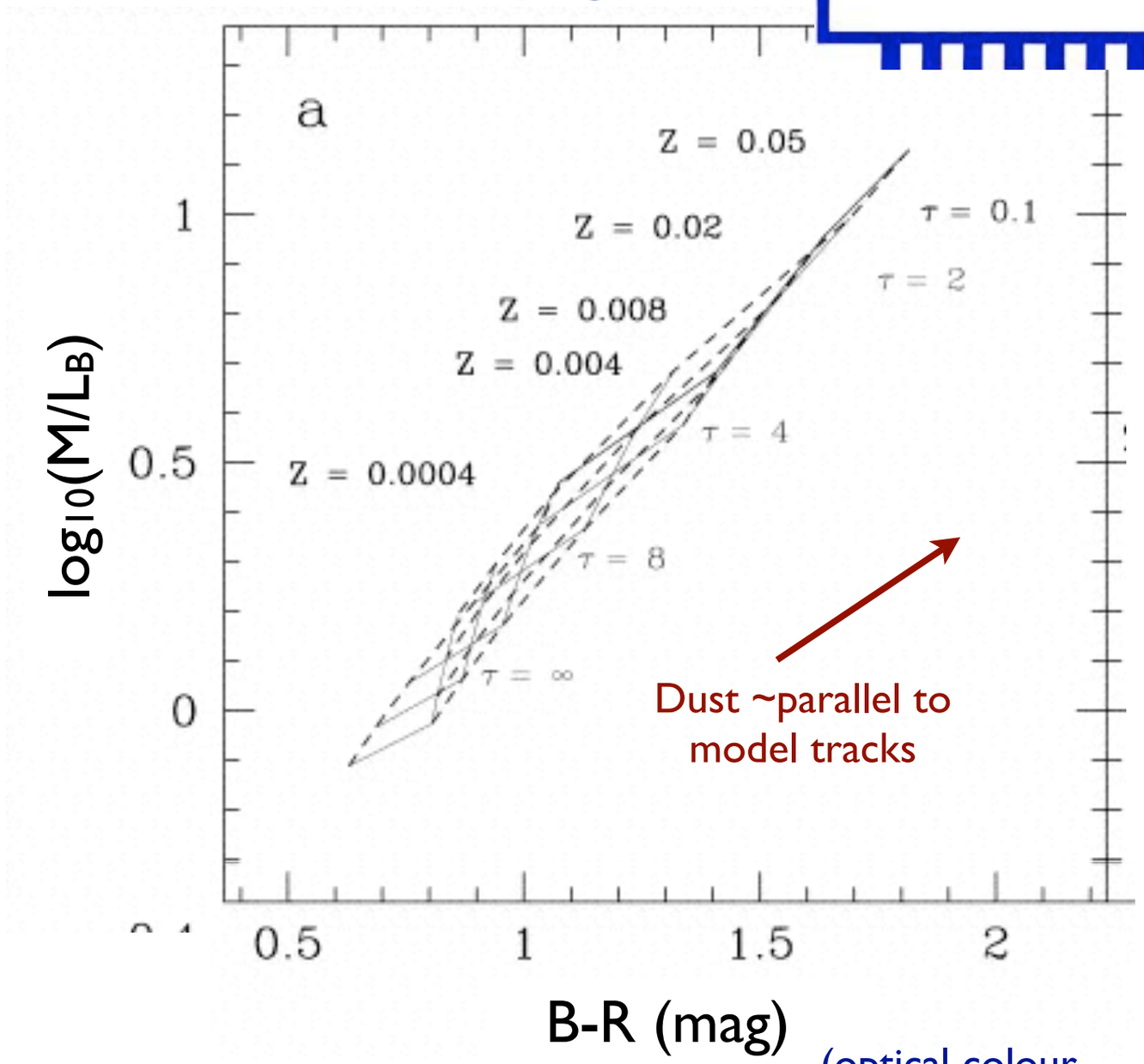

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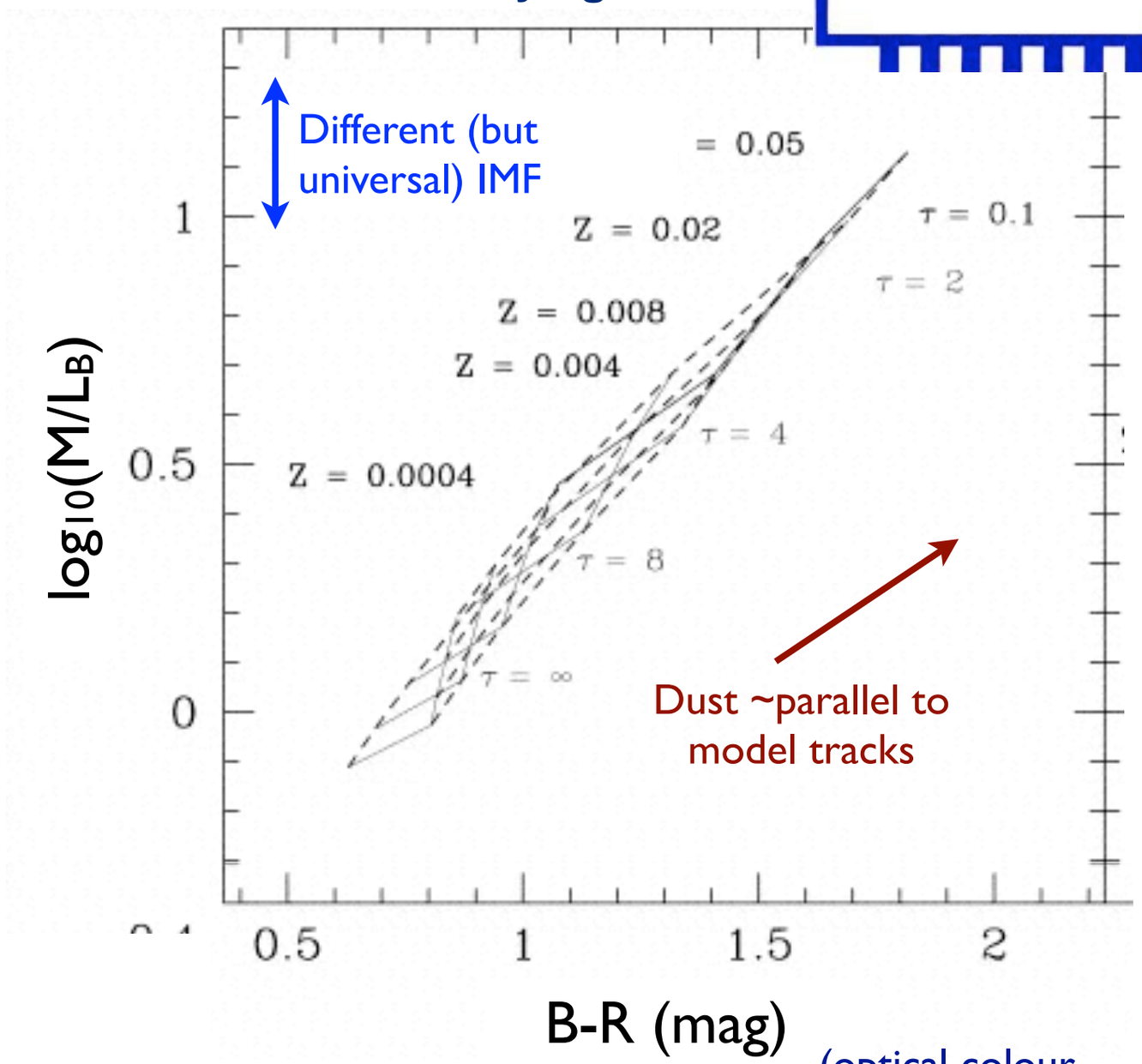


(optical colour works best)

(For once - degeneracy is good!)

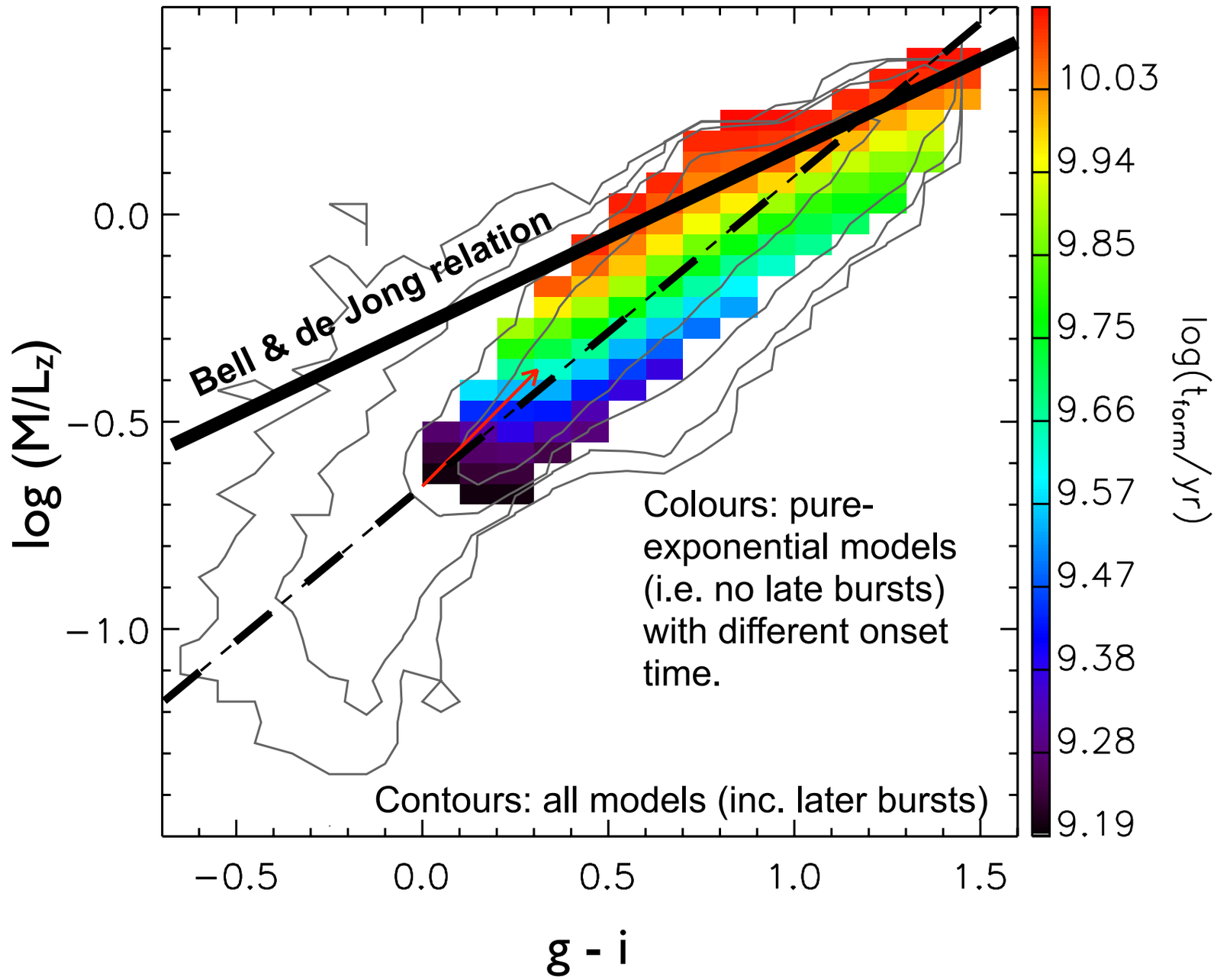
Cheap stellar masses

But the colour-M/L relation depends on the "library" of SFHs adopted.

Bell & de Jong assumed SFH ~ $e^{-t/\tau}$ starting from 12 Gyr ago.

A less restrictive SFH model set, with different onset time, and addition of later bursts, has a systematically different colour-M/L relation and much more scatter.

So the inferred masses (and errors) from this method will depend on our assumptions about distribution of SFHs...



Gallazzi & Bell 2009

Stellar masses from SED fitting

Fitting “spectral energy distribution” - for these purposes usually broad-band photometry in UV/Optical/NIR.

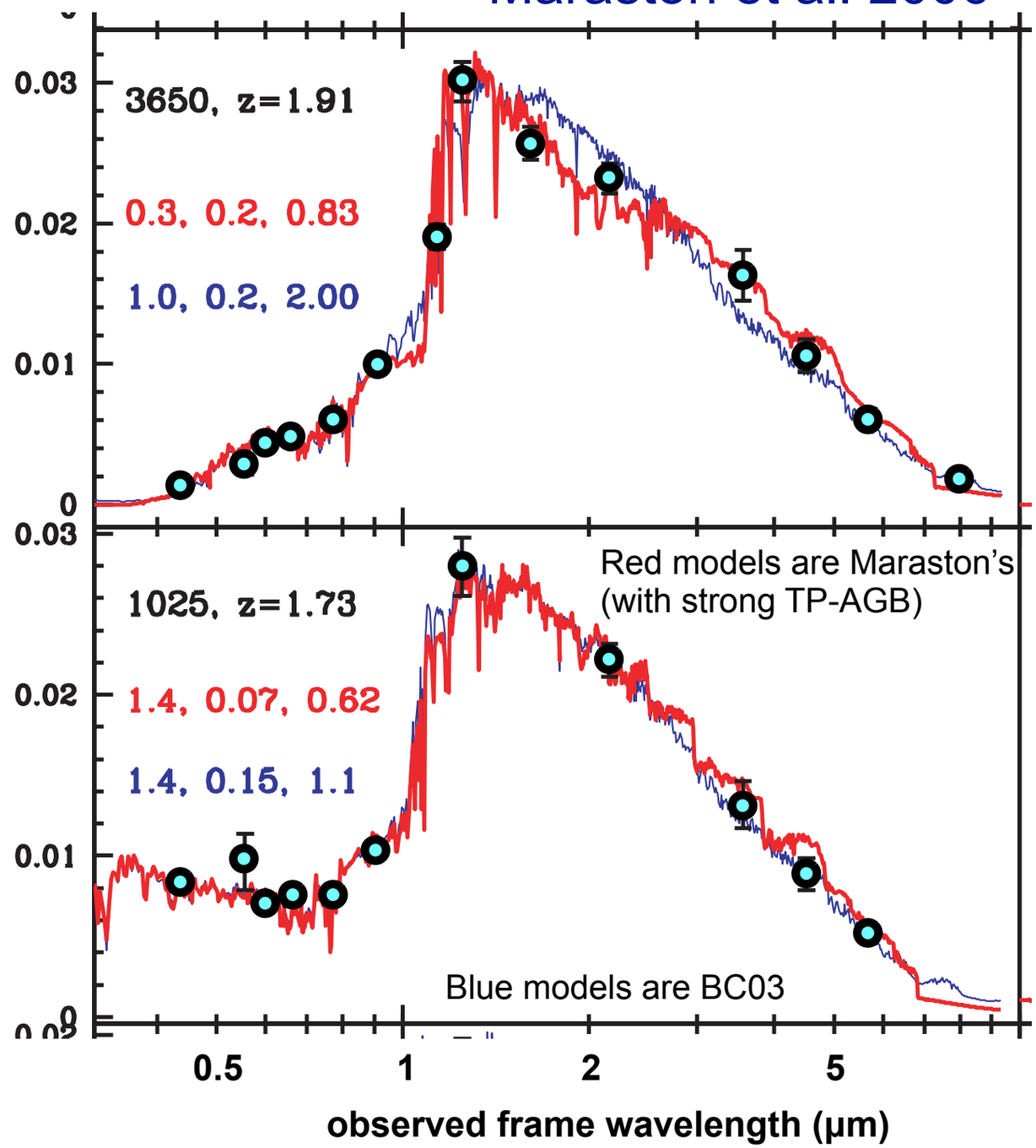
Find SFHs compatible with he observed fluxes.

M/L determined from the best-fitting models.

Often we don’t know the redshift in advance, so this is fit from the photometry at the same time. Hence photo-z codes and stellar mass codes are essentially the same thing.

Errors typically still ~0.3 dex, i.e. not great improvement over colour-M/L approach?

Maraston et al. 2006



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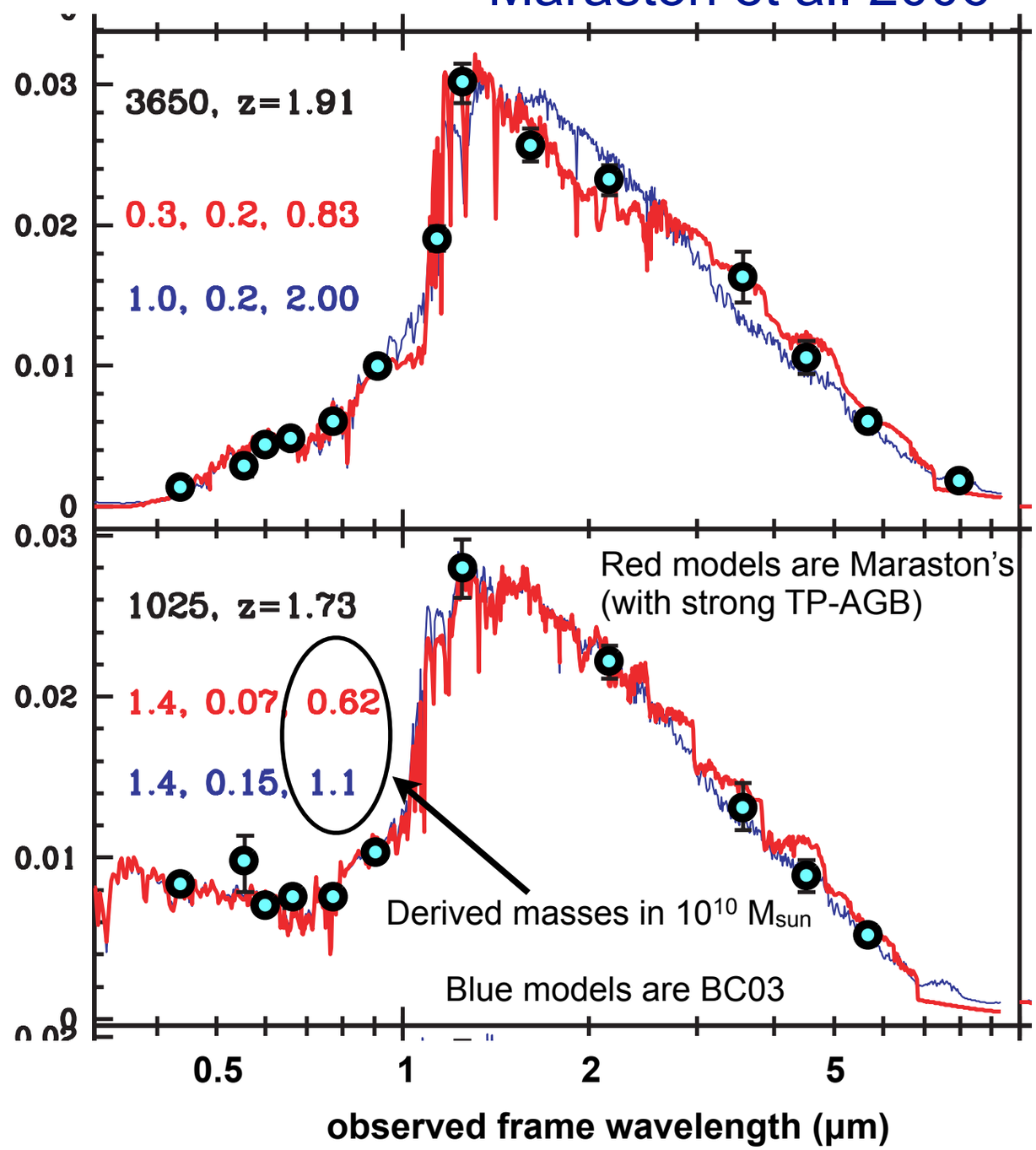


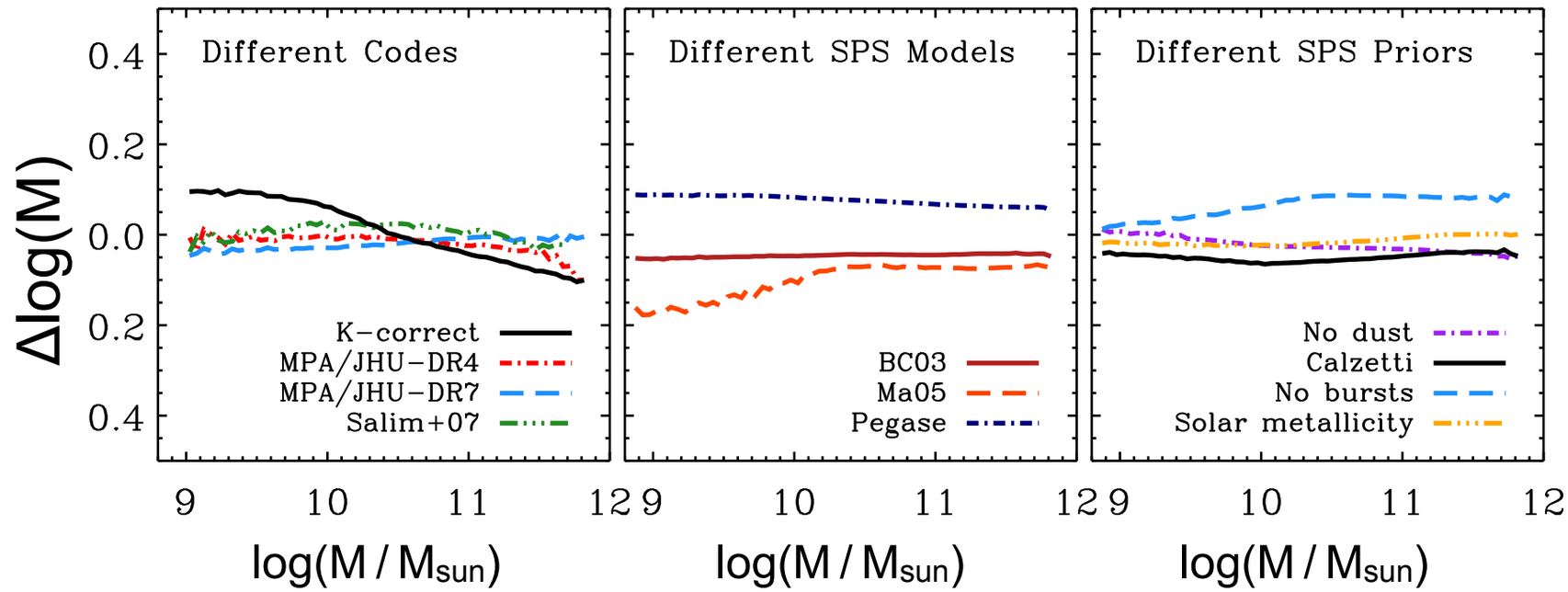
Stellar masses from SED fitting

The standard ~0.3 dex error doesn't include systematic errors.

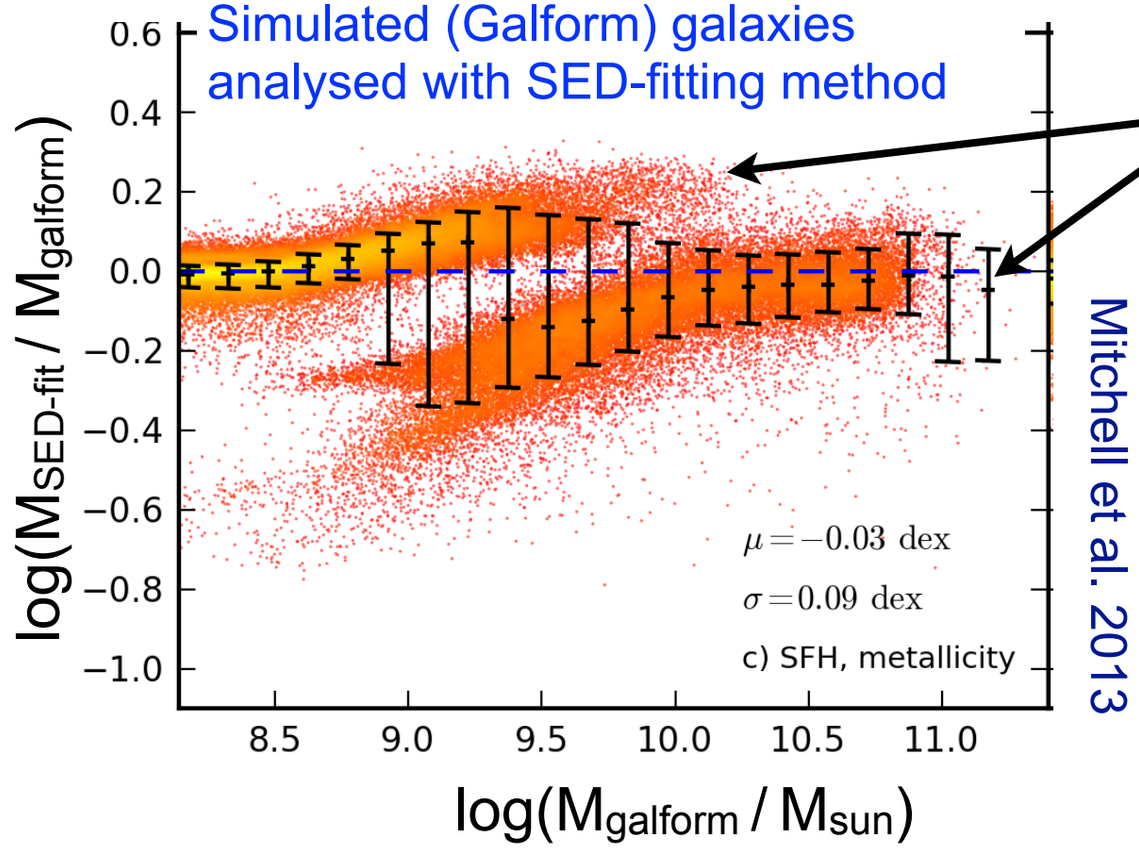
For general population of low-z galaxies, different approaches yield systematic offsets at ~0.1 dex (25%) level.

Changes to IMF trivially move all masses (e.g. factor 1.55 between Kroupa and Salpeter).

Also recall that many models share same underlying isochrones, fundamental calibrations, so some systematics shared by all.



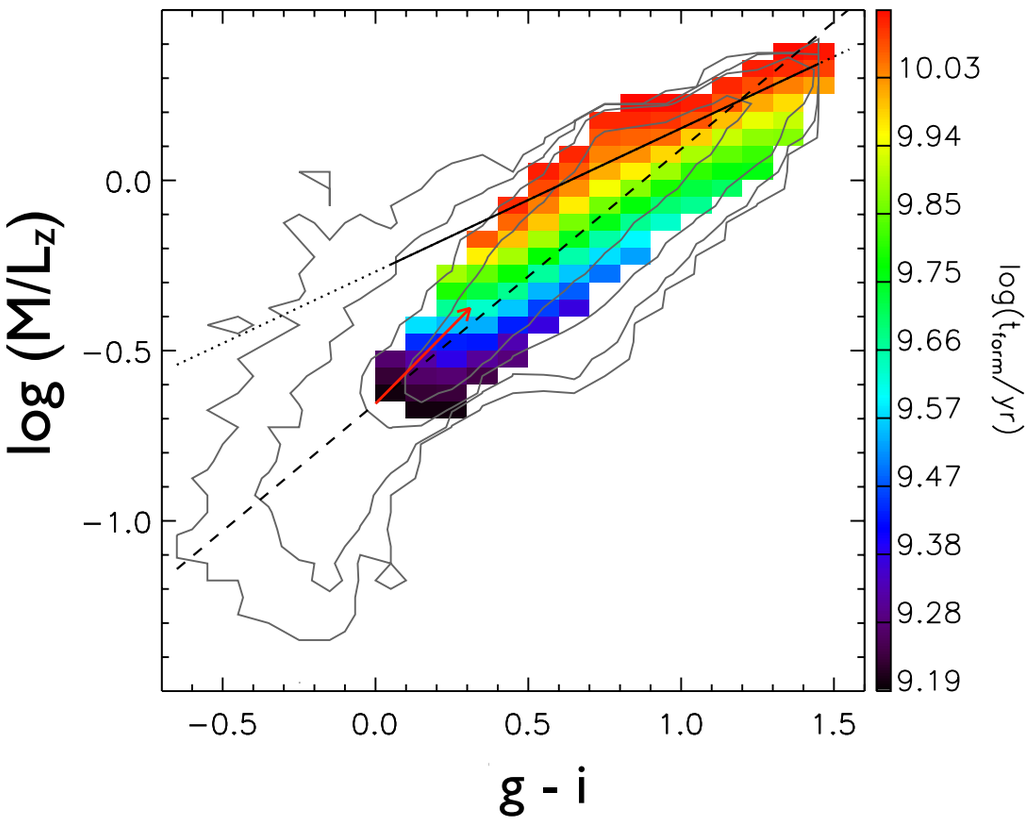
Moustakas et al. 2013



Mitchell et al. 2013

Multi-modality caused by models with coarse and discrete metallicity grid.

Stellar masses from spectroscopy

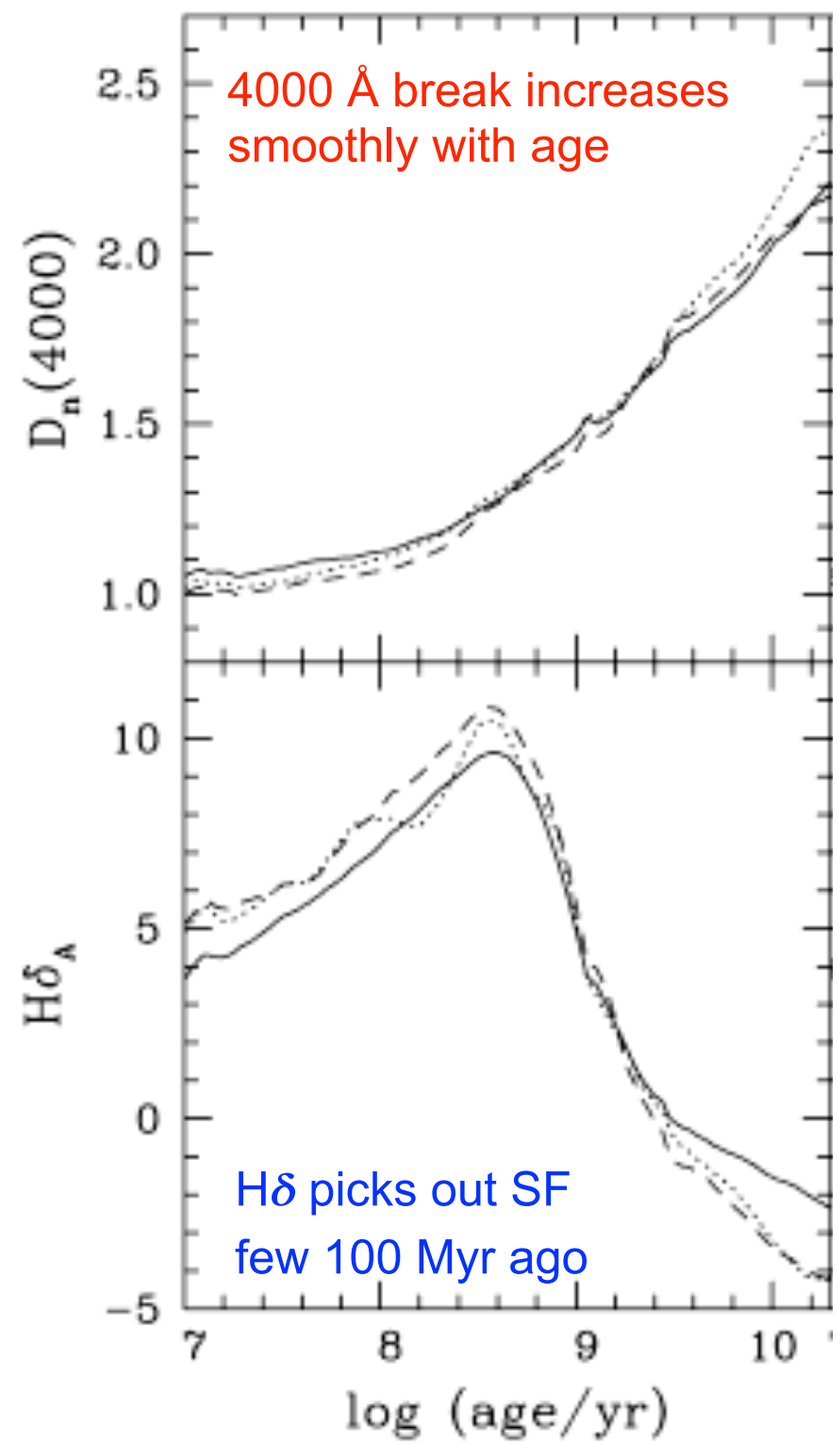


Recall that some of the scatter in the colour-M/L relation is due to late bursts, i.e. additional SF within past ~Gyr which lowers M/L more than expected from its effect on the colour.

To improve accuracy, want an indicator that is sensitive to this recent SF...

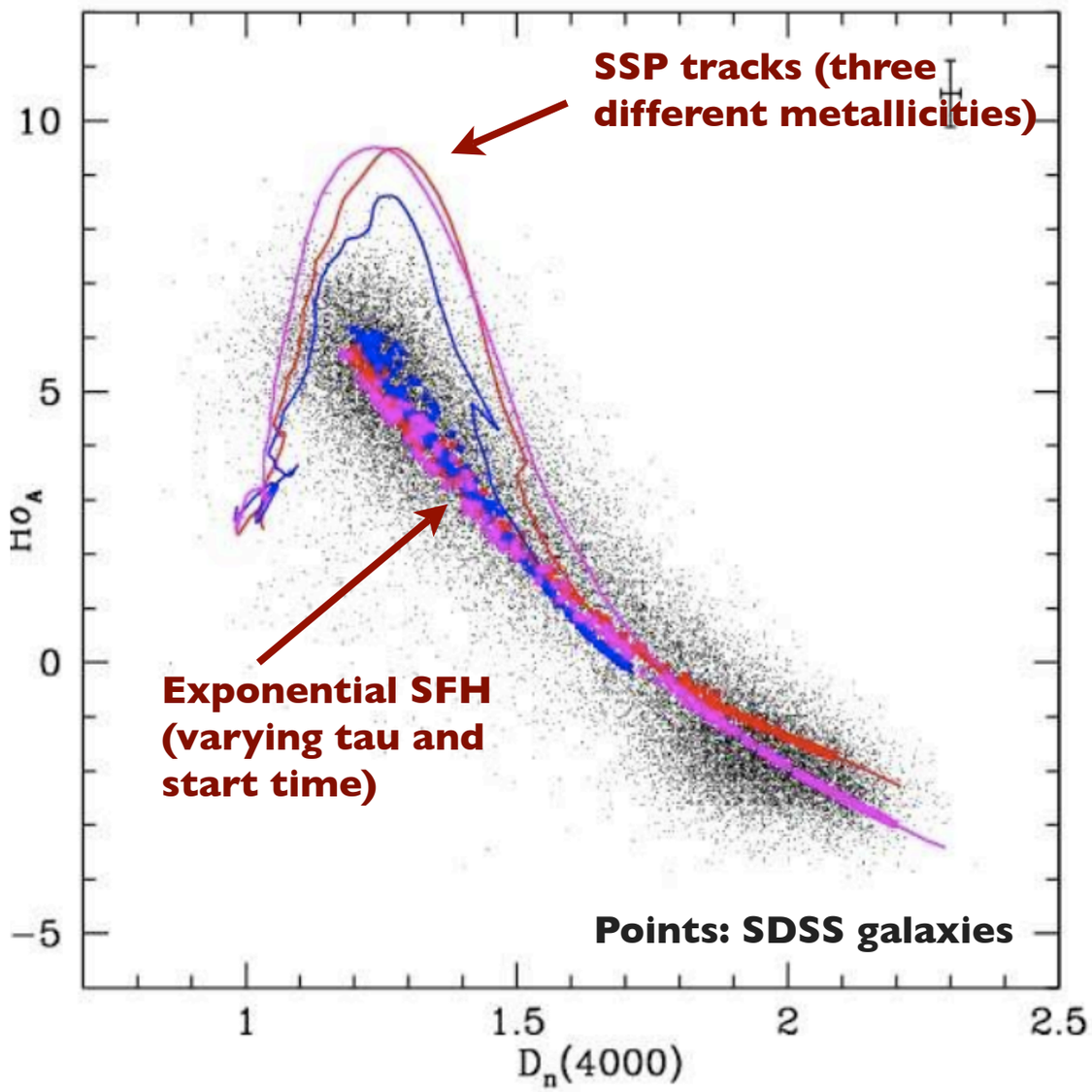
Approach taken by Kauffmann et al. (2003) focusses on specific spectral features: 4000Å break and an index measuring the Hδ line.

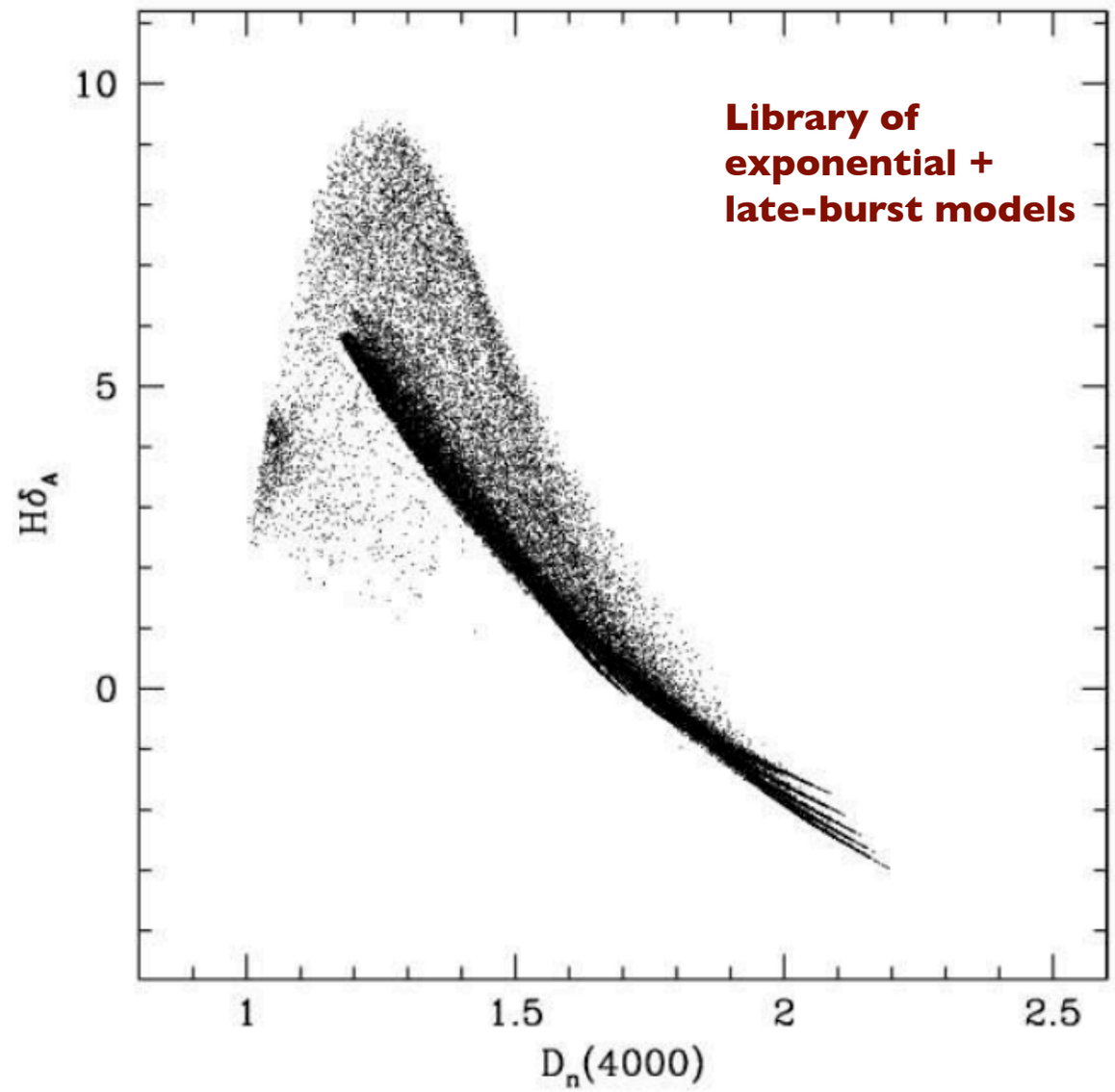
Feature behaviour in SSPs



Stellar masses from spectroscopy

Kauffmann et al. 2003





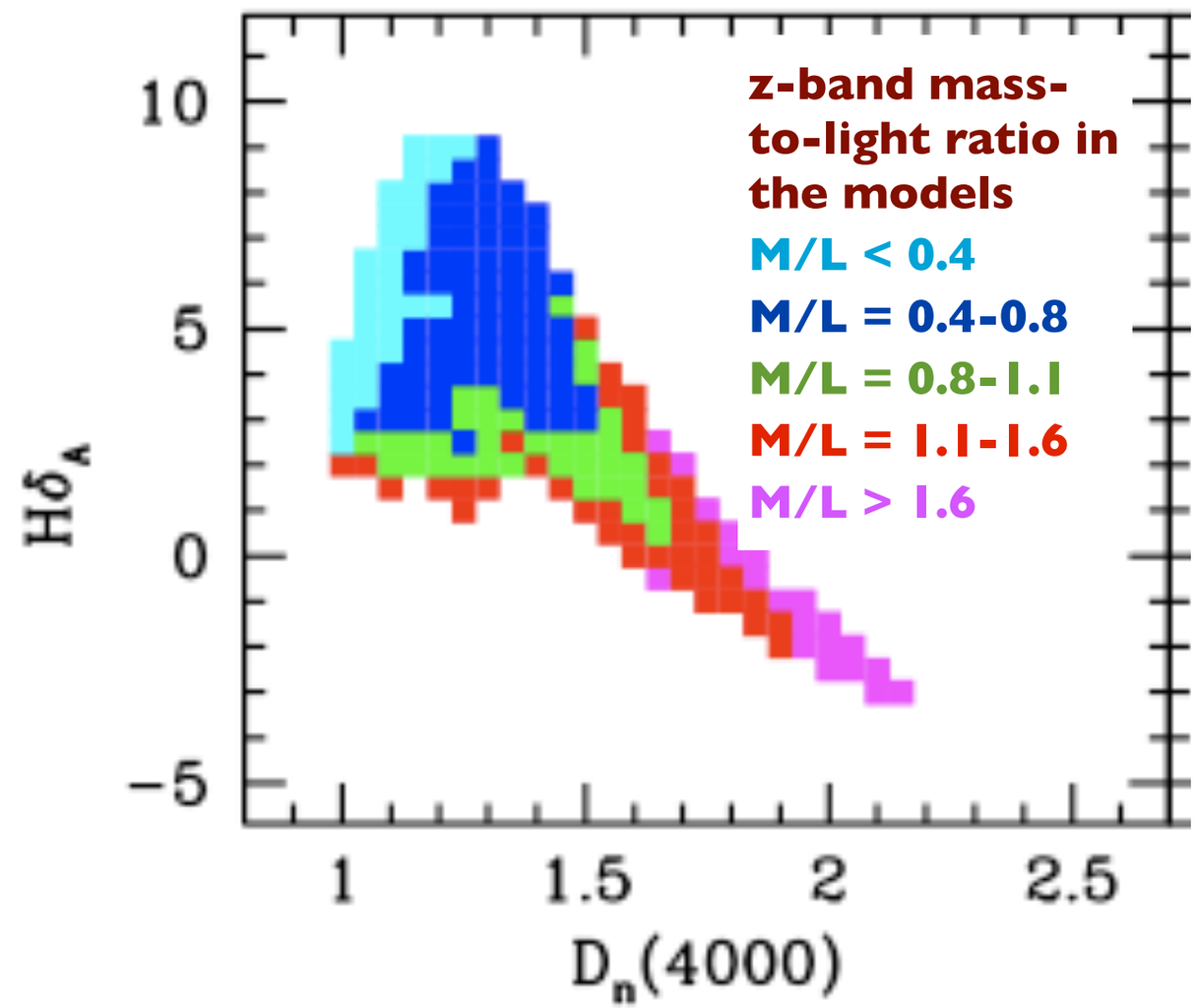
Note the galaxies mostly sit along the exponential models, with bimodal (SF-vs-passive) distribution.

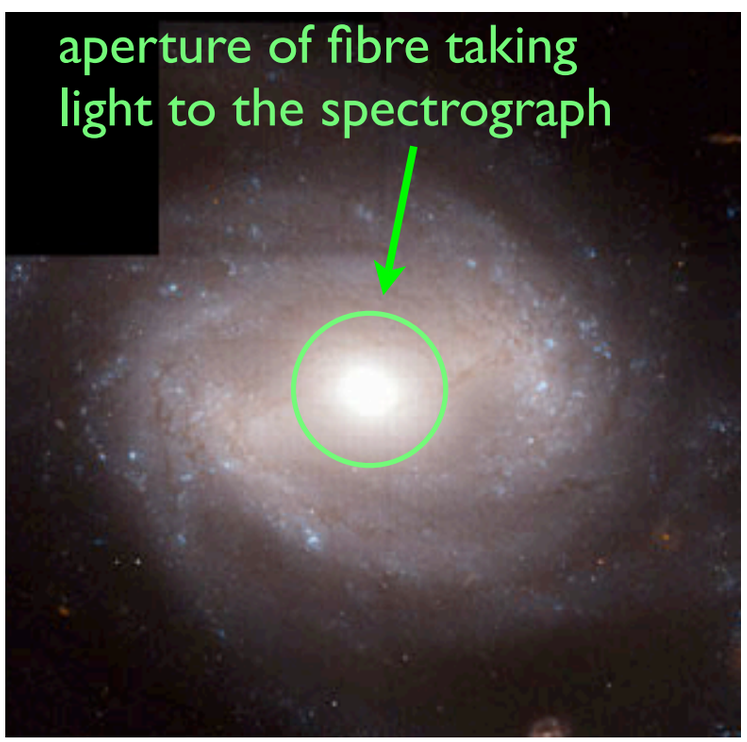
Stellar masses from spectroscopy

Assign to each galaxy the average M/L of the "models which match the index data".

As before, this will depend how we populated the model space.

Kauffmann et al. 2003





A concern about spectroscopic stellar masses: Is the spectrum representative of the whole galaxy?

Luminosity is measured from whole galaxy, but $(M/L)_{spec}$ generally only from the central part...

Non-parametric SFH from FSF

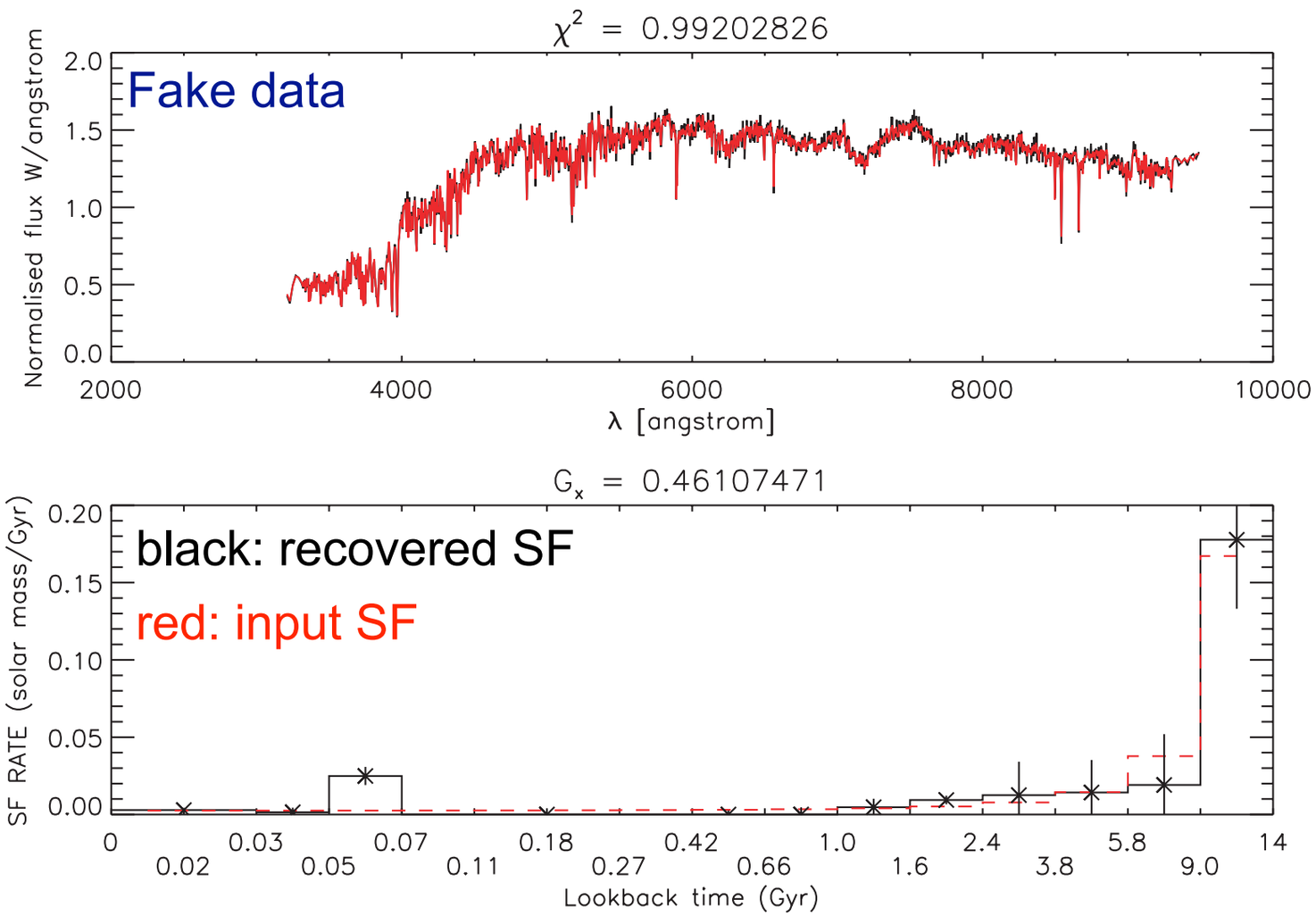
Real galaxies probably don't respect our SFH parameterisations (SSP, exponential, expon+bursts, etc).

Various codes exist to fit "binned" SFHs using full spectral fitting (MOPED, VESPA, ULYSS).

Can use such methods to derive M/L and also the SFHs.

But typically need high S/N to constrain many components.

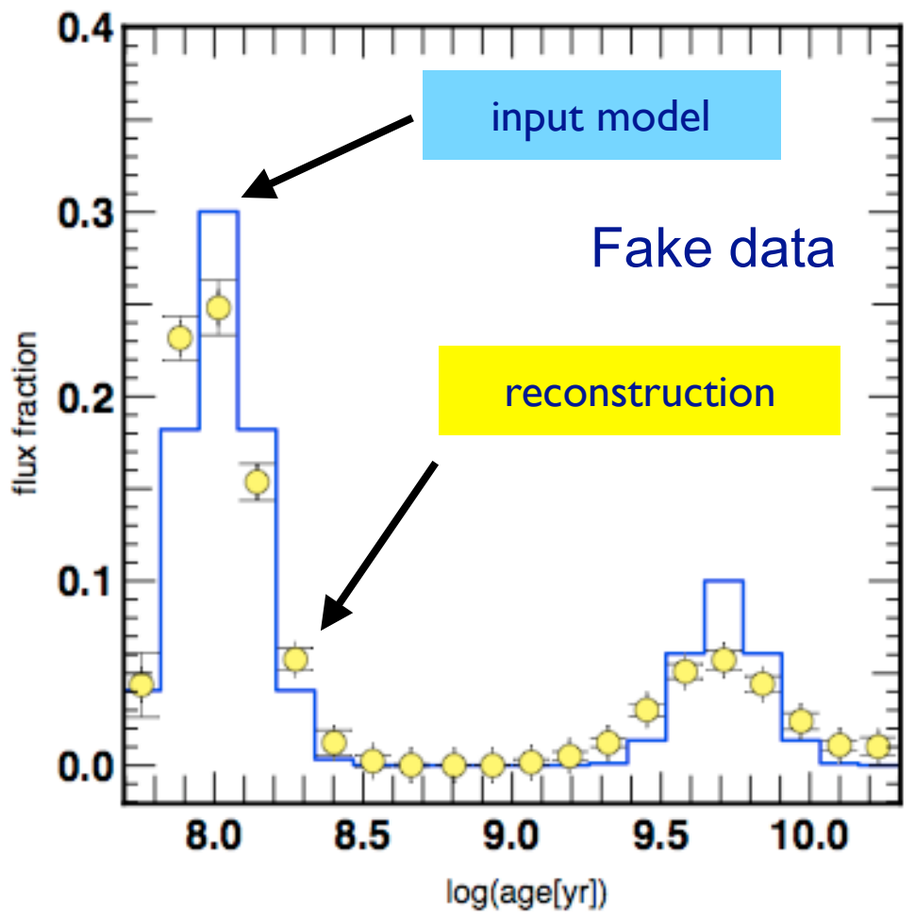
"VESPA" Tojeiro et al. 2007



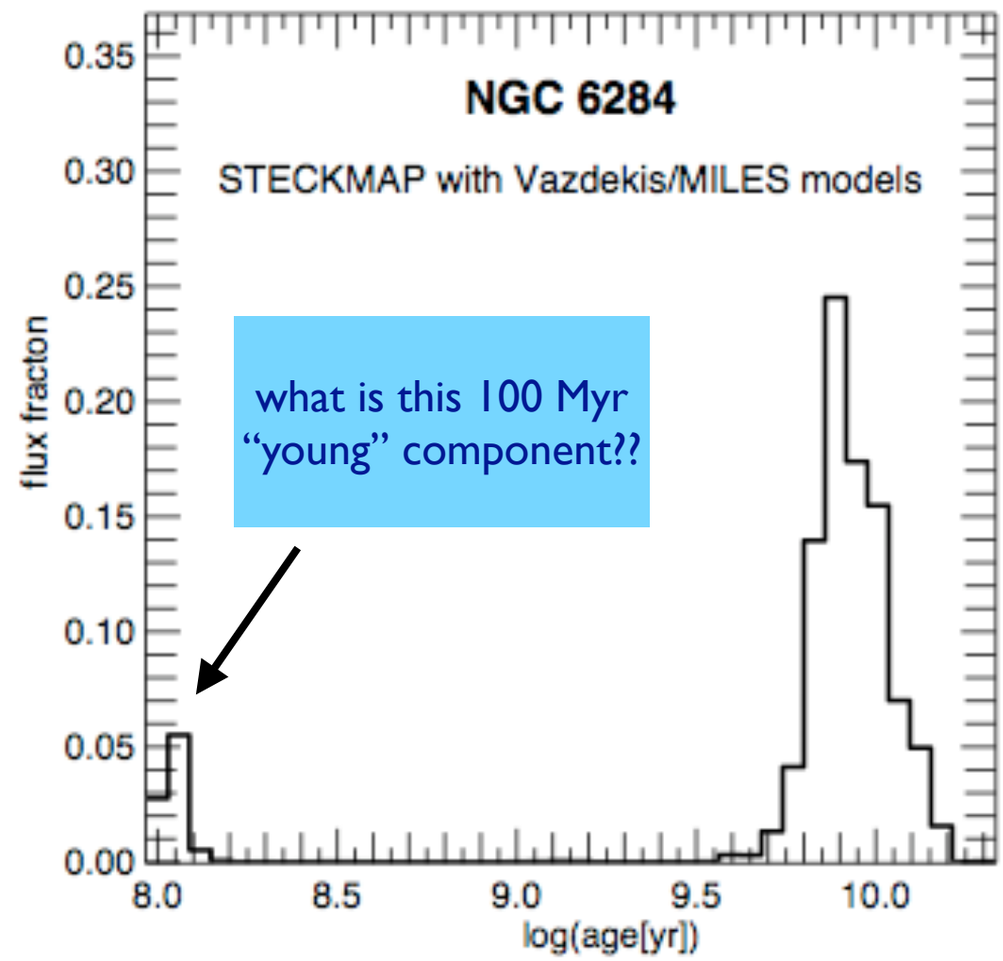
(An attractive feature of the VESPA method is adaptively tuning the time binning to match information content of spectrum)

Non-parametric SFH from FSF

"Steckmap" - Ocvirk et al. 2006



Koleva et al. (2007)



As always, still dependent on model ingredients, and intelligent interpretation.

Applied to a globular cluster NGC 6284, Steckmap recovers a "young" component which is actually fitting the old (but hot) blue horizontal branch stars.

Closing reflections

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. Most light in the rest-frame optical comes from fairly well understood stellar evolutionary phases.

But we have to be watchful of stepping onto more shaky ground...

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

Evidence for non-universal IMF seems to be building, but needs to be tested carefully. If necessary, how do we integrate this into galaxy formation models?

In some cases, confronting galaxy observations with models may tell us more about the stellar astrophysics than it does about galaxy evolution.