Stellar Populations - Lecture II

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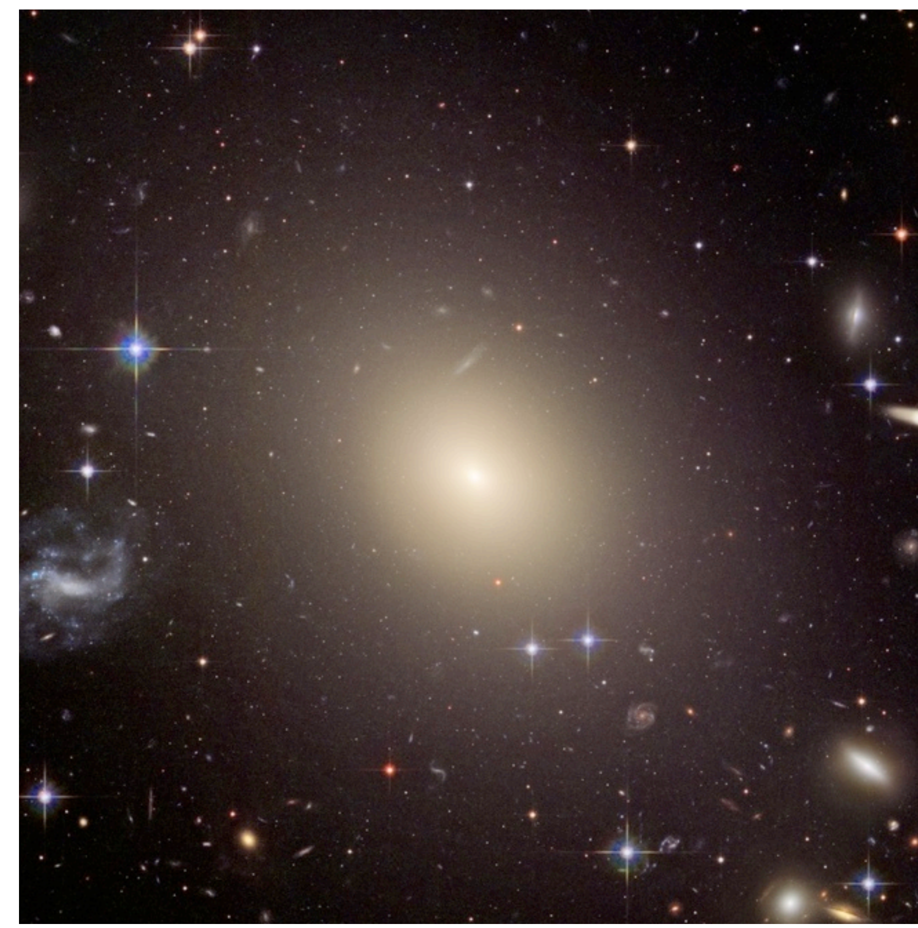
http://astro.dur.ac.uk/~rjsmith/stellarpops.html



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

    Stellar libraries

    Spectroscopic age/ metallicity indicators.

    IMF indicators

4. Applications

- Star-formation histories
- Stellar masses & photometric redshifts
- Chemical evolution.

Resolved stellar pops : summary

Review of stellar evolution.

Population model inputs: isochrones and initial mass function.

Observed cluster colour magnitude diagrams.

Isochrone fitting methods: ages, metallicities.

(We can learn a lot from this kind of data, if we can get it.)

More complicated cases & exotica.

(Maybe more common than we would like to think.)

Practical limitations.

(Resolved studies cannot fairly sample the population of galaxies.)

To go beyond the resolved populations in and near the LG, we need to understand how to learn from **unresolved** stellar pops.

Unresolved populations

Our aim is to learn about galaxies!

Specifically to "measure" their stellar ages and metallicities (or more generally SFH and MDF).

When we can measure fluxes for individual stars over a large luminosity range, the information content of the CMD is vast: star-formation rate as function of time, chemical abundance information, etc.

But of $\sim 10^{10}$ galaxies in the universe, only $\sim 10^{1-2}$ are resolved...

(And those that *are* resolved are not a fair sample of the universe - no giant ellipticals.)

So what about the rest?

What do we do when we can't see the individual stars?

Building galaxies from stars?

Even unresolved galaxies are made of stars.

So if we know the properties of their stars

- i.e. if their stars are similar to MW stars
- or their stars can be modelled from first principles

then we can “add up the stars” to build a model, and test this against the properties of an observed galaxy.

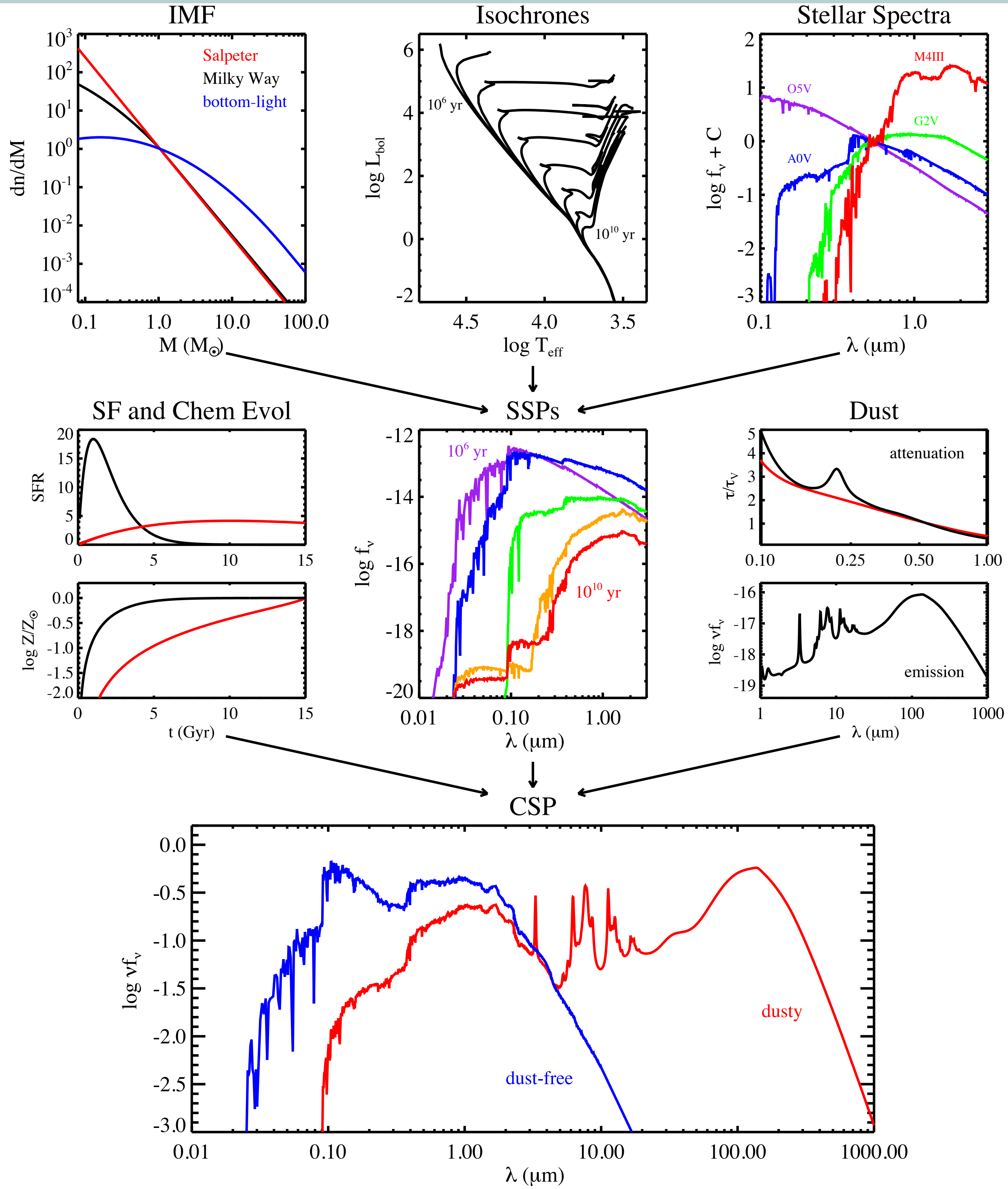
Early spectral synthesis models attempted to do just that: combine individual stars in varying proportion to match observed spectrum of a galaxy...

... but such models hugely under-constrained, as well as quite uninformative.

Building galaxies from SSPs

Modern methods take advantage of the “fundamental principle of stellar populations”: regularity in stellar content.

Instead of building unresolved galaxy from individual stars, use SSPs as the building blocks.



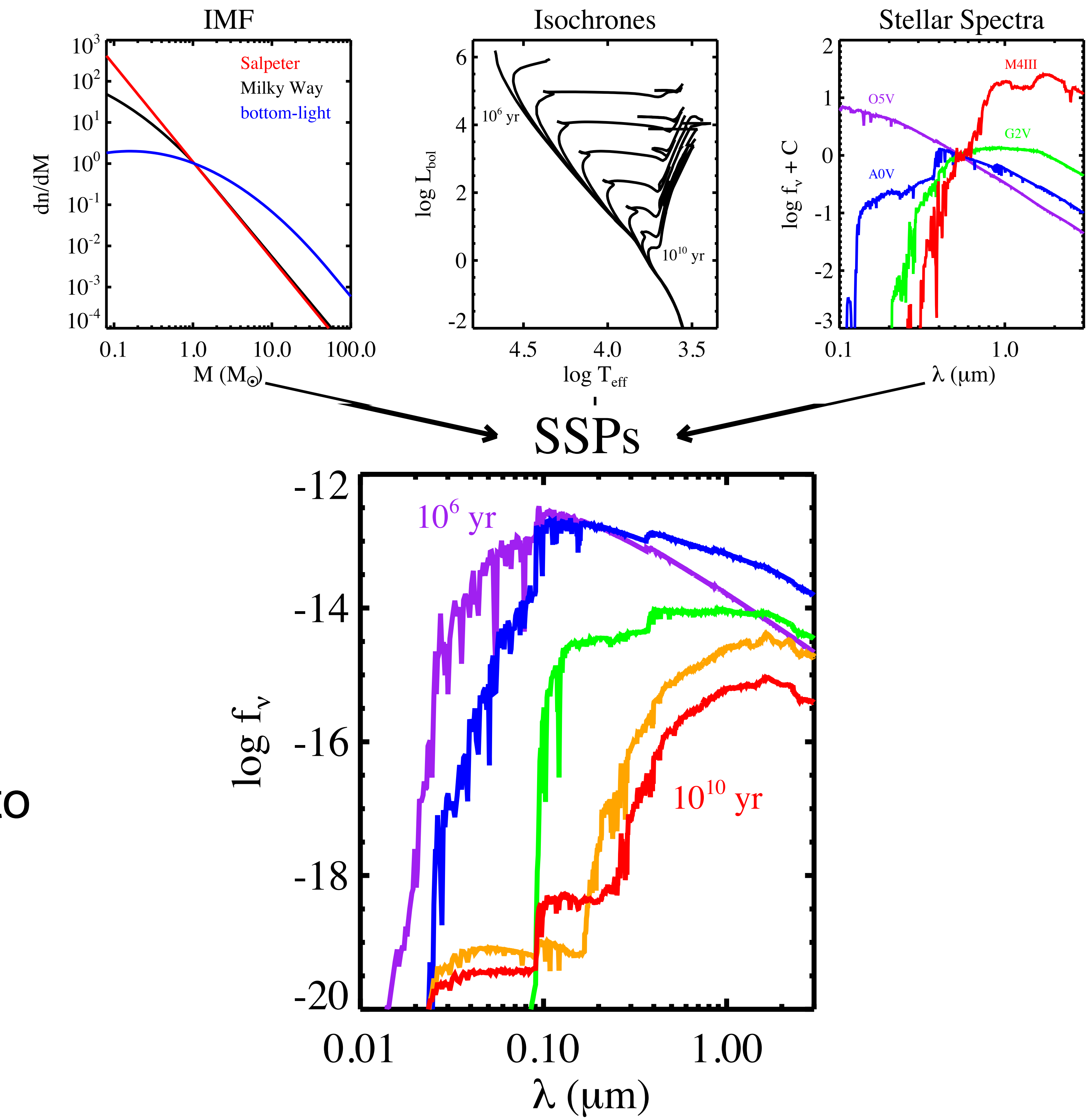
Spectral synthesis: SSPs

From ingredients:

- IMF
- isochrones
- stellar spectra,

we generate spectra of SSPs over range of age and metallicities.

Later, we can combine SSPs to generate composite stellar populations, and/or introduce effects of dust if necessary.



Conroy (2013)

SSP spectra: ingredients

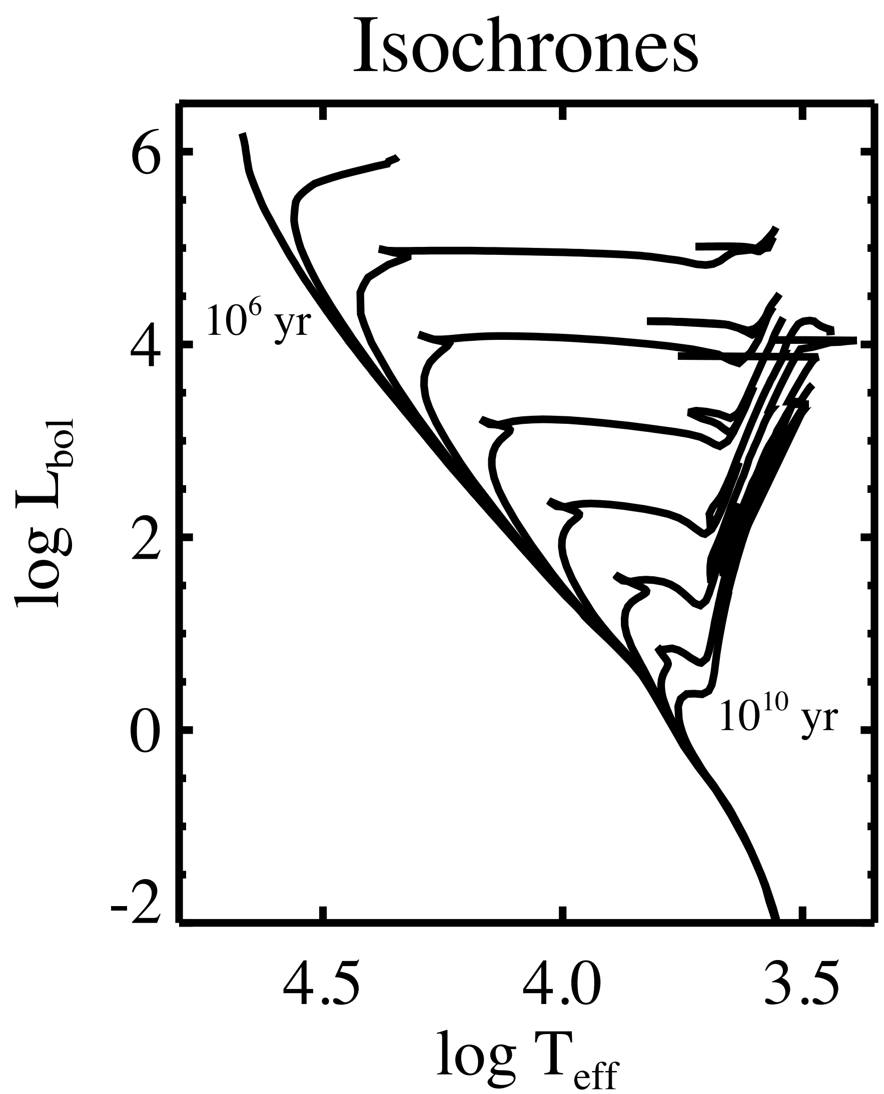
General principle:

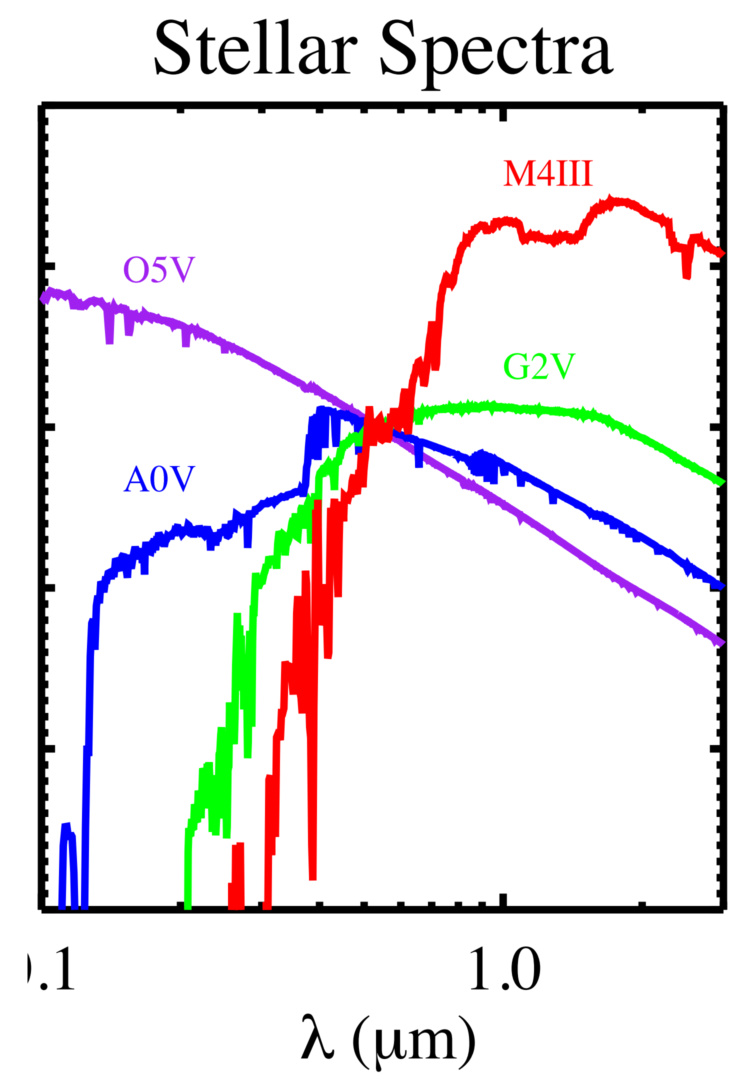
1) Assign a spectrum S_λ to each point on the isochrone.

[S_λ is physically determined by temperature, composition and surface gravity. Isochrone tells us which T_{eff} and Z to assign for each mass].

2) Sum spectra of stars, weighted by the IMF, N(M) along the isochrone.

Other approaches possible (e.g. "fuel consuption theorem" method - Renzini, Maraston)





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

Caveats

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

Conceptually simple, but many challenges in detailed application.

At a general level, we need to worry about:

* Are the isochrones correct, for stellar phases that contribute a lot of light?

* Do we have spectra for all the relevant phases / parameters that will be present in the galaxies we're going to model?

* Can we attach the right spectra to the right point on the isochrones (i.e. are the stellar parameters known)?

* Regimes of age/metallicity/wavelength where poorly-modelled stellar phases contribute a lot of flux.

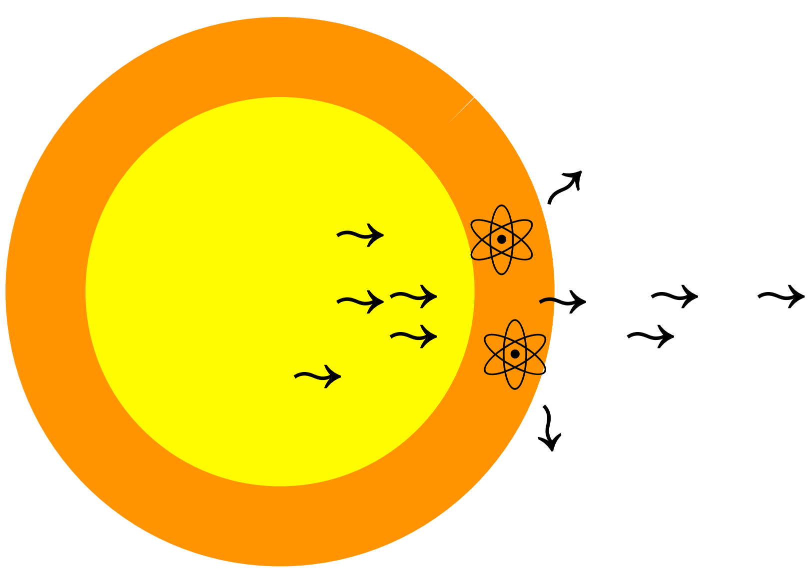
Stellar parameters: Temperature

Effective temperature T_{eff} : the dominant influence on stellar spectra.

Traditionally denoted by spectral type (OBAFGKM).

Continuum shape from black-body behaviour.

Modified by atomic/ molecular processes in the stellar atmosphere.



Peak in IR, strong molecular bands

Peak in red, metal lines and molecular bands

Peak in blue, atomic metal lines.

H-lines strongest

Peak in UV, all lines weak

TiO

4000A break

CH

Mgb

Ca H+K

H (Balmer series)

Balmer break

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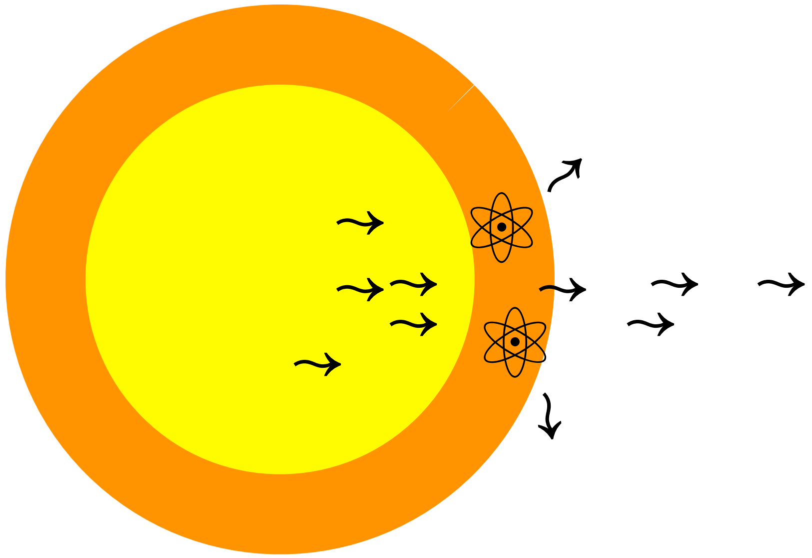

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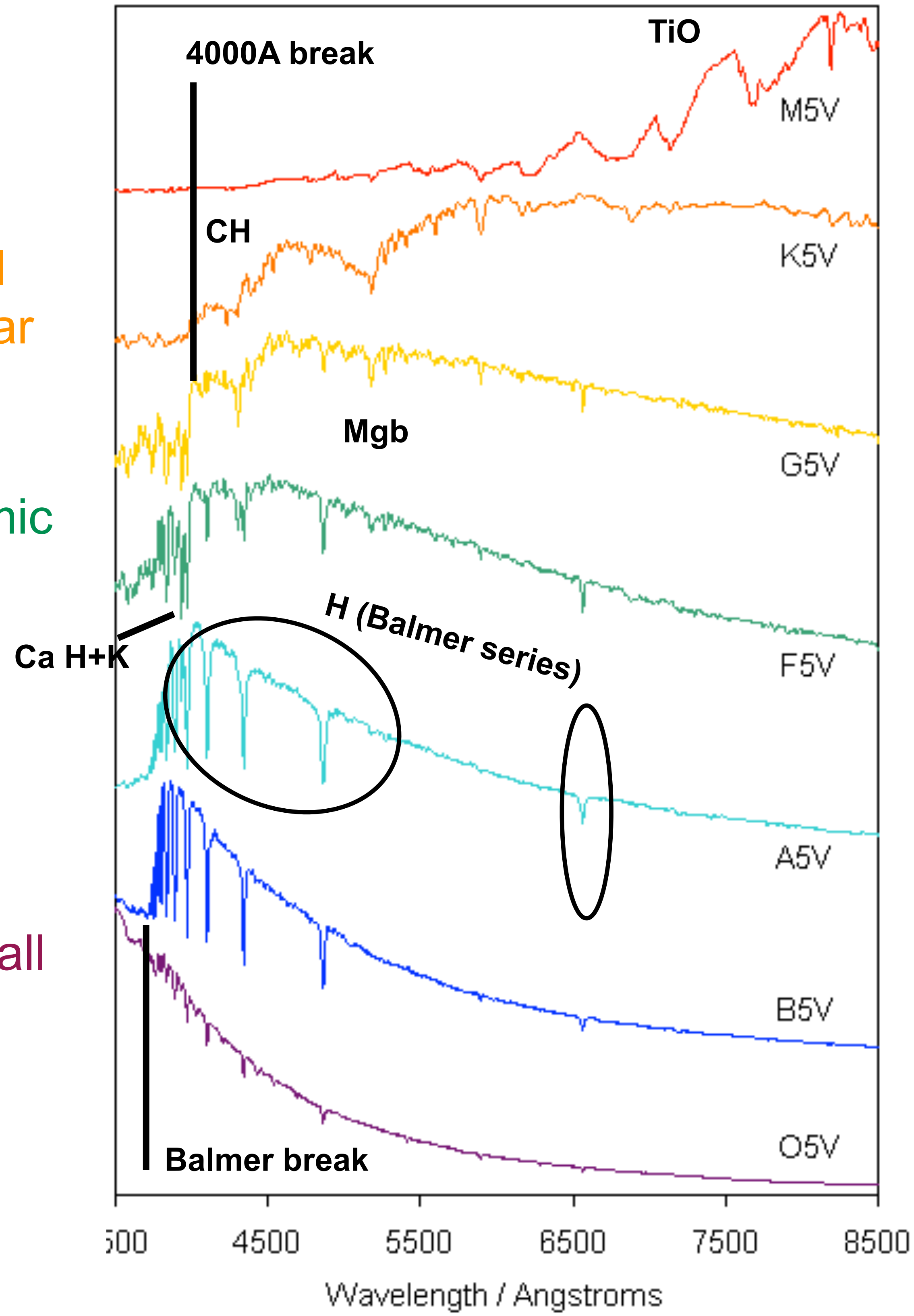


Metallicity effects

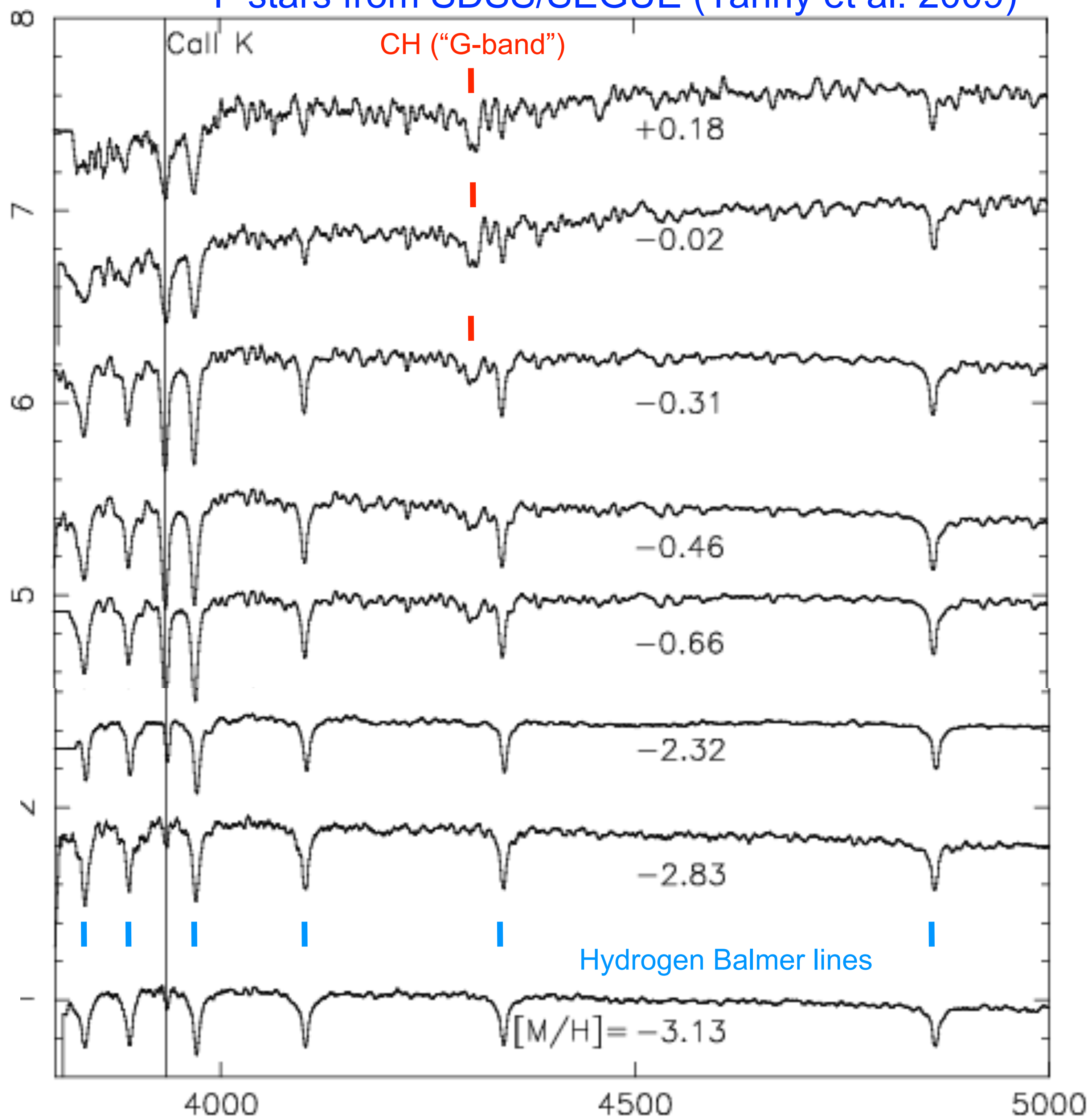
(1) Increasing metallicity shifts the isochrone to lower <u>temperature</u> (change in opacities in stellar interior).

The temperature effect changes the broad-band shape of the spectrum.

(2) Increasing metallicity increases absorption in atomic/molecular <u>transitions</u> in the atmosphere.

Line absorption affects narrow intervals for strong lines, but combined effect of many weak metal lines changes the broad-band shape too ("line-blanketing" strongest in the blue).

F stars from SDSS/SEGUE (Yanny et al. 2009)



Aside: what exactly is metallicity?

"METAL" CONTENT OF THE GAS THE STARS FORMED FROM

Core composition changes as the star evolves, but the surface layers reflect the original composition (at least until late evolutionary phases).

REMEMBER: ASTRONOMERS THINK OXYGEN IS A METAL....

When talking about the interiors of stars, modellers express chemical mixture of material as mass fractions:

X or H = <u>mass</u> fraction of H , Y = <u>mass</u> fraction of He

Z = <u>mass</u> fraction of everything else = "metals"

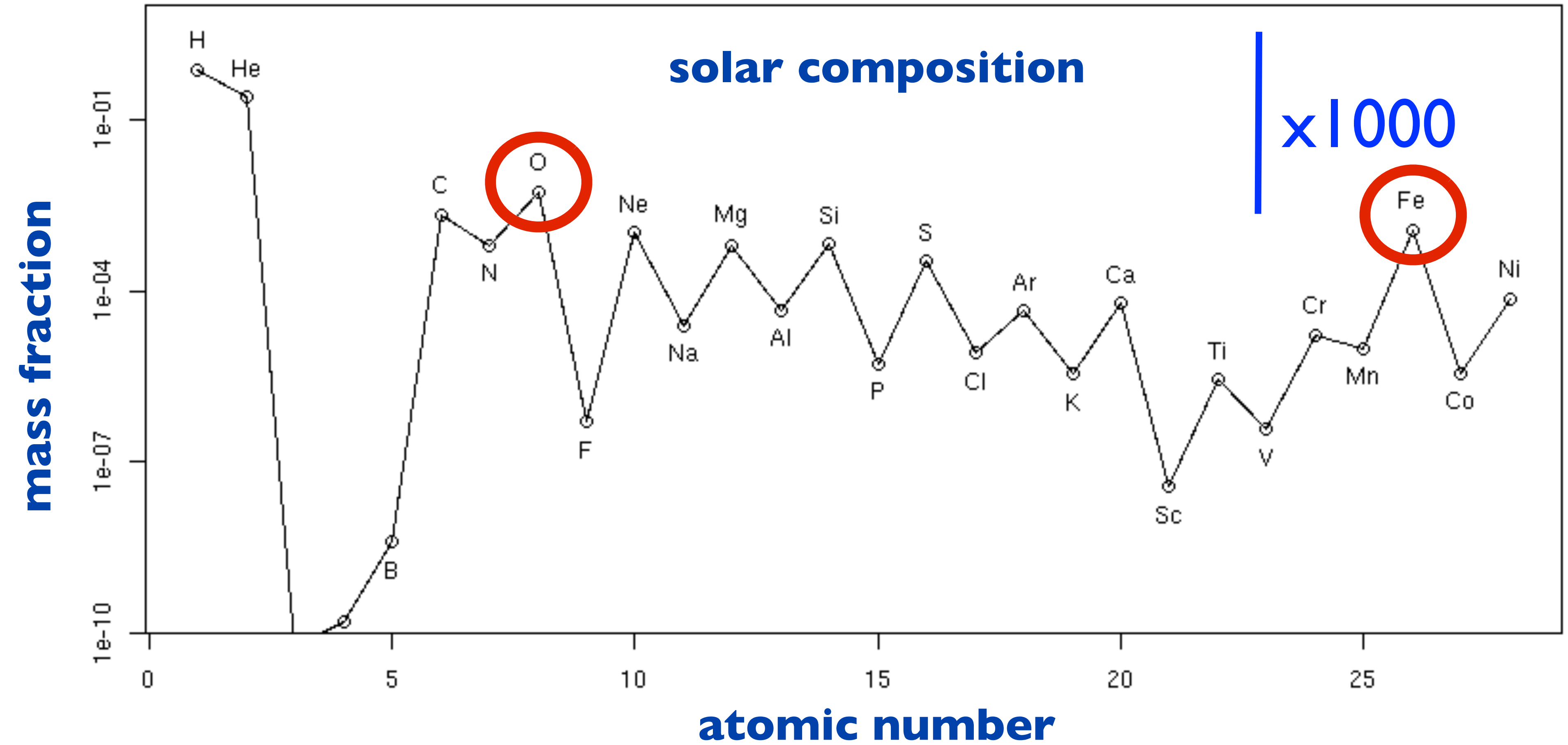
EMPIRICAL NOTATION

For measurements of metallicity in stellar atmospheres, we usually express abundances in terms of <u>number</u> density (not <u>mass</u> fractions).

Total metallicity is often expressed as $[Z/H] = \log_{10}(N_Z/N_H) - \log_{10}(N_Z/N_H)_{sun}$. Then:

[Z/H]=0 is solar metallicity, [Z/H]=+0.3 is twice-solar, [Z/H] = -1 is one tenth solar, &c.

Aside: what exactly is metallicity?



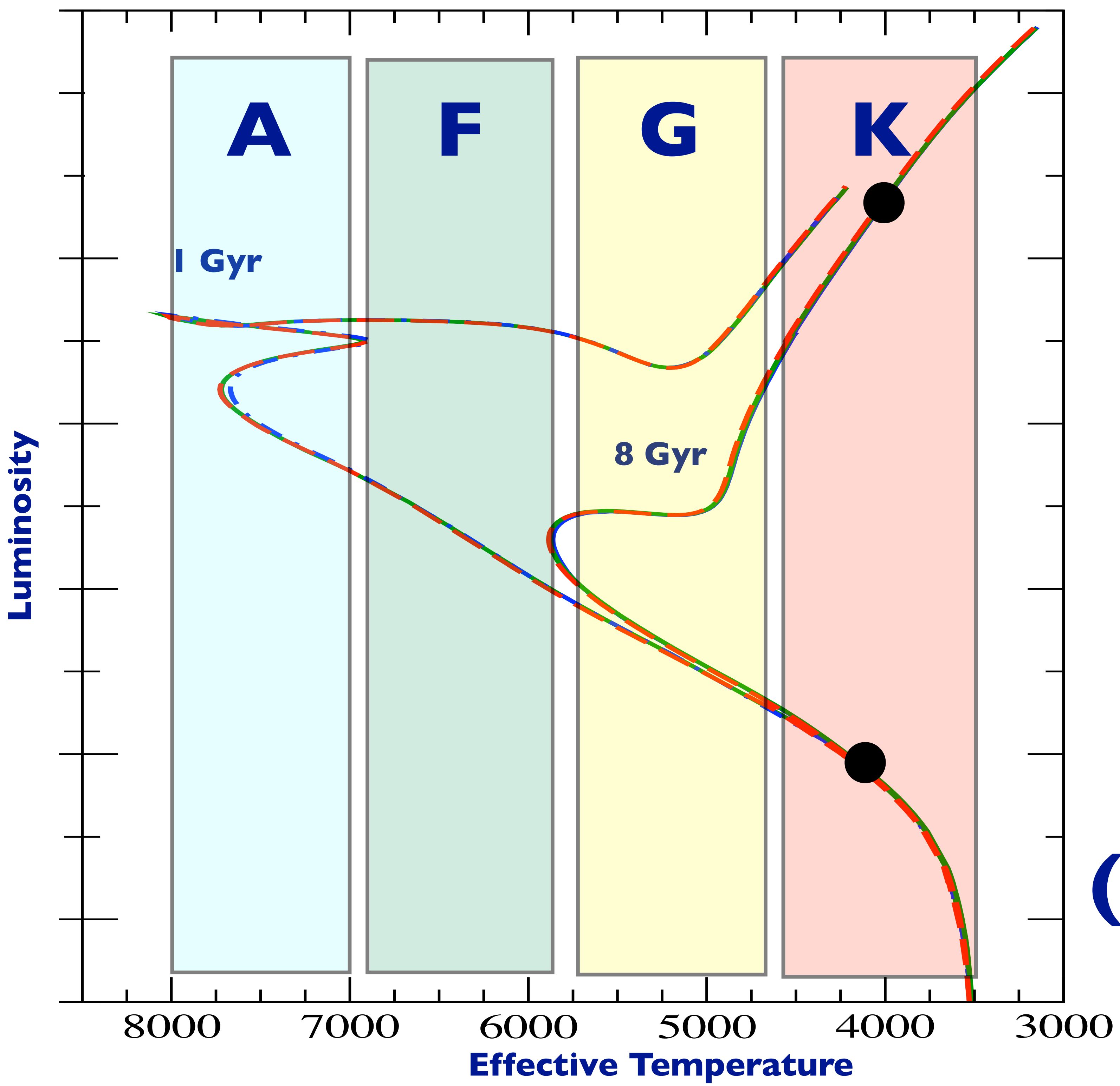
BUT WHAT IS COMPOSITION OF "Z" ?

Note that O is the most important element for stellar evolution: it is abundant and a big contributor to the opacities. Unfortunately it is hard to measure O from stellar spectra!

Much easier to measure Fe which has lots of absorption lines in the optical.

So we often talk about [Fe/H] instead. This is equivalent to [Z/H] or [O/H] if the abundance of all elements is varied proportionately (We'll come back to this...)

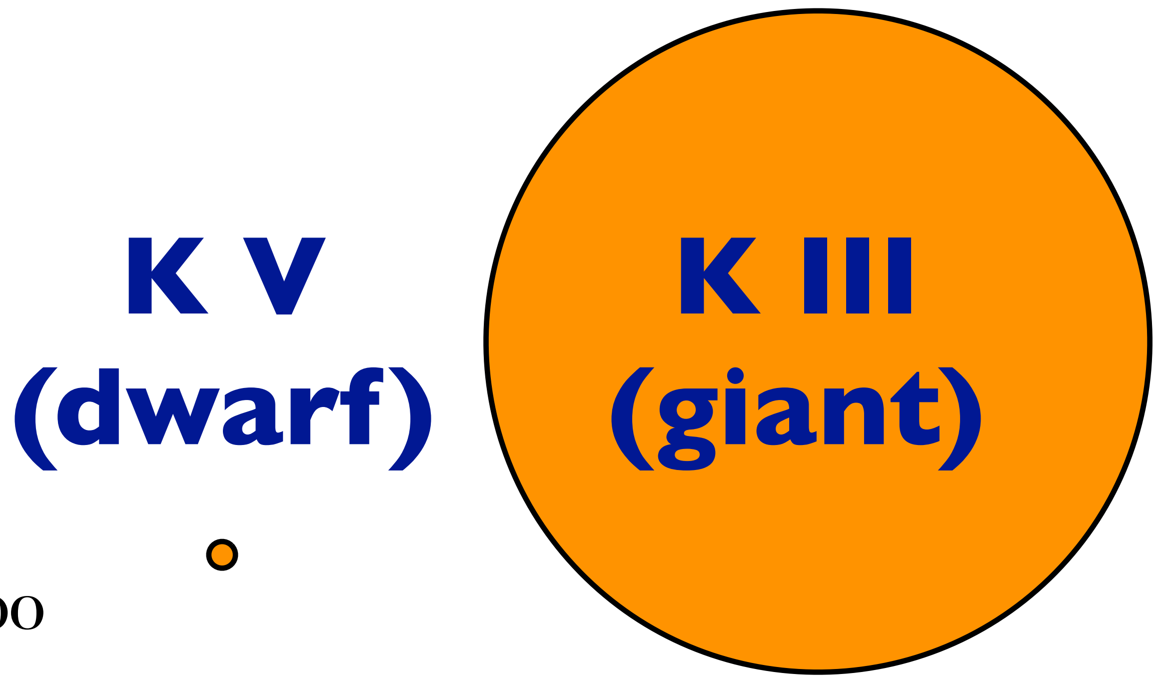
Gravity effects on spectra



Giants and dwarfs of same temperature and metallicity have similar mass (e.g. factor 2-3) but very different radius (e.g. factor 20-100)

Hence differ in their surface gravity / pressure.

Traditionally referred to through luminosity classes I-V.



Gravity effects on spectra

Affects balance between ionization states of atoms, and also the molecular equillibrium.

Prominent gravity indicators in IR:

Stronger in dwarfs:

- Wing-Ford band (FeH)

- Neutral alkali metal lines (Na, K)

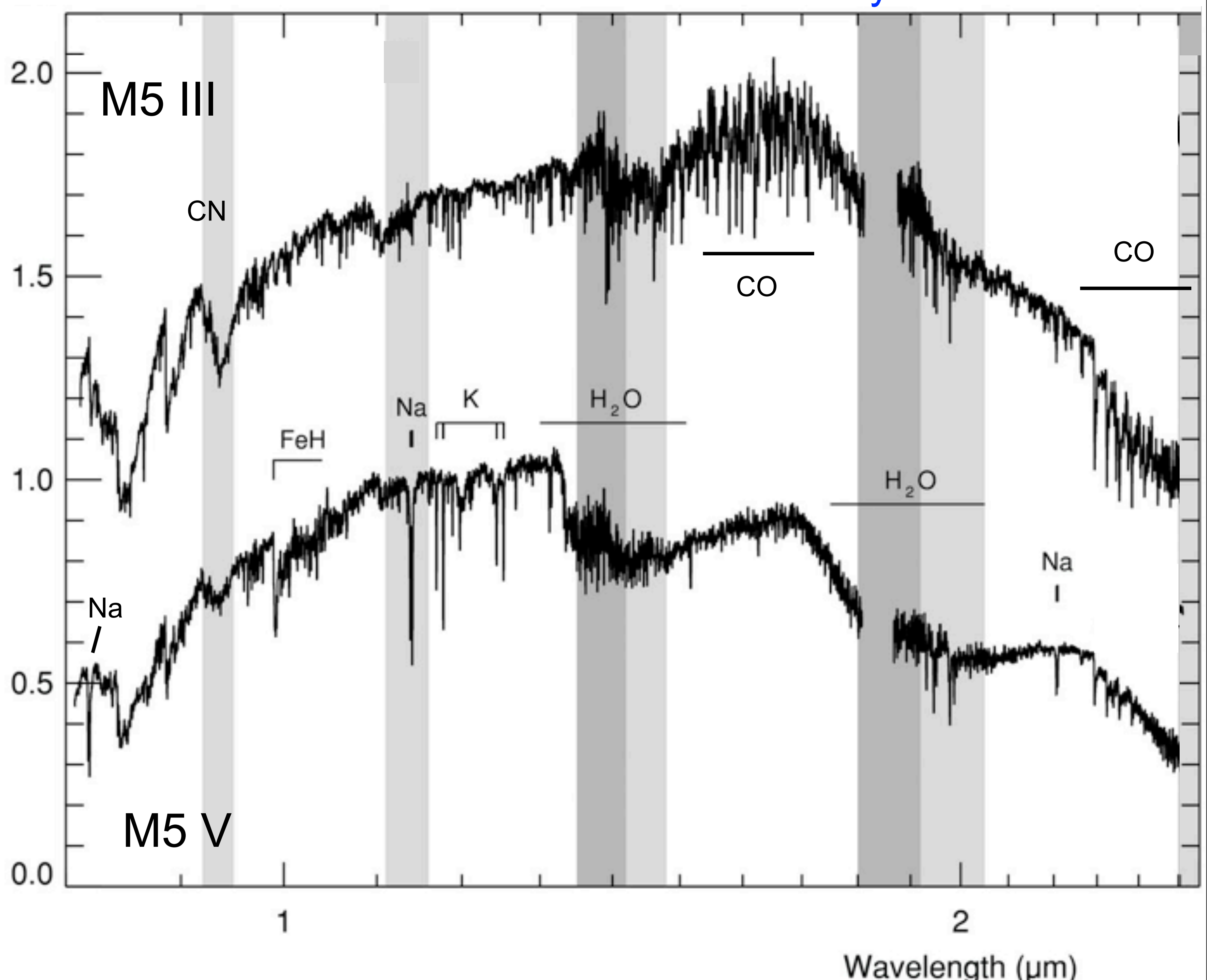
- Steam bands (hard to measure!)

Stronger in giants:

- CO and CN bands

- Ionized metal lines (Ca triplet - but not in M stars)

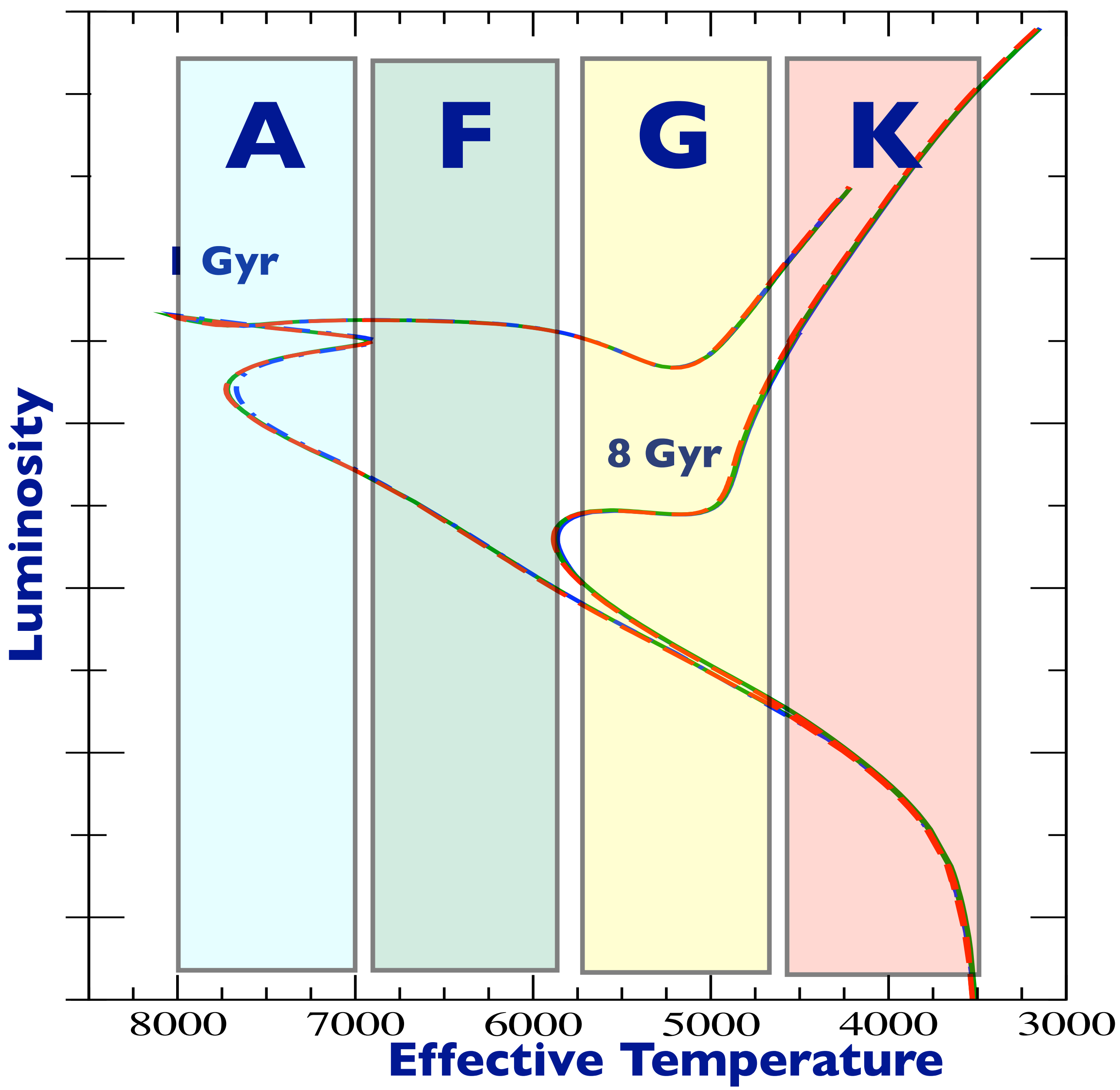
Rayner et al. 2009



Luminosity contributions and colours

For overall flux contributions and broad-band colours, can ignore details of the spectral features.

Transformation from L_{bol} to band luminosities: “bolometric corrections”

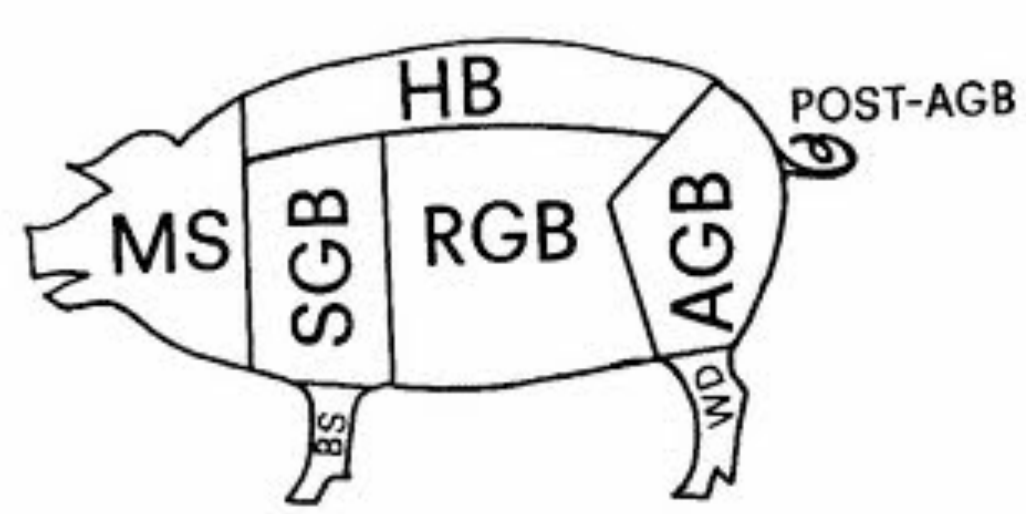


Most massive stars are few in number, but each is very luminous.

Low-mass stars are numerous, but individually very faint.

In fact, most of the integrated light comes from the more massive stars, but most of the mass in the is in the dwarfs!

Luminosity contributions: optical



Renzini (1986)

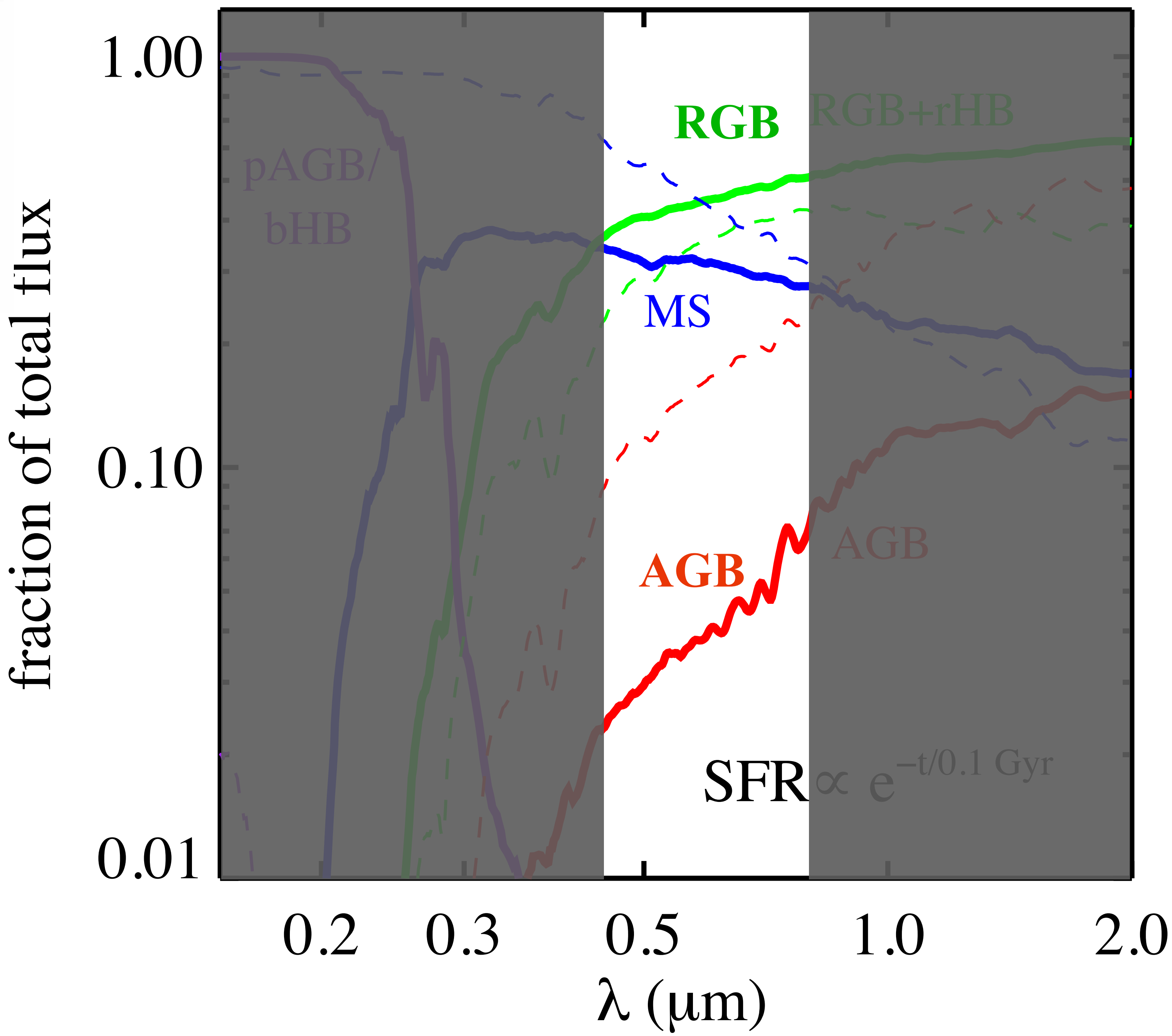
For old ages, solar metallcity, Chabrier IMF

Optical flux dominated by MS and RGB: the best understood phases.

(Balance to RGB in redder bands, MS in bluer.)

AGB at ~few per cent.

(solid lines: age=13 Gyr)



Conroy (2013)

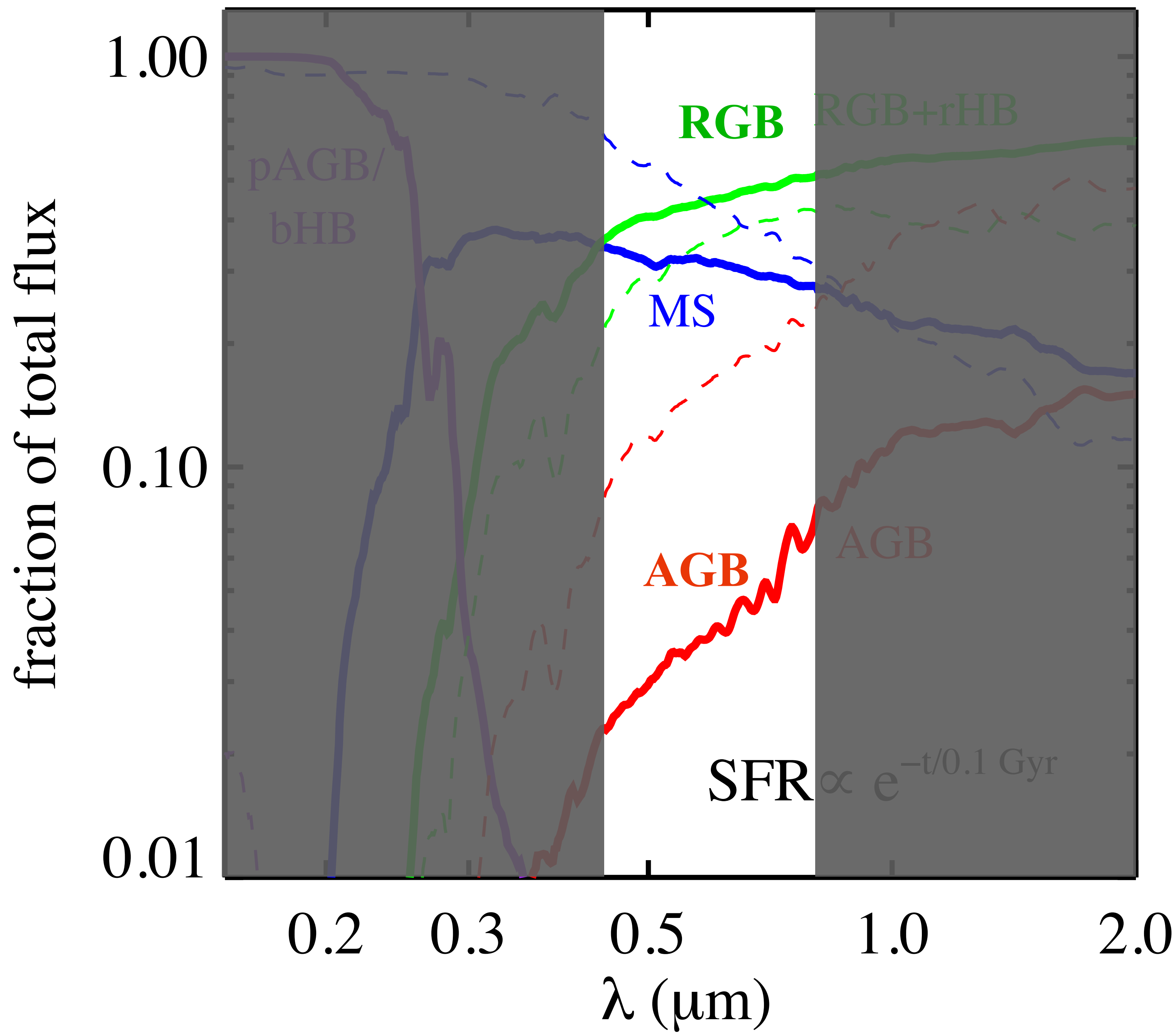
Luminosity contributions: UV-to-IR

Trends from optical continue into IR:

By K-band (2μm), RGB +AGB contributing ~80% of total flux.

In UV, new component from old-but-hot stars: post-AGB (central stars of planetary nebulae), blue HB stars.

NB this includes only the components *present* in the model...



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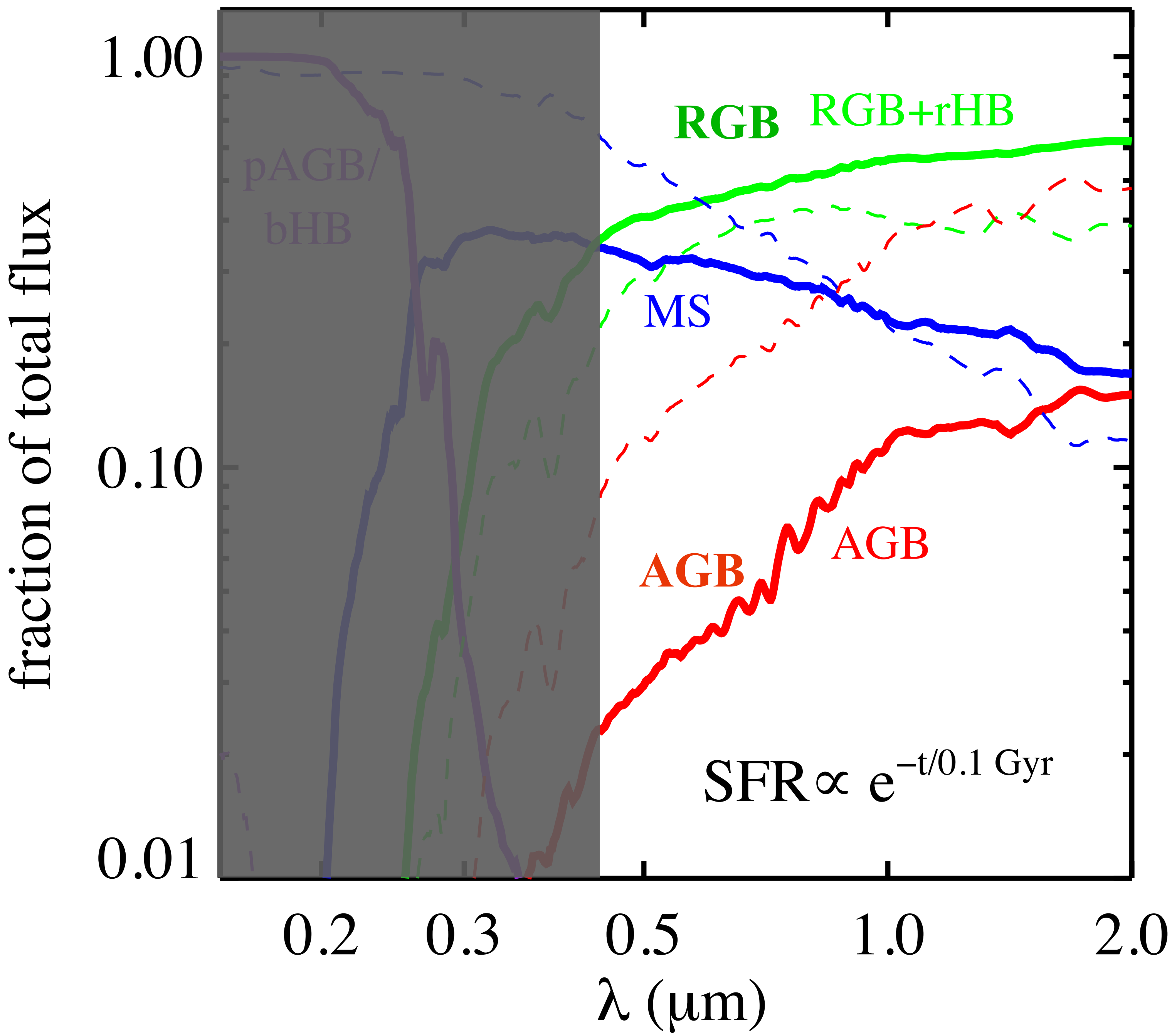

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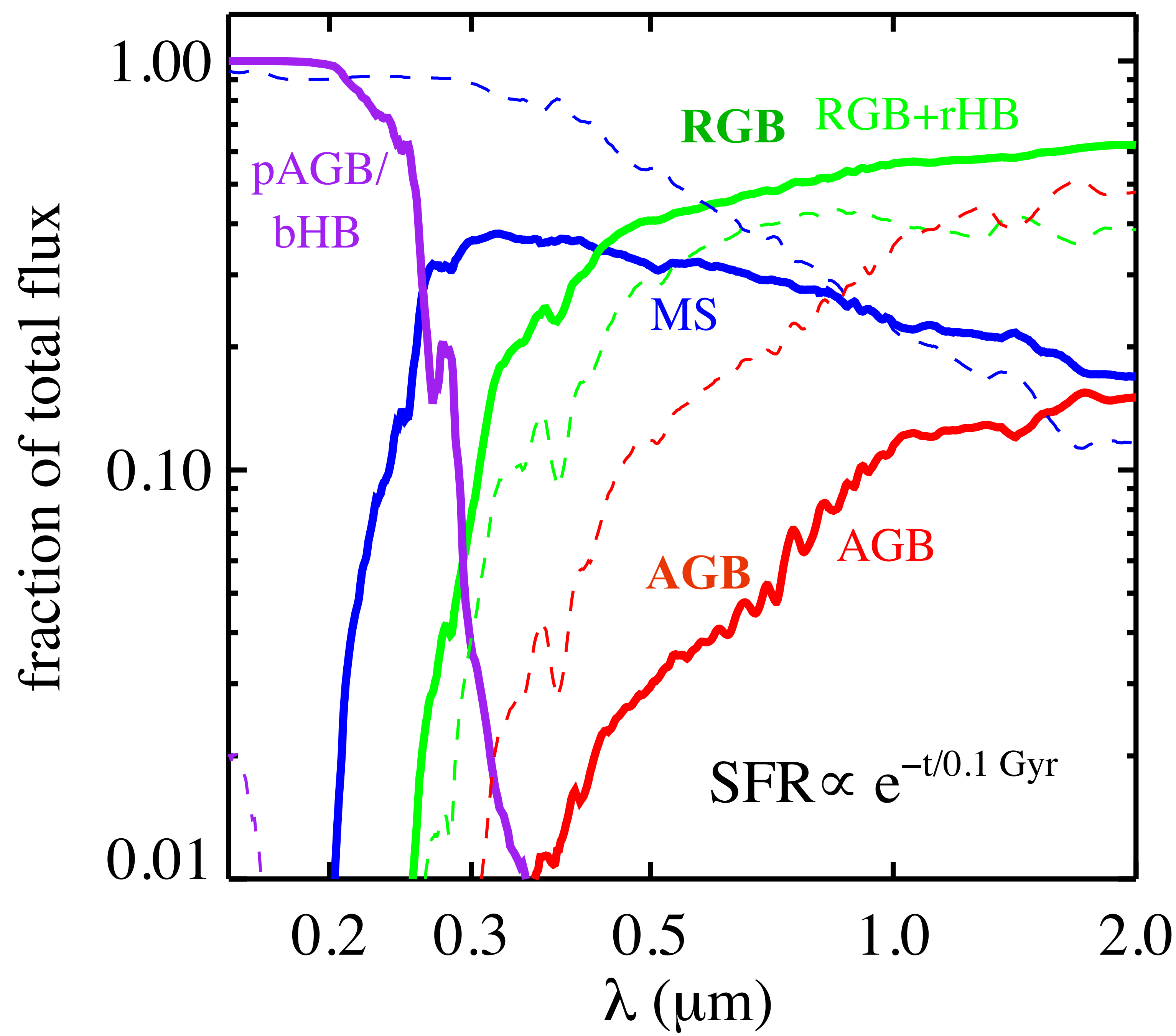
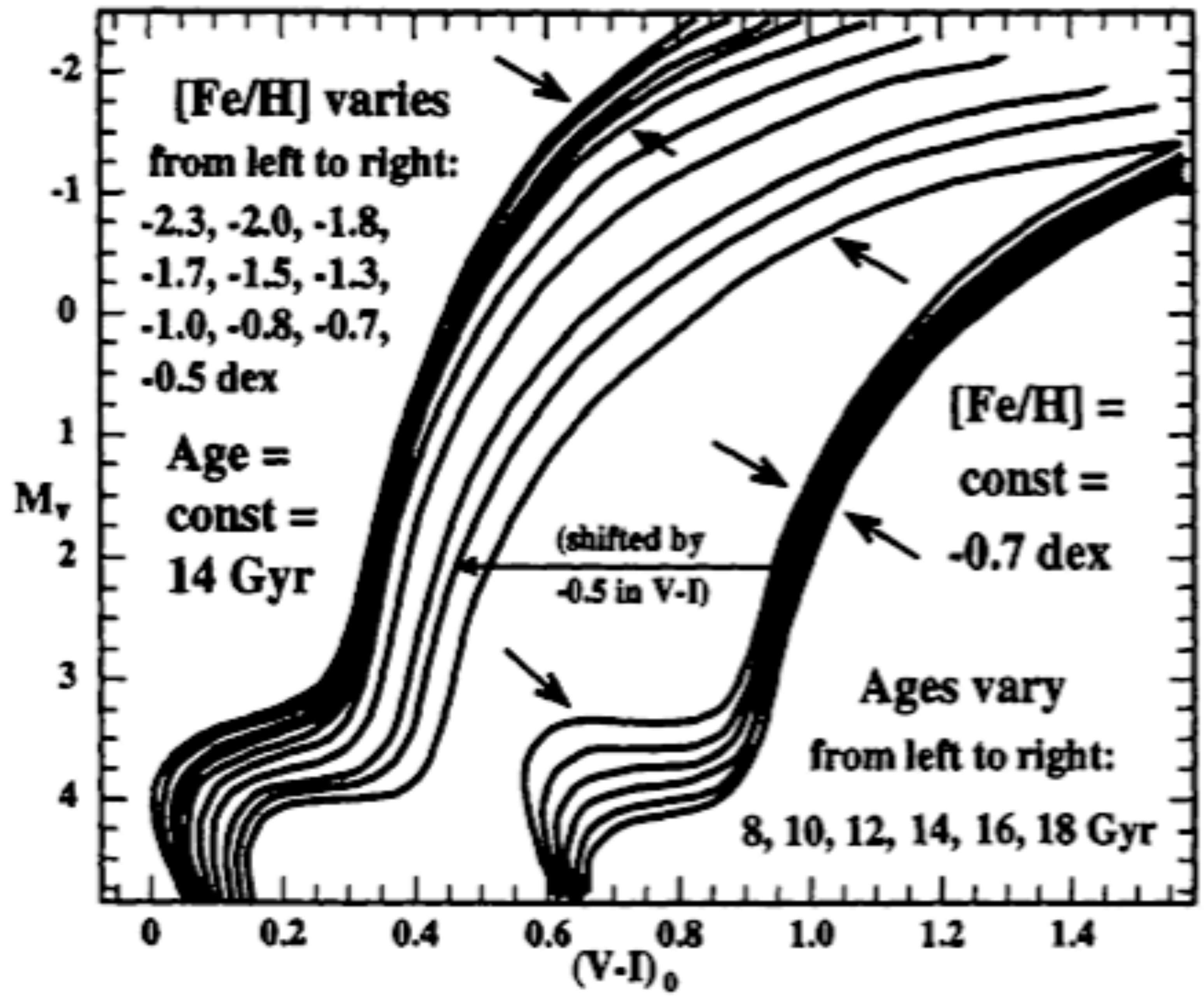


Conroy (2013)

Optical age-metallicity degeneracy

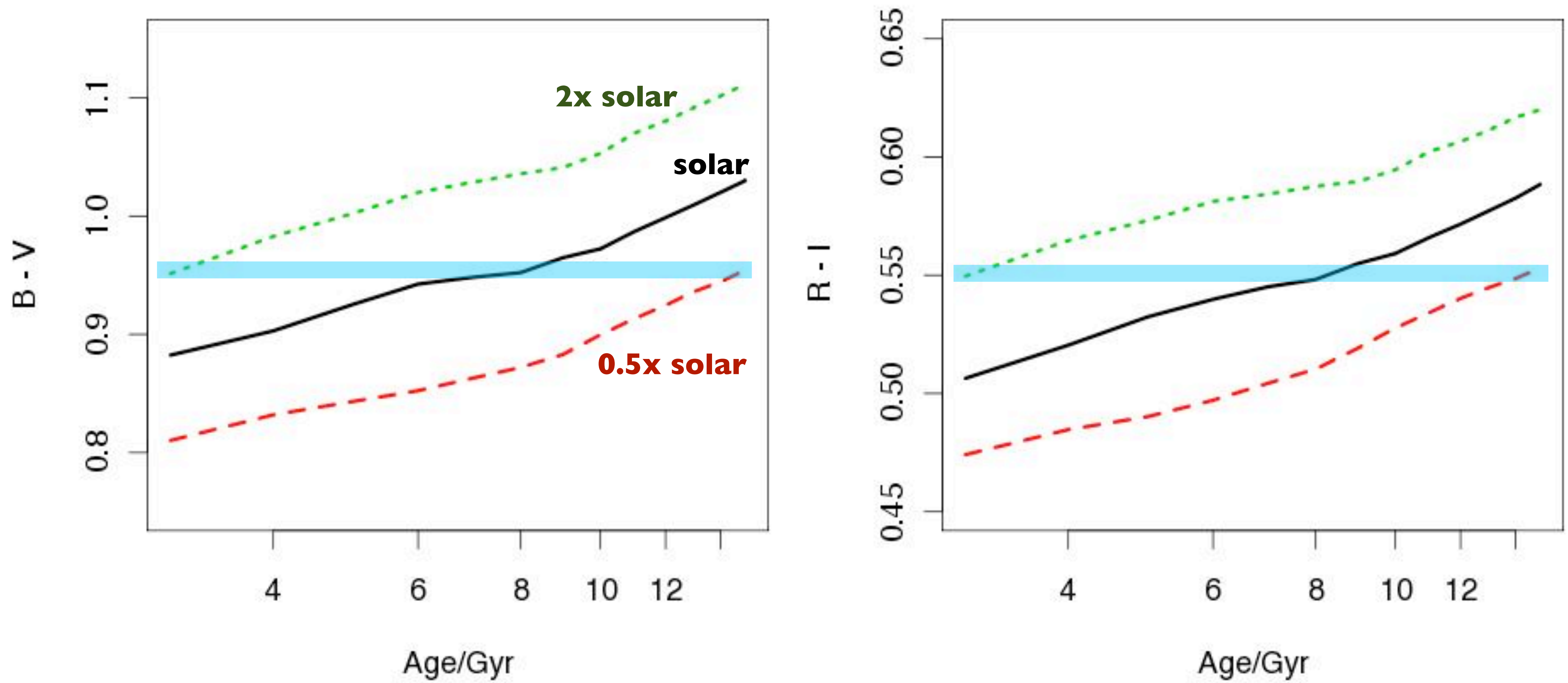
Classic problem in understanding "old-ish" populations like elliptical galaxies.

Because both age and metallicity cause the population to redden, a given measured colour doesn't distinguish an old-but-metal-poor vs young-but-metal-rich stellar population.



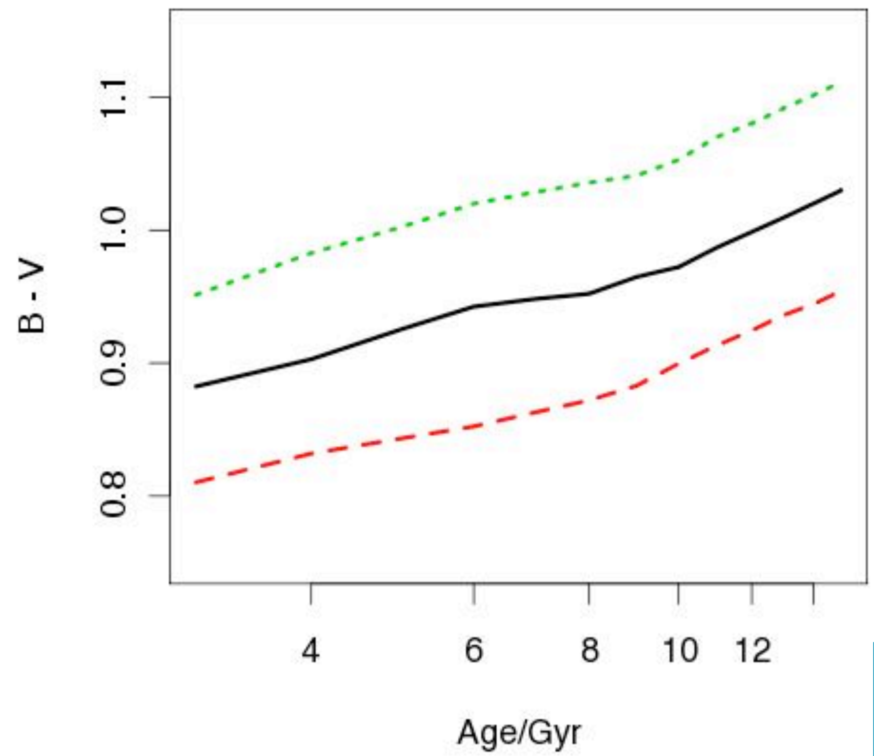
The age-metallicity degeneracy

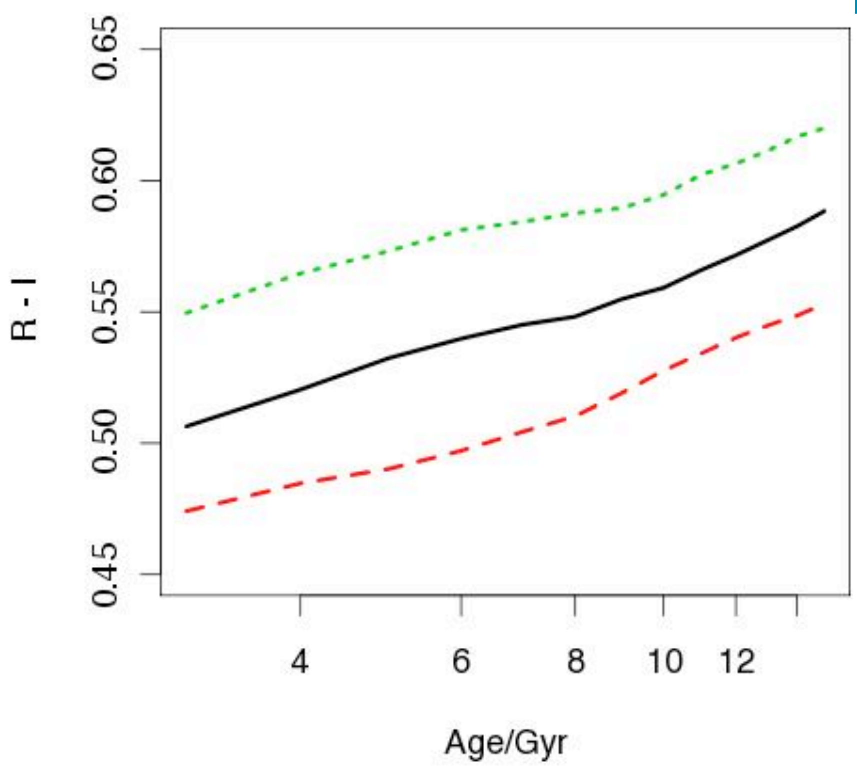
Models of Maraston (2005)

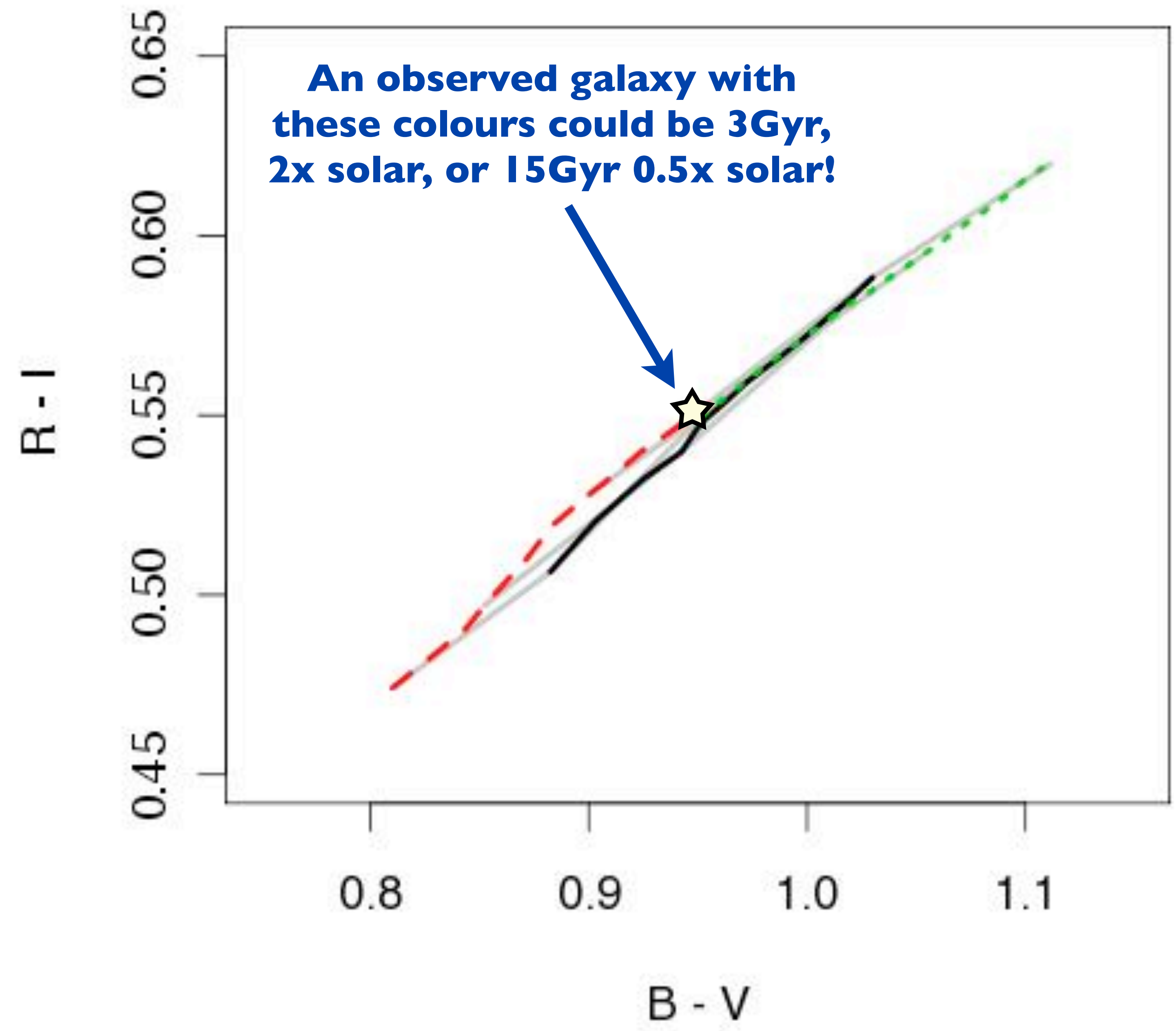


Because both age and metallicity cause the population to redden, a single measured colour is not enough to disentangle the parameters.

The age-metallicity degeneracy





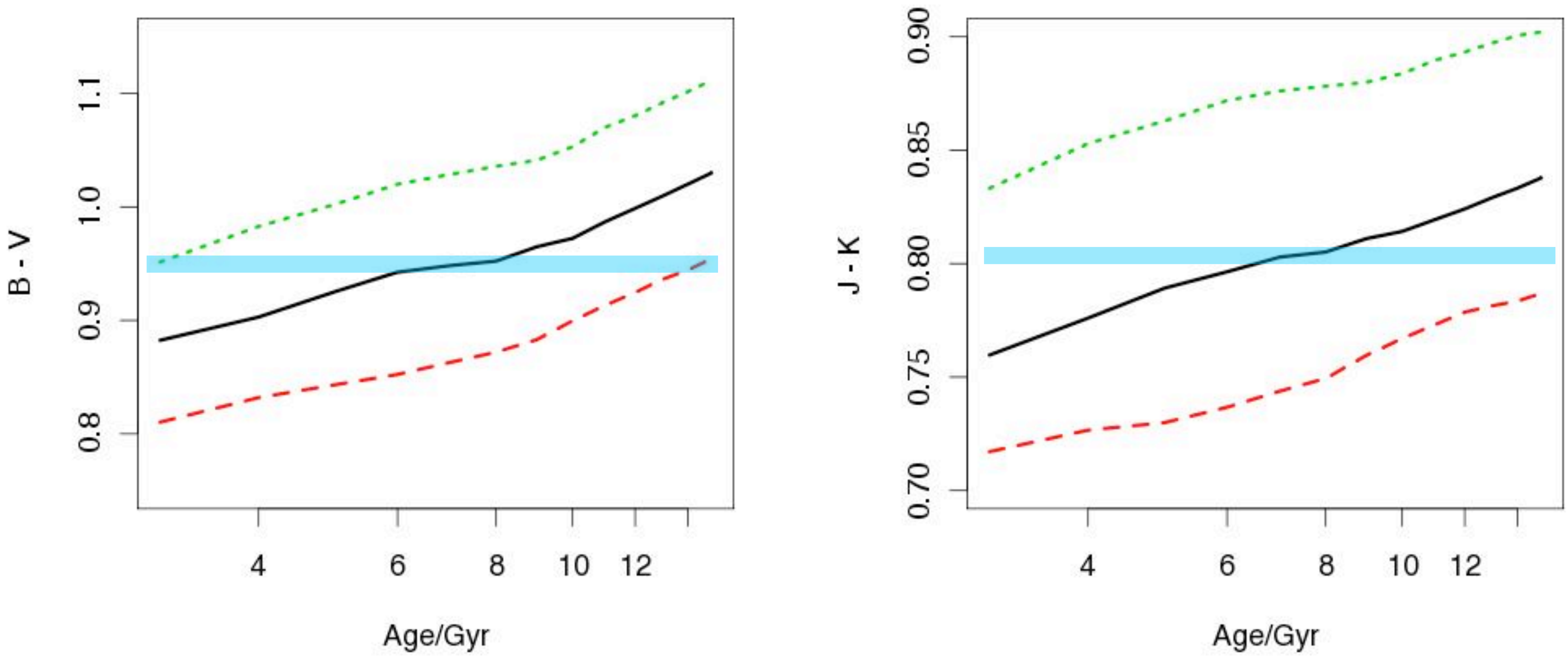


A pair of (optical) colours is no help either!

Beating the Age-Z degeneracy in the IR?

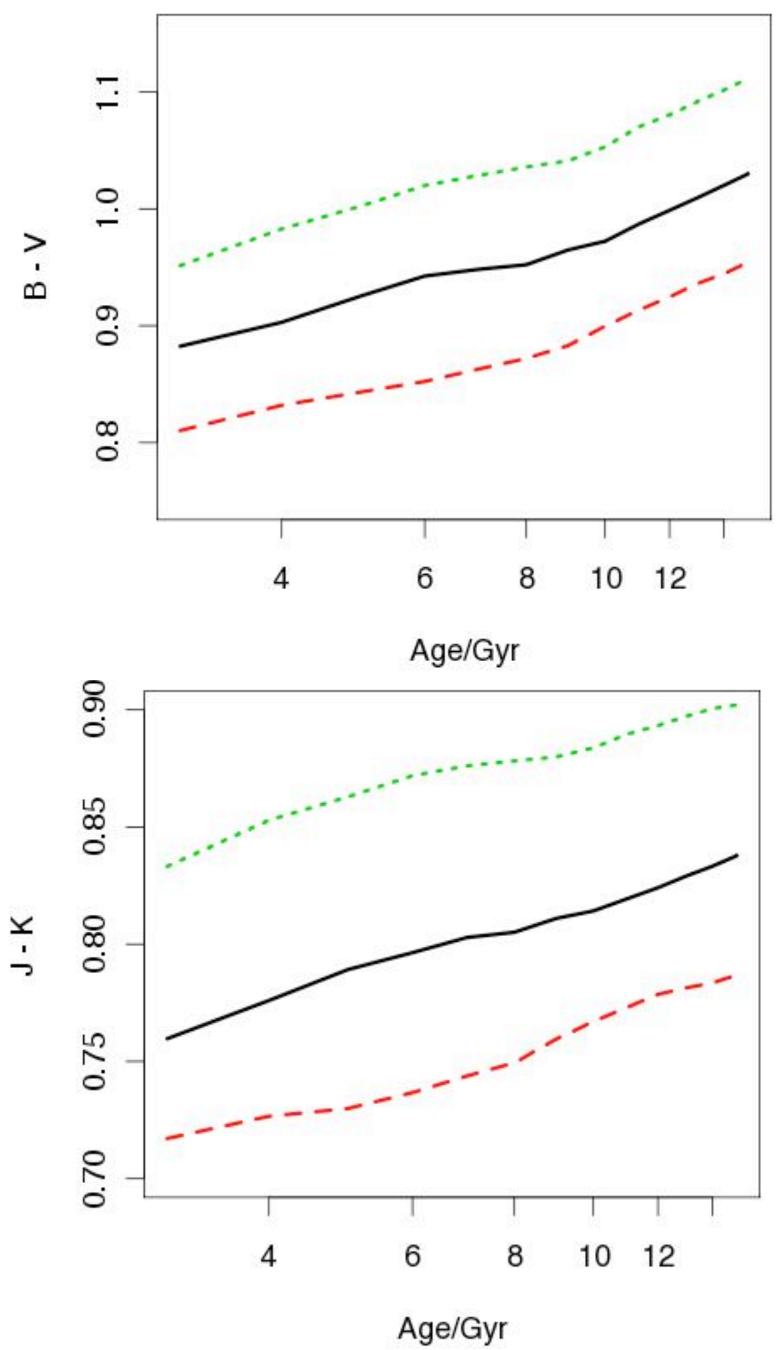
In the IR, more of the light comes from the RGB (affected by metallicity) and less from the MS/TO (affected by age and metallicity).

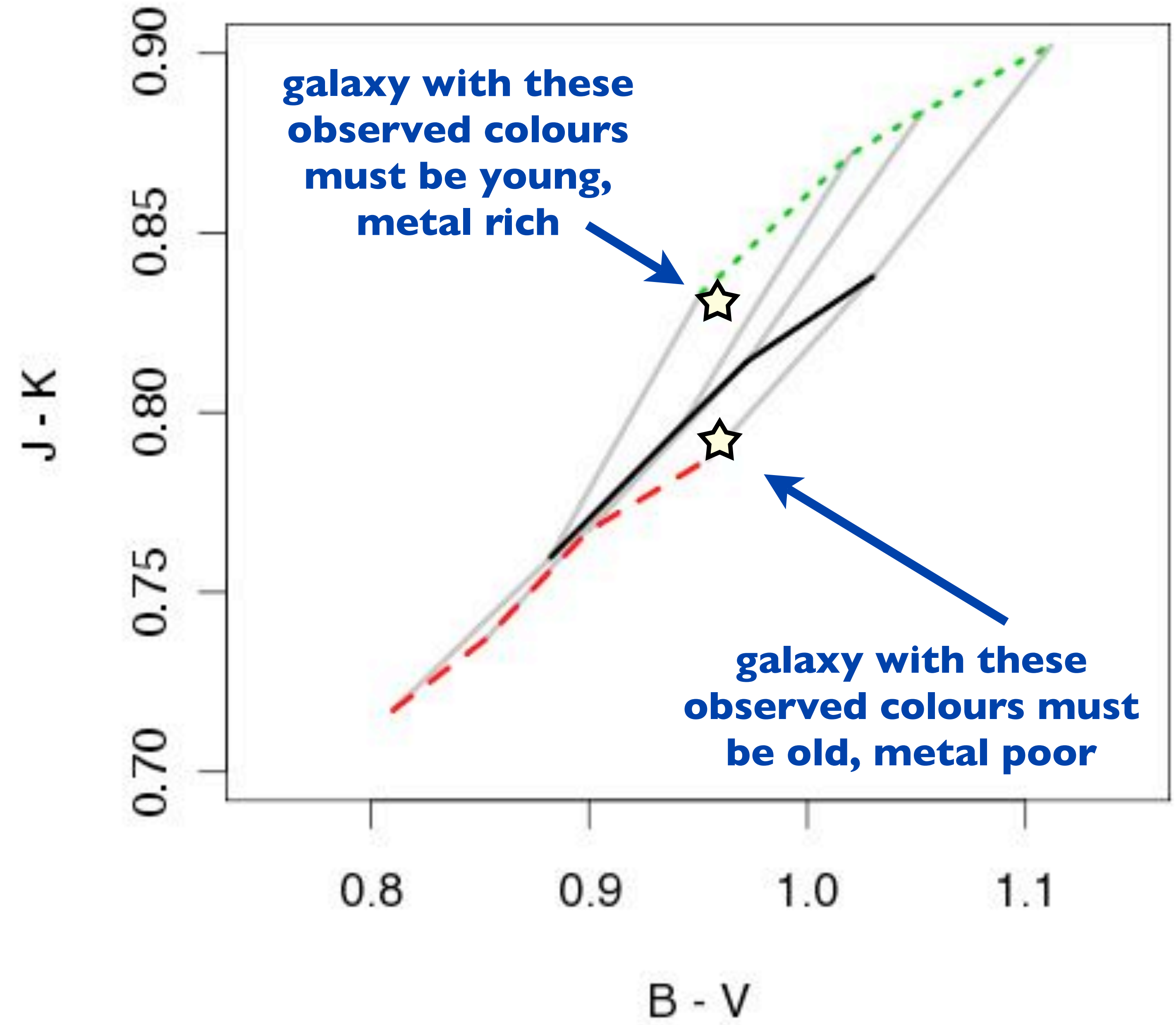
So the IR colours have greater metallicity dependence...



larger "spread" between lines (metallicity effect), relative to "slope" of each line (age effect)

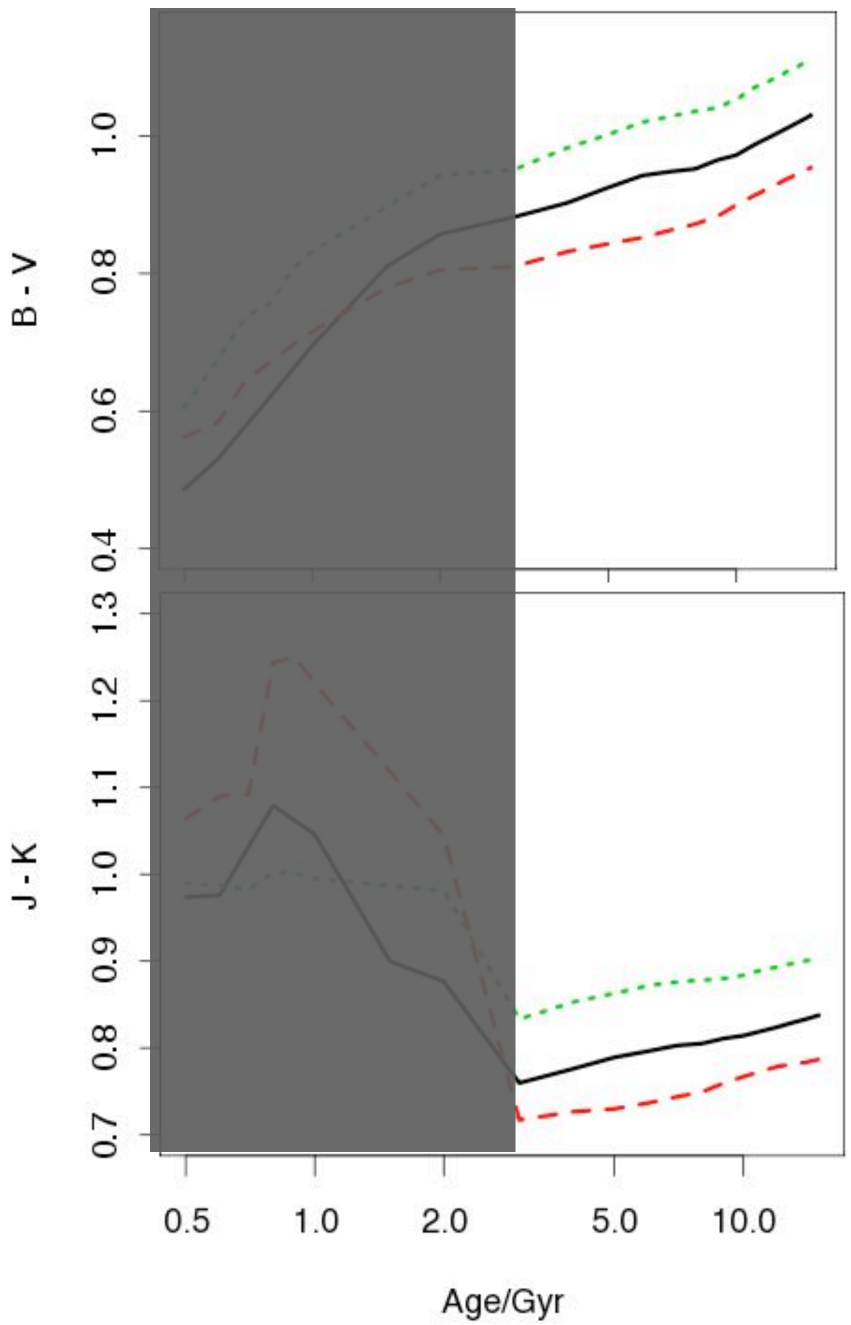
Beating the Age-Z degeneracy in the IR?





In principle, this is possible, but clearly requires very accurate photometry in the IR.

Younger ages in optical/IR



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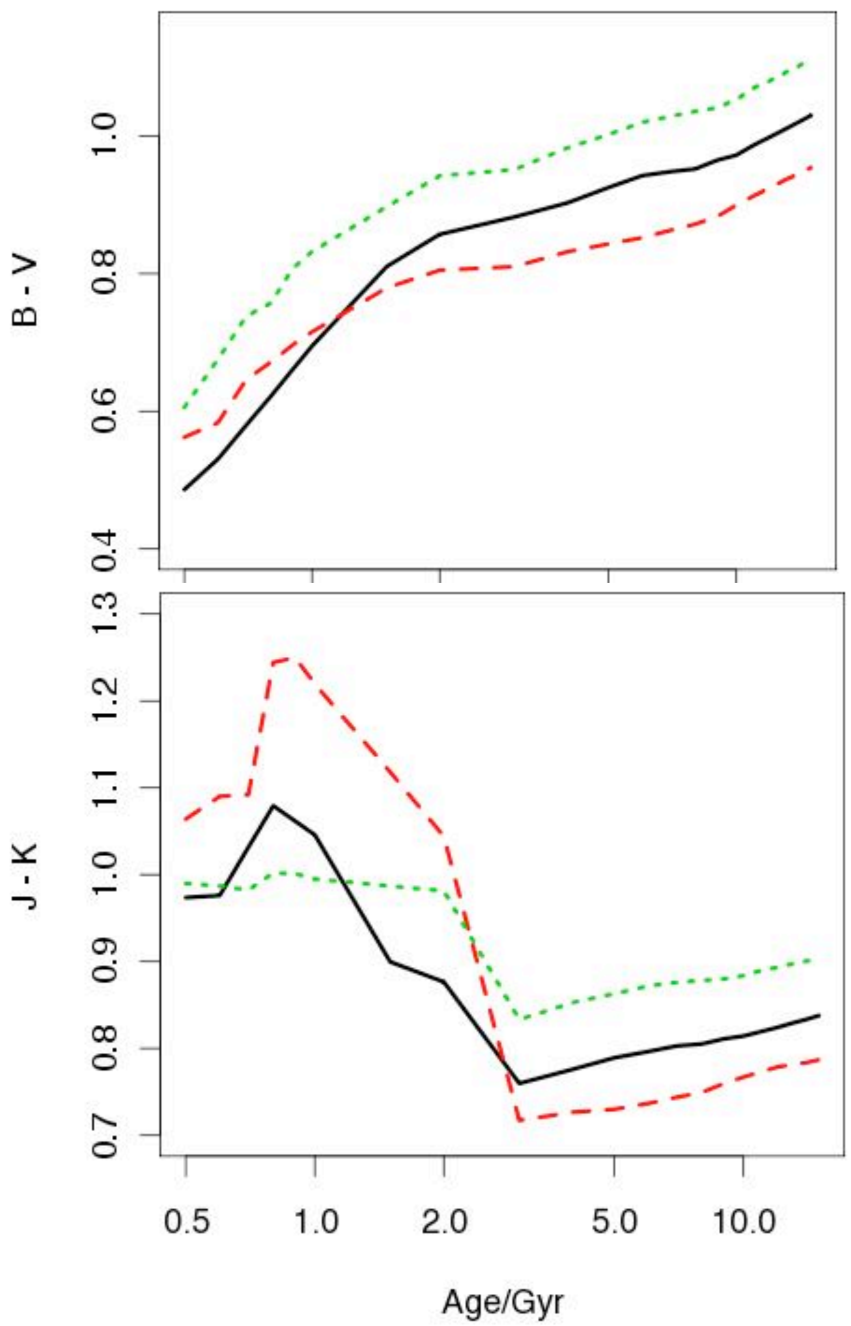

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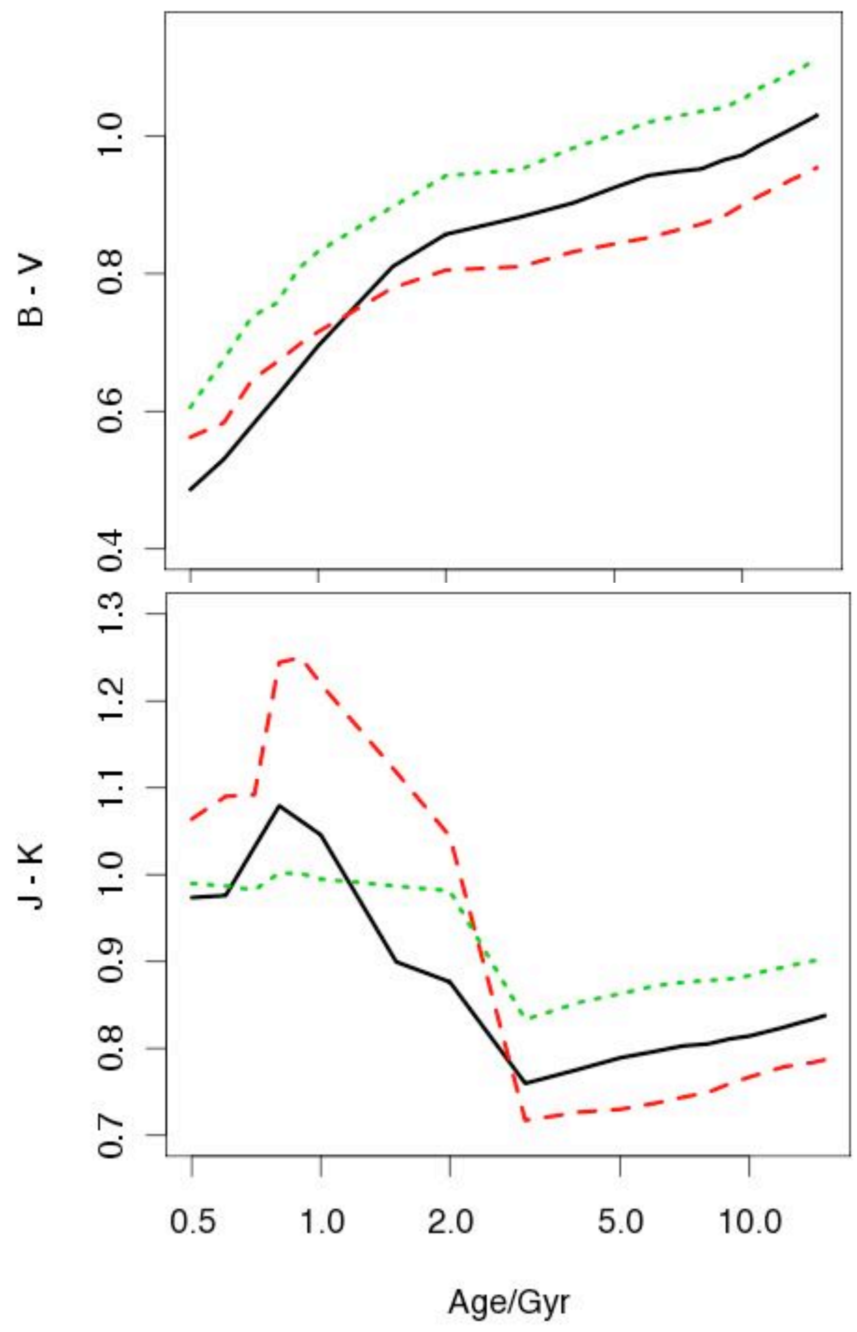

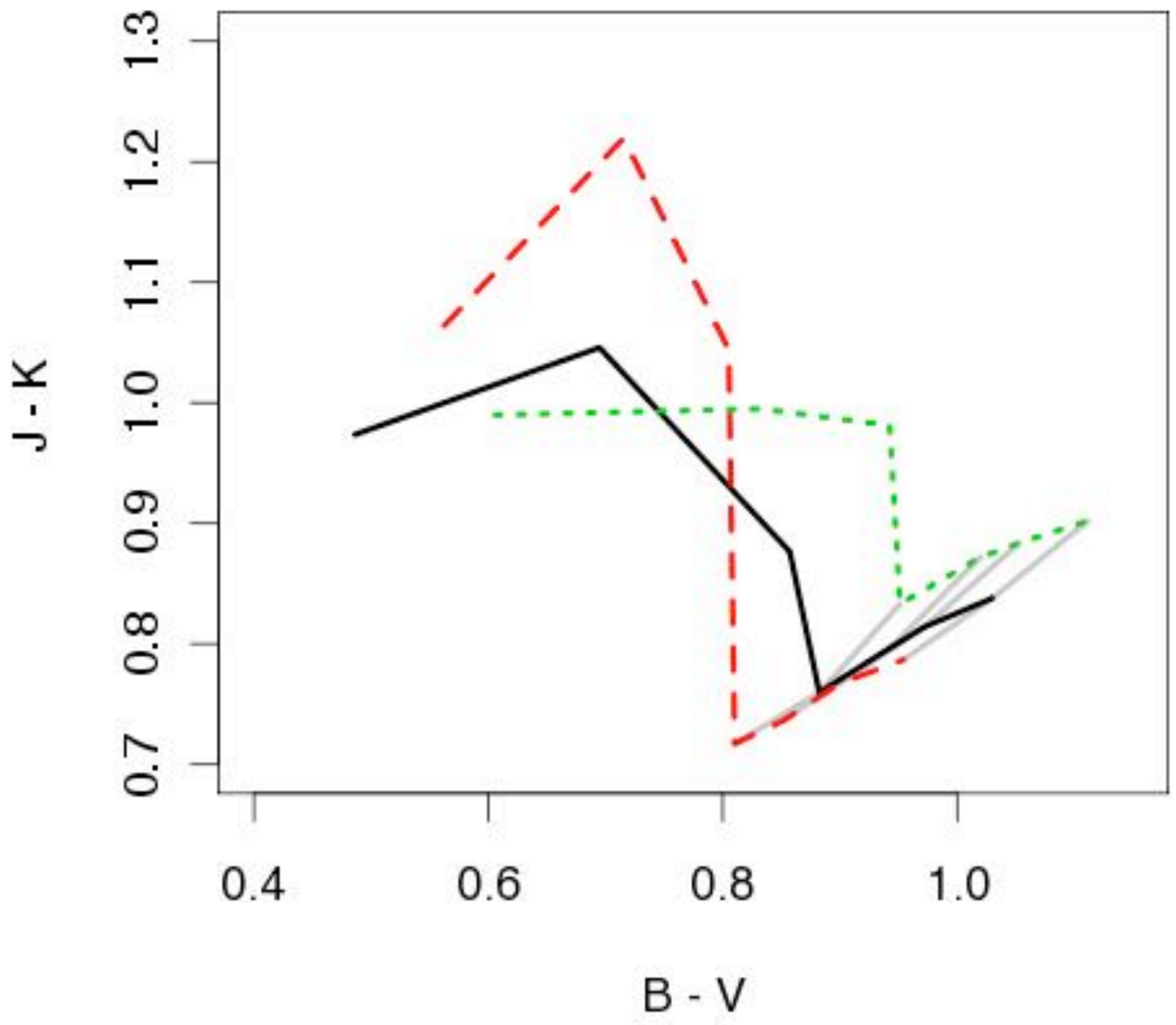

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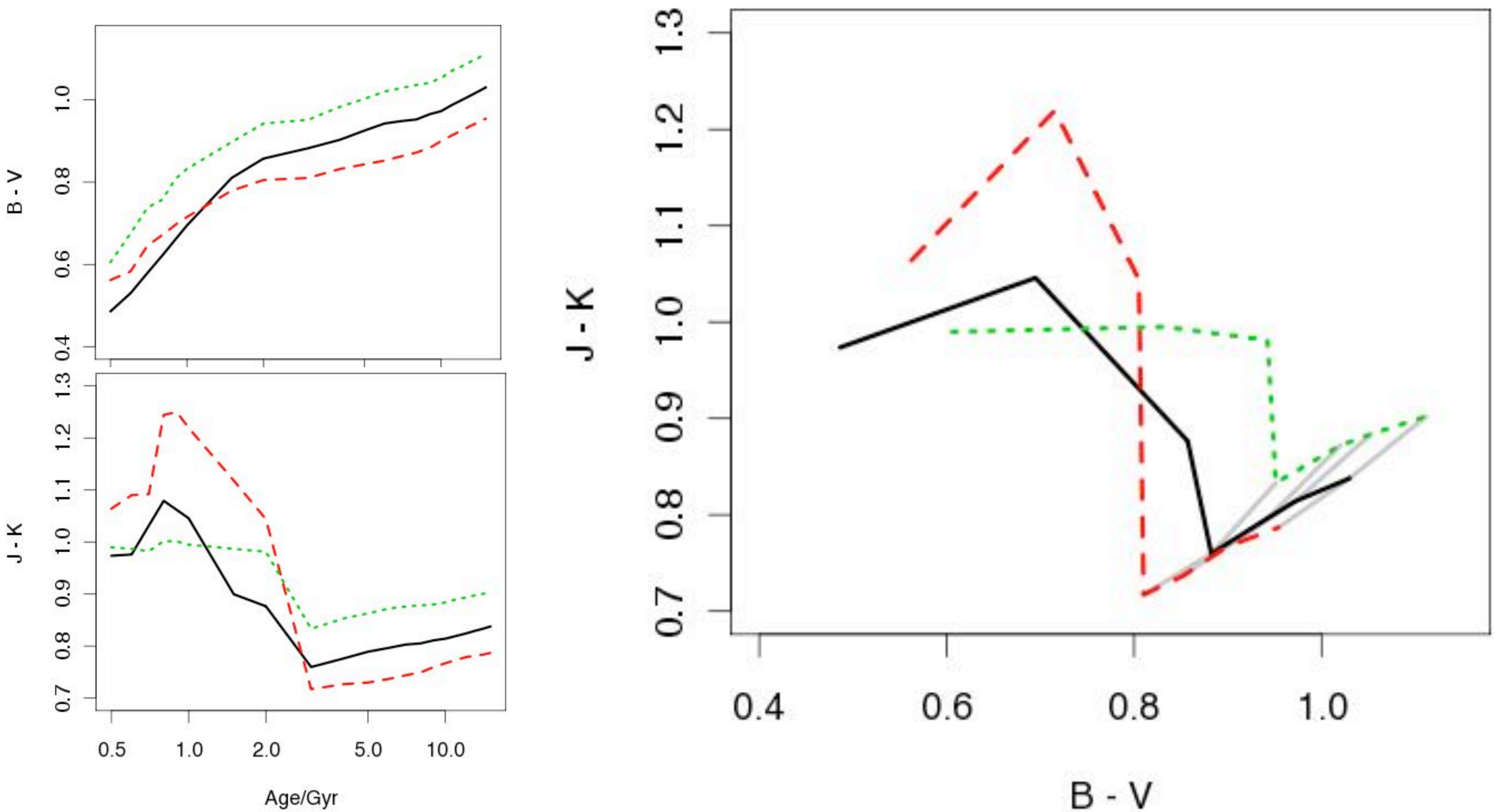


Good news: parts of this colour grid unambiguously signal 0.5-2 Gyr populations.

Bad news: this behaviour due to poorly-understood stellar physics!! (TP-AGB stars)

Thermally pulsing AGB stars

Maraston (2005):

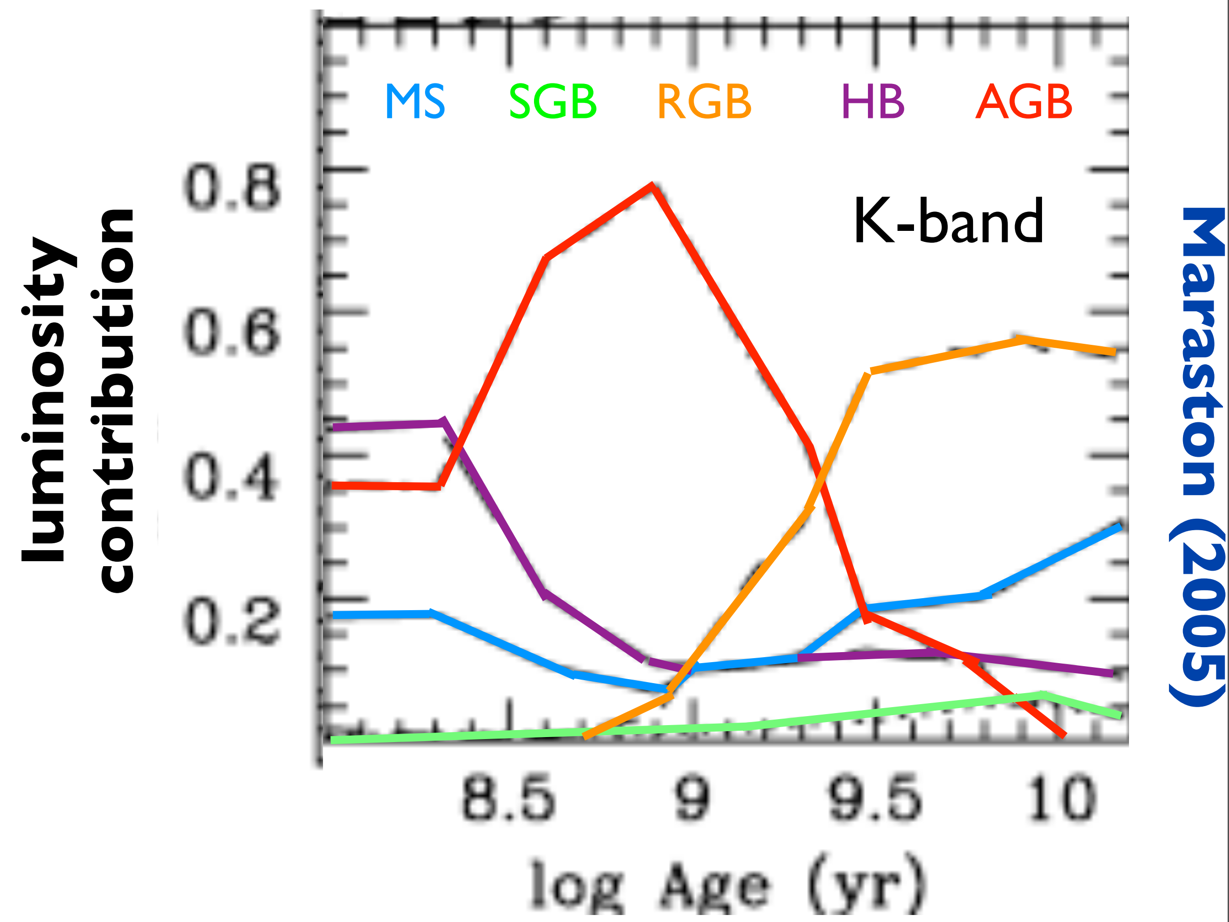
At age ~1 Gyr, stars on AGB are of masses which take them into very luminous "thermally pulsing" phase.

This phase very hard to model, since non-equilibrium state, explosive He shell ignitions at ~1000 yr intervals, dredge-up of processed material etc.

In Maraston's models ~80% of the IR luminosity from a 1 Gyr SSP arises from the AGB.

Most modern models indicate more modest, but still substantial contributions.

[NB: relevance to stellar mass estimates for z~2 galaxies!]



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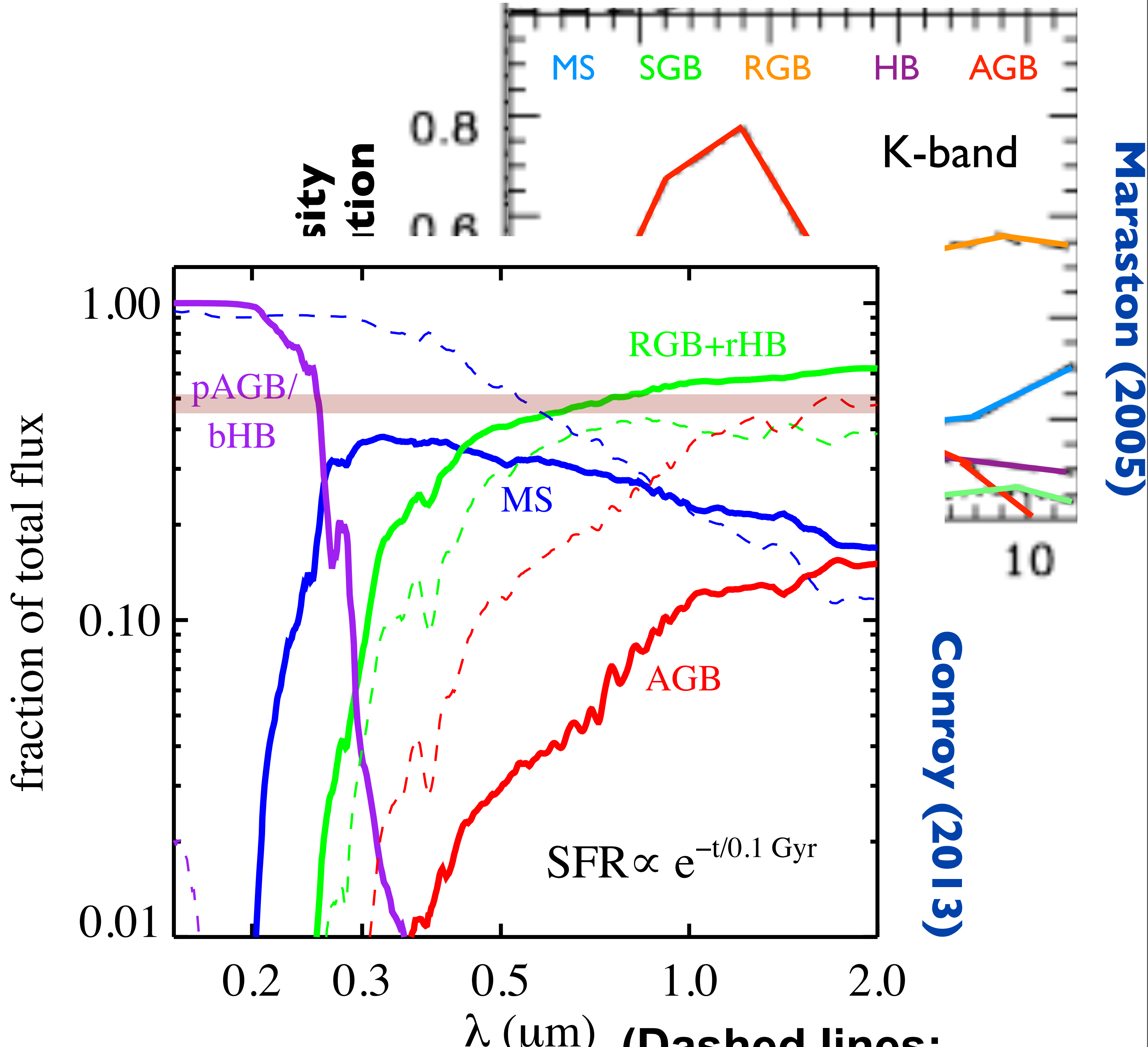


(Dashed lines: contributions at 1Gyr)

Beating the Age-Z degeneracy in the UV?

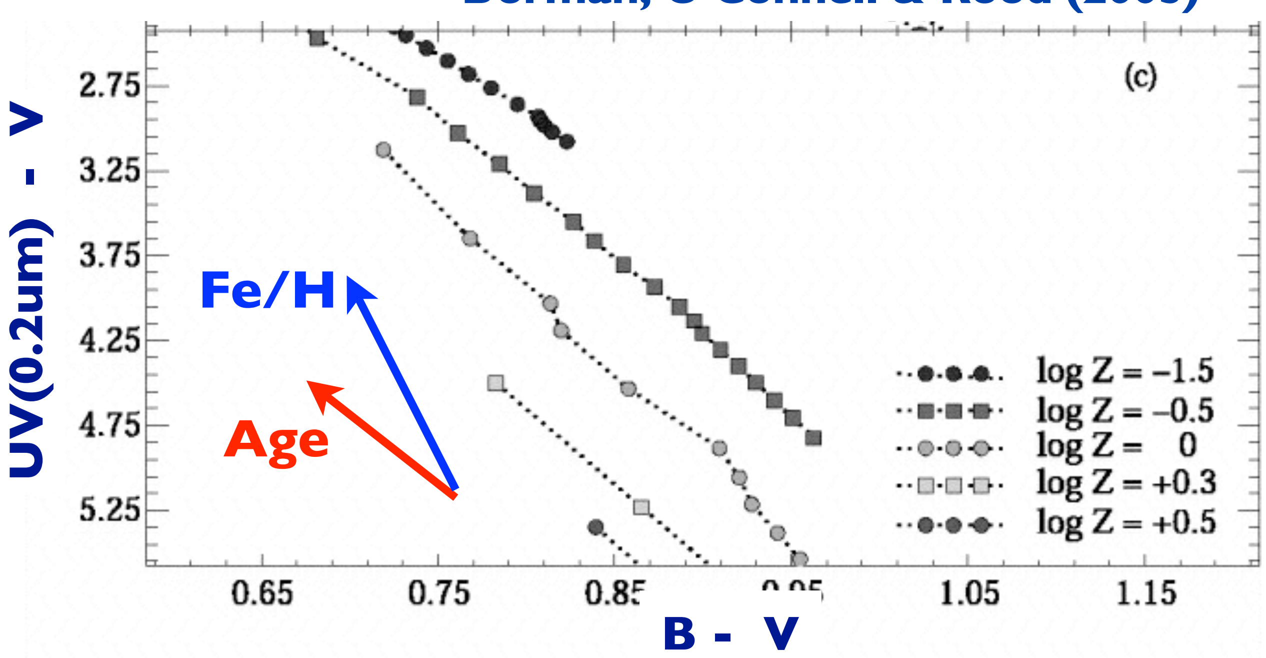
Based on MS+RGB alone, we would expect the UV to be dominated by the MSTO.

MSTO stars hotter and brighter at early time, so expect good age sensitivity.

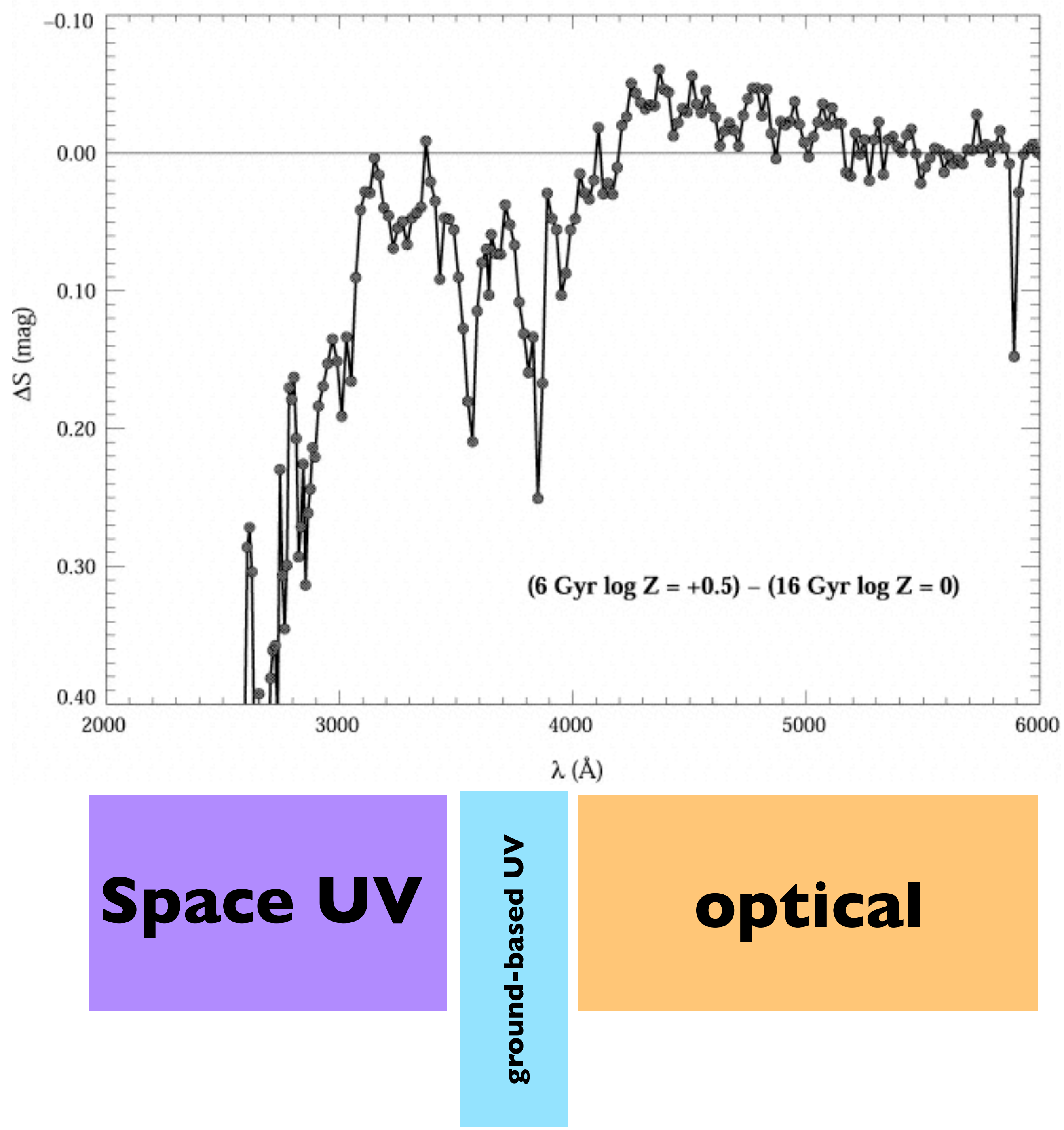
But still have some degeneracy effect from Fe/H dependence of isochrone...

...And have to worry about exotic old-but-hot star contributions: e.g. BHB, EHB, BS.

Dorman, O'Connell & Rood (2003)



Ratio of energy distribution for two populations that are indistinguishable in "optical"



A cautionary (resolved) case

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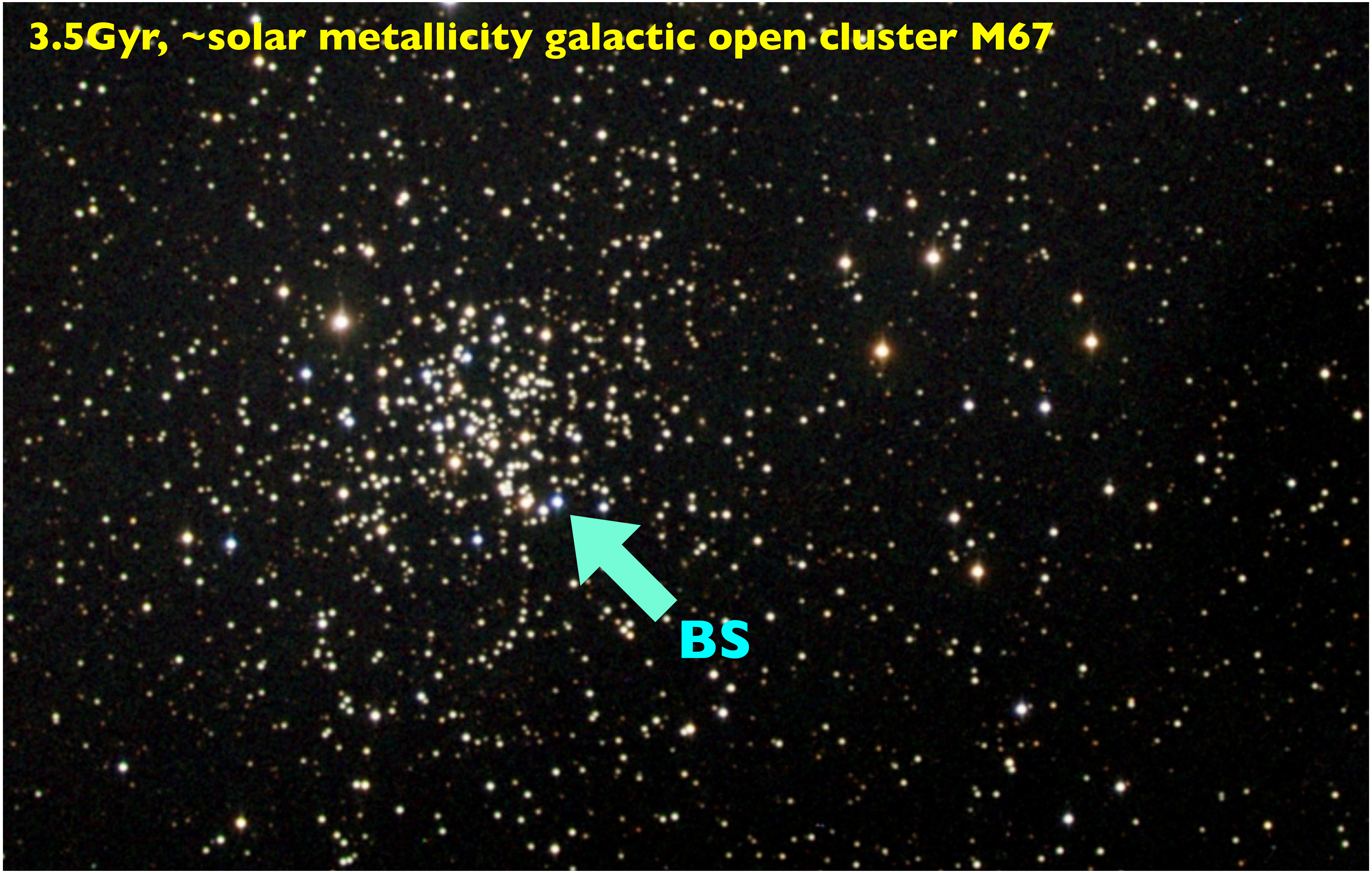

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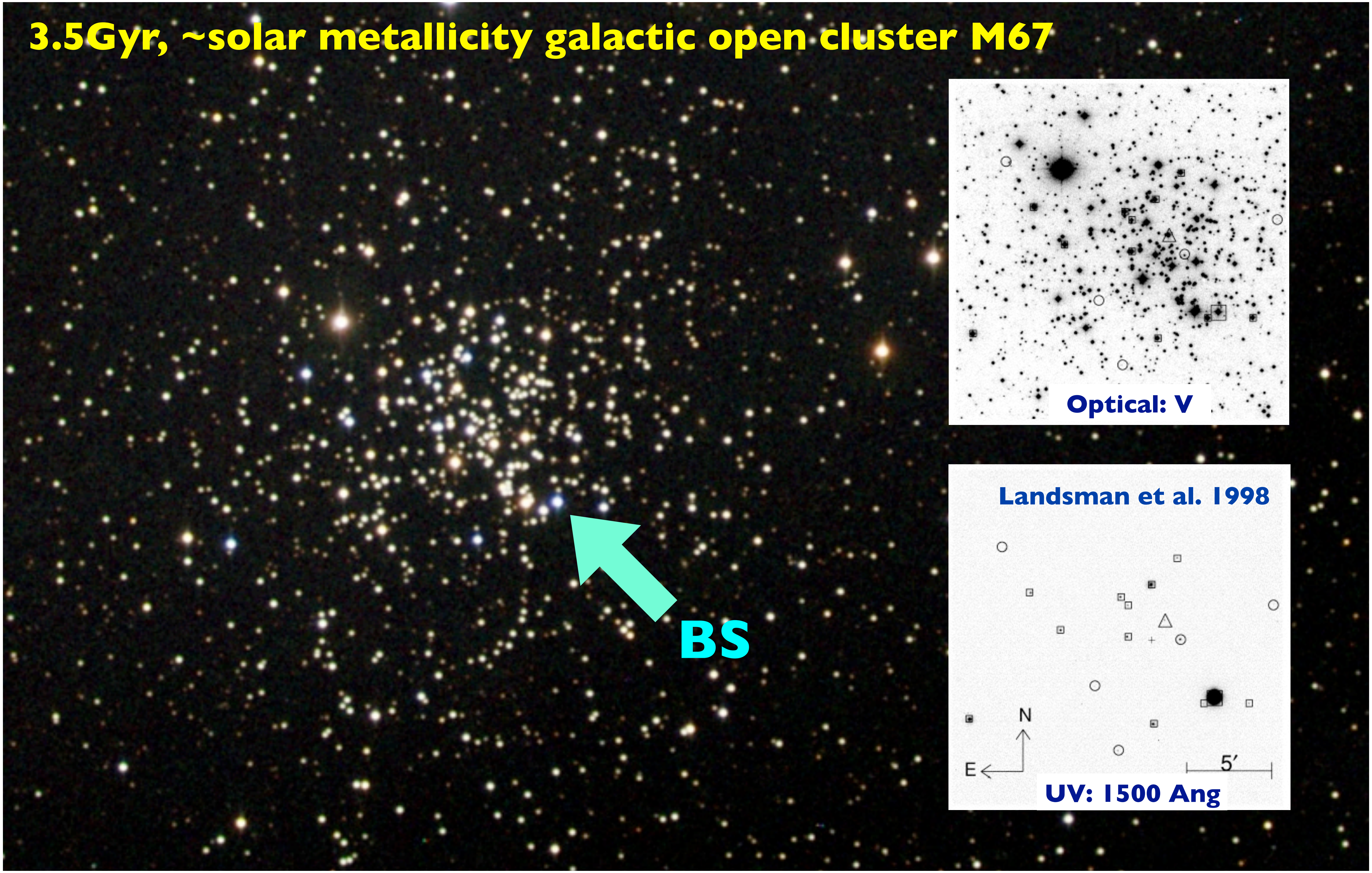

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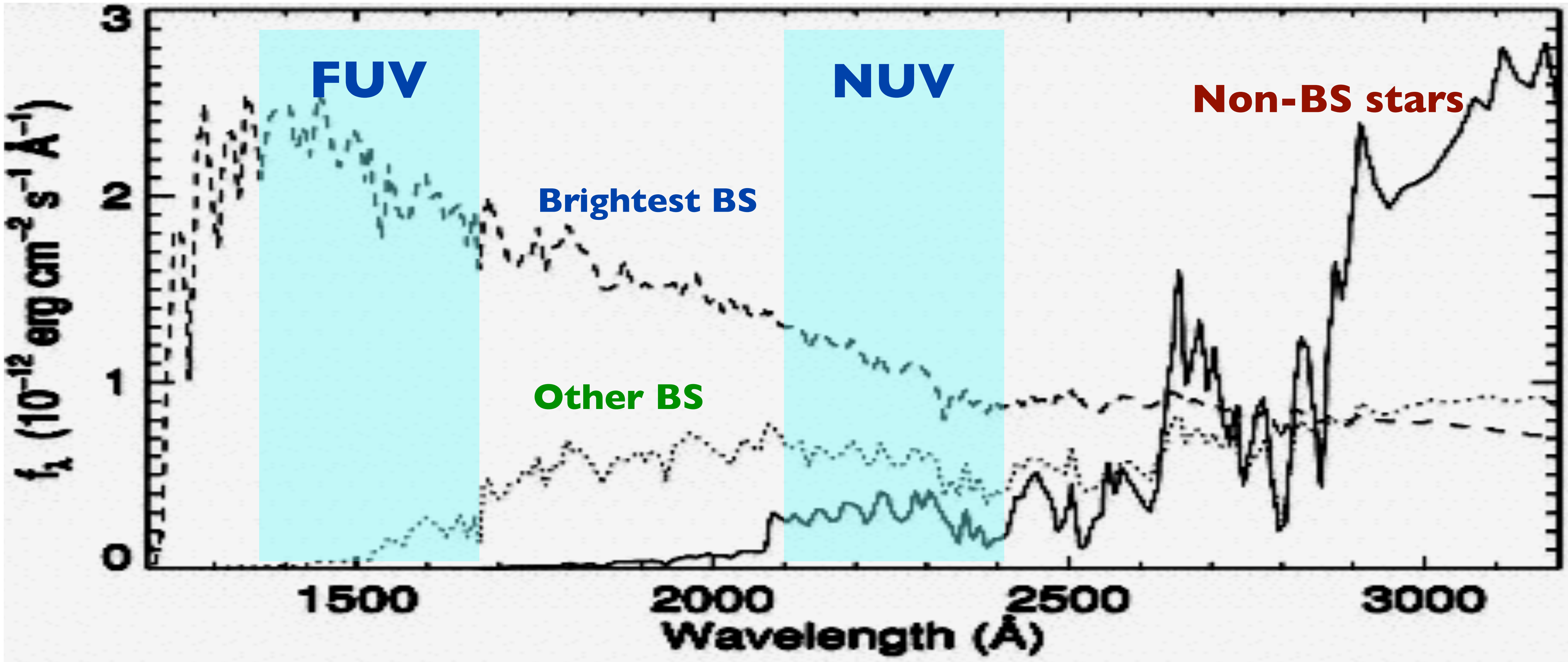


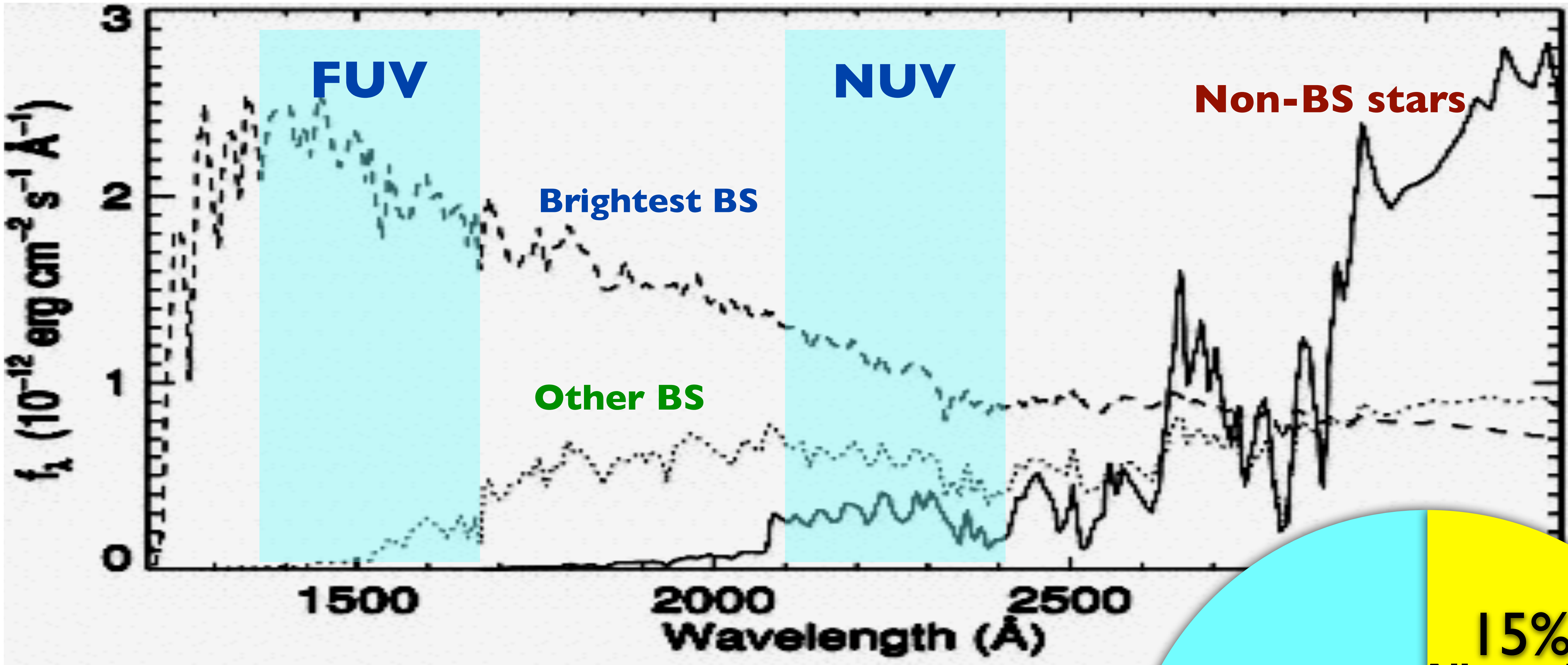
An old-ish, ~solar metallicity stellar population.

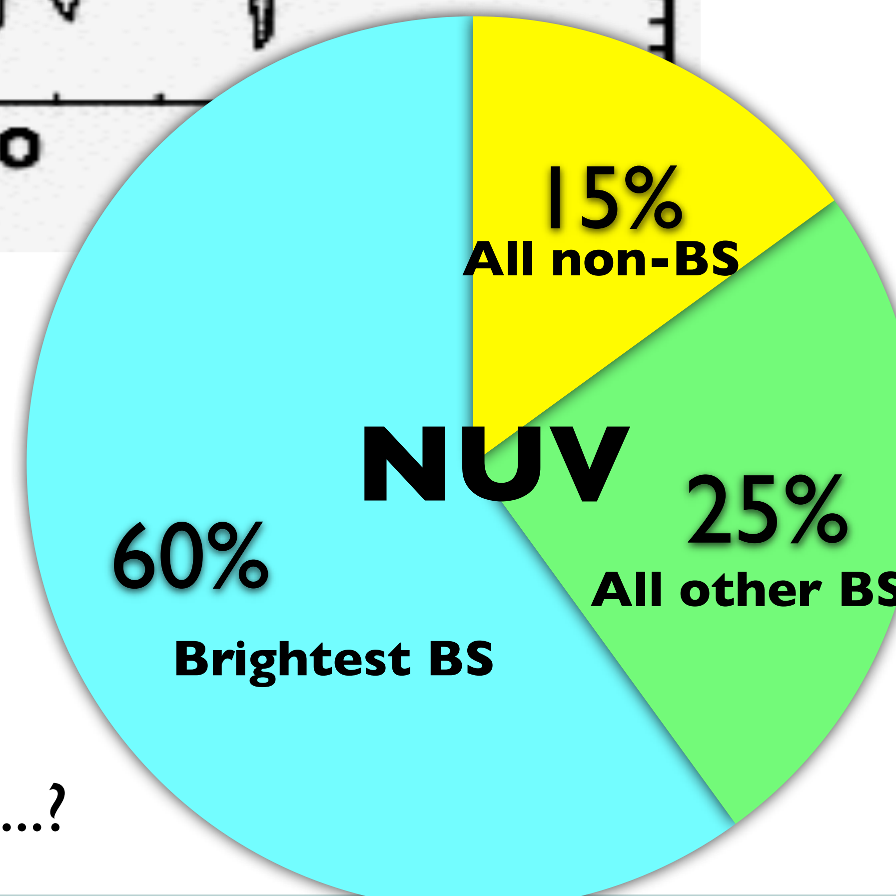
Blue stragglers dominate the UV emission.

BS content of M67 is extreme within MW...

But we don't know how to predict incidence of BS in a given population. So how much can we learn from UV in old galaxies...?

A cautionary (resolved) case





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Colours of unresolved populations: Summary

THE BAD NEWS:

Optical colours, which are easy to measure, can tell us very little about ages of unresolved stellar systems, after ~1 Gyr from their formation.

(They can, however, readily distinguish 1-10 Gyr galaxies from those with current star formation, where high-mass stars dominate the flux.)

THE NOT-MUCH-BETTER NEWS:

Colours involving the near infra-red and ultra-violet spectral regions, which are harder to measure, are only a little better than the optical. Sensitivity of the IR colours is poor (at least after the AGB-dominated phase), while the UV certainly tells us something, but maybe not what we hoped to learn.

Surface Brightness Fluctuations are a good tool, but only for fairly nearby galaxies.

THE GOOD NEWS:

In the next section we will look at narrow spectroscopic indices (which are more expensive to measure), and show that these are much more effective at distinguishing age and metallicity effects.