Stellar Populations - Lecture II

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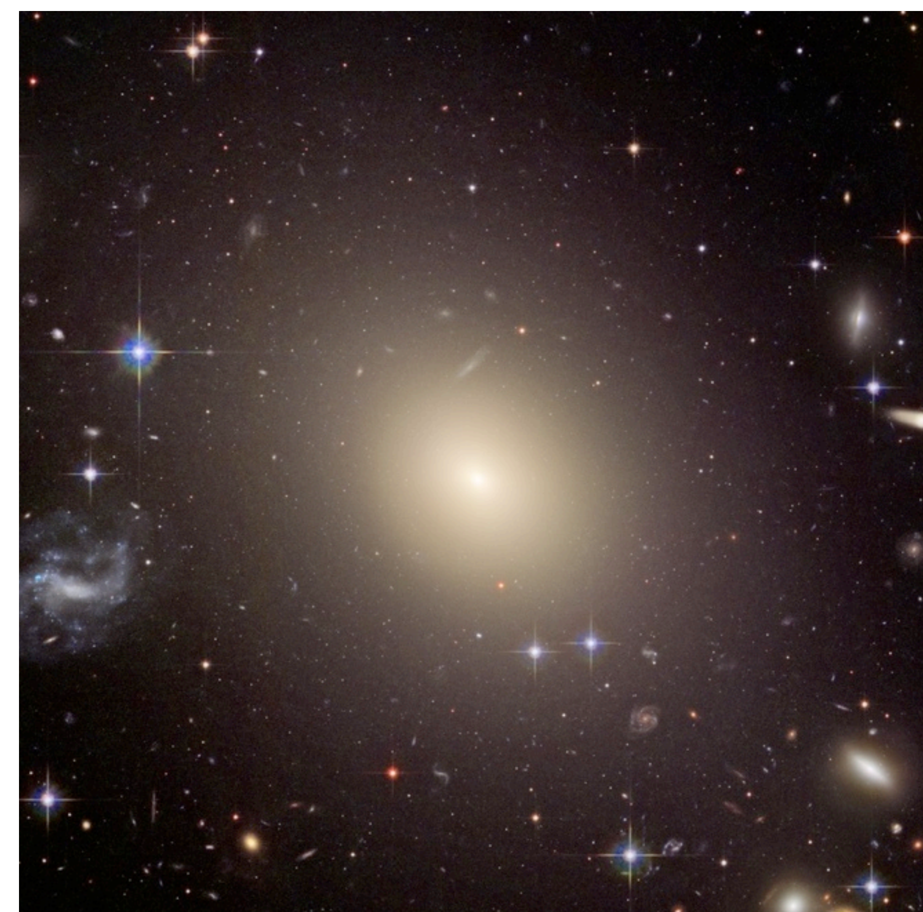


Course Outline

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.

Unresolved Stellar Populations

Our aim is to learn about galaxies!

Specifically to measure their stellar ages and metallicities.

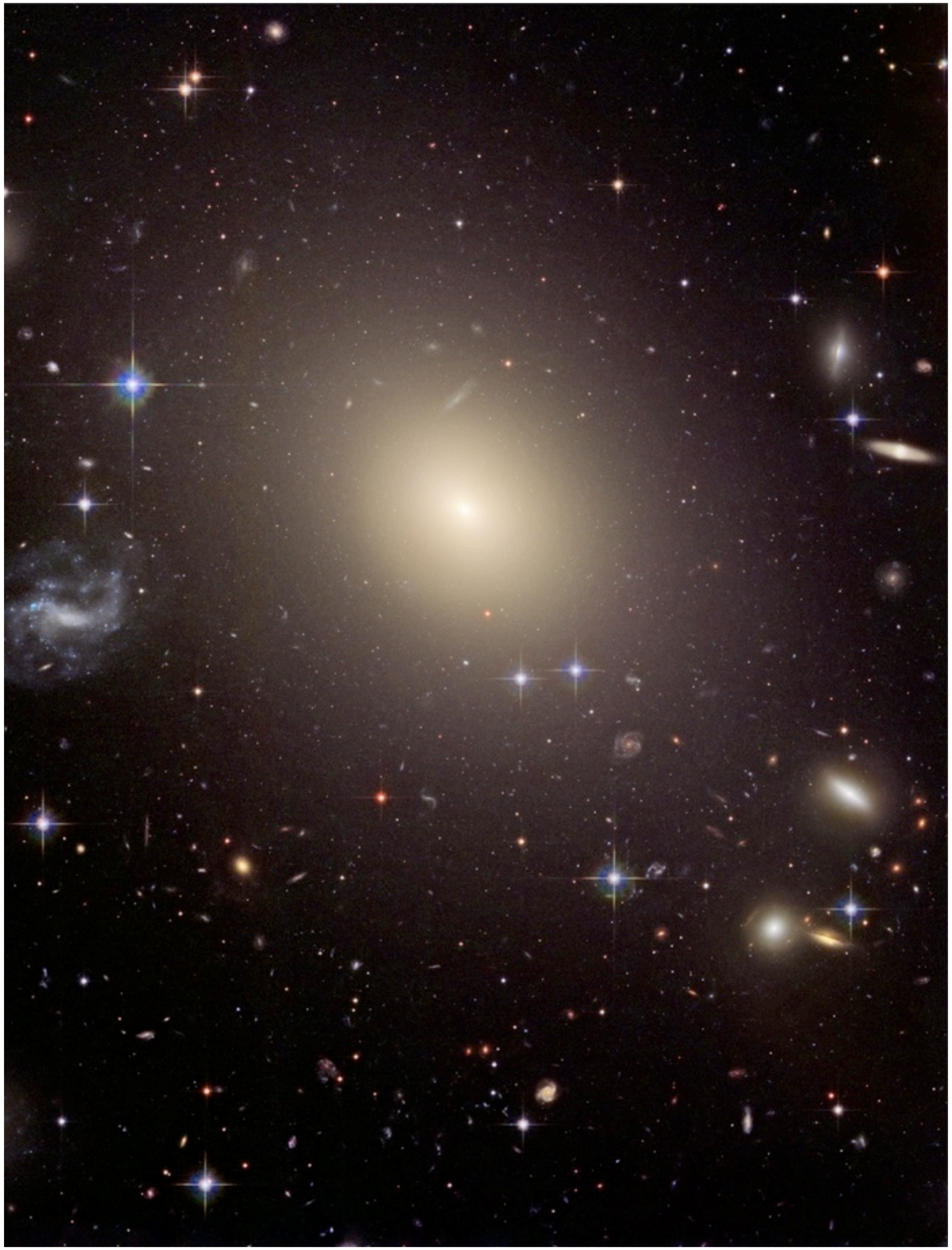
When we can measure fluxes for individual stars over a large luminosity range, the information content of the CMD is vast: star-formation rate as function of time, chemical abundance information, etc.

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

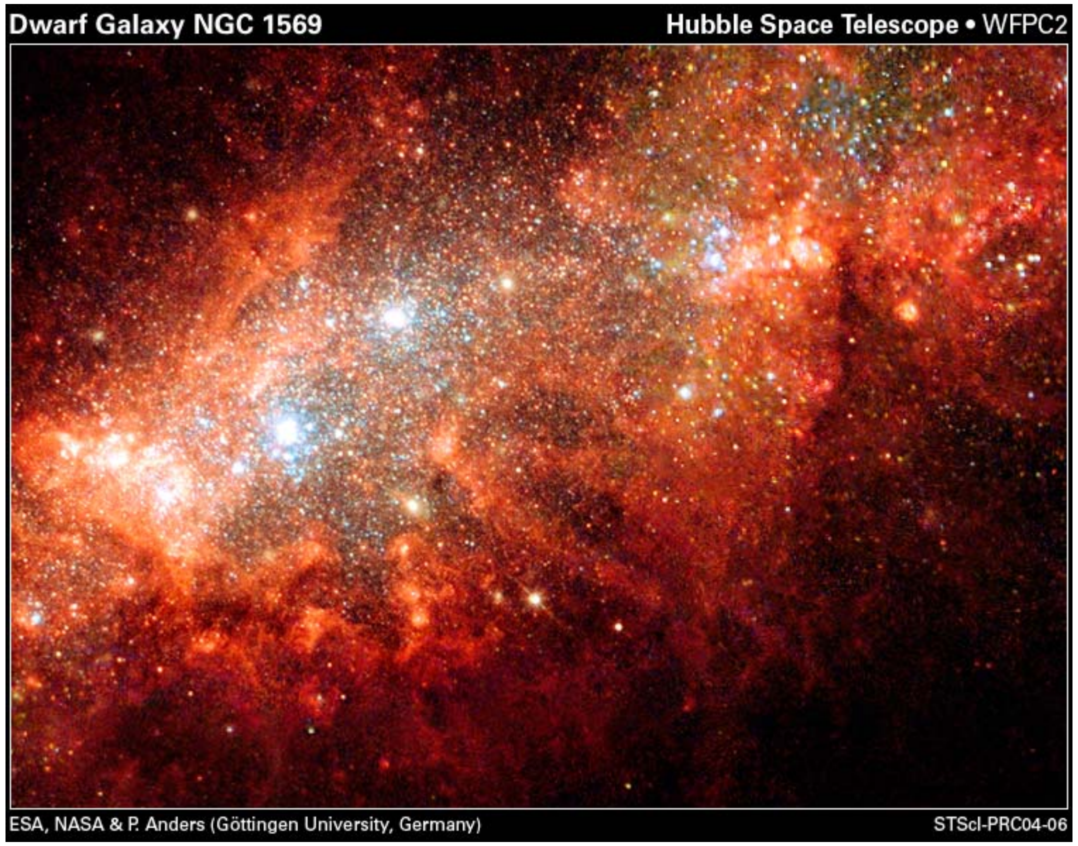
(And those that *are* resolved are not a fair sample of the universe.)

So what do we do with the rest?

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



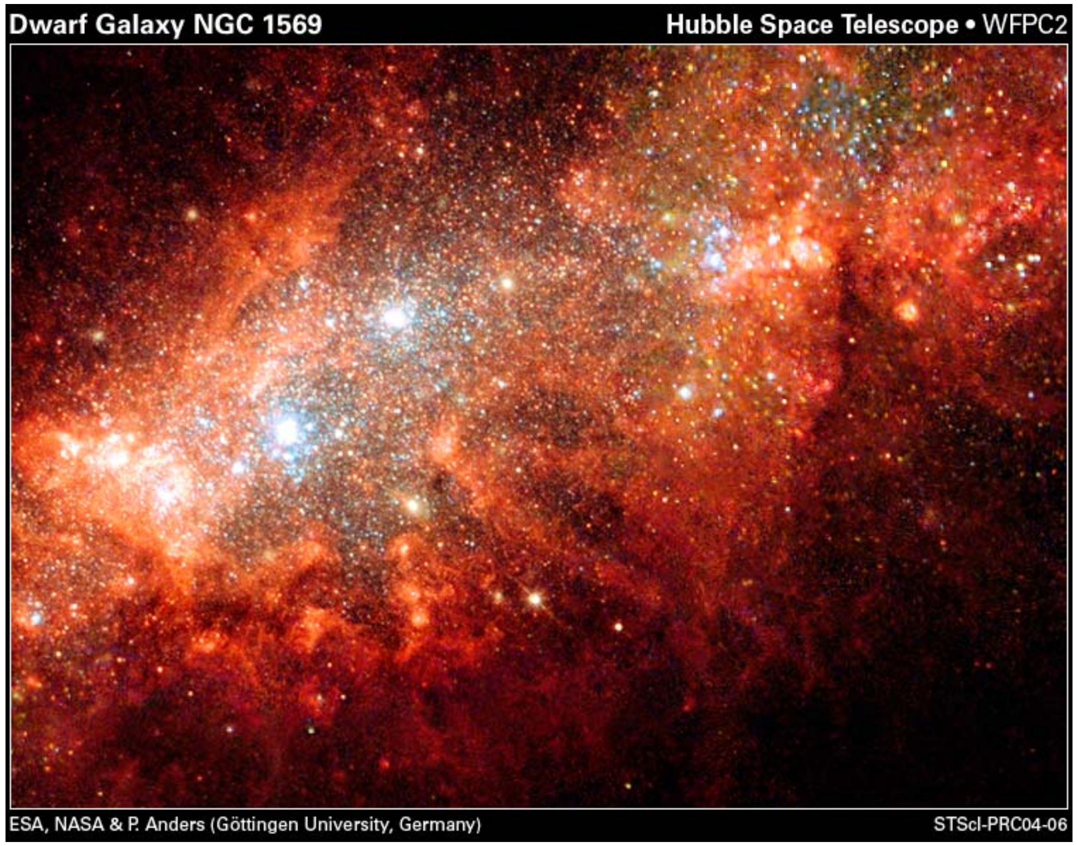
The Problem



"What you'd like to get"

(George Hau)

The Problem



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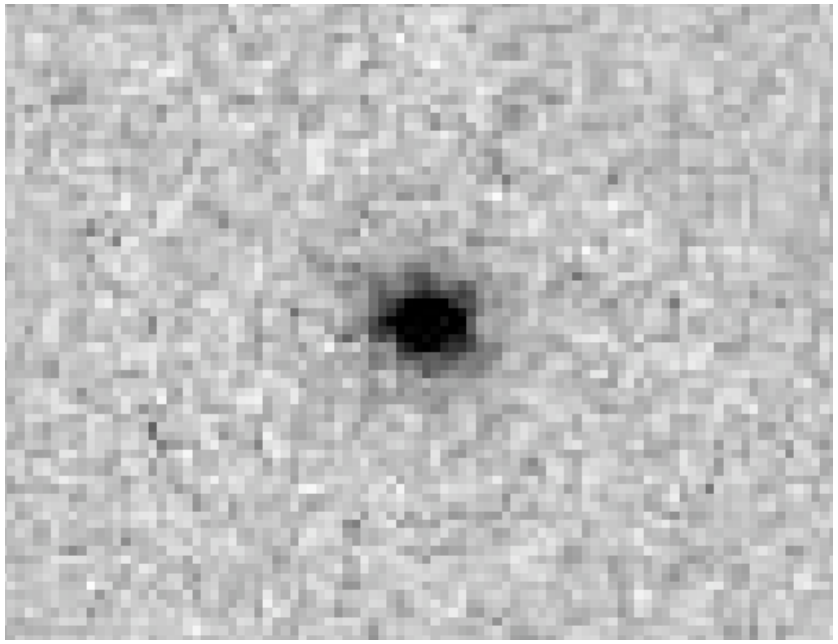

"What you get"

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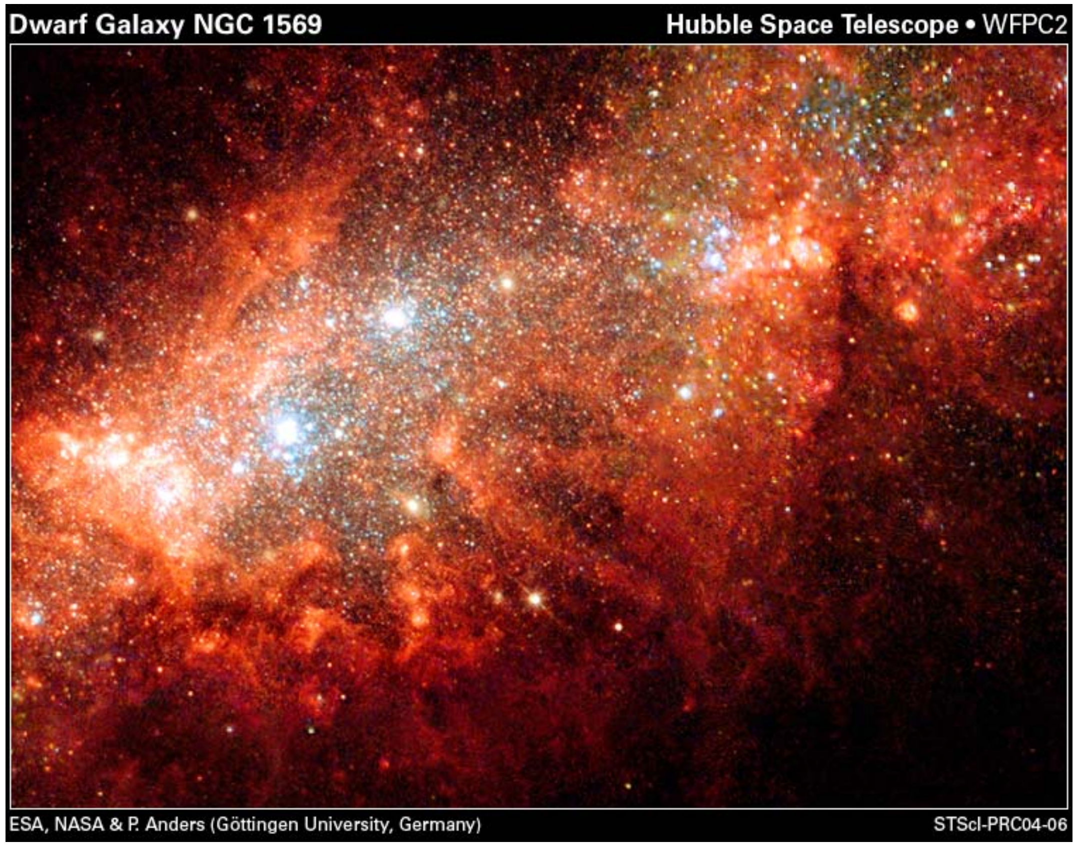

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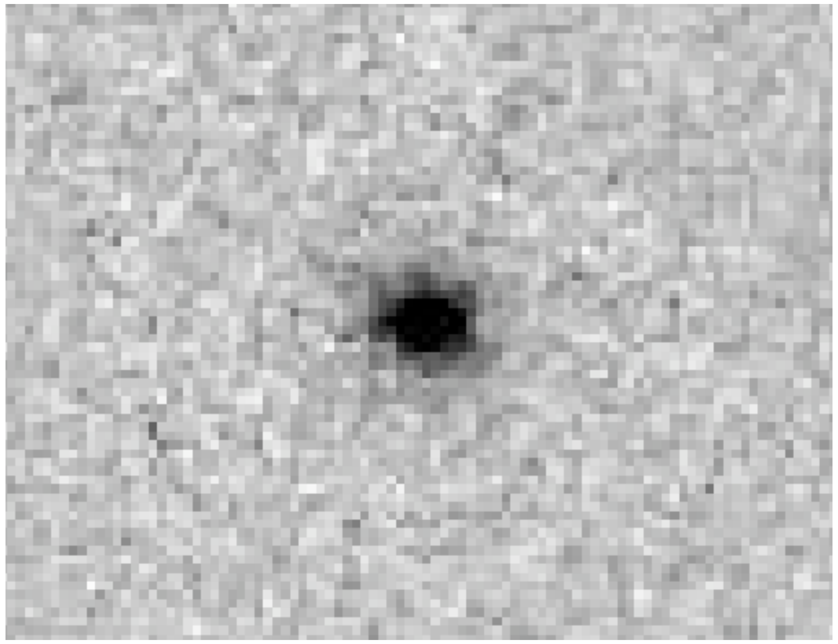


"What you get"

(George Hau)

WHAT CAN WE MEASURE?

Broad-band colours (B-V, J-K, etc).

Surface brightness fluctuations (sometimes)

Spectroscopic features (absorption lines)

Simple Stellar Population (SSP)

THE SIMPLEST STELLAR POPULATION MODEL

A burst of star-formation at a given time: all stars have the same age.

All stars form with the same initial chemical composition: a single "metallicity".

The distribution of initial masses is given by some functional form, e.g. power law $N(M)\, dM \propto M^{-x}\, dM$. Commonly assume x=2.35, the "Salpeter IMF", over $M=0.1\text{-}100\ M_{sun}$.

Modern studies show fewer low mass stars than in Salpeter, e.g. Kroupa IMF (but these make little contribution to the total light).

USEFUL BECAUSE...

For stellar systems without much recent SF (GCs, elliptical galaxies) the SSP is probably a good approximation.

More complex systems can be modelled using combinations of SSPs.

Aside: What Exactly is Metallicity?

"METAL" CONTENT OF THE GAS CLOUD FROM WHICH THE STARS FORMED

Usually assume the surface composition reflects the original composition.

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

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

X or H = mass fraction of H , Y = mass fraction of He

Z = mass fraction of everything else = "metals"

EMPIRICAL NOTATION

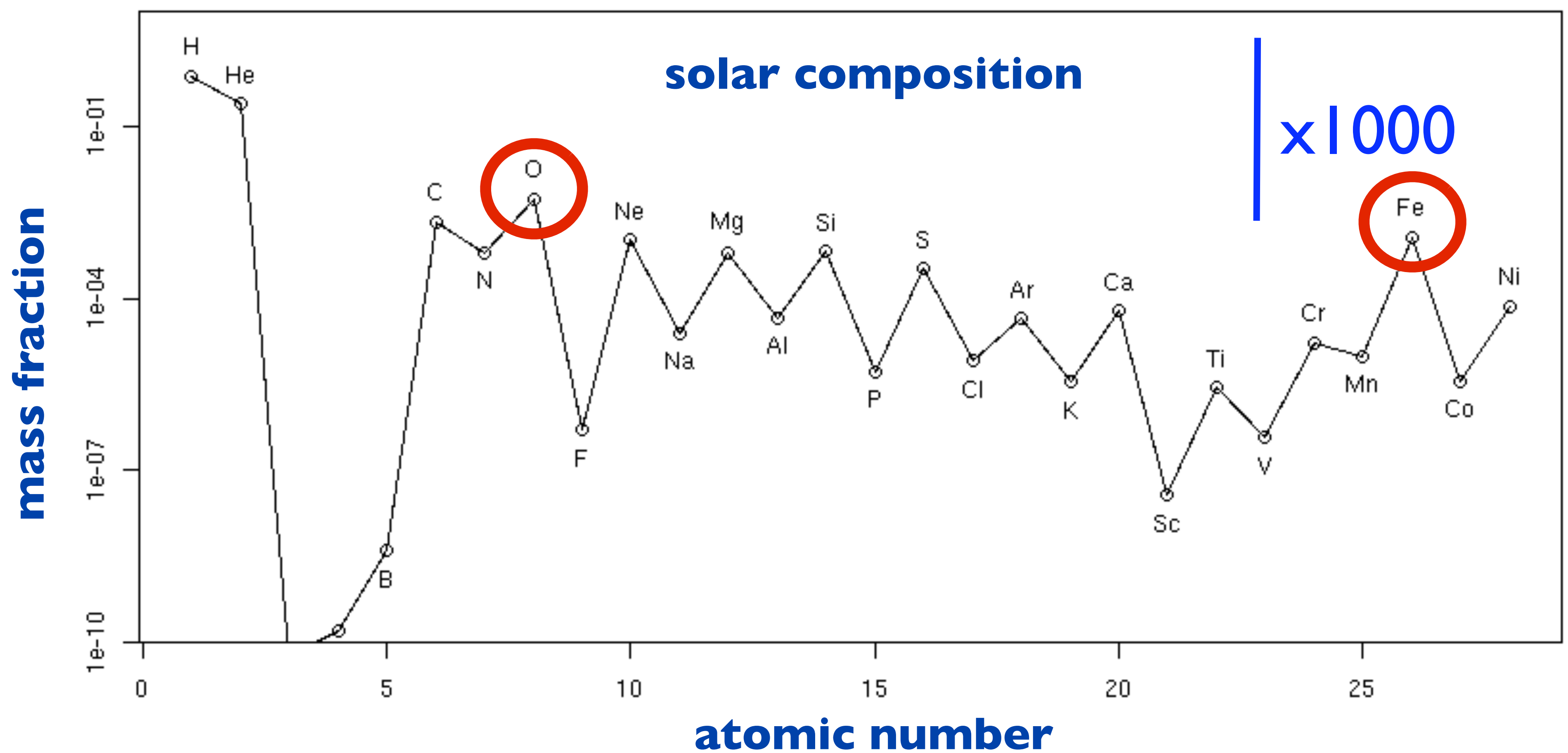
For measurements of metallicity in stellar atmospheres, we usually express abundances in terms of <u>number</u> density (not <u>mass</u> fractions). Total metallicity is often expressed as $[Z/H] = \log(N_Z/N_H) - \log(N_Z/N_H)_{sun}$. Then:

[Z/H] = 0 is "solar metallicity",

[Z/H]=+0.3 is "twice-solar",

[Z/H] = -1 is "one tenth solar", etc.

More on 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.

But unfortunately it is very hard actually to measure O from stellar spectra!

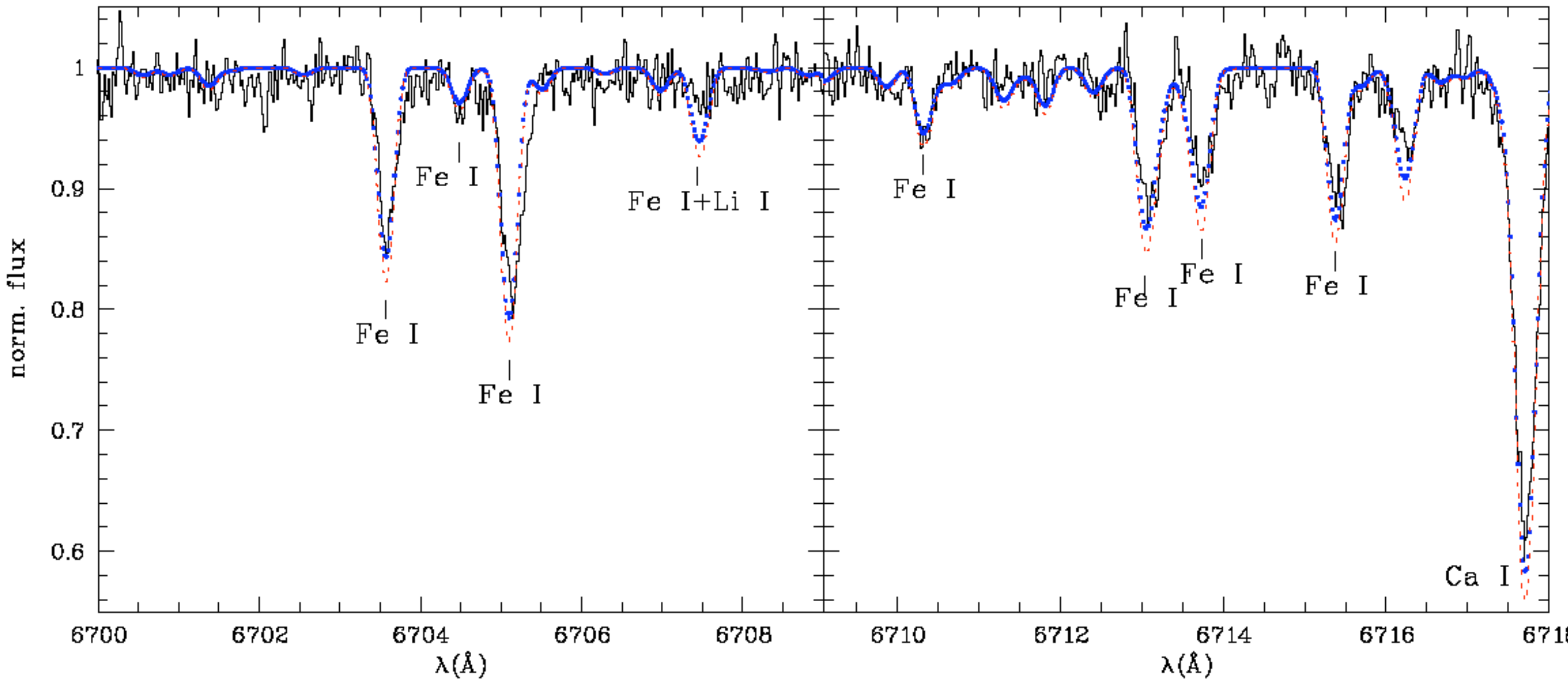
Much easier to measure Fe which has lots of absorption lines in the optical.

So we often talk about [Fe/H] instead. These are equivalent if [O/Fe] is solar, i.e. mixture between metals always the same. (We'll come back to this...)

Abundance measurement for stars

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)

Population Synthesis Models

TO COMPUTE FLUX FROM AN SSP IN A GIVEN BANDPASS:

1. Choose isochrone according to desired age and metallicity (Padova, BaSTI, etc)

2. Populate isochrone with stars drawn from an assumed IMF (e.g. Kroupa, etc)

3. Map atmospheric parameters (metallicity, temperature, gravity) to flux in a given bandpass (bolometric corrections) using model or empirical spectral energy distributions.

4. Integrate along isochrone, summing contribution from stars of each initial mass:

$$F_{tot} = \int L(M) \,.\, B\,(T_{eff}(M), g(M), Z) \,.\, N(M)\, dM$$

First factor is the total ("bolometric" luminosity)
Second factor is the bolometric correction for this bandpass;
Third factor is number of stars contributing for this mass.

Post RGB phases often added "by hand".

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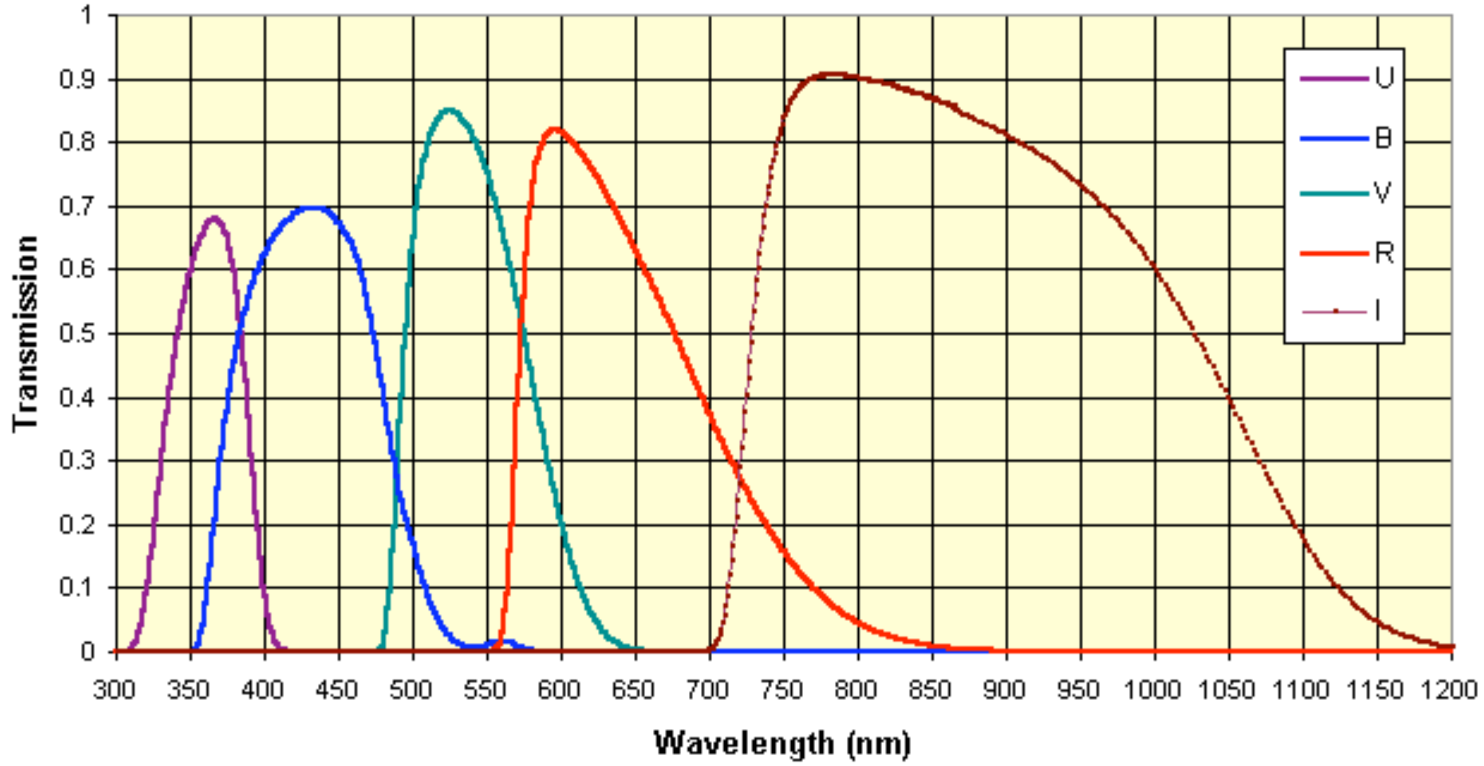
EASY!

Post RGB phases often added "by hand".

Population Synthesis Models

Main sequence star spectra (ordered by Teff)

Standard UBVRI filters

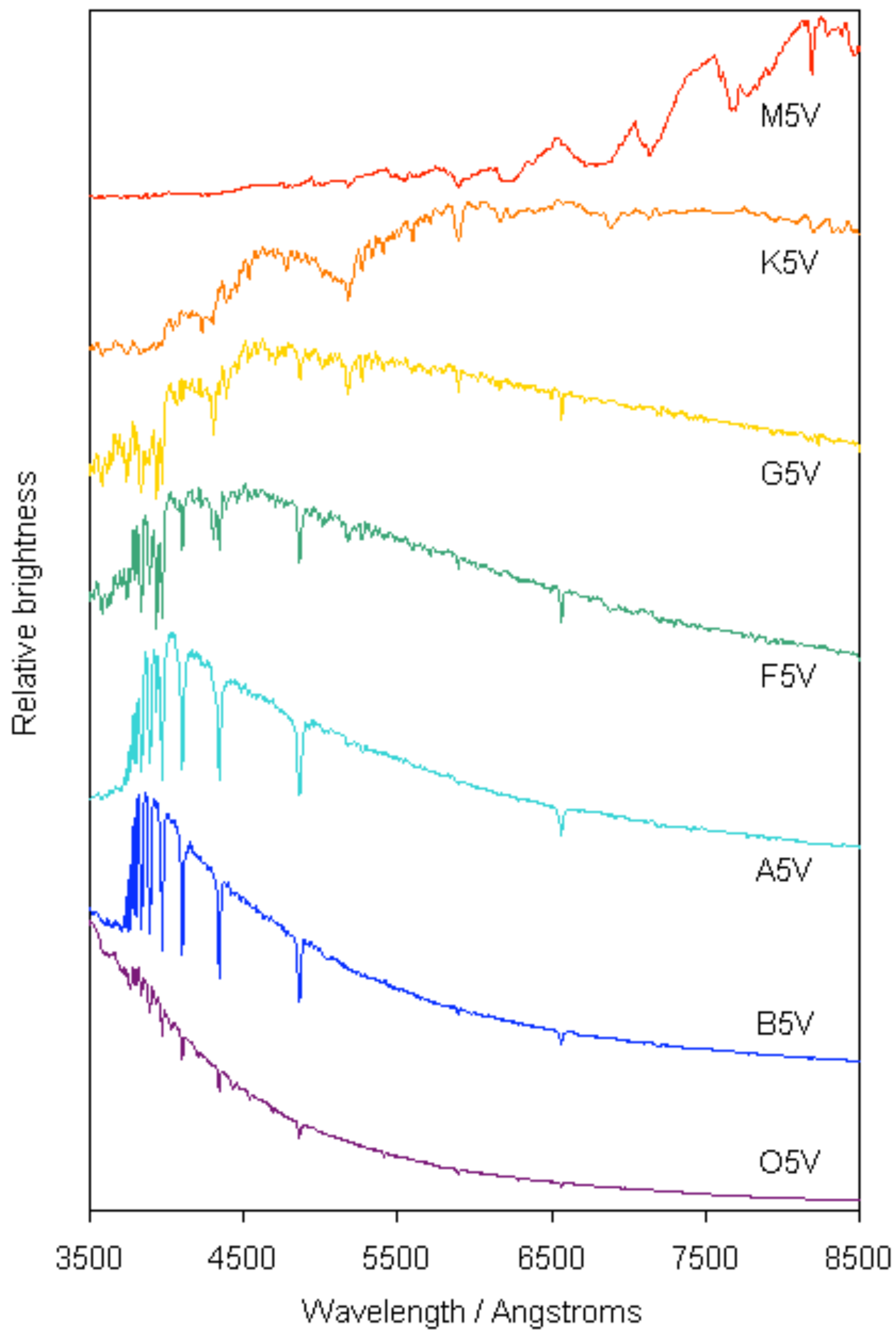


BOLOMETRIC CORRECTION

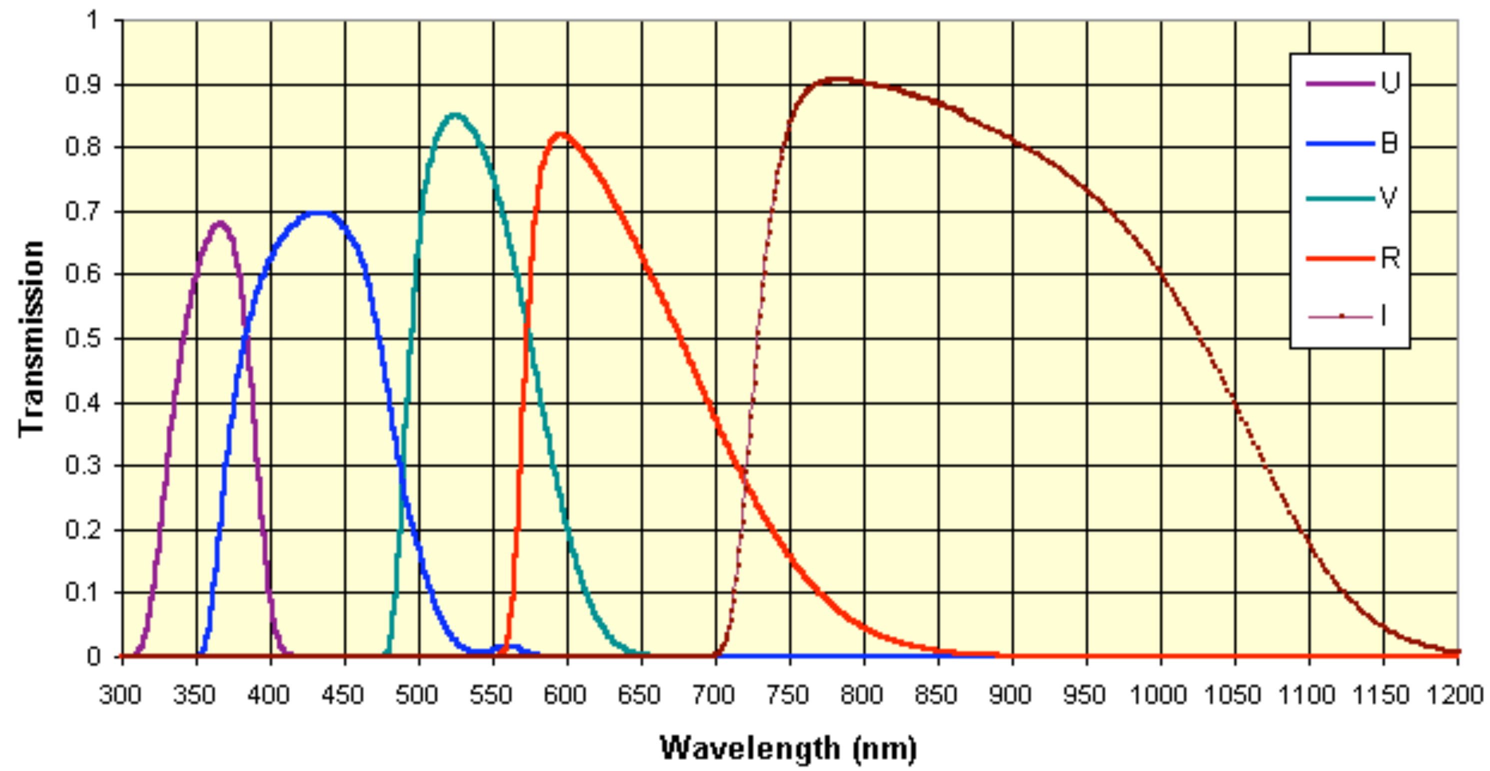
Describes how total luminosity translates to flux measured through a particular filter.

Population Synthesis Models

Main sequence star spectra (ordered by Teff)



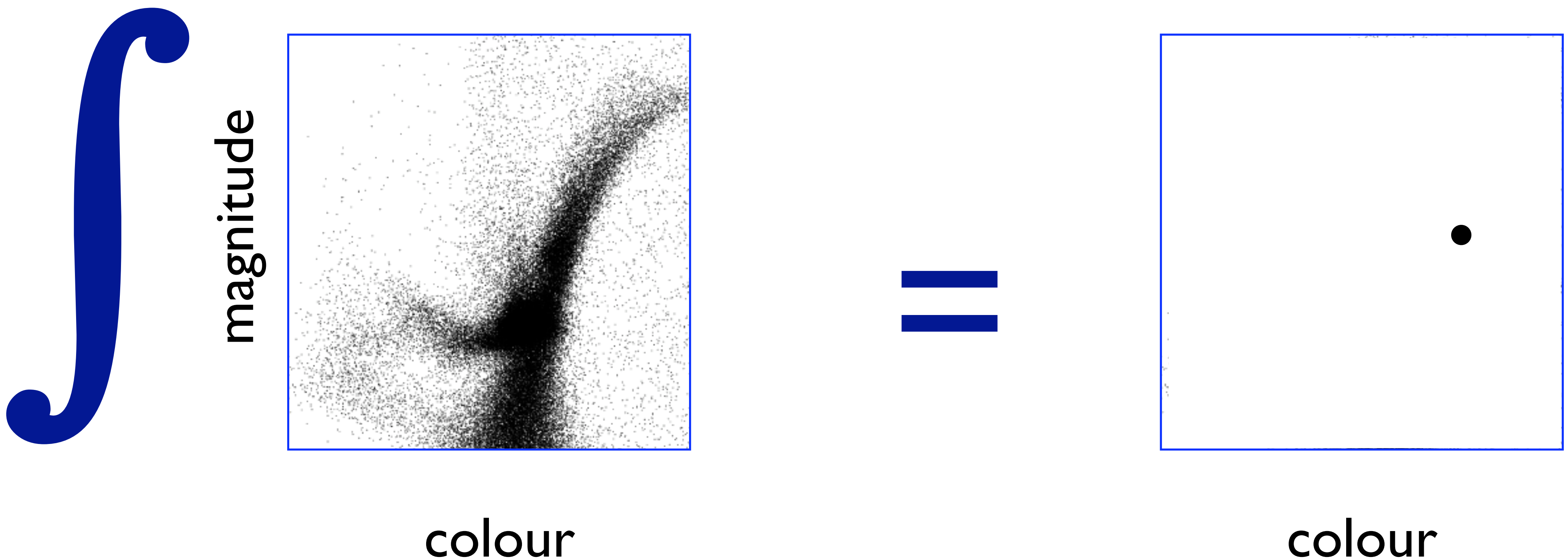
Standard UBVRI filters



BOLOMETRIC CORRECTION

Describes how total luminosity translates to flux measured through a particular filter.

The destructive integral



The integral destroys a lot of information!   How much information remains?

Light & Mass in an SSP

WHERE IS THE LIGHT?

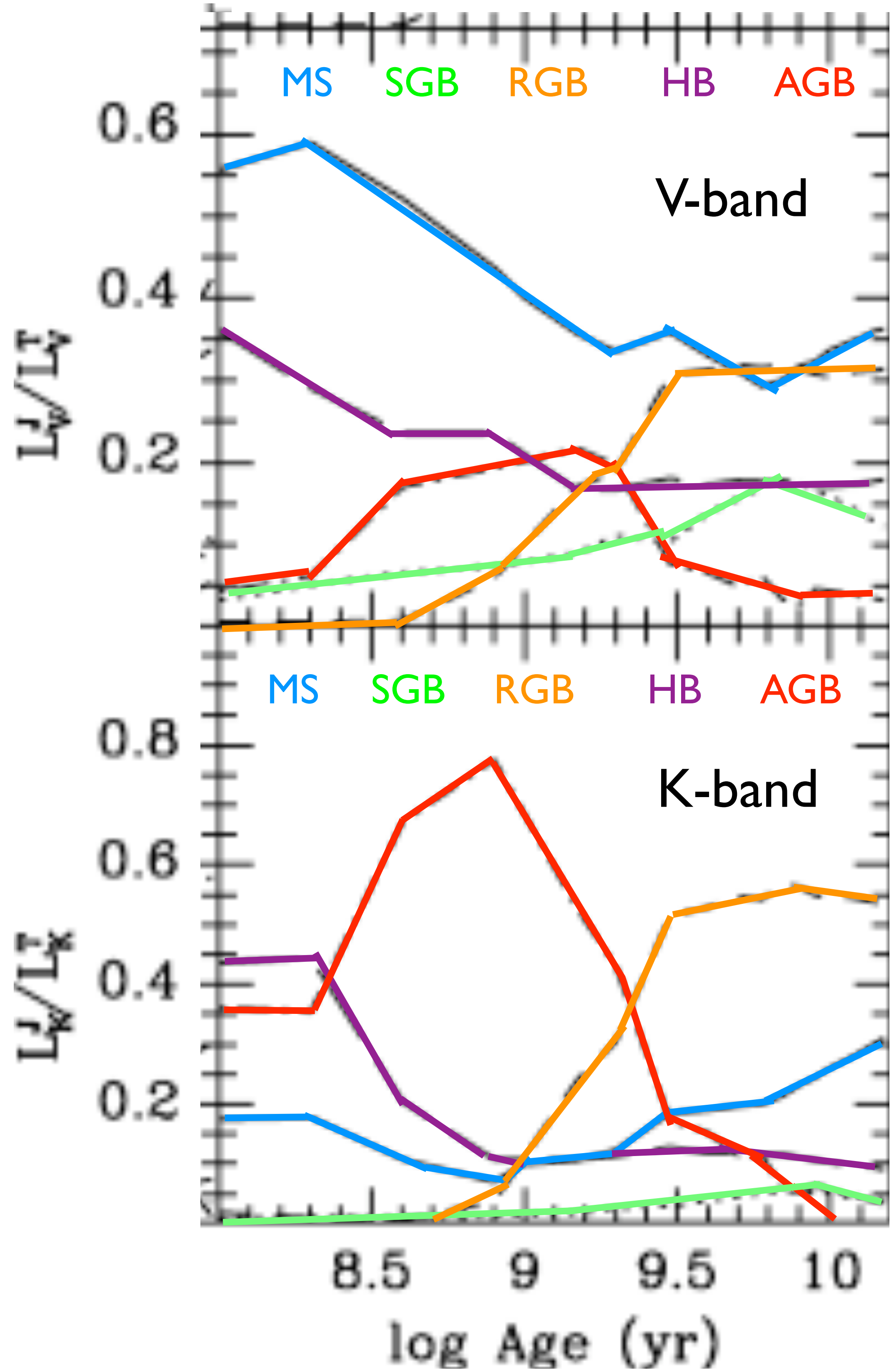
<u>The most luminous stars are few in number.</u>

<u>The most numerous stars are very faint.</u>

Total visible light in older populations dominated by RGB and upper MS.

For younger populations, most light on the MS (high mass stars not yet evolved.)

In K-band (infrared, 2.2um), RGB dominates for old ages, but note the huge contribution from AGB stars at 10^9 years - the TP-AGB.



Maraston (2005)

WHERE IS THE MASS?

On the MS, luminosity ~ $M^{3.5}$. So although light output of lower MS is small, its mass is significant. M-dwarfs are effectively dark matter, constrained only by gravity.

The Age-Metallicity Degeneracy

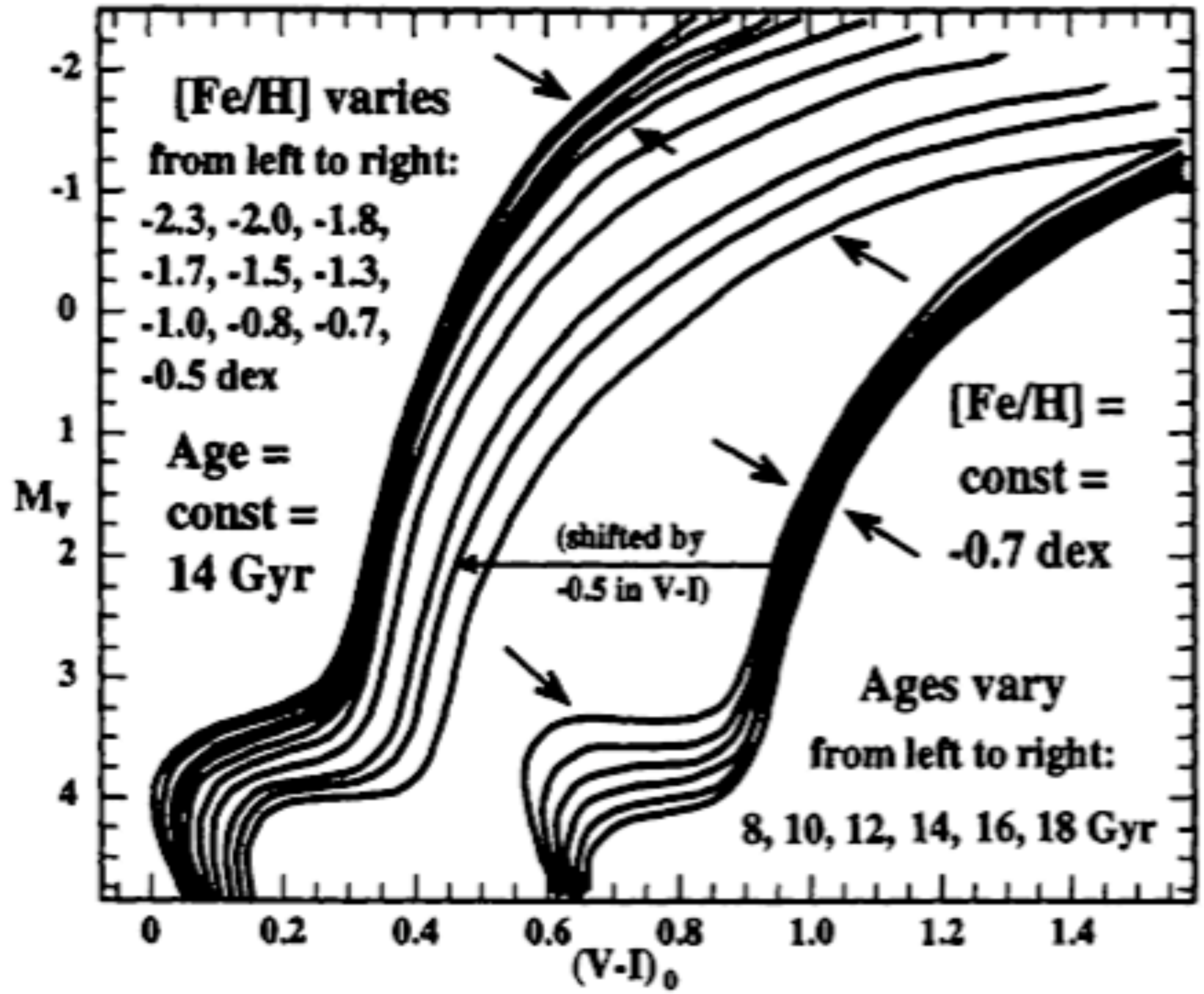
THE INFAMOUS DEGENERACY

Recall behaviour of isochrones:

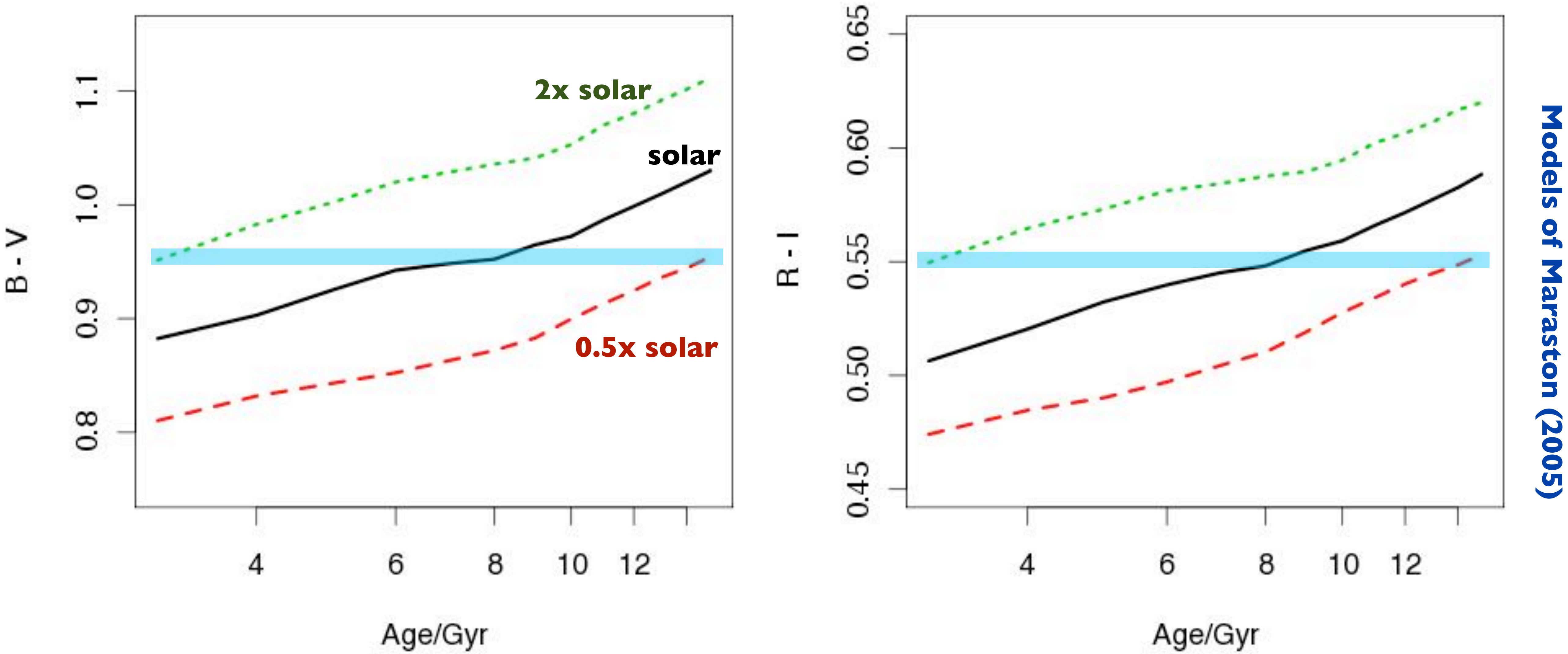
AGE -- Increasing age reddens the population by adding more luminosity to the RGB, removing hot stars from the MS.

METALLICITY -- Increasing Metallicity reddens the population by changing the high-temperature opacities.

(Metallicity also reddens the population through increased line blanketing in cool phases.)

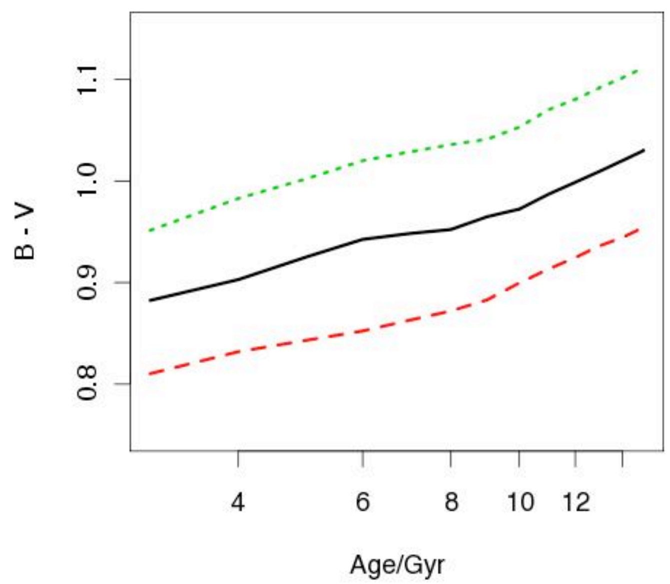


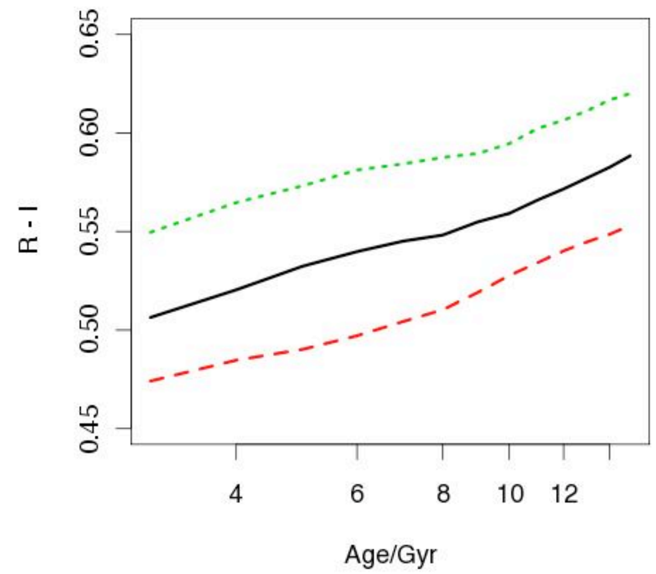
Age-Metallicity Degeneracy

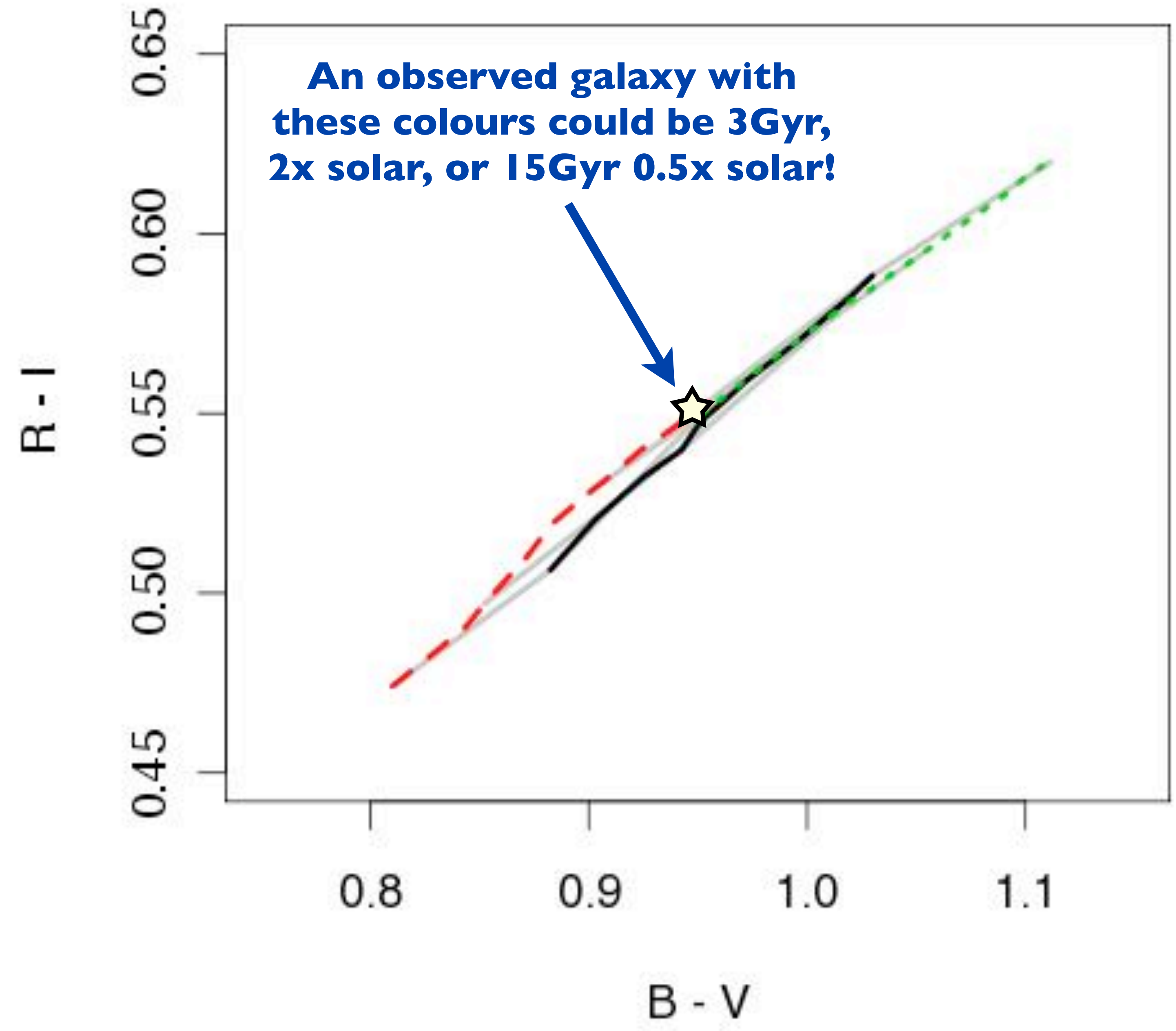


Because both age and metallicity cause the population to redden, a single colour is not enough to disentangle the parameters.

Age-Metallicity Degeneracy





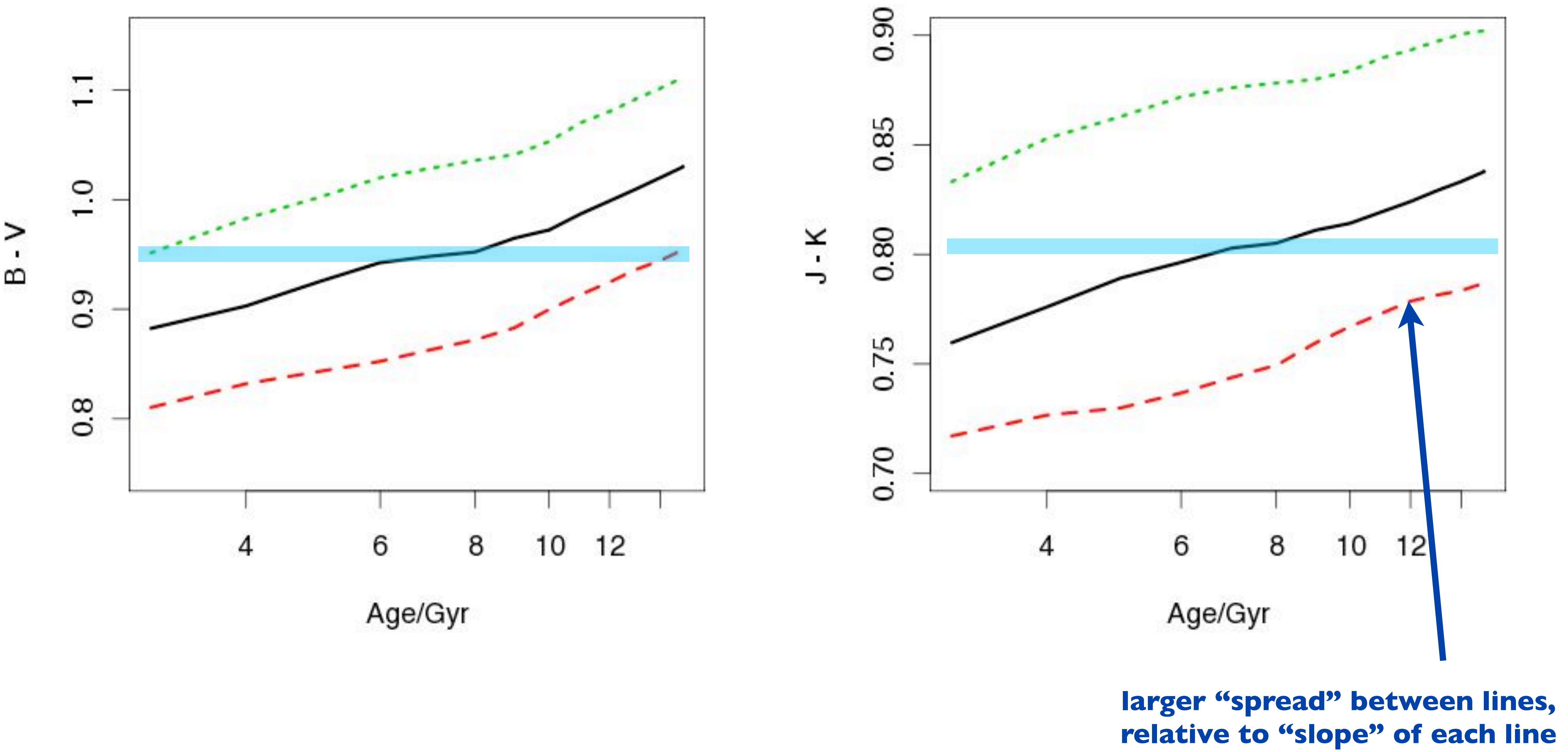


A pair of (optical) colours is no help either!

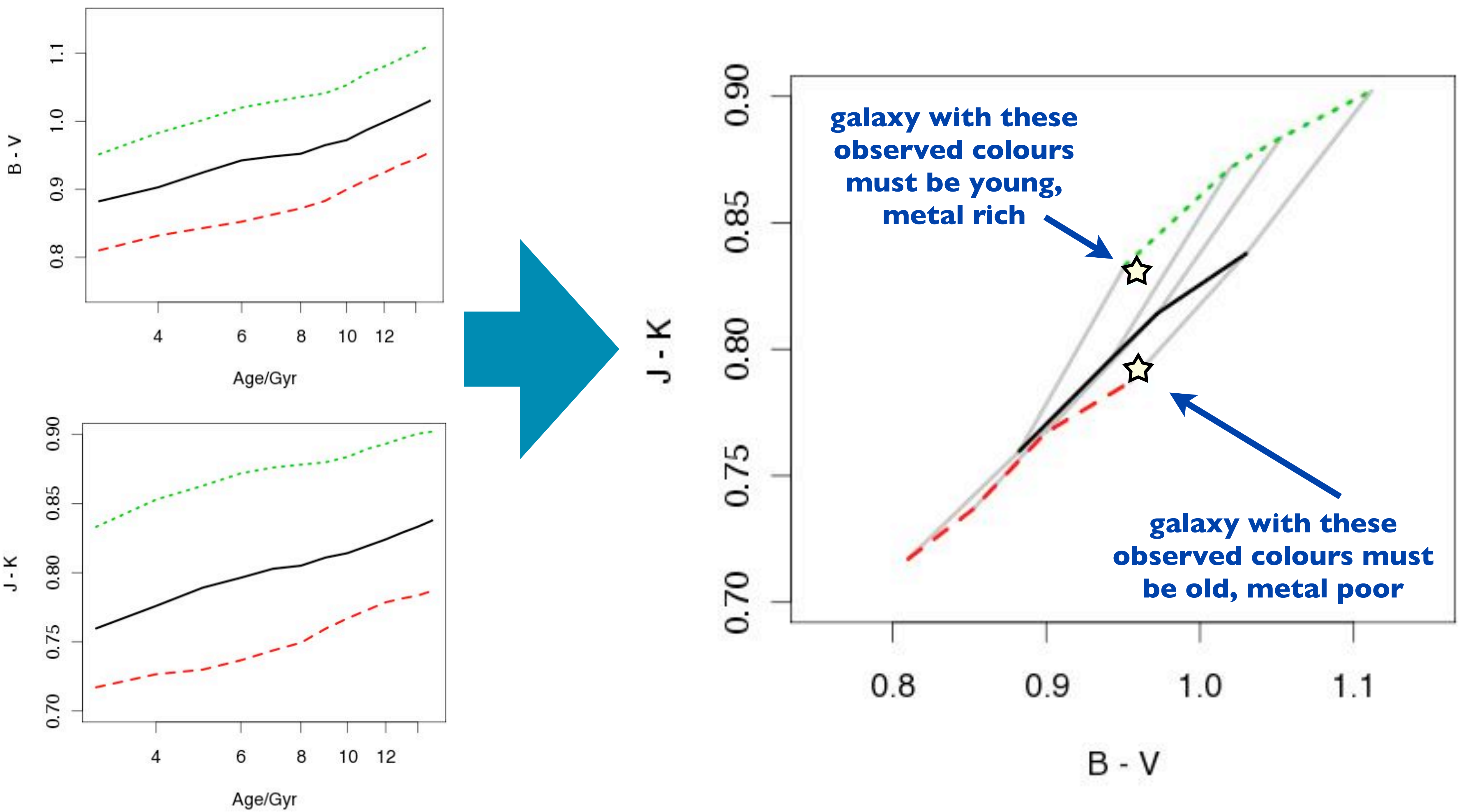
Beating the degeneracy in the IR?

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...

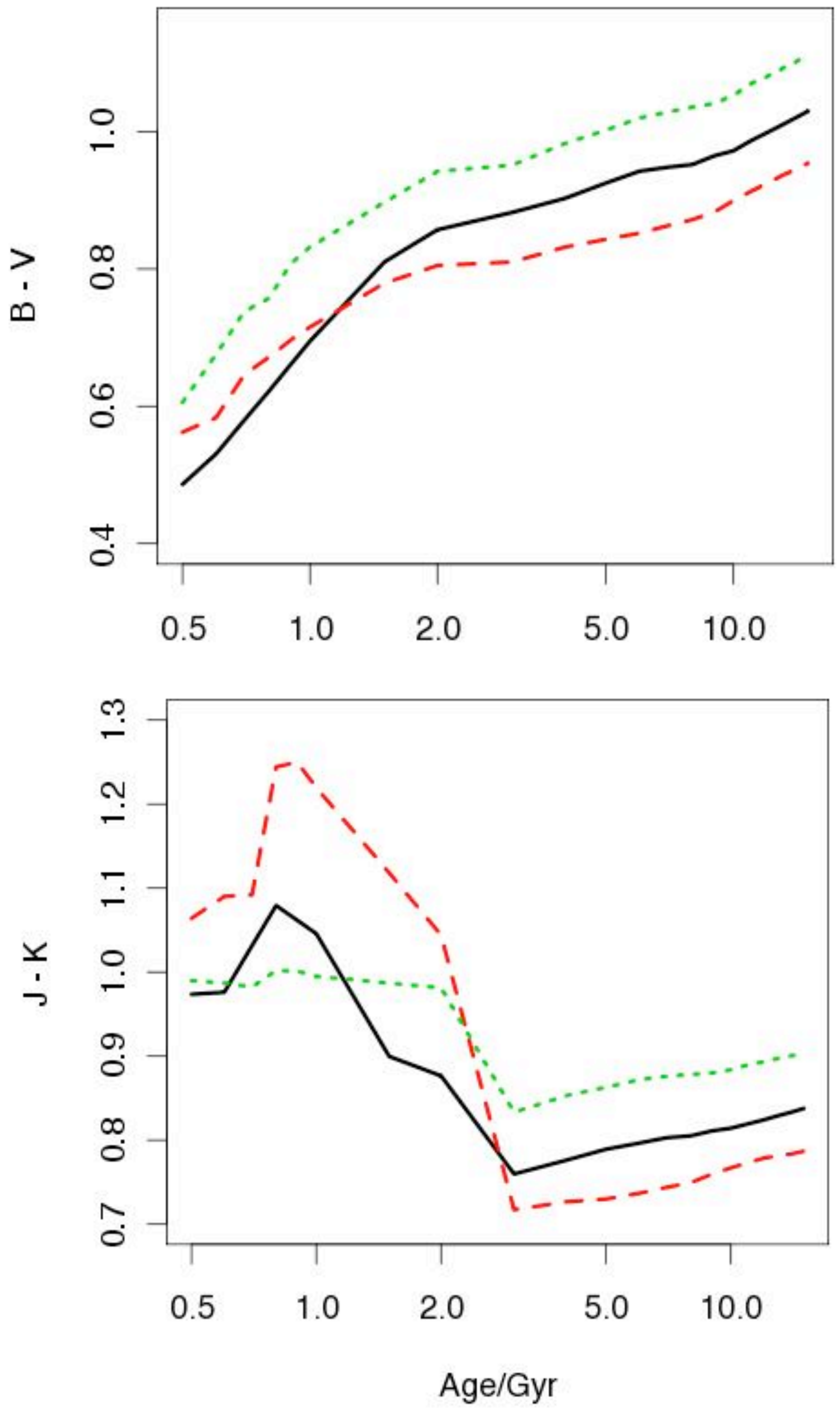


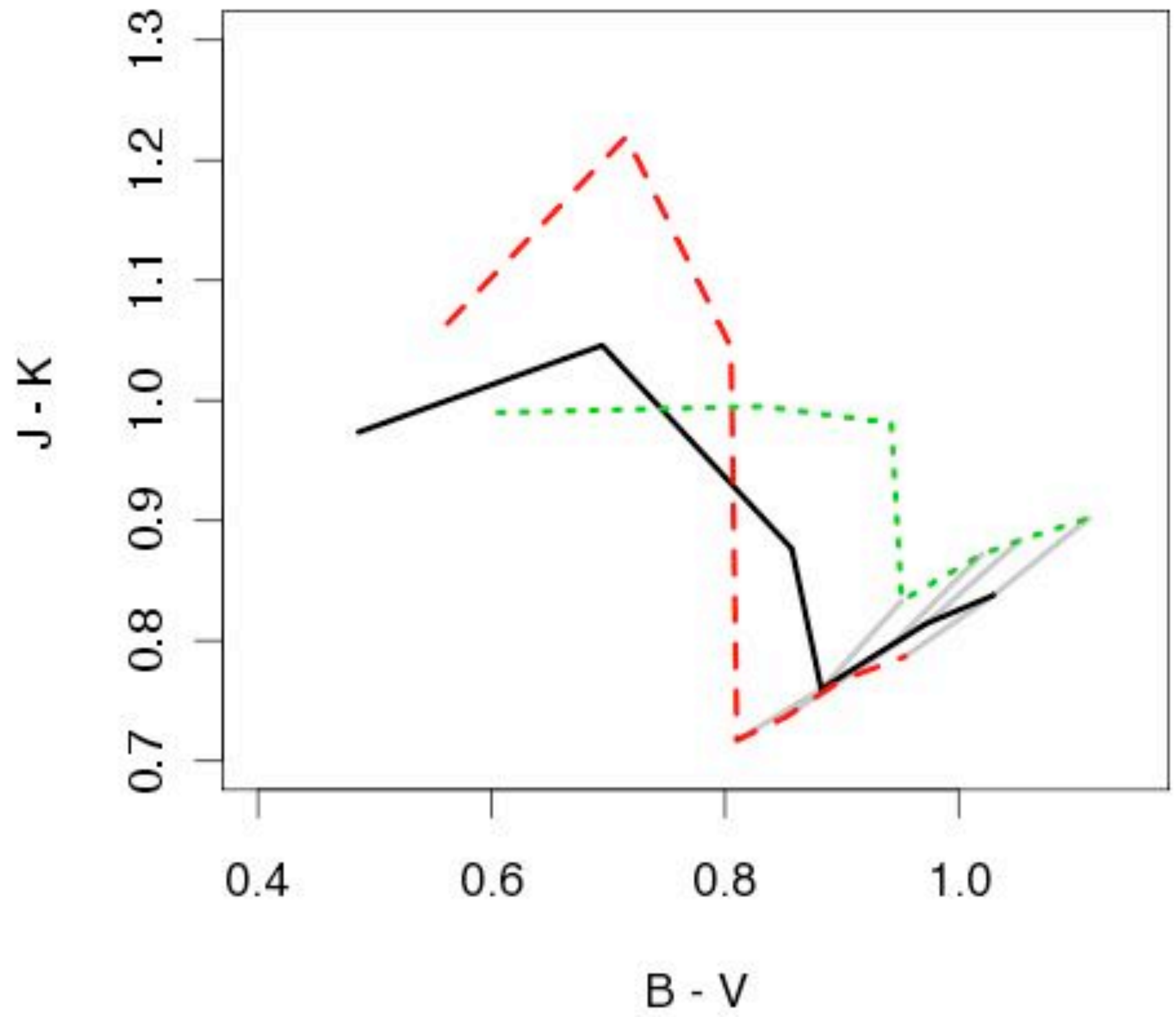
Beating the degeneracy in the IR?



In principle, this is possible, but it is clearly hard! Would need very accurate photometry in the IR. But it's a chink in the armour of the age-metallicity degeneracy.

At younger ages: TP-AGB effects





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)

Beating the degeneracy in the UV?

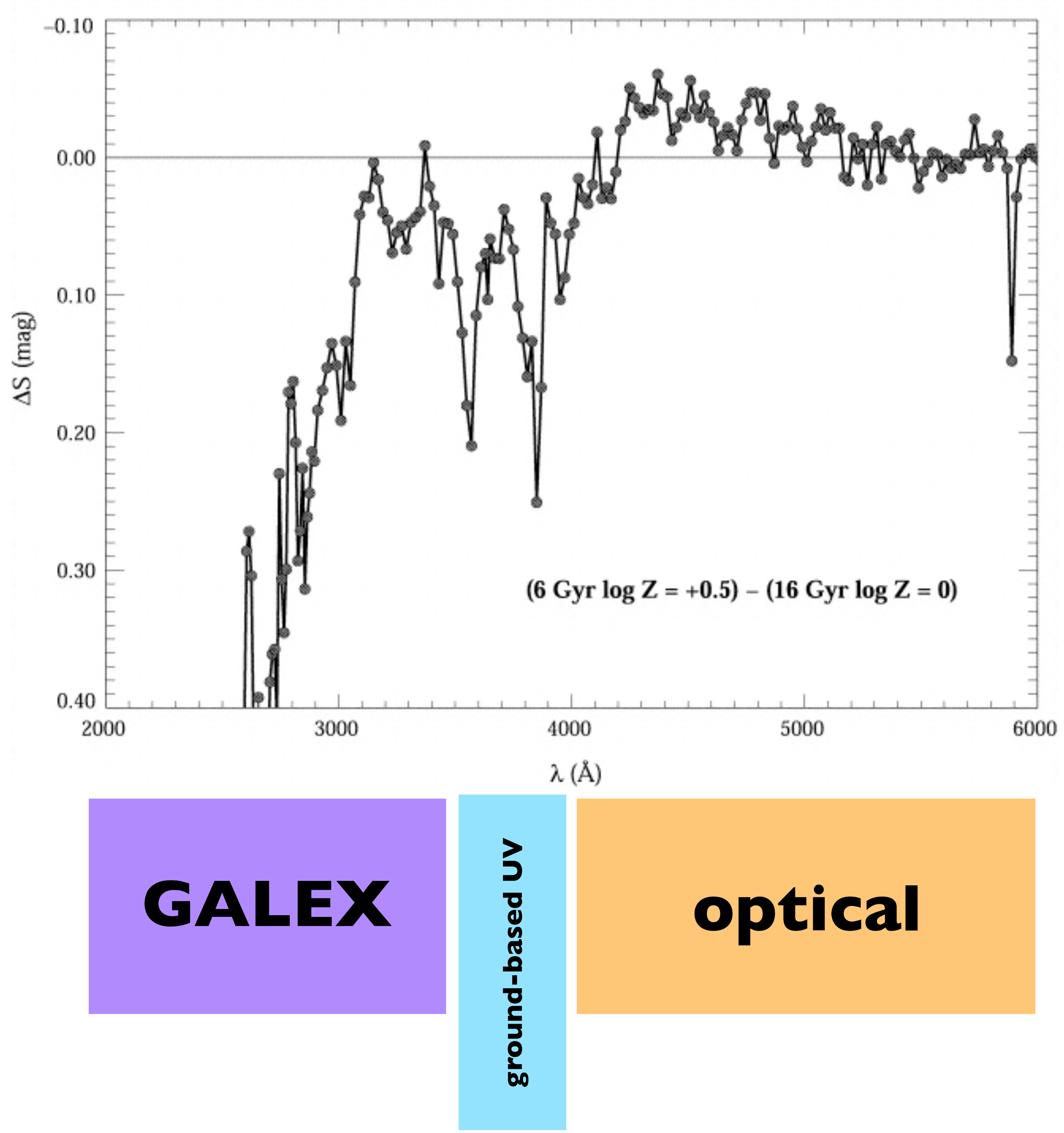
Based on MS+RGB alone, we would expect the UV to be dominated by the MSTO.

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

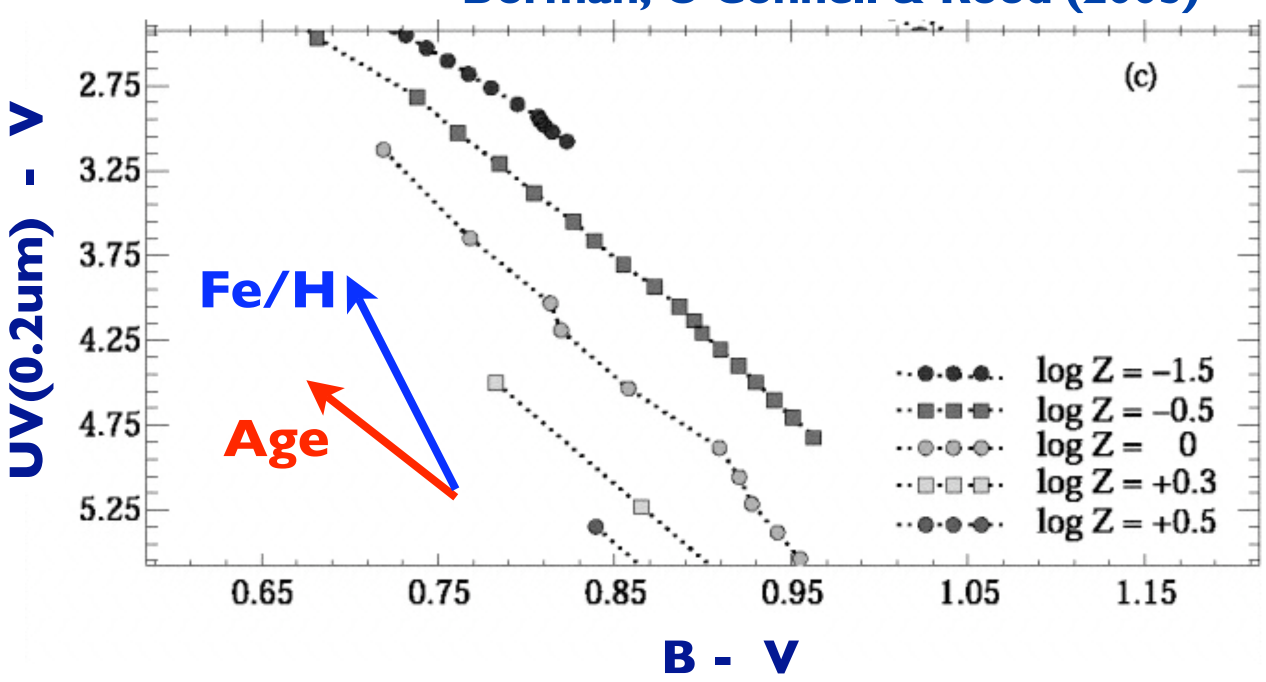
But still have some degeneracy effect from Fe/H dependence of isochrone...

...And have to worry about other hot star contributions: e.g. BHB, BS.

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



Dorman, O'Connell & Rood (2003)



M67: the scary cluster

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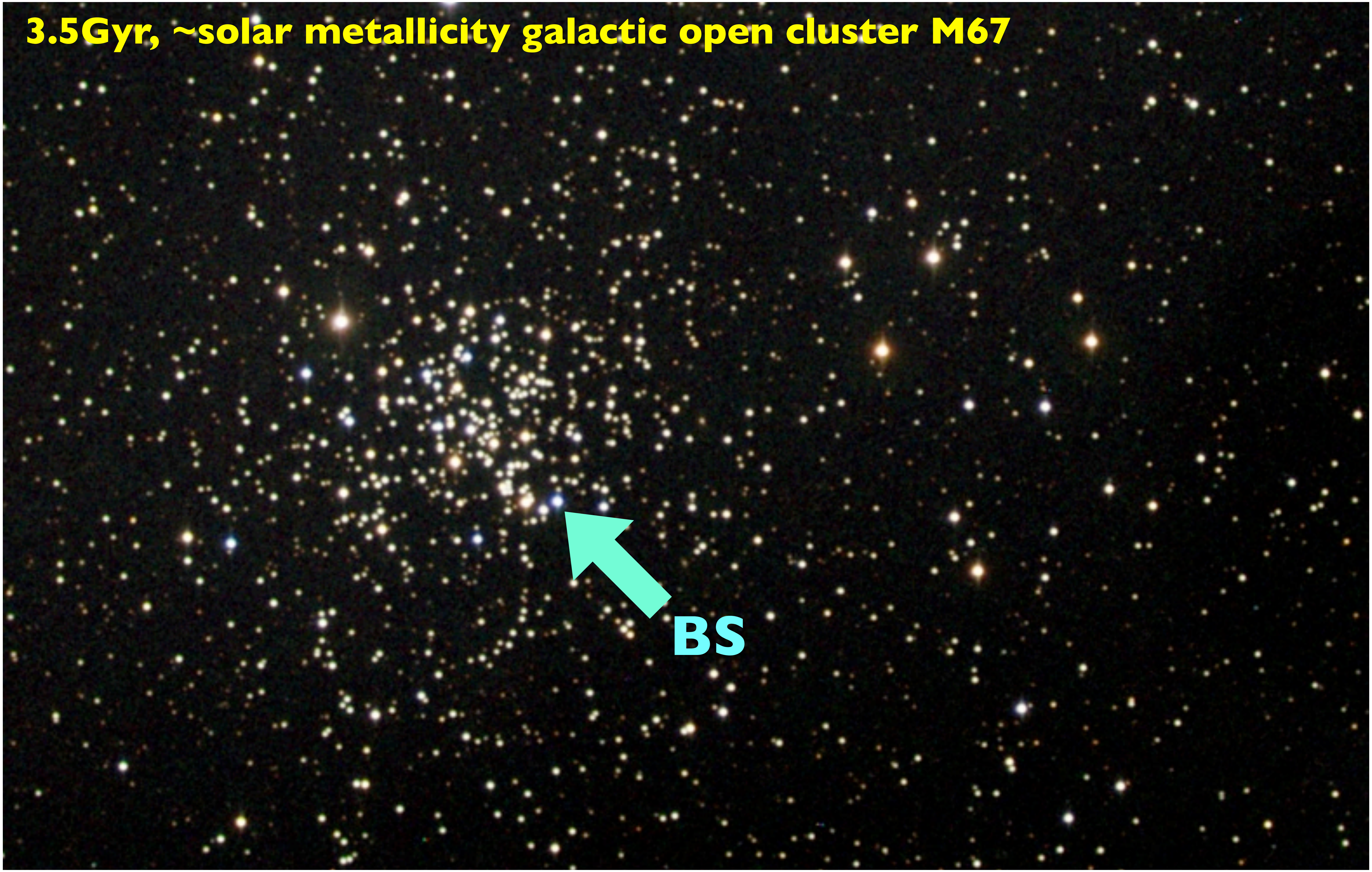
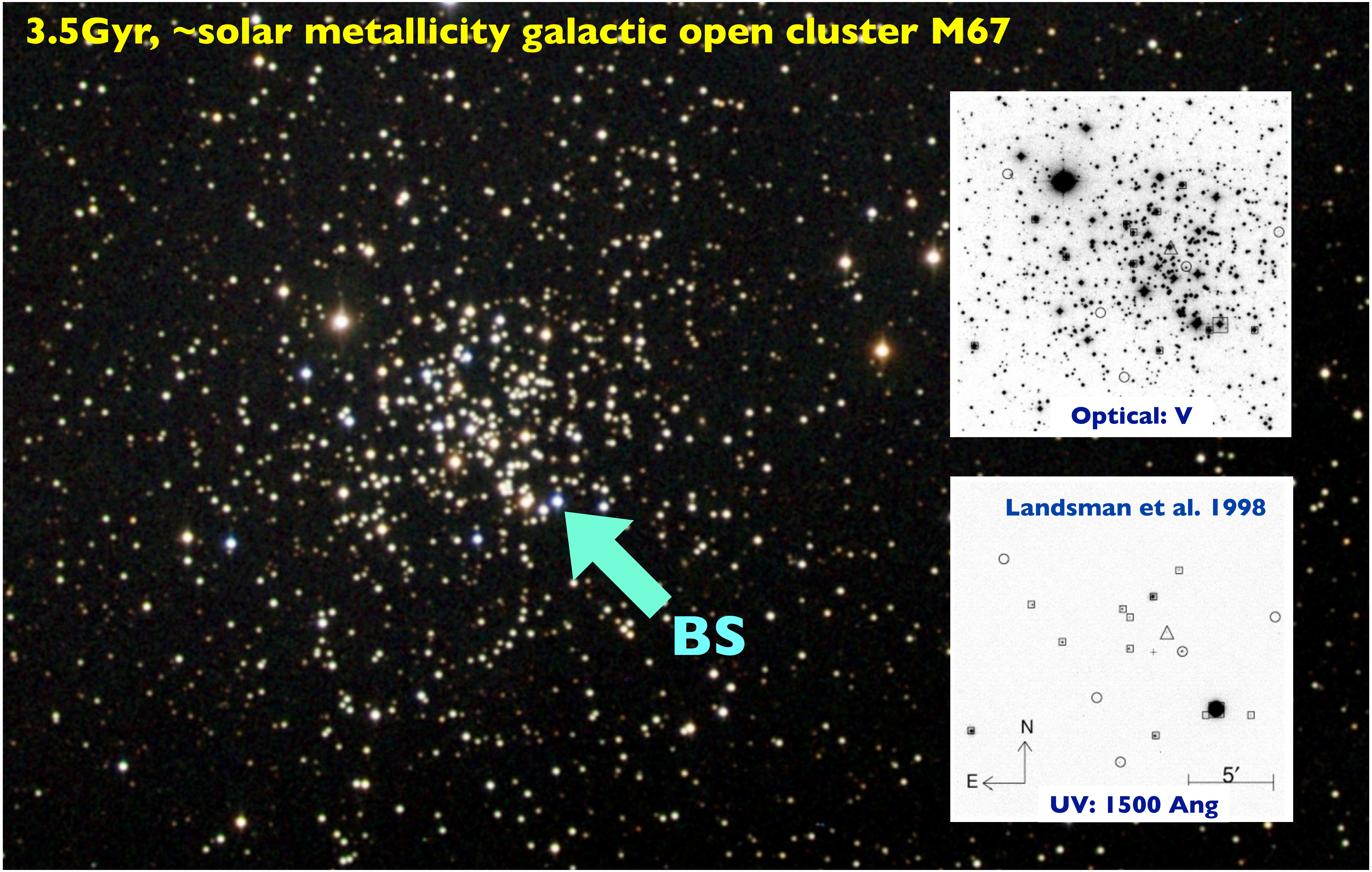


M67: the scary cluster



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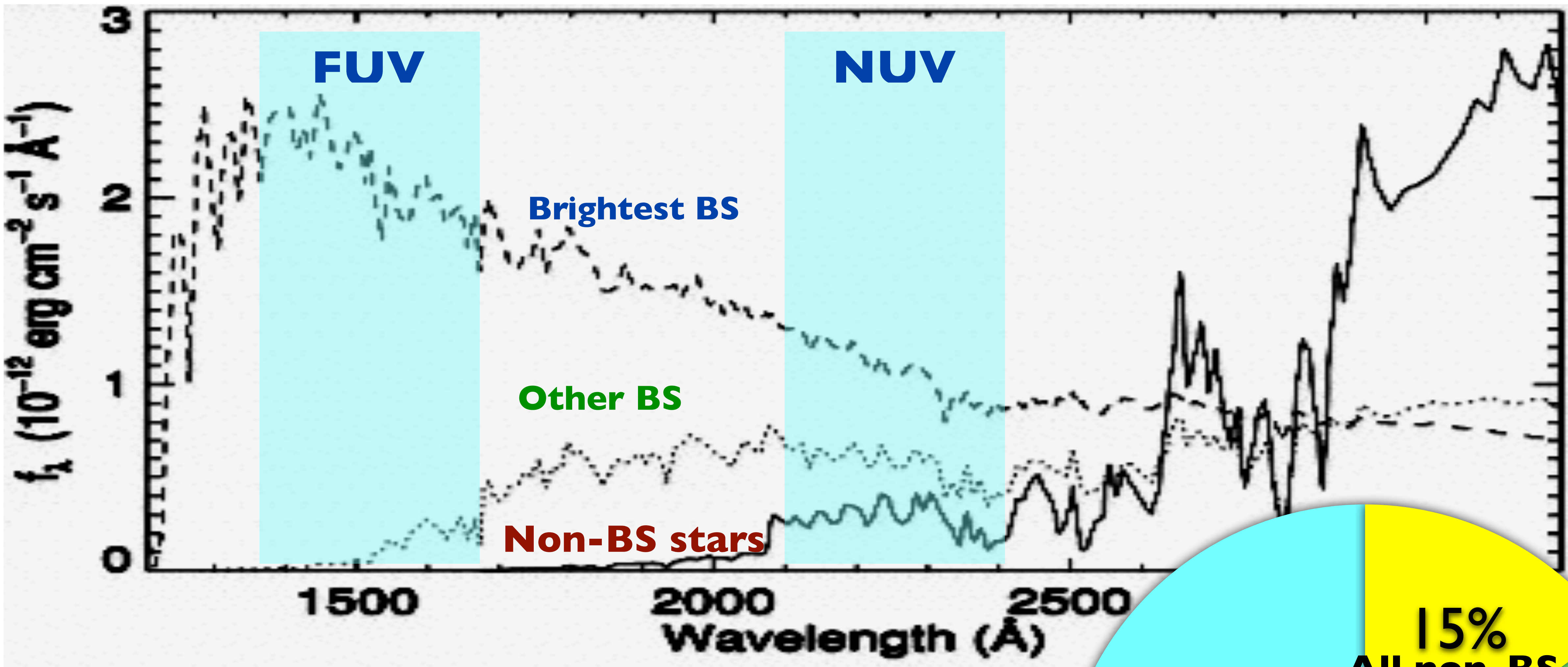
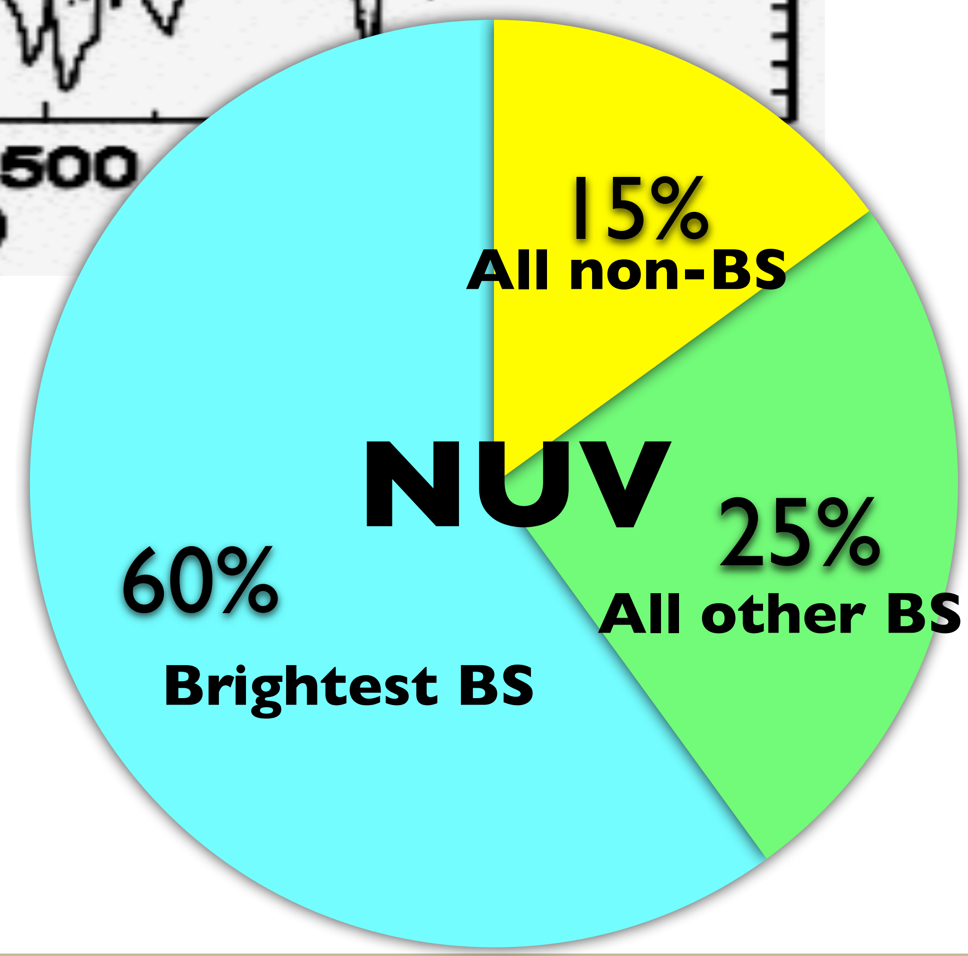




An old-ish, ~solar metallicity stellar population.

Blue stragglers dominate the UV emission.

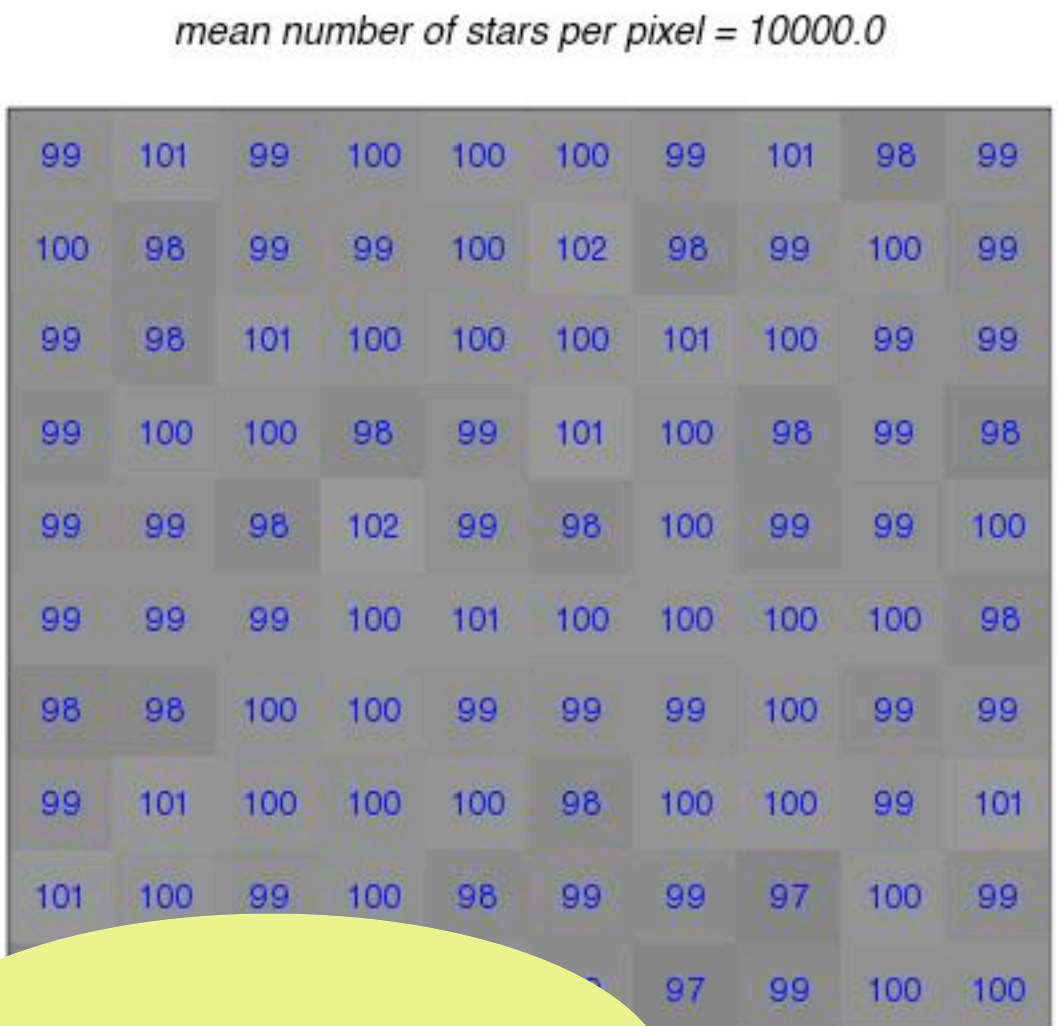
BS content of M67 is extreme within MW...

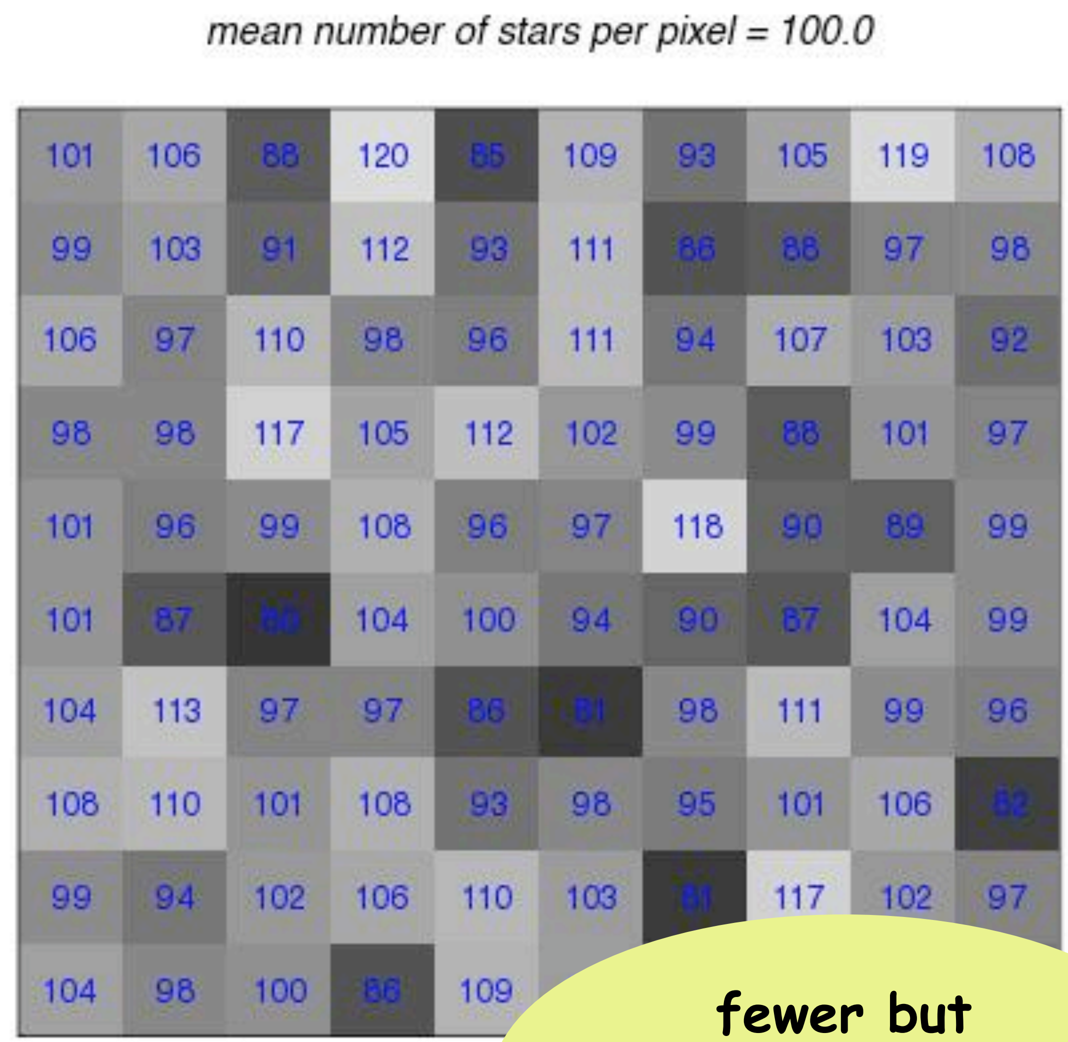
But we have no way to predict how many BS will be formed within a given population!!

So how much can we learn from UV in old galaxies??

Surface Brightness Fluctuations

Two "galaxies" with same total light per pixel, i.e. same surface brightness:





lots of faint stars (each star has flux=0.01)

fewer but brighter stars (each star has flux=1)

Speckly pattern arises from poisson fluctuations in the number of stars per pixel.

Surface Brightness Fluctuations

Consider a population composed of identical stars each contributing flux f.

Mean number of stars per spatial resolution element is N.

Mean total flux per element is

$\langle F \rangle = f\,N.$

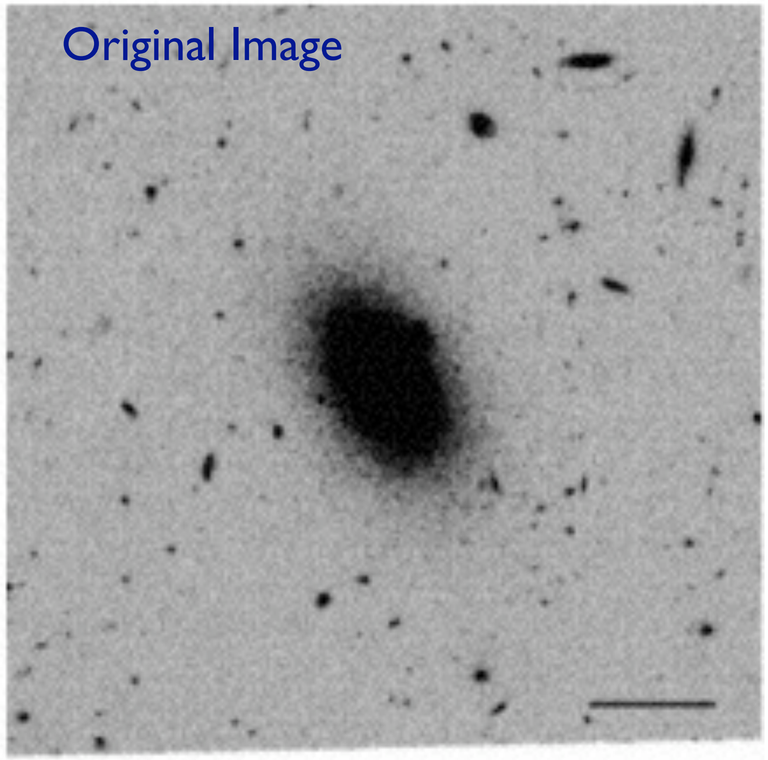
Variance in flux per element is

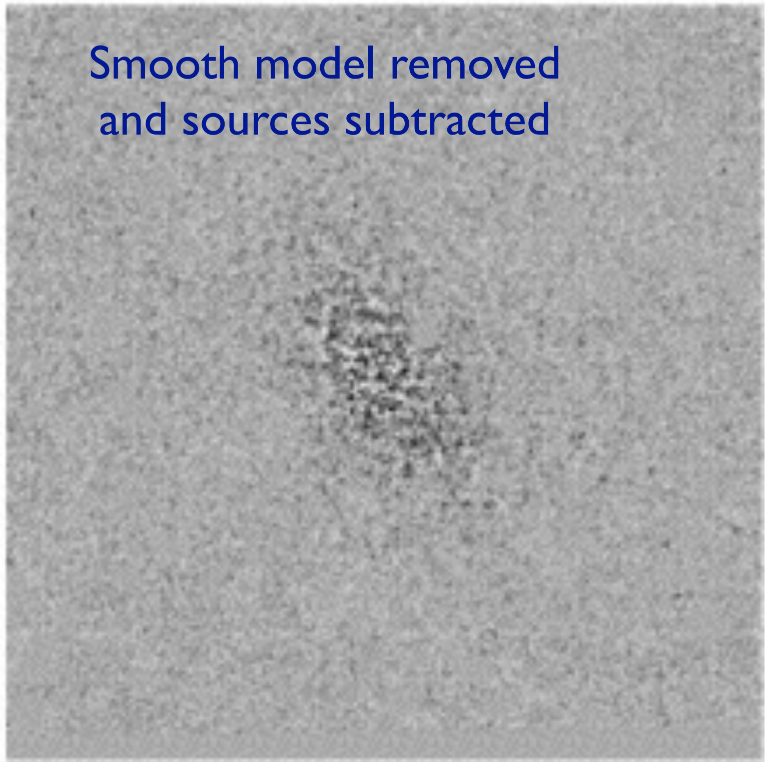
$Var(F) = f^2\,Var(N) = f^2\,N.$

And the ratio between these is

$R = Var(F) / \langle F \rangle = f$

So: fluctuations / surface-brightness --> flux of individual stars!





Cantiello et al. (2007)

Surface Brightness Fluctuations

$$\bar{L} = \frac{\int F^2(M) \, . \, N(M) \, dM}{\int F(M) \, . \, N(M) \, dM}$$

fluctuation luminosity

$F(M) = L(M) \, . \, B(Teff(M), g(M), Z)$ =
luminosity in band for star of initial mass M

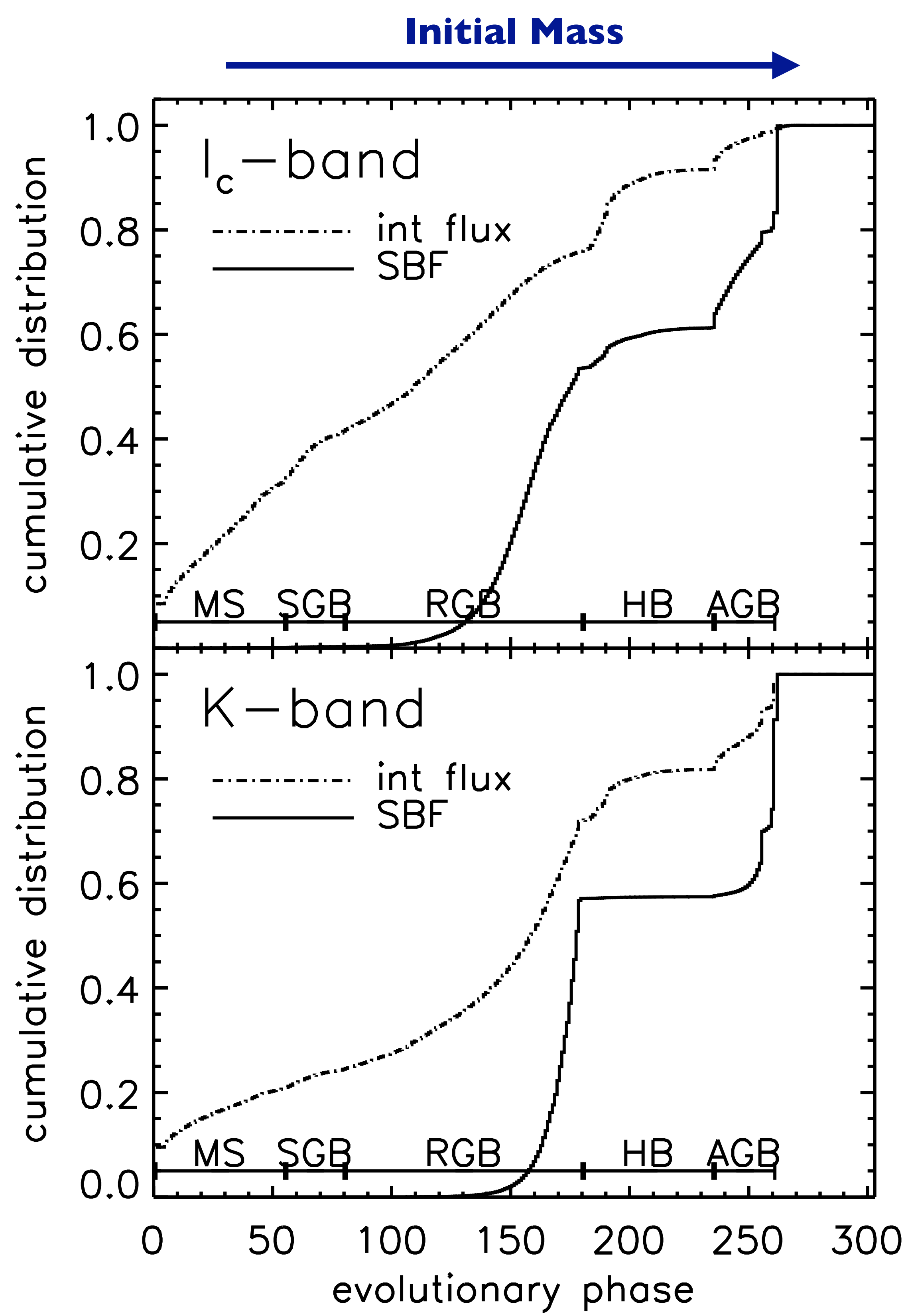
SBF for population of stars

In a real population, there is a distribution of star fluxes, and the fluctuations are given by ratio of first and second moments of the luminosity.

The L^2 dependence means that the SBFs are dominated by the brightest stars.

Integrated flux in a given band is widely distributed among evolutionary phases.

But SBFs are contributed overwhelmingly by the phases that are brightest within the band. For K-band this is the RGB tip, and the AGB.



Liu et al. (2000)

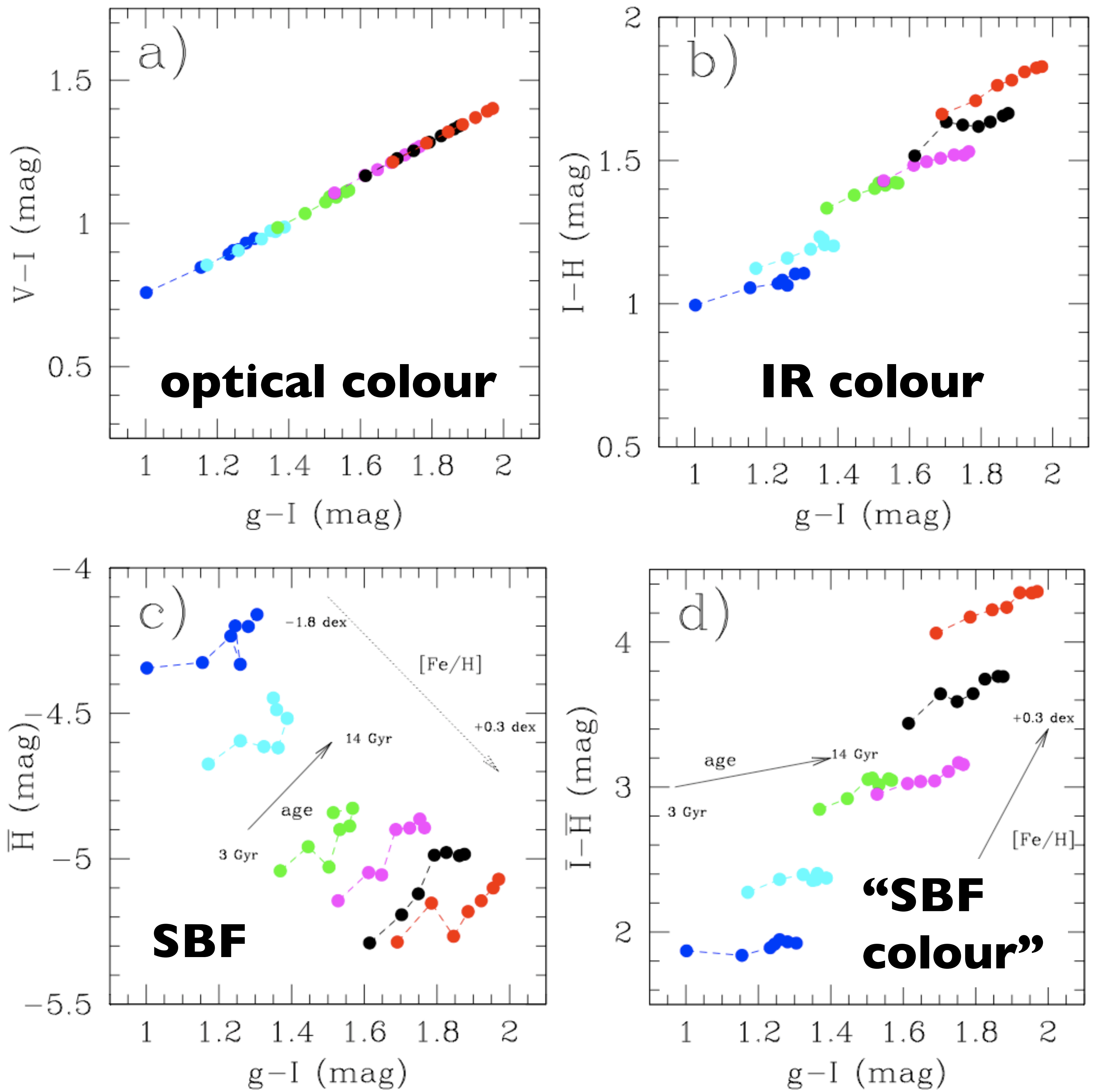
Surface Brightness Fluctuations

BREAKING THE DEGENERACY WITH SBF

Can easily compute fluctuation magnitudes from population sysnthesis models.

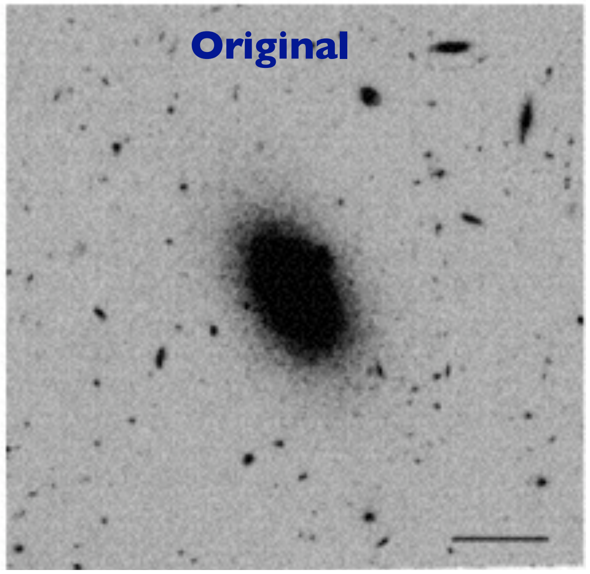
Can also form "SBF colour" from difference of SBF magnitude in different bands.

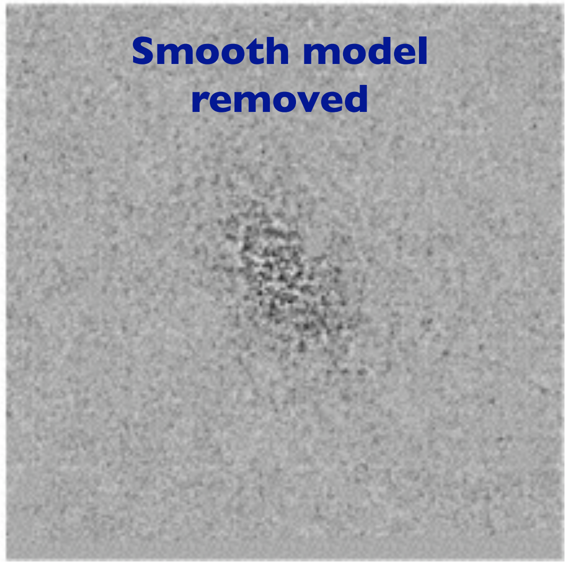
Include with other data to make grids that break the age-metallicity degeneracy.

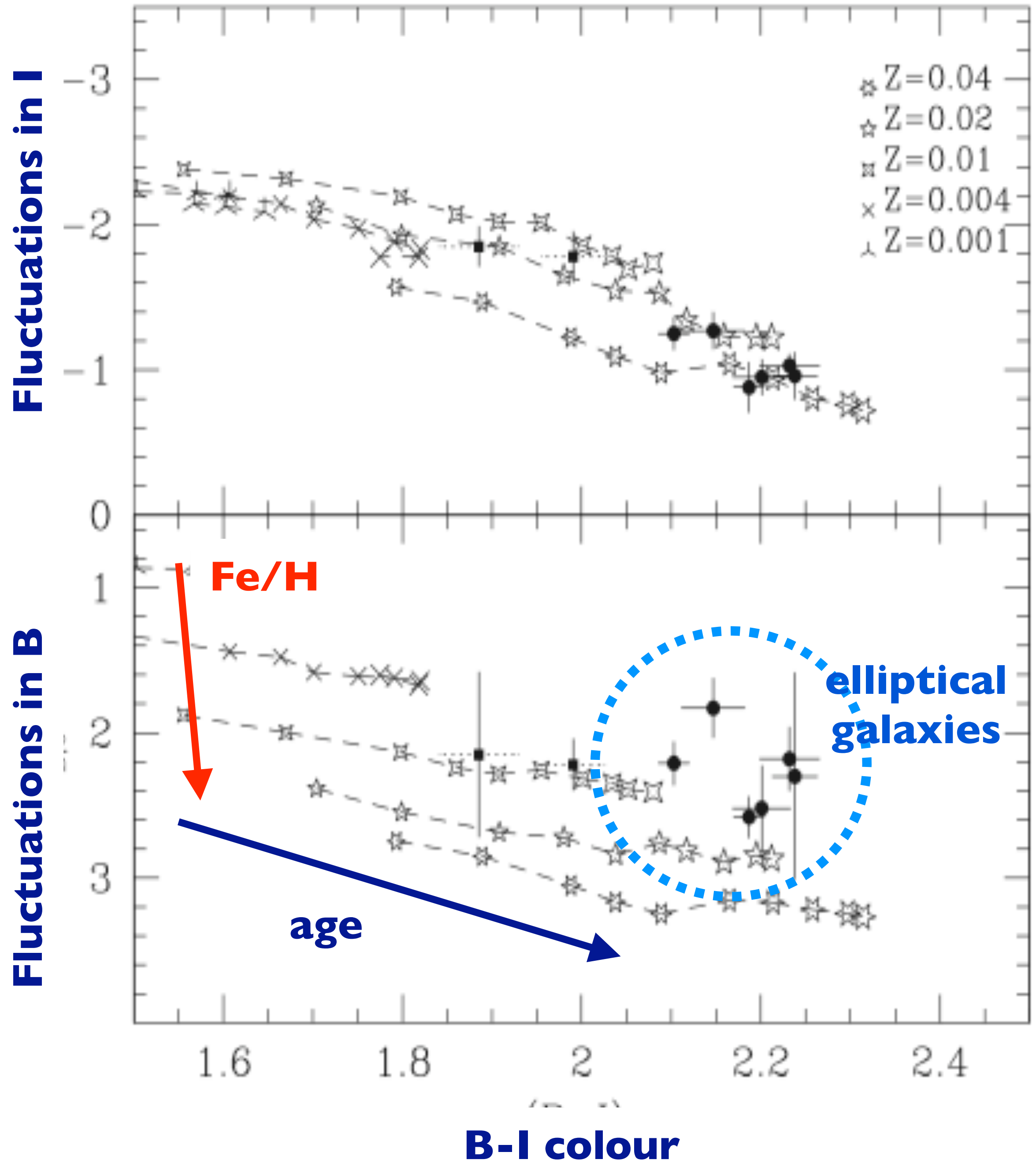


models of Raimondo et al. (2005)

SBF observations







Cantiello et al. (2007)

Need small N per independent spatial element, so high spatial resolution, but possible from ground-based telescopes out to 50 Mpc.

Careful work needed to subtract GCs etc.

Signal is stronger at redder wavelengths.

Stronger fluctuations at bluer wavelengths than expected in the models!

Suggests blue horizontal branch stars from a metal-poor sub-component of otherwise metal-rich galaxies.

Unresolved Stellar Pops: 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, which are dominated by very luminous blue OB stars.)

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 expensive to measure), and show that these are much more effective at distinguishing age and metallicity effects.

END OF LECTURE 11