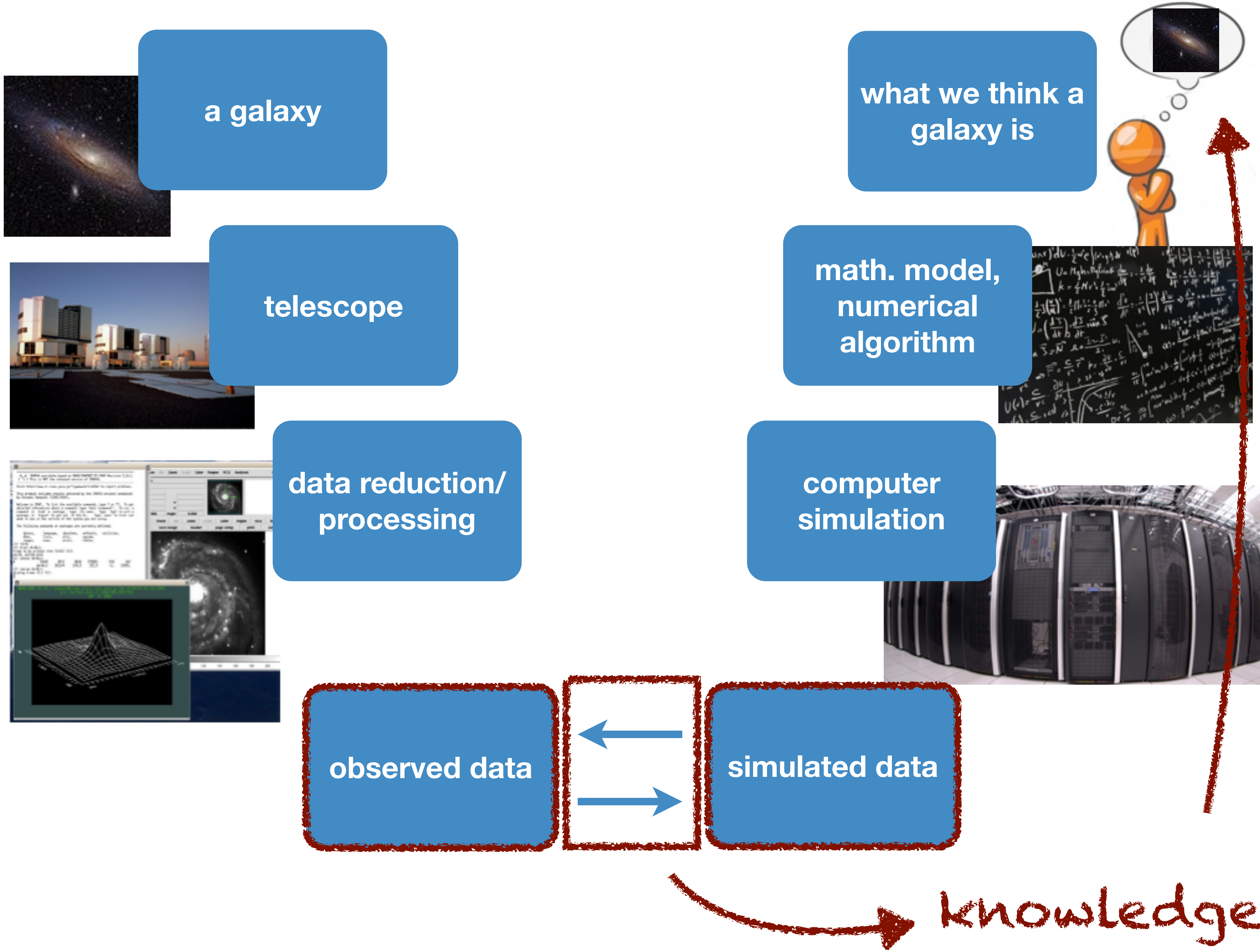
Síntese de Populações Estelares

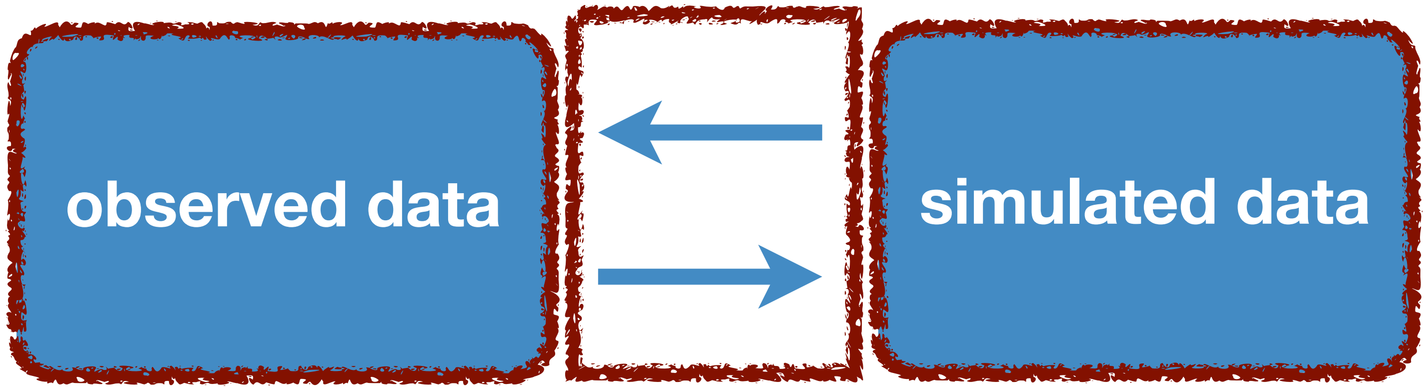
aula 10/junho

M. Salaris & S. Cassisi, 2006 "Evolution of Stars and Stellar Populations" e literatura

Contexto


a galaxy
telescope
data reduction/ processing
observed data
simulated data
computer simulation
math. model, numerical algorithm
what we think a galaxy is
knowledge

What kind of models we need to study the stellar content in an integrated spectrum?



Stellar population models

- The most important tool for deriving information on the stellar content of galaxies
    - dates back to Tinsley (1968)
    - citations to Bruzual & Charlot ’03 as of nov/12: > 3200

Why do we care to study the stellar content of a spectrum?

- **Science from stellar population modeling**
    - Age distributions => Star formation history
    - Metallicity distribution function, chemical abundances => Chemical evolution
    - Stellar masses and M/L ratios
    - Ionising population
    - Dust contribution

- But what is a stellar population model?
- What is their role in measuring ages and abundances in galaxies?

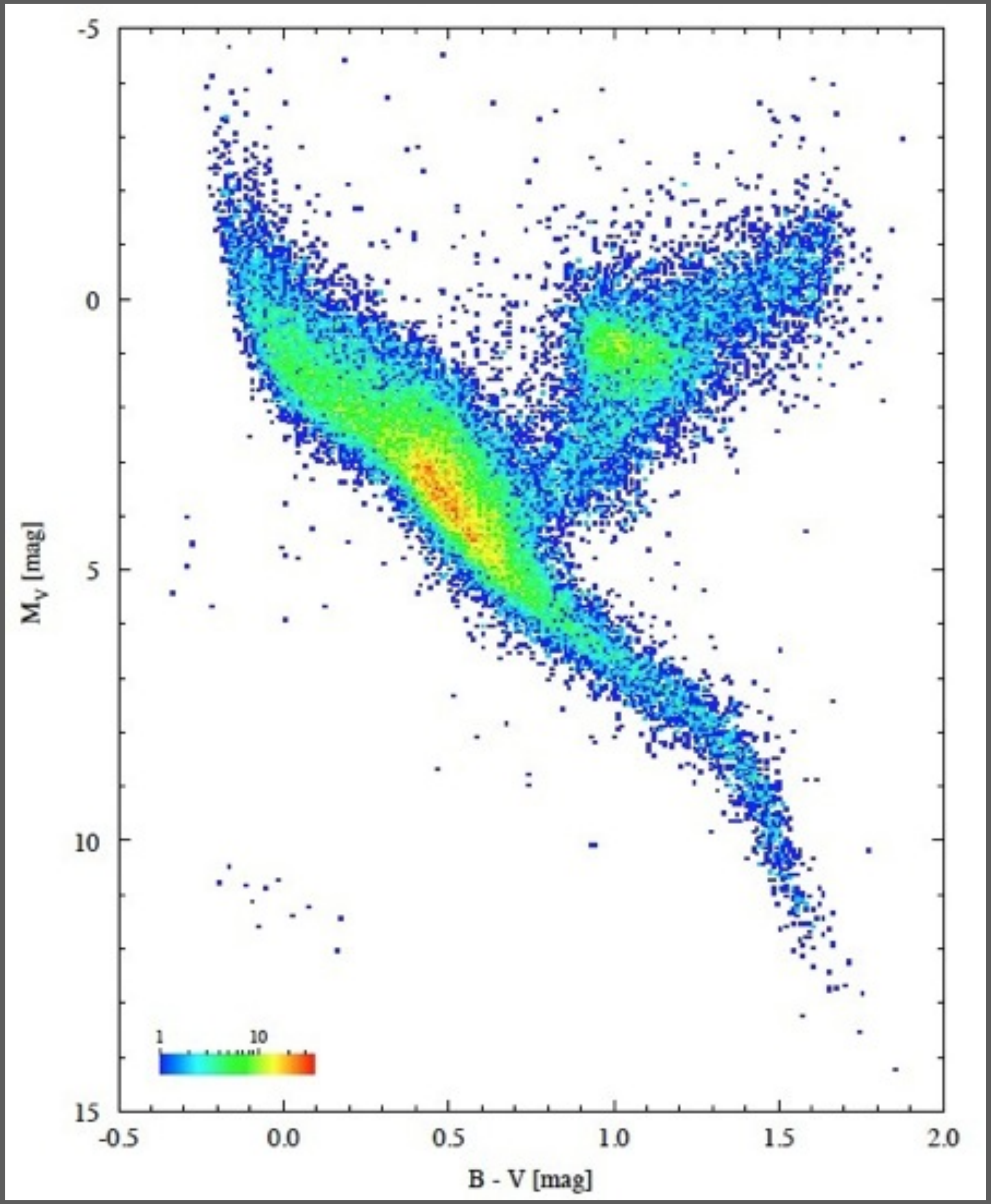
Revisão de diagrama HR e CMD

Diagrama HR

"Scatter plot" da posição as estrelas no plano:

- Tipo Espectral vs. Magnitude Absoluta (original)
- Cor versus Magnitude (CMD ou diagrama observacional)
- Teff vs. Luminosidade (diagrama HR teórico)

- Invariavelmente, a luminosidade cresce com *y* e a temperatura diminui com *x*



Hertzsprung-Russell (M_V, B-V) diagram for the 41704 single stars from the Hipparcos Catalogue with relative distance precision sigma_pi/pi < 0.2 and sigma_(B-V) less than or equal to 0.05 mag. Colours indicate number of stars in a cell of 0.01 mag in (B-V) and 0.05 mag in V magnitude (M_V).

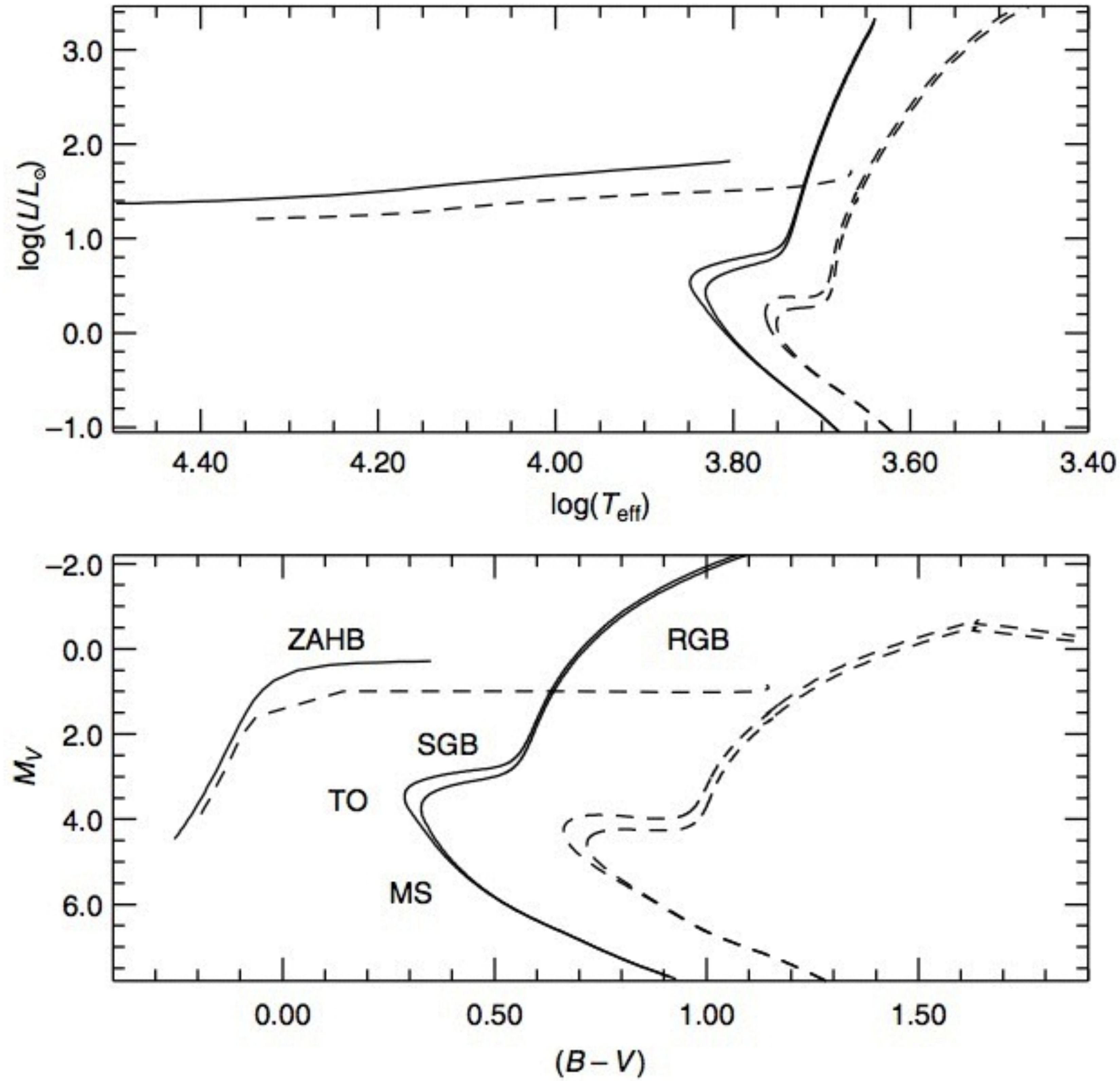


Figure 9.4 HRD and CMD of two pairs of isochrones from the ZAMS to the ZAHB, with ages $t = 10$ and 12.5 Gyr, $Z = 0.0001$ (solid line) and 0.02 (dashed line). The various evolutionary stages along the most metal-poor isochrone are marked

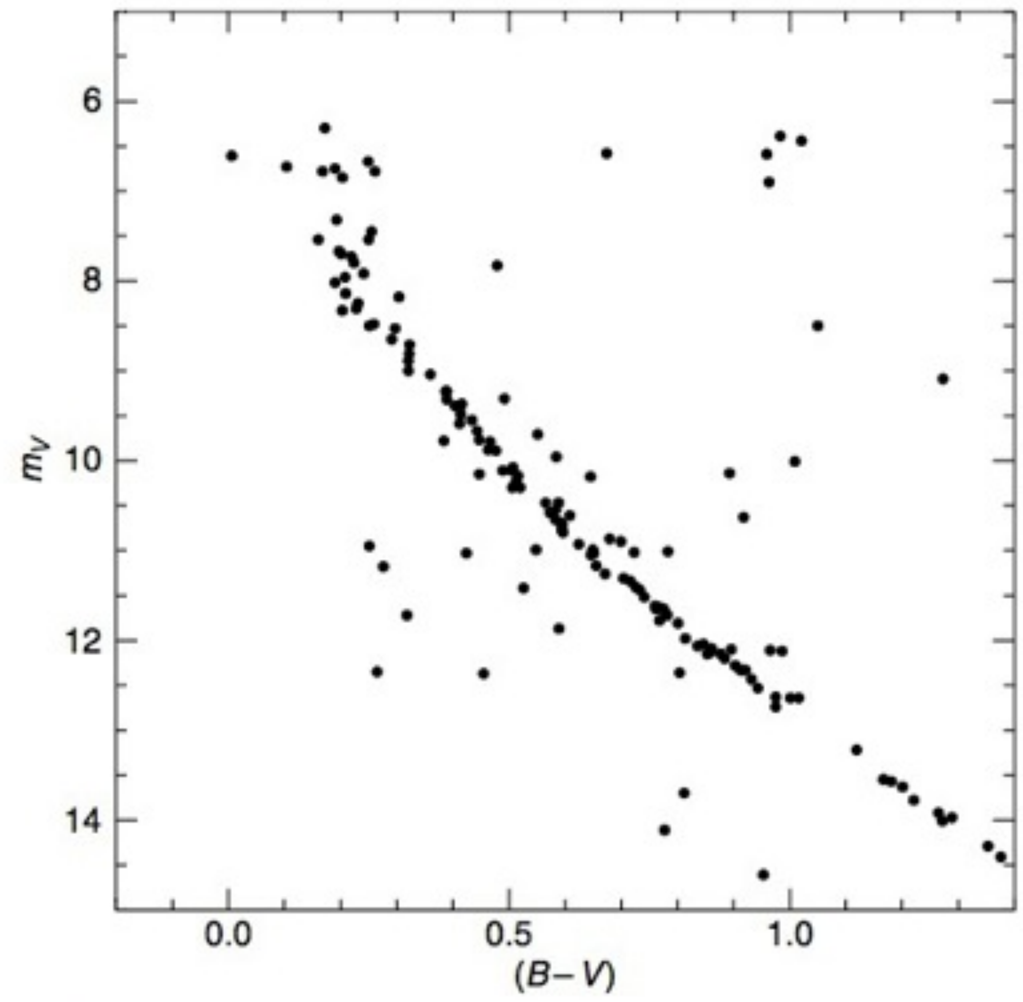


Figure 8.7 CMD of the open cluster Praesepe using the *BV* Johnson filters

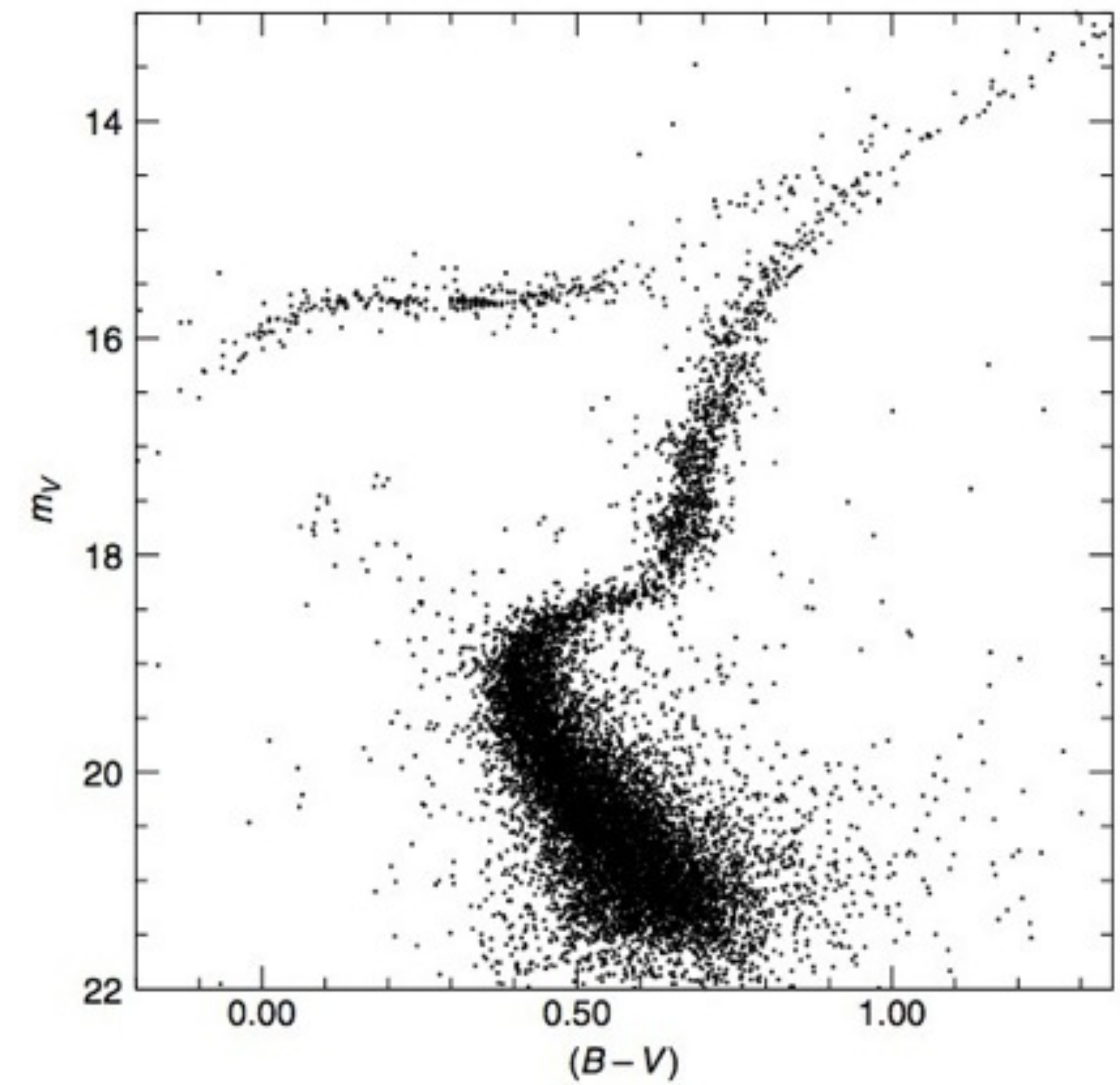
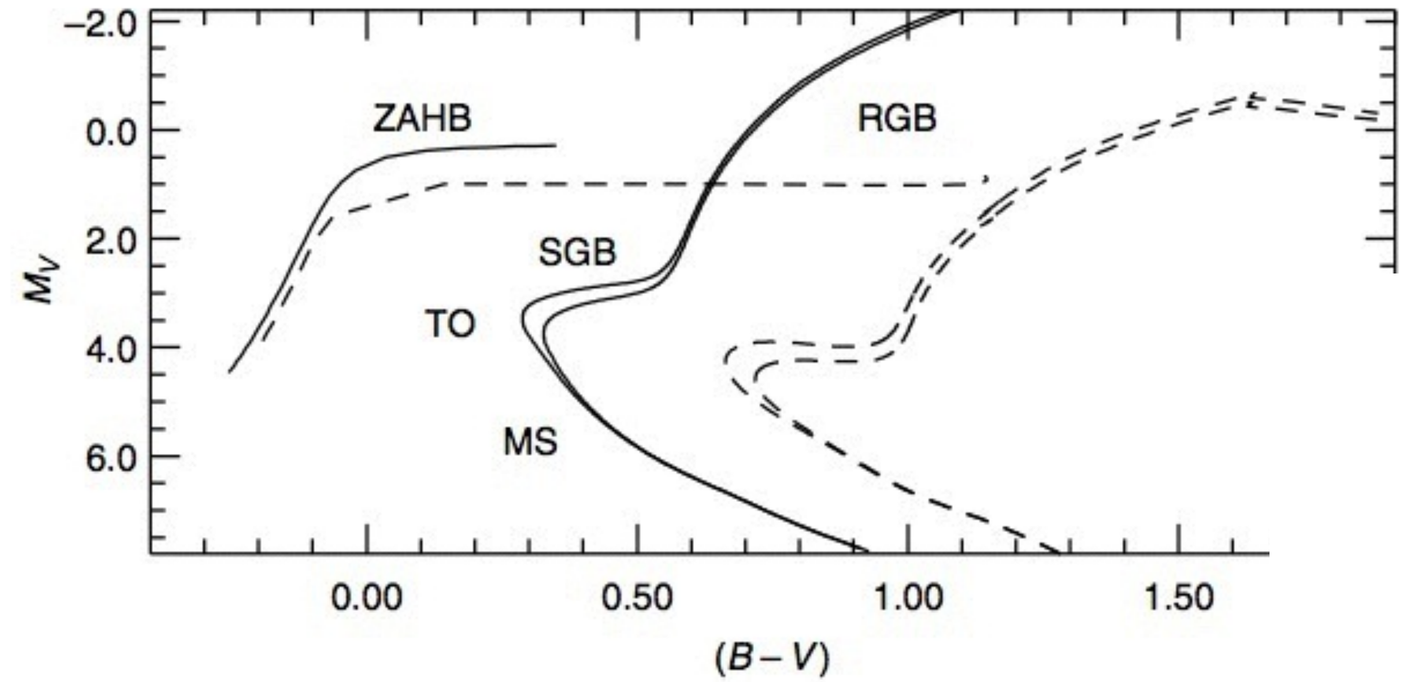


Figure 8.8 CMD of the globular cluster M3 using the Johnson *BV* filters

CMD

Aglomerados de diferentes idades



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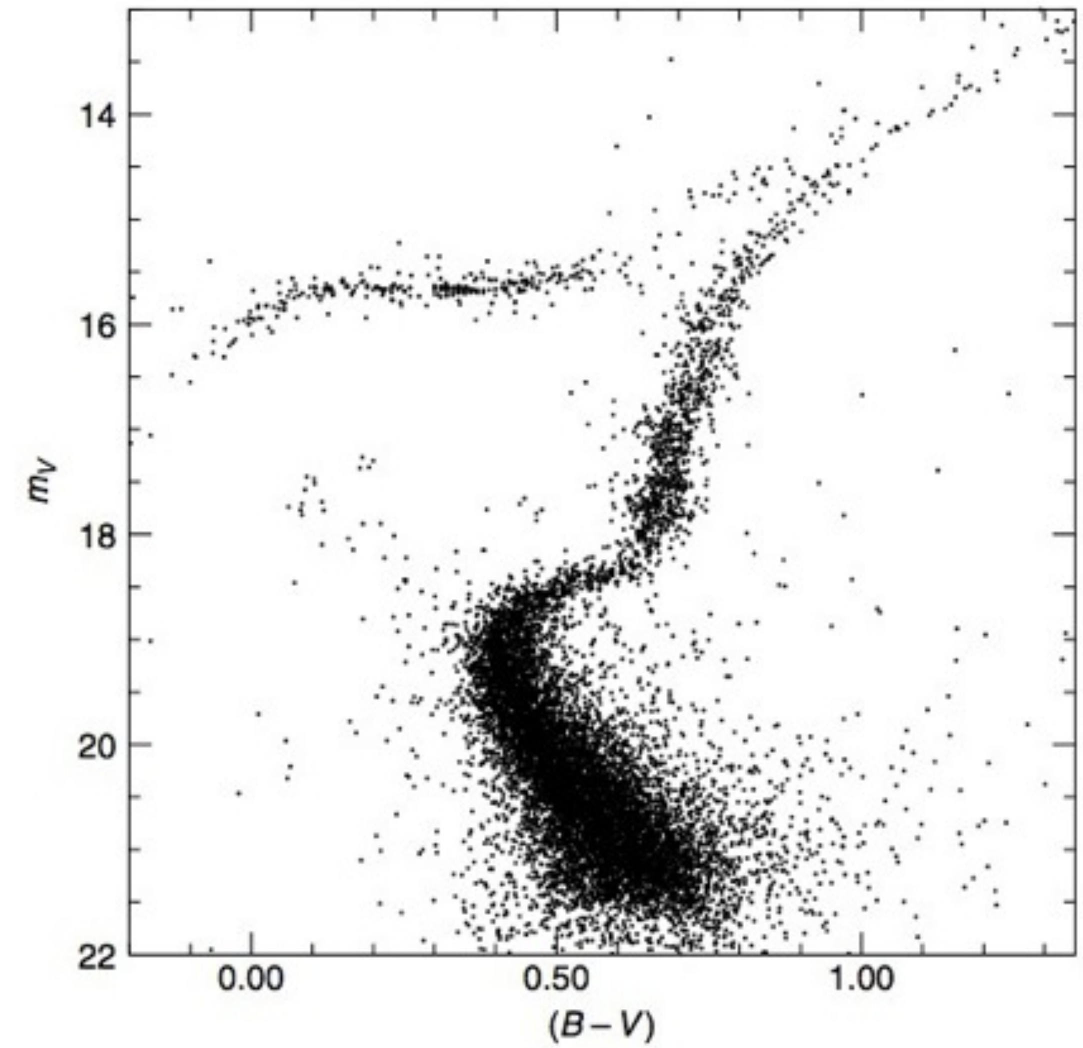


Figure 8.8 CMD of the globular cluster M3 using the Johnson *BV* filters

CMDs

Enxergando as fases de evolução estelar

Algumas definições úteis

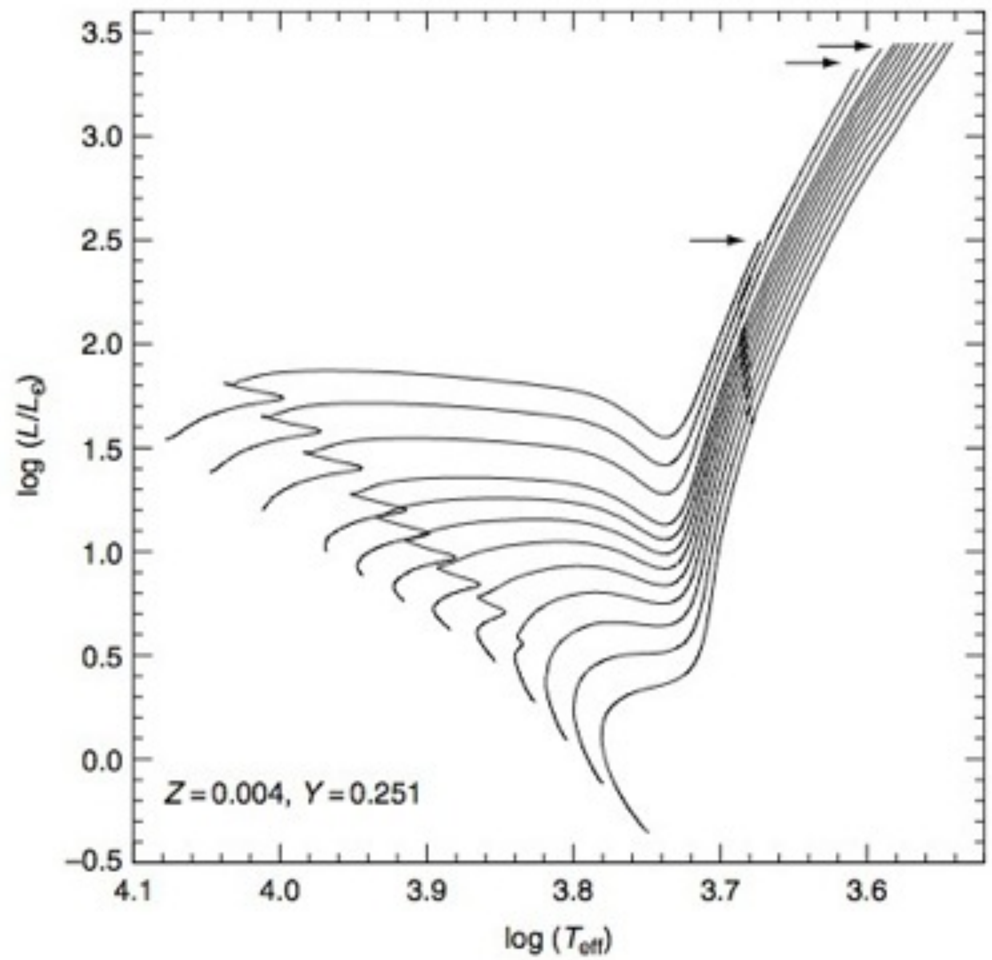


Figure 5.13 The HRD for both the core and shell H-burning phases of low-mass stars for the labelled chemical composition. The RG phase begins when the stars start to evolve at almost constant T_{eff} and increasing luminosity. The various evolutionary tracks correspond to the following stellar masses: $M/M_{\odot}$ =0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.8, 2.0, 2.2. The arrows mark the location of the tip of the RGB for the $2.2M_{\odot}$ and $2M_{\odot}$ models, and for those less massive (that has an approximately constant luminosity)

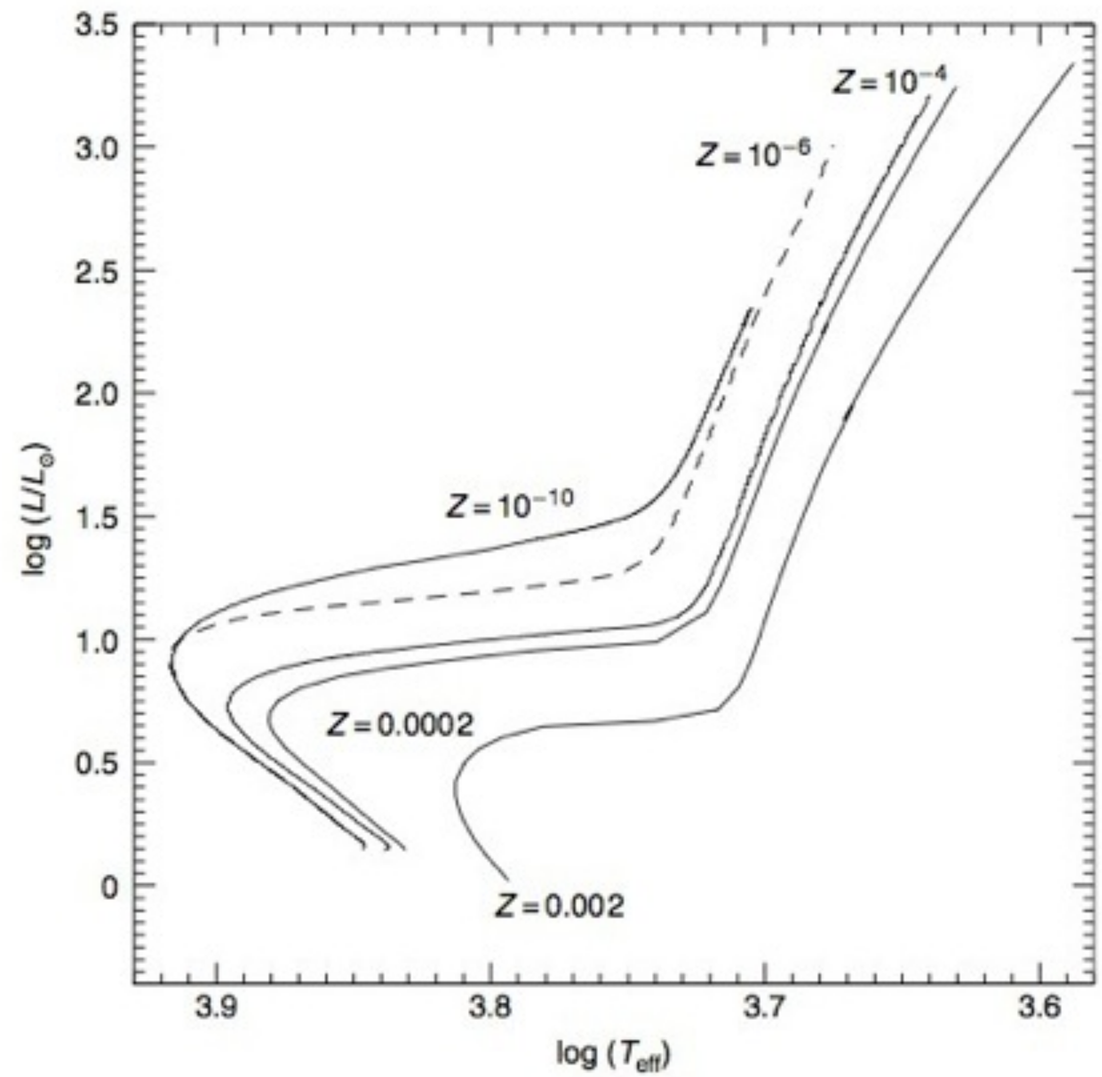


Figure 5.22 The HRD for a $1M_{\odot}$ star for different values of the stellar metallicity

Trajetórias estelares evolutivas

[…] the evolution of the surface (bolometric) luminosity L and Teff of a star is described by the so-called **stellar evolutionary track**, i.e. the path described in the log(L/L) vs log(Teff) diagram […] (HRD).

Isócronas e populações estelares simples

- The most elementary population of stars is the so-called Simple Stellar Population (SSP) consisting of objects born at the same time in a burst of star formation activity of negligible duration, with the same initial chemical composition.
- **The theoretical CMD for an SSP is called an isochrone.** A generic point along an isochrone of age t is determined by three quantities: bolometric luminosity, effective temperature and the value of the evolving mass.
- Once an isochrone of a given age and initial chemical composition is computed from stellar evolution tracks, it can be transferred to an observational CMD by applying to each point a set of appropriate bolometric corrections.

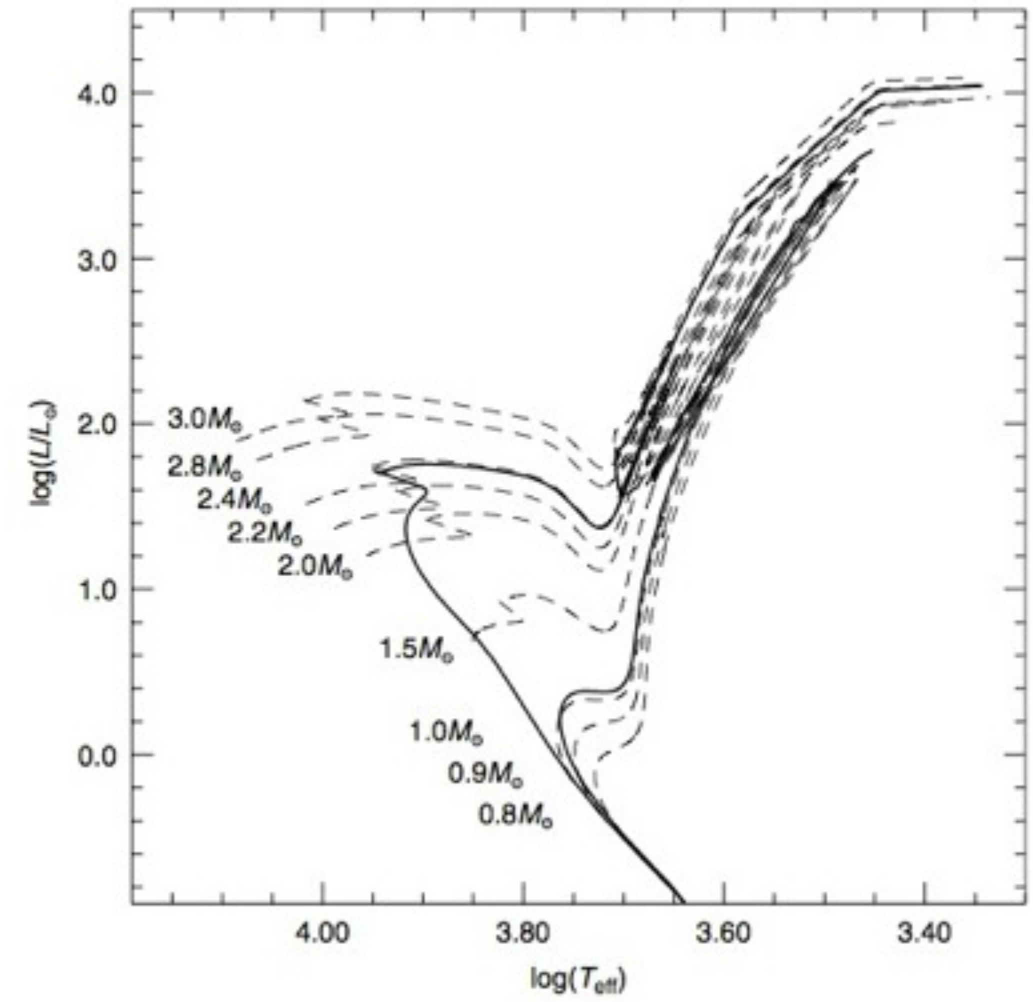


Figure 9.1 HRD of selected stellar evolutionary tracks (dashed lines) with the same initial solar chemical composition and the labelled masses (from [152]). The heavy solid lines display two ...) and

"Although this may seem just a theoretical toy model, there are very good observational counterparts of SSPs, namely globular and open clusters, elliptical galaxies and some dwarf galaxies" ????

line in the HRD that connects the points belonging to the various tracks (one point per track) where t=t. This means that when we move along an isochrone, time is constant whereas the value of the initial mass of the star populating the isochrone at each point is changing.

População estelar composta

- A Composite Stellar Population (CSP) is a collection of stars formed at different times and with different initial chemical compositions. The observational counterparts of this theoretical concept are galaxies, that in many cases are made of multiple generations of stars, and often show clear signs of current star formation activity.
- The fundamental information that characterizes a CSP is its Star Formation History (SFH), that is the evolution with time of the amount (i.e. total mass) of stars formed (Star Formation Rate – SFR) and their initial chemical composition (Age Metallicity Relation – AMR).

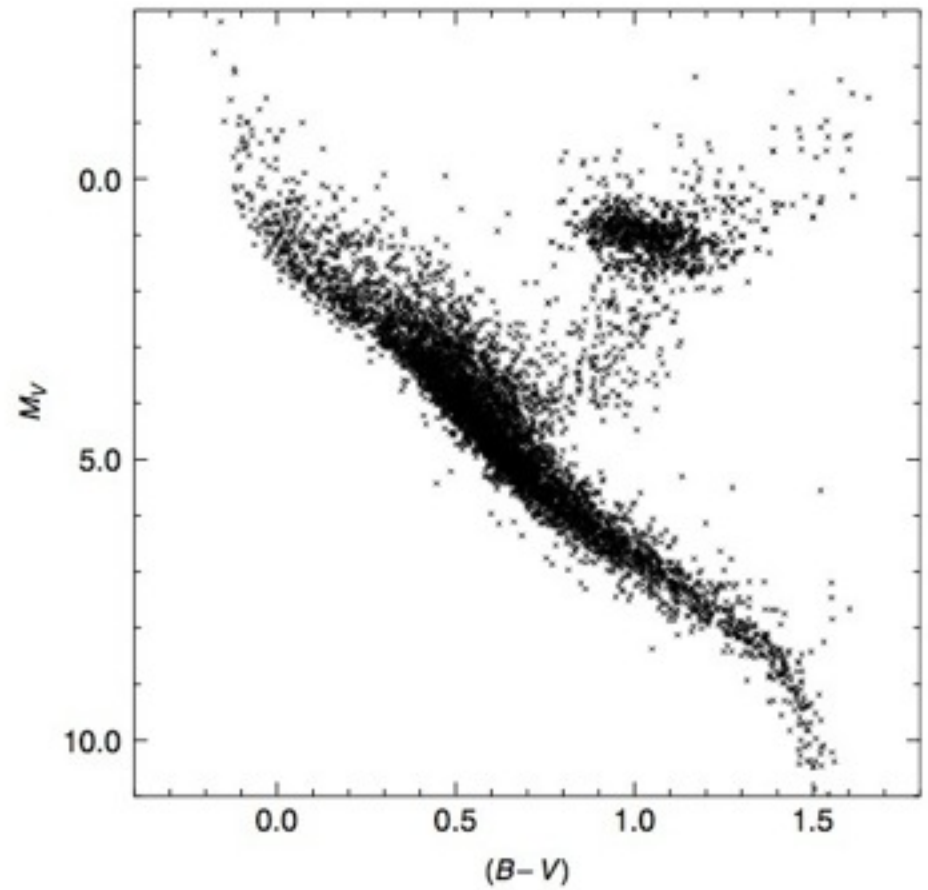


Figure 10.1 Extinction-corrected CMD of stars in the solar neighbourhood with precise parallax measurements from the Hipparcos satellite

- Figure 10.1 displays the CMD of the solar neighbourhood, that appears clearly to be a CSP, due to the coexistence of a bright MS and well-populated SGB and RGB, that reveal the presence of both young (the bright MS objects) and old (the SGB and RGB objects) stars.

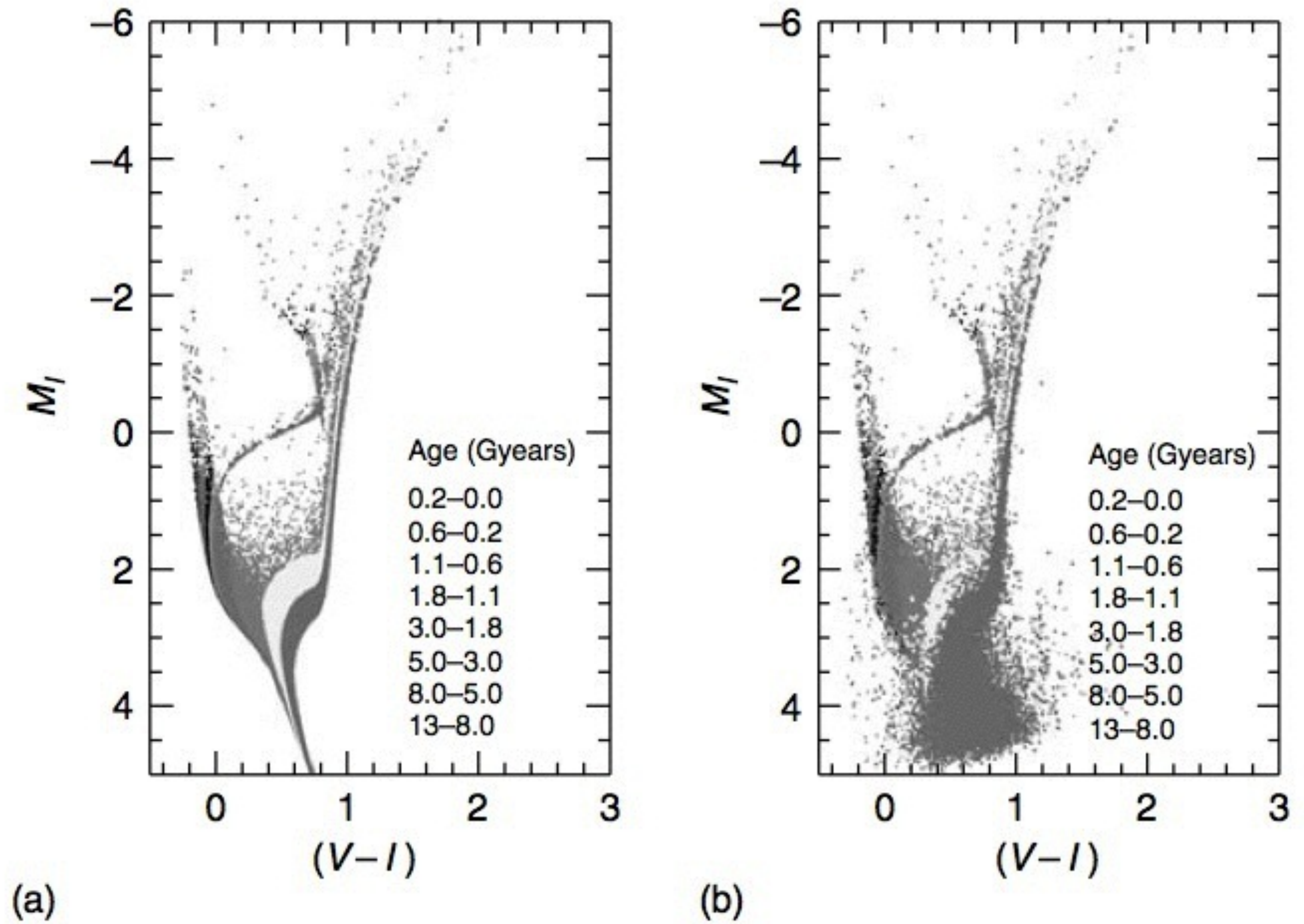
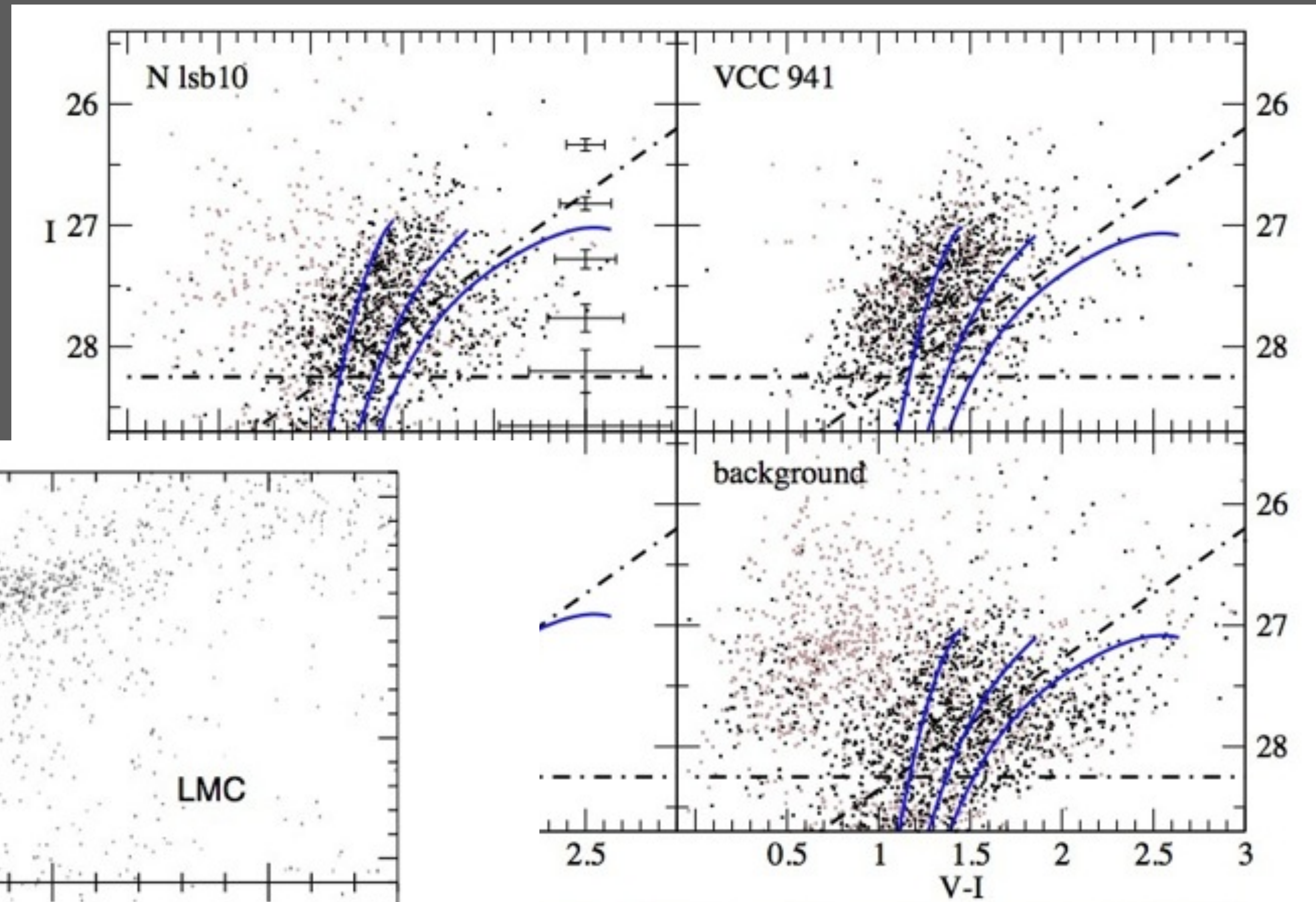


Figure 10.3 CMD of a set of elementary stellar populations covering the labelled age ranges, (a) without and (b) with the inclusion of photometric errors (courtesy of C. Gallart)

CMDs simulados

Os efeitos de erros instrumentais



giant branches are shown for comparison: M15 ([Fe/H]=-2.17), NGC1851 (-1.16),
erived distance modulus for each object, and for the assumed extinction. Faint
ludes some close stellar pairs near the centers of the target galaxies, but mostly
derived from DAOPHOT, are shown for the lsb10 field, at specific magnitudes.
s in the artificial star tests are not recovered. The area used for the cmd of lsb10
l N dSph are both 2% of the background area.

Caldwell 2006

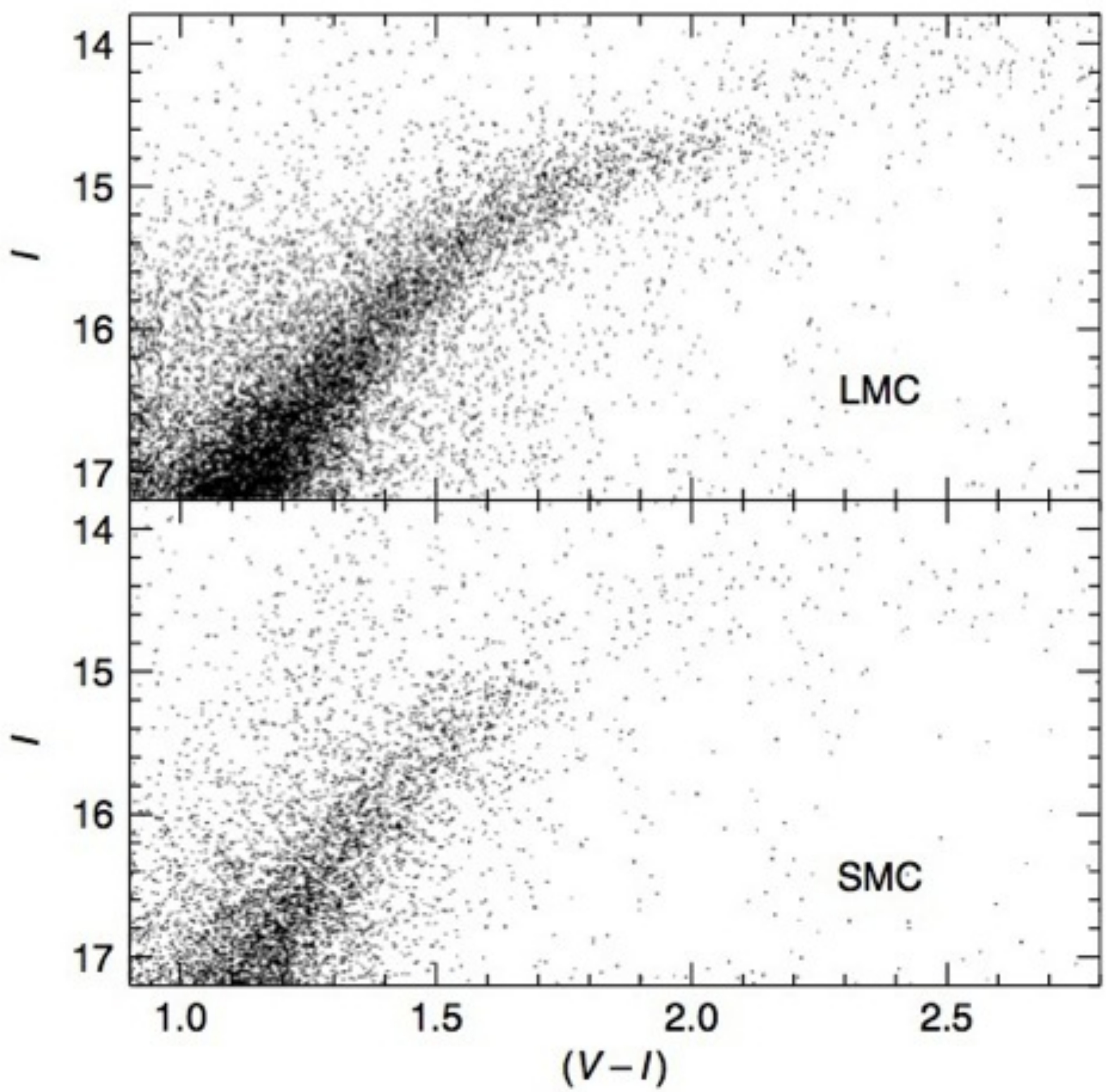


Figure 10.7 CMDs of the RGB observed in the LMC and SMC (from [223])

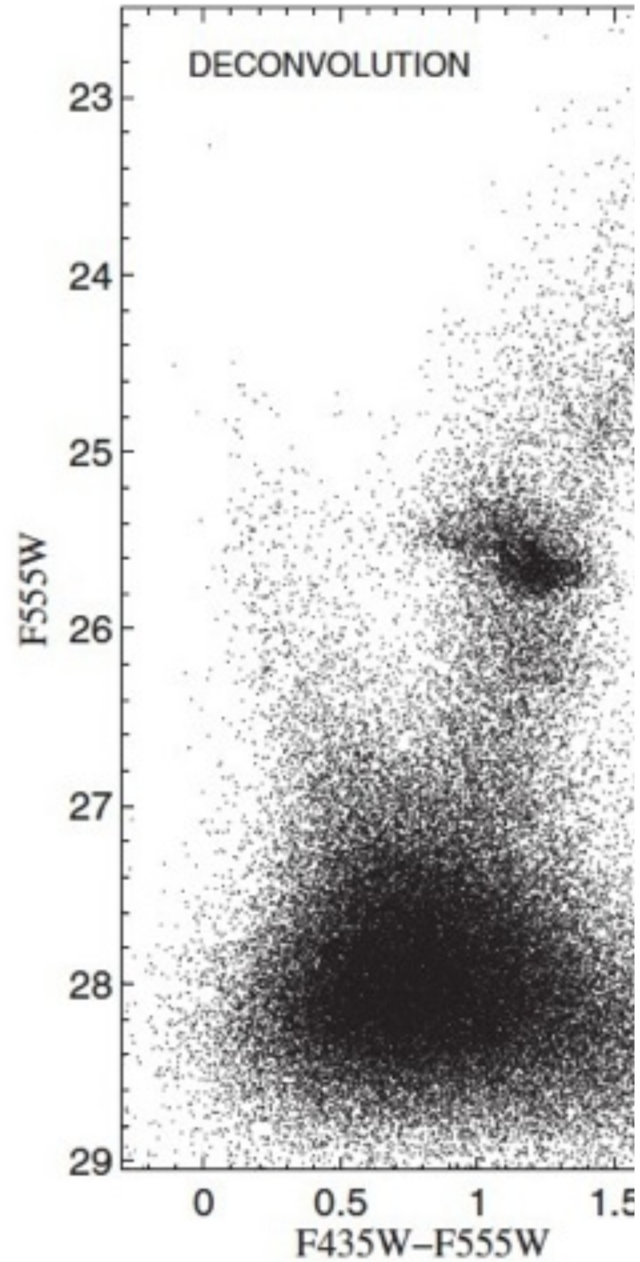


Figure 3. ($F435W - F555W$, $F555W$) CMDs of field F1 obtained from the
contain 58,143 and 50,583 stars, respectively, and are calibrated onto the VEGA
delineated than in the DAOPHOT CMD, at all luminosities. All of the features
Moreover, the outliers to the red of the RGB ($F435W - F555W > 1.5$, F55
DAOPHOT. We therefore only use the deconvolved CMD for further analysis. S

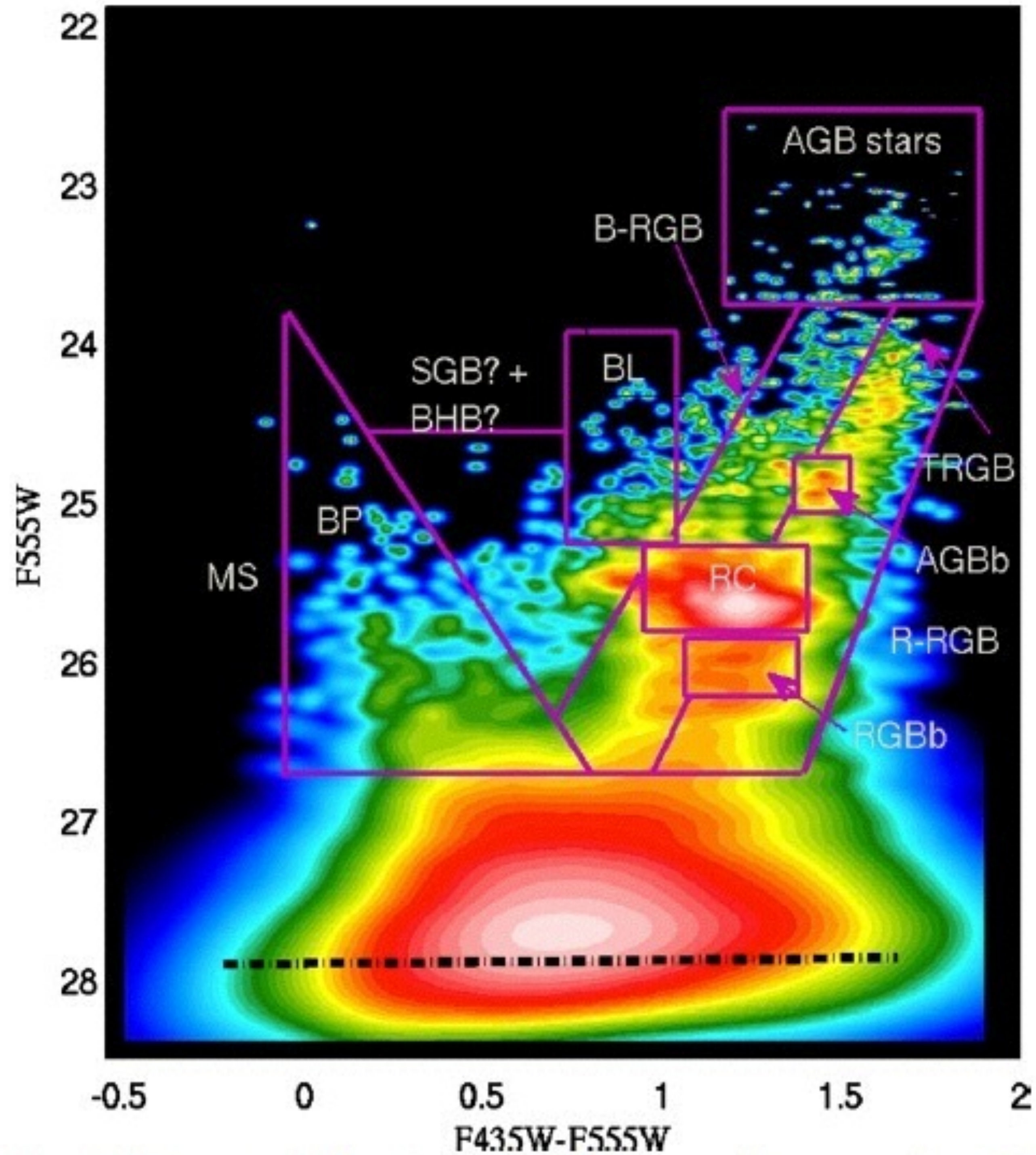
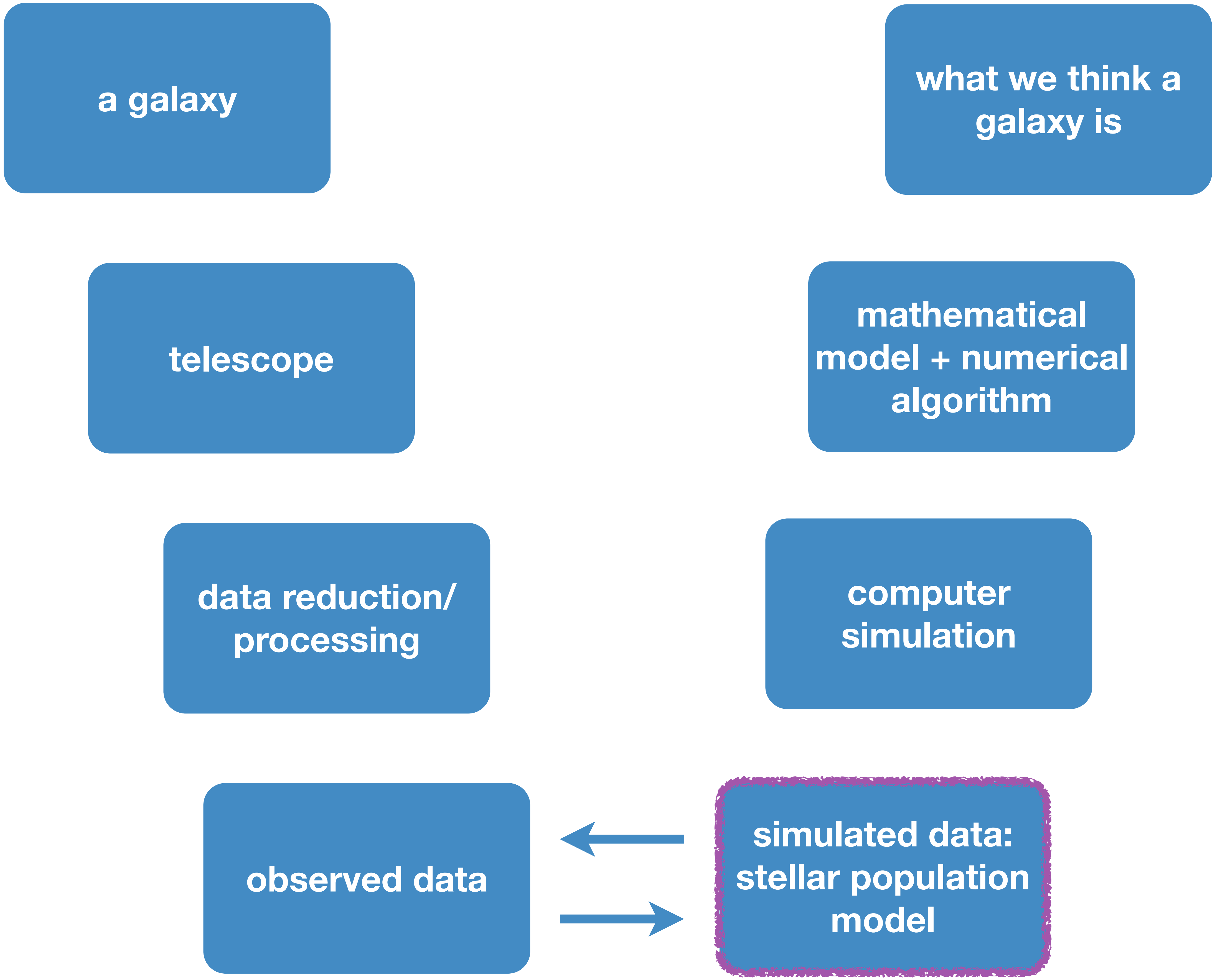


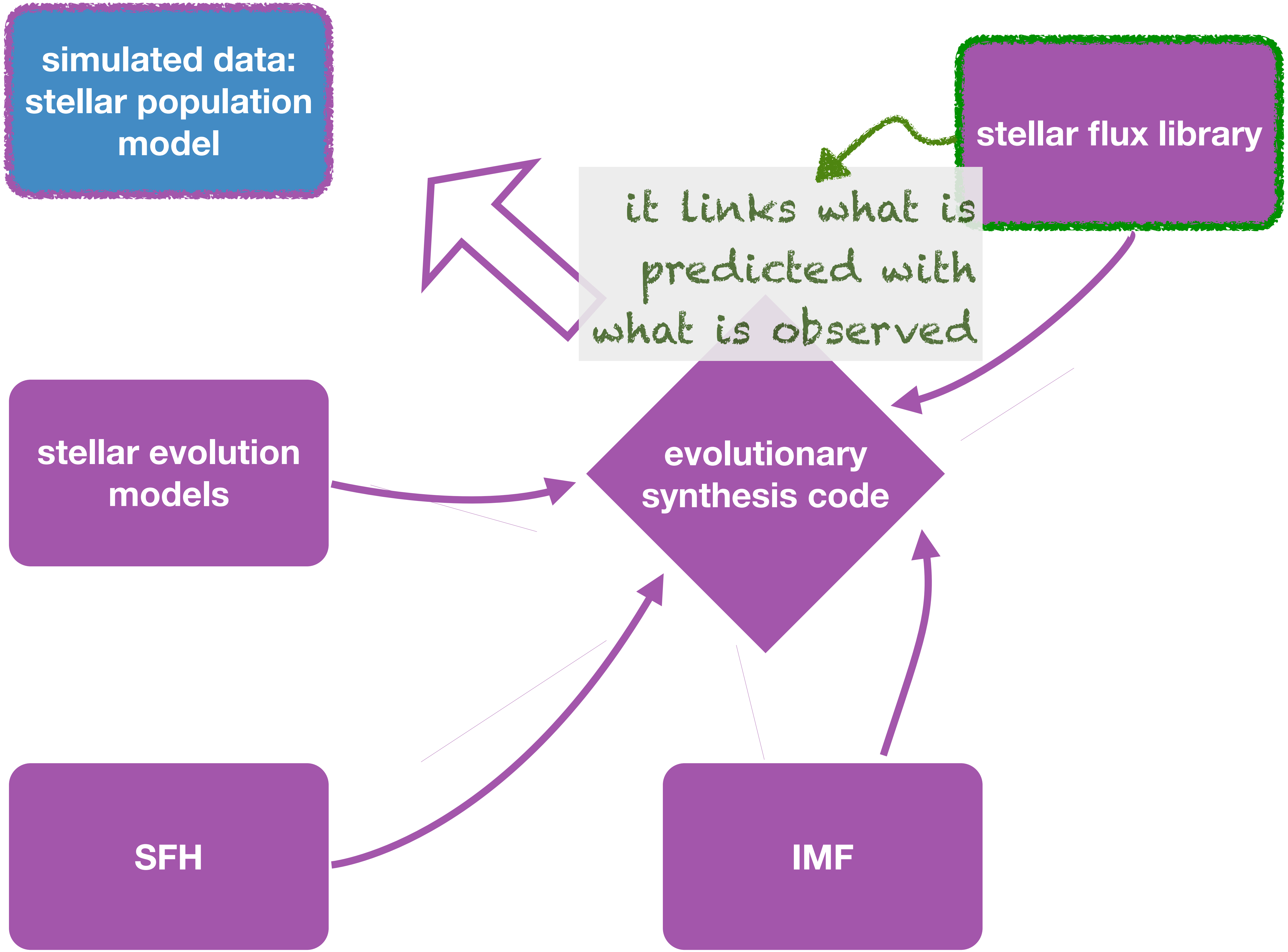
Figure 12. Error-based Hess diagram for M32, corrected for contamination by the M31 background stars. The boxes indicate various features that represent different stellar populations. MS: main sequence; BP: blue plume; SGB: subgiant branch; BHB: blue horizontal branch; BL: blue loop; RC: red clump; RGBb: red giant branch bump; R–RGB: red–red giant branch; B–RGB: blue–red giant branch; TRGB: tip of the red giant branch; AGB: asymptotic giant branch; and AGBb: asymptotic giant branch bump. The dotted-dashed line indicates the 50% completeness level of our data. Magnitudes are calibrated onto the VEGAmag system.

chesi et al. 2011

De volta aos modelos de população estelar…

Como é construído um modelo de população estelar?


a galaxy
what we think a galaxy is
telescope
mathematical model + numerical algorithm
data reduction/ processing
computer simulation
observed data
simulated data: stellar population model


simulated data: stellar population model
stellar flux library
it links what is predicted with what is observed
stellar evolution models
evolutionary synthesis code
SFH
IMF

The monochromatic integrated flux F_λ^{I} received from an unresolved SSP of age t and metallicity Z can be written as

$$F_\lambda^{\mathrm{I}}(t,Z)=\int_{M_1}^{M_u} f_\lambda(M,t,Z)\Phi(M)dM \qquad (11.1)$$

where $f_\lambda(M,t,Z)$ is the monochromatic flux emitted by a star of mass M, metallicity Z and age t, $\Phi(M)dM$ is the IMF (in the following we will always use the Salpeter IMF) M_1 is the mass of the lowest-mass star in the SSP, M_u is the mass of the highest-mass star still alive in the SSP. The value of M_u is typically the initial mass of the

In practice, the spectrum of a composite stellar population (CSP) such as a galaxy can be described as a convolution of the star formation rate (SFR) and spectra of SSP of a given formation age t' and abundances X:

$$F_\lambda^{CSP}=\int_0^t dt'\Psi(t-t')F_\lambda^{SSP}(t',X(t')) \qquad (2.1)$$

Where F_λ is the flux at wavelength λ, Ψ is the star formation rate and X is the detailed abundance pattern of the SSP (distinguished from Z which is global metal abundance). In order to compute the models for the present project, the SFR and $X(t')$ will be given by chemical evolution models. Fig. 2.4 shows the evolution in time of SFR and several chemical

Fluxos integrados

Integrando fluxos de estrelas para construir SSPs
Integrando fluxos de SSPs para construir CSPs

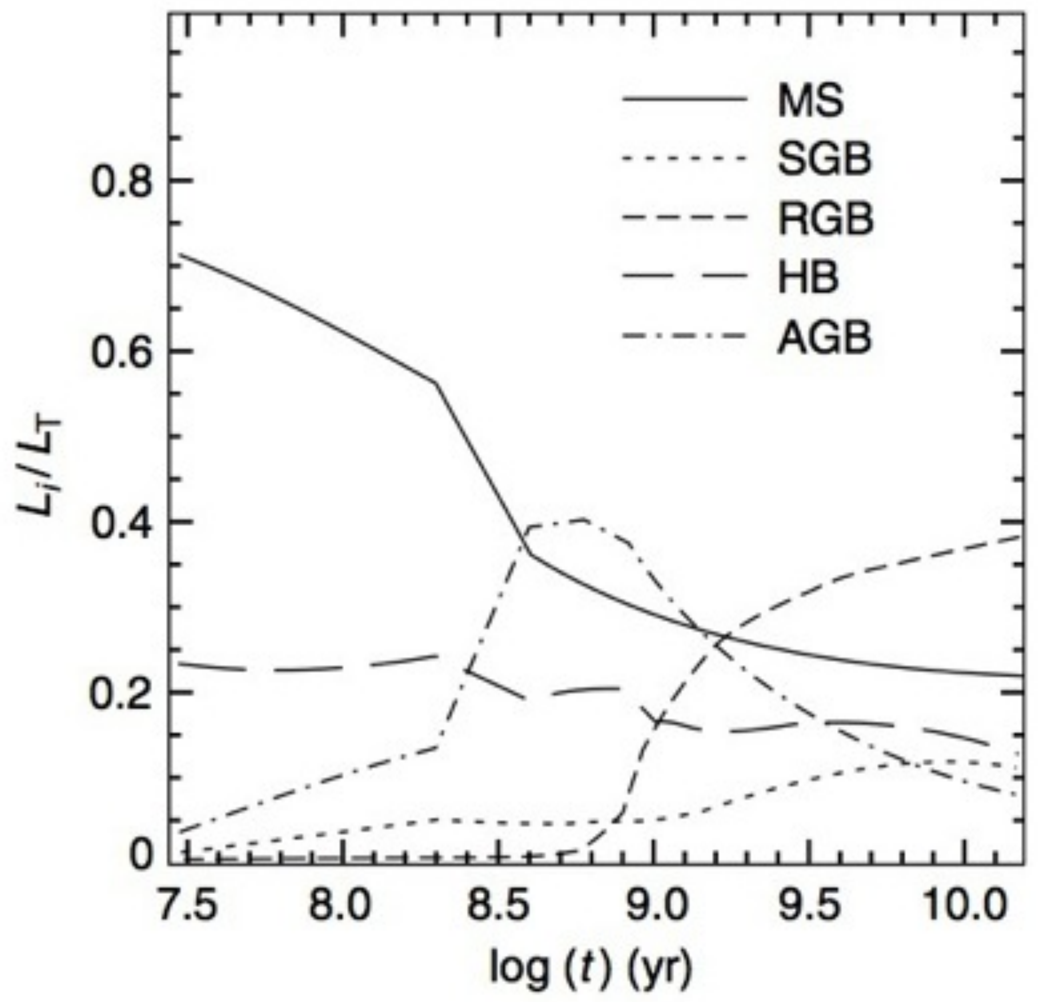


Figure 11.1 Contribution of different evolutionary phases to the total bolometric luminosity of an SSP (L_i/L_T is the ratio of the integrated bolometric luminosity produced by stars in the evolutionary phase i to the total integrated bolometric luminosity L_T of the population) with solar initial chemical composition and varying ages (data from [133]). Here the acronym HB denotes the phase of core He-burning, regardless of the value of stellar evolving mass. The contribution to L_T of phases not displayed in this diagram is negligible

Fluxos integrados

Contribuição de cada fase evolutiva estelar

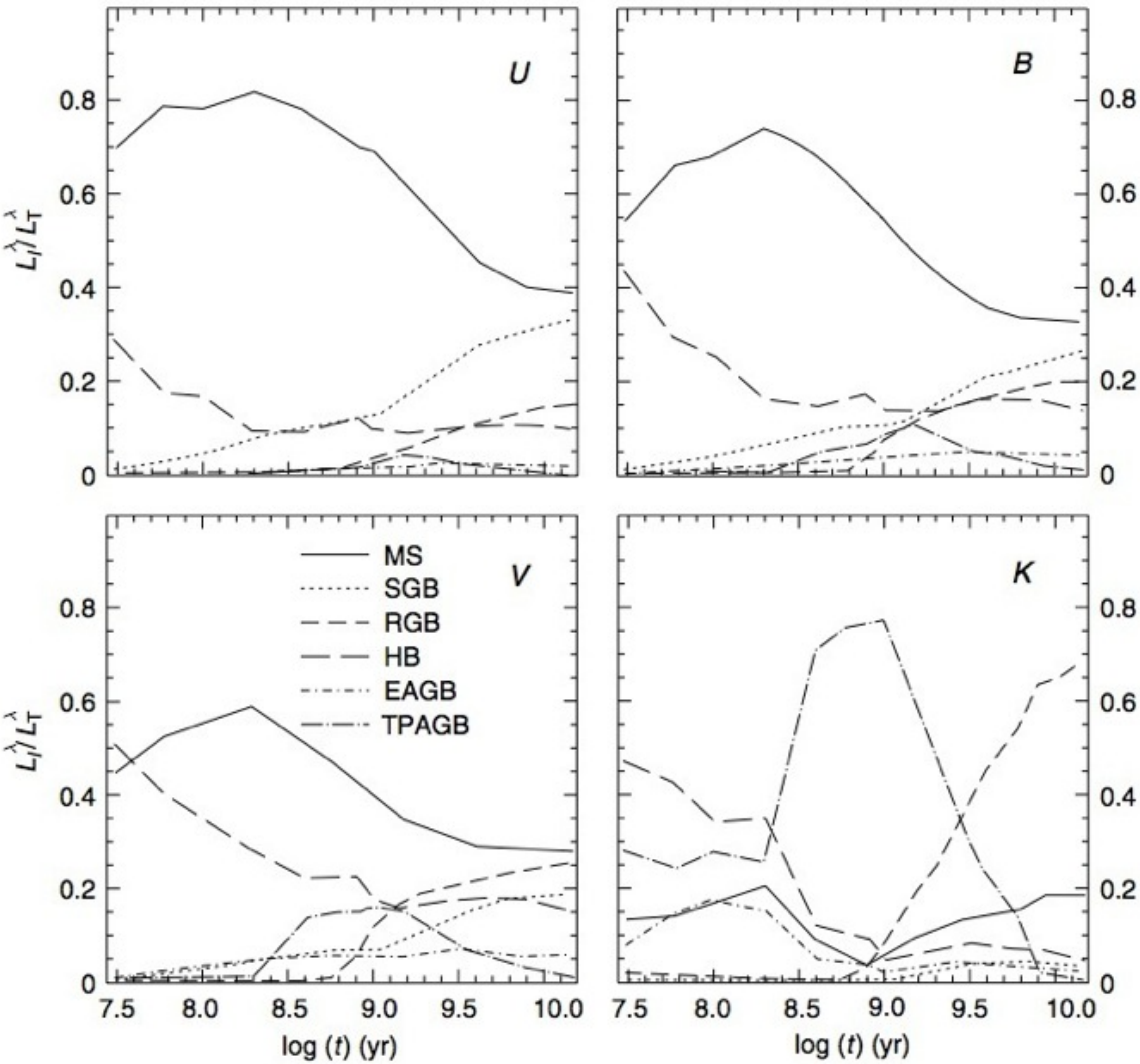


Figure 11.2 As in Figure 11.1 but for the luminosity in various wavelength bands (data from [133]). The AGB has been split into the phase up to the onset of thermal pulses (EAGB) and the thermal pulse phase (TPAGB)

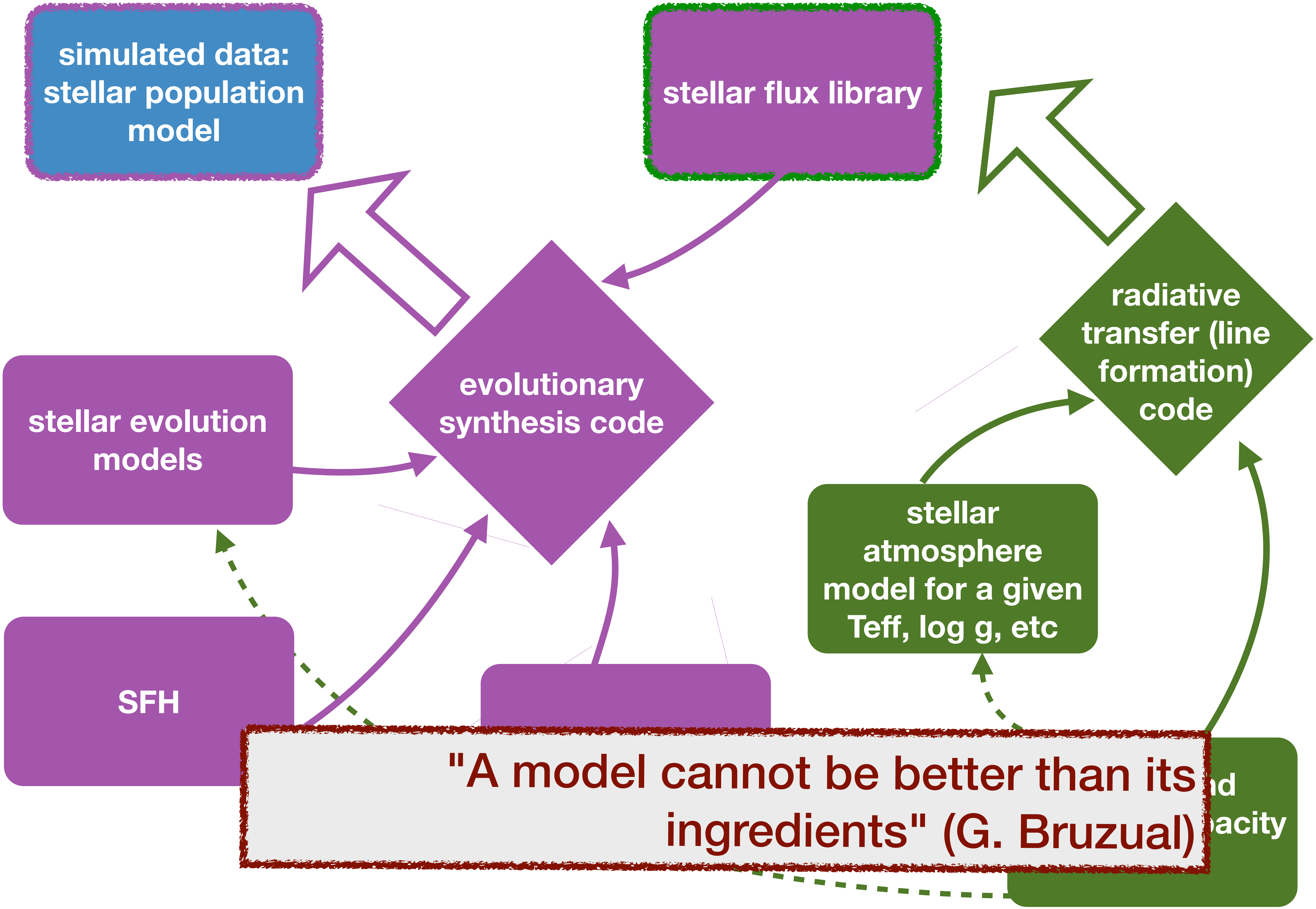
simulated data: stellar population model

stellar flux library

it links what is predicted with what is observed

ste

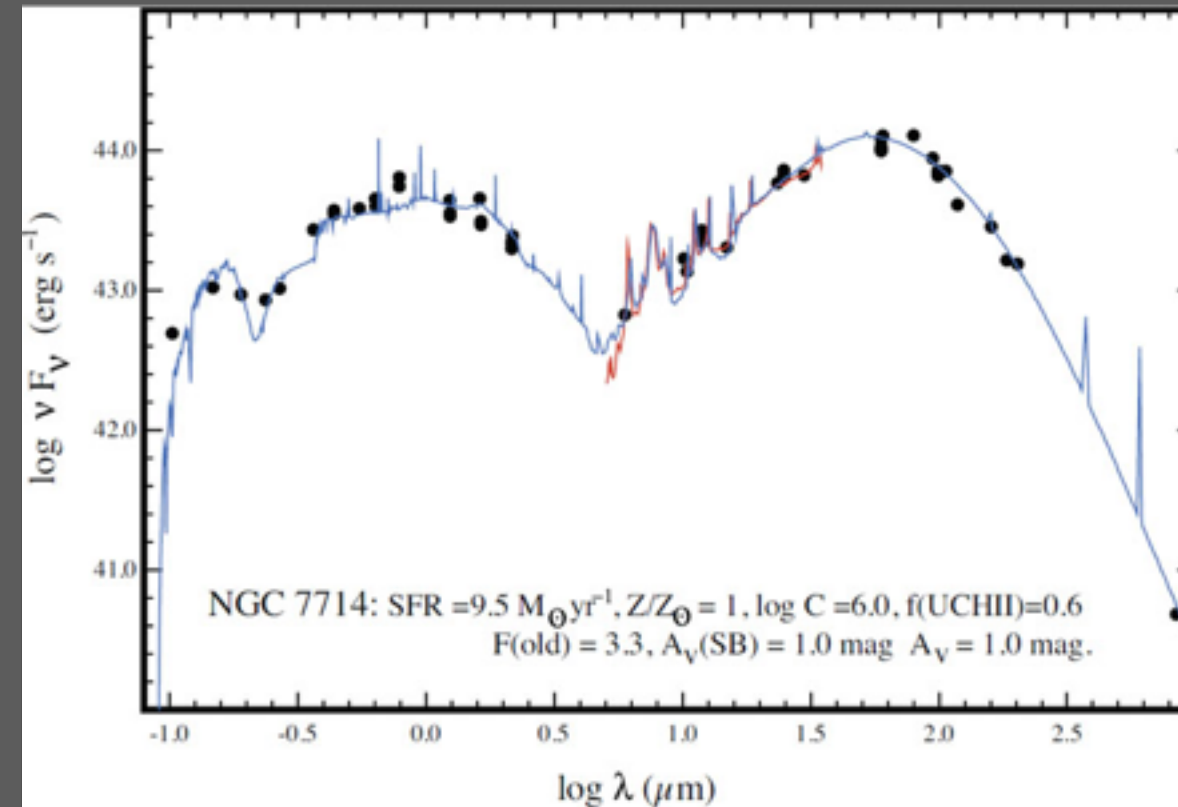
Empirical stellar flux library	vs	Theoretical stellar flux library
Semi-empirical SP models		**Fully theoretical SP models**
e.g. BC03 (high-res), Le Borgne et al. '04 (PEGASE-HR), Maraston & Stromback '11, Vazdekis et al. '99, '10		e.g. BC03 (03, low-res), Coelho et al. (2007), Leitherer et al. (99, STARBURT99 and cia).

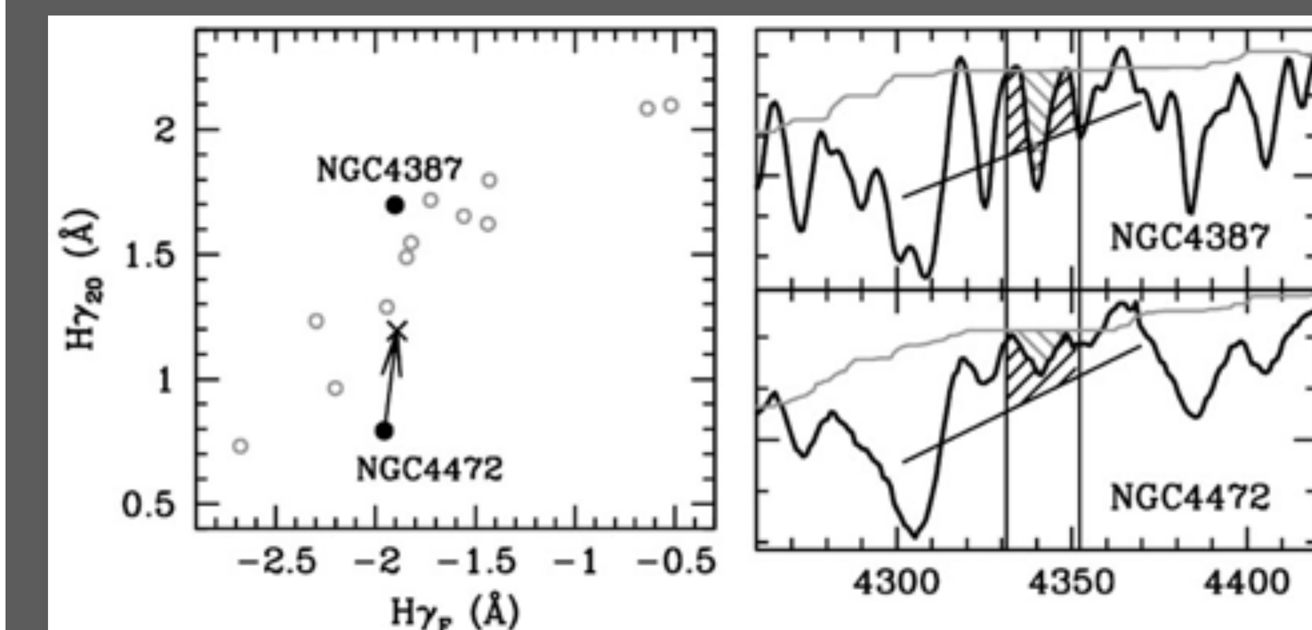

simulated data: stellar population model
stellar flux library
evolutionary synthesis code
radiative transfer (line formation) code
stellar evolution models
stellar atmosphere model for a given Teff, log g, etc
SFH
"A model cannot be better than its ingredients" (G. Bruzual)

E como os modelos são usados para extrair informações de observações?

Comparação estatística entre os observáveis

- Walcher et al. (2011)
- Observáveis: **cores** (entenda fluxos), **índices espectrais** (índices de Lick, D4000 break… ver por exemplo método de R. Proctor) ou **espectros**
- Principal Component Analysis
- Ajuste espectral por inversão ("Full Spectral Fitting", ajuste pixel a pixel do espectro). O mais usado recentemente para obter a história de formação estelar. Pode ser paramétrico ou não-paramétrico (Starlight, ULySS, etc)
- Inferência Bayesiana





http://ned.ipac.caltech.edu/level5/March10/Walcher/Walcher_contents.html

http://www.sedfitting.org/SED08/Fitting.html

How well do we measure age and metallicity in stellar clusters?

Stellar population in M31 globular clusters

Cezario et al. ’13.

Ages and metallicities derived for 38 clusters in M31 and 41 in Milky Way, via spectral fitting. Models by Vazdekis et al. 10.

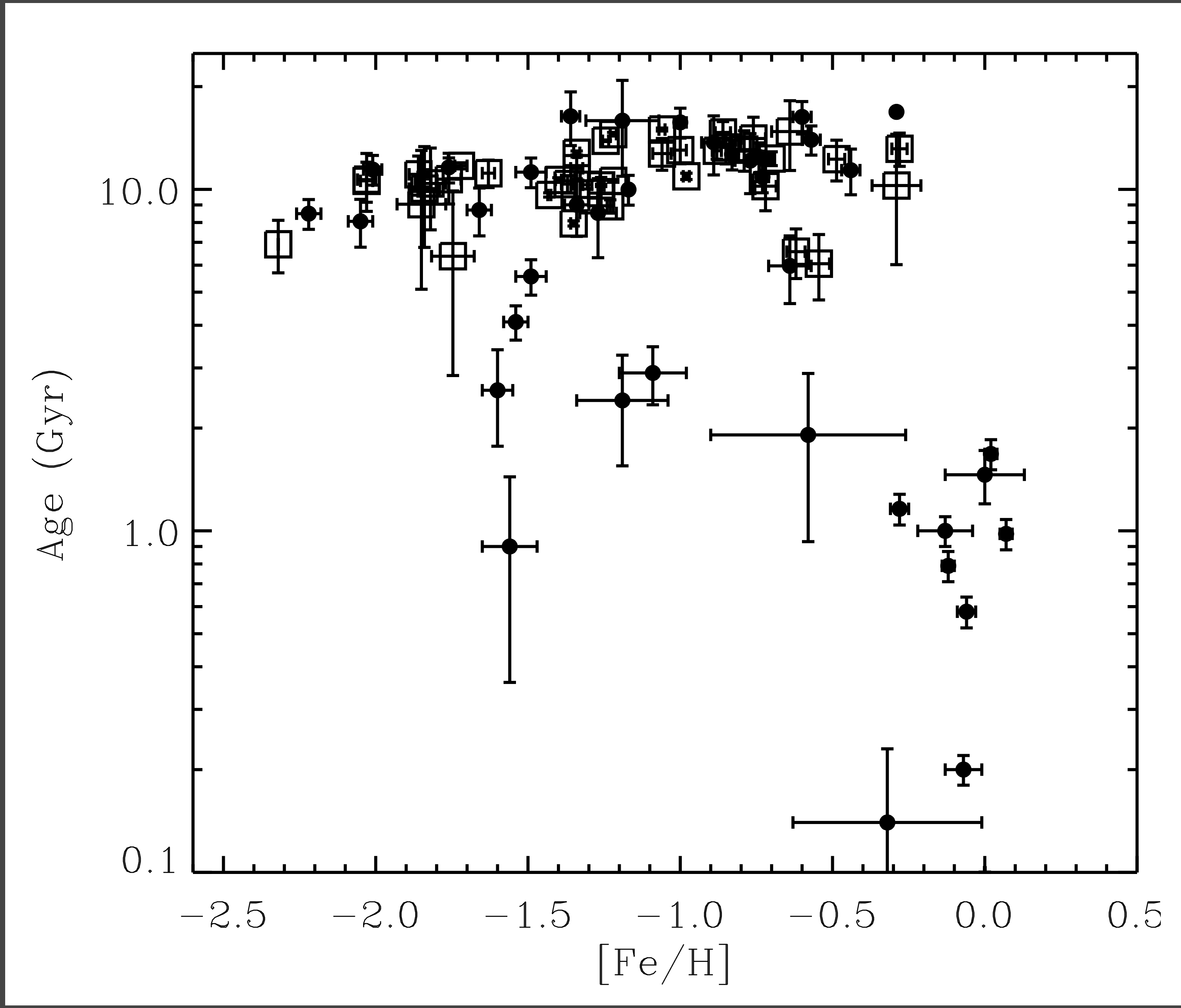


Fig 6 in Cezario et al. 12: age-metallicity relation obtained for M31 (filled circles) and Galactic GCs (open squares).

How accurately can we derive metallicities?

- Mean [Fe/H] differences (in dex):

  Cezario – Schiavon = –0.05 ± 0.16

  Cezario – Carretta = –0.15 ± 0.17

  Schiavon – Carretta = 0.10 ± 0.20

- It is a remarkable agreement between metallicities from integrated light at medium spectral resolutions and higher-resolution stellar analysis.

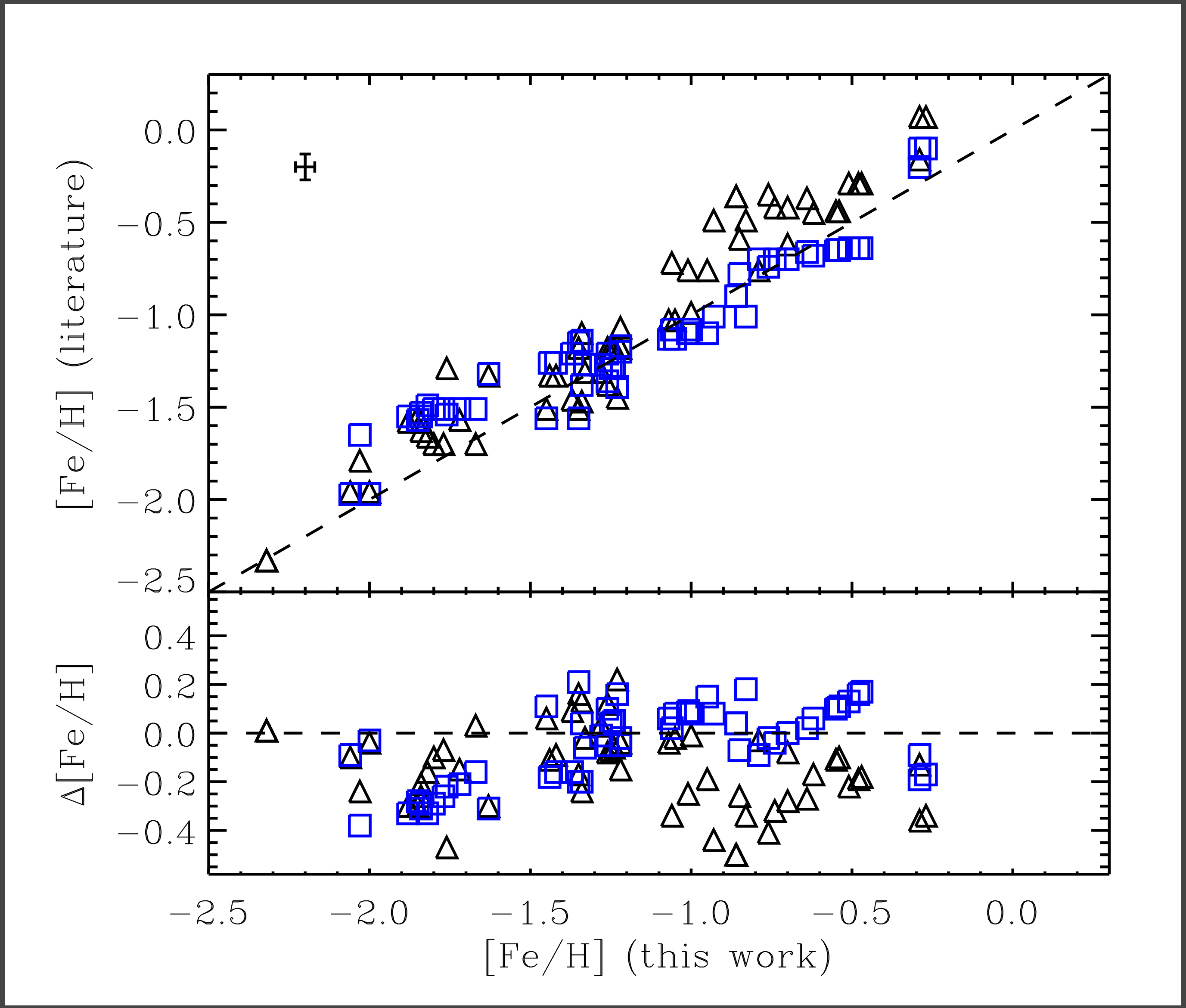
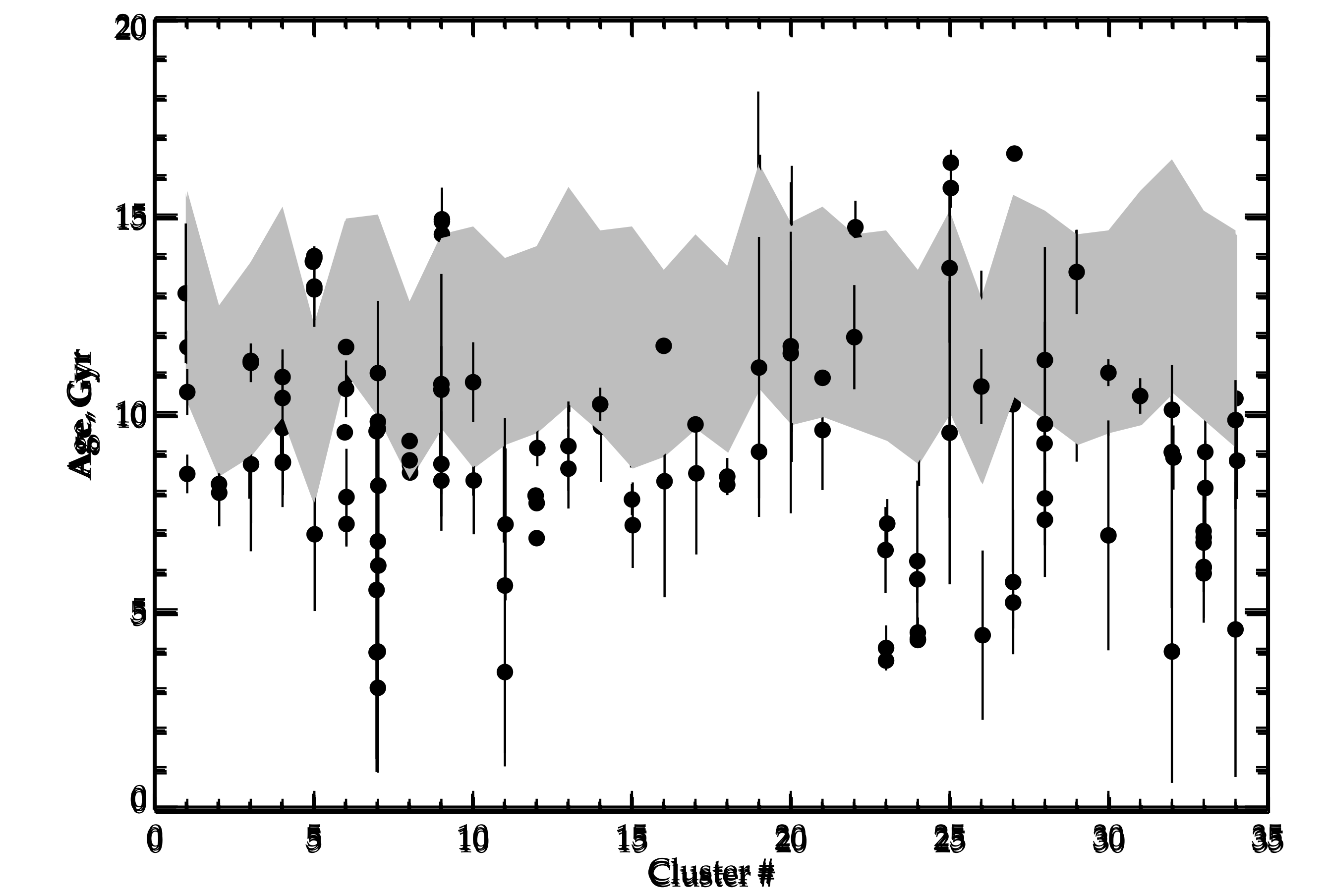


Fig 2 in Cezario et al. 12: metallicities from integrated spectral fitting vs. stellar analysis (blue squares from Schiavon et al. 05 and black triangles from Carretta et al. 09).

What about ages?

- Does it depend on wavelength range?
    - No (Koleva et al. ’09)
    - Yes (Walcher et al. ’09, Cezario et al. ’12)

- What is the origin of the false intermediate age results?

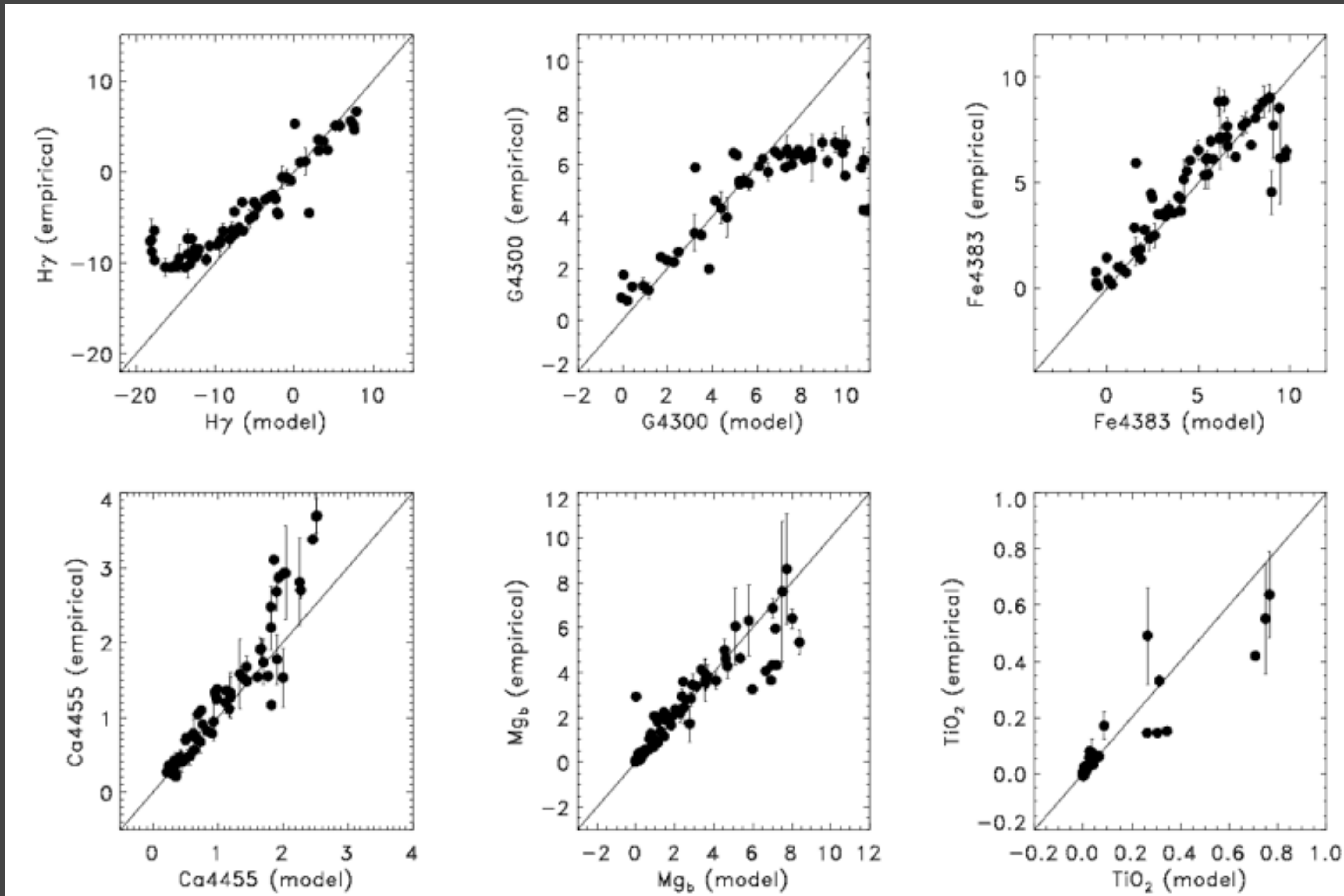


Intervals:
4000 - 5400
4000 - 5700
4828 - 5264
3650 - 6150

O papel de bibliotecas estelares teóricas

Empirical libraries	Theoretical libraries
★ The stars are real...	★ known atmospheric parameters ★ infinite S/N ★ large coverage in wavelength ★ high-resolution
★ S/N & flux calibration issues ★ compromise between wavelength coverage and resolution ★ (in)accuracy of stellar parameters (Teff, log g, Z)	★ time consuming, demands computing power
★ coverage of the parameter space in Teff, log g, metallicity and chemical pattern is limited	★ limited by the approximations and (in)accuracies of the models

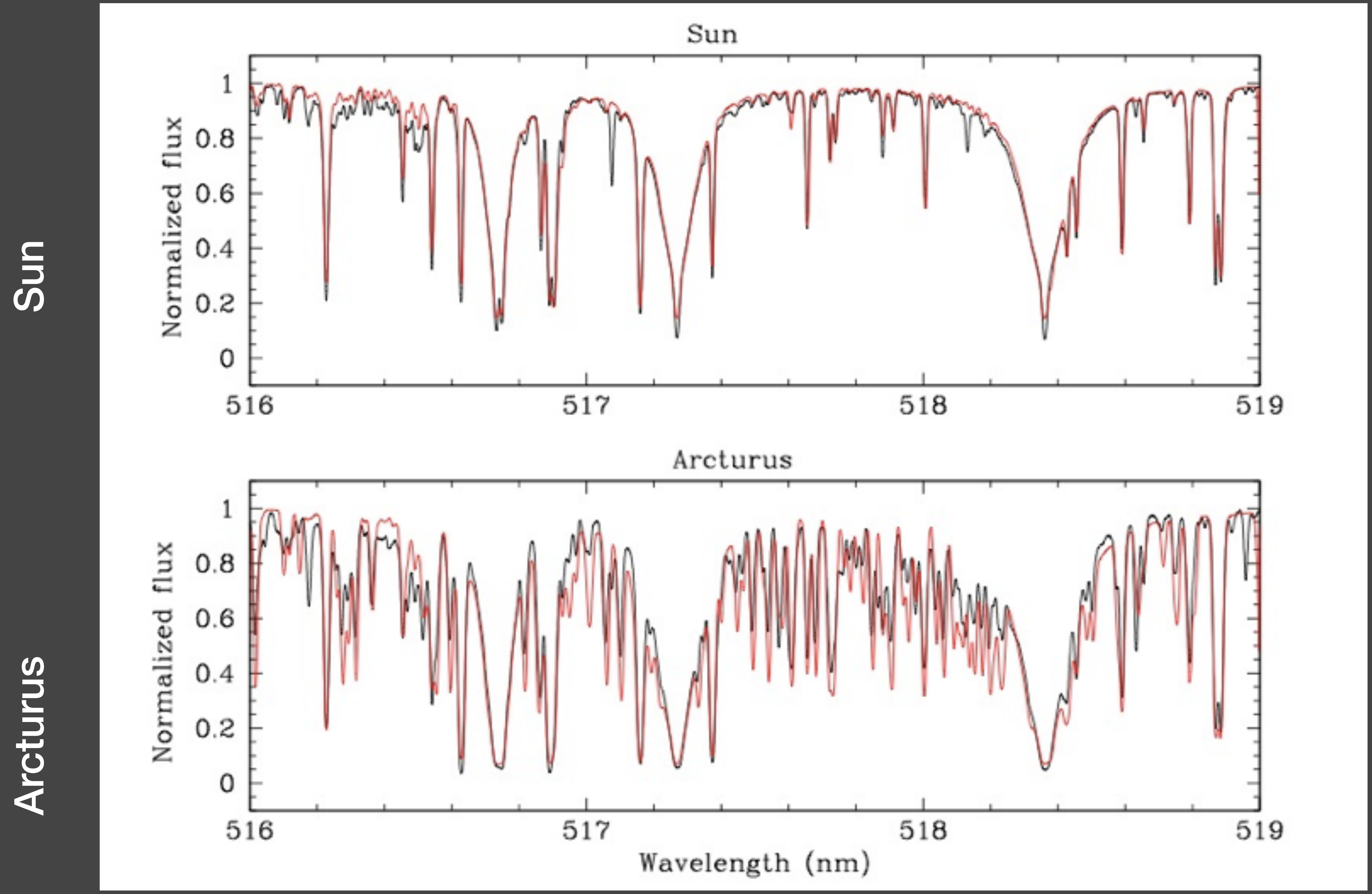
Observations : Sanchez-Blazquez et al. (2006)



Model : Coelho et al. (2005)

Theoretical vs. observed spectral indices

Martins & Coelho (2007)
Coelho (2009, AIPC)

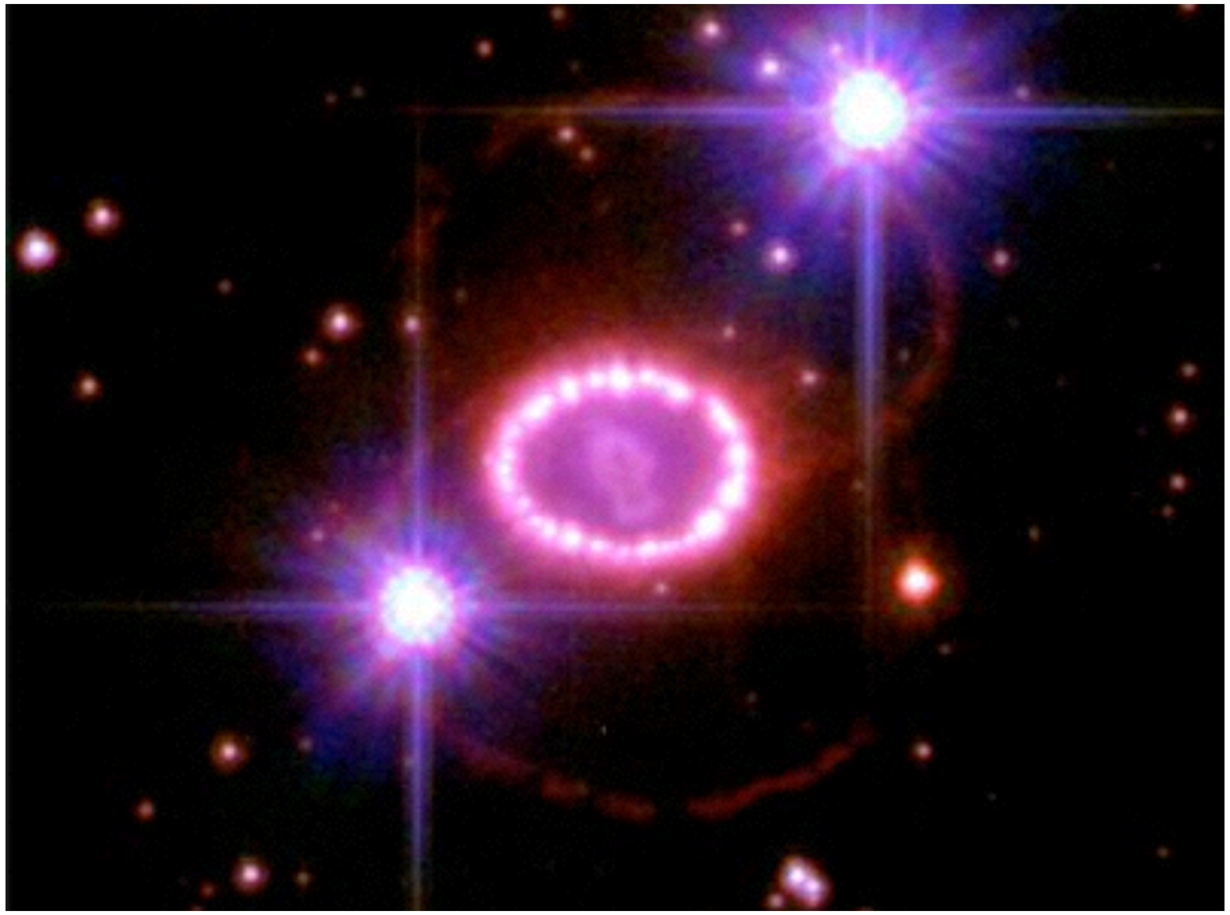


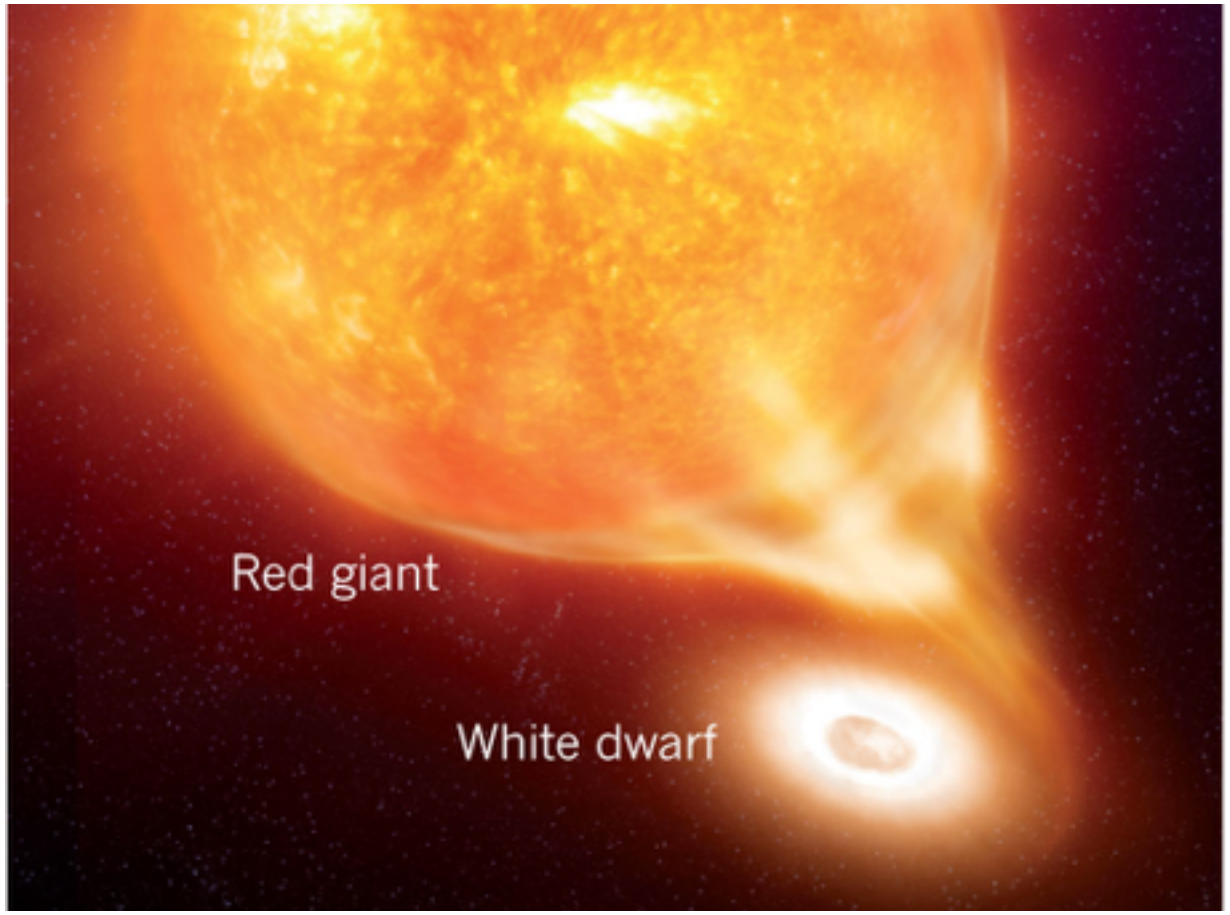
Theoretical vs. observed stellar spectra

Observations in black.
Models in red.
Coelho et al. (2005)

If theoretical stellar libraries have these deficiencies, why would we use them in stellar population models?

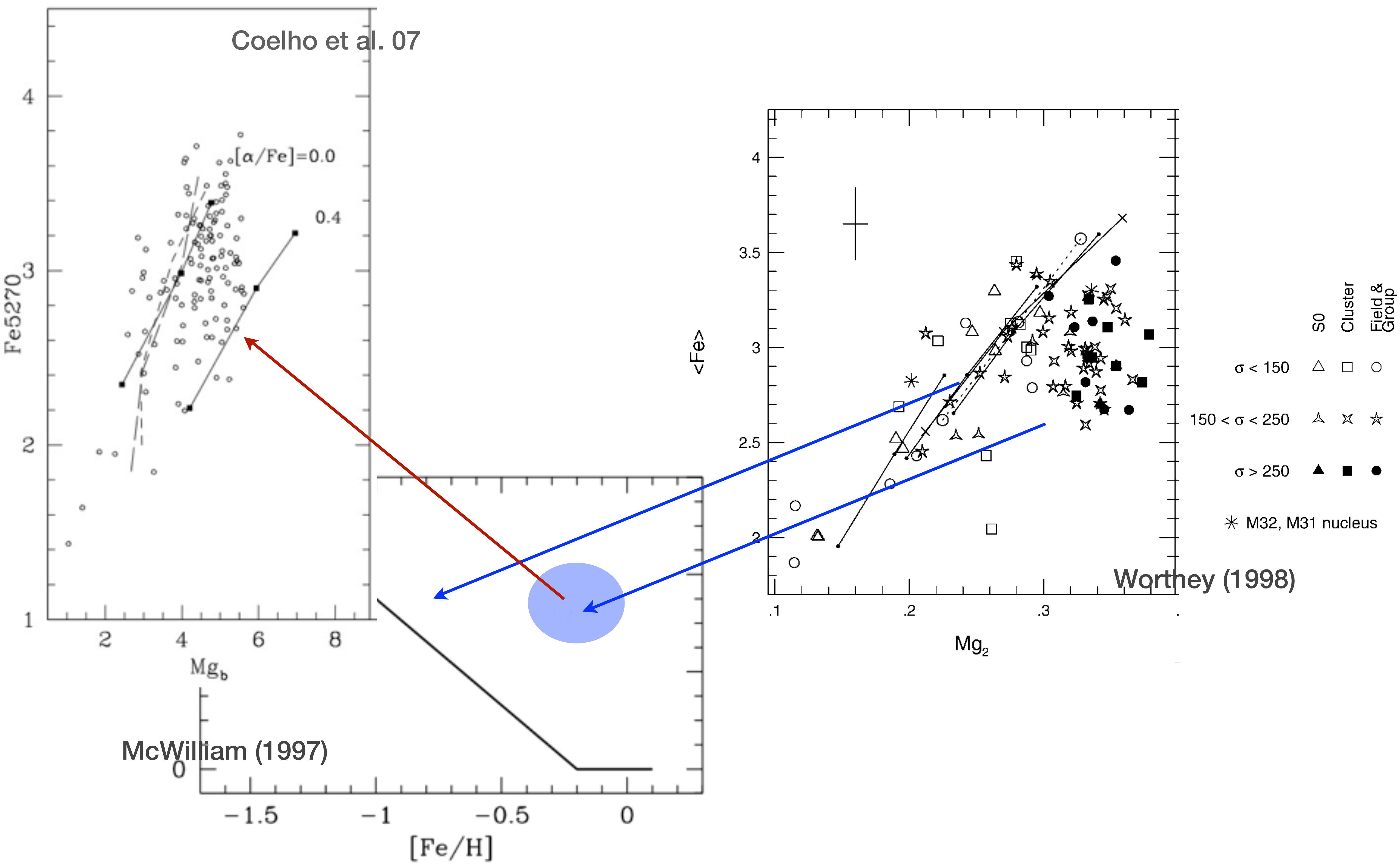
One of the main advantages of using theoretical libraries is the ability to explore the stellar parameter space at will.





alpha-enhancement [α/Fe] in 2 slides

The need for theoretical stellar spectra



Empirical stellar libraries are perfectly suited for studying neighbourhood populations

Different populations are a different matter...

We must rely on **theoretical stars** if we want to model the spectra of galaxies **different than our neighbourhood** ...

... but we can do that in different ways.

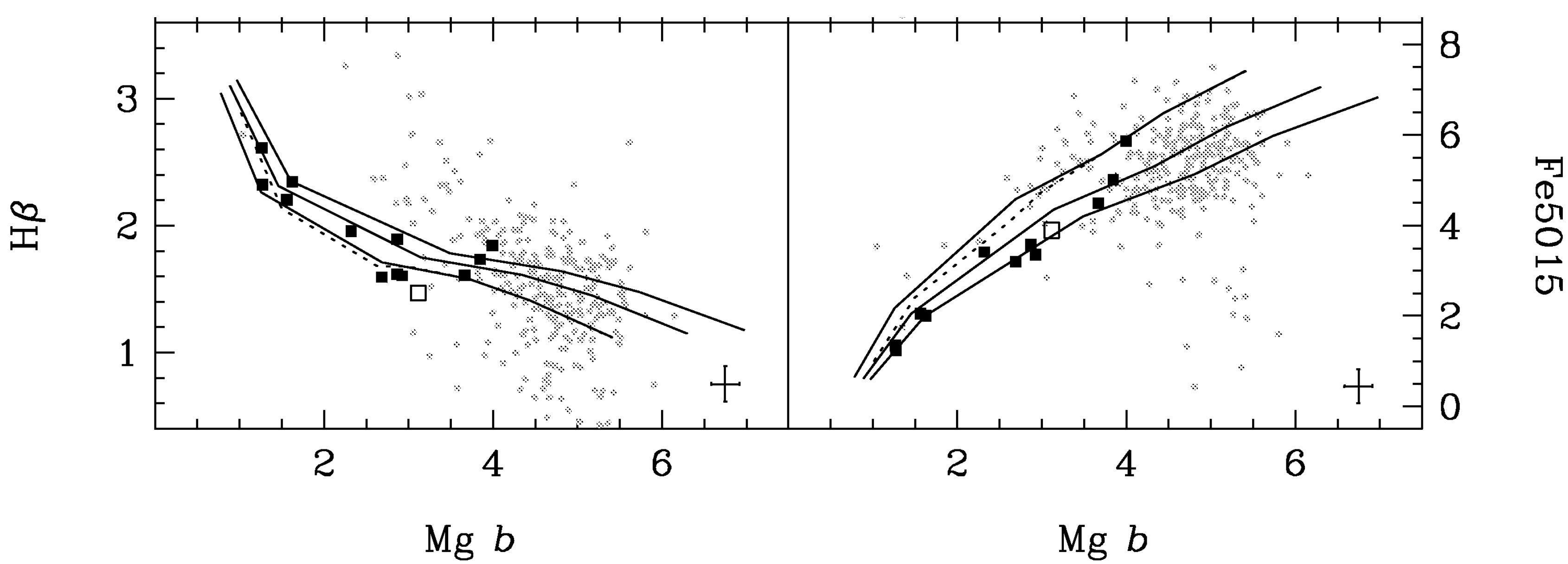
Response functions

- Trager et al. ’00 proposes how to correct model indices given the predictions of few synthetic stars from Tripicco & Bell ‘95.

$$\frac{\Delta I}{I_0} = \left\{ \prod_i \left[1 + R_{0.3}(X_i)\right]^{[X_i/H]/0.3} \right\} - 1$$

$R_{0.3}(X_i)$ is the TB95 response function for element i

- Widely used in literature.



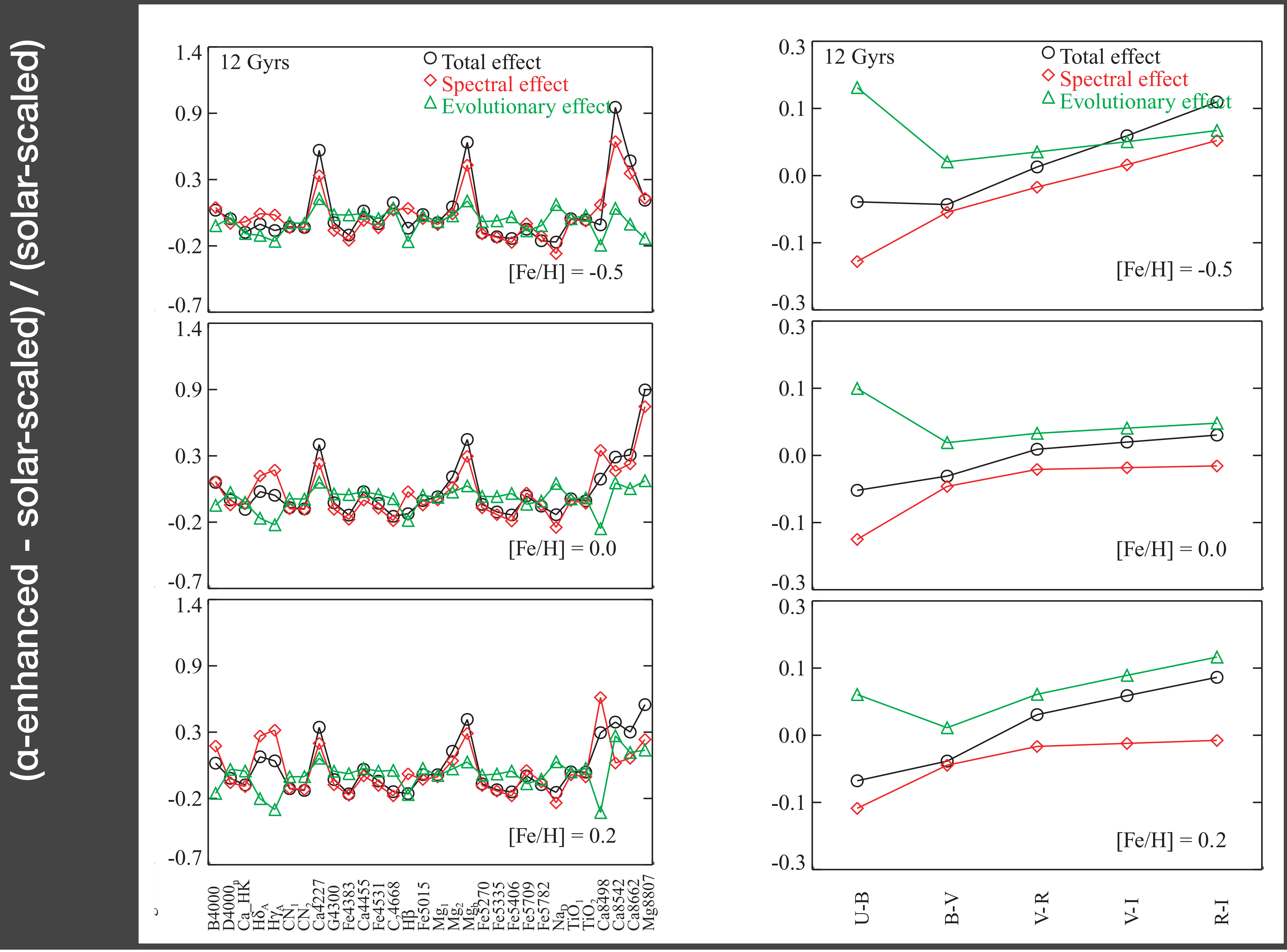
Models by Thomas et al. 03 at different α/Fe (solid lines). Gray points are galaxies from Trager et al. ’98. Credit: Thomas et al. ’03

Fully theoretical models with α-enhancement

- First appears in Coelho et al. '07

- **Advantages** over response functions based methods:
    - include a consistent treatment of the **evolutionary effect**
    - provide models that could be used in **spectral fitting**
    - **all stars** along the isochrone are corrected

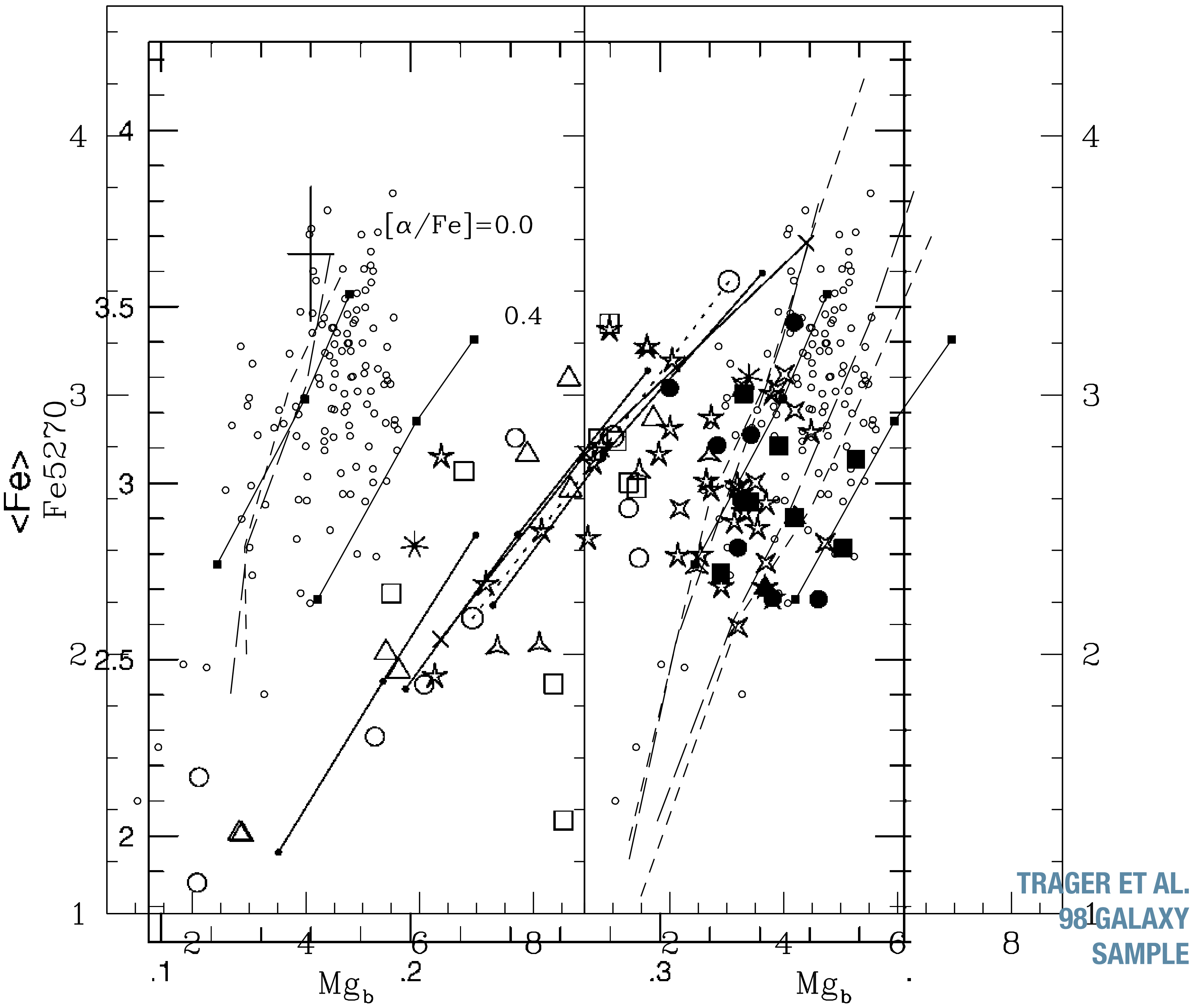
- **Disadvantages**:
    - carries through the **uncertainties from theoretical stars**
    - cannot model **individual abundance variations** easily



Spectral vs. evolutionary effect

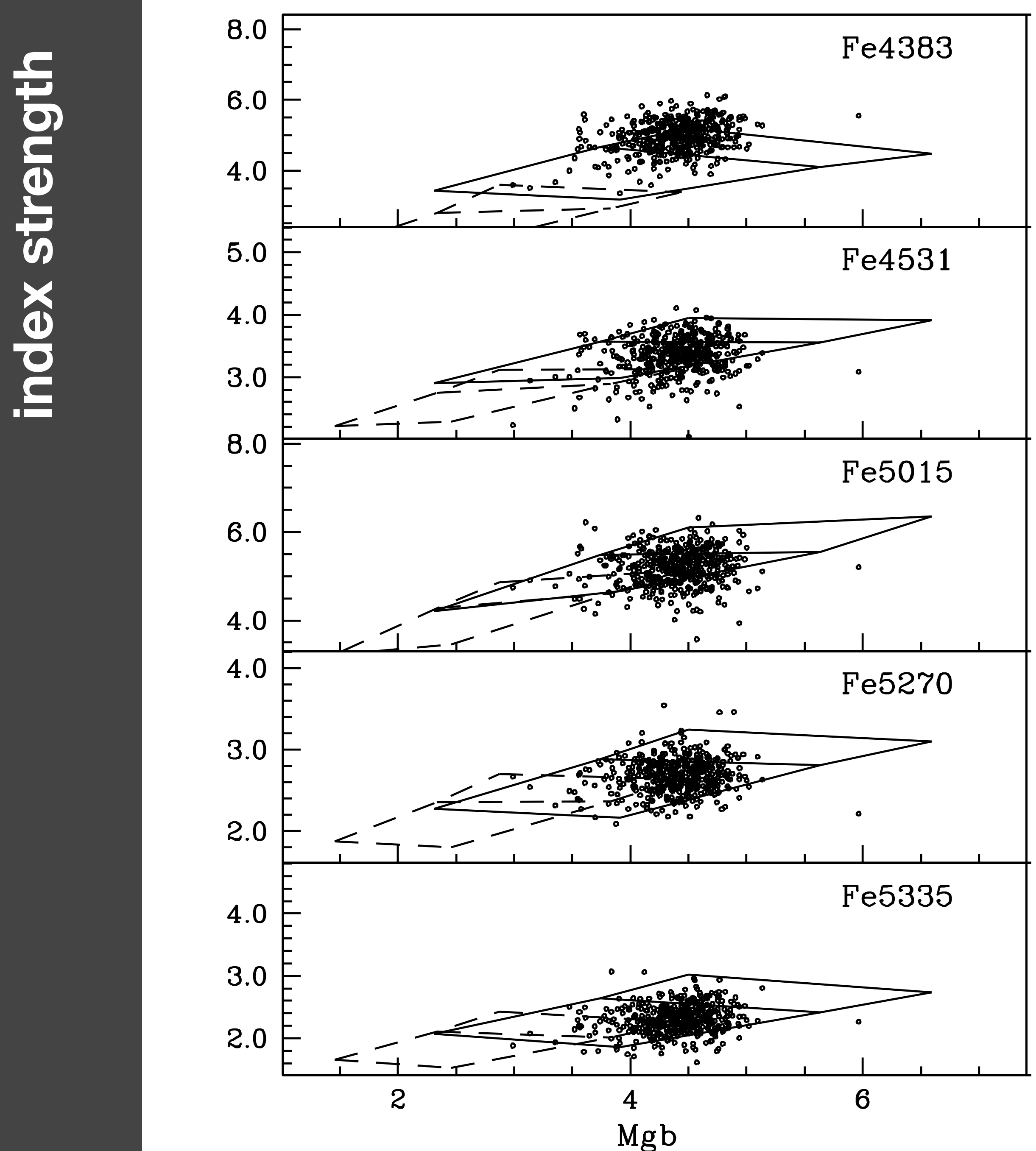
Effect from:
◊ the stellar spectra Δ the stellar evolutionary tracks ❍ both.

Our version of a classical plot



Plotted with other spectral models (BC03 and CB09)

Plotted with other Lick indices models (Thomas et al. 03, Schiavon 07)



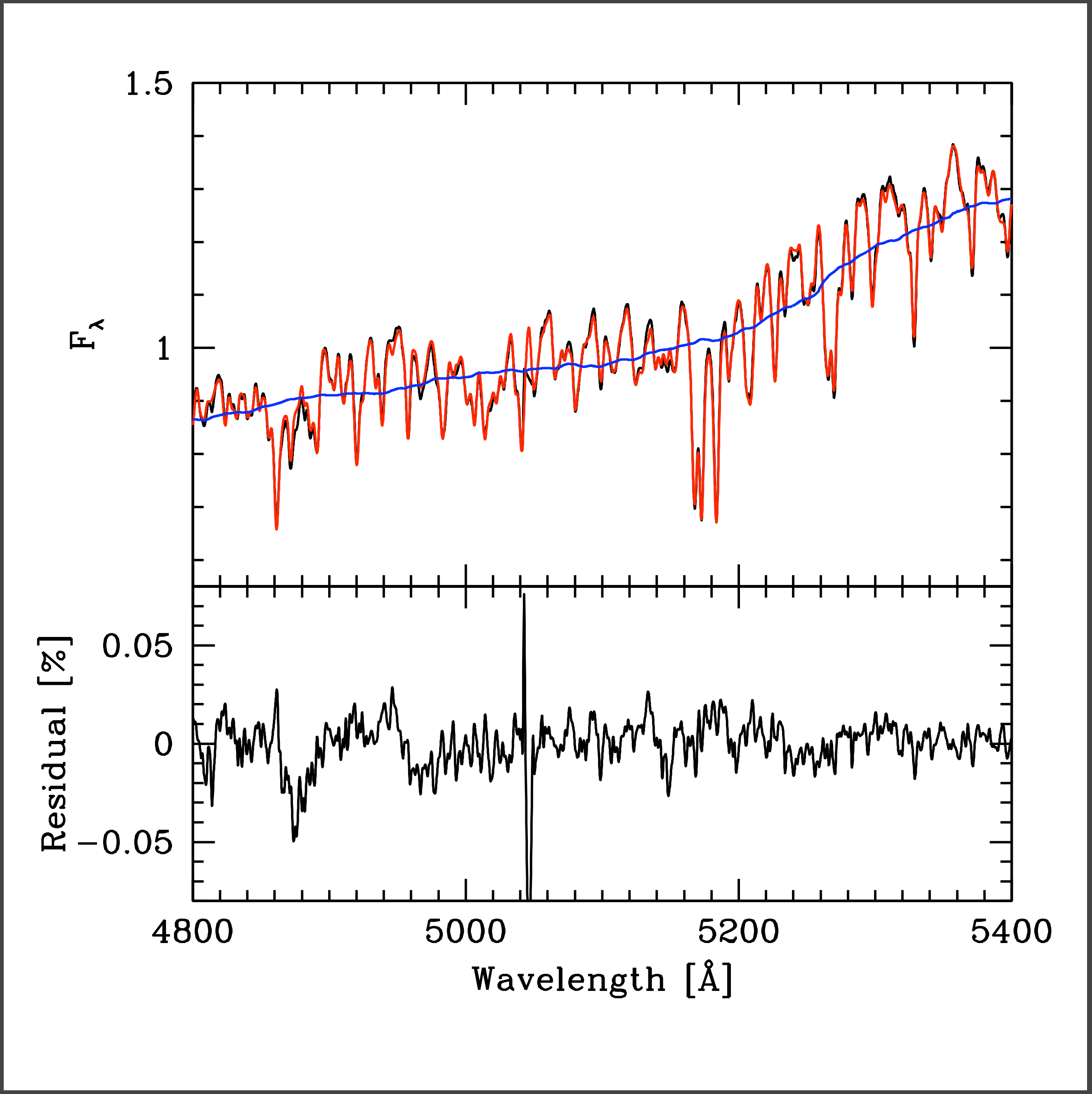
Coelho et al. ’07

Predictions from fully theoretical models

Solid lines: 12 Gyr models; dashed lines: 4 Gyr models. Data: SDSS elliptical galaxies.

Differential stellar population models

- Walcher et al. ’09 proposes to use semi-empirical and theoretical SP models combined.
- Differential spectra are obtained from theoretical SSP models, as a function of [Fe/H] and [α/Fe] independently
- The differential spectra are applied to semi-empirical SSP at solar-scaled solar-metallicity.
- see Prugniel et al. 07, Koleva et al. 07, Vazdekis et al. in prep.

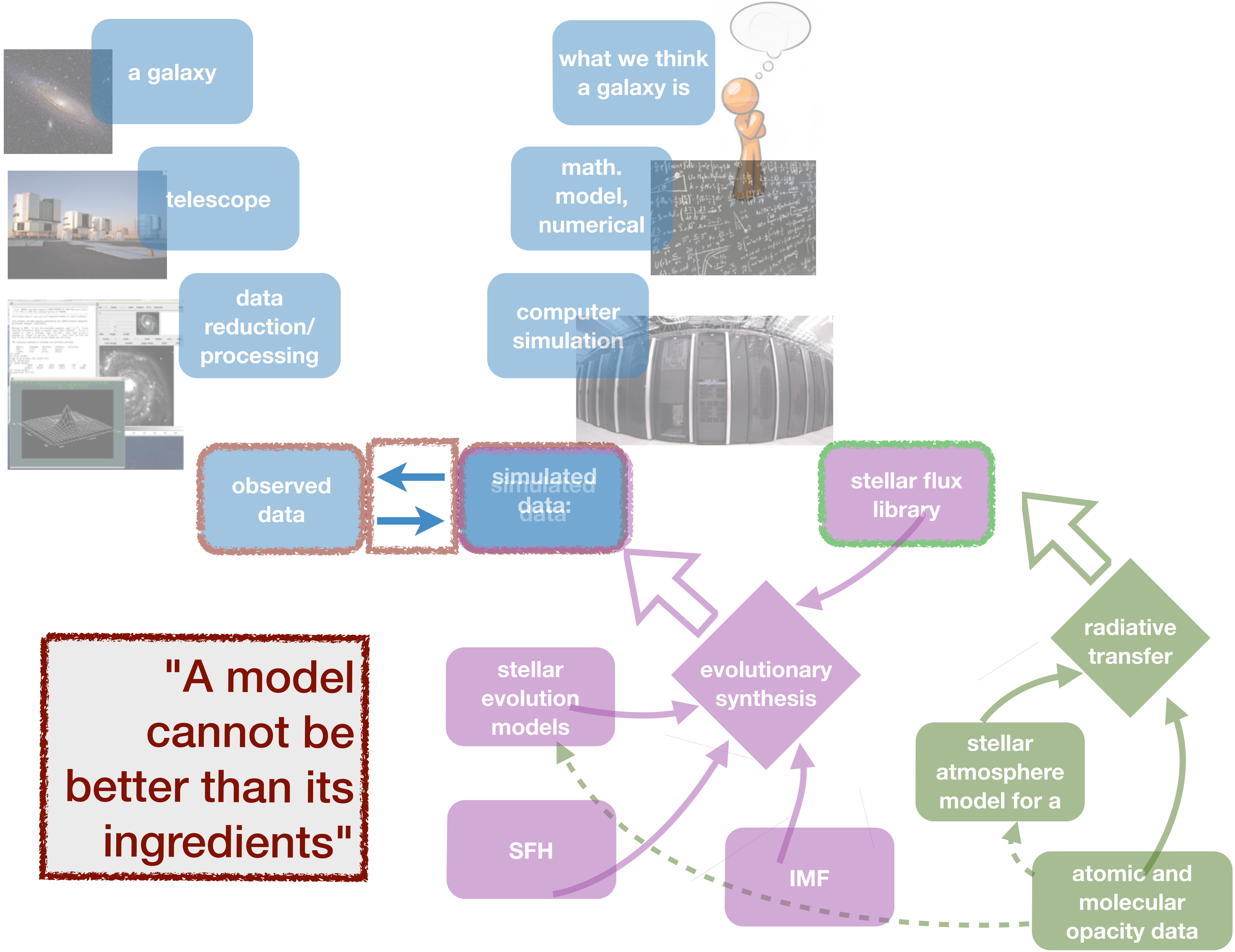


NGC6528 (black) and best-fitting model from PegHR+C07 (red). The blue line is the continuum. The fitting was performed in the wavelength range 4828 - 5364A.

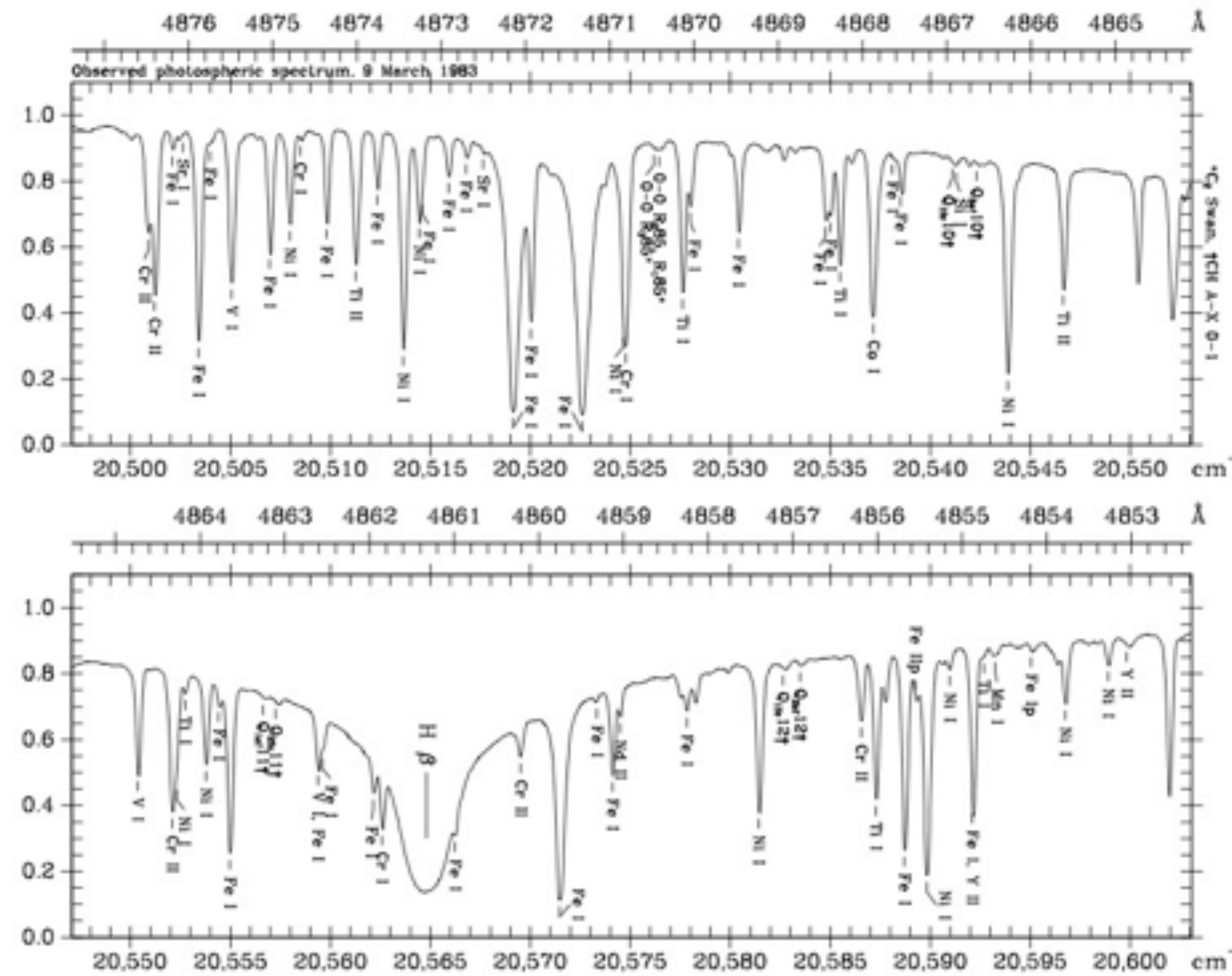
Flavours of stellar population models for studying chemical patterns

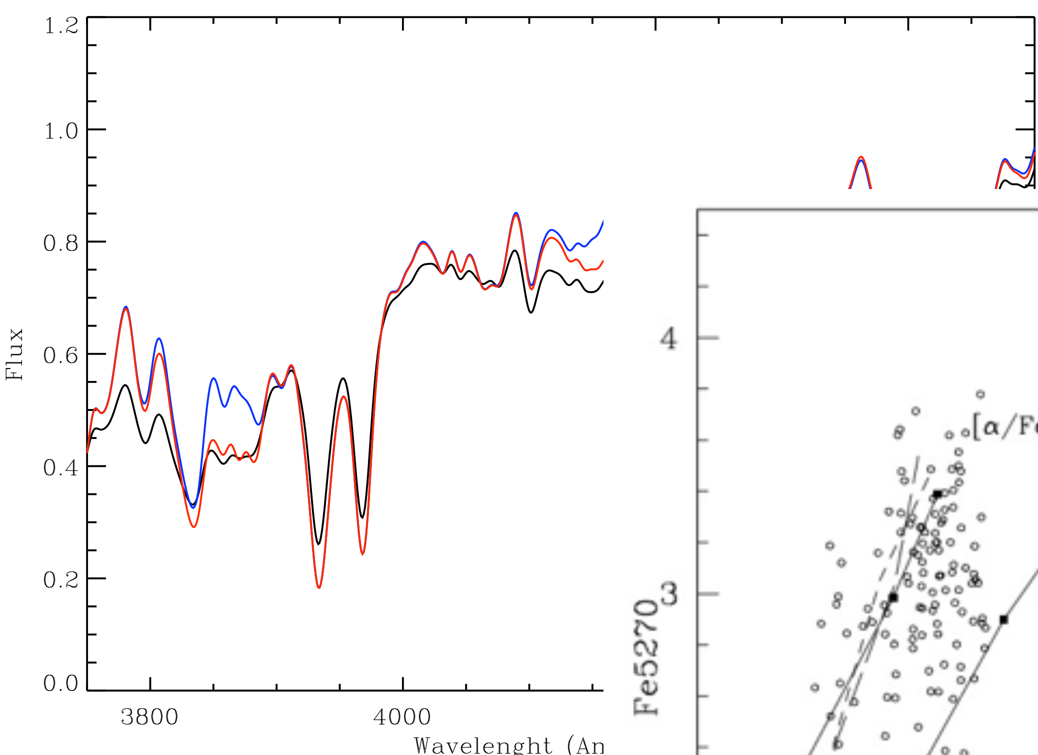
- Semi-theoretical models: combining empirical information and theoretical information
    - empirical fitting functions + theoretical responses tables (e.g. Trager et al. 2000, Proctor et al. 2002, Thomas et al. 2003 , Schiavon 2007)
    - differential spectral corrections (e.g. Cervantes & Vazdekis 2008, Prugniel et al. 2008, Walcher et al. 2009, Conroy et al. 2013, Vazdekis et al. in prep.,)
- Fully theoretical: using directly the theoretical libraries instead of empirical ones
    - e.g. Coelho et al. (2007), Percival et al. (2009), Lee et al. (2009)

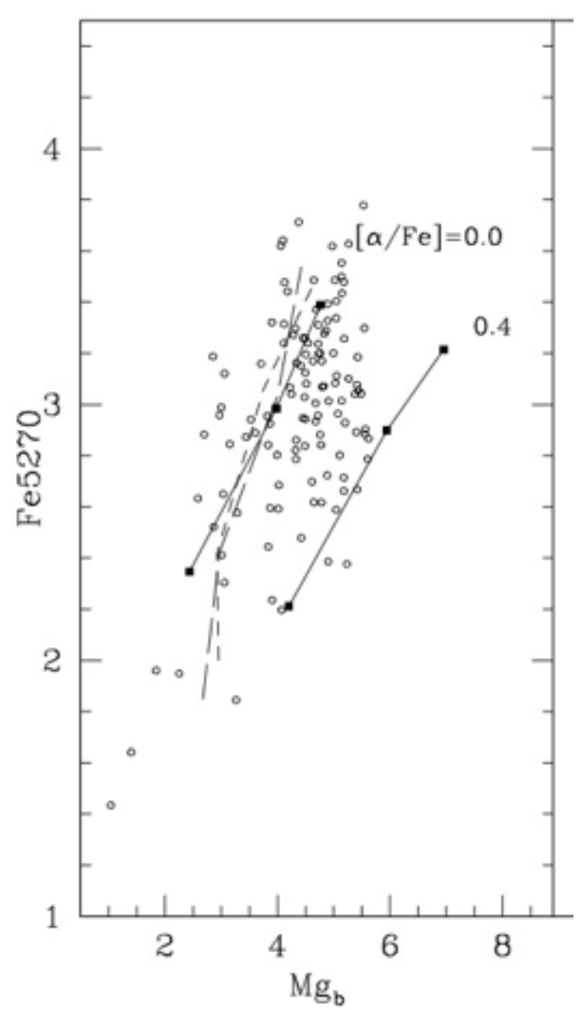
Ideas to take home…


a galaxy
telescope
data reduction/ processing
what we think a galaxy is
math. model, numerical
computer simulation
observed data
simulated data:
stellar flux library
evolutionary synthesis
radiative transfer
stellar evolution models
SFH
IMF
stellar atmosphere model for a
atomic and molecular opacity data
"A model cannot be better than its ingredients"

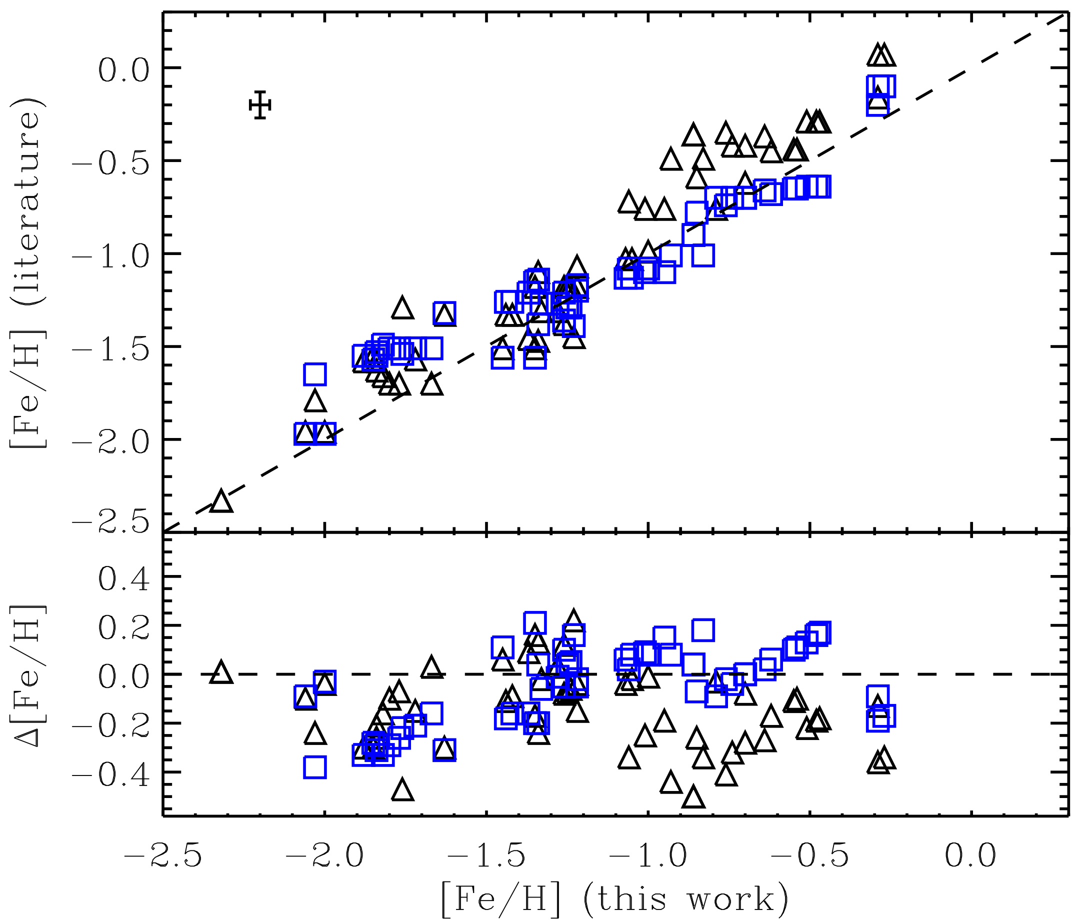
To reveal (and model) all the details of the absorption stellar spectra is far from complete.







Nevertheless, theoretical stars are a powerful tool to explore new dimensions on the spectral analysis of stellar populations.



Metallicities derived via spectral fitting are very robust.

Spectroscopic vs. CMD ages: discrepancies yet to be understood.