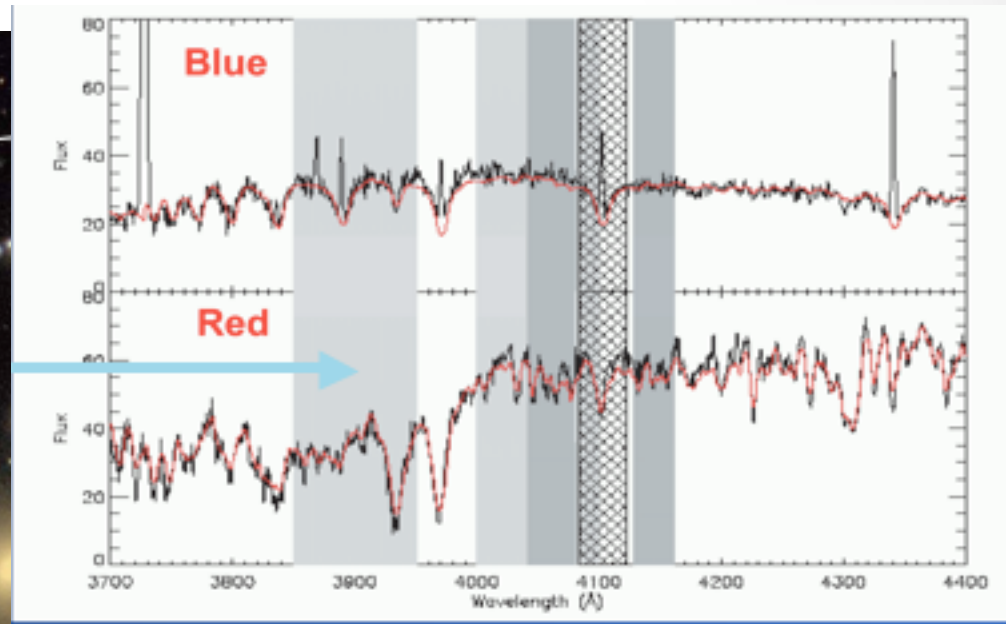
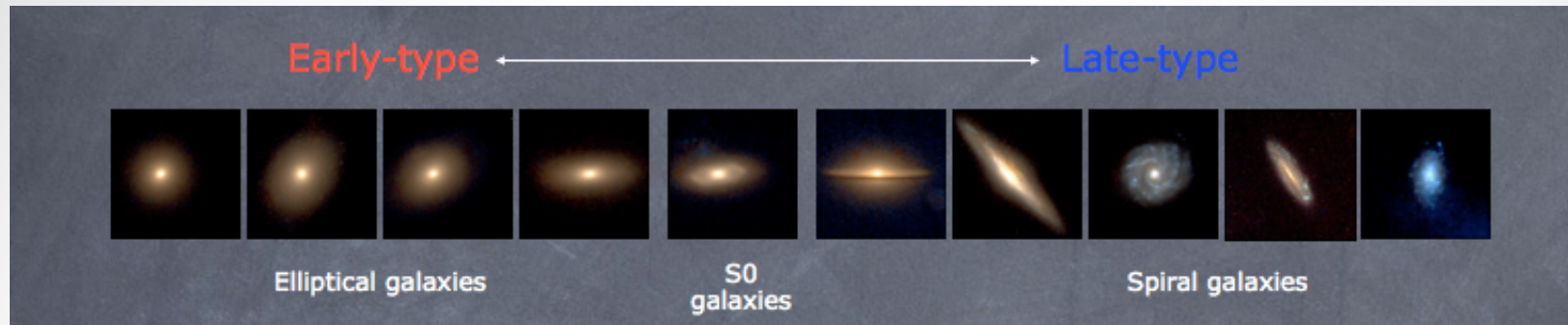


# Observational determination of physical properties: stellar mass, chemical abundances, star formation history



Study of Emission-Line  
Galaxies with  
Integral-Field Spectroscopy

Patricia Sanchez-Blazquez  
(UAM)



Stellar populations

SELGIFS school (2014) ●

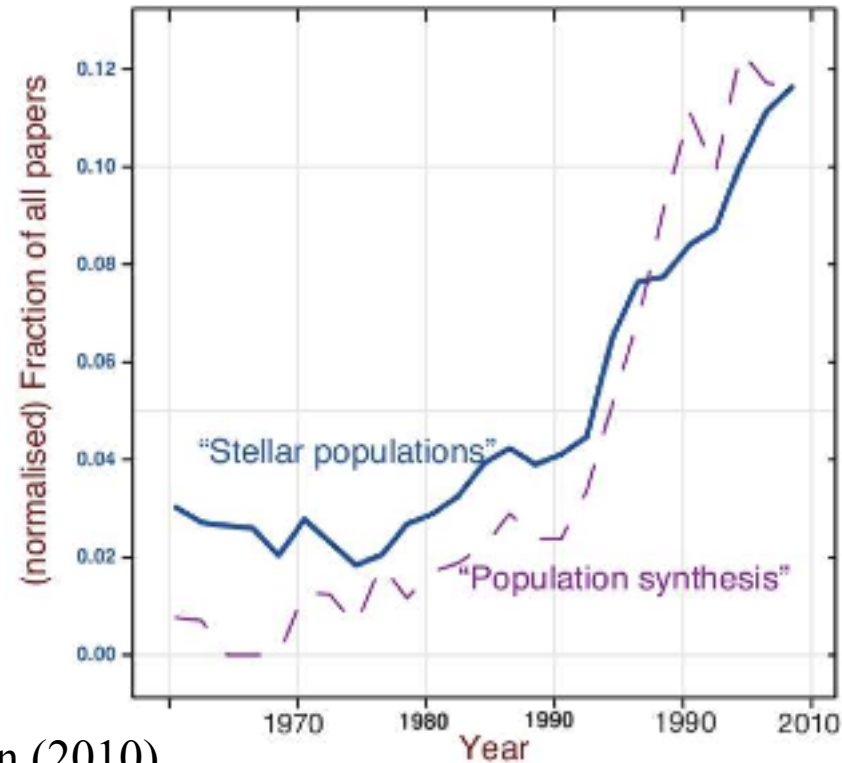
# Aims

- **Luminosity, colors and spectrum** depends on stellar content of the galaxy, and understanding these is the subject of stellar populations.
- Use **stellar evolution theory** to interpret differences in stellar pops between galaxies.
- **The limitations are twofold:**
  - (1) Our knowledge on stellar evolution
  - (2) The noise in our data

# What can be obtained from a spectrum?

- We will see the SPS techniques and discuss what can be reliably measured from galaxy SEDs.
- Star formation histories (or ages)
- Metallicities (normally expressed as the fractional abundance of Z of elements heavier than He and H  $[Z/H]=\log(Z/Z_{\text{sun}})$ )
- Abundance patterns (e.g.,  $[Mg/Fe]$ ,  $[O/Fe]$ ,  $[C/Fe]$ )
- Dust properties
- Stellar masses

# Papers published in the topic



From Brinchmann (2010)

# Outline

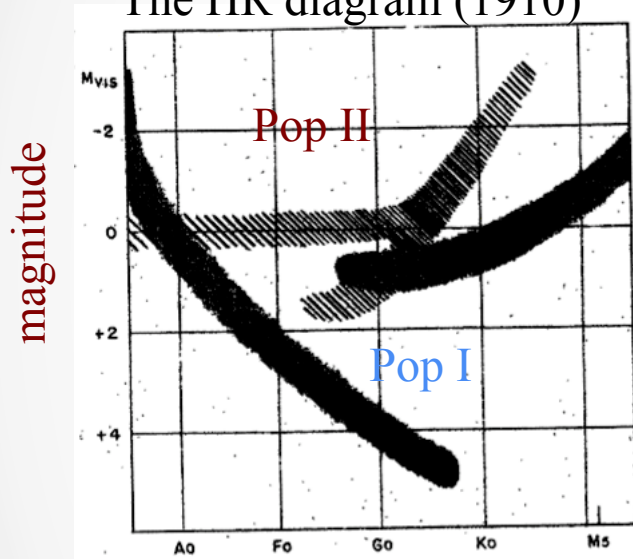
- (1) a brief introduction on the stellar population models
  - Concept of SSP
  - Concept of CSP as a combination of a SSP
- (2) techniques to derive physical quantities from integrated spectra
  - SSP-equivalent parameters
  - Parametric fitting techniques
  - non-parametric fitting techniques
- (3) The big assumption: The initial mass function

# The Concept of Stellar Populations

Population I (eg. Open clusters)

Population II (eg. Globular clusters of our galaxy)

The HR diagram (1910)



spectral type

Early-types only have Pop II

Both populations coexist in spirals



Walter Baade 1944

## A quick Tour

### Main Sequence (MS):

Core hydrogen burning phase. Longest phase of evolution

### Turn-Off:

Hydrogen exhausted in core.

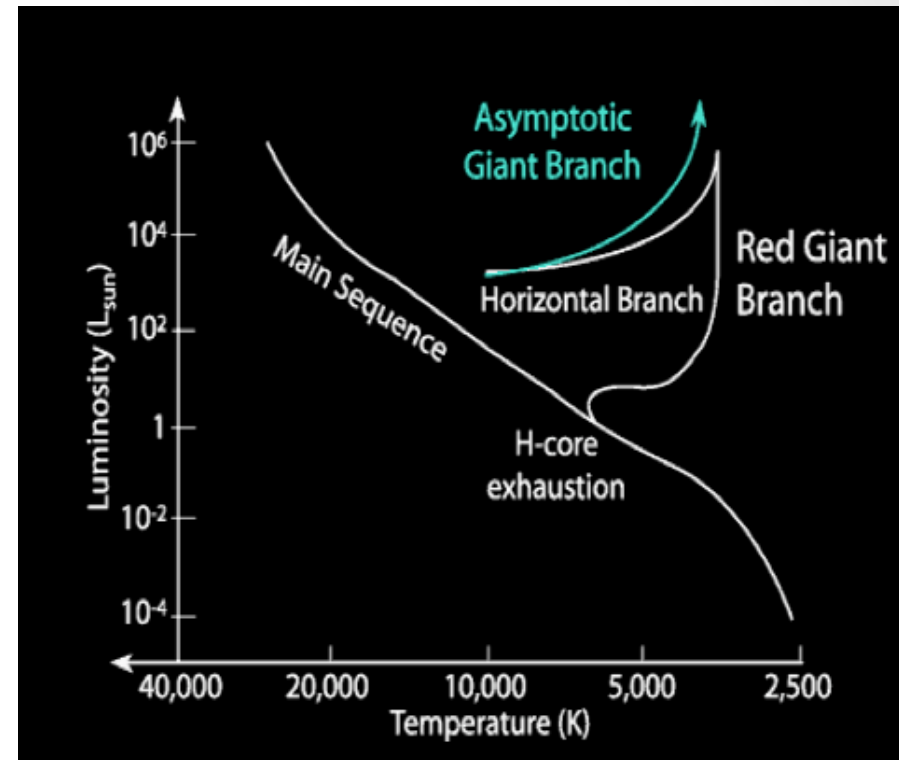
### Red Giant Branch (RGB):

Hydrogen Burning in shell around inert helium core.

### RGB tip: end of the RGB

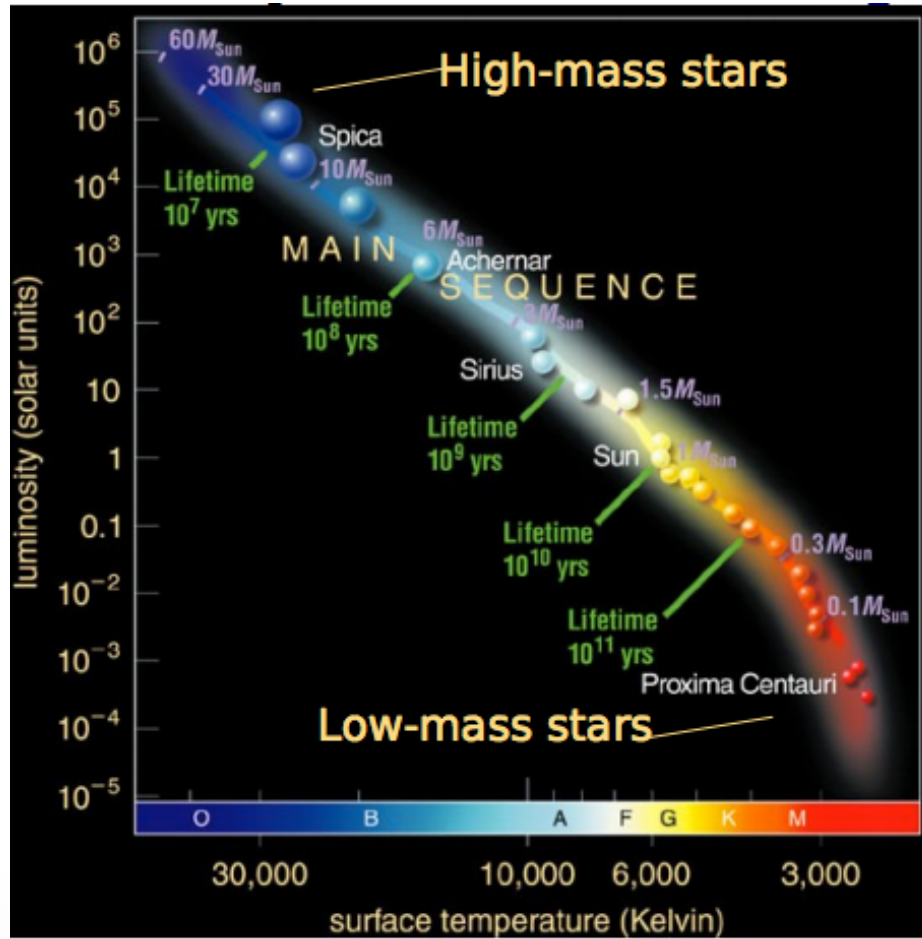
**HB (RC):** Helium burning in the core (details depends on the mass loss)

**Asymtotic Giant Branch (AGB):** He burning in shell around an inert C/O core. Complicated mass dependent evolution from now on.

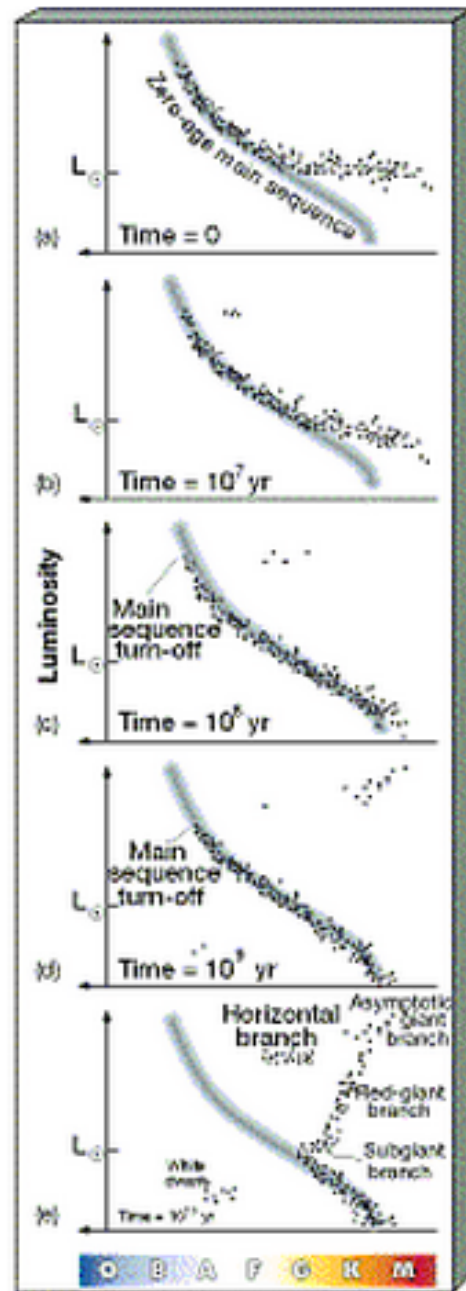




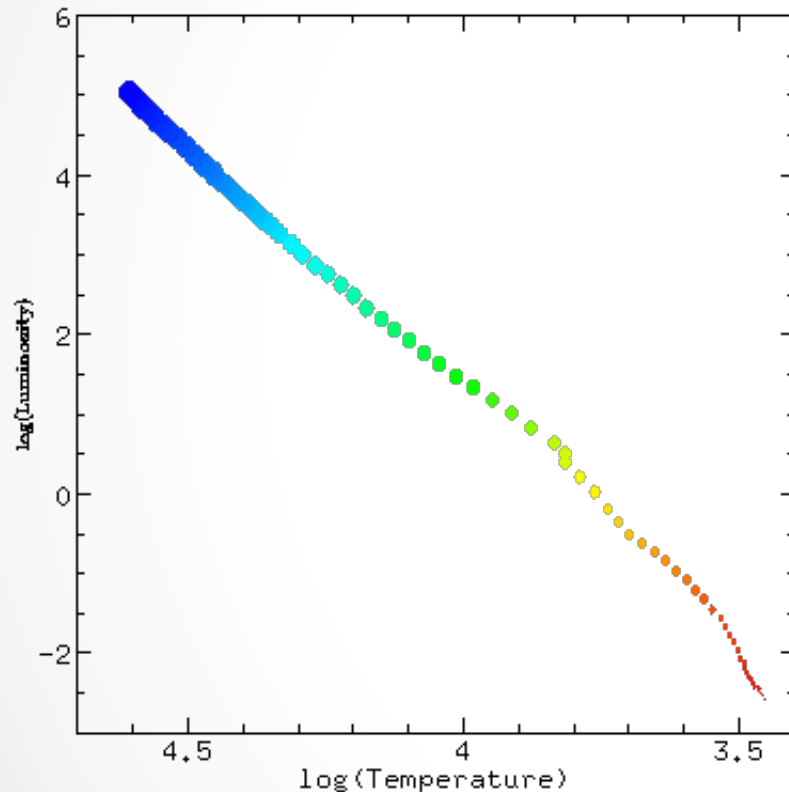
- [HR evolution](#)



## Evolution of the HR diagram with time: Isochrones



# The SED/colour of stellar populations



From the HR diagram for a generation of stars at different ages, we can predict what its combined spectral energy distribution will be. The SED is simply the distribution of light energy over wavelength, or color. The animation show the HR diagram of a generation changes with time. As the population ages, the main sequence “burns down” and the remaining stars become concentrated to the right part (redder) of the diagram]

# Simple stellar Populations

Stars consists of objects born at the same time in a burst of star formation activity of negligible duration, with the same initial chemical composition.

- contain 10-1000 stars
- loose structure



Open Cluster

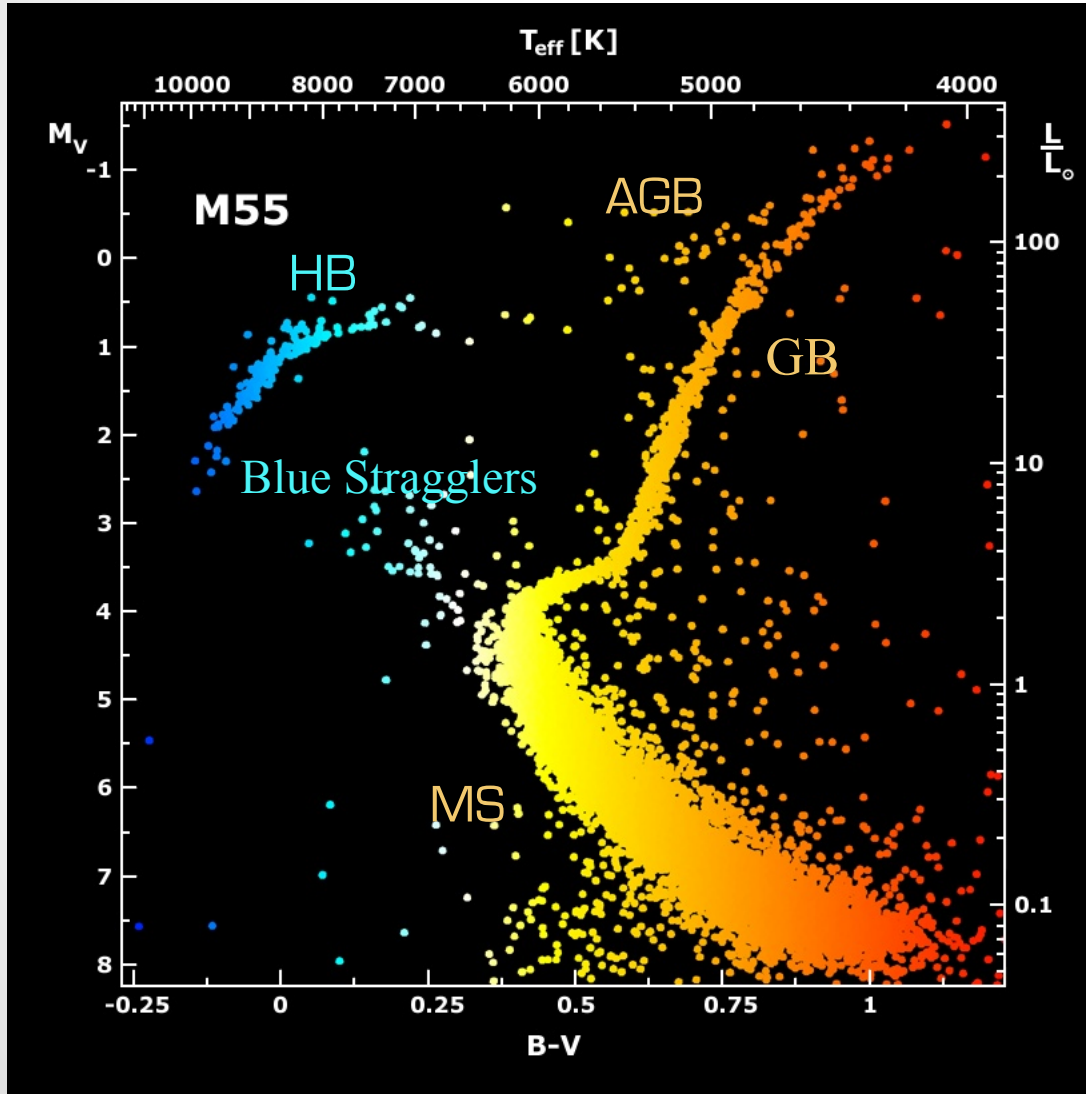
- centrally concentrated

~5 pc

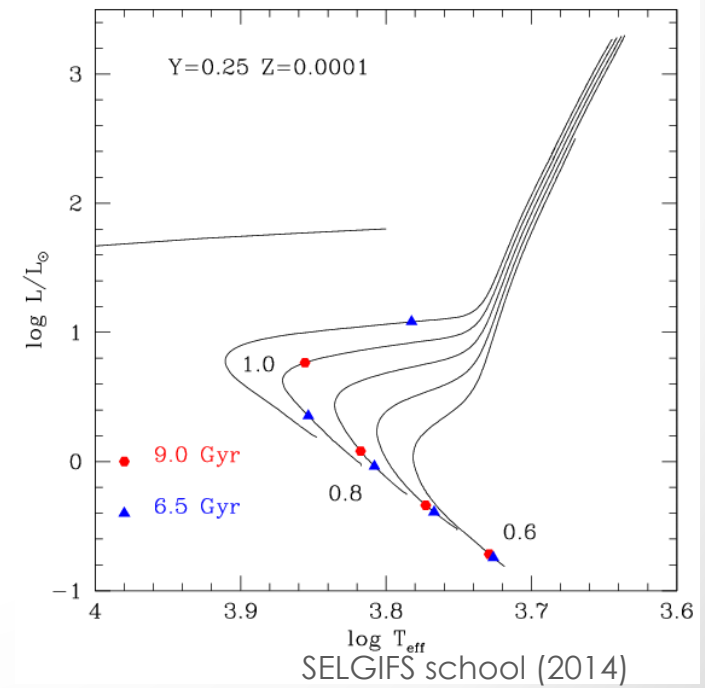


Globular Clusters

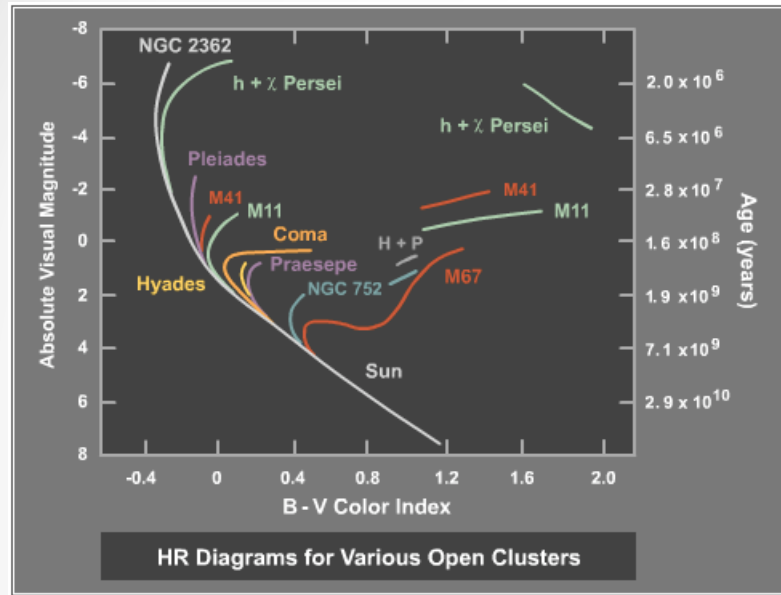
# Old Stellar Populations



● Stellar populations

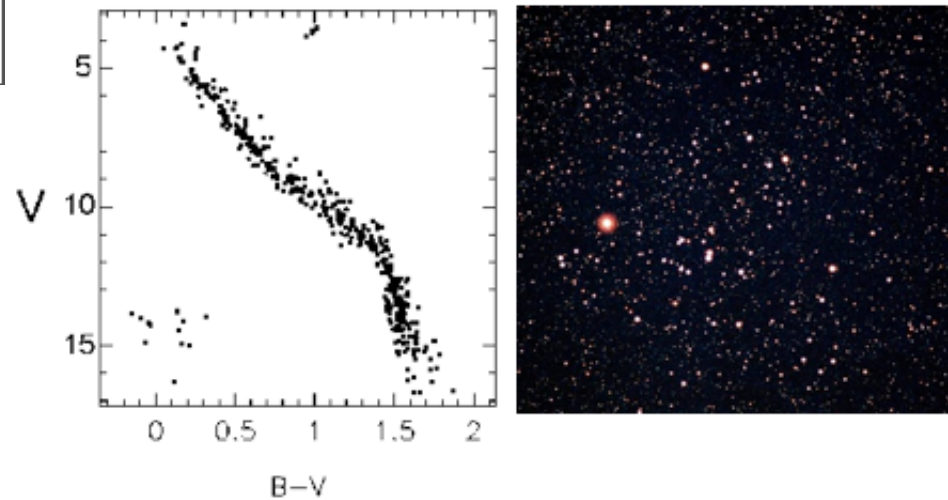


# Open Clusters

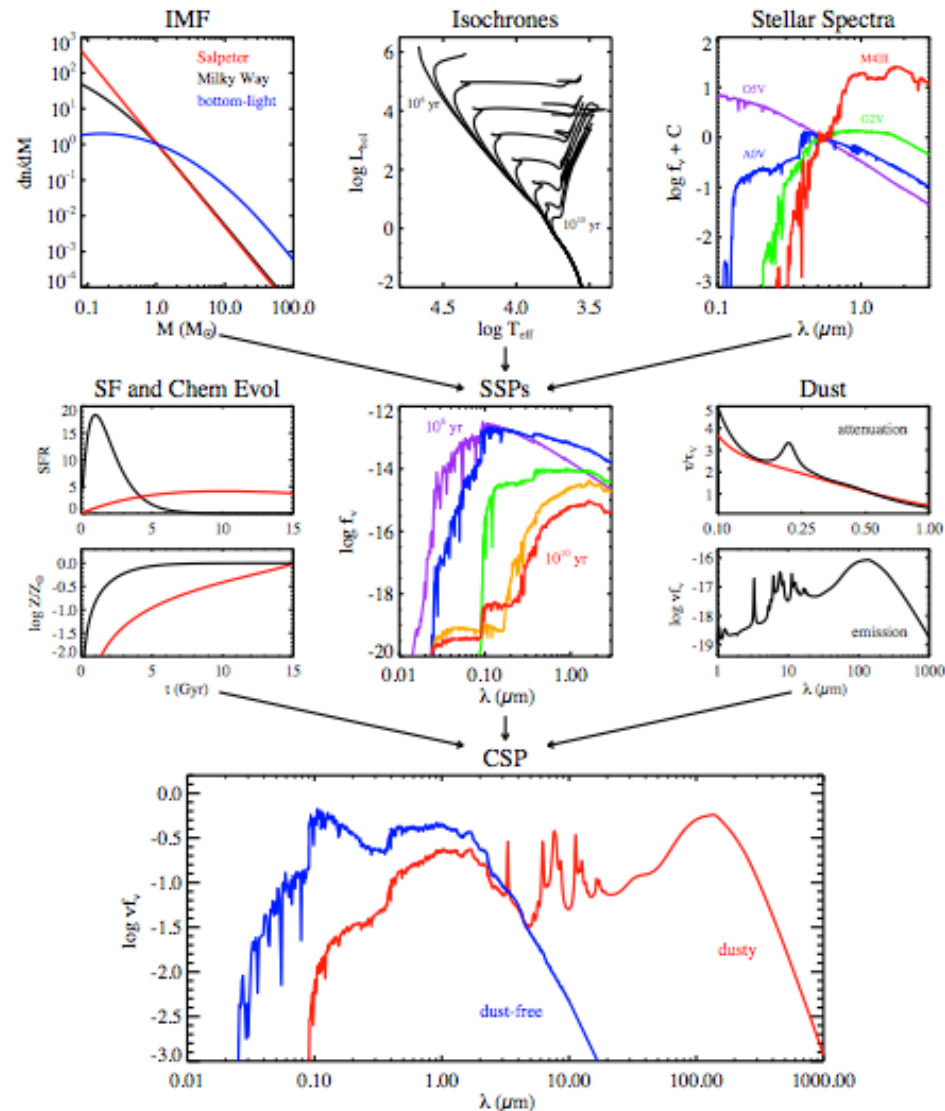


## A young cluster:

- The main sequence is the most prominent structure.
- There has not been enough time for stars to leave the main sequence

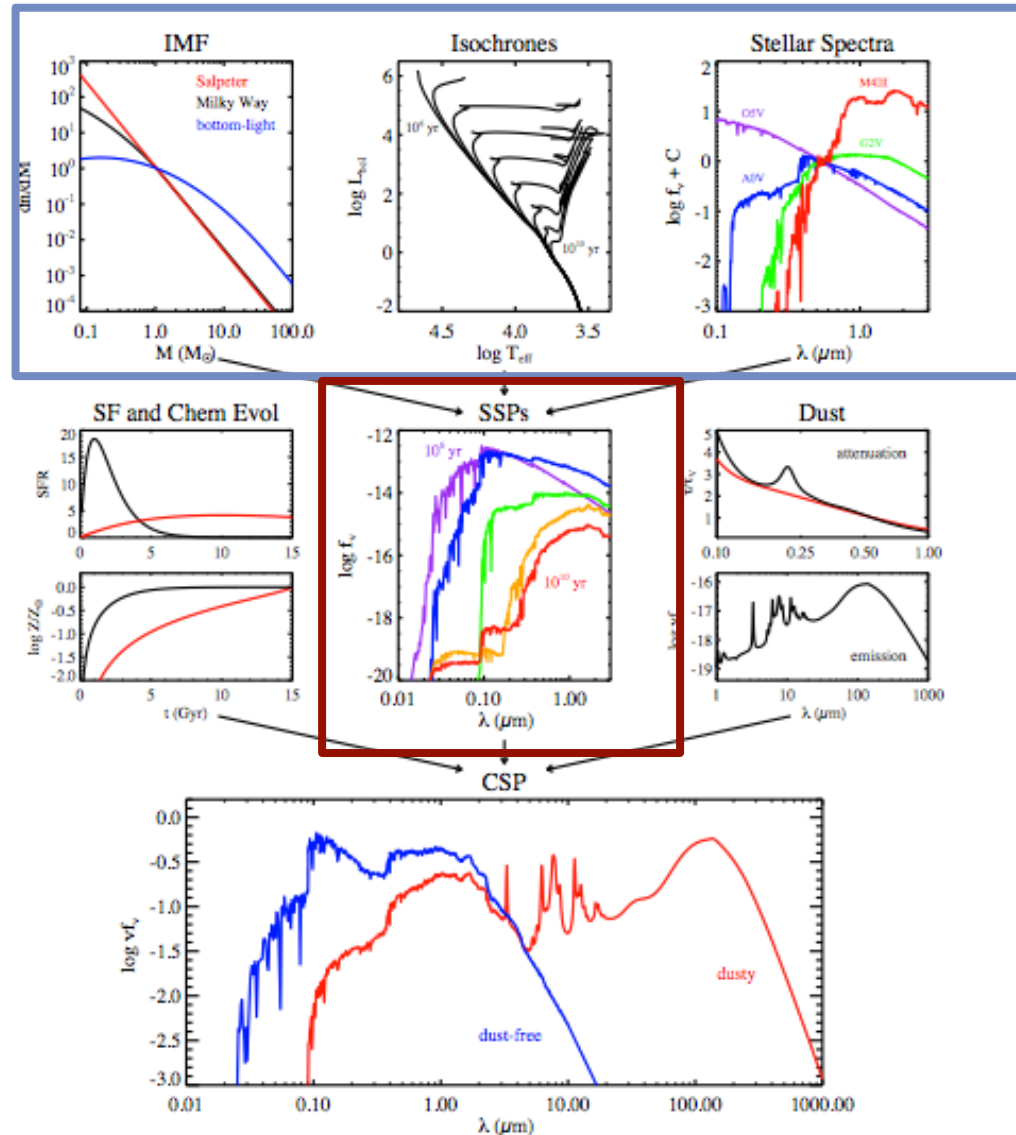


# Stellar population models



# Stellar population models

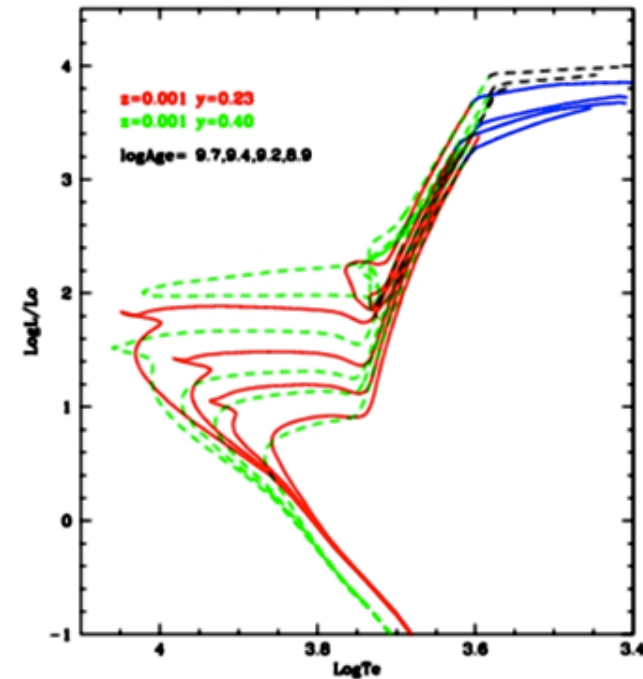
Main ingredients





# Stellar population synthesis ingredients

**Isochrones:** in the stellar evolution an isochrone is a curve on the HR diagram, representing a population of stars of the same age.



Padova tracks (Bertelli et al. 1994; Girardi et al. 2000; Salasnich et al. 2000)

BaSTI (Pietrinferni et al. 2004; Coier et al. 2007)

Geneva tracks (Schaller et al. 1992; Meynet & Maeder 2000)

# Isochrones

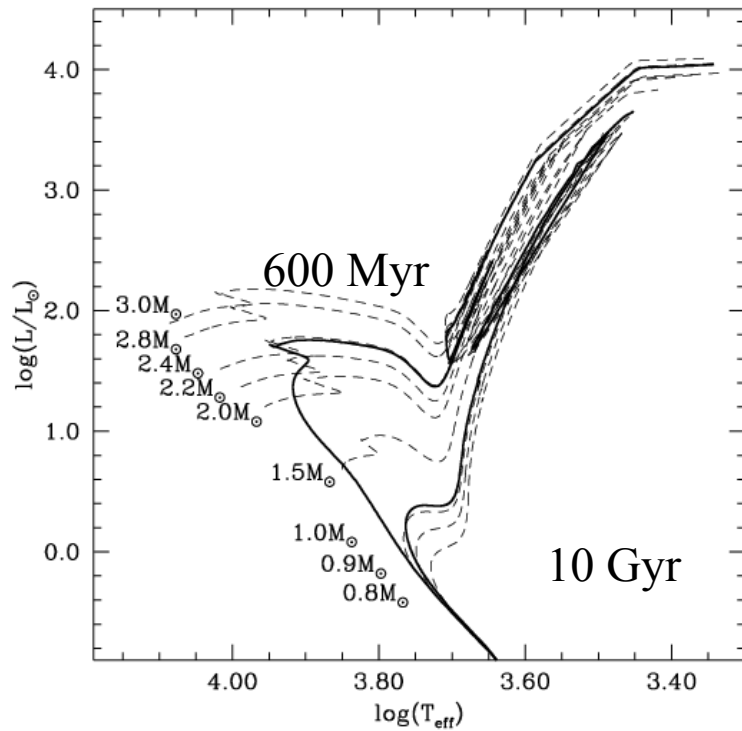


Figure 64: HRD of selected stellar evolutionary tracks (dashed lines) with the same initial solar chemical composition and the labelled masses. The heavy solid lines display two isochrones for the same chemical composition and ages of 600 Myr (the brighter sequence) and 10 Gyr.

The value of the stellar mass around the TO and along the RGB is a function of age, for a fixed initial chemical composition

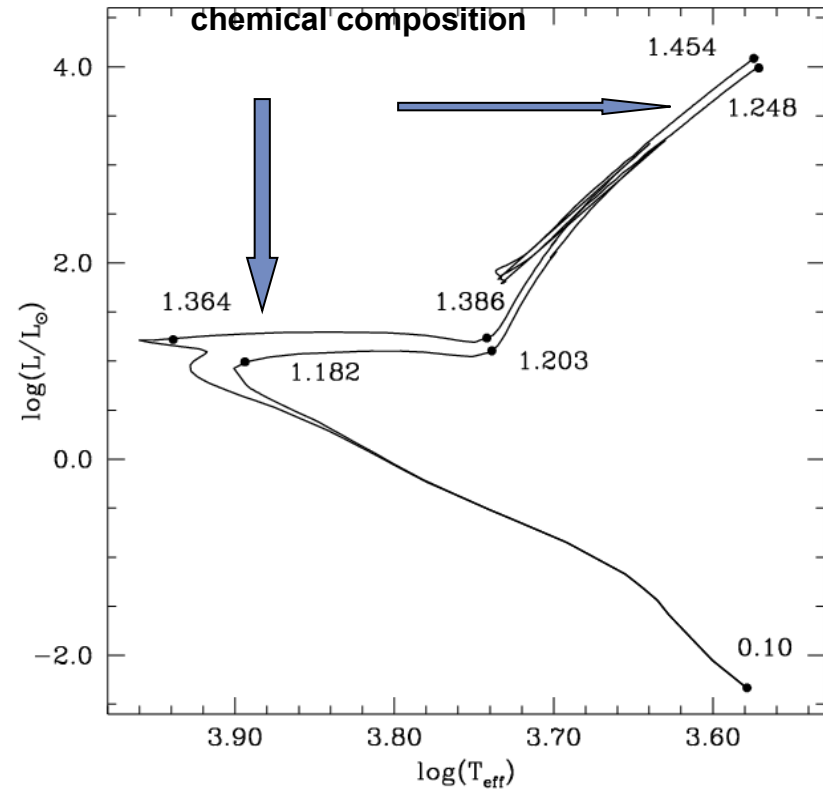


Figure 65: HRD of two isochrones (from the bottom of the MS until the end of the AGB phase) with ages equal to 2 and 3 Gyr

# Isochrones of different age

*50 million yr*

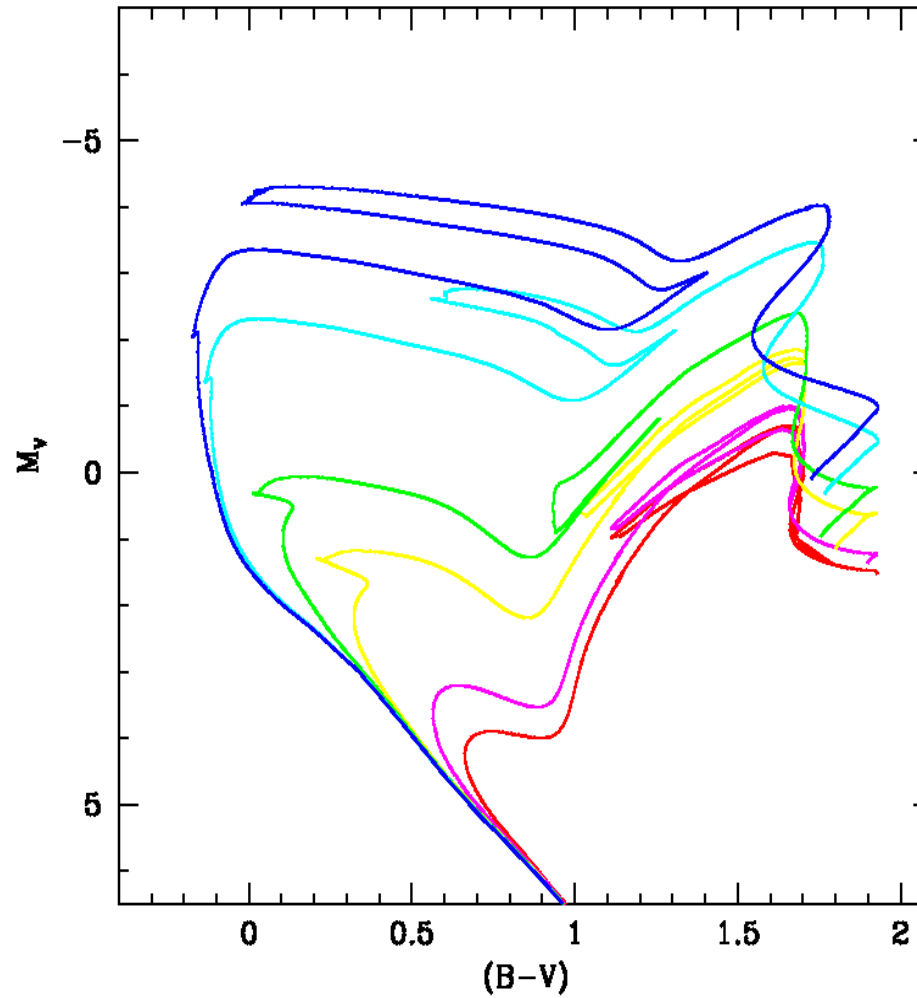
*100 million yr*

*500 million yr*

*1 billion yr*

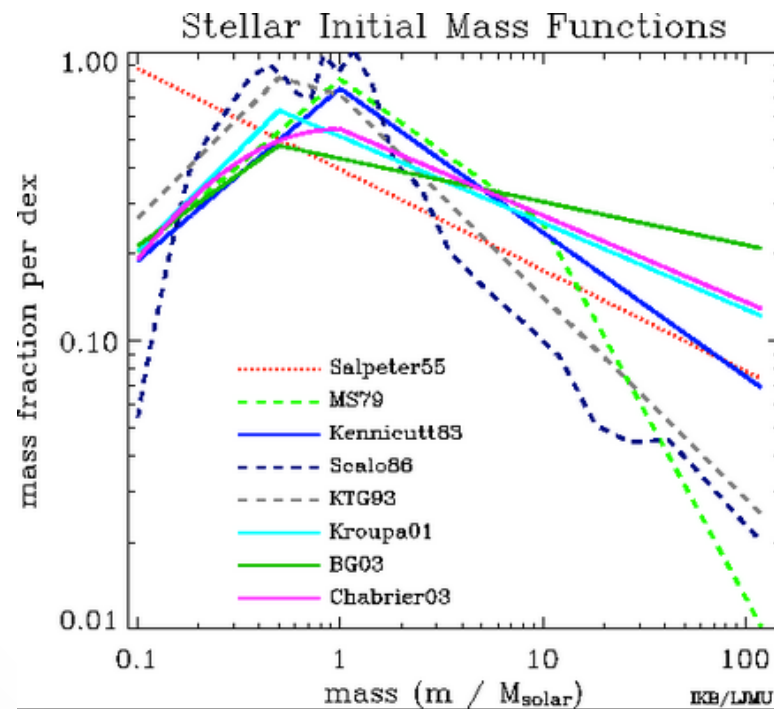
*5 billion yr*

*10 billion yr*



## Stellar population synthesis ingredients: IMF

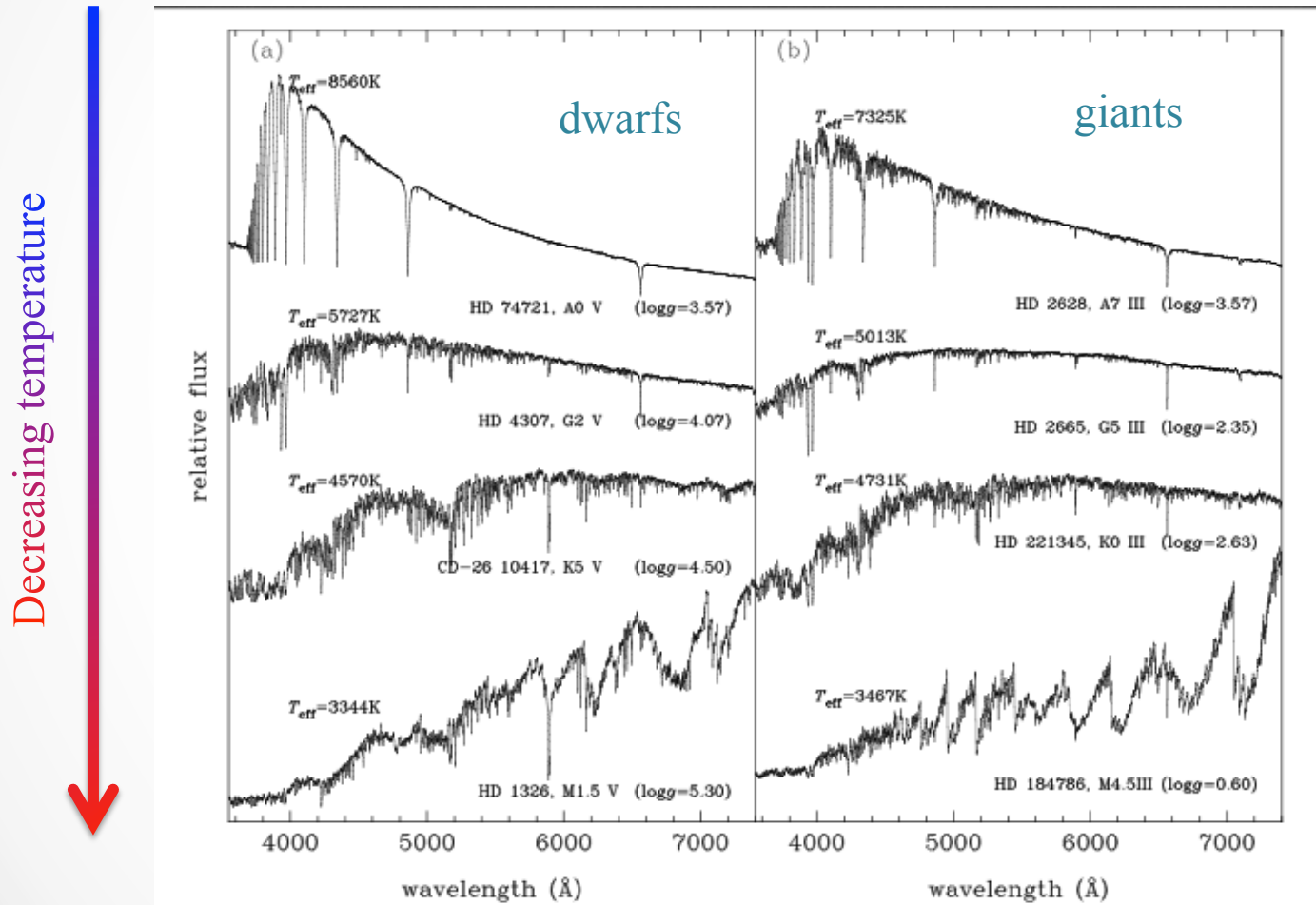
- (3) The IMF: The initial distribution of stellar masses along the main sequence (Salpeter 1995; Scalo 1986; Scalo et al. 1998, Kroupa 2001; Chabrier 2003). From the perspective of the SPS, the IMF:



Very difficult to measure in external galaxies!. It's a big assumption

# Stellar population synthesis ingredients

- (2) Stellar spectra (theoretical or empirical)



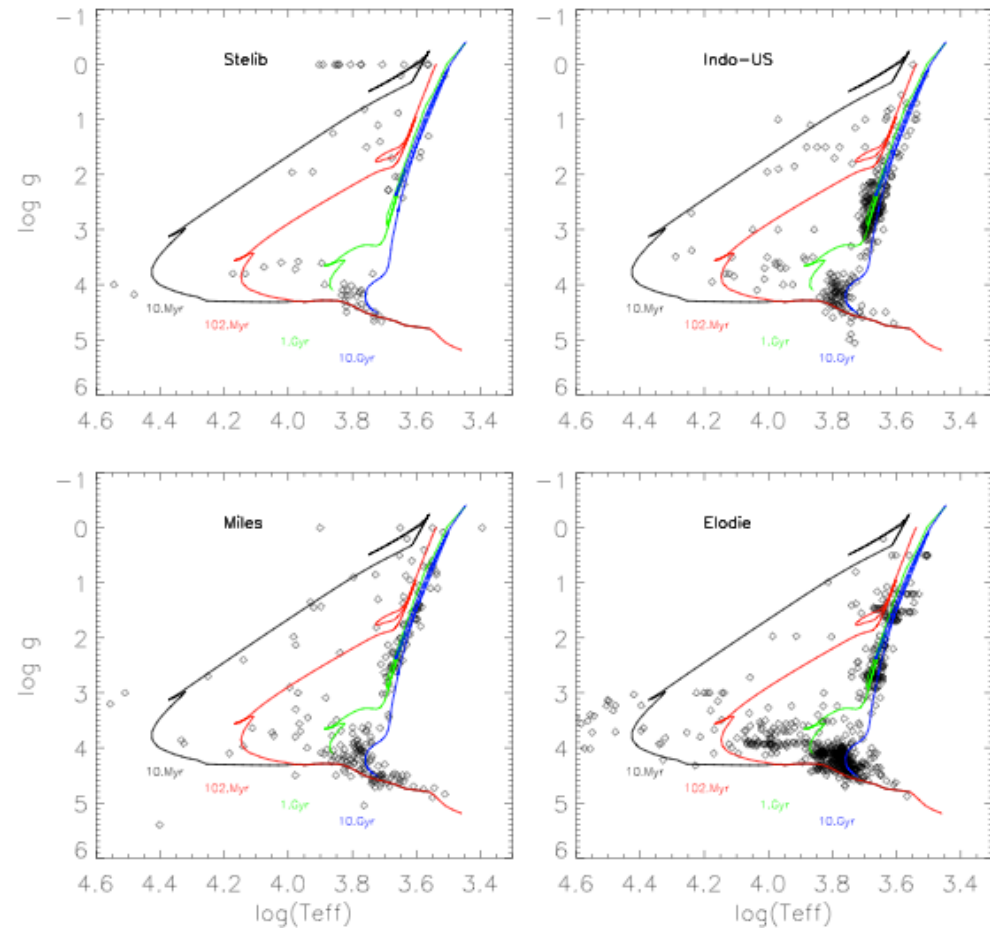
Sanchez-Blazquez et al. (2006)

# Stellar pop model ingredients:

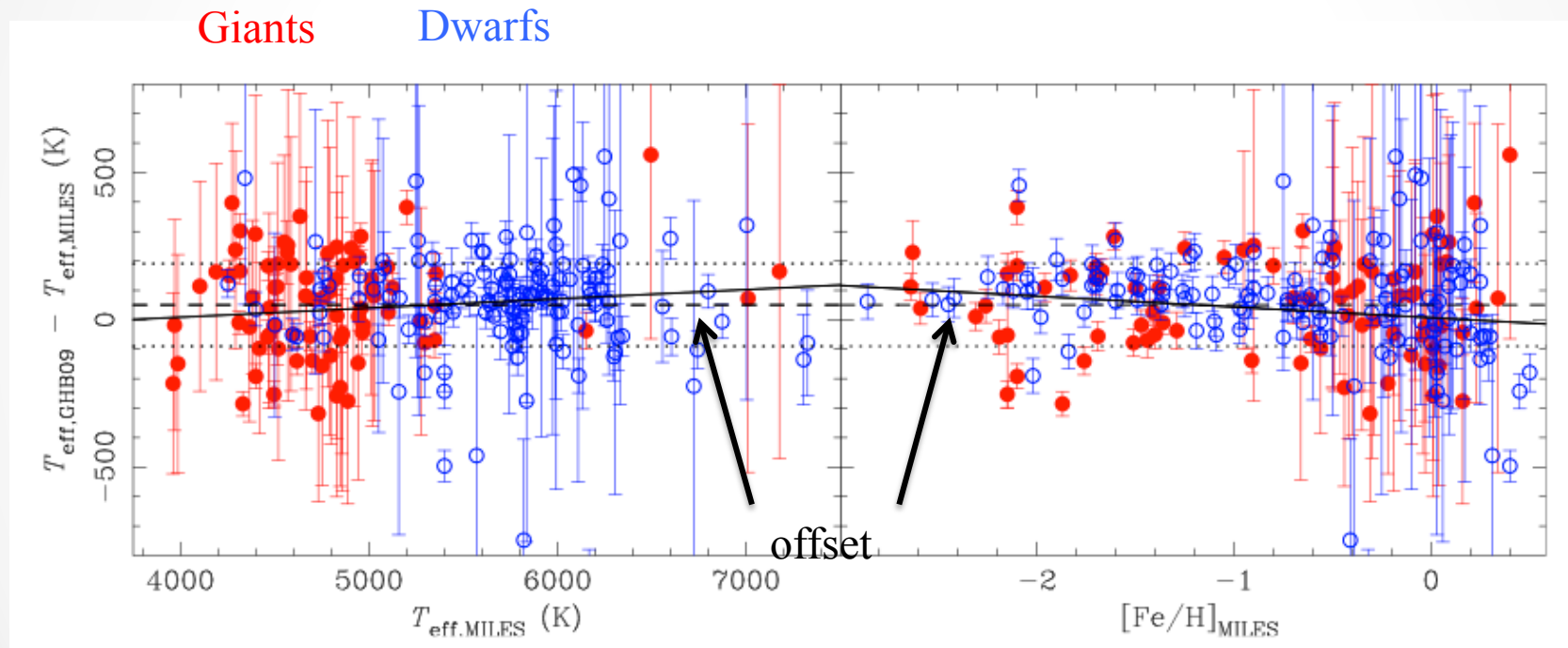
## Stellar libraries

Problems of empirical libraries:

- The atmosphere coverage is not complete (lack of hot stars of low metallicity)
- The abundance of the stars is limited to that of the Solar neighbourhood (and not known)
- The determination of stellar parameters is not trivial



# Uncertainties in the determination of stellar parameters



For the impact of uncertainties in the stellar parameters  $T_{\text{eff}}$ ,  $g$  and  $[\text{Fe}/\text{H}]$  in the final SSP predictions (Percival & Salaris 2009).

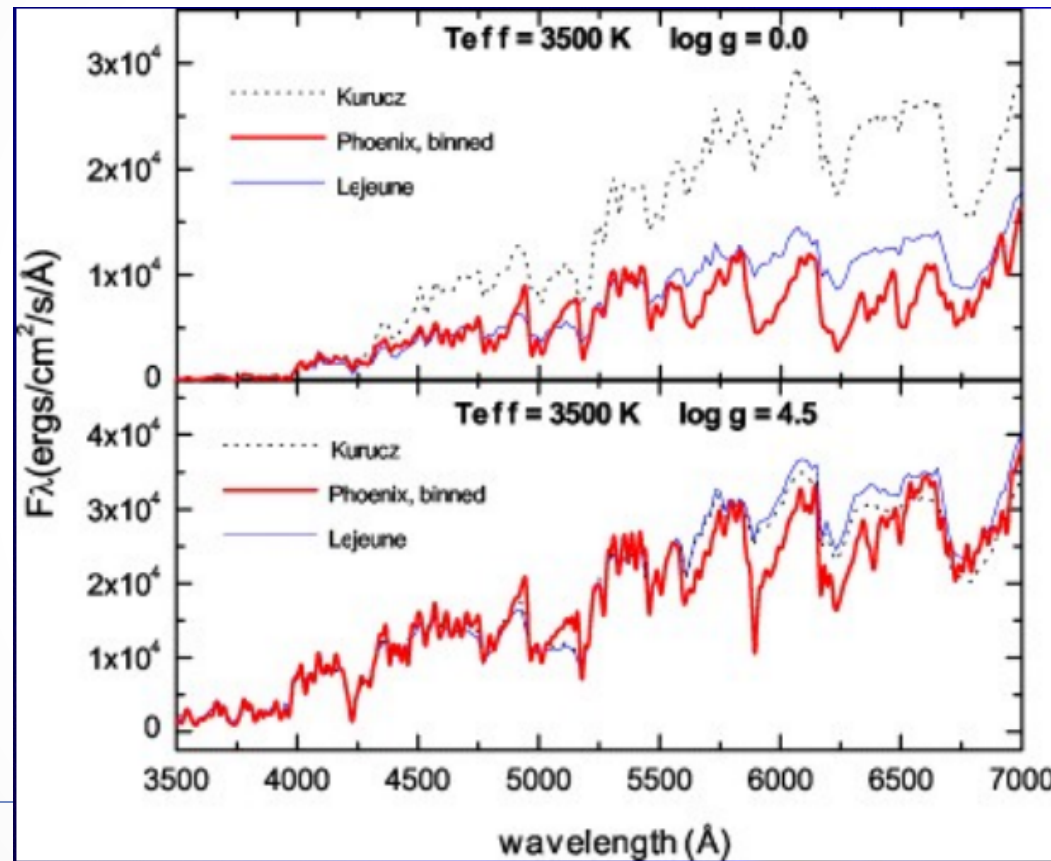
# Stellar libraries

- Theoretical libraries cover a much larger of parameter space and at any chosen resolution
- But still have problems reproducing cool stars and blue regions of the spectra (atomic and molecular opacity list are still incomplete)



# Theoretical stellar libraries

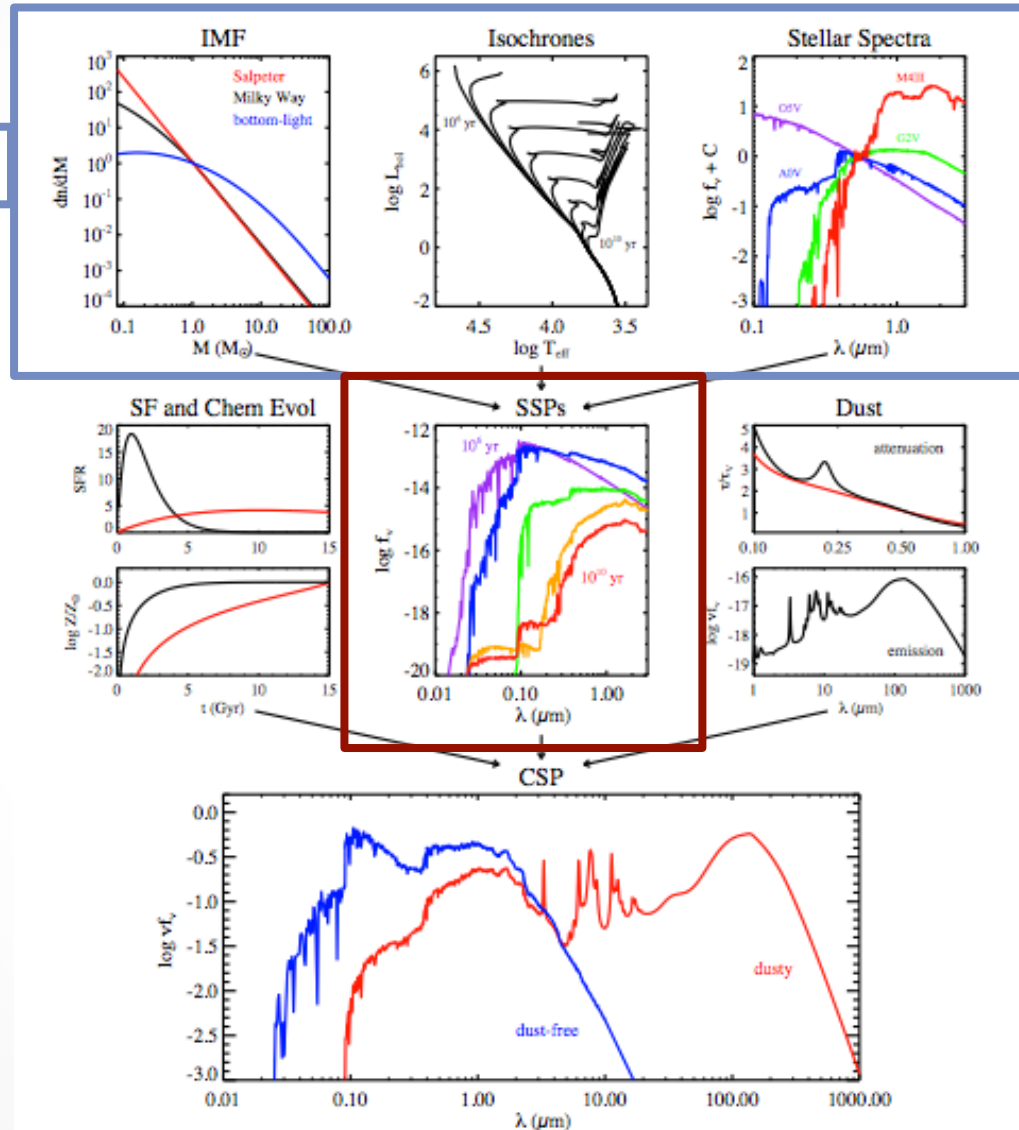
- Problems at low  $T_{\text{eff}}$



Martins et al. 2005

# Stellar population models

Main ingredients

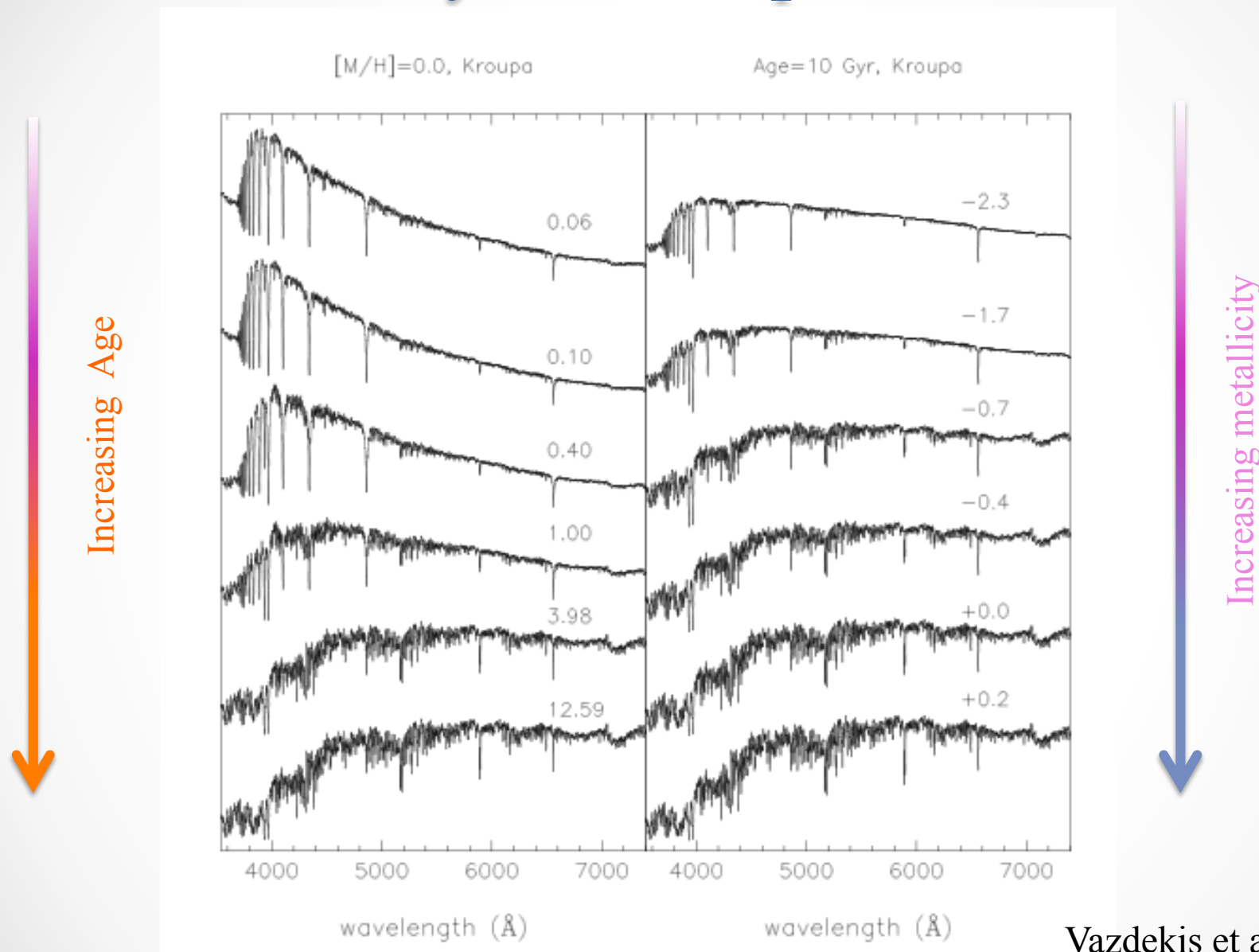


# The simple stellar population (SSP)

$$f_{SSP}(t, Z) = \int_{m_{lo}}^{m_{up}(t)} f_{star}[T_{\text{eff}}(M), \log g(M)|t, Z] \Phi(M) dM$$

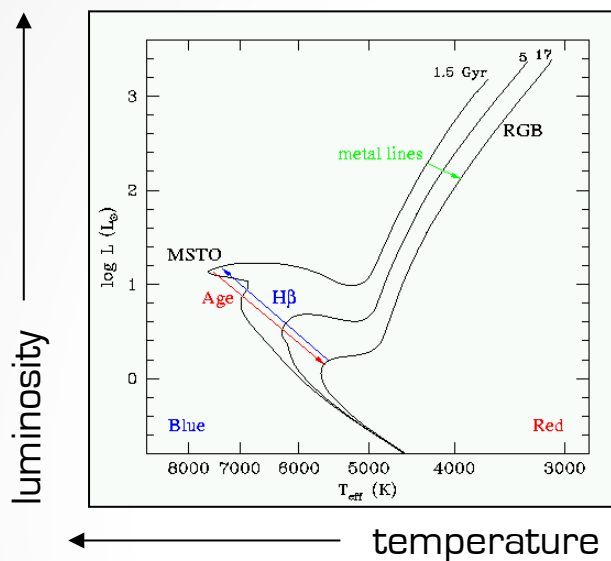
- $\phi(M)$  is the initial mass function
- $f_{rmstar}$  is a stellar spectrum
- $f_{SSP}$  is the resulting time and metallicity dependent SSP spectrum
- $m_{lo}$ : typically hydrogen burning limit (0.08 or 0.1  $M_{\odot}$ )
- $m_{up}(t)$ : dictated by stellar evolution

# Synthetic spectra

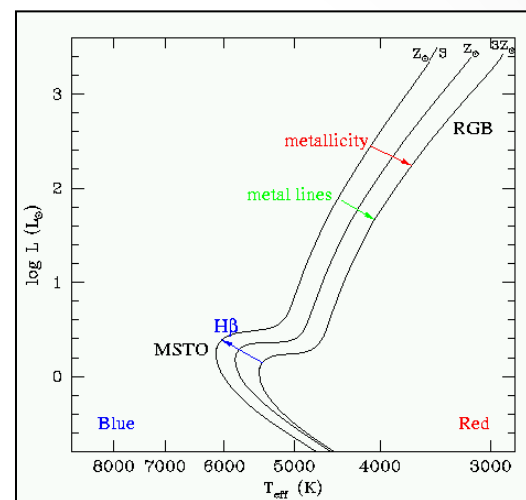


Vazdekis et al. (2010)

# The Age-metallicity degeneracy



**Different age isochrones**

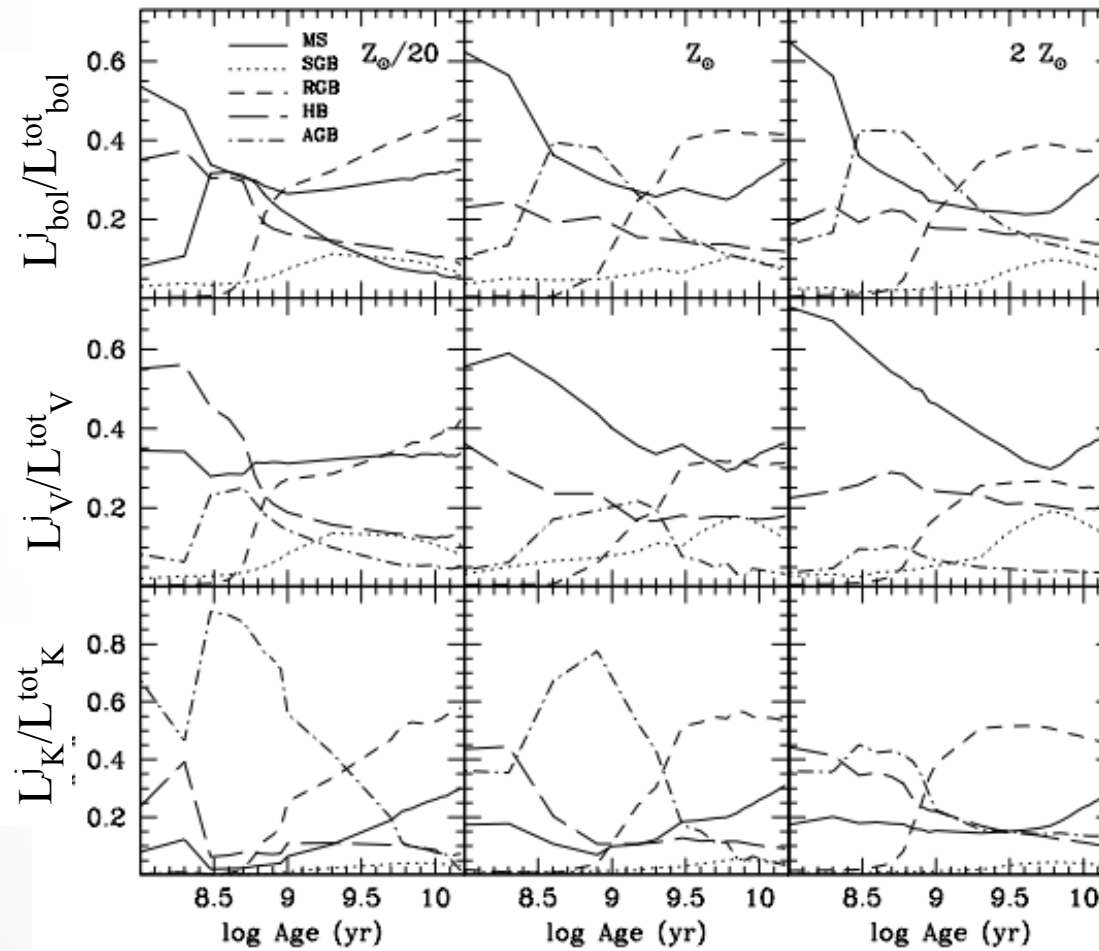


**Different metallicity isochrones**

The population of stars gets **redder** when the age increases and also when the metallicity increases  $\rightarrow$  Age-Metallicity degeneracy

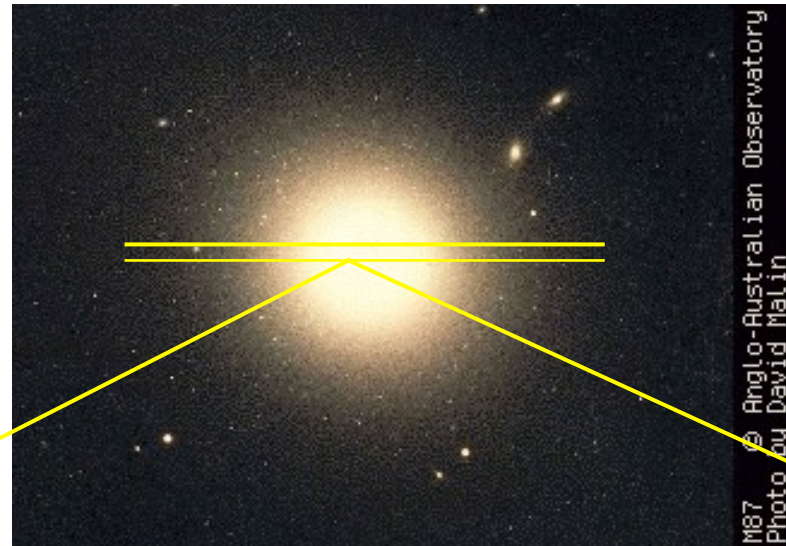
**MSTO is the clock to age-date galaxies**

# Contribution to the different stellar phases to the total luminosity

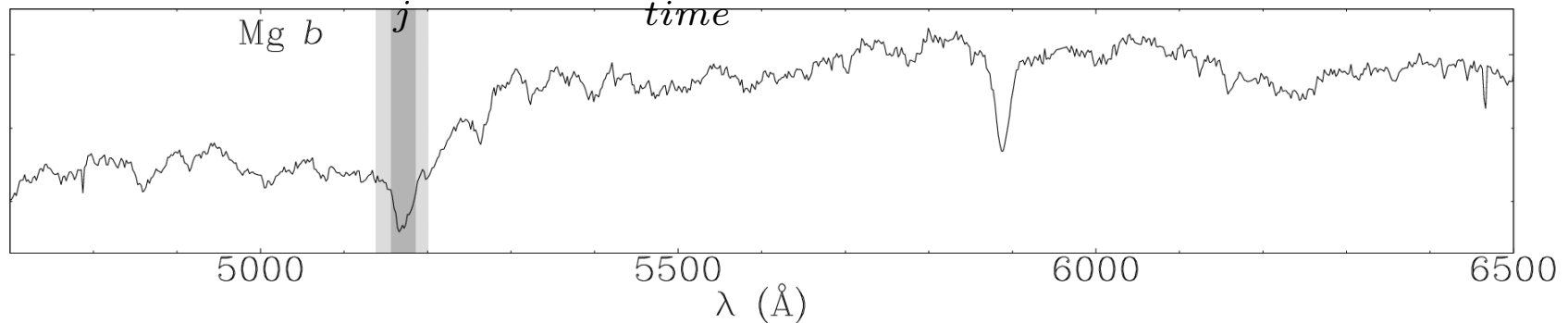


Maraston (2005)

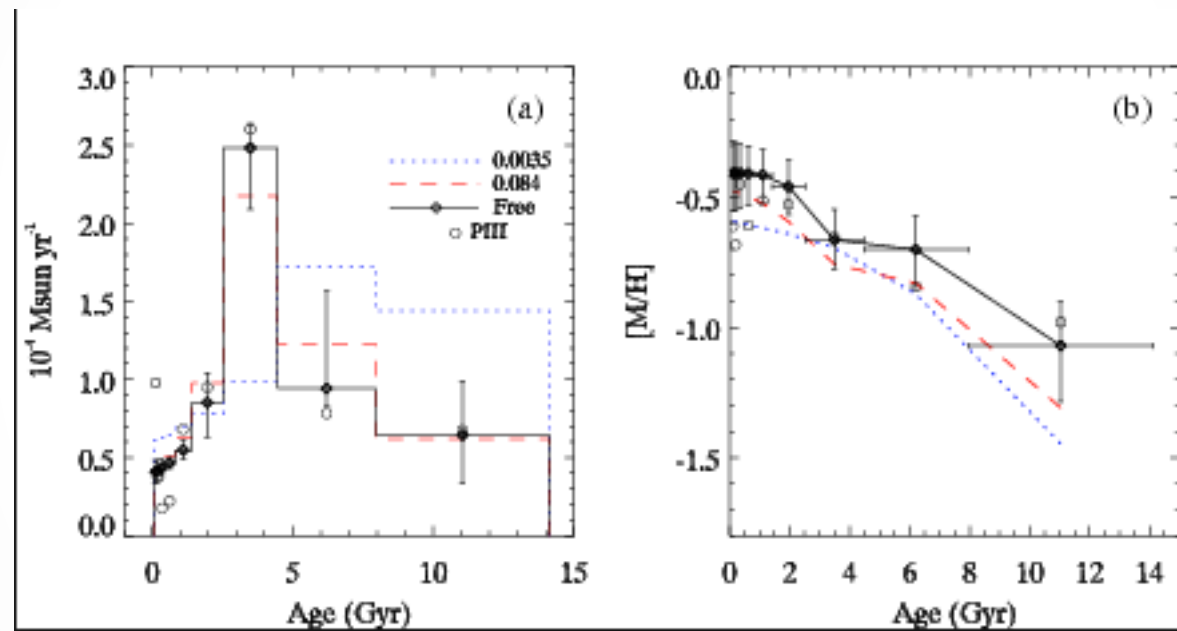
# Composite Stellar Populations



$$Galaxy = \sum_j SSP_j = \sum_{time} SFR(t) \times SSP(t, Y, Z, IMF)$$



# SFH and age-metallicity relation in M33





# Composite stellar populations

- Composite stellar populations (CSPs) differ from simple ones in three respects:
  - (1) They contain stars with a range of ages given by the SFH
  - (2) They contain stars with a range in metallicities as given by their time-dependent metallicity distribution function  $P(Z,t)$
  - (3) They contain dust and nebular emission

$$f_{CSP}(t) = \int_{t'=0}^{t'=t} \int_{Z=0}^{Z_{max}} \left( SFR(t-t')P(Z,t-t')f_{SSP}(t',Z)e^{-r_d(t')} + Af_{dust}(t',Z) \right) dt' dZ$$

# Composite stellar populations as a sum of SSP

$$f_{SSP}(t, Z) = \int_{m_{lo}}^{m_{up}(t)} f_{star}[T_{\text{eff}}(M), \log g(M)|t, Z] \Phi(M) dM$$

$$f_{CSP}(t) = \int_{t'=0}^{t'=t} \int_{Z=0}^{Z_{max}} \left( SFR(t-t') P(Z, t-t') f_{SSP}(t', Z) e^{-r_d(t')} + A f_{dust}(t', Z) \right) dt' dZ$$

# Some concepts

- **SSP-equivalent parameters:** Those that you obtain comparing your spectra with SSP-models, even if your population is not simple.

- **Luminosity weighted values:**

$$\langle \log age \rangle_{LW} = \frac{\sum_{i=1}^{n_{ages}} \log age_i flux_i}{\sum_i^{n_{ages}} flux_i}$$

- **Mass-weighted values:**

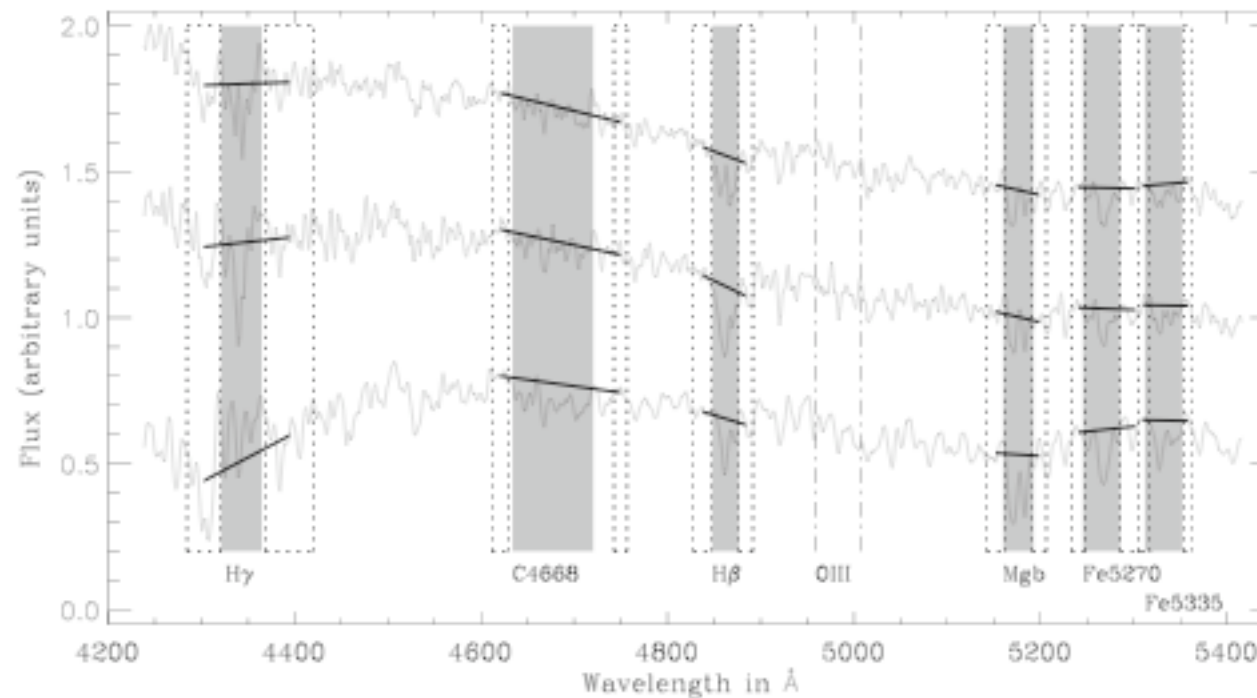
$$\langle \log age \rangle_{MW} = \frac{\sum_{i=1}^{n_{ages}} \log age_i mass_i}{\sum_i^{n_{ages}} mass_i}$$

## (2) Fitting techniques

# Fitting models to data

- The fitting can be done:
  - (a) Using a set of given absorption lines (indices)
  - (b) Using the whole available spectrum
- 3 basic methods to compare models with data
  - (1) Fitting data to **SSP** models (usually with a)
  - (2) Fitting data to **parametric** SFH (with both a and b)
  - (3) Fitting data to **non-parametric** SFH (usually with b)

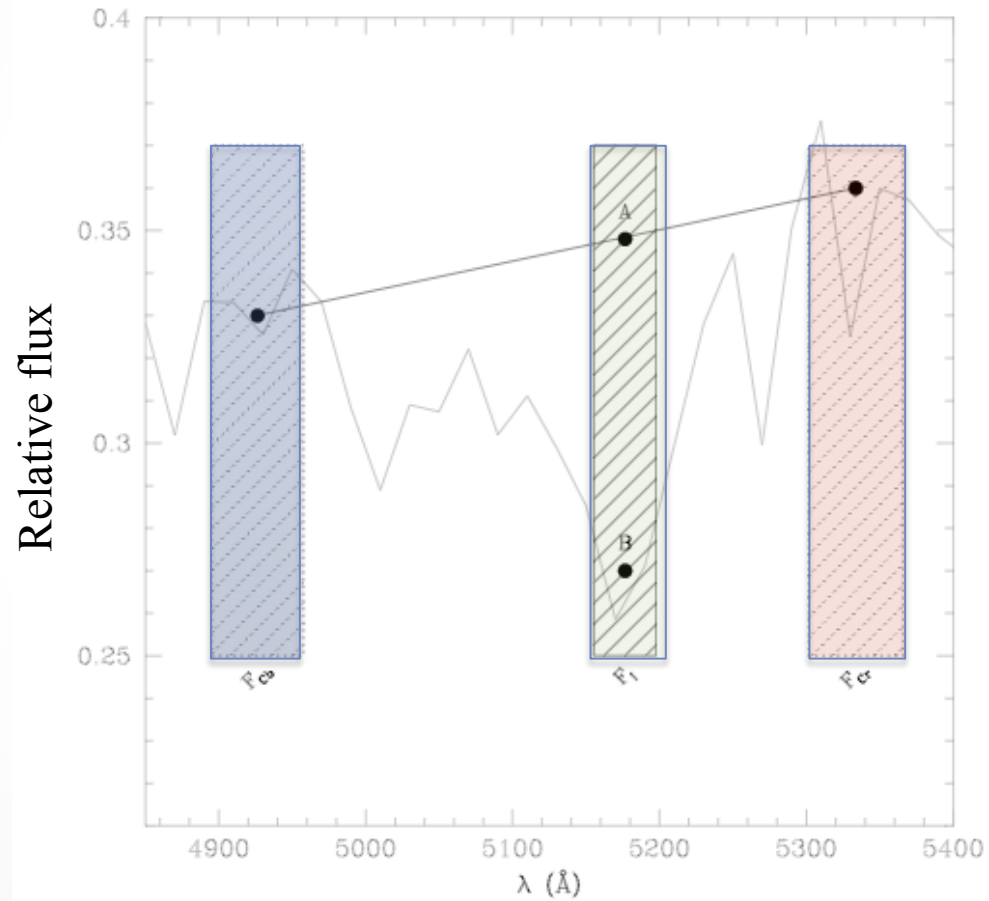
# Line strength Indices



S. Faber  
R. Bender  
D. Burstein  
J. Gorgas  
G. Worthey  
J.J.Gonzalez  
S.C. Trager

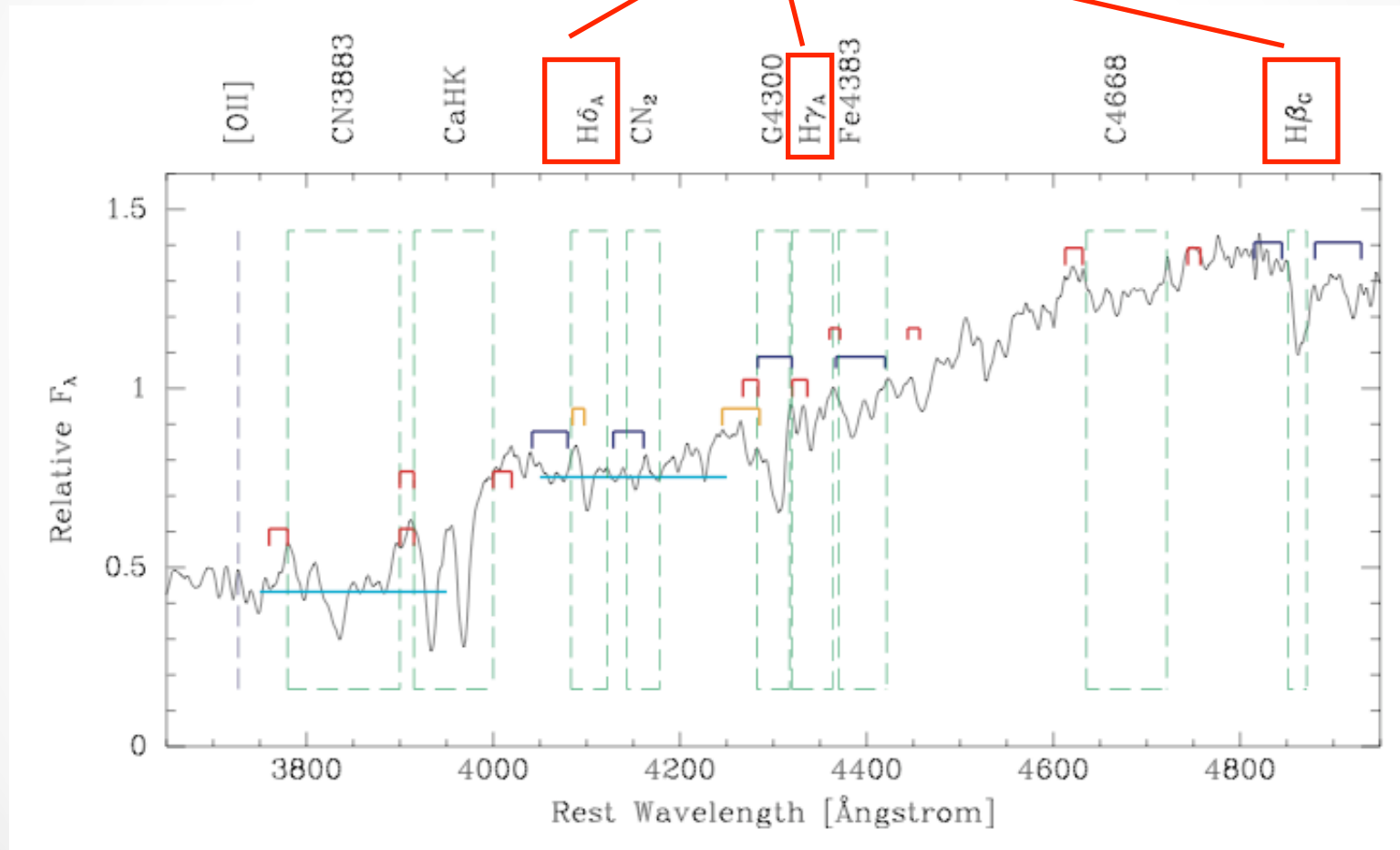
The definition consists in three bands:  
two lateral ones (pseudo-continuum)  
and the central one

# Lick/IDS indices



# Lick Indices

Balmer lines (hot stars)



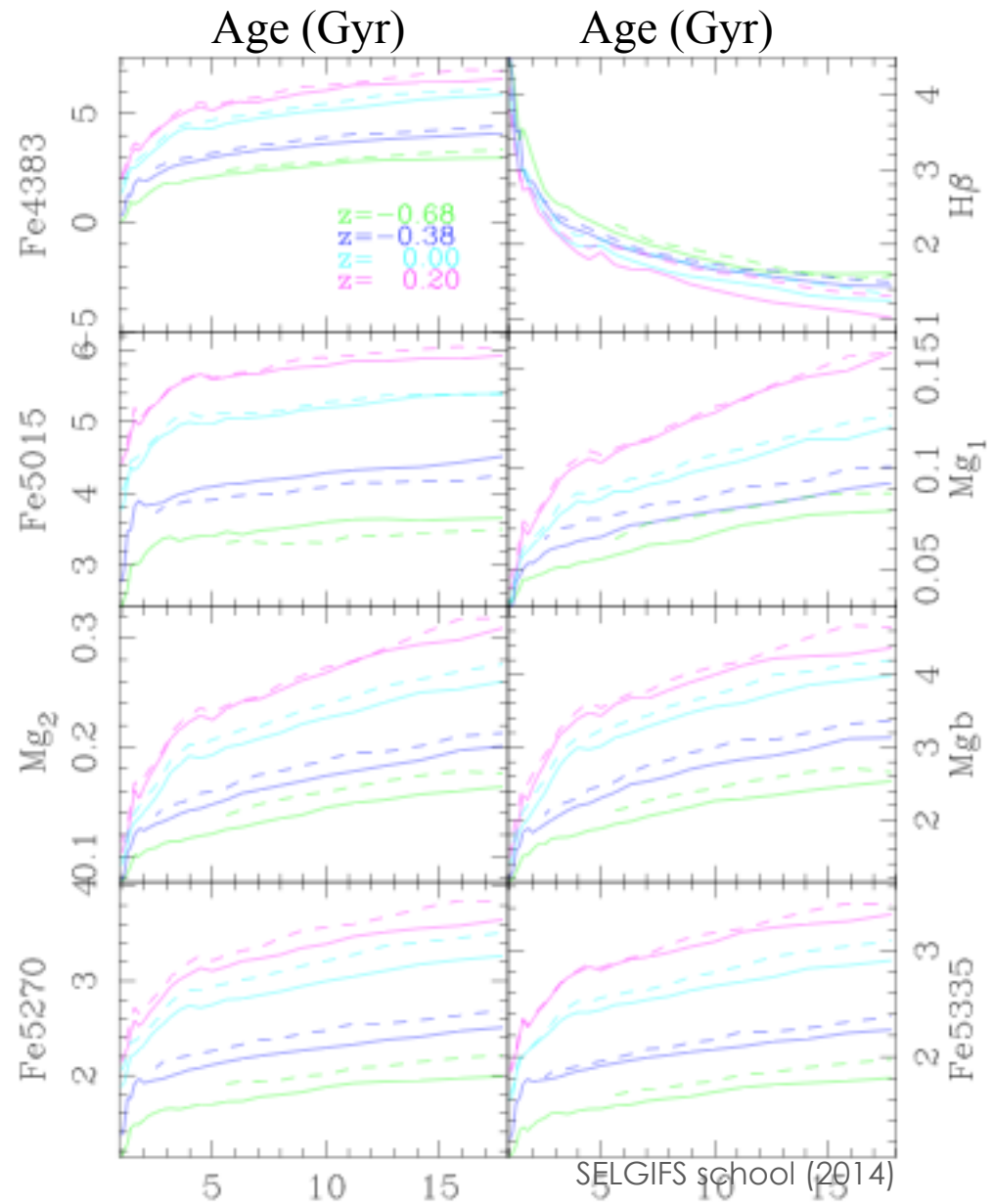


# Fitting techniques

- (1) SSP-equivalent parameters
- (2) Parametric SFH
- (3) non-parametric SFH

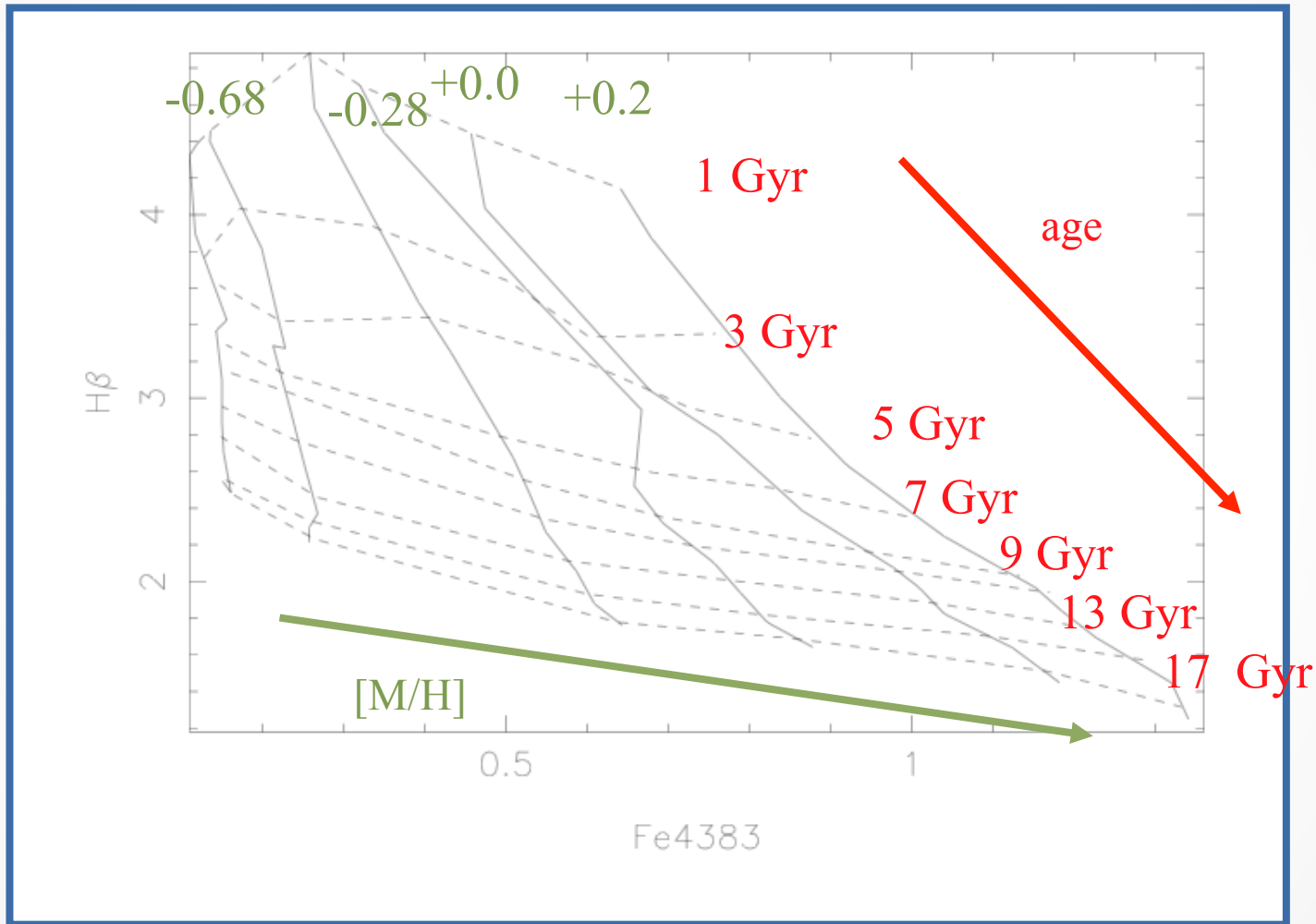
## Predictions from SSP models

Variations of line-strength indices with age at different metallicities

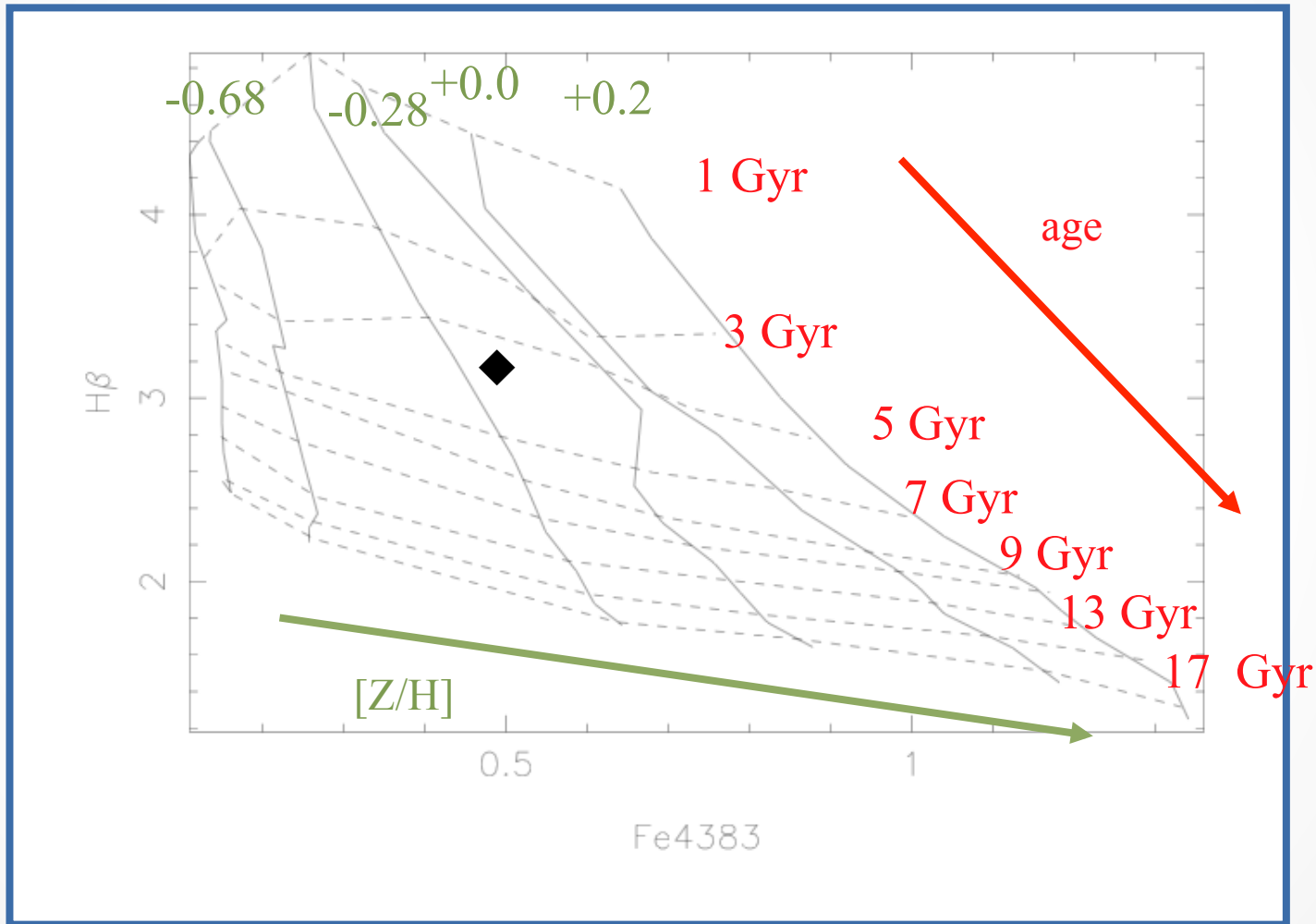


- Stellar populations

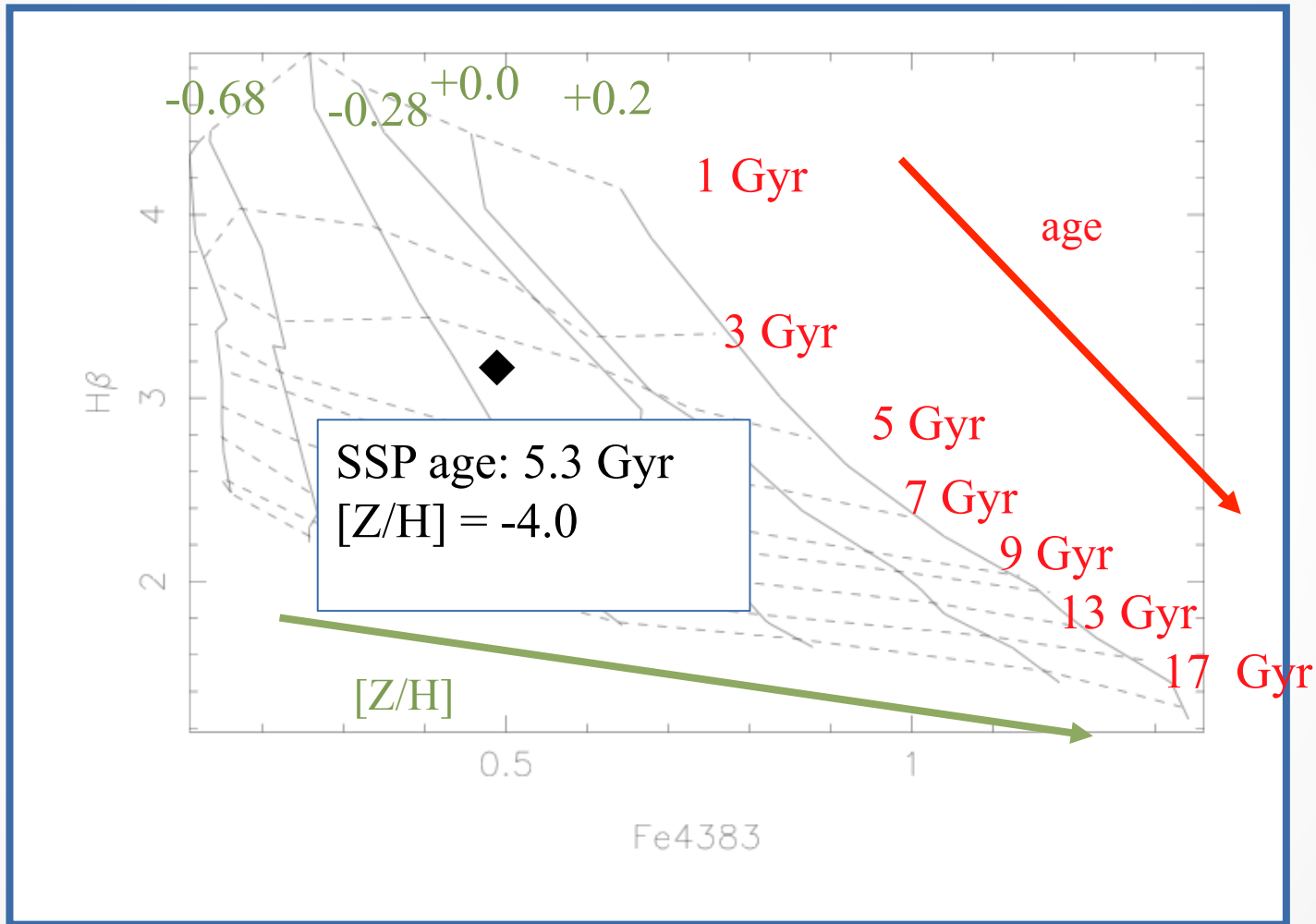
# Obtaining SSP-equivalent parameters



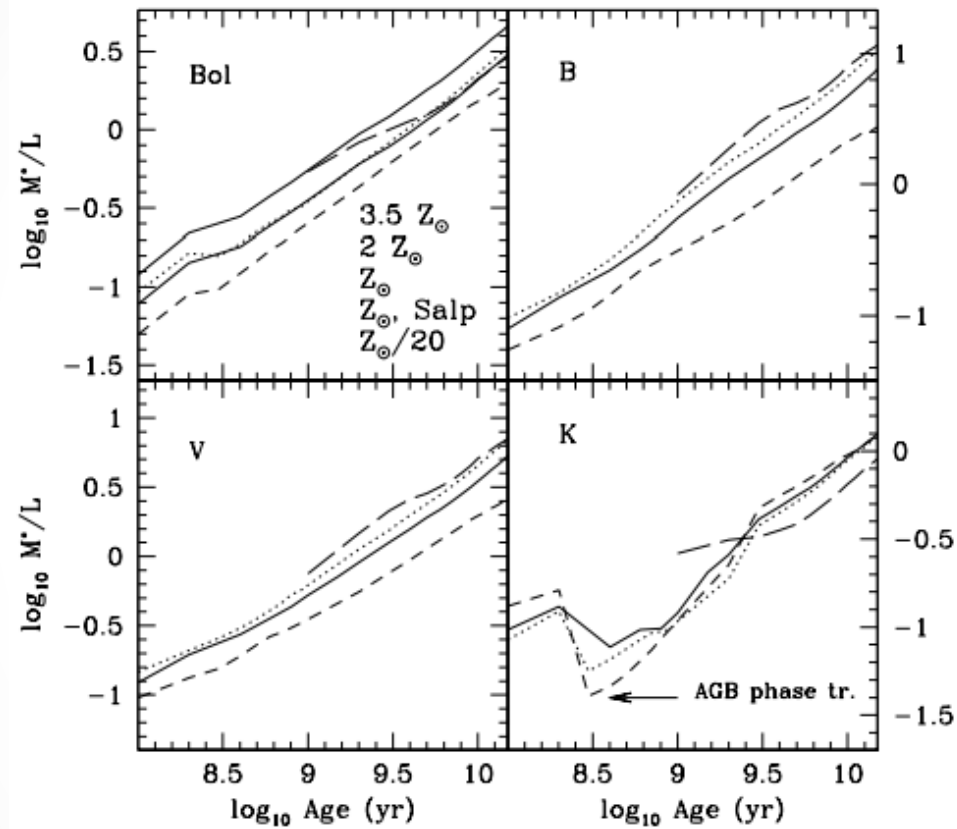
# Obtaining SSP-equivalent parameters



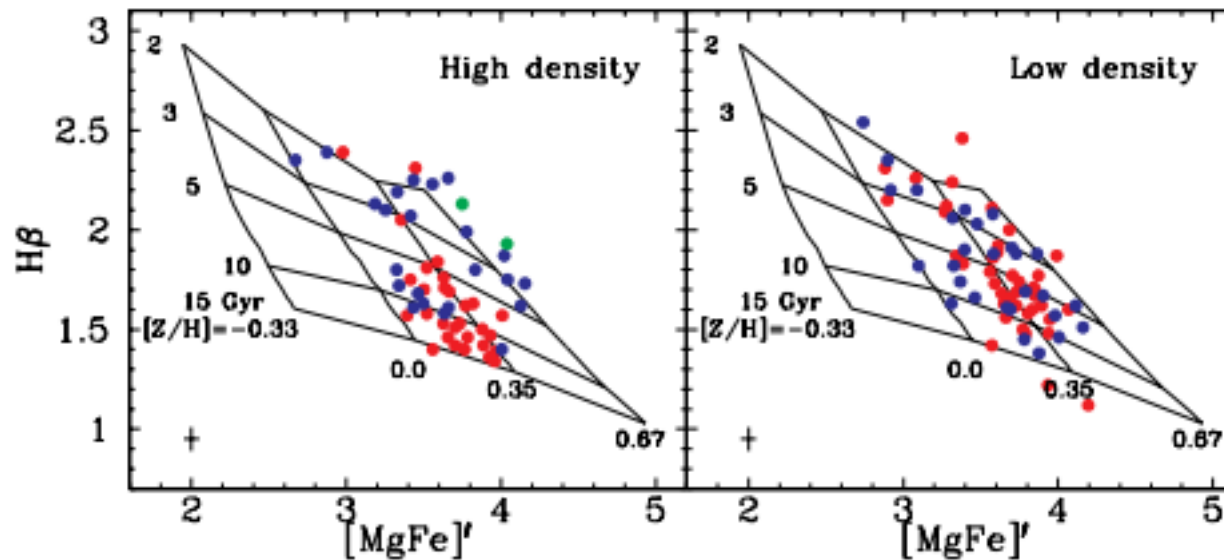
# Obtaining SSP-equivalent parameters



# SSP-equivalent stellar masses

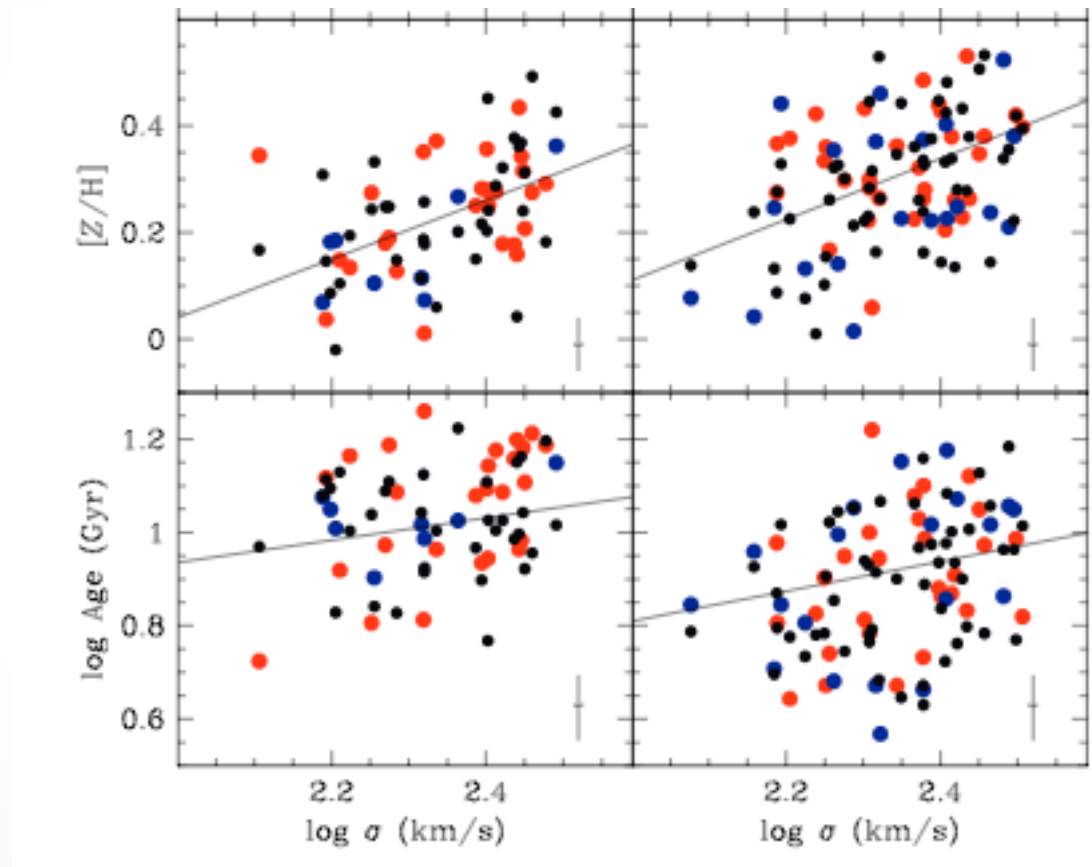


# SSP parameters for elliptical galaxies



Thomas et al. (2005)

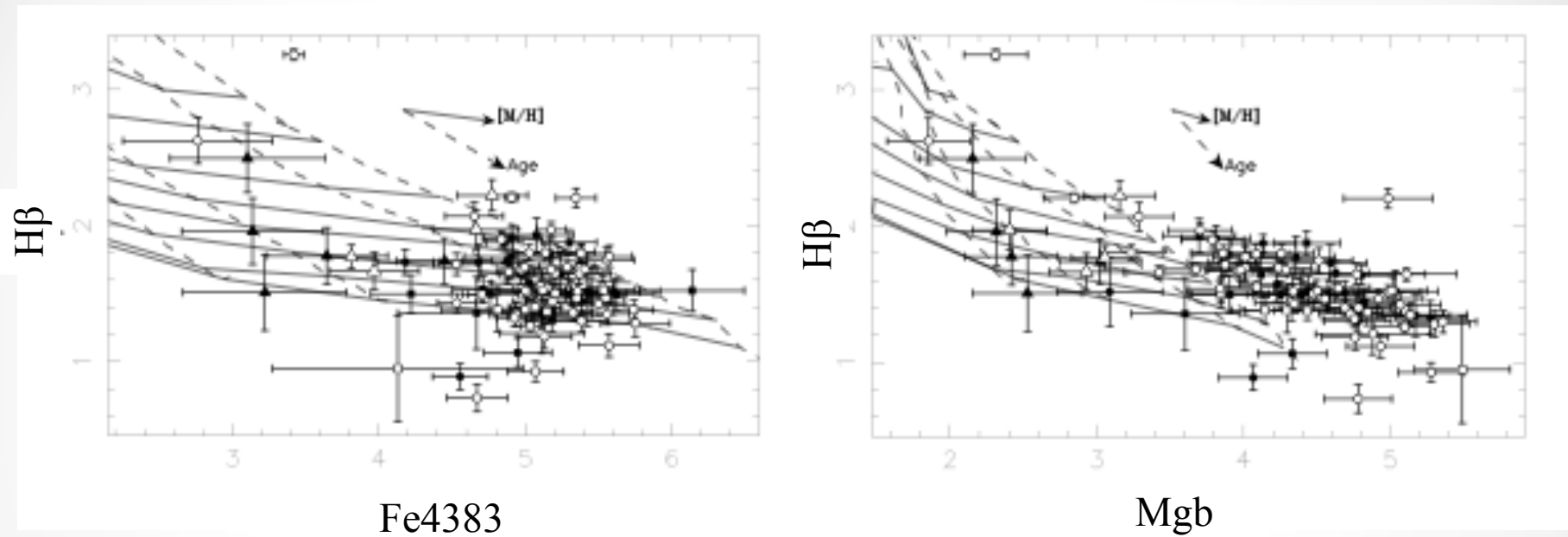
# Variations of SSP-parameters in elliptical galaxies



Thomas et al. (2005)

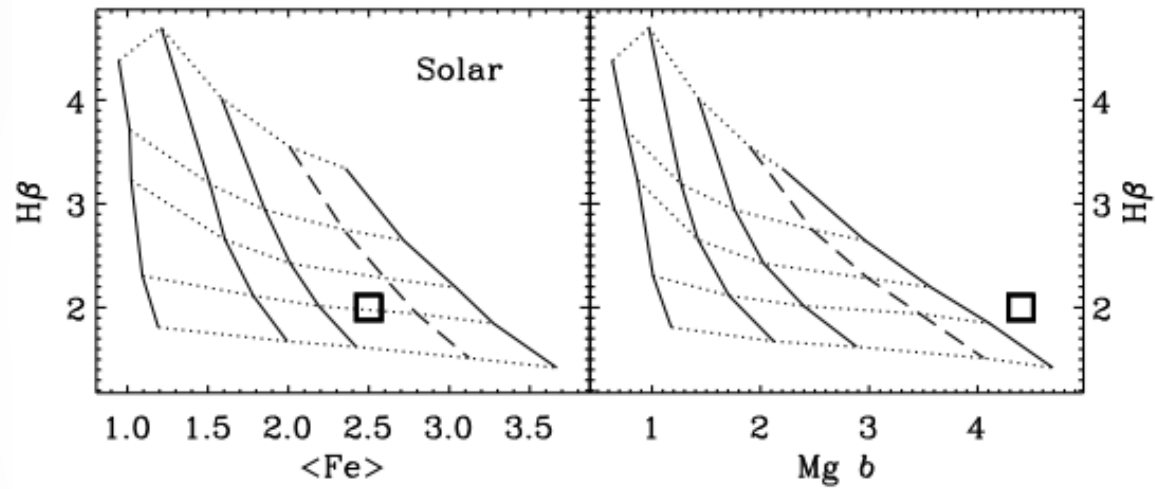


# Different indices give different answers!

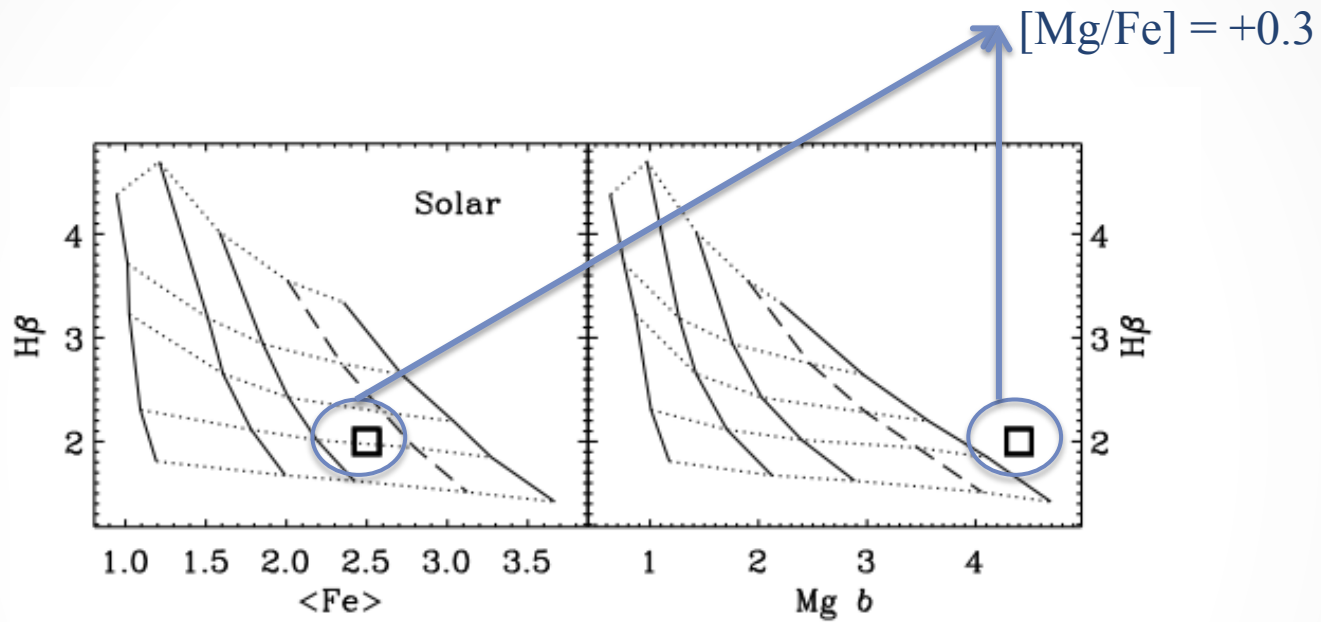


Some galaxies have abundance ratios different from Solar!  
 $[Mg/Fe] \neq 0$ ;  $[C/Fe] \neq 0$ ;  $[N/Fe] \neq 0$  ... etc

# Obtaining chemical abundance ratios



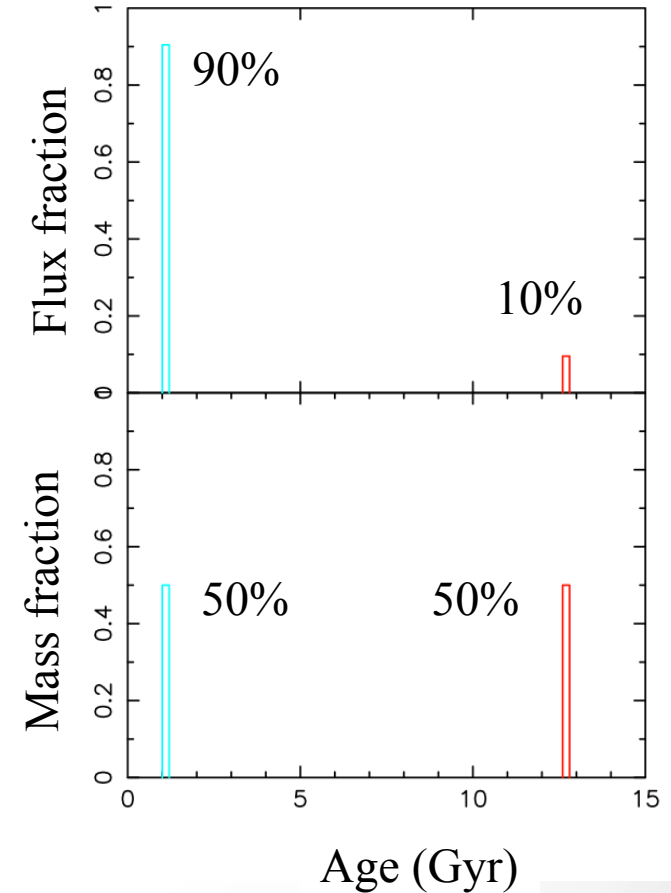
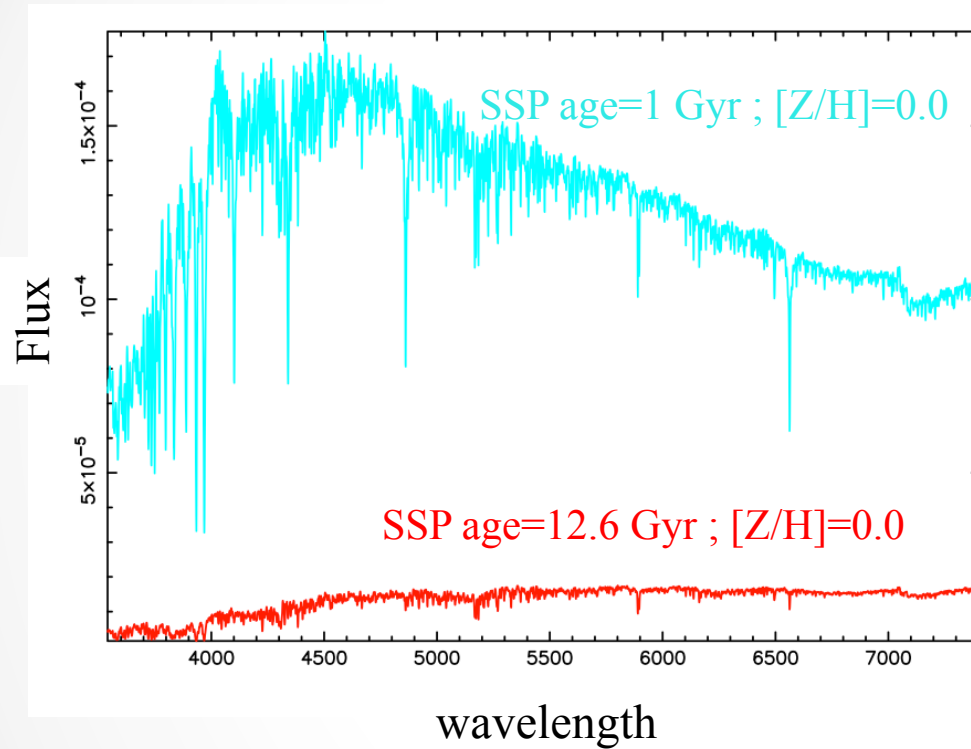
# Obtaining chemical abundance ratios



# Summary: what do we get comparing with SSP models?

- SSP-equivalent age
- SSP-equivalent metallicity
- SSP-equivalent masses
- SSP-equivalent abundance ratios  $[\text{Mg}/\text{Fe}]$ ,  $[\text{C}/\text{Fe}]$ ,  $[\text{N}/\text{Fe}]$

# What do we get with SSP when the SFH is more complicated?

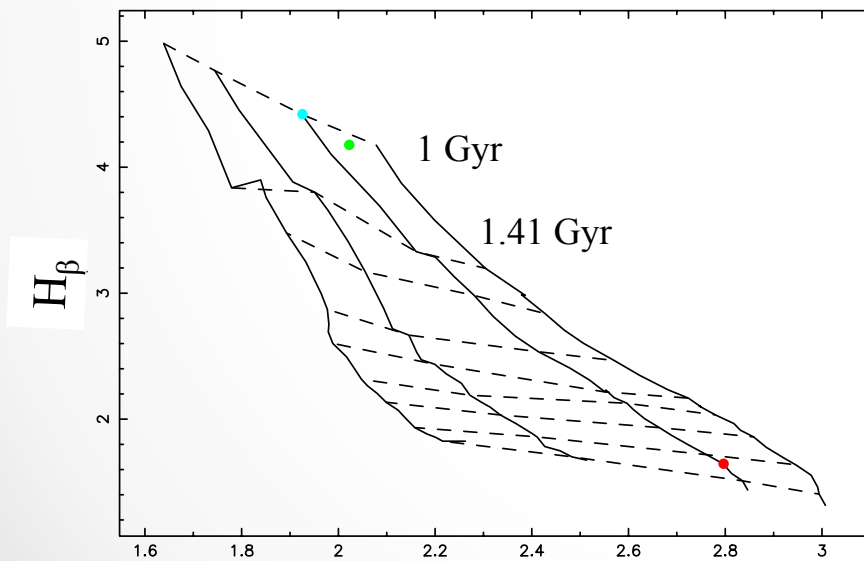


# What do we get with SSP when the SFH is more complicated?

MW age = 1 Gyr x 0.5 + 12.6 Gyr x 0.5 = 6.8 Gyr

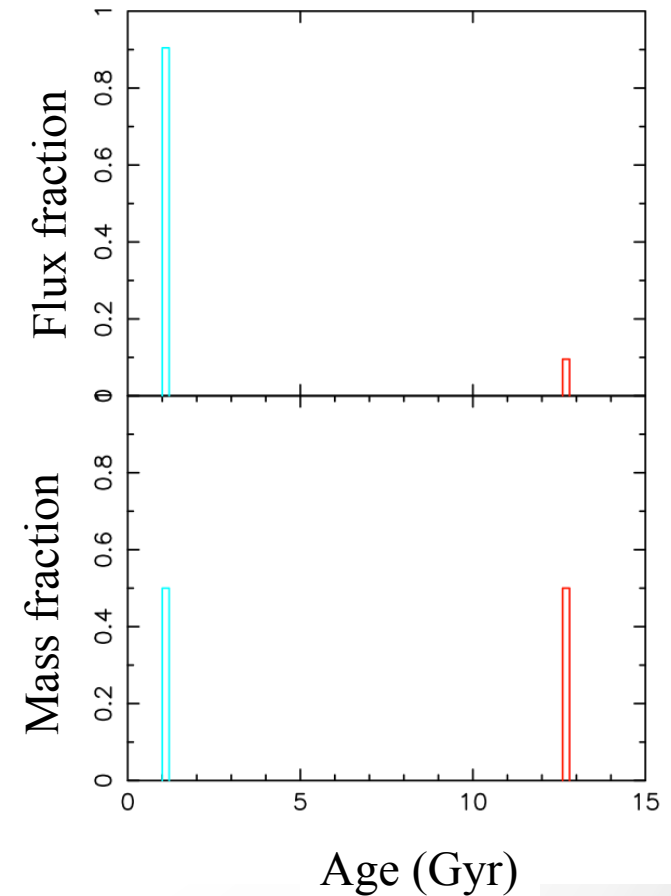
LW age = 1 Gyr x 0.9 + 12.6 Gyr x 0.1 = 2.16 Gyr

SSP age = 1.02 Gyr



● Stellar populations

[MgbFe]



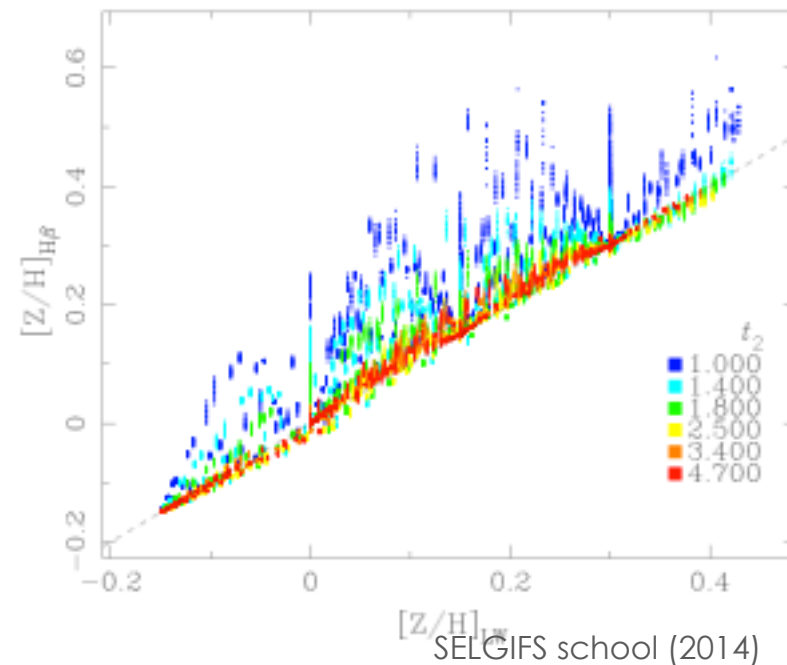
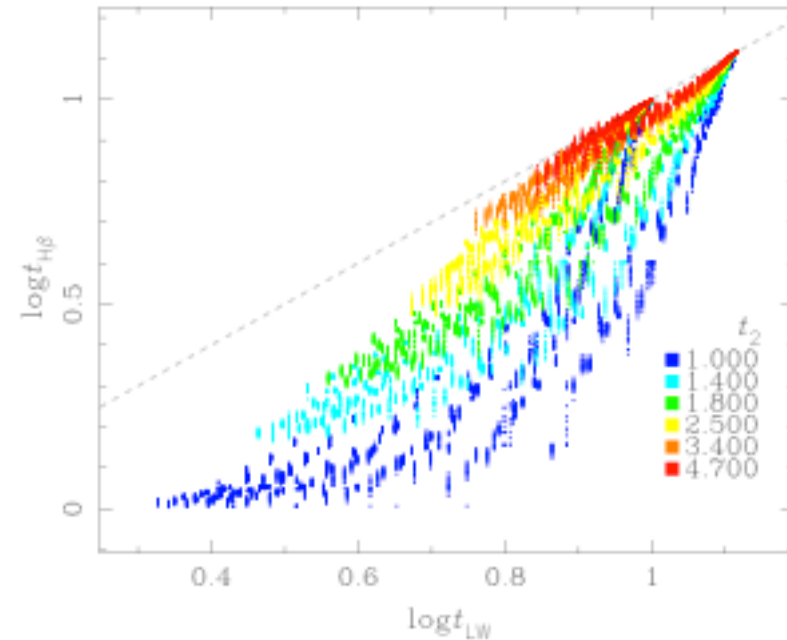
SELGIFS school (2014) ●

# What does SSP means?

Comparison of V-band Luminosity-weighted and SSP-equivalent age and metallicity of a SFH composed of and old population of 13 Gyr and a younger burst

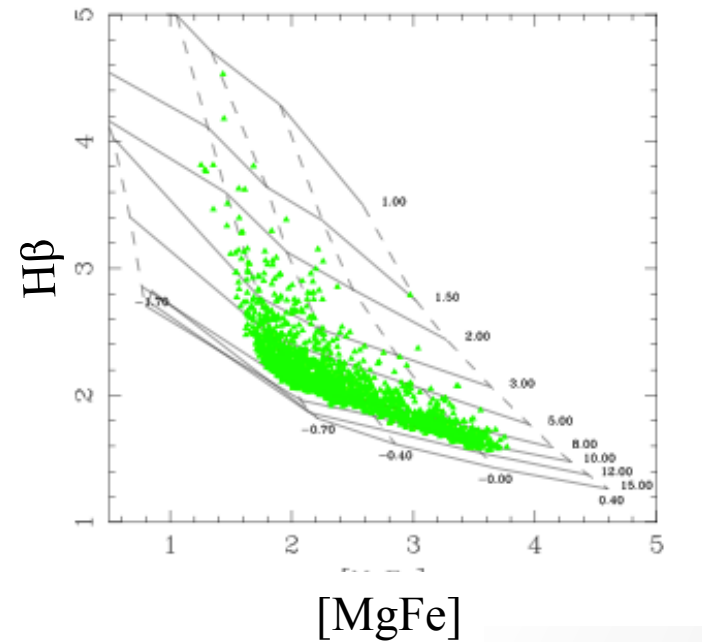
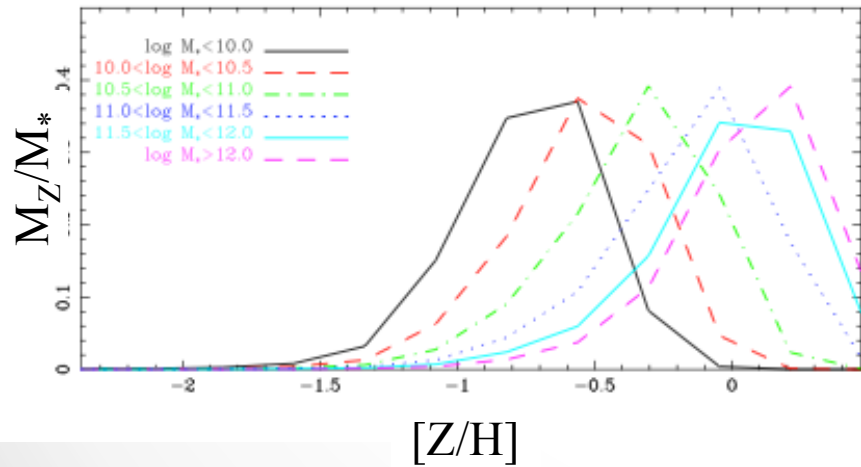
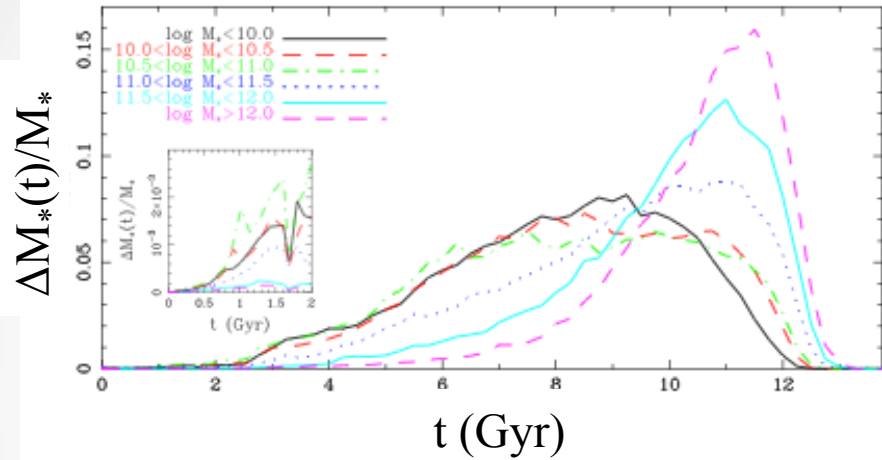
Serra & Trager (2007)

- Stellar populations



SELGIFS school (2014)

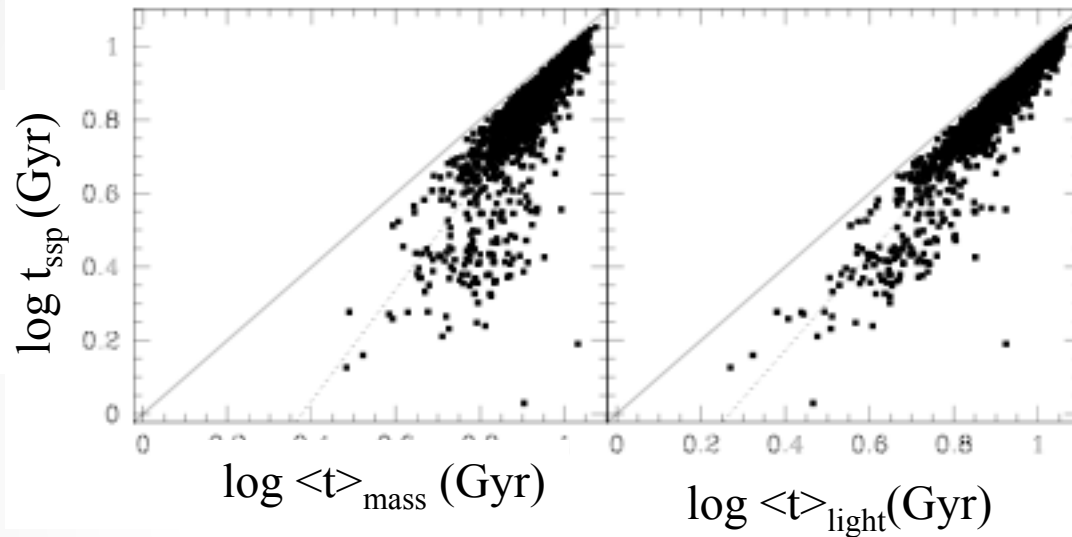
# What do we get with SSP?



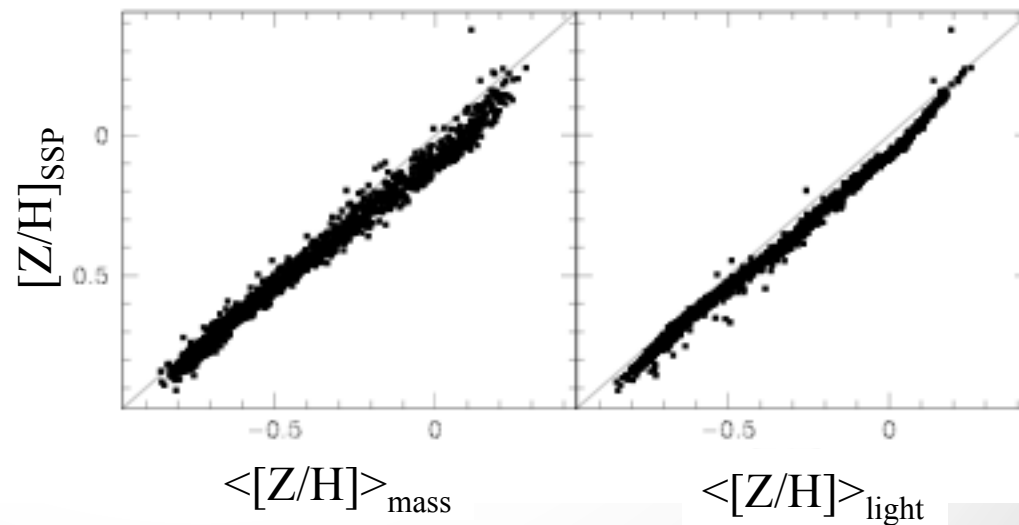
Trager & Somerville (2009)



# What do we get with SSP?



Trager & Somerville (2009)



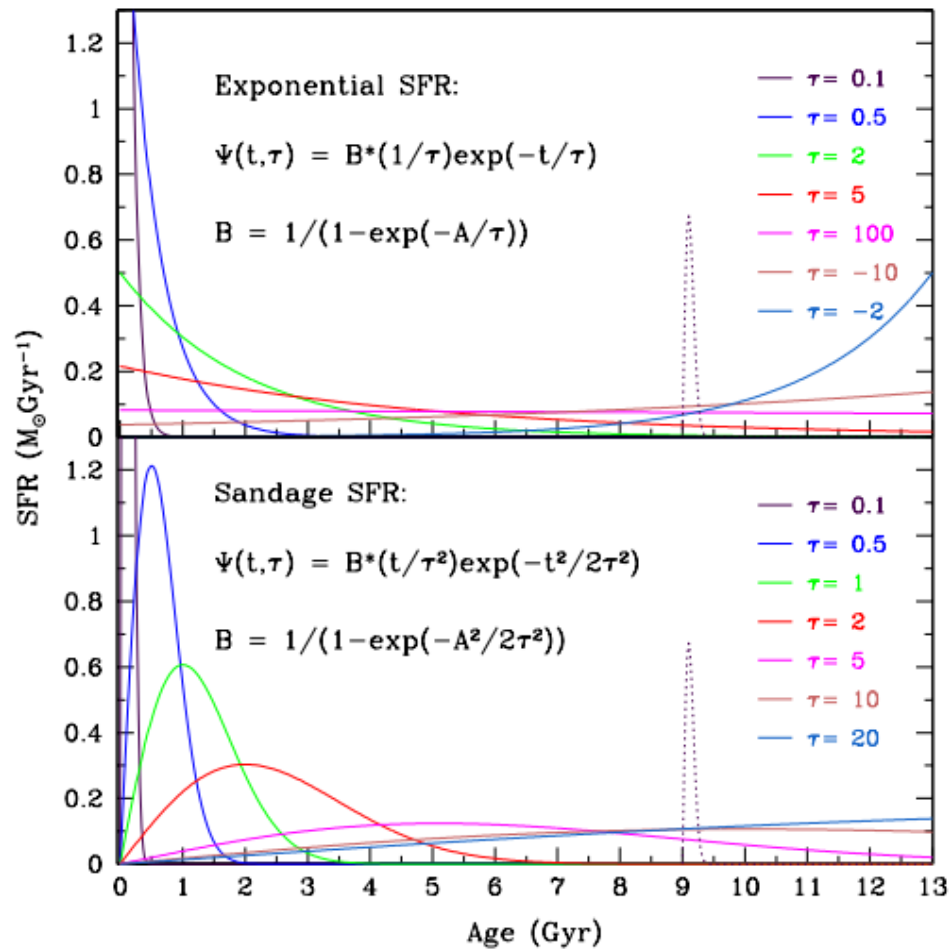
# What do we obtain with SSP?

- SSP-equivalent ages: very biased towards the youngest stars (even more than the LW ages)
- SSP-equivalent metallicity: Less biased

# Fitting techniques

- (1) SSP-equivalent parameters
- (2) Parametric SFH
- (3) non-parametric SFH

# Second method: Parametric SFH



CT2  
 Lopez Fernandez  
 Huang  
 Ortega-Minakata

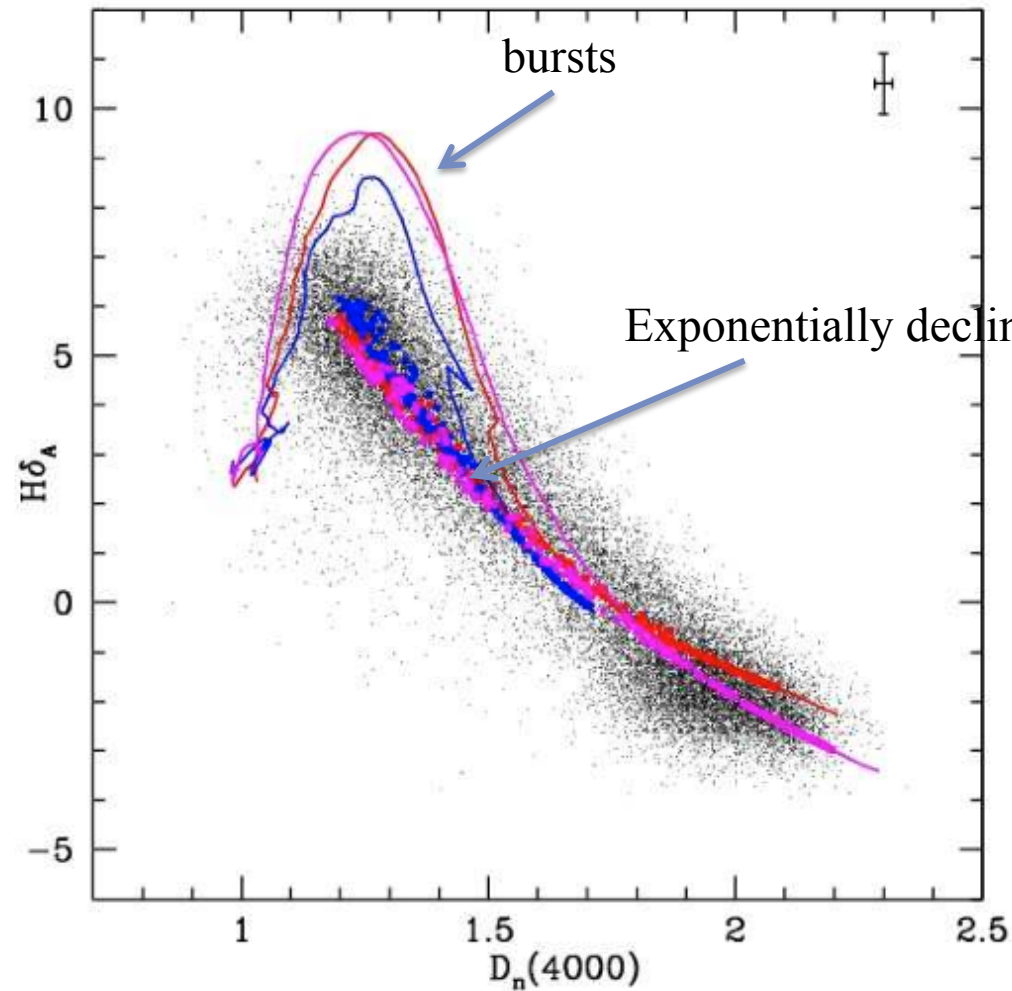
# Bayesian method

- Construct a library of stochastic star formation histories and derive median-likelihood estimates of ages and metallicities (Kauffmann et al. 2003; Gallazzi et al. 2005).
- Assign to each model a probability distribution in each parameter  $P = \exp(-\chi^2/2)$ , where  $\chi^2$  is calculated by comparing the line-strength indices (or the whole SED) with the models

# Kauffmann et al. (2003)

- The parametrize 2 different SFH:
- (1) exponentially decreasing
- (2) they superimpose burst of star formation on the exponentially declining SFH.

# $H\delta_A$ vs $D_{4000}$ for different SFH



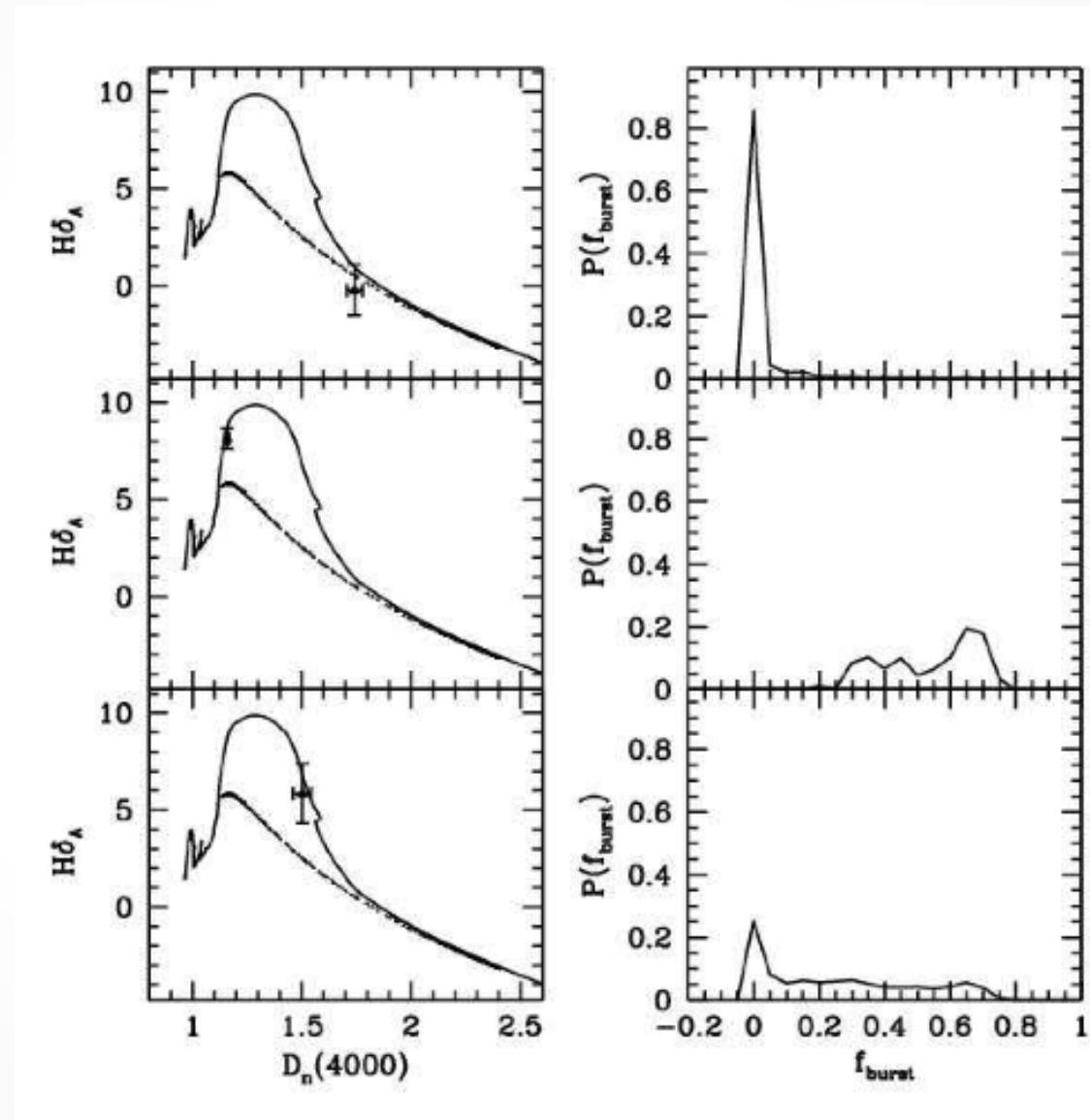
$[Z/H] = -0.7$

$[Z/H] = 0.0$

$[Z/H] = +0.22$

Exponentially declining star formation

# Probabilities on the burst fraction

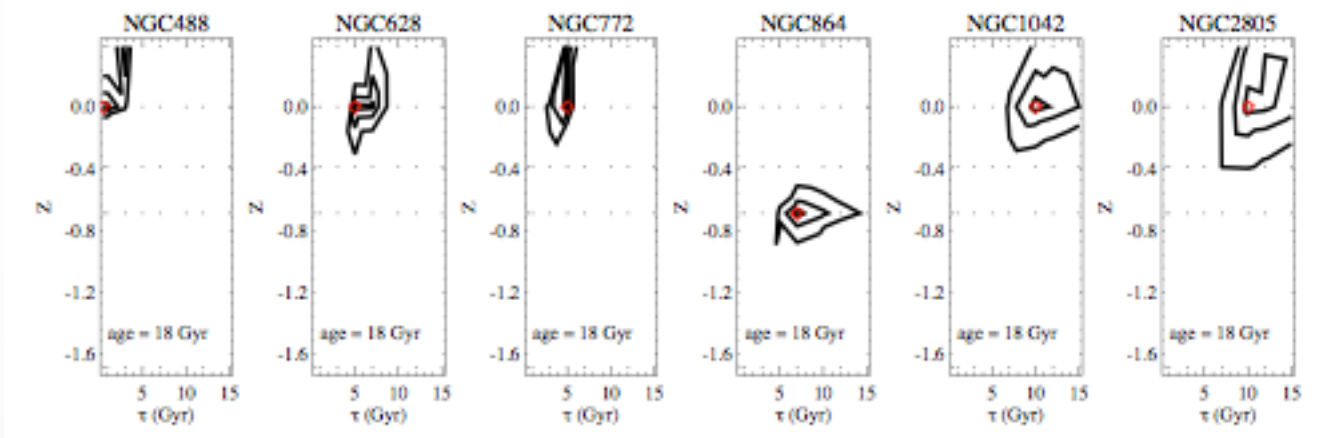




# Non-bayesian, parametric techniques

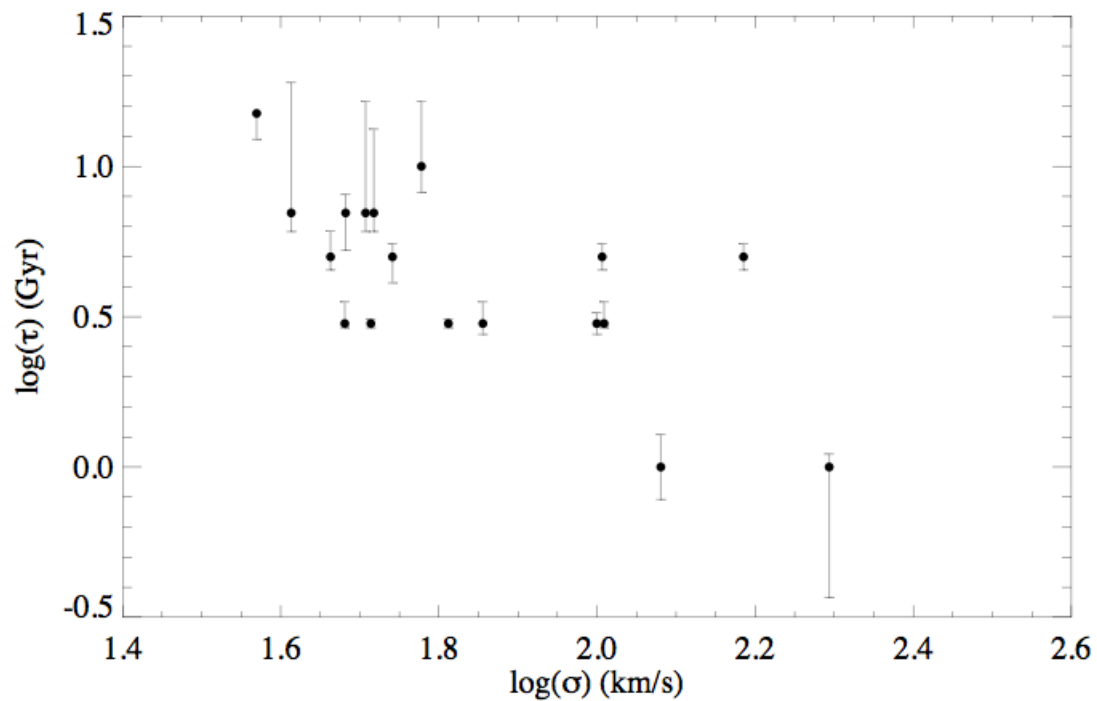
$$SFR = Ae^{-t/\tau}$$

Assume a metallicity and a starting time for the SF and minimize the differences in the indices



Ganda et al. (2007)

# Parametric techniques



Ganda et al. (2007)

# Caveats of the parametric approach

- They do not have into account the evolution in metallicity (assume a single metallicity for a given model)
- The wrong answer can be get with the wrong assumptions (either in the values or in the errors)

# Fitting techniques

- (1) SSP-equivalent parameters
- (2) Parametric SFH
- (3) non-parametric SFH

# Non-parametric SFH

- In the simplest implementation one specifies a fixed set of age bins and fits for the fraction of mass formed within each bin.
- MOPED (Heavens et al. 2000)
- STARLIGHT (Cid Fernandes et al. 2005)
- STECKMAP (Ocvirk et al. 2006)
- VESPA (Tojeiro et al. 2007)
- ULySS (Koleva et al. 2009)
- MacArthur et al. (2009)

# Method

- Briefly, fit an observed spectra,  $O_\lambda$  with a combination of  $N_*$  simple stellar populations (SSP) from an evolutionary synthesis models.
- **Extinction can be modelled** as due to foreground dust and parameterized by  $A_V$  adopting a Galactic extinction law (Cardelli, Clayton & Mathis 1989).
- **Line of sight stellar motions** can be modeled by a Gaussian distribution  $G$  centered at velocity  $v_*$  and with dispersion  $\sigma_*$

# Method

$$M_{\lambda} = \left[ \sum_{j=1}^N x_j b_{j,\lambda} r_{\lambda} \right] \otimes G(v_*, \sigma_*)$$

where  $b_{j,\lambda}$  is the spectrum of the  $j^{\text{th}}$  SSP

$r_{\lambda} = 10^{-0.4(A_{\lambda} - A_{\lambda_0})}$  is the reddening term

$M_{\lambda_0}$  is the synthetic flux

$\vec{x}$  is the population vector and  $\otimes$  denotes the convolution operator

Each component  $x_j$  ( $j=1, \dots, N_*$ ) represents the fractional contribution of the SSP with age  $t_j$  and metallicity  $Z_j$  to the model flux at  $\lambda_0$ .

# Deriving SFH

$$\chi^2 = \sum_{\lambda} [(O_{\lambda} - M_{\lambda})w_{\lambda}]^2$$

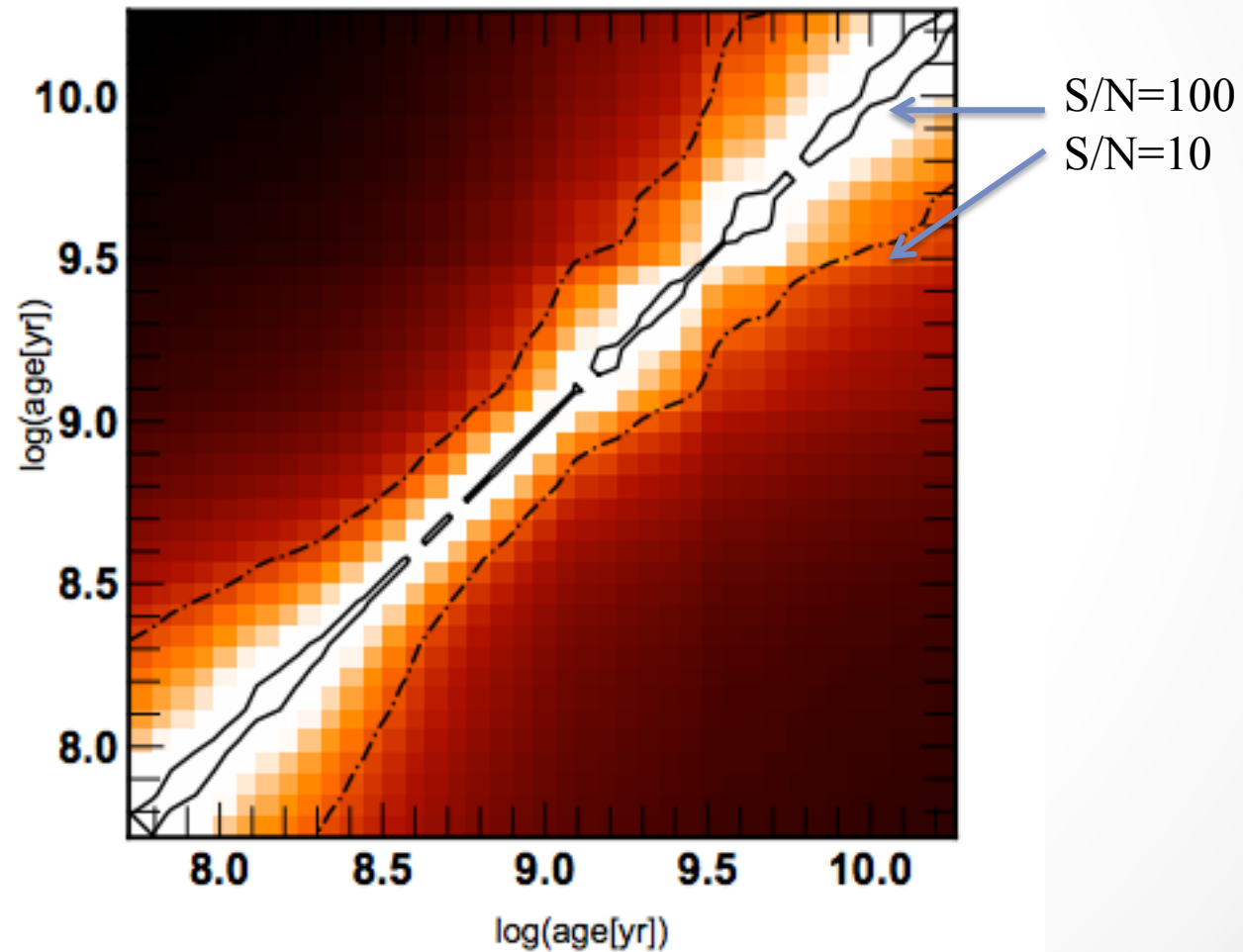
where  $w_{\lambda}^{-1}$  is the error in  $O_{\lambda}$

This **problem is non-linear and ill conditioned** -- small fluctuations in the data lead to large variations in the solution

This is due to the noise of the data and the presence of degeneracies



- The origins of the ill-condition
- (1) The degeneracies of the templates

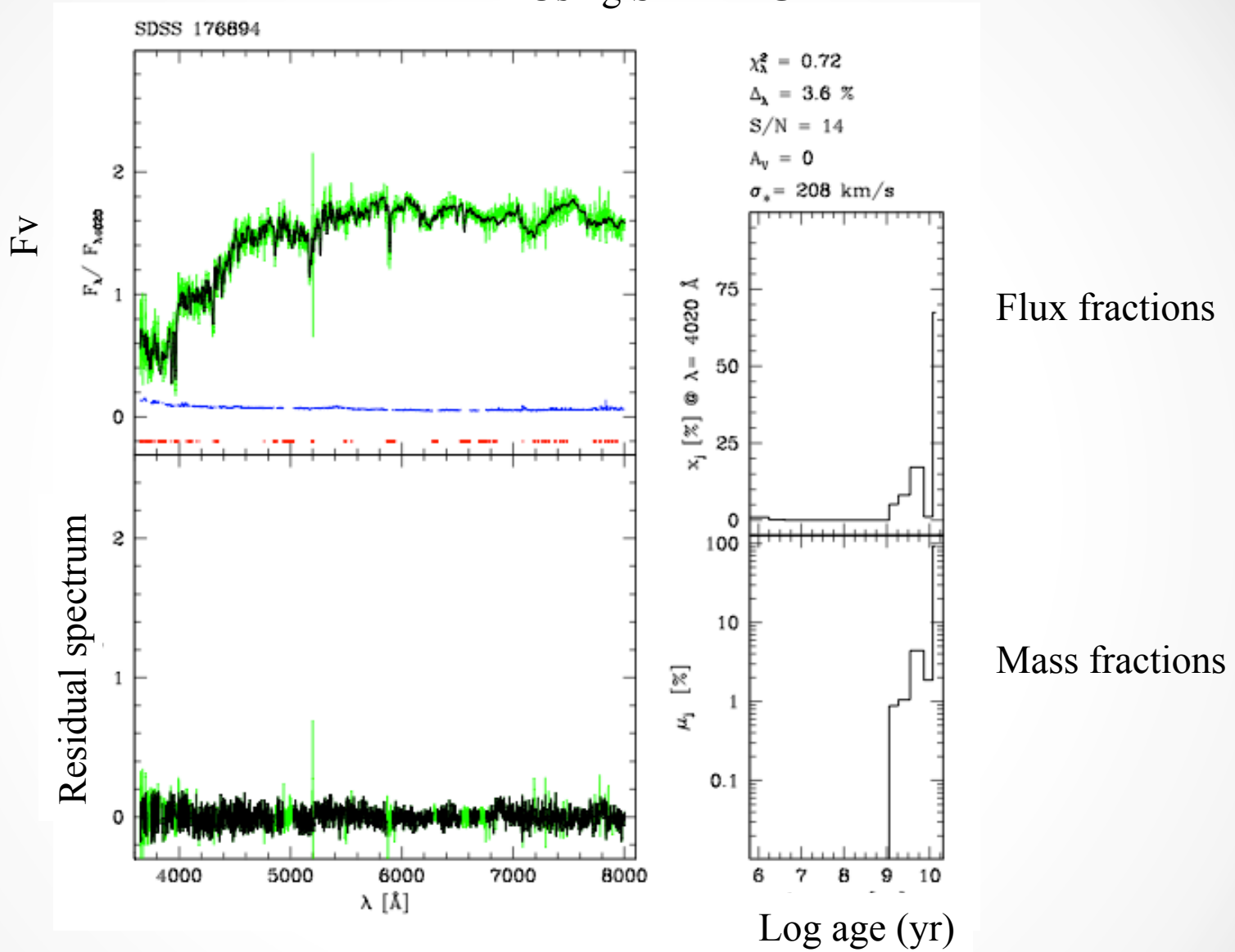


# How to ‘solve this problem’

- Some models look for the best templates to fit (e.g., VESPA, STARLIGHT)
- Some procedures adopt a regularization to the problem (e.g., STECKMAP)

$$Q_{\mu} = \chi^2(x, Z, g) + P_{\mu}(x, Z, g)$$

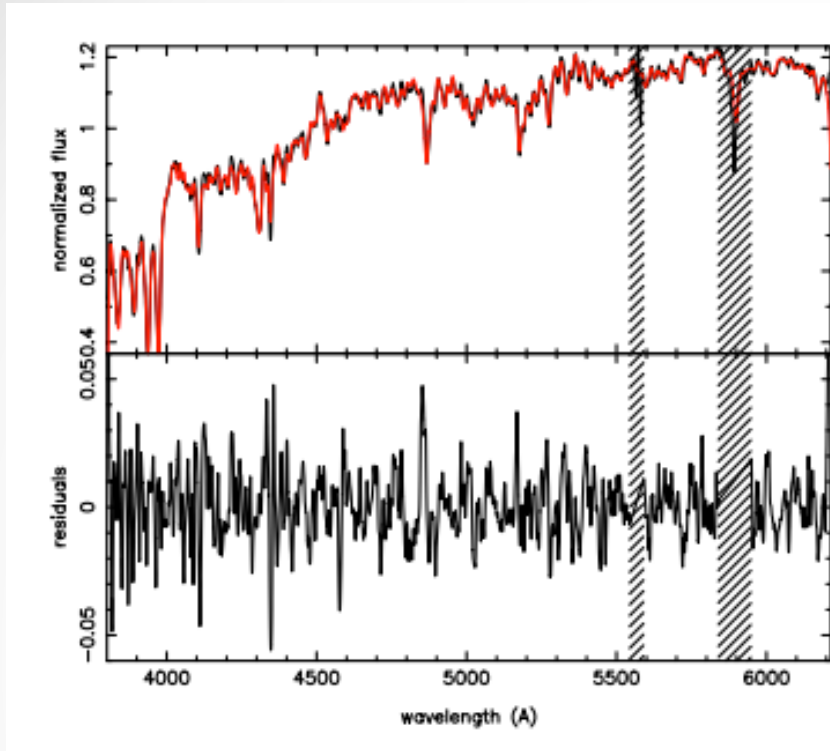
# Using STARLIGHT



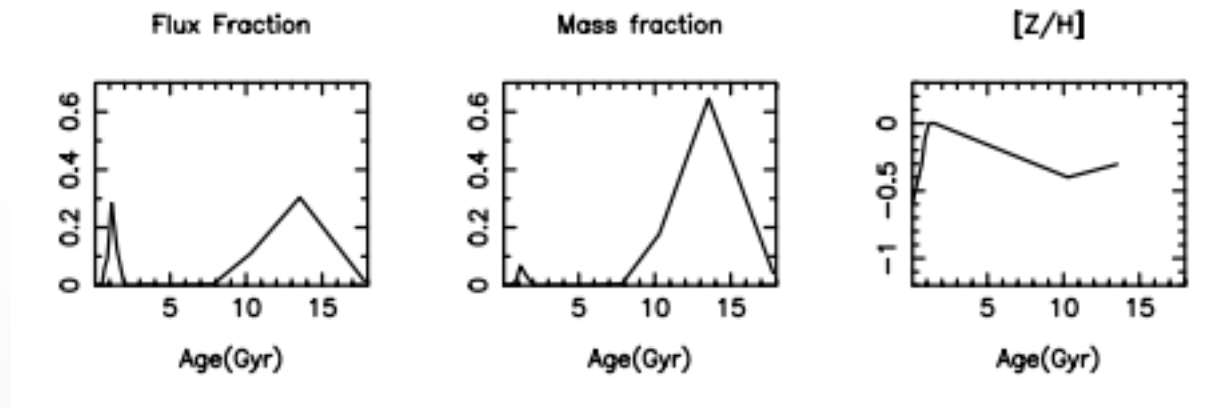
Cid Fernandes et al. (2005)

- Stellar populations

Using STECKMAP



Sanchez-Blazquez et al. (2011)

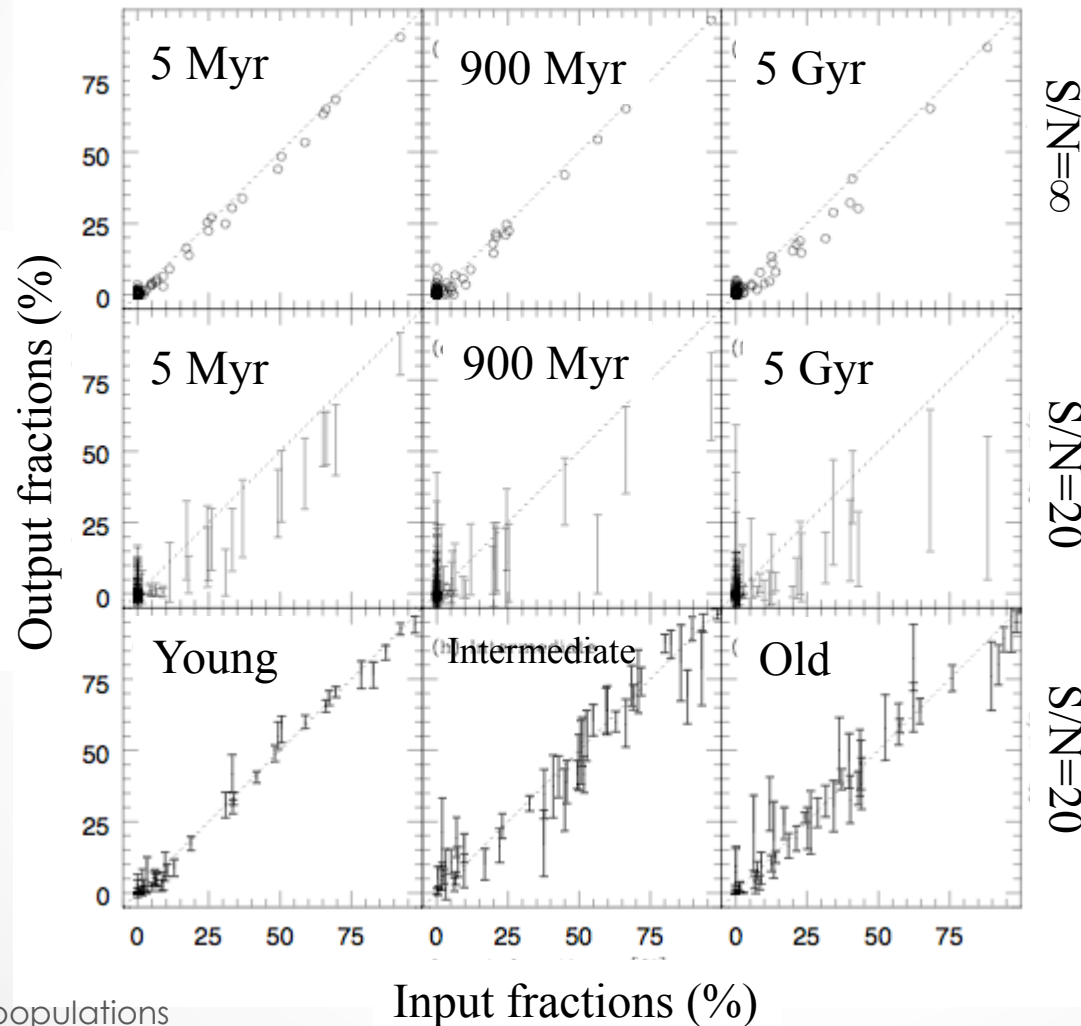


- The reability of these methods are usually estimated by means of **simulations** which feed the code with spectra generated with known parameters, add noise, and then examine the correspondence between input and output values.

# Effect of the S/N

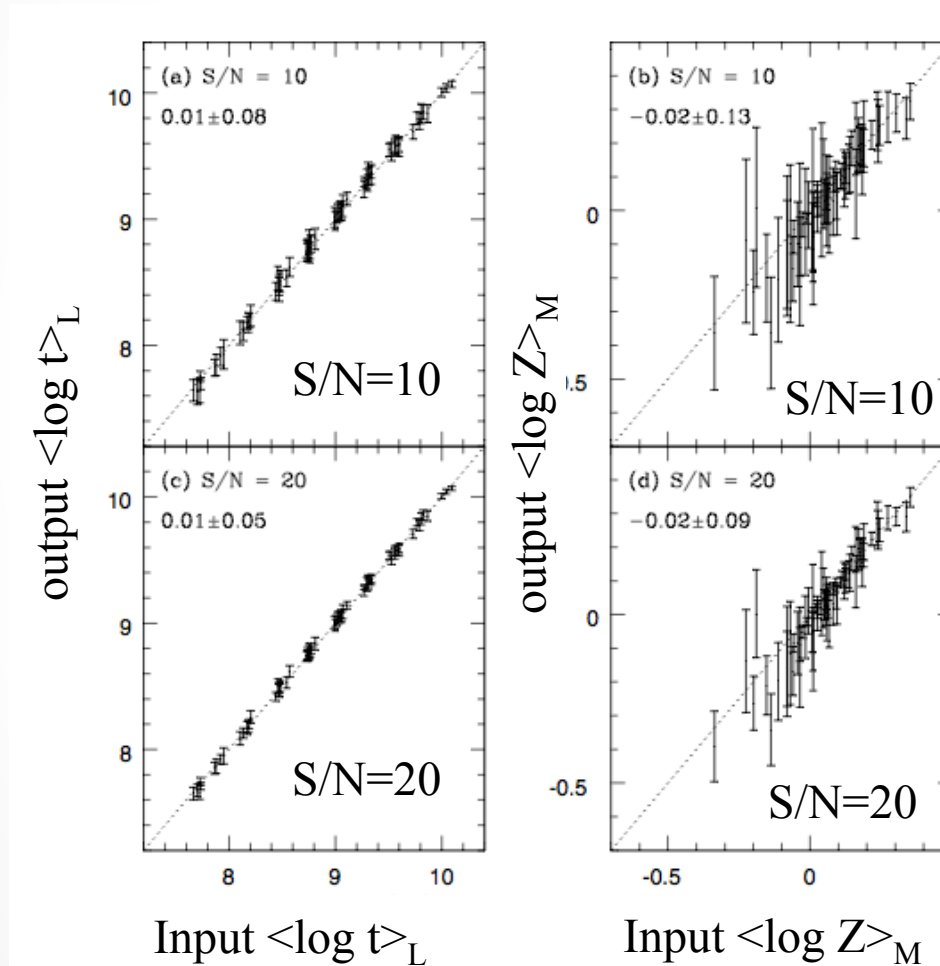
The number of recoverable populations depend on the S/N

Cid Fernandes et al. (2004)



# Simulations: testing the method

The luminosity-weighted values are more robust

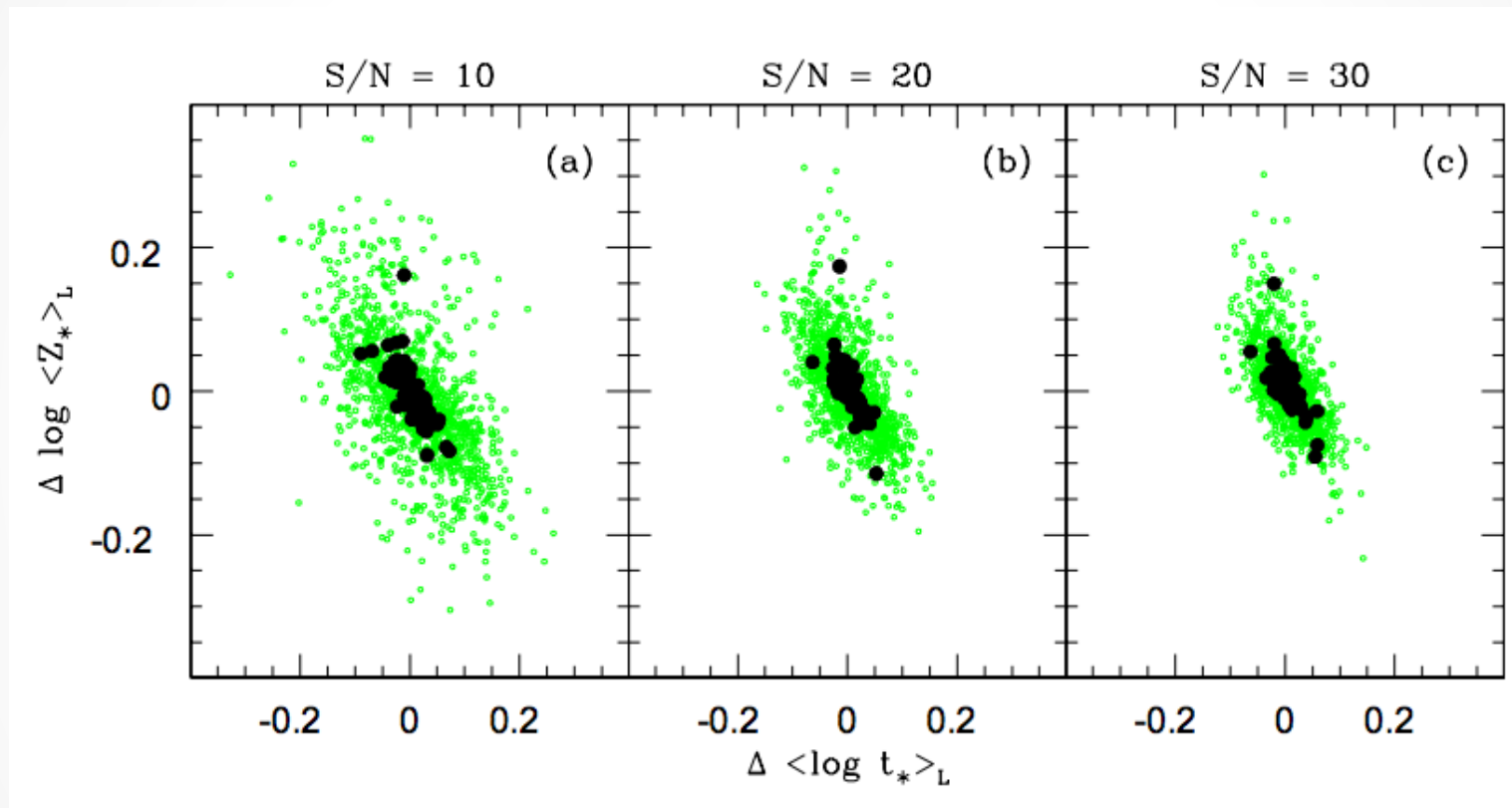


$$\langle \log t_* \rangle_L = \sum_{j=1}^{N_*} x_j \log t_j$$

$$\langle Z_* \rangle_L = \sum_{j=1}^{N_*} x_j Z_j$$

Cid Fernandes et al. (2005)

# The age-Z degeneracy: always there

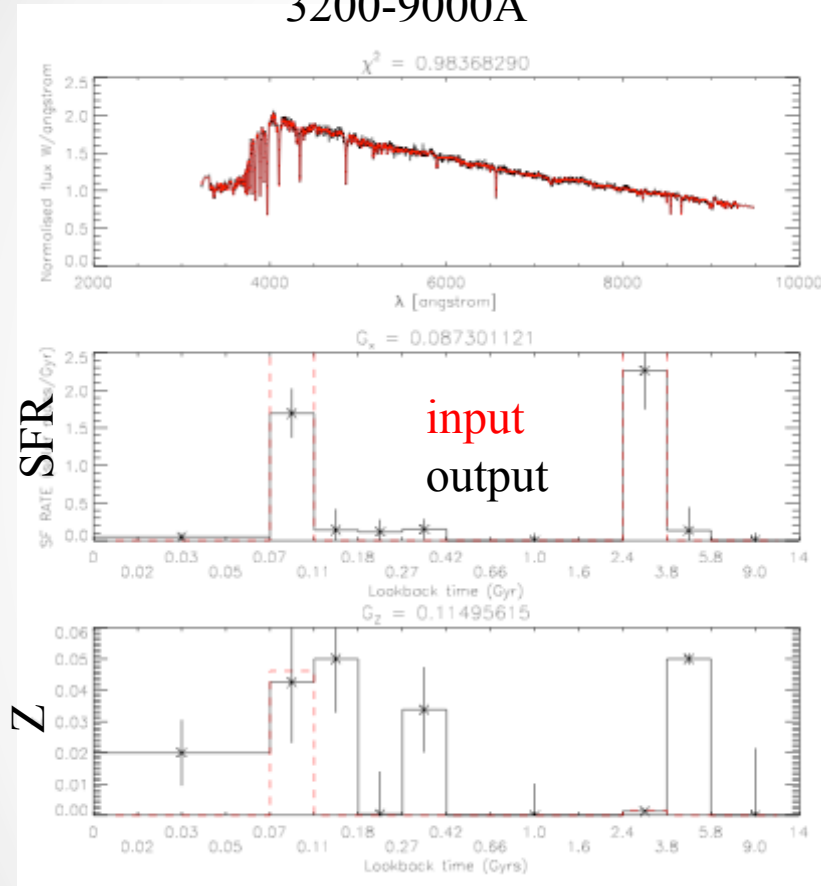


Cid-Fernandes et al. (2005)

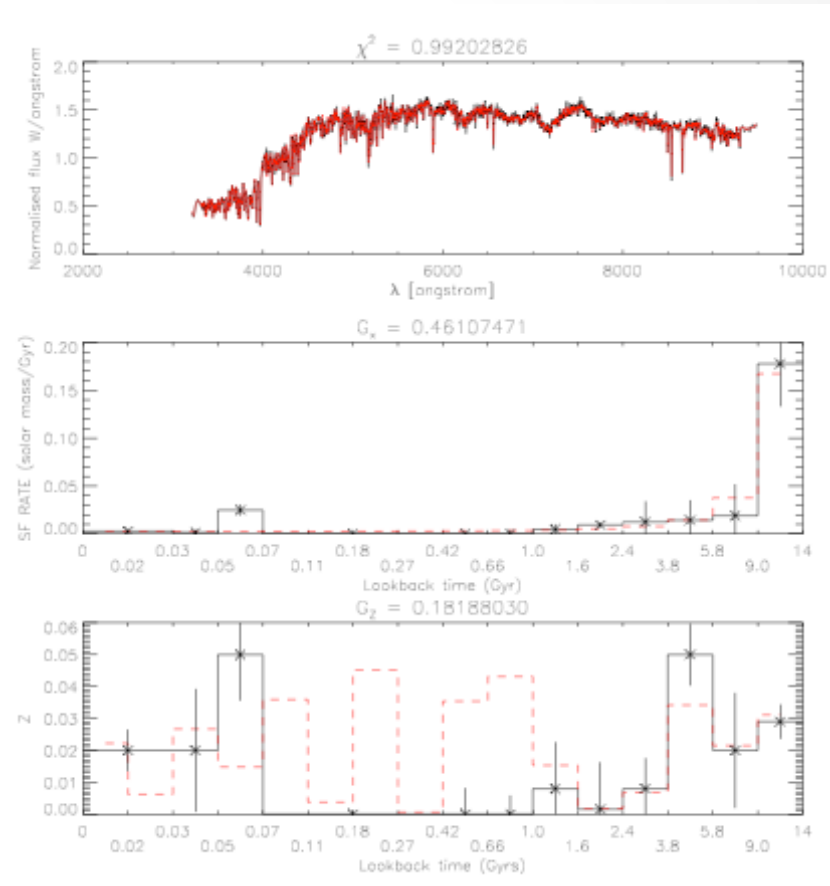


# Effect of wavelength range

3200-9000Å



lookback time (Gyr)

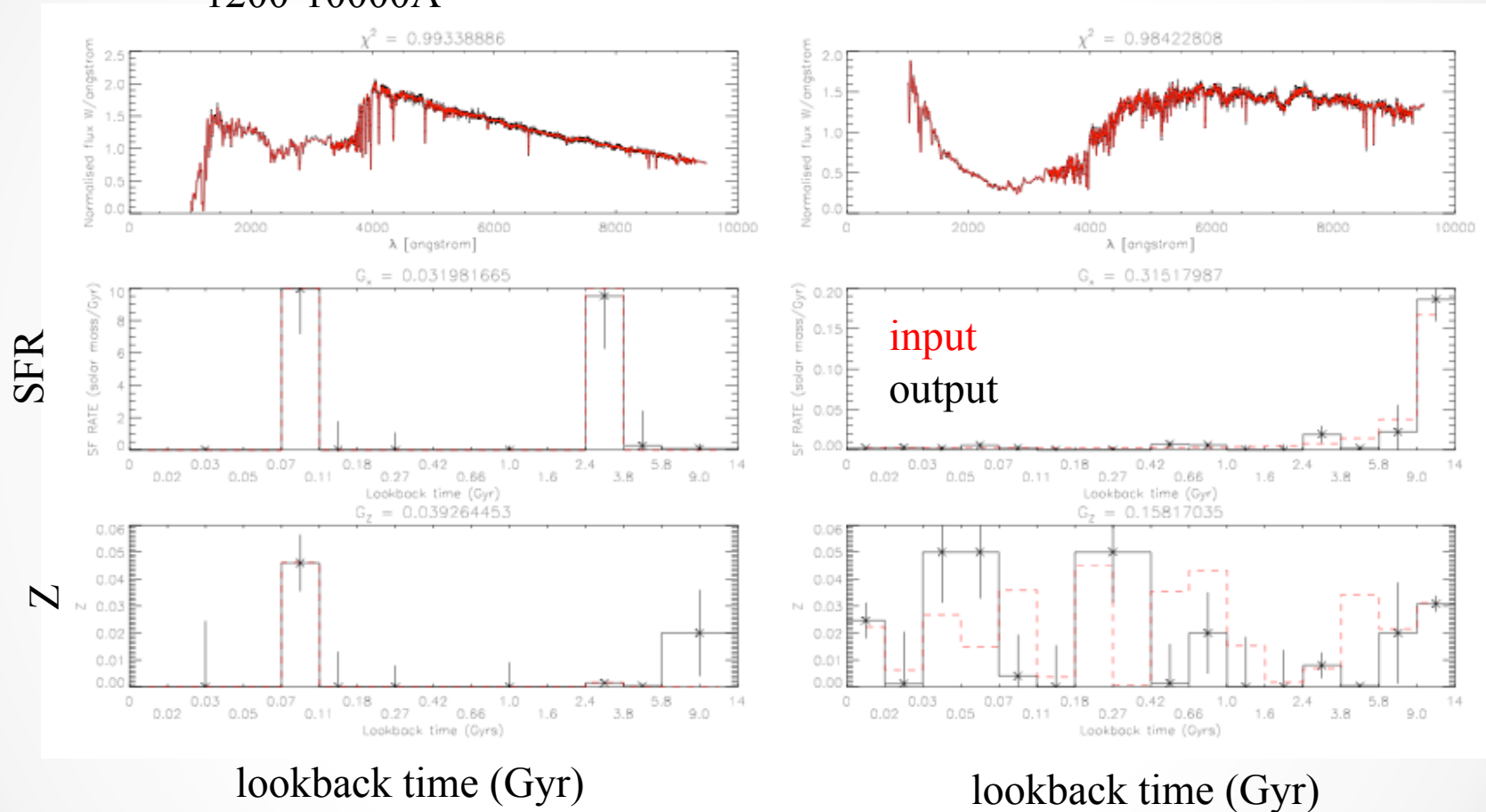


lookback time (Gyr)

Tojeiro et al. (2007)

# Effect of wavelength range

1200-10000Å

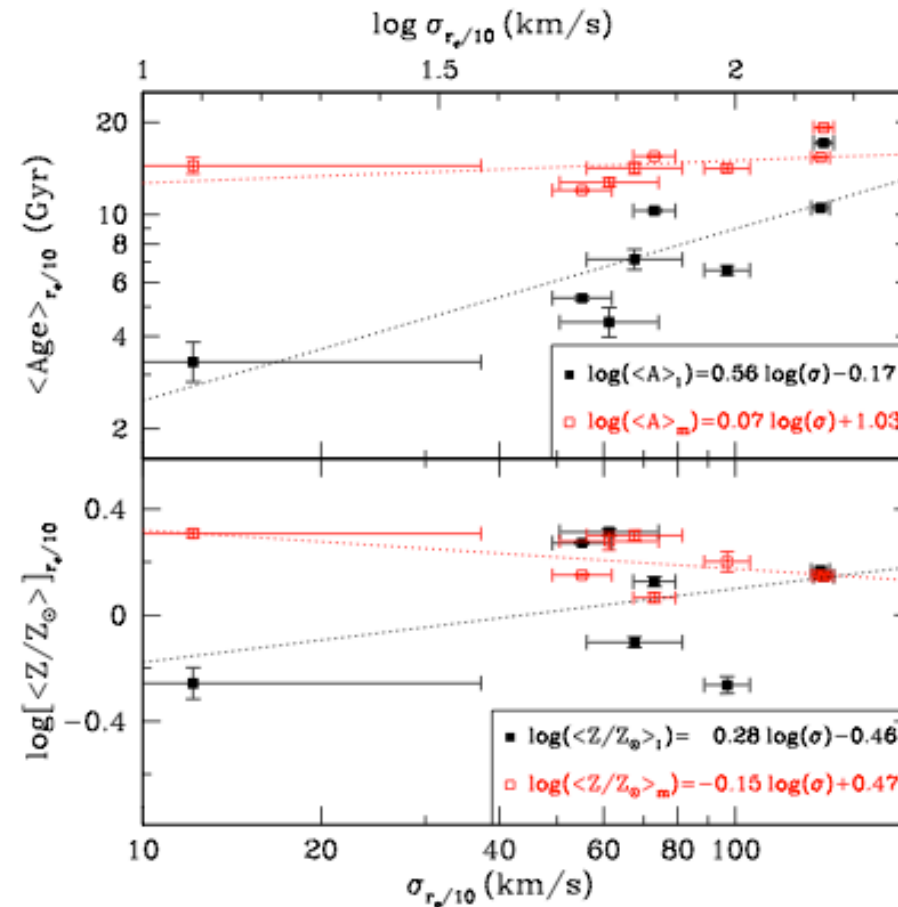


Tojeiro et al. (2007)

# SN and wavelength range

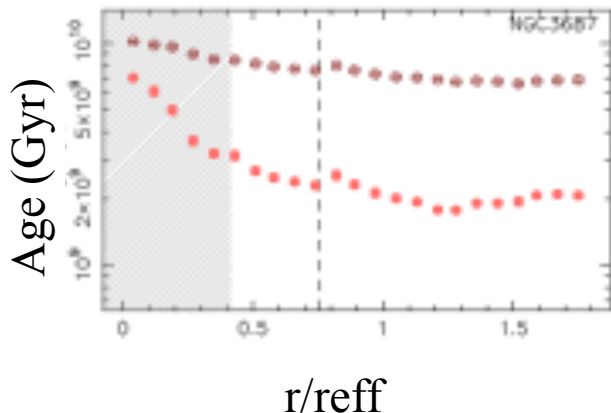
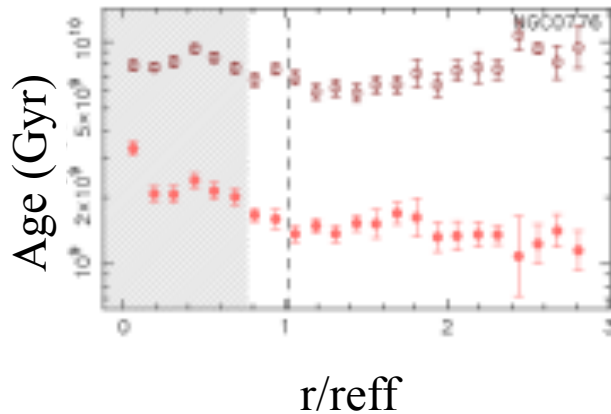
- The results of the experiments:
  - For spectra of **SN~20**, optical wavelength range, one **can recover between 2 and 3 stellar** populations described by and age and a metallicity.
  - For spectra of **SN~50** these values can be **improved** by a **factor of 2**. Also by enlarging the wavelength range to include not only the optical but also the UV and IR range.

# Results: Mass- and light-weighted values for galaxy bulges



MacArthur et al. 2009

# Light and mass-weighted values



Gradients of disk galaxies

- There is a decrease of age towards the external parts in LW age
- The gradients are much flatter in MW Age

→ There is a larger ratio of young/old stars in the external parts but the majority of stars are old everywhere.

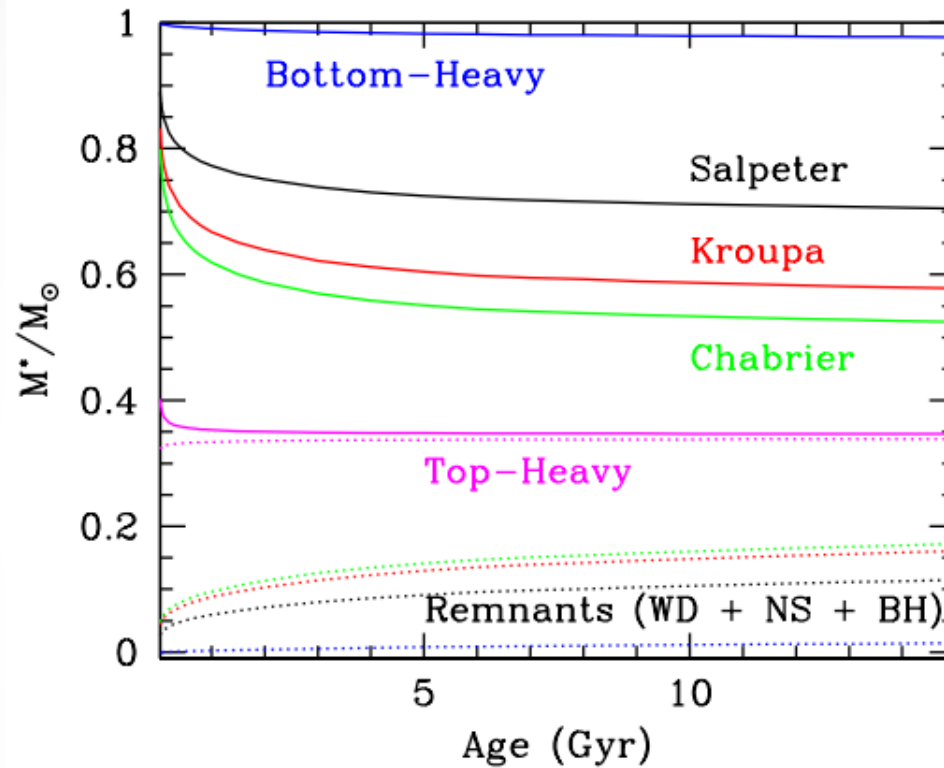
Sanchez-Blazquez et al. (2014)

# The initial mass function

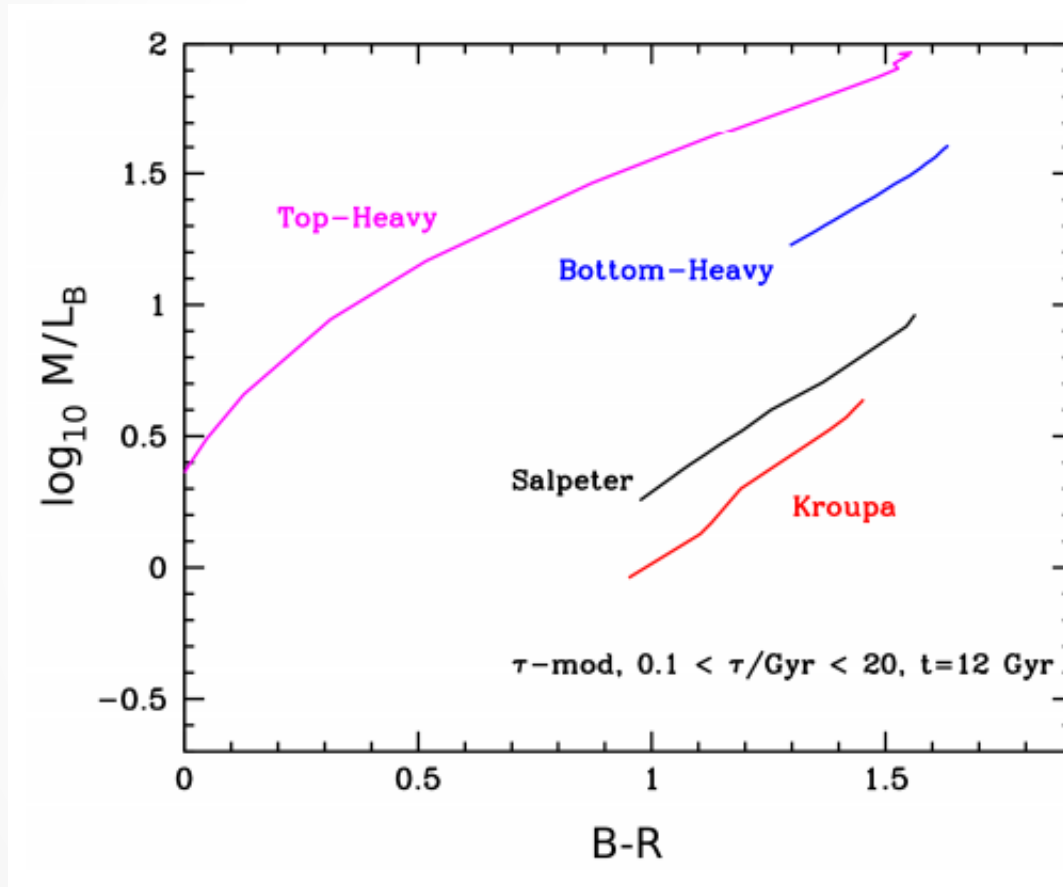
## The Big assumption

- Spectra of SSP are fairly insensitive to the IMF:
  - good : allows to make predictions without worrying about the IMF
  - bad: the  $M/L$  ratio is very uncertain. Colors and line-strengths can be fitted well with different IMFs giving differences in the  $M/L$  of more than a factor of 2! .

# Dependence of mass fraction on IMF



# Dependence of the M/L on the IMF

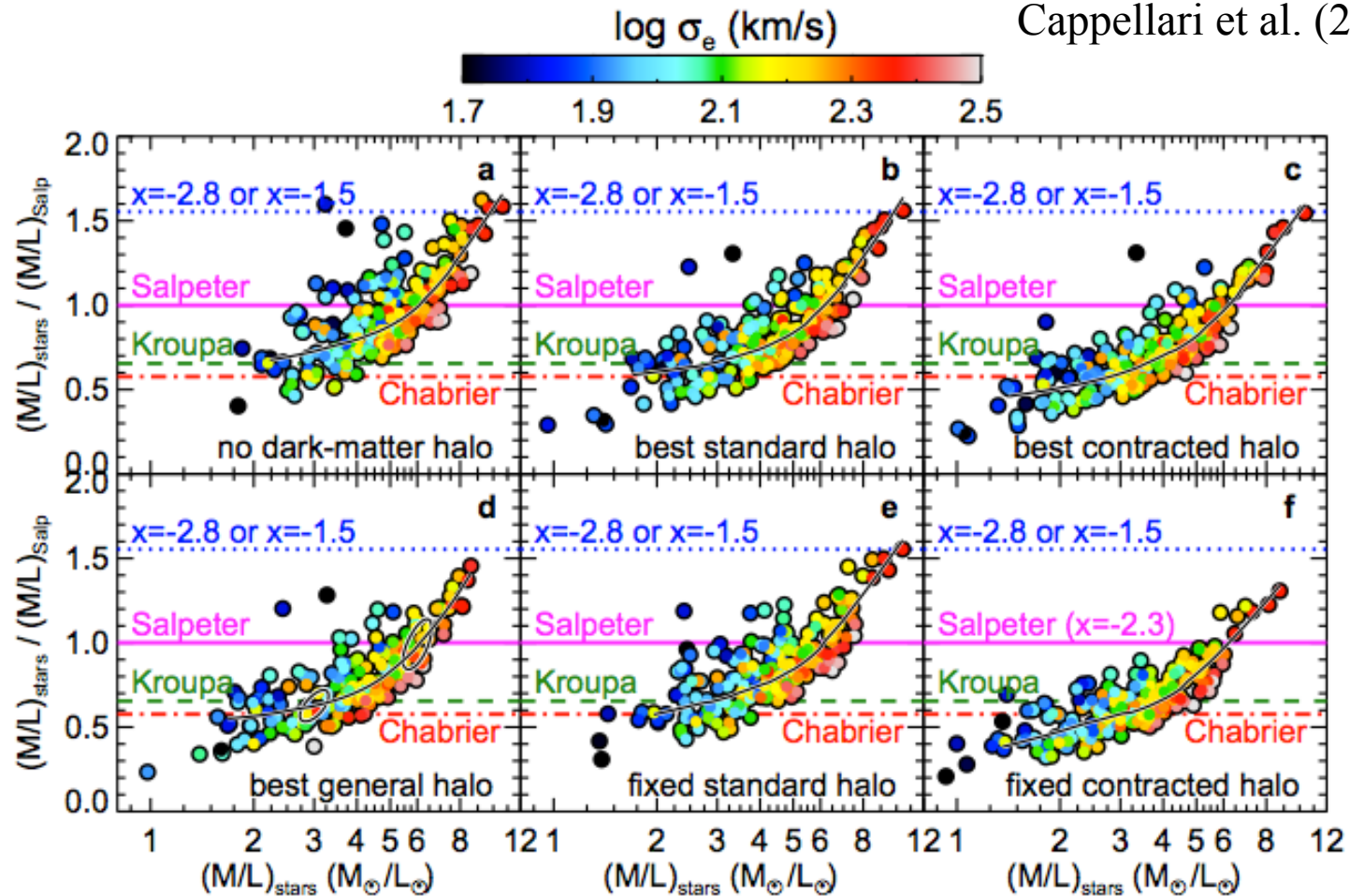


Exponentially declining models of 12 Gyr and solar metallicity



# The comparison of M/L with stellar pop and with dynamical models

Cappellari et al. (2013)



# Measuring the IMF in the integrated spectra

## Very challenging

The faint low mass stars ( $M < 0.4 M_{\text{sun}}$ ) which dominate the total stellar mass budget in galaxies, contribute only of **order 1% in the integrated light**.

The stars that dominate the light in EG (K and M giants) have a similar spectral type as the stars that dominate the mass budget (K and M dwarfs)

Detecting IMF variations using line-strength indices requires measurements with very high accuracy ( $< 0.3\%$ ).

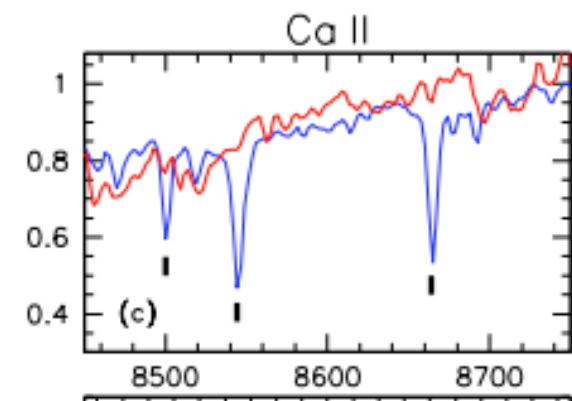
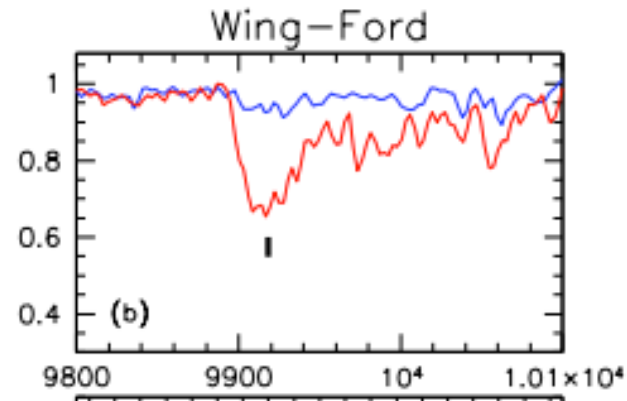
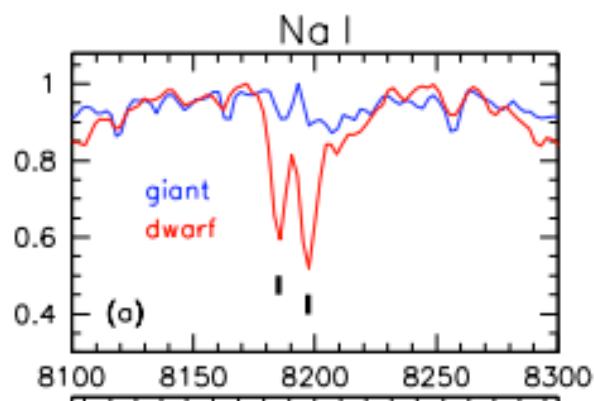
# Counting dwarf stars

It can be done quantifying the amount of dwarf stars using gravity-sensitive absorption features. The strongest dwarf-sensitive features are:

NaI  $\lambda$ 8183,8195 doublet

FeH  $\lambda$ 9916 wing Ford band

The strongest giant-sensitive features (in the optical) is the CaII  $\lambda$ 8498,8542,8662 triplet.



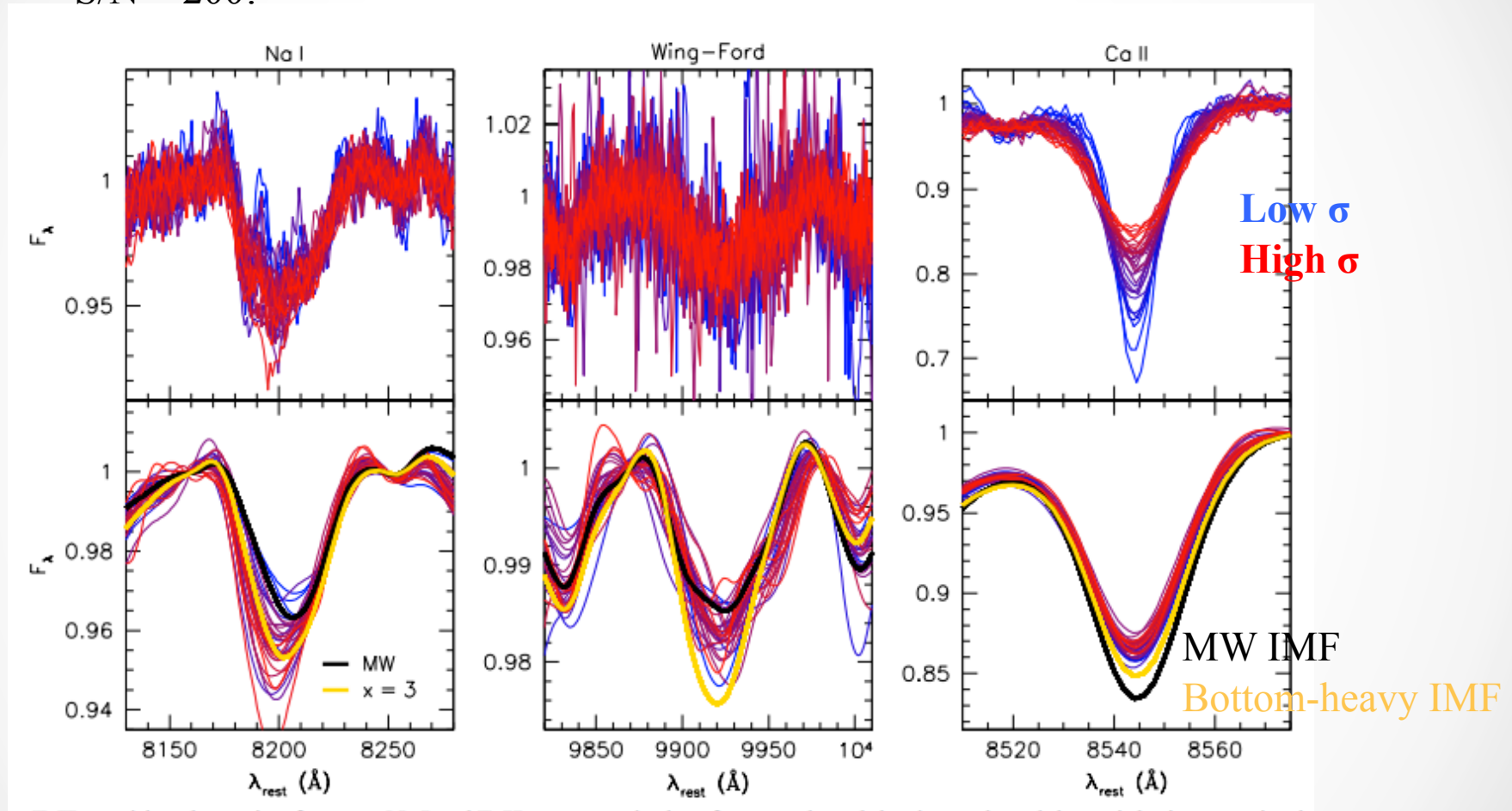
# Other problems

- (1) The lines are affected by telluric absorptions
- (2) Abundante ratios affect the strength of these lines
  - The Wind-Ford band is sensitive to Fe abundance
  - NaI is sensitive to [Na/Fe]
  - CaII triplet is very sensitive to [Ca/Fe] (and the overall  $\alpha$  enhancement).

All three indices also depends on age in complex ways.

# Measuring the IMF in ETG

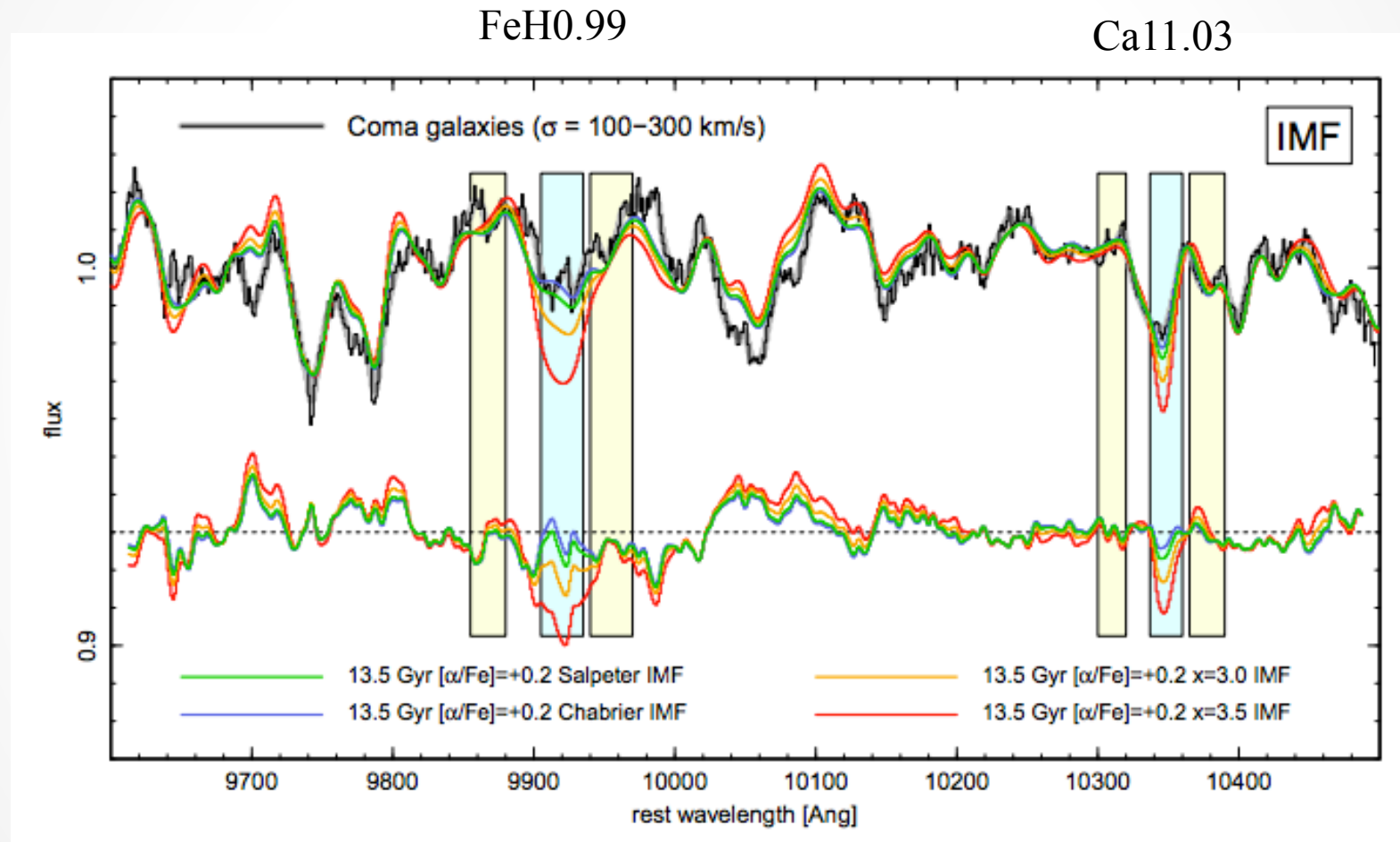
S/N > 200!



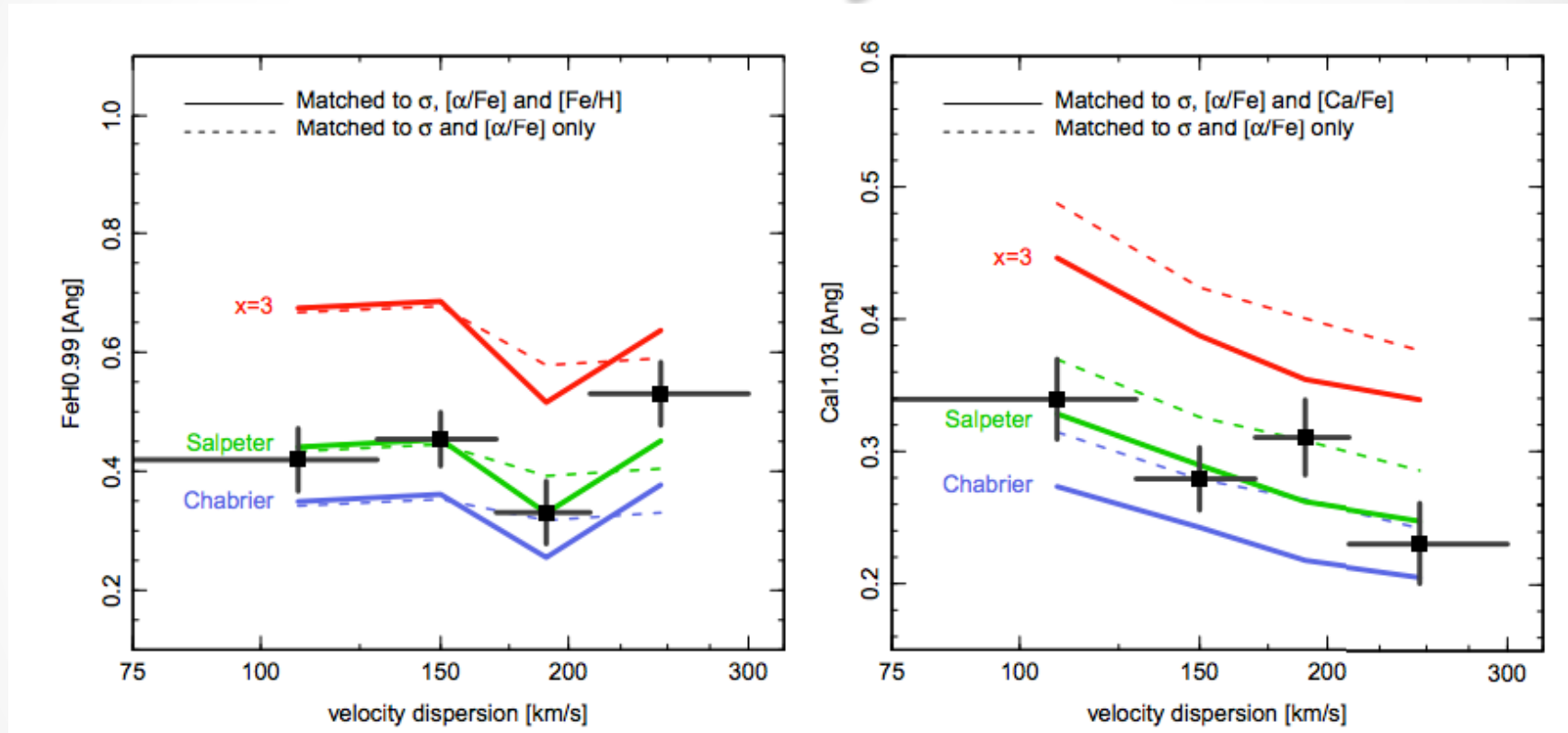
Conroy & van Dokkum (2012)

SELGIFS school (2014)

# Contradictory results



# Contradictory results



Smith et al. (2012)

# Summary

- The comparison of integrated spectra with stellar population models allow us to obtain information of:
  - (1) The age of the stars in the galaxy
  - (2) The overall metallicity
  - (3) The abundance ratios of different elements ( $[Mg/Fe]$ ,  $[C/Fe]$ ,  $[N/Fe]$  (not seen here))
  - (4) The stellar mass
  - (5) The IMF



# Summary

- A lot of progress has been done in the last few years but still be careful:
  - With the method you use!.. (SSP, parametric, non parametric)... they all have their advantages and caveats, but they all give different information.
  - There are still many uncertainties in the models.. Be careful!

# A non exhaustive list of uncertainties

- (1) the treatment of the core convective boundary in main-sequence stars (ie., convective core overshooting);
- (2) metallicity dependent mass loss along the red giant branch (RGB) and (related) the morphology of the HB.
- (3) the treatment of the thermally pulsating asymptotic giant branch (TP-AGB) phase.
- (4) the spectral libraries, especially for M giants, TP-AGB stars, and stars at non-solar metallicities (e.g., Martins & Coelho 2007).
- (5) blue stragglers (BS) stars and their ubiquity (e.g., Preston & Sneden 2000; Li & Han 2008)
- (6) the effects of binarism, which might be especially relevant for massive star evolution (e.g., Eldridge et al. 2008) and BS stars.
- (7) the importance of rotation on massive star evolution (e.g., Meynet & Maeder 2000)
- (8) non-solar abundance ratios, which affect not only the stellar evolution calculations but also the stellar spectra.
- (9) The unknown dependence of the IMF on ISM properties such as metallicity and pressure.

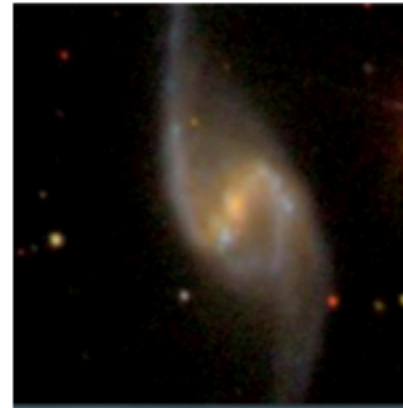
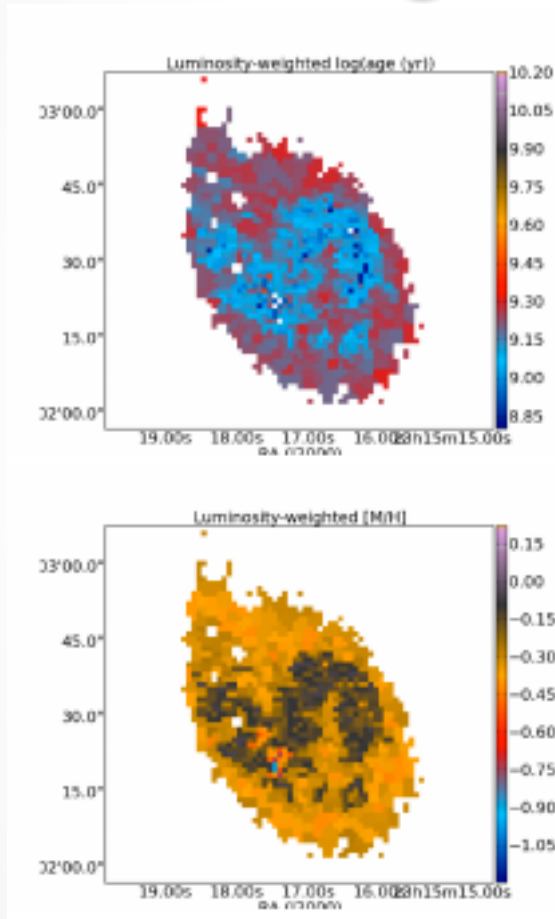
# Summary

## In the next few years:

-- Improving our understanding of phases that influence the flux in the IR and UV (to use those ranges!).

3D spectroscopy will help us to understand the connection between stellar populations, morphology and kinematics

# Learning about stellar populations using 2D spectroscopy



Allow us to study the stellar populations together with the morphology, dynamics, etc., which enhance our understanding of these components.

Sanchez-Blazquez et al. (2014)

# NGC5406

