ESTALLIDOS collaboration

MINISTERIO DE EDUCACIÓN Y CIENCIA

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Models for (spiral) galaxies

- Spectra
- Brightness Profiles
- Colors
- Spectral Indices

Stellar Populations Indicators: Synthesis Models

Averaged along the evolutionary history Properties

Constraints Chemical Evolution Models

- HII regions, emission lines Abundances
- Hα fluxes : (recent) Star formation rate
- Atomic and molecular gas densities

Present time

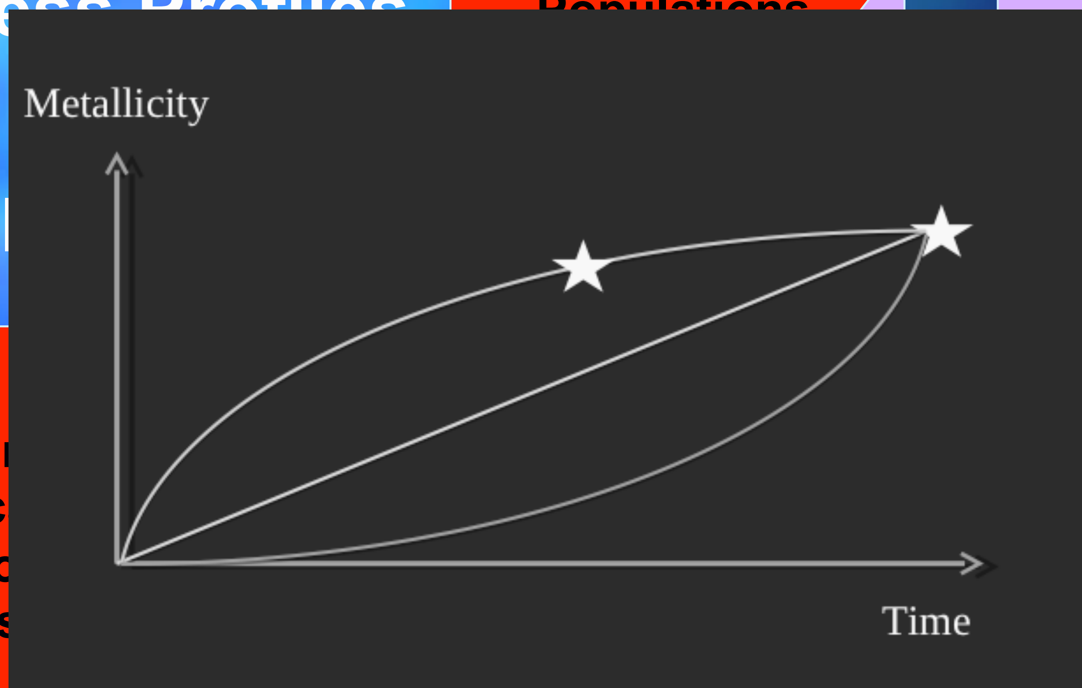
Models for spiral galaxies

- Spectra
- Brightness Profiles
- Colors
- Spectral

Stellar Populations

Averaged along the volutionary history Properties

Constrai Chemic Evolutio Models



Present time

STELLAR POPULATIONS

A stellar population is a set of stars with the same age, the same chemical composition and the same kinematical properties. It is therefore thought that all of them formed simultaneously in a same burst

Baade (1944)

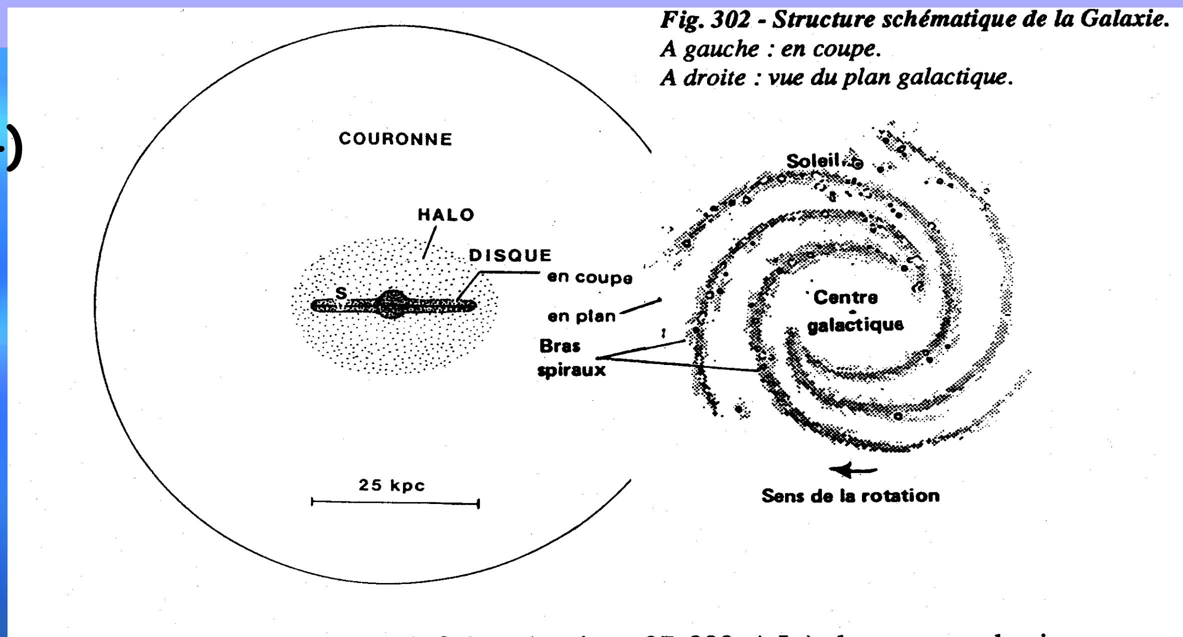


Fig. 302 - Structure schématique de la Galaxie.
A gauche : en coupe.
A droite : vue du plan galactique.

– Population I: stars as those seen in the Solar Vicinity, associated to the galactic disk.

Young objects, with a high metallic content and with small velocity dispersions

– Population II: Stars asociated to the halo and spheroidally distributed

Old objects, metal-poor and with high velocity

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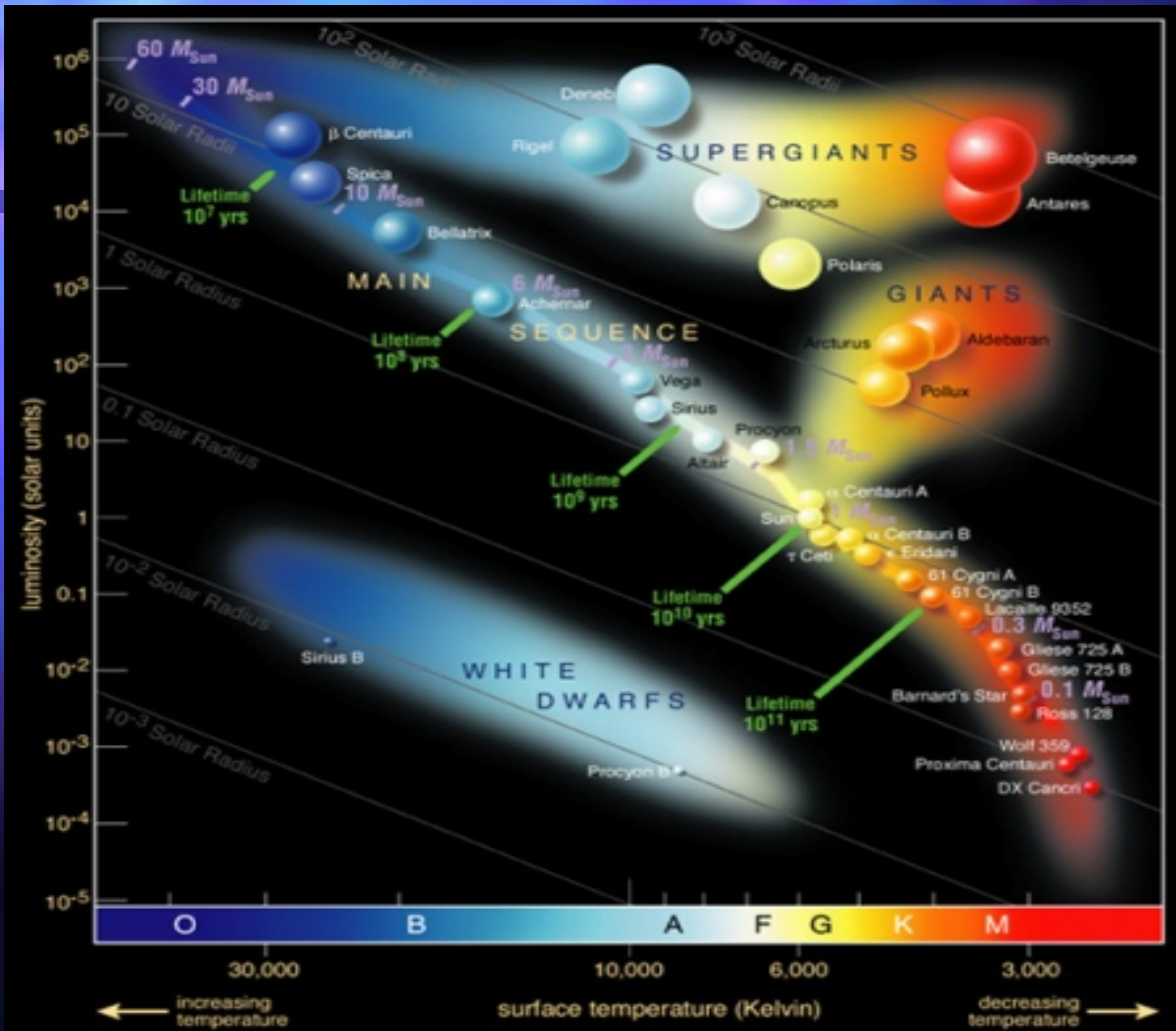
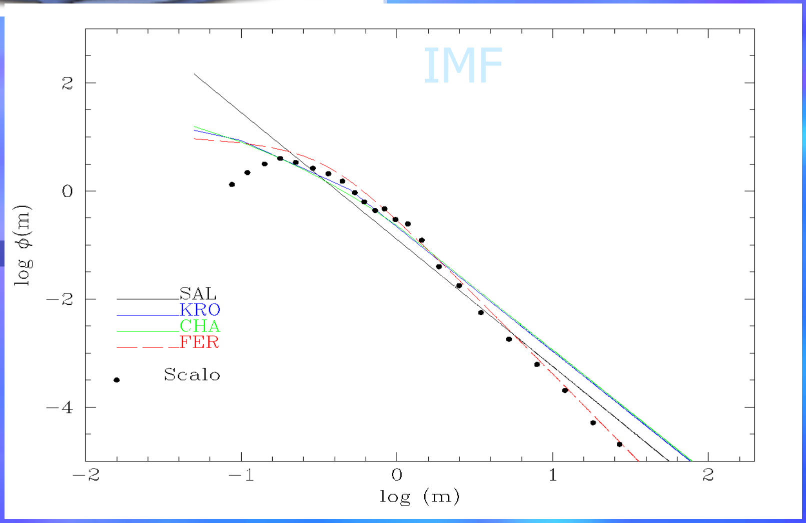


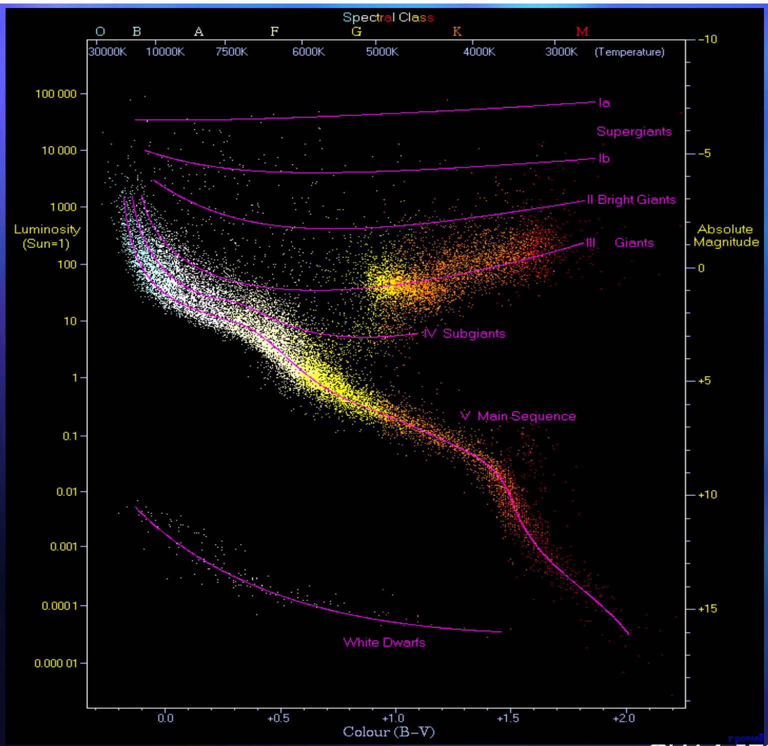
The position of a star in the HR diagram depends on its mass

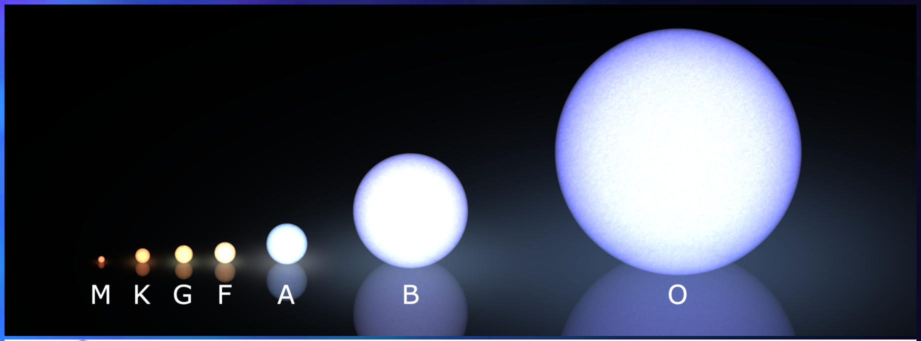
The most massive ones are in the top, the smaller in the lower part of the diagram

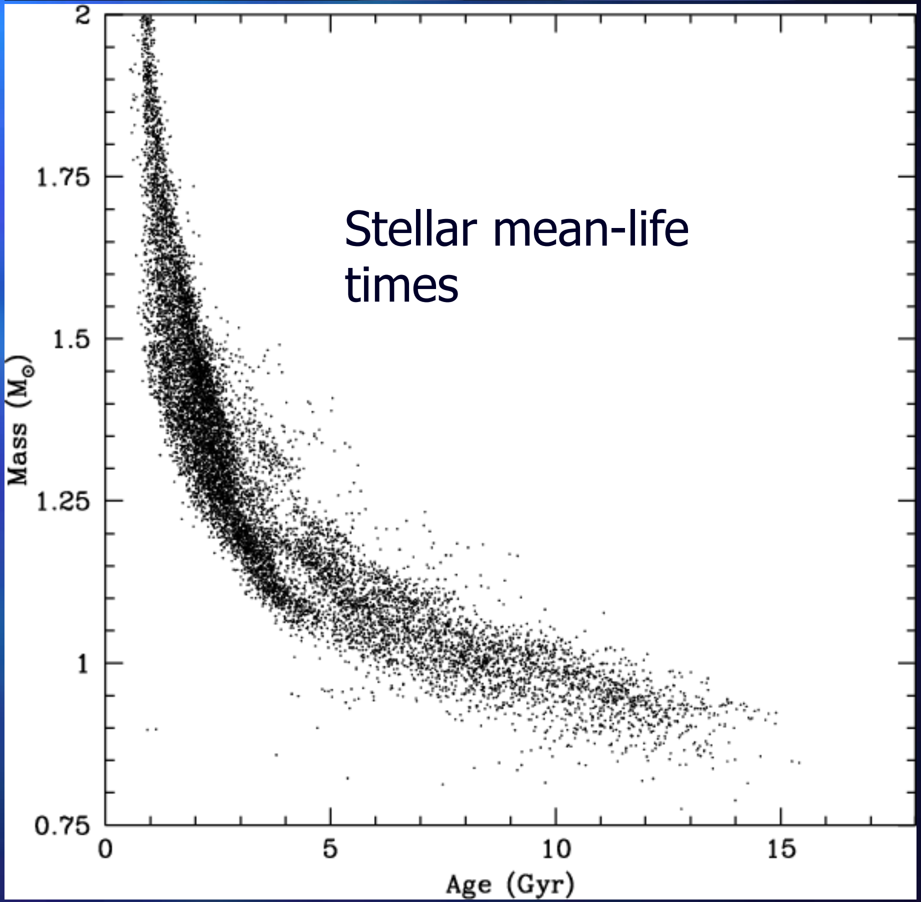
When stars age run out of the MS towards the high part of the diagram and to the right

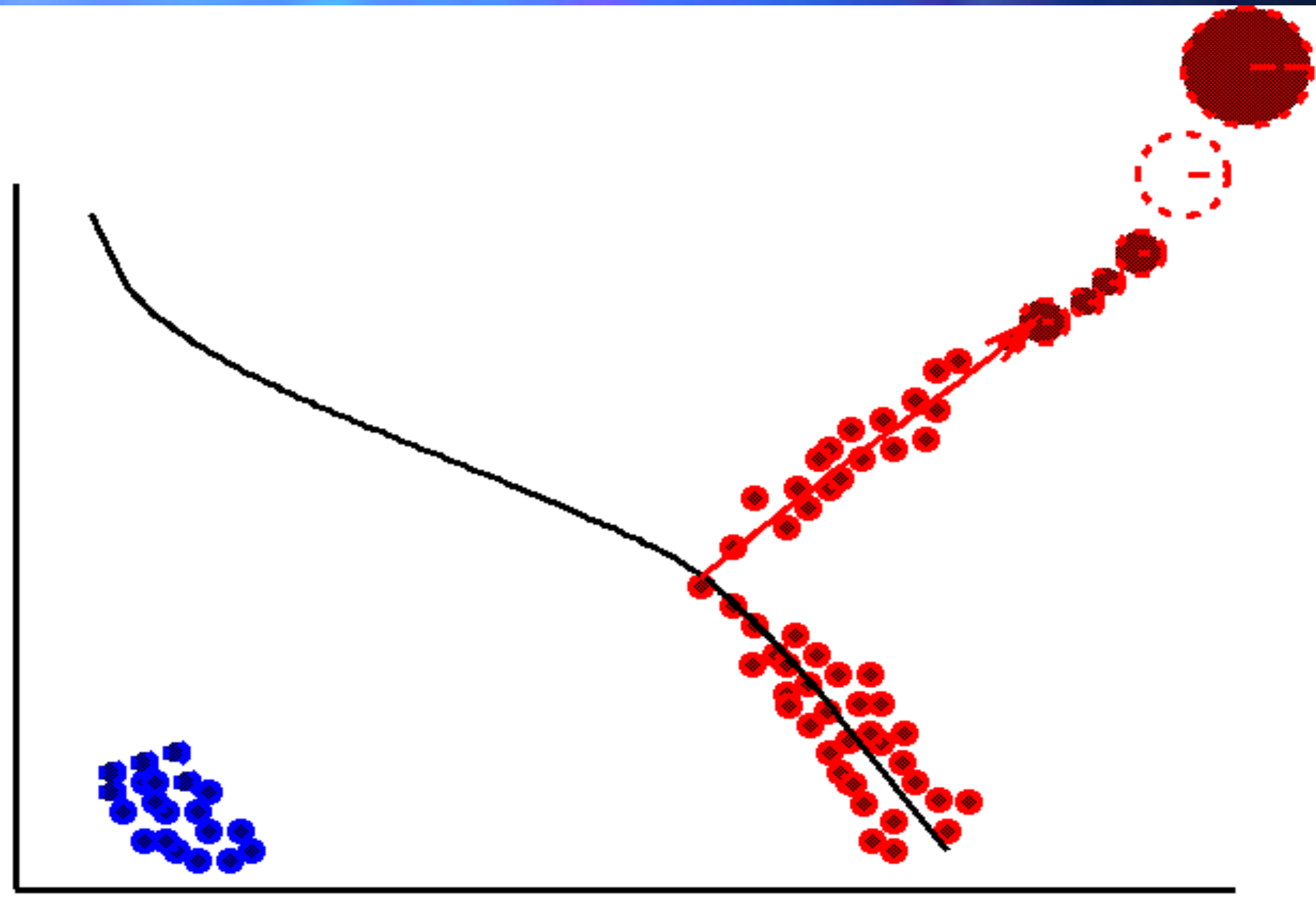
When they die, when there is no more material to burn, they finish as white dwarfs or neutron stars.


IMF
log φ(m)
log (m)
SAL
KRO
CHA
FER
Scalo


Spectral Class
O B A F G K M
30000K 10000K 7500K 6000K 5000K 4000K 3000K (Temperature)
Luminosity (Sun=1)
Absolute Magnitude
Ia
Supergiants
Ib
II Bright Giants
III Giants
IV Subgiants
V Main Sequence
White Dwarfs
Colour (B–V)

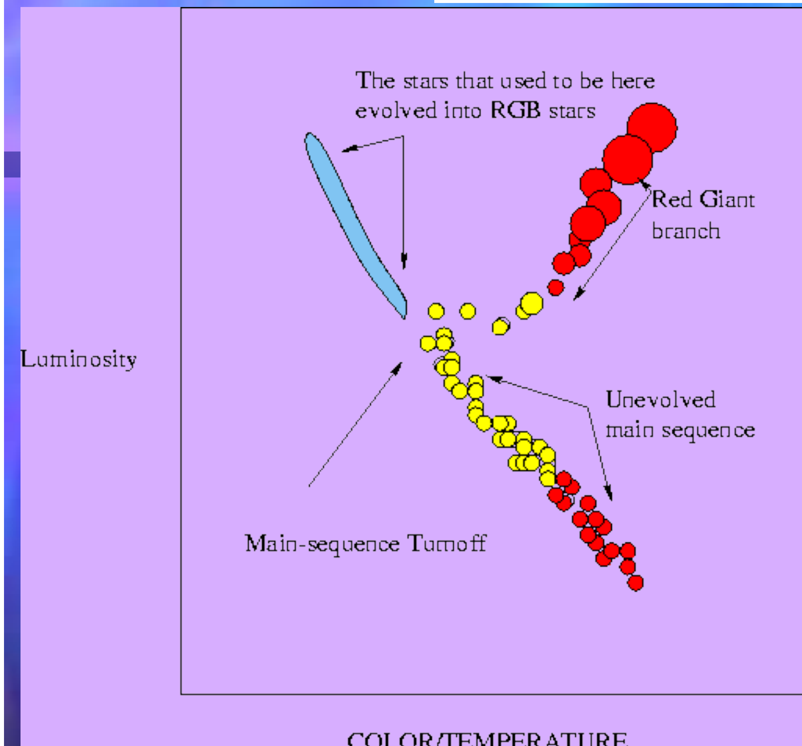

M K G F A B O


Stellar mean-life times
Mass ($M_\odot$)
Age (Gyr)

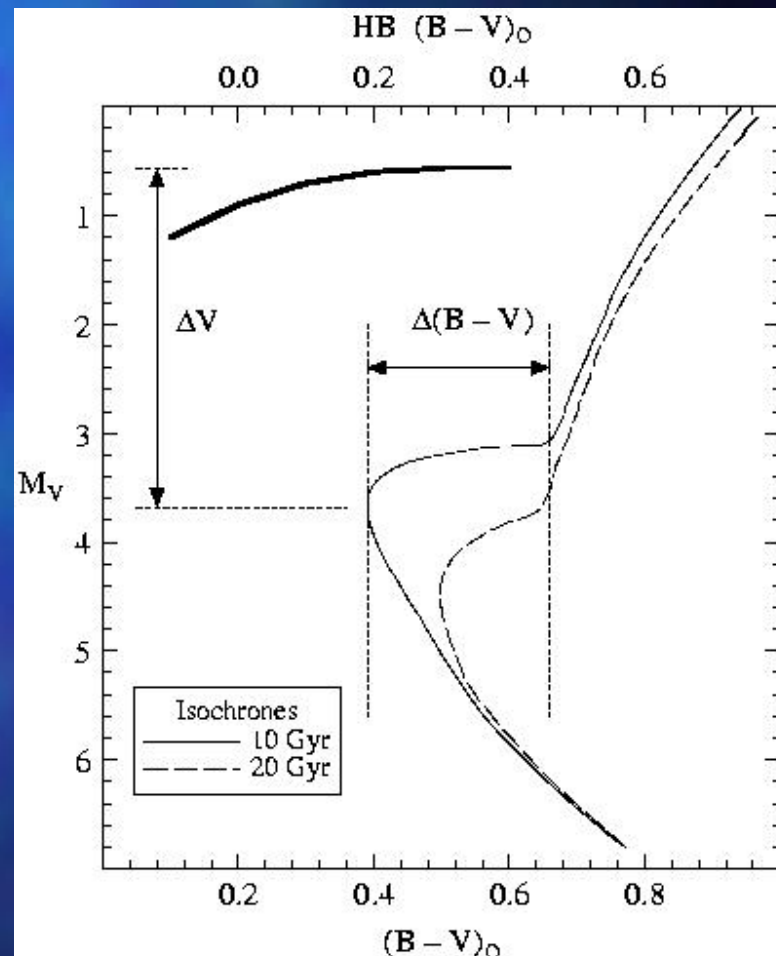


T = 10 billion years old --> just red stars left; lots of white dwarfs; no stars more massive than one solar mass left on the main sequence

COLOR-MAGNITUDE DIAGRAMS

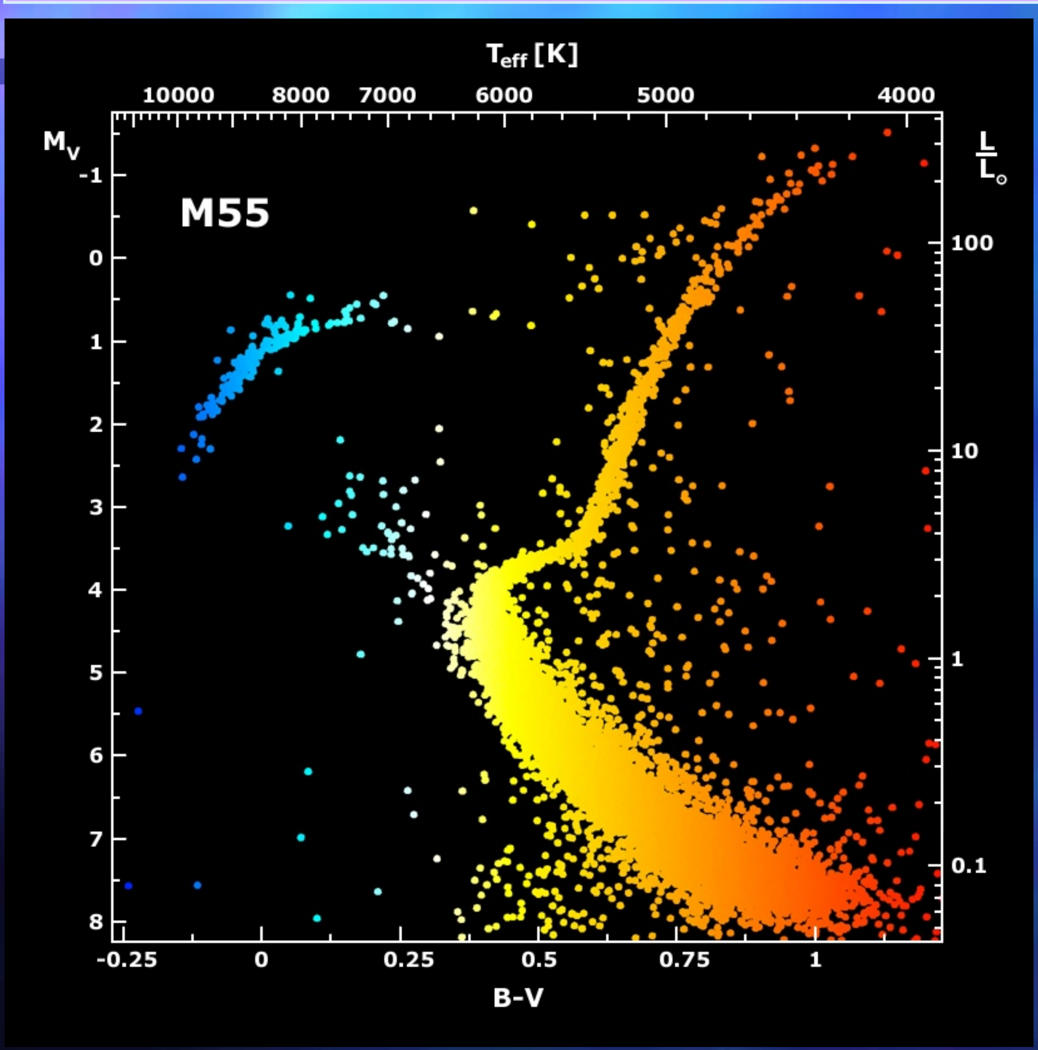


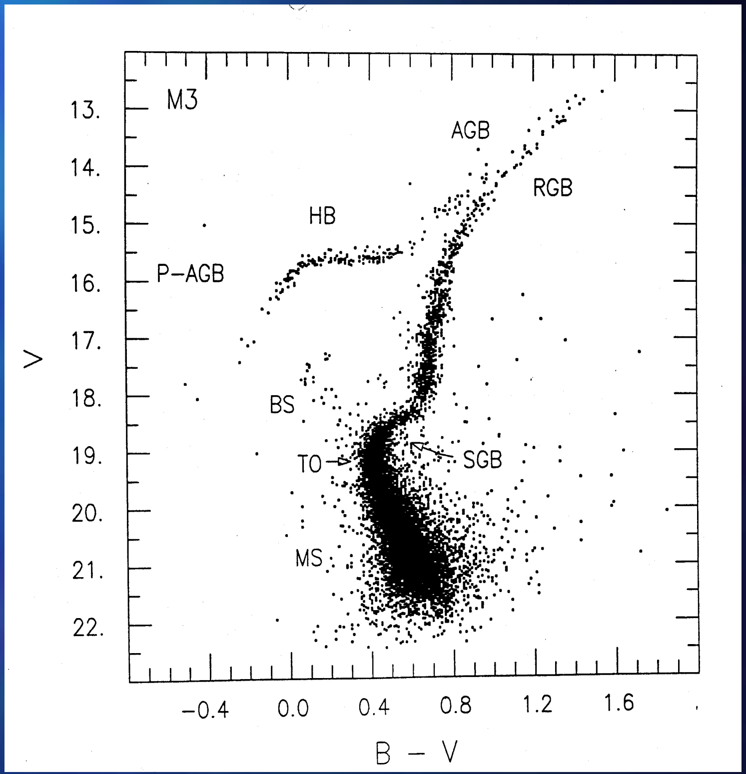
Equivalent to the H-R diagram of stars for stellar clusters



- •Relationship between the turnoff and the MS
- •The distance of the turnoff with the RSG branch
- •The extension of the *blueloop*
- •Subgiants branchs

The number of stars in each CMD increased extraordinarily with HST





GLOBULAR CLUSTERS

The globular clusters group several millions of stars, even hundred of million of stars

- **They are distributed in the halo and in the bulge in a spherical structure.**
- **They move in very elongated orbits which pass near of the galactic center.**
- **In the nearby galaxies as M31 or M33, it has been also seen globular clusters around the disk.**

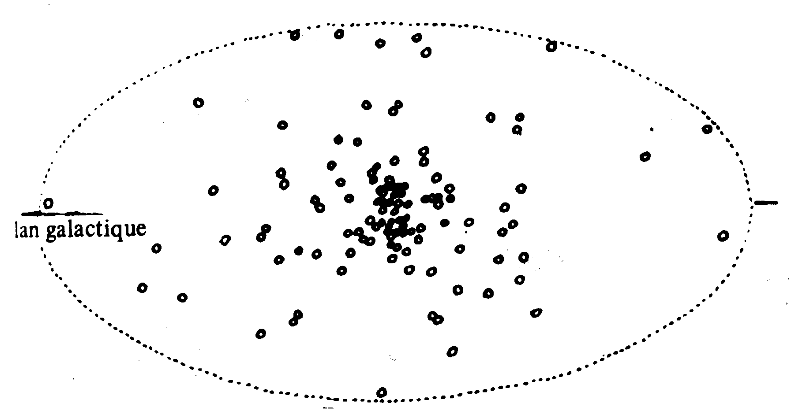
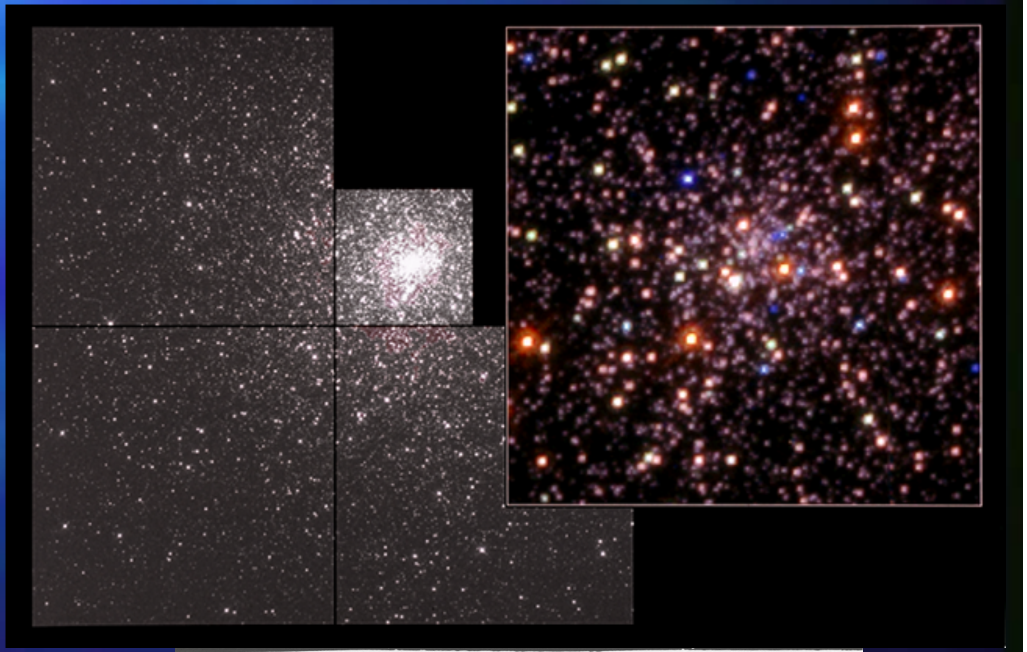
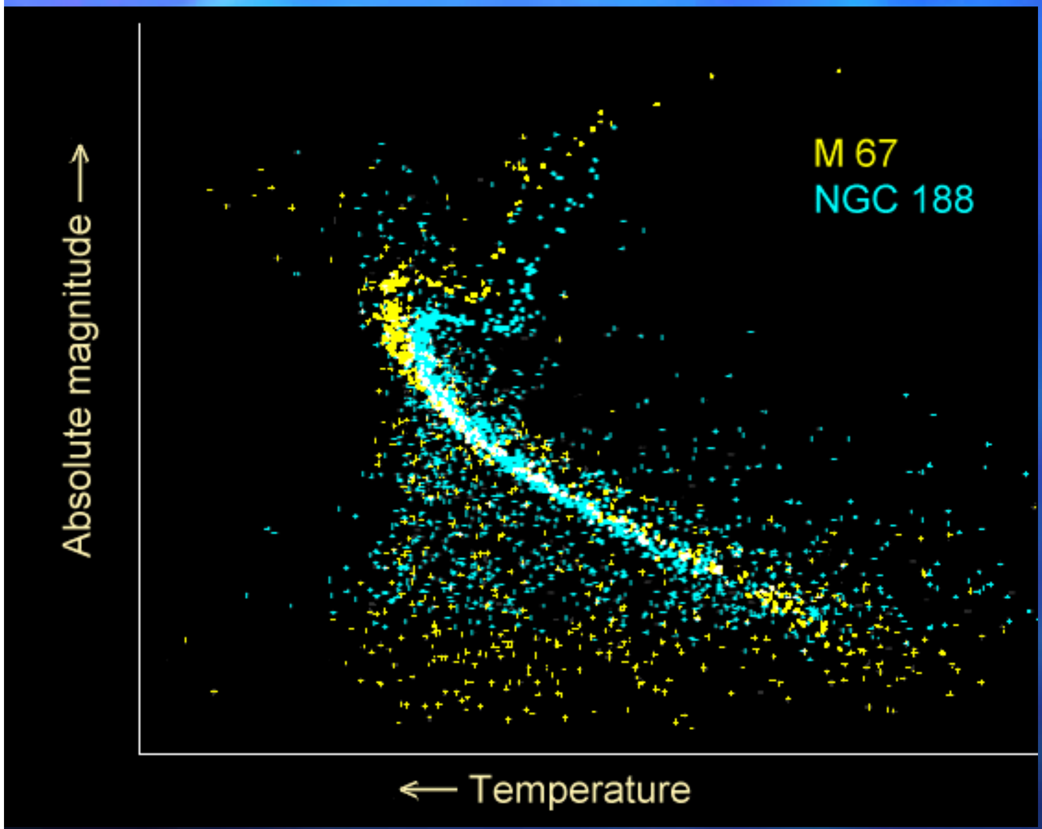


Fig. 292 - Distribution galactique des amas globulaires
A droite : Amas globulaire M 13 - Hercules



OPEN CLUSTERS & ASSOCIATIONS



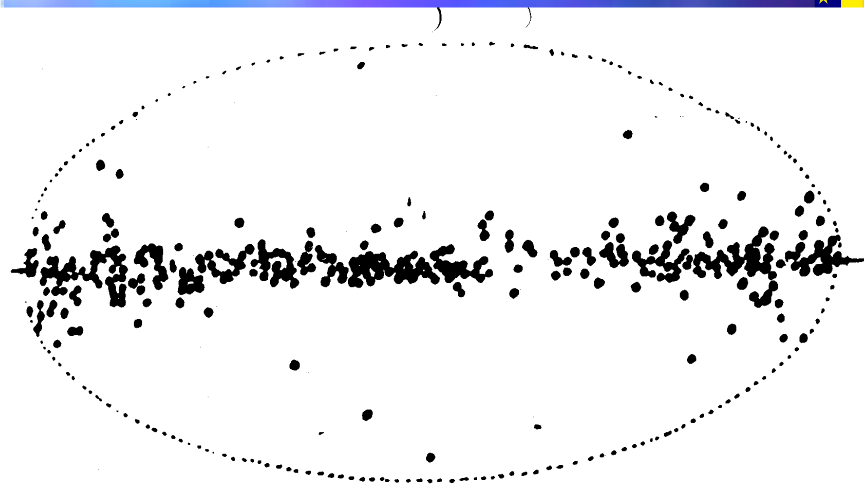


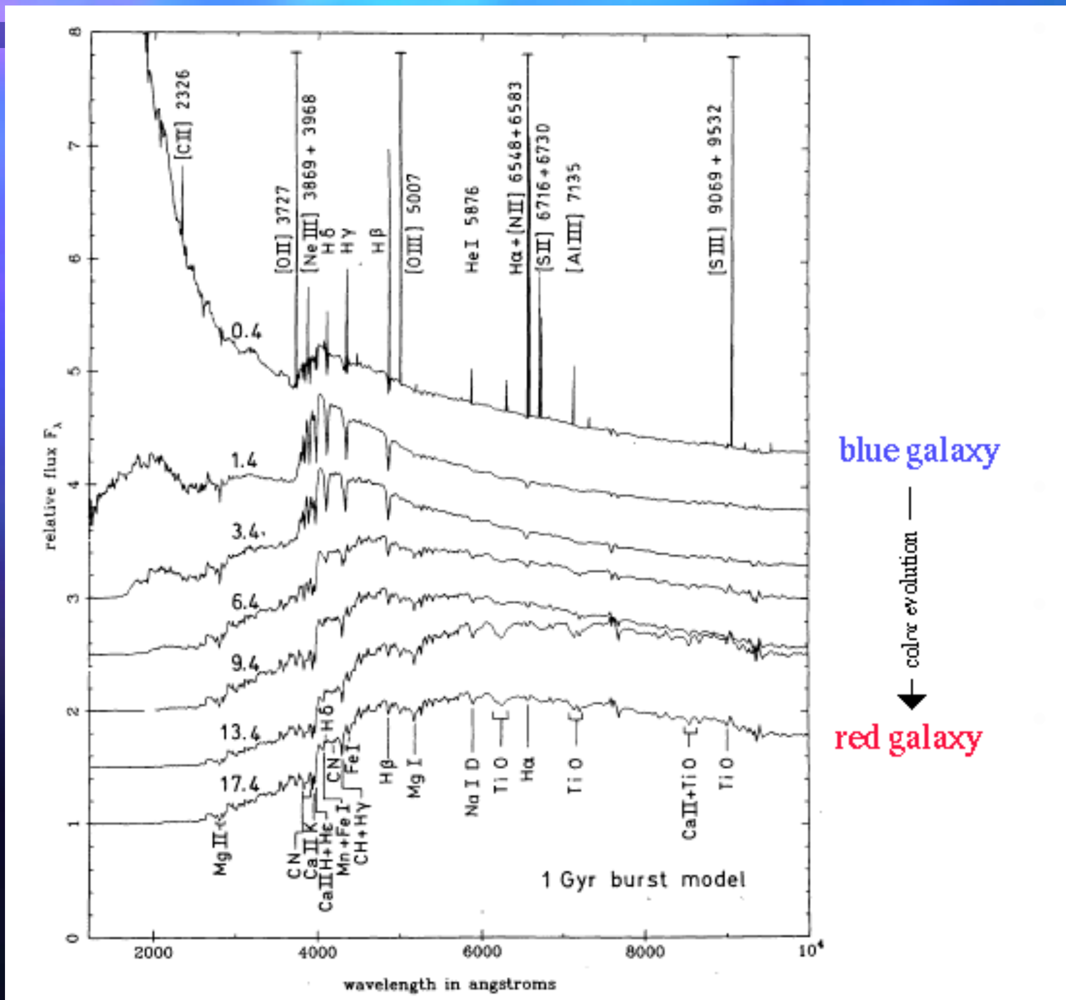
Fig. 295 - Distribution galactique des amas ouverts
A droite : Amas galactique des Pléiades

Open clusters with a high dispersion in age and Z

- They have a structure much more open than the CG and only several hundred of stars
- They move following the galactic rotation
- The formed from interstellar clouds which were rich in metals
- They are in the galactic disk and their stellar population is I
- There is a large number of blue giants and variable Cefeids stars
- The age is variable from 70 Myr to several hundreds of Gyr

INTEGRATED STELLAR POPULATIONS:

STELLAR POPULATIONS MODELS



For years the external galaxies studies were performed by using integrated spectra (sometimes only colors or magnitudes in some bands were available)

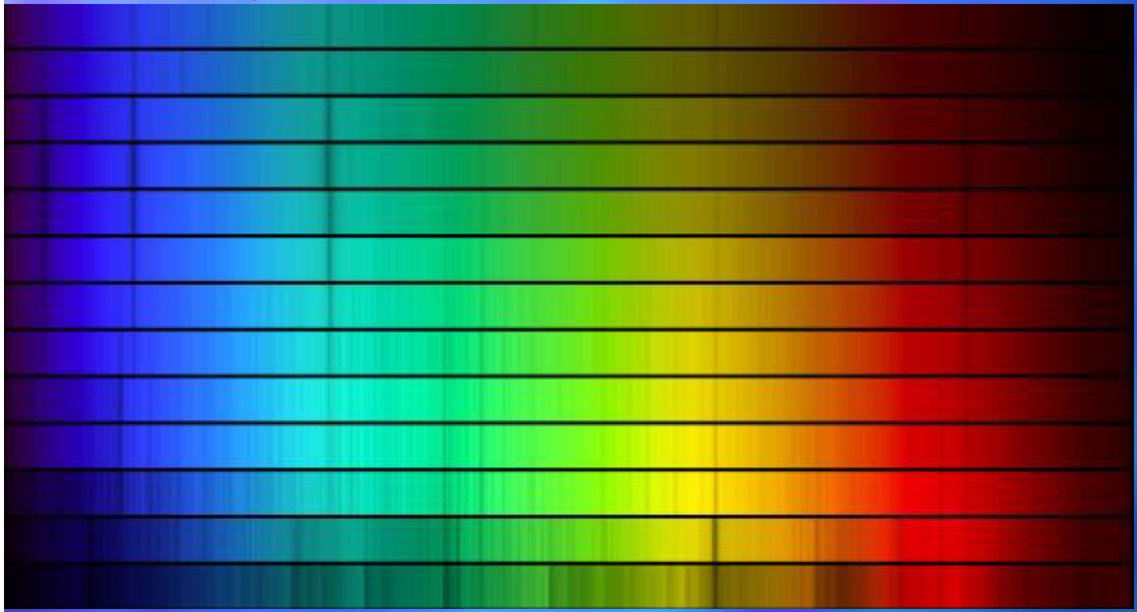
Since the whole region was observed, all stars were included: it was impossible to solve stars individually

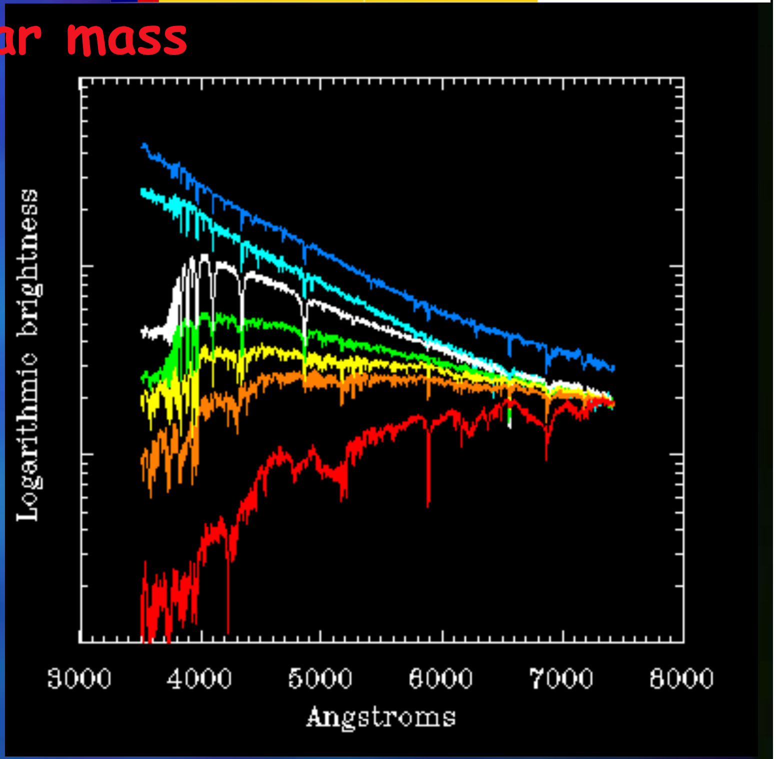
The interpretation is based in the so-called **stellar population models**.

Objective: To find the mix of stars which best fit the observed spectrum

The method was specially good to study globular clusters and elliptical galaxies, for which a single star burst was assumed

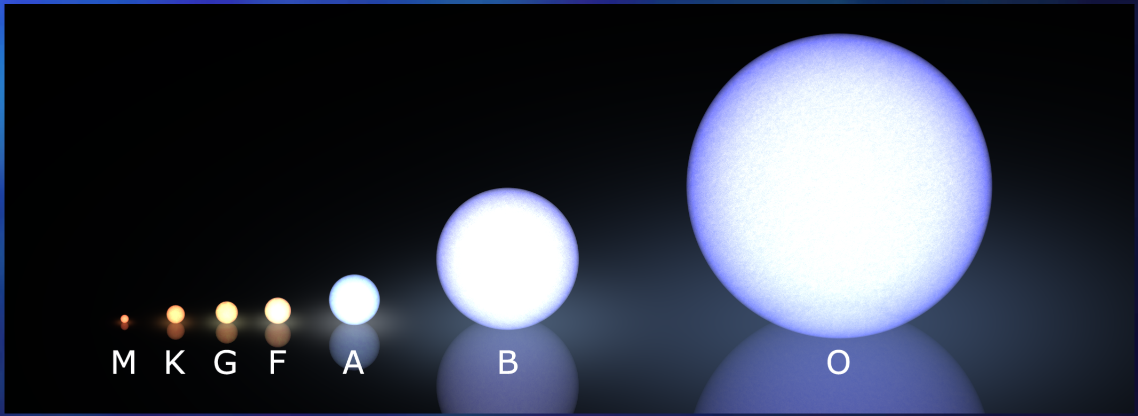
Stellar spectra: the relation with the stellar mass



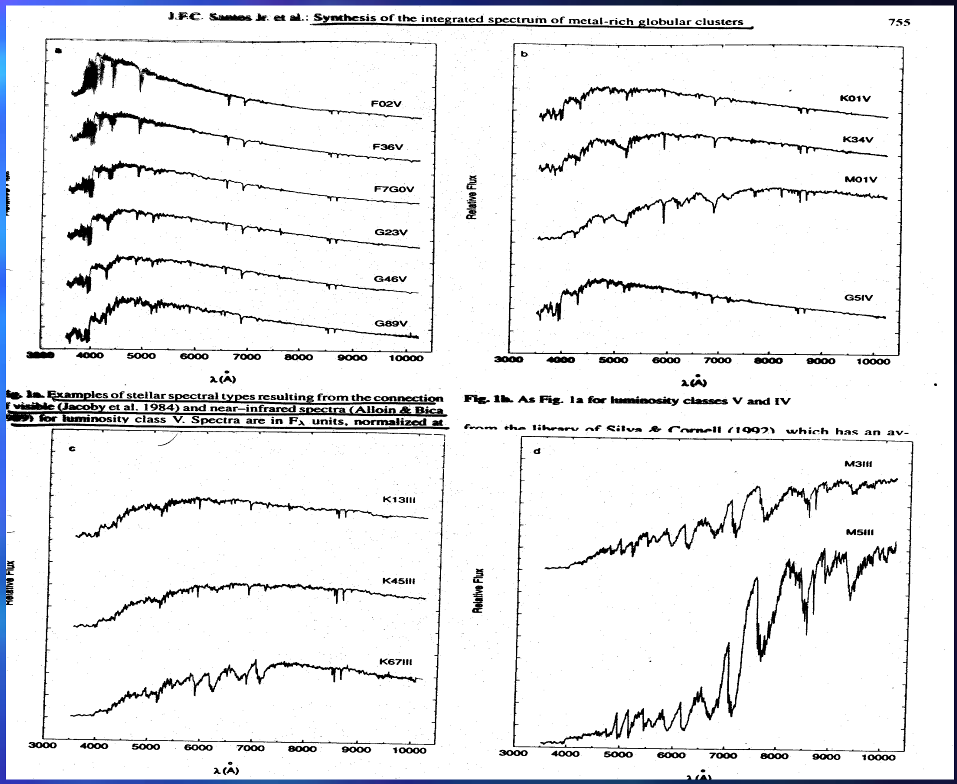


Effective Temperature

O	> 25.000°
B	11.000° - 25.000°
A	7.500° - 11.000°
F	6.000° - 7.500°
G	5.000° - 6.000°
K	3.500° - 5000°
M	<3.500°



STELLAR SPECTRA



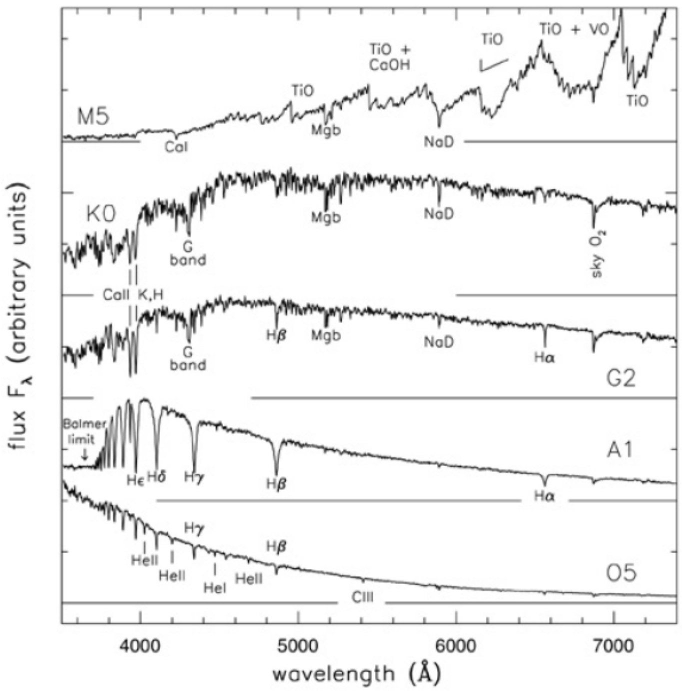


Fig 1.1 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Figura 2.1: Espectros ópticos de estrellas de la *secuencia principal* (MS) con abundancia aprox. solar. ($\lambda \lesssim 3800$ Å: Salto de Balmer.)

STELLAR POPULATION MODELS

There exist several methods to calculate a spectrum or magnitude:

- **ANALYTICAL APROXIMATIONS**

  By using theoretical expressions to calculate the luminosity in each phase of the HR diagram

- **POPULATION SYNTHESIS MODELS**

  Trying to find the best proportion of stars able to reproduce the data

  Algorithms of quadratical program. & errors

  The non-plausible solutions were eliminated

- **EVOLUTIONARY SYNTHESIS**

  The use of theoretical isochrones + IMF

HOW TO DO A SYNTHESIS MODEL

- Synthesis for a globular cluster
  - Using the Jacoby 1994 library
  - A CMD V vs V-I divided in 5 boxes
  - A spectral type is associated to each box depending on the color
  - By taking into account the number of stars in each box and their luminosities they estimated the contribution of each star j, Cj
  - They added the spectra and obtain the final one

$$F_\lambda = \sum_{j=1}^{N} C_j f_{\lambda,j}$$

The final spectrum is similar to the observed one

By using the Salpeter IMF their results are that:
un 15% de la luz procede de estrellas en la MS
- A 60% of stars in the RG branch
- A 15% of light comes from MS stars
- A 20% of stars in the Horizontal Branch

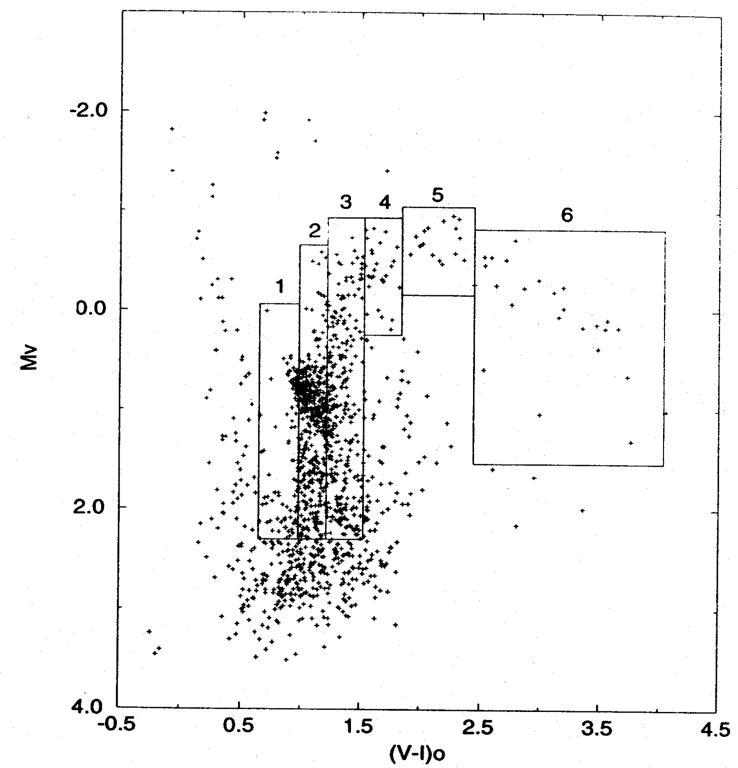
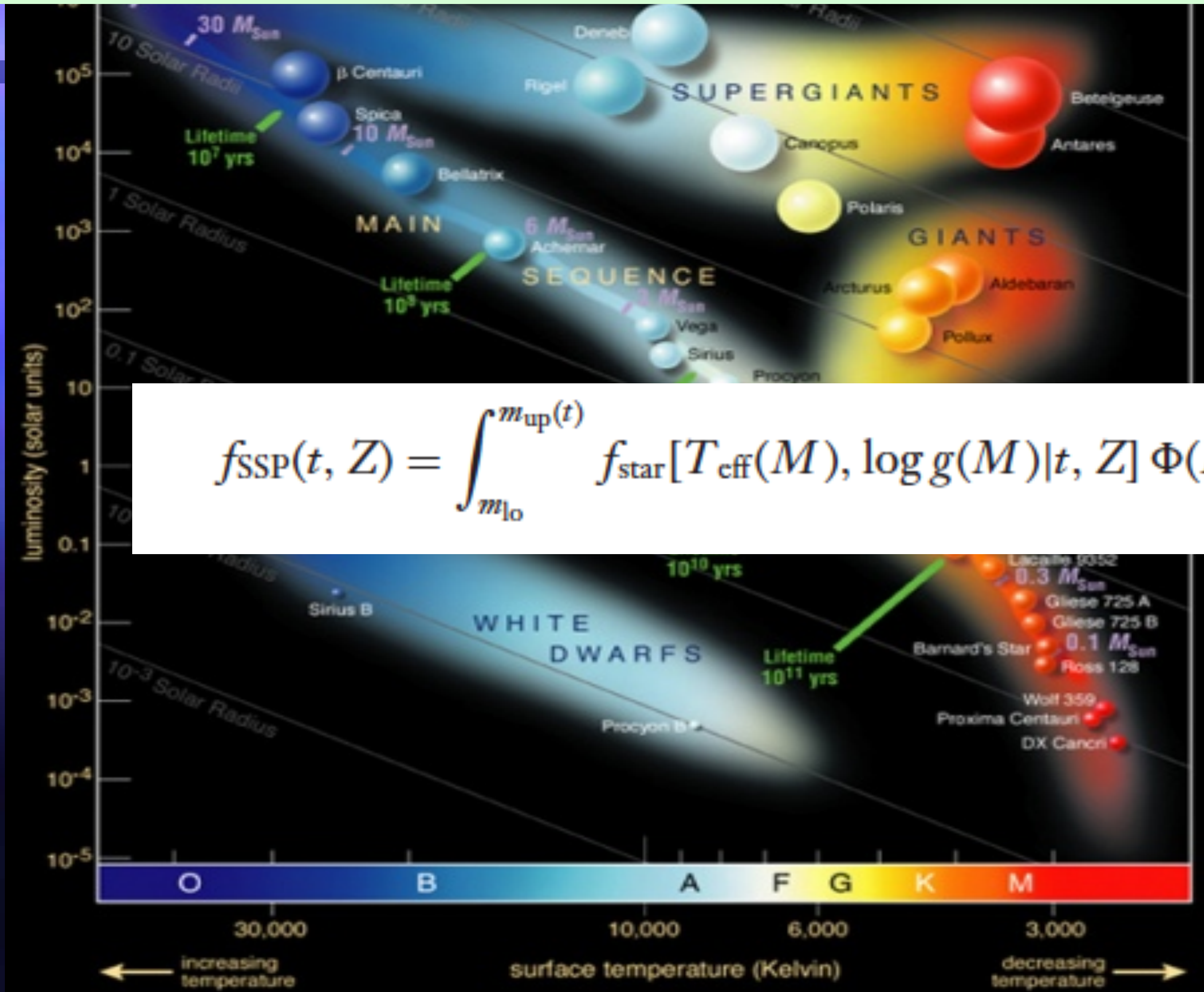


Fig. 2. Distribution of stars in the $V \times (V-I)$ colour–magnitude diagram of NGC 6553. The boxes indicate stars which are associated to spectral types in the stellar library

Table 2. CMD synthesis

Group	n	$< M_v >$	C
G8K0III	144	1.17	6.09
K13III	417	1.00	22.19
K45III	259	0.72	18.83
K67III	22	-0.39	4.87
M3III	17	-0.69	5.33
M5III	24	-0.04	4.65

The proportions of the different stars come determined by the evolution of the isochrones and the IMF



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

- In each position a spectrum is assigned depending on Teff and g
- ...sition ...r of ... calculated from an IMF
- The spectrum is calculated adding all stellar spectra

MODEL INPUTS

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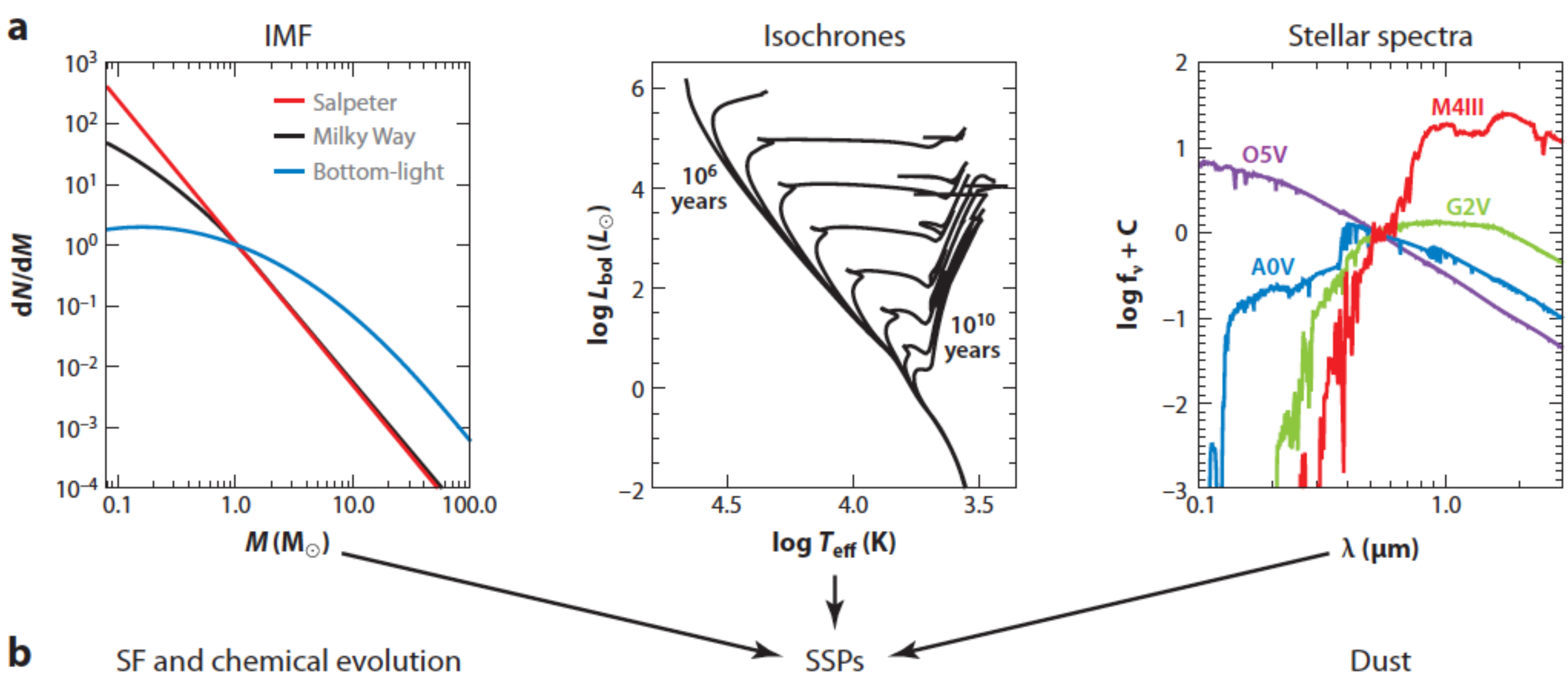
- **EVOLUTIONARY TRACKS**
  - Geneve group:(Maeder; Schaller et
  - Chabrier et al.(2003)
  - Van Dokkumm (2008) bottom-light
  - Bottom-heavy x=-3
- **ATMOSPHERE MODELS**
  - Lejeune 1997 compilation from Kurucz
  - STELIB (Le Borgne et al 2003)
  - INDO-US (Valdes et al. 2004)
  - NGSL (Gregg et al. 2006)
  - MILES (Sánchez-Blàzquez et al 2006, Cenarro 2007)
  - X-Shooter (Chen et al. 2011)



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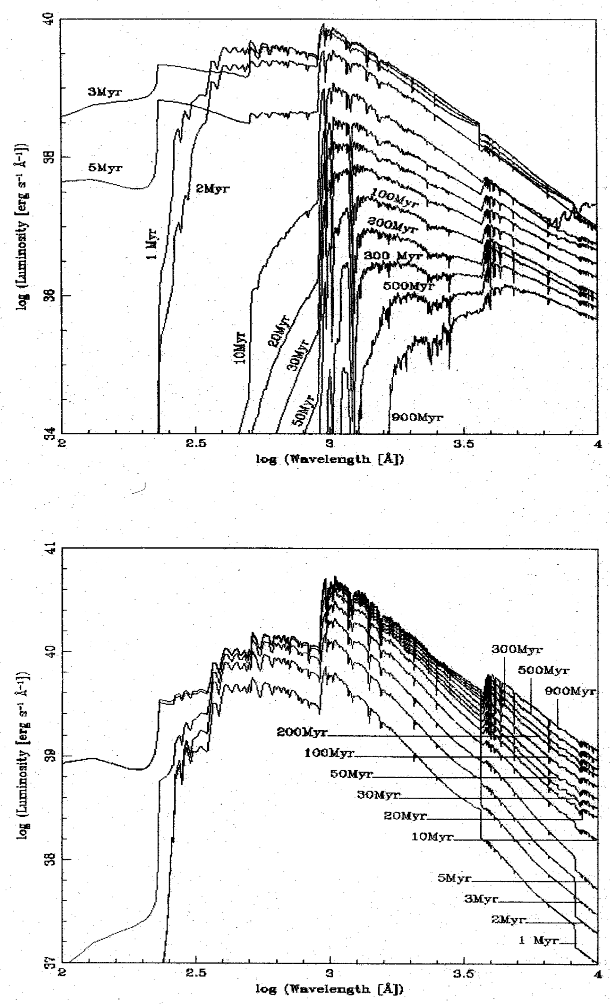
MODEL INPUTS

- **EVOLUTIONARY TRACKS**
  - Geneve group;(Maeder: Schaller et al.1992; Charbonnel etal 1996)
  - Padova group; (Chiosi: Alongi etal. 1983; Bressan et al. 1993; Fagotto et al. 1994a,1994b,1994c; Girardi et al 1996).
  - Victoria-Regina models (Vandenberg & Bell 1985, VandenBerg, et al 2006).
  - BaSTI models (Pietrinferni et al. 2004, Cordier et al. 2007)
- **IMF**
  - Salpeter (1955)
  - Miller & Scalo (1979)
  - Kroupa (2001)
  - Chabrier et al.(2003)
  - Van Dokkumm (2008) bottom-light
  - Bottom-heavy x=-3
- **ATMOSPHERE MODELS**
  - Lejeune 1997 compilation from Kurucz 1995; and others
  - Smith et al. (2002), Lanz & Hubeny 2003
  - Rauch 2003
  - Coelho et al 2005
  - Martins et al. 2005
  - Munaru et al 2005
  - Rodriguez-Merino et al 2005
  - Coelho (2014)
- **STELLAR LIBRERIES**
  - Gunn & Stryker 1983, res 20 A λ < 5740 A, res 40 A λ > 5740 A
  - Alloin & Bica, 1989 7299 A < λ < 10230 A
  - Jacoby 1994, Res 5 A 3510 < λ < 7427
  - Jones 1997, 1.8A, around 4000 -- 5000 A
  - Pickles 1998
  - ELODIE (Prugniel & Soubiran 2001)
  - STELIB (Le Borgne et al 2003)
  - INDO-US (Valdes et al. 2004)
  - NGSL (Gregg et al. 2006)
  - MILES (Sánchez-Blàzquez et al 2006, Cenarro 2007)
  - X-Shooter (Chen et al. 2011)



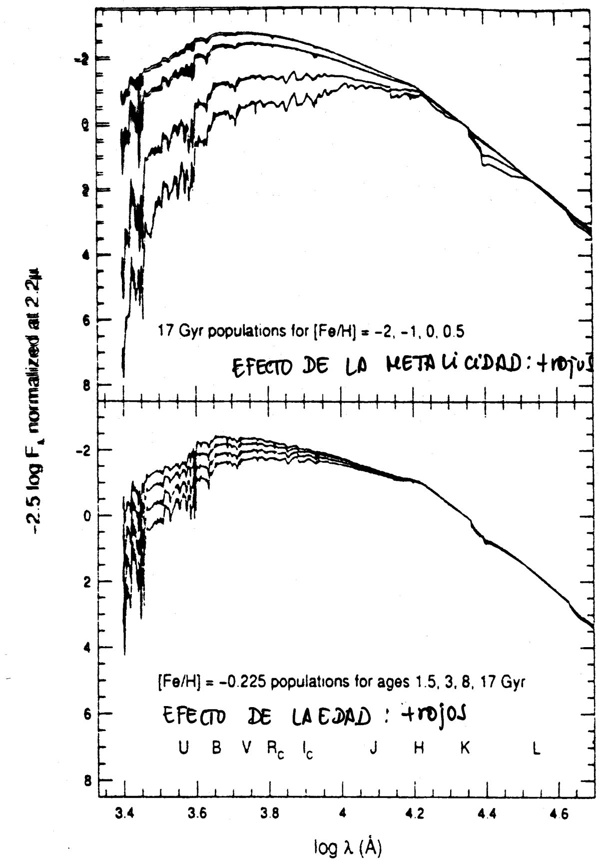


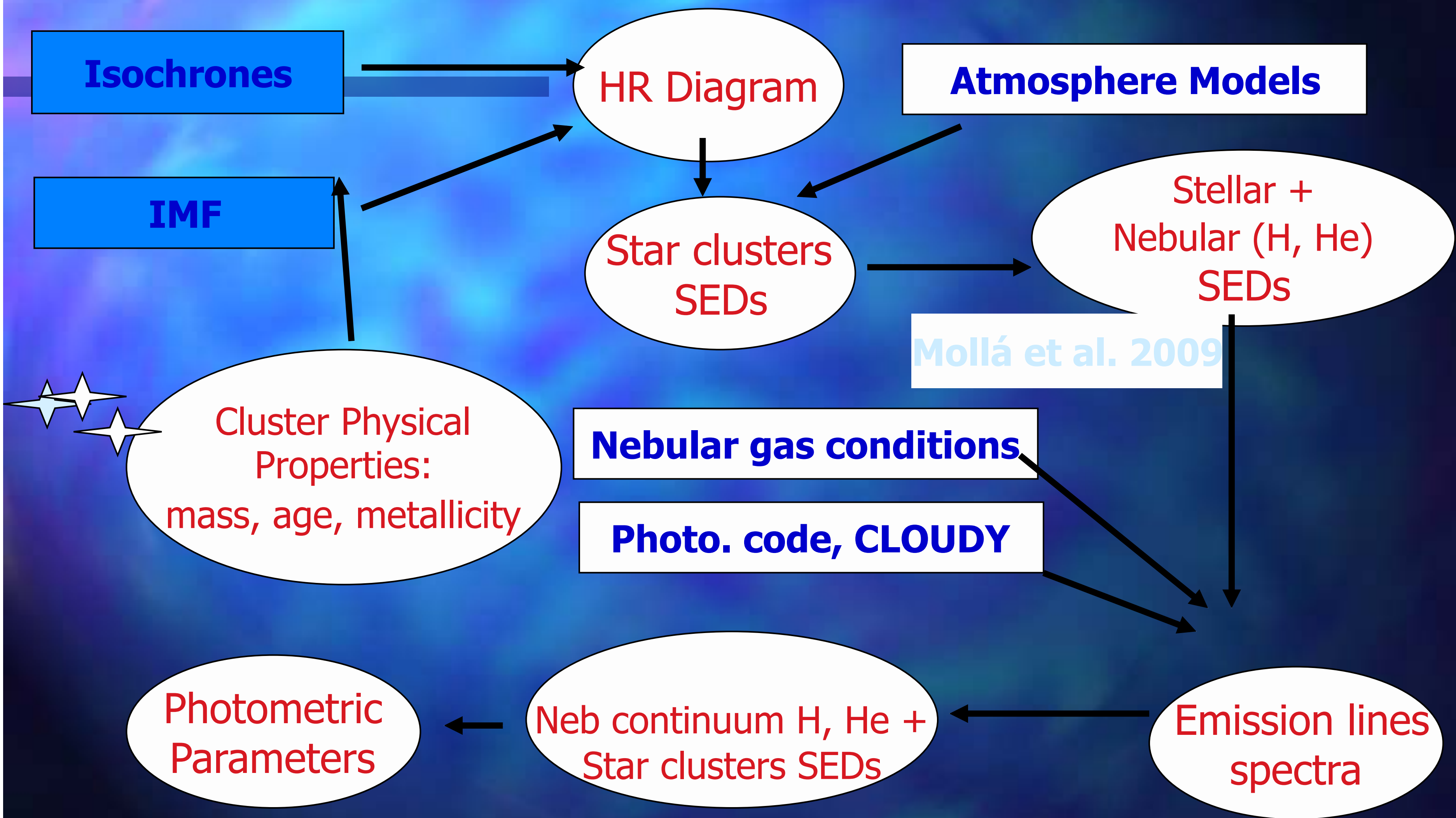
FIG. 38.—(*a*) Spectral energy distributions (SEDs) for 17 Gyr popula-
:ions of [Fe/H] = −2, −1, 0, and 0.5 dex. Note that the presence of M stars
eaves a strong signature in the optical red. (*b*) SEDs for [Fe/H] = −0.225
oopulations of ages 1.5, 3, 8, and 17 Gyr. The vertical scale is in magni-
udes of F_λ, normalized to zero at 2.2 μm. Approximate locations of broad-
oand filters are marked in (*b*).

EVOLUTIONARY SYNTHESIS MODELS

- Buzzoni et al. 1992, 1994: IMF Salpeter, empirical spectra
- Worthey 1994: IMF Salpeter, isochrones from Vandenberg, atmosphere models from Kuruzc 92, fitting functions from Worthey etal 1994
- Bressan et al. 1996: IMF Salpeter, isochrones from Padova, stellar spectra from Kuruzc 1992, fitting functions from Worthey et al 1994, infall
- Vazdekis et al. 1996: IMF bimodal, isochrones from Padova, spectra from Kuruzc, fitting functions from Worthey et al 1994
- Idiart et al. 1996: IMF Salpeter, isocrhones from Padova & Vandenberg, empírical librery for stars, fitting functions
- PEGASE (Fioc & Rocca Volmerange 1997)
- STARBURST99, Leitherer et al 1999, isochrones from Geneve, Lejeune 1997
- Vazdekis et al 1999: IMF bimodal, isochrones from Padova empirical spectra with HR to measure spectral indices
- GALAXEV: Bruzual & Charlot 2003, C&B 2007
- Maraston 2005
- Gonzalez-Delgado et al. 2005, Cerviño 2002
- GALEV: Kotulla et al 2008
- FSPS Conroy etal 2009
- MILES: Vazdekis et al. 2010, MILES library
- STARBURST99 Leitherer et al. 2014

Conroy 2013, ARAA

PopStar Model Description



García-Vargas et al. 2013

Martín-Manjón et al. 2010

POPSTAR

- Colors in Johnson and SDSS systems, Hα and Hβ luminosities and equivalent widths, and ionizing region size, have been computed for a wide range of metallicities Z = 0.0001, 0.0004, 0.004,0.008,0.02 and 0.05, and ages, from 0.1 Myr to 20 Gyr in Mollá et al. (2009, Paper I).
- Emission lines are shown in Martín-Manjón et al. (2010, Paper II).
- Colors calculated with the contribution of emission lines to the broad-band filter magnitudes (García-Vargas, Mollá & Martín-Manjón, 2013 Paper III)

SINGLE STELLAR POPULATIONS

- Isochrones: Padova group set, Bressan, Granato & Silva (1998)
- Five different IMF have been used
- Broad age and metallicity coverage and detailed treatment of mass-loss at both, young (O, B, WR) and old ages (post-AGB until planetary nebula)
- **Z = 0.0004, 0.001, 0.004, 0.008, 0.02 and 0.05** (1/50 to 2.5 solar)
- **Ages, logt = 5.00 to 10.30**. High time-resolution (up to logt=0.01)
- WN and WC are identified in the isochrones to ease the spectra assignation.
- Atmosphere Models: Lejeune etal. (1997) , Teff<25000 K ; Smith et al. (2002) for OB and WR stars; Rauch (2003) for PN
- **Code:** We have used the synthesis code by García-Vargas, Mollá & Bressan (1998), updated by Mollá & García-Vargas (2000) and revised Mollá, García-Vargas etal. (2009) with new isochrones and atmosphere models

ATMOSPHERE MODELS

- For stars with Teff < 25.000 we use the models by Lejeune Th. Cuisinier F. & Buser R. (1997). Excellent coverage in Teff, Z and logg.
- For O, B and WR we use non-LTE line blanketed models by Smith, Norris & Crowther (2002) at Z=0.001, 0.004, 0.008, 0.02 and 0.04

  To assign an appropriate model to the WR, we do not use the effective temperature (since isochrones give the hydrodynamic one while atmospheres use the Teff at a Rosseland optical depth of 10). We use the relationships among opacity, mass loss and velocity wind.
- For post-AGB and PN we have included the NLTE models by Rauch (2003) up to 220.000 K and black bodies for higher temperatures. These models include all elements from H to Ni. Teff ranges between 50.000K and 190.000K and logg between 5.00 and 8.00

A new model spectral stellar library 1029

R by at.models

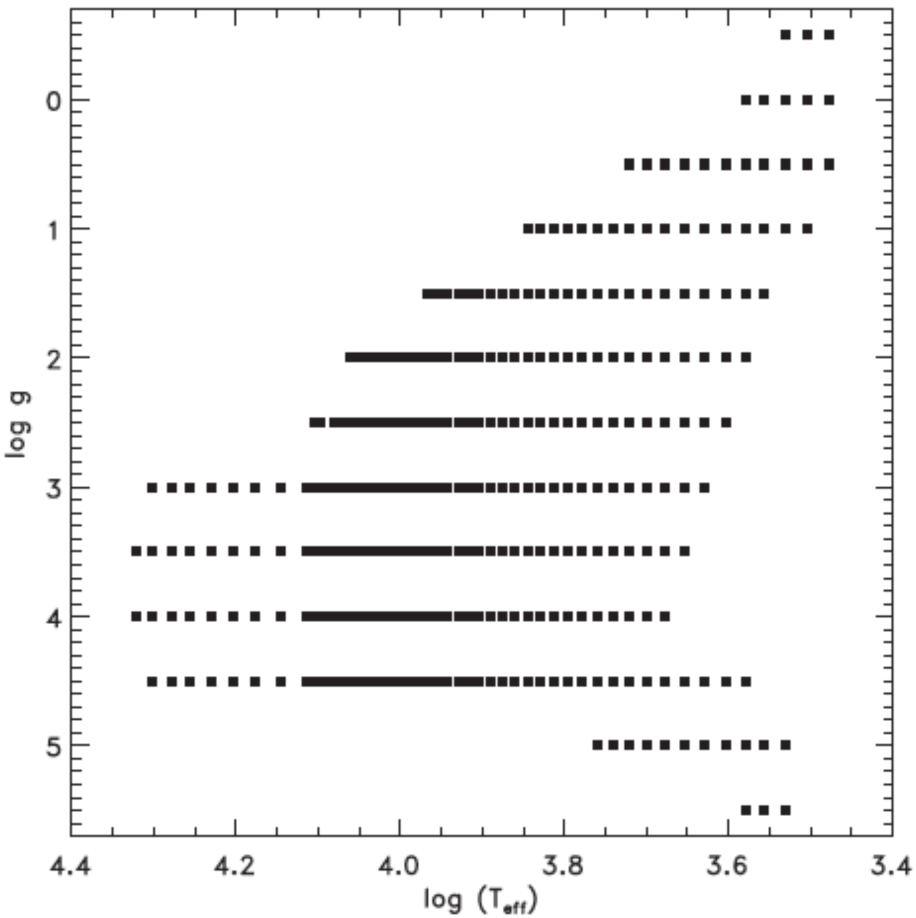


Figure 1. The coverage of the stellar library in the plane $T_{\rm eff}$ (x-axis) versus $\log g$ (y-axis), for the solar mixture (p00p00 in Table 1).

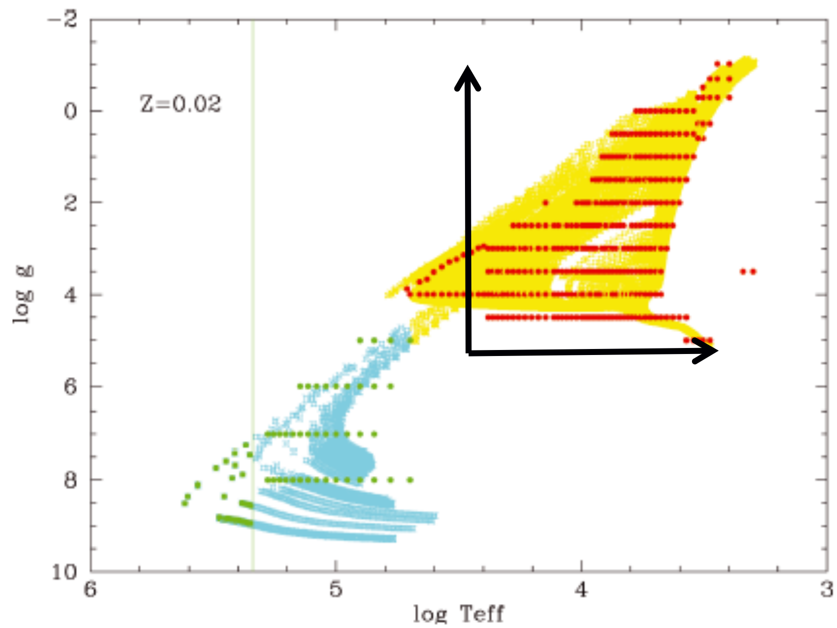
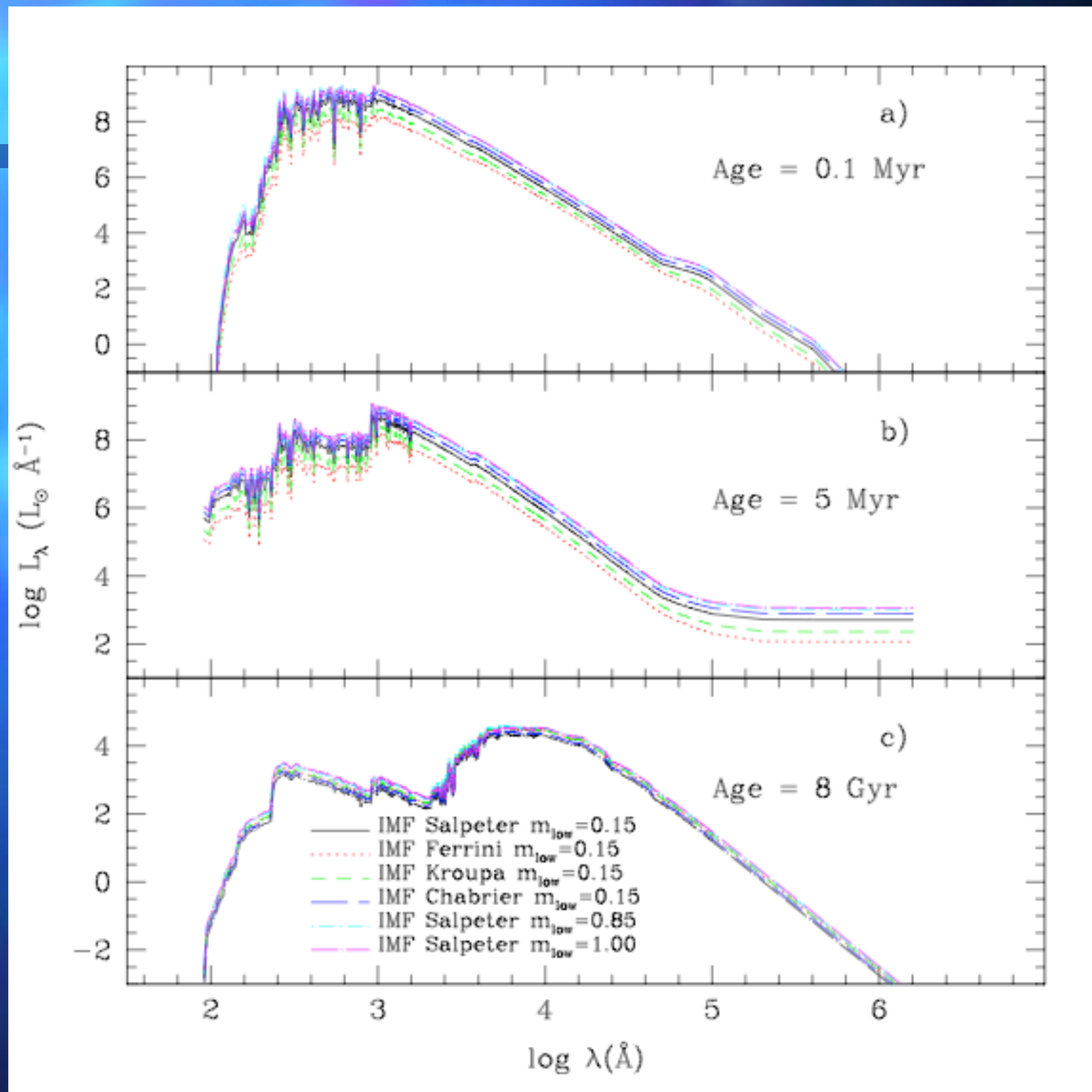


Figure 5. Model assignation for $Z = 0.02$: yellow and cyan asterisks correspond to NS, and those which end their life as PN, respectively, according to Padova isochrones. The available atmosphere models for these stars are shown overplotted as red and green solid dots. Note that the coverage is

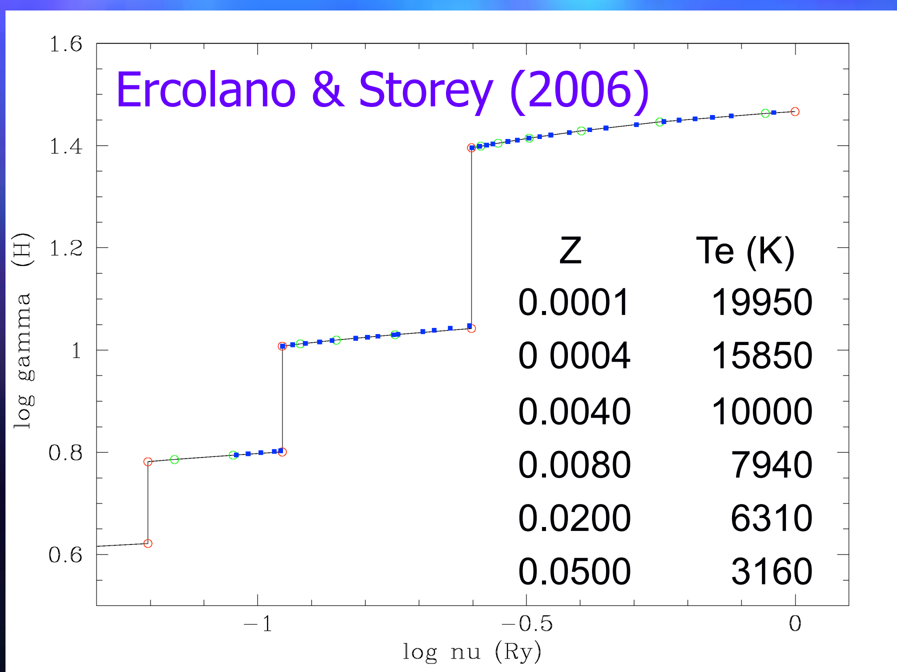
Stellar SEDs for different ages and different IMFs

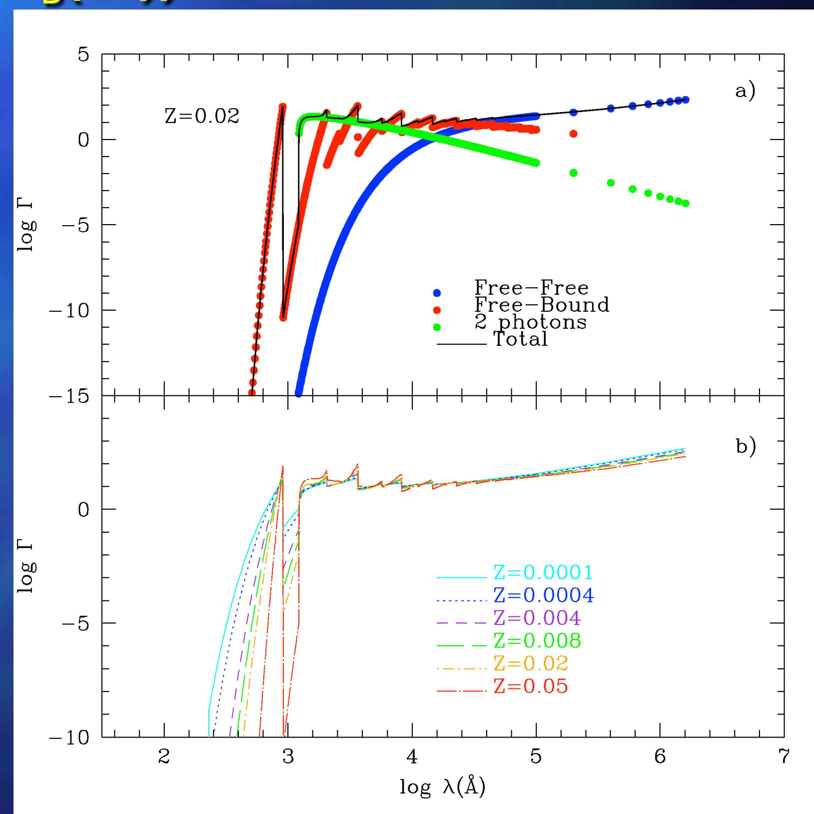


NEBULAR CONTINUUM CONTRIBUTION

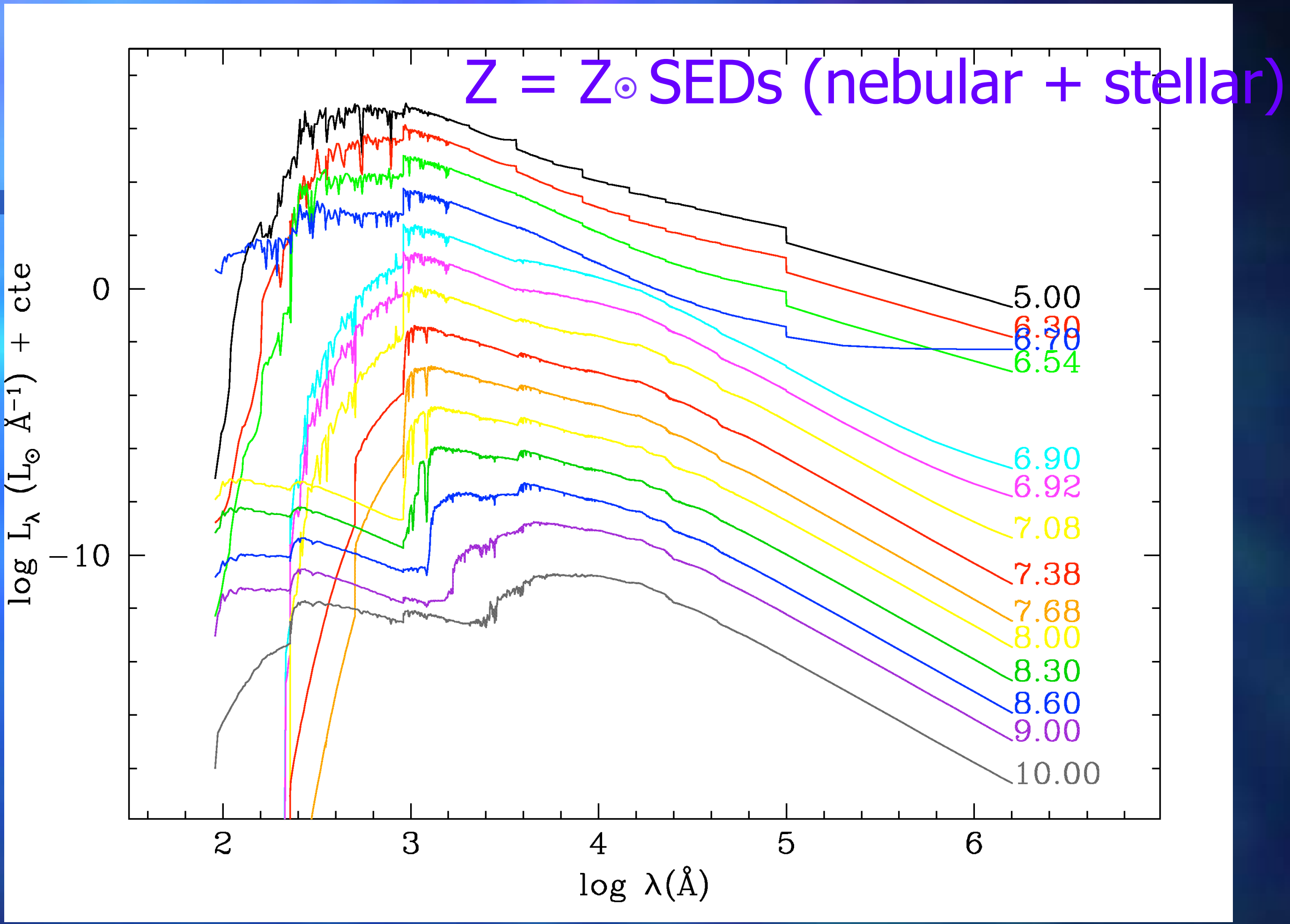
- We included the hydrogen and helium (both He and He+) free-free and free-bound emission processes as well as the 2-photon continuum.
- We used the expression from Osterbrock (1989):

$$L\lambda\ (erg.s^{-1}Å^{-1}M_{\odot}^{-1}) = \Gamma \times Q(H) \times c\,/\,(\lambda^{2}\alpha_{B}(HI))$$





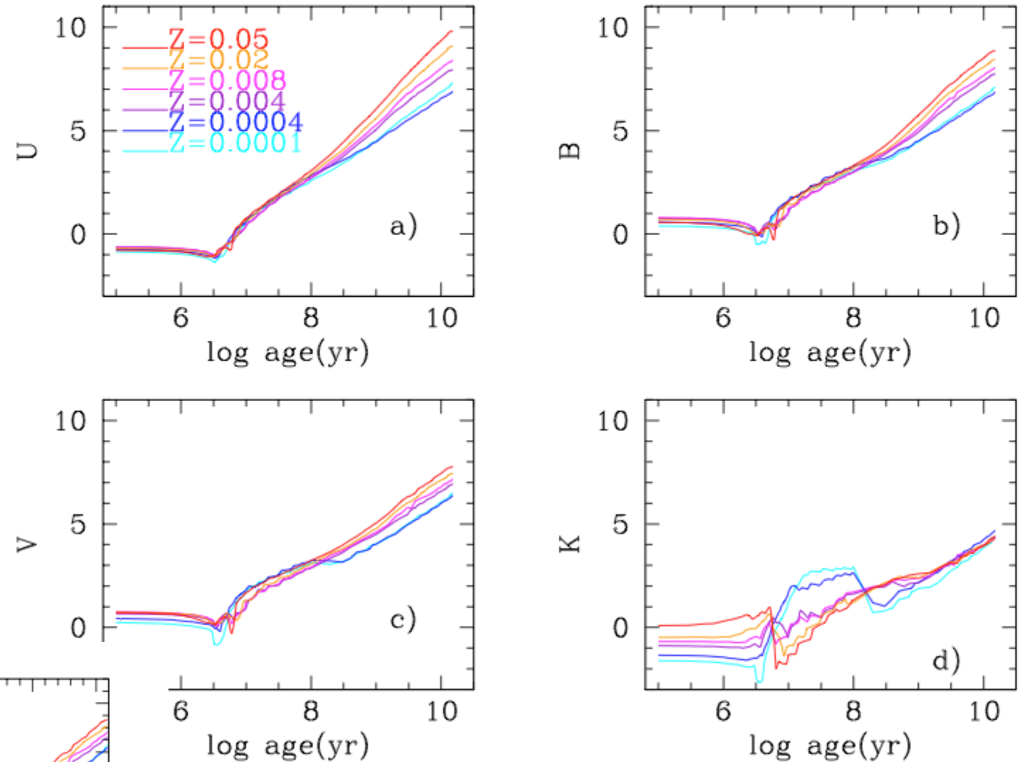
SPECTRAL ENERGY DISTRIBUTIONS

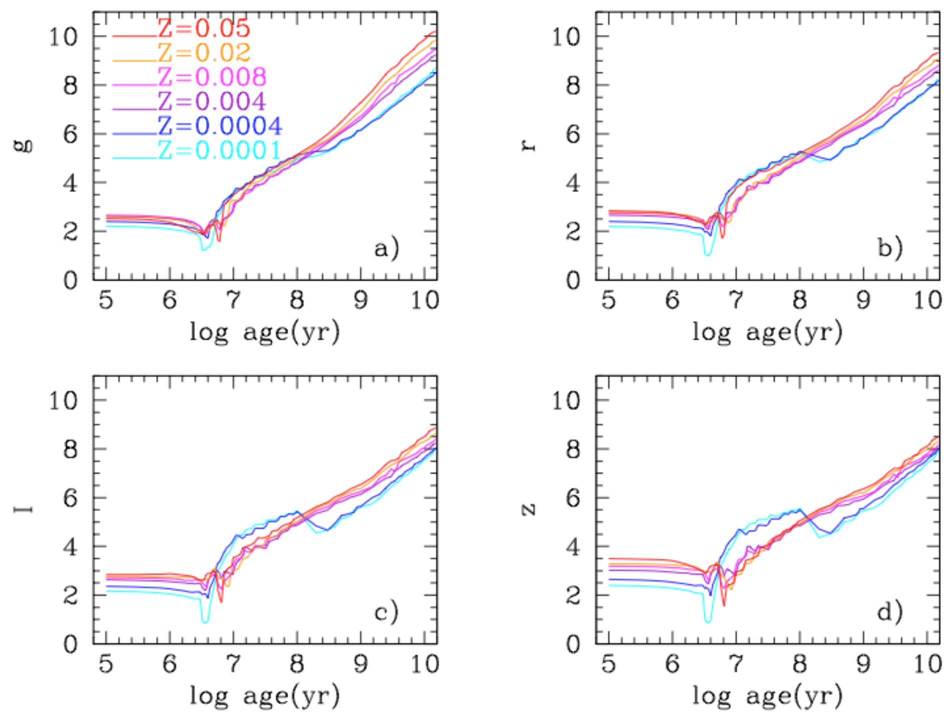


Spectral Energy Distributions for a Salpeter IMF and Z = Zo including both stellar and nebular contributions at the ages labeled in log. scale

Each age, starting at 0.1 Myr (log = 5:00), is shifted downward by one order of magnitude, for sake of clarity.

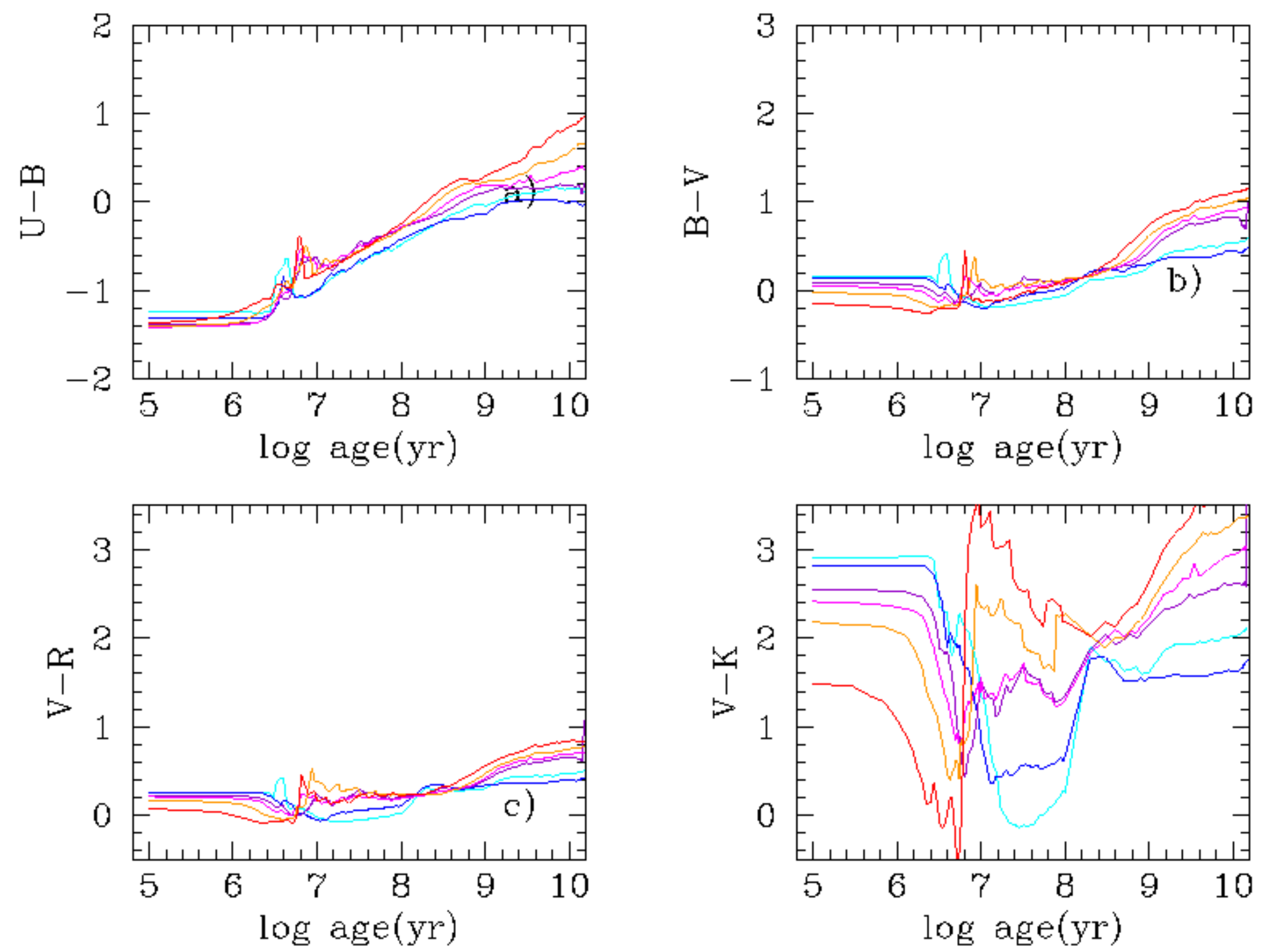
Stellar + Nebular magnitudes photometrical evolution





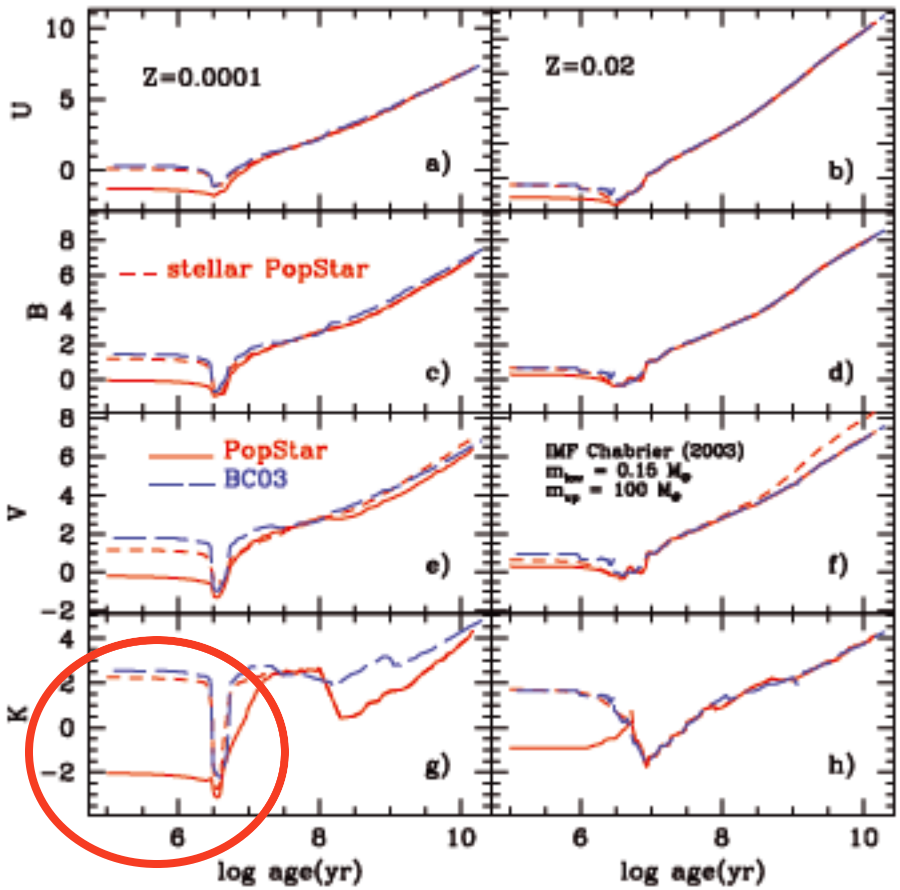
s and analysis

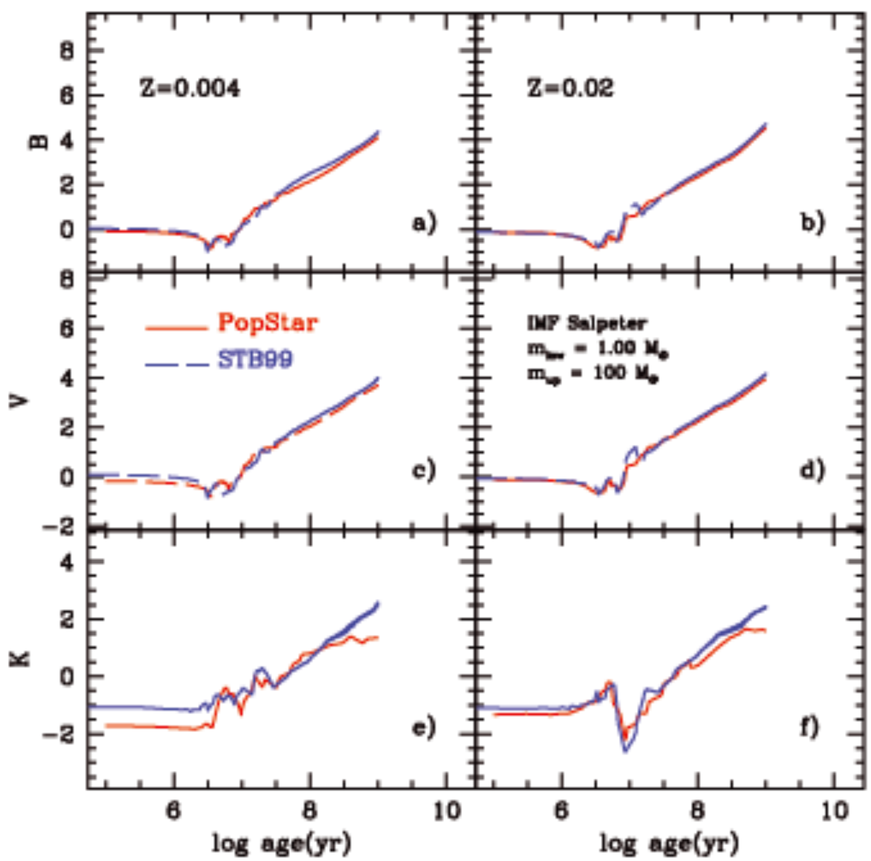
COLOR EVOLUTION



COMPARISON WITH MODELS FOCUSED ON OLD/YOUNG STELLAR POPULATIONS

- GALAXEV models (Bruzual & Charlot, 2003), Maraston (2005),STB99
- Nebular continuum: Not included in BC03, MAR05





PHOTOIONIZATION MODELS: CLOUDY

Clusters mass: M = 0.12, 0.20, 0.40, 0.60, 1.0, 1.5 and 2.0 x 10^5 M_{SUN}

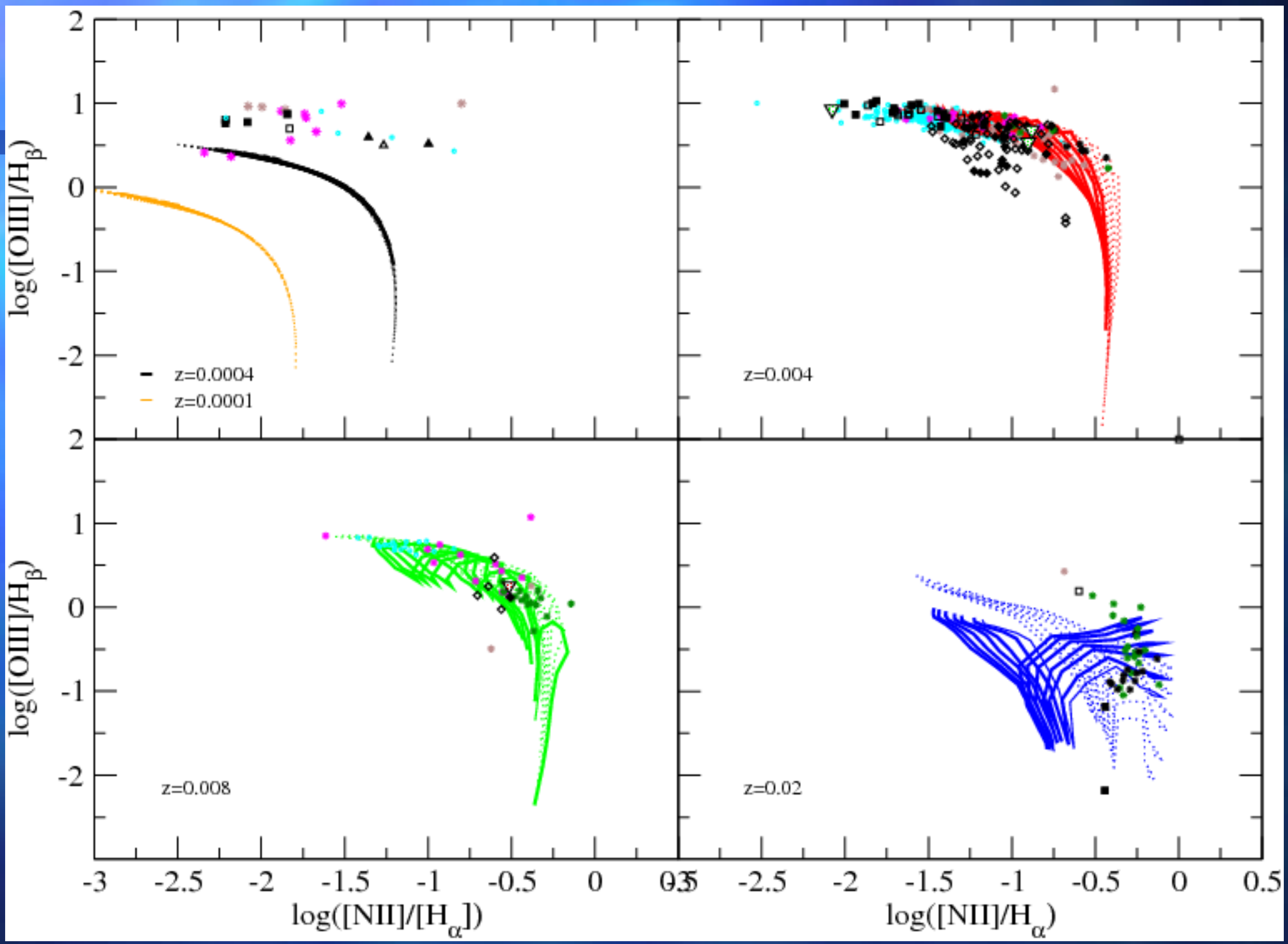
n=10 or 100 at.cm^{-3}

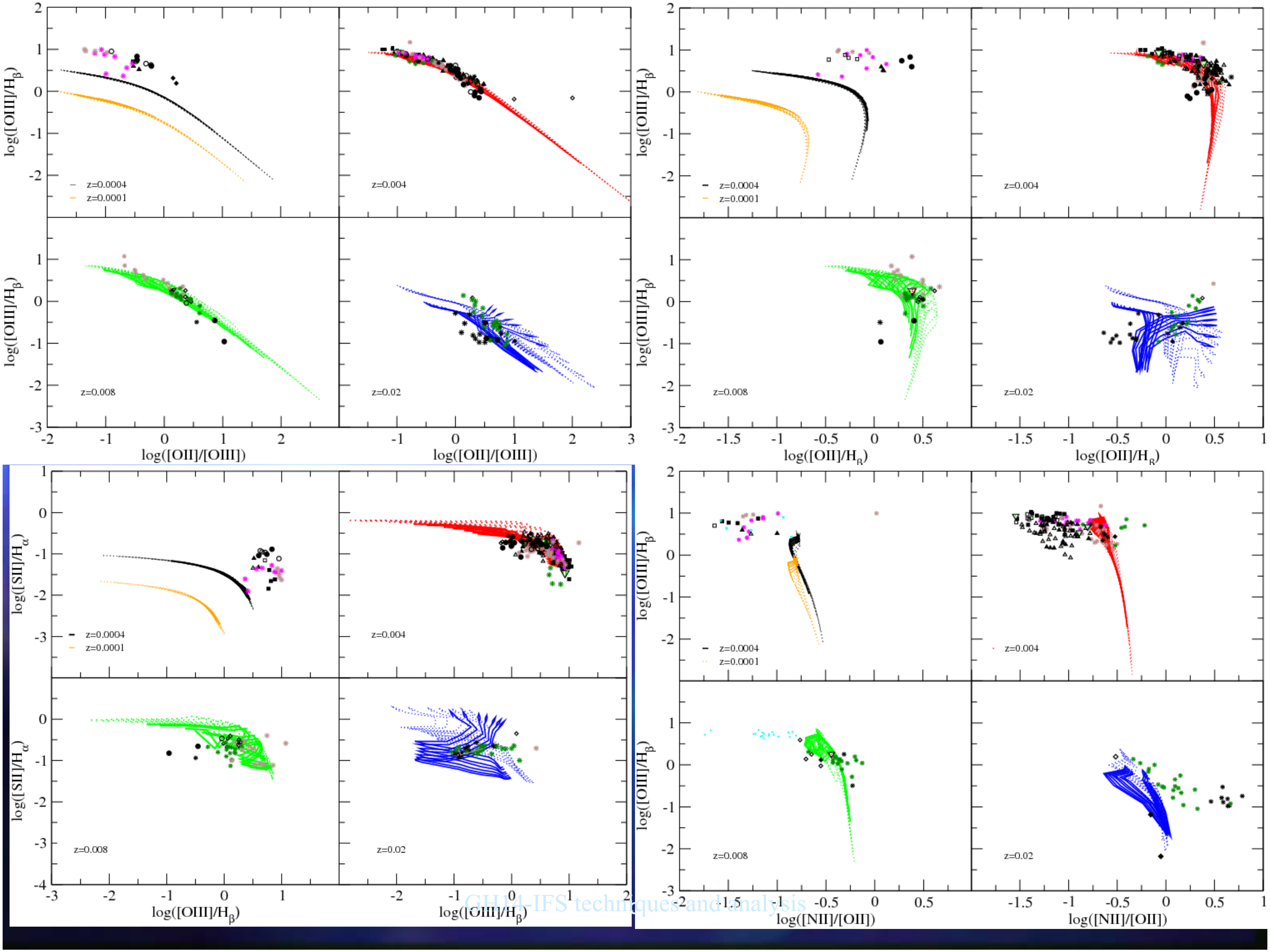
- A shell structure formed by the combined effects of the mechanical energy deposition from the winds coming from massive stars in the ionizing cluster and from SN explosions.
- This energy can blow out a large cavity or "bubble" in the surrounding. The radius of the outer shock, Rs, evolves as:

$$Rs=1.6 \times (\varepsilon/n)^{1/5}\, t^{3/5}\ \mathrm{pc}$$ (Castor etal. 1975)

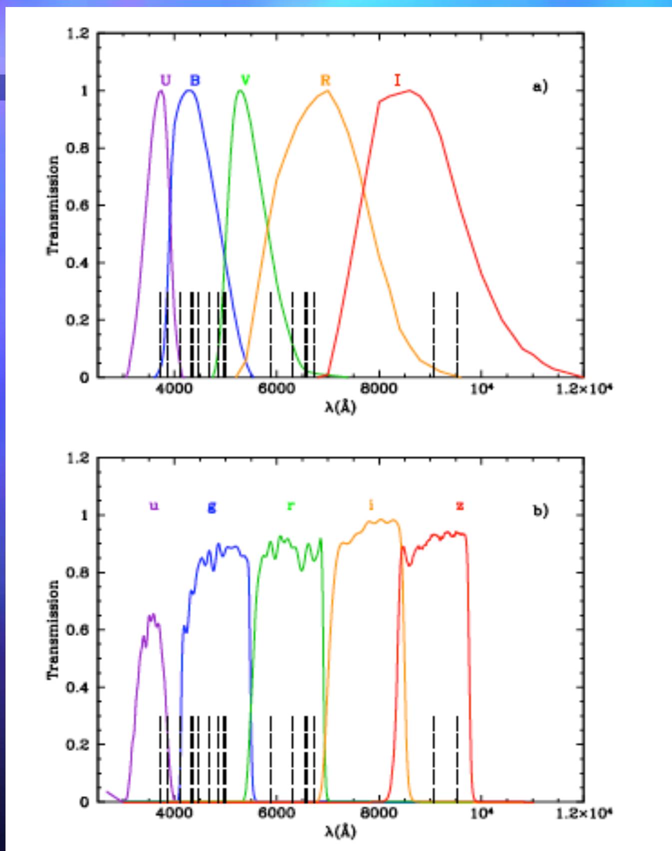
where ε is the total mechanical energy (SN + stellar winds) per unit time injected in units of 10^{36} ergs s^{-1}, n is the interstellar medium density in units of cm^{-3}, and t the age of the shell in units of 10^4.

- We eliminate the ionization parameter as a free variable in the models: It is computed from the physical parameters of the evolving young cluster, M, Z and age


log([OIII]/Hβ)
log([NII]/[Hα])
log([NII]/Hα)
z=0.0004
z=0.0001
z=0.004
z=0.008
z=0.02

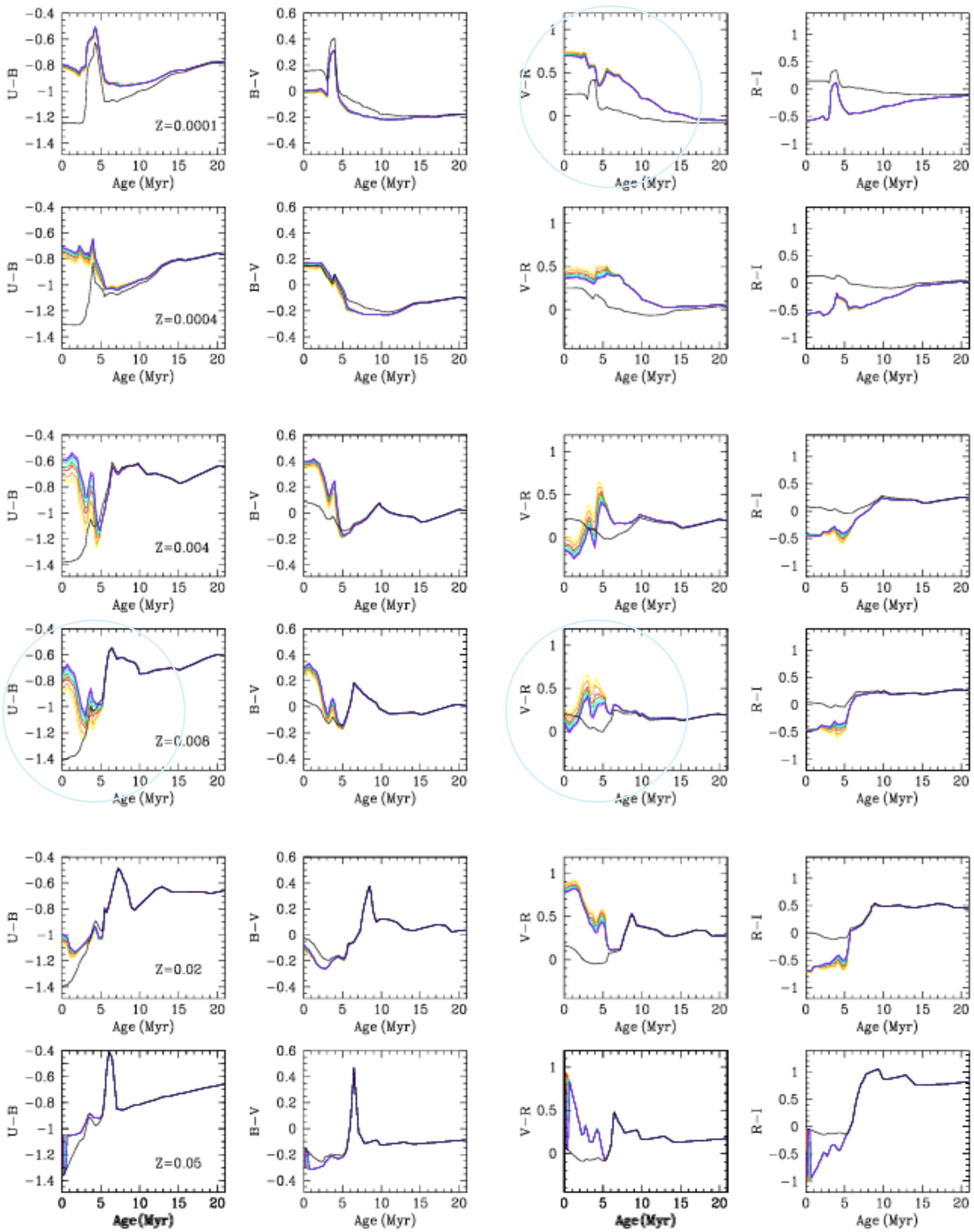


log([OIII]/Hβ)
log([OII]/[OIII])
log([OII]/Hβ)
log([SII]/Hα)
log([NII]/[OII])
z=0.0004
z=0.0001
z=0.004
z=0.008
z=0.02



- **Once the photoionization models with SSP-SEDs have been included as inputs of CLOUDY, we get the intensities of the optical emission lines.**
- **Some intense emission lines fall in the Johnson and SDSS broad band filters. The contribution depends on the filter transmission curve and the redshift, which places a given line in a different wavelength within the passband.**
- **We have calculated the contribution at z=0 in the U, B,V, R, I, and Z Johnson filters and the u, g, r, i and z SDSS filters.**
- **We include the contributions of the emission line to the magnitudes calculation:**

$$m = -2.5 log \int_{\lambda_1}^{\lambda_2} L_\lambda d\lambda + \sum_{i=1}^{20} T_i \times L_i + C$$



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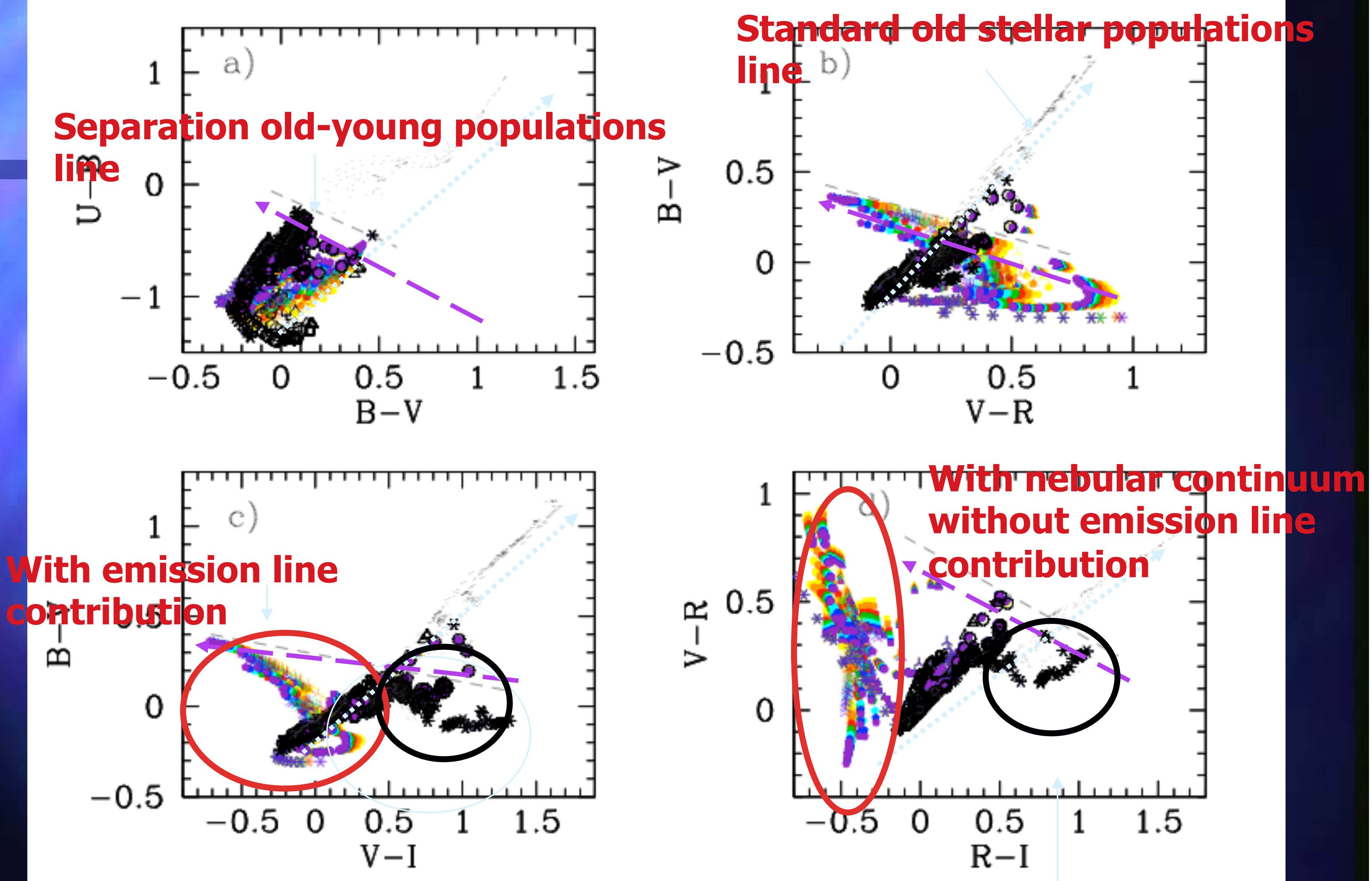
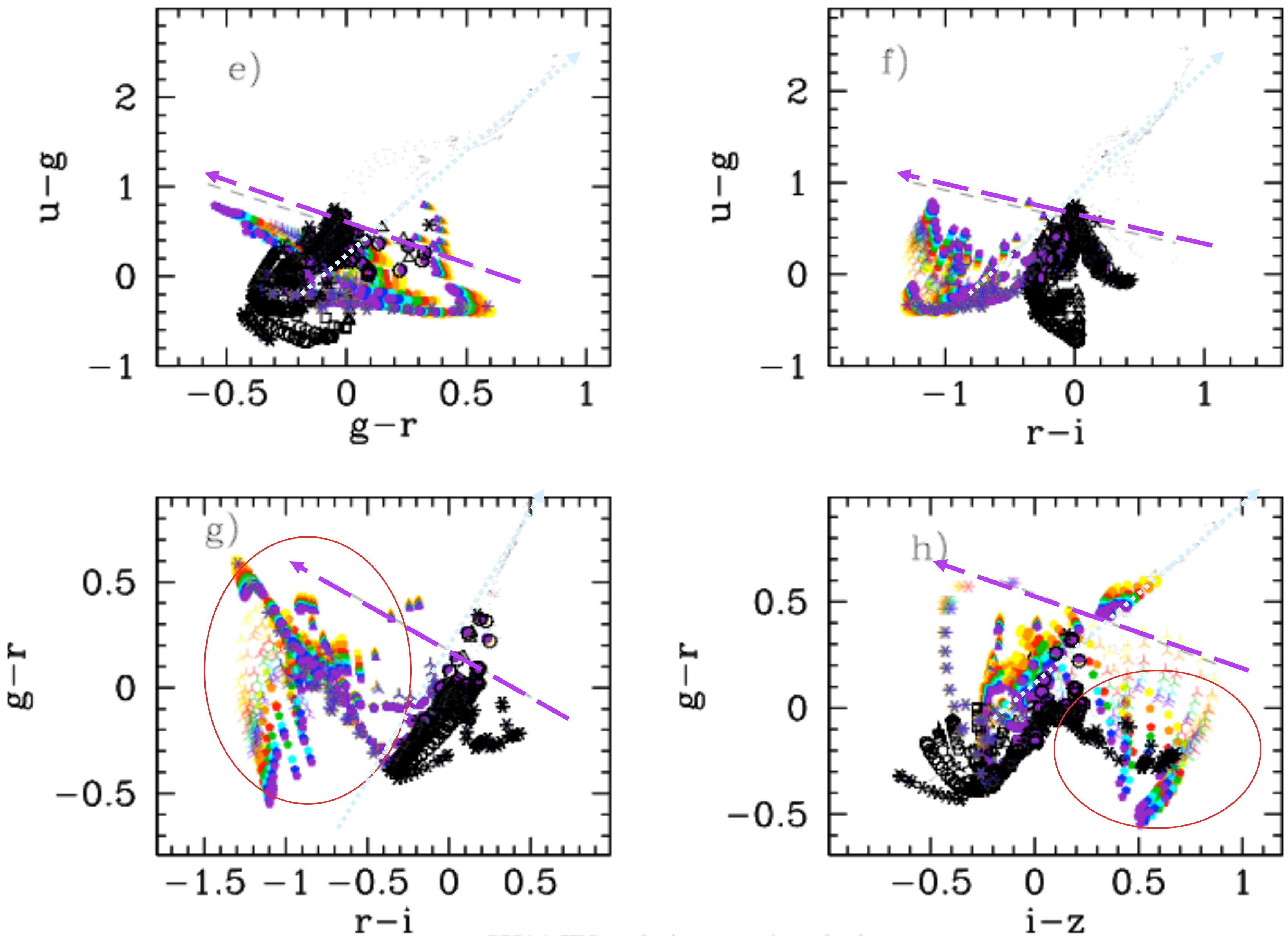
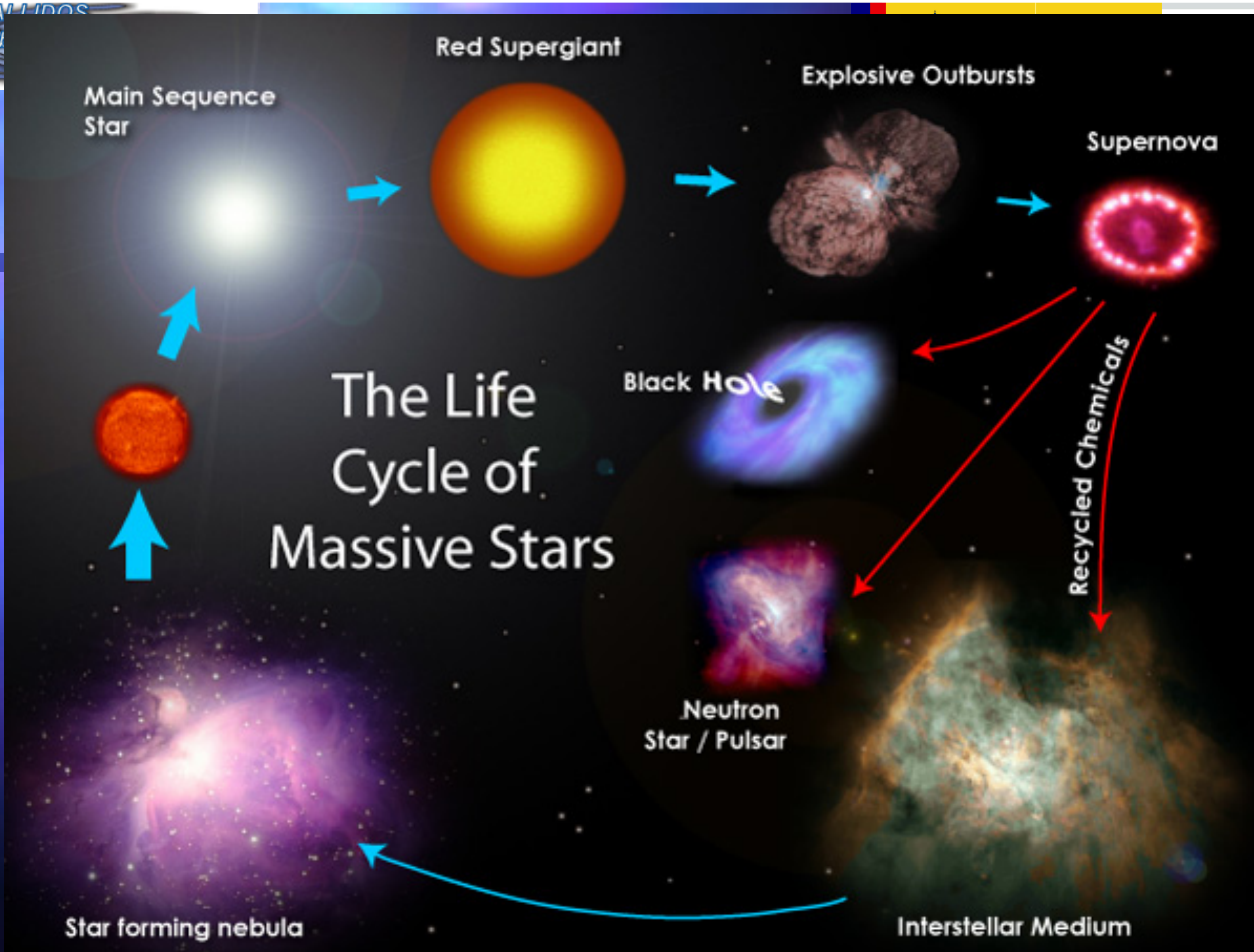
Different colors evolution without and with emission lines contribution


Standard old stellar populations line
Separation old-young populations line
With emission line contribution
With nebular continuum without emission line contribution
a)
b)
c)
d)
U−B
B−V
B−V
V−R
B−V
V−I
V−R
R−I


e)
u−g
g−r
f)
u−g
r−i
g)
g−r
r−i
h)
g−r
i−z


Red Supergiant
Main Sequence Star
Explosive Outbursts
Supernova
Black Hole
Recycled Chemicals
The Life Cycle of Massive Stars
Neutron Star / Pulsar
Star forming nebula
Interstellar Medium

ESTALLIDOS collaboration

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- EVOLUT
  - Geneve
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  - Padova
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    al. 199
    1996).
  - Victori
    & Bell
    2006).
  - BaSTI
    2004, C
- IMF
  - Salpet
  - Miller
  - Kroup
  - Chabri
  - Van D
  - Bottom

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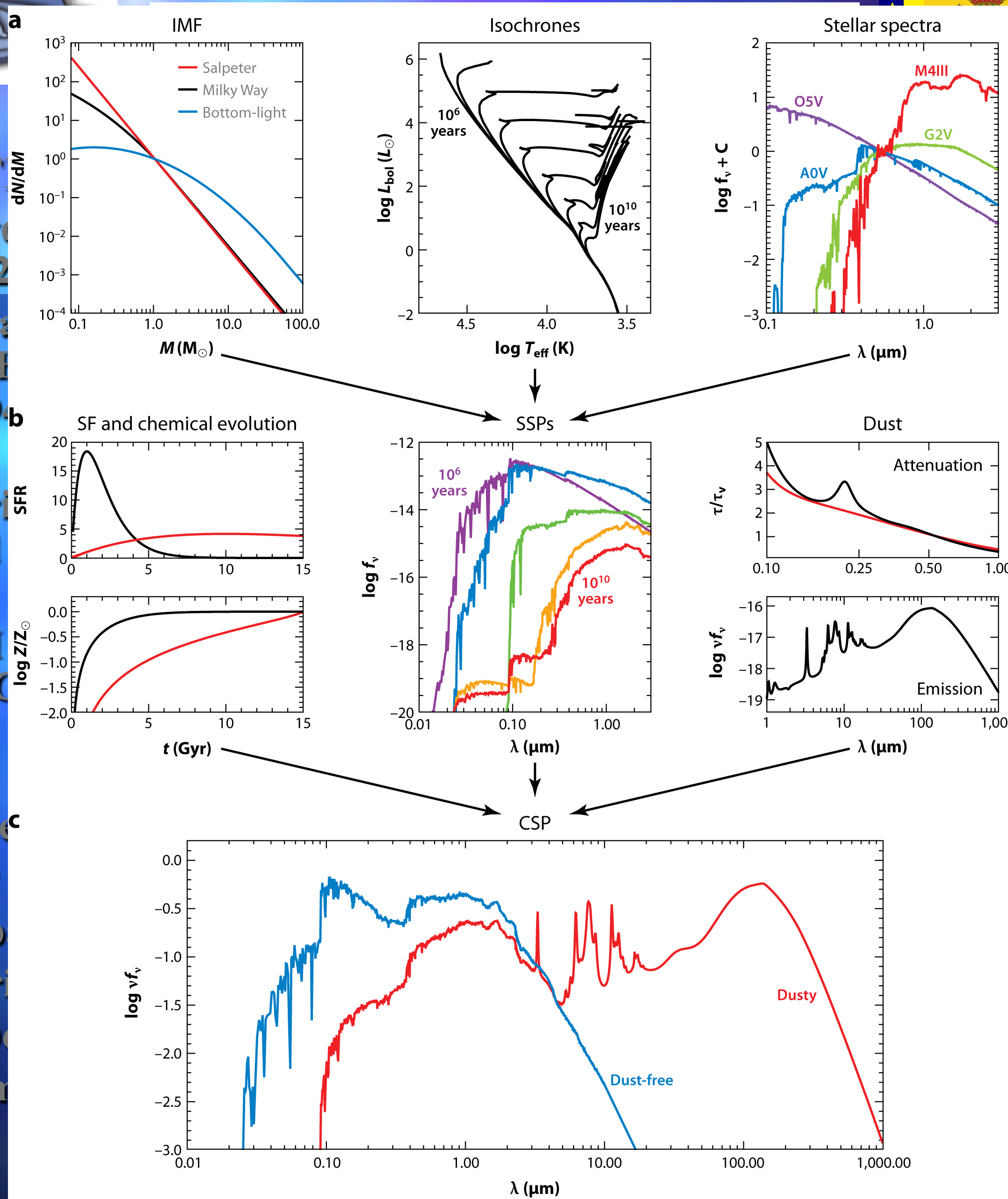

Conroy C. 2013.
Annu. Rev. Astron. Astrophys. 51:393–455

SUMMARY

1. The SSP models are only valid to interpret regions or galaxies where all stars form simultaneously, otherwise the results are only average values of the estimated quantities (age, metallicity, etc…)
2. Differences among SSPs codes are due to the selection of inputs (isochrones set, IMF, stellar libraries), and also to the method of calculation.
3. Main differences: a) the range of ages-stellar mass used, b) the phases of stars included in the isochrones (TP-AGB) ,c) the overshooting of the stars <7Msun…
4. The problems of the isochrone synthesis method was that isochrones are calculated in discrete steps in time and therefore phases where stellar evolution is more rapid than theses timesteps were not well represented
5. The binaries are not taken into account in most of these calculations
6. The rotation of stars is (only) included in the new version STB99 (Leitherer + 2014)
7. The empirical libraries usually do not cover the whole parameters space of HRs. Furthermore it is sometimes difficult to assign stellar parameters (log g, Teff, [M/H])
8. Atmosphere models produce stellar spectra that not always reproduce the observations
9. The nebular continuum must be included in calculations. Its contribution changes very much some broad band filter magnitudes for ages $\tau < 20$Myr
10. Emission lines also may change the colors, and this contribution may be higher at higher redshifts