Stellar population synthesis models

Lluís Galbany (RyC fellow, ICE-CSIC)

Galaxies and extragalactic astrophysics

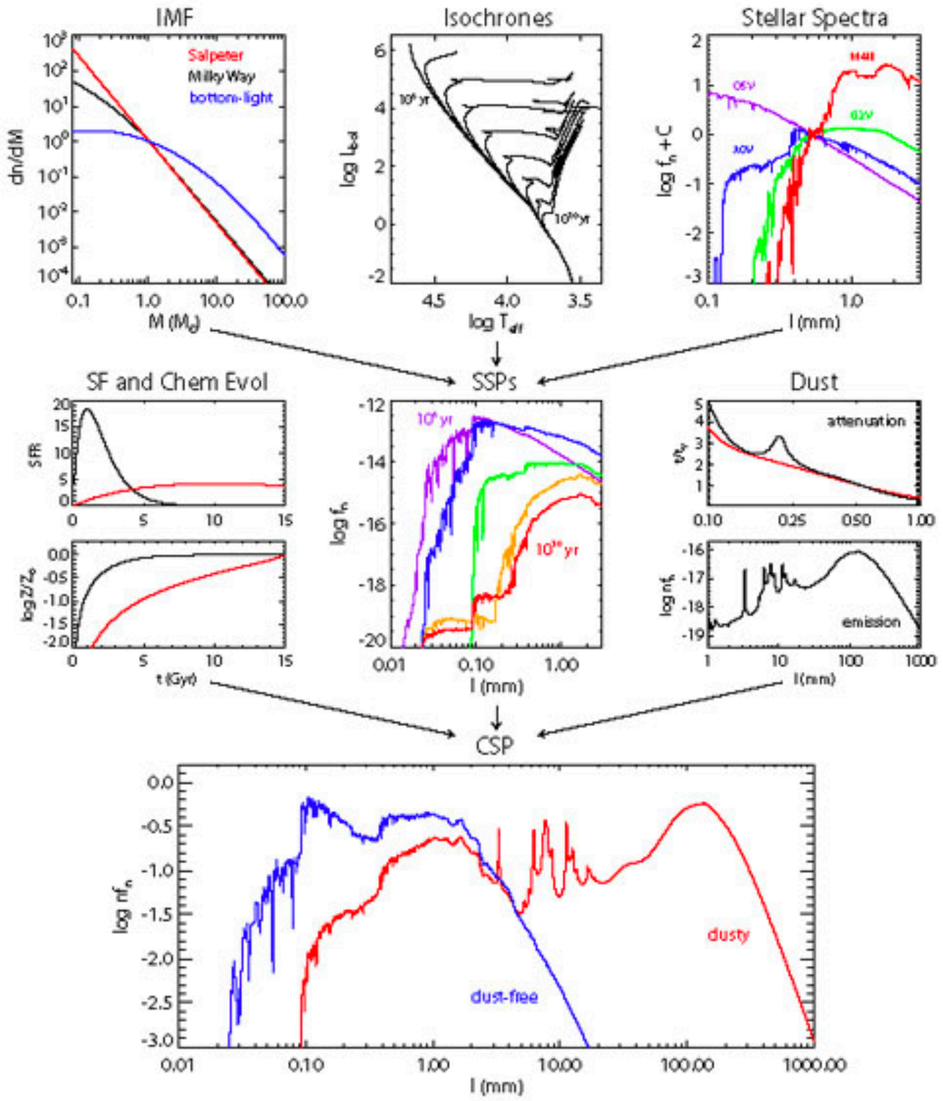
Introduction

- The light coming from a galaxy is the sum of all the contribution to the emission of its **stars** and **gas** content and therefore has the information of its stellar formation history (which and how many stars have been formed and when)

- The stellar Population Synthesis models predict the spectra of galaxies (stellar populations) changing the number of stars that are formed and the time at which they are formed

- Fundamental to interpret galaxy spectra

Ingredients



IMF, isochrones for a range of ages and metallicities, and stellar spectra spanning a range of $T_{\rm eff}$, $L_{\rm bol}$, and metallicity.

SFH and chemical evolution, SSPs, and a model for dust attenuation and emission.

final CSPs both before and after a dust model is applied.

Conroy 2013

Ingredients

- Star Formation Rate (SFR): gives the number of stars formed per unit time

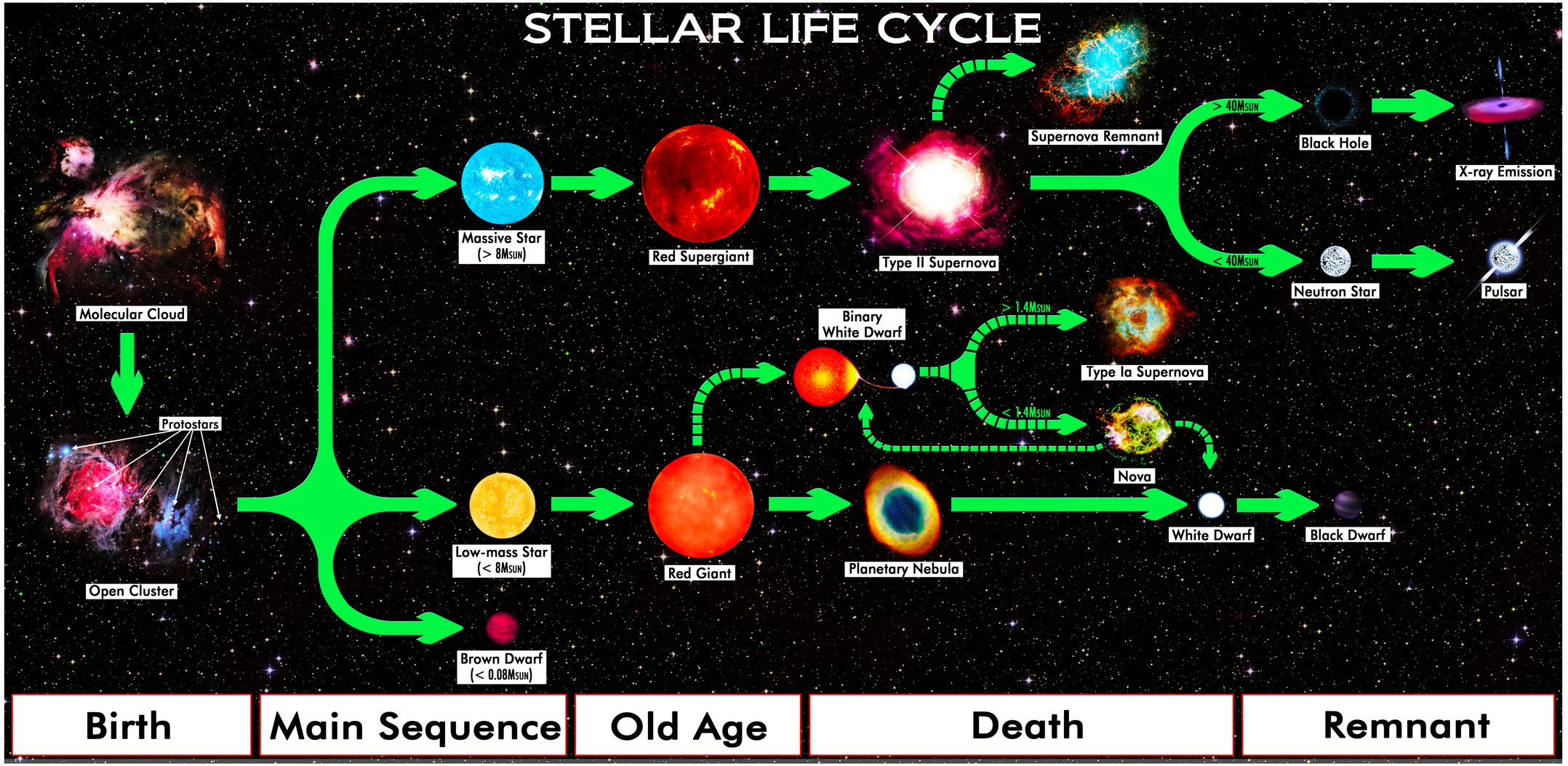
  exponential law

- Initial mass function (IMF): gives the number of stars formed as a function of the mass

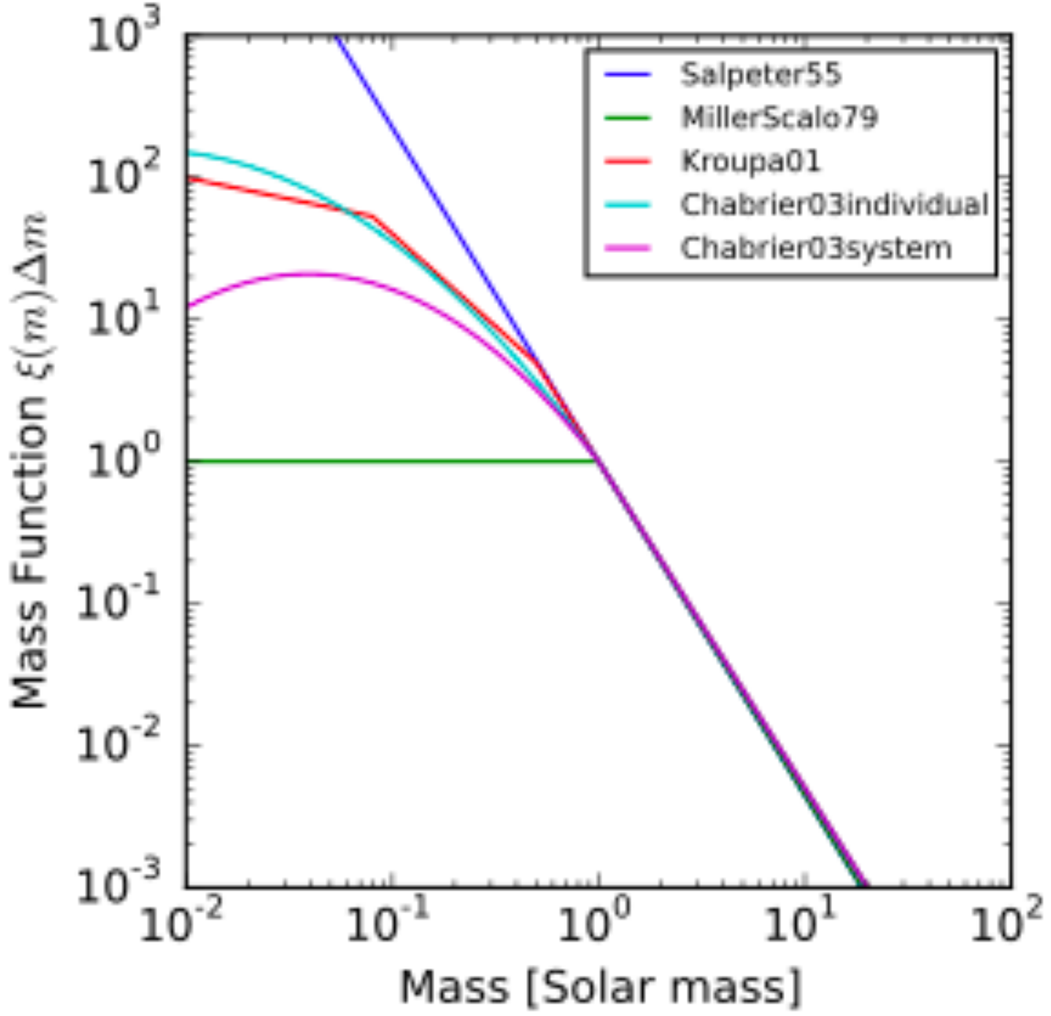
  Salpeter: $IMF(m) \alpha m^{-2.35}$

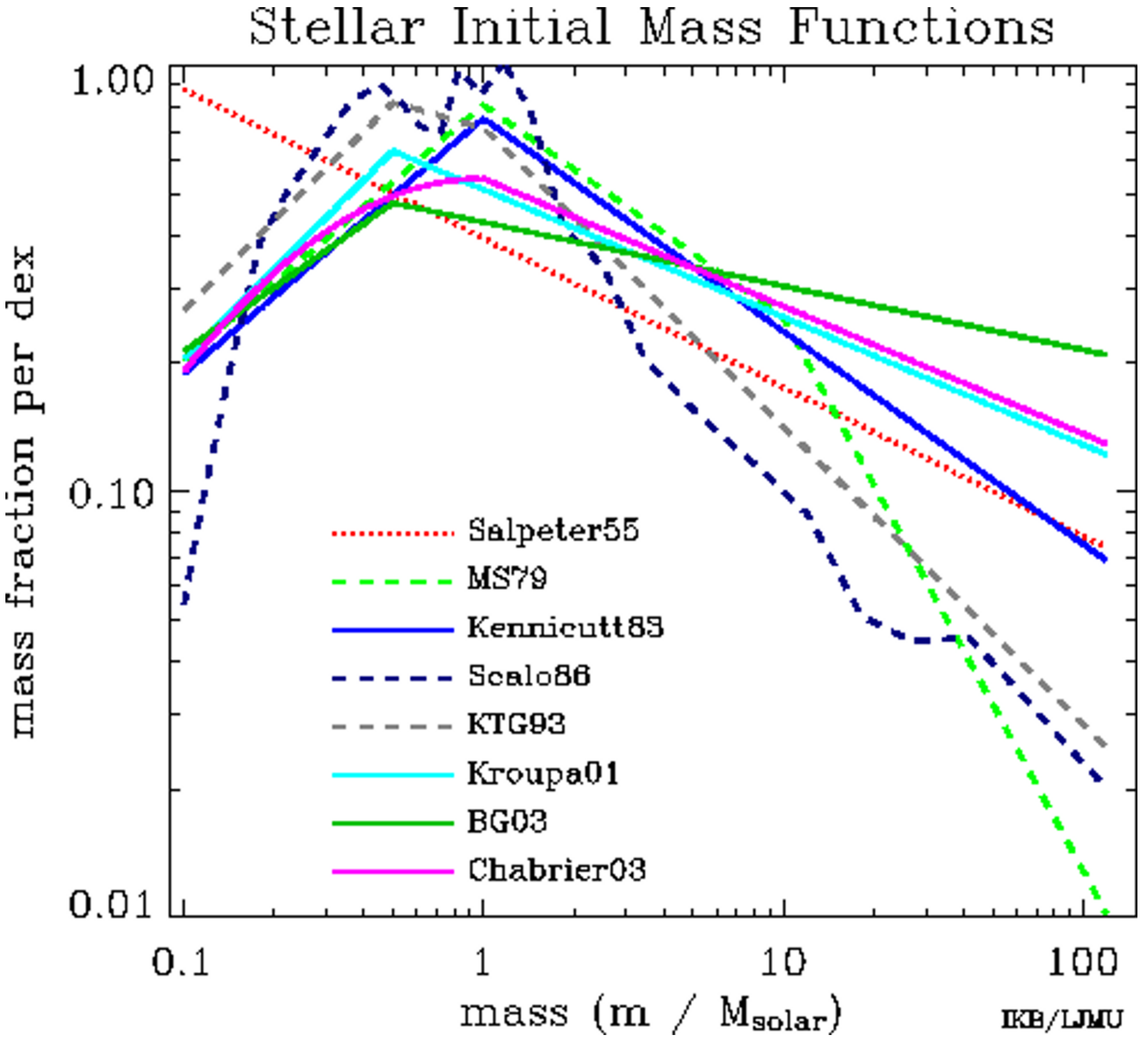
- Evolutionary tracks: evolution in the HR diagram of stars of a given mass
- Isochrones: position in the HR diagram of stars of different mass at the same evolutionary stage

Initial Mass Function

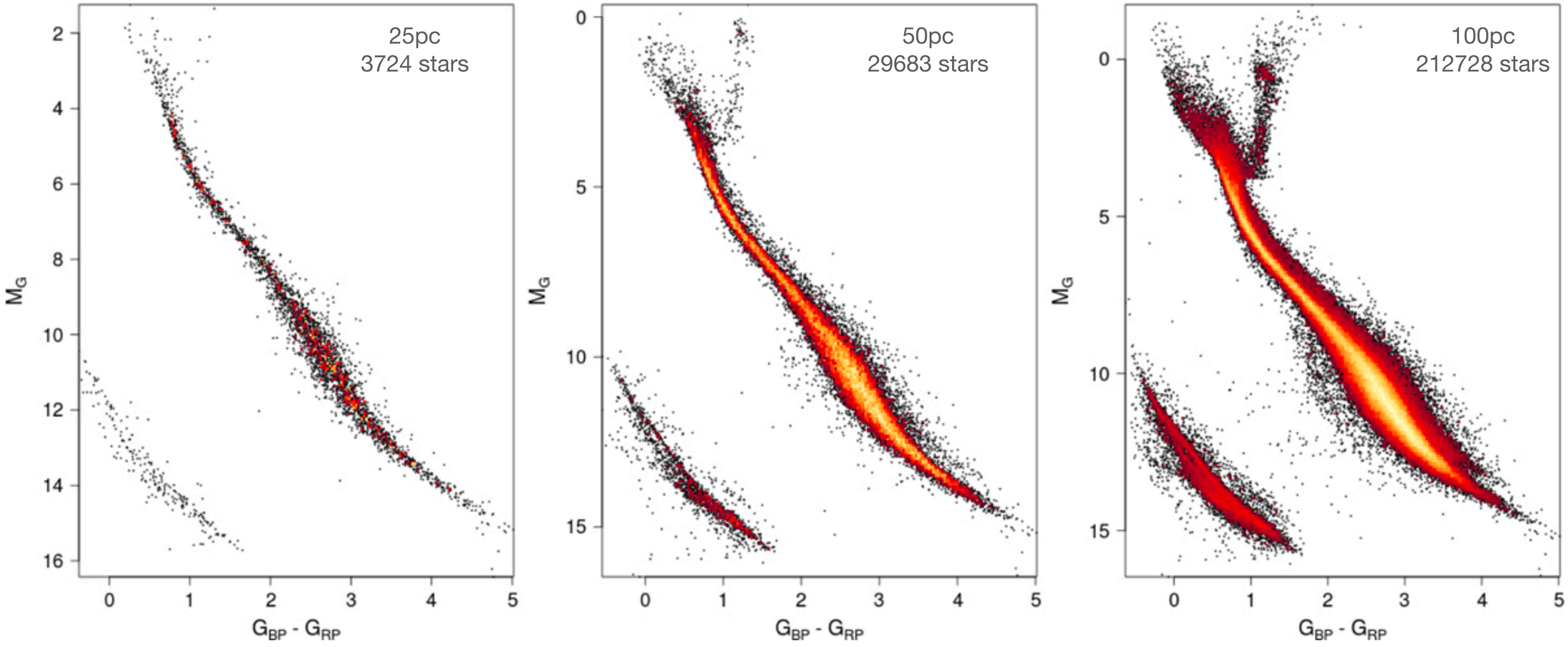


Initial Mass Function





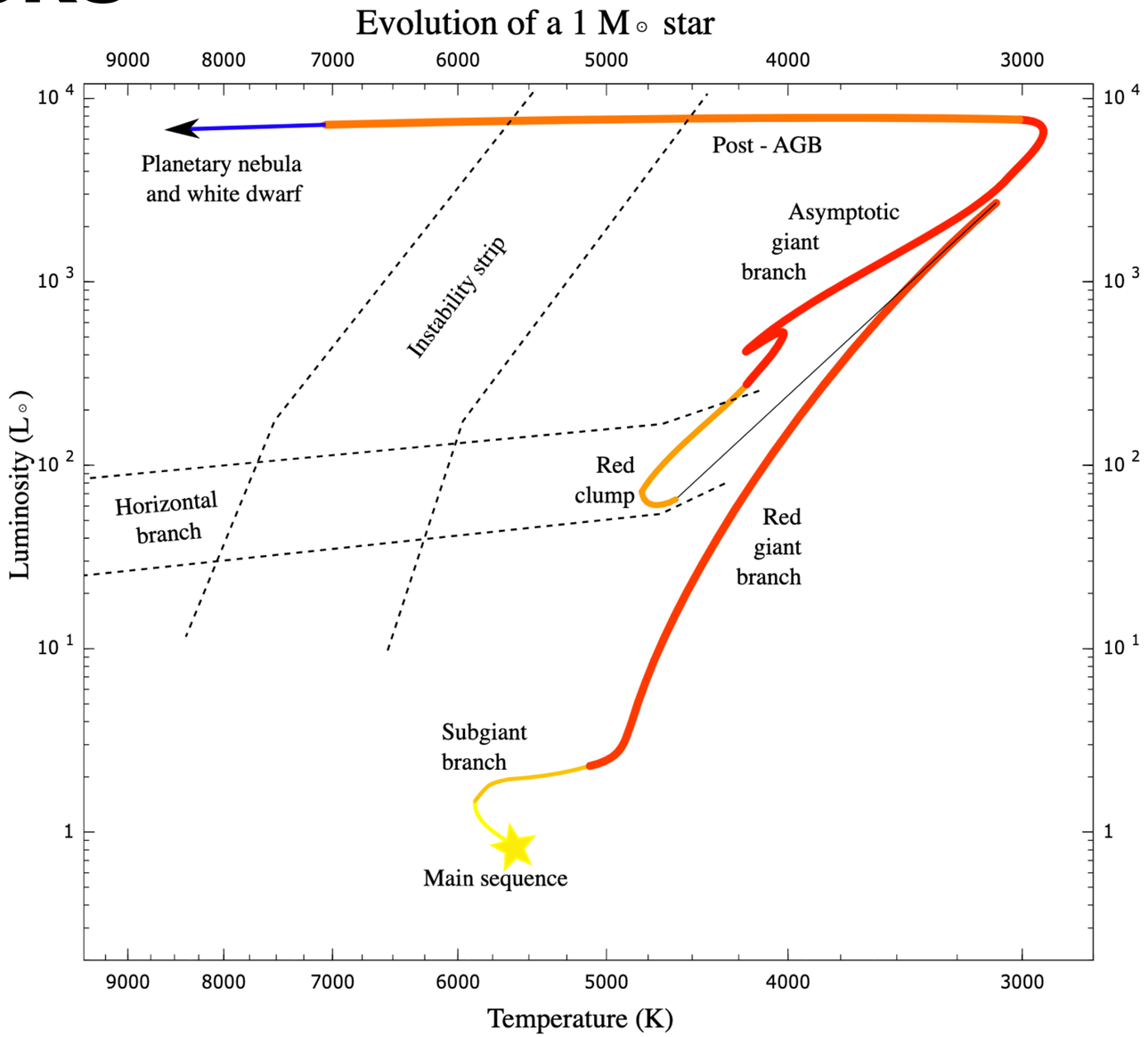
Gaia Solar neighbourhood HRD



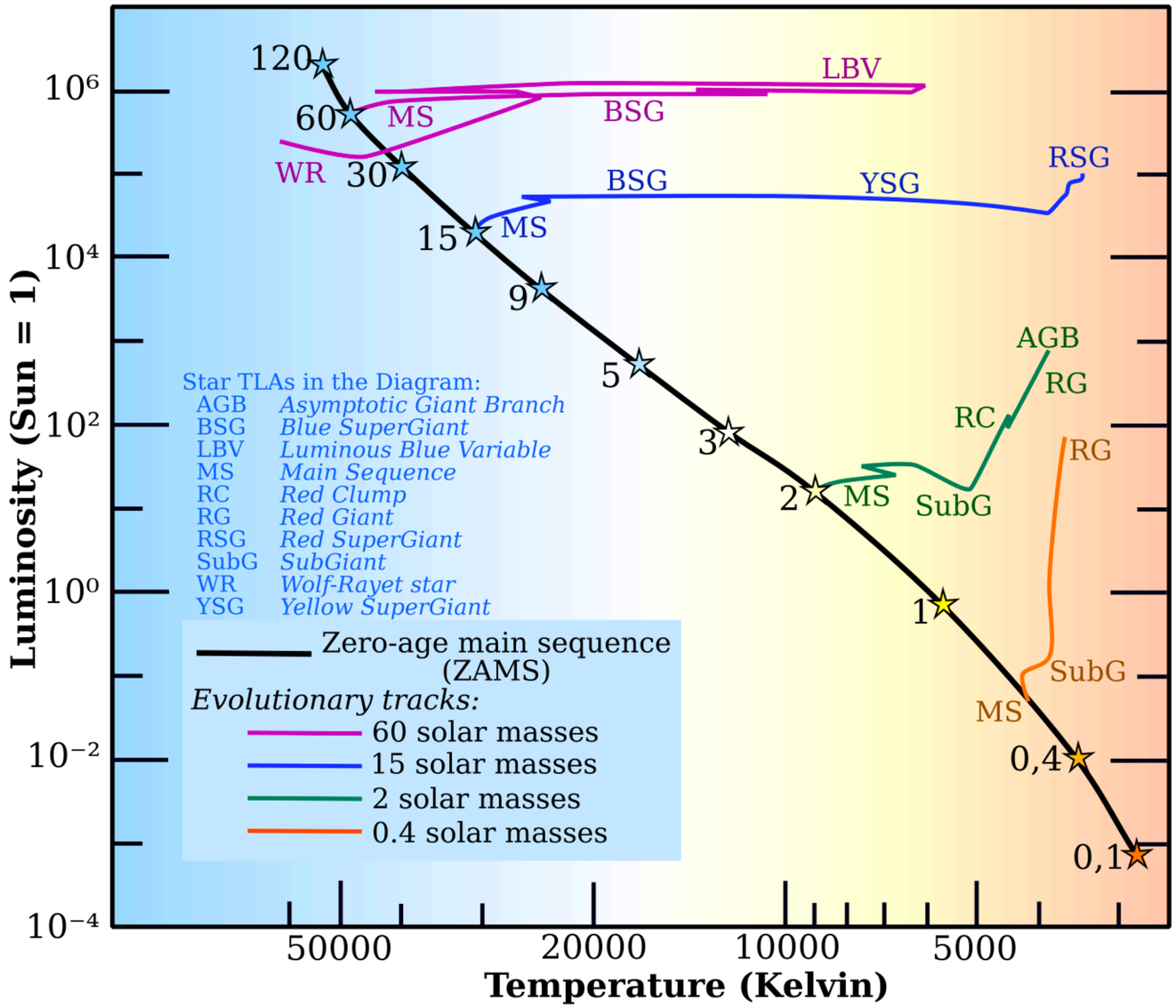
Evolutionary tracks

Table 5.1 Features in the CM diagram

Feature	Physical significance
Main sequence (MS)	Core H burning
Subgiant branch (SGB)	Transition from core to shell H burning
Red giant branch (RGB)	Shell burning of H
Horizontal branch (HB)	Core He burning
Red clump (RC)	Stubby red HB formed by more metal-rich stars
Asymptotic giant branch (AGB)	Shell He burning
Instability strip	He^+ ionization zone gives rise to regular variables
White-dwarf sequence	Cooling electron-degenerate stars



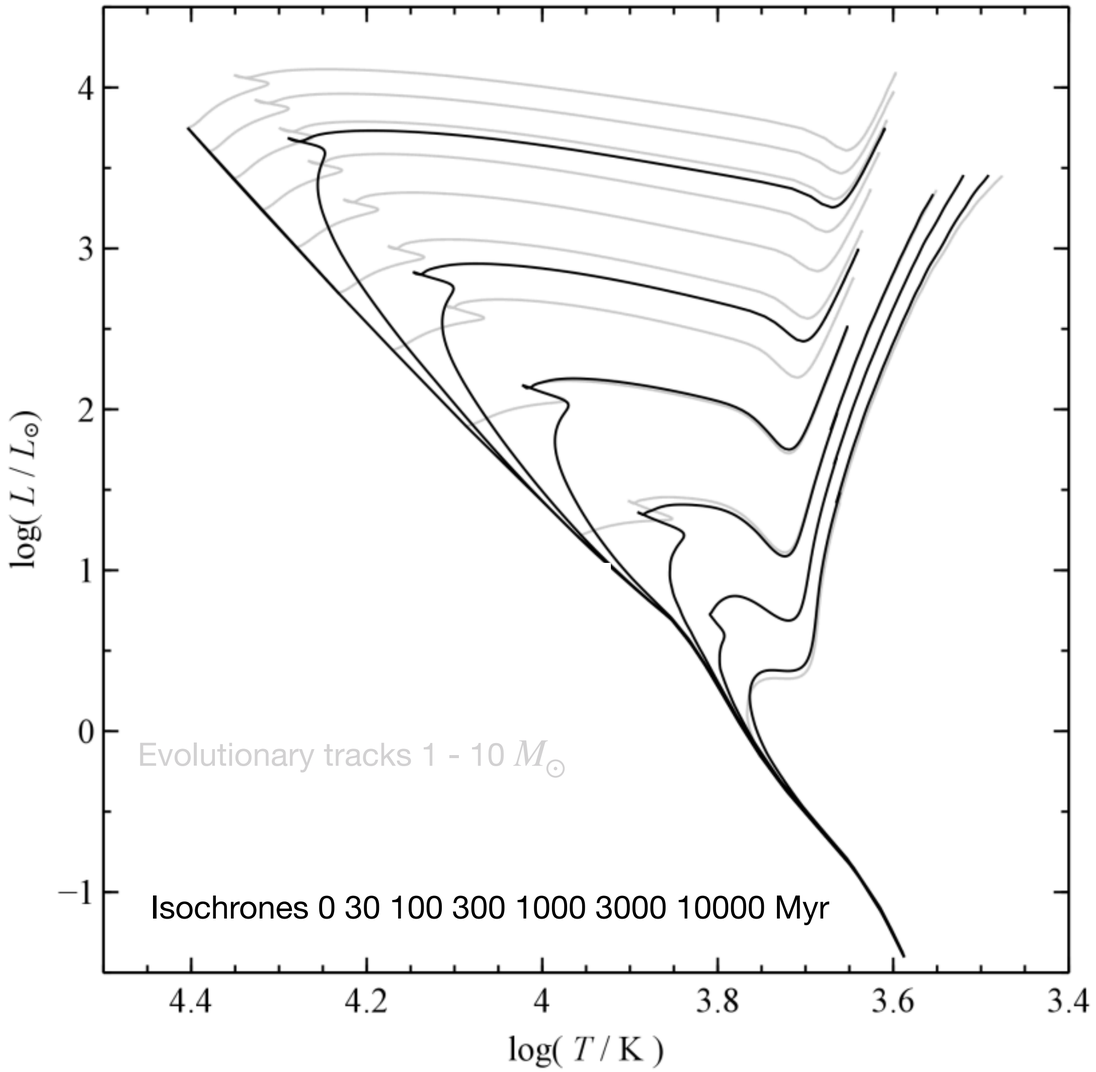
Evolutionary tracks



HR diagram

Dependence (~shift) on metallicity, rotation, binary…

Isochrones



Isochrones: set of stellar models compute at the **same** (*iso*) **age** (*chrone*).

use a stellar evolution code to compute evolutionary tracks for a number of stars of different masses, and then they connect all the models of different masses at the **same age**.

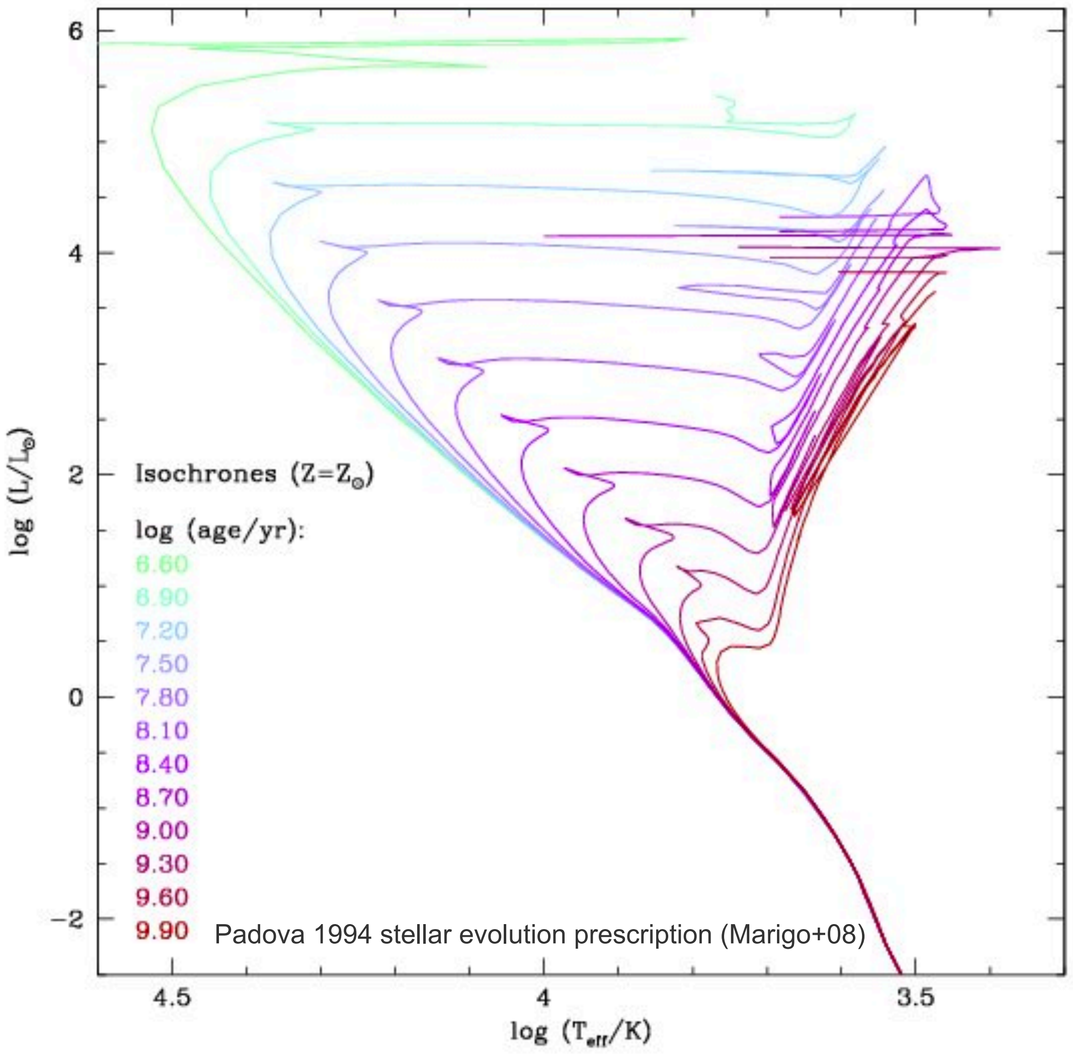
grey lines are evolutionary tracks for stars with masses from 1 to 10 solar masses

they all evolve at different rates

30 Myr: most massive stars have already disappeared
Stars around 6-7 Msun exhausted H in the core,
lower mass stars have barely budged.

As the isochrones get older, more and more stars "peel away" from the ZAMS. But the very low-mass stars don't budge at all.

Isochrones



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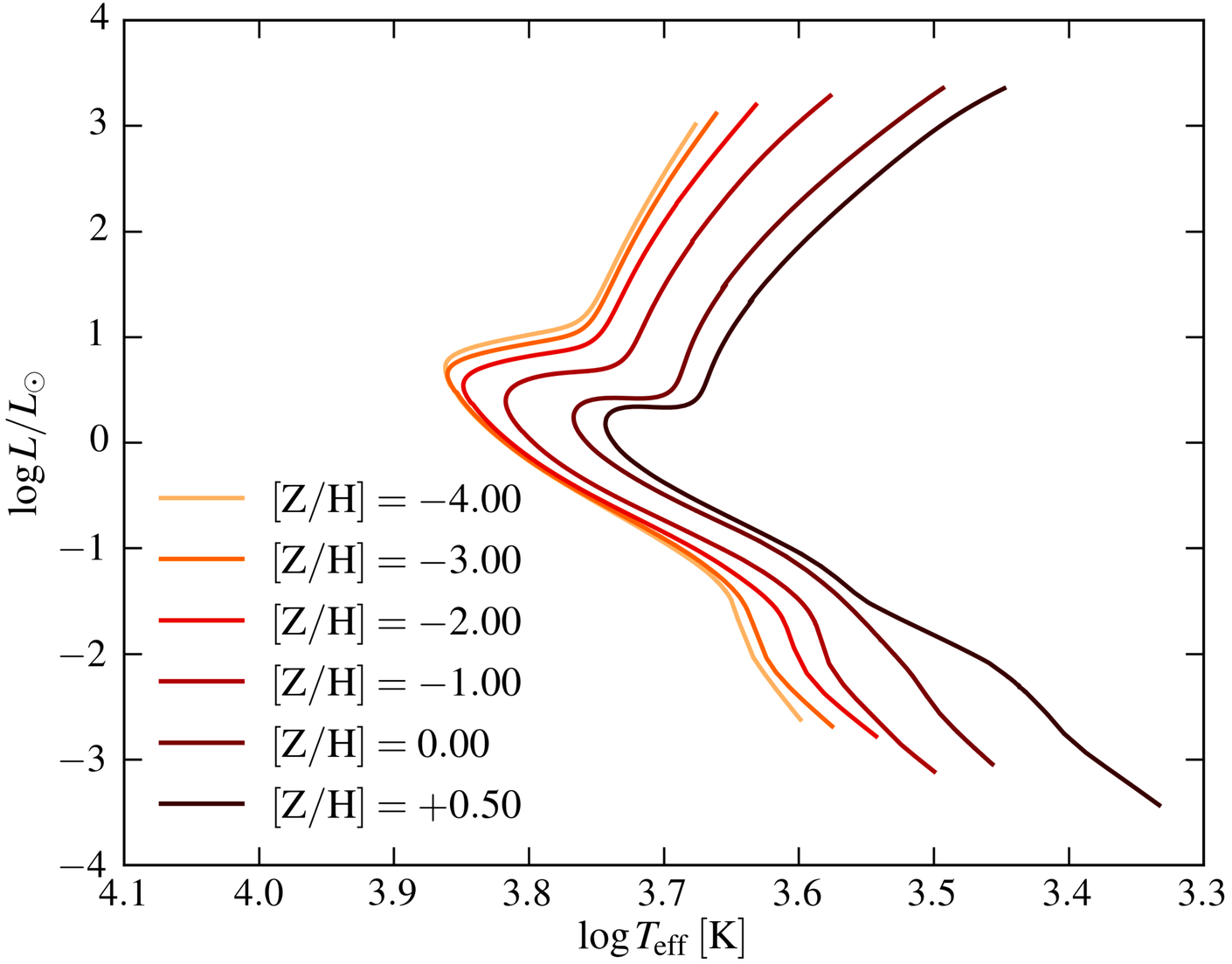
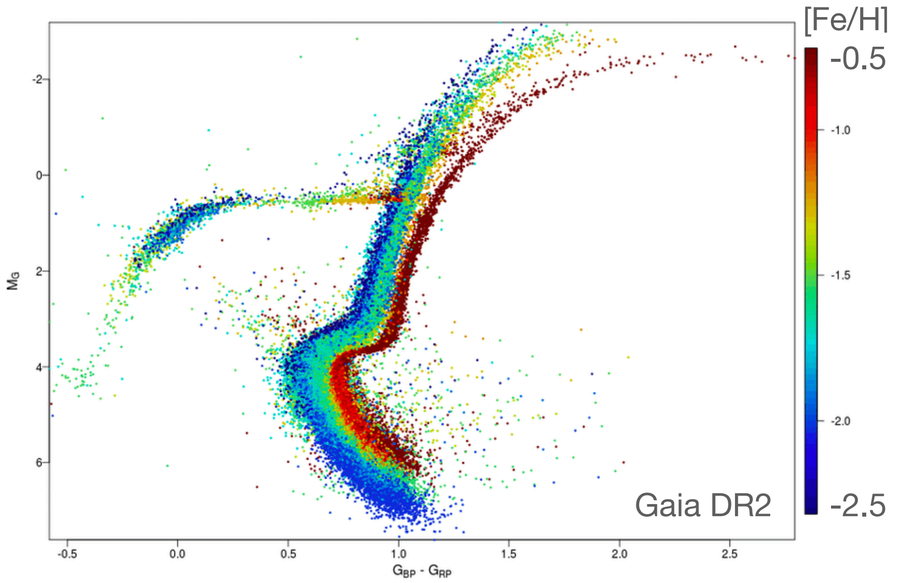
Isochrones - dependence on metallicity





MESA Isochrones & Stellar Tracks

Ingredients

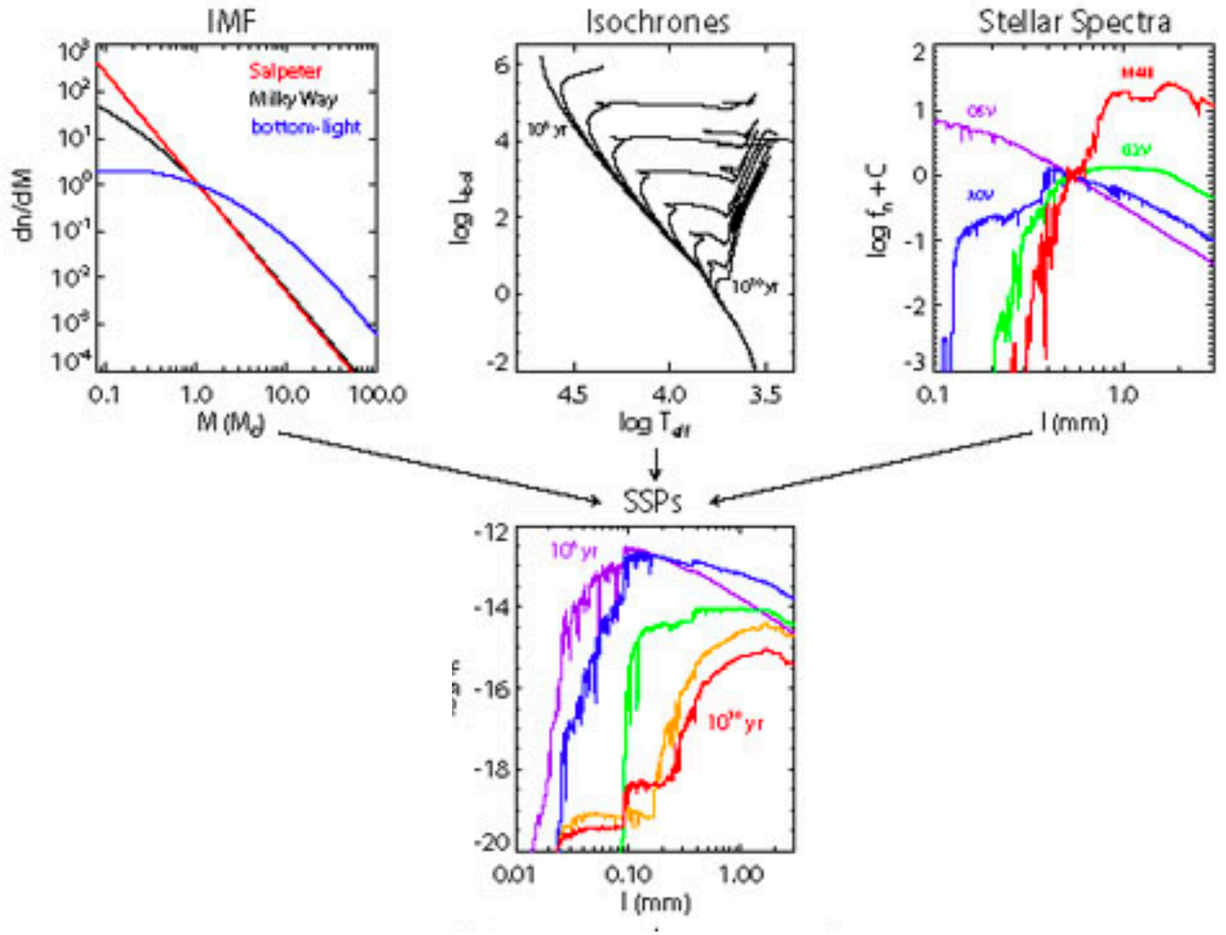
- SFR -> IMF (Salpeter, Kroupa, Chabrier…)
- Evolutionary tracks -> isochrones (Padova, Geneva…)
- Stellar library: spectra that sample parameter space: (T, g, Z) and t
    - BaSeL: theoretical synthetic spectra
    - STELIB: observational spectra
    - Kuruc models: theoretical synthetic models
    - MILES: observational spectra

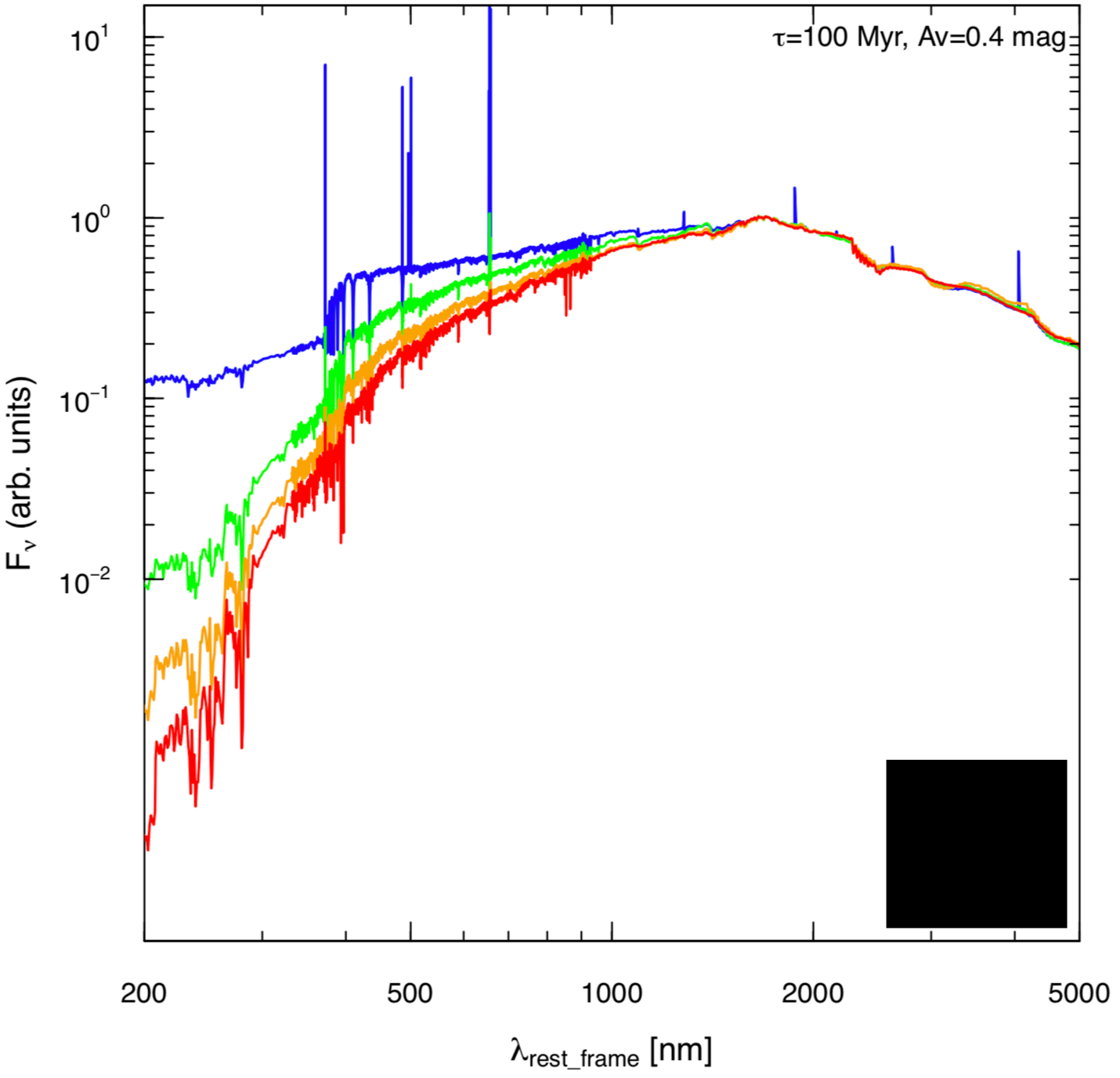
SSP Models

- Goal: reproduce the integrated light of stellar populations adding the contributions of the individual stars forming a galaxy

- Isochrone synthesis or adding of single stellar populations (SSP):

  - Bruzual & Charlot
  - Fioc, Rocca-Volmerange: PEGASE
  - Leitherer et al: STARBURST99
  - Maraston
  - FSPS (Conroy)

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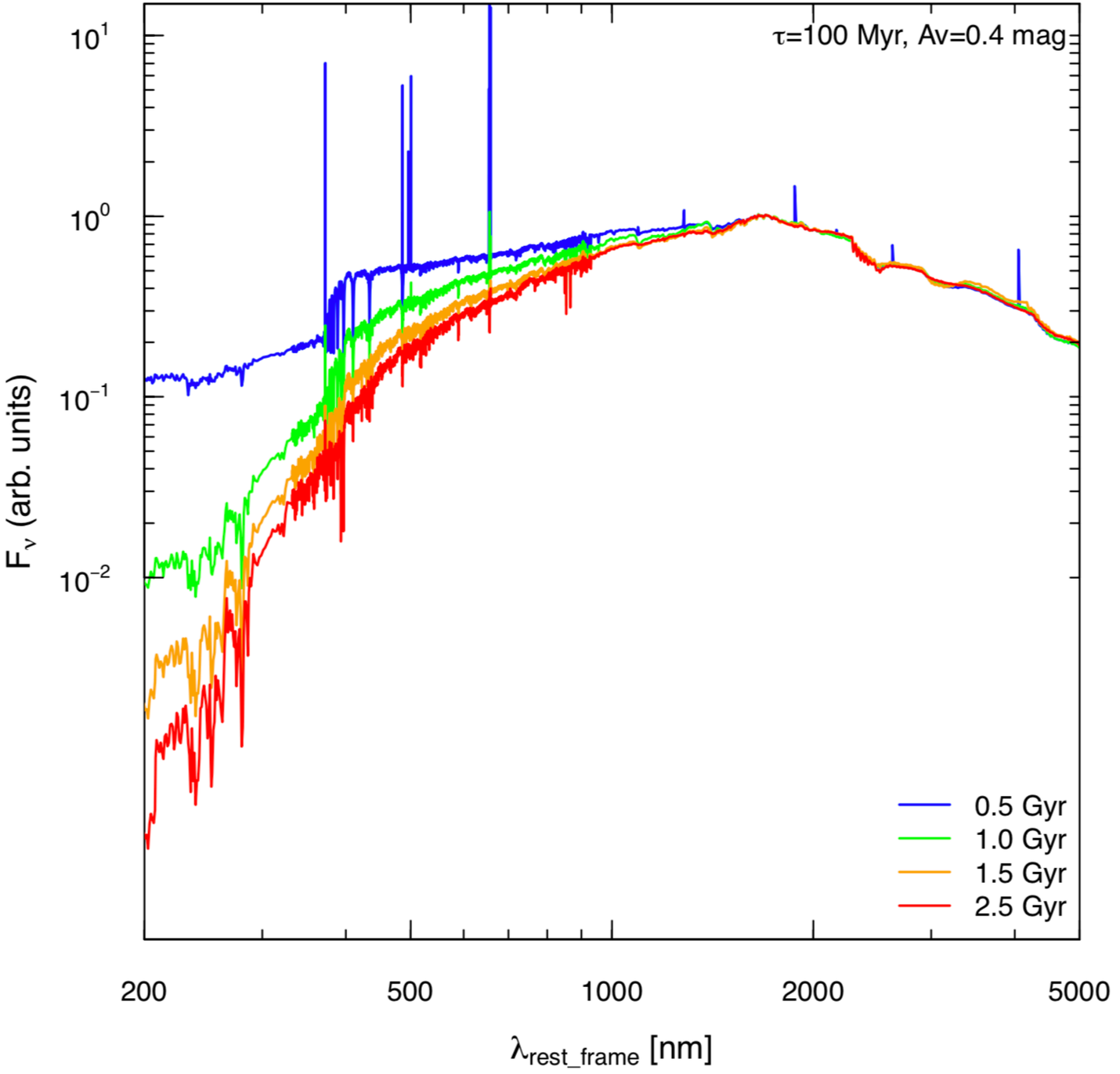
10^{1}
10^{0}
10^{-1}
10^{-2}
F_ν (arb. units)
200
500
1000
2000
5000
λ_{rest_frame} [nm]


τ=100 Myr, Av=0.4 mag
10^1
10^0
10^{-1}
10^{-2}
F_ν (arb. units)
200
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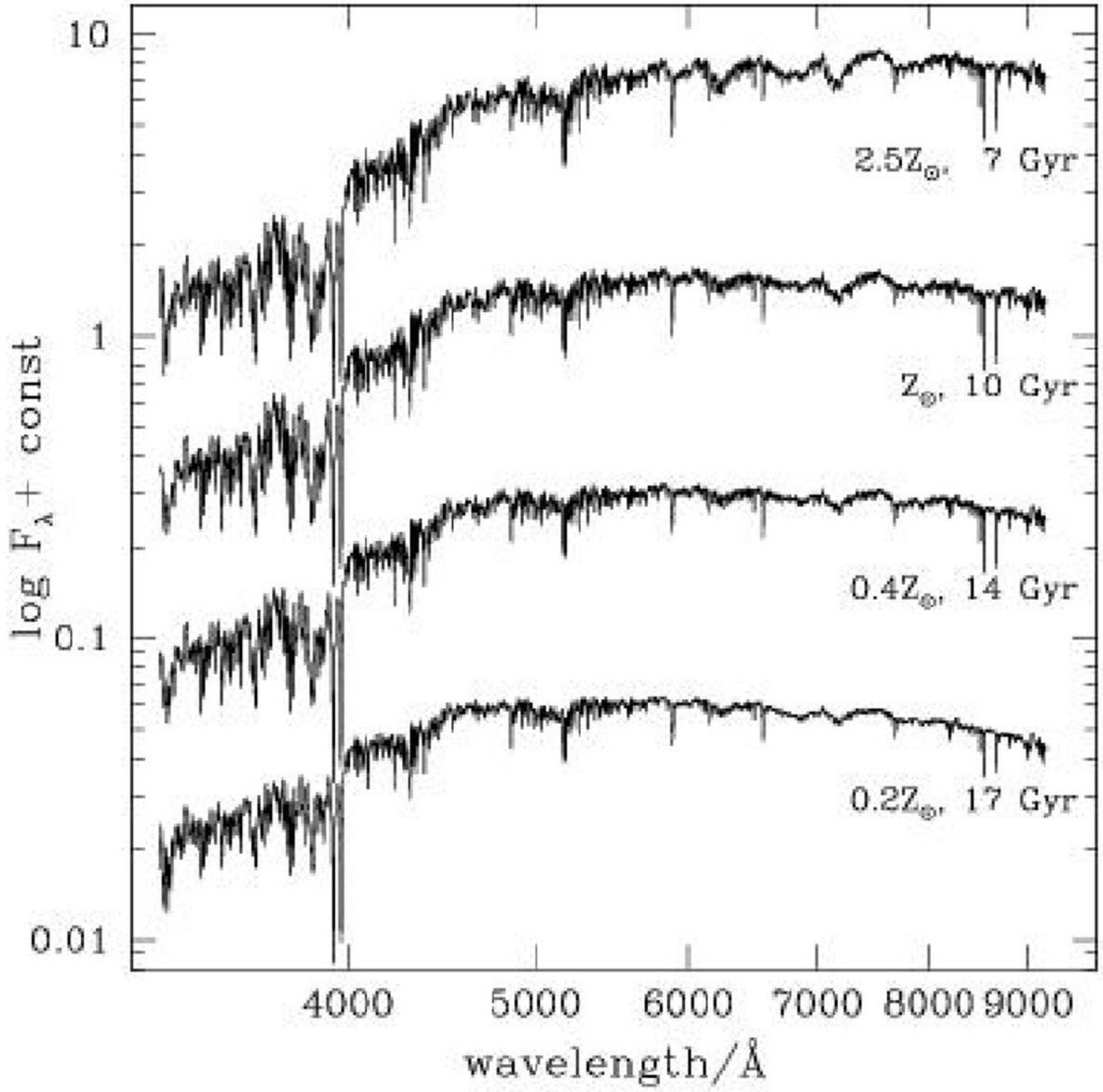
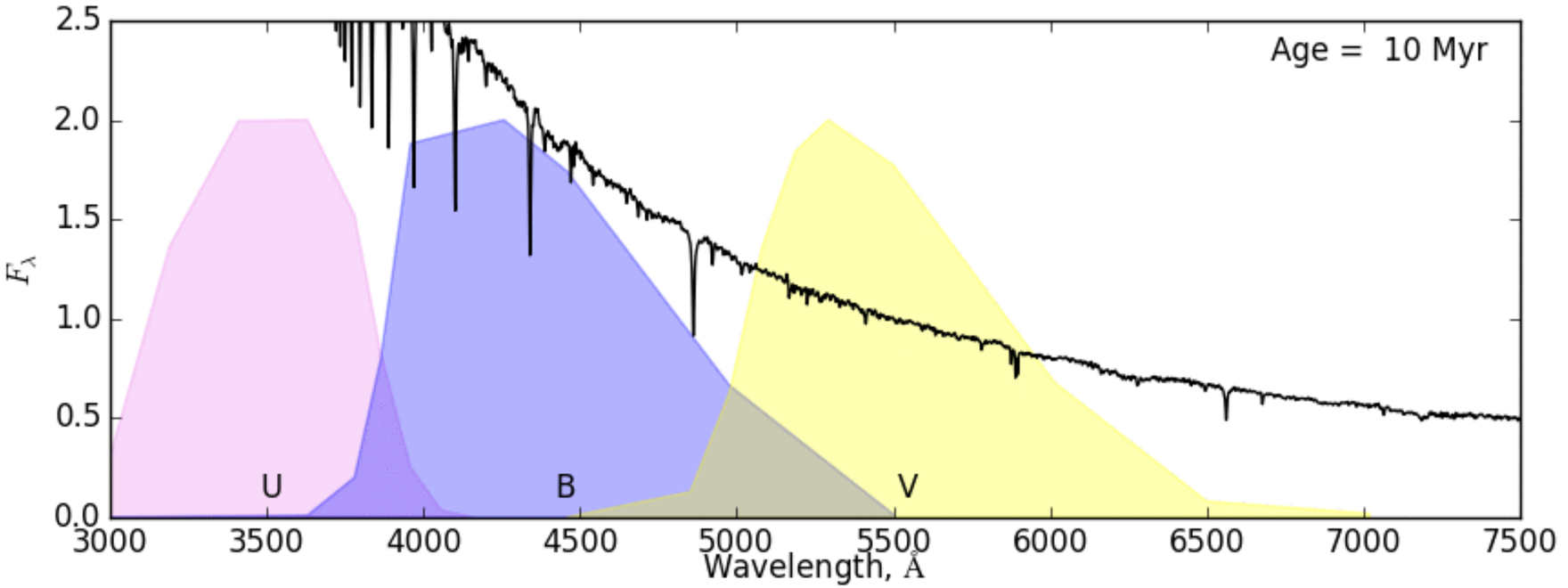
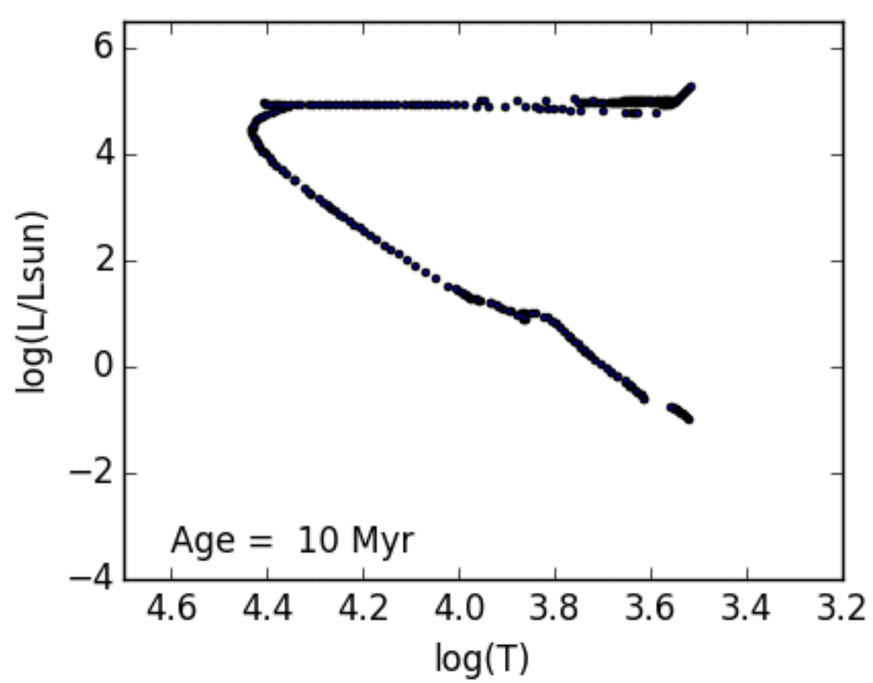
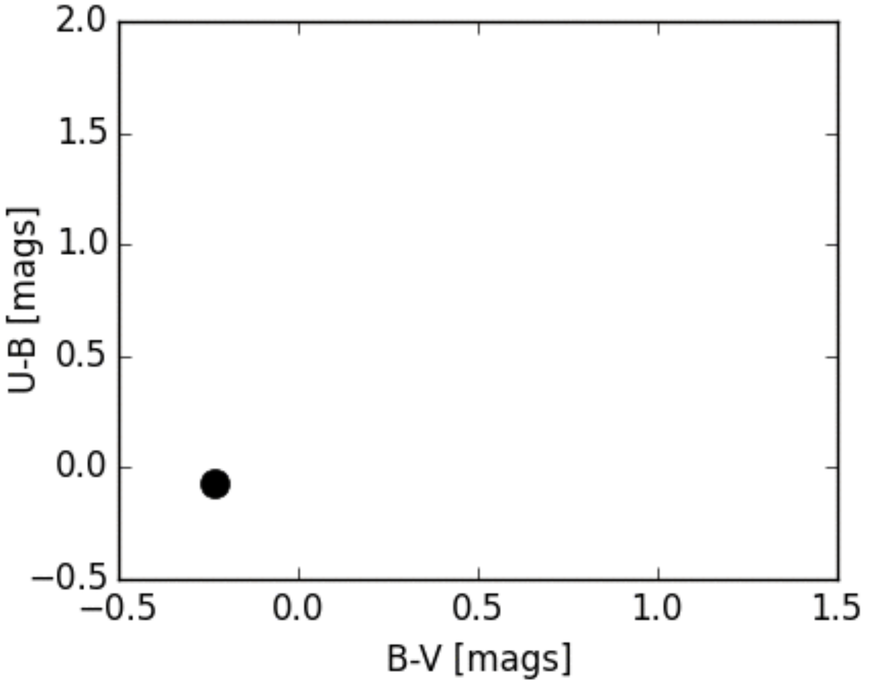
λ_{rest_frame} [nm]
0.5 Gyr
1.0 Gyr
1.5 Gyr
2.5 Gyr

Age-metallicity degeneracy









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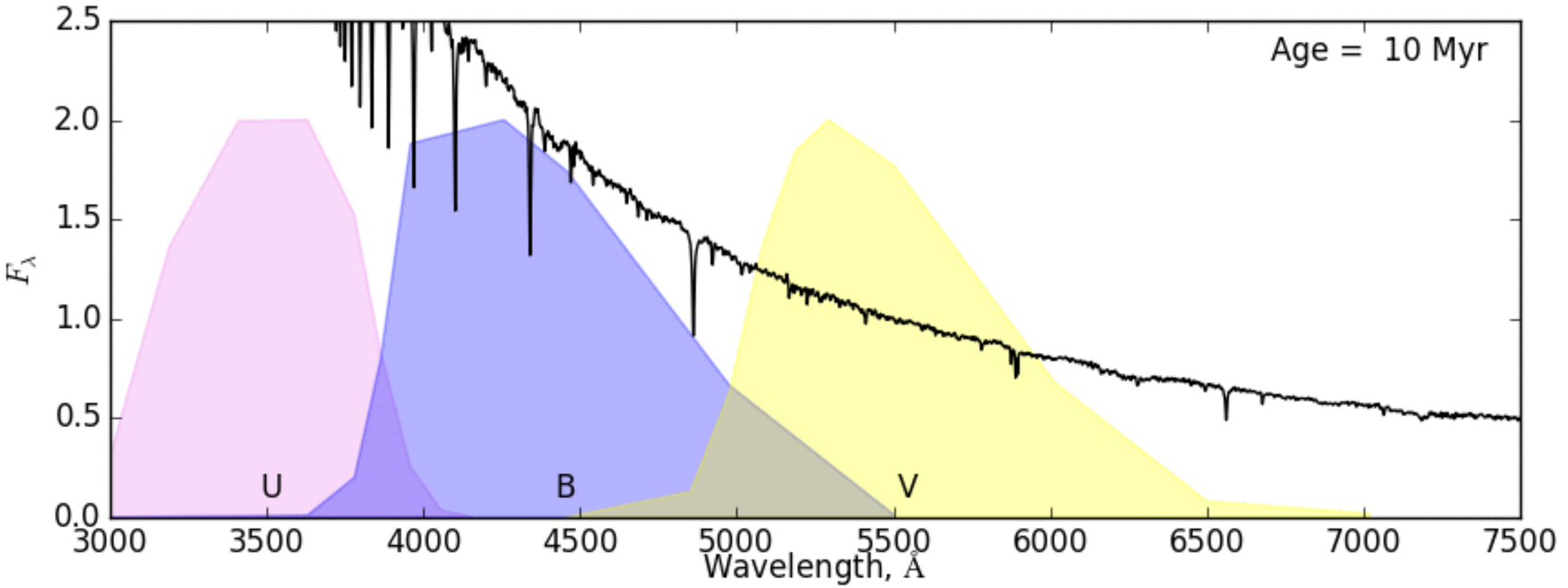

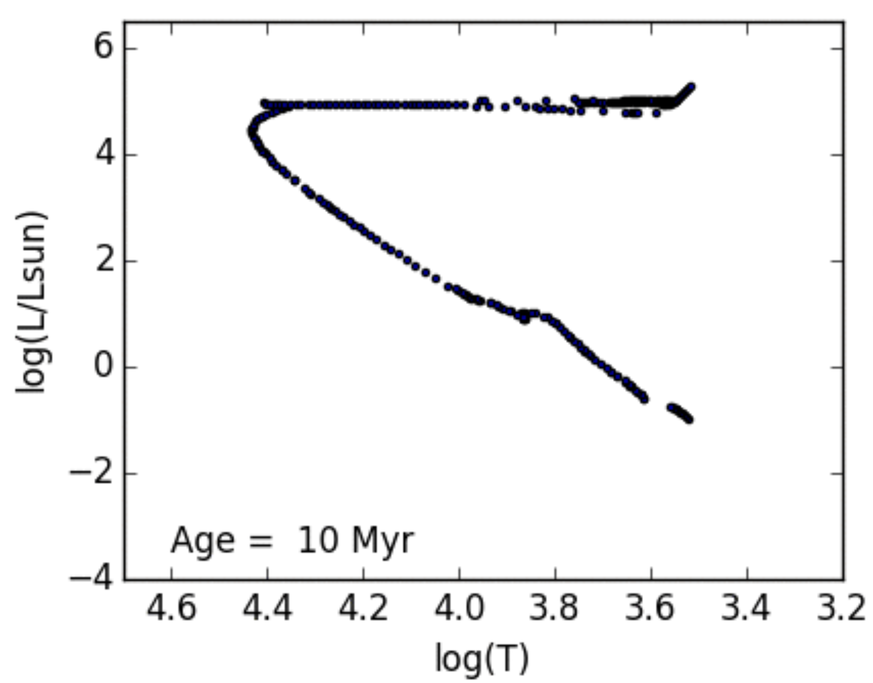

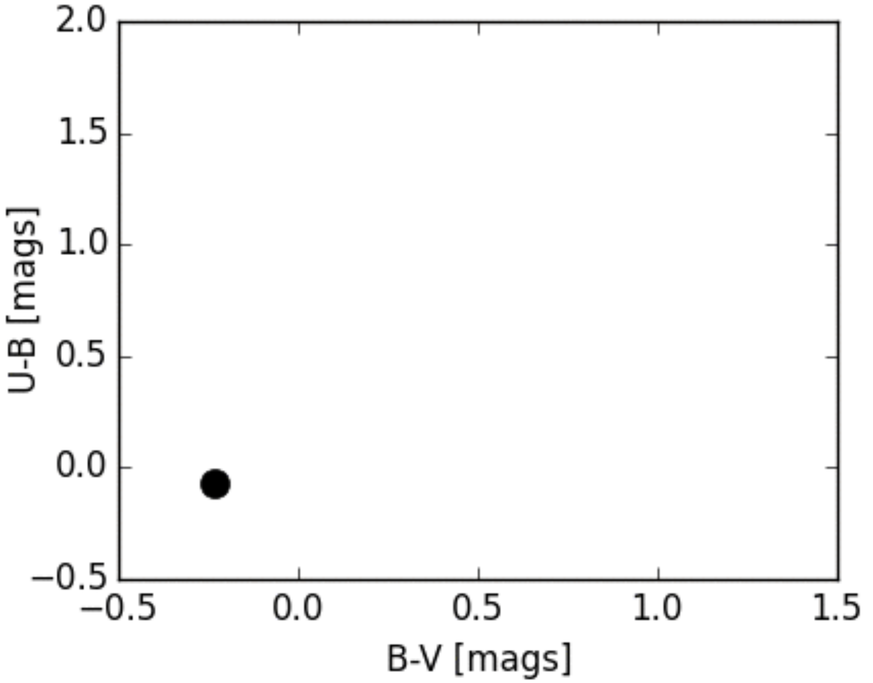

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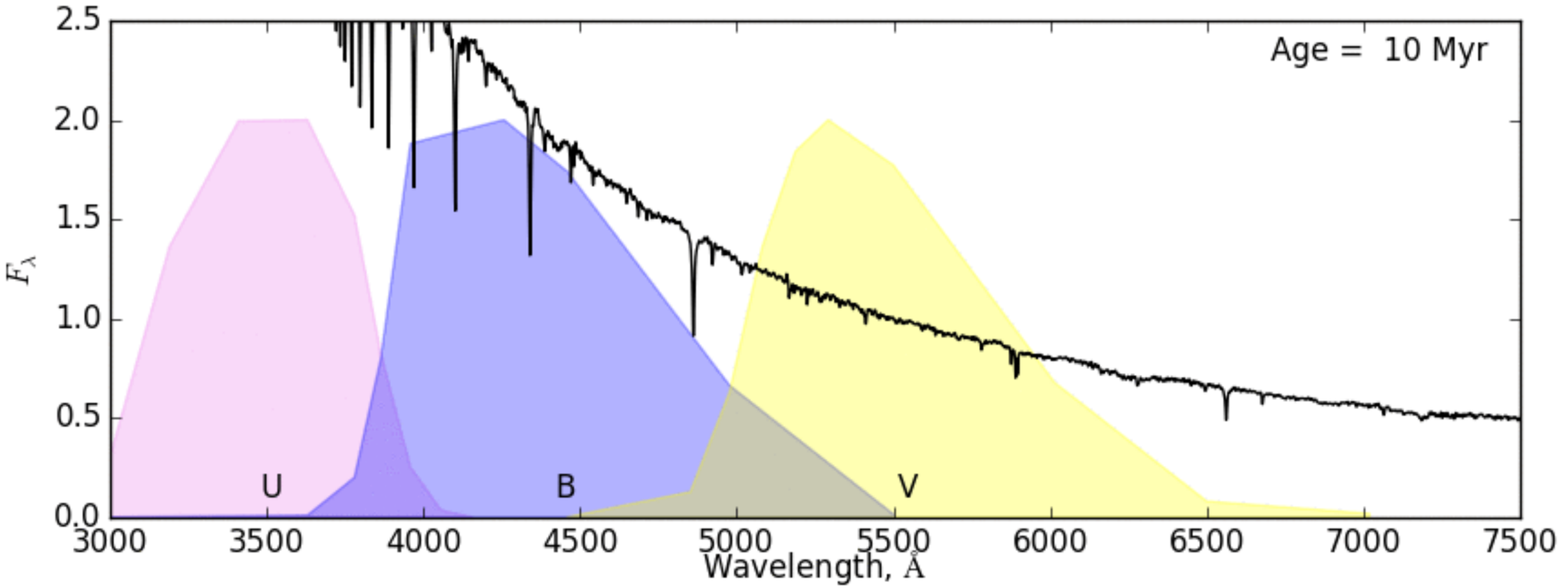

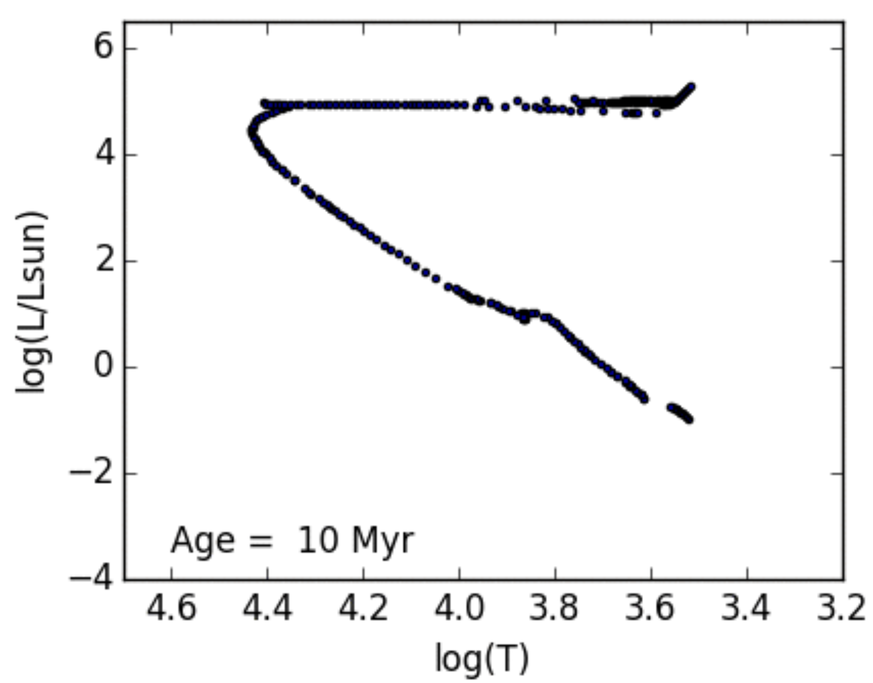

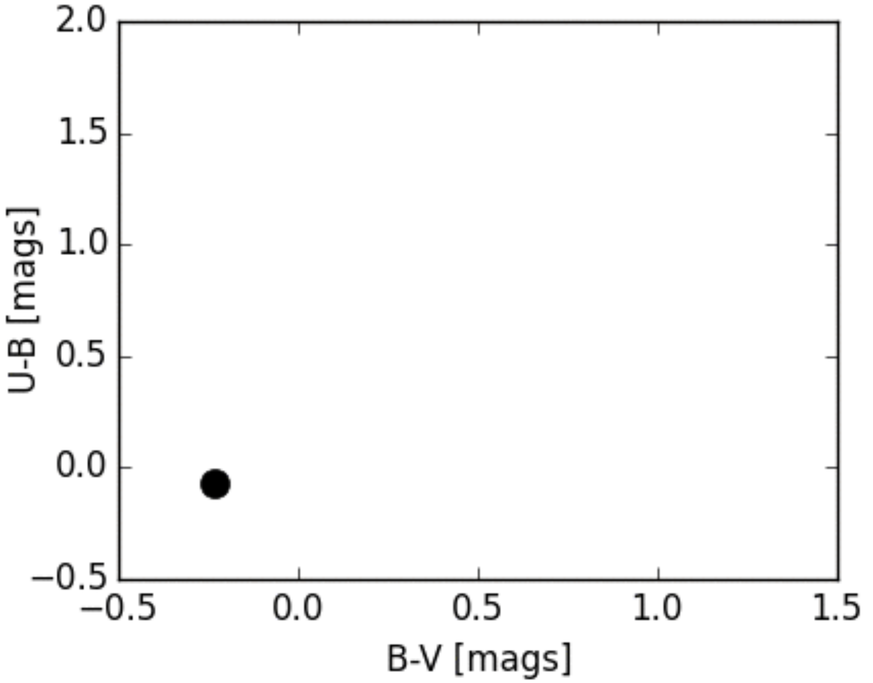

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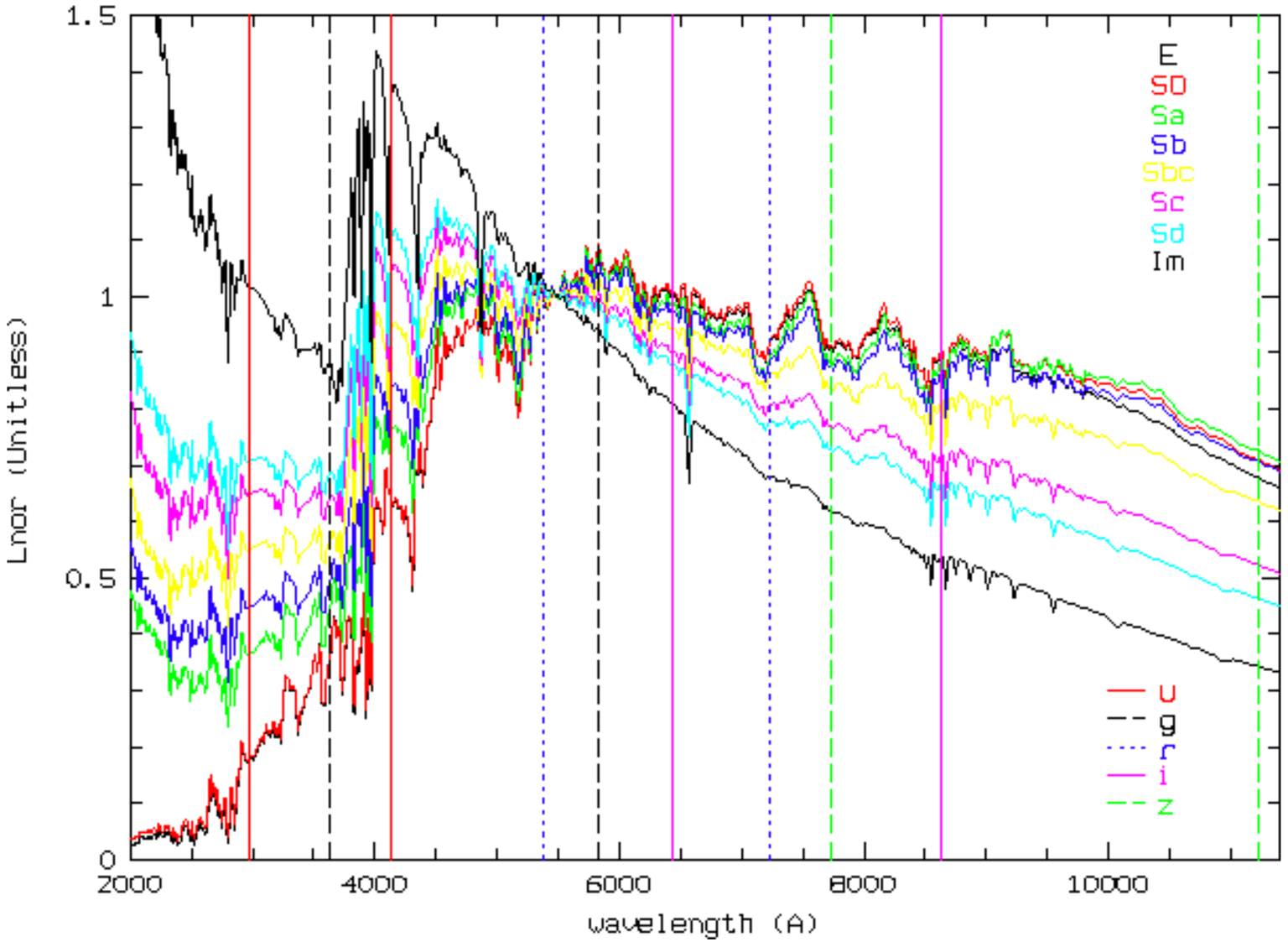
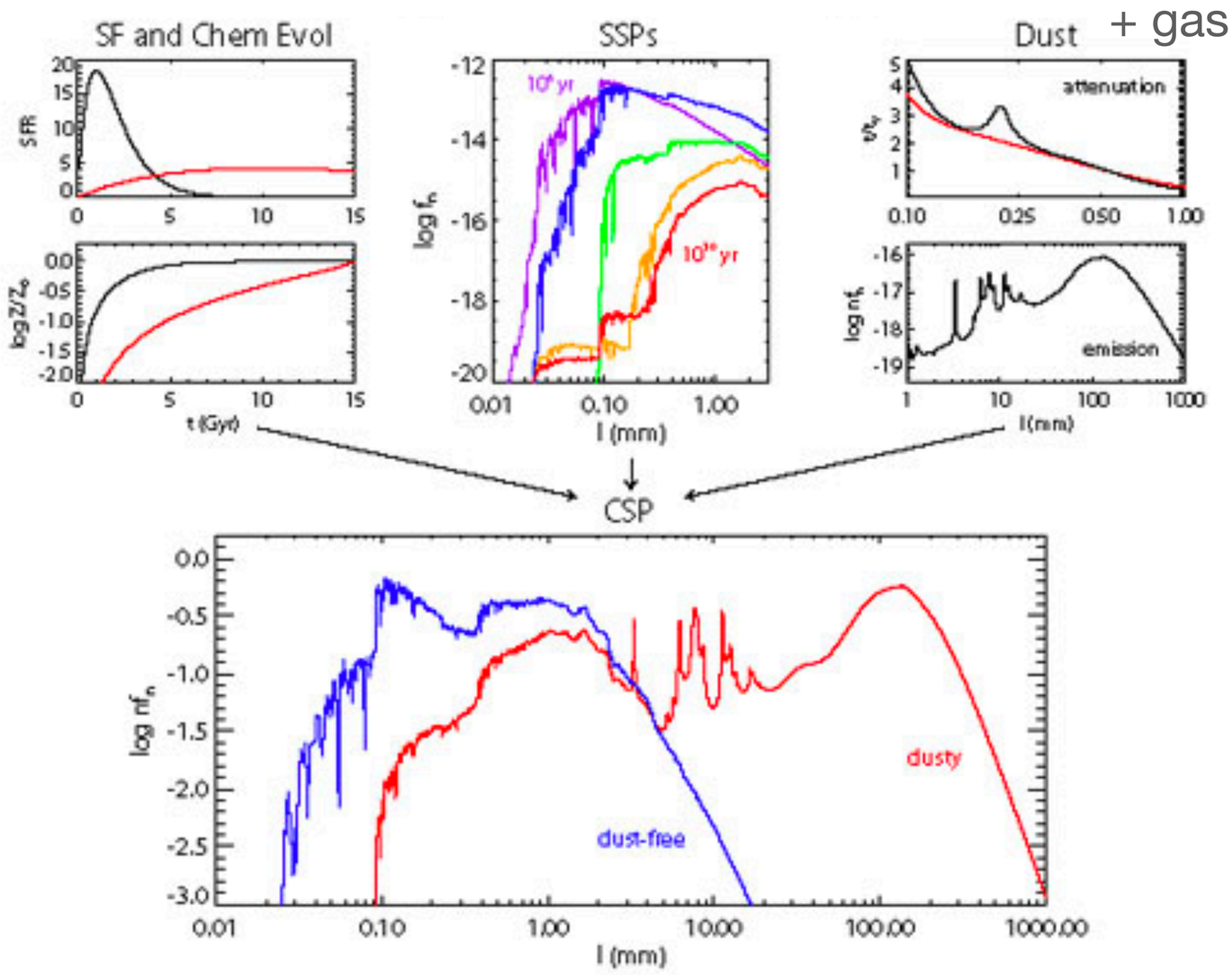
Morphology


1.5
1
0.5
0
Lnor (Unitless)
2000
4000
6000
8000
10000
wavelength (A)
E
SO
Sa
Sb
Sbc
Sc
Sd
Im
u
g
r
i
z

Composite SP - Ingredients

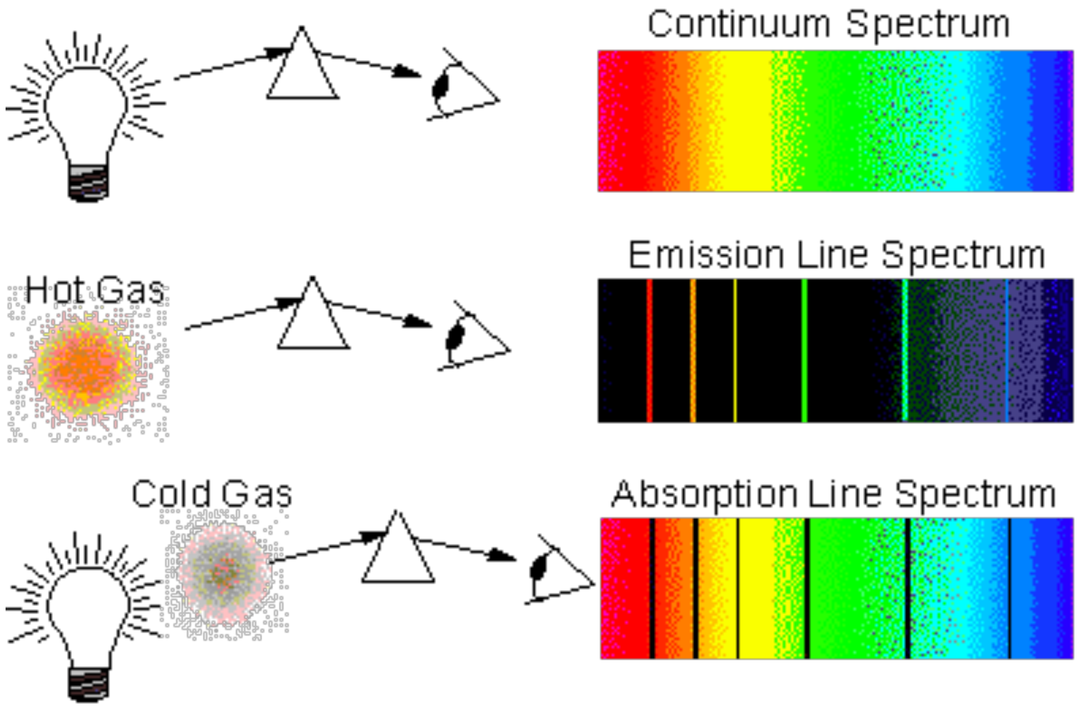


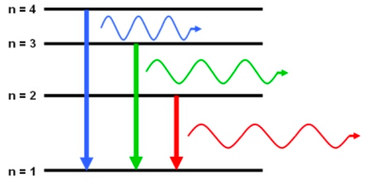
+ gas

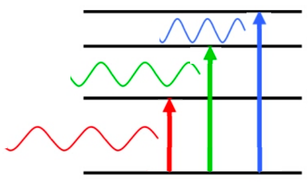
Ionized gas

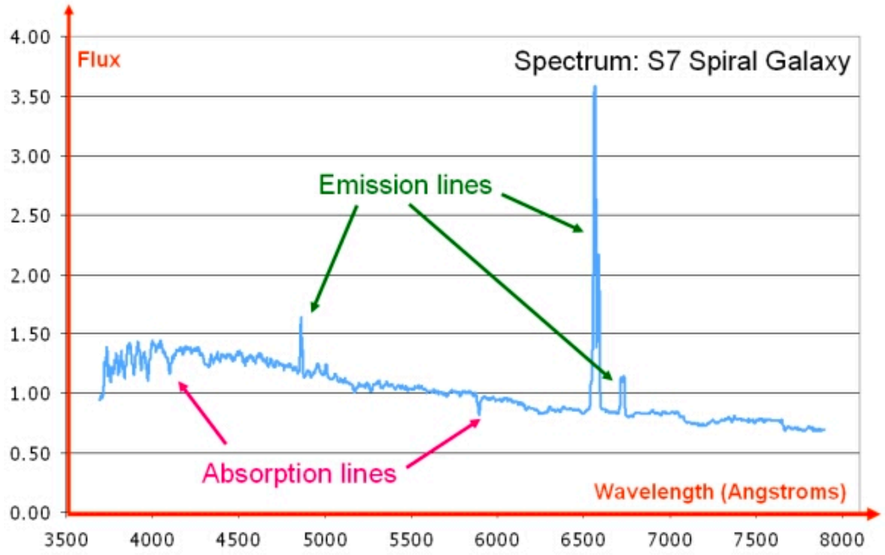
- UV emission: massive young stars are bright in the UV; direct probe of young stellar population
- Nebular lines: zones of ionised gas around young star clusters that still contain OB stars; Ha is the brightest
- Far-IR emission: light absorbed by dust and re-emitted at longer wavelengths
- Radio, CO, …

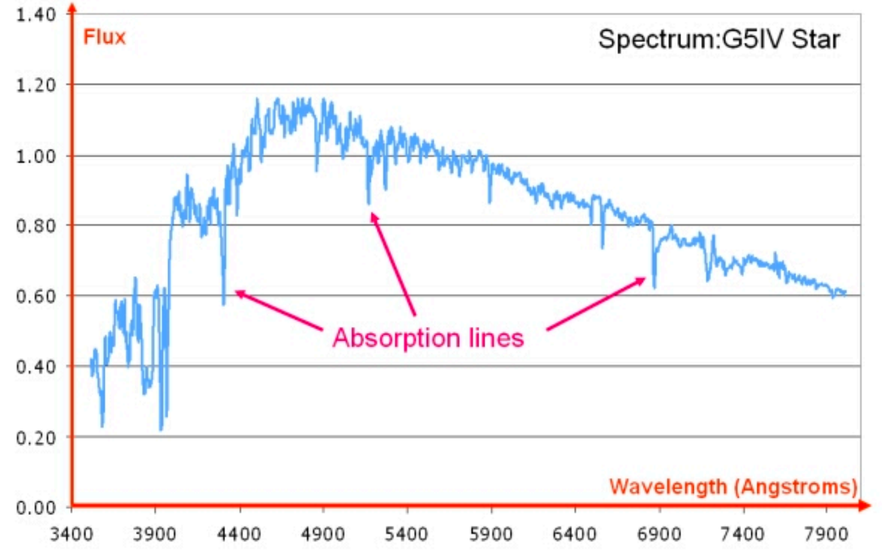
Absorption/emission lines



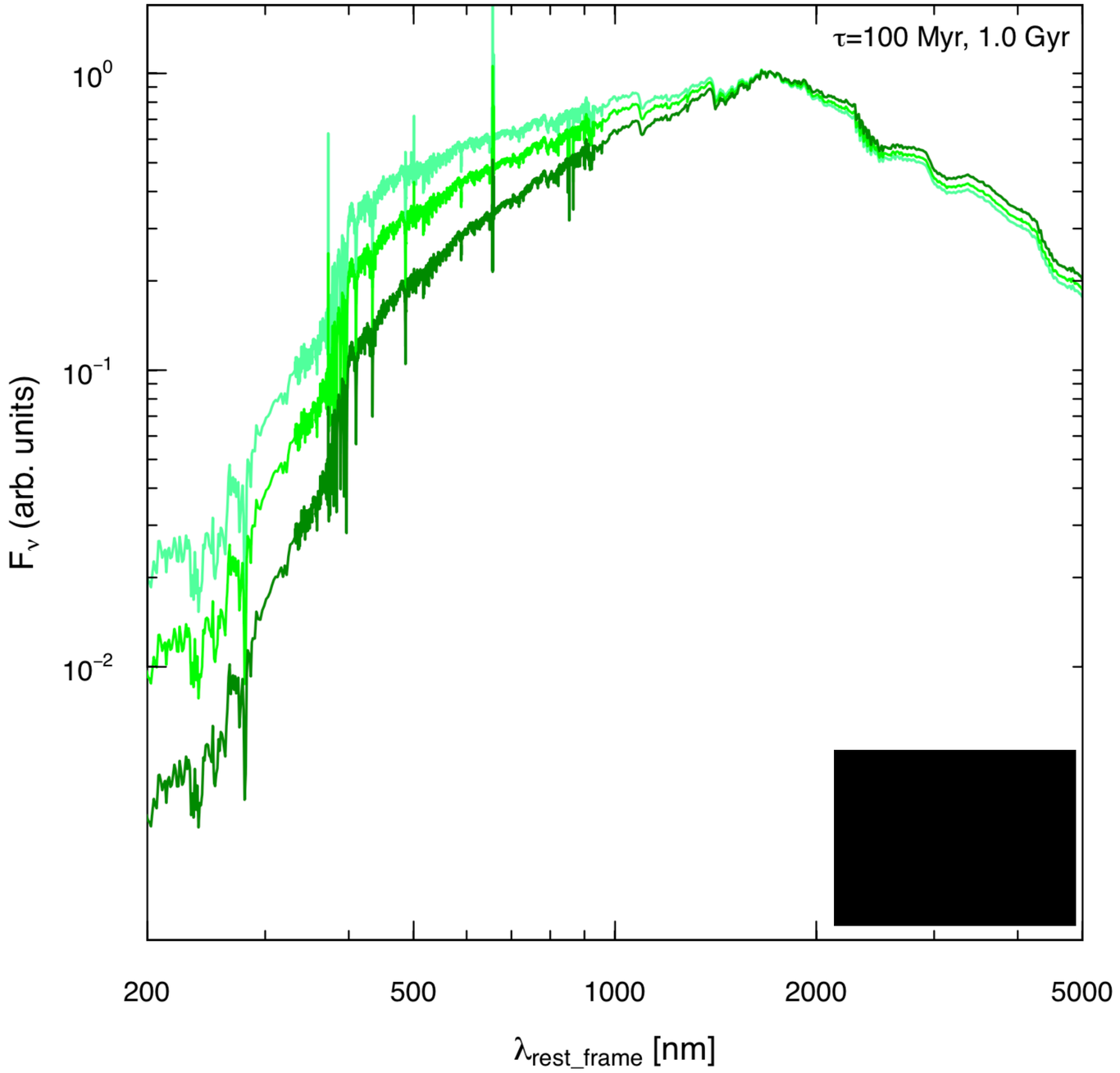








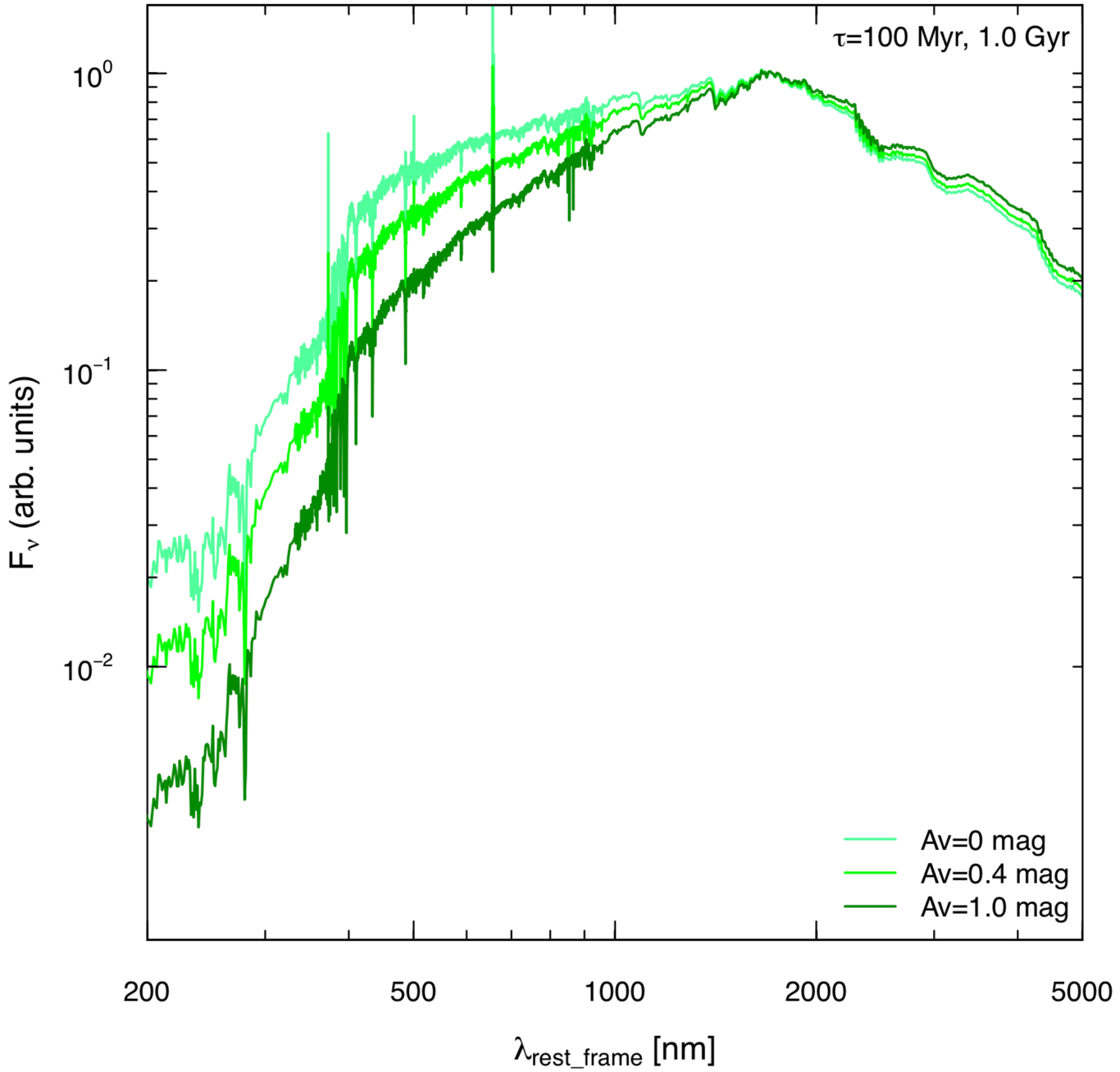
…and dust



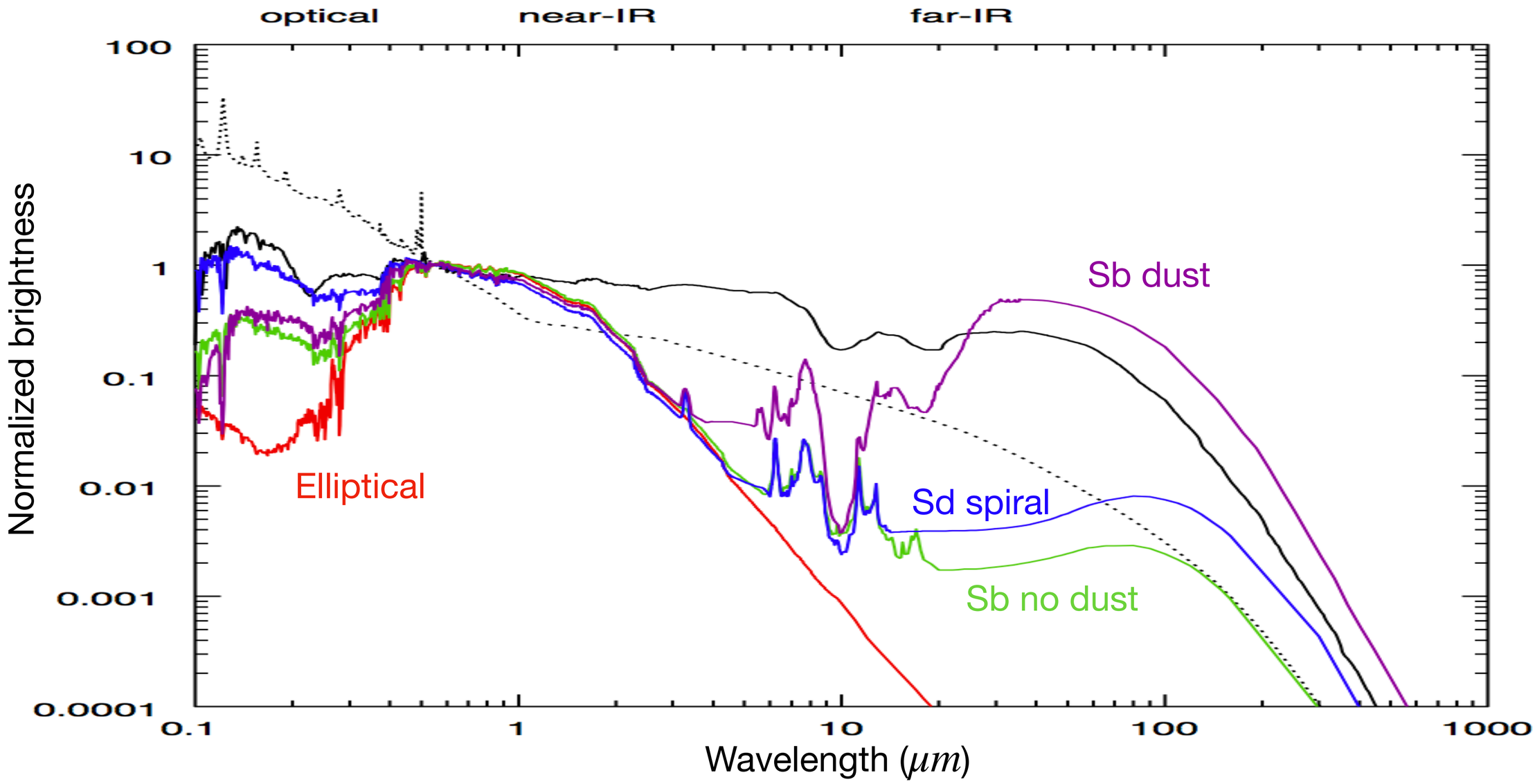
Absorbs high-energy (blue) light which is reemitted at infrared wavelegths.

…and dust

Absorbs high-energy (blue) light which is reemitted at infrared wavelegths.

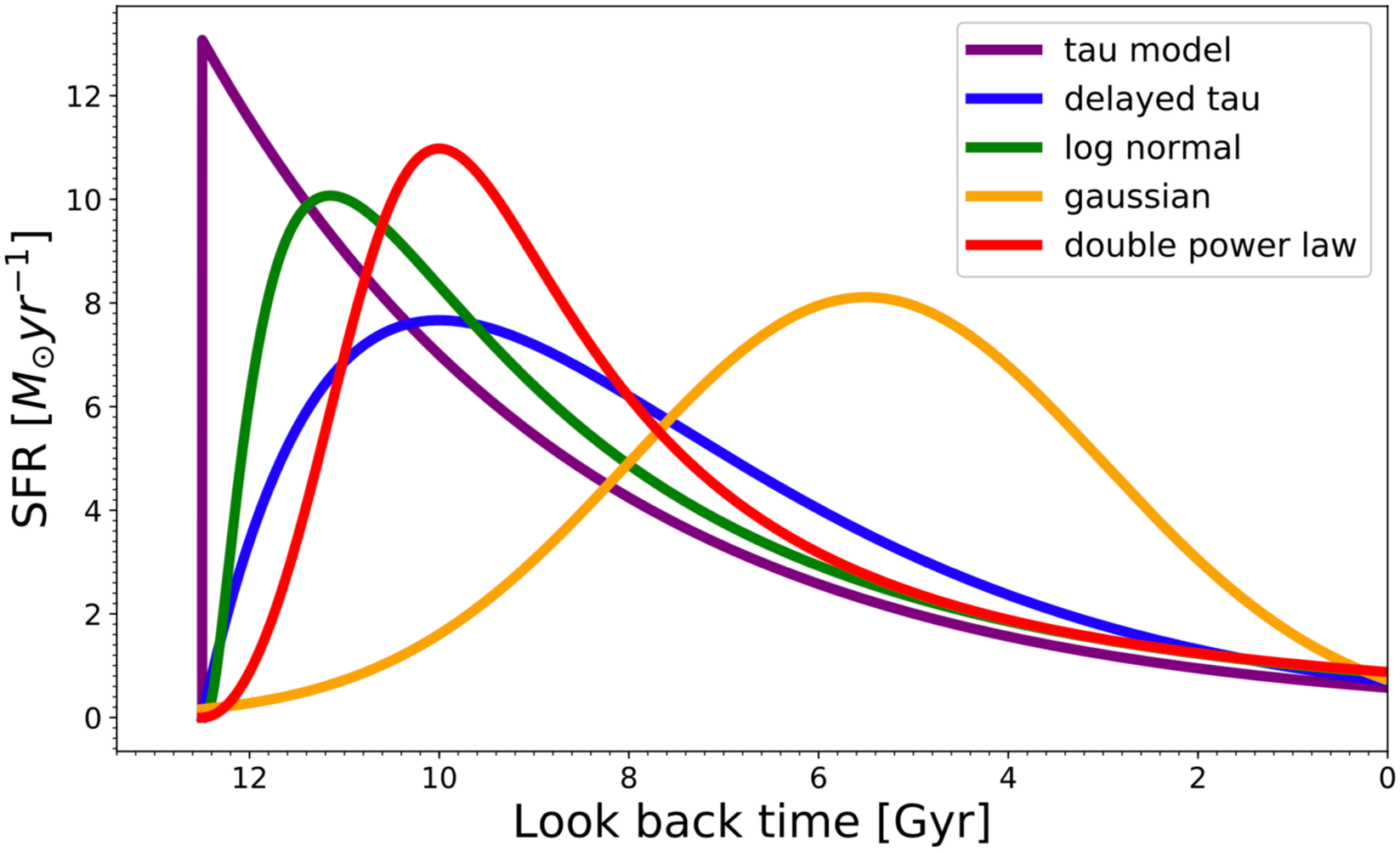


Absorption, reddening, and reemission



Star formation histories

$$SFR(t) \approx t \exp(-t/\tau)$$



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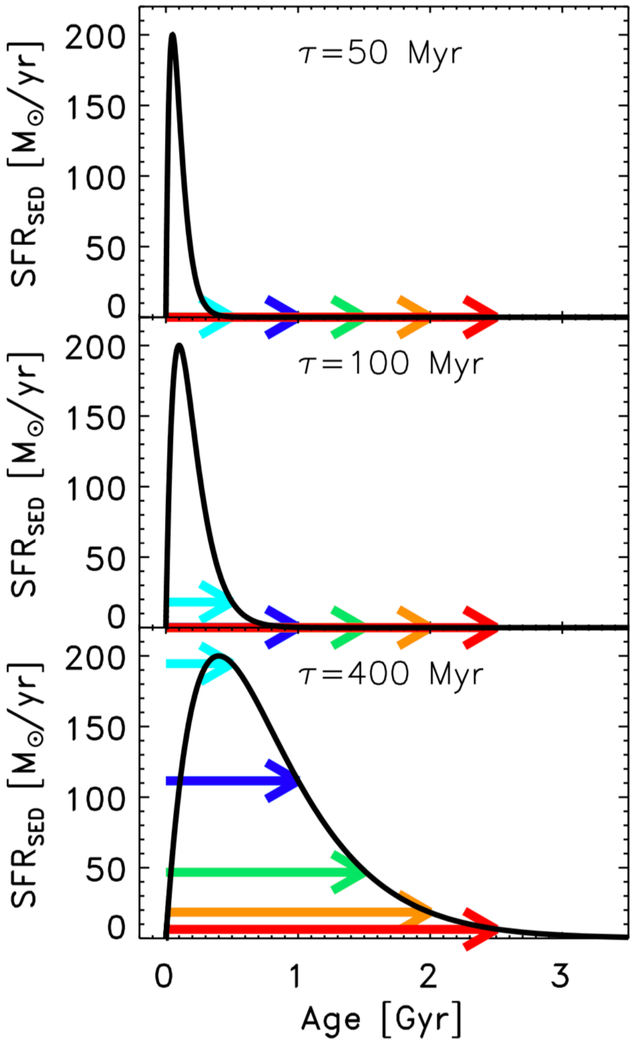
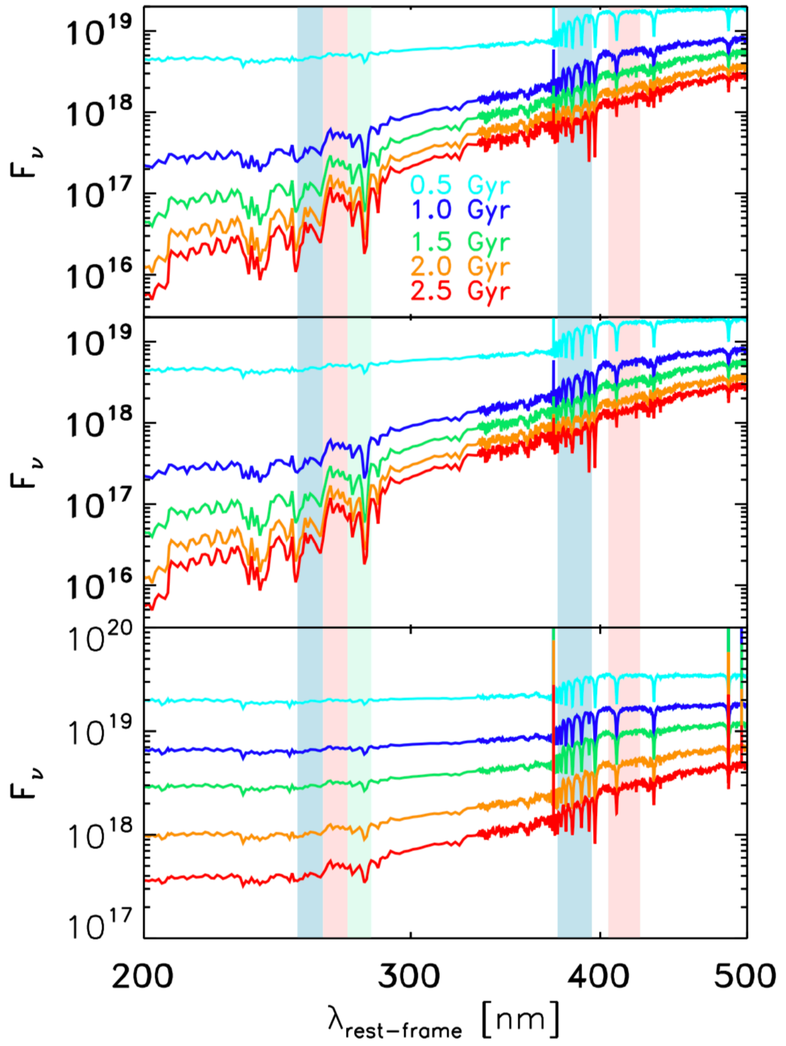
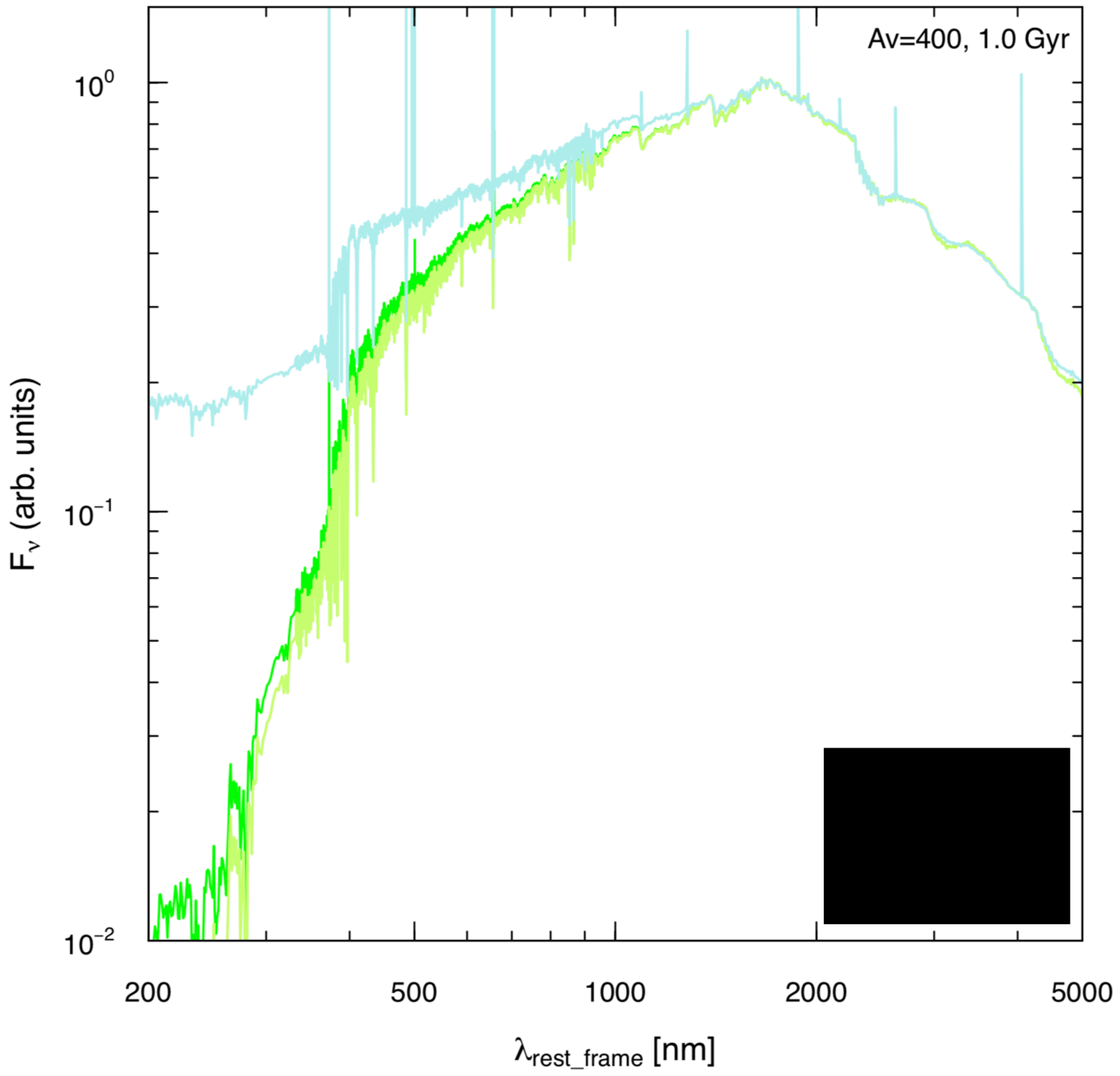
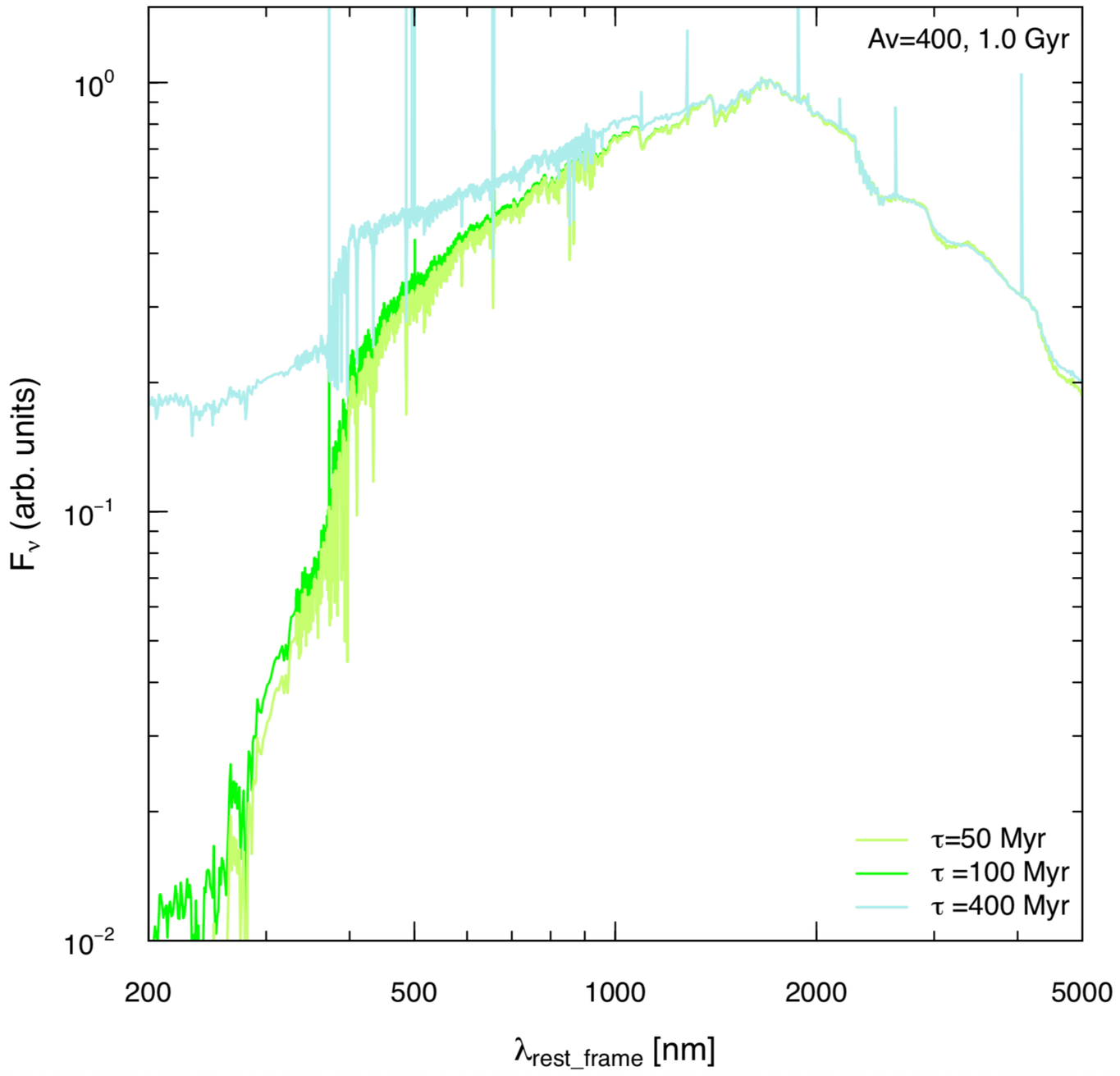





Av=400, 1.0 Gyr
10^0
10^{-1}
10^{-2}
F_ν (arb. units)
200
500
1000
2000
5000
λ_{rest_frame} [nm]

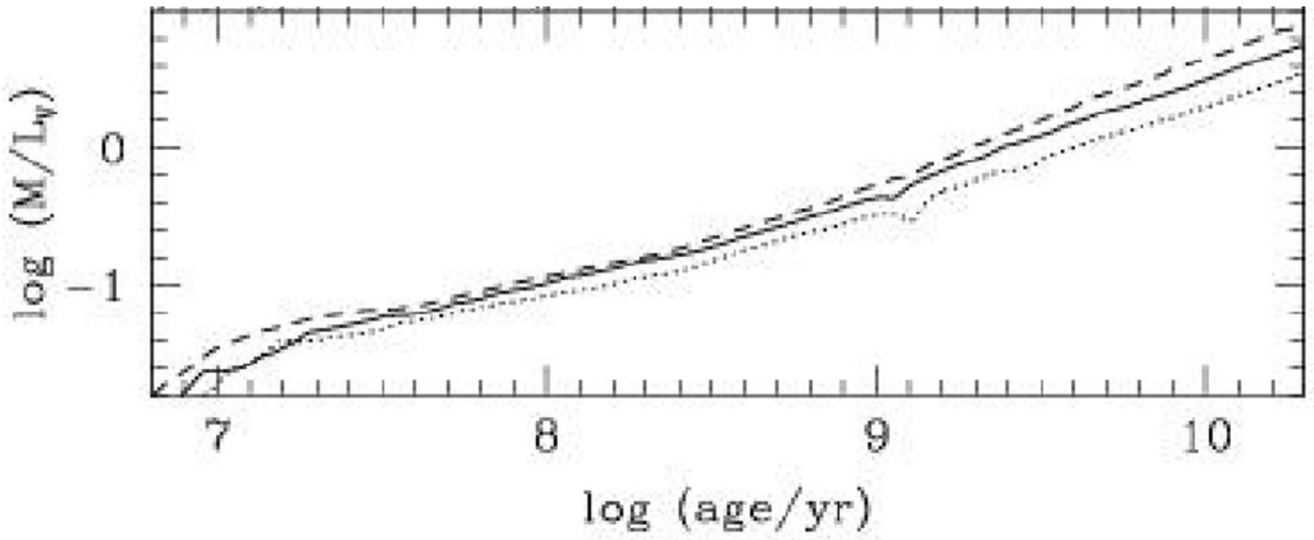

Av=400, 1.0 Gyr
10^0
10^{-1}
10^{-2}
F_ν (arb. units)
200
500
1000
2000
5000
λ_{rest_frame} [nm]
τ=50 Myr
τ =100 Myr
τ =400 Myr

Real galaxy spectra

http://skyserver.sdss.org/dr16/en/tools/chart/list.aspx

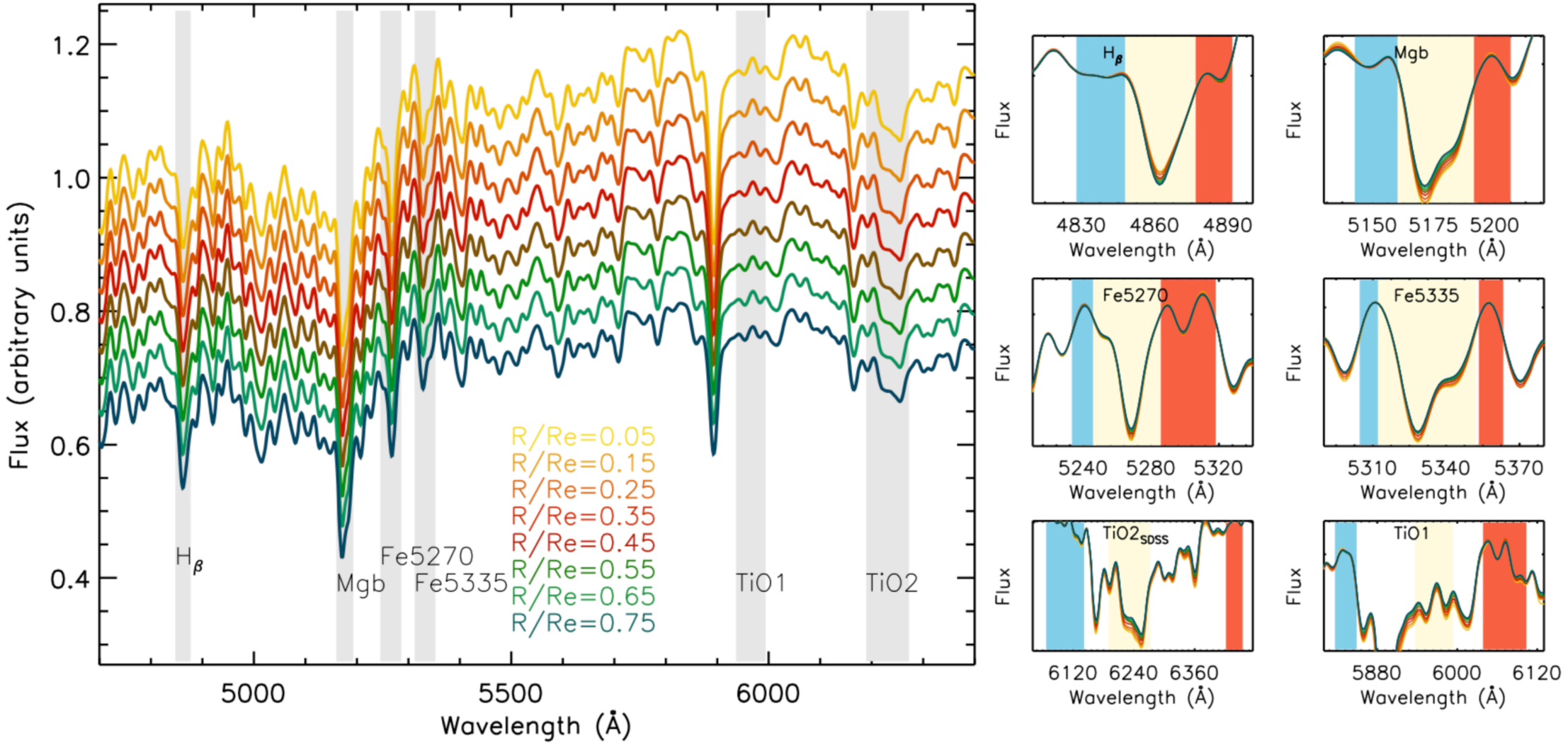
Mass-to-light ratio

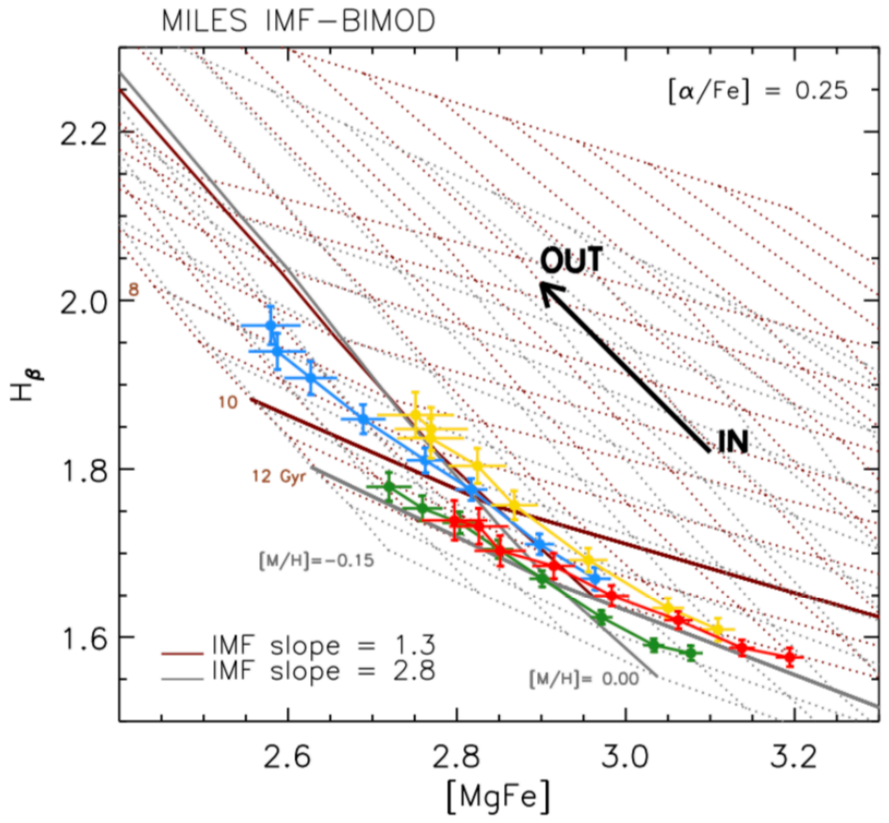
- If we understand the properties of SP, we can use L to infer M in stars by invoking M/L
- It has units of $M_\odot/L_\odot$, so the Sun has M/L=1
  - An A-type MS star with $L = 12L_\odot$ and $M = 2M_\odot$, it has $(M/L) = 0.17M_\odot/L_\odot$
  - A K-type MS star with $L = 0.3L_\odot$ and $M = 0.75M_\odot$, has $(M/L) = 2.5M_\odot/L_\odot$

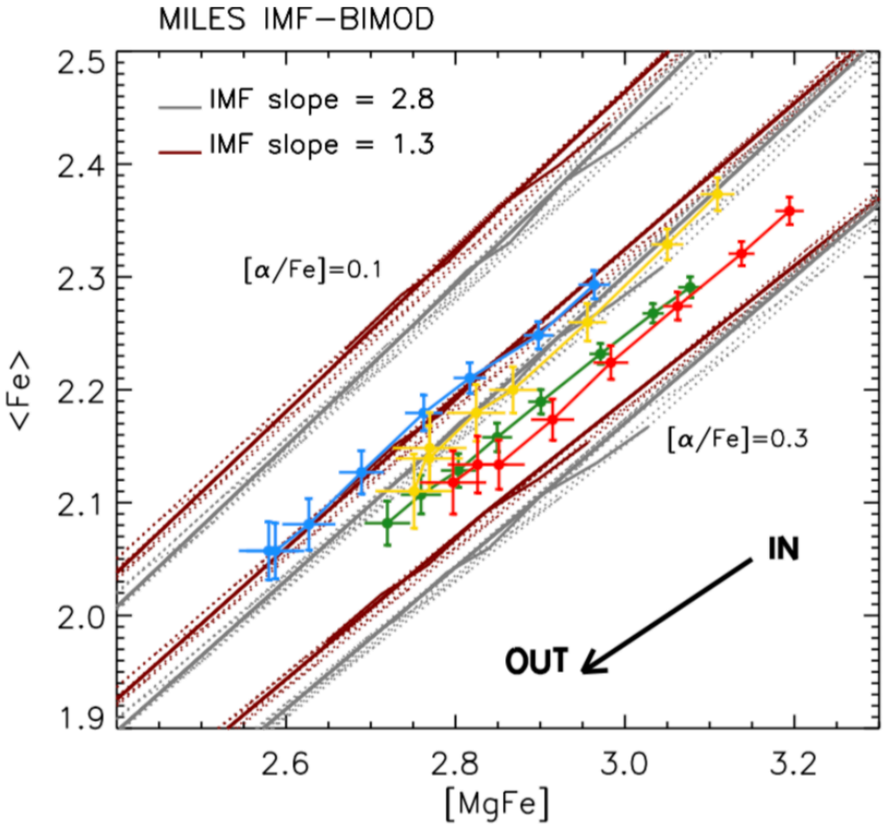


- Q: Does the M/L increase or decrease with time for a SSP?

Lick indices

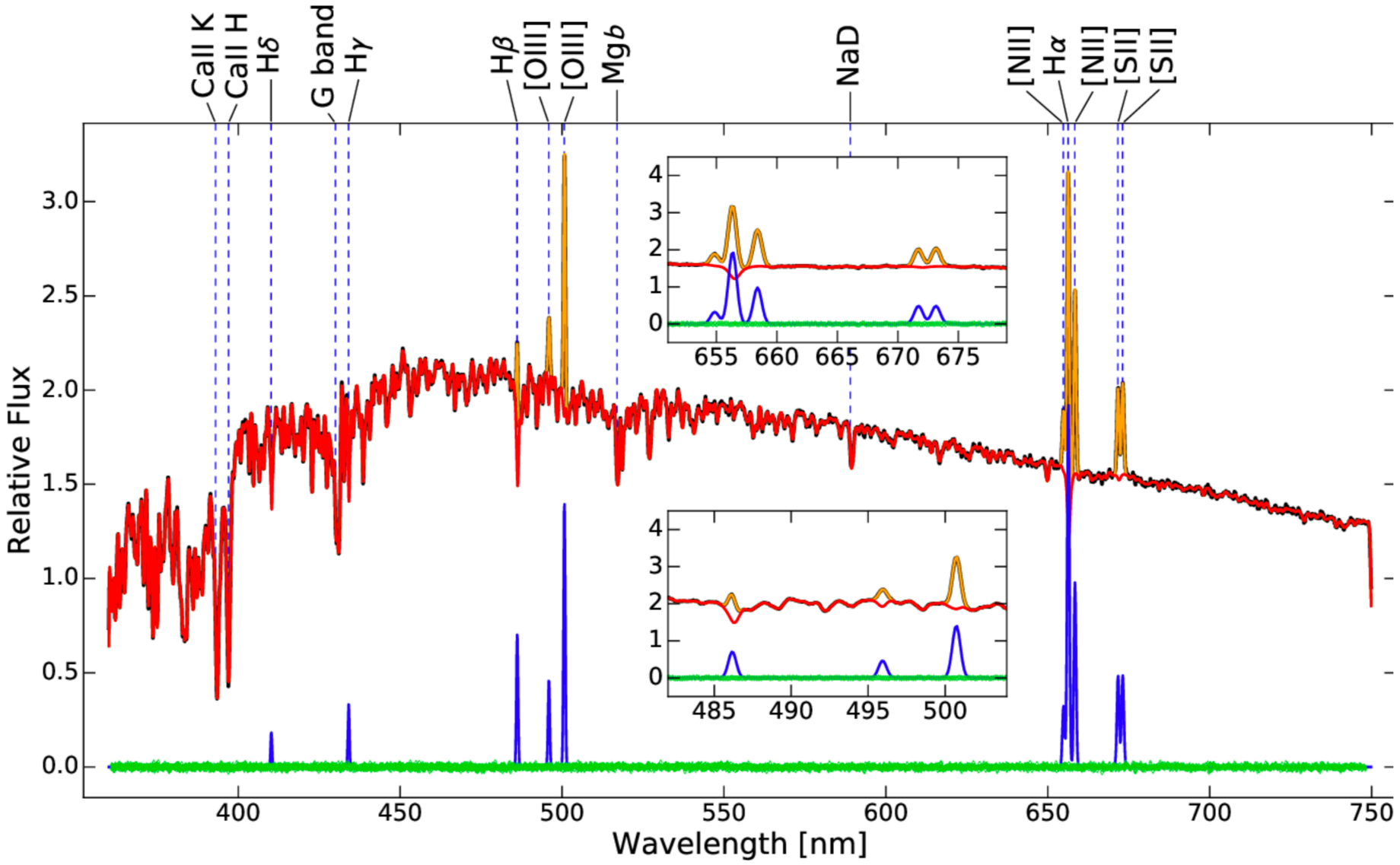






- Lick indices are measured on observed spectra and compared to the predictions of theoretical models.
- Hb-MgFe good indicator of age-metallicity.
- <Fe>-MgFe good alpha-enhancement indicator.
- Tio2 good IMF indicator.

Spectral synthesis



- FIREFLY
- PPXF
- Starlight
- Prospector
- …

- Q: What are the ‘output’ parameters of a spectral fitting?

→ SFH(t,Z): 2 approaches

SFH → $L_{gal}(\lambda)$

Given a SFH, what is the resulting galaxy spectrum?

Evolutionary Population Synthesis

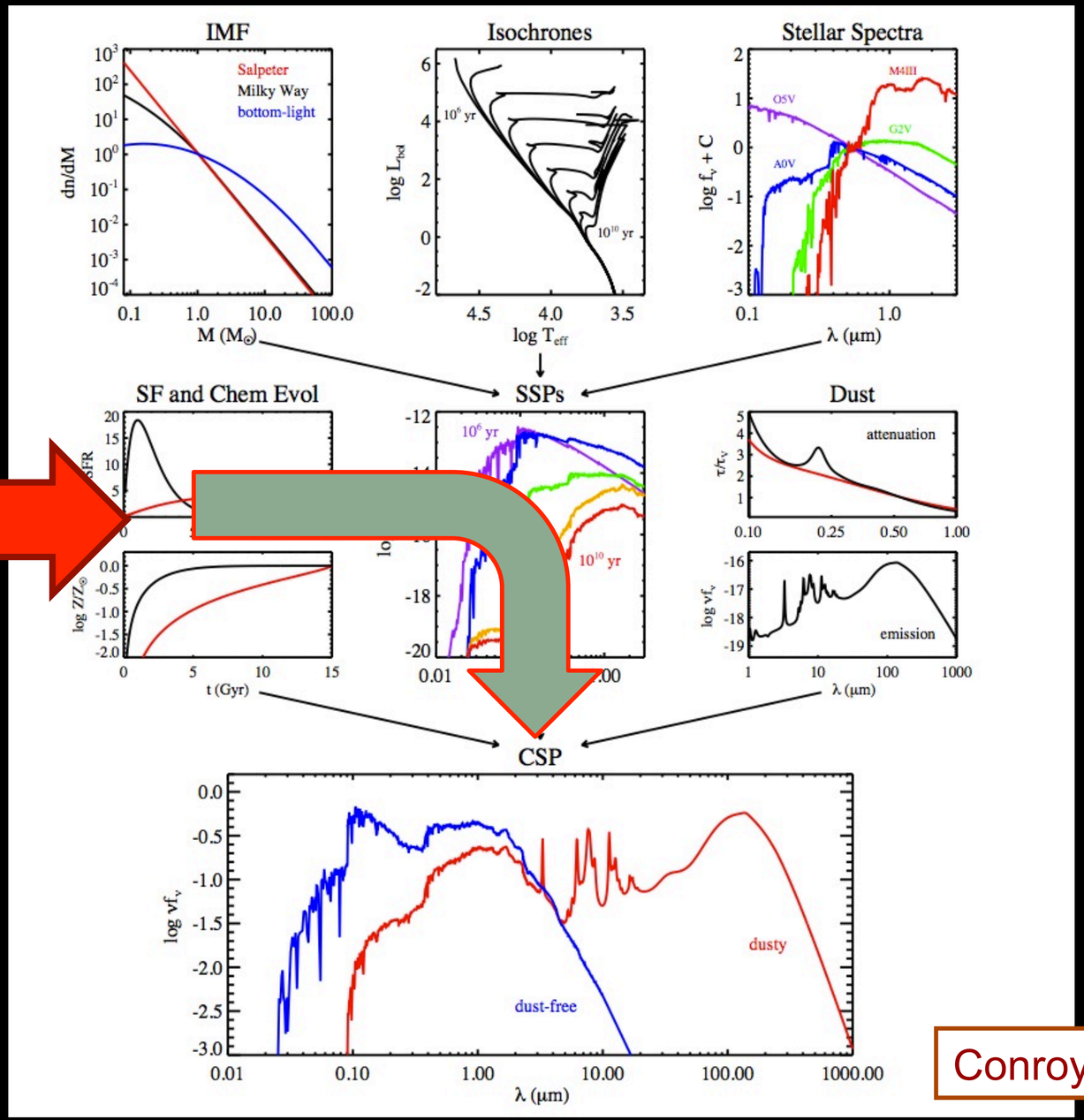
$L_{gal}(\lambda)$ → SFH

Given a galaxy spectrum, what is the SFH?

Inverse Population Synthesis

Forward spectral synthesis

ASSUME
Star Formation History



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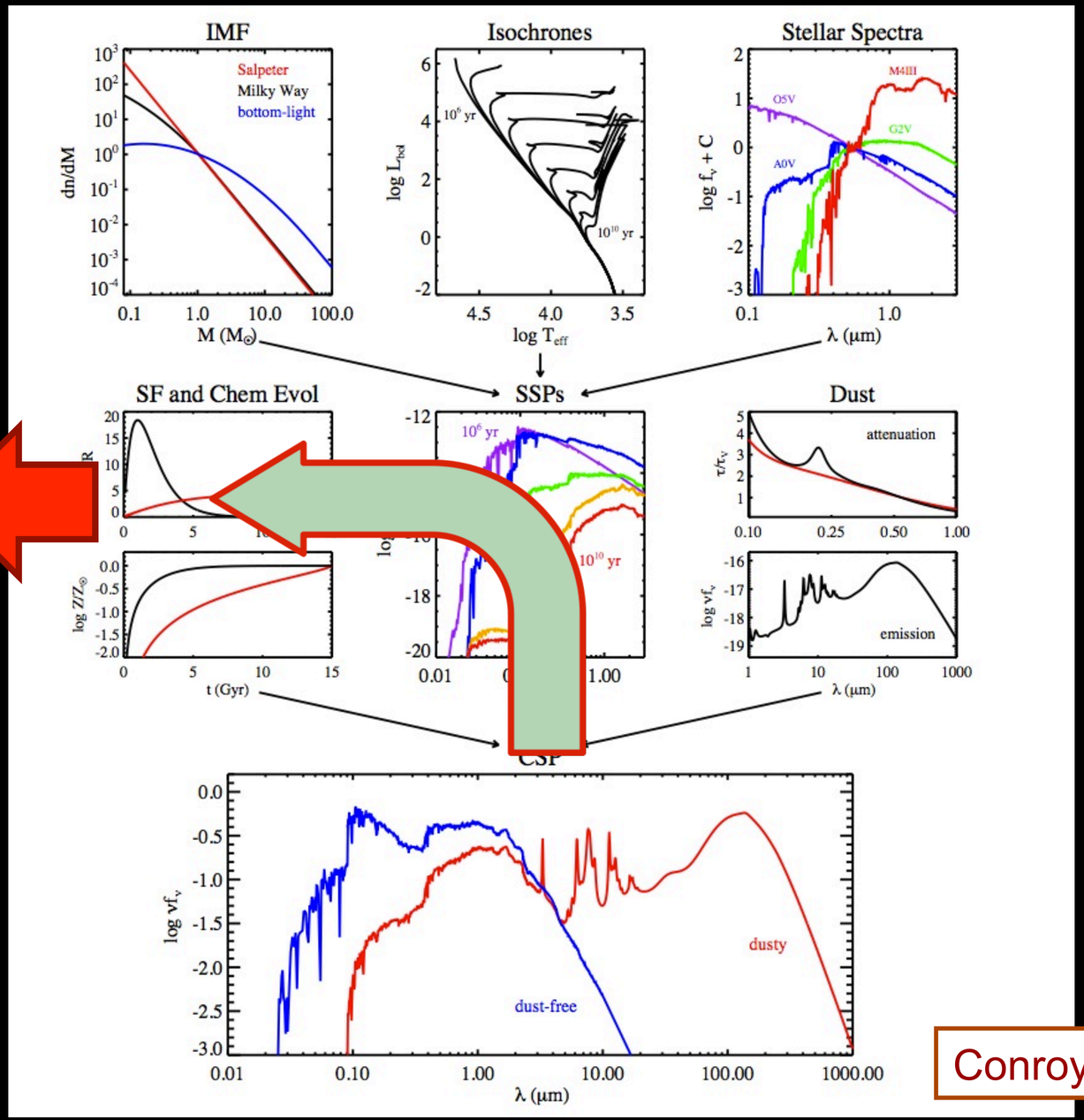
Inverse spectral synthesis



DERIVE Star Formation History

Conroy 2013

→ SFH(t,Z): 2 approaches

Evolutionary Pop Synthesis

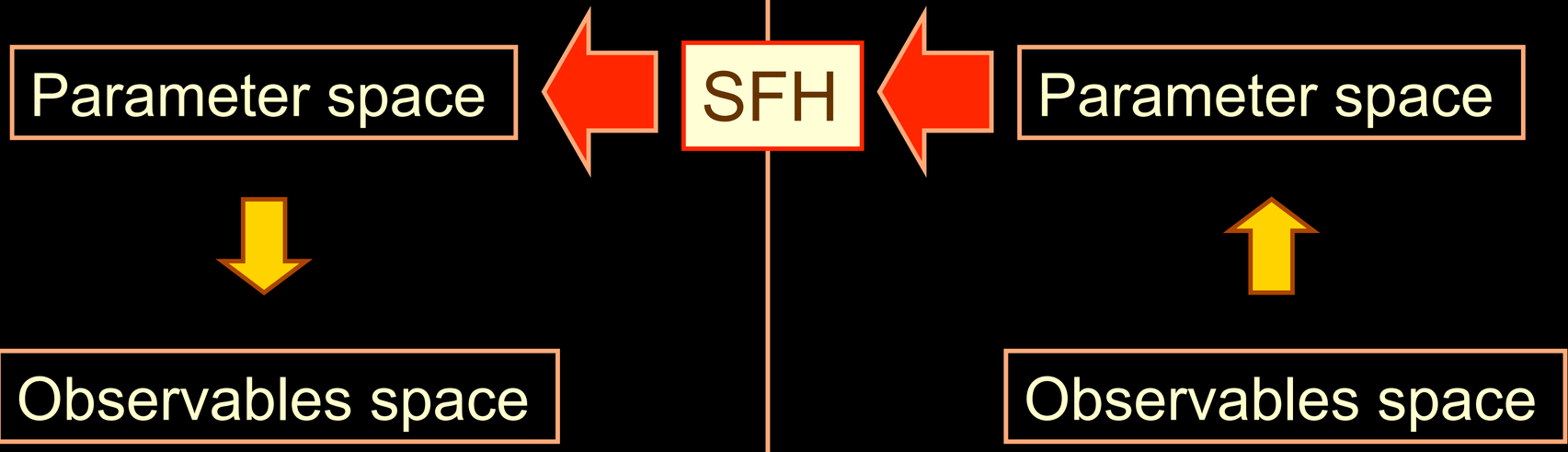
= Forward Modeling
Predict spectra(t,Z,...)
Ab initio calculation of

$L_{gal}(\lambda \mid \text{SFH parameters})$

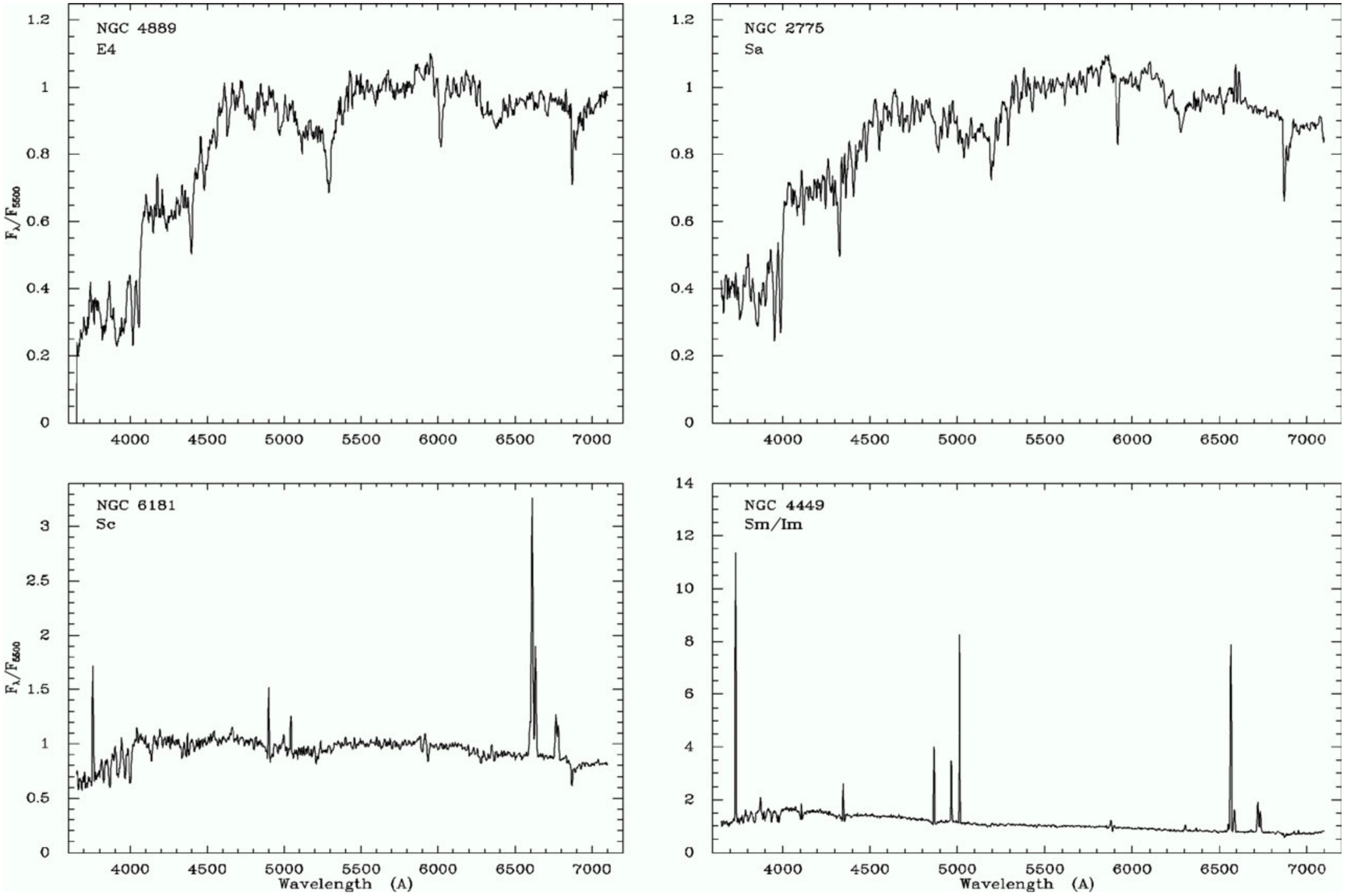
Inverse Pop Synthesis

= "Paleontology"
"Reverse engineering"
"Fossil Method"

Infer population parameters
from an observed $L_{gal}(\lambda)$

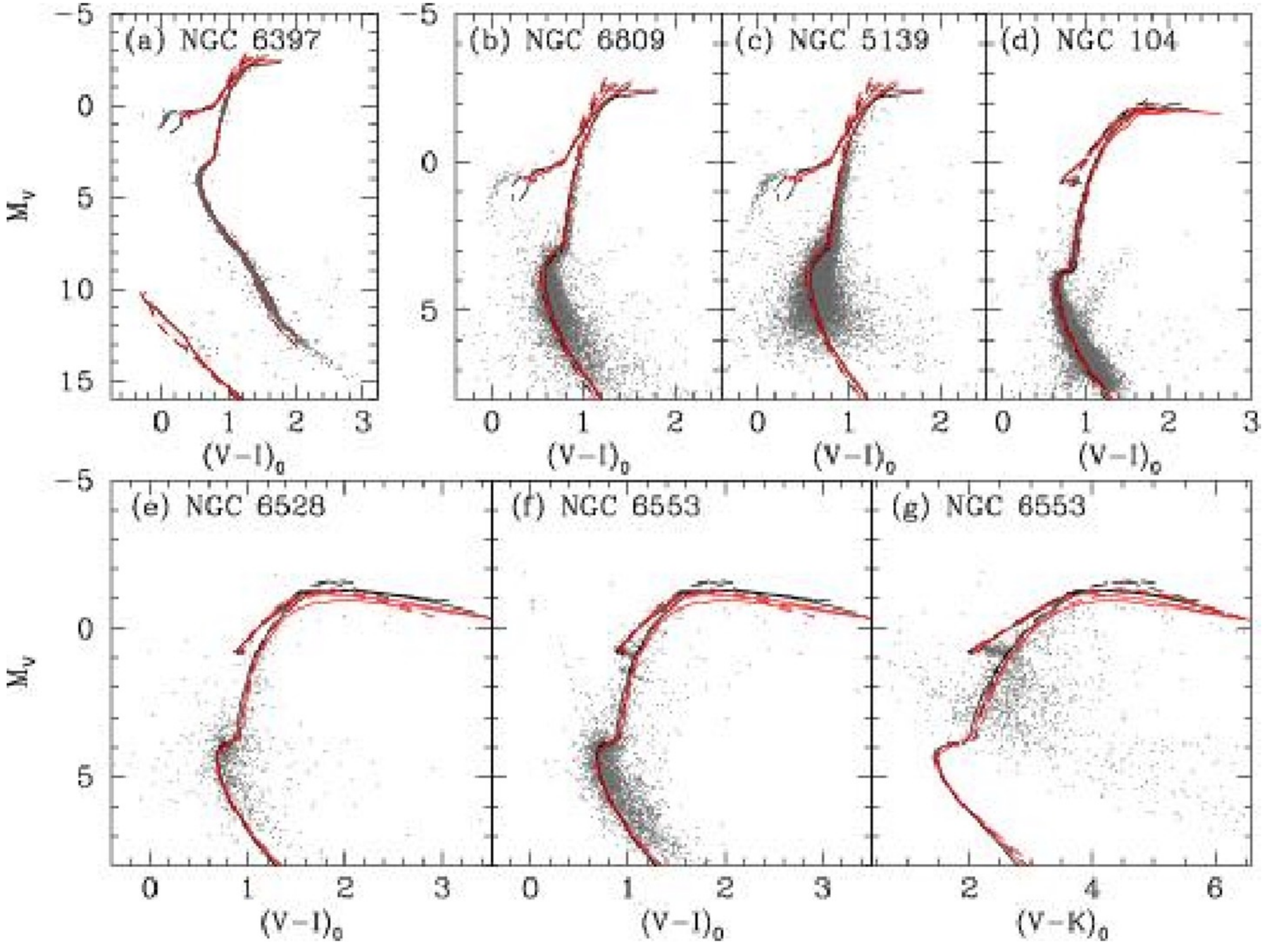


Q: : Which morphological class corresponds to each spectra?



More at https://www.zooniverse.org/talk/1268/582784

Backup


(a) NGC 6397
(b) NGC 6809
(c) NGC 5139
(d) NGC 104
(e) NGC 6528
(f) NGC 6553
(g) NGC 6553
M_V
$(V-I)_0$
$(V-K)_0$

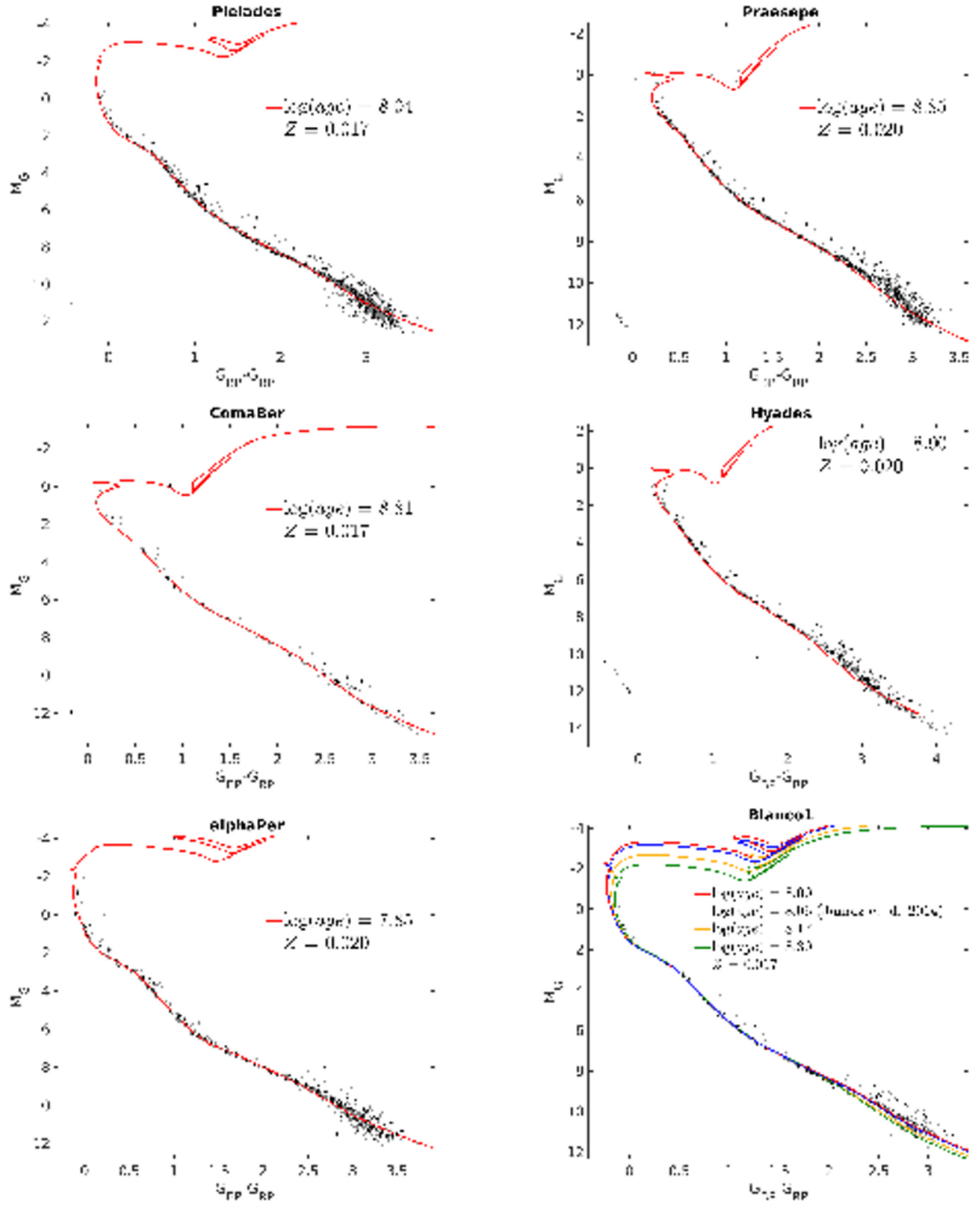
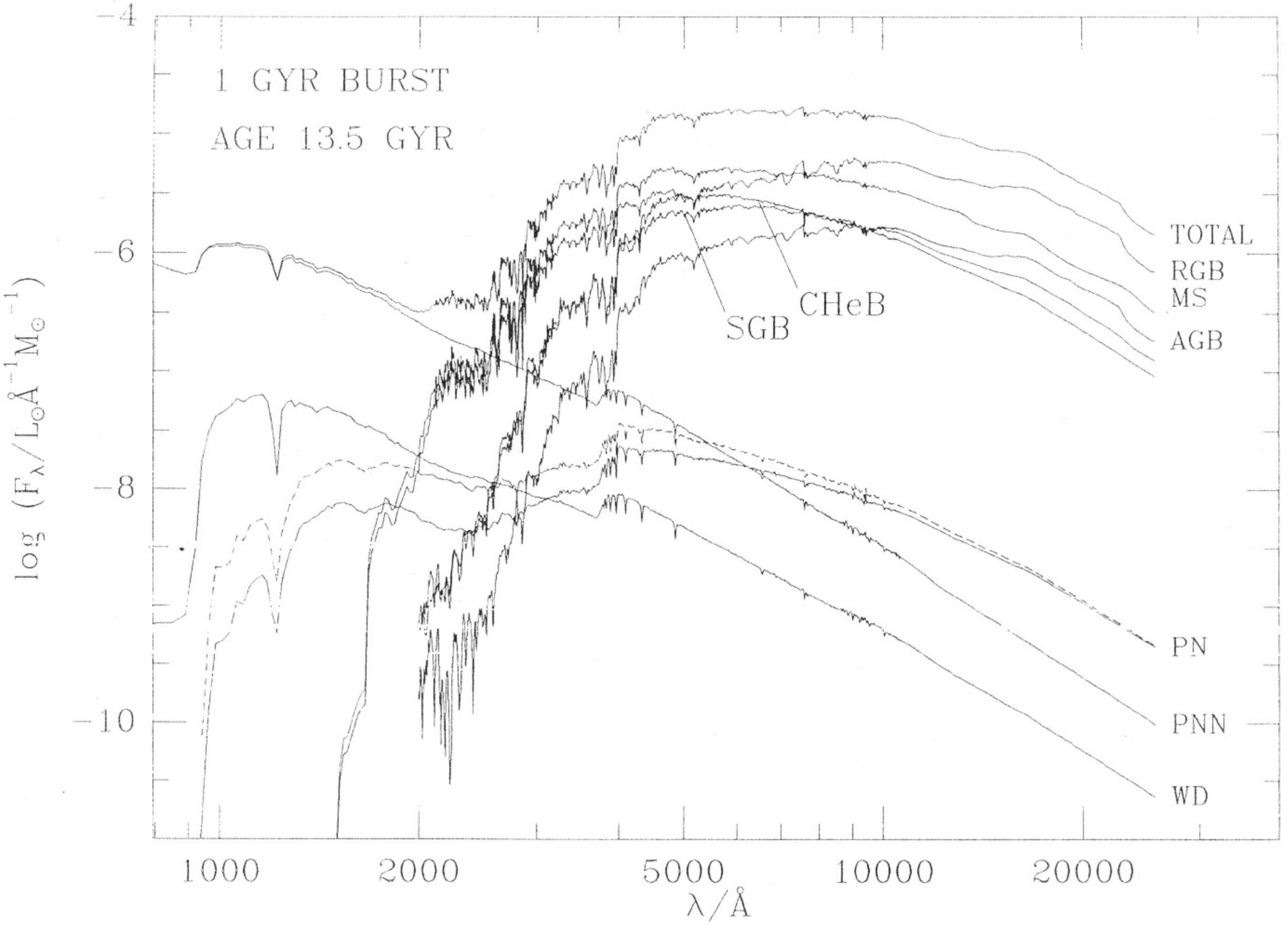
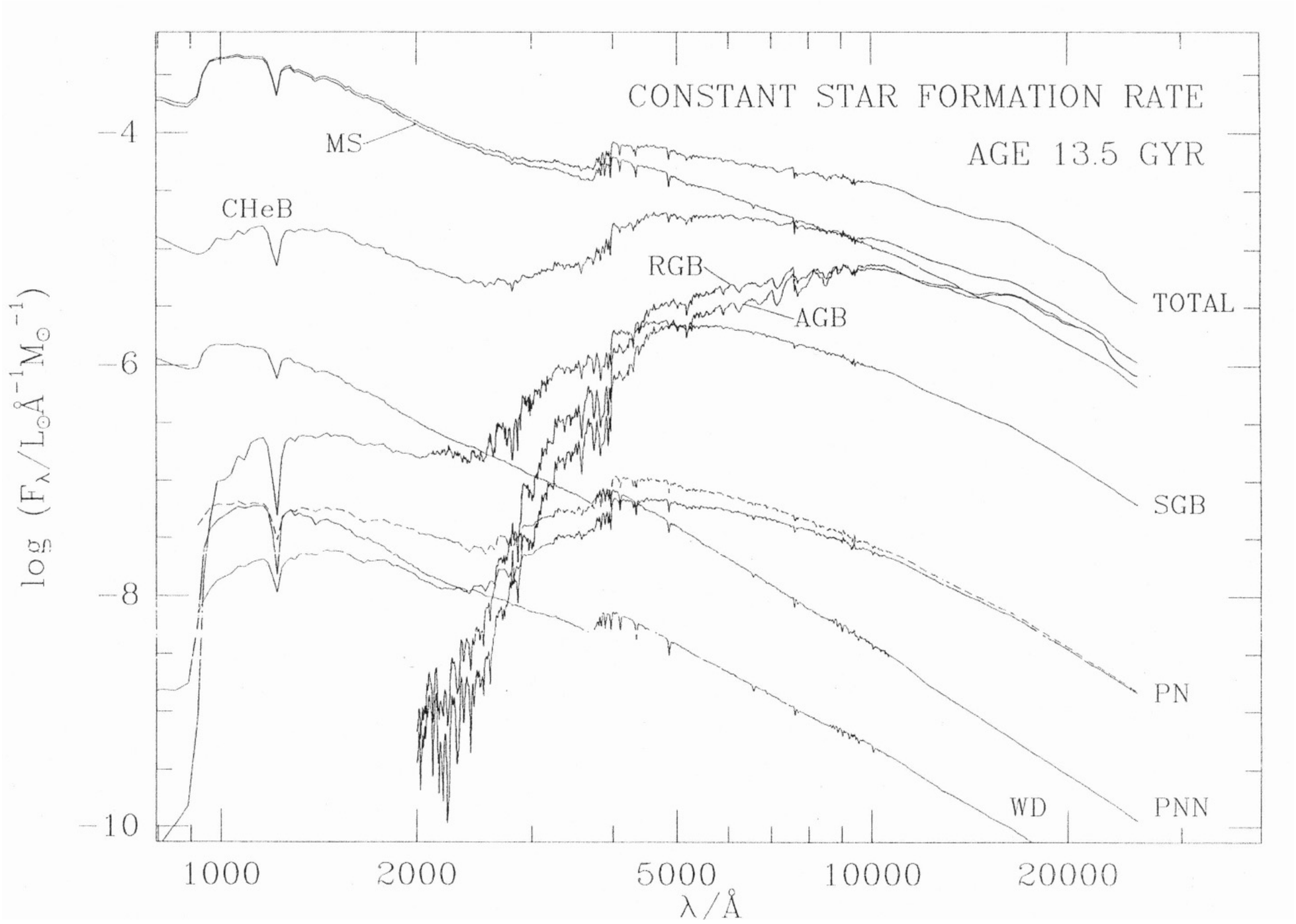
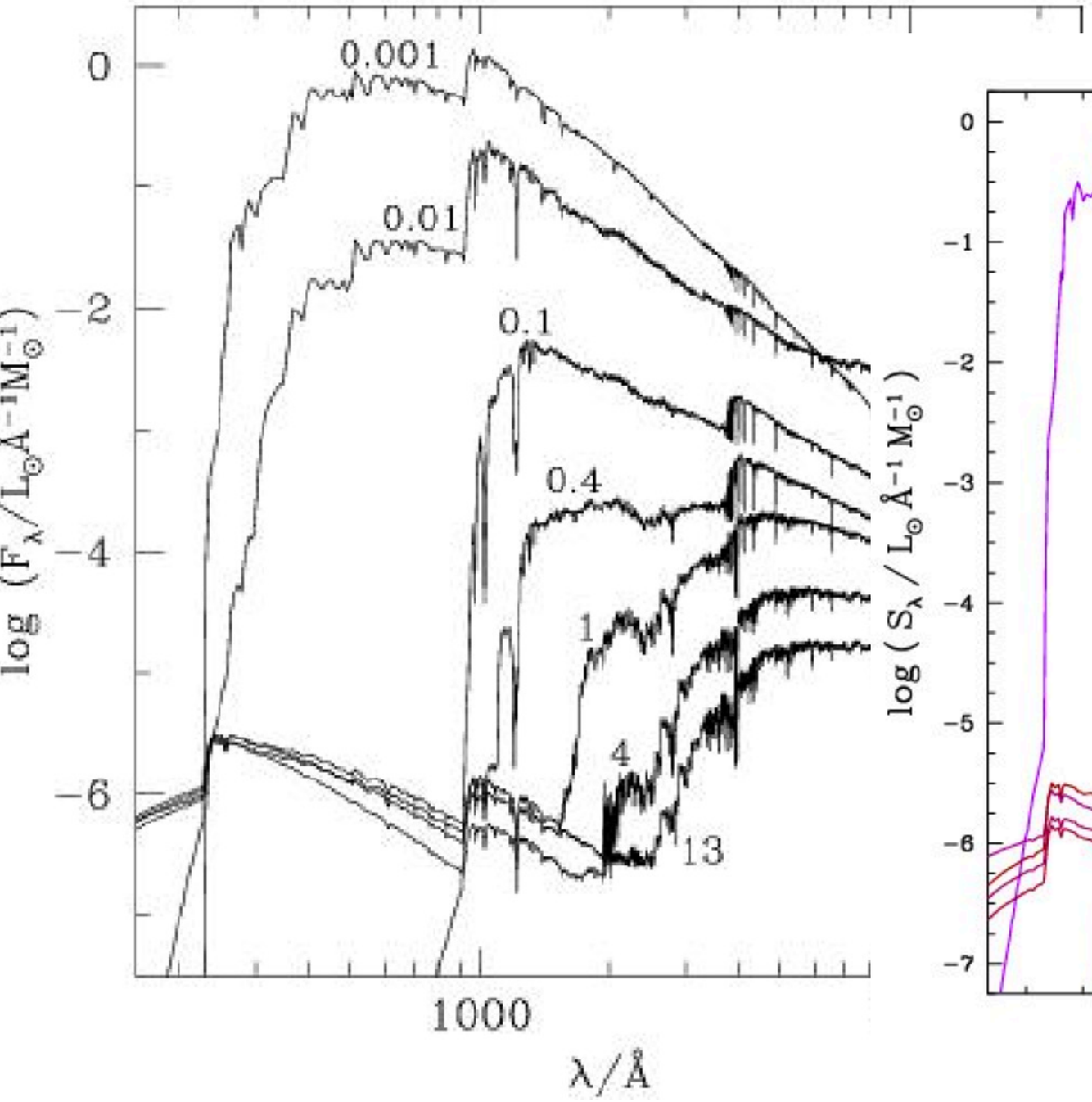


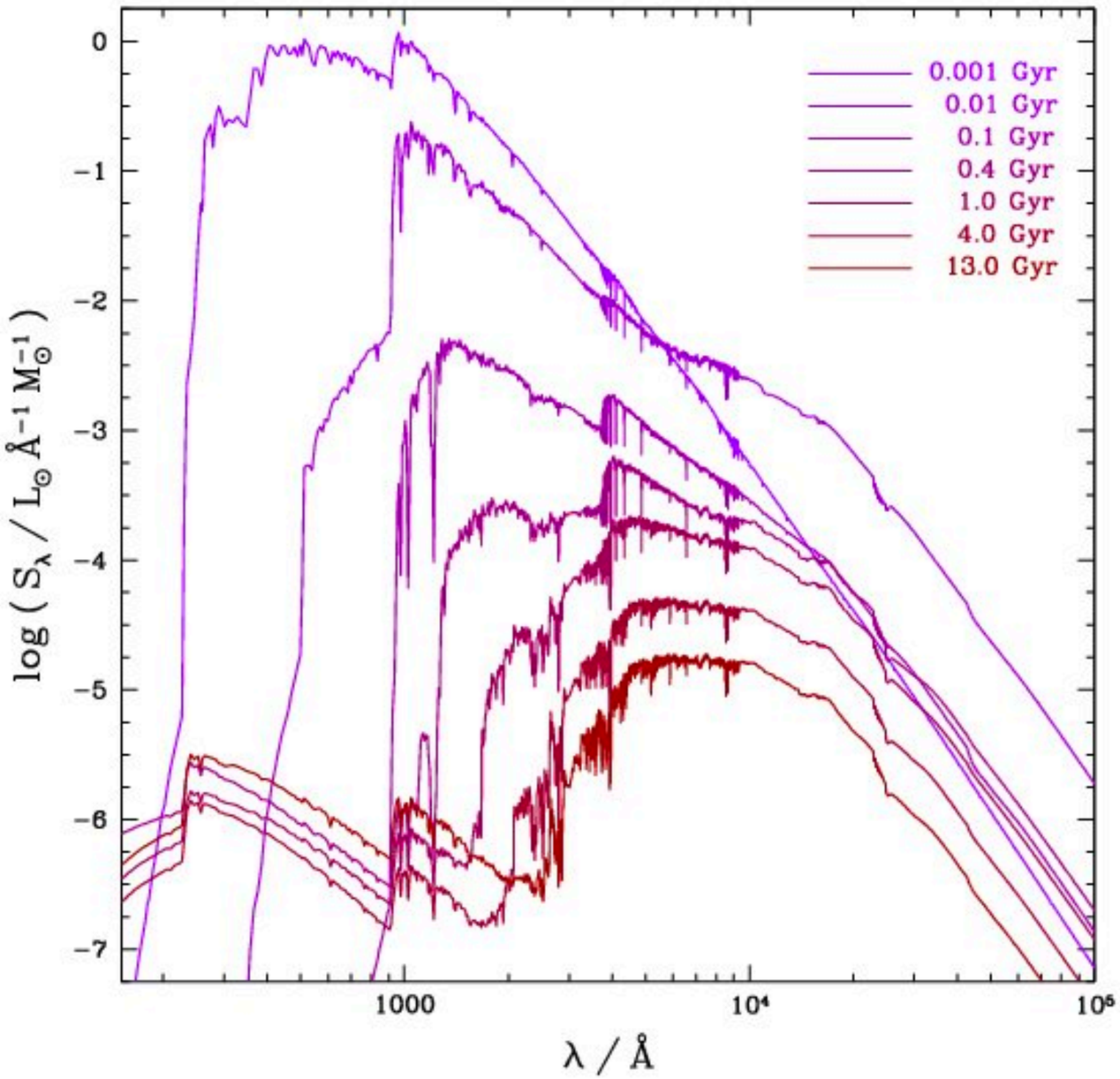
Fig. 17. HRDs of nearby clusters compared with PARSEC isochrones (see text for details) of the Pleiades (*panel a*), Praesepe (*panel b*), Coma Ber (*panel c*), Hyades (*panel d*), Alpha Per (*panel e*), and Blanco 1 (*panel f*). Praesepe, Hyades, and Alpha Per are fitted with $Z = 0.02$, while the others are reproduced using $Z = 0.017$.

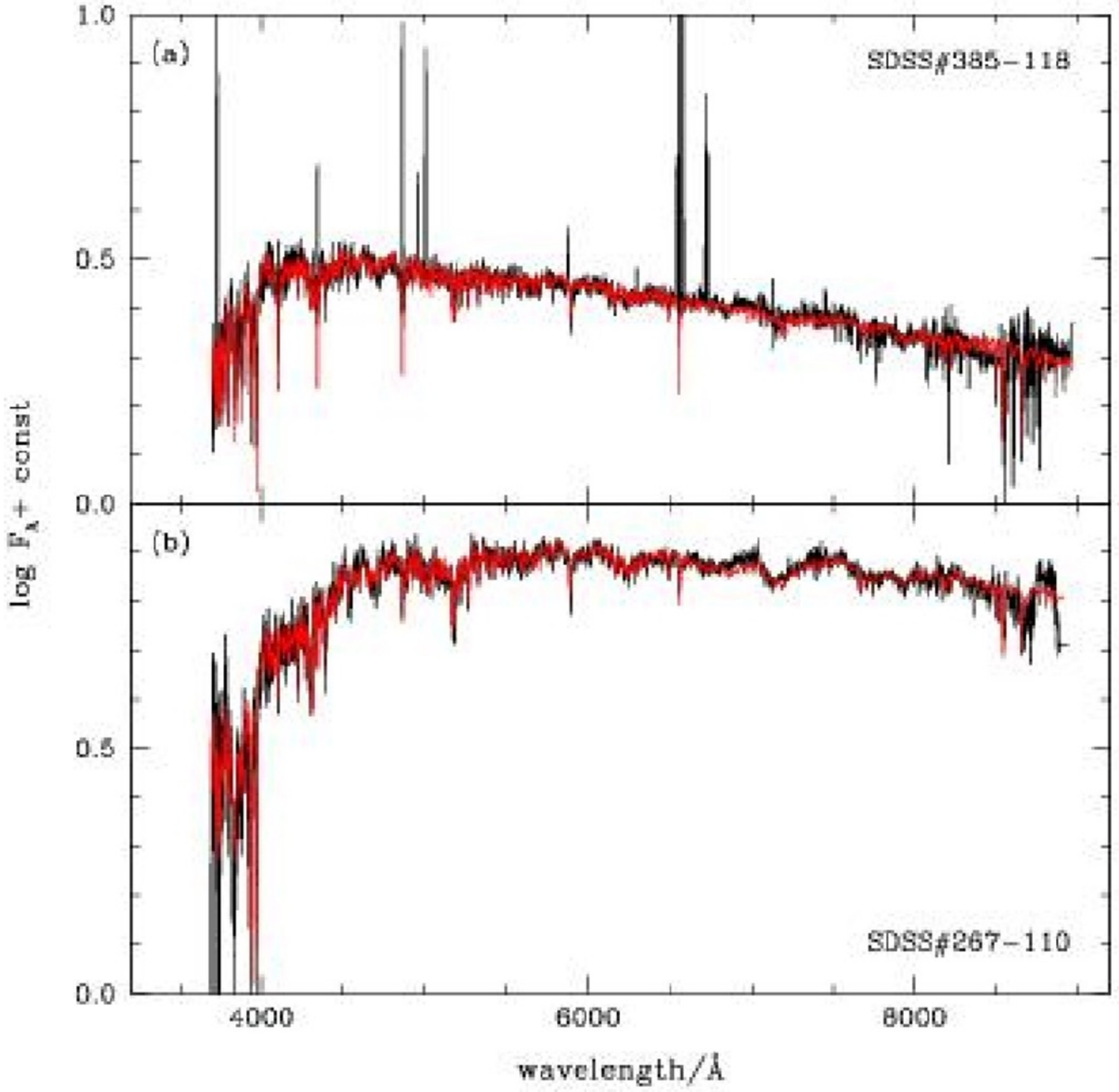

1 GYR BURST
AGE 13.5 GYR
TOTAL
RGB
MS
AGB
SGB
CHeB
PN
PNN
WD
-4
-6
-8
-10
1000
2000
5000
10000
20000
λ/Å
log (F_λ/L_⊙Å^-1 M_⊙^-1)

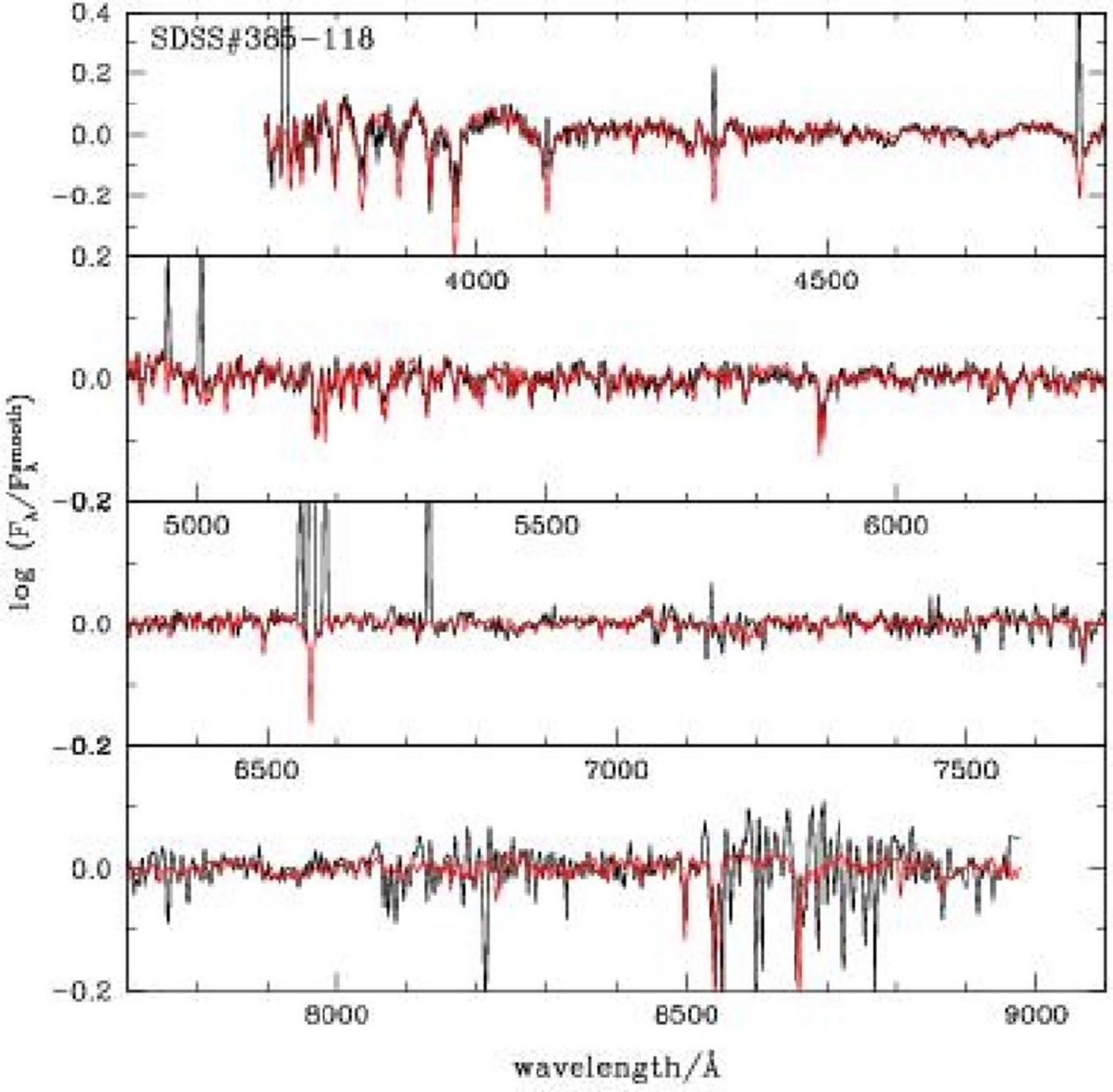

CONSTANT STAR FORMATION RATE
AGE 13.5 GYR
MS
CHeB
RGB
AGB
TOTAL
SGB
PN
PNN
WD
log (F_λ/L_⊙Å^-1 M_⊙^-1)
λ/Å
−4
−6
−8
−10
1000
2000
5000
10000
20000

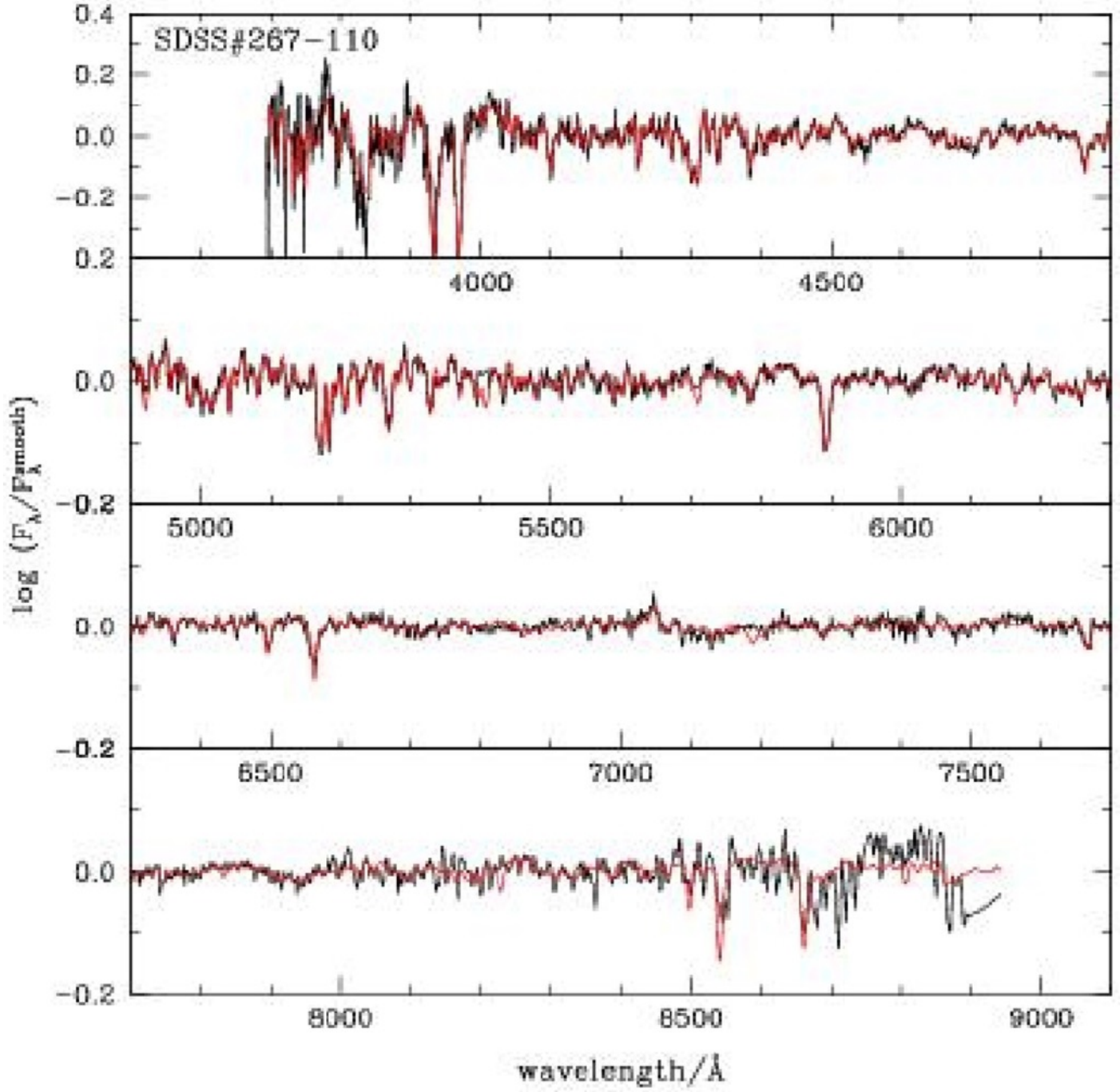
models, with ages indicated on the top right corner.
Figure adapted from Bruzual & Charlot (2003).






(a)
SDSS#385−118
(b)
SDSS#267−110
1.0
0.5
0.0
0.5
0.0
4000
6000
8000
log F_λ + const
wavelength/Å


SDSS#385−118
log (F_λ/F_λmsesh)
wavelength/Å


SDSS#267−110
0.4
0.2
0.0
−0.2
4000
4500
5000
5500
6000
6500
7000
7500
8000
8500
9000
log (F_λ/F_λ^smooth)
wavelength/Å