Stellar population synthesis models

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Galaxies and extragalactic astrophysics

Outline

- What is a stellar population?
- Stellar populations synthesis models
- Why we need SP models?
- Ingredients and uncertainties of the models
- Methodology. How to apply models to data?

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)

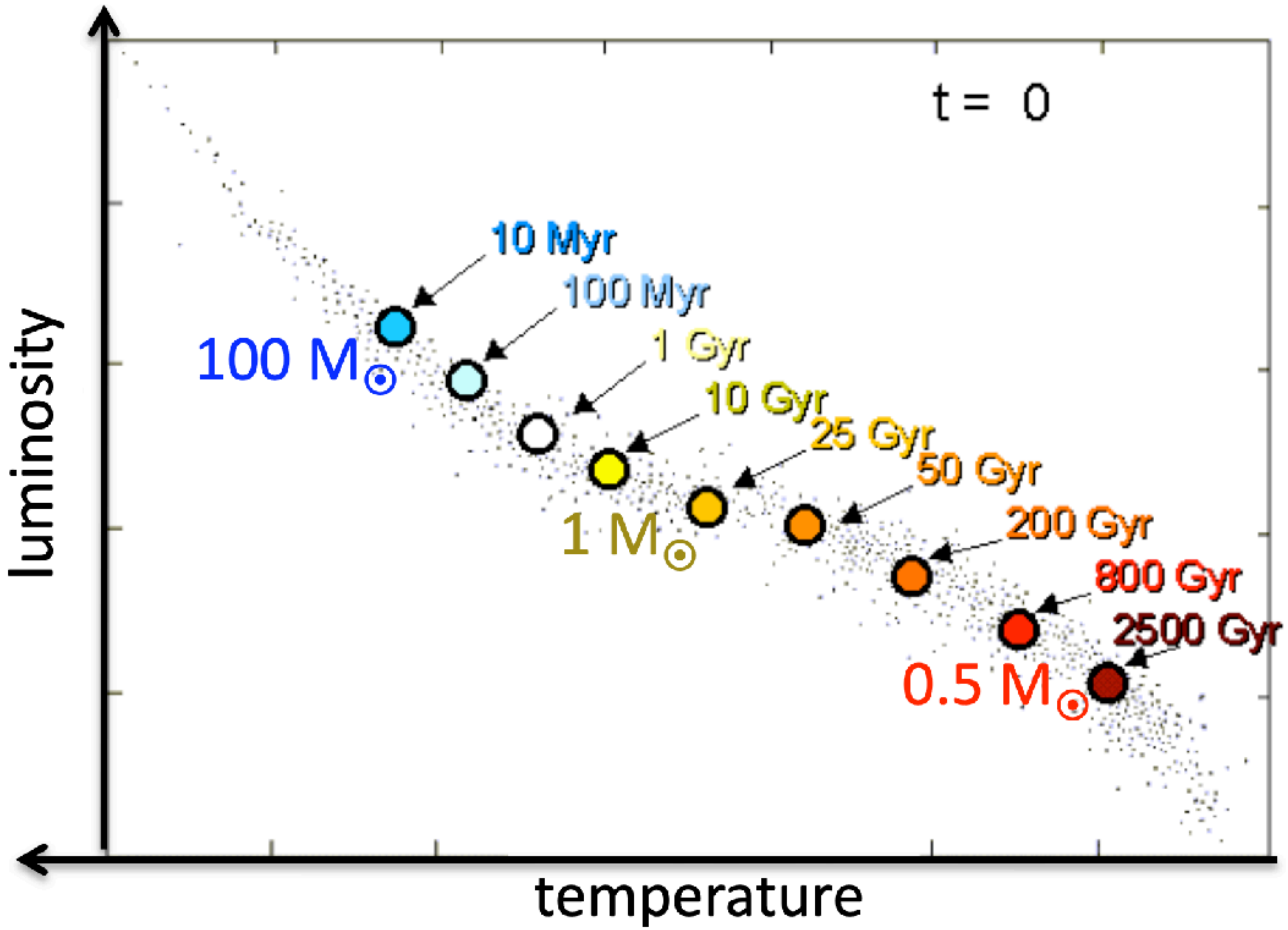
Simple stellar populations (SSP)

group of stars with same age (t) and same initial metallicity (Z)

M67

M4

Resolved populations - CMD



Resolved populations

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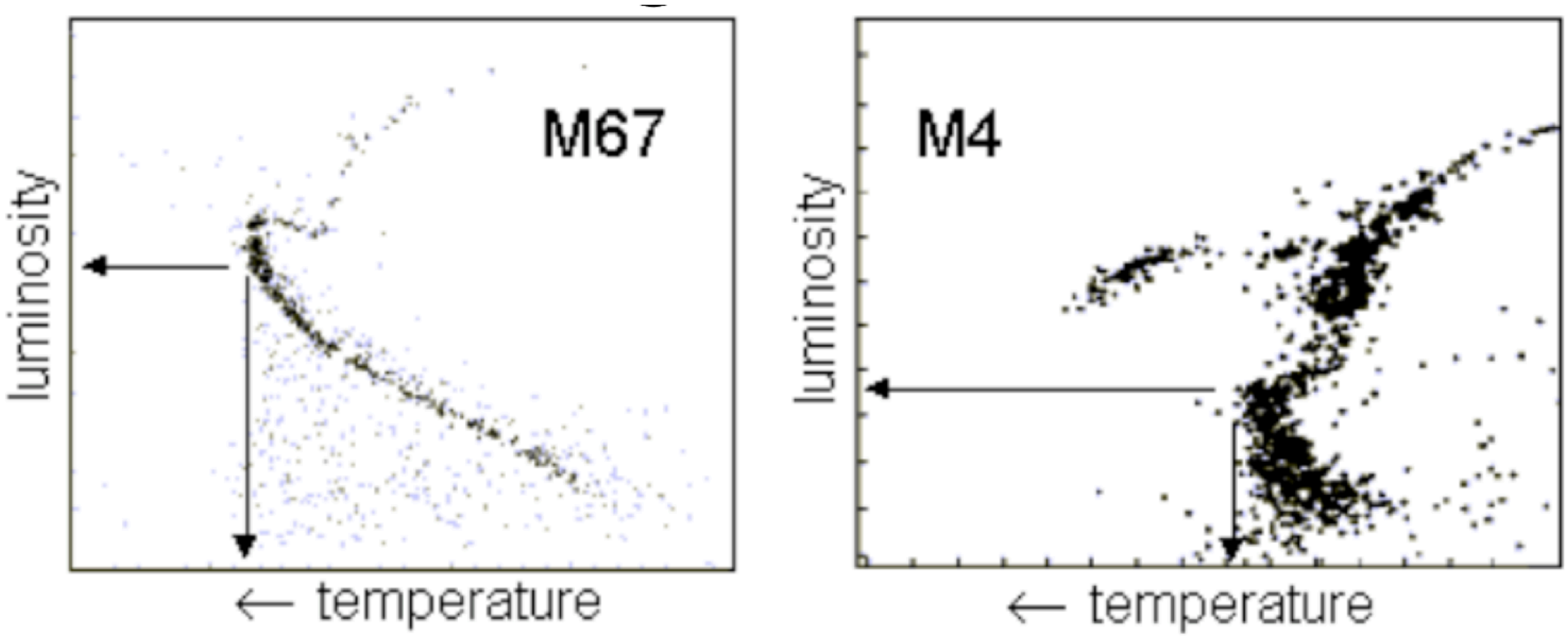
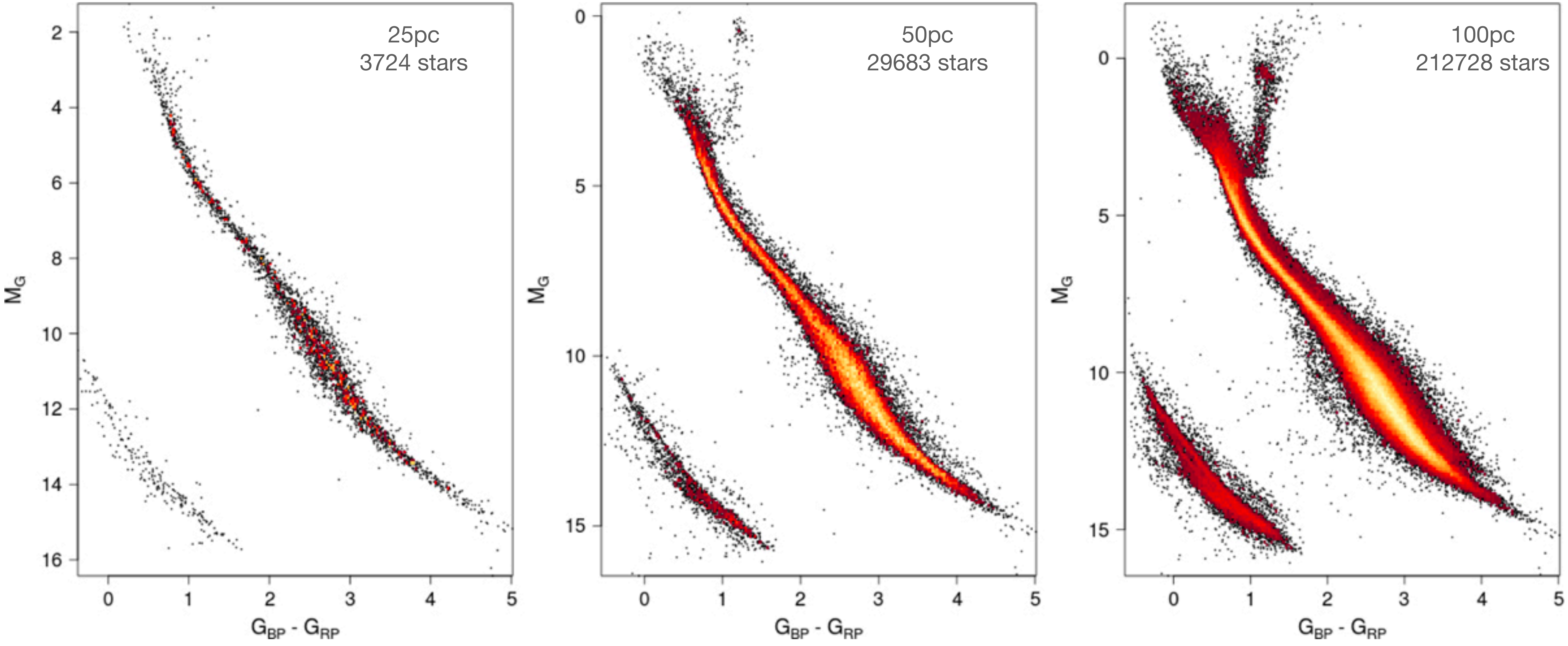
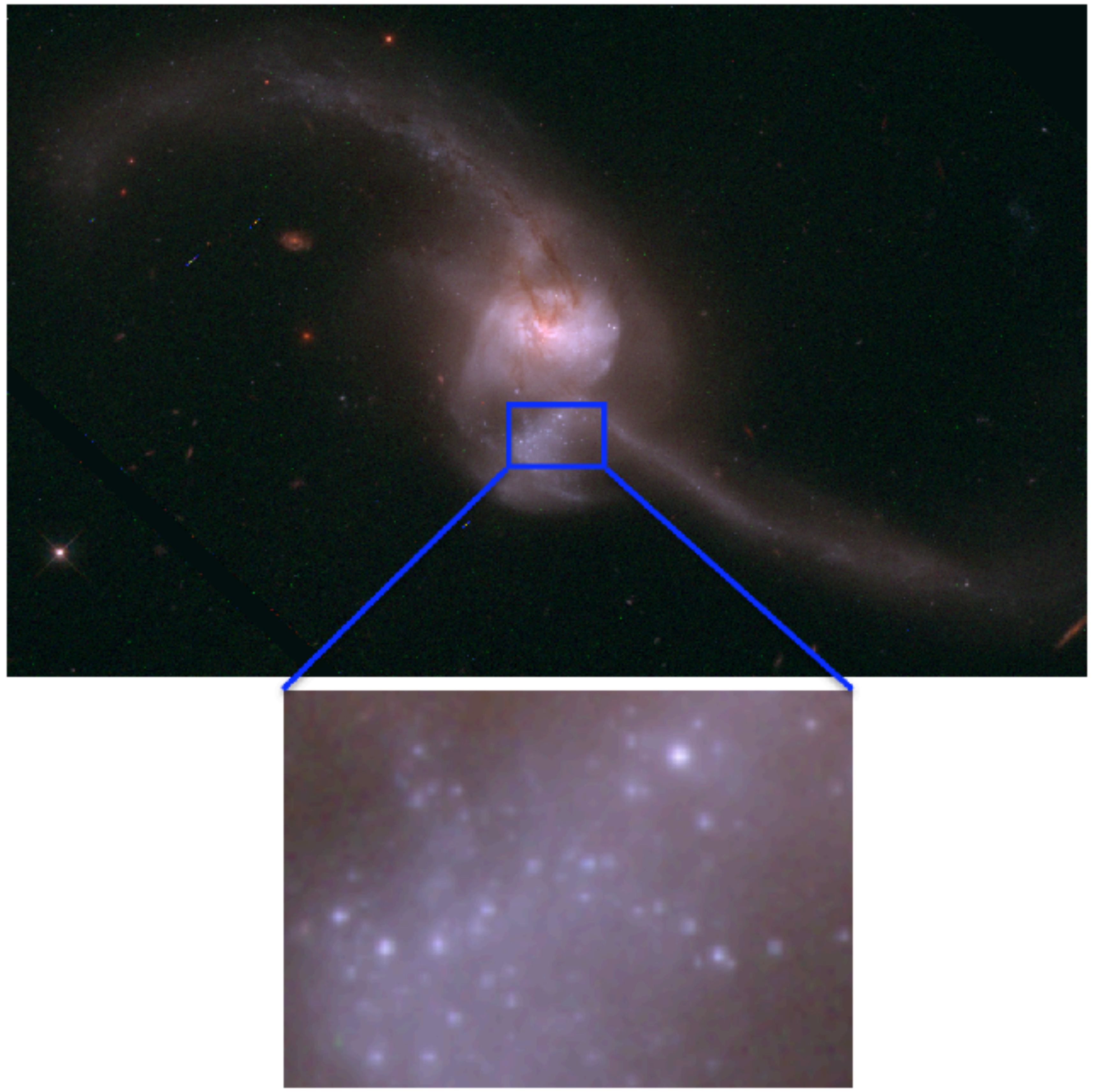


Ex: Gaia Solar neighborhood HRD

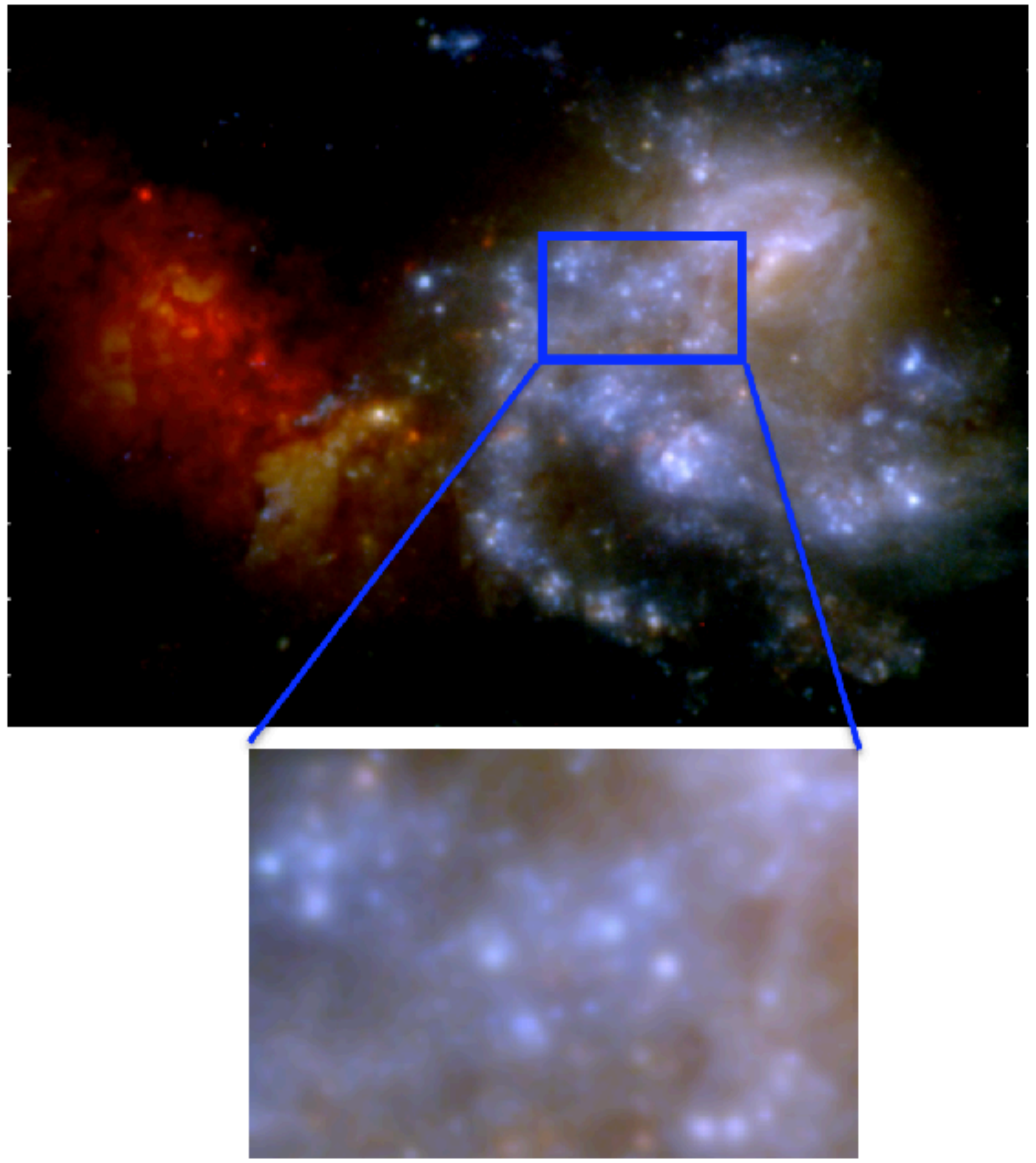


Un-resolved populations

Galaxies formed by several SSPs, we only know their **integrated** light spectra.



NGC 2623



IC 1623

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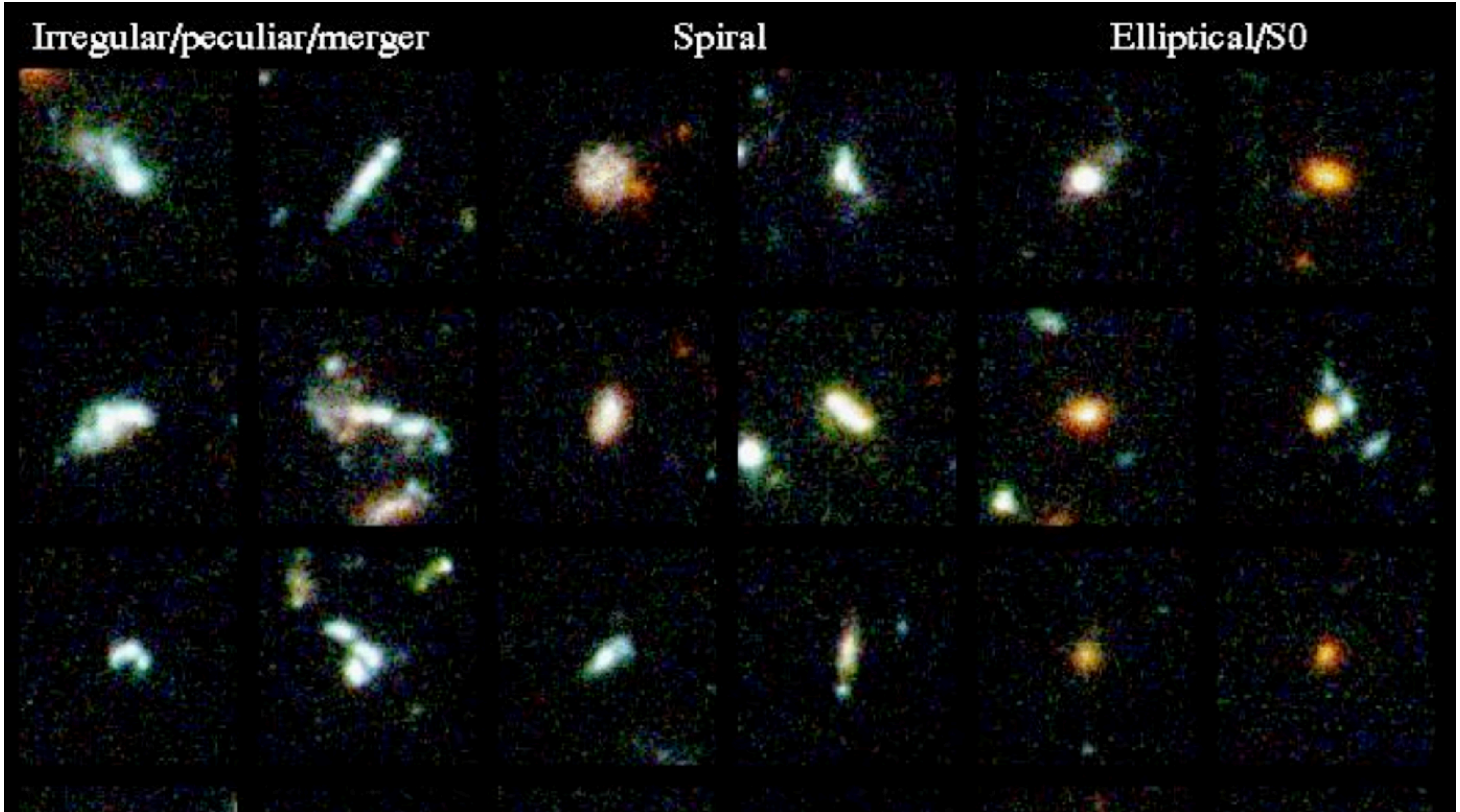
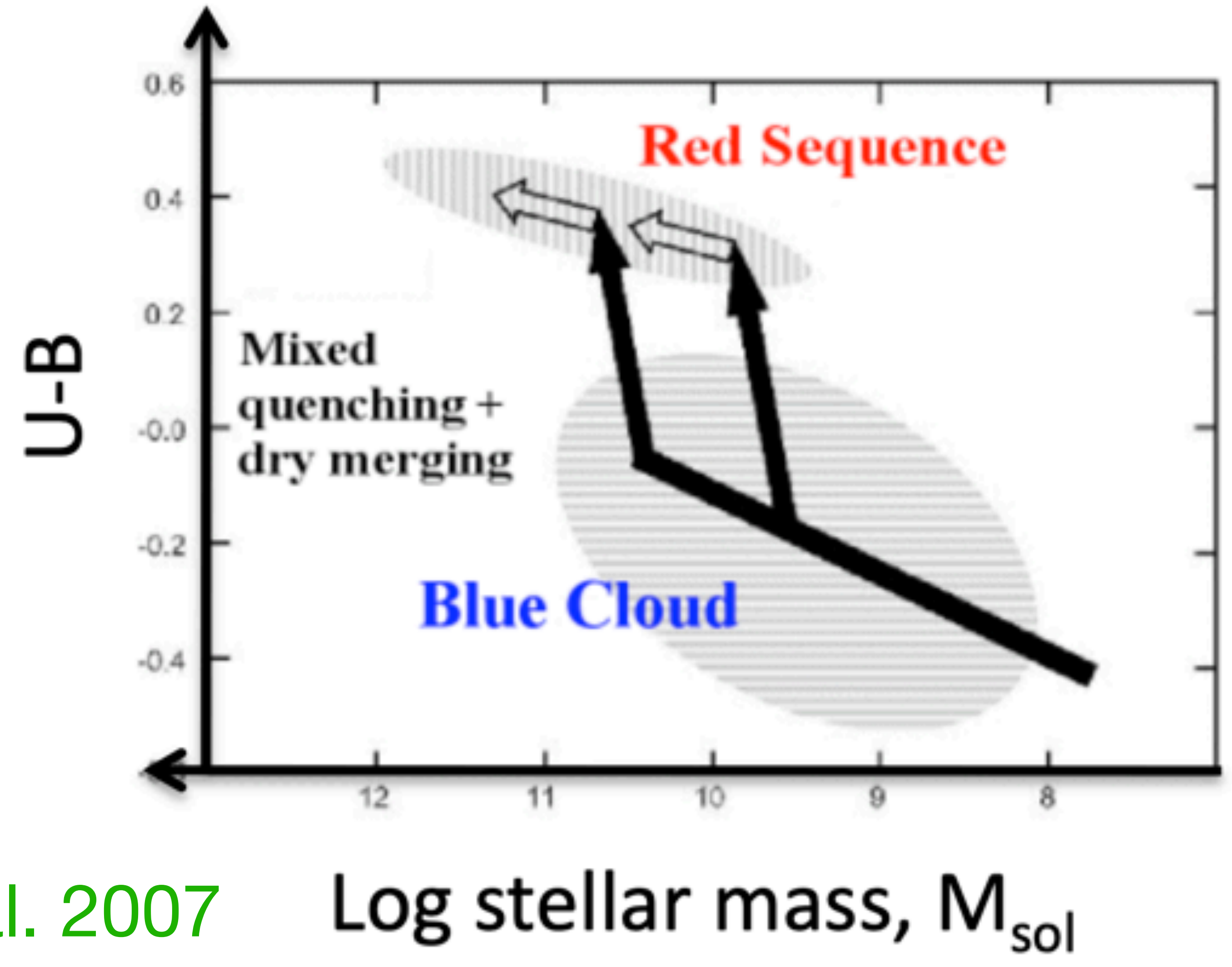


Galaxy evolution

- Evolution imprinted in stellar populations
- Models allow us to know when galaxies have formed and evolved
- The better the models the better the knowledge

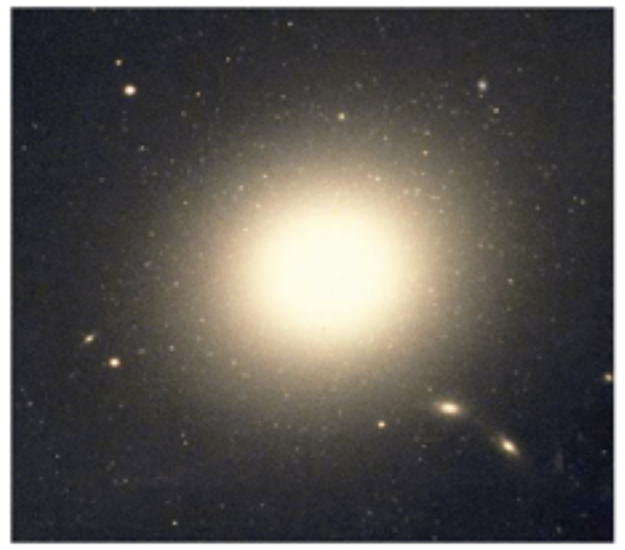


Fabber et al. 2007

Late type

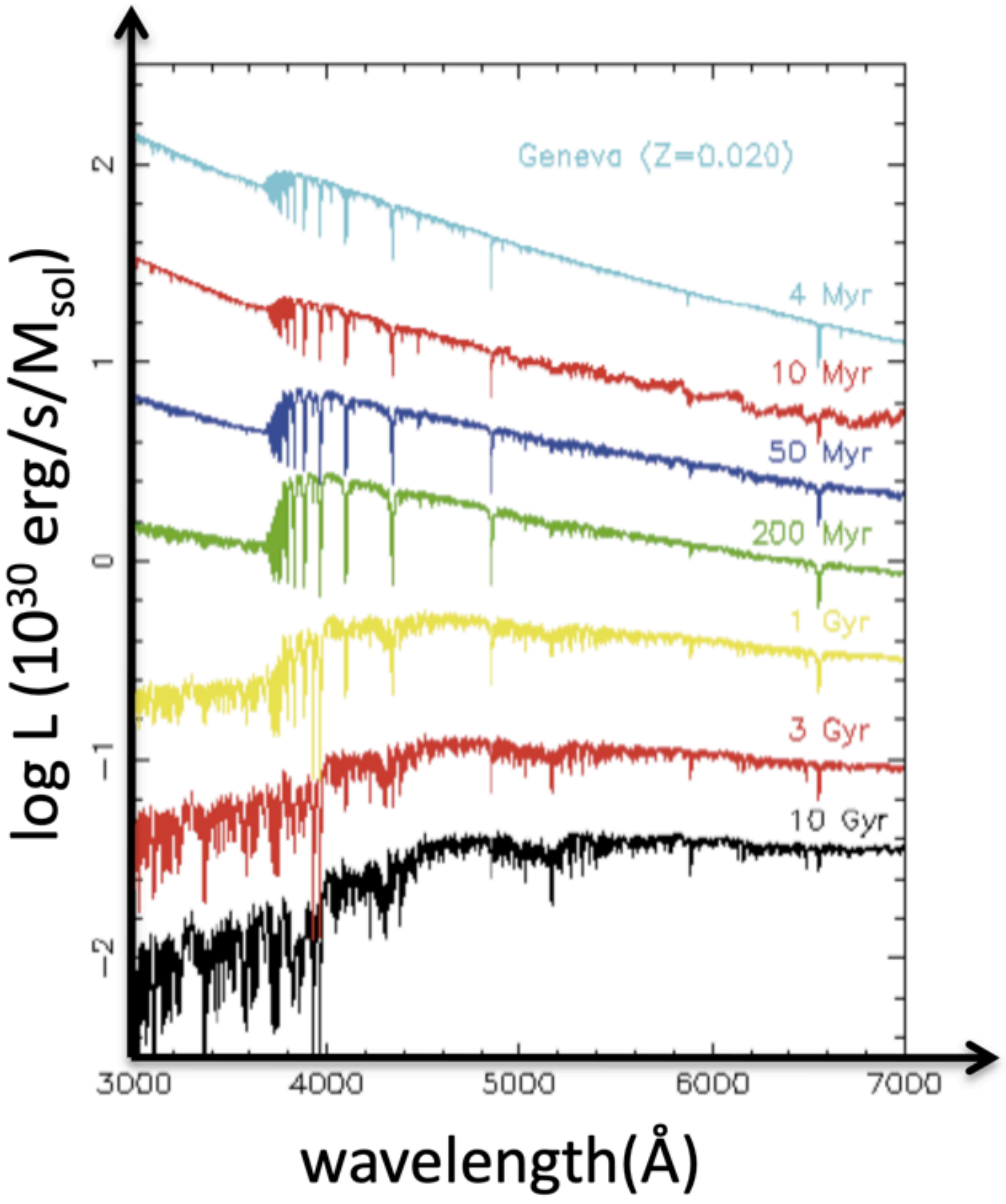
low-mass
blue
young

Early type



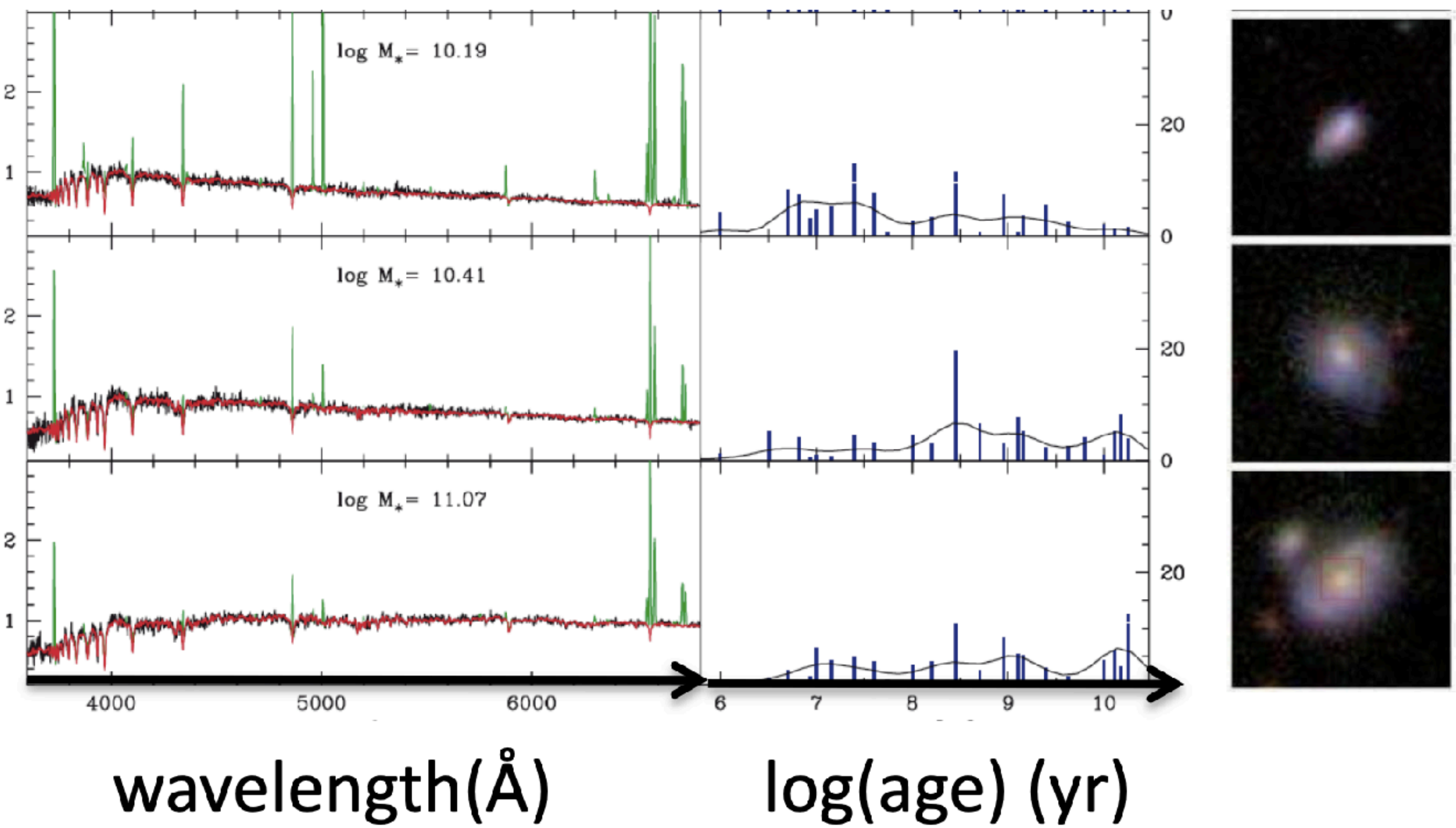
massive
red
old

Stellar Population Synthesis models

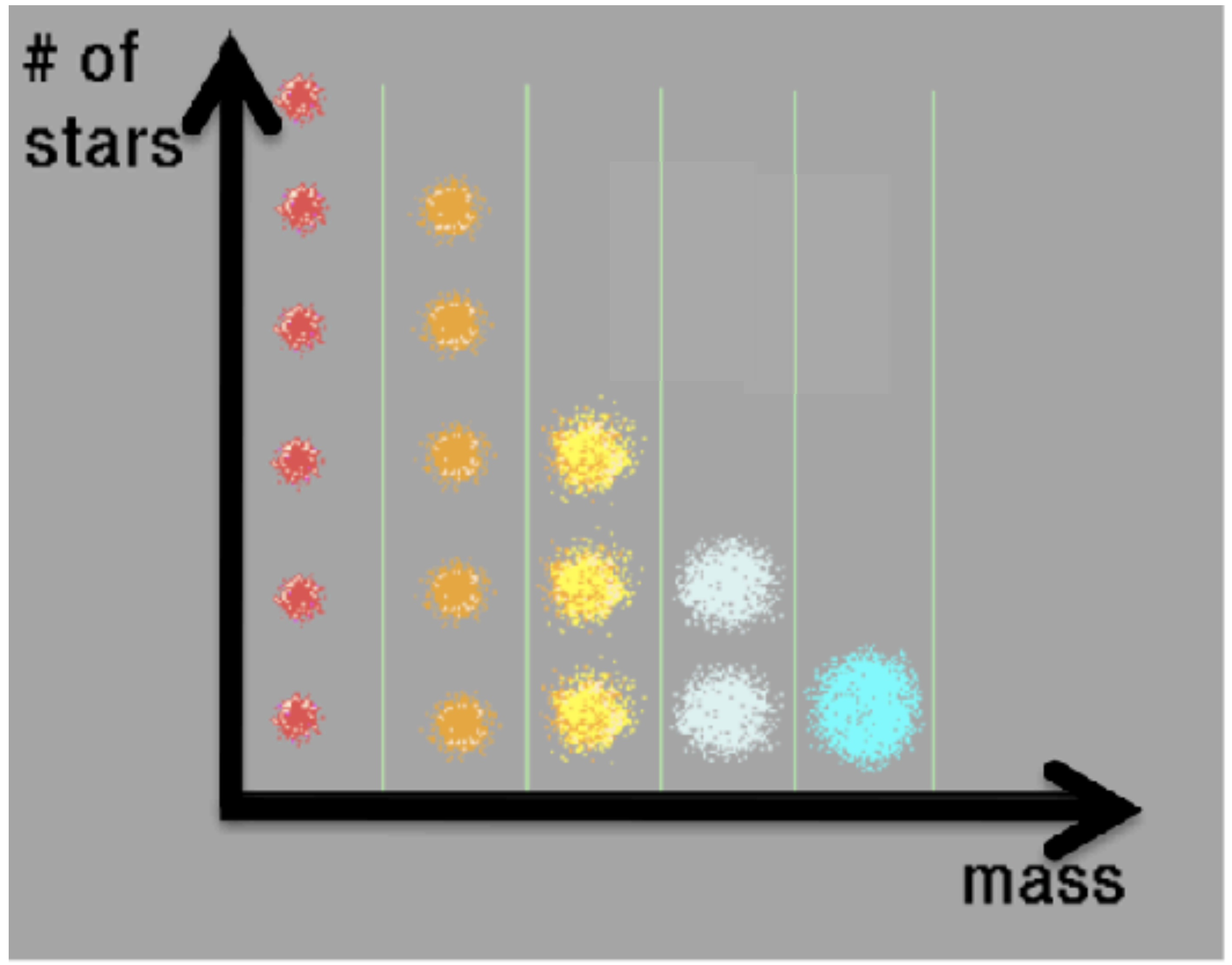


- The **Stellar Population Synthesis** (SPS) models predict the spectra of galaxies (unresolved stellar populations) changing the number of stars that are formed and the time at which they are formed
- Theoretical SED of a population with t, Z
- Fundamental to interpret galaxy spectra
- Necessary to derive physical properties from observations: spectra, color, age, metallicity, masses

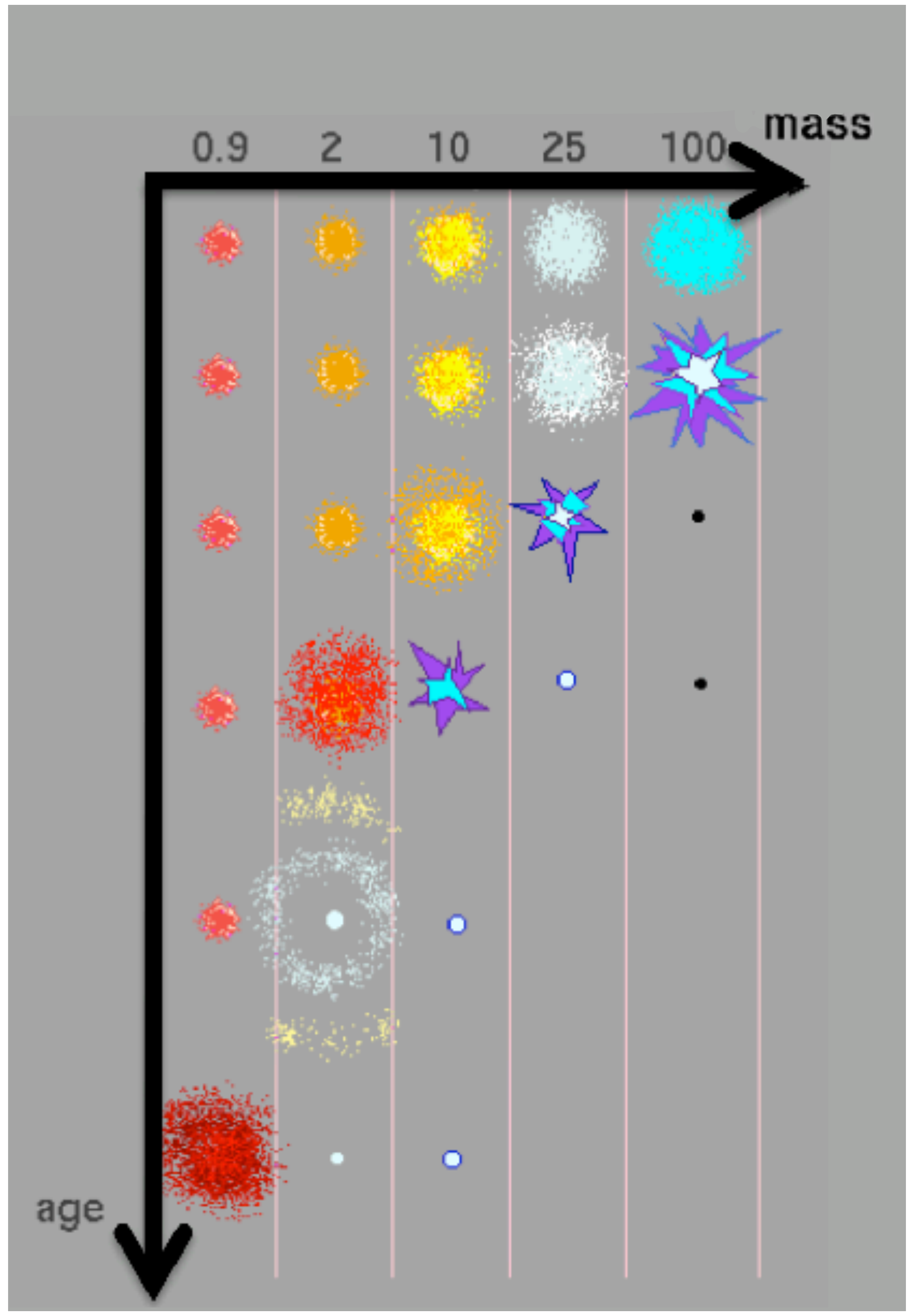
Stellar population models



Ingredients

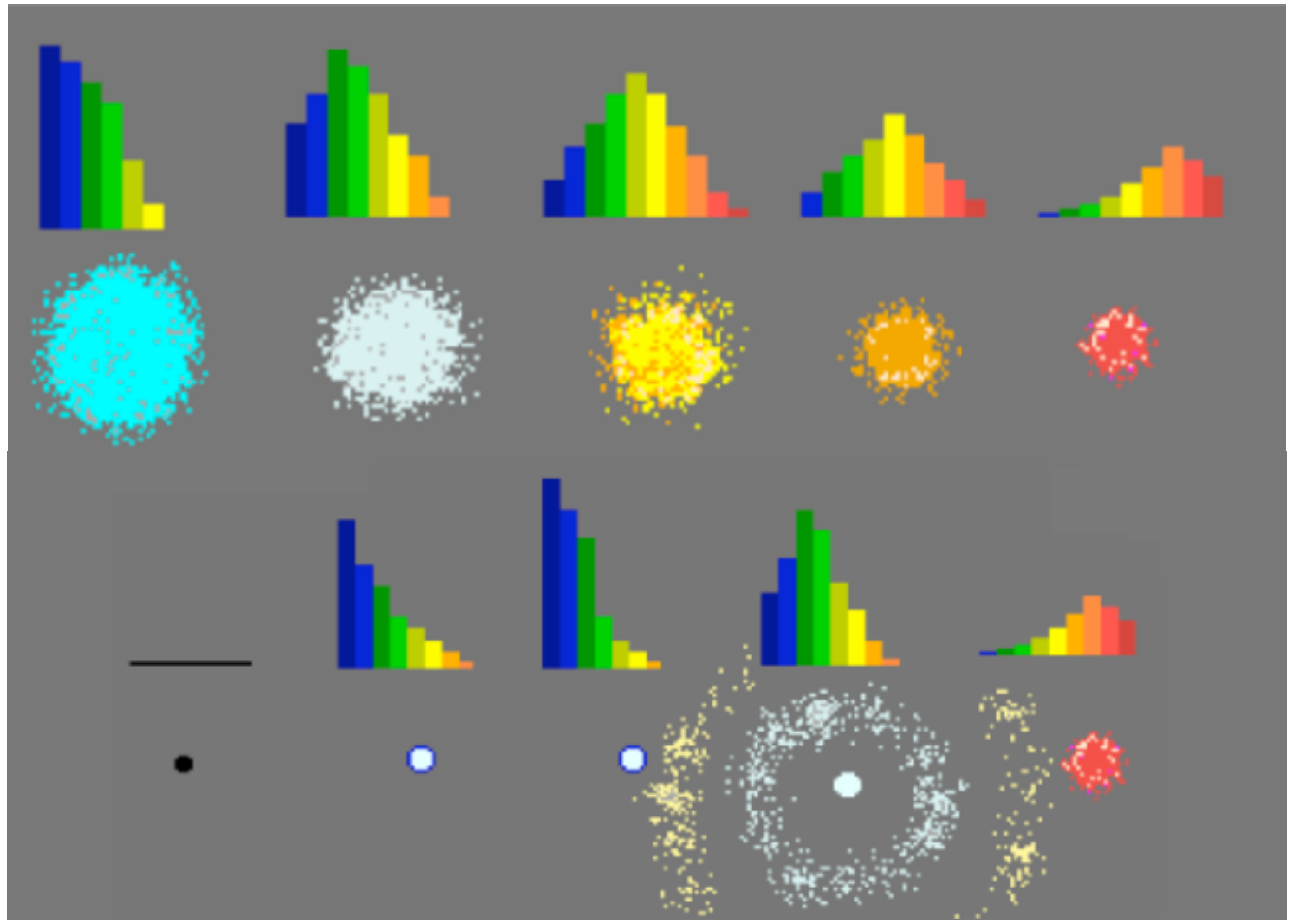


Initial mass function (IMF)



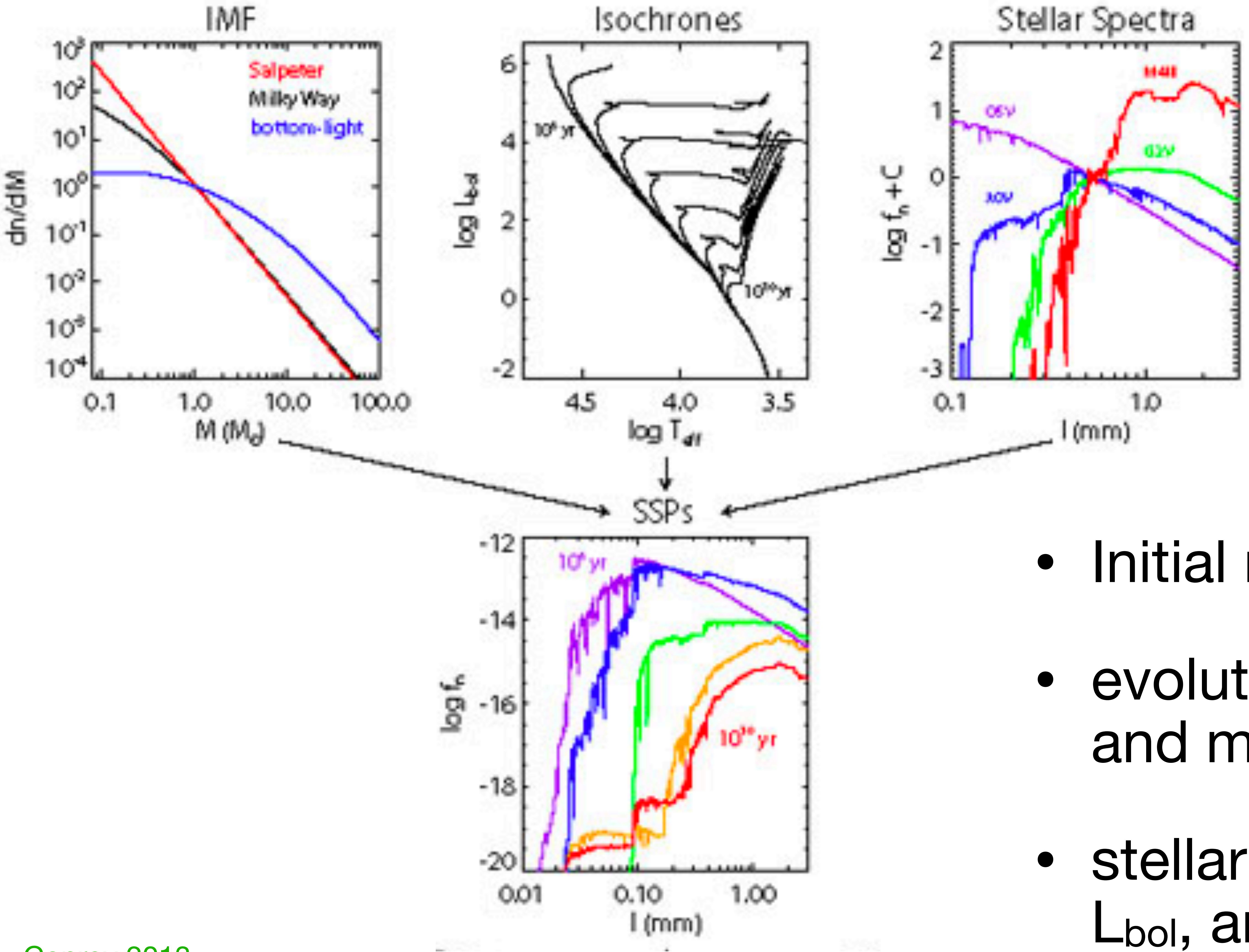
Evolutionary tracks for a range of ages and metallicities

-> isochrones



stellar spectra spanning a range of T_{eff}, L_{bol}, and metallicity

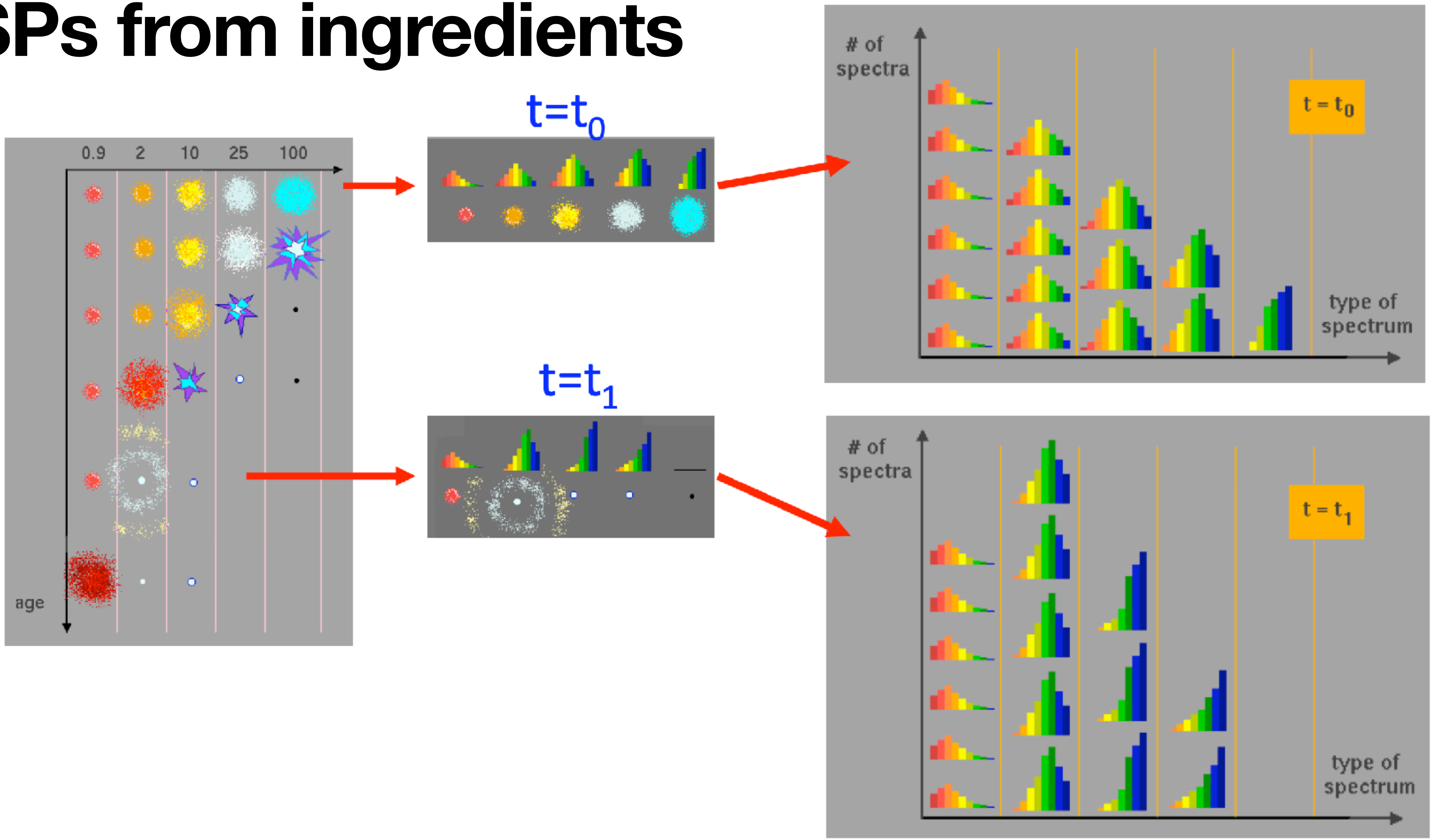
Ingredients



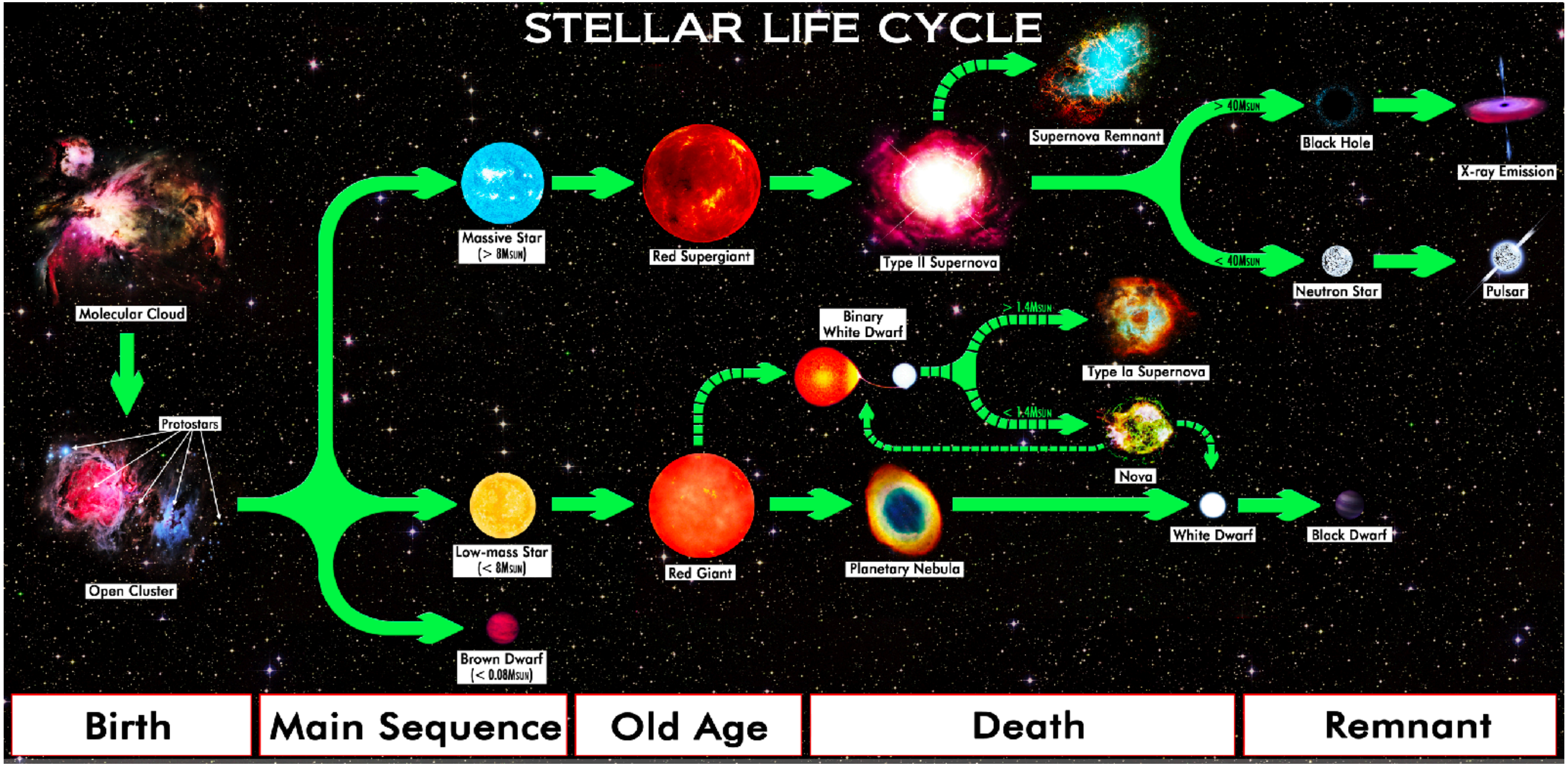
Conroy 2013

- Initial mass function (IMF)
- evolutionary tracks for a range of ages and metallicities -> isochrones
- stellar spectra spanning a range of T_{eff}, L_{bol}, and metallicity

SSPs from ingredients



Initial Mass Function



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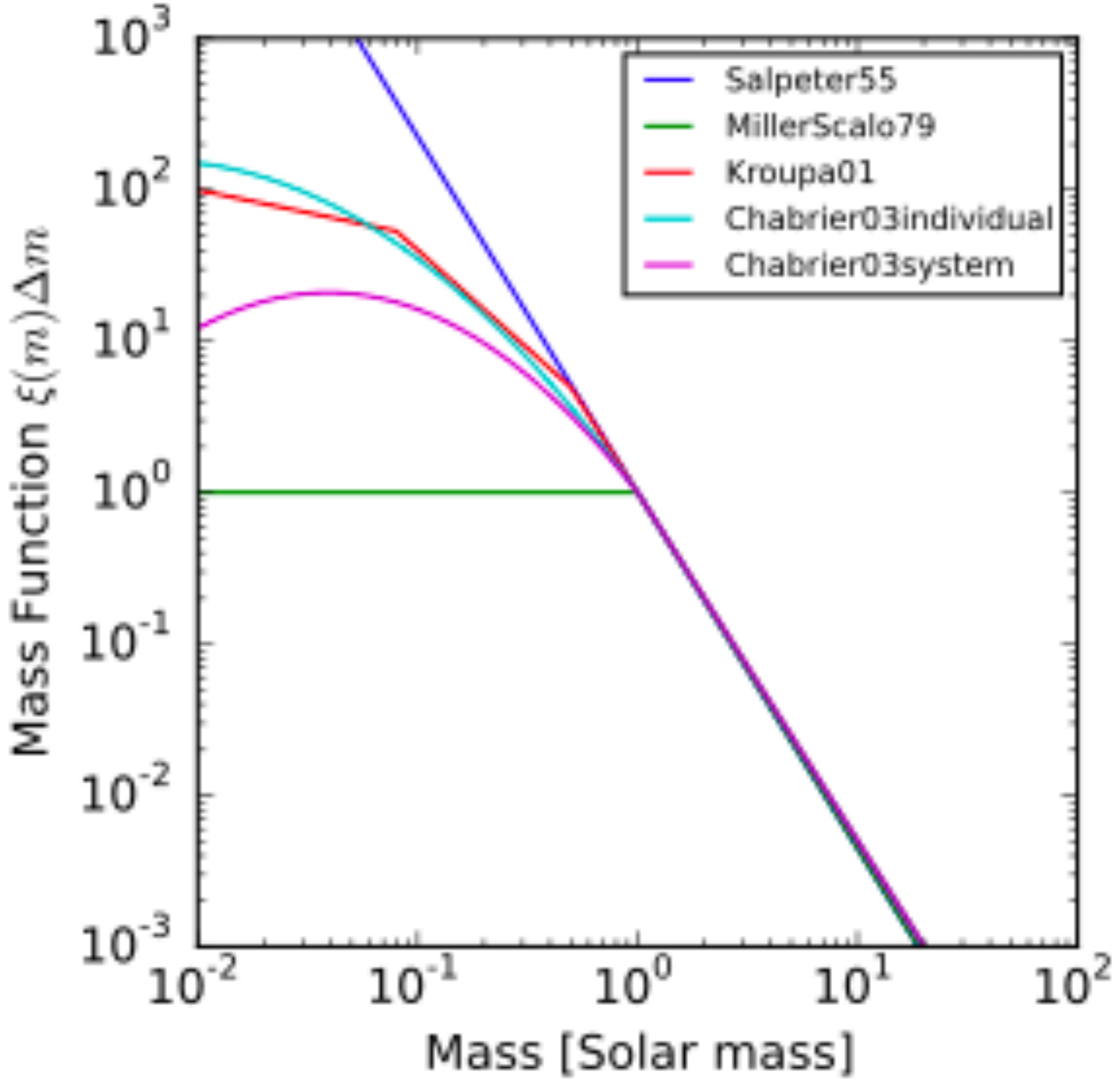


- Star Formation Rate (SFR): gives the number of stars formed per unit time

  exponential law

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

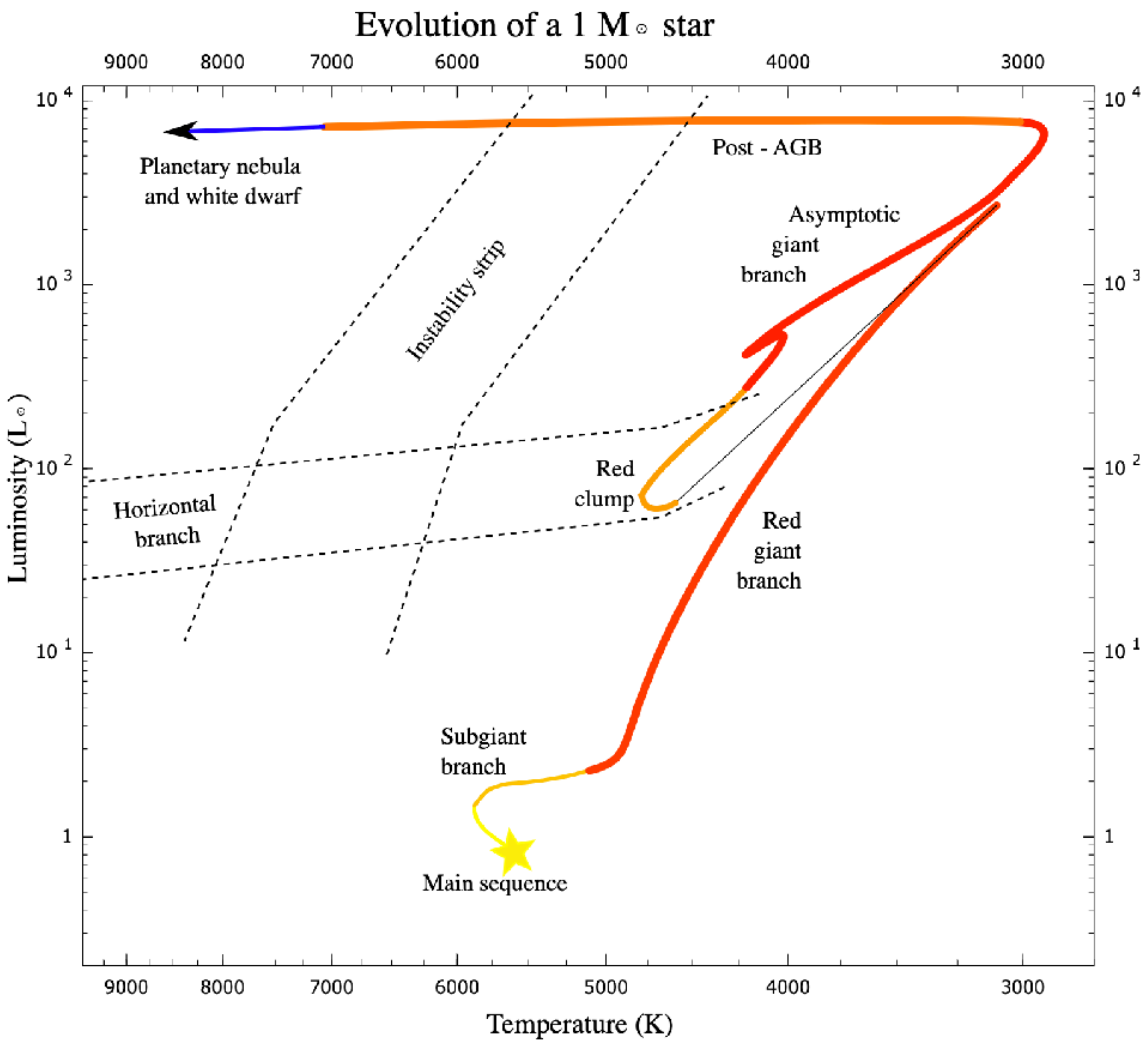
$dN/dm = m^{-1}\, dN/d(\log m) = m^{-\alpha}$

- Salpeter: $m^{-2.5}$
- Kroupa: $m^{-2.3}$ $m/m_{\odot} > 0.5$
  $m^{-1.3}$ $0.5 > m/m_{\odot} > 0.08$
  $m^{-0.35}$ $m/m_{\odot} < 0.08$
- Chabrier: $m^{-2.3}$ $m/m_{\odot} > 1$
  $m^{-1} \exp[-(\log m - \log m_c)^2/2\sigma^2]$ $m/m_{\odot} < 1$
- IMF impacts on:
  - Mass estimations: M/L depends on IMF
  - SFR estimations, depends on m_{up} and slope
- IMF UNIVERSALITY?? Bastian et al. 2010

Evolutionary tracks

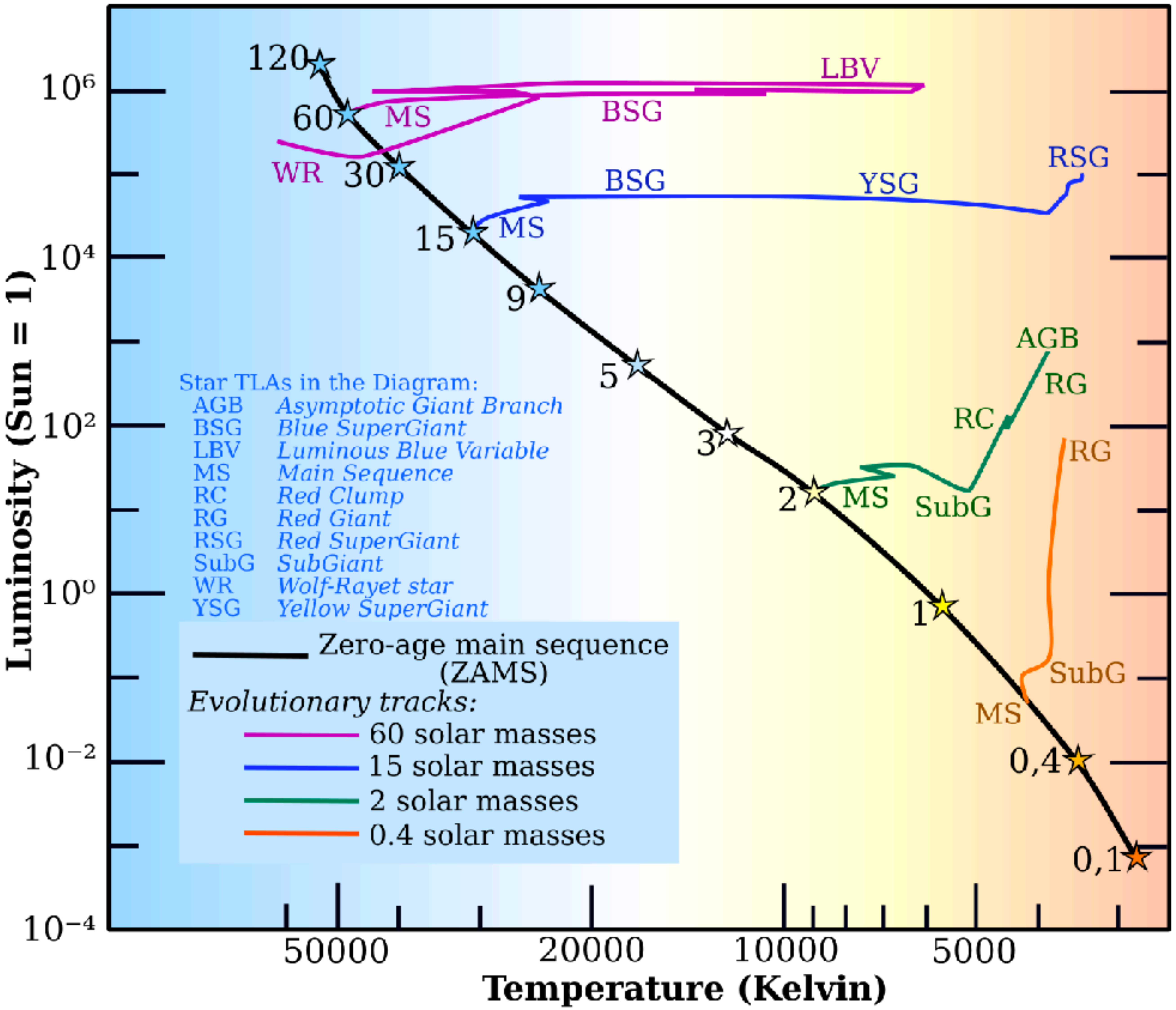
Table 5.1 Features in the CM diagram

Feature	Physical significance	Remarks
Main sequence (MS)	Core H burning	
Subgiant branch (SGB)	Transition from core to shell H burning	Prominent in globular-cluster CM diagrams
Red giant branch (RGB)	Shell burning of H	For lower-mass stars terminated by He flash
Horizontal branch (HB)	Core He burning	Has characteristic luminosity; color sensitive to metallicity
Red clump (RC)	Stubby red HB formed by more metal-rich stars	Prominent in disk CM diagrams
Asymptotic giant branch (AGB)	Shell He burning	Associated with significant and increasing mass loss; stars often irregular variables
Instability strip	He^{+} ionization zone gives rise to regular ariables	RR Lyrae and W Virginis stars lie at intersection with HB; Cepheids are massive stars that lie in strip
White-dwarf sequence	Cooling electron-degenerate stars	Blue and faint



- Evolutionary tracks: evolution in the HR diagram of stars of a given mass

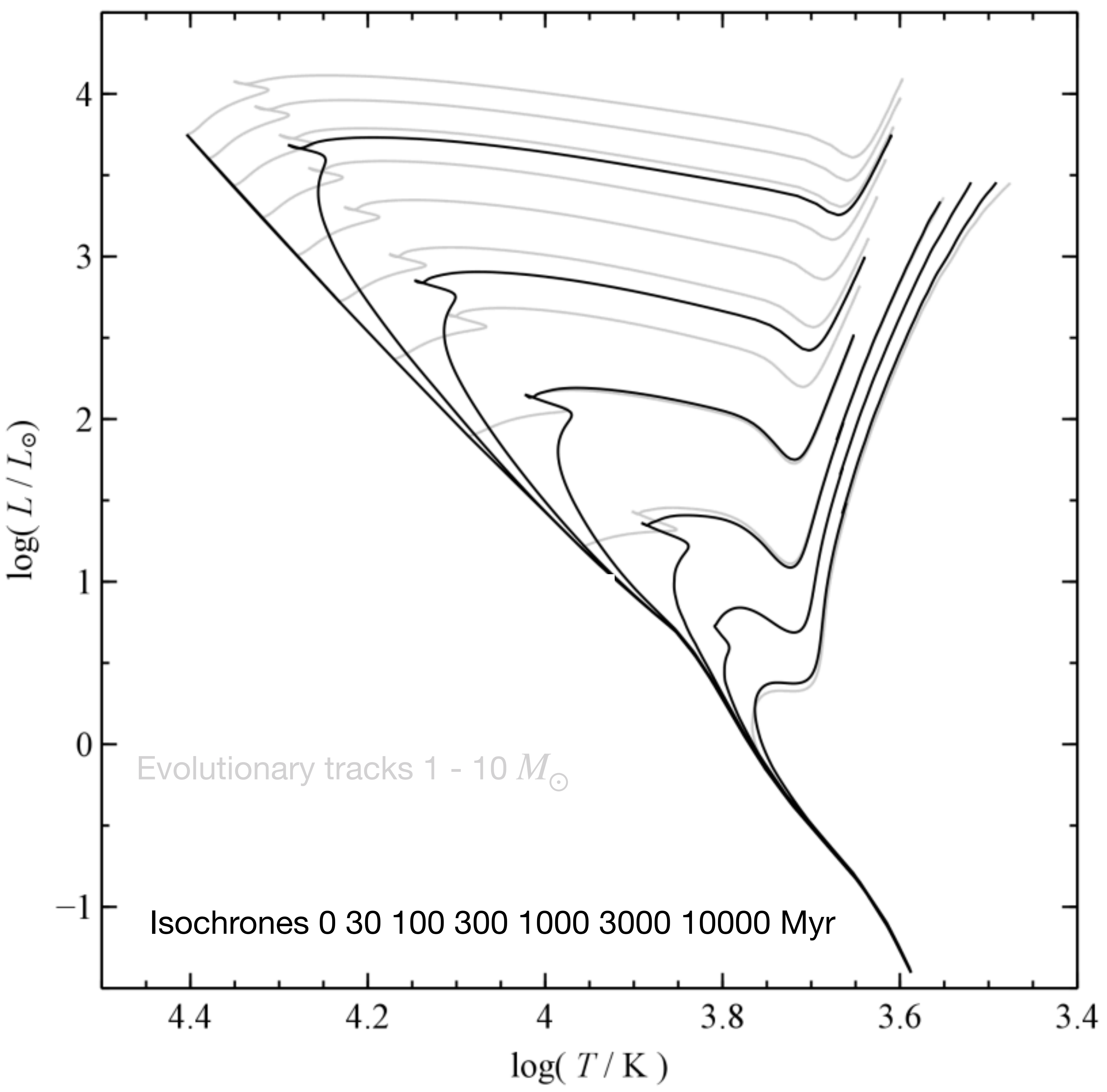
Evolutionary tracks



HR diagram

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

Isochrones



Isochrones: position in the HR diagram of stars of different mass at the same evolutionary stage

Set of stellar models compute at the **same** (*iso*) **age** (*chrone*).

Stellar evolution codes compute **evolutionary tracks** for a stars of different masses, and connect all the models of different masses at the **same age**.

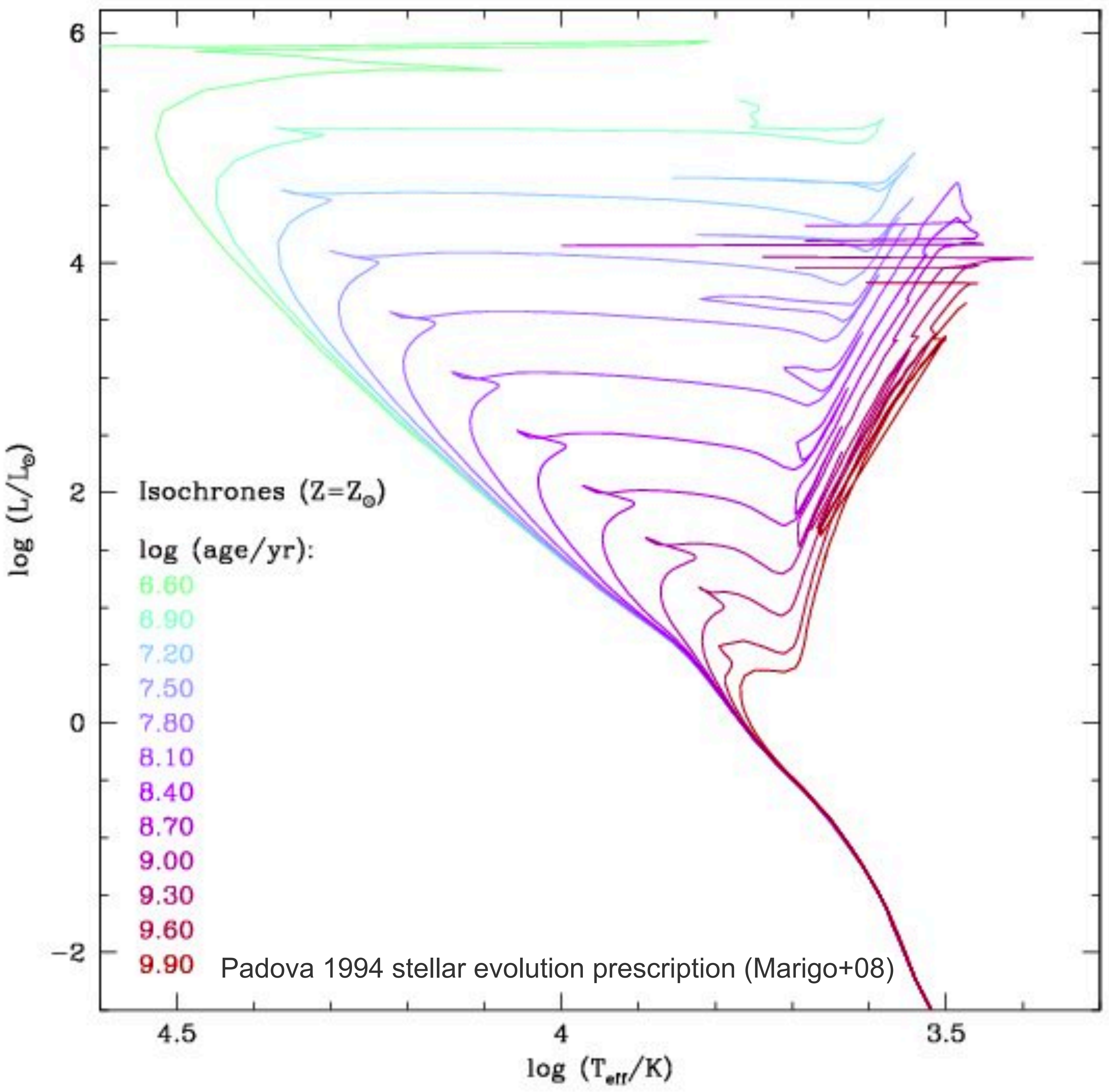
Coloured lines are evolutionary tracks for stars with masses from 1 to 10 solar masses

They all evolve at different rates

e.g: at 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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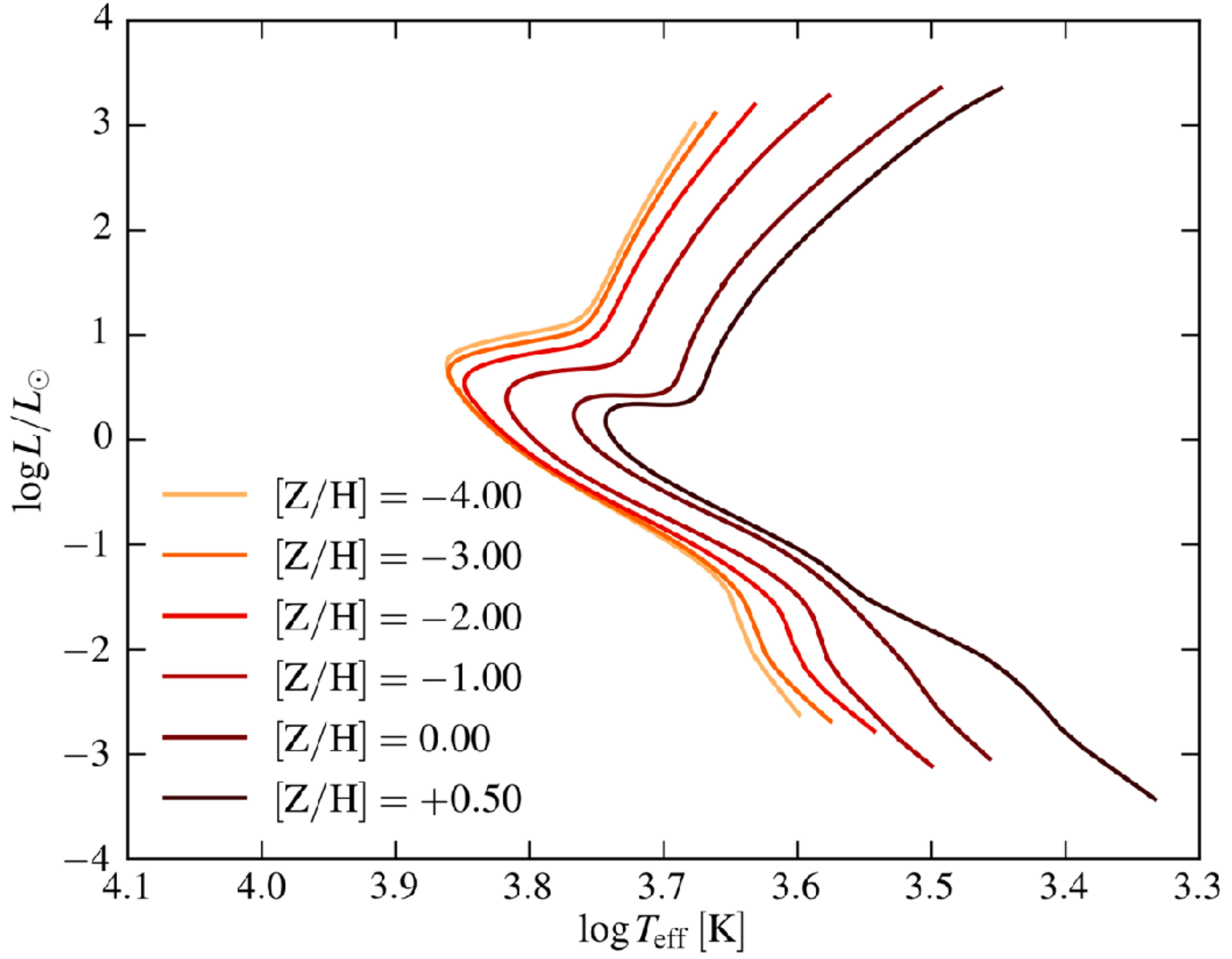
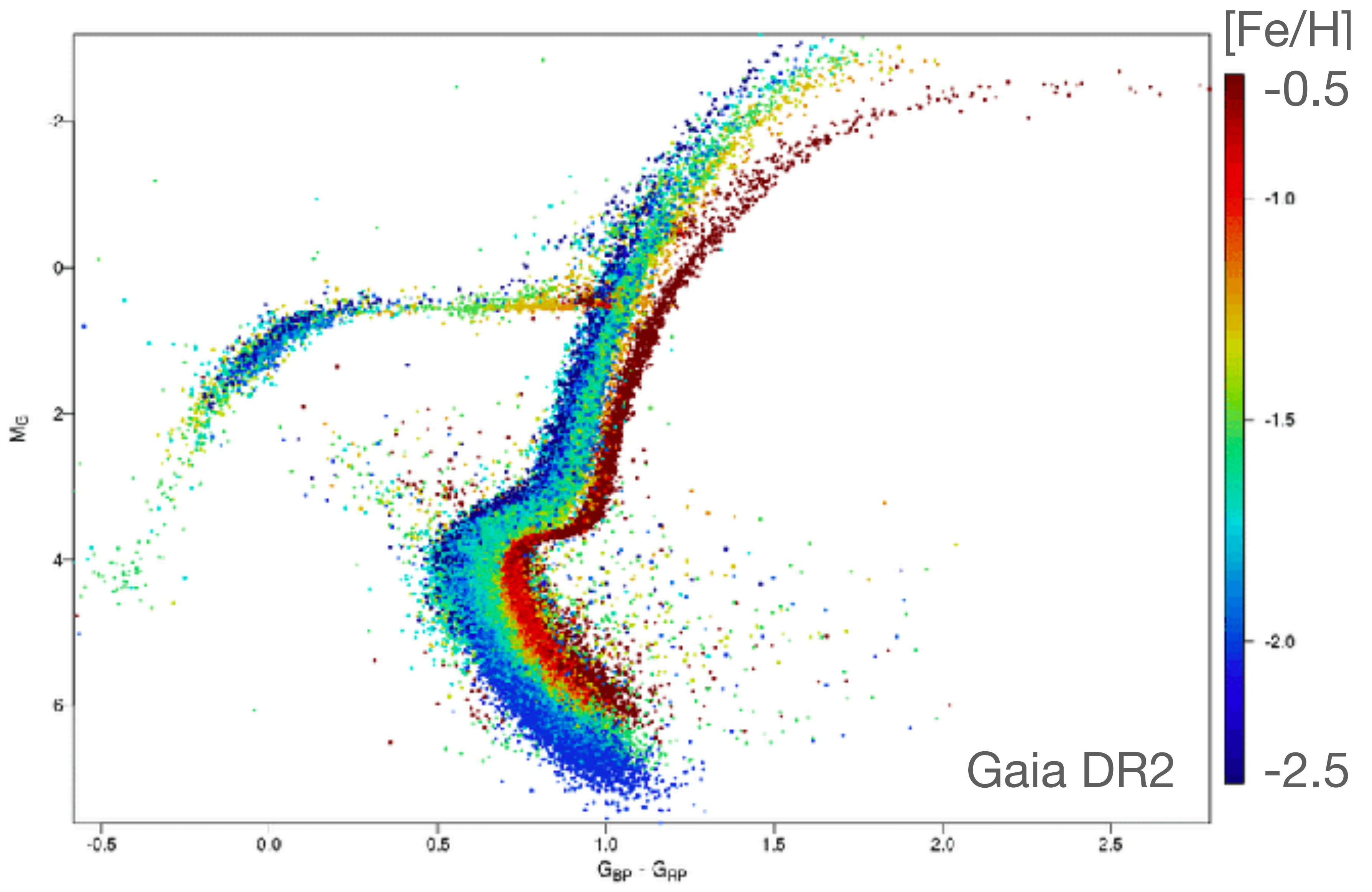
Isochrones - dependence on metallicity





[MESA Isochrones & Stellar Tracks]

Stellar libraries

- spectra that sample parameter space: (T, g, Z) and t

- Empirical → Observations

Library	FWHM (Å)	Spectral Range (Å)	No. Stars	Commens	Liders
ELODIE	0.1	4100-6800	1388	Echelle	Prugniel & Soubiran 2004 PEGASE (Le Borgne et al 2005)
STEBLIB	3.0	3200-9500	249	Flux calibrated	Le Borgne et al 2003 GALAXEV (BC03)
INDO-US	1.0	3460-9464	1273	Poor flux calibrated	Valdés et al 2004 GALAXEV (CB07)
MILES	2.3	3500-7500	985	Flux calibrated	Sánchez-Blázquez et al 2006 GALAXEV (CB07) Vazdekis et al.
HNGSL		1700-10200	Few 100	Flux calibrated	Heap & Lanz (2003) GALEXV (CB07)

- Synthetic → Stellar Atmospheres models

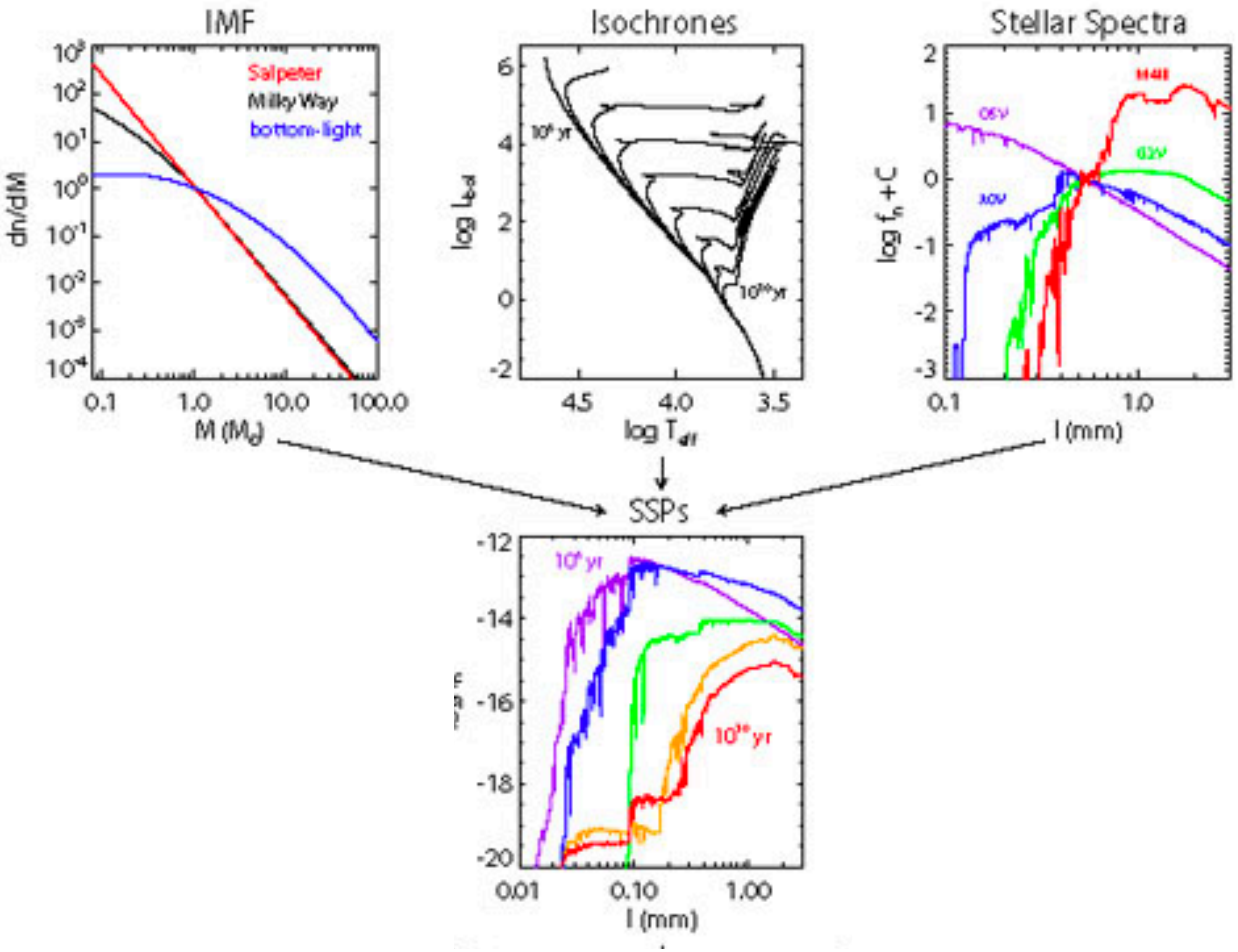
Models	Resolution	Spectral Range (Å)	Atmosph	Teff Log g	Metals
Rodríguez-Merino et al 2005	50000	850-4700	Kurucz	3000-50000 Log g= 0--5	[M/H]= -2.0, -1.5, -0.5, 0.0, 0.3, 0.5
Peterson et al 2005	330000	2280-3160	Kurucz	Specific Teff and log g	1/100 to solar
Munari et al 2005	20000 2000	2500-10500	Kurucz	3500-47500 K log g= 0--5	-2.5<[M/H]<0.5 [α/Fe]=0.0, 0.4
Coelho et al 2005	High	3000-18000	Kurucz	3500- 7000 K log g= 0--5	[M/H]= -2.5, -2.0, -1.5, -1.0,-0.5, 0.0, 0.2, 0.5 [α/Fe]=0.0, 0.4
Martins et al 2005 González-Delgado et al 2005	0.3 Å	3000-7000	TLUSTY + Kurucz +PHOENIX	3000-55000 K log g= -0.5--5	Z= 0.04, 0.02, 0.008, 0.004 and 0.001

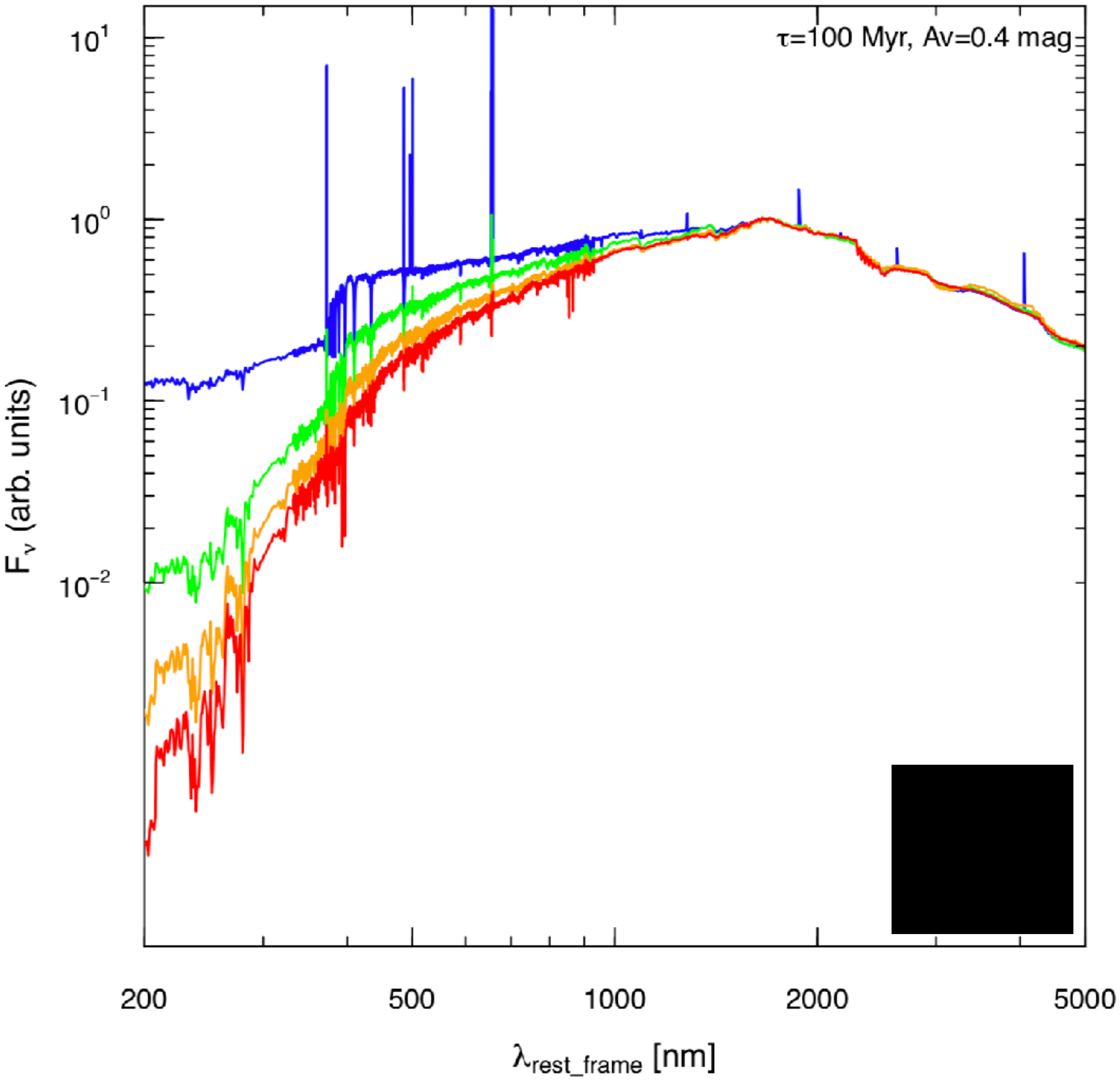
SSP Models summary

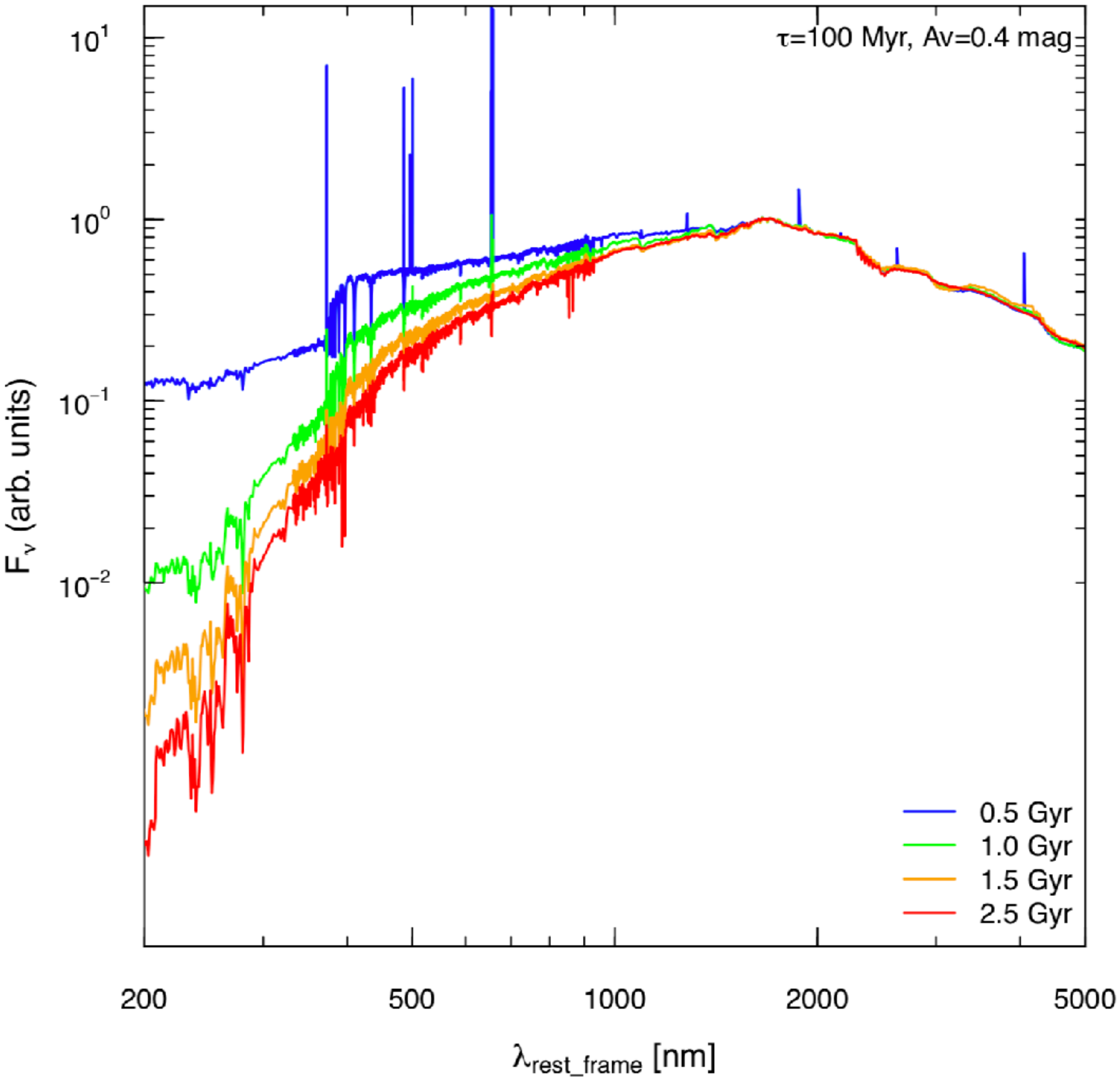
- Goal: reproduce the integrated light of stellar populations adding the contributions of the individual stars forming a galaxy

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

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

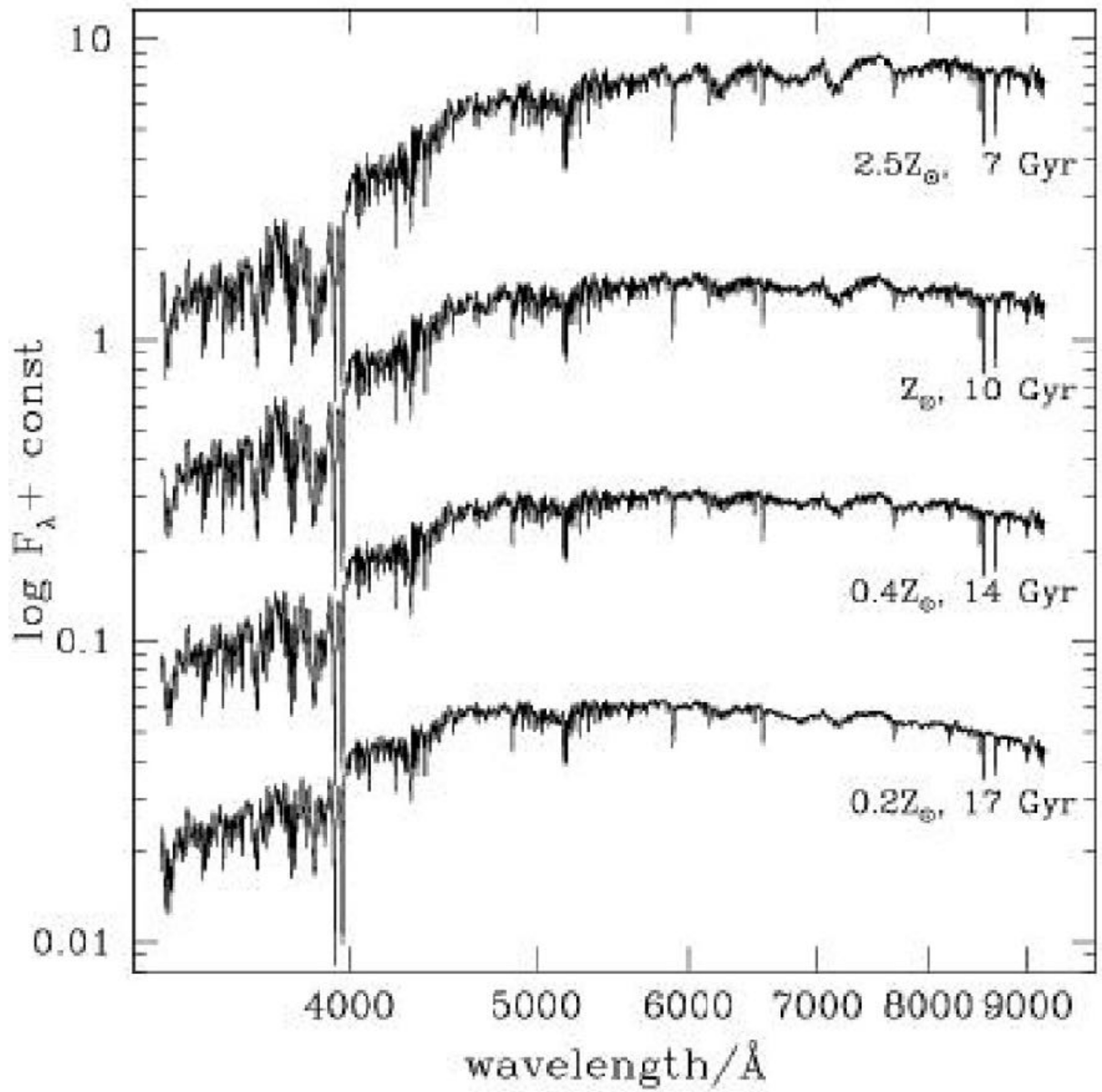


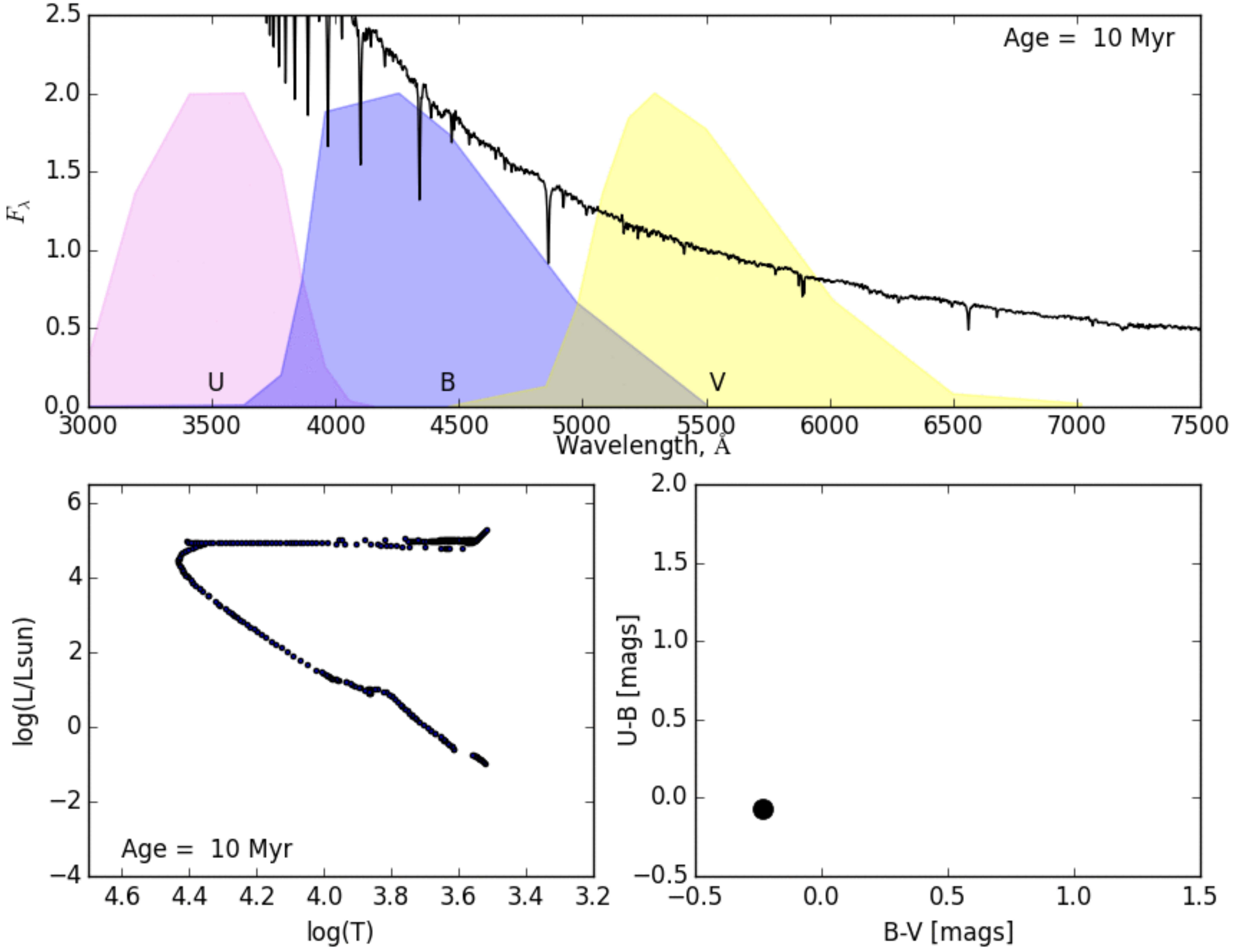

τ=100 Myr, Av=0.4 mag
F_ν (arb. units)
10^1
10^0
10^{-1}
10^{-2}
200
500
1000
2000
5000
λ_{rest_frame} [nm]
[redacted]



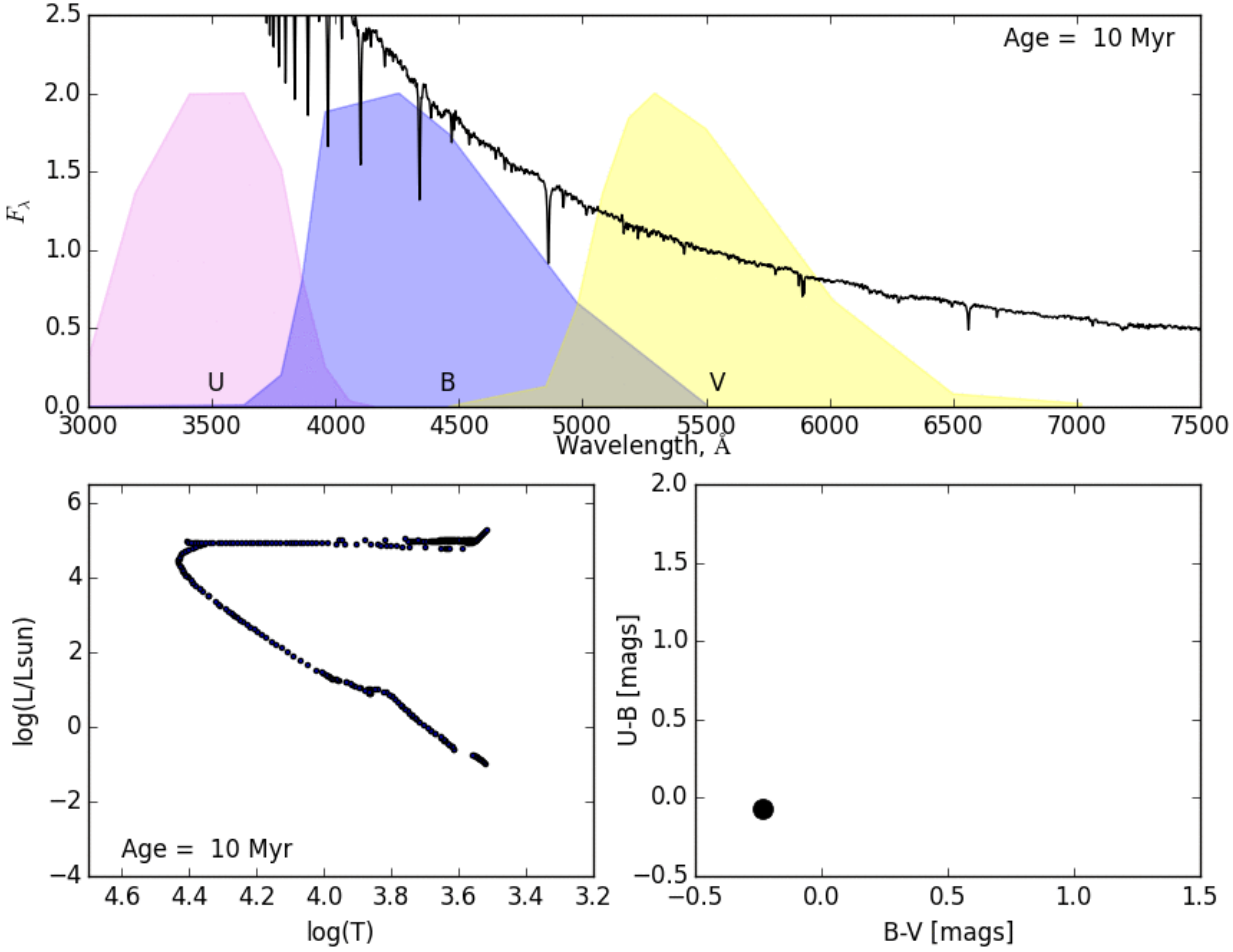
τ=100 Myr, Av=0.4 mag
0.5 Gyr
1.0 Gyr
1.5 Gyr
2.5 Gyr
F_ν (arb. units)
10^1
10^0
10^{-1}
10^{-2}
200
500
1000
2000
5000
λ_{rest_frame} [nm]

Age-metallicity degeneracy





http://burro.case.edu/Academics/Astr222/Galaxies/Intro/sfrprops.html



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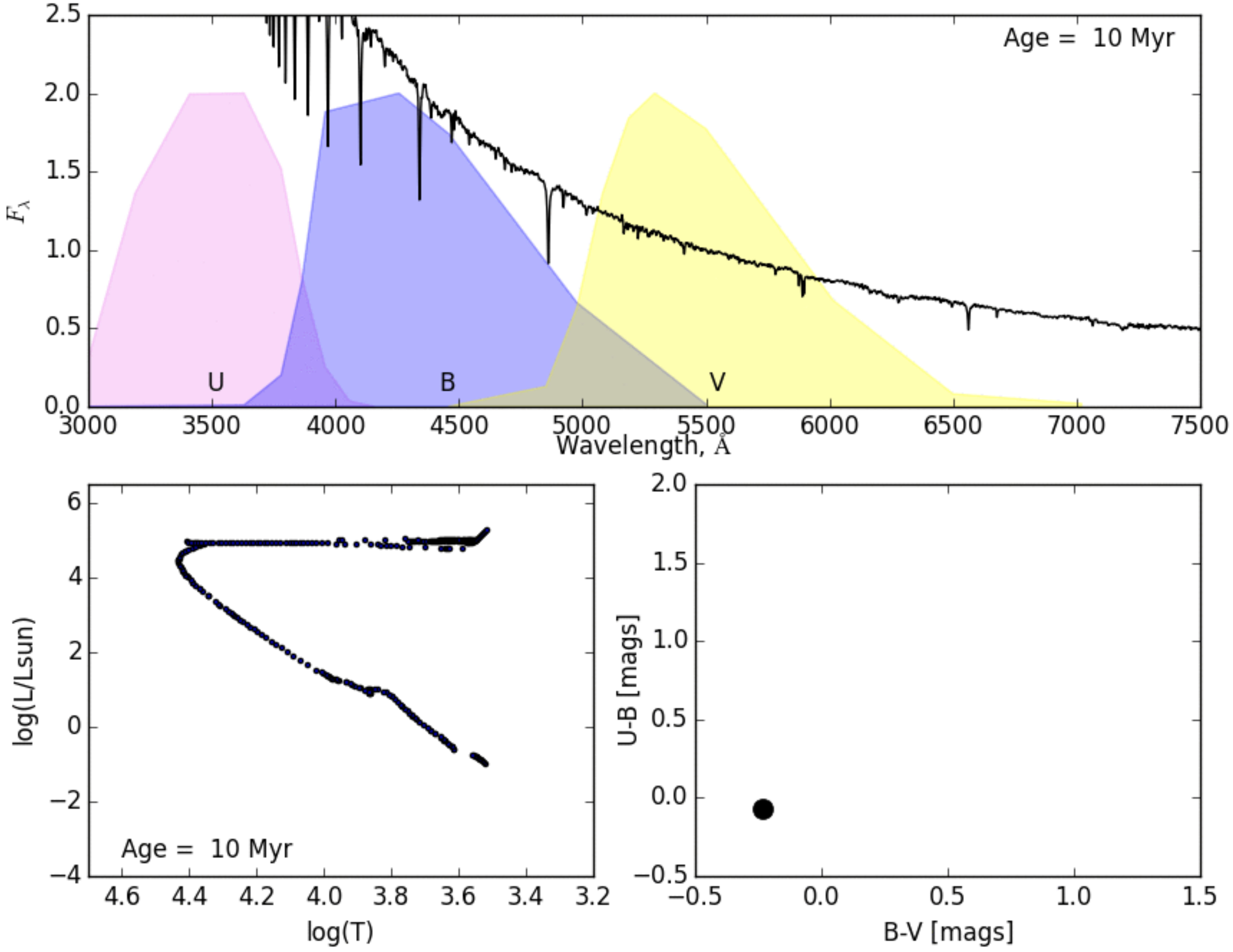

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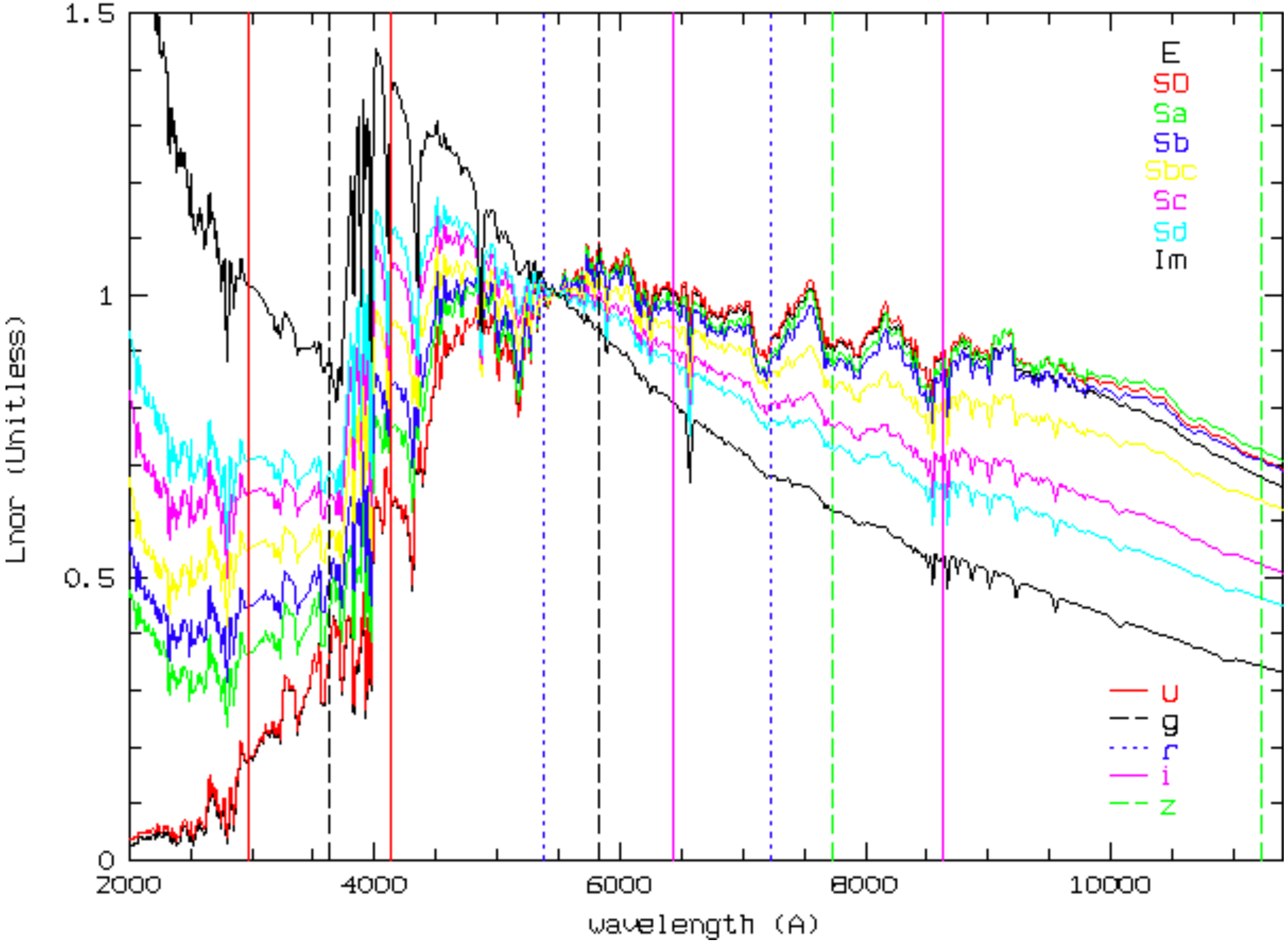
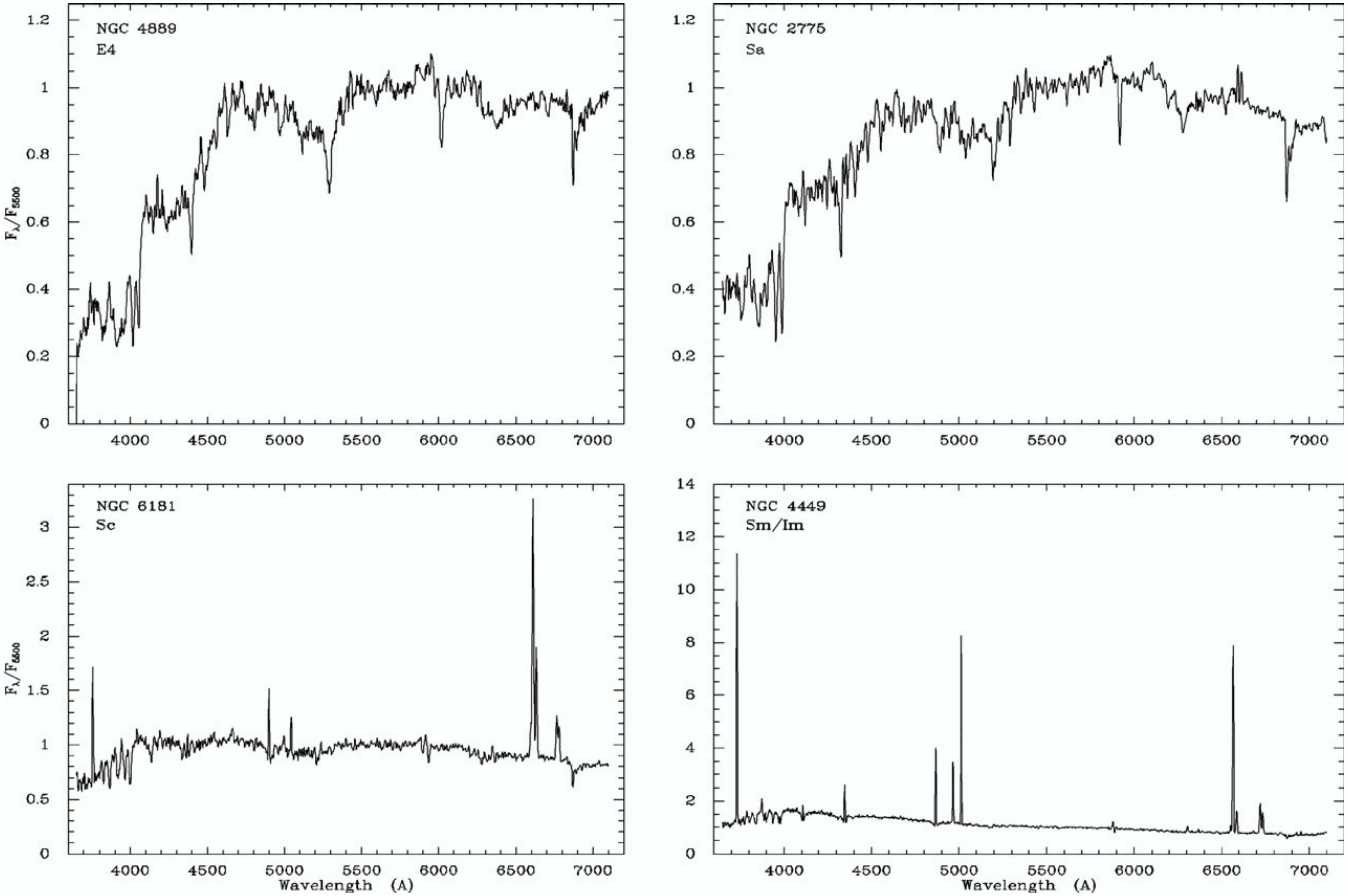
Morphology



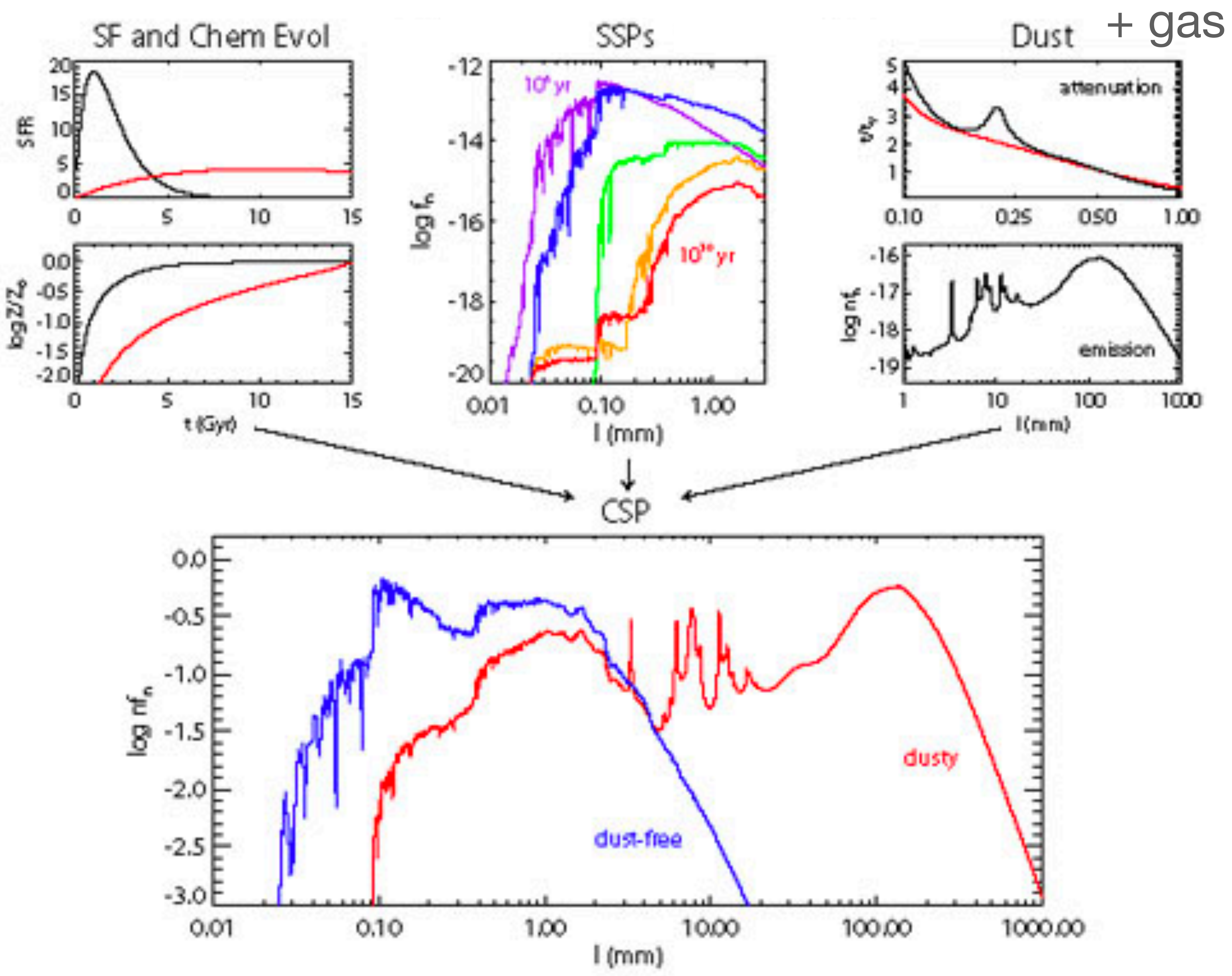
1.5
1
0.5
0
Lnor (Unitless)
2000
4000
6000
8000
10000
wavelength (A)
E
S0
Sa
Sb
Sbc
Sc
Sd
Im
u
g
r
i
z

Q: : Which morphological class corresponds to each spectra?



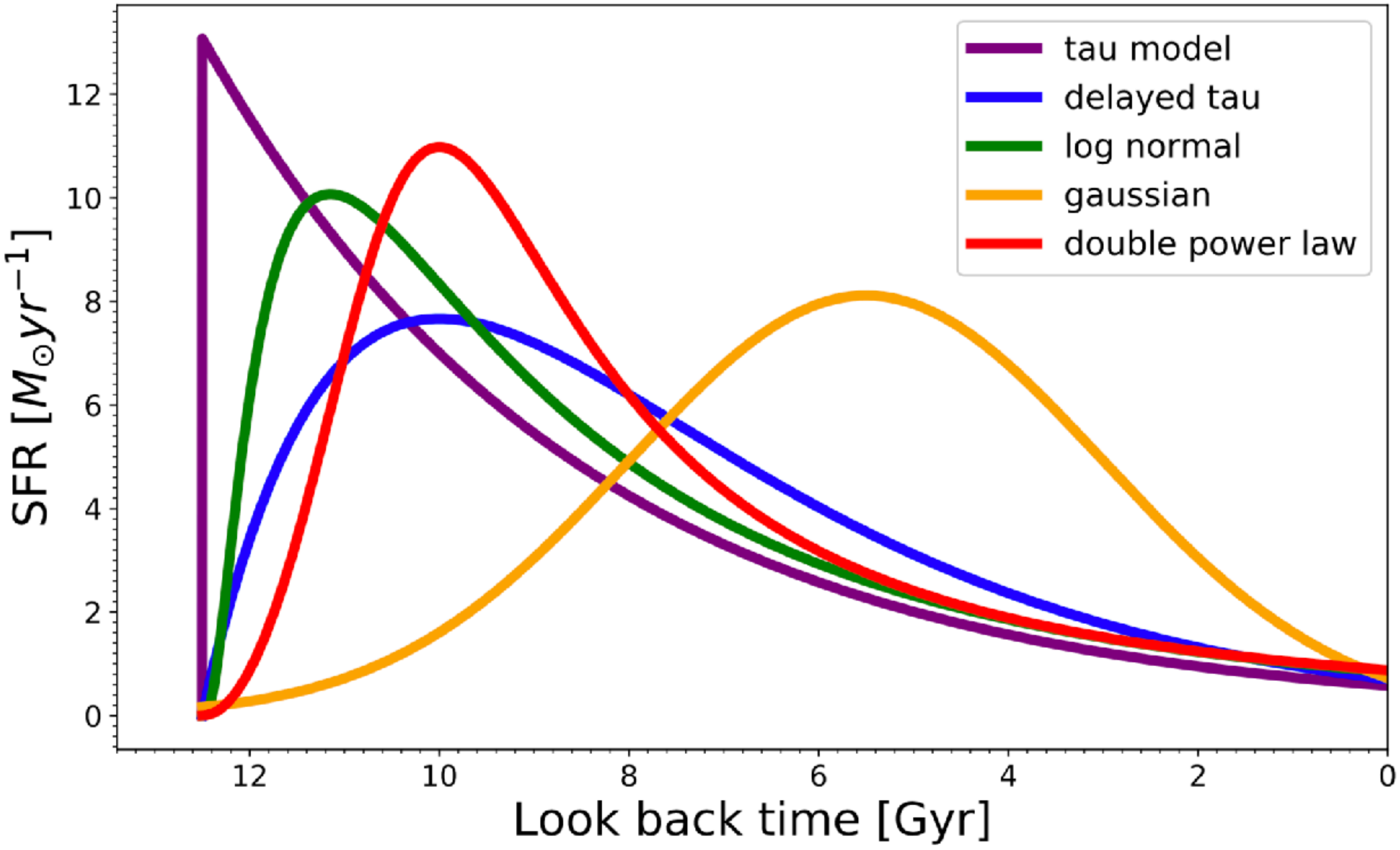
More at https://www.zooniverse.org/talk/1268/582784

Composite SP - Ingredients



Star formation histories

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



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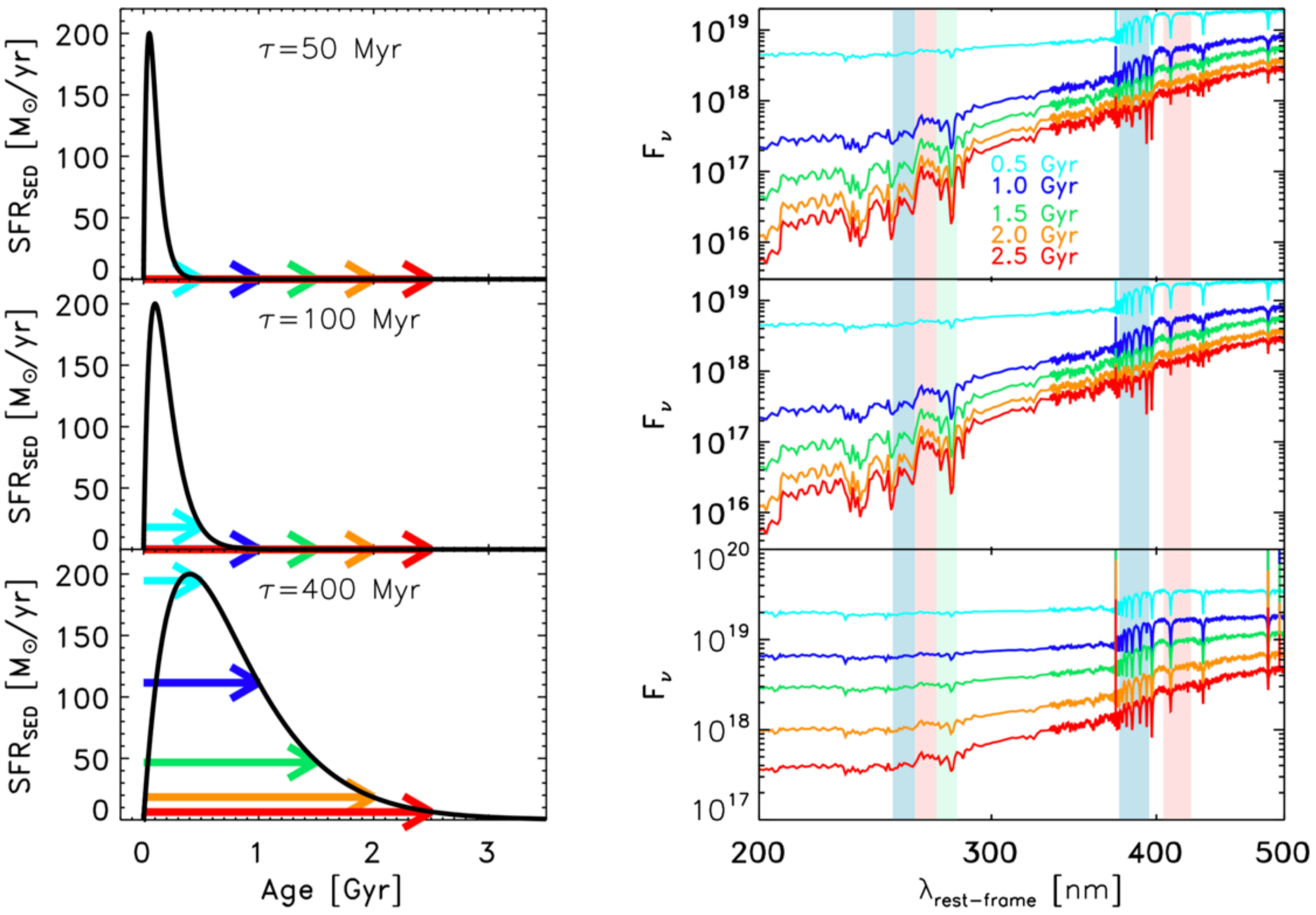
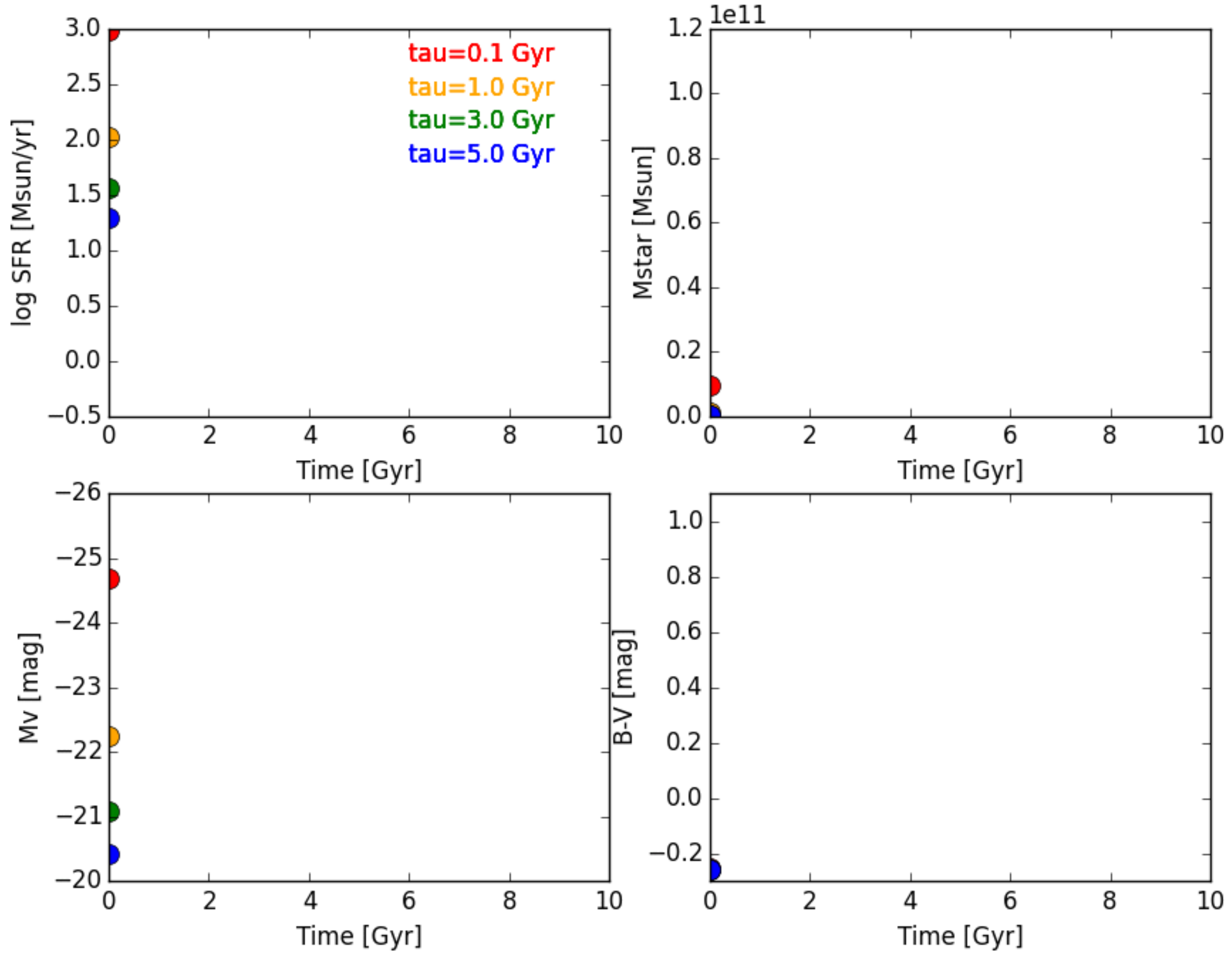


One very simple parameterization of star formation history would be an exponentially declining star formation rate, with differing e-folding timescales: SFR(t) ~ $e^{-(t/tau)}$ where tau is left as a free parameter. (These are, not surprisingly, called "tau models"). Imagine galaxies with four different star formation histories (different taus) and watch how evolve differently in color:



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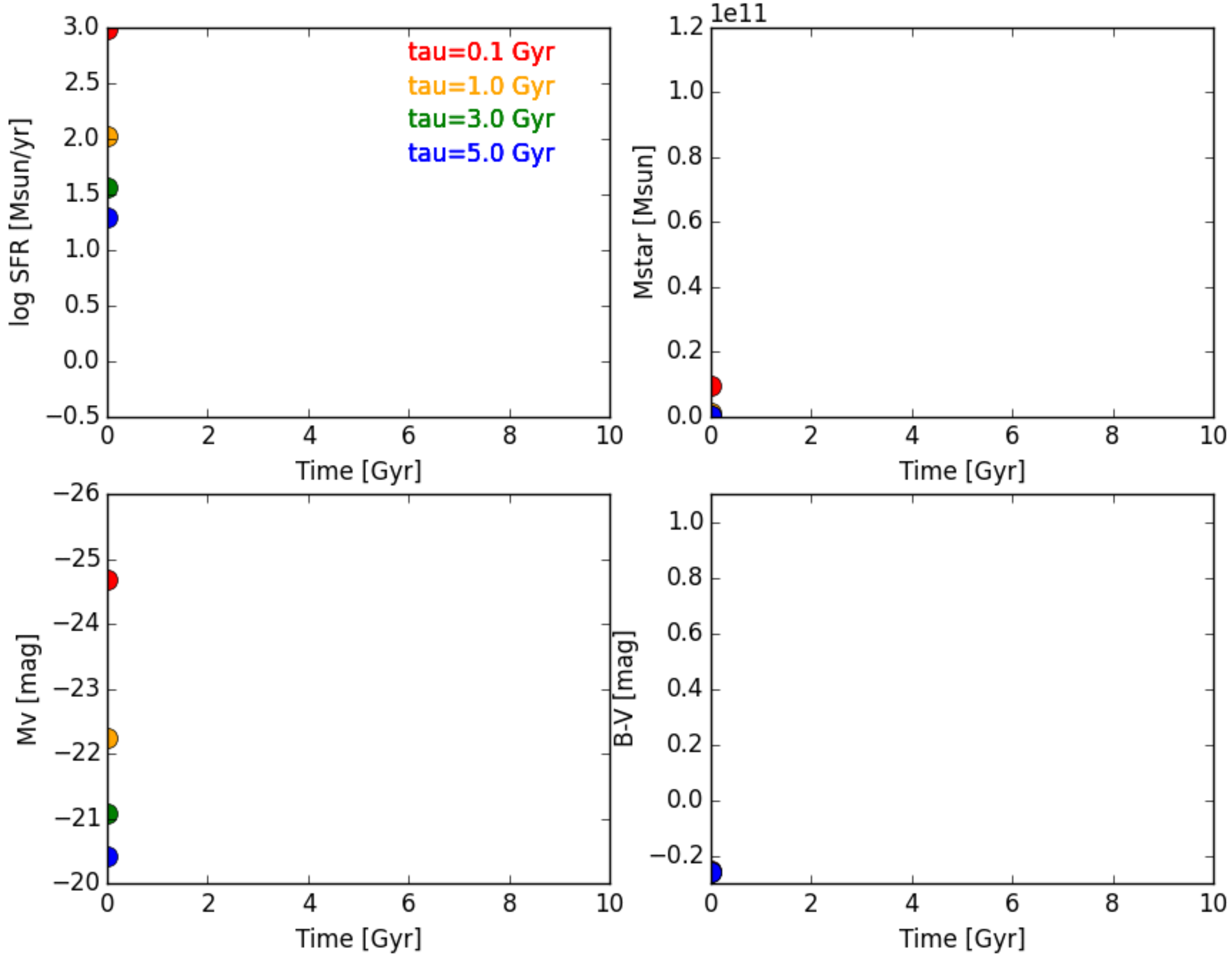

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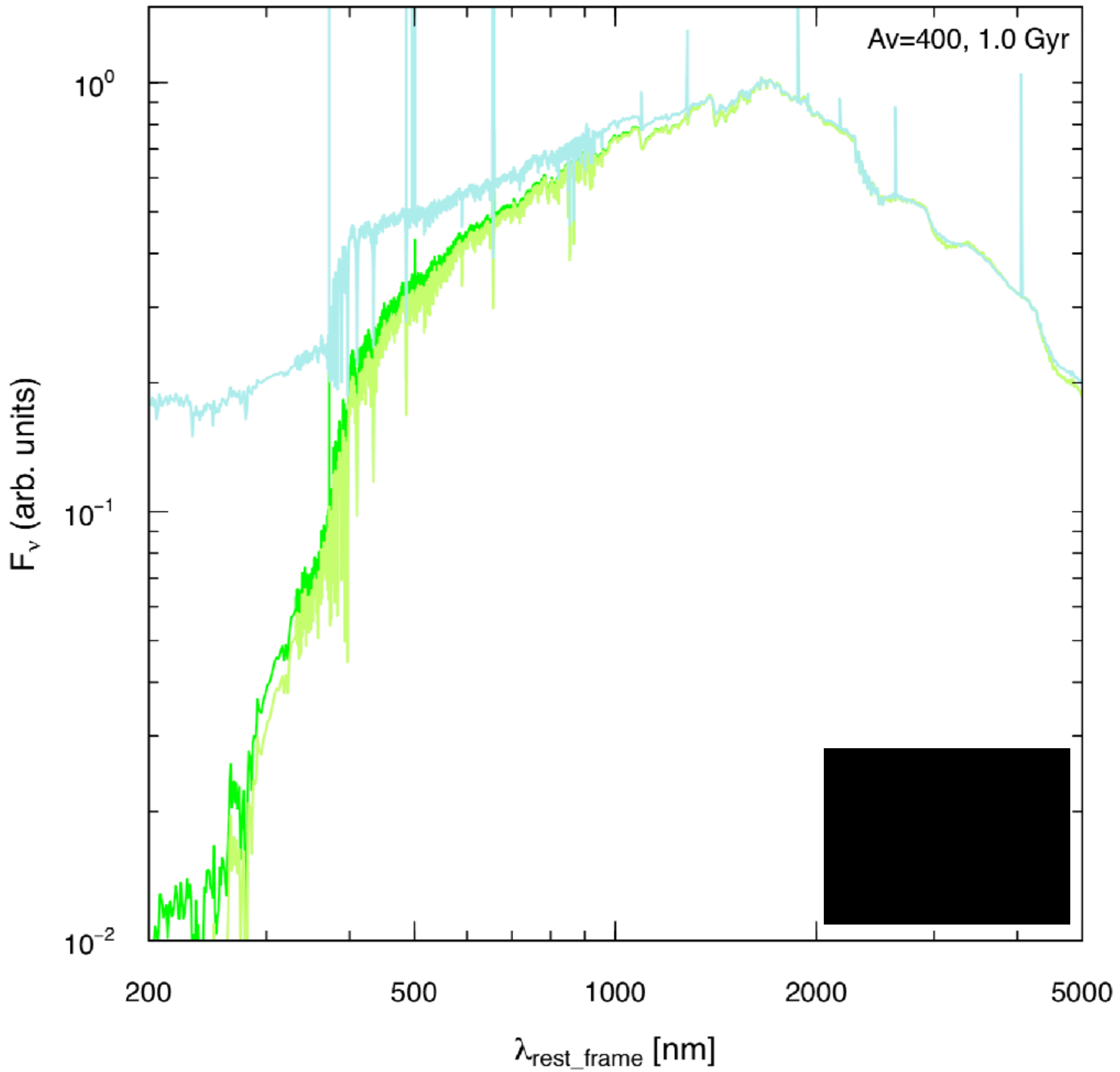
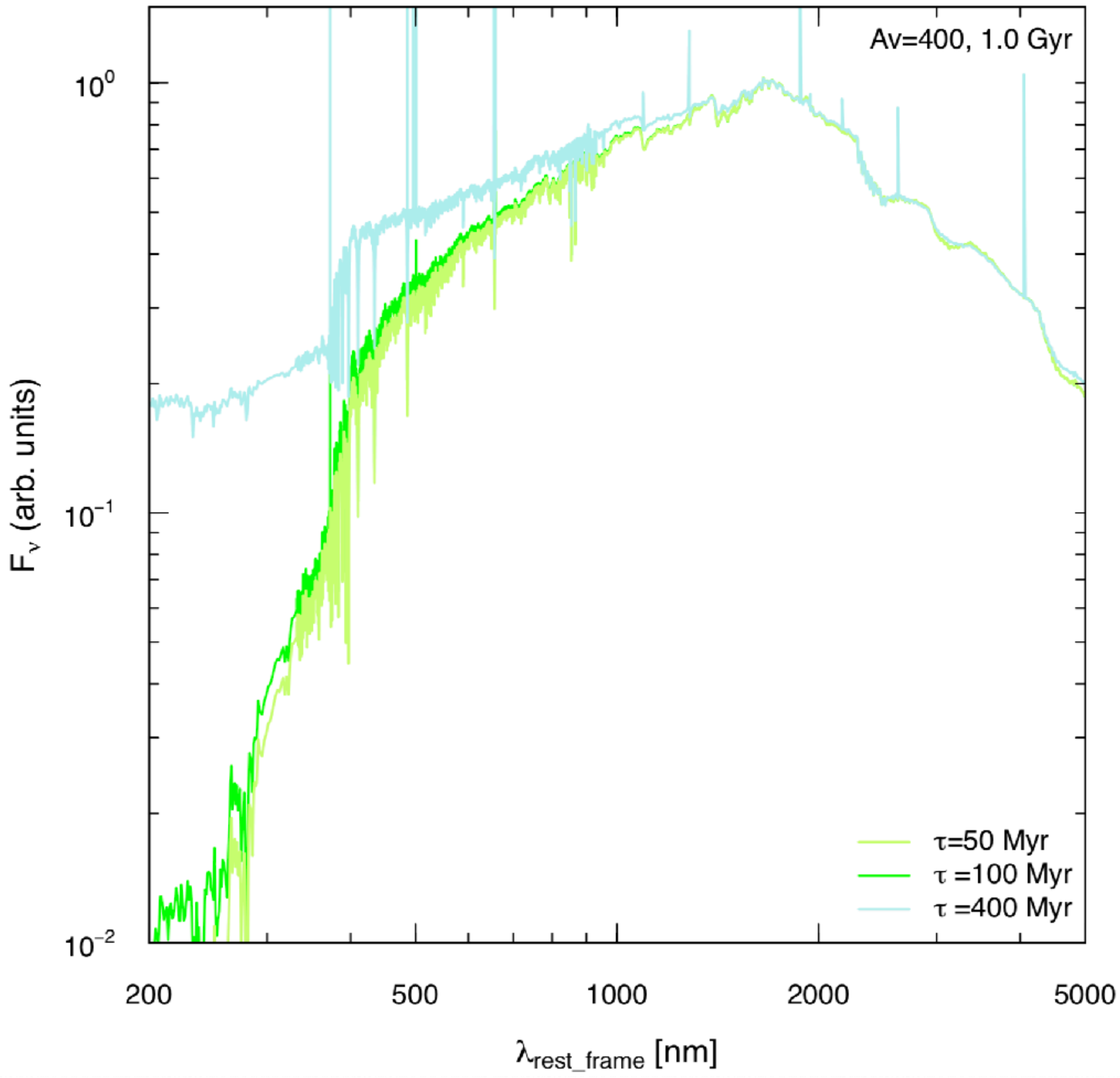

Av=400, 1.0 Gyr
10^{0}
10^{-1}
10^{-2}
F_{ν} (arb. units)
200
500
1000
2000
5000
λ_{rest_frame} [nm]
[redacted]

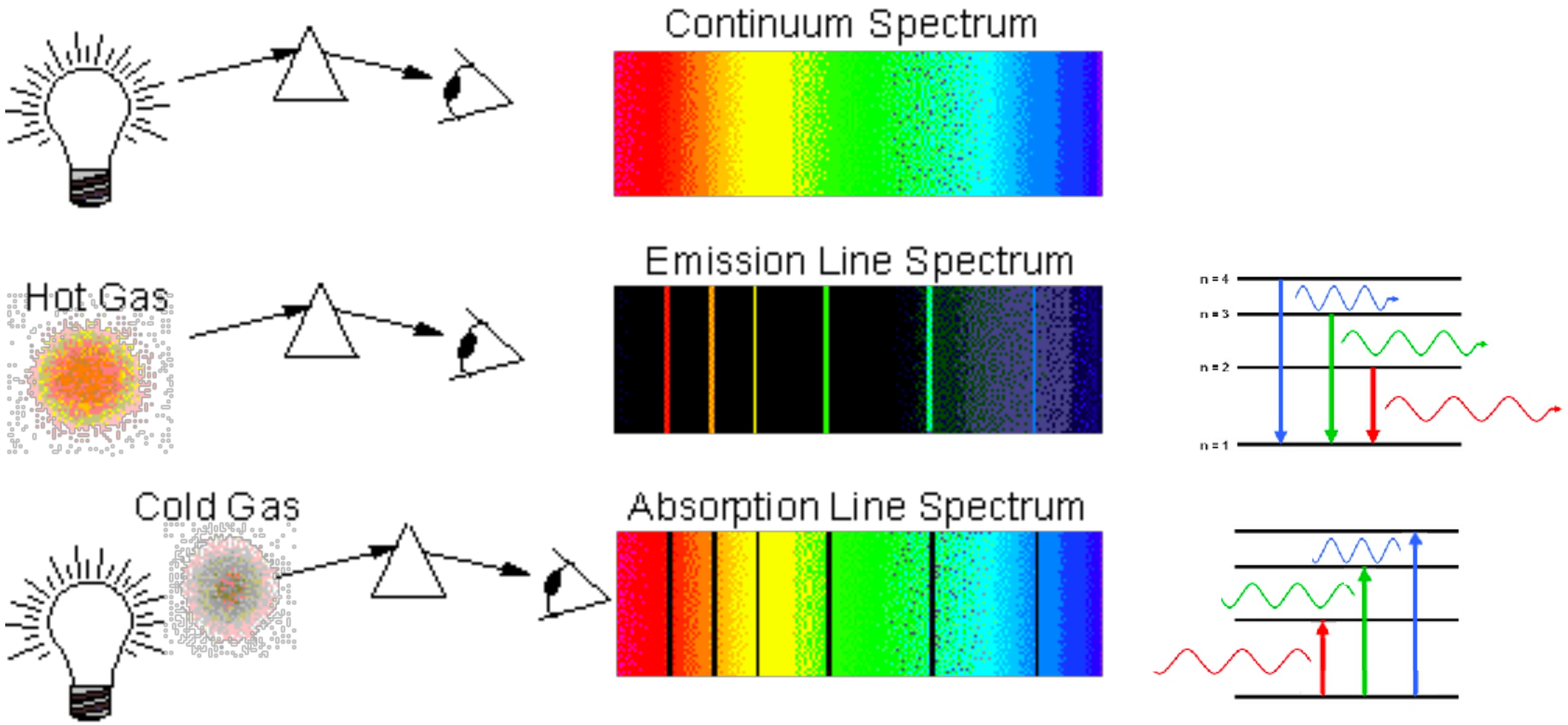


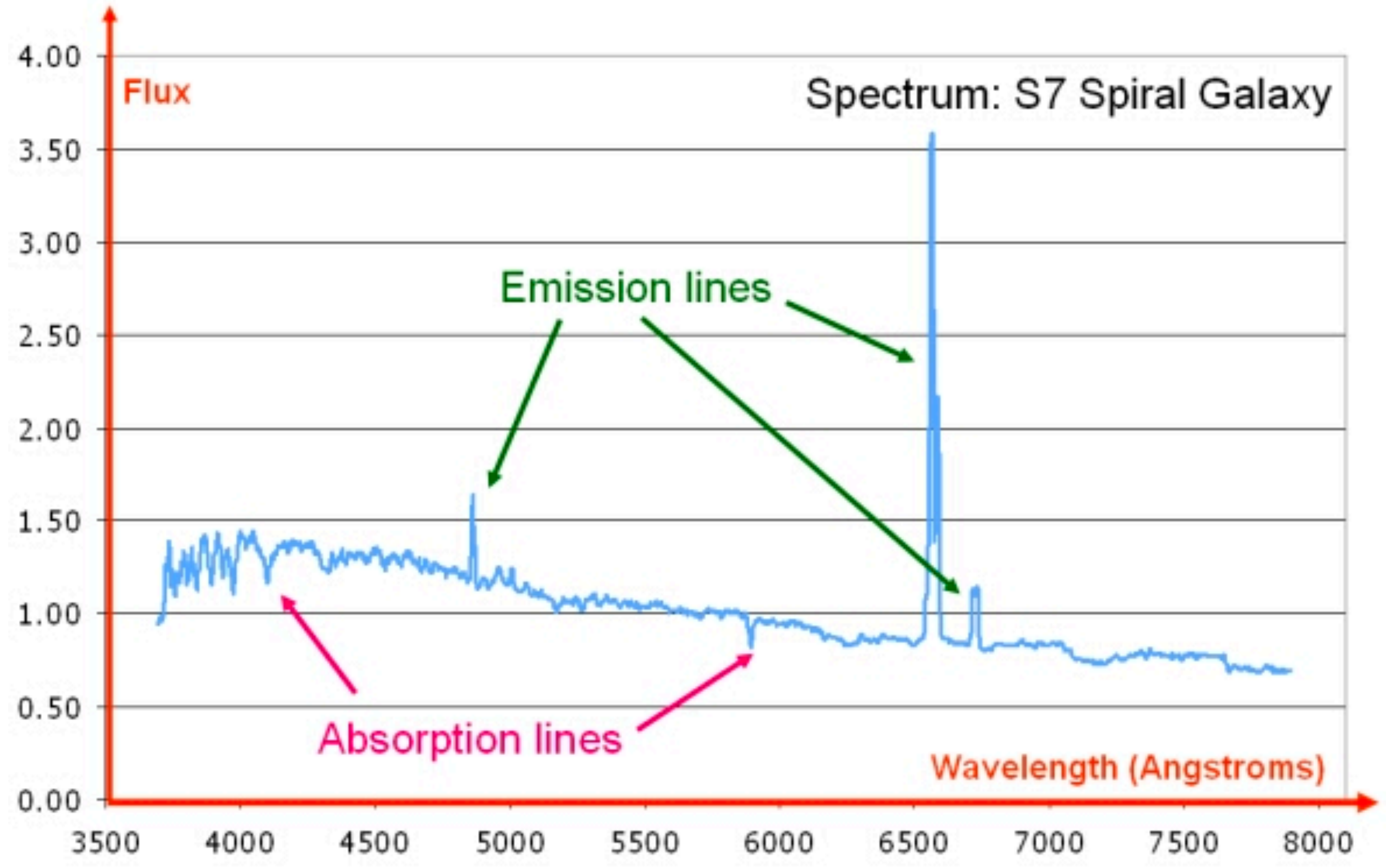
Av=400, 1.0 Gyr
F_ν (arb. units)
10^0
10^{-1}
10^{-2}
200
500
1000
2000
5000
λ_{rest_frame} [nm]
τ=50 Myr
τ =100 Myr
τ =400 Myr

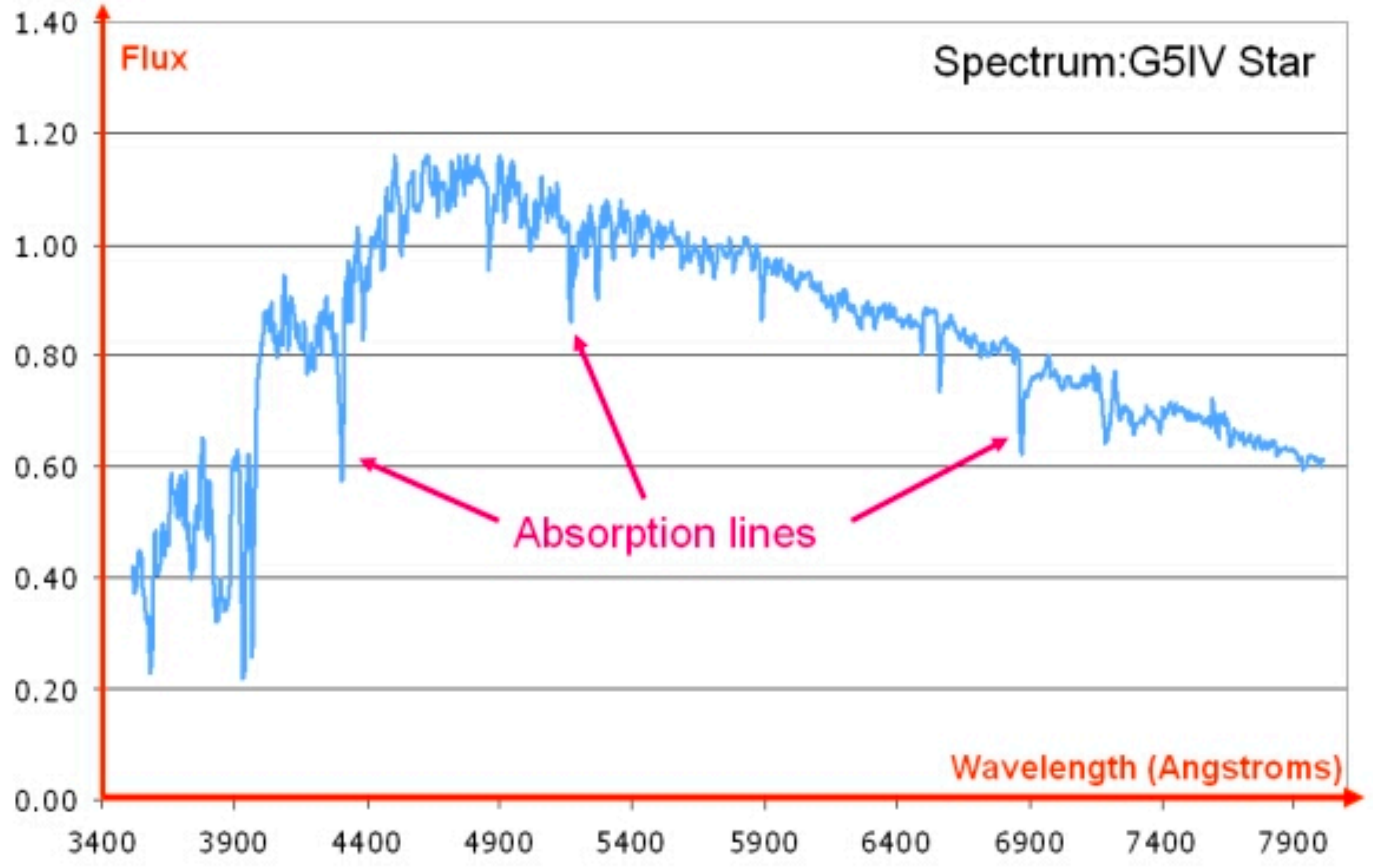
Ionized gas

- UV emission: massive young stars are bright in the UV; direct probe of young stellar population
- Nebular lines: zones of ionized 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

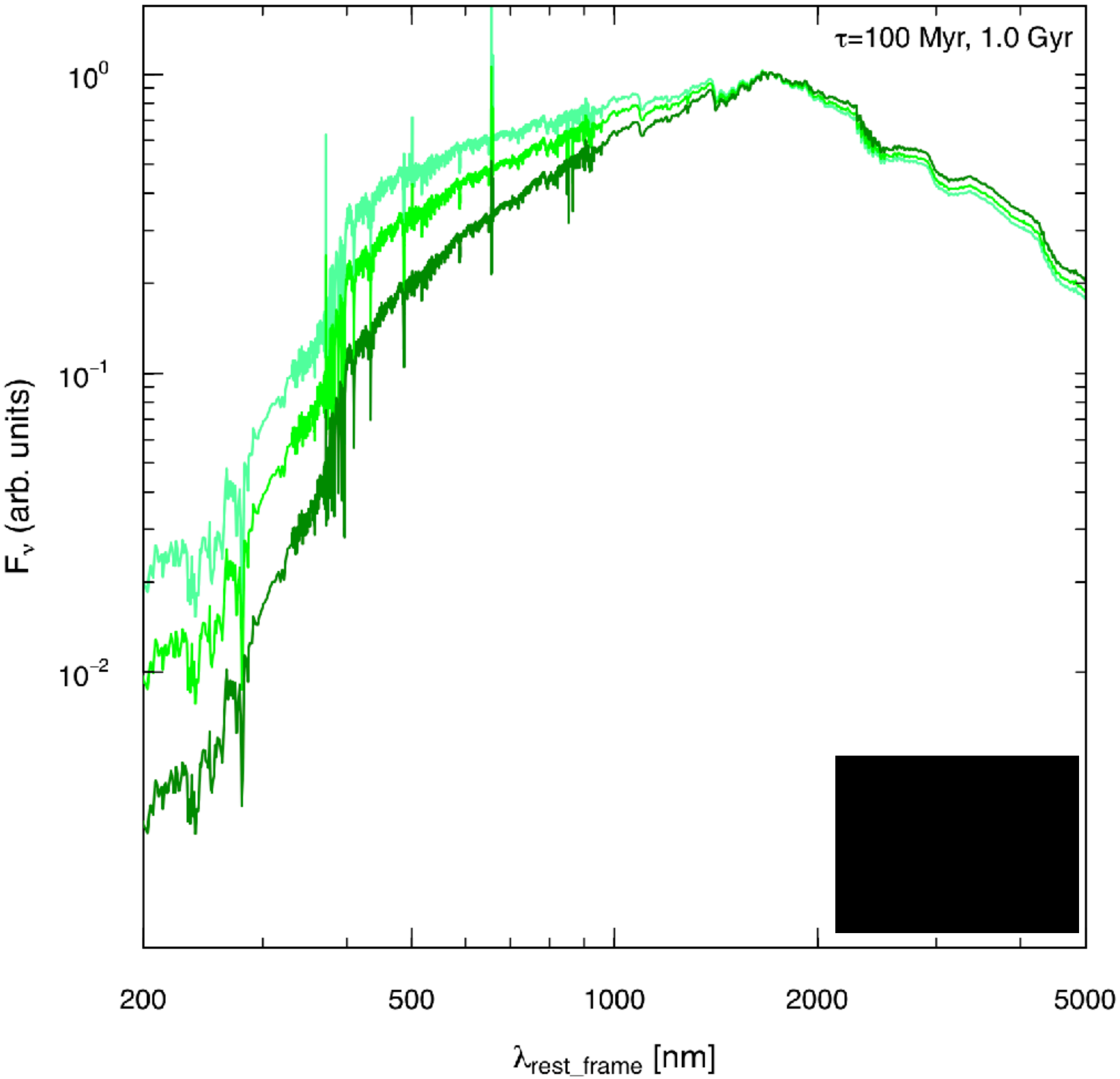






…and dust

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



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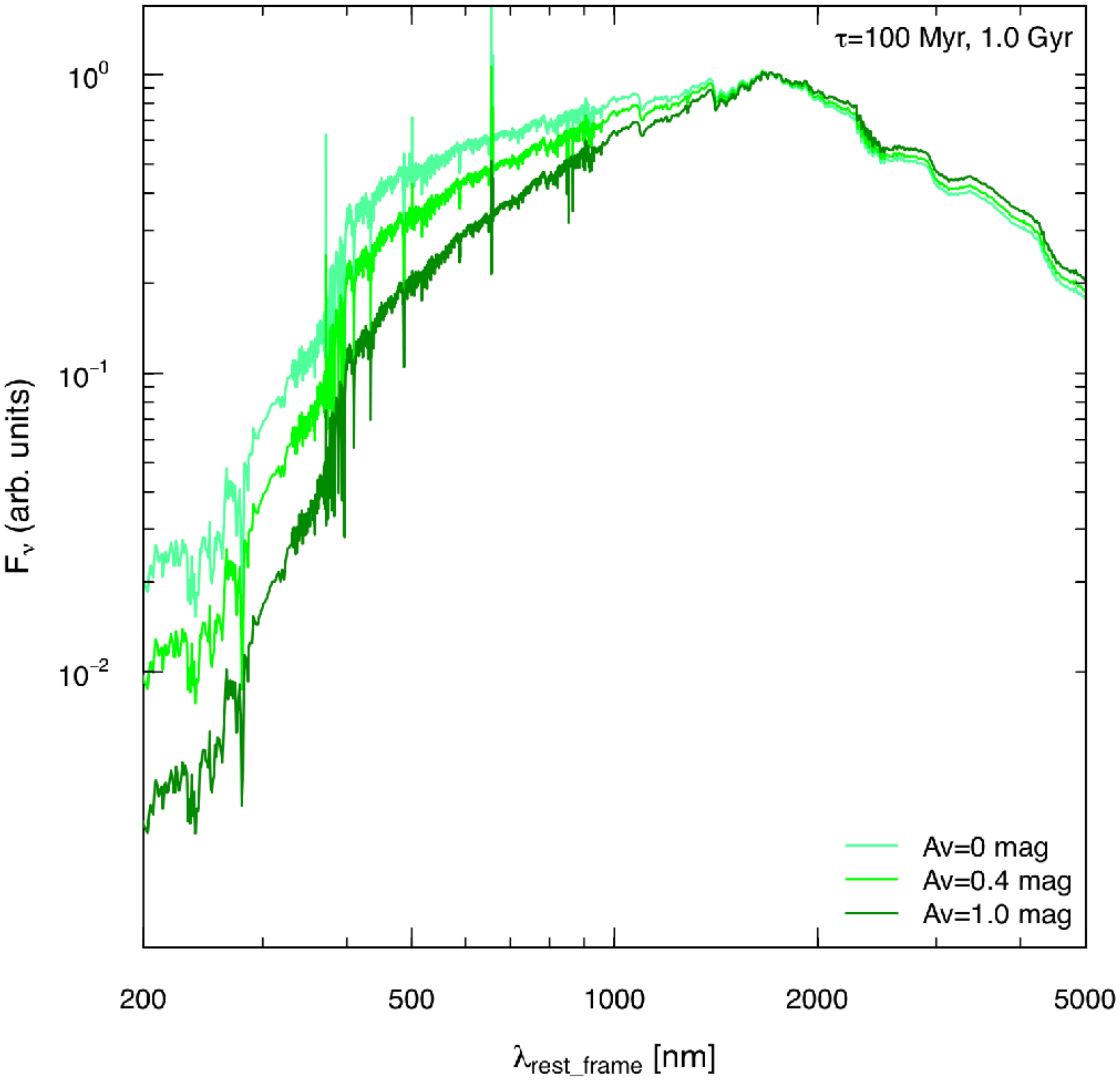
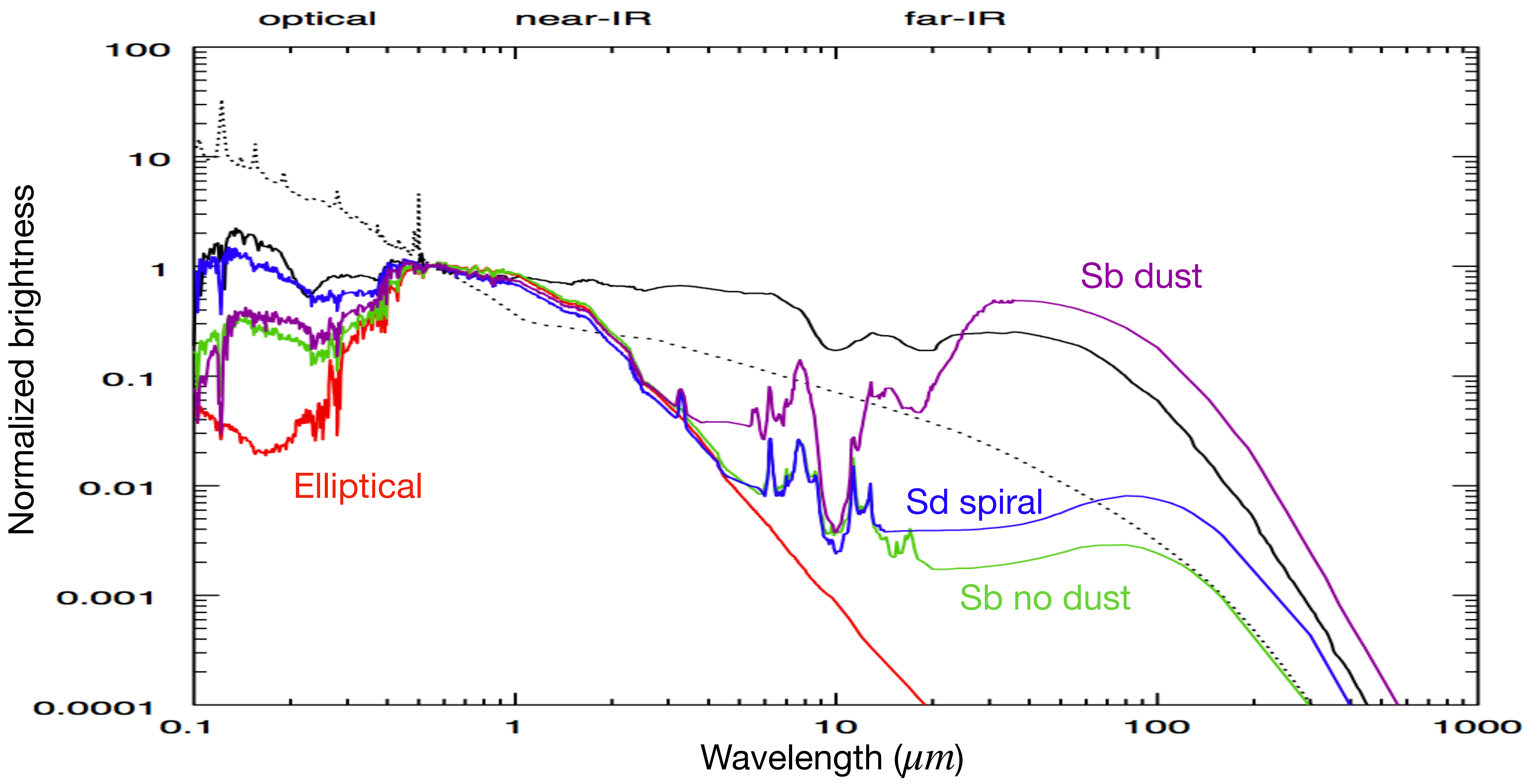


Absorbs high-energy (blue) light which is reemitted at infrared wavelegths.

Absorption, reddening, and reemission



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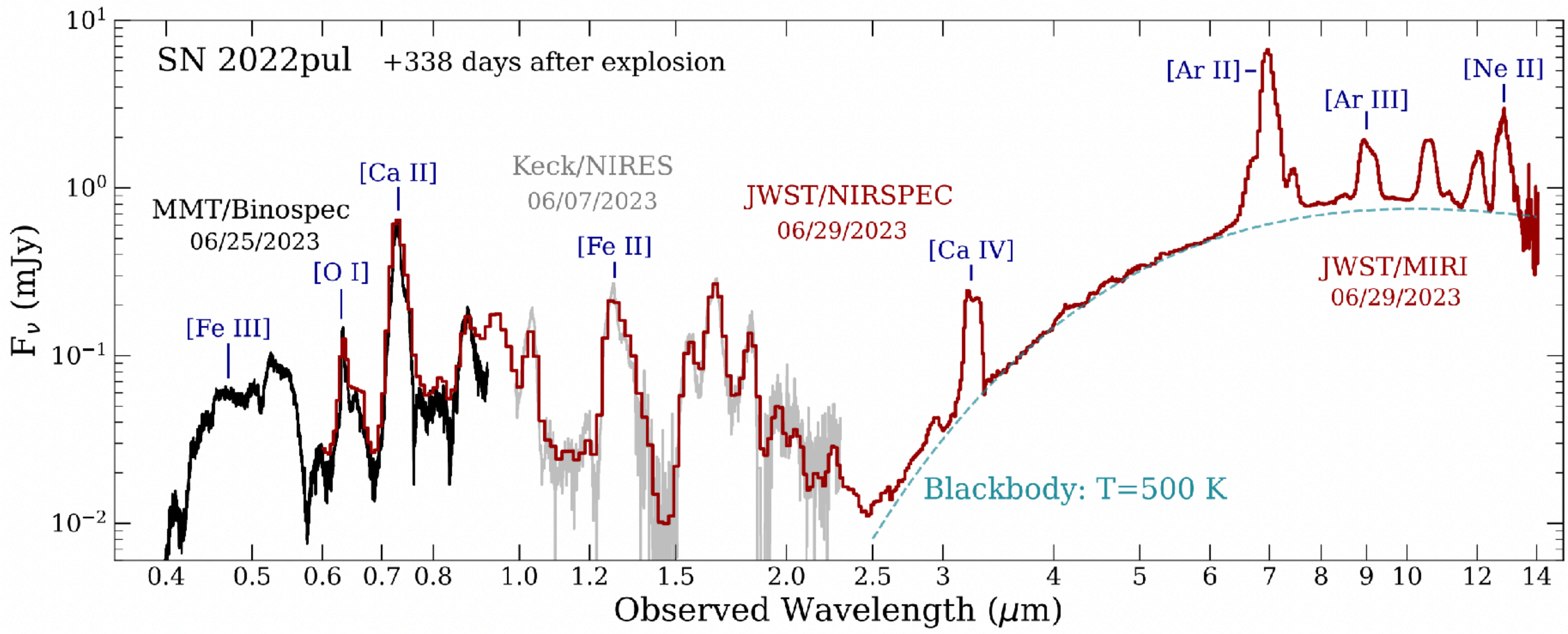


Real galaxy spectra

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

Mass-to-light ratio

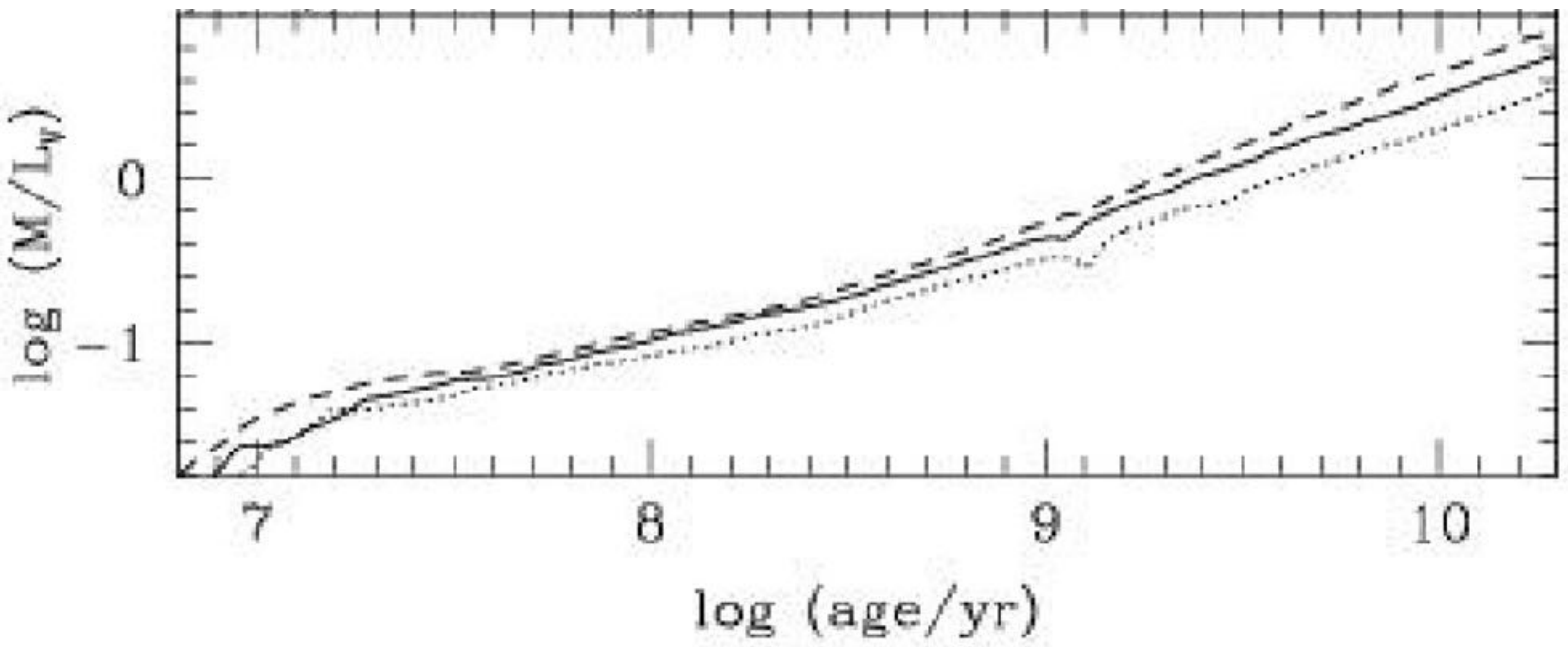
- If we understand the properties of SP, we can use L to infer M in stars by invoking M/L
- It has units of $M_\odot/L_\odot$, so the Sun has M/L=1
  - An A-type MS star with $L = 12L_\odot$ and $M = 2M_\odot$, it has $(M/L) = 0.17M_\odot/L_\odot$
  - A K-type MS star with $L = 0.3L_\odot$ and $M = 0.75M_\odot$,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

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

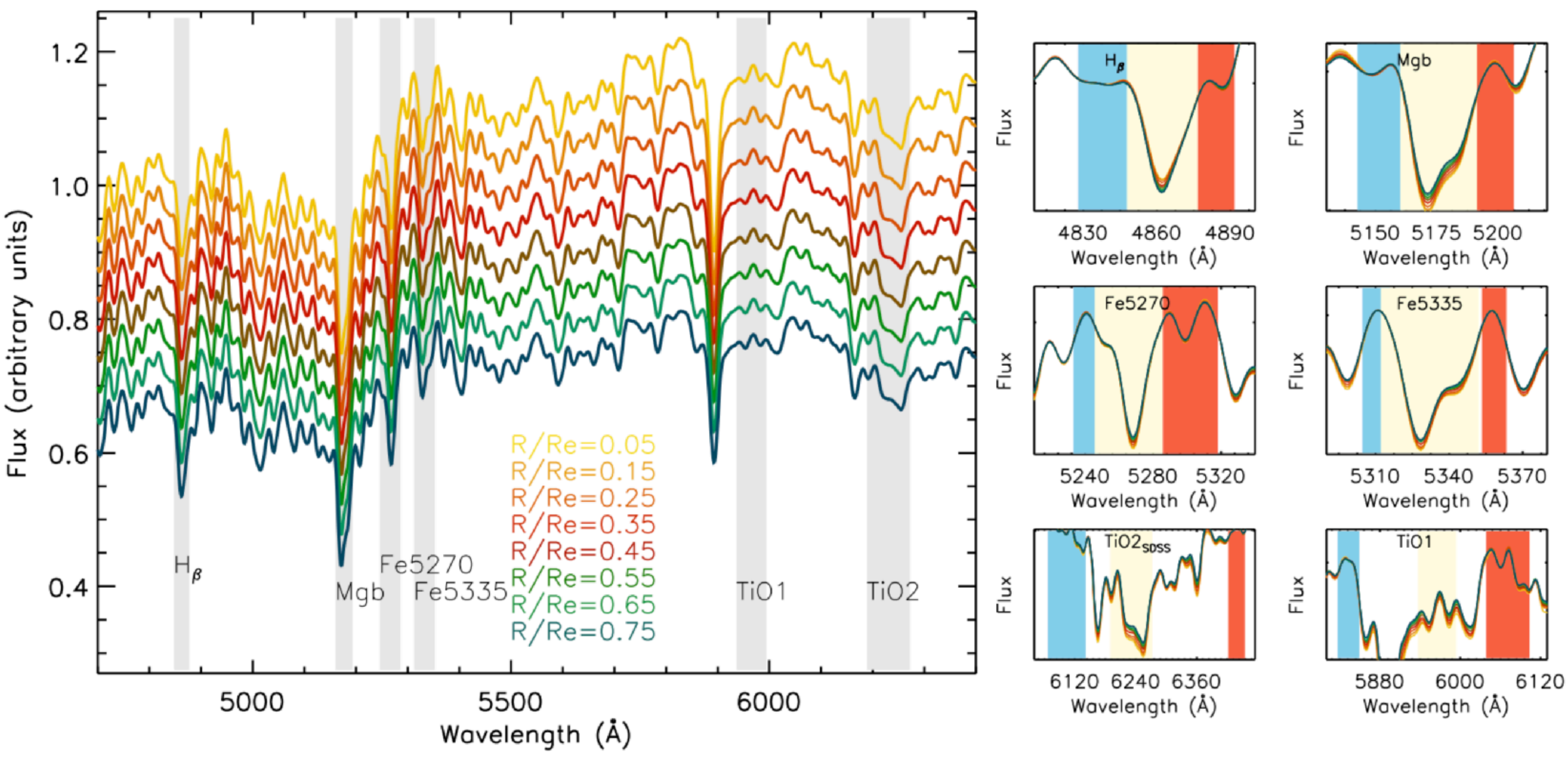
Mass-to-light ratio

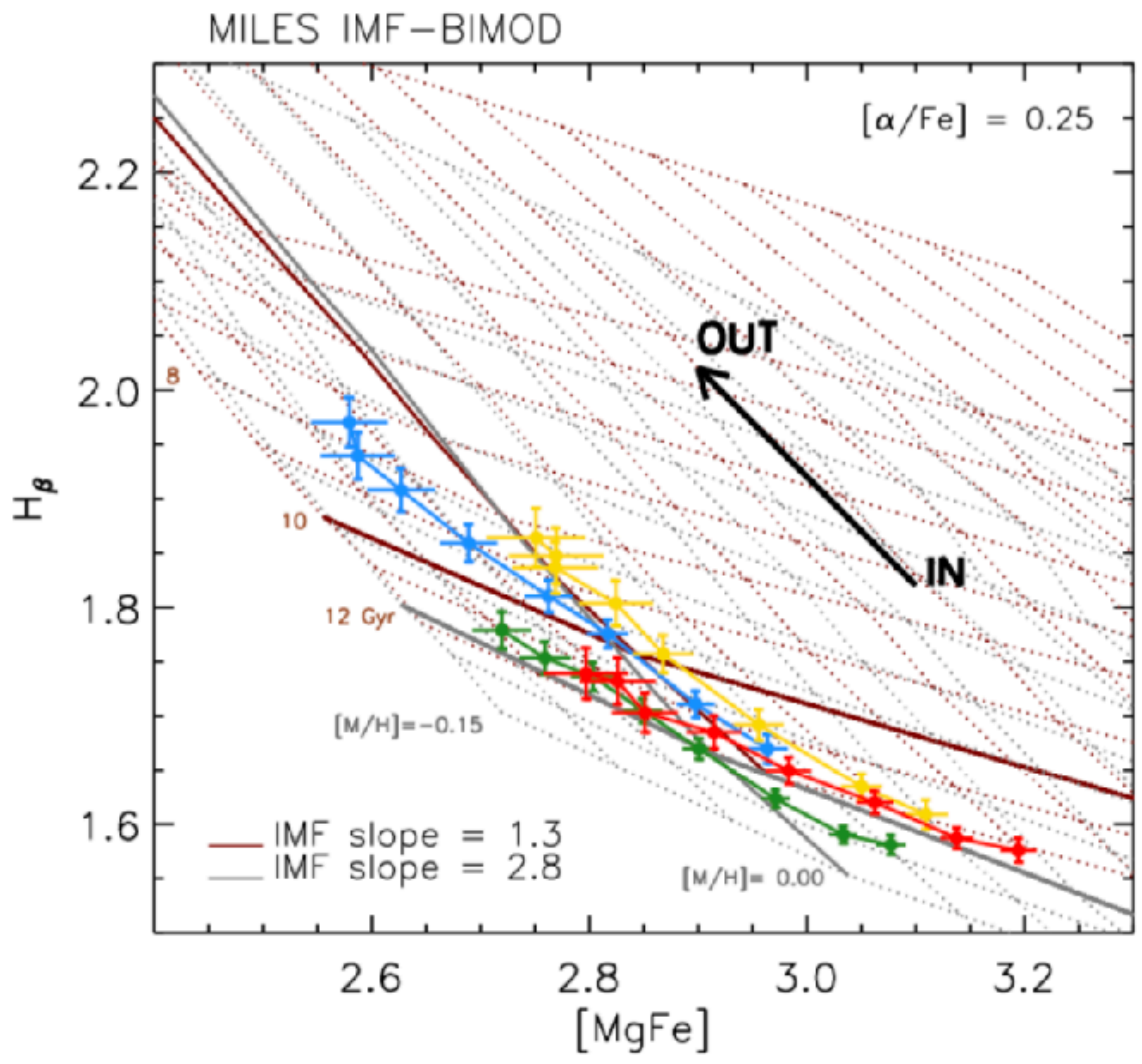
- If we understand the properties of SP, we can use L to infer M in stars by invoking M/L
- It has units of $M_\odot/L_\odot$, so the Sun has M/L=1
    - An A-type MS star with $L = 12L_\odot$ and $M = 2M_\odot$, it has $(M/L) = 0.17M_\odot/L_\odot$
    - A K-type MS star with $L = 0.3L_\odot$ and $M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

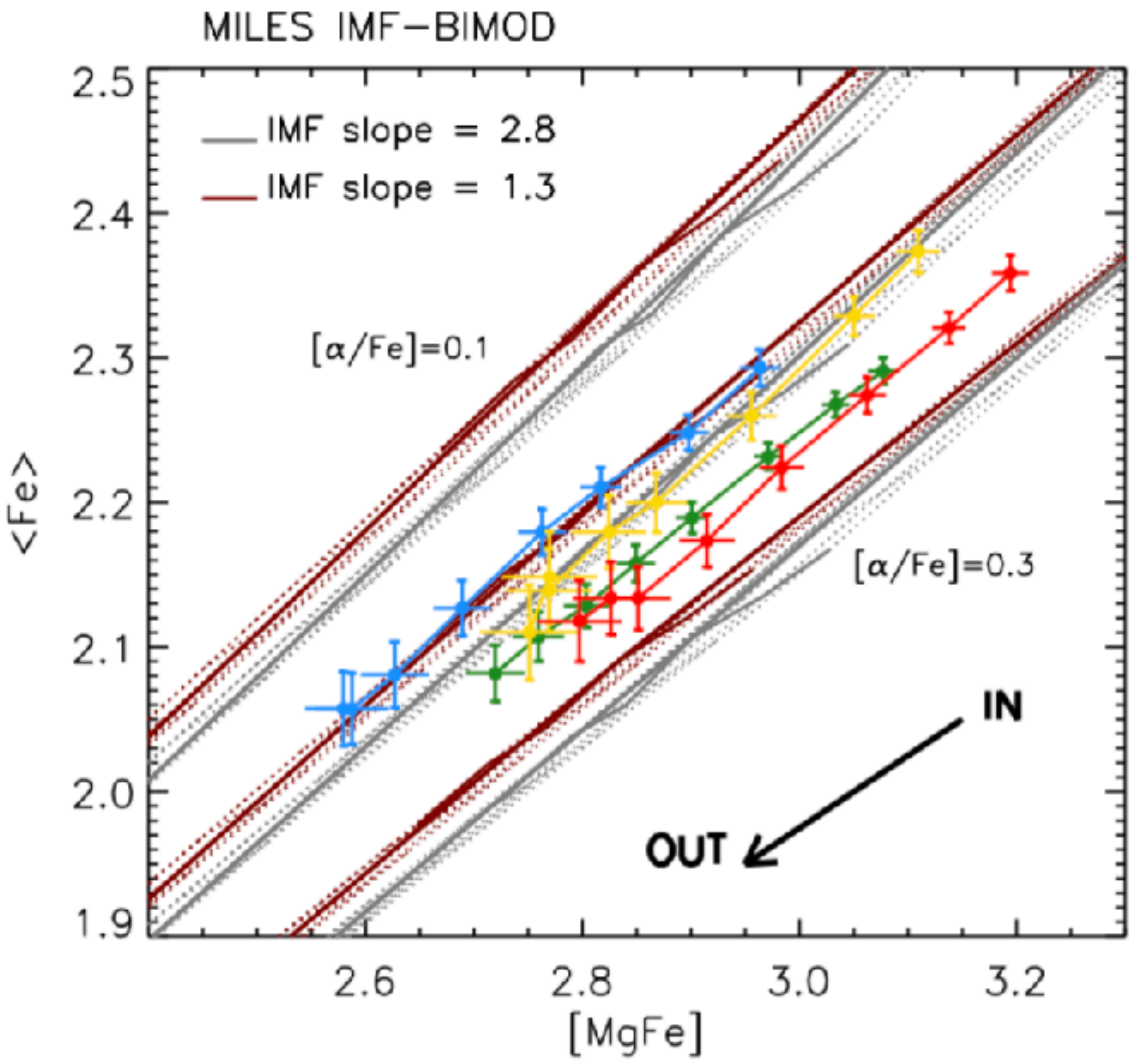
- Q: Does the M/L increase or decrease with time for a SSP?



Lick indices

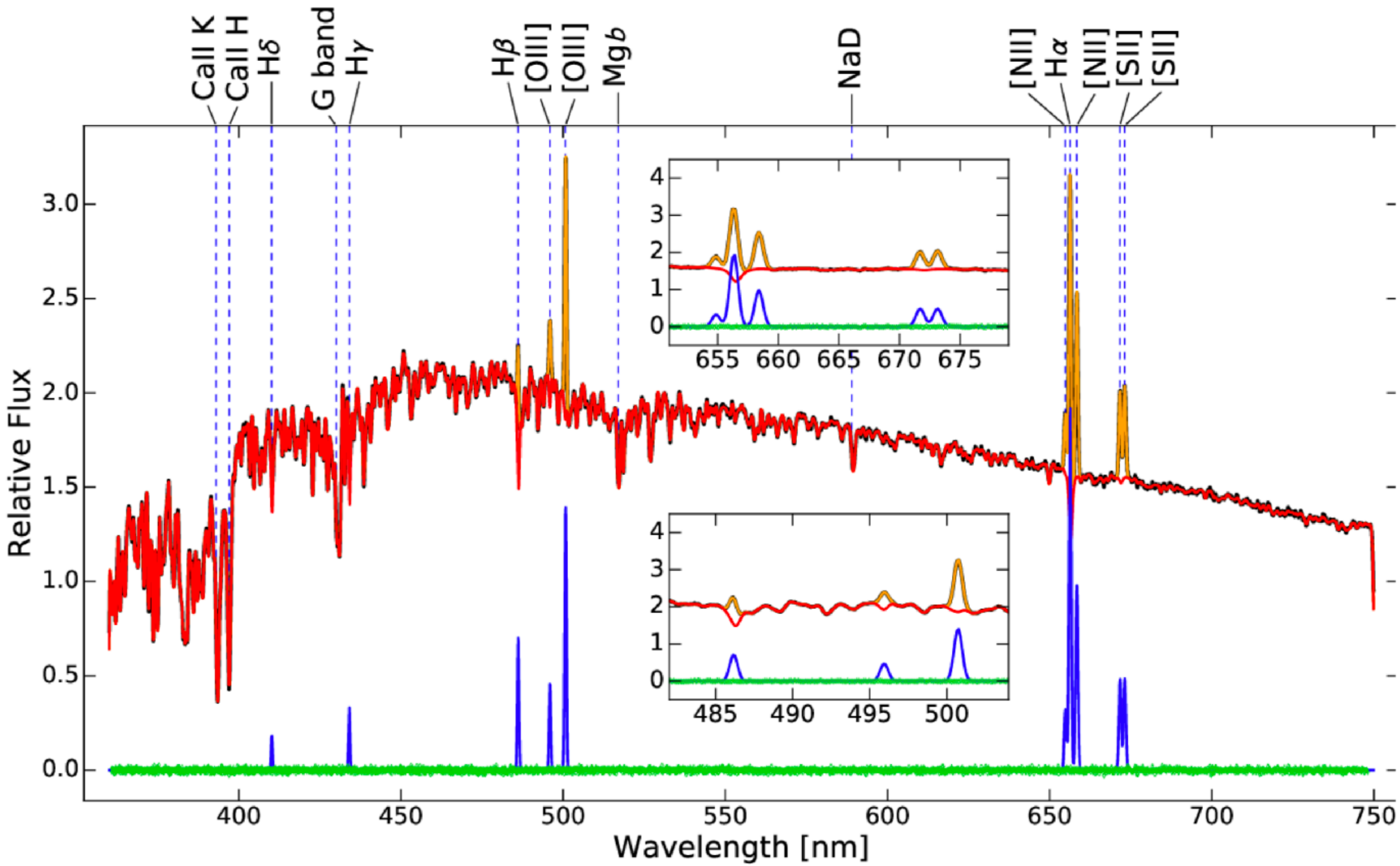






- Lick indices are measured on observed spectra and compared to the predictions of theoretical models.
- Hb-MgFe good indicator of age-metallicity.
- <Fe>-MgFe good alpha-enhancement indicator.
- Tio2 good IMF indicator.

Spectral synthesis



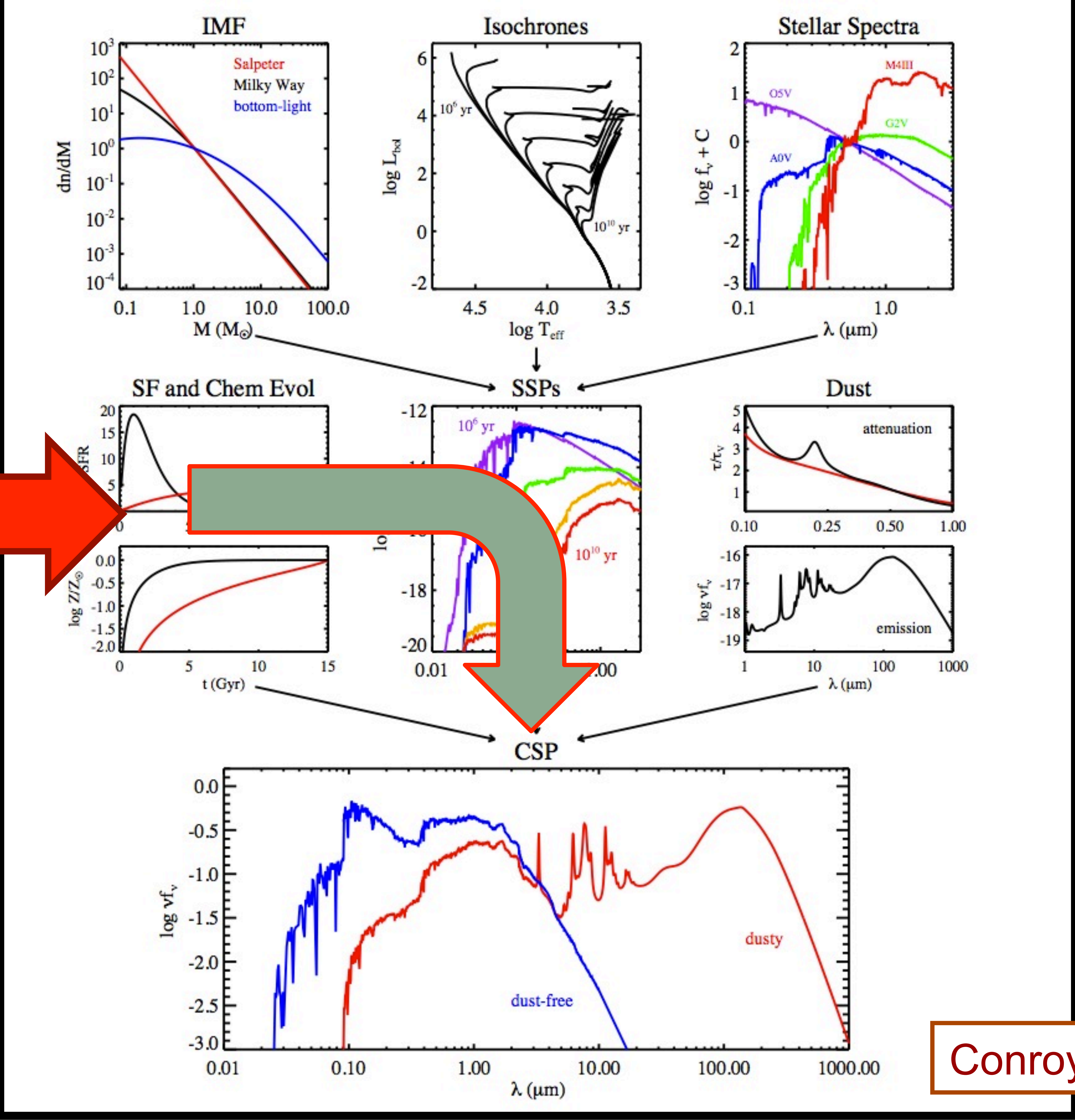
- FIREFLY
- PPXF
- Starlight
- Prospector
- …

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

→ SFH(t,Z): 2 approaches

SFH → $L_{gal}(\lambda)$	$L_{gal}(\lambda)$ → SFH
Given a SFH, what is the resulting galaxy spectrum?	***Given a galaxy spectrum, what is the SFH?***
⇓	⇓
Evolutionary Population Synthesis	Inverse Population Synthesis

Forward spectral synthesis

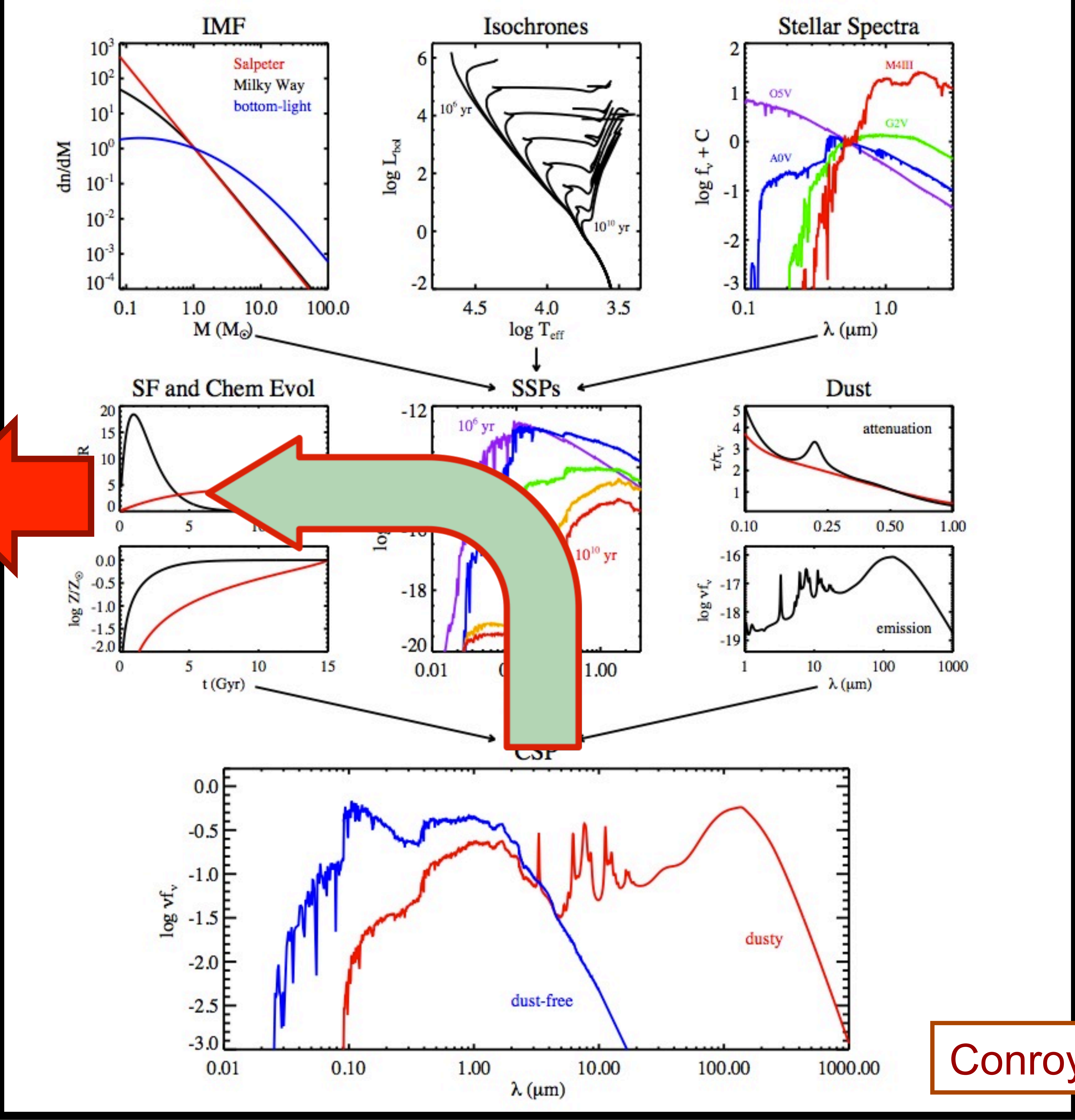


ASSUME
Star Formation History

Conroy 2013

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

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

Parameter space ← SFH

↓

Observables space

Inverse Pop Synthesis

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

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

SFH ← Parameter space

↑

Observables space