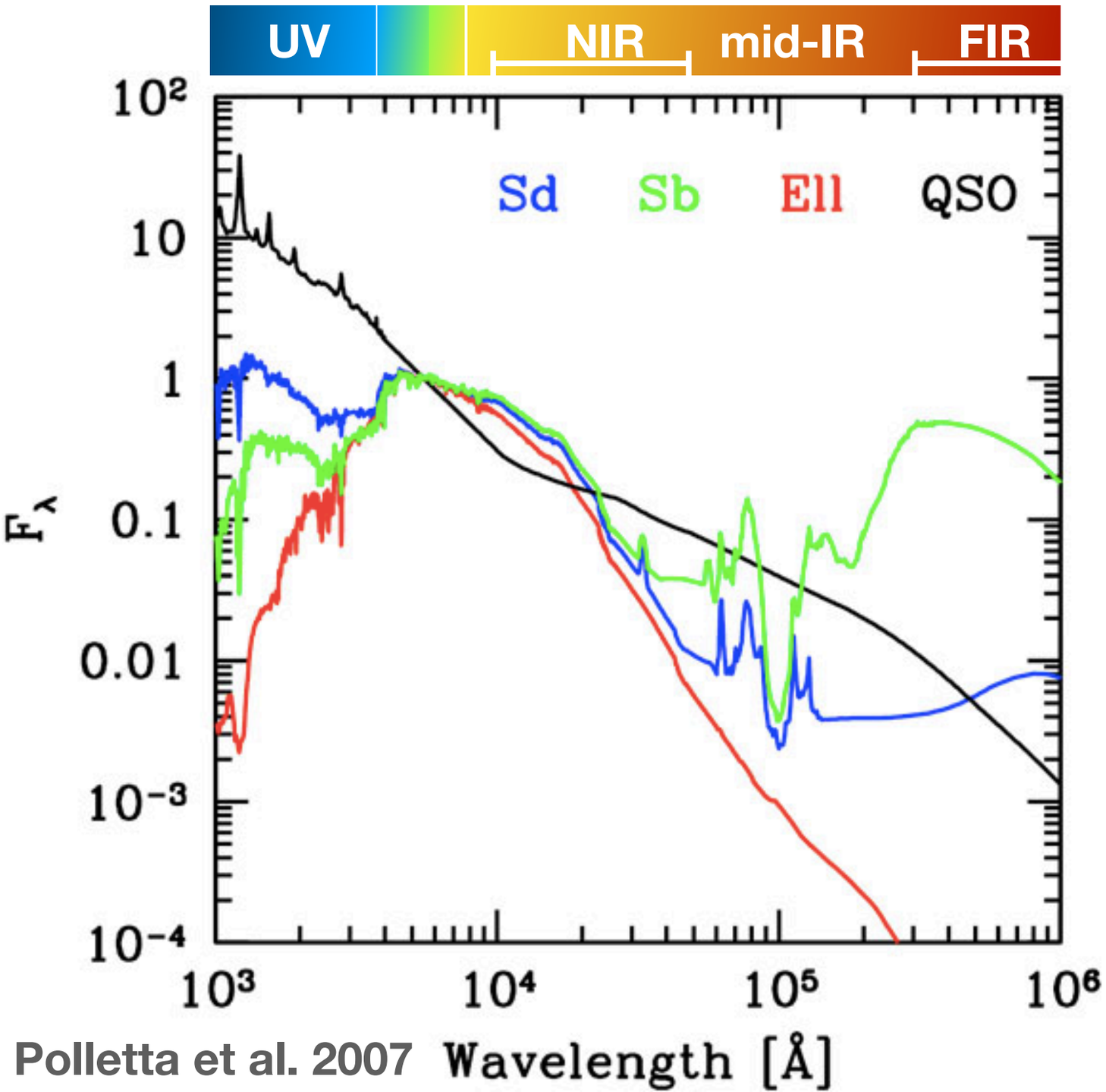
Galaxy spectral energy distributions (UV to IR)

What is a galaxy SED

The SED measures the galaxy flux (luminosity/cm²/s) in wavelength range dλ (F_λ, units of erg/s/cm²/Å) or in frequency range dν (F_ν, units of erg/s/cm²/Hz)



Polletta et al. 2007

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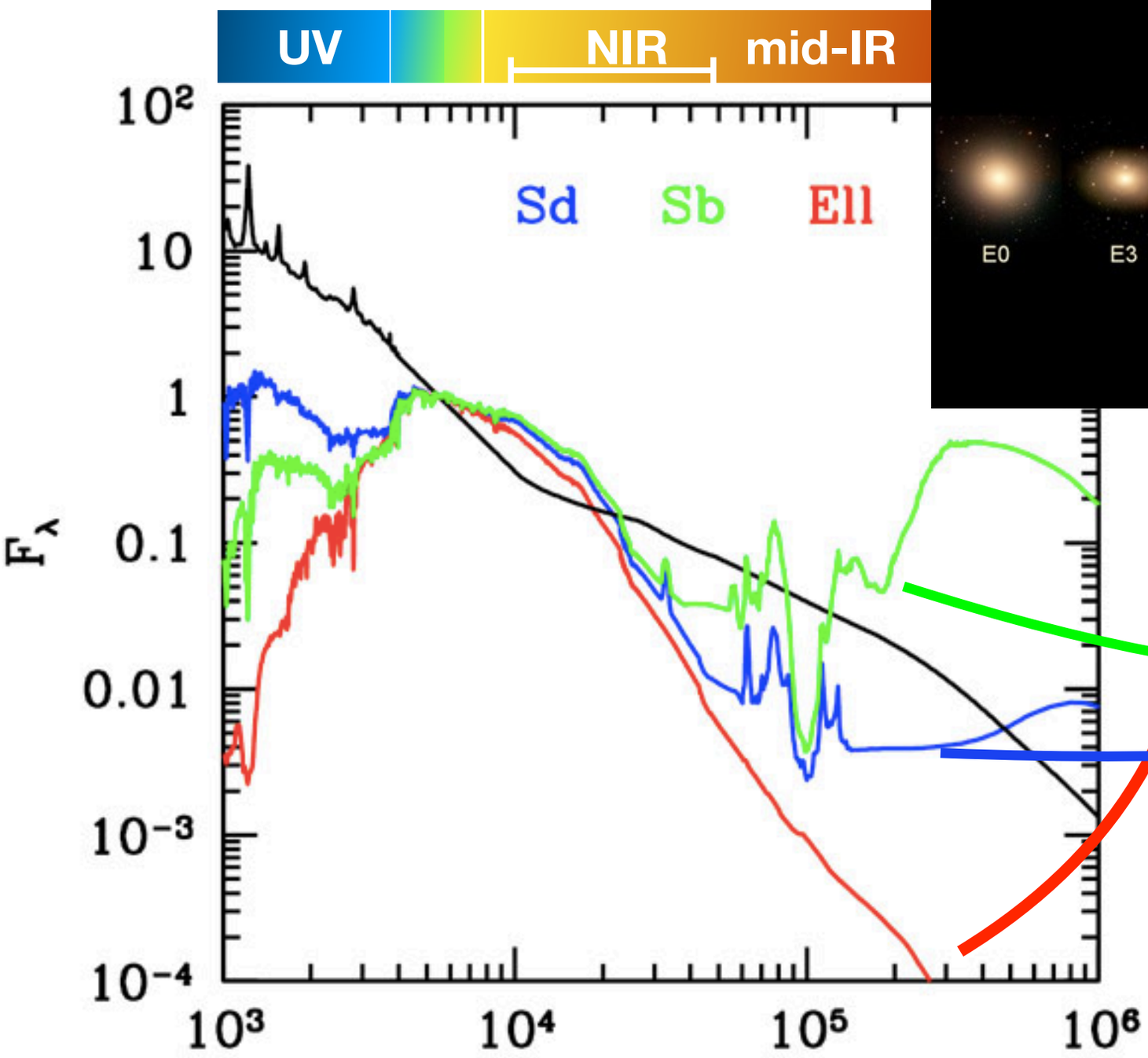
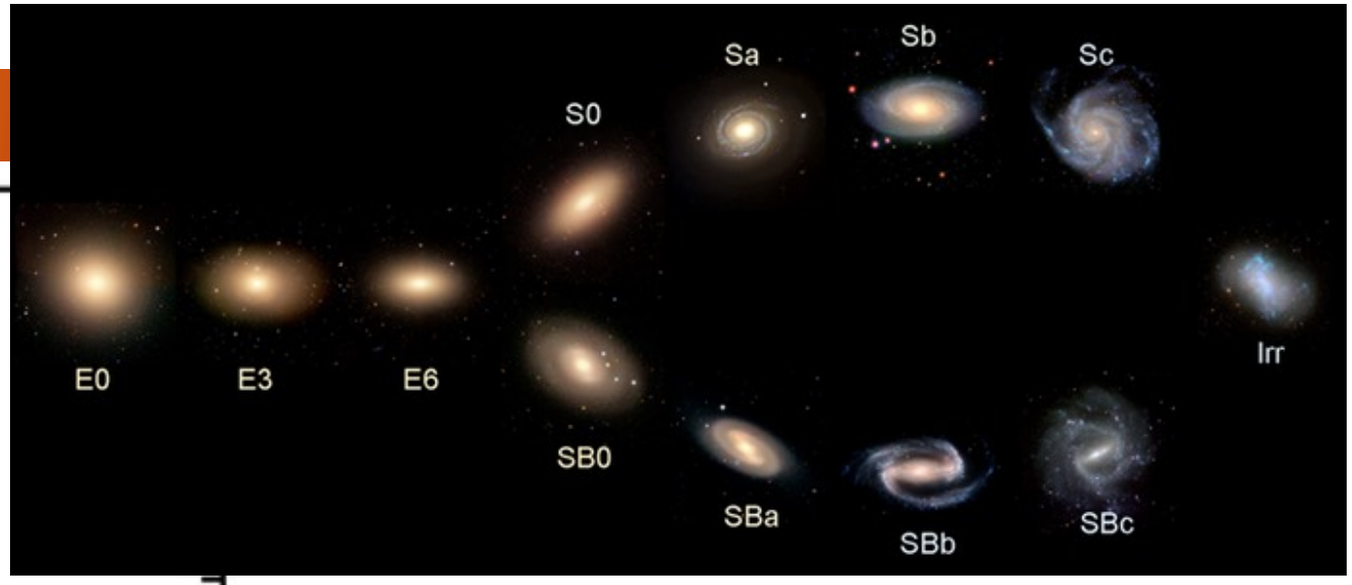


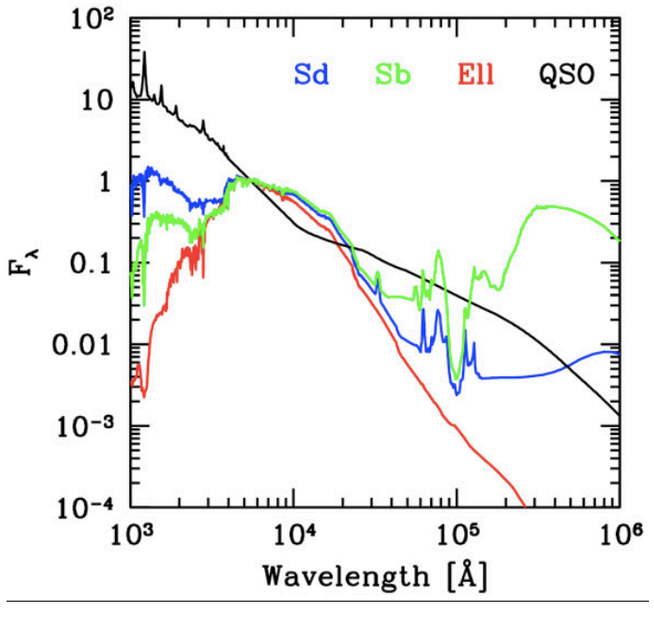


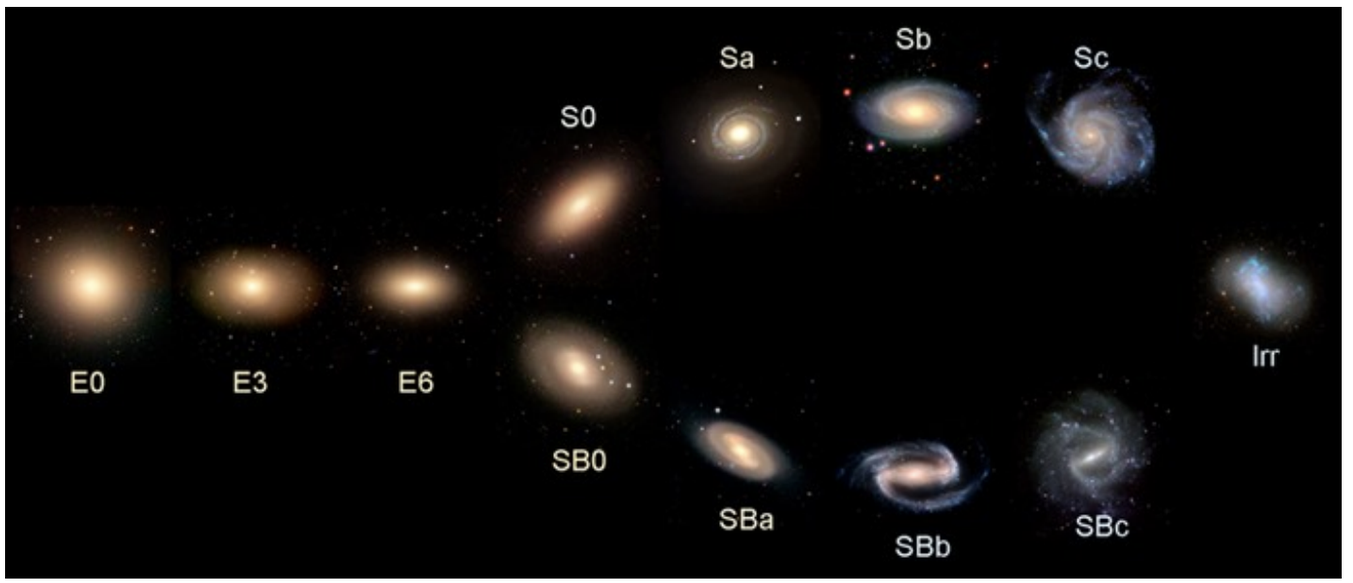
Polletta et al. 2007

Where does a galaxy SED come from

Galaxy spectral energy distributions are the result of the combination of light emission and absorption from the (baryonic) galaxy consituents:

- ☐ stars
- ☐ gas
- ☐ AGN
- ☐ dust





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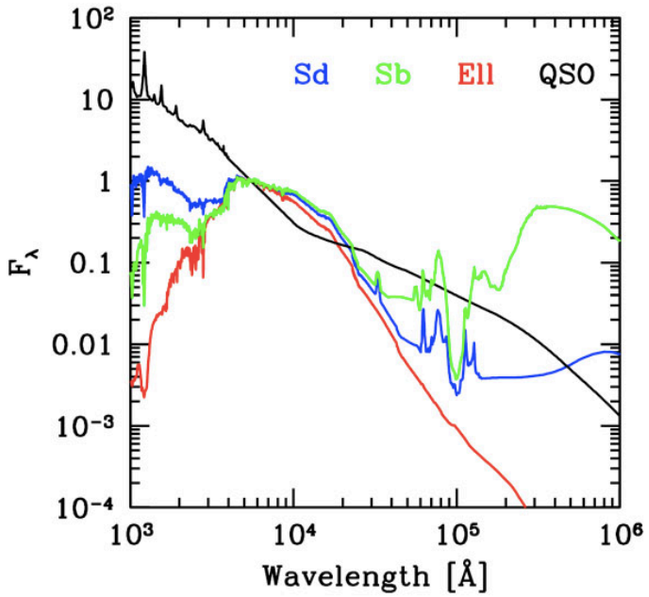

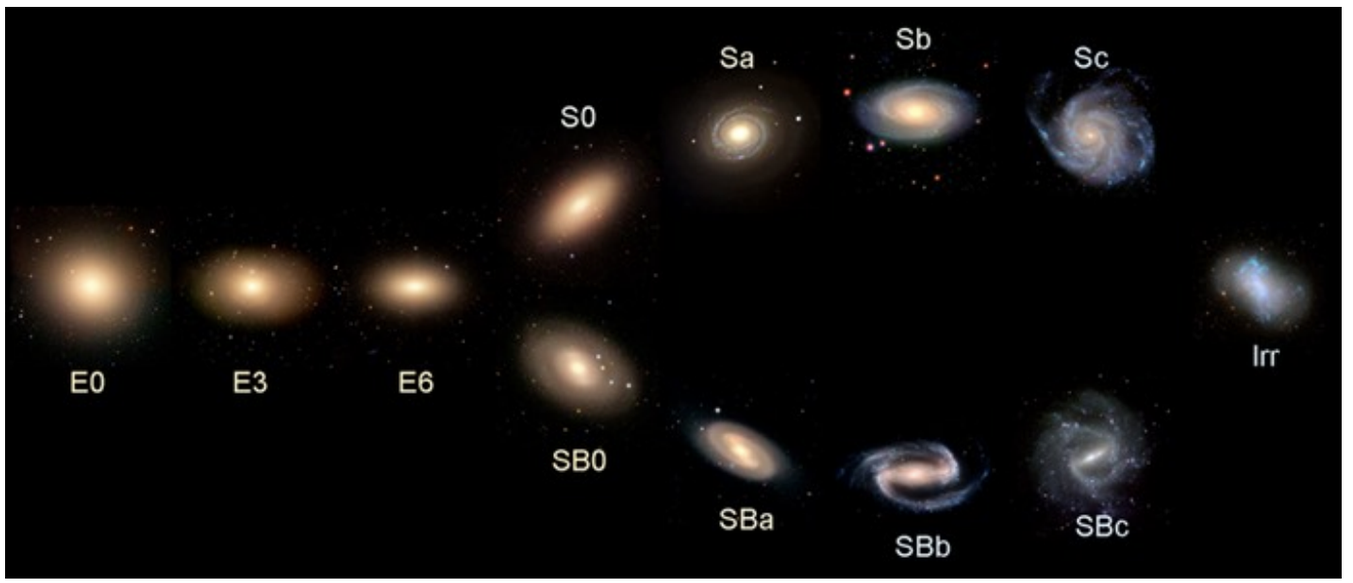

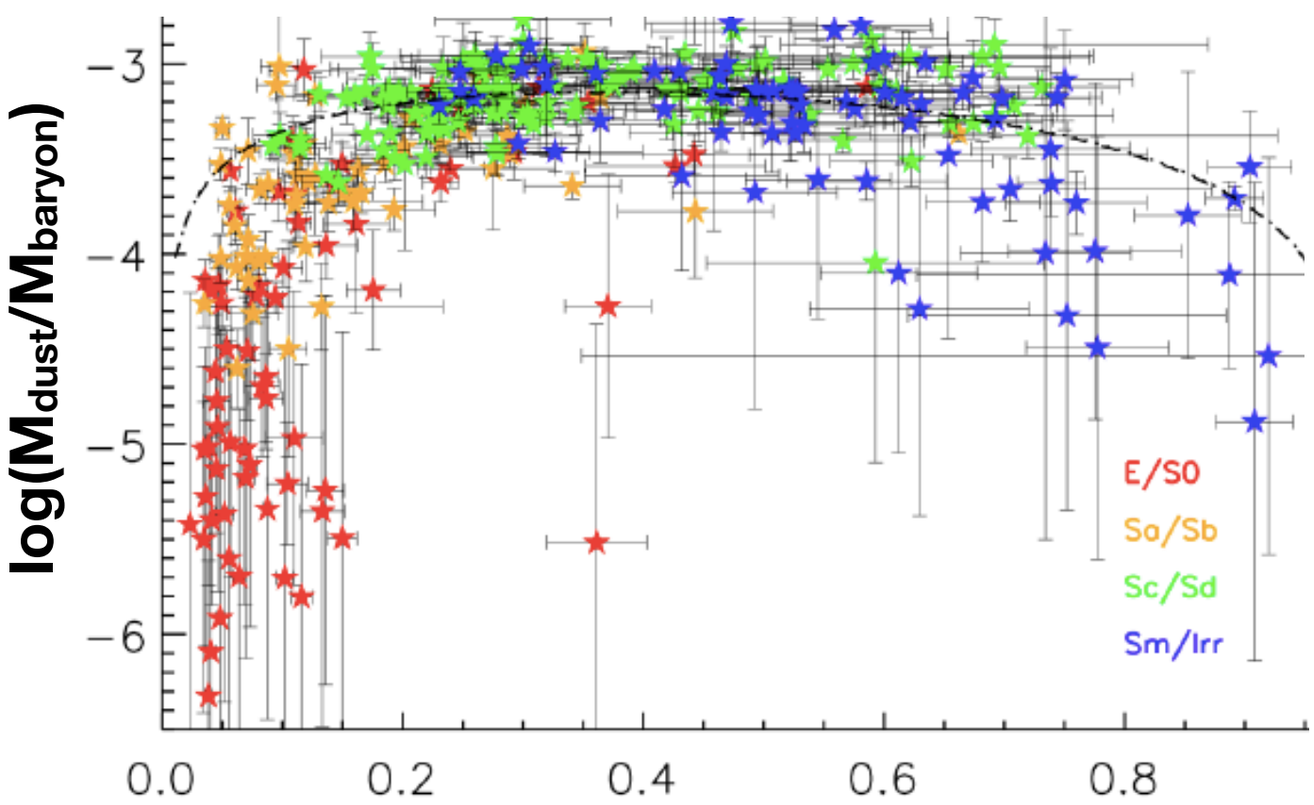

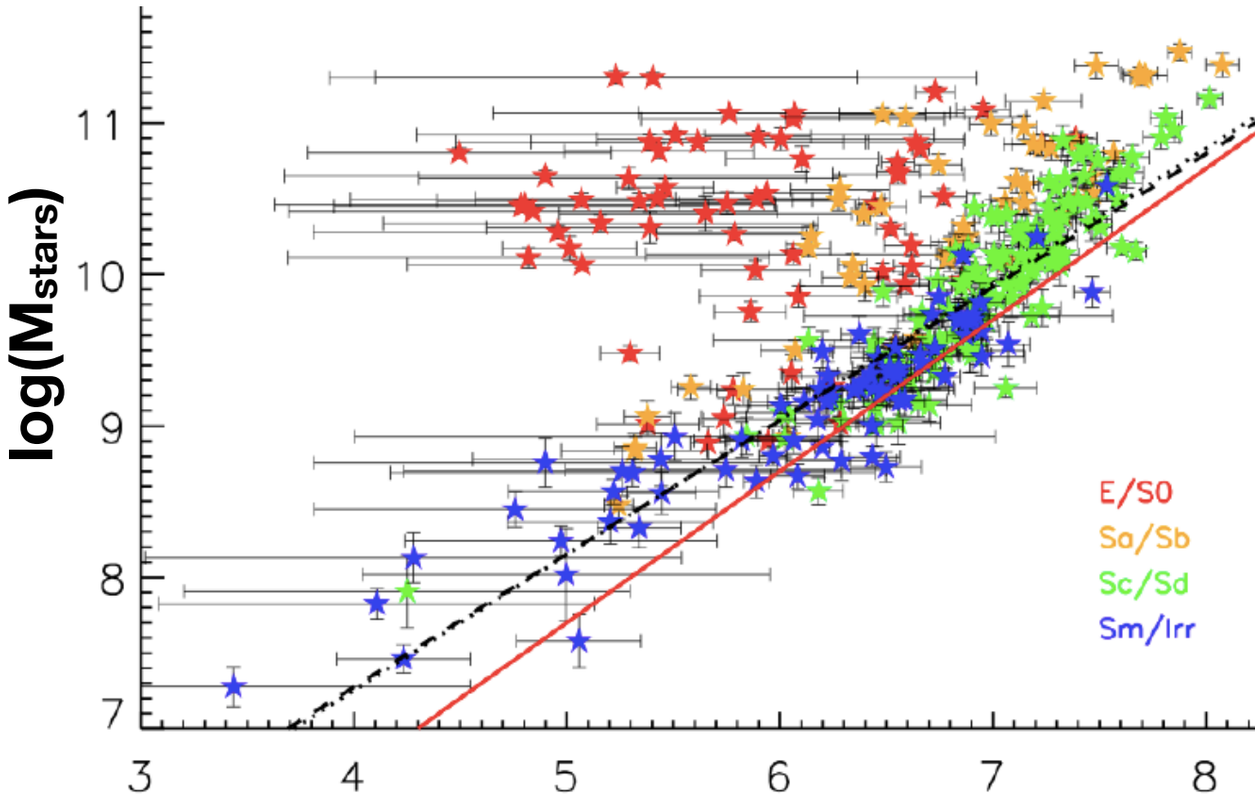

Davies et al. 2019

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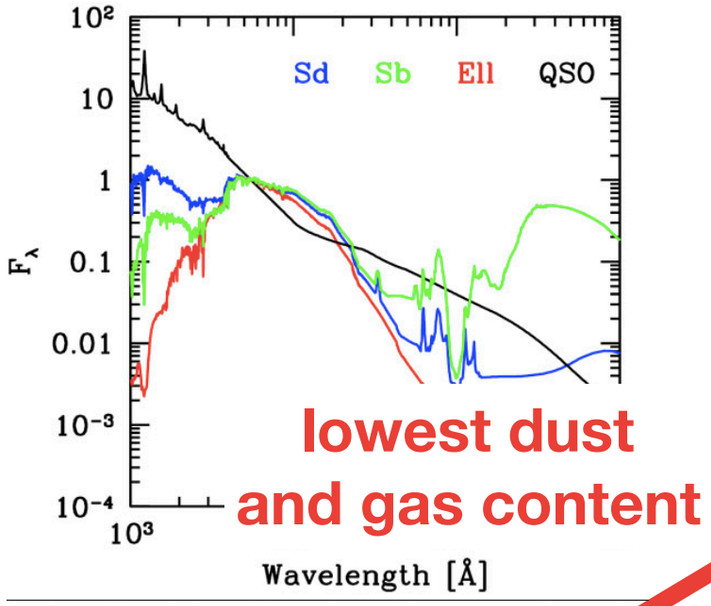
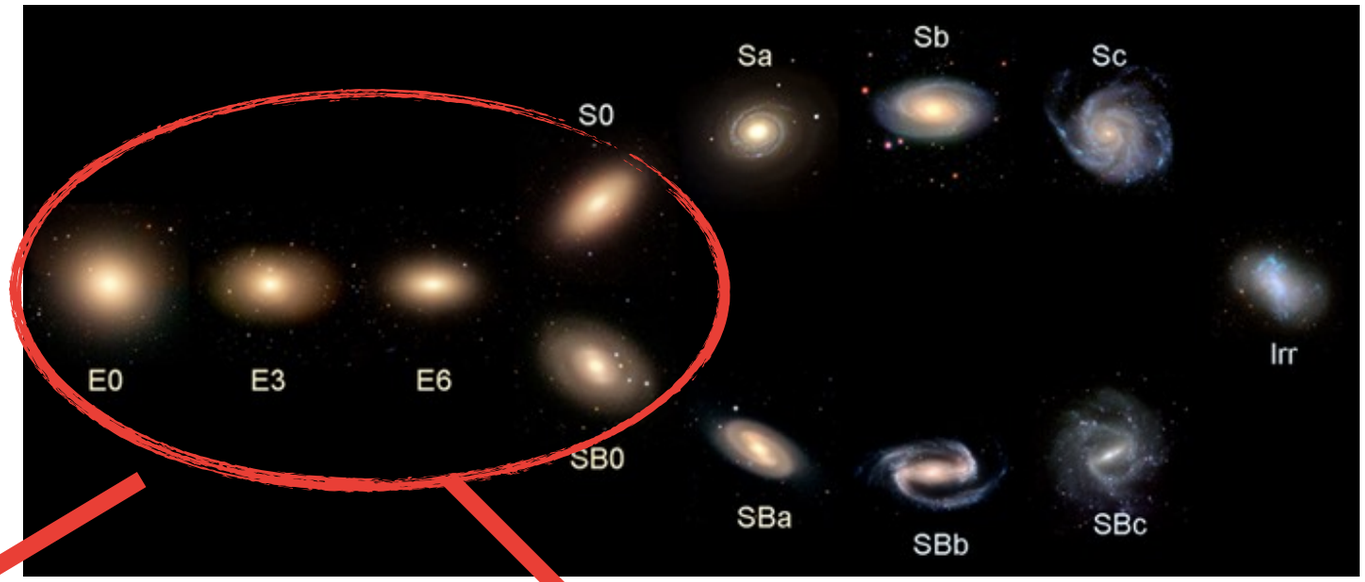
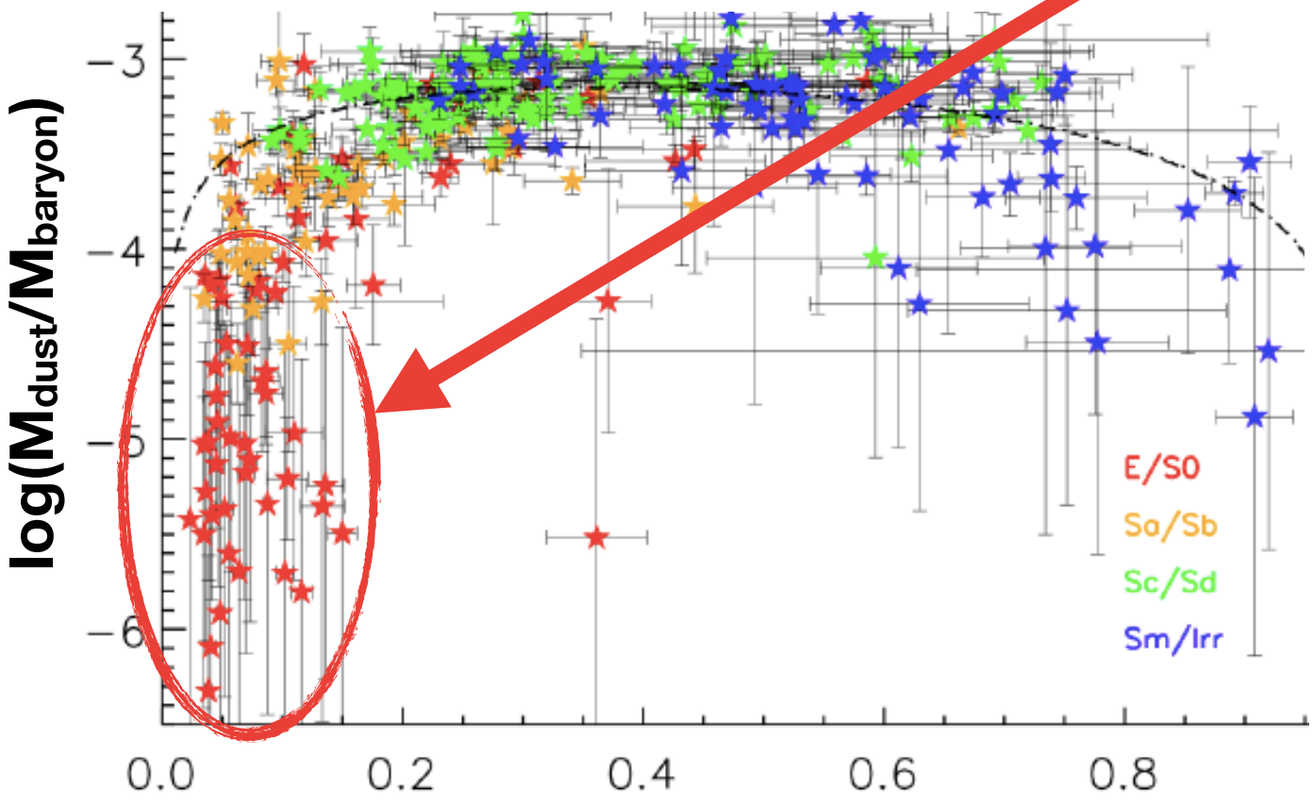
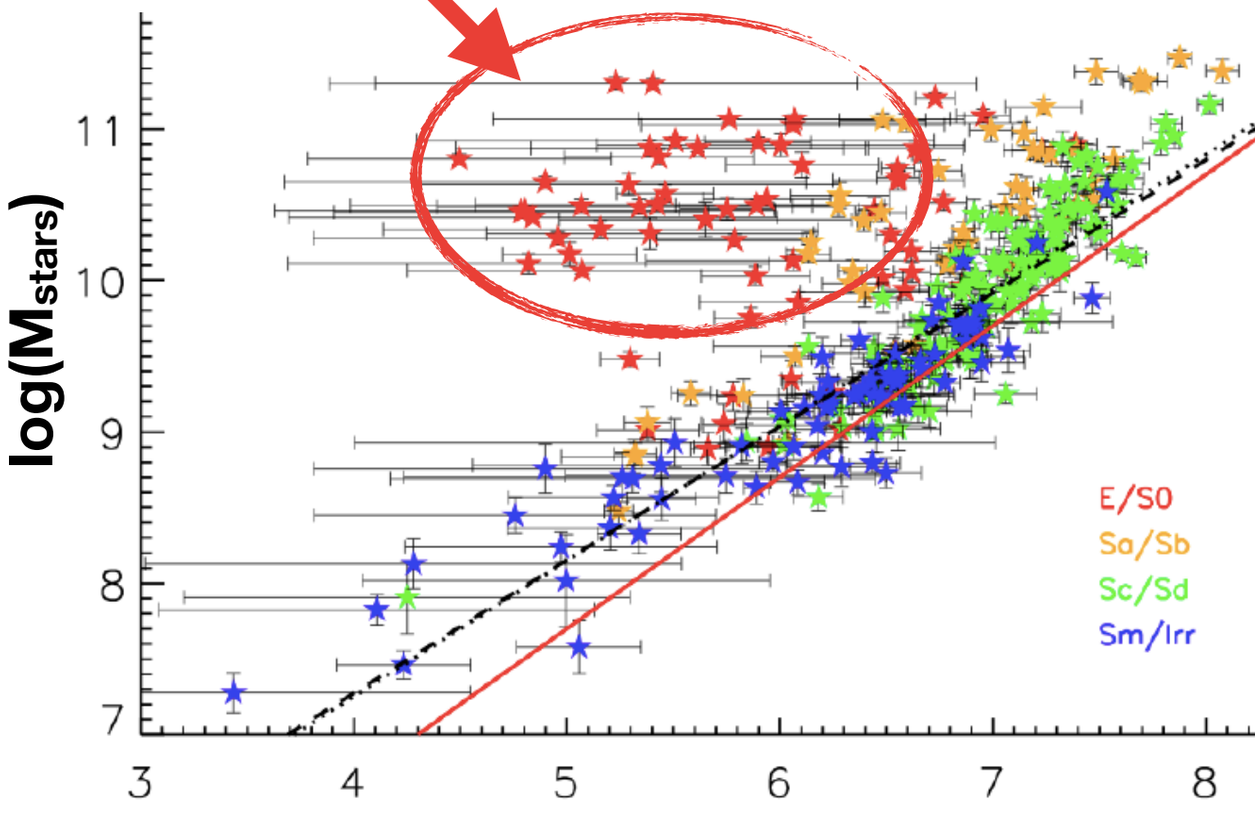


lowest dust and gas content







Davies et al. 2019

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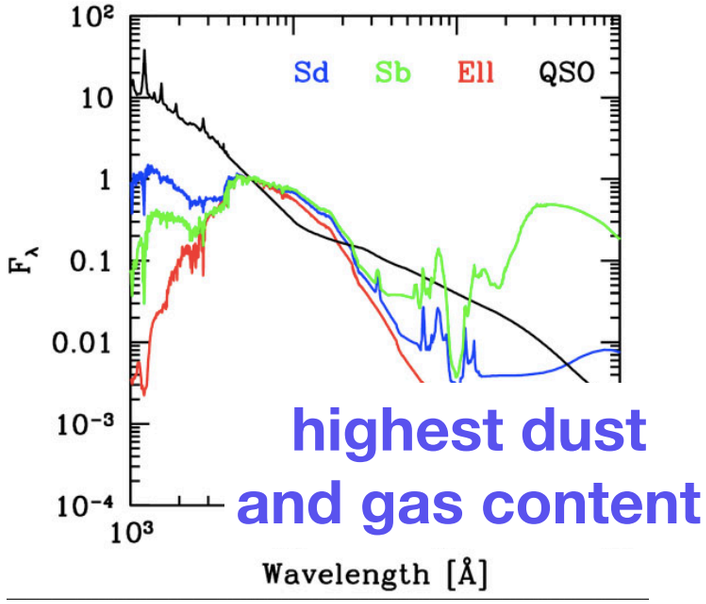
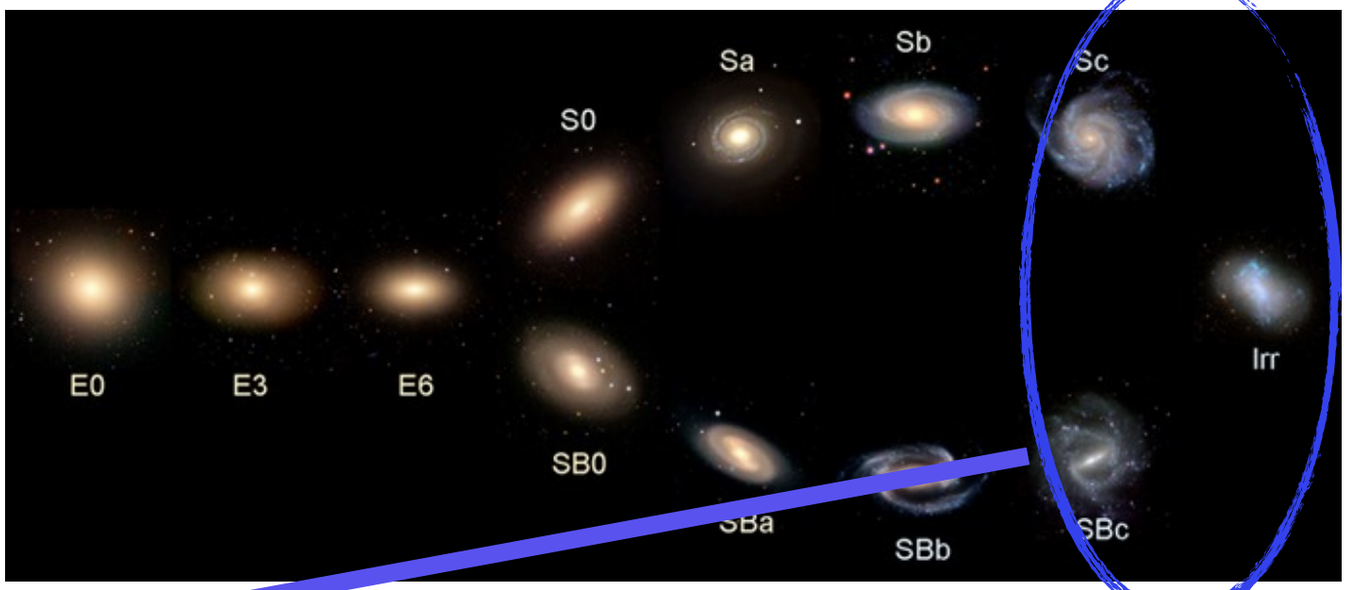
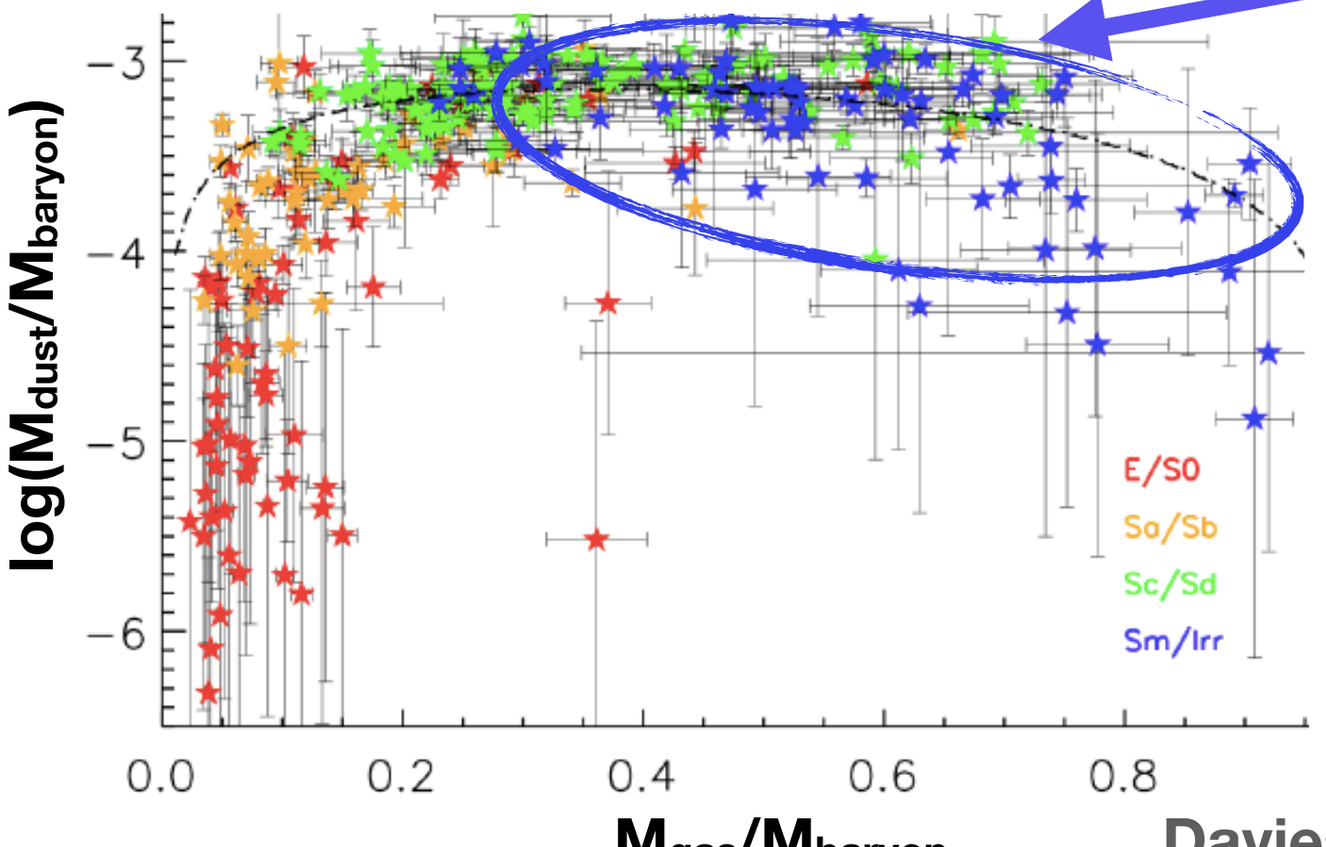
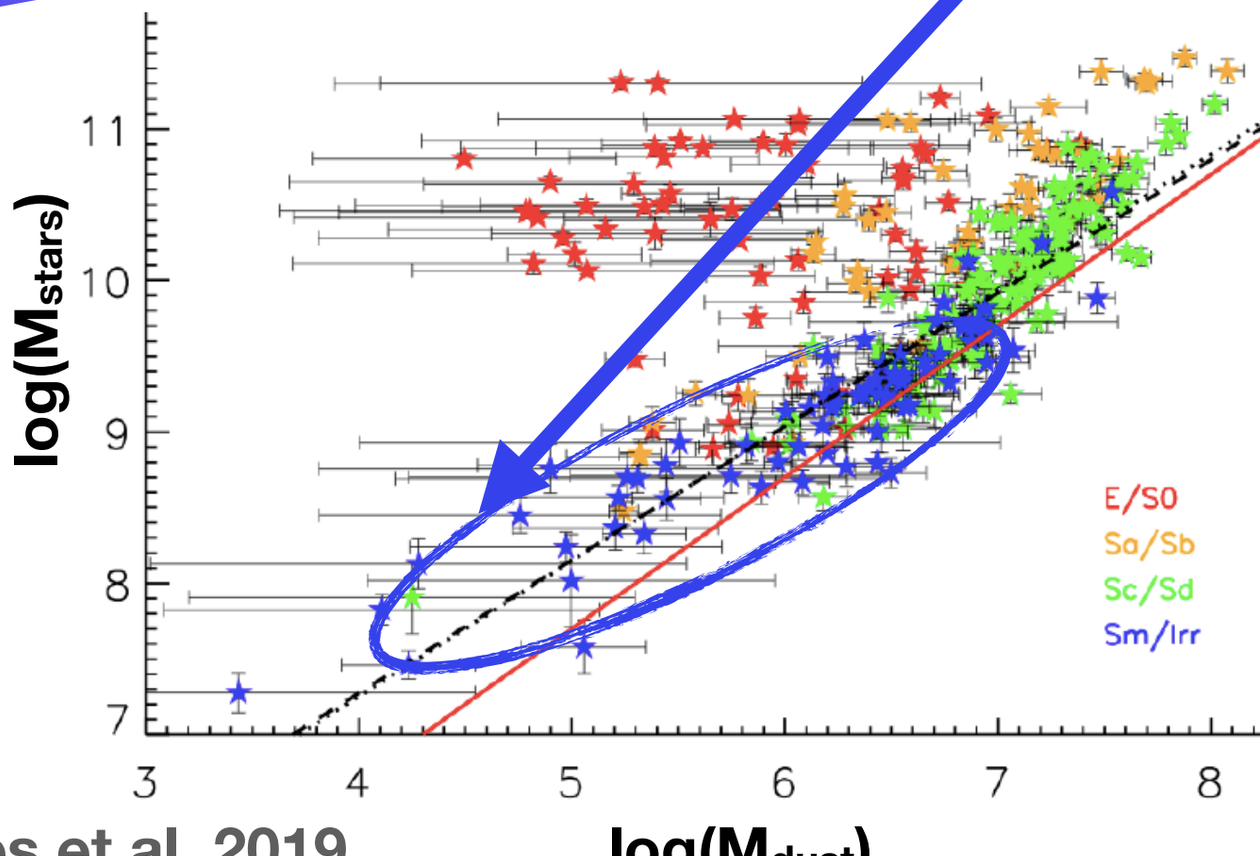


highest dust and gas content







Davies et al. 2019

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- ☐ **gas**
- ☐ **AGN**
- ☐ **dust**

Stars - the primary source of light in (most) galaxies

The light of a galaxy is to first order "the sum of the light from all its stars" (see later) -> to build a galaxy SED start by summing up the spectra of all its stars:

- **how many stars ?**
- **what type of stars (which spectra) ?**

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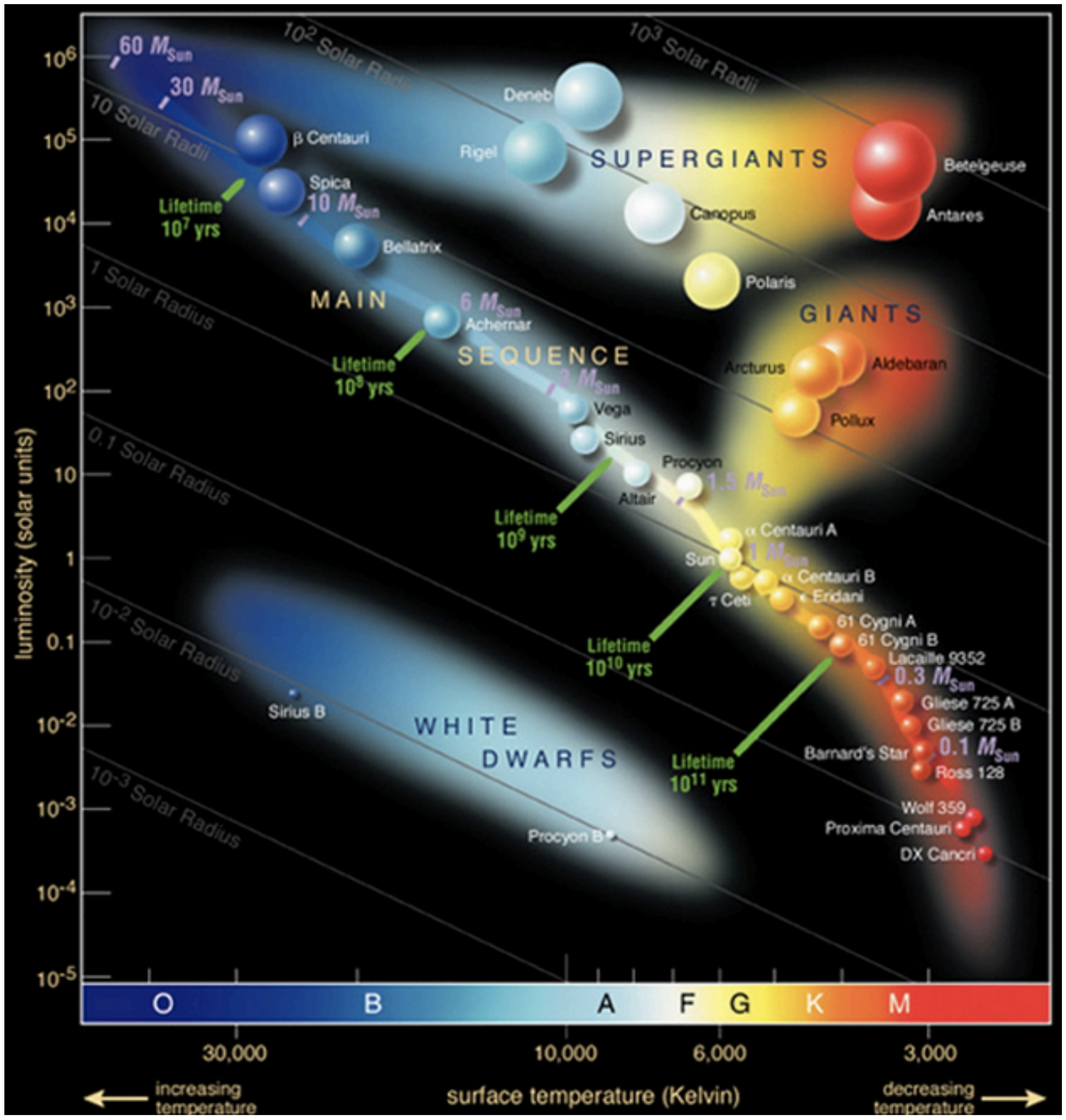
- **what type of stars (which spectra) ?**

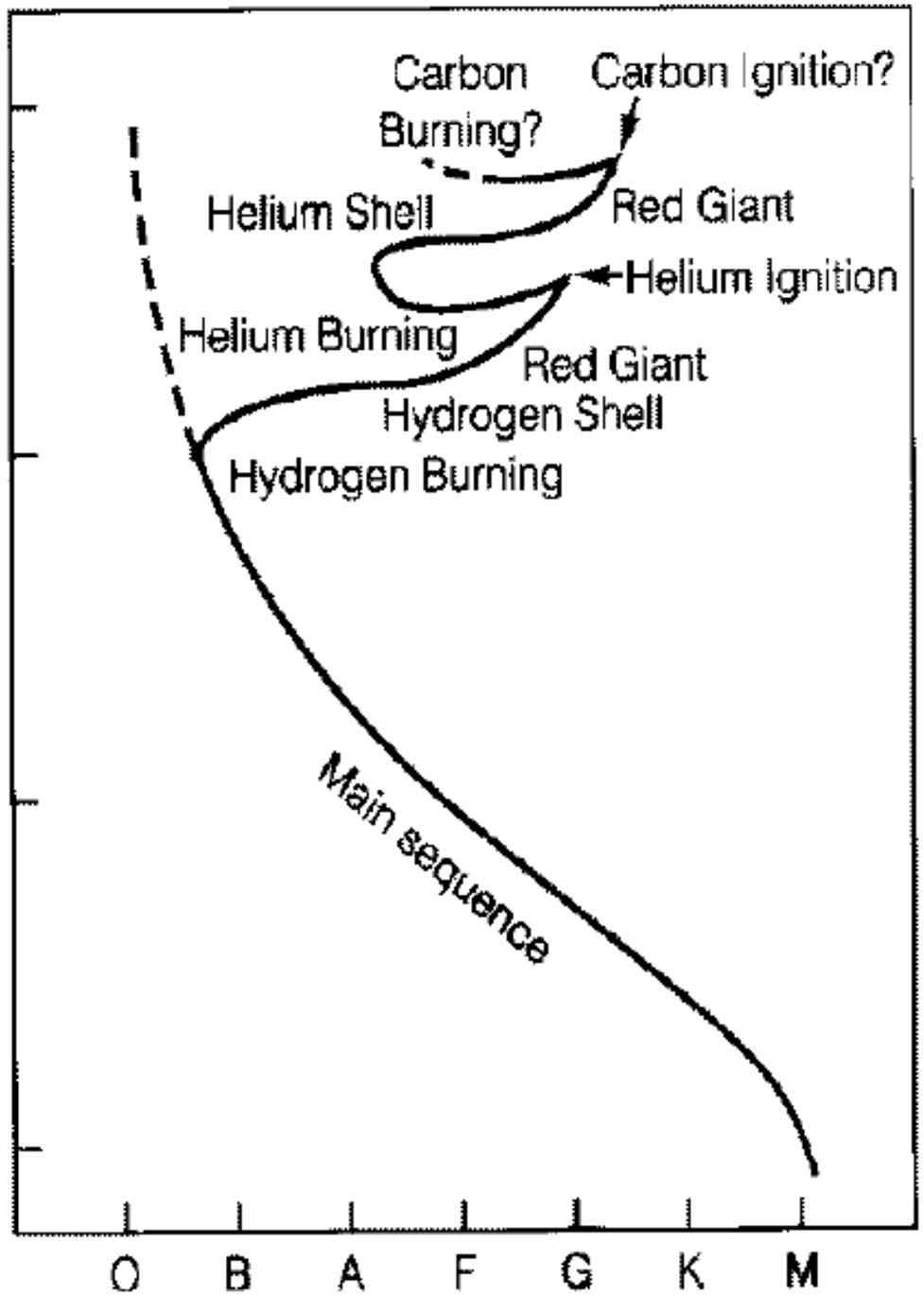
The total number of stars of a given kind (spectral class), at a given time in the galaxy life, depends on:

- **the total stellar mass of the galaxy**
- **the initial stellar mass function (IMF)**
- **the evolution of stars (that is, the evolution of the stellar mass function and the evolution of individual stellar spectra)**

Main ingredients

The Hertzsprung-Russell diagram





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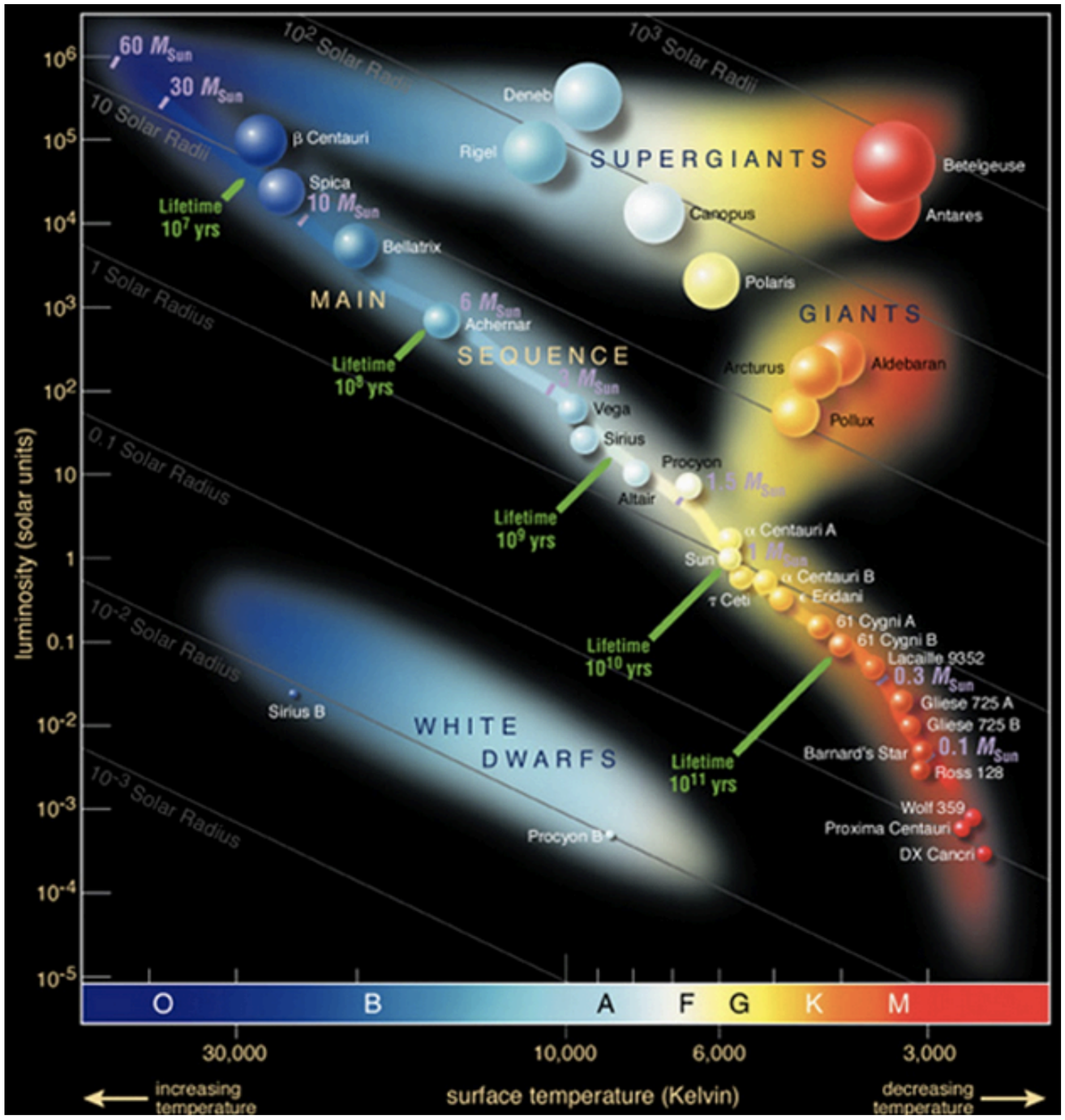
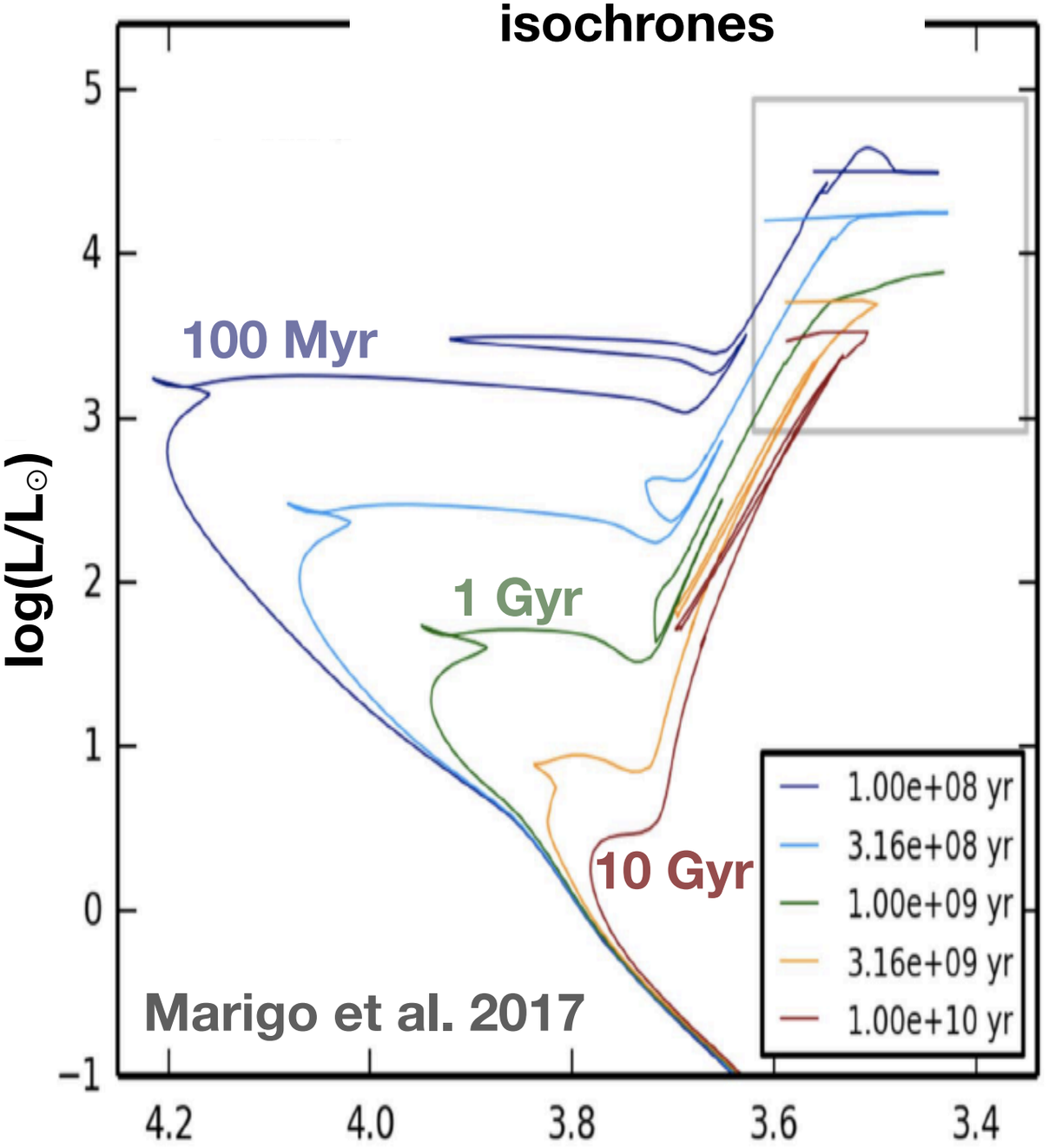


isochrones

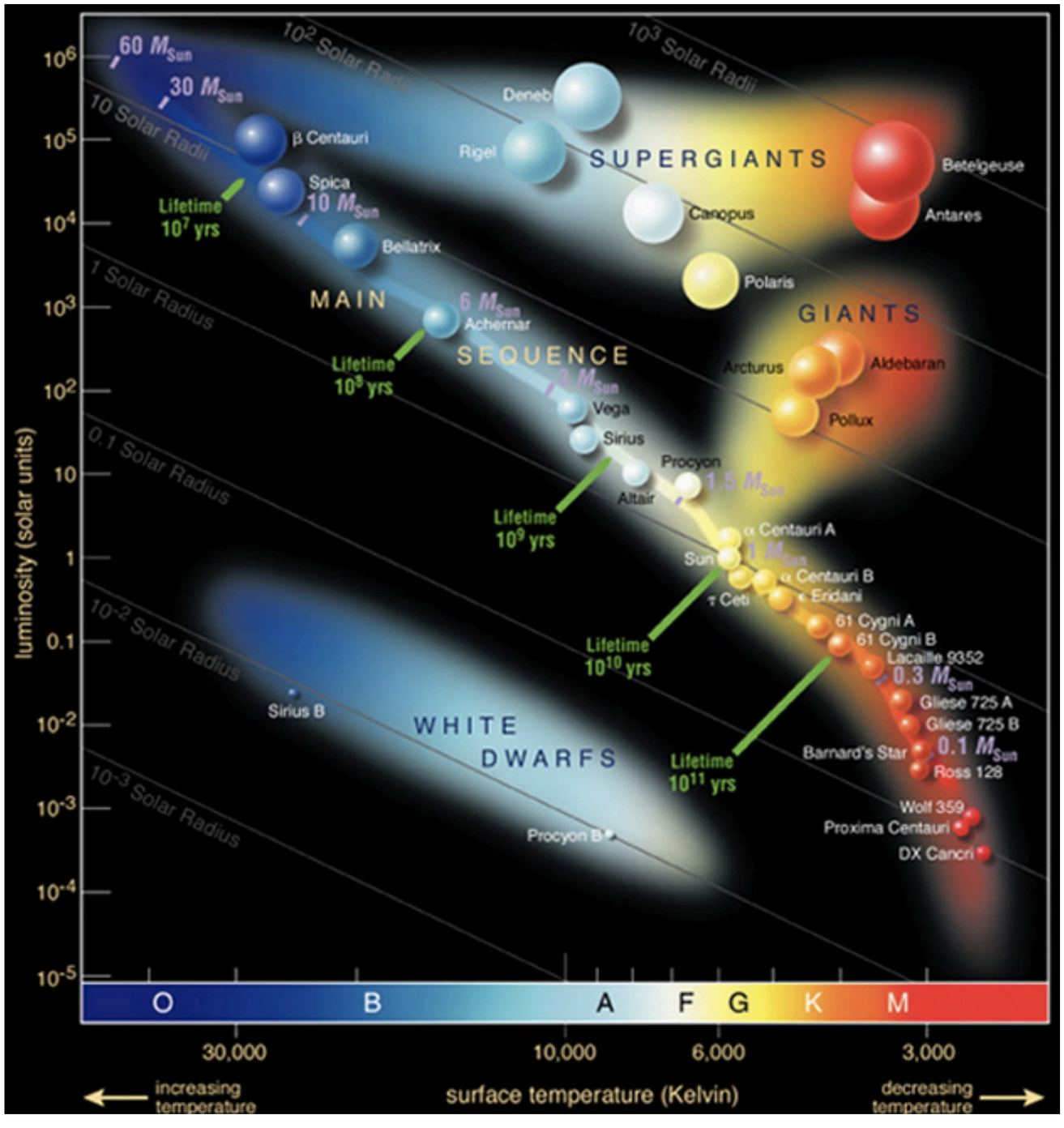


log(T_{eff}/K)

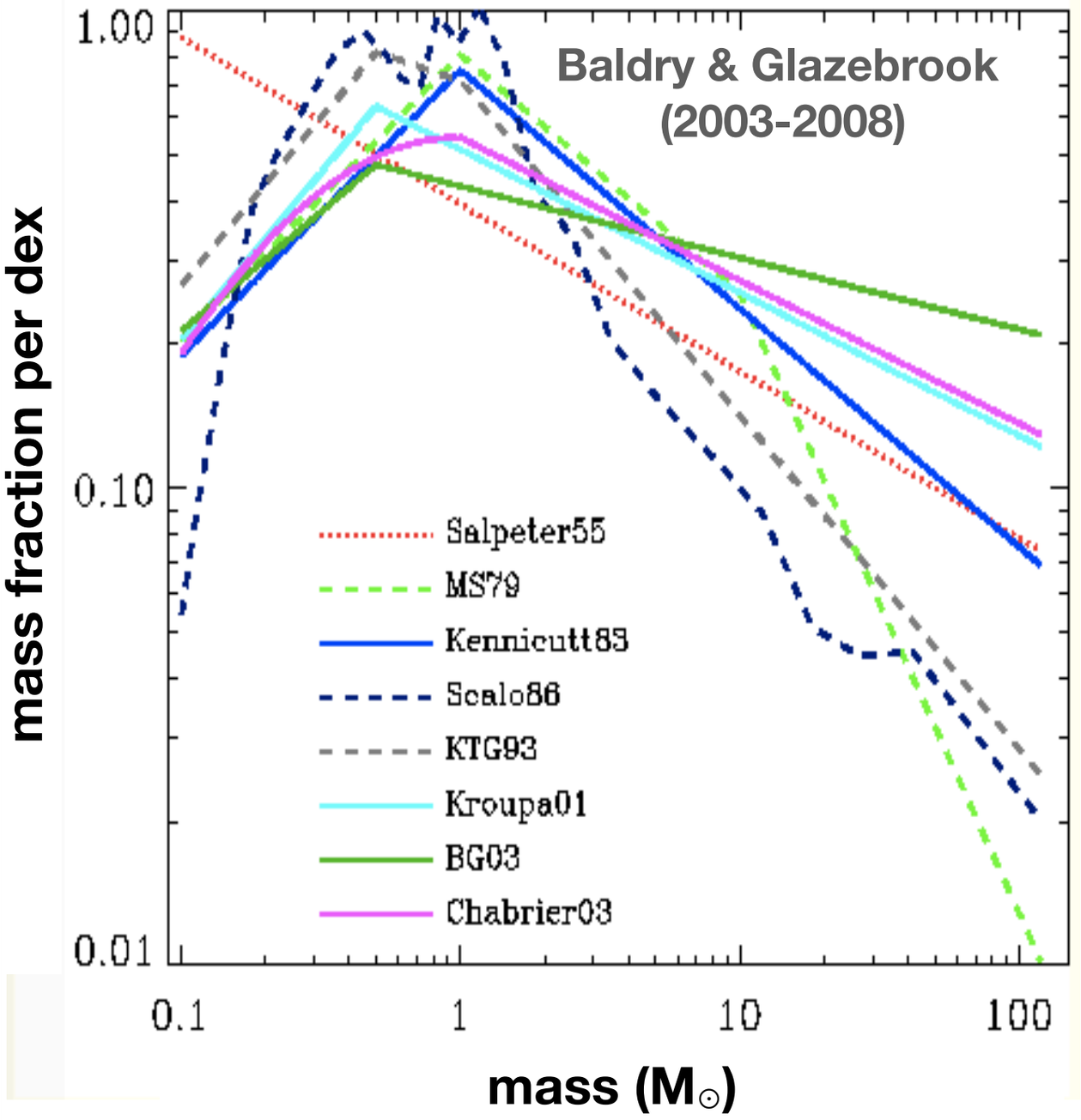
(the location in the HR diagram of stars with same age and metallicity)

Main ingredients

The Hertzsprung-Russell diagram



stellar initial mass function (IMF)



(the initial (zero-age main sequence) mass distribution of stars)

Main ingredients

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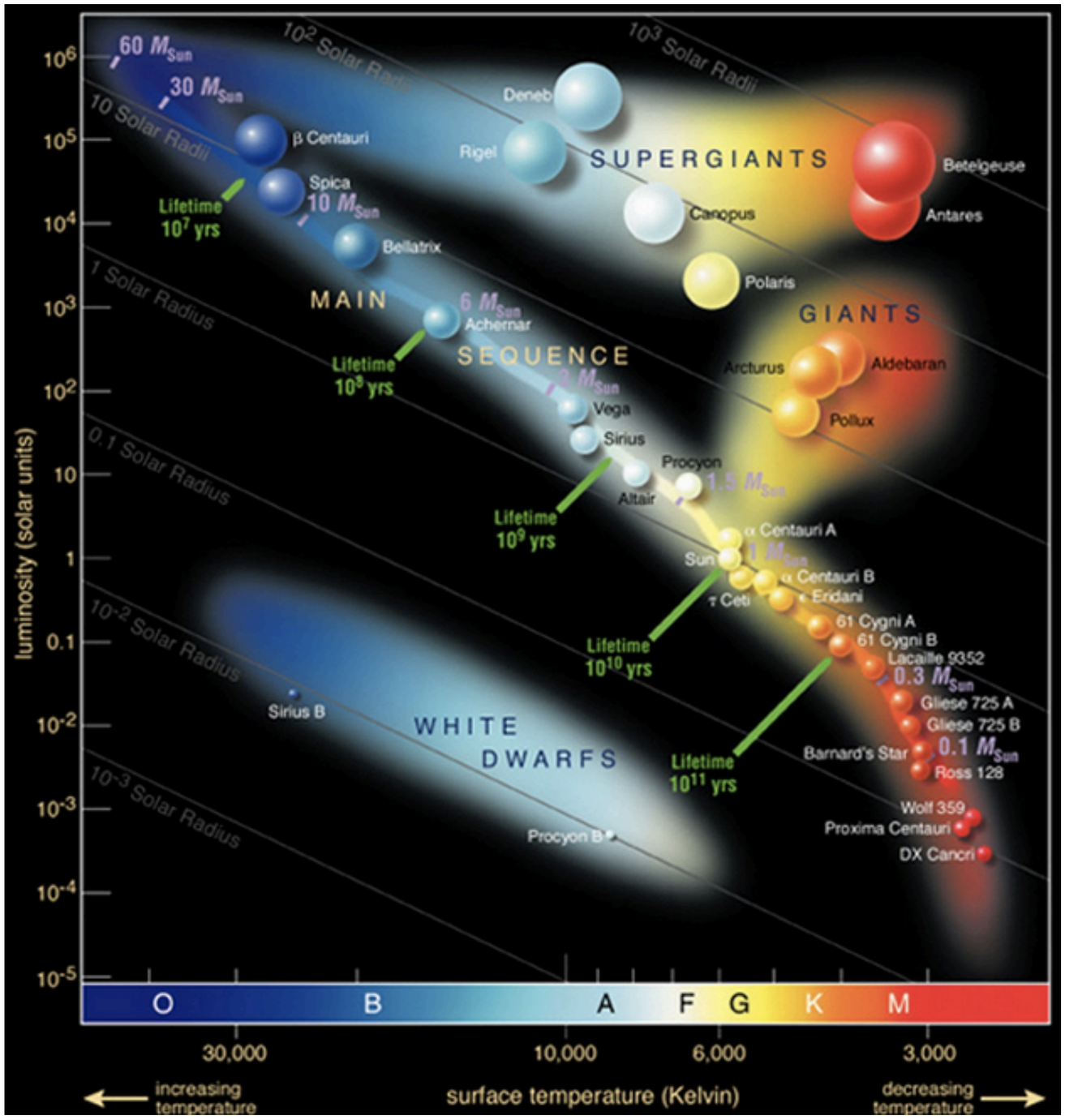
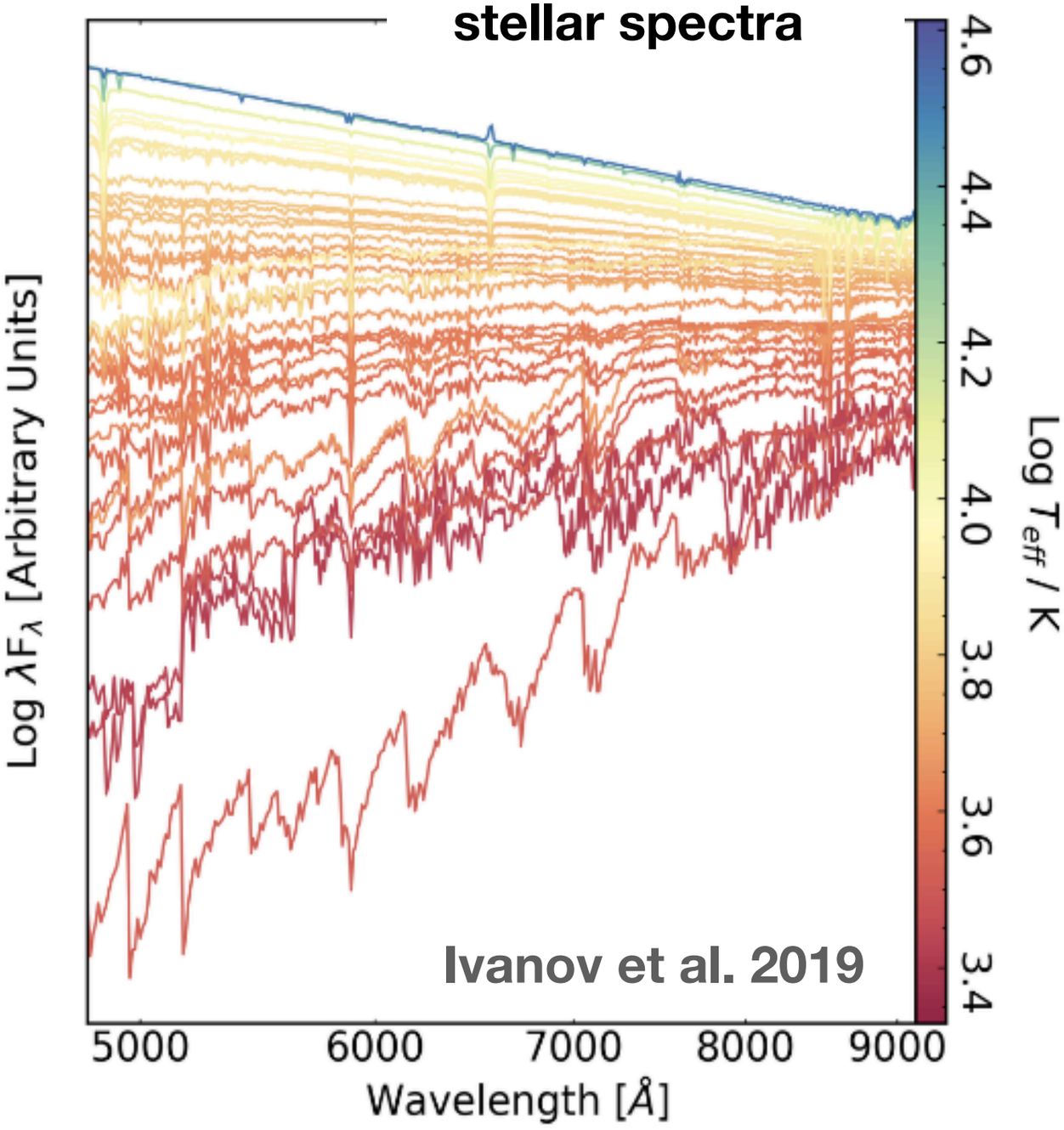


stellar spectra



(spectra of different classes of stars, to translate stellar evolution calculations into SEDs)

Main ingredients

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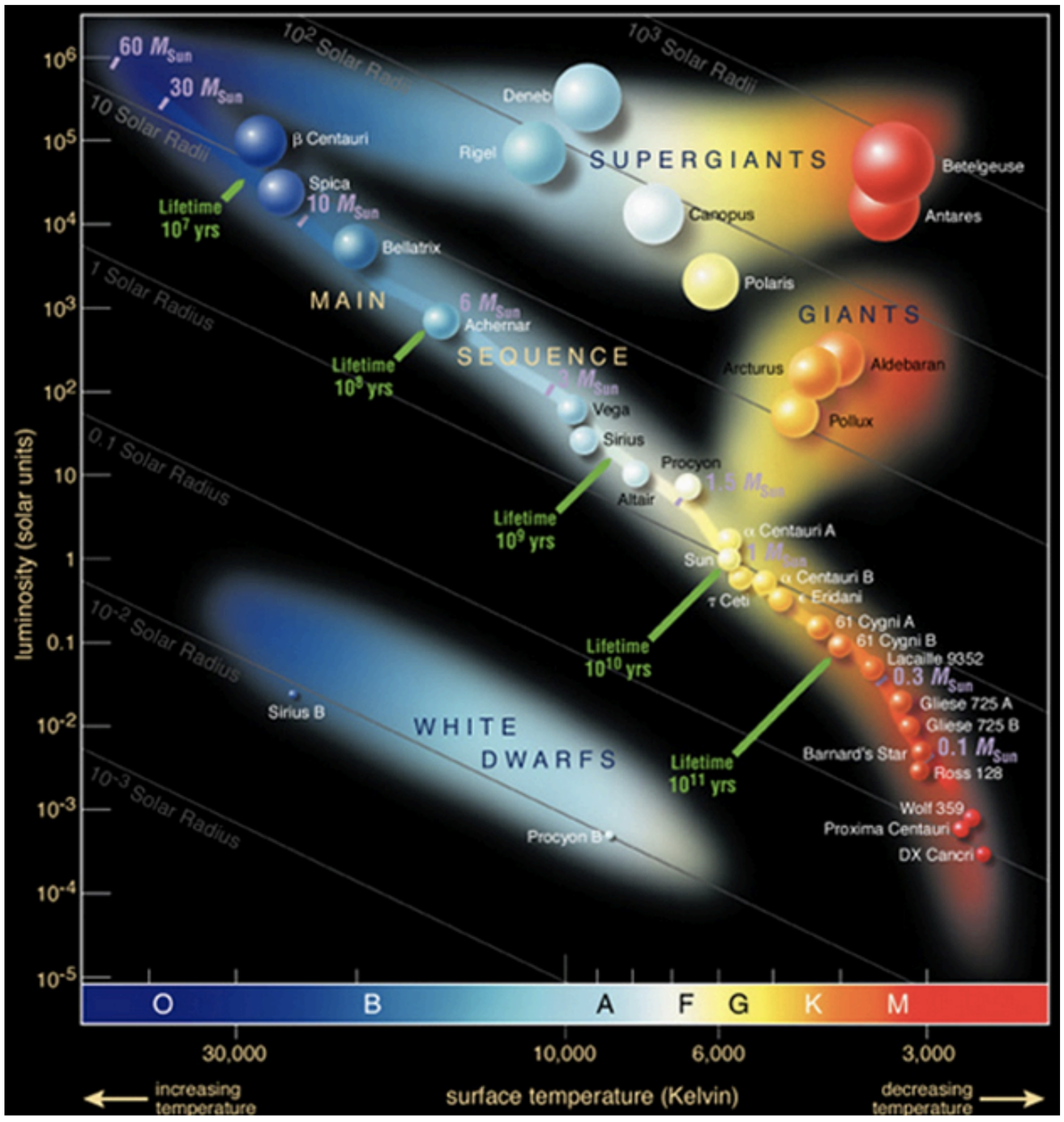

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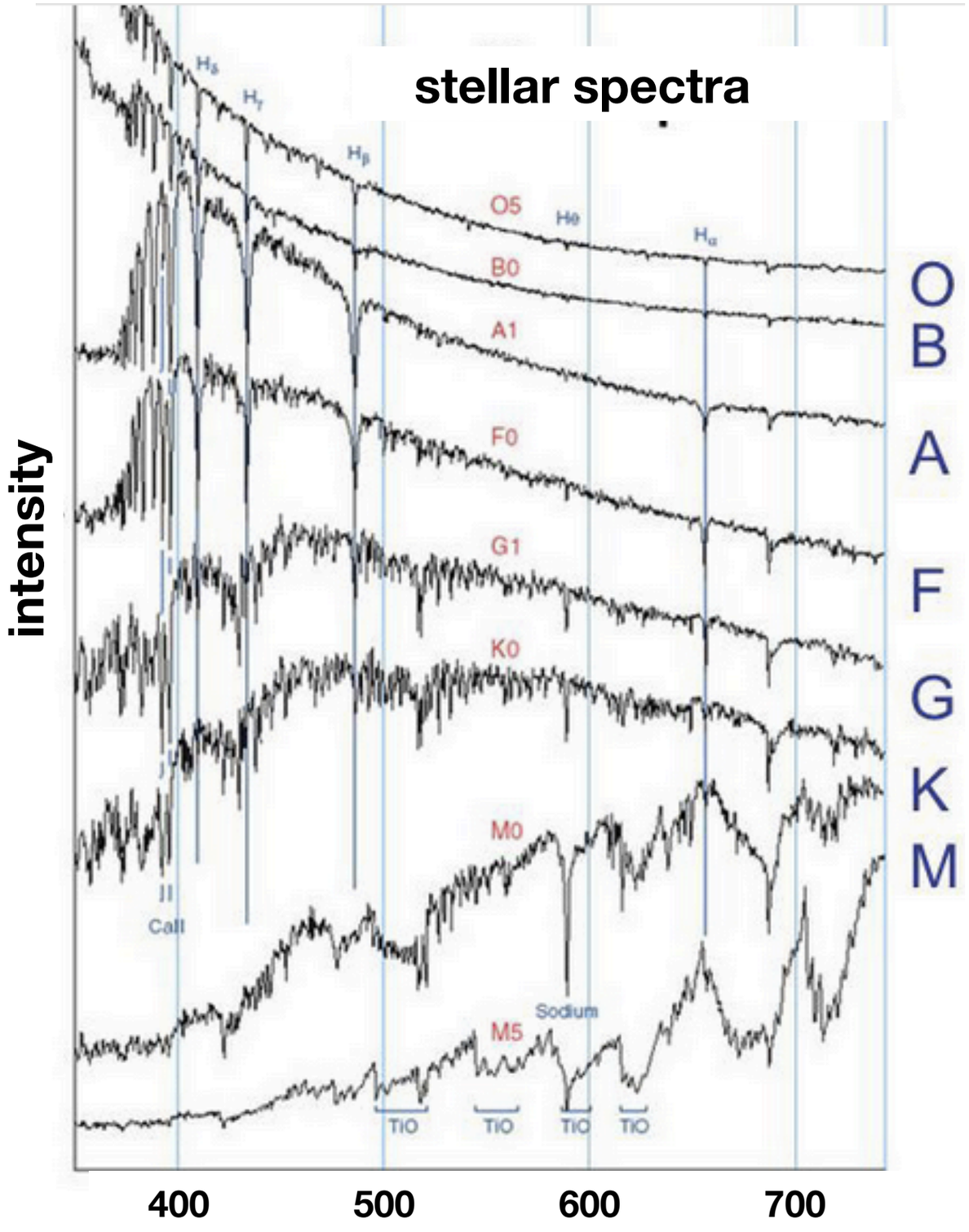

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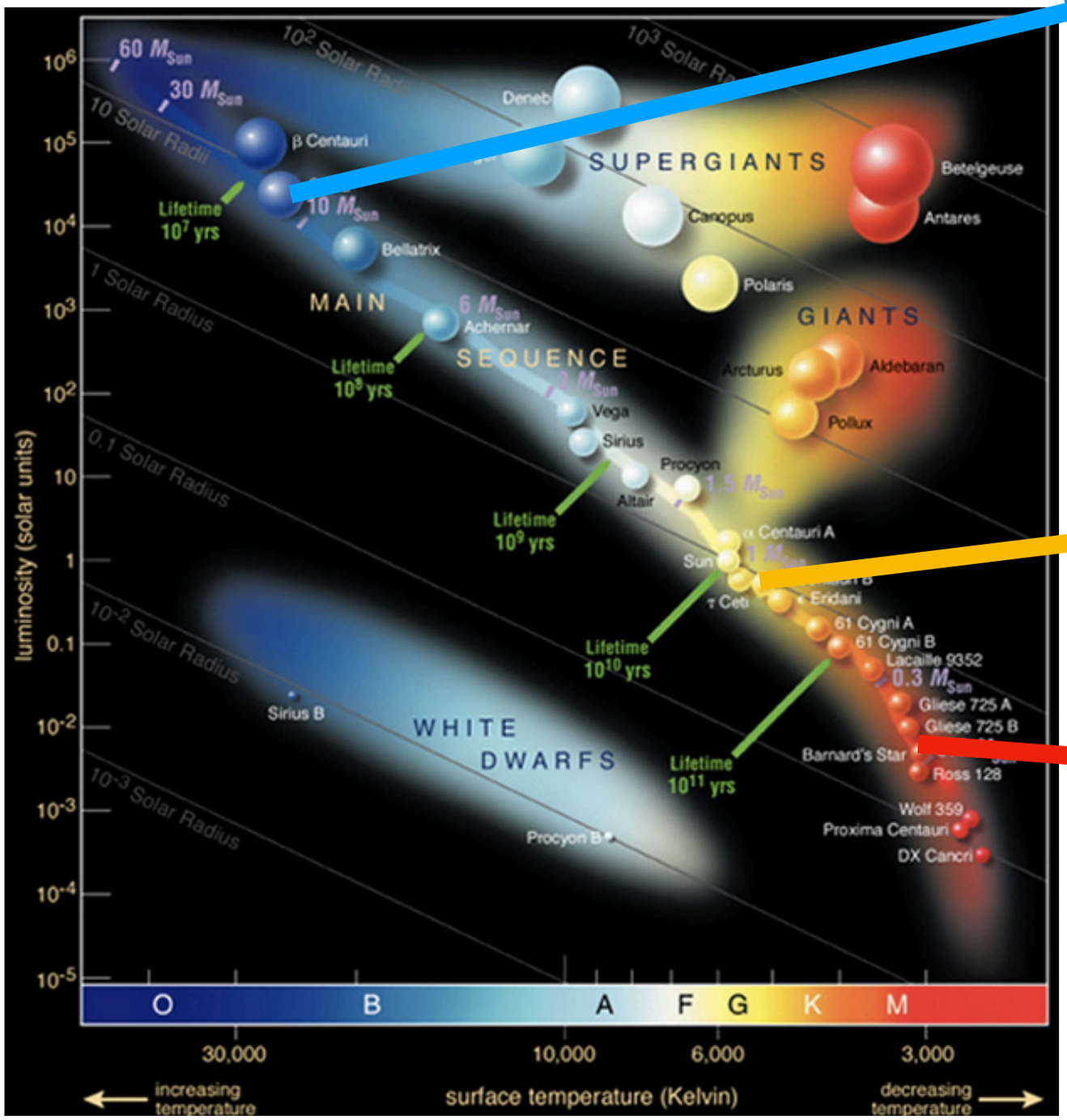

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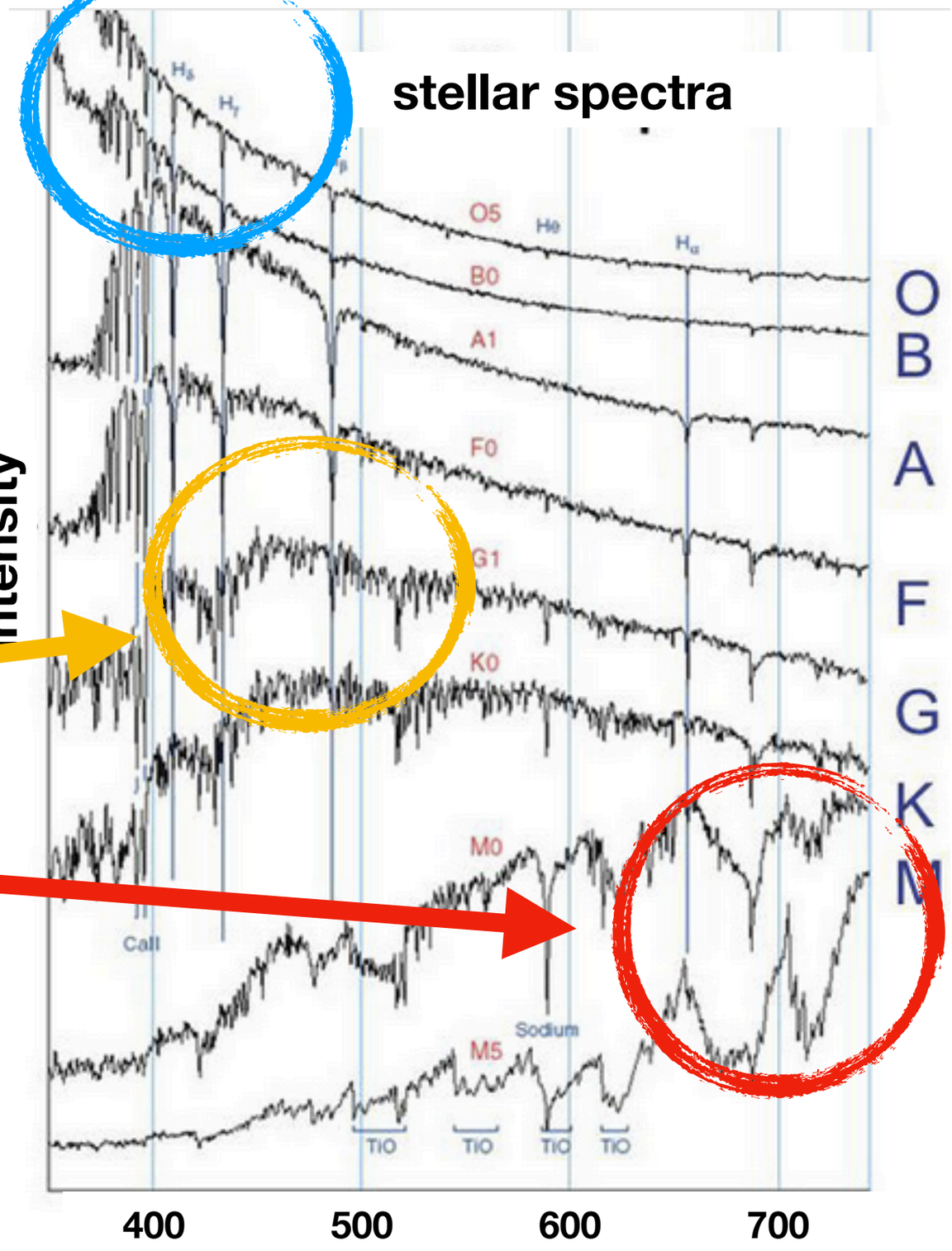

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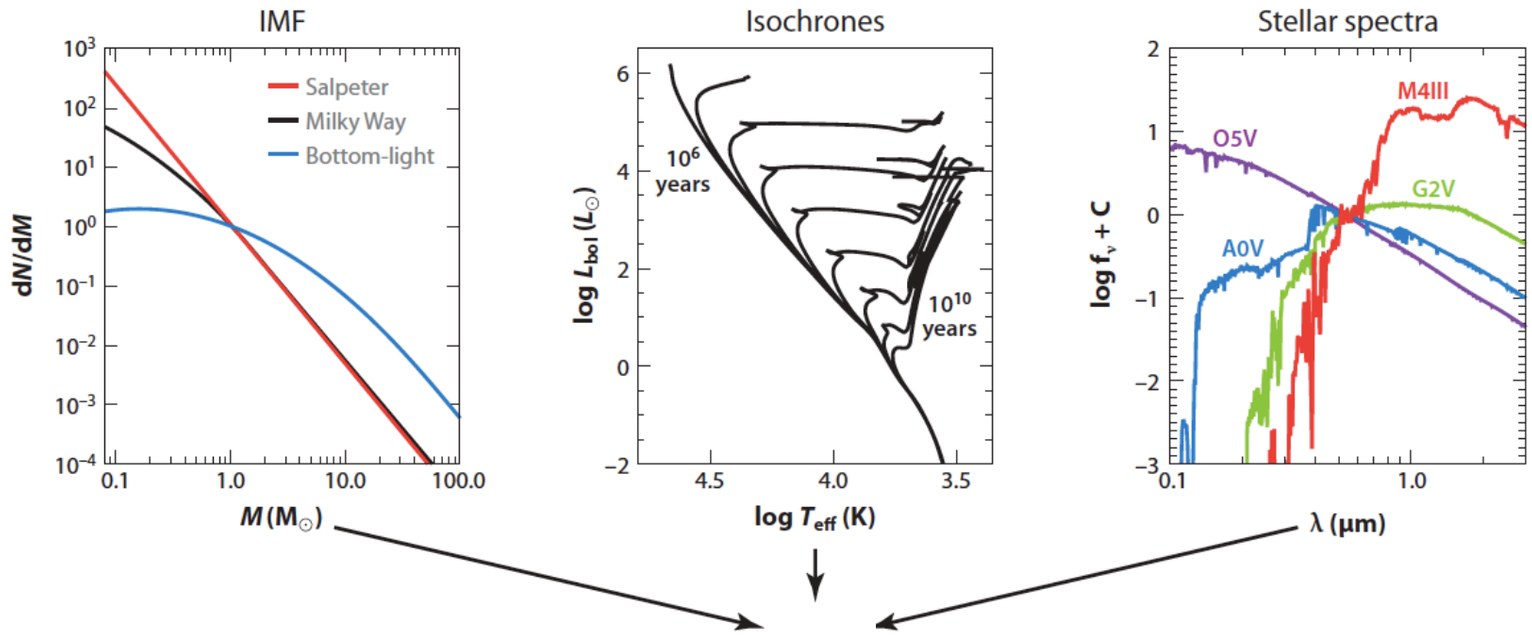
Stellar Population Synthesis (SPS) - First step: SSPs



Conroy 2013

Time evolution of a SSP

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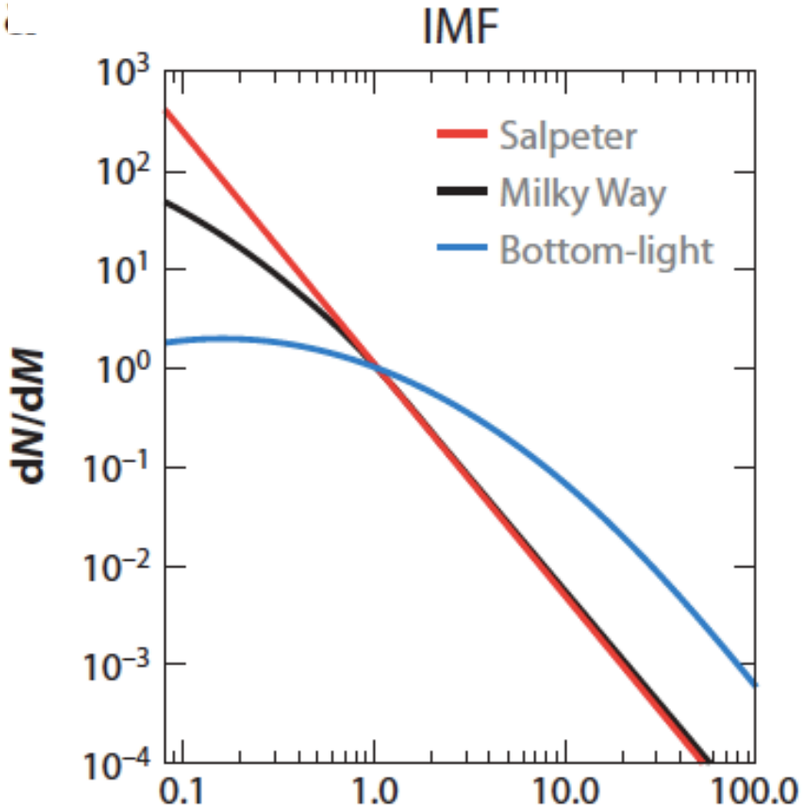
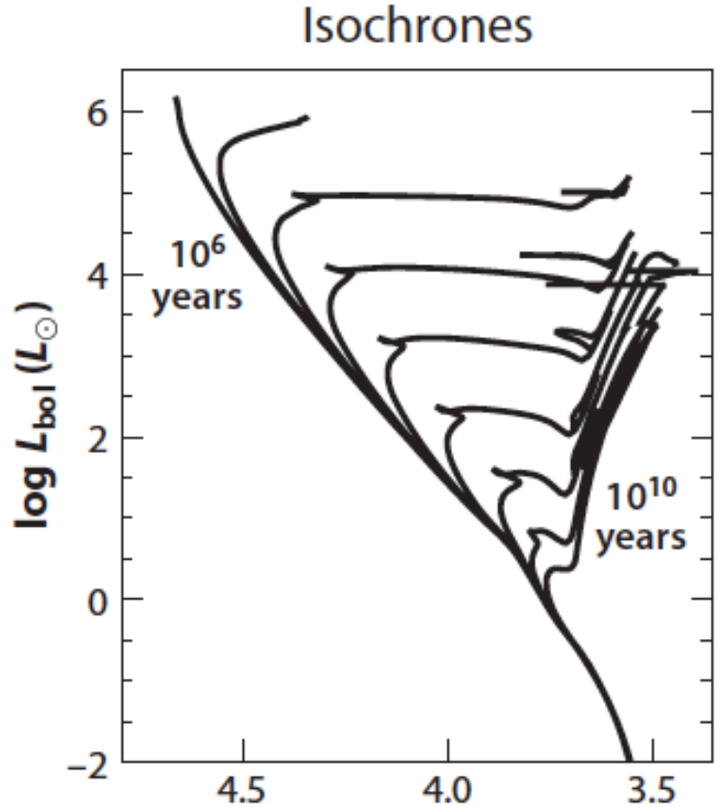
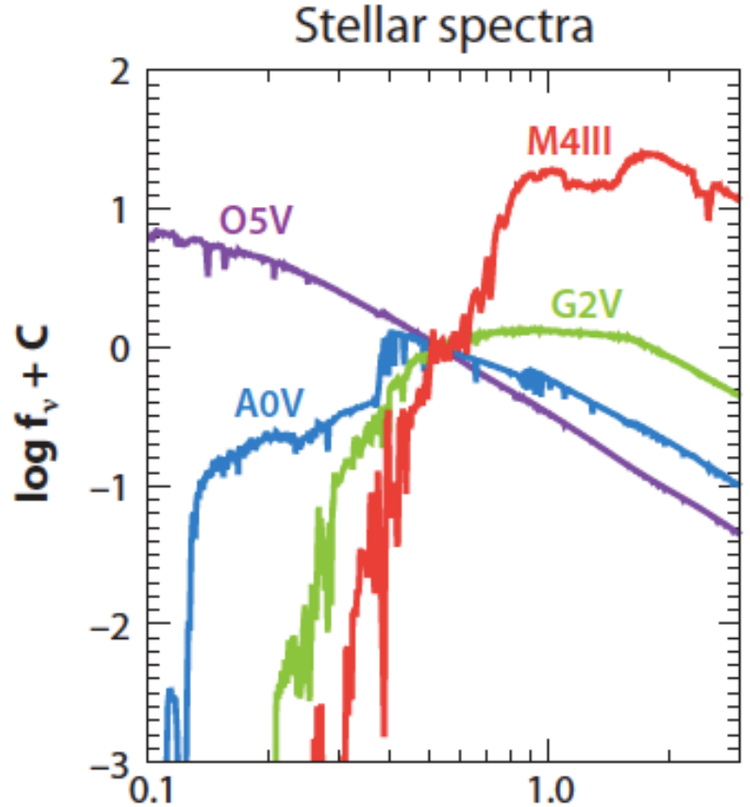
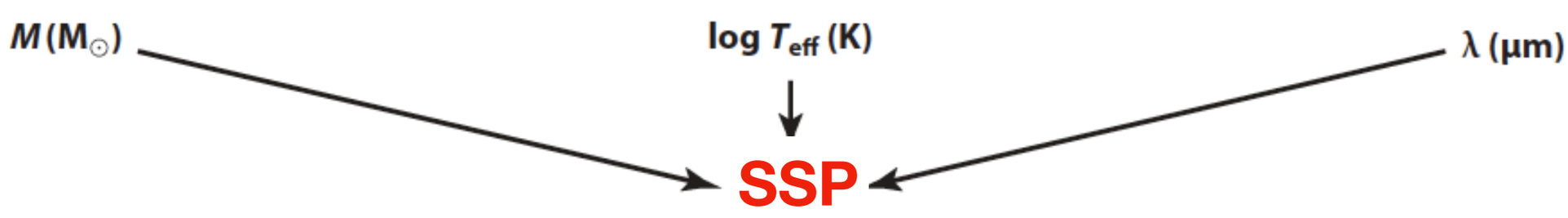






Conroy 2013



Simple Stellar Population

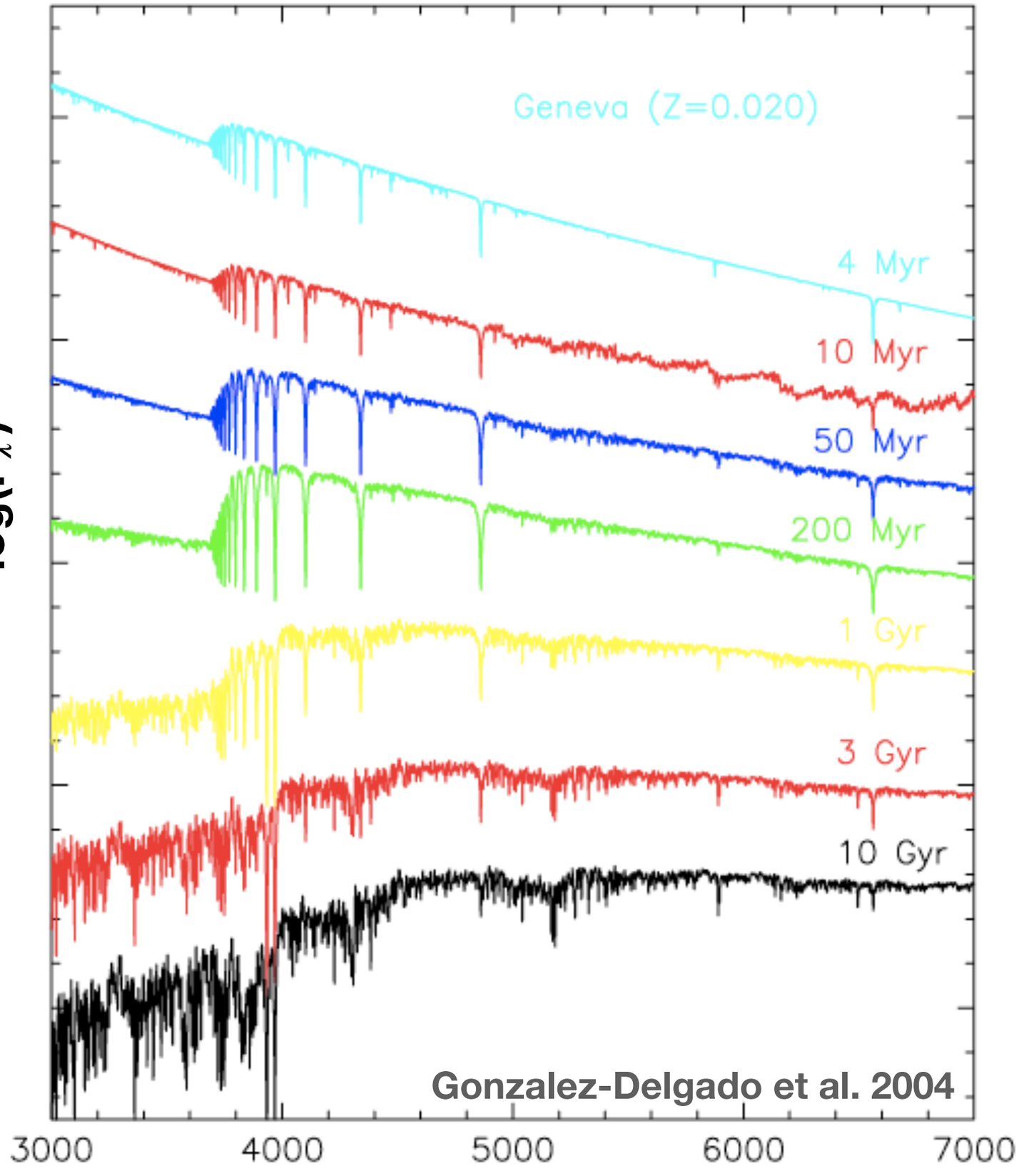
(The simplest case of) a population of coeval stars drawn from a given IMF

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

SSP spectrum — metallicity — stellar spectrum — isochrones — IMF — stellar mass

Conroy 2013: https://doi.org/10.1146/annurev-astro-082812-141017

Time evolution of a SSP



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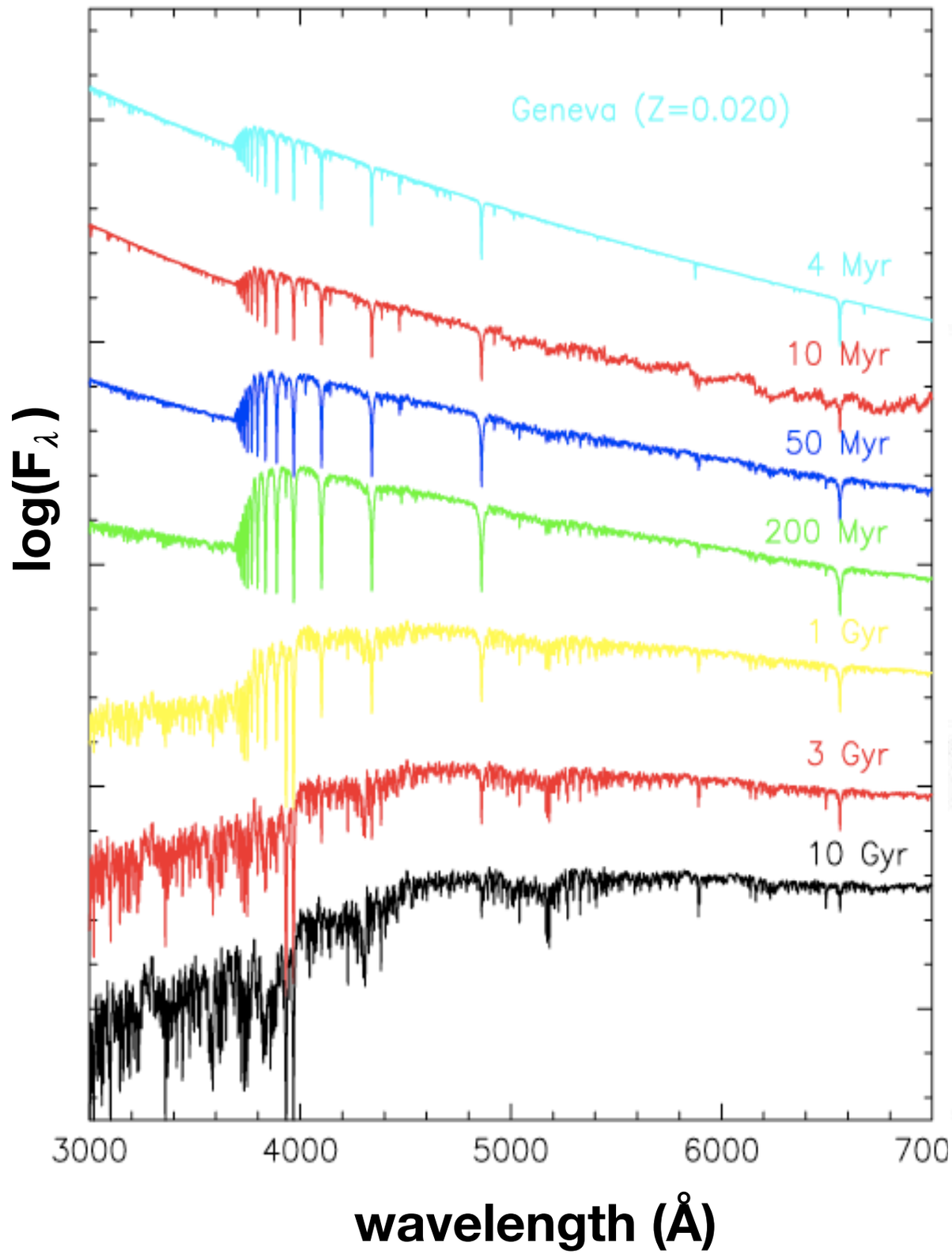
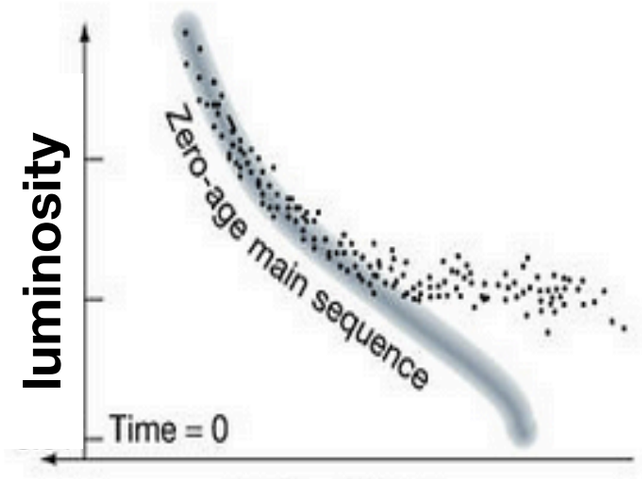
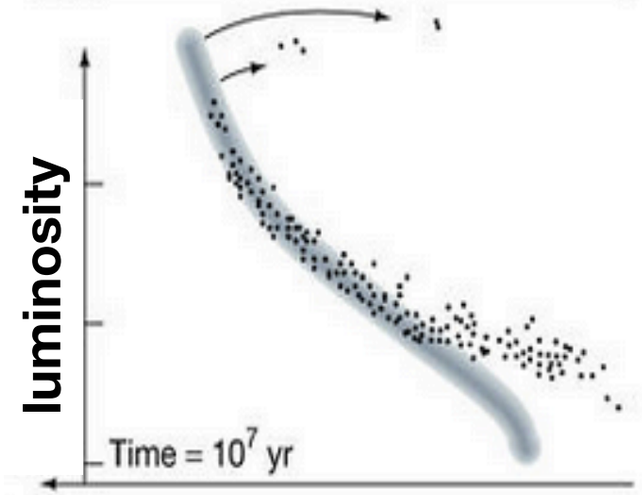
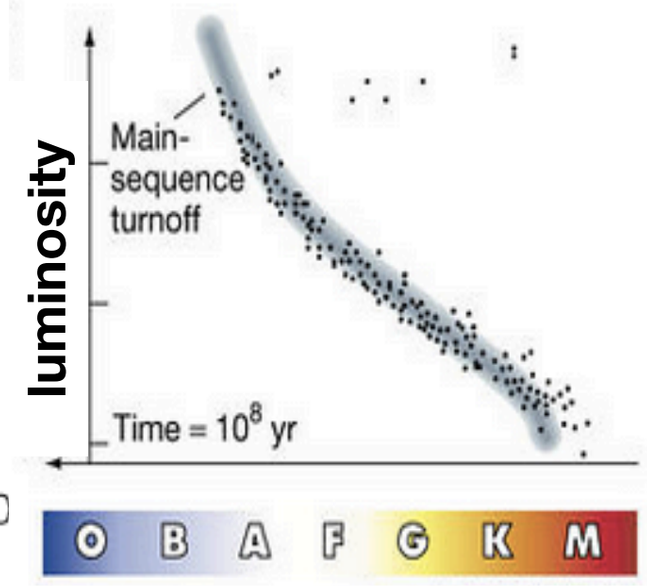
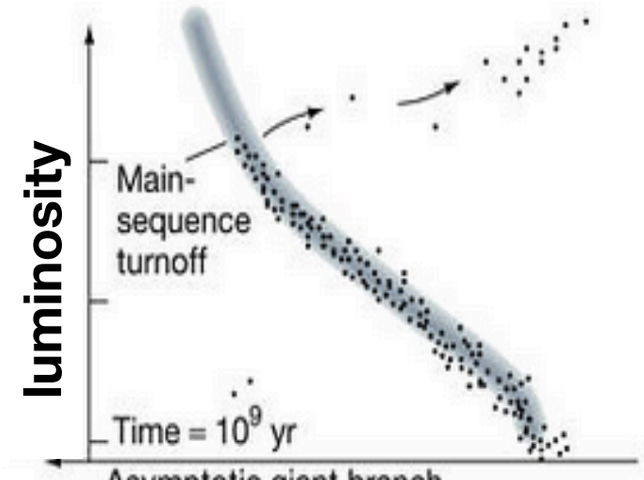
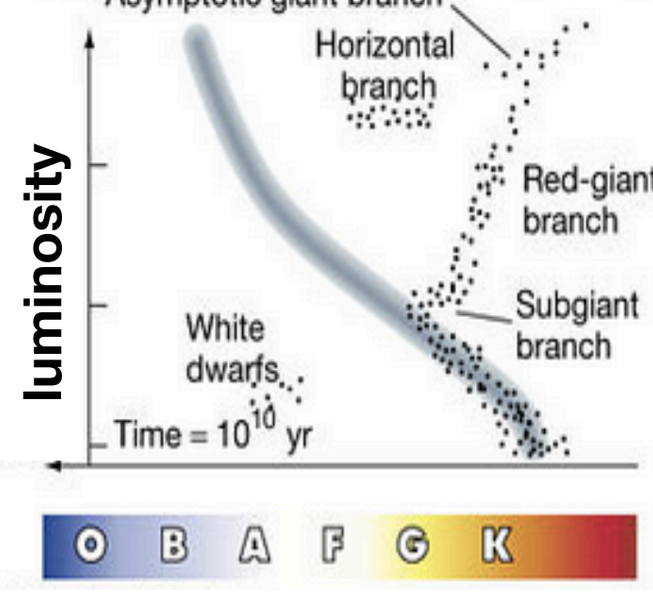






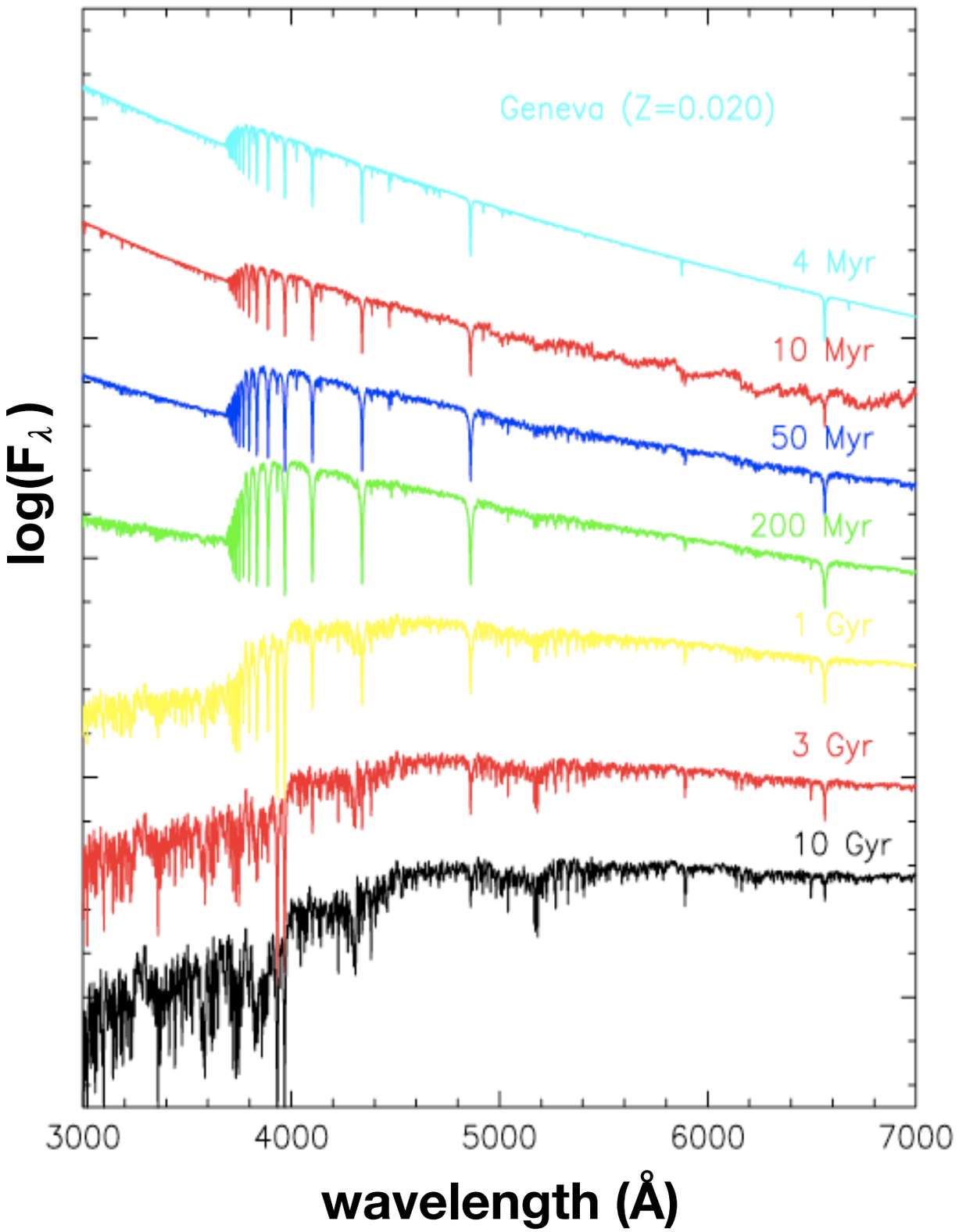


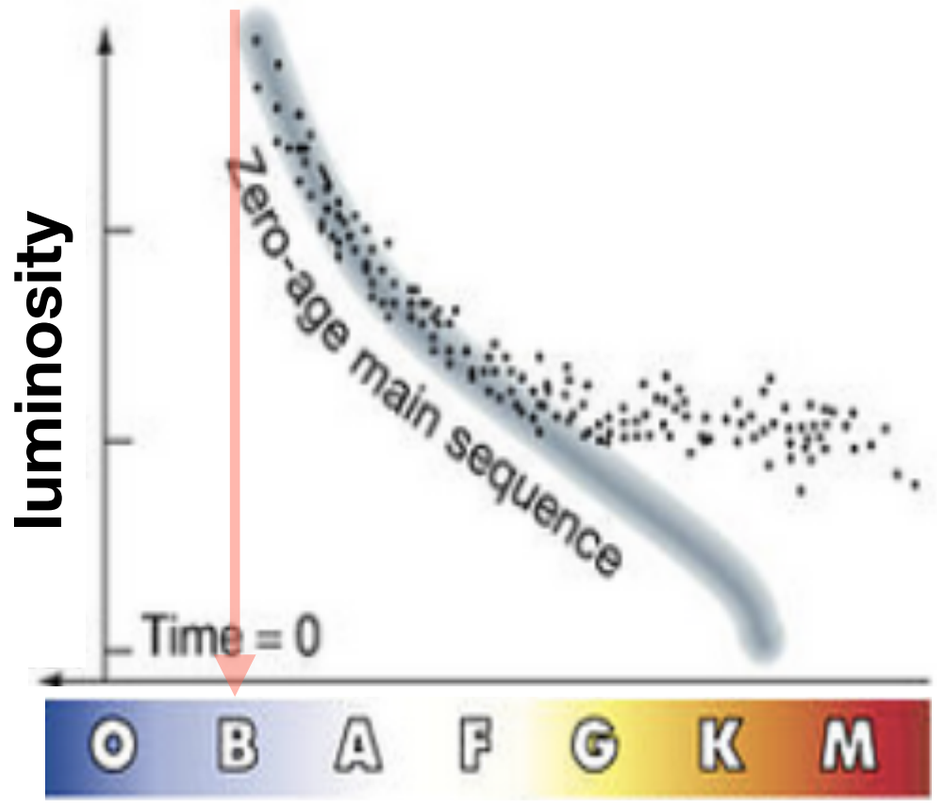




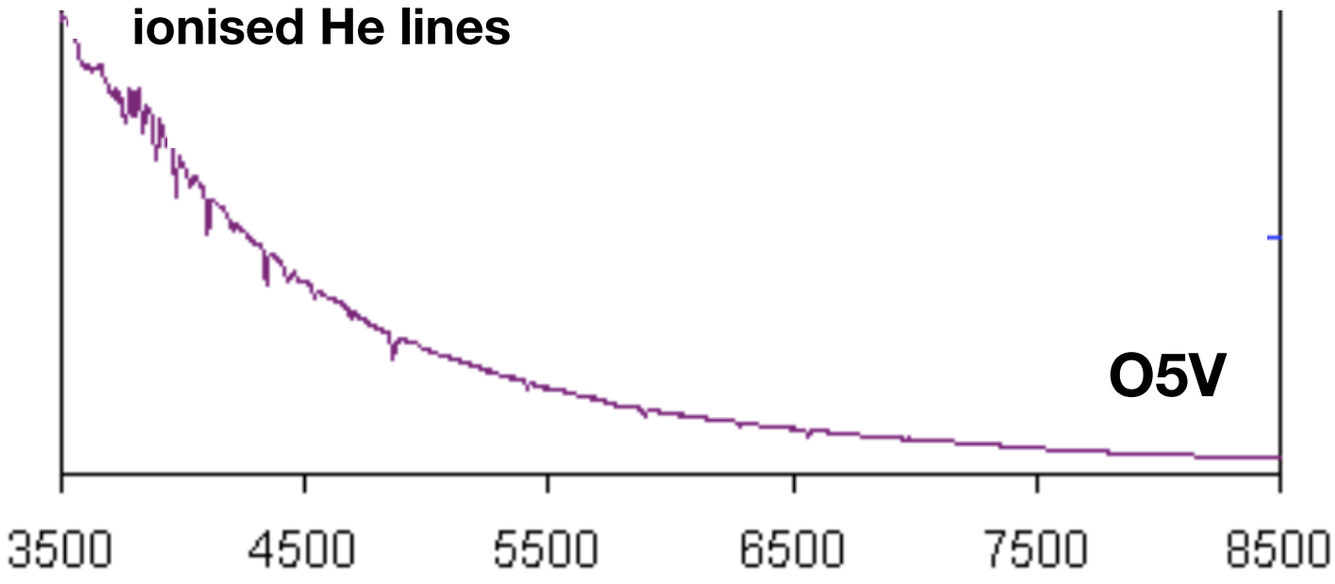
temperature

Time evolution of a SSP

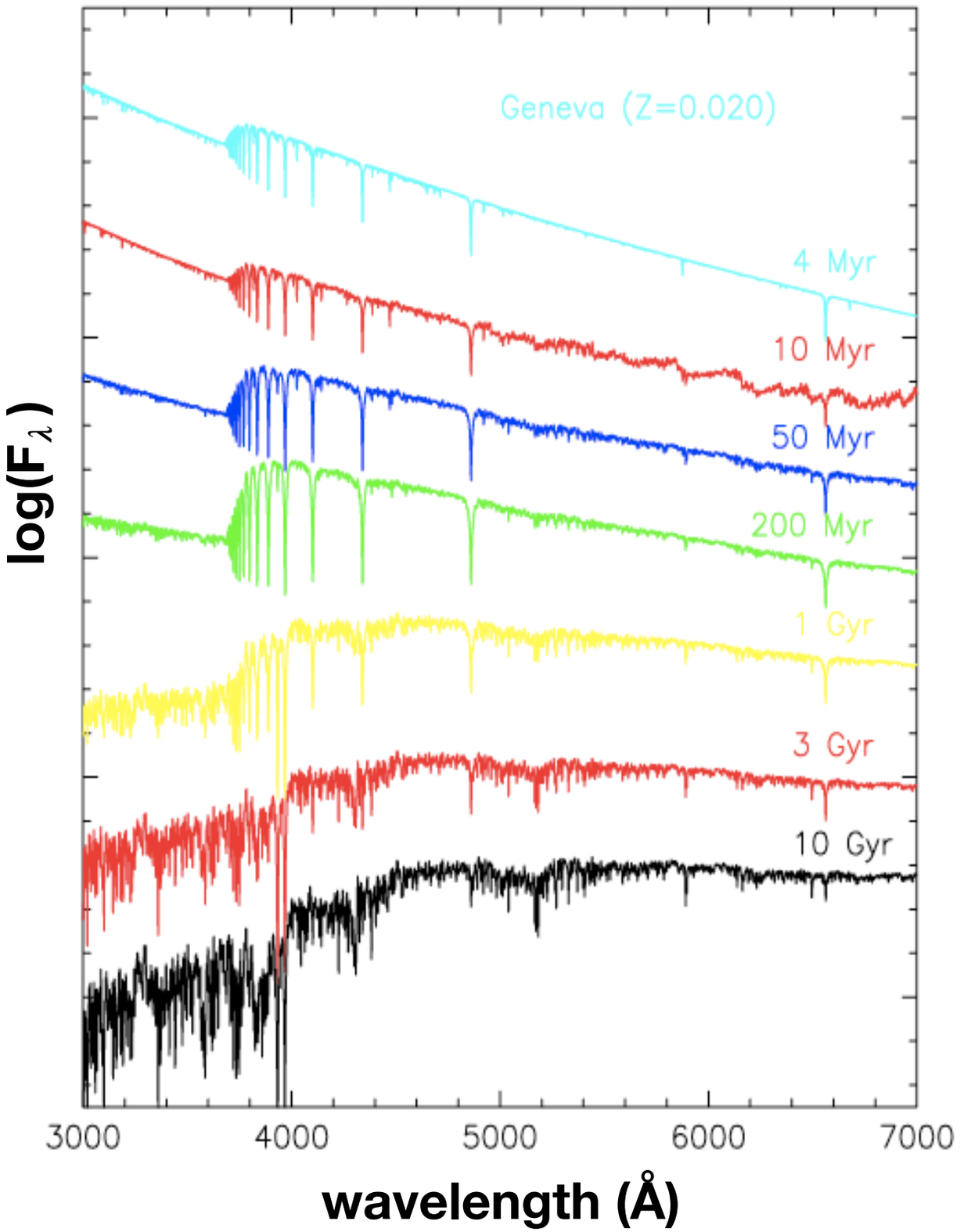


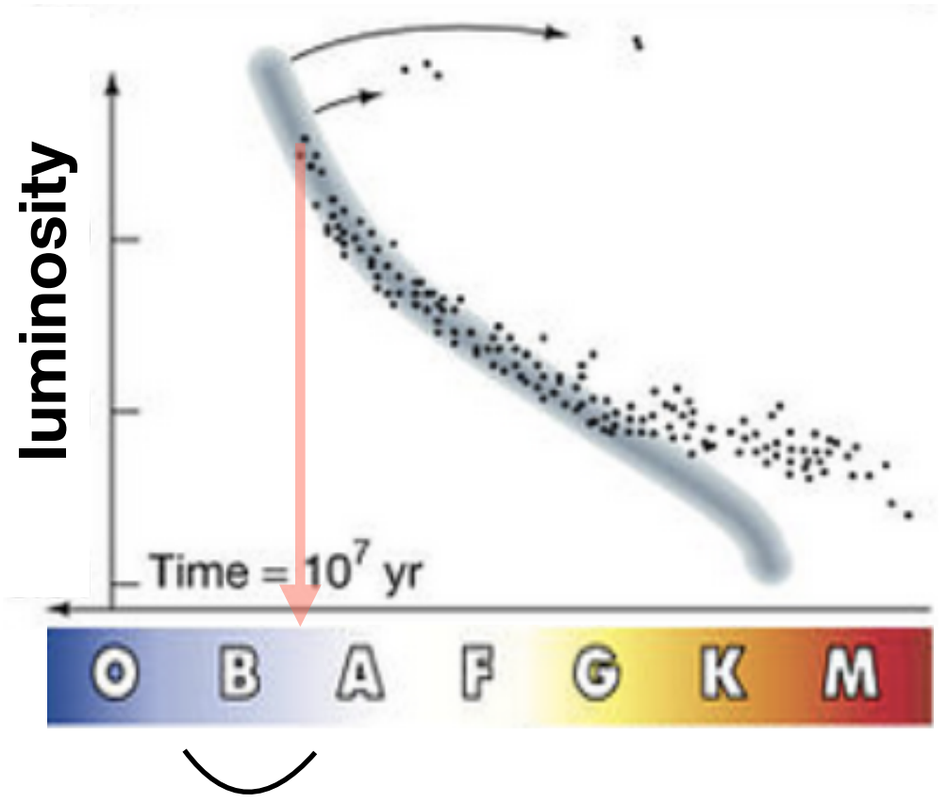


T>25000 K
strong UV continuum
ionised He lines

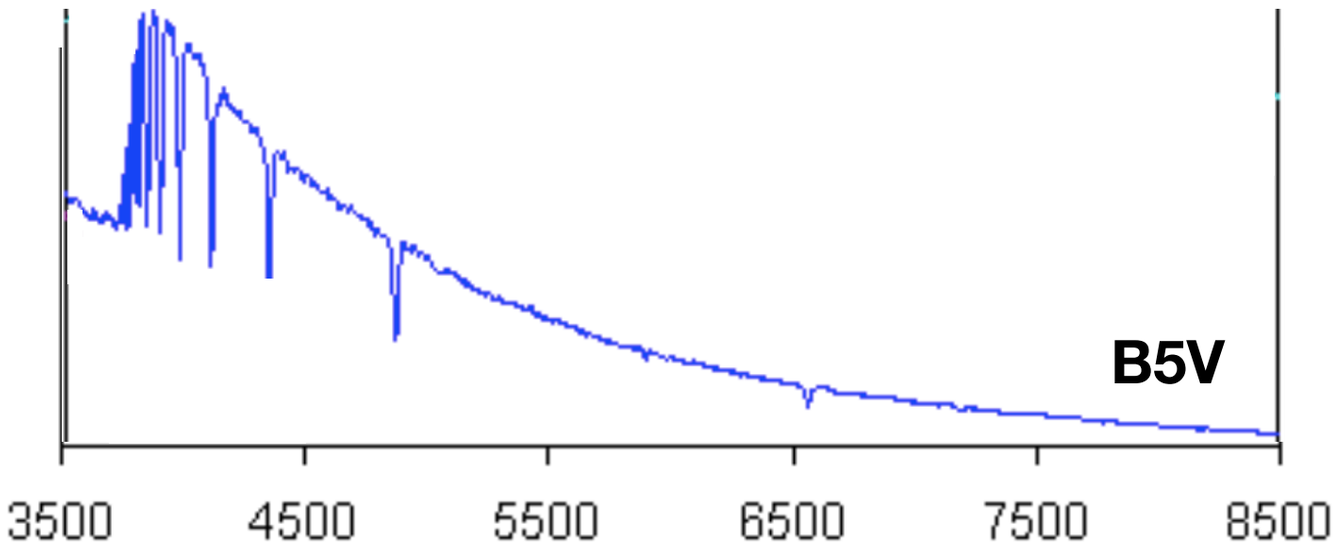


Time evolution of a SSP

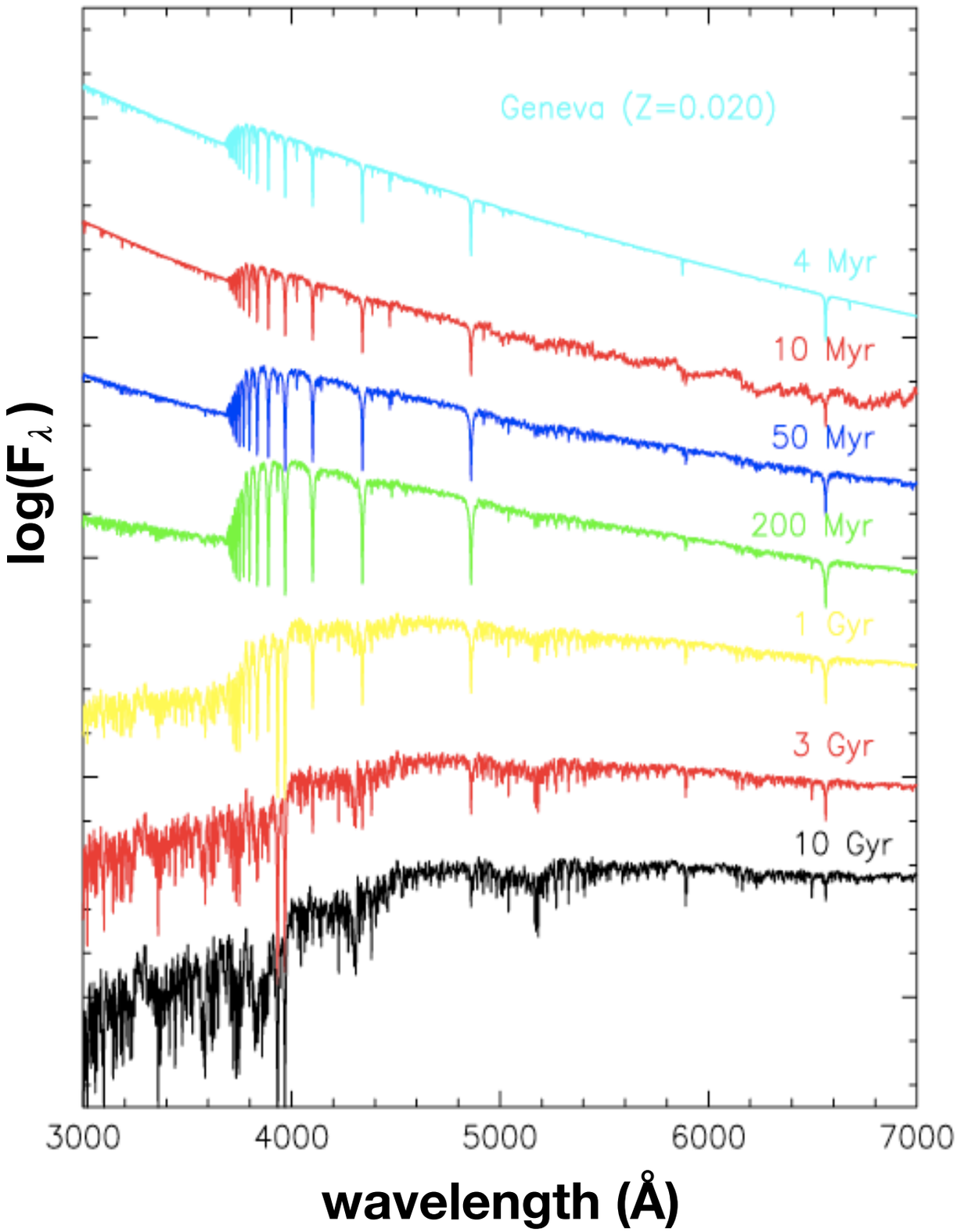


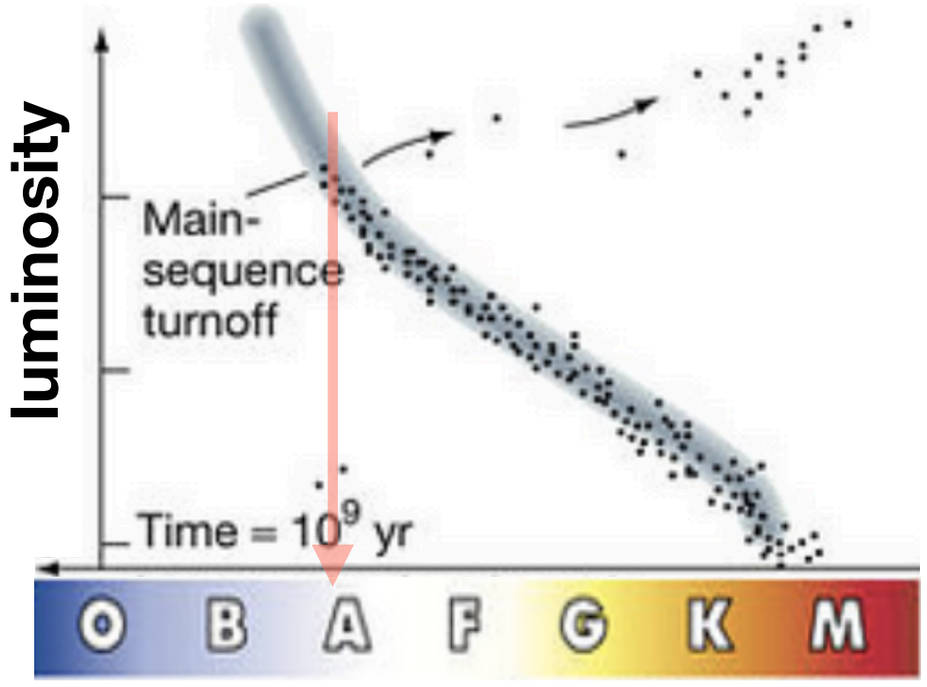


T~11000-25000 K
neutral He lines

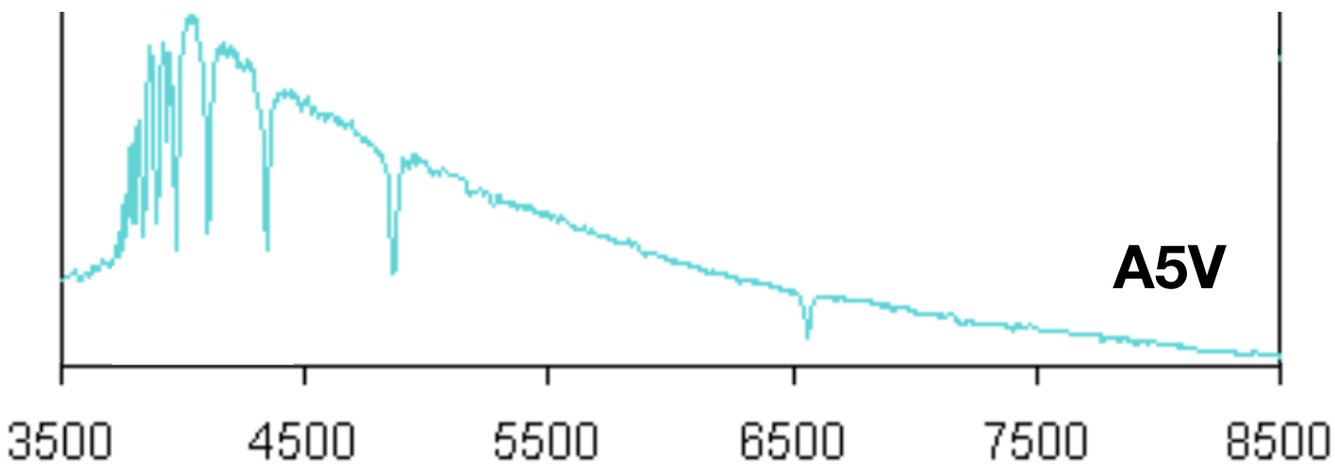


Time evolution of a SSP

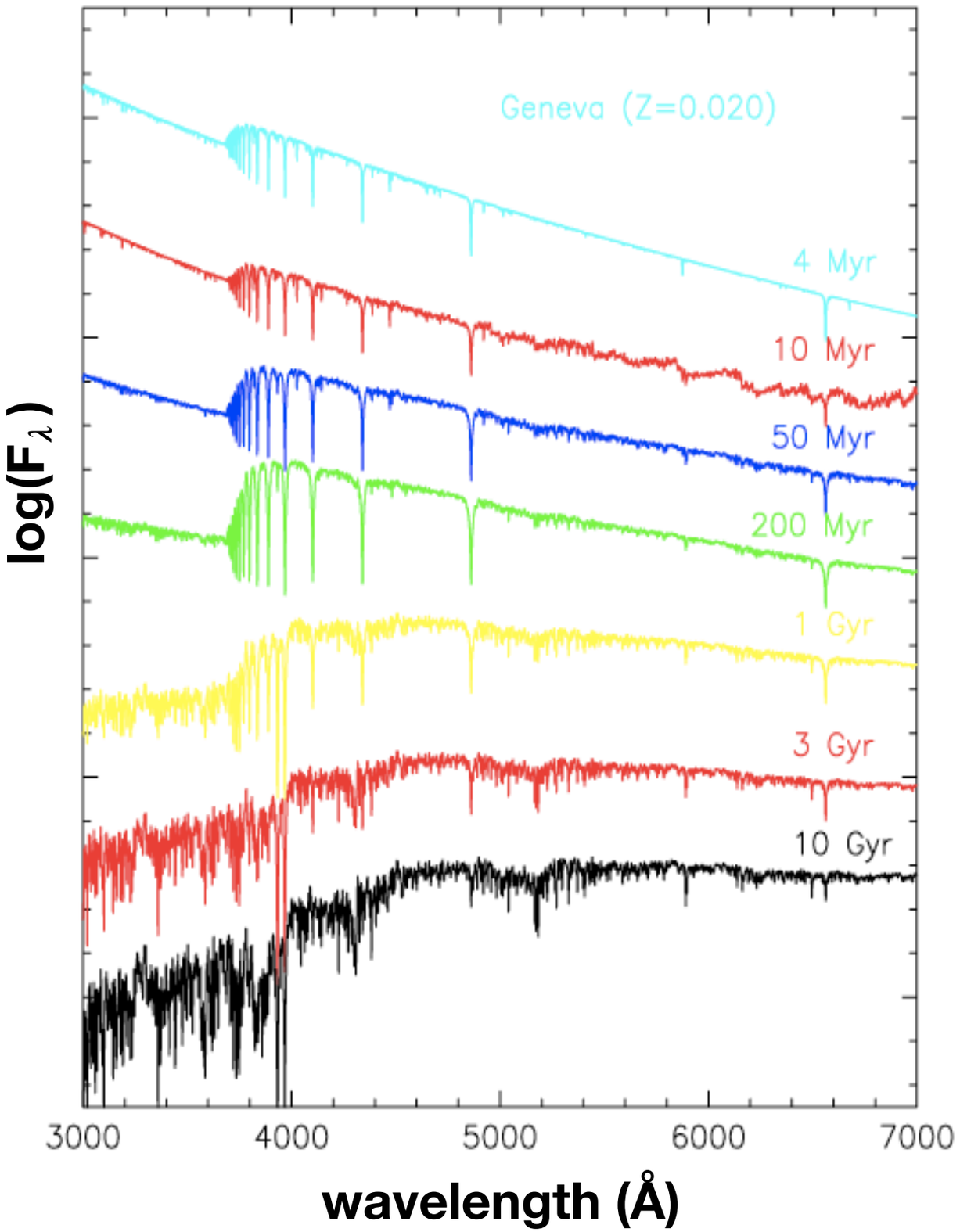


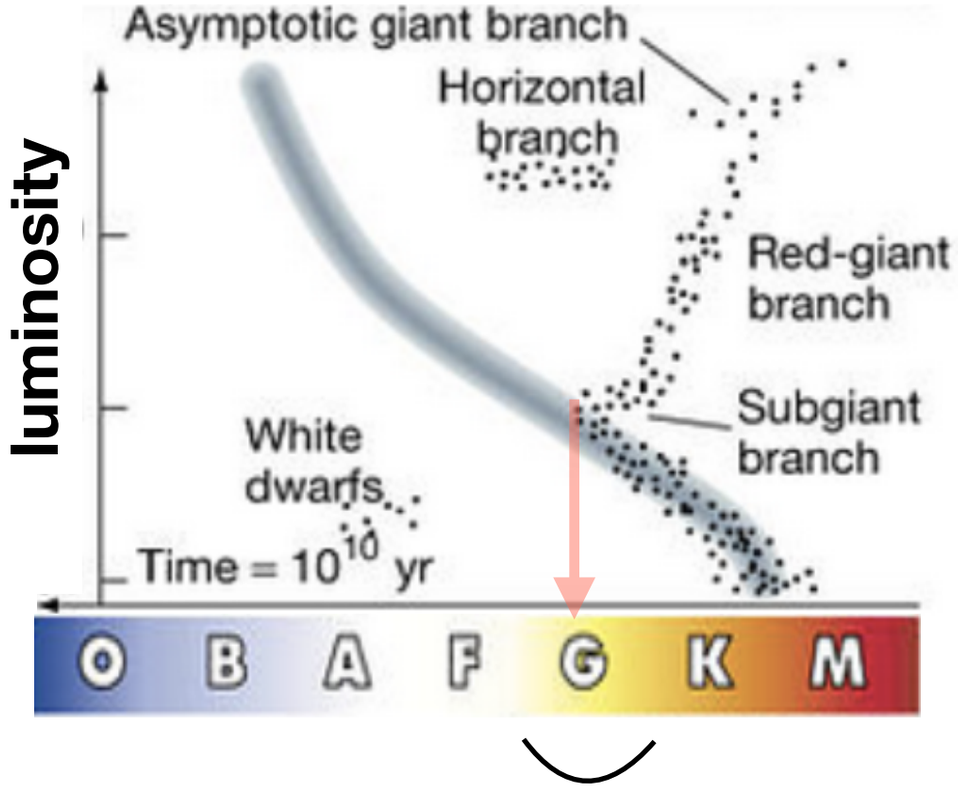


T~7500-11000 K
maximum strength H lines (for A0 stars)

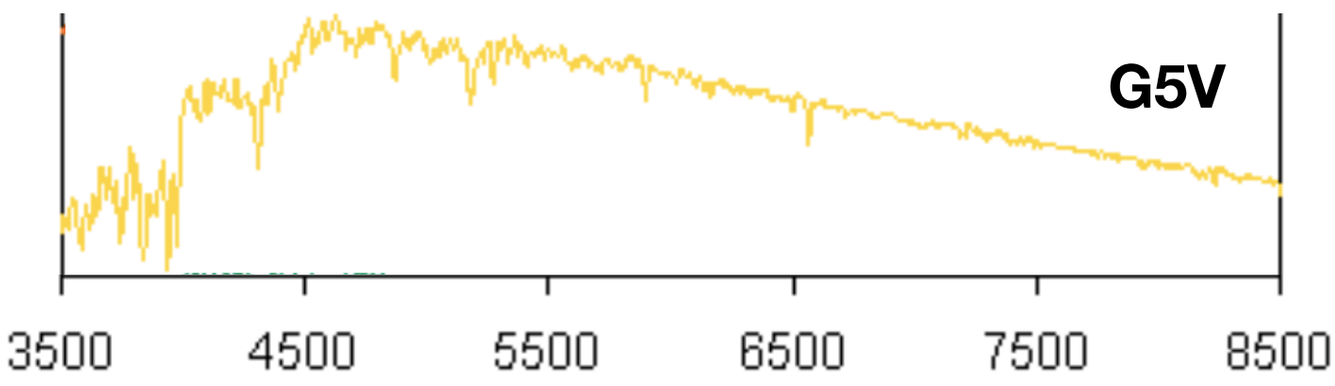


Time evolution of a SSP

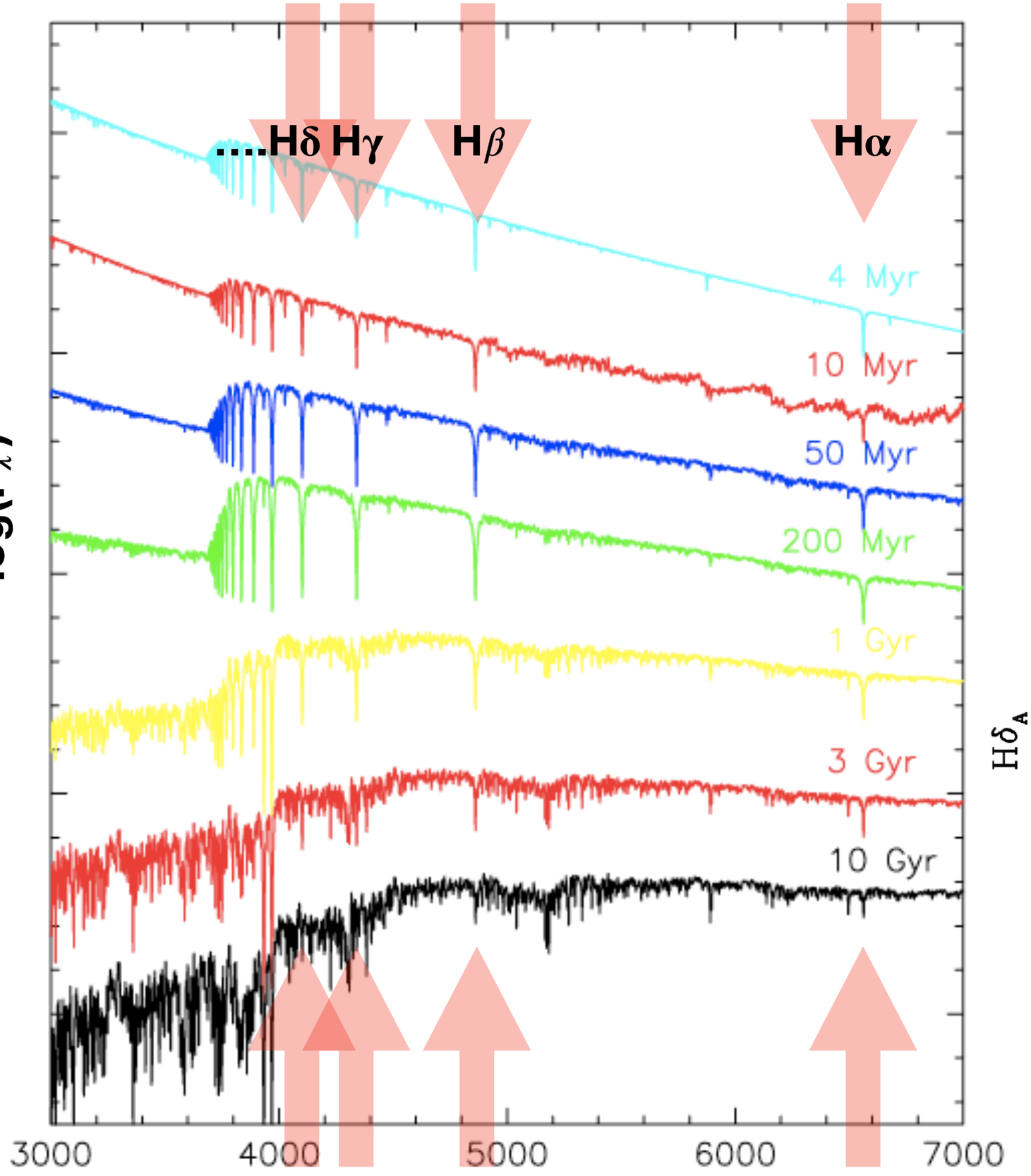




T~5000-6000 K
metallic lines (atoms and ions)

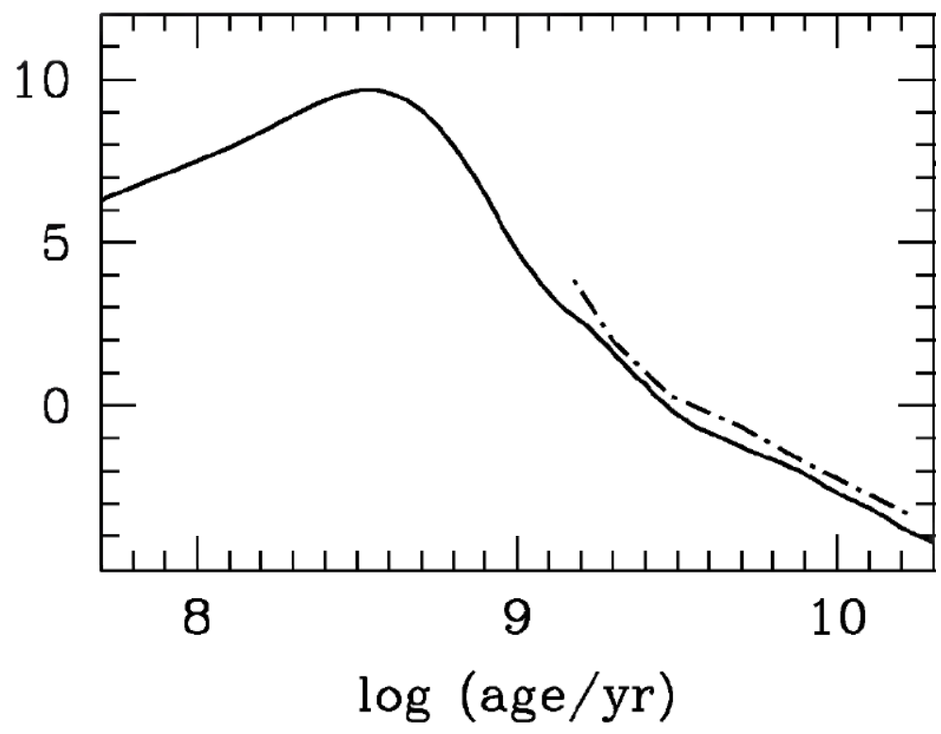


Time evolution of a SSP

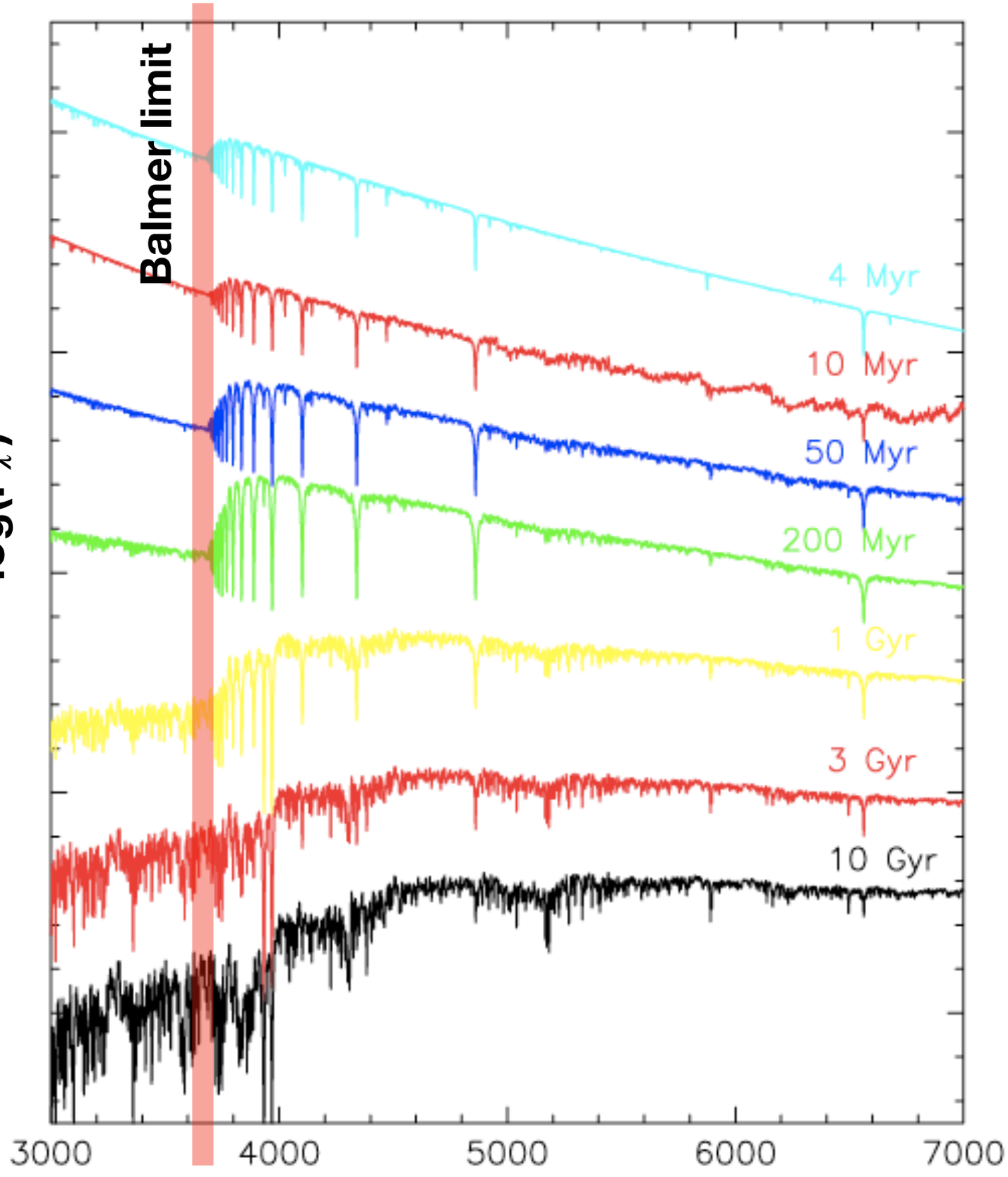


and thus:
[note time evolution of most prominent features]

- ☐ **Balmer break**
- ☐ **4000Å break**
- ☐ **Balmer lines**
- ☐ **metallic lines**



Time evolution of a SSP



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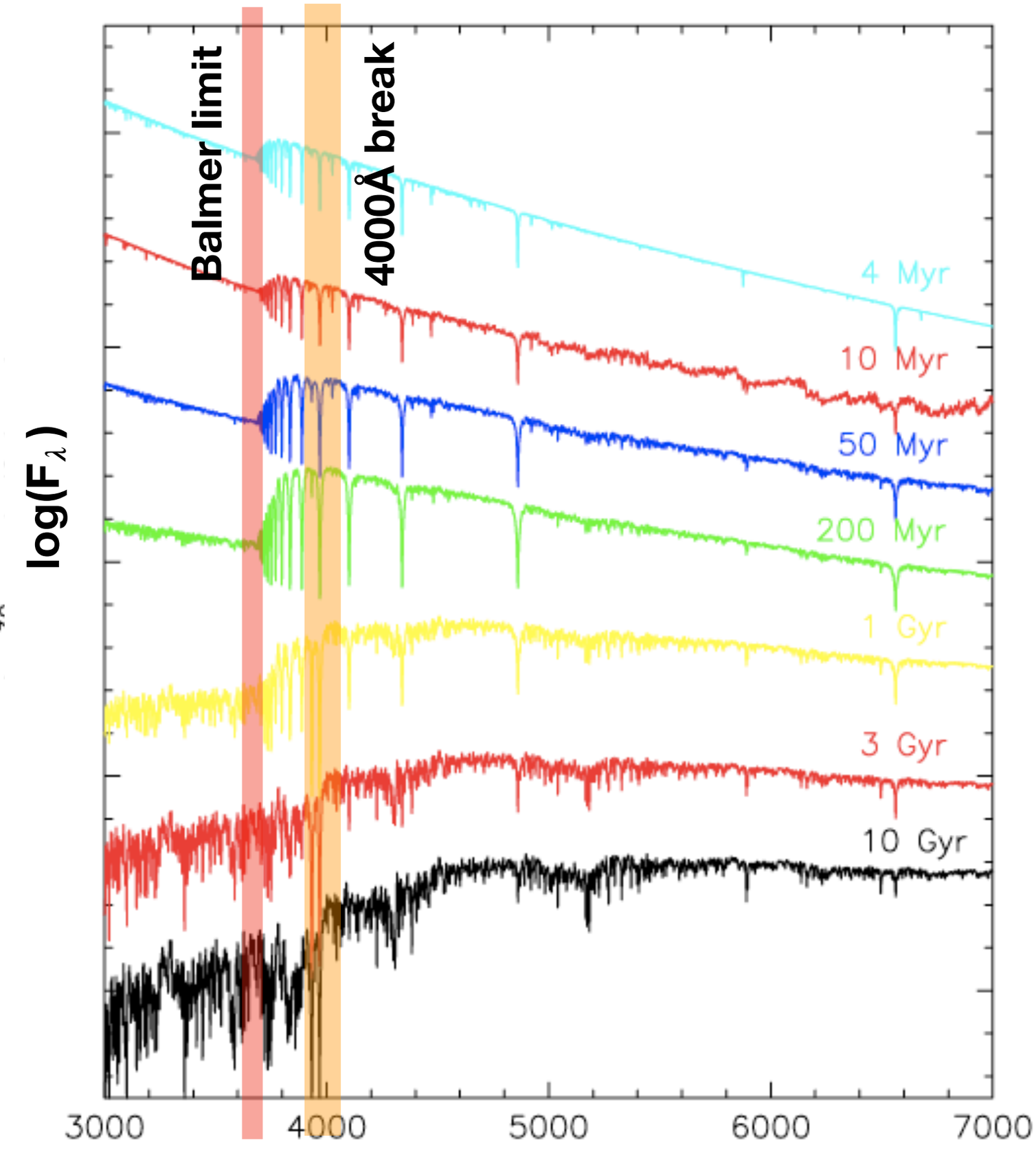

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- ☐ **Balmer break**
- ☐ **4000Å break**
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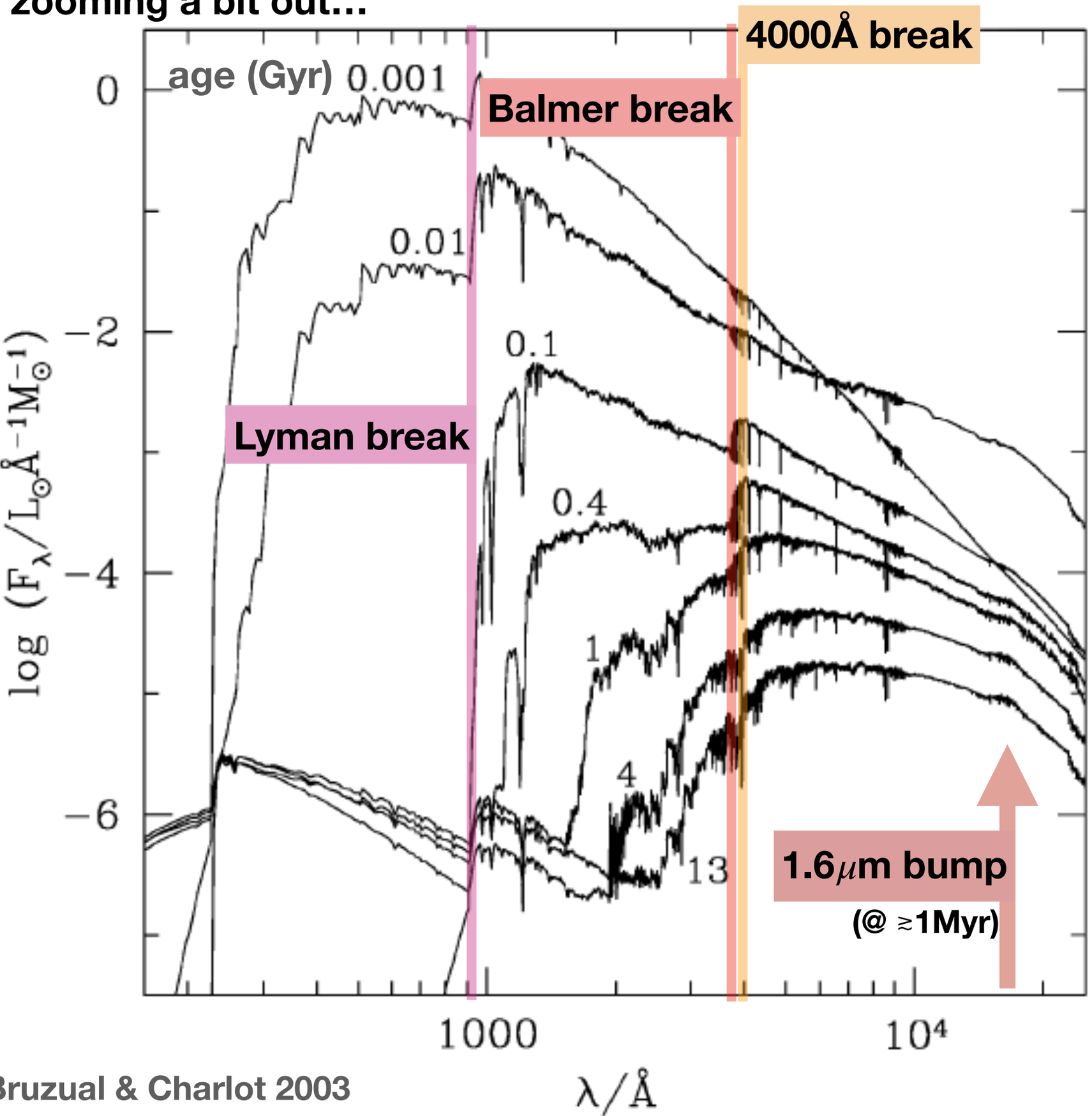
- ☐ **metallic lines**

Time evolution of a SSP

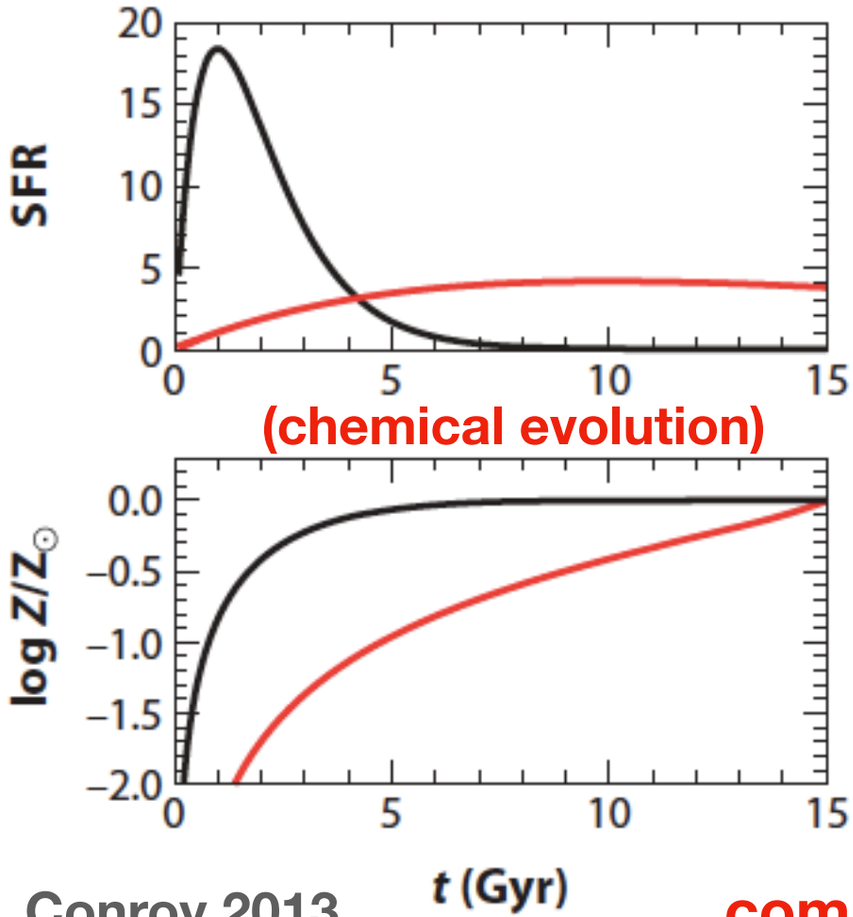
zooming a bit out…



Bruzual & Charlot 2003

Stellar Population Synthesis (SPS) -The next step: CSPs

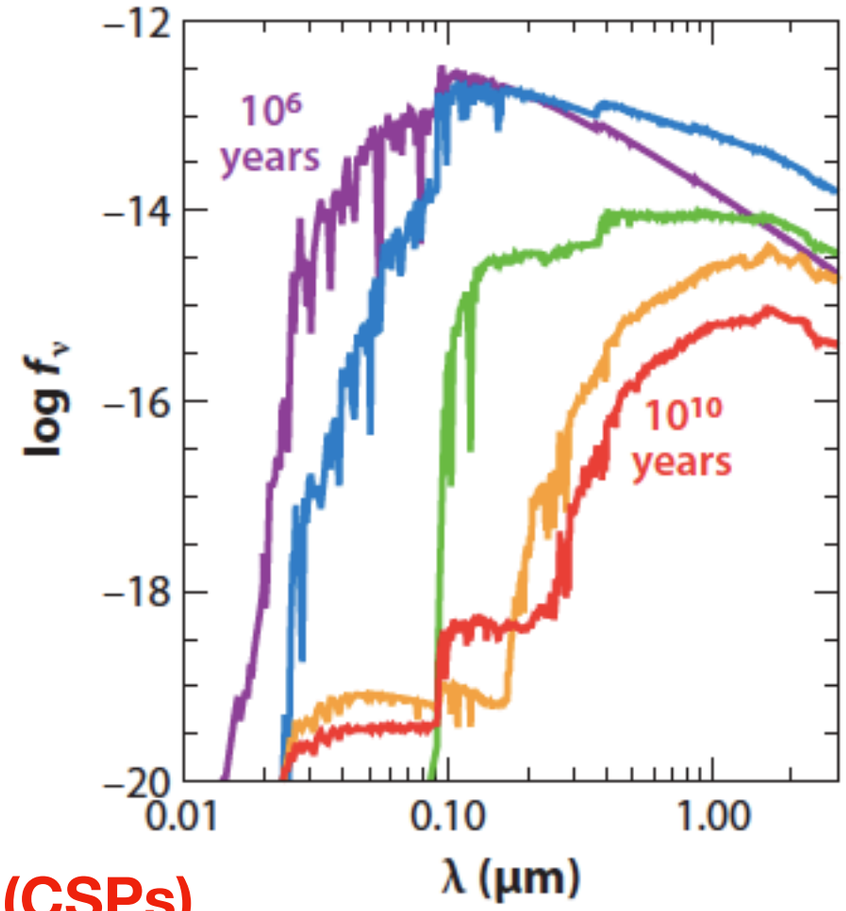
star formation history (SFH)



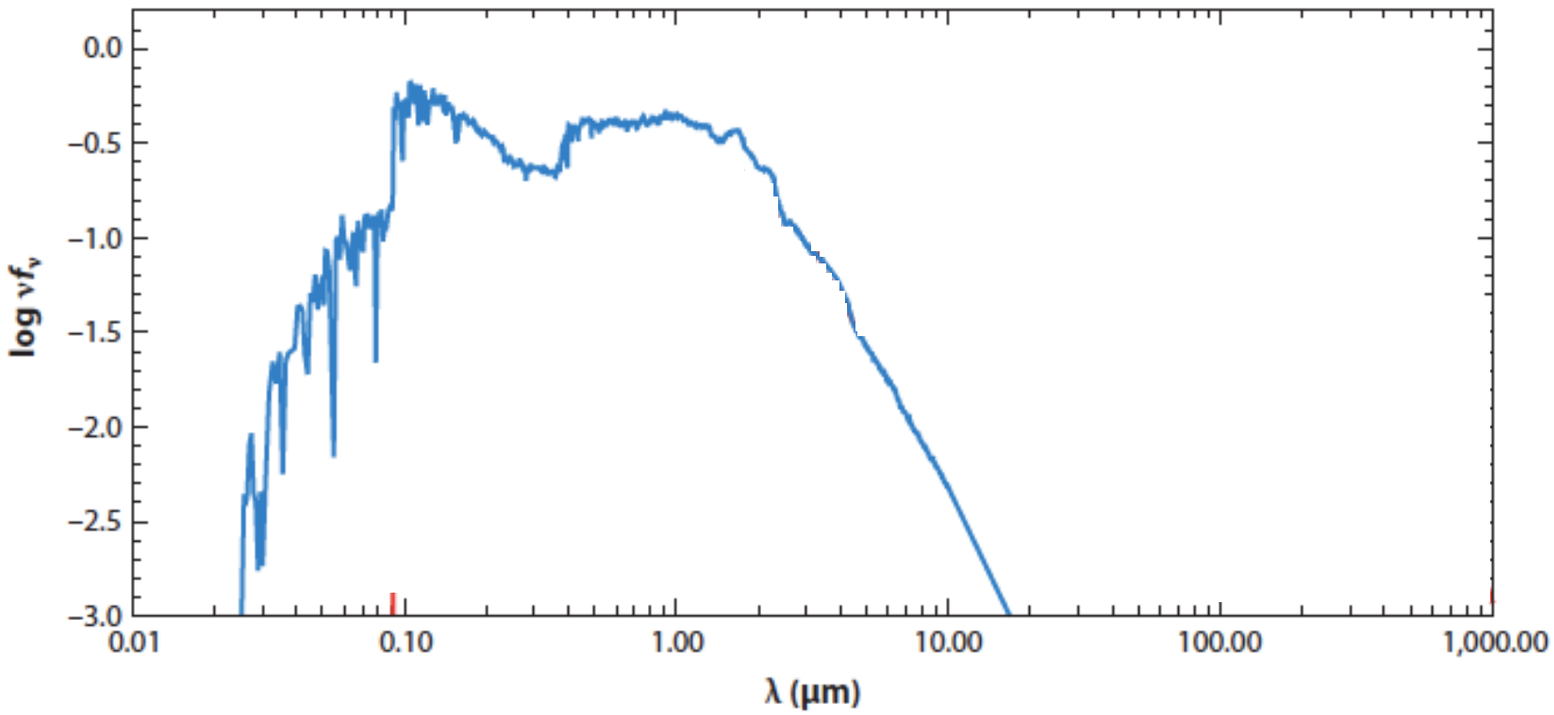
(chemical evolution)

Conroy 2013

SSP (time evolution)

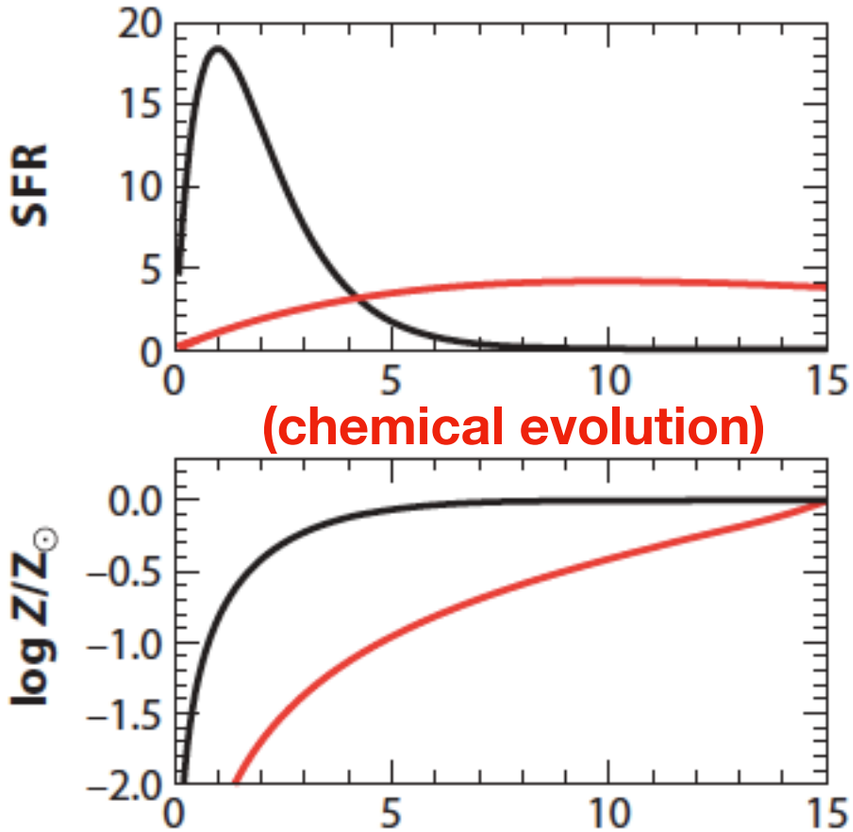


composite stellar populations (CSPs)



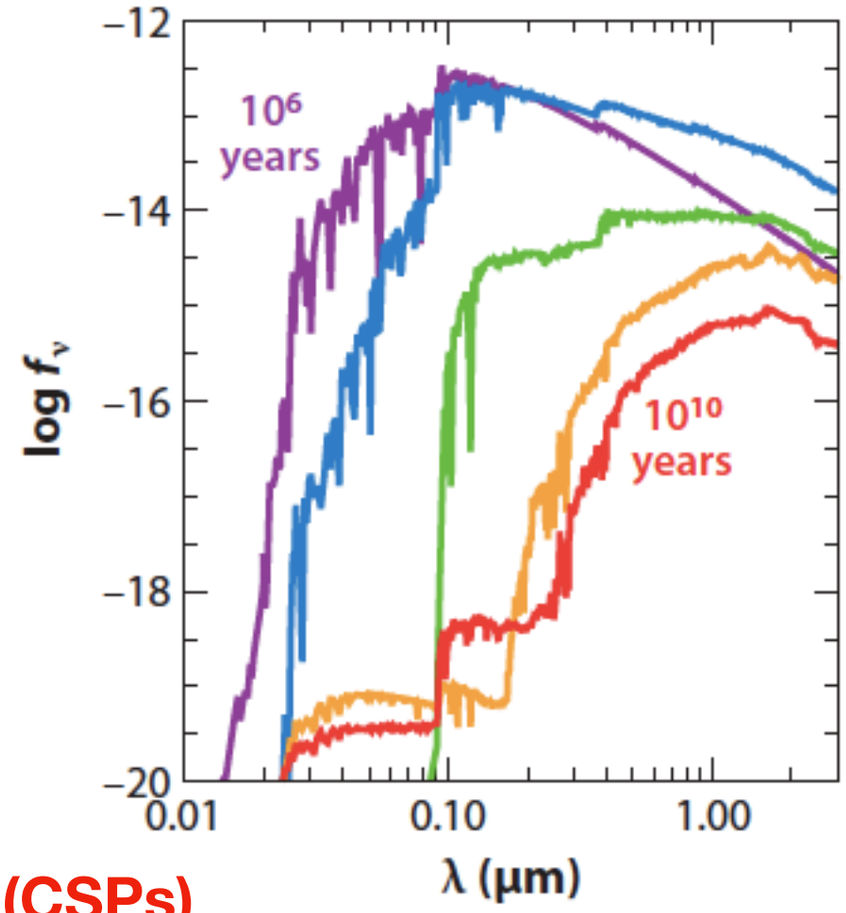
Stellar Population Synthesis (SPS) -The next step: CSPs

star formation history (SFH)



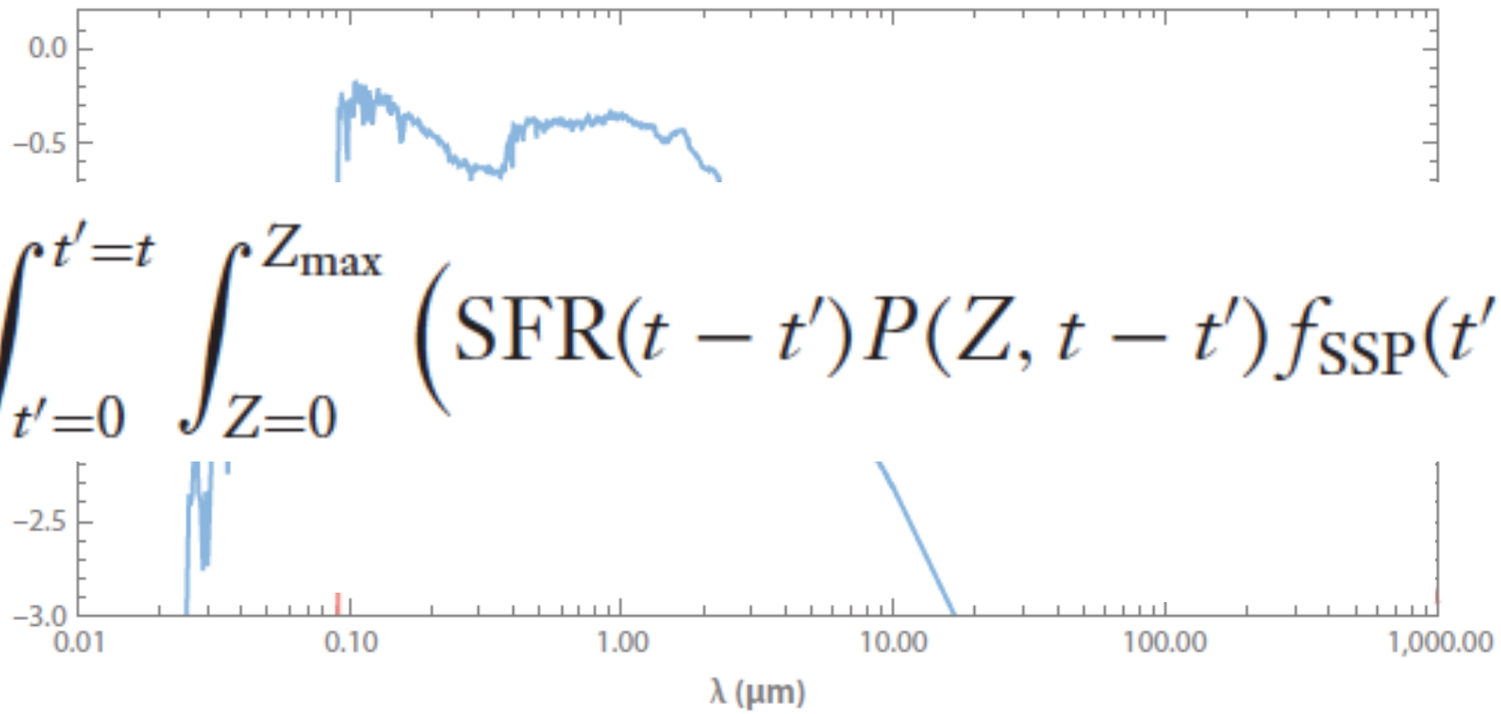
(chemical evolution)

SSP (time evolution)



Conroy 2013

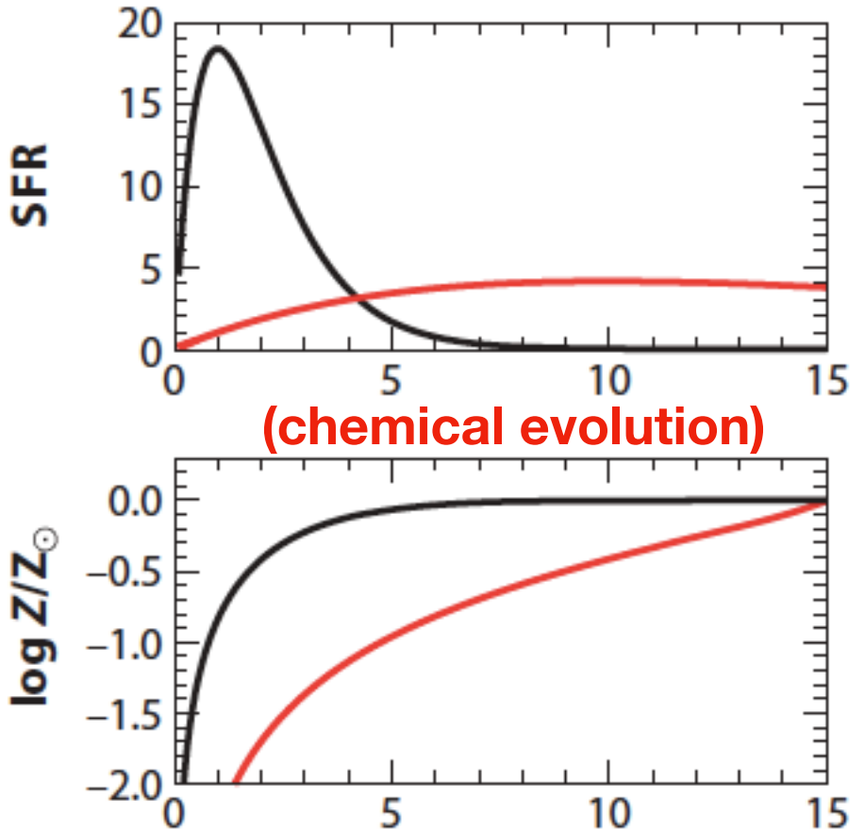
composite stellar populations (CSPs)



$$f_{\mathrm{CSP}}(t) = \int_{t'=0}^{t'=t} \int_{Z=0}^{Z_{\max}} \Big(\mathrm{SFR}(t-t') P(Z, t-t') f_{\mathrm{SSP}}(t', Z) \Big) \, \mathrm{d}t' \, \mathrm{d}Z$$

Stellar Population Synthesis (SPS) -The next step: CSPs

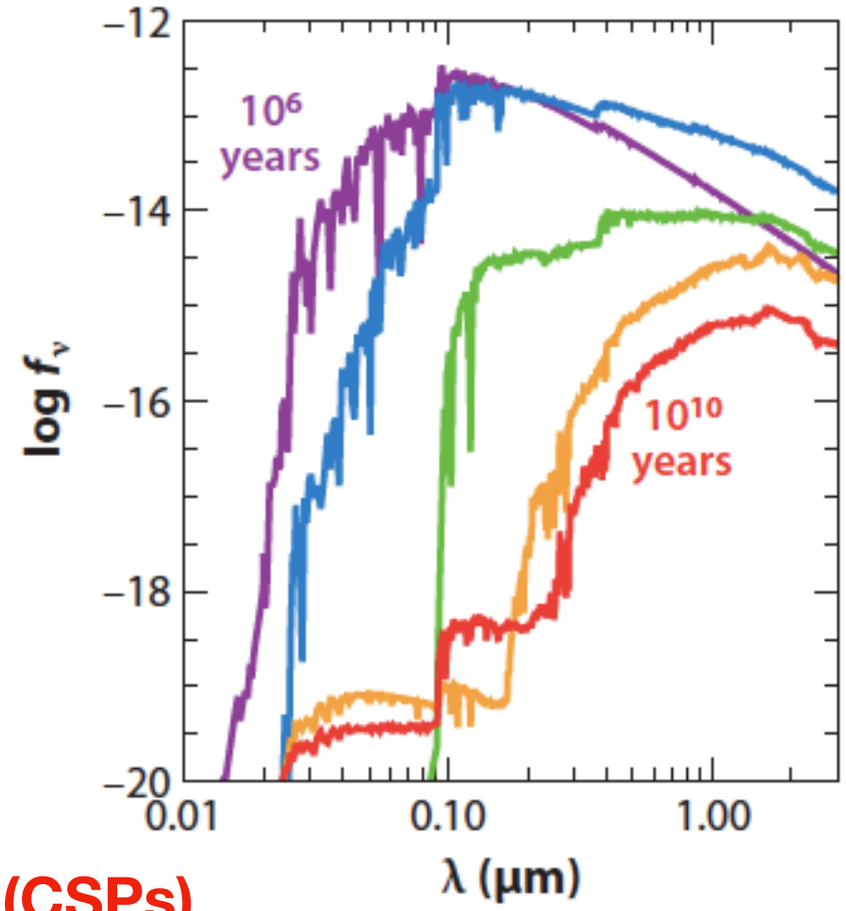
star formation history (SFH)



(chemical evolution)

Conroy 2013

SSP (time evolution)



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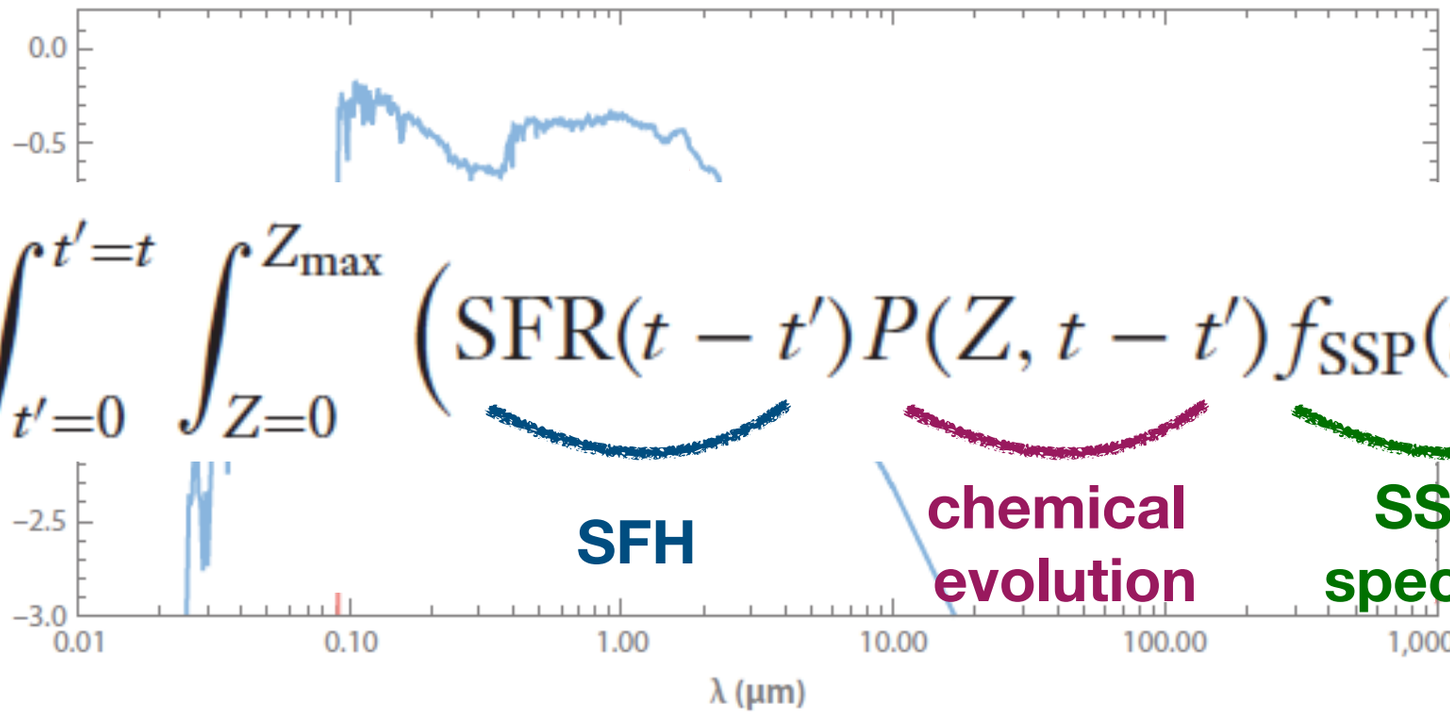

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SFH

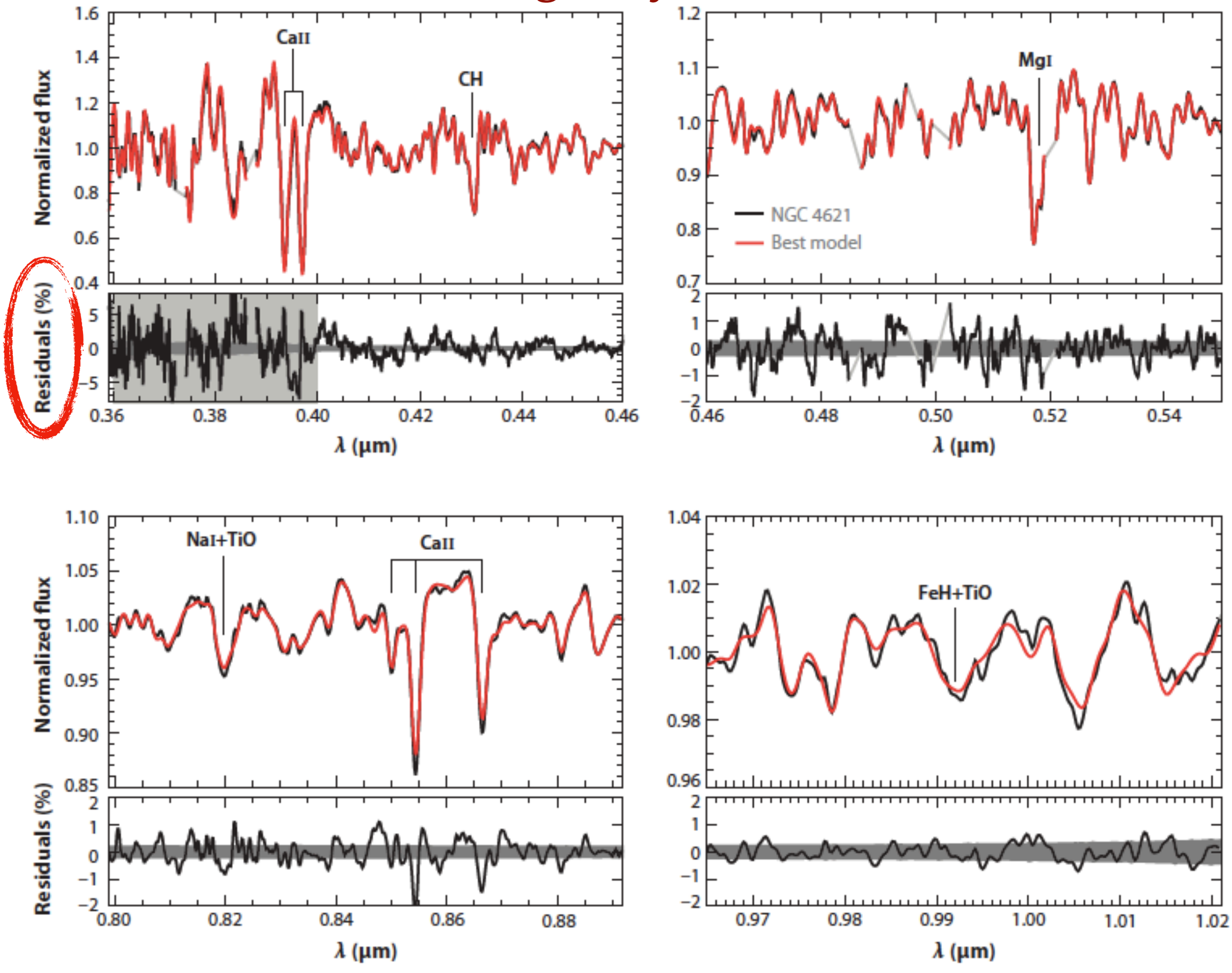
chemical evolution

SSP spectra

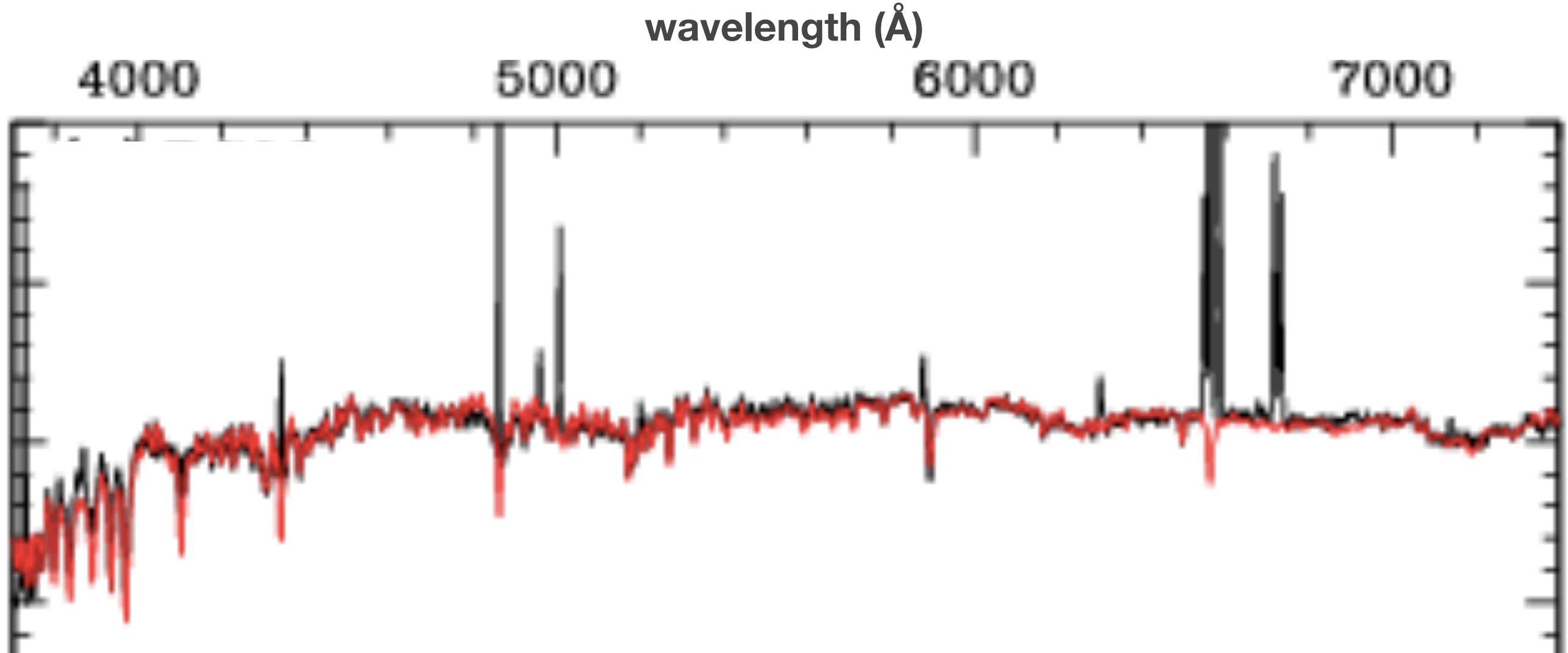
SSP age

SSP metallicity

Where does a galaxy SED come from



Where does a galaxy SED come from

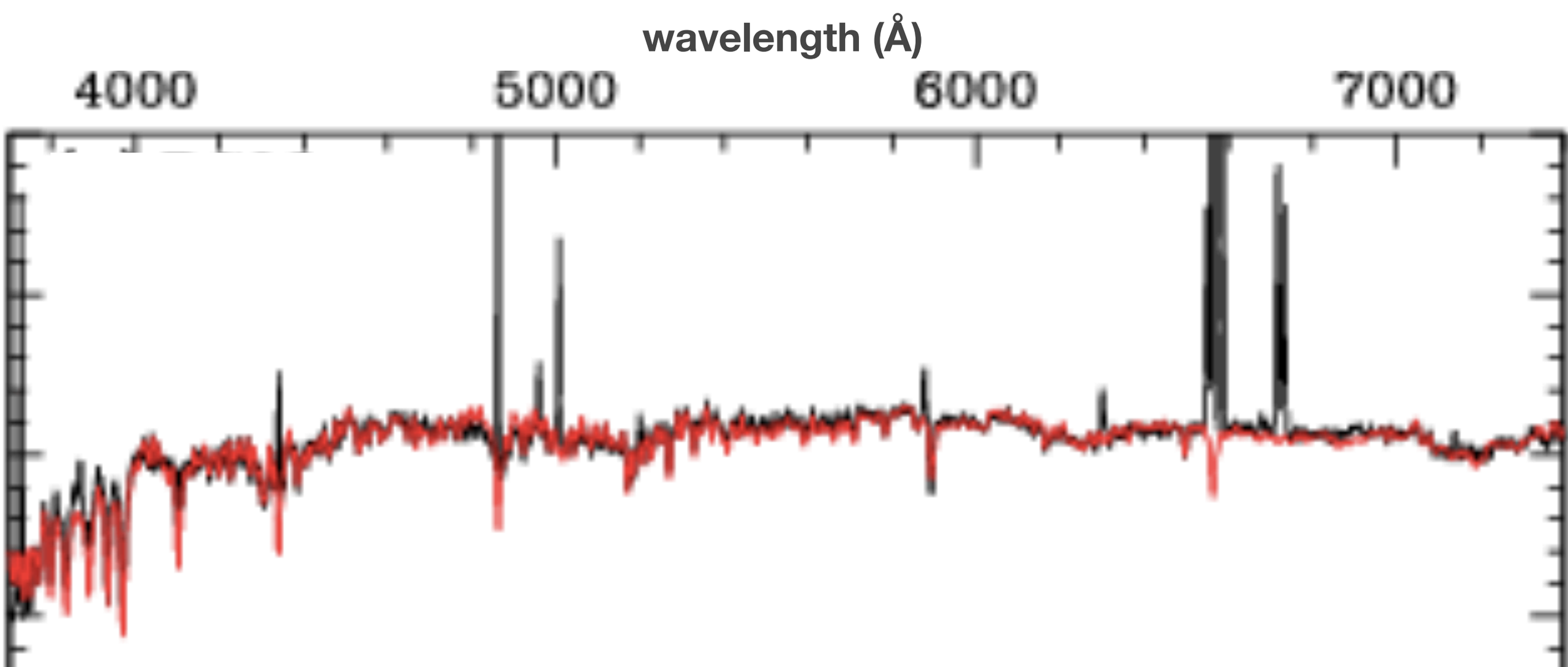


Where does a galaxy SED come from

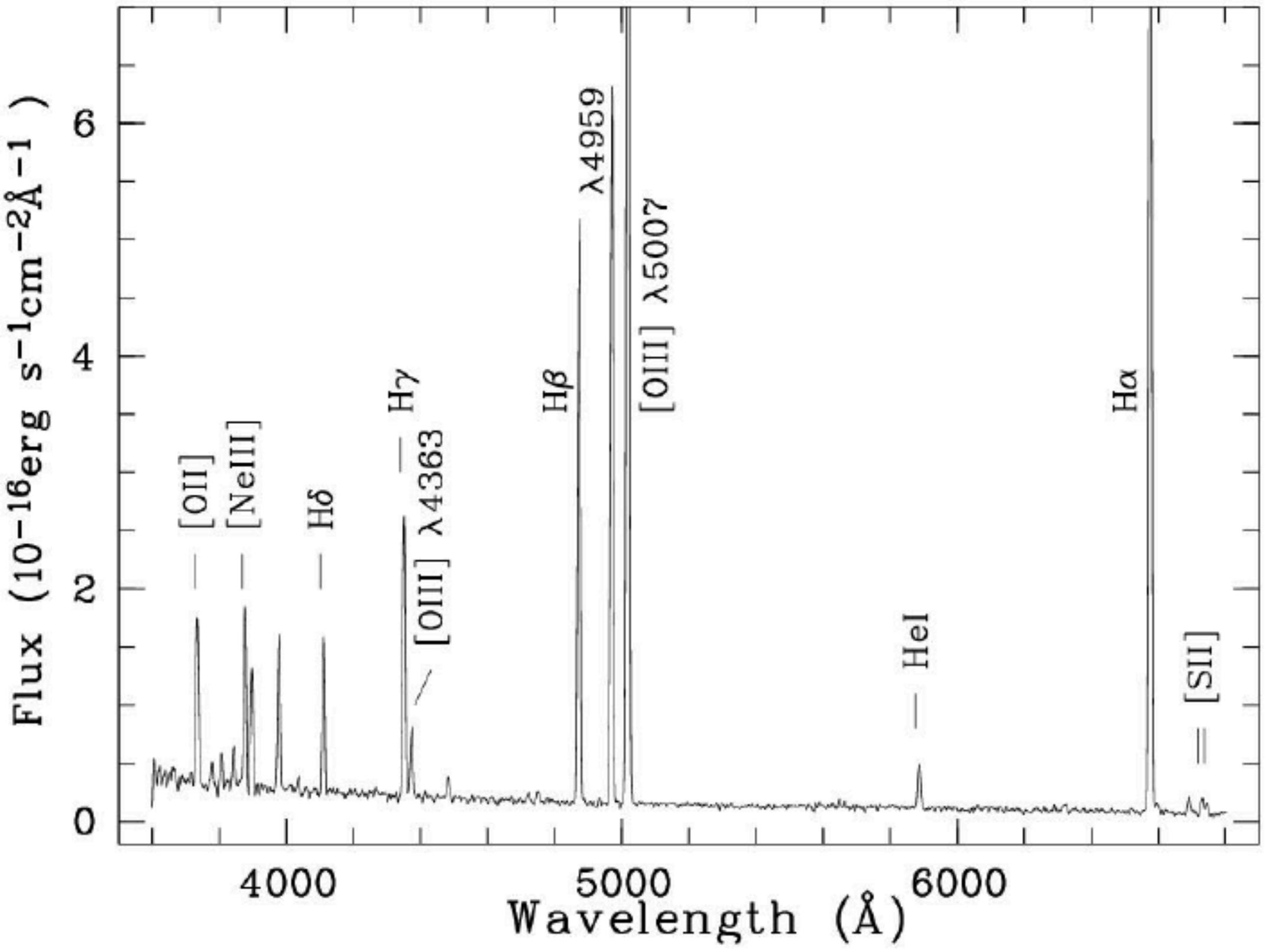
Galaxy spectral energy distributions are the result of the combination of light emission and absorption from the (baryonic) galaxy consituents:

- ☐ stars
- ☐ gas
- ☐ AGN
- ☐ dust

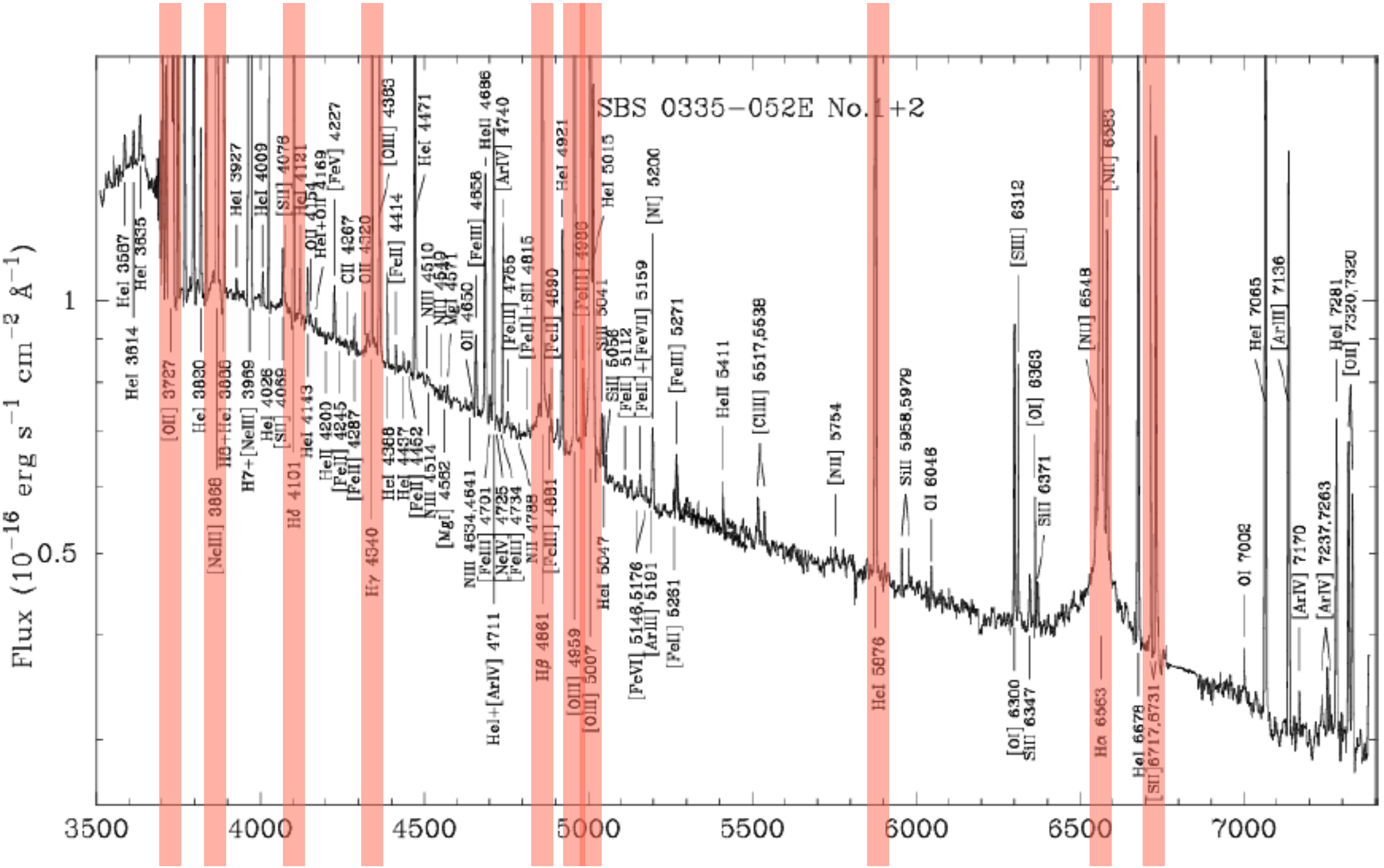
Nebular emission from ionised (HII) regions of the ISM (continuum and emission lines). Associated with star-forming galaxies, because only massive O and early B stars emit UV photons that efficiently ionise HI gas to HII. Emission lines from heavier elements are also observed - depending on ionization level and metallicity of the gas.



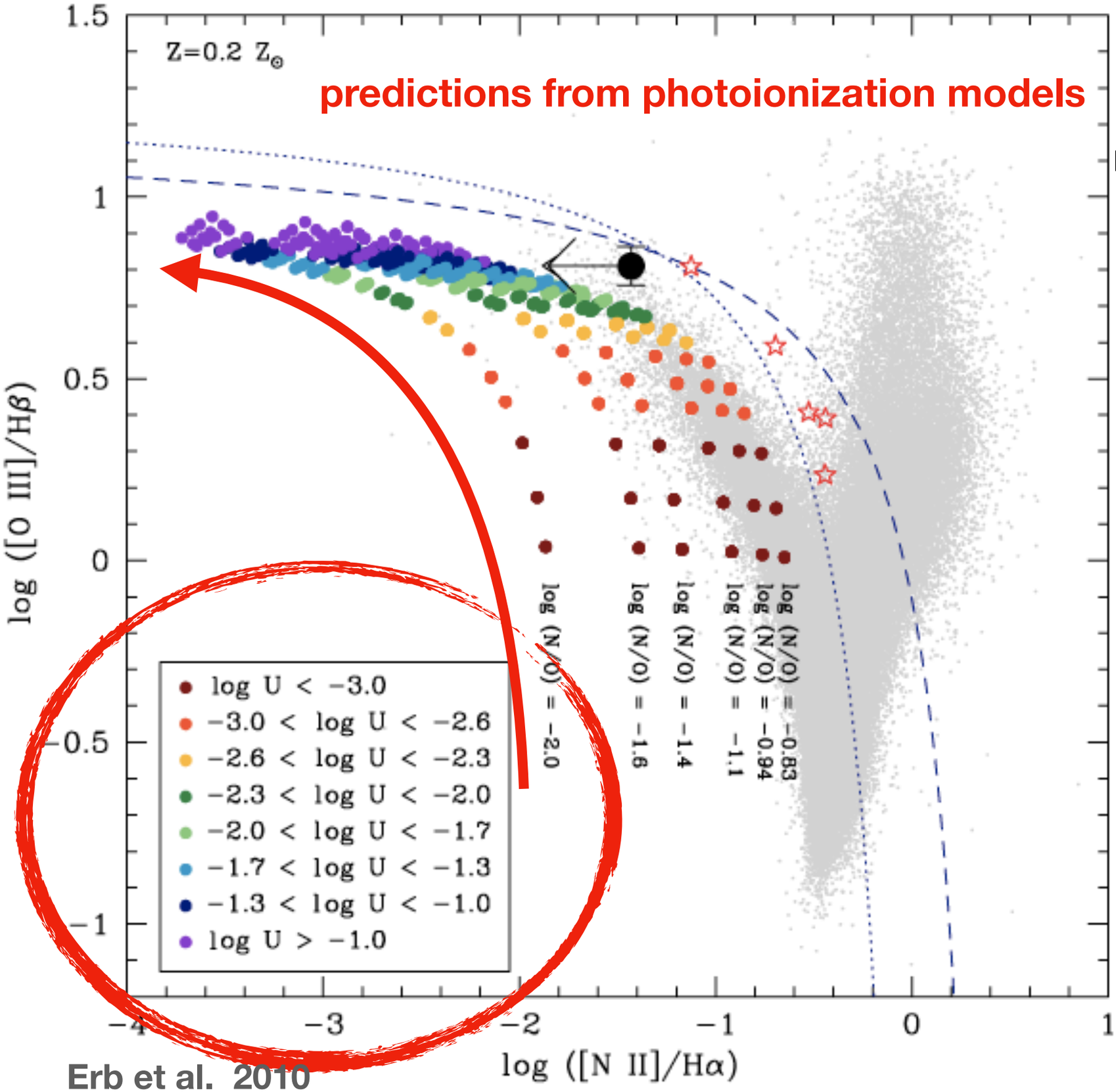
Line emission from ionised gas



Line emission from ionised gas



Line emission from ionised gas

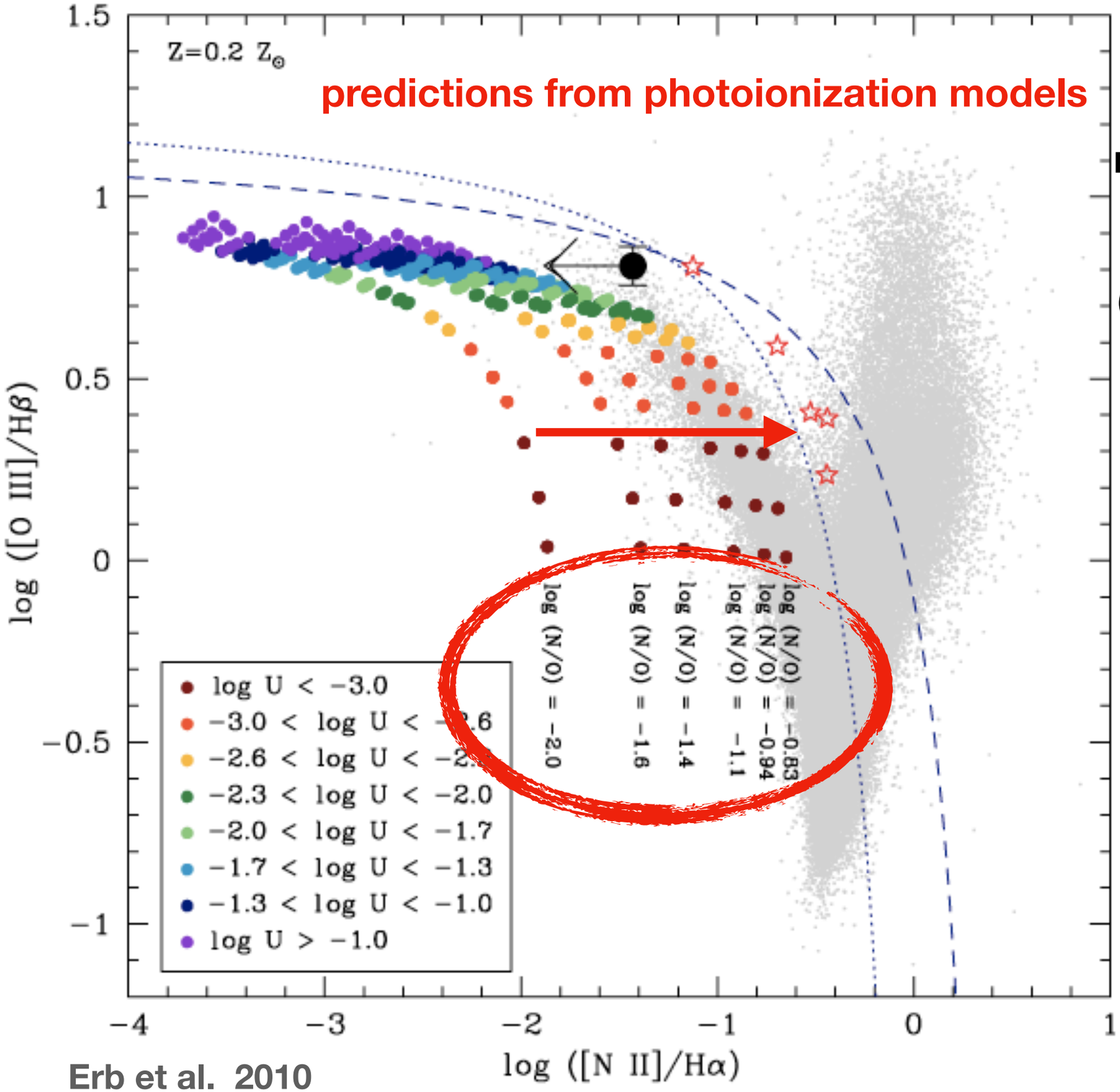


note dependence on:
- ionization parameter

(~the ratio of ionizing photon density to hydrogen density)

Erb et al. 2010

Line emission from ionised gas



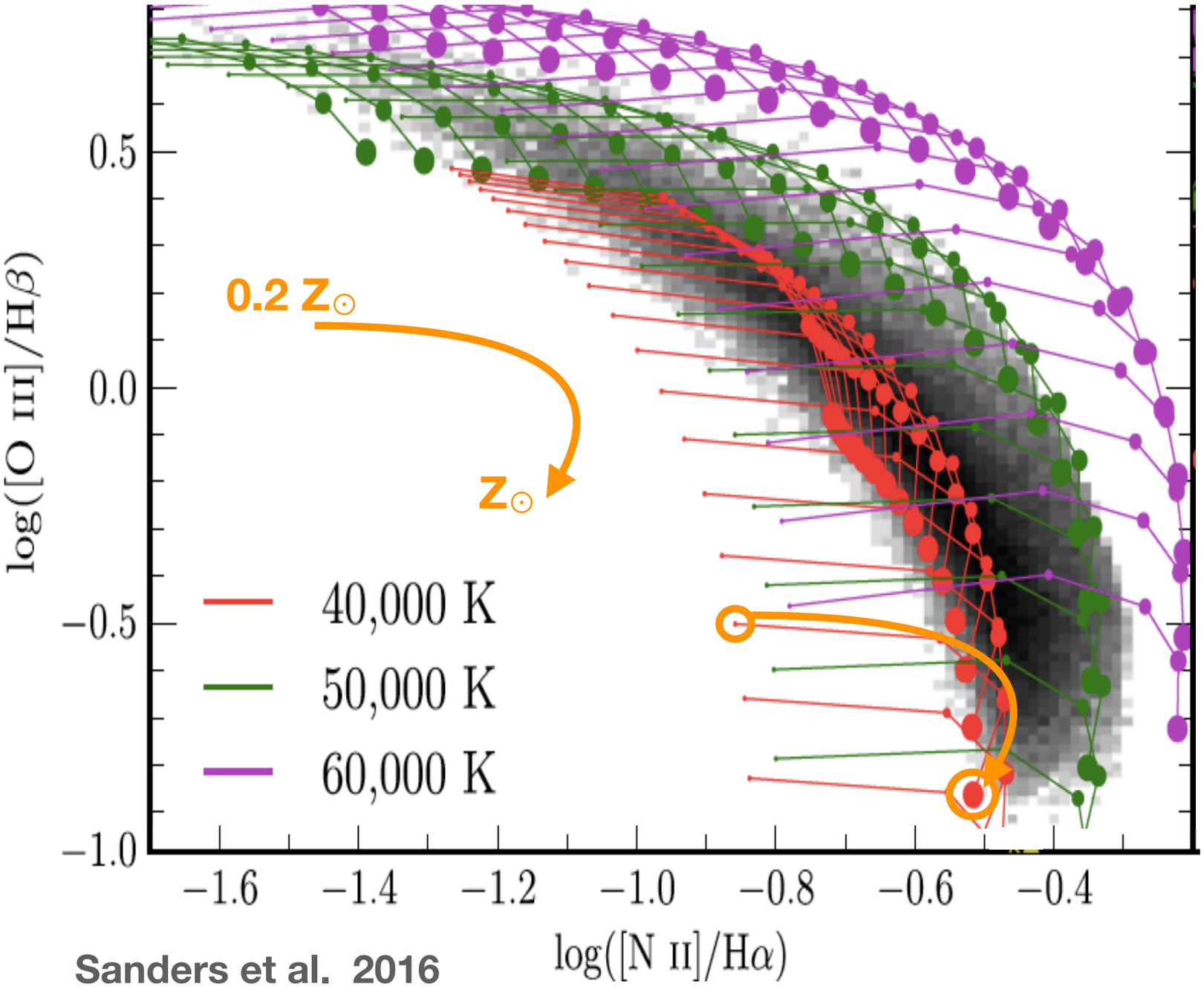
note dependence on:
- **ionization parameter**
- **N/O abundance**

(SF history, chemical enrichment history, inflows/outflows)

Erb et al. 2010

Line emission from ionised gas

predictions from photoionization models



Sanders et al. 2016

note dependence on:

- **ionization parameter**
- **N/O abundance**

(SF history, chemical enrichment history, inflows/outflows)

- **metallicity**
- **…**

Where does a galaxy SED come from

Galaxy spectral energy distributions are the result of the combination of light emission and absorption from the (baryonic) galaxy consituents:

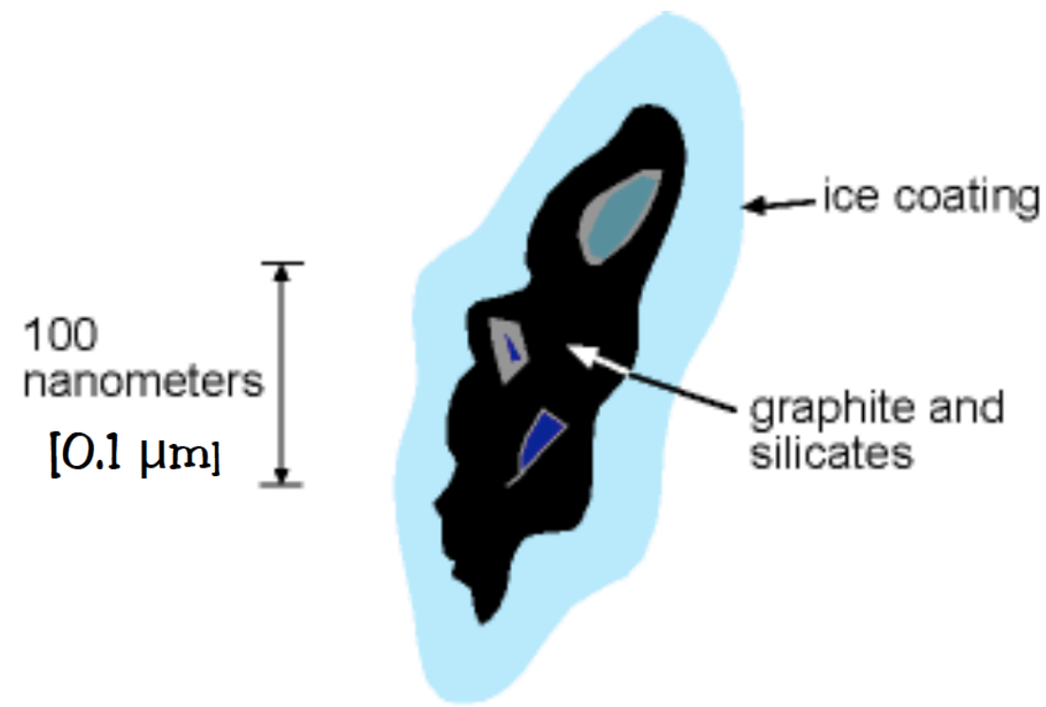
- ☐ **stars**
- ☐ **gas**
- ☐ **AGN**
- ☐ **dust**

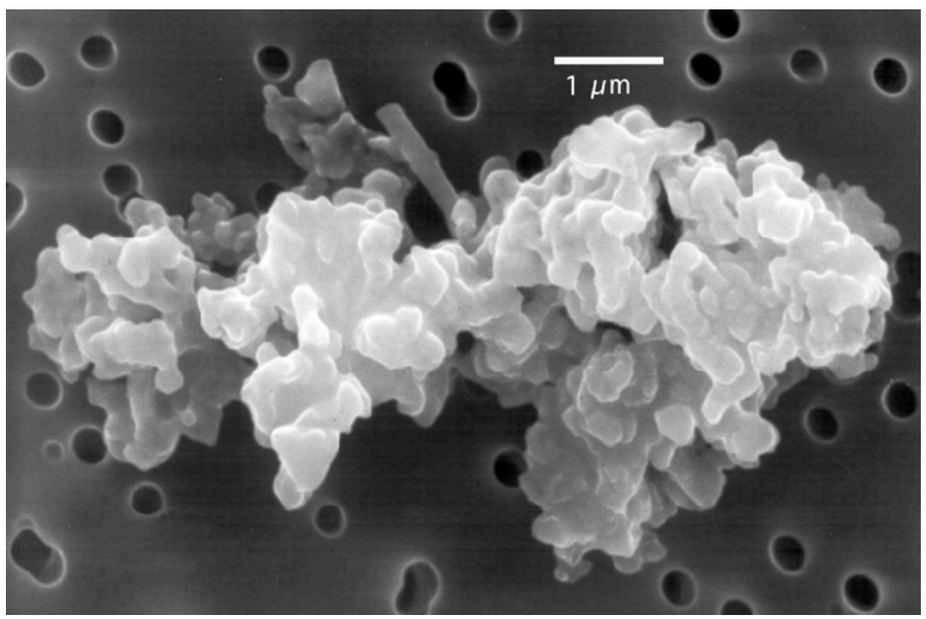
Where does a galaxy SED come from

Galaxy spectral energy distributions are the result of the combination of light emission and absorption from the (baryonic) galaxy consituents:

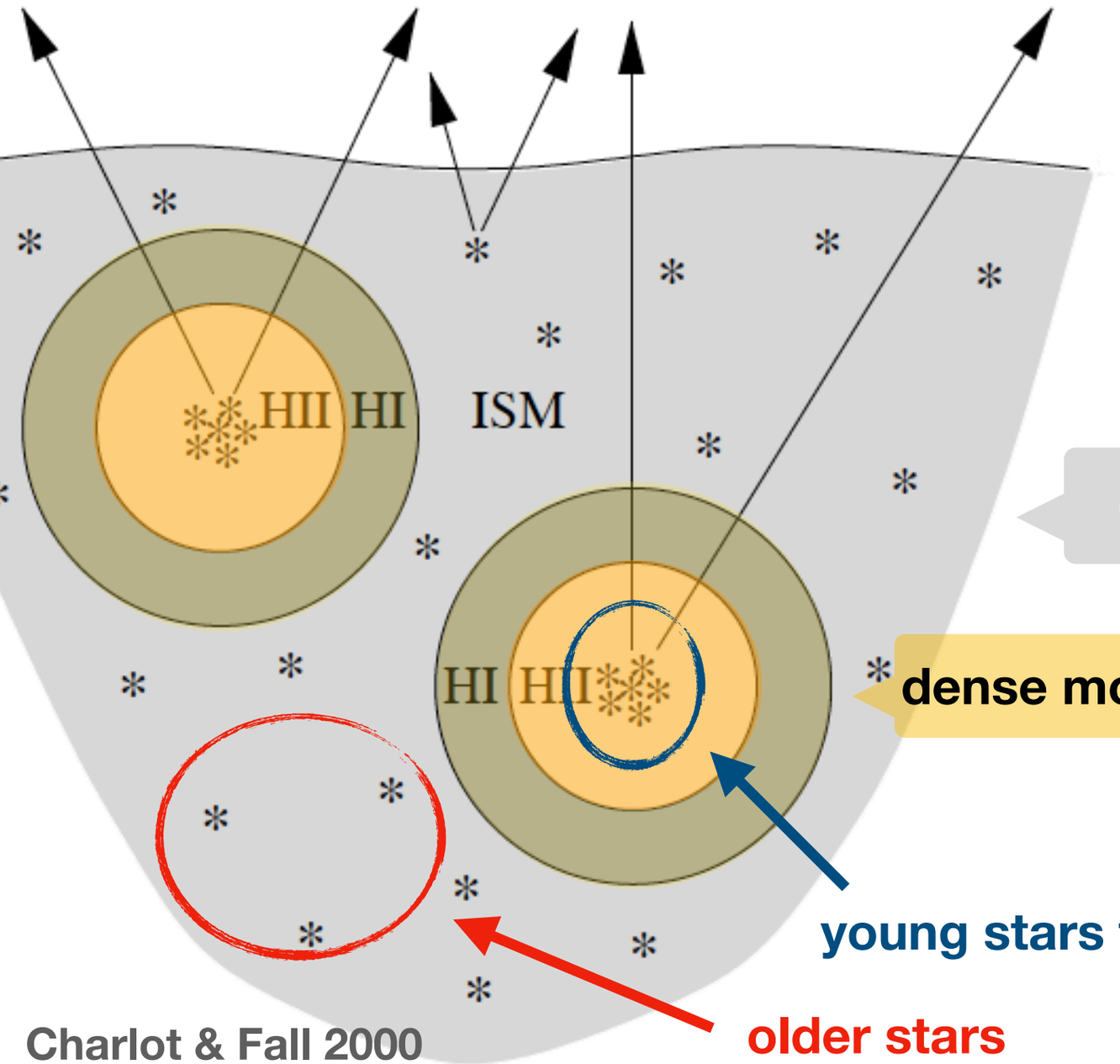
- ☐ **stars**
- ☐ **gas**
- ☐ **AGN**
- ☐ **dust**

Cosmic dust is made of aggregates of sub-μm grains - silicates and carbonaceous grains (graphite, polycyclic aromatic hydrocarbons). It may scatter starlight, absorb it, and re-radiate it a different wavelengths.





Dust extinction



diffuse interstellar medium (ISM)

dense molecular clouds

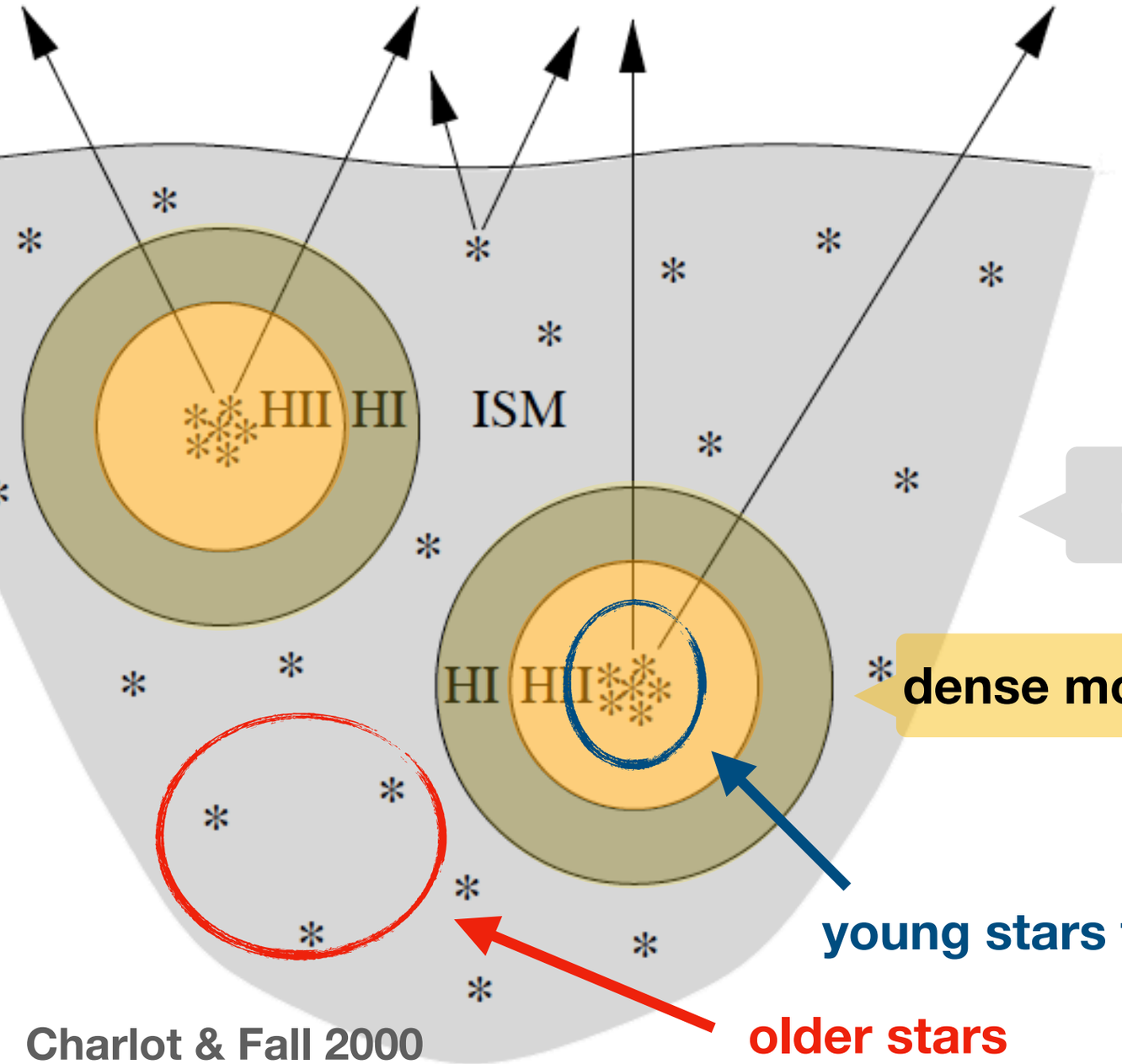
young stars forming in the clouds

older stars

Charlot & Fall 2000

Dust extinction

the emerging starlight is affetcted by <u>extinction</u>
(due to <u>absorption</u> and <u>scattering</u> in/out of the line of sight)
- to different extent depending on wavelength



diffuse interstellar medium (ISM)

dense molecular clouds

young stars forming in the clouds

older stars

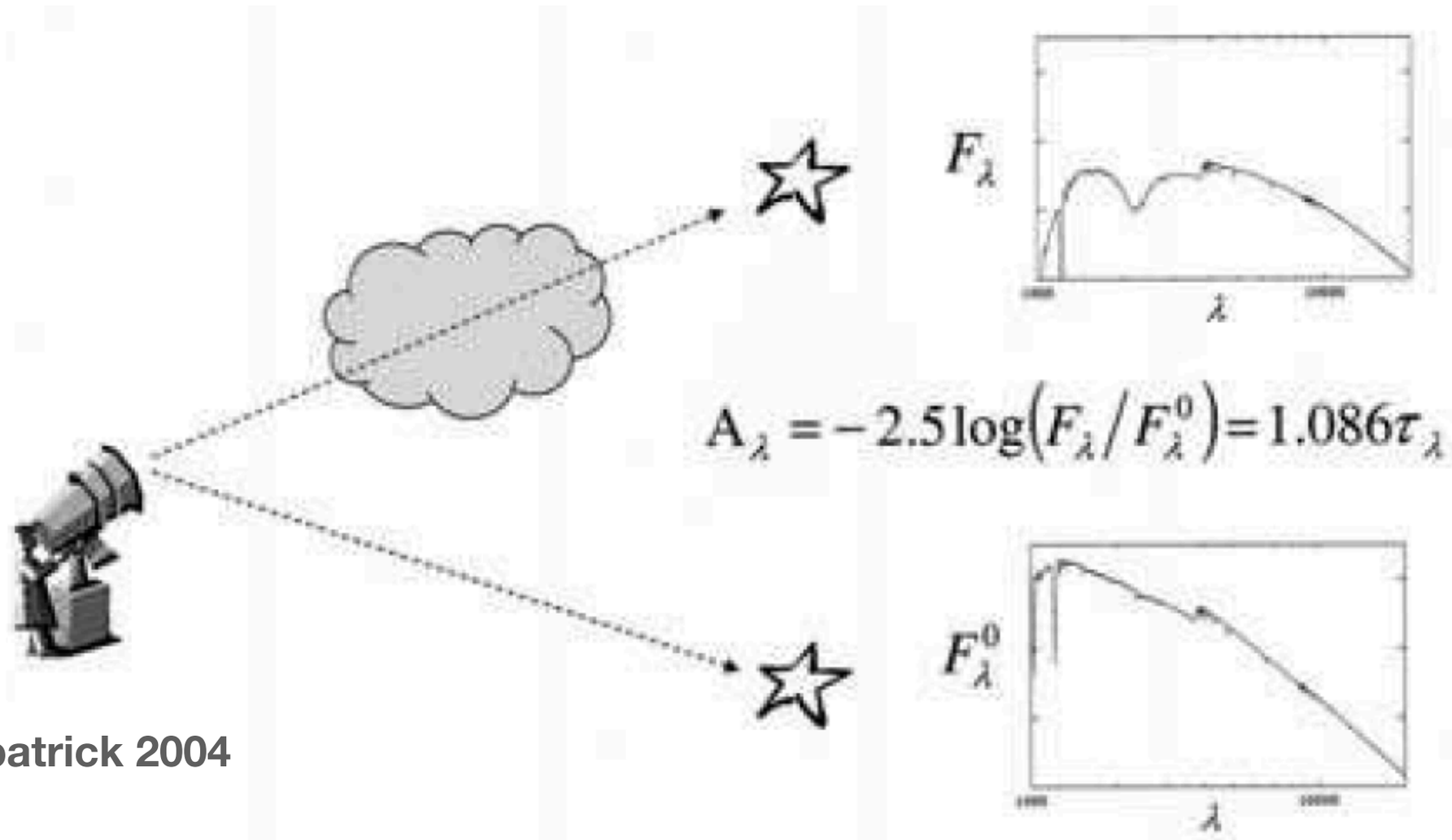
Charlot & Fall 2000

Dust extinction

Comparing the SEDs of two stars of same spectral class, one of which with negligible foreground, we determine the extinction as a function of wavelength:

$$A_\lambda \equiv 2.5 \log_{10}(F^0_\lambda / F_\lambda)$$

"intrinsic" flux **observed flux**

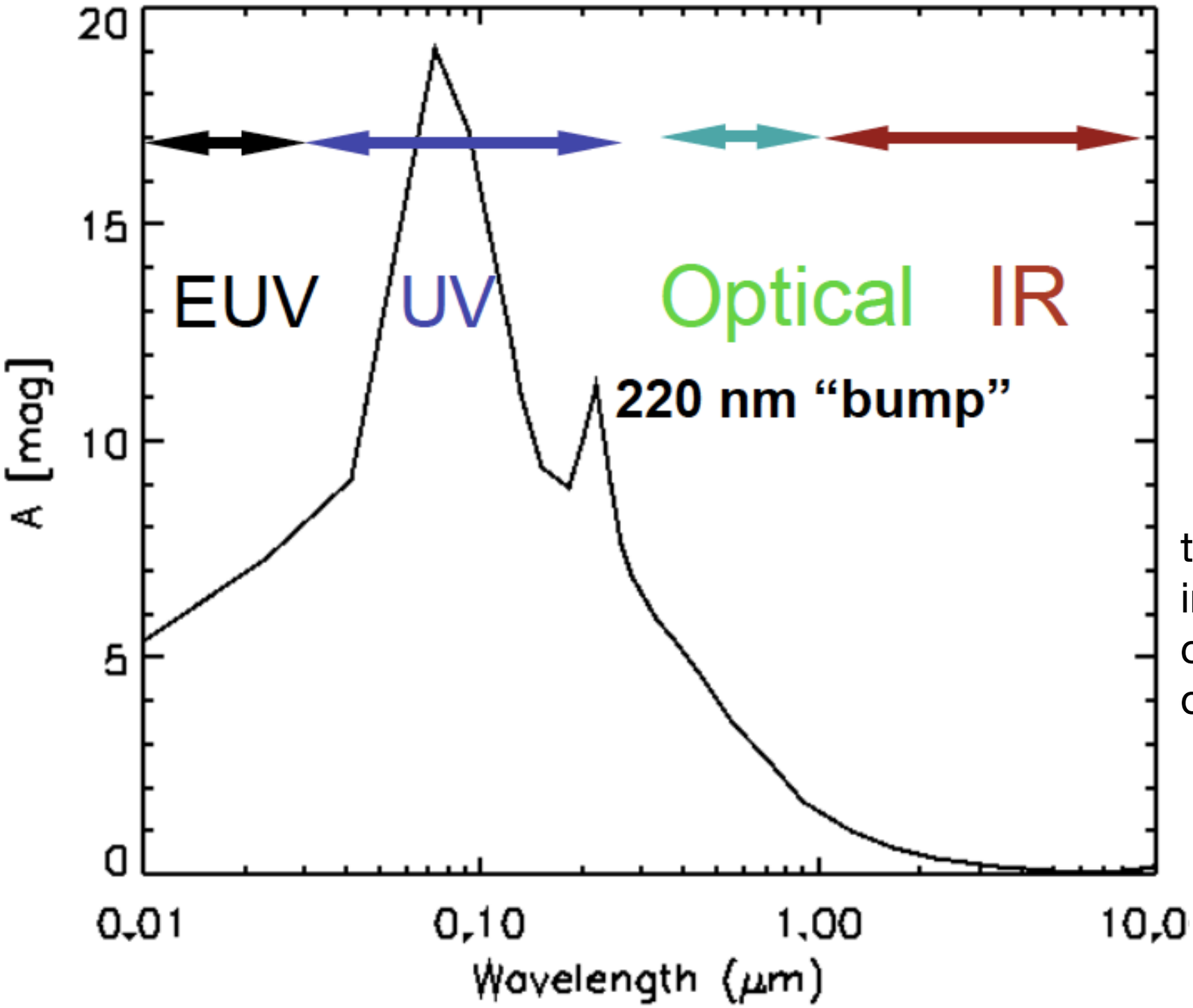


Fitzpatrick 2004

Dust extinction

$$A_\lambda \equiv 2.5 \log_{10}(F^0_\lambda / F_\lambda)$$

Very schematically:

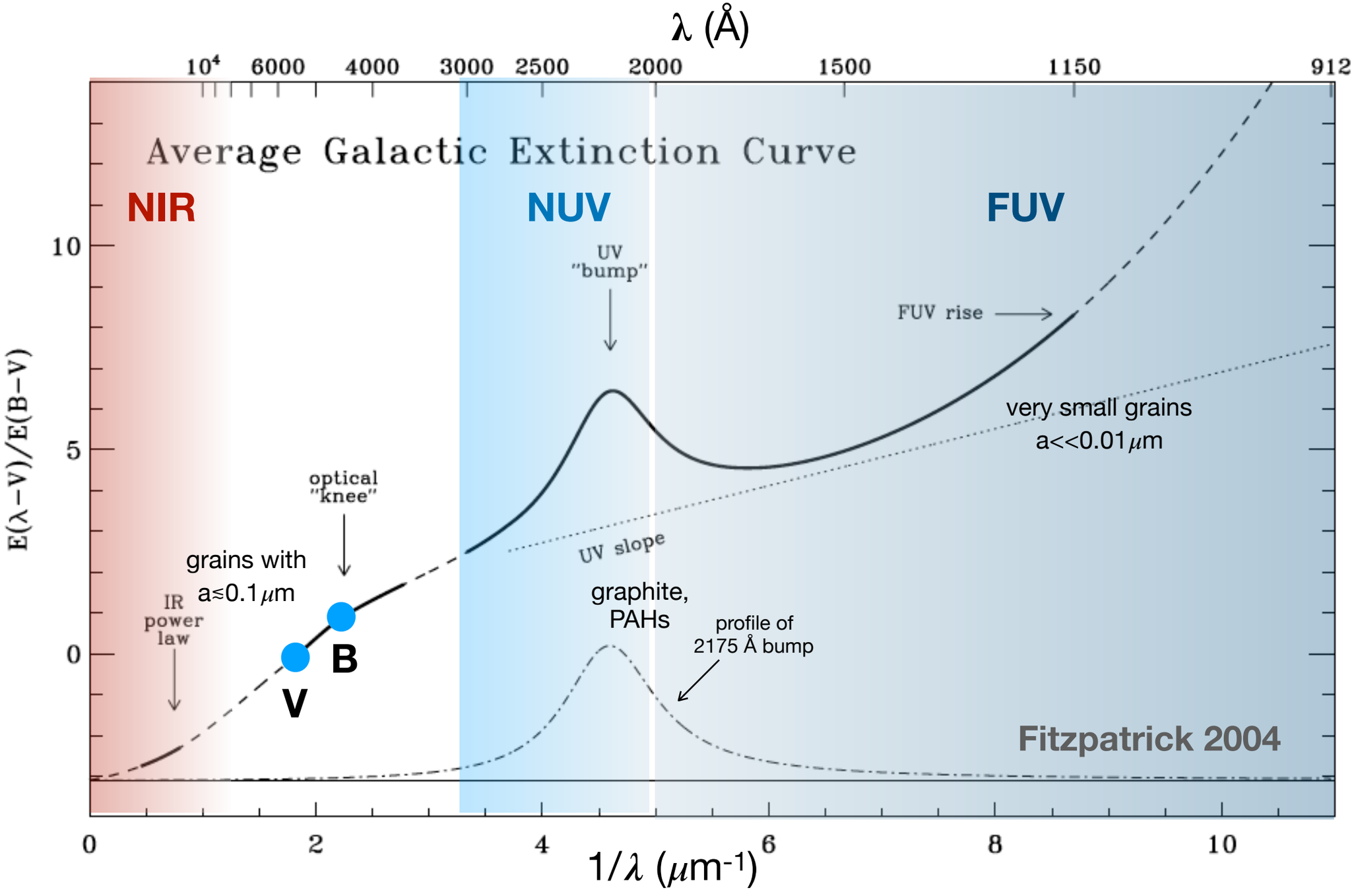


the extinction curve carries information on the composition of dust and size distribution of dust grains

Dust extinction

$$A_\lambda \equiv 2.5 \log_{10}(F^0_\lambda / F_\lambda)$$

A closer look in the FUV to NIR regime:



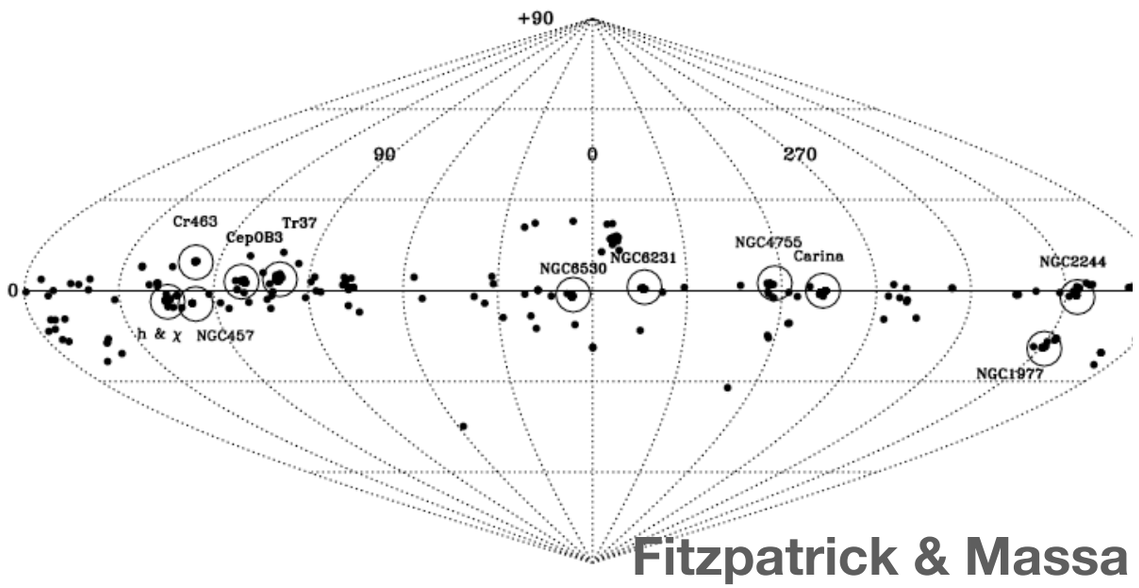
remember related quantities:

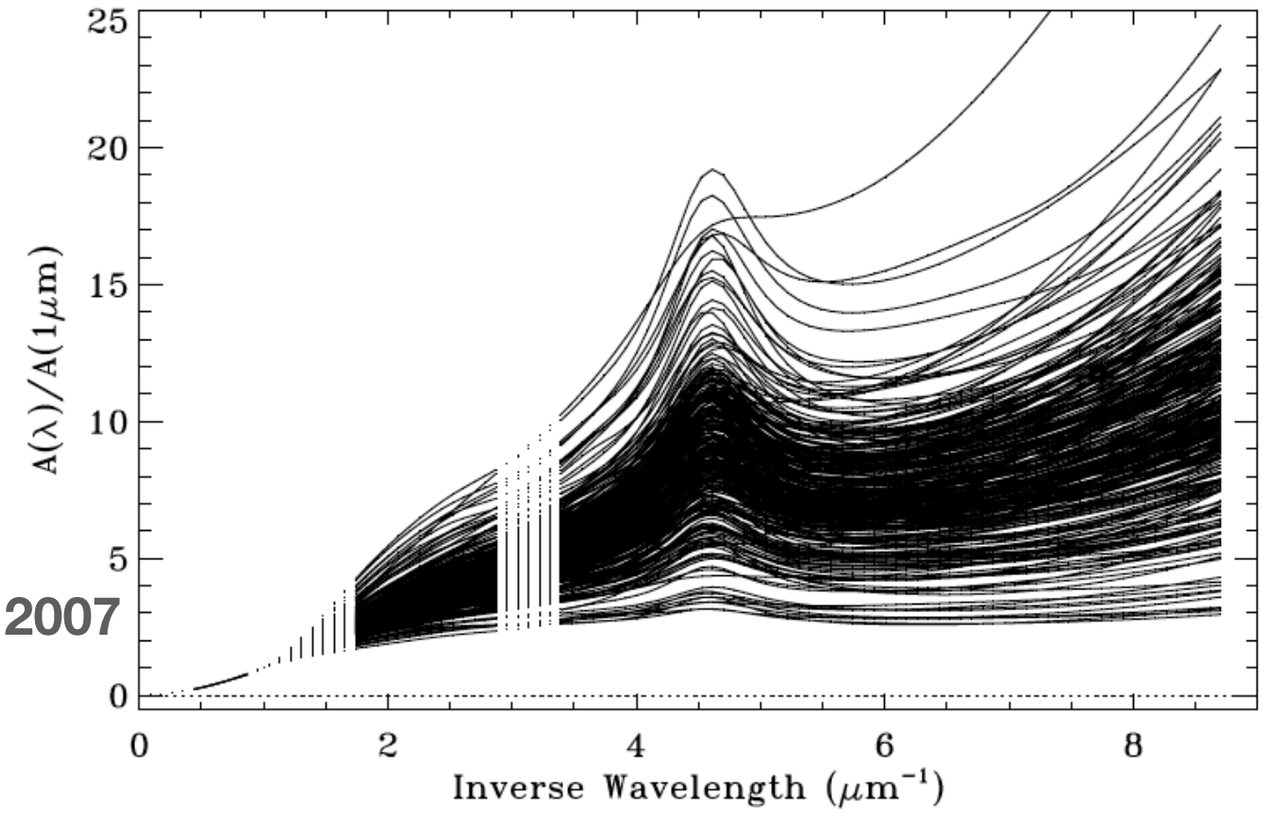
color excess E(B-V) = $(B-V)_{observed}$ - $(B-V)_{intrinsic}$

R(V) = A_V / E(B-V) [where A_V is A_λ in V band]

Dust extinction

Different lines of sight (within one galaxy) have different extinction curves





Fitzpatrick & Massa 2007

Dust extinction

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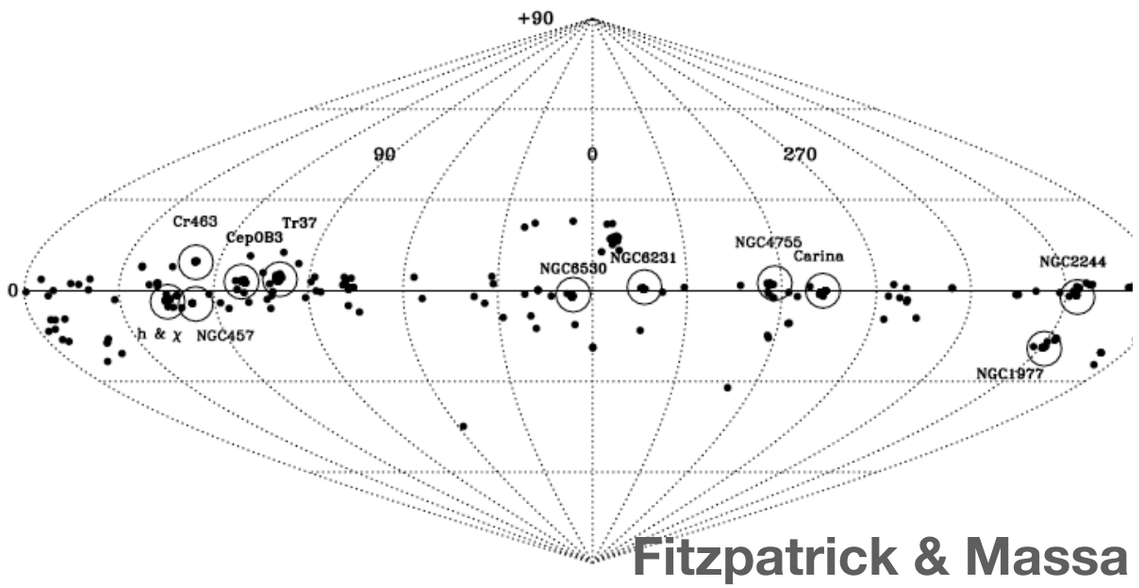
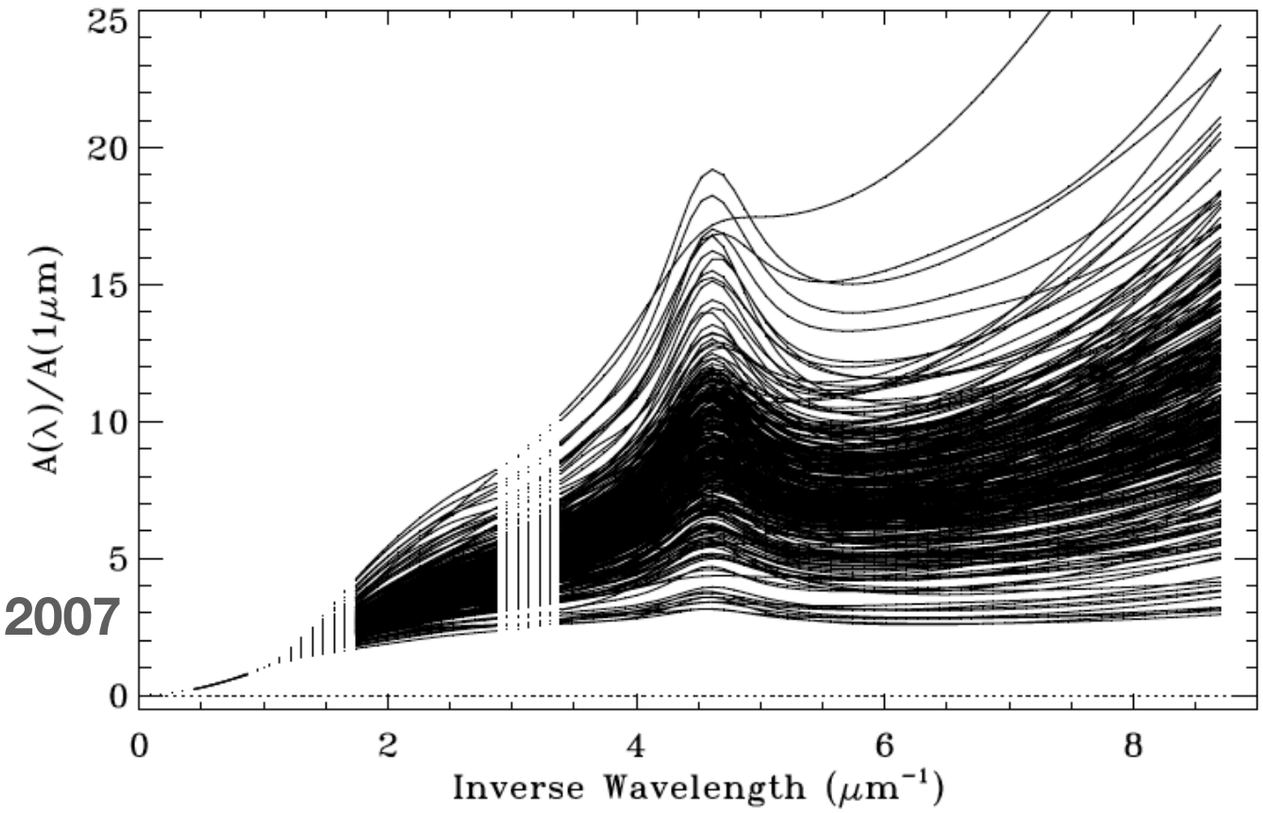
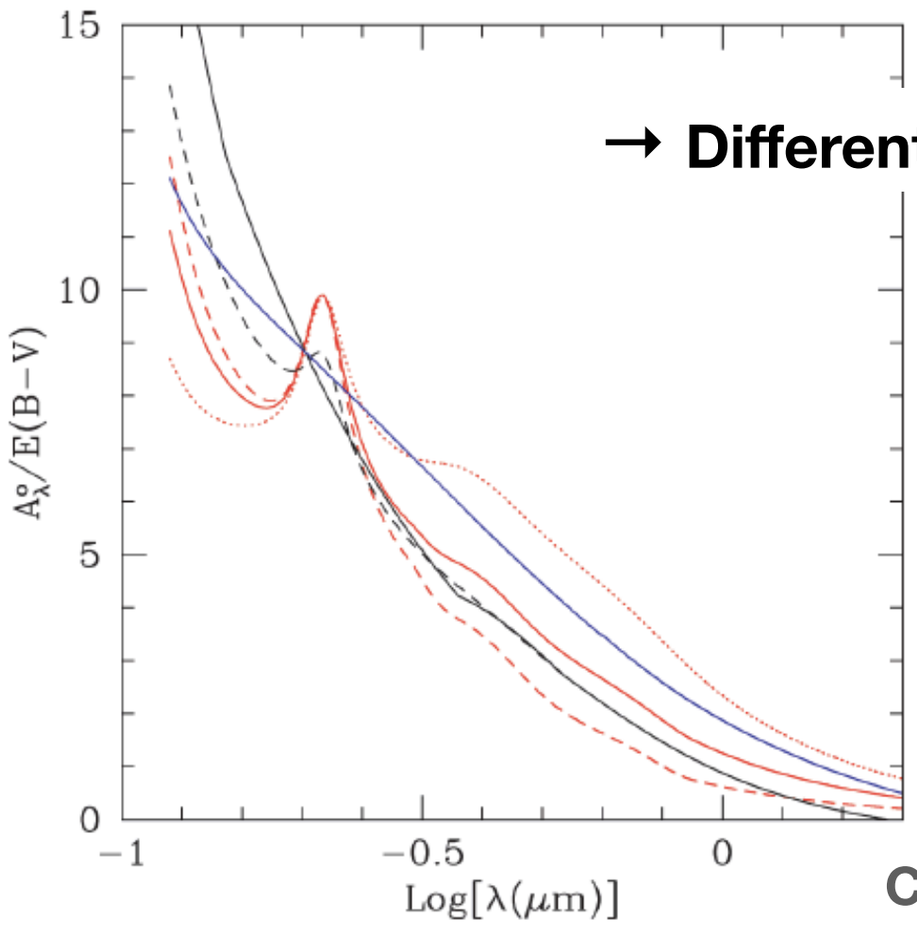
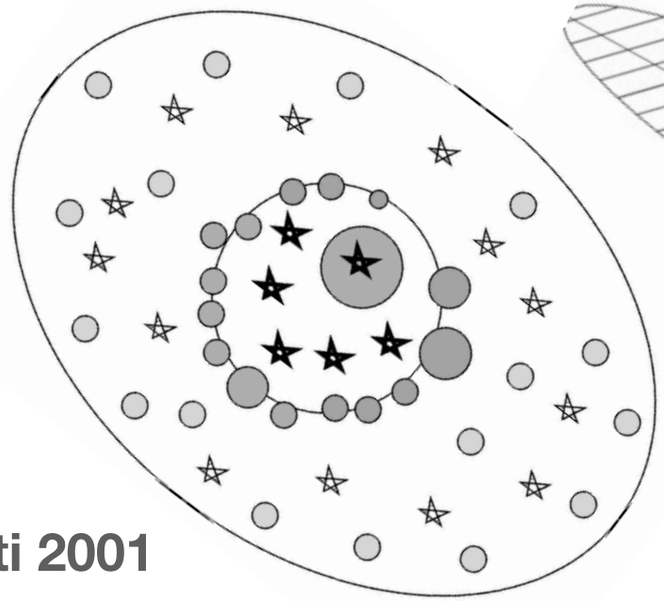




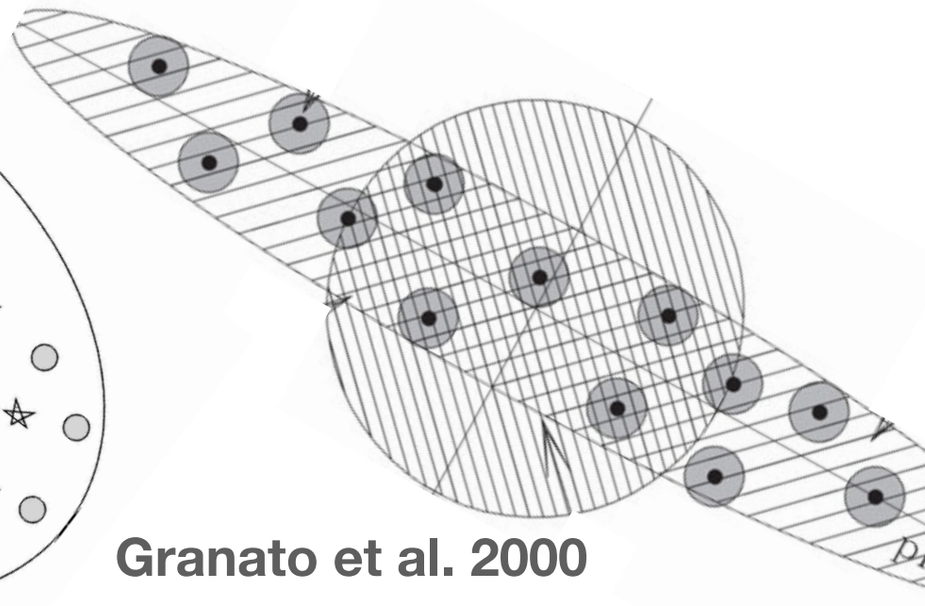
Fitzpatrick & Massa 2007



→ **Different galaxies have different extinction curves depending on properties, distribution and geometry of dust vs. stars**



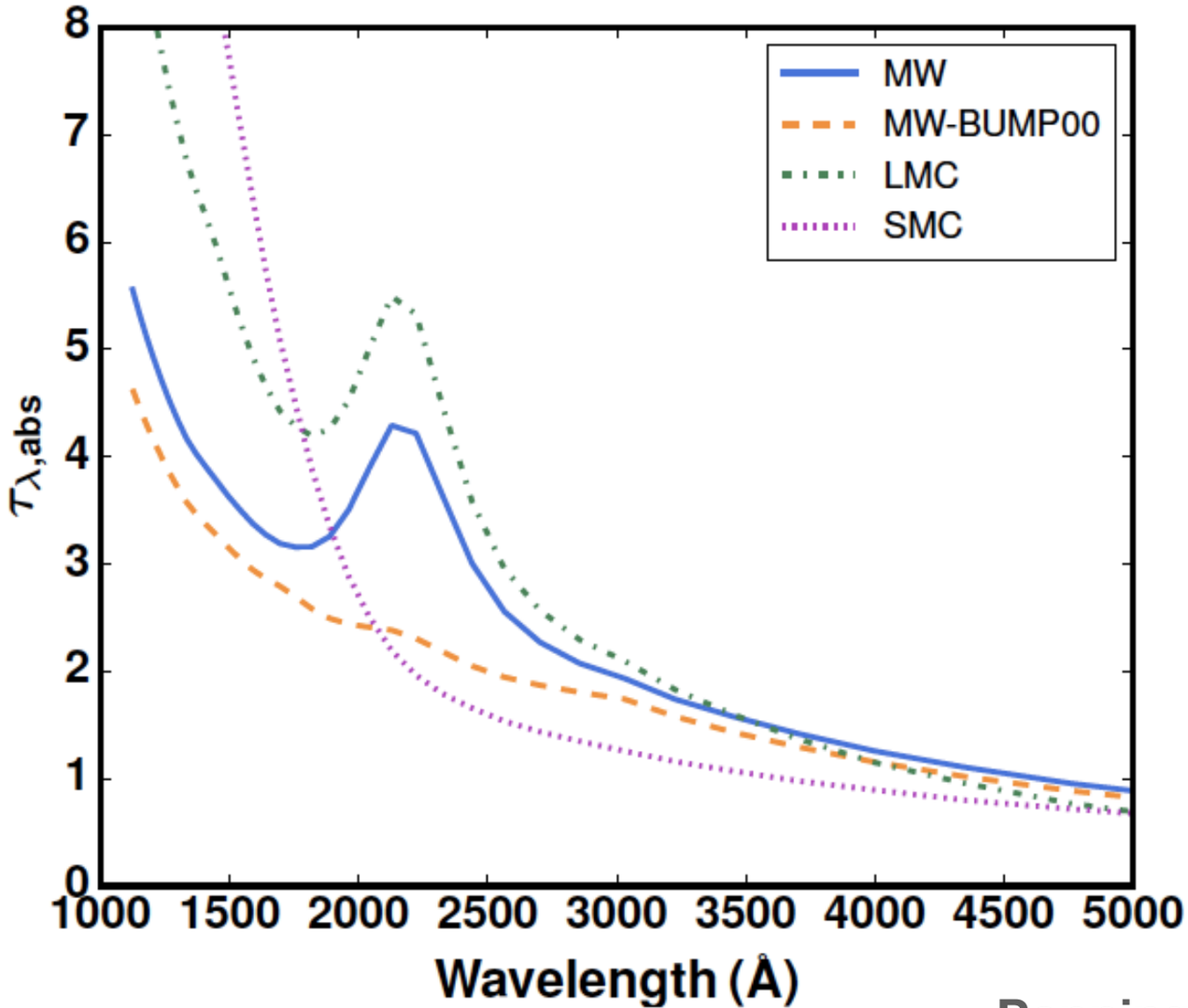
Calzetti 2001

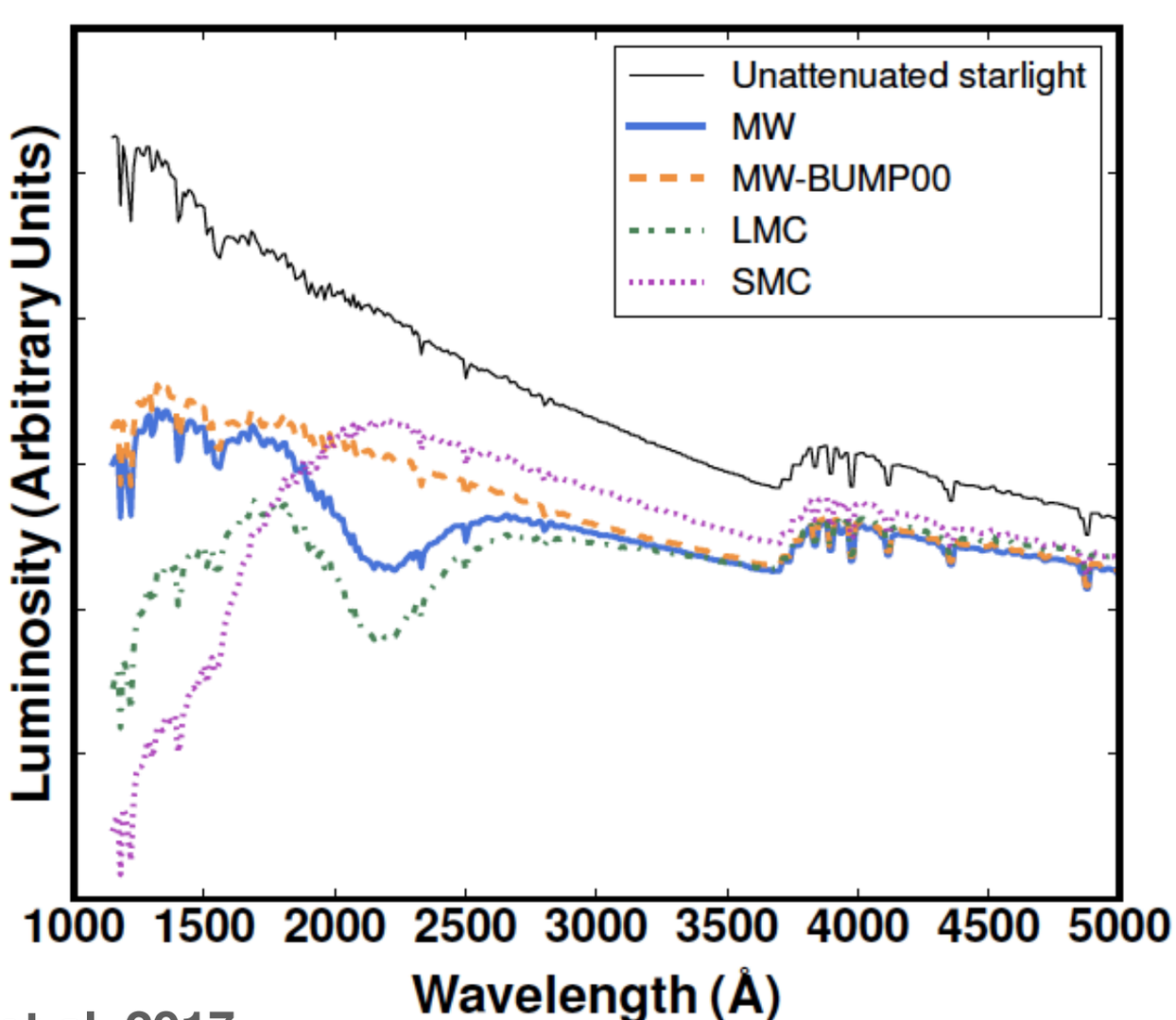


Granato et al. 2000

Dust extinction

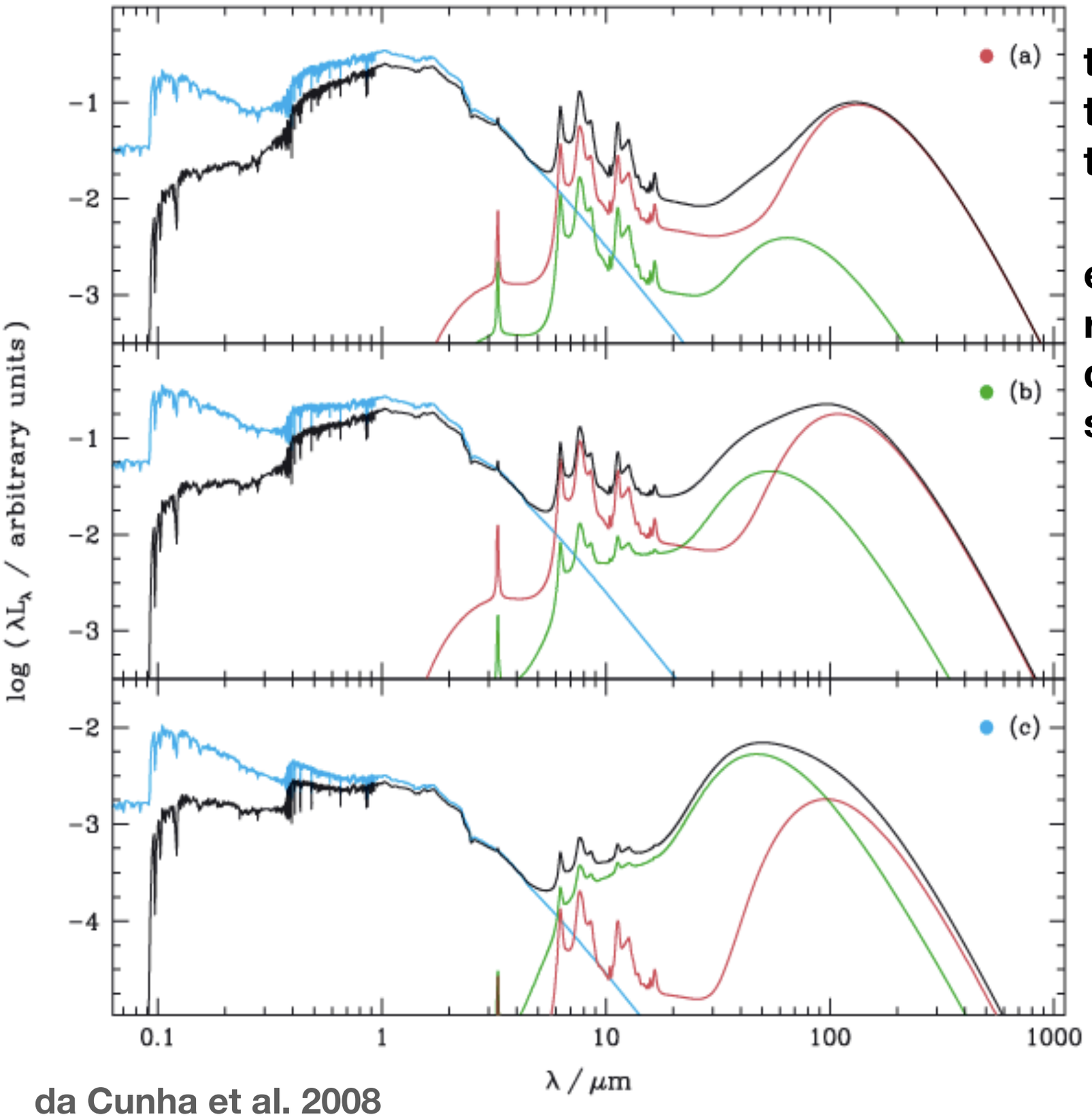
… thus impacting the galaxy SED in different ways





Popping et al. 2017

Dust emission

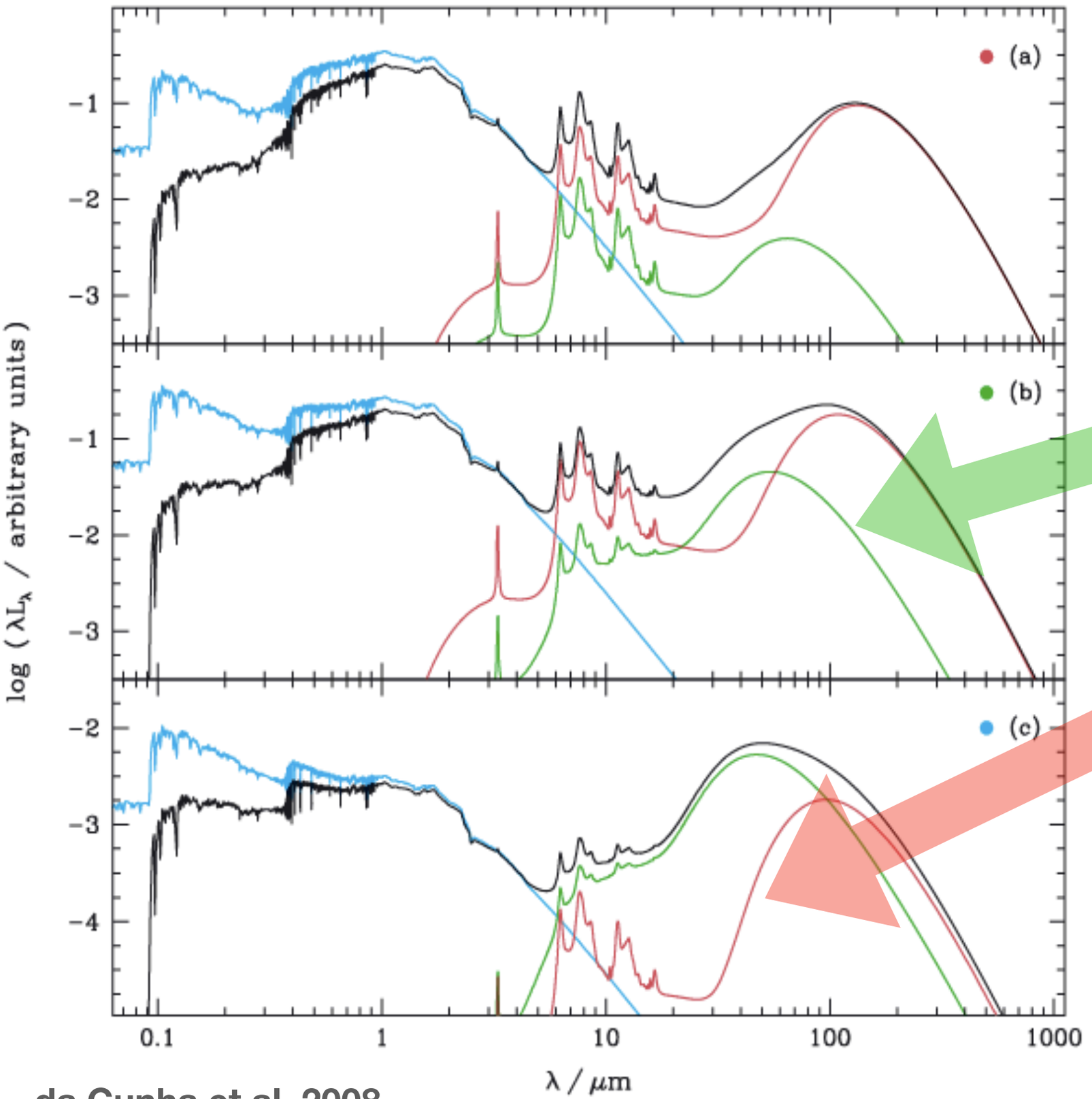


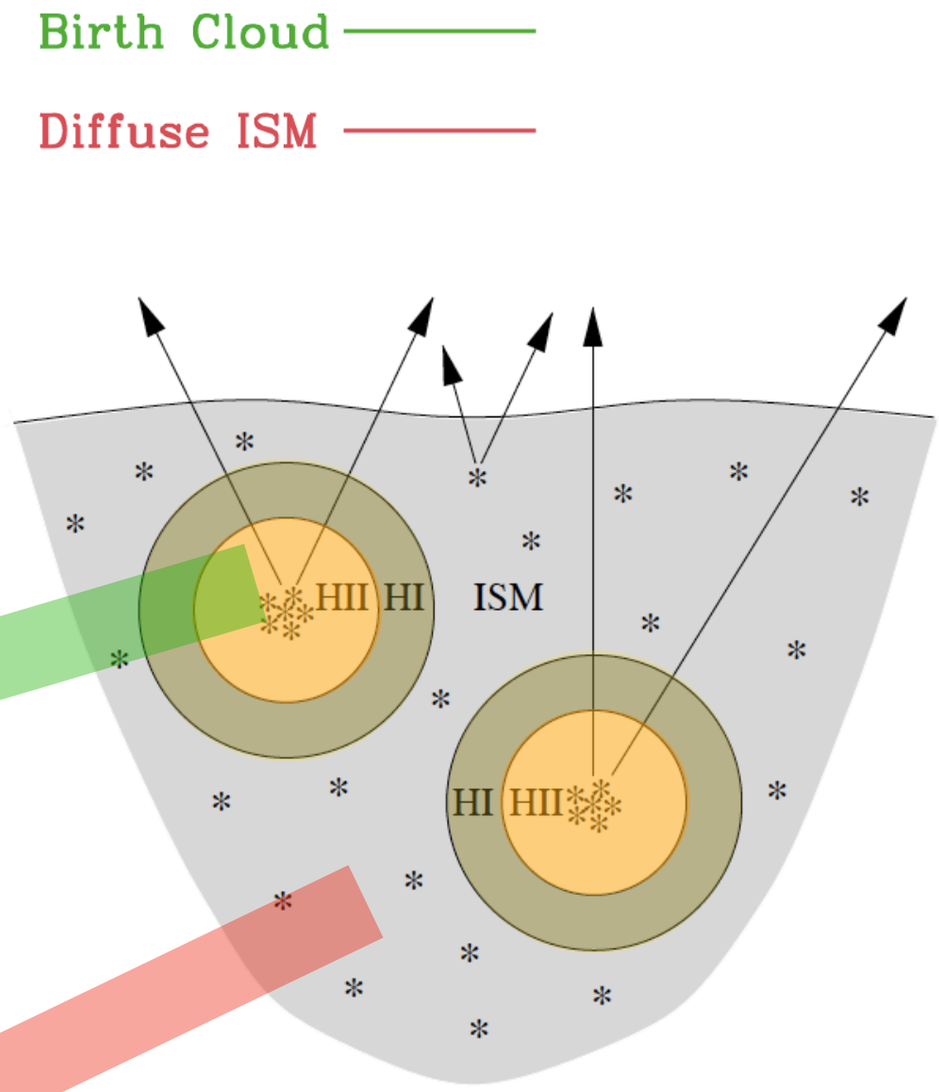
da Cunha et al. 2008

the absorbed starlight heats the dust, which re-radiates this energy in the IR

emission in the mid-/far-IR range reflects the heating of dust in different ISM components from stars of all ages

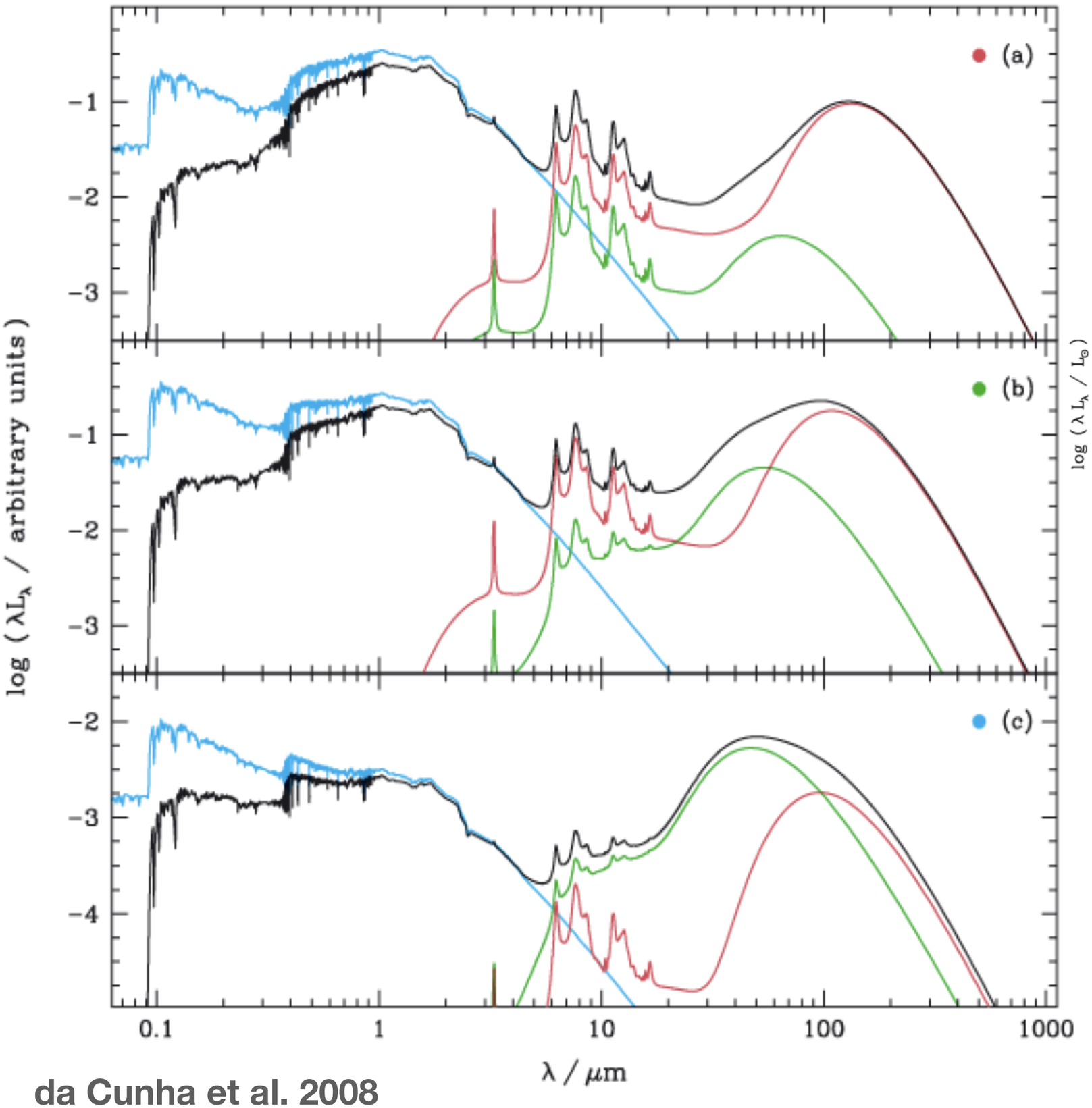
Dust emission





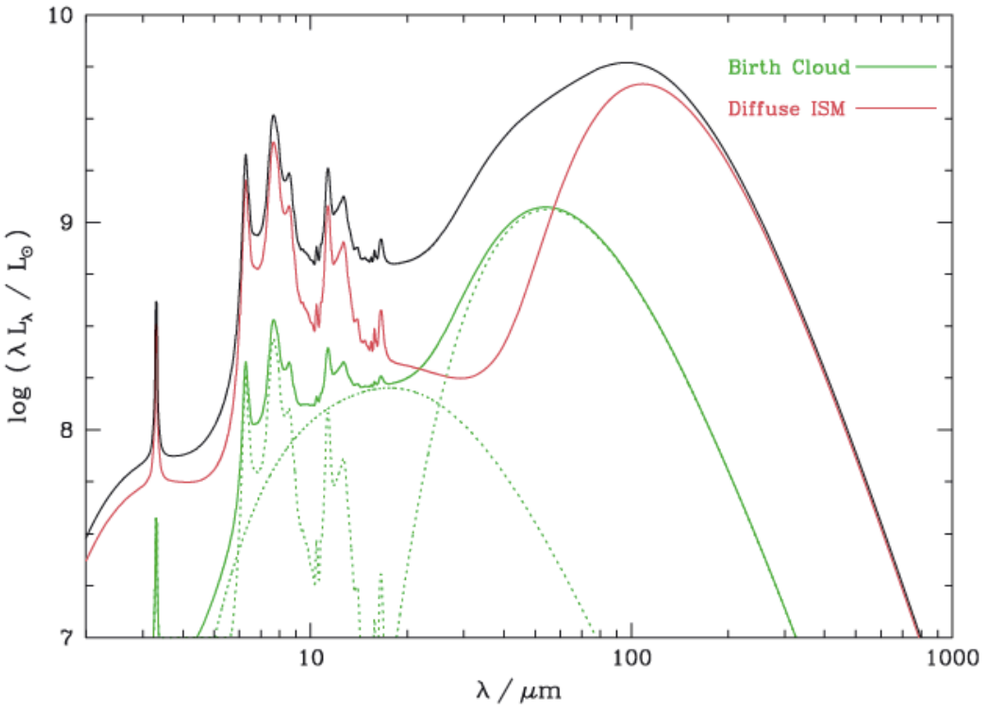
da Cunha et al. 2008

Dust emission



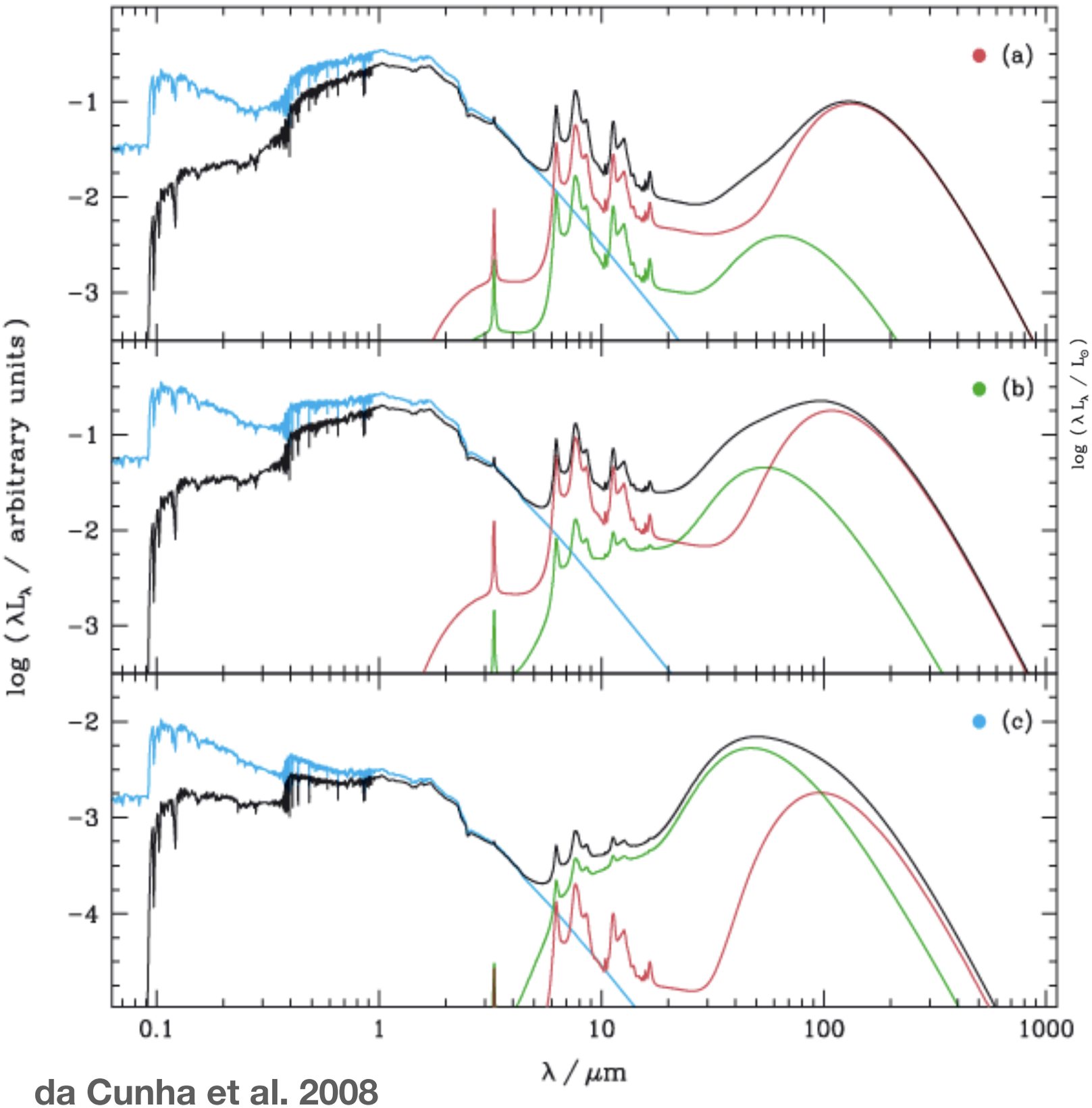
Birth Cloud

Diffuse ISM



da Cunha et al. 2008

Dust emission



da Cunha et al. 2008

Birth Cloud

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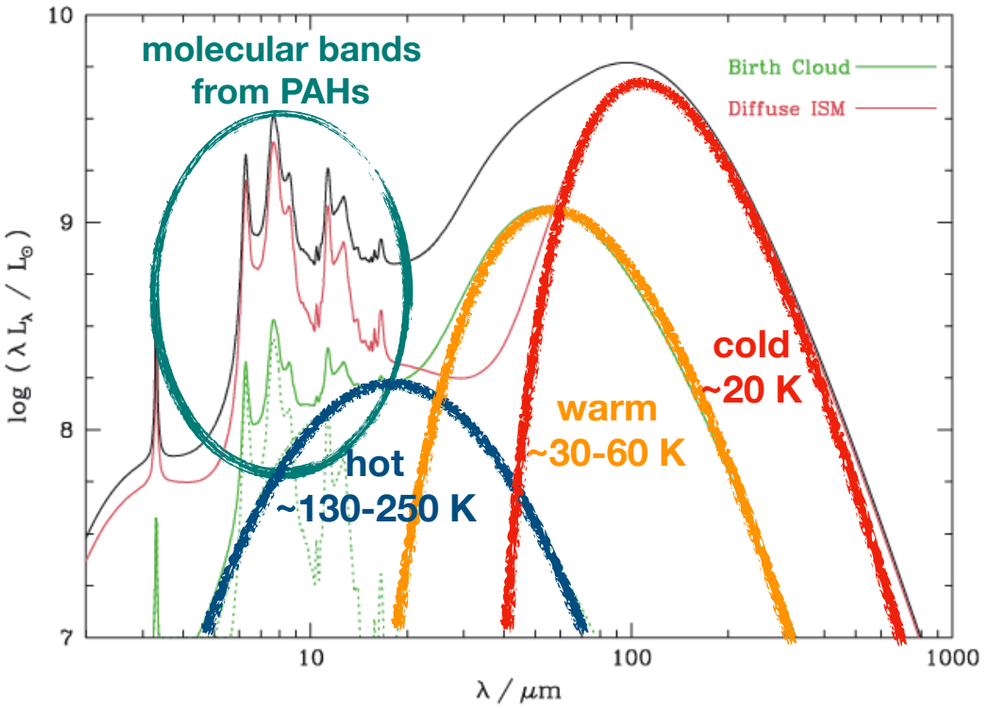
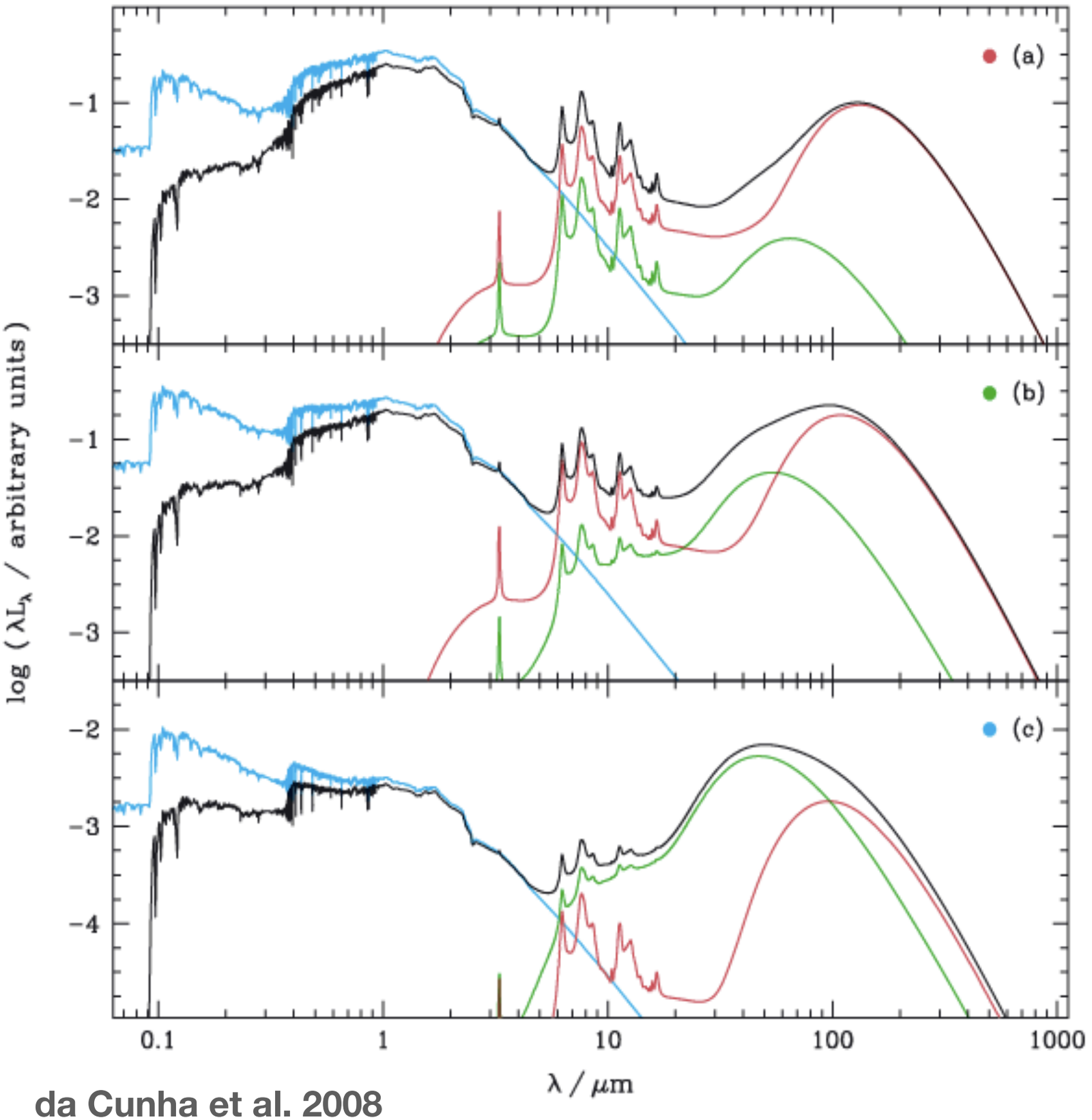


< 30μm continuum:
emission from small grains (5-50 Å)
T~10^2-10^3 K

FIR continuum:
emission from larger grains (>100 Å) in thermal equilibrium with ambient radiation field
T≲40 K

Dust emission



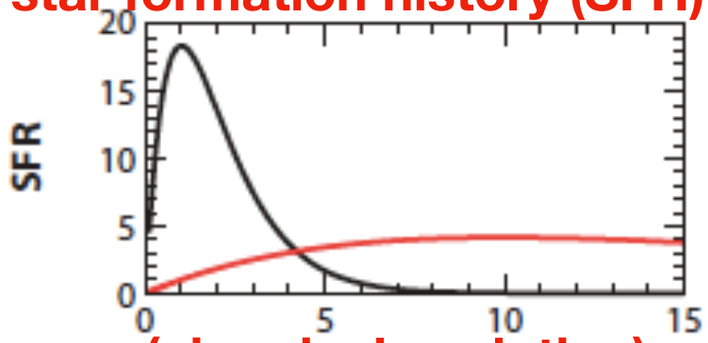
da Cunha et al. 2008

more “quiescent” star-forming galaxy with colder IR emission

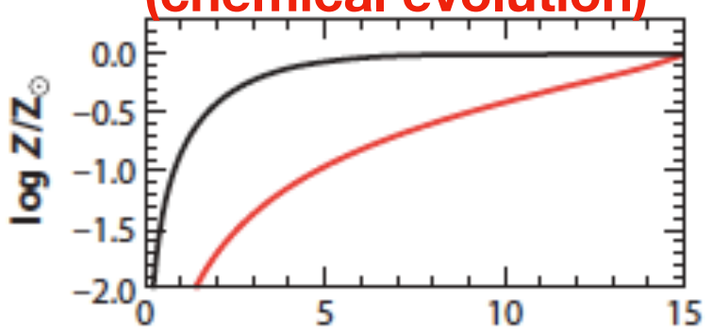
more “starburst" star-forming galaxy with hotter IR emission

Effects of dust on galaxy SEDs

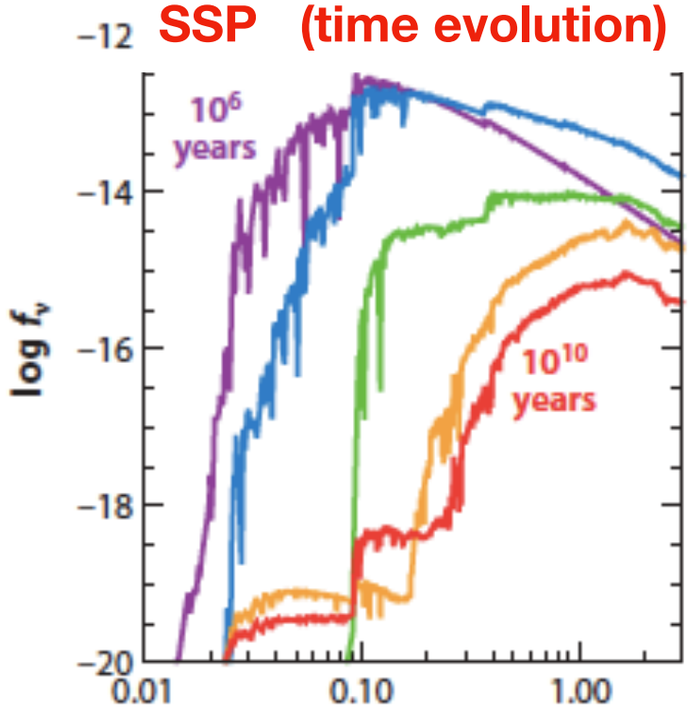
star formation history (SFH)



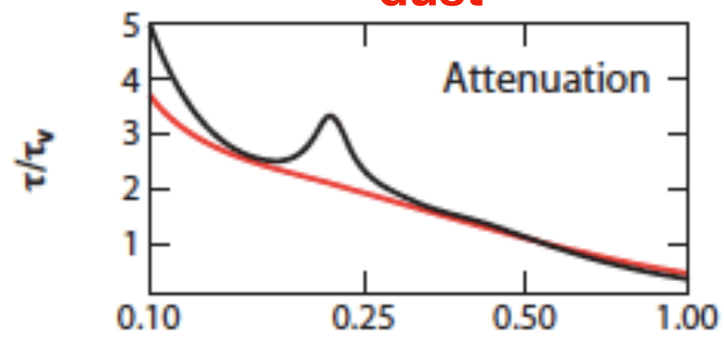
(chemical evolution)

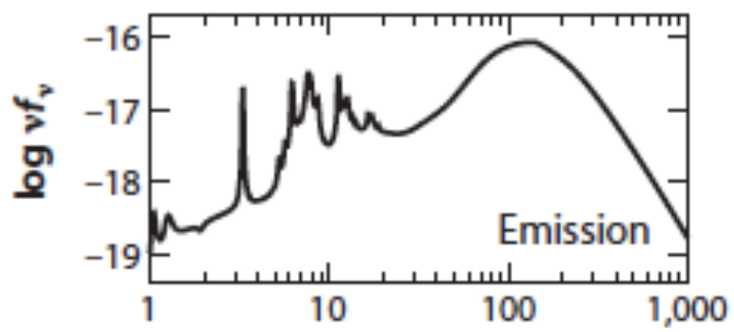


SSP (time evolution)



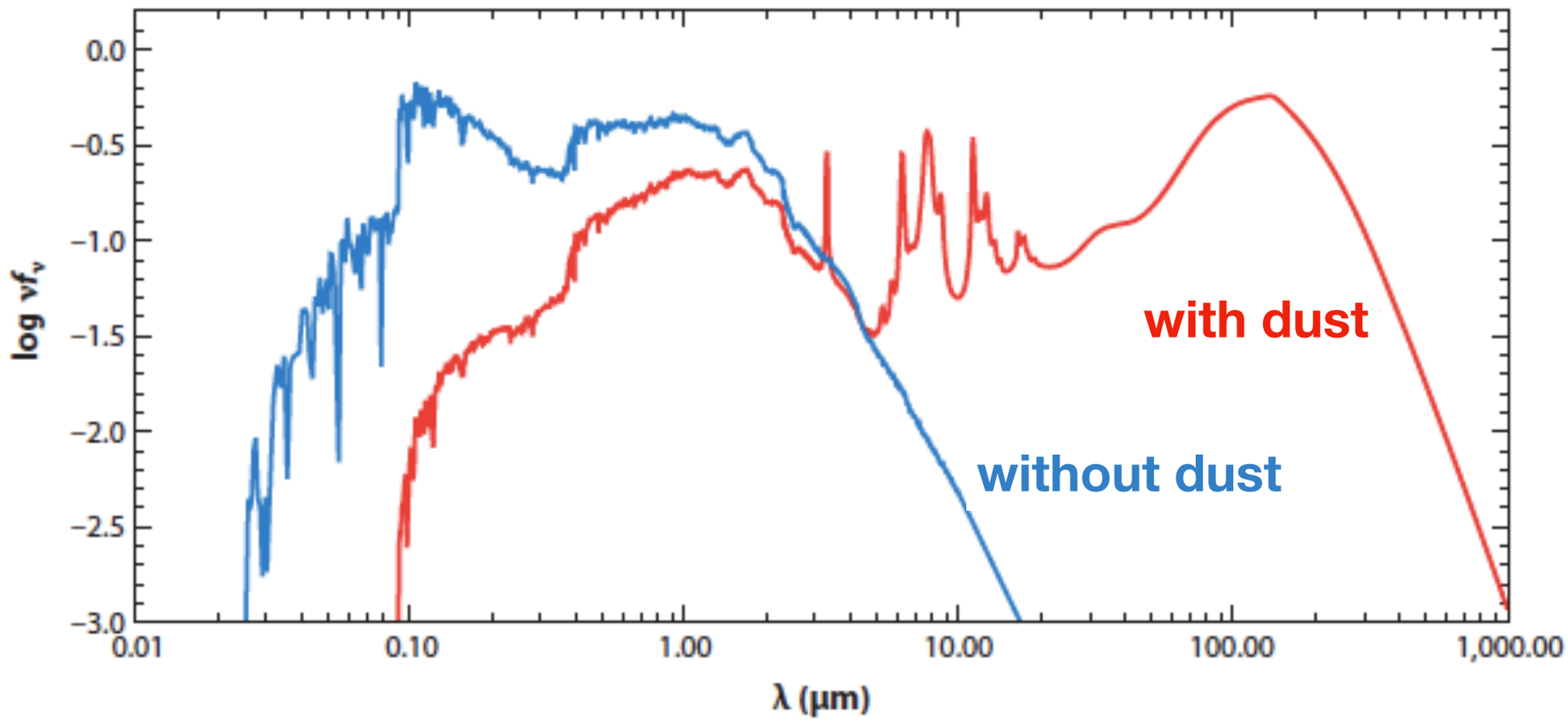
dust





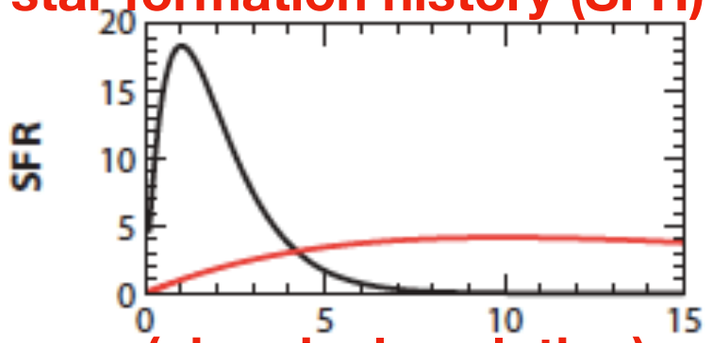
Conroy 2013

CSP



Effects of dust on galaxy SEDs

star formation history (SFH)



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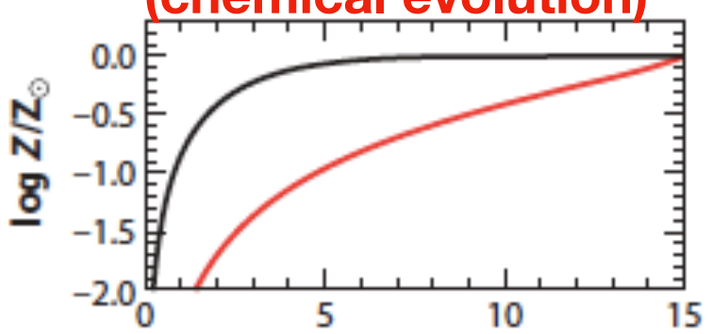
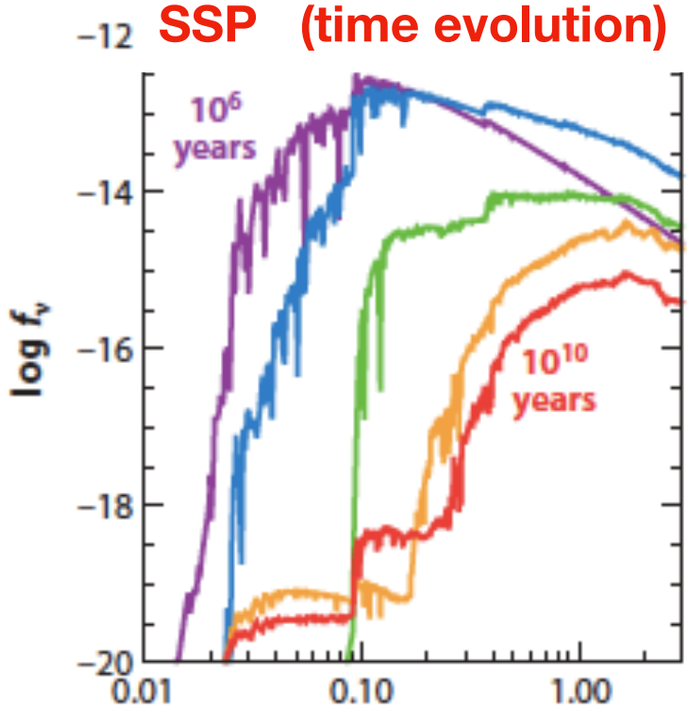


SSP (time evolution)



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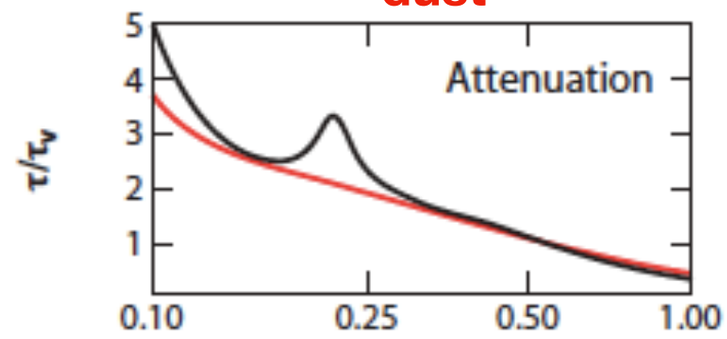

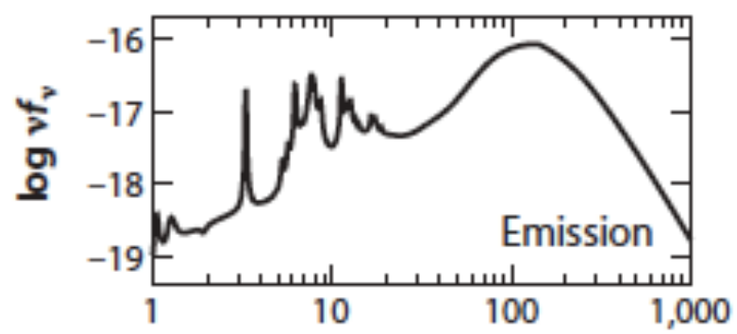

Conroy 2013

CSP

energy balance

dust attenuation

dust emission

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

SFH

chemical evolution

SSP spectra

SSP age

SSP metallicity

Where does a galaxy SED come from

Galaxy spectral energy distributions are the result of the combination of light emission and absorption from the (baryonic) galaxy consituents:

- ☐ **stars**
- ☐ **gas**
- ☐ **AGN**
- ☐ **dust**

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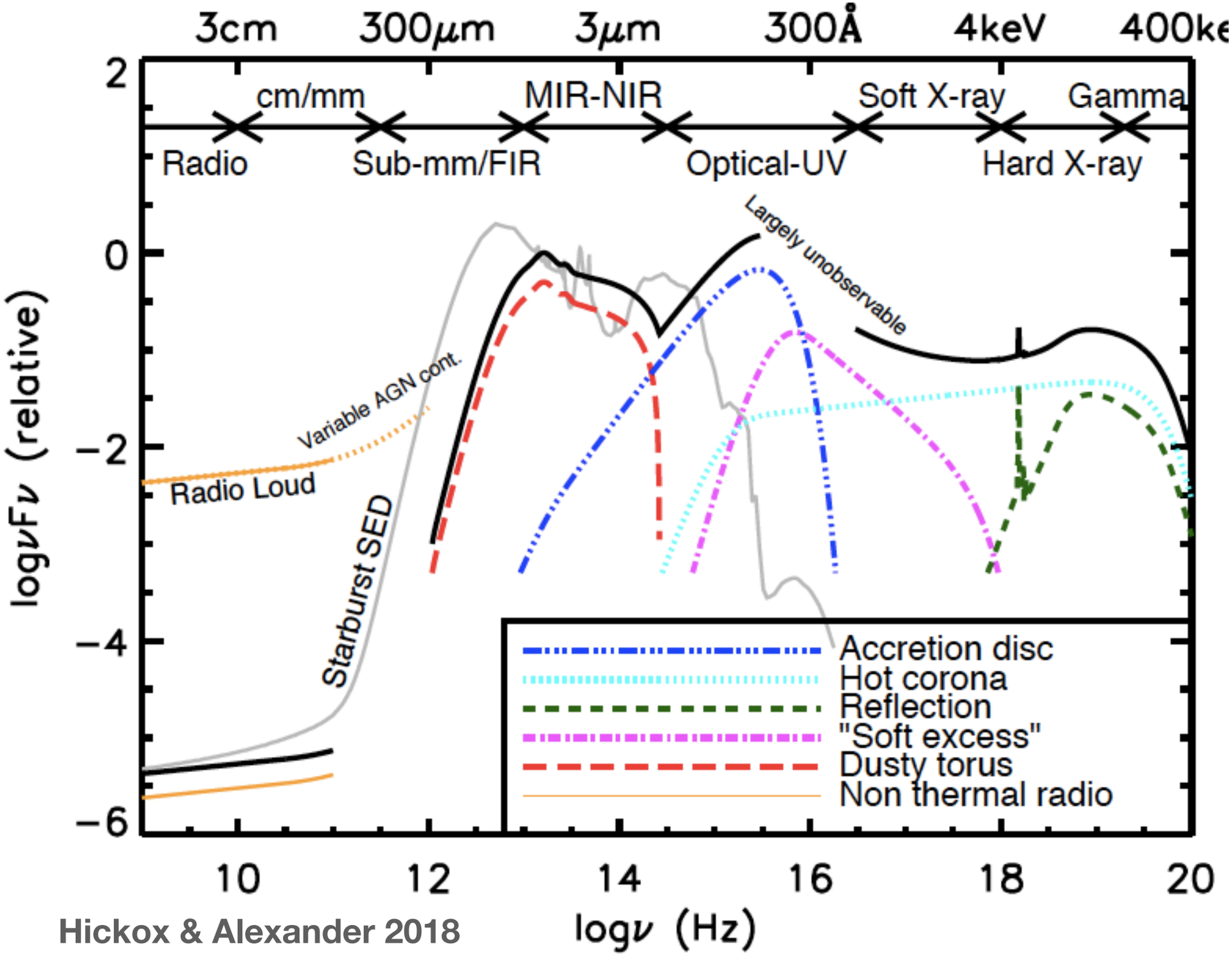

Hickox & Alexander 2018

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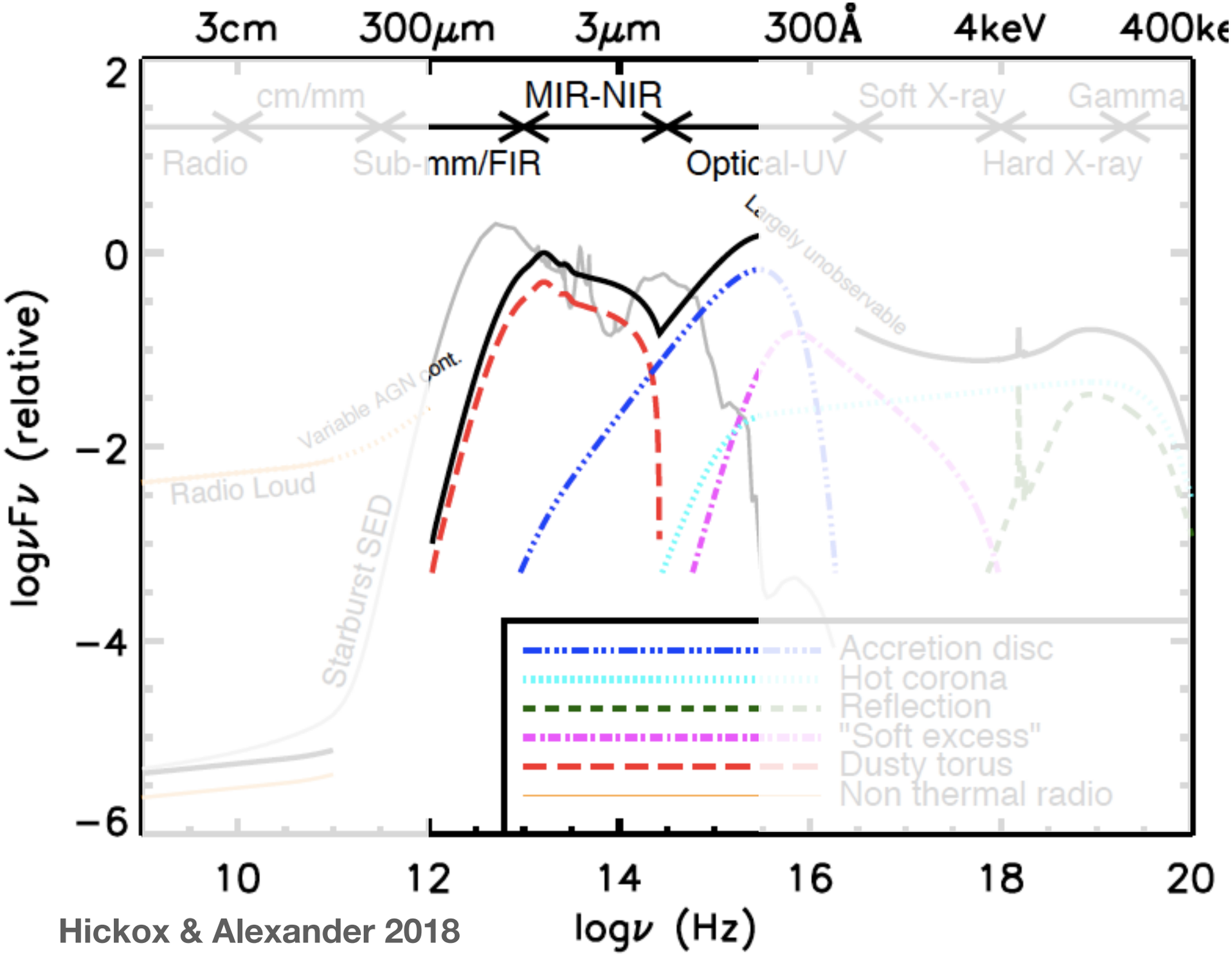
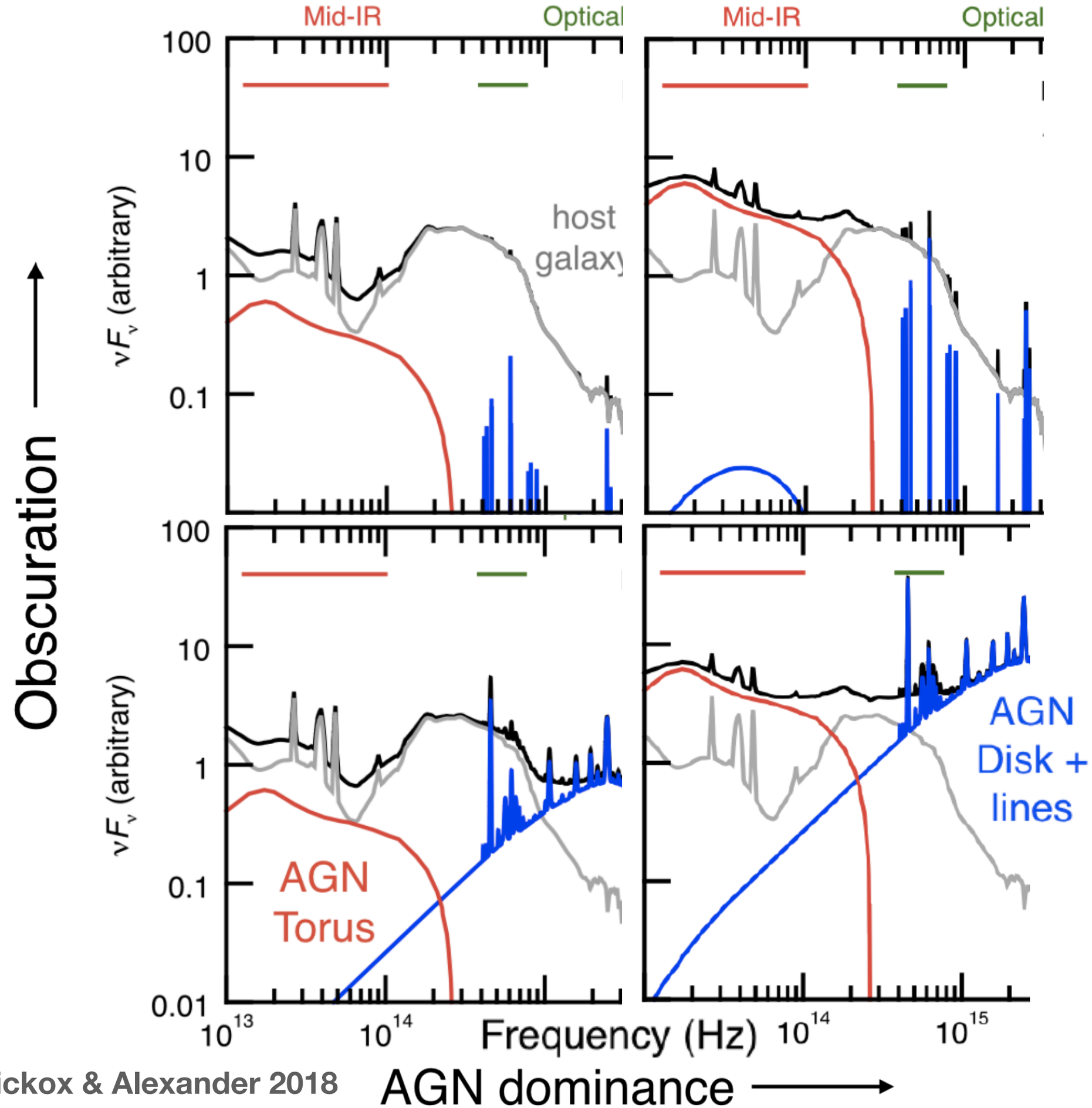
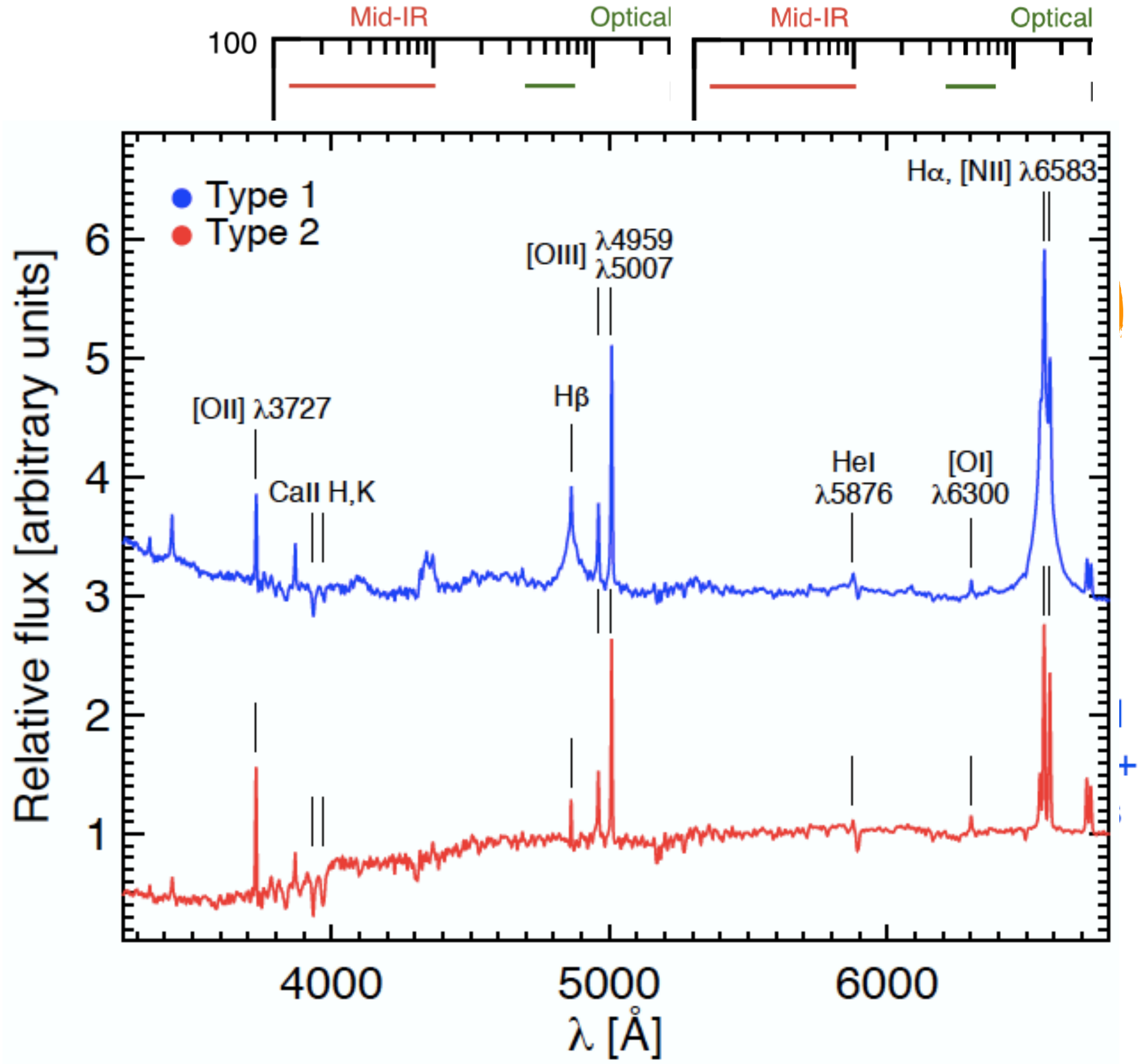


Hickox & Alexander 2018



Hickox & Alexander 2018

Mid-IR
Optical
Mid-IR
Optical
100
10
1
0.1
100
10
1
0.1
0.01
νF_ν (arbitrary)
νF_ν (arbitrary)
host galaxy
AGN Torus
AGN Disk + lines
emission lines
10^{13}
10^{14}
Frequency (Hz)
10^{14}
10^{15}
Obscuration
AGN dominance
Hickox & Alexander 2018



emission lines

Hickox & Alexander 2018

AGN dominance ⟶

Mid-IR
Optical
Mid-IR
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νF_ν (arbitrary)
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