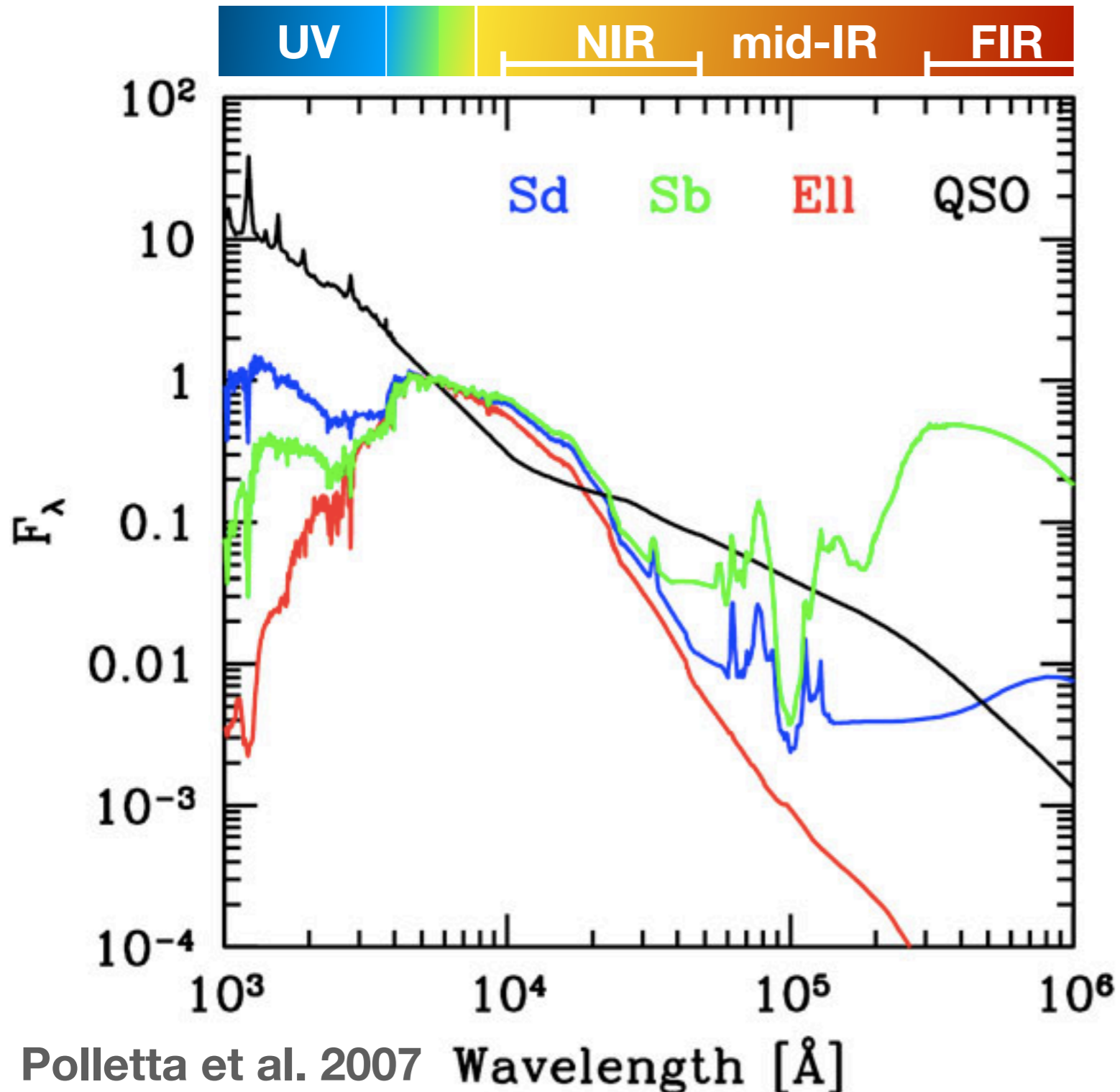


Galaxy spectral energy distributions (UV to IR)

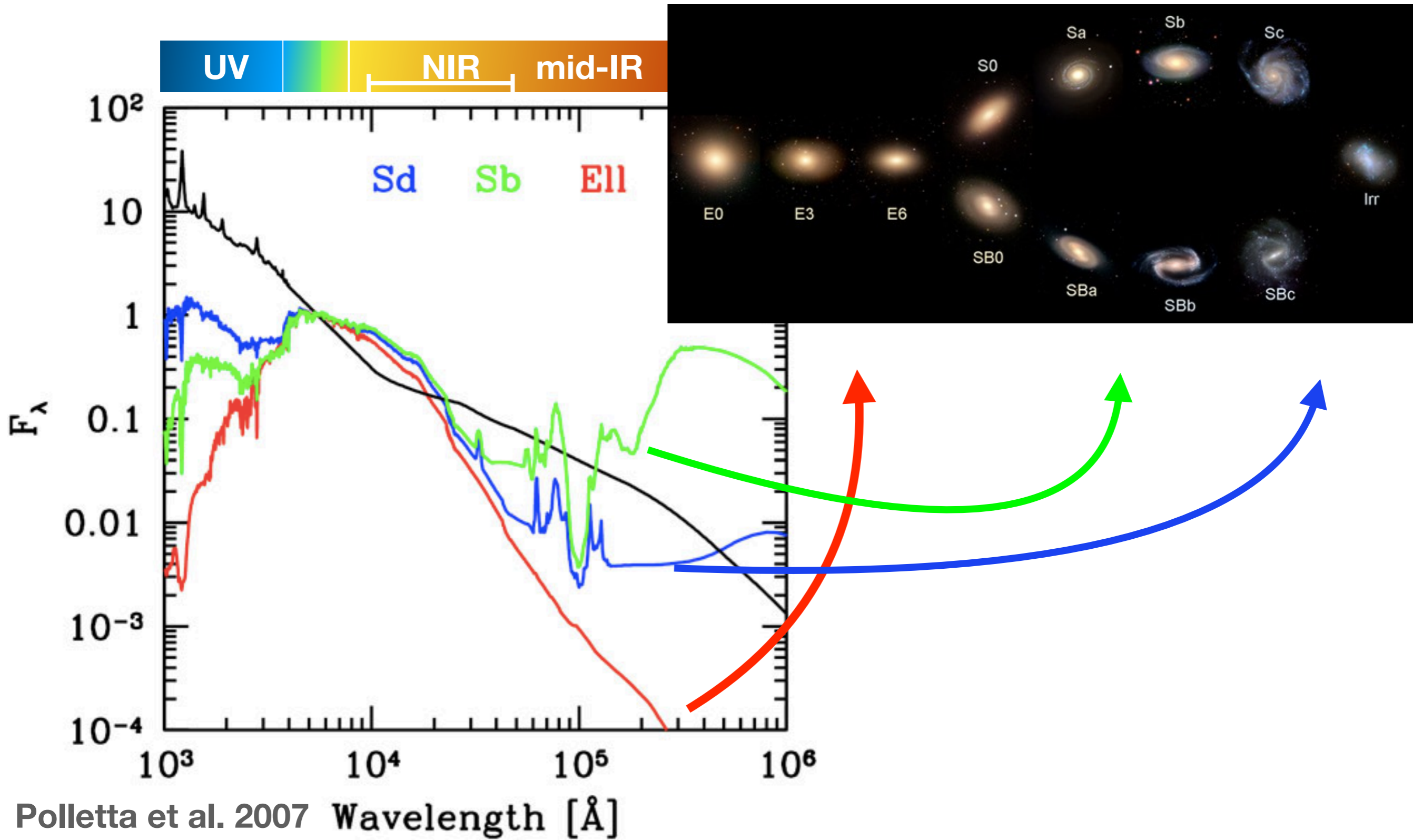
What is a galaxy SED

The SED measures the galaxy flux (luminosity/cm²/s) in wavelength range $d\lambda$ (F_λ , units of erg/s/cm²/Å) or in frequency range dv (F_ν , units of erg/s/cm²/Hz)



What is a galaxy SED

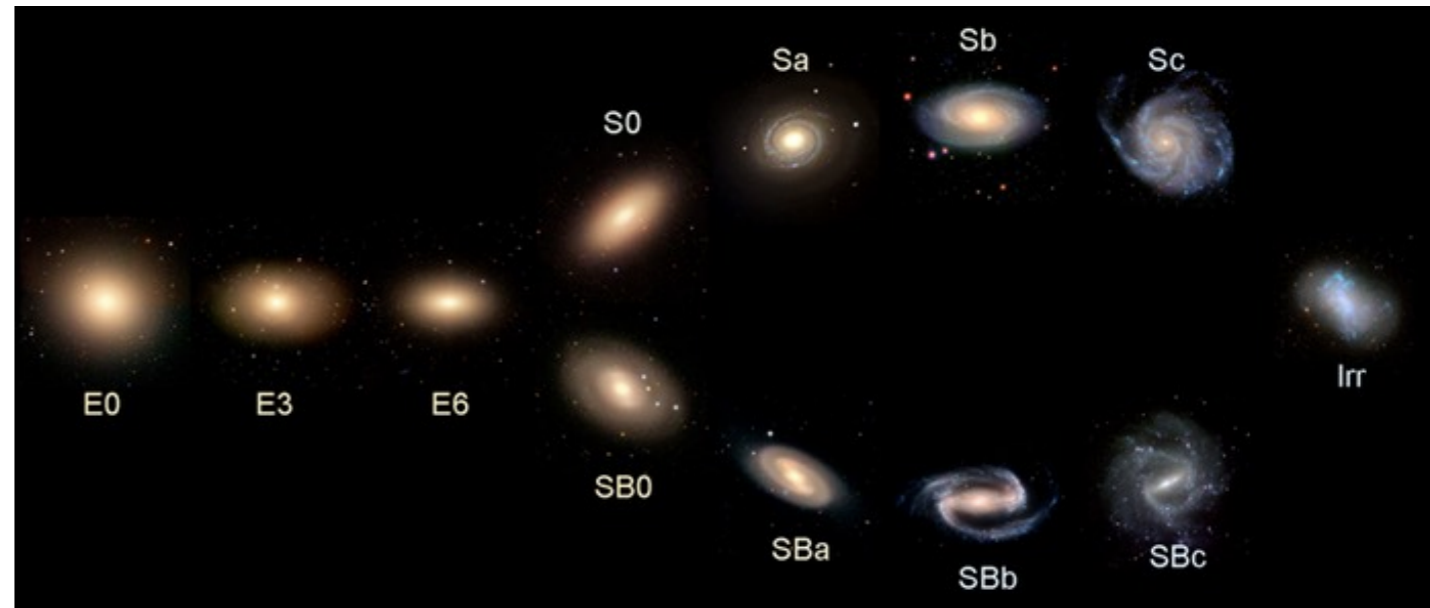
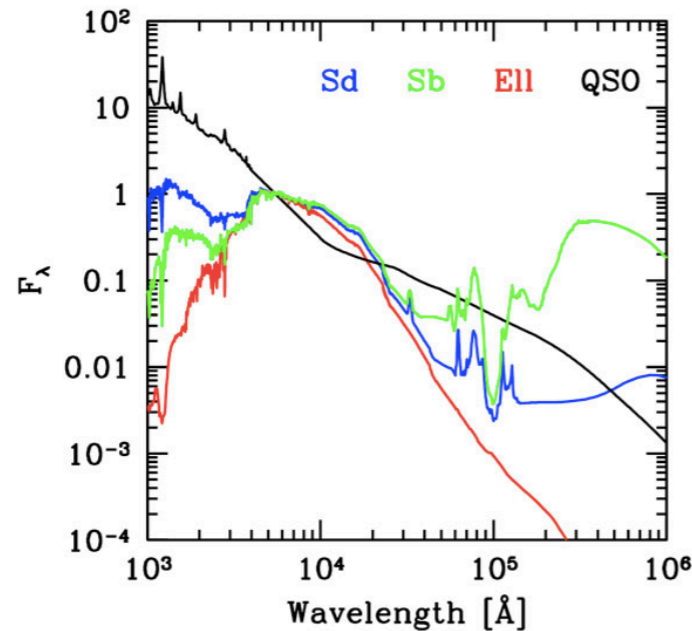
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Where does a galaxy SED come from

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

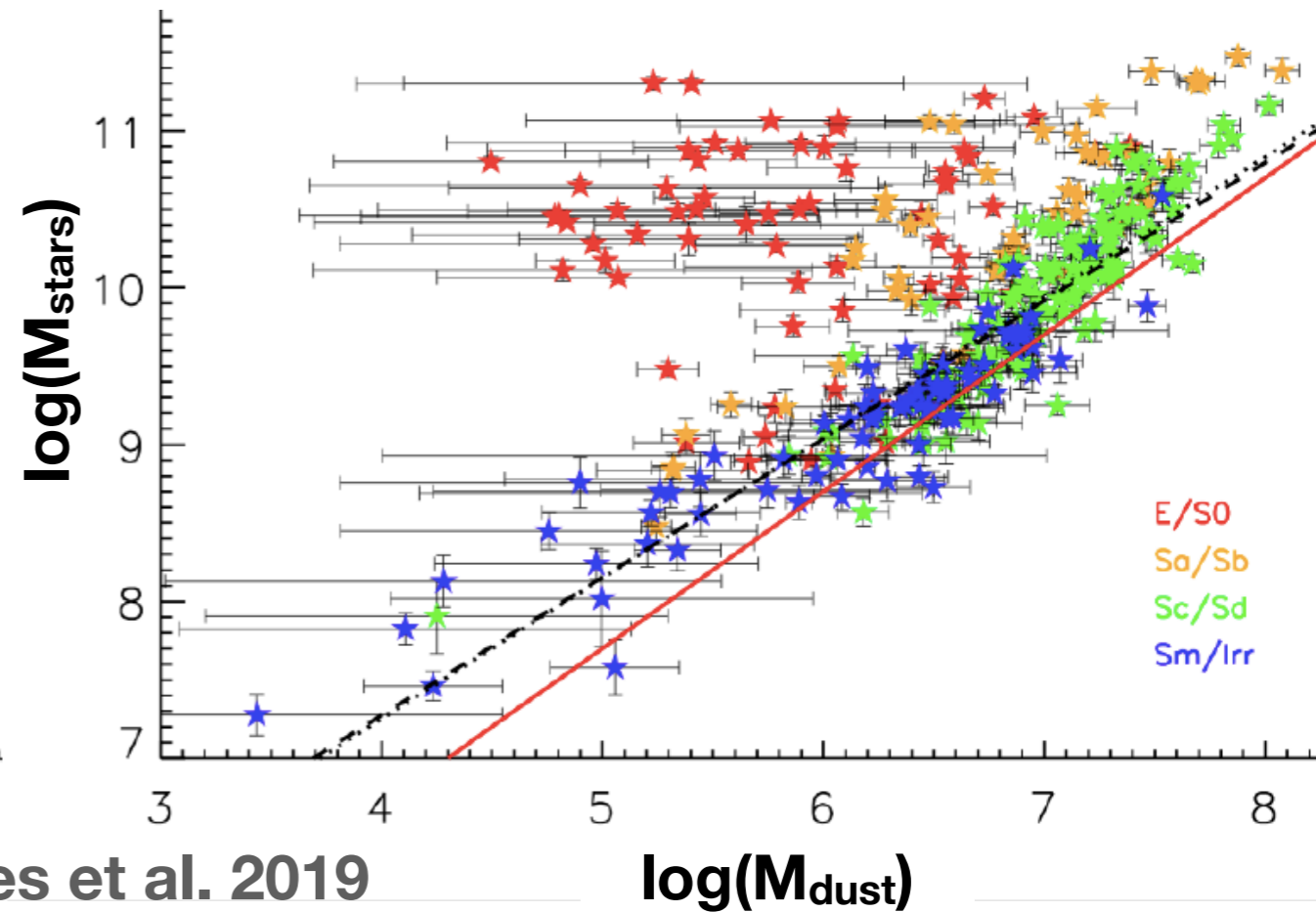
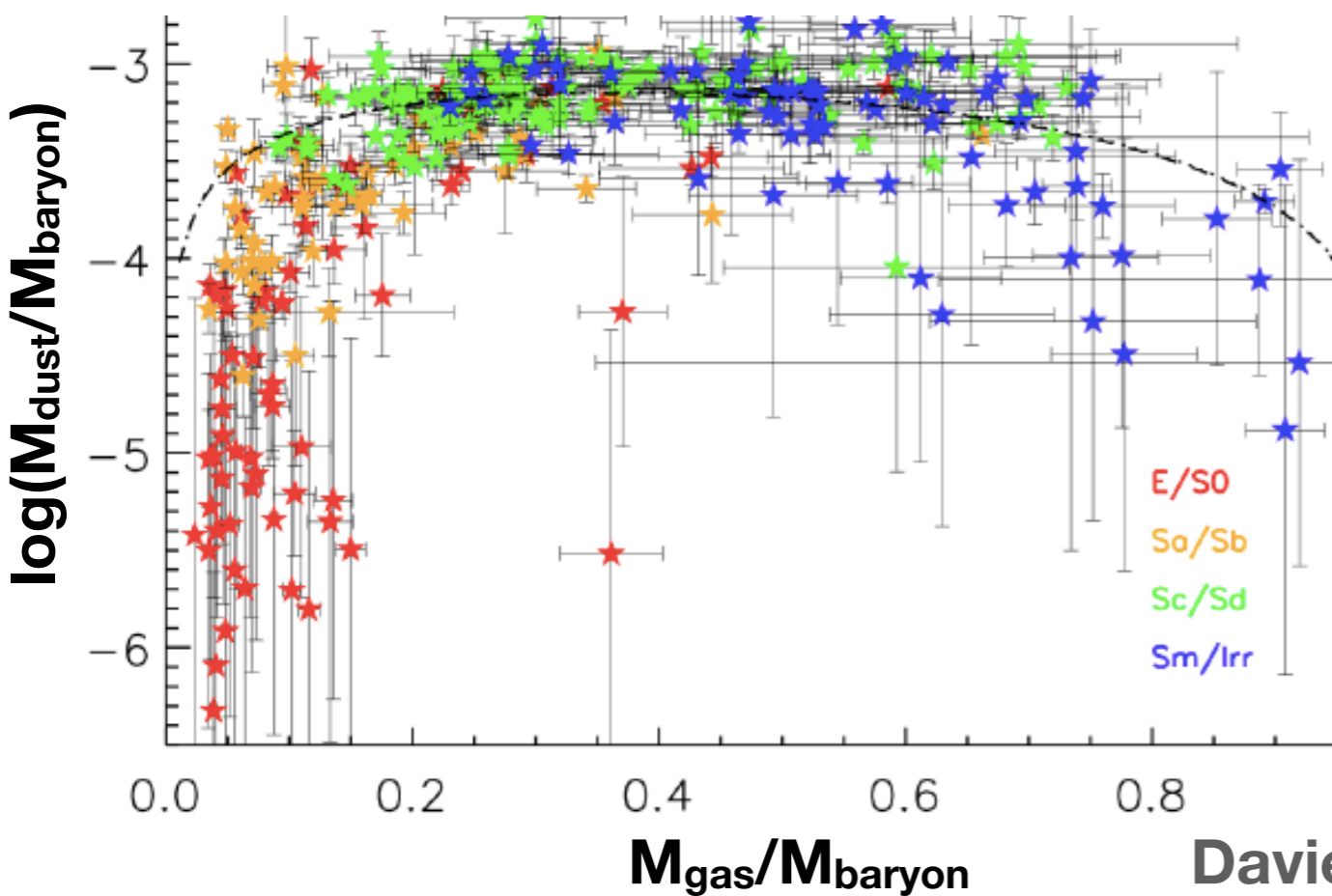
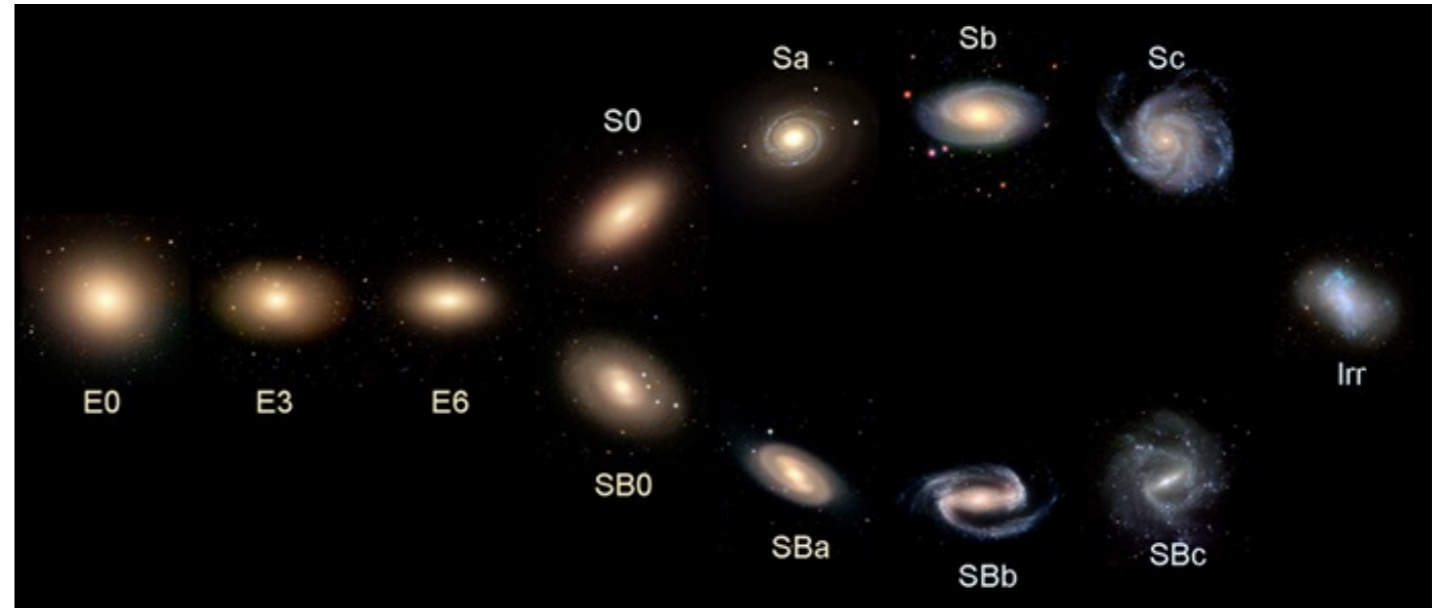
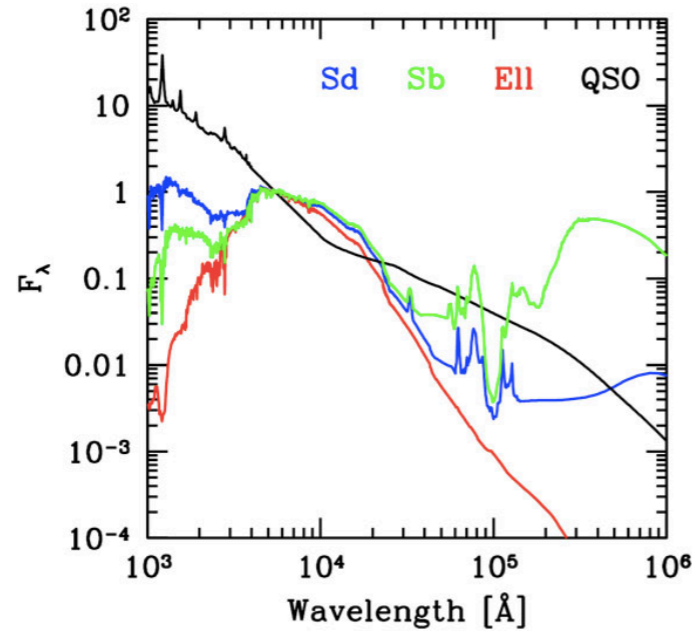
- stars
- gas
- AGN
- dust



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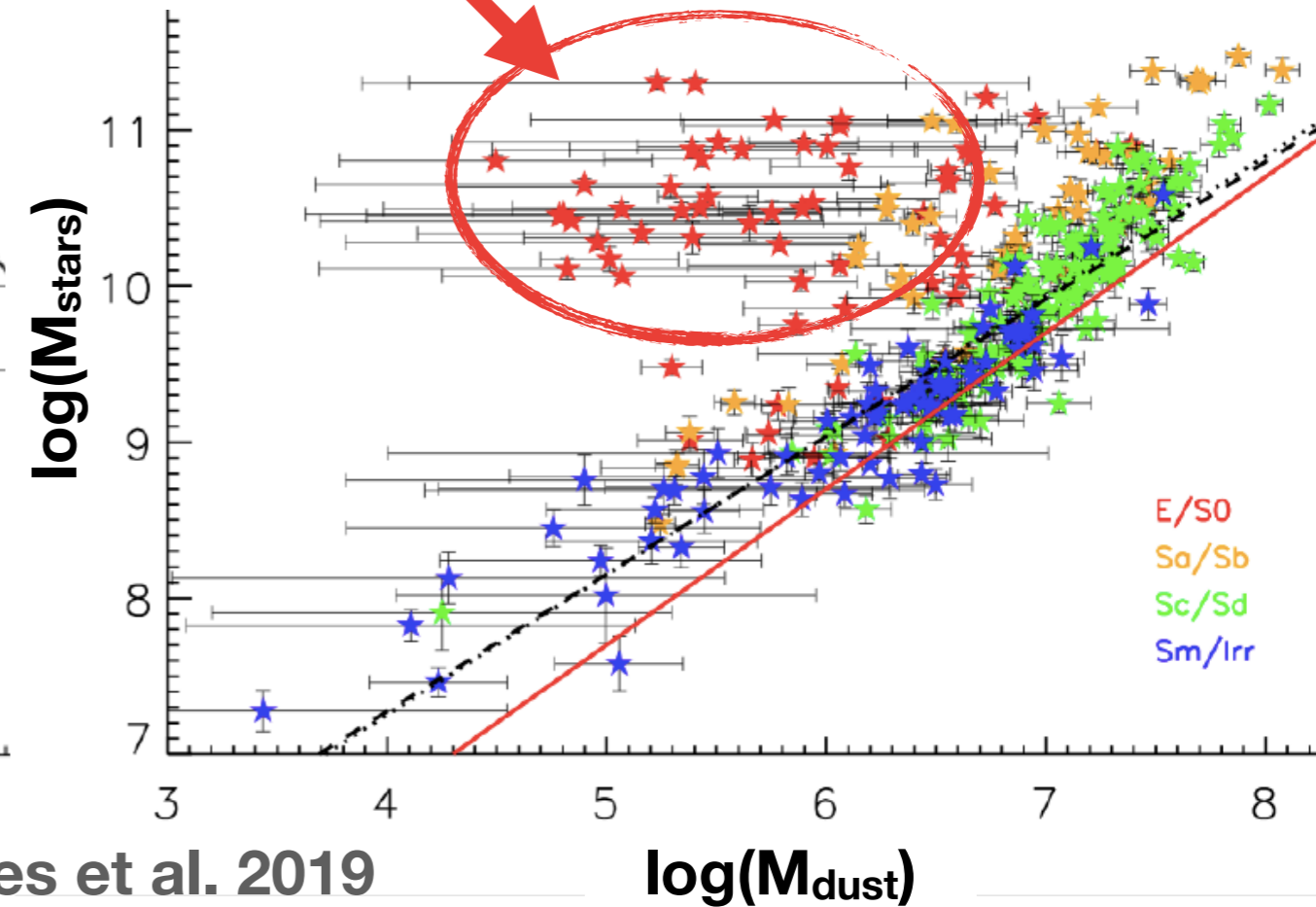
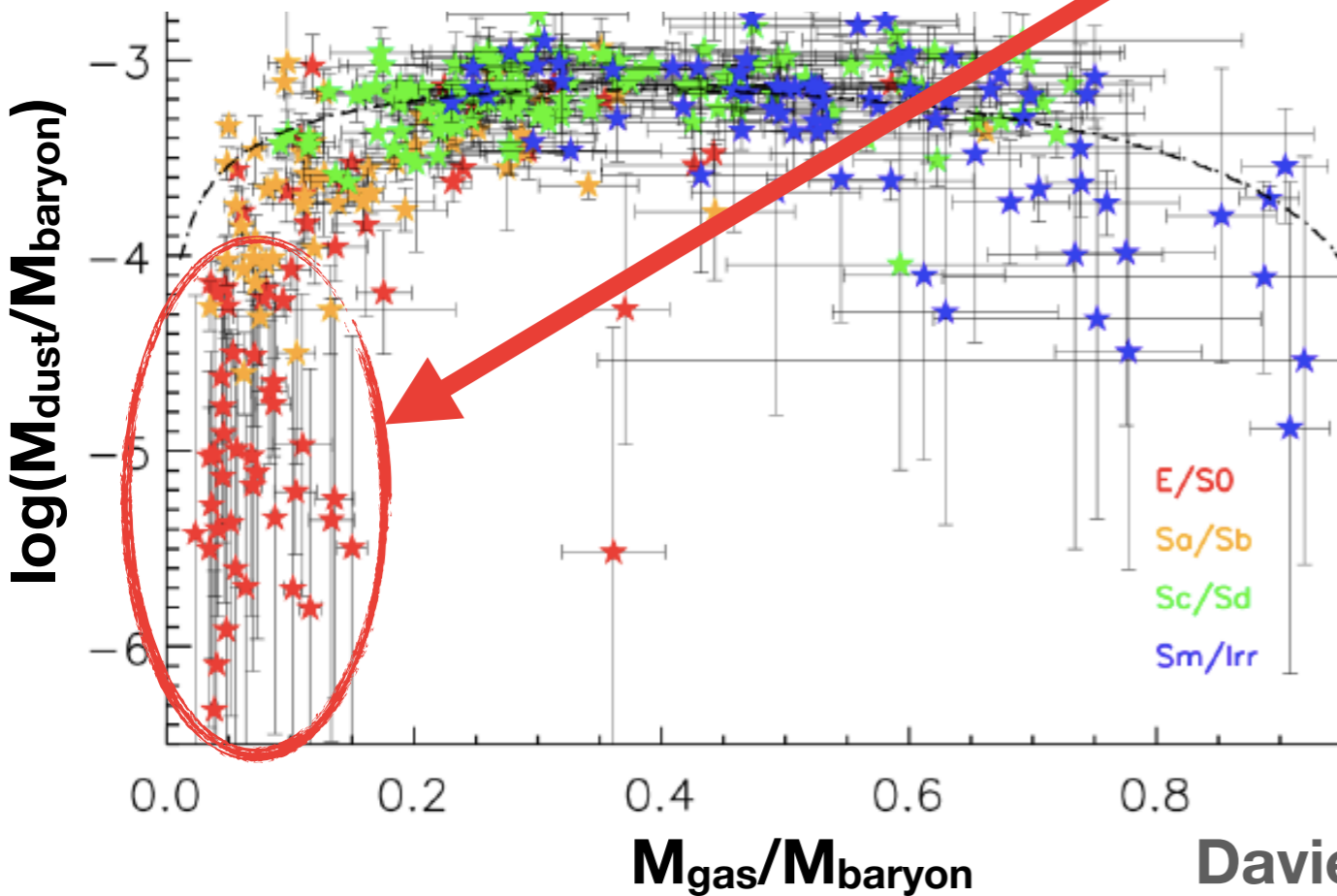
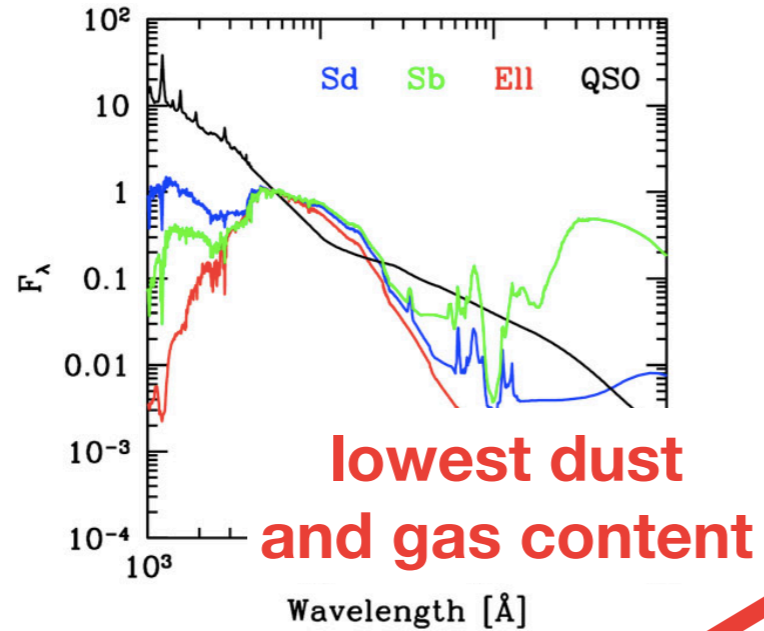
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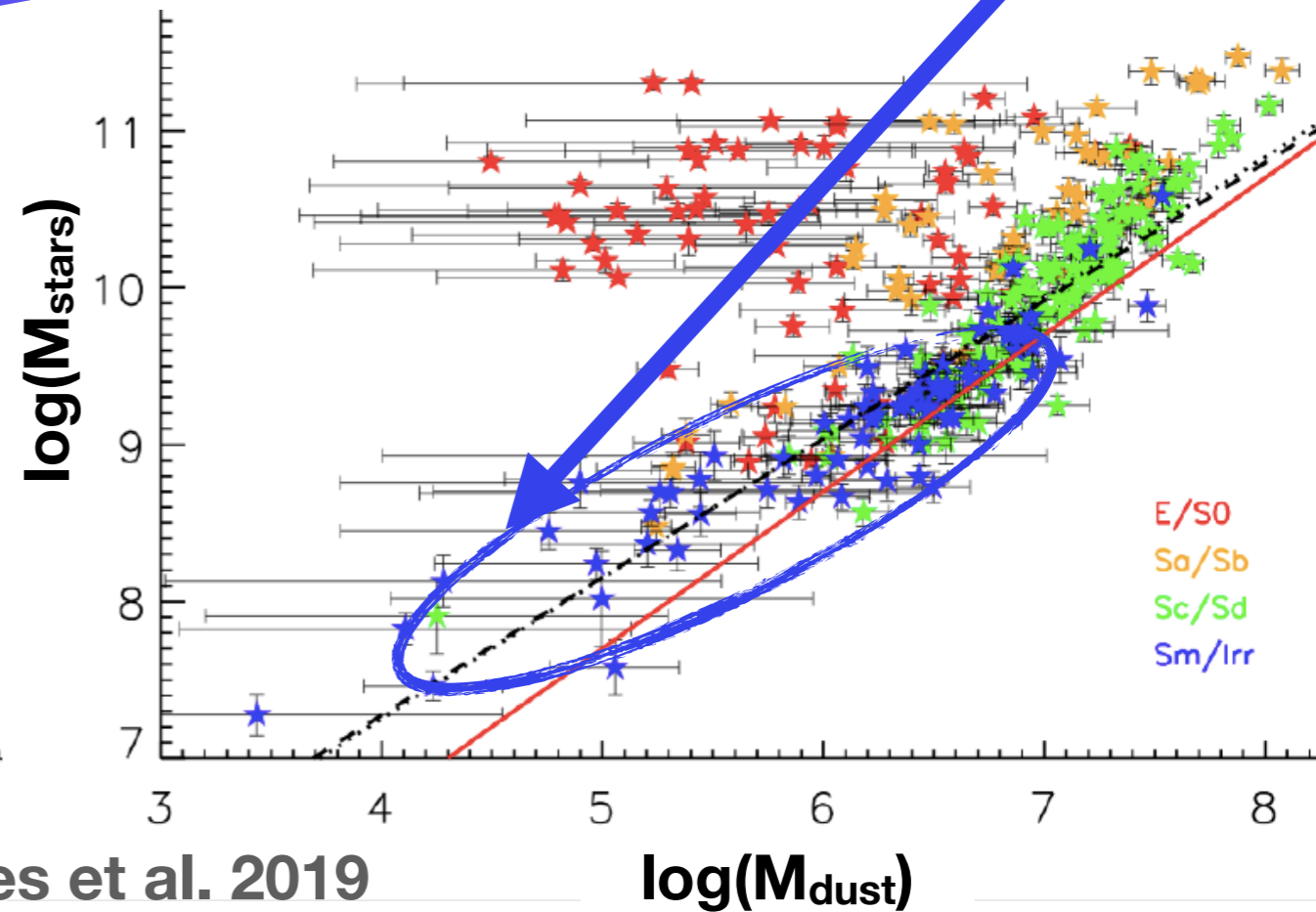
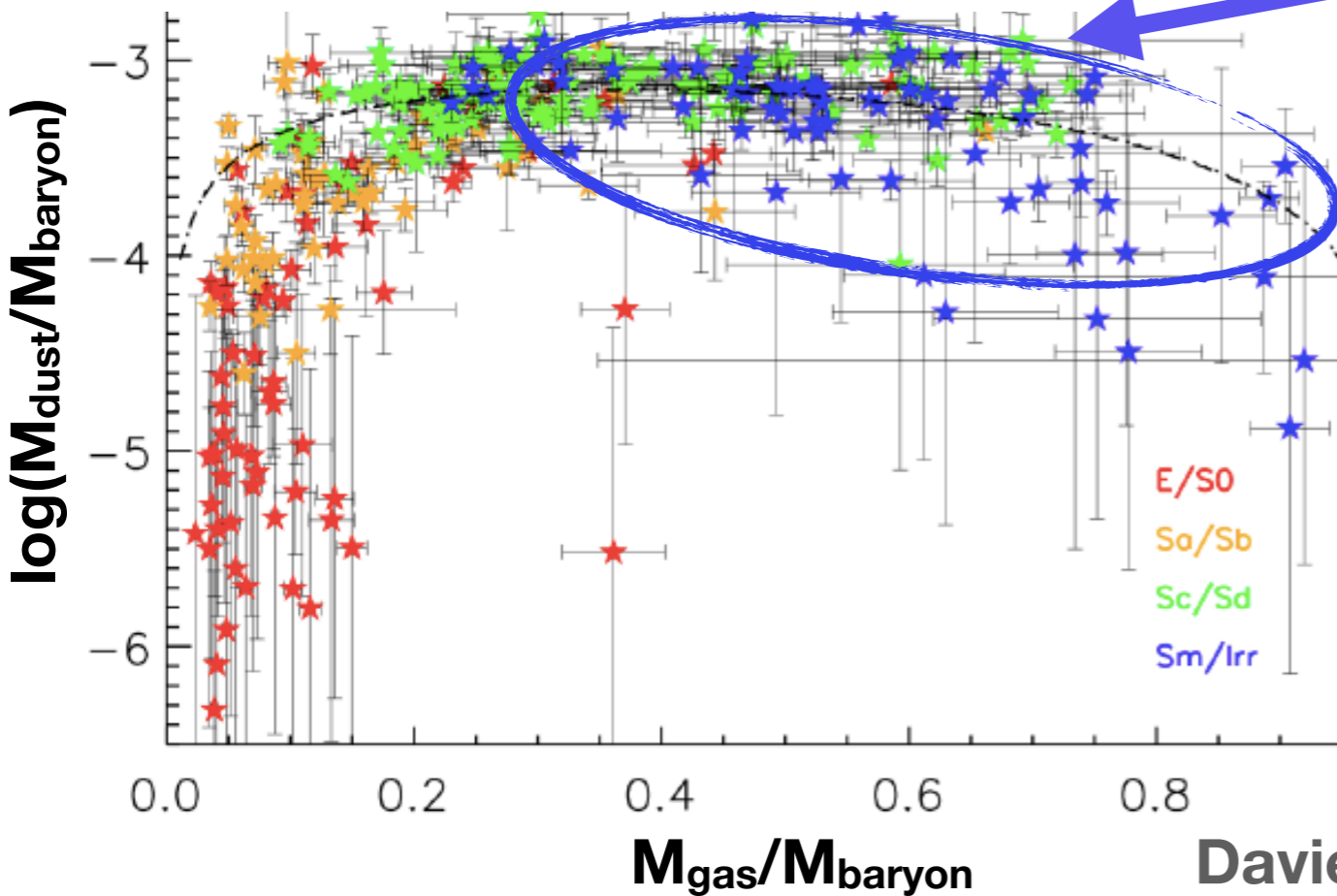
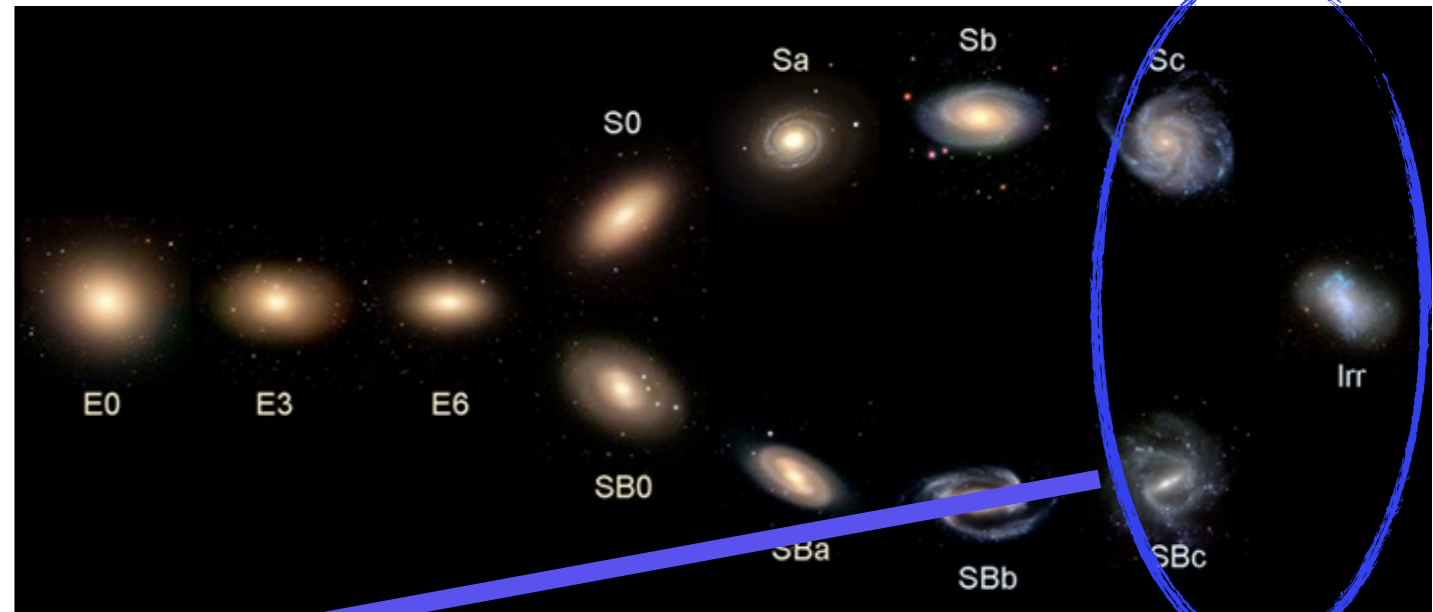
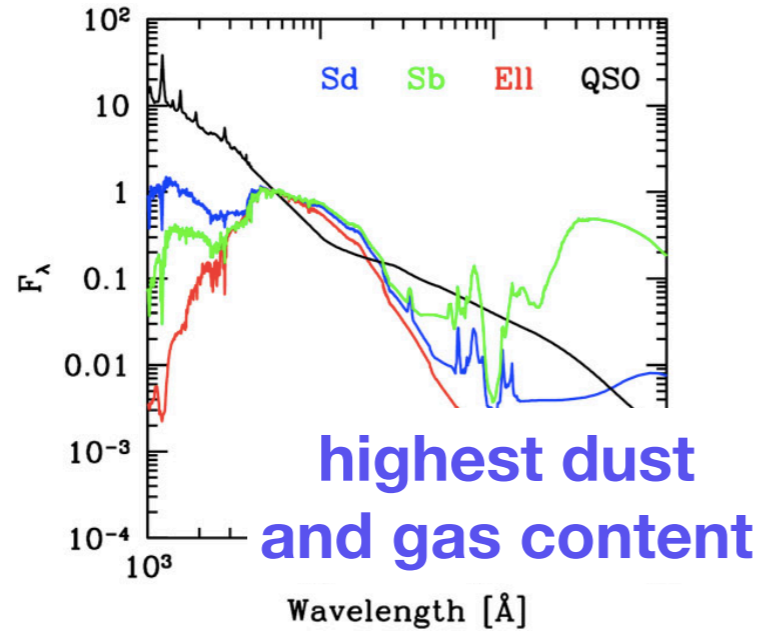


Davies et al. 2019

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 constituents:

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Davies et al. 2019

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 constituents:

- stars
- gas
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- 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) ?

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

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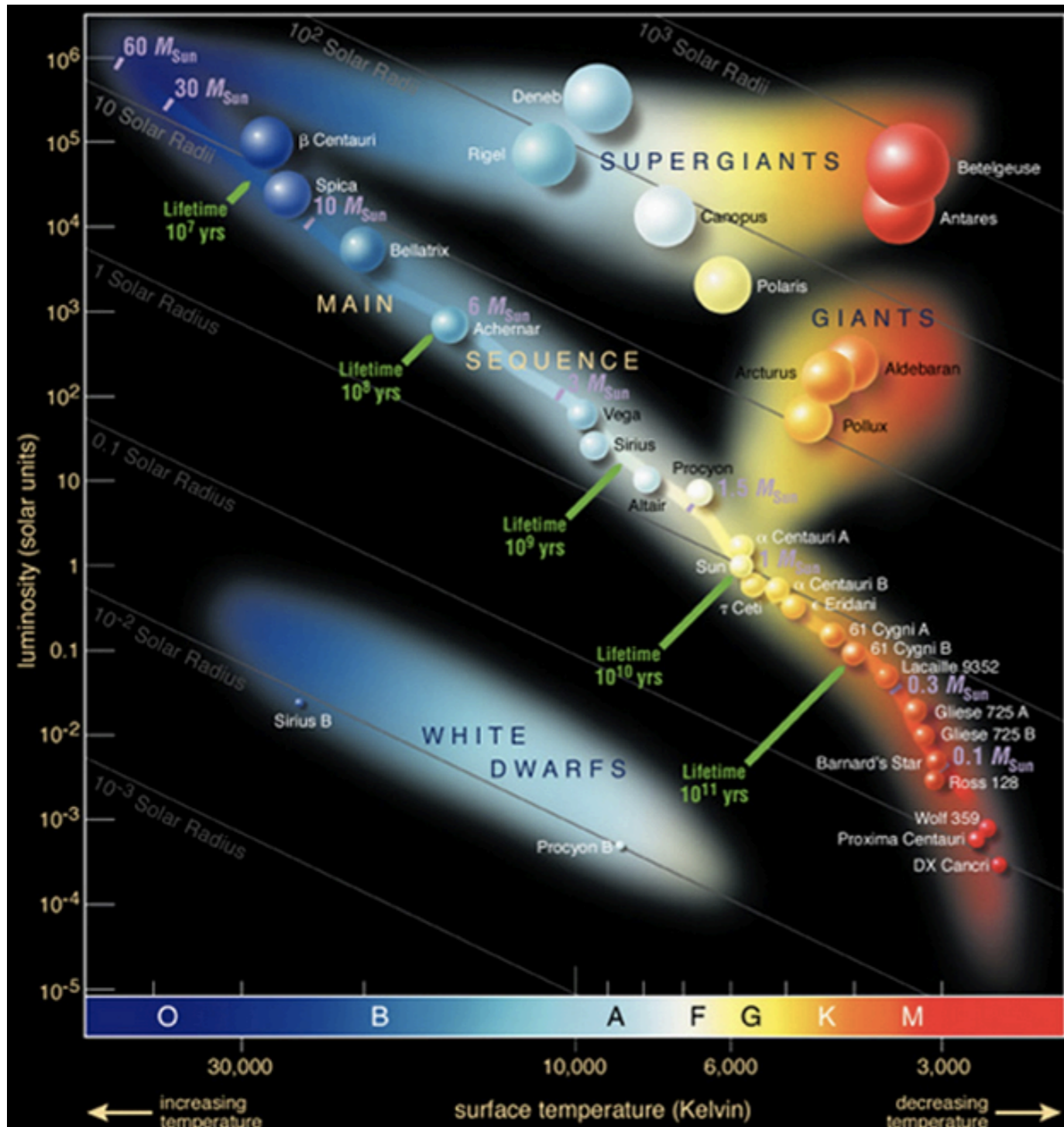
- how many stars ?
- what type of stars (which spectra) ?

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

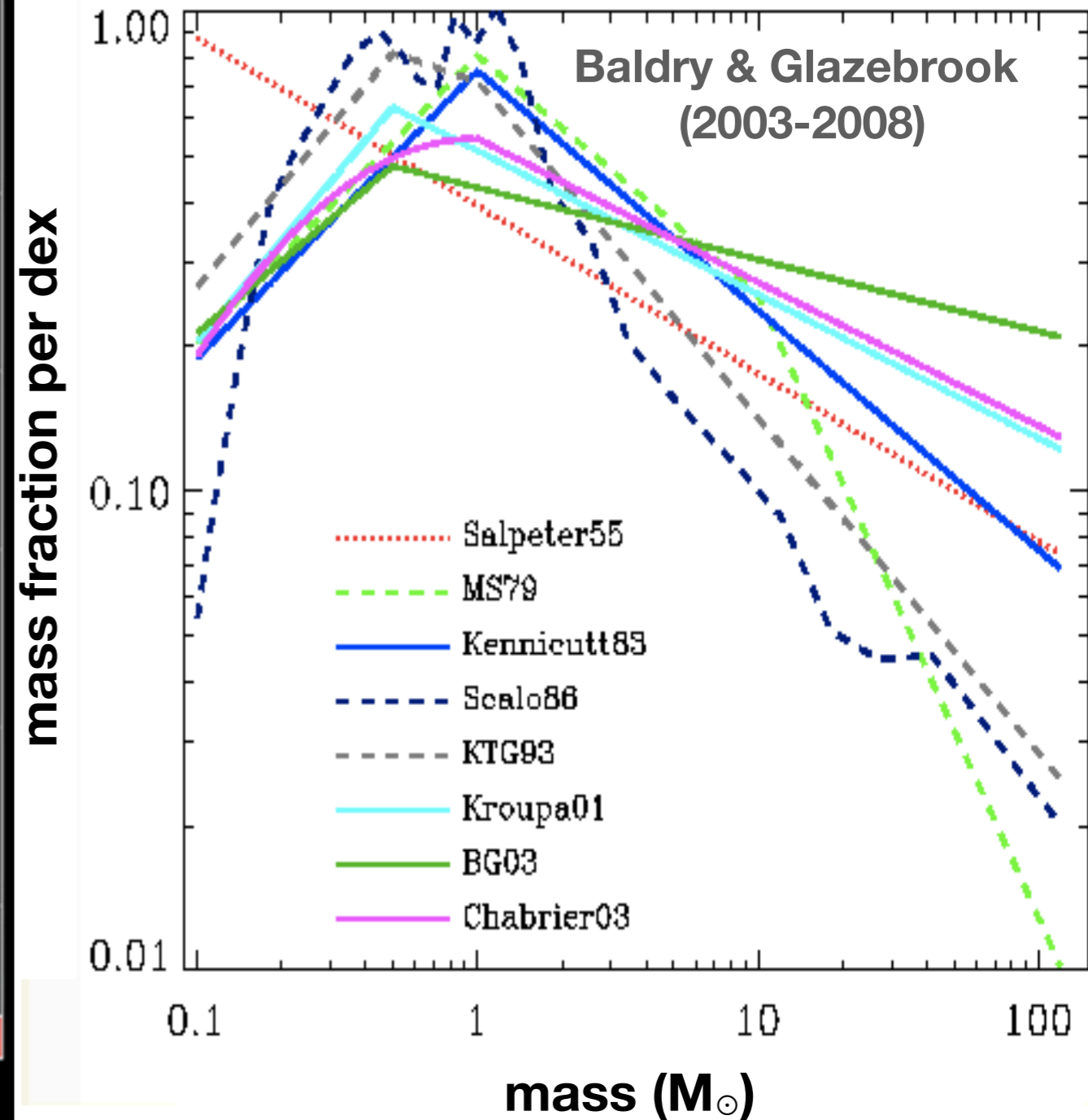
- the total stellar mass of the galaxy
- the initial stellar mass function (IMF)
- the evolution of stars (that is, the evolution of the stellar mass function and the evolution of individual stellar spectra)

Main ingredients

The Hertzsprung-Russell diagram



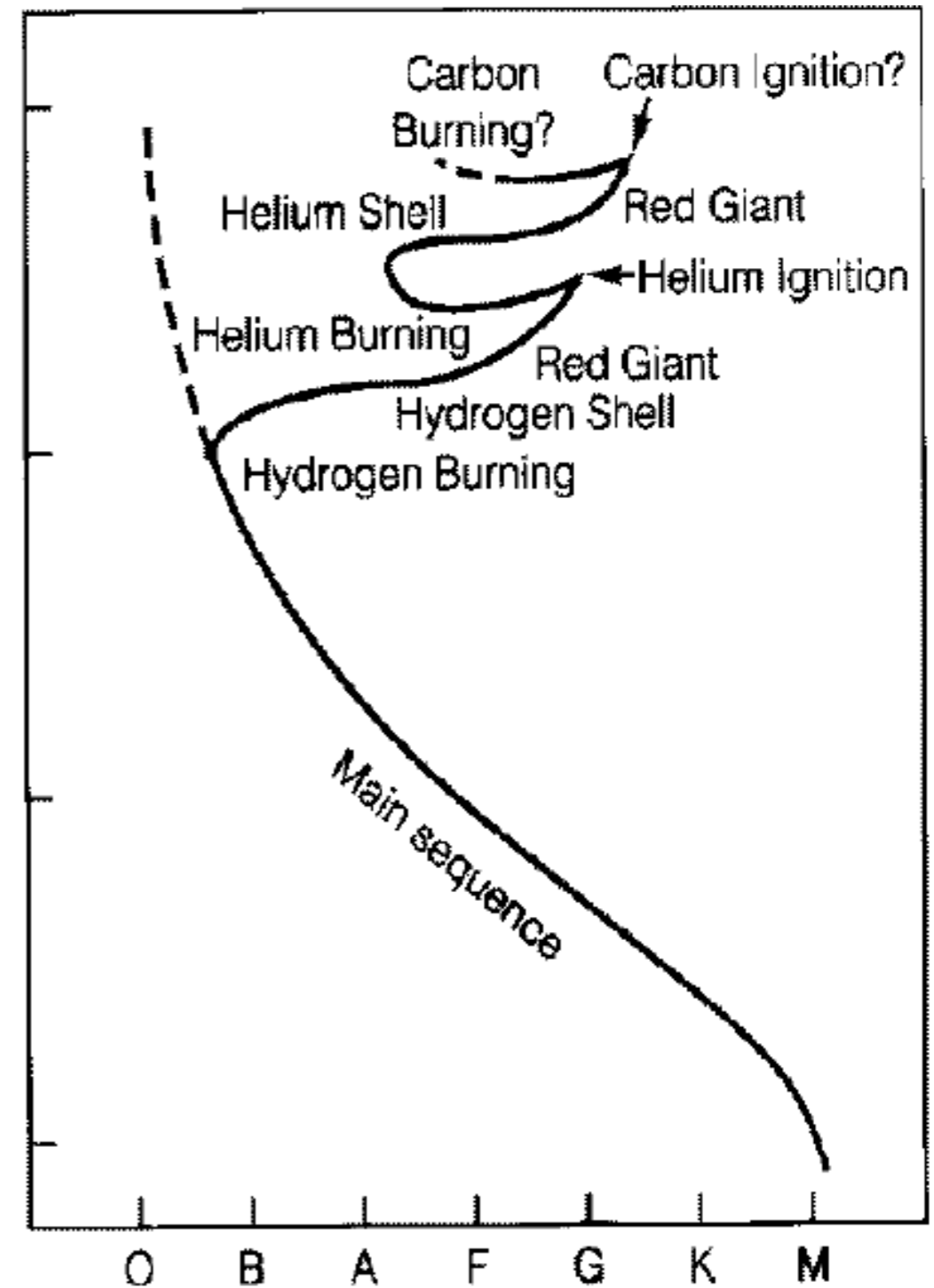
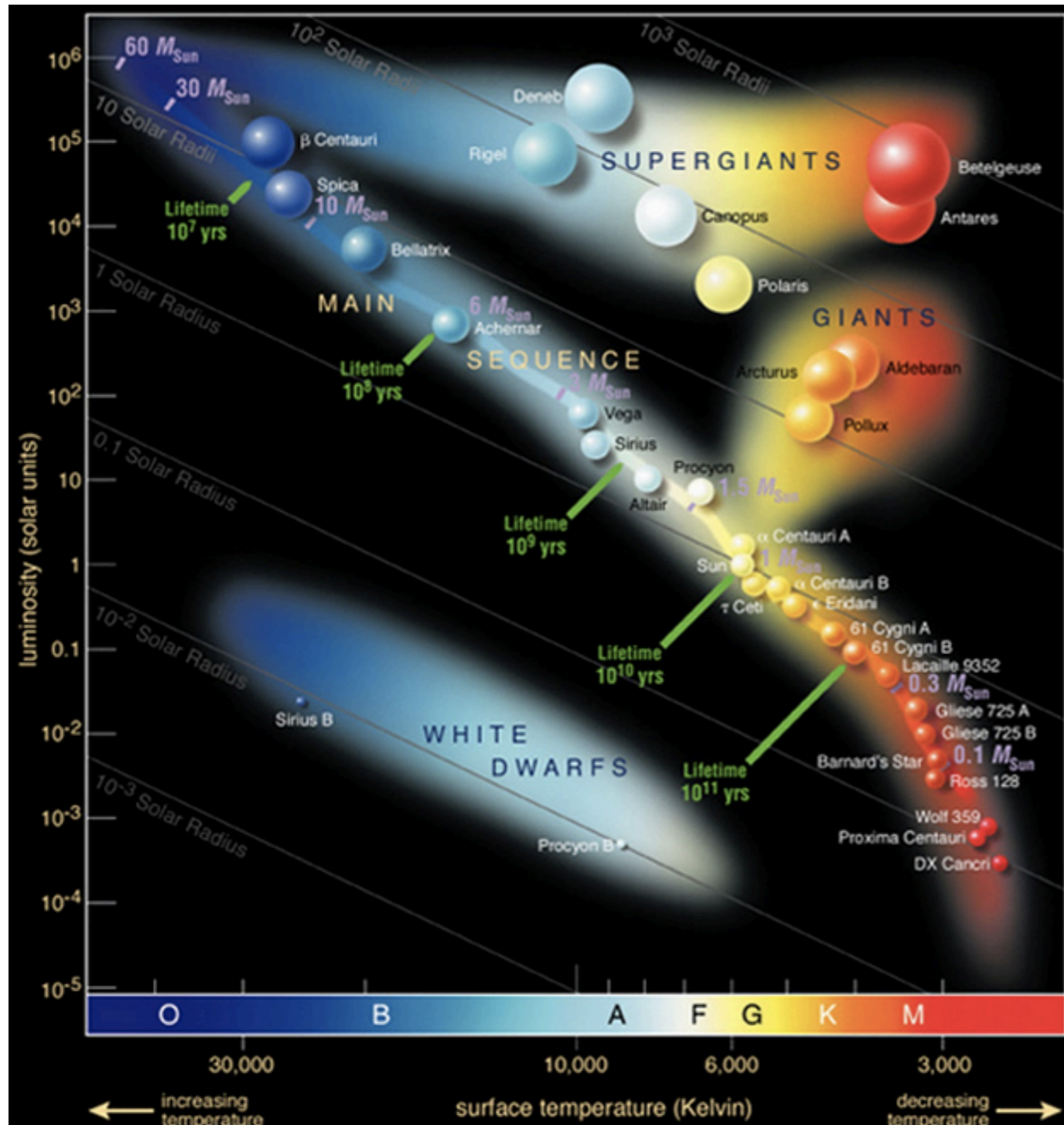
stellar initial mass function (IMF)



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

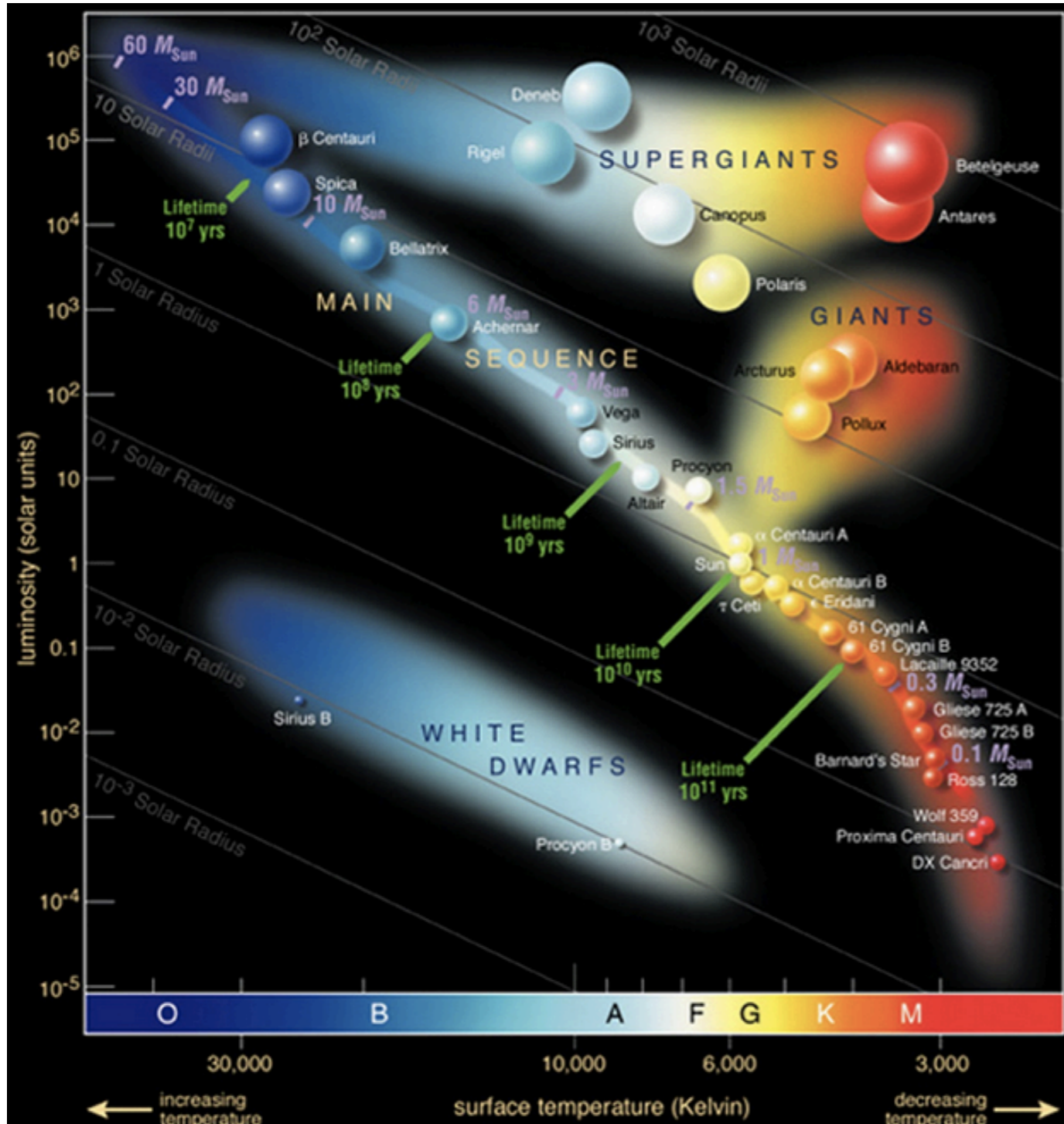
Main ingredients

The Hertzsprung-Russell diagram

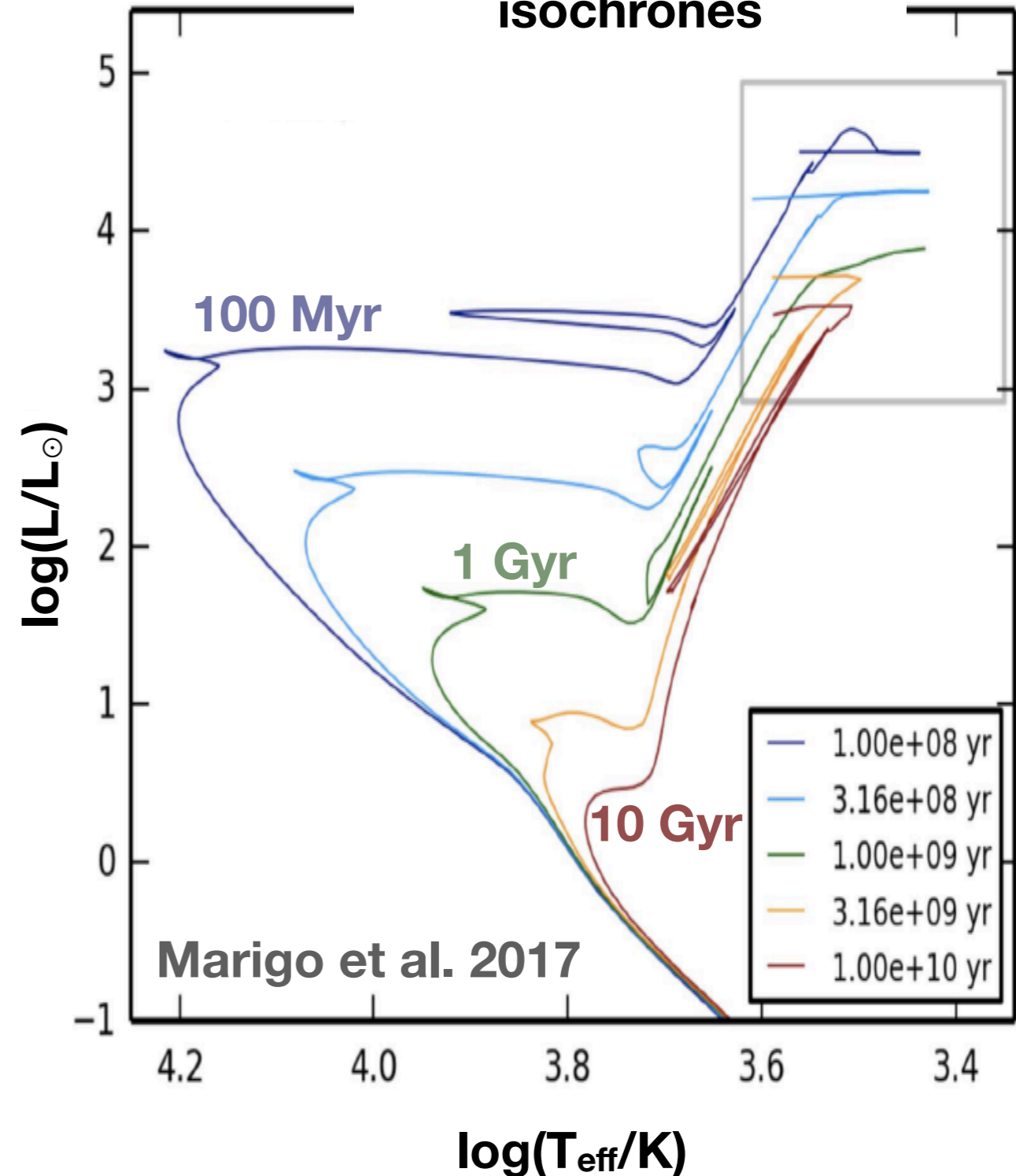


Main ingredients

The Hertzsprung-Russell diagram



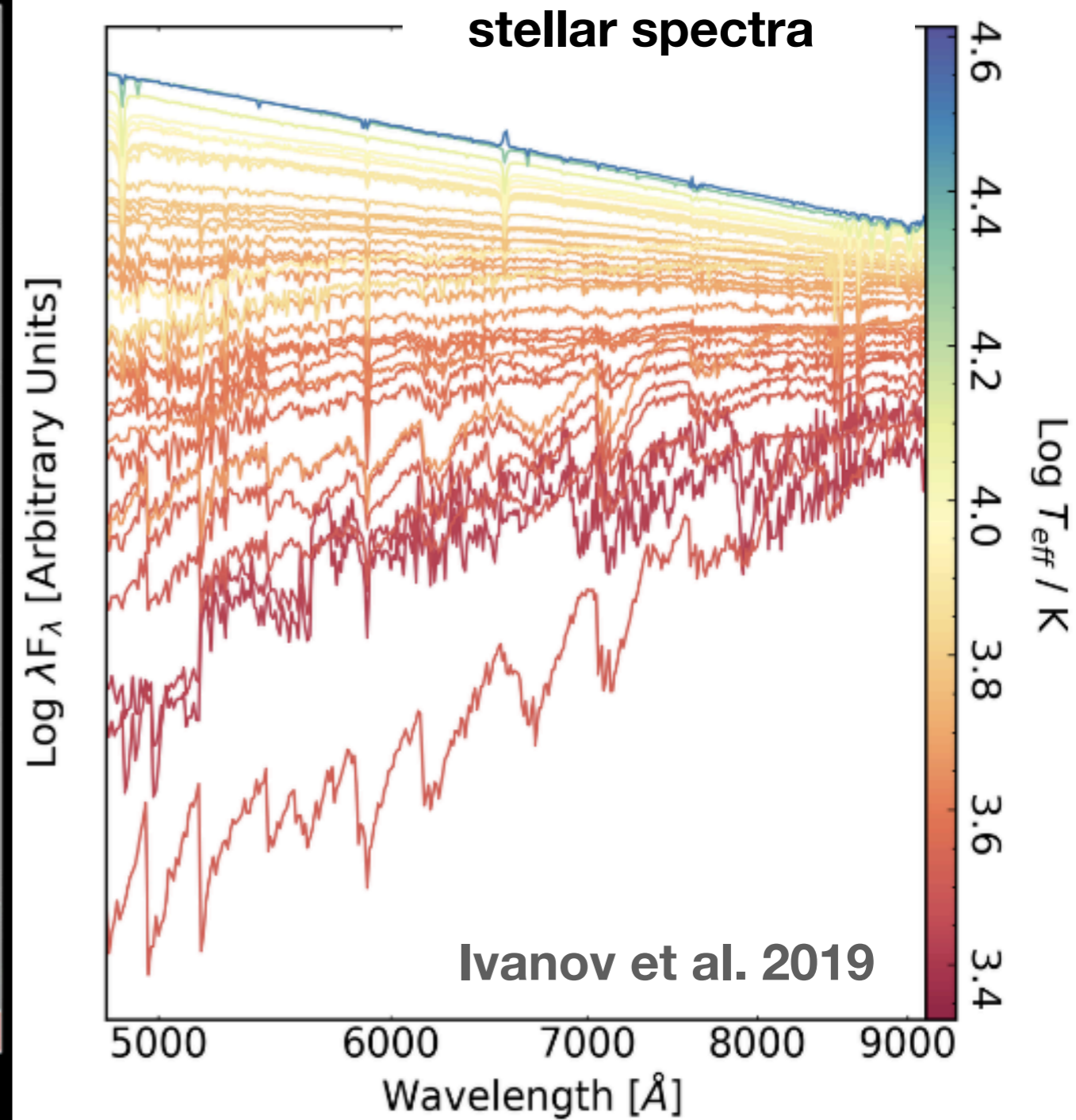
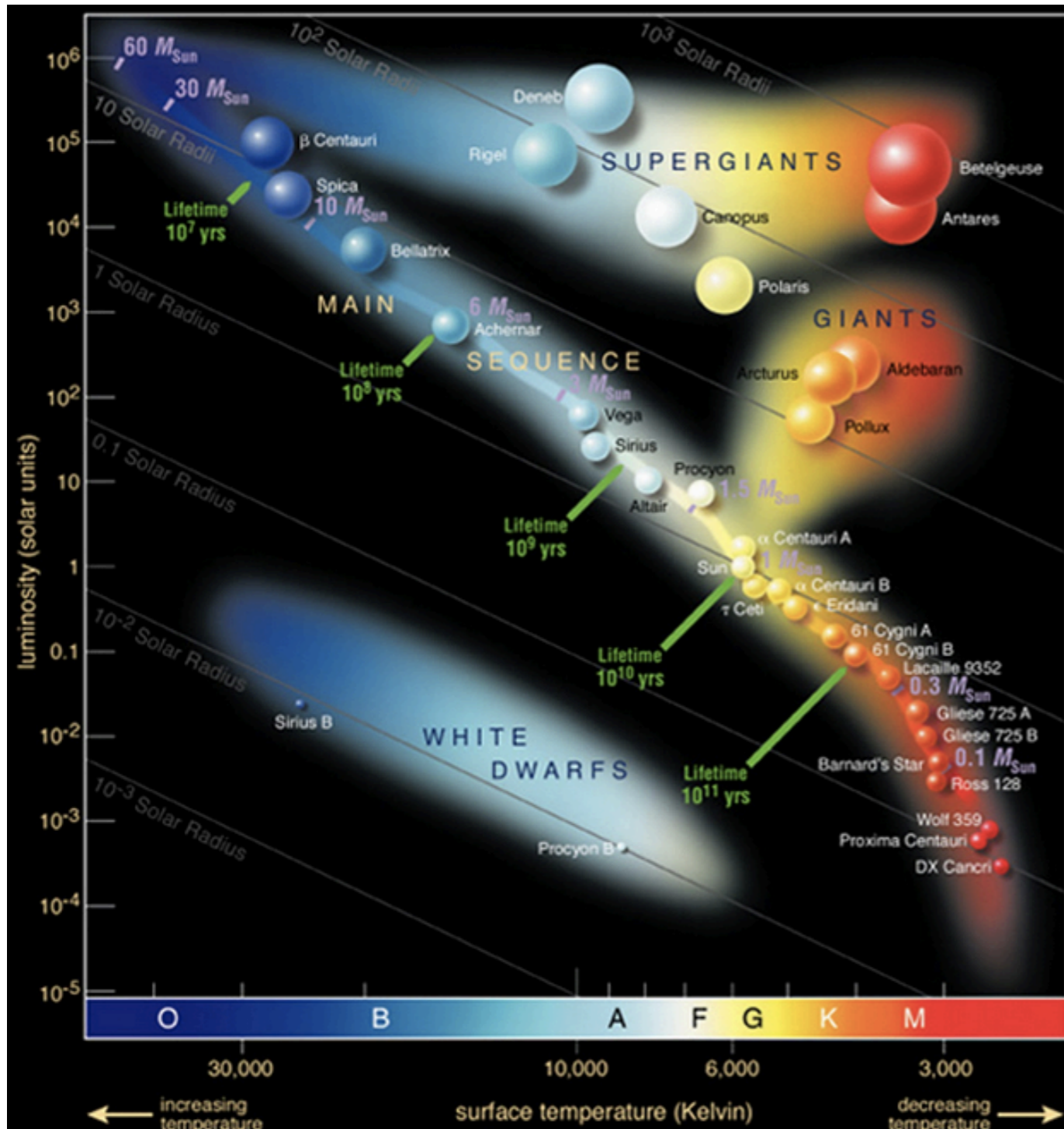
isochrones



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

Main ingredients

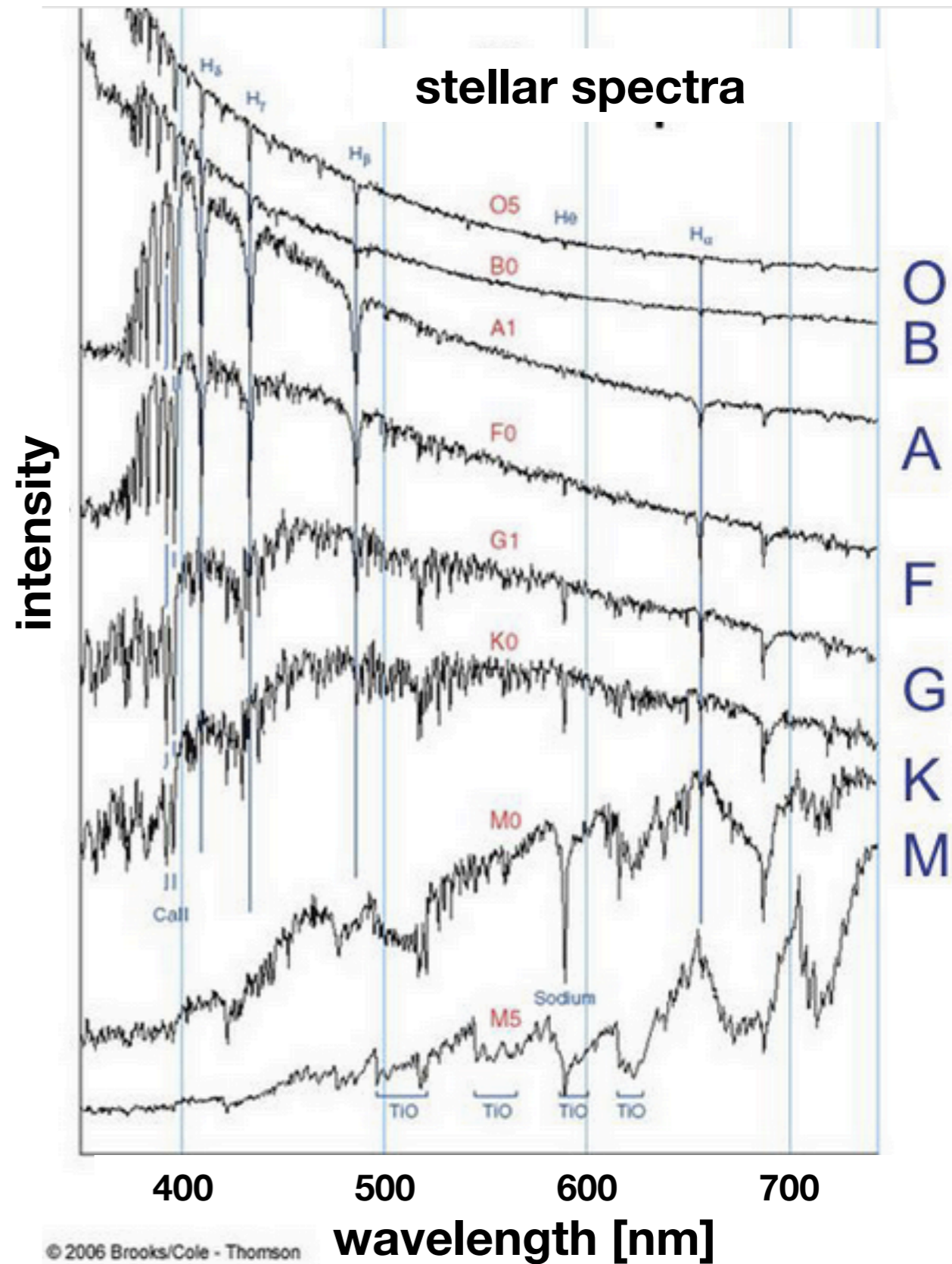
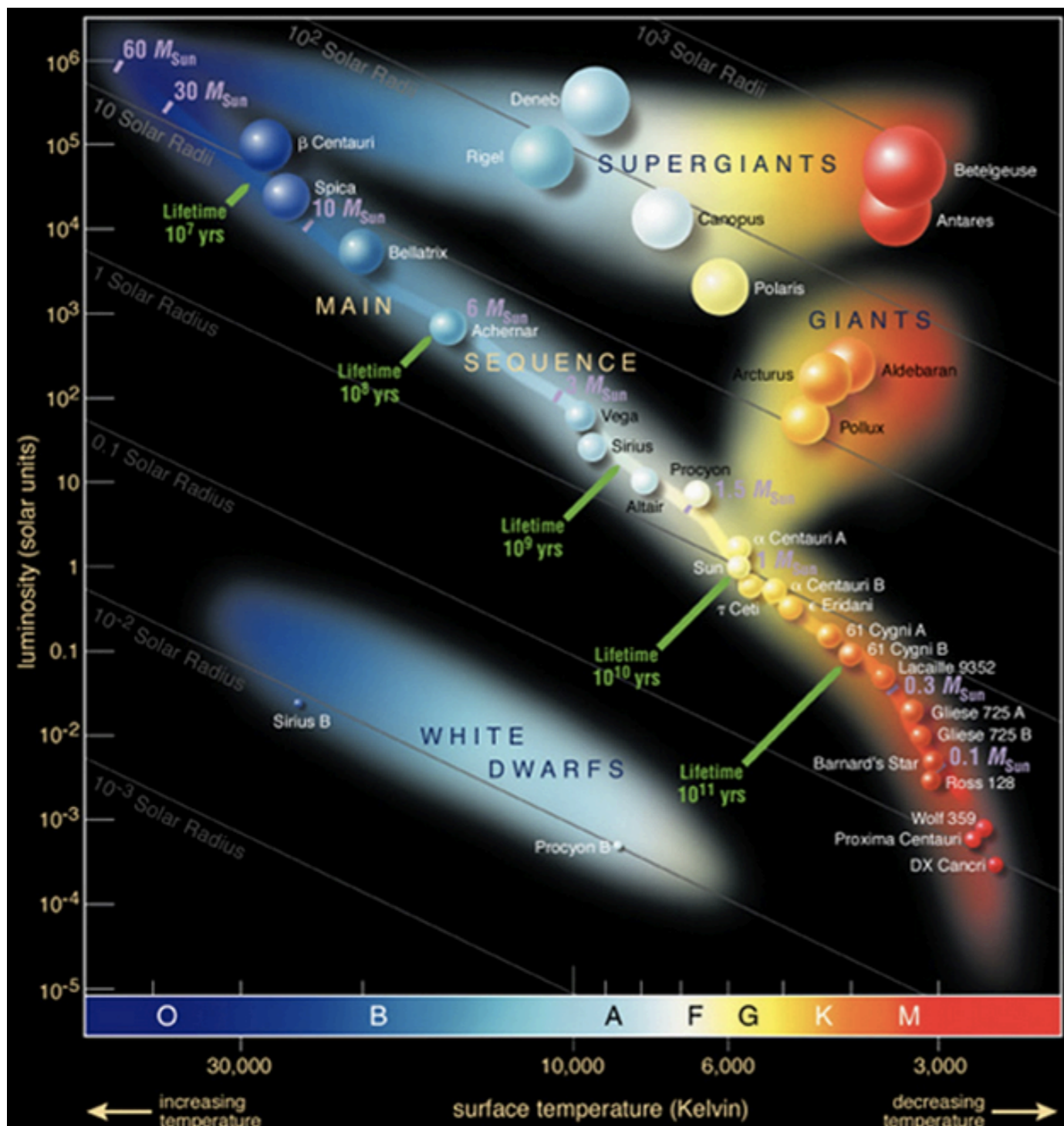
The Hertzsprung-Russell diagram



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

Main ingredients

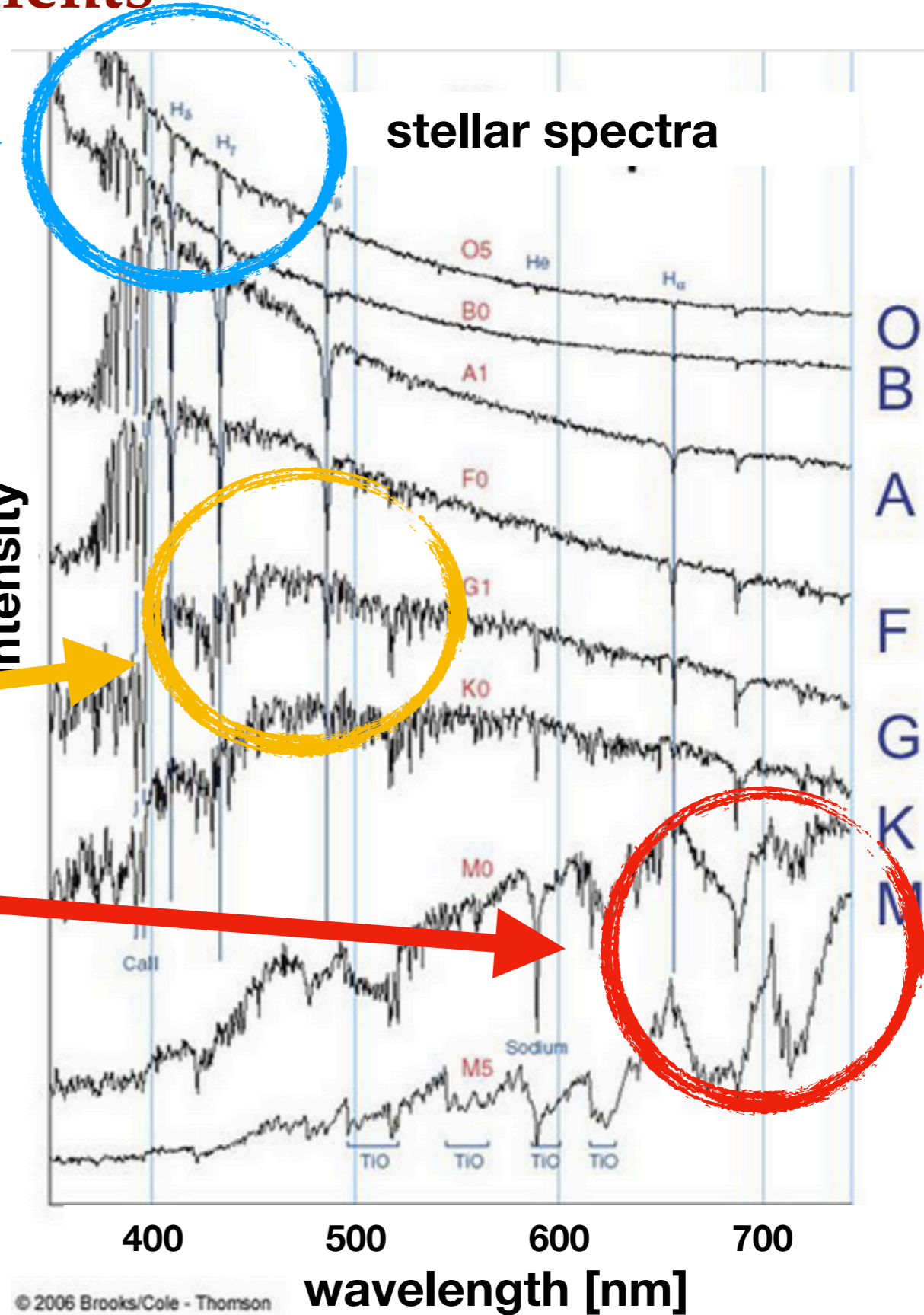
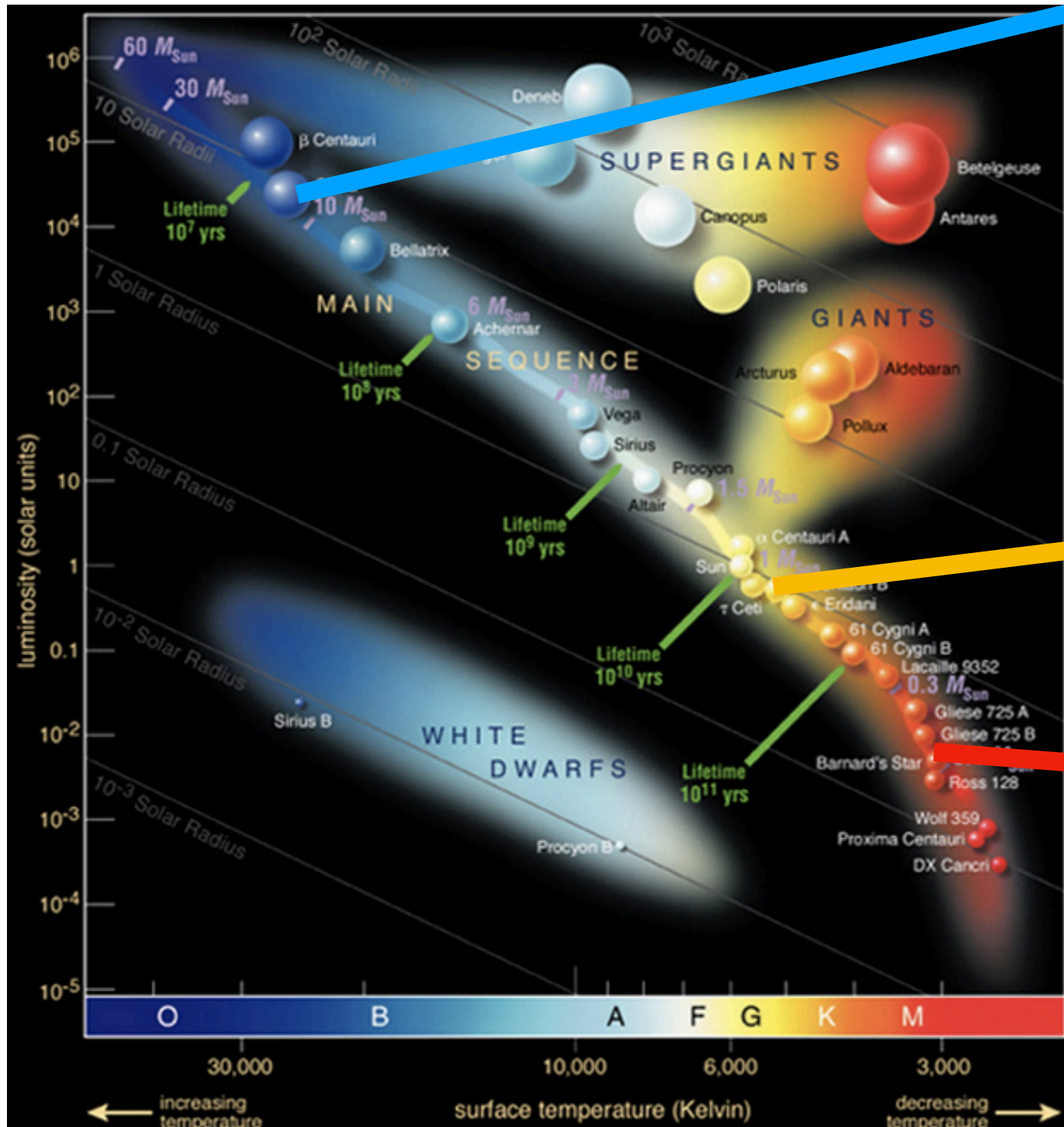
The Hertzsprung-Russell diagram



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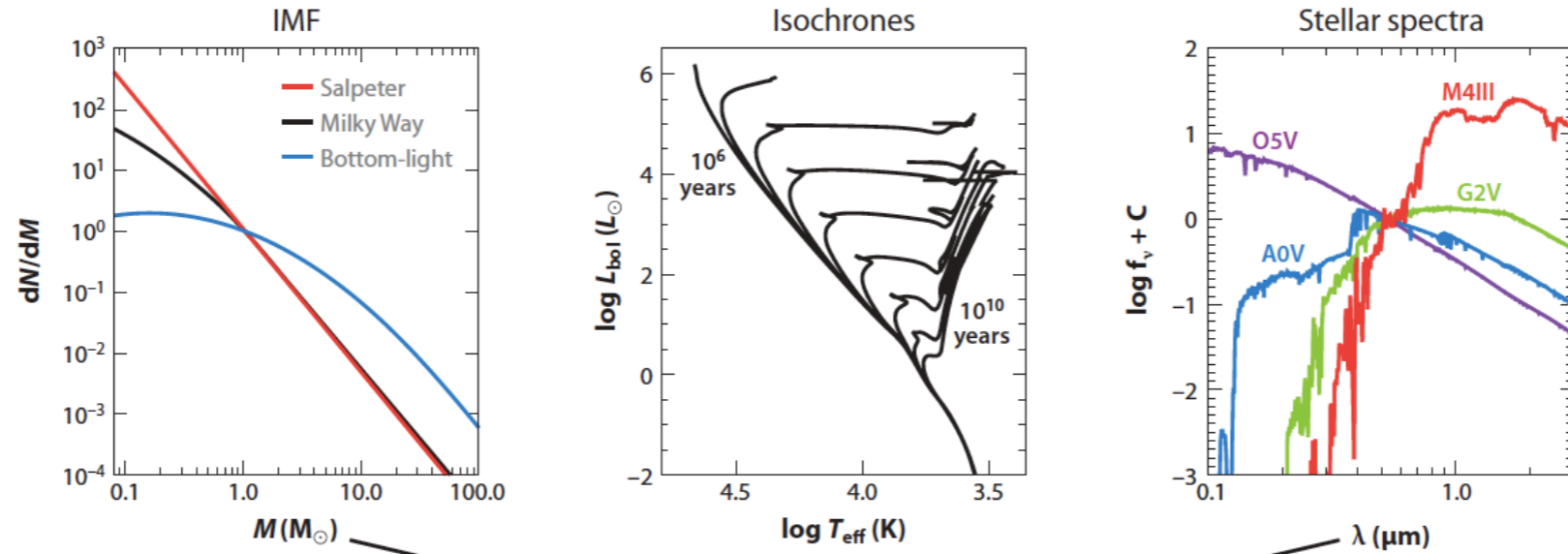
Main ingredients

The Hertzsprung-Russell diagram

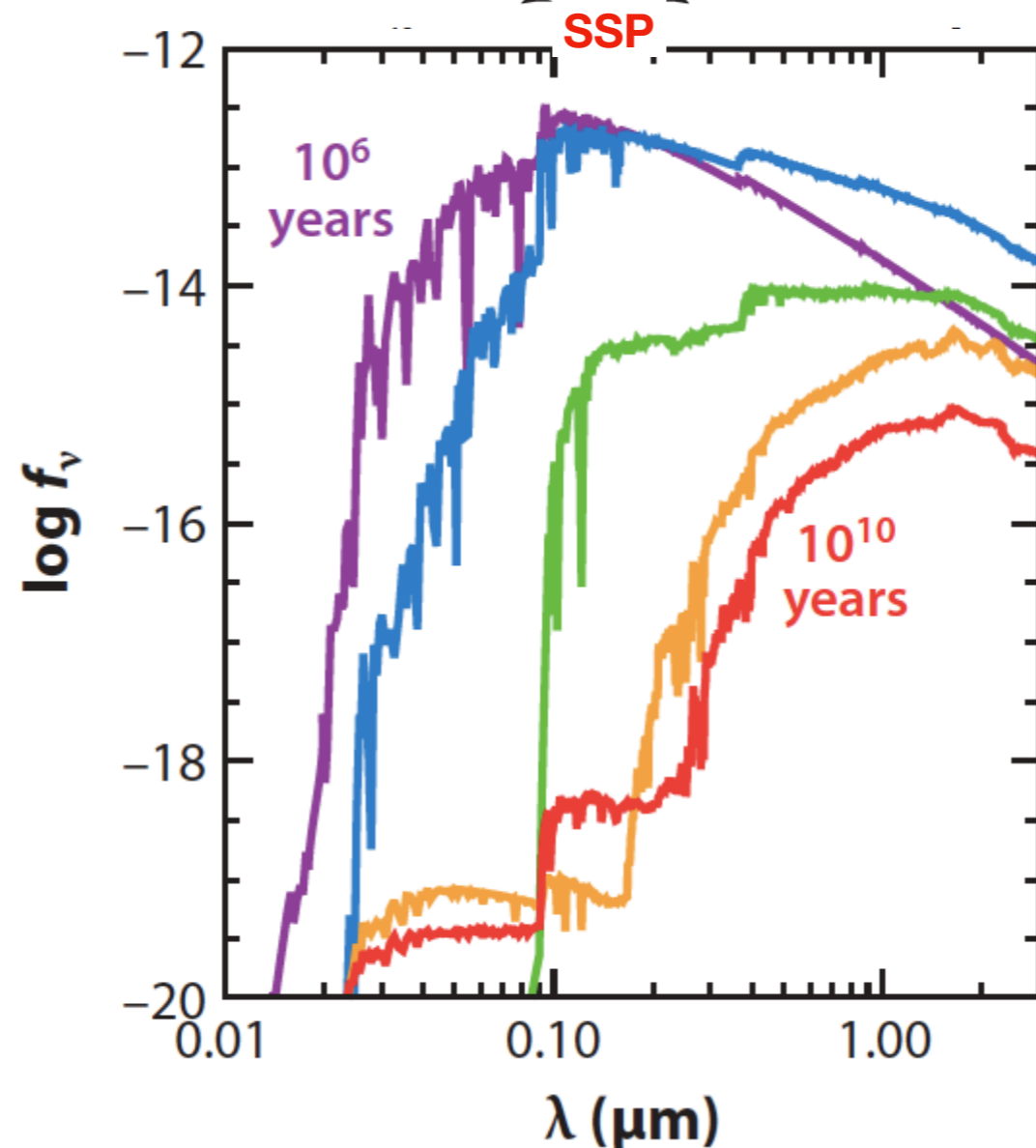


(spectra of different classes of stars, to translate stellar evolution calculations into SEDs)

Stellar Population Synthesis (SPS) - First step: SSPs

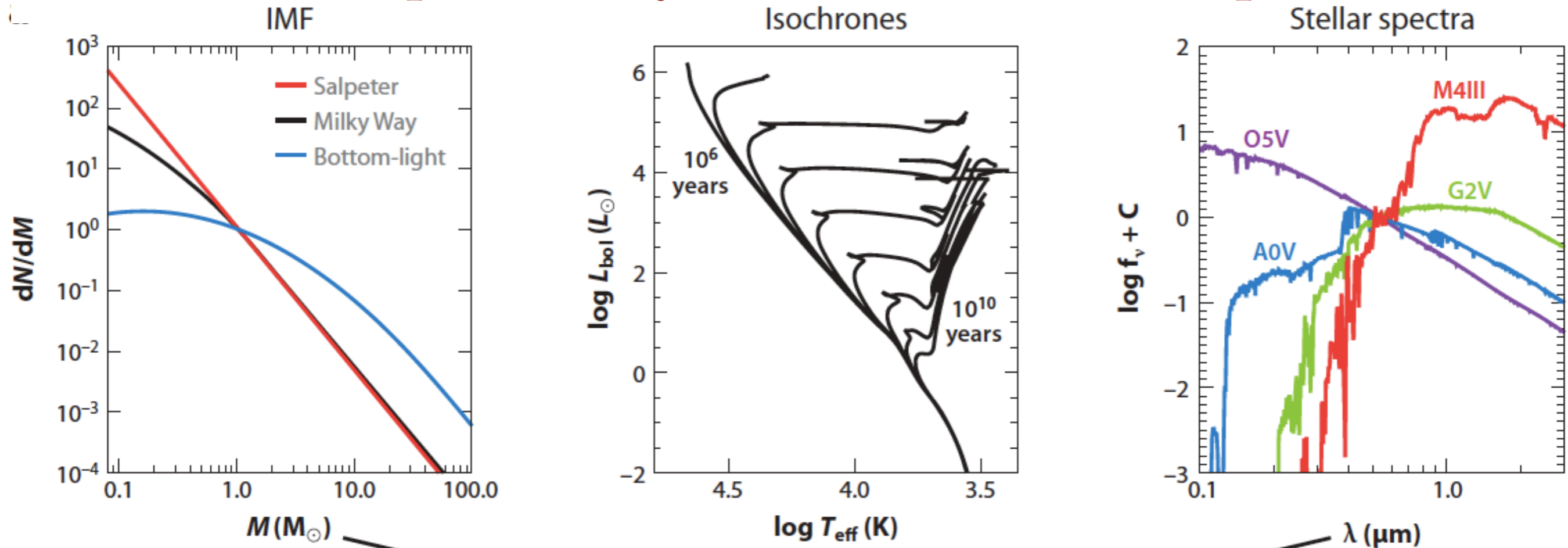


Conroy 2013



Time evolution
of a SSP

Stellar Population Synthesis (SPS) - First step: SSPs



Conroy 2013

SSP

Simple Stellar Population

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

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

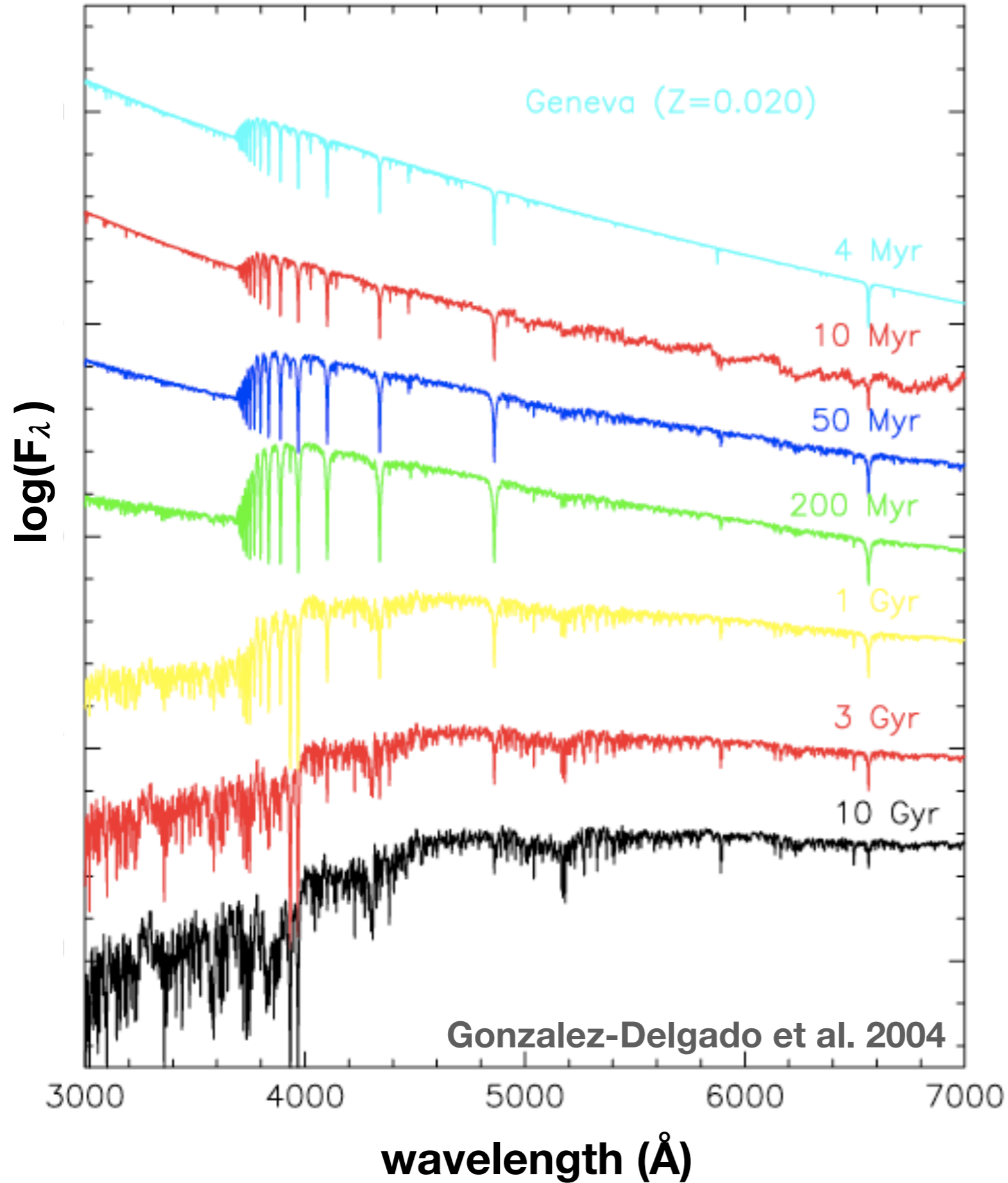
Labels for the equation components:

- $f_{\text{SSP}}(t, Z)$: SSP spectrum
- Z : metallicity
- $f_{\text{star}}[T_{\text{eff}}(M), \log g(M)|t, Z]$: stellar spectrum
- $\Phi(M)$: IMF
- M : stellar mass

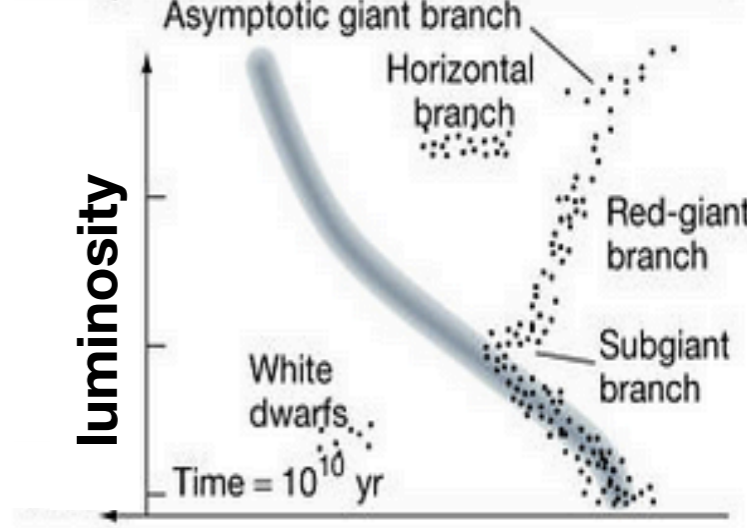
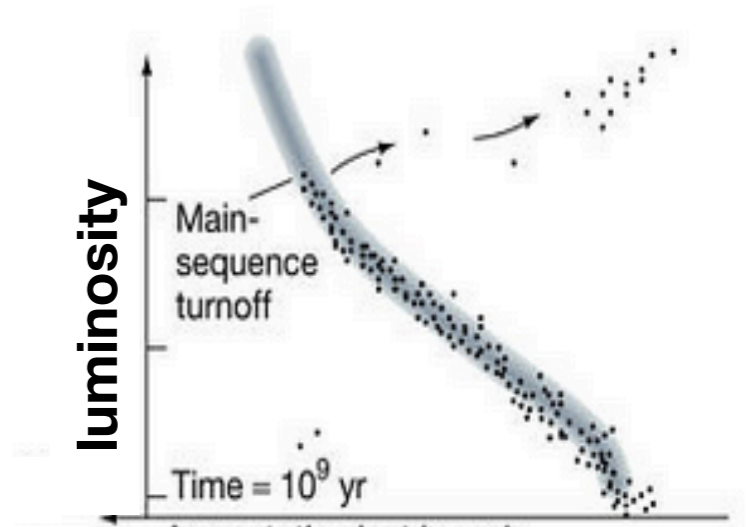
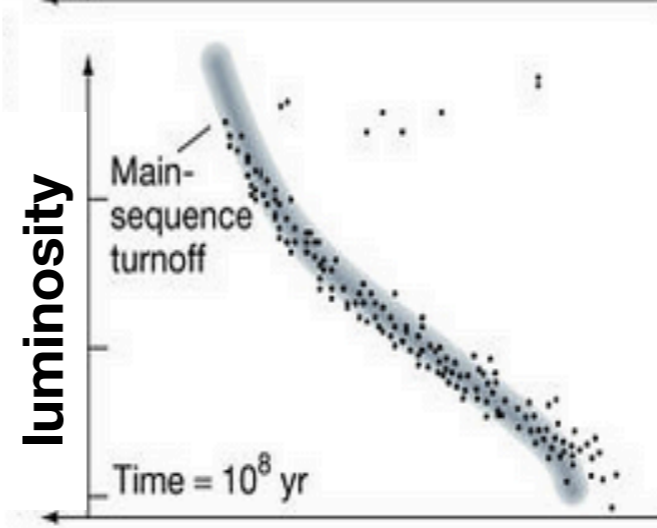
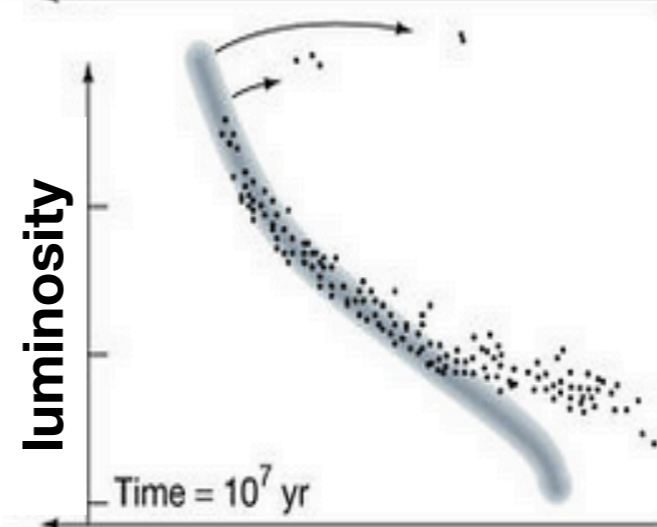
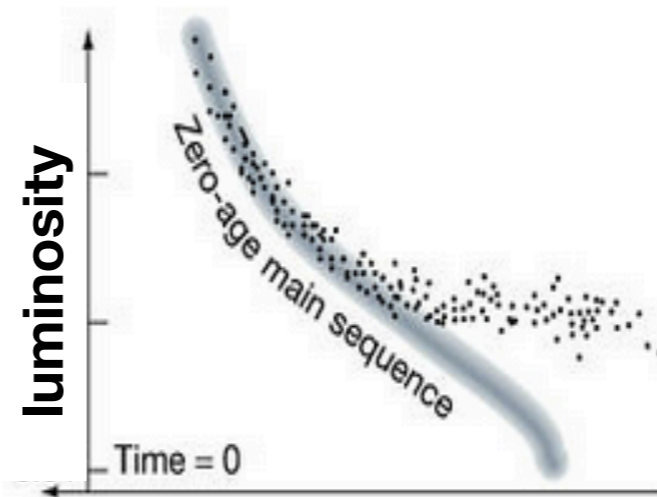
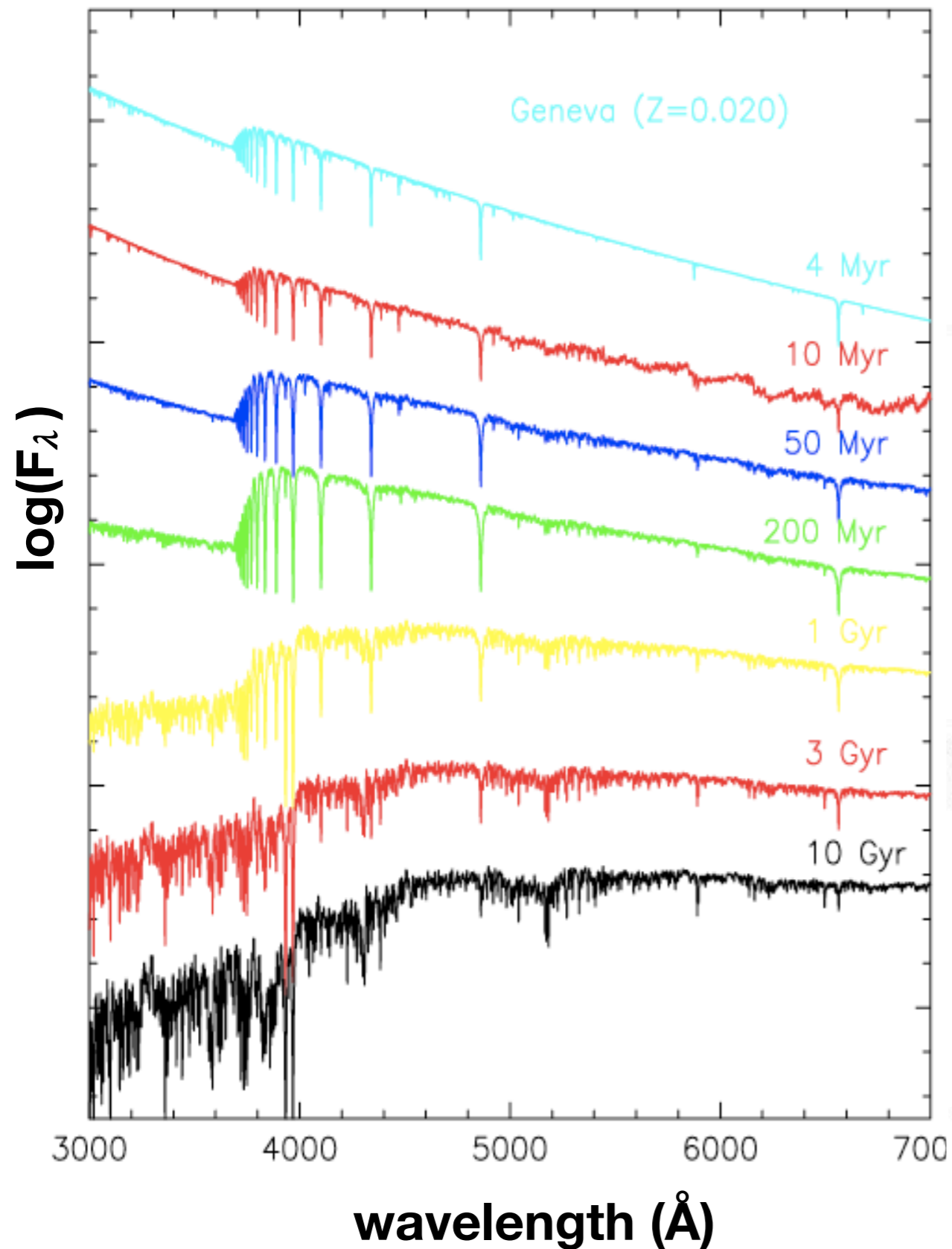
A curved arrow under the f_{star} term is labeled 'isochrones'.

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

Time evolution of a SSP

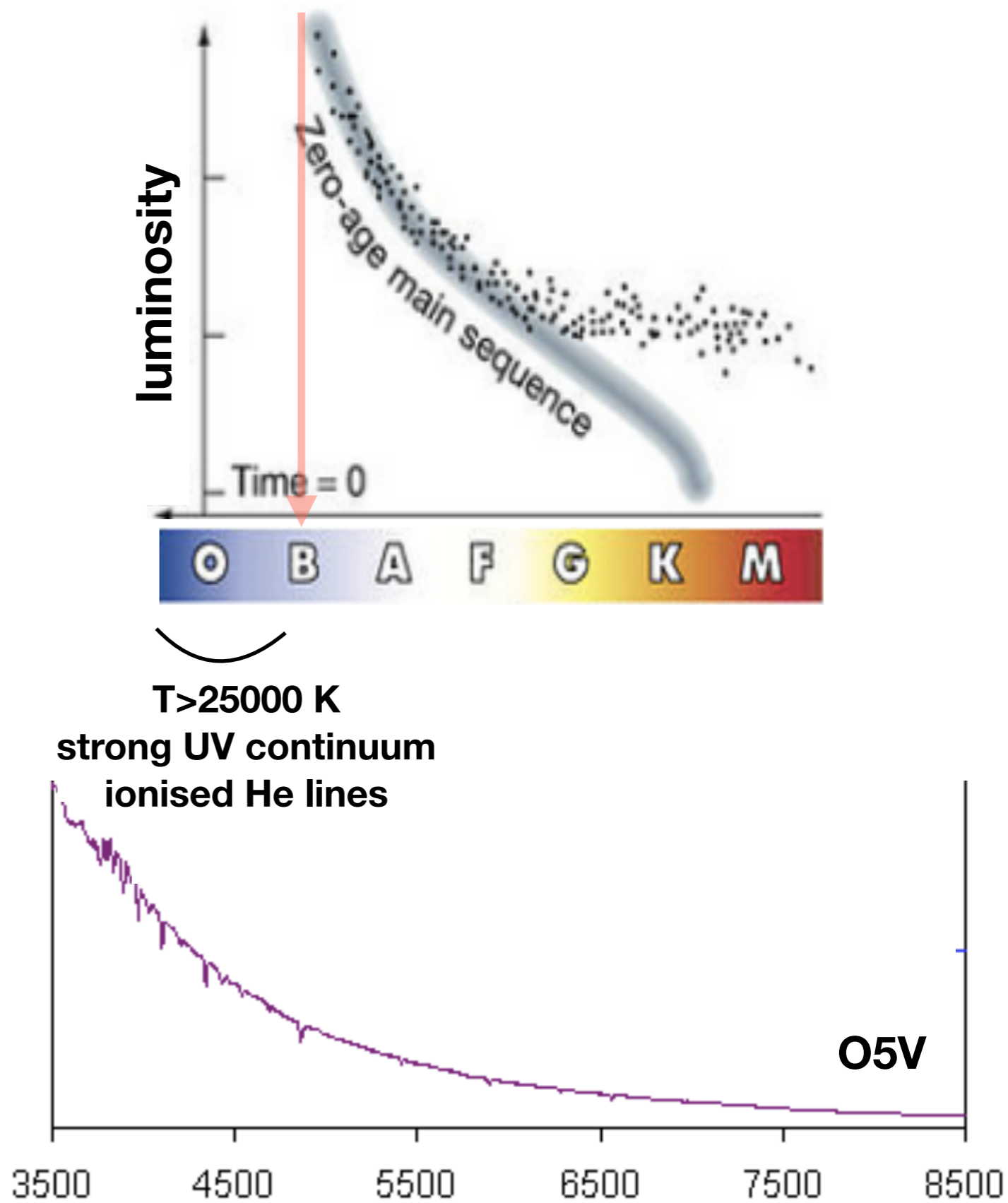
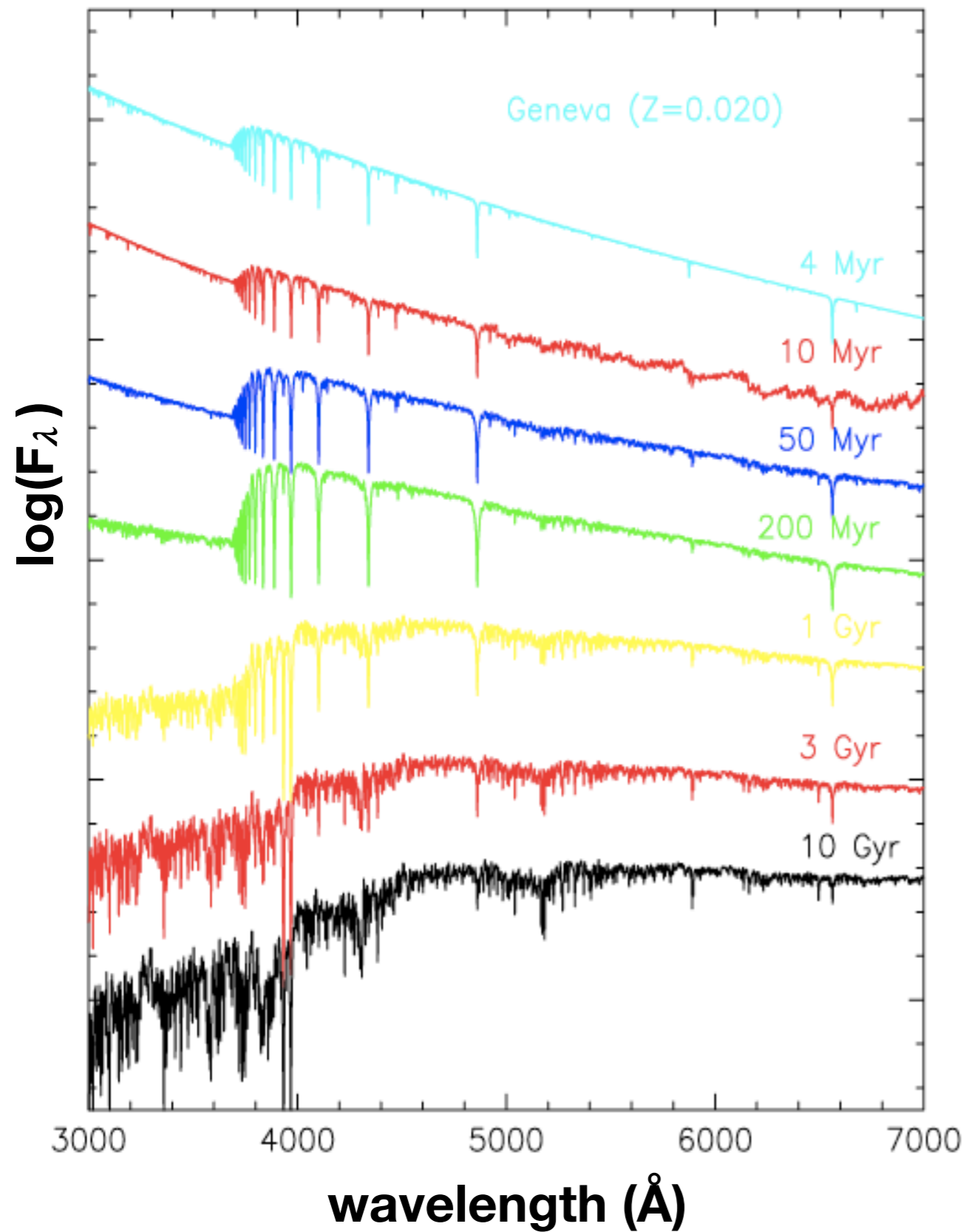


Time evolution of a SSP

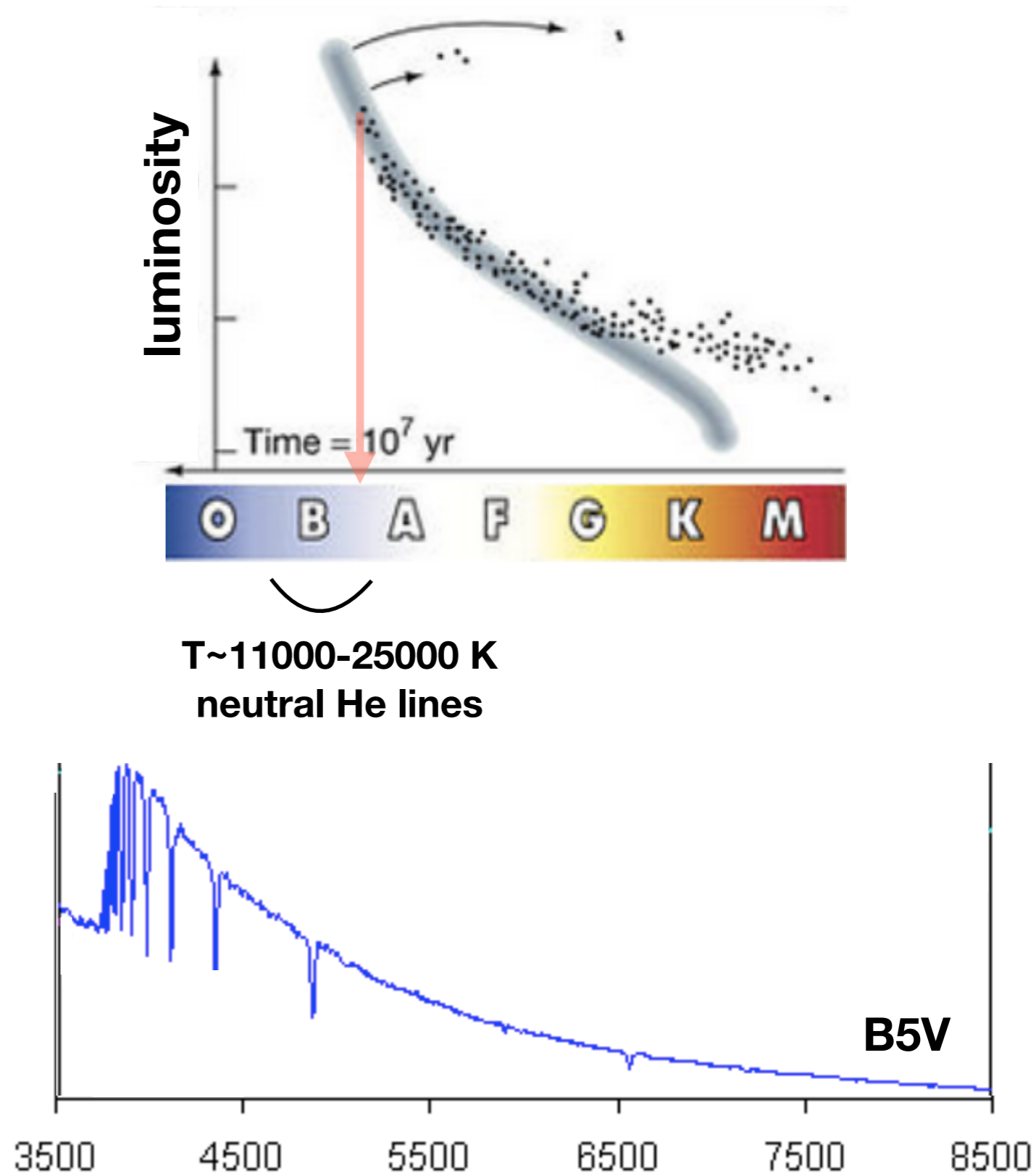
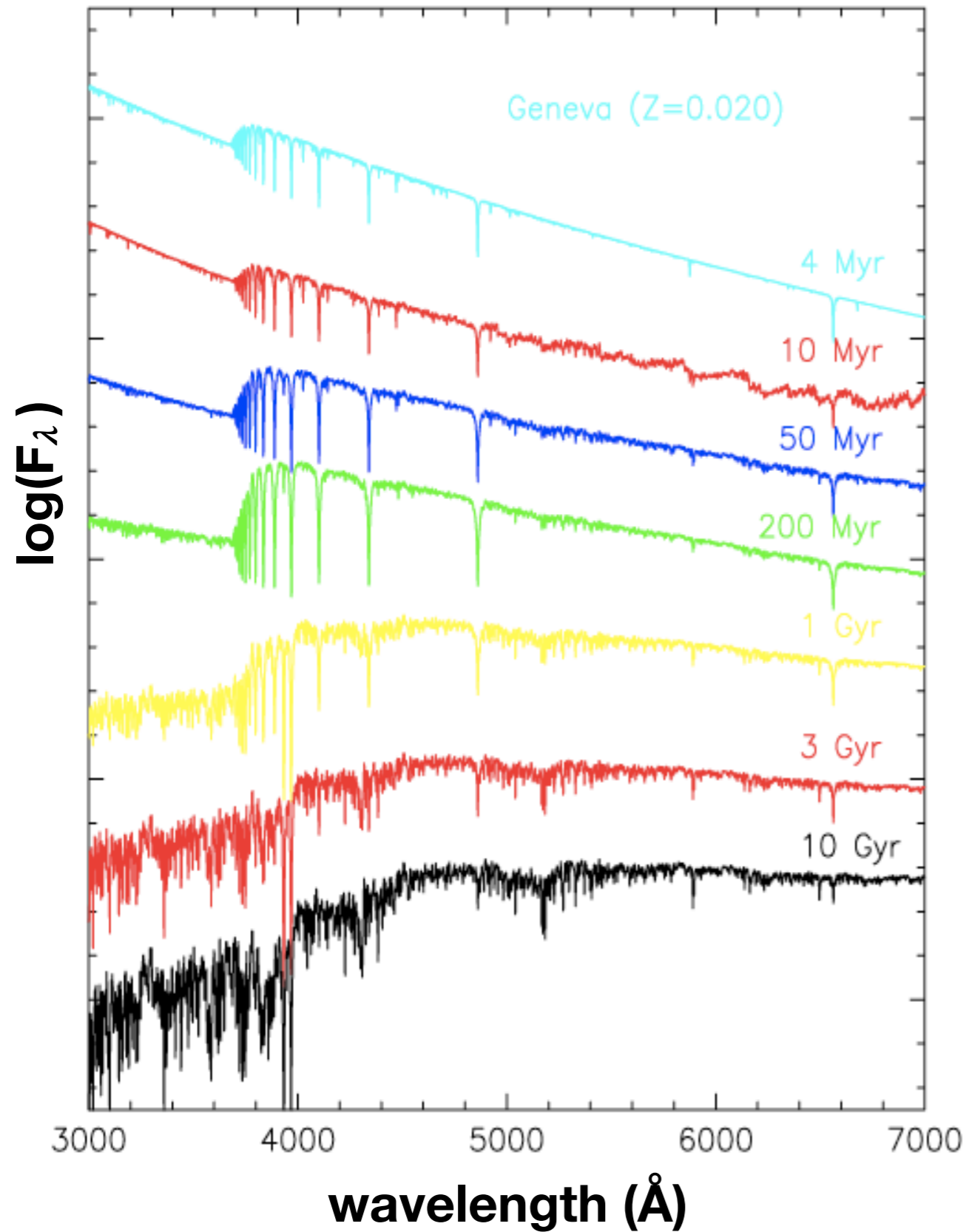


← temperature →

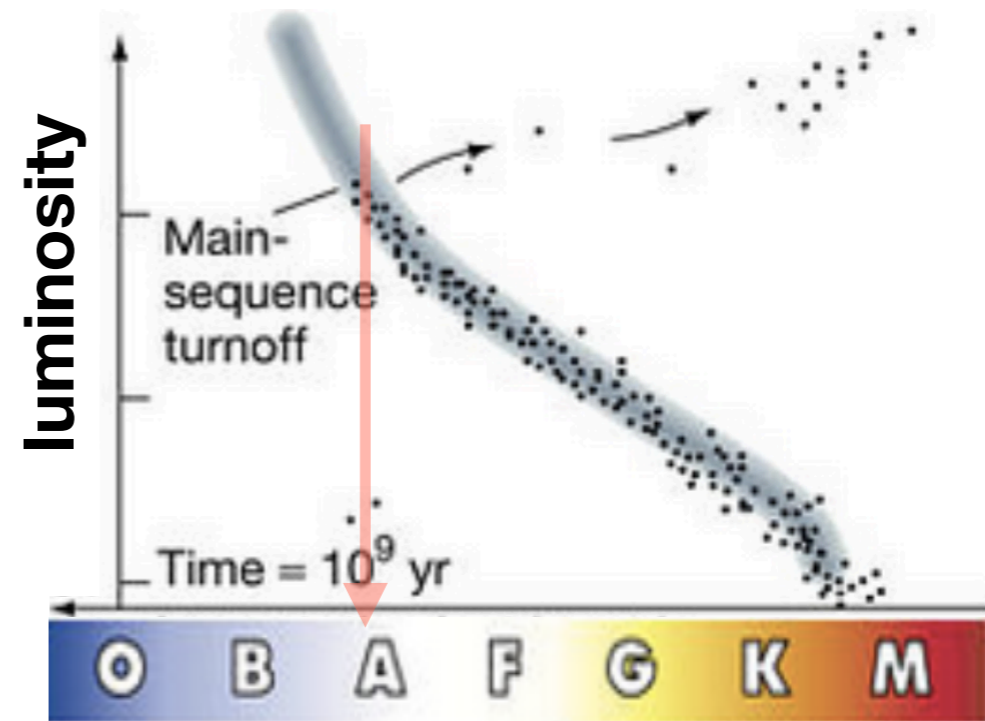
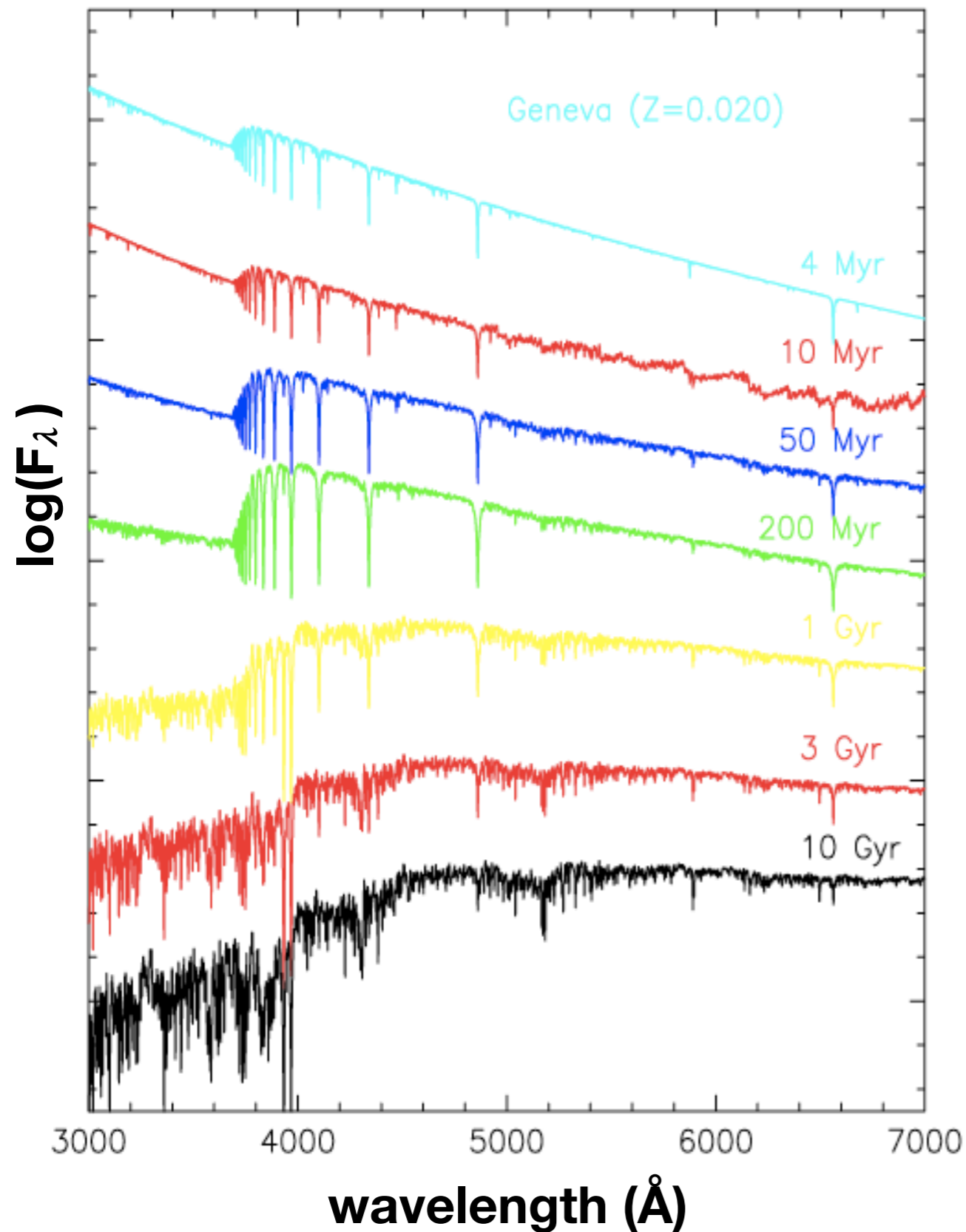
Time evolution of a SSP



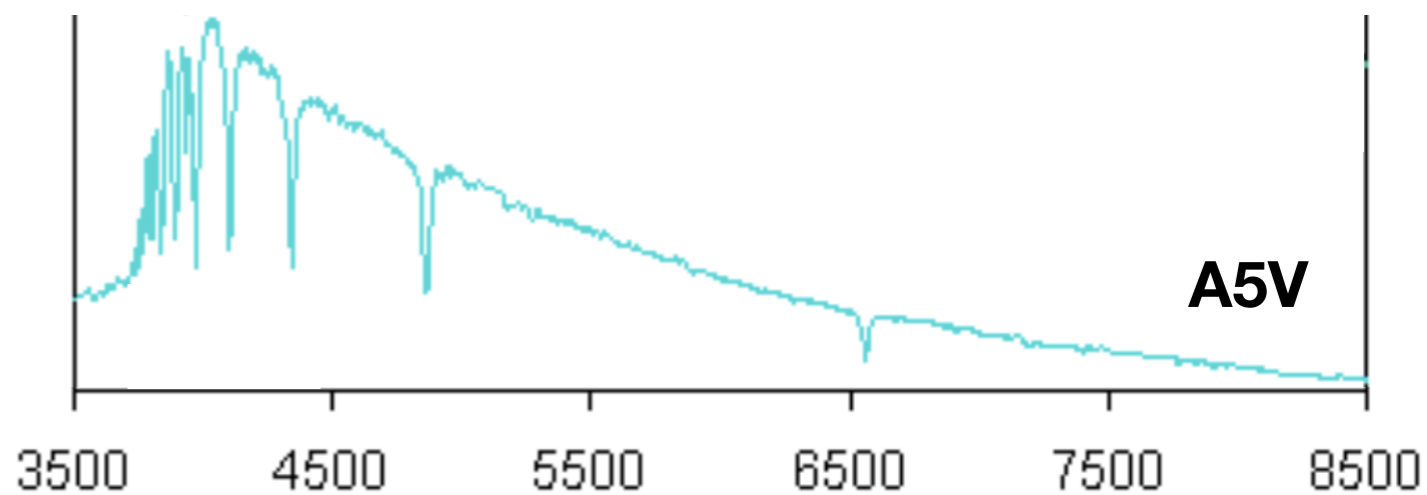
Time evolution of a SSP



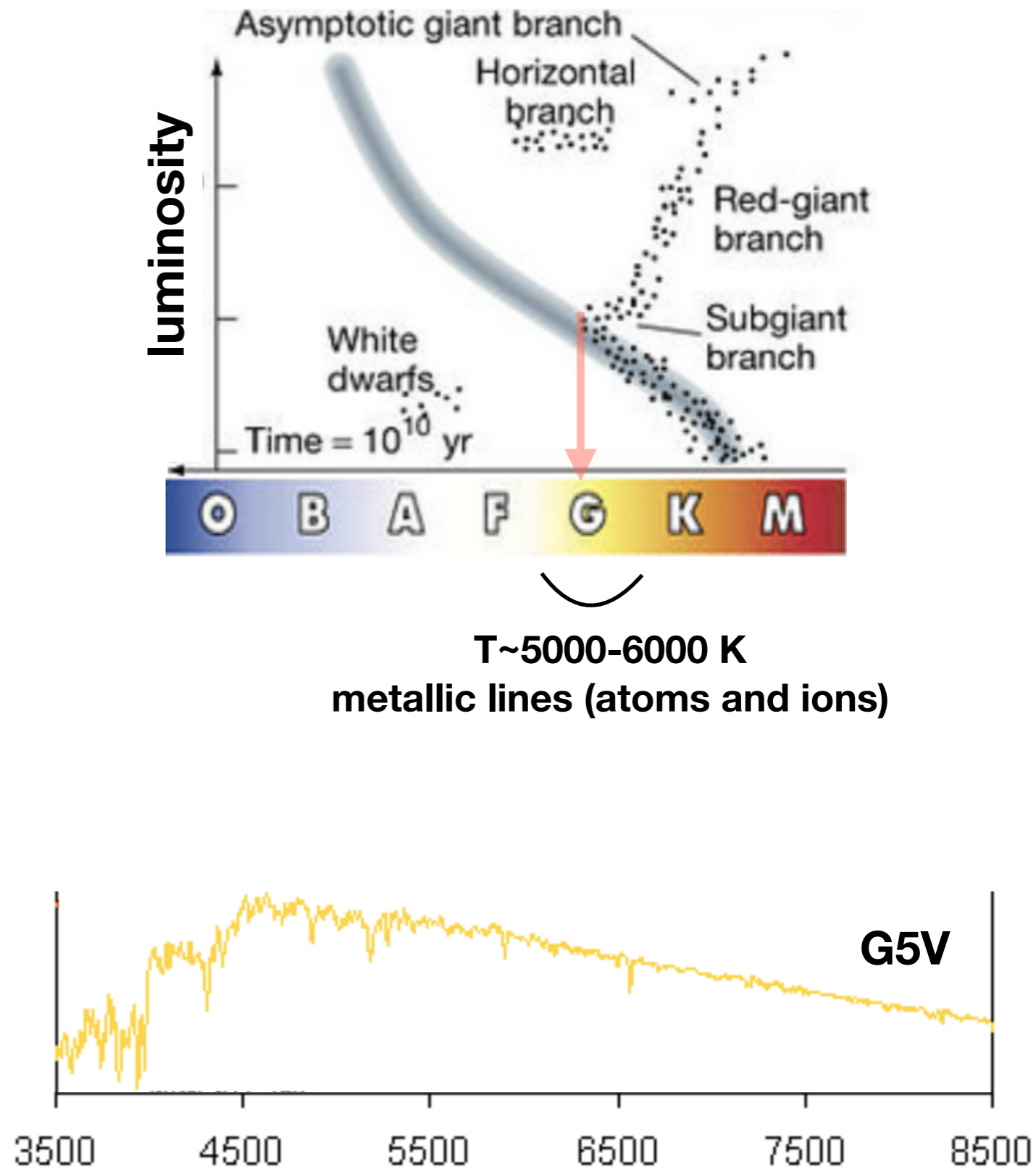
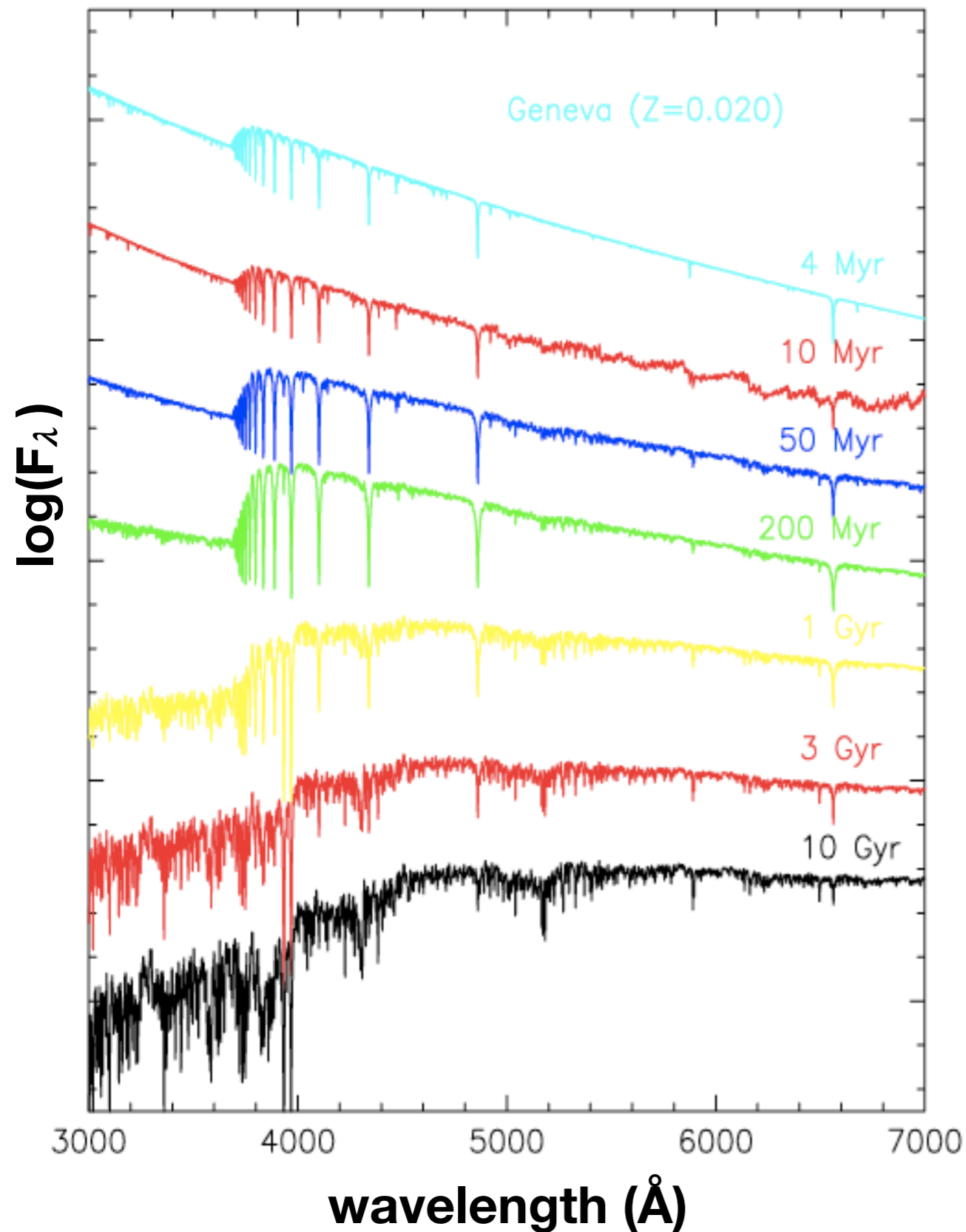
Time evolution of a SSP



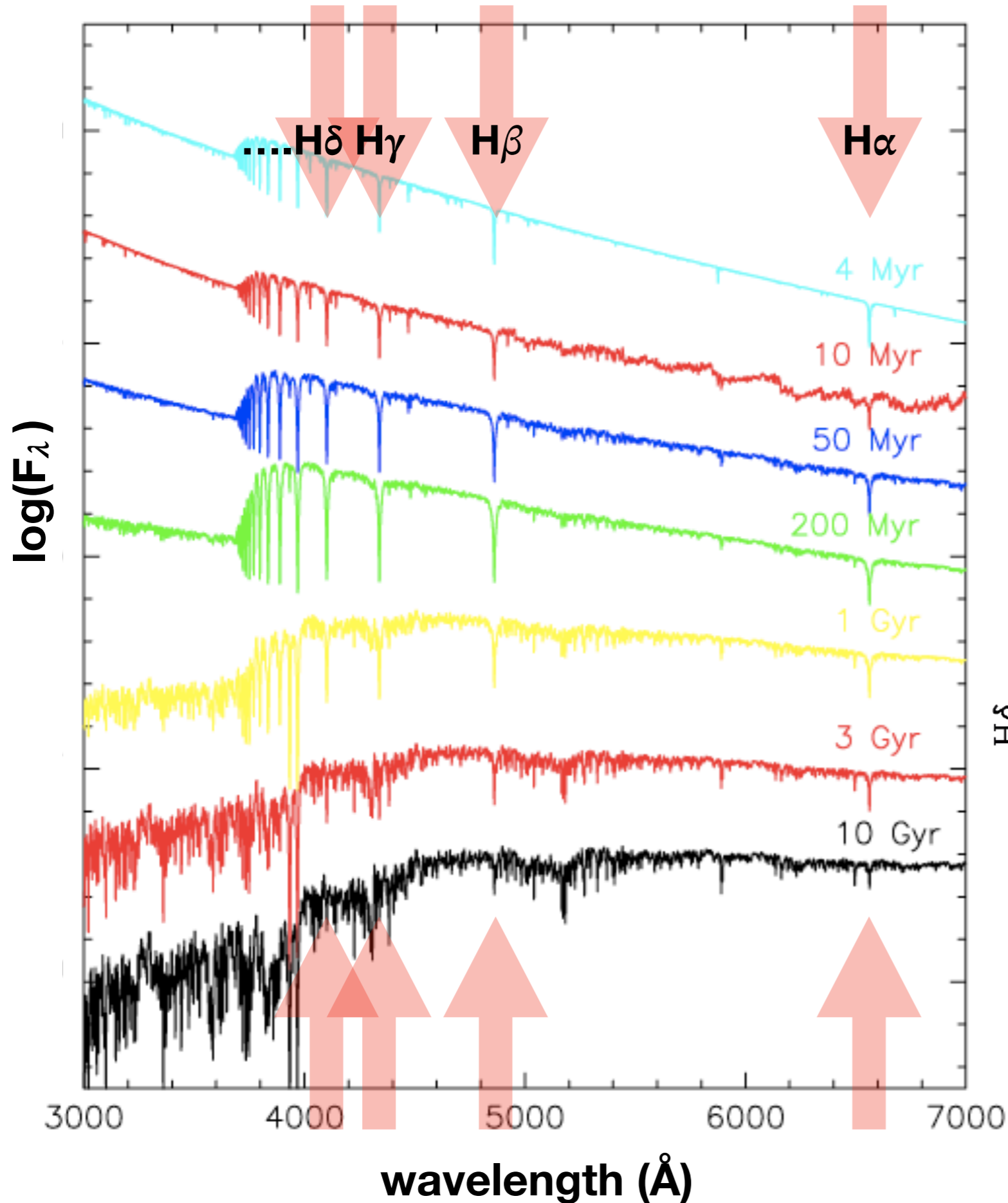
$T \sim 7500-11000$ K
maximum strength H lines (for A0 stars)



Time evolution of a SSP



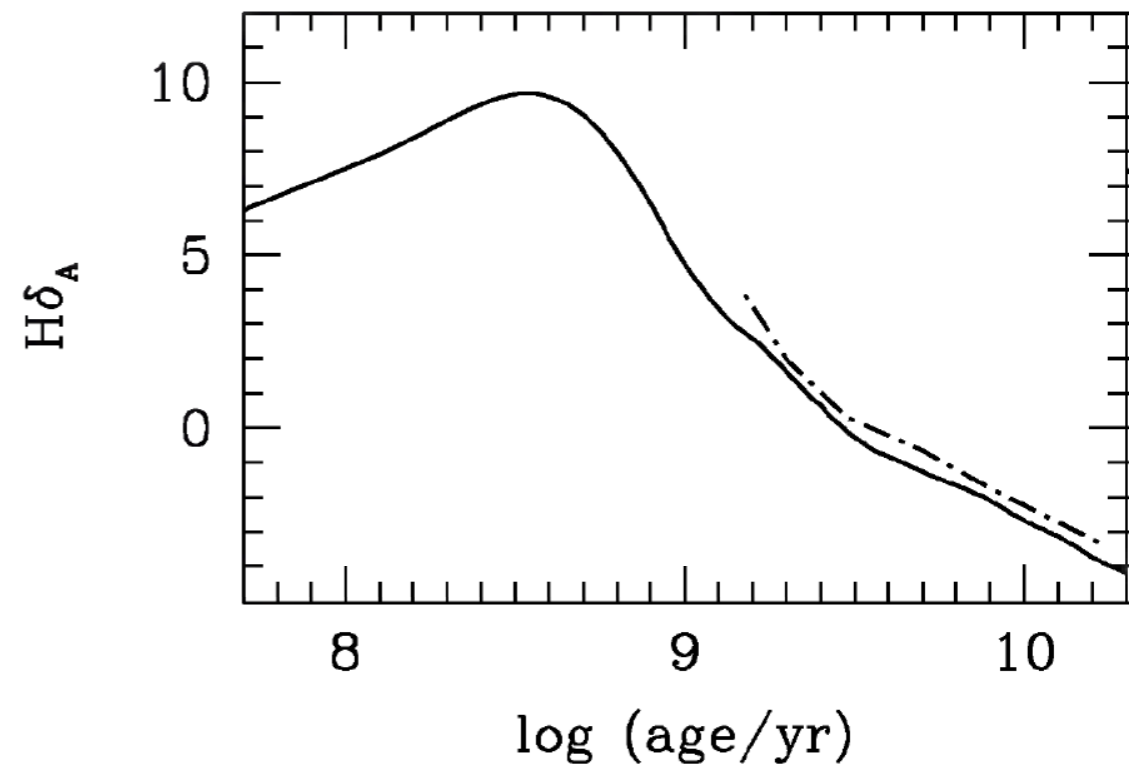
Time evolution of a SSP



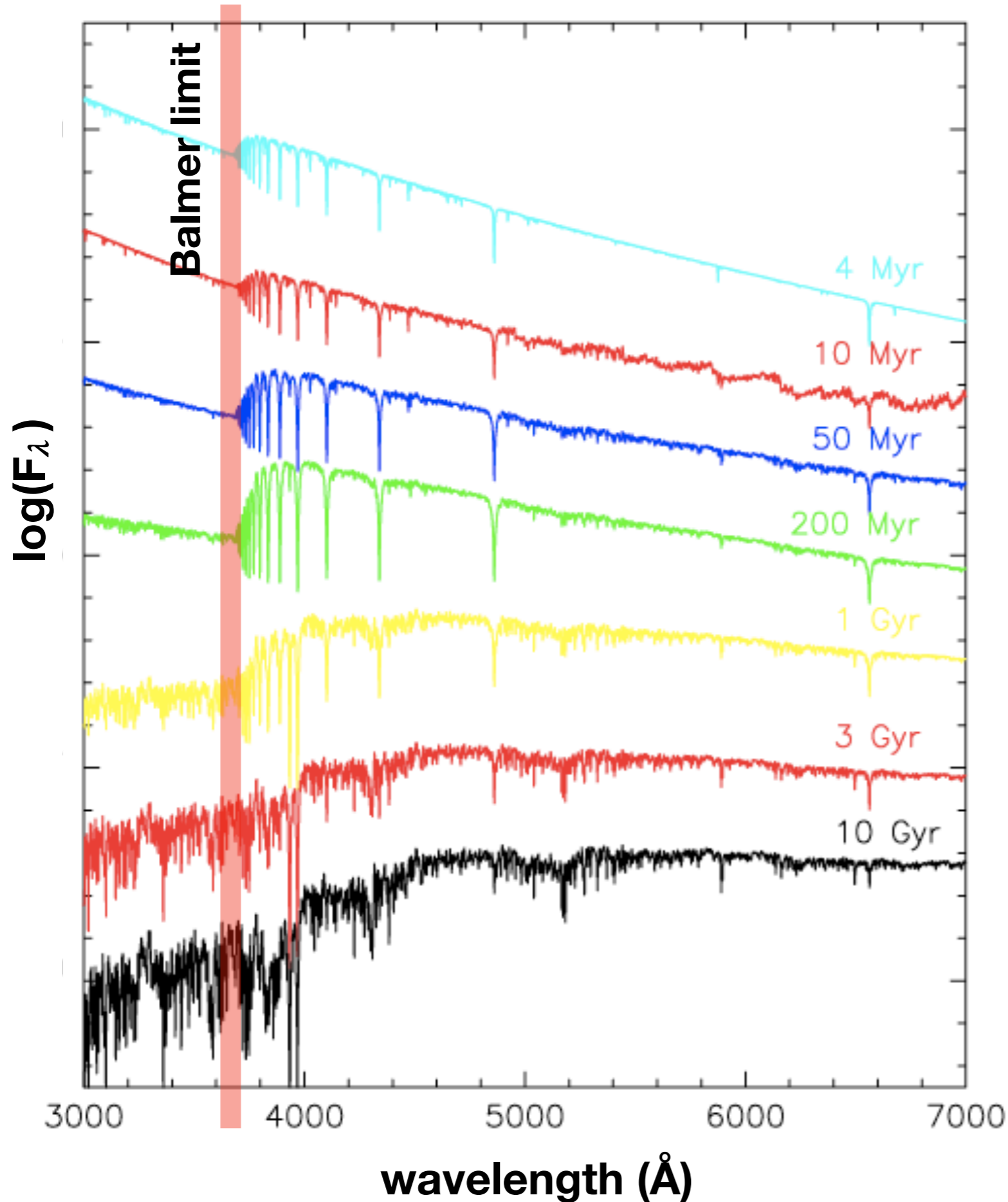
and thus:

[note time evolution of most prominent features]

- Balmer break
- 4000Å break
- Balmer lines
- metallic lines



Time evolution of a SSP

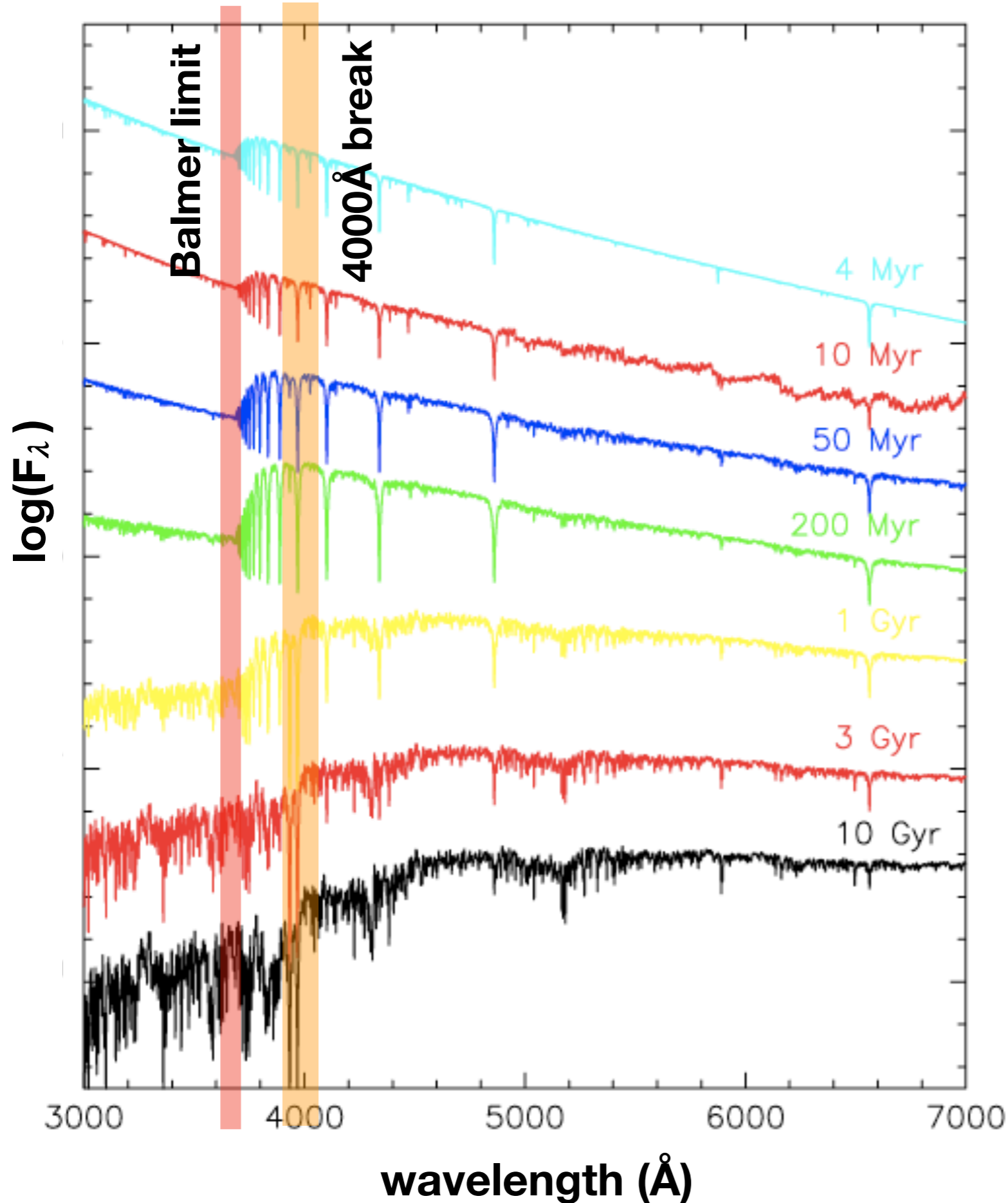


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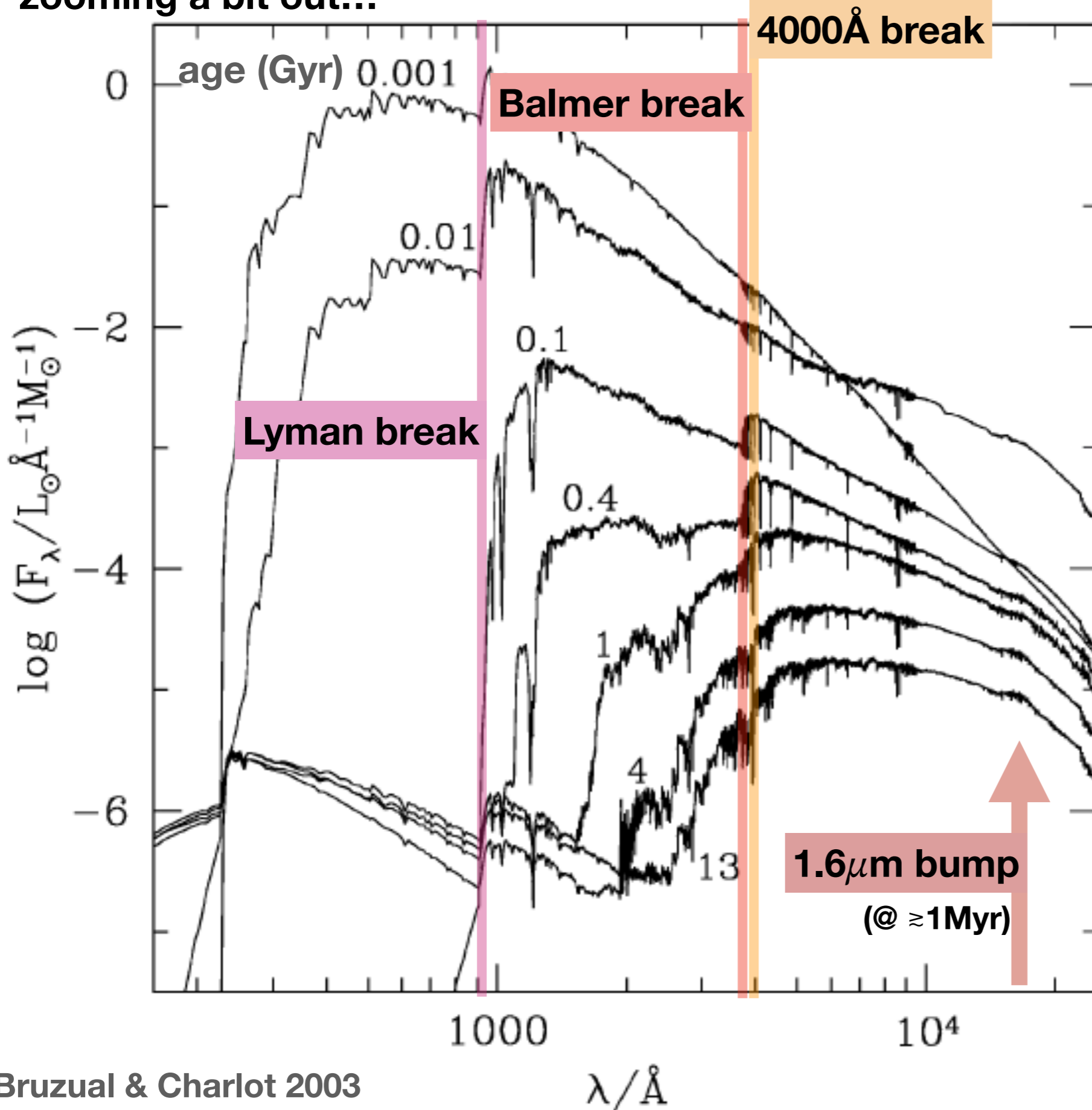
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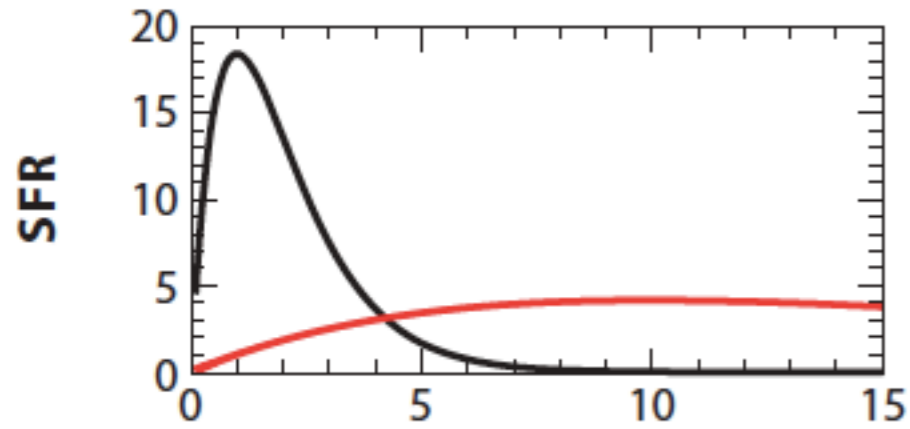
Time evolution of a SSP

zooming a bit out...

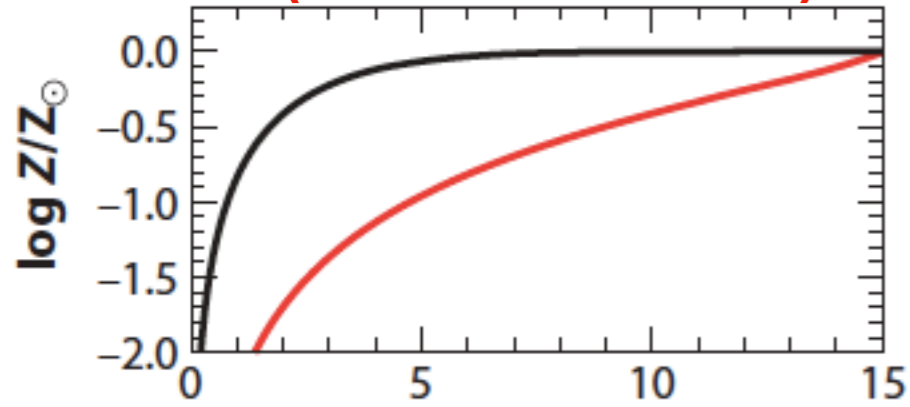


Stellar Population Synthesis (SPS) -The next step: CSPs

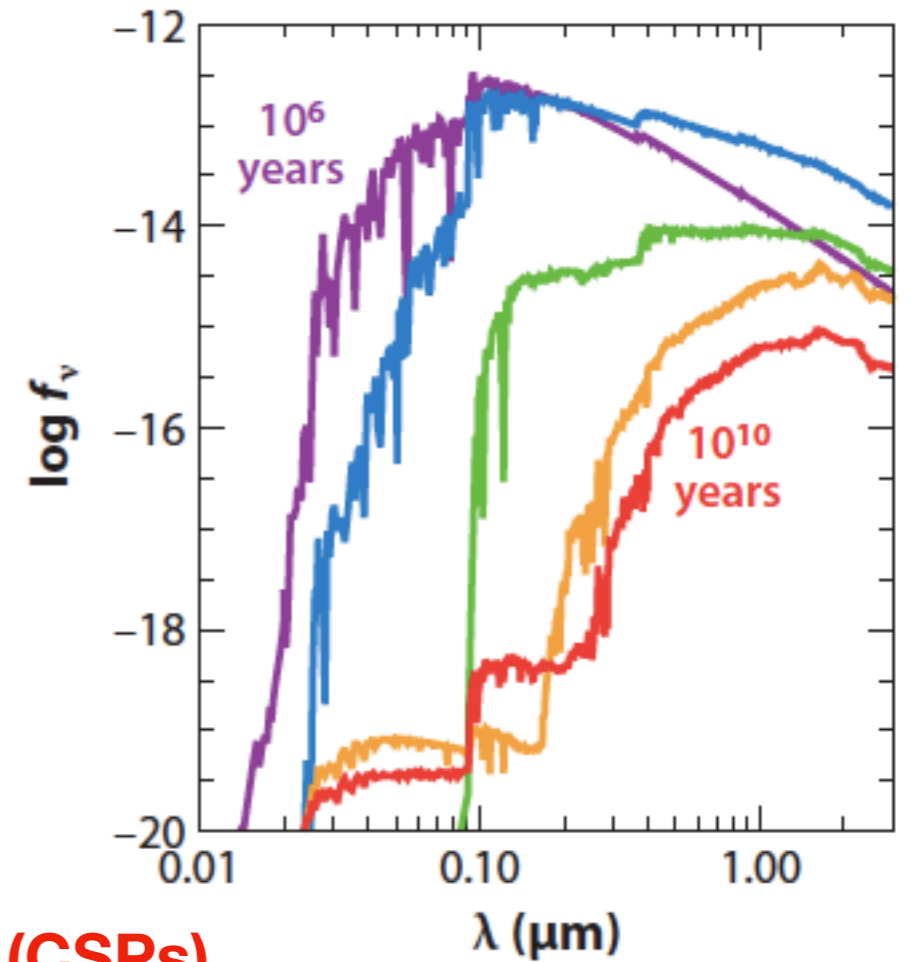
star formation history (SFH)



(chemical evolution)



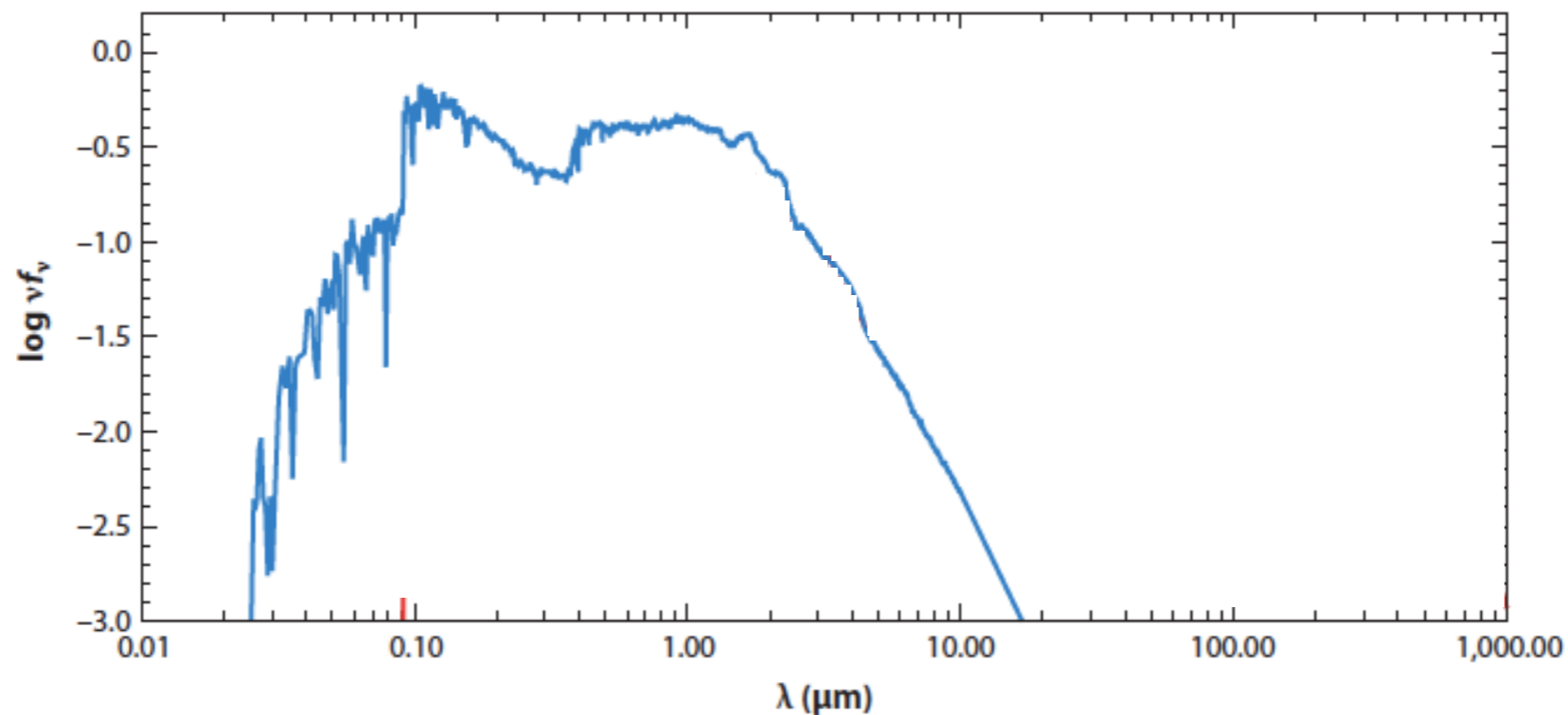
SSP (time evolution)



Conroy 2013

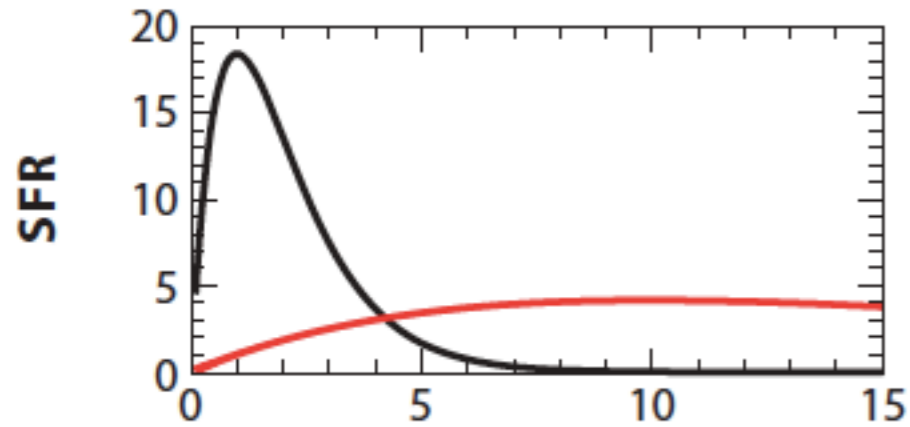
t (Gyr)

composite stellar populations (CSPs)

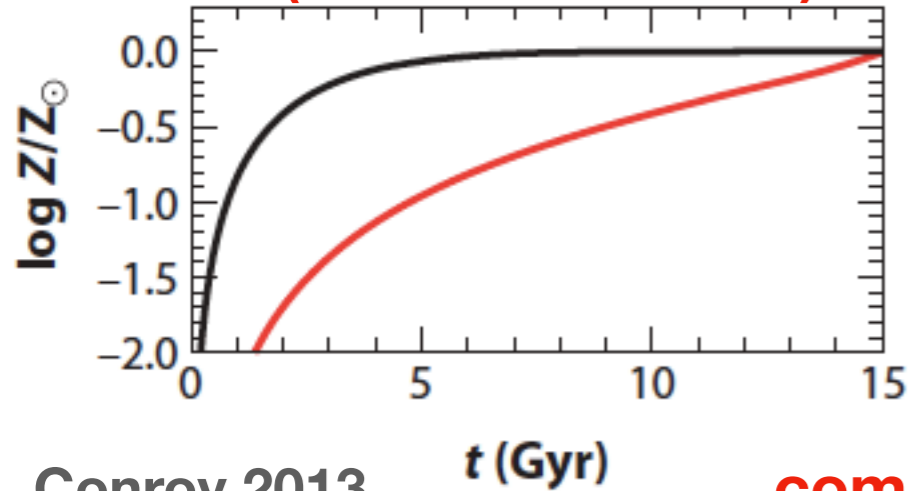


Stellar Population Synthesis (SPS) -The next step: CSPs

star formation history (SFH)



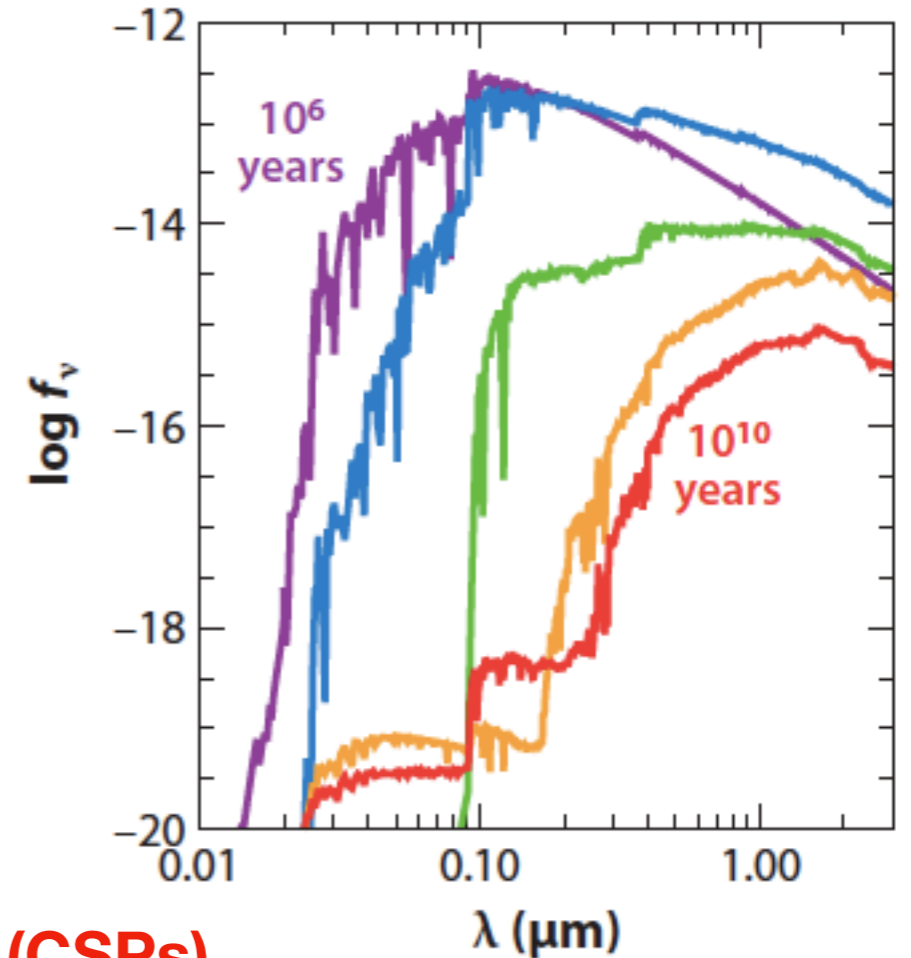
(chemical evolution)



Conroy 2013

t (Gyr)

SSP (time evolution)

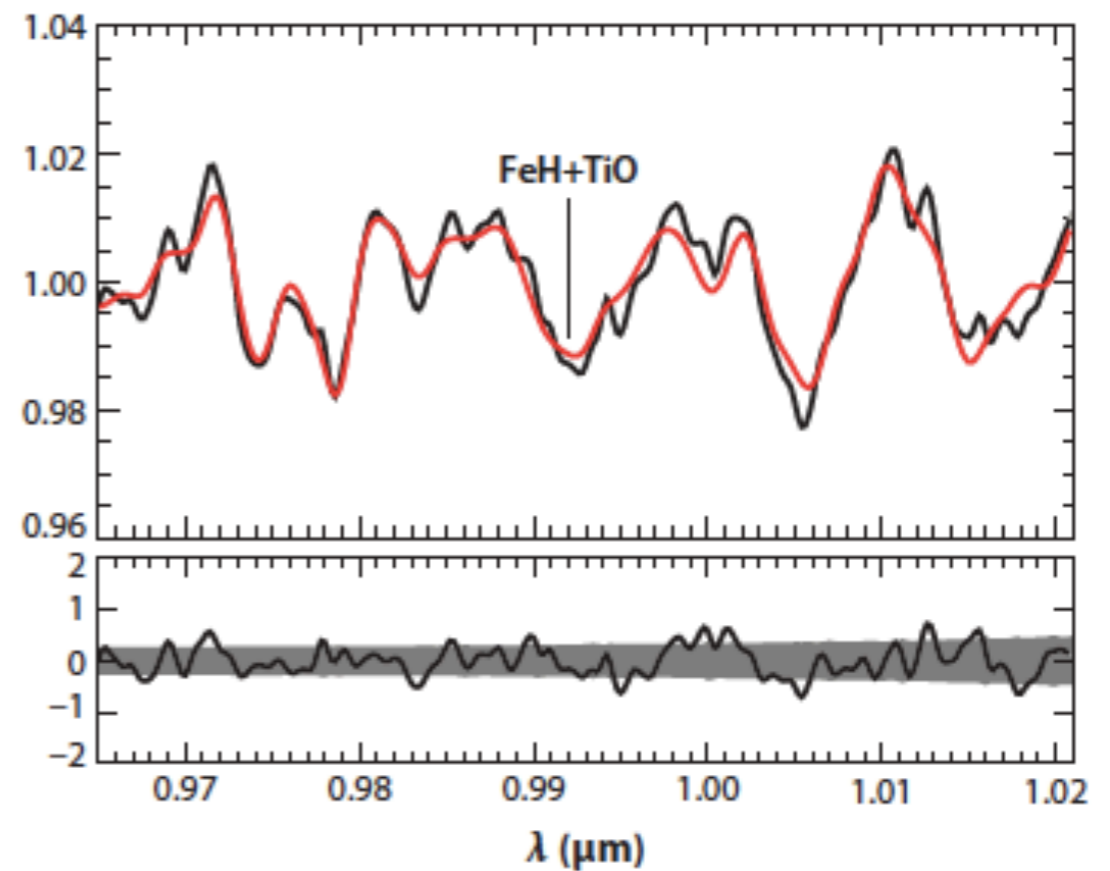
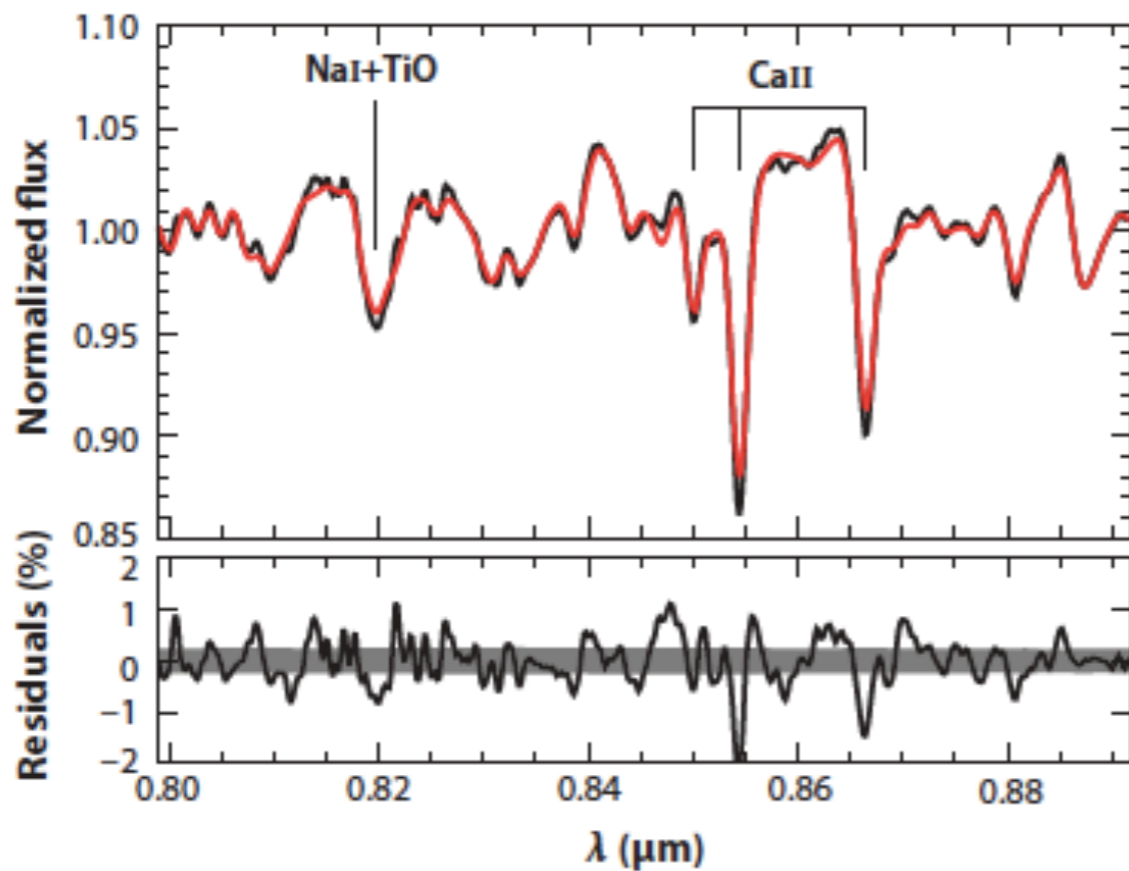
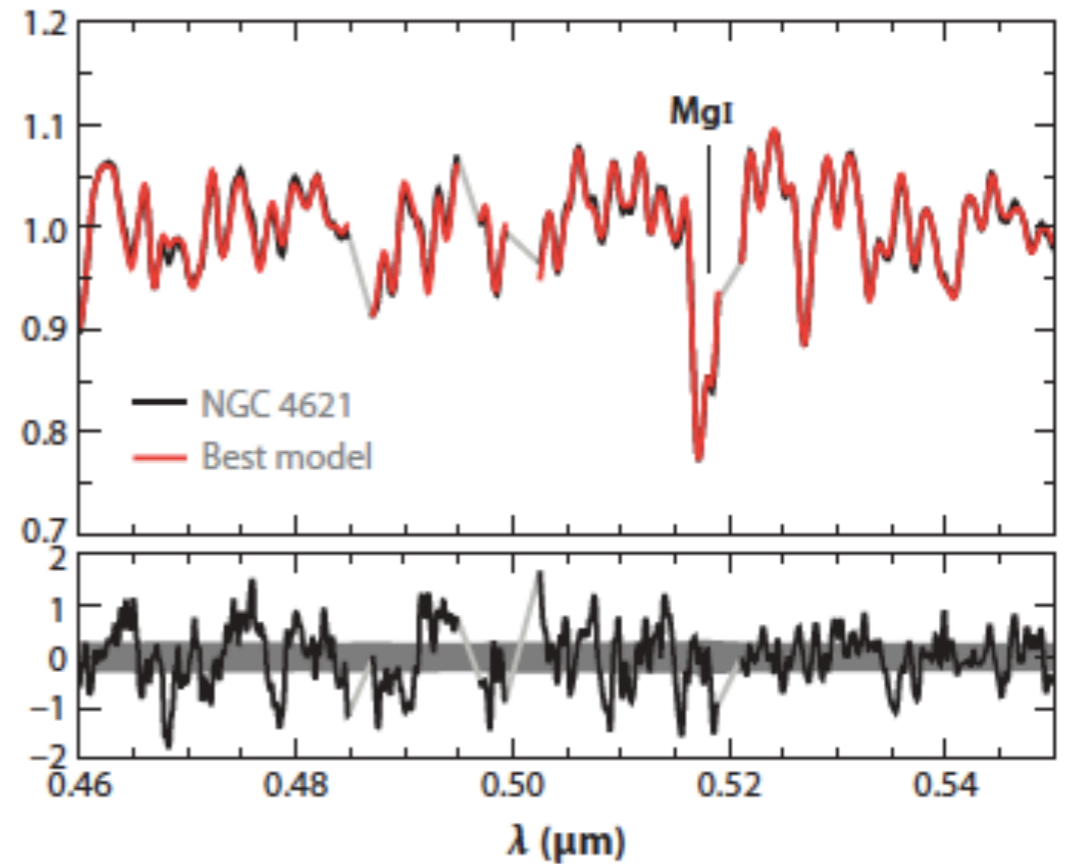
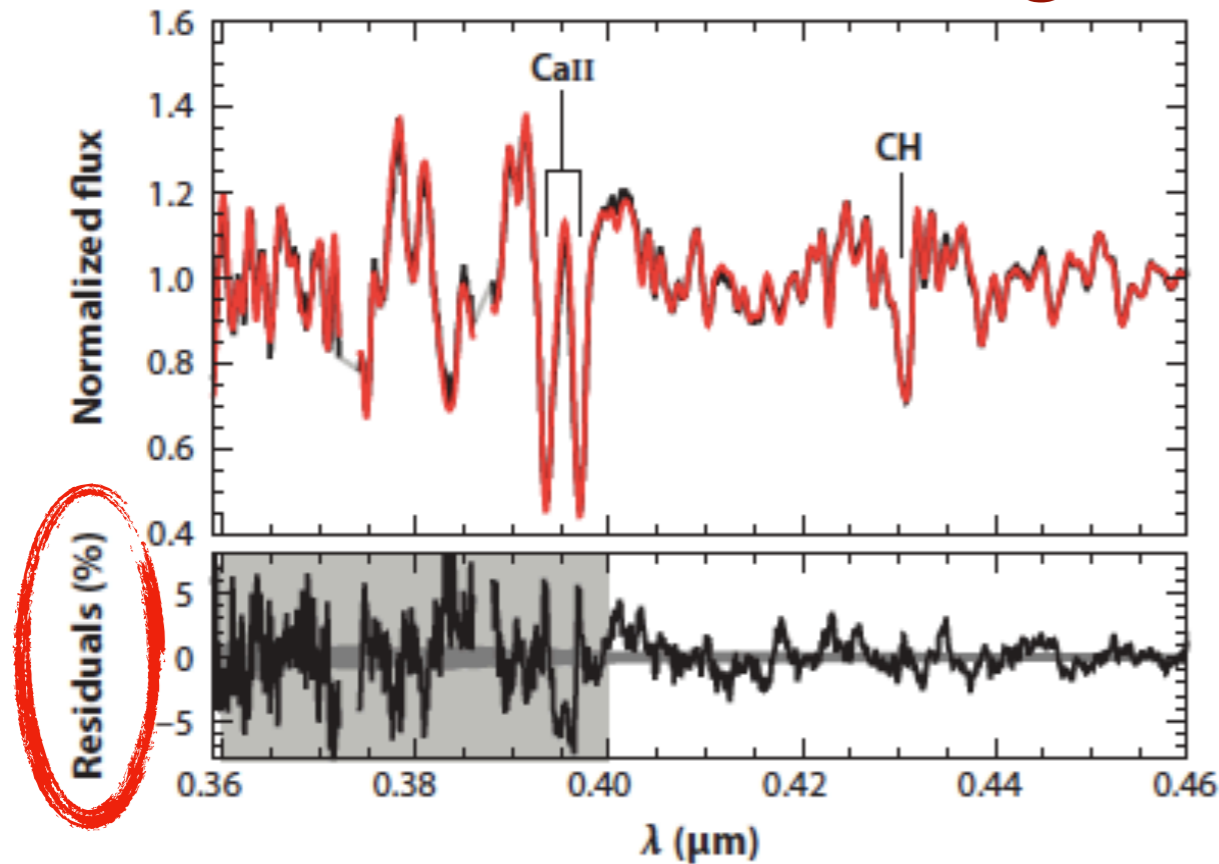


composite stellar populations (CSPs)

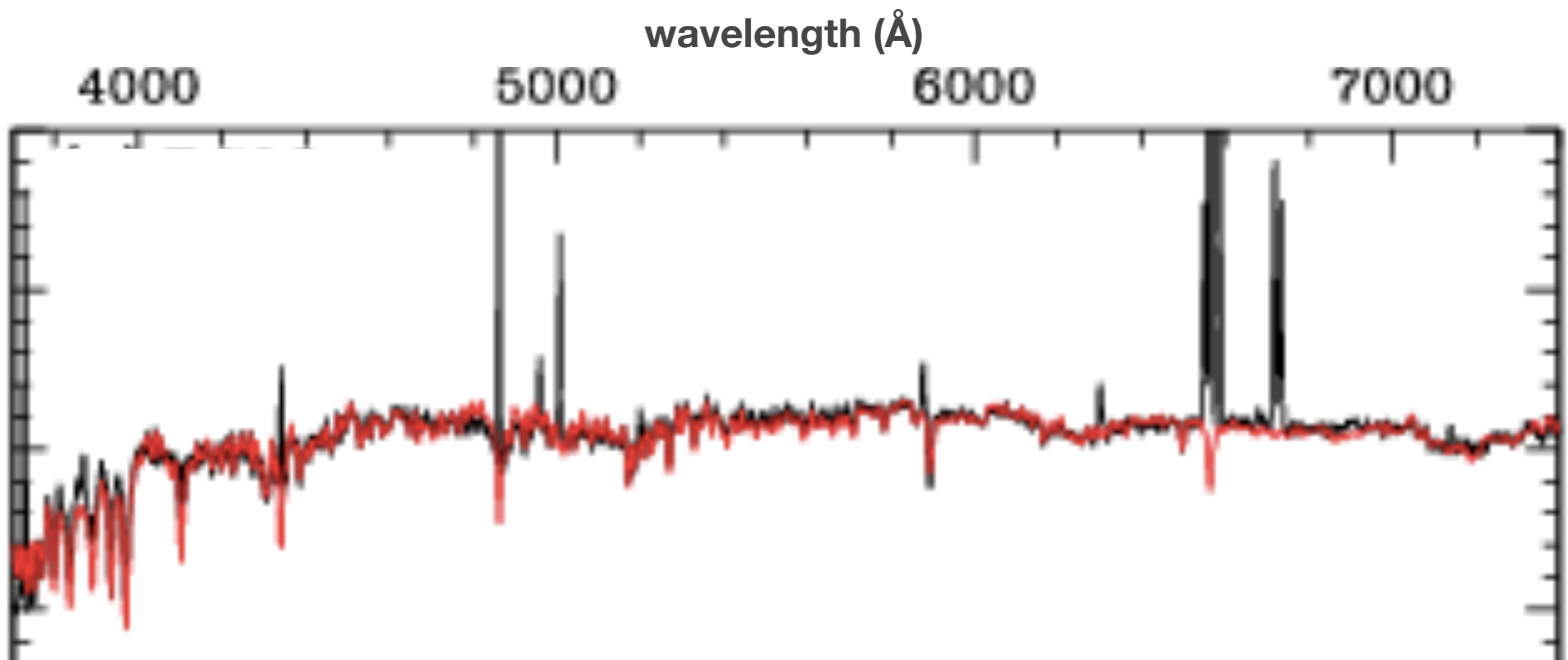
$$f_{\text{CSP}}(t) = \int_{t'=0}^{t'=t} \int_{Z=0}^{Z_{\text{max}}} \left(\underbrace{\text{SFR}(t-t')}_{\text{SFH}} \underbrace{P(Z, t-t')}_{\text{chemical evolution}} \underbrace{f_{\text{SSP}}(t', Z)}_{\text{SSP spectra}} \right) dt' dZ$$

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 constituents:

- 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.

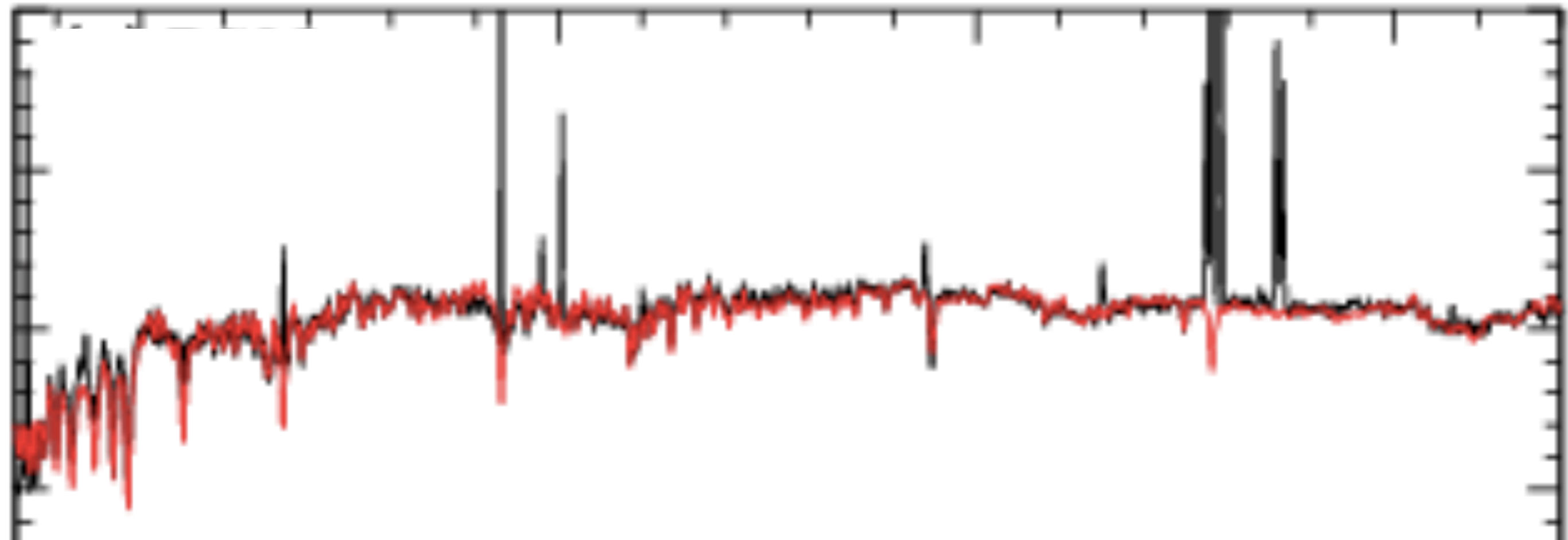
wavelength (Å)

4000

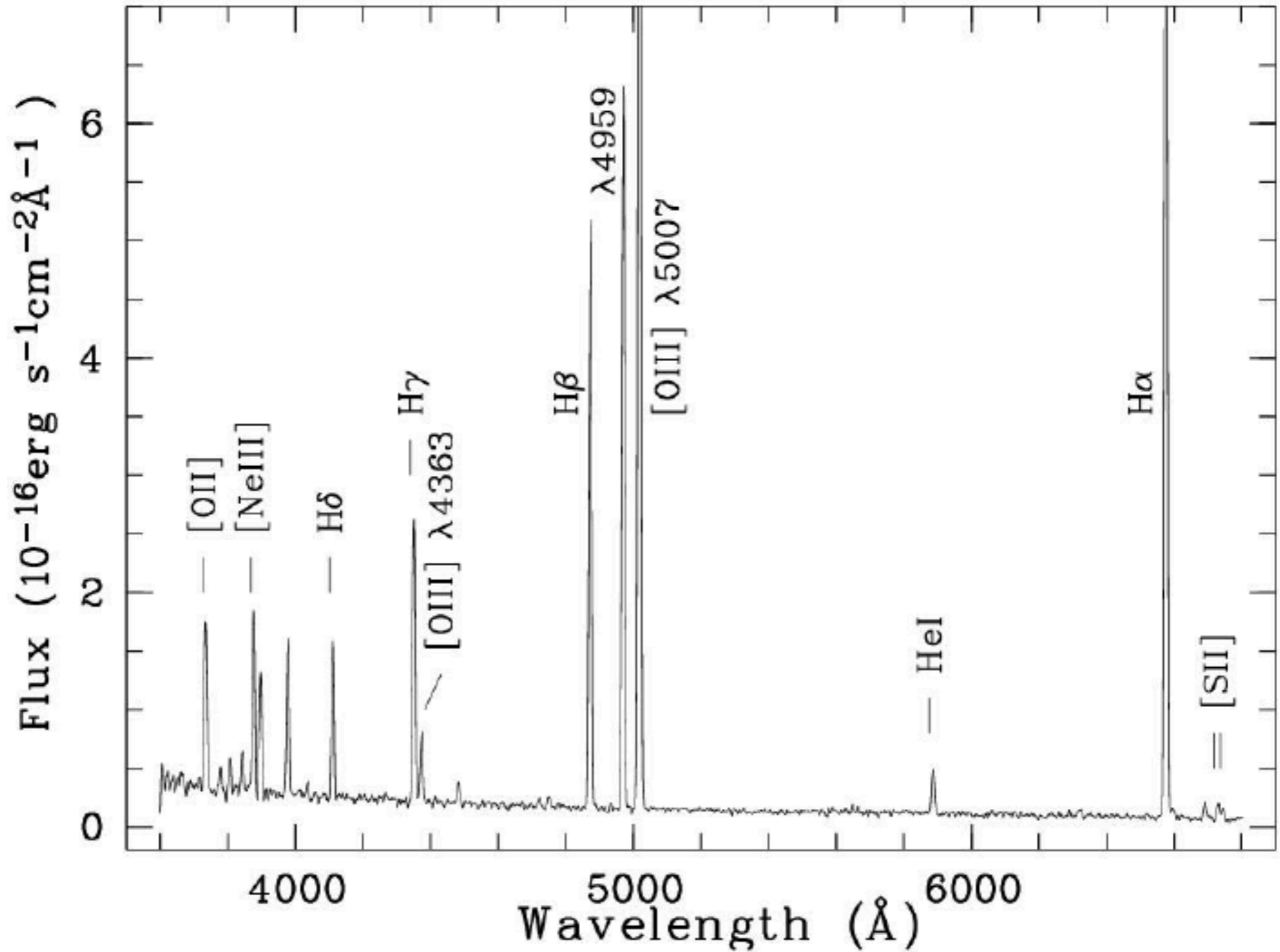
5000

6000

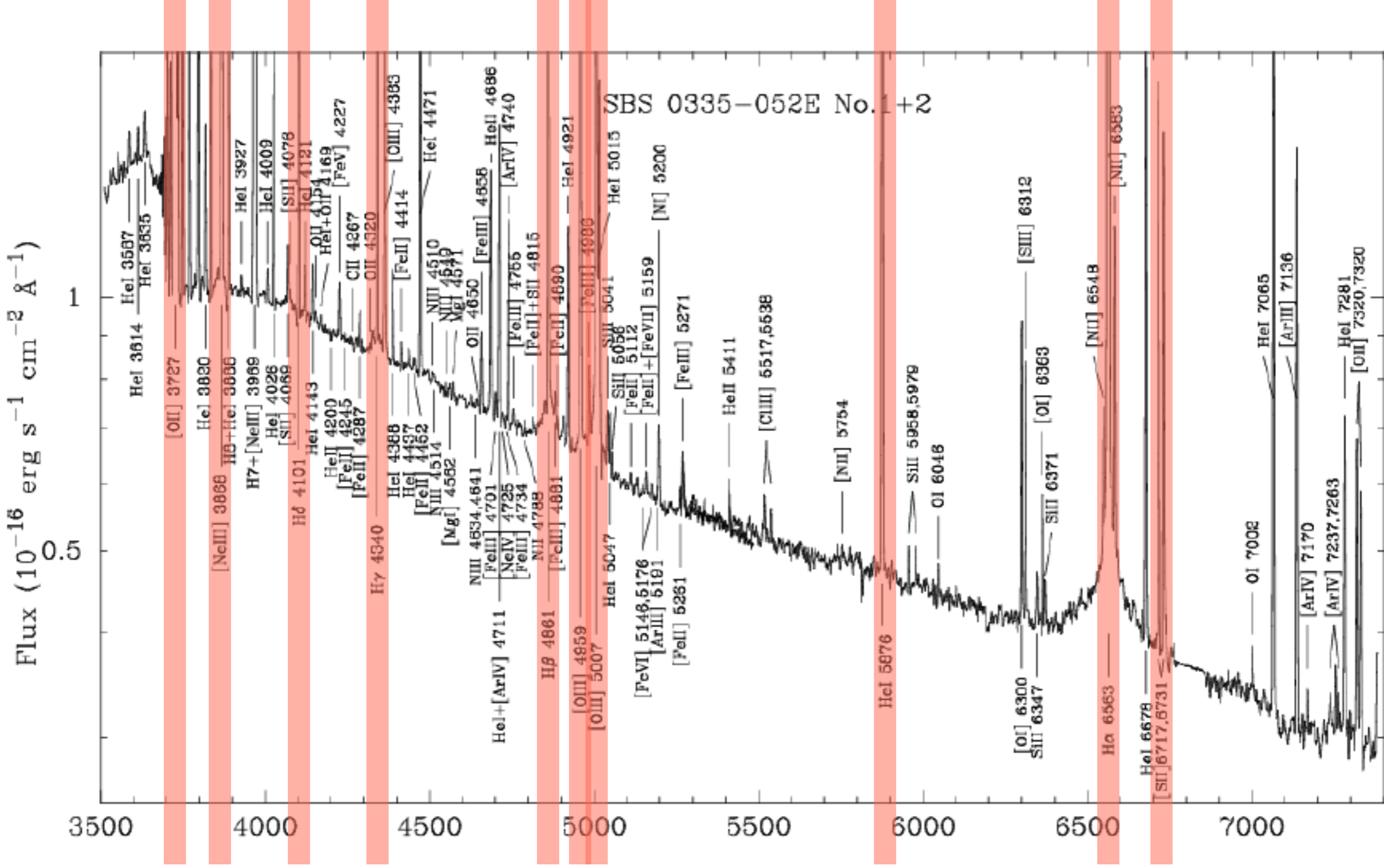
7000



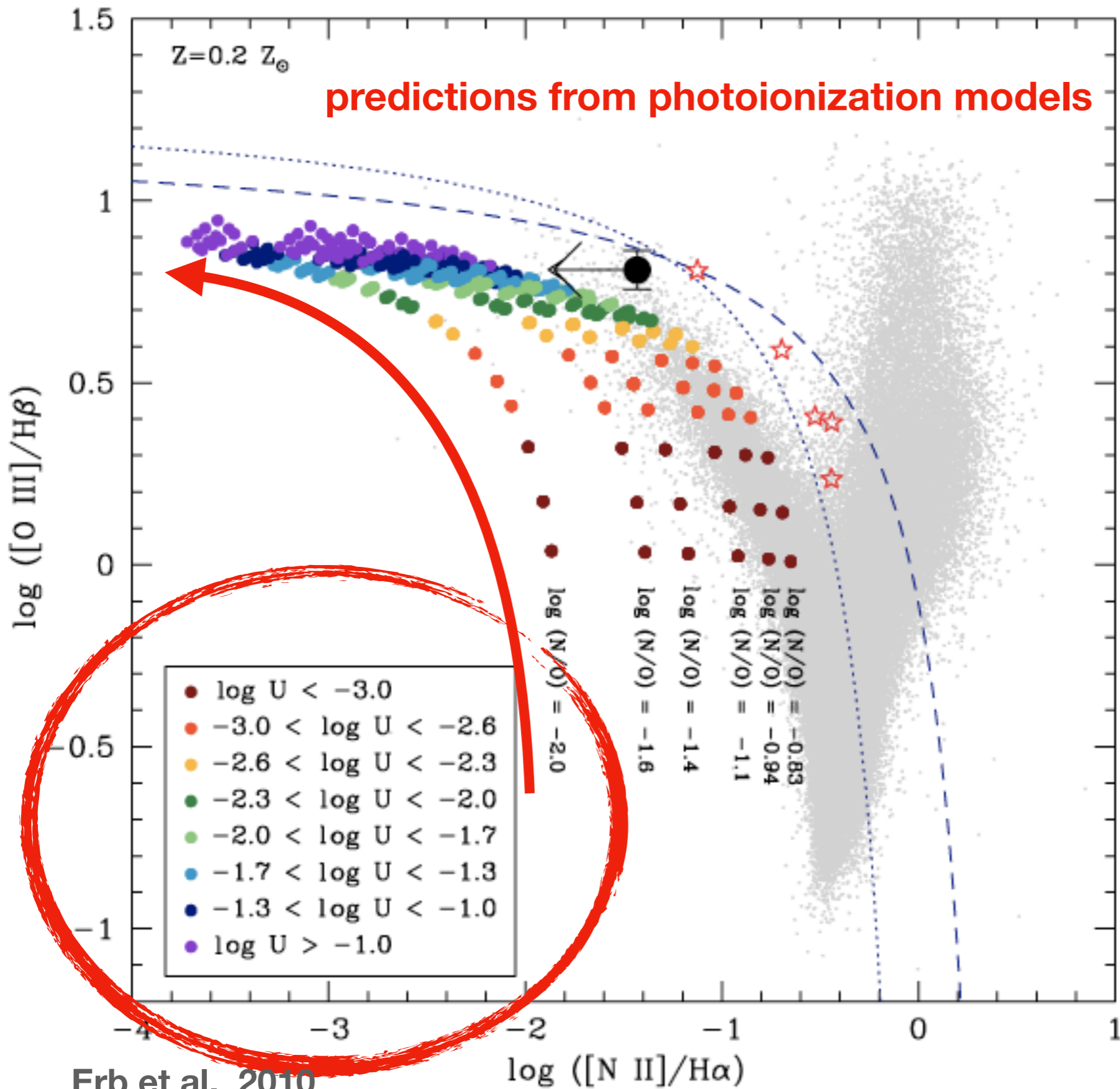
Line emission from ionised gas



Line emission from ionised gas



Line emission from ionised gas

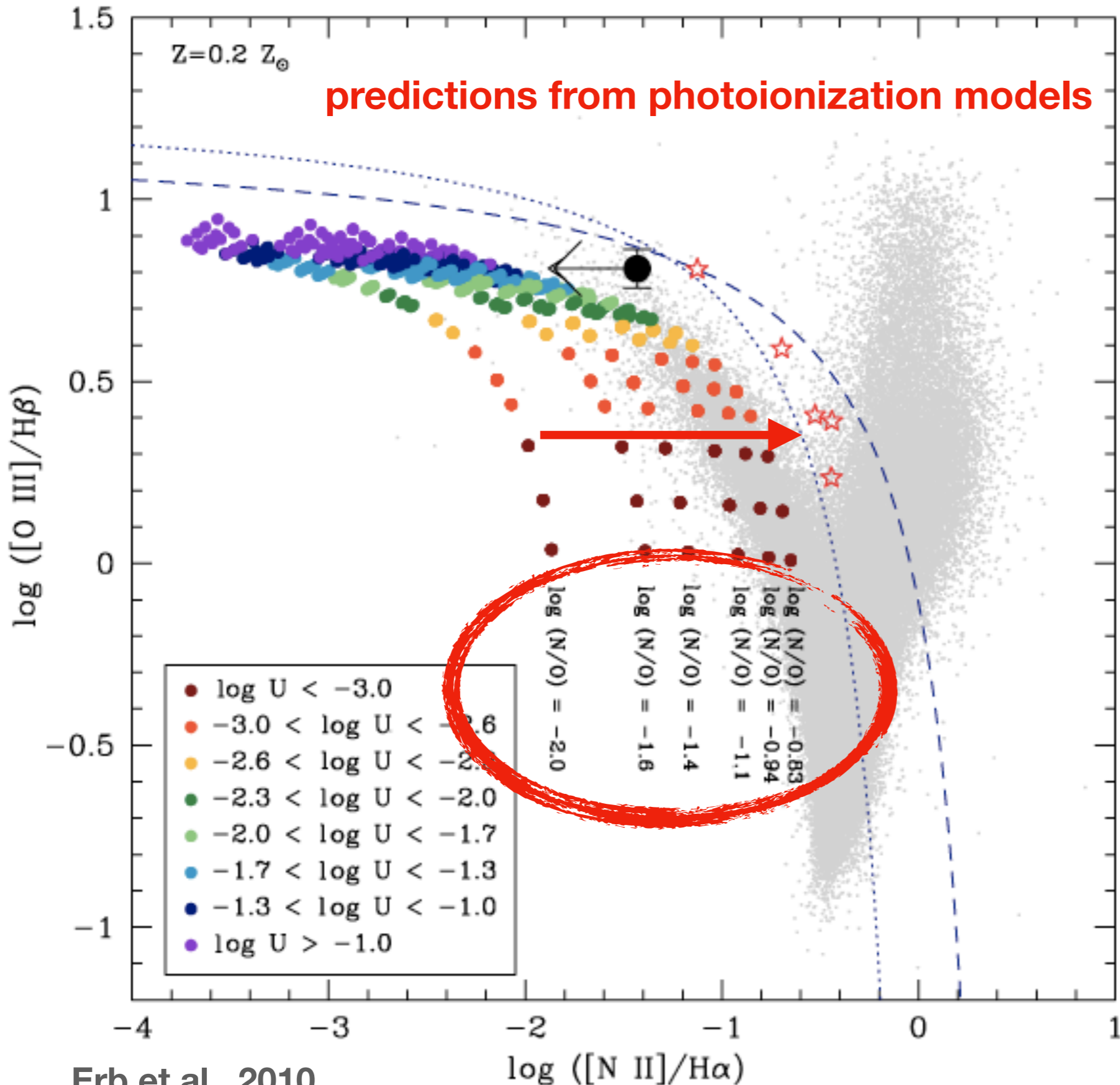


note dependence on:

- **ionization parameter**

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

Line emission from ionised gas



note dependence on:

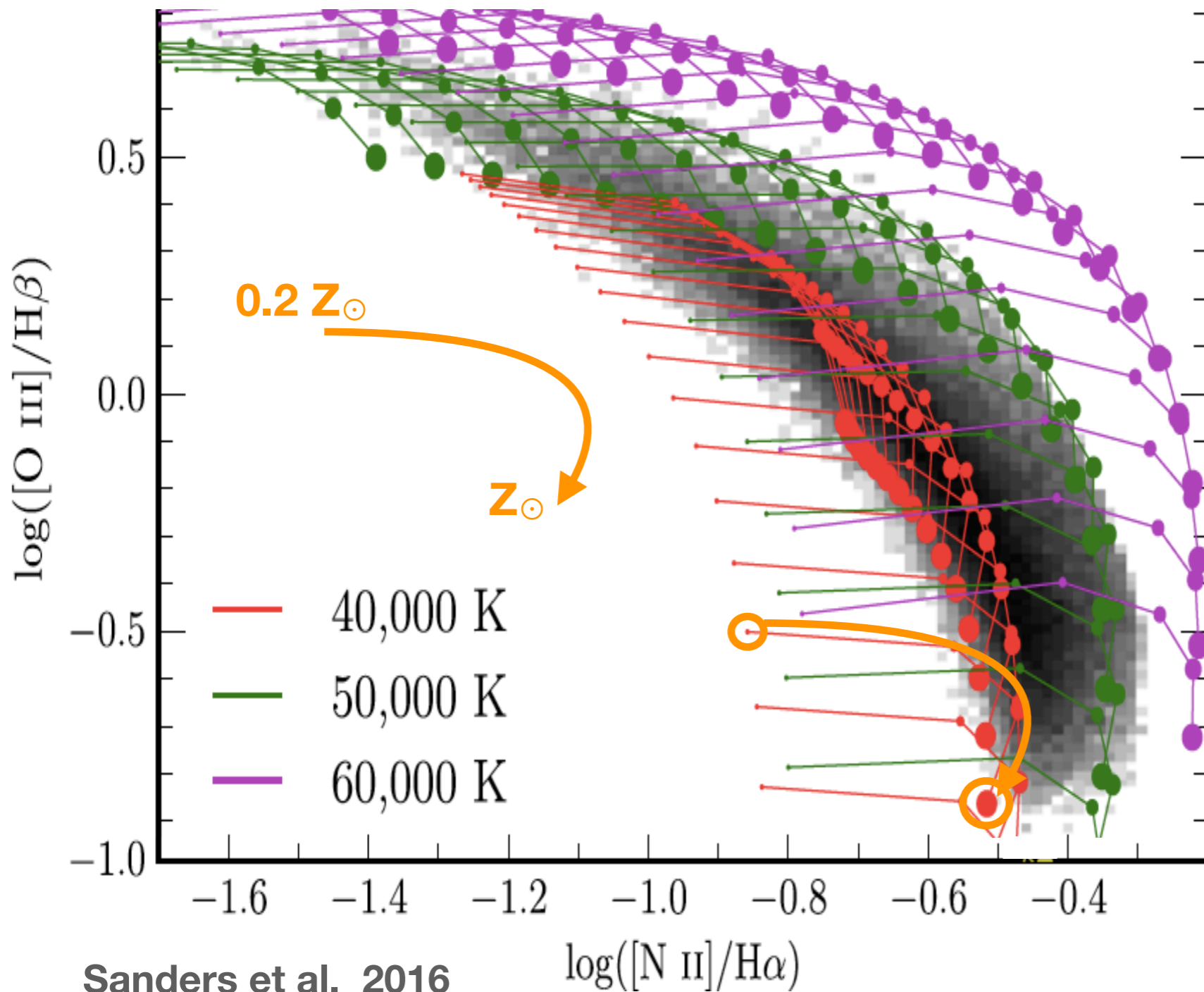
- ionization parameter
- N/O abundance

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

Line emission from ionised gas

predictions from photoionization models

note dependence on:
- ionization parameter
- N/O abundance
(SF history, chemical enrichment history, inflows/outflows)
- metallicity
- ...



Sanders et al. 2016

Where does a galaxy SED come from

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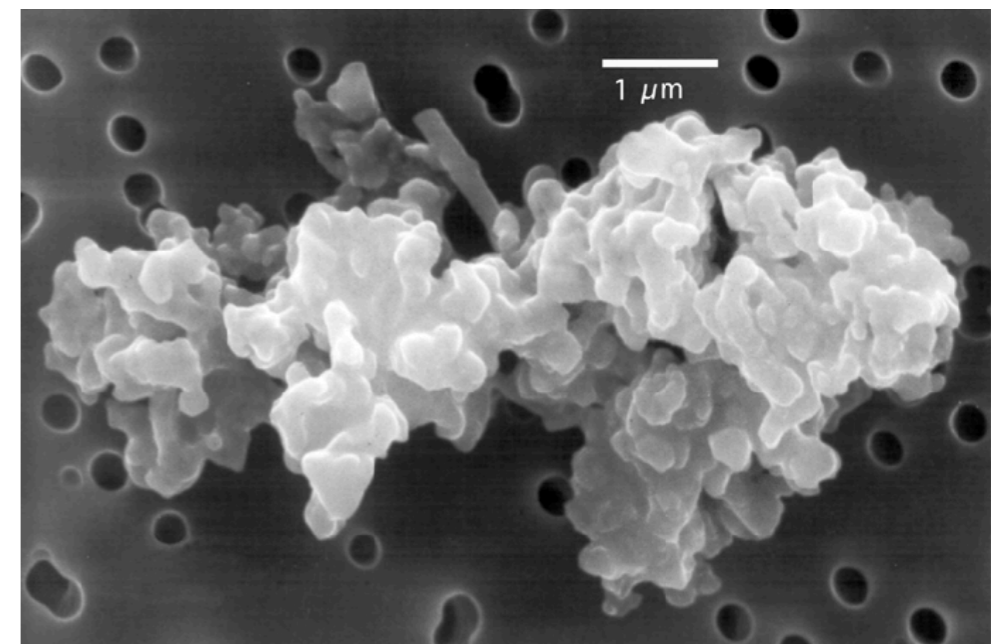
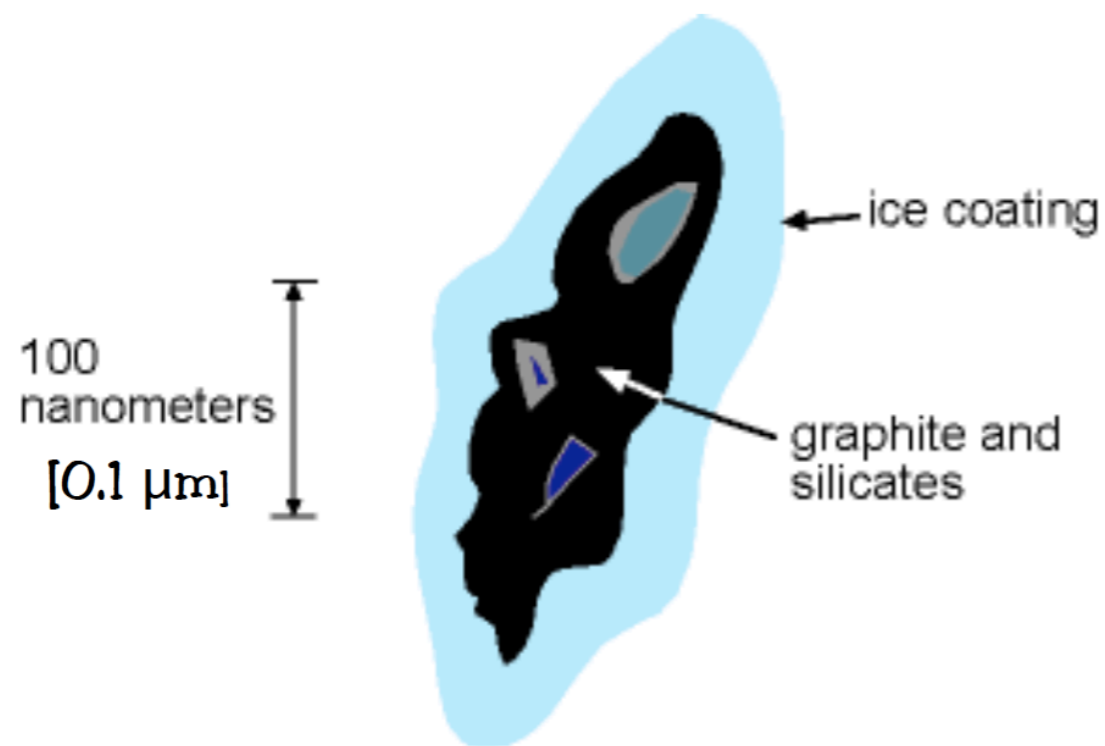
- stars
- gas
- AGN
- dust

Where does a galaxy SED come from

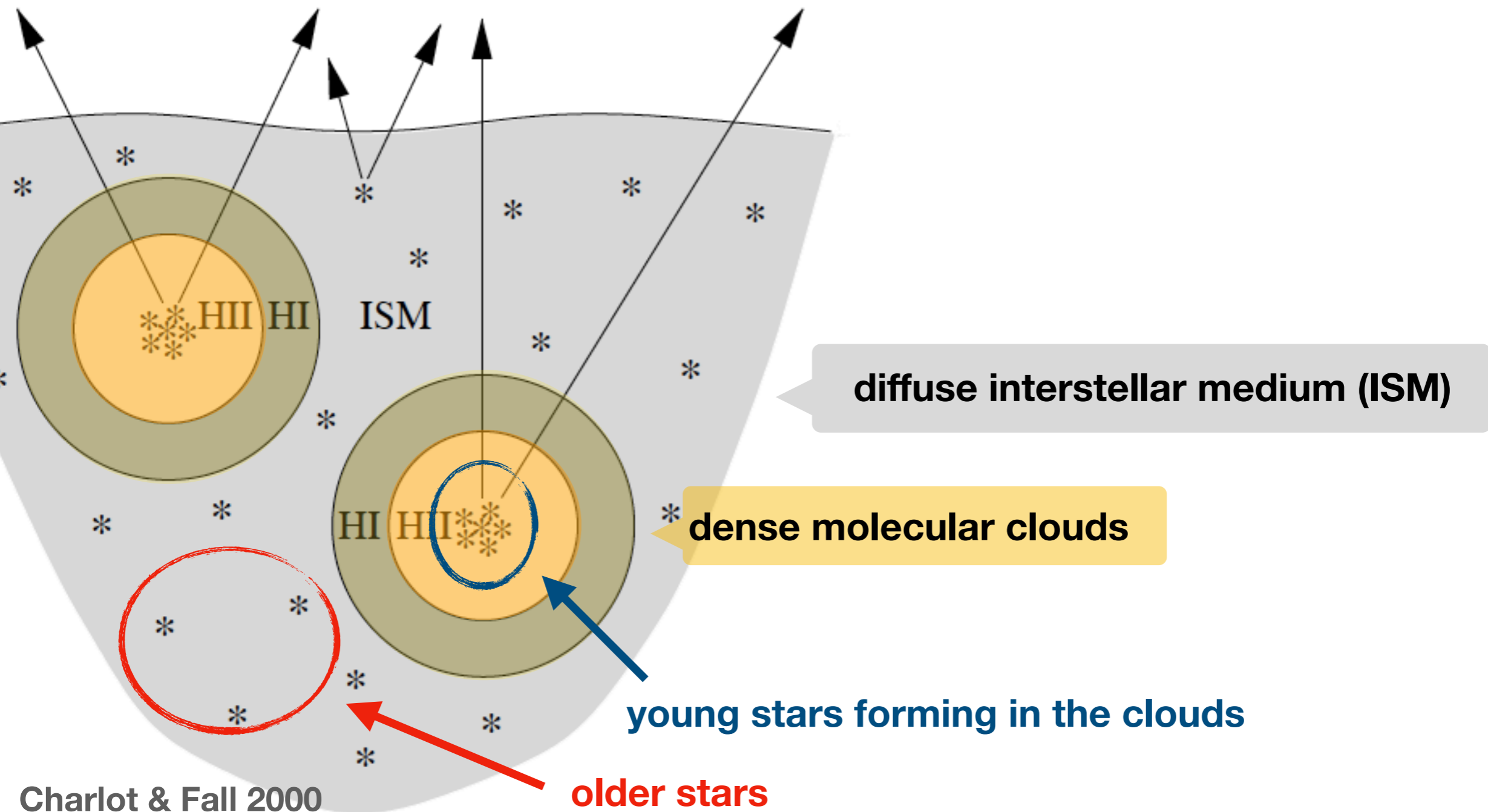
Galaxy spectral energy distributions are the result of the combination of light emission and absorption from the (baryonic) galaxy constituents:

- 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 at different wavelengths.

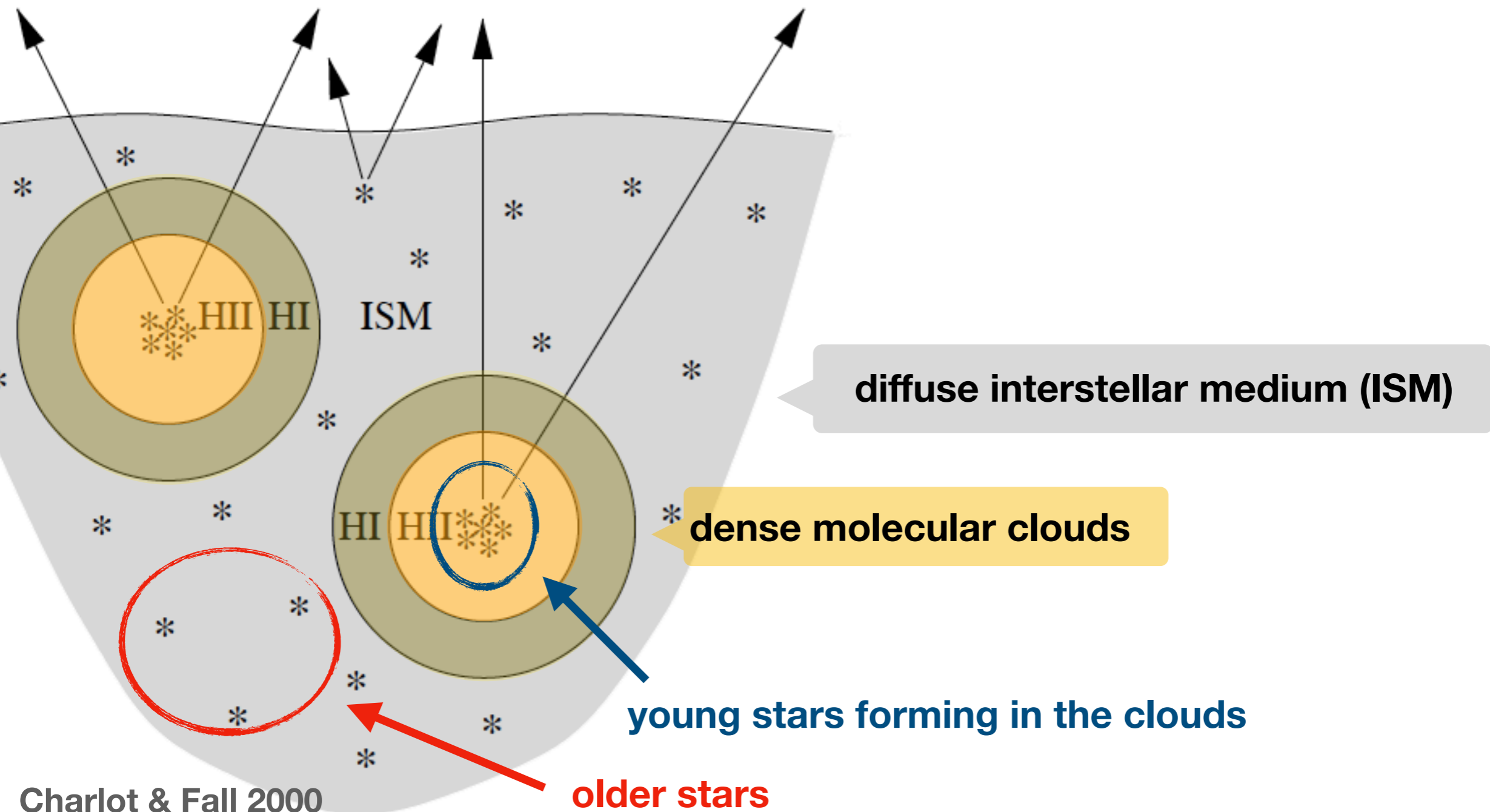


Dust extinction



Dust extinction

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

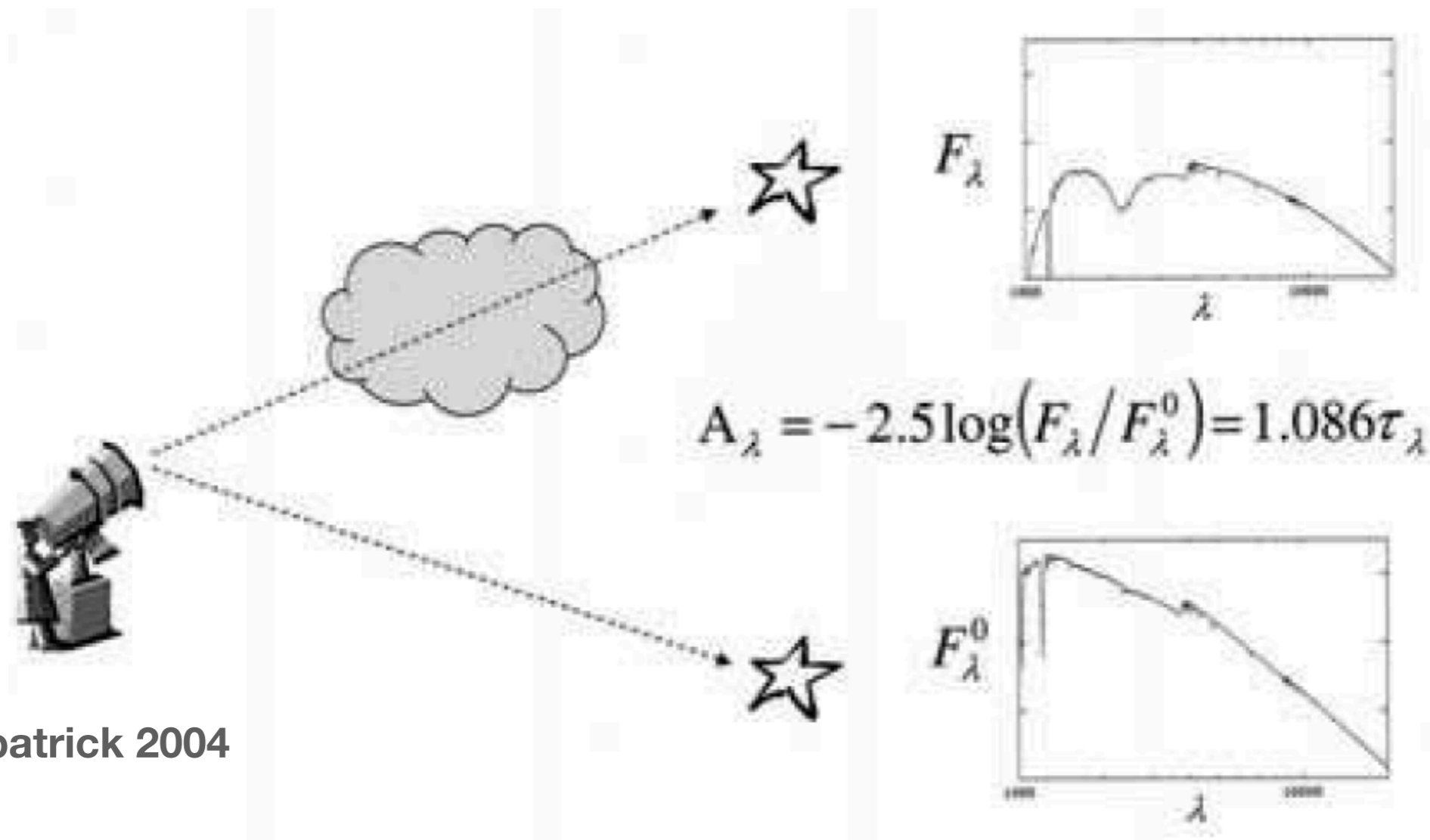


Dust extinction

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**:

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

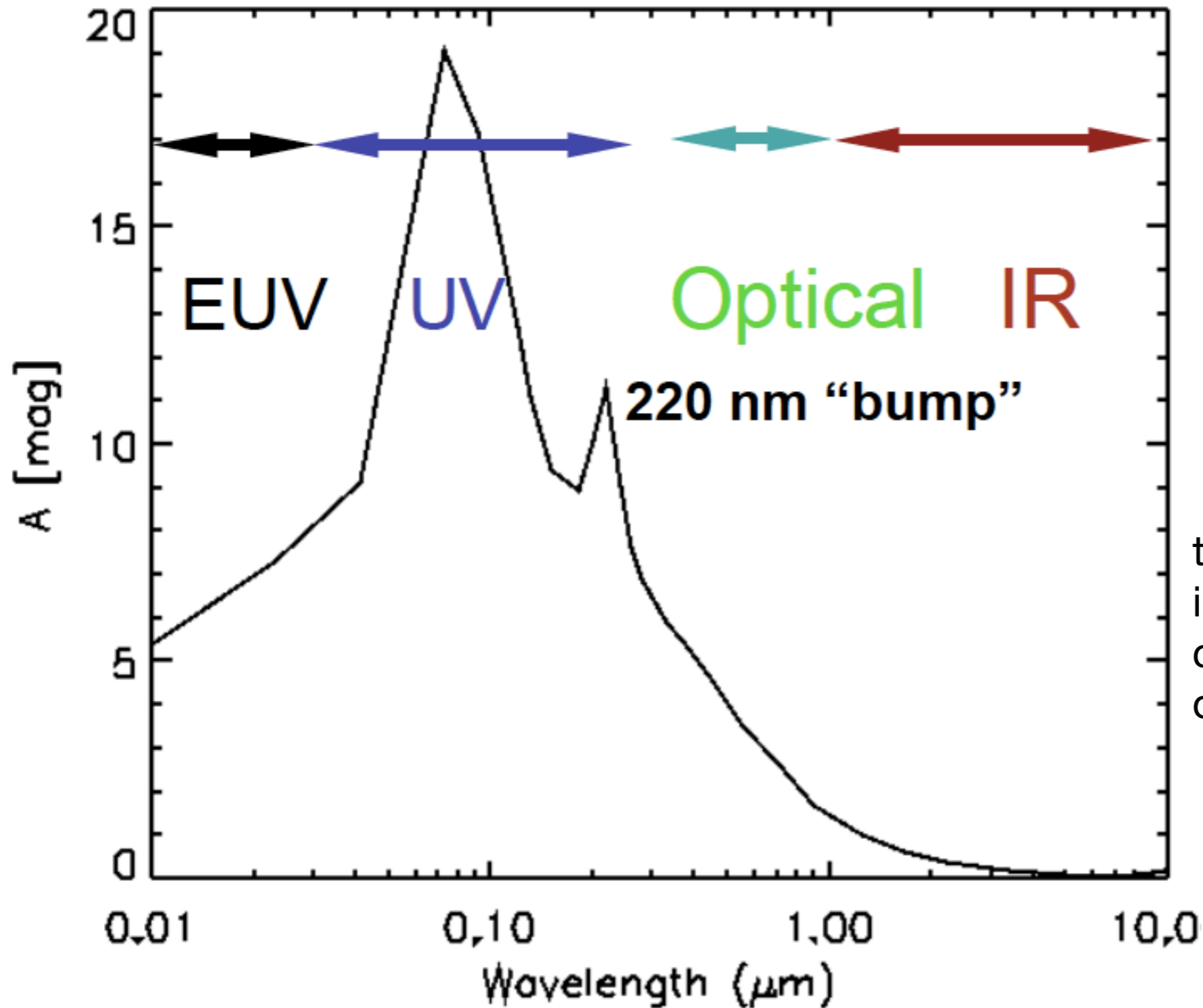
“intrinsic” flux observed flux



Dust extinction

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

Very schematically:

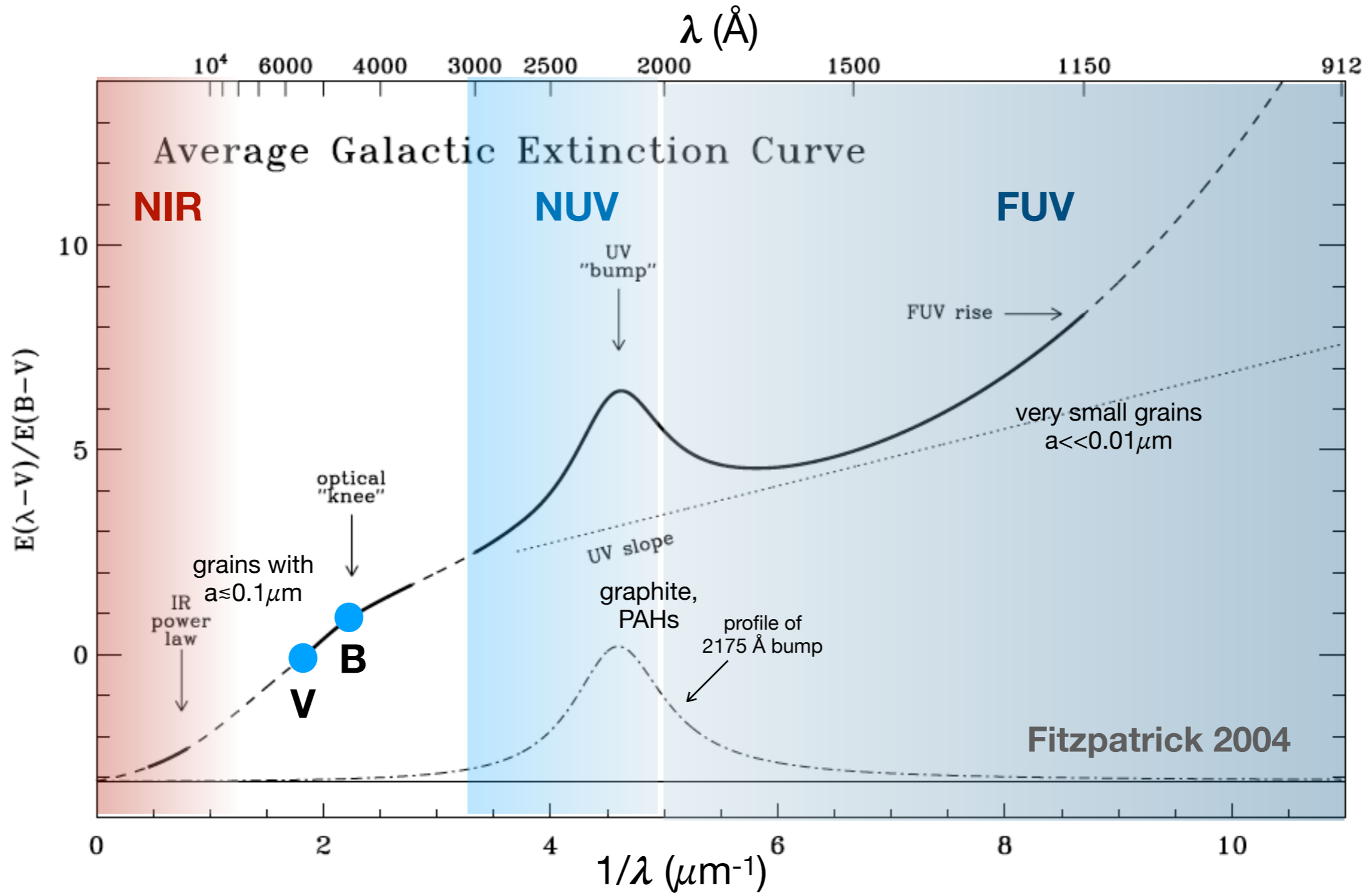


the extinction curve carries information on the composition of dust and size distribution of dust grains

Dust extinction

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

A closer look in the FUV to NIR regime:

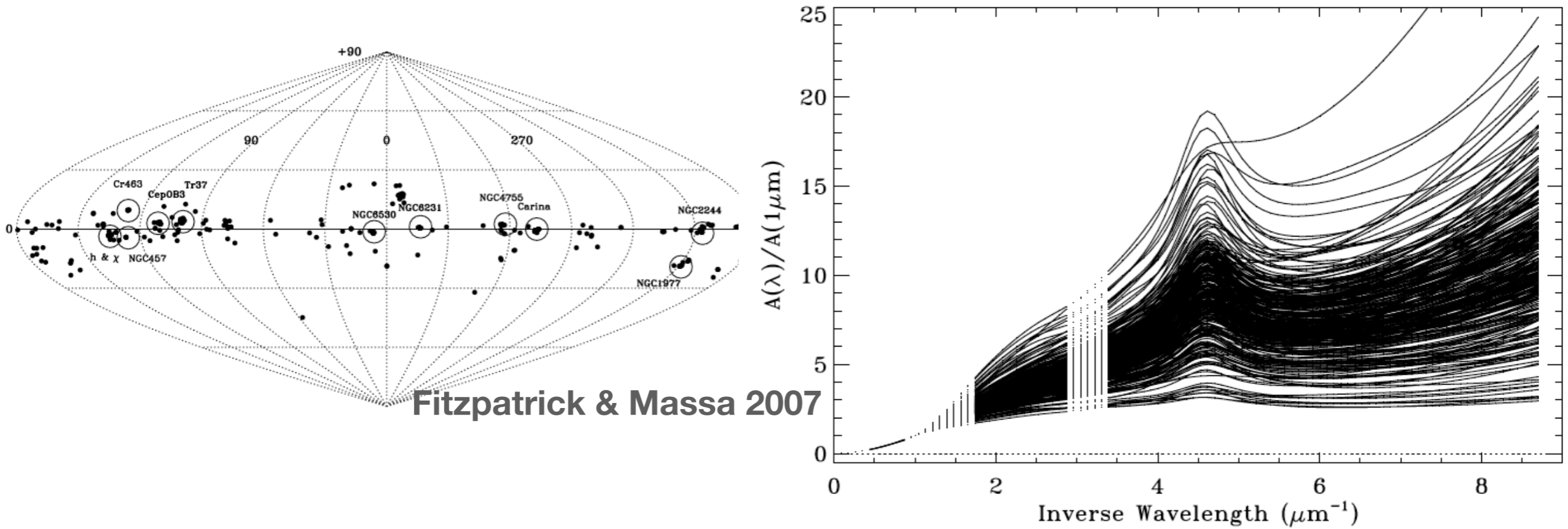


remember related quantities:

color excess $E(B-V) = (B-V)_{\text{observed}} - (B-V)_{\text{intrinsic}}$
 $R(V) = A_V / E(B-V)$ [where A_V is A_λ in V band]

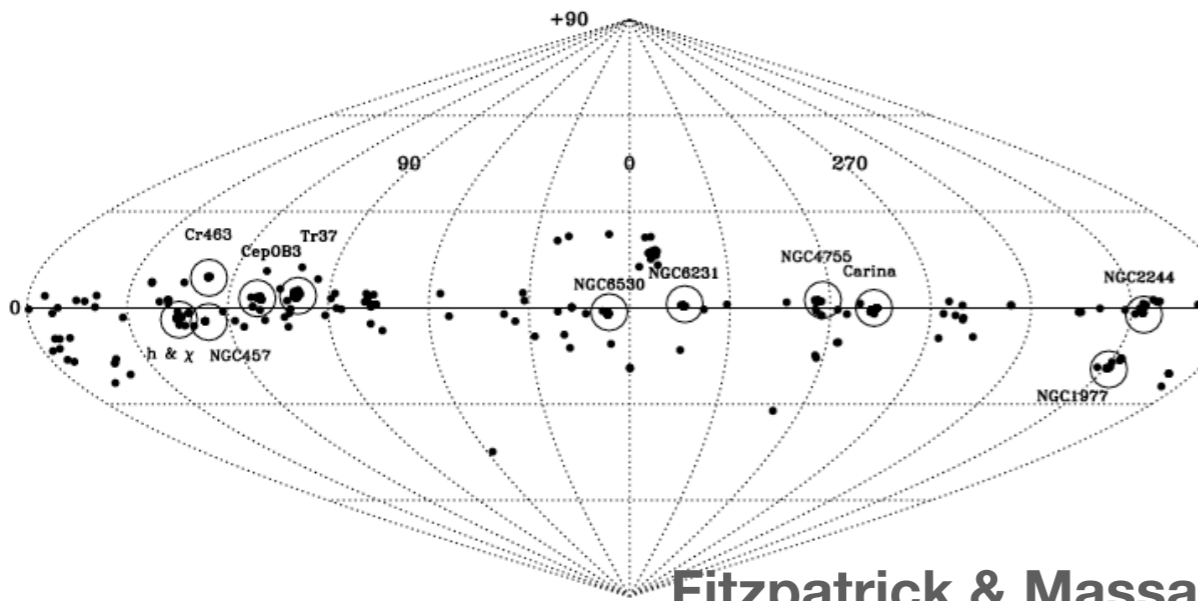
Dust extinction

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

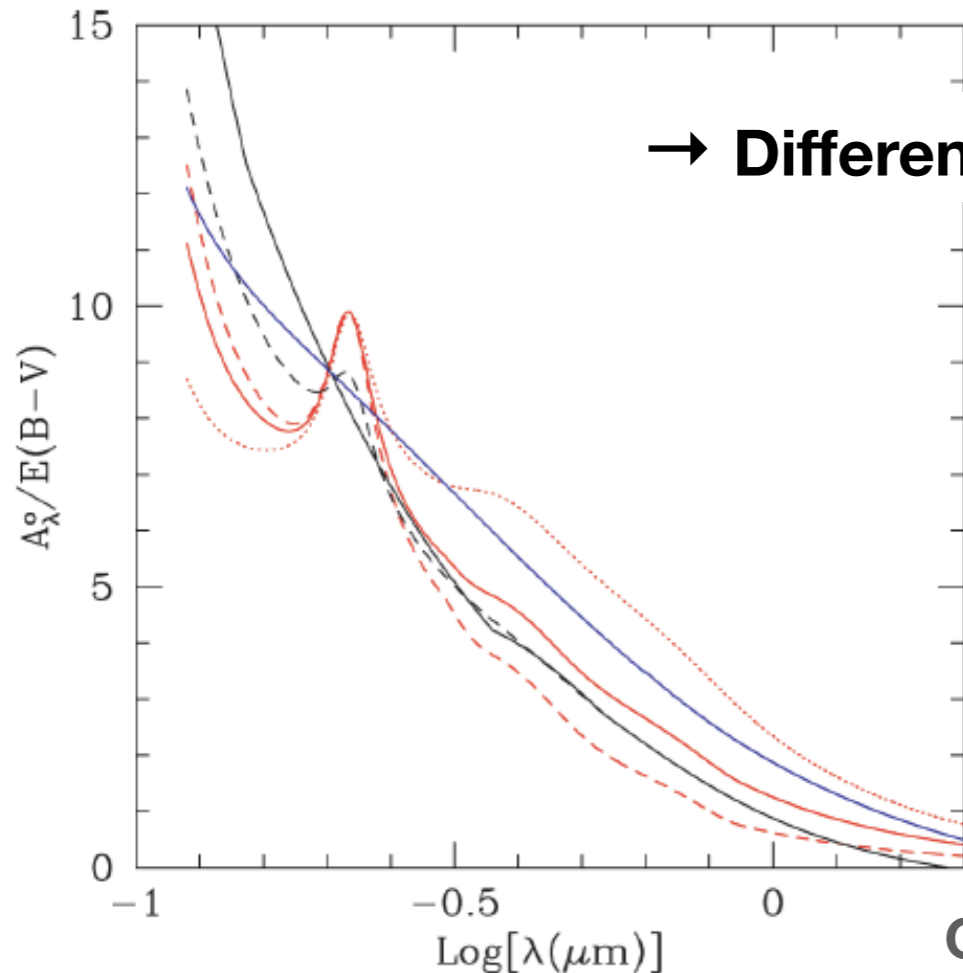
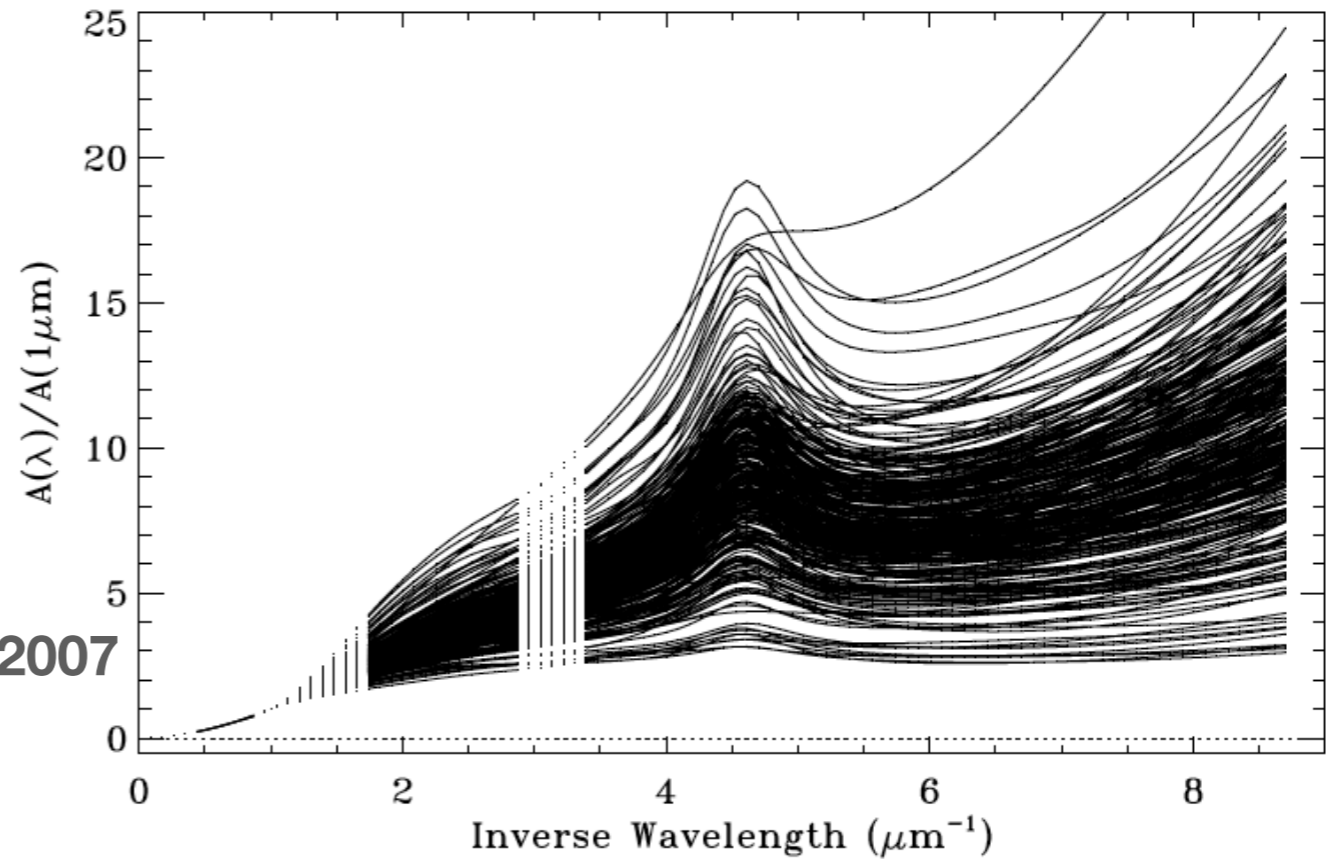


Dust extinction

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

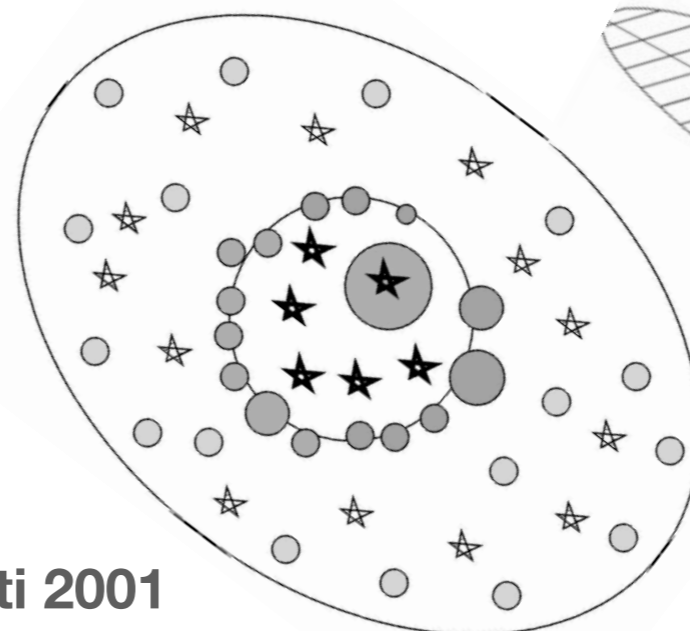


Fitzpatrick & Massa 2007

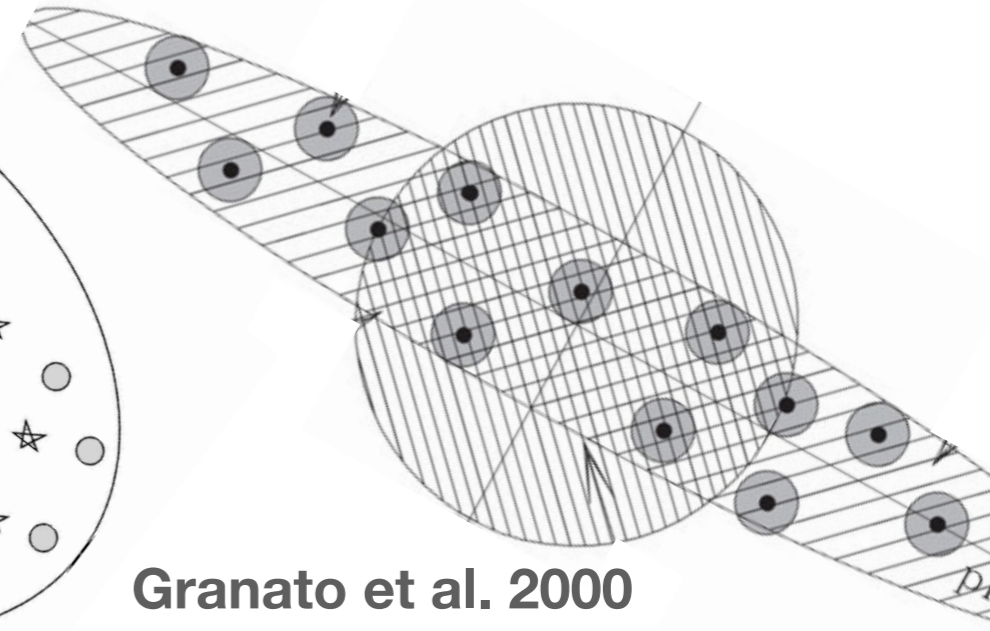


→ Different galaxies have different extinction curves depending on properties, distribution and geometry of dust vs. stars

Calzetti 2001

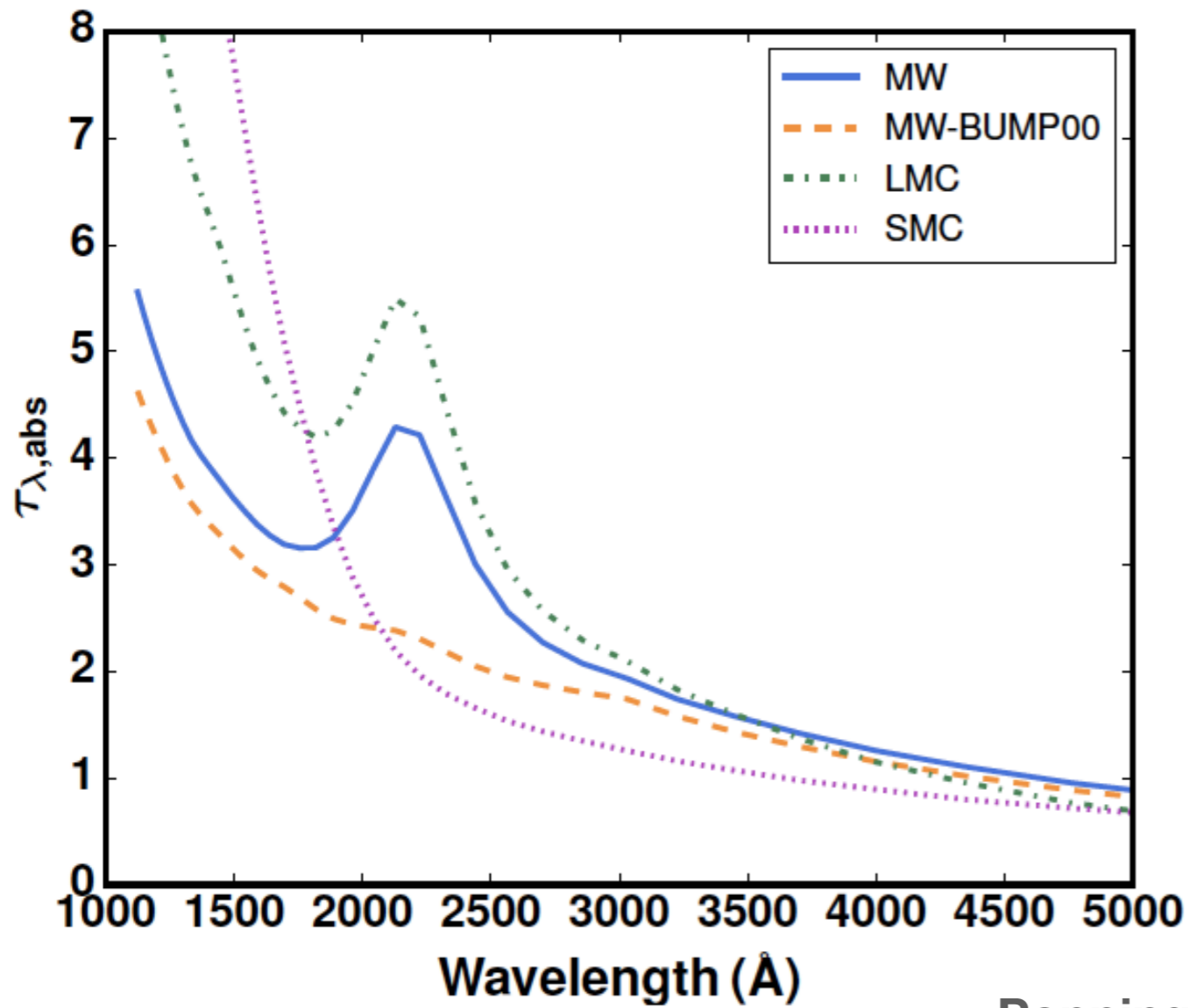


Granato et al. 2000

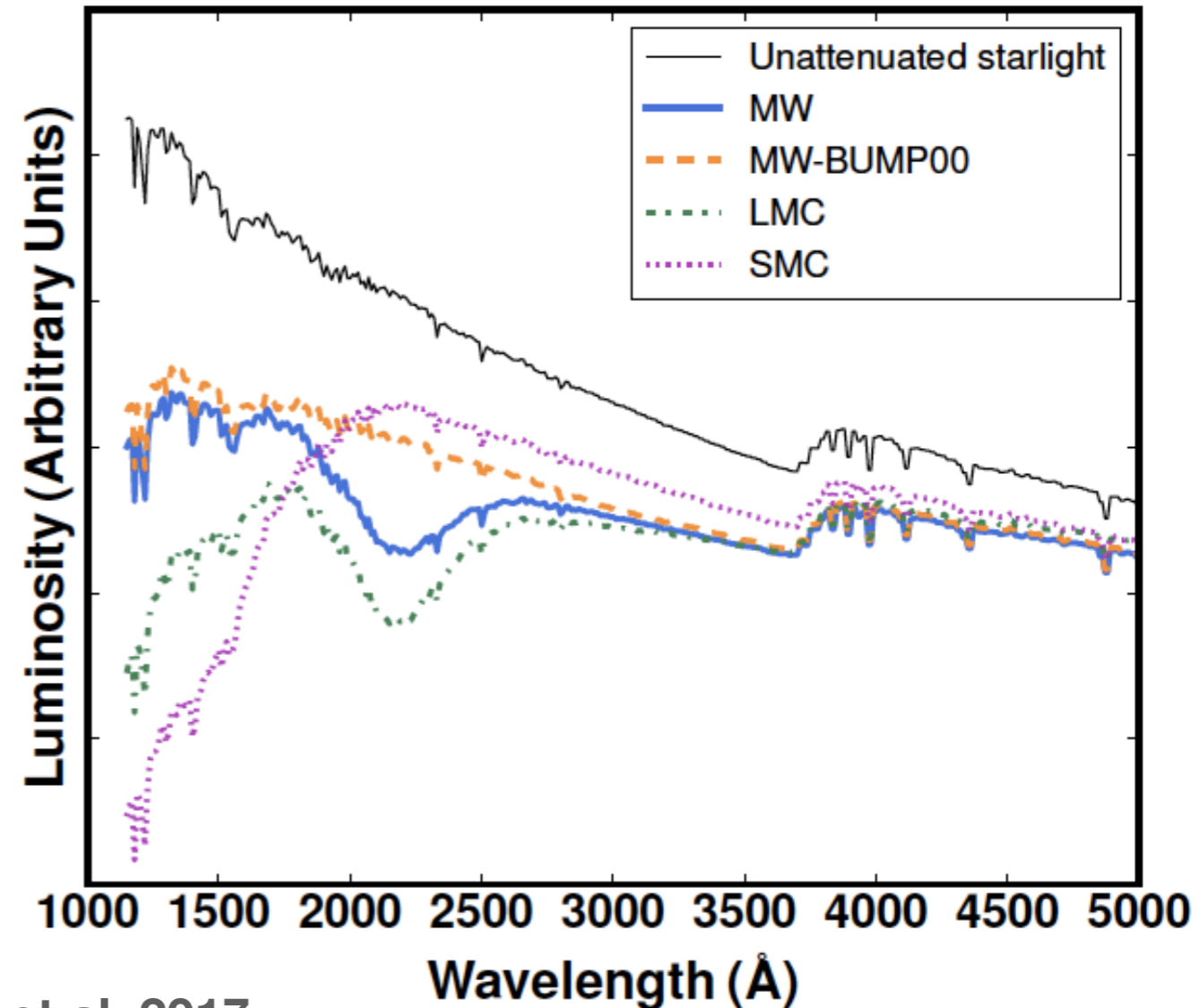


Dust extinction

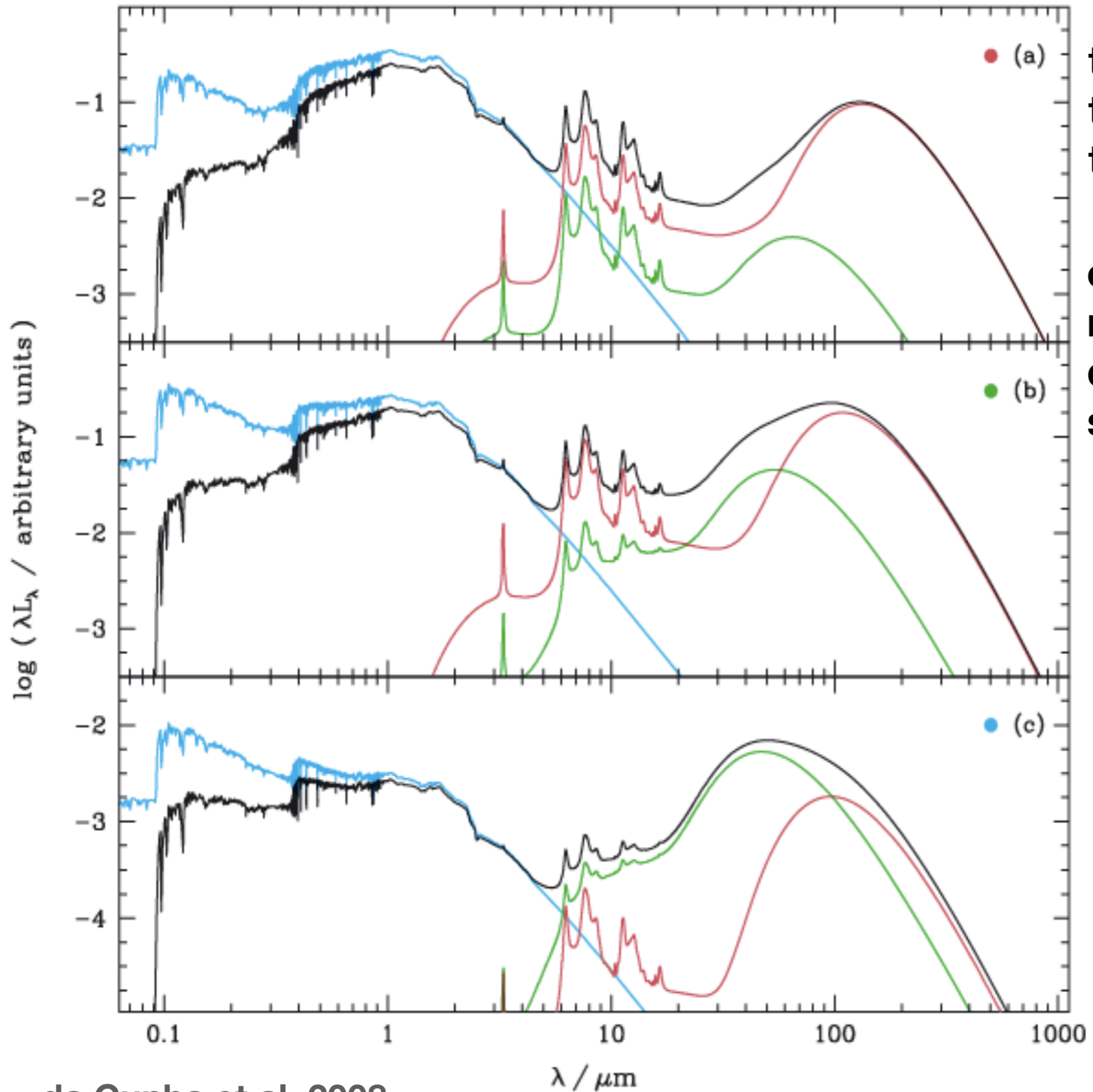
... thus impacting the galaxy SED in different ways



Popping et al. 2017



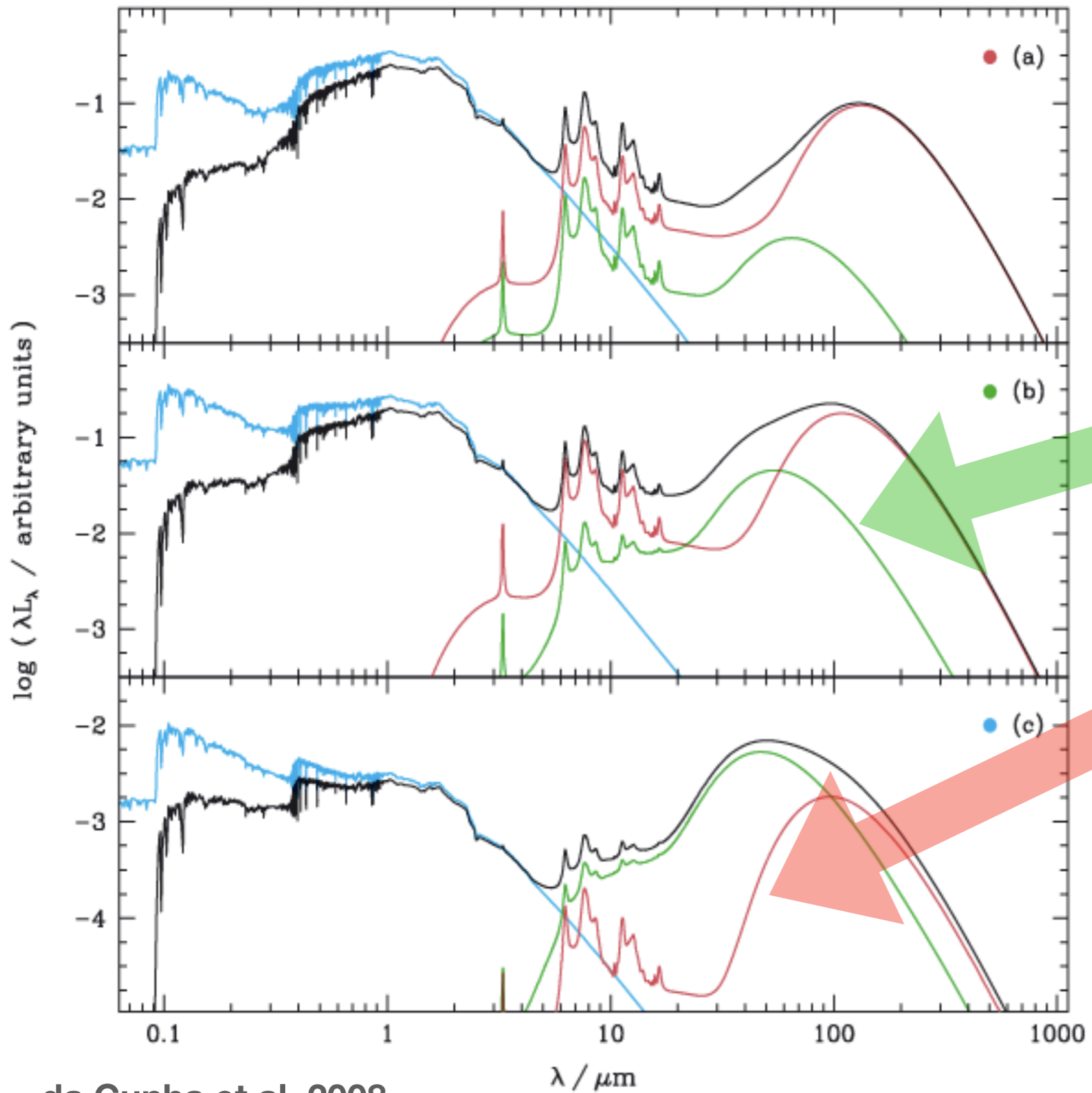
Dust emission



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

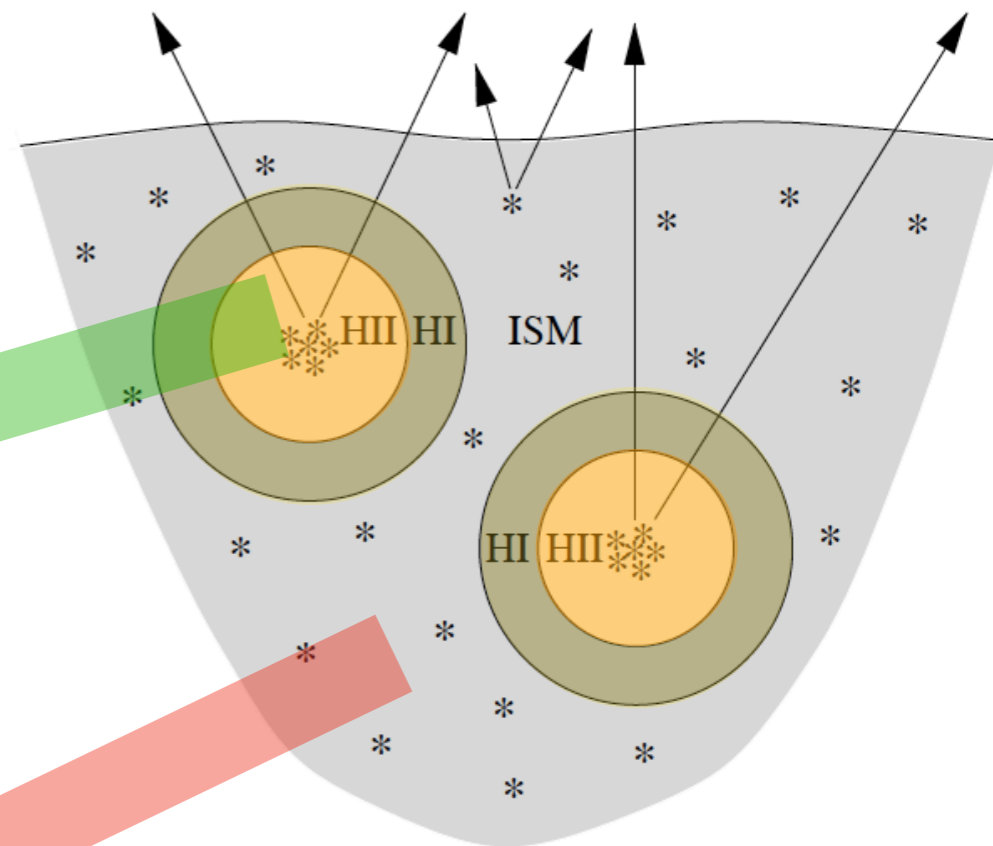
emission in the mid-/far-IR range reflects the heating of dust in different ISM components from stars of all ages

Dust emission

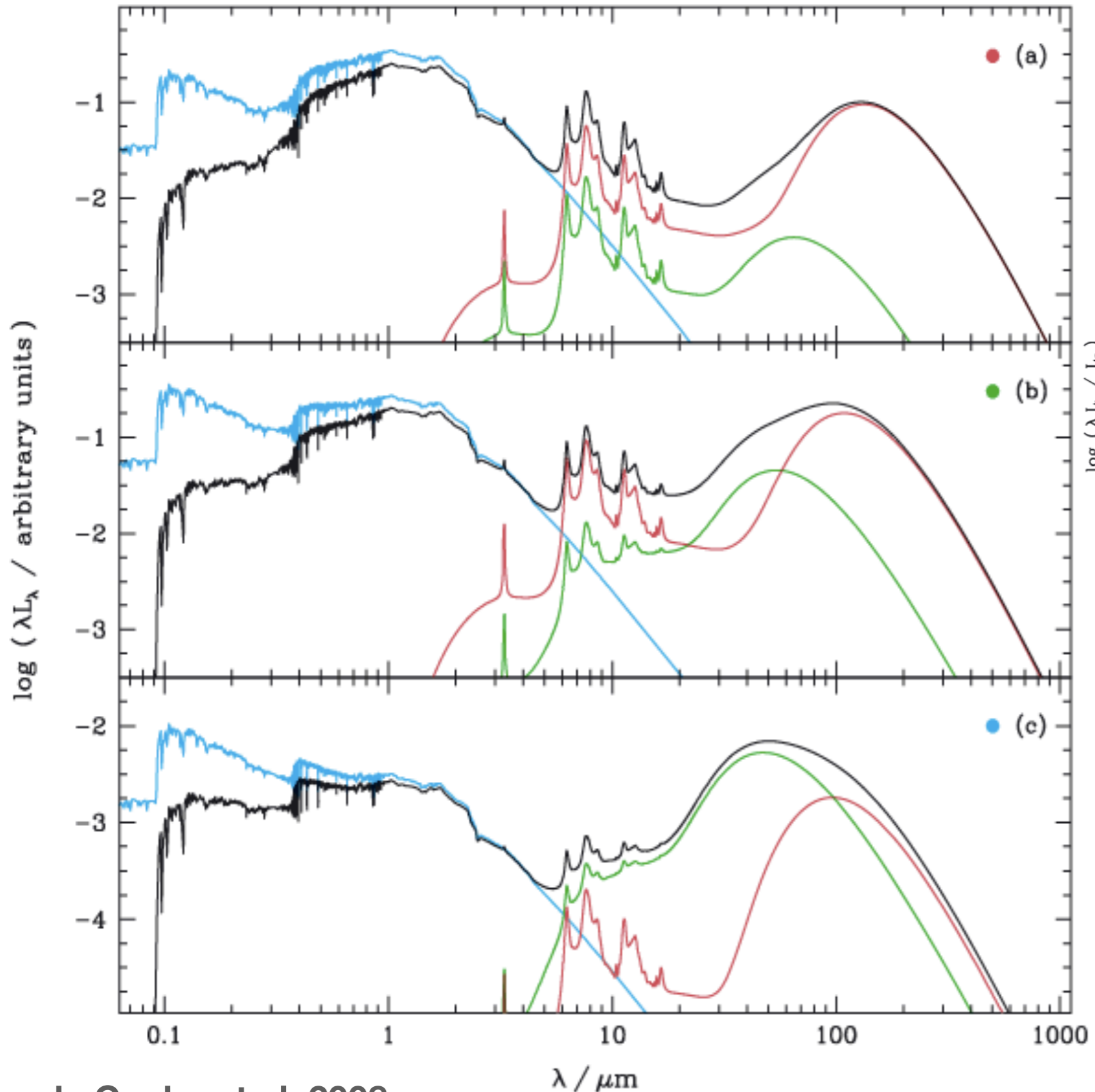


Birth Cloud

Diffuse ISM

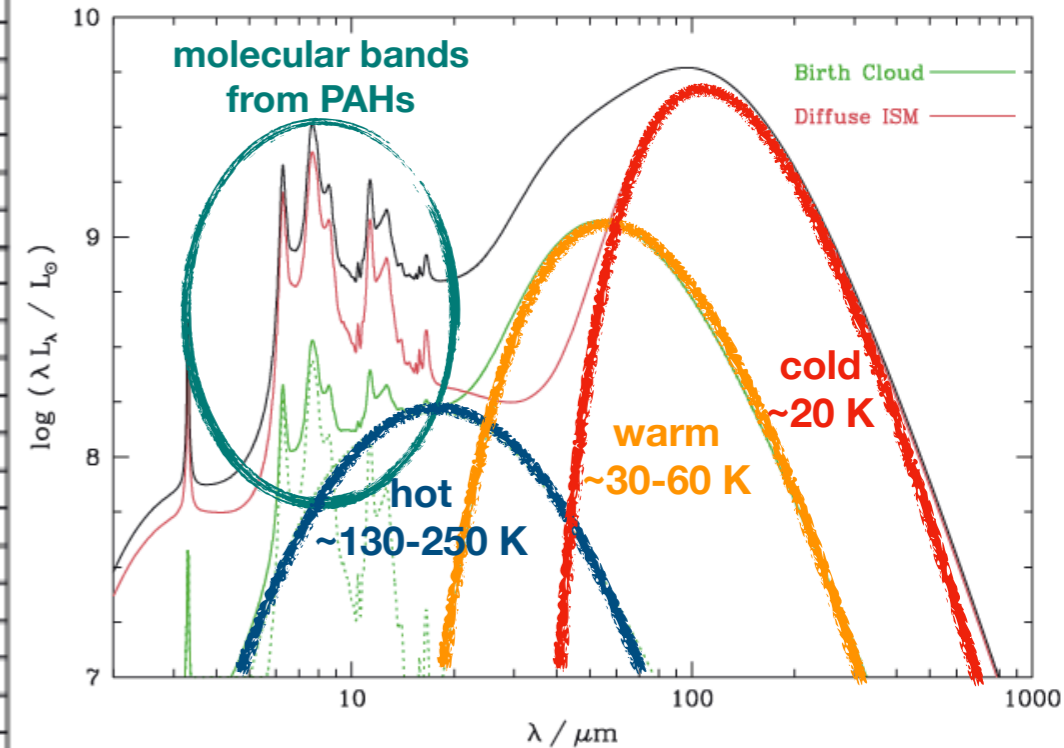


Dust emission



Birth Cloud

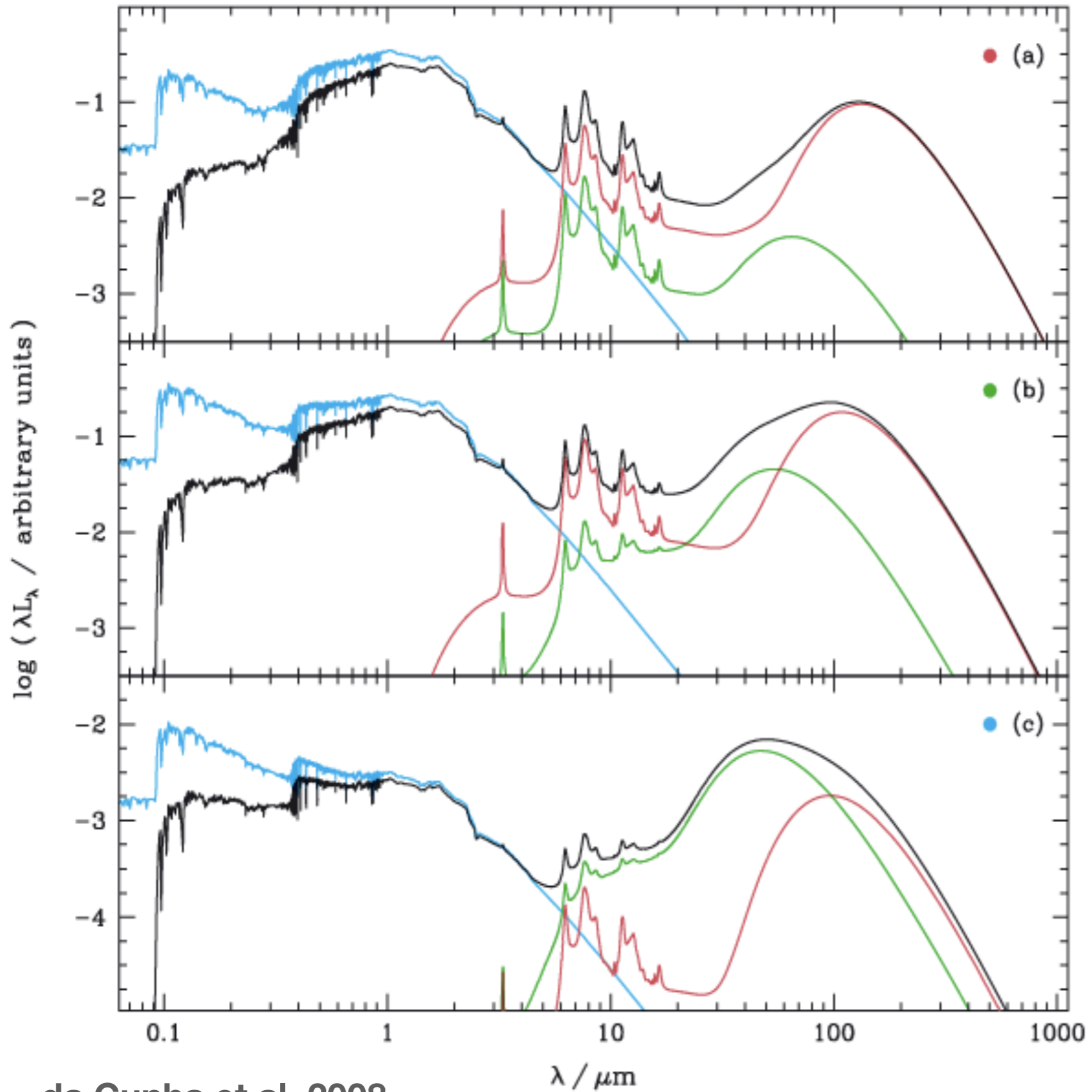
Diffuse ISM



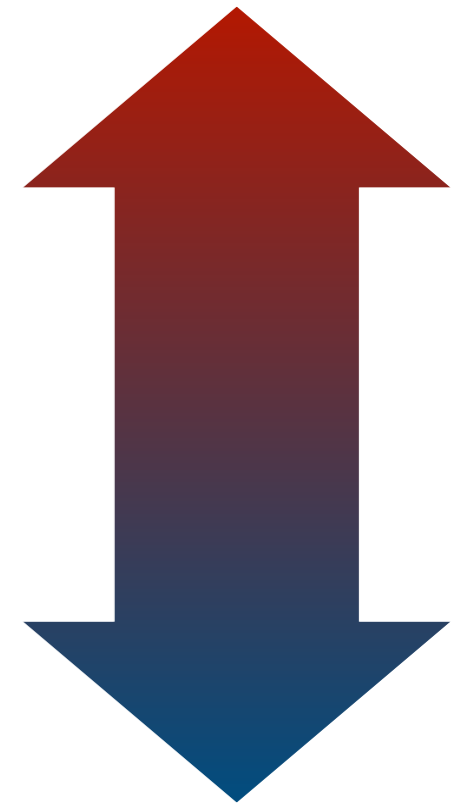
< 30 μm continuum:
emission from
small grains (5-50 \AA)
 $T \sim 10^2-10^3$ K

FIR continuum:
emission from
larger grains (>100 \AA)
in thermal equilibrium with
ambient radiation field
 $T \lesssim 40$ K

Dust emission



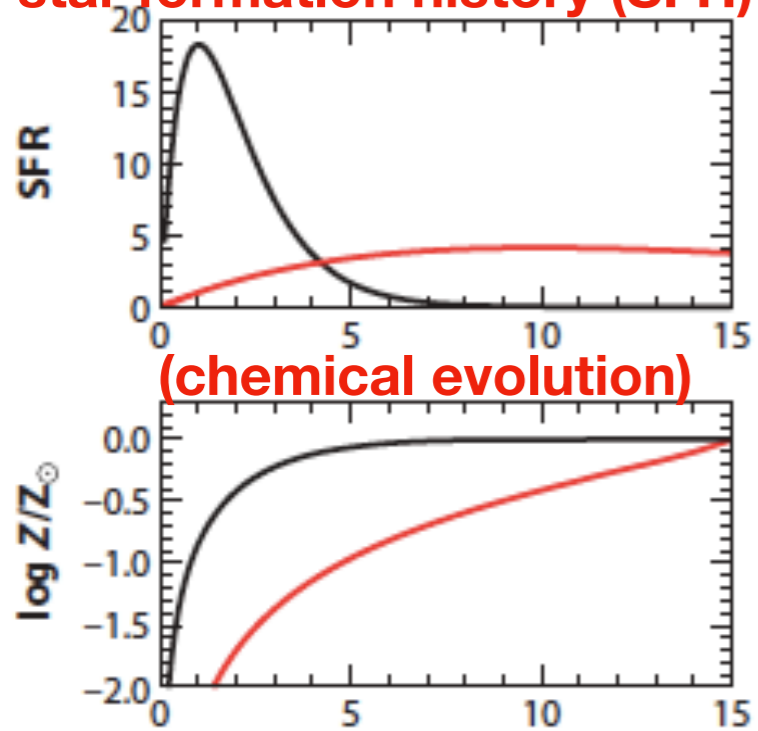
more “quiescent” star-forming galaxy with colder IR emission



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

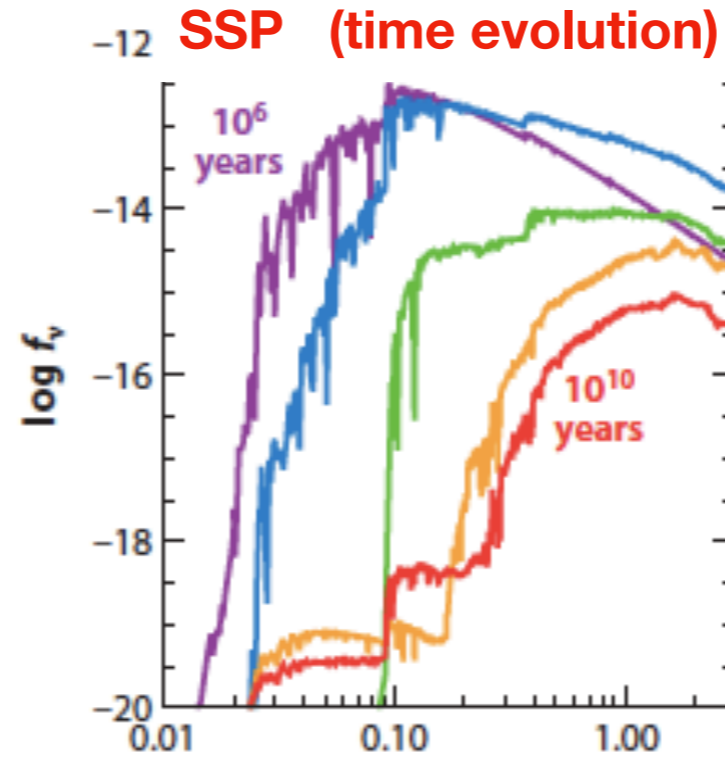
Effects of dust on galaxy SEDs

star formation history (SFH)

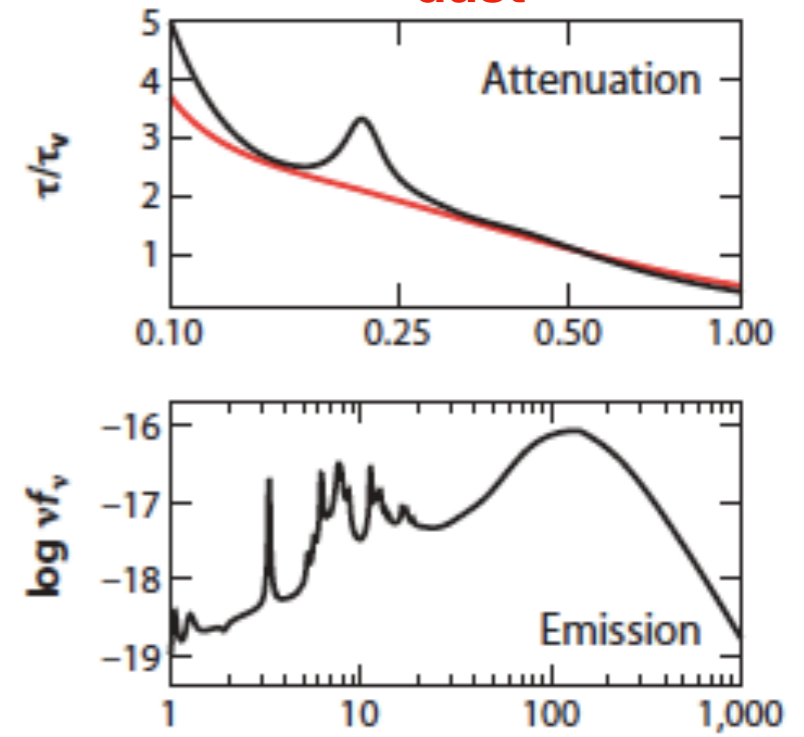


(chemical evolution)

SSP (time evolution)

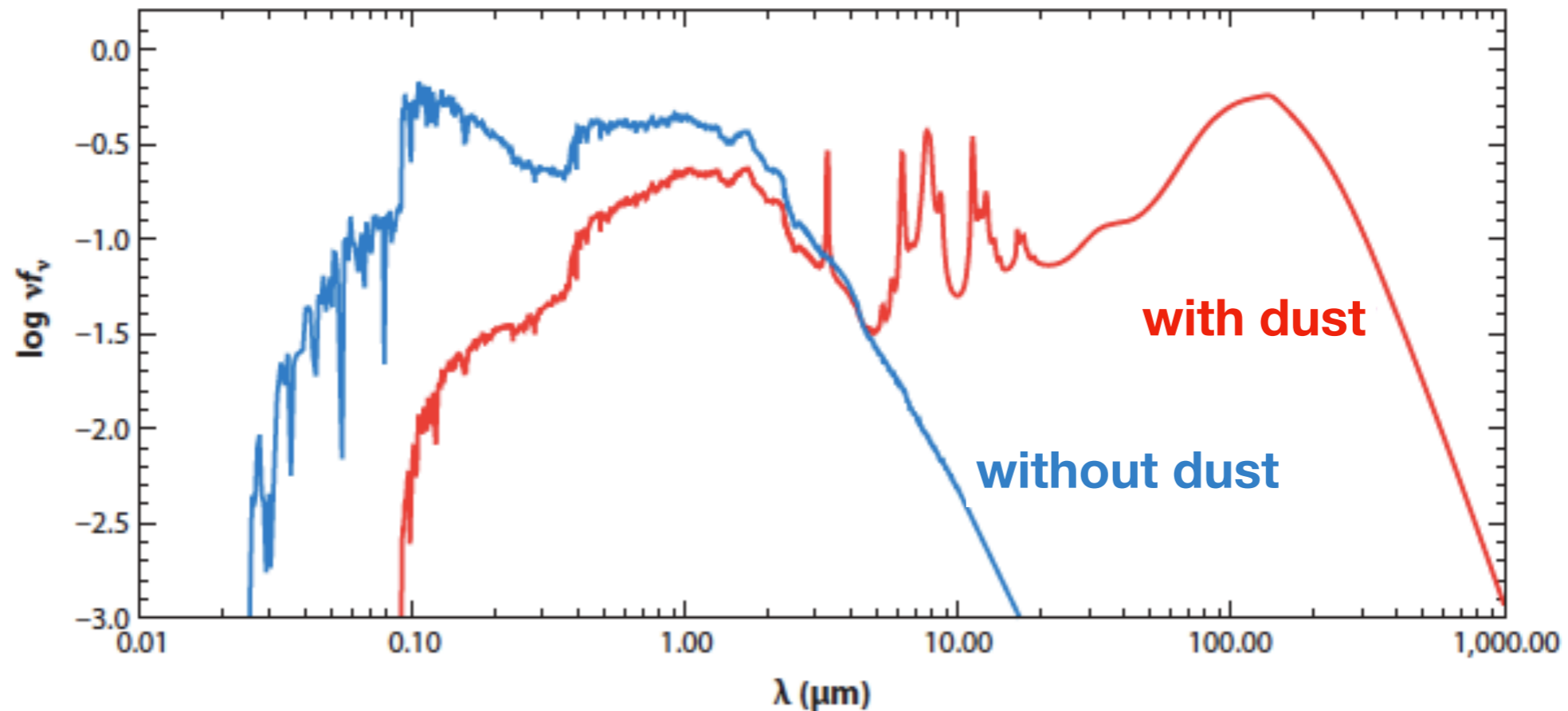


dust



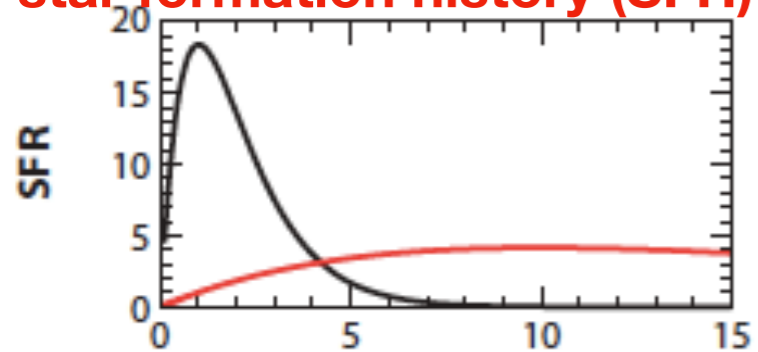
Conroy 2013

CSP

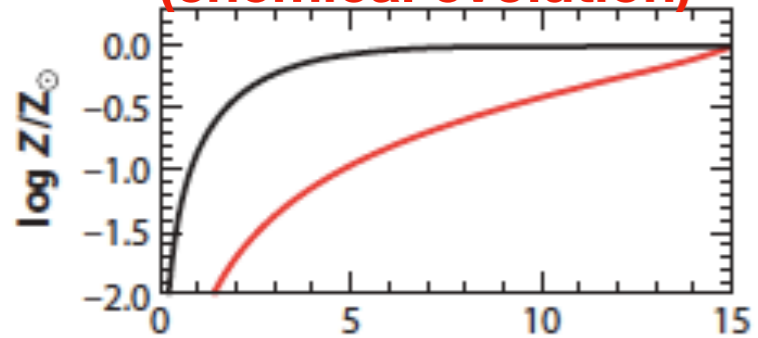


Effects of dust on galaxy SEDs

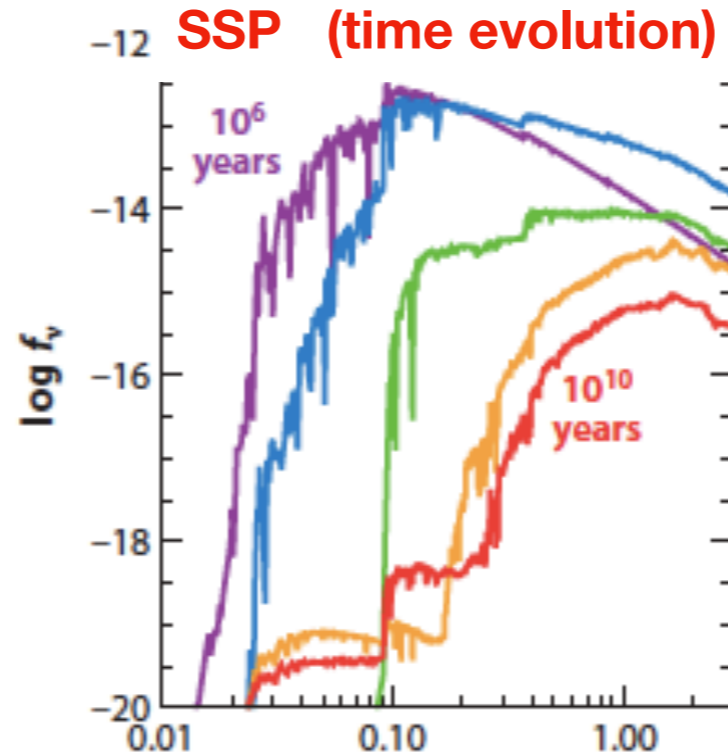
star formation history (SFH)



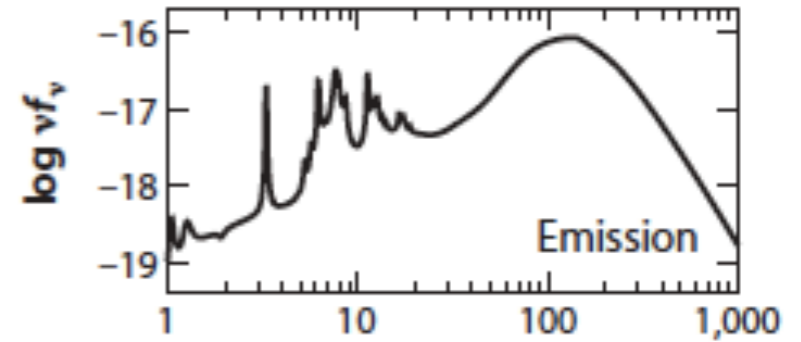
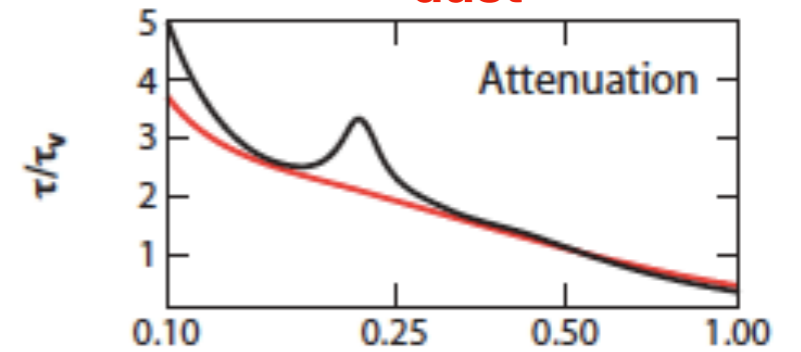
(chemical evolution)



SSP (time evolution)

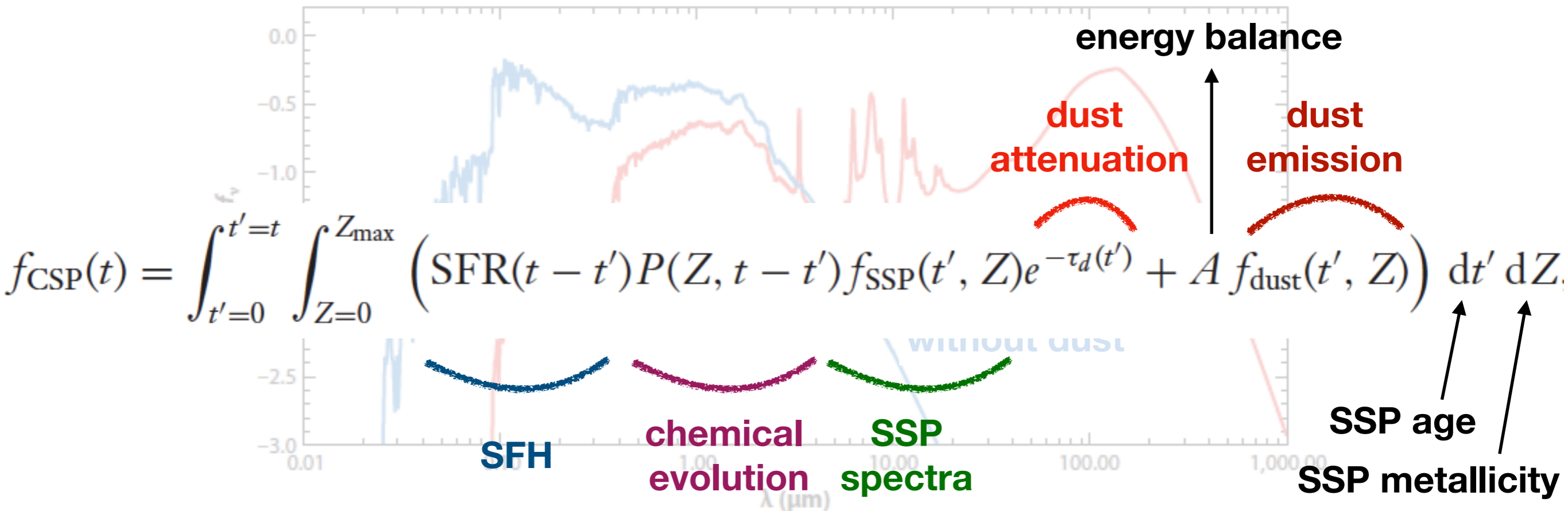


dust



Conroy 2013

CSP



Where does a galaxy SED come from

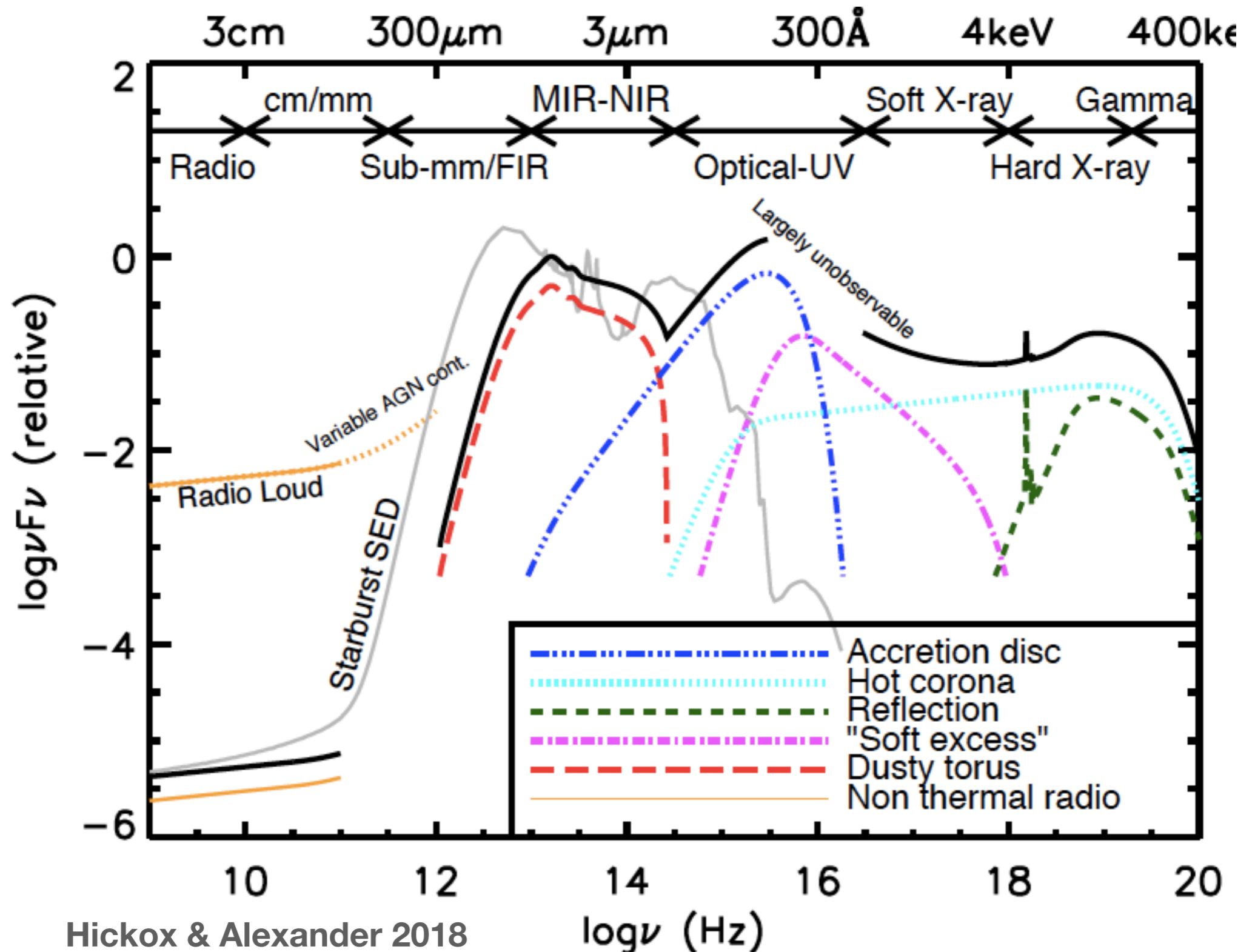
Galaxy spectral energy distributions are the result of the combination of light emission and absorption from the (baryonic) galaxy constituents:

- 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 constituents:

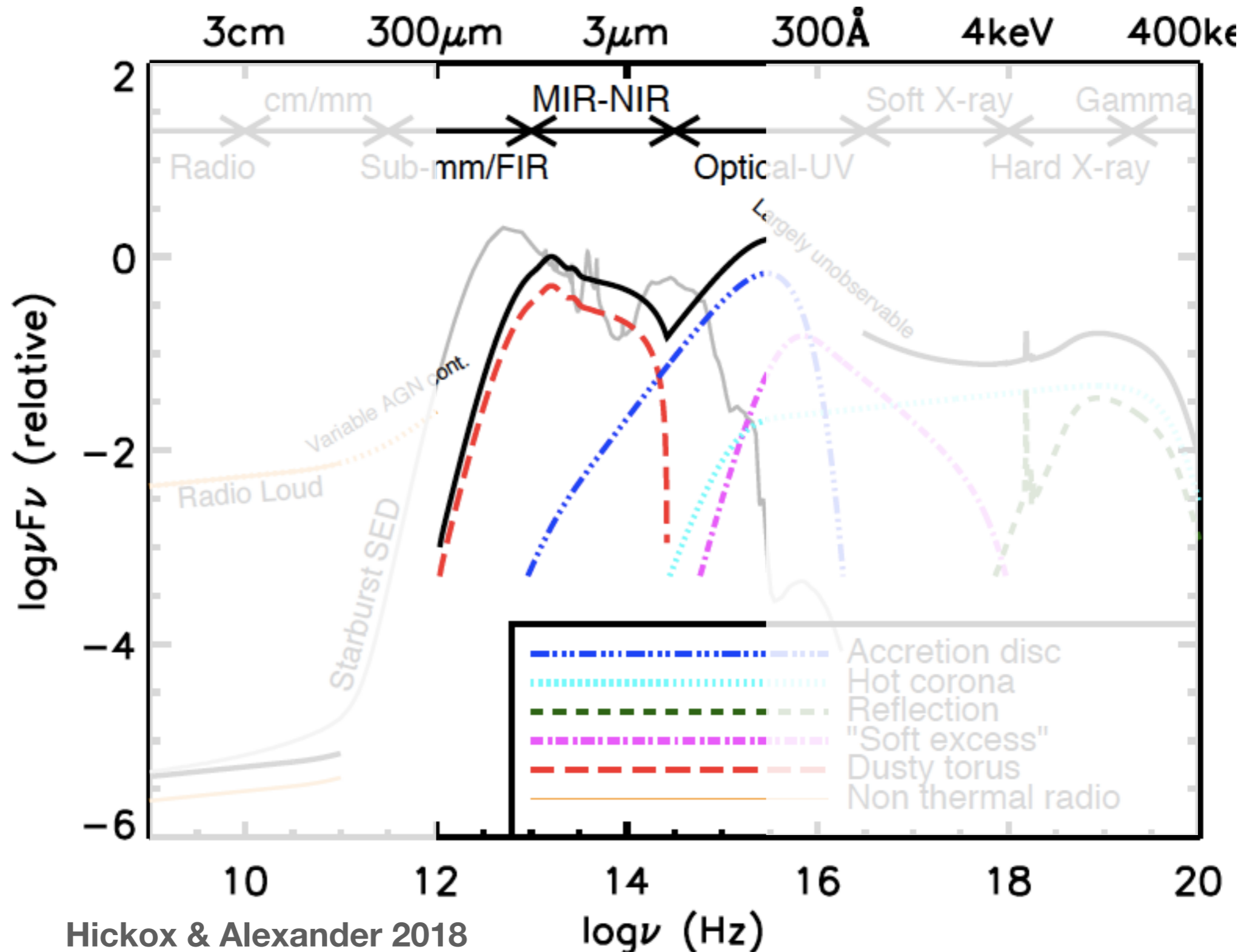
- stars
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- AGN**
- dust

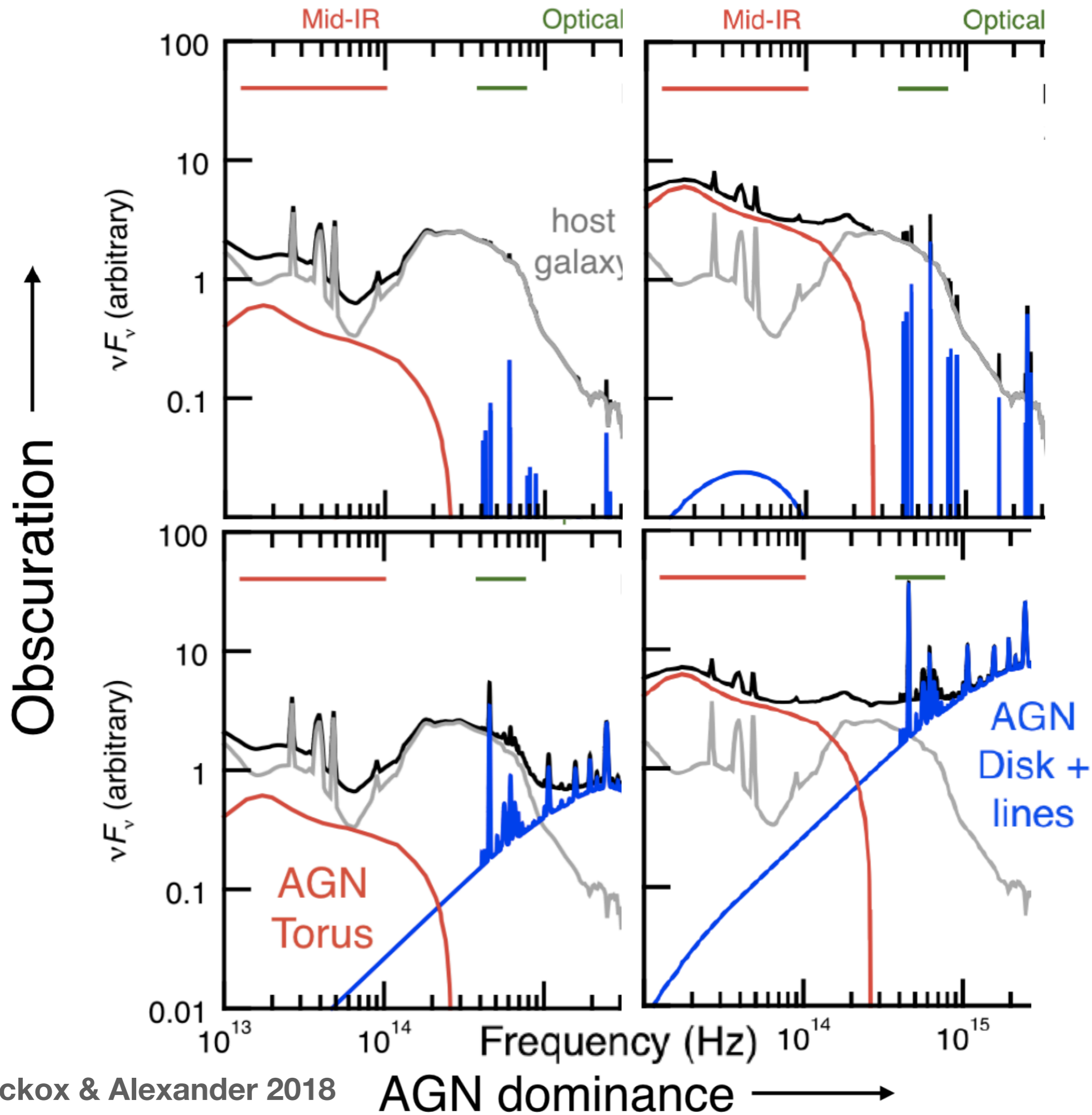


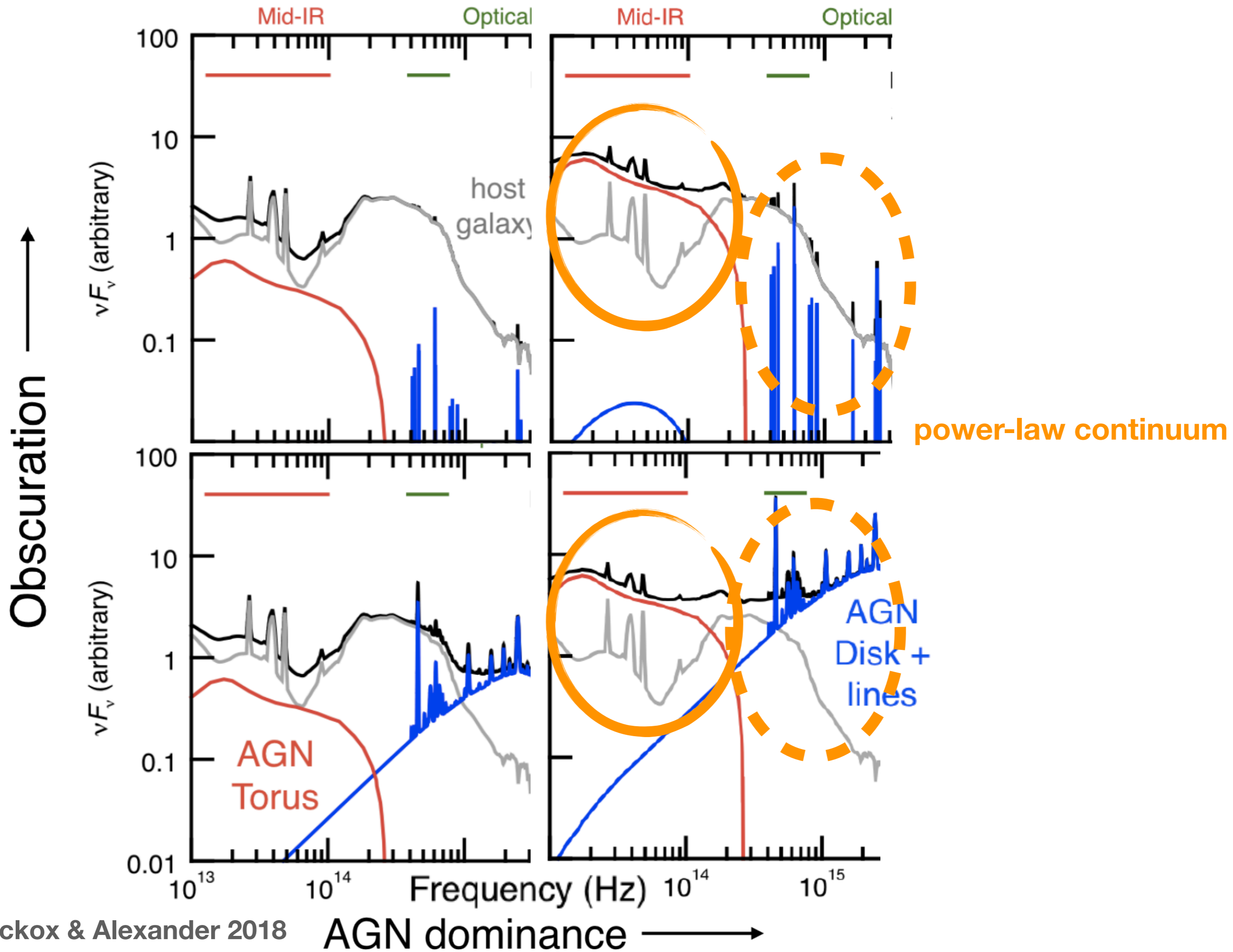
Where does a galaxy SED come from

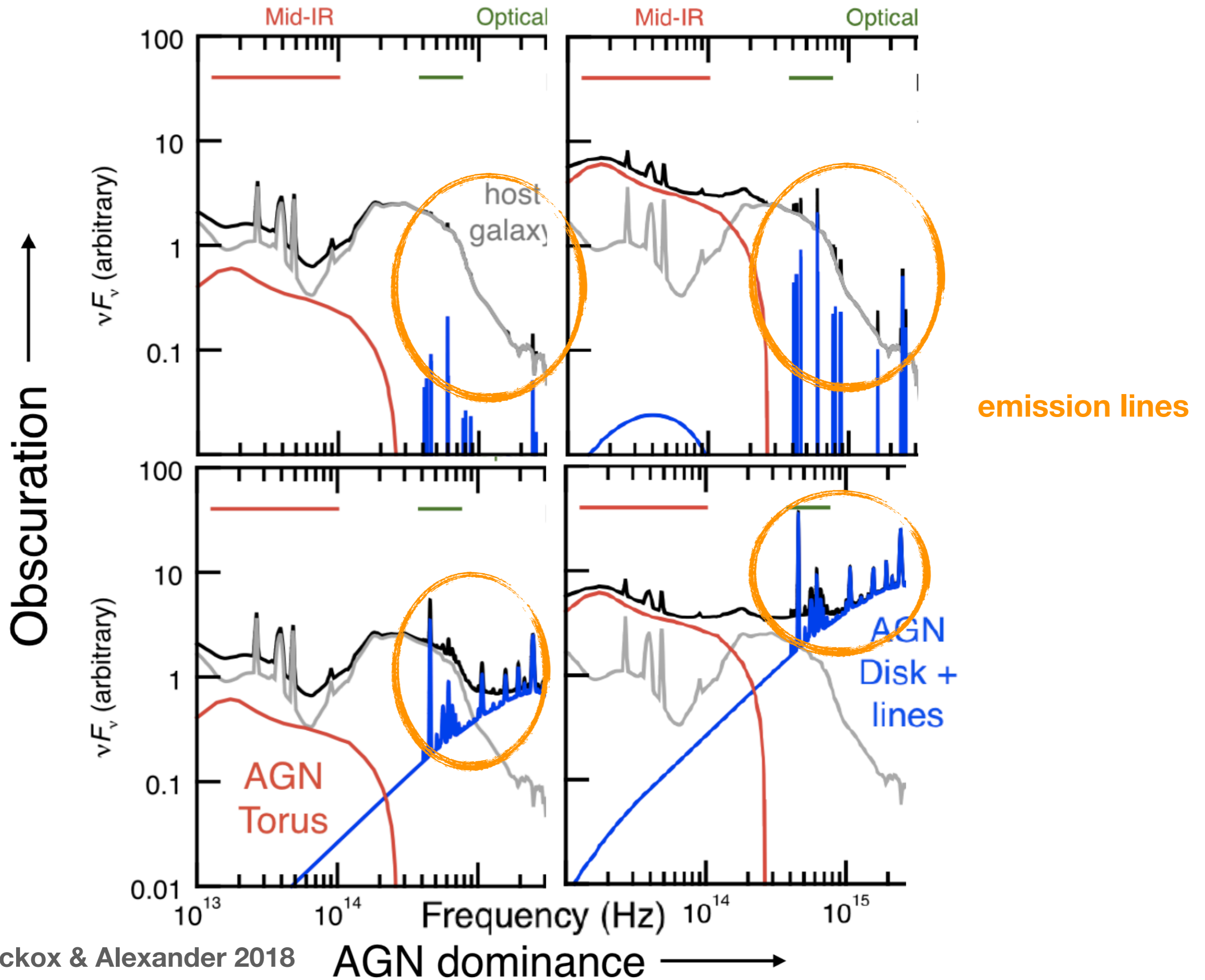
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- stars
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Obscuration ↑

