Modelling the SEDs of high-redshift galaxies: recent progress & future challenges

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Back to the edge of the Universe
Sintra, 15 - 19 March 2015

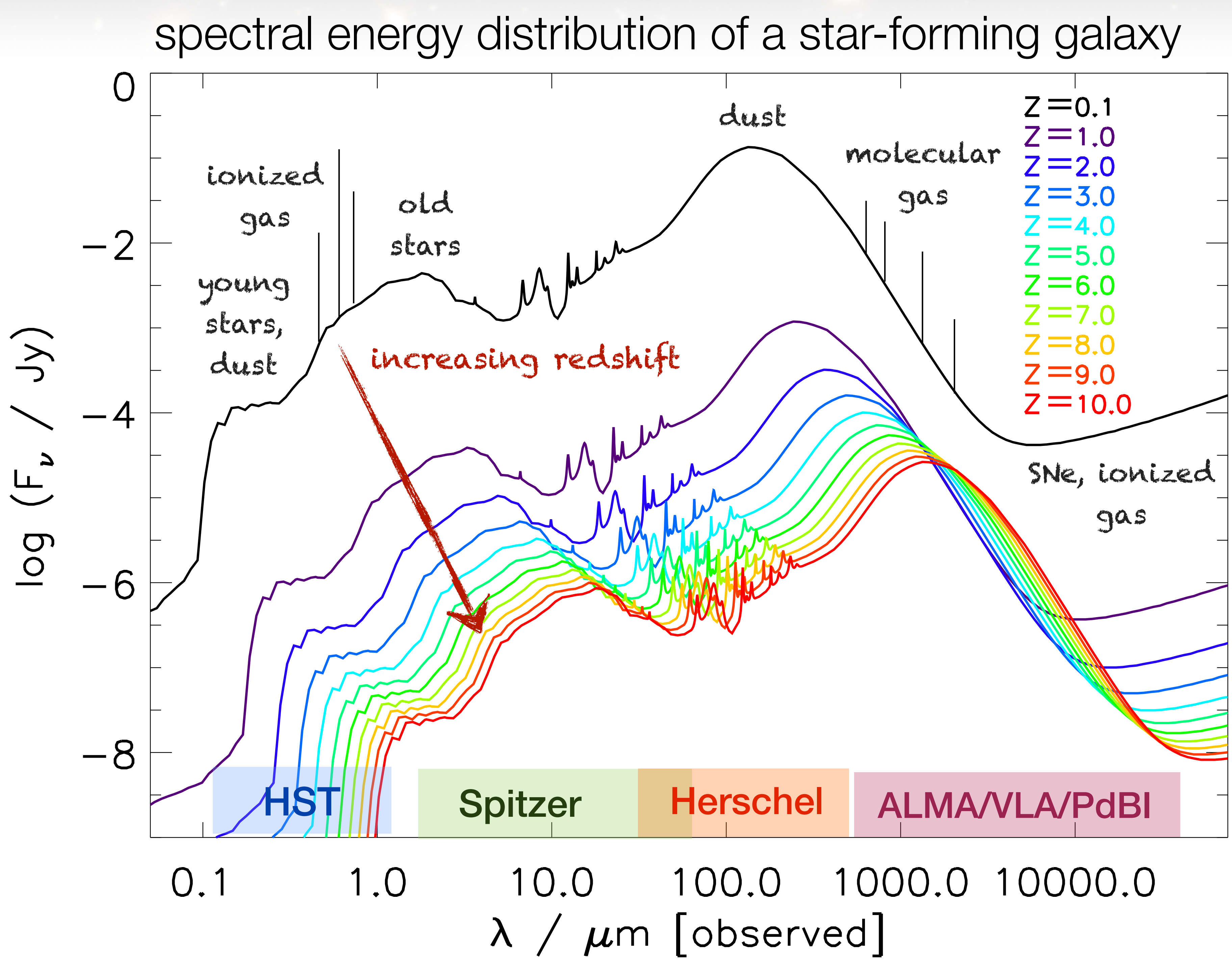
Spectral models: an essential tool for galaxy evolution

Observed UV, optical, IR emission

Spectral energy distribution model

Physical parameters: **SFR**, stellar mass, metallicity, dust content...

Galaxy evolution models



Spectral models for high-redshift galaxies

Recent & ongoing developments / challenges:

- **Emission by stellar populations**
  Evolution of ‘young’ stellar populations
  Star formation histories
- **The interstellar medium: dust & ionized gas**
  Dust attenuation, self-consistent infrared emission
  Nebular emission & impact on SEDs
- **Active galactic nuclei**
  Correct for contamination in the mid-IR (and other wavelengths)
- **‘Cosmological effects’**
  UV absorption by the IGM
  Effect of the CMB in (sub-)mm observations
- **Statistical constraints on physical parameters**
  Fitting SEDs using a Bayesian approach

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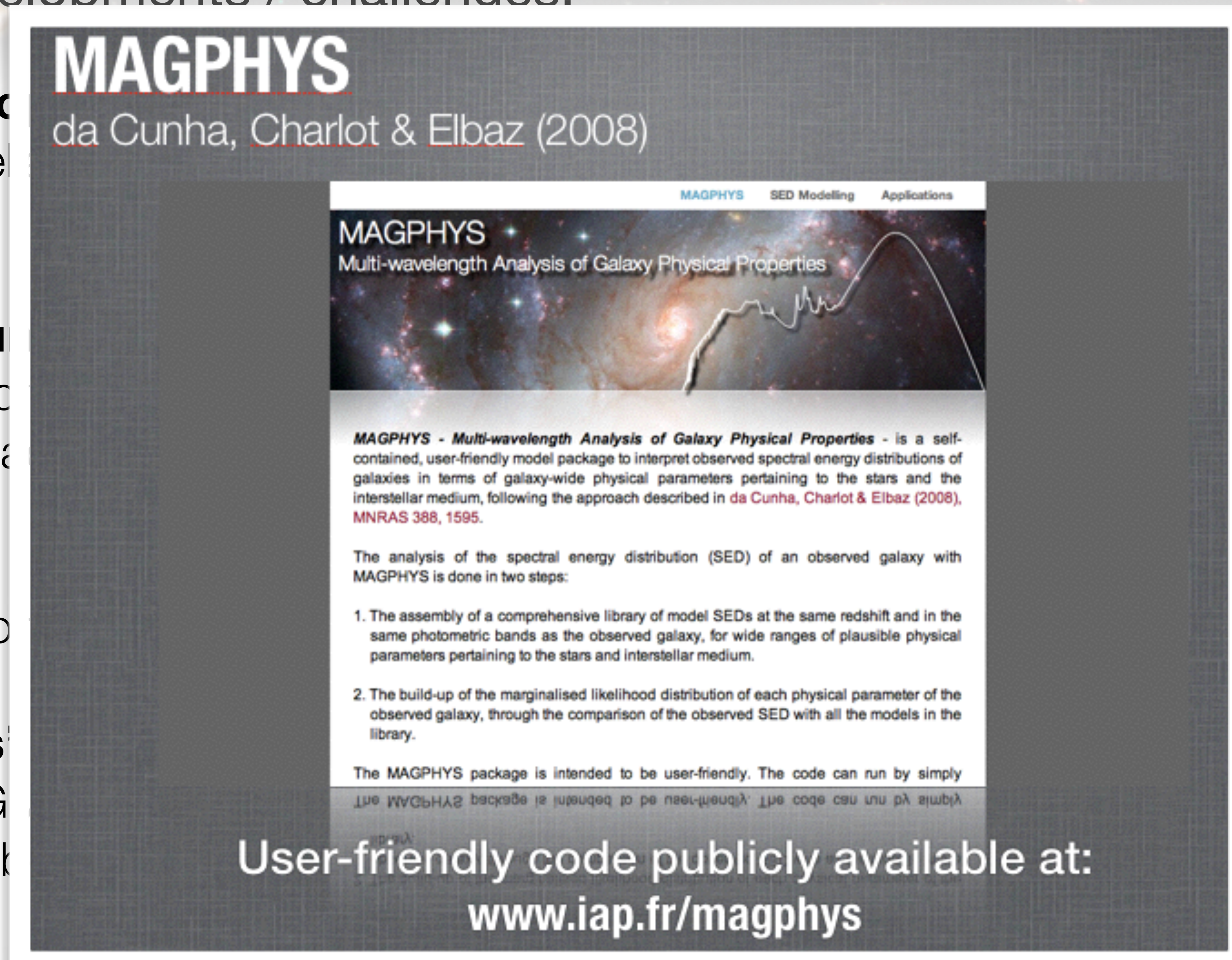
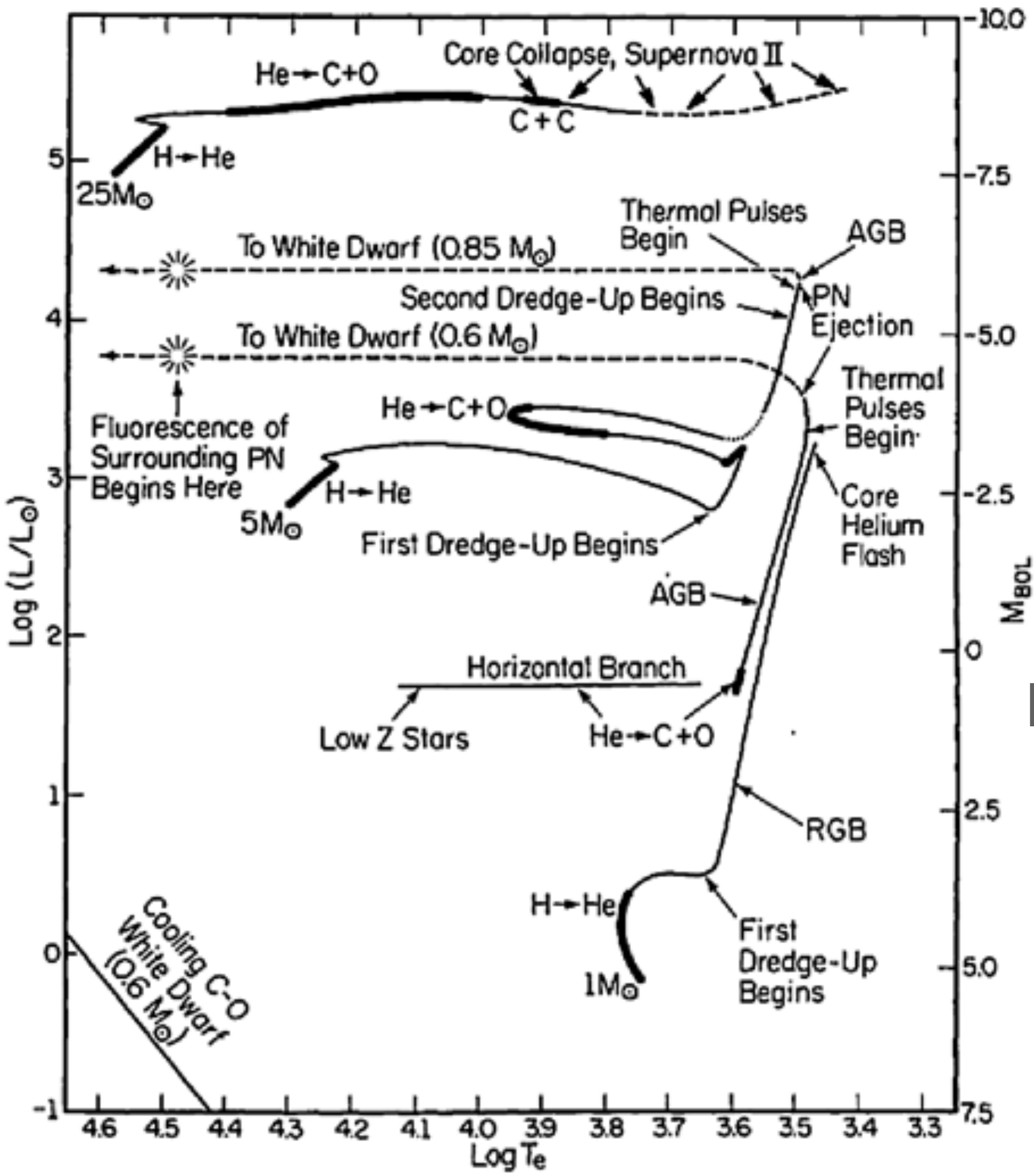


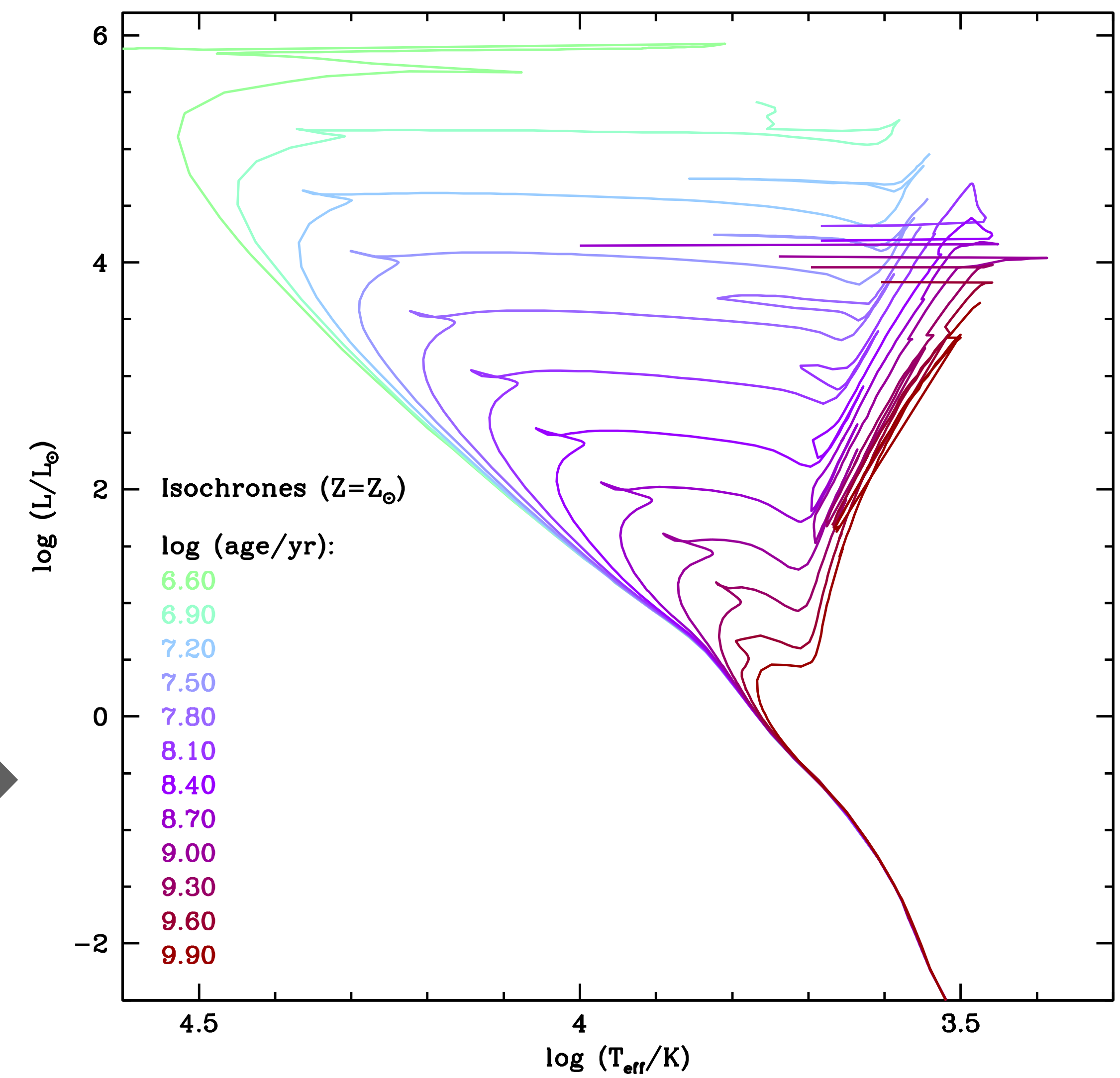
emission by stellar populations

Spectral evolution of a simple stellar population

Stellar evolution prescription

HR evolutionary tracks for stars of different initial masses & metallicities.





computed using evolutionary tracks by Marigo et al. (2008)

Spectral evolution of a simple stellar population

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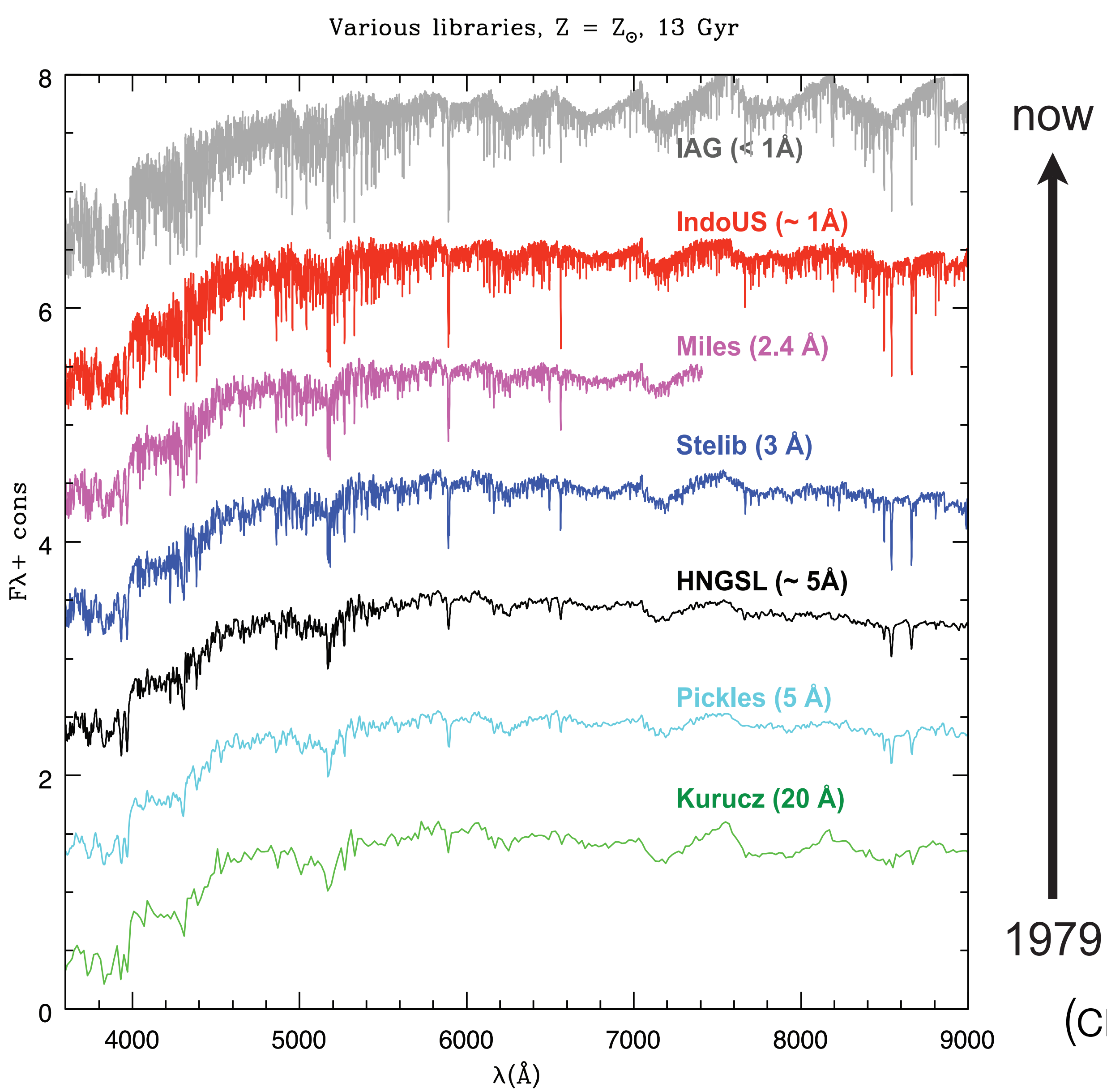
HR evolutionary tracks for stars of different initial masses & metallicities.

Spectral libraries

assign spectrum to a star of given mass, age and metallicity.



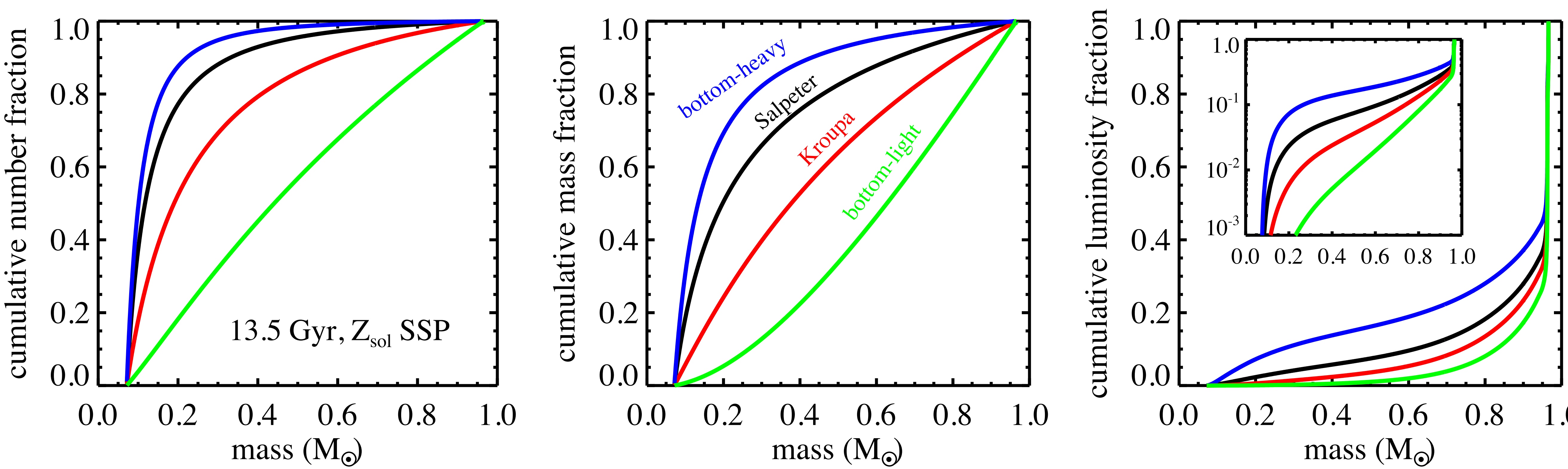
(credit: S. Charlot)

Spectral evolution of a simple stellar population

Stellar evolution prescription
HR evolutionary tracks for stars of different initial masses & metallicities.

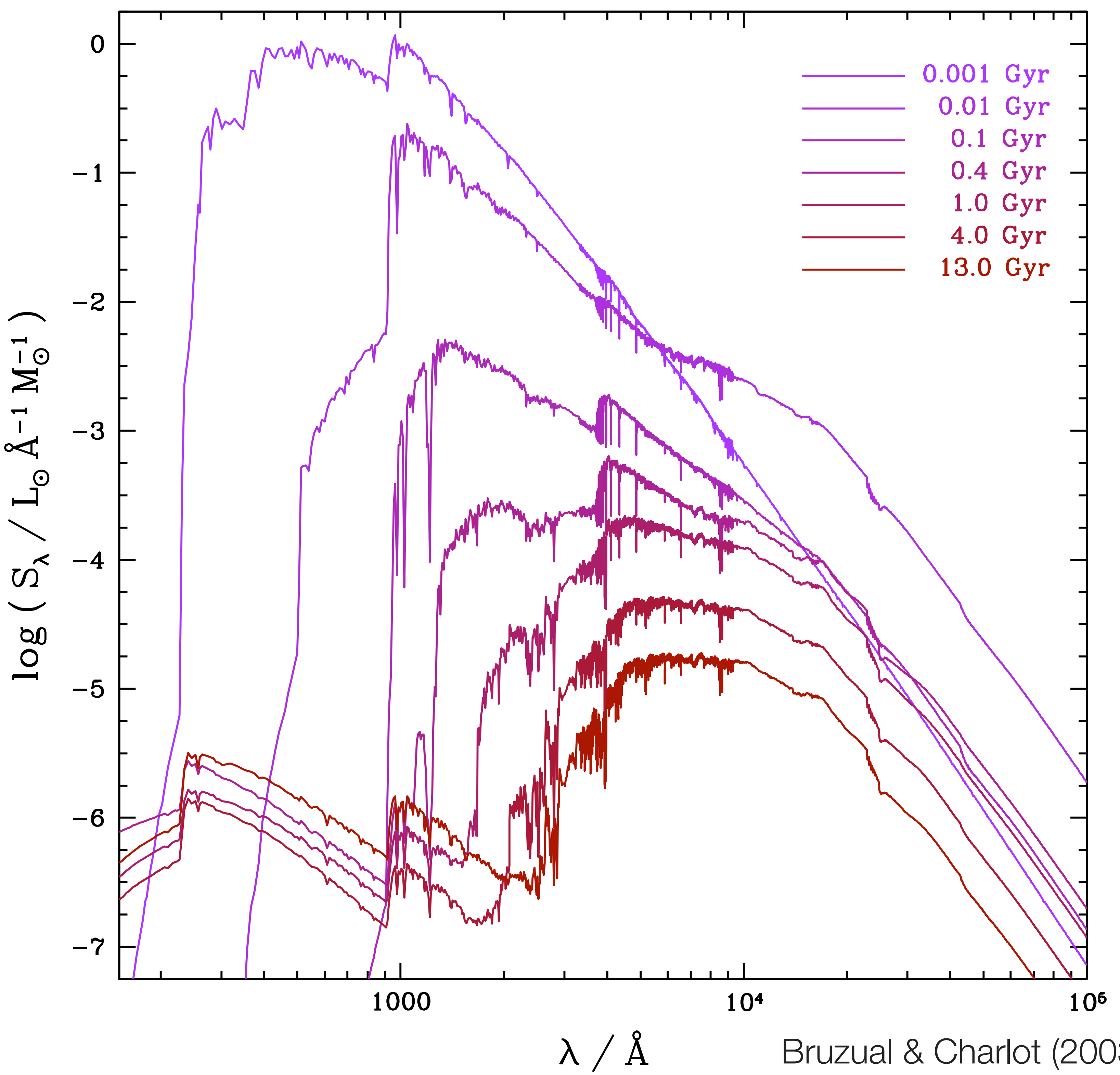
Spectral libraries
assign spectrum to a star of given mass, age and metallicity.

Initial Mass Function
how many stars of each mass form in each generation.



Conroy (2013)

Spectral evolution of a simple stellar population

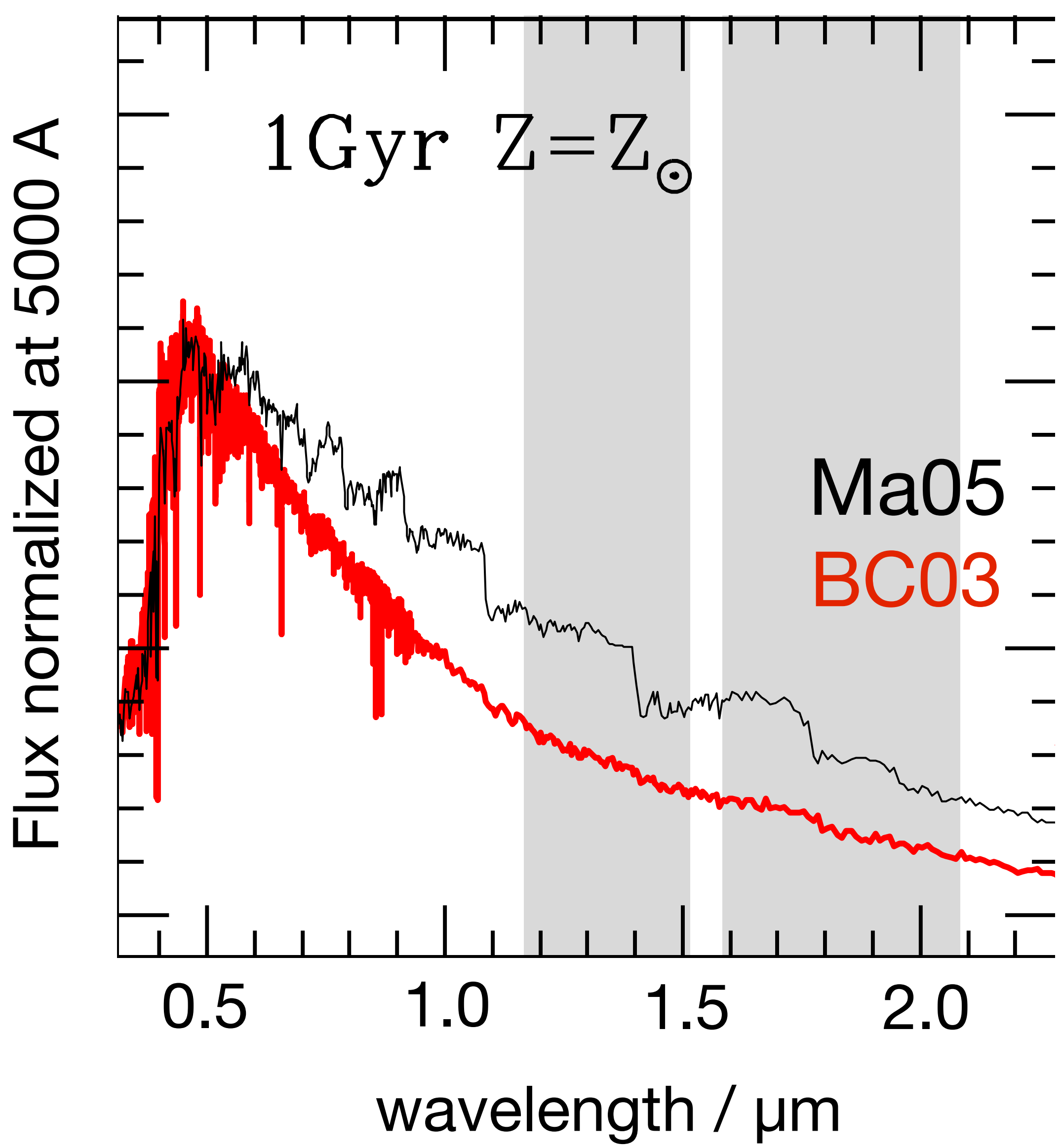


Bruzual & Charlot (2003)

spectrum of a SSP at a given age = IMF-weighted sum of the spectra of stars along the isochrone at that age

TP-AGB stars: a closer look

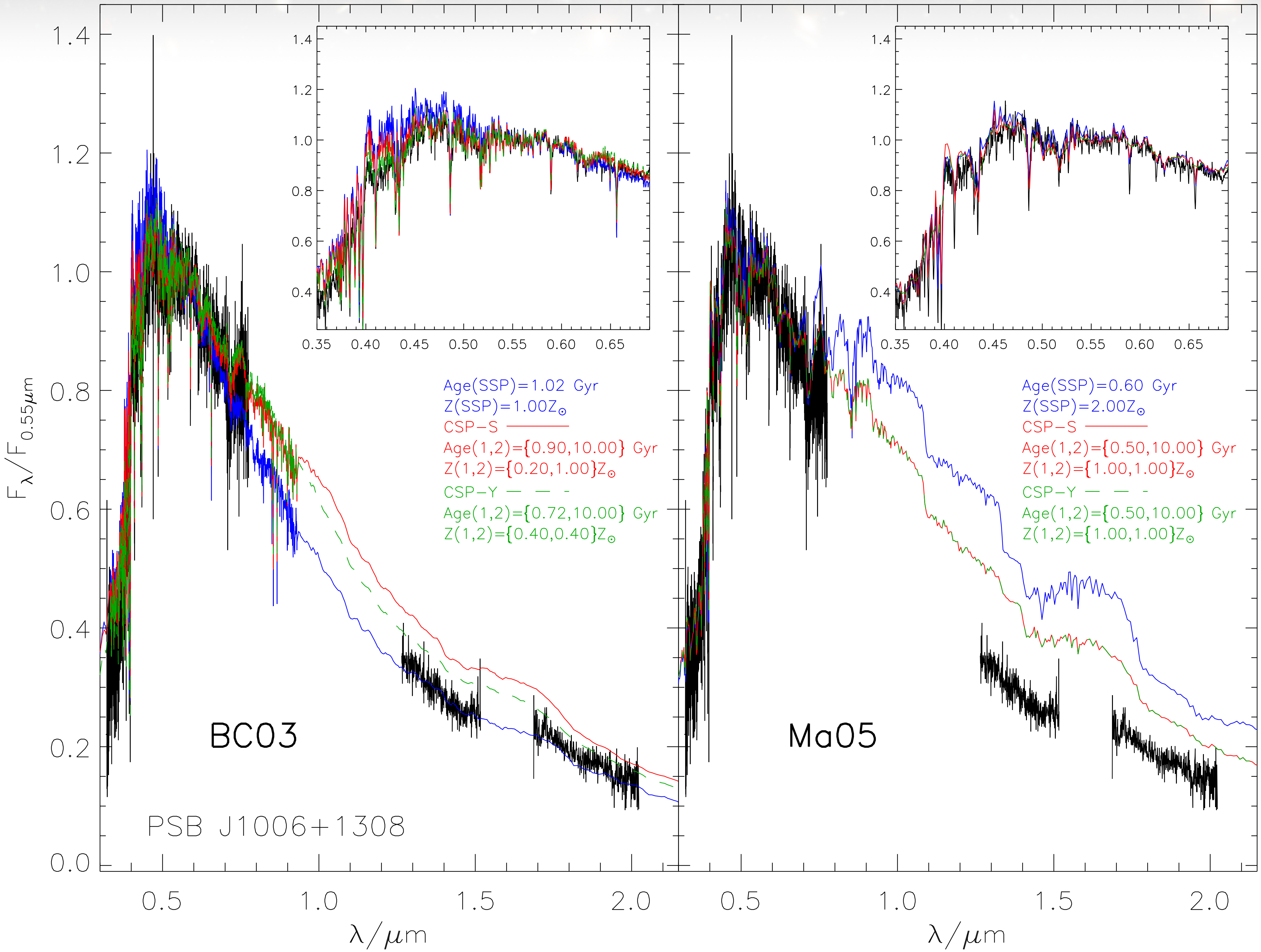
- Can be important for stellar populations with ages 0.5 to 1.5 Gyr
- Maraston (2005) models predicted NIR fluxes up to 3x higher than BC03 models, and also sharp absorption features at 1.1 - 1.8 μm
- Systematic differences in M/L from 0.2 to 0.4 dex



Zibetti+2012:
ISAAC spectroscopic follow-up of a sample of z~0.2 post-starburst galaxies (where contribution by TP-AGB stars should be maximal)

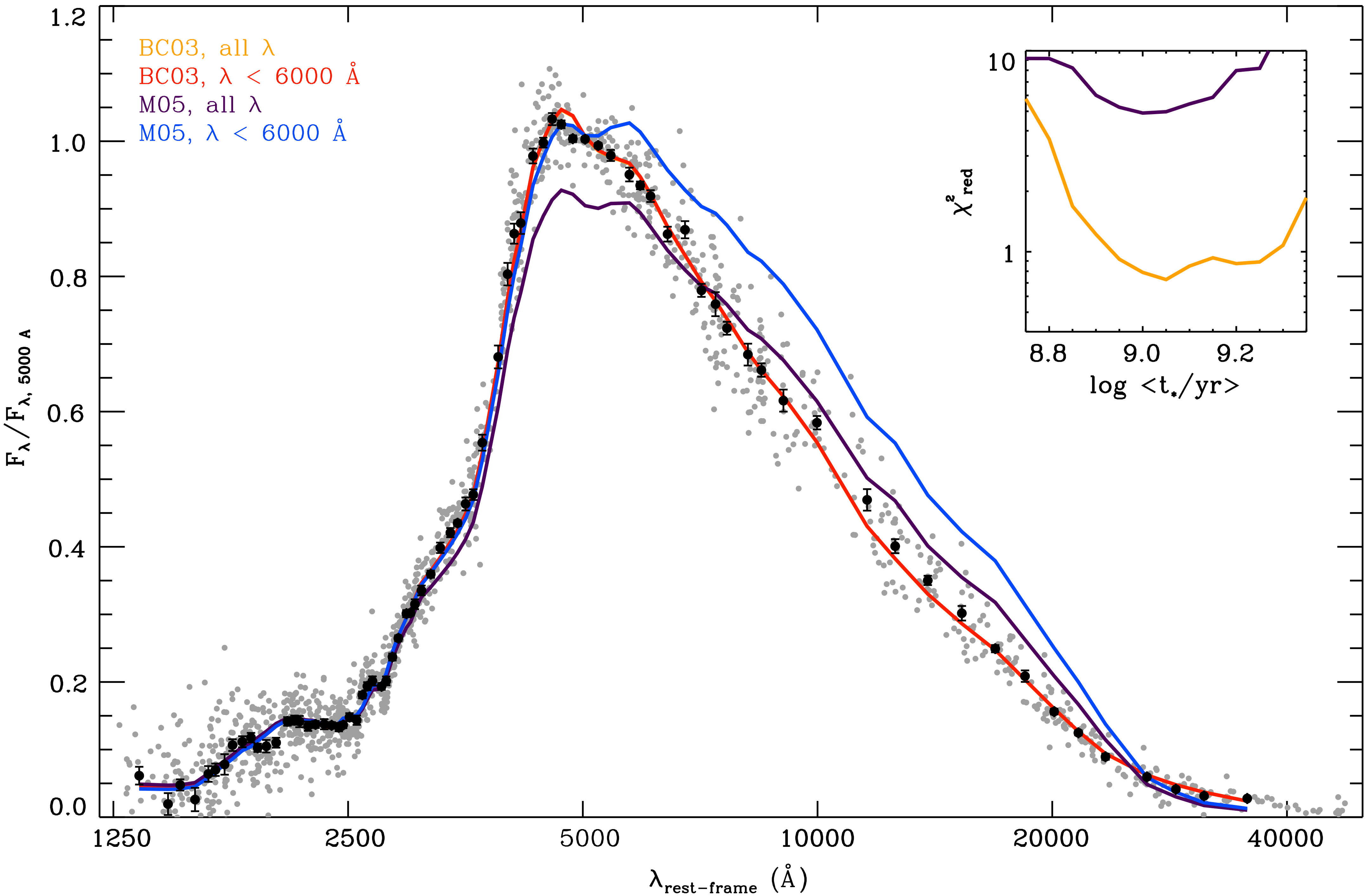
TP-AGB stars: a closer look

Zibetti+2012



TP-AGB stars at higher redshifts

Kriek+2010 : Composite post-starburst SED at 0.7 < z < 2.0



Impact of rotation in the evolution of massive stars

Levesque+2012: discussion of adding rotation to Starburst99 models

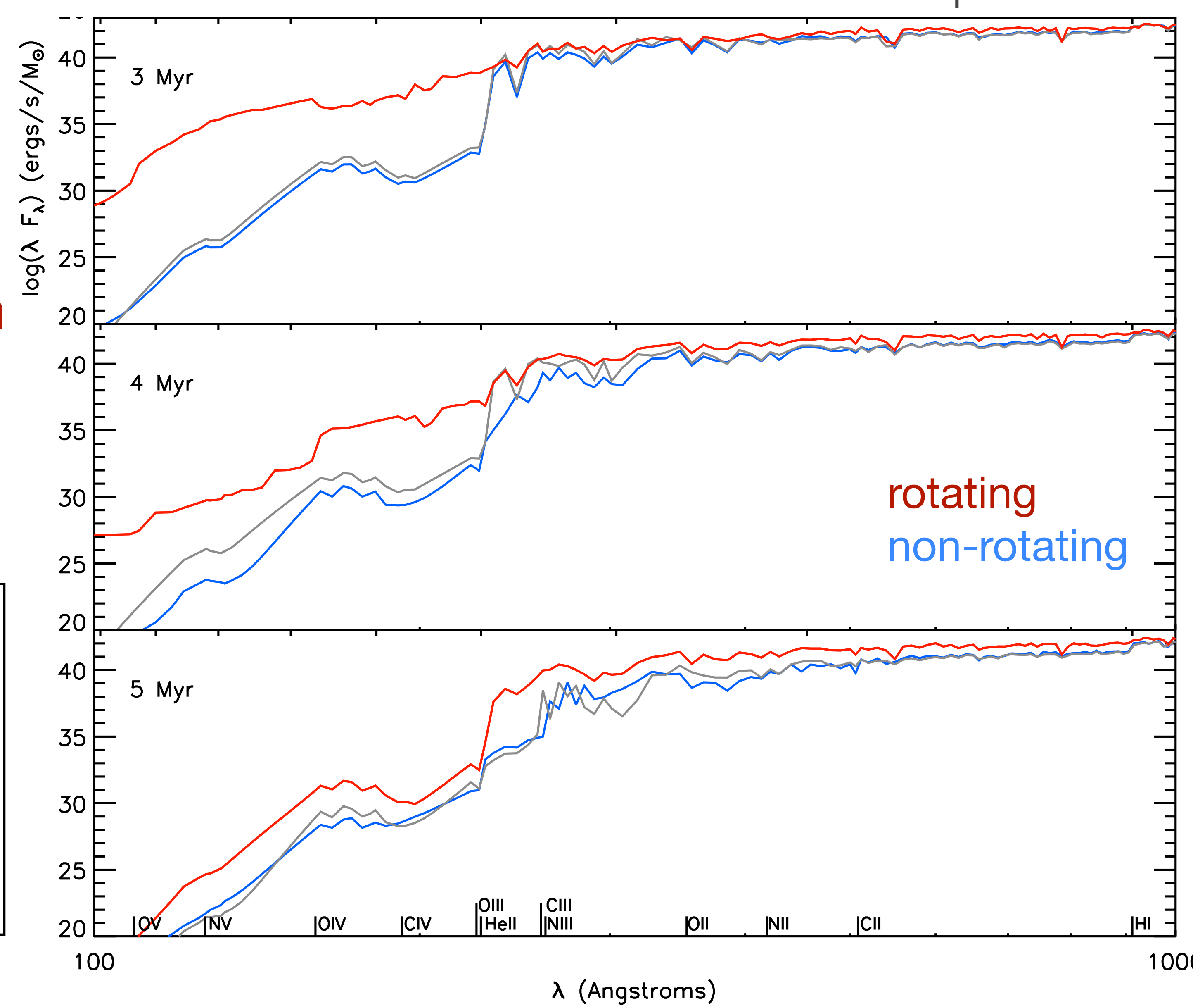
- Rotational mixing affects stellar lifetimes (e.g. Ekstroem+2012)
- Higher effective temperatures & luminosities (e.g. Leitherer+2008)
- Stronger mass loss; more (& longer-lived) WR stars

More hot massive stars at both early and later ages - stronger ionizing UV continuum over a longer lifetime.

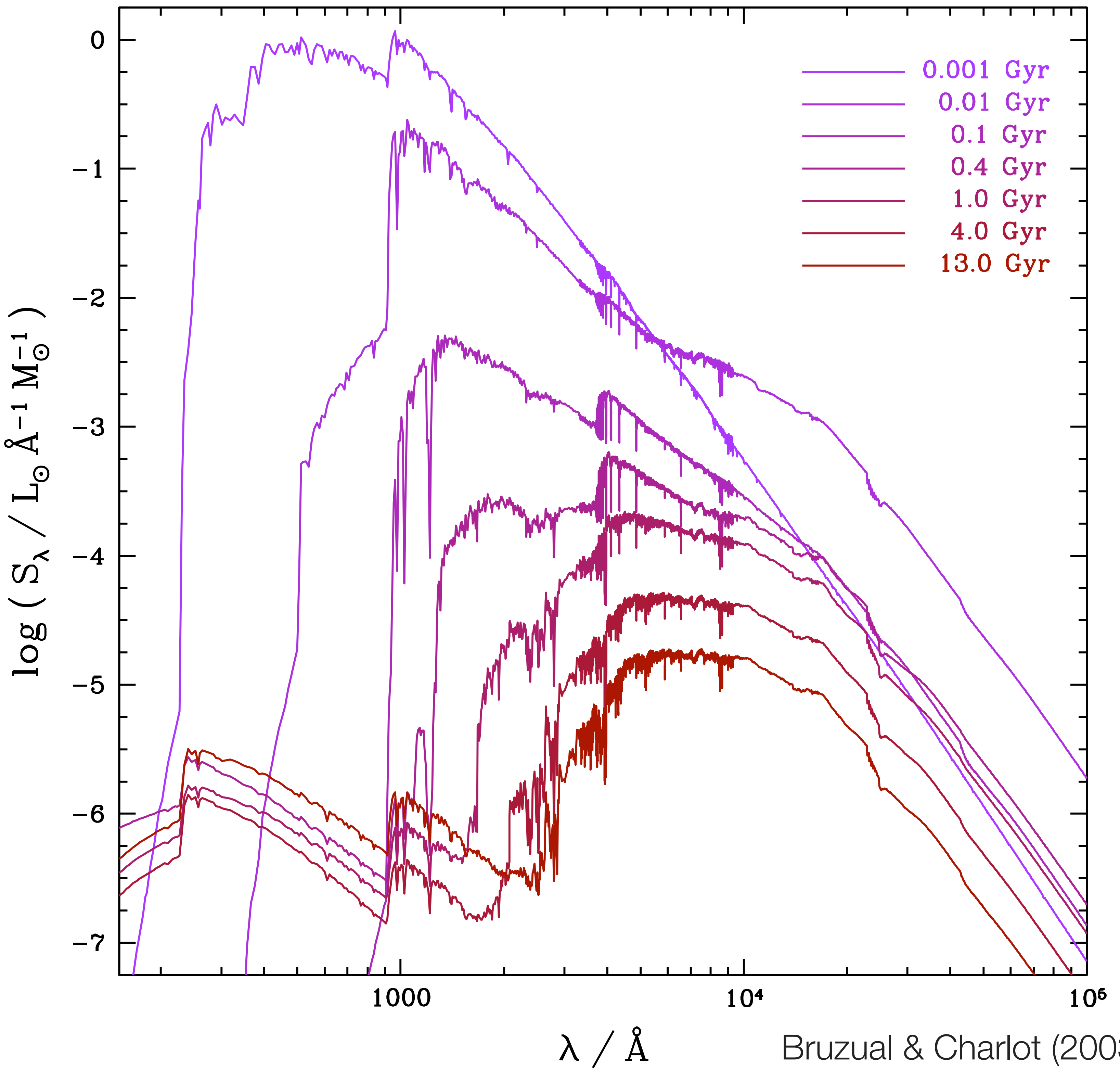
Large impact in UV & nebular emission studies of high-z galaxies.

Effects of rotational mixing on stellar evolution & new massive stellar spectra also being currently implemented in the newest version of the **Bruzual & Charlot models (in prep.).**

Levesque+2012



Spectral evolution of a simple stellar population

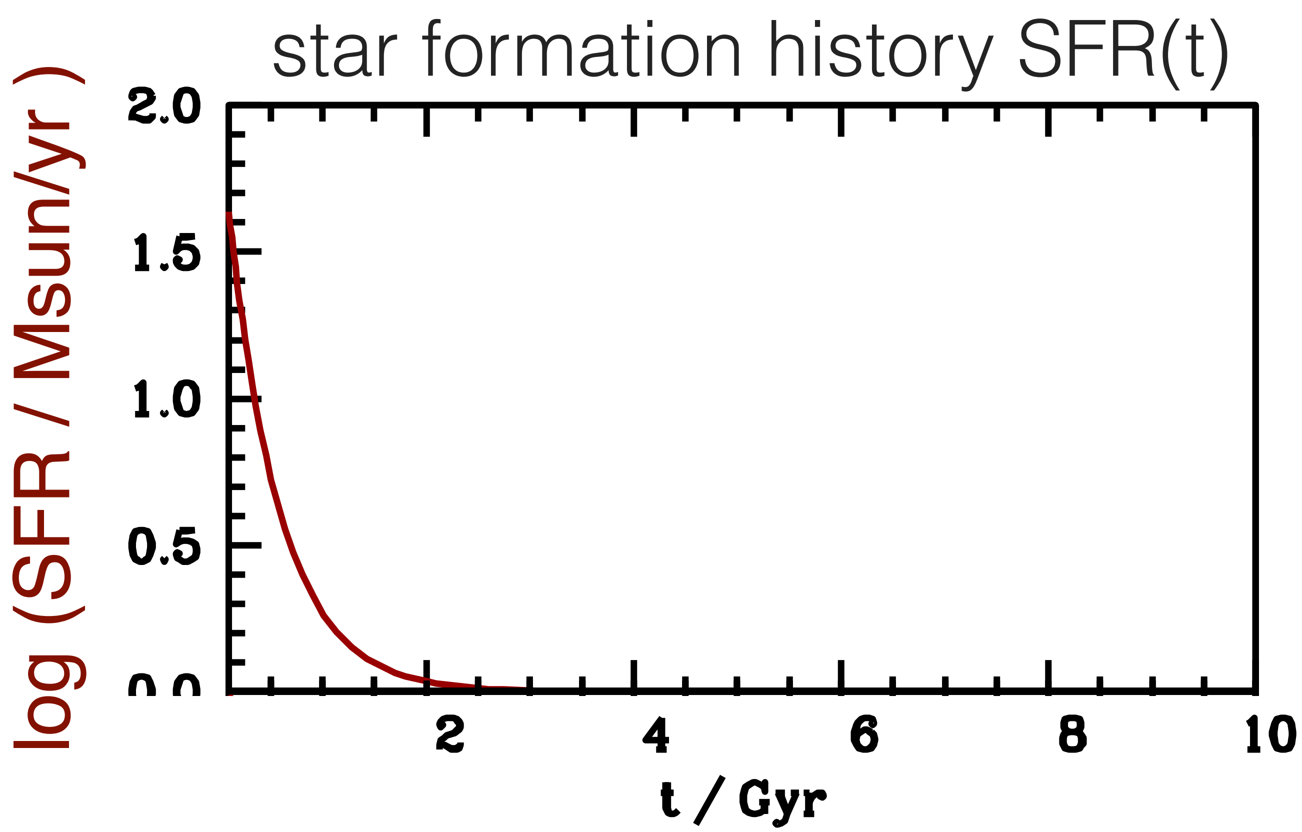


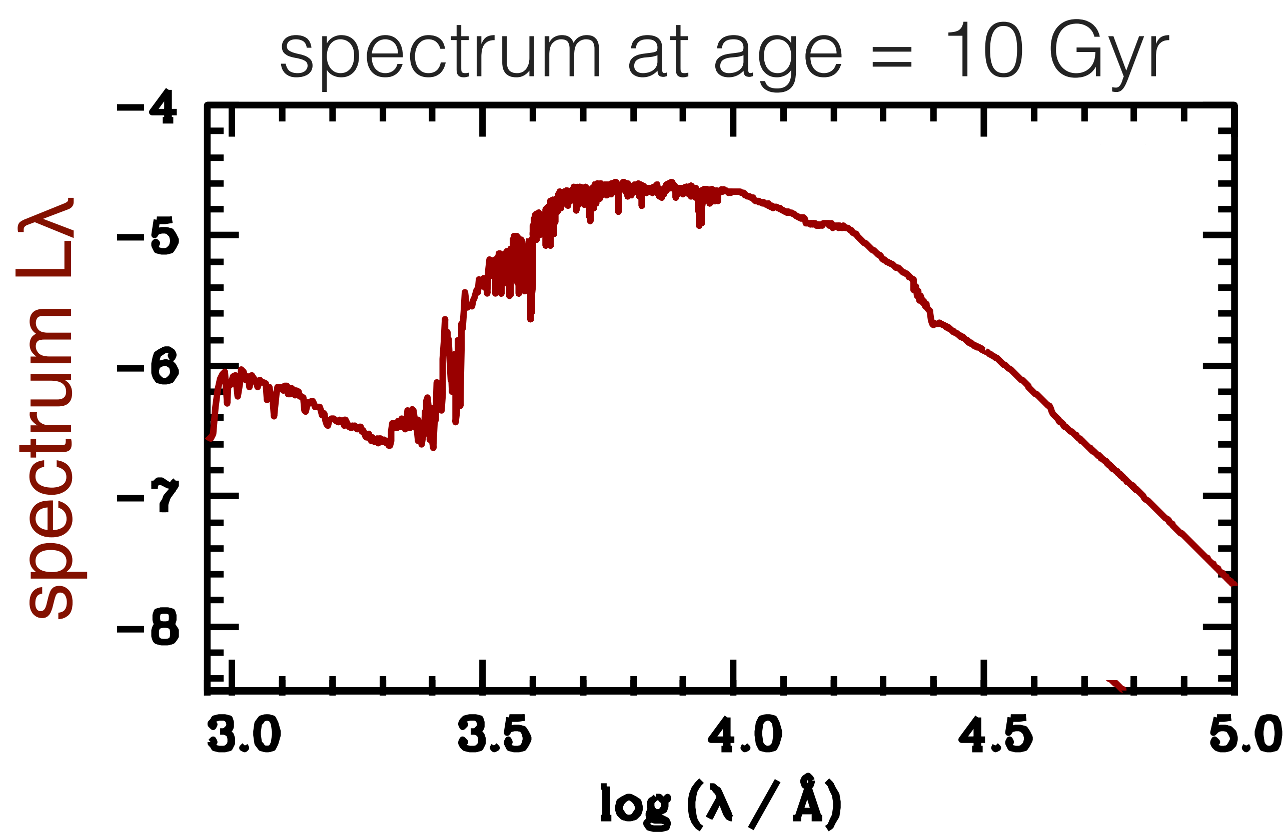
Bruzual & Charlot (2003)

spectrum of a SSP at a given age
=
IMF-weighted sum of the spectra of stars along the isochrone at that age

Galaxy = many stellar populations

Spectrum of all the stars in a galaxy i.e. ‘composite stellar population’
$= \int$ SSP(age,metallicity) x SFR(t)





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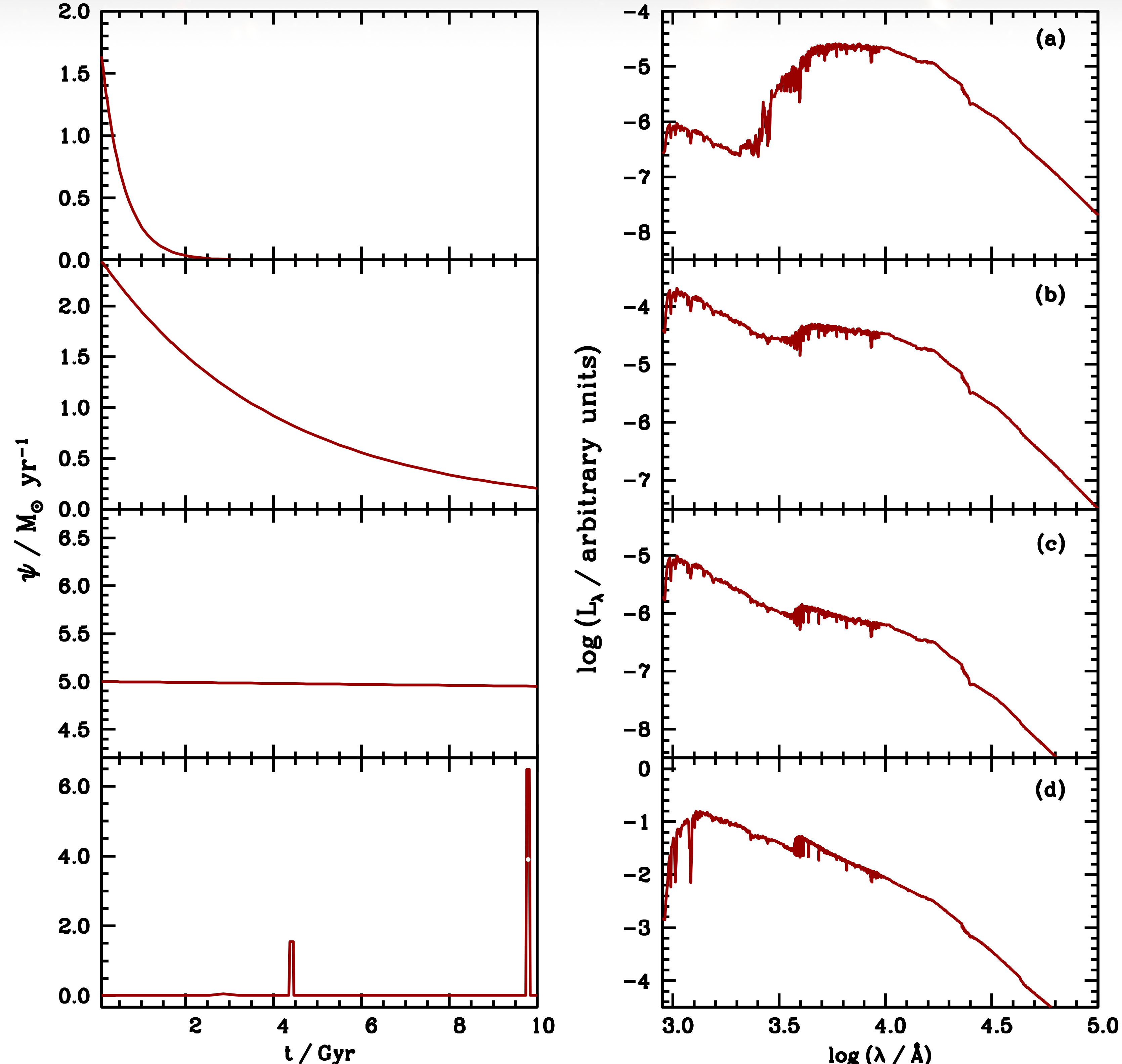
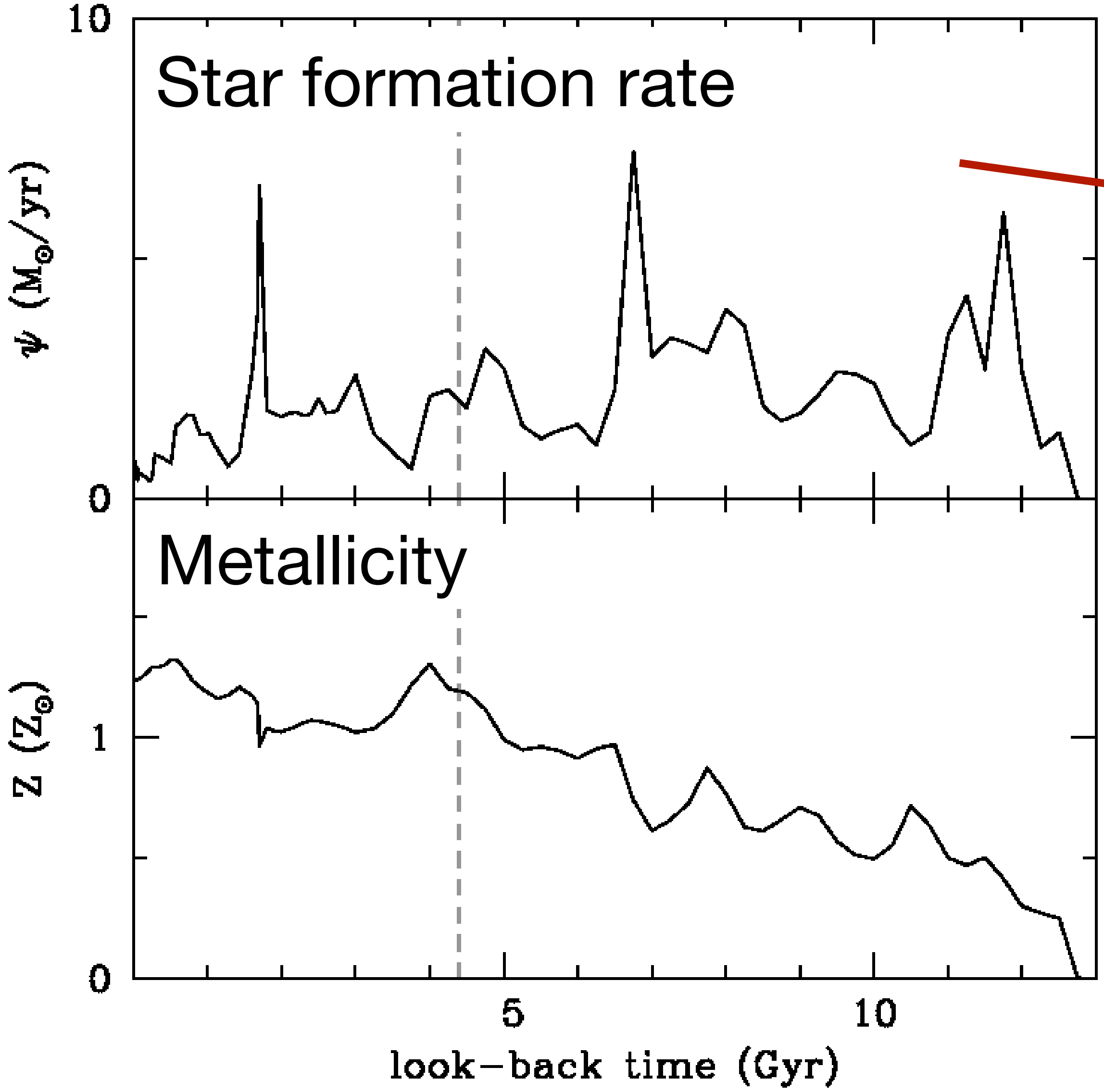


Main parameters:

- IMF
- age (onset of SF)
- **star formation history**
- **metallicity (evolution)**

Star formation & chemical enrichment histories

Post-processing of the Millenium simulation by De Lucia & Blaizot (2007)

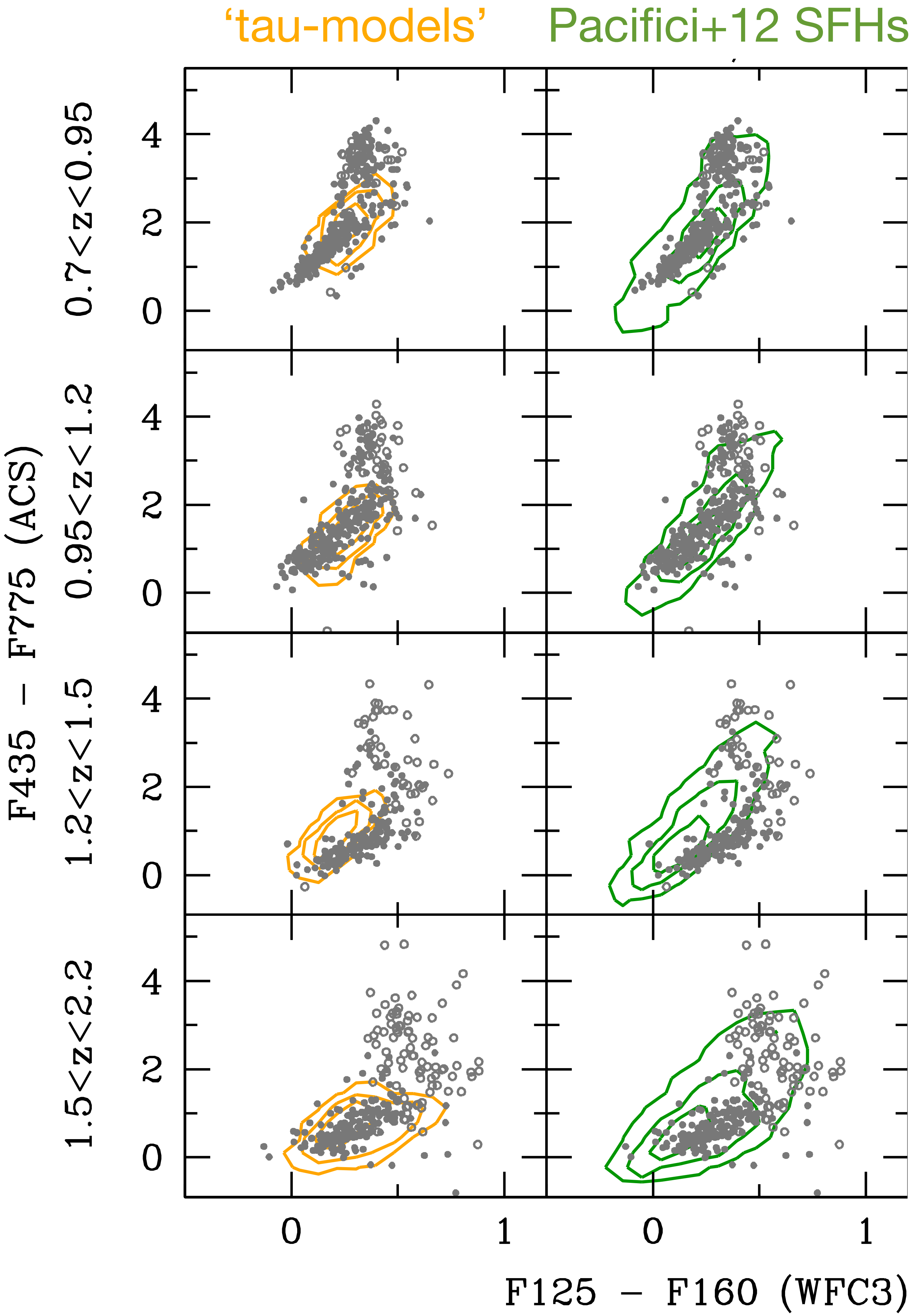


Pacifici+2012

Looks nothing like a continuous tau-model!

Increasing evidence that the SFHs of high-redshift galaxies need to increase with time.

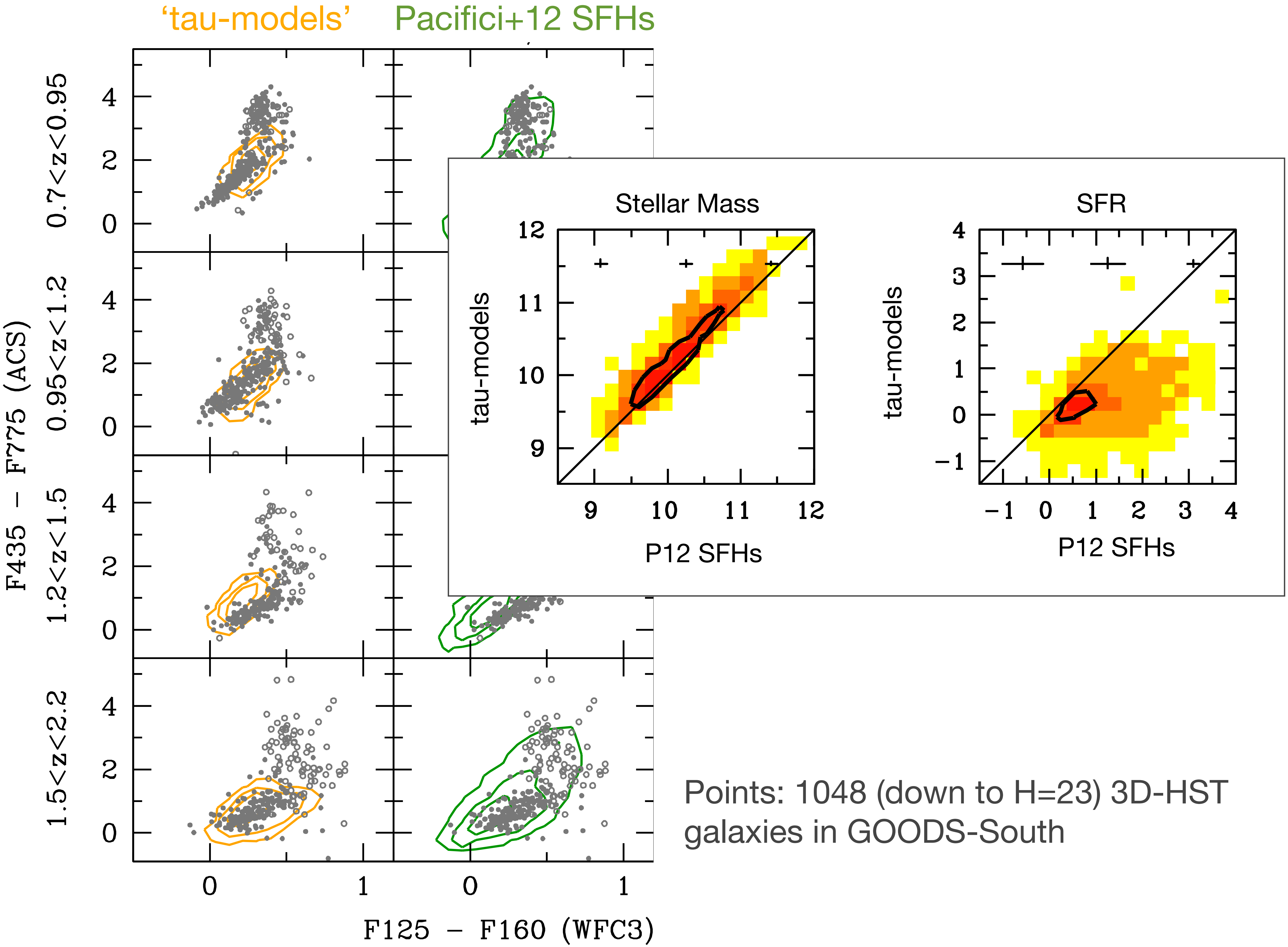
e.g. Maraston+2010, Lee+2010, Wuyts+2011, Pforr+2012, Behroozi+2013, Pacifici+2013



(Pacifici, da Cunha, Charlot,+2015)

We need complex (realistic) SFHs to reproduce the observed HST colours of galaxies

Points: 1048 (down to H=23) 3D-HST galaxies in GOODS-South

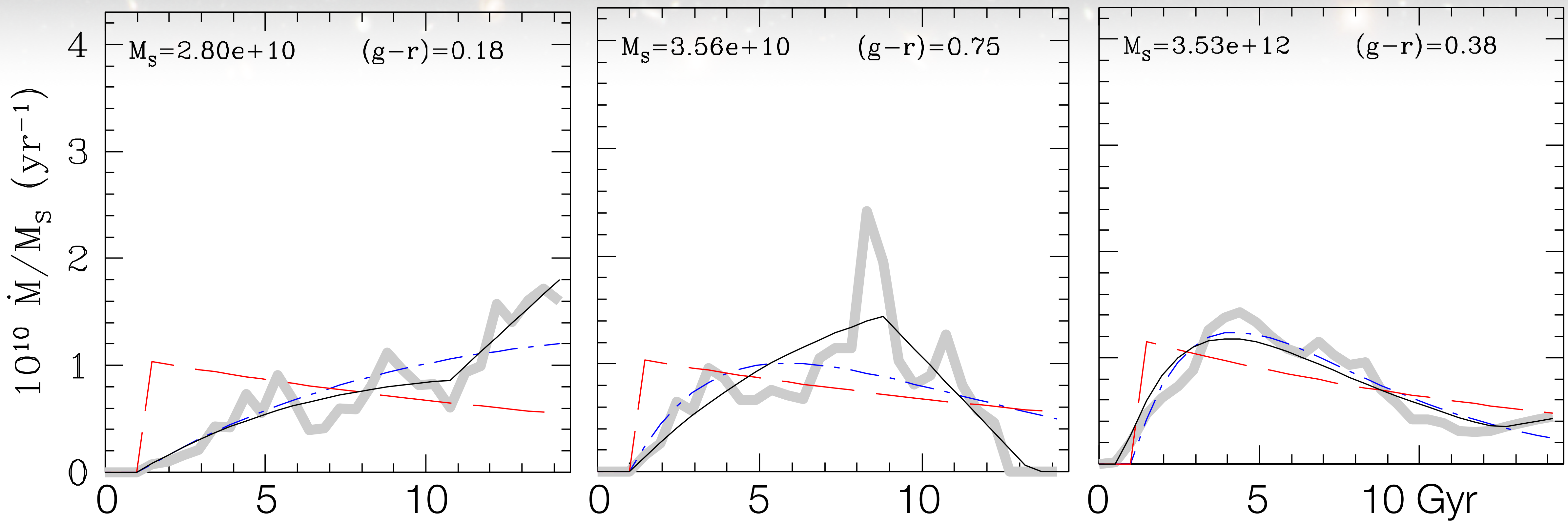


Points: 1048 (down to H=23) 3D-HST galaxies in GOODS-South

(Pacifici, da Cunha, Charlot,+2015)

How should we parameterize the SFH?

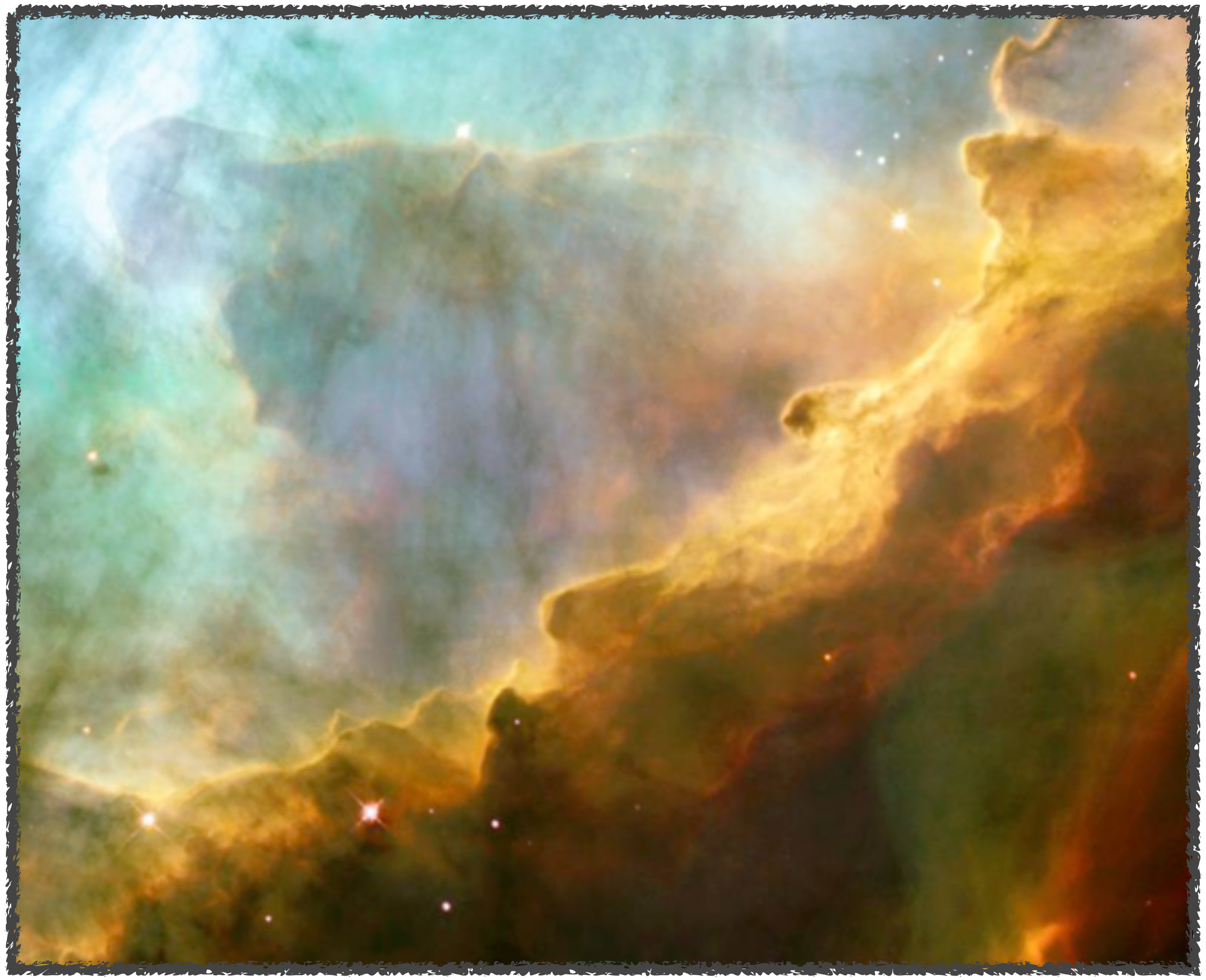
Simha+2014



- exponentially declining tau-models
- exponentially rising tau-models (Maraston+2010,Pforr+2012)
- delayed tau-models (Lee+2010)
- 4-parameter analytical model (Simha+2014)

New MAGPHYS SFHs:

delayed tau-models (spanning a wide range of timescales) + random bursts

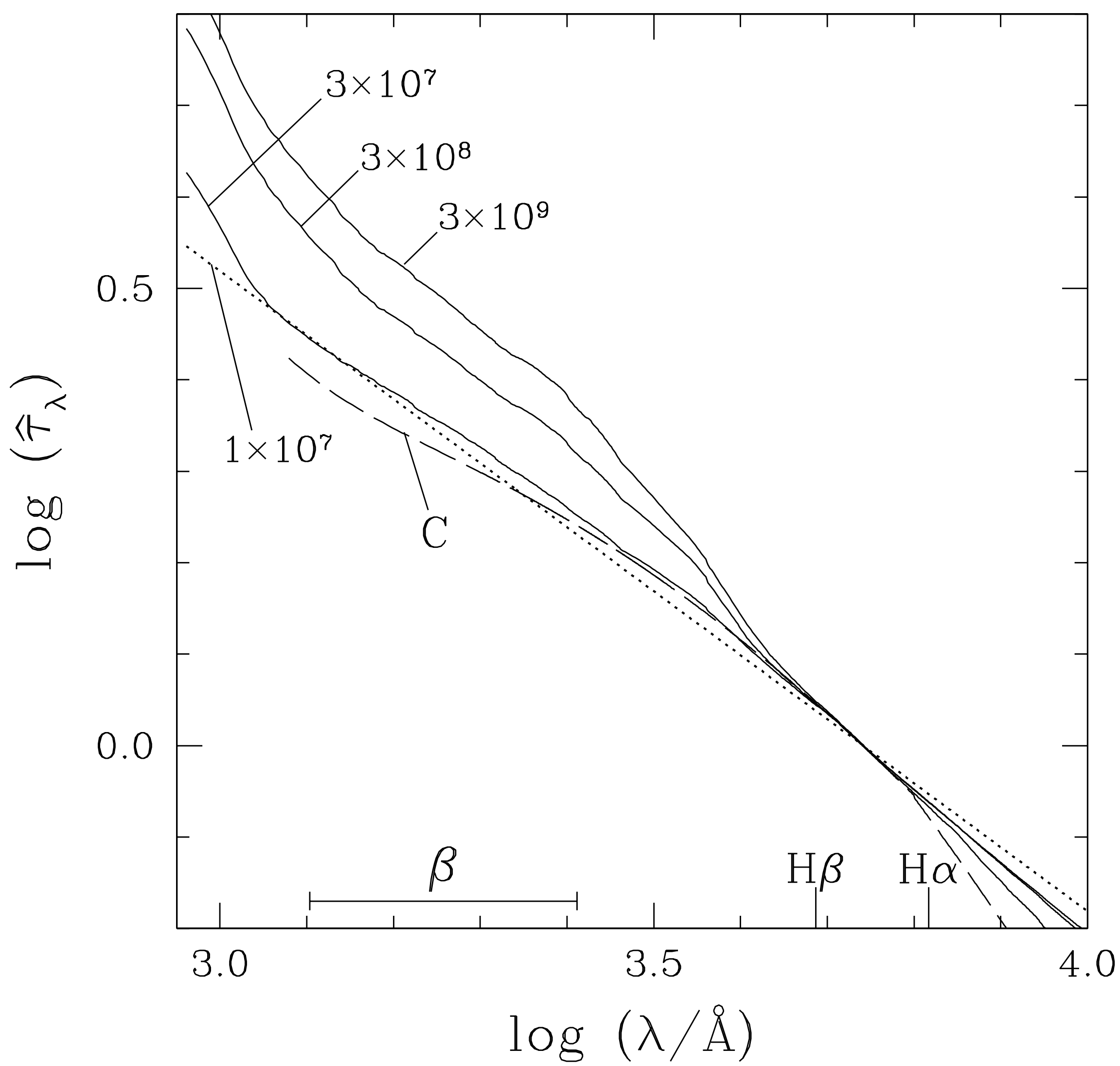


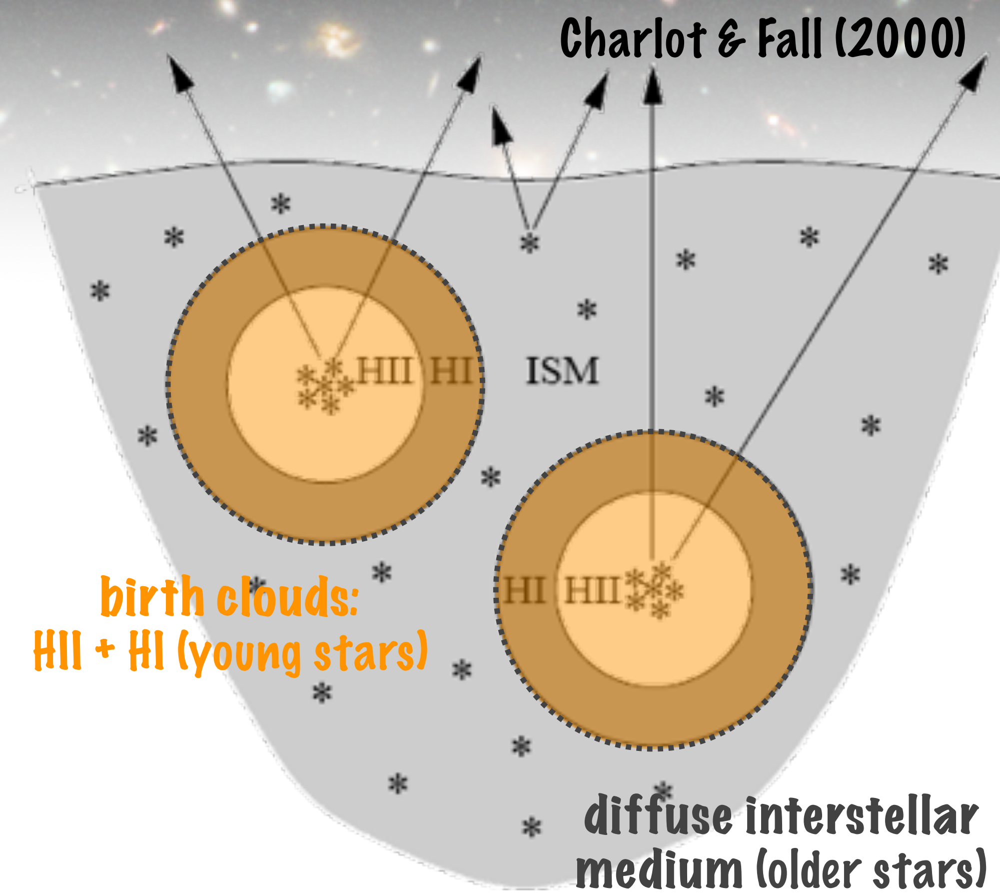
the interstellar medium:
dust & ionized gas

The interstellar medium: dust

- Stellar **birth clouds** with lifetime t_0.
- Attenuation affecting stars older than t_0 in the **diffuse ISM** is only a fraction of that affecting young stars in the birth clouds.

age-dependent attenuation





$$\hat{\tau}_\lambda(t') = \begin{cases} \hat{\tau}_\lambda^{\rm BC} + \hat{\tau}_\lambda^{\rm ISM} & \text{for } t' \le t_0 \\ \hat{\tau}_\lambda^{\rm ISM} & \text{for } t' > t_0 \end{cases}$$

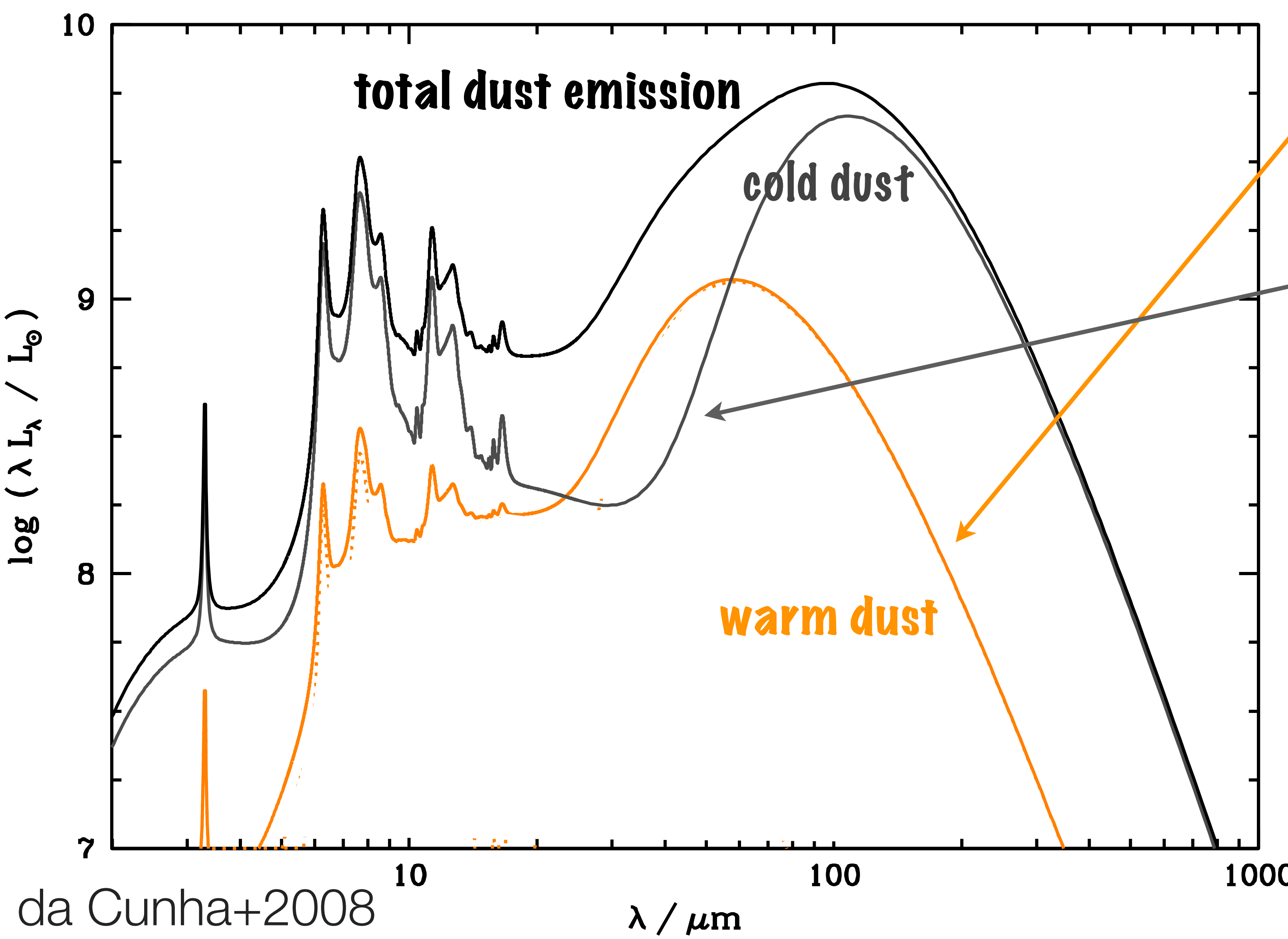
$$\hat{\tau}_\lambda^{\rm BC} = (1-\mu)\hat{\tau}_V(\lambda/5500\,\text{Å})^{-1.3}$$

$$\hat{\tau}_\lambda^{\rm ISM} = \mu\hat{\tau}_V(\lambda/5500\,\text{Å})^{-0.7}$$

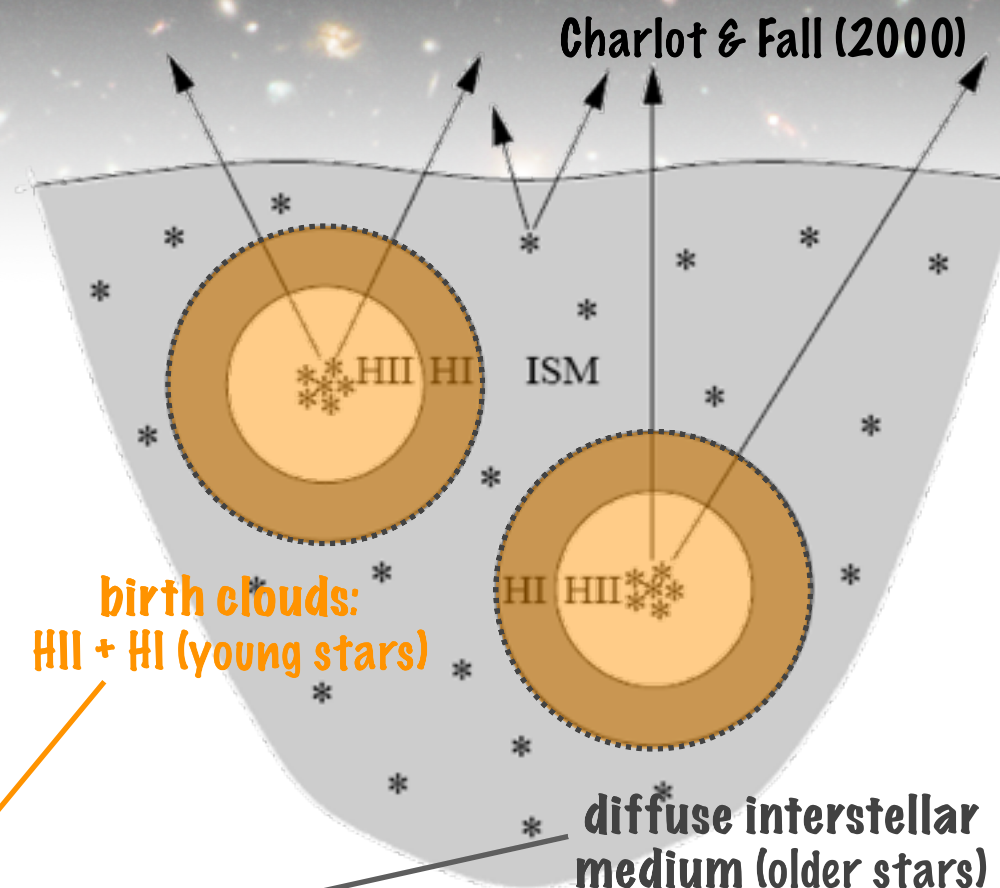
The interstellar medium: dust

- Stellar **birth clouds** with lifetime t_0.

- Attenuation affecting stars older than t_0 in the **diffuse ISM** is only a fraction of that affecting young stars in the birth clouds.



da Cunha+2008



- **Energy balance**

- **Dust components:**

. PAHs

. Hot mid-IR continuum

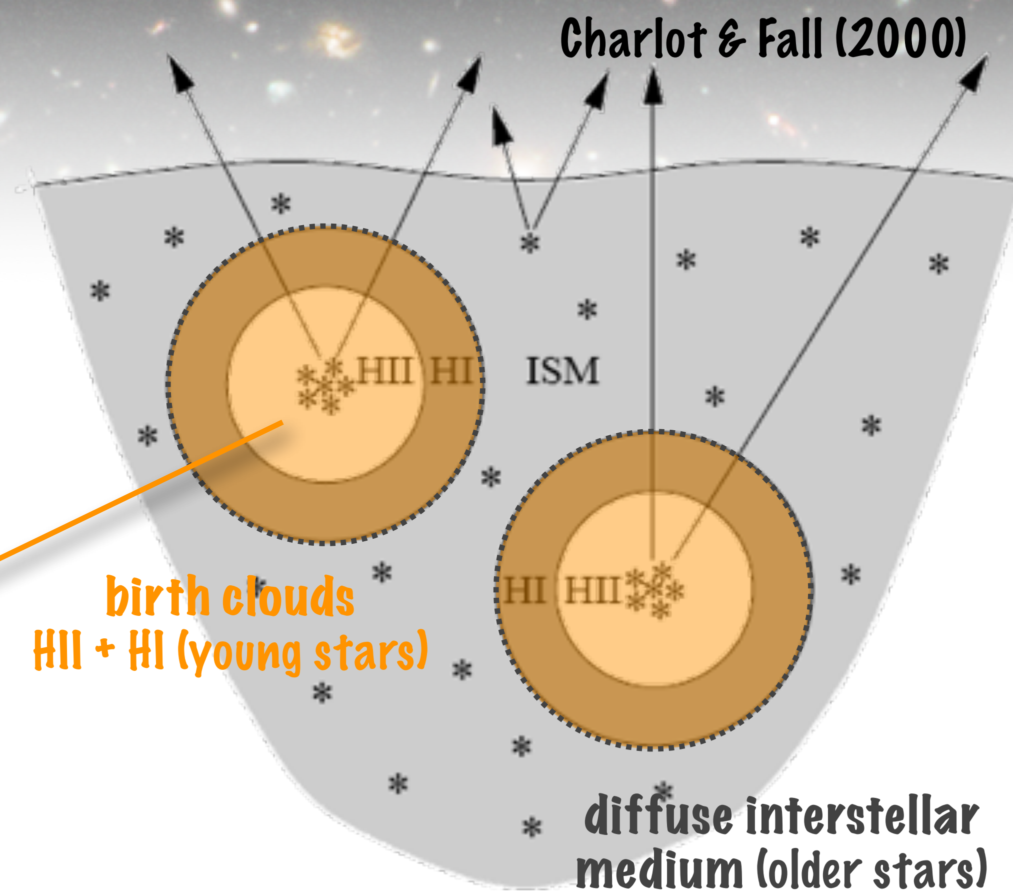
. Warm dust in thermal equilibrium (30 - 60 K)

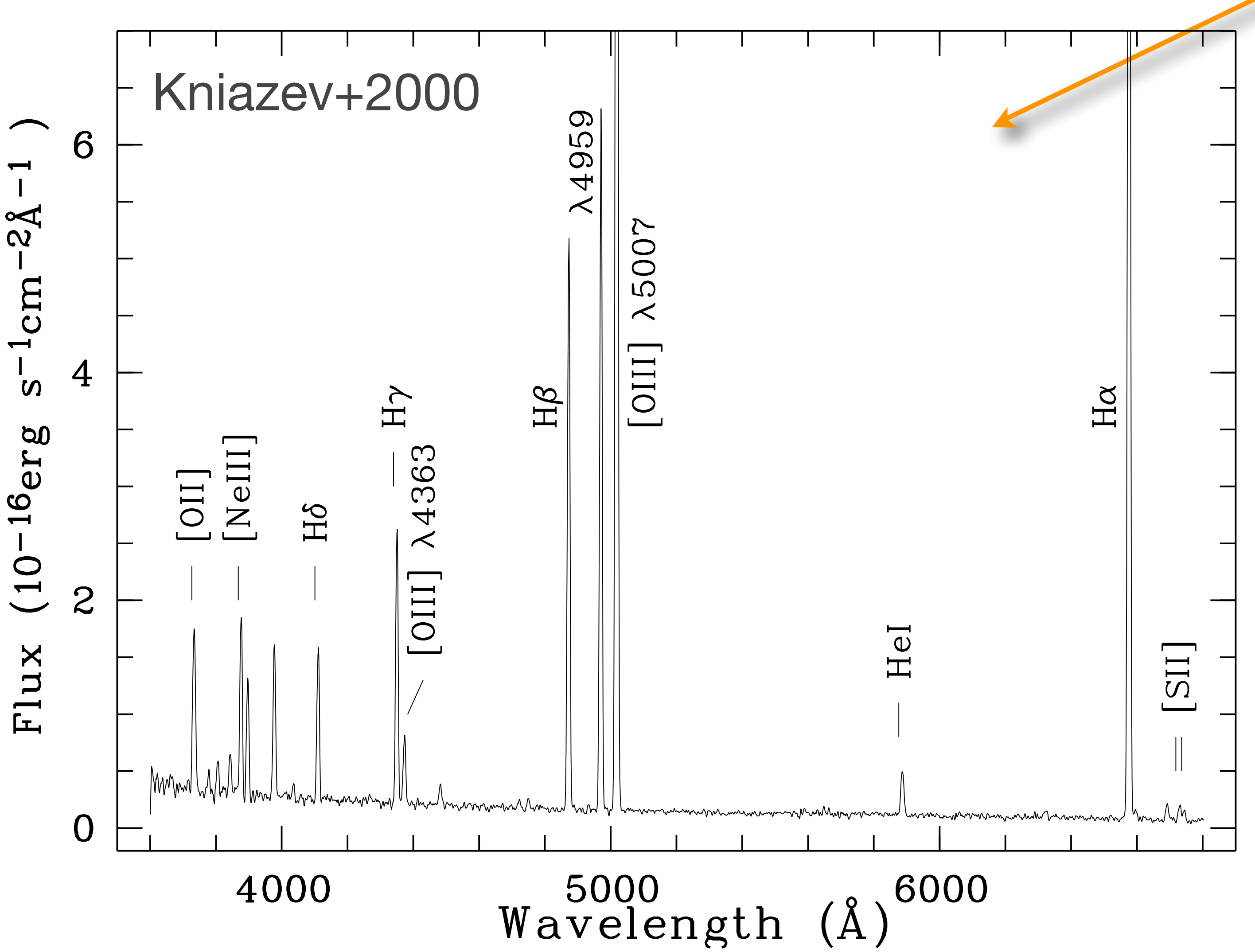
. Cold dust in thermal equilibrium (15 - 25 K)

The interstellar medium: ionized gas

- Stellar **birth clouds** with lifetime t_0.

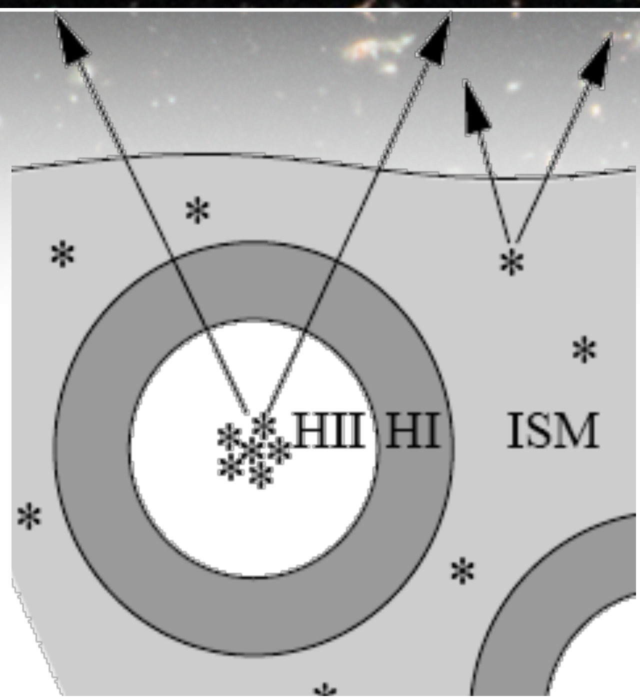
- Attenuation affecting stars older than t_0 in the **diffuse ISM** is only a fraction of that affecting young stars in the birth clouds.

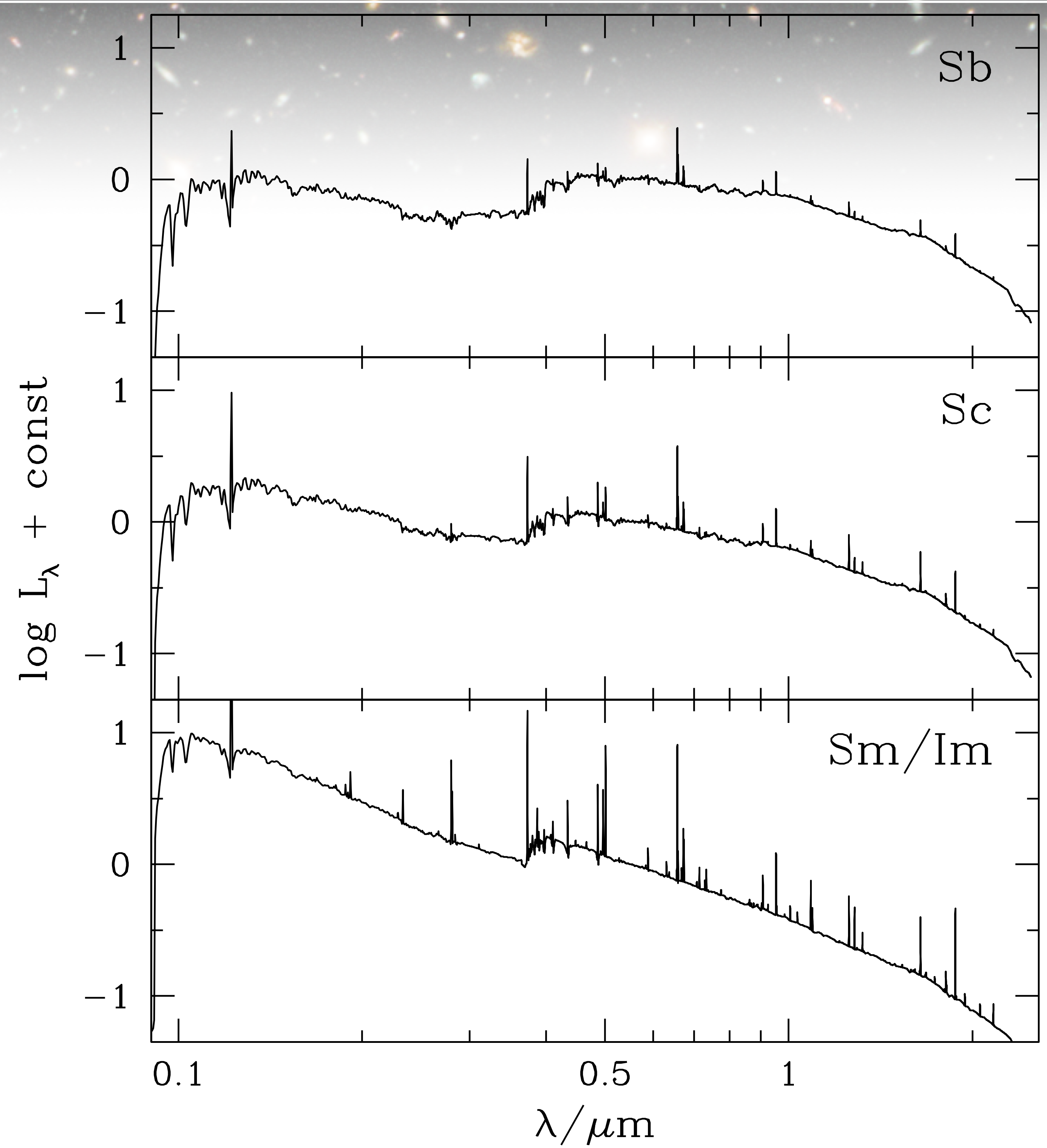




NEW! nebular emission **computed self-consistently** using the CLOUDY photo-ionization code by Ferland 1996 (Pacifici+2012, Charlot & Longhetti 2001)

The interstellar medium: ionized gas





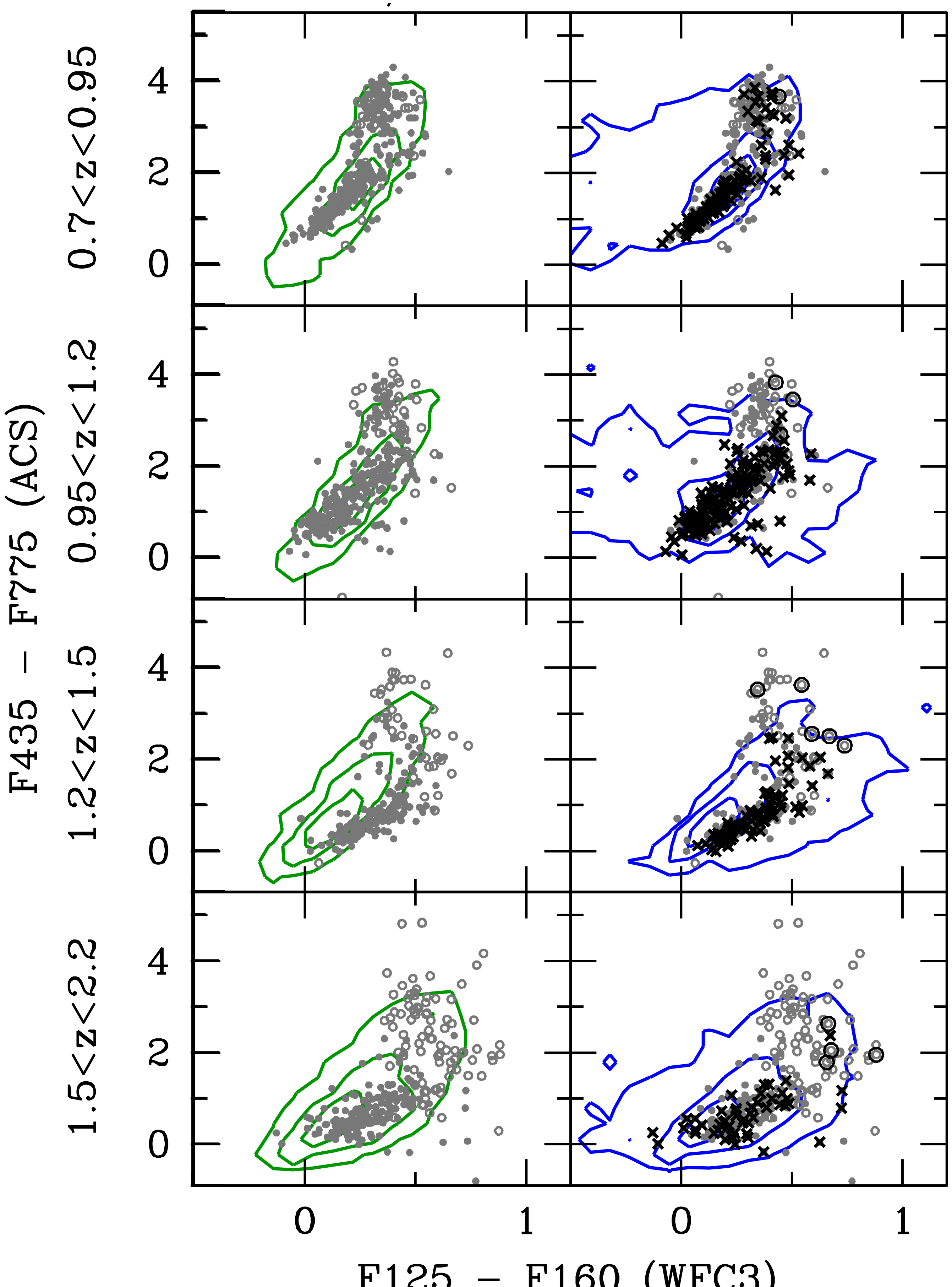
Ionizing radiation set by the stellar population model + SFH

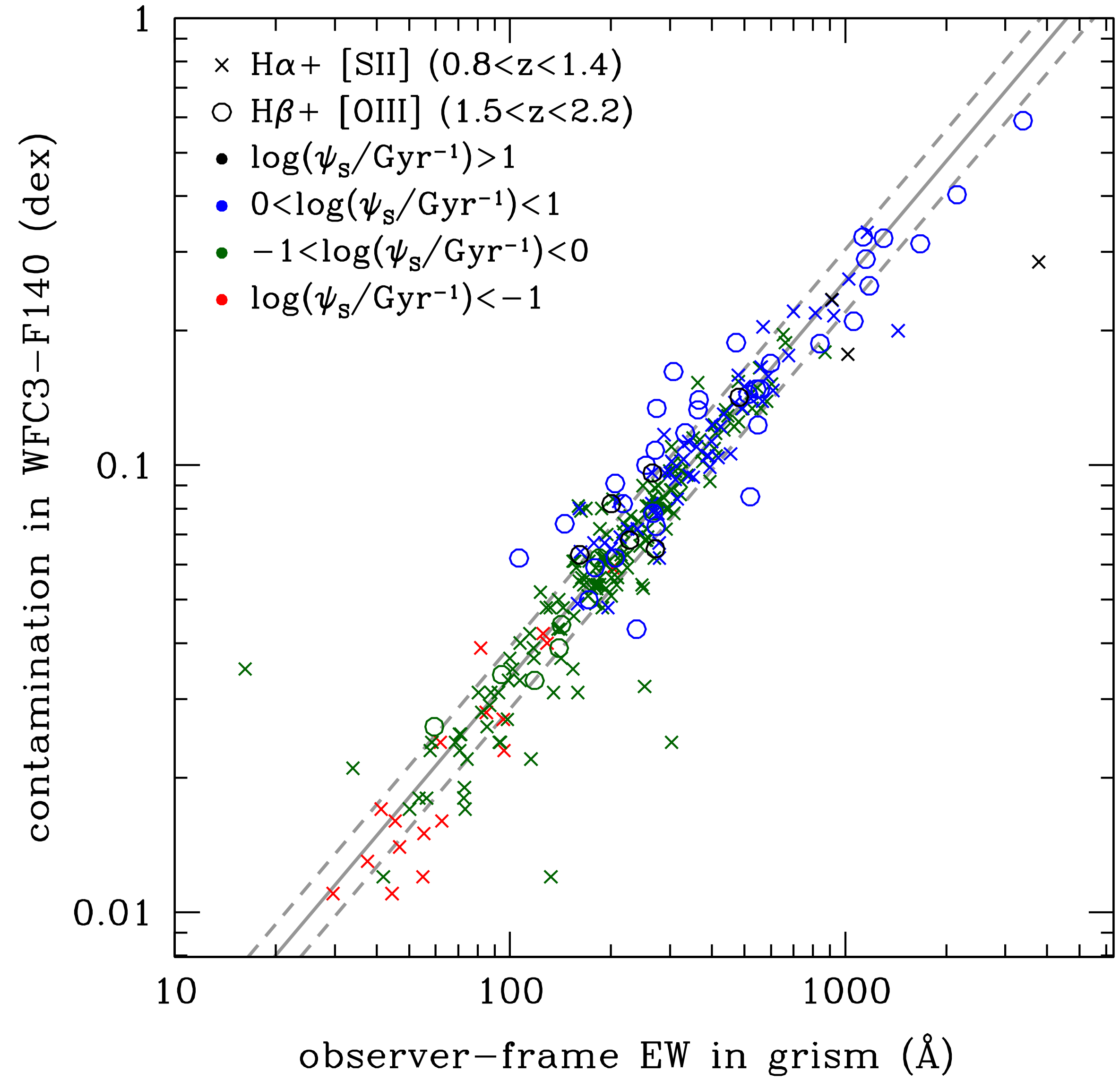
Dust attenuation already implemented (CF00)

Additional parameters (CLOUDY):

- Zero-age ionization parameter
- Gas-phase metallicity
- Gas-to-dust ratio
- Depletion of metals onto dust grains

Charlot & Longhetti (2001), Pacifici+2012
[see also e.g. Groves et al. 2008]

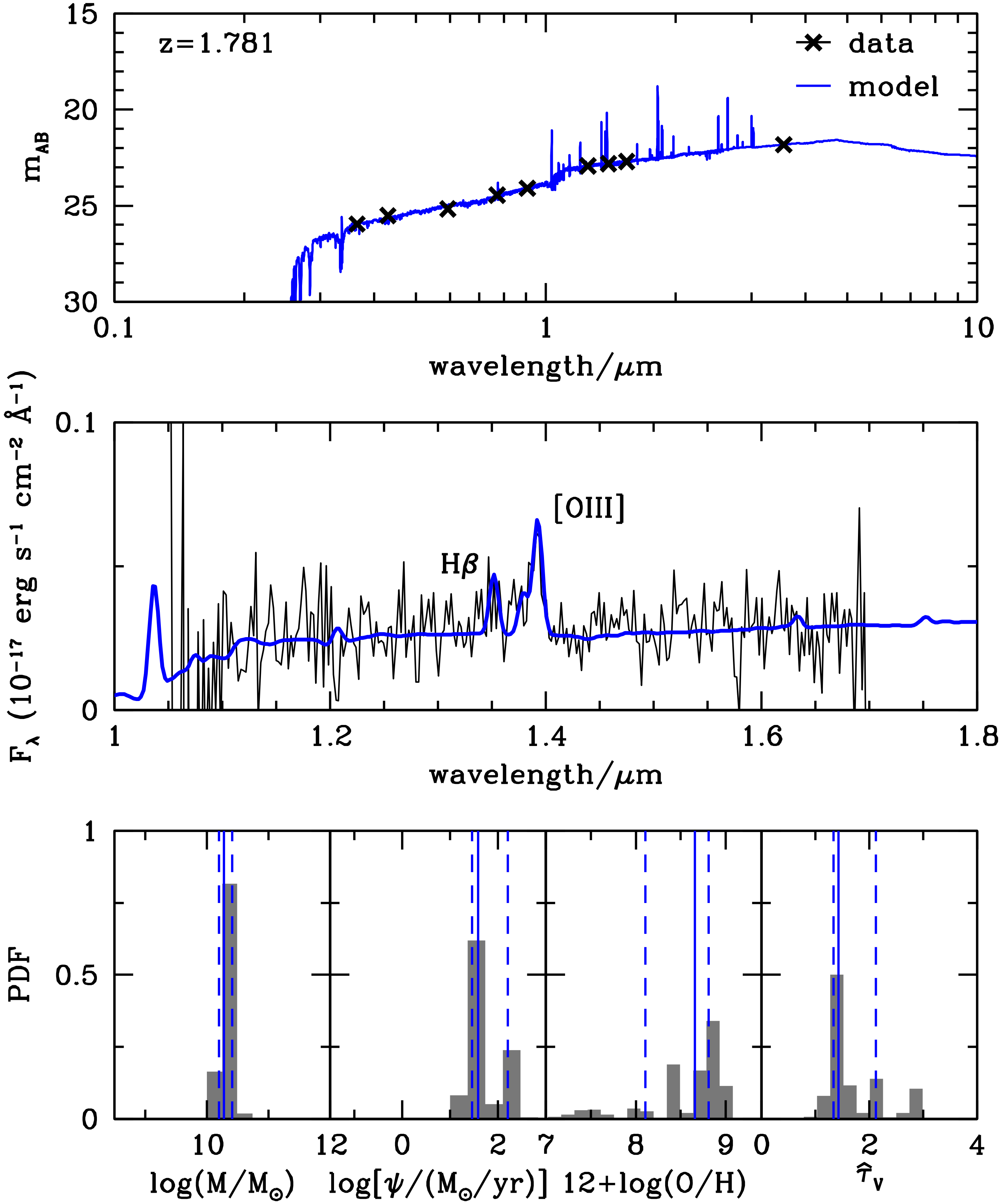




contamination by nebular emission can be important even at 'moderate' redshifts!

[see also de Barros+2014]

Example broad-band photometry + emission line fit



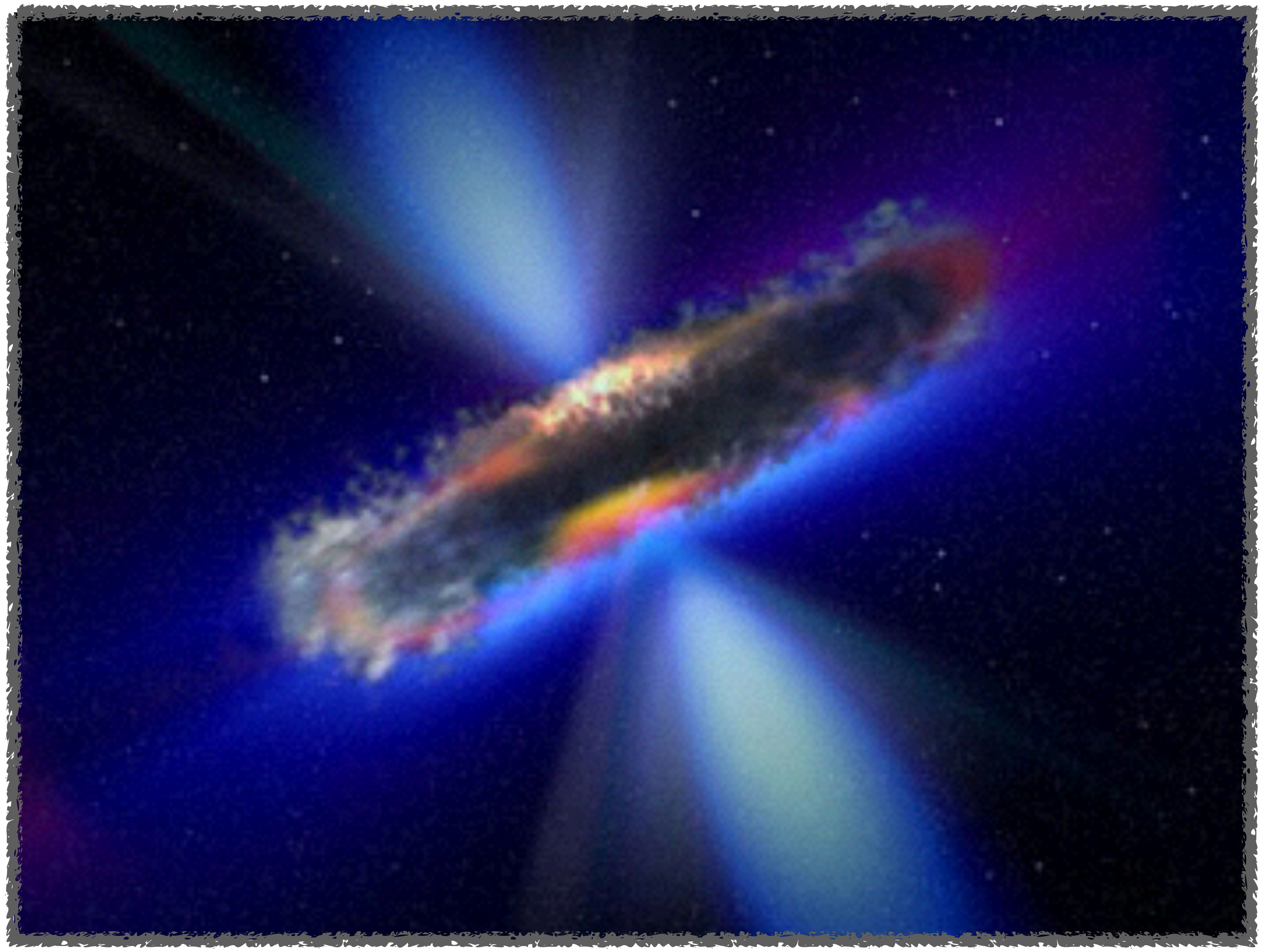
Spectral energy distribution

3D-HST WFC3 grism spectrum

Parameter likelihood distributions

Pacifici, da Cunha+2015

[see also Maseda+2014]



AGN contamination

Challenges in modelling AGN contamination

AGN component challenging to compute: large dependence on torus parameters, viewing angle, accretion rate etc.

Emission template:

- models: large parameter space/ degeneracies
(e.g. Nenkova+, Fritz+, Siebenmorgen+)

- empirical: challenging to separate torus/SF contributions

<u>Start simple:</u> empirical template (Mullaney+2011)

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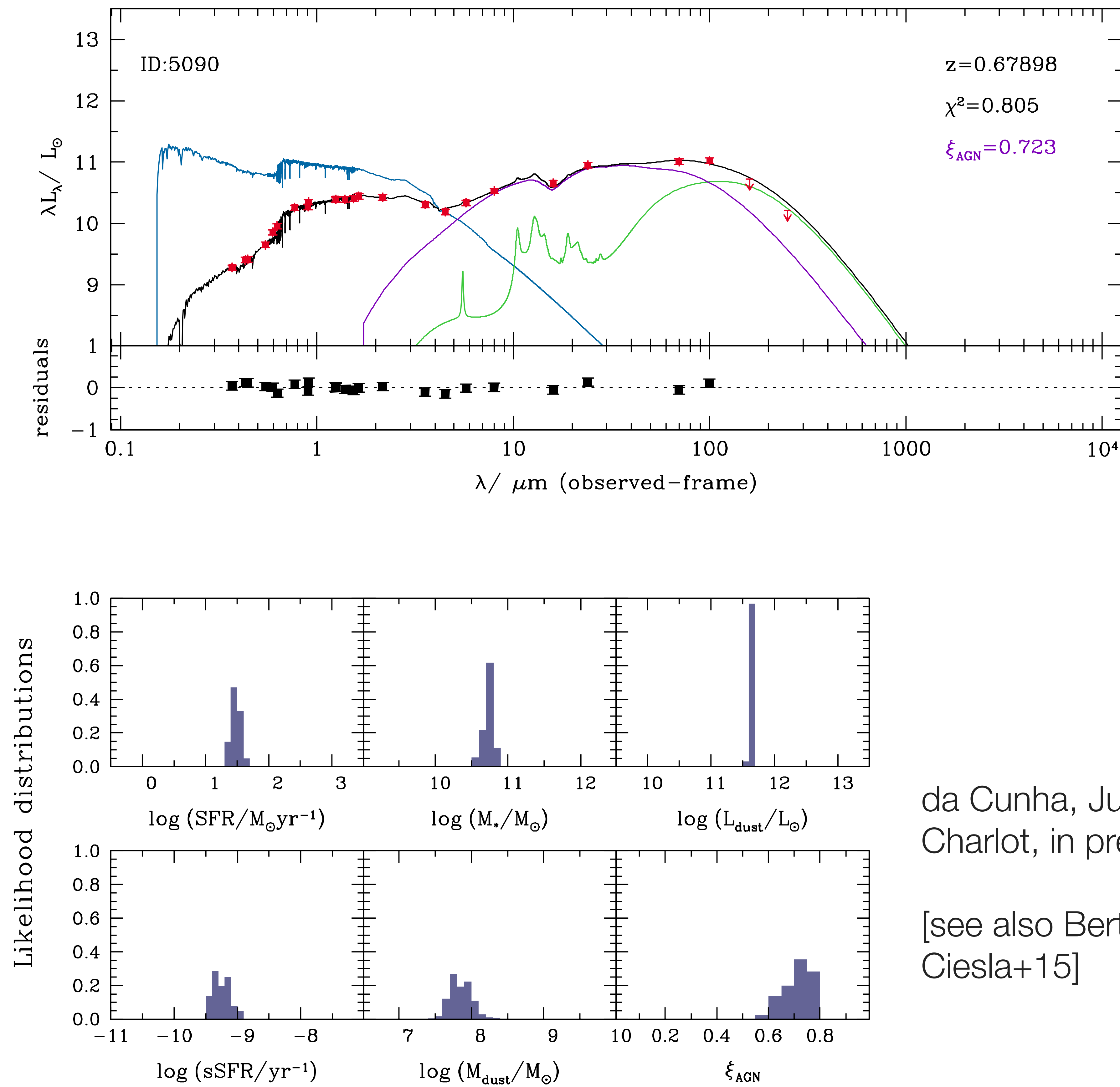
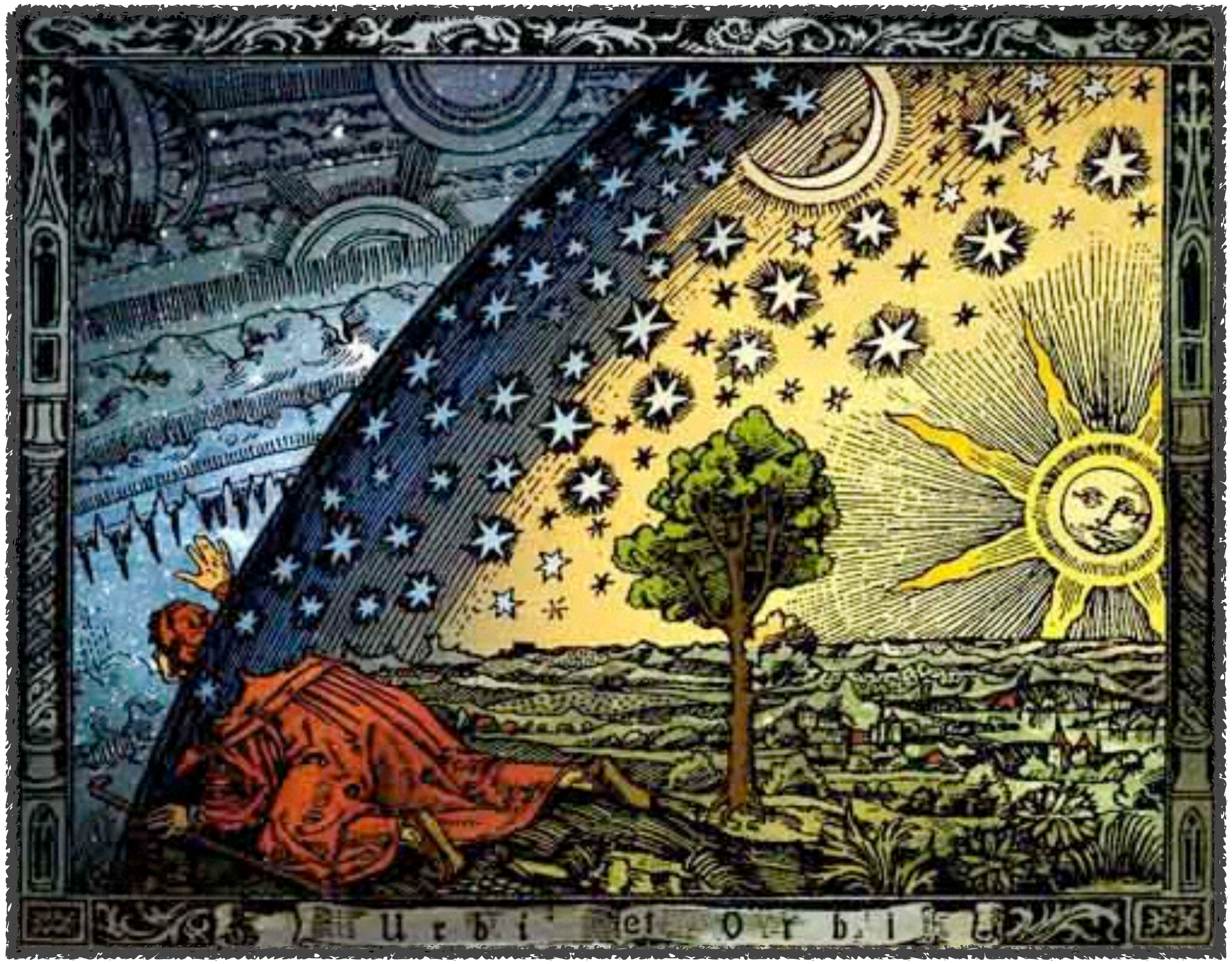
Star



da Cunha, Juneau, Charlot, in prep.

[see also Berta+12, Ciesla+15]

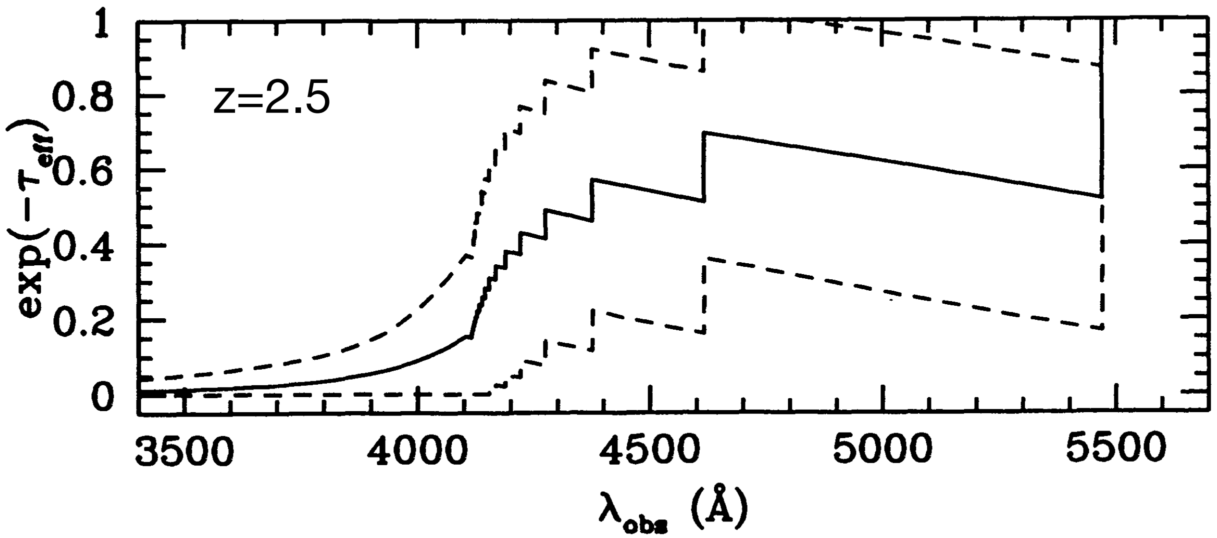


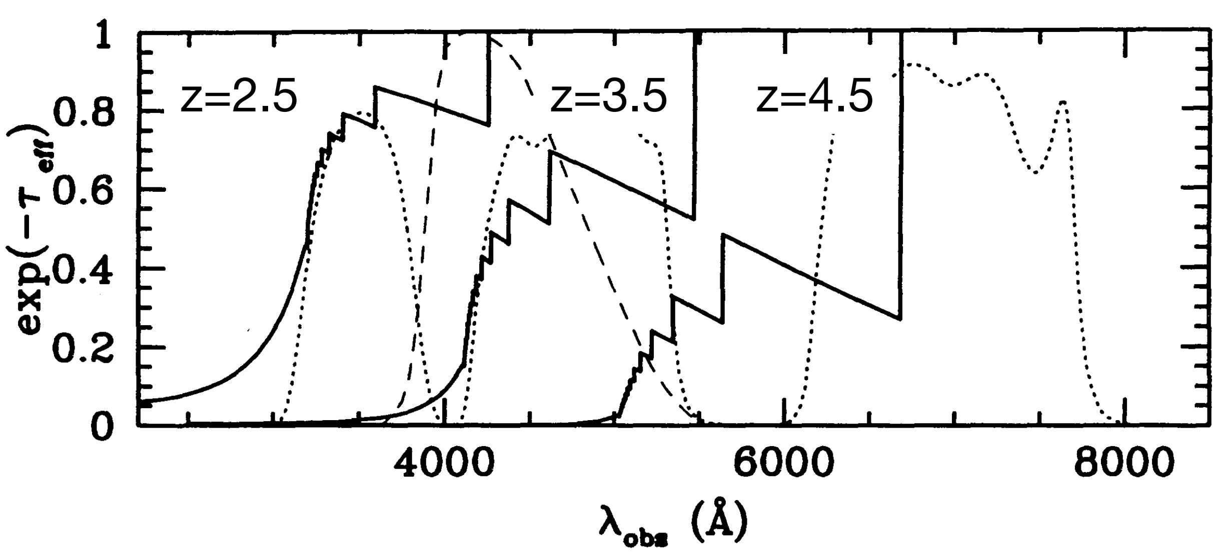
‘cosmological effects’: the IGM and the CMB

Absorption of UV photons by the IGM

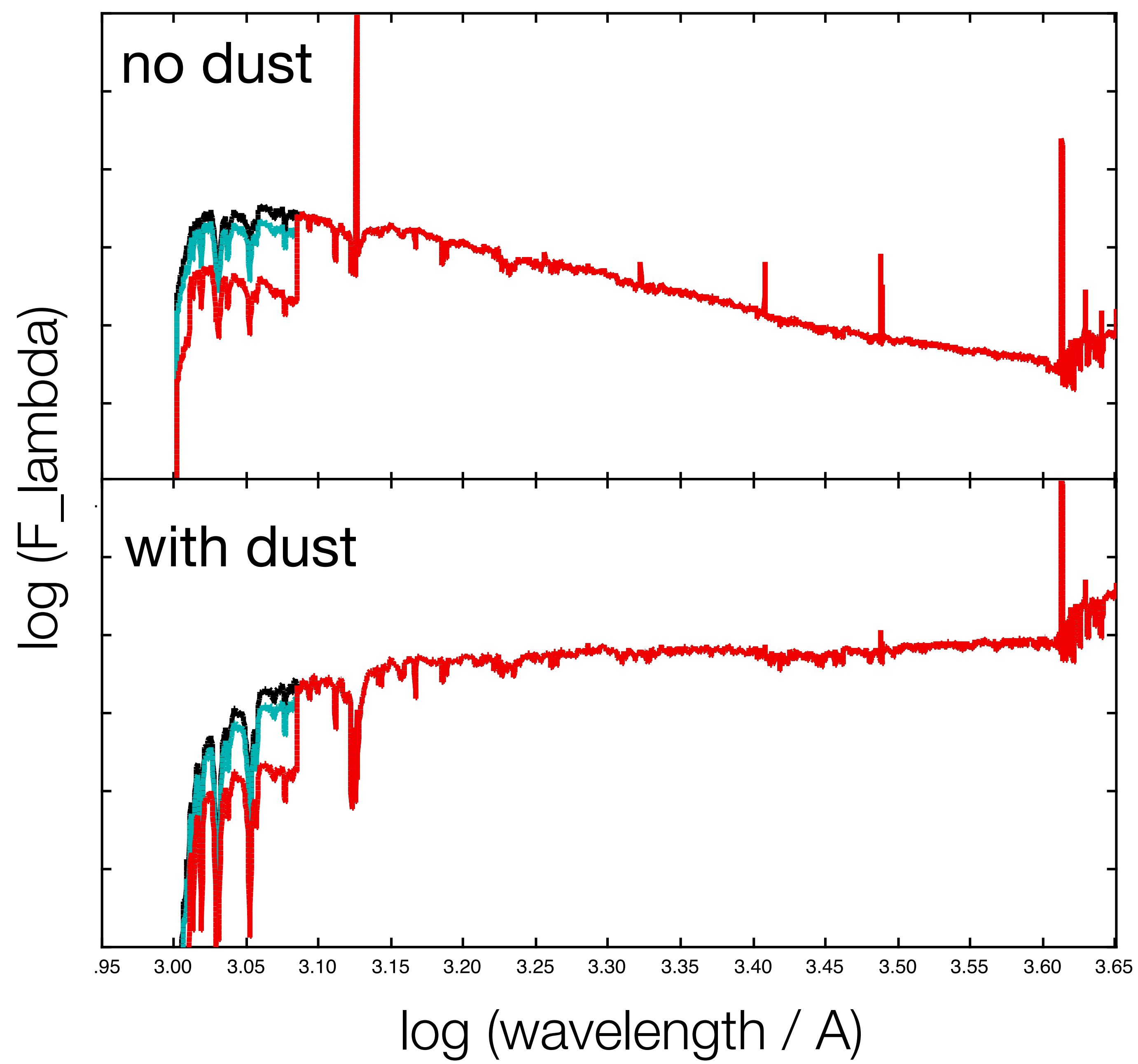
$$F_\nu^{\rm obs} = \frac{(1+z)L_\nu^{\rm em}}{4\pi d_L^2}\exp(-\tau_{\rm eff})$$

Average attenuation (e.g. Madau 1995)



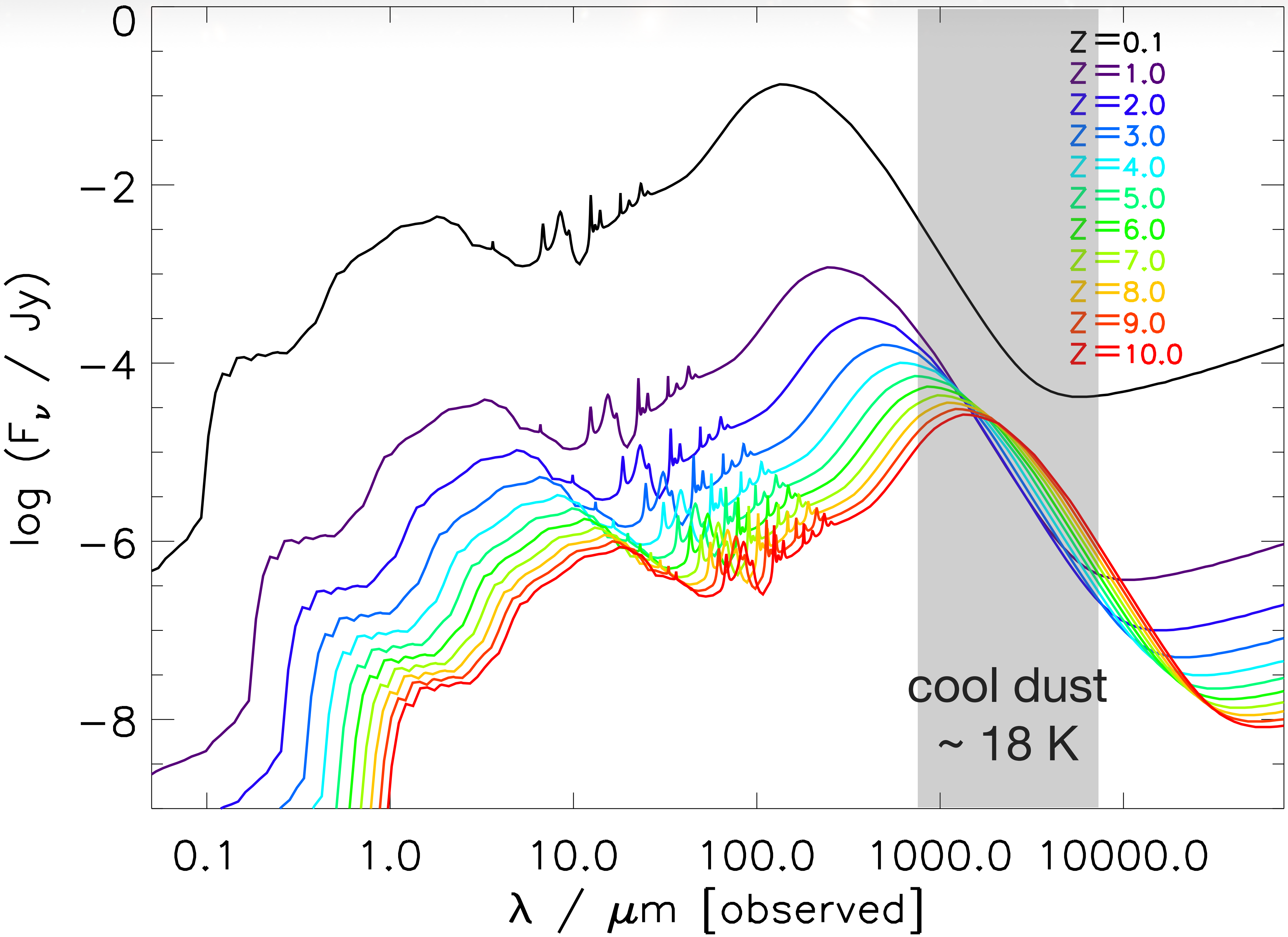


IGM absorption: z=0 z=2.5 z=4.5



Effect of the CMB in (sub-)mm observations

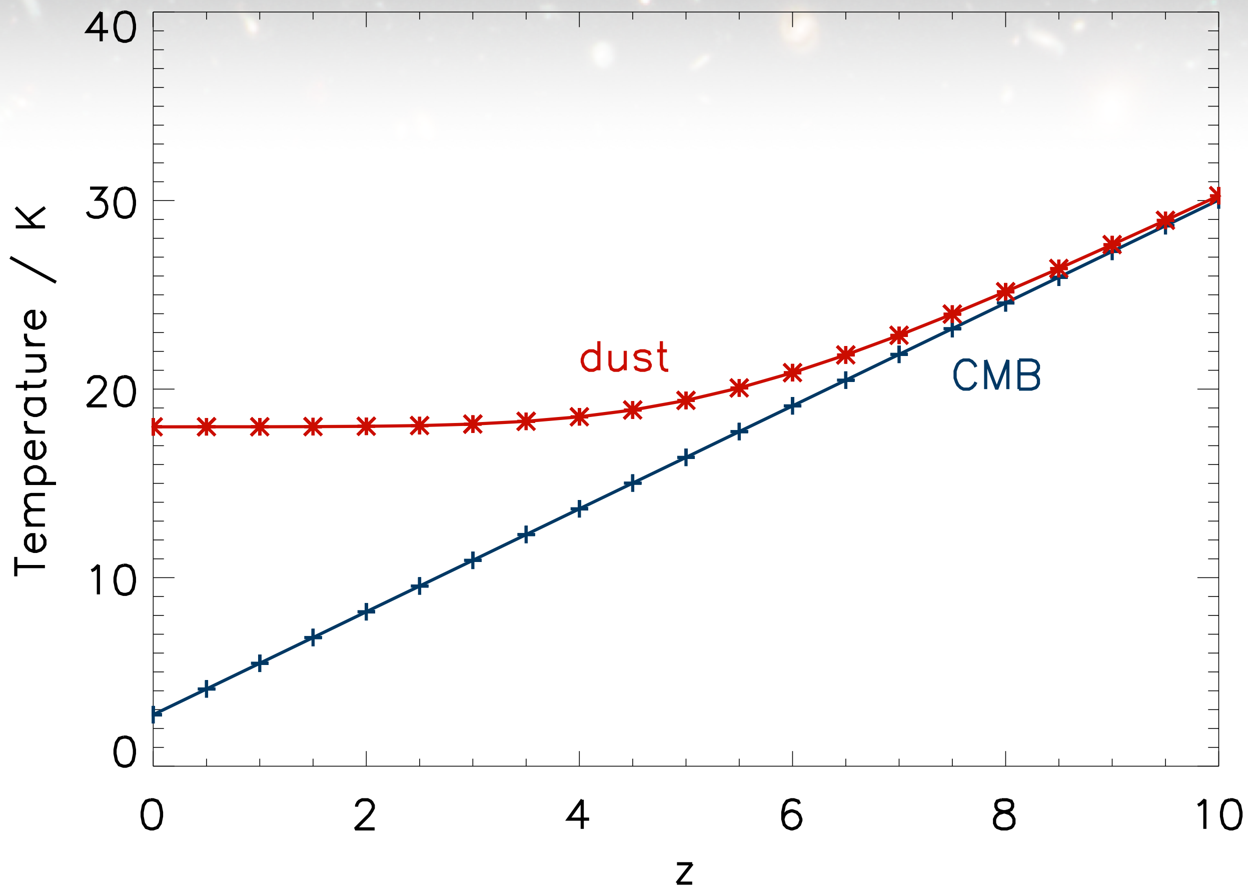
da Cunha, Groves, Walter+2013



Effect of the CMB in (sub-)mm observations

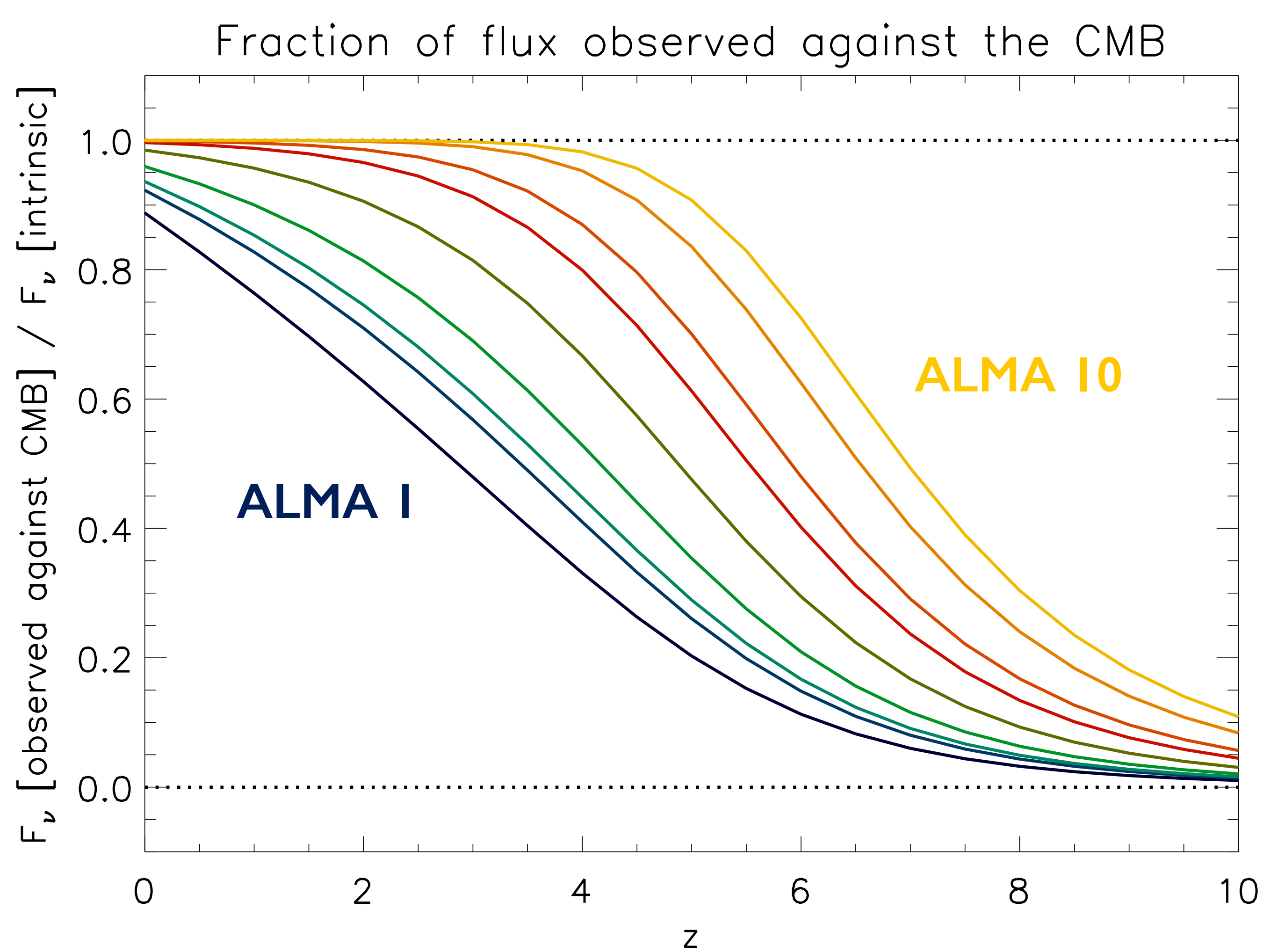
da Cunha, Groves, Walter+2013

1. Extra heating by the CMB

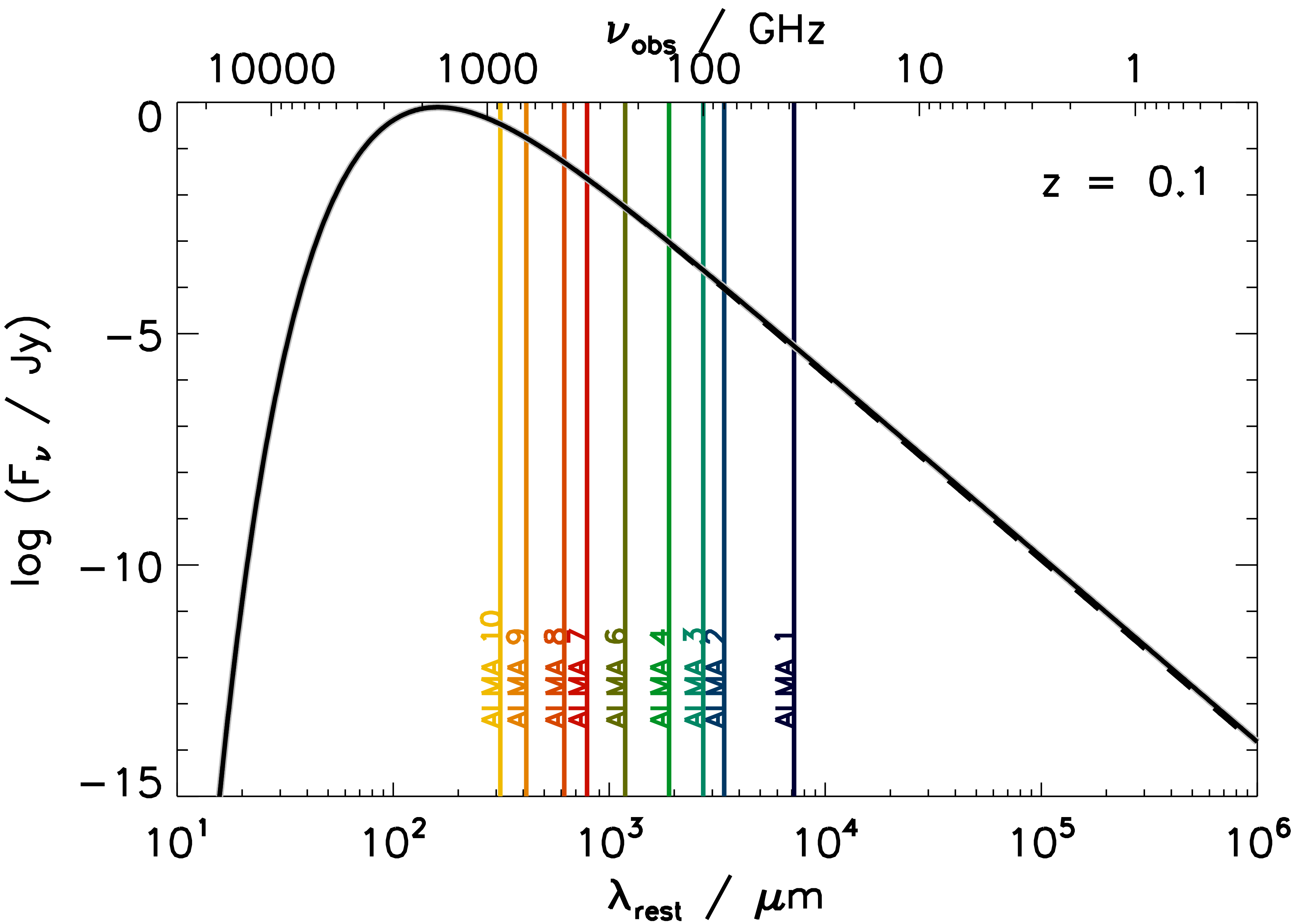


$$\frac{F_\nu^{\text{obs against CMB}}}{F_\nu^{\text{intrinsic}}} = 1 - \frac{B_\nu(T_{\text{CMB}})}{B_\nu(T_{\text{dust}})}$$

2. CMB is a strong background at high z



Effect on the far-IR/sub-mm dust SEDs

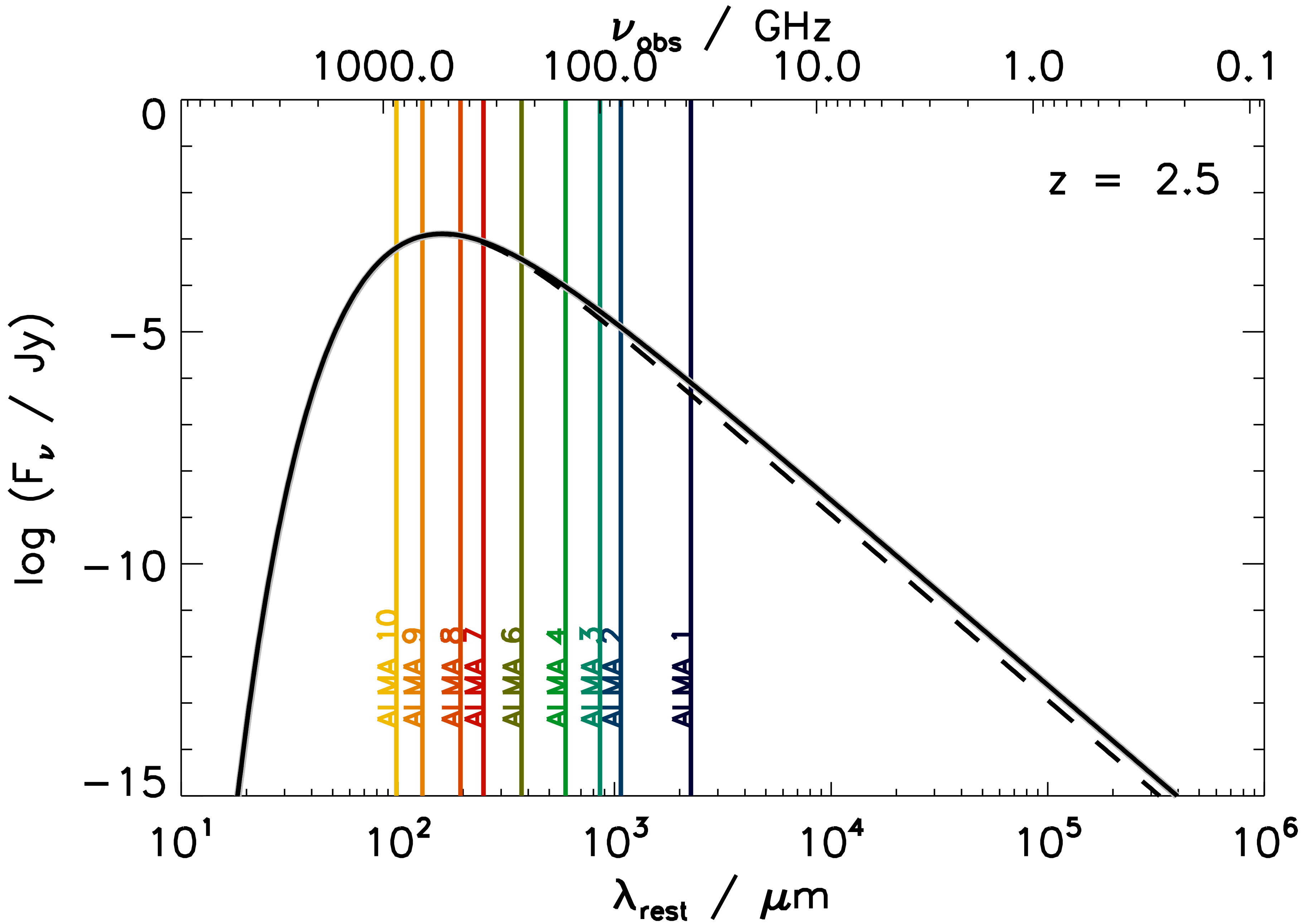


intrinsic SED, no CMB heating

intrinsic SED, with CMB heating

measured SED

Effect on the far-IR/sub-mm dust SEDs



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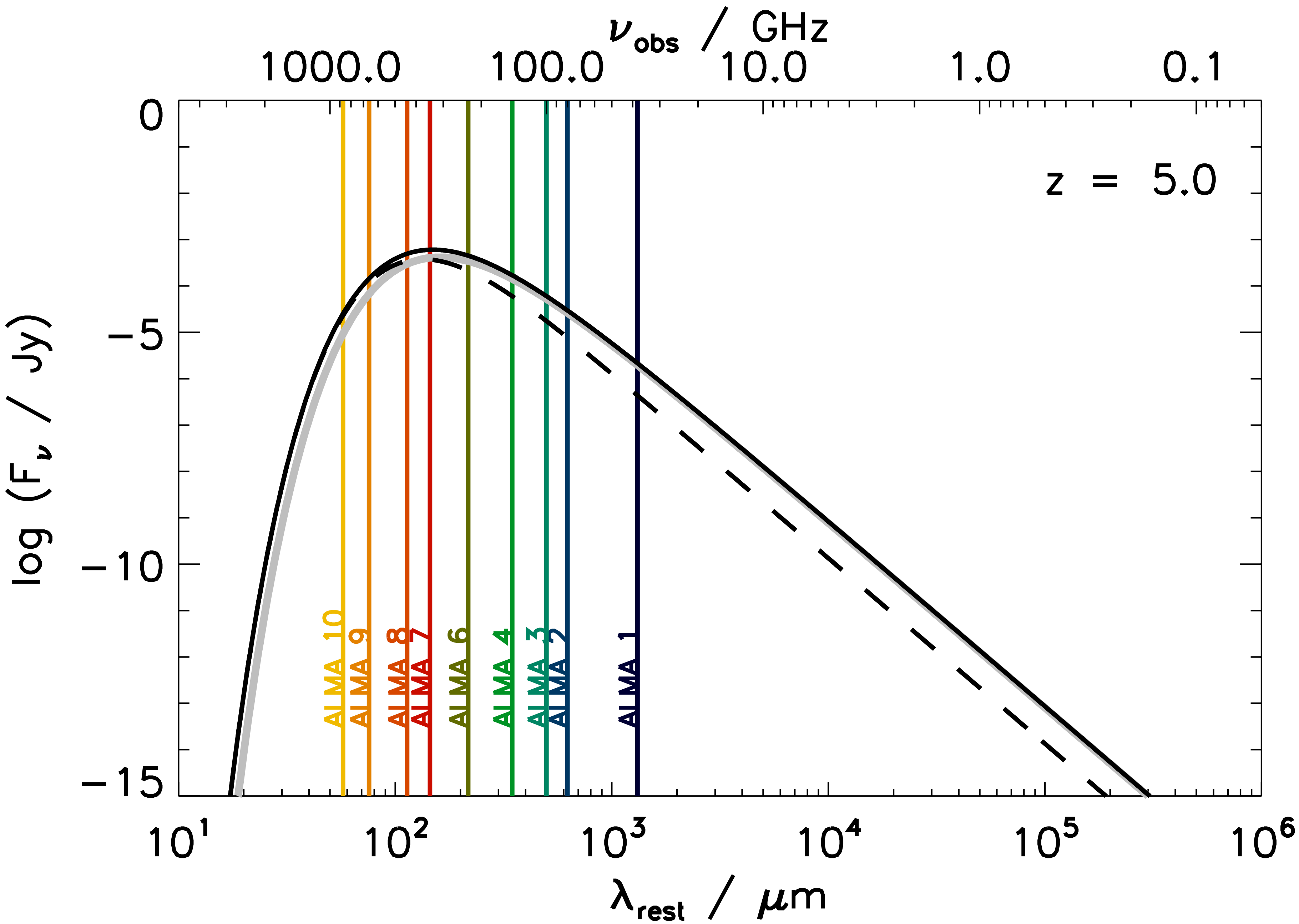

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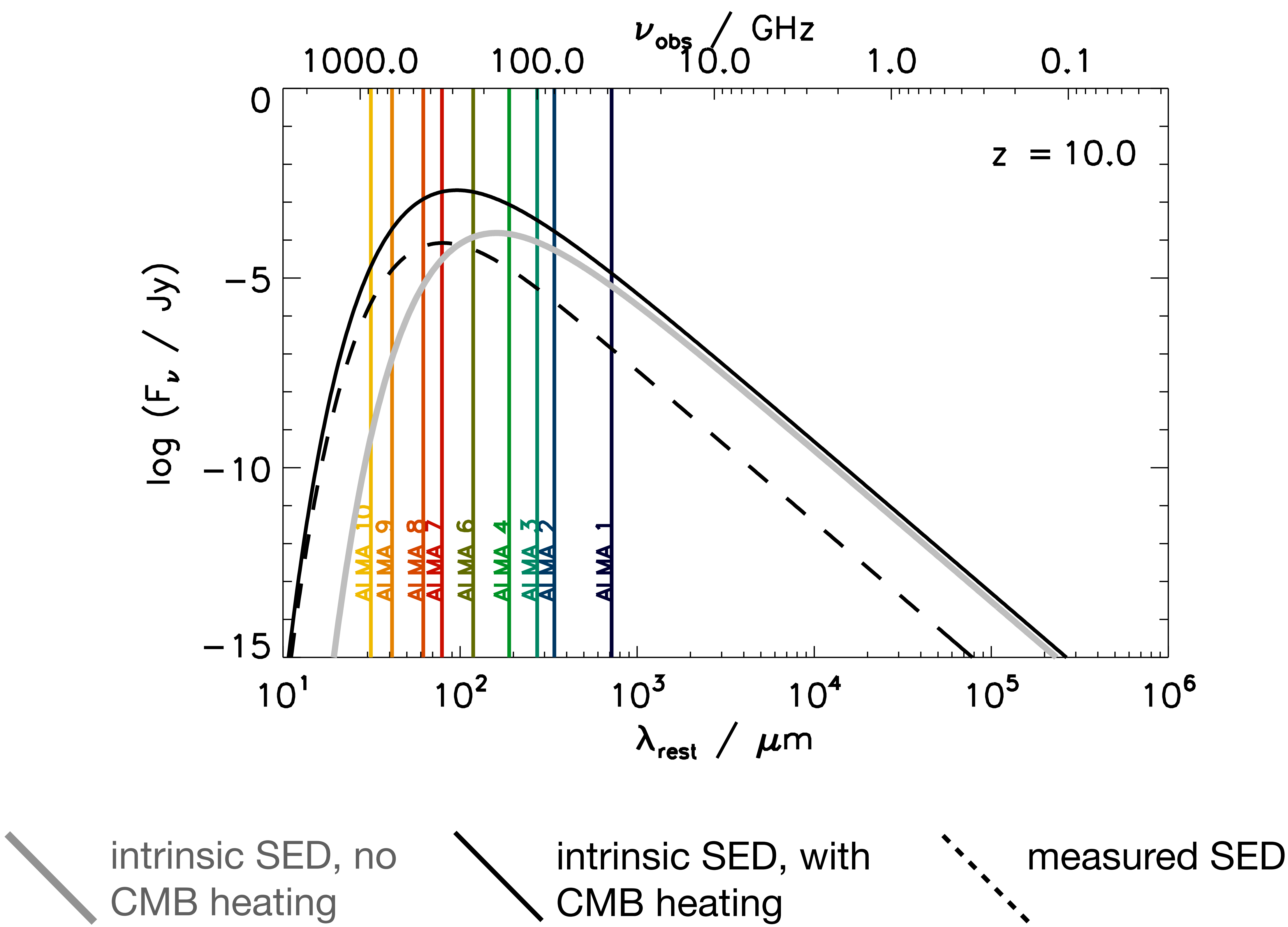
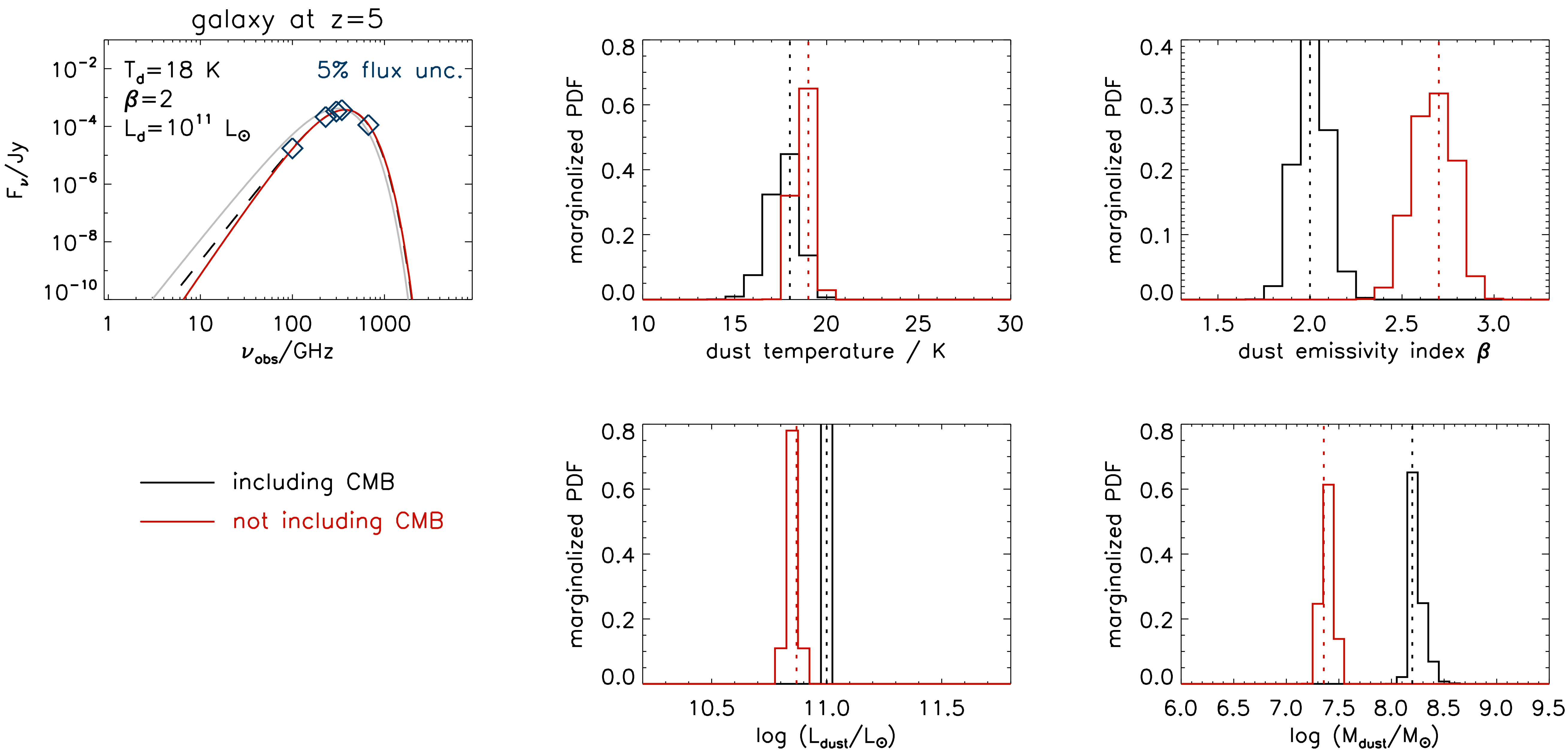


Effect on the derived intrinsic dust properties



Temperature & emissivity index overestimated

Dust luminosity & mass underestimated

constraining the physical properties from observed SEDs

SED fitting: Bayesian Method

Kauffmann+2003, Gallazzi+2005, Salim+2007, da Cunha+2008

MODEL PARAMETERS → PRIOR DISTRIBUTIONS → STOCHASTIC MODEL LIBRARIES

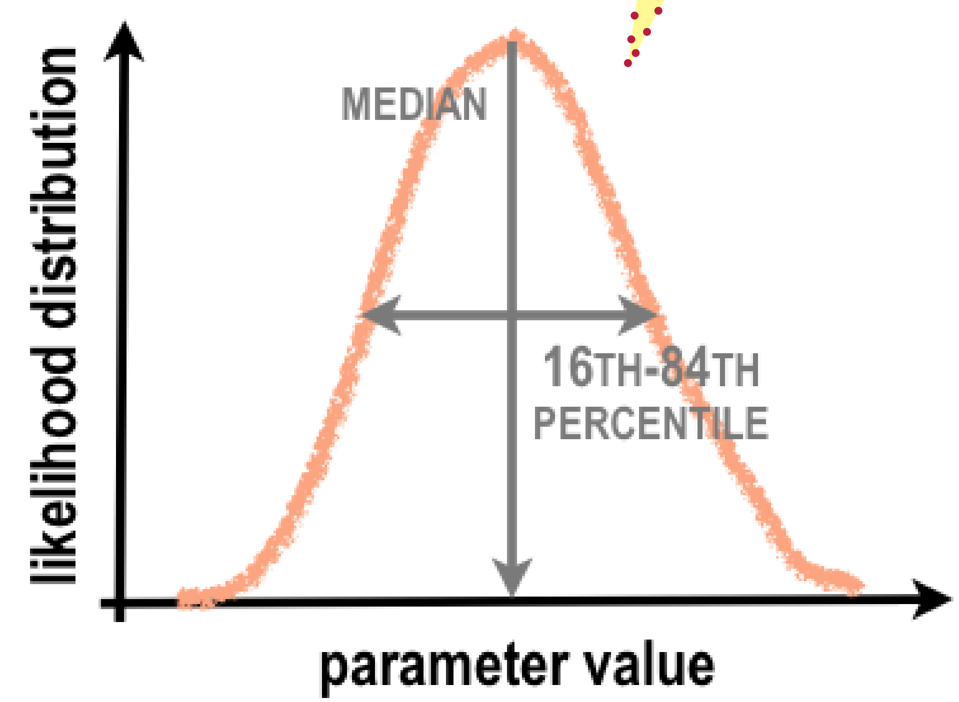
↓

OBSERVED GALAXY SED ↔ COMPUTE CHI2 EACH MODEL ↔ MODEL SEDs

For a given model j described by a random set of parameters:

$$\chi_j^2 = \sum_{i=1}^{N_{\rm obs}} \left(\frac{L_i^{\rm obs} - a_j \times L_j^{\rm mod}}{\sigma_i^{\rm obs}} \right)^2$$

P=EXP(-1/2 CHI2), MARGINALISE →

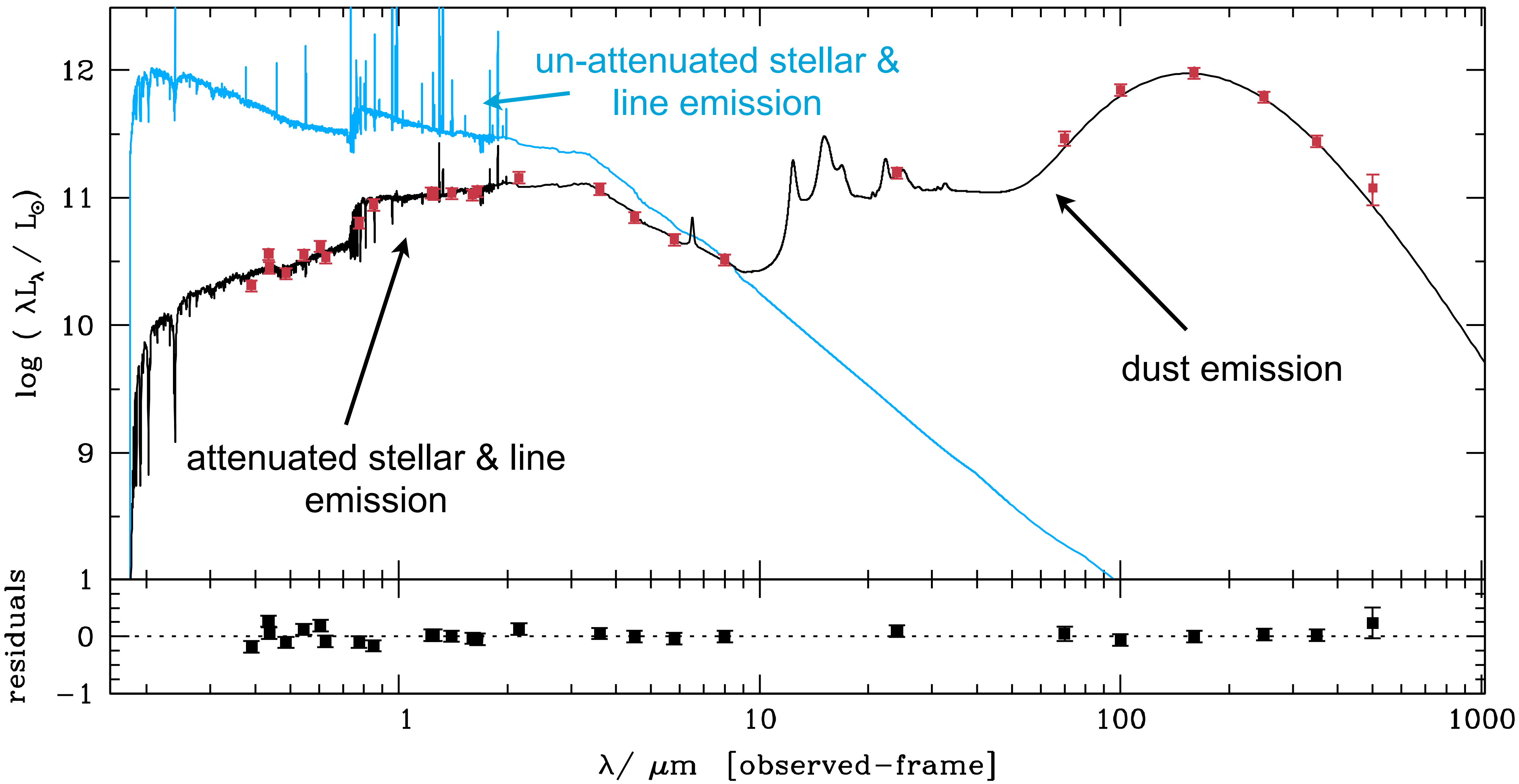


robust parameter estimate + error bar!

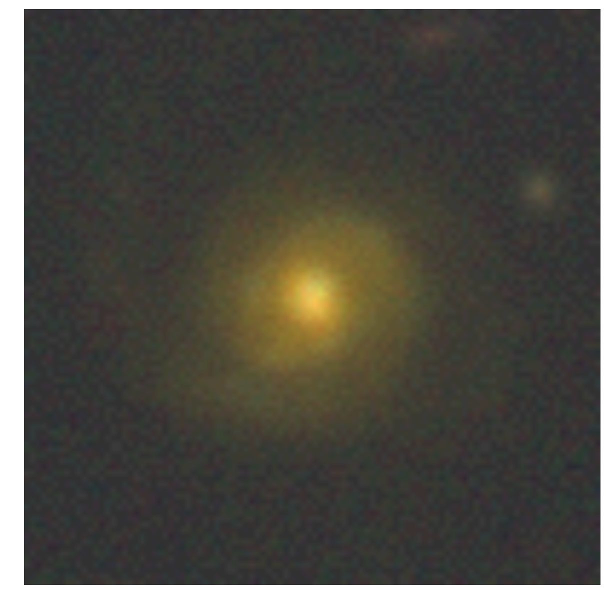
GOODS
J123646.67+620833.3

z_{spec}=0.971

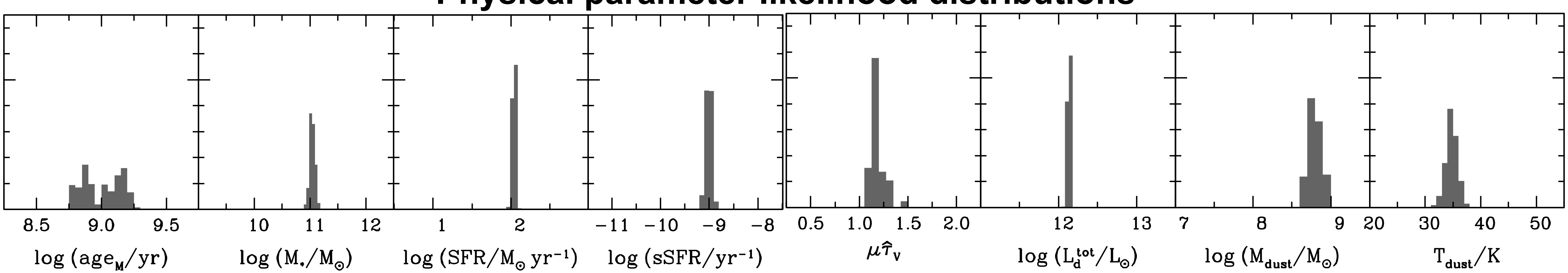
New MAGPHYS spectral energy distribution fit



HST *VJH* composite



Physical parameter likelihood distributions



Spectral models for high-redshift galaxies

- **Evolution of 'young' stellar populations**
  The effect of TP-AGB stars - not as high as previously thought
  Rotation changes the UV emission of young massive stars

- **Star formation histories**
  We need to do better than tau-models at high redshift

- **Nebular emission**
  Include self-consistently in the SEDs; contamination of broad-band photometry

- **Dust attenuation & dust infrared emission**
  Model dust attenuation and emission self-consistently

- **AGN contamination**
  Empirical template to correct SFRs, stellar masses for excess emission

- **'Cosmological effects'**
  IGM absorption in the UV
  CMB: heating source & strong observational background in the (sub-)mm

Coming soon at www.iap.fr/MAGPHYS

Spectral models for high-redshift galaxies

- **Evolution of ‘young’ stellar populations**
  The effect of TP-AGB stars - not as high as previously thought
  Rotation changes the UV emission of young massive stars

- **Star formation histories**
  We need to do better than tau-models at high redshift

- **Nebular emission**
  Include self-consistently in the SEDs; contamination

- **Dust attenuation & dust infrared emis**
  Model dust attenuation and emission self-

- **AGN contamination**
  Empirical template to correct SFRs, stellar

- **‘Cosmological effects’**
  IGM absorption in the UV
  CMB: heating source & strong observational b

See also reviews on SED modelling by Walcher+2010 and Conroy 2013

Hayward & Smith 2015 (comparison with RT models)

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