Spectral energy distribution analyses of high-redshift galaxies in the JWST era

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Australian Research Council

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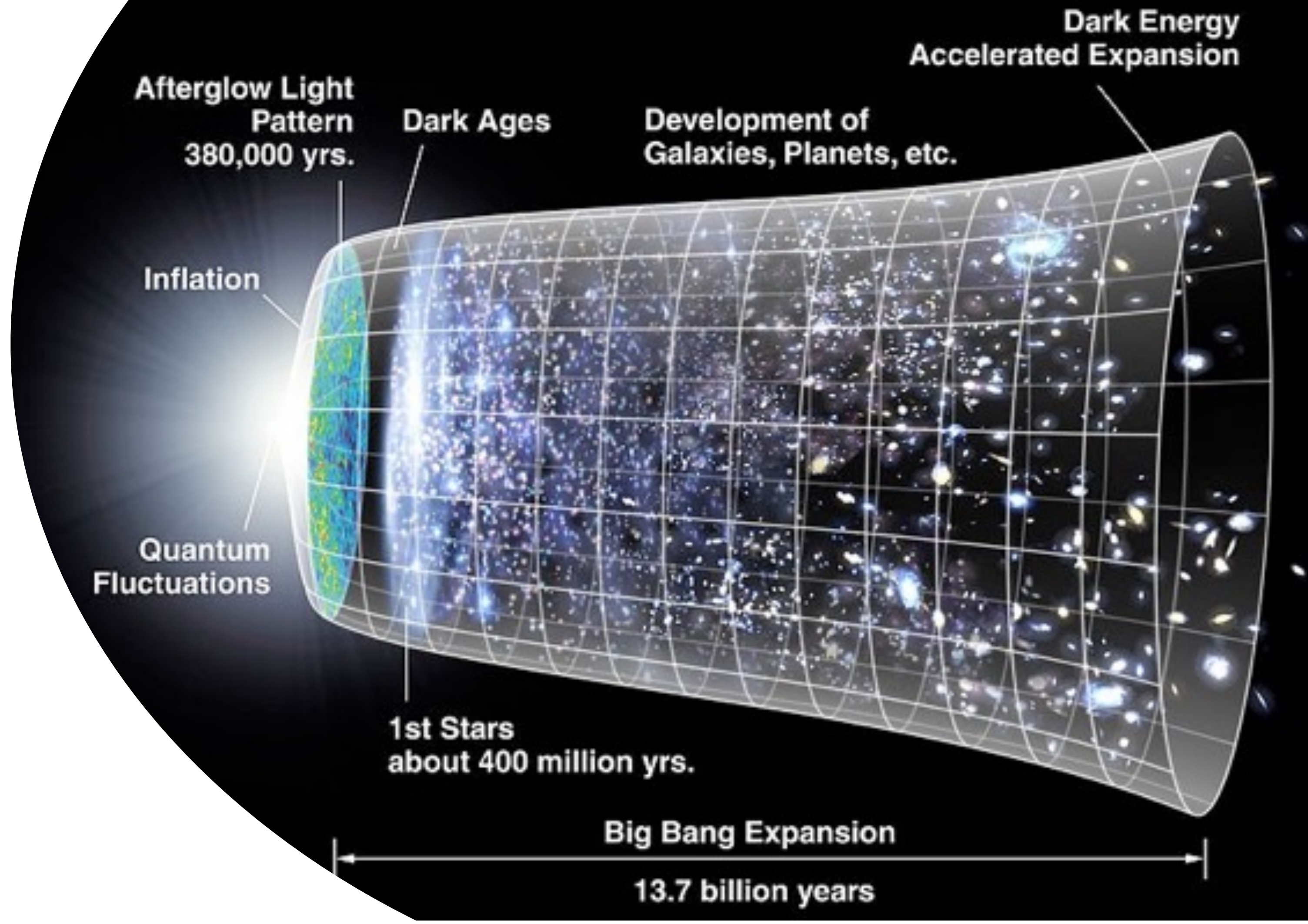
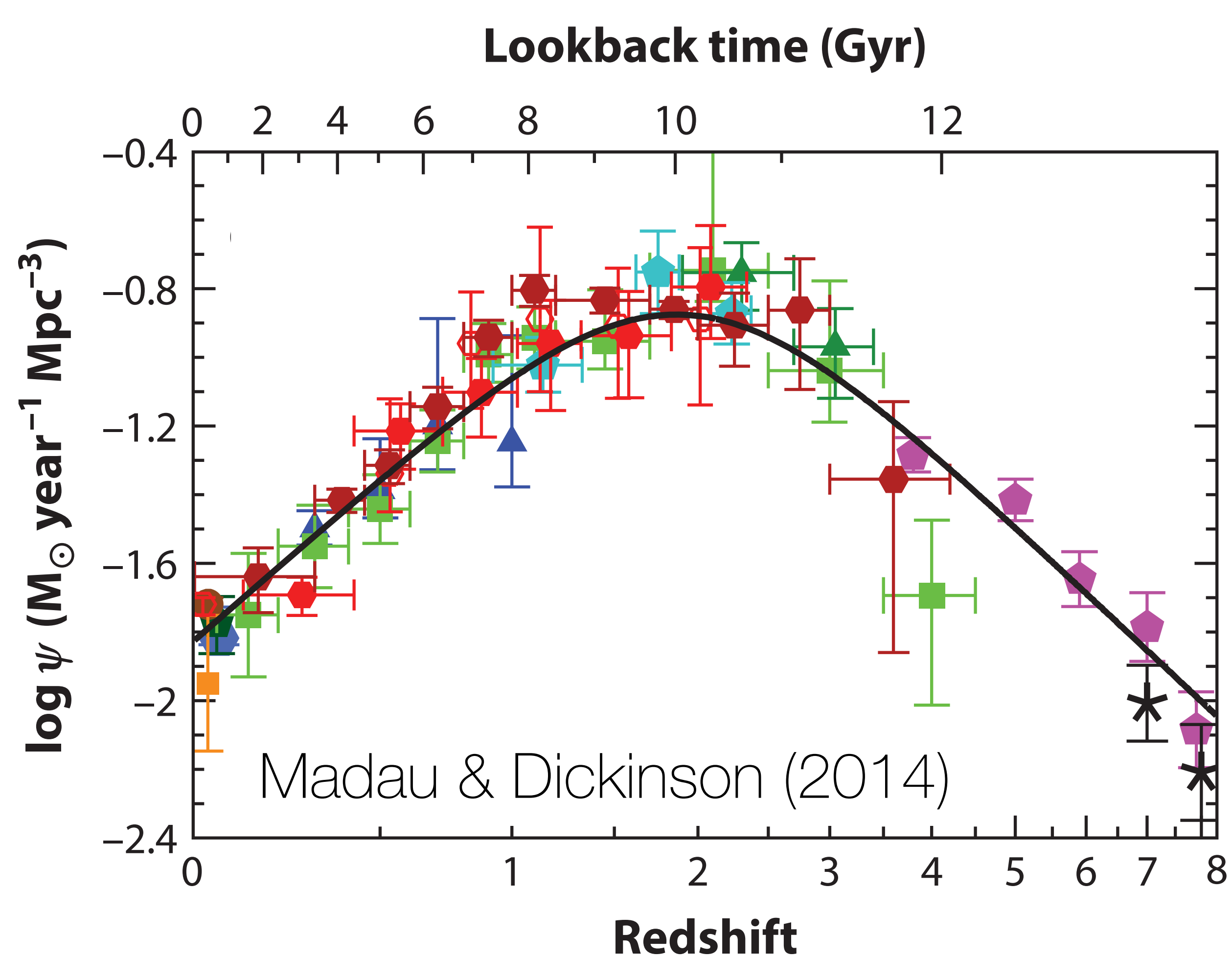
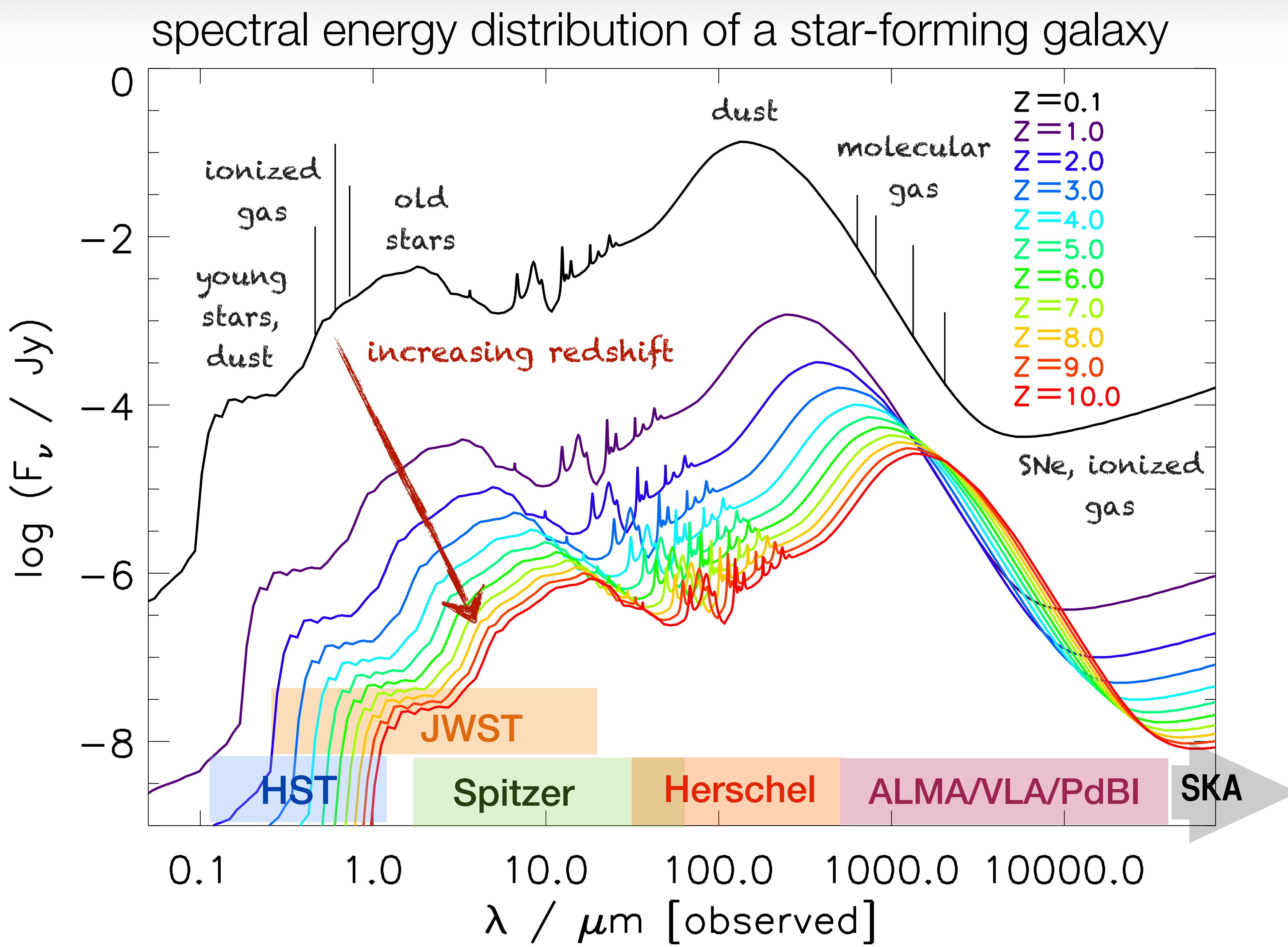
The era of JWST: cosmic reionization and the rise of galaxies

- Emergence of the first stars, black holes (AGN), and galaxies
- Energetics: production and output of UV photons, or how the Universe was re-ionized
- Detailed physical properties of galaxies at z~1-3: 'epoch of galaxy assembly'
- Synergies with sub-mm and radio facilities: gas content, ISM properties





Spectral models: an essential tool for galaxy evolution



Spectral models: an essential tool for galaxy evolution

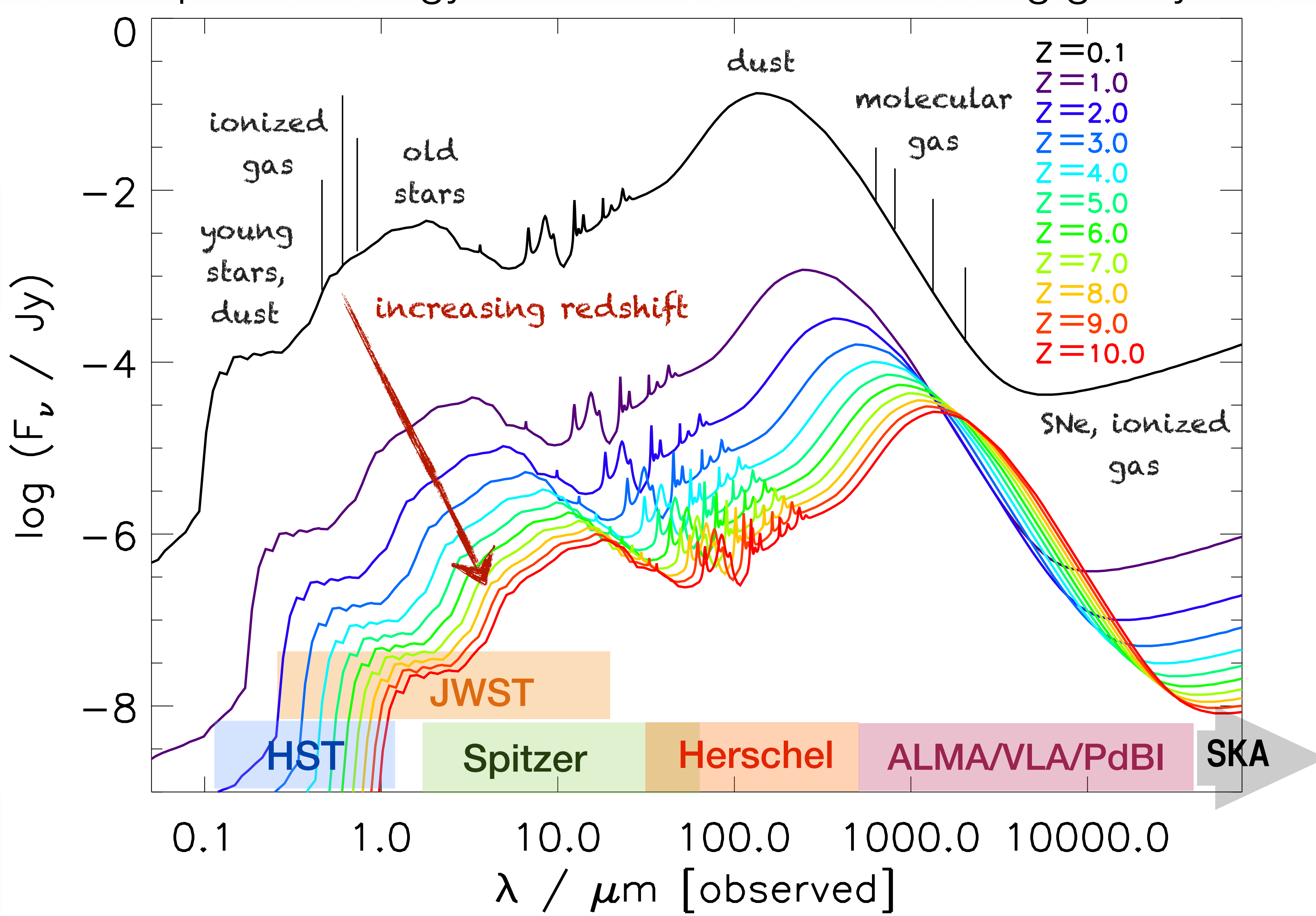
Observed UV, optical, IR emission

Spectral energy distribution model

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

Galaxy evolution models

spectral energy distribution of a star-forming galaxy



Spectral models for high-redshift galaxies

Recent & ongoing developments:

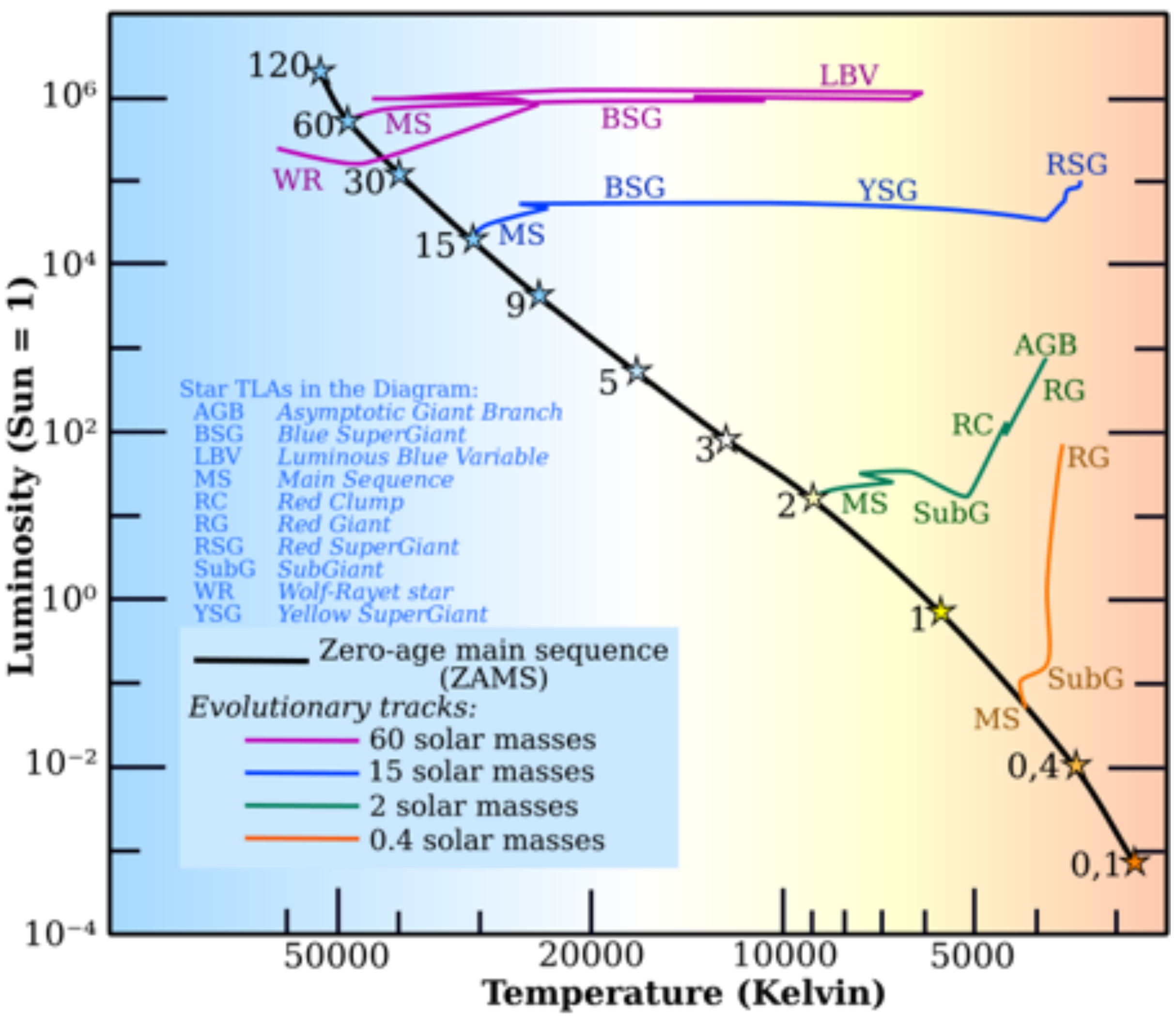
- **Emission by stellar populations**
  Evolution of massive stars, 'young' stellar populations
  Star formation histories
- **The effects of the interstellar medium**
  Transfer of starlight through the ISM (gas and dust)
  Nebular emission & impact on SEDs
- **Statistical constraints on physical parameters**
  Fitting SEDs using Bayesian methods

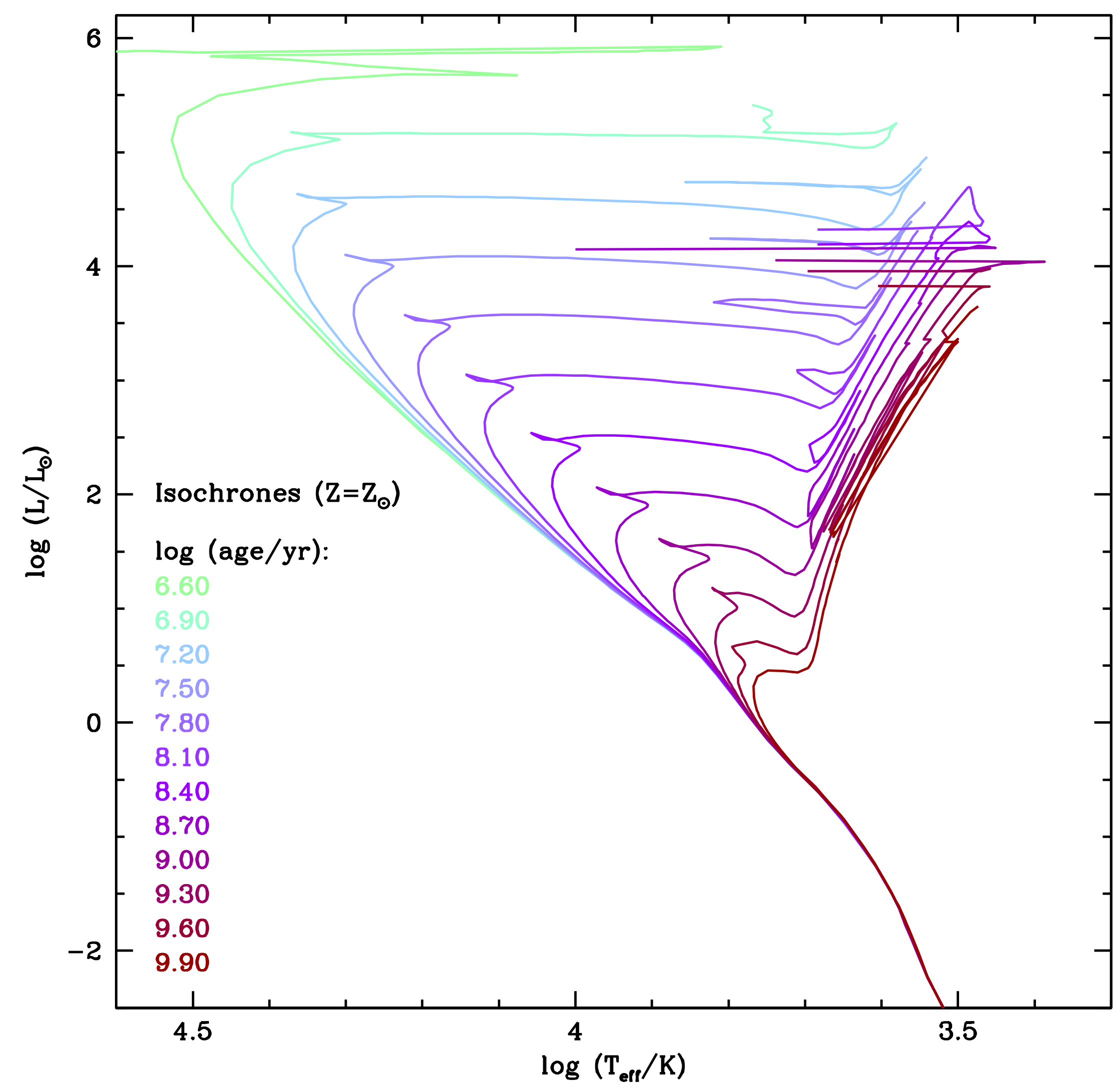
emission by stellar populations

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)

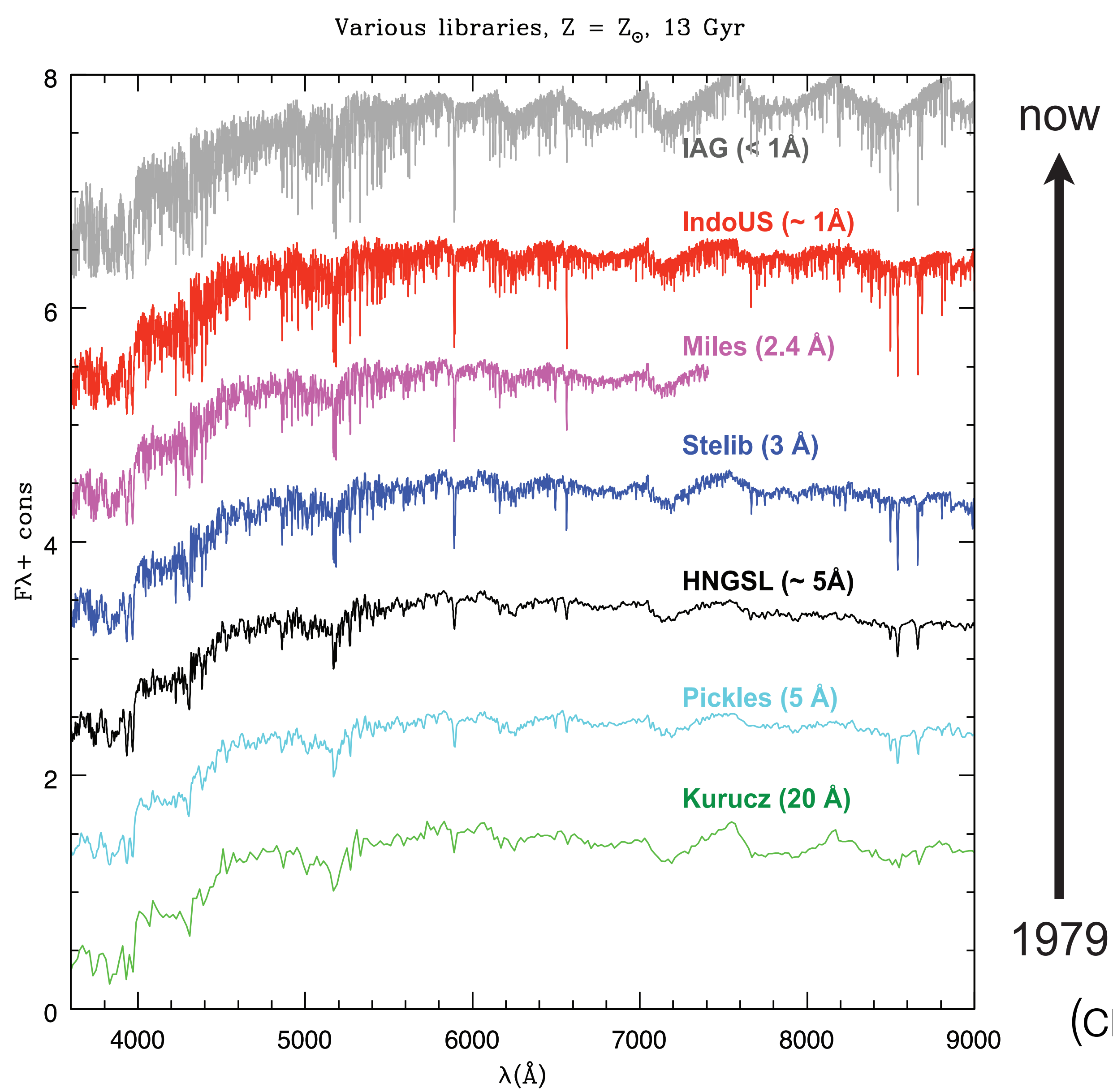
Spectral evolution of a simple stellar population

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.



(credit: S. Charlot)

Spectral evolution of a simple stellar population

Stellar evolution prescription

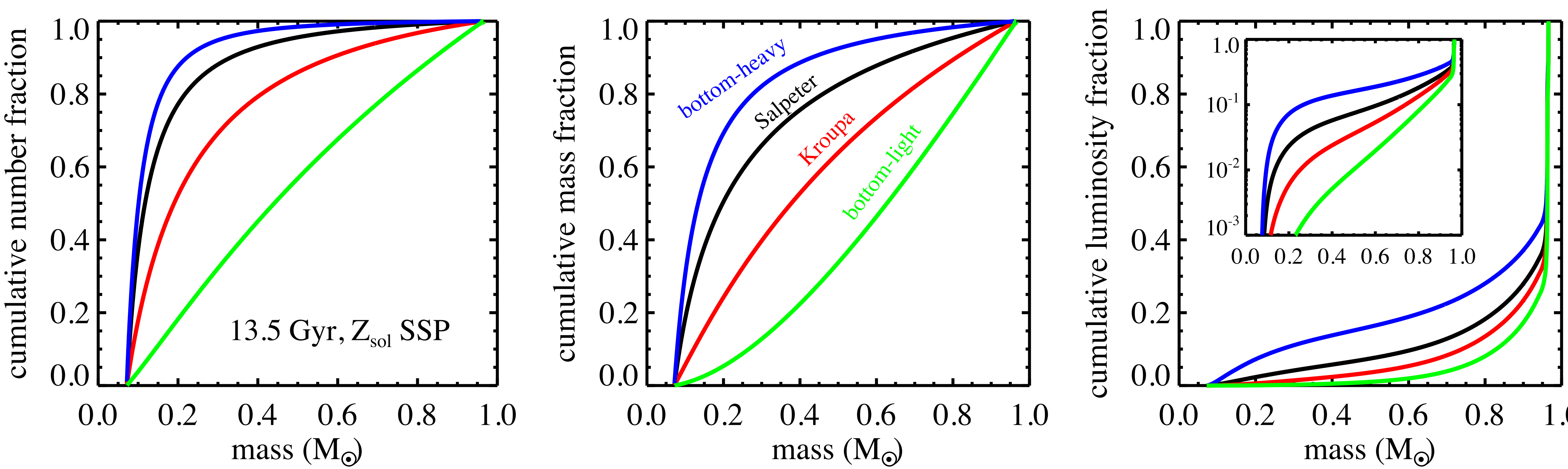
HR evolutionary tracks for stars of different initial masses & metallicities.

Spectral libraries

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

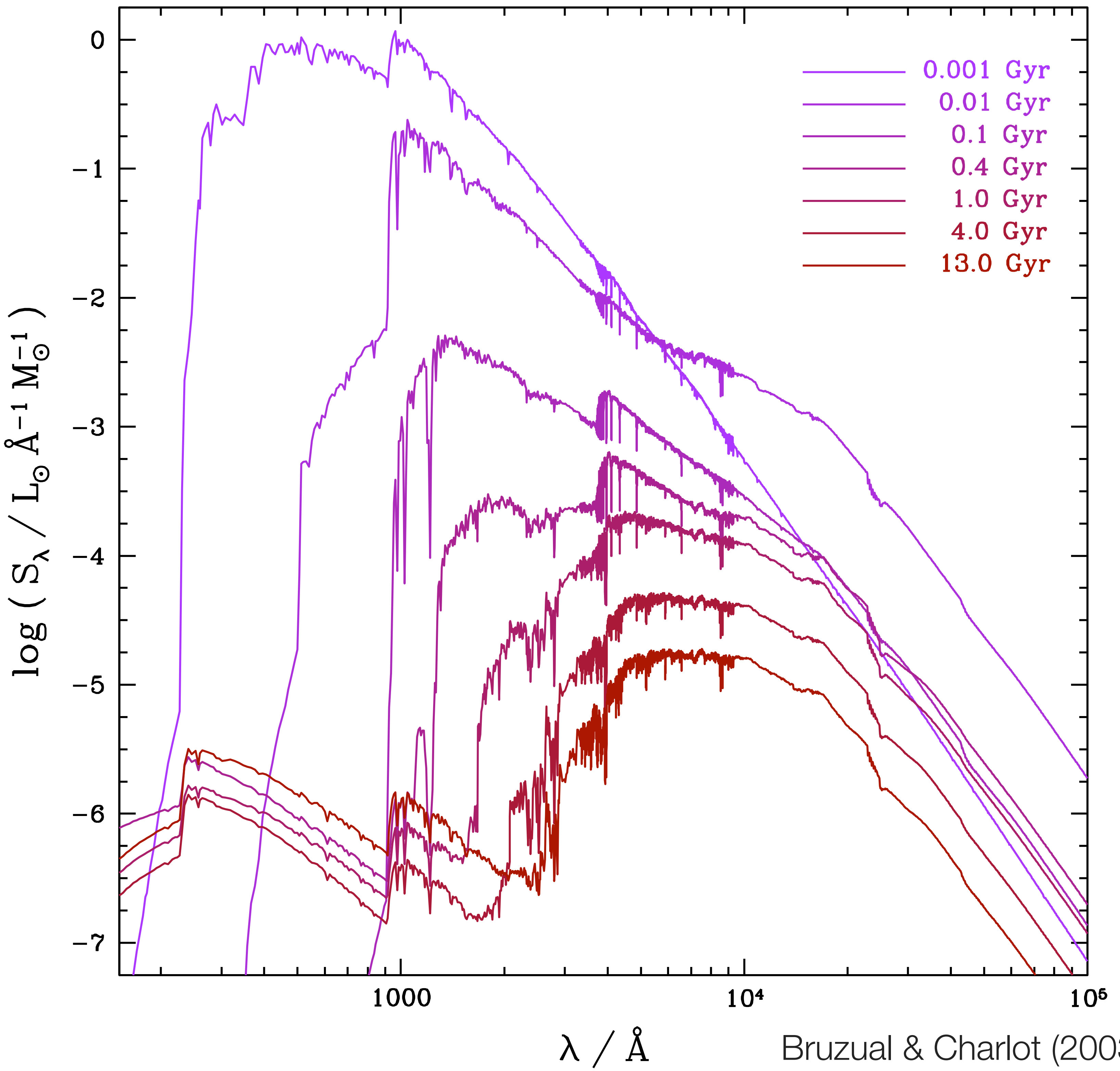
Initial Mass Function

how many stars of each mass form in each generation.



Conroy (2013)

Spectral evolution of a simple stellar population



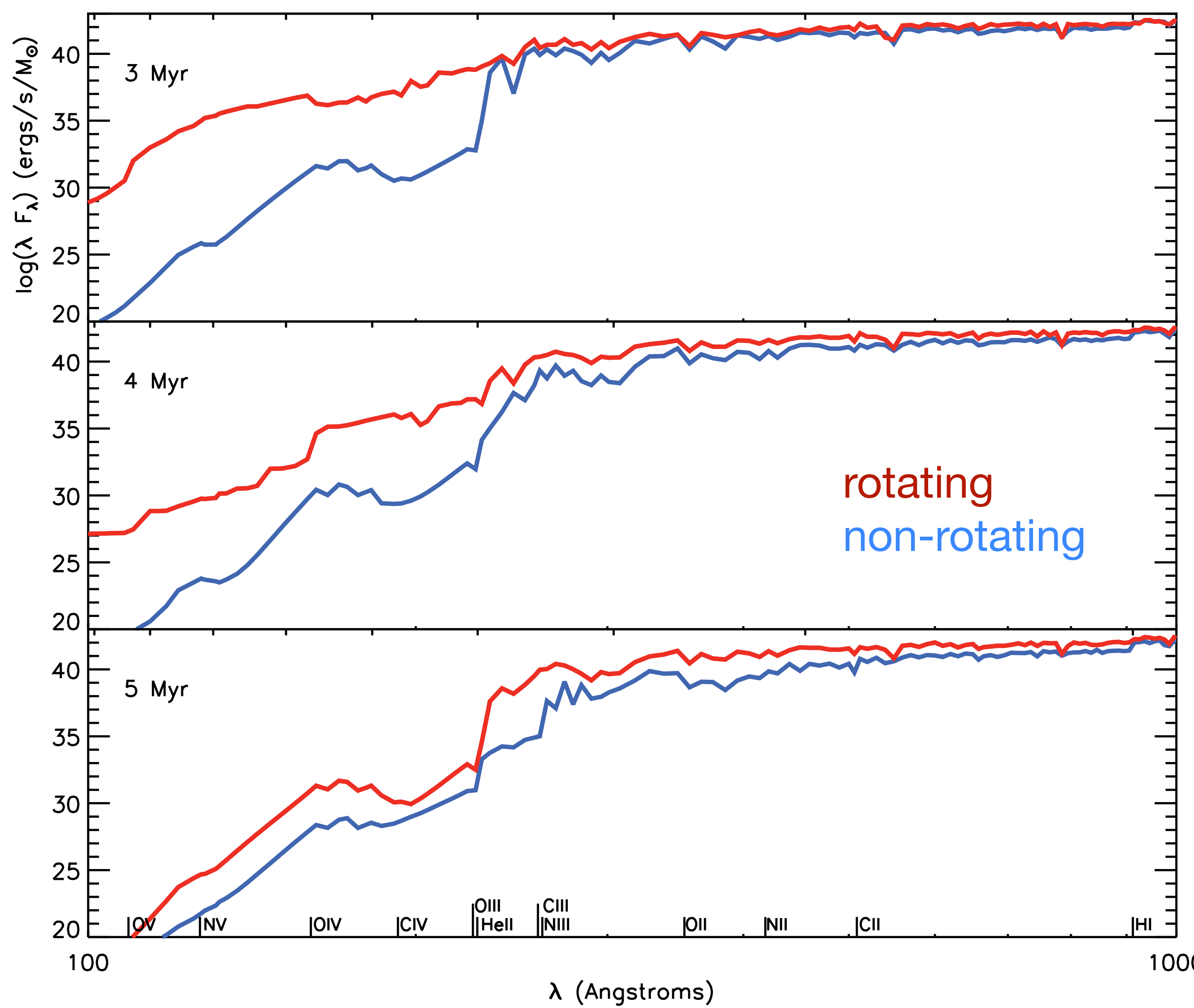
Bruzual & Charlot (2003)

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

Impact of rotation in the evolution of massive stars

- Rotational mixing affects stellar lifetimes (e.g. Ekstroem+2012)
- Higher effective temperatures & luminosities (e.g. Leitherer+2008, 2014)
- Stronger mass loss; more (& longer-lived) WR stars

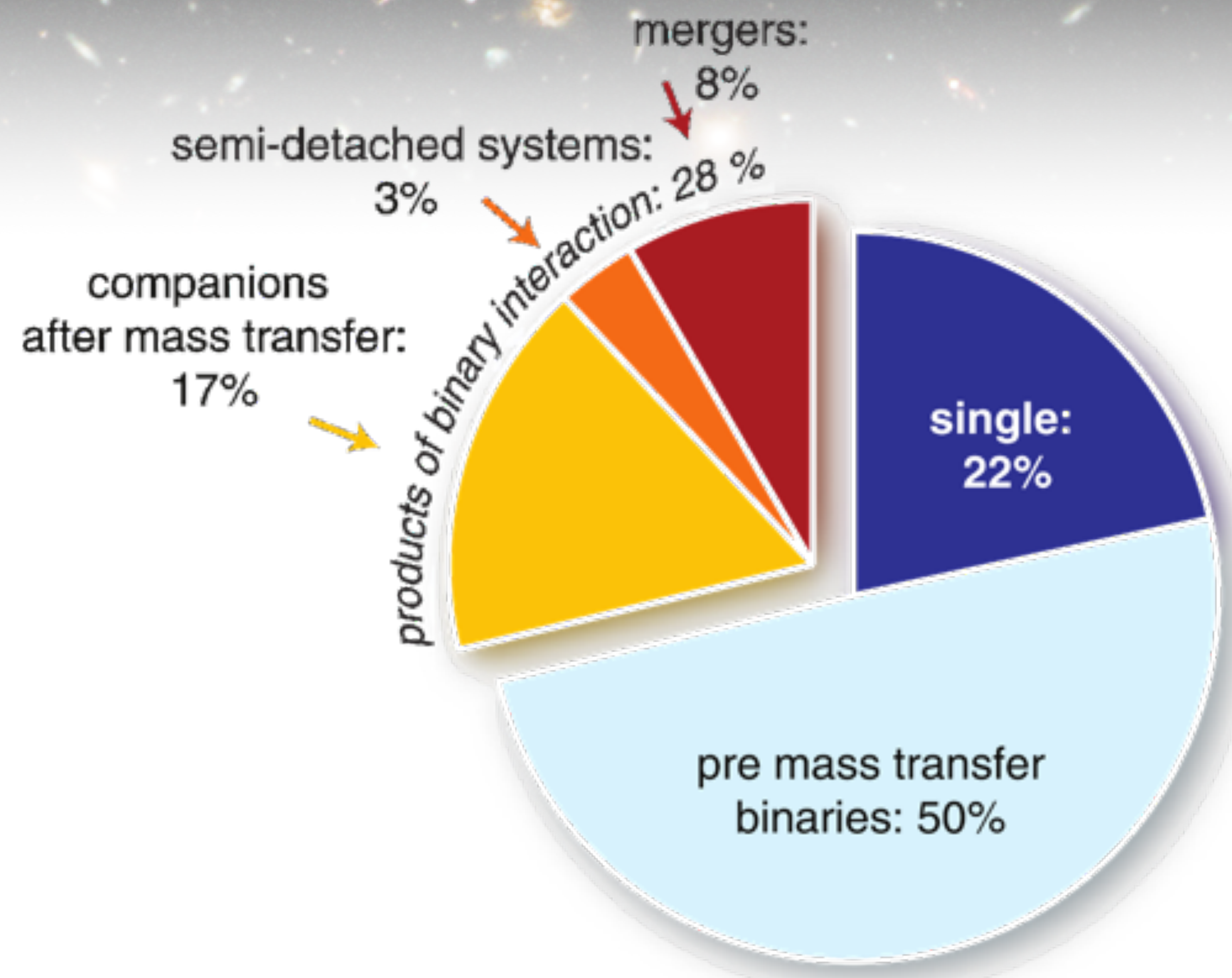
Levesque+2012



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.

Massive stars are very often in binaries



de Mink+2014

1. massive primary star overfills Roche lobe

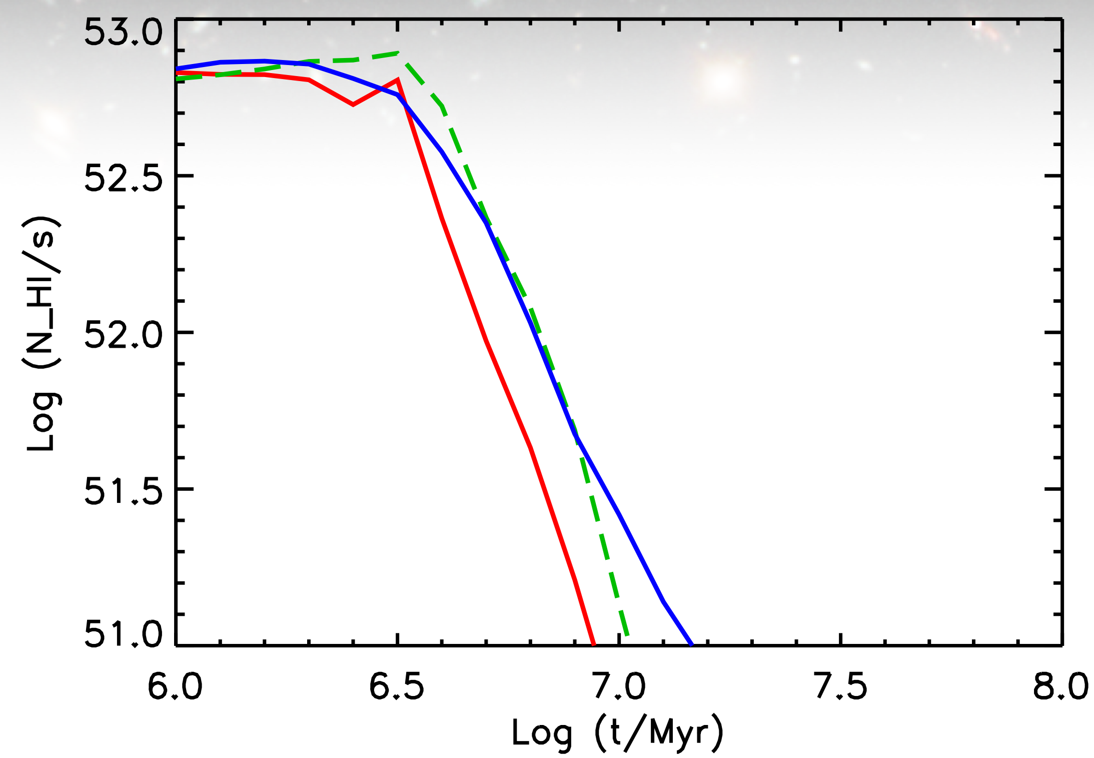
2. mass and angular momentum transfer to secondary star

3. **rejuvenation** of secondary star

Stronger ionizing UV continuum over a longer lifetime (e.g. Eldridge & Stanway 2012).

Impact of rotation & binaries on ionizing radiation

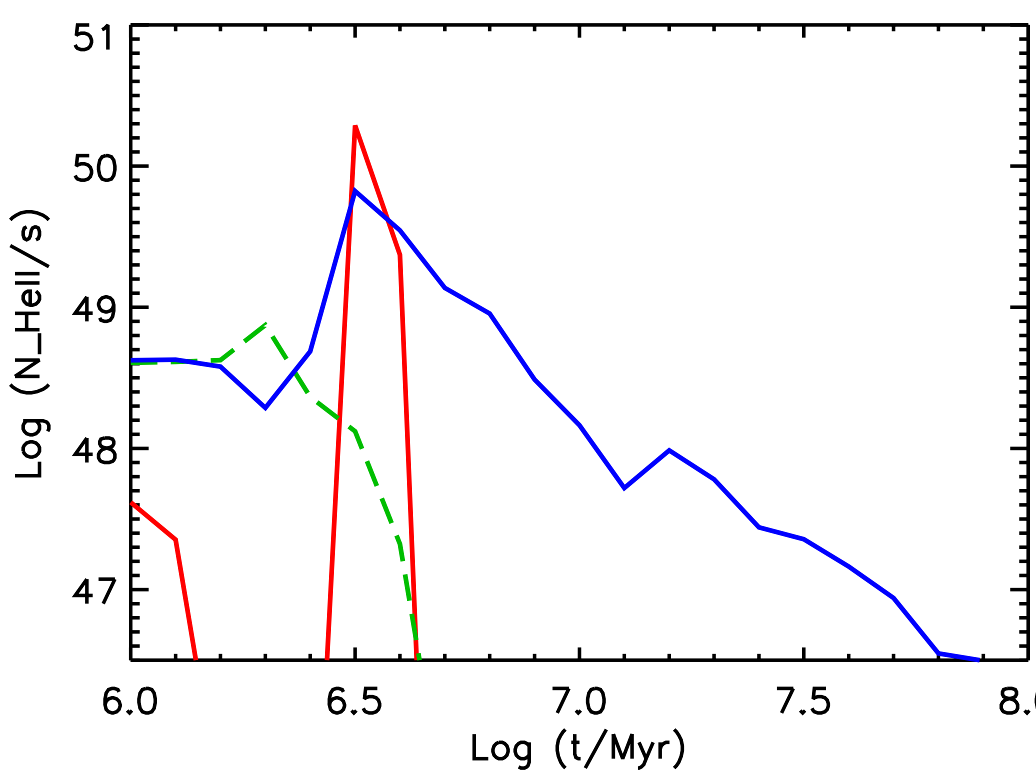
Low metallicity ($Z=0.004$)
10^6 M_{sun} SSP

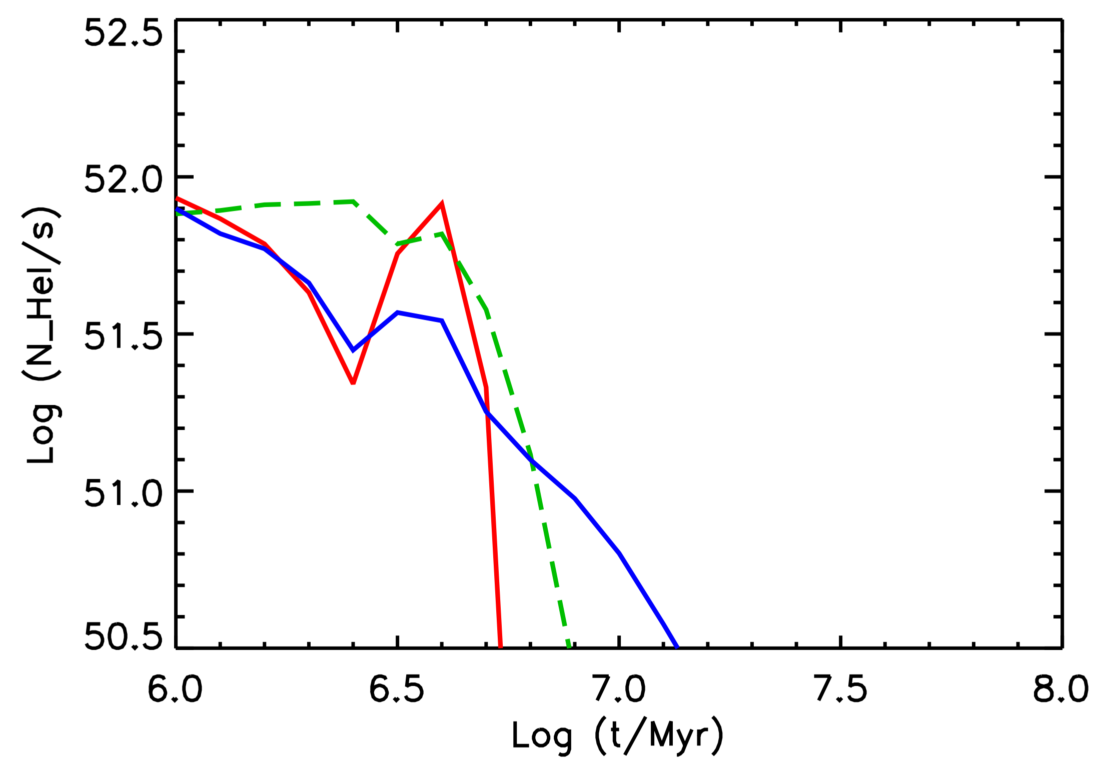


GALAXEV (Bruzual & Charlot 2003): single, non-rotating

Starburst 99 (Leitherer+2014): single, rotating

BPASS (Eldridge & Stanway 2012): interacting binaries





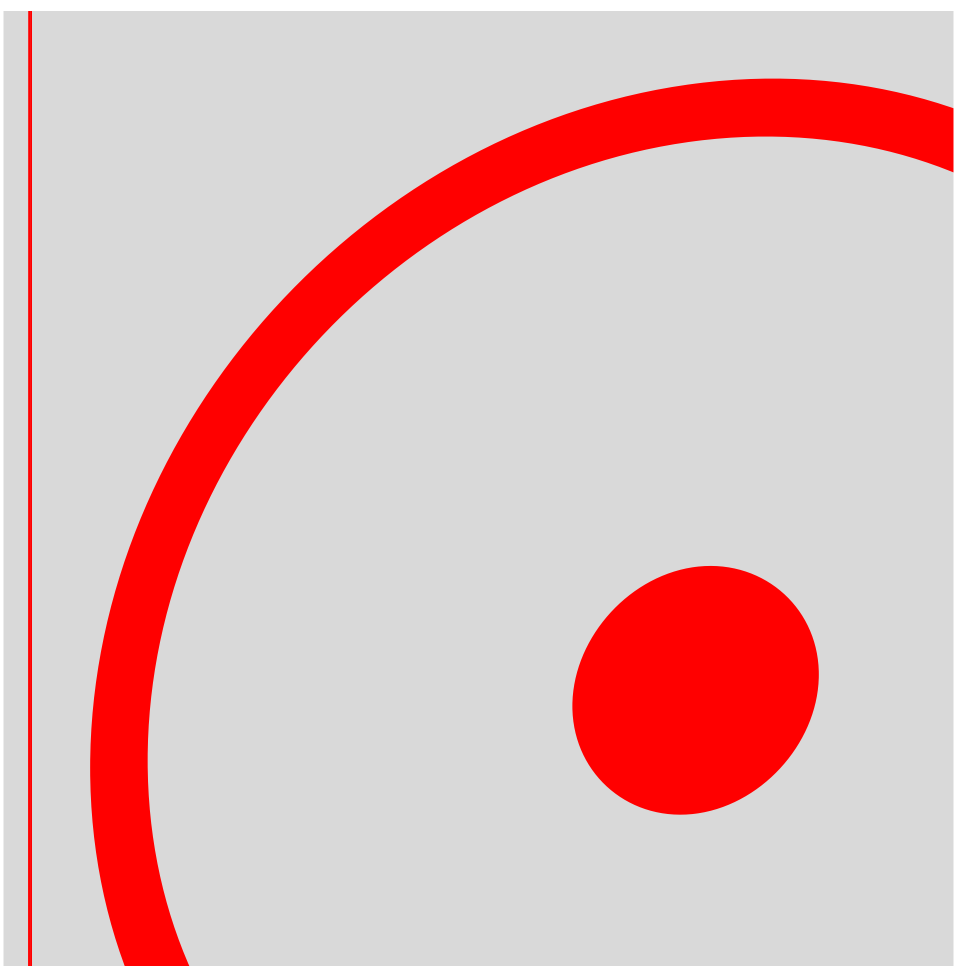
(adapted from Wofford+2016)

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

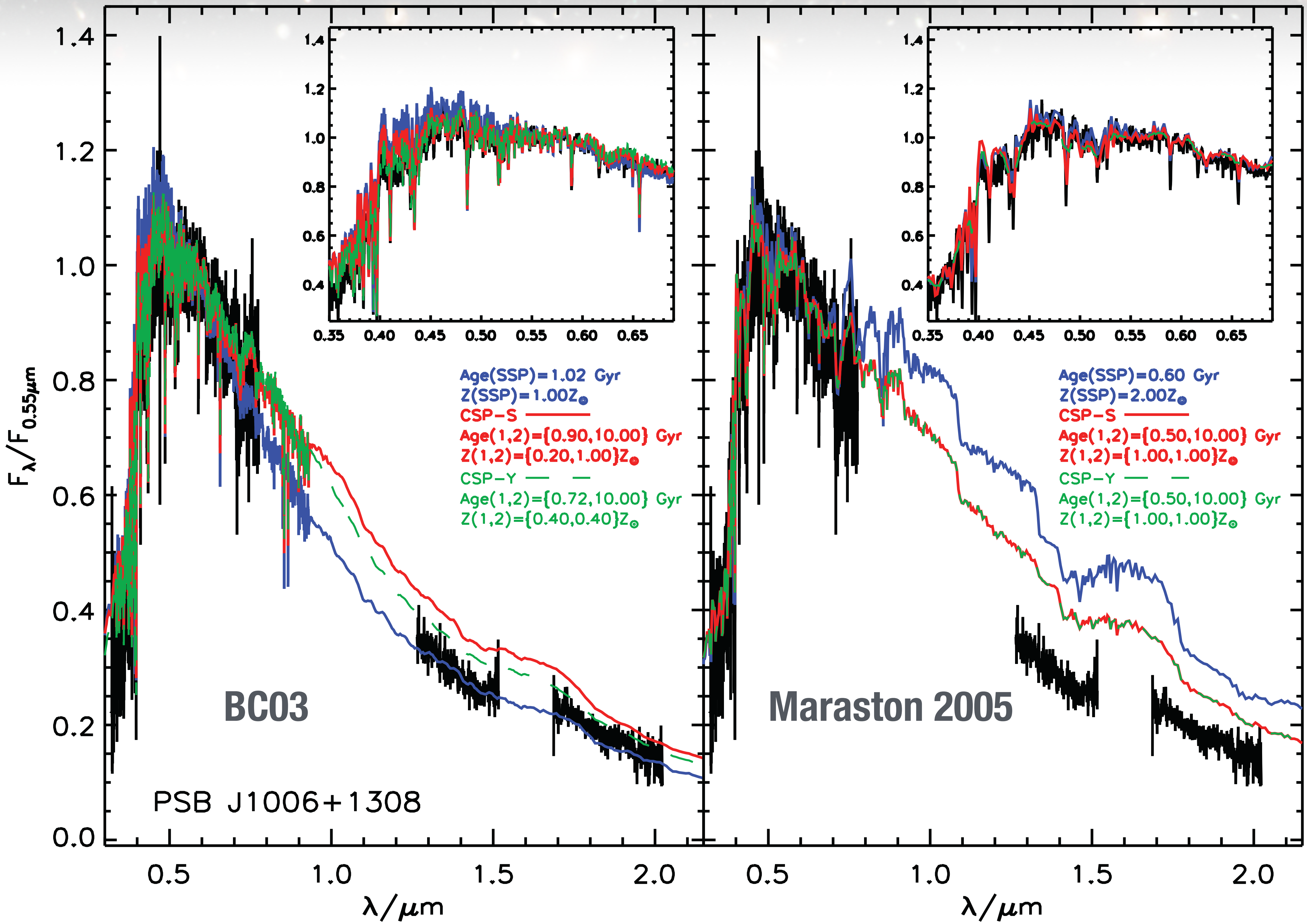
- Systematic differences in M/L from 0.2 to 0.4 dex



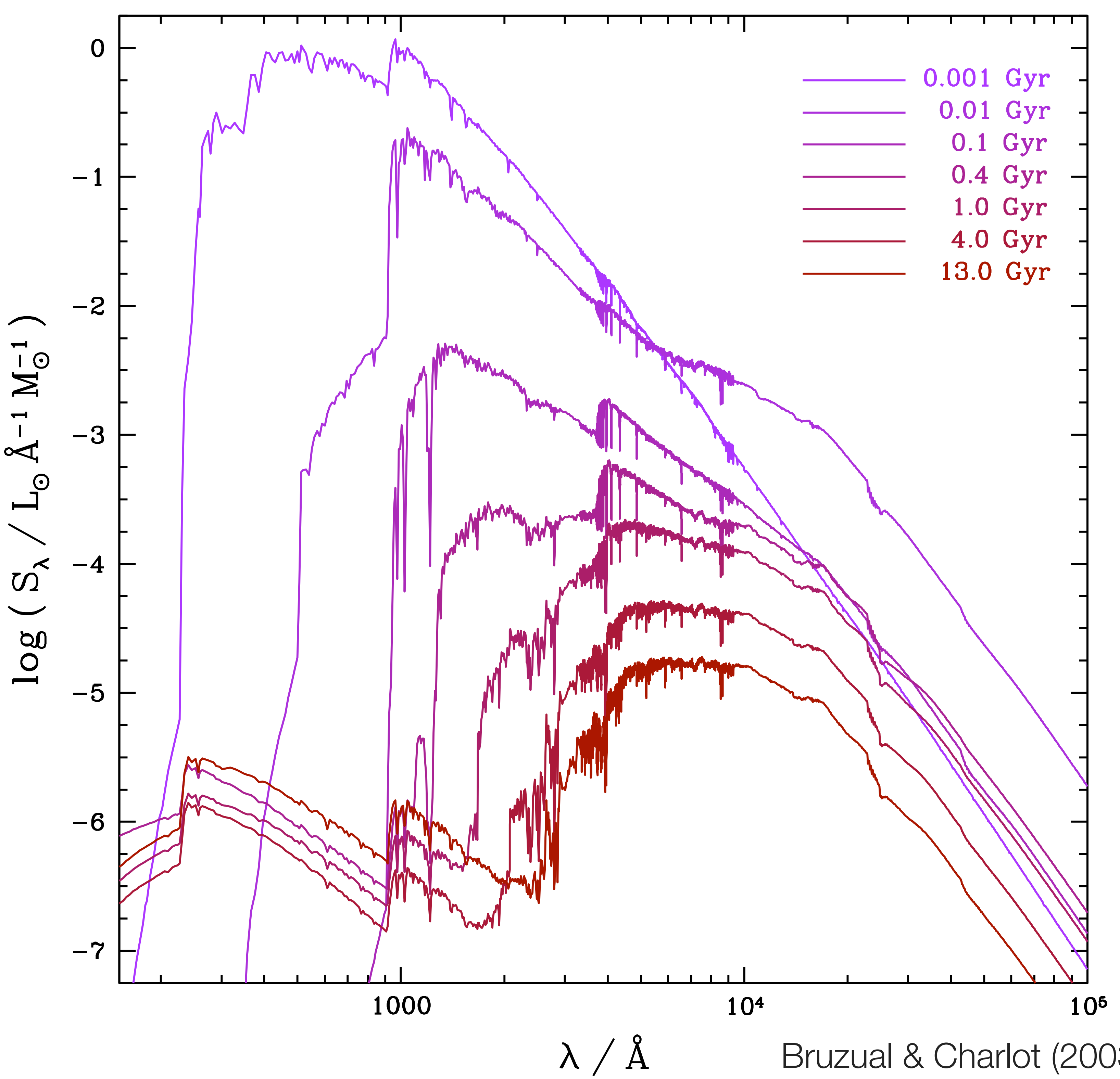
Zibetti+2012:
ISAAC spectroscopic follow-up of a sample of z~0.2 post-starburst galaxies (where contribution by TP-AGB stars should be maximal)

TP-AGB stars: a closer look

Zibetti+2012



Spectral evolution of a simple stellar population

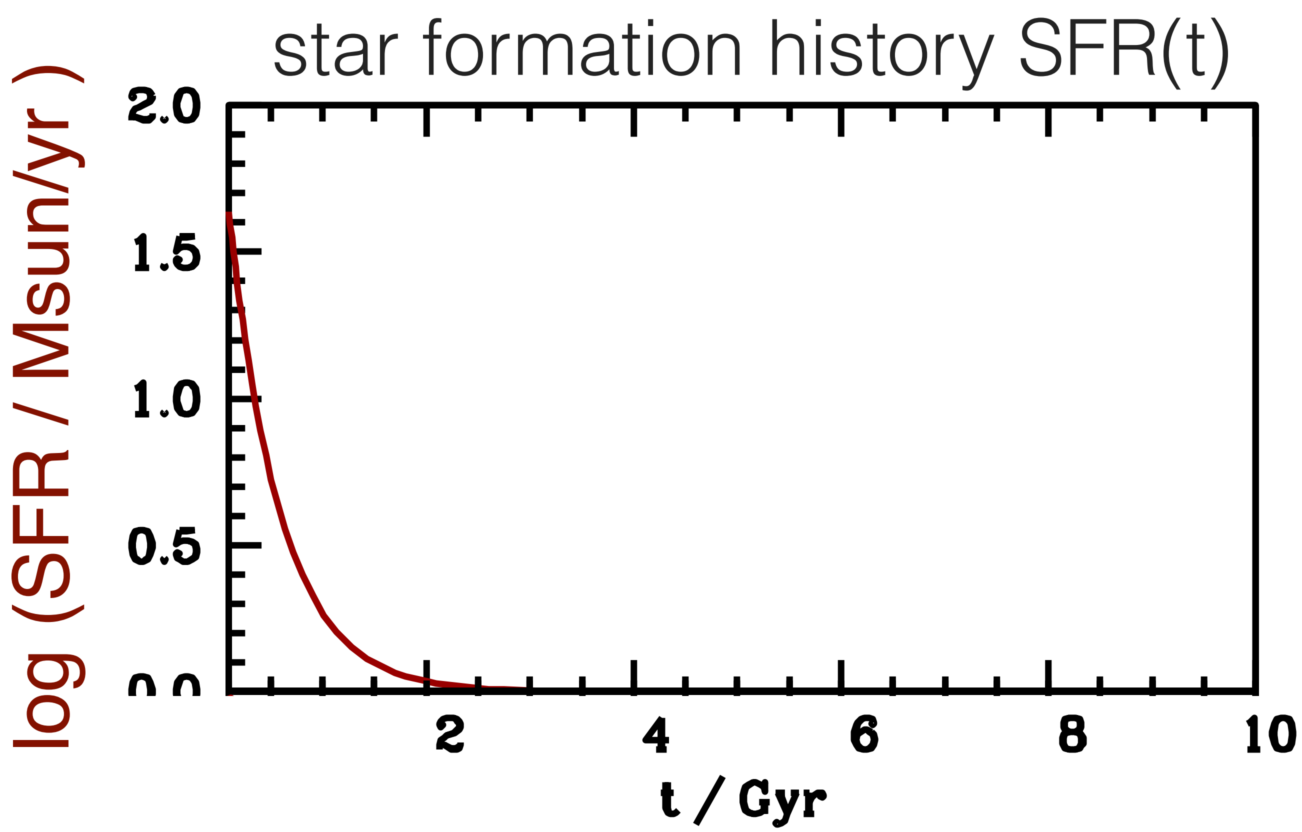


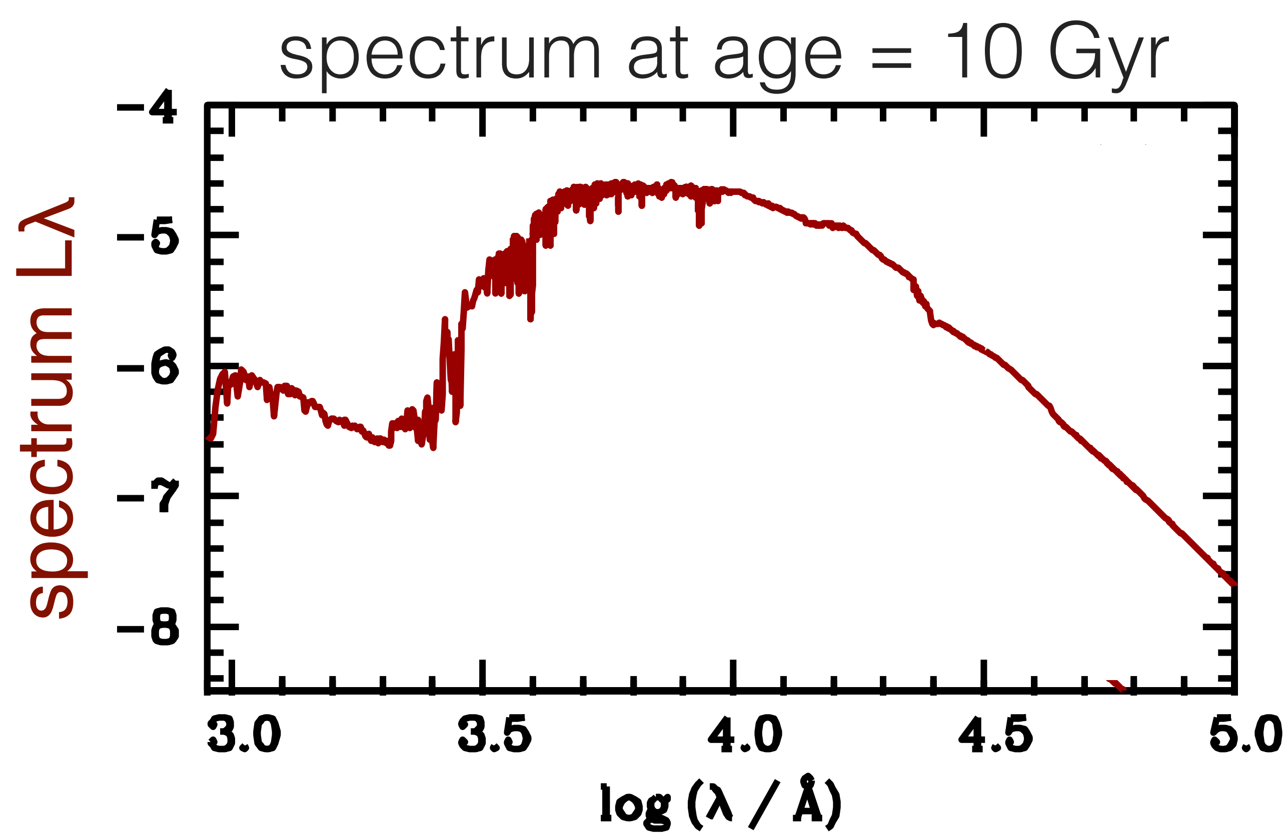
Bruzual & Charlot (2003)

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’
= ∫ SSP(age,metallicity) x SFR(t)





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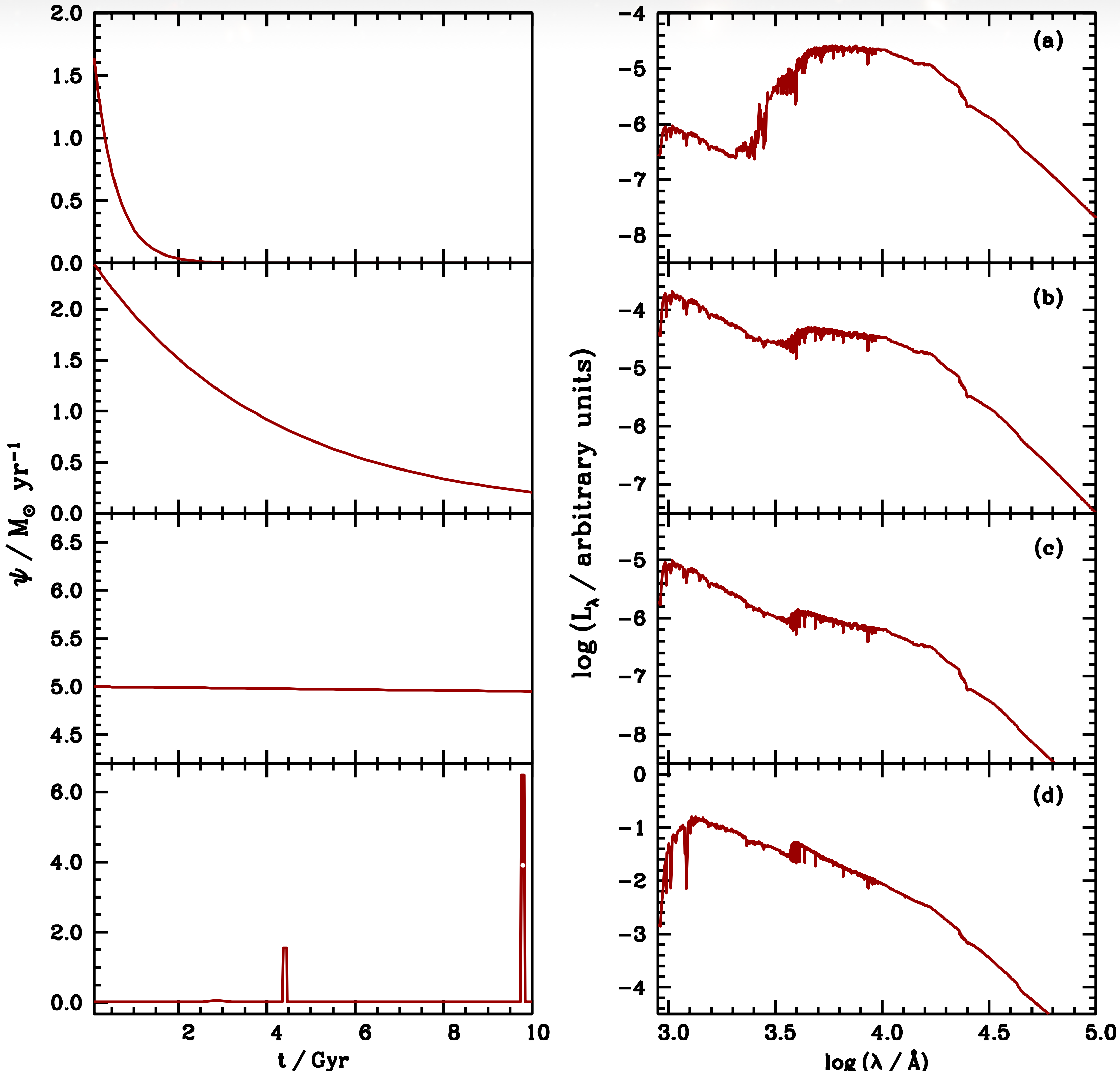
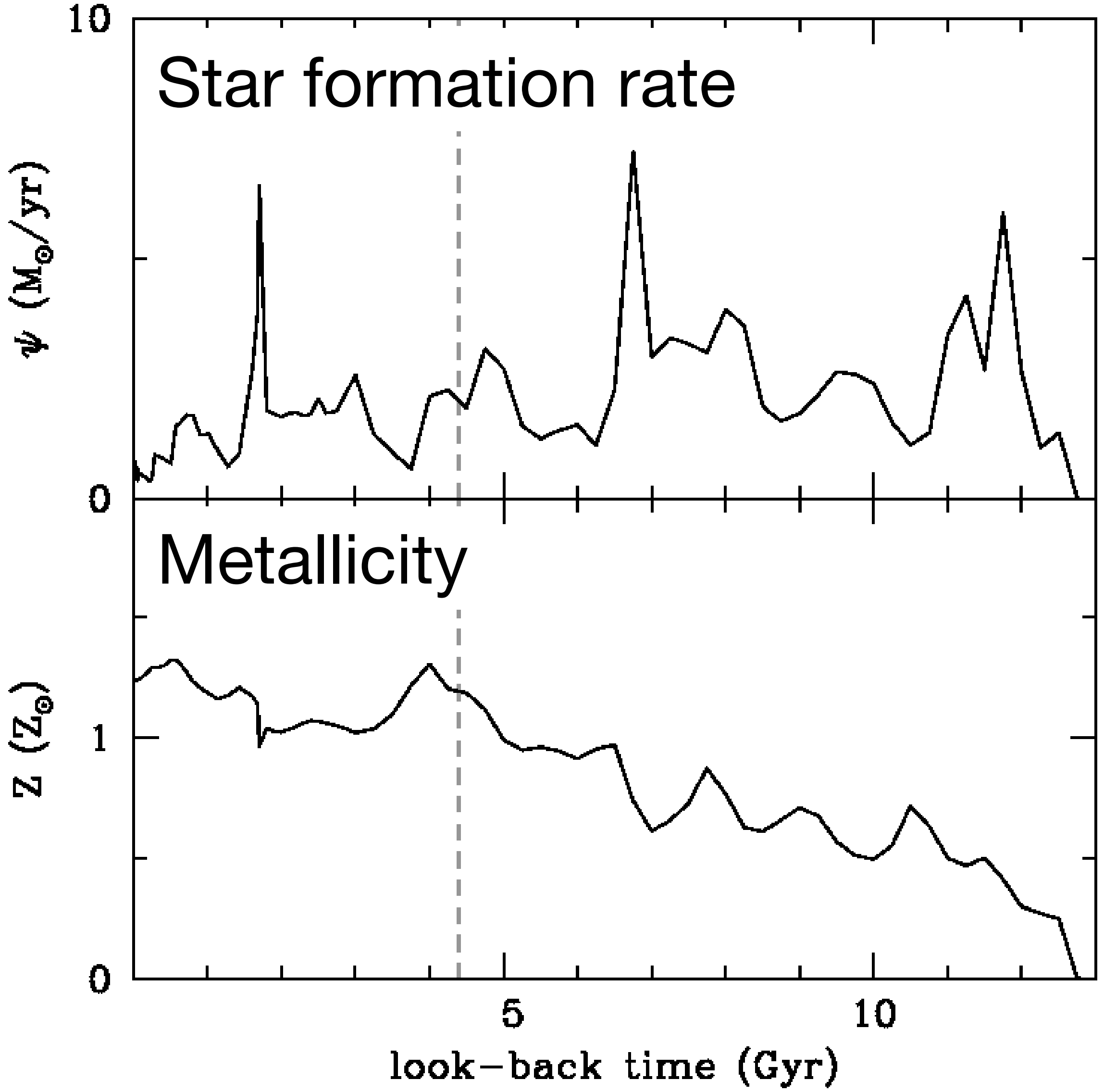


Main parameters:

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

Star formation & chemical enrichment histories

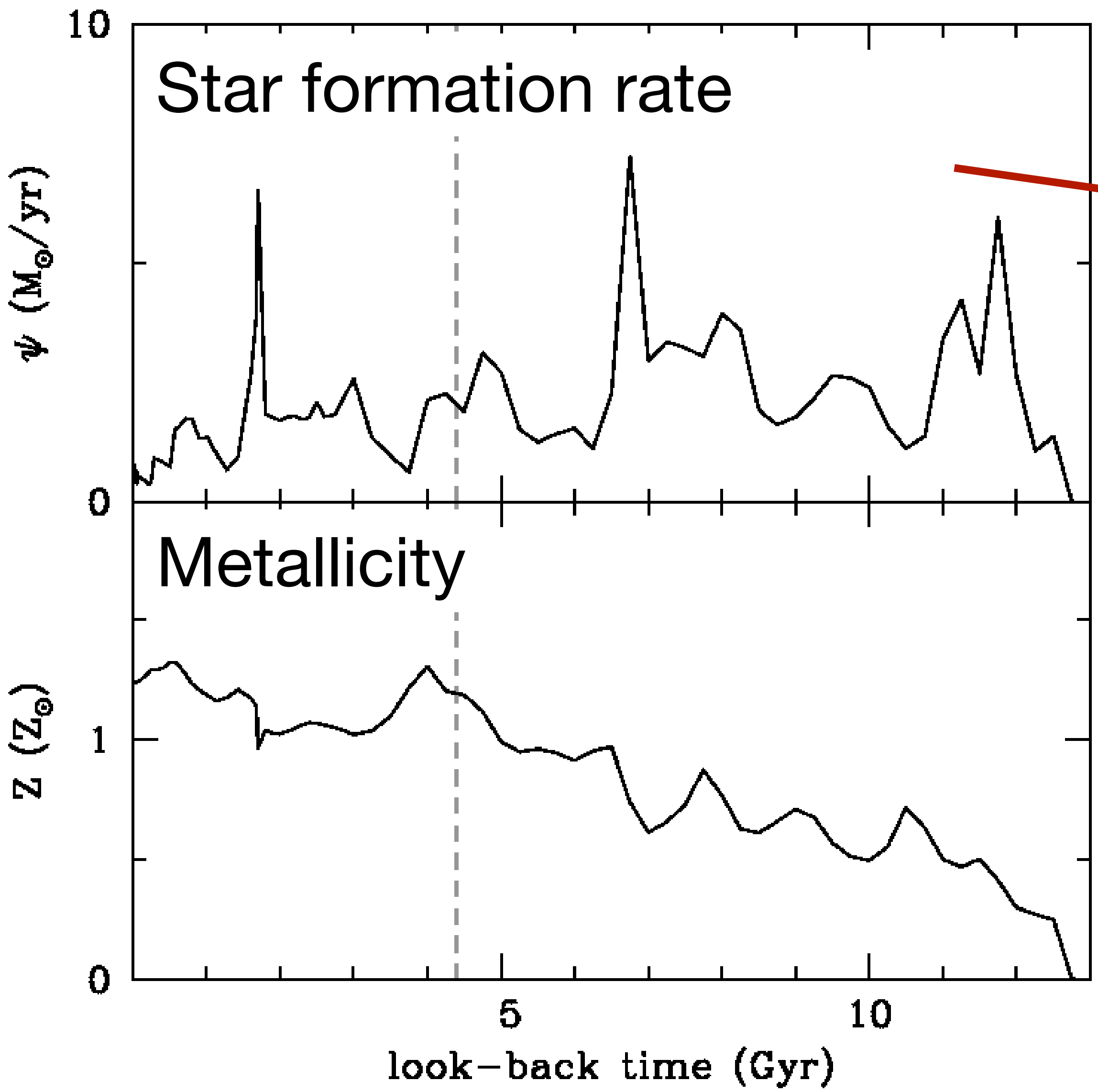
Post-processing of the Millenium simulation by De Lucia & Blaizot (2007)



Pacifici+2012

Star formation & chemical enrichment histories

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

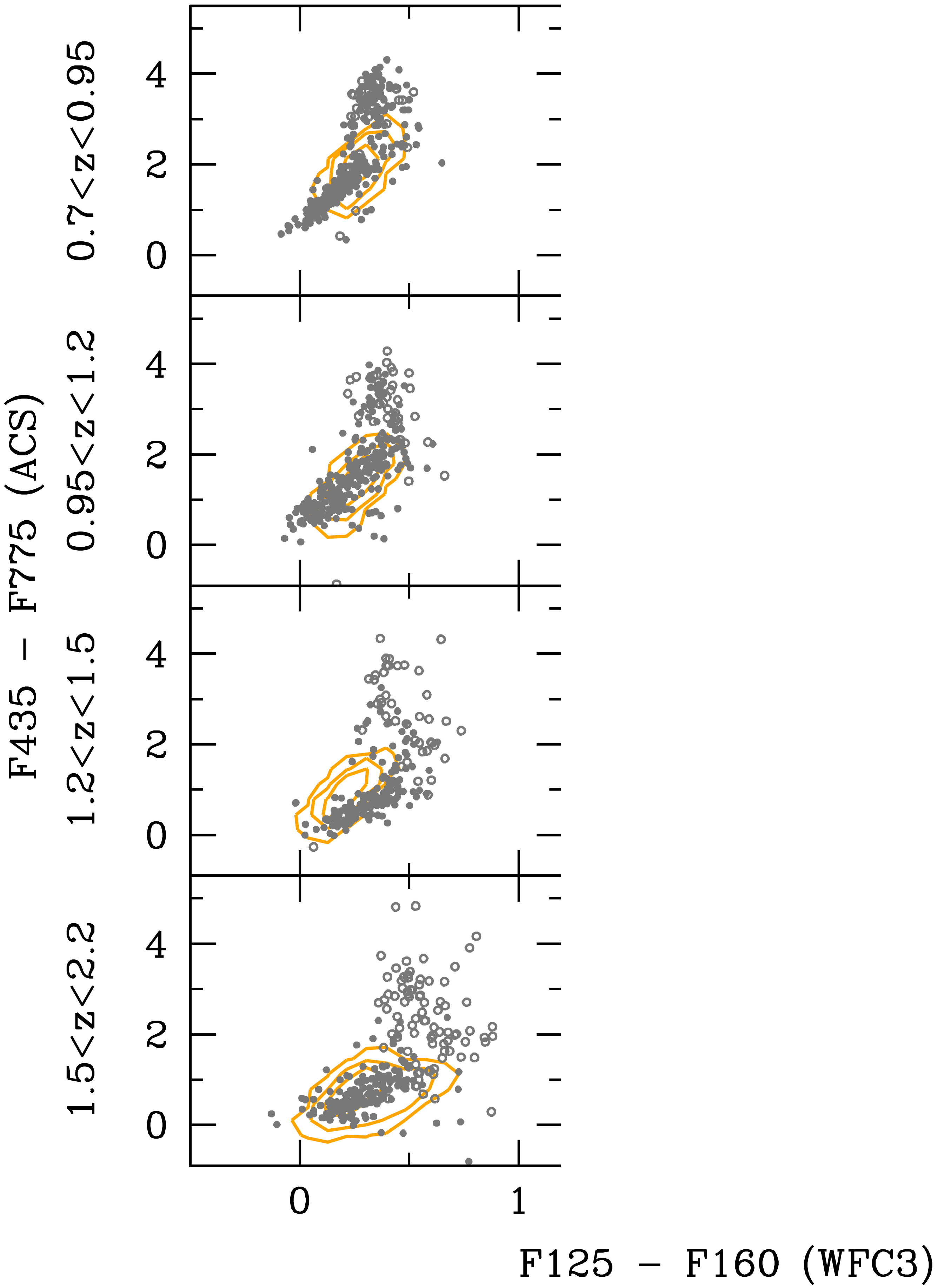


Pacifici+2012

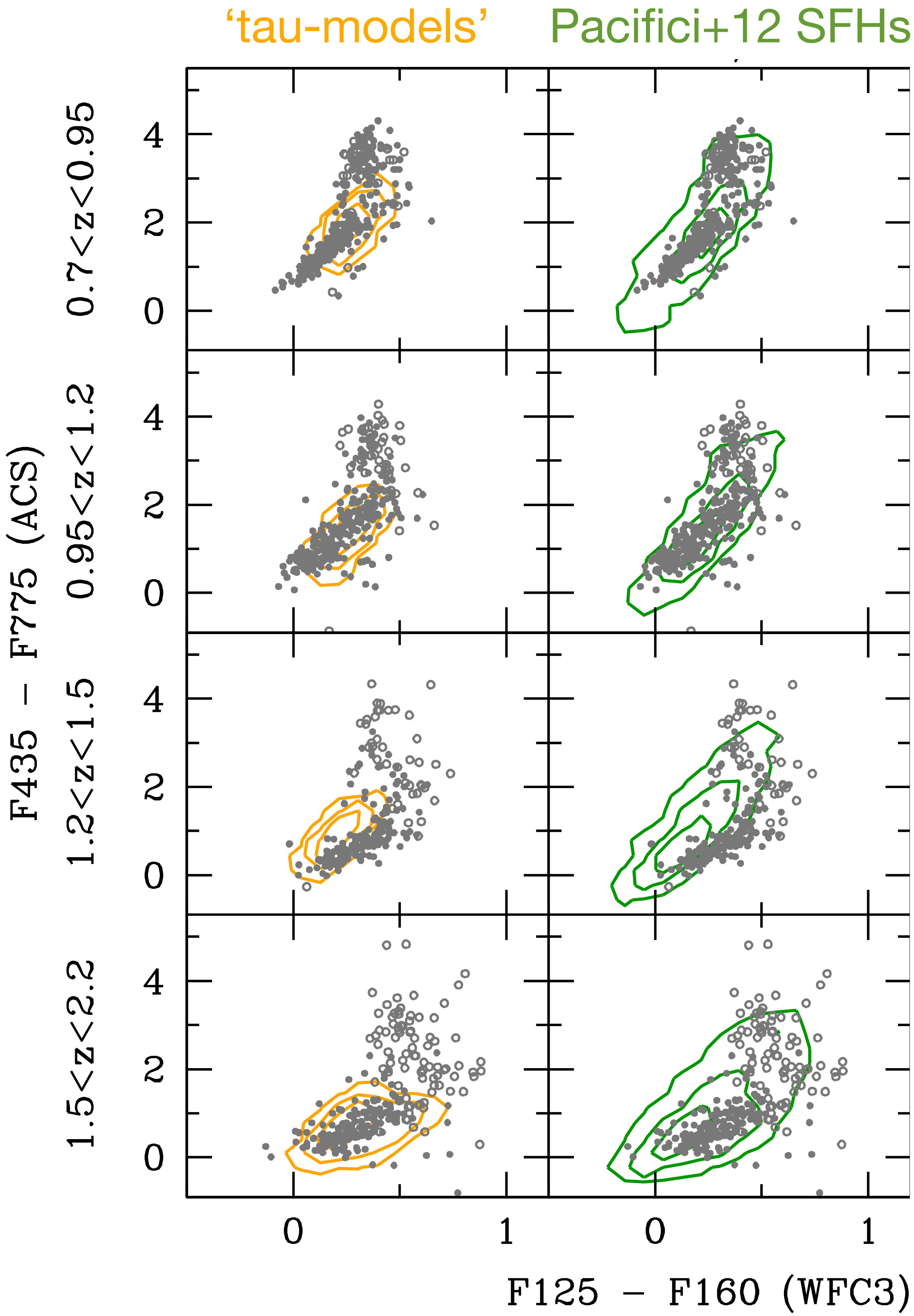
Looks nothing like a continuous tau-model!

Need to include increasing SFHs for of high-redshift galaxies.

e.g. Maraston+2010, Lee+2010, Wuyts+2011, Pforr+2012, Behroozi+2013, Pacifici+2013 'tau-models'



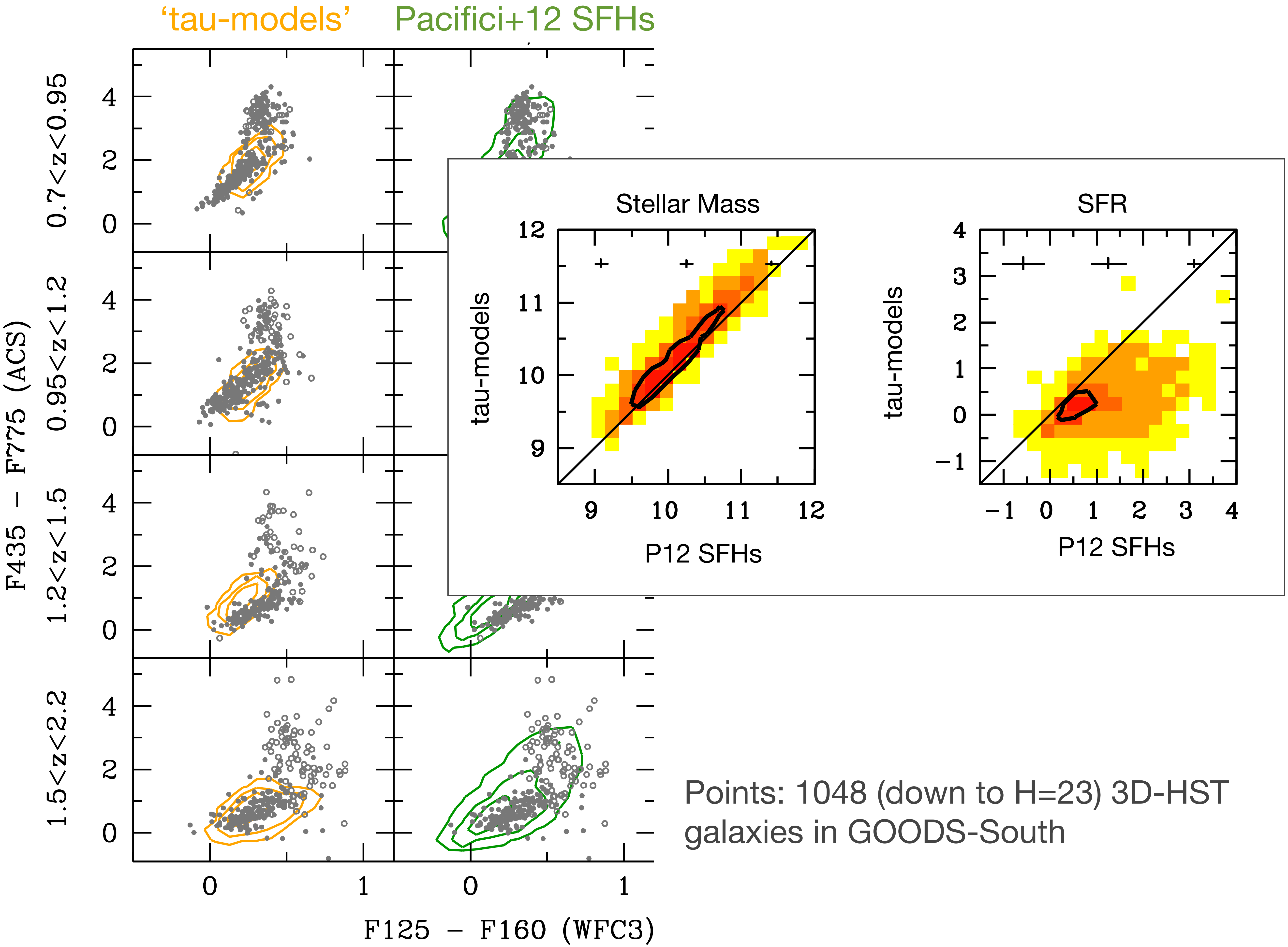
(Pacifici, da Cunha, Charlot,+2015)



(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

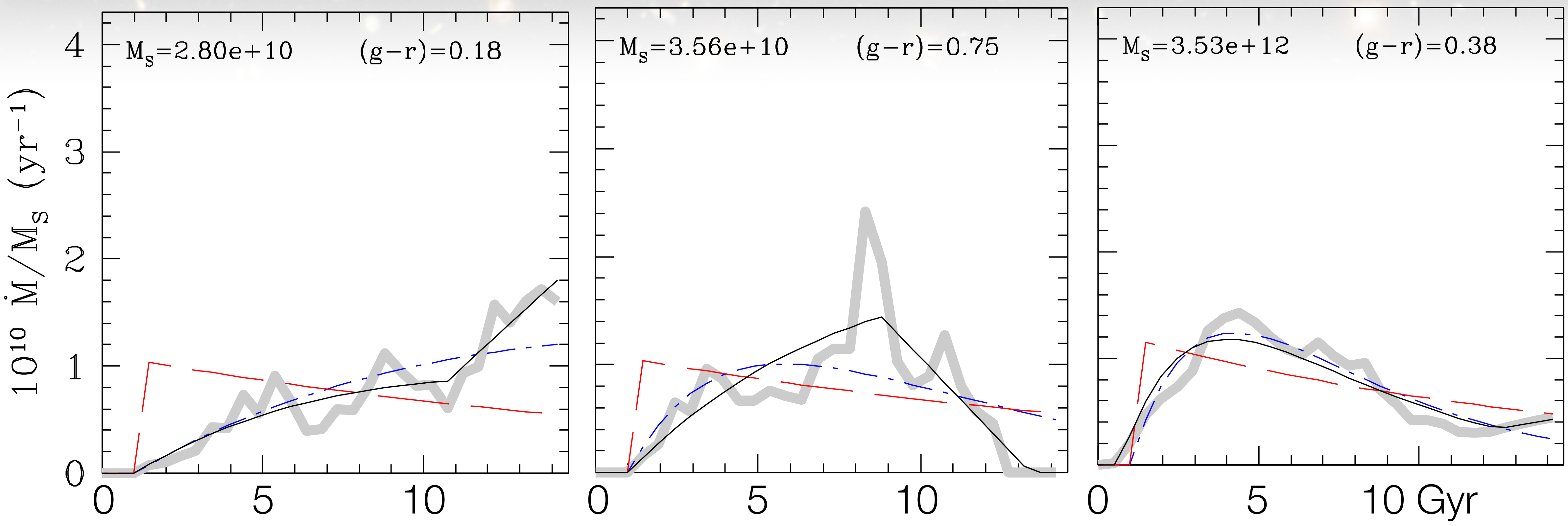


Points: 1048 (down to H=23) 3D-HST galaxies in GOODS-South

(Pacifici, da Cunha, Charlot,+2015)

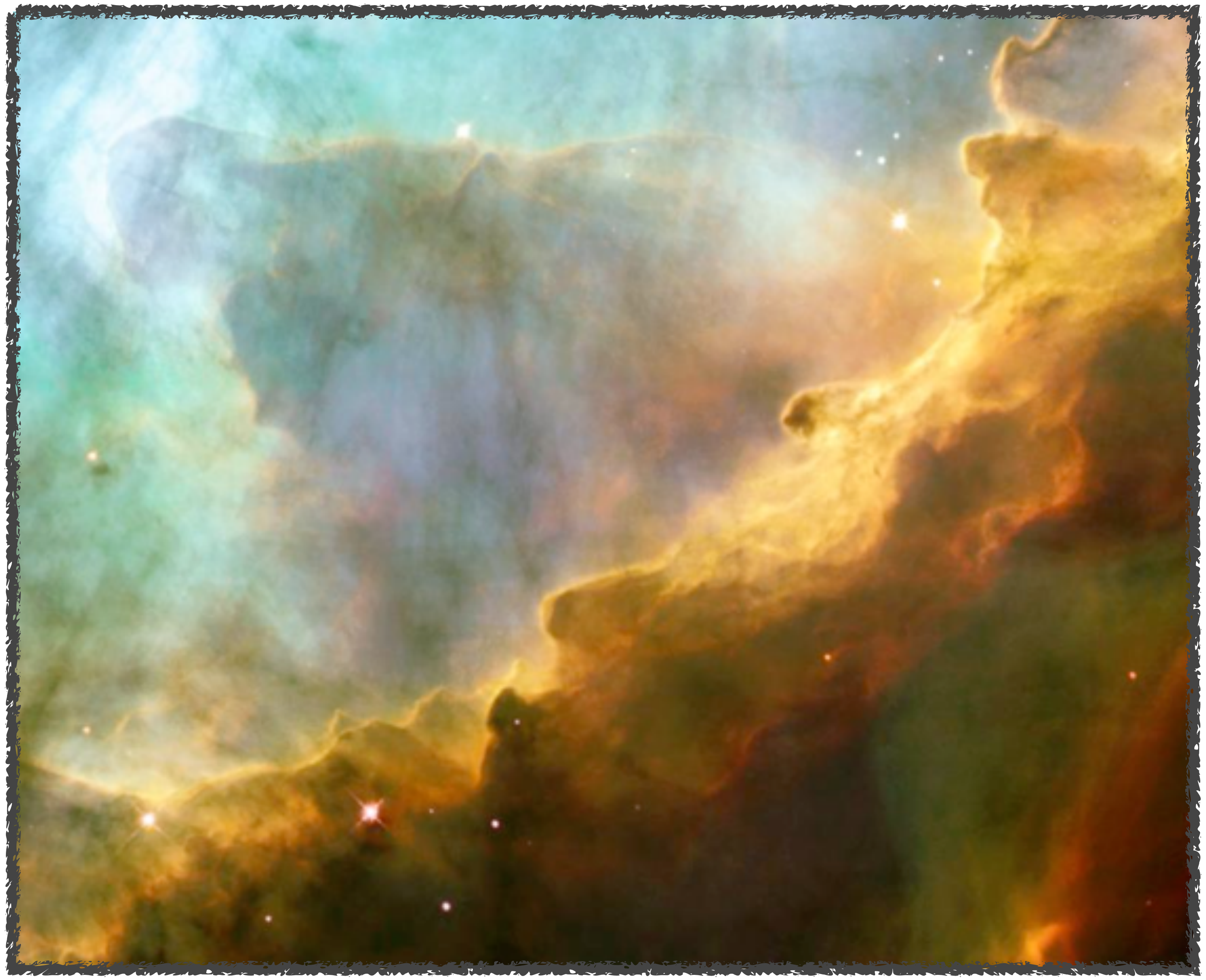
How should we parameterize the SFH?

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)

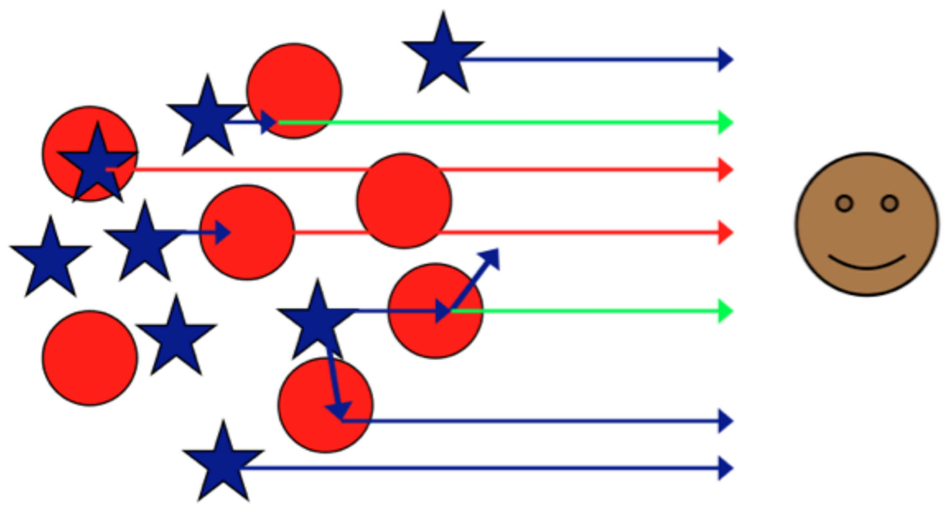
New MAGPHYS SFHs (da Cunha + 2015):
delayed tau-models (spanning a wide range of timescales) + random bursts

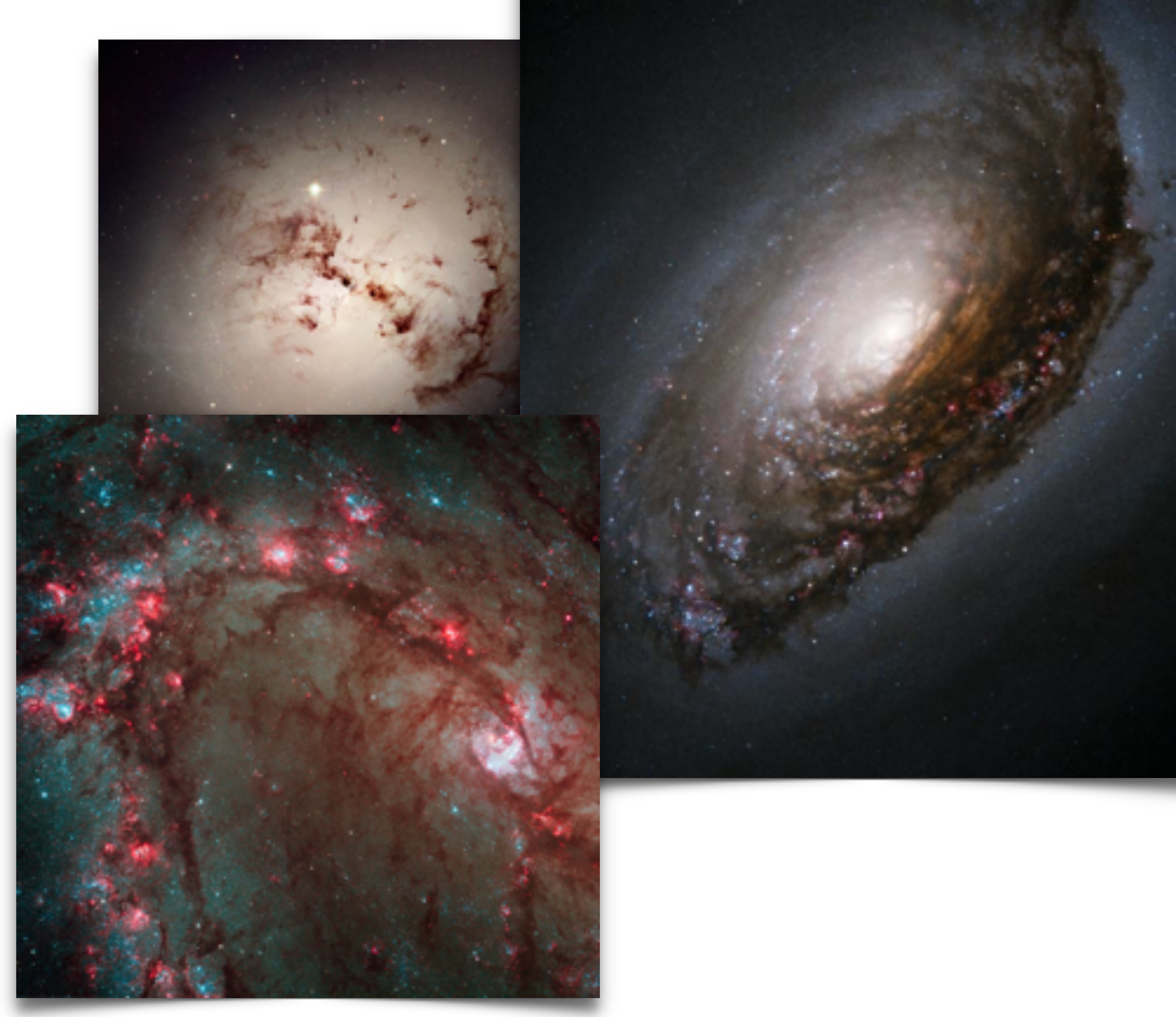


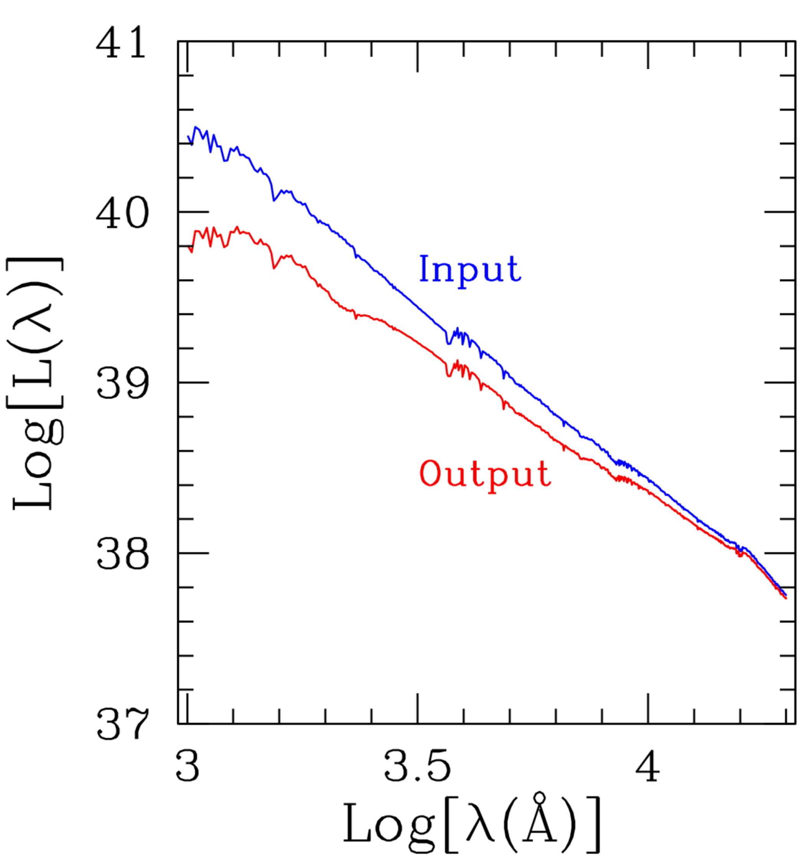
the interstellar medium: transfer through dust & gas

Interstellar dust

Typically interstellar dust is ~1% of the mass of a galaxy, but dust grains scatter and absorb a large fraction (typically 50%) of the UV/optical light emitted by stars.







$$L_\lambda^{\mathrm{out}} = L_\lambda^{\mathrm{in}} \exp(-\tau_\lambda)$$

Dust attenuation optical depth:
depends on physical properties of the dust grains & stars/dust geometry

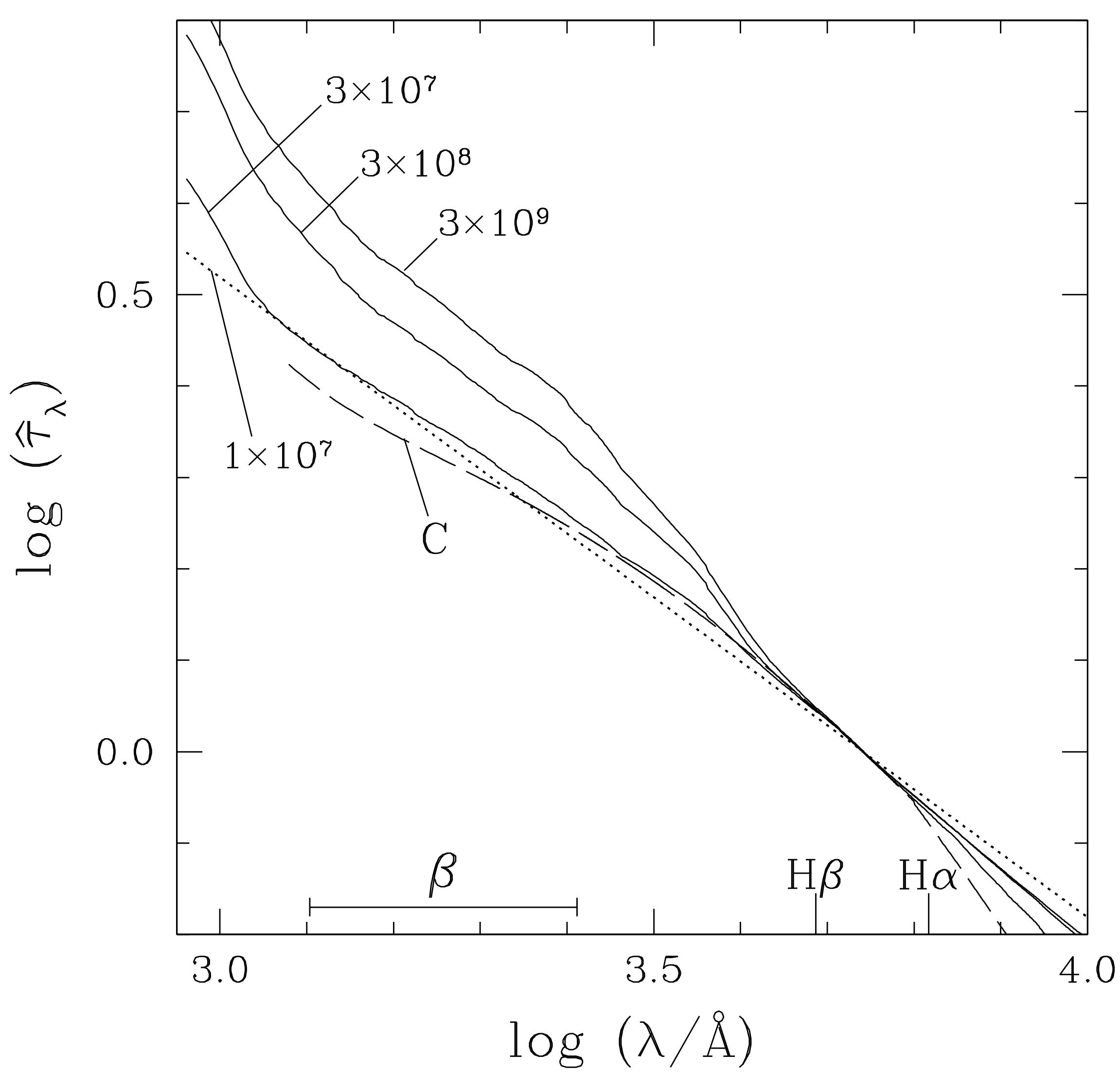
(after Calzetti 2012)

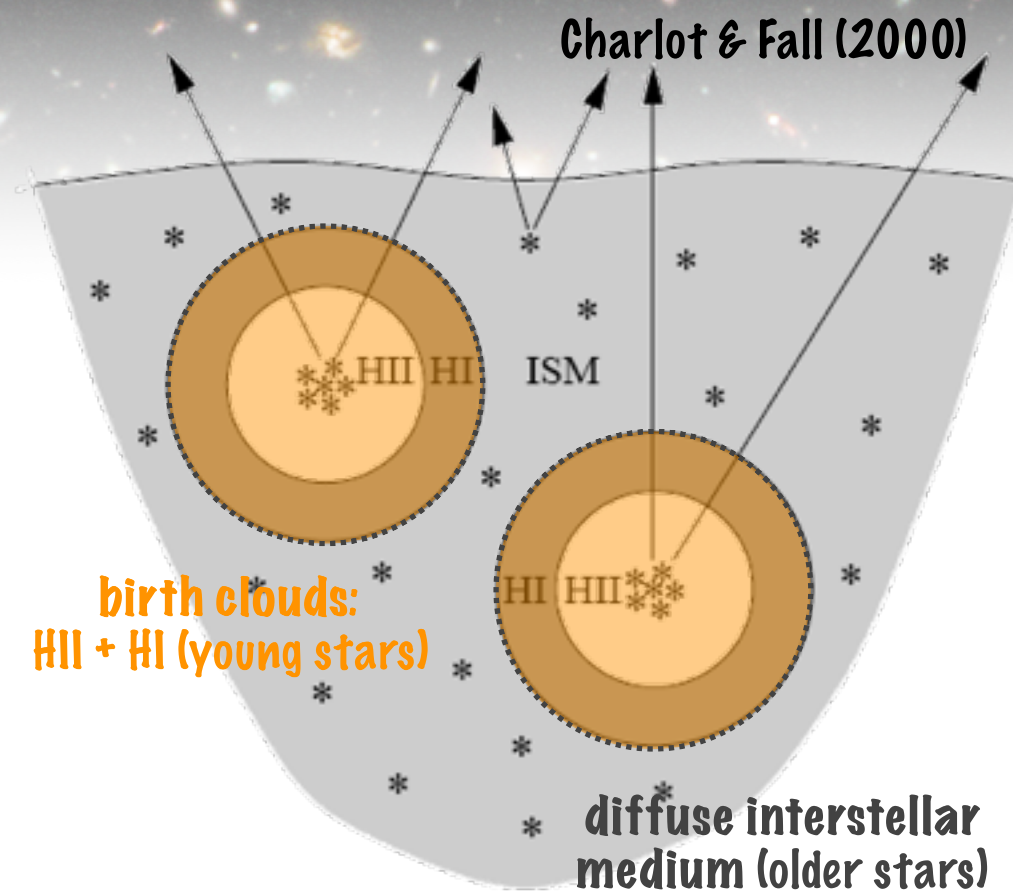
The interstellar medium: dust

- 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





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

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

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

The interstellar medium: dust

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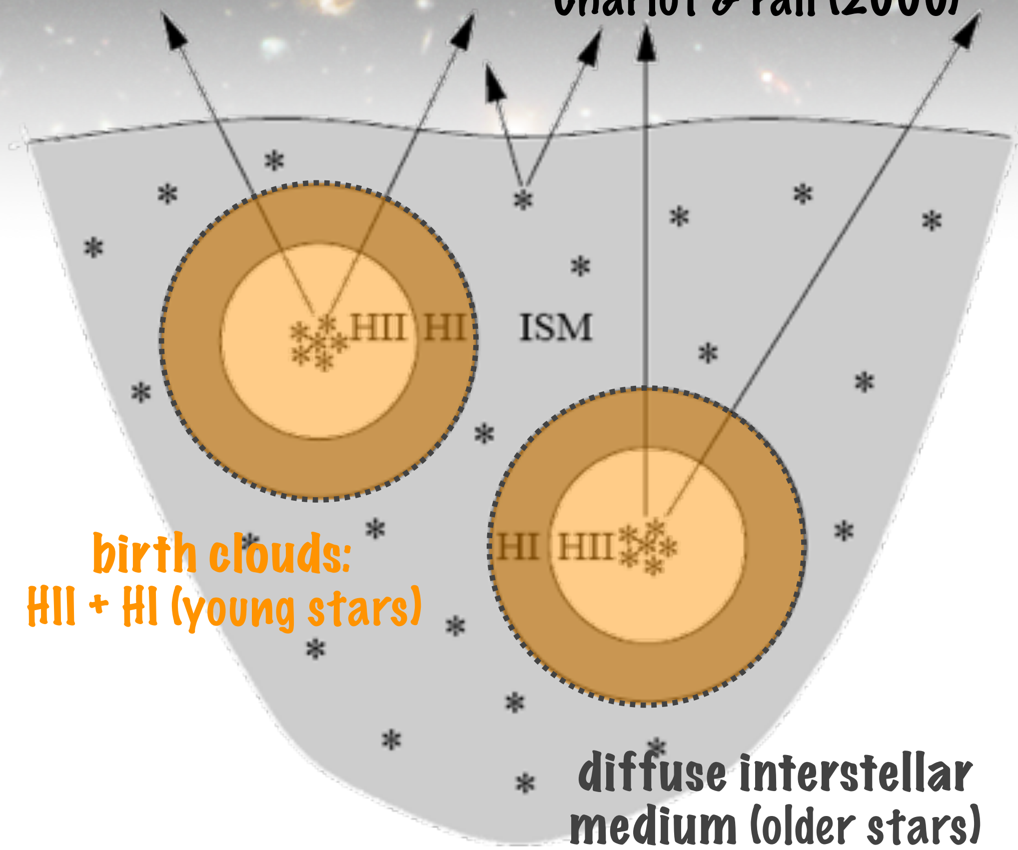
Charlot & Fall (2000)



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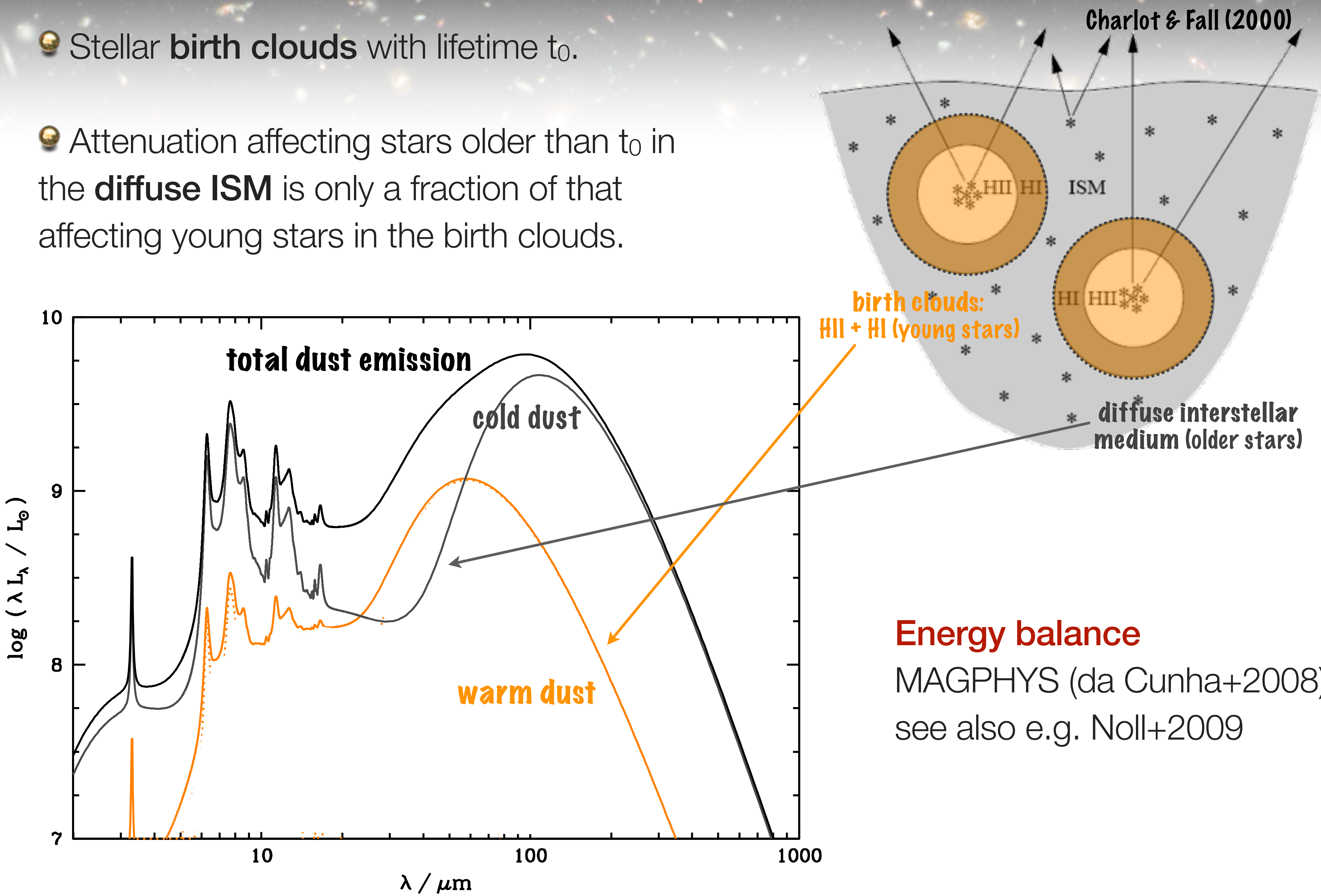


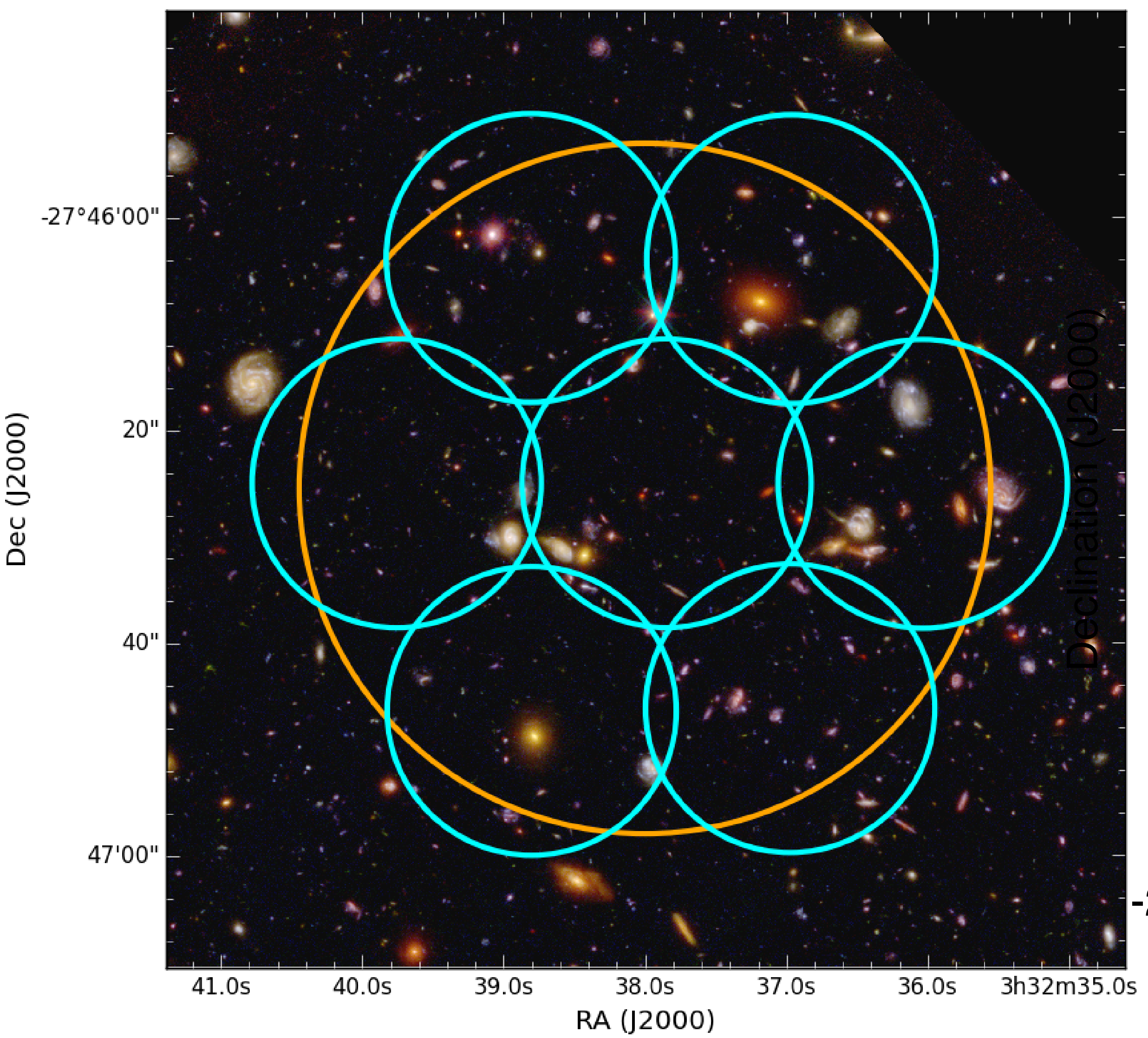
Energy balance

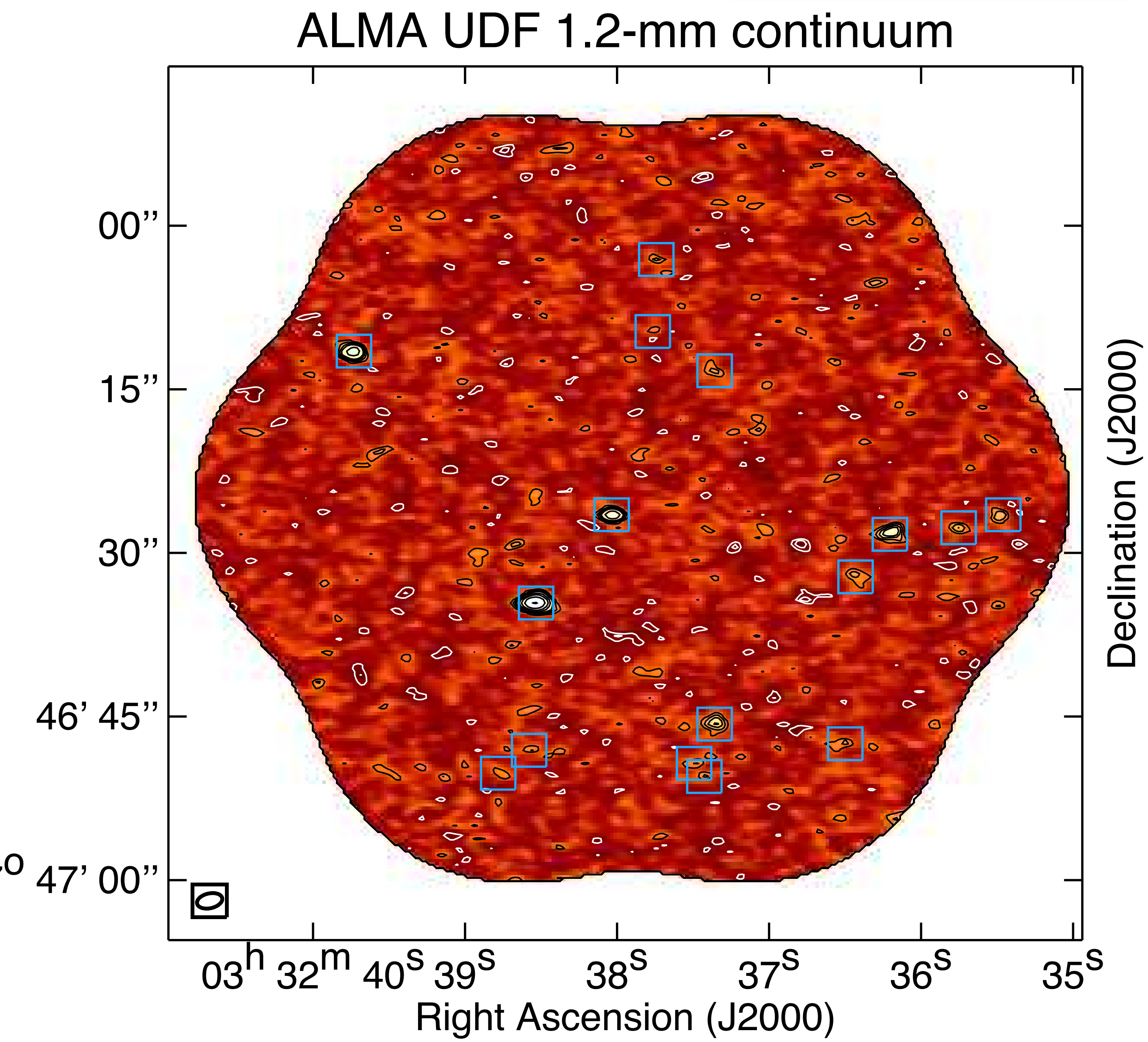
MAGPHYS (da Cunha+2008)

see also e.g. Noll+2009

Dust evolution at high redshift?

ASPECS:
ALMA spectroscopic survey of the HUDF

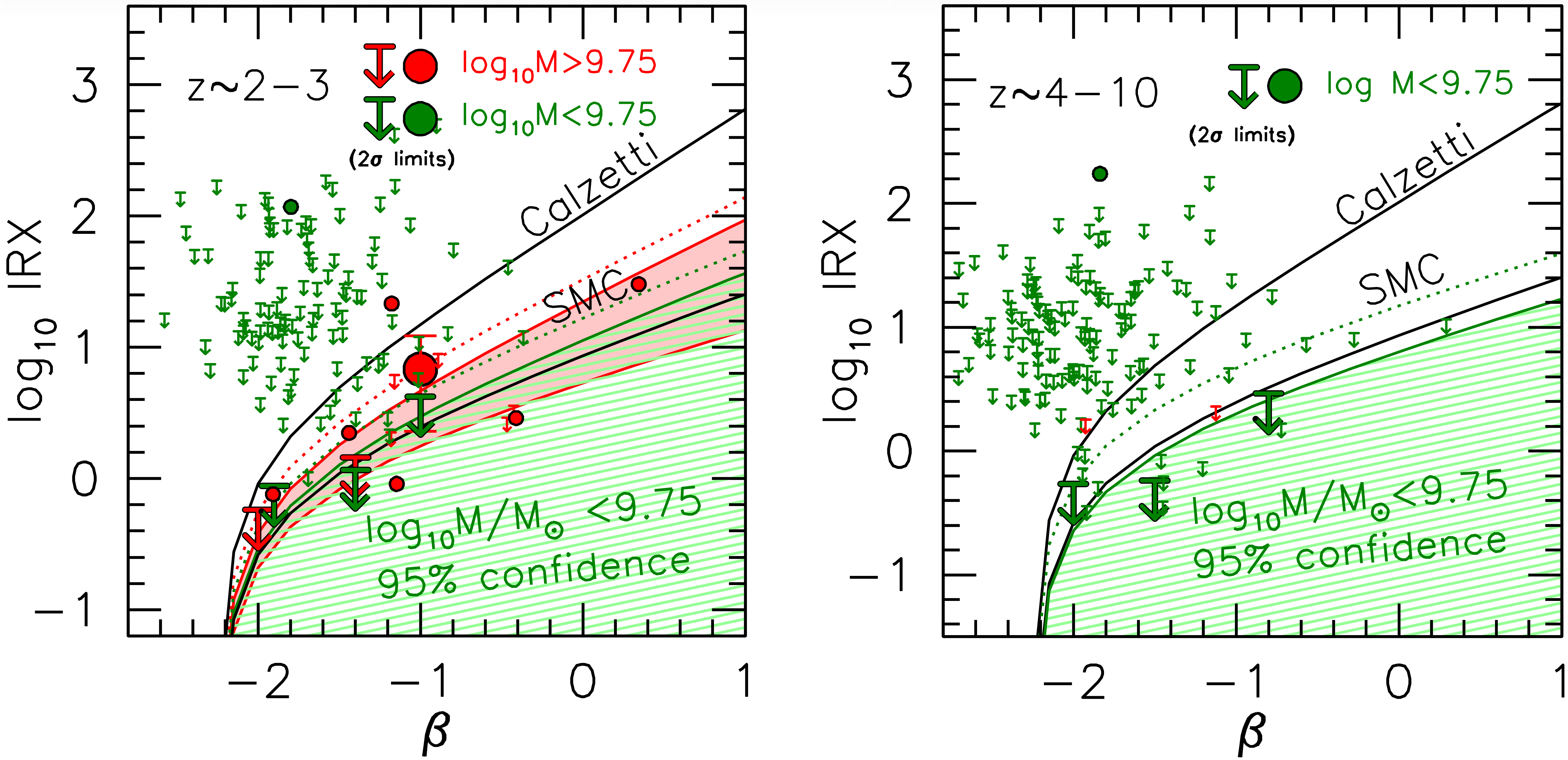




Walter+2016

Aravena+2016

Dust evolution at high redshift?



(note: assumes T_{dust}=35 K)

Bouwens+2016

The interstellar medium: ionized gas

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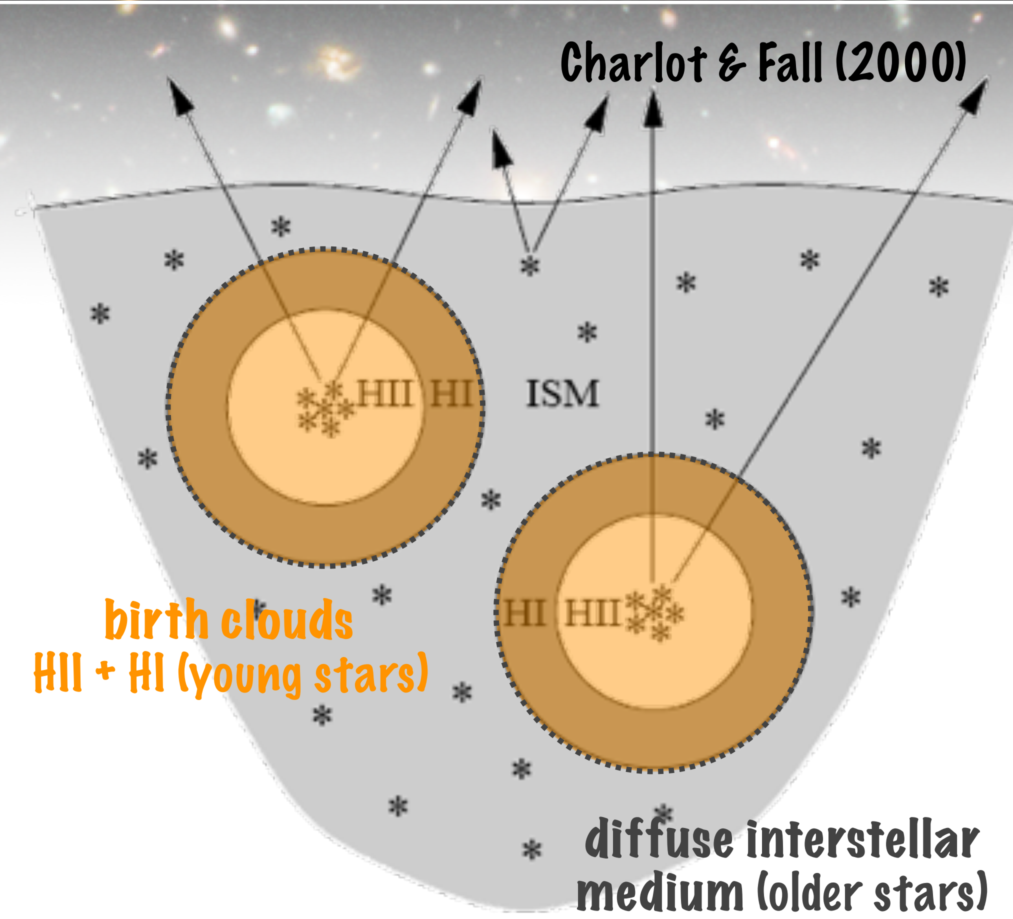

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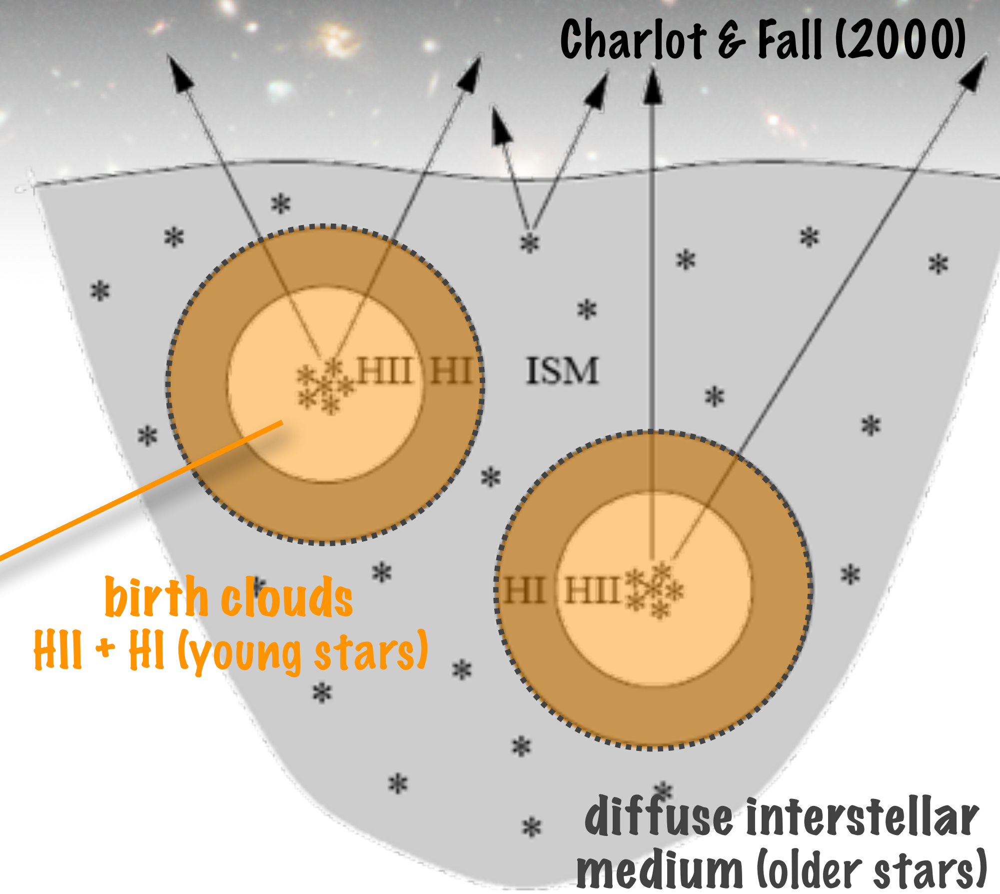
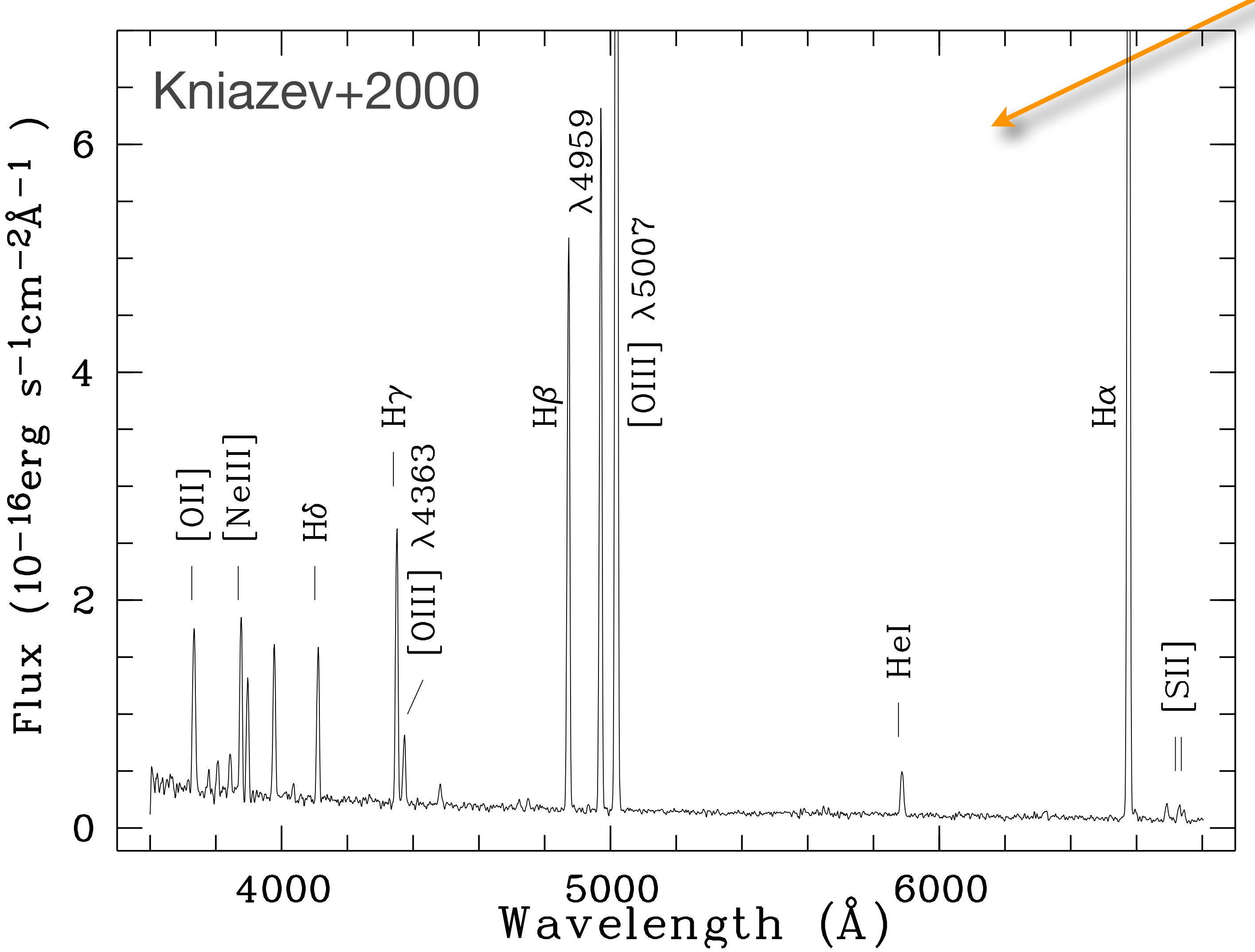
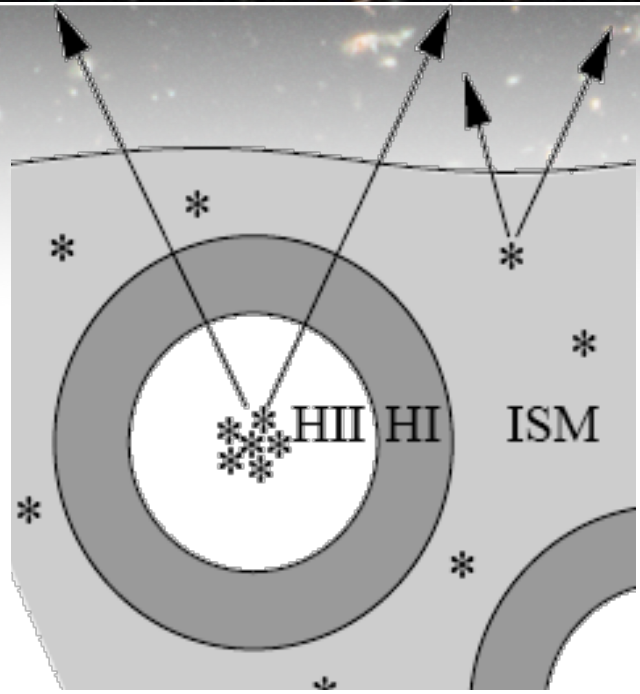
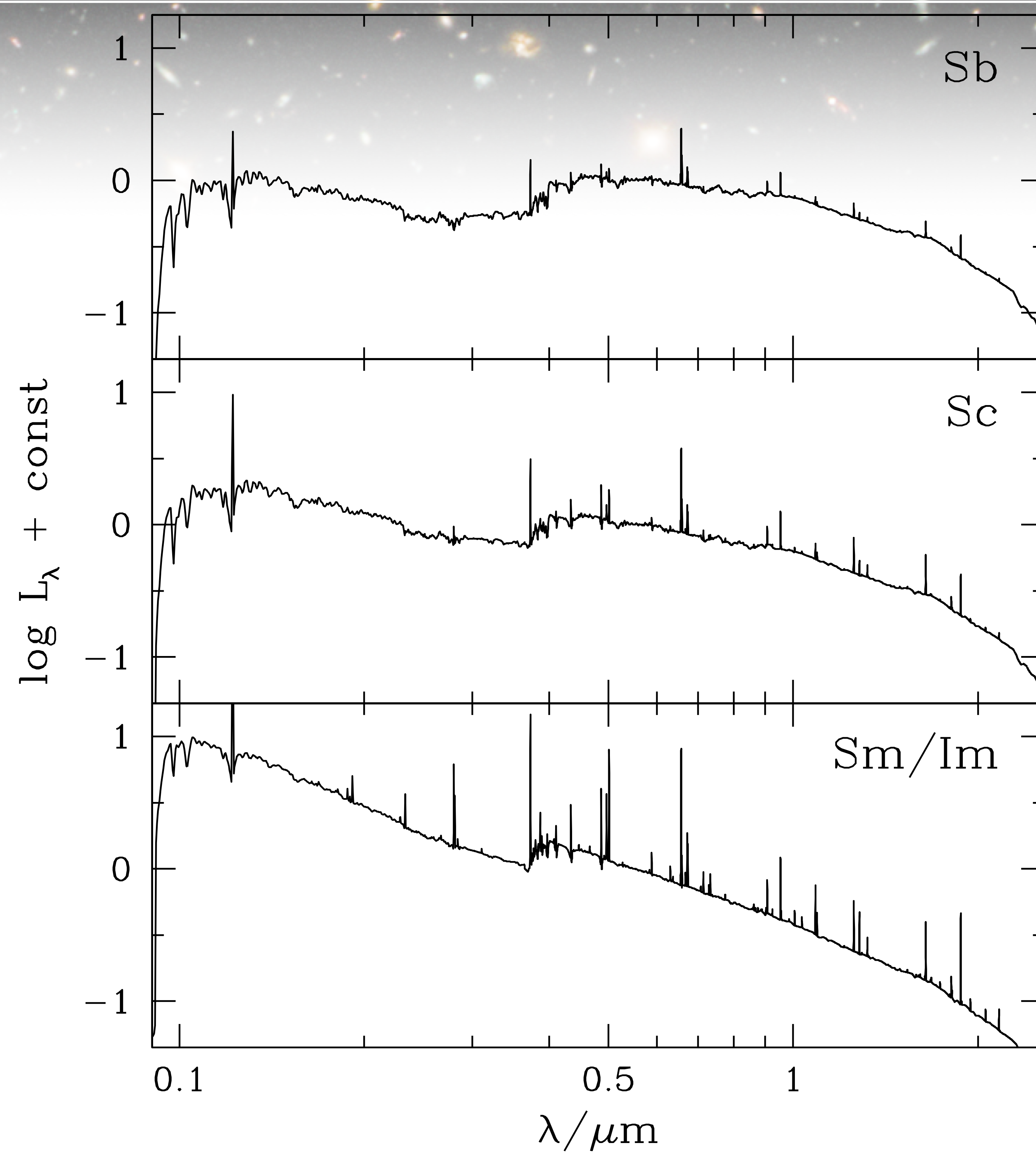




Nebular emission **computed self-consistently** using the CLOUDY photo-ionization code by Ferland 1996 (Pacifici+2012, Charlot & Longhetti 2001)

The interstellar medium: ionized gas





Ionizing radiation set by the stellar population model + SFH

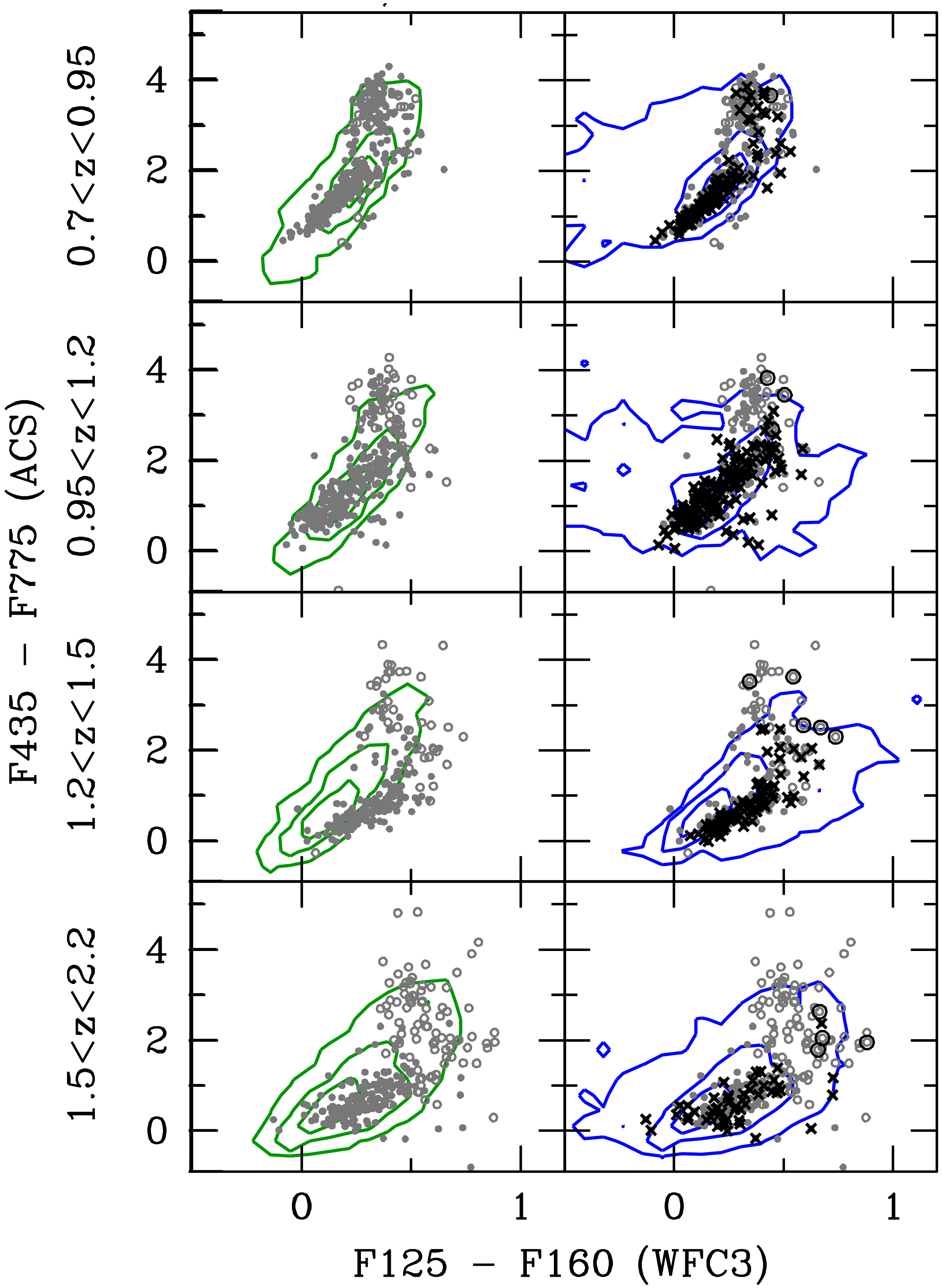
Dust attenuation already implemented (CF00)

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, Feltre+2016, Gutkin+ in prep.]

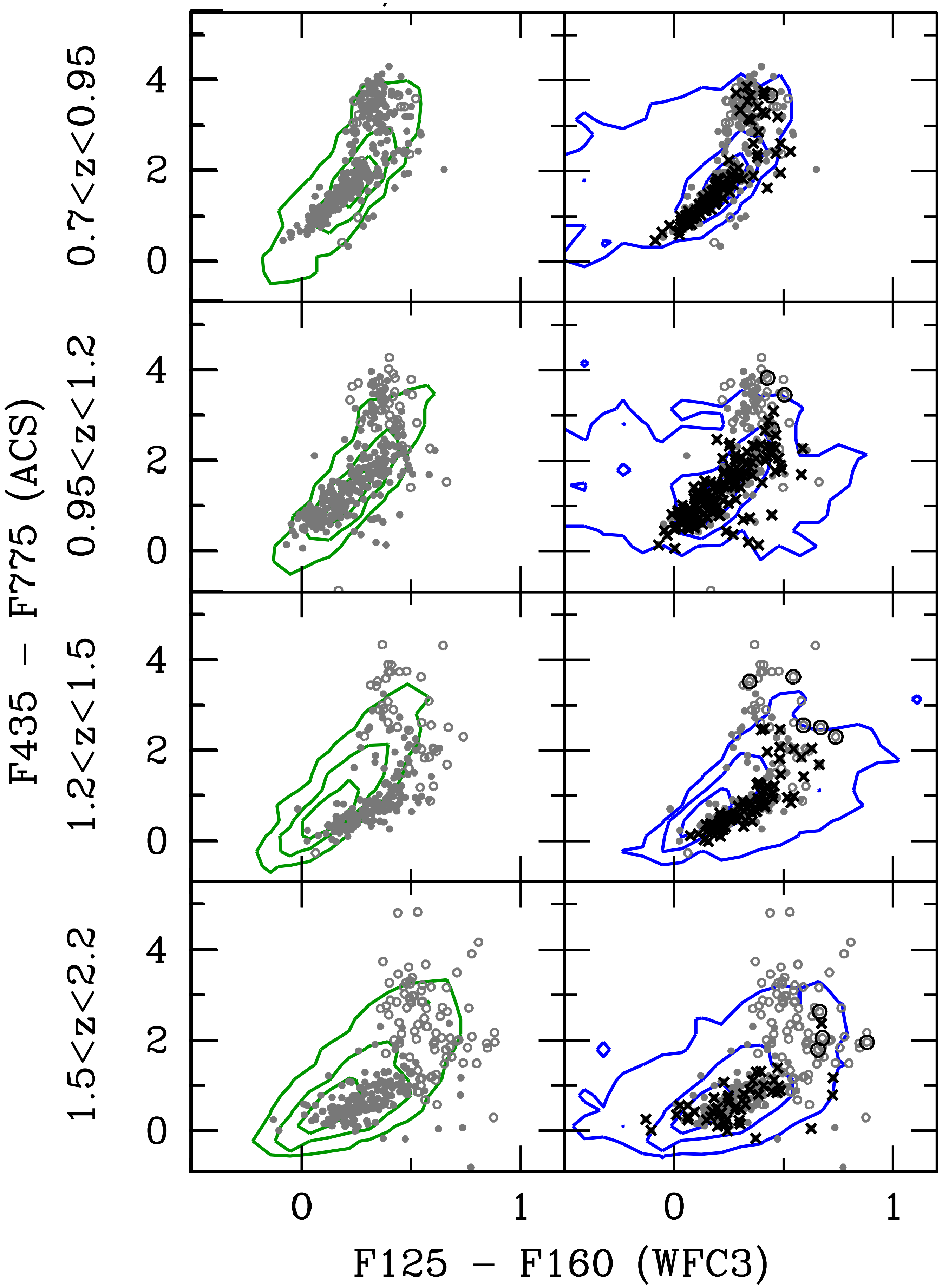
Pacifici+12 SFHs nebular emission

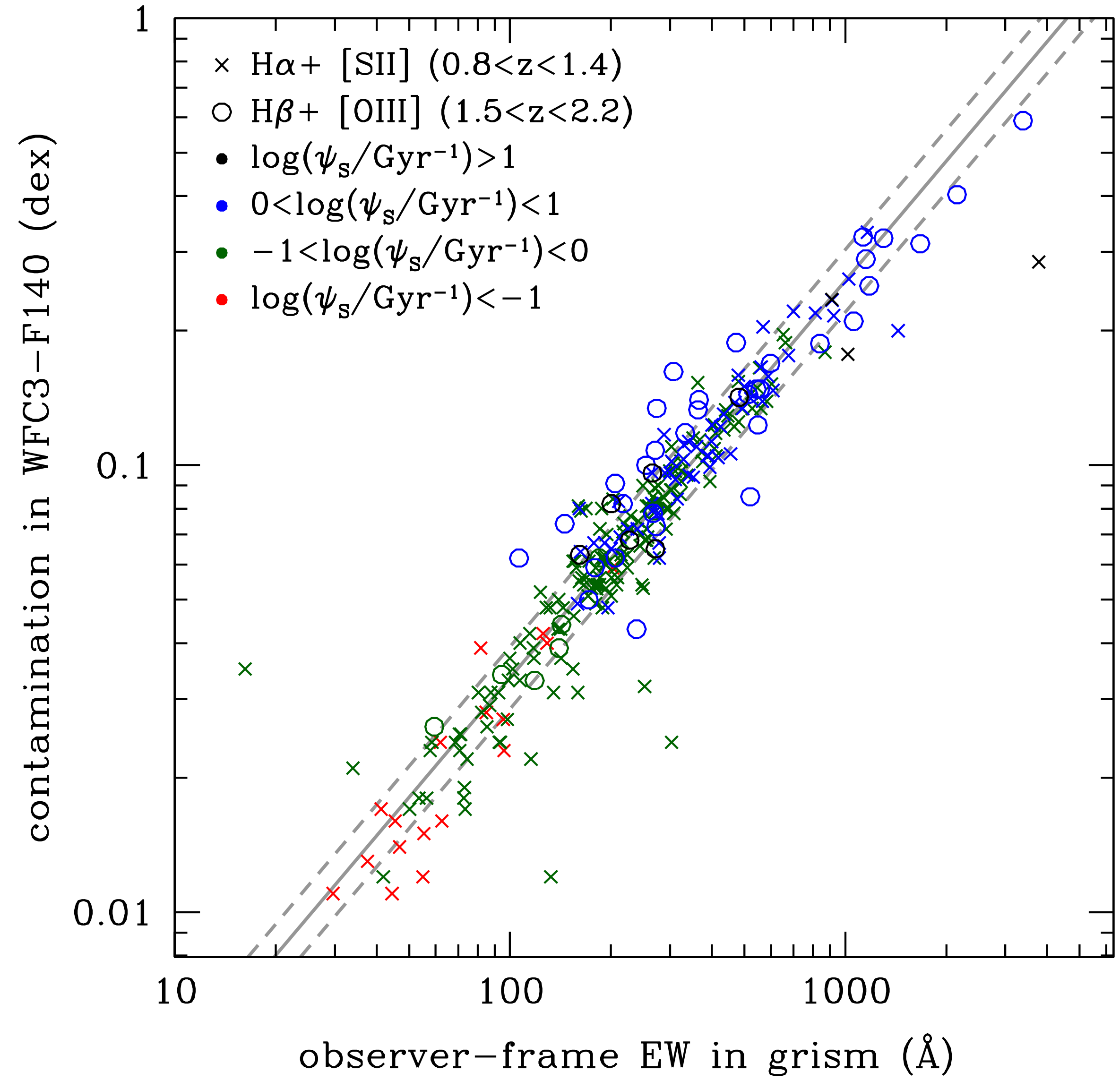


contamination by nebular emission
can be important even at
'moderate' redshifts!

[see also e.g. de Barros+2014]

Pacifici+12 SFHs nebular emission

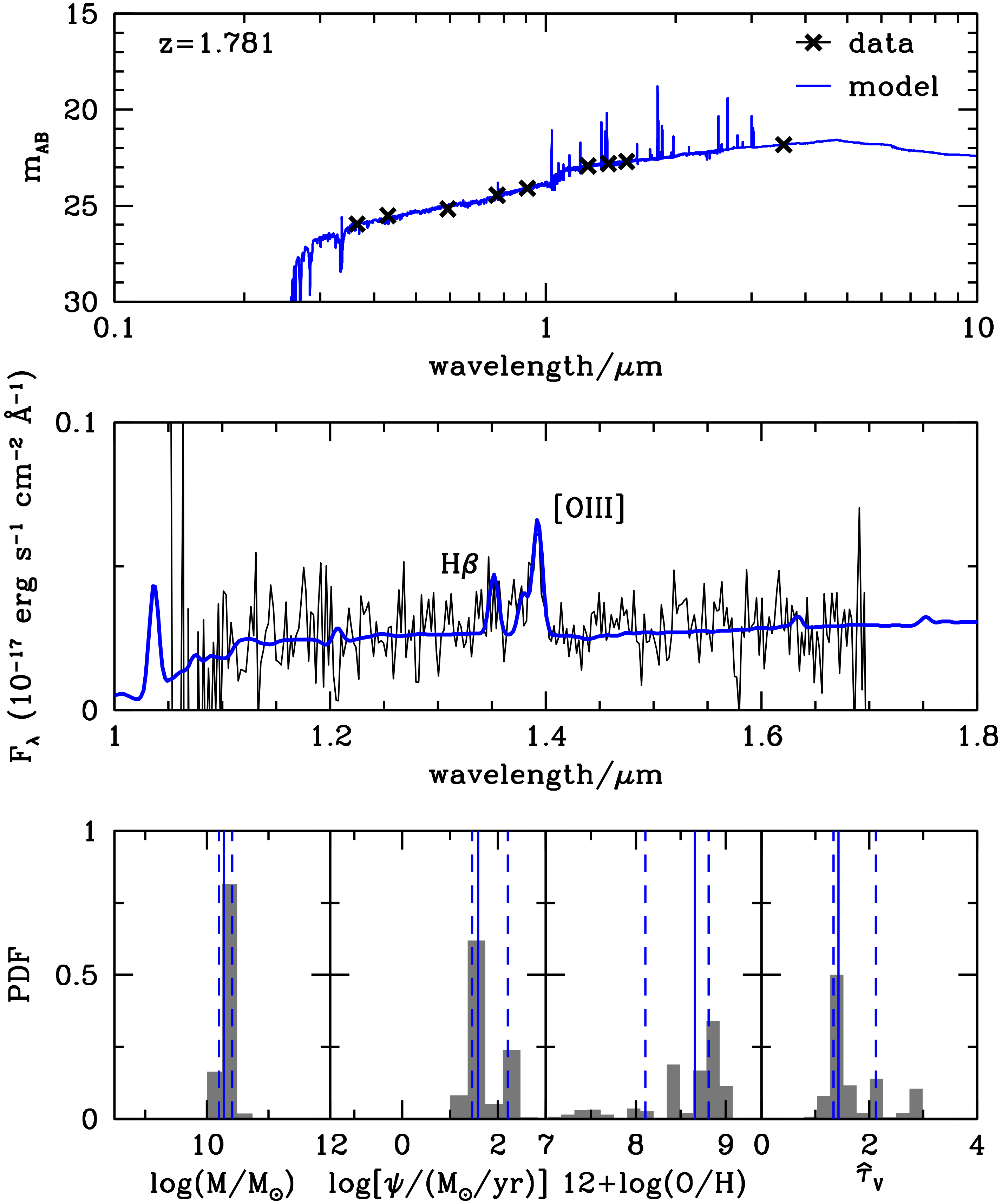




contamination by nebular emission can be important even at 'moderate' redshifts!

[see also e.g. 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]

constraining the physical properties from observed SEDs

SED fitting: Bayesian Method

Kauffmann+2003, Gallazzi+2005, Salim+2007, MAGPHYS (da Cunha+2008)

MCMC: e.g. BEAGLE (Chevallard & Charlot 2016), CIGALE, Prospector

MODEL PARAMETERS → PRIOR DISTRIBUTIONS → STOCHASTIC MODEL LIBRARIES

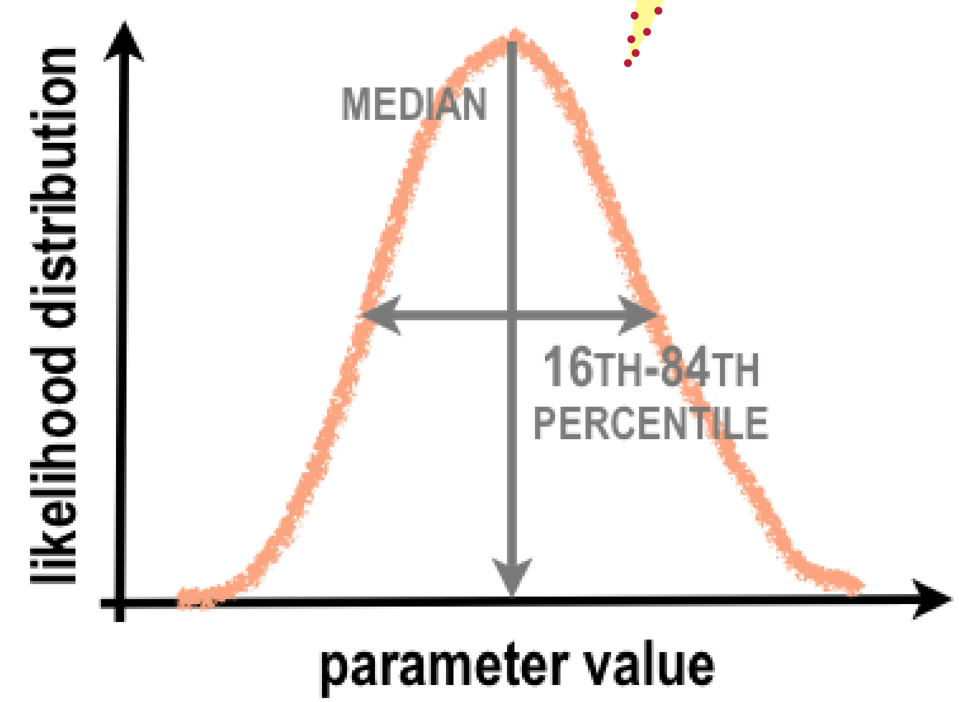
↓

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 →

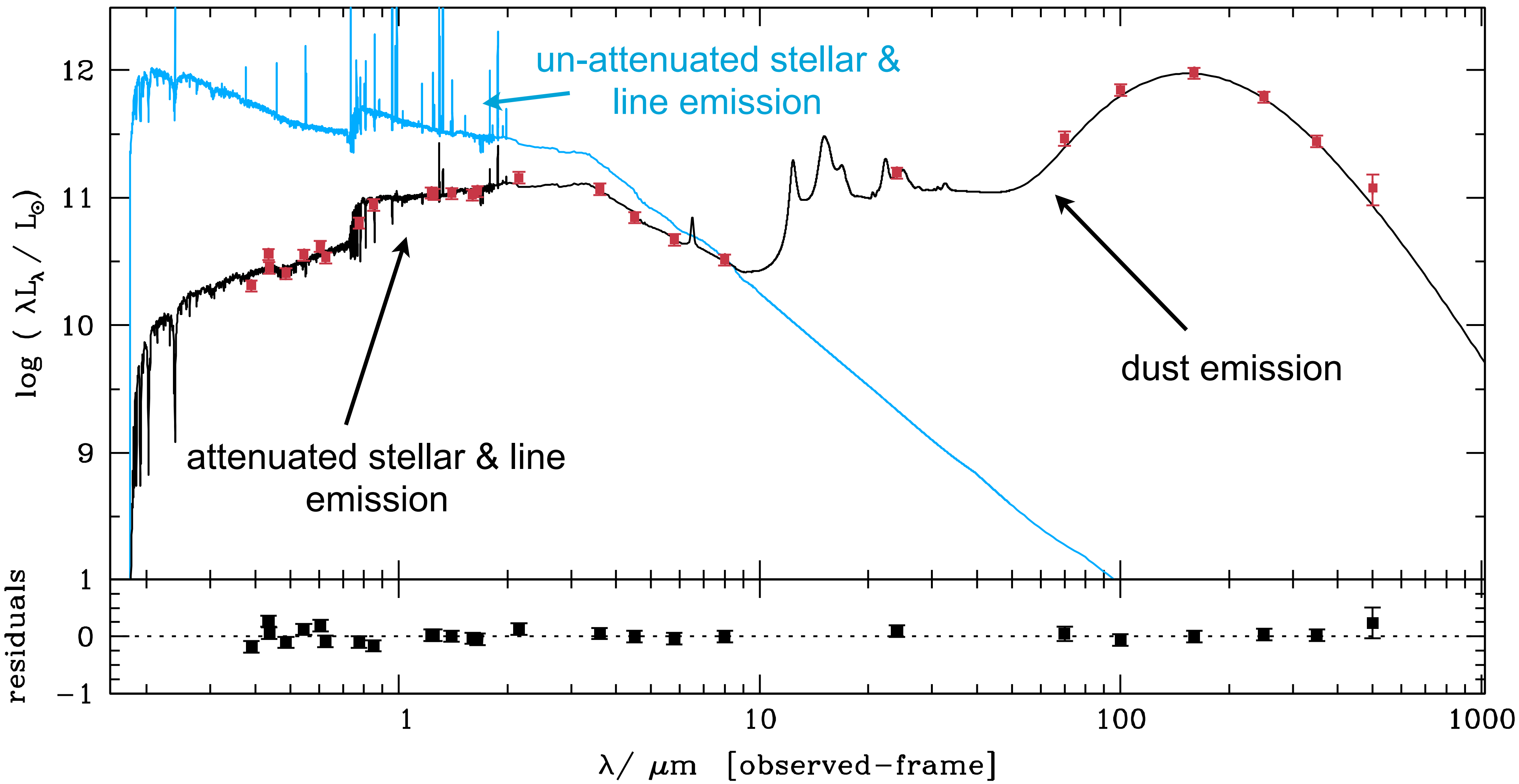


robust parameter estimate + error bar!

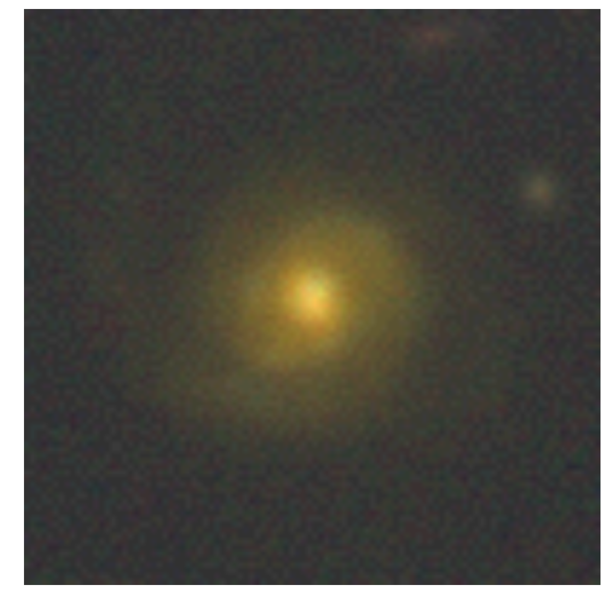
GOODS
J123646.67+620833.3

z_{spec}=0.971

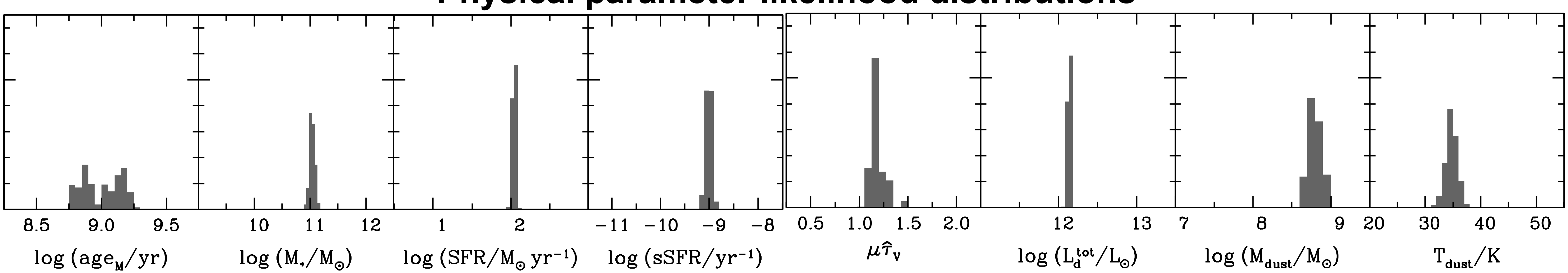
MAGPHYS spectral energy distribution fit



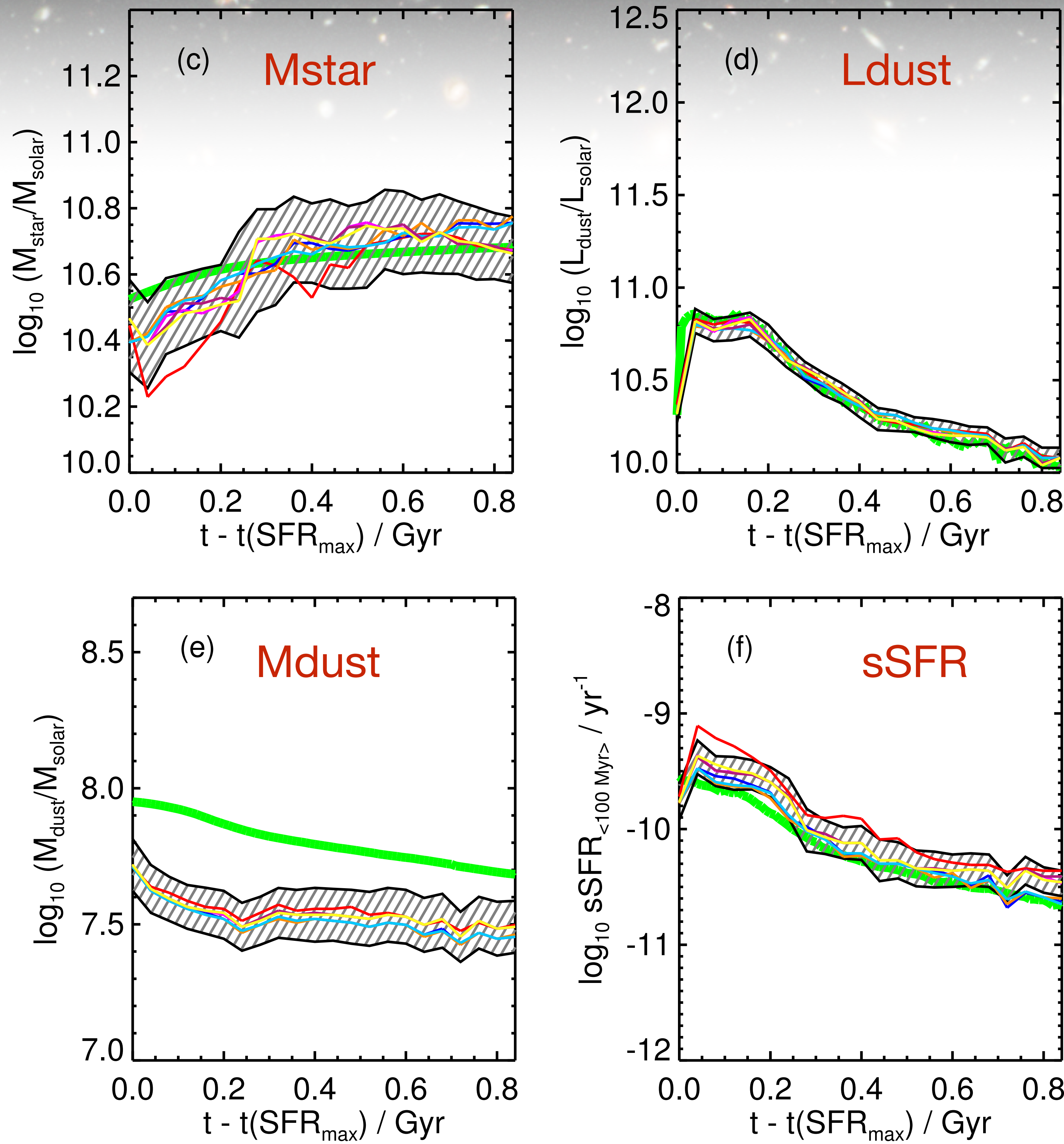
HST *VJH* composite



Physical parameter likelihood distributions



Testing MAGPHYS with hydro+RT simulations



green: "true value"

colours/shade: MAGPHYS, different viewing angles

MAGPHYS recovers the physical parameters well for different viewing angles with smooth time step variation. 😊

Hayward & Smith 2015

Spectral models for the JWST era

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  Rotation and multiplicity change the UV emission of young massive stars
  The effect of TP-AGB stars - not as high as previously thought

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  We need to do better than tau-models at high redshift

- **Nebular emission**
  Include self-consistently in the SEDs (photo-ionization models)
  Important to interpret spectra & contamination of broad-band photometry

- **Dust attenuation & dust infrared emission**
  Model dust attenuation and emission self-consistently
  Dust evolution at high redshift: complementarity with ALMA

- **Modern fitting techniques**
  Bayesian fitting to account for degeneracies, marginalise over nuisance parameters, explore parameter space, etc.

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