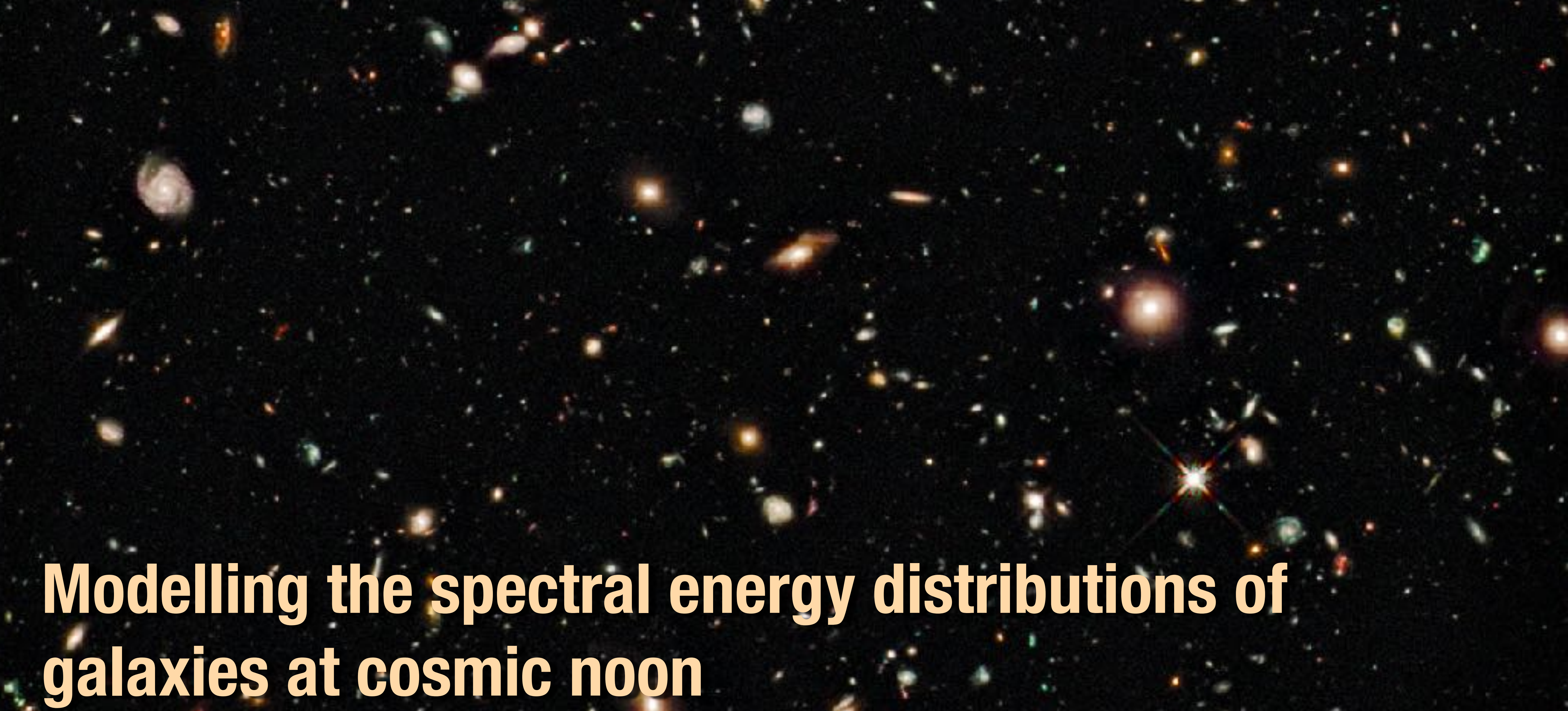


Modelling the spectral energy distributions of galaxies at cosmic noon

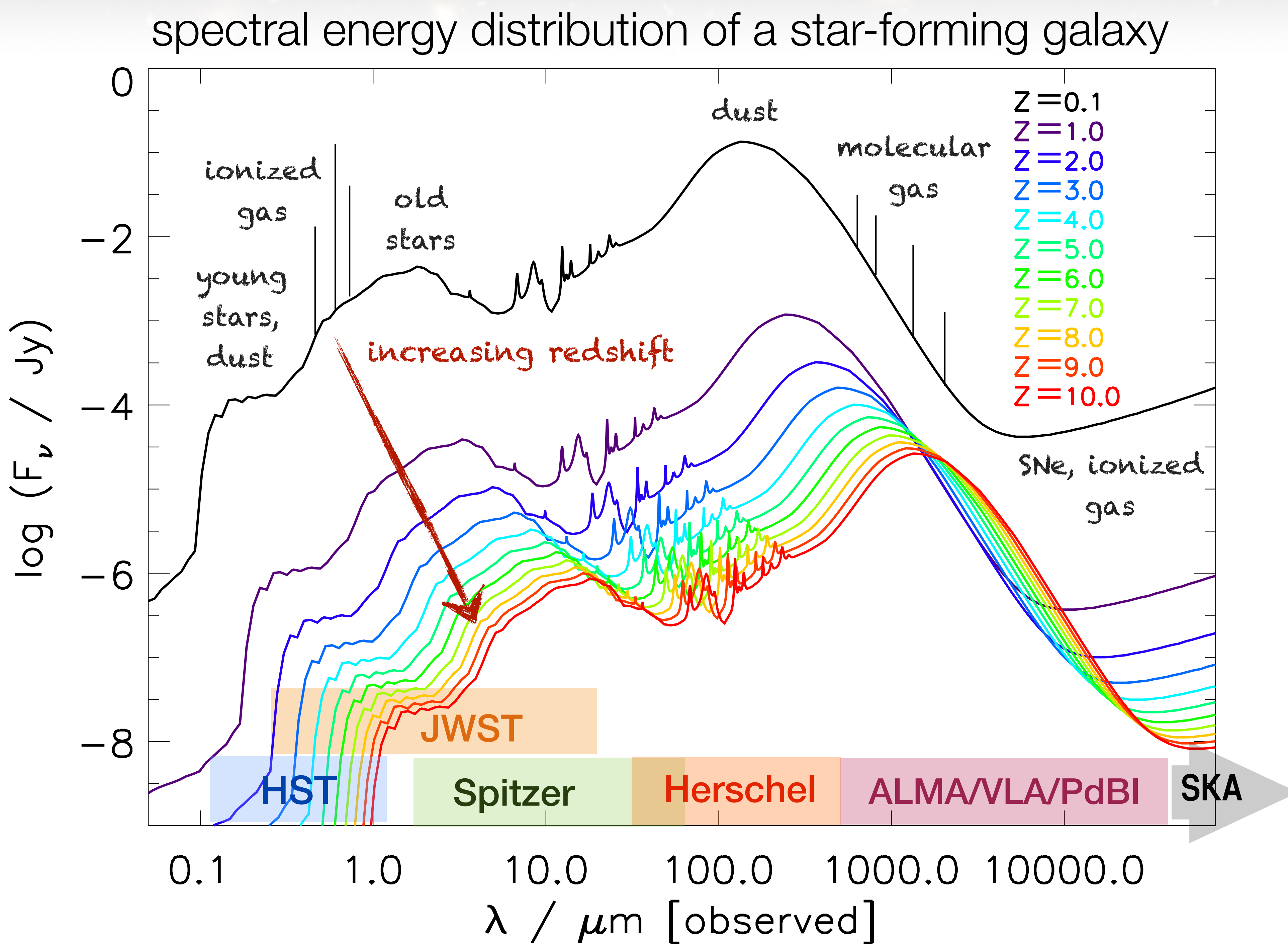
Elisabete da Cunha

ARC Future Fellow • Australian National University

Australian Government
Australian Research Council

Australian National University

Spectral models: an essential tool for galaxy evolution



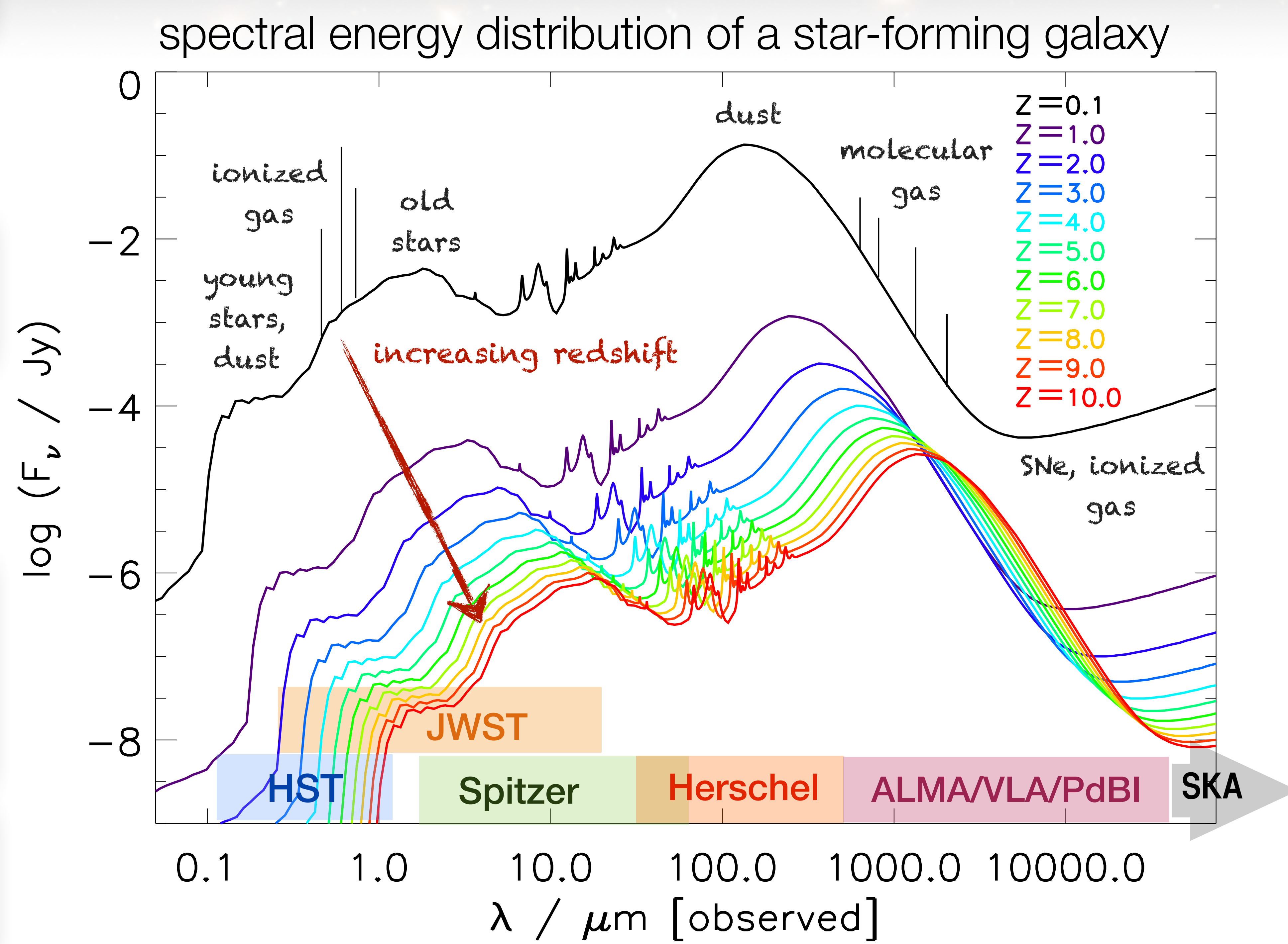
Spectral models: an essential tool for galaxy evolution

Observed UV, optical, IR emission

Spectral energy distribution model

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

Galaxy evolution models



Main ingredients for high-z galaxy SEDs

- **Emission by stellar populations**
  Evolution of stellar populations of different ages & metallicities
  Star formation histories

- **The interstellar medium: dust & ionized gas**
  Dust attenuation, self-consistent infrared emission
  Nebular emission & impact on spectral energy distributions

- **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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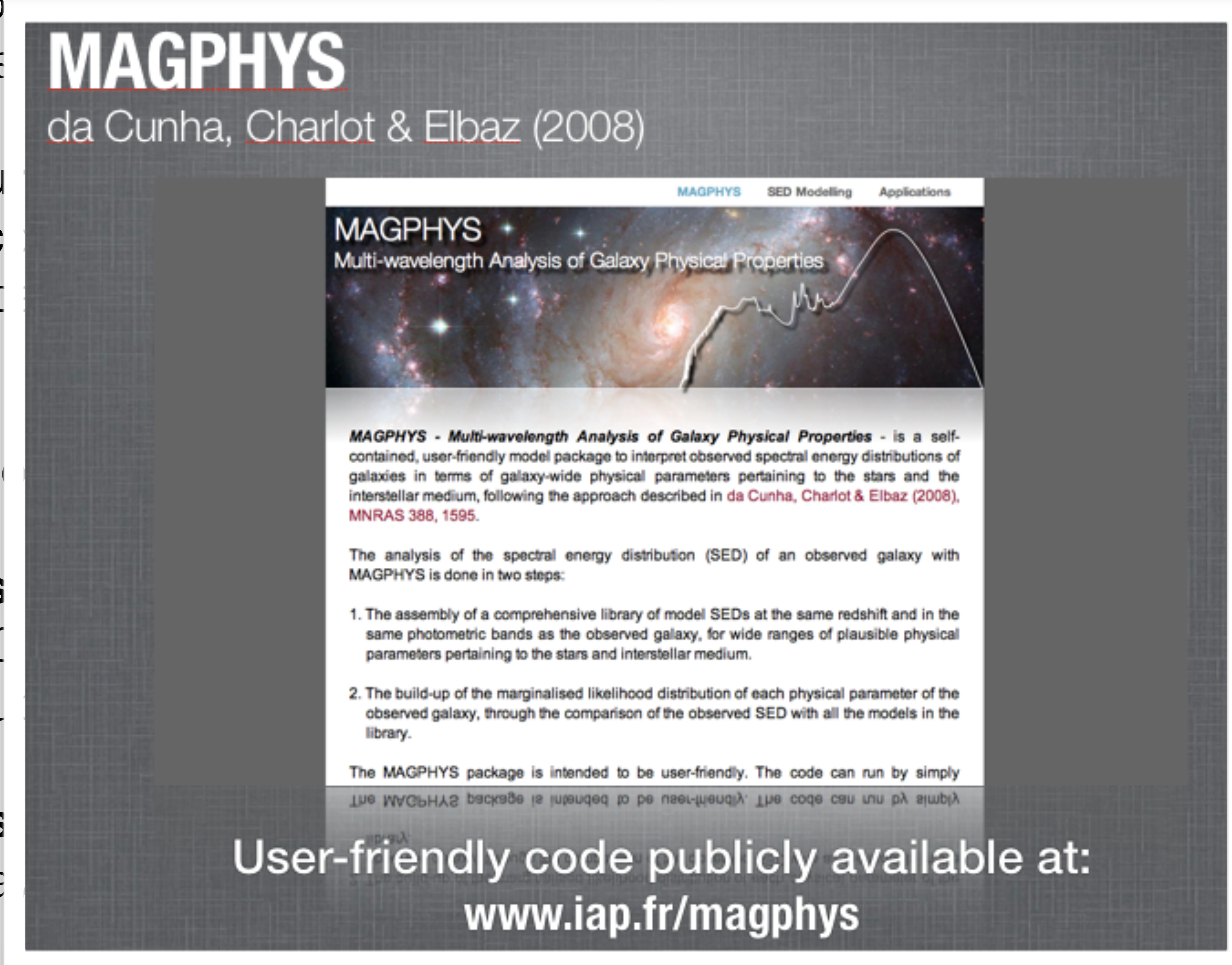
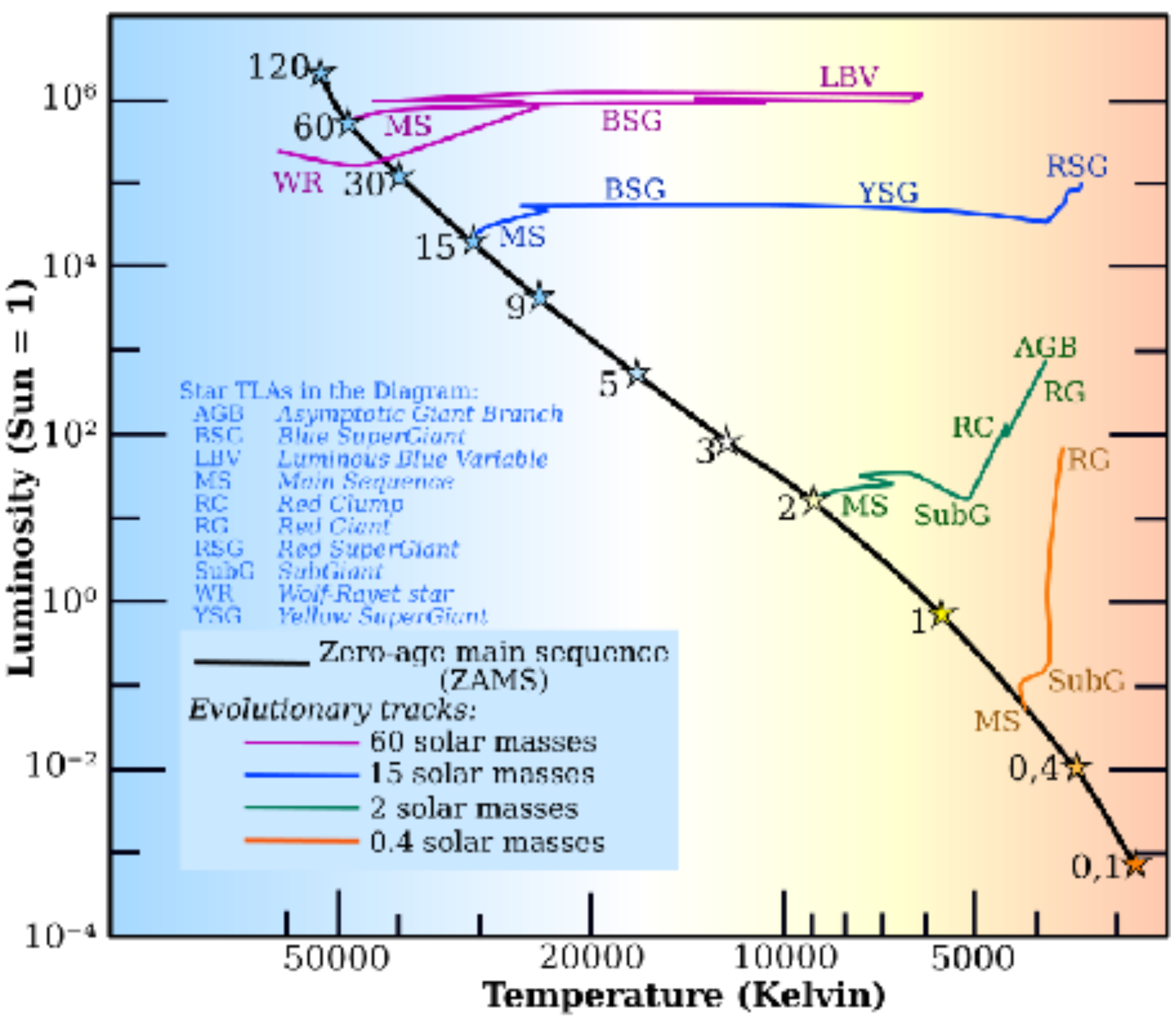


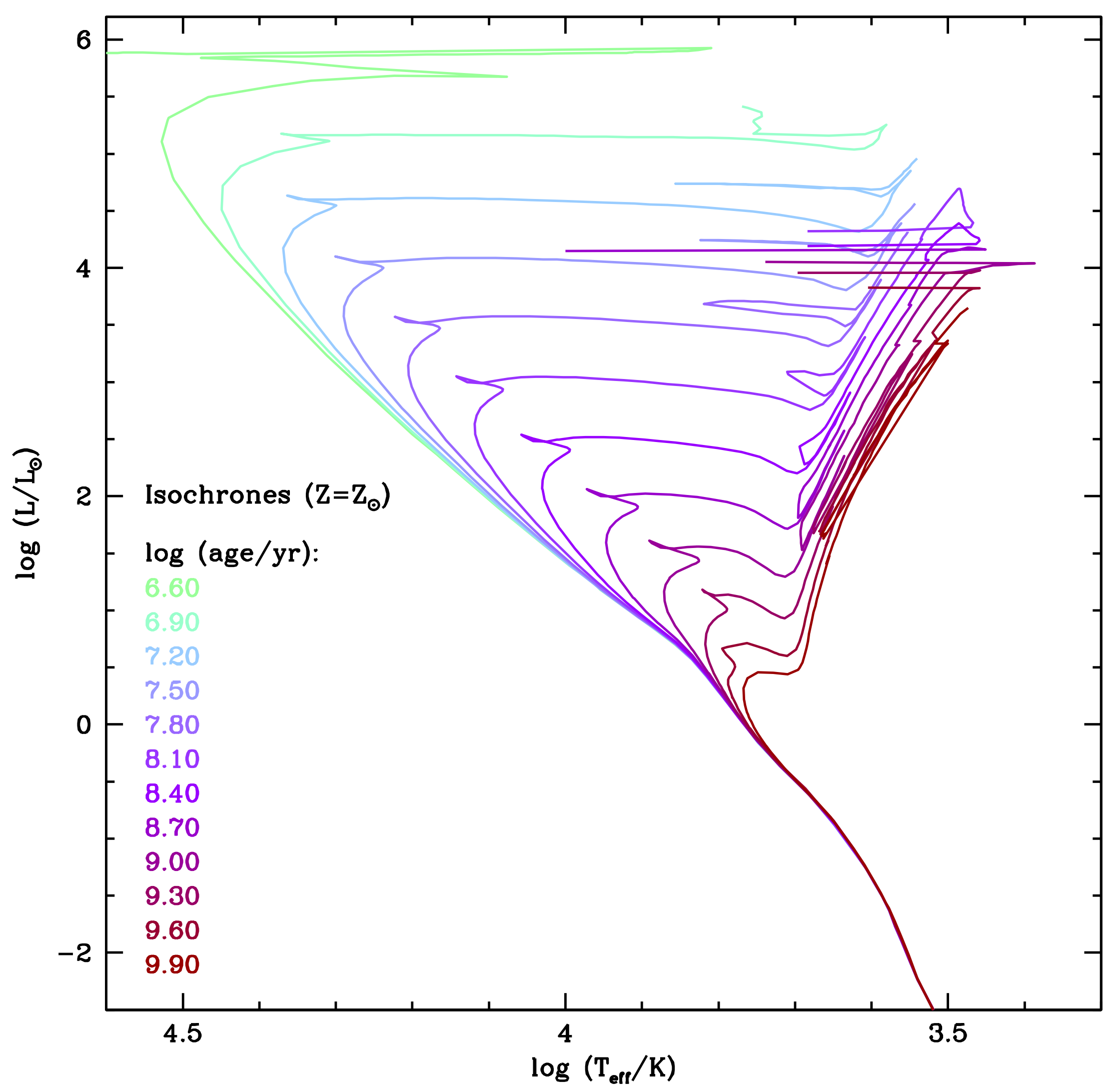
emission by stellar populations

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)

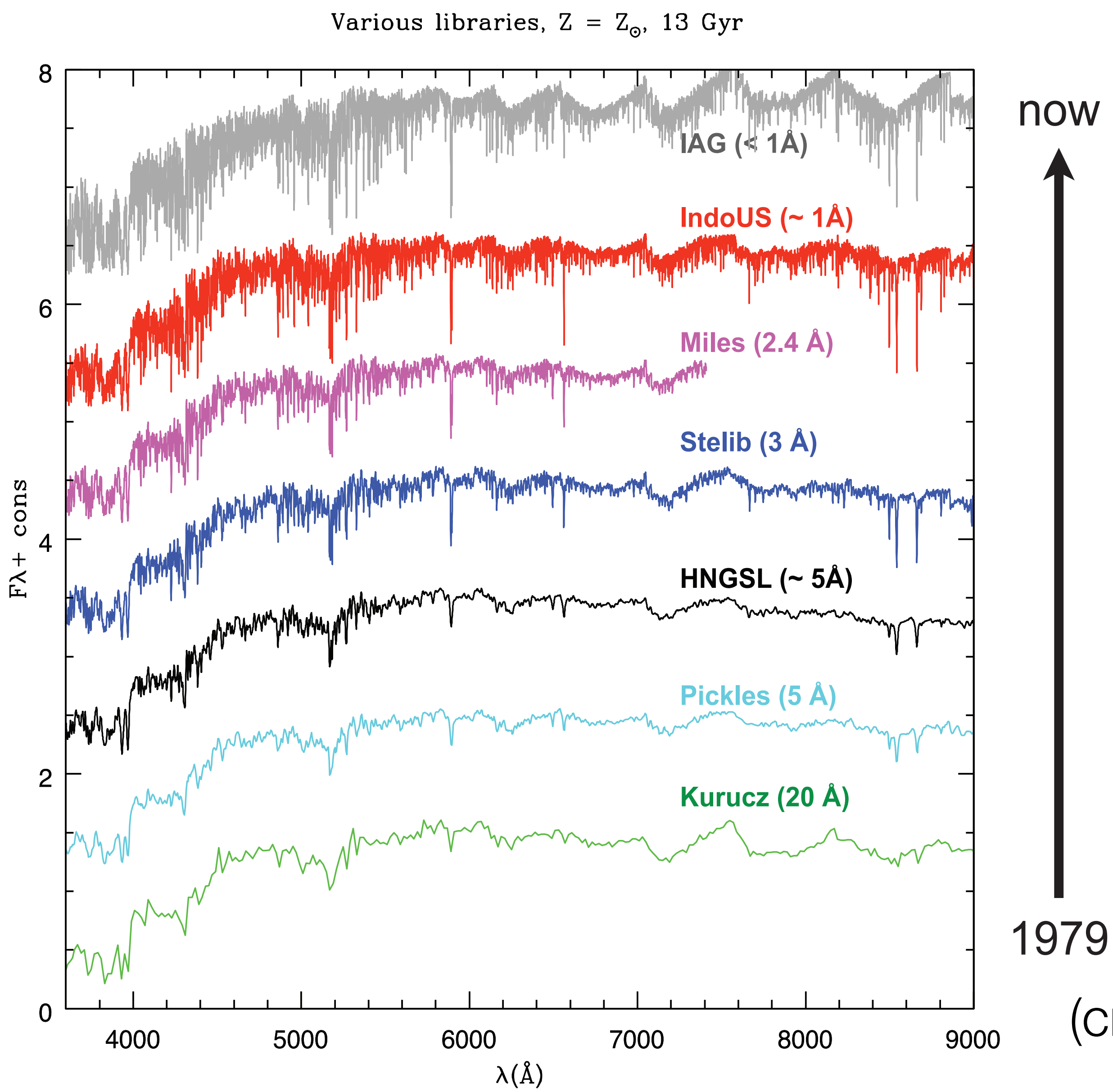
Spectral evolution of a simple stellar population

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.



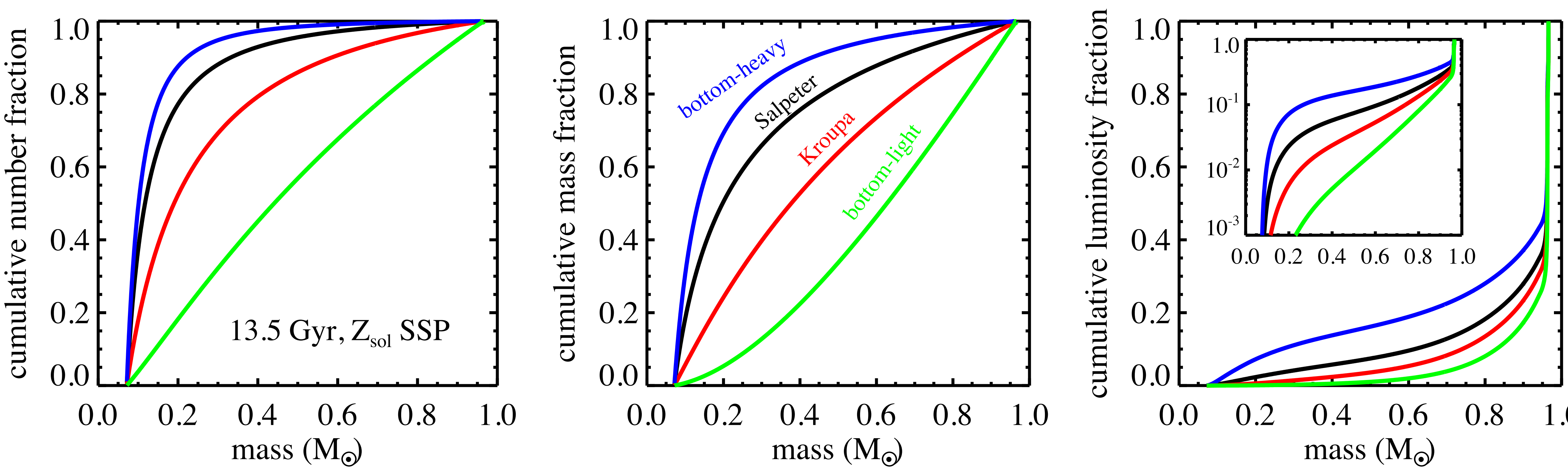
(credit: S. Charlot)

Spectral evolution of a simple stellar population

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

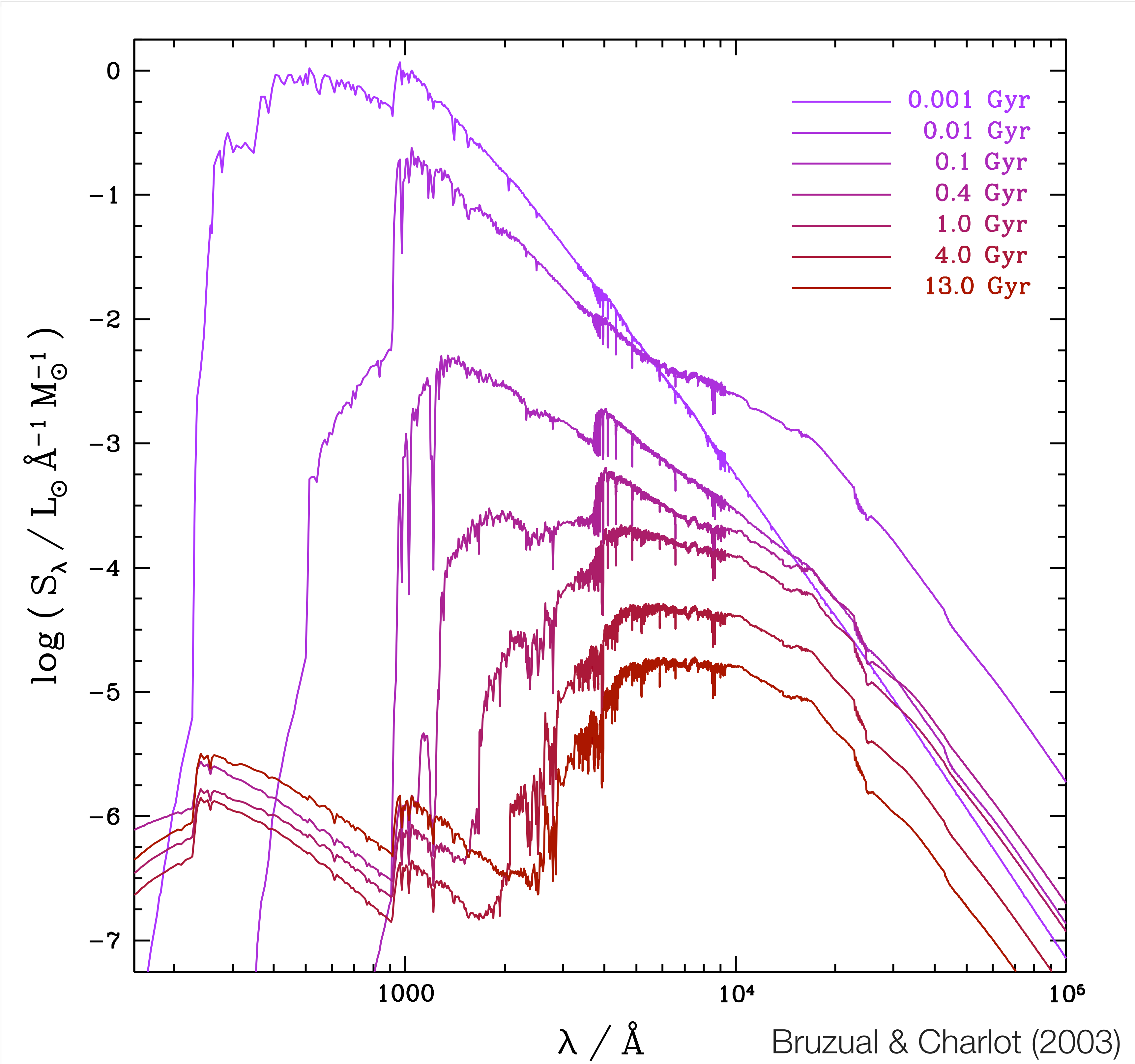
Spectral libraries
assign spectrum to a star of given mass, age and metallicity.

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

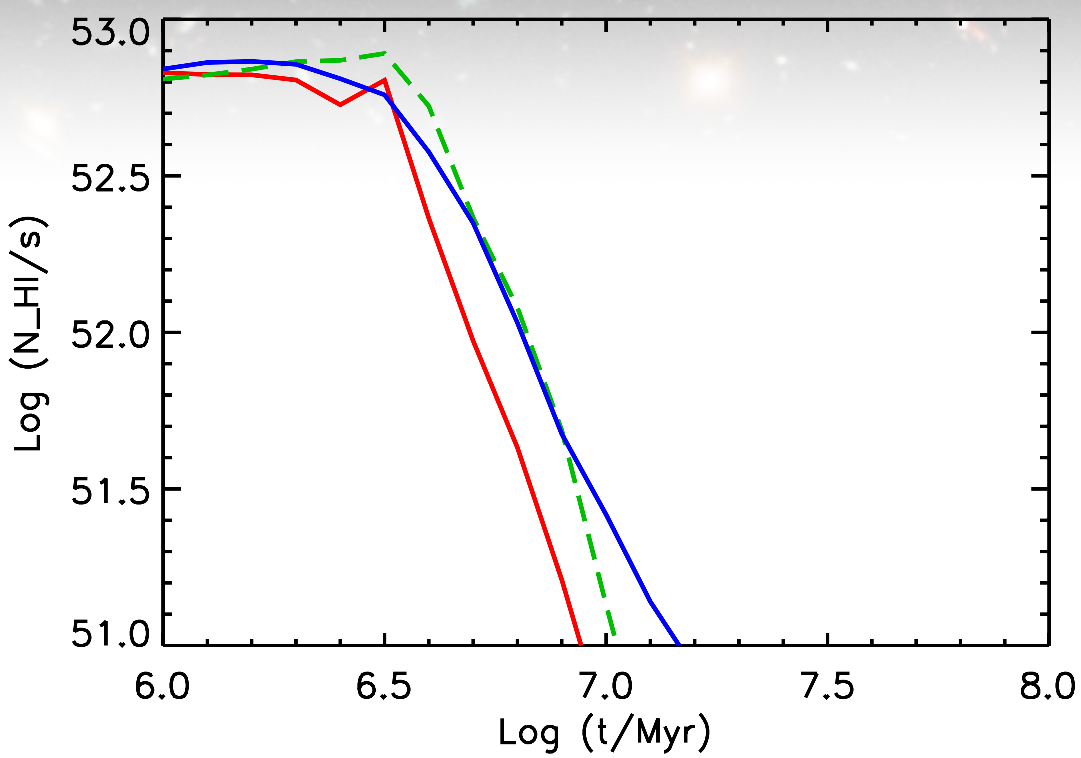
Impact of rotation & binaries on ionizing radiation

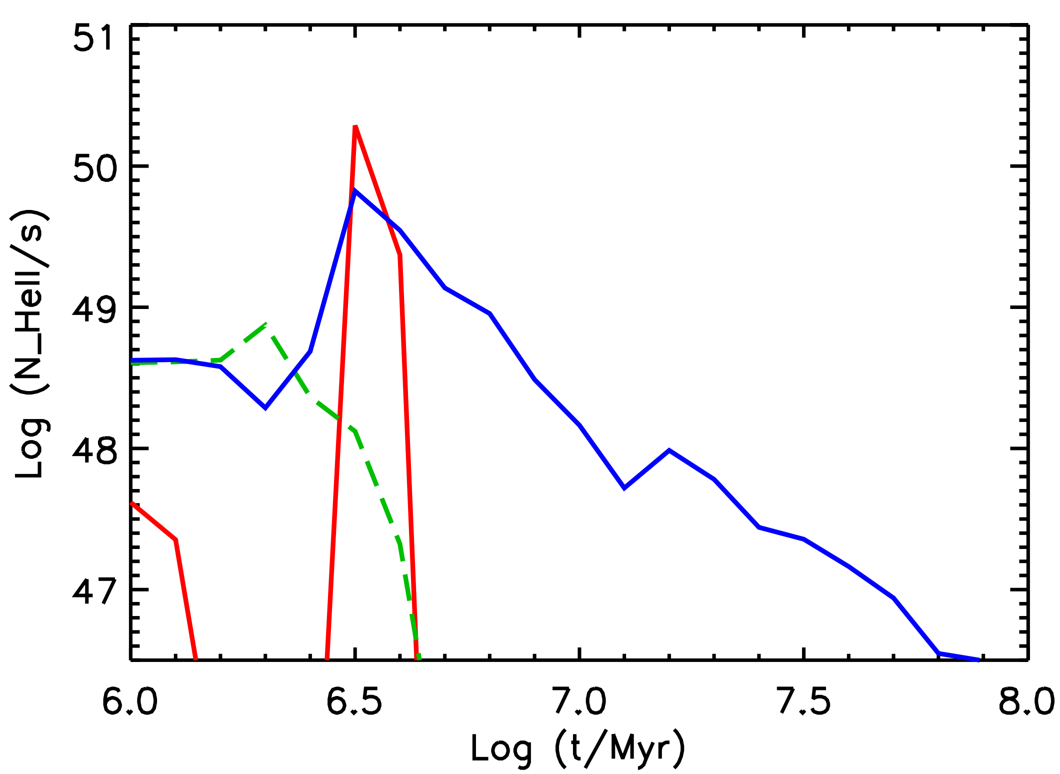
Low metallicity (Z=0.004)
10^6 M_{sun} SSP

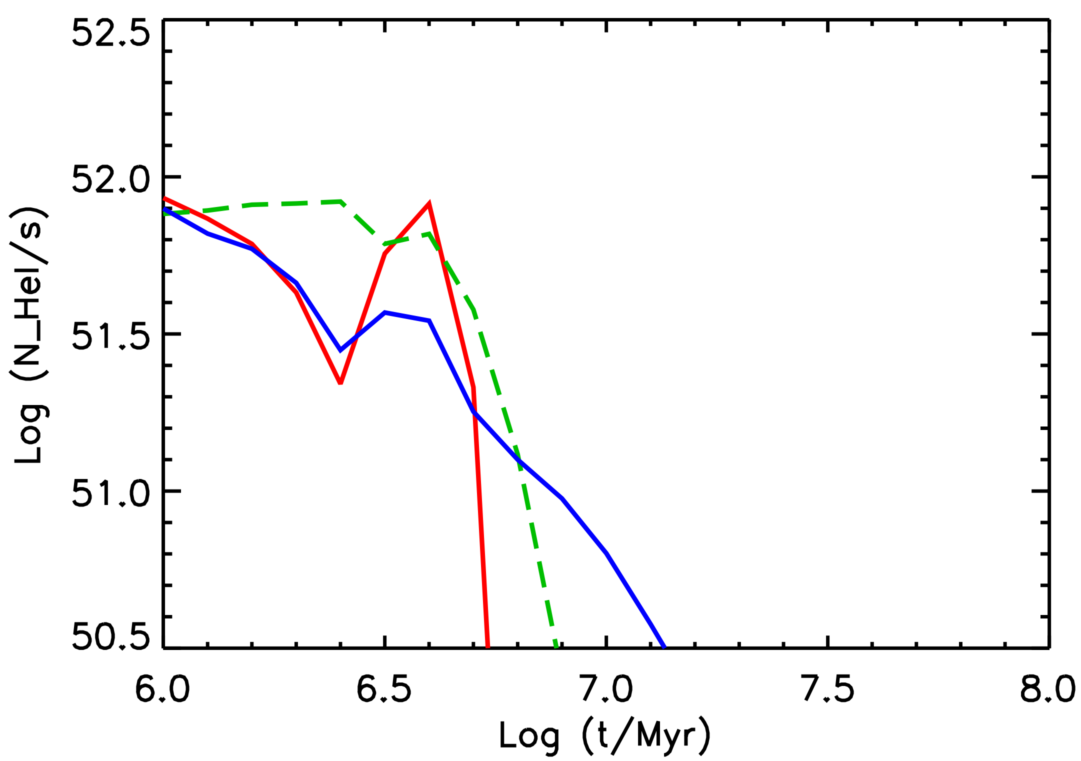
GALAXEV (Bruzual & Charlot 2003): single, non-rotating

Starburst 99 (Leitherer+2014): single, rotating

BPASS (Eldridge & Stanway 2012): interacting binaries







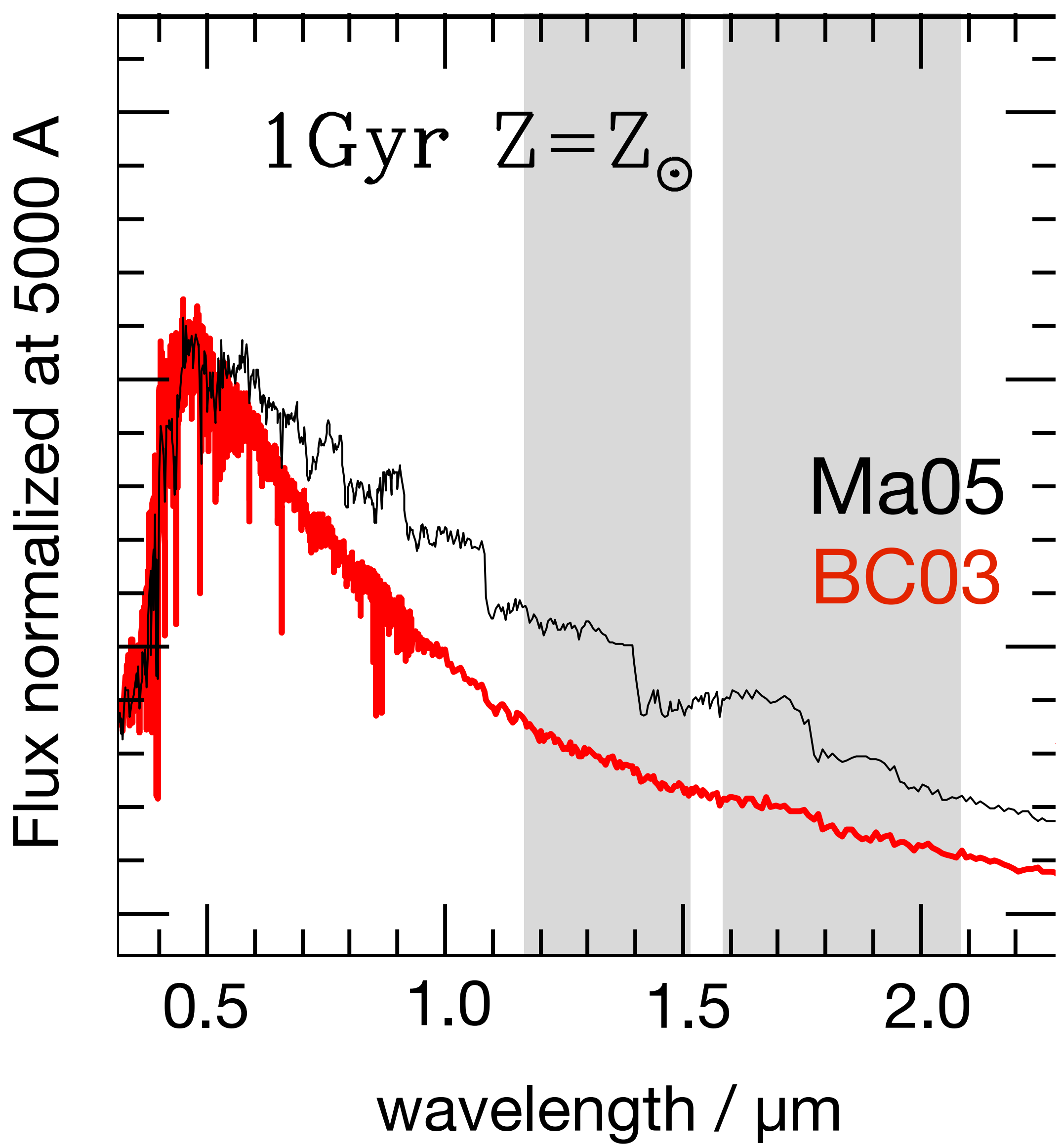
(adapted from Wofford+2016)

TP-AGB stars: a closer look

- Can be important for stellar populations with ages 0.5 to 1.5 Gyr

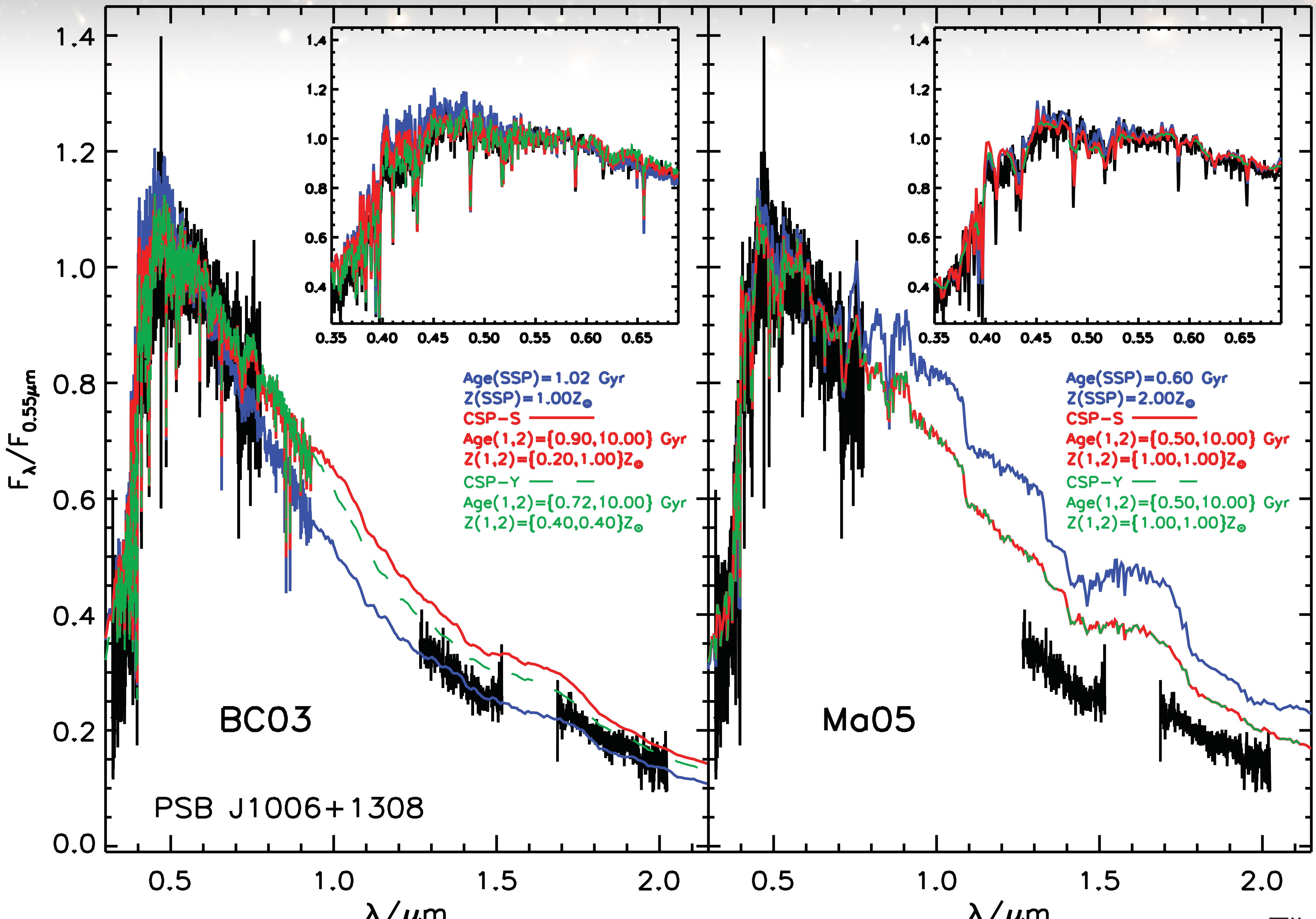
- Maraston (2005) models predicted NIR fluxes up to 3x higher than BC03 models, and also sharp absorption features at 1.1 - 1.8 μm

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



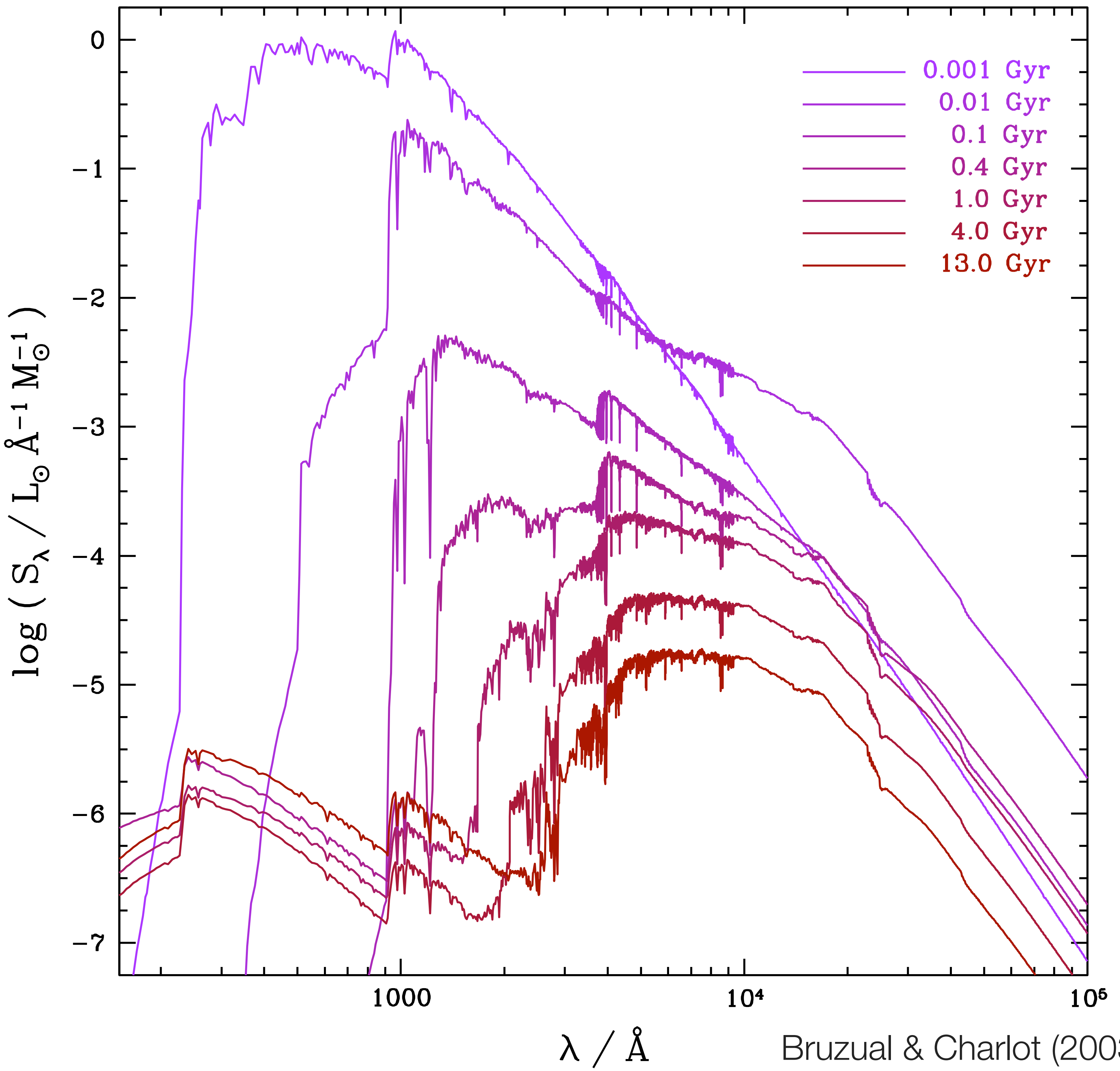
Zibetti+2012:
ISAAC spectroscopic follow-up of a sample of z~0.2 post-starburst galaxies (where contribution by TP-AGB stars should be maximal)

TP-AGB stars: a closer look



Zibetti+2012

Spectral evolution of a simple stellar population

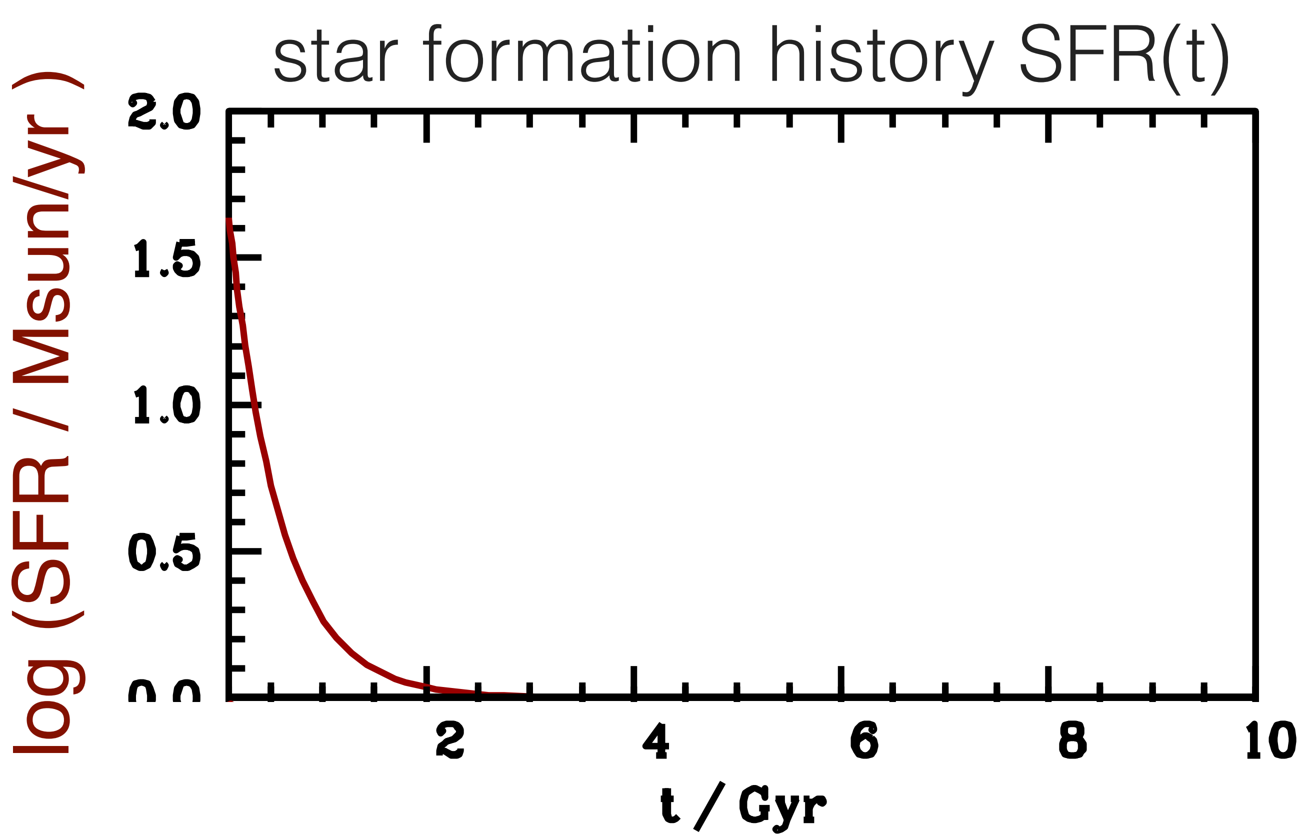


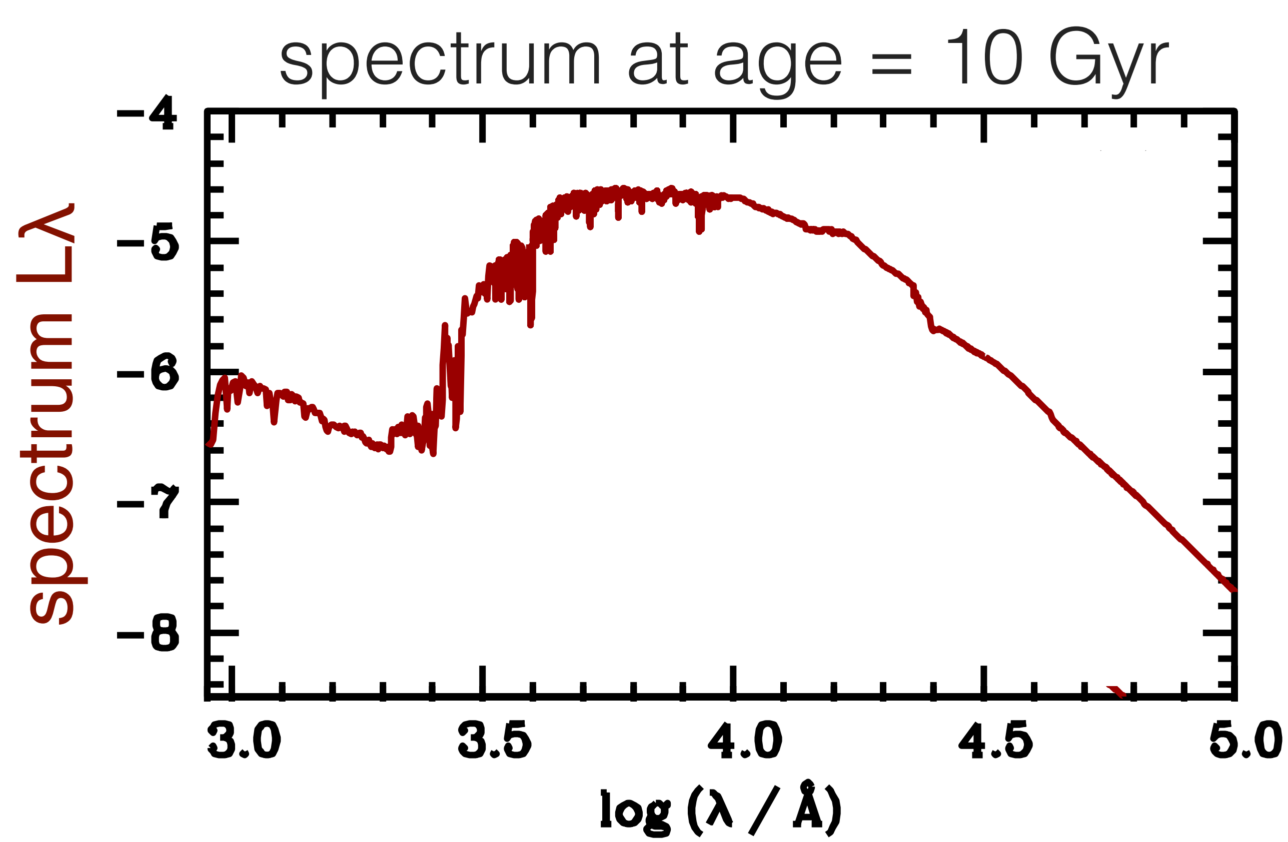
Bruzual & Charlot (2003)

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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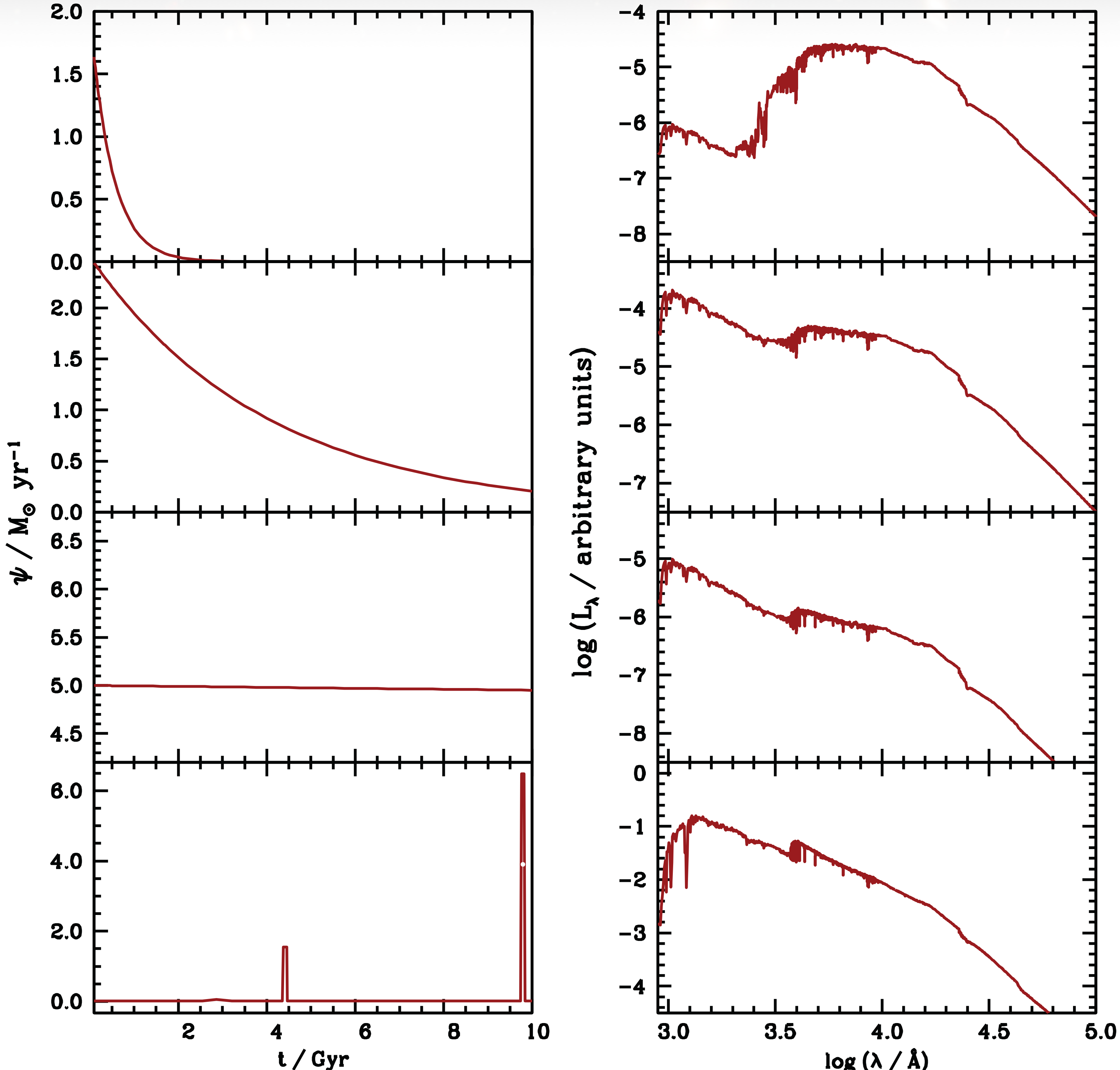
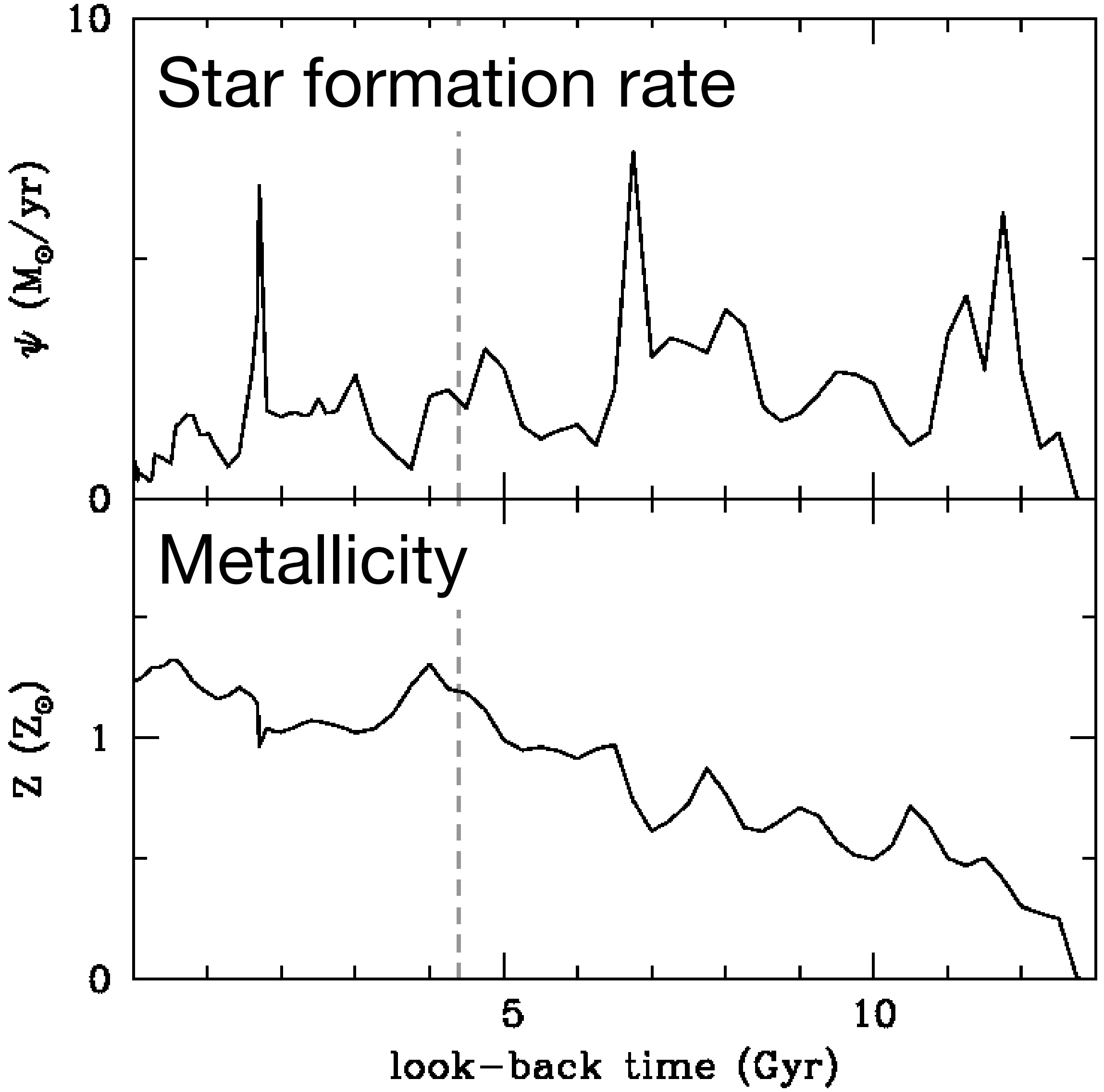


Main parameters:

- 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

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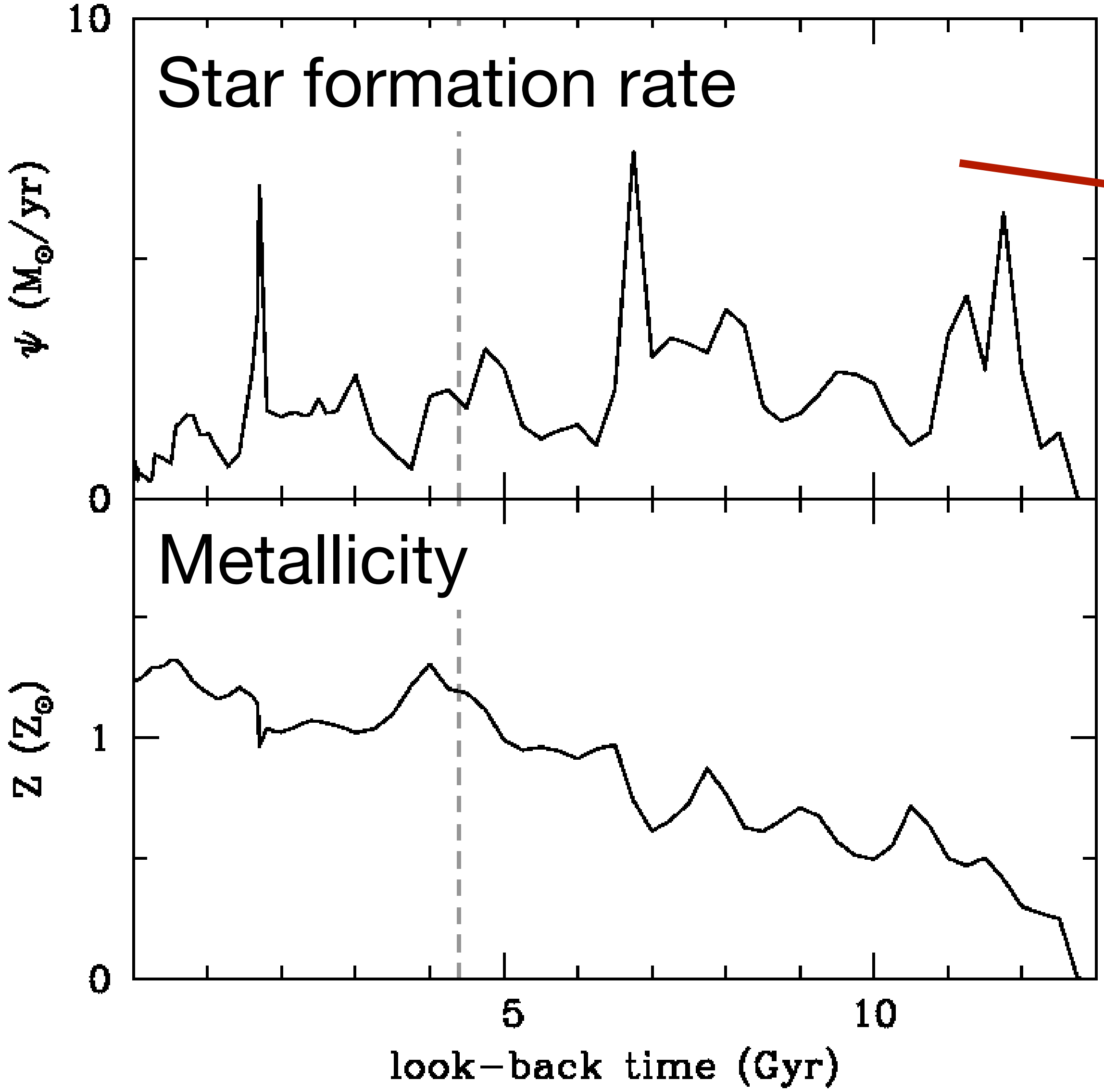
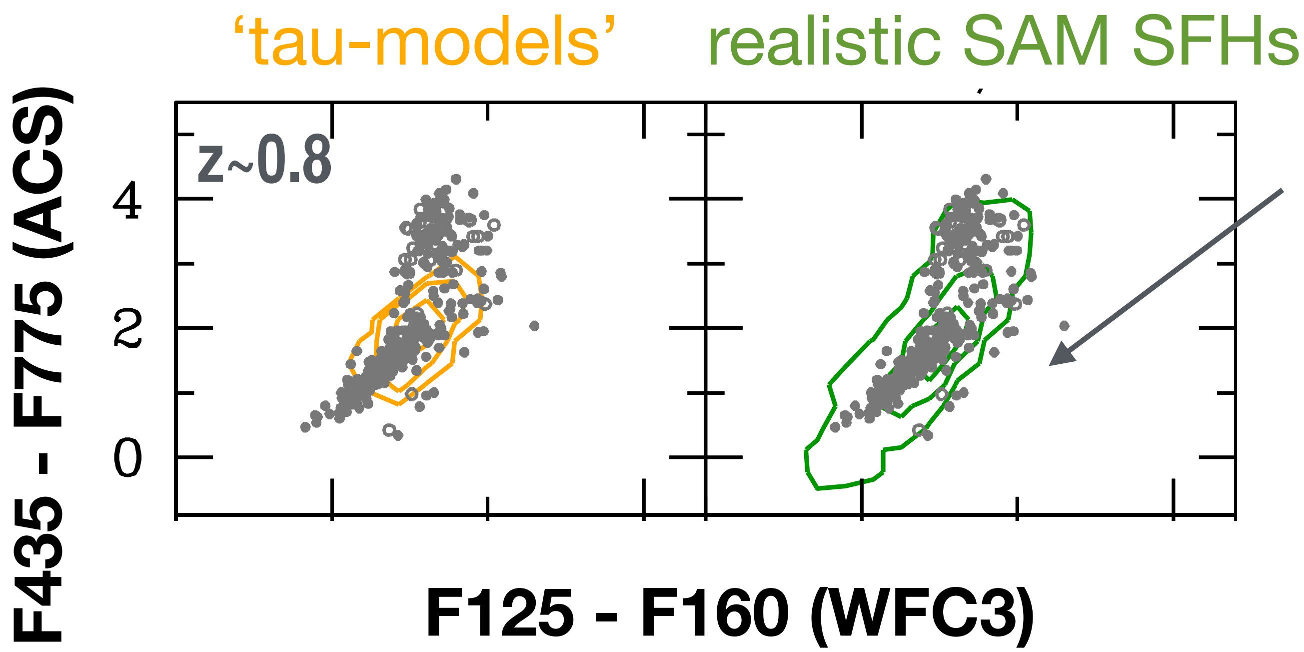


Pacifici+2012

Looks nothing like a continuous tau-model!

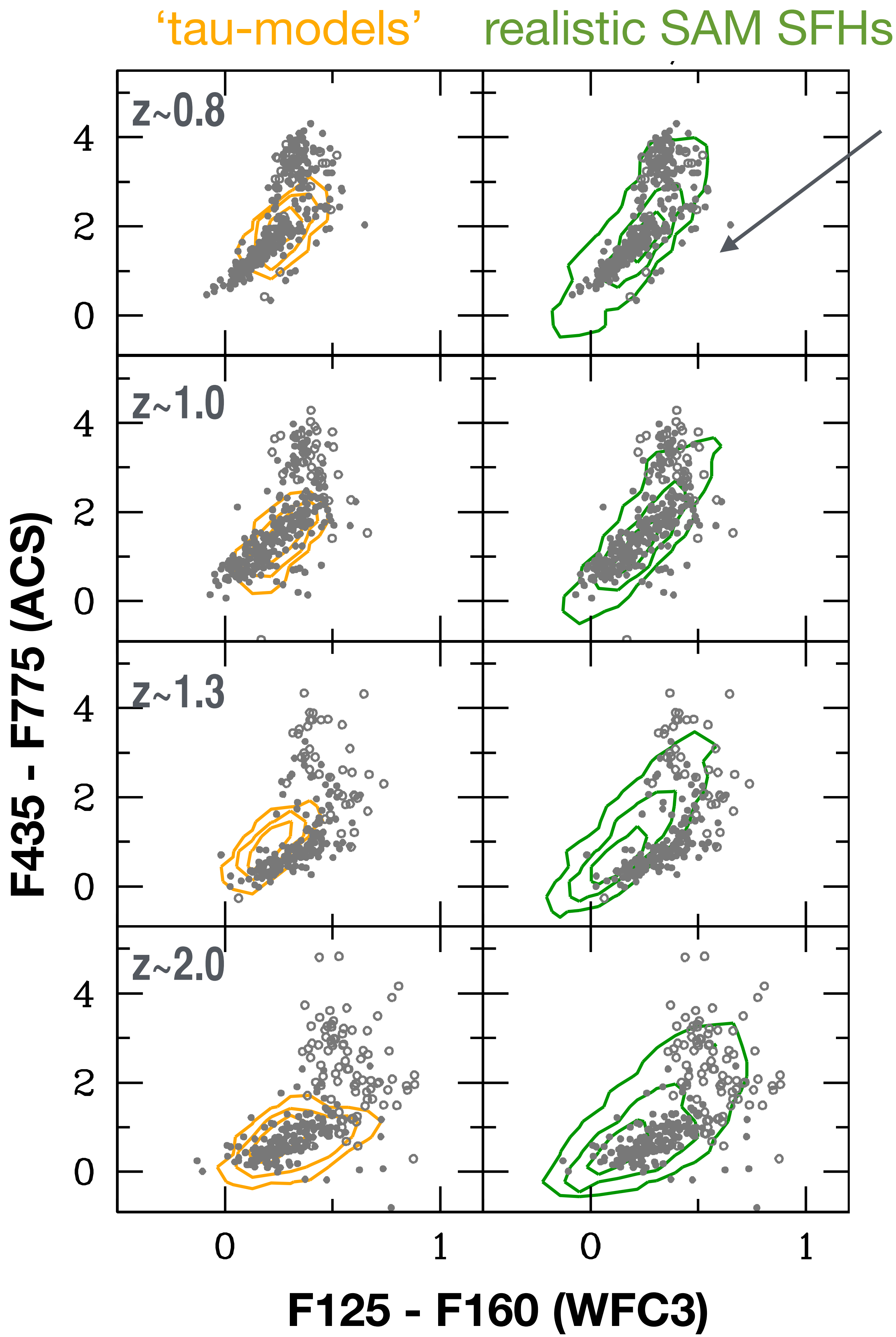
Need to include increasing SFHs for of high-redshift galaxies.

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



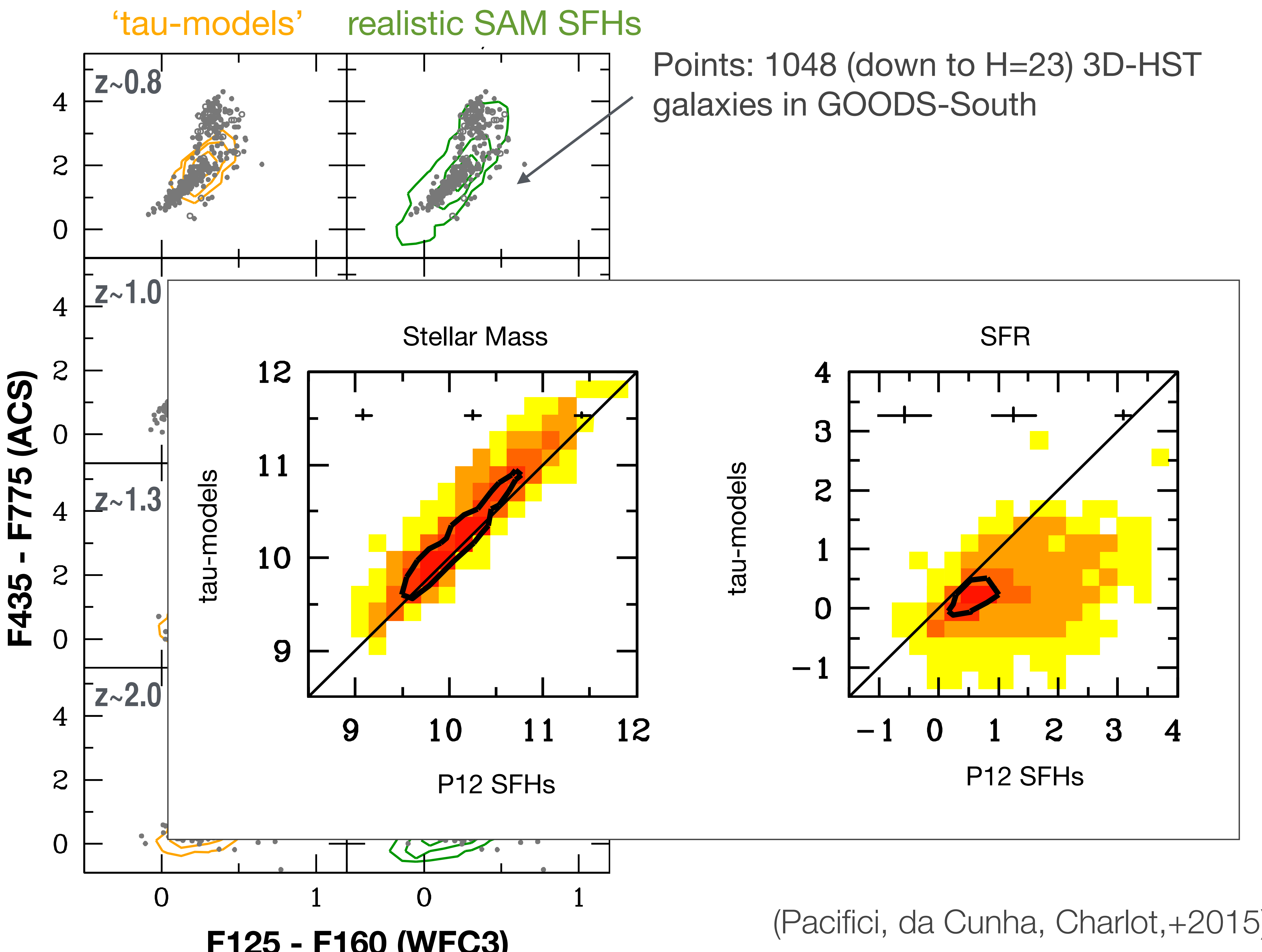
Points: 1048 (down to H=23) 3D-HST galaxies in GOODS-South

(Pacifici, da Cunha, Charlot,+2015)

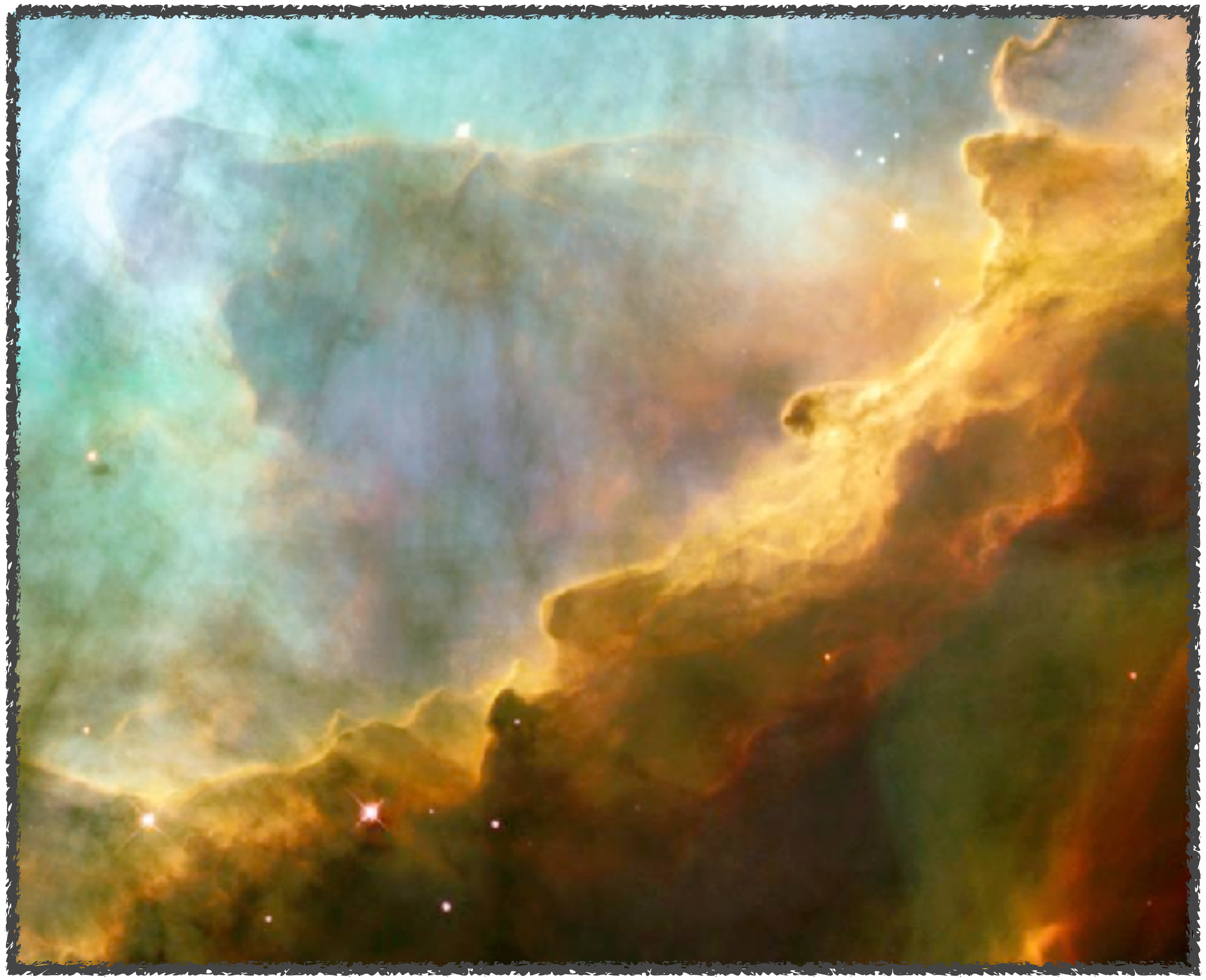


We need complex (realistic) SFHs to reproduce the observed HST colours of galaxies!

(Pacifici, da Cunha, Charlot,+2015)



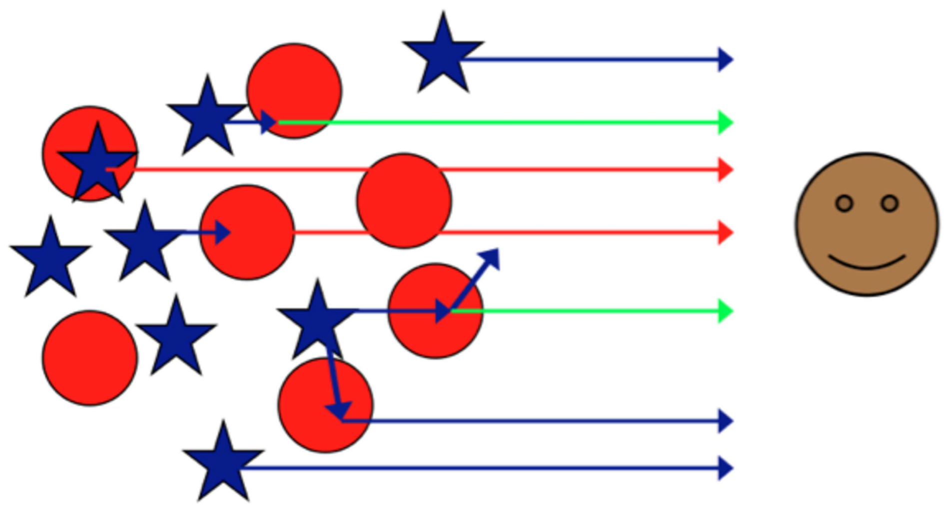
'tau-models'
realistic SAM SFHs
Points: 1048 (down to H=23) 3D-HST galaxies in GOODS-South
z~0.8
z~1.0
z~1.3
z~2.0
F435 - F775 (ACS)
F125 - F160 (WFC3)
Stellar Mass
SFR
tau-models
P12 SFHs
(Pacifici, da Cunha, Charlot,+2015)

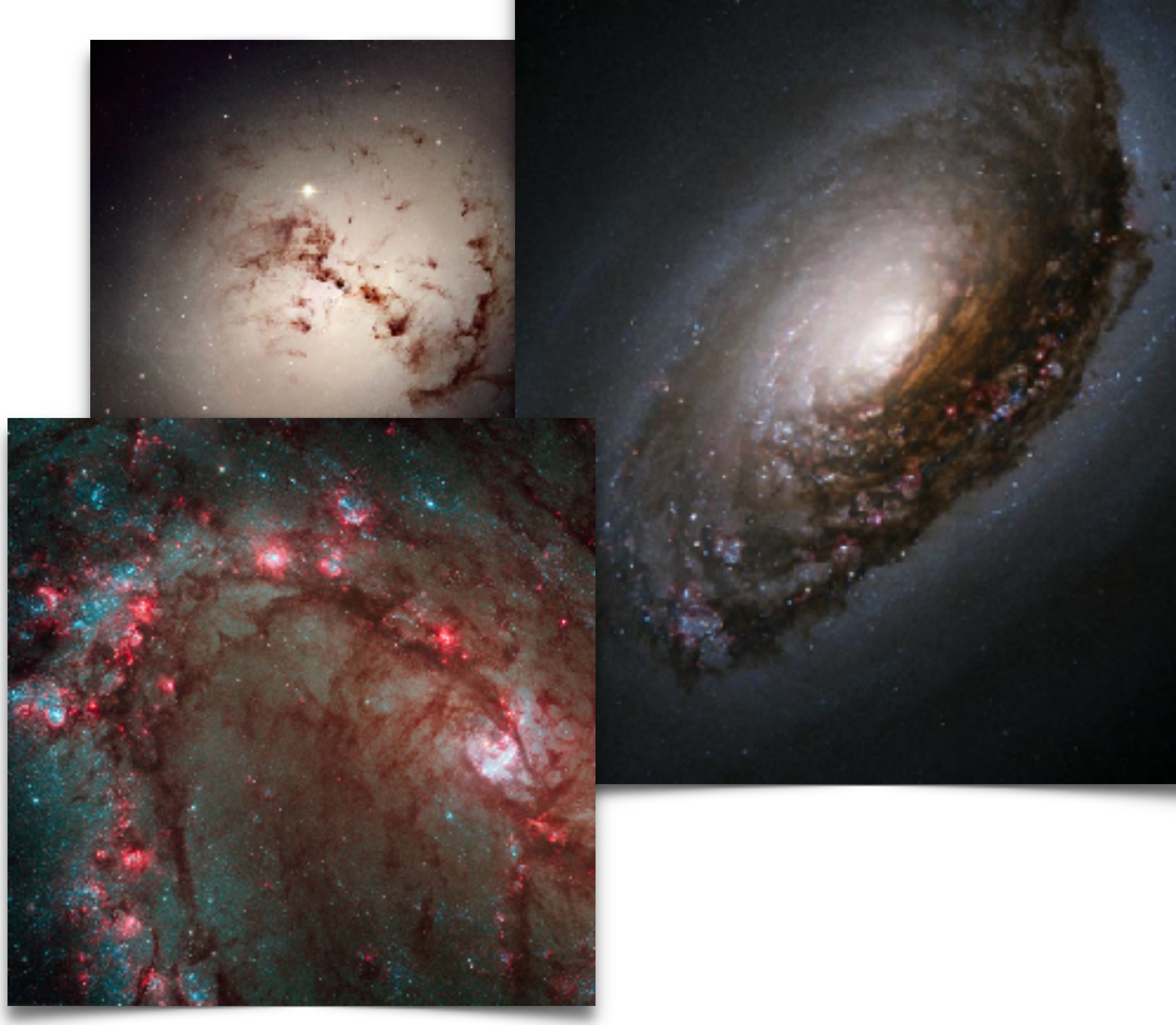


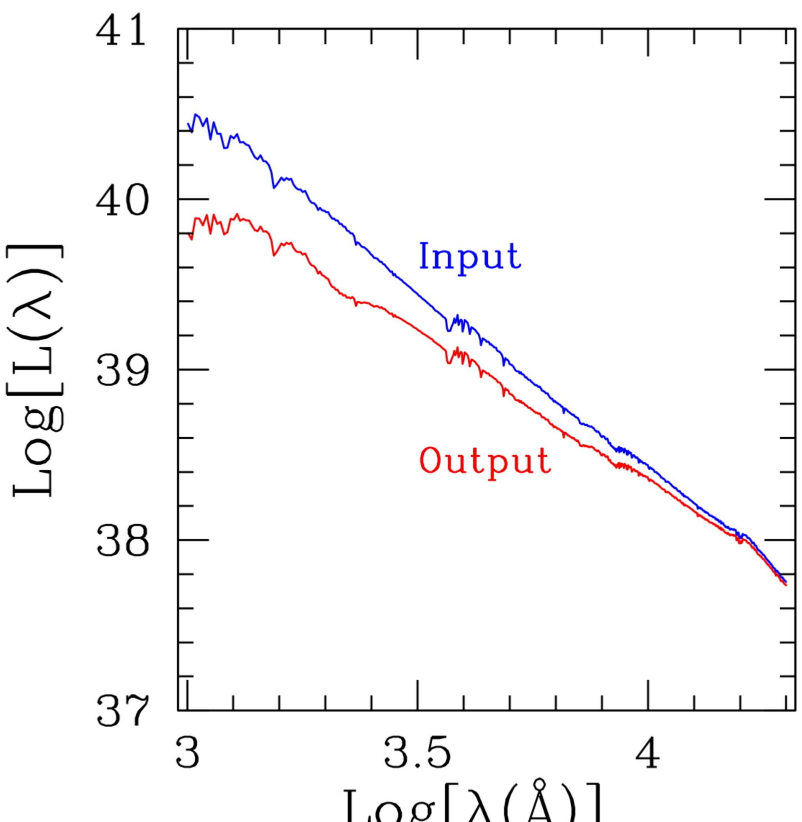
the interstellar medium: transfer through dust & gas

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.







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

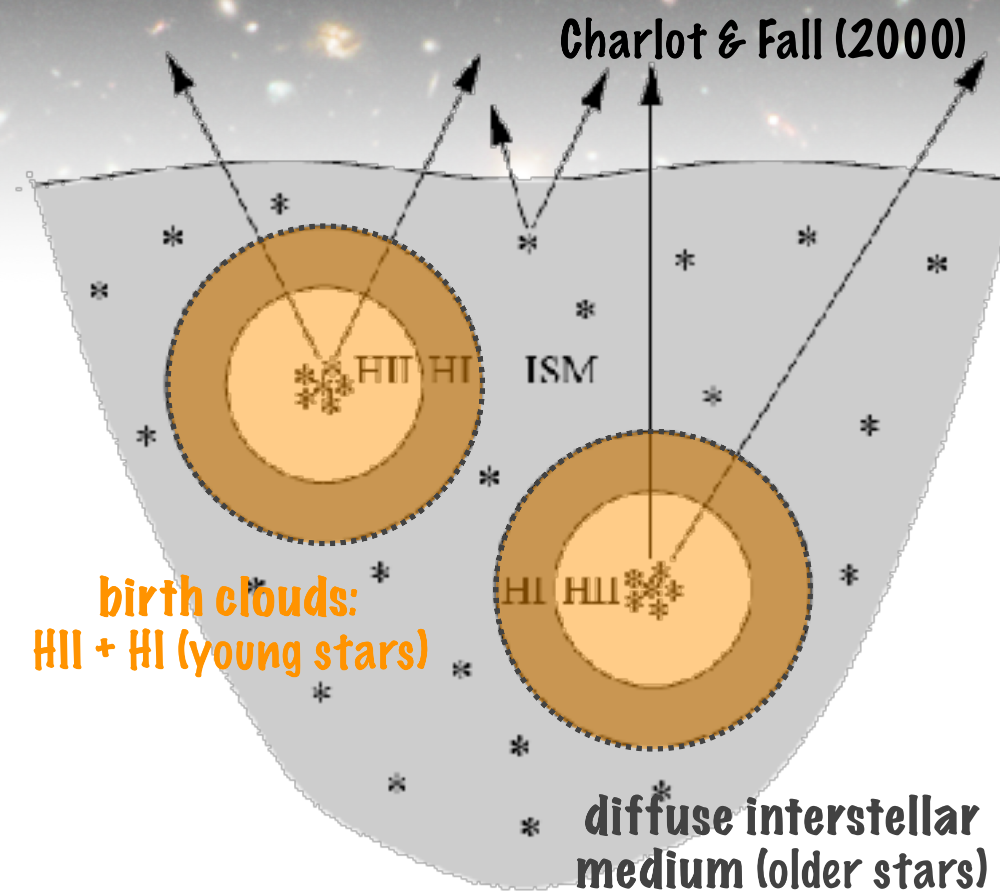
Dust attenuation optical depth:
depends on physical properties of the dust grains & stars/dust geometry

(after Calzetti 2012)

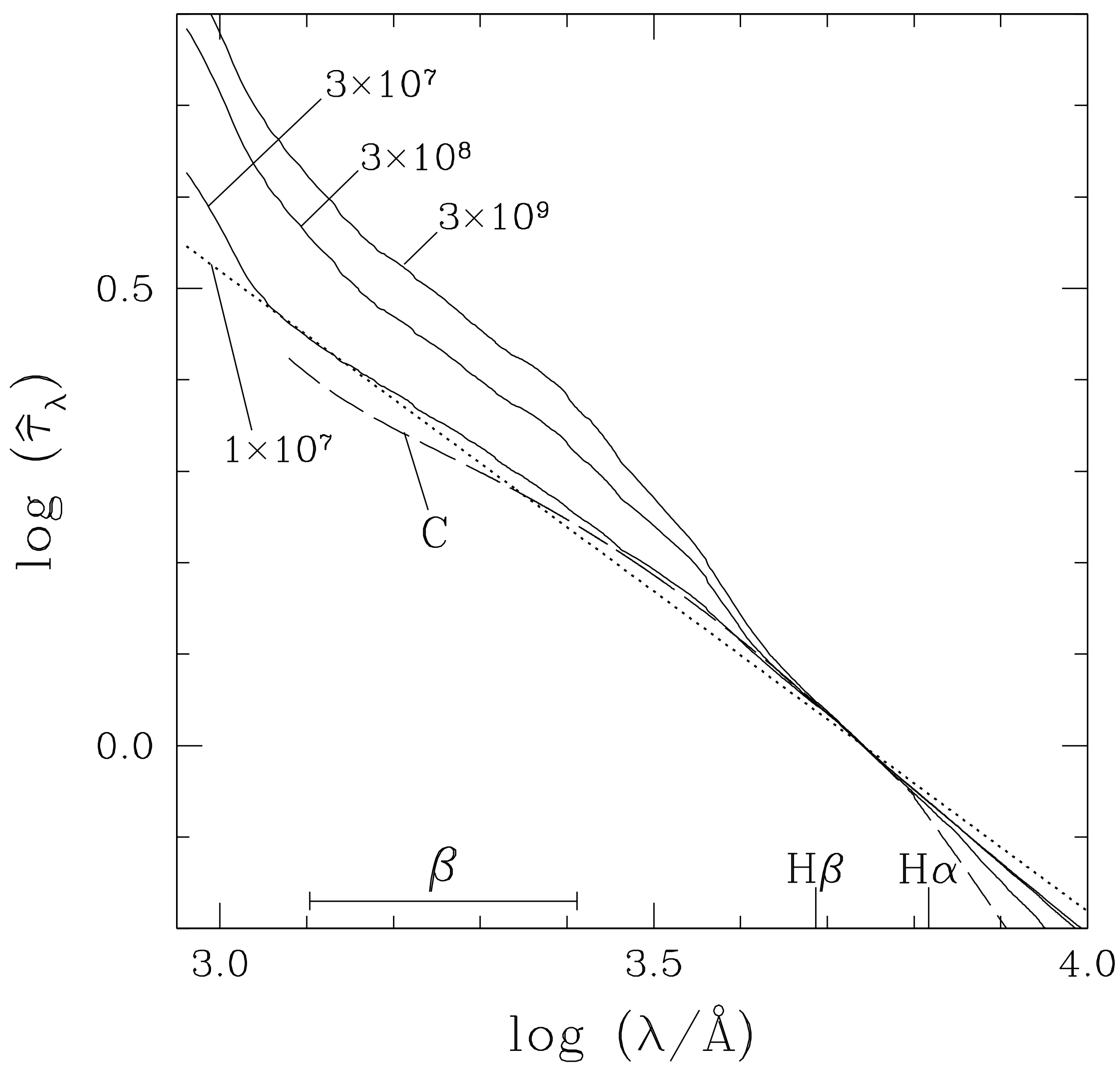
The interstellar medium: dust

- 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



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

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

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

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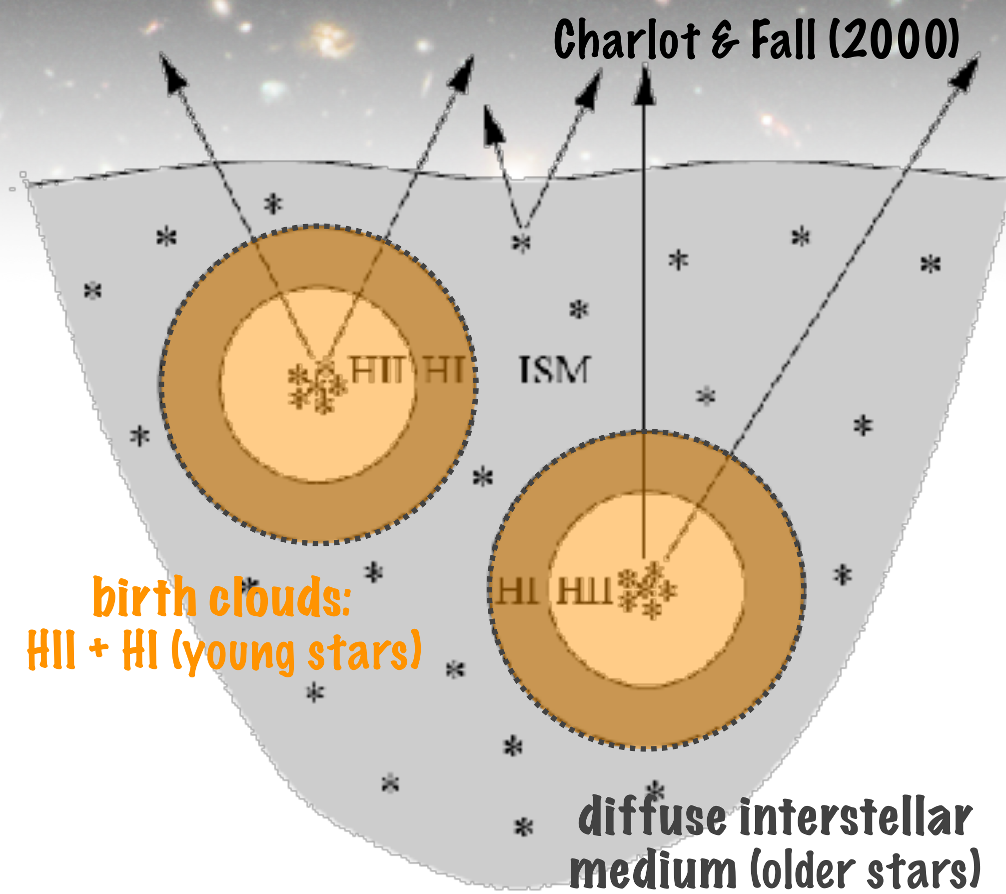

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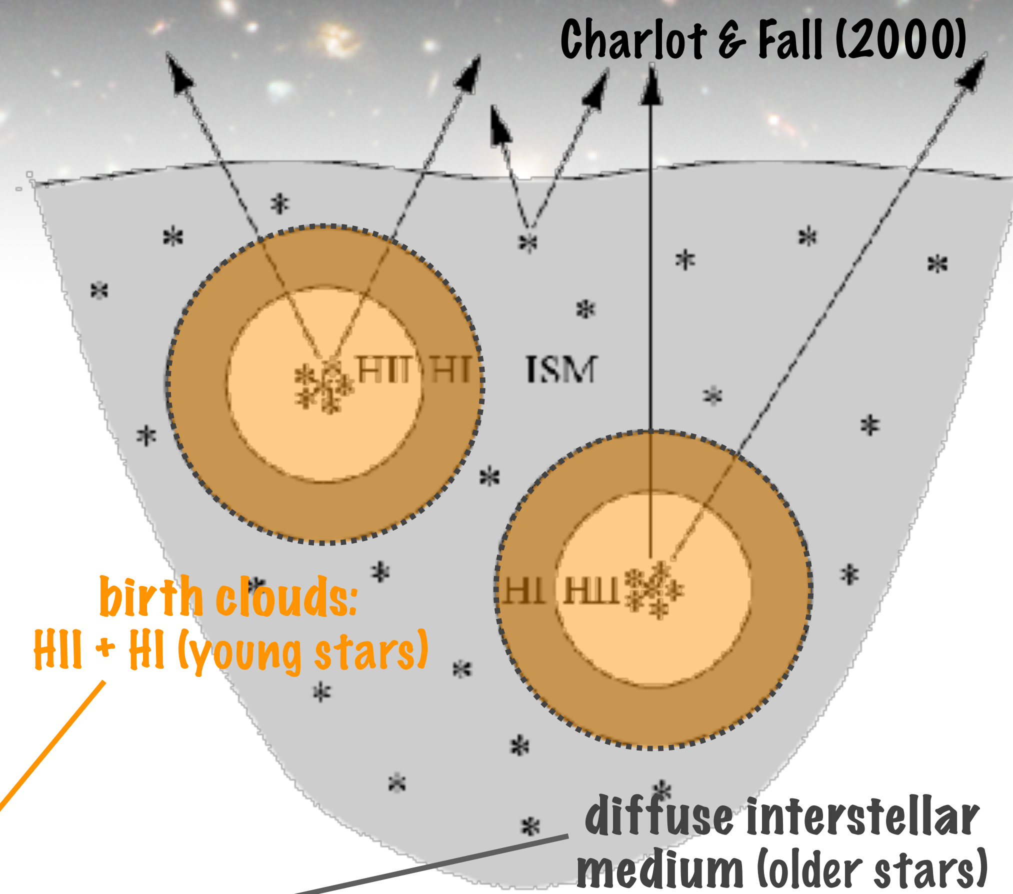
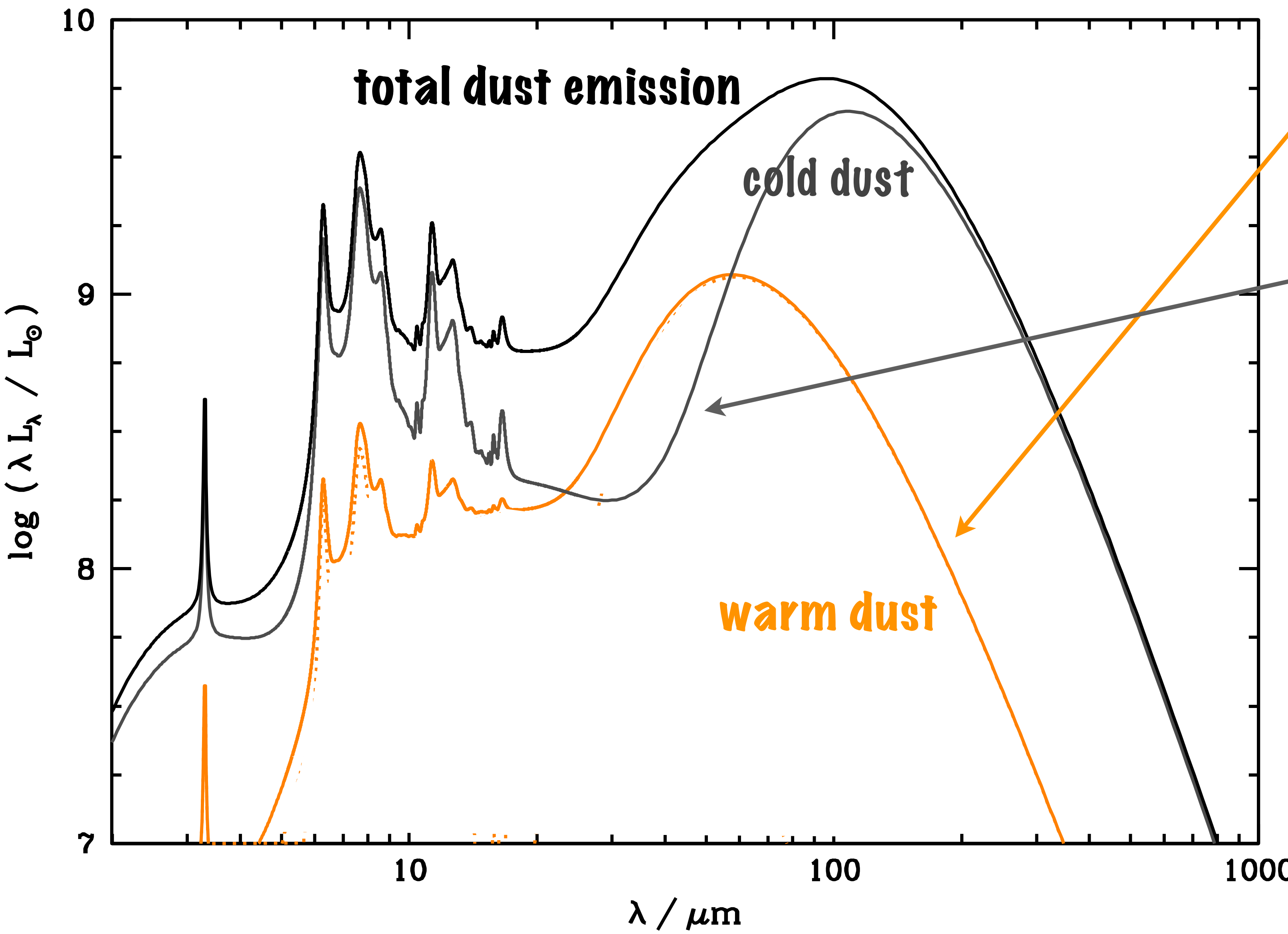




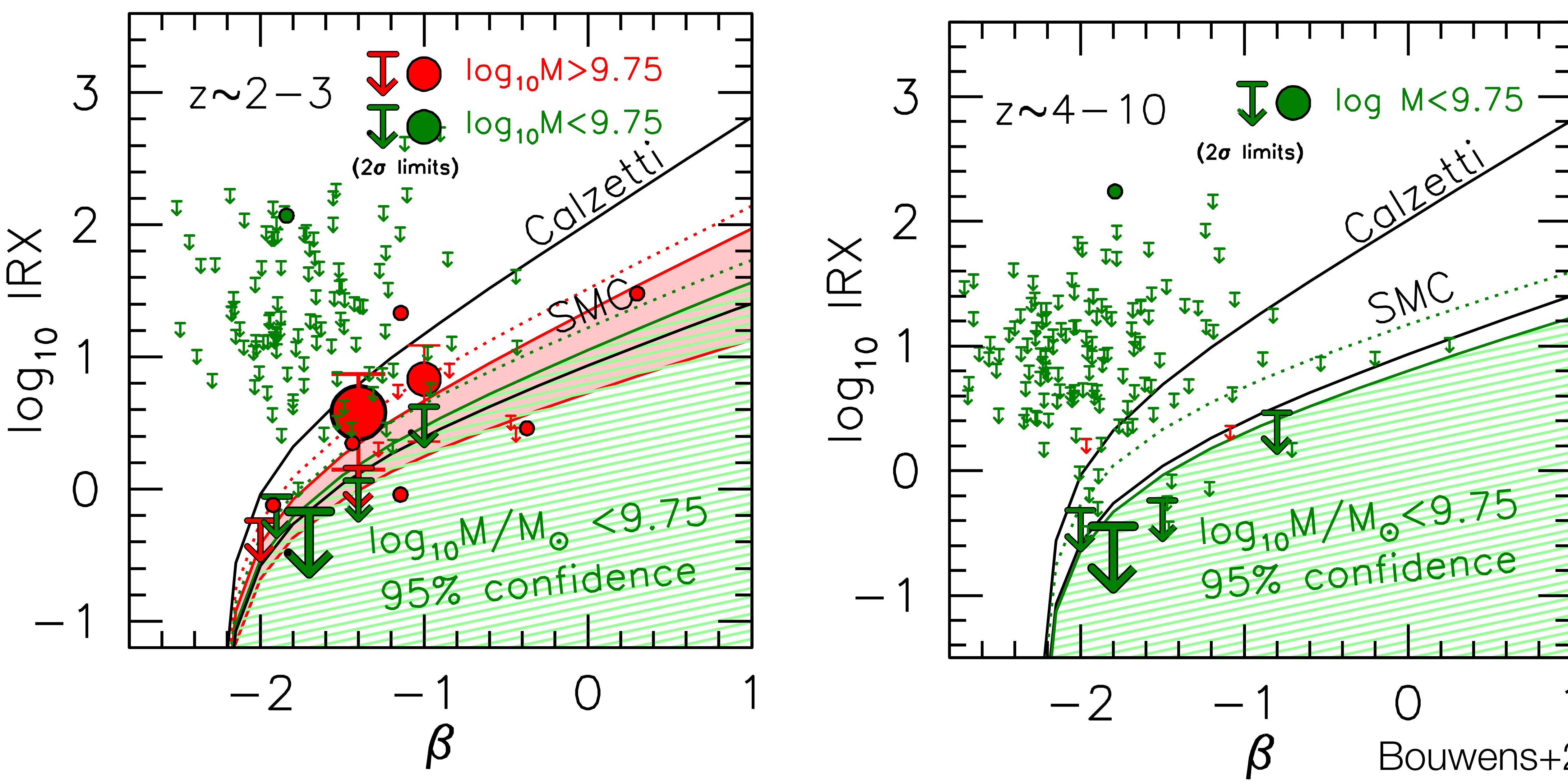
Energy balance

MAGPHYS (da Cunha+2008)

see also e.g. Noll+2009

Dust evolution at high redshift?

330 Lyman-break galaxies at z~2-10;
From extrapolating local IRX-β relation (assuming Td=35 K),
expected **35** detections with ALMA; found **6** detections.



Bouwens+2016

The interstellar medium: ionized gas

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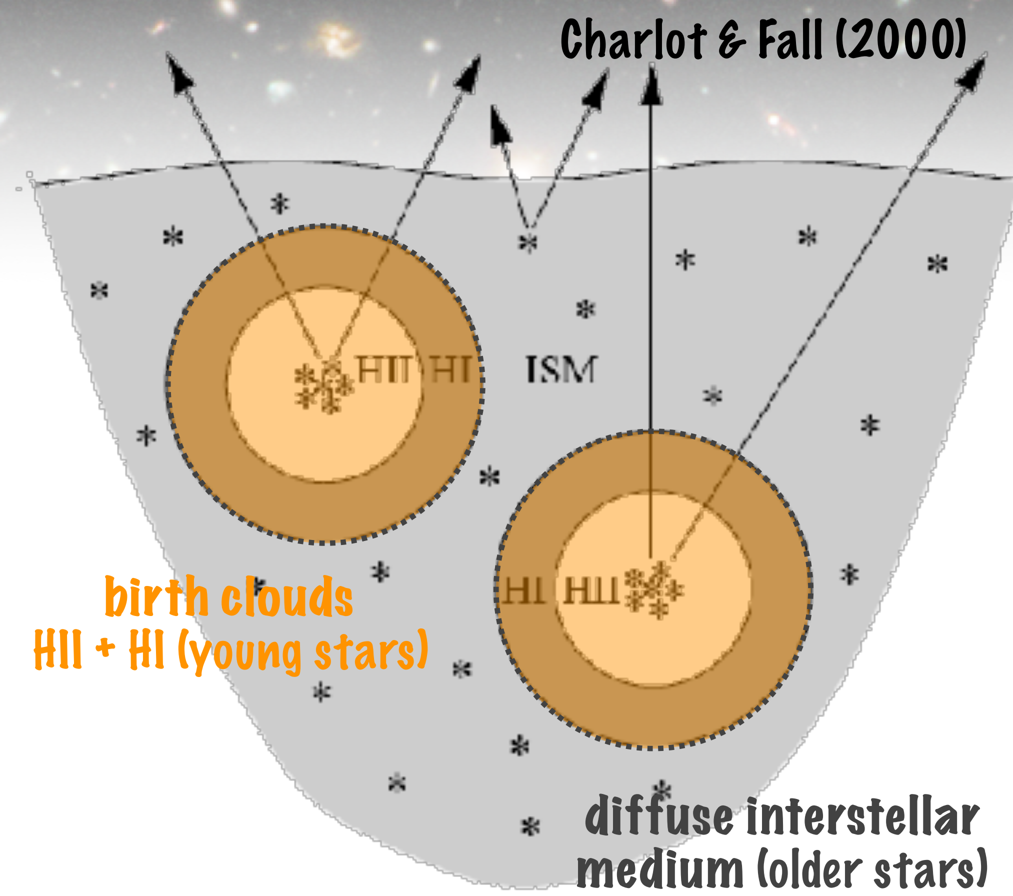

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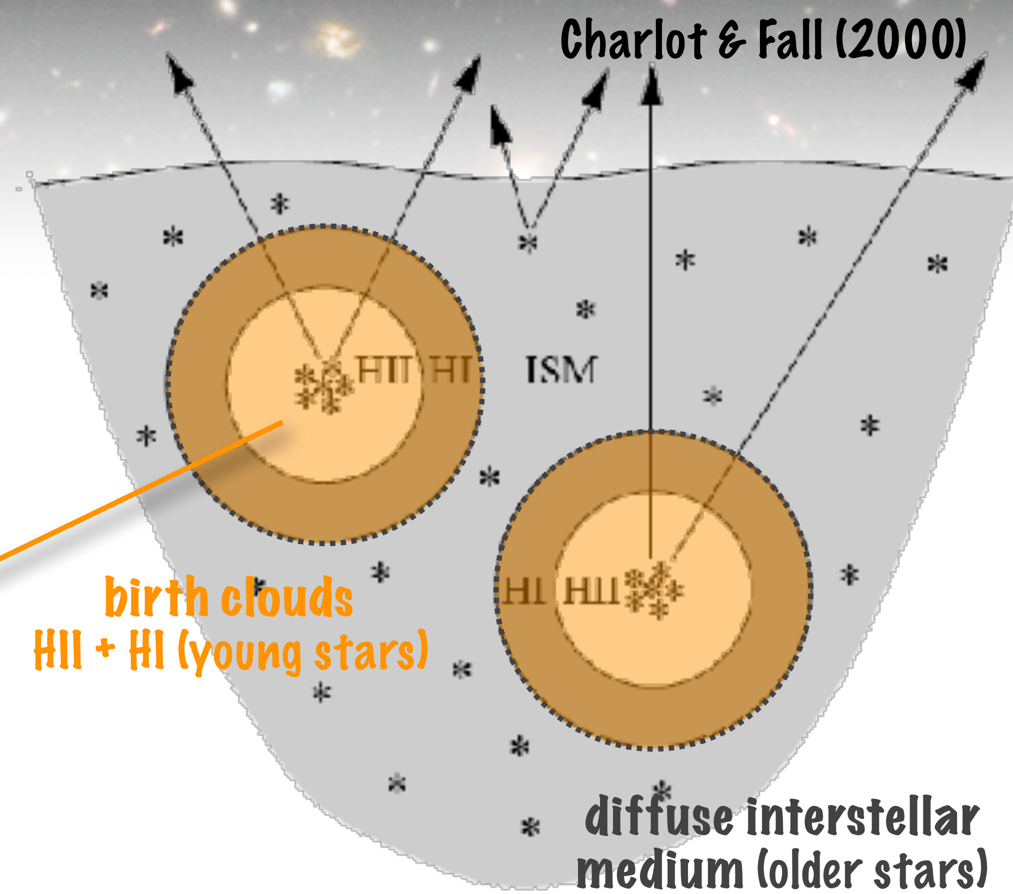
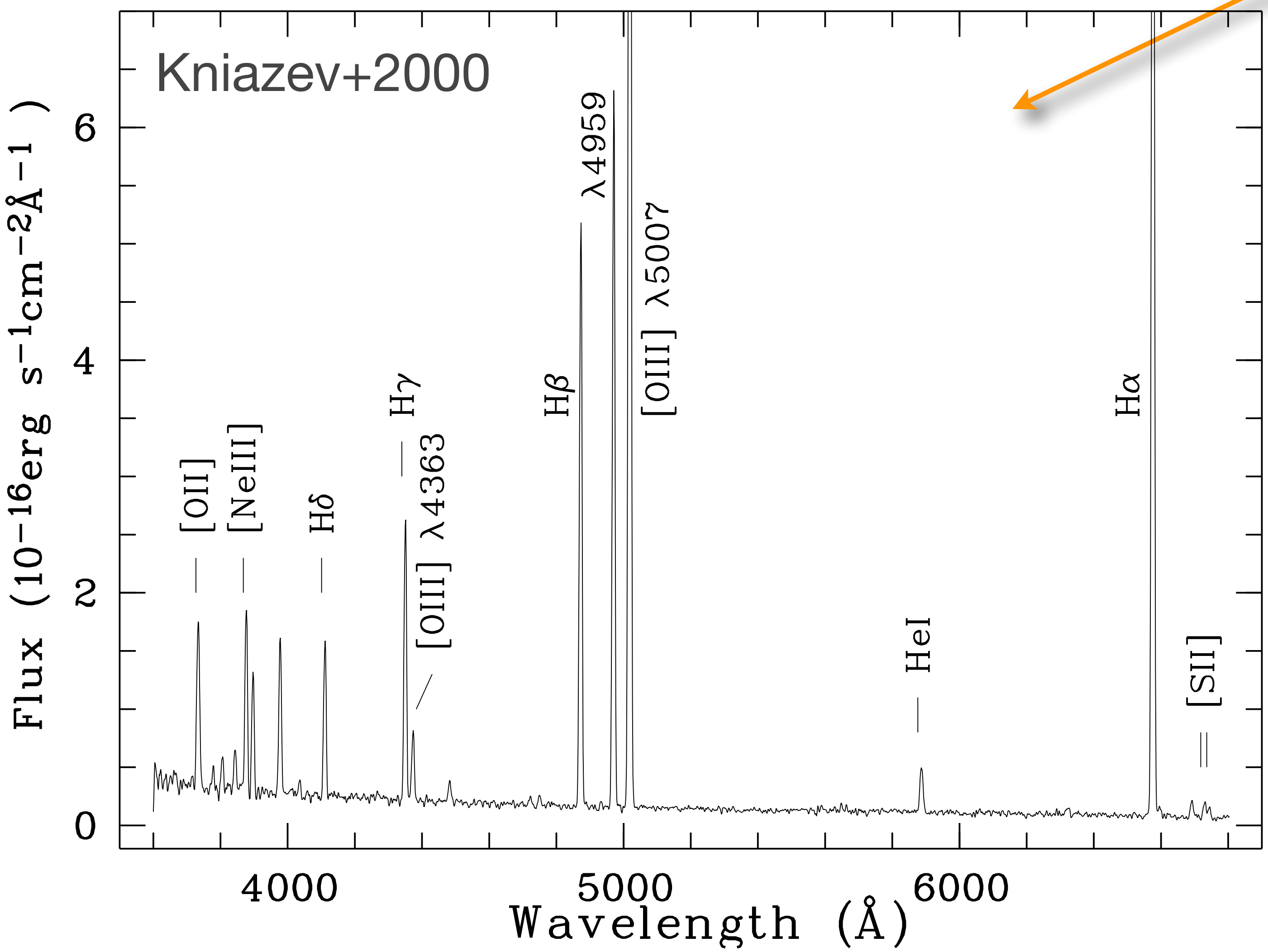
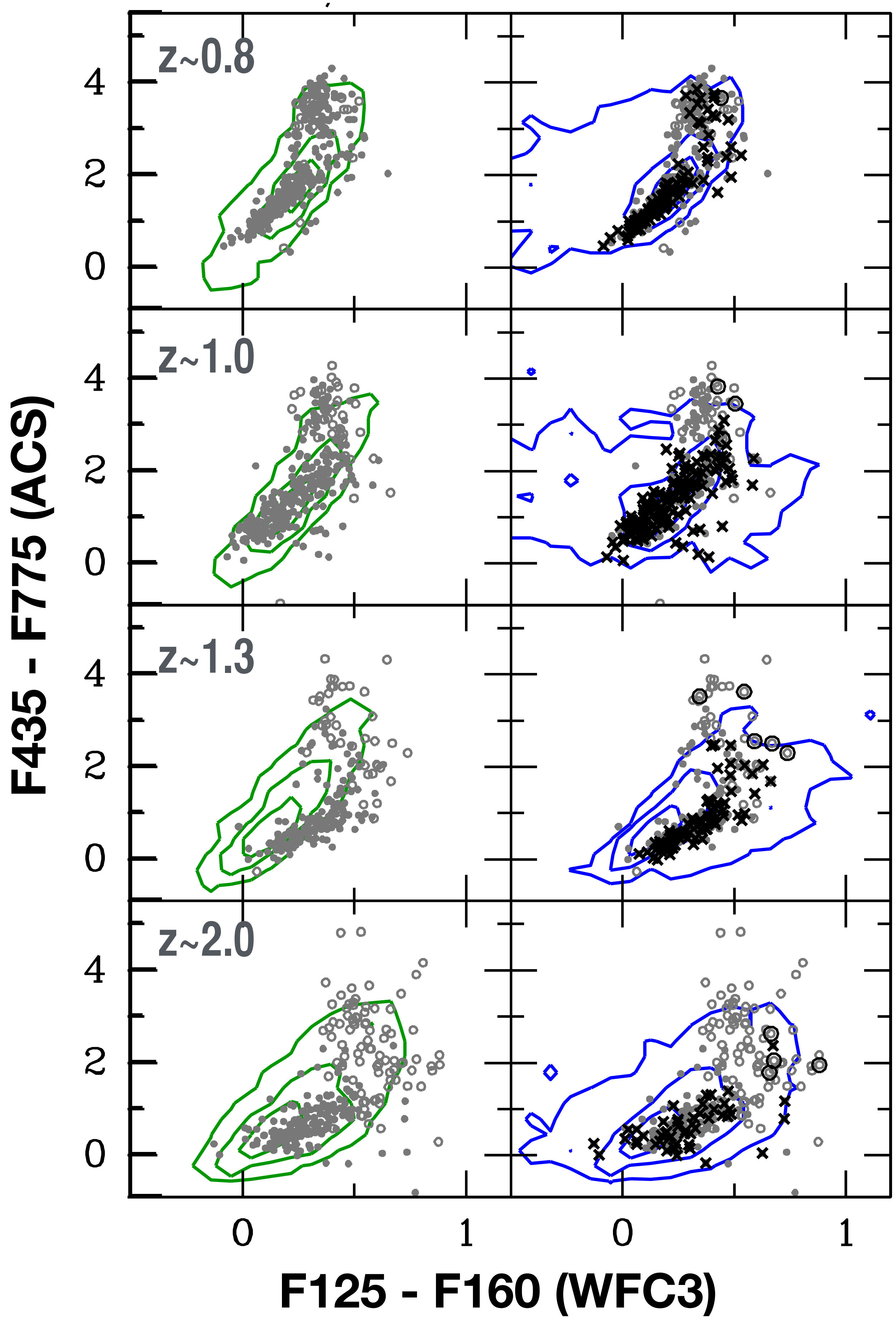
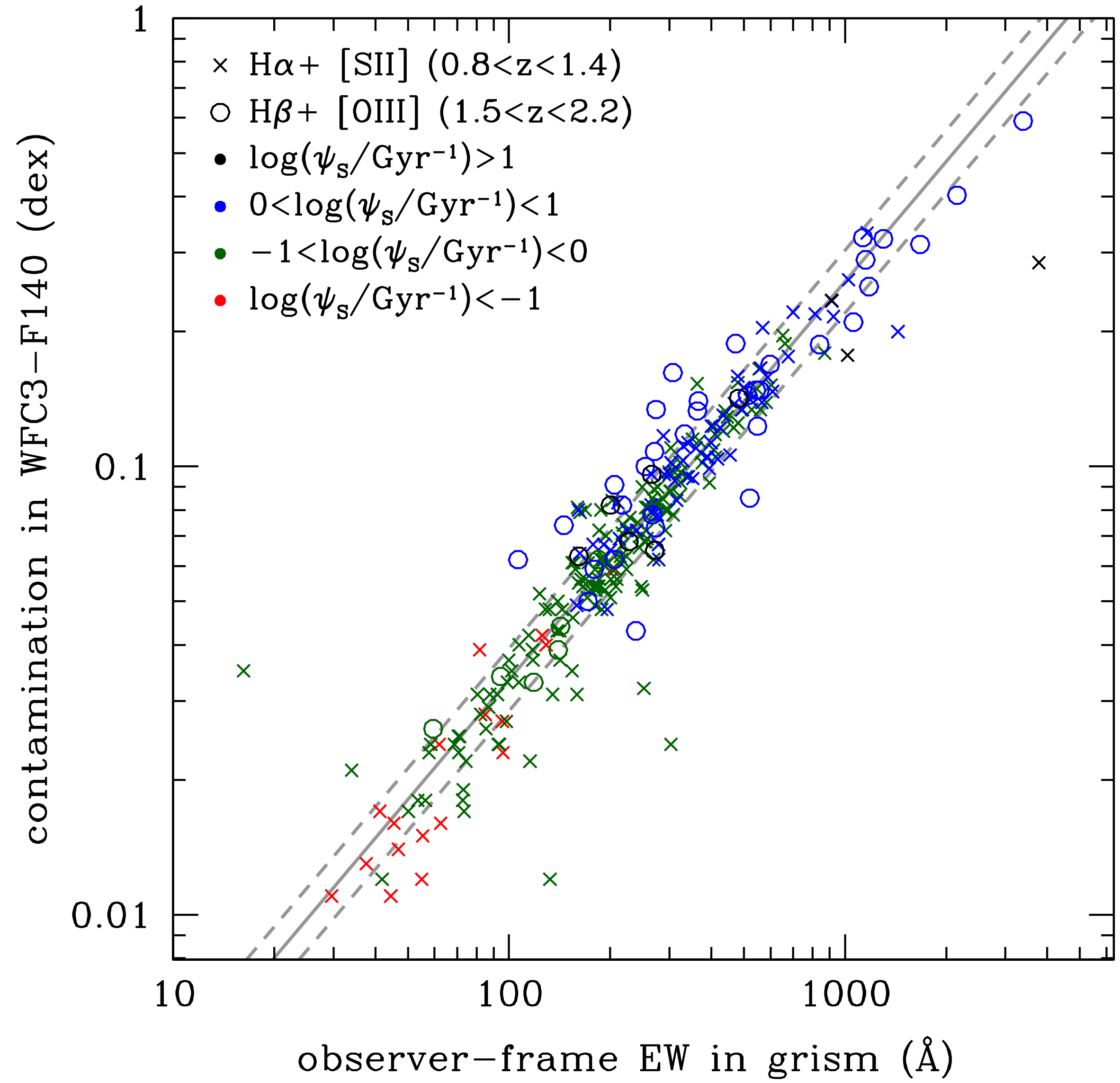




Nebular emission **computed self-consistently** using photo-ionisation code (Pacifici+2012, Charlot & Longhetti 2001; Gutkin+2016) realistic SAM SFHs nebular emission





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

Pacifici, da Cunha+2015; also e.g. de Barros+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), Prospector (Leja+2016)

MODEL PARAMETERS

PRIOR DISTRIBUTIONS

STOCHASTIC MODEL LIBRARIES

OBSERVED GALAXY SED

COMPUTE CHI2 EACH MODEL

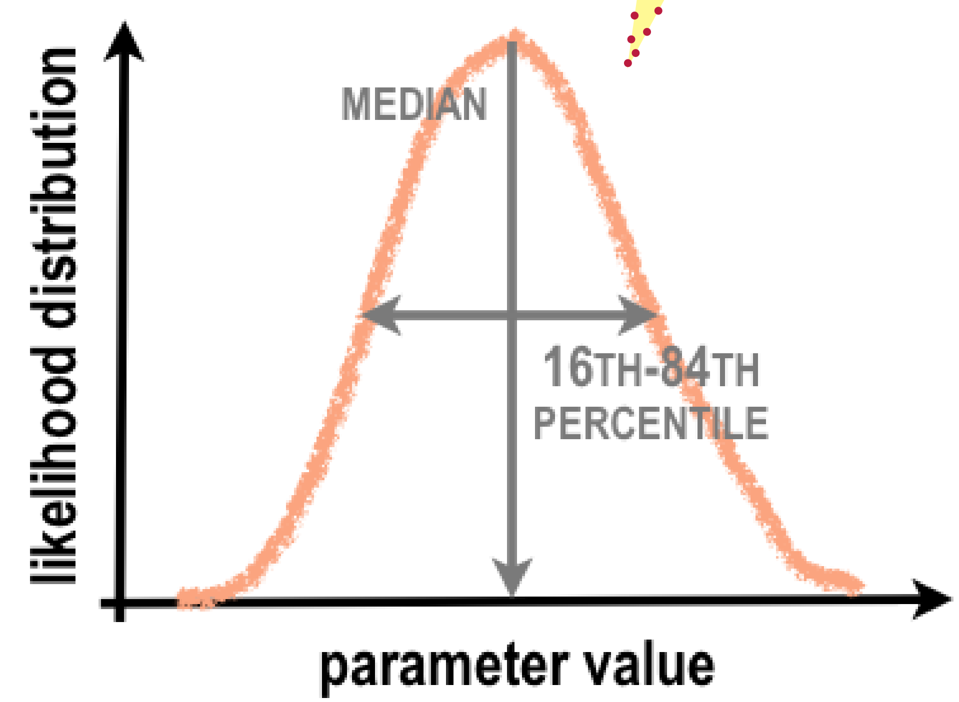
MODEL SEDs

robust parameter estimate + error bar!

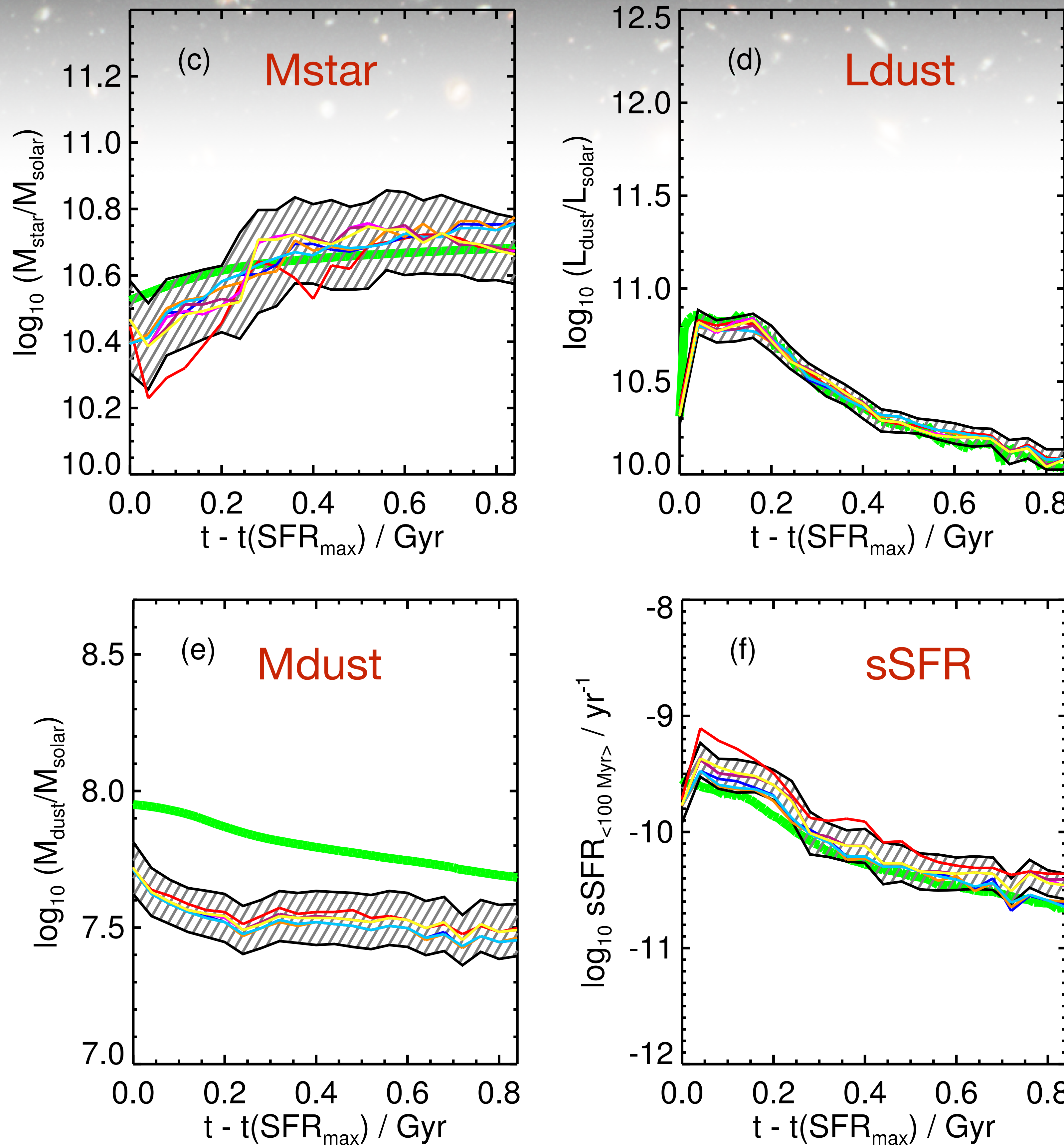
For a given model j described by a random set of parameters:

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

P=EXP(-1/2 CHI2), MARGINALISE



Testing MAGPHYS with hydro+RT simulations



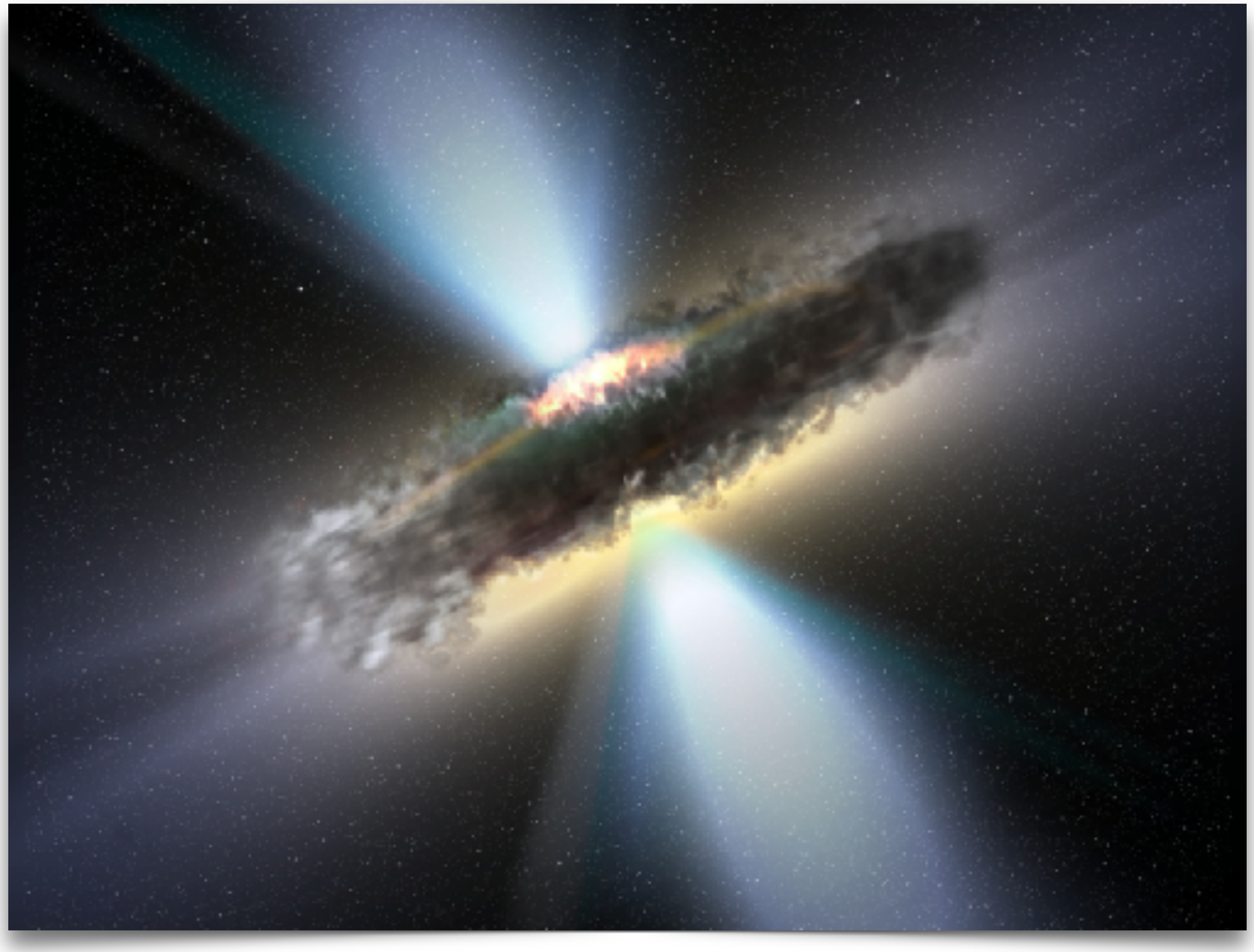
green: "true value"

colours/shade: MAGPHYS, different viewing angles

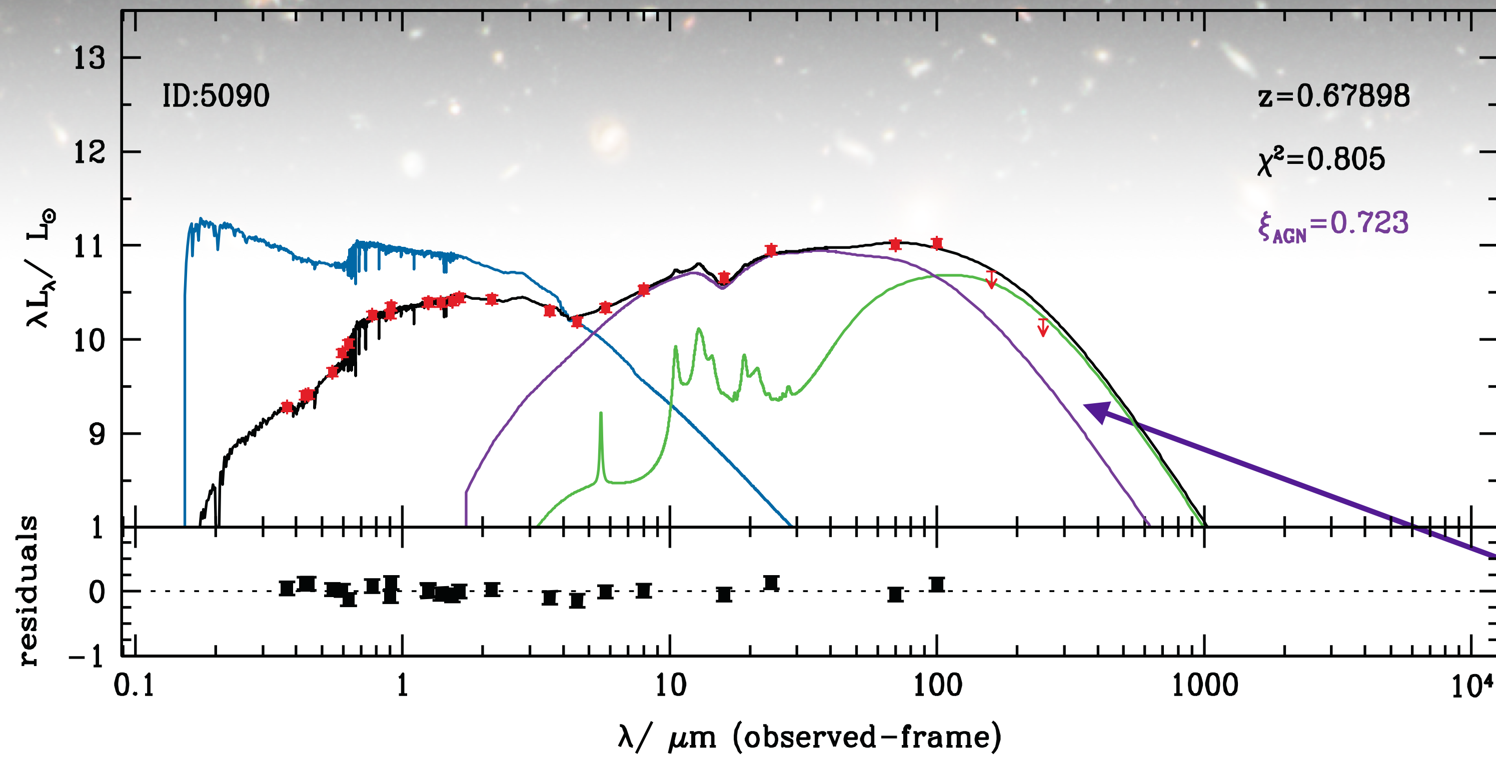
MAGPHYS recovers the physical parameters well for different viewing angles with smooth time step variation. 😊

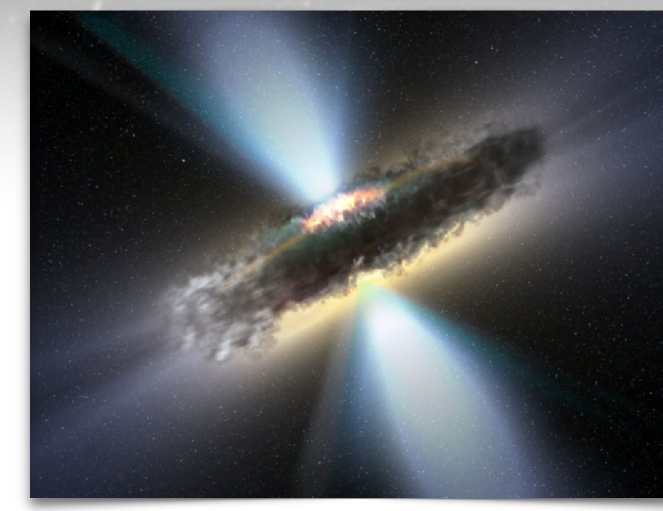
Hayward & Smith 2015

Ongoing upgrade: modelling the AGN contribution

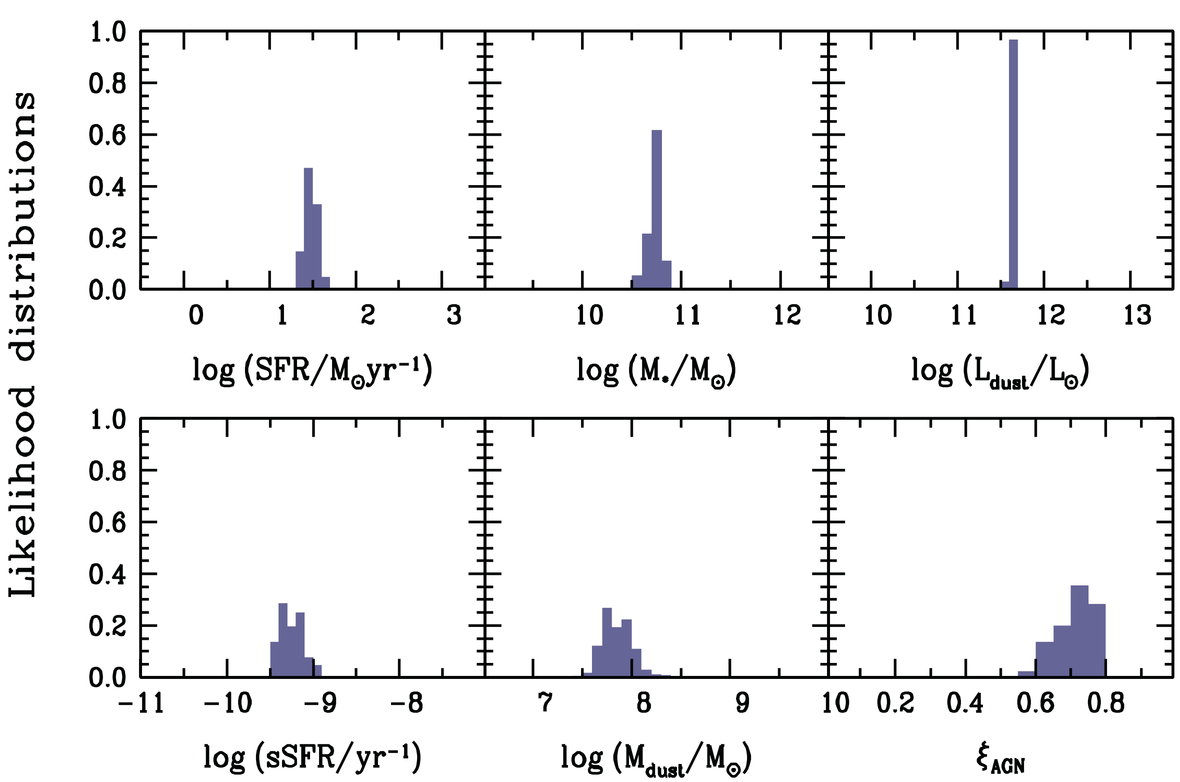


Ongoing upgrade: modelling the AGN contribution



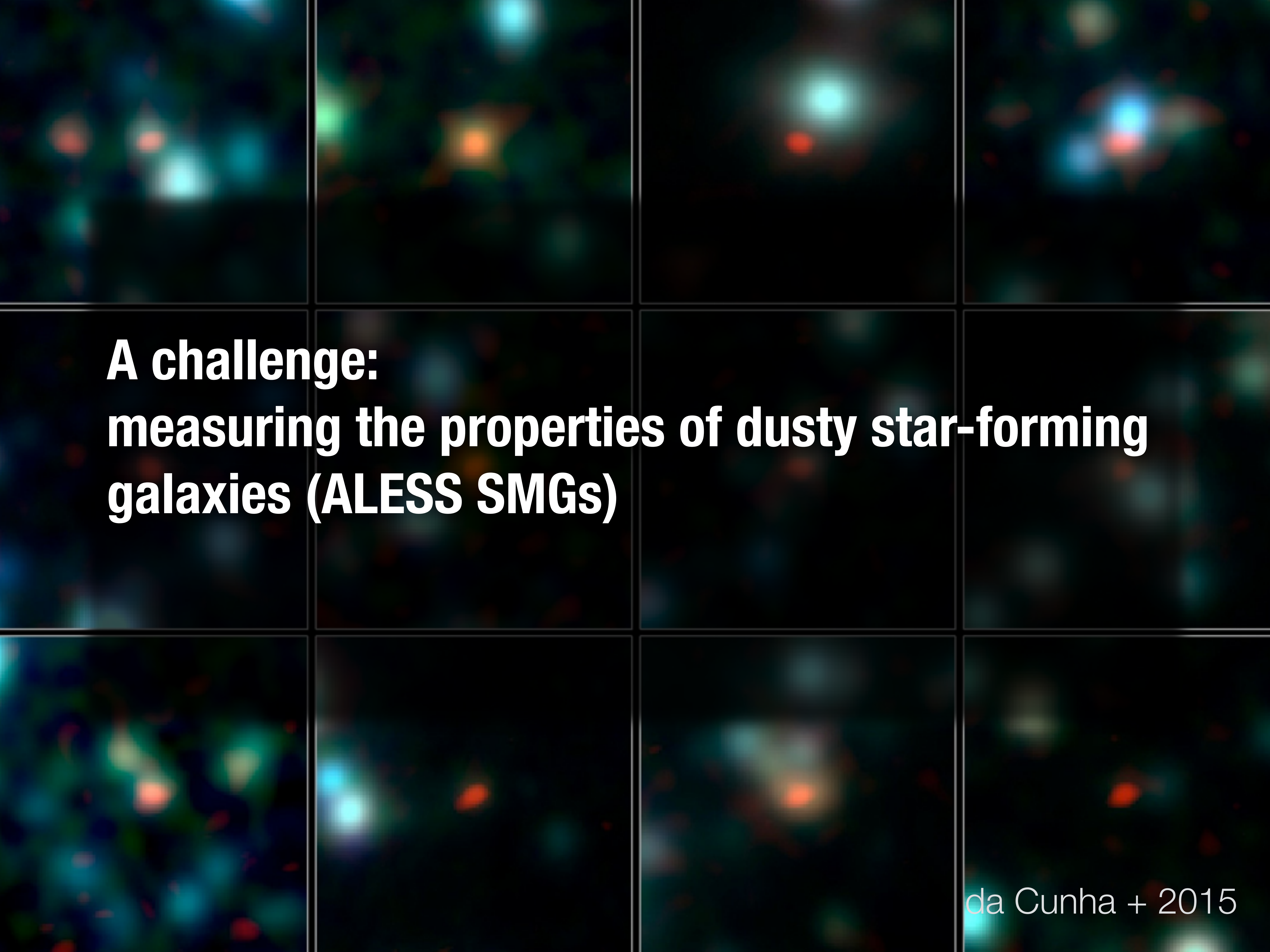


dusty torus emission



- energy balance + excess mid-IR help constrain the AGN contamination
- corrected stellar mass, SFR

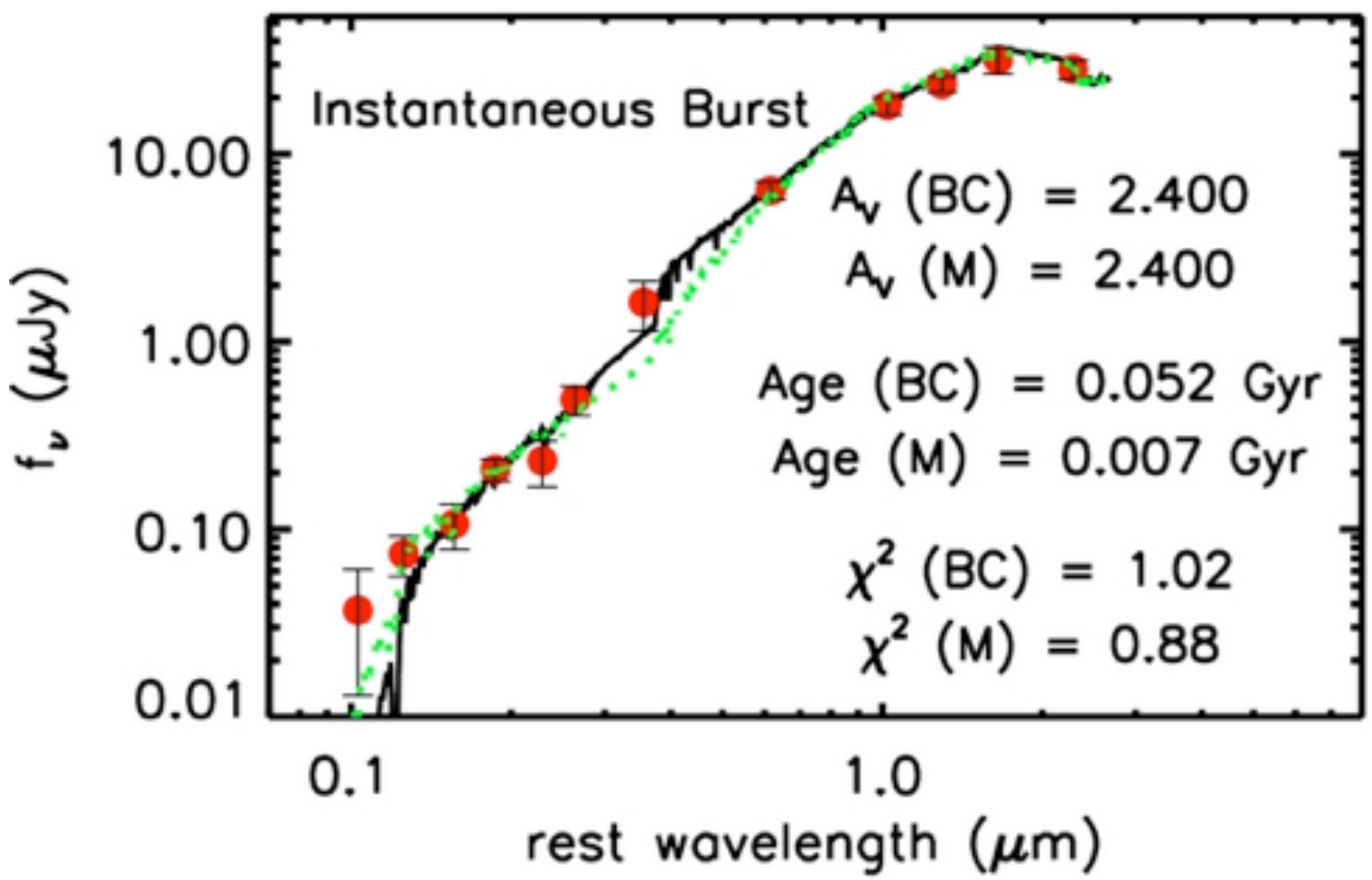
da Cunha, Juneau+, in prep.



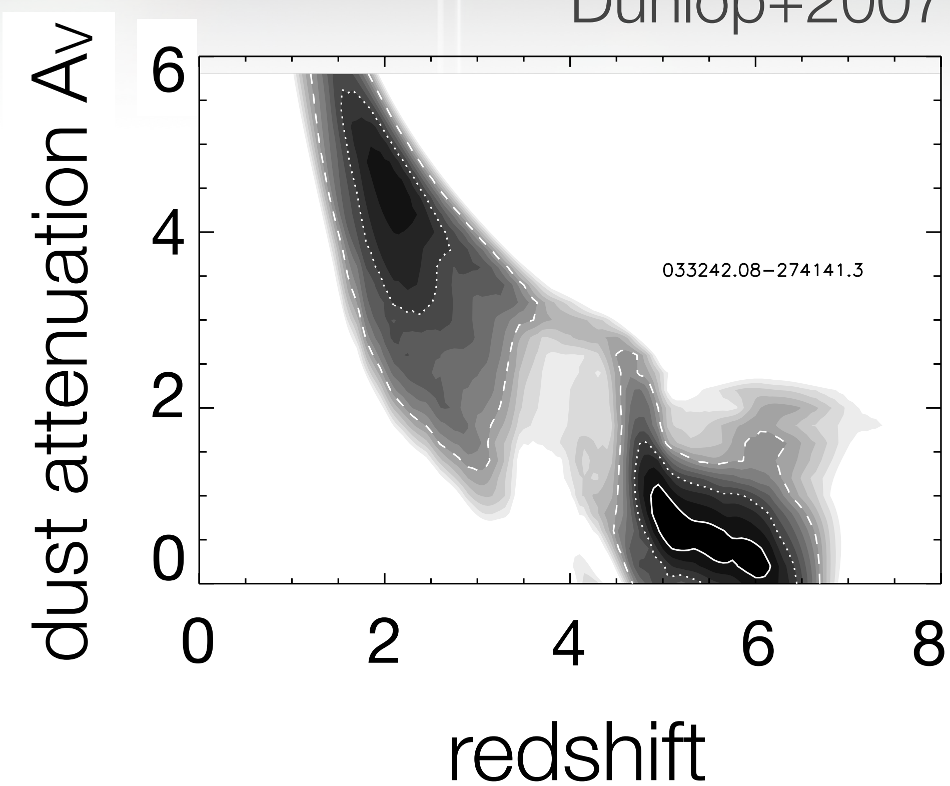
A challenge:
measuring the properties of dusty star-forming galaxies (ALESS SMGs)

da Cunha + 2015

Degeneracies in optical SEDs: dusty galaxies

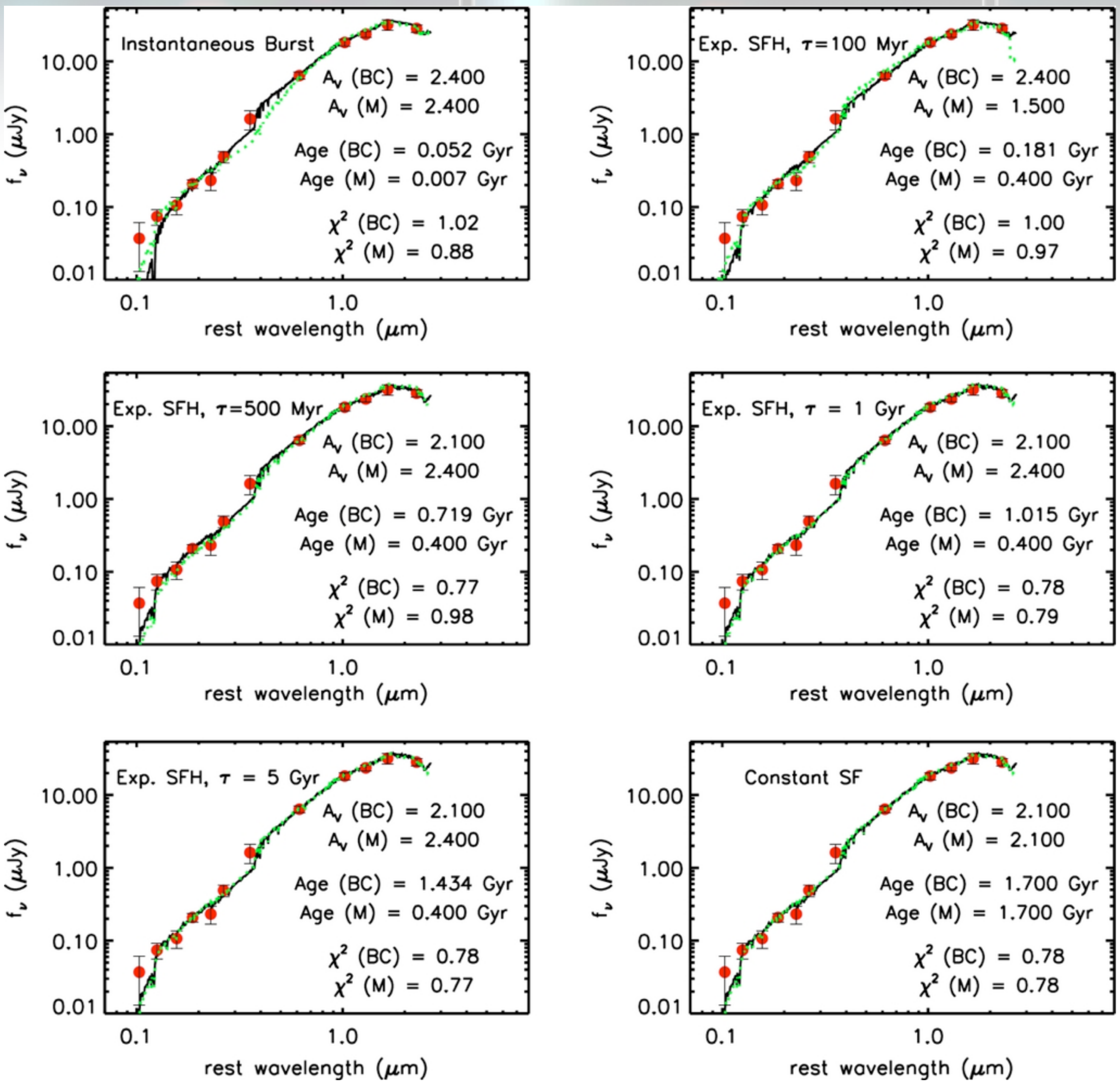


Dunlop+2007

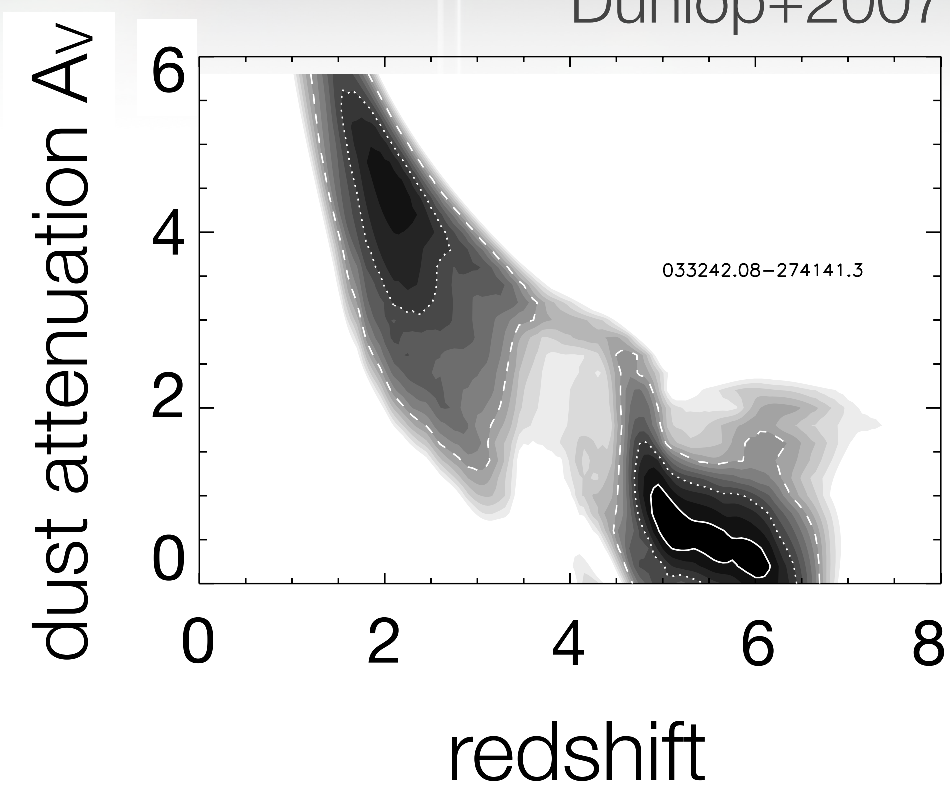


- SFH is usually unknown
- redshift, age, dust and metallicity have very similar effect on the broad-band SEDs

Degeneracies in optical SEDs: dusty galaxies



Dunlop+2007



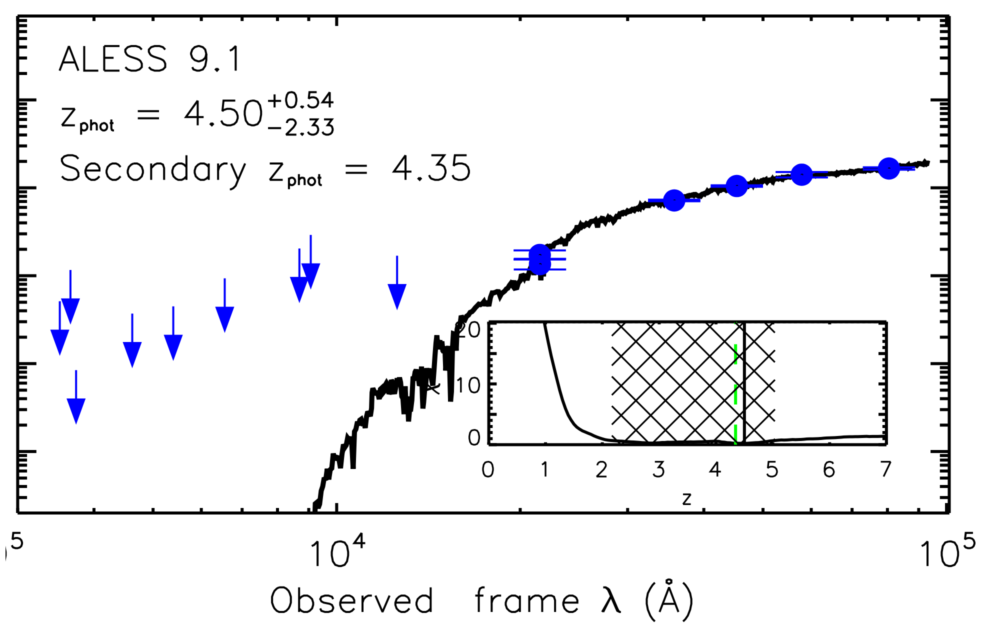
- SFH is usually unknown
- redshift, age, dust and metallicity have very similar effect on the broad-band SEDs

Hainline+2010

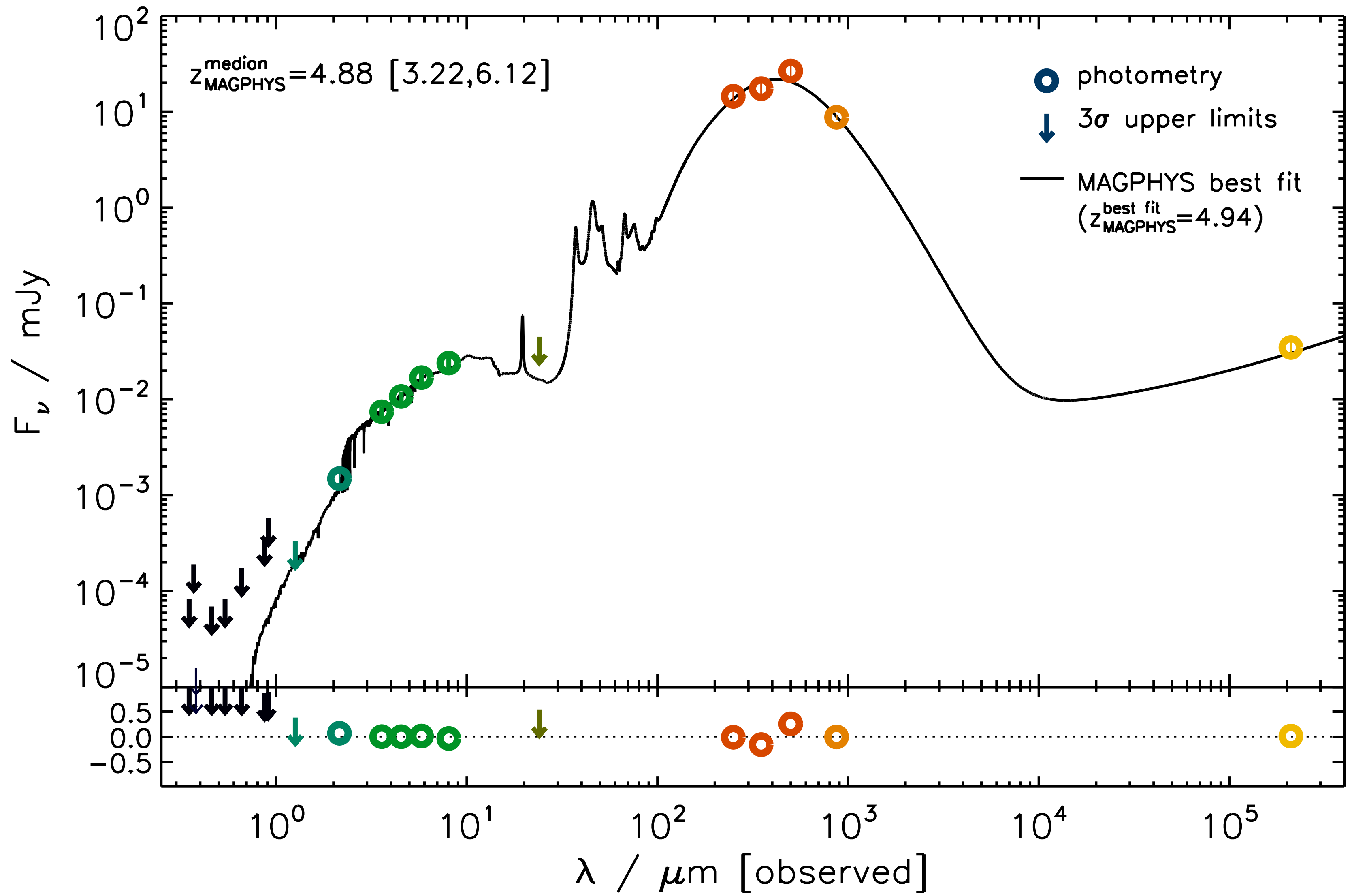
see also Michalowski+2014

Example SED fit: ALESS009.1

Hyper-z fit (Simpson+2014)

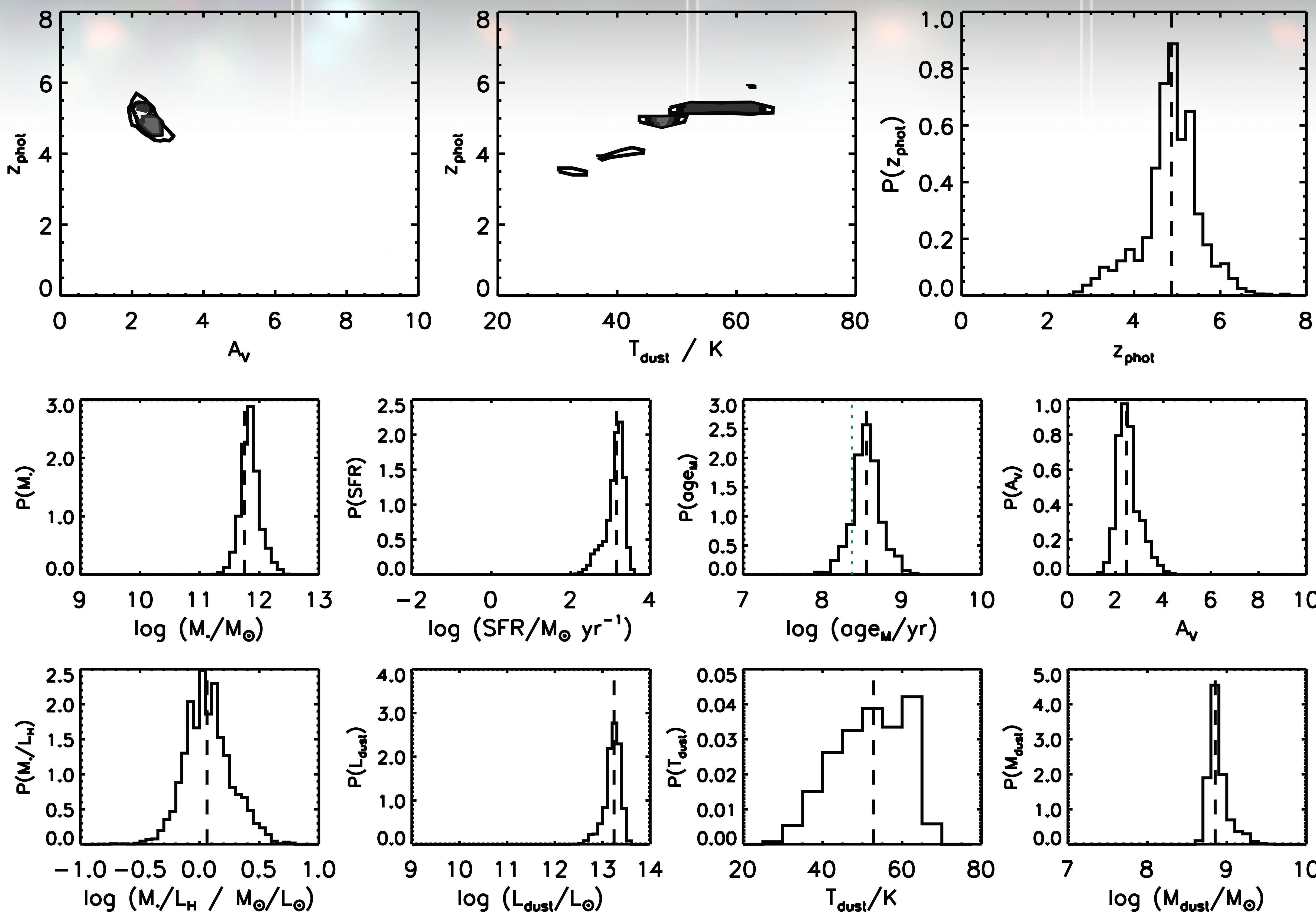


ALESS009.1: MAGPHYS fit

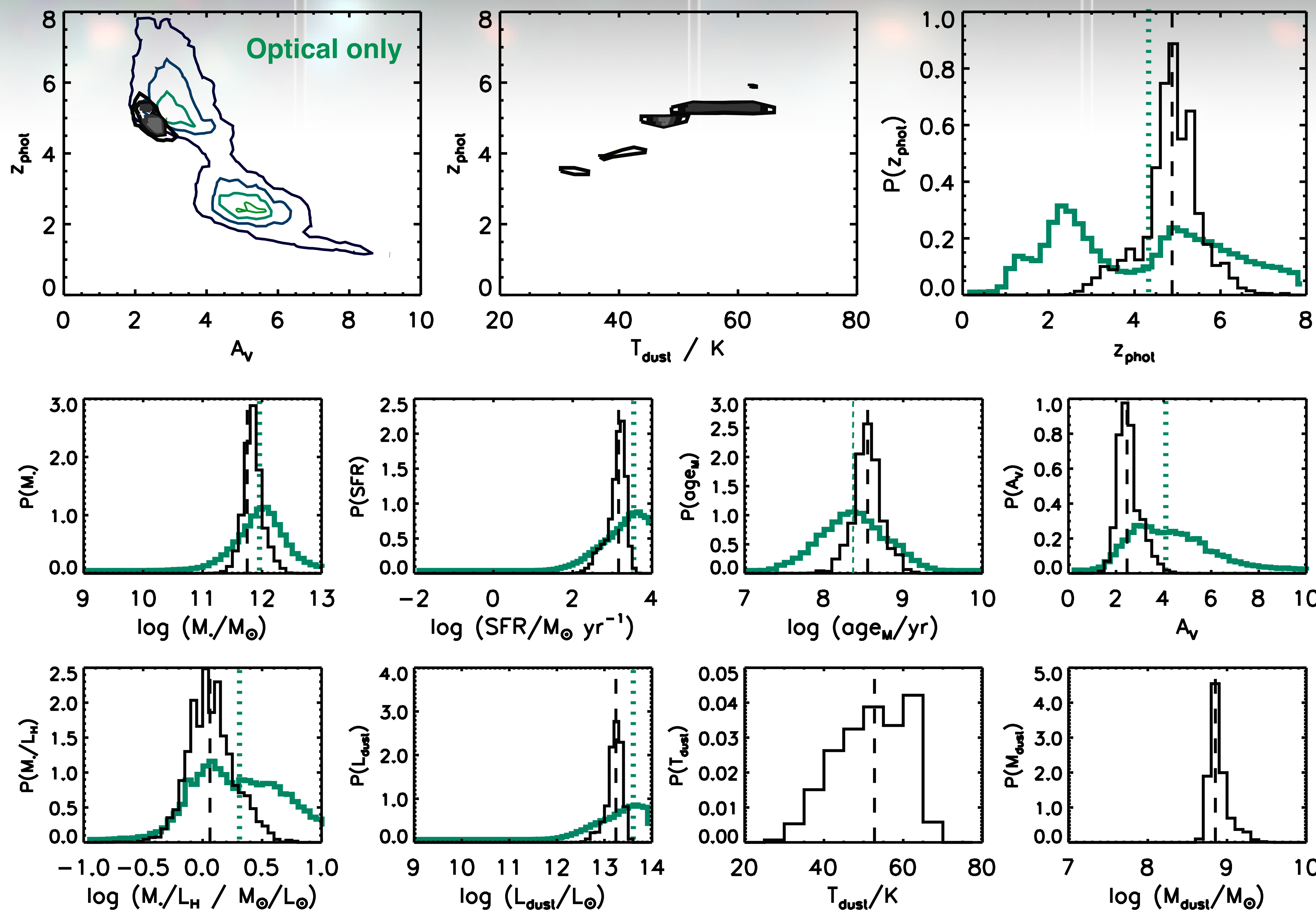


da Cunha + 2015

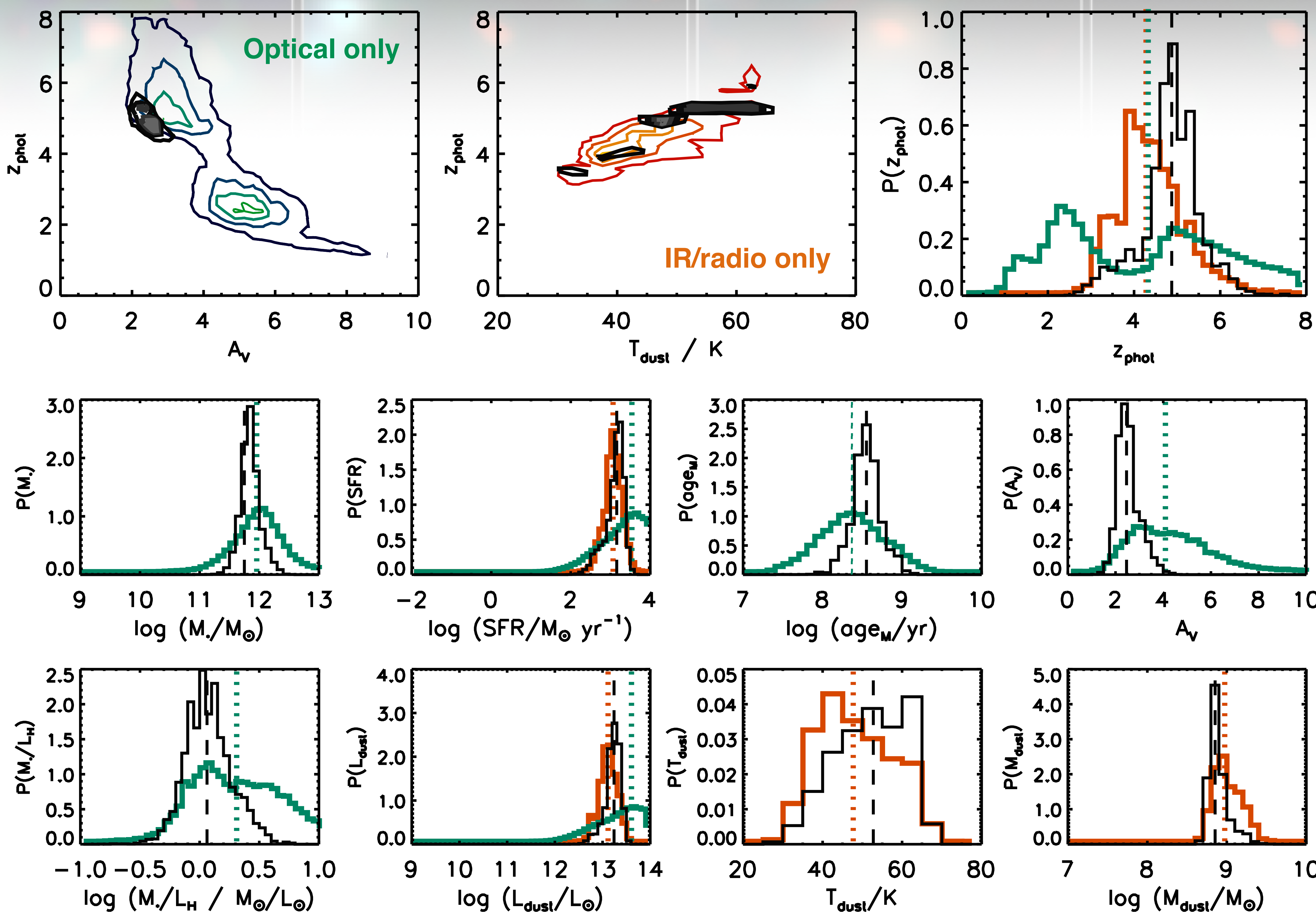
ALESS009.1: parameter likelihood distributions



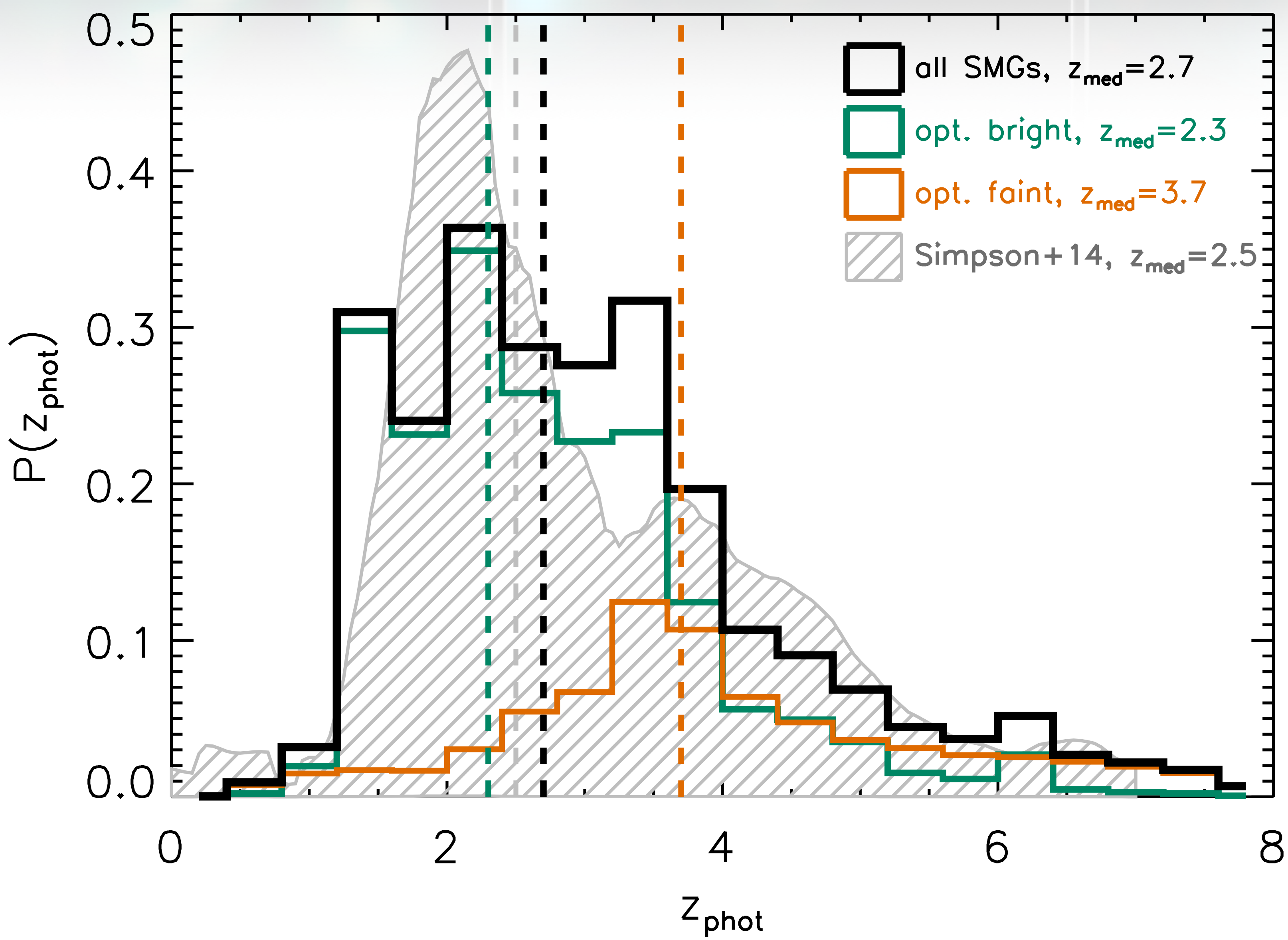
ALESS009.1: parameter likelihood distributions

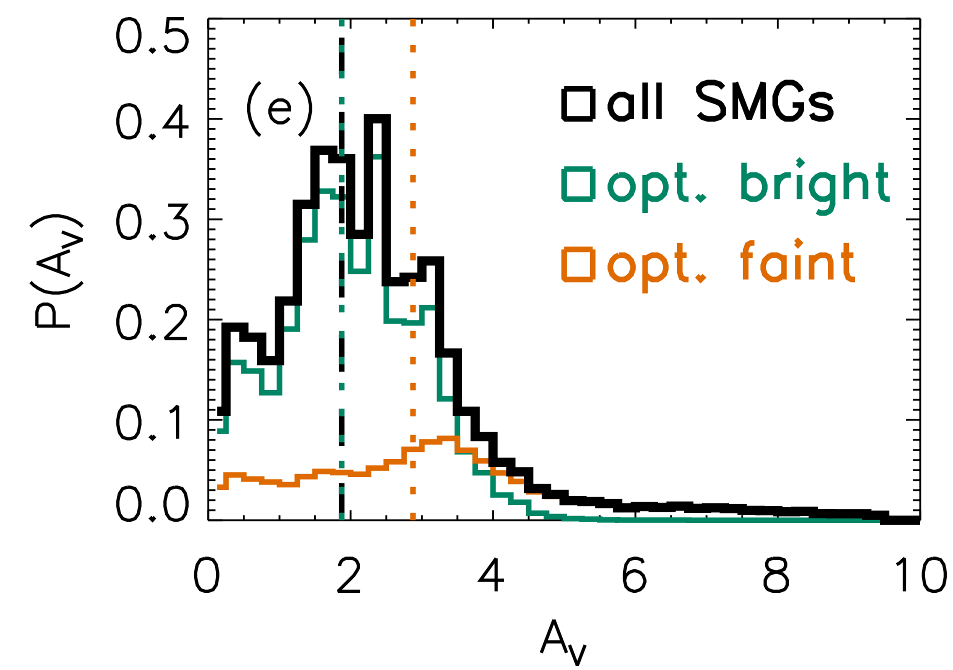


ALESS009.1: parameter likelihood distributions



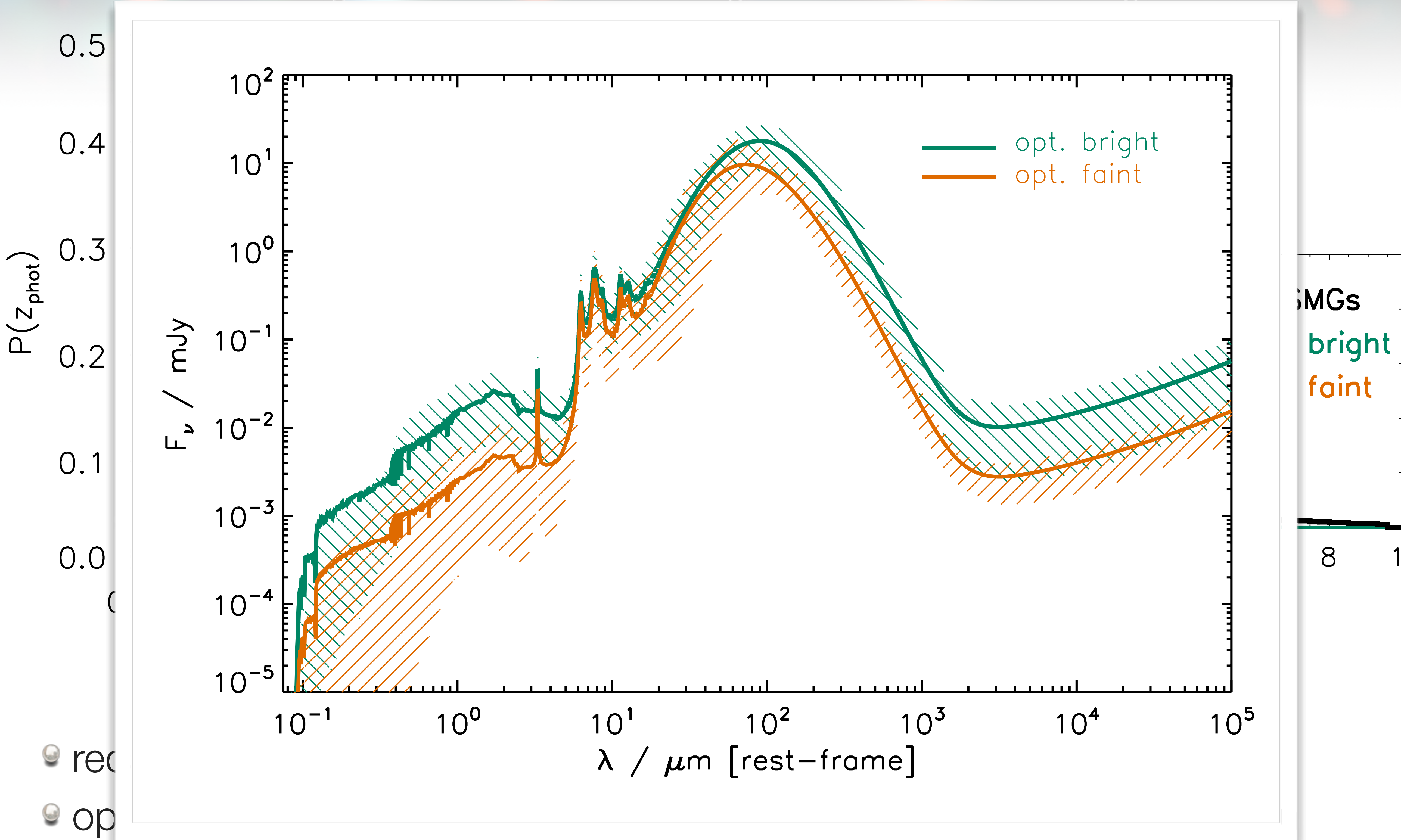
Stacked likelihood distributions





- redshift distribution consistent with previous estimates
- optically-faint SMGs tend to have higher redshifts and dust attenuation

Stacked likelihood distributions



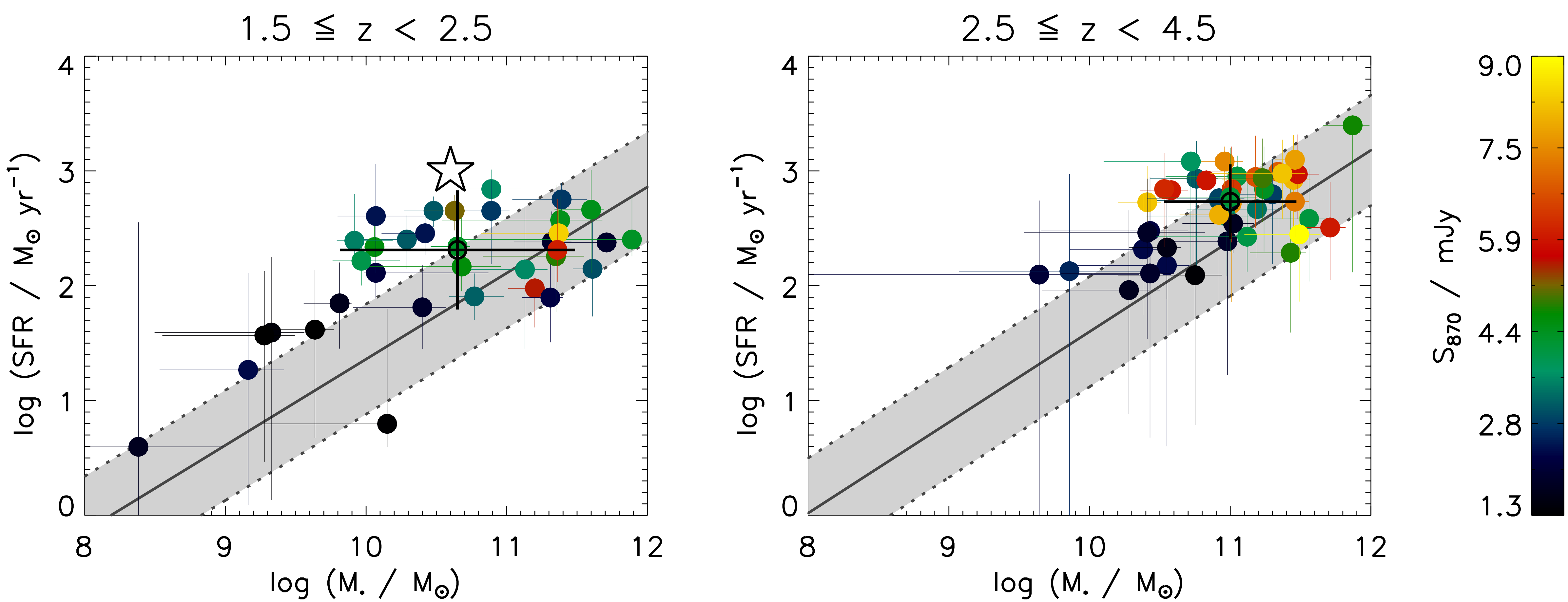
- rec
- op

Are the ALESS SMGs on the ‘main sequence’?

…are they extreme starbursts or just the high-mass end of the main sequence of star formation?

Are the ALESS SMGs on the 'main sequence'?

…are they extreme starbursts or just the high-mass end of the main sequence of star formation?

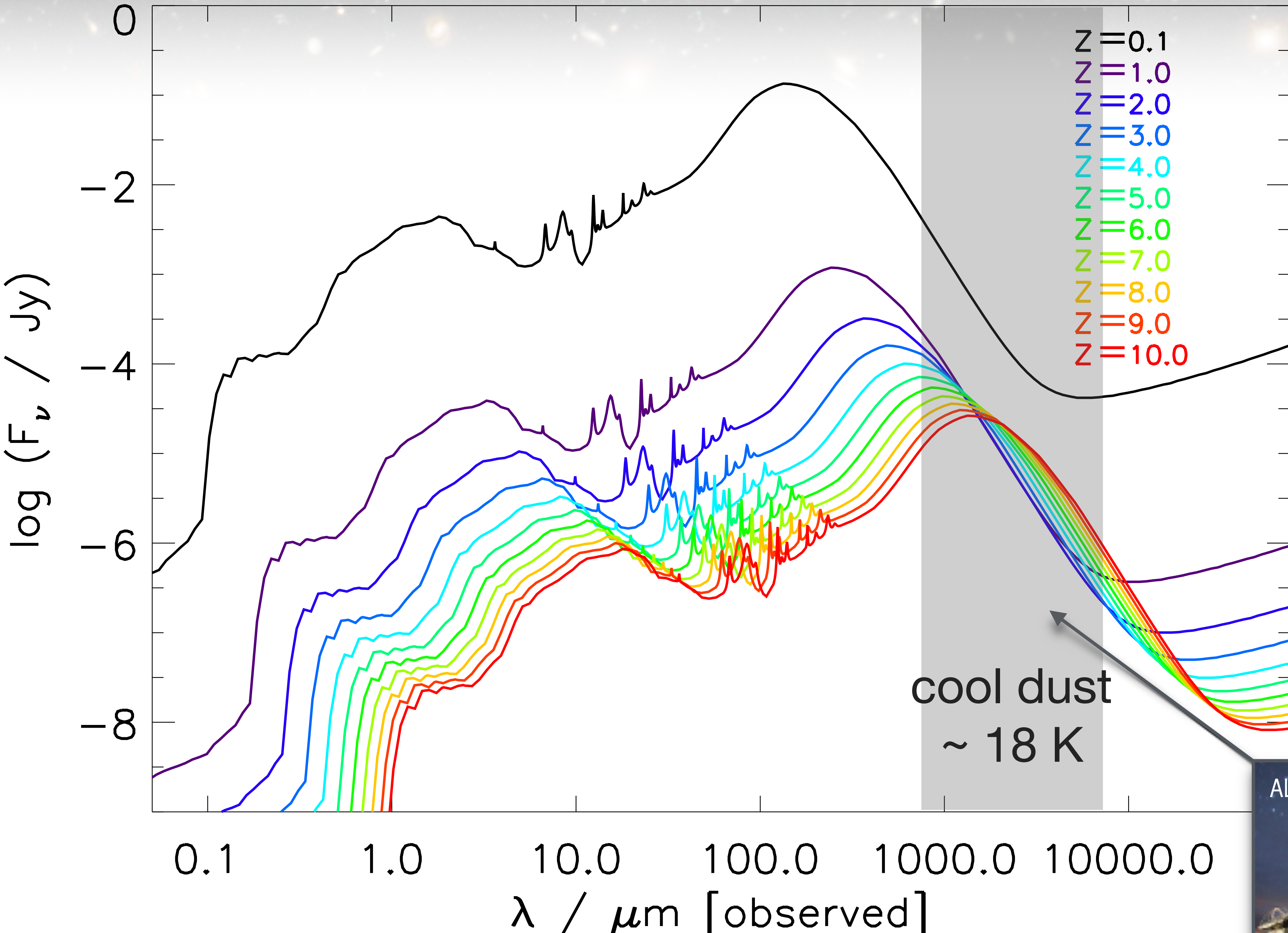


49% significantly above the main sequence. **27% significantly above the main sequence.**

Our results suggest that SMGs may not be a uniform galaxy population (as suggested by e.g. Hayward+2011,2012).

The effect of the CMB in (sub-)mm high-z observations

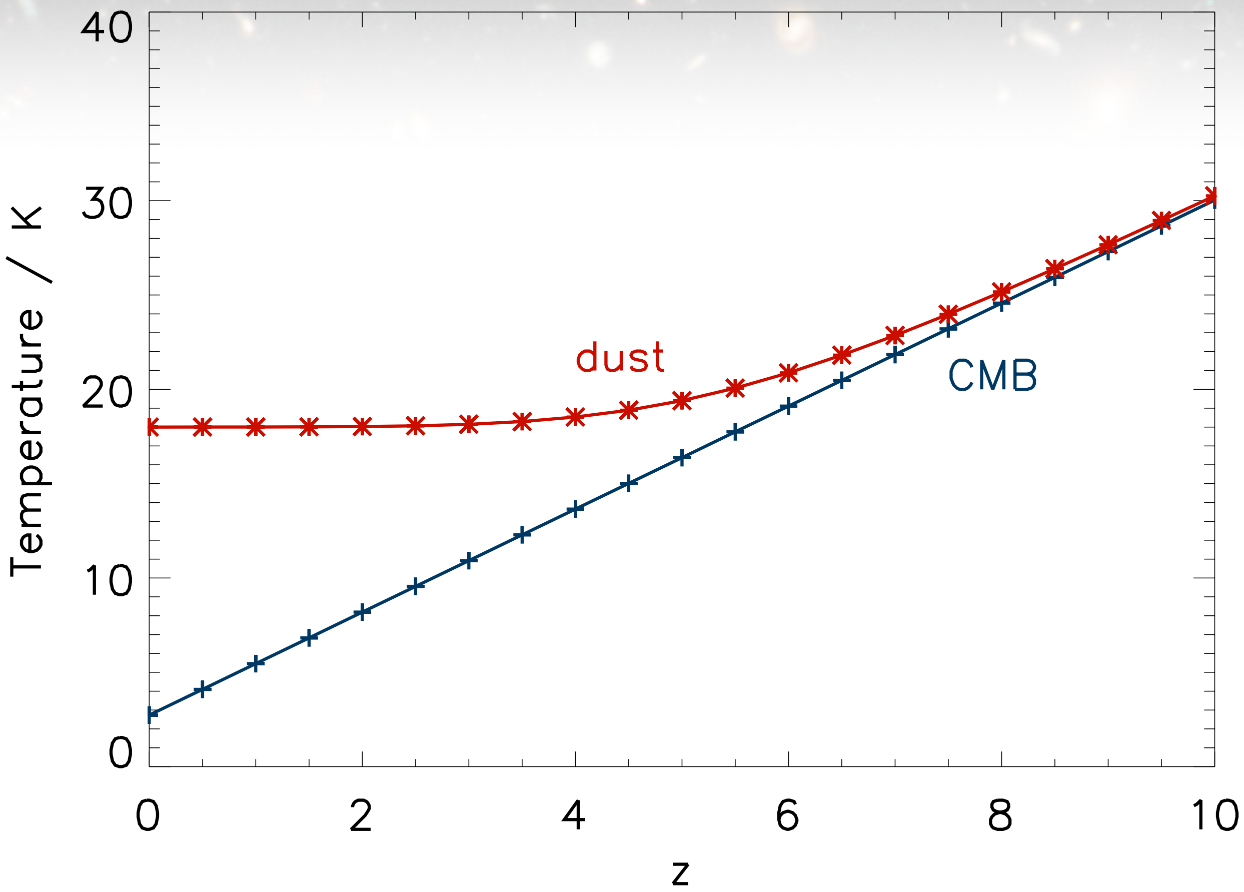
Effect of the CMB in (sub-)mm observations



Effect of the CMB on continuum dust emission

1. **Extra heating** by the CMB

da Cunha+2013



Effect of the CMB on continuum dust emission

da Cunha+2013

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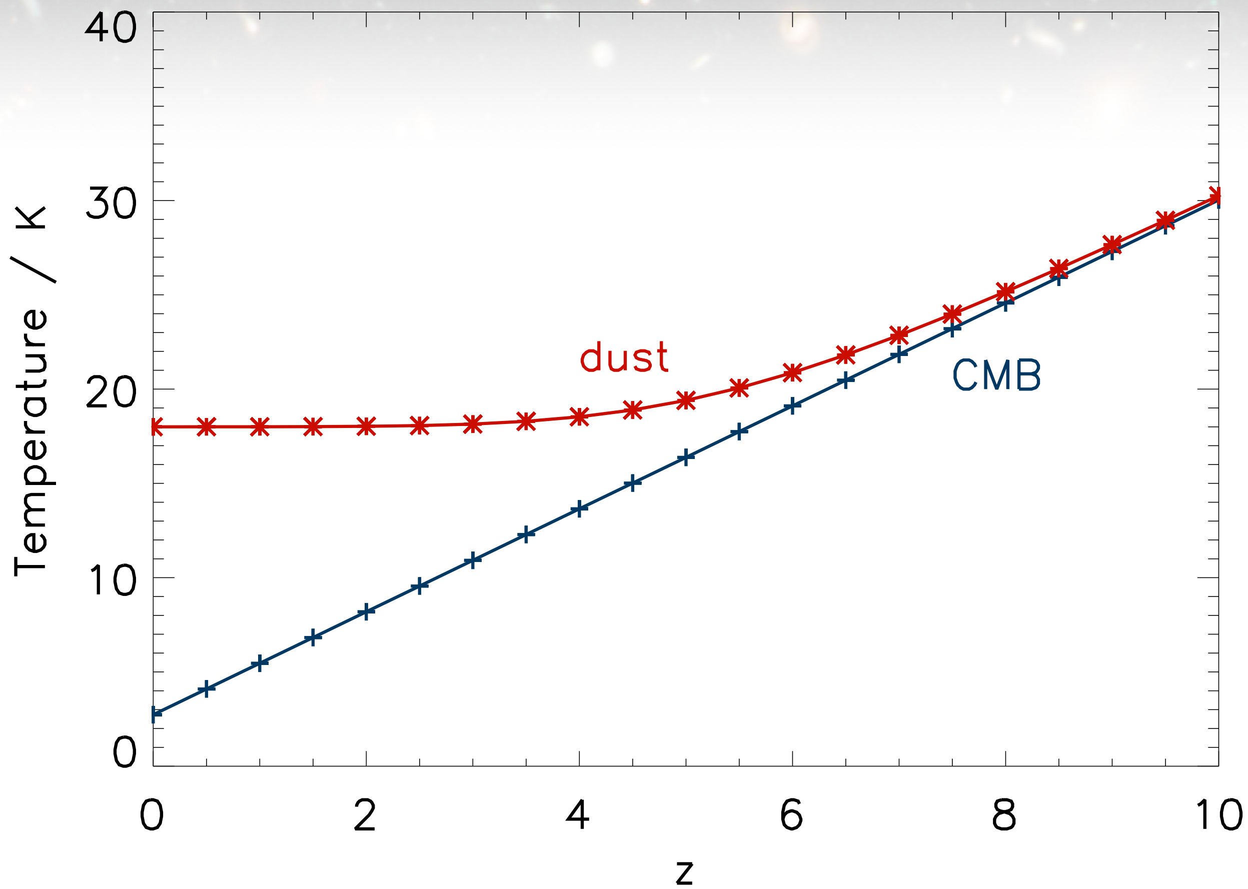
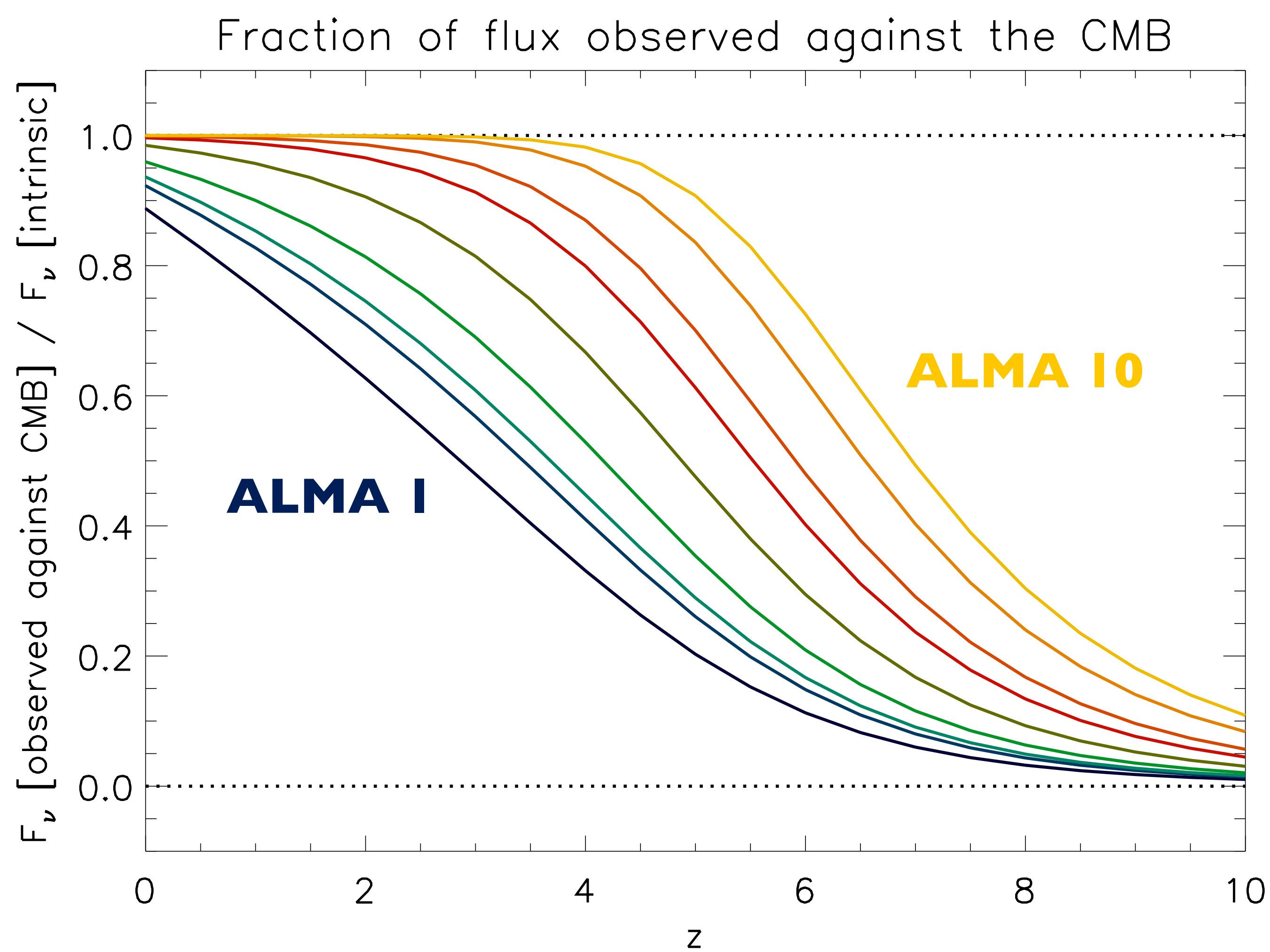


2. CMB is a **strong background** at high z



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

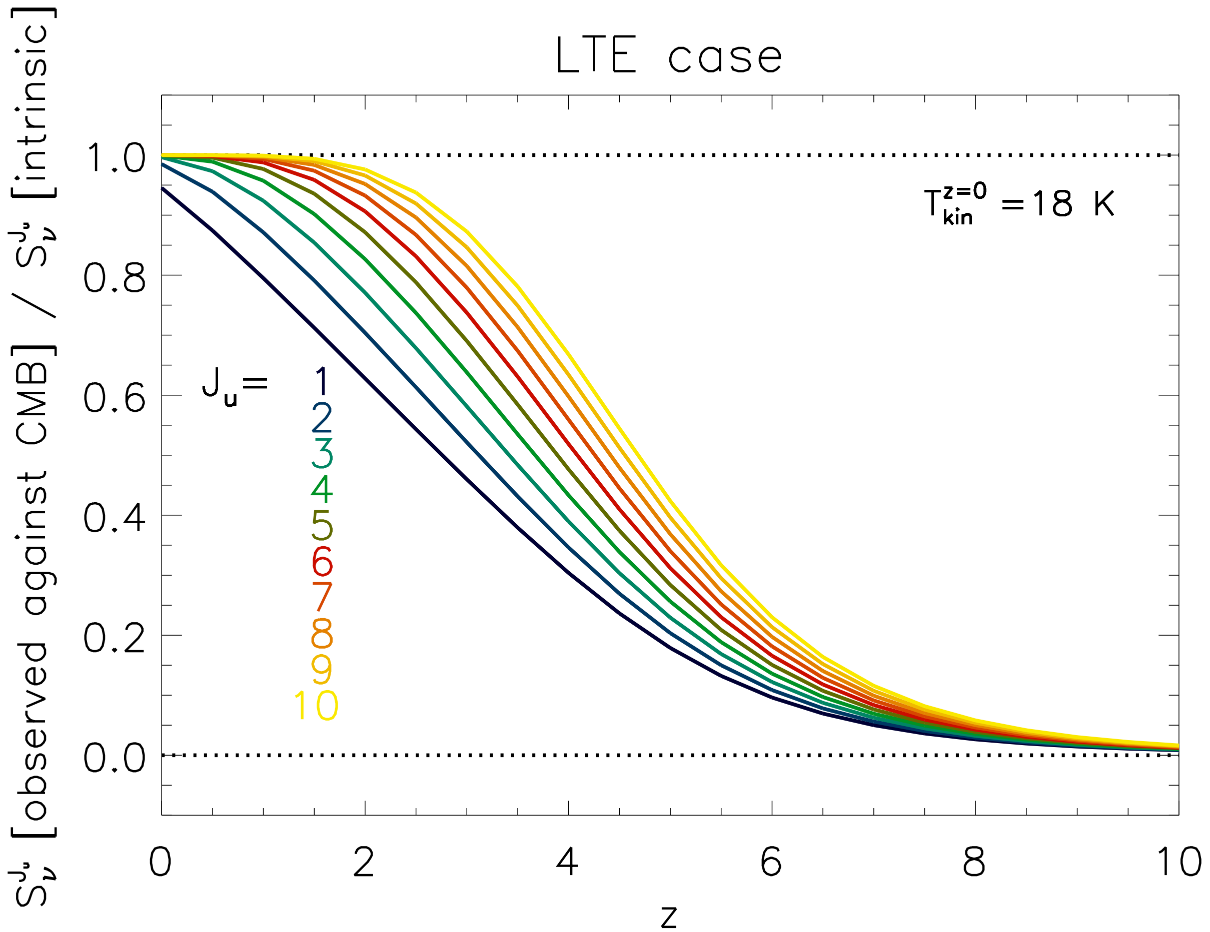
Effect of the CMB on CO line emission

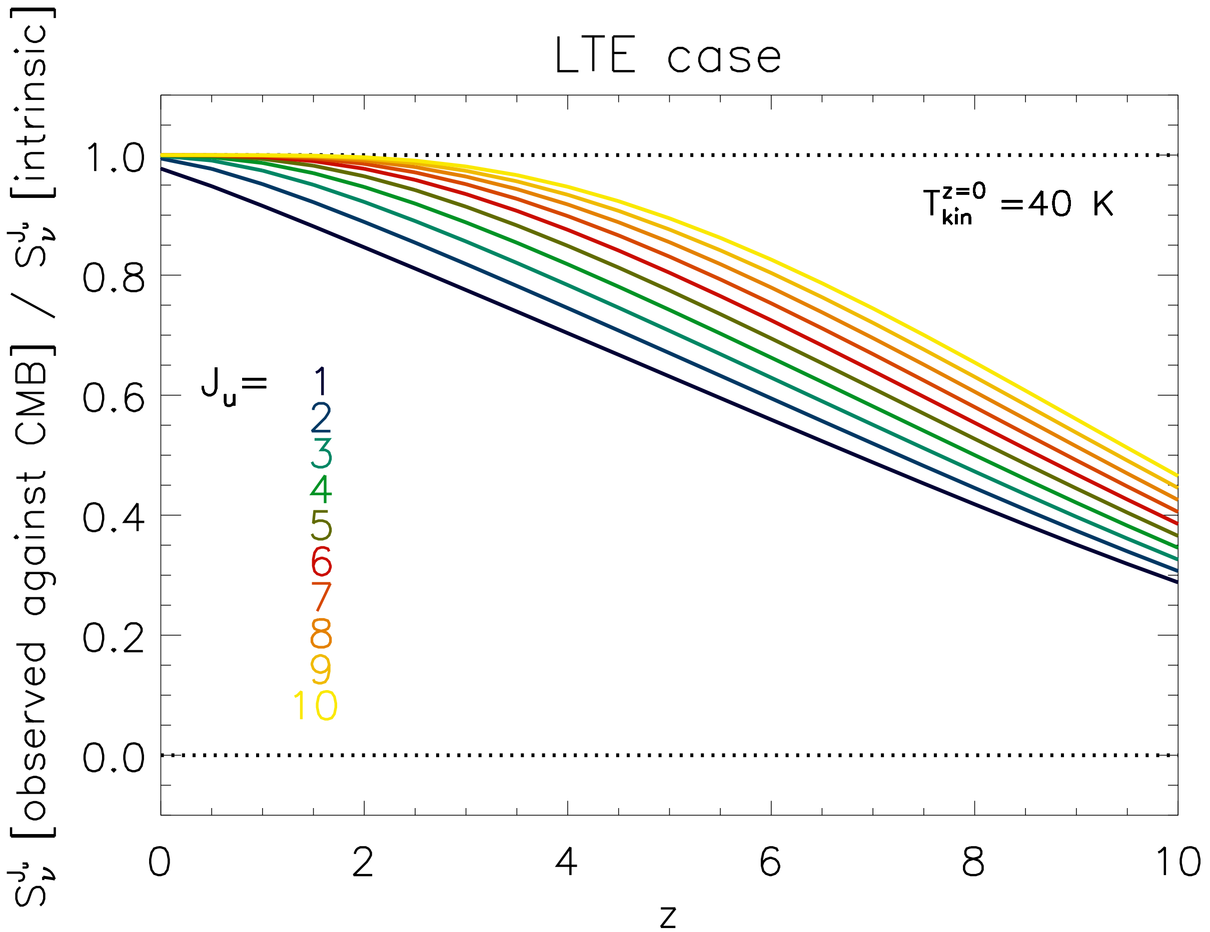
(see also e.g. Combes+1999, Papadopoulos+2000, Obreschkow+2009)

- Extra heating by the CMB: increase in excitation temperature of the gas

- Fraction of intrinsic flux of each line that is observed against the CMB:

$$\frac{S^J_{\nu/(1+z)}[\text{obs. against CMB}]}{S^J_{\nu/(1+z)}[\text{intrinsic}]} = 1 - \frac{B_\nu[T_{\text{CMB}}(z)]}{B_\nu[T^J_{\text{exc}}]}$$





Spectral models for cosmic noon & beyond

- **Evolution of young stellar populations**

  Rotation & multiplicity affect the UV emission of low metallicity massive stars

  TP-AGB stars - not as near-IR bright as previously thought

- **Star formation histories**

  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? Need flexible prescriptions.

- **Modern fitting techniques**

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