Galaxy physical parameters from spectral modelling:

recent successes and future challenges

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Outline

1) Motivation and ‘historical’ perspective
2) Overview of SED modelling ingredients
3) A brief summary of current models/codes
4) Some successes
5) Some challenges

Motivation

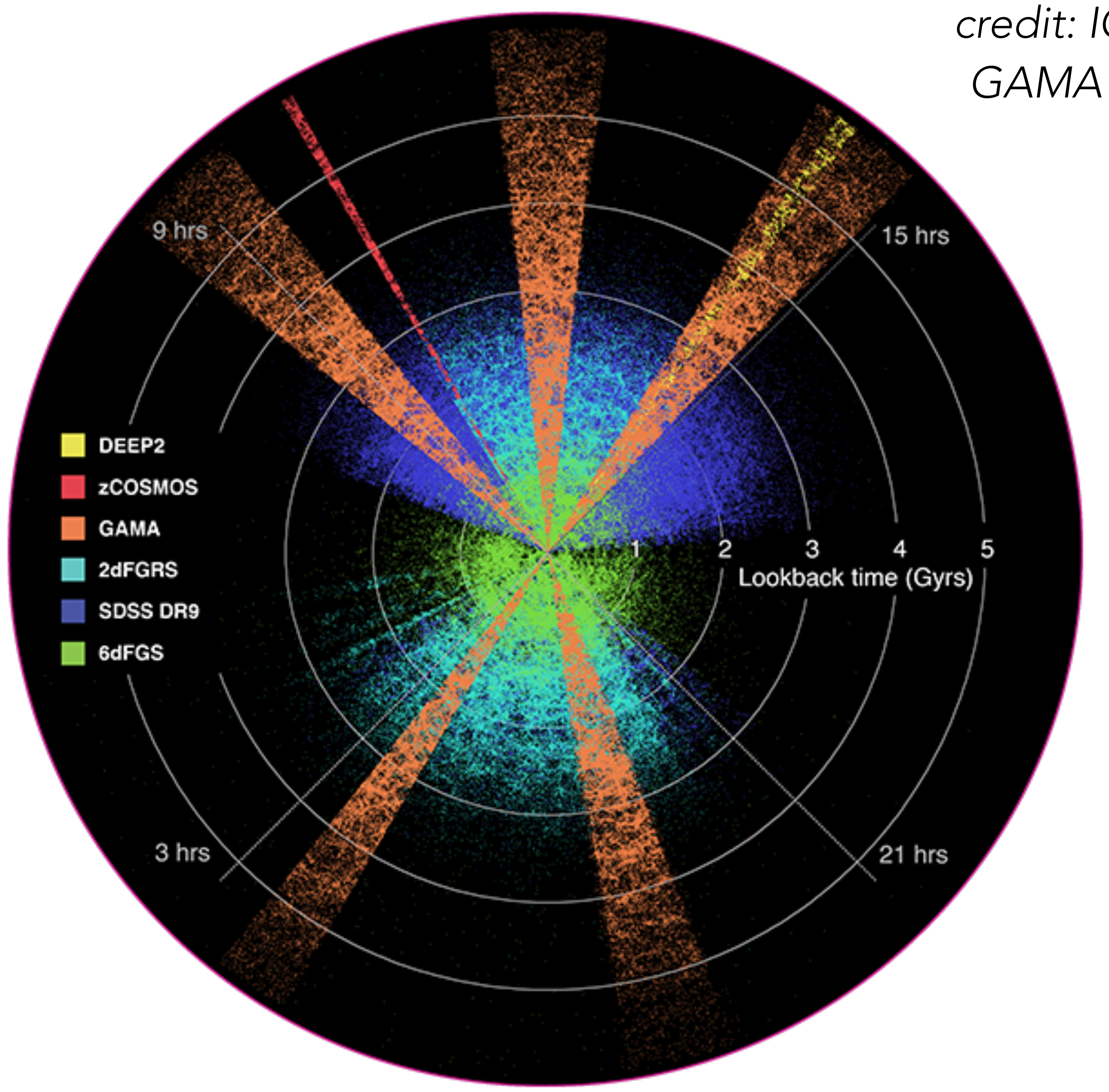
In the last ~20 years we have had an explosion of large `statistical' surveys of galaxies, sampling their emission **from the ultraviolet to the infrared/radio**, with surveys spanning most of the history of the Universe, and pushing towards increasingly higher redshifts.

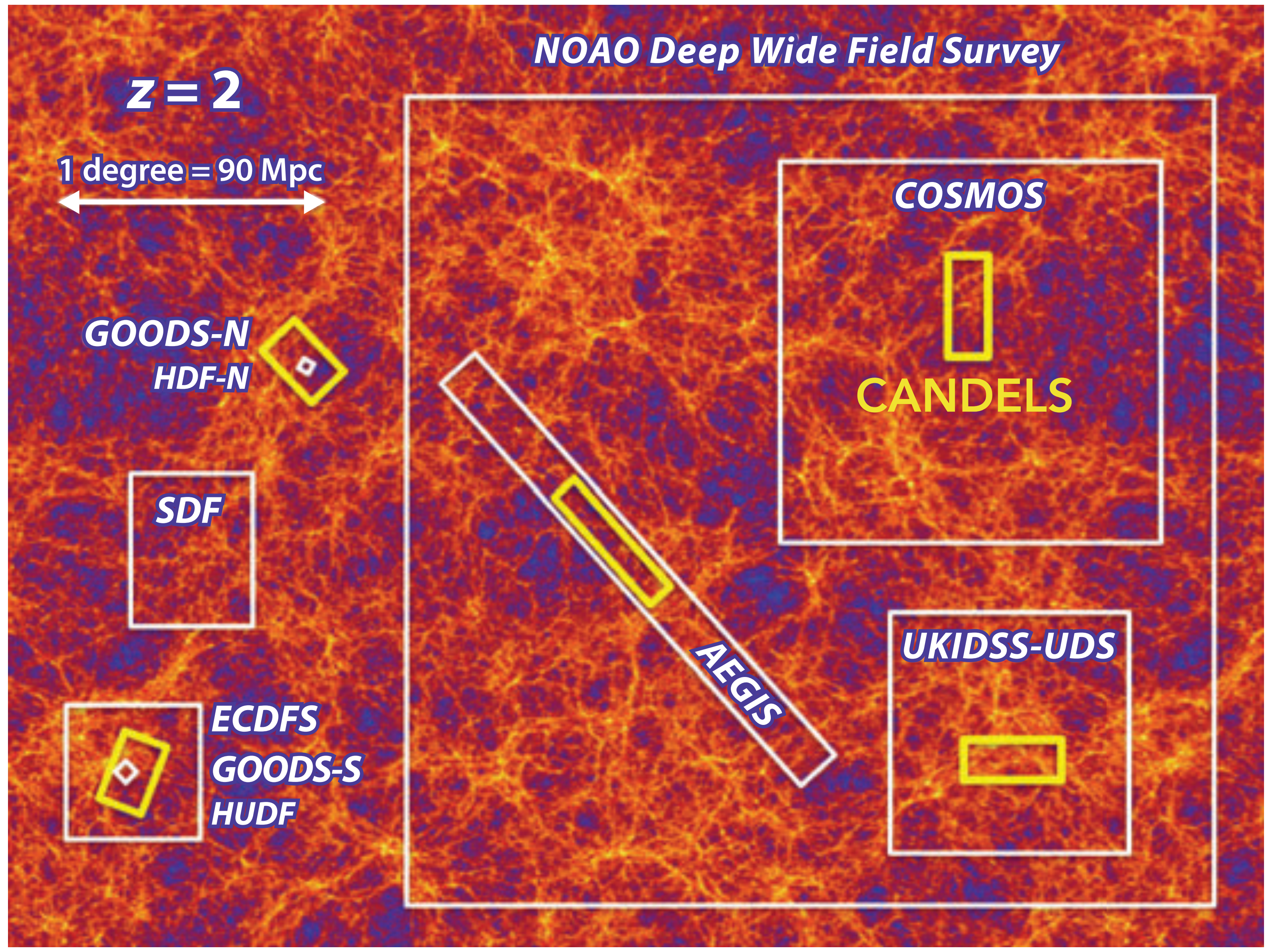
e.g., local galaxy surveys:
SDSS [+GALEX, WISE, etc]
(Kauffmann+2003, Brinchmann+2004, Chang+2015, Salim+2016)

e.g., multi-wavelength local galaxy surveys [GALEX to Spitzer/Herschel]
SINGS (Kennicutt+2003), KINGFISH (Kennicutt+2011),
GAMA (e.g., Driver+2011)

e.g., deep `cosmological surveys'
COSMOS (e.g., Capak+2007, Laigle+2016, Weaver+2022)
3D-HST/CANDELS (Koekomoer+2011,Brammer+2012)
now: JWST (and ALMA!)

credit: ICRAR/ GAMA team





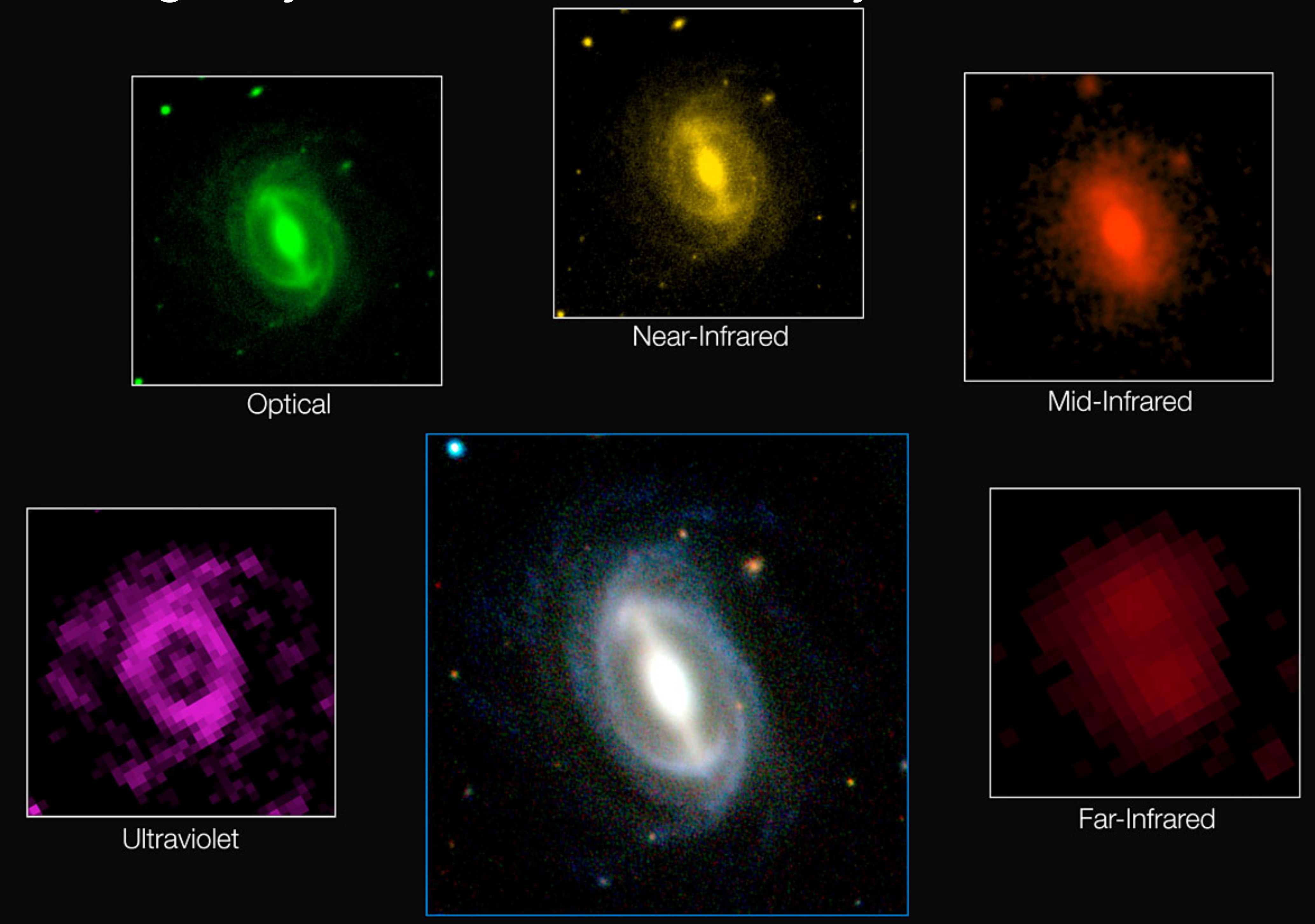
Madau & Dickinson (2014)

The multi-wavelength view of galaxies

We now have access to the multi-wavelength spectral energy distributions of galaxies across cosmic time, from the UV to the (sub-)millimetre/radio.

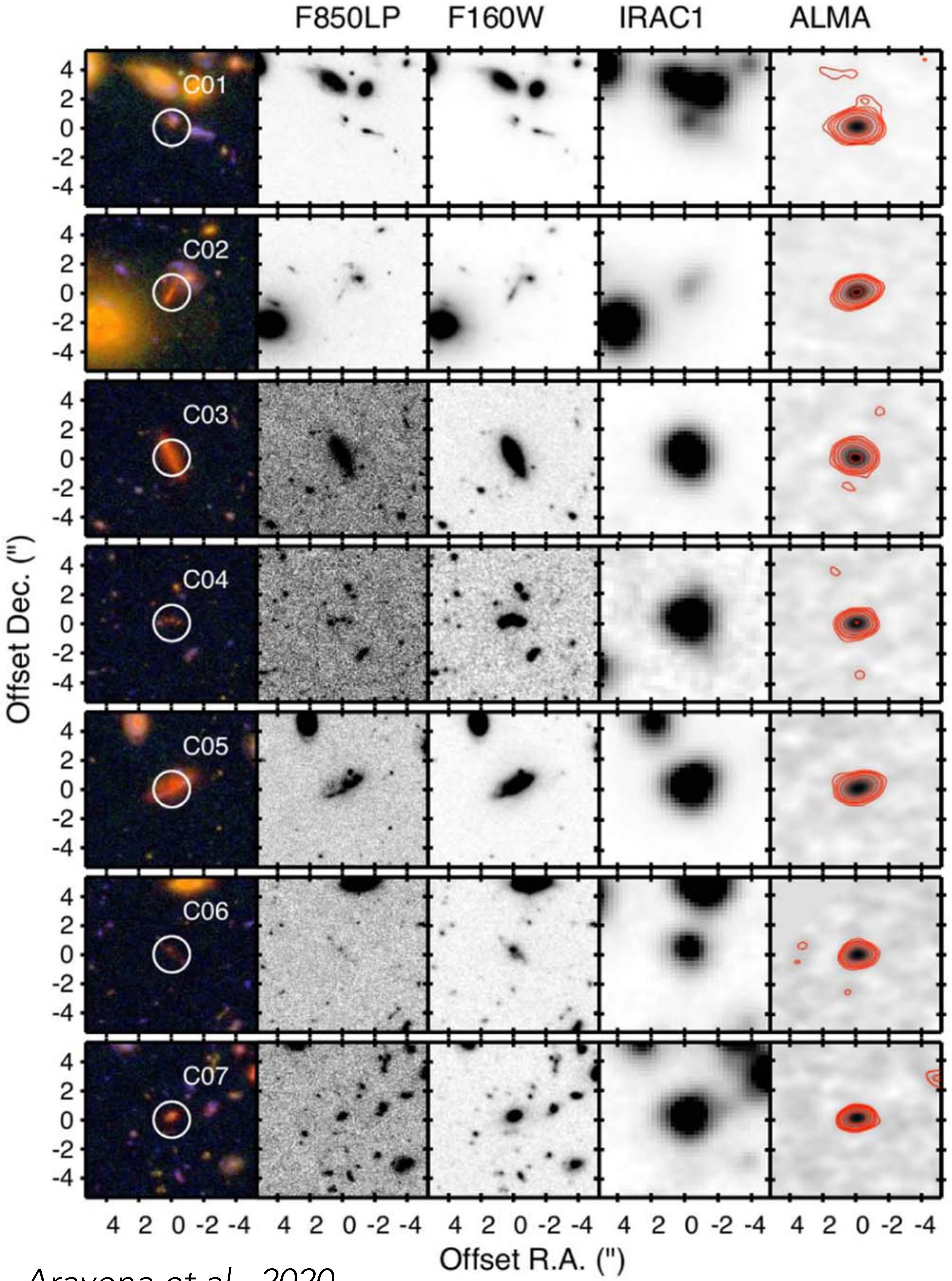
A challenge: obtaining matched photometry across all wavelengths

A local galaxy from the GAMA survey



credit: *ICRAR/GAMA and ESO*

z~1-3 galaxies from the ASPECS survey



Aravena et al., 2020

The need for SED models

Observed multi-wavelength emission
(UV, optical, infrared, radio)

↓↑

Spectral energy distribution model

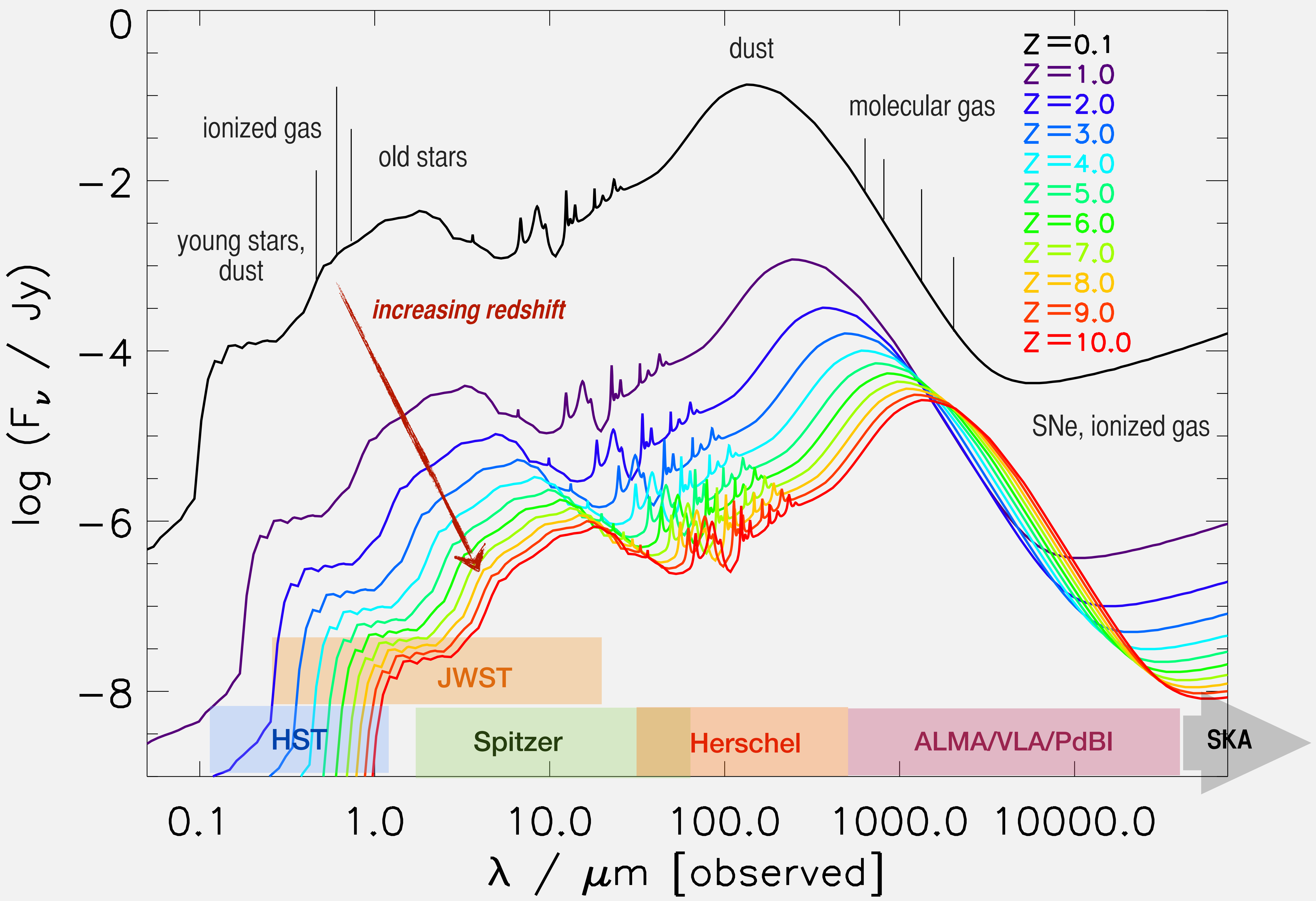
↓↑

Physical parameters:
star formation rate (history?)
stellar mass
stellar & gas-phase metallicity
dust attenuation
dust mass, dust temperature
AGN properties

↓↑

Galaxy formation and evolution
model / theory predictions

(simplified) spectral energy distribution of a star-forming galaxy



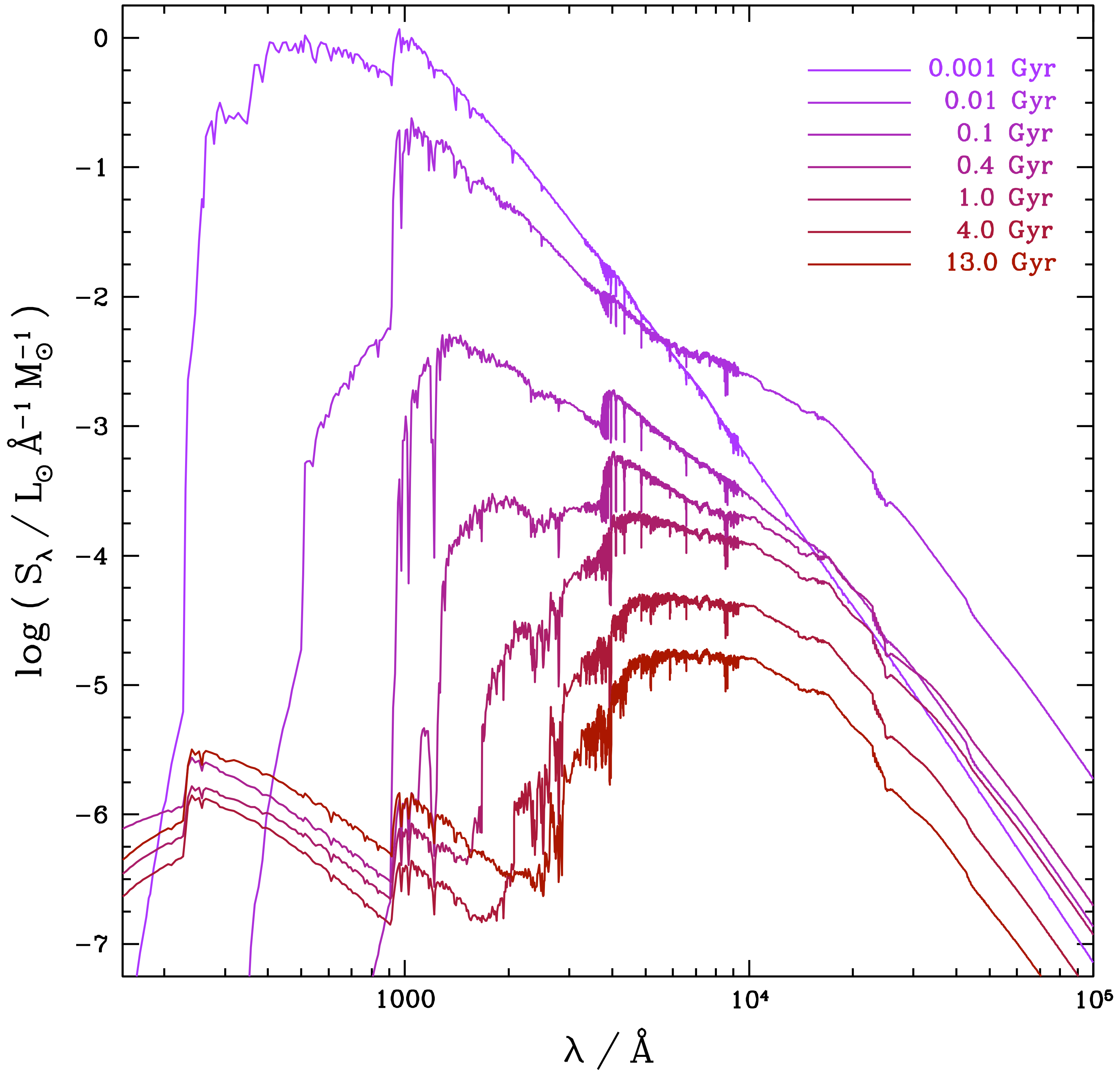
Ingredients

1) Stellar emission
2) Interstellar medium
3) AGN
4) 'Cosmological effects'

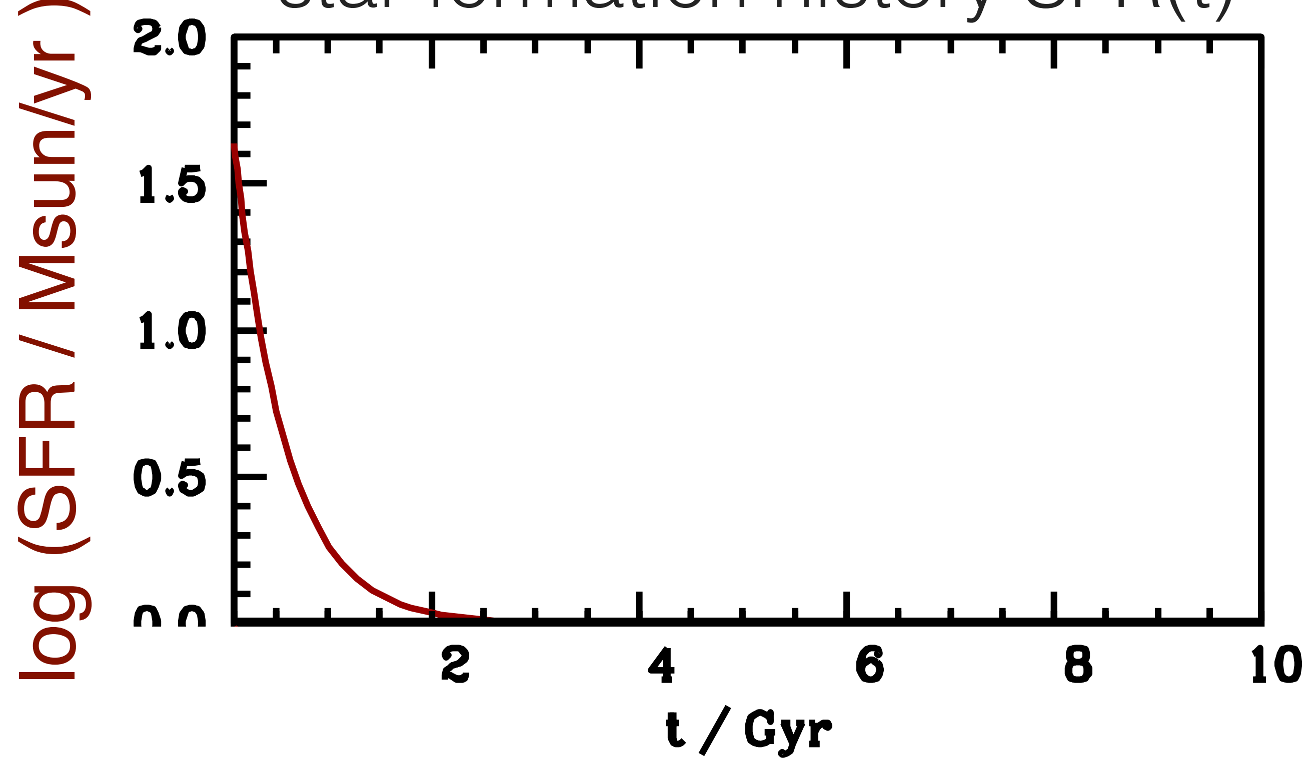
Stellar emission

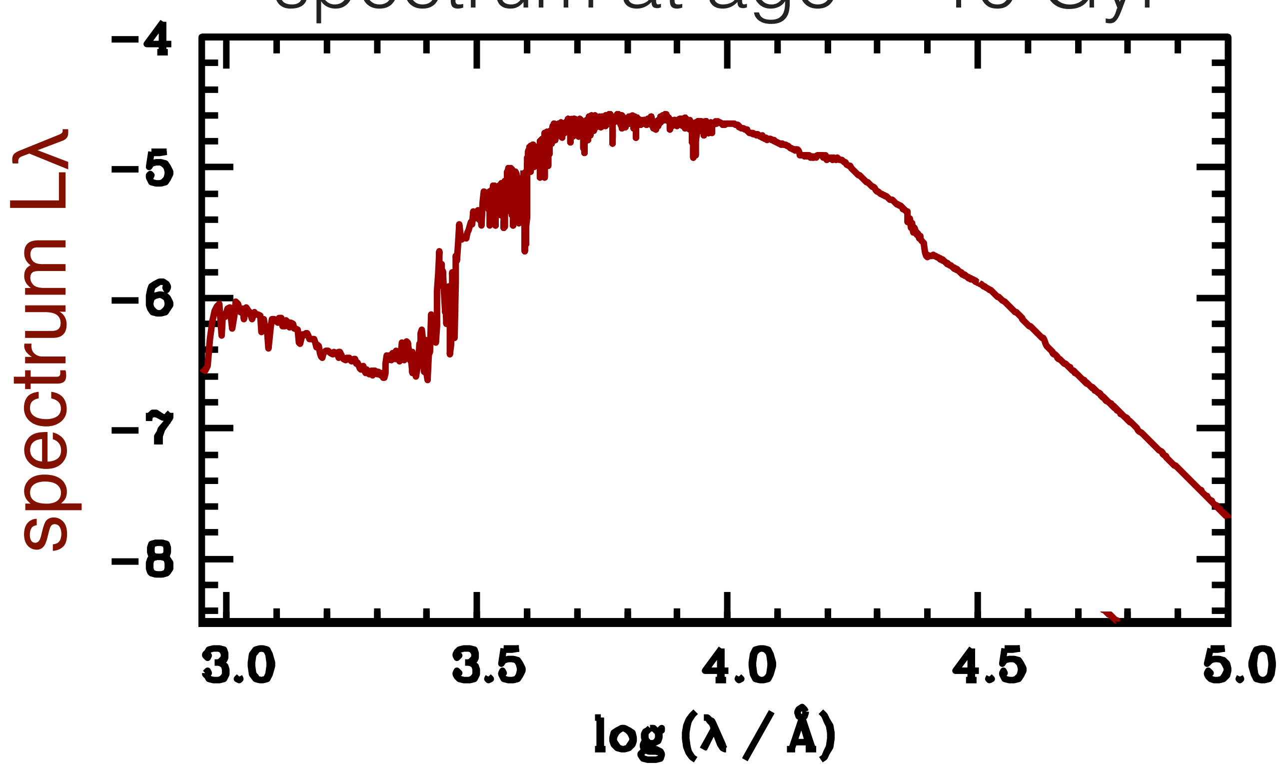
1) Isochrones (i.e. stellar evolution)
2) Initial mass function
3) Spectral libraries
4) Star formation histories
    - parametric/non-parametric
    - continuous/bursty
5) Metallicity evolution

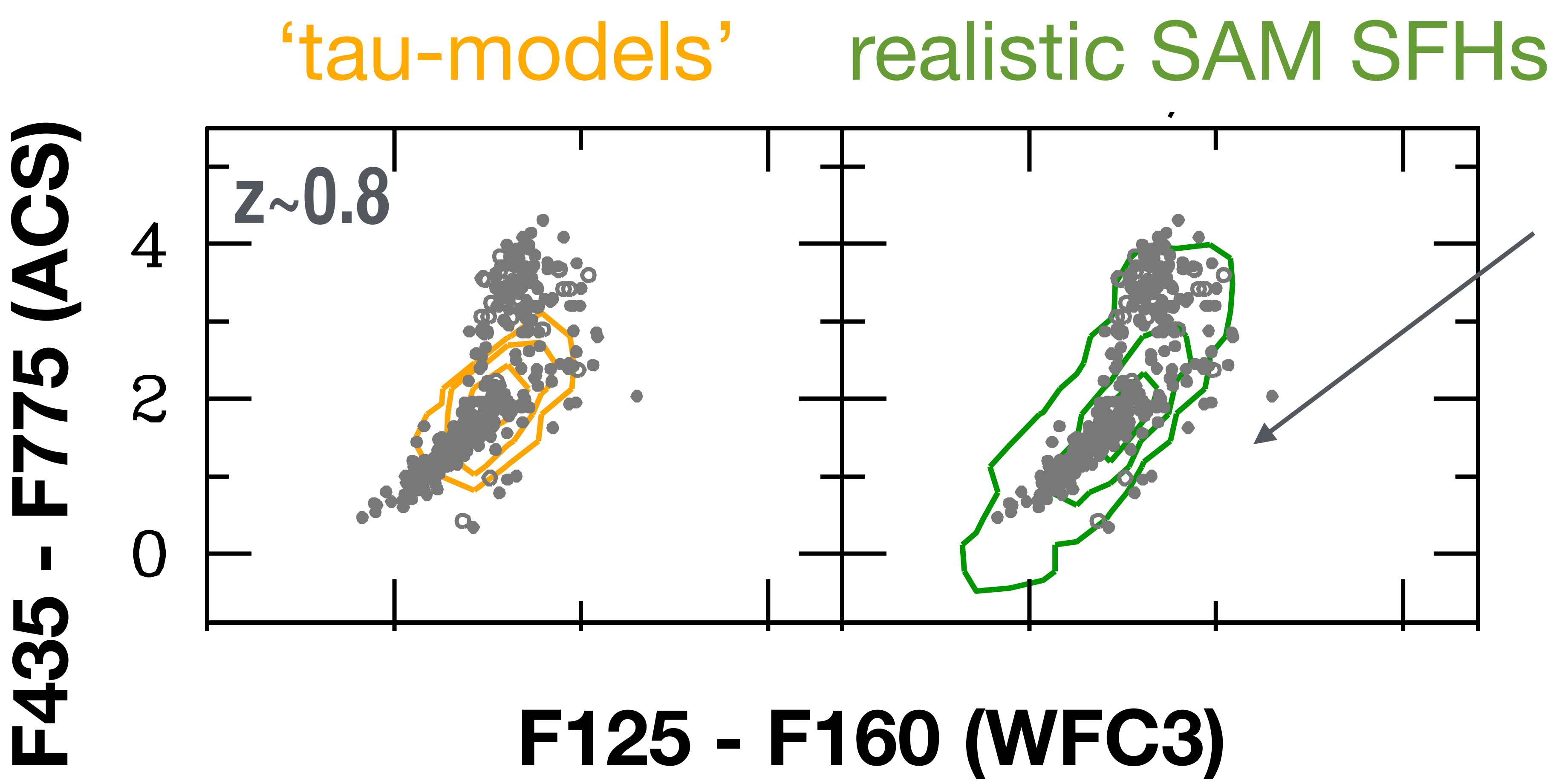
Bruzual & Charlot (2003)



spectrum of a SSP at a given age
=
IMF-weighted sum of the spectra of stars along the isochrone (location in the HR diagram) at that age

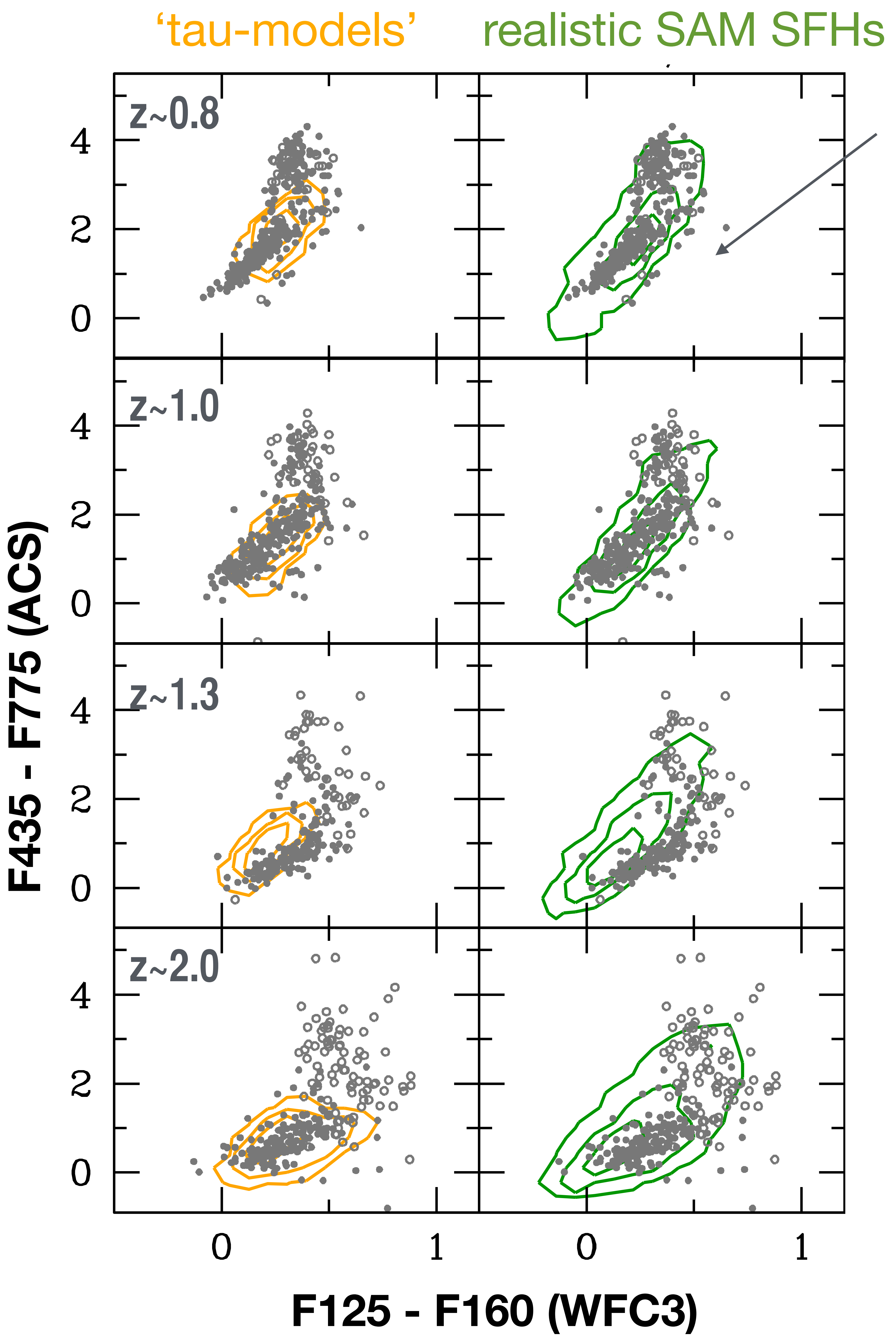






Points: 1048 (down to H=23) 3D-HST galaxies in GOODS-South

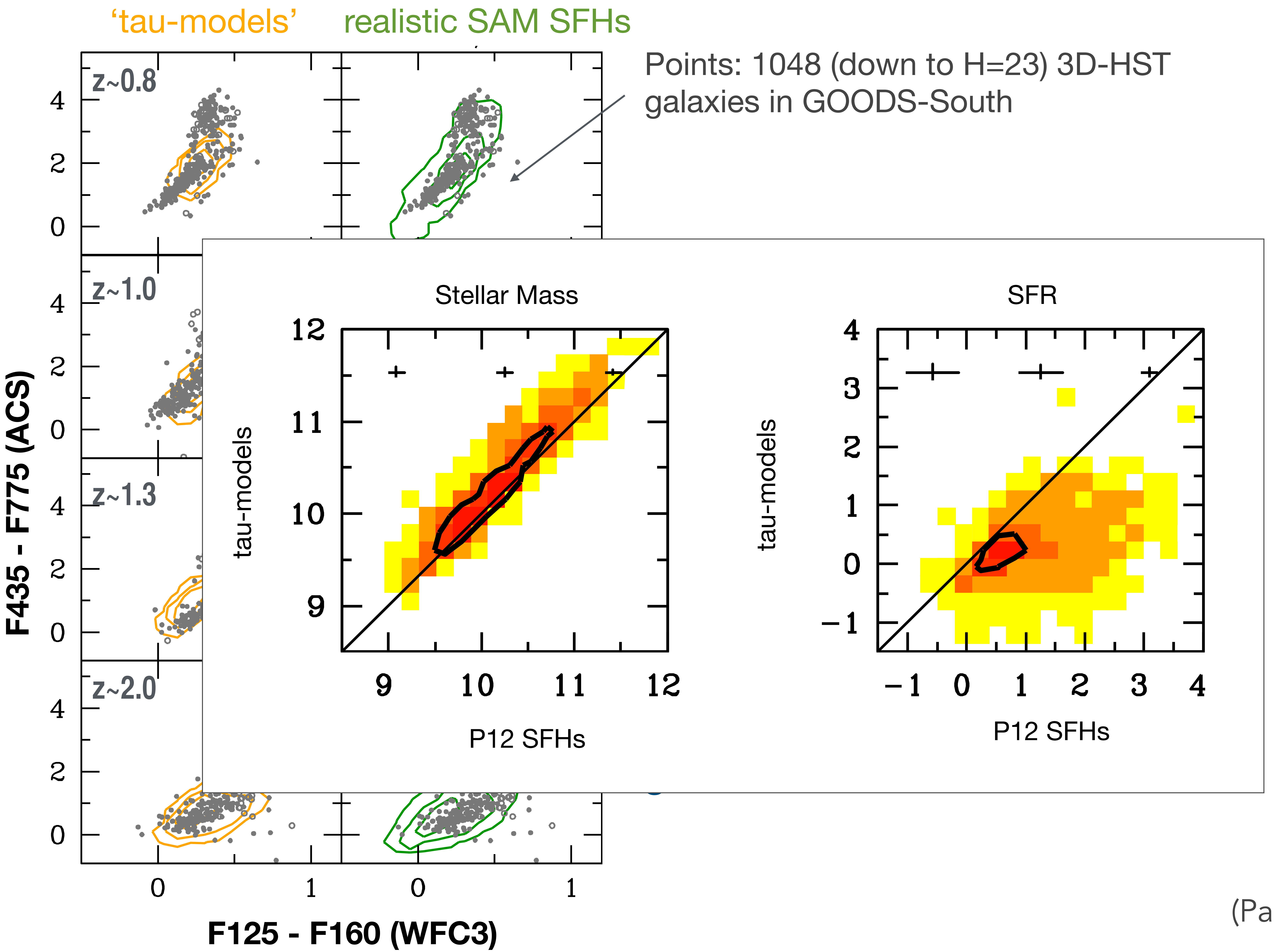
(Pacifici+2015)



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

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

(Pacifici+2015)



(Pacifici+2015)

Interstellar medium

1) Dust attenuation

2) Dust emission

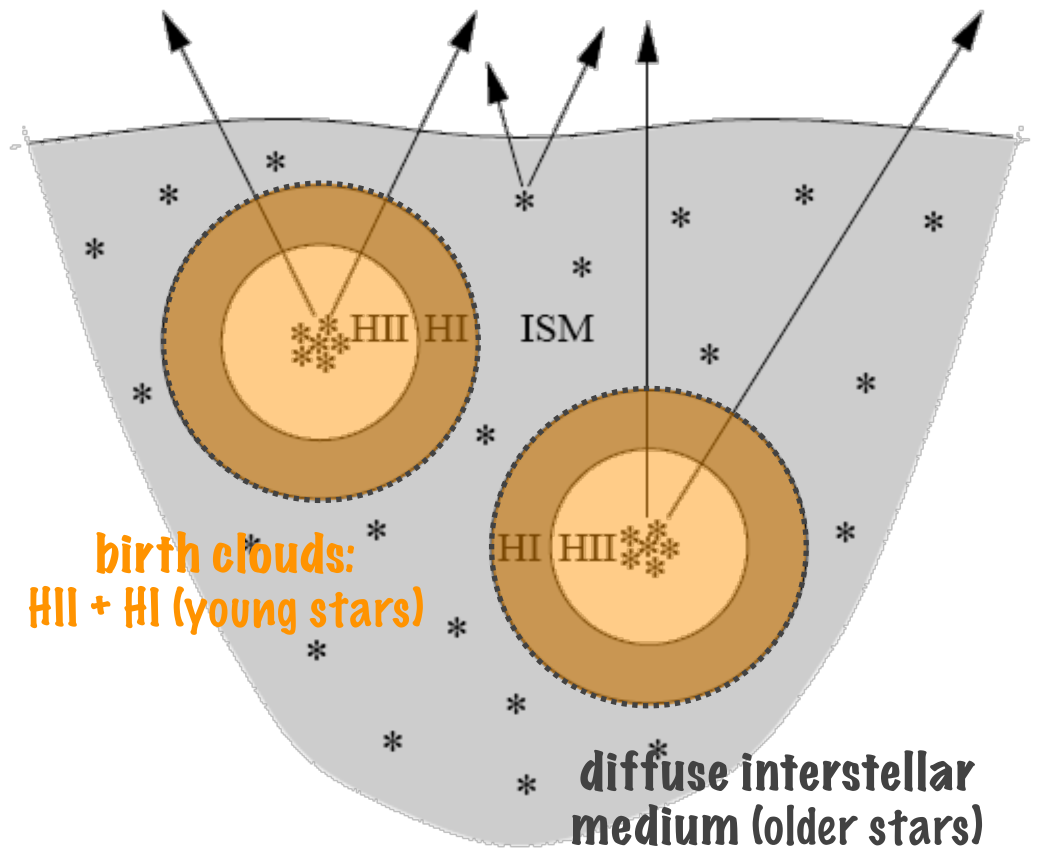
3) Nebular emission

(lines+continuum)

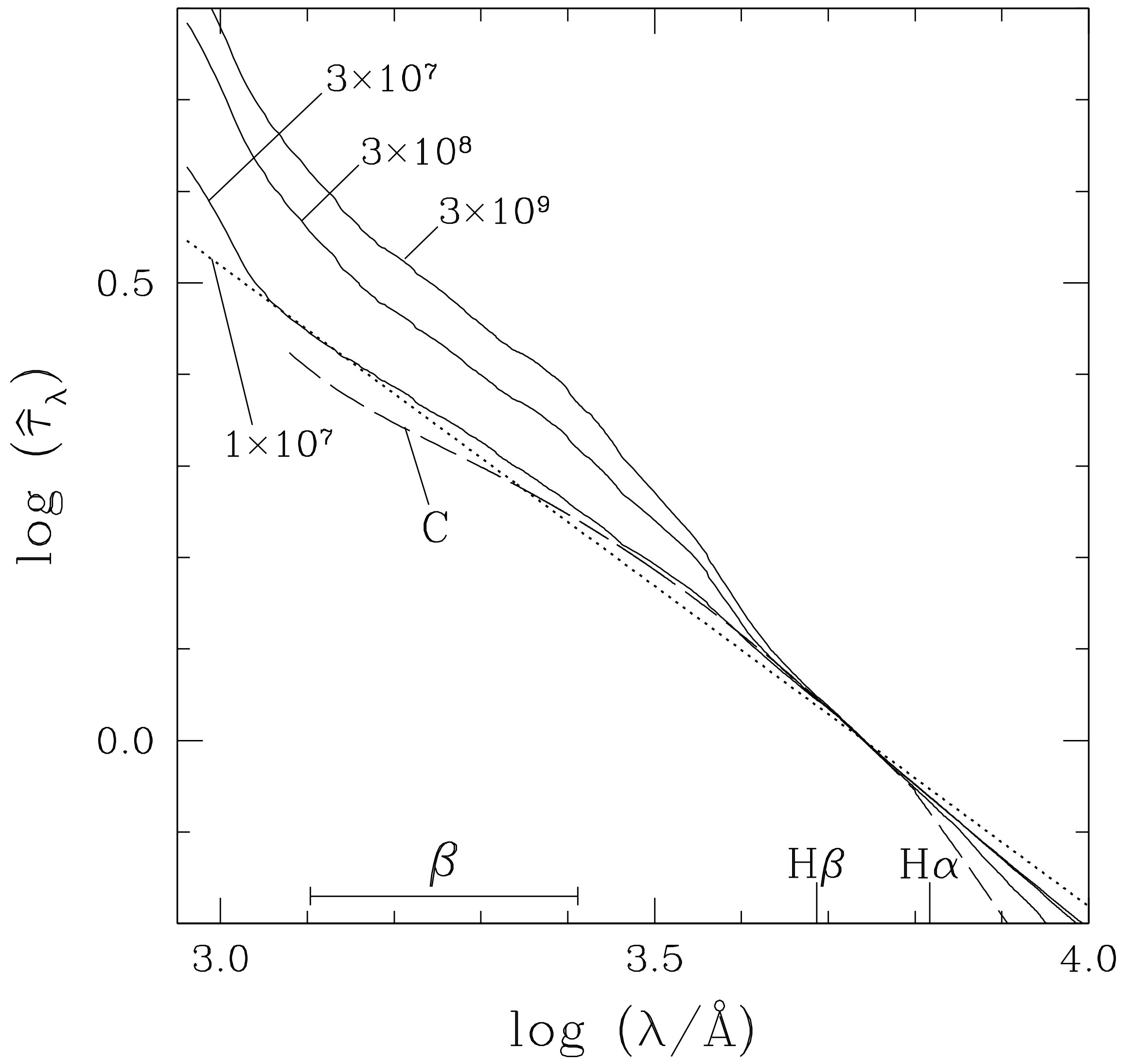
4) Radio emission

- 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.

Charlot & Fall (2000)



age-dependent attenuation



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

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

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

For an excellent review on dust attenuation see Salim & Narayanan (2020)

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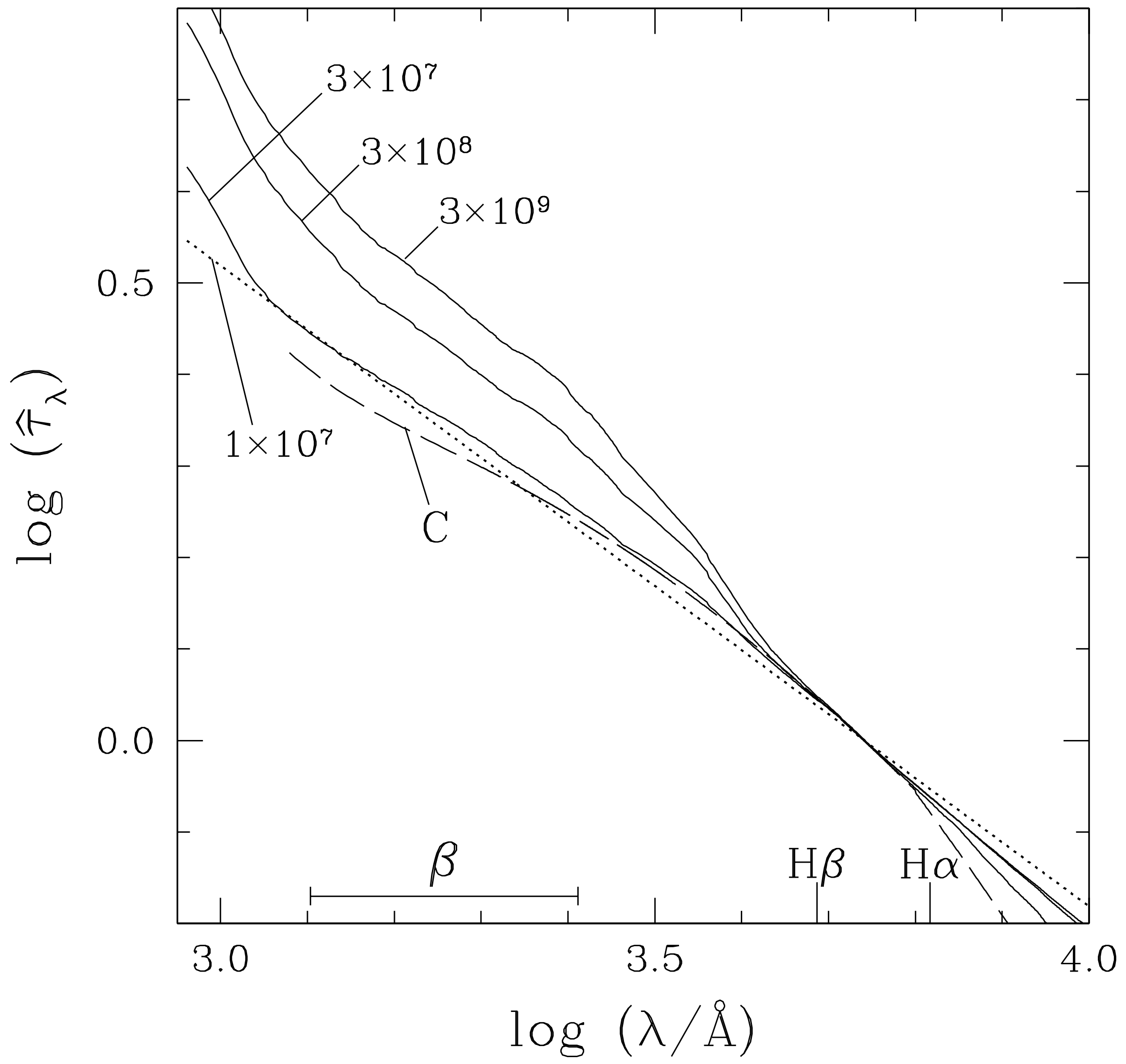

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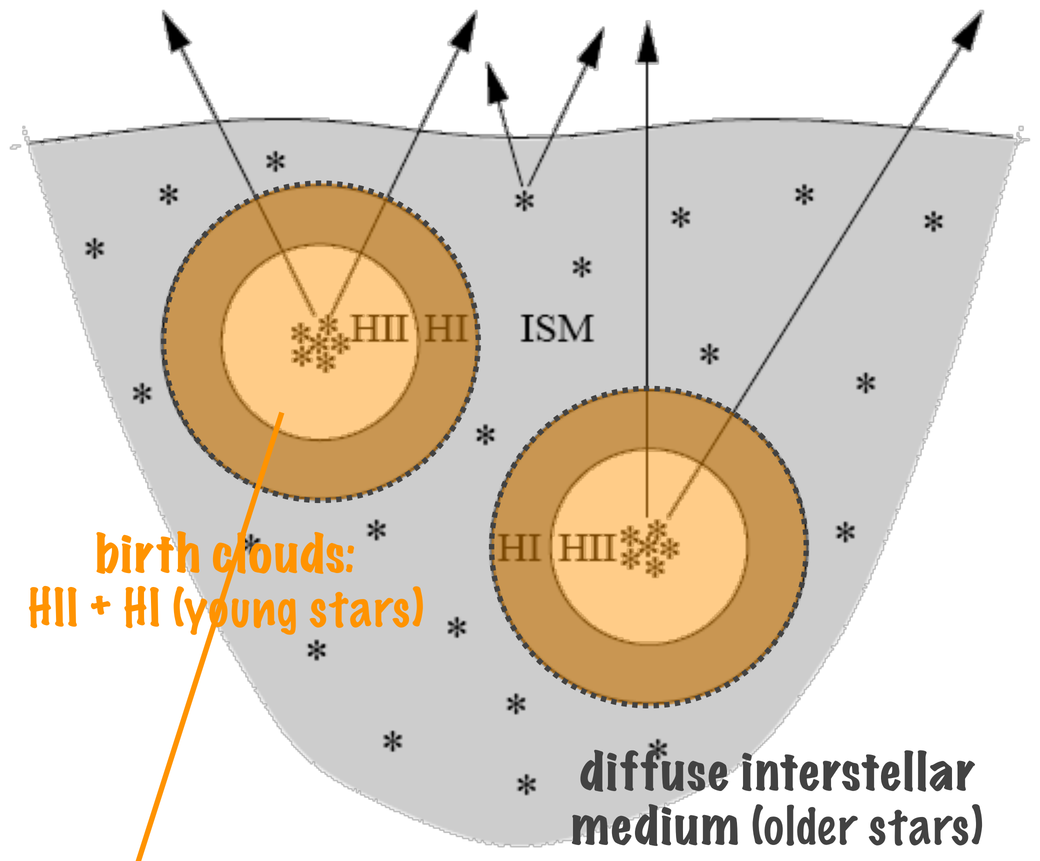
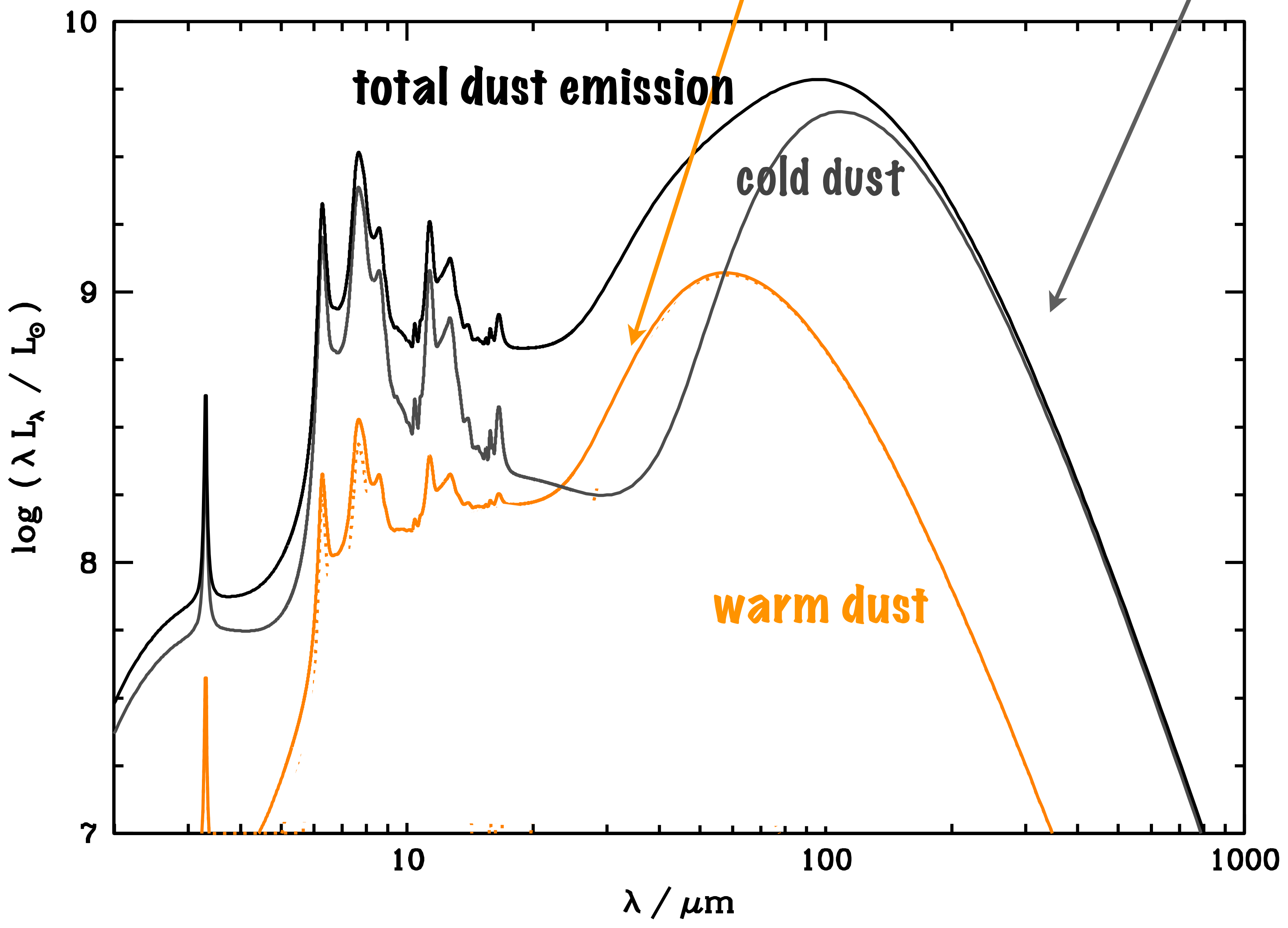




Energy balance

e.g. MAGPHYS (da Cunha+2008)

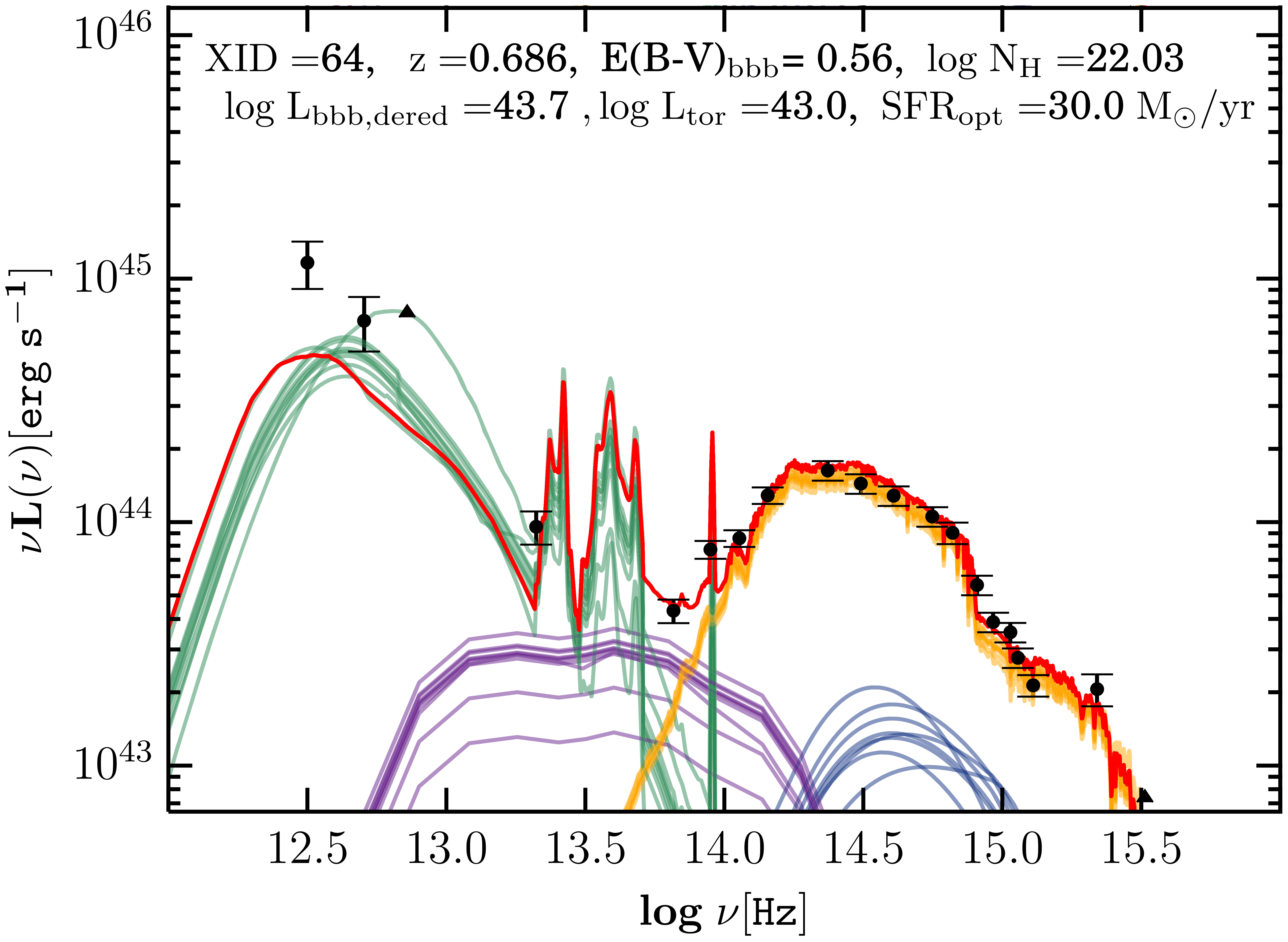
AGN

1) X-ray/UV/optical continuum

2) Emission lines (NLR and BLR)

3) Torus emission (dust)

4) Radio emission



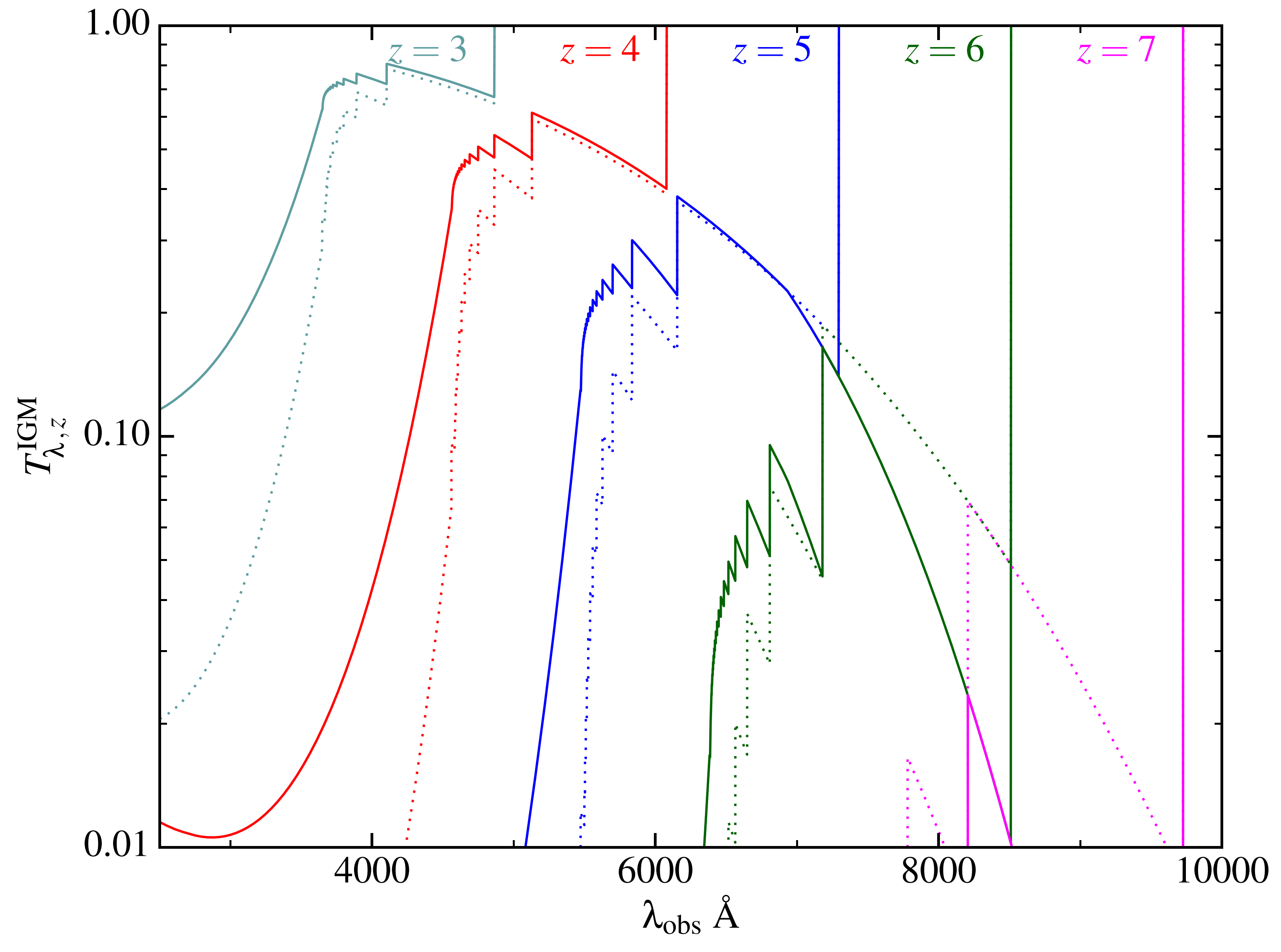
(Calistro Rivera et al 2016)

‘Cosmological effects’

1) IGM absorption (UV)

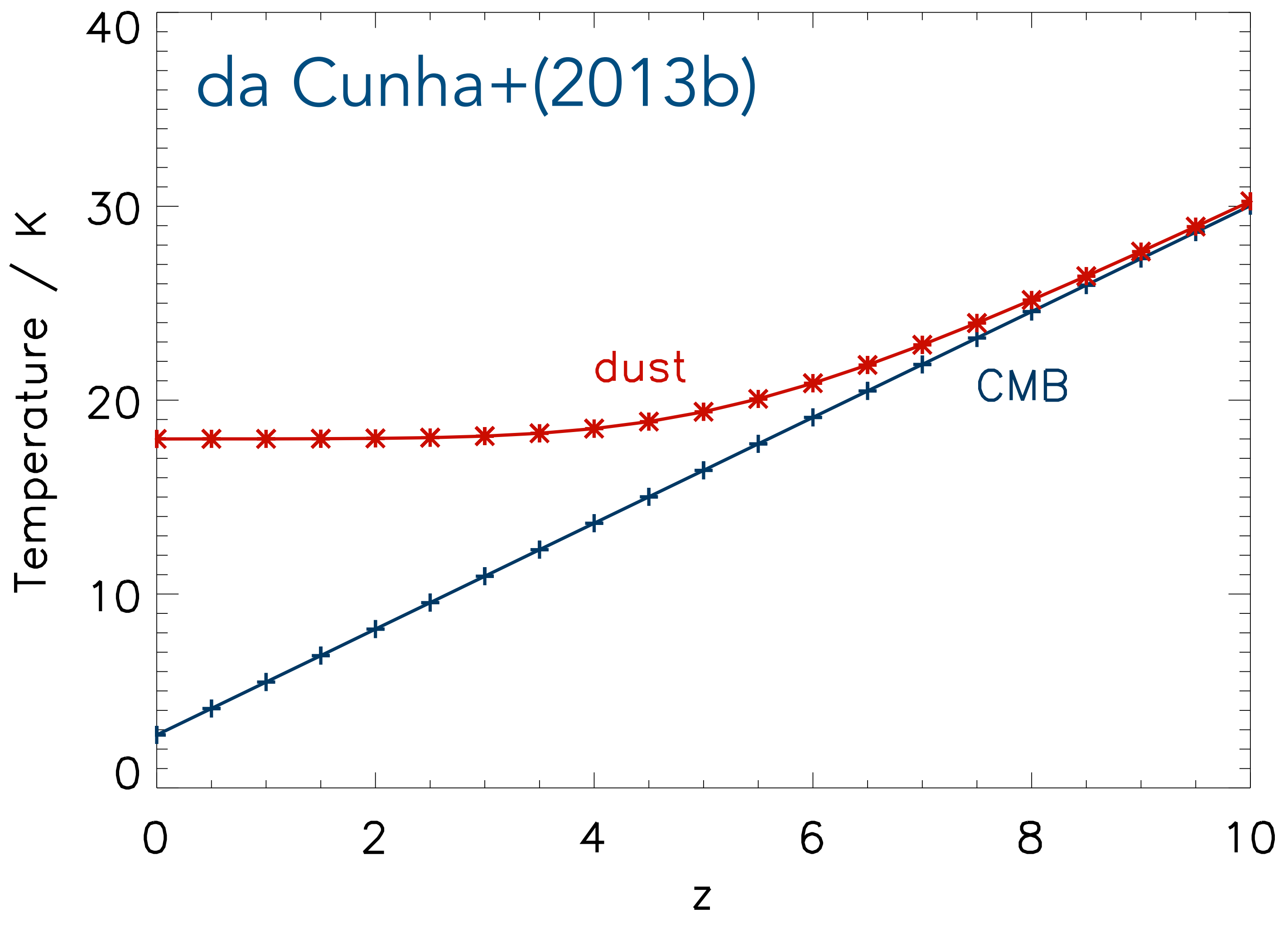
2) Effect of the CMB on cold dust emission

1) IGM absorption models



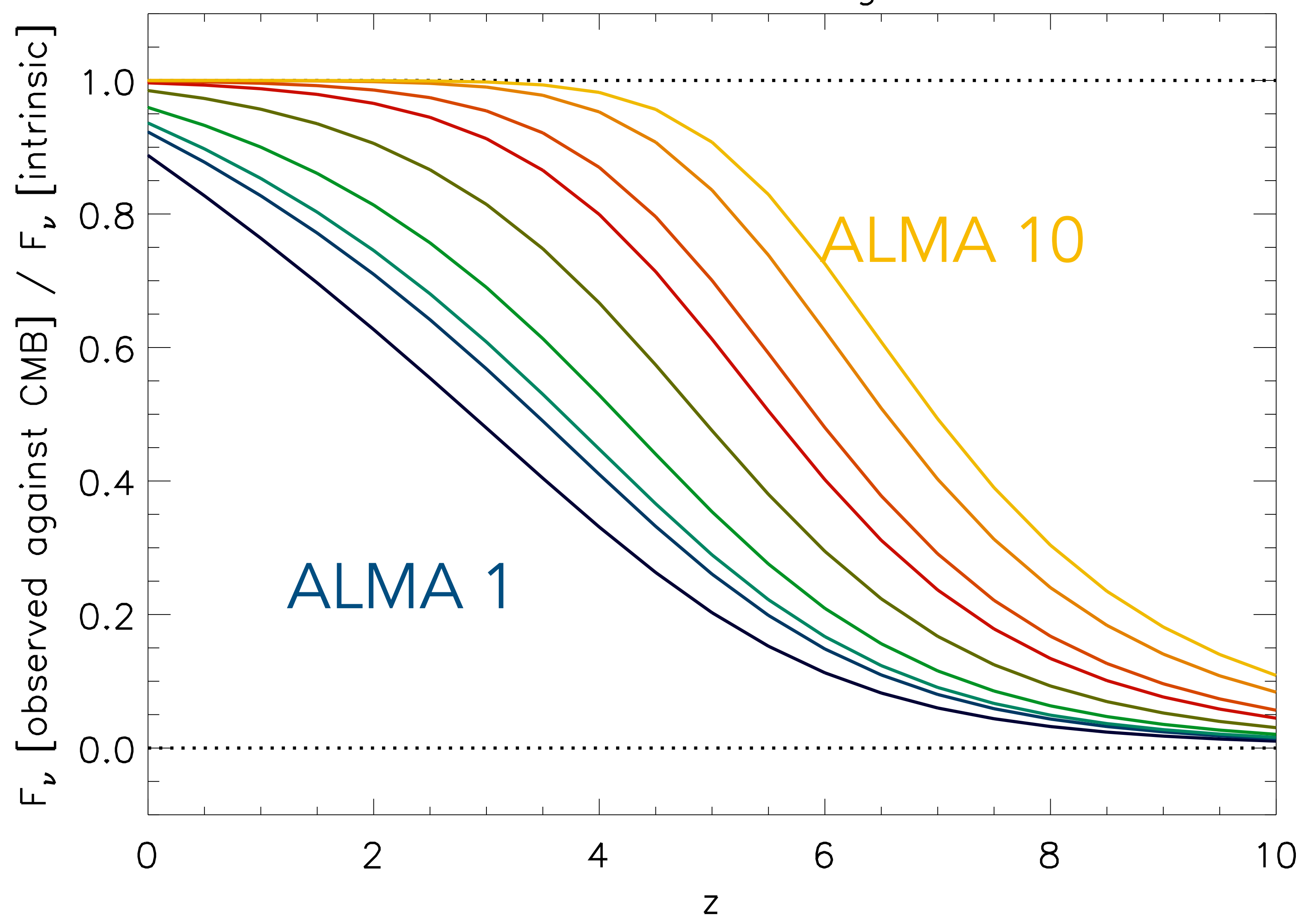
Chevallard & Charlot (2016)

2.1) **Extra heating** by the CMB

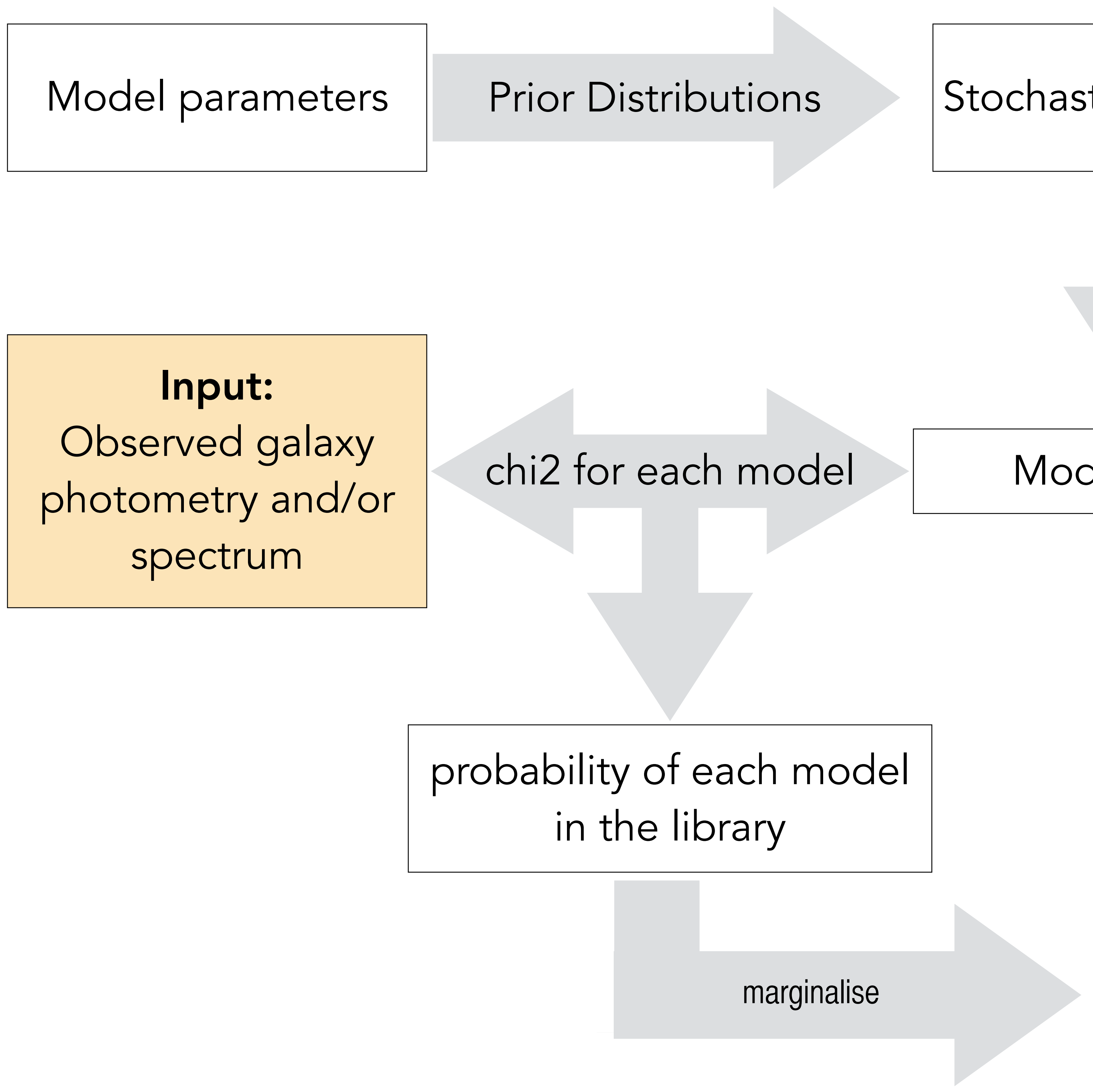


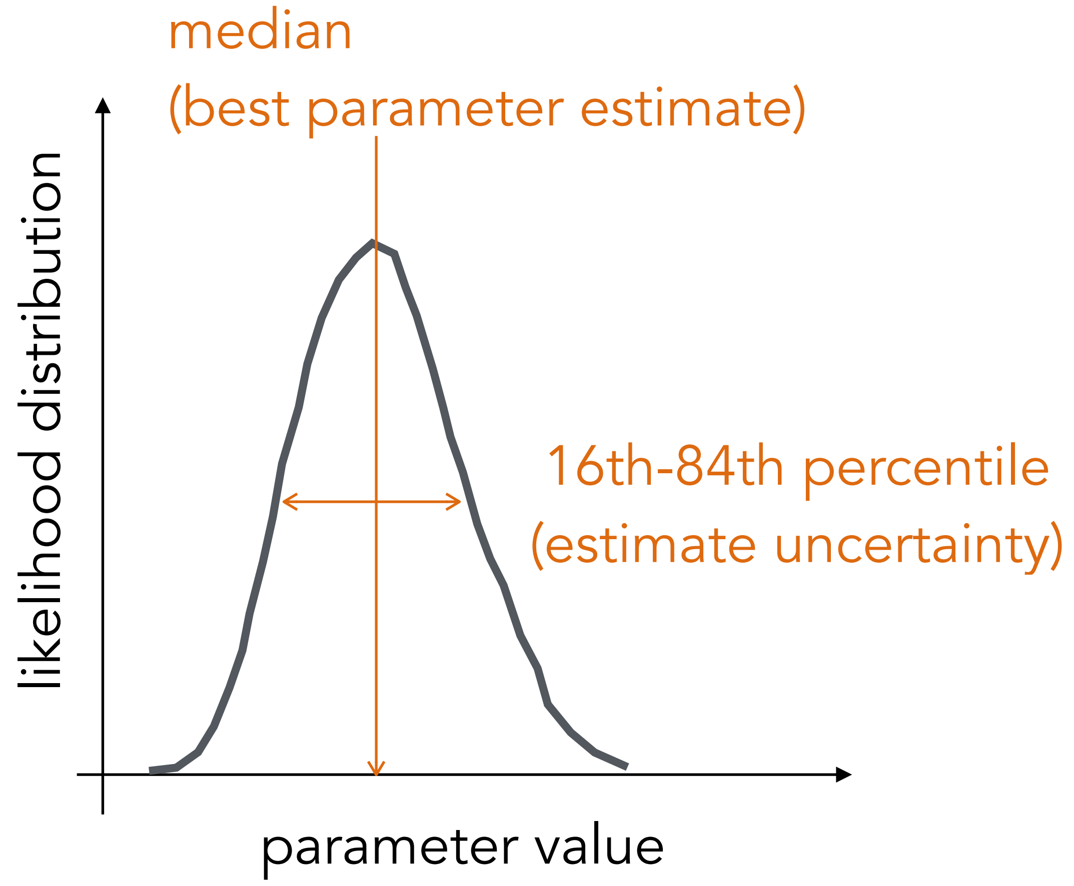
2.2) CMB is a **strong background** at high z

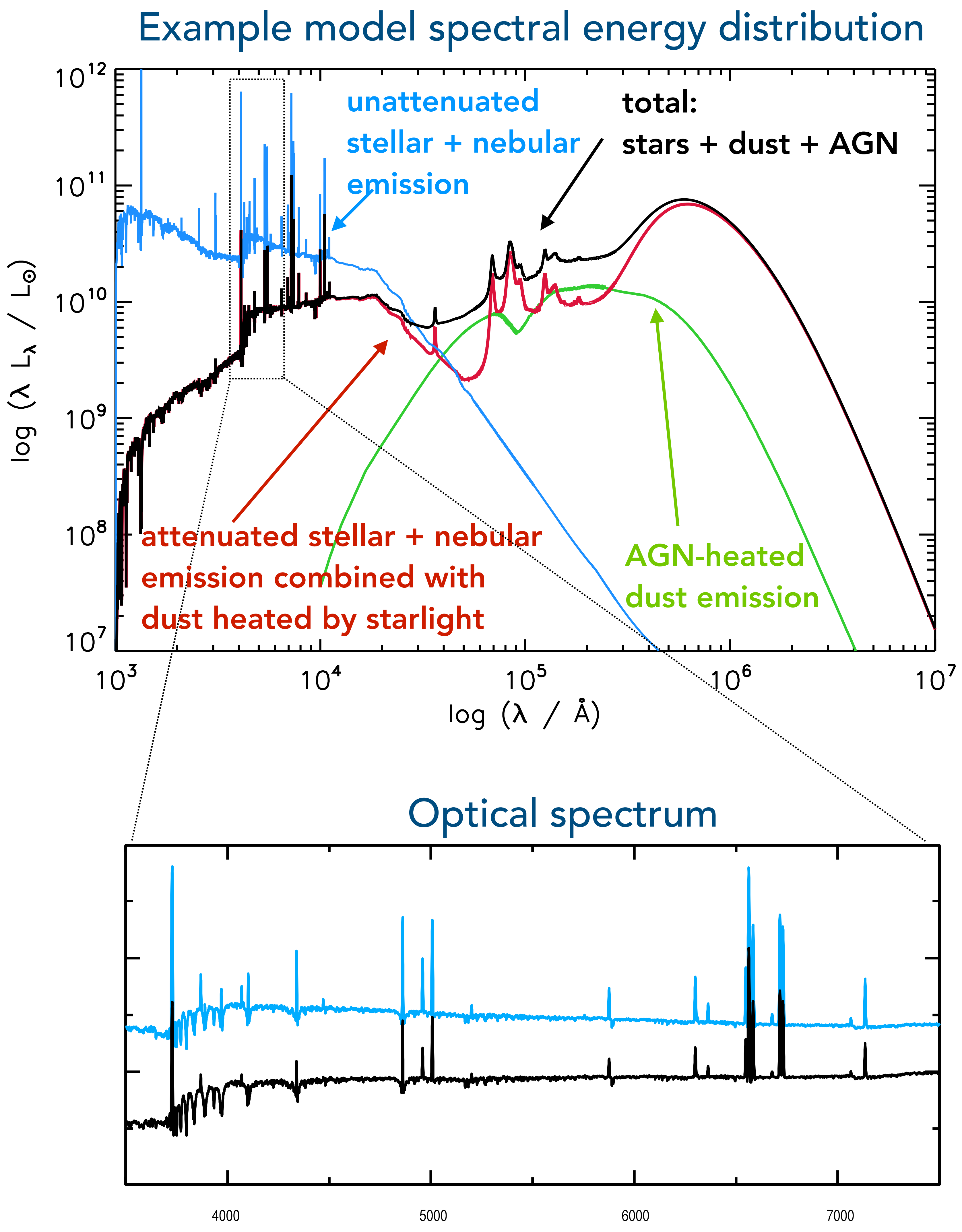
Fraction of flux observed against the CMB



Bayesian fitting methods

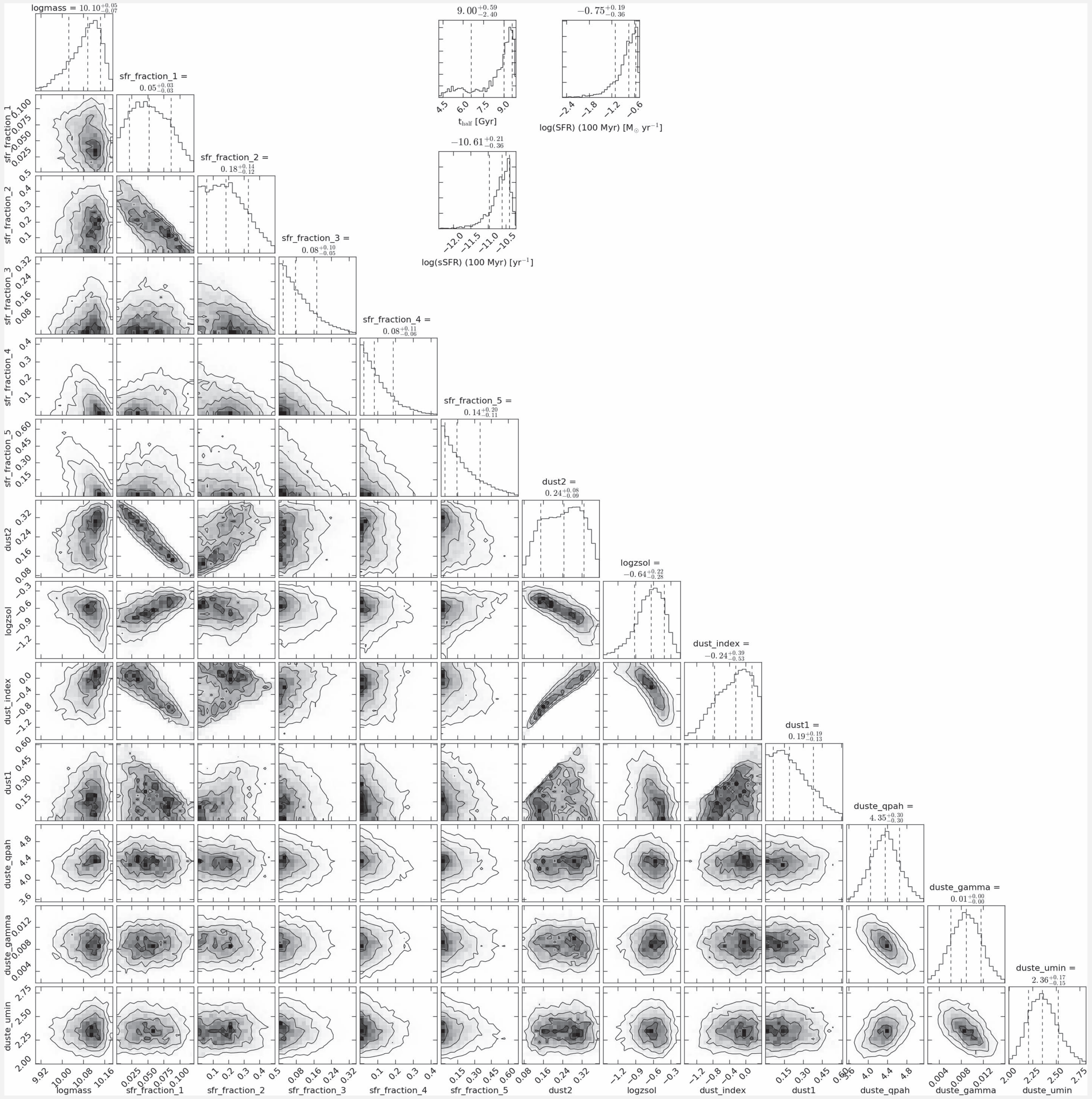




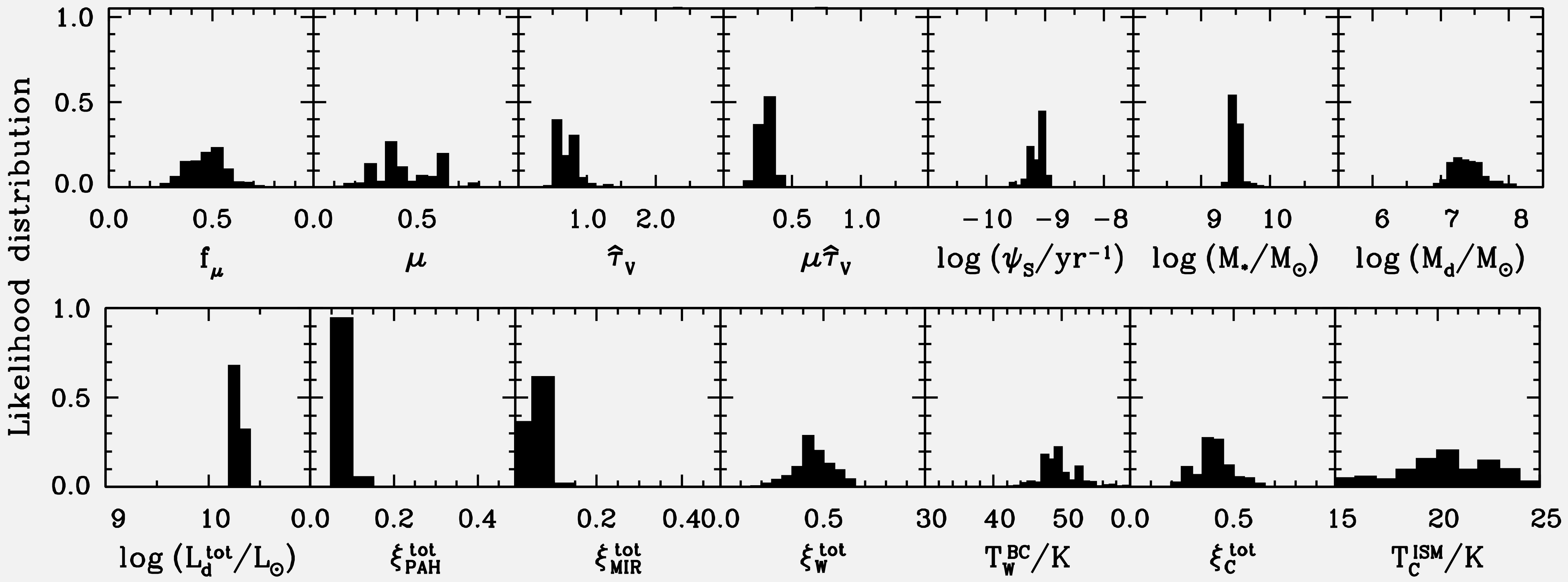


...How it's going

Leja+2017



How it started...



da Cunha+2008

Increasingly complex outputs: lots of information about parameter degeneracies and uncertainties

SED codes*,**

*biased/incomplete list
**all codes have things in common; each has some unique aspects and its own strengths

MAGPHYS (da Cunha+2008, 2015, Battisti+2019)

CIGALE (Noll+2009, Boquien+2019)

GalMC (Acquaviva+2011, 2015)

BAYESED (Han & Han 2012, 2014)

BEAGLE (Chevallard & Charlot 2016)

AGNfitter (Calistro Rivera+2016)

Iyer & Gawiser (2017)

Prospector (Leja+2017)

BAGPIPES (Carnall+2018)

Prospect (Robotham+2020)

PiXedfit (Abdurro'uf+2021)

Some things all codes have in common

Quality of results depends on the quality of input data:

- how well sampled is the SED?
- spectral and photometric calibration
- matching of multi-wavelength data of widely different spatial resolutions, different apertures, etc.

Uncertainties in all the different model ingredients

- stellar evolution/spectra
- dust models/dust evolution
- AGN torus models

'Bayesian methods' are great to quantify uncertainties, impact of degeneracies, and even model selection, but: we need to beware of results that are not informed by the data, but rather a consequence of the priors.

How do we test/falsify these models?

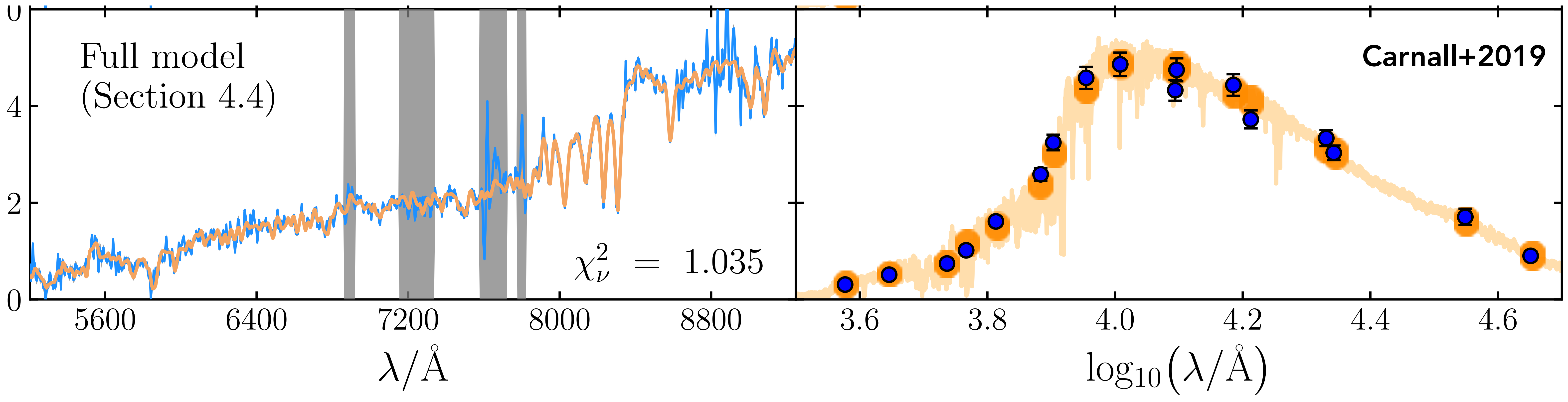
Some recent successes (where SED models pass tests)

The success of these codes is obvious: they have allowed us to constrain the physical properties (star formation rates, stellar masses, dust properties, etc etc), of large sample of galaxies in the nearby Universe and out to high redshifts. They have shown us how the cosmic SFRD and stellar mass evolve, the main sequence of star-forming galaxies, shown us how dust content evolves with galaxy properties and time, etc.

But how well have these codes/models been tested/falsified?

Spectrophotometric fits & the ability to constrain SFHs

Ability to fit photometry+spectra simultaneously, use information on the stellar absorption features to obtain more reliable SFHs (or, at least, average stellar ages), thus breaking degeneracies and reducing uncertainties in purely photometric fits.



E.g. Carnall+2019 studied the SFHs of massive quiescent galaxies at z~1 from VANDELS. They find a steep trend between formation time and stellar mass, indicating downsizing. Need to sensitivity to stellar ages to do this (i.e. spectroscopy).

Note: other SED codes also have this capability e.g., Chevallard & Charlot (2016), Abdurro'uf+(2021)

Testing the models I: predicting observables

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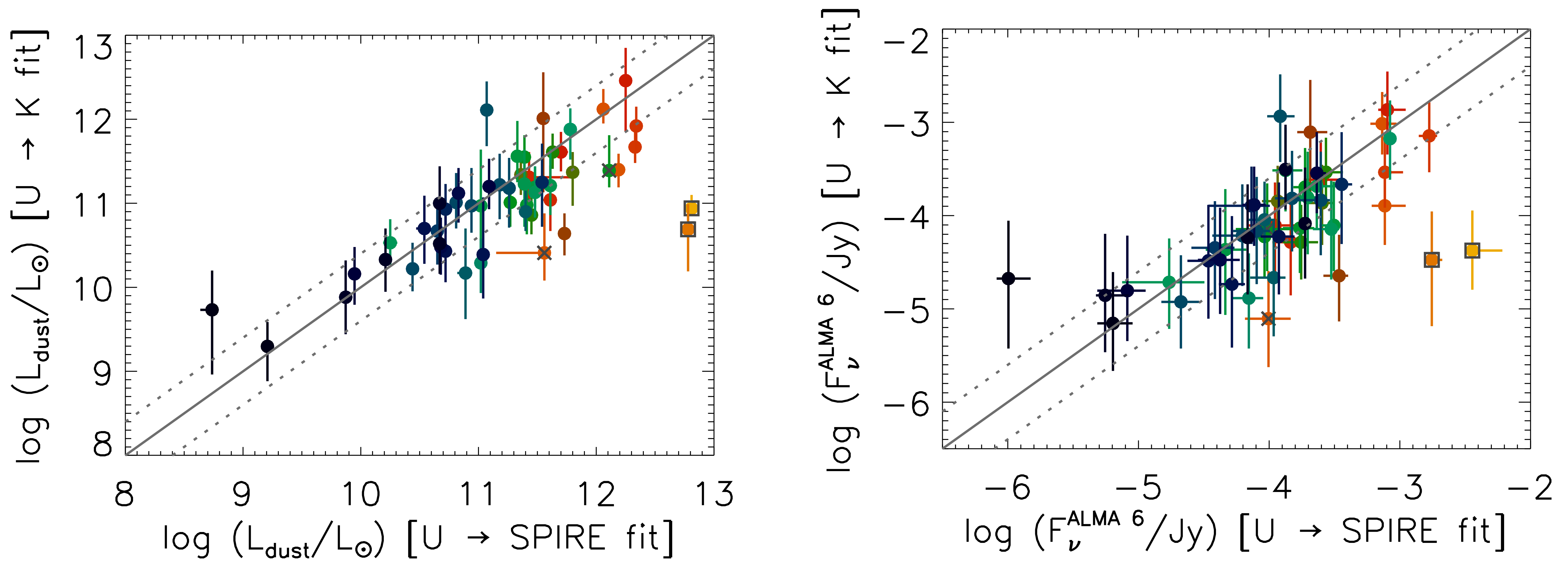
example 1: For optically-selected galaxies, MAGPHYS predicts the correct IR dust luminosity and the 1-mm flux from only UV-to-NIR SED fits (da Cunha+2013a).



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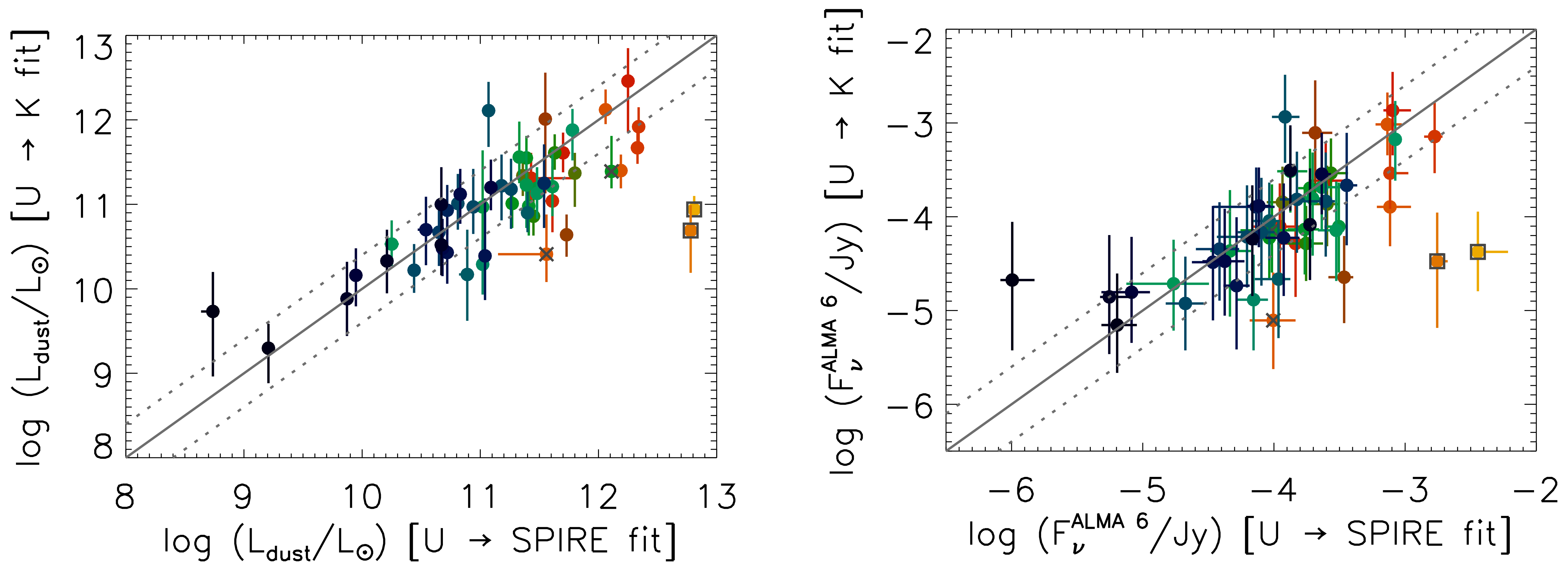
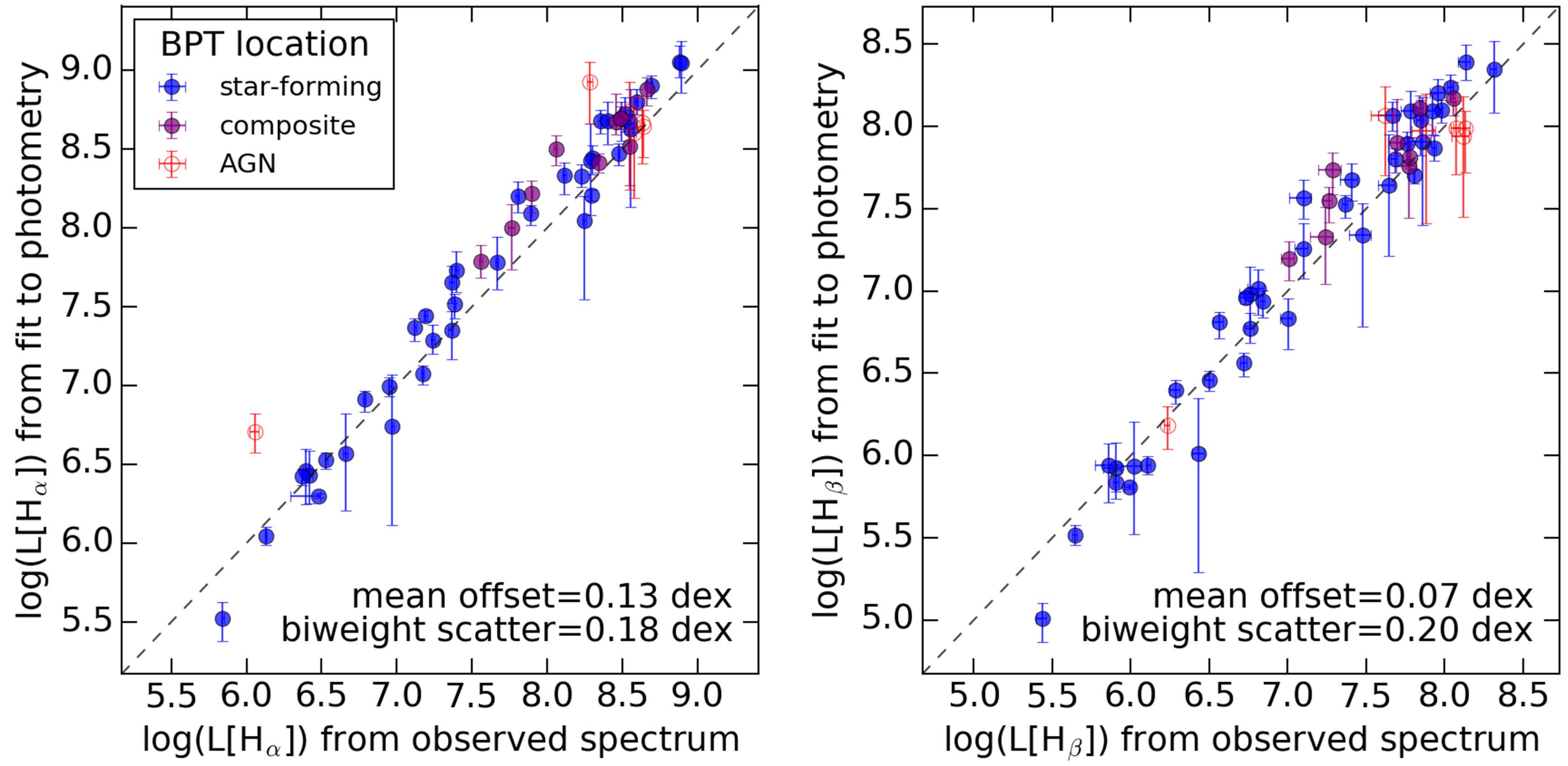
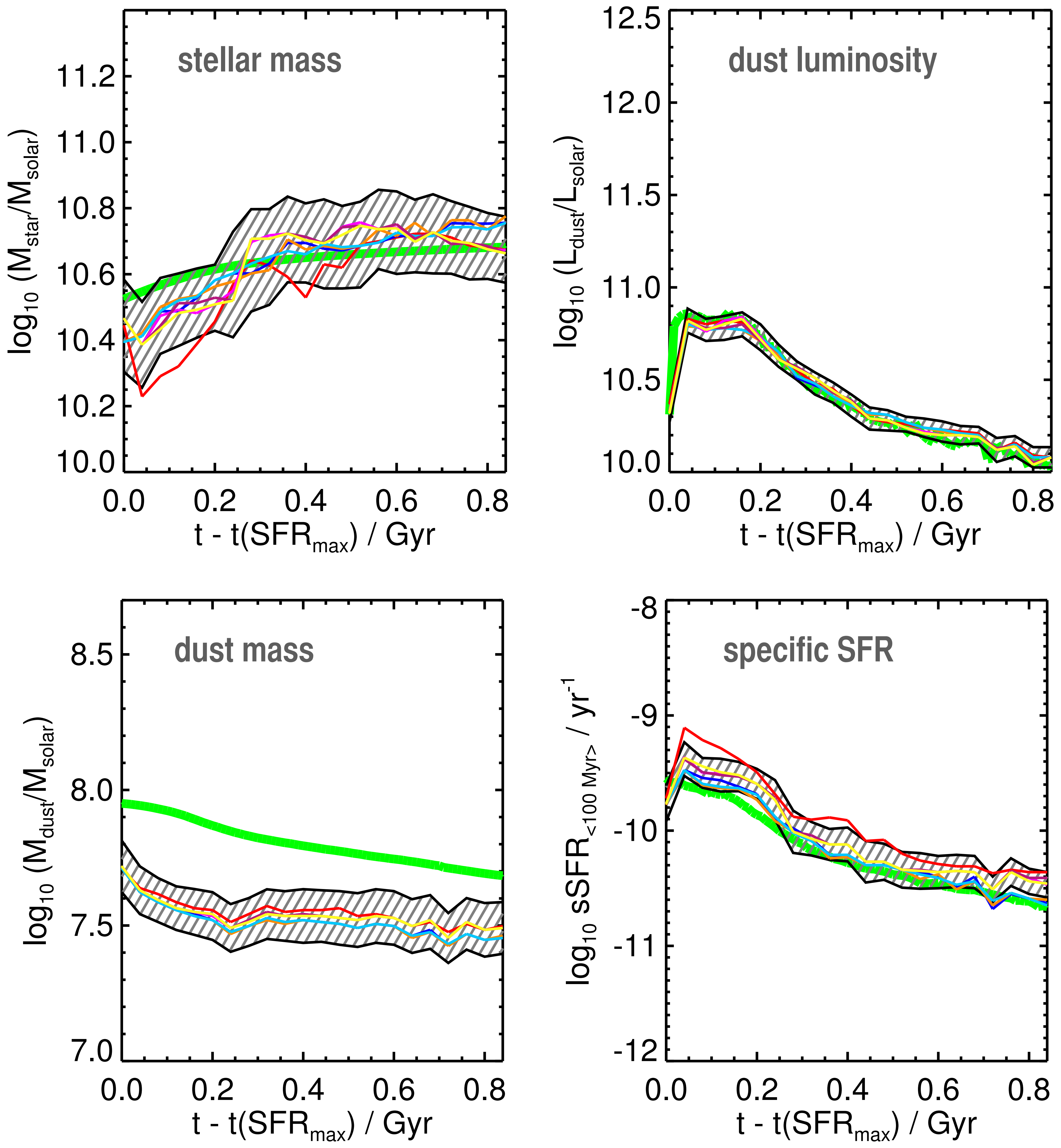


example 2: For local galaxies, Prospector predicts the right Hα and Hβ luminosities from broad-band photometry fits (Leja+2017).



Testing the models II: Comparison with simulated galaxies

An independent test of MAGPHYS using a model galaxy from a hydrodynamic+radiative transfer simulation



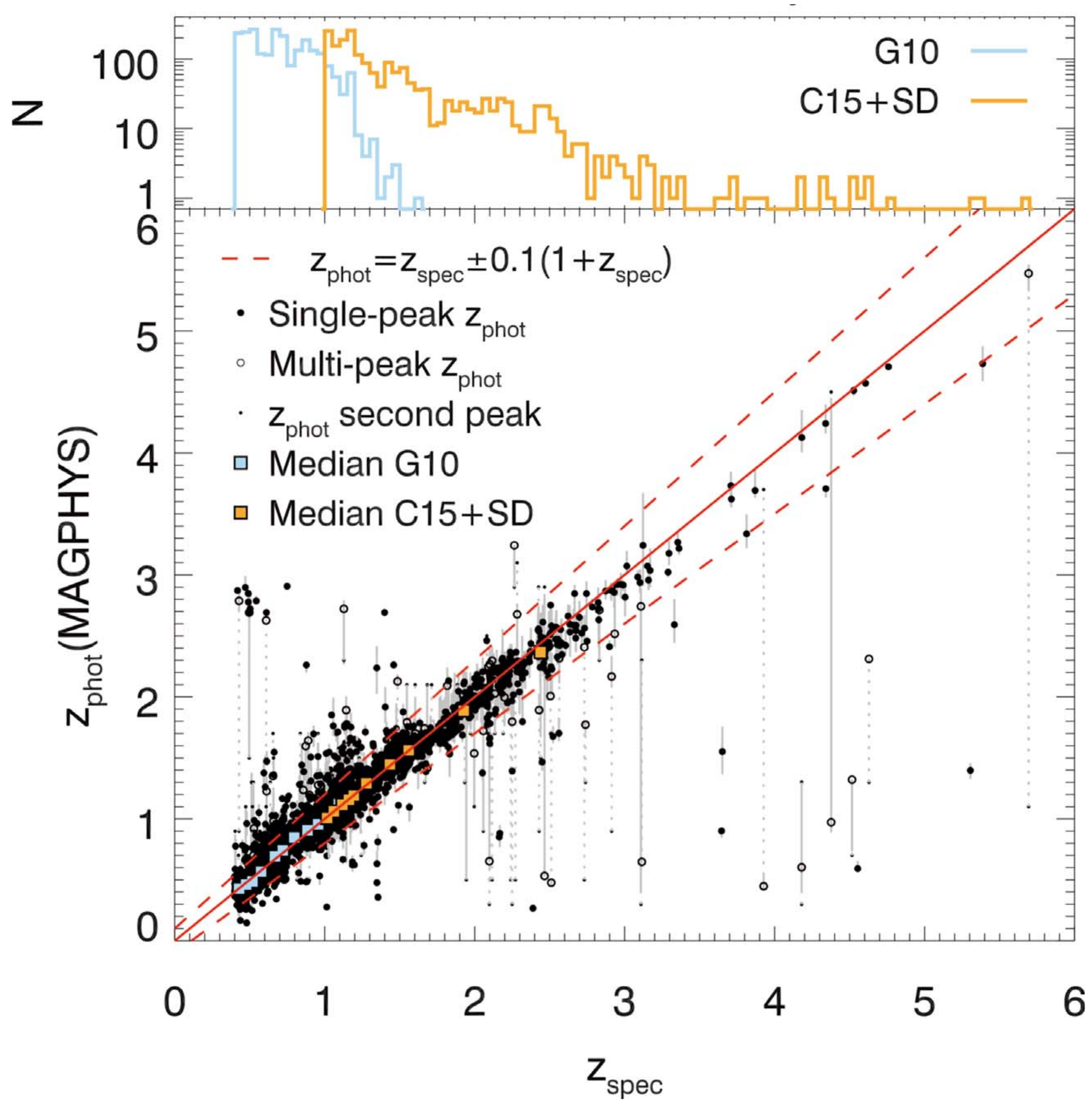
green: "true value"

colours/shade: MAGPHYS, different viewing angles

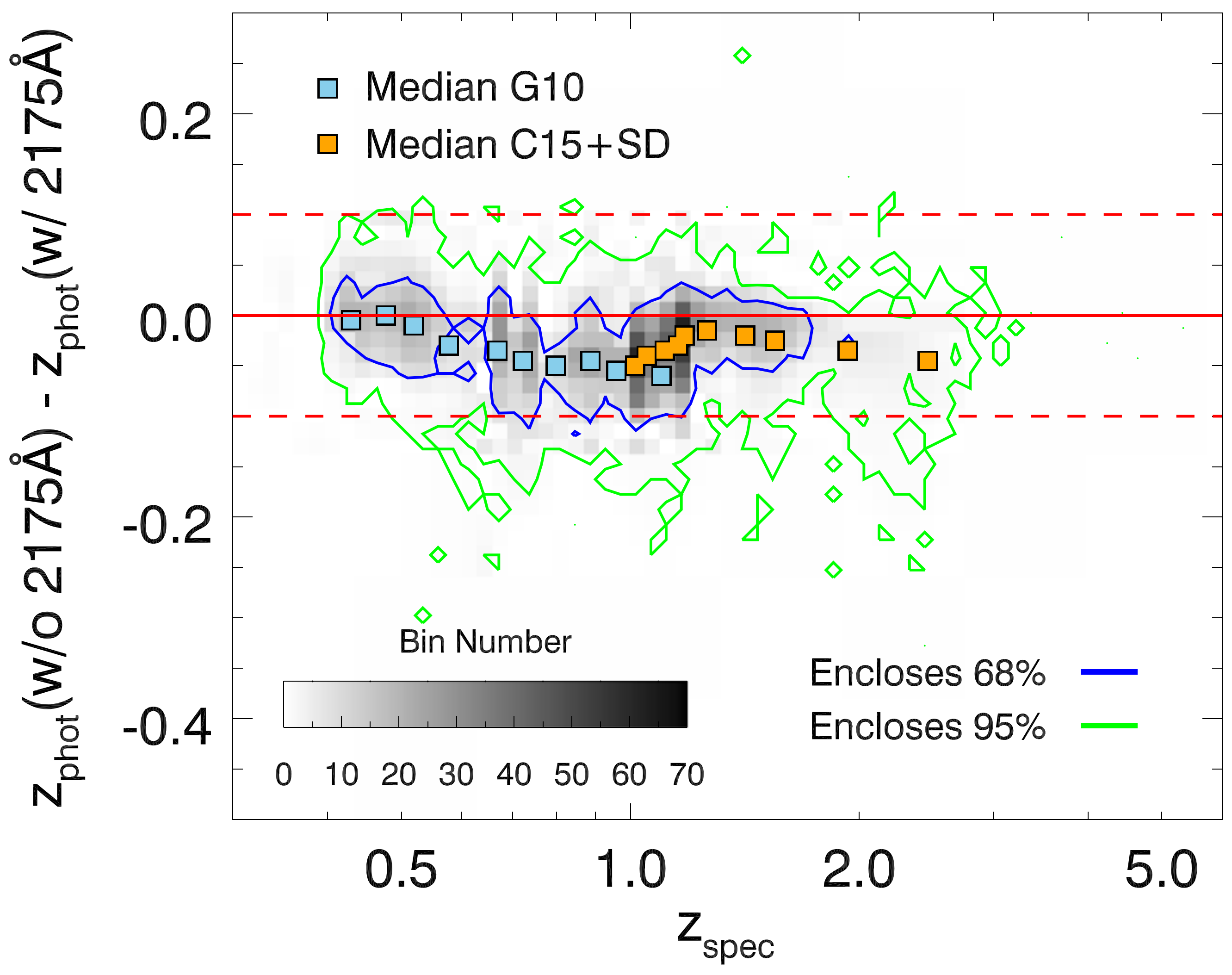
MAGPHYS recovers the physical parameters well for different viewing angles with smooth time step variation. 😊

Hayward & Smith 2015

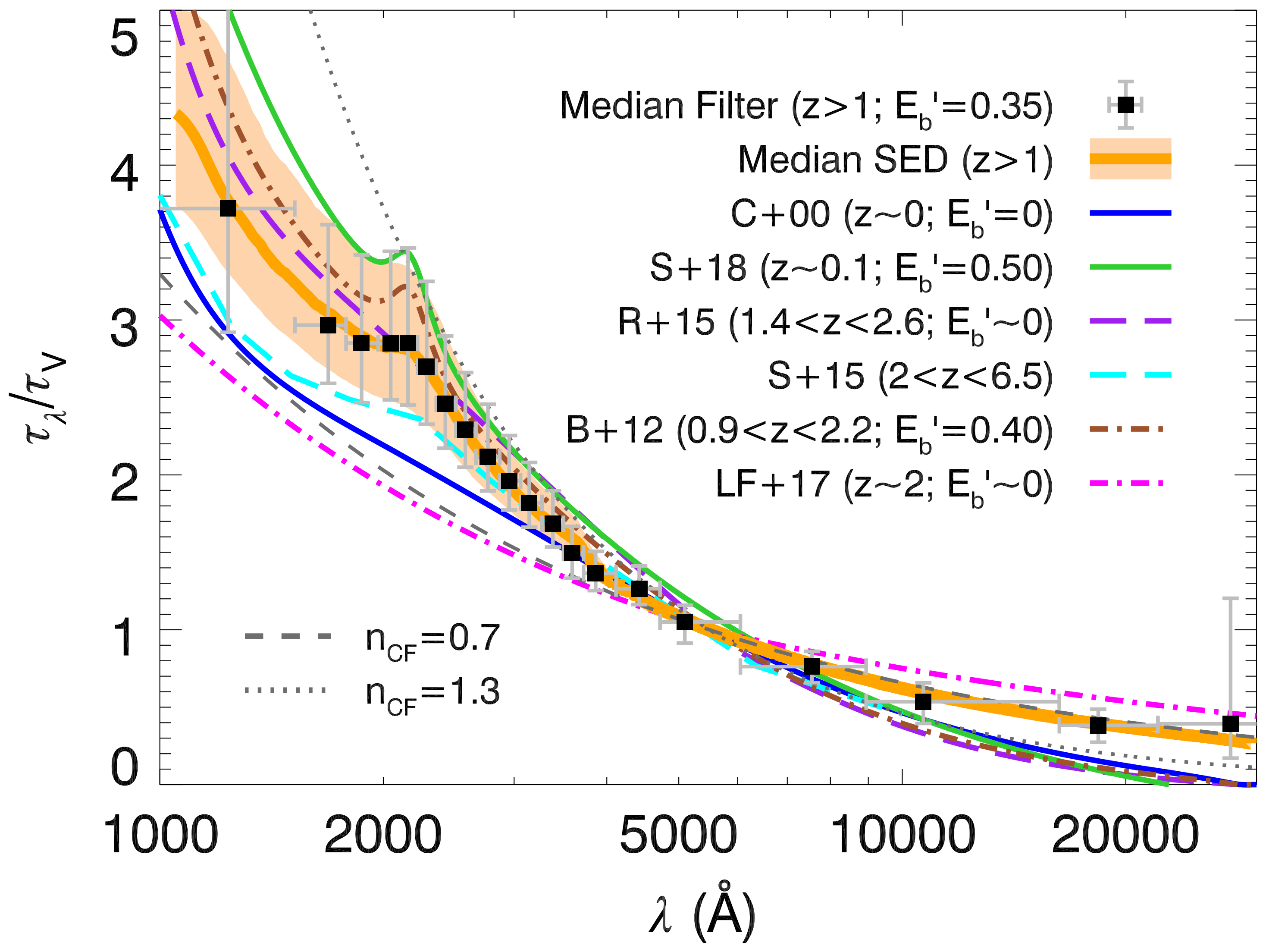
Testing SED models using spectroscopic redshifts



Battisti+2019



Battisti+2020

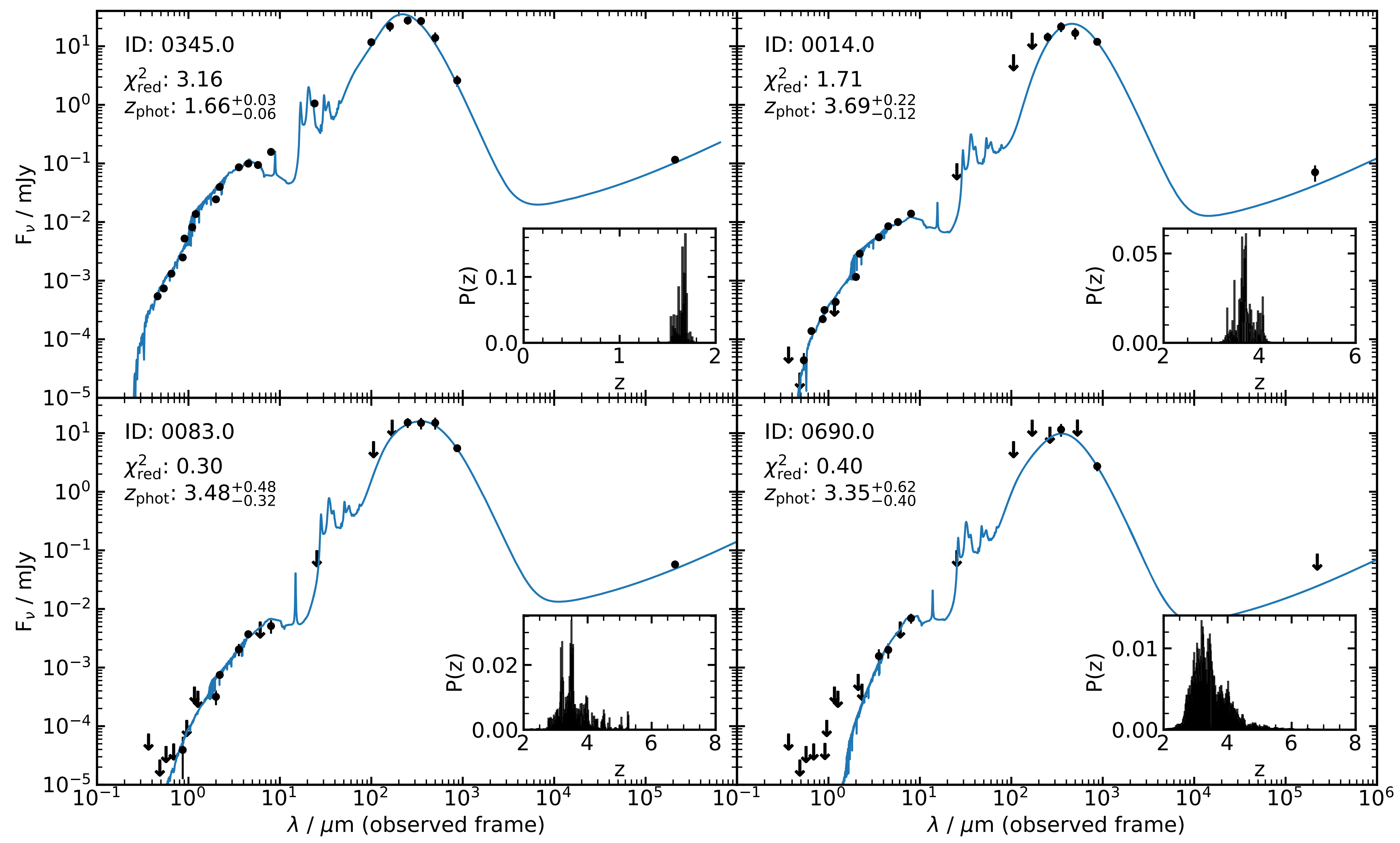


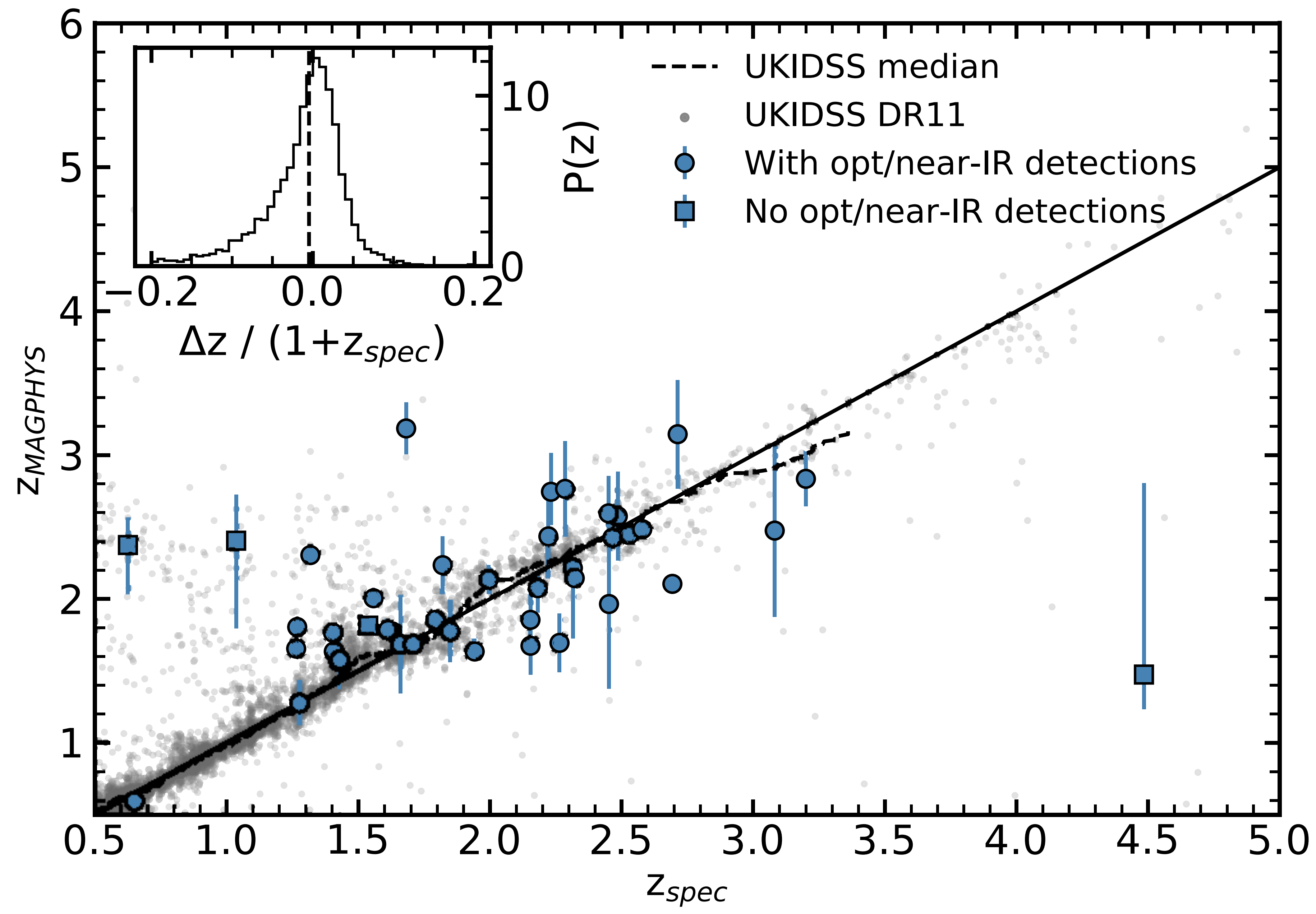
4,000 galaxies at 0.4<z<6 with UV-to-IR SEDs and known spectroscopic redshifts from COSMOS.

MAGPHYS-photoz gets the redshifts right with regular priors and no need to use zero point corrections…

…but for sources with narrow and median bands, redshifts and SED fits are improved if we include a UV bump in the dust attenuation curve (we find on average 1/3 of MW bump strength, similar to e.g. Salim+2018 for local galaxies)

Testing SED models using spectroscopic redshifts





Dudzevičiūtė+2020 confirmed the accuracy of MAGPHYS-photoz using ~6,700 K-band selected UDS galaxies and 44 sub-millimetre galaxies with known spectroscopic redshifts.

$(z_{spec}-z_{phot})/(1+z_{spec})=-0.005\pm0.003$ with a dispersion of 0.13.

Some current/ future challenges

Some current/ future challenges

1) SED physics at high-redshift, e.g.,

- Low metallicity stellar populations [ionizing flux, especially HeII excess]: importance of stellar binarity (e.g., Eldridge & Stanway 2012), rotation (e.g., Levesque+2012), low-mass X-ray binaries (e.g., Schaerer+2019)
- Possible evolution of dust content and dust attenuation curves
- IMF???

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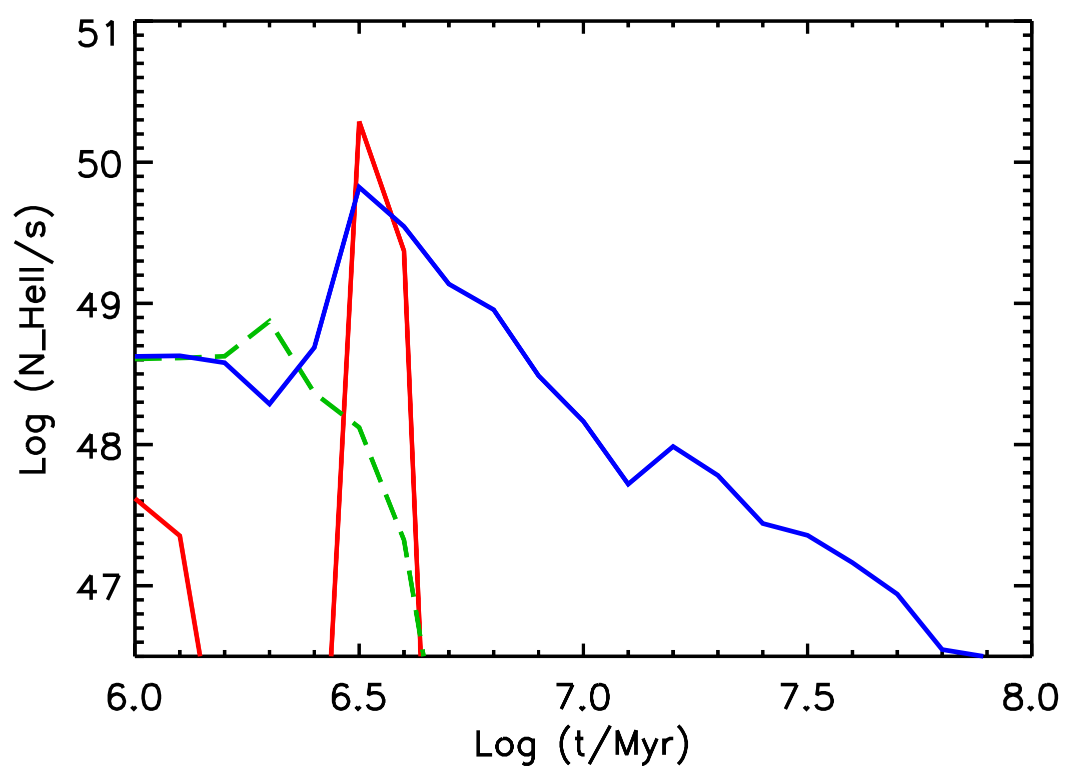
HeII ionizing photons as a function of time for different stellar models

GALAXEV (Bruzual & Charlot 2003): single, non-rotating
Starburst 99 (Leitherer+2014): single, rotating
BPASS (Eldridge & Stanway 2012): interacting binaries



(adapted from Wofford+2016; see also Stanway+2016)

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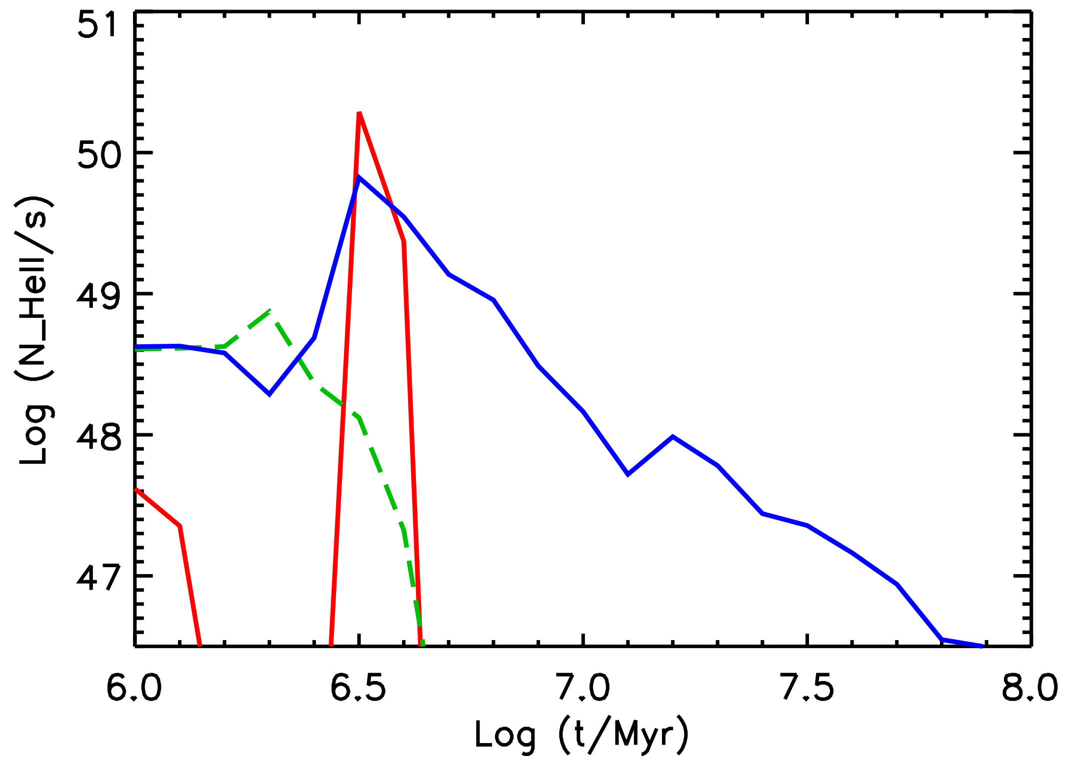

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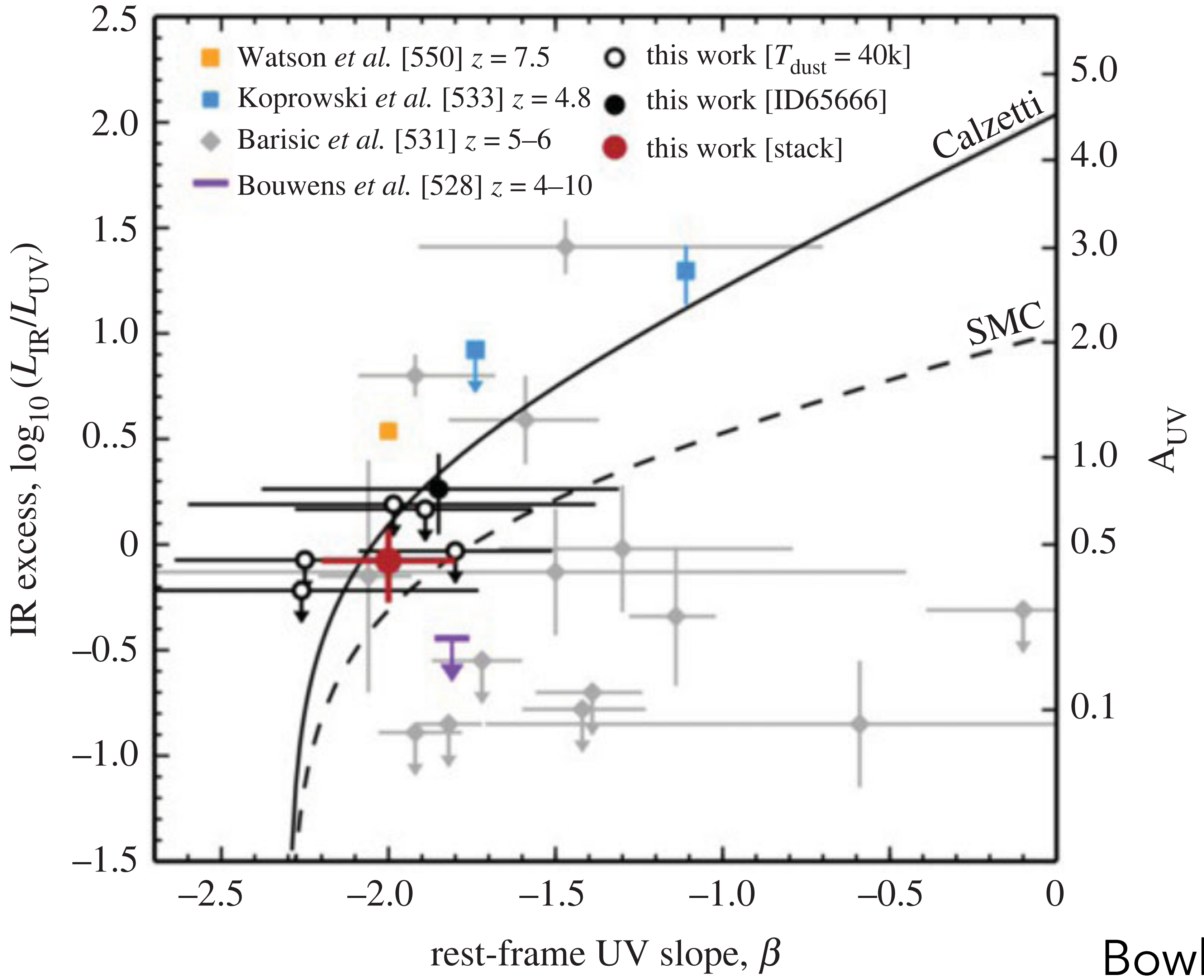

ALMA: Evolution in the dust attenuation curve at high-redshift?

Bowler+2018

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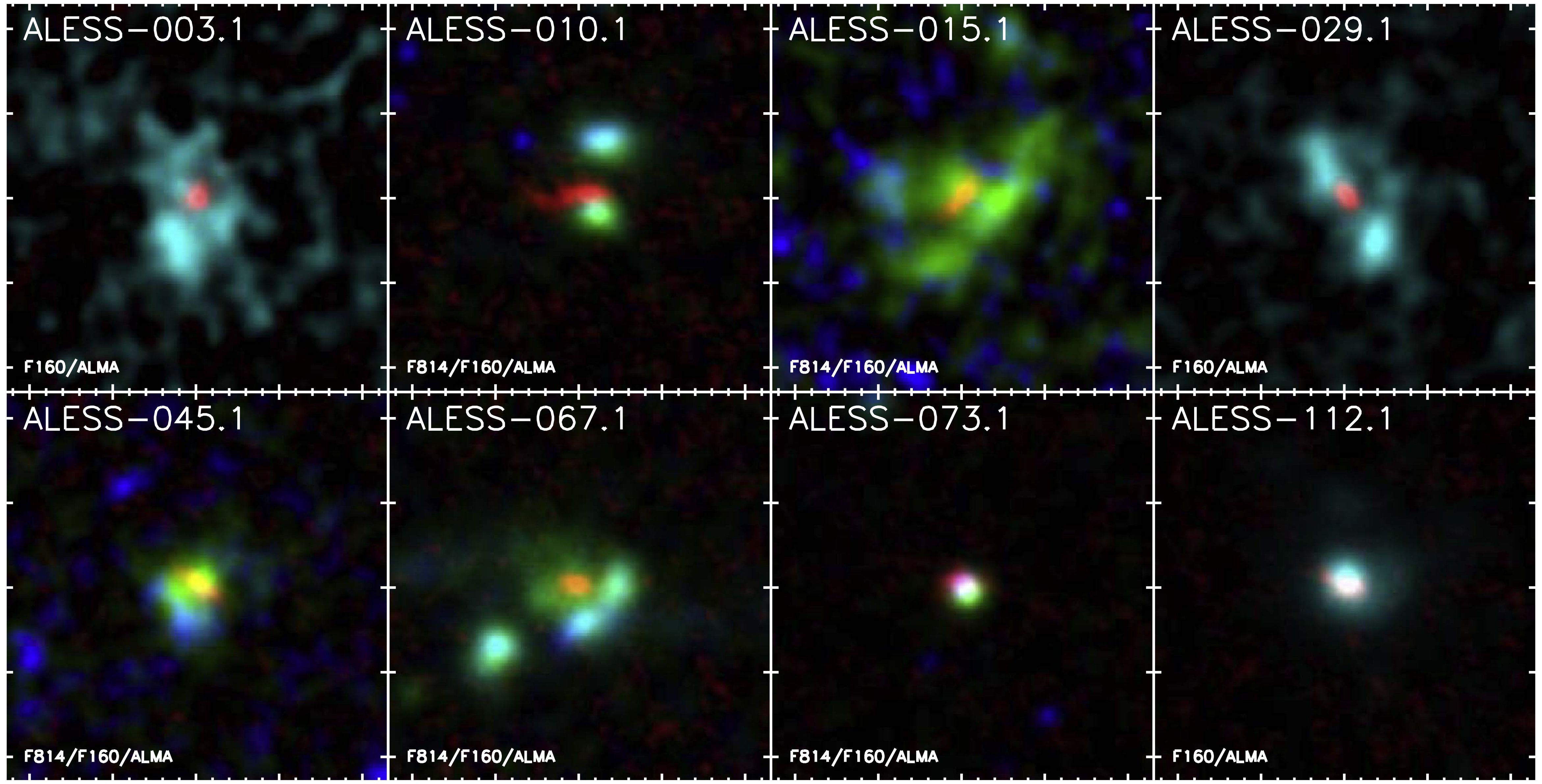
2) Spatial offsets between stellar and dust emission: at what point does the energy balance assumption break down?

HST (stellar emission) and ALMA (dust emission) in z~2 starbursts (SMGs)



Hodge+2016; see also Inami+2022

How do we deal with this?

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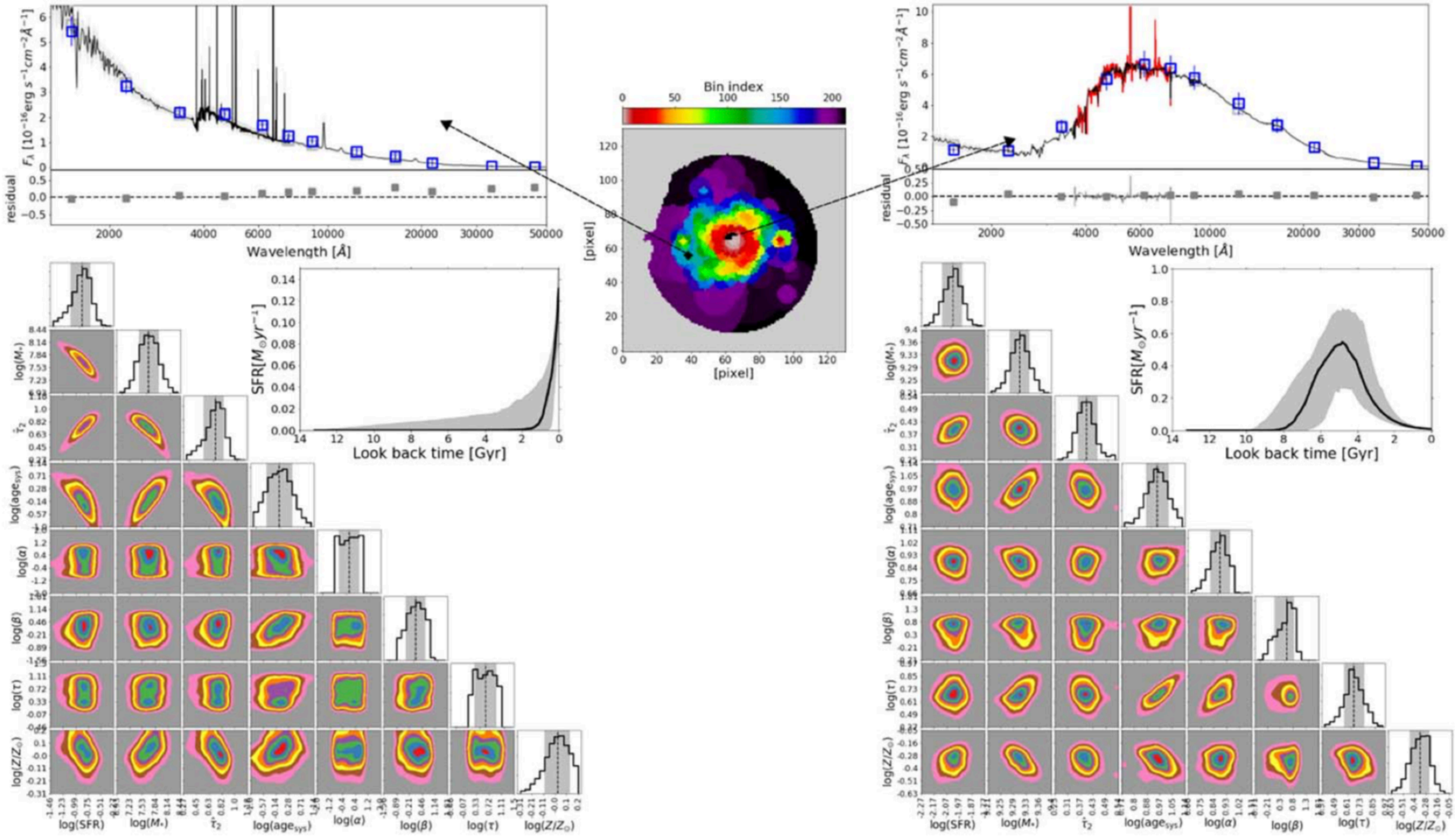
2) Spatial offsets between stellar and dust emission: at what point does the energy balance assumption break down?

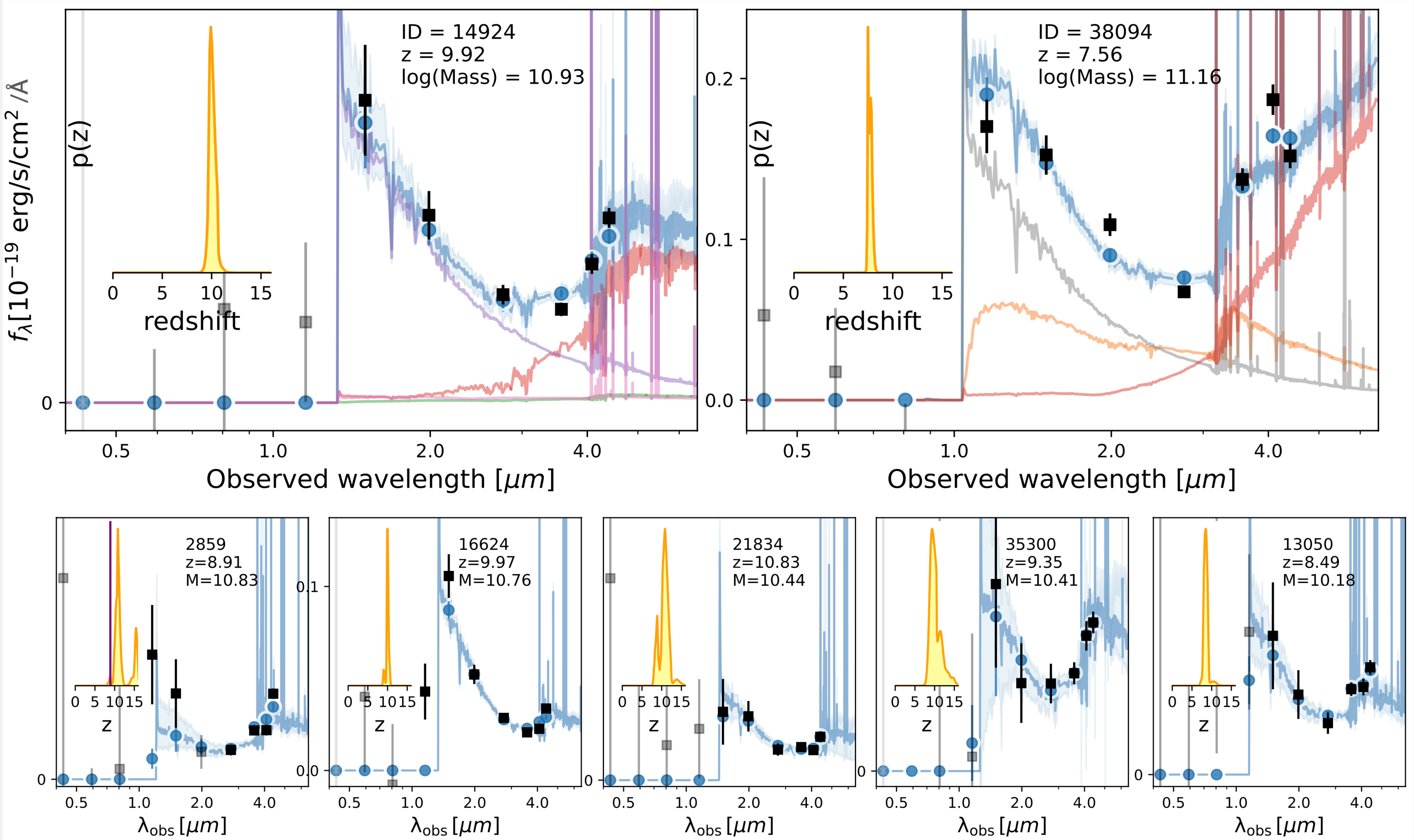
3) In the IFU era, what is the best way to combine spatially-resolved spectral and photometric information?

example: spatially-resolved SED fitting (including spectra) in NGC 309



Abdurro'uf+2021

JWST - are there really massive galaxies at z~10?



Labbé+2022

Many more massive galaxies at high-z than previously thought!

Did the formation of massive galaxies start earlier than we thought?

But: all this relies on heavily on SED modelling!

Conclusion

- Amazing developments in SED modelling in the last decade or so: many new codes suited for many purposes

- Code sophistication is increasing, with the goal of extracting as much information as possible from observations

- But: we must continue testing the assumptions and physical ingredients that go into the models, especially when starting to explore new regions of the parameter space and observations

- For discussion: what is missing in the models? How can we test them/falsify them better?