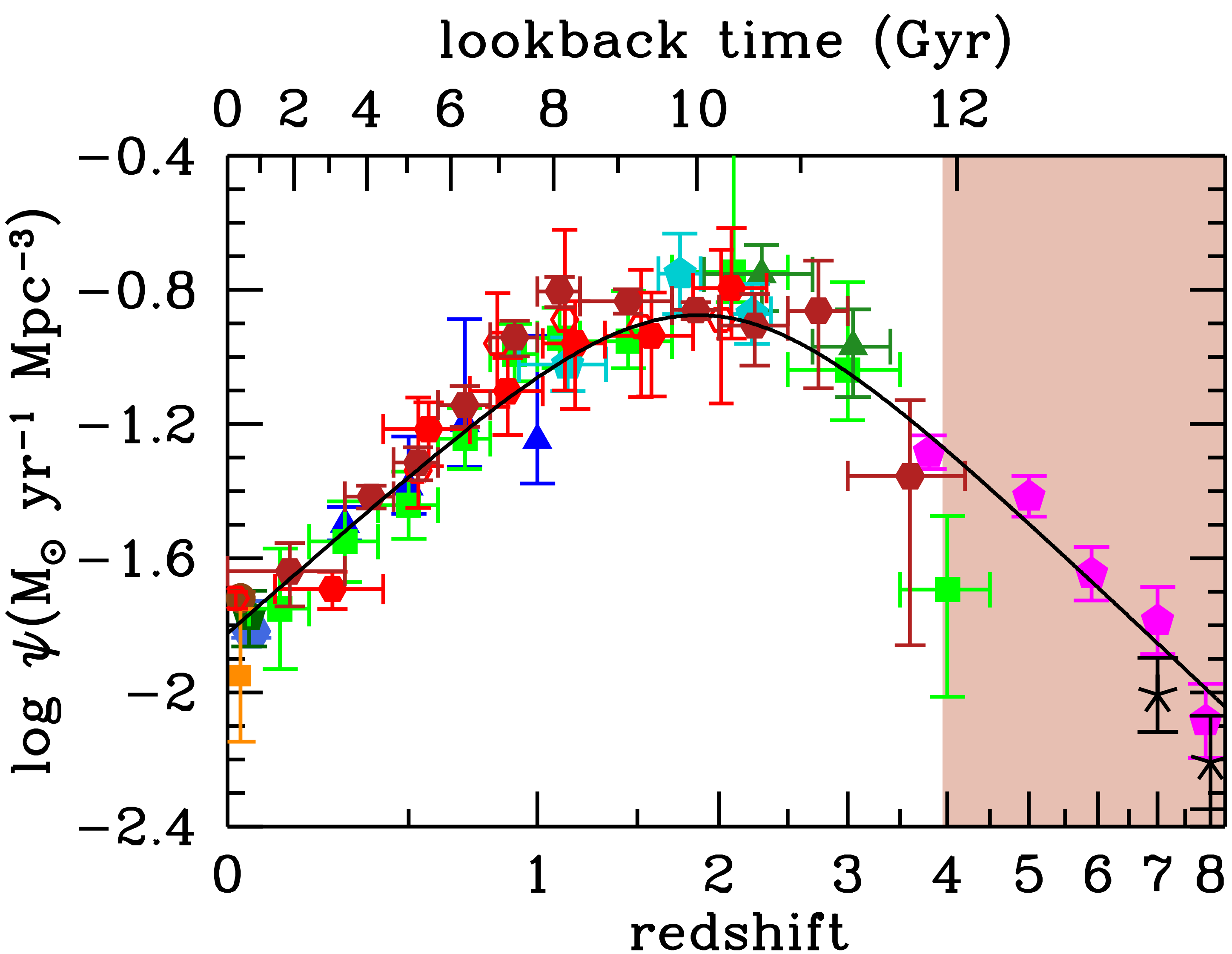
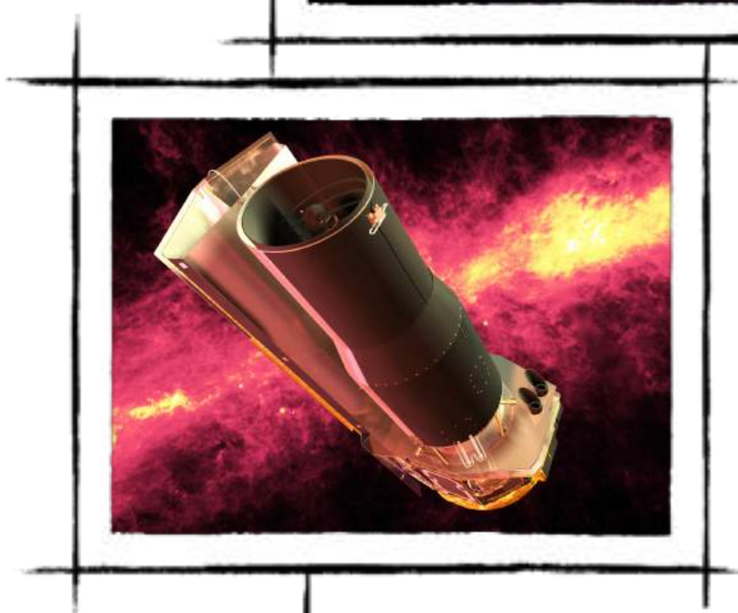
First galaxies: observations
Lecture 2

Renske Smit
Newton-Kavli fellow - University of Cambridge

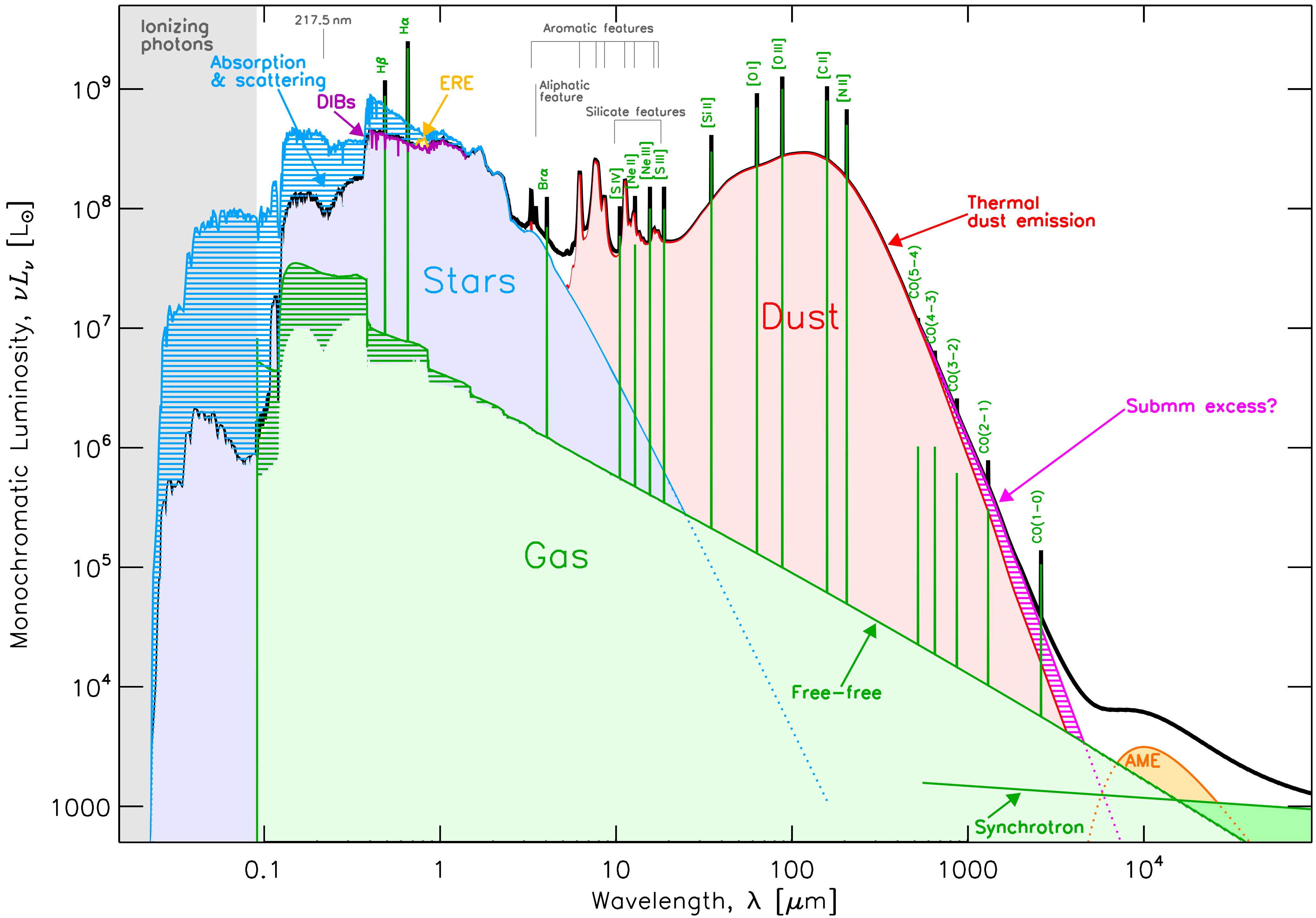
Lecture 1: census of star-formation activity





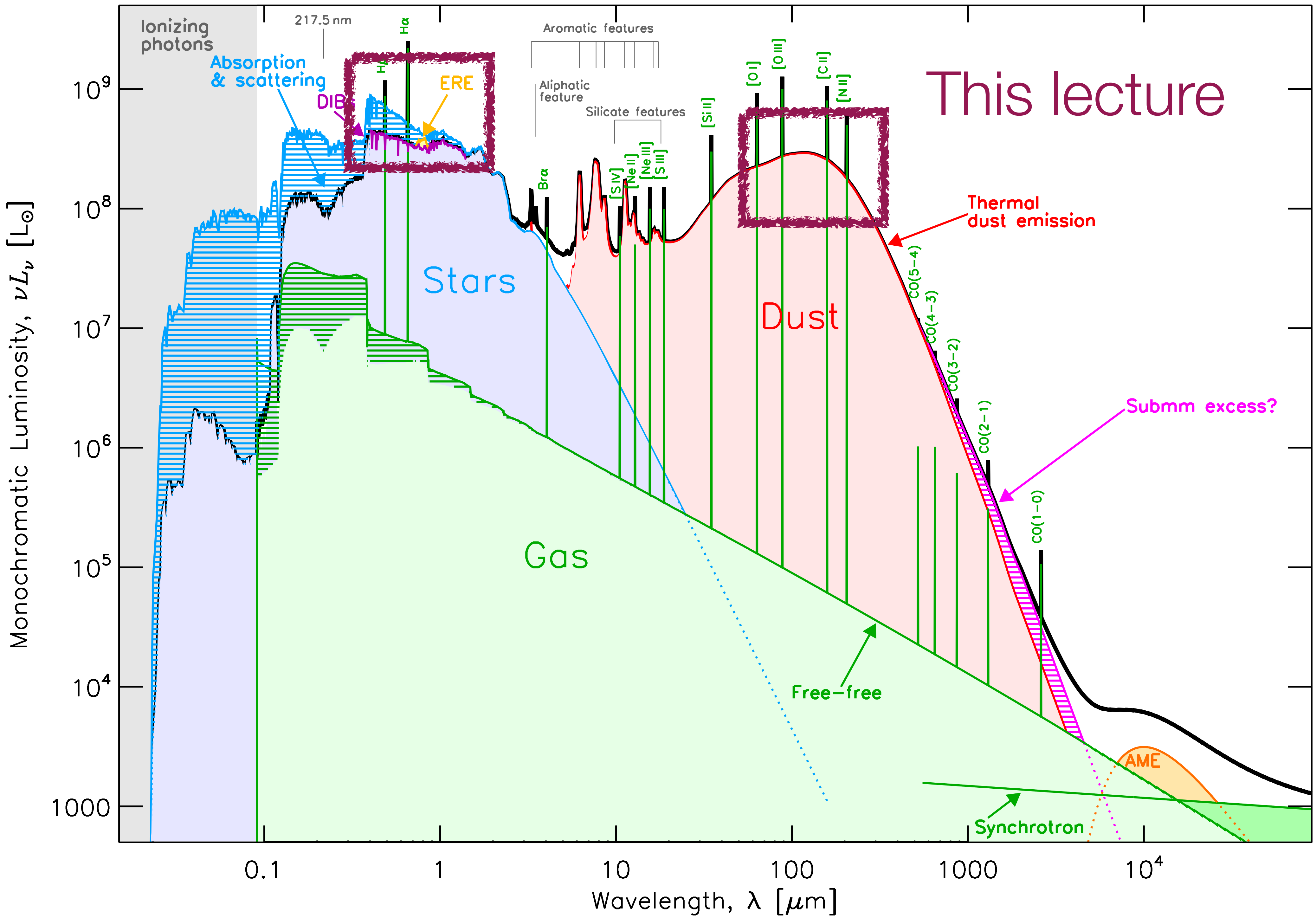
Madau & Dickenson 2017

The spectral energy distribution



Adapted from Galliano et al. 2018

The spectral energy distribution



Adapted from Galliano et al. 2018

Overview

Lecture 1: Detection methods and the galaxy census

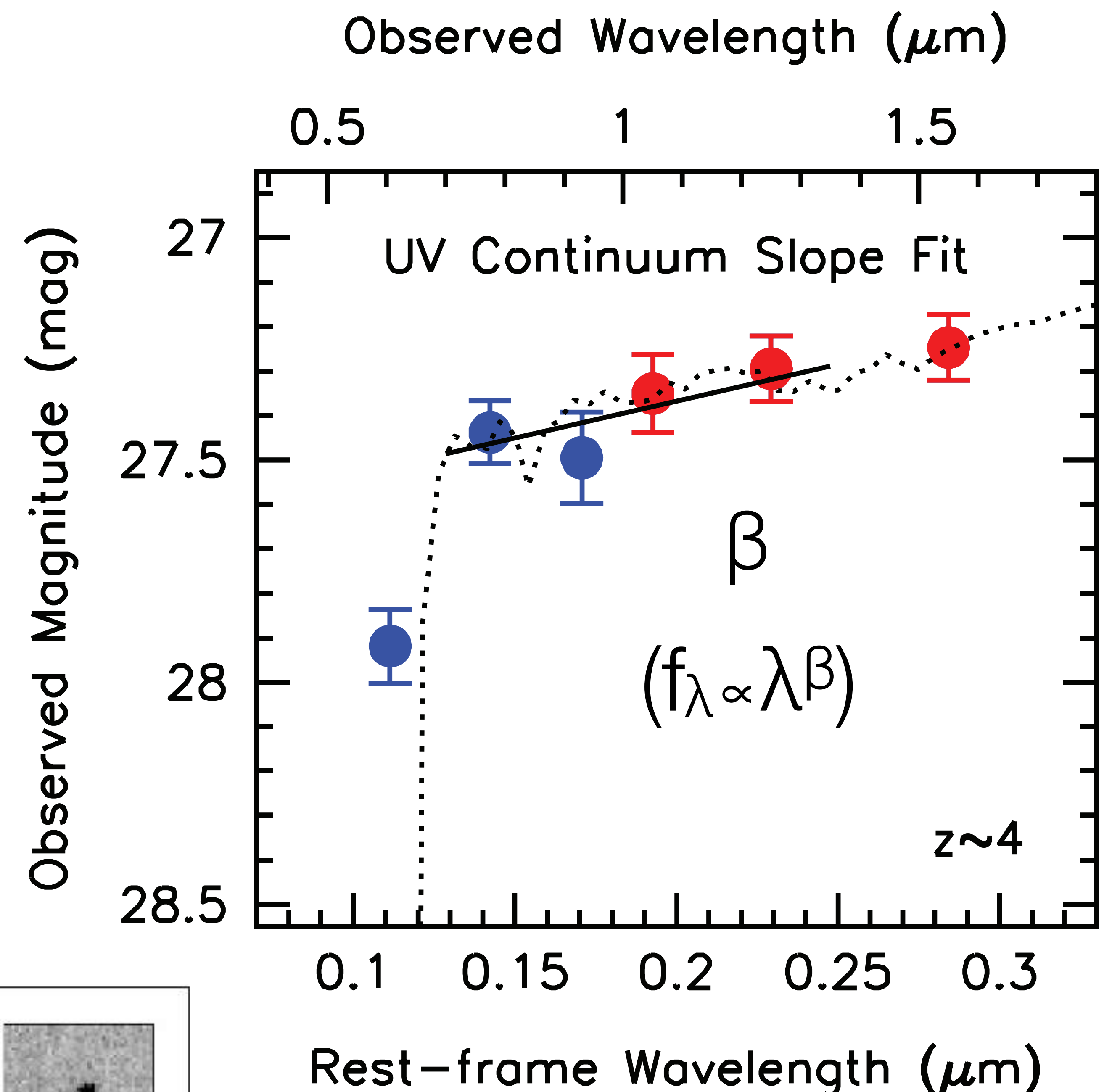
Lecture 2: Dust and stellar mass

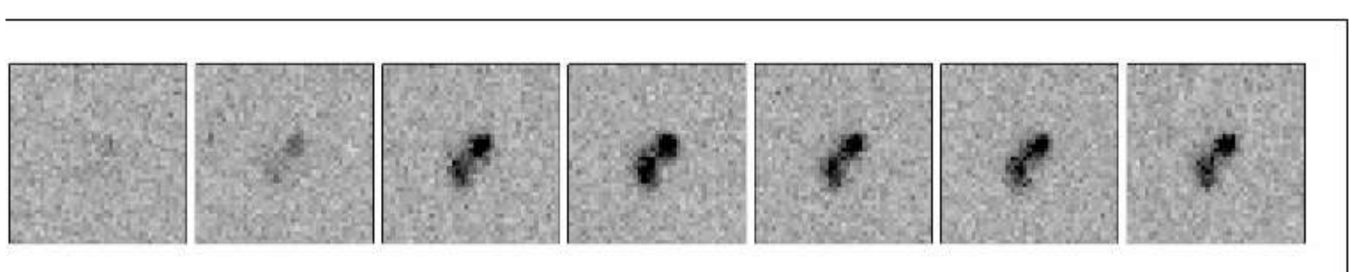
- UV continuum slope measurements
- Dust obscuration
- Ages and stellar masses
- Specific star formation rate evolution
- Ionising photon production efficiency

Lecture 3: Optical and sub-mm spectroscopy

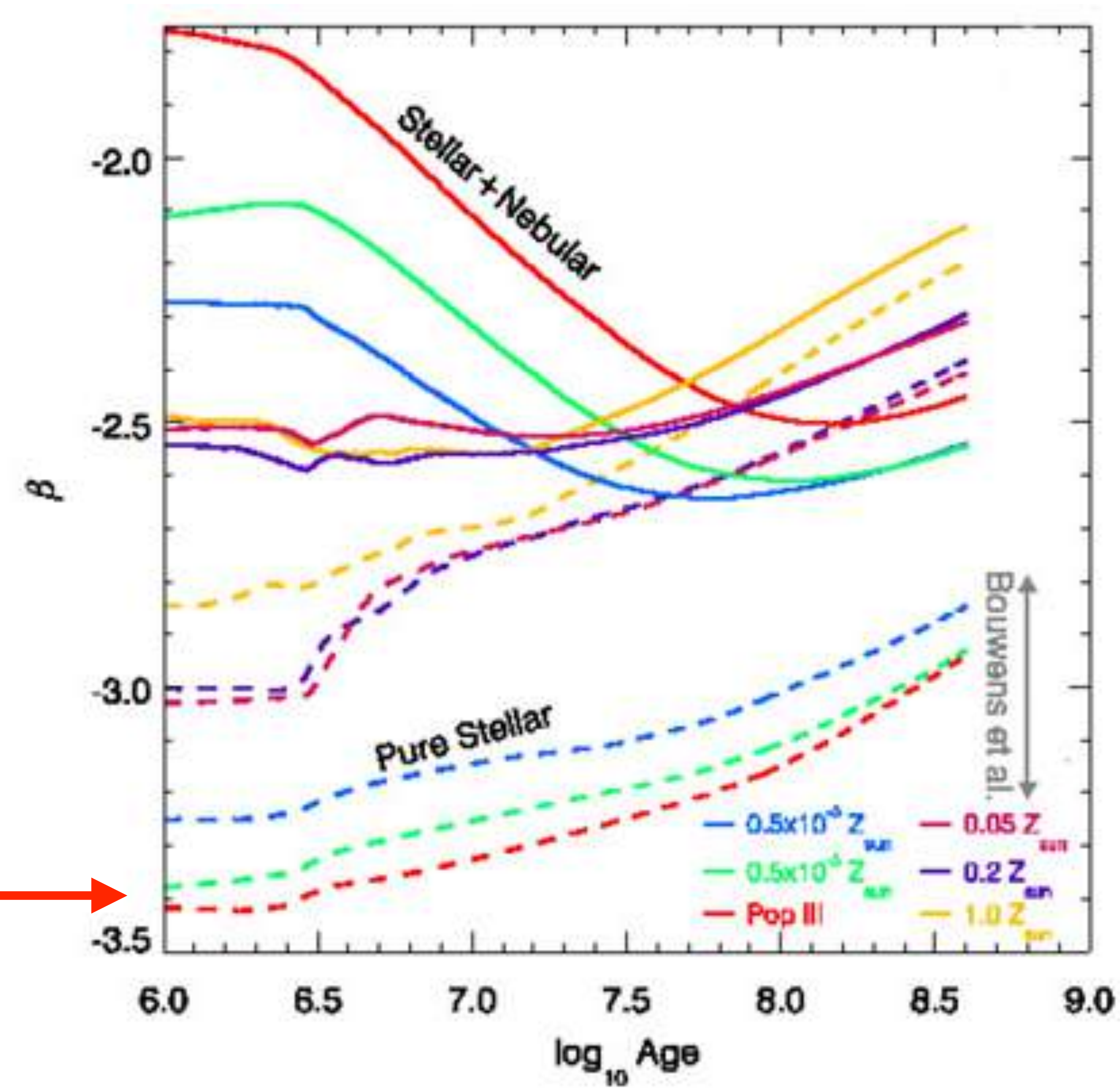
Basic properties derived from Hubble

If you observe galaxies in magnitudes or F_ν a flat slope indicates β=-2





Extremely blue sources?

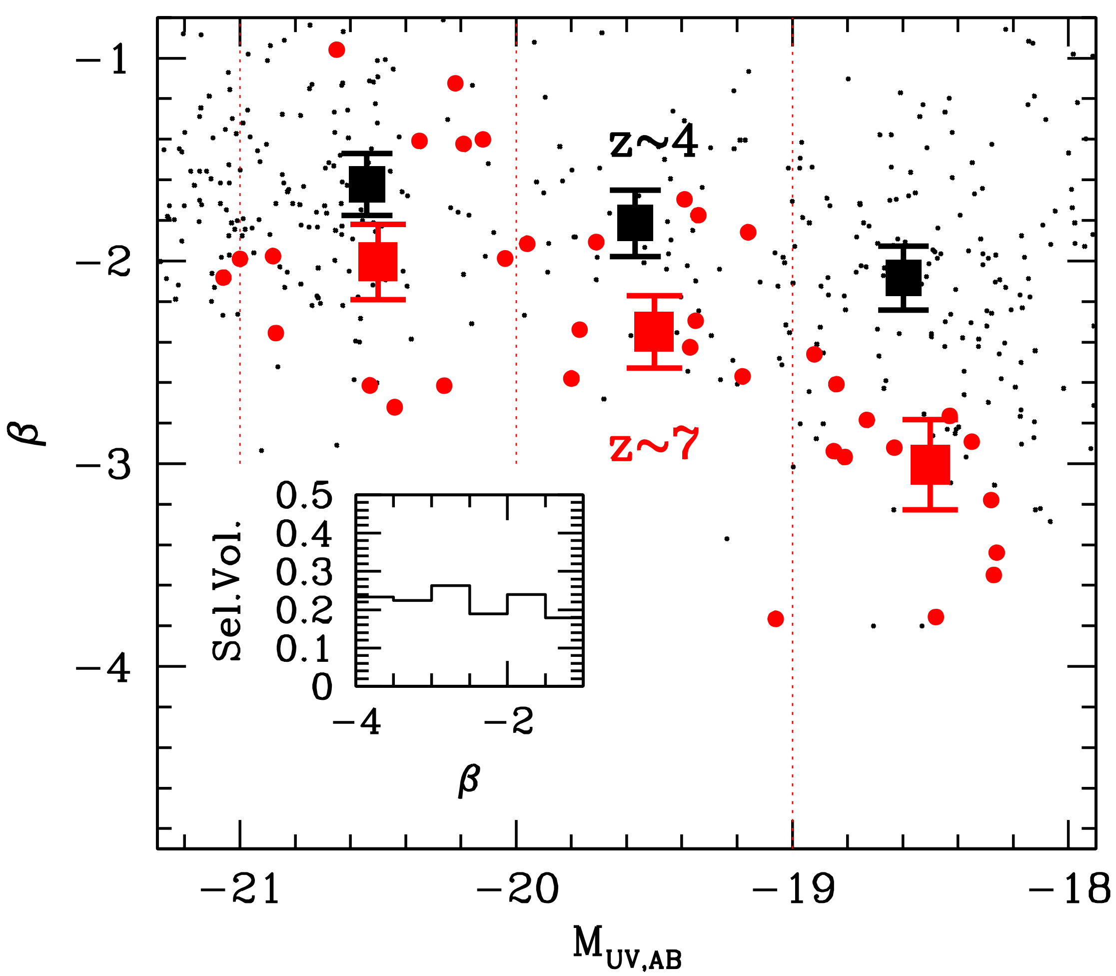


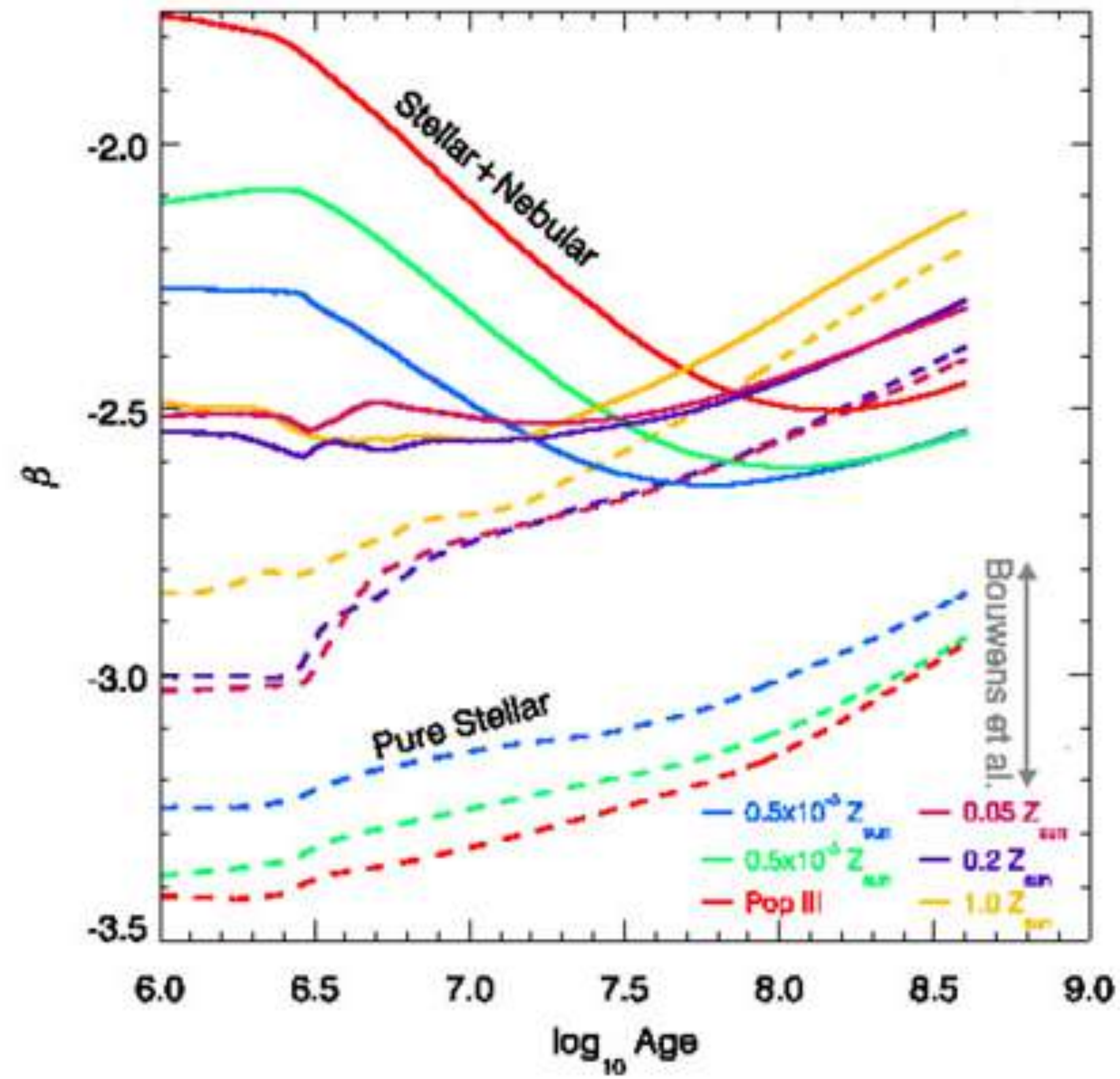
Pop III sources

Dunlop 2013; Bouwens et al. 2010

Extremely blue sources?

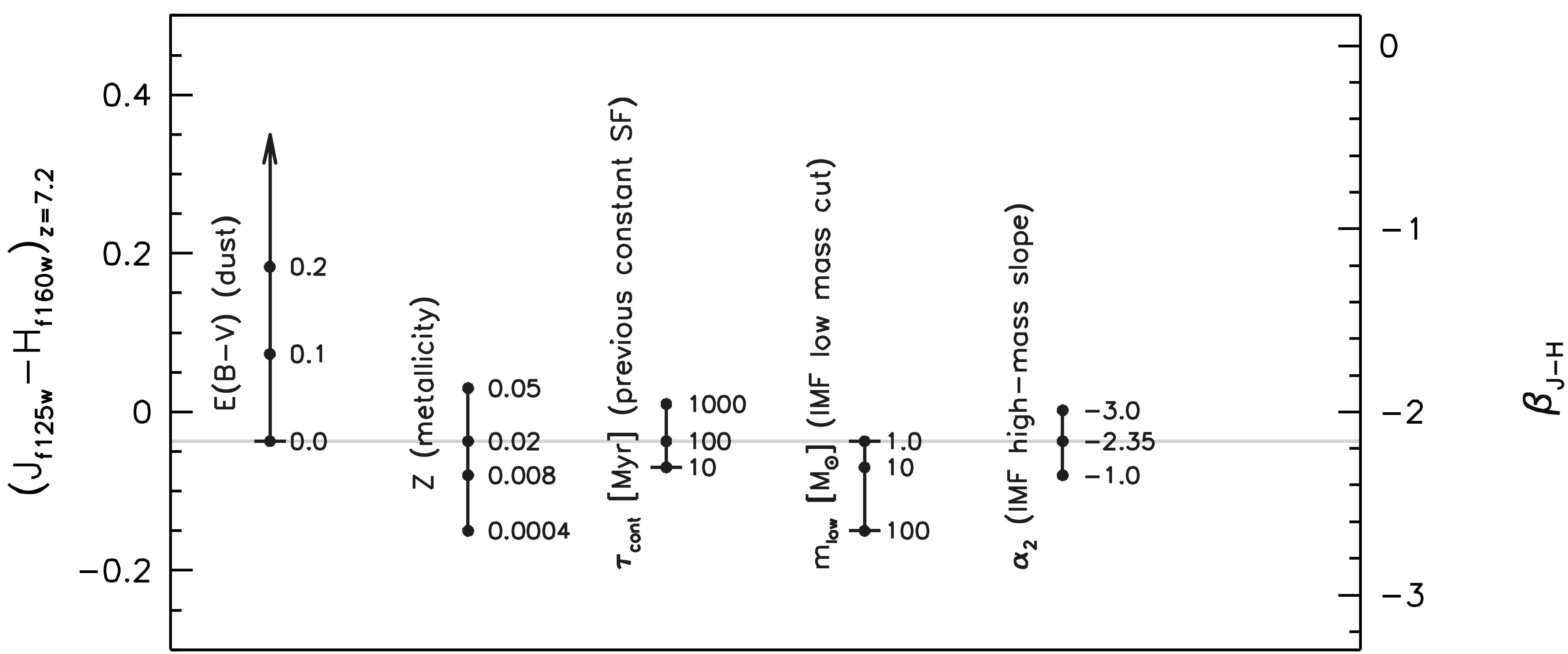
Individual error-bars are still too large to identify a ‘zero’ metallicity galaxies from the UV-slope





Dunlop 2013; Bouwens et al. 2010

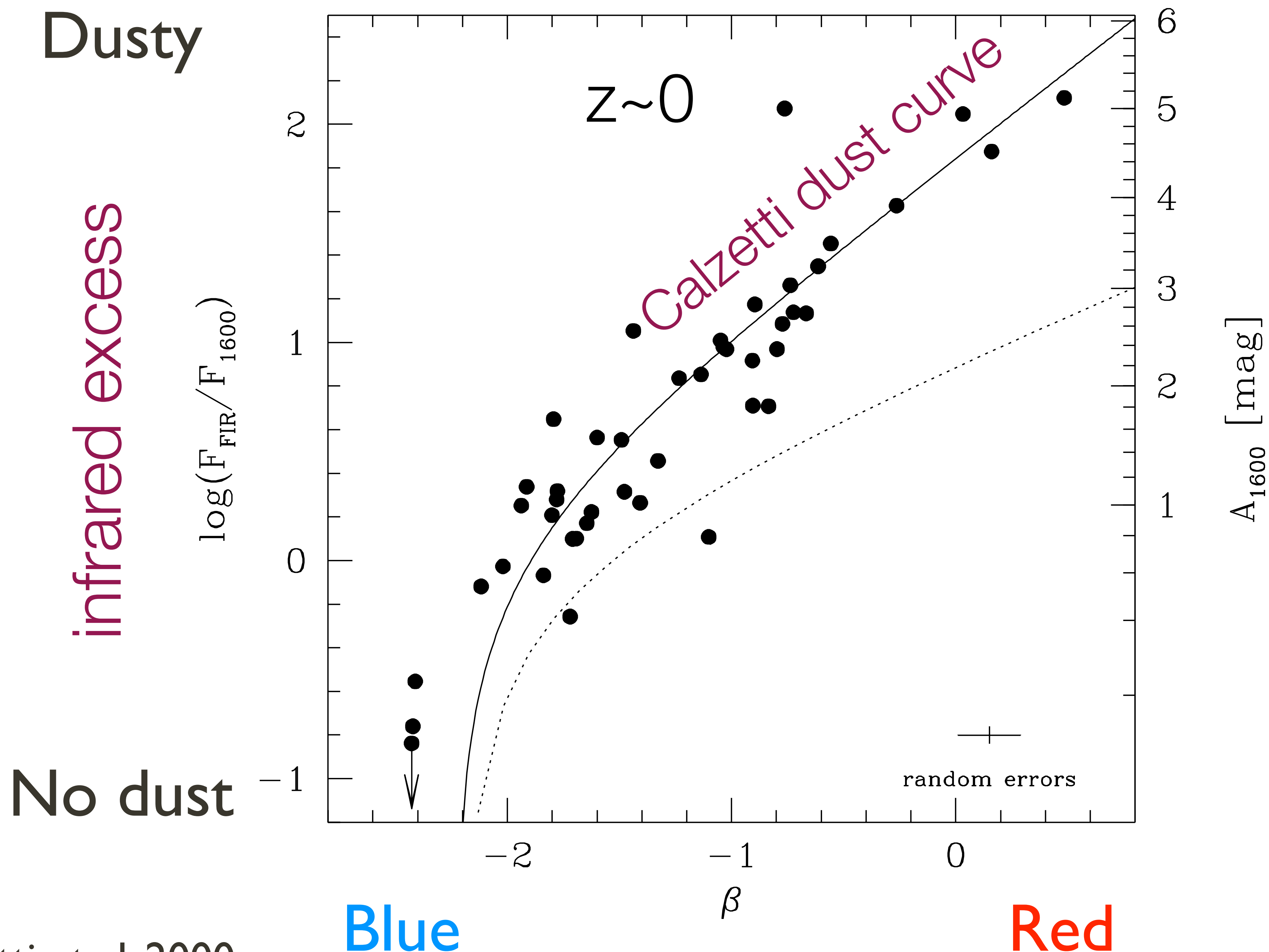
What is the UV slope sensitive to?



Wilkins et al. 2011

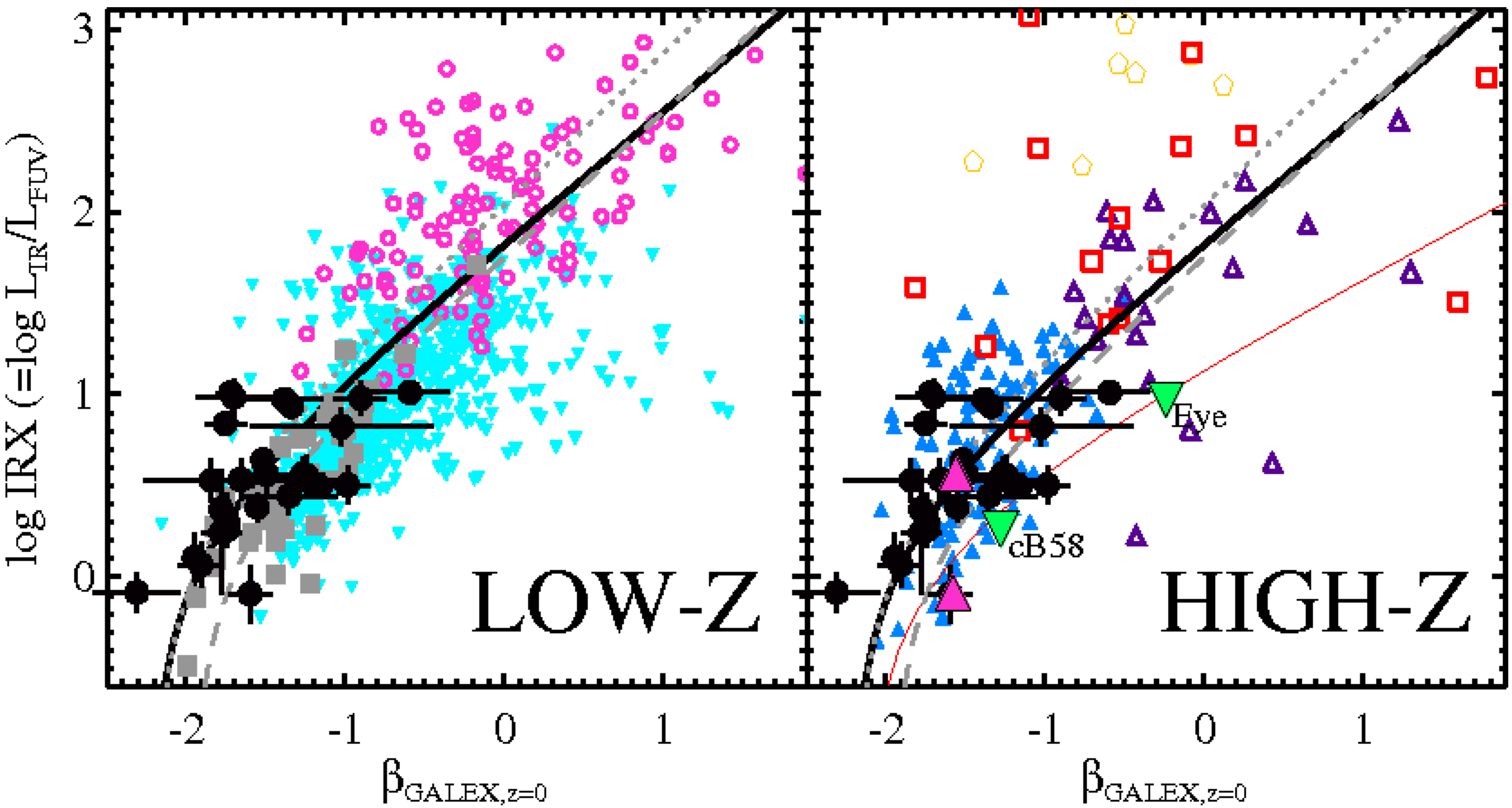
Can we calibrate dust?

‘Meurer relation’



Meurer et al. 1999; Calzetti et al. 2000

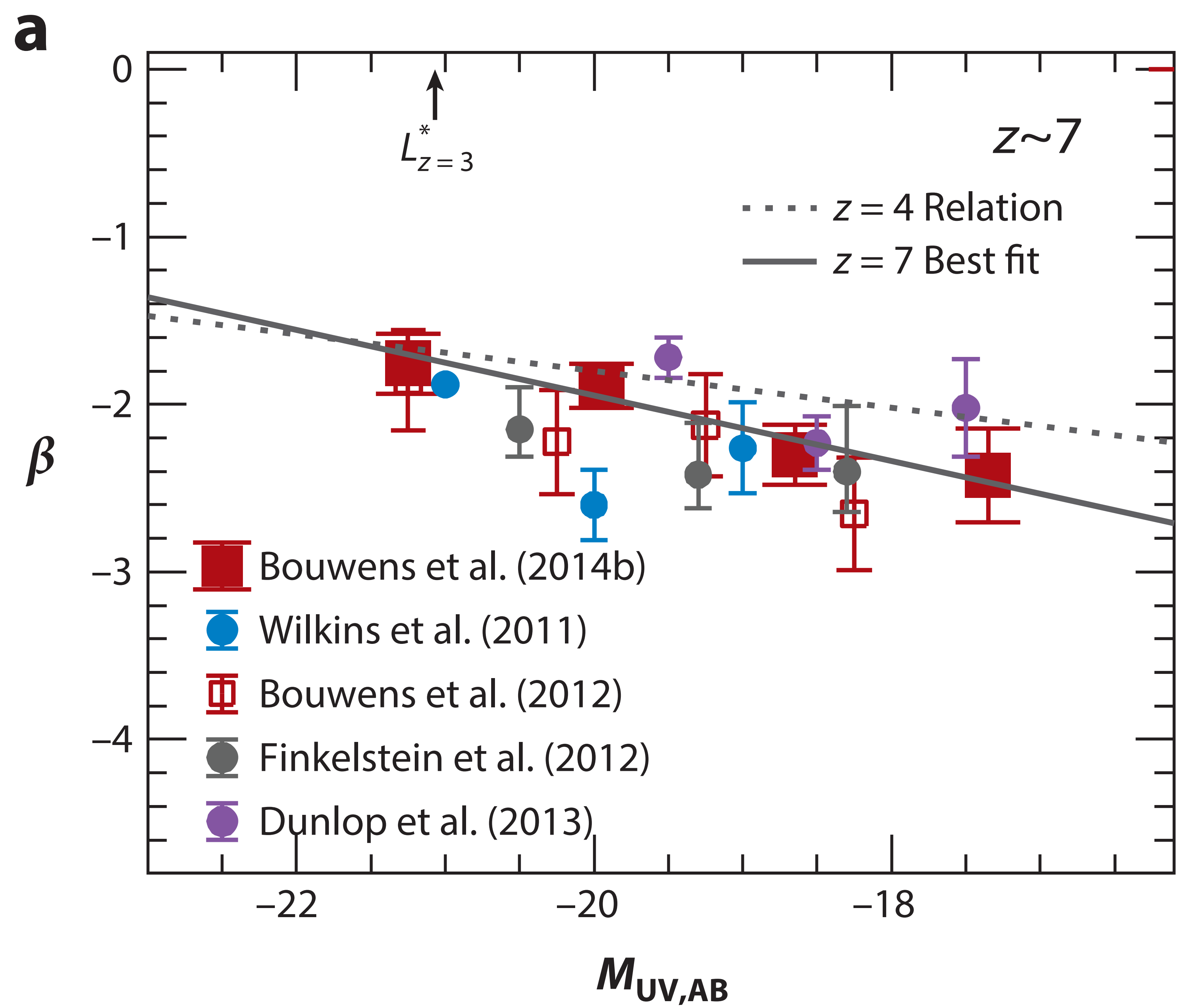
Wide range of samples are consistent



Overzier et al. 2011

Luminosity dependence of the UV slope

UV -bright sources are likely the most massive and most metal rich - which is needed to produce dust

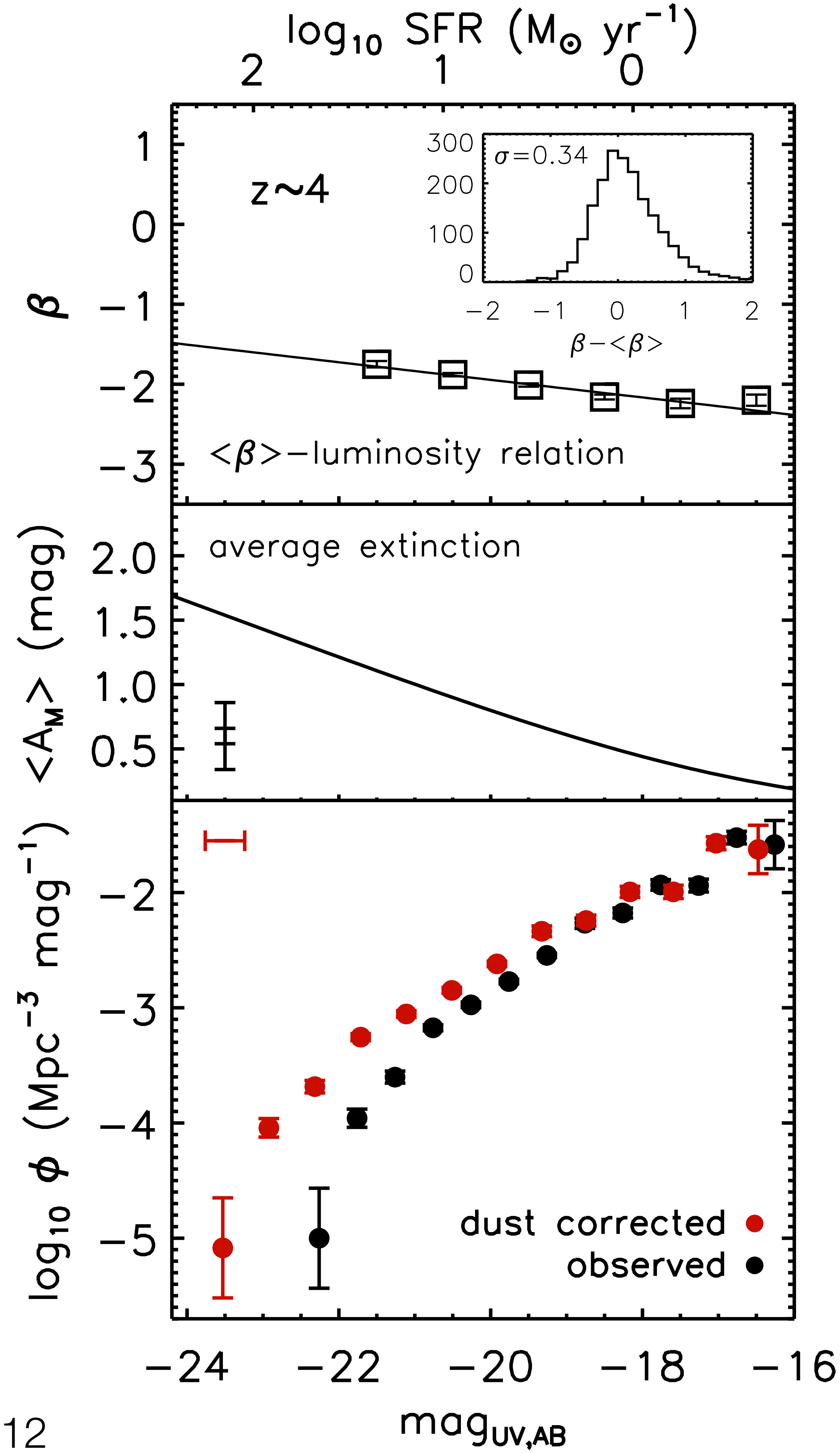


Stark et al. 2016

Application: UV LF

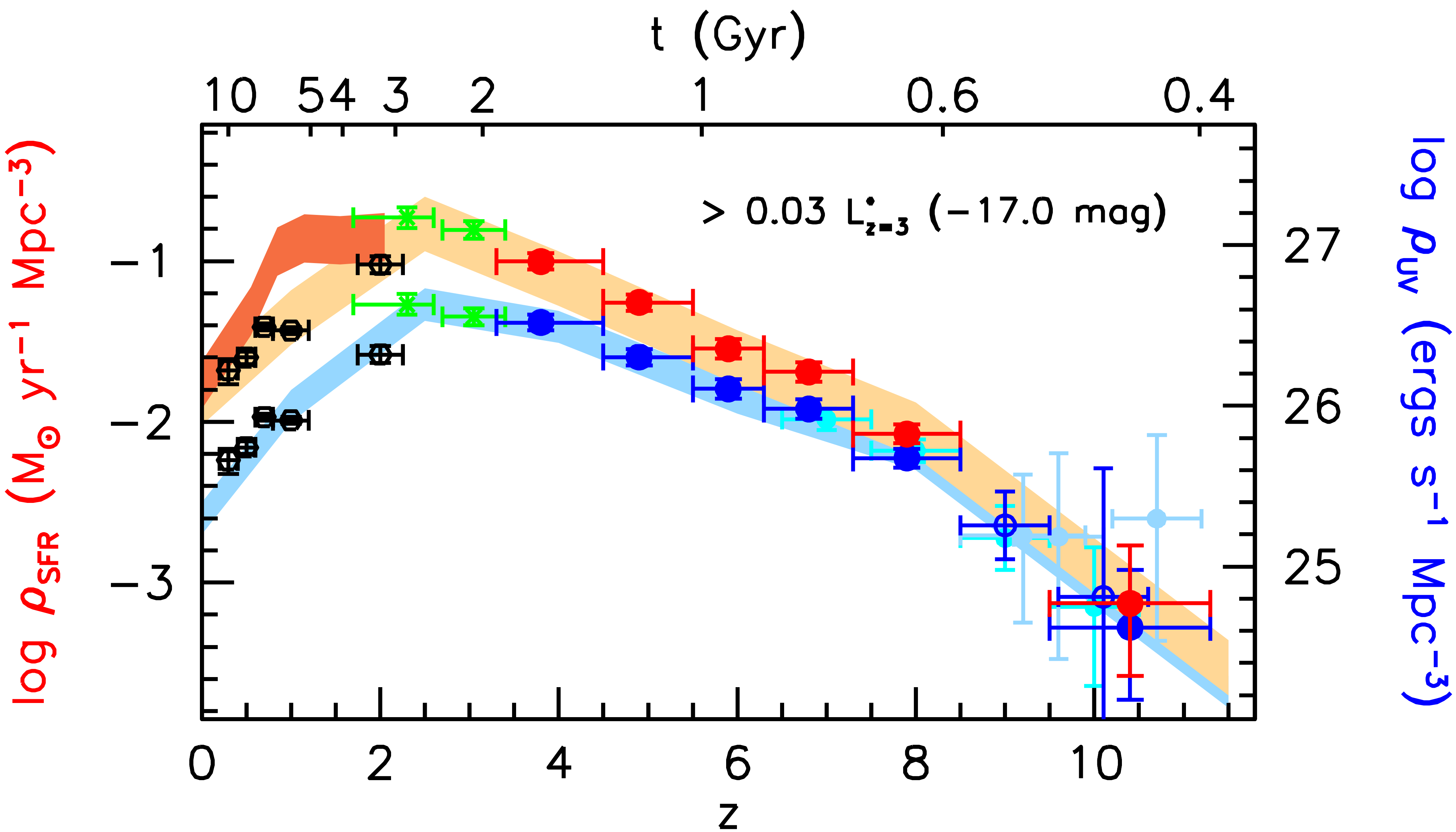
Assuming β is a proxy for dust - we can create dust corrected UV LF

One of the most important systematics is understanding the scatter!



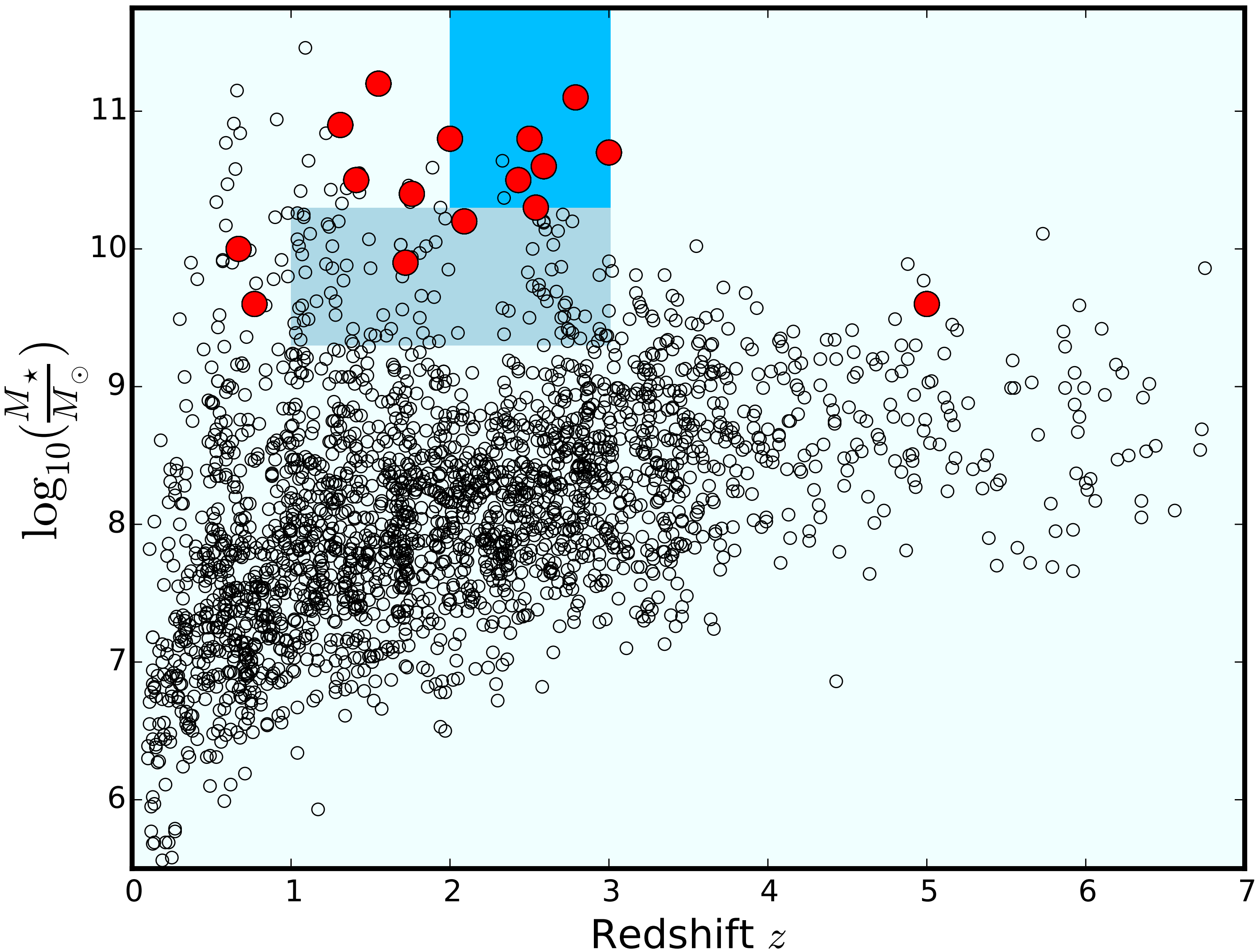
Smit et al. 2012

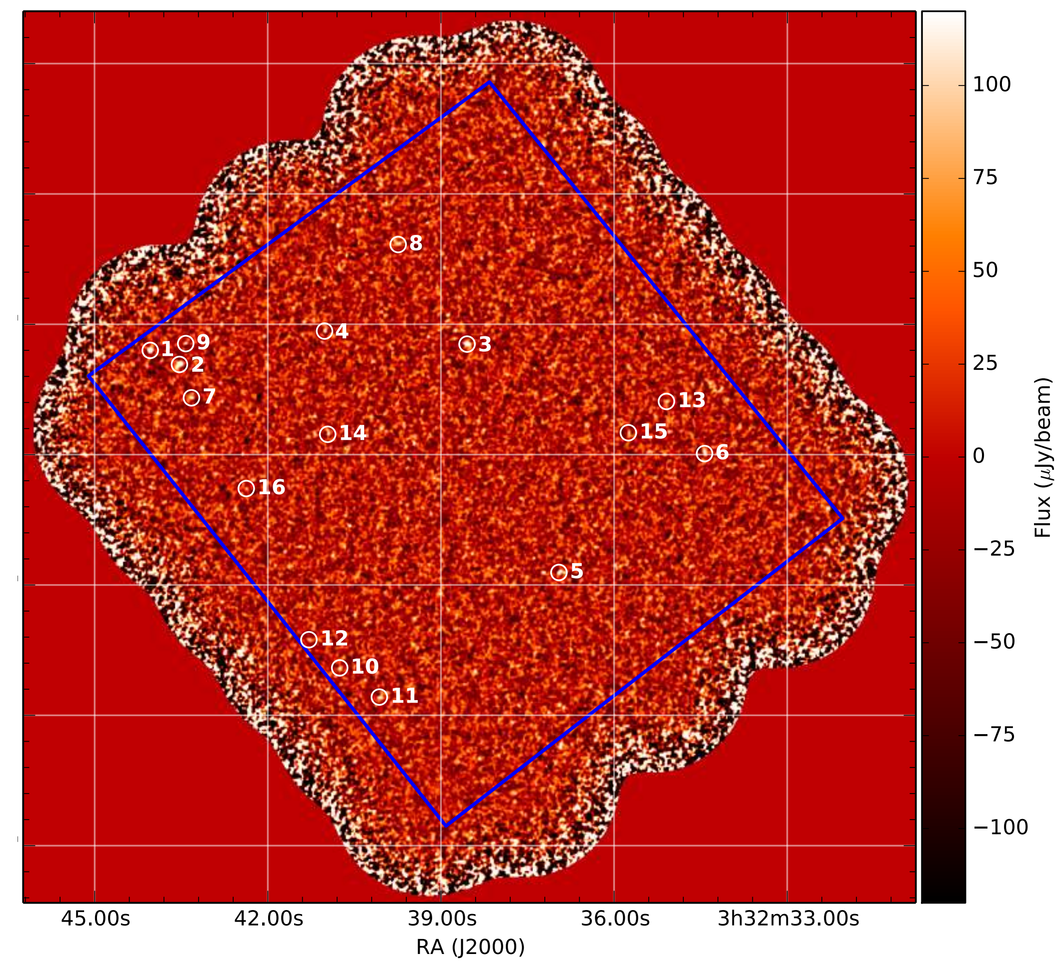
Application: SFR density



An ALMA view of dust in the Early Universe

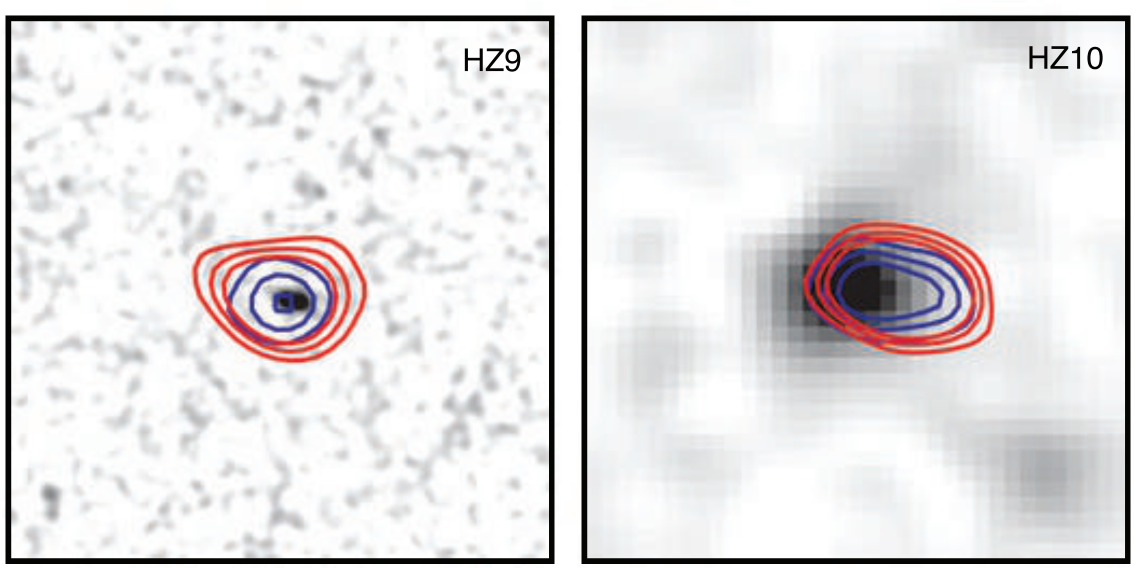
ALMA imaging over the Hubble Ultra Deep Field

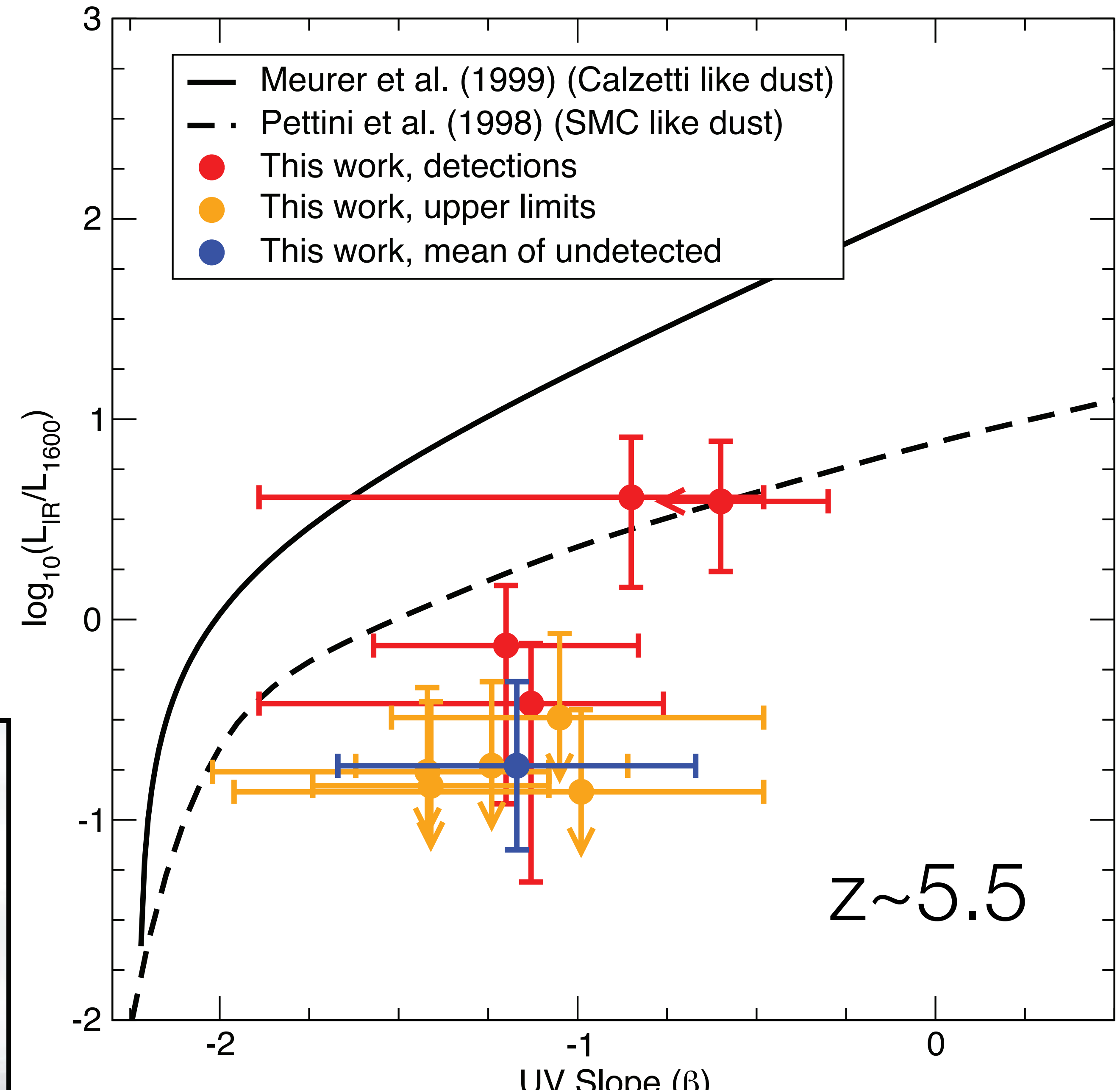




Dunlop et al. 2017

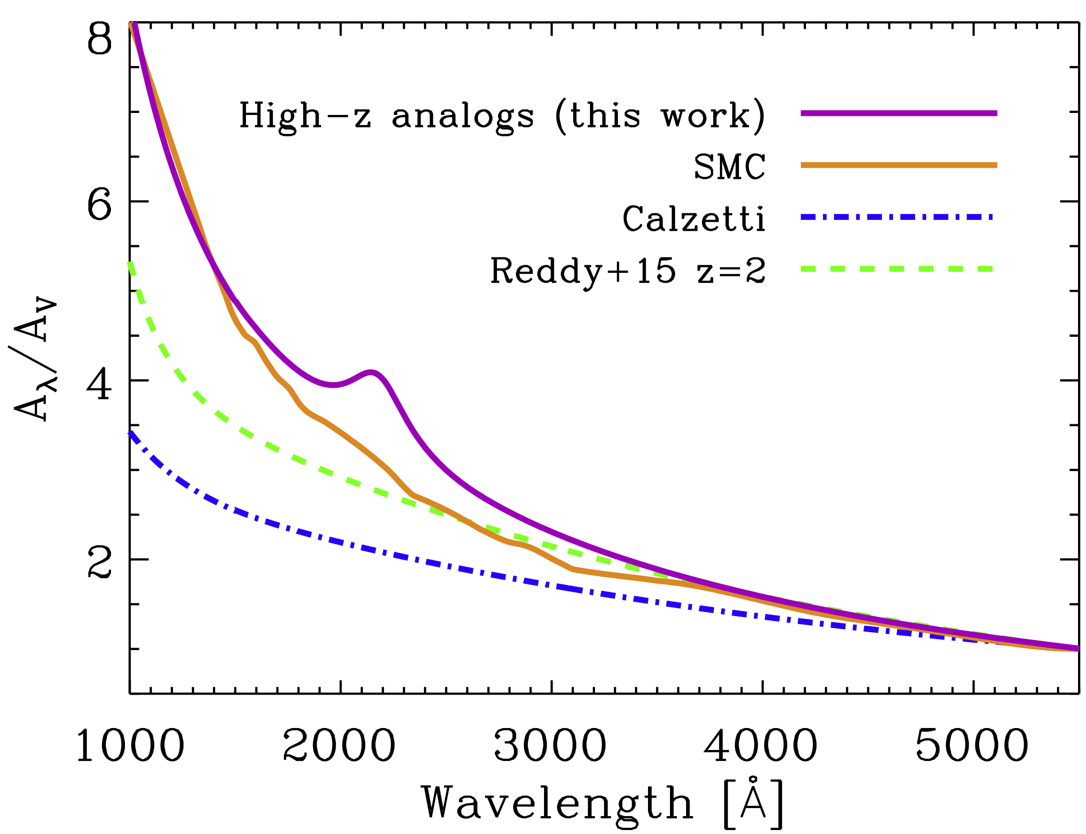
No dust in modestly red LBGs

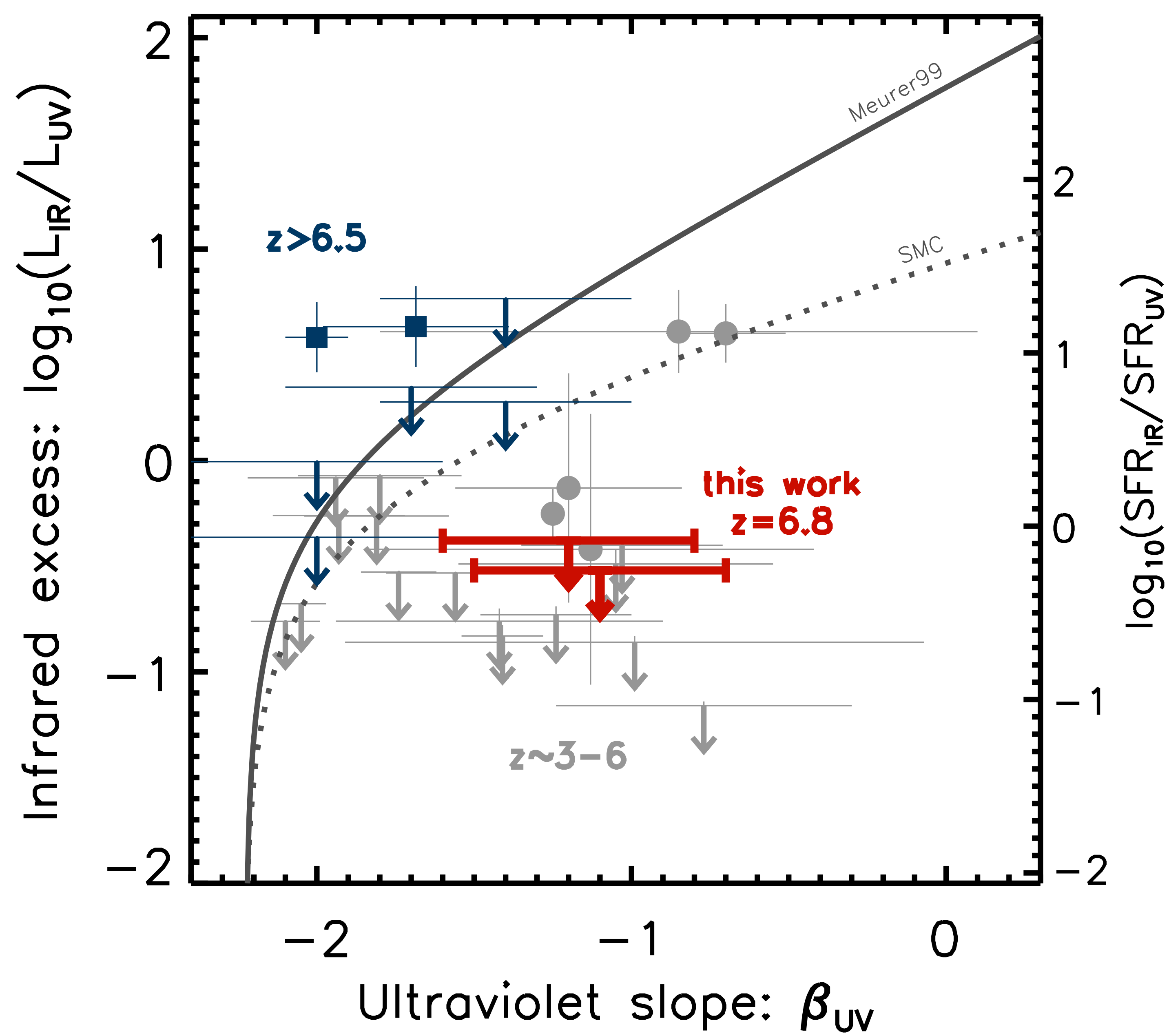




Capak et al., 2015

SMC dust curve?



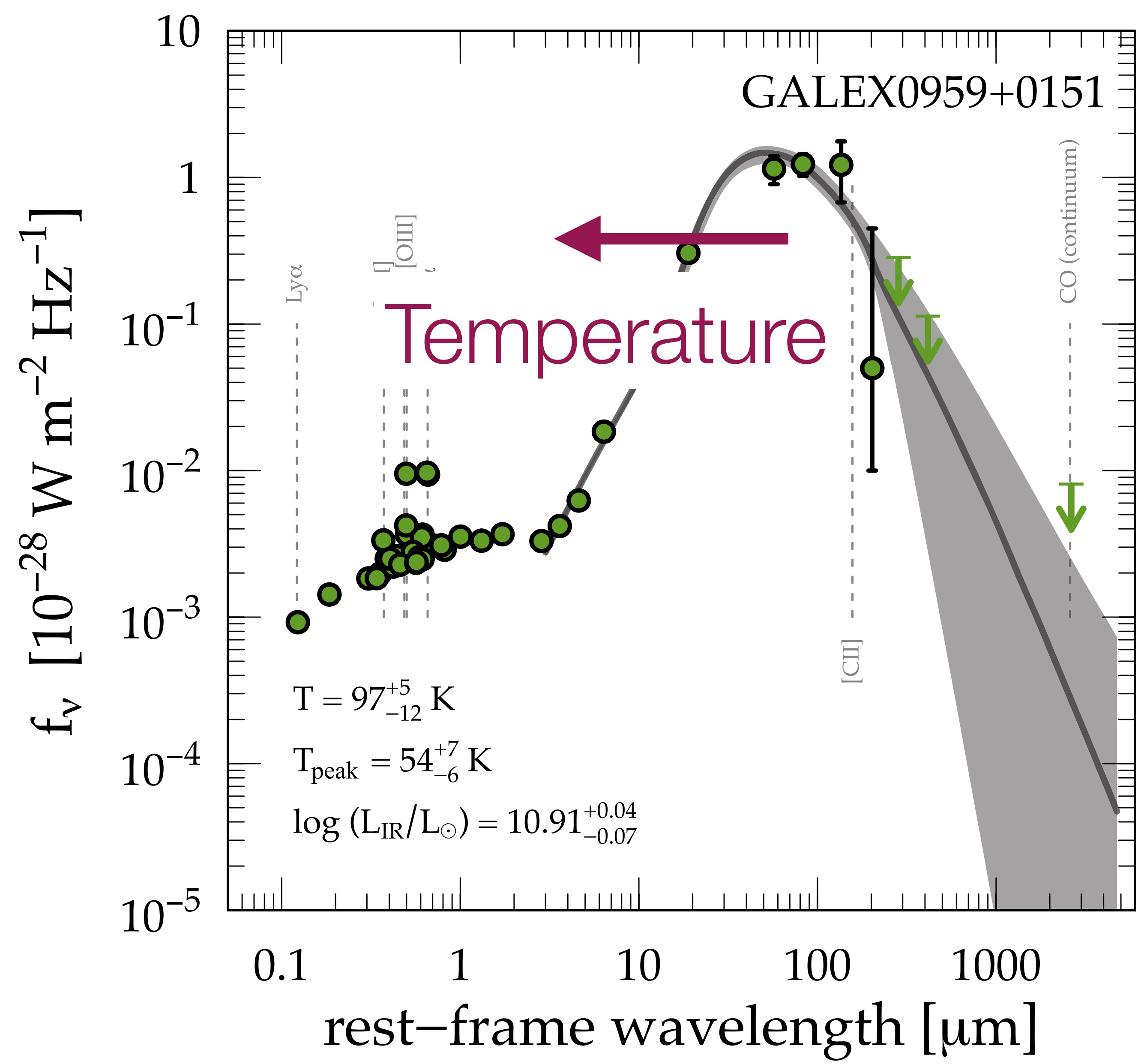


Salim et al., 2018

Smit et al., 2018

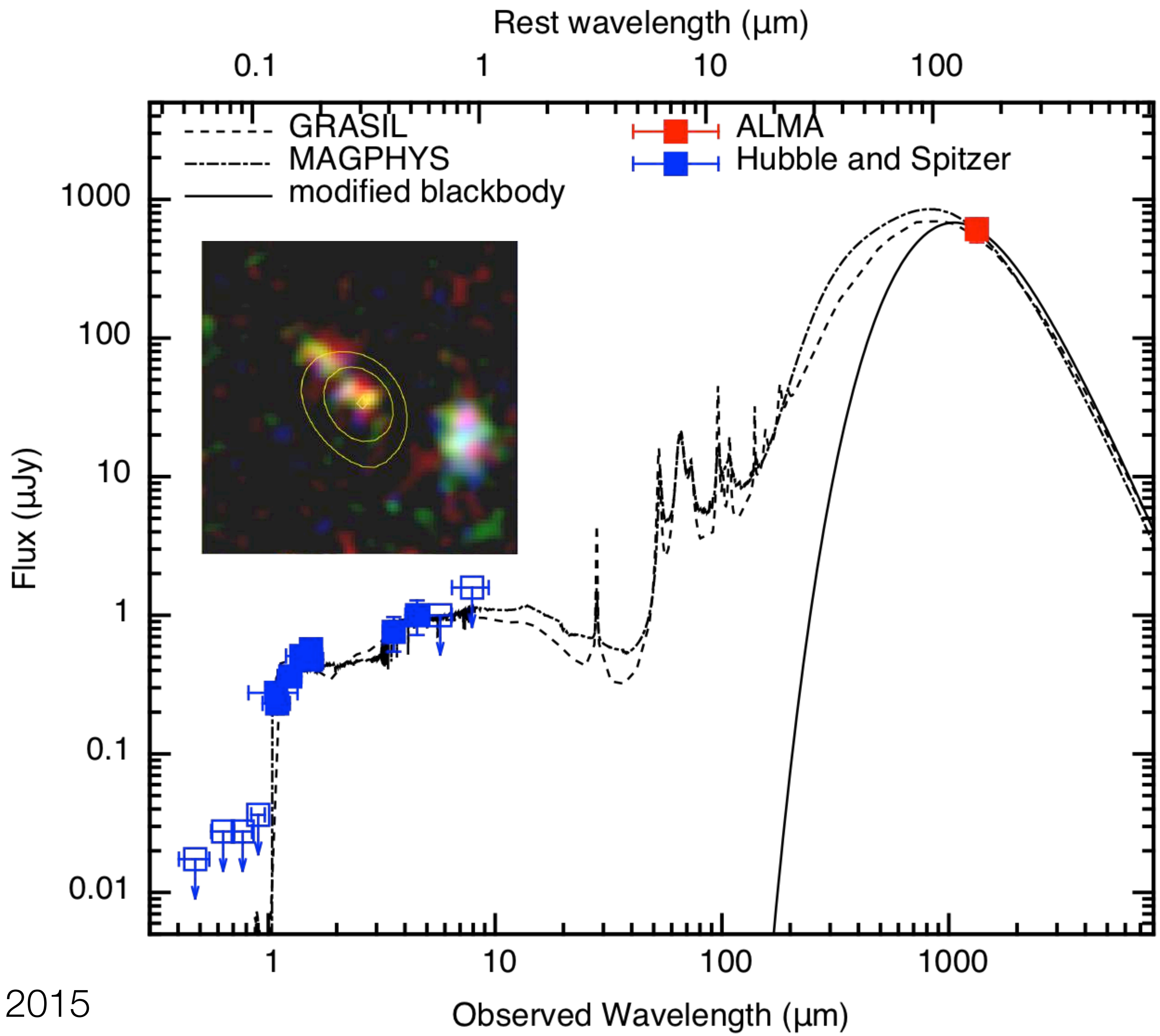
Other possible effects…

- Some local analogs show a shift in the dust peak that might indicate hot dust temperatures…
- For ALMA observations at 200 micron this give non-detections despite significant dust content
- Other possible effects include the dust opacity and dust grain composition



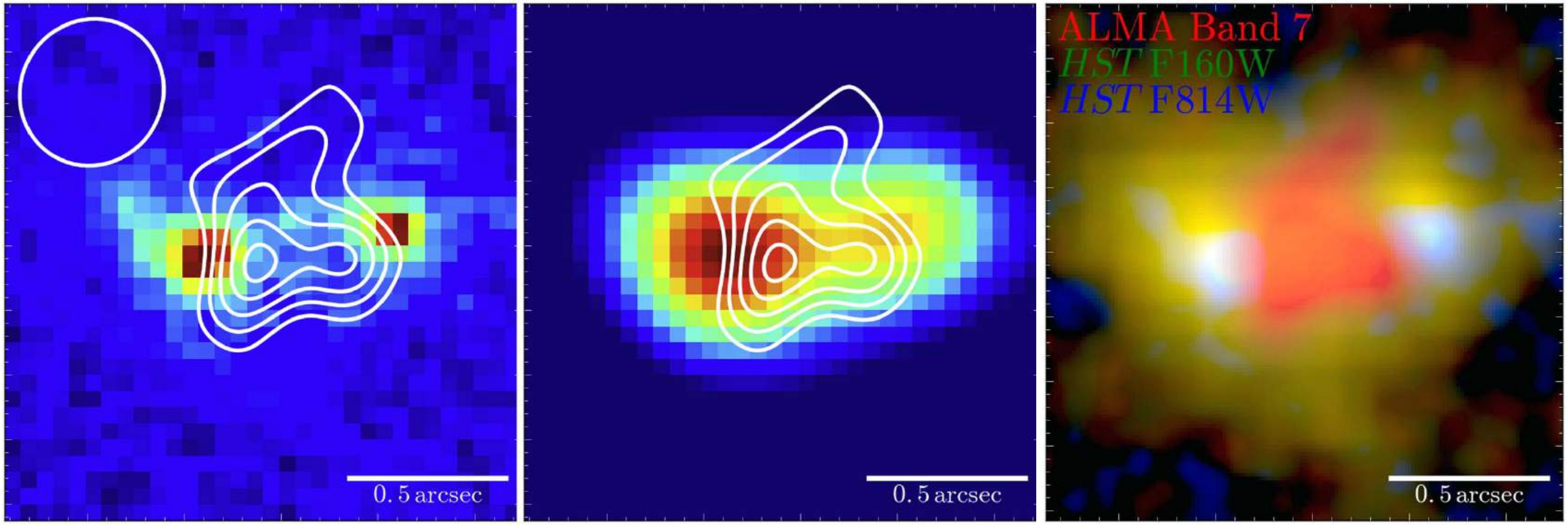
Faisst et al., 2017

Dust in blue galaxies?



Watson et al., 2015

Spatial offsets UV and IR continuum



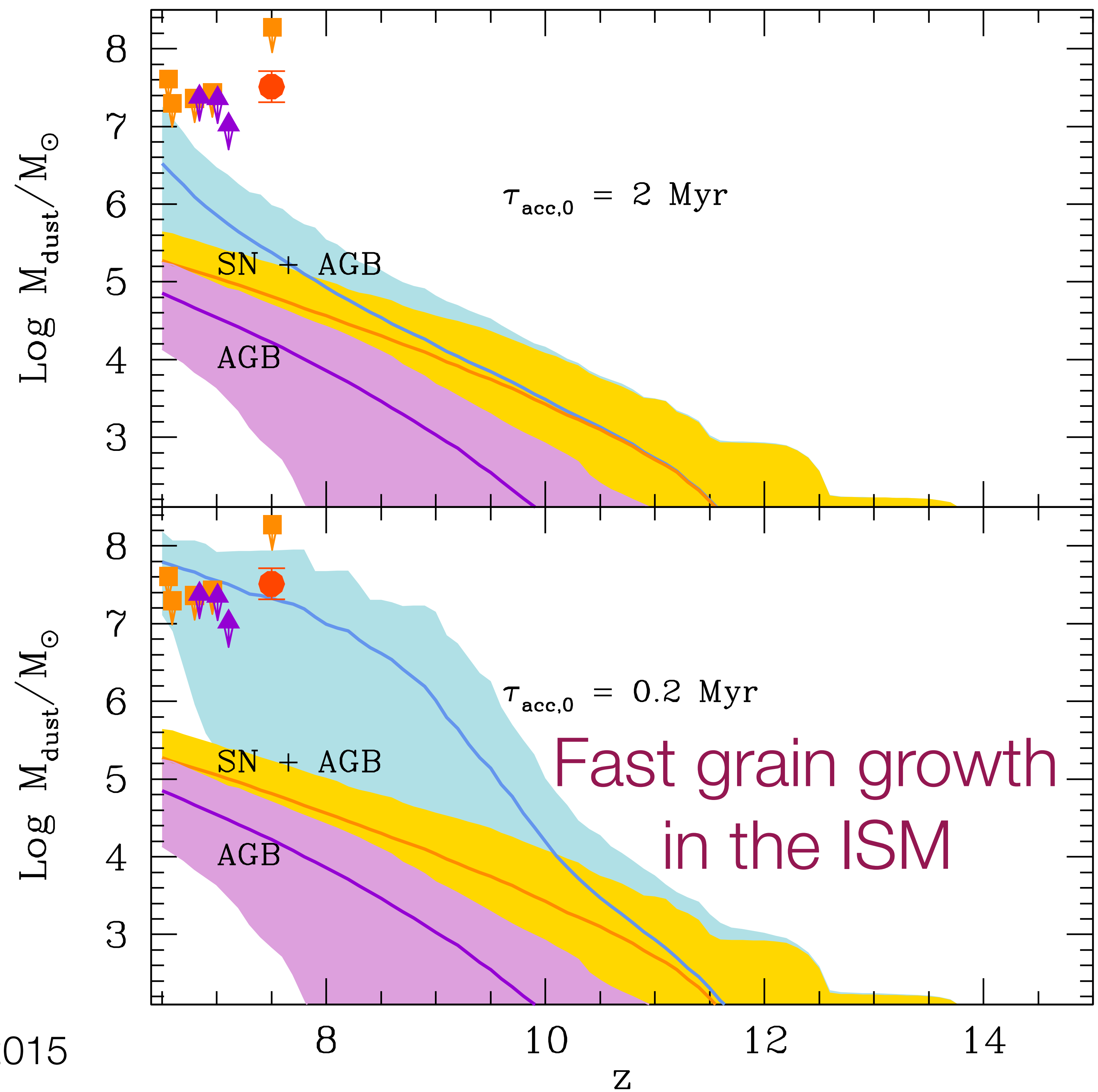
z=3.1

Koprowski et al., 2016

Dust geometry also affects the [CII] morphology

Dust formation models

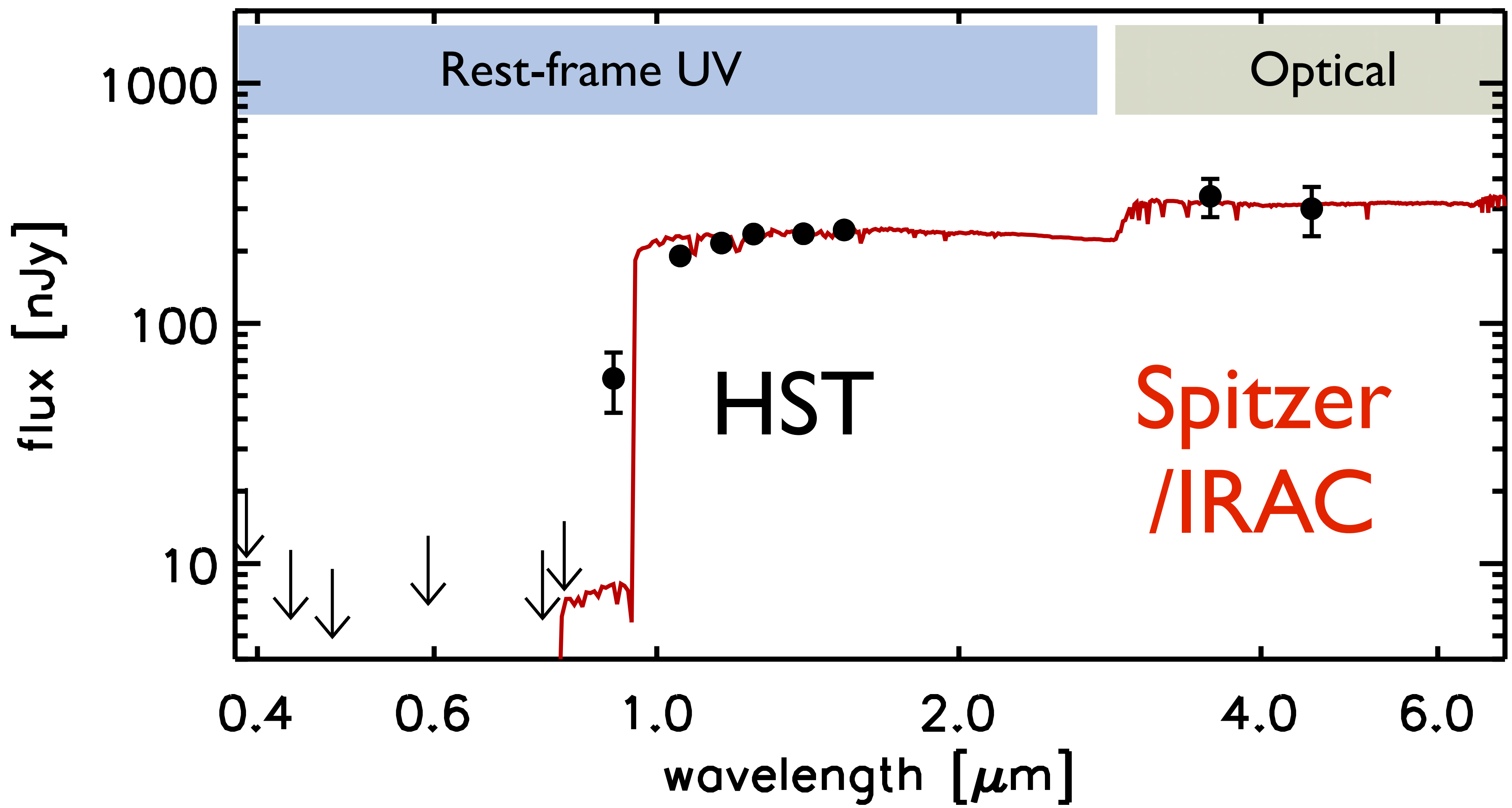
- AGB pulsations produce a lot of dust but on a longer timescales
- SN produce (and destruct) dust on short timescales
- The least understood and most debated form of dust formation is ISM grain growth



Mancini et al., 2015

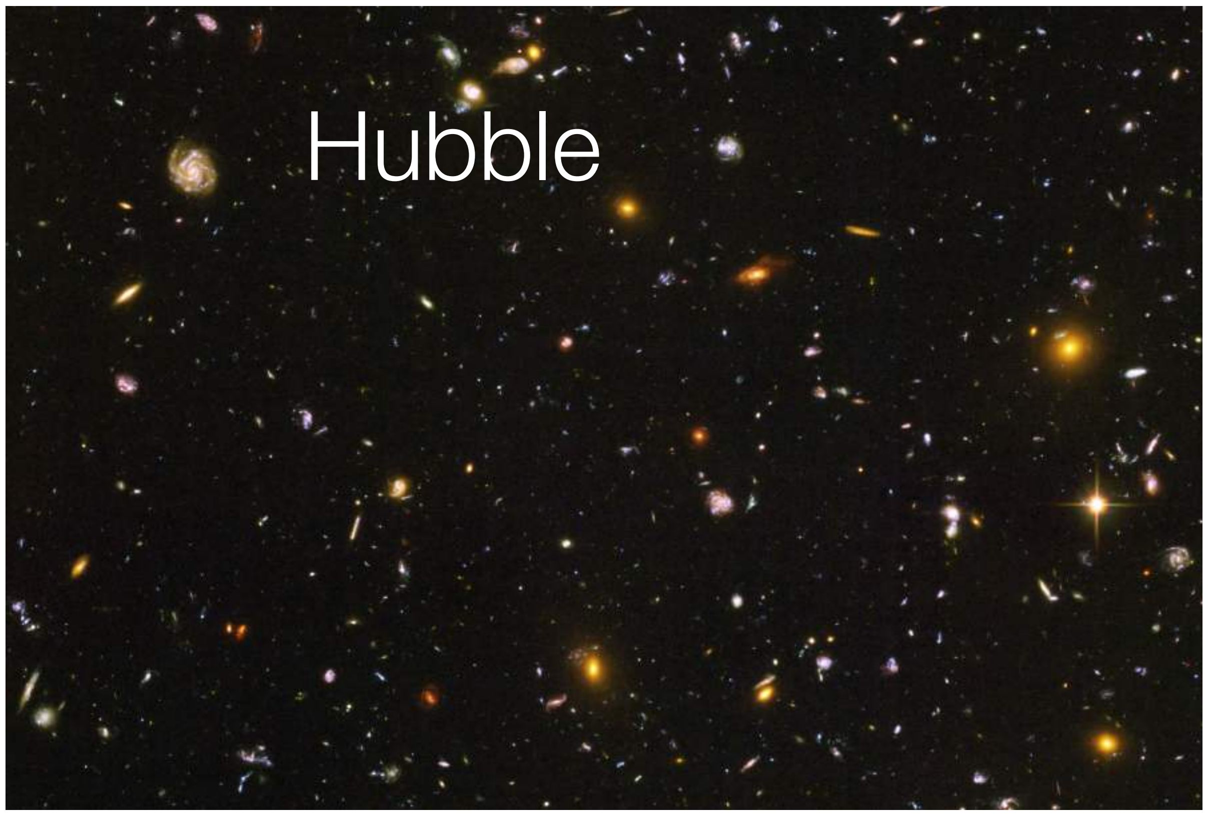
A Spitzer view of stellar mass build-up

Rest-frame UV to optical SED

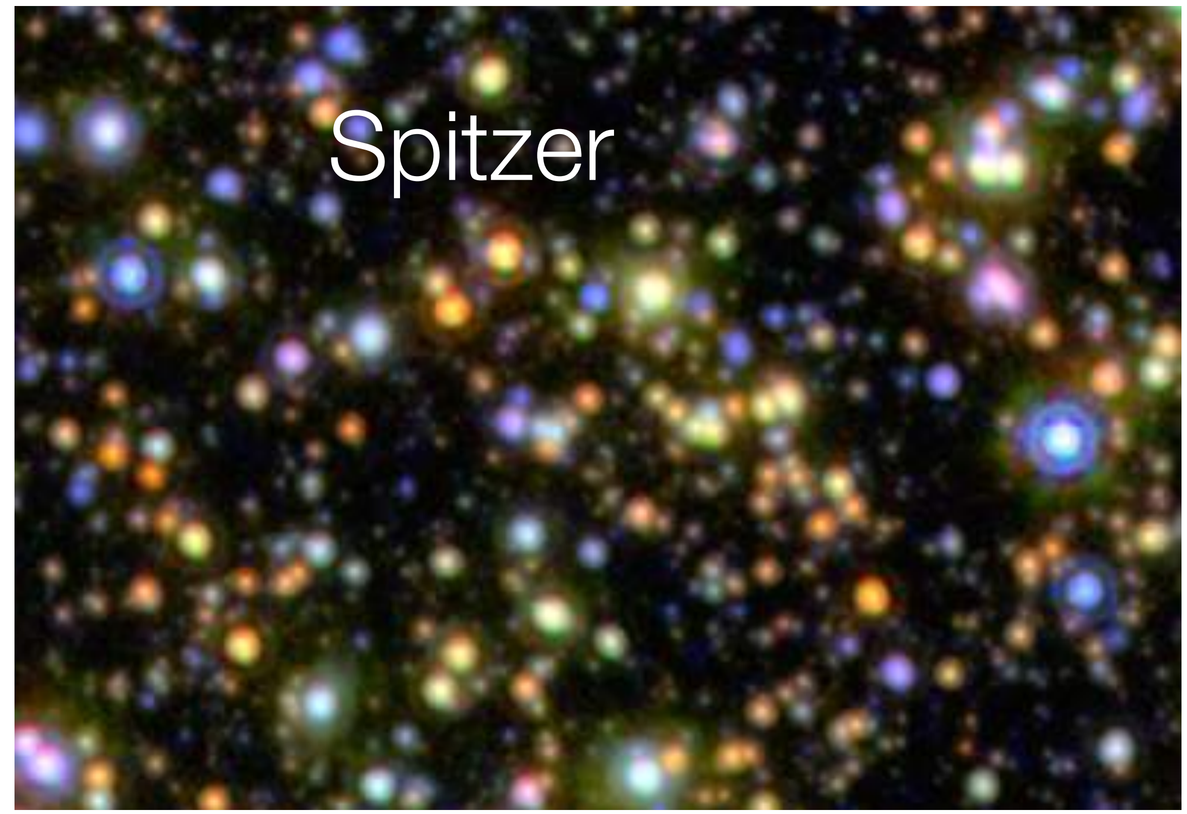


Need the older stars in the rest-frame optical to derive accurate masses, ages and specific star formation rates

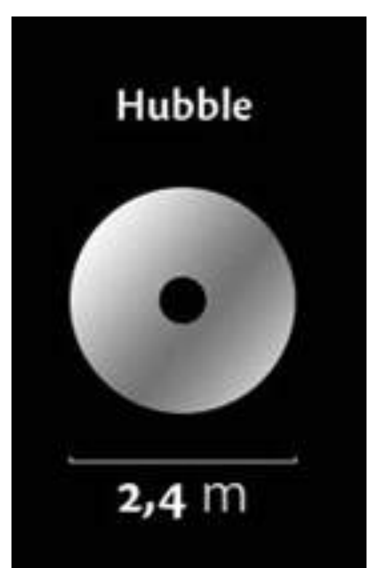
Spitzer deep imagine over the HUDF

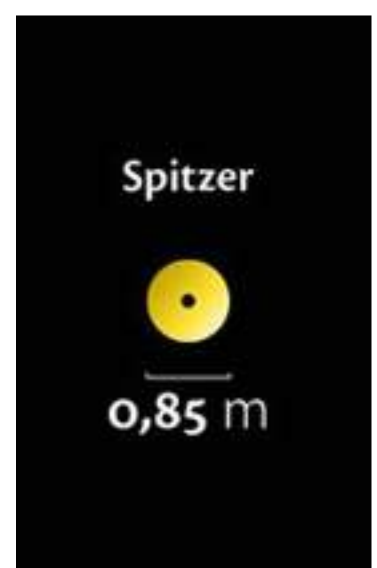


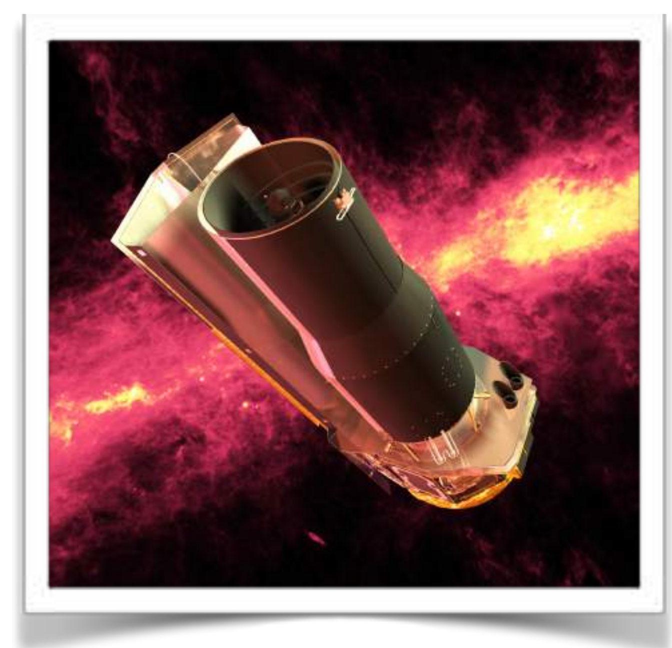
Credit: NASA, ESA, and S. Beckwith (STScI) and the HUDF Team



Labbé et al. (2015)





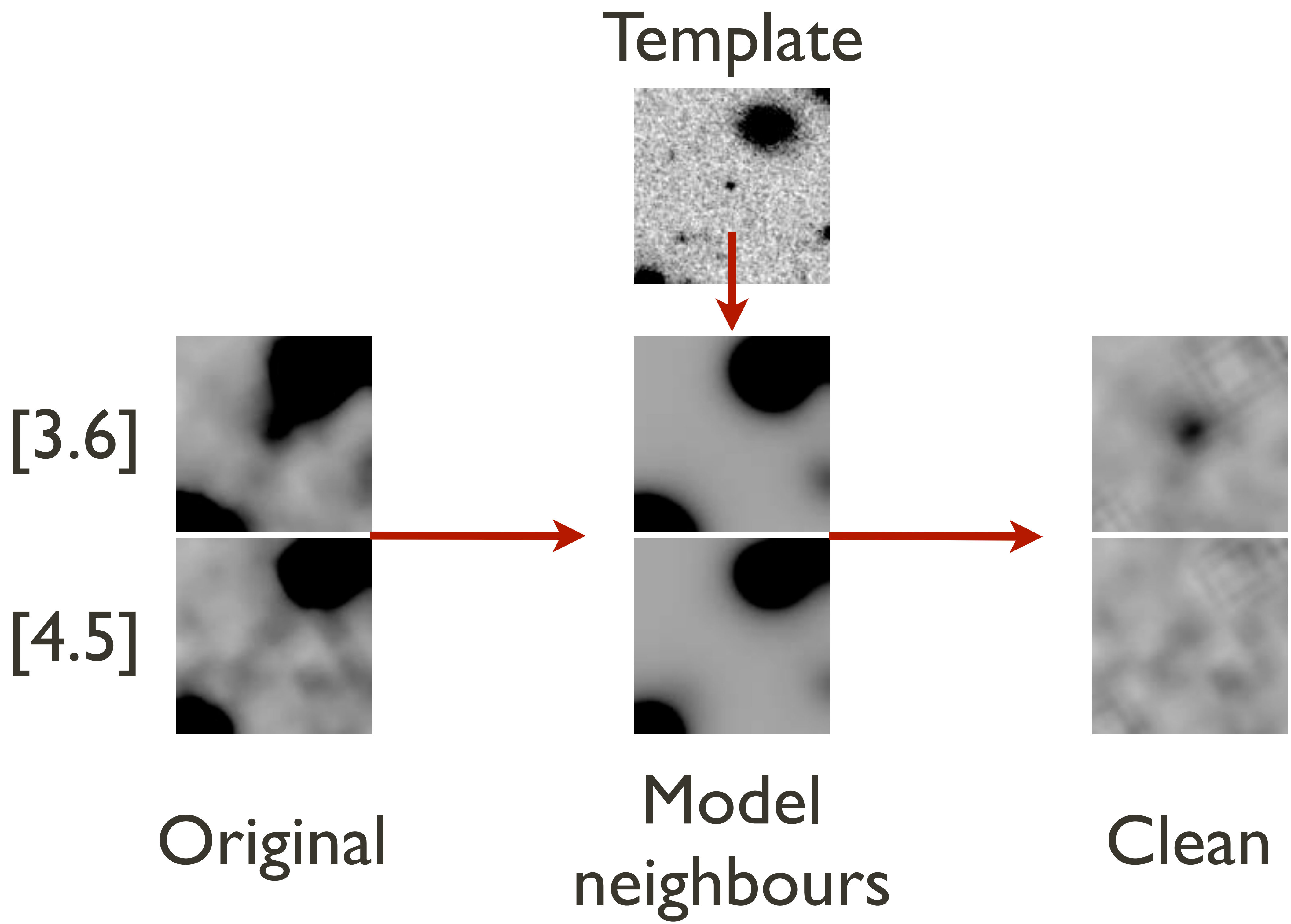


Spitzer Space Telescope

Credit: A. Zitrin

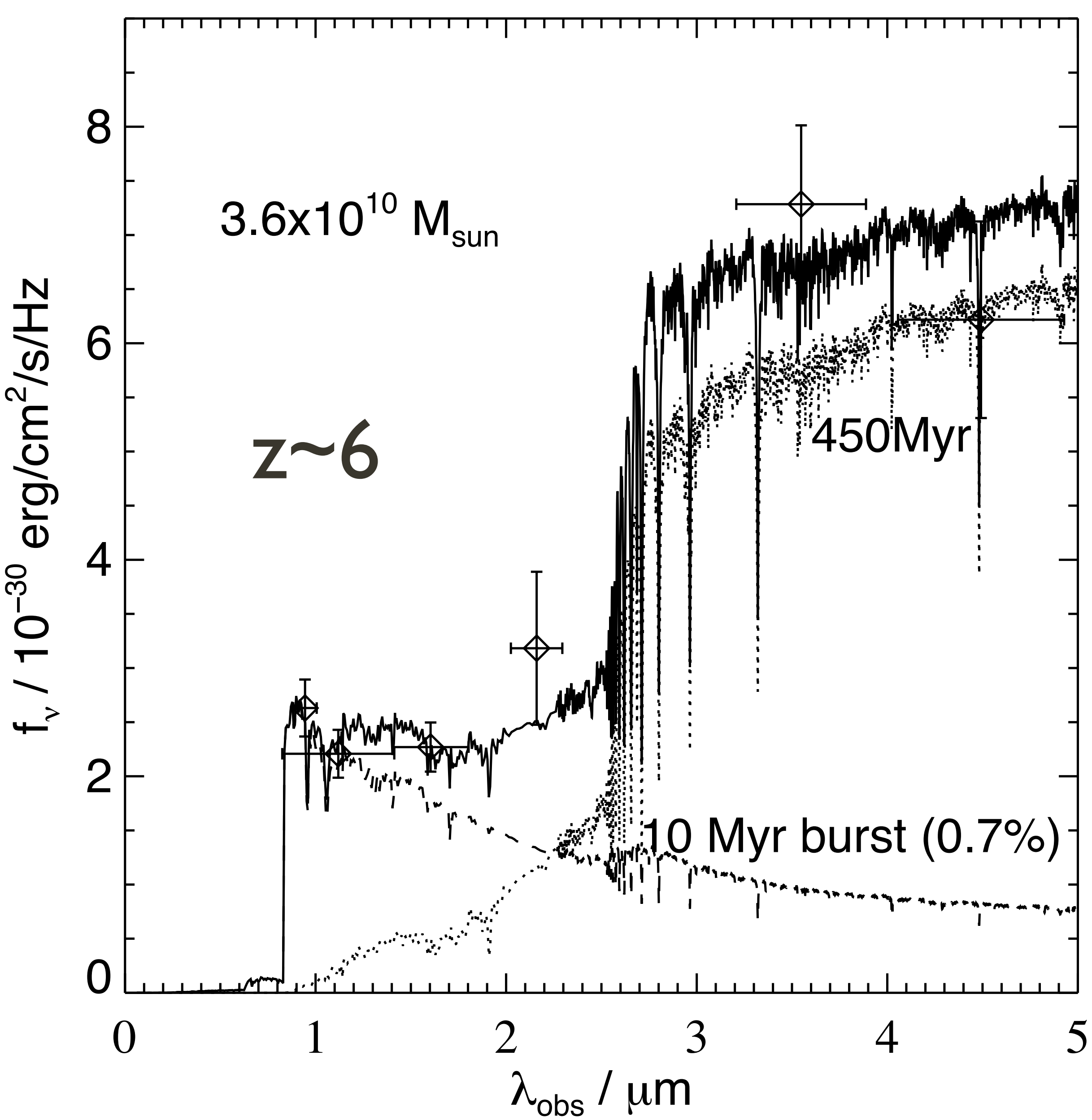
- Cold mission: 2003 - 2009
  Mid-infrared Universe
- Warm Mission 2009 - 2019:
  Liquid helium to cool the instruments ran out
- Shortest wavelength filters produce images that are still sensitive enough to detect distant galaxies found with Hubble

Source de-confusion



Results on galaxy properties z>3: surprisingly old ages, high masses

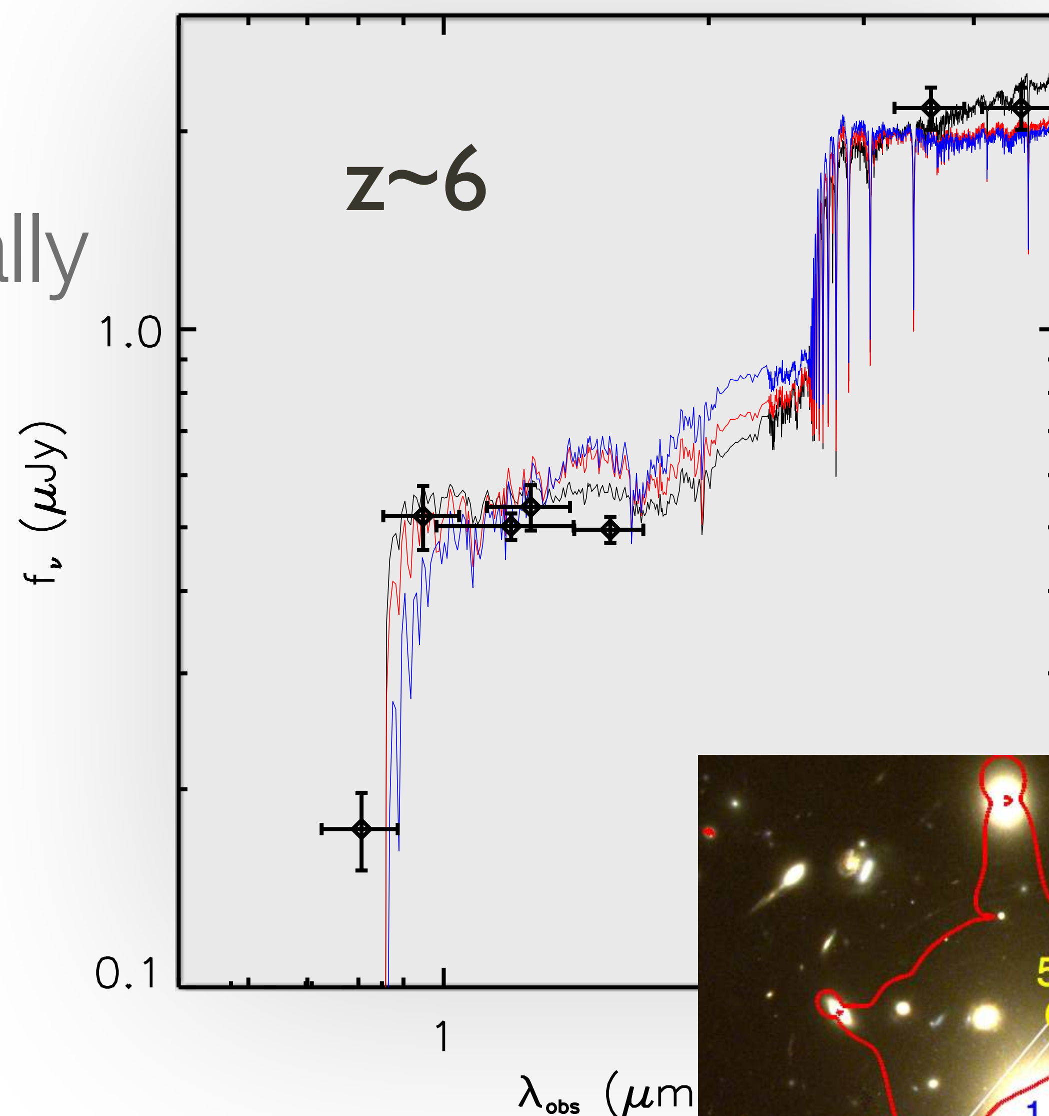
- z~6 Lyman break galaxy with a large Balmer break indicating a stellar population 450Myr old
- Calculating back assumes quite a lot of star-formation already at z~12



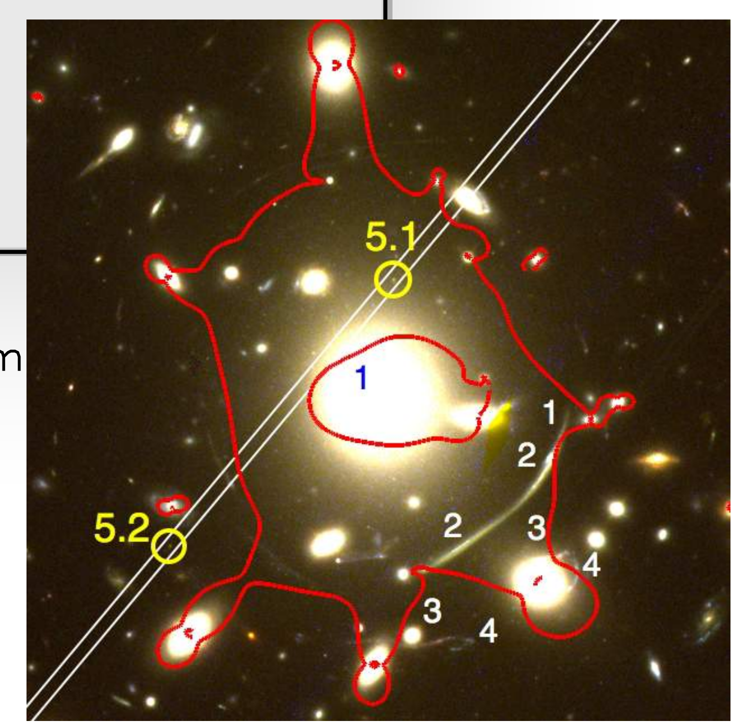
Eyles et al. 2005

Results on galaxy properties z>3: surprisingly old ages, high masses

- High S/N example of a strongly lensed, intrinsically faint galaxy
- 1-1.5 magnitude Balmer break indicates:
  Estimated formation redshift **z~18**
  Mass $M_{*} = 6.3 \cdot 10^{9}\, M_{\odot}$

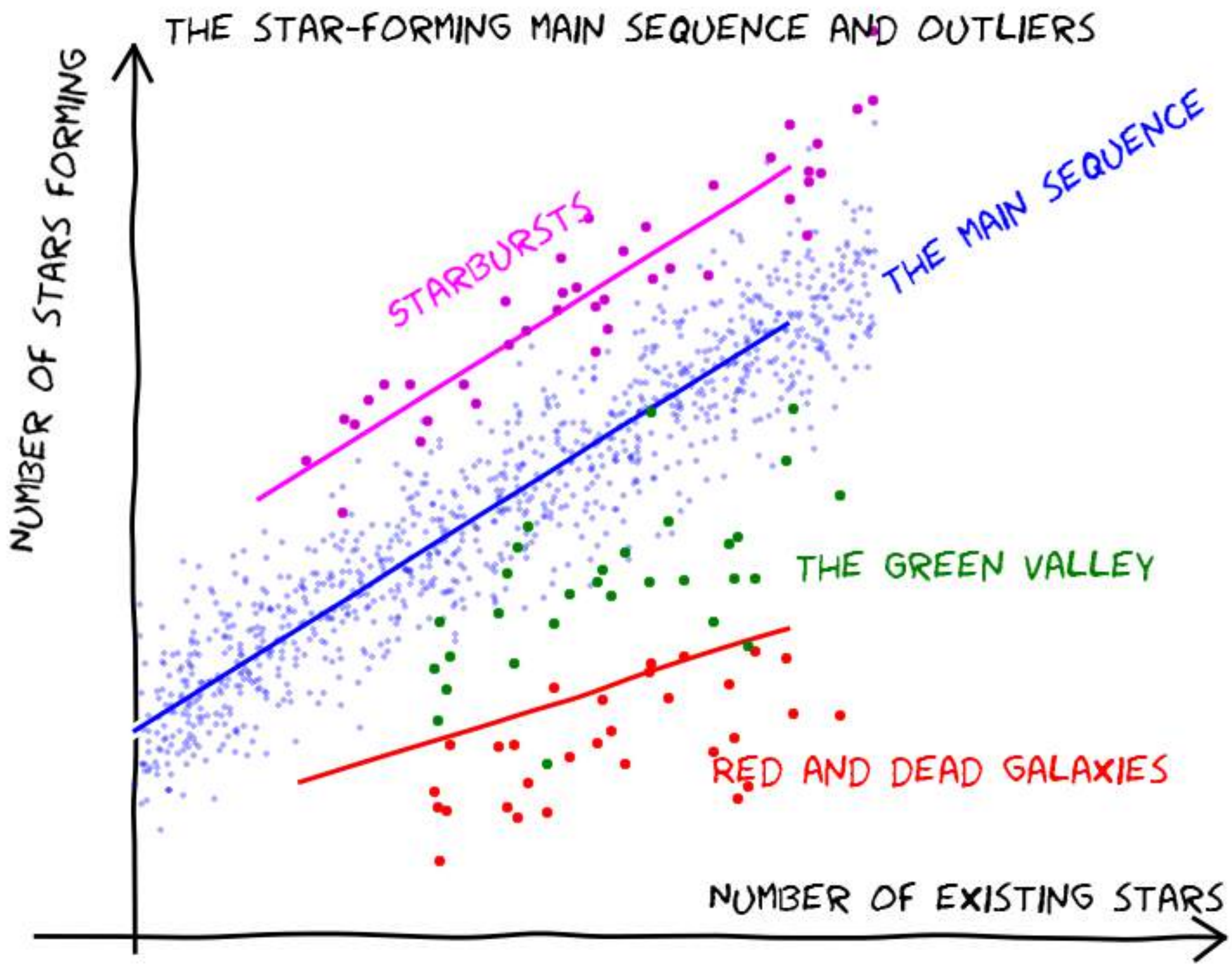


Abell 383

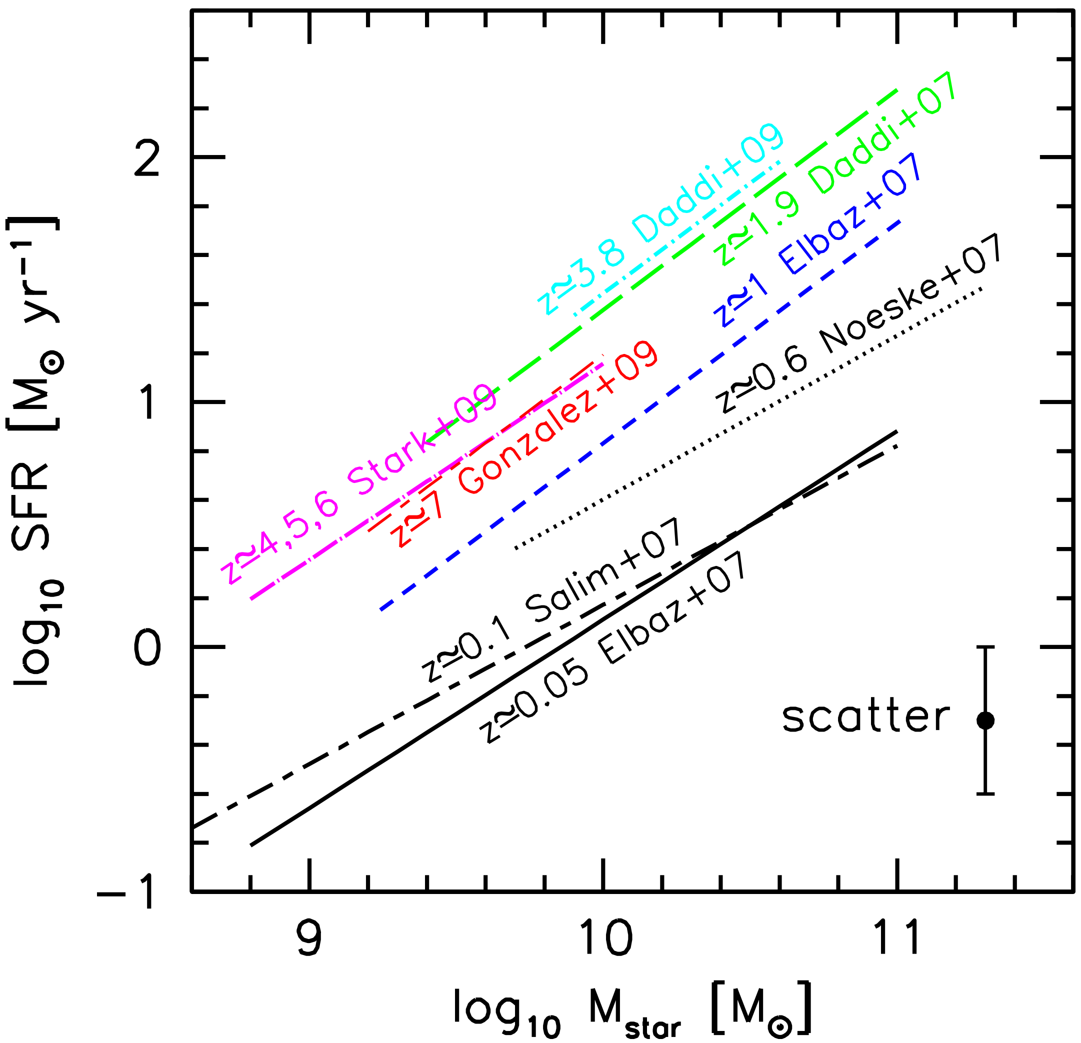


Richard et al. 2011

The main sequence of star-forming galaxies

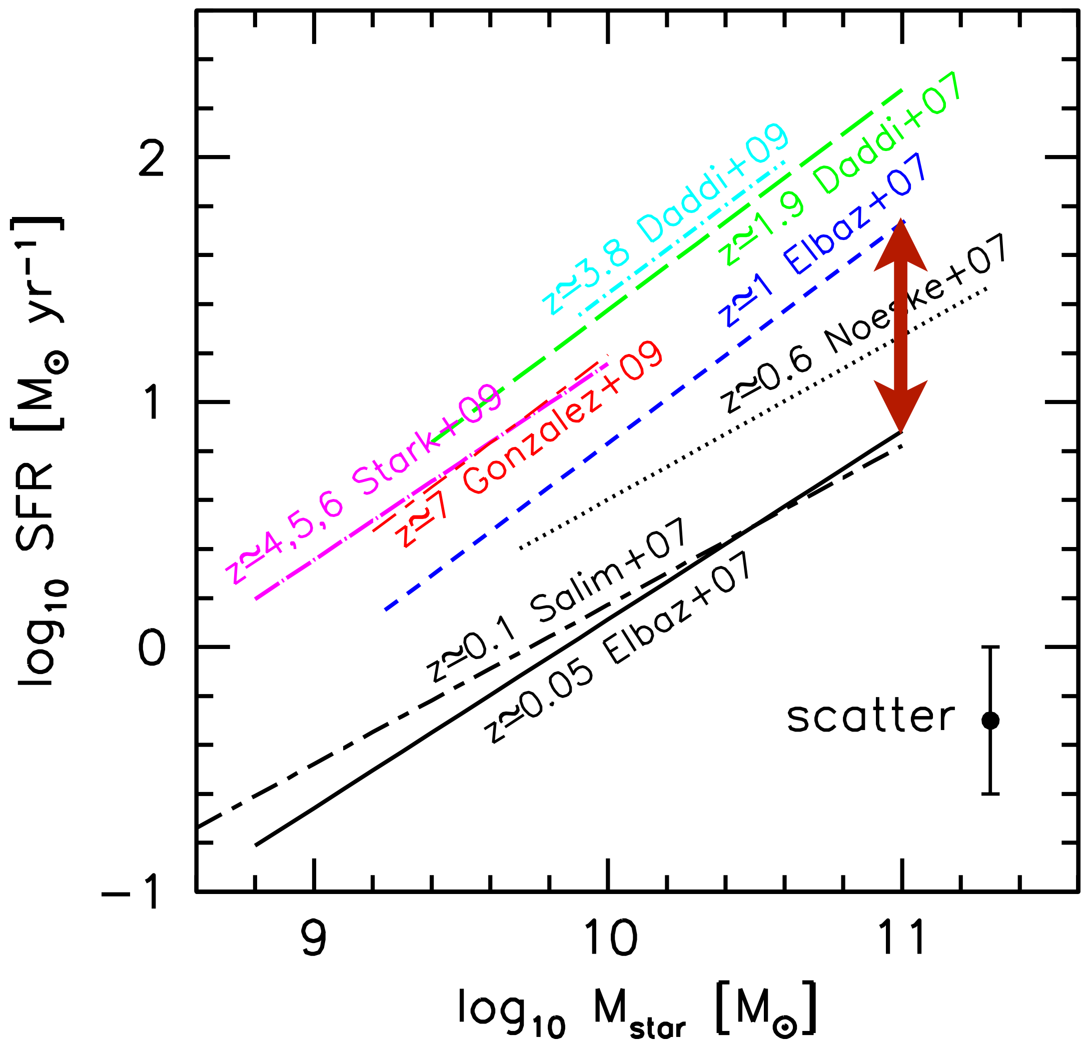


SFR - Mass sequence out to z~7



Dutton et al. 2010

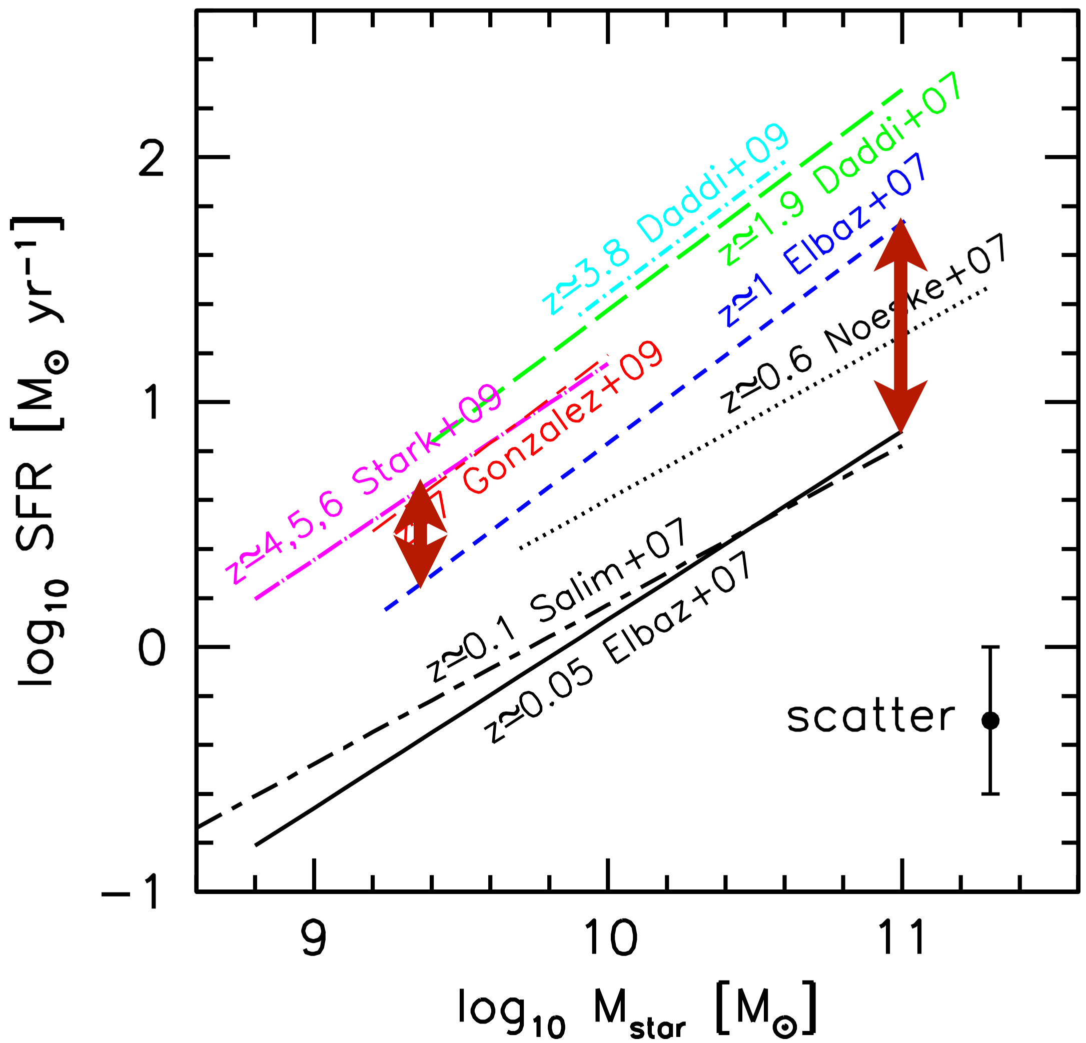
SFR - Mass sequence out to z~7



Dutton et al. 2010

Strong evolution between redshift z~0-1

SFR - Mass sequence out to z~7

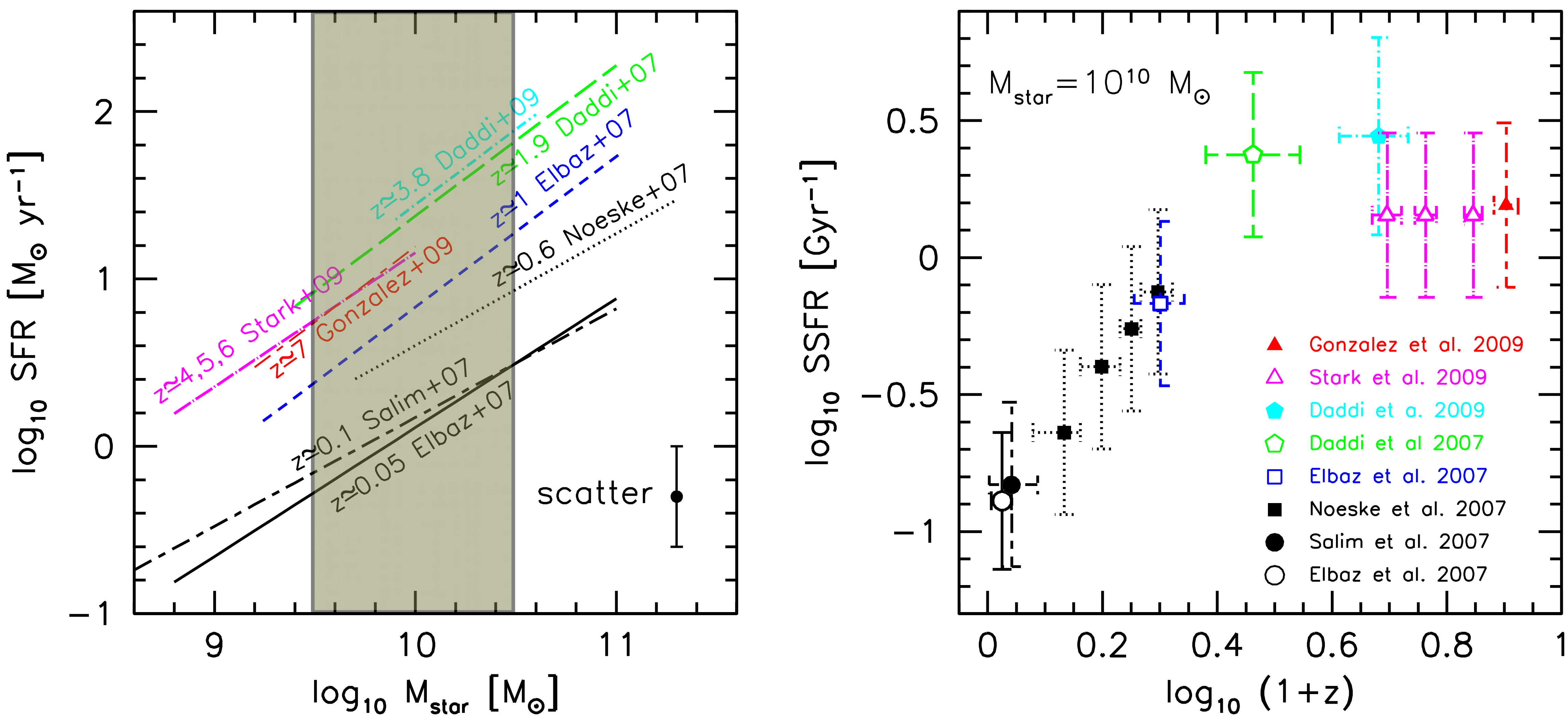


Dutton et al. 2010

Strong evolution between redshift z~0-1

Weak evolution z~1-7

SFR - Mass sequence out to z~7

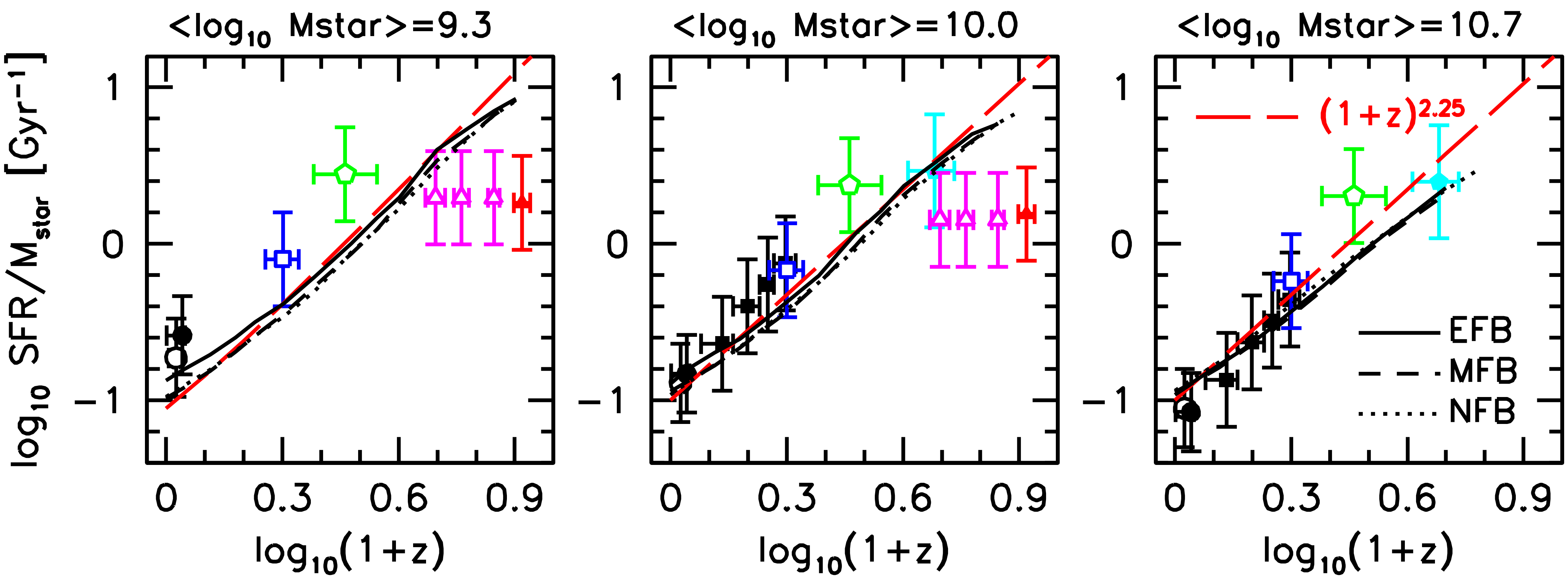


Dutton et al. 2010

sSFR (SFR / M$_\star$) vs. redshift - zeropoint evolution of the main sequence

Semi-analytical models

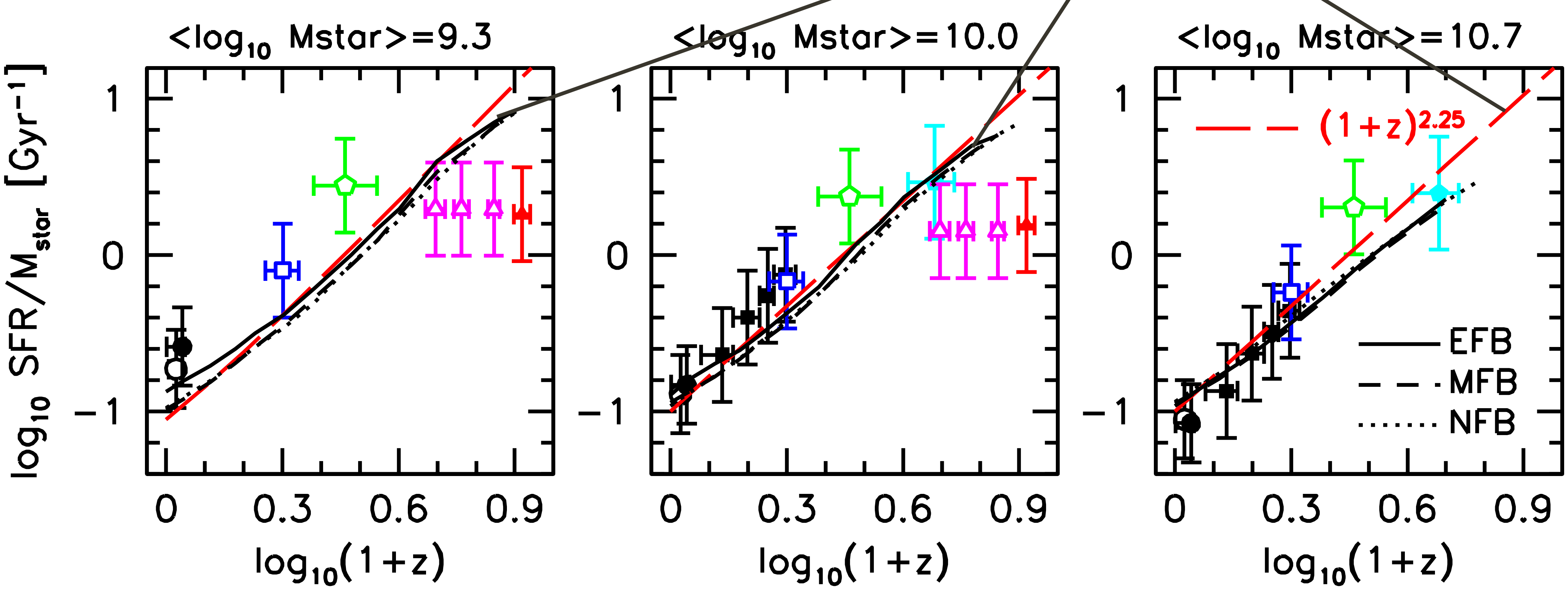
sSFR = SFR / M$_\star$ = inverse growth time scale



Dutton et al. 2010

Semi-analytical models

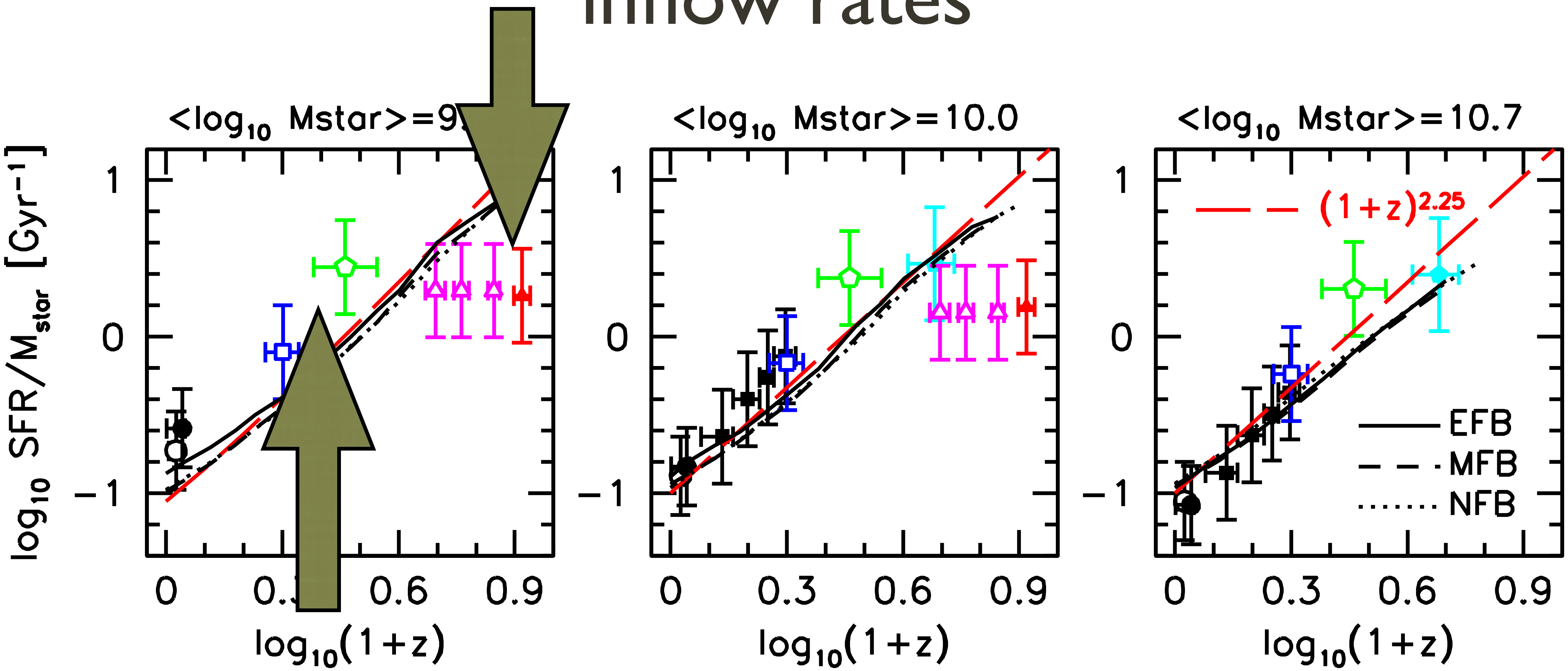
Prediction sSFR ~ specific accretion rates ~ $(1+z)^{2.5}$



Dutton et al. 2010

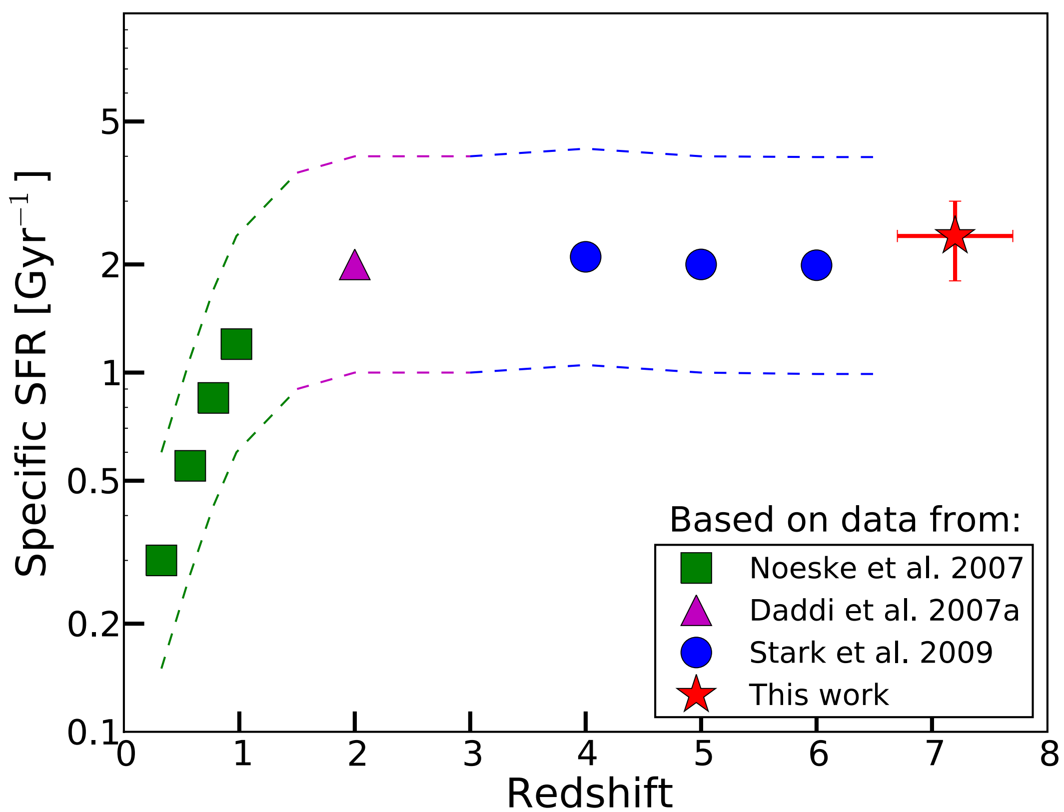
Semi-analytical models

Baryonic processes needed to decouple SFR from inflow rates

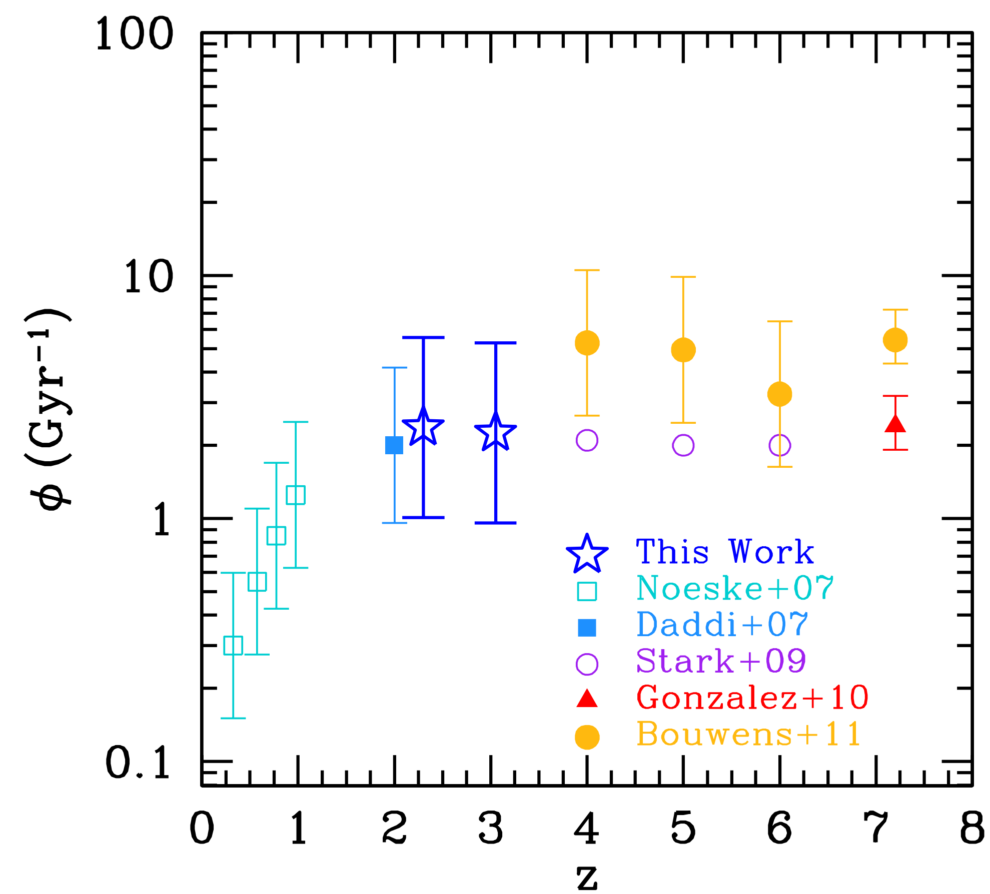


Dutton et al. 2010

Early results showed a 'plateau' at z>2



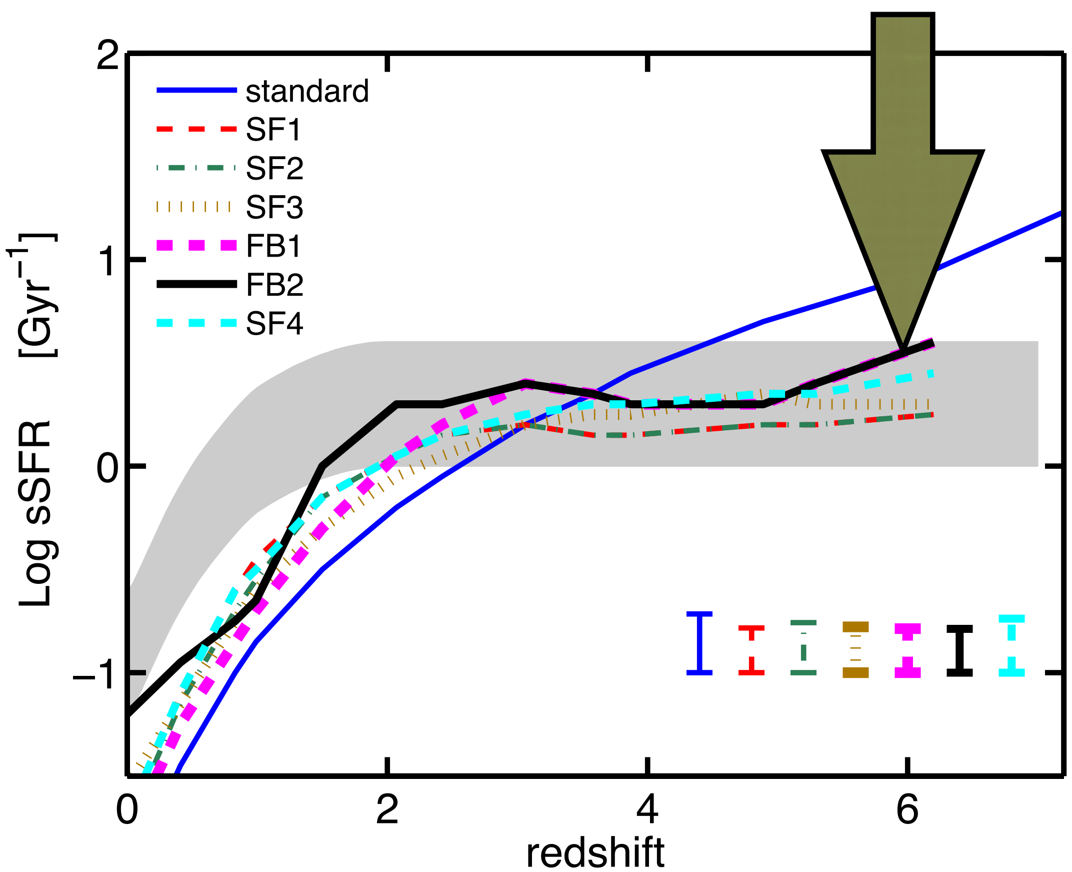
Gonzalez et al. 2010

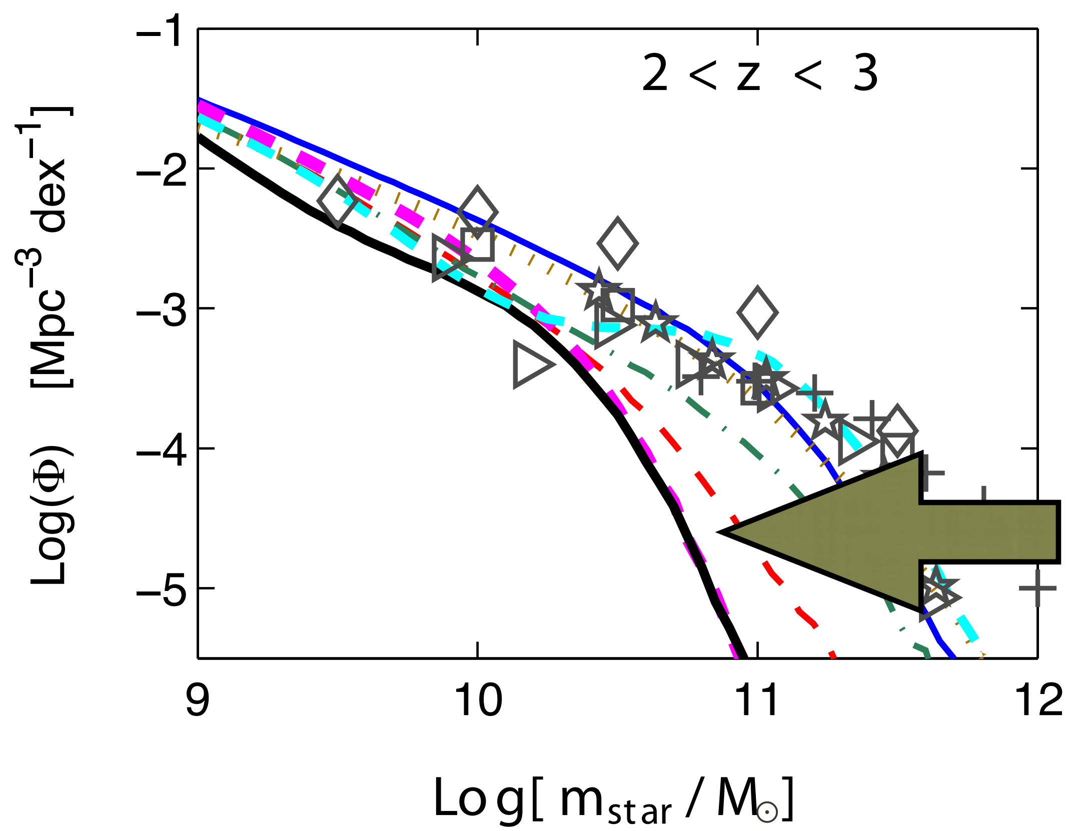


Reddy et al. 2012

See also Feulner+05, Yan+06, Eyles+07, Stark+09, Labbe+10a,b, Schaerer+10, McLure+11

Problem for galaxy formation?

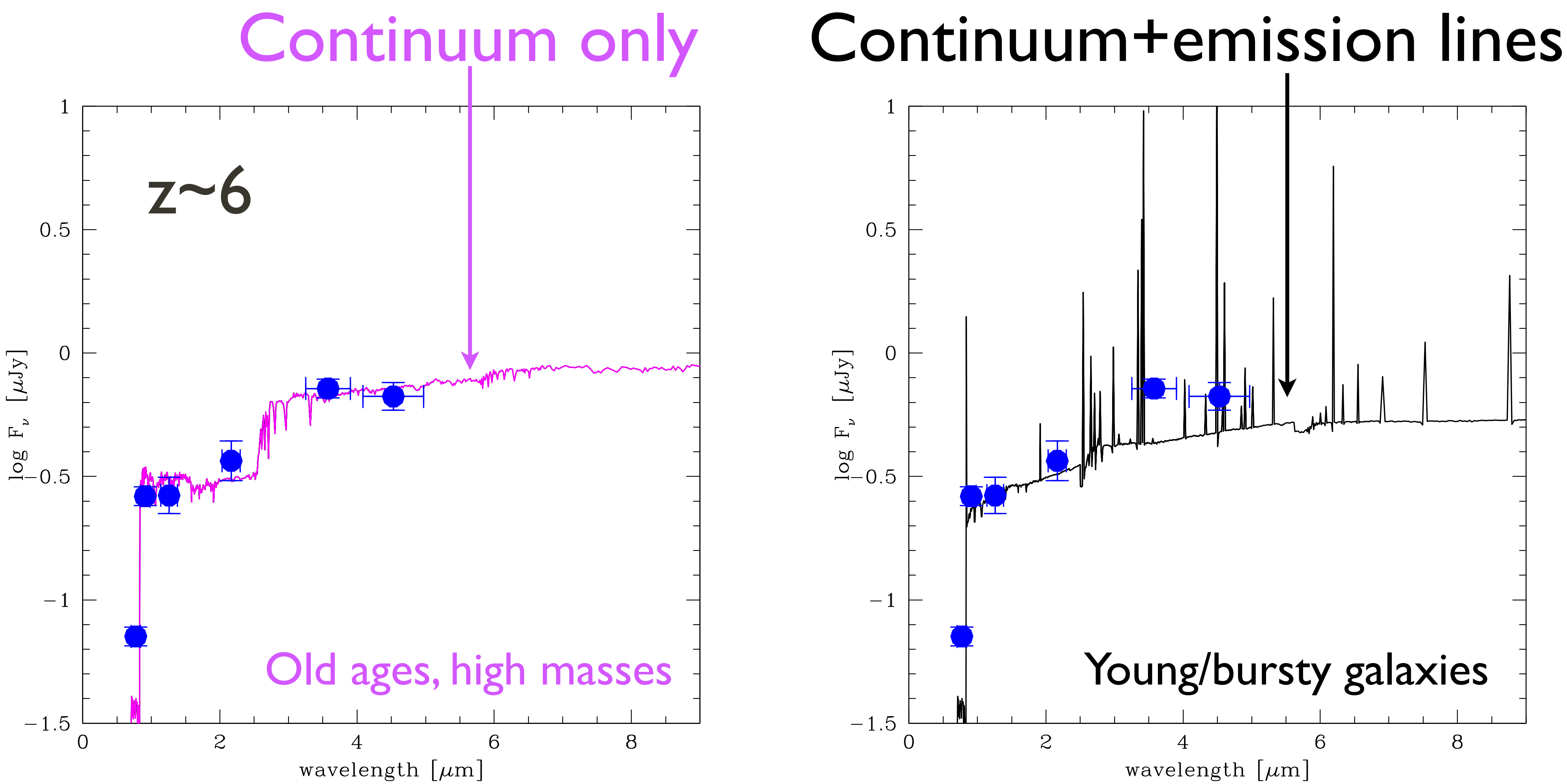




Weinmann et al. 2011

See also Bouche+10, Davé+11

Nebular emission lines: two degenerate solutions



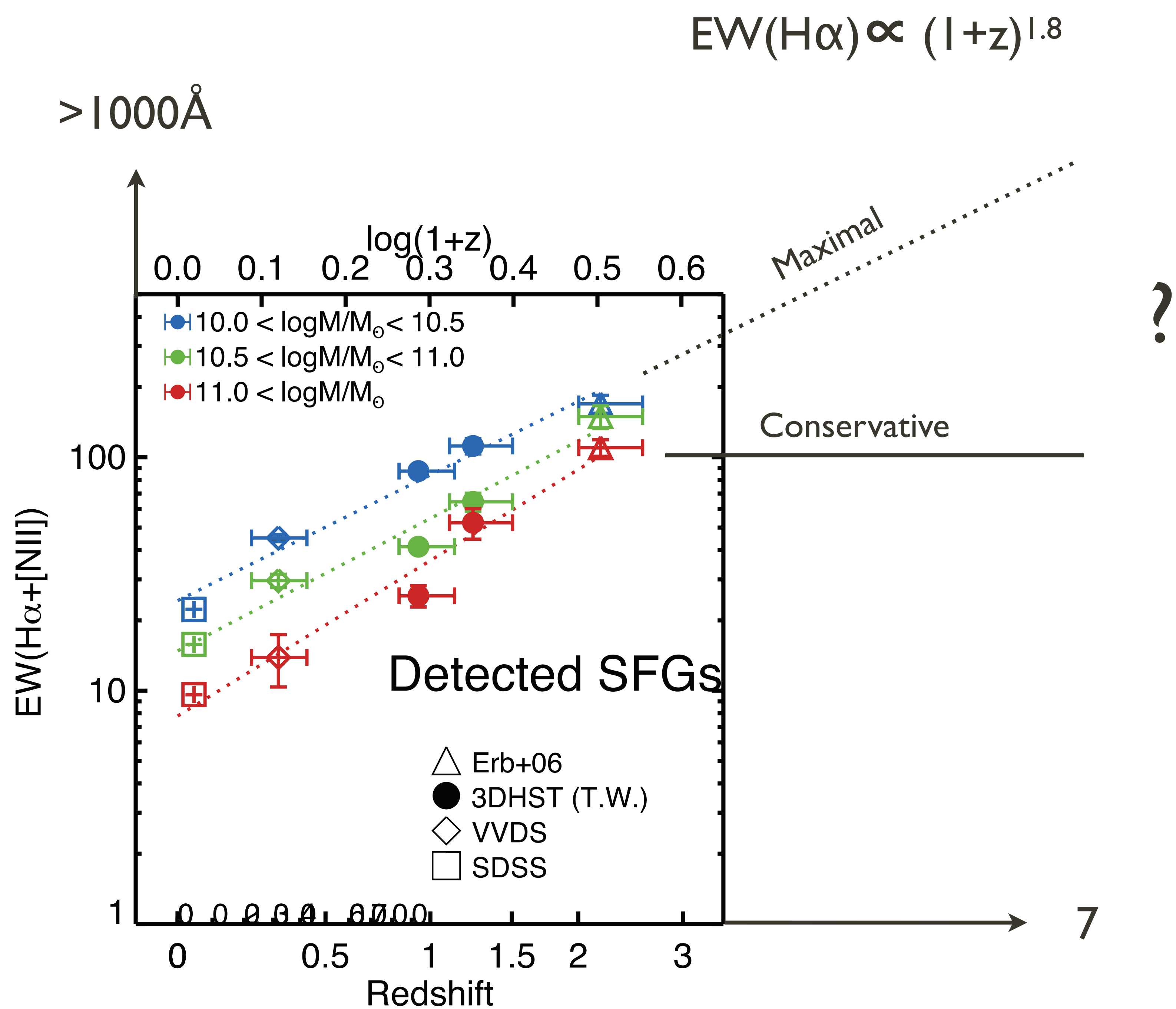
Schaerer & de Barros. 2009

Are stellar masses and ages overestimated?

Assumptions on emission lines contamination

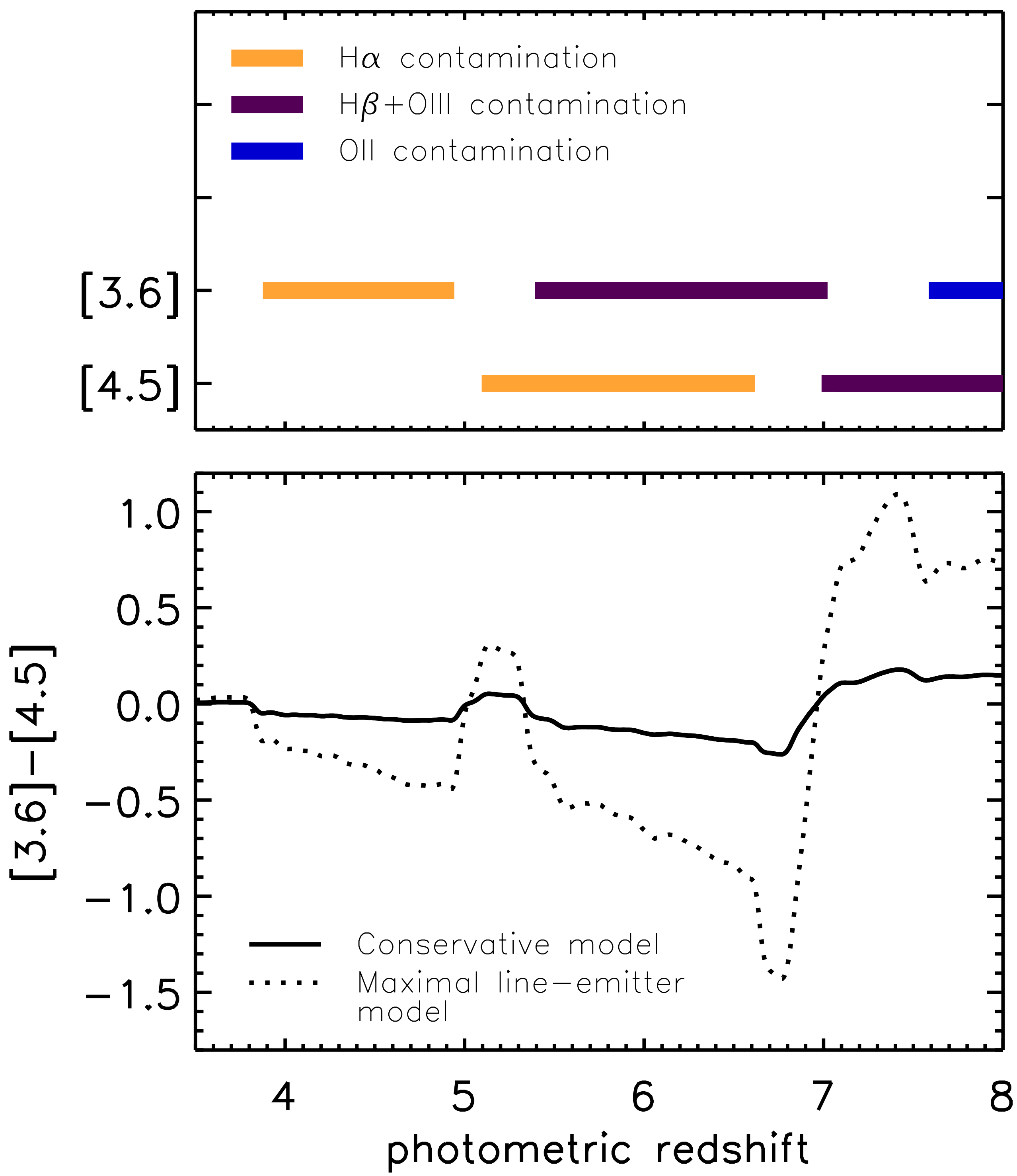
Equivalent width of strong lines such as Hα and [OIII] > 1000Å?

Direct spectroscopy not available above z>3.5

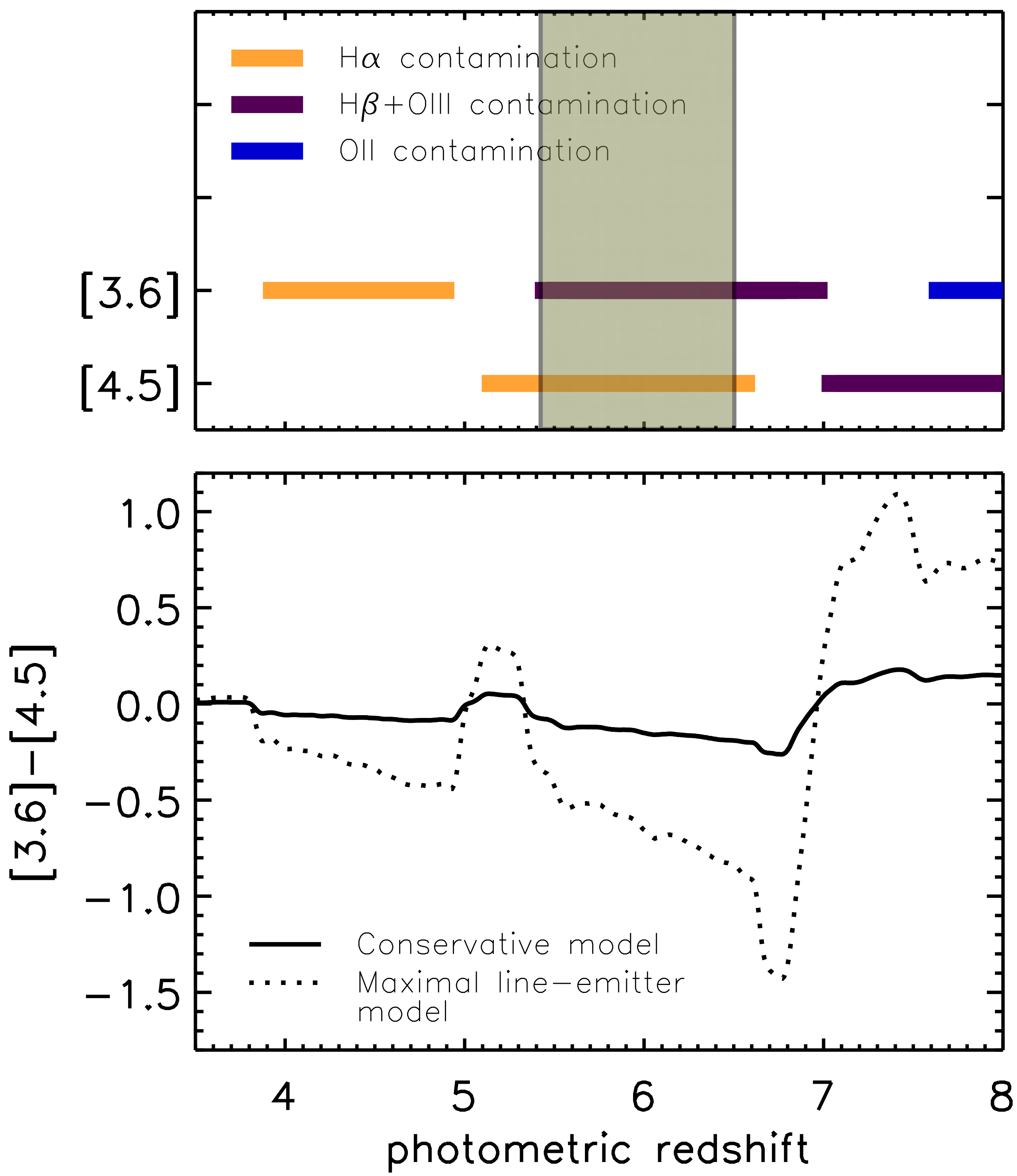


Fumagalli et al. 2012

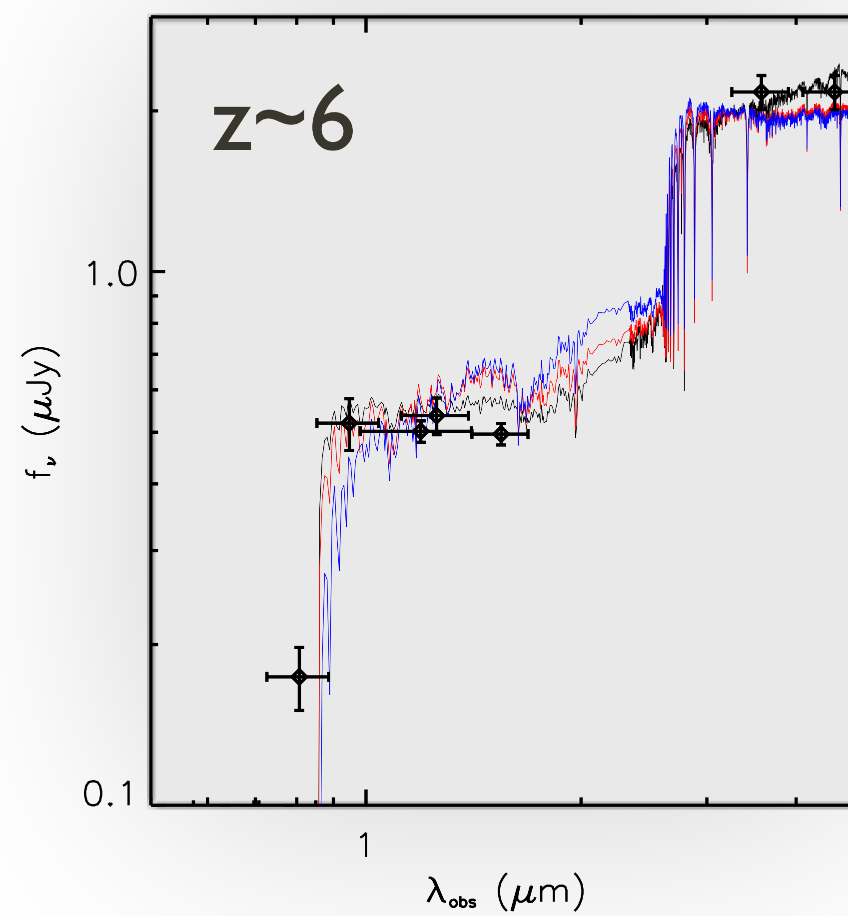
Using redshift samples without degeneracies



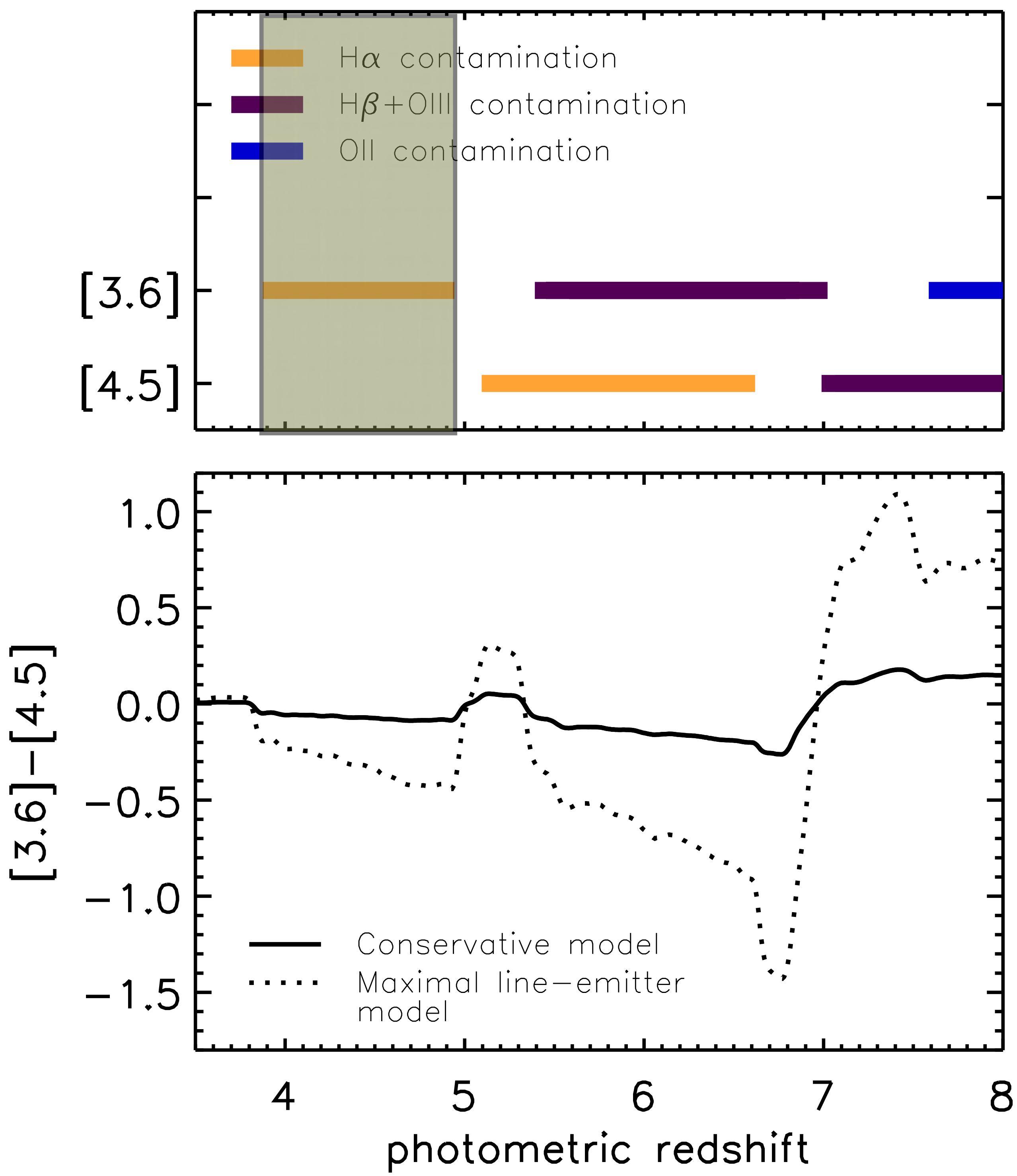
Using redshift samples without degeneracies



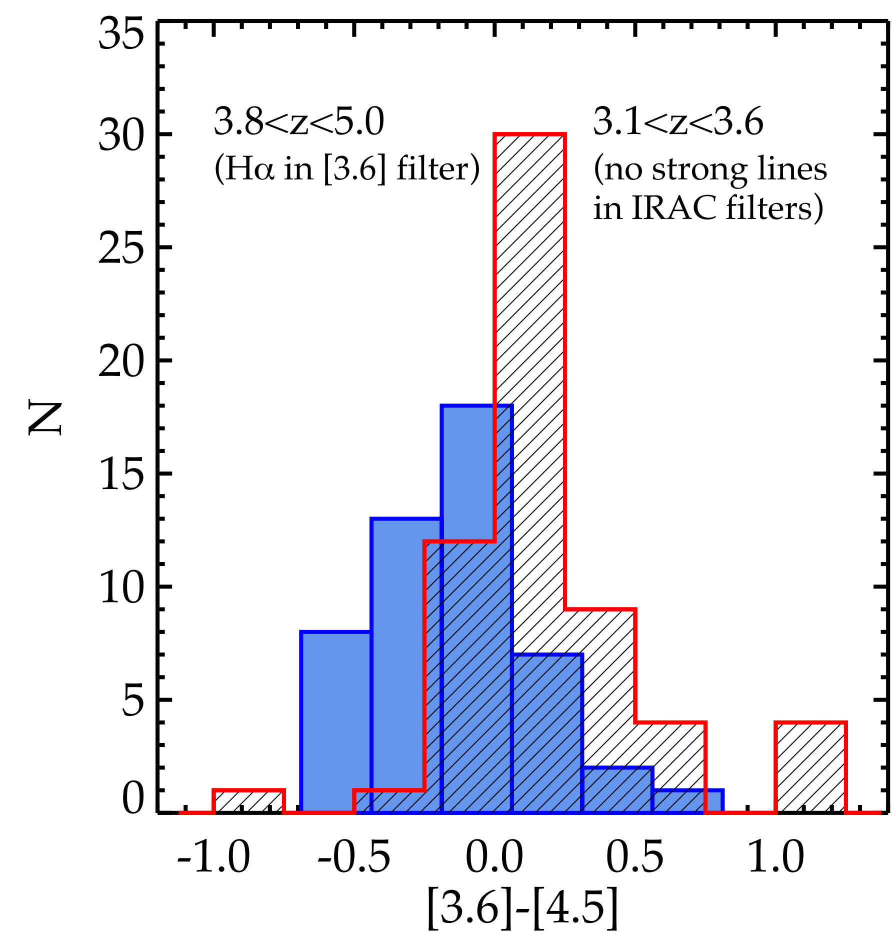
5.5<z<6.5 particularly bad for emission line contamination



Using redshift samples without degeneracies

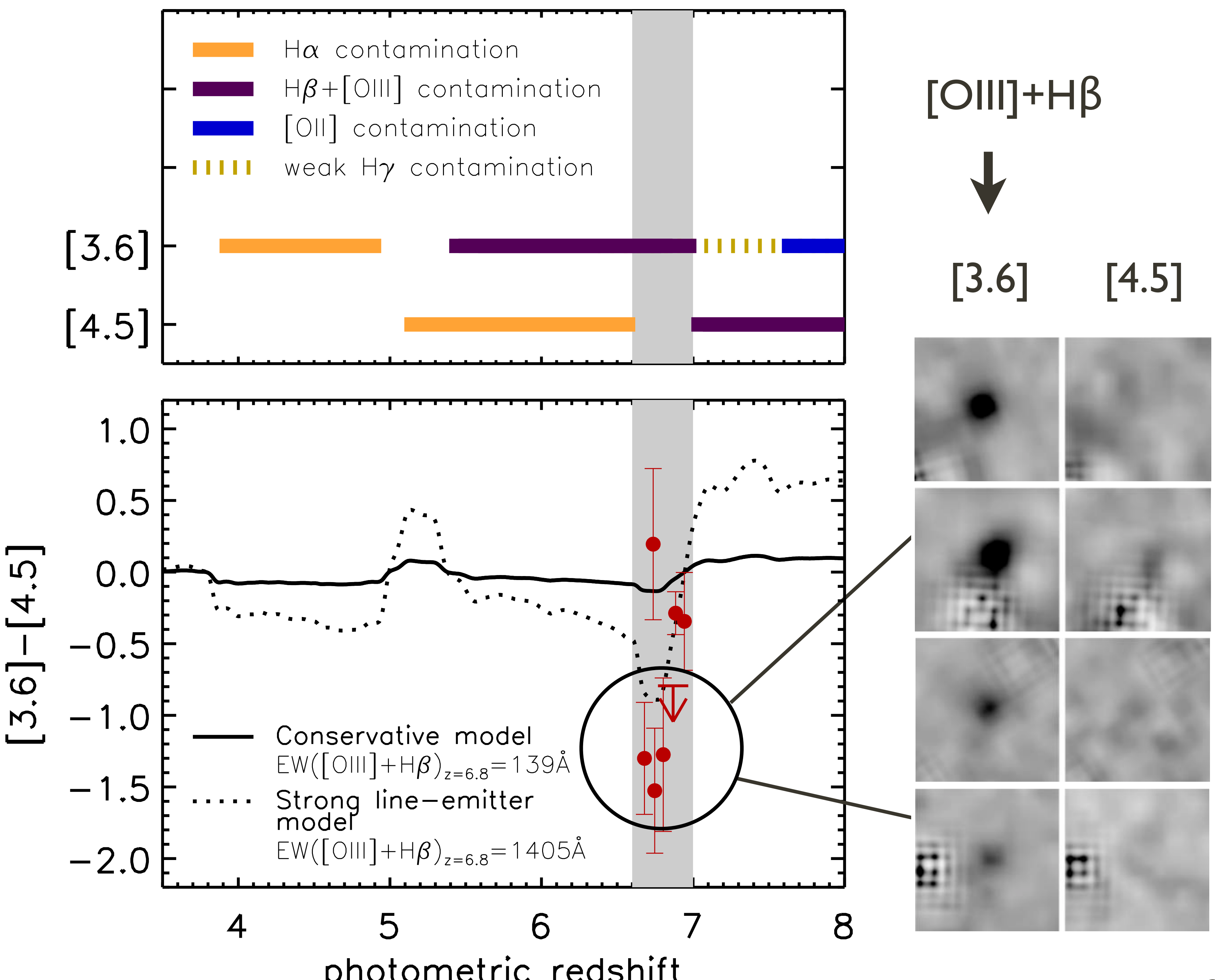


4<z<5 good for estimating Hα EW estimates



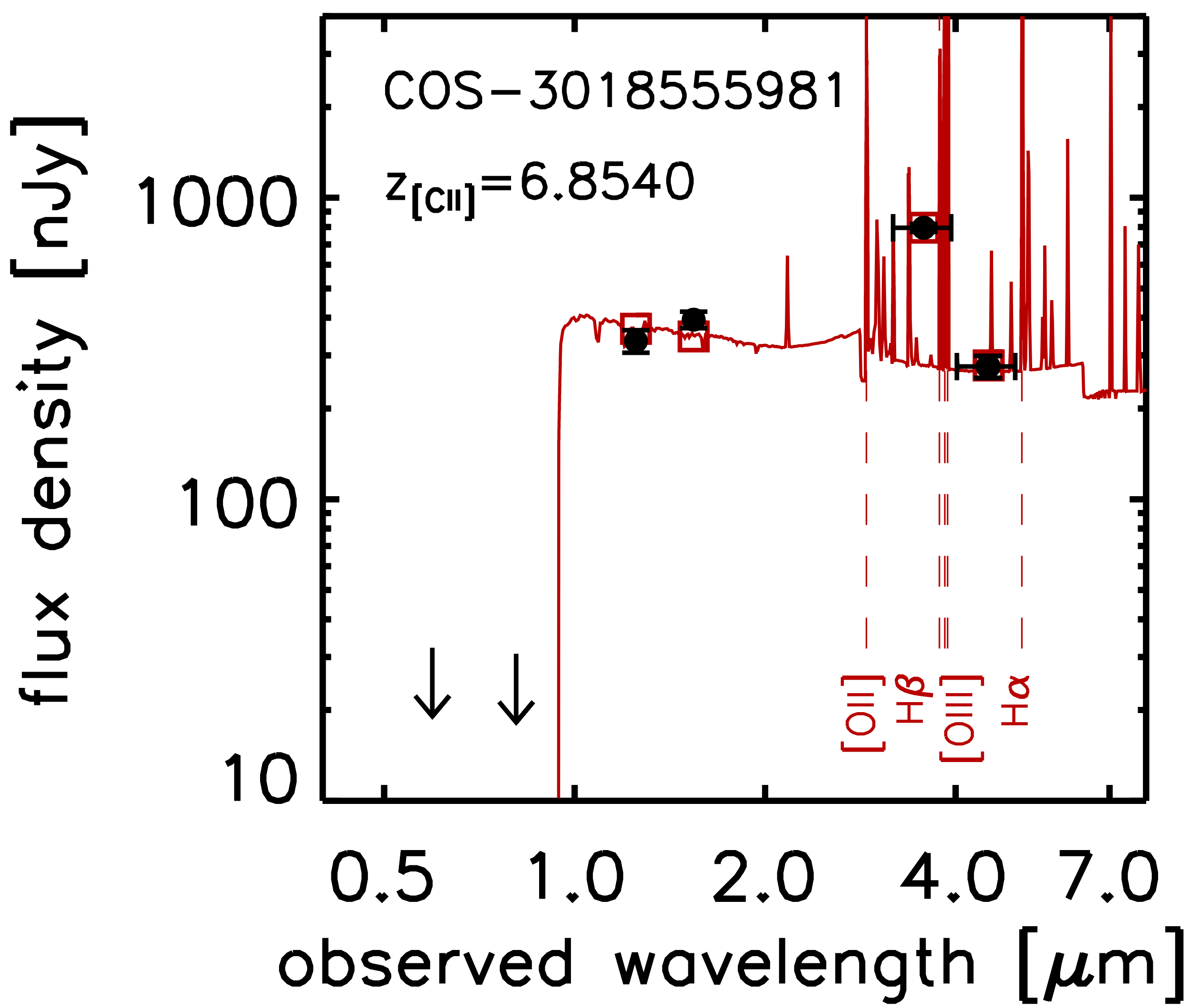
Shim et al. 2011; Stark et al. 2012

Using redshift samples without degeneracies



Smit et al. 2014;2015

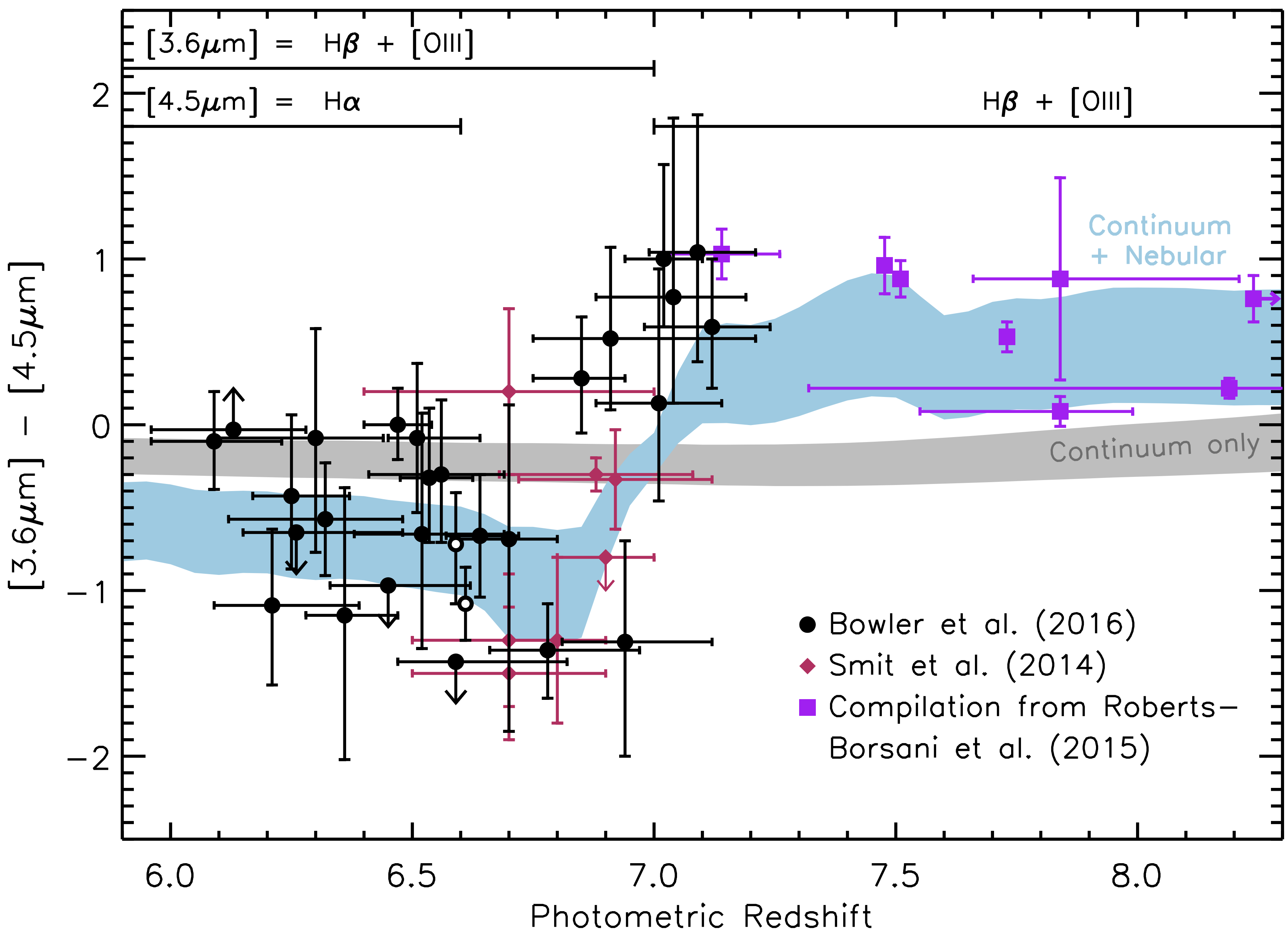
Modest samples of z~7 [OIII] emitters



- Spitzer photometry dominated by optical emission lines
- Large fraction of sources (~50%) show 'extreme' emission lines → **ubiquitous** in early galaxies

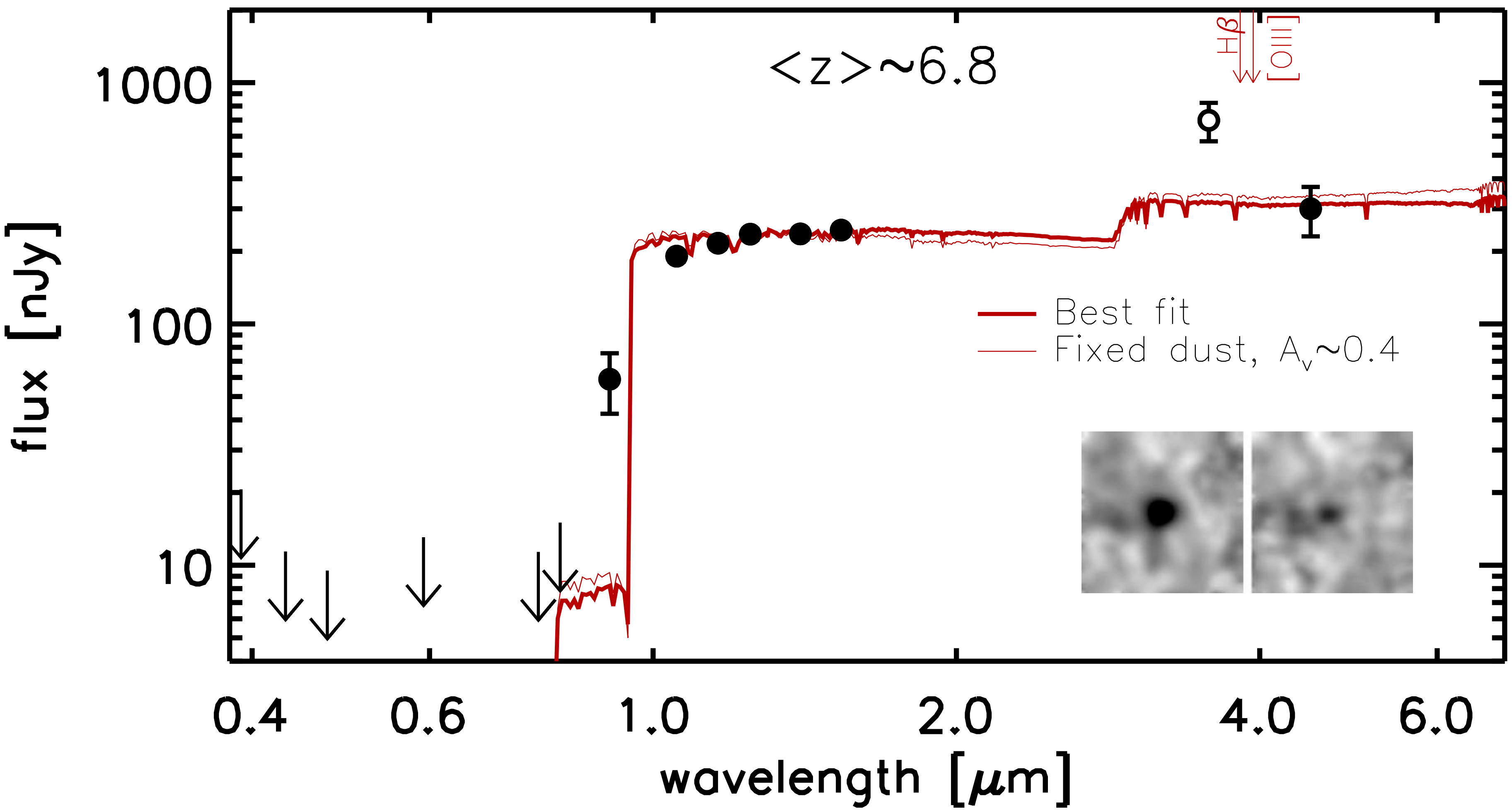
Smit et al., 2014; 2015, Roberts-Borsani et al. 2016

Modest samples of z~7 [OIII] emitters



Bowler et al. 2017

Mass estimates without contamination



Mass estimate with clean [4.5] band log(M)~9.0 $M_\odot$

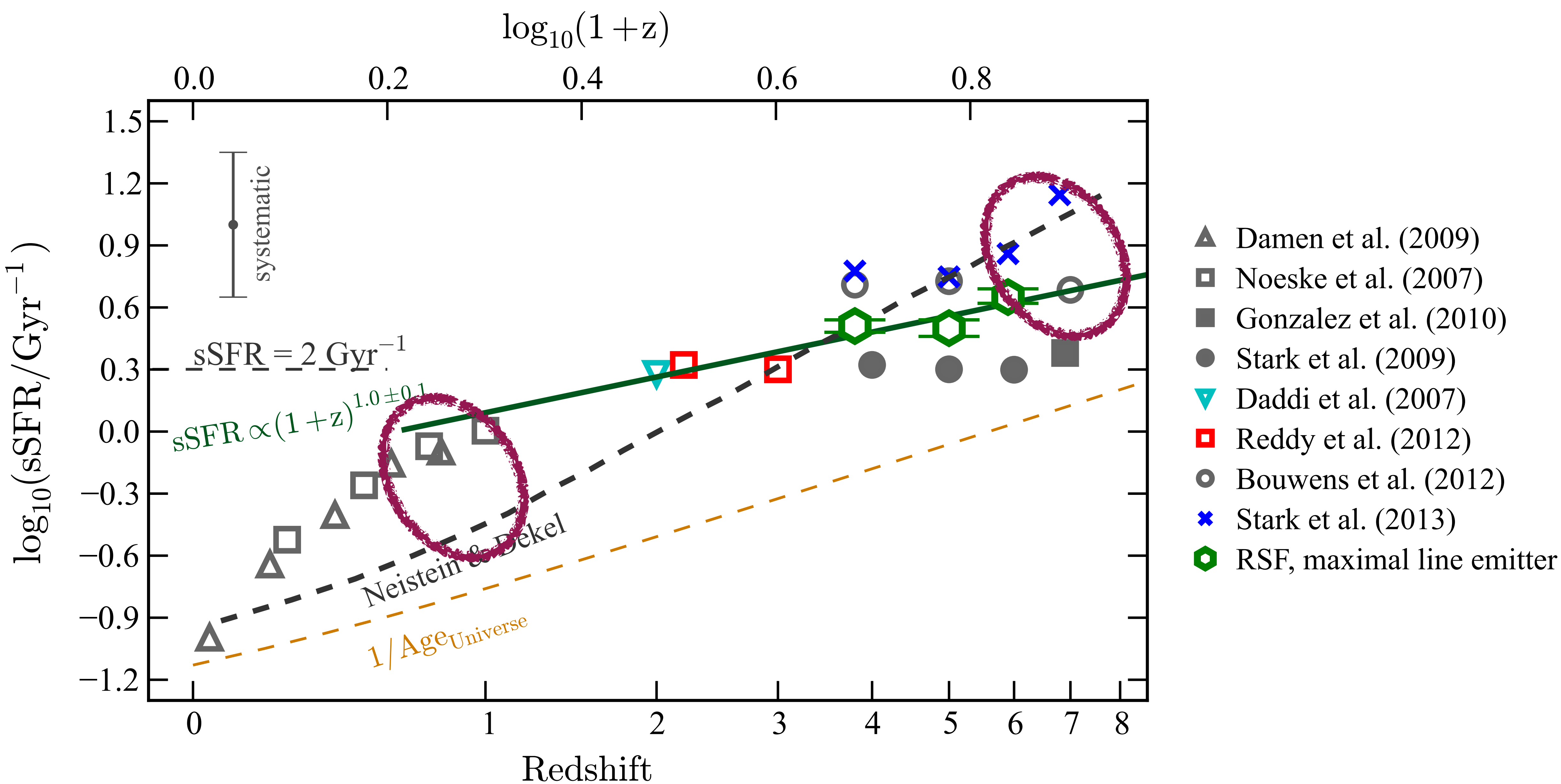
Mass estimate with [3.6]+[4.5] log(M)~9.5 $M_\odot$

0.5-1.0 dex offset in mass estimate

Smit et al. 2014

Updated sSFR evolution

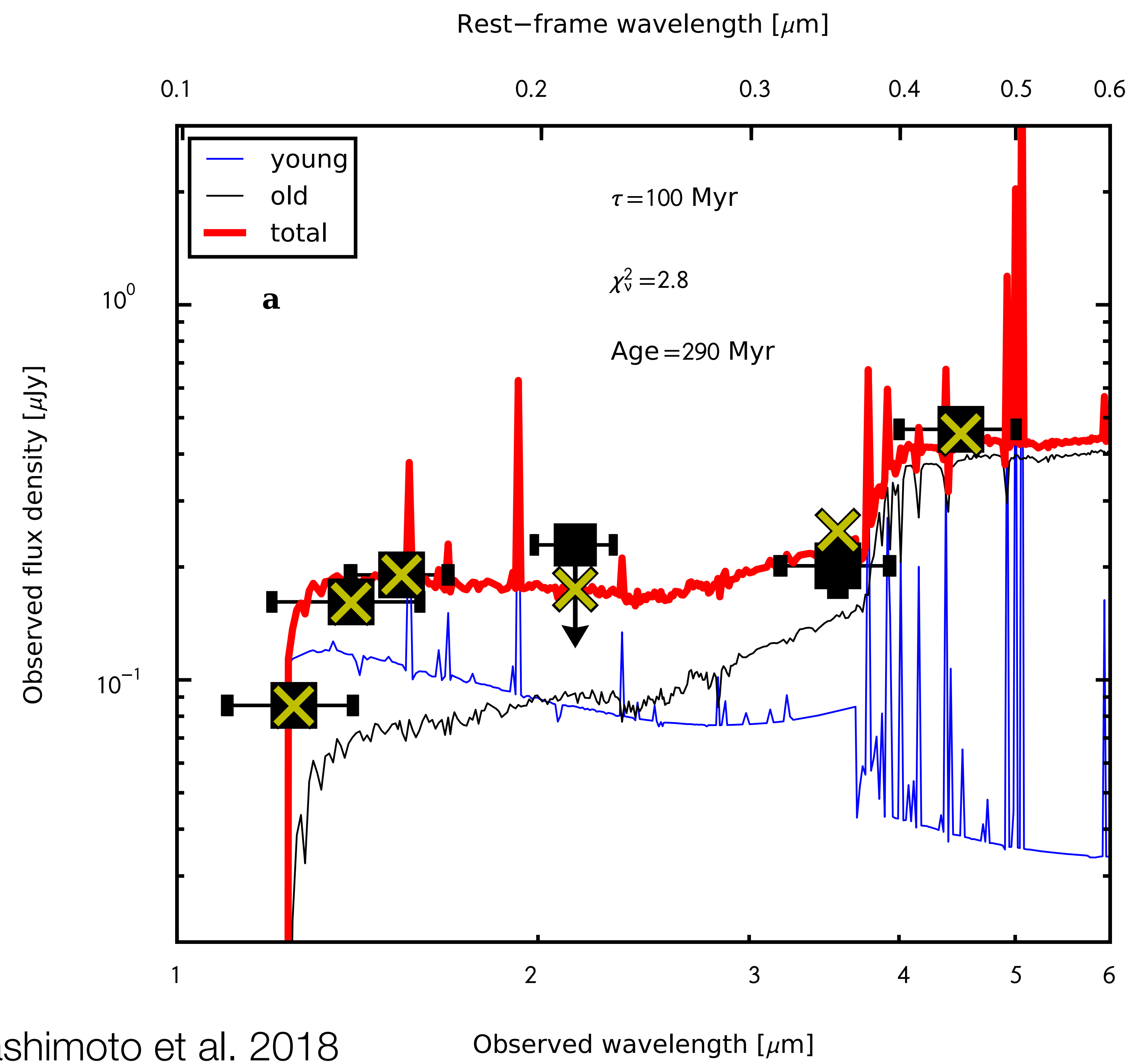
Mild discrepancy still at the highest redshifts and redshift =1



Gonzalez et al. 2012

New evidence for older stellar populations?

Spectroscopic redshift at z=9.1 - no contribution of [OIII] nebular lines to IRAC flux

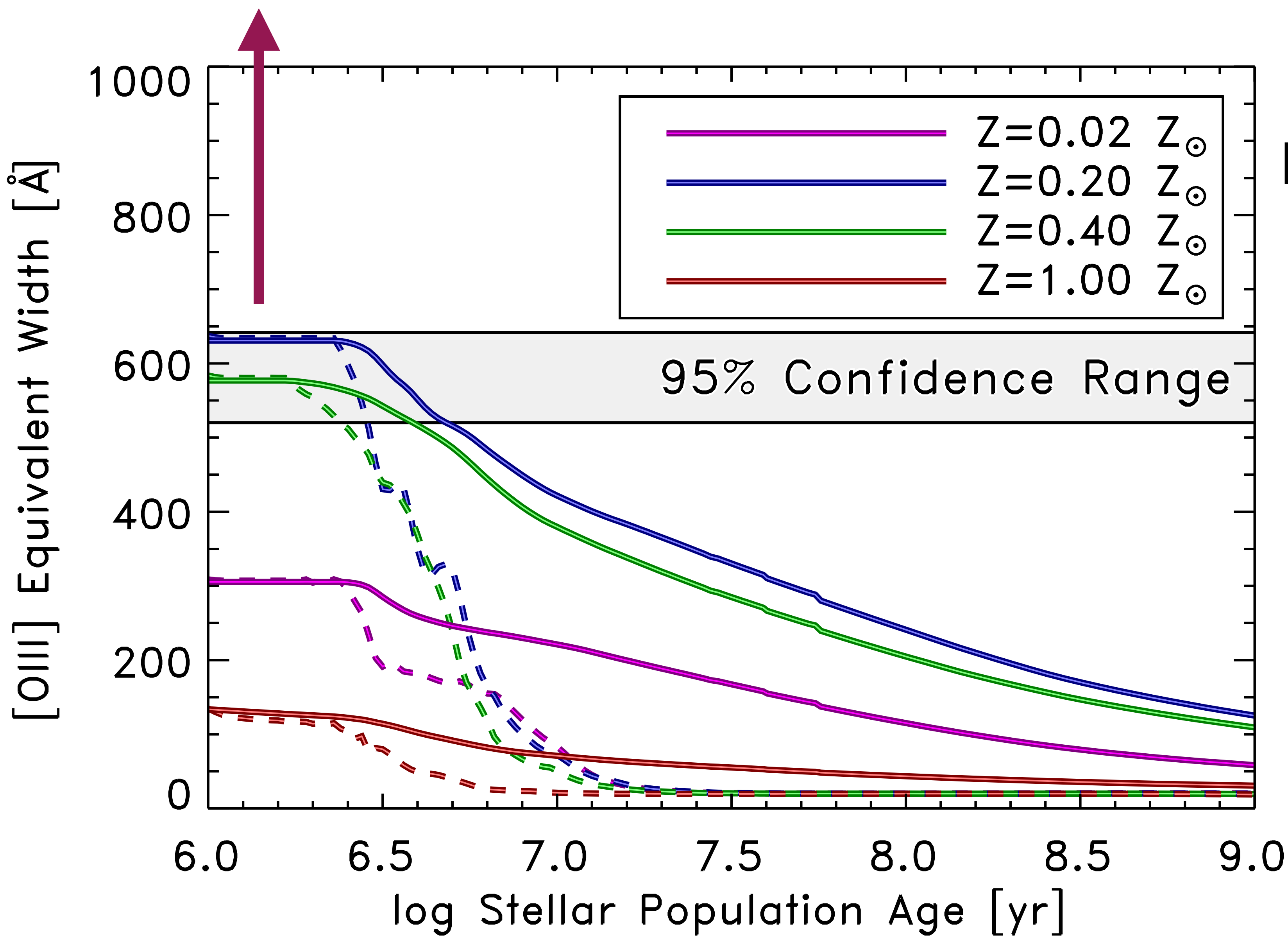


Hashimoto et al. 2018

Interpreting extreme emission lines and implications for cosmic Reionisation

How to explain extreme equivalent widths?

>1000Å EW lines are not reproduced by 'classic' models

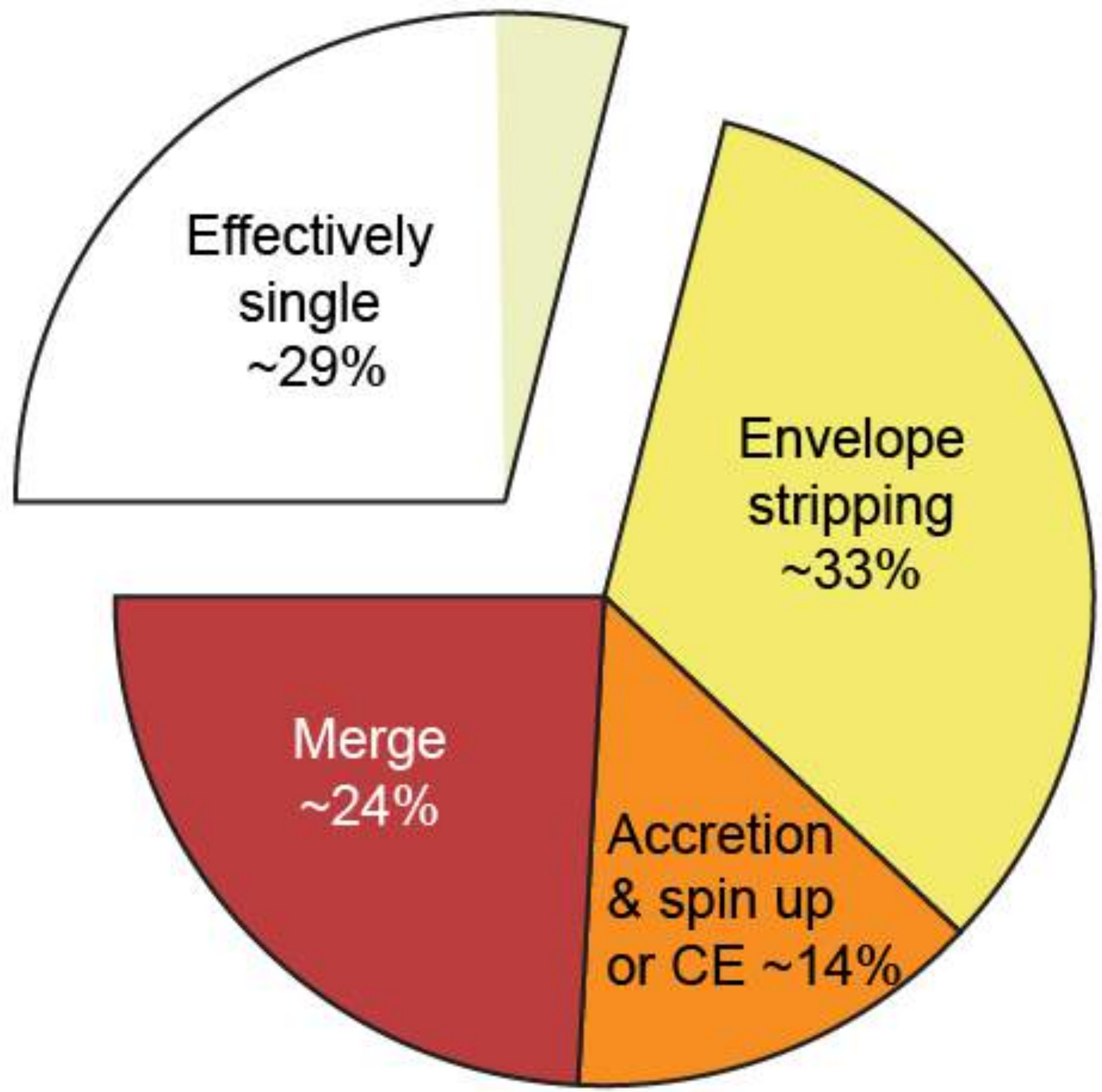


Bruzual & Charlot 2003 stellar populations models

Finkelstein et al. 2013

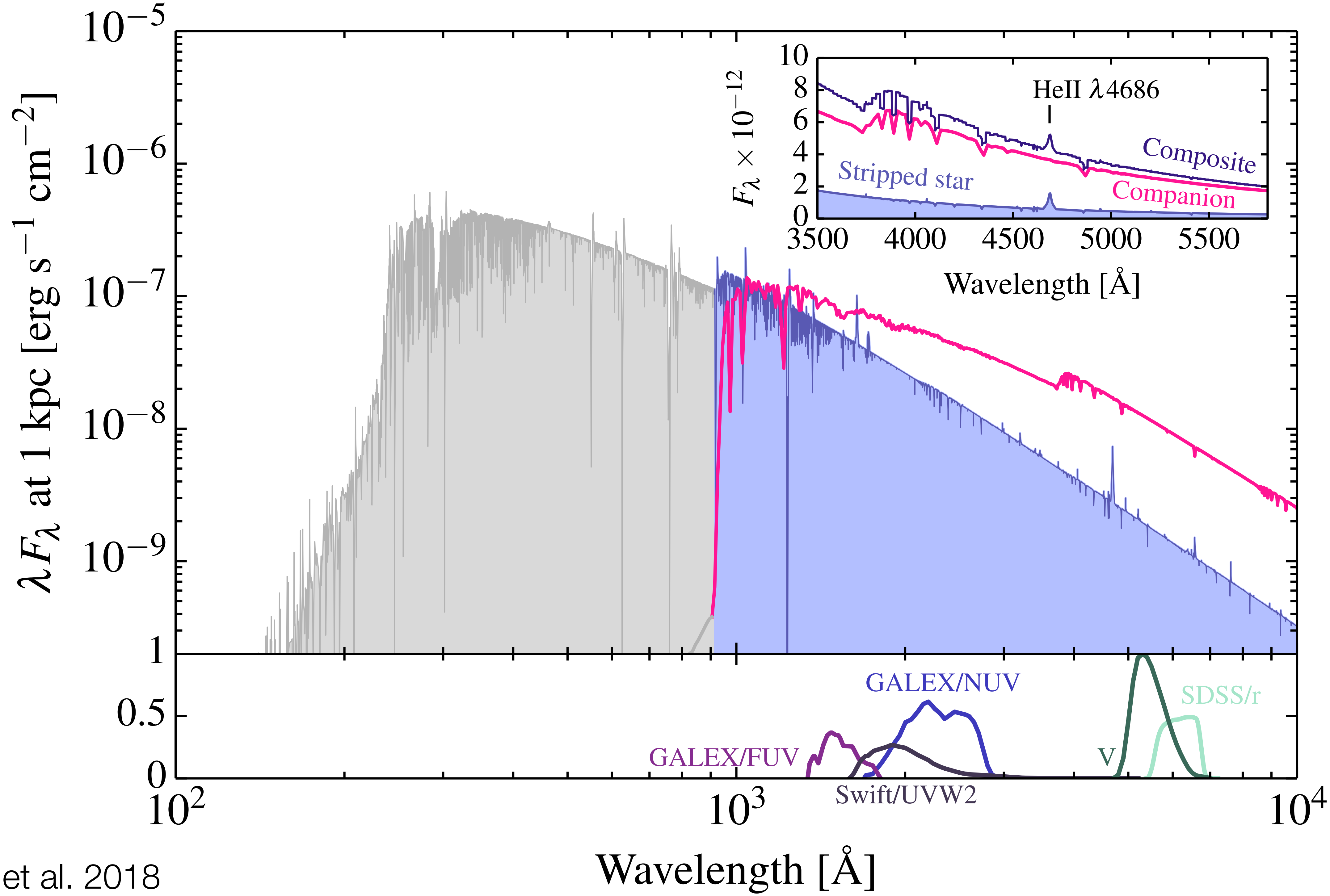
Missing components on stellar populations?

The majority of O and B stars might be in binaries - binary effects such as envelope stripping can not be neglected!



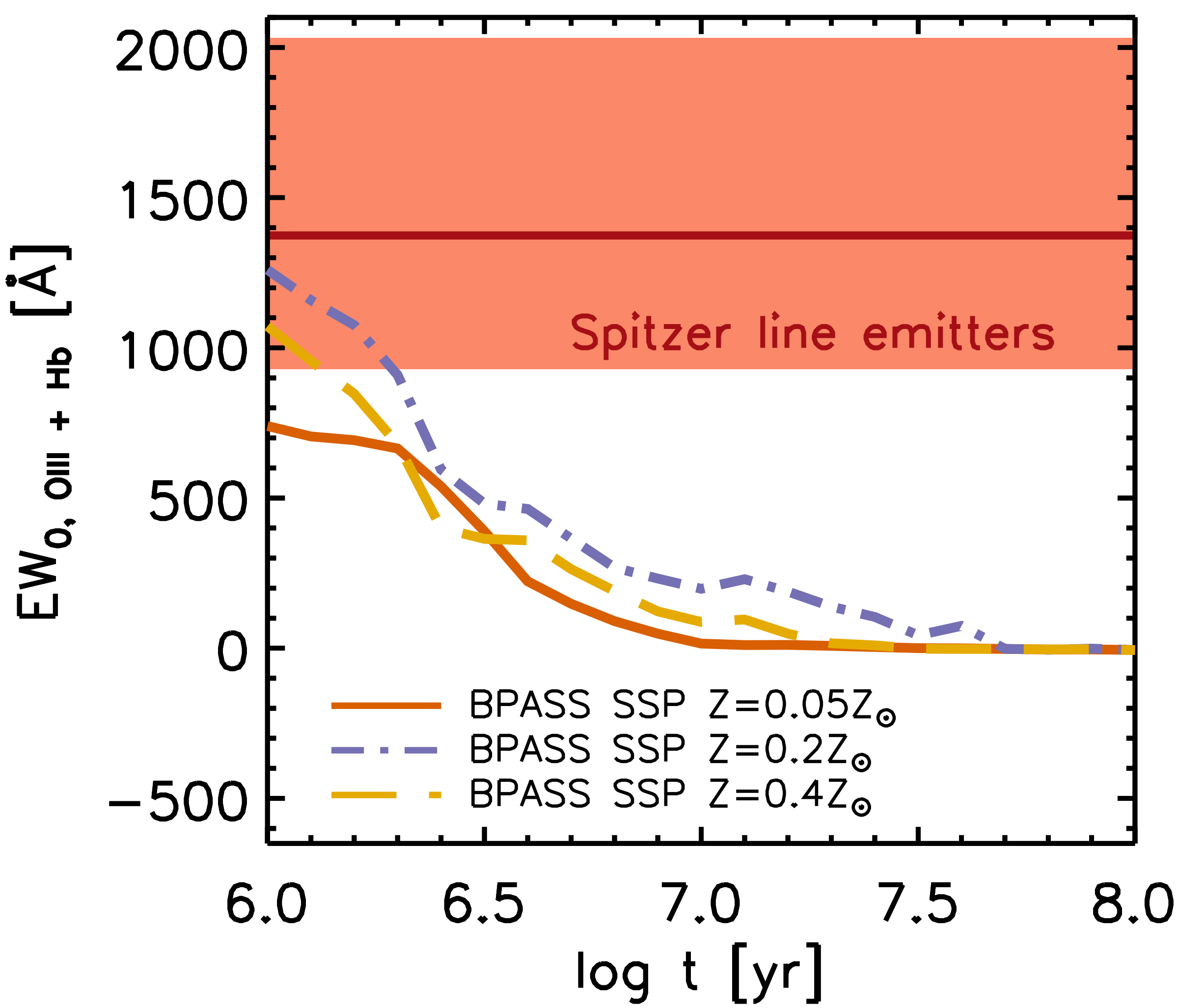
Sana et al. 2012

Ionising flux from binary stars



Gottberg et al. 2018

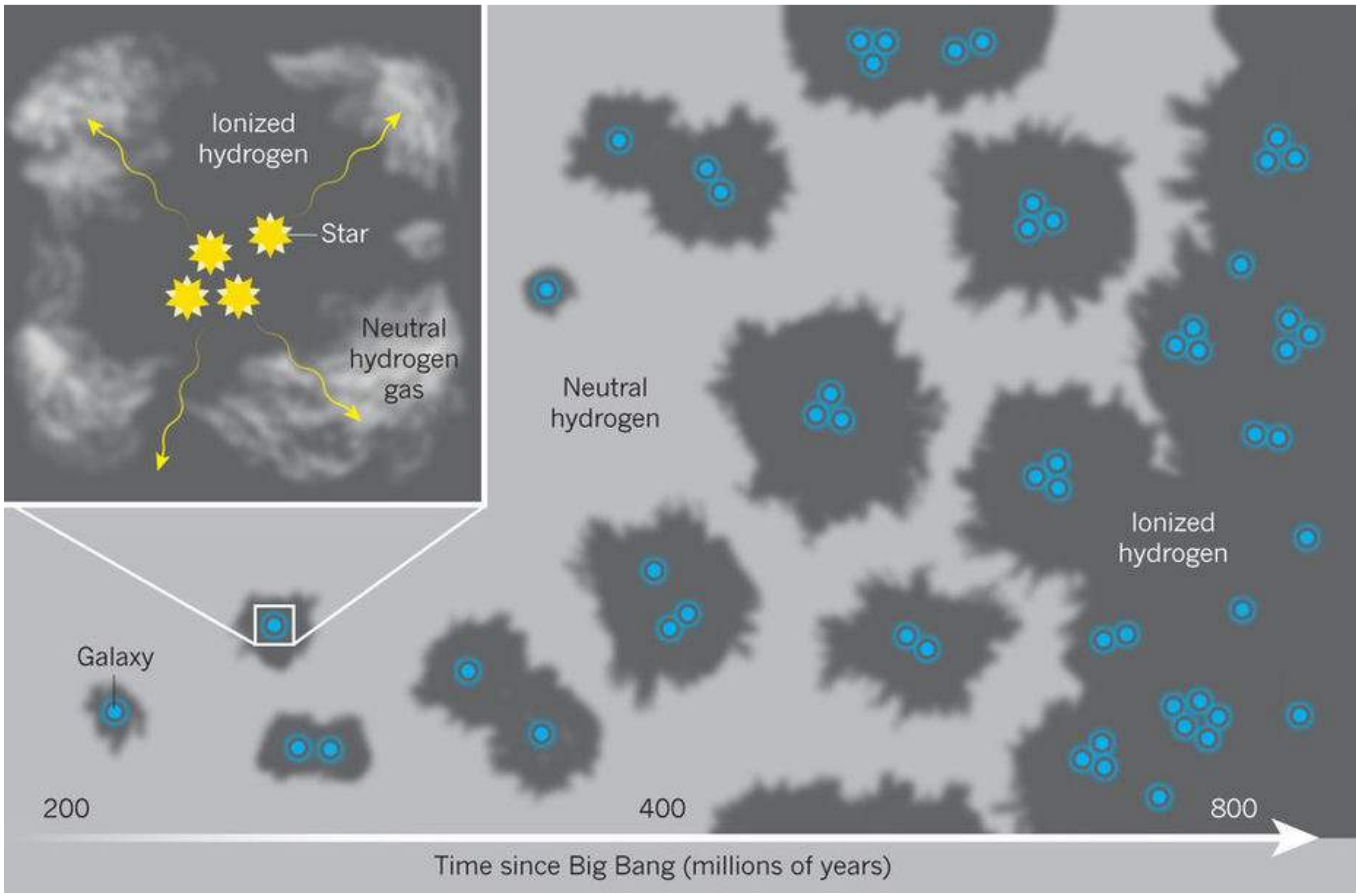
Models including binary stellar models



- BPASS models (e.g. Eldridge & Stanway 2012) include binary effects

- Another possible explanation is the ubiquitous presence of faint/obscured AGN (see tomorrow's lecture!)

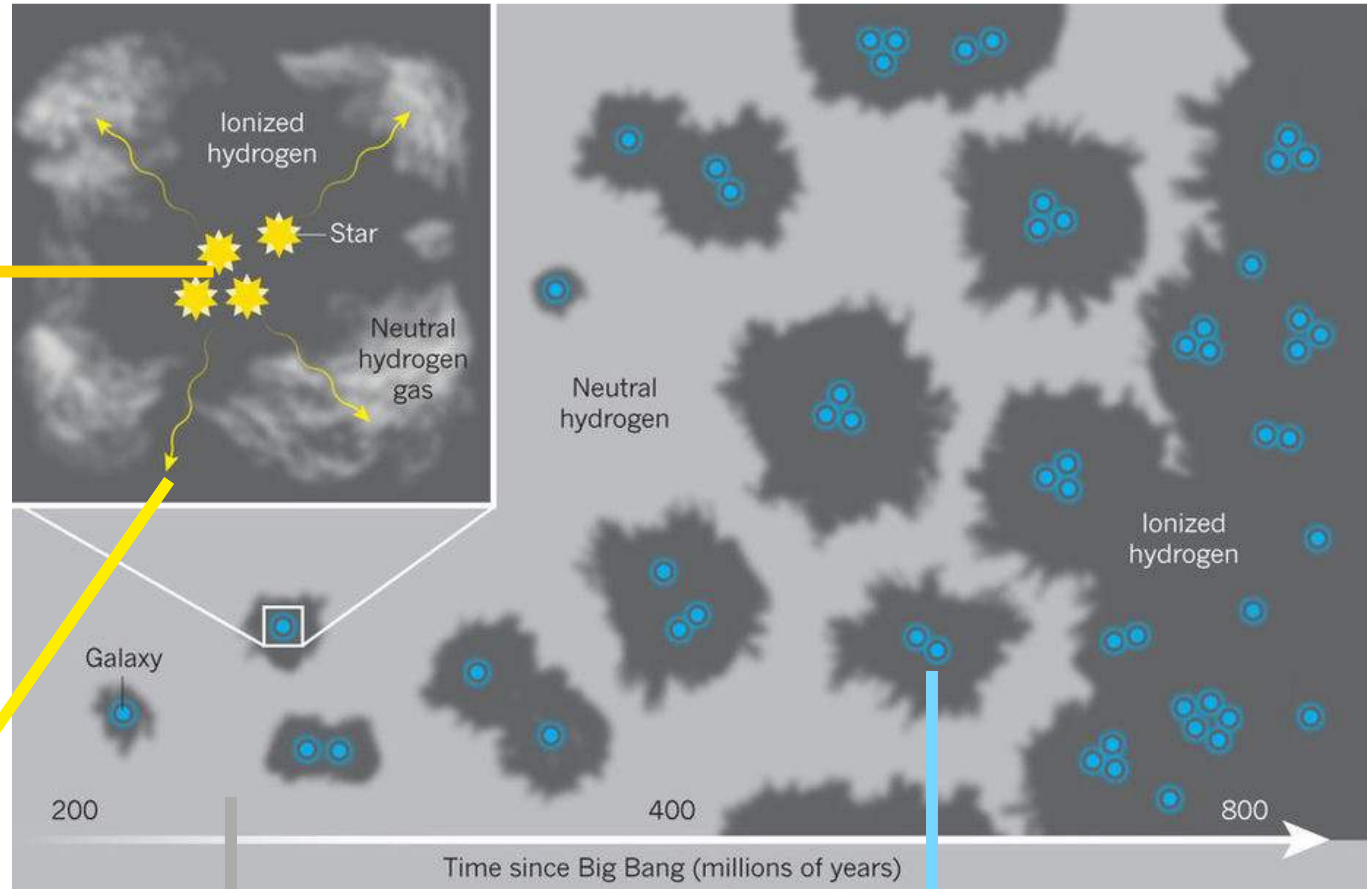
The photons needed to sustain an ionised Universe



Credit: Dawn Erb

Stellar populations
(models and observations)
efficiency of ionising photon production

Lyman continuum observations
(lower redshift)
fraction of photons that escape into the IGM



Credit: Dawn Erb

Simulations
recombination rate depending on IGM properties (n,T)

Deep field surveys
total number density of galaxies

Implications for cosmic reionisation

- Available number density of ionising photons :

$$n_{\rm ion} = f_{\rm esc}\,\xi_{\rm ion}\,\rho_{\rm UV},$$

Robertson et al. 2015

- Lyman continuum production efficiency (**ξion**) = the number of ionising photons produced per visible UV photon (at ~1600Å)

- Escape fraction (**Fesc**) = fraction of those ionising photons that makes it out of the galaxy

Implications for cosmic reionisation

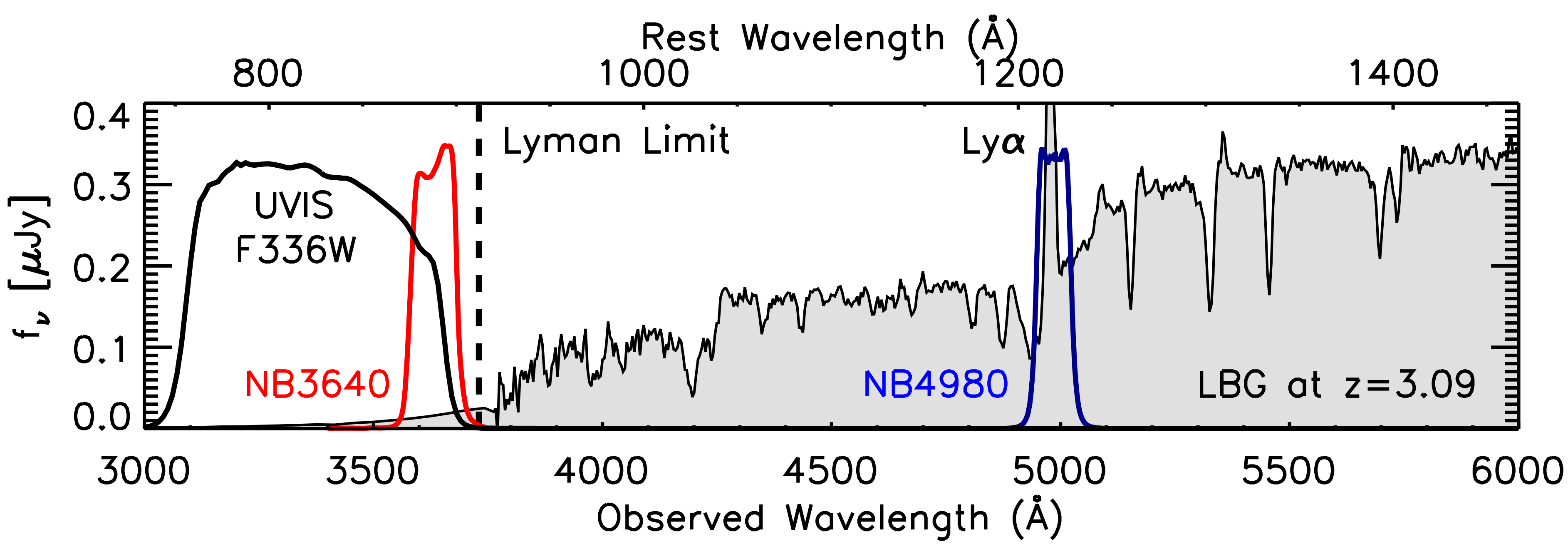
- Available number density of ionising photons :

$$n_{\rm ion} = f_{\rm esc}\, \xi_{\rm ion}\, \rho_{\rm UV}\,,$$

Robertson et al. 2015

- Escape fraction of ionising photons can only be assessed at z~3 due to the absorption in the IGM at z>4

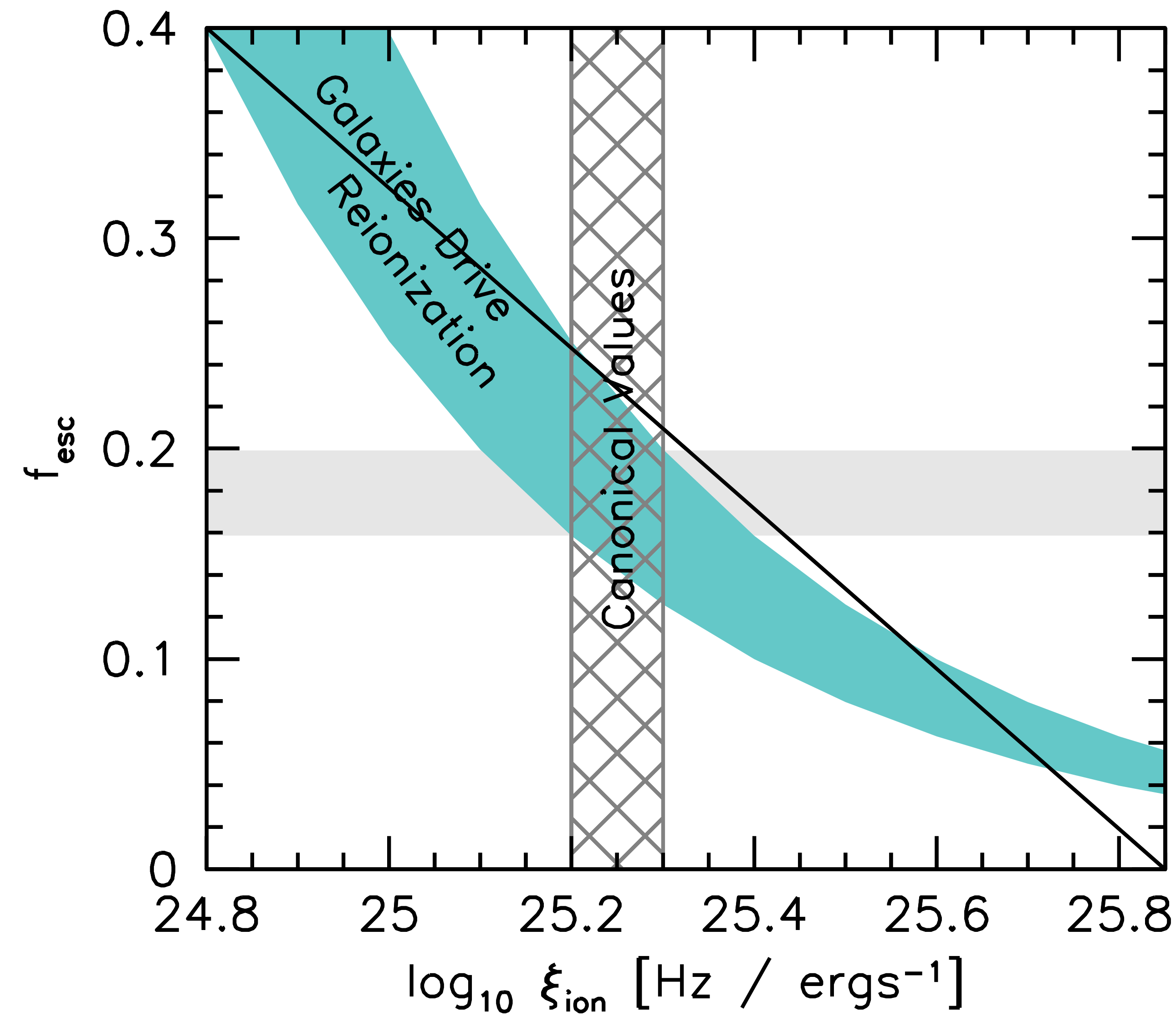
Best estimates at z~3: $f_{esc} < 0.09$



Siana et al. 2015

Implications for cosmic reionization

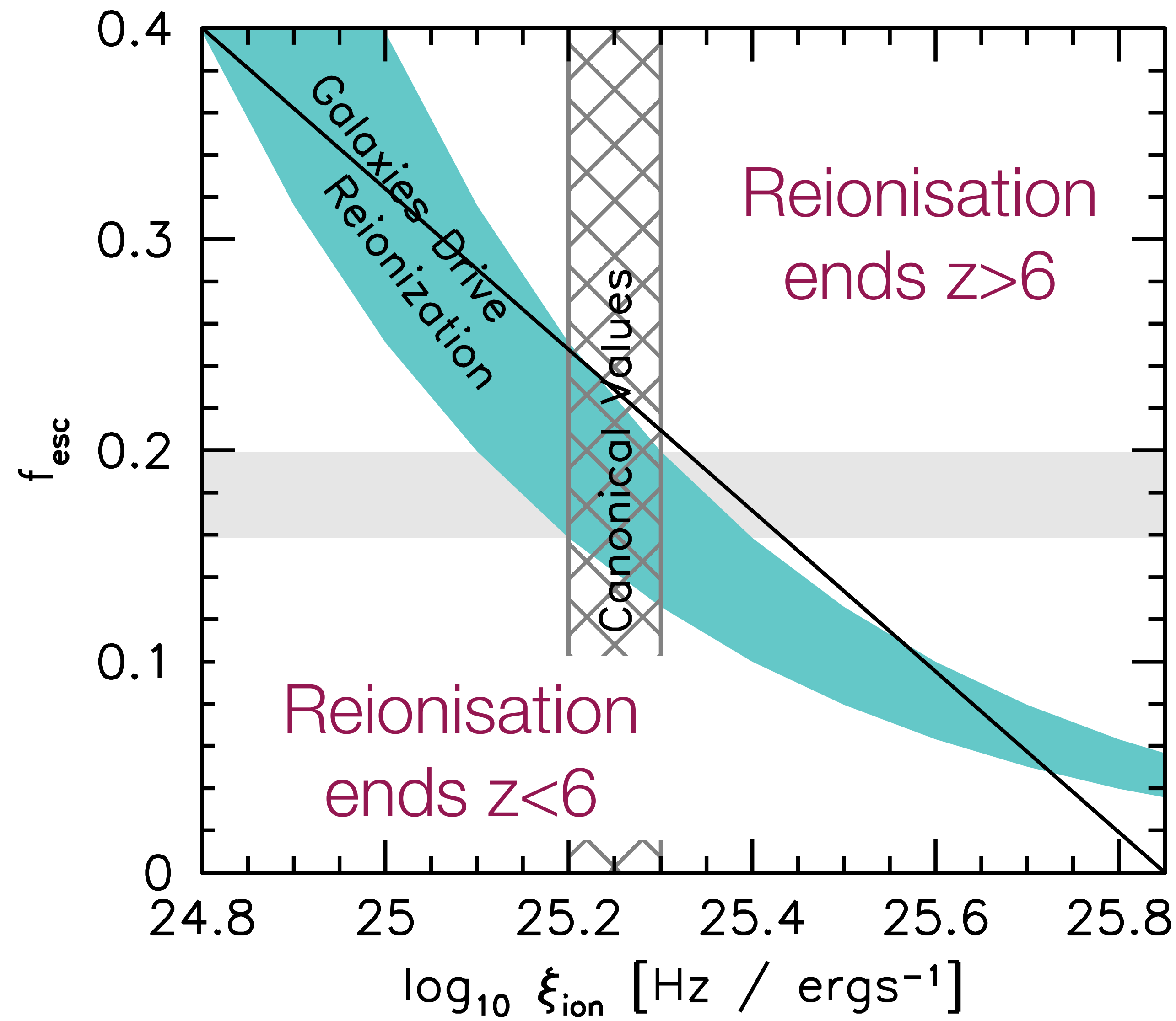
- z~3 measurements of Fesc between 7-9% (e.g. Siana et al. 2015)
- Canonical values for ξion assume Bruzual and Charlot 2003 stellar population models, modest age (~100Myr) and metallicity (~0.2 solar)
- Given most recent UV LFs and canonical values of ξion, higher escape fractions - 16-20% - are needed



Bouwens, Smit et al. 2016

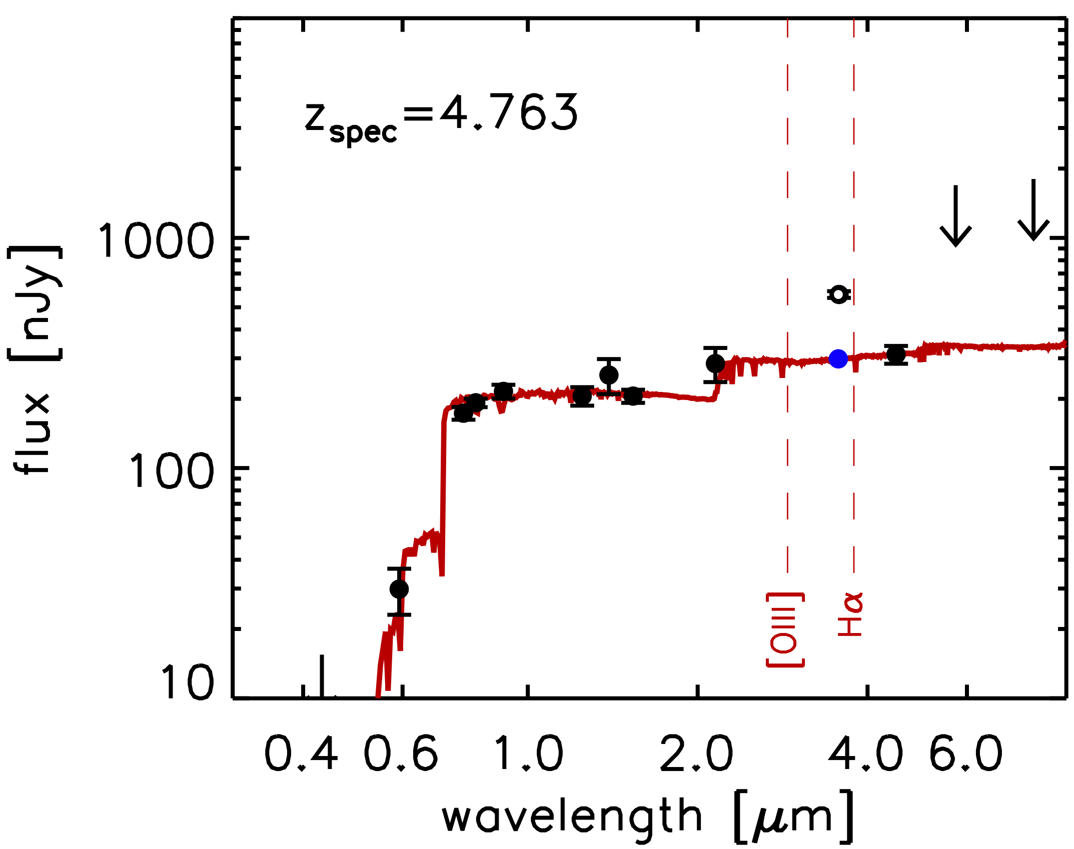
Implications for cosmic reionization

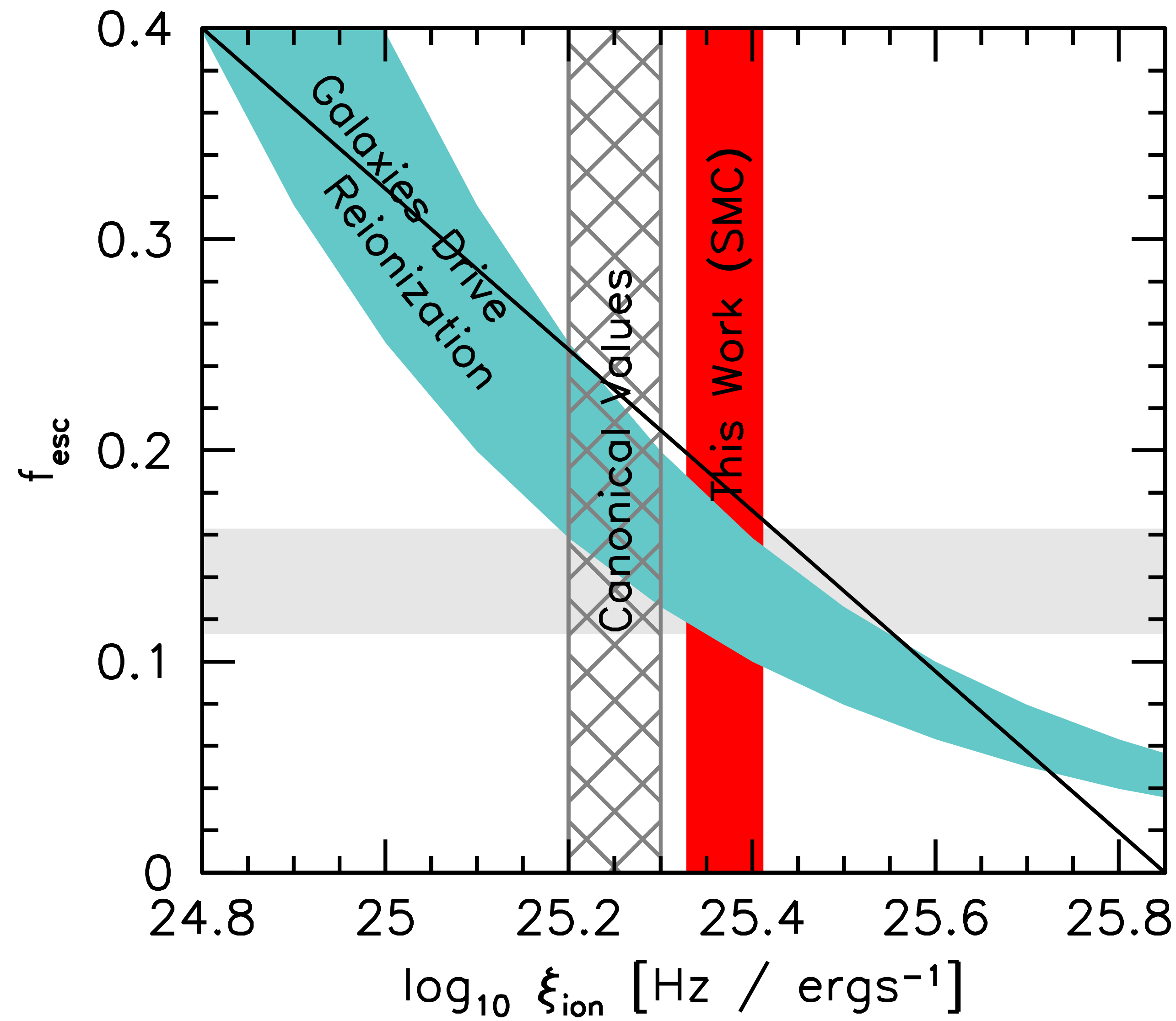
- z~3 measurements of Fesc between 7-9% (e.g. Siana et al. 2015)
- Canonical values for ξion assume Bruzual and Charlot 2003 stellar population models, modest age (~100Myr) and metallicity (~0.2 solar)
- Given most recent UV LFs and canonical values of ξion, higher escape fractions - 16-20% - are needed



Bouwens, Smit et al. 2016

Implications for cosmic reionization

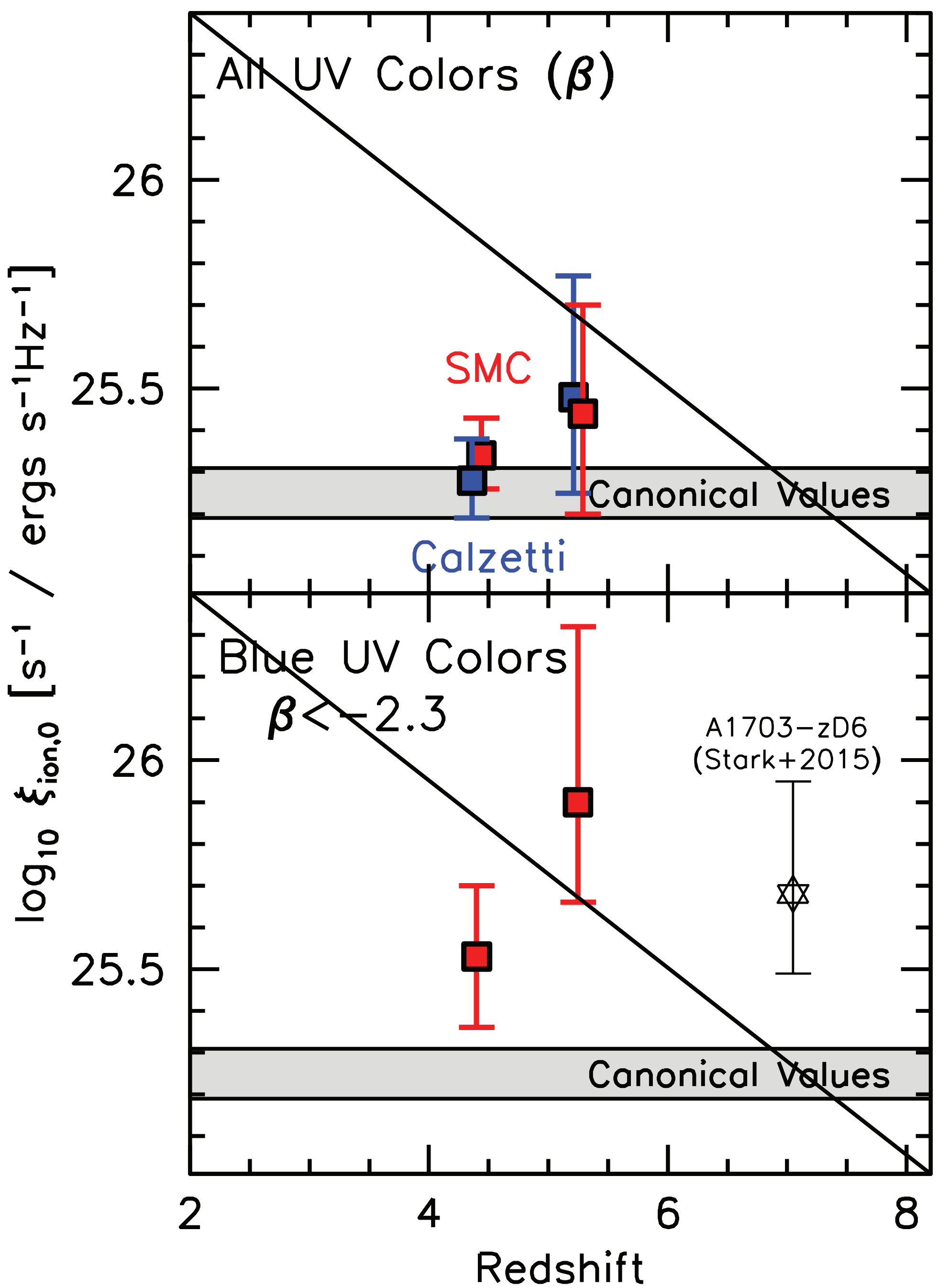


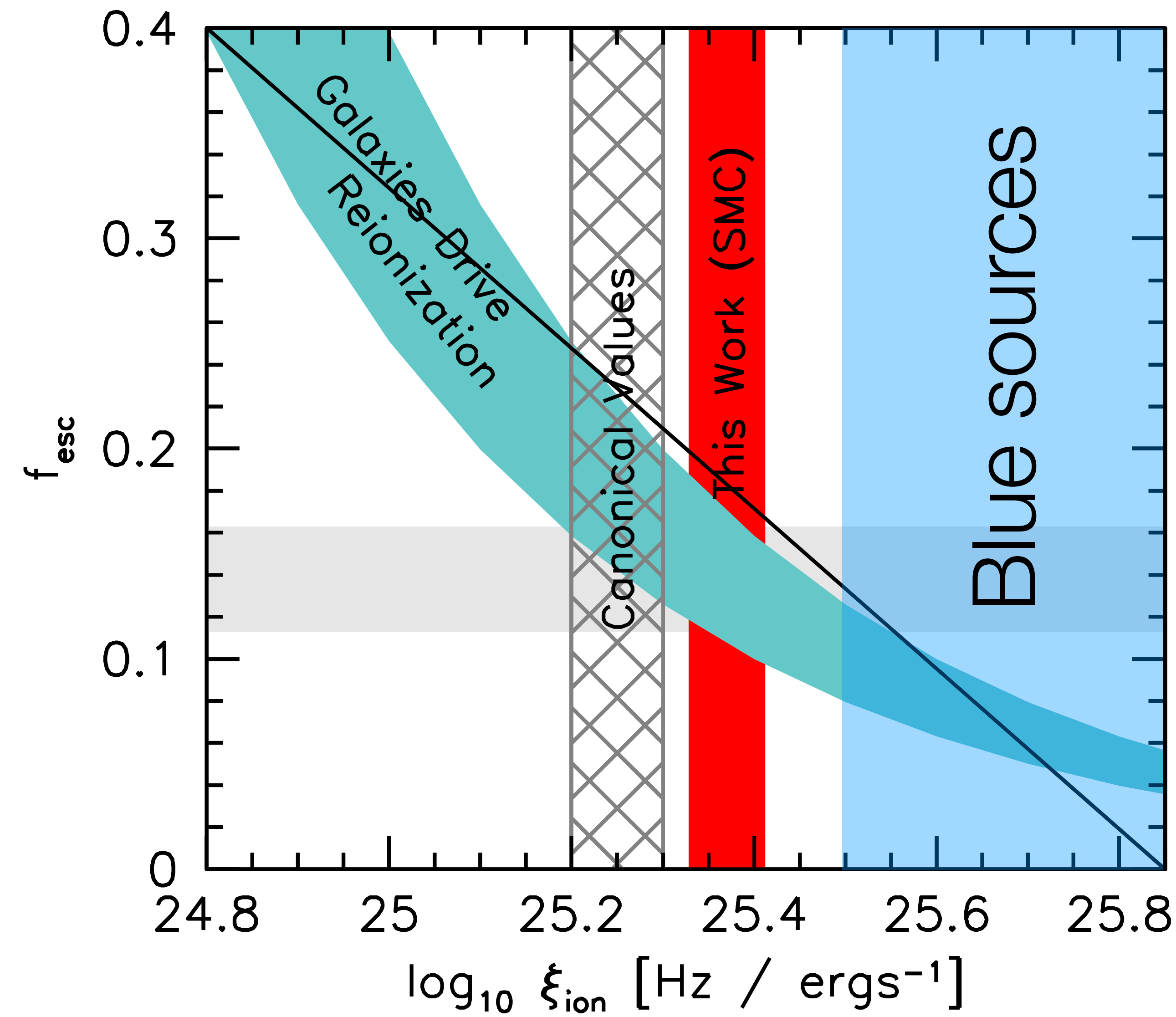


- Ha/UV luminosity ratio **systematically** higher than predicted by low-redshift SFR calibrations

Smit et al., 2016; Bouwens, Smit et al. 2016

Implications for cosmic reionization





Smit et al., 2016; Bouwens, Smit et al. 2016

Summary

- ALMA shows dust obscuration is more complex than previously assumed: standard calibrations are uncertain
- A better understanding of rest-frame optical colours has decreased tension with DM accretion rates
- Detection of high-EW ionisation lines indicate a hard radiation field in the highest redshift galaxies
- High values of ionising production efficiency can possibly alleviate the tension of low escape fraction to bring about cosmic Reionisation