Characterizing the Colors, Physical Properties, and Specific Star Formation Rates of the Faint Galaxies that Reionized the Universe

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Thanks to Pascal Oesch, Garth Illingworth, Ivo Labbe, Renske Smit, Adi Zitrin, Wei Zheng (and other members of HUDF09+XDF and CLASH teams)

"Reionization in the Red Centre"
July 16, 2013 (Uluru, Australia)

Talk Outline

I. Stellar Masses of Galaxies at z~7

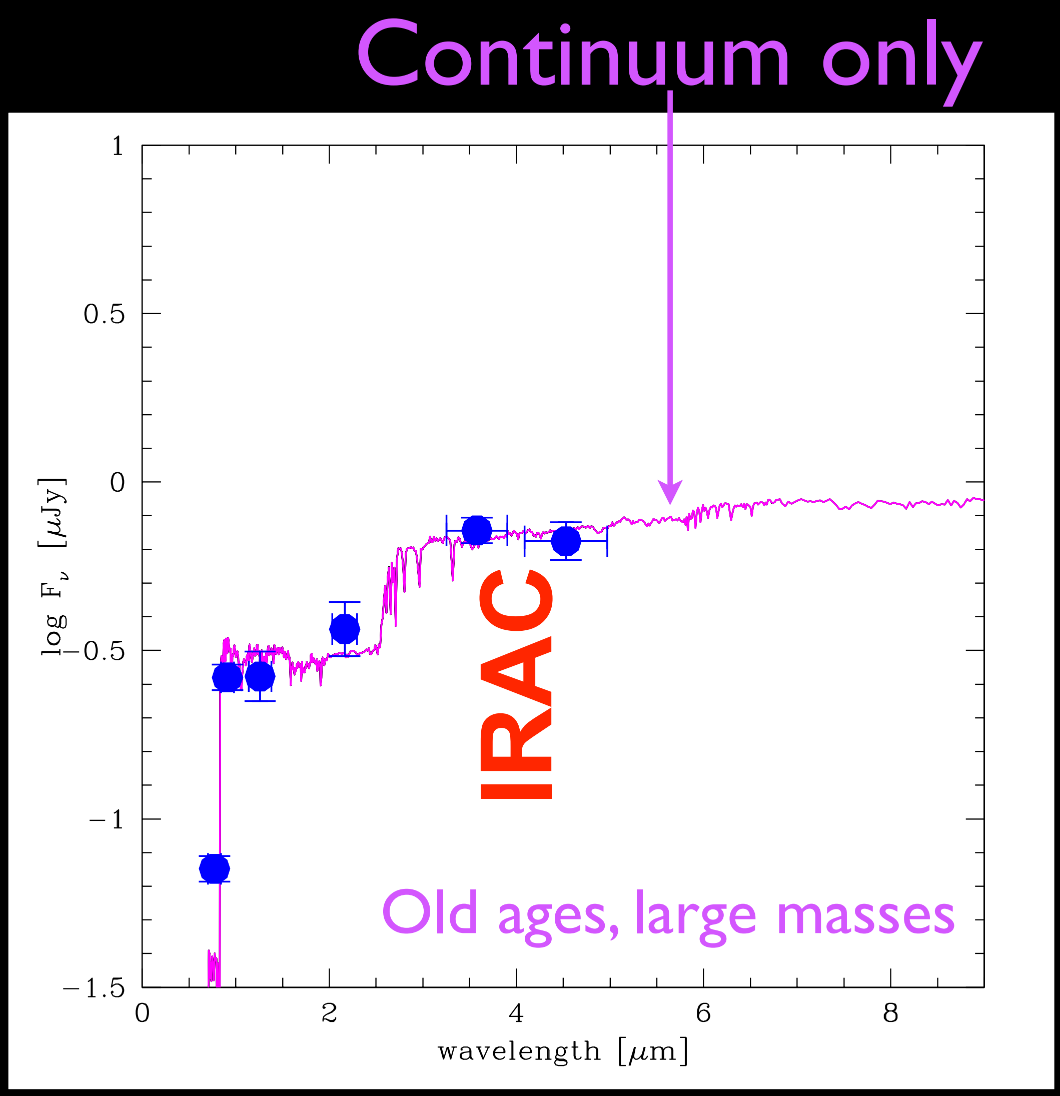
II. UV Colors of Star Forming Galaxies at z~4-7: What is their dependence on luminosity/mass ? What is the likely physical cause?

III. Does the faint-end slope of galaxies evolve at early times? What impact does this have on reionization?

IV. Deeper Reduction of HUDF optical + near-IR Data Available

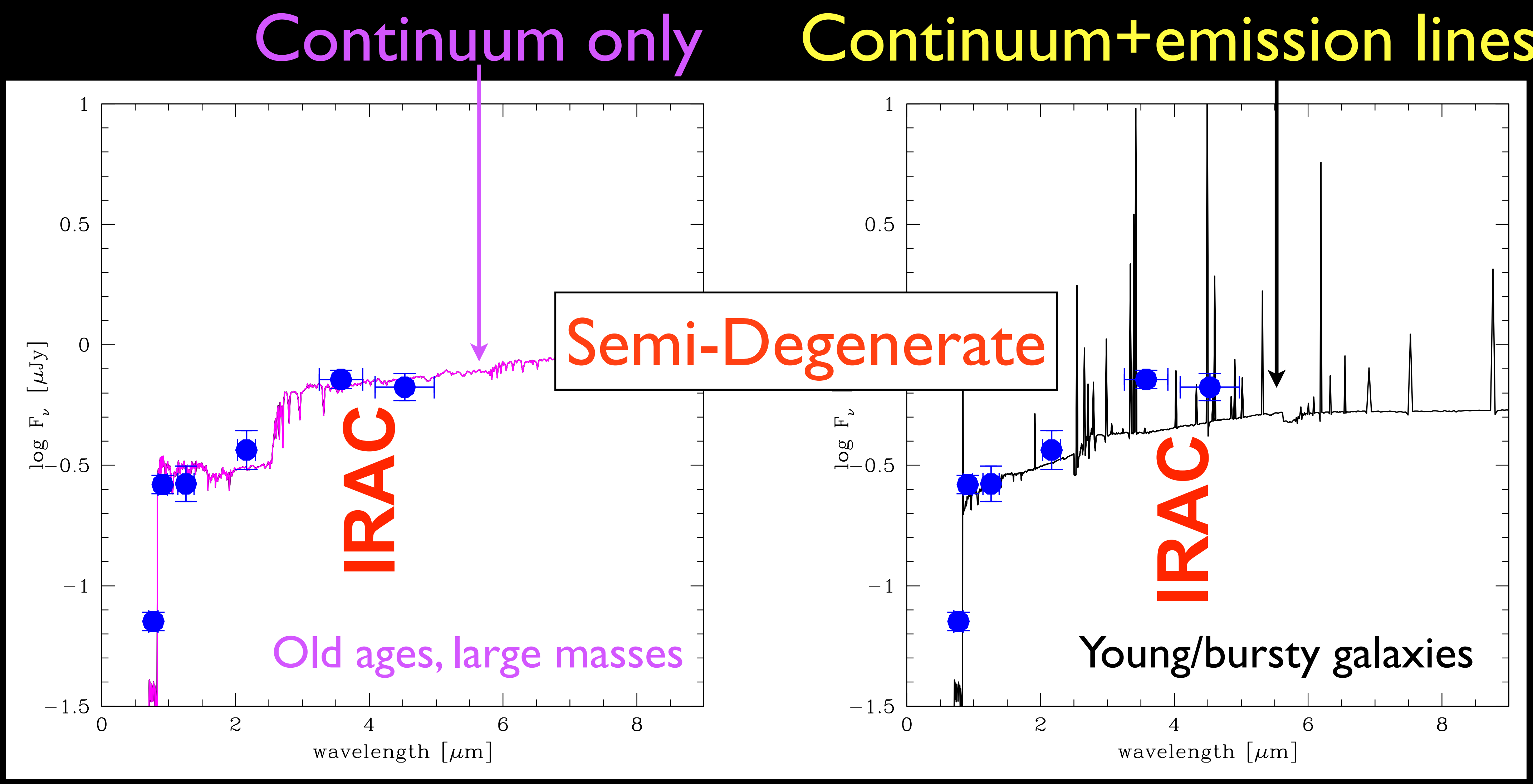
What can we learn about the stellar masses of galaxies at z~7?

Quantifying the Stellar Masses at z~7 is Challenging, since Light from Old Stars



Schaerer et al. 2009

Quantifying the Stellar Masses at z~7 is Challenging, since Light from Old Stars has essentially effect on rest-frame optical light seen with Spitzer/IRAC, as nebular line emission from young stars



Schaerer et al. 2009

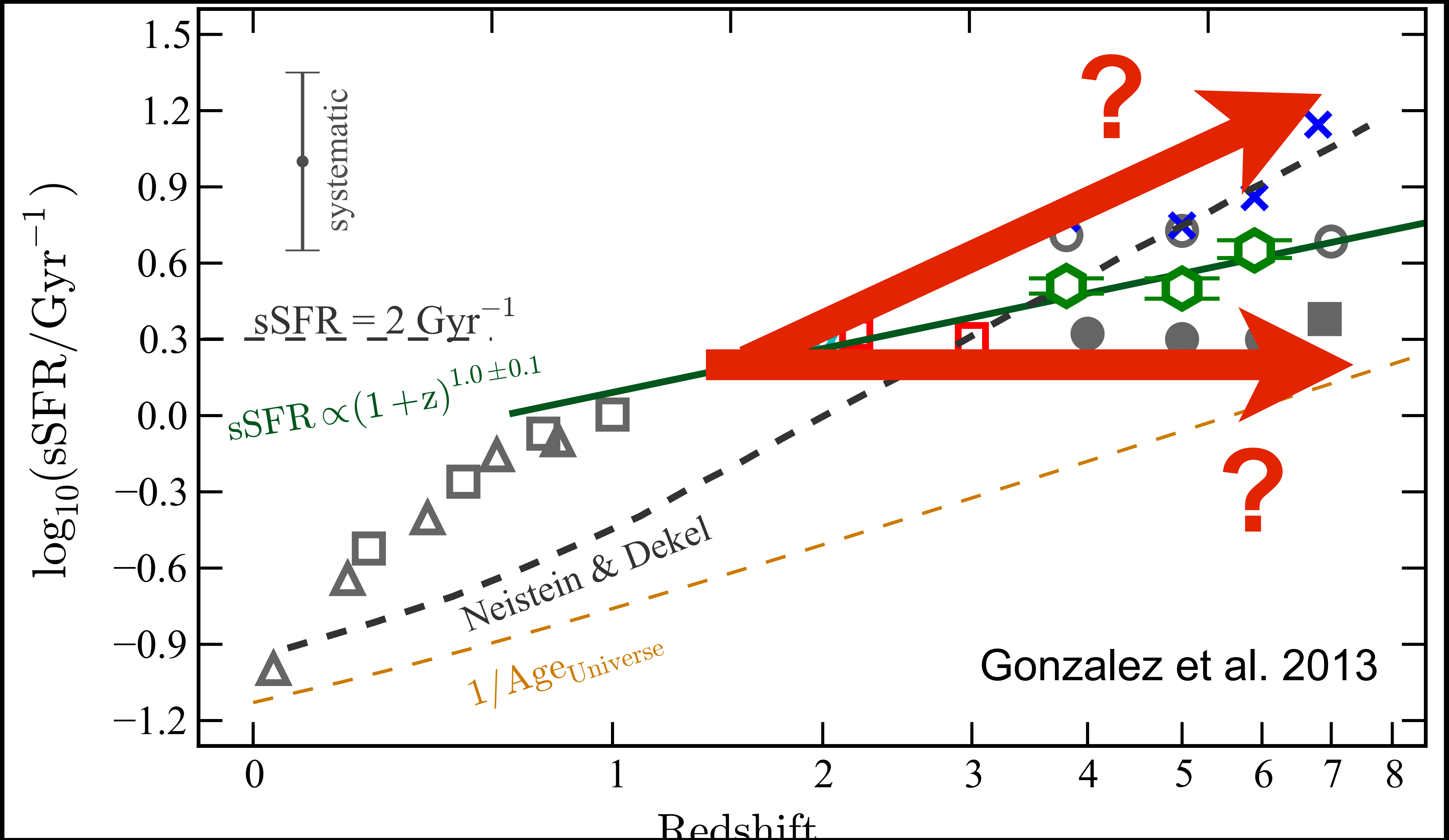
Quantifying Stellar Masses at z~7 is Important since it helps us understand the rate at which galaxies are growing!

Knowing whether sources at z~7 are dominated by (1) stellar continuum or (2) emission lines at rest-frame optical wavelengths is essential for knowing whether sSFR is significantly higher at z>4 as predicted by theory

sSFR

SFR / Stellar Mass

= 1 / growth time scale



Gonzalez et al. 2013; Stark et al. 2013; Tilvi et al. 2013; de Barros et al. 2013

Knowing whether sources at z~7 are dominated by (1) stellar continuum or (2) emission lines at rest-frame optical wavelengths is essential for knowing whether sSFR is significantly higher at z>4 as predicted by theory

from Stark et al. 2013

sSFR

SFR / Stellar Mass

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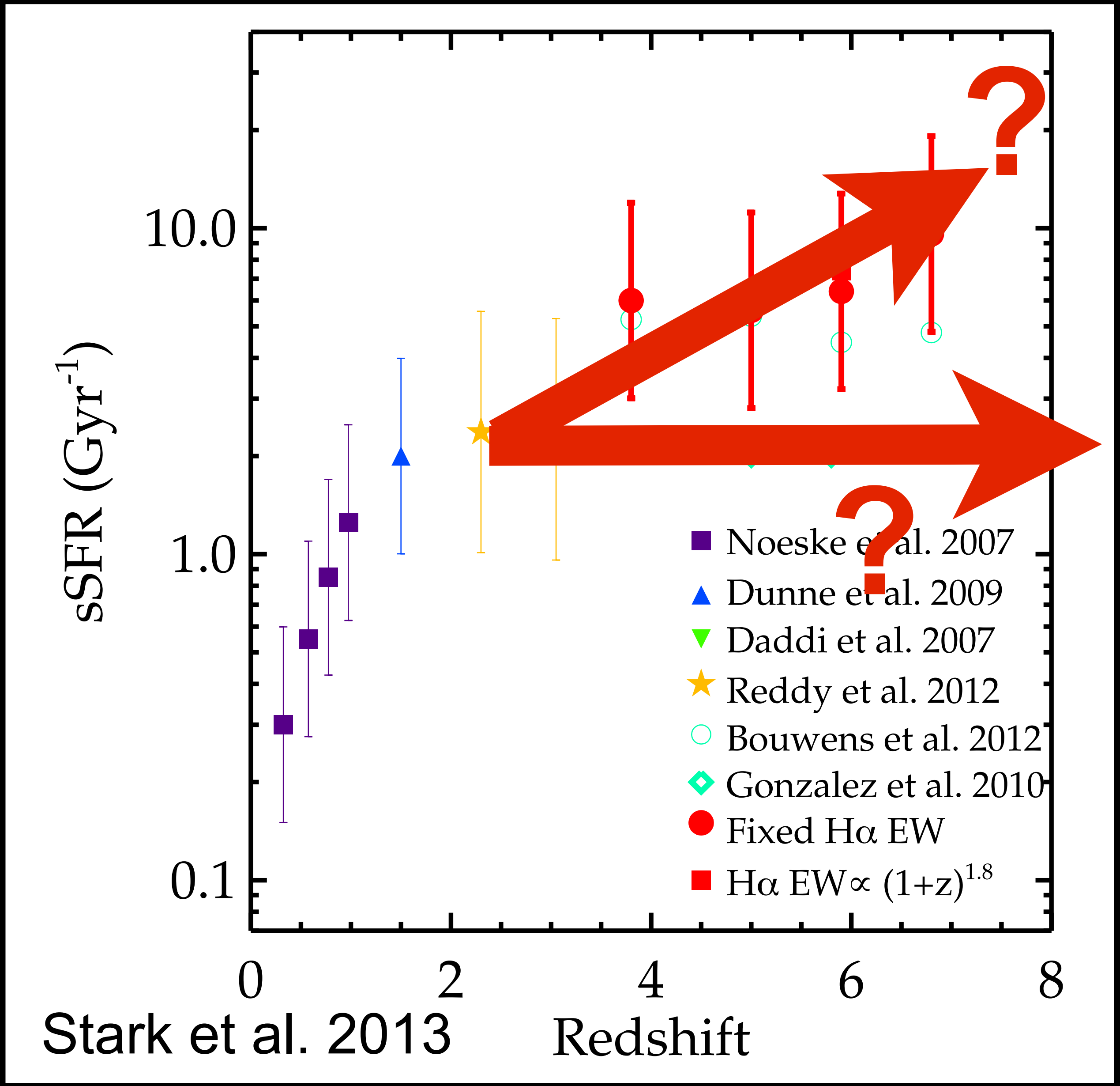


Gonzalez et al. 2013; Stark et al. 2013; Tilvi et al. 2013; de Barros et al. 2013

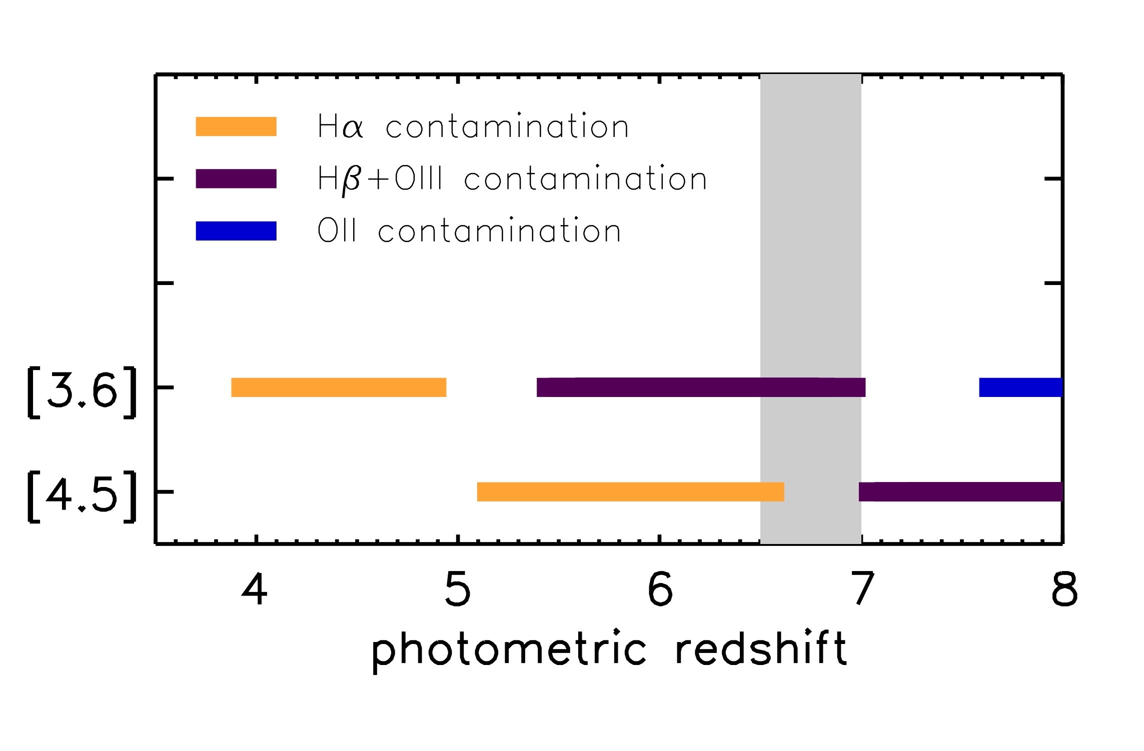
Require Clean Measurement of Stellar Continuum Light in z~7 Galaxies

Fortunately Possible with IRAC Camera on the Spitzer Space Telescope

Clean Measurements of Stellar Continuum Possible in Select Redshift Windows Where There are No Strong Nebular Lines

One such window is at z~6.8

Spitzer Space Telescope IRAC Bands →



[4.5]-band clean at z~6.8, while [3.6] is contaminated by [OIII]+Hβ

Renske Smit

Smit et al. 2013

To take advantage of this window to characterize the stellar populations of z~7 galaxies, we selected a sample of magnified galaxies behind clusters from the CLASH program and other programs.

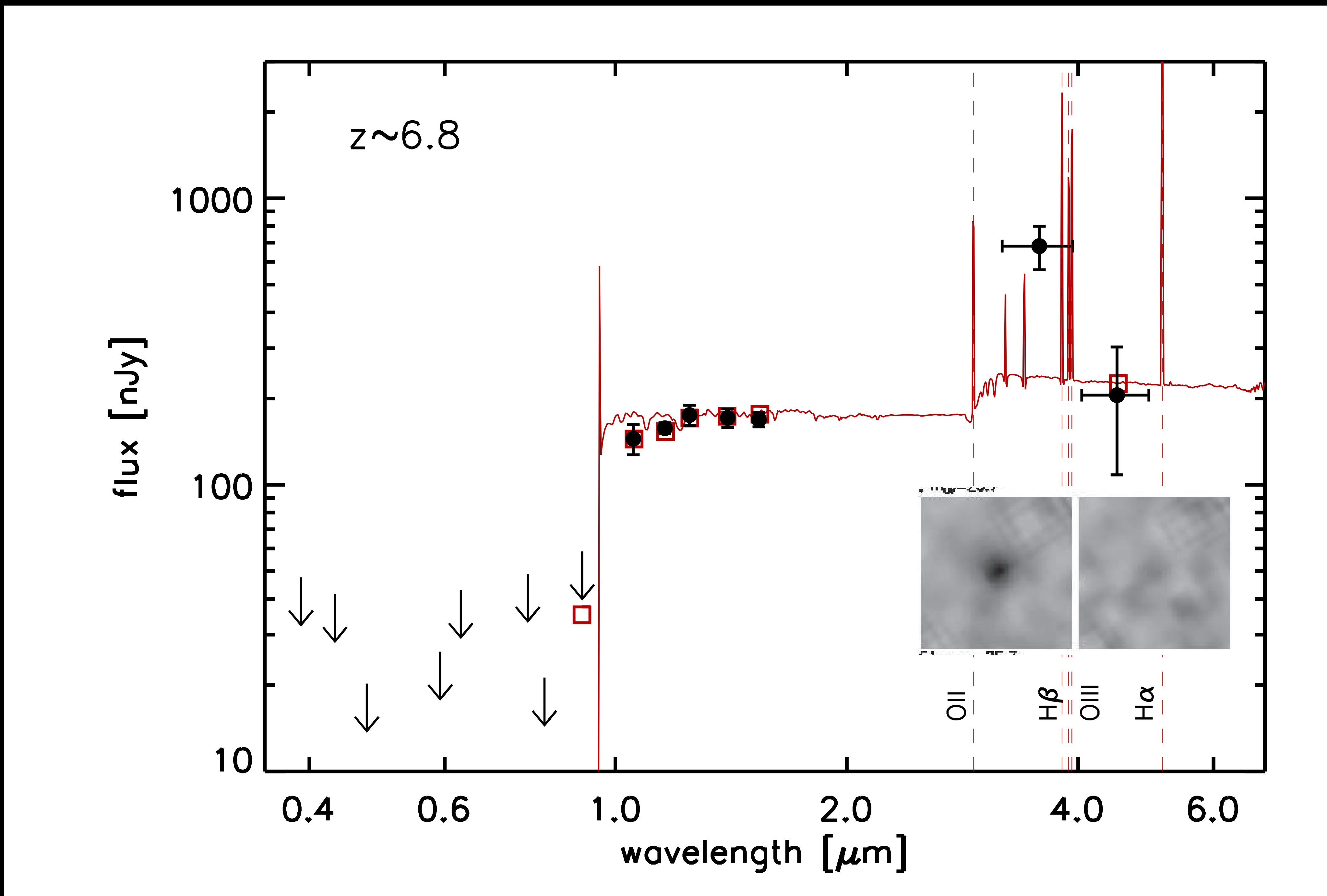
- We select a sample at z~6.6-7.0 with $m_{UV} < 26$ mag
- [3.6] and [4.5] Spitzer/IRAC bands measured with (relatively) high S/N
- Good estimates of photometric redshift

Renske Smit

Smit et al. 2013

What do the sources look like?

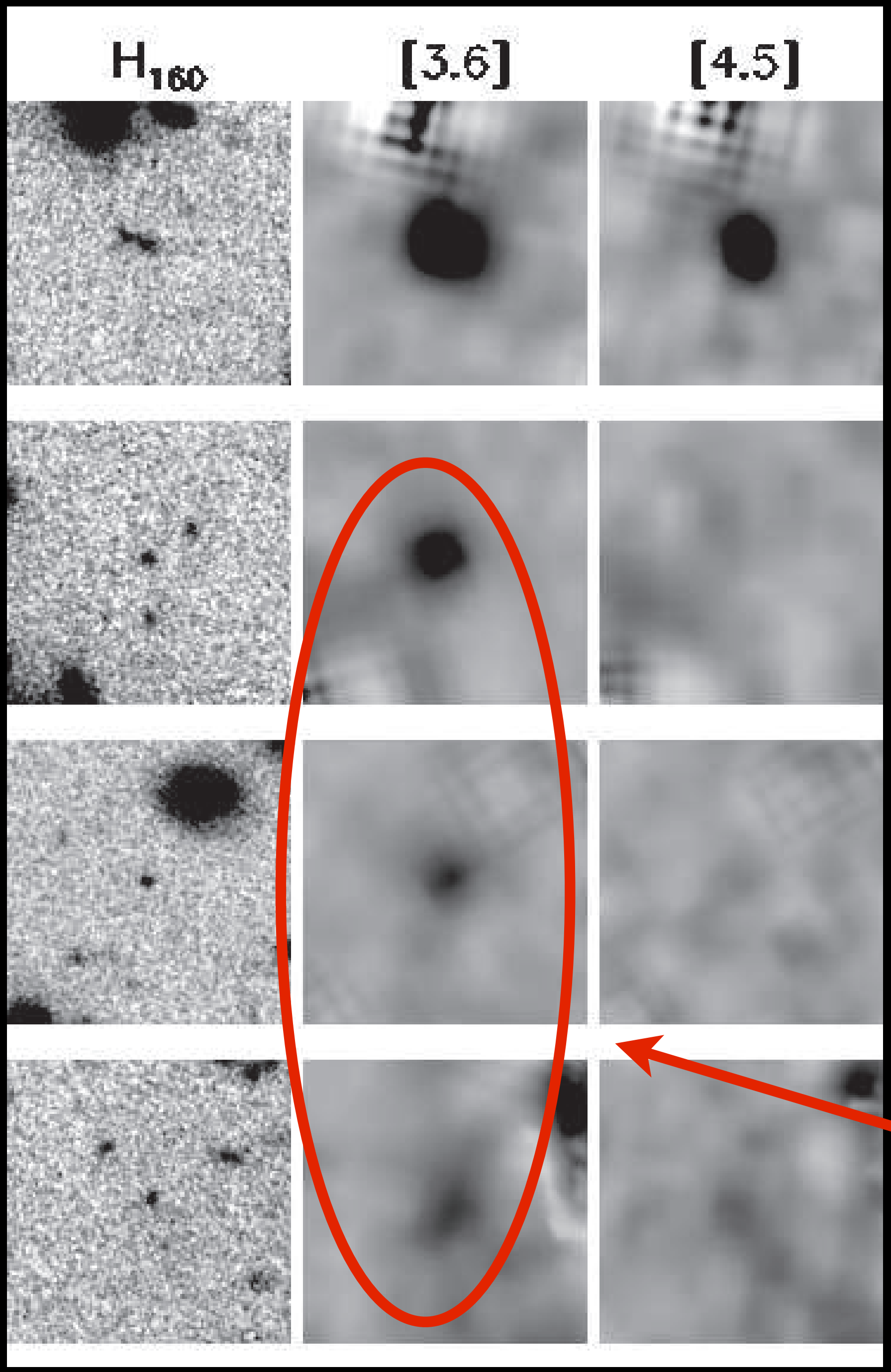
Here's one:

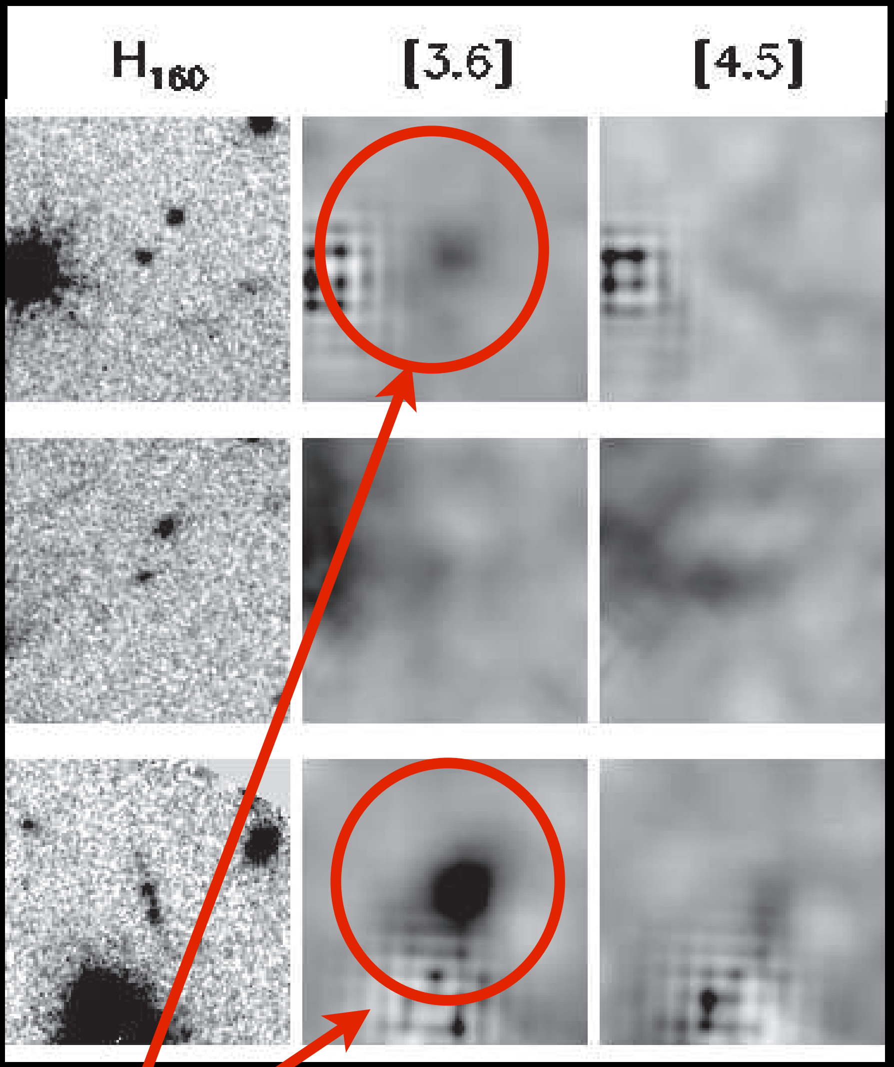


Smit et al. 2013

Renske Smit

What do other sources in sample look like?



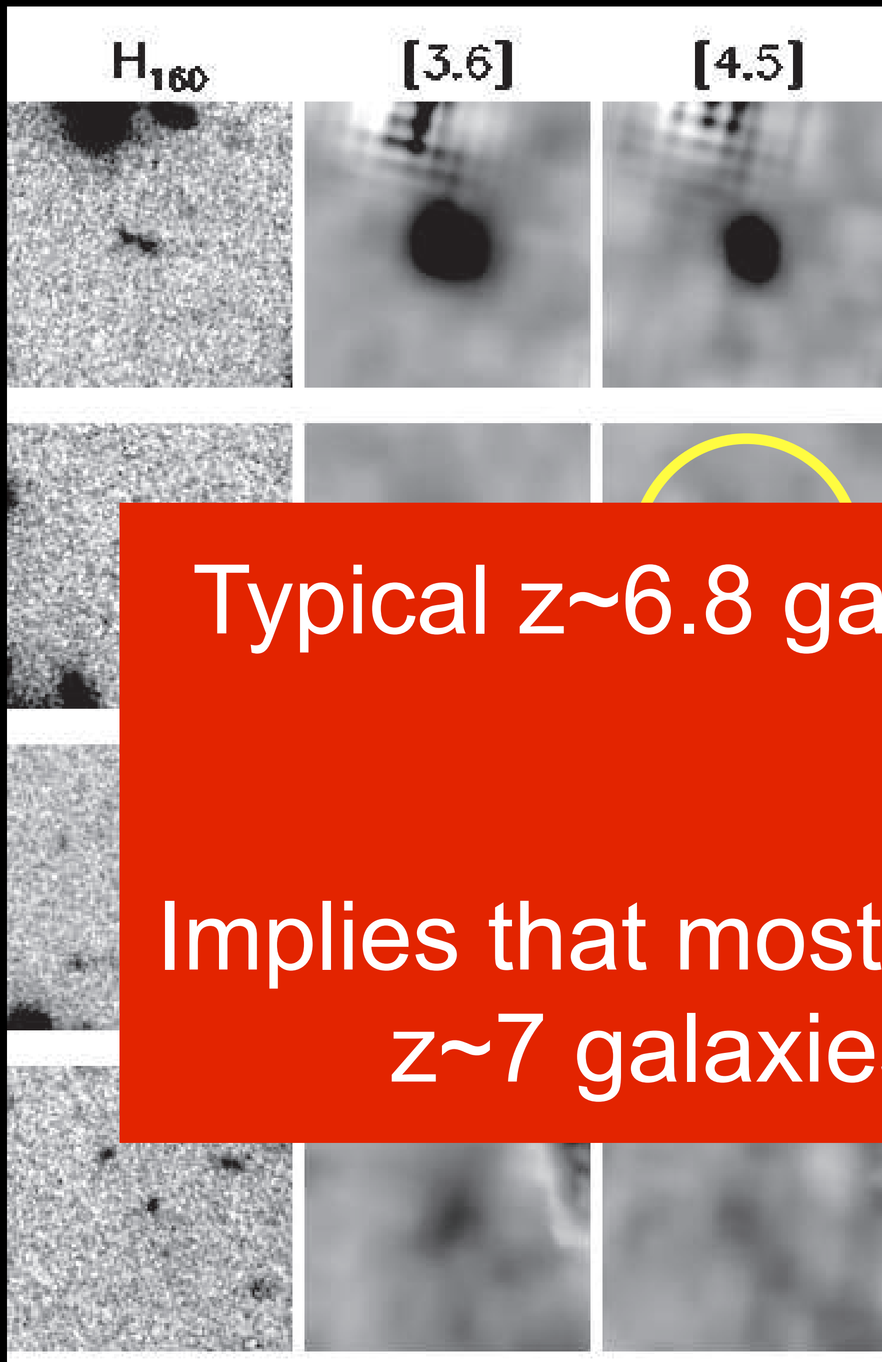


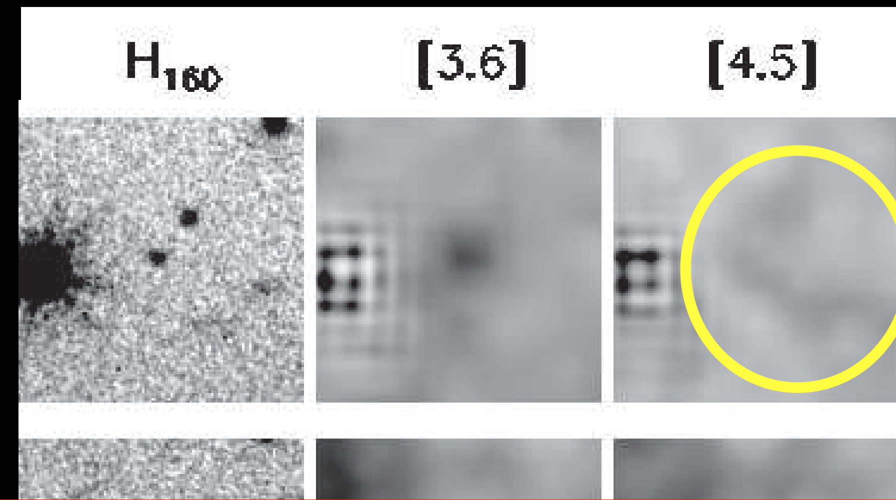
Nebular Line Emission

Smit et al. 2013

Renske Smit

What do other sources in sample look like?

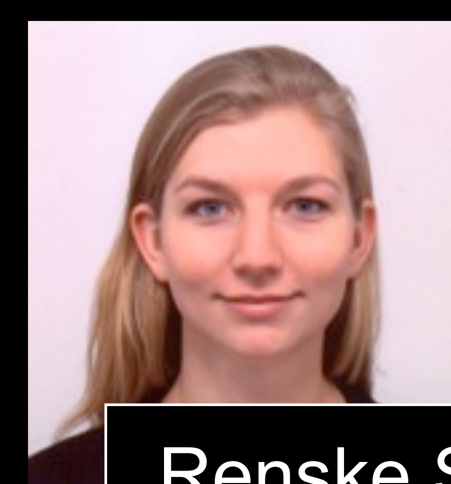




Typical z~6.8 galaxy has extremely blue 3.6-4.5 colors!

Implies that most of light at IRAC wavelengths for z~7 galaxies is from nebular emission!

Smit et al. 2013

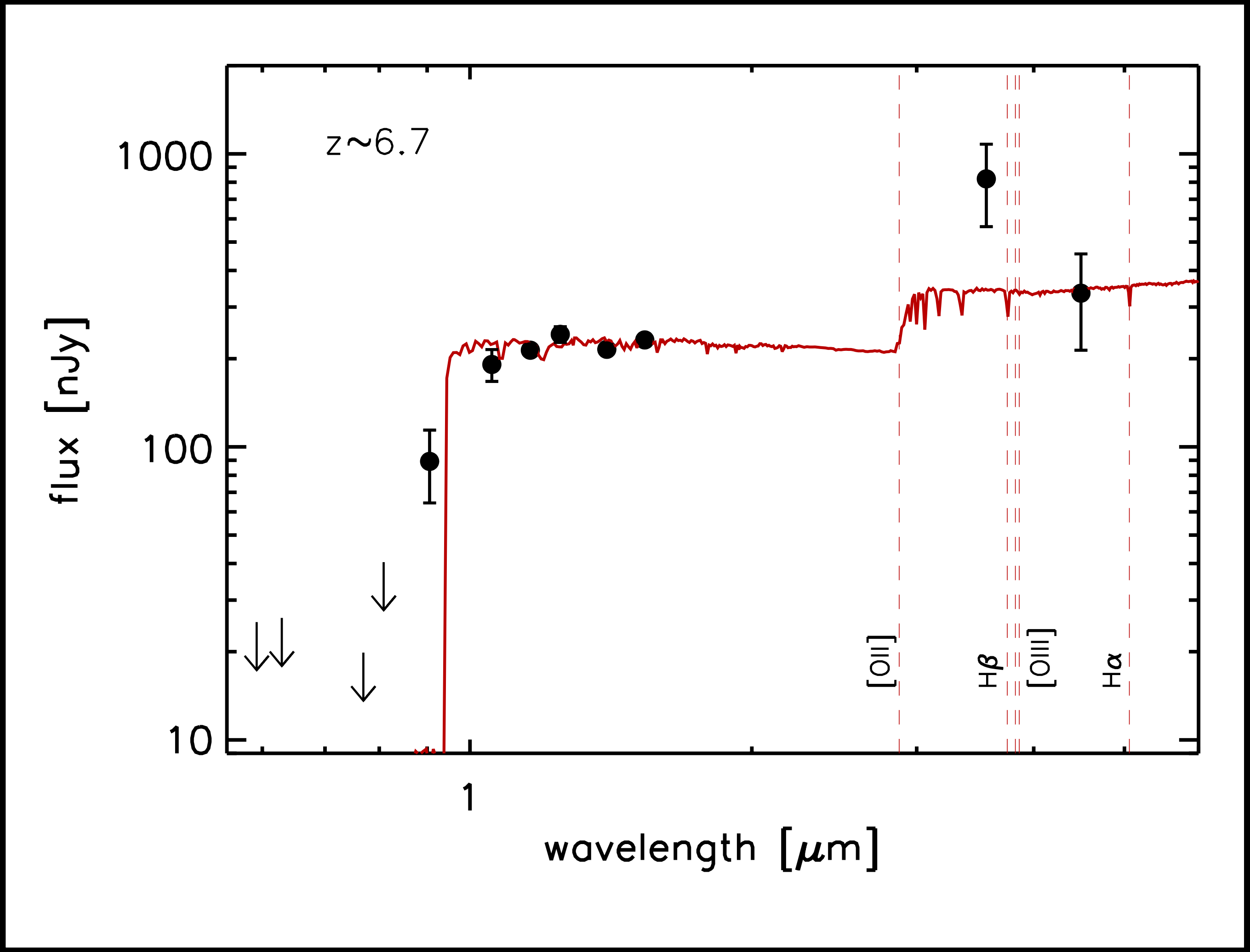


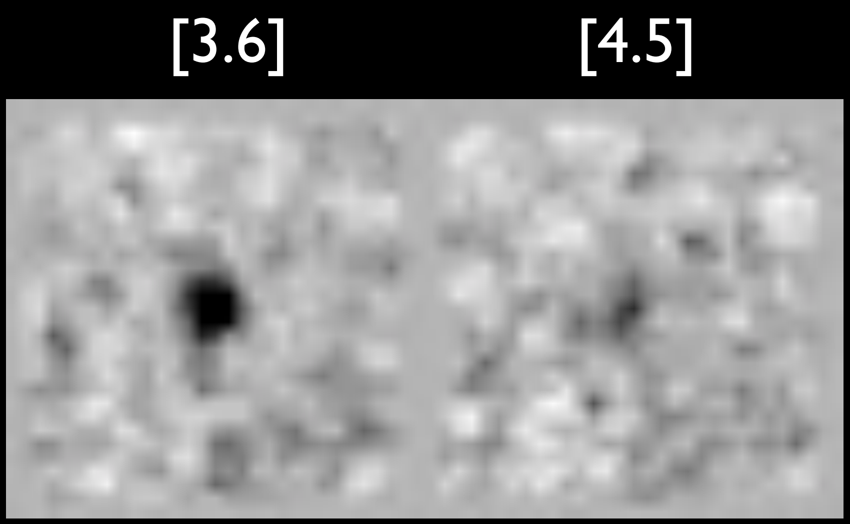
Renske Smit

What does the stacked SED look like?

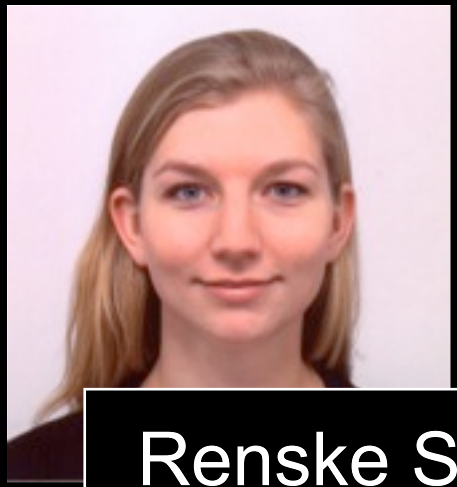
Stacking results for lensed z~6.7 sample

7 brightest lensed z~6.7 sources from CLASH





Smit et al. 2013



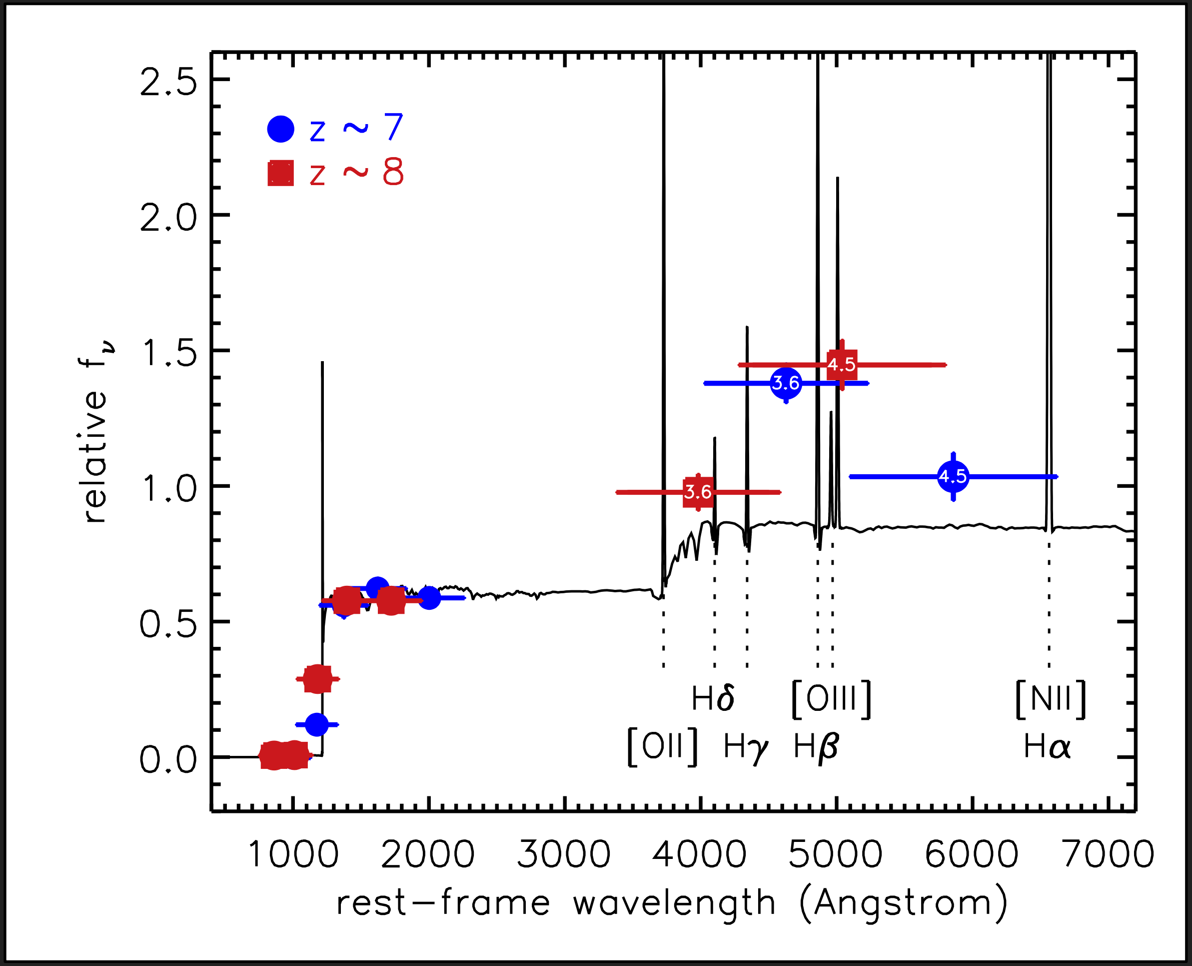
Renske Smit

These results imply that the specific star formation rates (or inverse growth times) are high at z~7 -- consistent with other recent results!

Previous studies derived high estimates of the sSFR at z~7 *assuming* that the nebular emission lines

Best previous evidence was from the Labbe et al. 2012 study looking at a sample of z~7 and z~8 galaxies from the HUDF

Modest EW emission lines inferred from stacked results.



al. 2013 on the sSFRs at z~5-7 were correct.

Smit et al. 2013; Gonzalez et al. 2013; Stark et al. 2013; Tilvi et al. 2013; de Barros et al. 2013

These results imply that the specific star formation rates (or inverse growth times) are high at z~7 -- consistent with other recent results!

SFR / Stellar Mass

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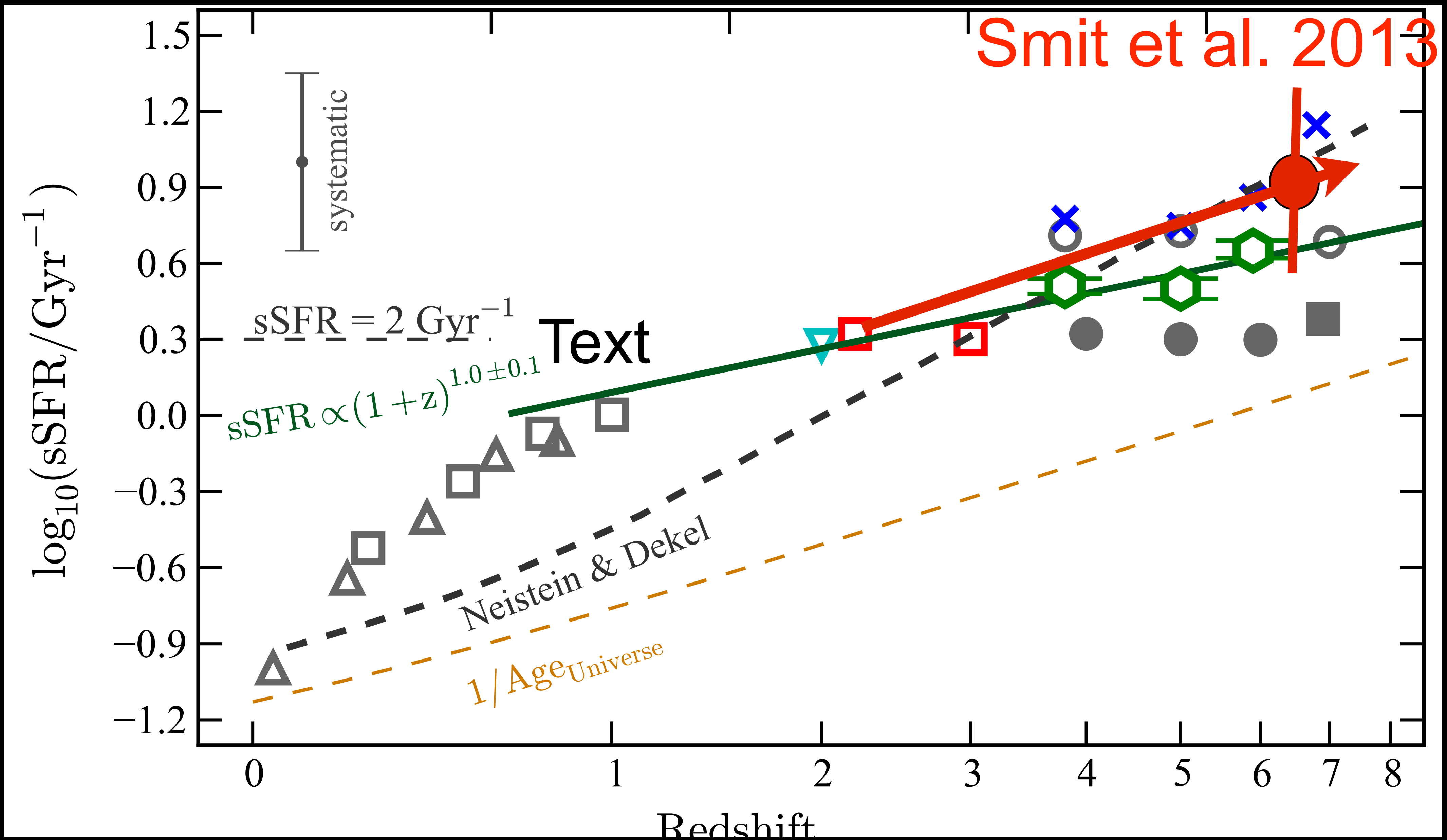


Smit et al. 2013; Gonzalez et al. 2013; Stark et al. 2013; Tilvi et al. 2013; de Barros et al. 2013

What about the dust properties or stellar populations of z>=4 galaxies?

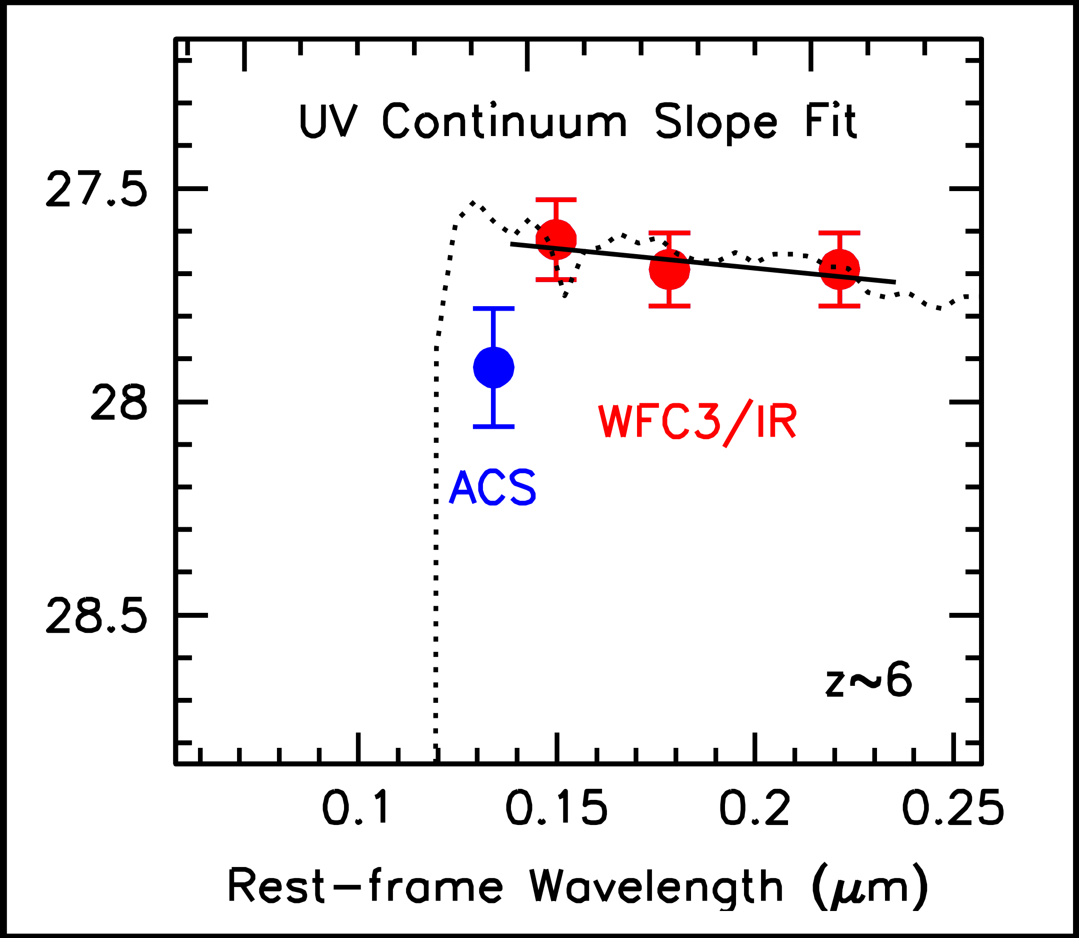
How do they depend on the stellar mass (or equivalently luminosity of galaxies)?

Are there systematic trends in the colors of galaxies as a function of luminosity (or mass)?

good place to look is in UV continuum slopes!

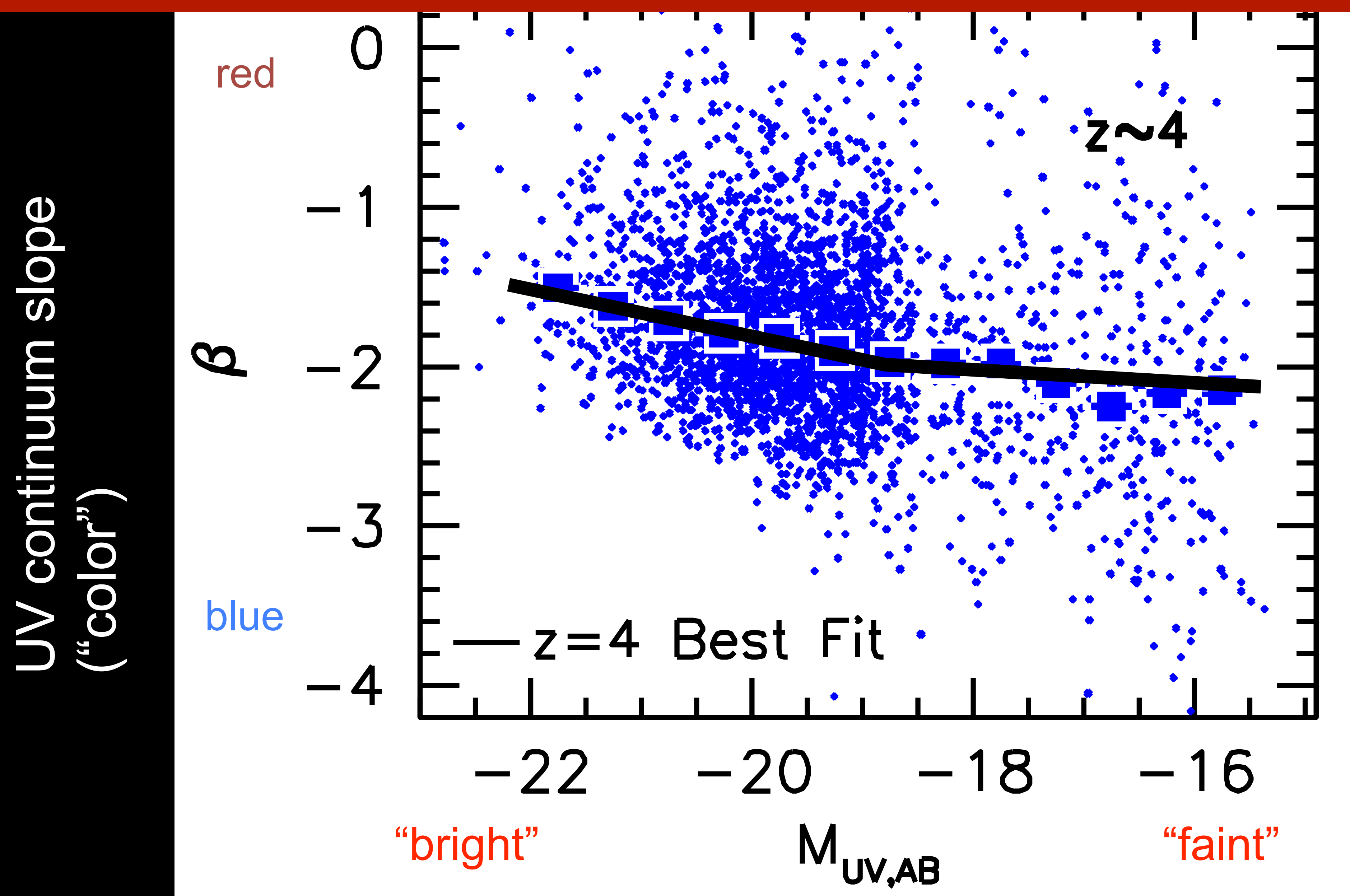
UV Continuum Slopes
are just colors
in the rest-frame UV

$$f_\lambda \propto \lambda^\beta$$



What does this dependence of color on

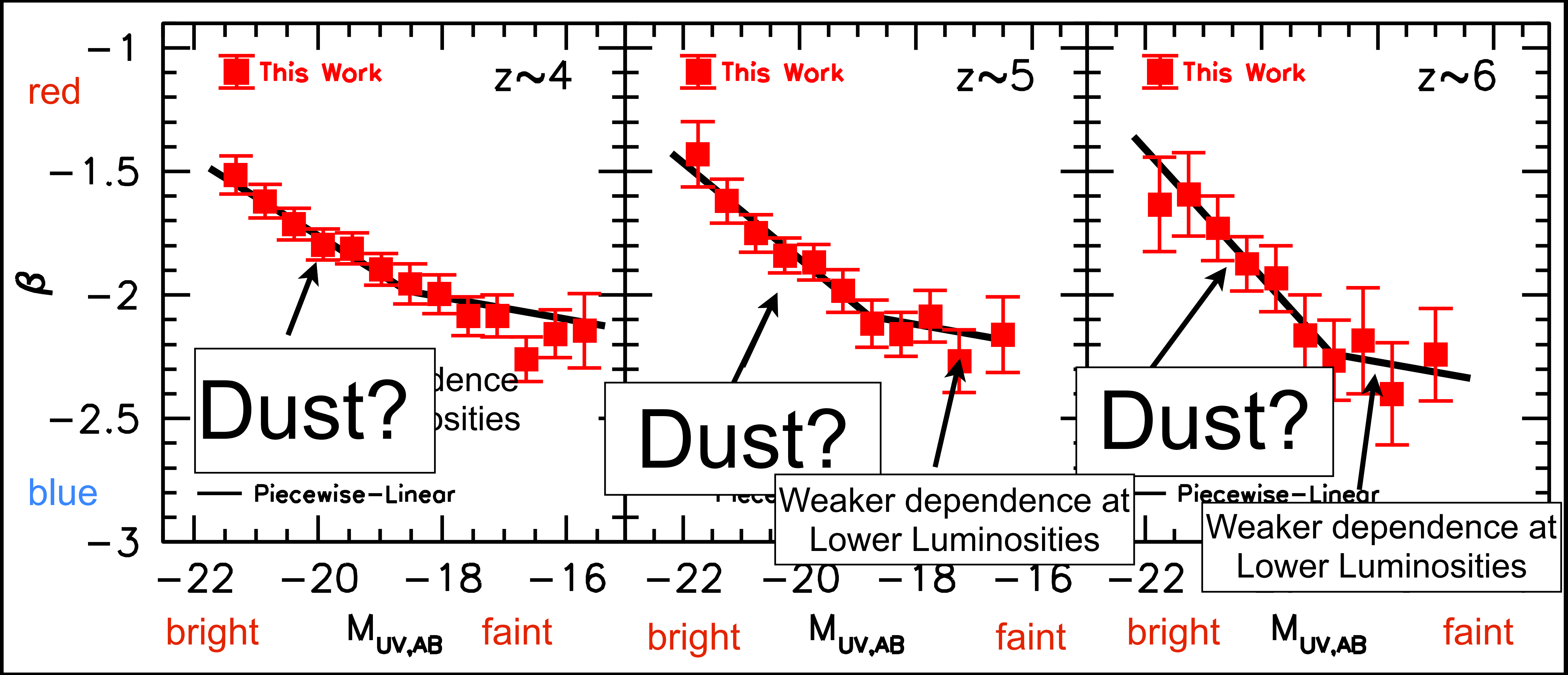
I’ve shown similar results before, but now we have bigger samples, better measurements



Bouwens et al. 2013; see also Bouwens et al. 2009, 2010, 2012; Wilkins et al. 2011; Dunlop et al. 2012; Castellano et al. 2012; Finkelstein et al. 2012

What does this dependence of color on luminosity/mass look like at z~4-6?

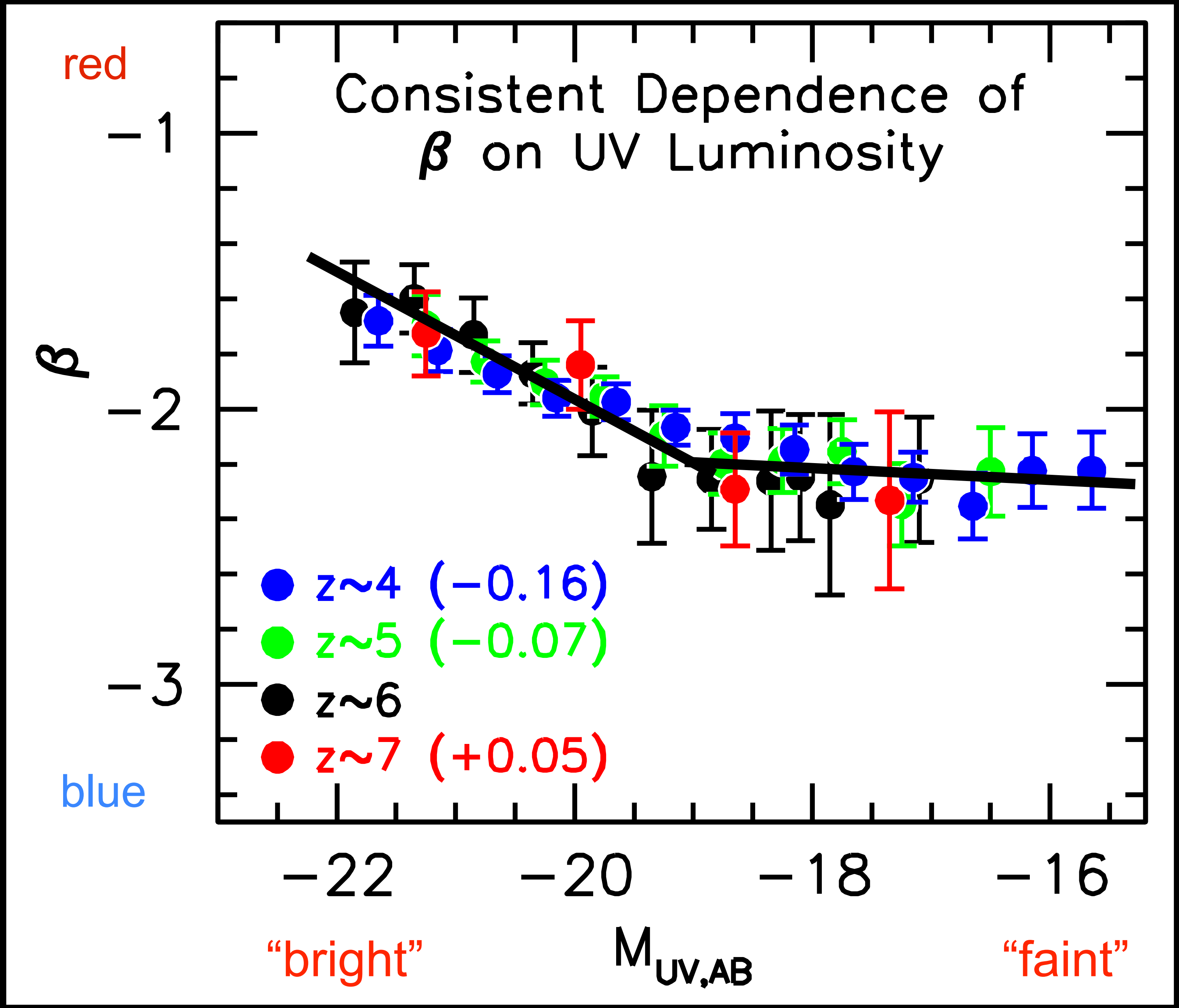
Evidence for two different luminosity dependencies



Bouwens et al. 2013

Do we find evidence for similar relationship at all redshifts?

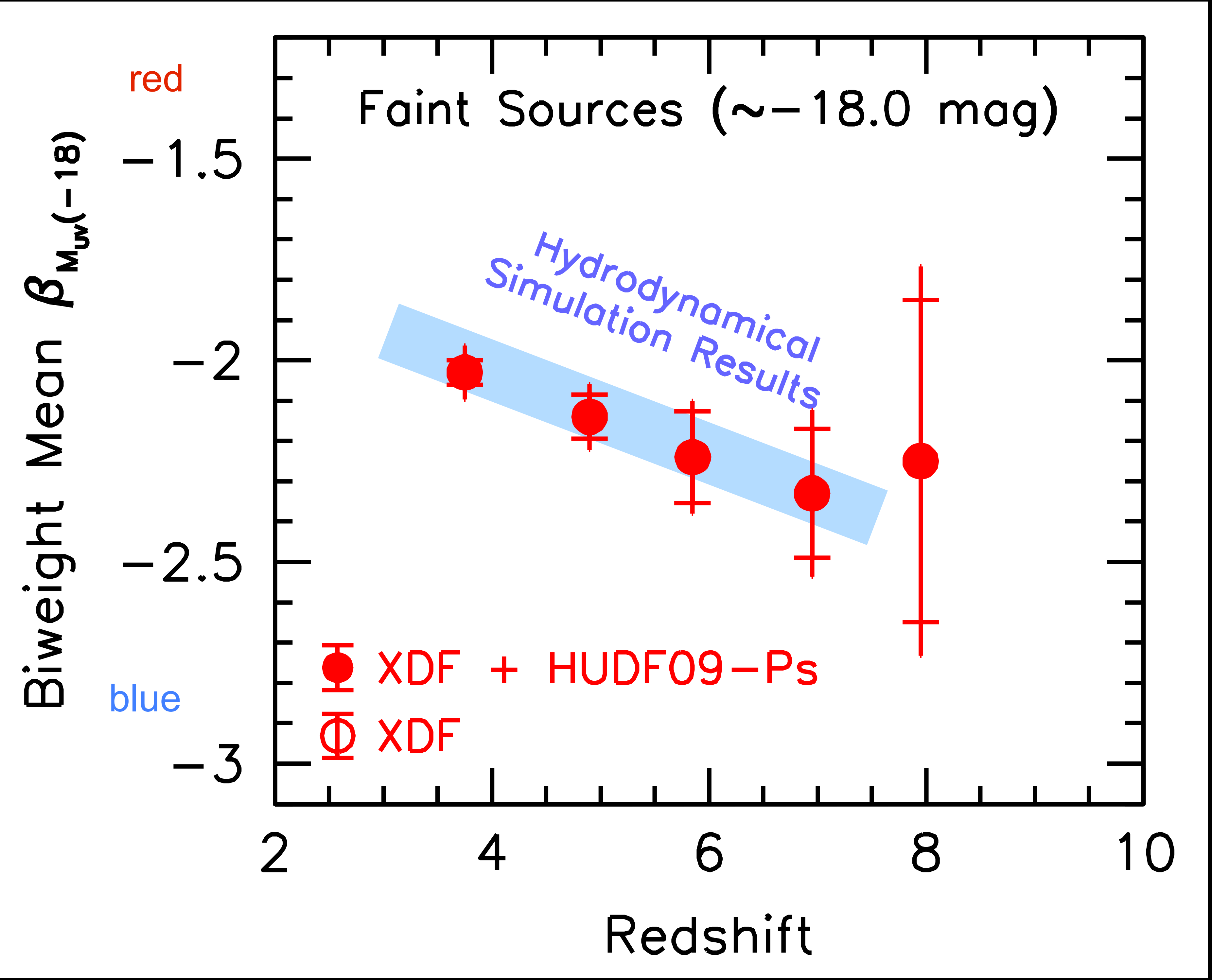
UV continuum slope ("color")



only applying small offsets to sources as function of redshift

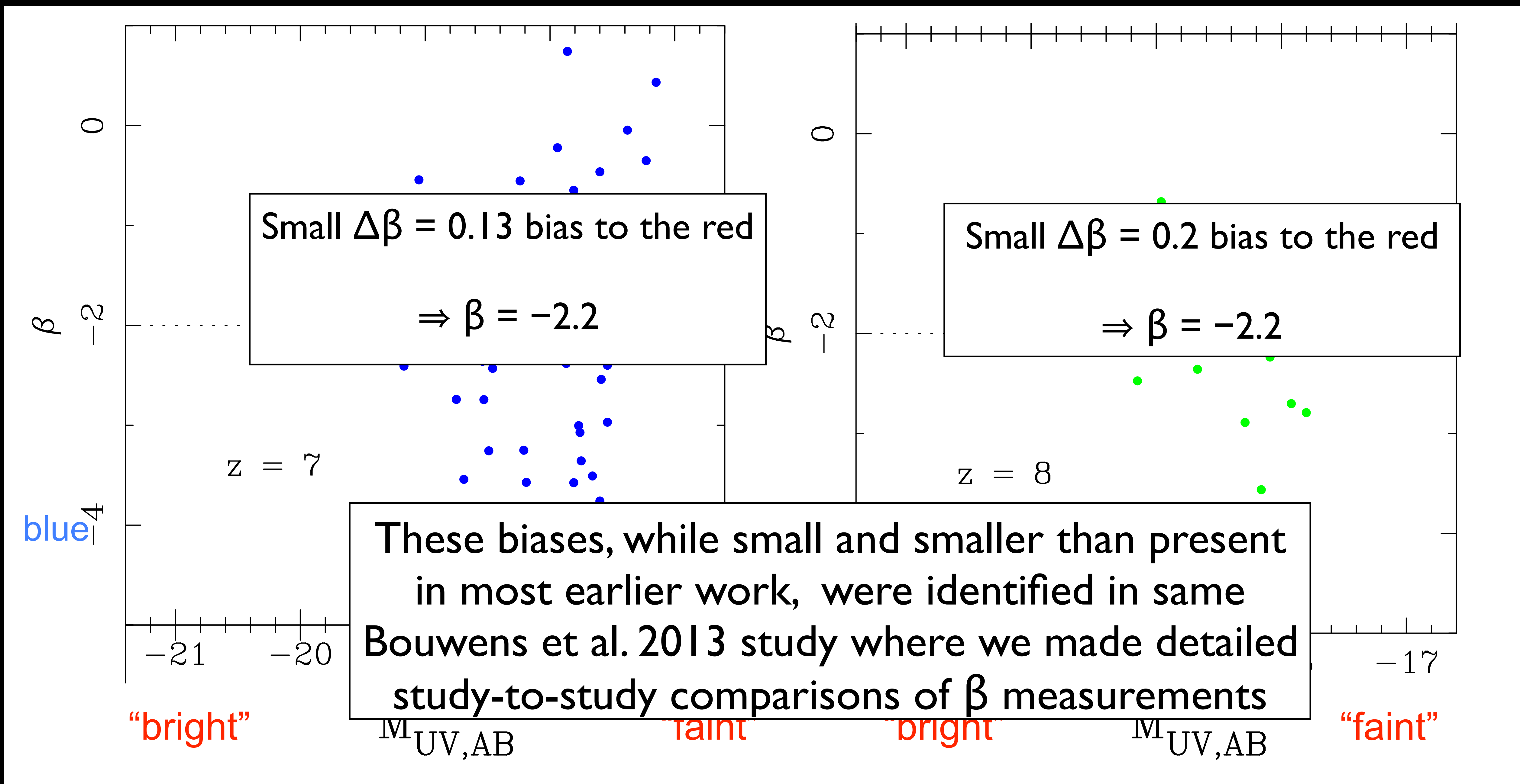
Bouwens et al. 2013; Dunlop et al. 2013; FInkelstein et al. 2012; Bouwens et al. 2012

How do the colors of the lowest luminosity galaxies evolve with redshift?



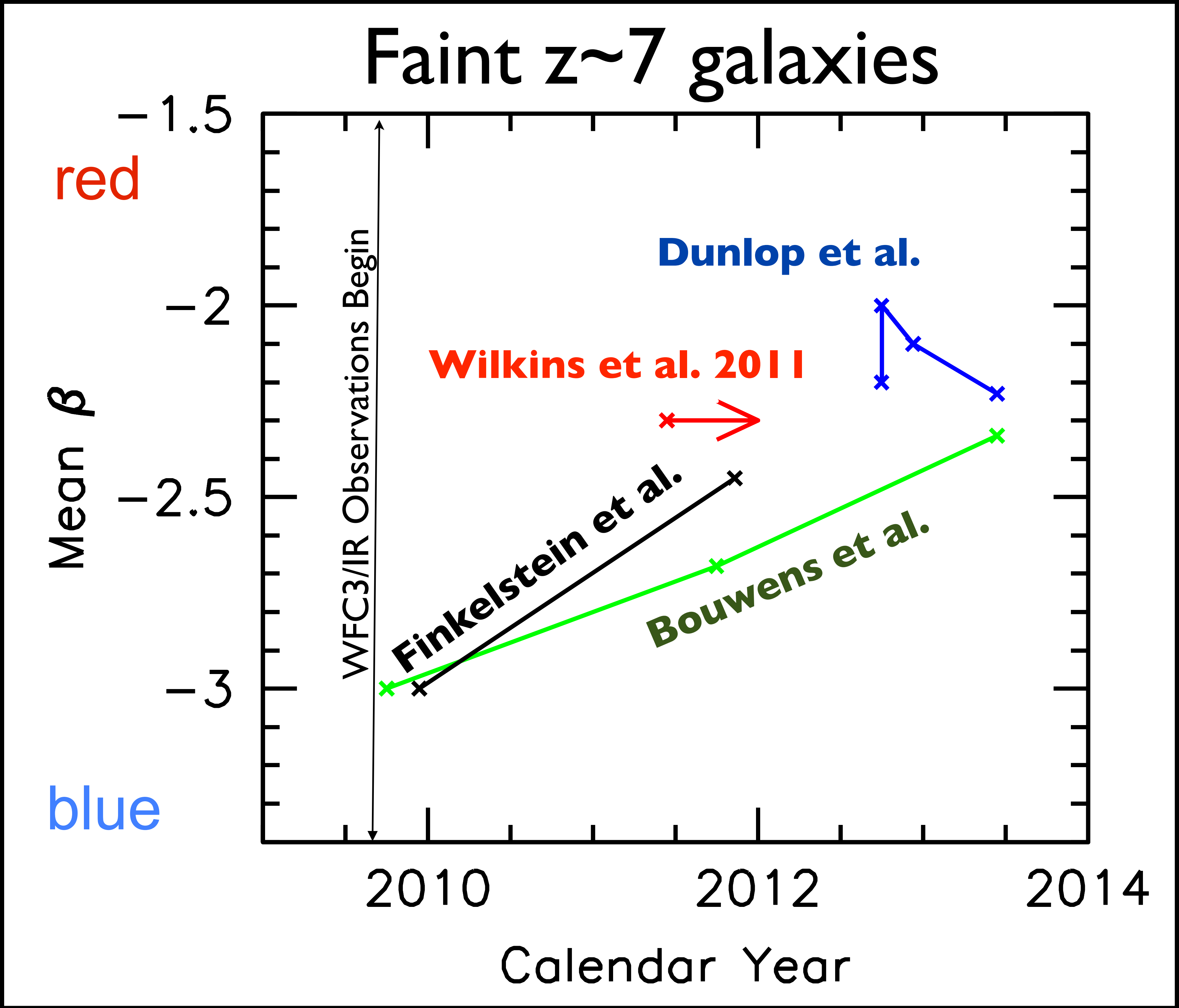
Bouwens et al. 2013; see also Bouwens et al. 2012; Finkelstein et al. 2012

You may wonder how this relates to the HUDF12 team's apparent finding that β ~ −2 for faint z~7-8 galaxies



Dunlop et al. 2013

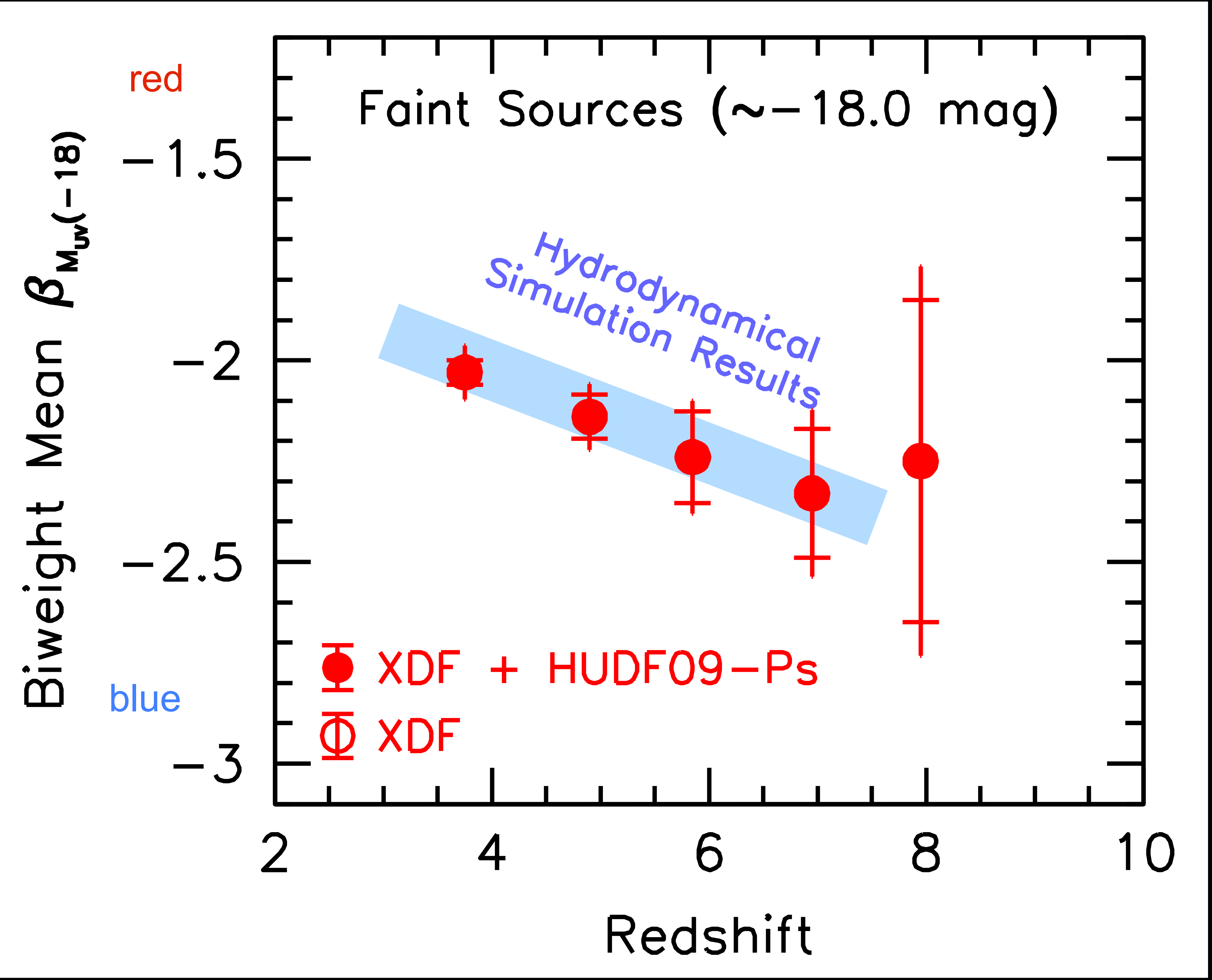
Convergence of β measurements



← −2.35?

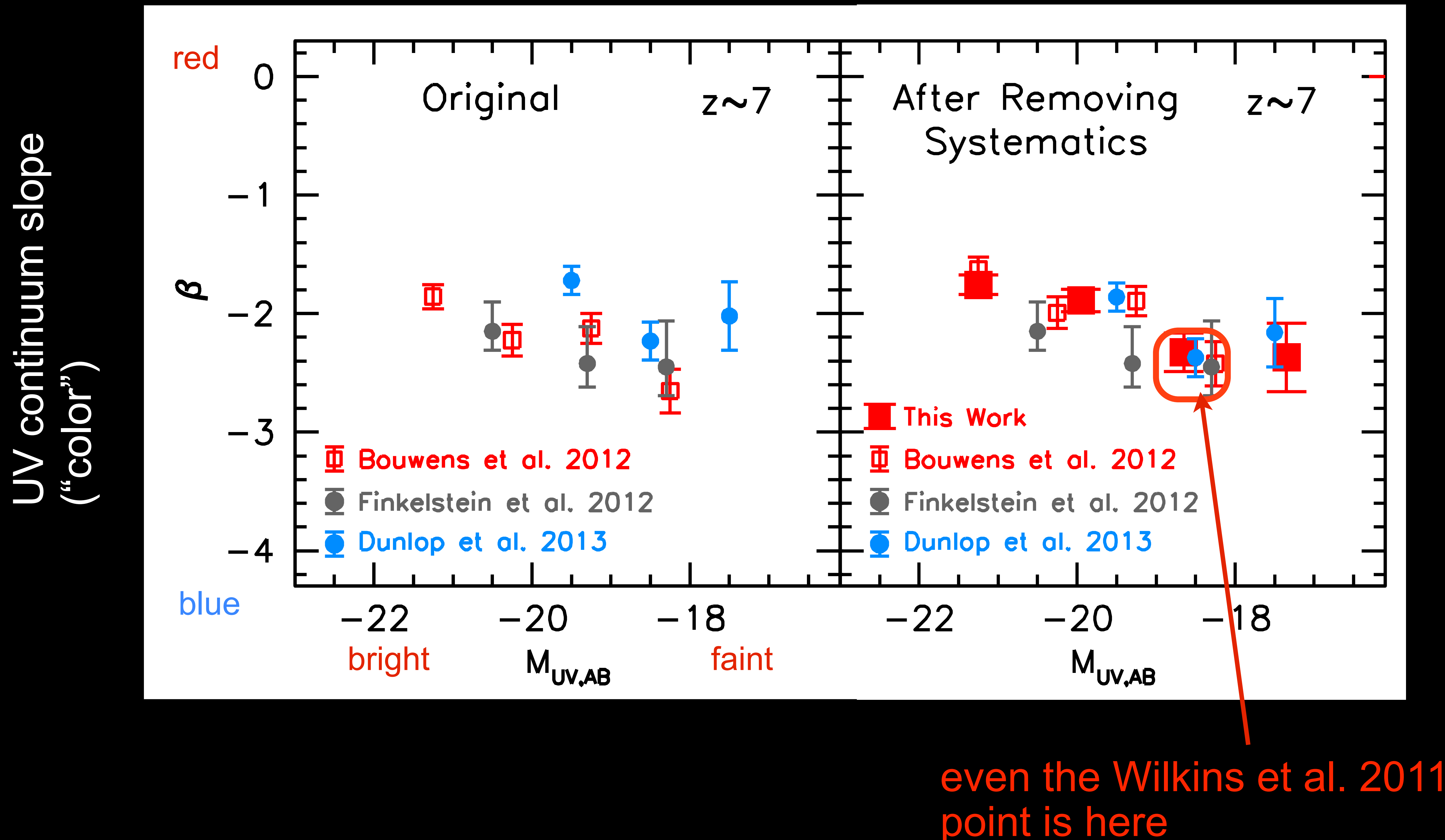
Bouwens et al. 2013; Dunlop et al. 2013; Finkelstein et al. 2012; Wilkins et al. 2011

Value of −2.3 also supported by determining trend from lower redshift...



Bouwens et al. 2013; see also Bouwens et al. 2012; Finkelstein et al. 2012

Improved agreement the result of our recent study (Bouwens et al. 2013) where we attempt to identify and remove remaining systemics in various works in the literature



Bouwens et al. 2013; Dunlop et al. 2013; FInkelstein et al. 2012; Bouwens et al. 2012

Does the faint-end slope evolve with redshift?

What sort of effect can this have in matching various constraints like the Thomson optical depth?

What effect do the steep faint-end slopes -- and their evolution -- have in reionizing the universe and on the observed Thomson optical depths?

How can we answer?

-- Determine the total flux density of ionizing photons emitted by galaxies as function of redshift based on observed LFs

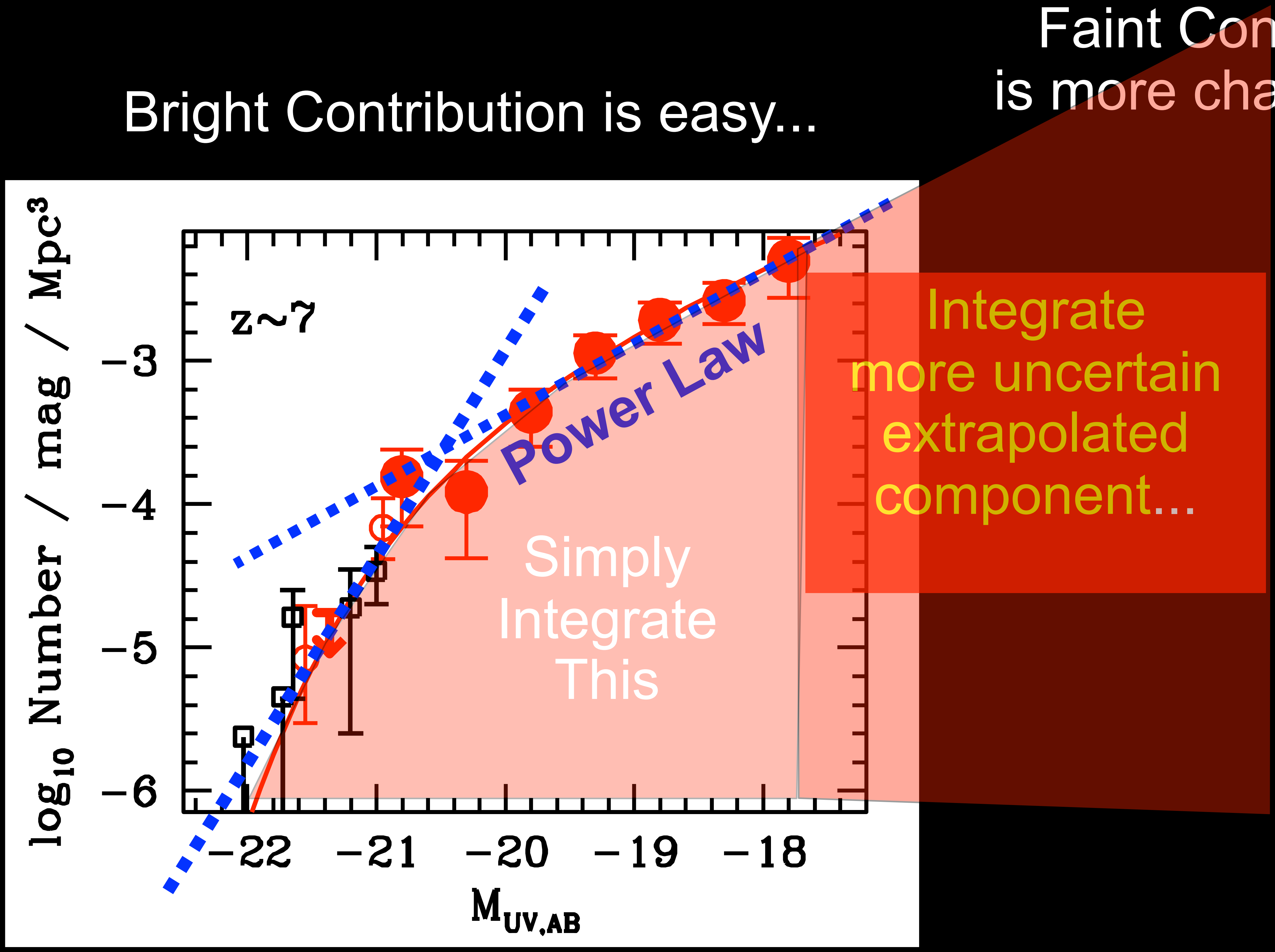
-- Make reasonable assumptions about clumping factor for HI in IGM and fraction of ionizing photons escaping

What effect will it have on the Thomson optical depth?

How many ionizing photons do galaxies produce
(ignoring escape fraction considerations)?

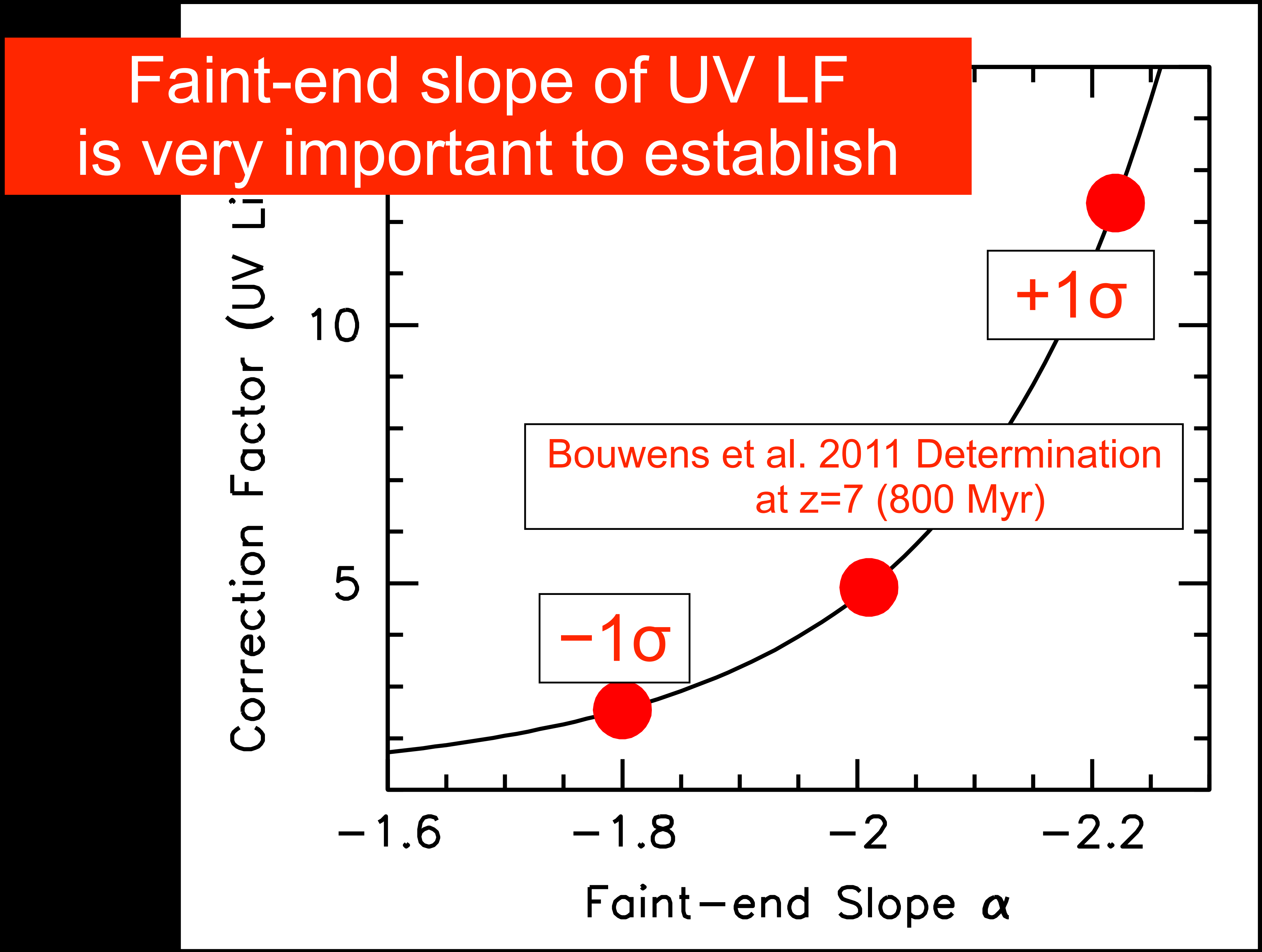
Bright Contribution is easy...

Faint Contribution
is more challenging...



How many ionizing photons do galaxies produce (ignoring escape fraction considerations)?

Correction (for unseen sources) depends very sensitively on faint-end slope
(integrated to -10 AB mag: approximate limiting luminosity expected in many models)

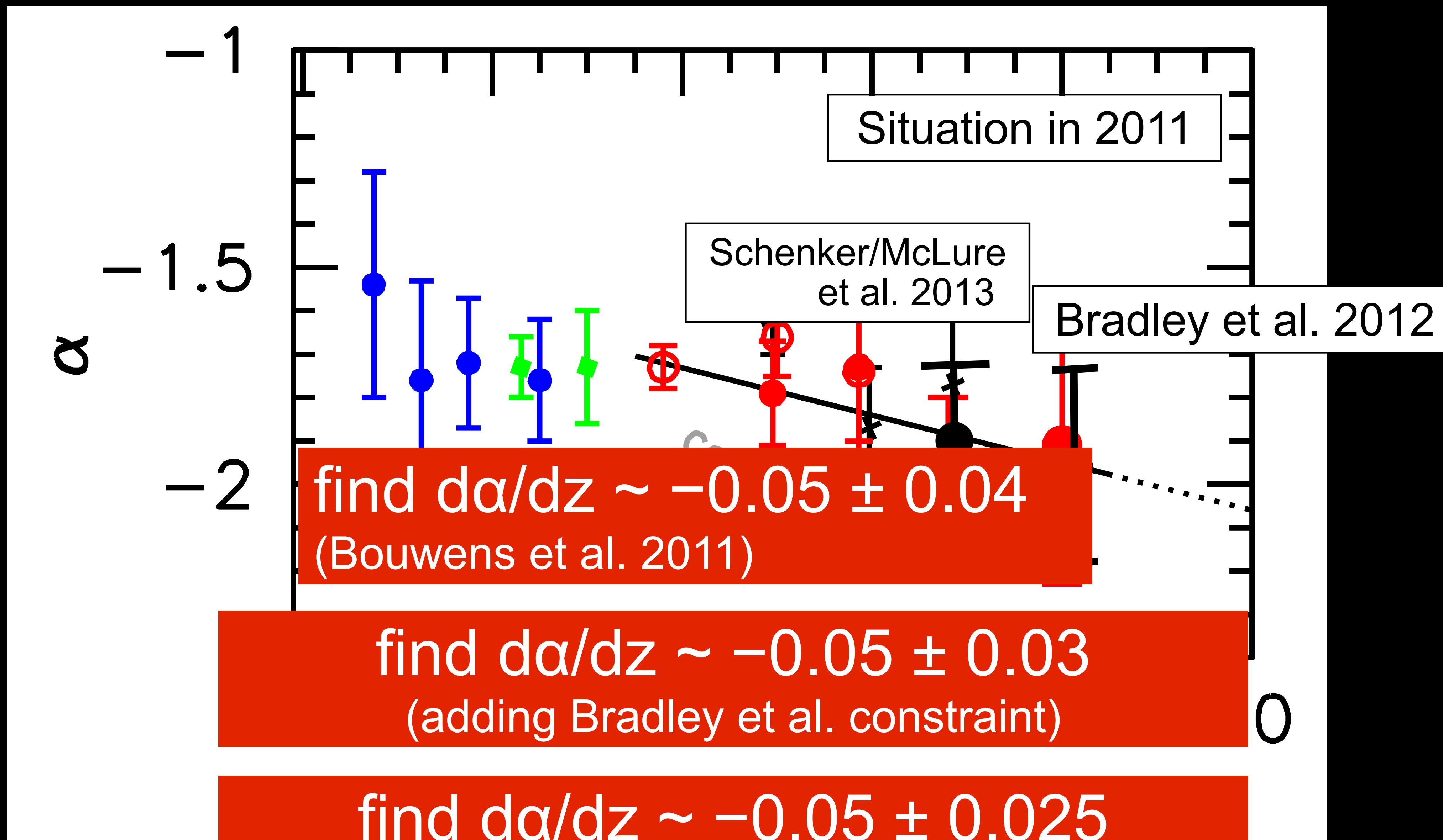


Bouwens et al. 2011

What are our current constraints on the faint-end slope?

Is there evidence for evolution?

Shallow slope



Steep slope

find dα/dz ~ −0.05 ± 0.04
(Bouwens et al. 2011)

find dα/dz ~ −0.05 ± 0.03
(adding Bradley et al. constraint)

find dα/dz ~ −0.05 ± 0.025
(rough estimate: adding HUDF12 data)

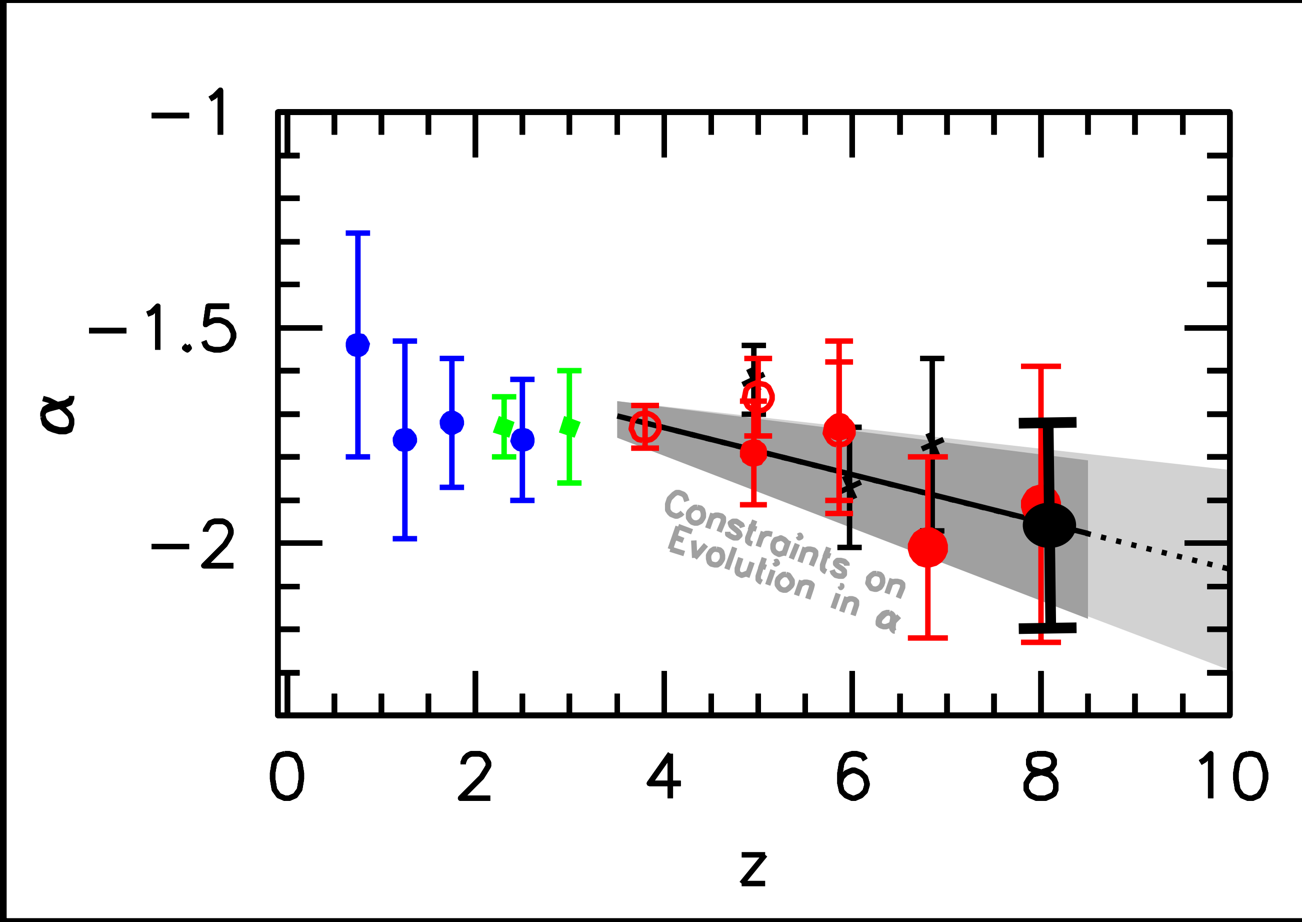
Bouwens et al. 2007
McLure et al. 2013 (s

(also predictions from theory suggest such an evolution: Trenti et al. 2010; Jaacks et al. 2011; Salvaterra et al. 2011)

Can galaxies reionize the universe?

(how much light do they produce?)

Faint-end slope is steeper
at higher redshifts (evolving)



What can we learn from
these constraints?

- Extrapolate LF constraints to lower luminosities and higher redshifts
- Make reasonable assumptions about clumping factor, escape fraction

clumping factor of 3, $f_{esc} = 0.2$

Reionization at z=8

Thomson optical depth is
0.062 ↔ 0.079 ↔ 0.142

Matches WMAP constraints!

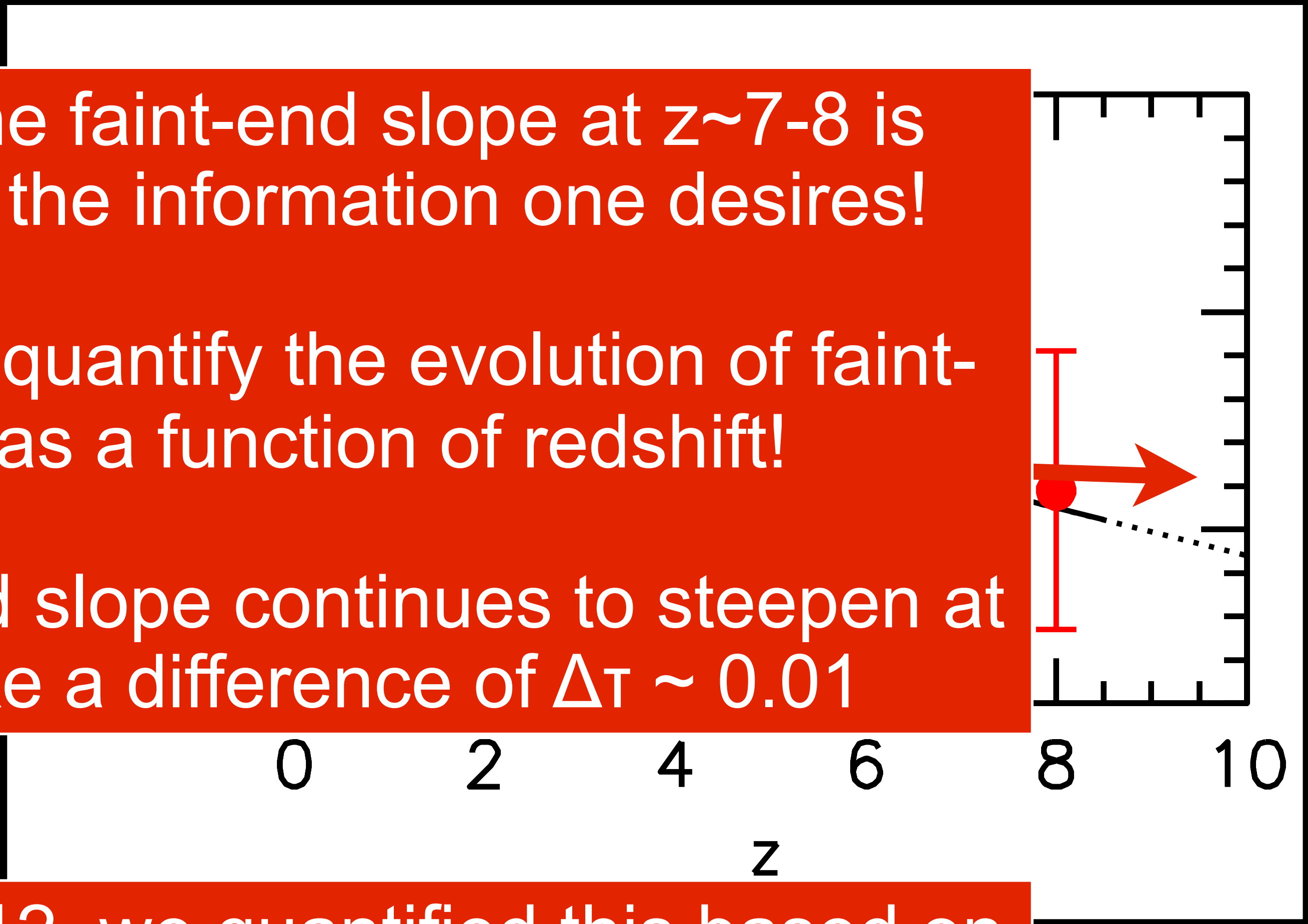
Bouwens et al. 2012; Kuhlen et al. 2013; see also Robertson et al. 2013

Can galaxies reionize the universe?

(how much light do they produce?)

Faint-end slope is steep
−1.87 ± 0.13 (but not evolving)

What if w
slop
observ



Establishing that the faint-end slope at z~7-8 is steep is not all the information one desires!

It is also valuable to quantify the evolution of faint-end slope as a function of redshift!

Whether the faint-end slope continues to steepen at z>8 can make a difference of Δτ ~ 0.01

clumping f

In Bouwens et al. 2012, we quantified this based on the data available at the time.

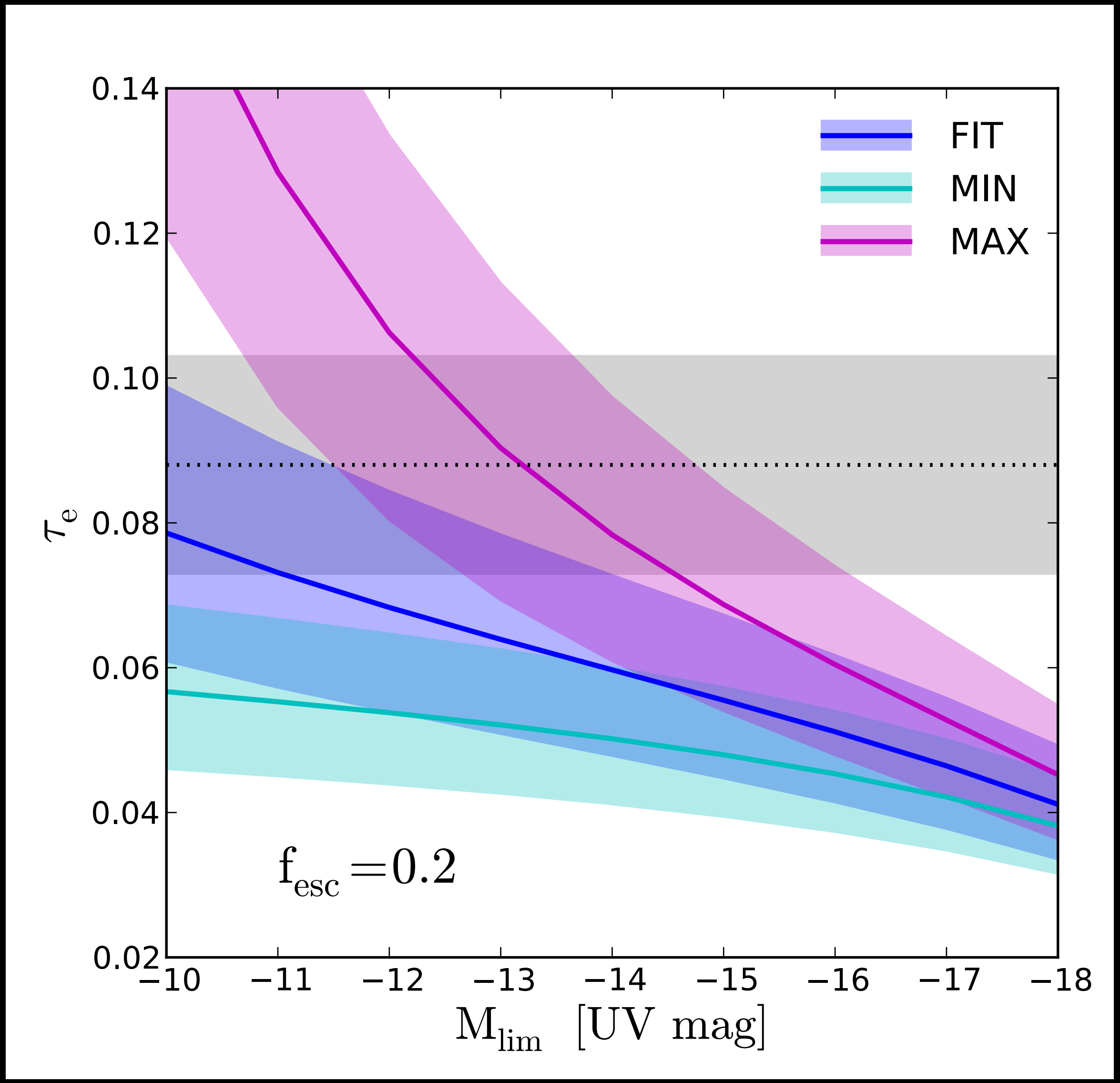
Thomson optical depth is
0.055 ↔ 0.061 ↔ 0.070

Fall short of WMAP constraints!

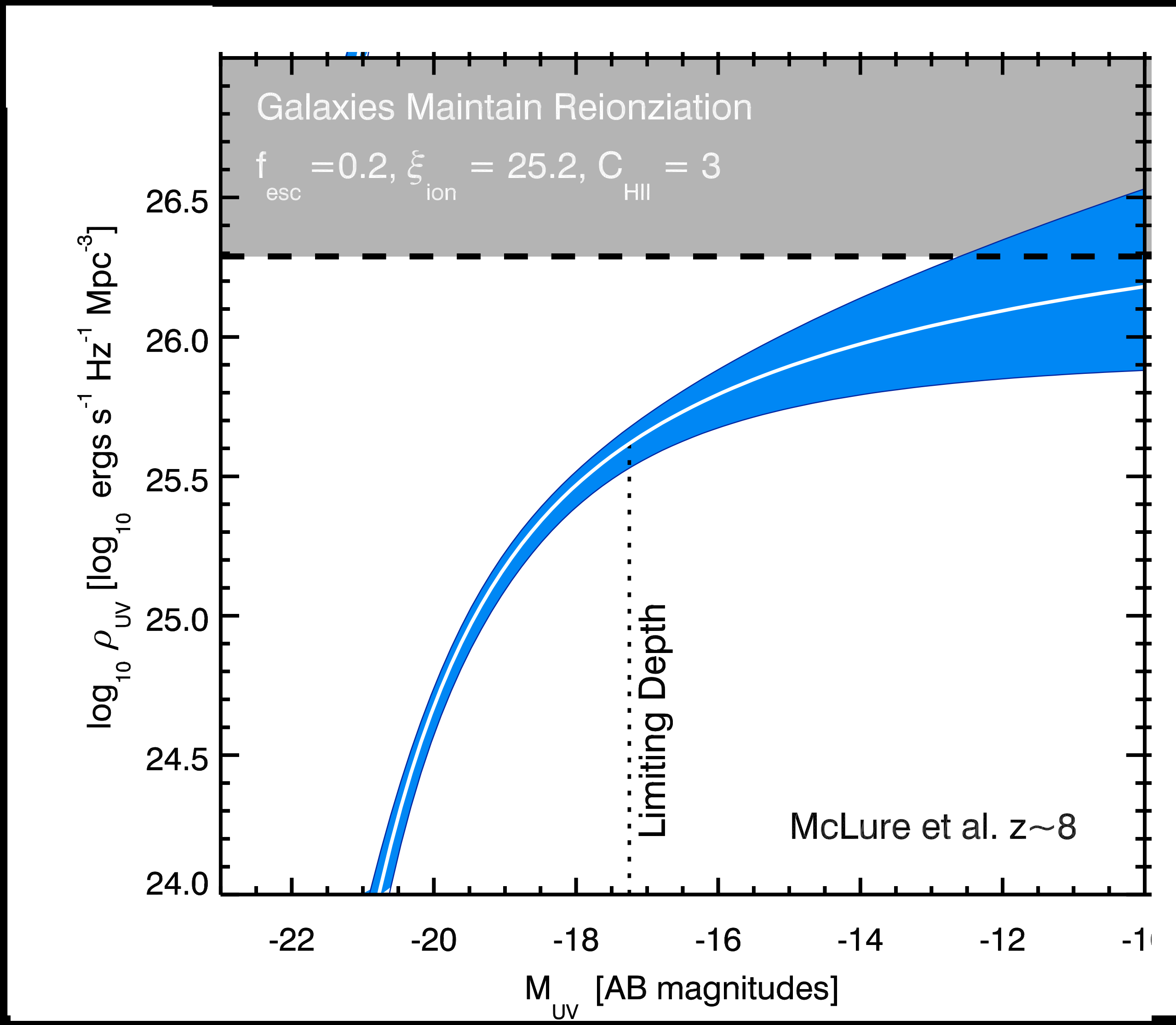
Bouwens et al. 2012; Kuhlen et al. 2013; see also Robertson et al. 2013

Evolution of faint-end slope -- which give us the volume density of ultra-faint galaxies -- is important to establish to better constrain the contribution of galaxies to reionization

One needs to include the contribution from galaxies to -13 or even -11 mag to keep universe largely reionized out to z>~8!



Kuhlen et al. 2012



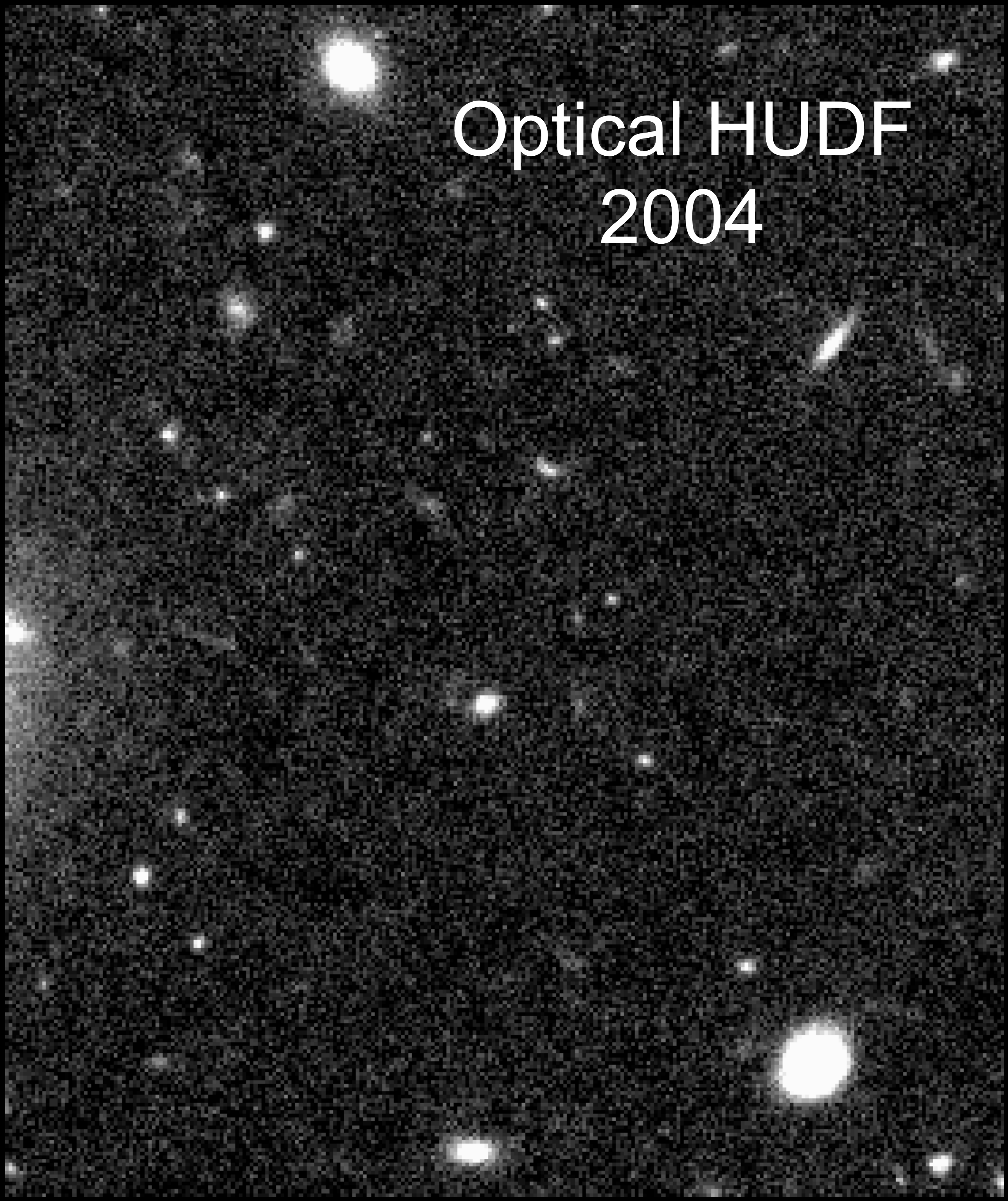
Robertson et al. 2013

Are you familiar with the Hubble Ultra Deep Field released in 2004?

lots of additional data have been taken over this region which allow us to probe deeper than before...

New (and Deeper) Reduction of All the Data over the HUDF region is now publicly available.

Including all the optical data ever taken over the HUDF region, the “XDF” optical reduction offers a 0.2 mag gain over the original HUDF...



Illingworth et al. 2013

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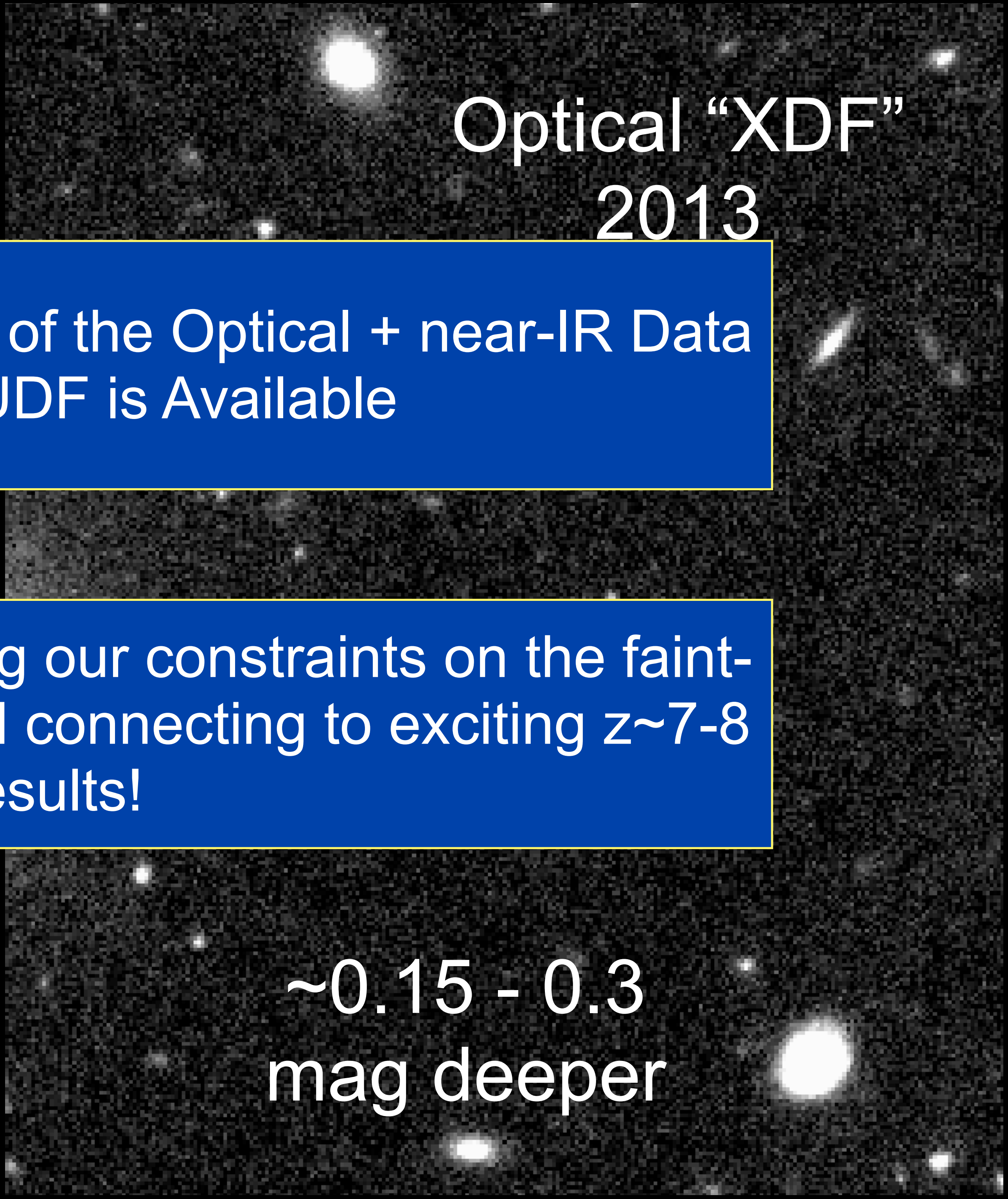
0.2 m
original HUDF...



Deeper Public Reduction of the Optical + near-IR Data over the HUDF is Available

Will be useful to improving our constraints on the faint-end slope at z~4-6... and connecting to exciting z~7-8 results!

Illingworth et al. 2013

What Current Observations Can Teach Us About the Properties of Galaxies in the Early Universe

Determining Stellar Masses of z~5-7 galaxies is challenging, given the challenge in distinguishing rest-frame optical stellar continuum light from nebular line emission

We can hope to measure true stellar masses by looking at galaxies in redshift windows uncontaminated by nebular emission lines. One such window is at z~6.8.

We have selected a sample of 7 bright, magnified galaxies at z~6.8 in such a window. A large fraction of such sources are very bright at 3.6 microns -- where we expect a contribution from the OIII line -- but faint at 4.5 microns where we expect only a contribution from the stellar continuum.

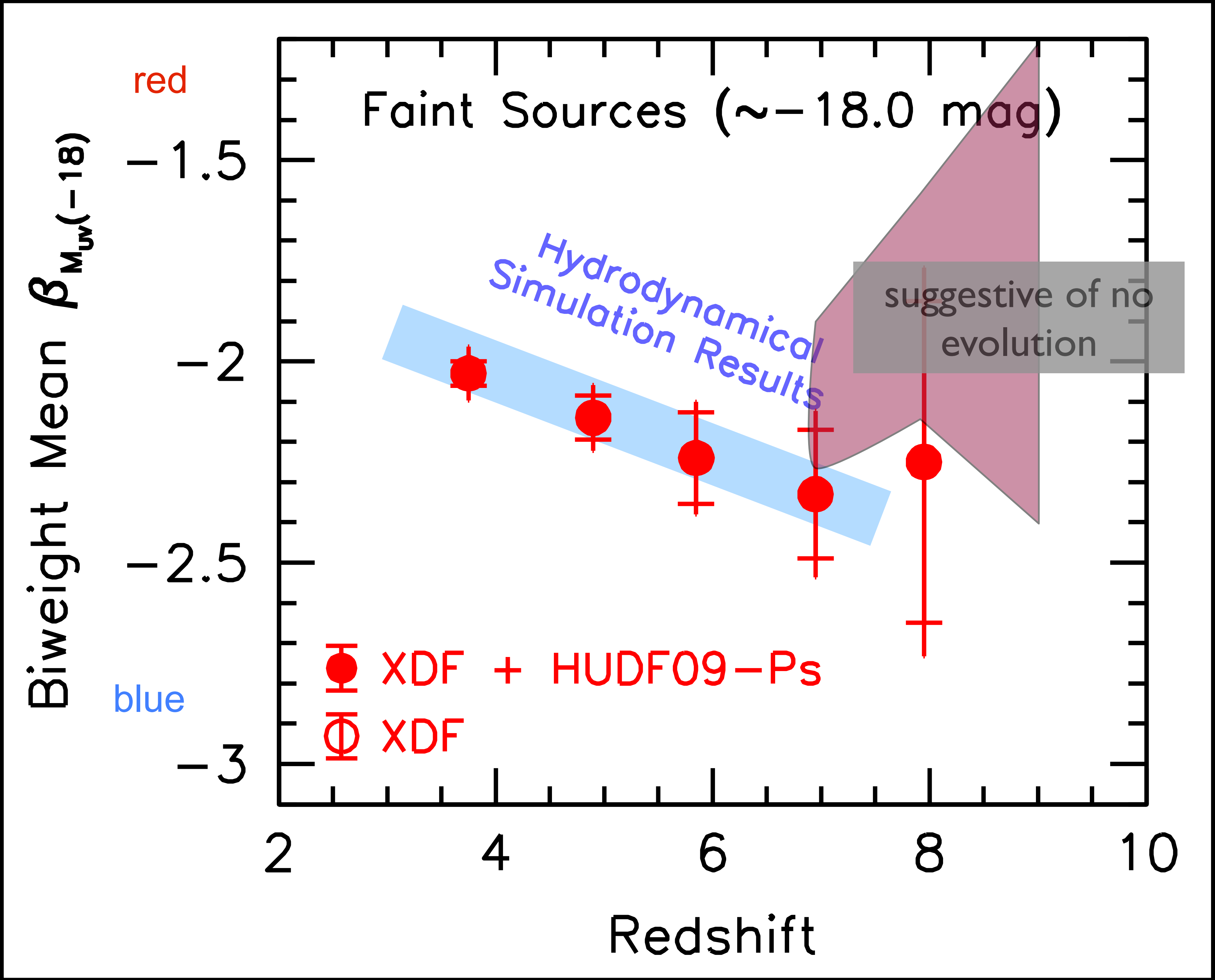
The implication is that the stellar masses in galaxies at z~7 are low and the specific star formation rates at z~7 are very high. This provides direct evidence for high sSFRs at z~7 using a sample of galaxies.

Similar UV-continuum slope vs. luminosity relationships found for galaxies at z~4-7. At higher luminosities, the slopes depend very sensitively on luminosity (likely due to changes in the dust extinction). At lower luminosities, the slopes/colors depend much less sensitively on luminosity (likely because dust not so important).

The total flux density in ionizing photons is very sensitive to the faint-end slope. If the faint-end slope of the UV LF at z~6-8 continues to steepen towards high redshift, it may help in reionizing the universe.

A new, deeper reduction of optical + near-IR data over the HUDF region exists which take advantage of all data taken over past 10 years. It should be useful for improving our constraints on faint-end slope at z~4-6...

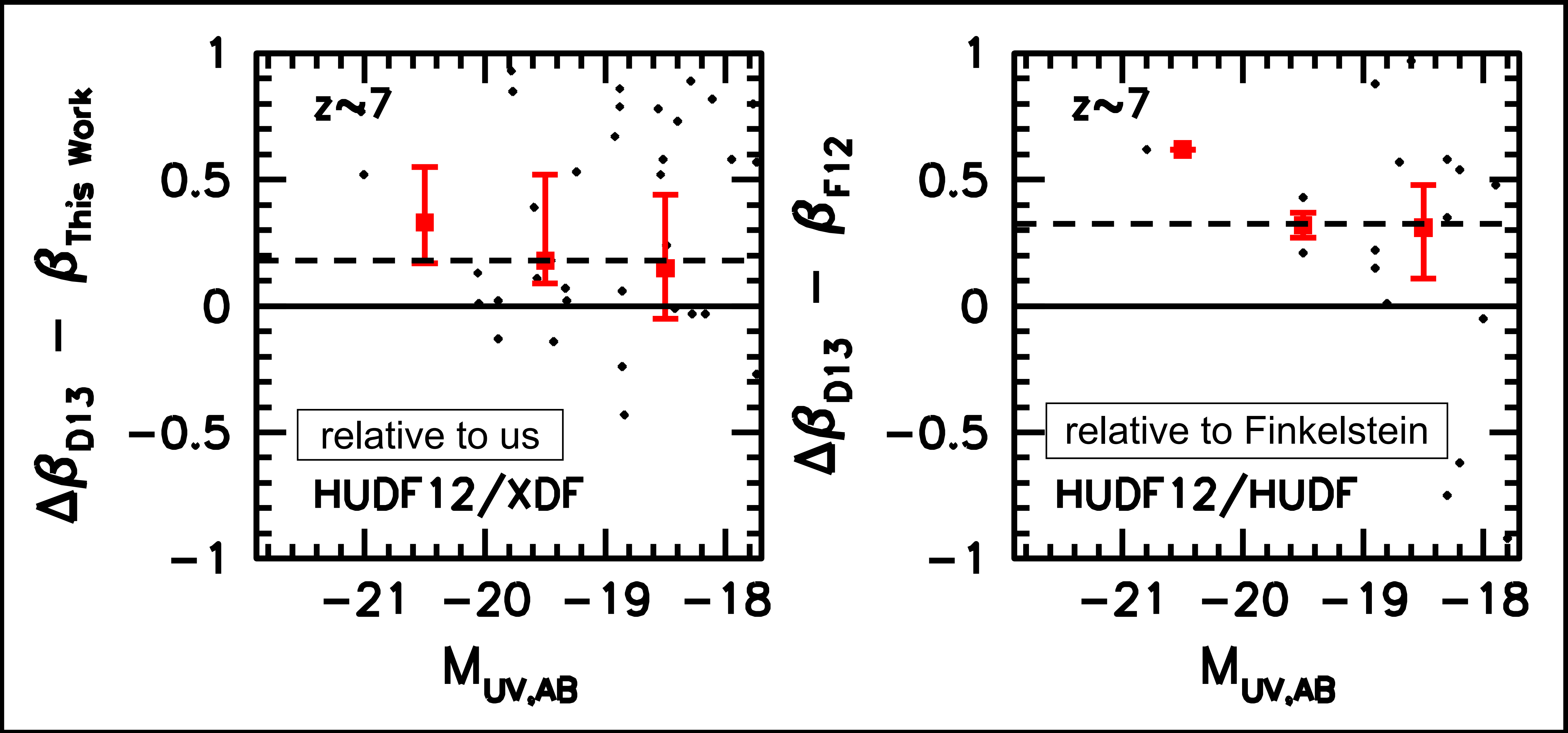
Do the present results significantly differ from what was obtained in Dunlop et al. 2012?



Bouwens et al. 2013; see also Bouwens et al. 2012; Finkelstein et al. 2012

What efforts were made to quantify possible biases in the Dunlop et al. 2013 study?

Dunlop et al. 2013: Too red by >~0.13



3% systematic error in color measurements

Bouwens et al. 2013

What efforts were made to quantify possible biases in the Dunlop et al. 2013 study?

Why would Dunlop et al. suffer from a bias in the measured colors?

Dunlop et al. use filter-dependent fixed apertures to measure colors

0.40”, 0.44”, 0.47”, 0.50” for the F105W, F125W, F140W, F160W

The color measurements should be perfect for point sources.

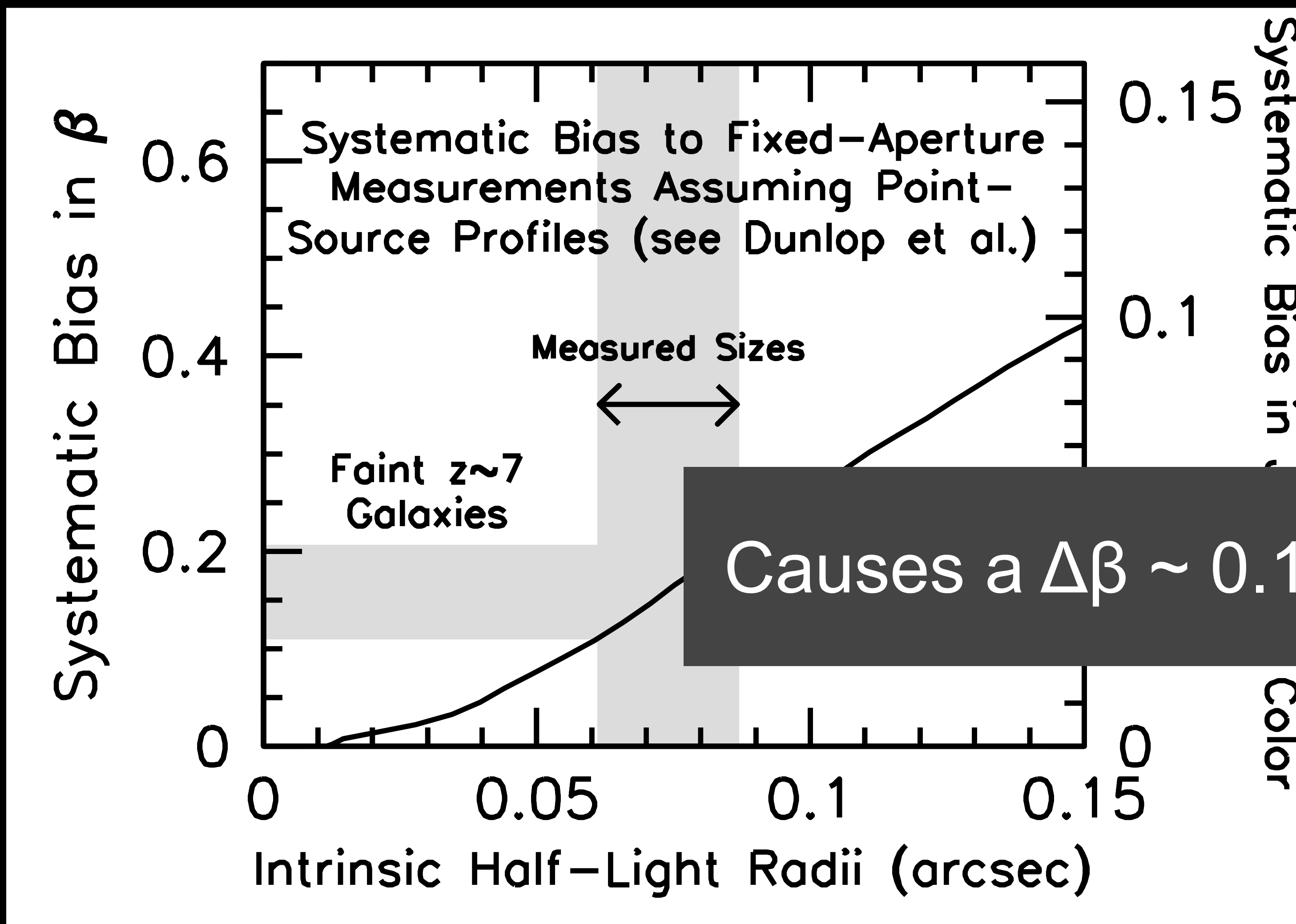
However, z~7-8 galaxies are not point sources.

Faint z~7-8 galaxies (while small) have non-zero size.

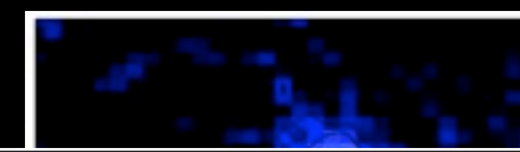
Bouwens et al. 2013

What efforts were made to quantify possible biases in the Dunlop et al. 2013 study?

How large of bias would we expect for the typical faint source?



For a large z~7 source:



Obviously this is an extreme example, but it …trates the point

Causes a Δβ ~ 0.13 bias.

Dunlop β = −1.40

vs.

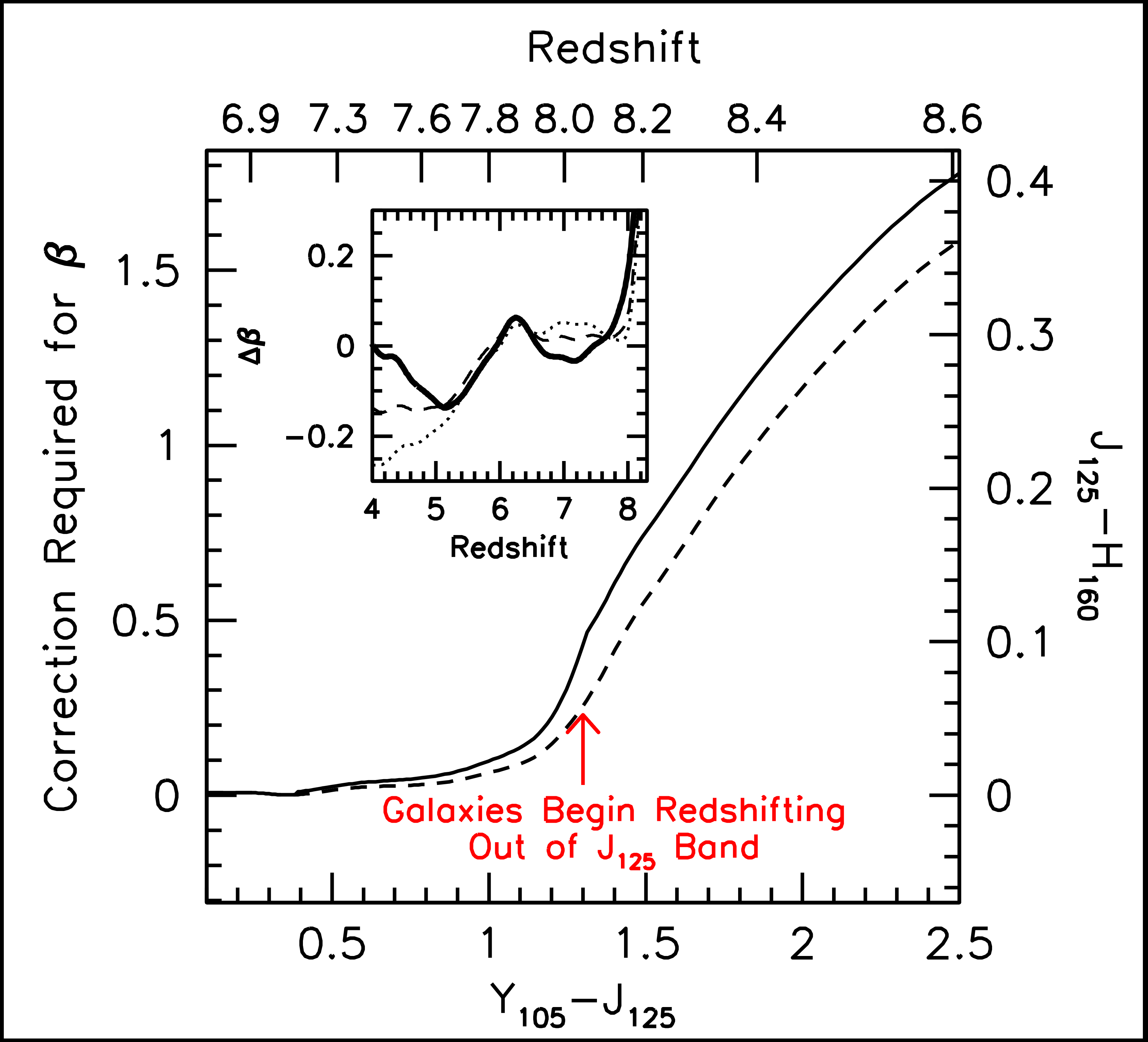
Bouwens β = −2.02

Finkelstein β = −2.17

The predicted bias is similar to the offset relative to our own results

Bouwens et al. 2013

What other biases are present at z~8 in the Dunlop et al. 2013 results?



Expect attenuation in the J_{125}-band fluxes for z>~8 galaxies due to attenuation from the IGM. Causes a $\Delta\beta$ ~ 0.1 bias.