Build-up of Galaxies in the First 3 Gyr of Universe:

- How Fast Do Galaxies Grow: SFR Functions
- How Do Galaxies Grow: Self-Similar Color-Mag Sequences
- Can Growing Galaxies Reionize the Universe?

Rychard Bouwens
(Leiden University / Leiden Observatory)

thanks also to HUDF09 team: Garth Illingworth, Pascal Oesch, Ivo Labbe, Marijn Franx, Michele Trenti, Pieter van Dokkum, Renske Smit, ...

Santa Cruz Galaxy Formation Meeting
August 13, 2012 (Santa Cruz, California)

High-Redshift Galaxies: Current Questions

Wide Variety of Questions we can try to answer with these Data...

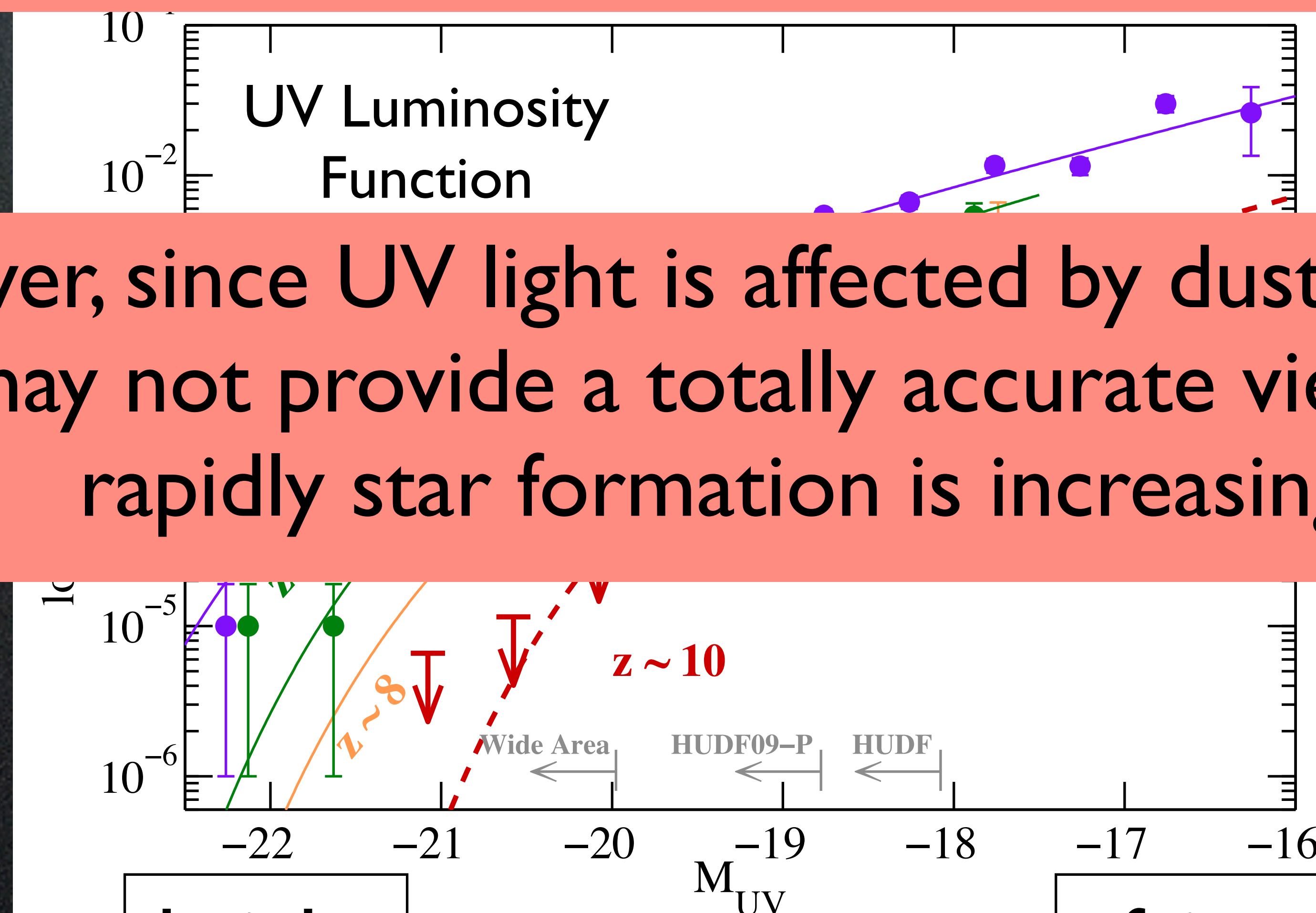
One of the most interesting topics to study is galaxy growth.

Since the halos of L* and sub-L* galaxies assemble from z~30 to z~3... the growth of galaxies themselves is expected to be profound.

High-Redshift Galaxies: Galaxy Growth

In previous meetings, I have advocated quantifying the growth of galaxies in terms of the luminosity function in the ultraviolet

This is useful since it provides a measure of how rapidly the galaxy population is forming stars at a given redshift



Vo

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However, since UV light is affected by dust extinction, this may not provide a totally accurate view of how rapidly star formation is increasing...

bright

faint

UV Luminosity

Oesch et al. 2011; Bouwens et al. 2007, 2011

High-Redshift Galaxies: Galaxy Growth

To study the growth of the SFR in the galaxy population in a more physical manner, we want to apply a dust correction to the UV LFs...

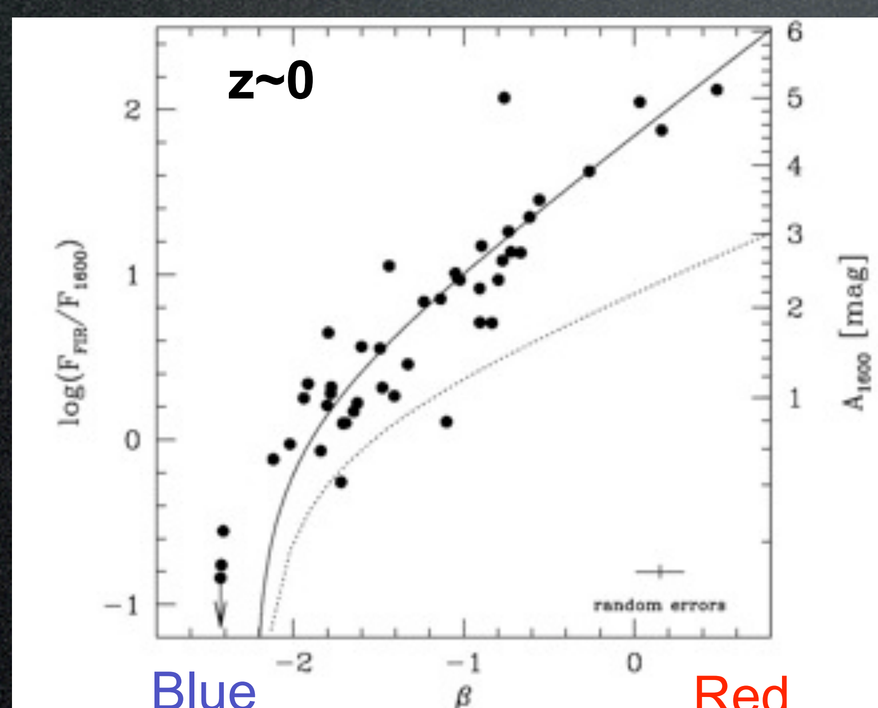
Fortunately, we can now estimate dust corrections at z>3 using the IRX-beta relationship and the UV colors of galaxies.

Correction Factor (Meurer, Heckman, and Calzetti 1999)

Most Light Absorbed By Dust

Infrared Light / UV Light

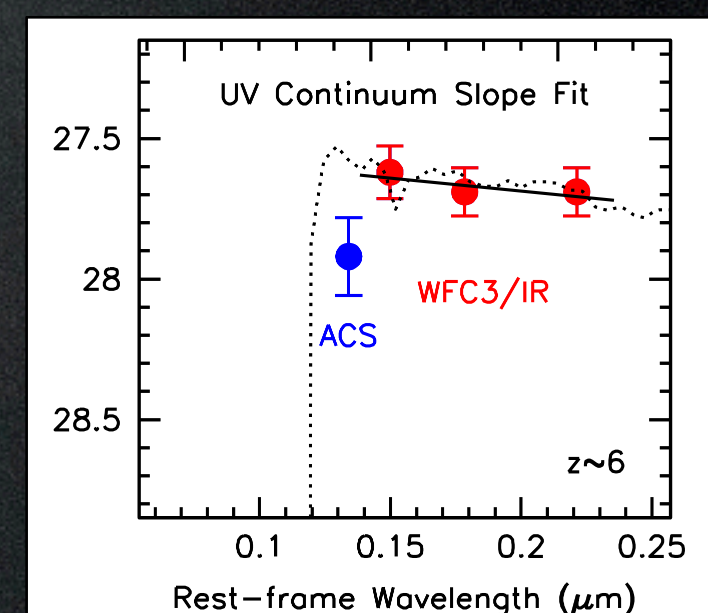
Most Light Escapes Without Absorption



UV continuum slope (β)

+

UV colors of z~4 galaxies in the new WFC3/IR data



High-Redshift Galaxies: Galaxy Growth

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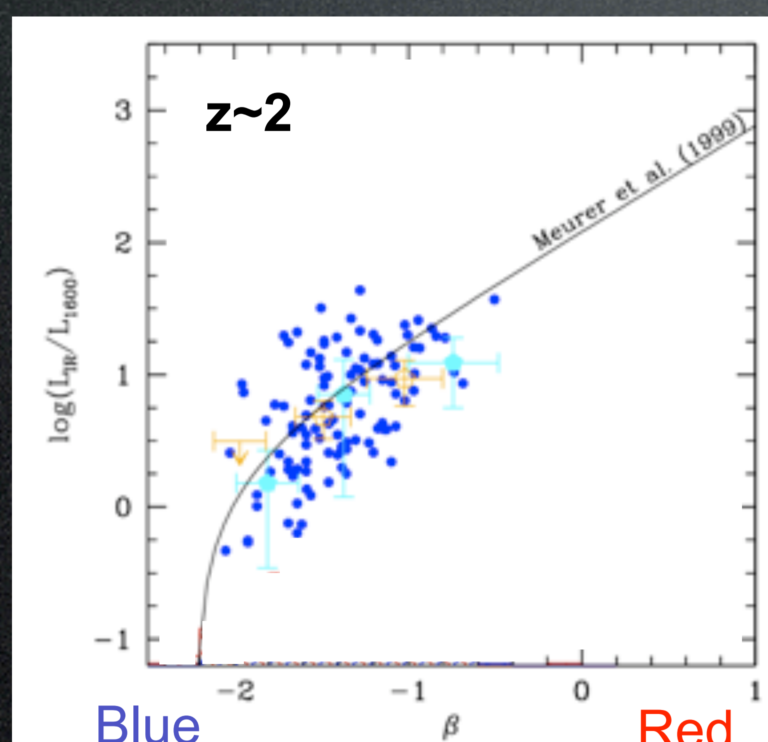

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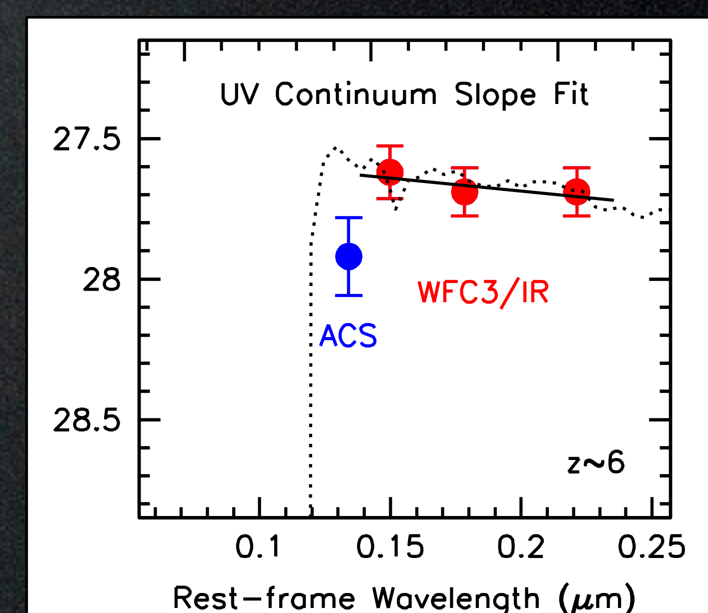

High-Redshift Galaxies: Galaxy Growth

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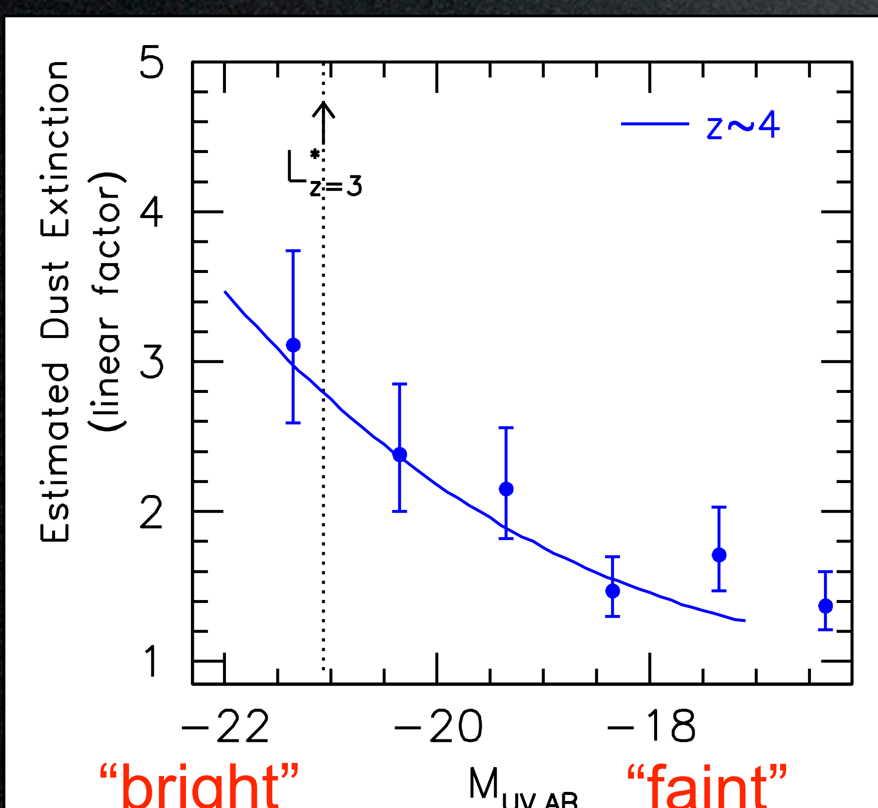
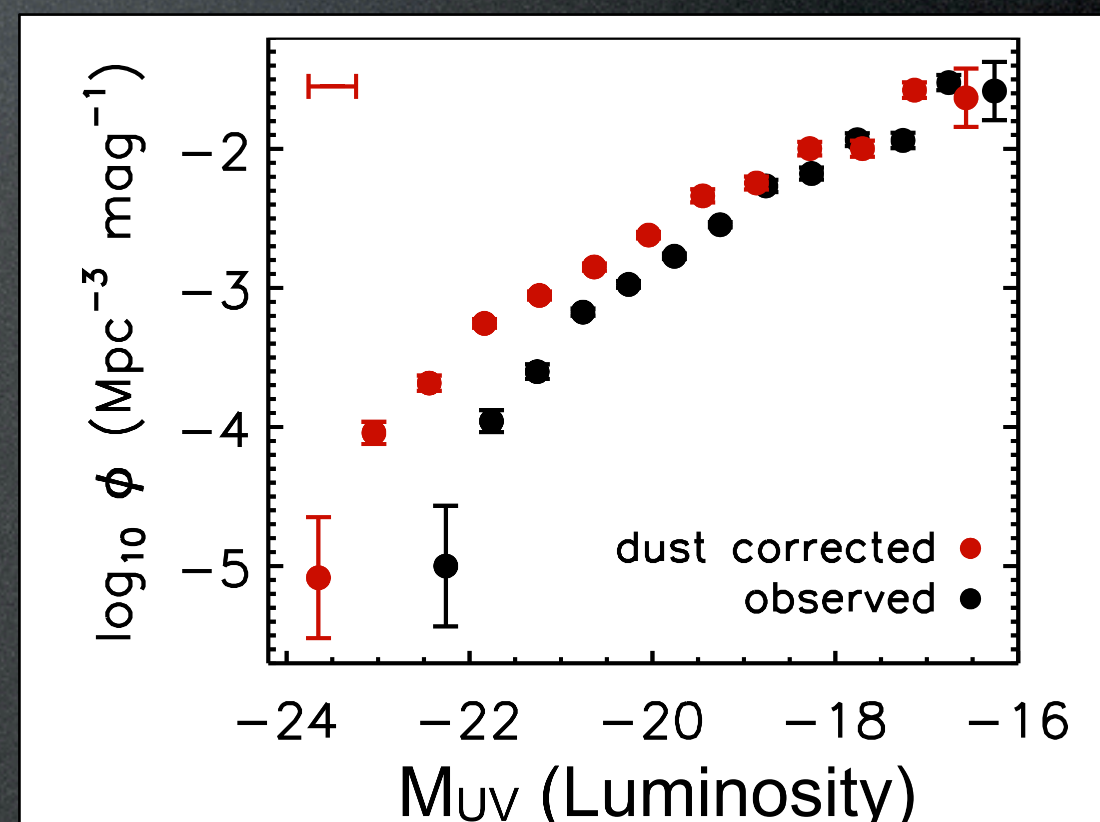
Dust Correction



Example: Dust-correcting the UV LF at z~4

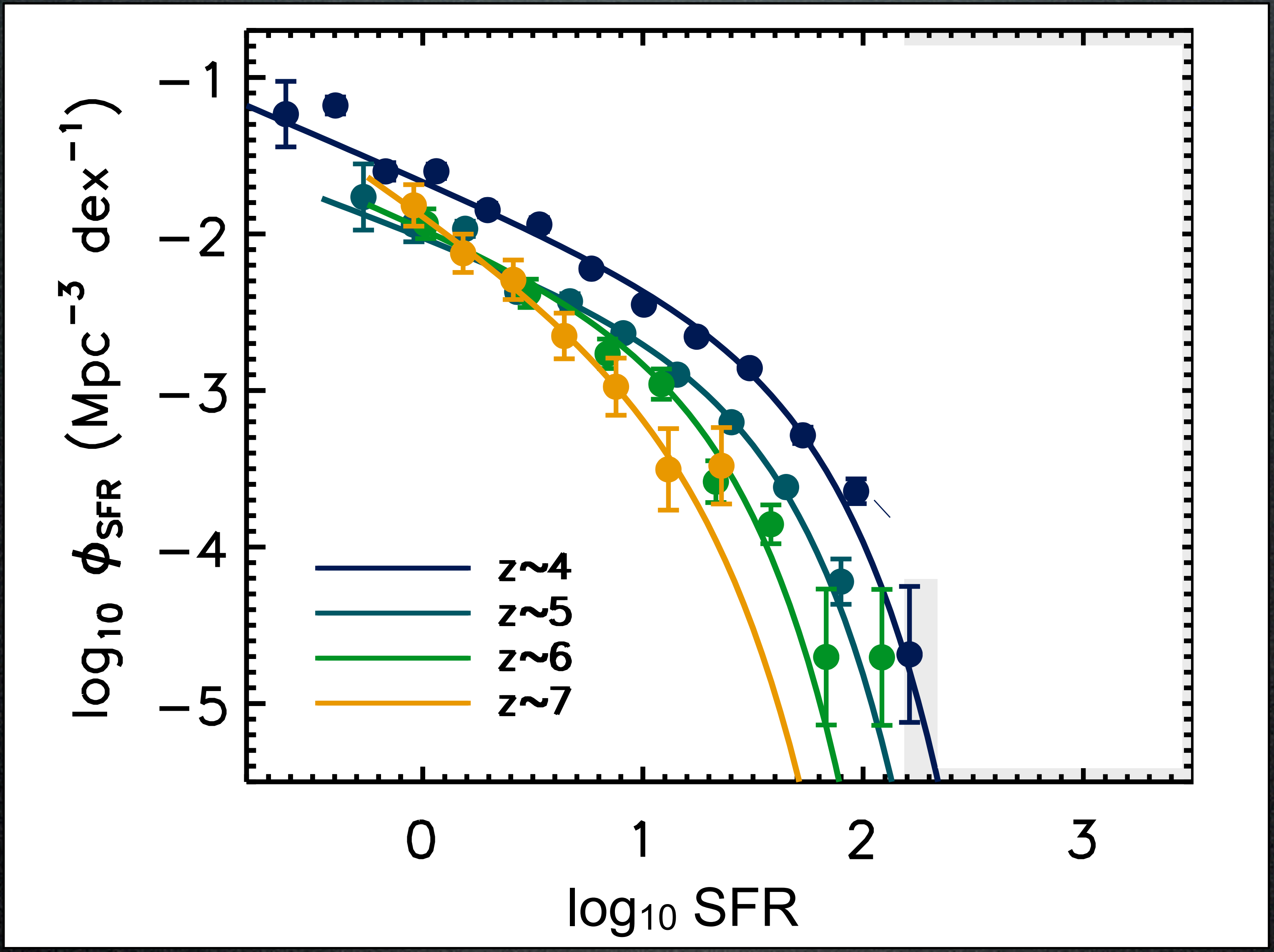


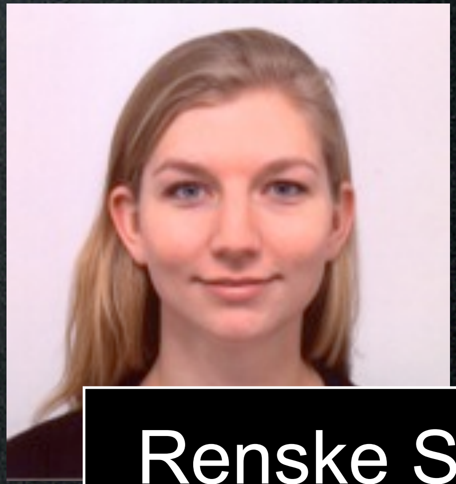
High-Redshift Galaxies: Galaxy Growth

What do the SFR function results look like?

SFR functions at z~4-7

Volume Density





Renske Smit

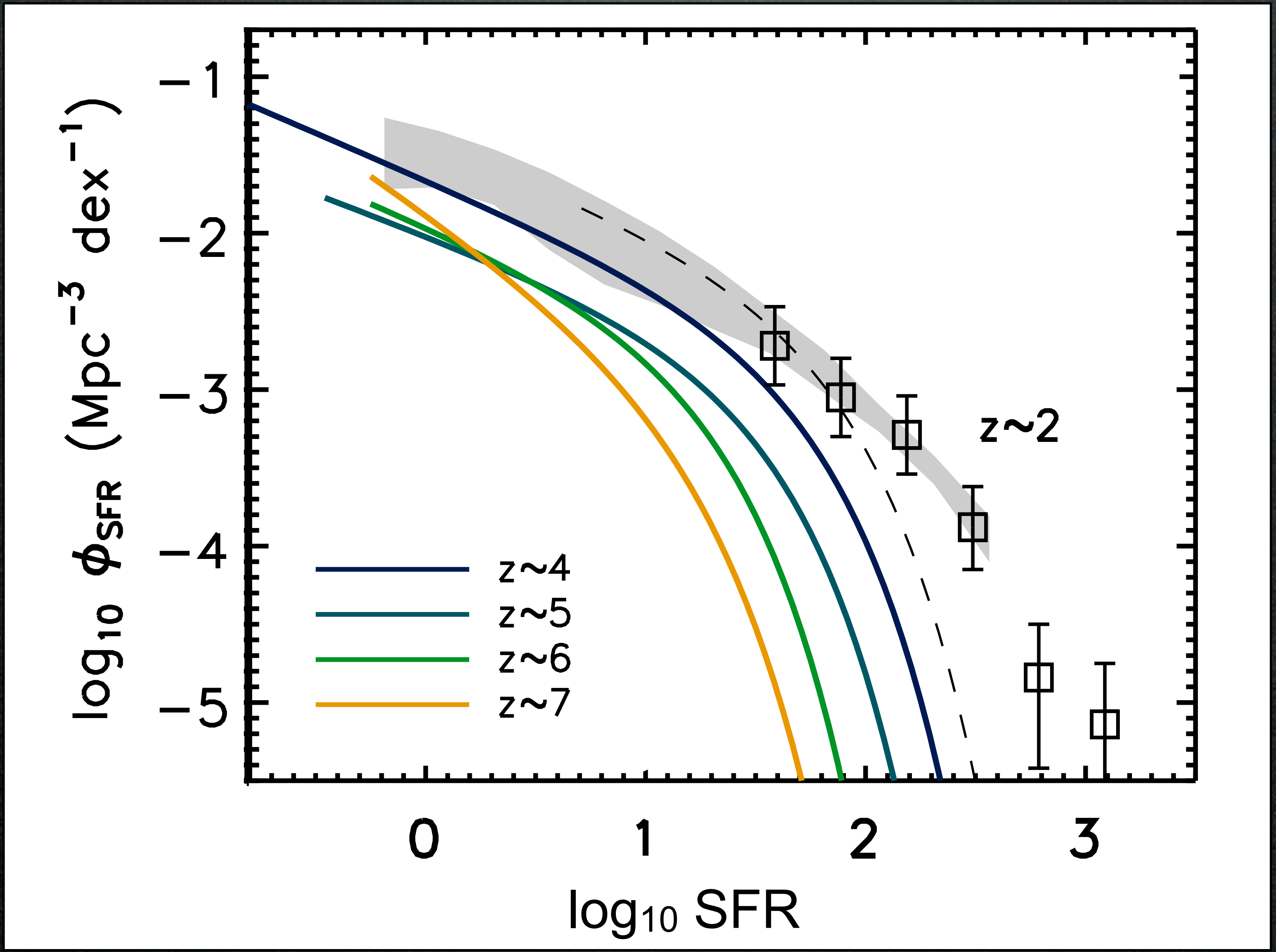
Smit et al. (2012)

High-Redshift Galaxies: Galaxy Growth

What do the SFR function results look like?

SFR functions at z~2-7

Volume Density



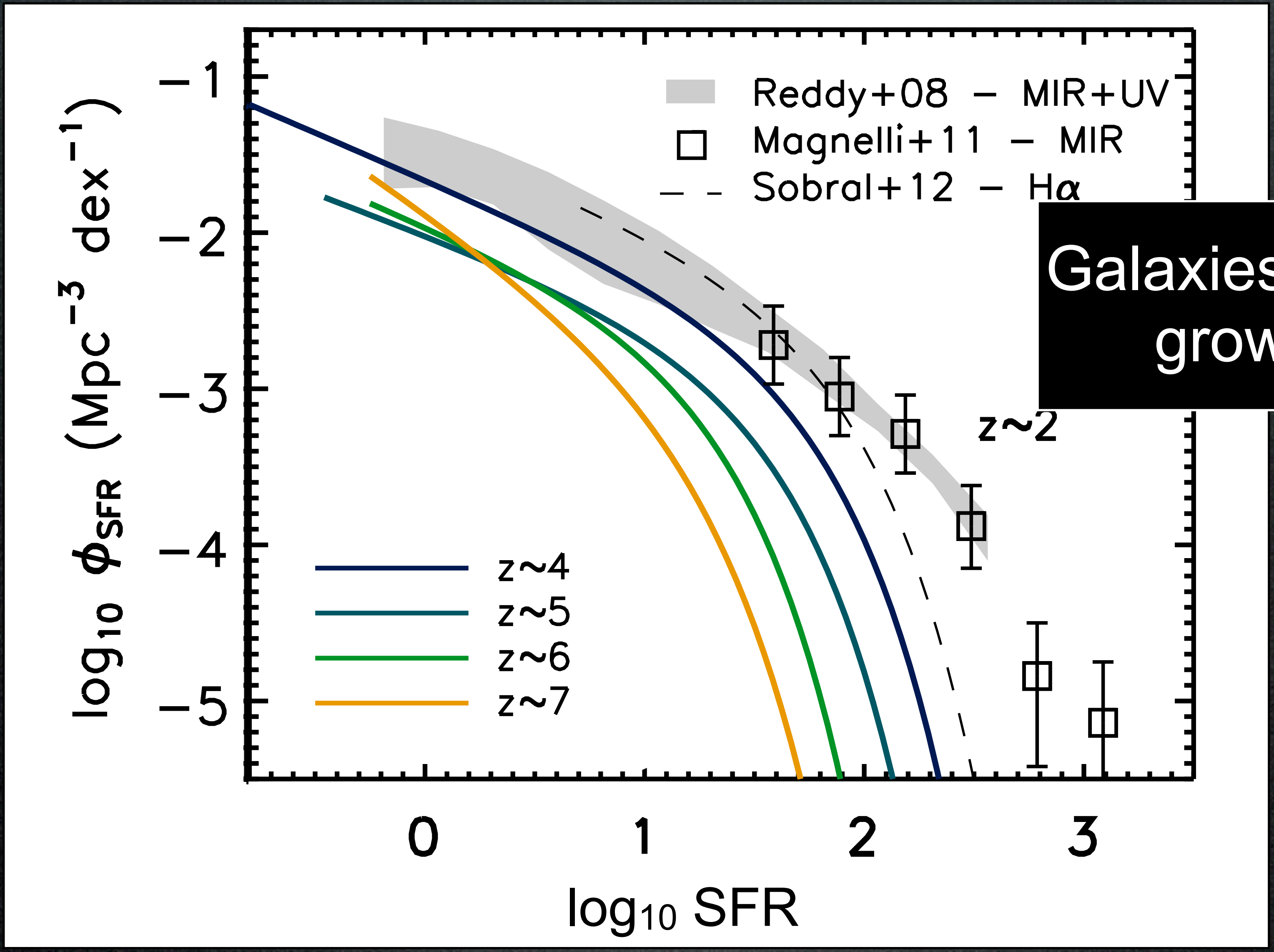
Smit et al. (2012)

High-Redshift Galaxies: Galaxy Growth

What do the SFR function results look like?

SFR functions at z~2-7

Volume Density



Galaxies seem to continue to grow from z~4 to z~2

By looking at SFR functions (dust-corrected LFs), we can see this growth

Smit et al. (2012)

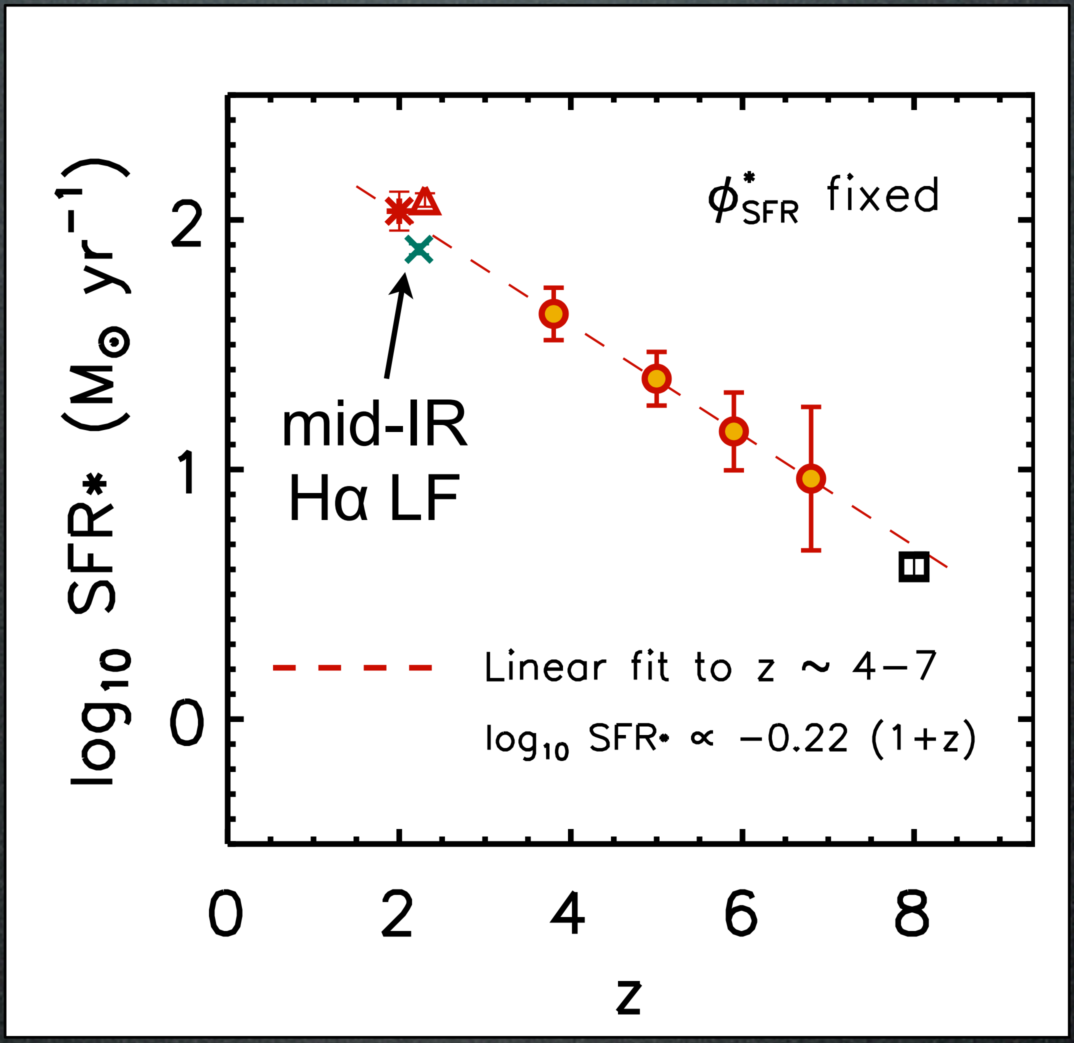
High-Redshift Galaxies: Galaxy Growth

What do the SFR function results look like?

SFR function Results at z~2-7

Characteristic Star Formation Rate

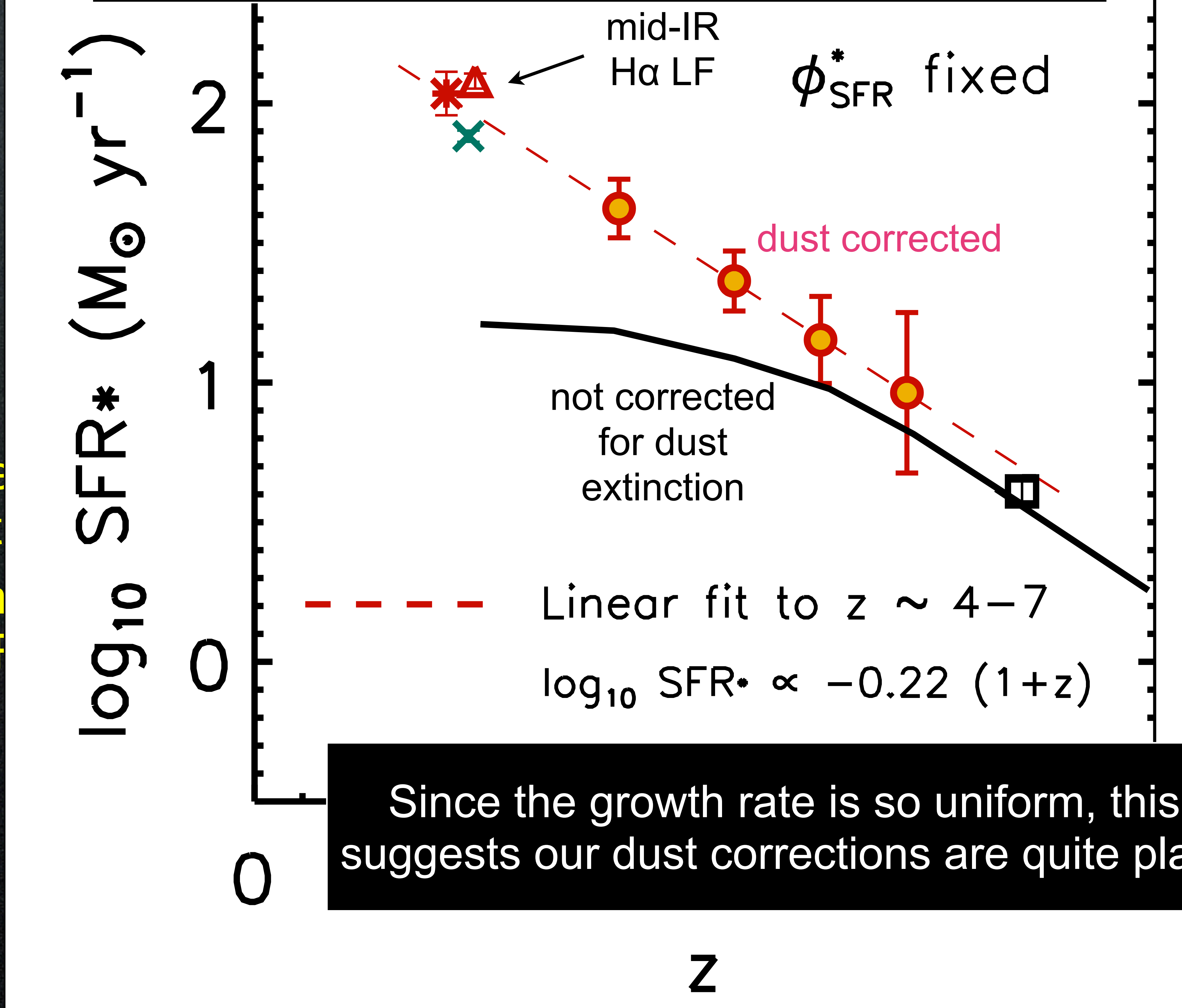
(~ maximum typical SFR)



SFR* assumes Schechter form for SFR function

Smit et al. (2012)

Using the SFR function, we find evidence for very uniform build-up of galaxies from z~8 to z~2...



Since the growth rate is so uniform, this also suggests our dust corrections are quite plausible.

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SF

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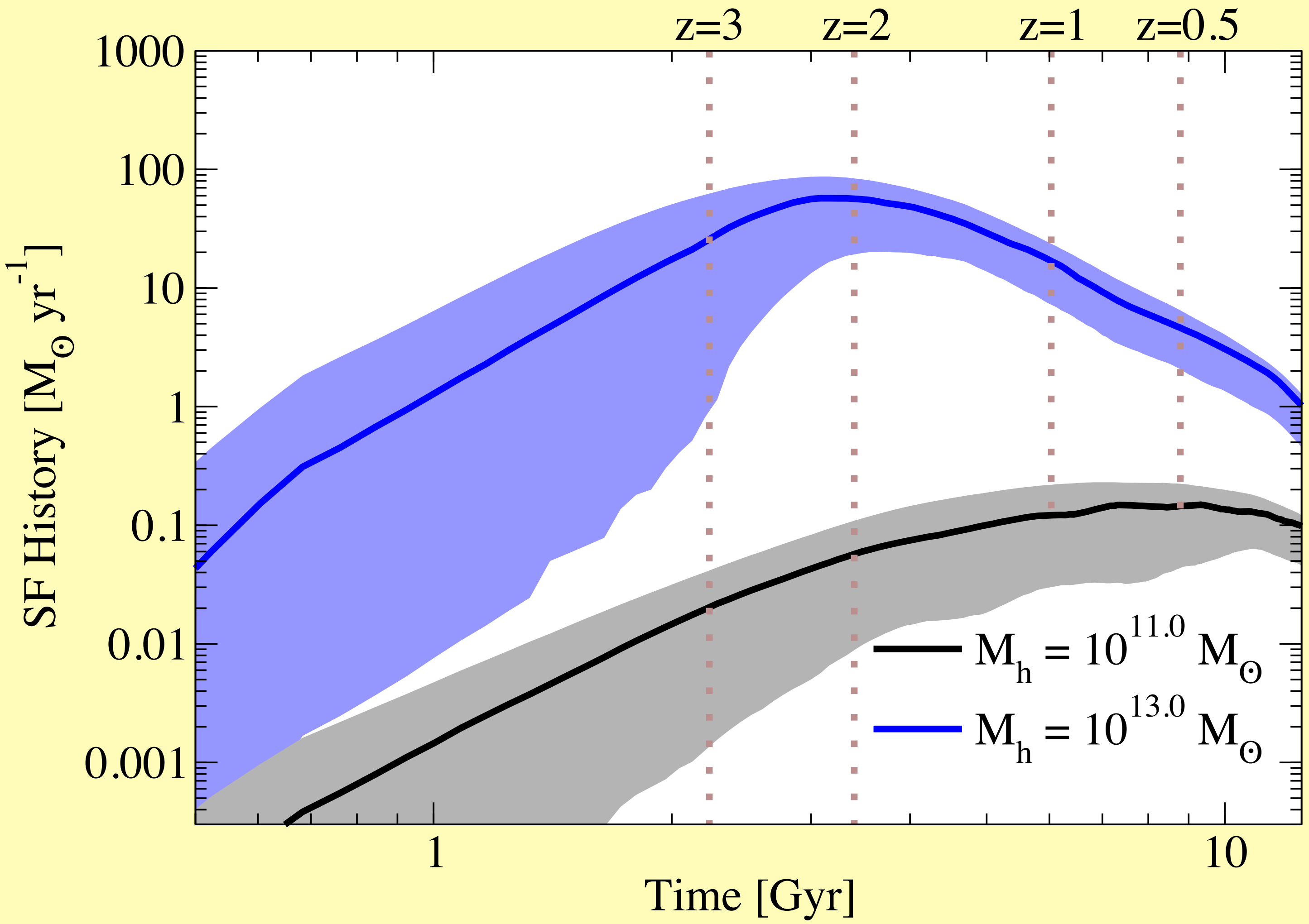
function

Smit et al. (2012)

High-Redshift Galaxies: Galaxy Growth

What d

Similar results on SF histories are being obtained in detailed theoretical modeling (Behroozi et al. 2012), from detailed HOD modelling...



Characteristic Sta
Formation Rate
(~ maximum typic
SFR)

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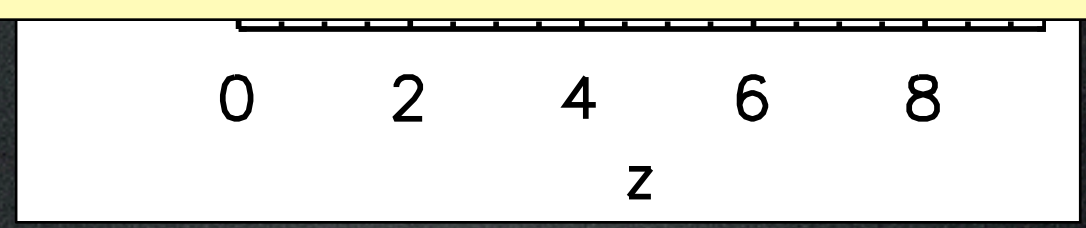


Smit et al. (2012)

High-Redshift Galaxies: Galaxy Growth

Besides the SFR function, we can also study the growth of the galaxy population by looking at the galaxy stellar mass function and UV LFs (see Pascal's talk)...

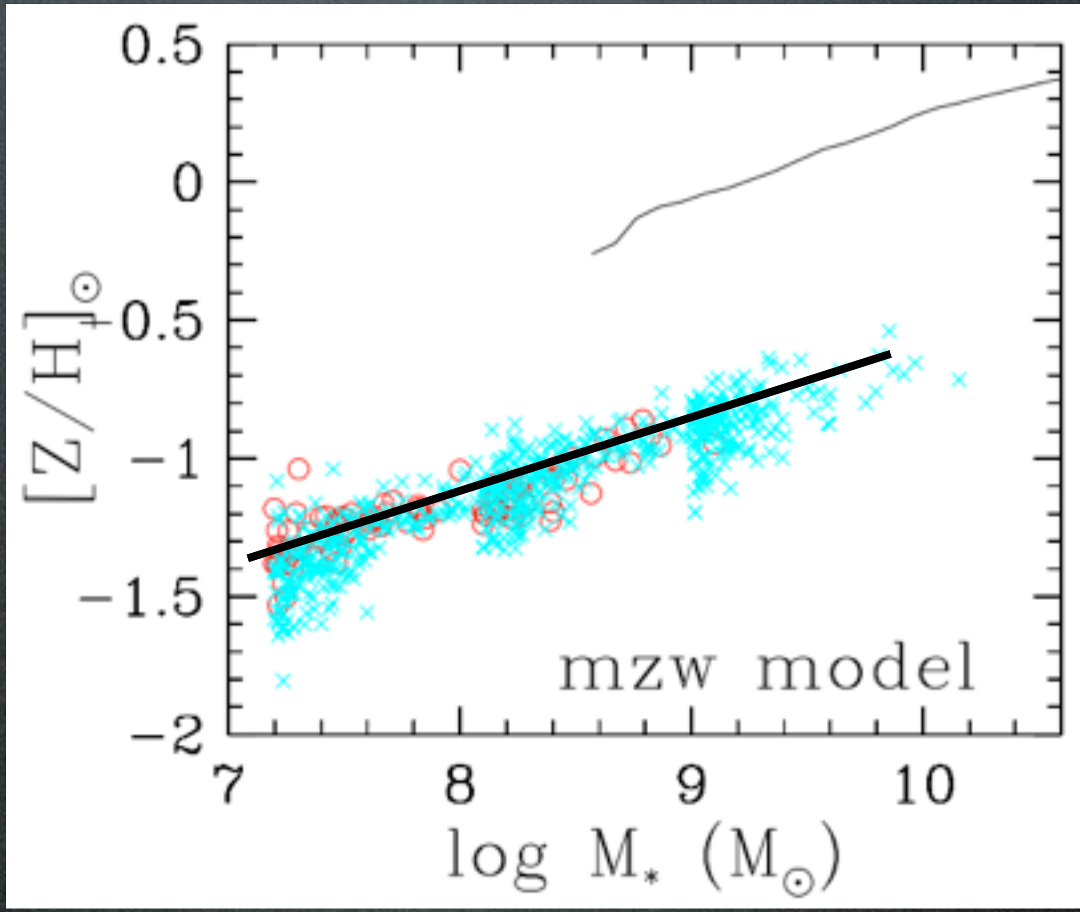
While we see clear evidence that galaxies grow with cosmic time, one might reasonably ask how they grow.

Do galaxies grow smoothly with cosmic time or do they grow through a smaller number of large starbursts?

High-Redshift Galaxies: Galaxy Growth

Theoretically, a tight relationship between galaxy properties and galaxy mass/luminosity is expected

Metallicity



Stellar Mass

Dave et al. 2006; but see also Nagamine et al.; Dayal et al.

High-Redshift Galaxies: Galaxy Growth

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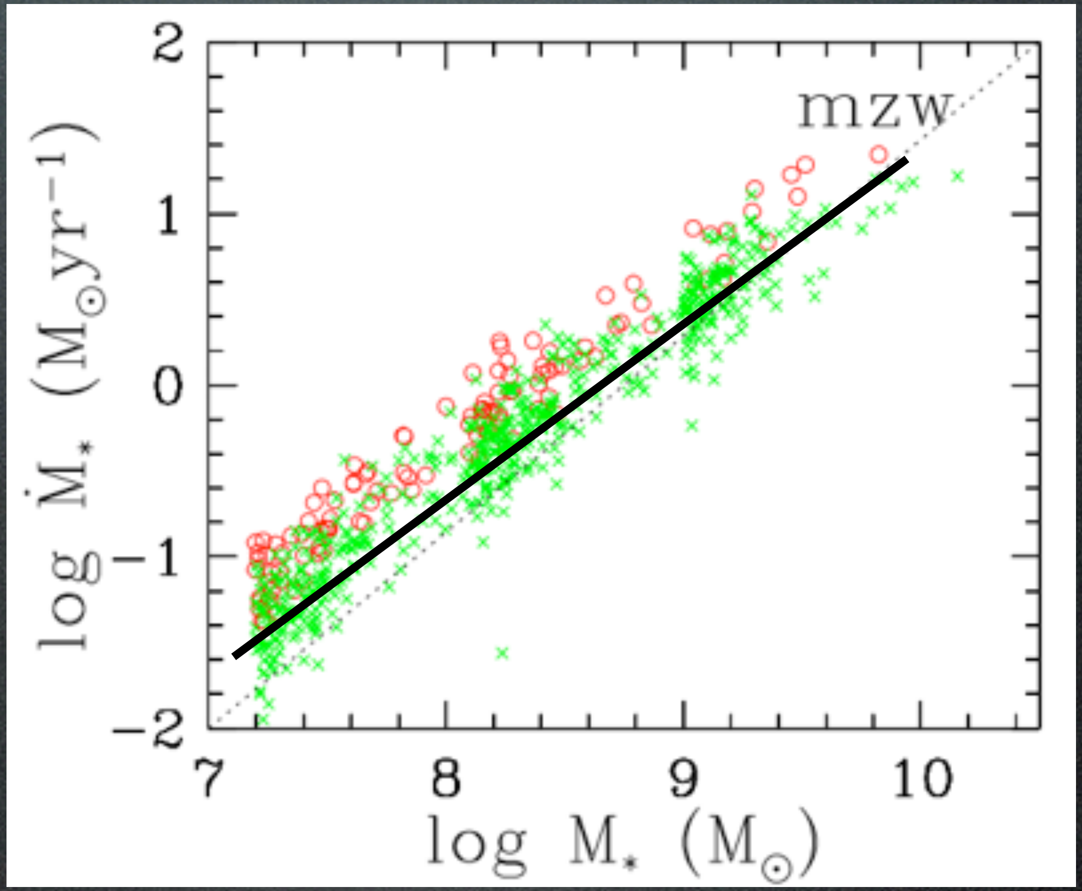
Star Formation Rate



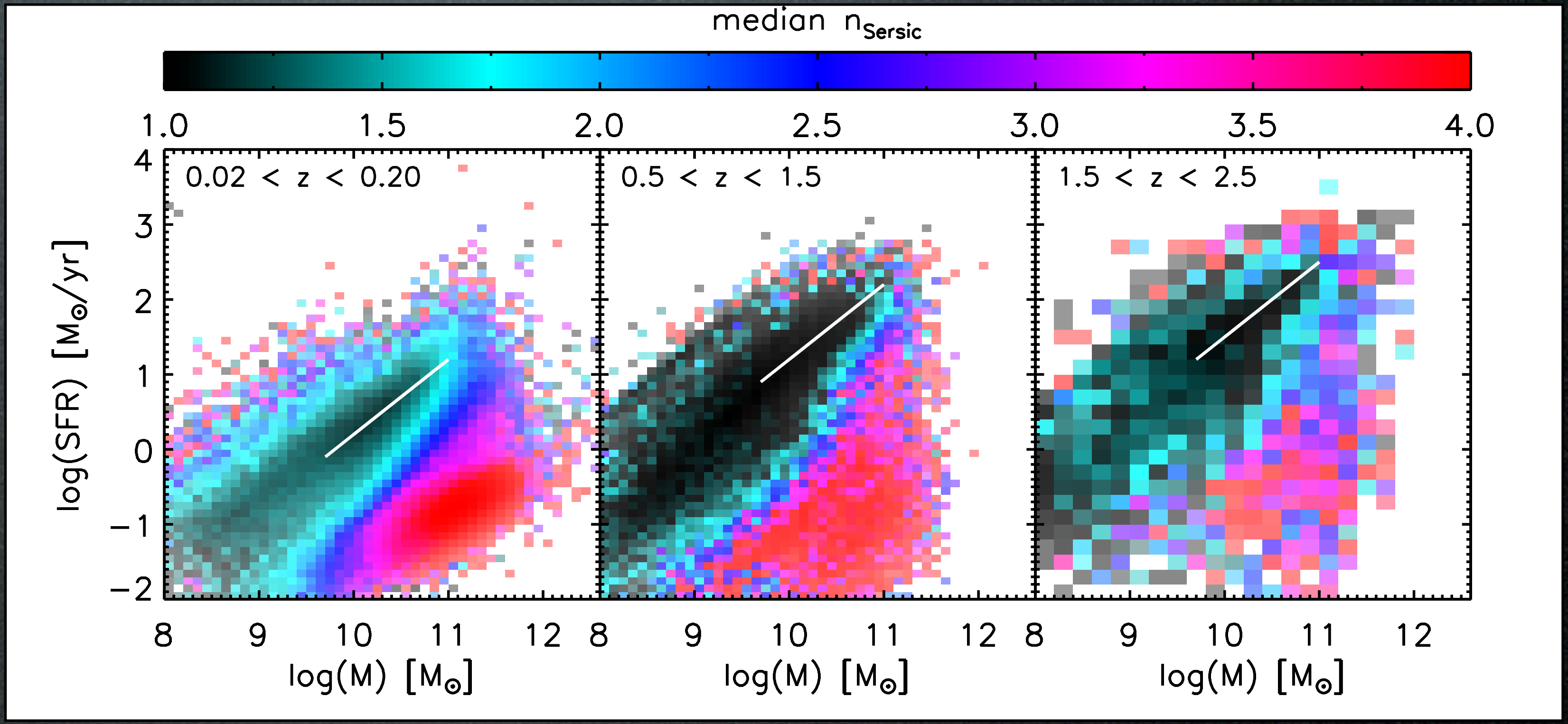
Stellar Mass

Dave et al. 2006; but see also Nagamine et al.; Dayal et al.

High-Redshift Galaxies: Galaxy Growth

Such a tight relationship between galaxy properties and galaxy mass/luminosity also observed at low redshift

Star Formation Rate



Stellar Mass

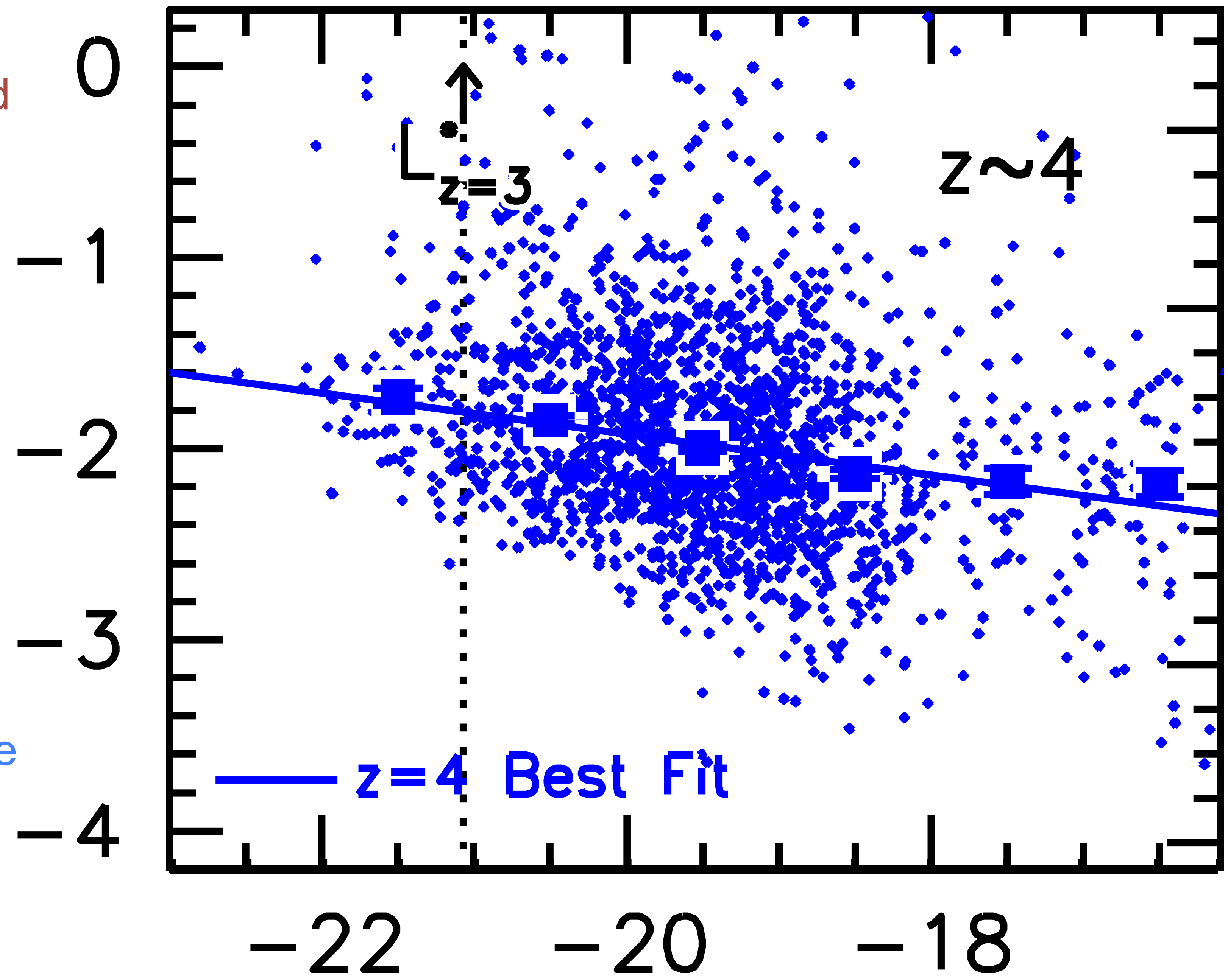
Wuyt et al. 2011

Do we find a similarly tight relationship between observables as a function of mass? (results from Bouwens et al. 2011)

UV continuum slope β
("color")

red

blue



"bright"

"faint"

M_{UV} (Luminosity)

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

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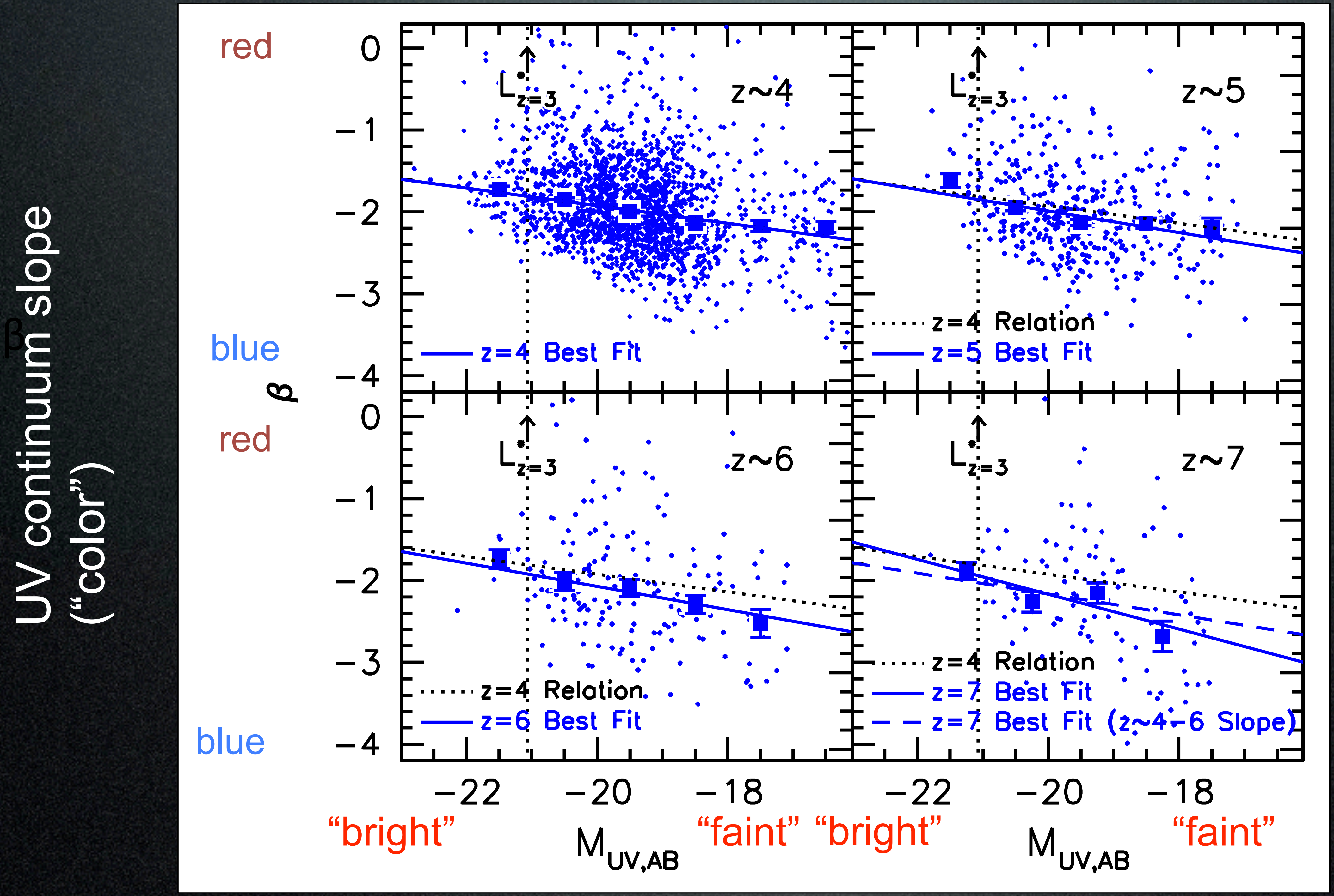
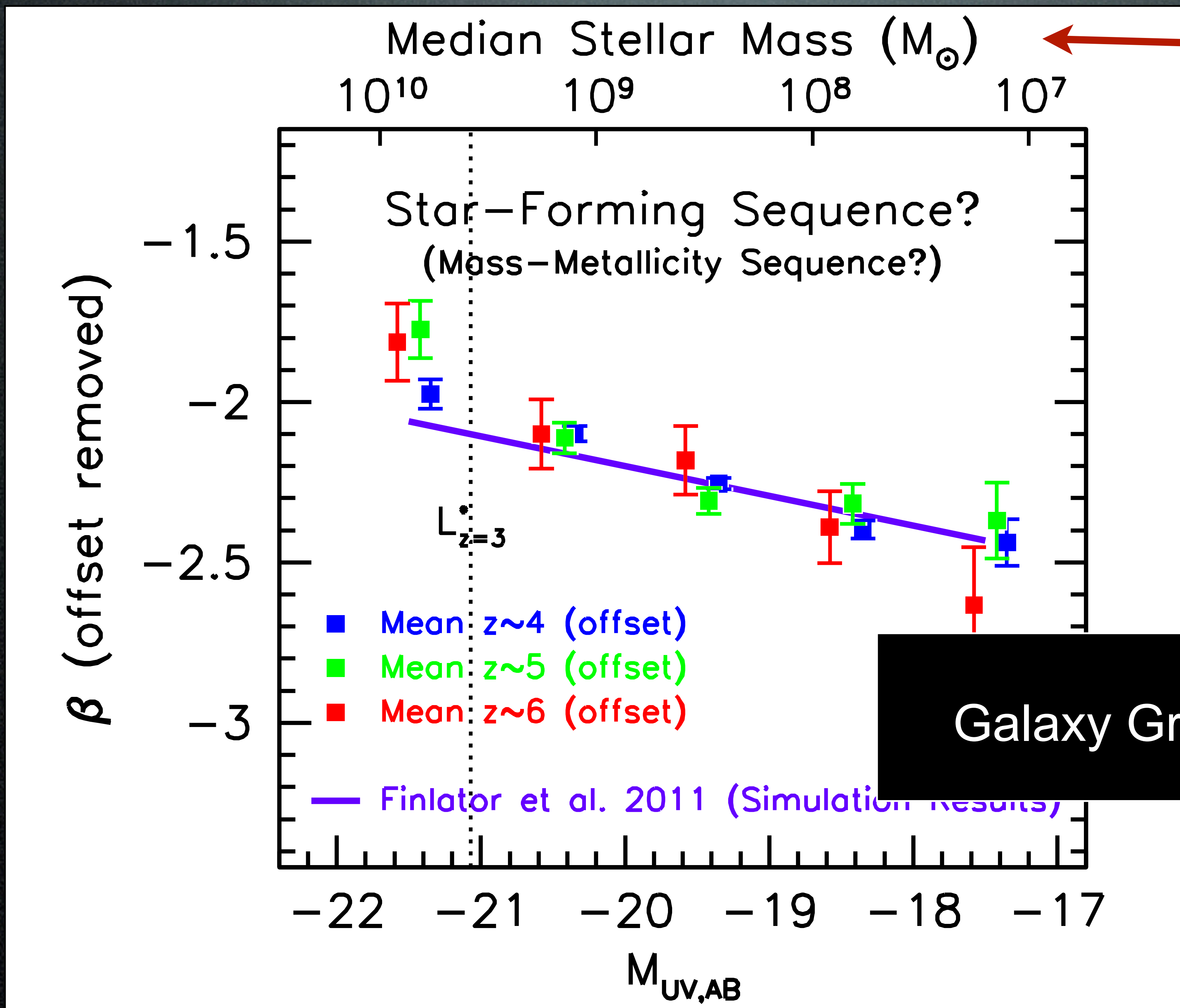


Bouwens et al. 2012; see also Bouwens et al. 2009, 2010; Wilkins et al. 2011; Dunlop et al. 2012

Do we find a similarly tight relationship between observables as a function of mass?

UV continuum slope ("color")



Median Stellar Mass @ sp. UV Luminosity from

Gonzalez et al. 2011

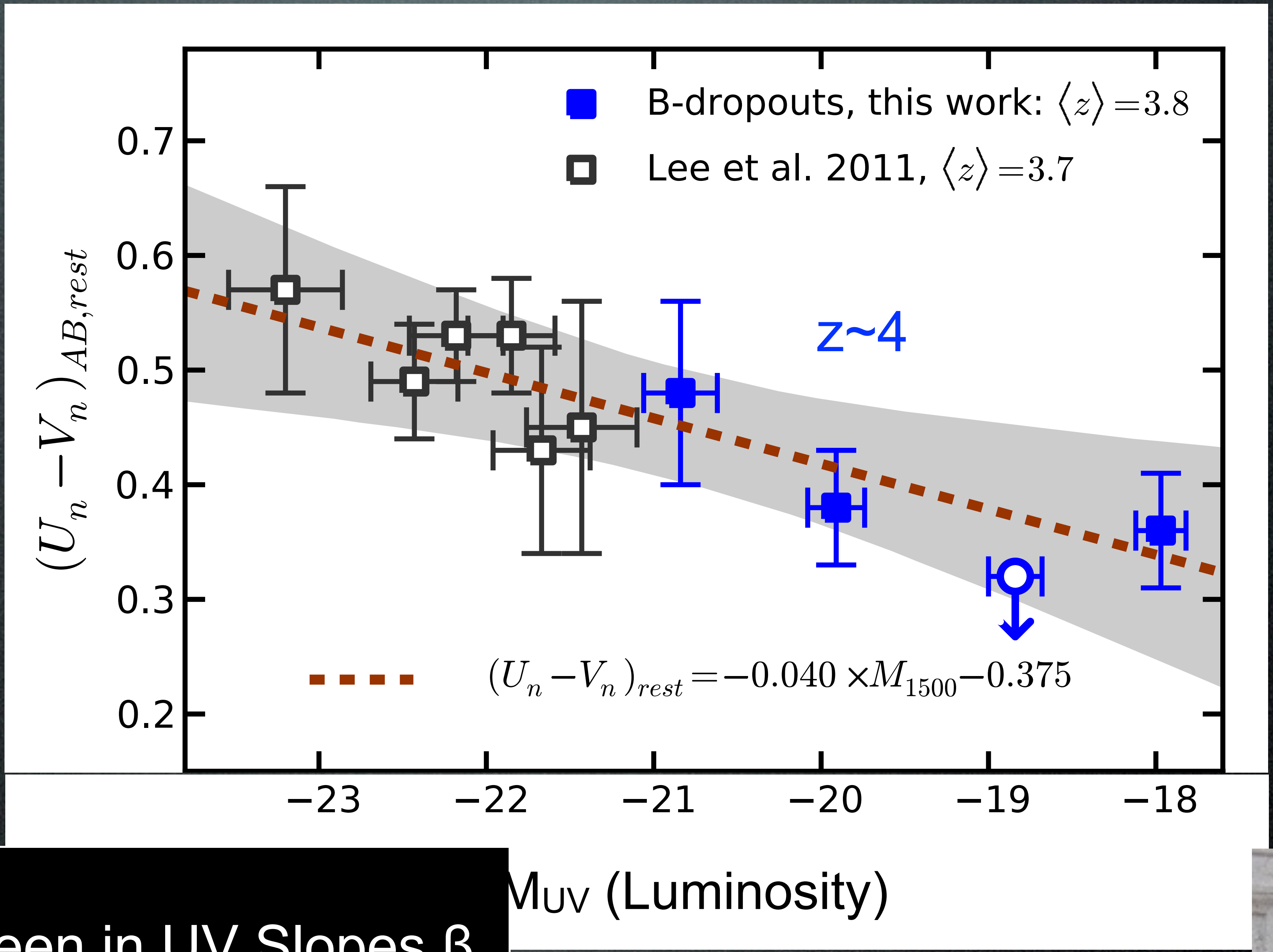
Galaxy Growth Self Similar

Bouwens et al. 2012; Finlator et al. 2011; see also Finkelstein et al. 2012

Do we find a similarly tight relationship between observables as a function of mass?

UV-Optical Color

"Amplitude of Balmer Break"



Parallels trends seen in UV Slopes β

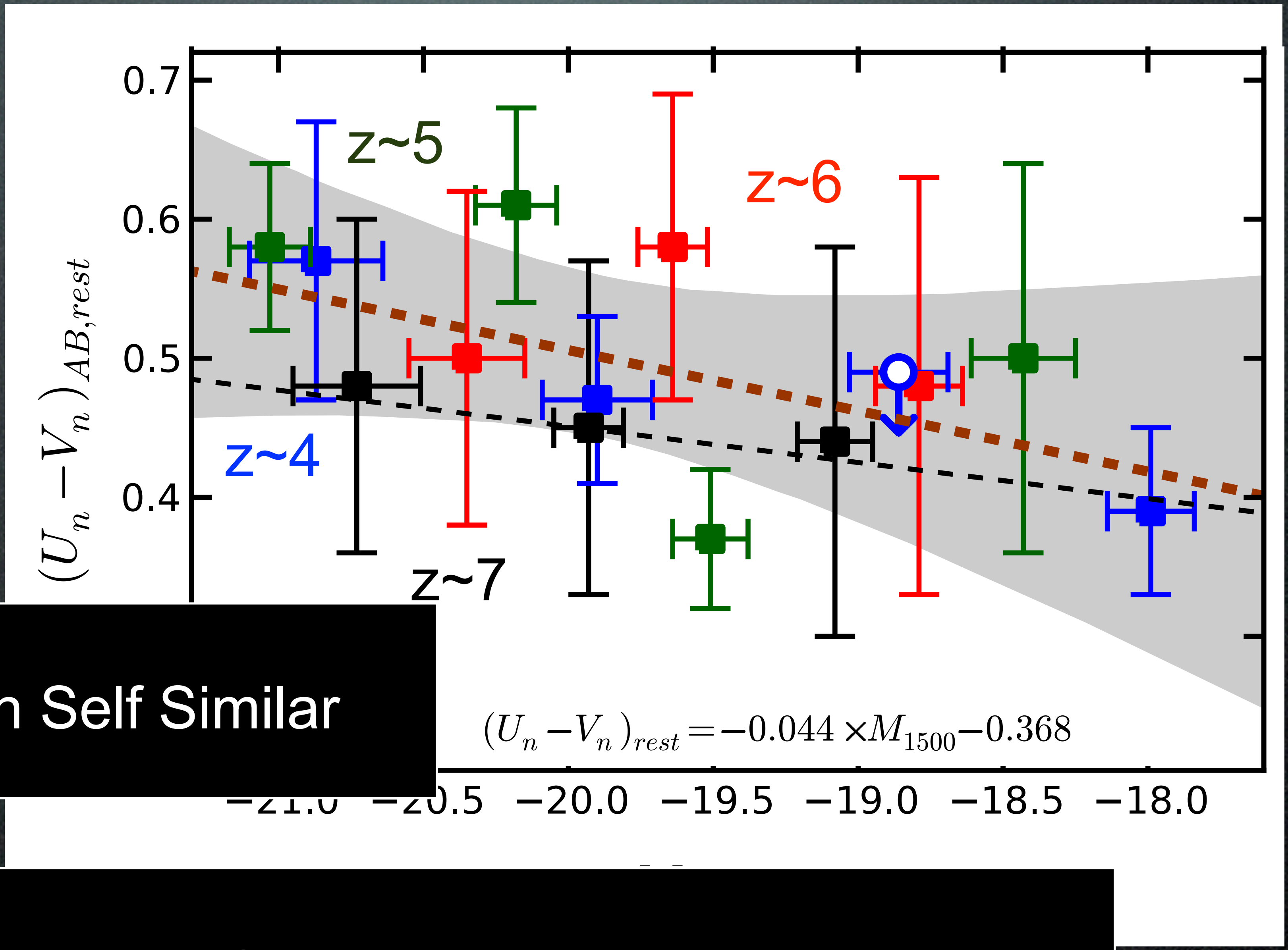
Valentino Gonzalez

Gonzalez et al. 2011; see also Stark et al. 2009; Lee et al. 2012

Do we find a similarly tight relationship between observables as a function of mass?

UV-Optical Color

"Amplitude of Balmer Break"



Galaxy Growth Self Similar

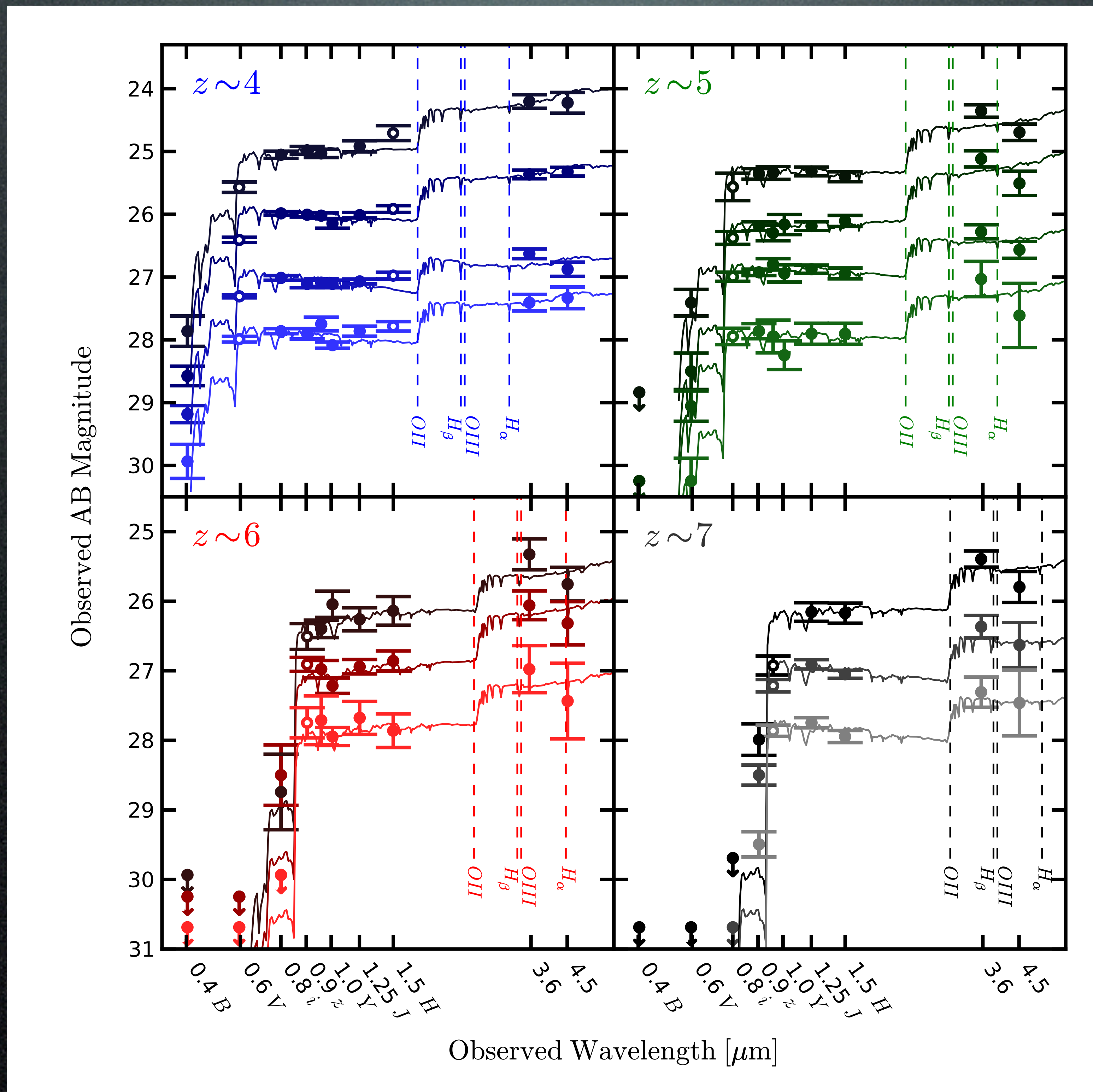
if we look at a galaxy of a given luminosity or mass at many different redshifts or cosmic times, that its properties are largely determined by luminosity or mass.

Valentino Gonzalez

Gonzalez et al. 2011; see also Stark et al. 2009; Lee et al. 2012

Do we find a similarly tight relationship between observables as a function of mass?

Stacked SEDs of z~4-7 galaxies

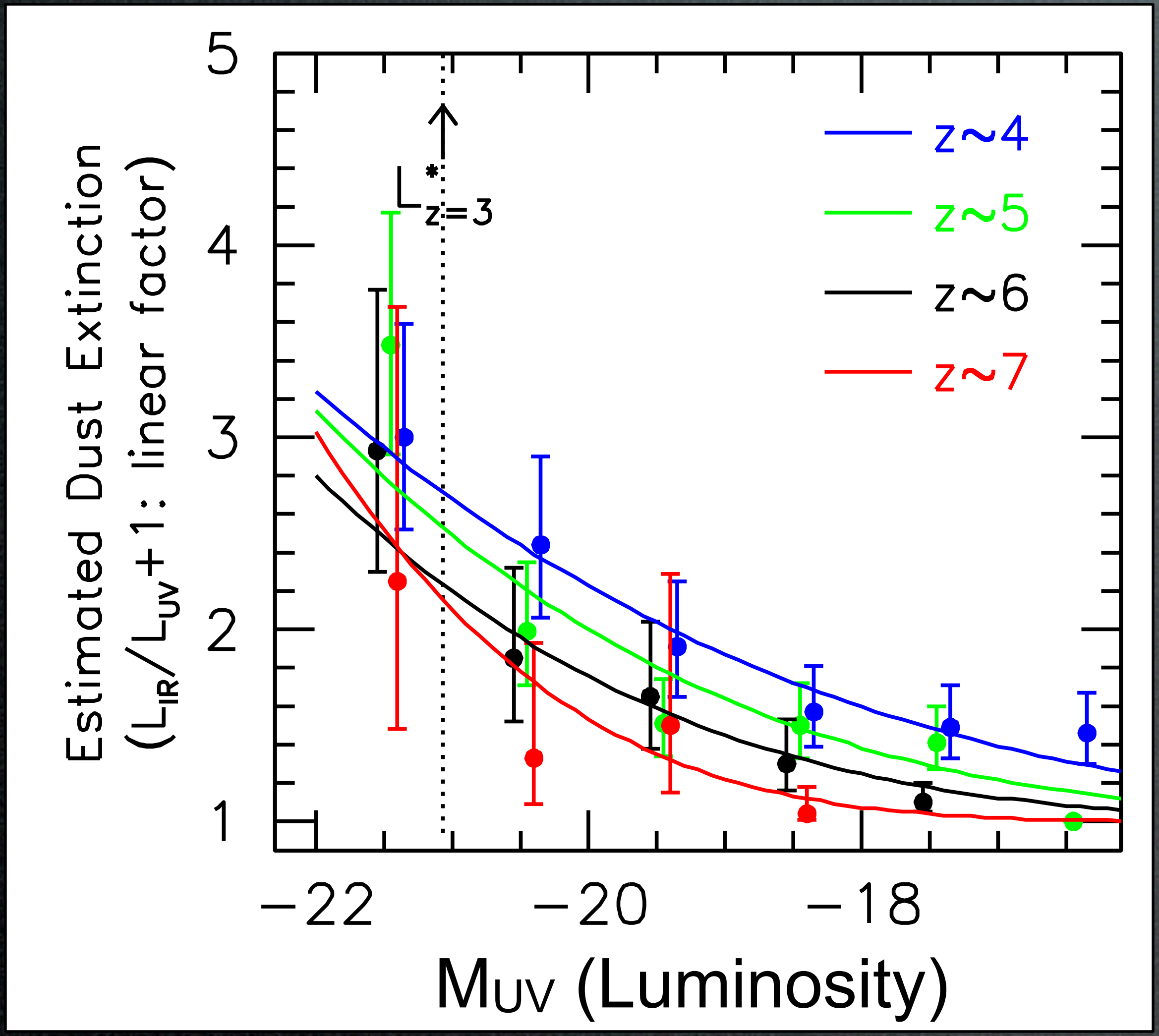


Gonzalez et al. 2011; see also Stark et al. 2009; Lee et al. 2012

Valentino Gonzalez

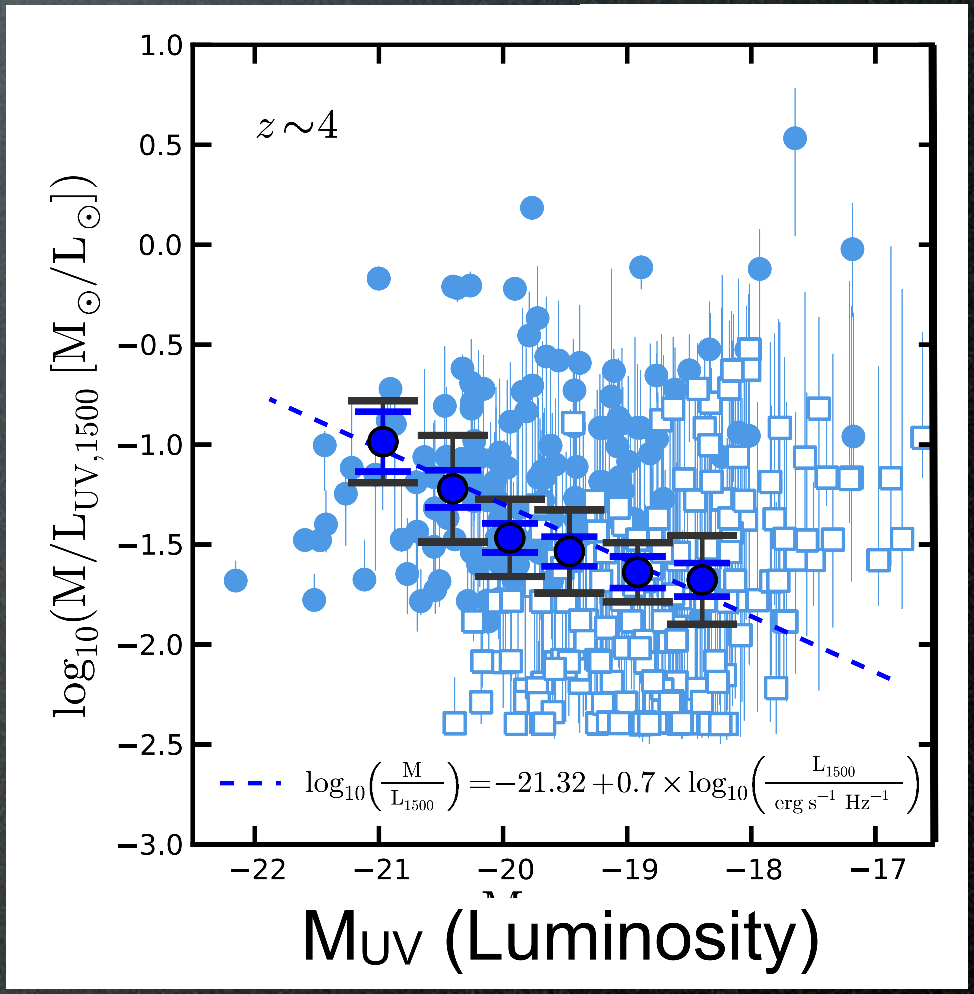
Self-similar UV colors + UV-optical colors imply dust extinction + M/L ratios

Dust Extinction



Mass to Light Ratio

M/L Ratio

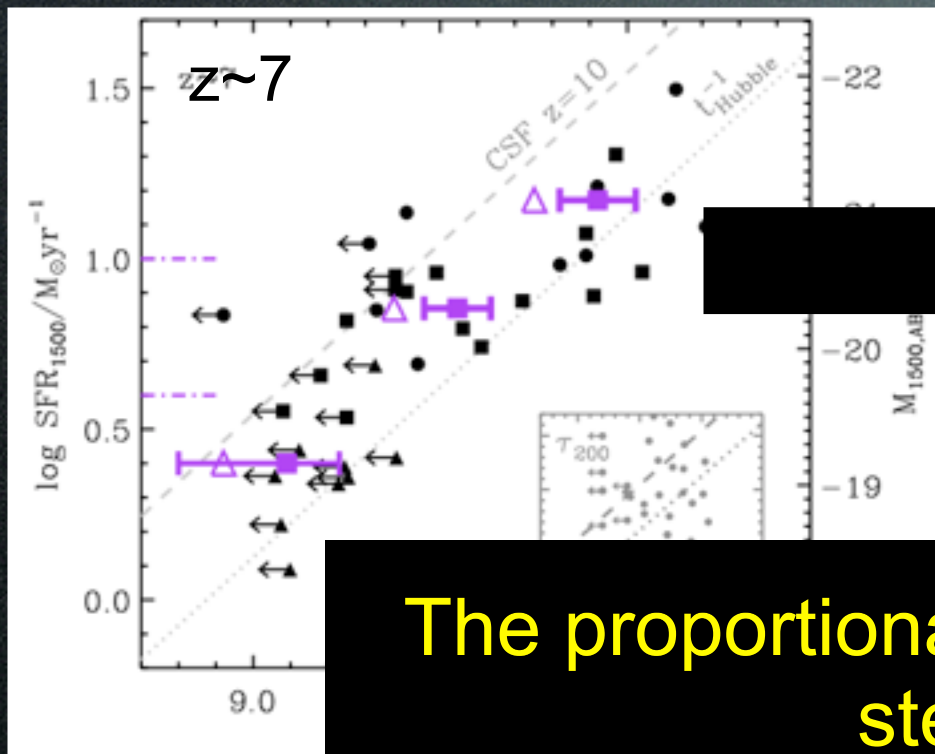


(Modulo Duty Cycle Uncertainties)

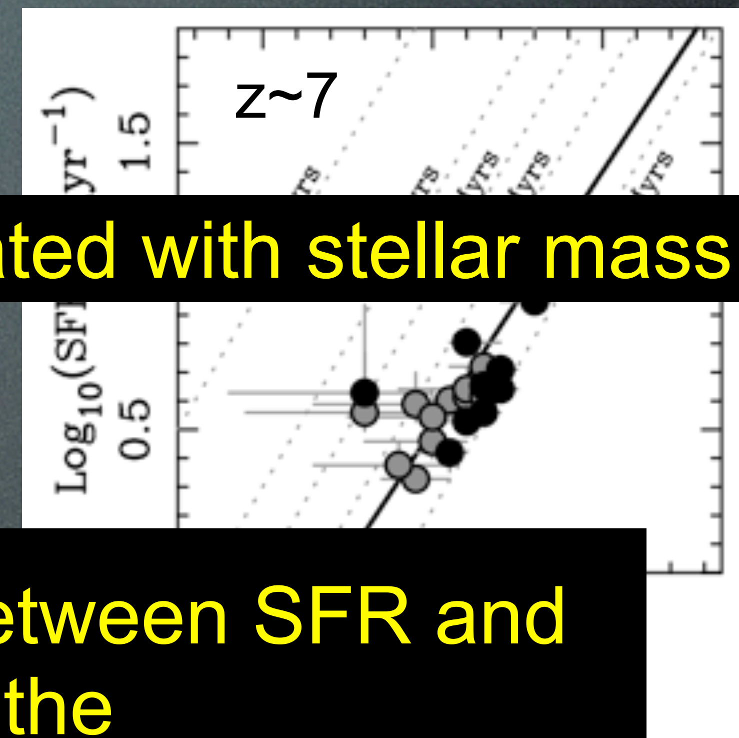
Bouwens et al. 2012; Gonzalez et al. 2011; see also Stark et al. 2009; Lee et al. 2012

==> Sequence of Star-forming Galaxies

Labbe et al. 2010



McLure et al. 2011



SFR

SFR correlated with stellar mass

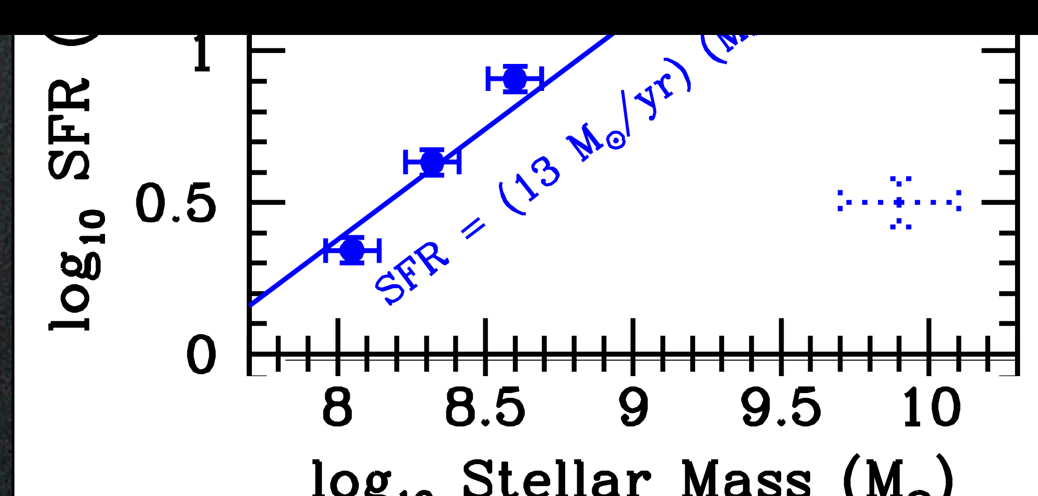
The proportionality factor between SFR and stellar mass is the

specific star formation rate

which is a key quantity of interest

SFR

(dusted corrected)

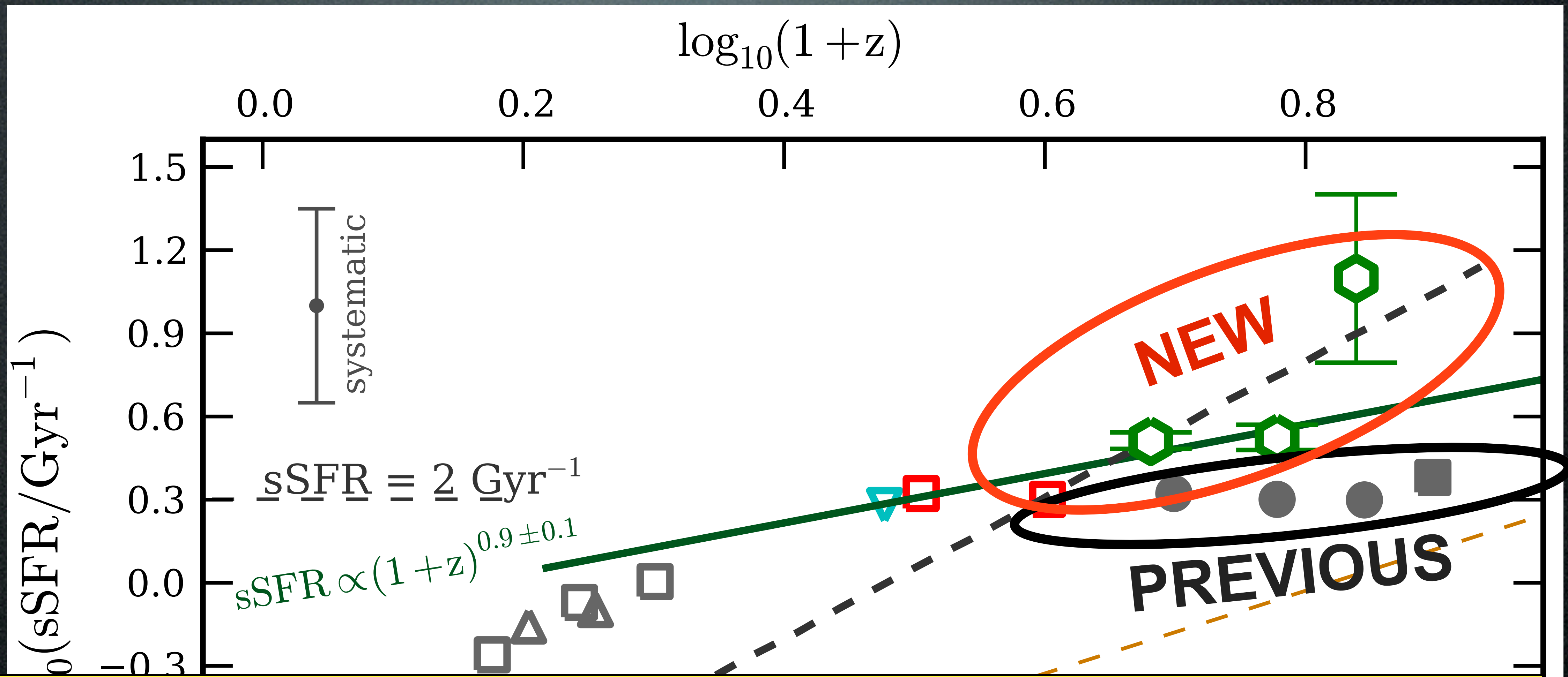


Stellar Mass

see also Stark et al. 2009

==> Evolution of specific star formation rate

SFR / stellar mass



Higher values of the sSFRs are due to

(1) better accounting for dust extinction in z>4 galaxies (SFRs → higher)

(2) correcting for the contribution of emission lines to rest-frame optical light (stellar masses → lower)

González et al. 2012, see also Schaerer et al. 2012, Bouwens et al. 2012, Reddy et al. 2012

Thus far, I’ve told you the SED shapes of galaxies
are largely self similar

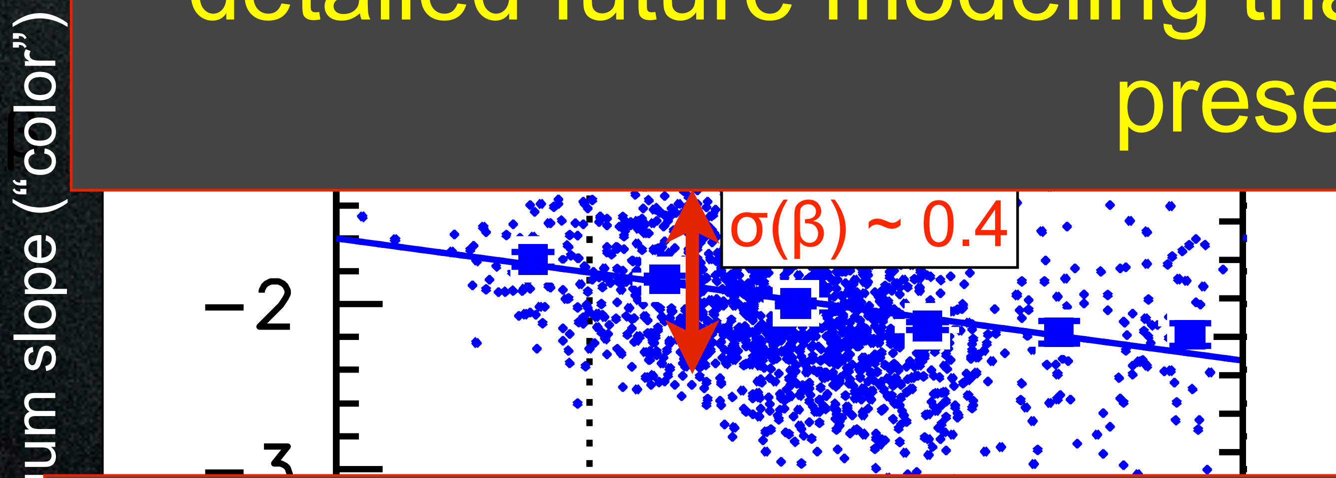
depending only on luminosity or mass

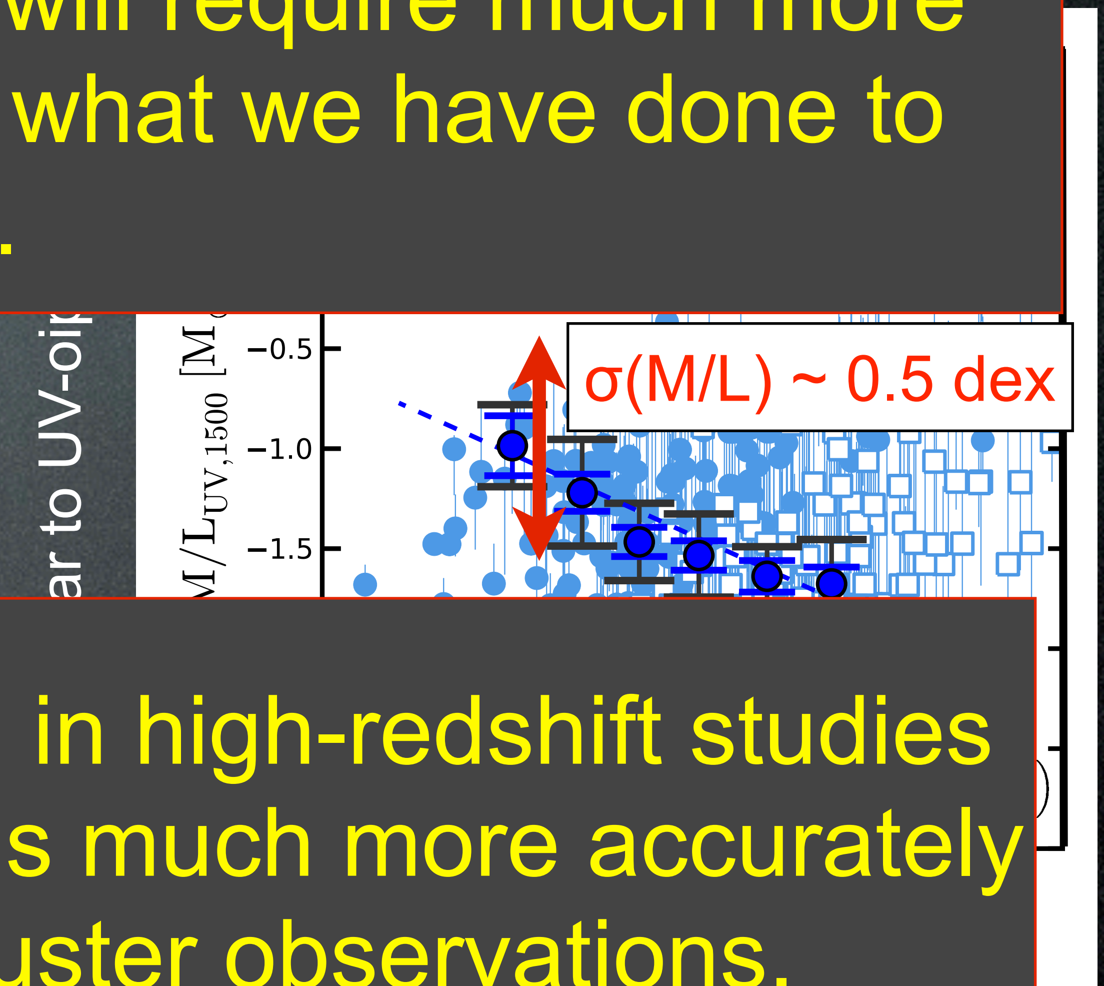
This is not entirely true.

-- There is scatter in the properties of galaxies at a
given luminosity/mass

Bouwens et al. 2012

There is scatter in galaxy properties



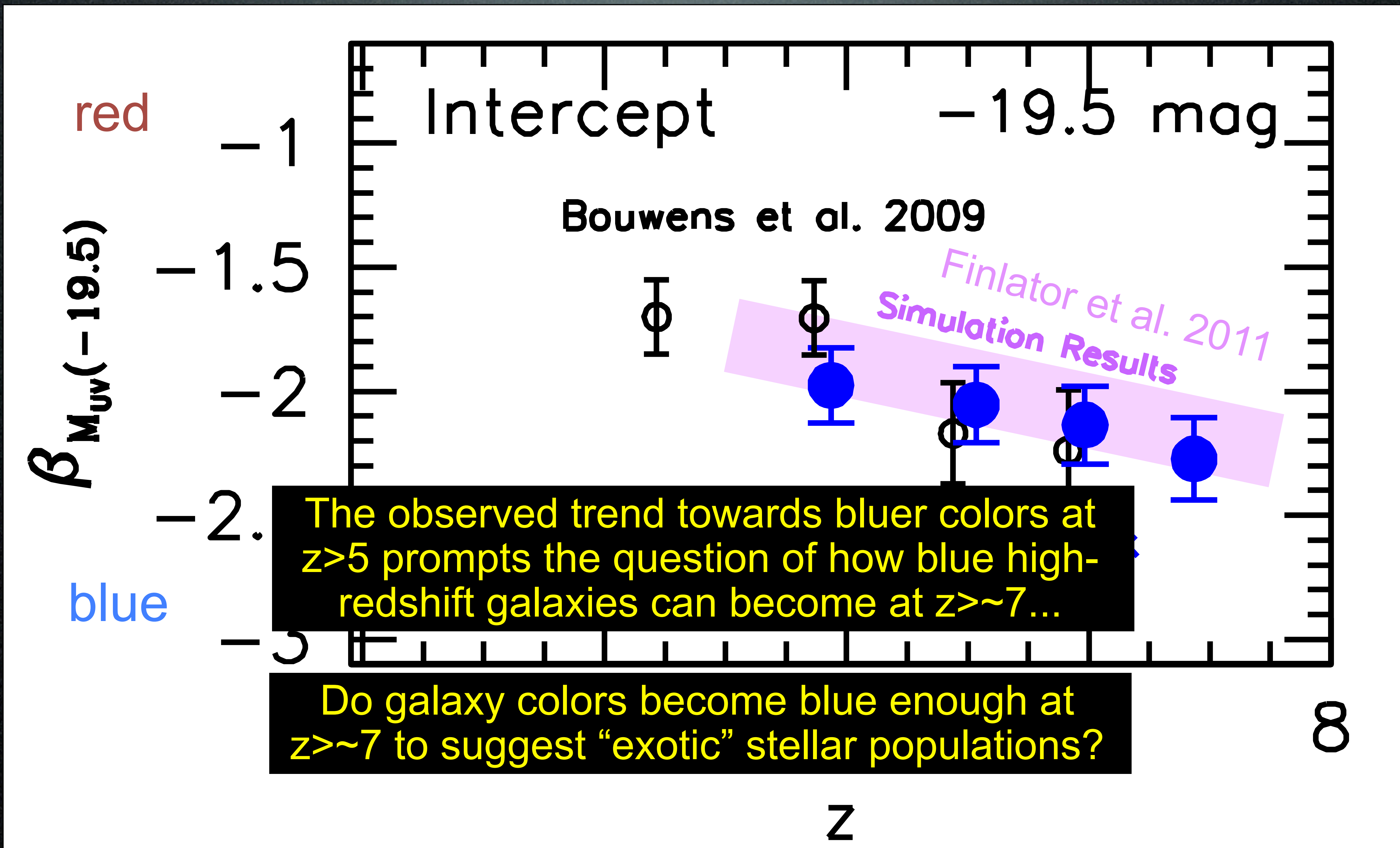


The scatter we observe here points to some considerable non-uniformity of the star formation history of individual galaxies, but this will require much more detailed future modeling than what we have done to present.

An important goal going forward in high-redshift studies will be to quantify these variations much more accurately from the available field + cluster observations.

Bouwens et al. 2012; Castellano et al. 2012; Gonzalez et al. 2011; see also Stark et al. 2009; Lee et al. 2012

UV slopes also show a modest dependence on redshift

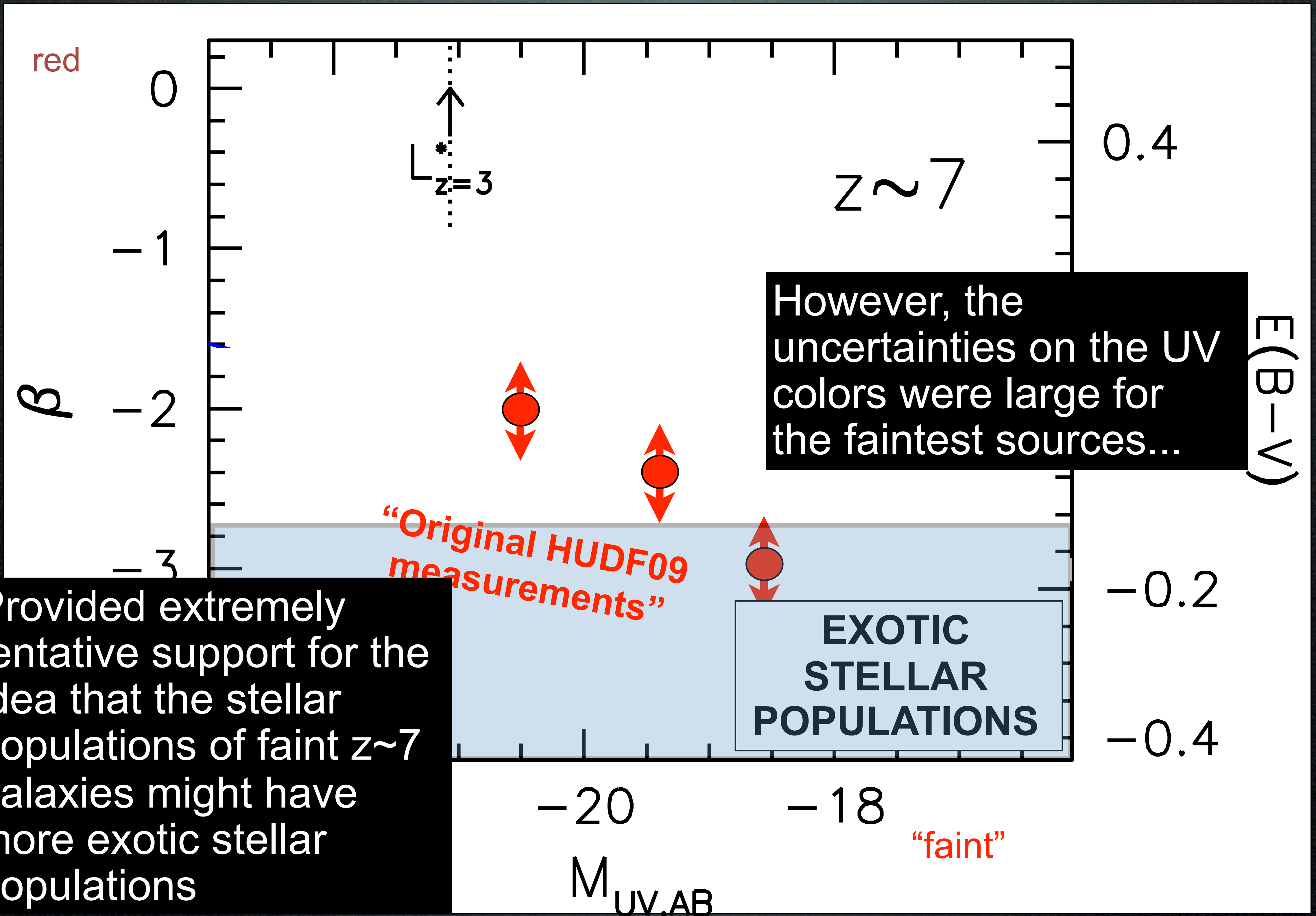


The observed trend towards bluer colors at z>5 prompts the question of how blue high-redshift galaxies can become at z>~7...

Do galaxy colors become blue enough at z>~7 to suggest “exotic” stellar populations?

Bouwens et al. 2012; see also work by Finkelstein et al. 2012

Initial Observations over the HUDF with WFC3/IR allowed people to look at UV colors of faint z~7 galaxies...

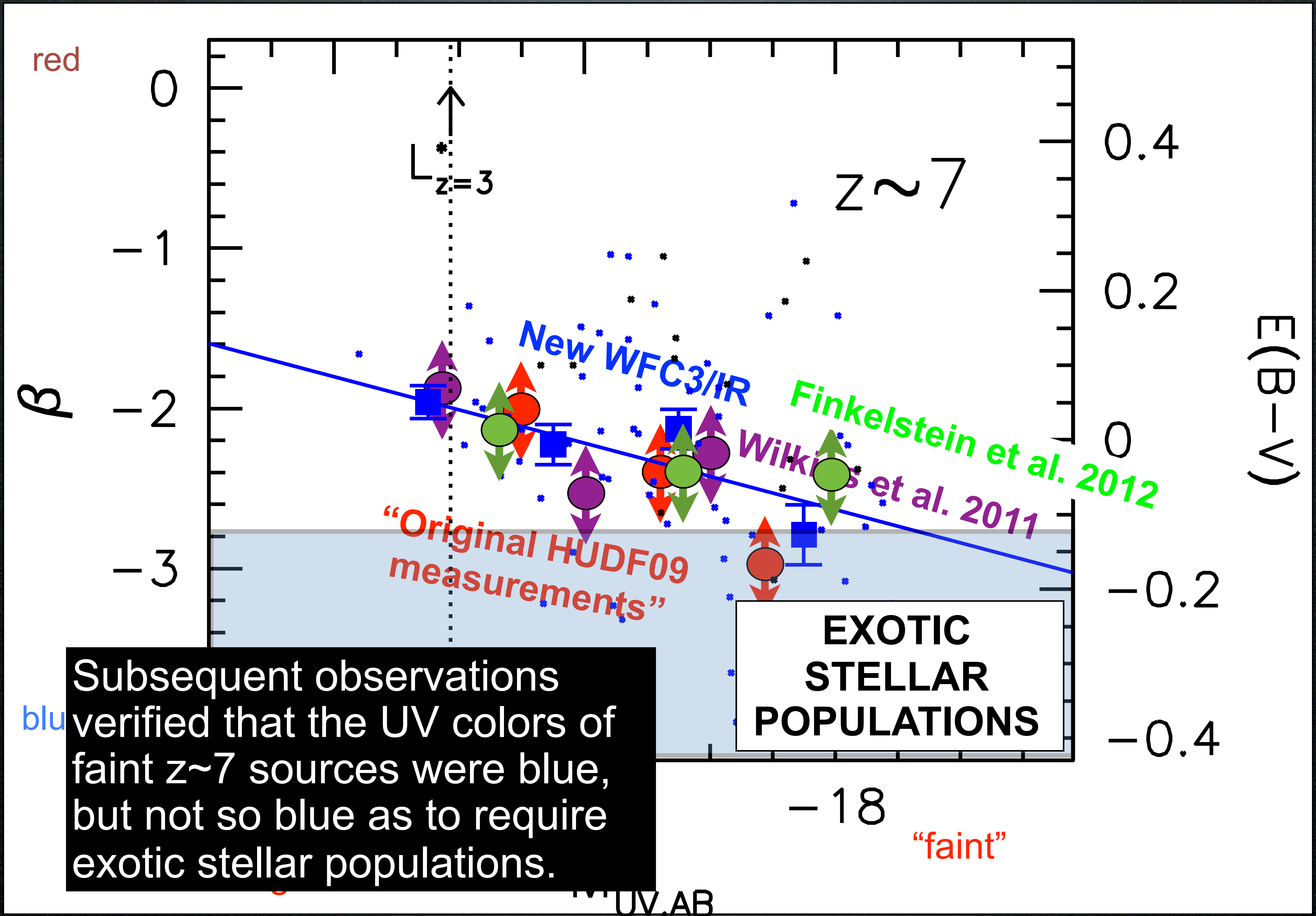


However, the uncertainties on the UV colors were large for the faintest sources...

Provided extremely tentative support for the idea that the stellar populations of faint z~7 galaxies might have more exotic stellar populations

Bouwens et al. 2010; Finkelstein et al. 2010

Are very low luminosity galaxies at z>6 extraordinarily blue (providing evidence for exotic or extreme stellar pops)?



Subsequent observations verified that the UV colors of faint z~7 sources were blue, but not so blue as to require exotic stellar populations.

Bouwens et al. 2010, 2012; Wilkins et al. 2011; Finkelstein et al. 2012

Reionization of the Universe

Can growing galaxies reionize the universe?

Can galaxies reionize the universe?
(how much light do they produce?)

How can we answer?

-- We have good constraints on the UV LF to z~10
-- Extrapolating current measures of the LF to higher redshifts and lower luminosities, we can estimate ionizing photons from galaxies
-- Make reasonable assumptions about clumping factor for HI in IGM and fraction of ionizing photons escaping

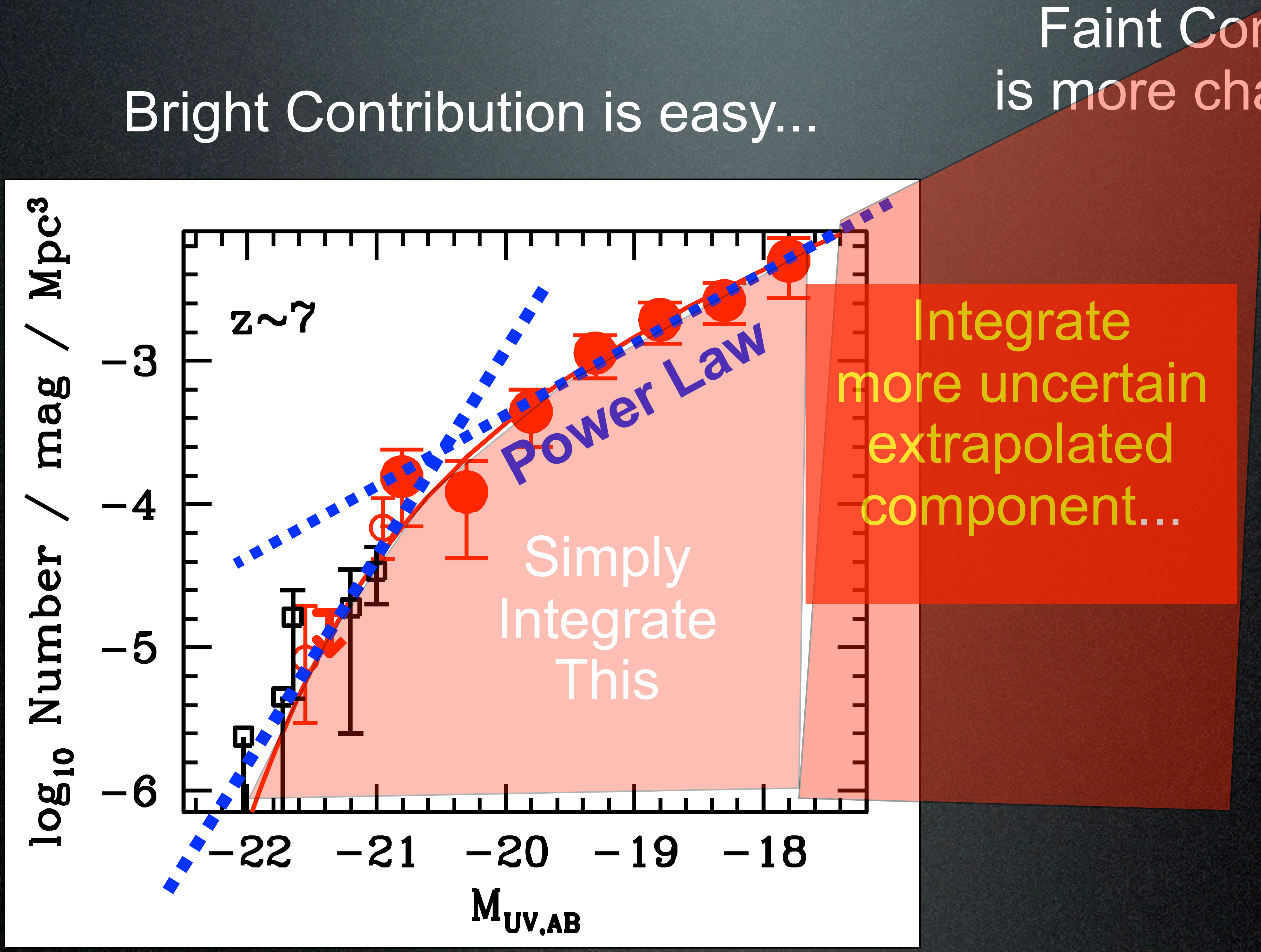
What do we need to match to plausibly explain reionization?

-- Reionize the universe by z>~6
-- Match WMAP Thomson optical depths ~ 0.087 +/- 0.018
-- Match other observables...
  * Lyα constraints on ionizing photon injection rate
  * Kinetic SZ constraints from SPT (Zahn et al. 2011)

How many ionizing photons do galaxies produce?

Bright Contribution is easy...

Faint Contribution is more challenging...

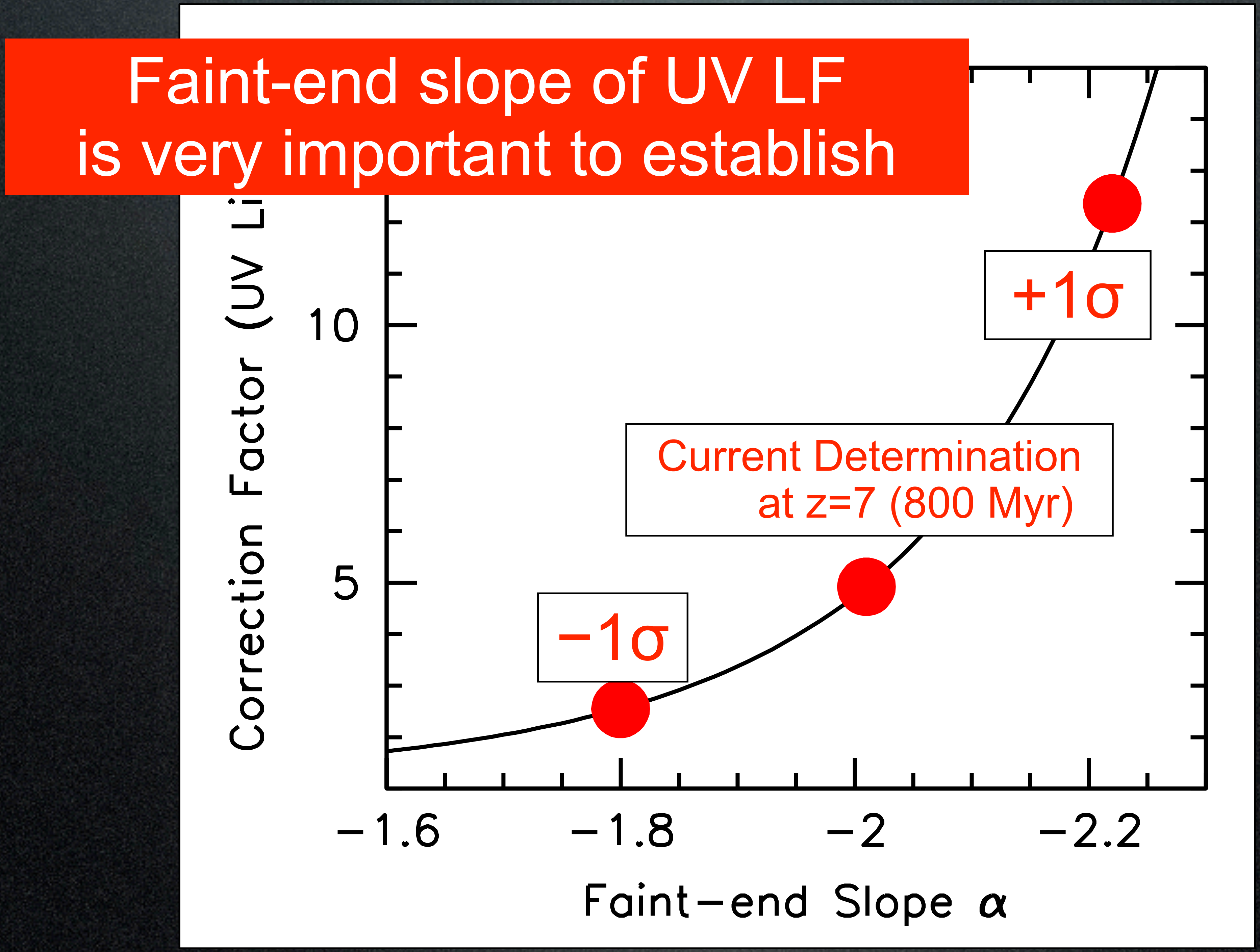


Can galaxies reionize the universe?

(how much light do they produce?)

Correction (for unseen sources) depends very sensitively on faint-end slope

(integrated to -10 AB mag: approximate limiting luminosity expected in many models)



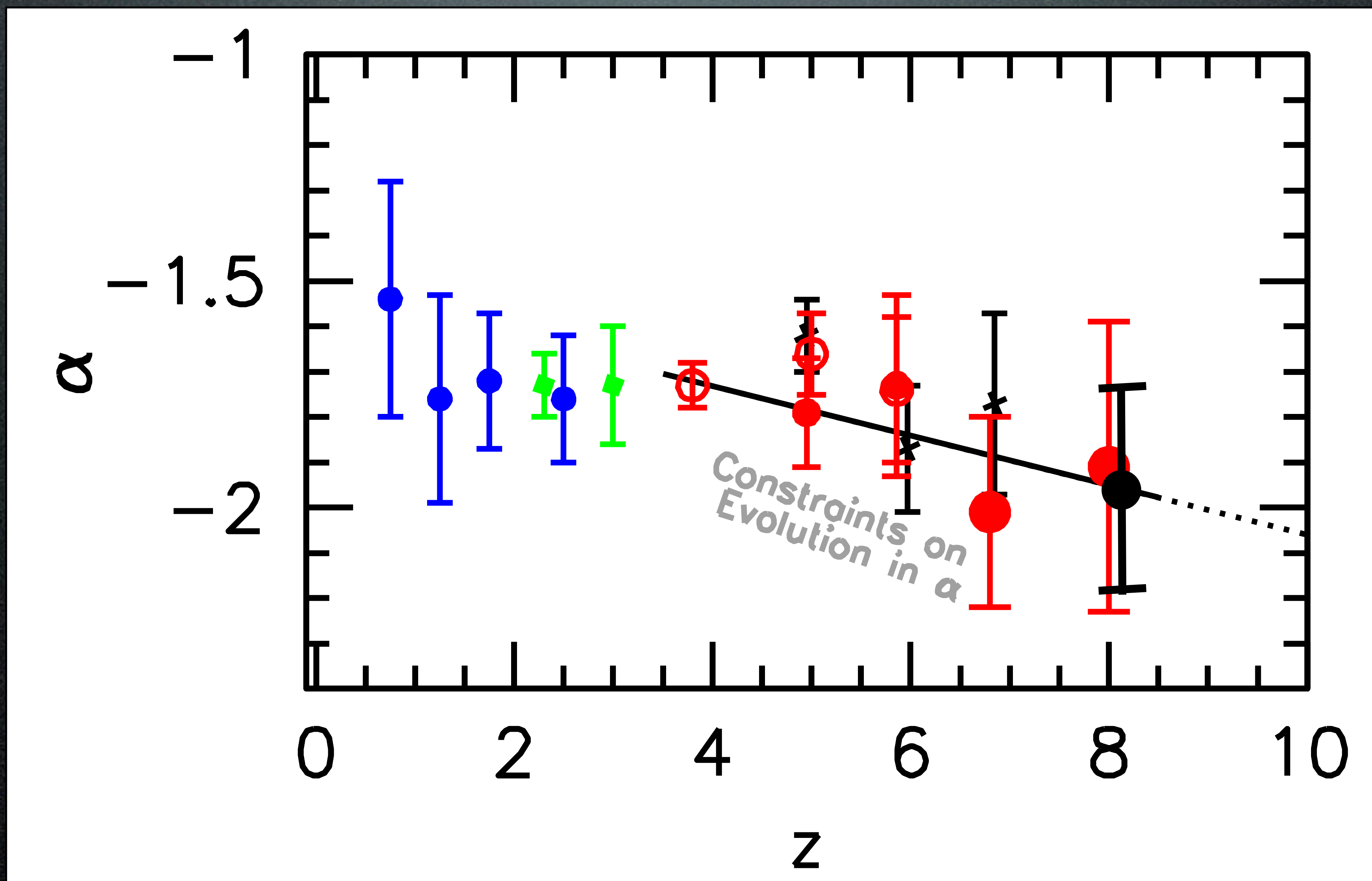
Bouwens et al. 2011

Can galaxies reionize the universe?

(how much light do they produce?)

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

Shallow slope



Steep slope

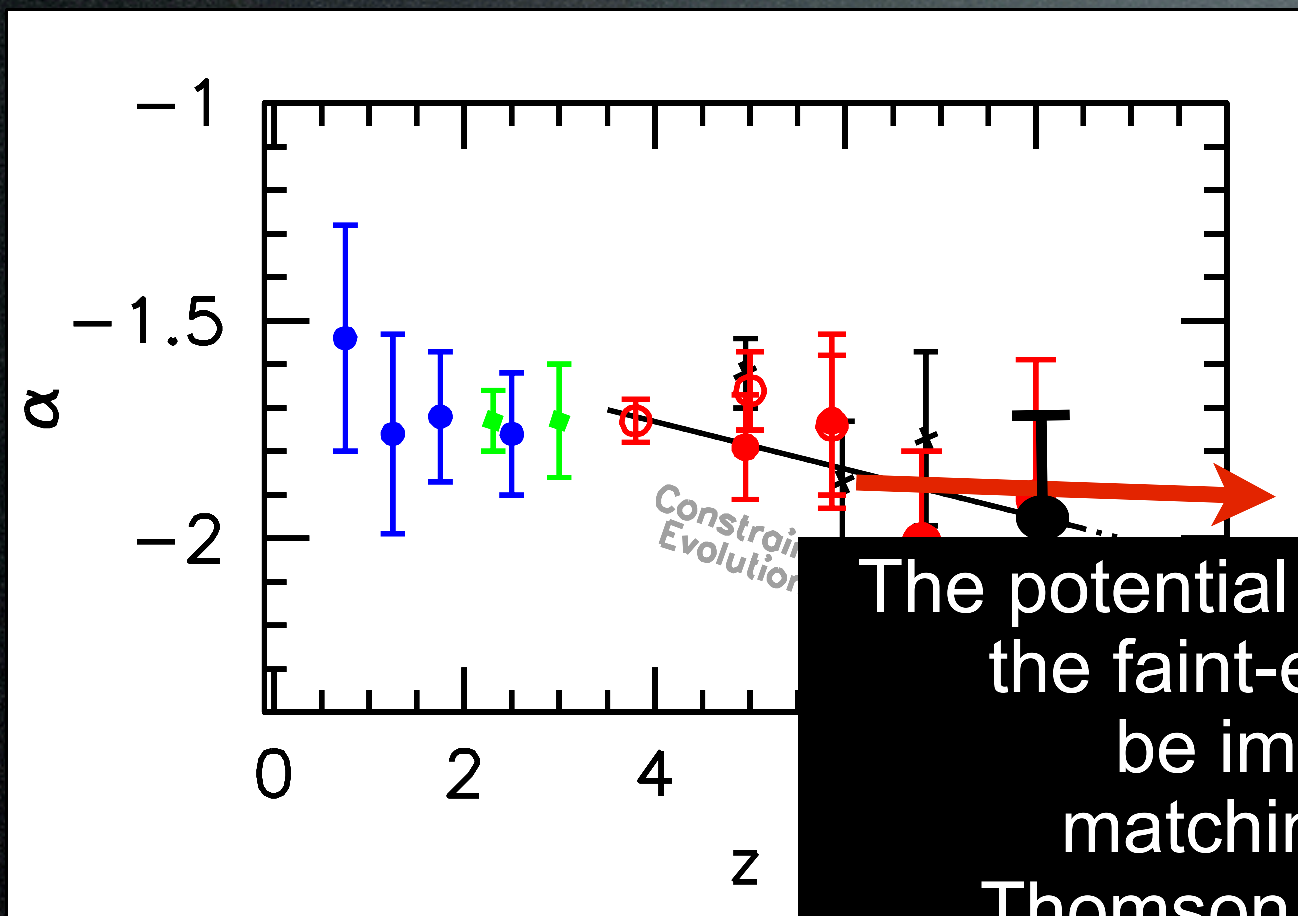
(and predictions from theory suggest such an evolution: Trenti et al. 2010; Jaacks et al. 2011; Salvaterra et al. 2011)

Bouwens et al. 2007, 2011, 2012; Reddy al. 2009; Bradley et al. 2012
(see also Ouchi et al. 2009; Oesch et al. 2010; Yoshida et al. 2006)

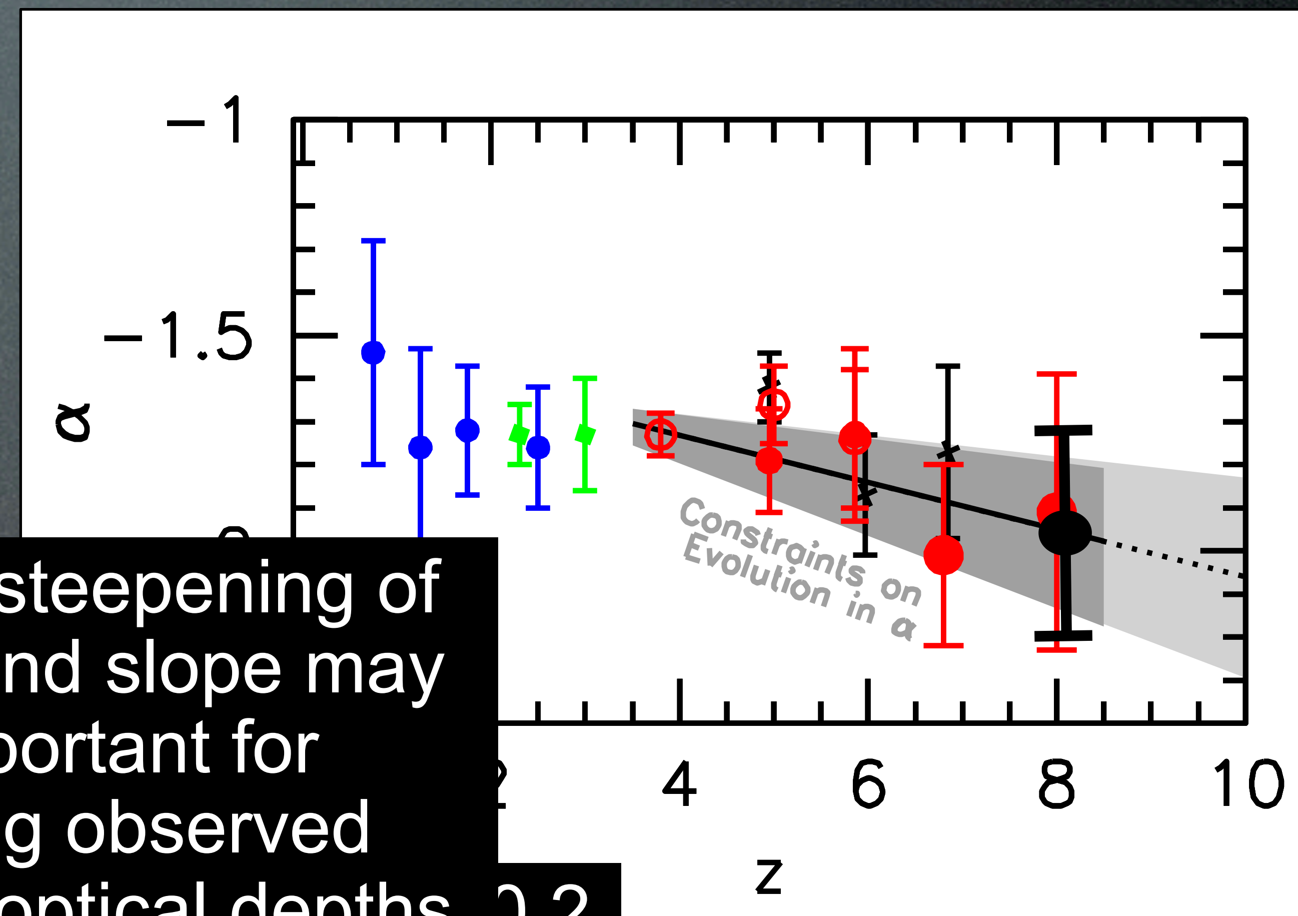
Can galaxies reionize the universe?

(how much light do they produce?)

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



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



The potential steepening of
the faint-end slope may
be important for
matching observed
Thomson optical depths 0.2

Reionization at z=7

Thomson optical depth is
0.055 ↔ 0.061 ↔ 0.070

Reionization at z=8

Thomson optical depth is
0.062 ↔ 0.079 ↔ 0.142

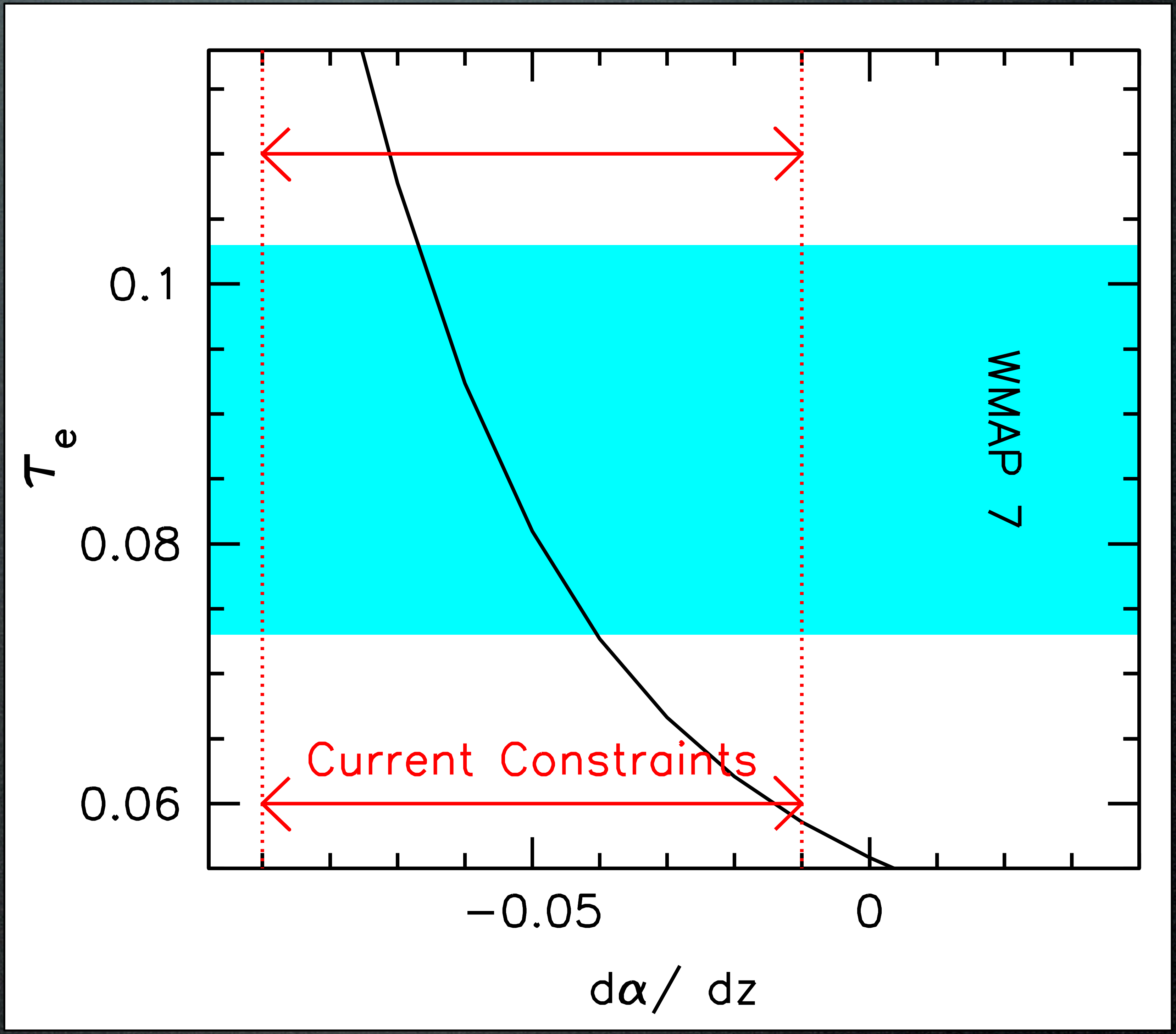
Matches WMAP constraints!

Bouwens et al. 2012

Can galaxies reionize the universe?

(how much light do they produce?)

Predicted τ_e very sensitive to evolution in faint-end slope...



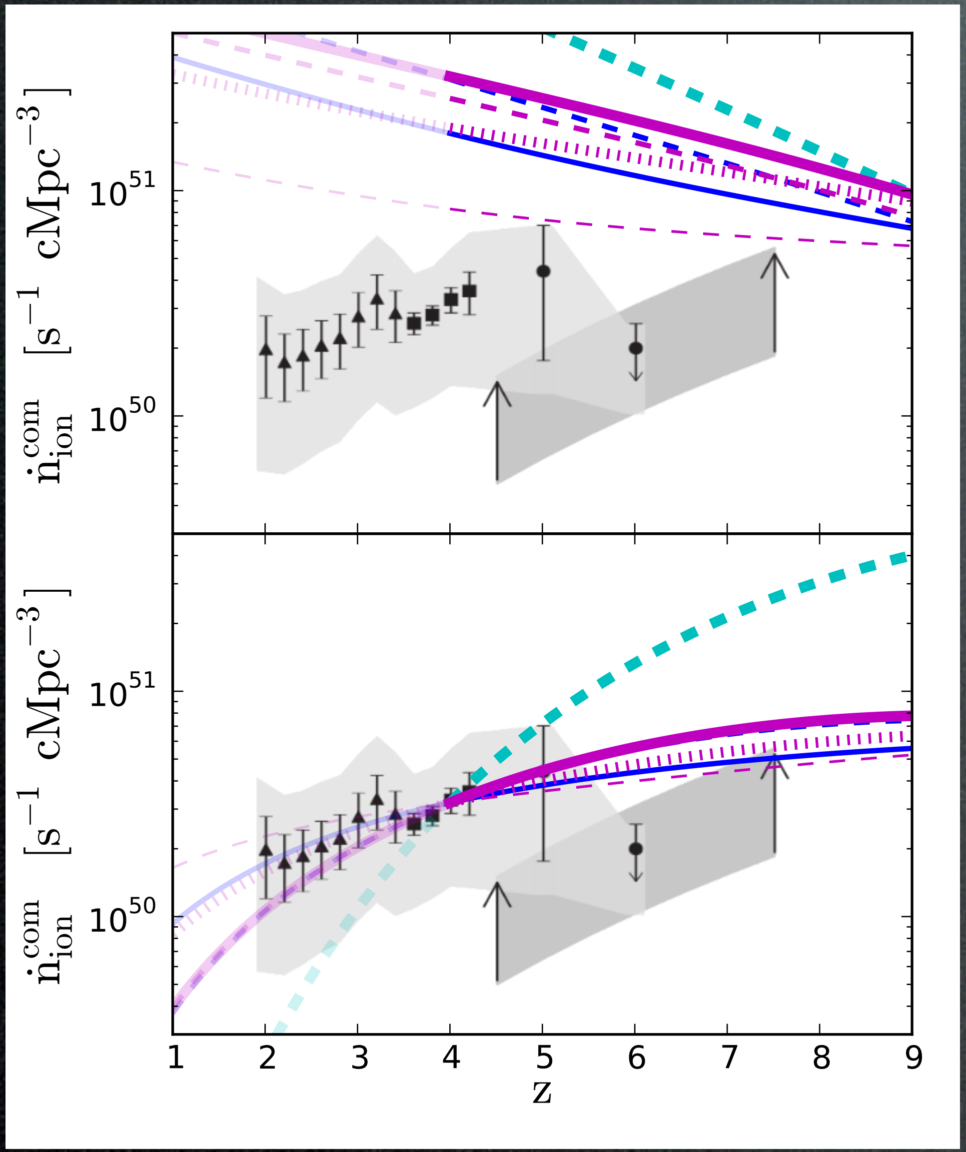
Bouwens et al. 2012

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

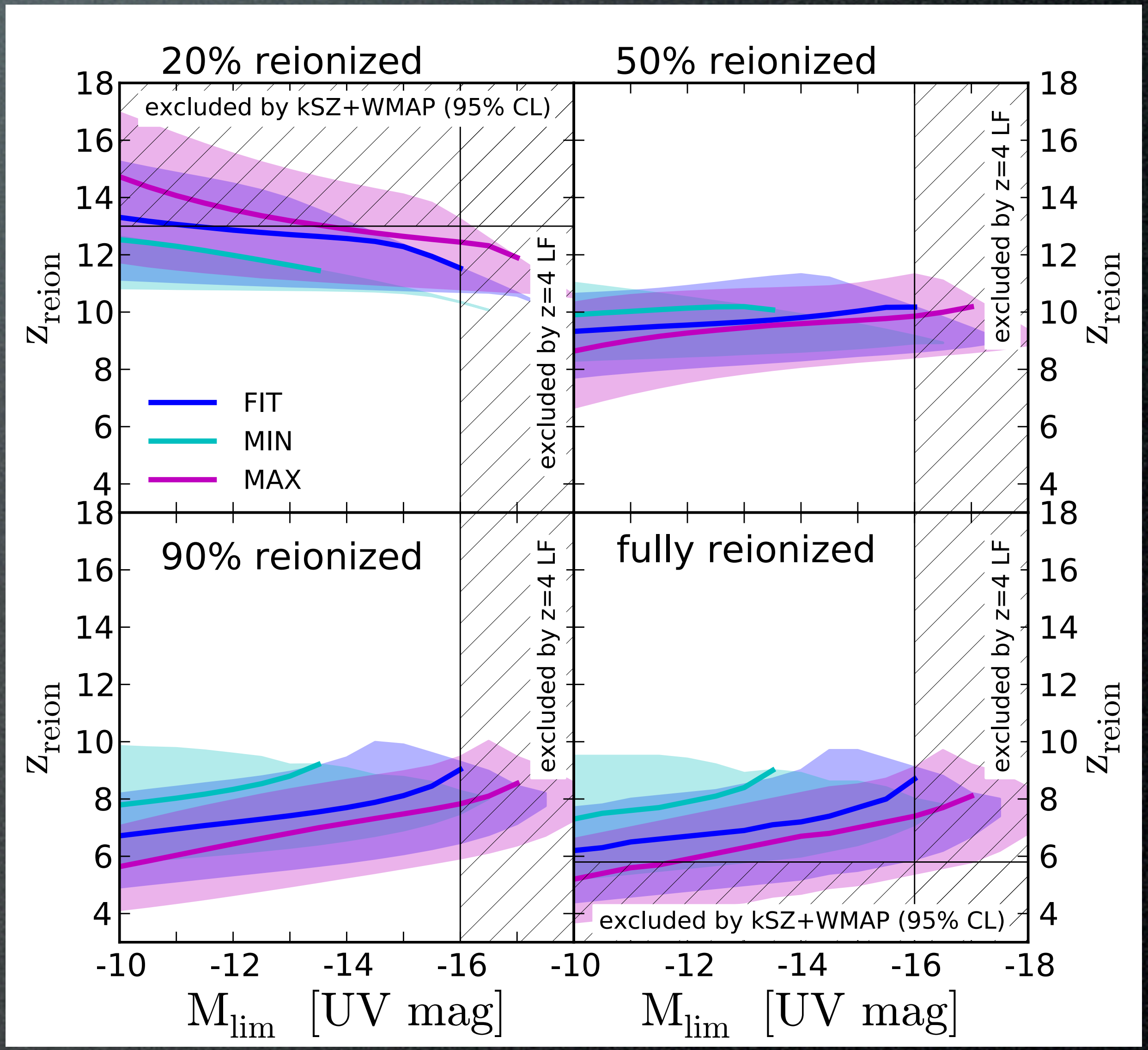
Can galaxies reionize the universe?
(how much light do they produce?)

In addition, we want to match other observables, i.e.,

Lyα constraints on ionizing photon injection rate



Kinetic SZ constraints from SPT (Zahn et al. 2011)

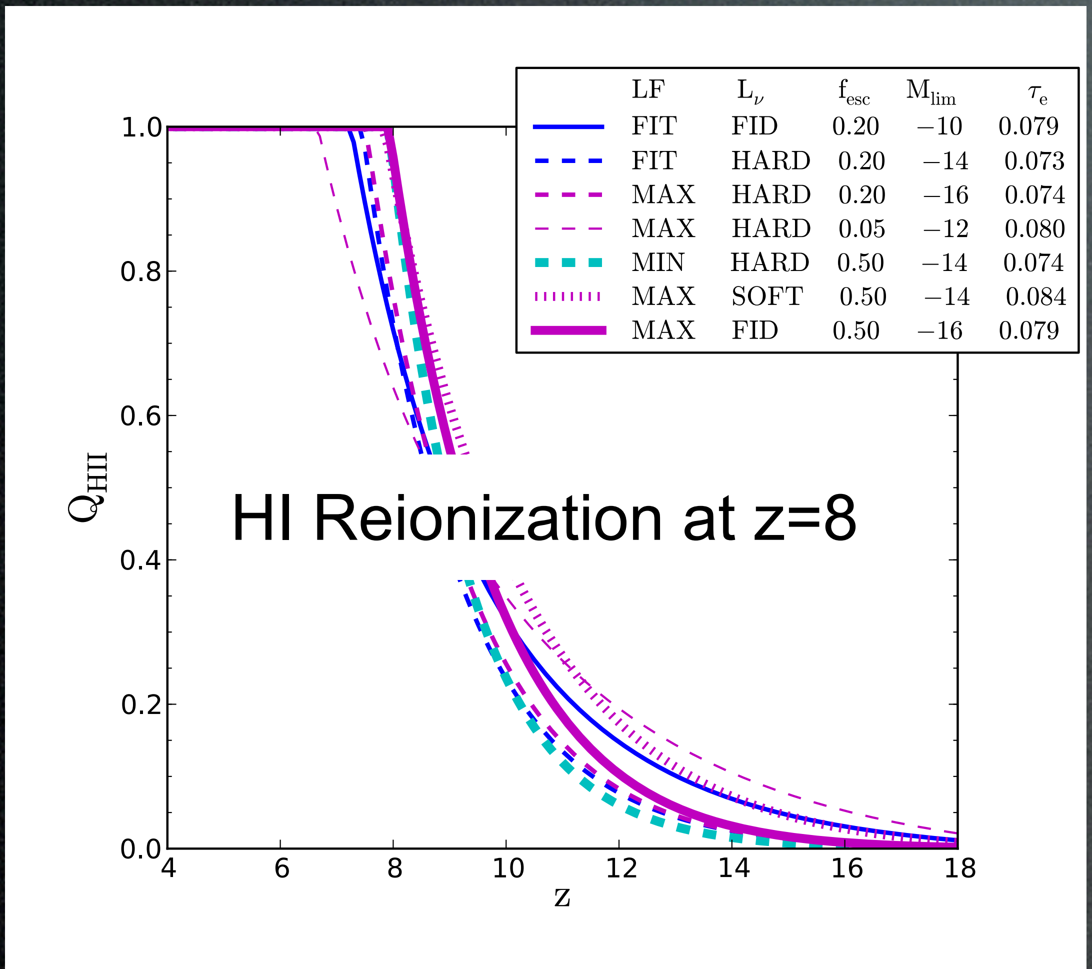


Kuhlen & Faucher-Giguere (2012)

Can galaxies reionize the universe?
(how much light do they produce?)

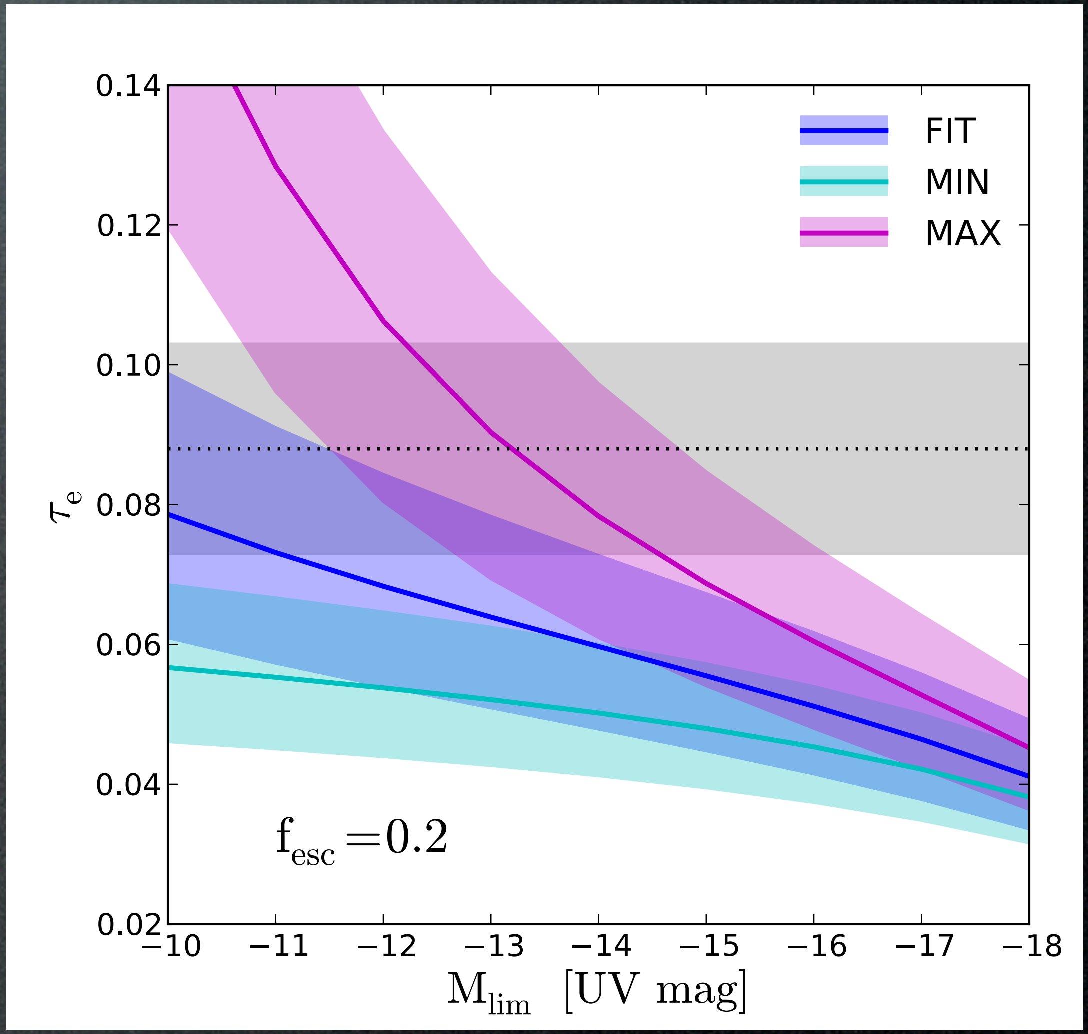
Matching to the observed UV LF evolution, Lyα constraints on ionizing photon injection rate, and the Kinetic SZ constraints from SPT (Zahn et al. 2011), Kuhlen et al. derive the following estimates of...

HI Ionized fraction vs. redshift



Reionization at z=8

WMAP Thomson optical depths



Kuhlen & Faucher-Giguere (2012)

Build-up of Galaxies in the First 3 Gyr of Universe

Correcting for dust extinction from new WFC3/IR observations we can derive SFR functions at z>=2. Suggests galaxy growth continues from z~8-10 to z~2 (3 billion years after Big Bang).

Similar UV-continuum slope vs. luminosity relationships found for galaxies at z~4-7. The origin of this is likely the mass-metallicity relationship. This suggests that galaxies at high-redshift evolve in a largely self-similar manner.

UV-optical colors show a similar dependence on luminosity as the UV slopes -- again suggesting self similarity.

Galaxies at the highest redshift are bluer than galaxies at lower redshift.

Modest variation in the UV and UV-optical colors are seen as a function of a galaxy mass. This provides us with some constraint on how uniform the star formation history is for individual galaxies, though this will require future work.

The total flux density in ionizing photons is very sensitive to the faint-end slope. The faint-end slopes measured at z>=6 are very steep and may steepen towards high redshift.   As a result, galaxies may be capable of reionizing the universe.