The First Galaxies (z>5)

(What we can learn about their early build-up and contribution to reionization from the observations)

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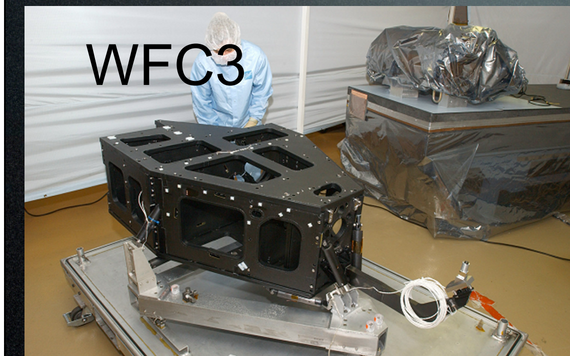
(Leiden University / Leiden Observatory)

Galaxy Formation, An international conference
July 22, 2011 (Durham, UK)

Many New Facilities to Push High-Redshift Science Forward

Installation of the WFC3 camera on HST



Hubble Space Telescope

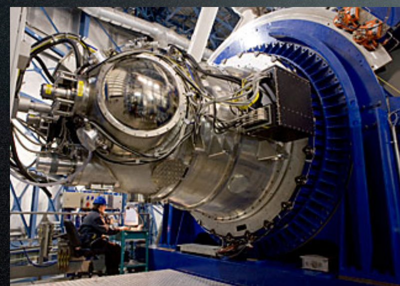
-- 6.5x larger field-of-view than previous camera (NICMOS)

-- 3-4x more sensitive than previous camera

-- 2x higher spatial resolution (not undersampled)

Many New Facilities to Push High-Redshift Science Forward

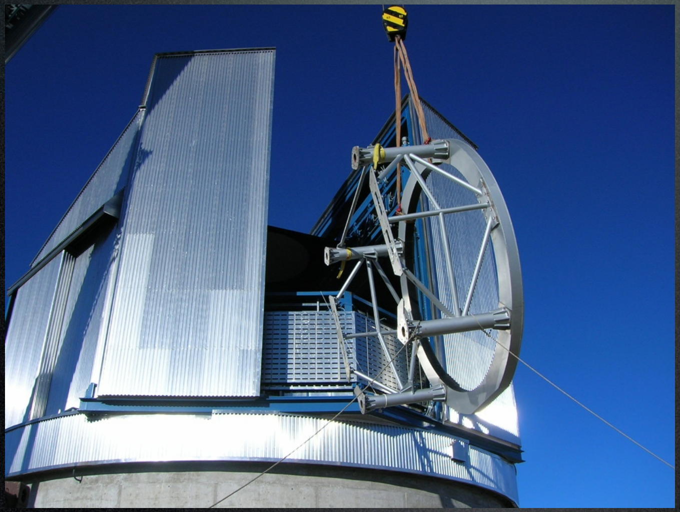
Wide-area near-IR imagers
from ground, i.e., HAWK-I on VLT



-- very large field of view (8’ x 8’)
-- very sensitive (reaches to ~27 mag in ~10 hours)

Many New Facilities to Push High-Redshift Science Forward

Ultra Wide-area surveying telescopes like VISTA



Many New Facilities to Push High-Redshift Science Forward

Installation of the WFC3 camera on HST

~40x more efficient for exploring high redshift universe

Telescope

-- 6.5x larger field-of-view than previous camera (NICMOS)

-- 3-4x more sensitive than previous camera

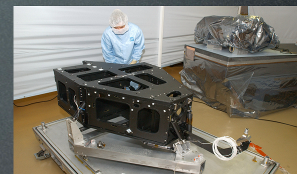
-- 2x higher spatial resolution (not undersampled)

Substantial progress in # of high-redshift galaxies discovered when universe was < 900 million years old

i.e., redshift > 6.5

PRE-2009 (PREVIOUS GENERATION INSTRUMENTS)

NEW CAMERA (WFC3/IR)



~10-15 galaxies (< 2009) → ~20 galaxies (1st week of observations) → >100 galaxies (now)

Published Samples of z>6.5 Galaxies (photometric selection from new WFC3/IR data)

Bouwens et al. 2011a,b
~73 z~7
~59 z~8
~1 z~10

Finkelstein et al. 2010
~41 z~6-9

McLure et al. 2011
~60 z~6-9

Wilkins et al. 2011; Lorenzoni et al. 2011
~44 z~7
~24 z~8

Grazian et al. 2010
~42 z~7

Yan et al. 2010
~20 z~7
~15 z~8
~20 z~10

Published *Spectroscopically* confirmed z>6.5 galaxies

Vanzella et al. (2011)
2 z~7

Ono et al. (2011)
2 z~7

Schenker et al. (2011)
3 z~7

Iye et al. 2011
1 z~7

↓

~8 spectroscopically
confirmed z~7 galaxies

(since z~7 galaxies tend to be spectroscopically confirmed only through the detection of Lyα emission, the small # of confirmations is not an important concern)

Why are studies of z>5 galaxies interesting?

-- It is when galaxies first form...

(halos of L* and sub-L* galaxies built up from z~30+ to z~3)

-- It is when the universe was reionized...

(galaxies are most likely driver, so by studying the formation of first galaxies perhaps we can gain insight)

-- It is when metals are first produced in significant abundance

(could result in changes in various spectral properties, e.g., IMF, dust properties)

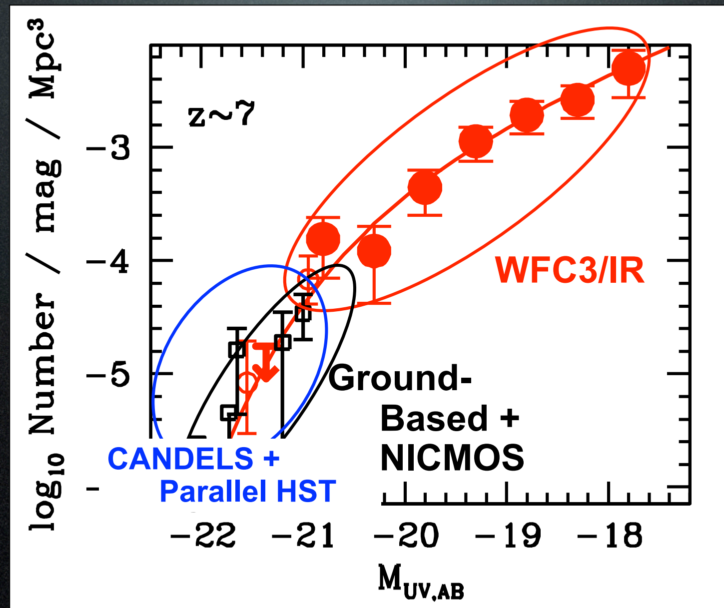
How fast do galaxies build-up and grow?

Quantifying Galaxy Build-up using The Luminosity Function of Galaxies

In rest-frame UV -- since easiest to quantify observationally
and likely proportional to stellar mass...

What does the galaxy LF at z>5 look like?

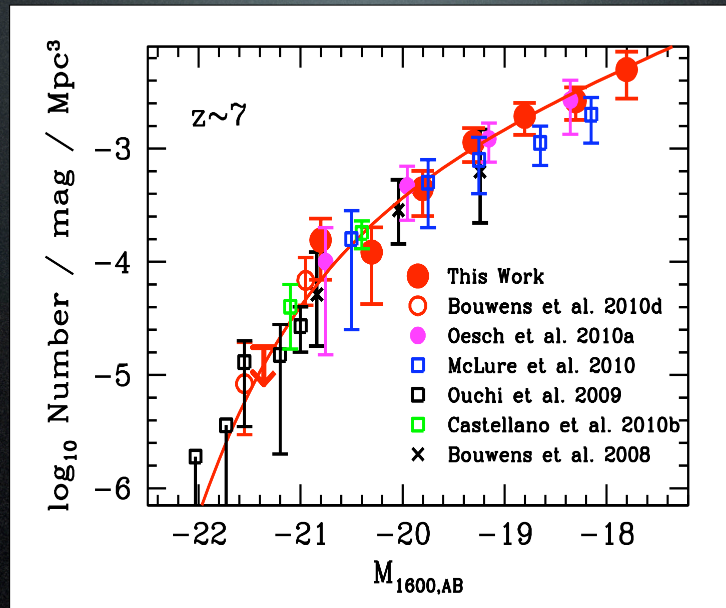
(z~7 LF from Bouwens et al. 2011; Ouchi et al. 2011)



Bouwens et al. 2010a,b; Ouchi et al. 2009; see also Castellano et al. 2010

What does the galaxy LF at z>5 look like?

(comparison of many different LFs)

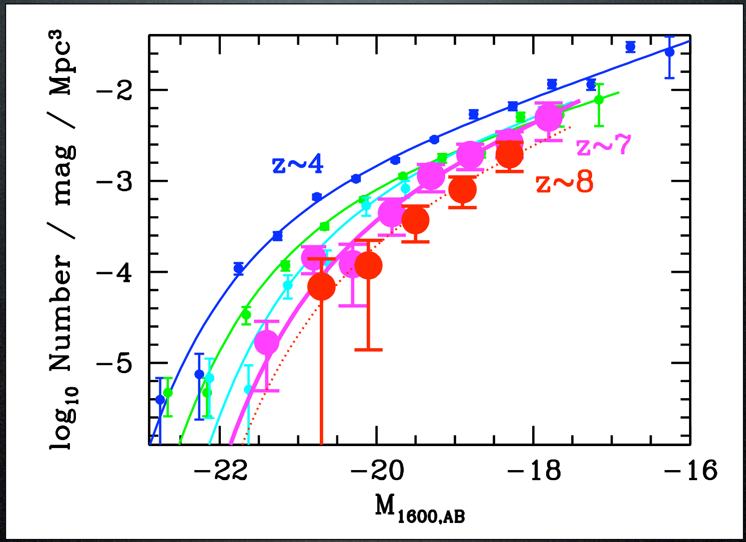


Bouwens et al. 2010a,d; Ouchi et al. 2009; Castellano et al. 2010; Wilkins et al. 2011

How rapidly does the UV LF evolve from z~8 to z~3?

(from Bouwens et al. 2011; but similar results from other groups)

Log # mag^{-1} Mpc^{-3}



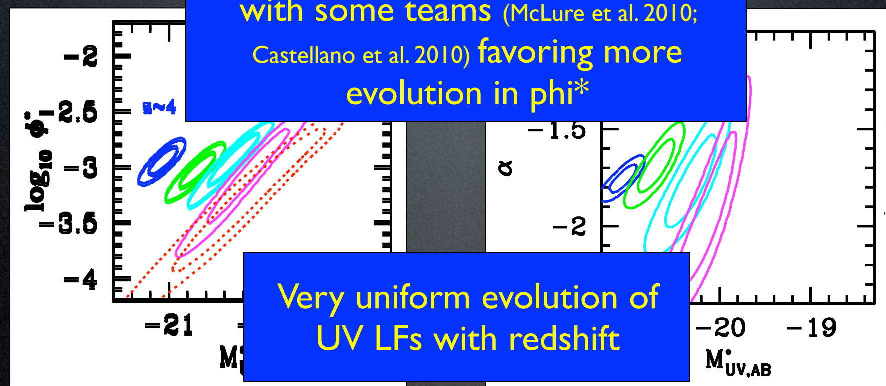
Bright Faint

Bouwens et al. 2011

How rapidly does the UV LF evolve from z~8 to z~3?

(Bouwens et al. 2011; but similar results from other groups)

Results from other teams similar -- with some teams (McLure et al. 2010; Castellano et al. 2010) favoring more evolution in phi*



Very uniform evolution of UV LFs with redshift

68% and 95% confidence intervals

Bouwens et al. 2011

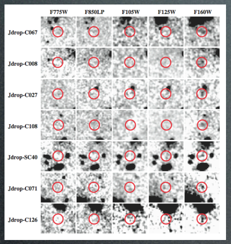
How early in the universe can we begin tracing galaxy buildup?

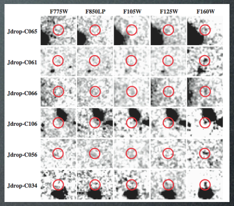
Can we do this at z~10?

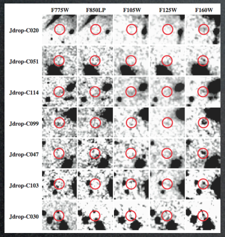
(500 Myr after Big Bang)

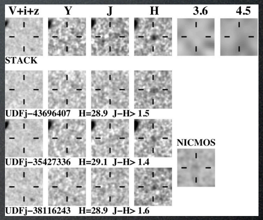
Extensive efforts to identify z~10 sources in the first half of the HUDF WFC3/IR data

~23 weak z~10 candidates in early data ("lottery tickets")









Yan et al.. (2010); Bouwens et al. (2010, arXiv)

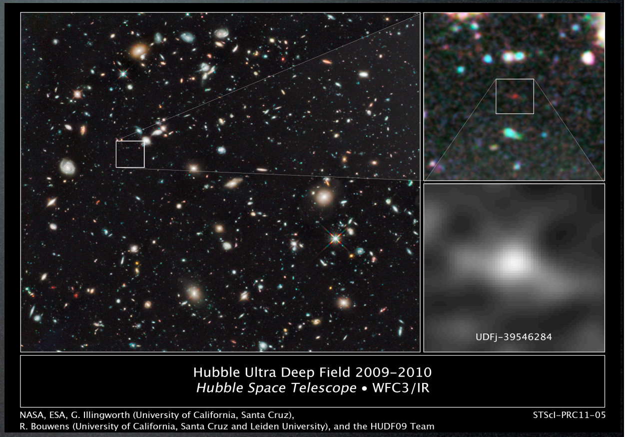
Efforts continued after 100% of the HUDF WFC3/IR data were available

Single high-quality z~10 Candidate

1st Year (~50%)
+
2nd year (~50%)

HUDF WFC3/IR data

→

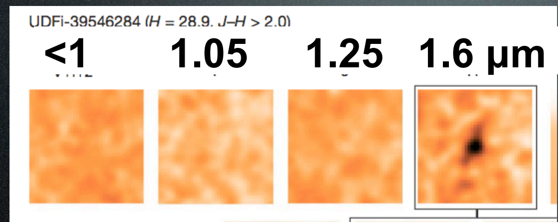


Bouwens et al. 2011; Oesch et al. 2011; other teams (e.g. Haojing Yan, Steve Wilkins) find candidate too

Is it probable a z~10 galaxy has been found?

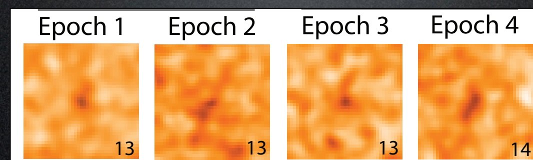
-- z~10 galaxy candidate in HUDF is plausible

Disappears at < 1.4 microns, deep ~100 hour IRAC data over HUDF demonstrate source is blue (Bouwens et al. 2010; Oesch et al. 2011)



-- z~10 candidate is not 100% secure yet (obviously!)

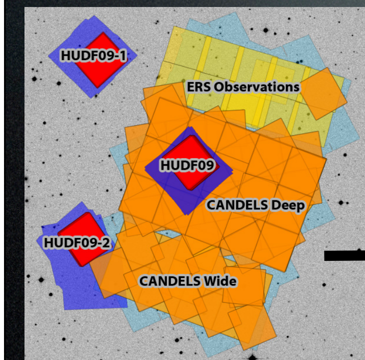
While it is detected (>2.5σ) in 4 independent splits of the observations



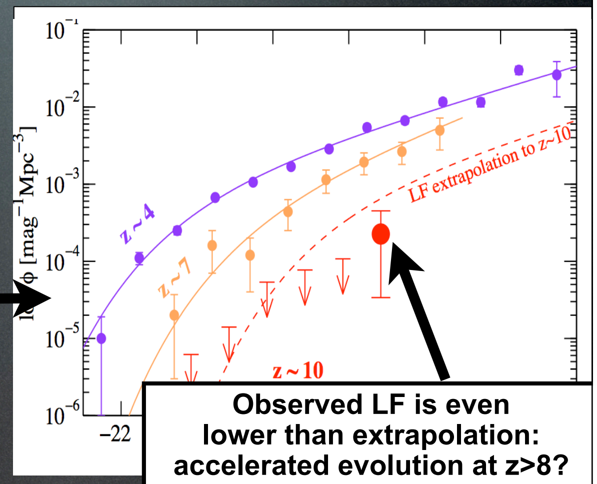
and >5.5σ, there is a small probability it could be spurious

What do z~10 searches teach us about galaxy build-up?

Search over HUDF, HUDF parallel fields, CDF-South (ERS+CANDELS)



Oesch et al. 2011 search (1 z~10 candidate)



Oesch et al. 2011; but see also Bouwens et al. 2011

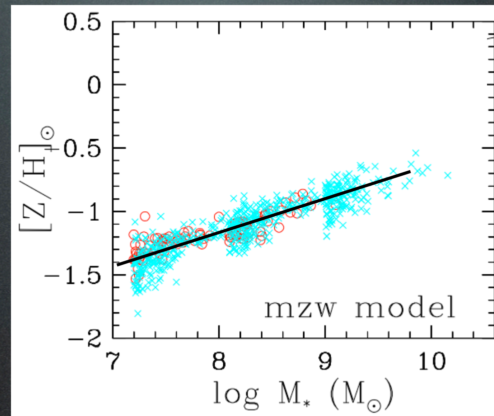
Galaxy LF grows rapidly...

But how quickly do *individual* galaxies build up at early cosmic times?

Does it occur regularly along a star-forming sequence?

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

Metallicity

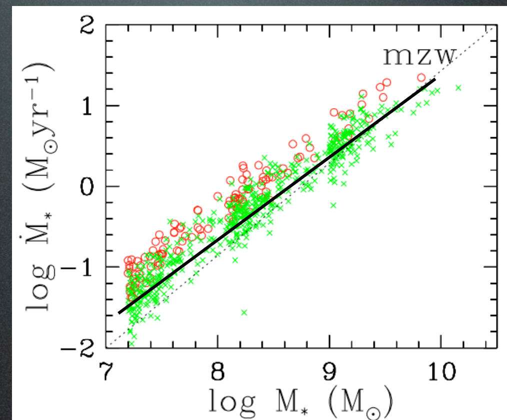


Stellar Mass

Dave et al. 2006; but see also results from other teams (Nagamine)

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

Star Formation Rate



Stellar Mass

Dave et al. 2006

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

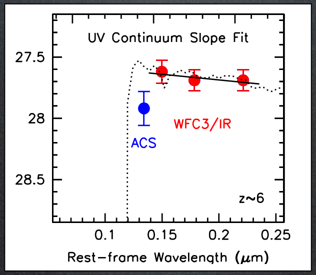
β

Do we find a tight color-magnitude relation in high redshift galaxies?

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

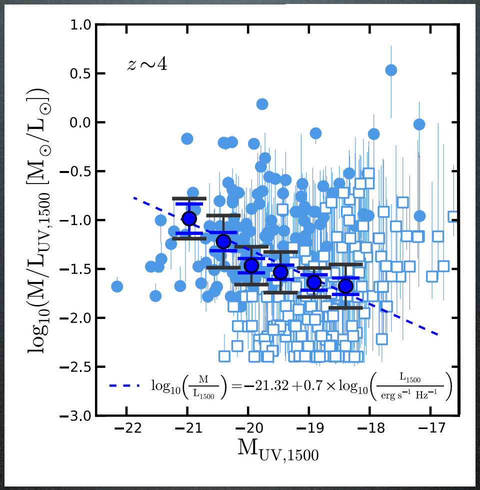
β

WFC3/IR allows us to probe the UV colors of $z \geq 4$ galaxies to high accuracy



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

Mass to Light Ratio



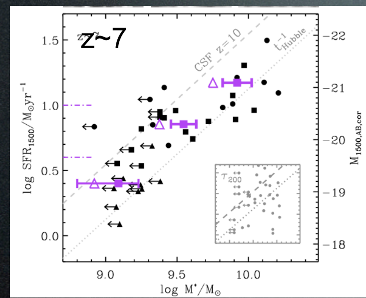
(Modulo Duty Cycle Uncertainties)

Gonzalez et al. 2011; Stark et al. 2009

==> Sequence of Star-forming Galaxies

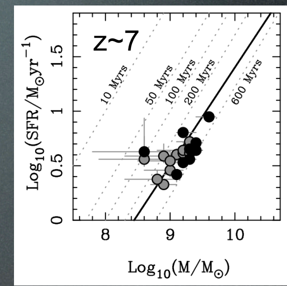
Labbe et al. 2010

SFR



Stellar Mass

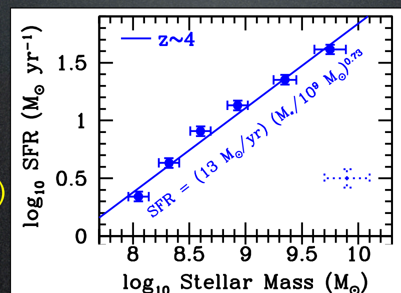
McLure et al. 2011



Stellar Mass

Bouwens et al. 2011

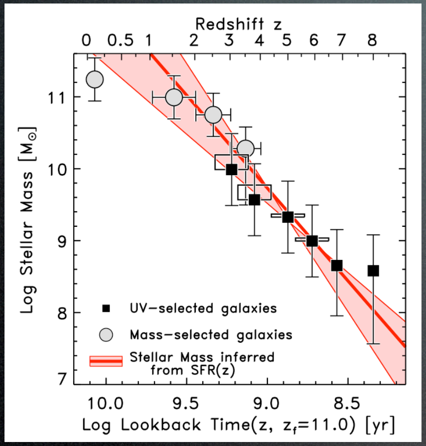
SFR (dusted corrected)



Stellar Mass

see also Stark et al. 2009

Once you have the LFs, SFR vs. stellar mass relationships, dust properties, and taking galaxies at a given part of the LF and integrating the evolution of galaxies forward, can we match the stellar mass in galaxies at late times?



While this works using the data and assumptions adopted by Papovich et al. 2011, it seems quite likely that this will need to be revisited based on future data...

as we determine the masses, dust properties, duty cycles, LFs, ... better

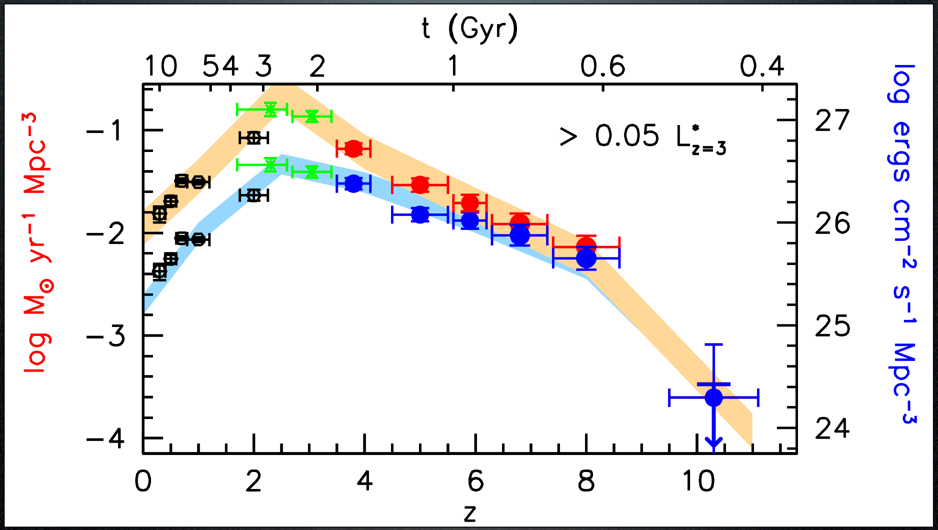
This will likely be an important activity going forwards...

Papovich et al. 2011

We can of course use the much better constraints on UV colors -- or UV continuum slopes of galaxies -- to update the SFR density or specific SFR evolution?

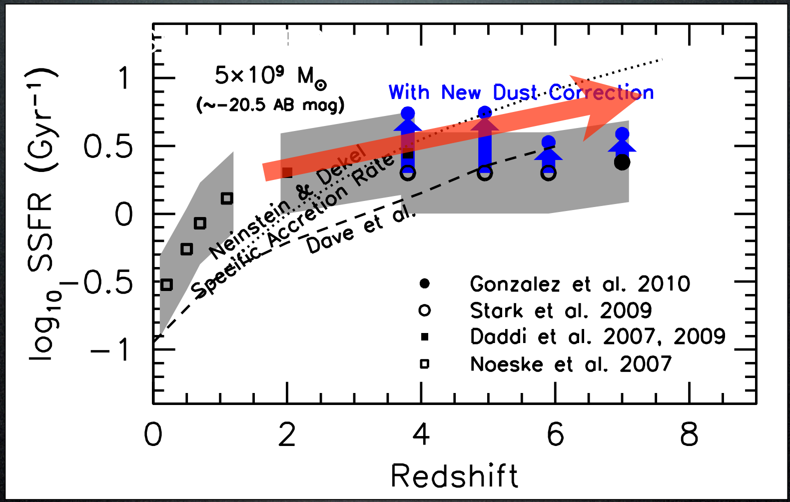
Integrating the UV LFs, we derive the SFR density

(illustrative results from Bouwens et al. 2011: similar results from other groups)



An interesting puzzle has been the mild evolution of SSFR(z)

Improved UV slopes imply higher dust extinction



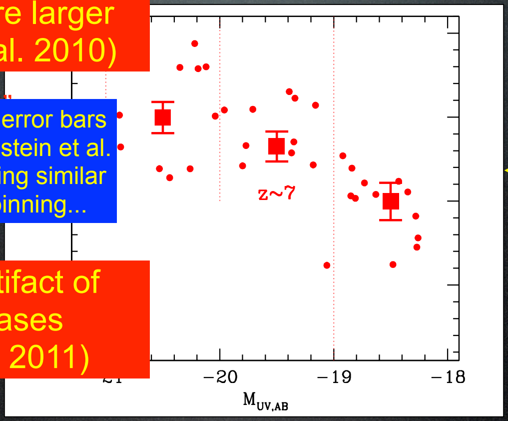
Bouwens et al. 2011; Gonzalez et al. 2010; Stark et al. 2009; Daddi et al. 2007, 2009; Noeske et al. 2007

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

Suggested real uncertainties are larger (Finkelstein et al. 2010)

Bouwens et al. 2010 error bars consistent with Finkelstein et al. 2010 errors when using similar sample sizes and binning...

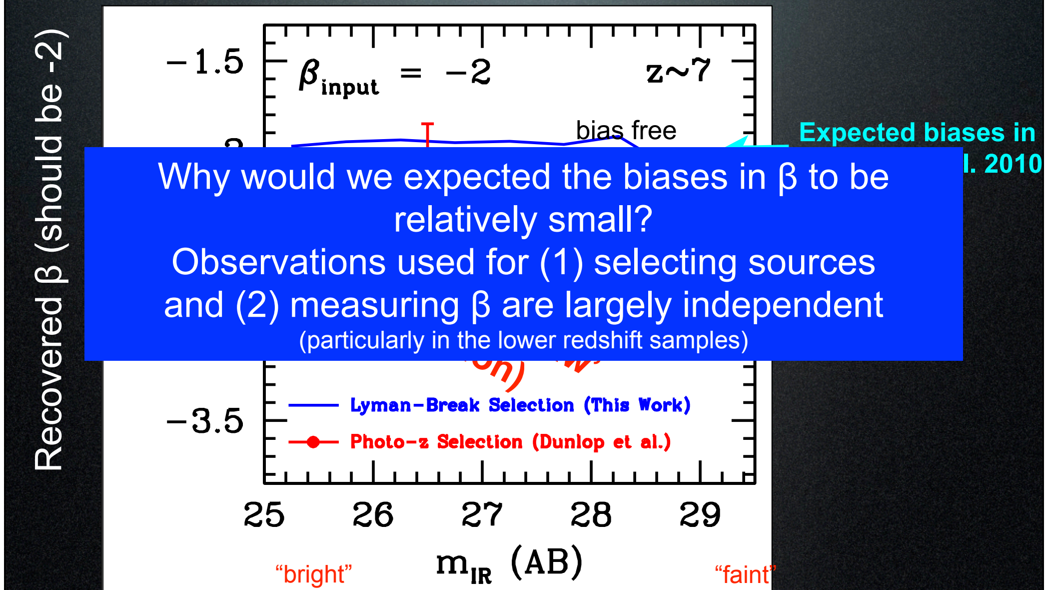
Blue colors artifact of selection biases (Dunlop et al. 2011)



bright Luminosity faint

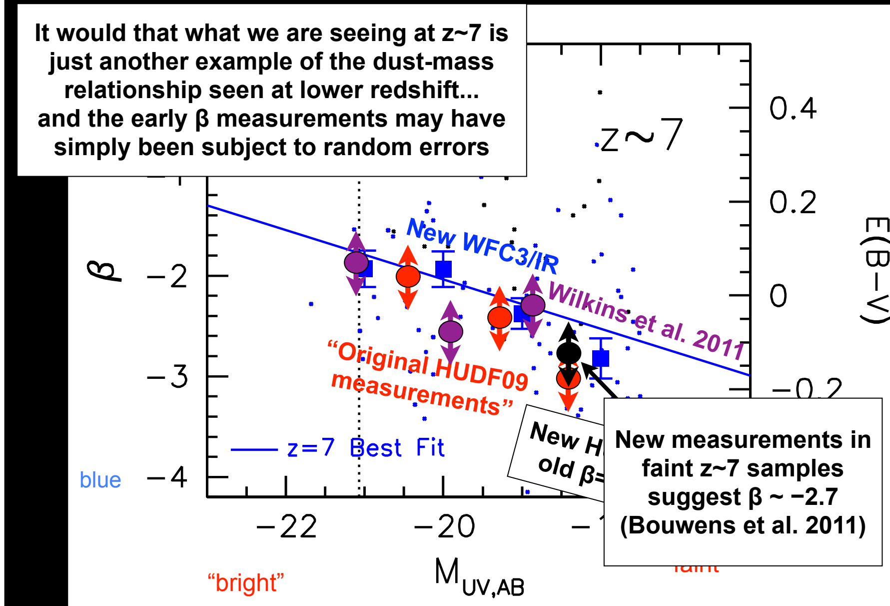
Early finding from WFC3/IR data (Bouwens et al. 2010)

Dunlop et al. (2011) suggested β = −3 measurement
was likely due to a bias....



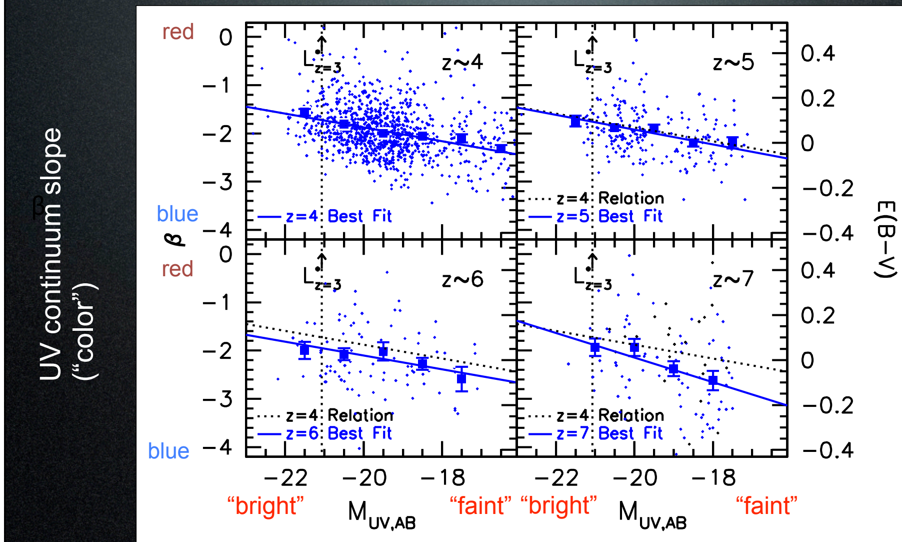
Why would we expected the biases in β to be relatively small?
Observations used for (1) selecting sources and (2) measuring β are largely independent
(particularly in the lower redshift samples)

Old versus new measurements of the UV-continuum slope β at z~7



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

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



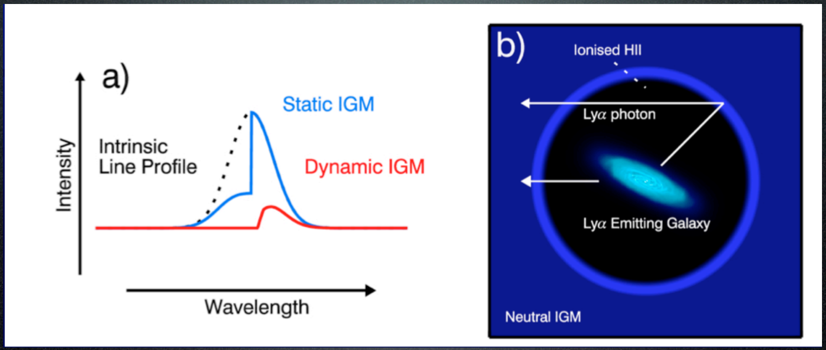
Bouwens et al. 2011; see also Bouwens et al. 2009, 2010; Wilkins et al. 2011; Dunlop et al. 2011

Reionization of the Universe

When? Are galaxies responsible?

Reionization of the Universe

Can we learn anything about when reionization occurs -- due to the effects of a more neutral IGM in weakening Lyα emission from galaxies?



-- Neutral hydrogen in IGM will weaken the Lyα emission from galaxies

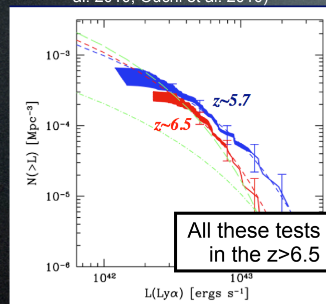
-- The fraction of Lyα emitters in a high-redshift galaxy population should decrease as the universe becomes more neutral.

(Slide adapted from one by Dan Stark)

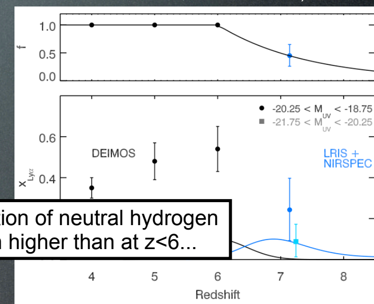
Reionization of the Universe

-- Neutral hydrogen in IGM will weaken the Lya emission from galaxies

Kashikawa et al. 2011 (but see also Hu et al. 2010; Ouchi et al. 2010)



Schenker et al. 2011 (but see also Pentericci et al. 2011; Ono et al. 2011)



All these tests suggest the fraction of neutral hydrogen in the z>6.5 universe is much higher than at z<6...

Lyα LF shows a substantia
from z~5.7 t

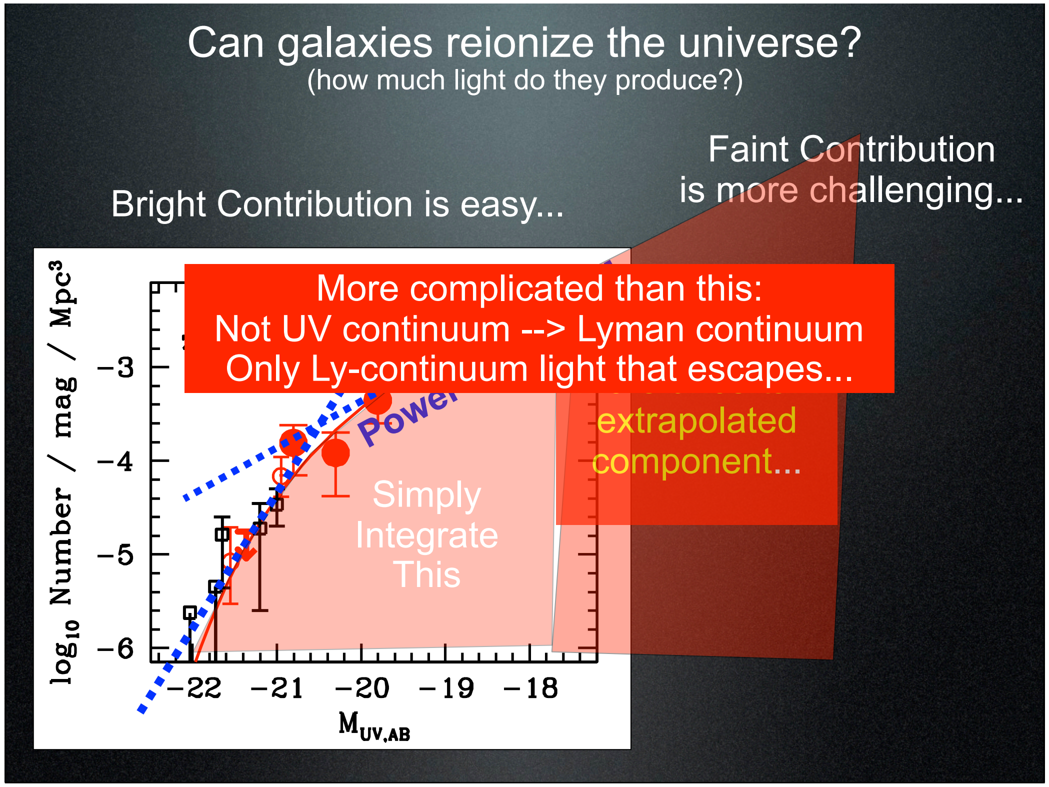
Of course, caution is advised since such changes can also occur due to evolution in the galaxy population... or even the density of the universe itself

of Lyα emitters seen in
we would expect 50% to
α emission

with spectroscopy shows a prevalence of Lyα emission that is >5x smaller

Kashikawa et al. 2011; Hu et al. 2010; Ouchi et al. 2010; Stark et al. 2010; Schenker et al. 2011; Pentericci et al. 2011; Fontana et al. 2011; Ono et al. 2011

Do galaxies drive reionization?


Can galaxies reionize the universe?
(how much light do they produce?)
Bright Contribution is easy...
Faint Contribution
is more challenging...
More complicated than this:
Not UV continuum --> Lyman continuum
Only Ly-continuum light that escapes...
Power
extrapolated
component...
Simply
Integrate
This
log10 Number / mag / Mpc3
−3
−4
−5
−6
−22
−21
−20
−19
−18
MUV,AB

Can galaxies reionize the universe?

(how much light do they produce?)

How big is the correction for unseen faint sources?

Very sensitive to faint-end slope...

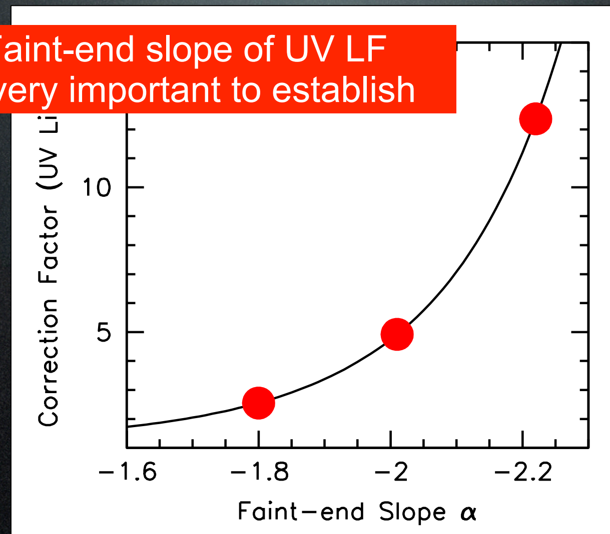
Can galaxies reionize the universe?

(how much light do they produce?)

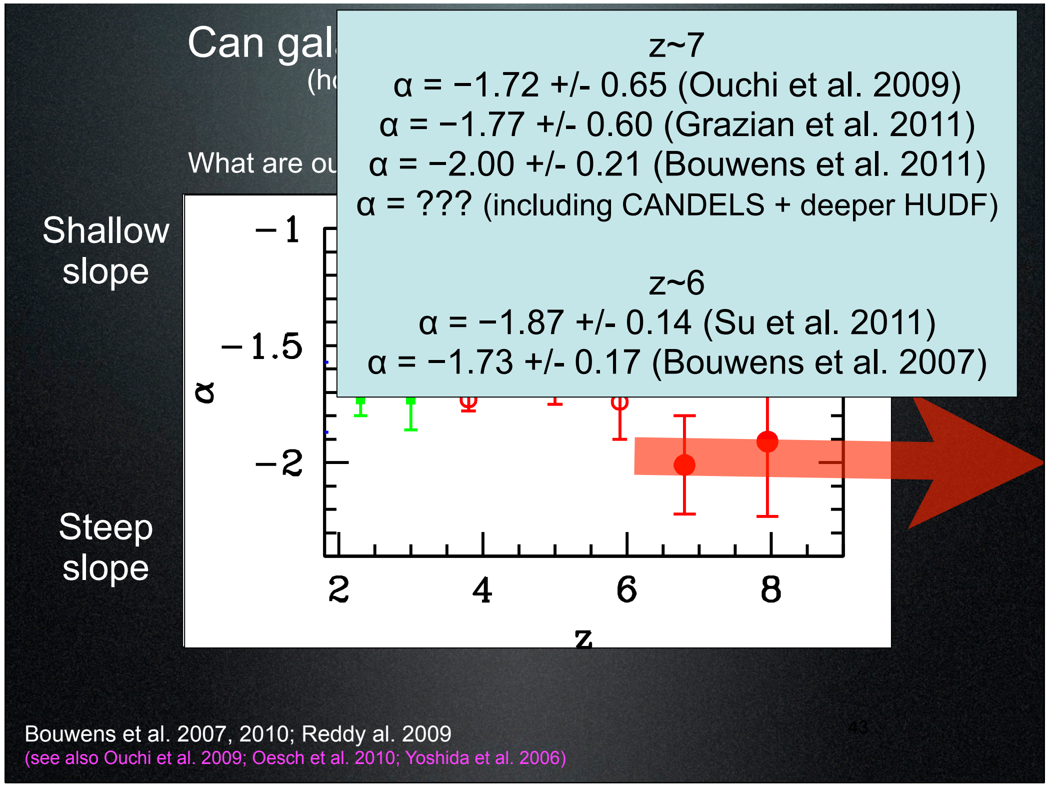
Correction (for unseen sources) depends very sensitively on faint-end slope

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

Faint-end slope of UV LF is very important to establish



Bouwens et al. 2011


Can gal
(h
What are ou
z~7
α = −1.72 +/- 0.65 (Ouchi et al. 2009)
α = −1.77 +/- 0.60 (Grazian et al. 2011)
α = −2.00 +/- 0.21 (Bouwens et al. 2011)
α = ??? (including CANDELS + deeper HUDF)
z~6
α = −1.87 +/- 0.14 (Su et al. 2011)
α = −1.73 +/- 0.17 (Bouwens et al. 2007)
Shallow slope
Steep slope
−1
−1.5
−2
α
2
4
6
8
z
Bouwens et al. 2007, 2010; Reddy al. 2009
(see also Ouchi et al. 2009; Oesch et al. 2010; Yoshida et al. 2006)

Can galaxies reionize the universe?

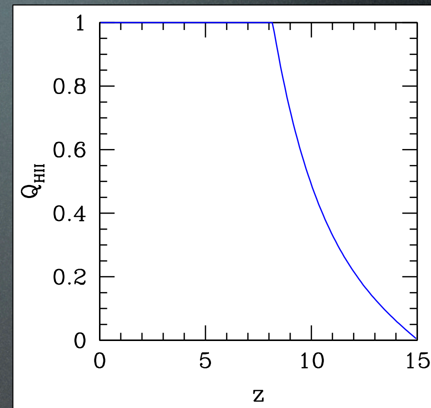
(how much light do they produce?)

Adopt observed UV LFs and extrapolate to higher redshifts

Other Details:

- Integrate to Very Low luminosities: -10 mag
- Clumping Factor ~3 (Bolton et al. 2005; Pawlik et al. 2009)
- Escape Fraction ~20%

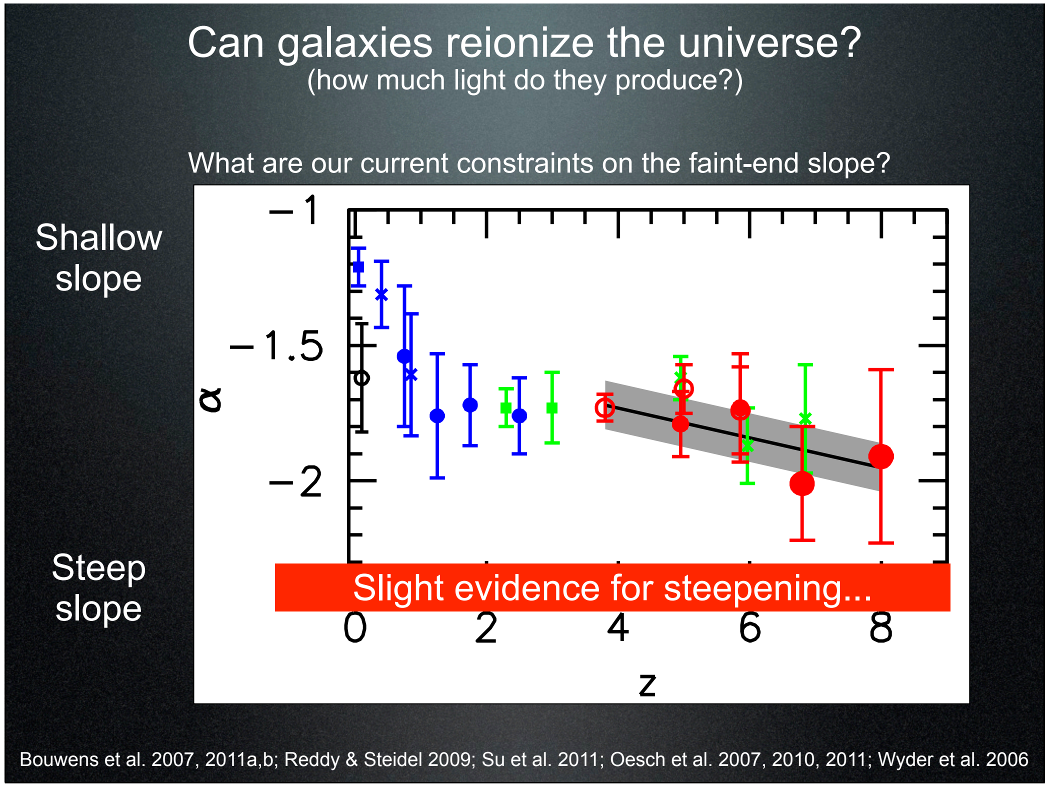
→



Can we match the Thompson optical depth found by WMAP, τ ~ 0.088 ± 0.015?

→ Thomson optical depth τ ~ 0.066

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
−1
−1.5
−2
α
0
2
4
6
8
z
Slight evidence for steepening...
Bouwens et al. 2007, 2011a,b; Reddy & Steidel 2009; Su et al. 2011; Oesch et al. 2007, 2010, 2011; Wyder et al. 2006

Can galaxies reionize the universe?

(how much light do they produce?)

Adopt observed UV LFs and extrapolate to higher redshifts

Other Details:

- Integrate to Very Low luminosities: -10 mag
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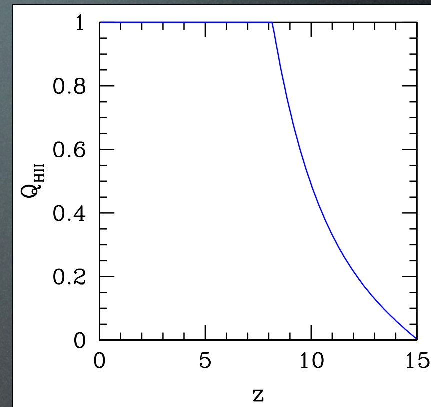
- Escape Fraction ~20%

→



Can we match the Thompson optical depth found by WMAP, $\tau \sim 0.088 \pm 0.015$?

→ Thomson optical depth $\tau \sim 0.080$

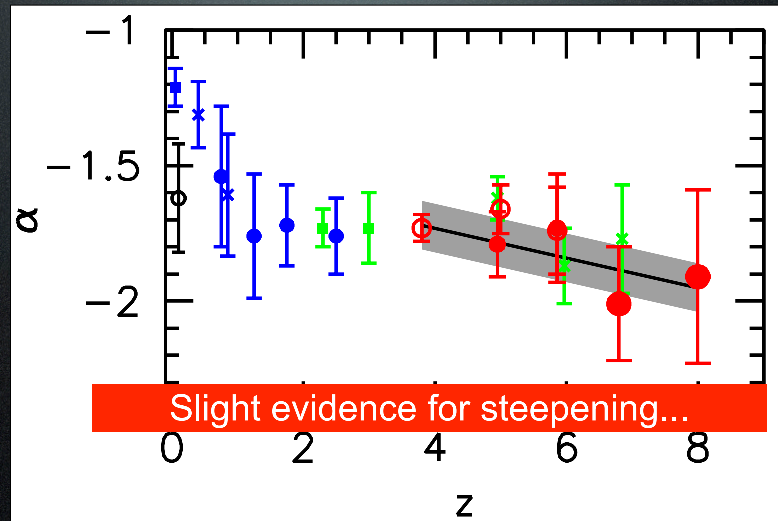
Bouwens et al. 2011

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

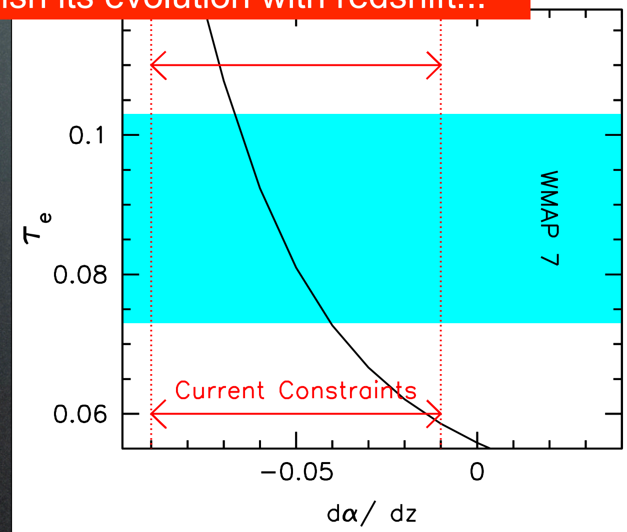
Bouwens et al. 2007, 2011a,b; Reddy & Steidel 2009; Su et al. 2011; Oesch et al. 2007, 2010, 2011; Wyder et al. 2006

Can galaxies reionize the universe?

(how much light do they produce?)

Establish its evolution with redshift...

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



Bouwens et al. 2011; see also Yan & Windhorst 2004

The First (z>5) Galaxies: What we can learn from the observations

New instrumentation -- especially WFC3/IR -- allows us to very efficiently identify galaxies at high redshift. More than 100 galaxy candidates known at z>6.5. Soon the number will be > 200.

The evolution of the UV LF continues very smoothly from z~8 to z~4, with continued exponential growth in the LF.

One plausible z~10 candidate in current observations. Its volume density is even lower than that expected extrapolating LF evolution to z>8 -- suggesting accelerated evolution.

A tight UV-continuum slope vs. luminosity sequence is found for z~4-7 galaxies. This presumably a mass metallicity relationship.

Current observations support the existence of a sequence of star-forming galaxies at z>4, similar to what is found at lower redshift.

Integrating this forward, one can plausibly match the evolution seen in the stellar masses of galaxies at bright end of LF

The total flux density in ionizing photons is very sensitive to the faint-end slope. Given current uncertainties in the slope, deeper observations are absolutely necessary.

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.