Observational constraints on the first stellar generations, galaxies, and black holes

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32nd IAP Colloquium

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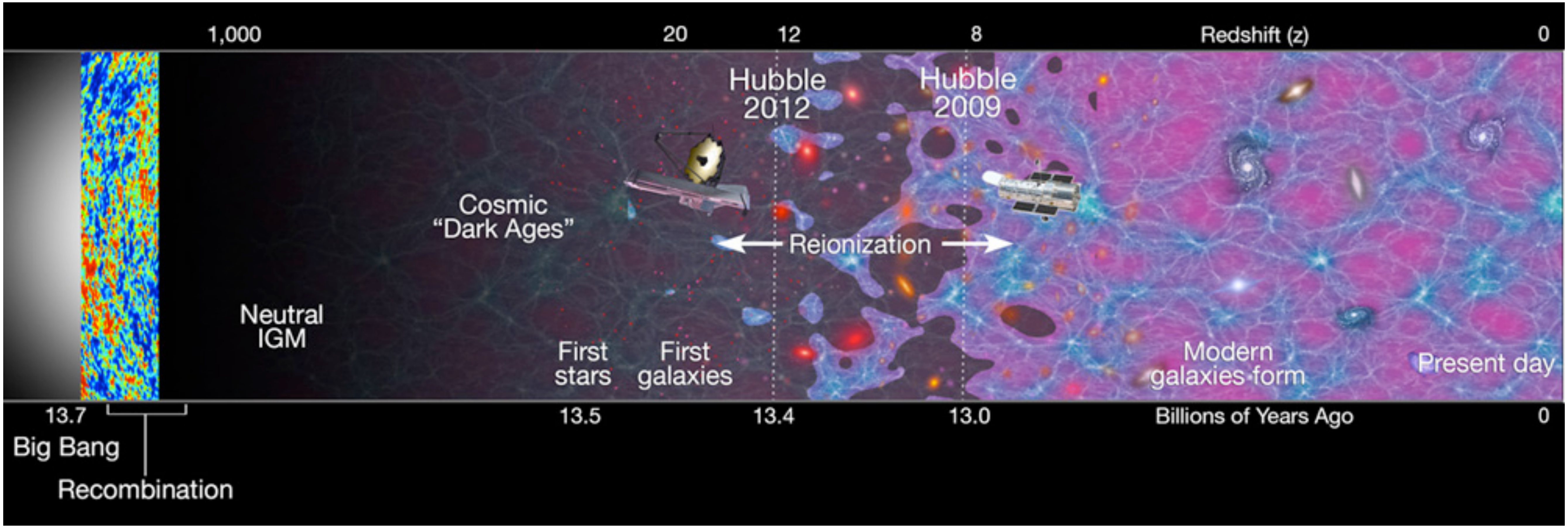
Overview

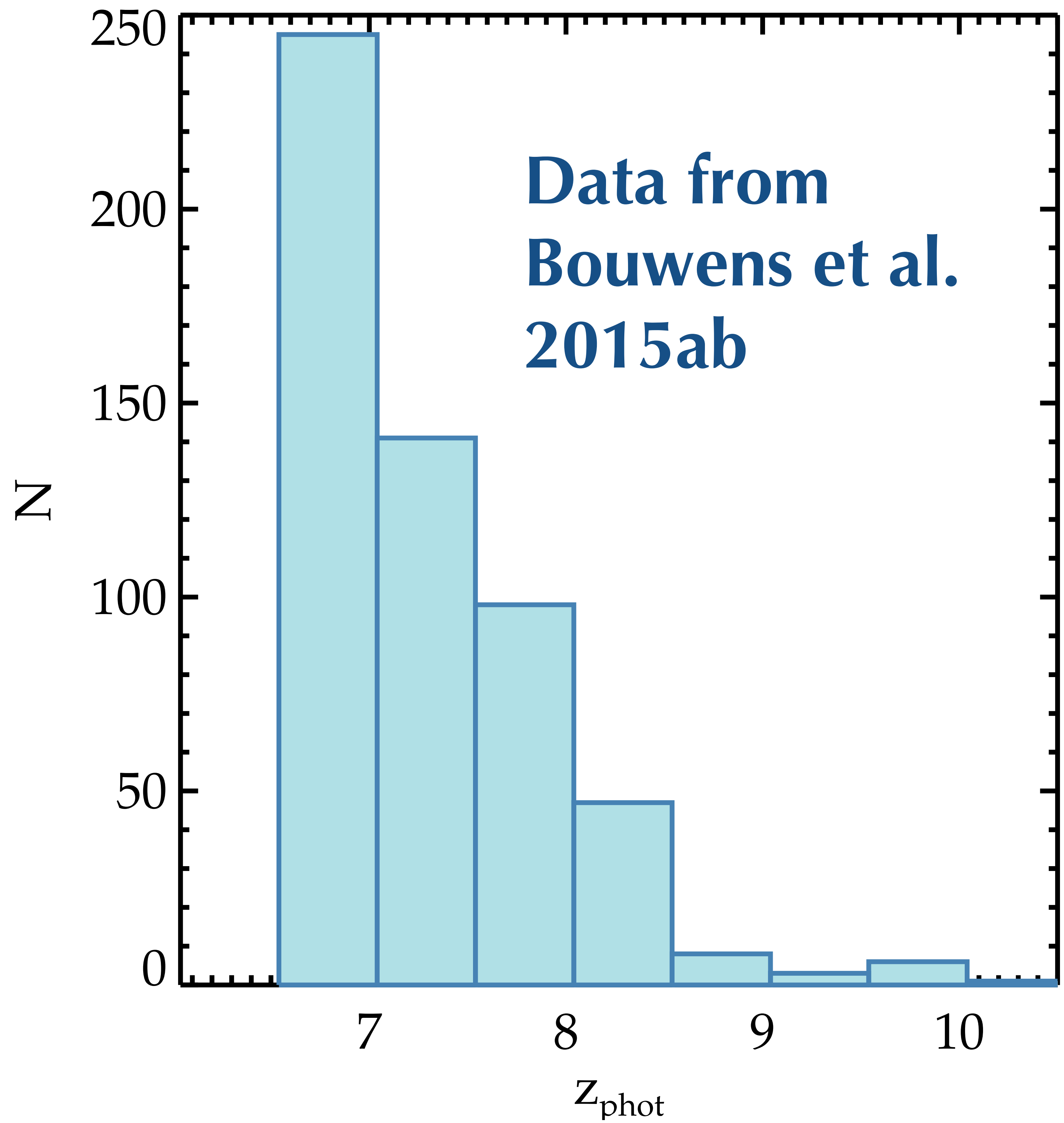


I. Census of Galaxies and Quasars in the Reionization Era

II. Spectral Properties of Galaxies at z>6

III. Reionization

Galaxies in the Reionization Era



Large samples: ~550 z>6.5 galaxies from HST imaging

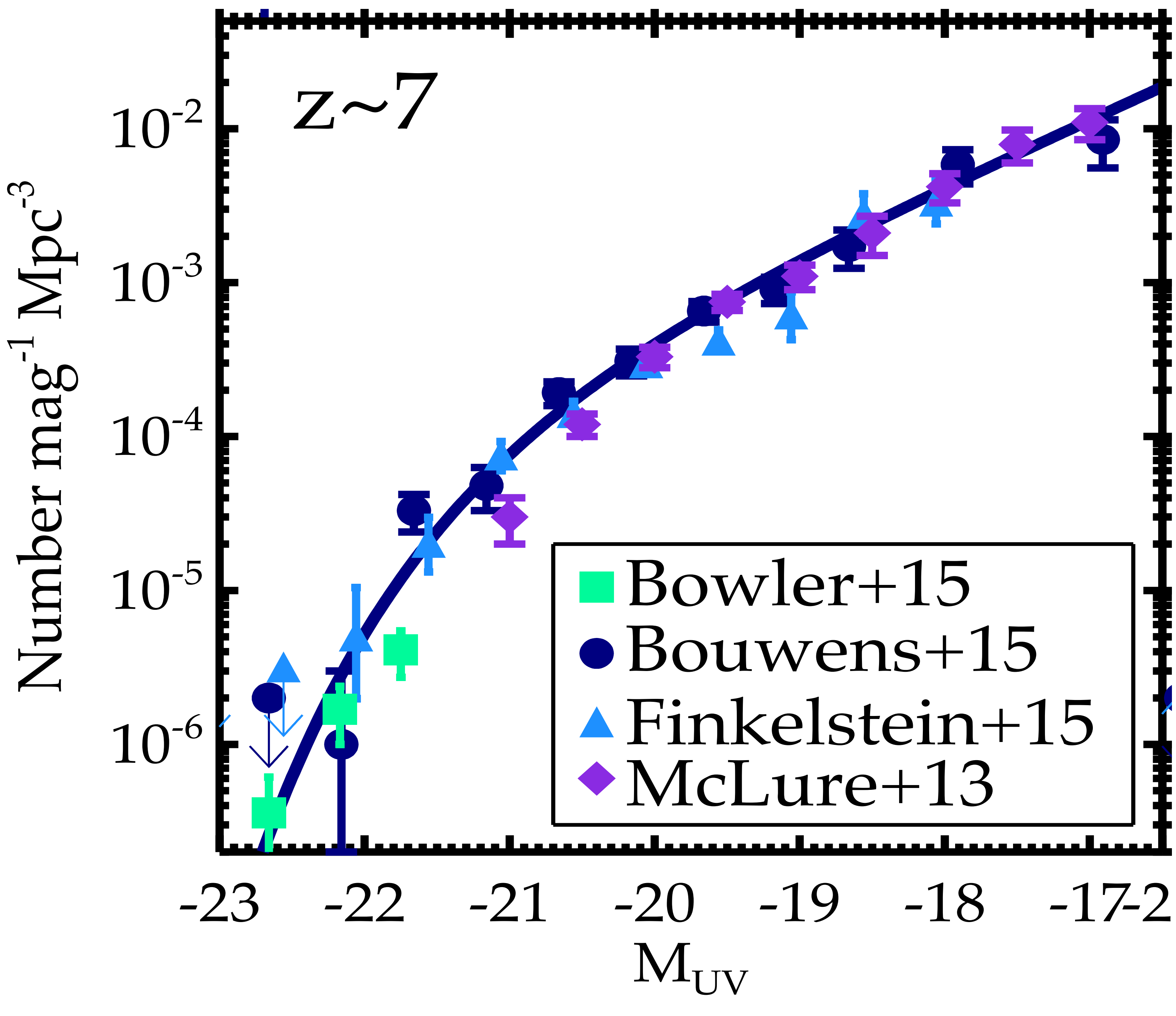
Large dynamic range in luminosity: ΔM_{UV} ~ 6

SFR ~ 0.5 - 300 $M_\odot$/yr

(from z~7-8 SFR functions in Smit+15, arXiv:1511.08808)

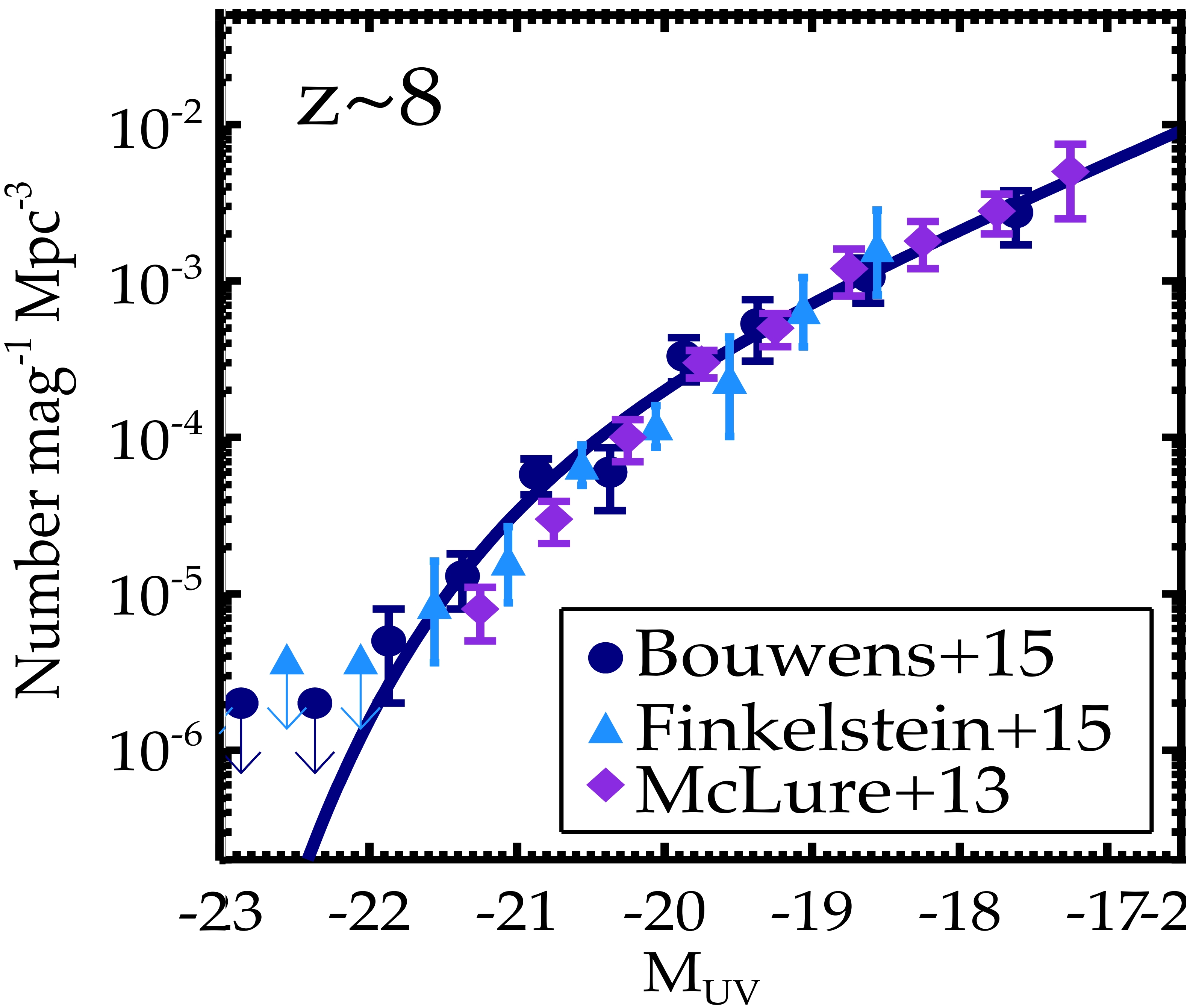
see also Finkelstein+15, McLure+13, Bowler+14,15, McLeod+15

Census of Galaxies in the Reionization Era



from Stark 2016, ARAA

Census of Galaxies in the Reionization Era

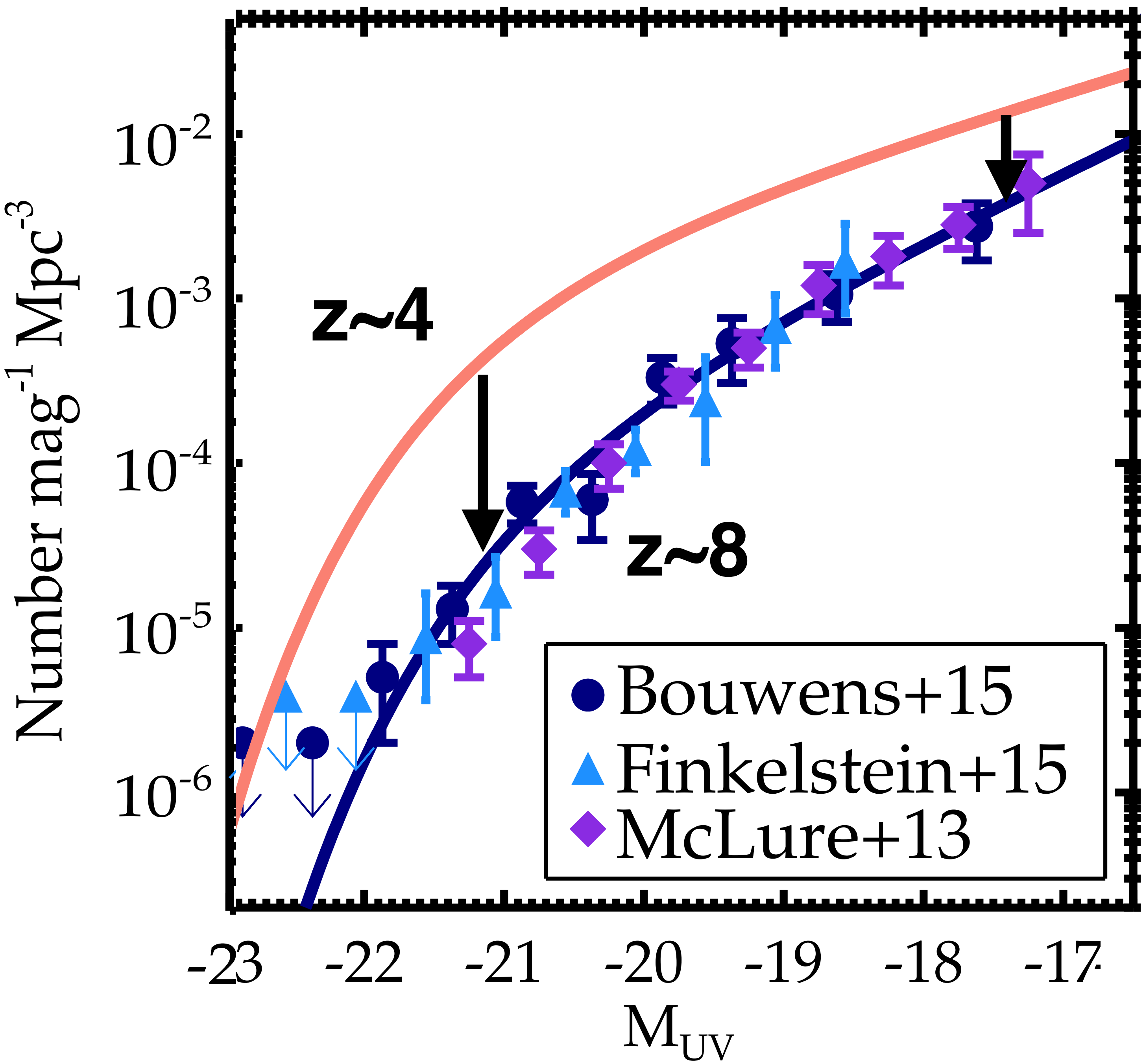


Rapid evolution at 7<z<8:

In just 125 Myr, volume density of luminous (M_{UV}=-21.5) galaxies decreases by ~2.5x

from Stark 2016, ARAA

Census of Galaxies in the Reionization Era



Evolution more pronounced over 4<z<8

Volume density of M_{UV}=-21 galaxies decreases by 15-20x

Volume density of M_{UV}=-18.5 galaxies decreases by 2-3x

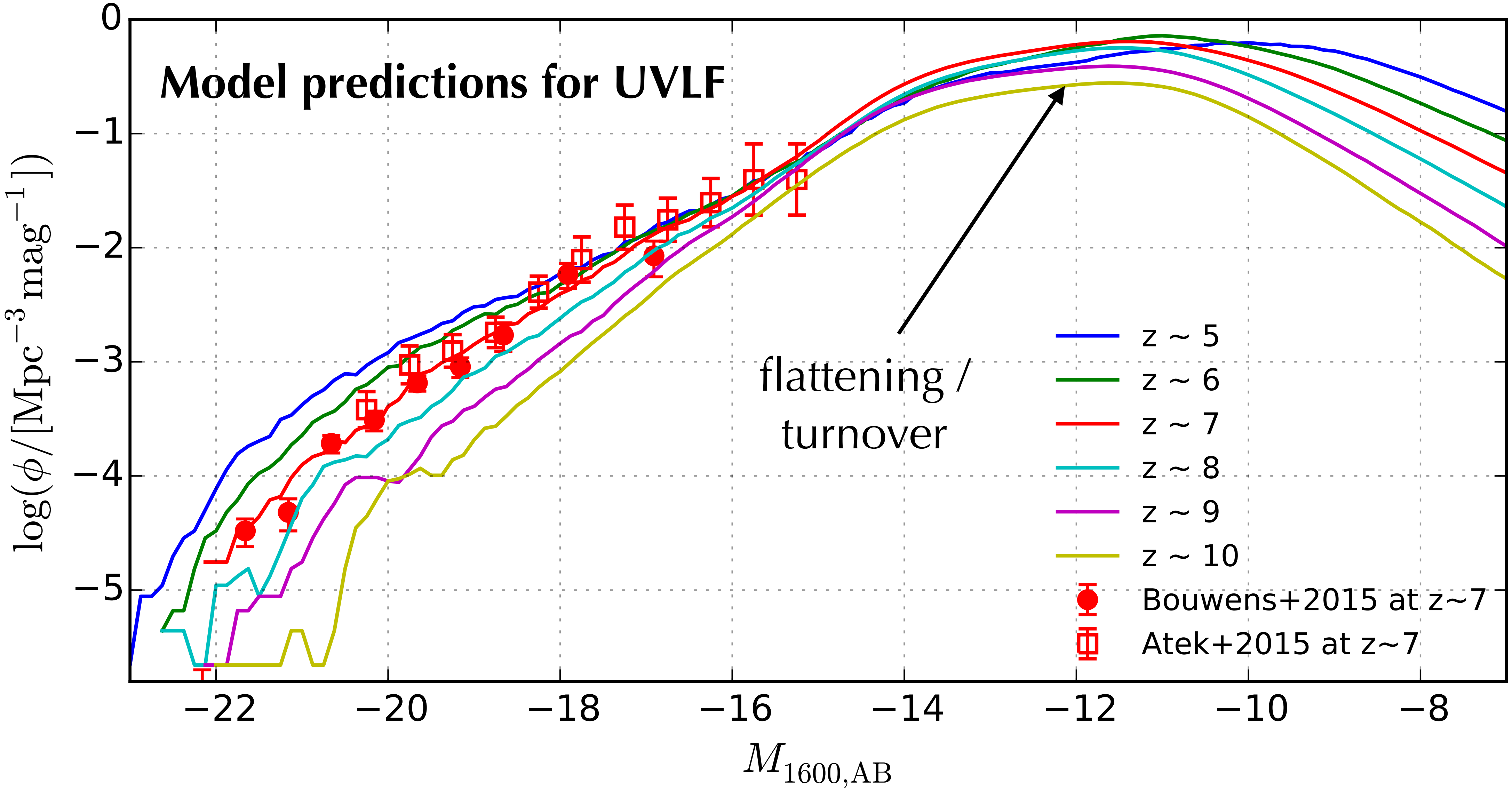
Faint end slope steepens

$\boldsymbol{\alpha}$(z~4)=-1.6 -> $\boldsymbol{\alpha}$(z~7)=-2.1

adapted from Stark 2016, ARAA

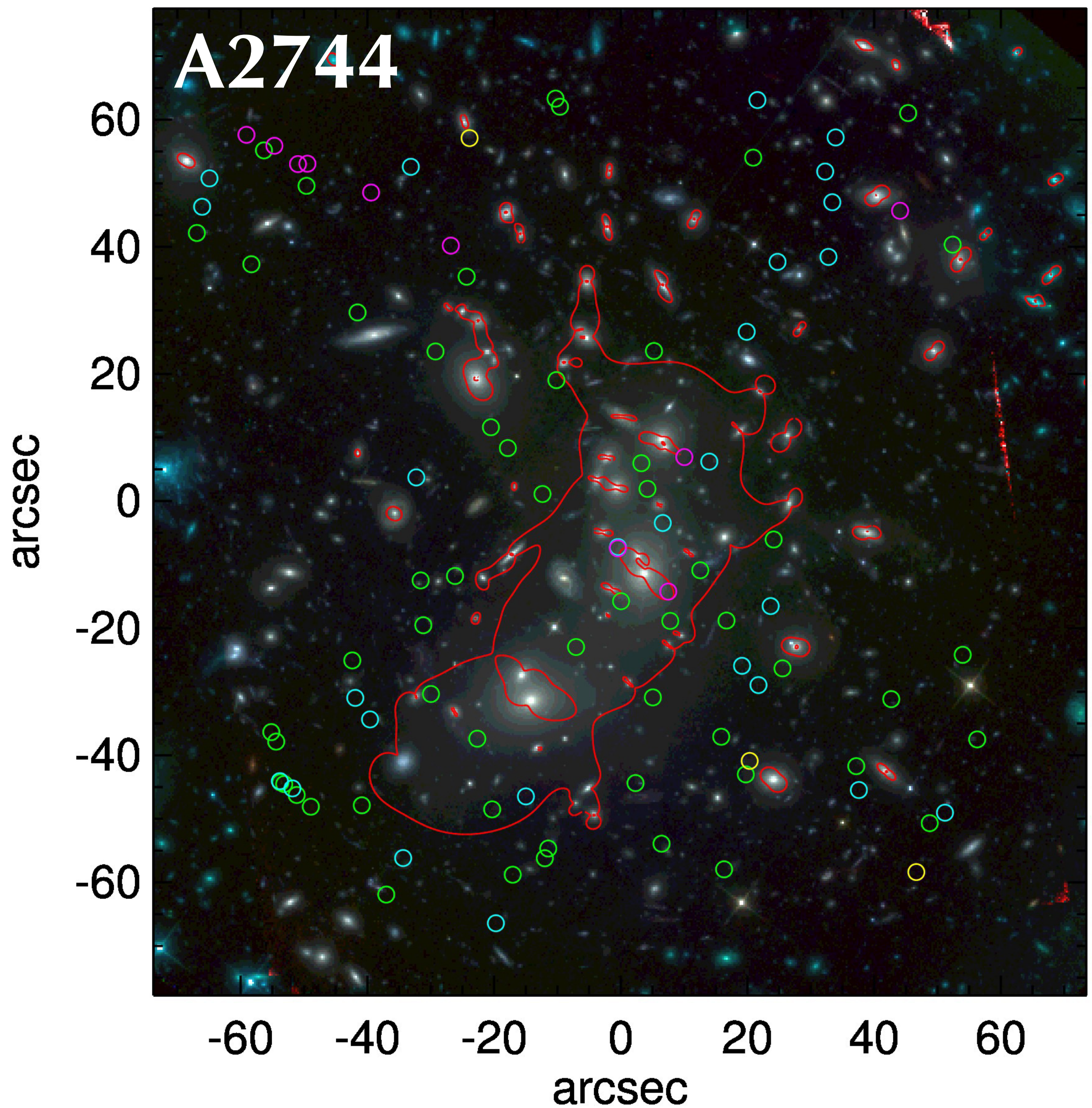
How faint can UV LF be extrapolated?

Liu+15, arxiv:1512.00563



Turnover expected due to inefficient cooling in halos below ~10^8 $M_\odot$

Progress from Hubble Frontier Fields



New constraints on UV LF from HST Frontier Field (HFF) Initiative.

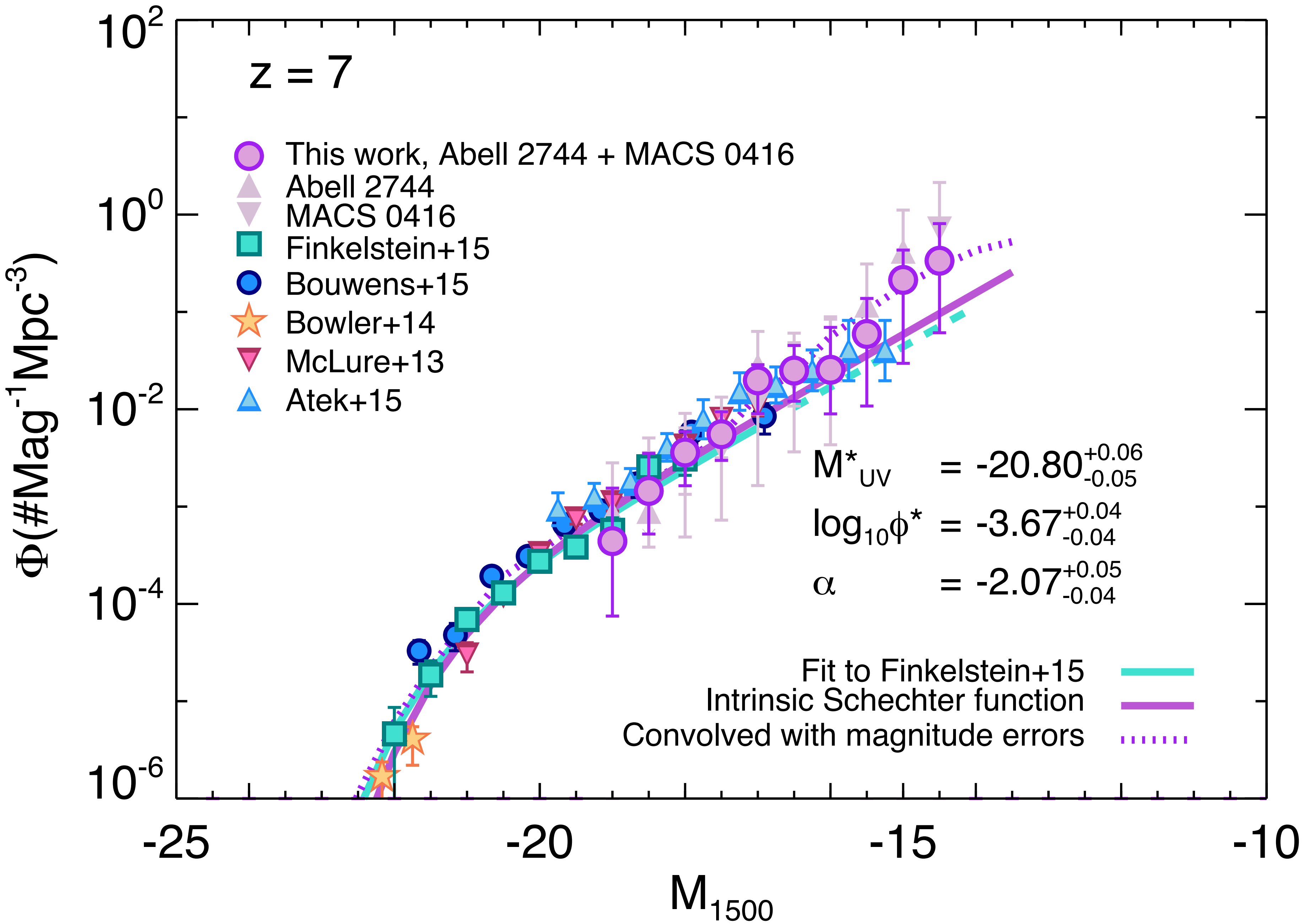
- WFC3 imaging of 6 cluster lensing fields
- deep parallel blank field imaging

Magnification provided by cluster enables investigation of where UV LF turns over.

Livermore+16, arXiv:1604.06799

No evidence for turnover in UV LF?

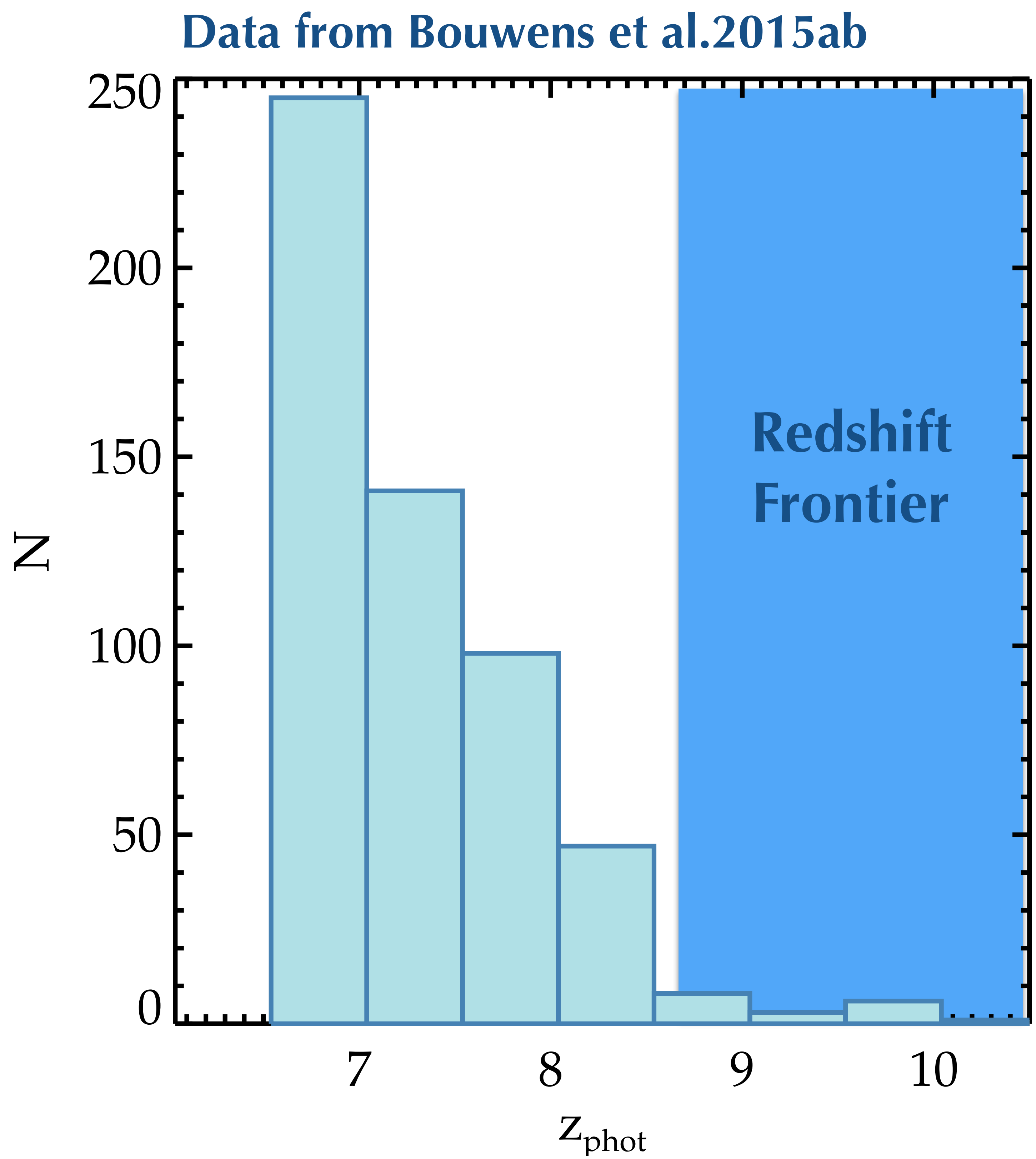
Livermore+16, arXiv:1604.06799



Recent studies suggest UV LF continues to rise to $M_{UV} \sim -15$ at z~7.

see also Atek et al. 2015, Oesch et al. 2015, Ishigaki et al. 2015, McLeod et al. 2016.

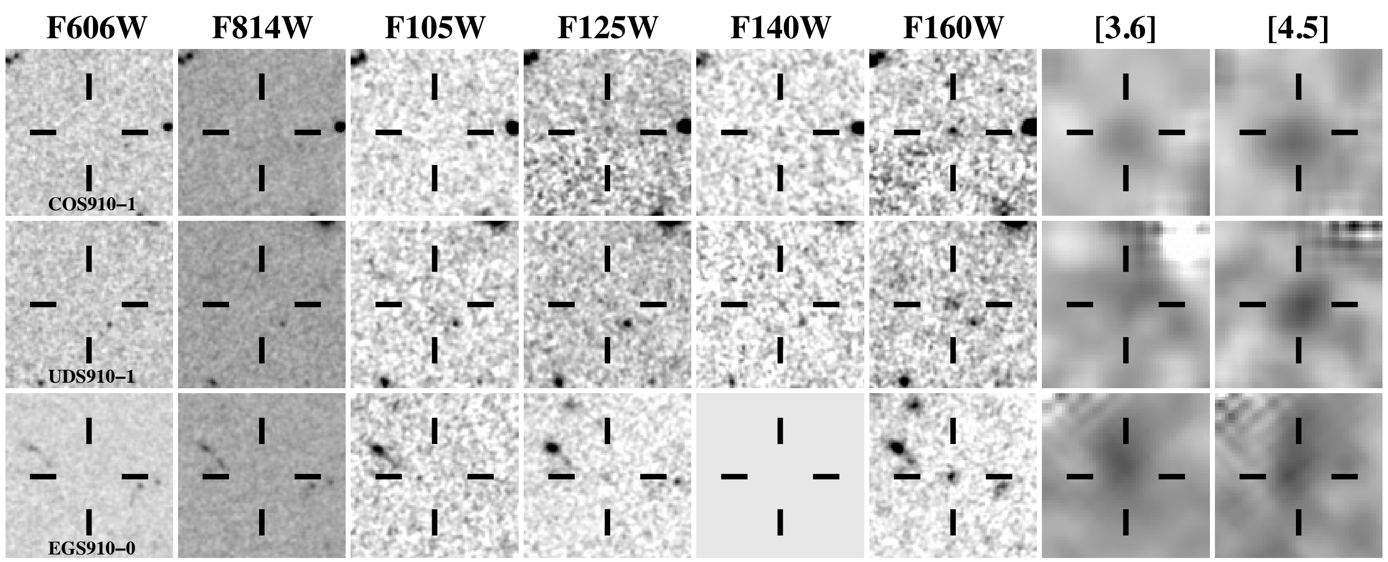
Star Forming Galaxies at z>8: The Redshift Frontier



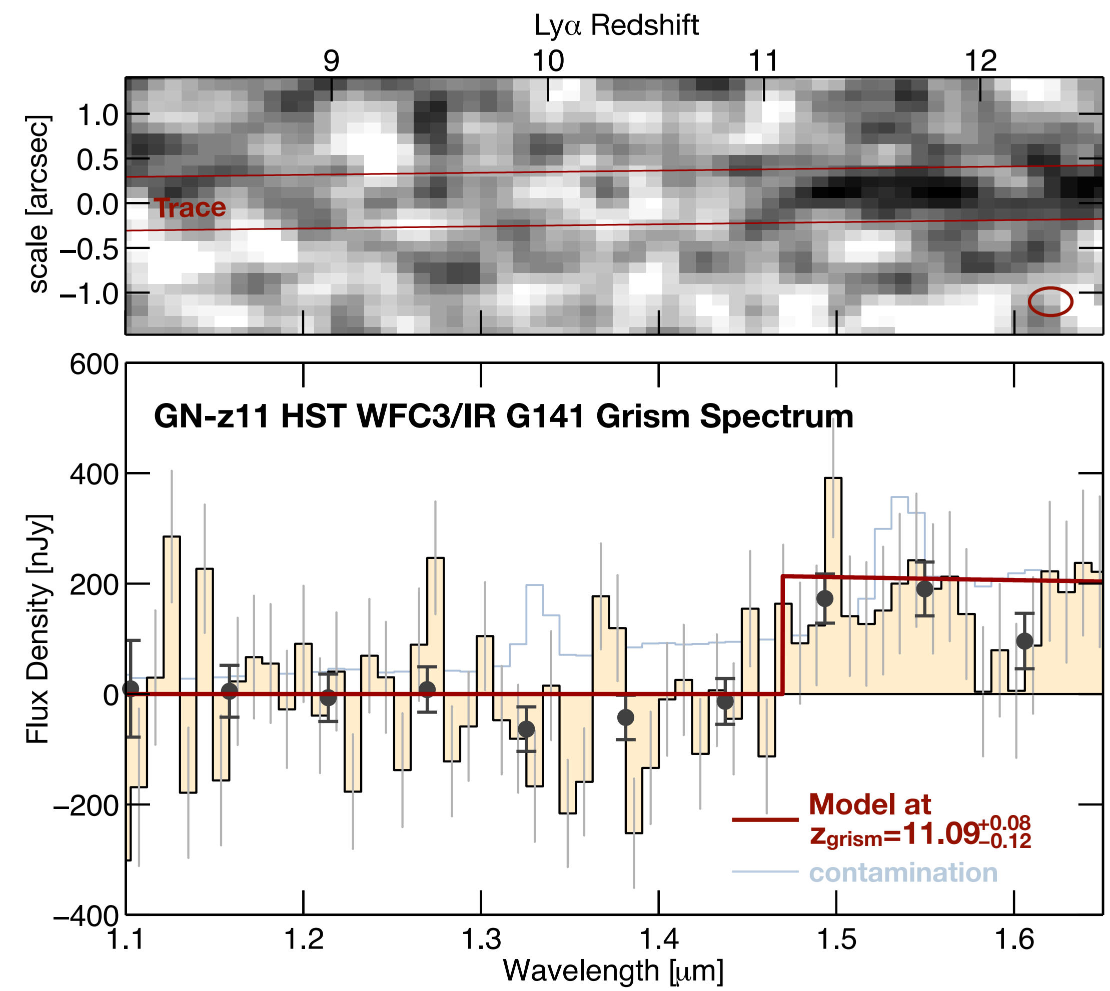
see also Finkelstein+15, McLure+13, Bowler+14,15, McLeod+15

Galaxies at z>8

Bouwens et al. 2015b, arXiv:1506.01035



Oesch et al. 2016, ApJ, 819, 129



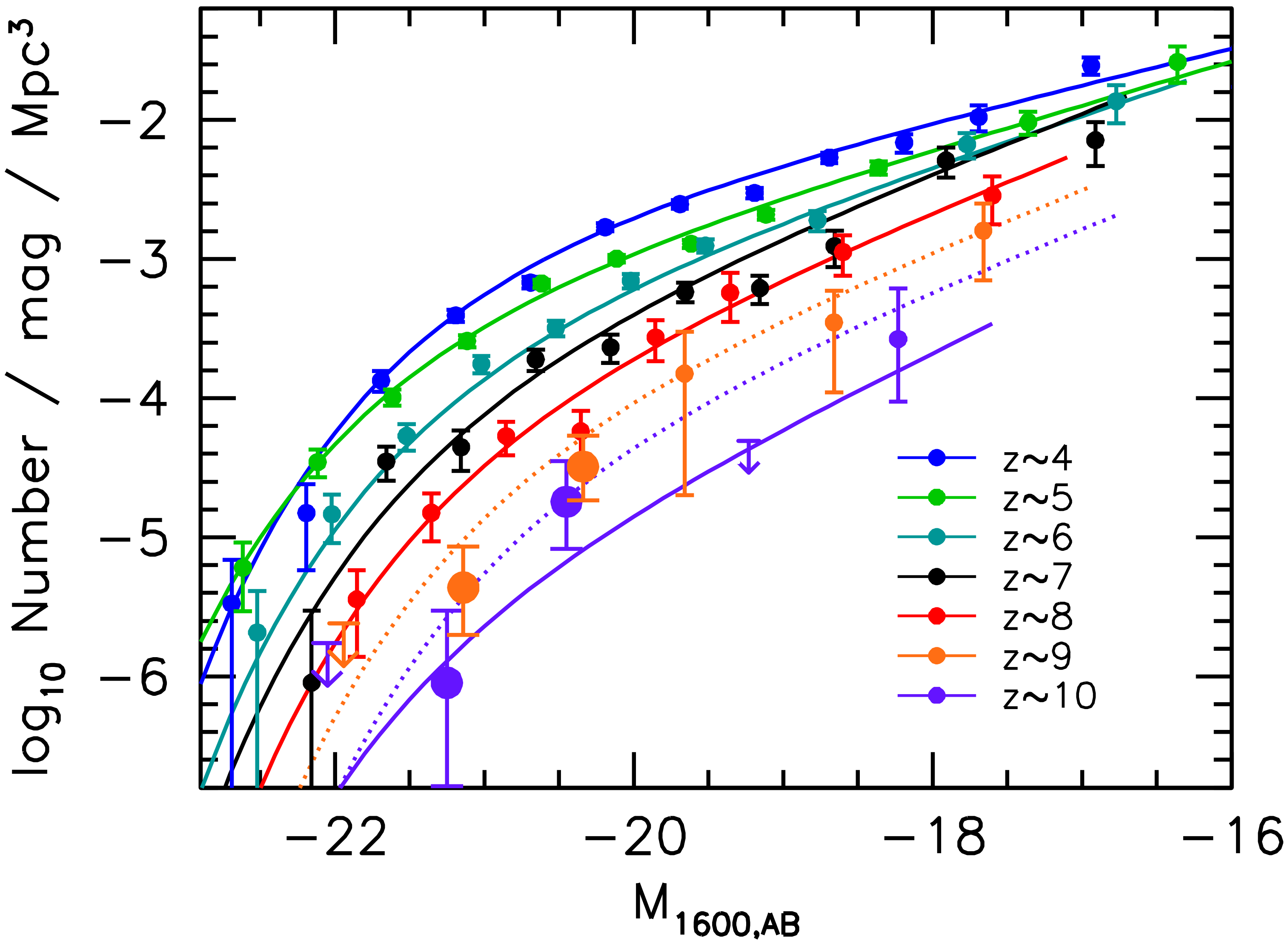
McLeod McLure, & Dunlop 2016, MNRAS, 459, 3812

10s of z~9-10 candidates now identified in CANDELS, UDF, HFF

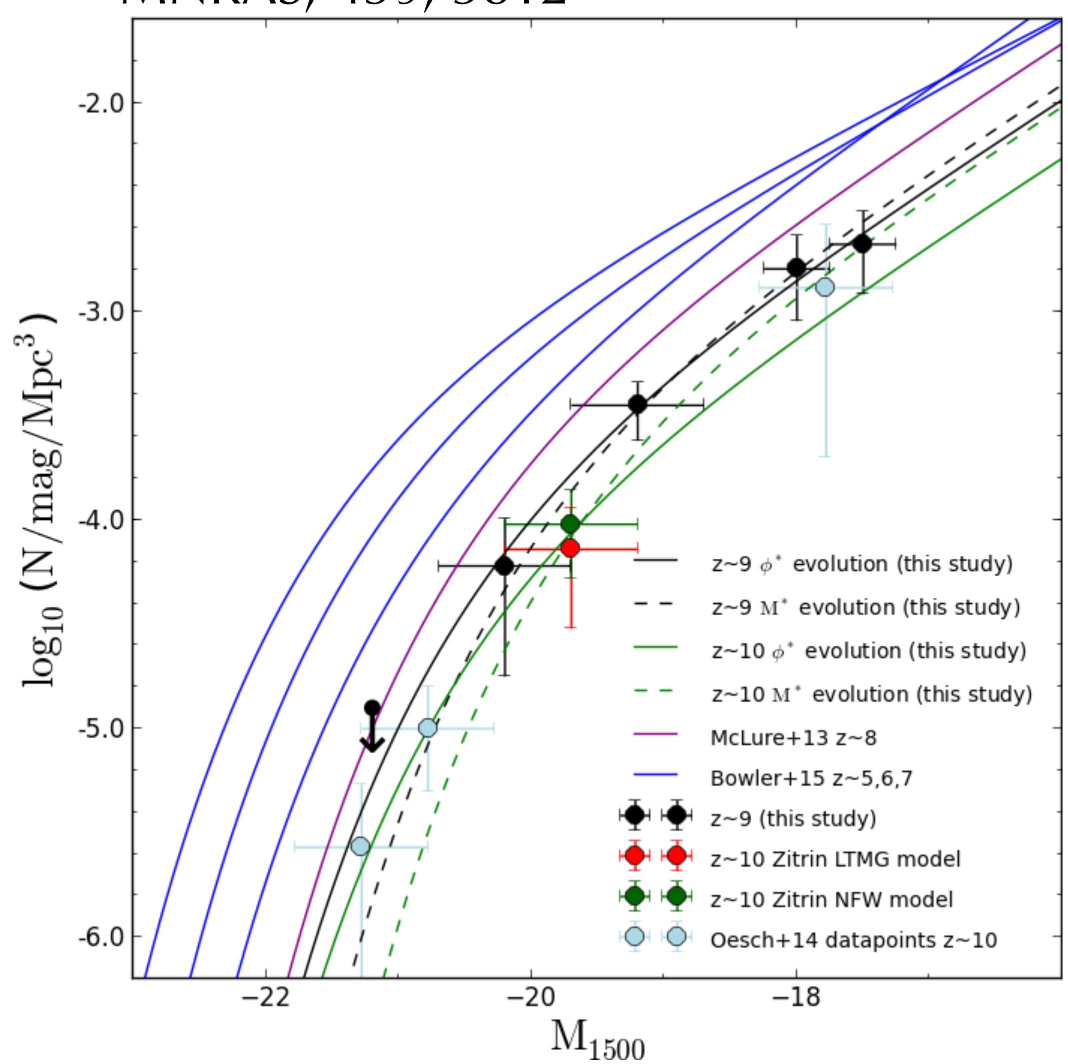
WFC3/IR grism confirmation of a z~11 galaxy (Oesch+16).

The z~9-10 UV luminosity function

Bouwens et al. 2015, arXiv:1506.01035



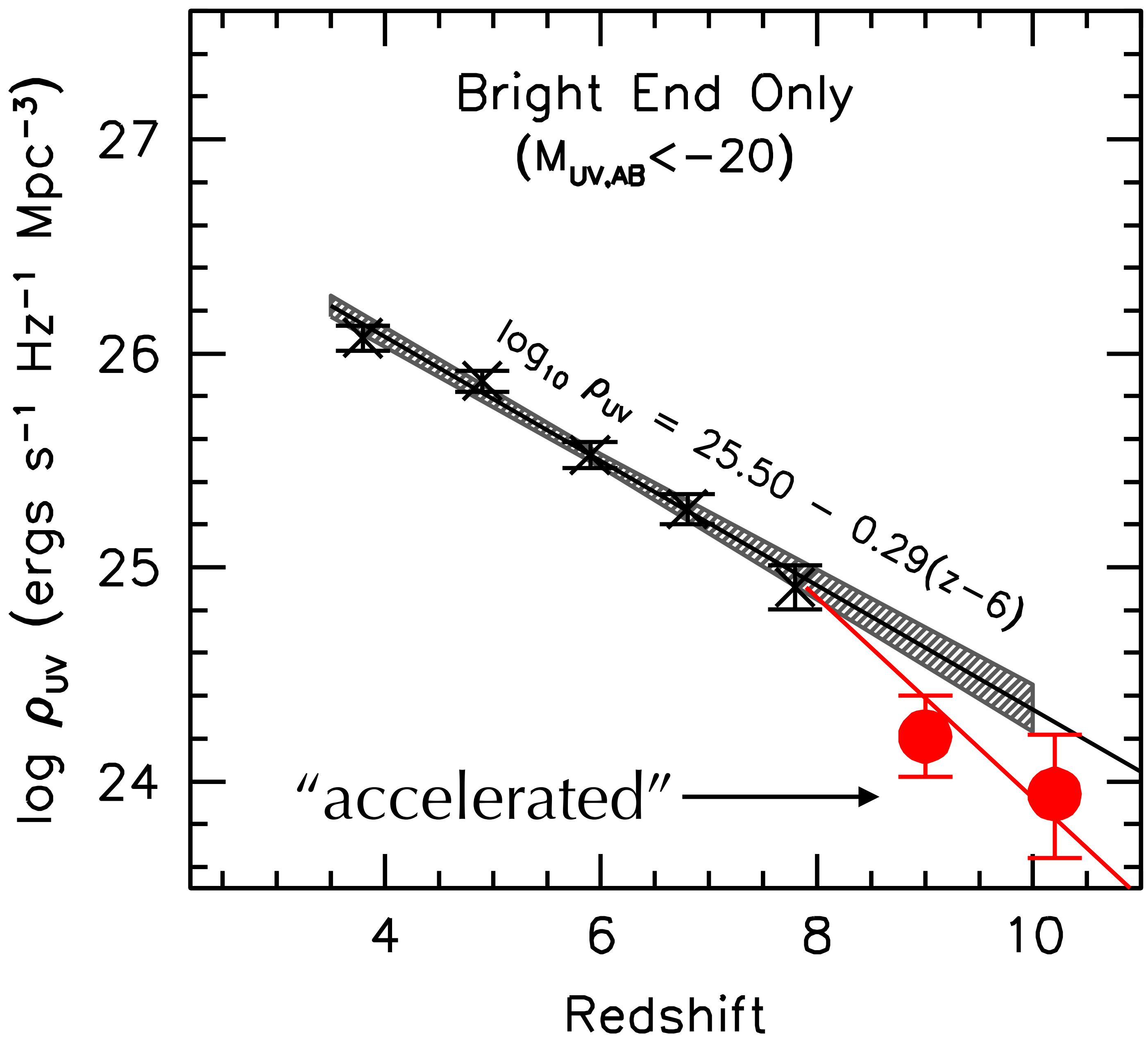
McLeod, McLure, & Dunlop, 2016, MNRAS, 459, 3812



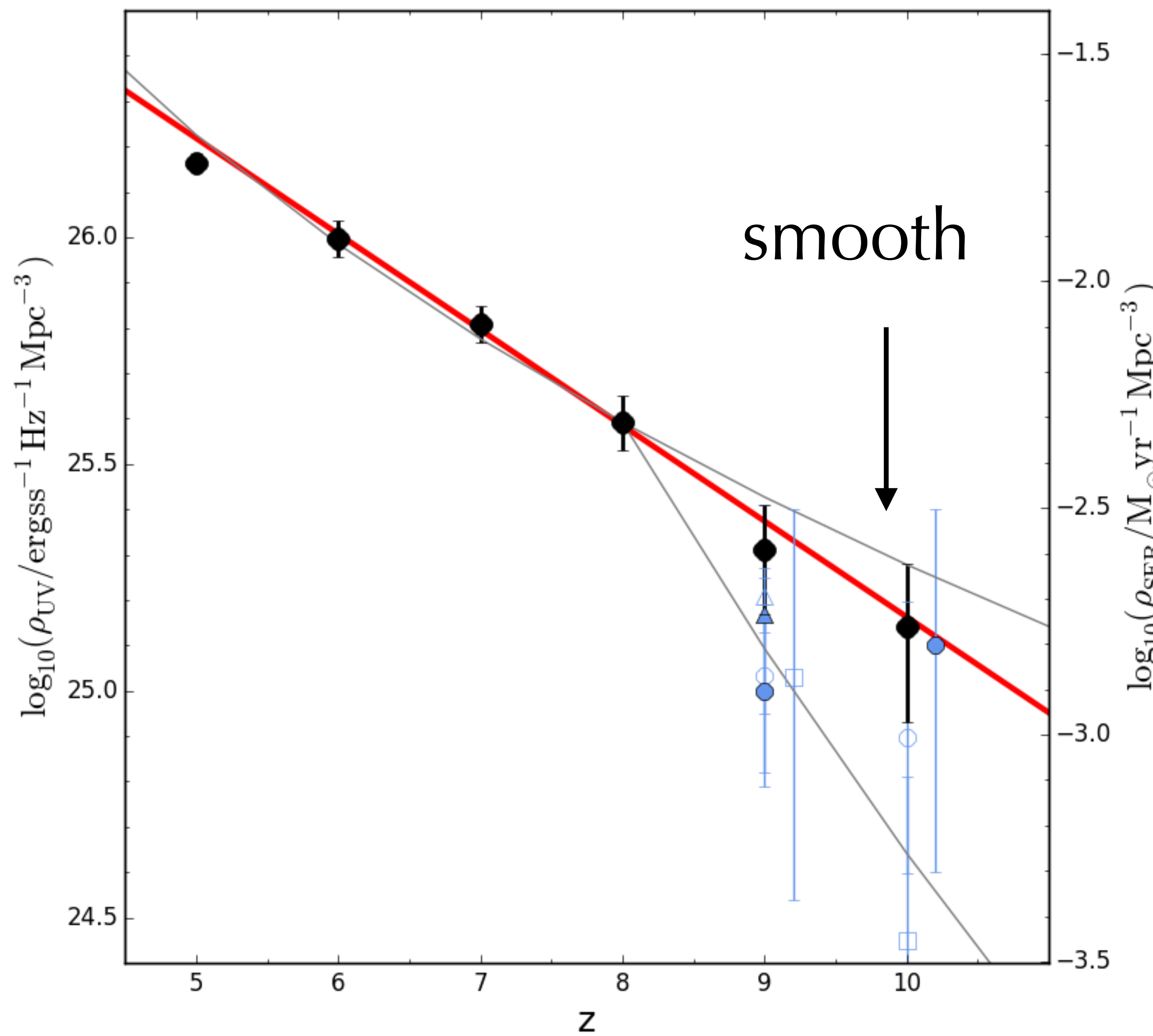
Continued downward evolution in volume density

UV Luminosity Density at z>8

Bouwens et al. 2015, arXiv:1506.01035



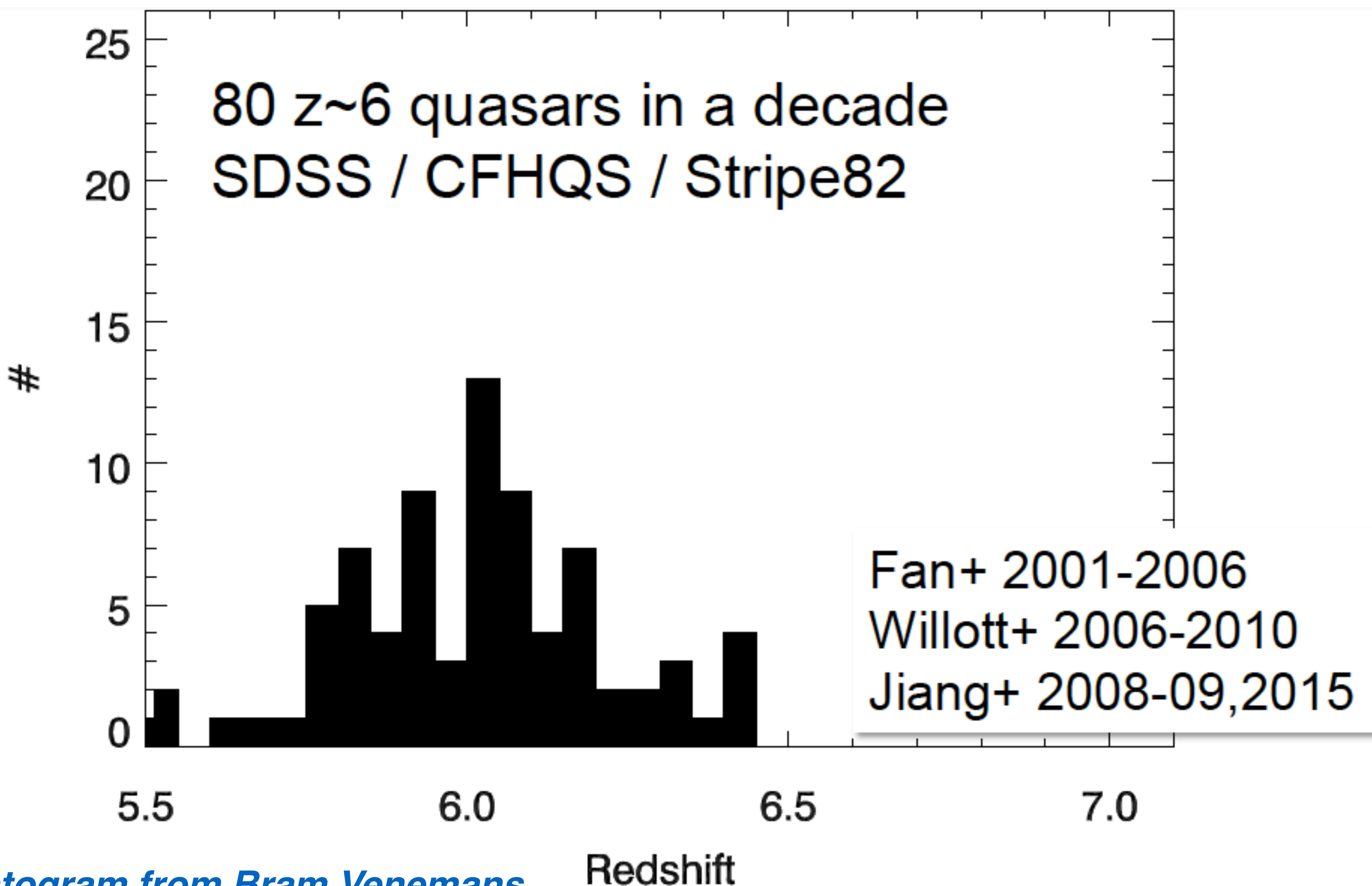
McLeod, McLure, & Dunlop, 2016, MNRAS, 459, 3812



Is 8<z<10 ρ_{UV} evolution 'accelerated' (Bouwens/Oesch) or smooth (McLeod/McLure/Dunlop)?

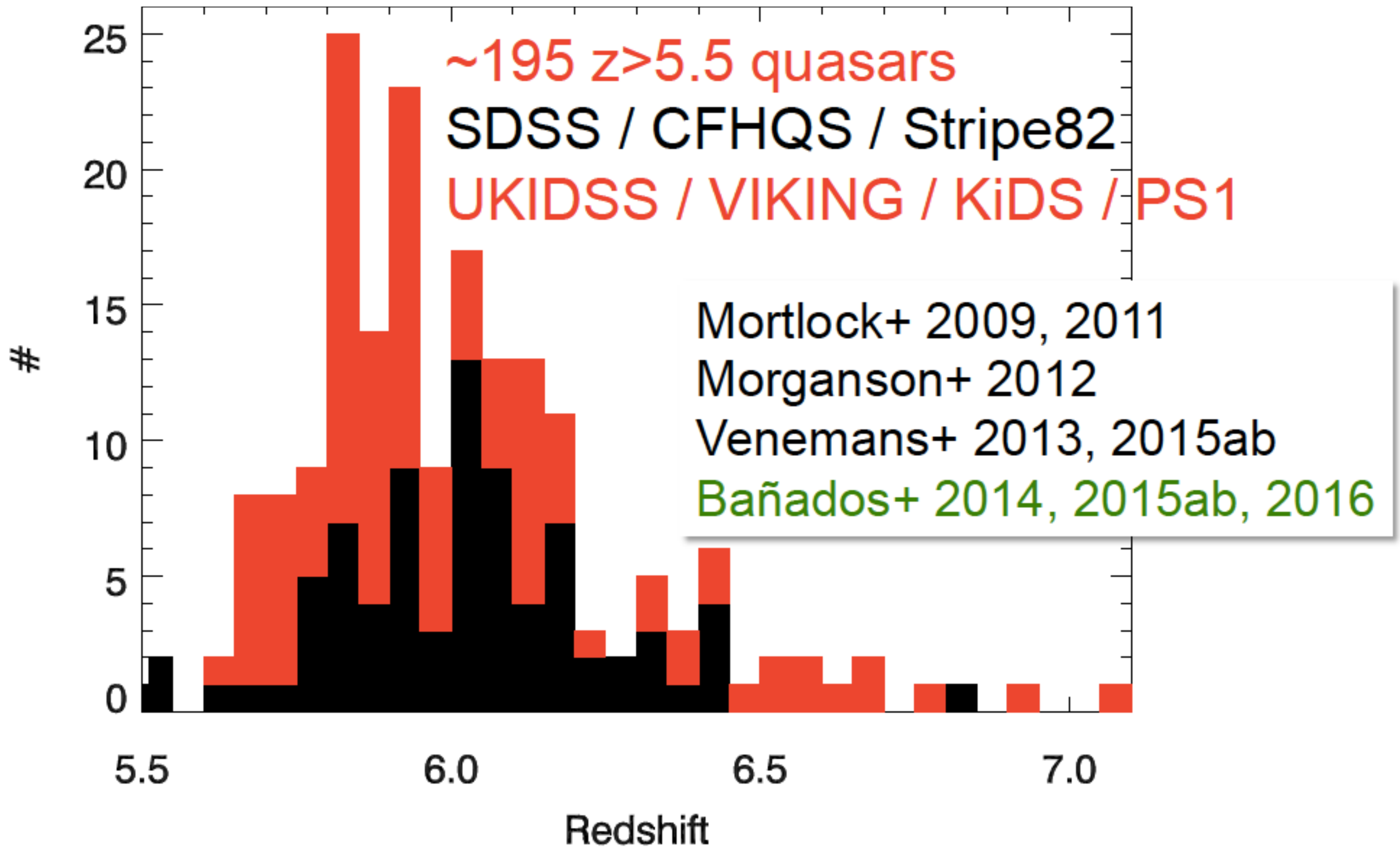
What about the quasars?

Quasars in the Reionization Era



histogram from Bram Venemans

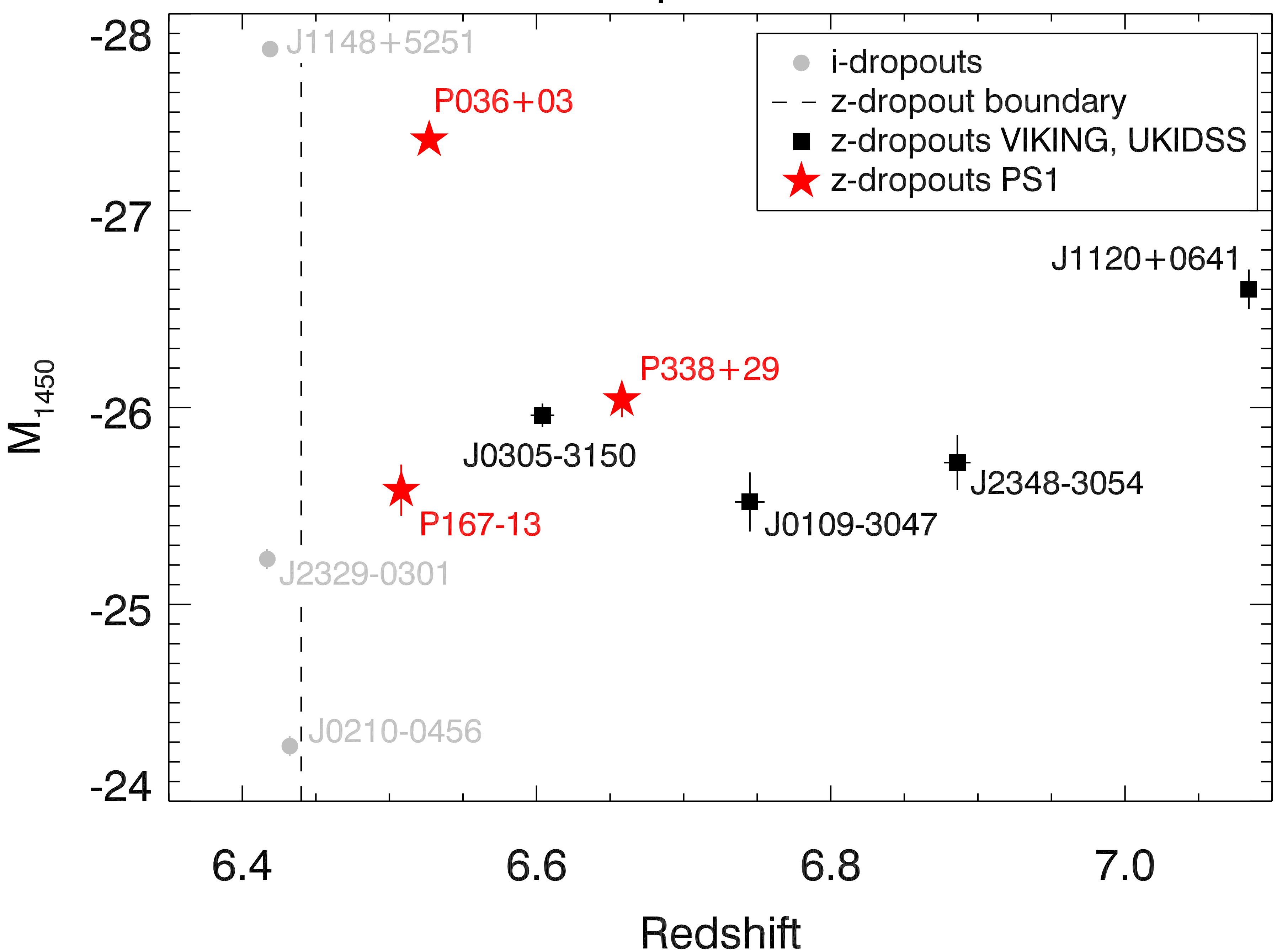
Quasars in the Reionization Era



histogram from Bram Venemans

Quasars in the Reionization Era

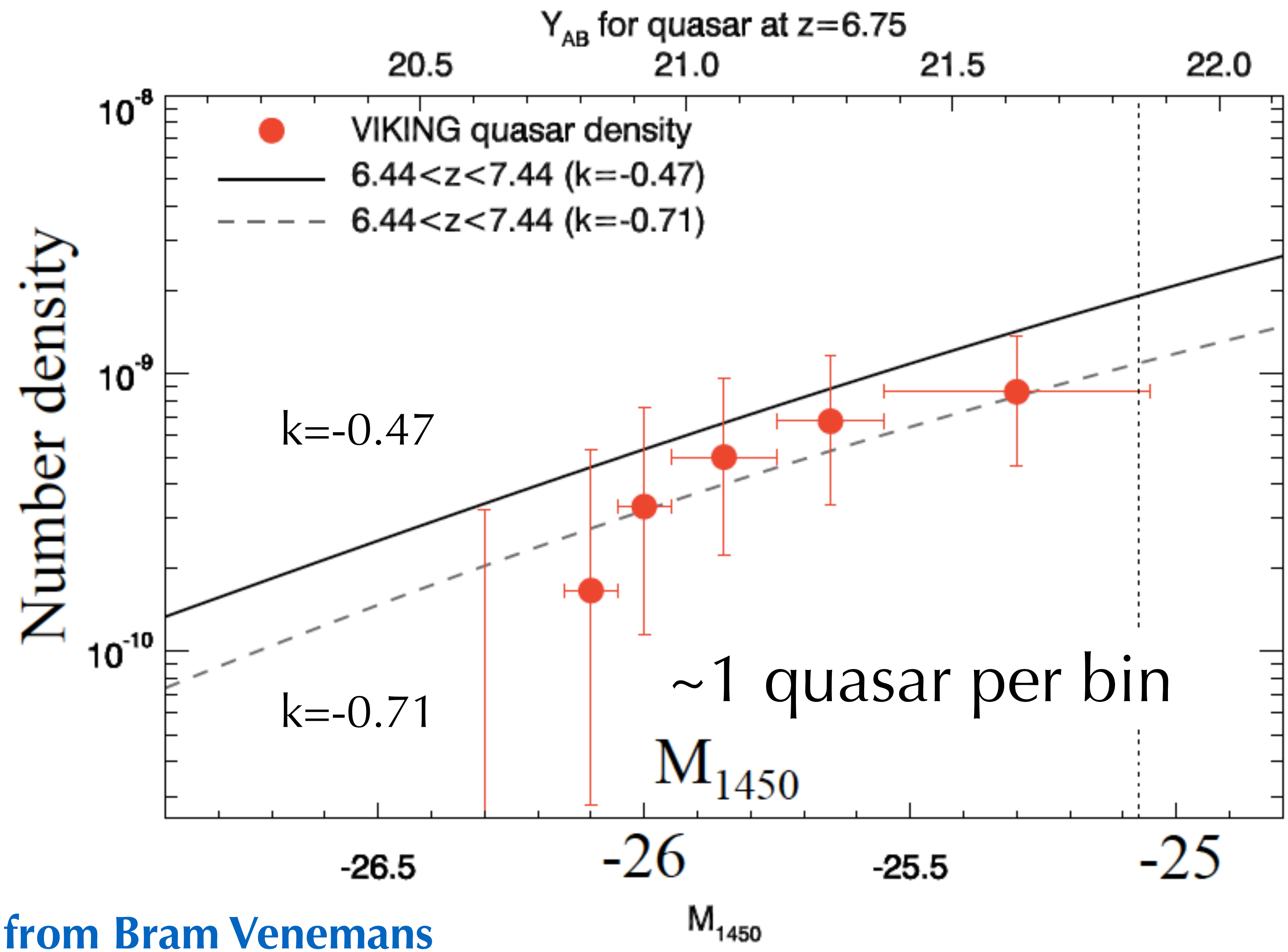
Venemans et al. 2015, ApJL, 801, 11



Sample size

- 6 at 6.5<z<7.0
- 1 at z>7

Rapid evolution in the Quasar Luminosity Function



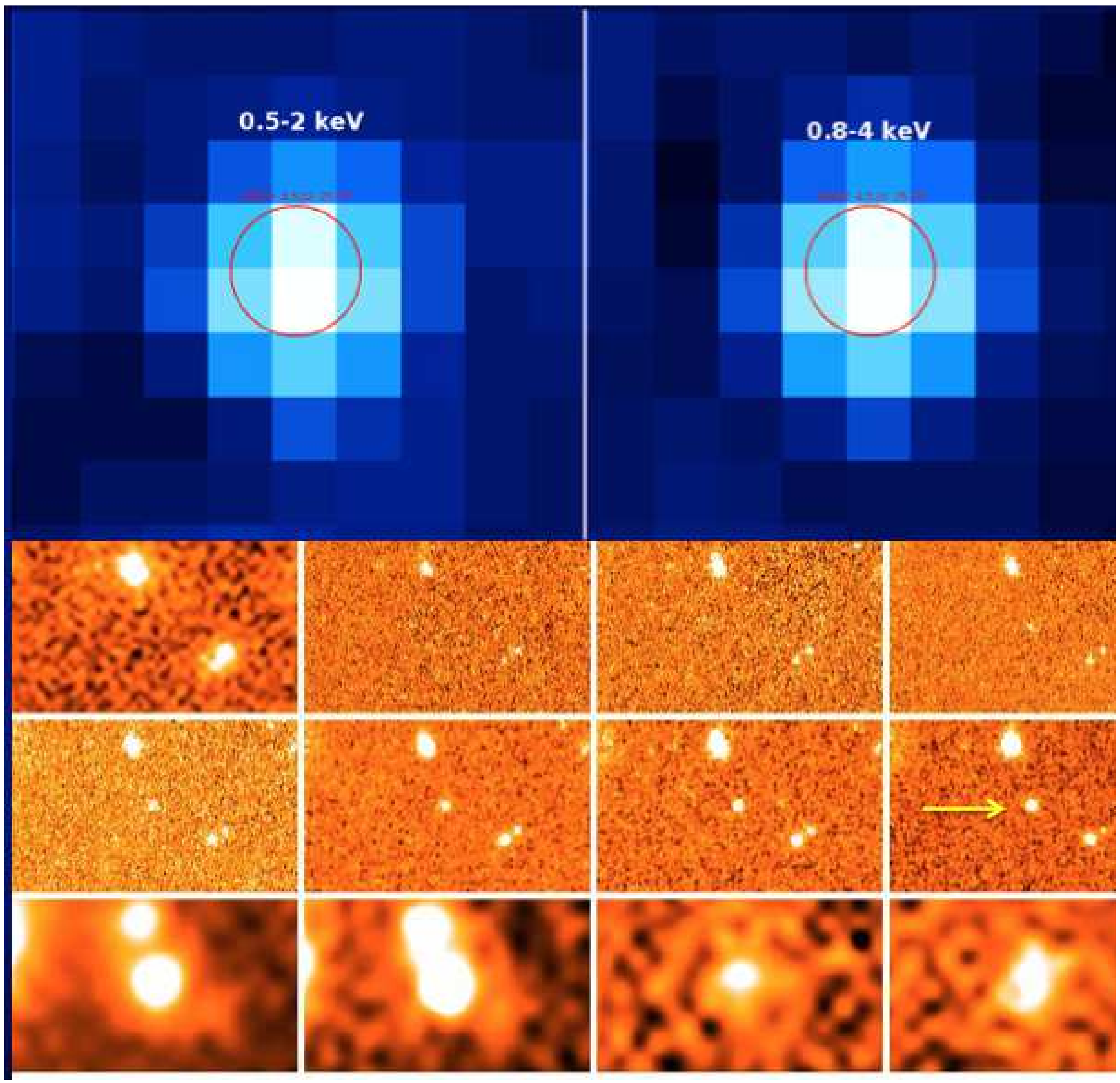
from Bram Venemans

$\phi^*(z=7) = \phi^*(z=6)\ 10^{k(z-6)}$

3-5x drop in volume density of bright quasars between z=6 and z=7.

Faint z~5 Quasars in GOODS?

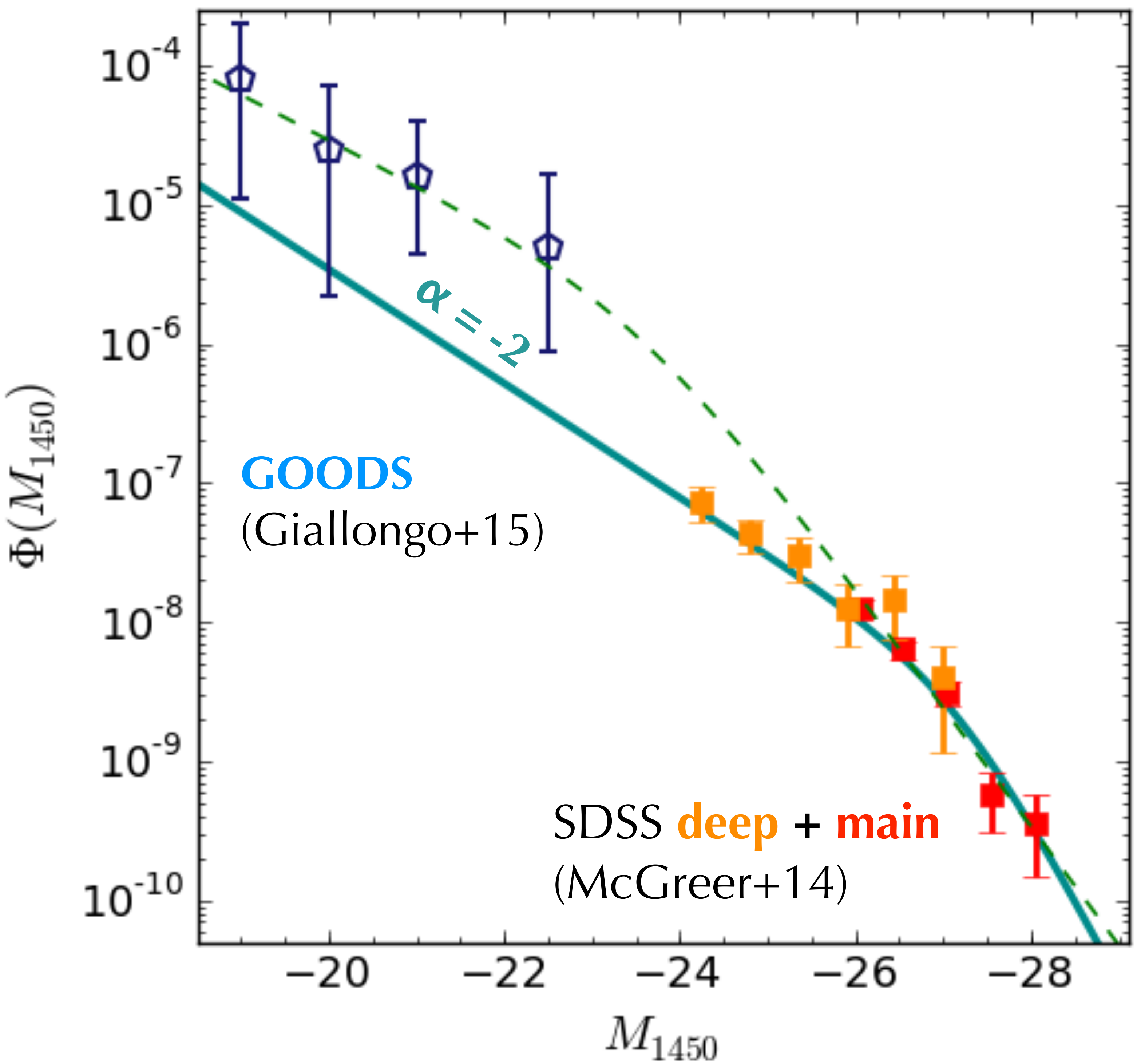
Giallongo et al. 2015, A&A, 578, 83



22 faint AGN candidates identified in GOODS-South.

Photometric redshifts (z>4) with Chandra detections.

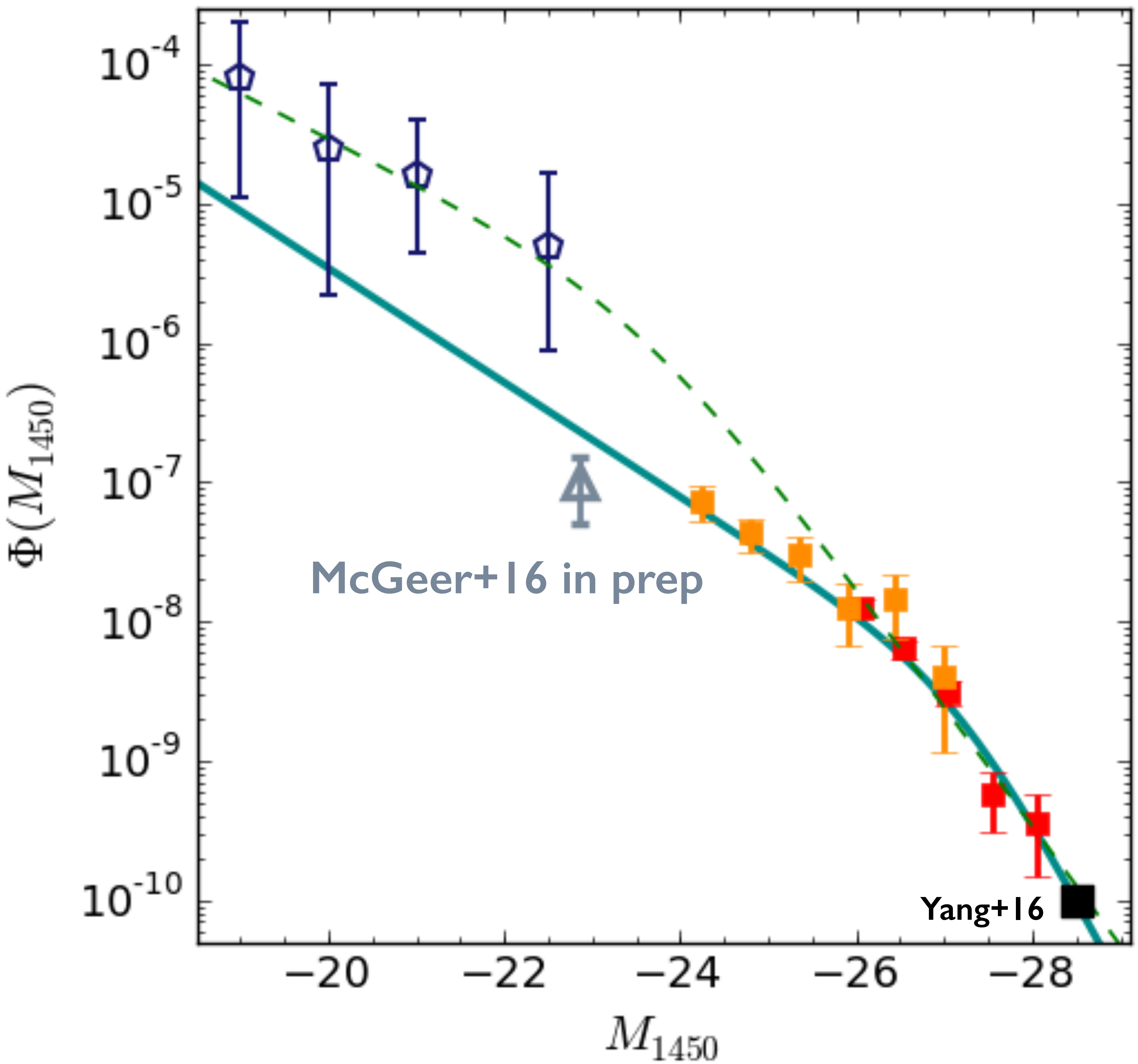
Census of Quasars at z~5



Large volume density of faint z~5 quasars (Giallongo+15) —> *AGN contribution to reionization?*

Discontinuity with McGreer+14 SDSS results?

The faint end of the z=5 QLF

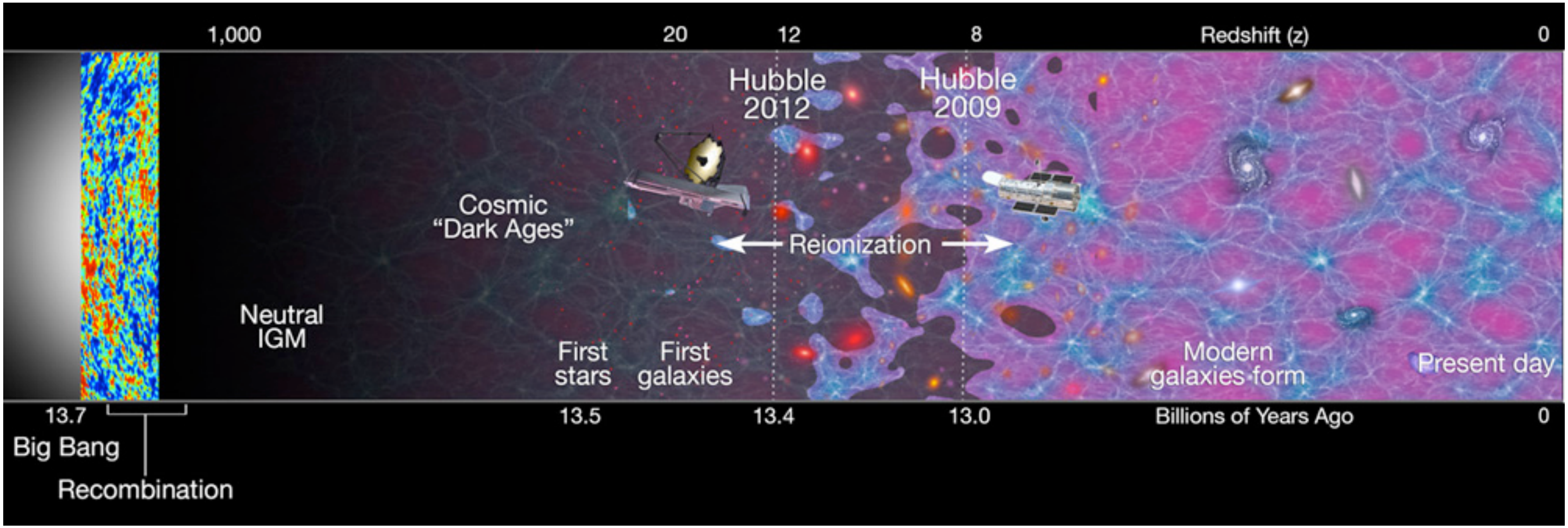


New spectroscopic survey of faint quasars in the CFHTLS (McGreer+16, in prep).

Inconsistent with large volume density of faint z~5 quasars.

Spectroscopic confirmation of Giallongo+15 candidates needed.

Overview



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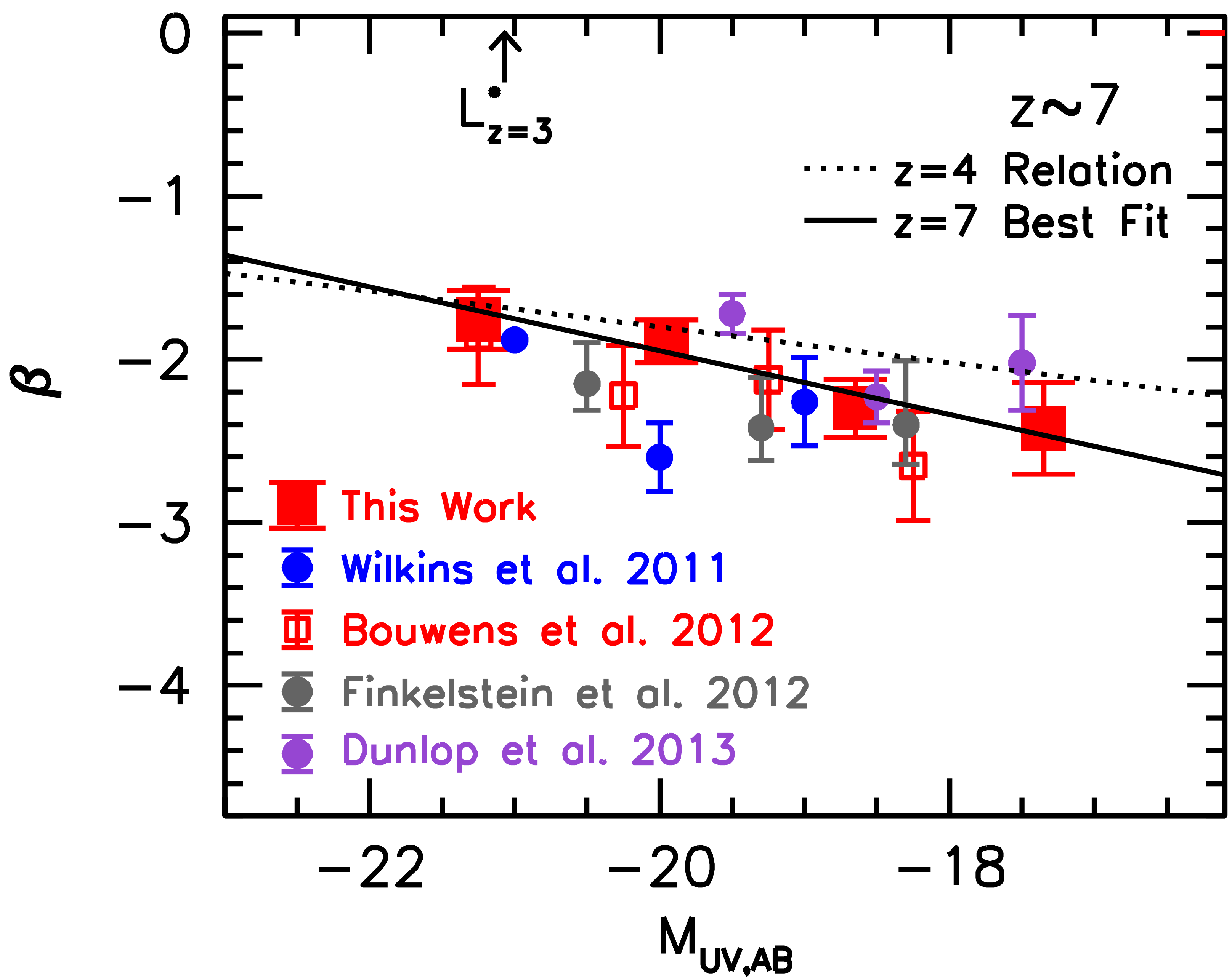
UV Continuum Slopes are Blue



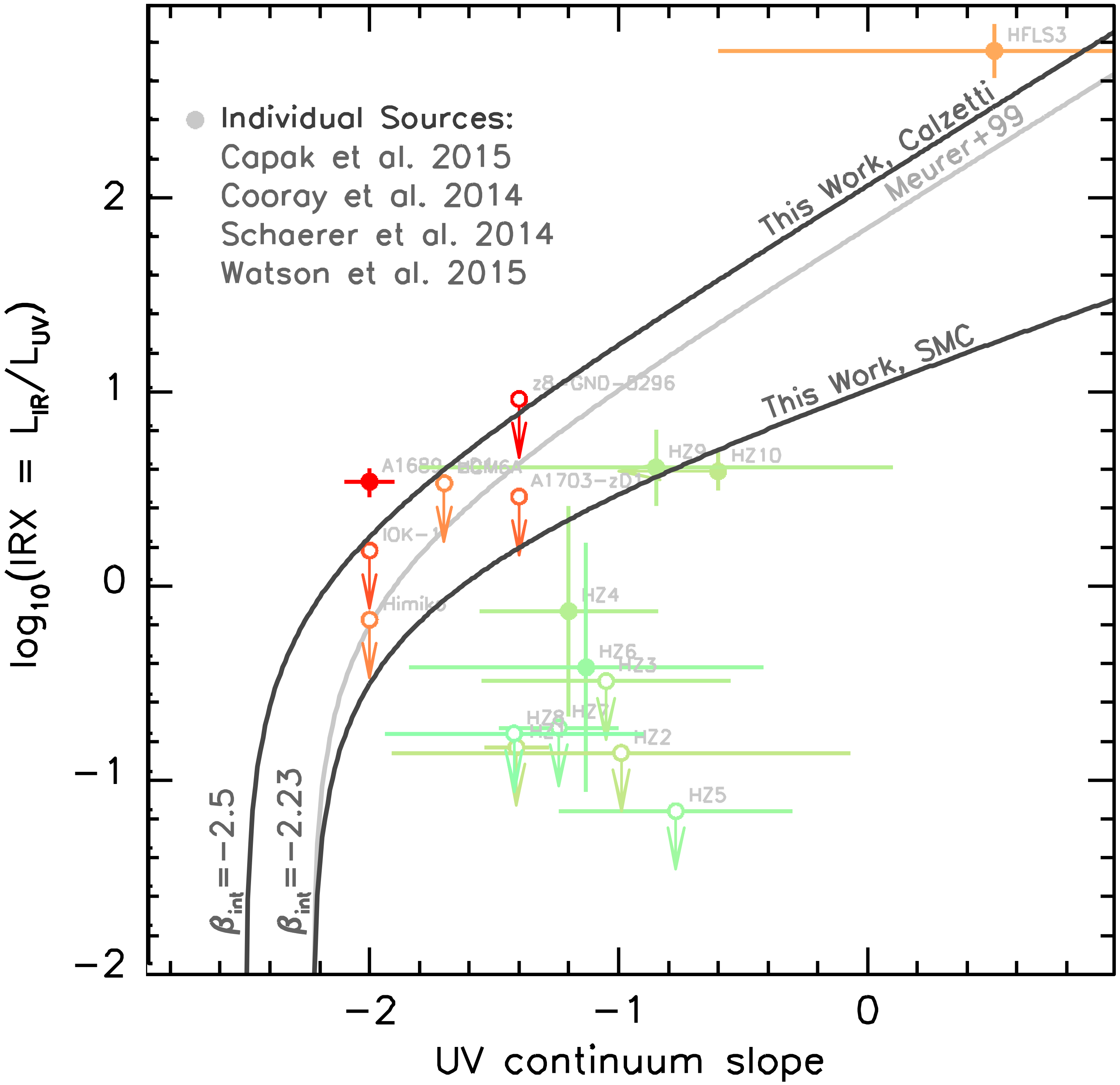
Consensus that UV slopes of z~7 galaxies are very blue (β~-2 to -2.5)

Suggests little reddening from dust.

Bouwens+14, ApJ, 793, 115

ALMA Confirming Low Dust Content

Smit+15b, arxiv:1511.08808



Far IR continuum is weak in z>6 UV-selected galaxies.

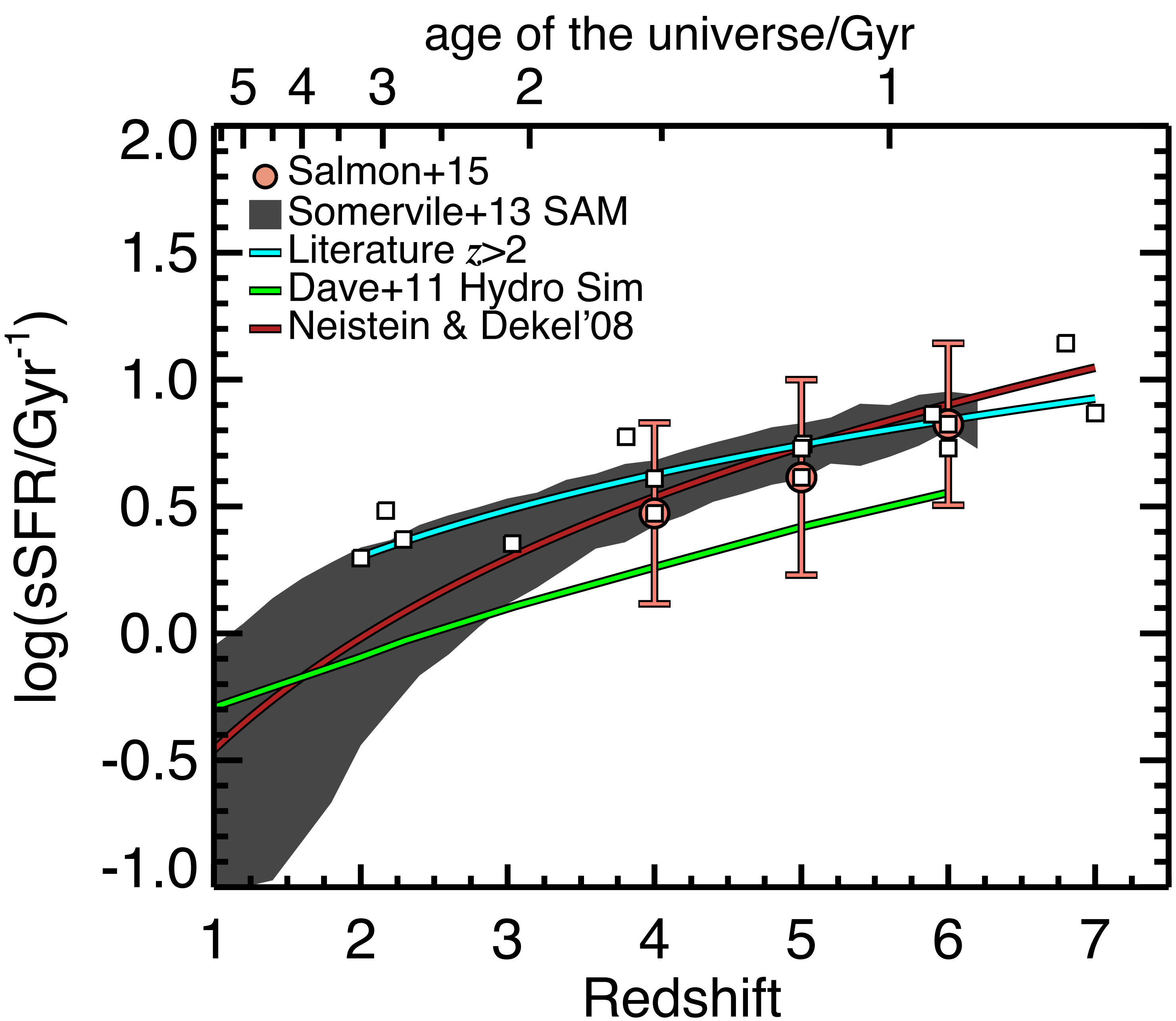
Typical dust content below Meurer relation.

Dust attenuation law closer to SMC?

see also Dunlop+16, Bouwens+16

Specific star formation rates are large

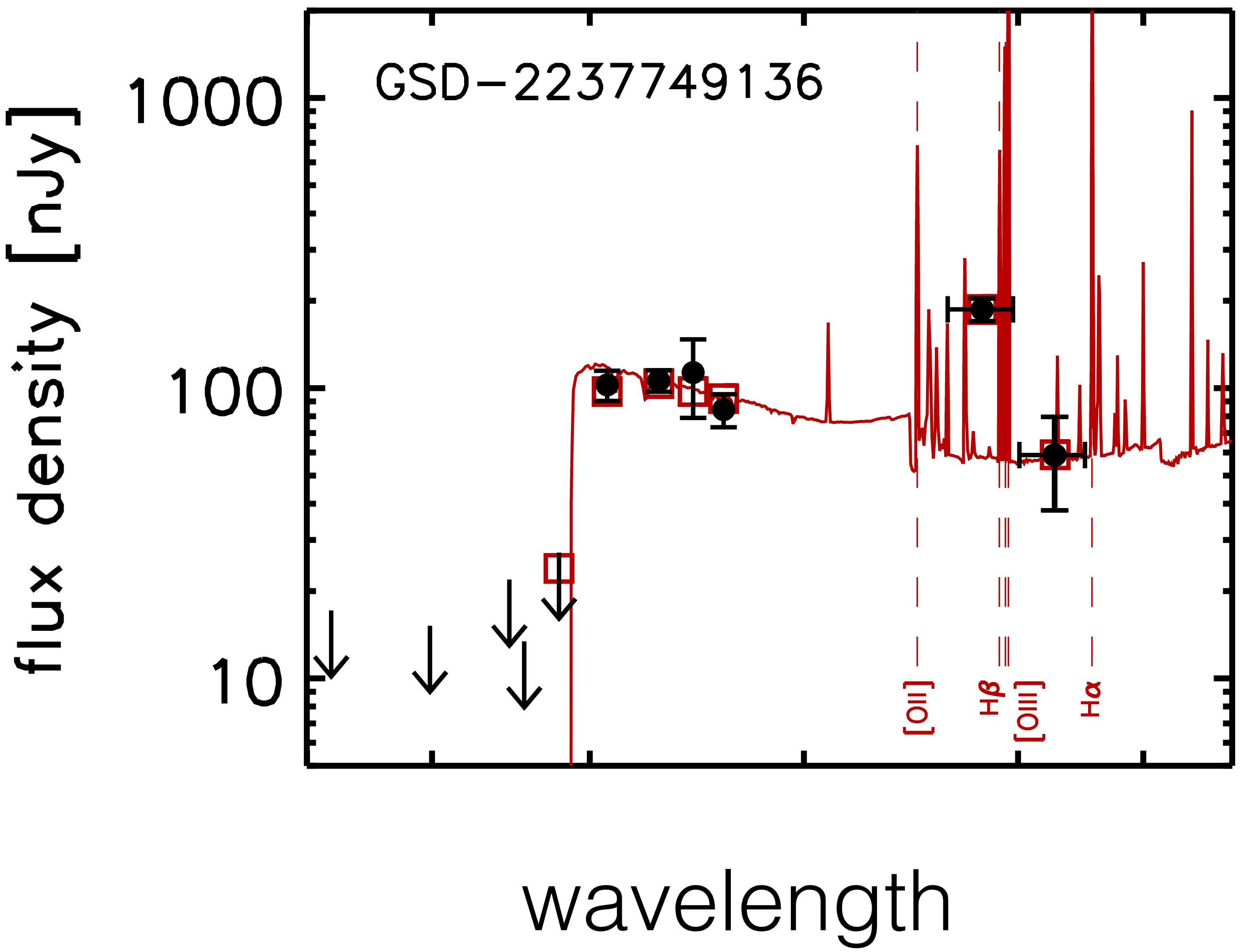
Salmon+15, ApJ, 799, 183



Specific star formation rates in z~7 galaxies are ~5x greater than at z~2.

Extreme Optical Line Emitters at z~6.6-6.9

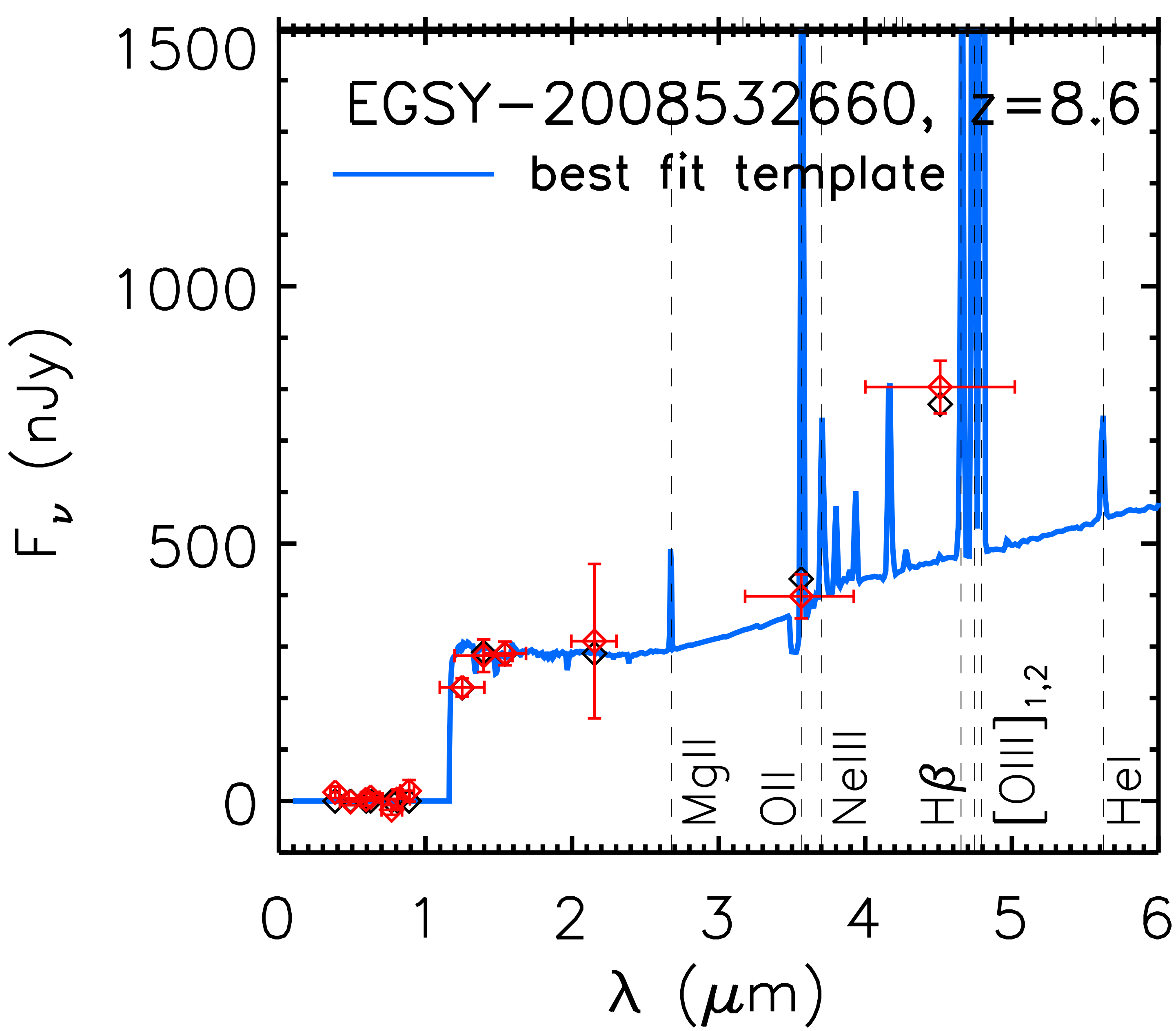
Smit+15, ApJ, 801,122



Extremely large EW [OIII]+Hβ emission (>1500 Å) evident from Spitzer photometry.

Extension to z~7-9

Roberts-Borsani et al. 2016, ApJ, 823, 143



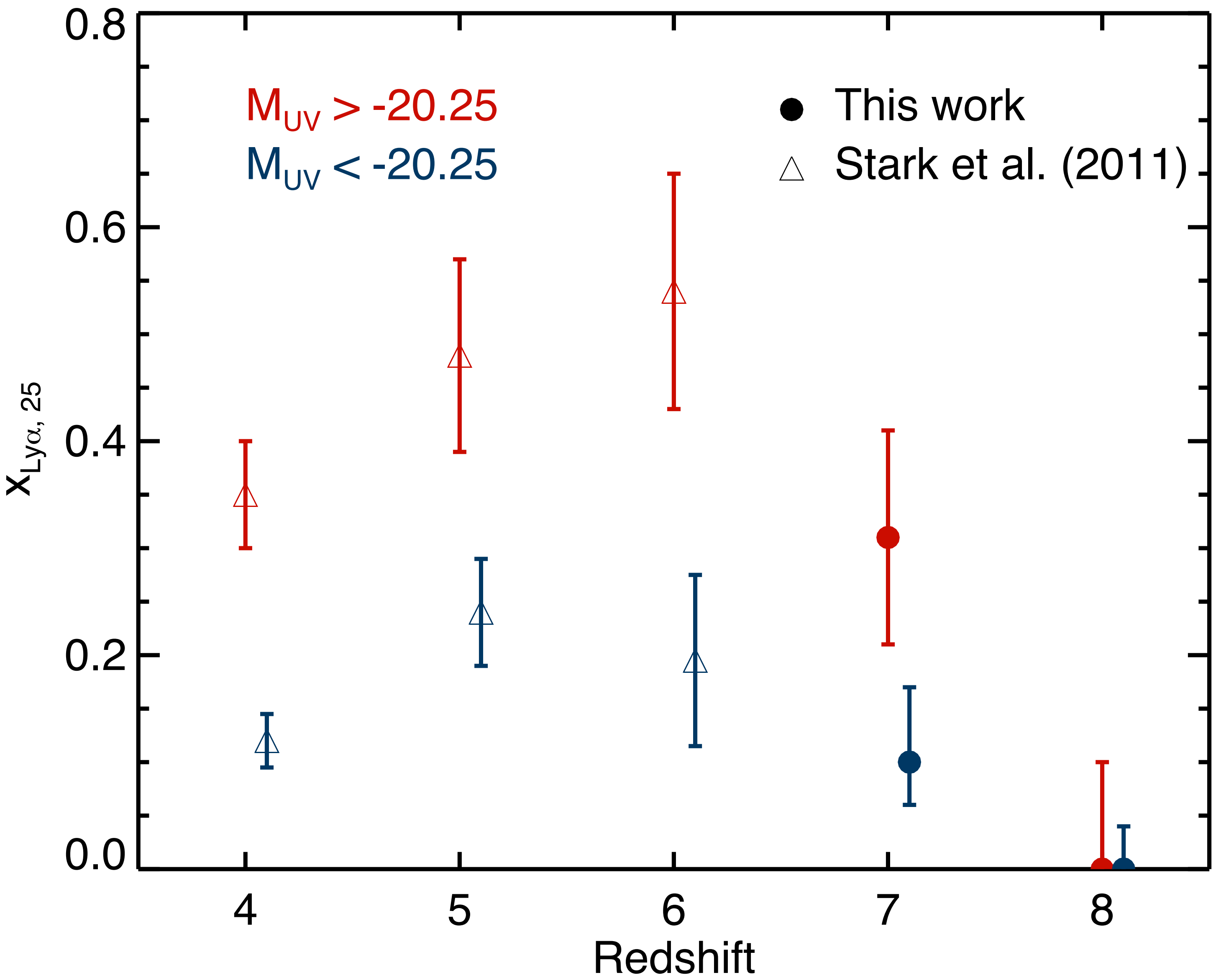
New sample of large EW [OIII]+Hβ emitters recently located at z~7-9.

Perhaps up to 50% of z>7 galaxies in extreme optical line EW phase.

Suggests very young stellar populations, with large ionizing output per unit 1500Å luminosity -> **expect different spectral properties.**

What about actual spectra?

Schenker (+DPS) et al. 2014

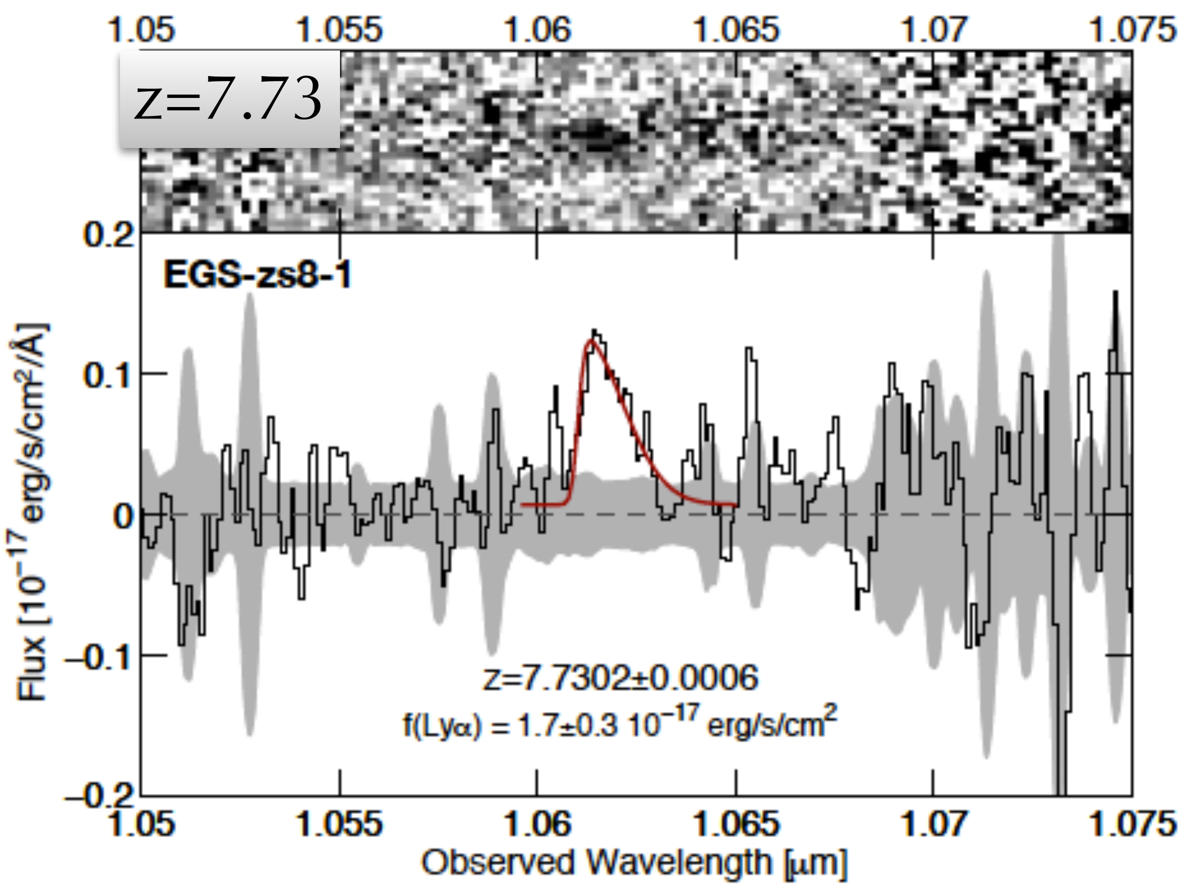


Lyman-alpha emission is rare in z>7 UV-selected galaxies.

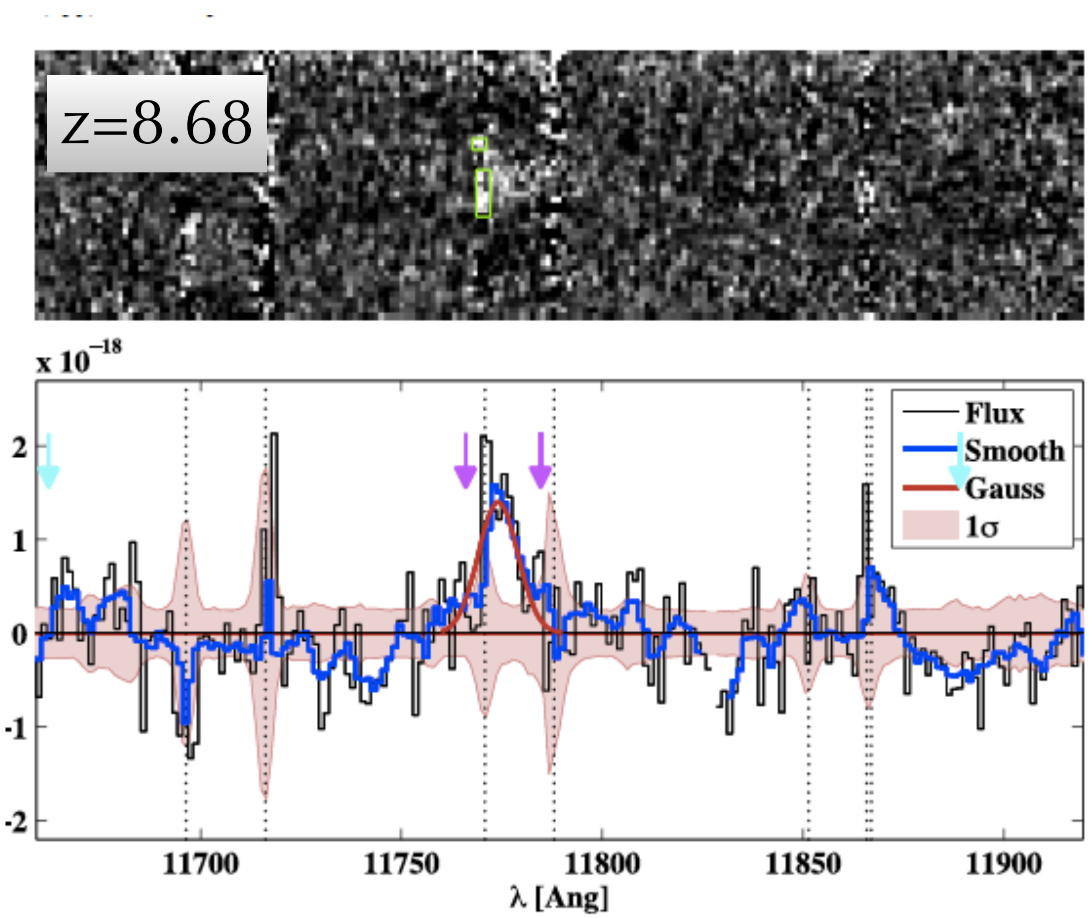
see also Fontana et al. 2010, Vanzella et al. 2011, Ono et al. 2012, Pentericci et al. 2011, 2014, Treu et al 2012, 2013, Tilvi et al. 2014, Bian et al. 2014, Schmidt et al. 2015.

New Lyman-alpha Detections from MOSFIRE

Oesch+15



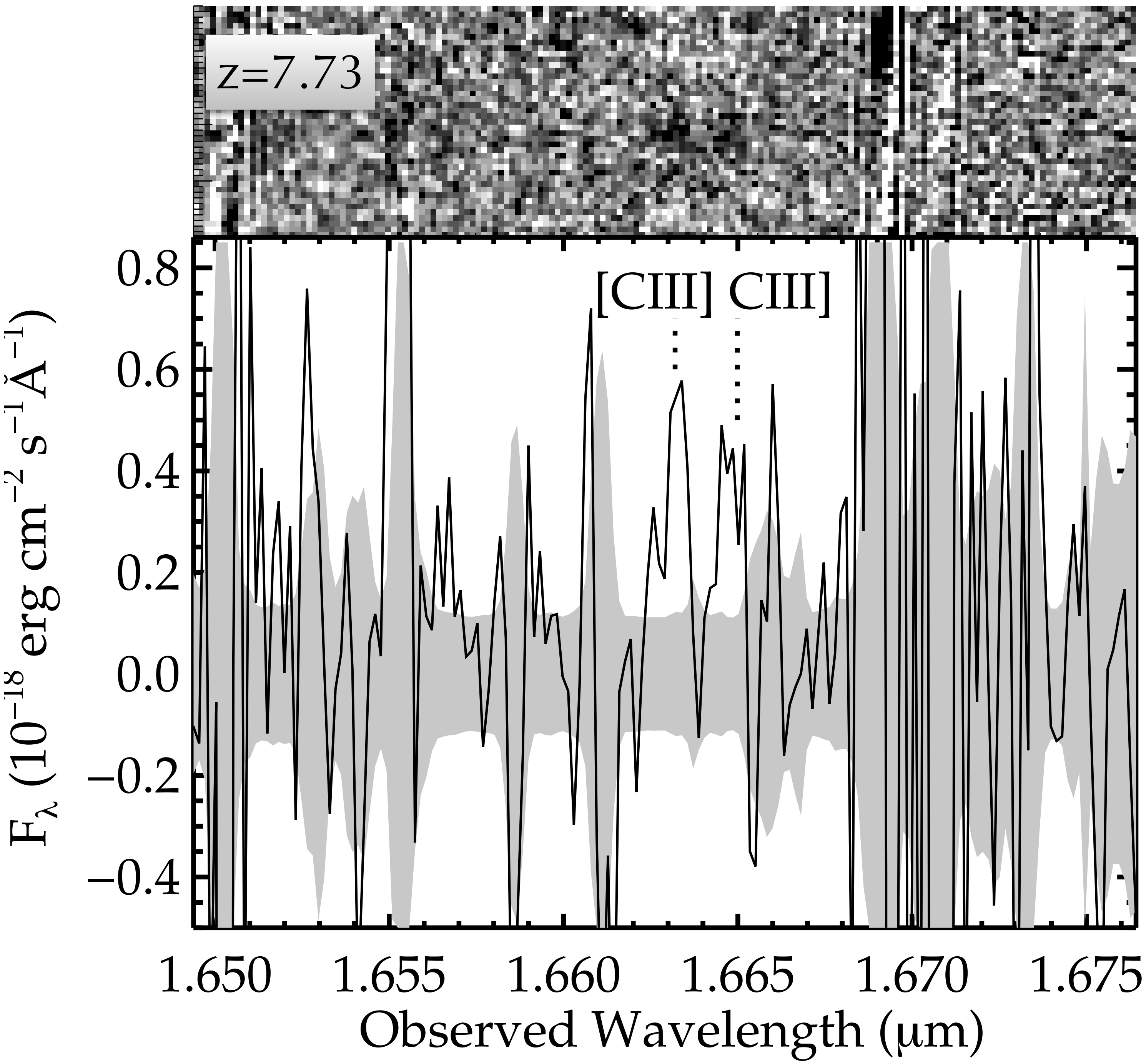
Zitrin+15



- In last 9 months, 5 new galaxies spectroscopically confirmed with MOSFIRE (Oesch+15, Zitrin+15, Roberts-Borsani+16, Stark+16, Song+16).
- **11 galaxies now have Lyman-alpha confirmation at z>7.**

CIII] emission is strong in z>6 Lyman-α Emitters

Stark+16, arXiv:1606.01304



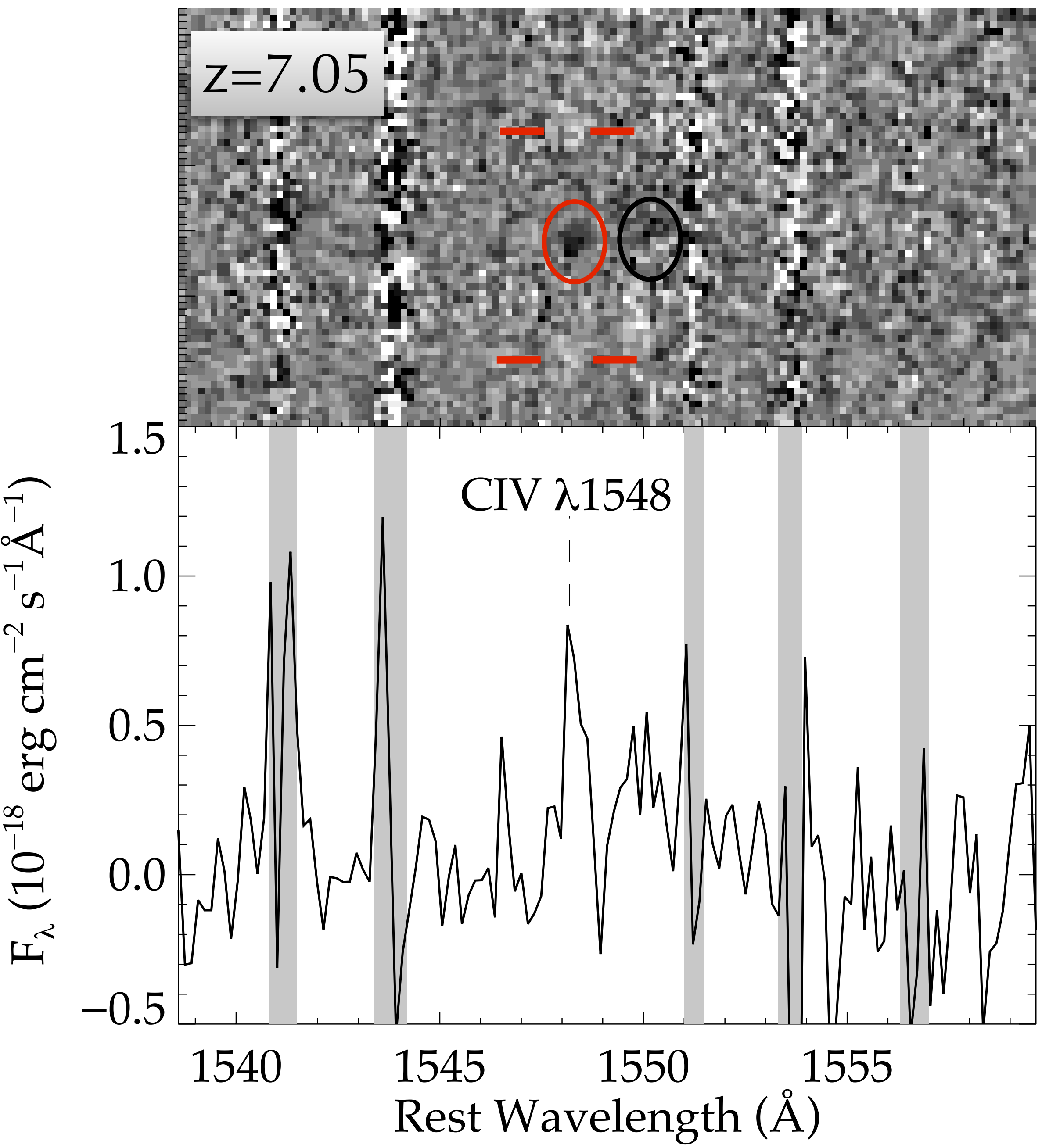
CIII] equivalent width of 22Å in z=7.73 galaxy.

Similar to z=6.024 CIII] emitter (EW = 23Å) in Stark +15a.

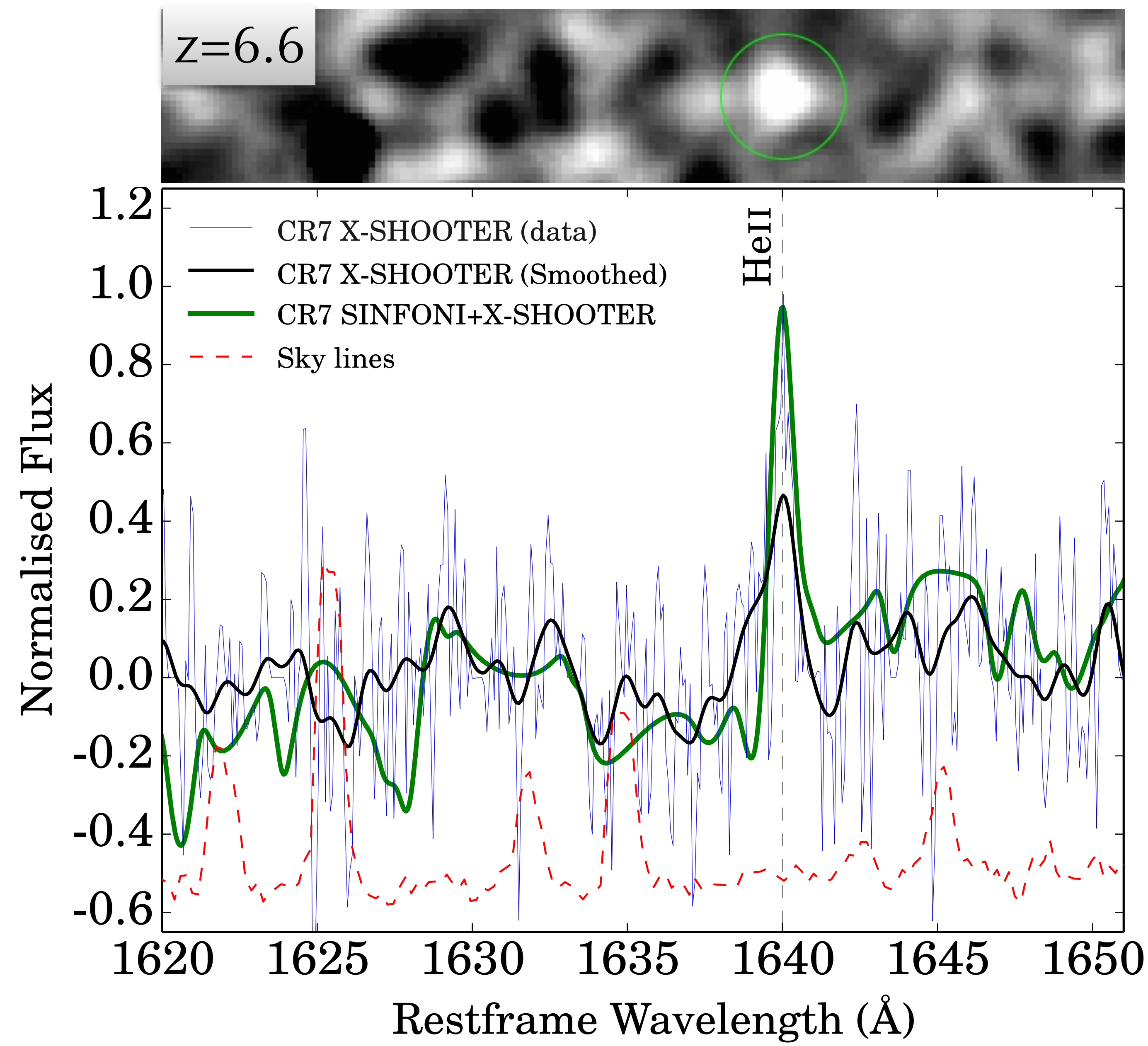
More than 10x greater than CIII] EW in Shapley+03 z~3 LBG composite.

High Ionization Emission Lines are Common

Stark+15b, 2015, 450, 1846



Sobral+15, ApJ, 808, 139



Requires substantial flux of ionizing photons > 48 eV

Are such features a natural consequence of low metallicity stellar populations / gas?

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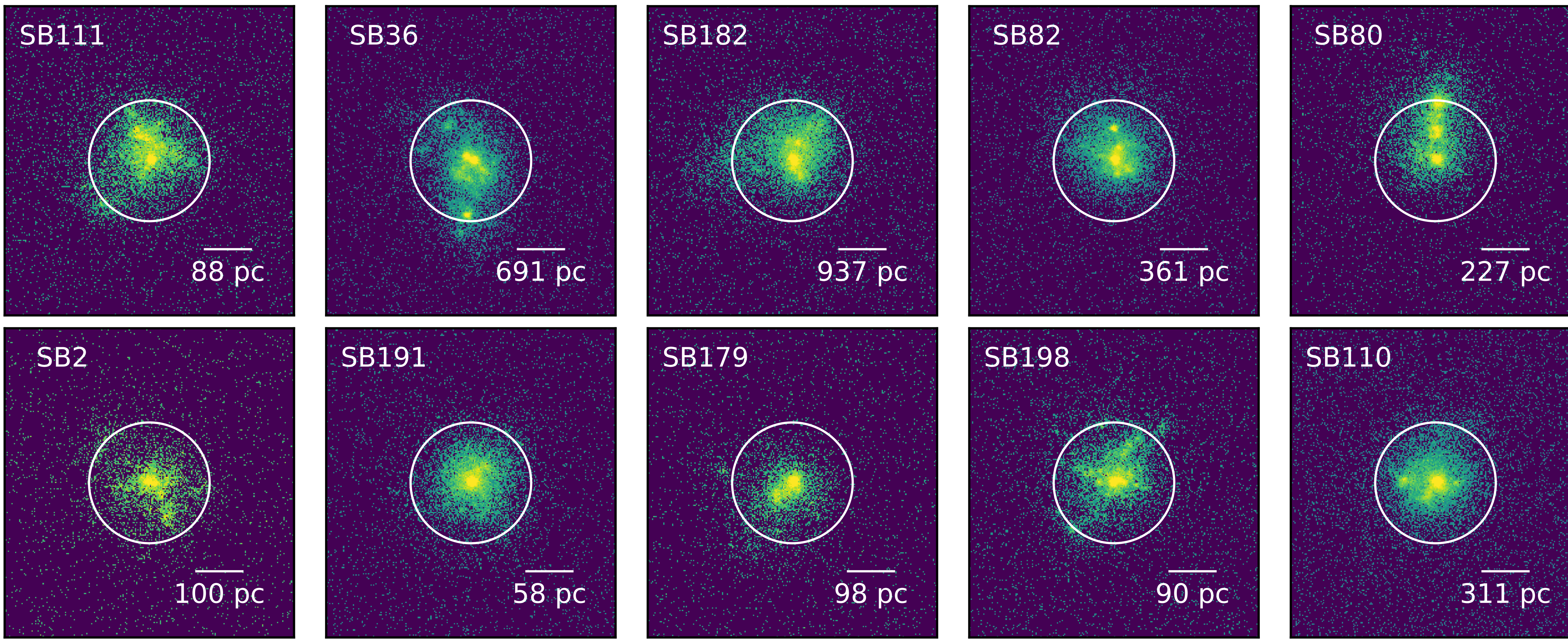
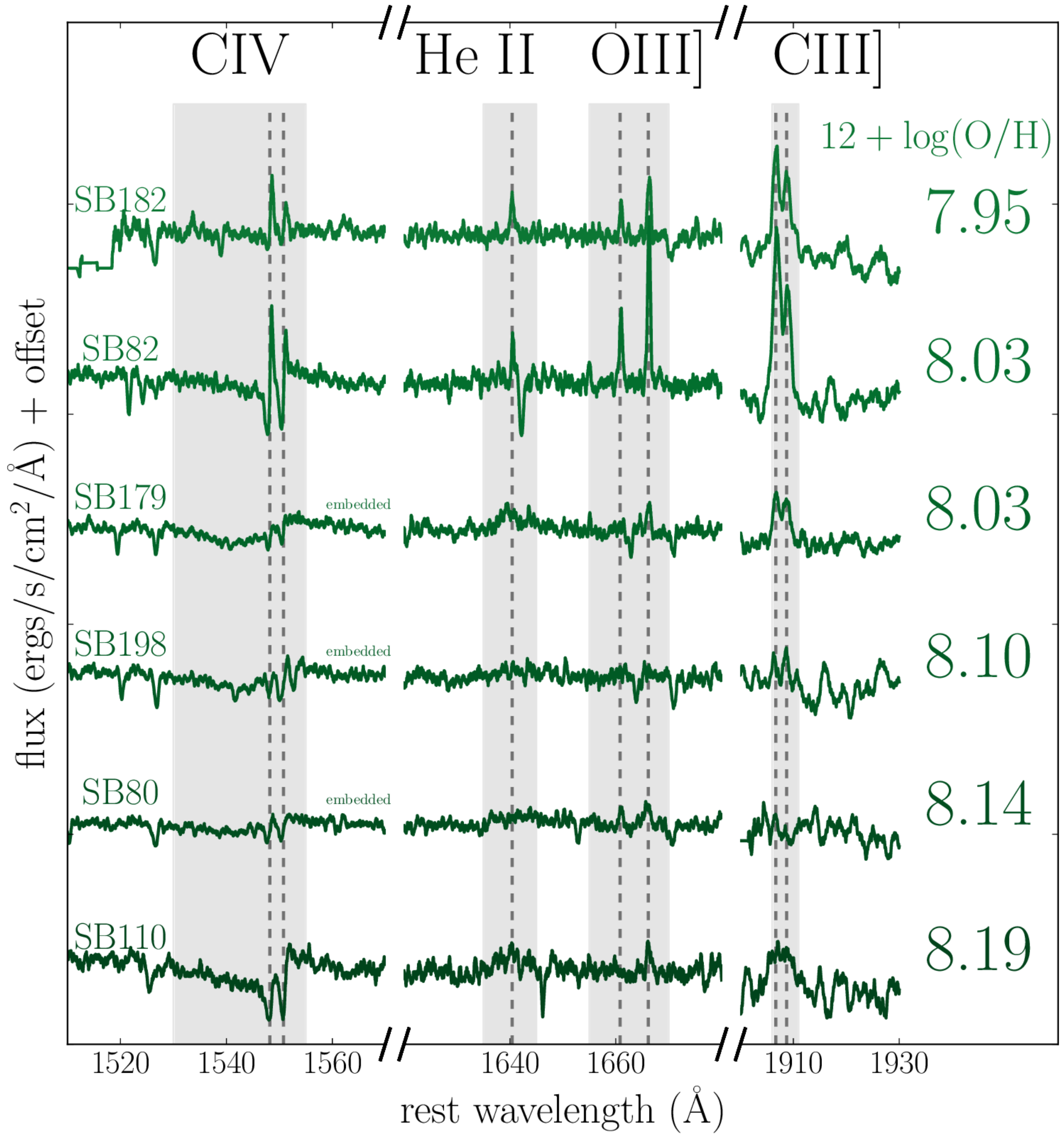
Need local reference sample!

Senchyna, Stark, Charlot+16, in prep



Local Reference Spectra of Metal Poor Galaxies

Senchyna, Stark, Charlot+16, in prep



UV spectra change dramatically at 12+log O/H~8.0 (0.2 $Z_\odot$)

- CIII] equivalent width increase
- CIV P-Cygni disappears
- Broad He II (from WR stars) disappears
- High ionization nebular lines appear.

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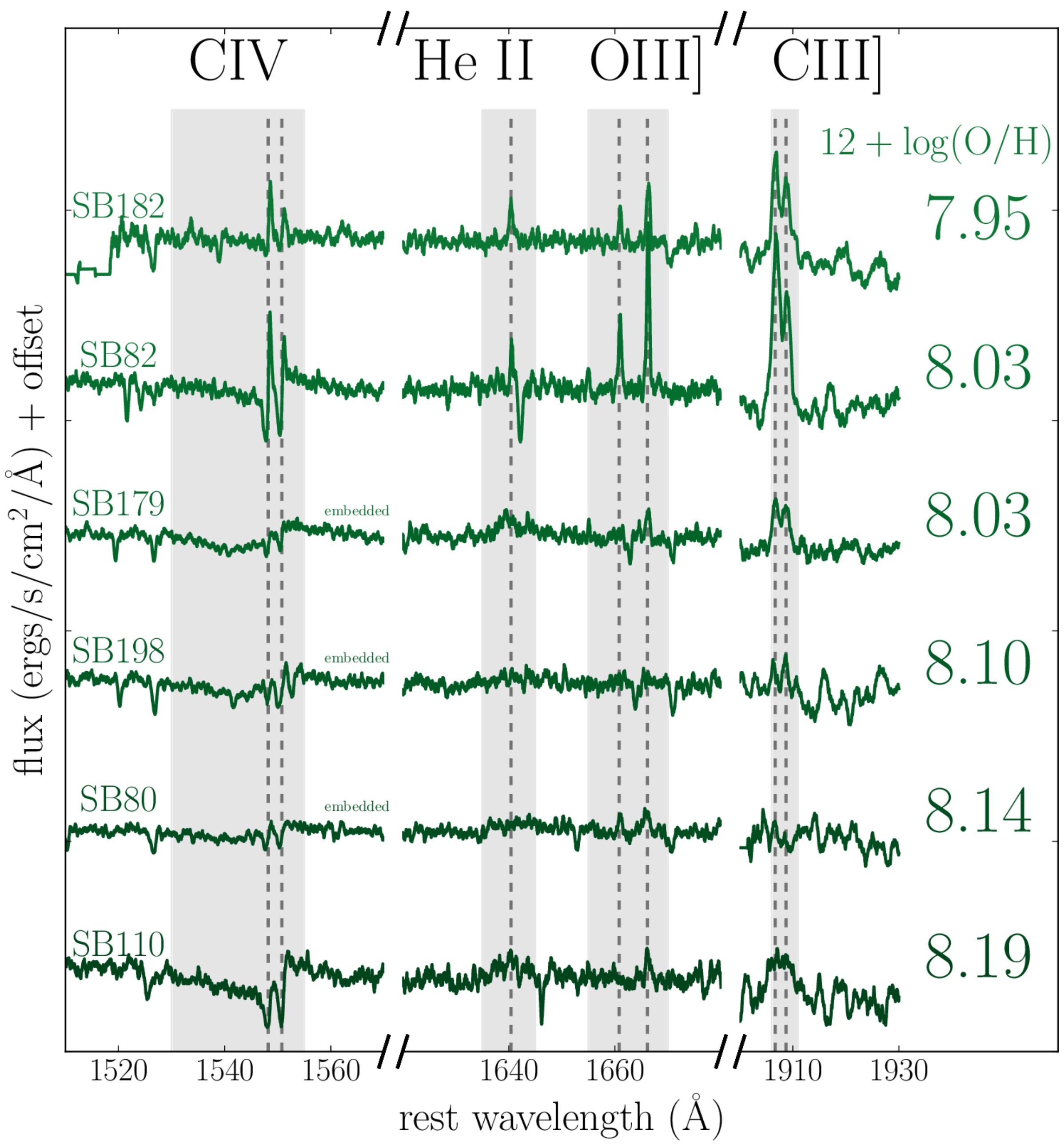

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- CIII] equivalent width increase
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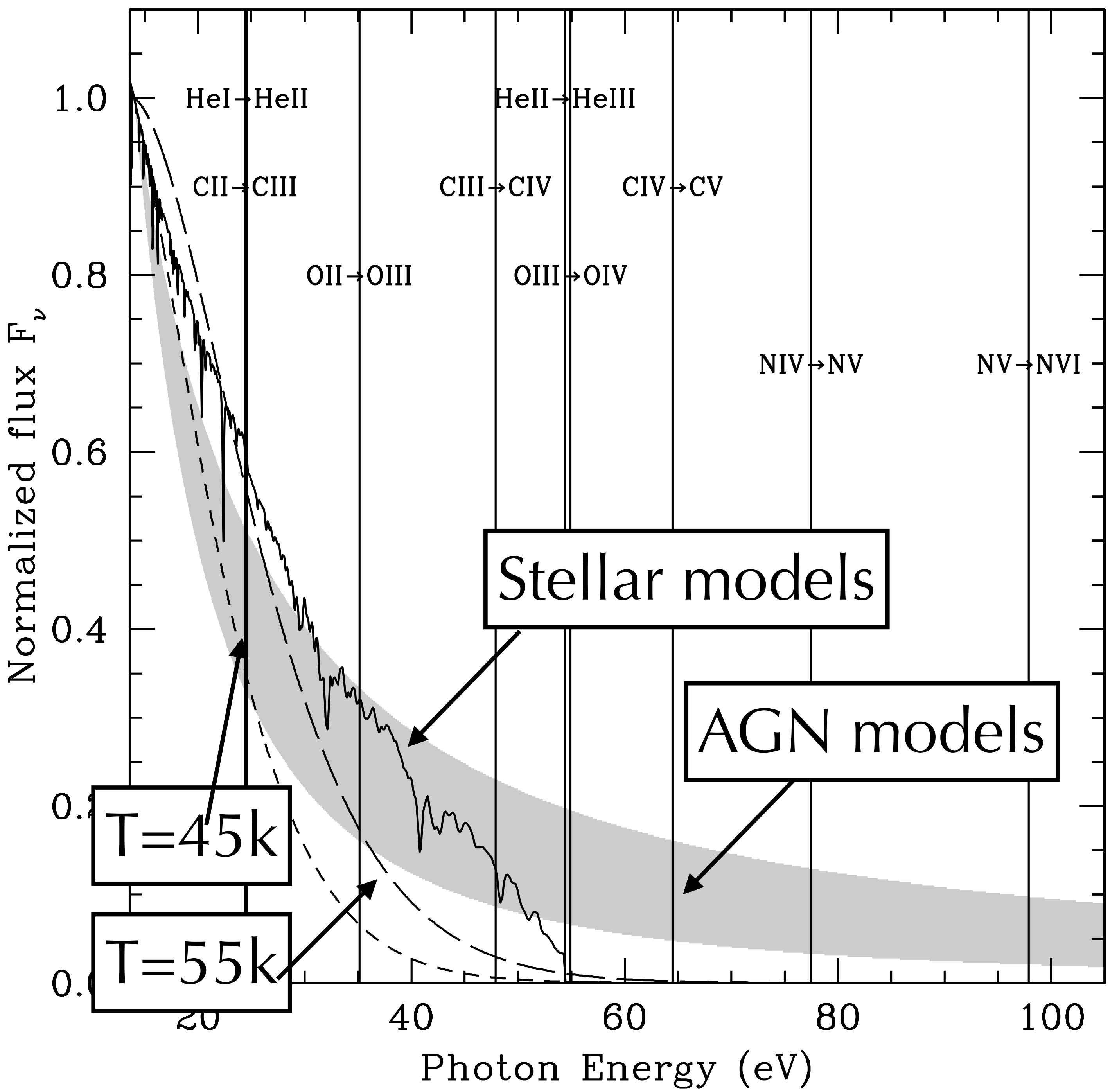
CIII] equivalent widths approach 15Å, comparable to those at z~7-8.

Nebular CIV and He II present but much weaker (< 1.7, 1.5 Å)!

Origin of Nebular CIV at z=7.05

Stark+15b, 2015, 450, 1846



Stellar and AGN photoionization models (Feltre+16, Gutkin+16) can both reproduce z~7 CIV detection.

Stellar models (CB16):

12+log O/H =7.05 (0.02 $Z_\odot$)

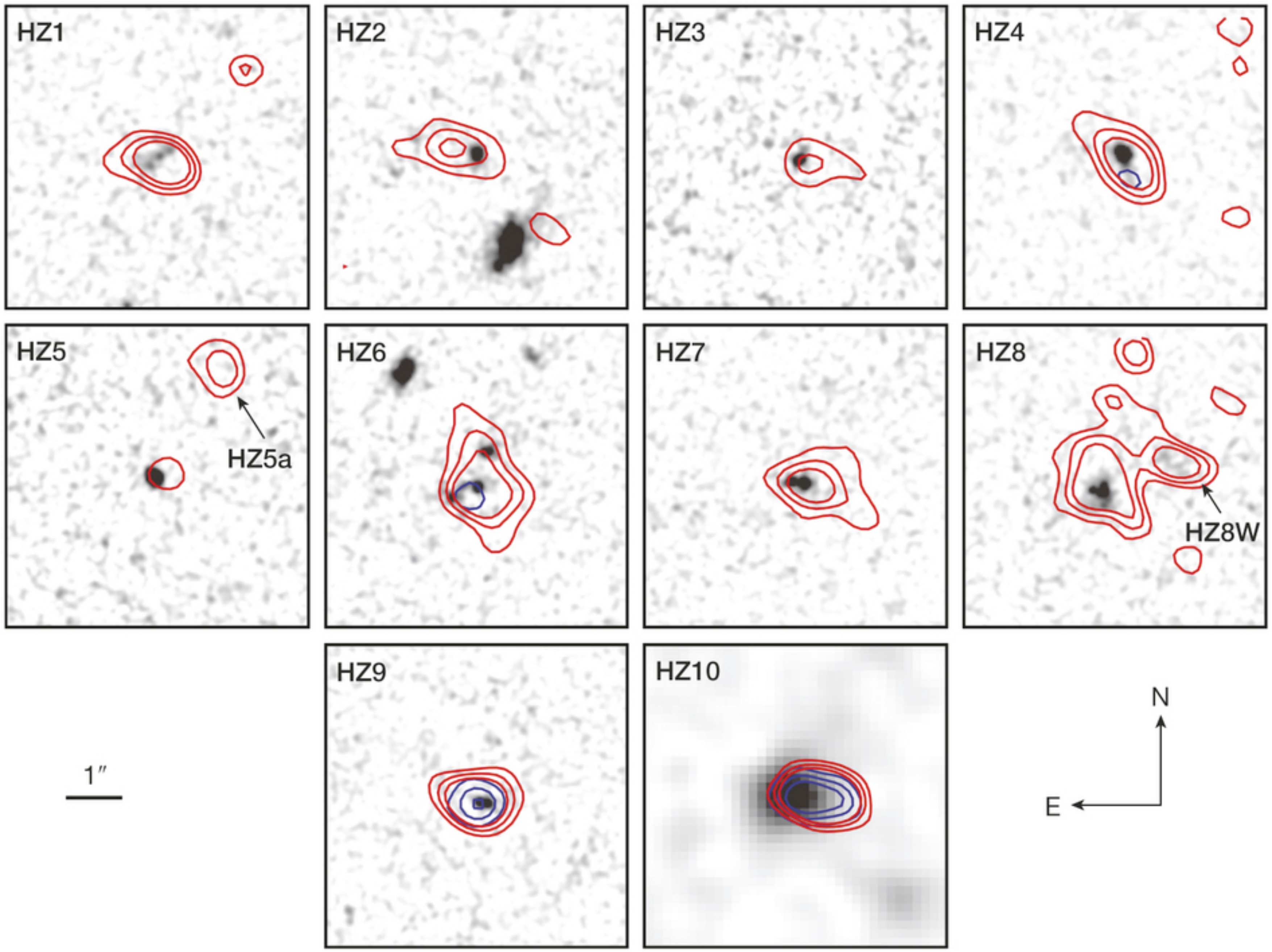
log U = -1.35

Regardless of origin, hard radiation field required to produce nebular CIV line emission.

Spectroscopy with ALMA?

Detections of [CII] in normal star forming galaxies at z~5-6

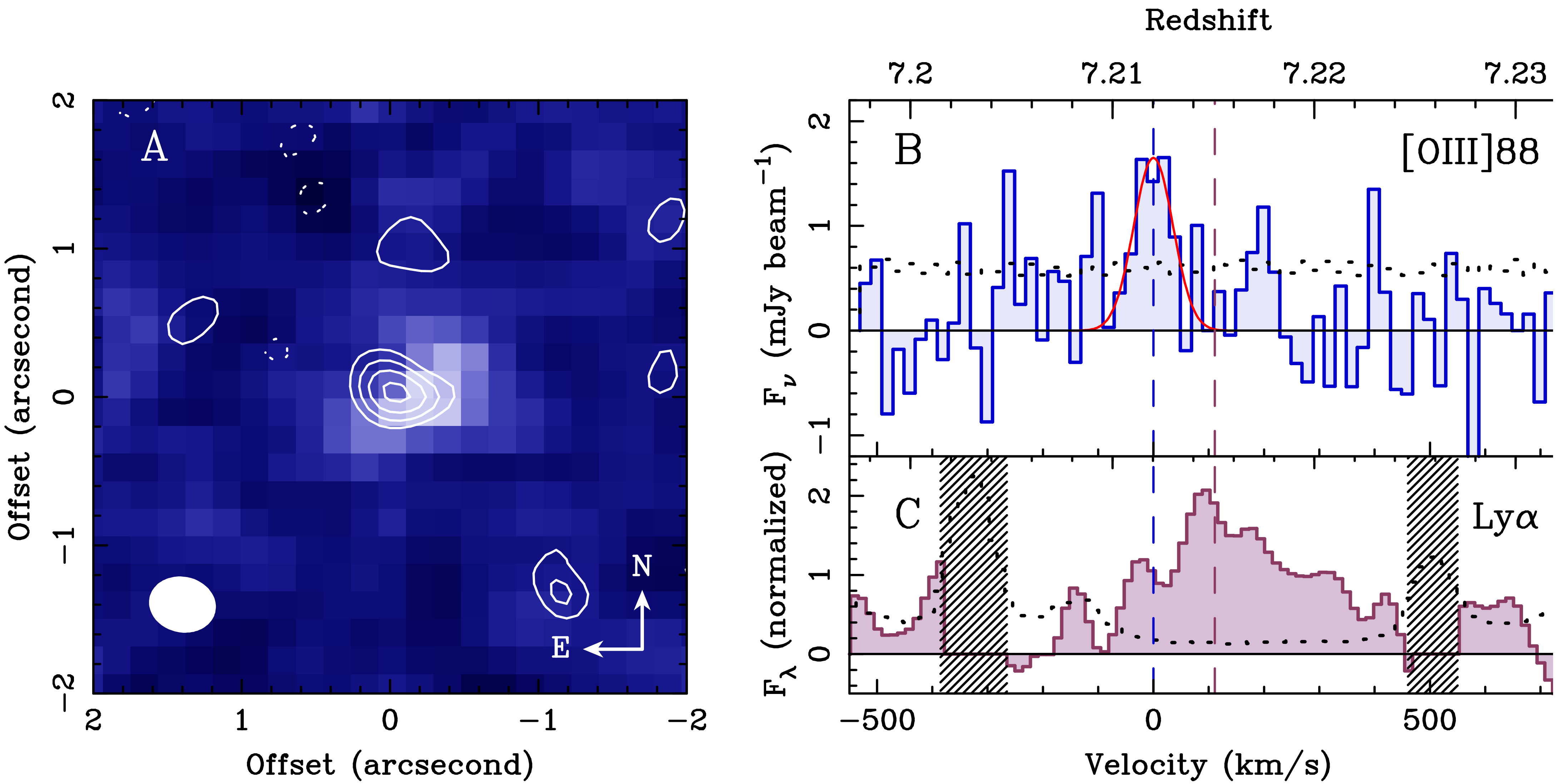
Capak+15, Nature, 522, 455



First [CII] detections emerging at z~5-6.

ALMA Detection of [OIII]88μm at z=7.2

Inoue+16, Science, arxiv:1606.04989

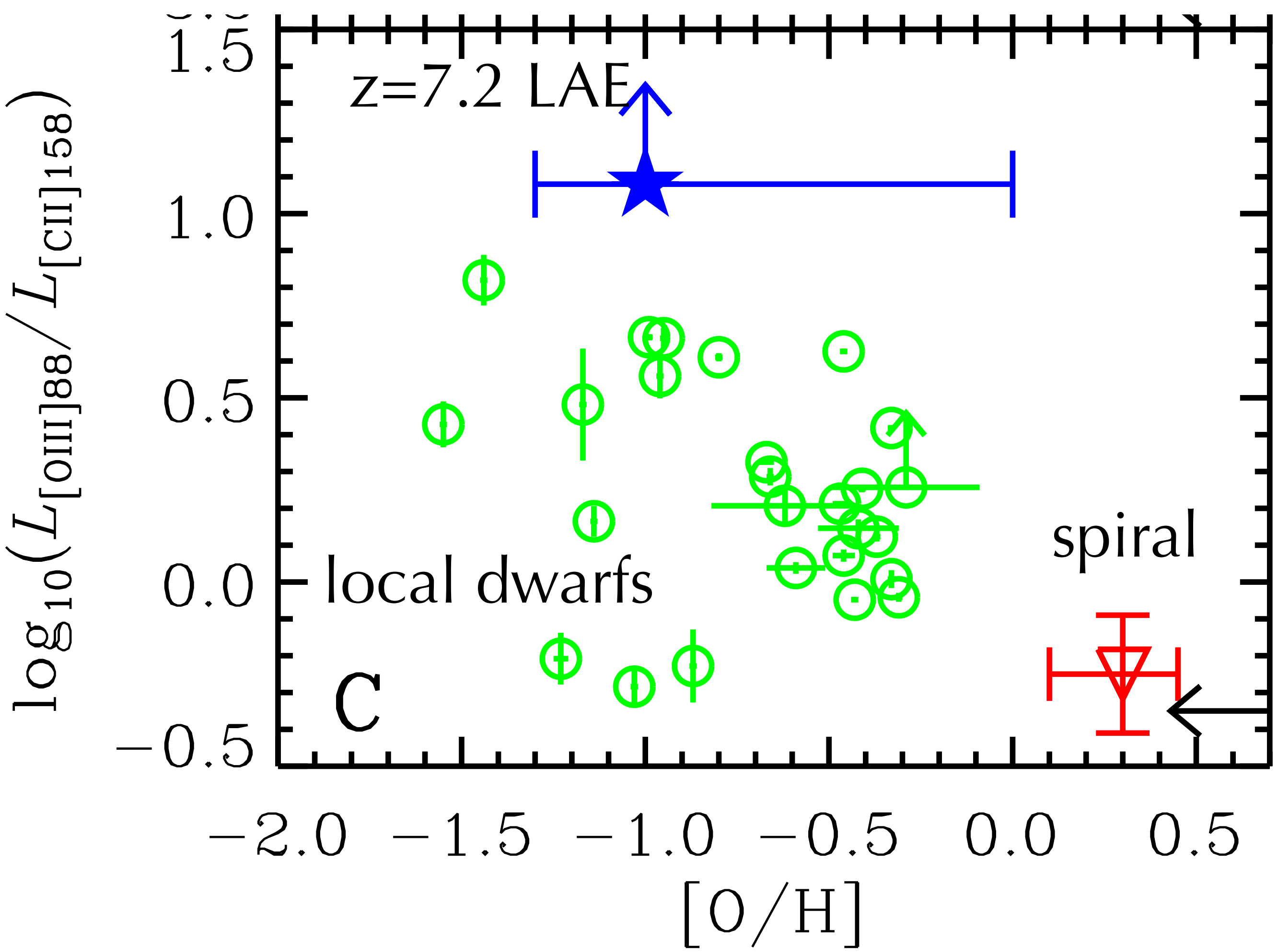


Lyman-alpha emitter discovered by Shibuya+12 (1 of 11 known at z>7).

No [CII] detected.

Low Neutral Gas Filling Factor in Metal Poor Galaxies at z>7?

Inoue+16, Science, arxiv:1606.04989



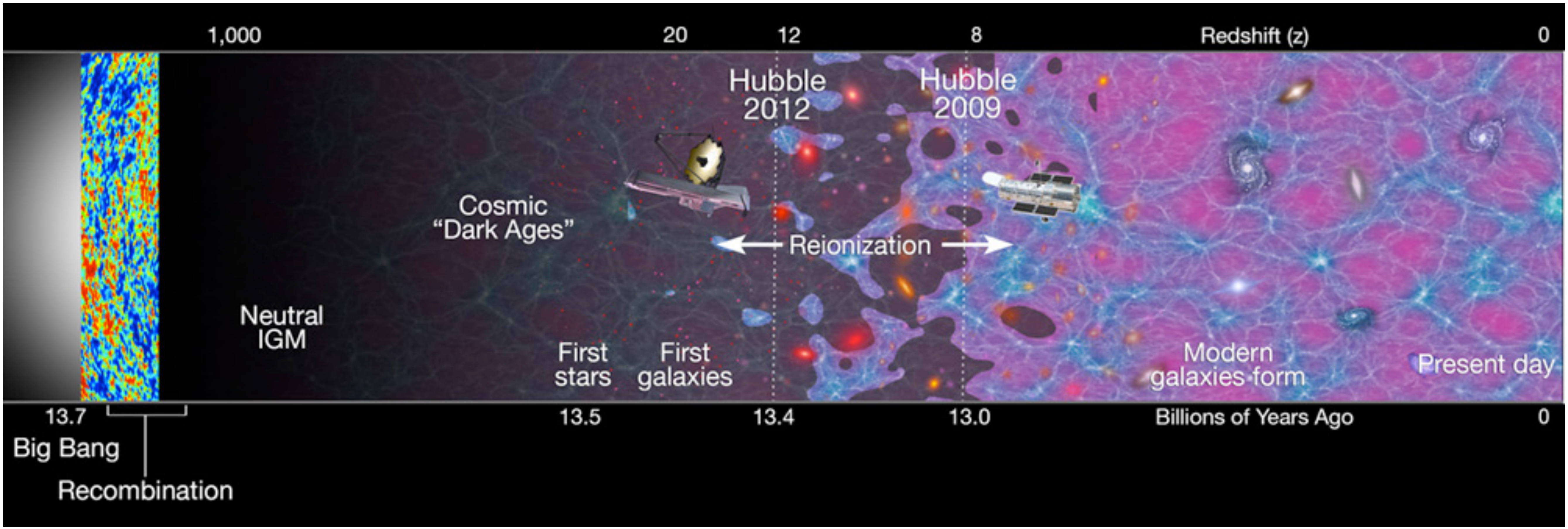
[OIII] luminosity is >12x that of [CII].

Broadly consistent with trends in nearby local dwarfs (De Looze+14, Cormier+15).

Neutral gas content lower at low metallicity?

Emerging picture: galaxies at z>7 are low metallicity with hard radiation fields which produce a large filling factor of highly ionized gas.

Overview



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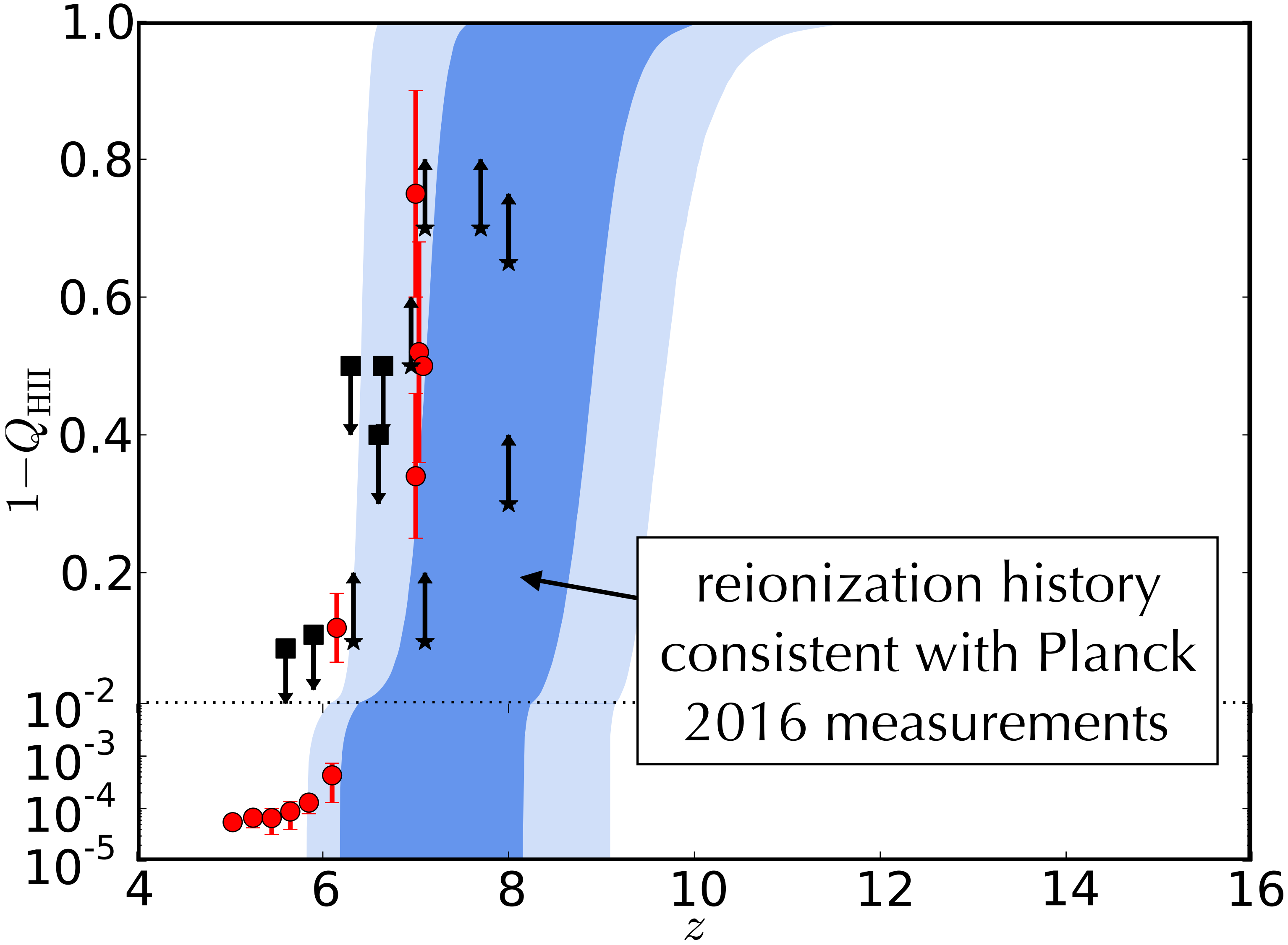
New Results from Planck 2016

Planck Collaboration et al. 2016



Thomson scattering optical depth keeps coming down!

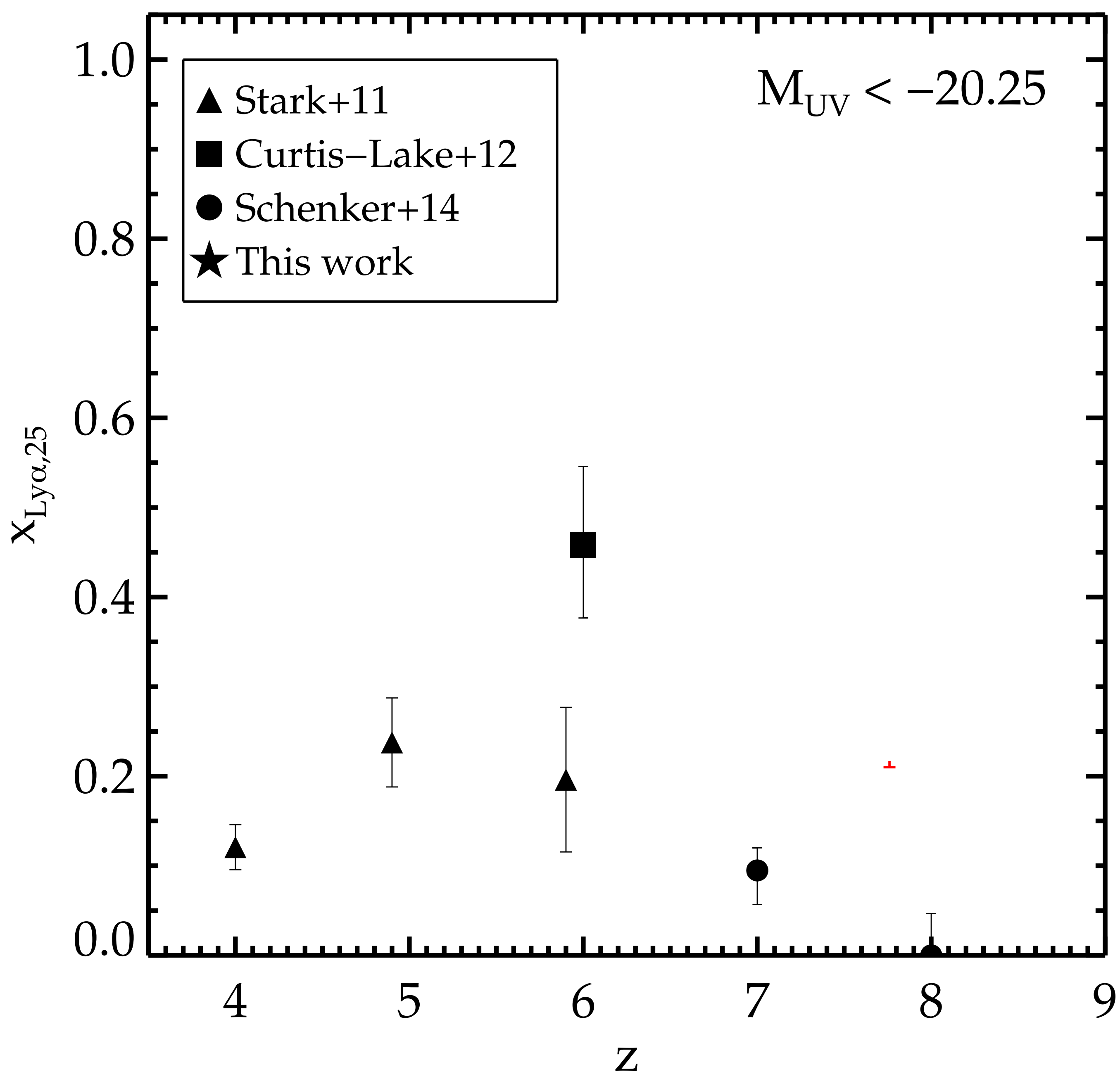
- **Planck 2016 (τ_e=0.058)**

Suggests reionization happened late (6<z<9).

No longer require abundant population of star forming systems at z>10.

Late Reionization Implied by Lyα Emission

Stark+16, arXiv:1606.01304

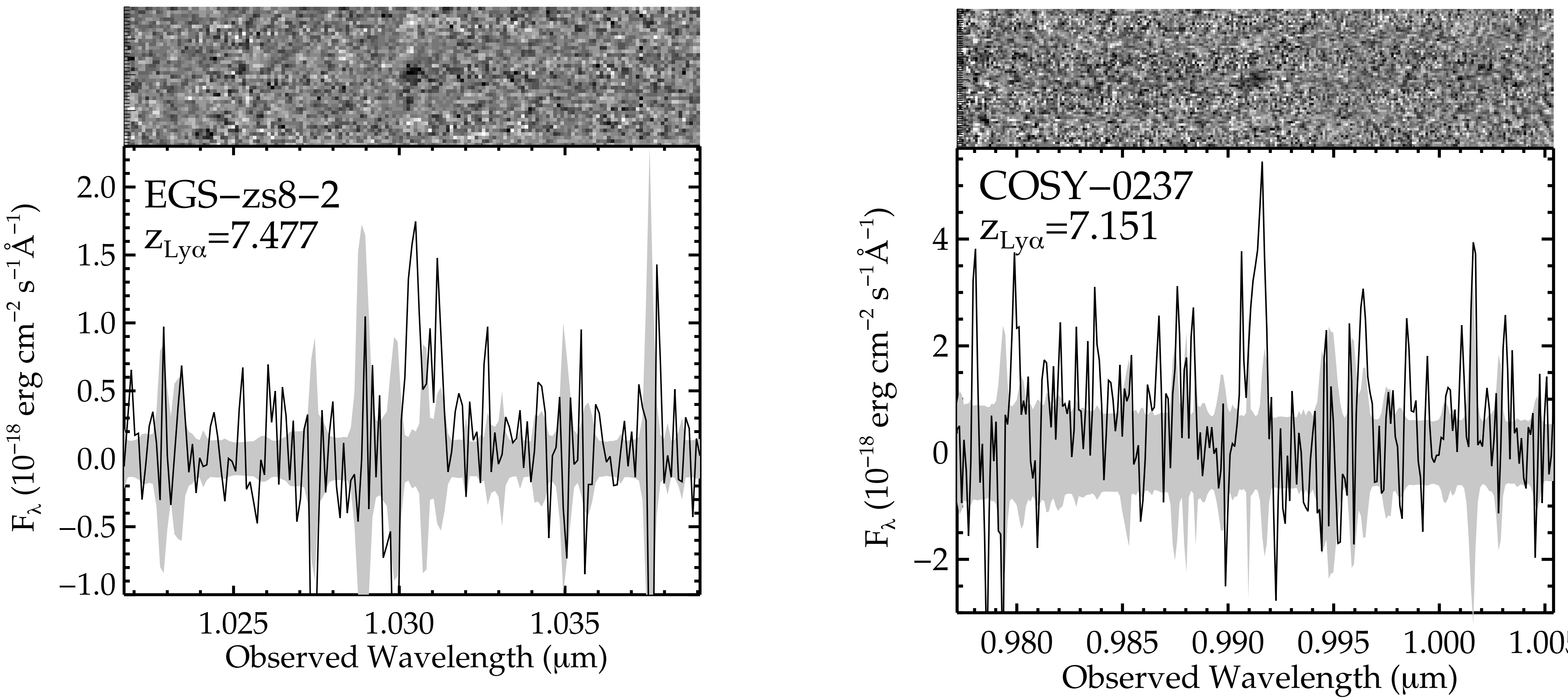


Drop in Lyman-alpha fraction suggests IGM is partially neutral (>10%) at z~7-8.

Reionization likely comes to an end late, at z~6.

100% Lyman-alpha fraction in Luminous [OIII]+Hβ Emitters?

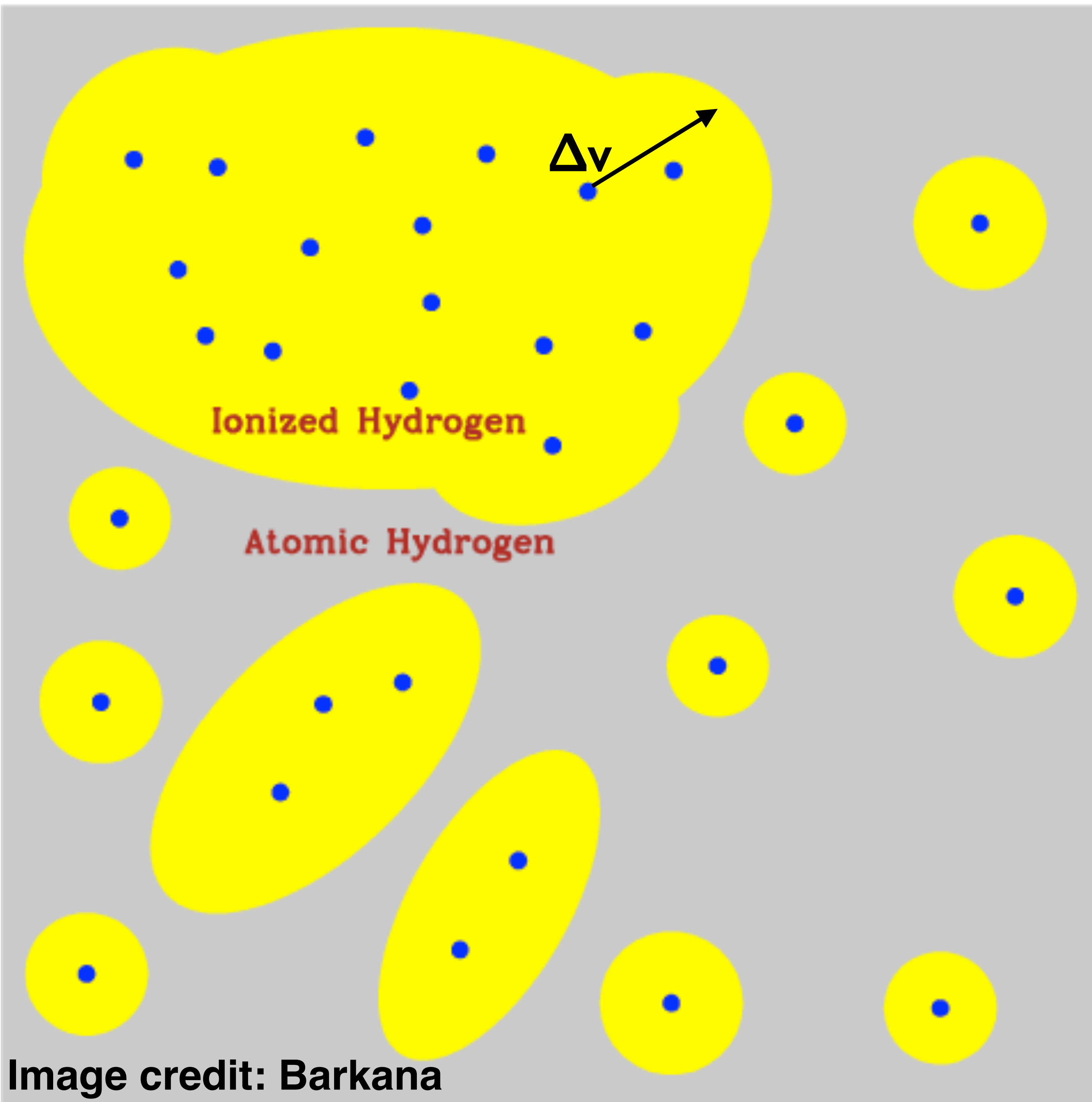
Stark+16, arXiv:1606.01304



How does Lyman-alpha escape from this sample while being so strongly attenuated in other galaxies at z>7?

Accelerated Reionization around the Most Luminous Galaxies?

Stark+16, arXiv:1606.01304



Transmission is boosted in most luminous galaxies by

(1) Location in largest ionized bubbles.

(2) Larger Lyα velocity offsets which transfer line further away from resonance.

Larger samples of luminous galaxies needed to confirm.

Summary

I. Census of Galaxies and Quasars in the Reionization Era

- Rapid decline in density of bright galaxies at quasars at z>4.
- First constraints on luminosity density at z~9-10.
- No turnover in galaxy UV LF to M_{UV}~-15?

II. Spectral Properties of z>6 Galaxies

- Large sSFRs, low dust content, and extreme EW optical line emission.
- High ionization emission lines (CIV, He II) and intense CIII] emission, suggesting hard ionizing spectrum may be common in reionization-era galaxies.
- [CII] detections emerging at z~5-6. First [OIII]88um detection reported at z>7, revealing much larger luminosity than [CII]

III. Reionization

- Lyman-alpha transmission appears highly luminosity-dependent at z~7-8.
- Lyman-alpha aided in most luminous galaxies by (a) larger ionized bubbles and (b) larger velocity offsets.