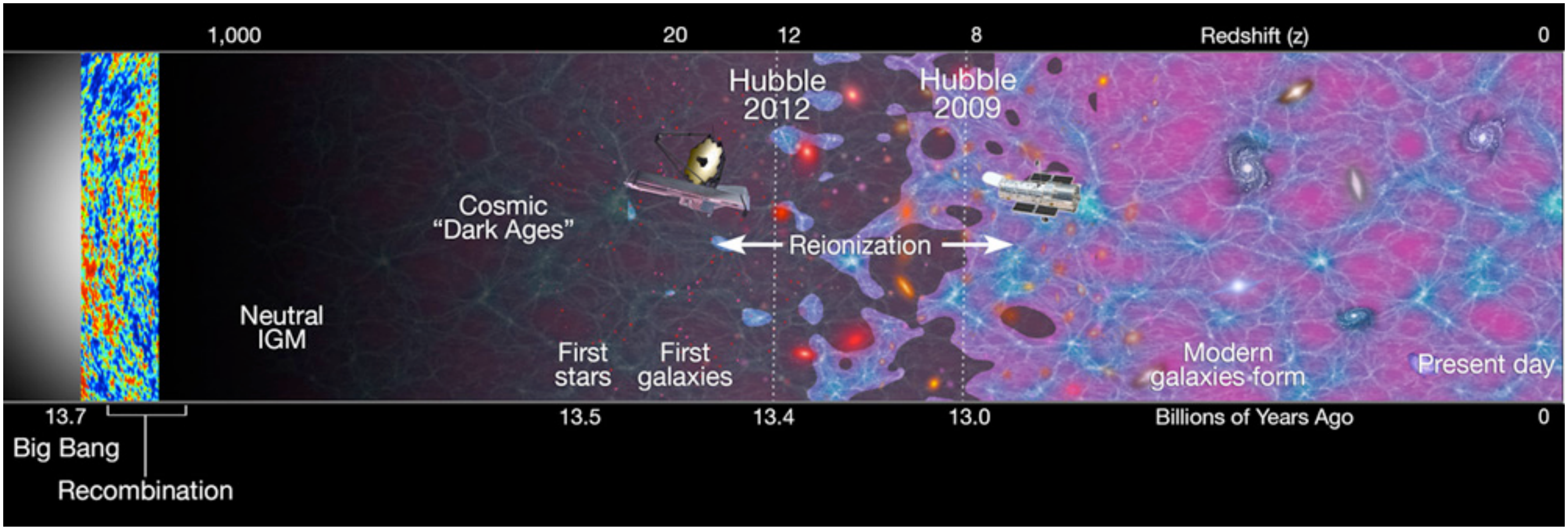
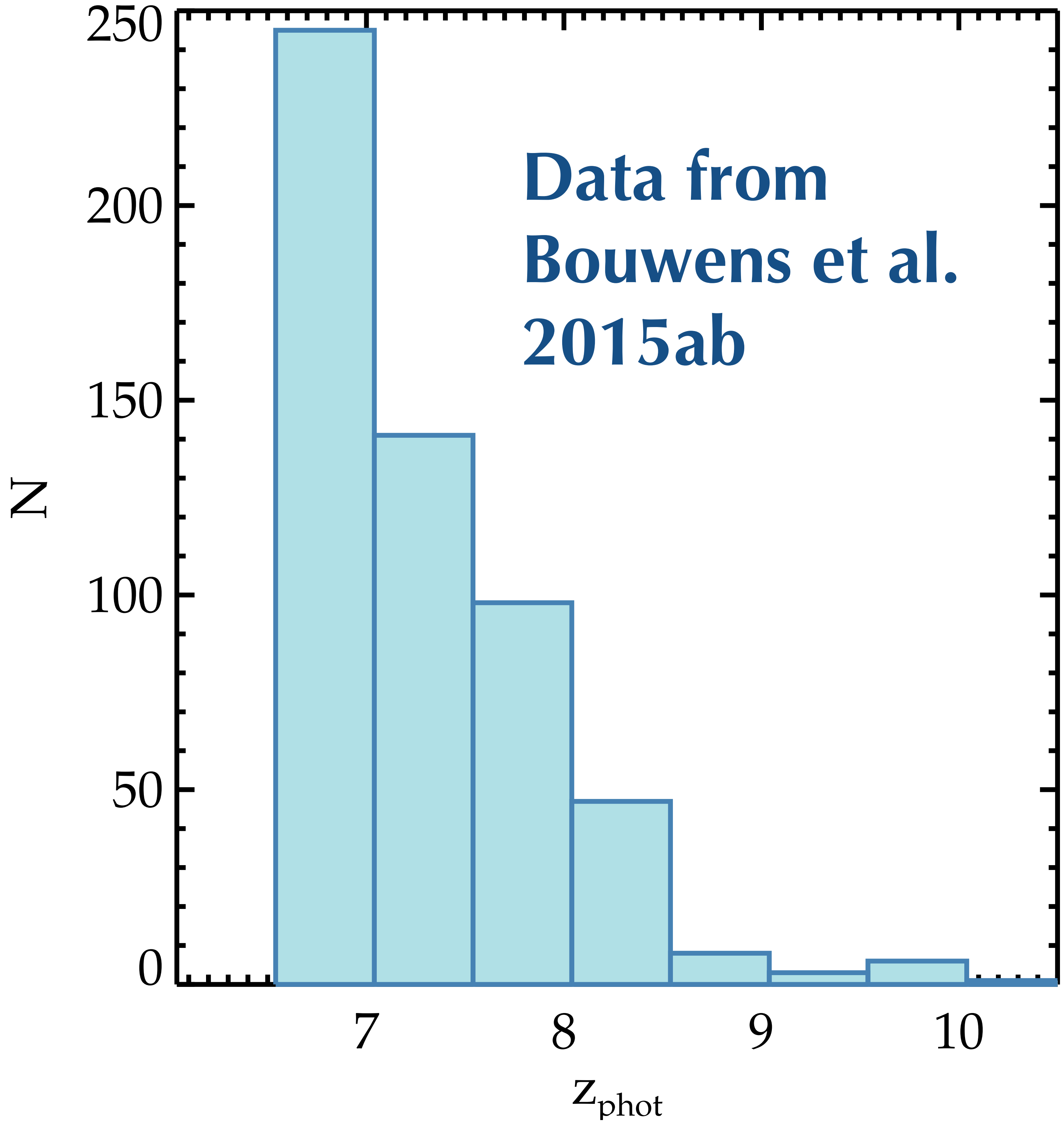
# New Insight into the Reionization Era from Spectroscopy of z>6 Galaxies




Dan Stark (University of Arizona)
with Peter Senchyna, Ramesh Mainali (Arizona)
Richard Ellis (ESO/UCL), Stéphane Charlot (IAP)

# Galaxies in the Reionization Era




**Large samples:** >600 z>6.5 galaxies from HST+ground-based imaging

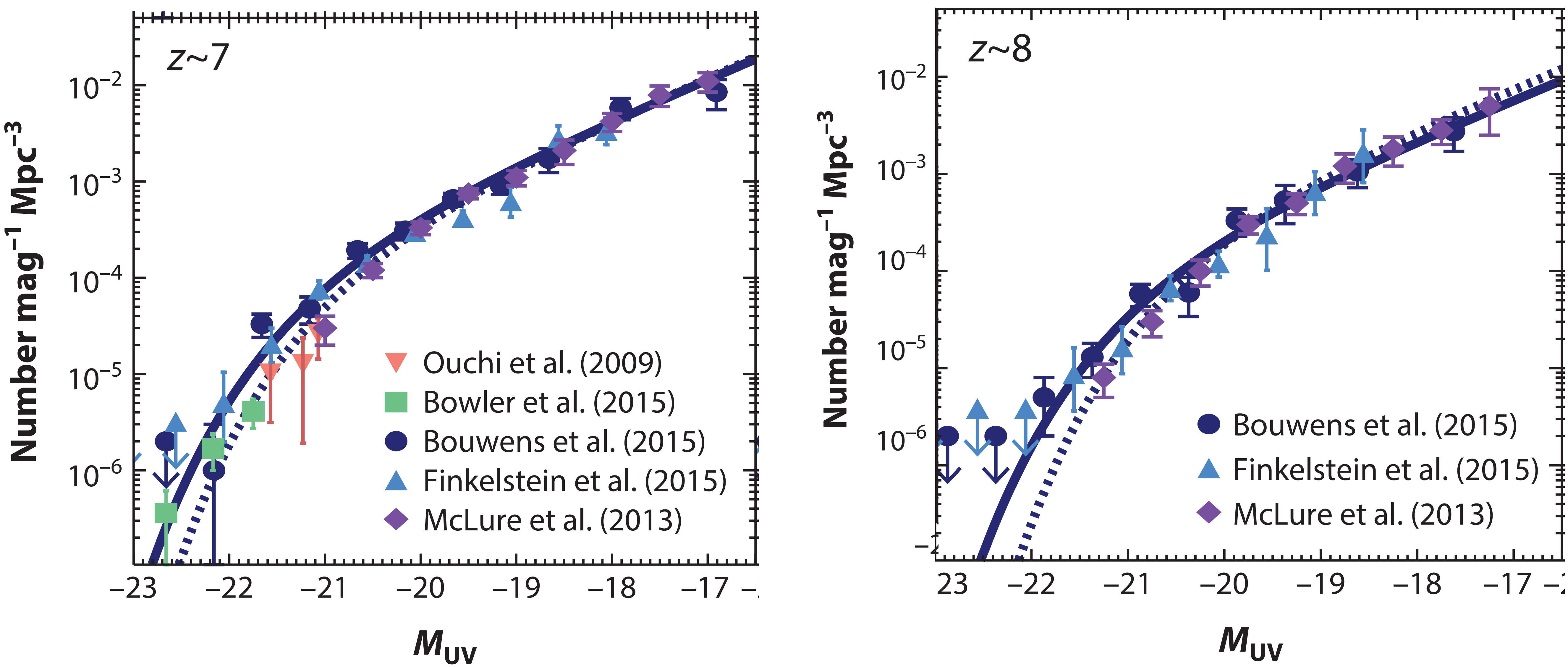
**Large dynamic range in luminosity:** $\Delta M_{UV} \sim 6$

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*

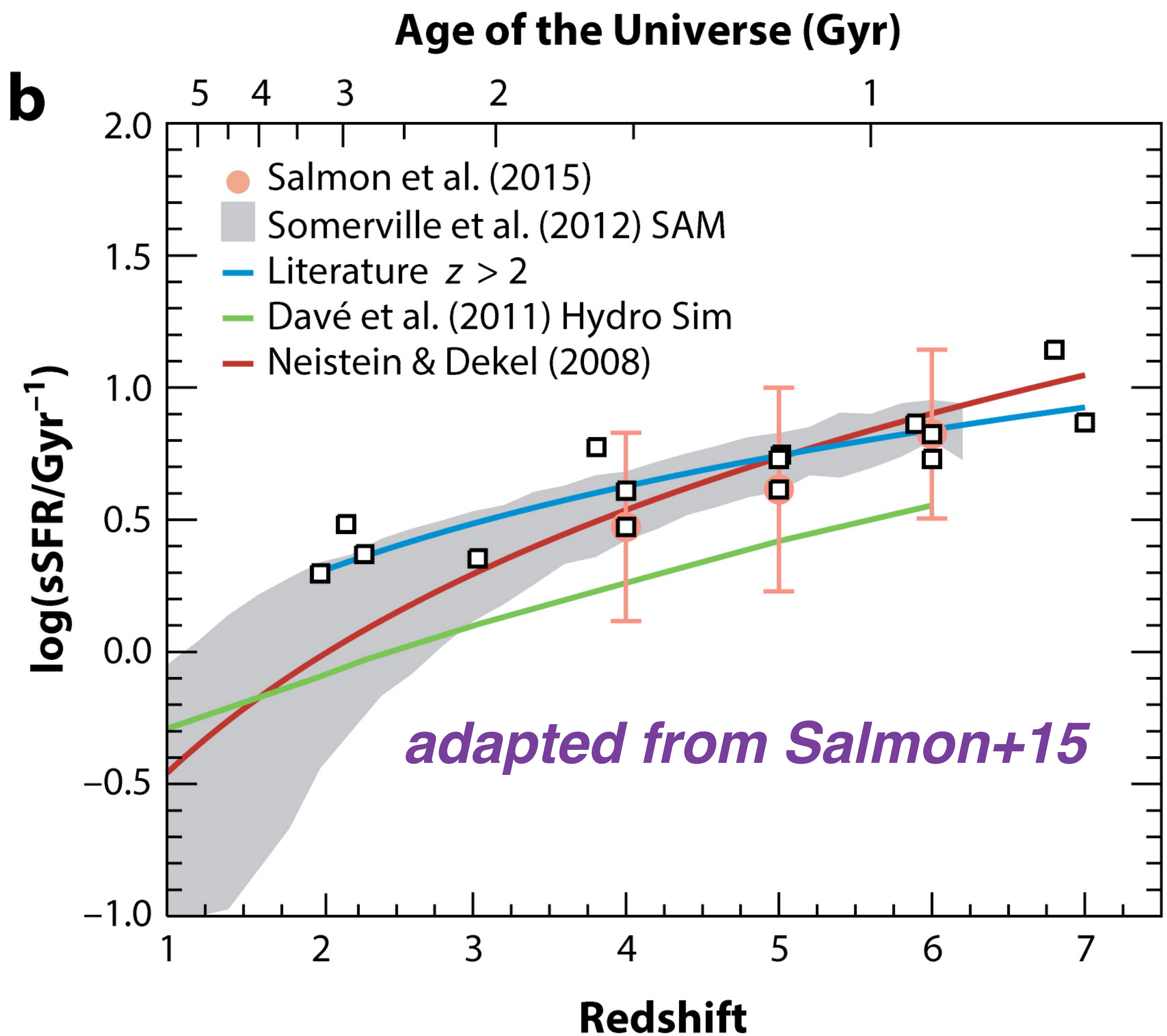
# Census of Galaxies in the Reionization Era




- Next step: detailed spectroscopic studies
    - Bright, luminous sources uncovered in wide area imaging campaigns
    - Intrinsically faint galaxies discovered via gravitational lensing

**Stark 2016, ARAA, 54, 761**

# Specific Star Formation Rates Increase at z>2

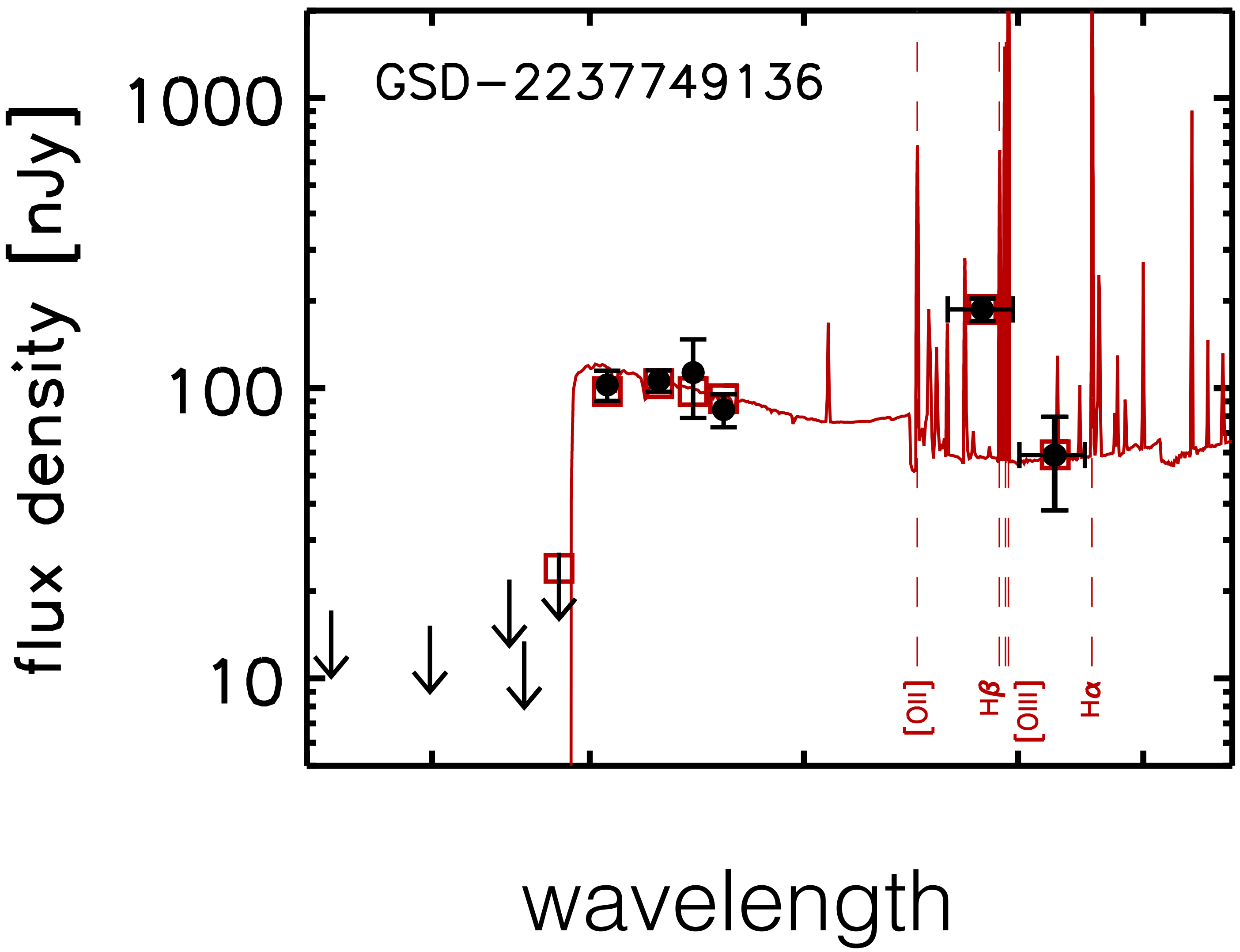



(see also Gonzalez+14, Duncan+14)

Stark 2016, ARAA, 54, 761

# Extreme Optical Line Emitters at z~6.6-6.9

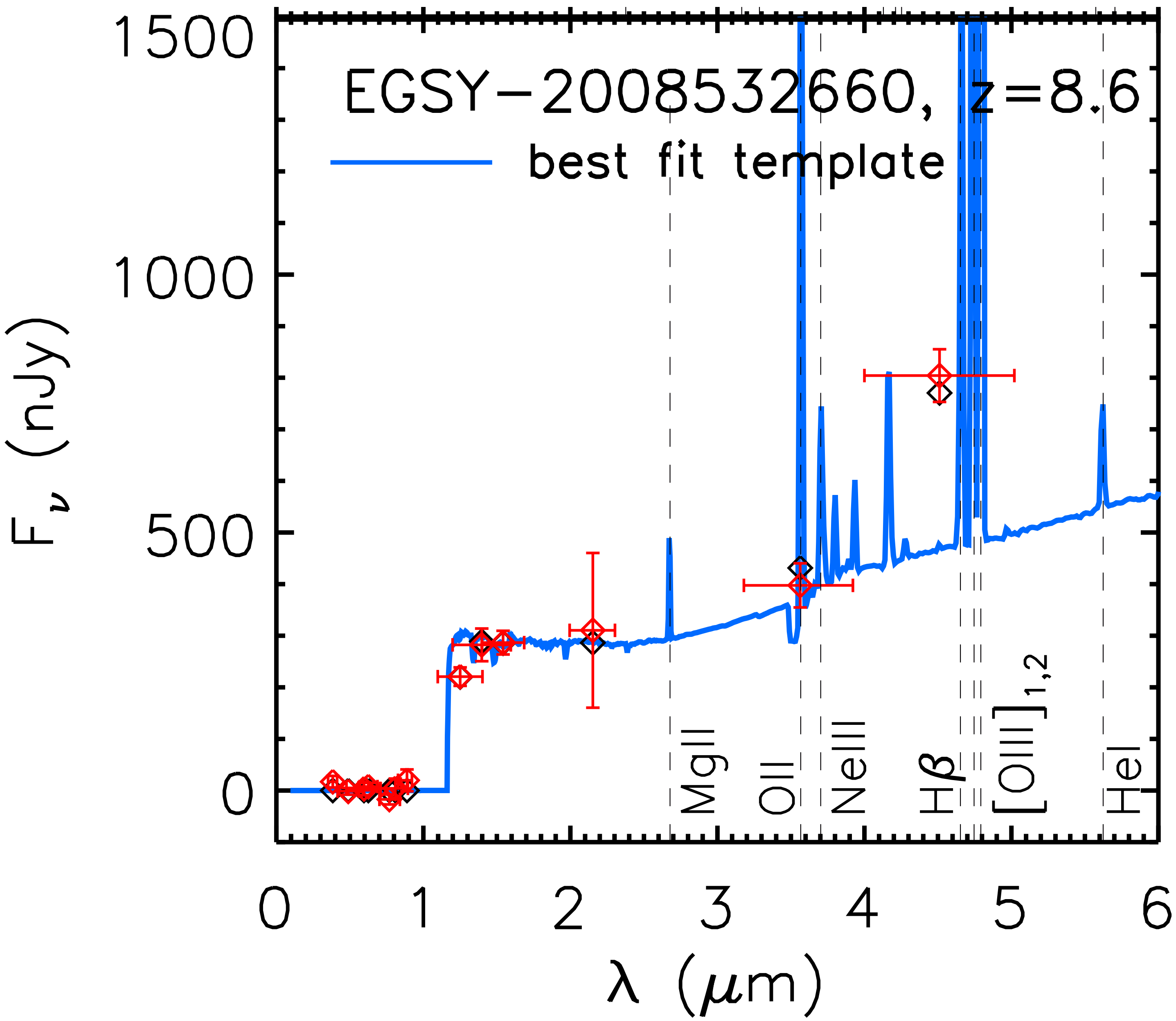
**Smit+15, ApJ, 801,122**




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

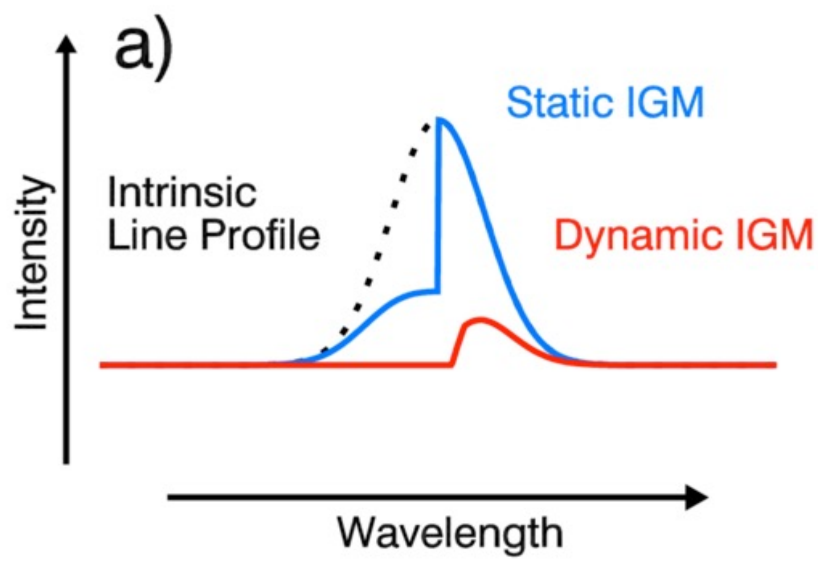



New sample of large EW [OIII]+Hβ emitters recently located at z~7-9.

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

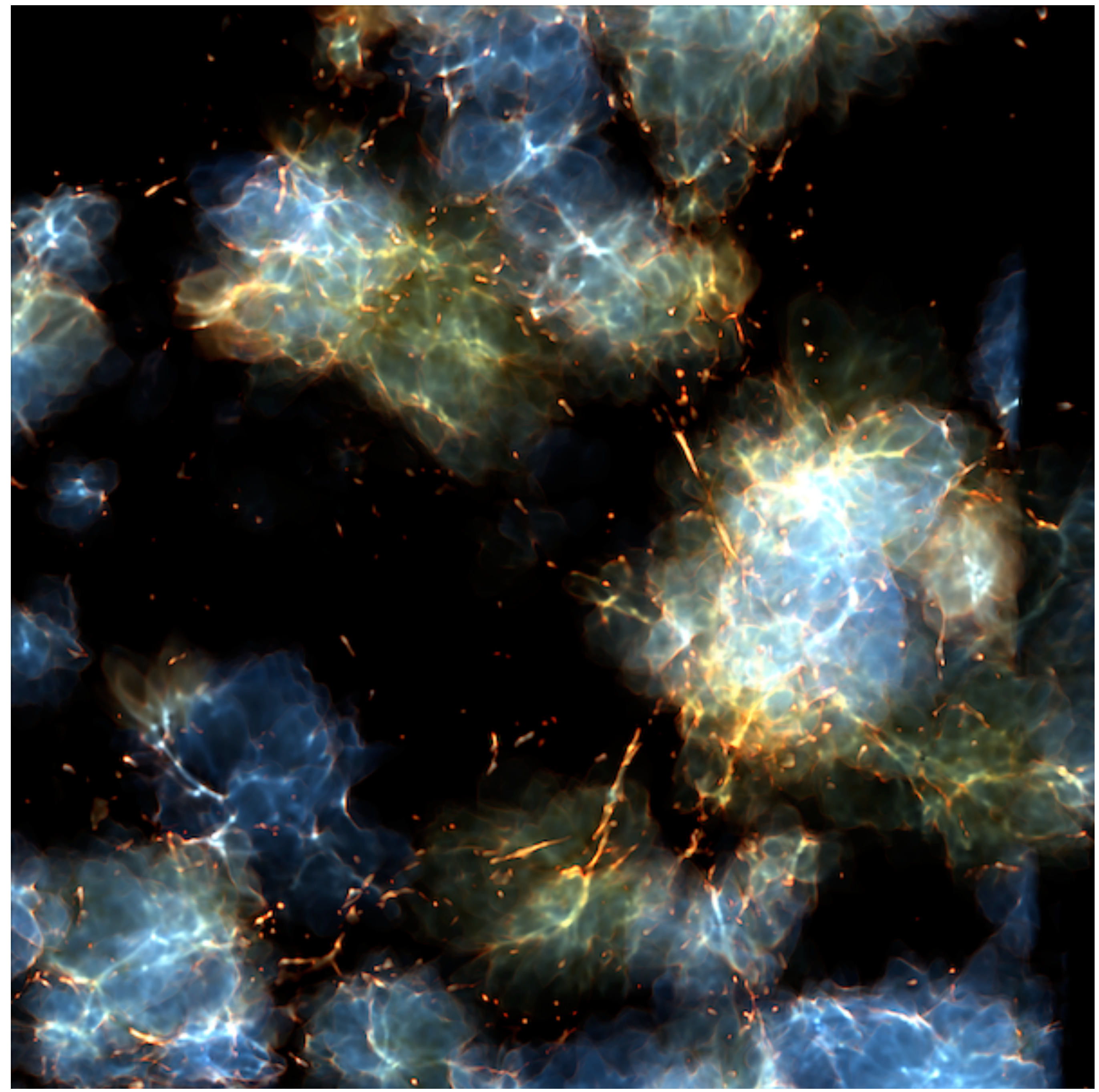
Suggests very young stellar populations, with large ionizing output per unit 1500Å luminosity -> **expect different spectral properties.**

# Spectroscopic Studies of z>7 Galaxies: Ly$\alpha$ Emission as Probe of Reionization




Partially neutral IGM will scatter Ly$\alpha$ from early galaxies.

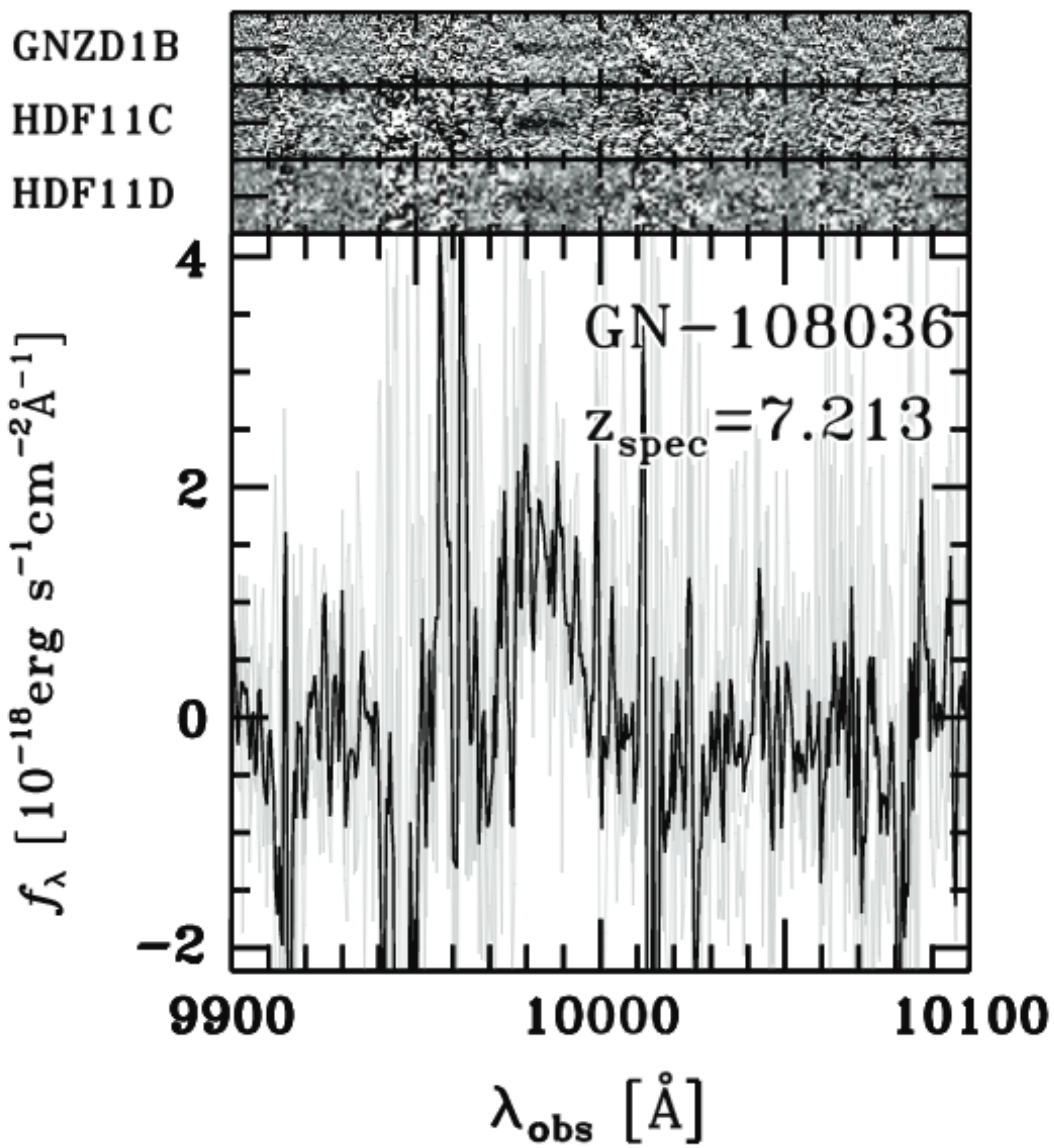
Expect Ly$\alpha$ emission to be less common in UV-selected sample of galaxies in reionization era



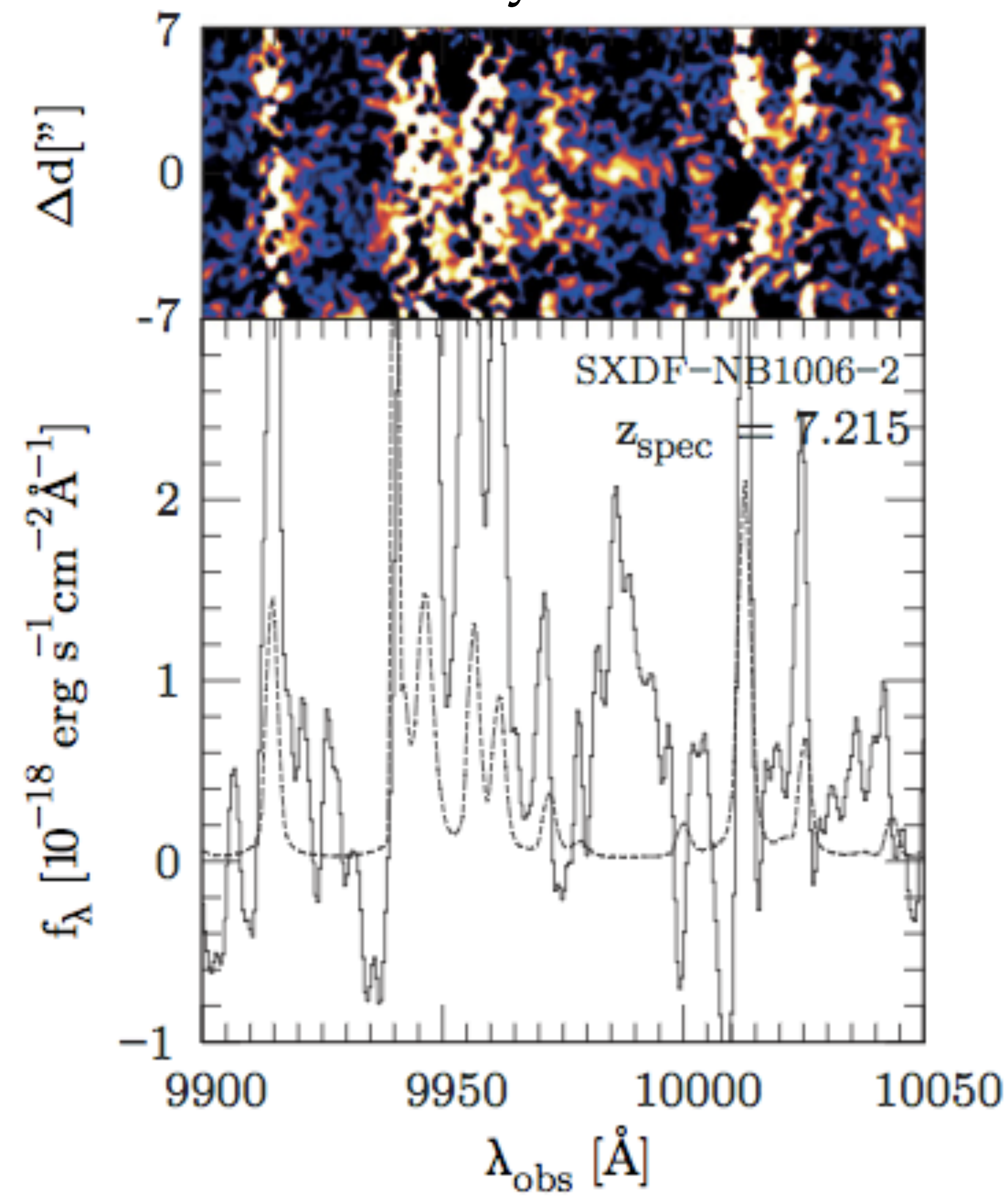
credit: Wise, Cen, and Abel

# Spectroscopically Confirmed z>7 Lyman-alpha Emitters

Ono et al. 2012



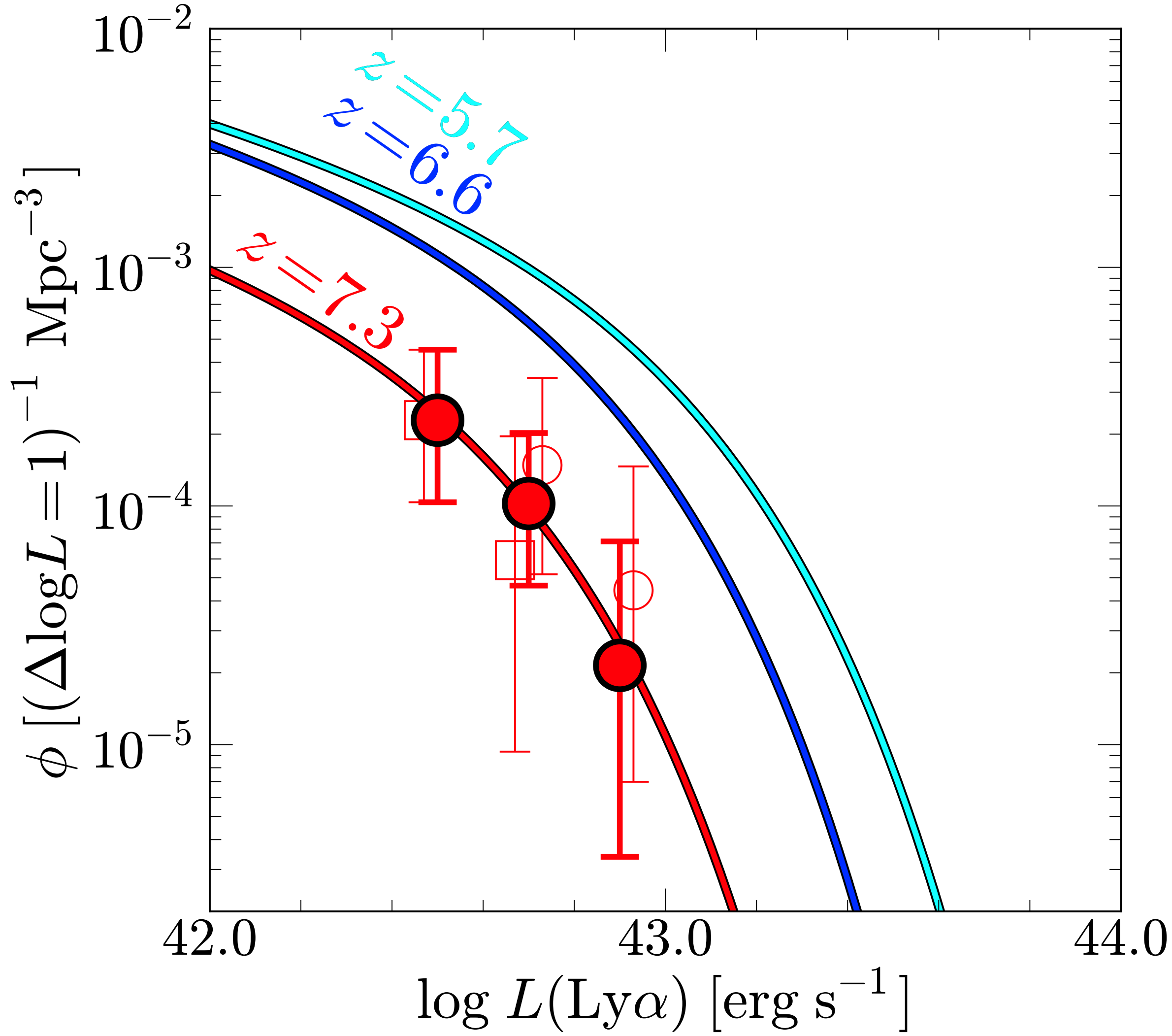

Shibuya et al. 2012



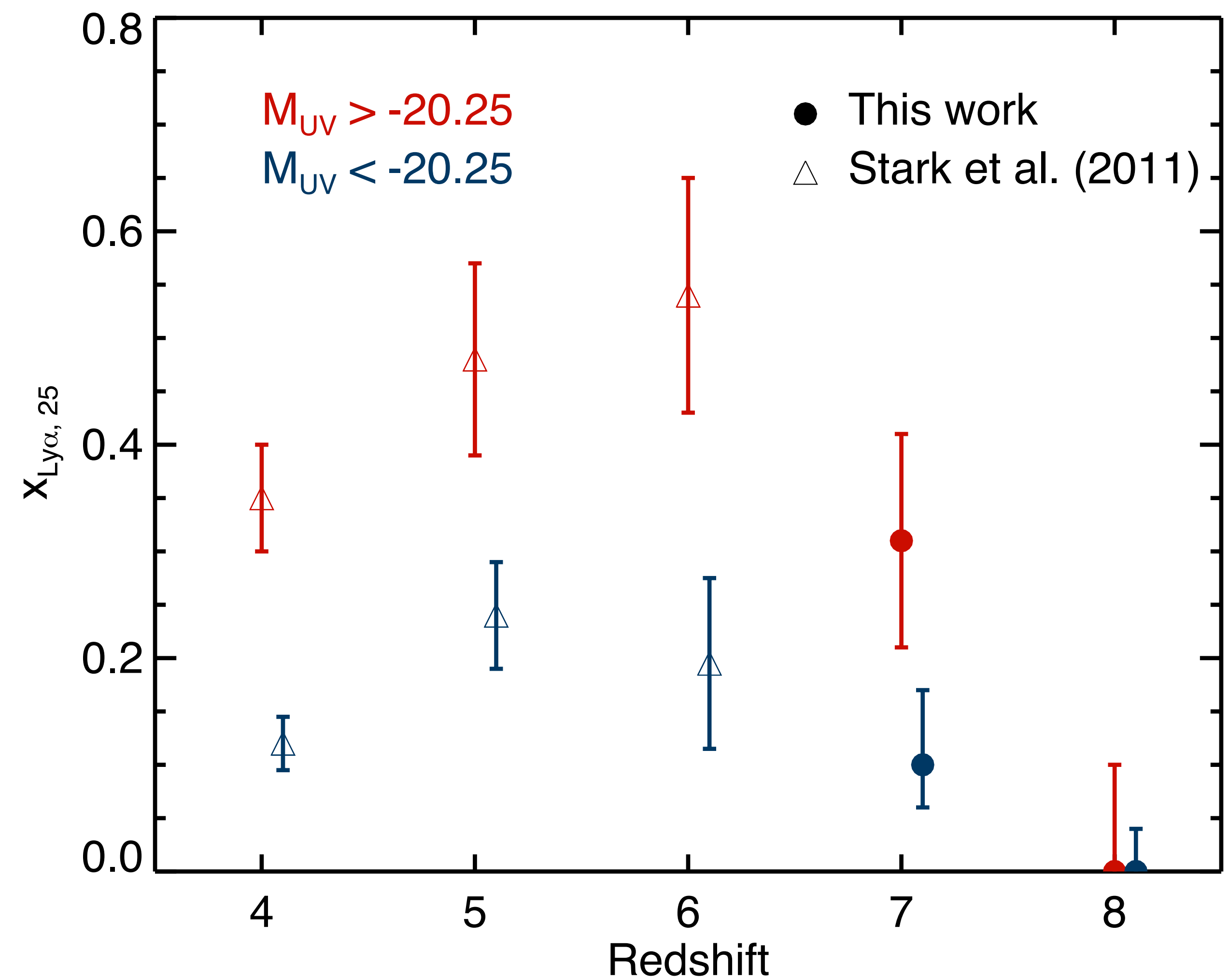

Influx of new LAEs confirmed at z>7 in 2010-2012 following deep imaging campaigns from ground (Subaru, VLT) and with HST.

# Lyman-alpha Disappearance?

Konno et al. 2014




Schenker et al. 2014

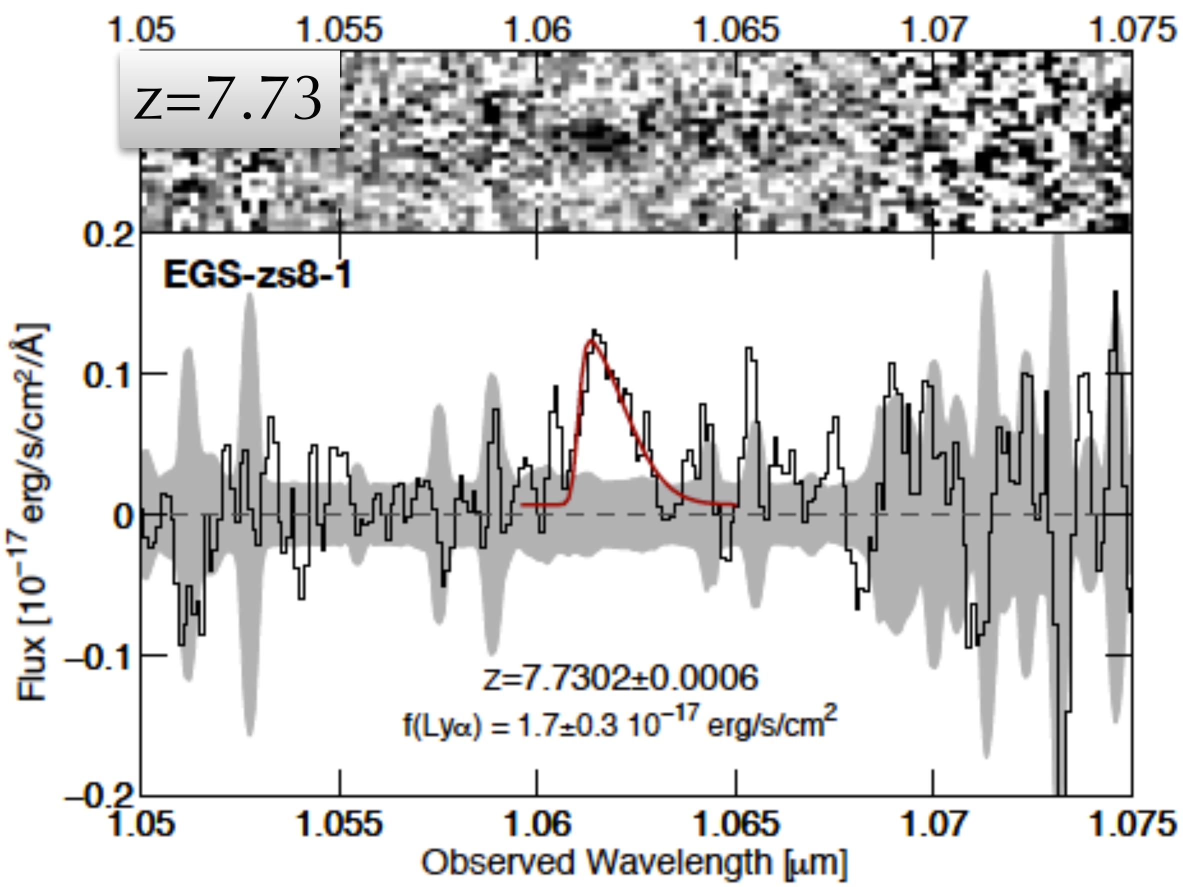



- *Lyman-alpha emission is rare in z>7 star forming galaxies.*
- *Consistent with reionization coming to end over 6<z<7*

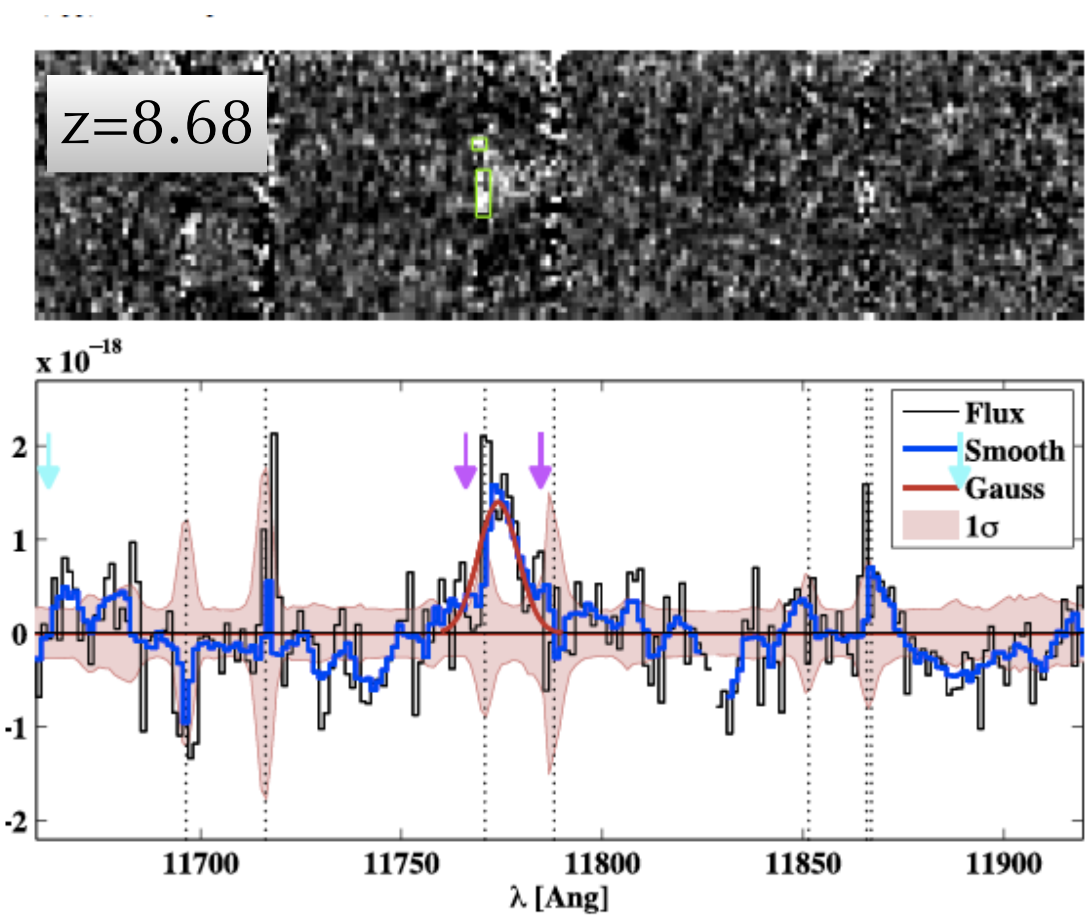
(see also Fontana et al. 2010, Vanzella et al. 2011, Ono et al. 2012, Pentericci et al. 2011, 2014, Treu et al 2012, 2013, Tilvi et al. 2014, Bian et al. 2014, Schmidt et al. 2015, Furusawa et al 2016).

# New z>7 Lyman-alpha Detections in Luminous Galaxies

**Oesch+15**



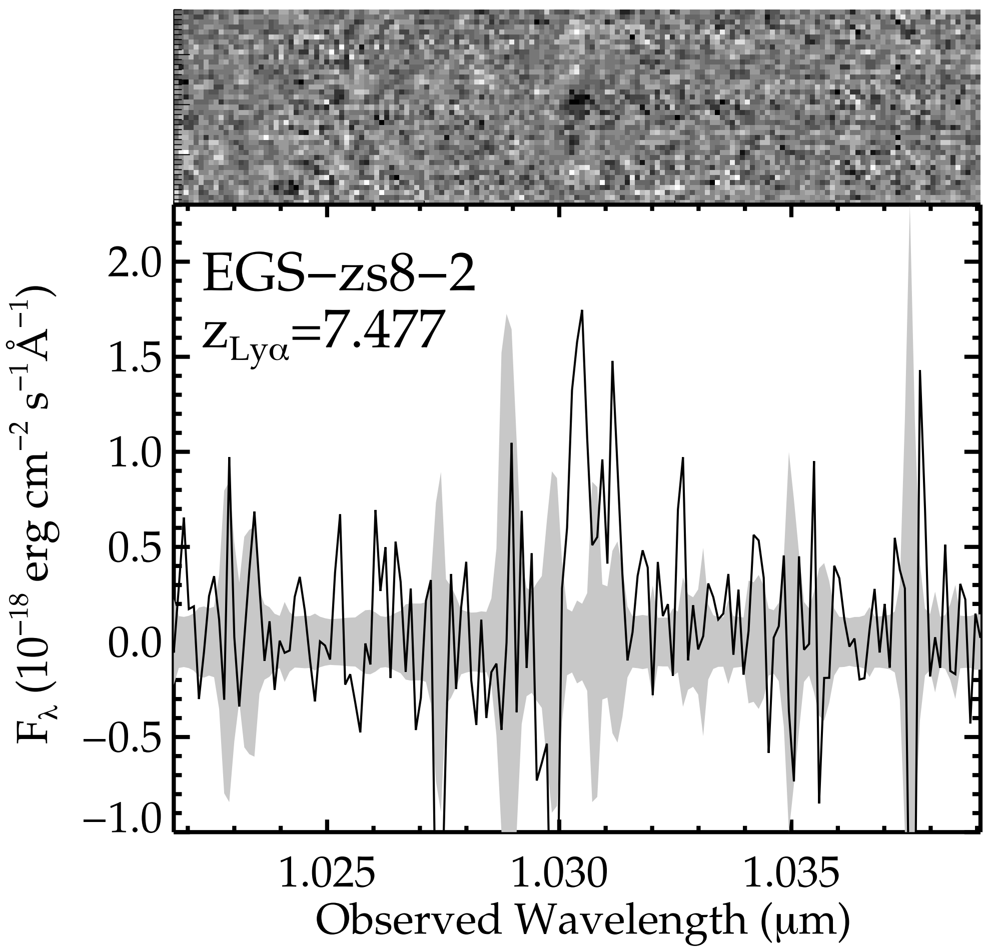

**Zitrin+15**

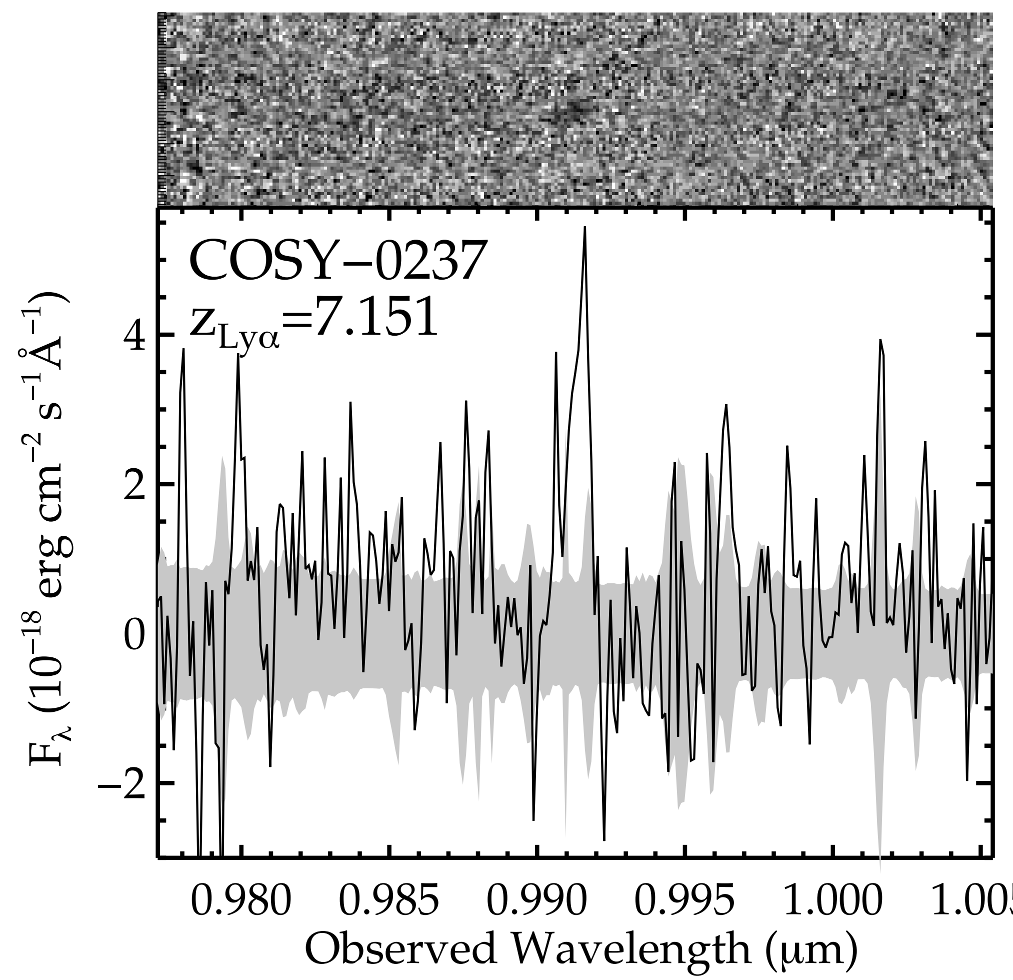



- In last year, 5 new galaxies spectroscopically confirmed with MOSFIRE (Oesch+15, Zitrin+15, Roberts-Borsani+16, Stark+16, Song+16).
- **11 galaxies now have Lyman-alpha confirmation at z>7.**

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

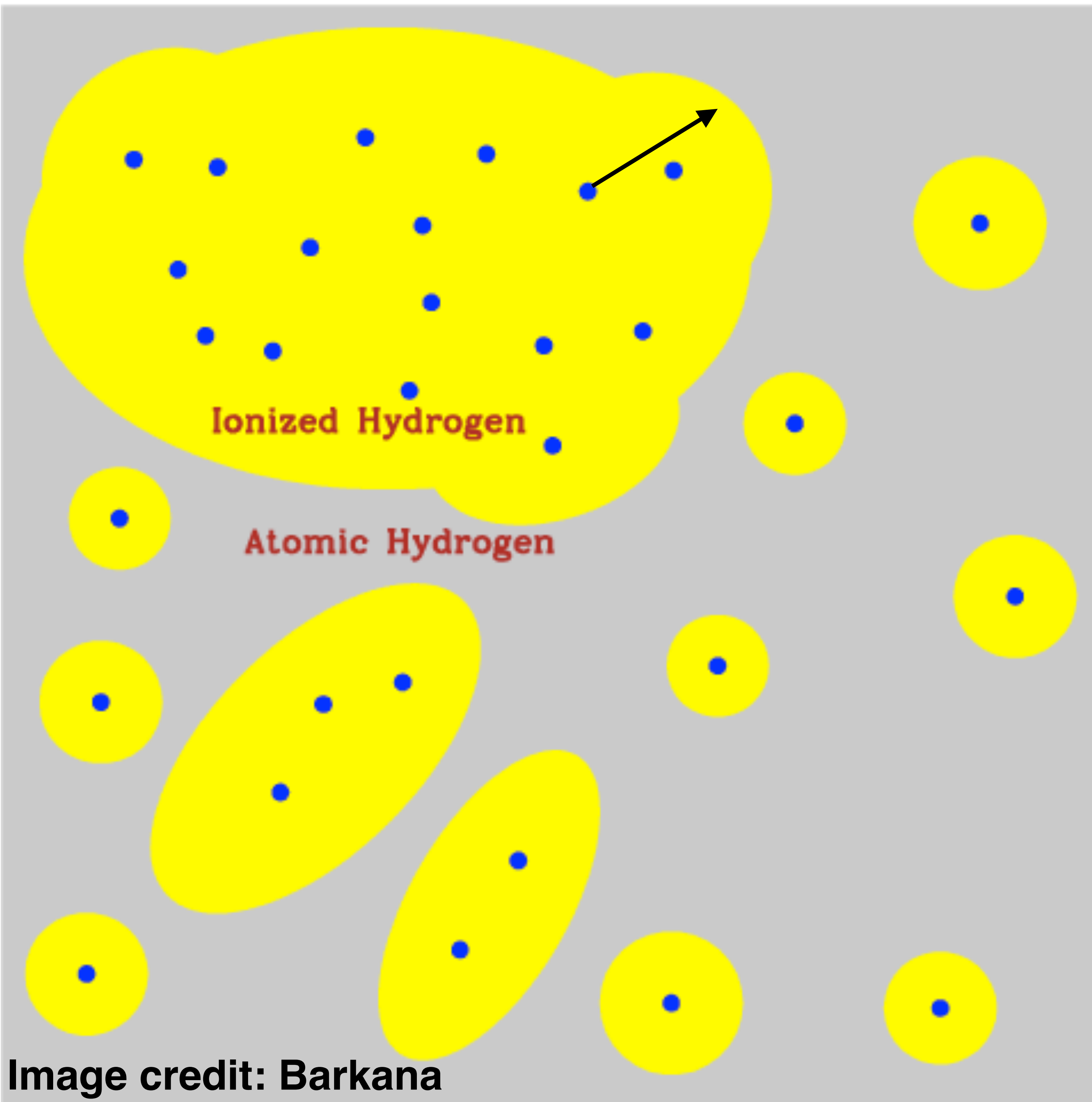
Stark+17




*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?



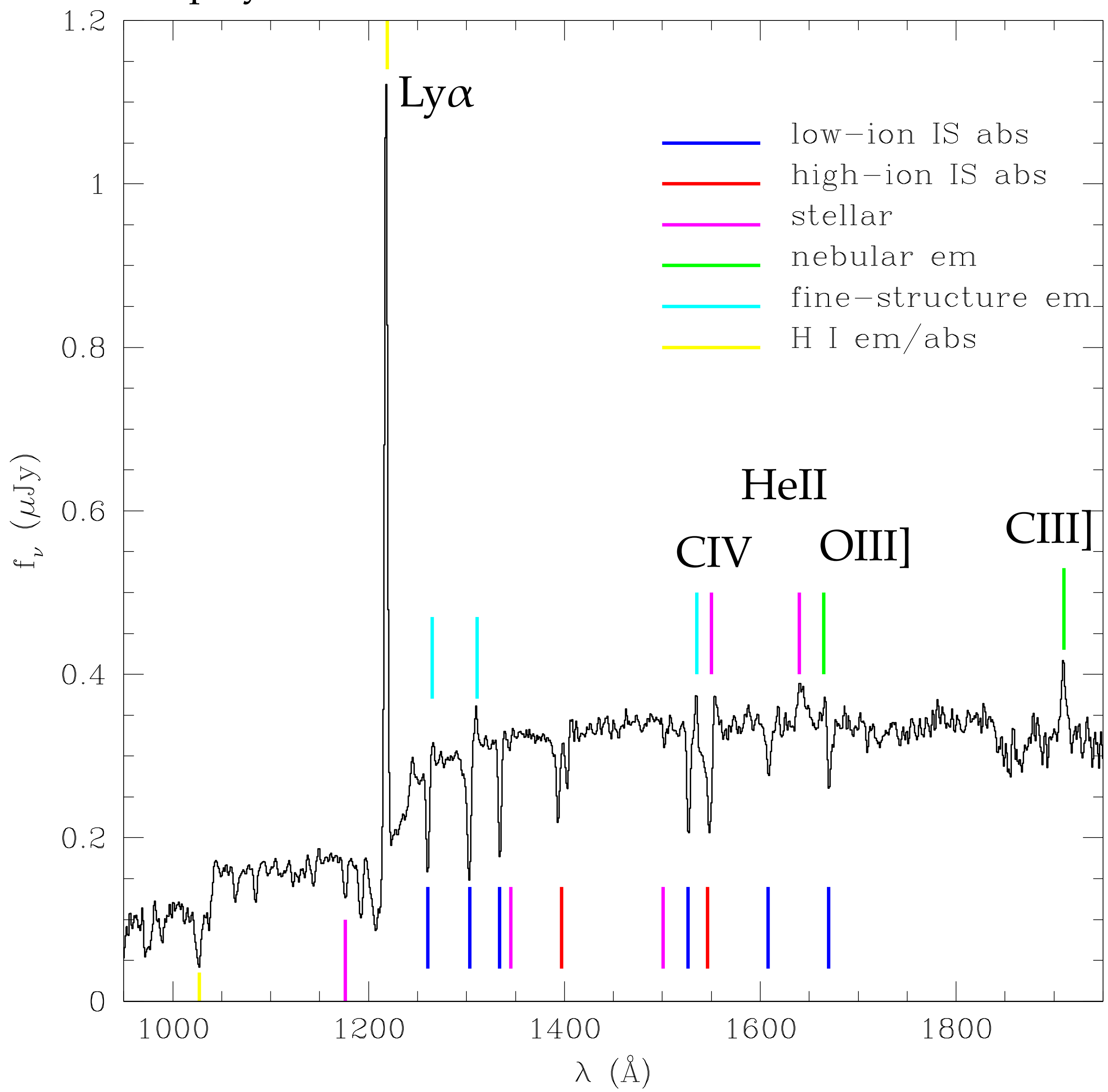

Transmission is boosted in most luminous galaxies by

(1) Location in largest ionized bubbles.

(2) Hard ionizing spectra associated with extreme EW [OIII] emitters? Effective at ionizing surrounding HI.

# How can we learn more about the spectroscopic properties of reionization-era galaxies?

Shapley et al. 2003




z~3 composite of ~900 LBGs

$W_{CIII]} = 1.7$ Å

$W_{HeII} = 1.3$ Å

$W_{OIII]\lambda1661+1666} = 0.2$ Å

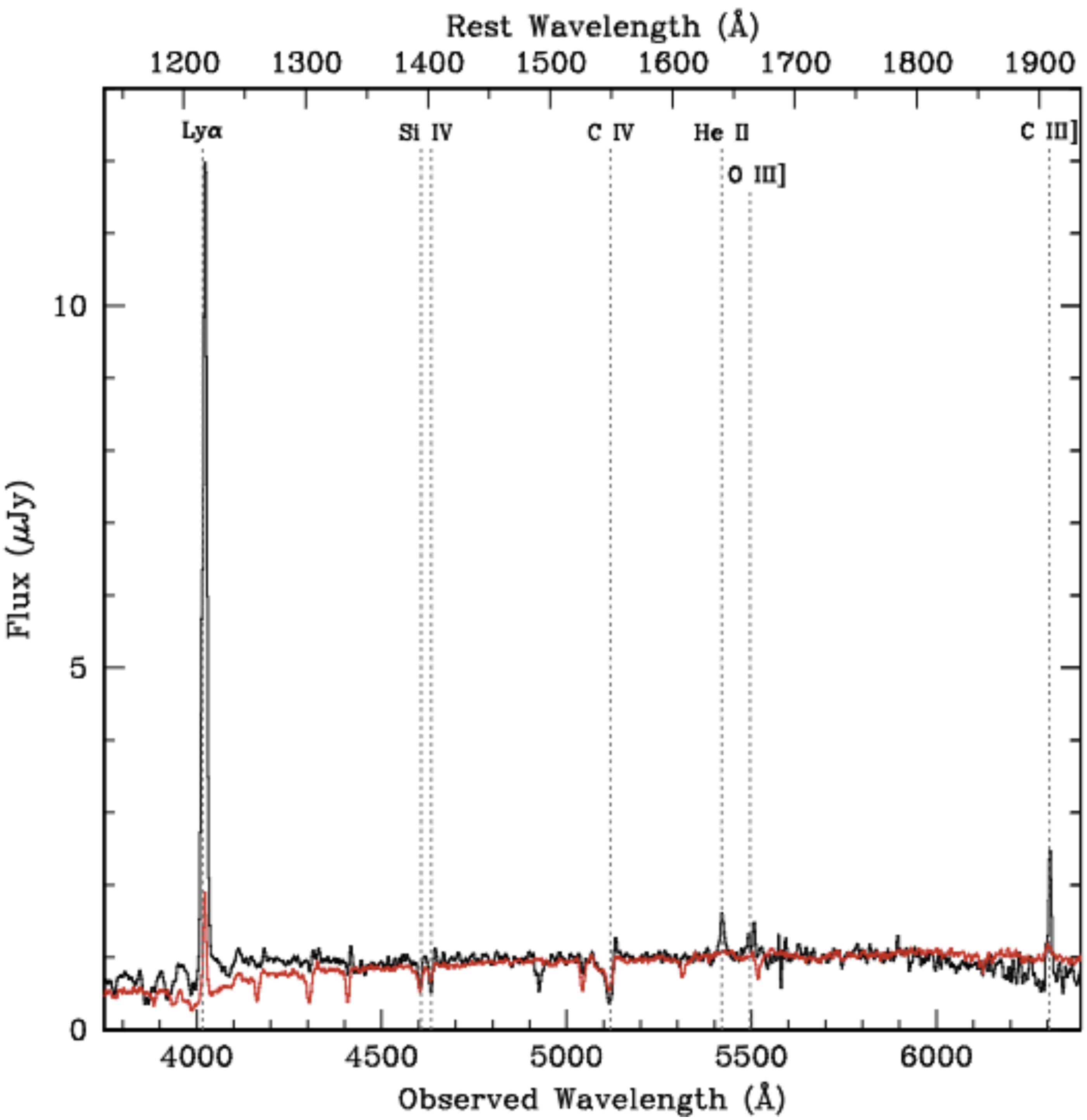
UV lines provide insight into gas conditions and radiation field.

If same EW as z~3 composite, they will be undetectable ($\lesssim 7\times10^{-19}$ erg cm$^{-2}$ s$^{-1}$) in z>7 galaxies.

***Far UV spectra of metal poor, large sSFR galaxies at z>6 may be very different!***

# Early Indications of Intense CIII] at Large sSFR

Erb et al. 2010

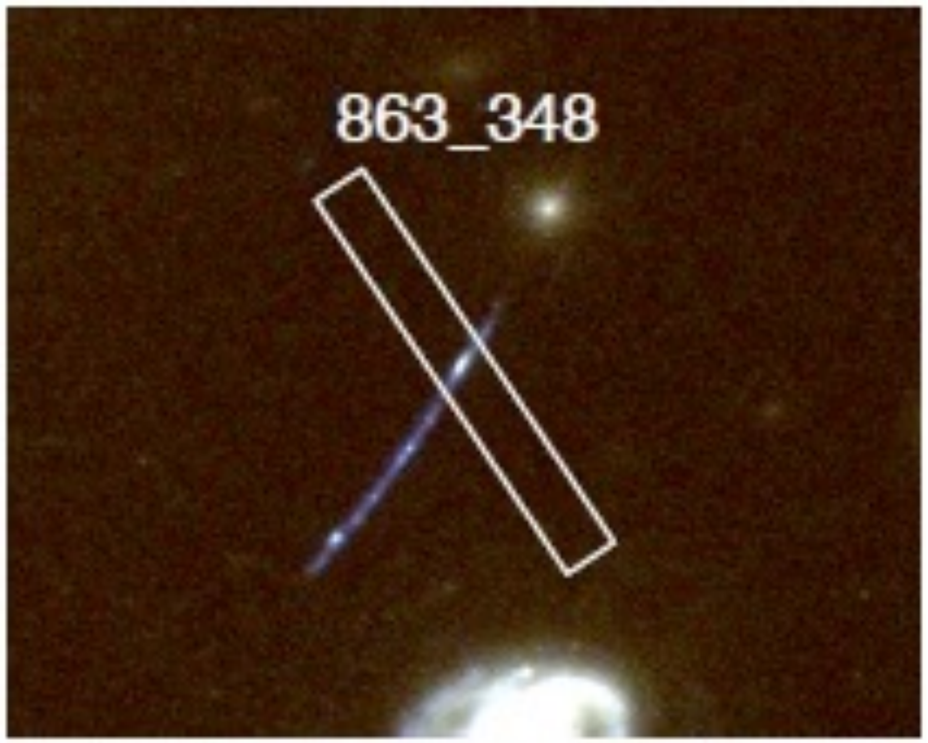


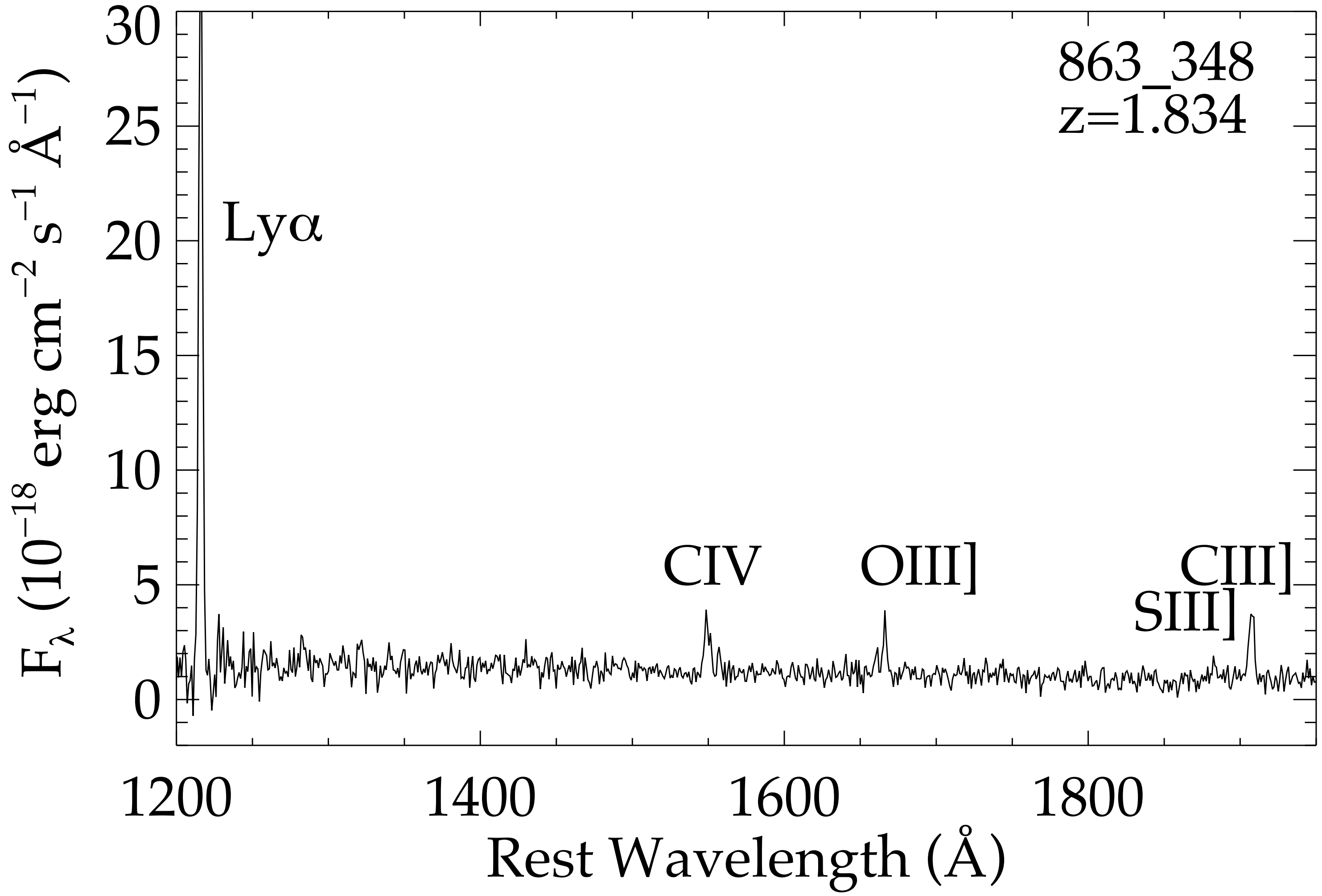

Low stellar mass (~$10^9$ $M_\odot$), metal poor (Z~0.17 $Z_\odot$) galaxy with large sSFR (17 $Gyr^{-1}$).

$W_{\rm He\,II} = 2.7$ Å
$W_{\rm OIII]1661,1666} = 2.3$ Å
$W_{\rm [CIII]1907,CIII]1909} = 7.1$ Å

# High Ionization Lines Present at Low Metallicity

Stark et al. 2014




$M^\star \sim 2.9\text{x}10^7\ M_\odot$

β=-2.0

sSFR=35 Gyr$^{-1}$

$W_{Ly\alpha,0}$ =73 Å

$W_{CIII]\lambda1908,0}$ = 14 Å

$W_{CIV\lambda1549,0}$ = 8 Å

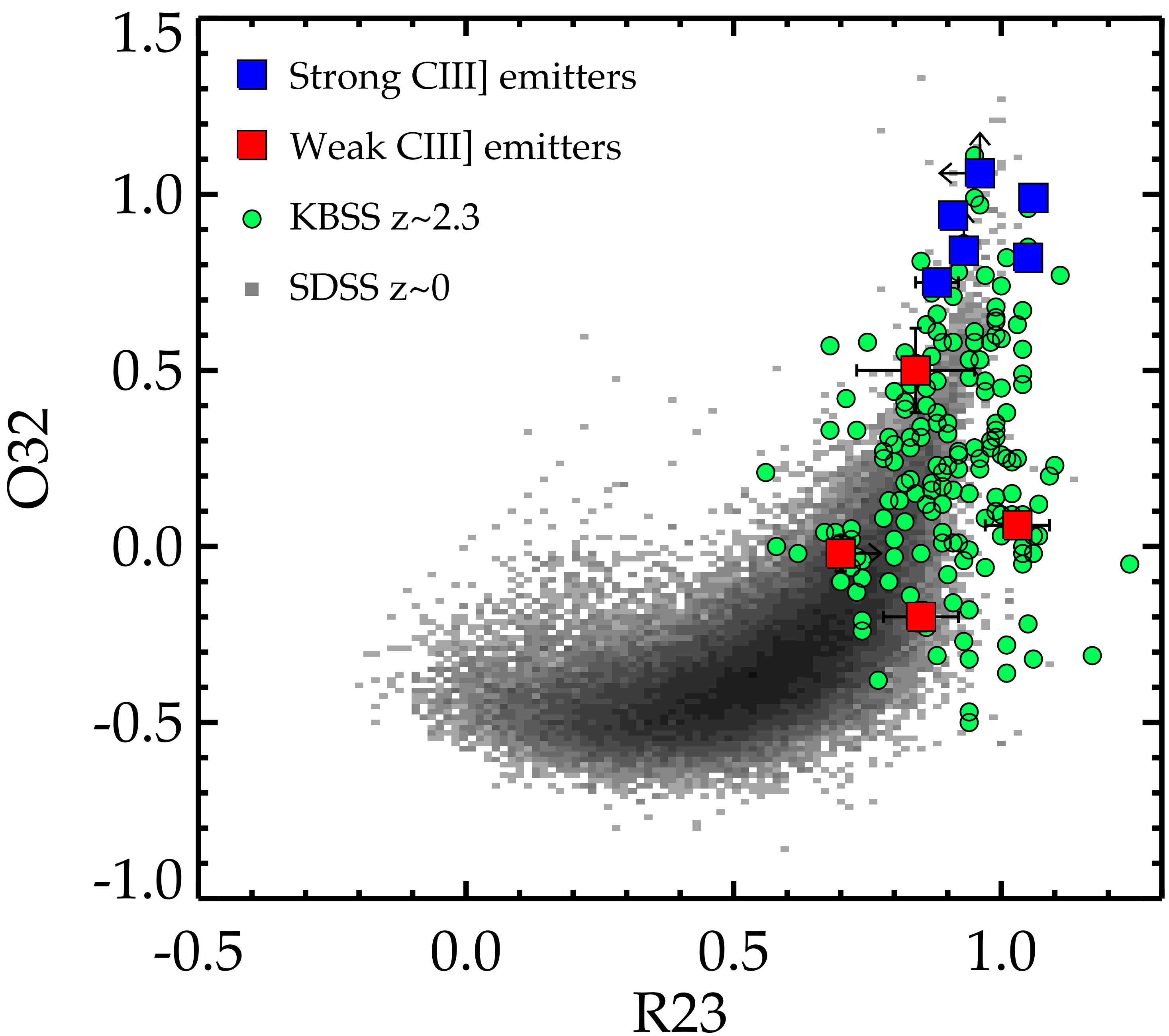
$W_{OIIII]\lambda1666,0}$ = 7 Å

$W_{Si\ IIII]\lambda1883,0}$ = 3 Å

$W_{HeII\lambda1640,0}$ < 1.4 Å

# New Rest-Optical Spectroscopy of CIII] Emitters

Mainali+2017



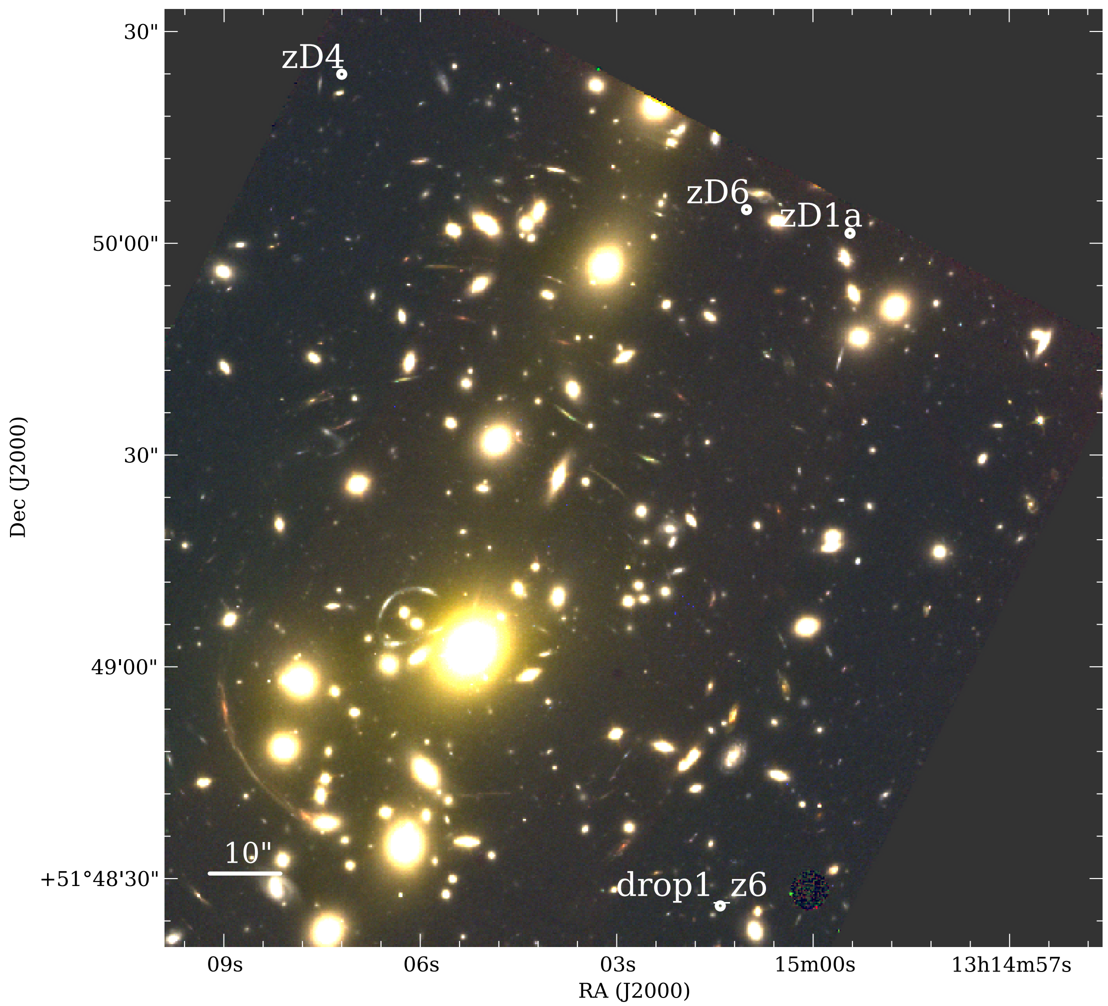

Large EW CIII] found in galaxies with

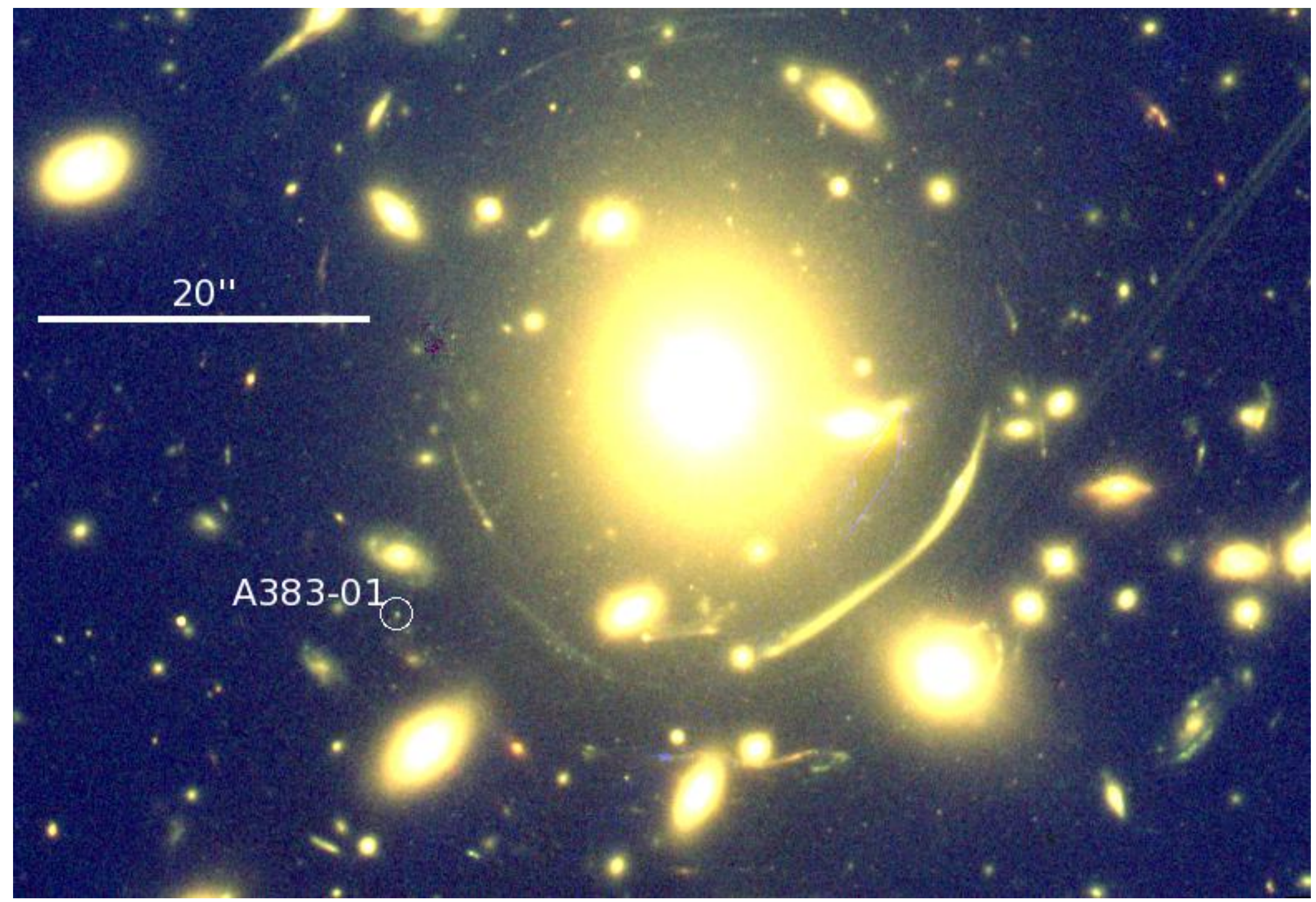
- large specific star formation rate.
- large ionization parameter
- large EW [OIII]+H-beta
- moderately low metallicity

Similar to properties of reionization-era galaxies.

# Characterizing the Far-UV Spectra of Reionization Era Galaxies

Stark et al. 2015a, 2015b, 2017, Mainali et al. 2016, arXiv:1611.07125

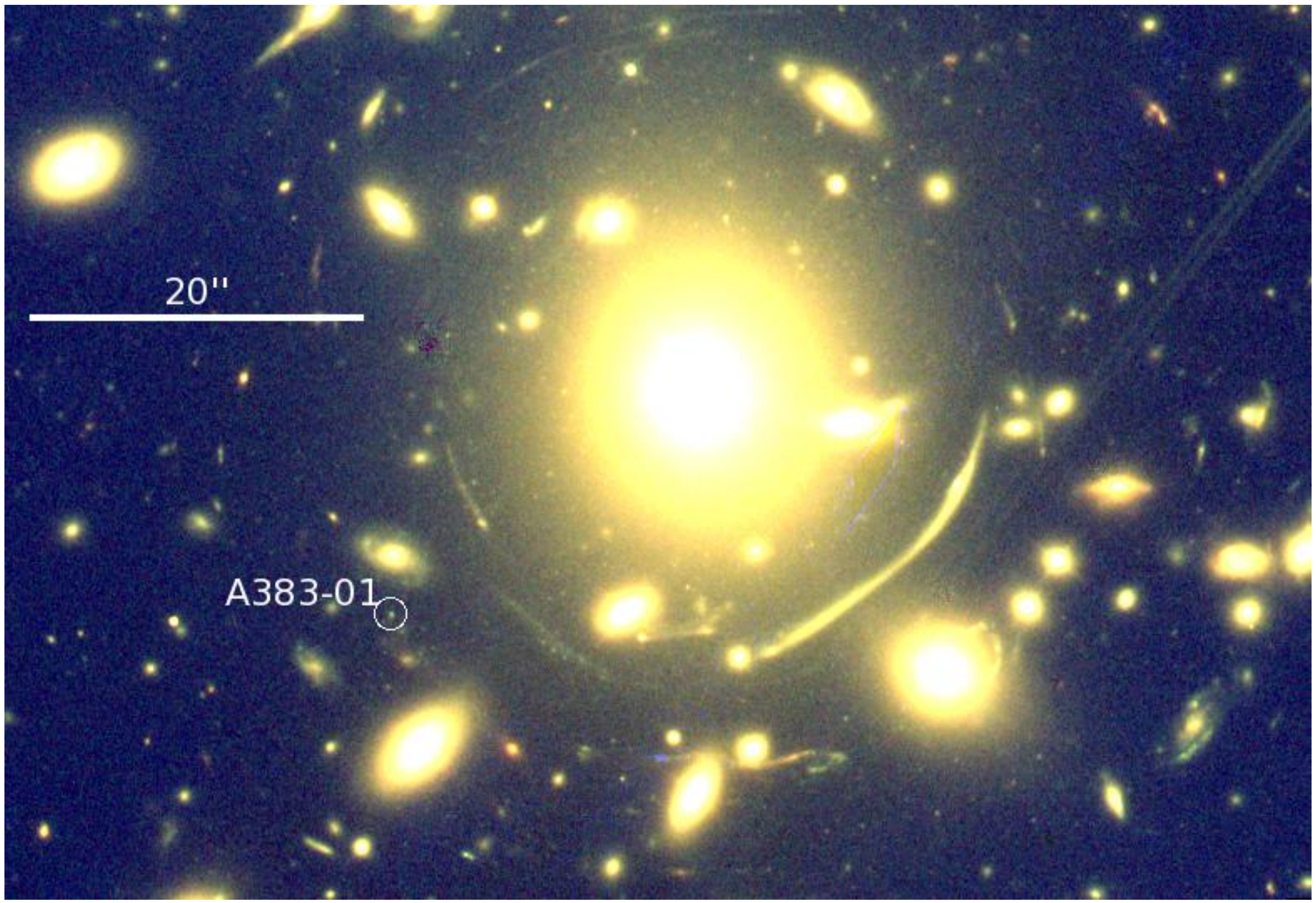


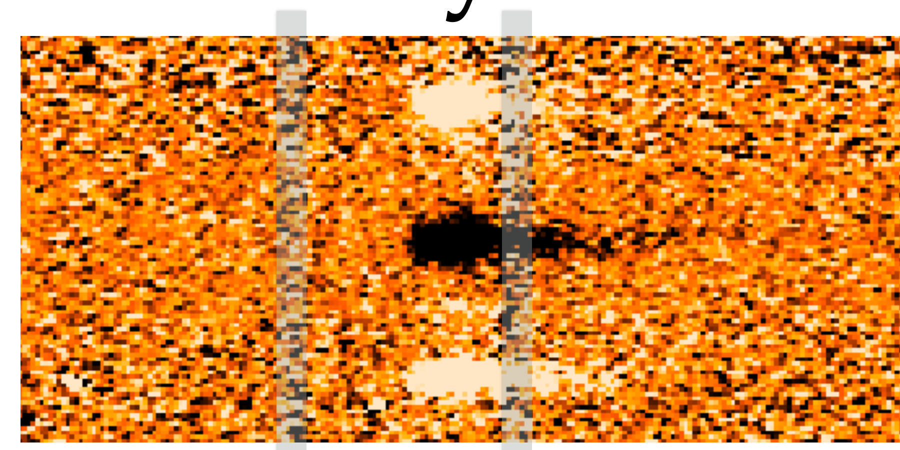

- Measure strength of far-UV lines in bright (24<H<26) galaxies at z~6-9.
- First prioritize galaxies with spectroscopic redshift from Ly$\alpha$.

# First CIII] detection at z≳6

Stark et al. 2015a, MNRAS




Ly-$\alpha$

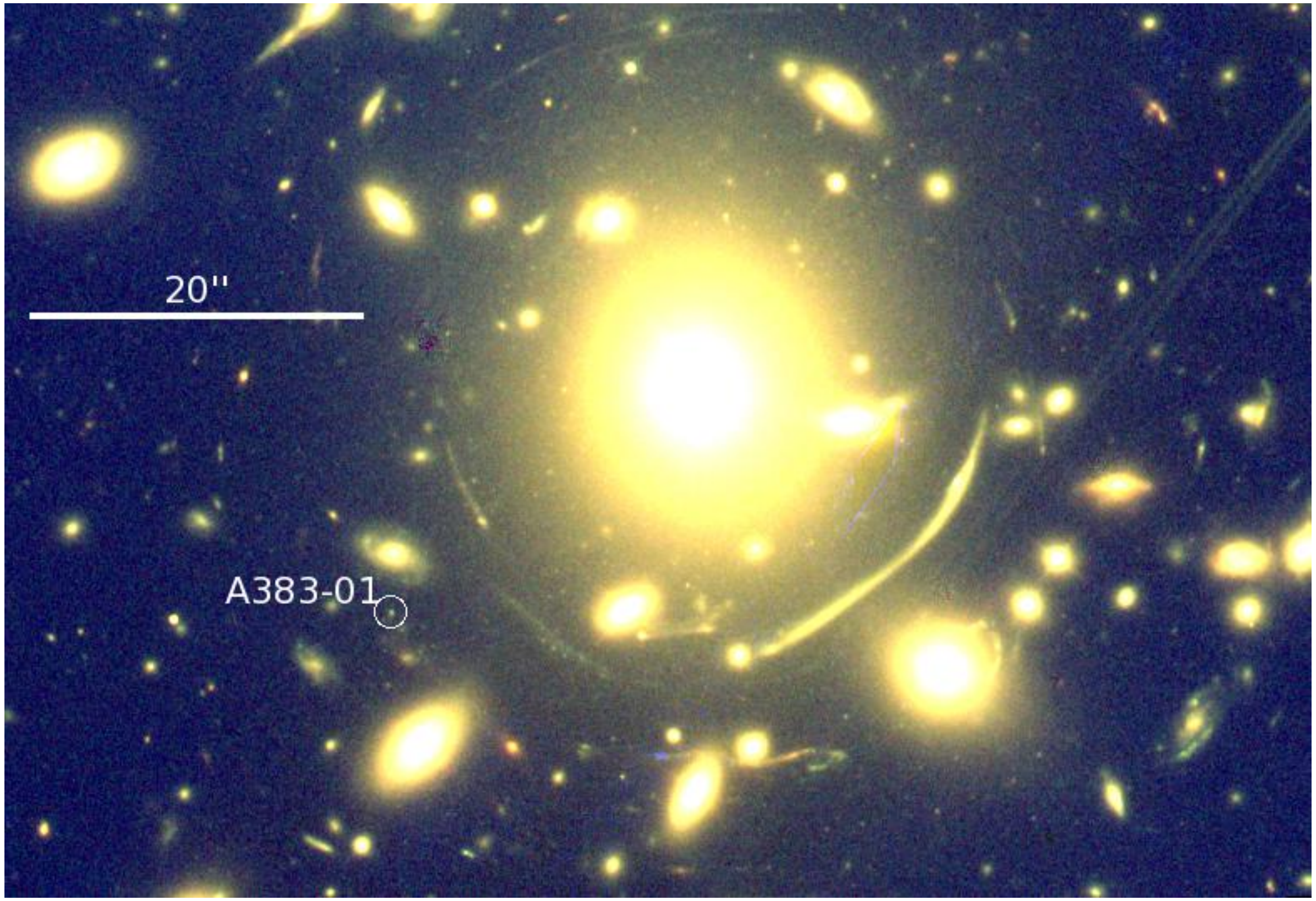


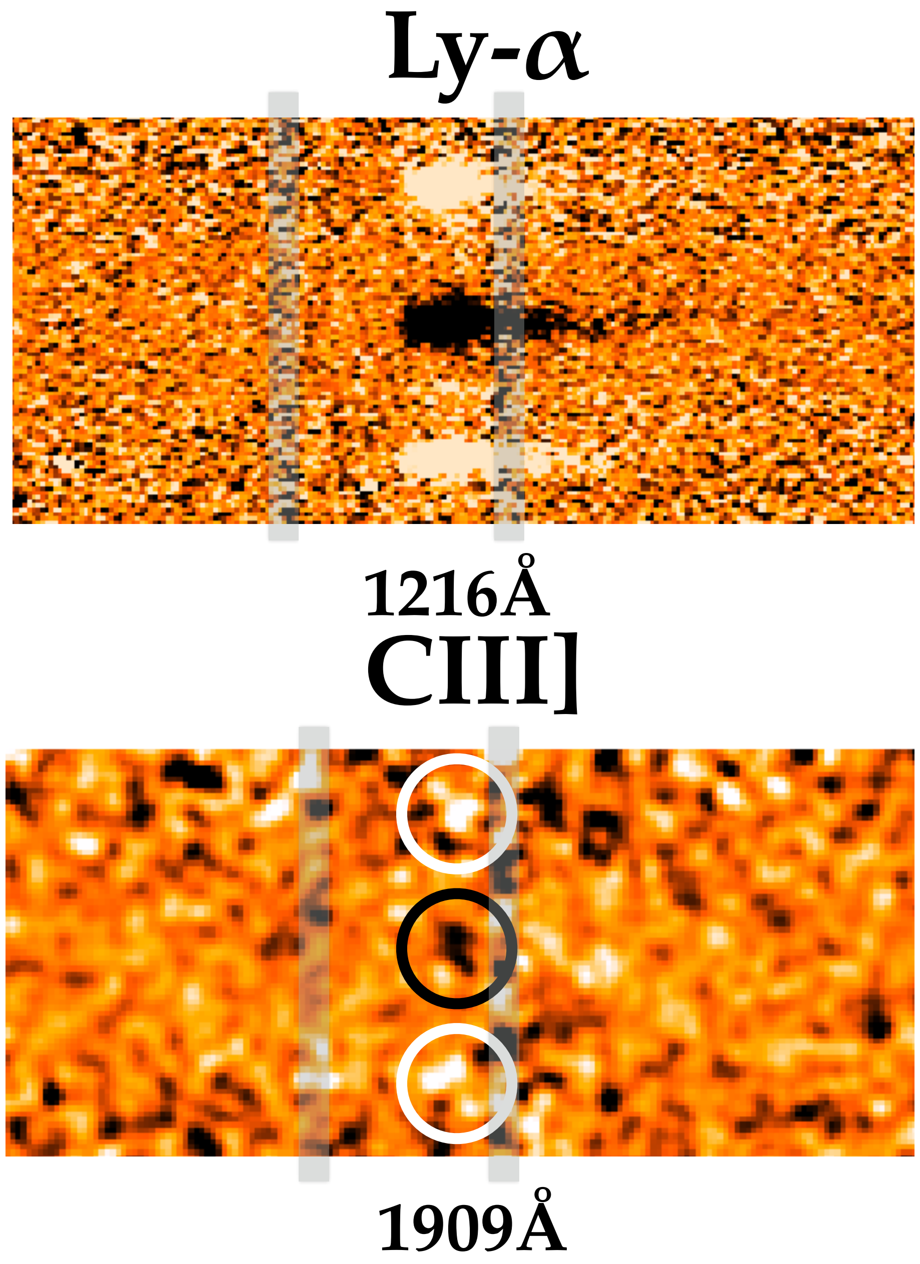
1216Å

- Ly$\alpha$ redshift allows us to nail down observed wavelength of CIII] (1.341$\mu$m).

# First CIII] detection at z≳6

Stark et al. 2015a, MNRAS

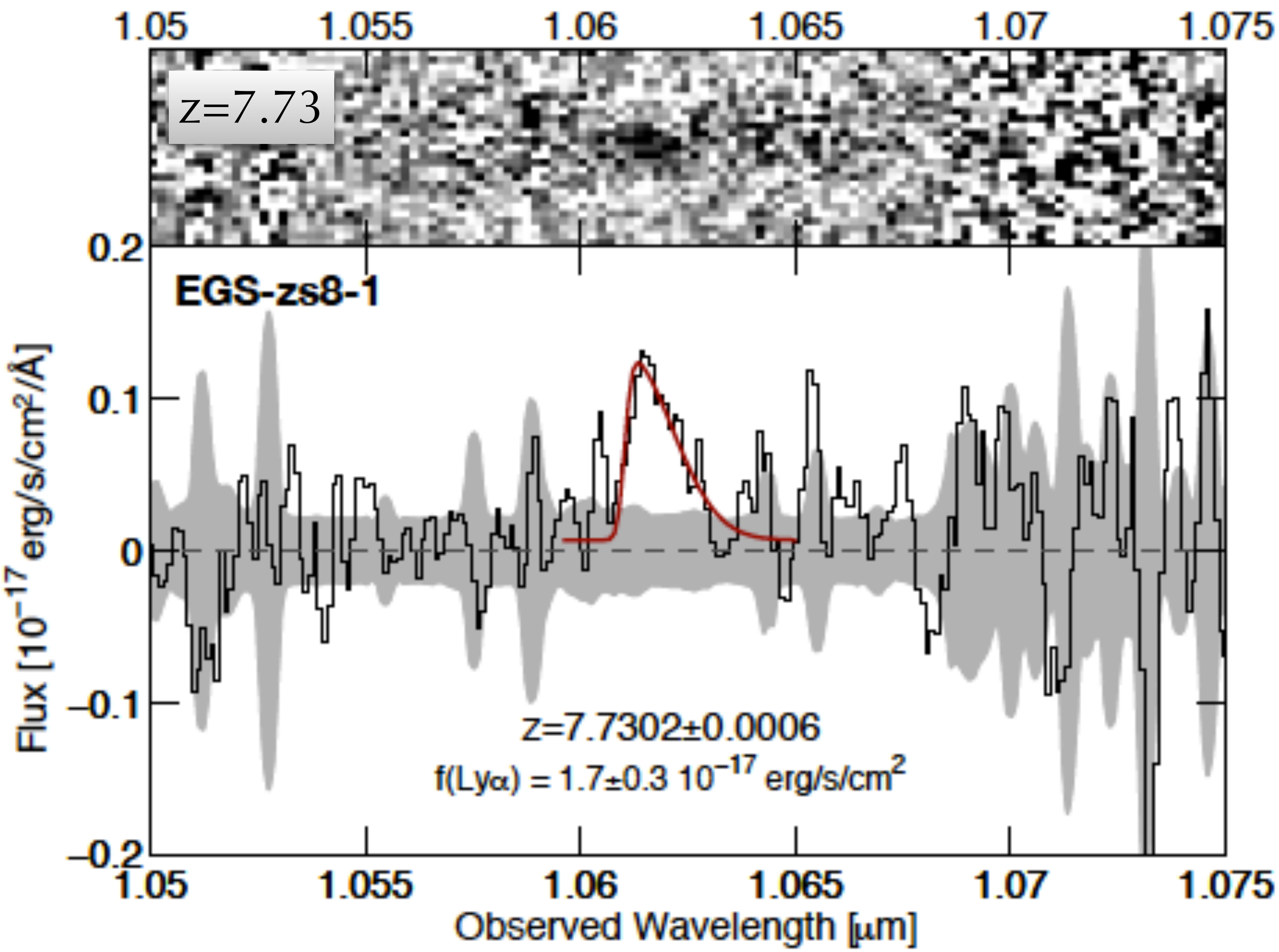



- CIII]$\lambda$1909 detected at expected wavelength with EW ~ 22Å using X-Shooter.
- More than 10x larger EW than z~3 composite LBG spectrum.

# CIII] in z=7.73 Lyman-alpha Emitter

**Oesch+15**

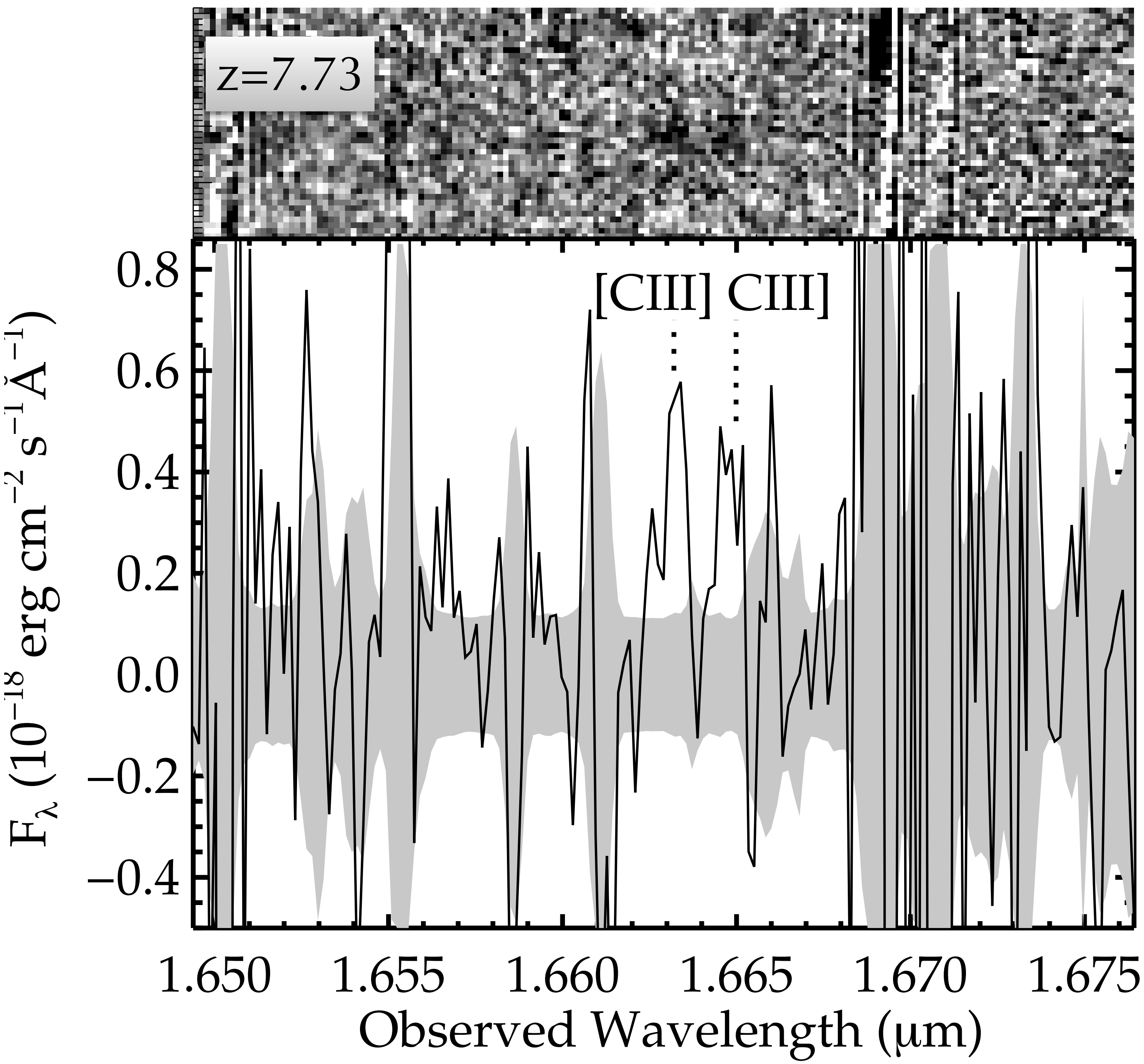



z=7.730 galaxy in EGS, confirmed in Oesch+15

- H=25.0
- $W_{Ly\alpha,0}$ = 21 Å
- $W_{[OIII]+H\beta}$ ~ 900 Å

# CIII] in z=7.73 Lyman-alpha Emitter

Stark+16




[CIII]1907,CIII]1909 detected in 3.5 hrs with MOSFIRE.

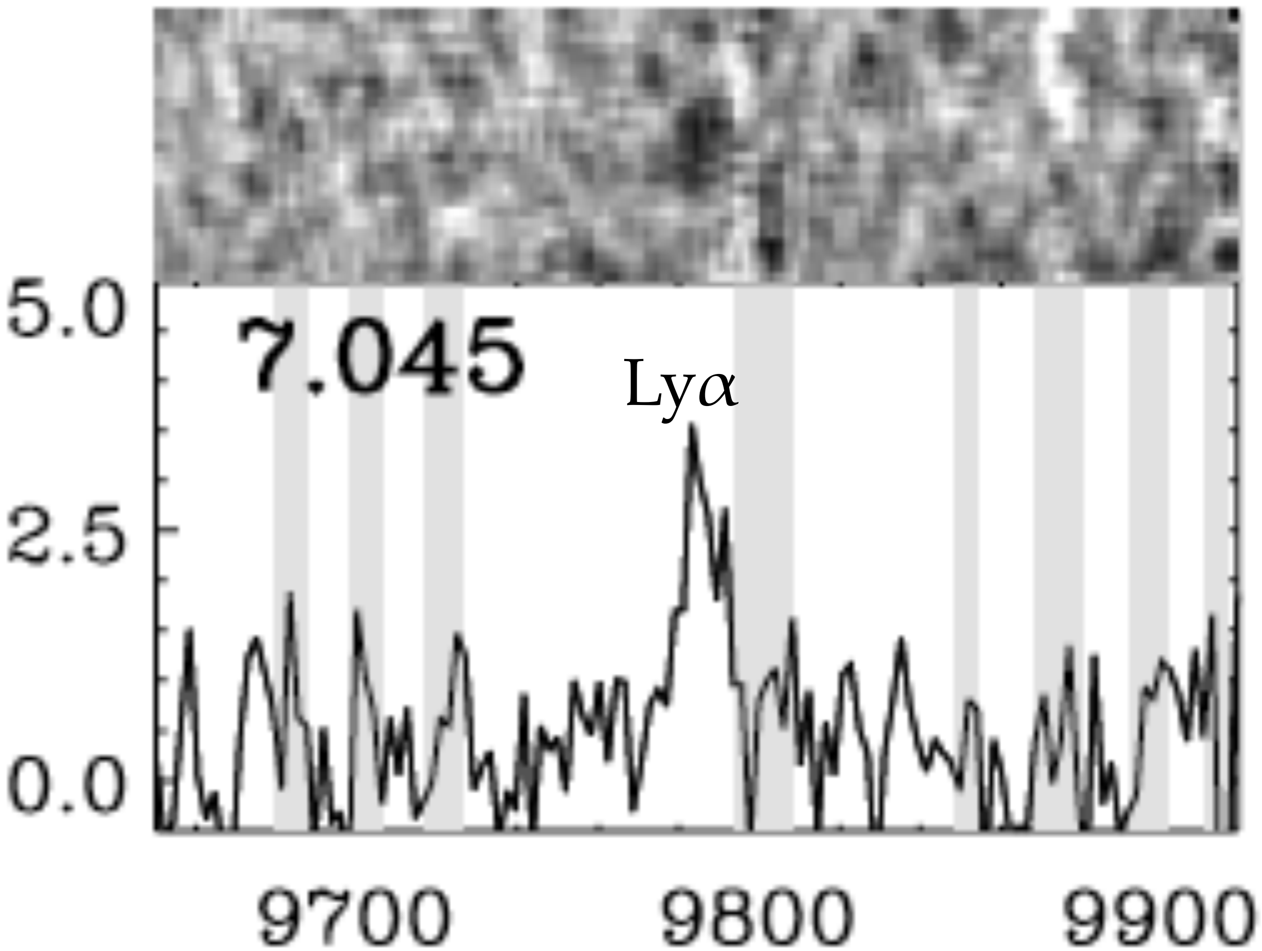
Total CIII] doublet equivalent width of 22Å.

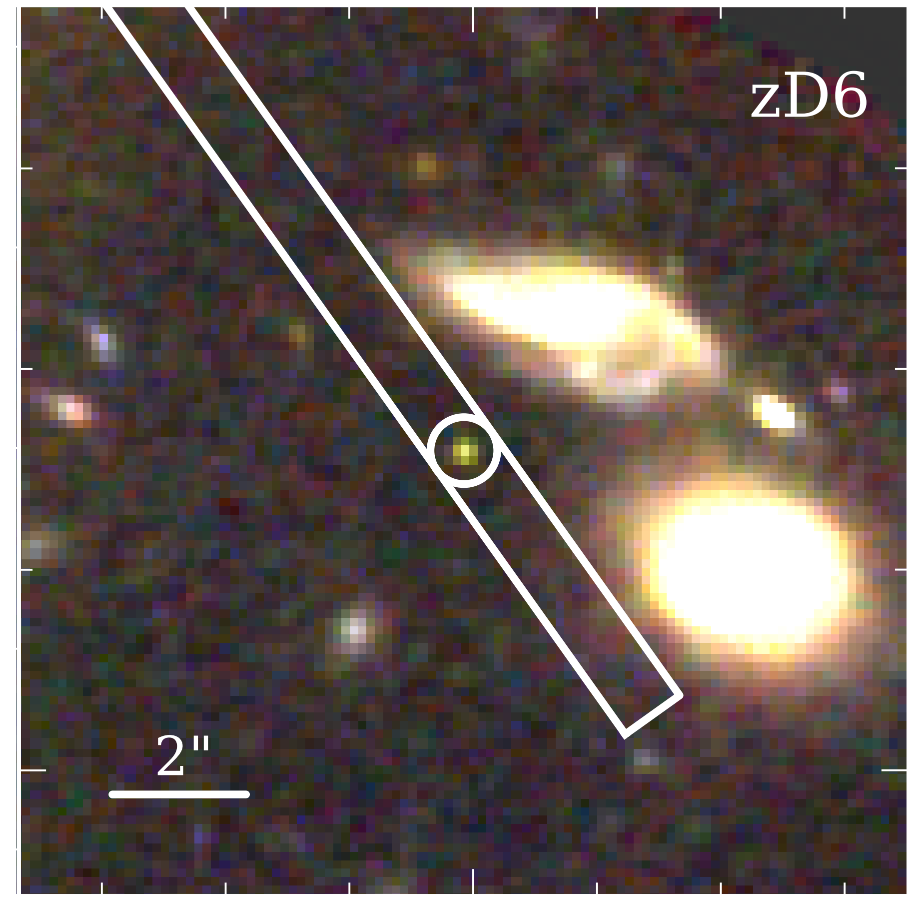
- ~10x greater EW than in composite z~3 galaxies.
- Larger than most z~2-3 metal poor galaxies.

***CIII] EWs in Lyman-alpha Emitters at z~6-7 very large in some systems***

# What about High Ionization Lines?

Stark et al. 2015b

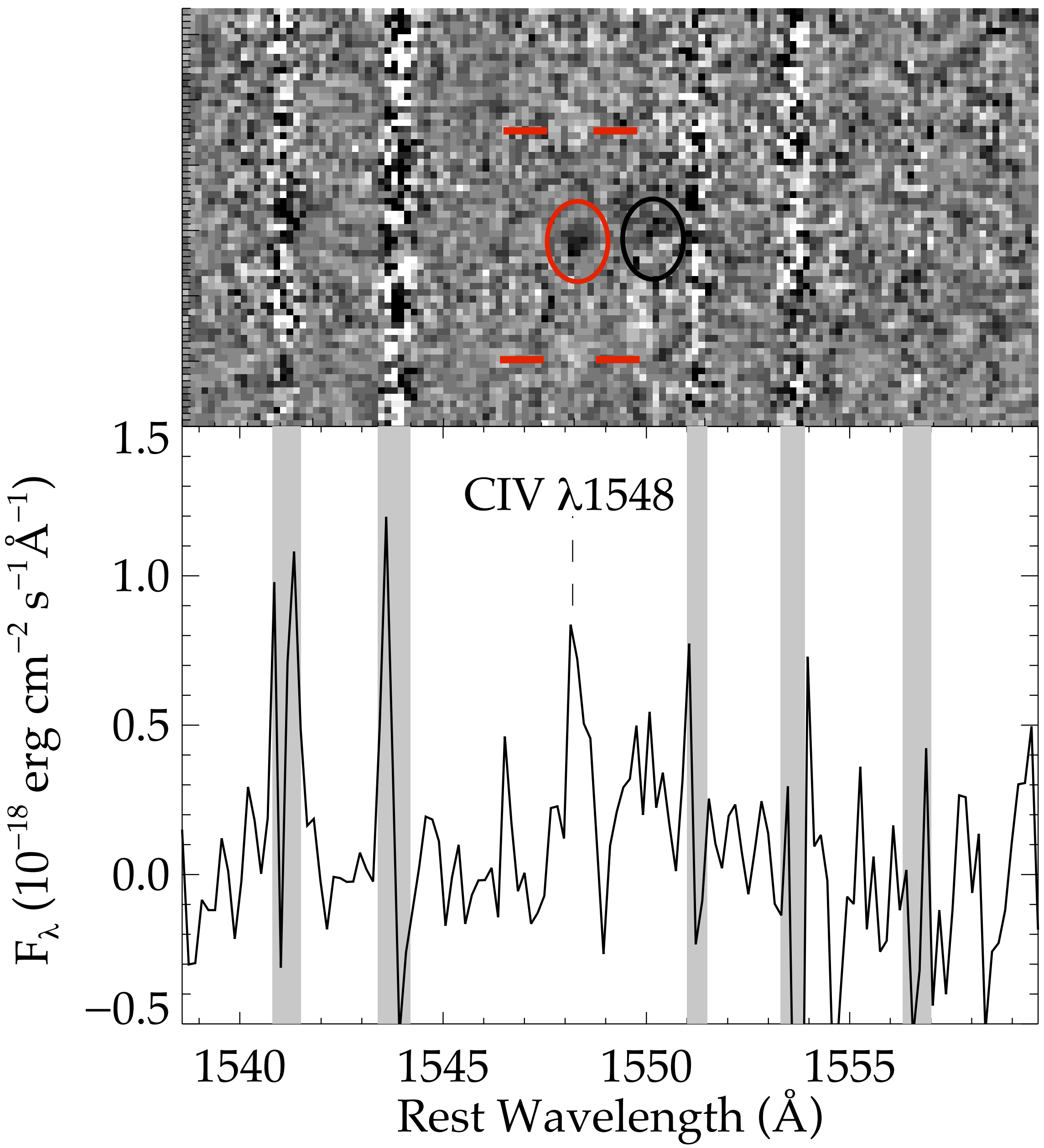



- H=25.9, z=7.045 galaxy previously confirmed via Ly$\alpha$ (Schenker+12).
- Gravitationally-lensed, low mass Lyman-alpha emitter
- SED similar to typical z~7 galaxies.

# Detection of CIV in z=7.045 Galaxy

Stark+15b

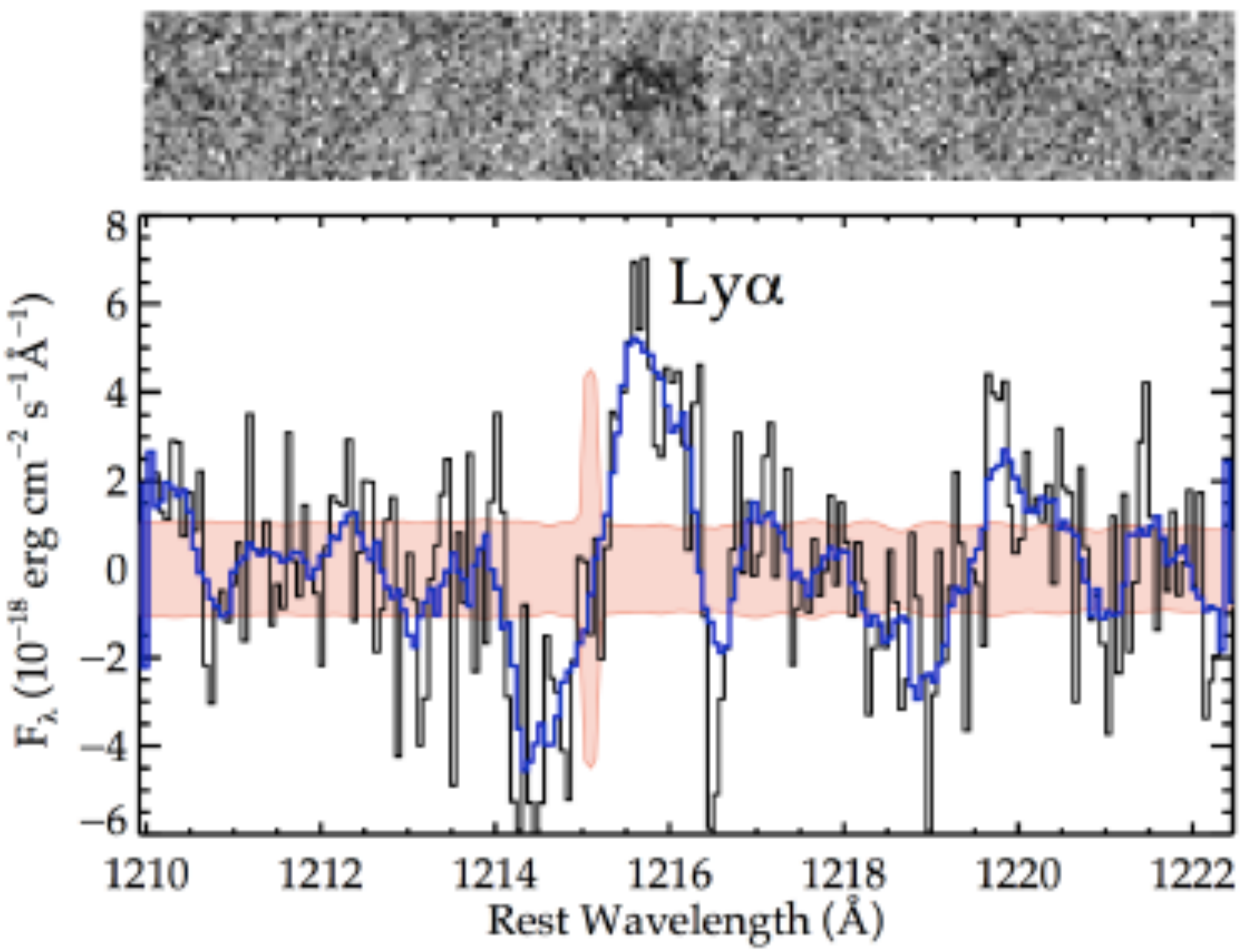


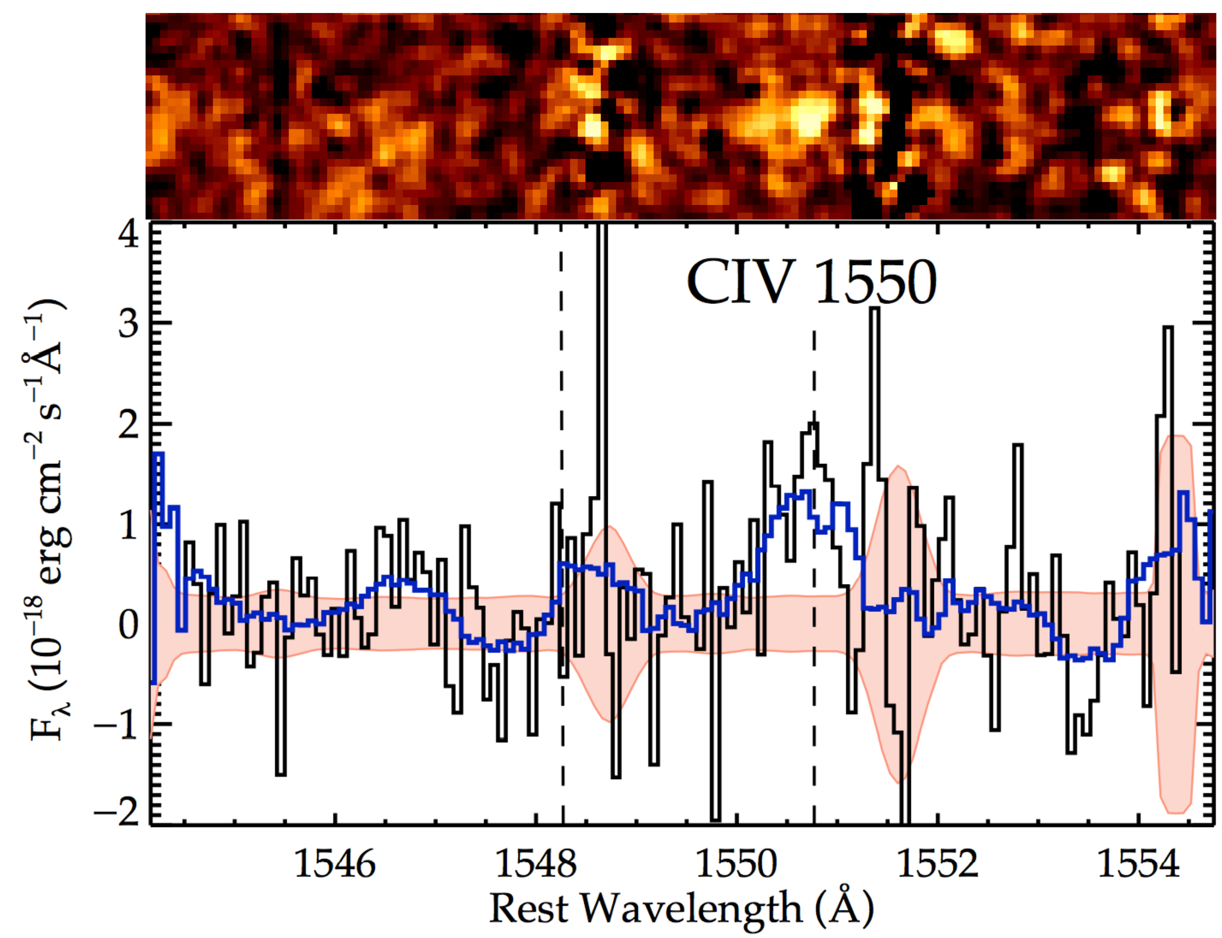

- 2.78 hrs with MOSFIRE in J-band (1435-1678 Å)
- 3 emission features (nebular CIV +OIII]1661) visible in single J-band exposure.
- Nebular CIV EW ~ 20 Å

***Requires very hard ionizing spectrum with large supply of >47.9eV photons***

# High Ionization Emission Lines are Common among Low Mass Lyman-alpha Emitters

Mainali+16, submitted, arXiv:1611.07125



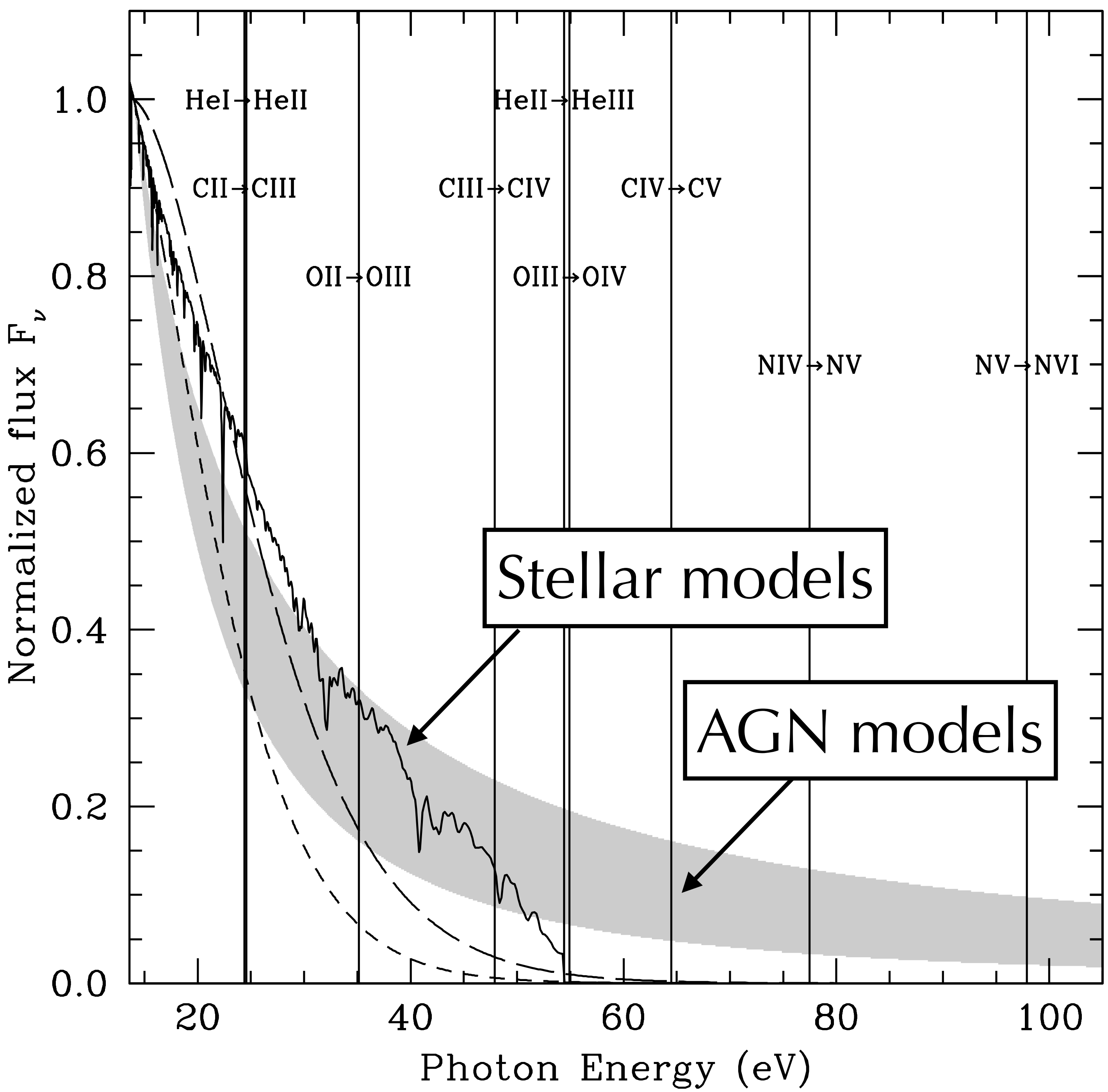




- CIV + OIII] detection in gravitationally lensed LAE at z=6.11 with FIRE
- CIV1549+1551 EW ~ 24.5 Å

***Radiation field implies greater contribution to reionization than often assumed***

# Origin of UV Metal Lines: Stars or AGN?

Stark+15b




## 1. CIV and OIII]

- Requires spectrum with substantial flux of 34-48 eV photons.

## 2. OIII]

- If significant flux of 55 eV photons, OIII] weakens as oxygen becomes triply ionized.

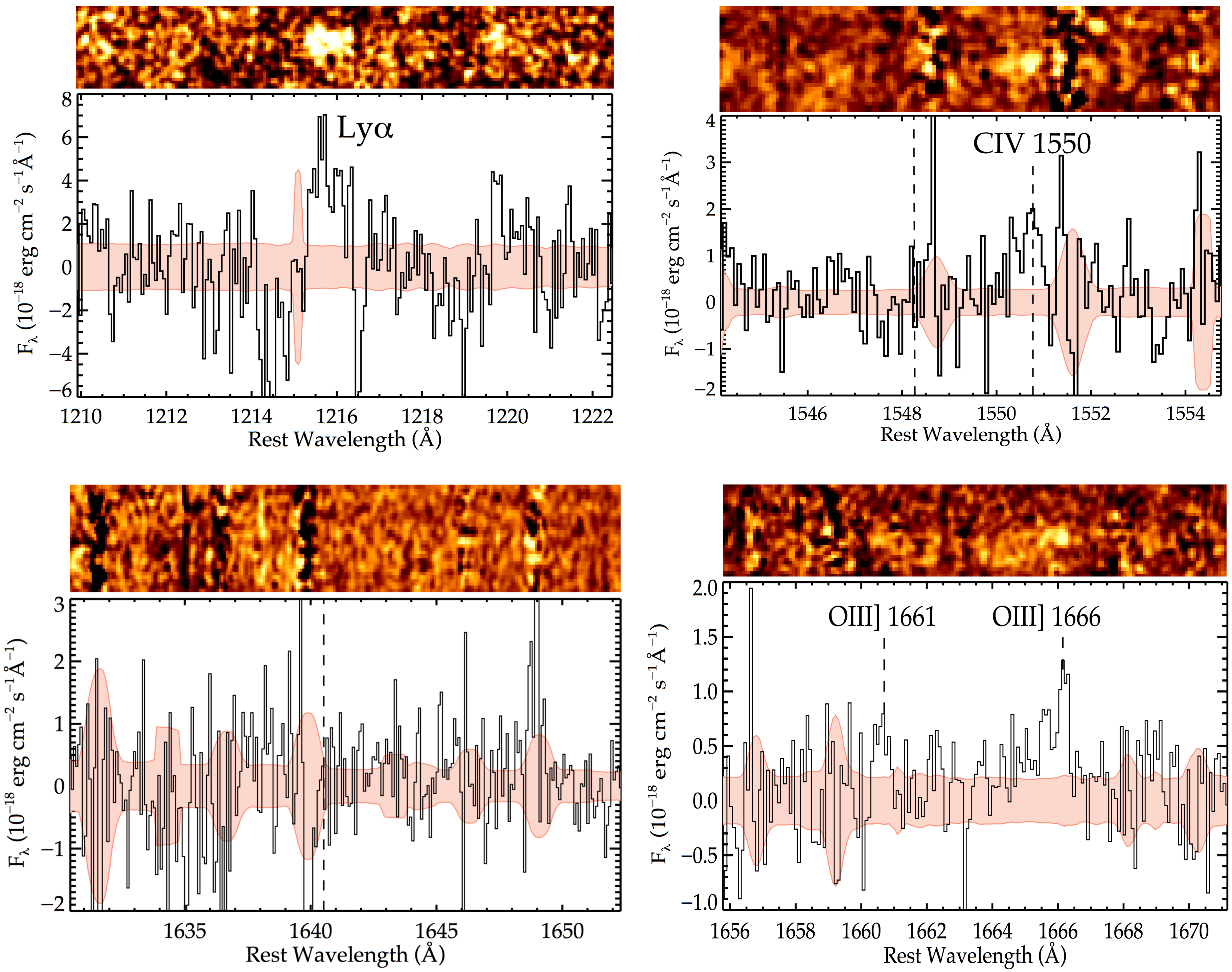
## 3. He II

- Powered by 54.4 eV photons.

*UV flux ratios constrain shape of ionizing spectrum*

# Progress with Magellan/FIRE Spectroscopy

Mainali+16, submitted, arXiv:1611.07125




Faint lensed LAE at z=6.11

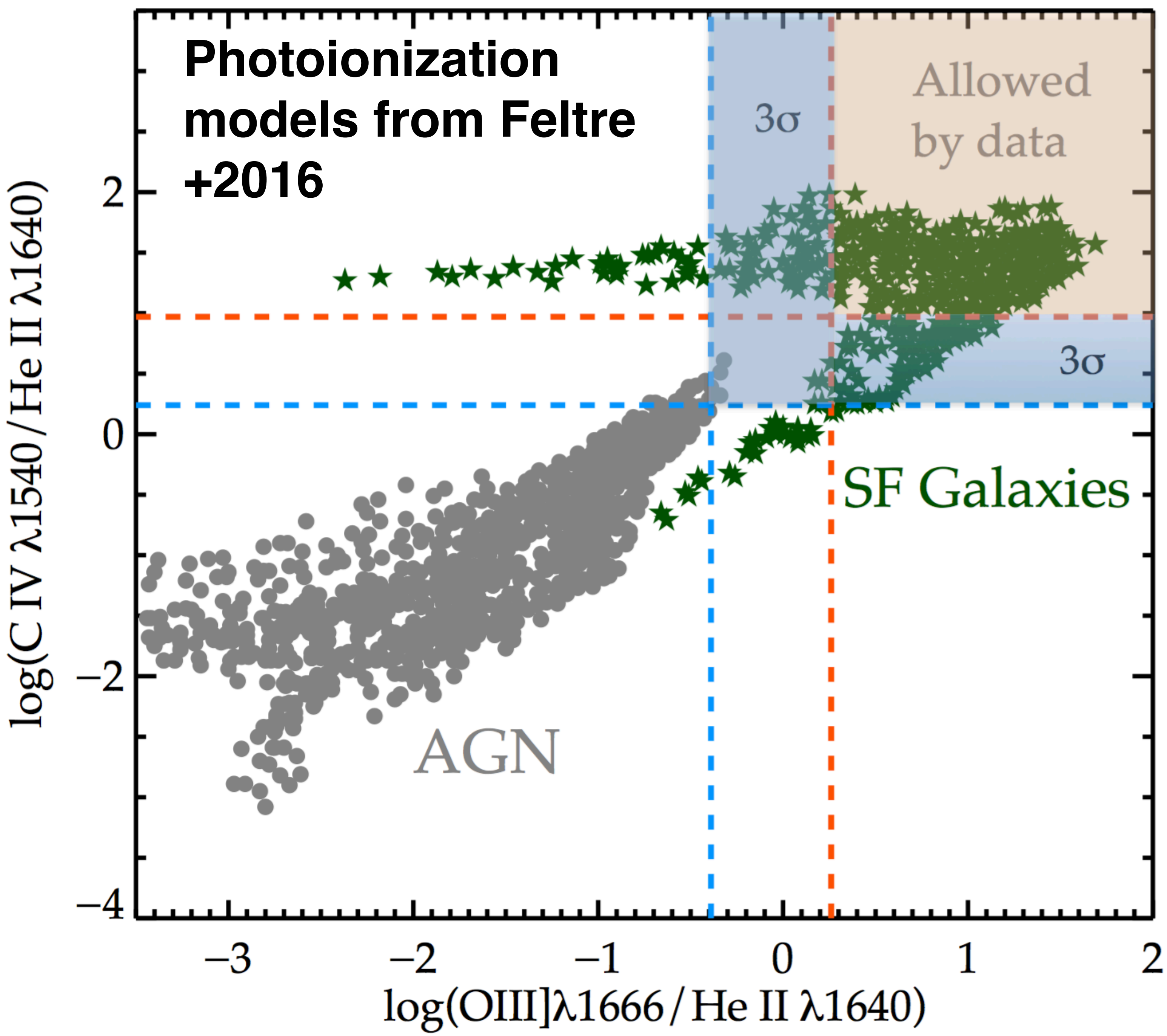
- Strong CIV, OIII] emission.
- Non-detection of He II.

Implies hard spectrum with break at ~54 eV.

- Low metallicity stellar spectrum.

# Evidence of Hard Ionizing Spectrum Powered by Low Metallicity Stars

Mainali+16, submitted, arXiv:1611.07125



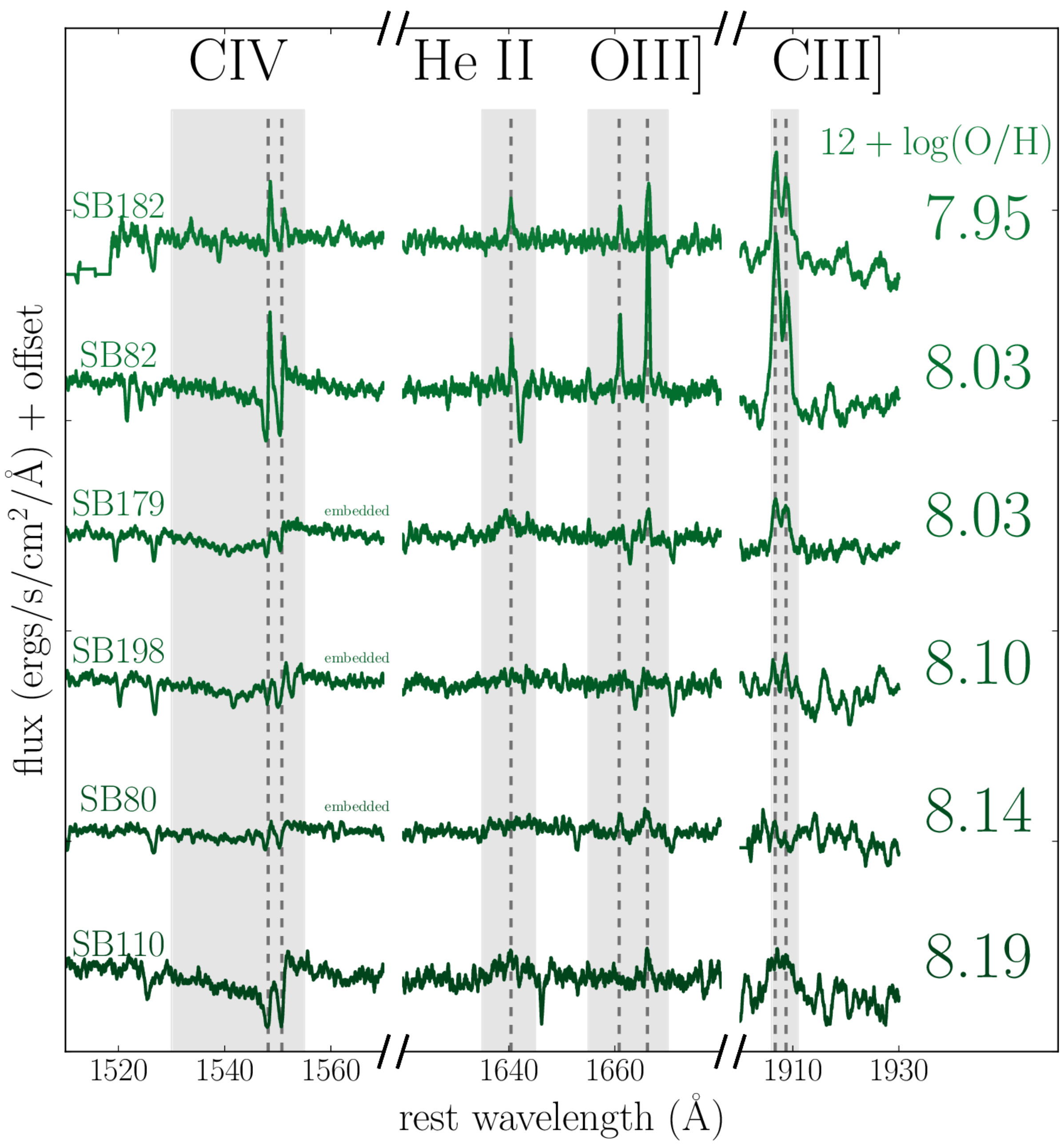

## OIII]/He II ratio

- Inconsistent with AGN photoionization models
- Can be explained by ionization from metal poor (<10%) stars.

***Do we see such intense radiation fields in nearby metal poor galaxies?***

# Stellar Populations at Low Metallicity: Lessons from Nearby Galaxies

Senchyna, Stark, Charlot+17, in prep




HST/COS spectra from cycle 23

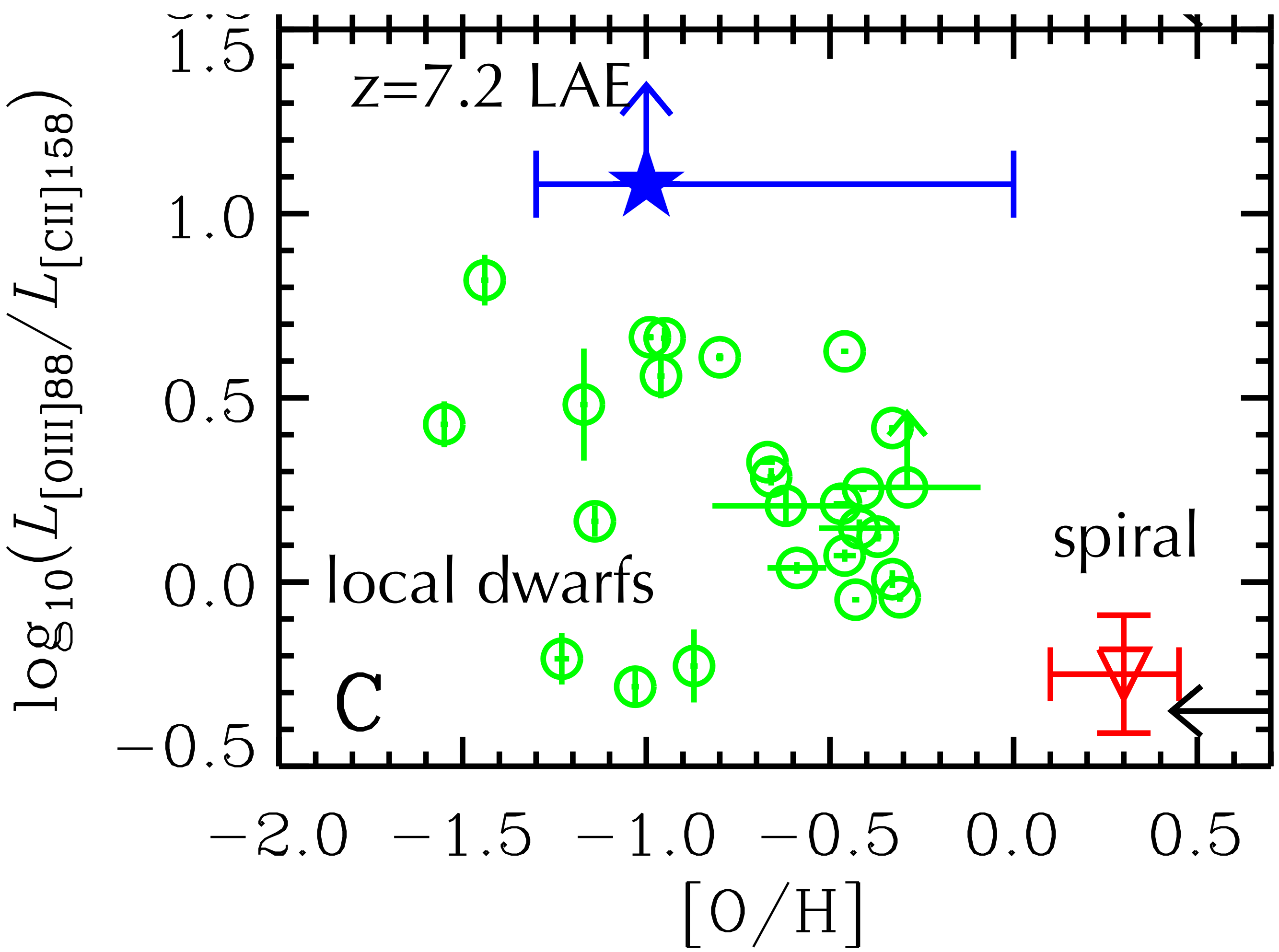
UV spectra change dramatically at 12+log O/H~8.0 (0.2 $Z_\odot$)

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

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

# Implications of Hard Radiation Fields: I. Impact on [CII] / [OIII]

**Inoue+16, Science, arxiv:1606.04989**



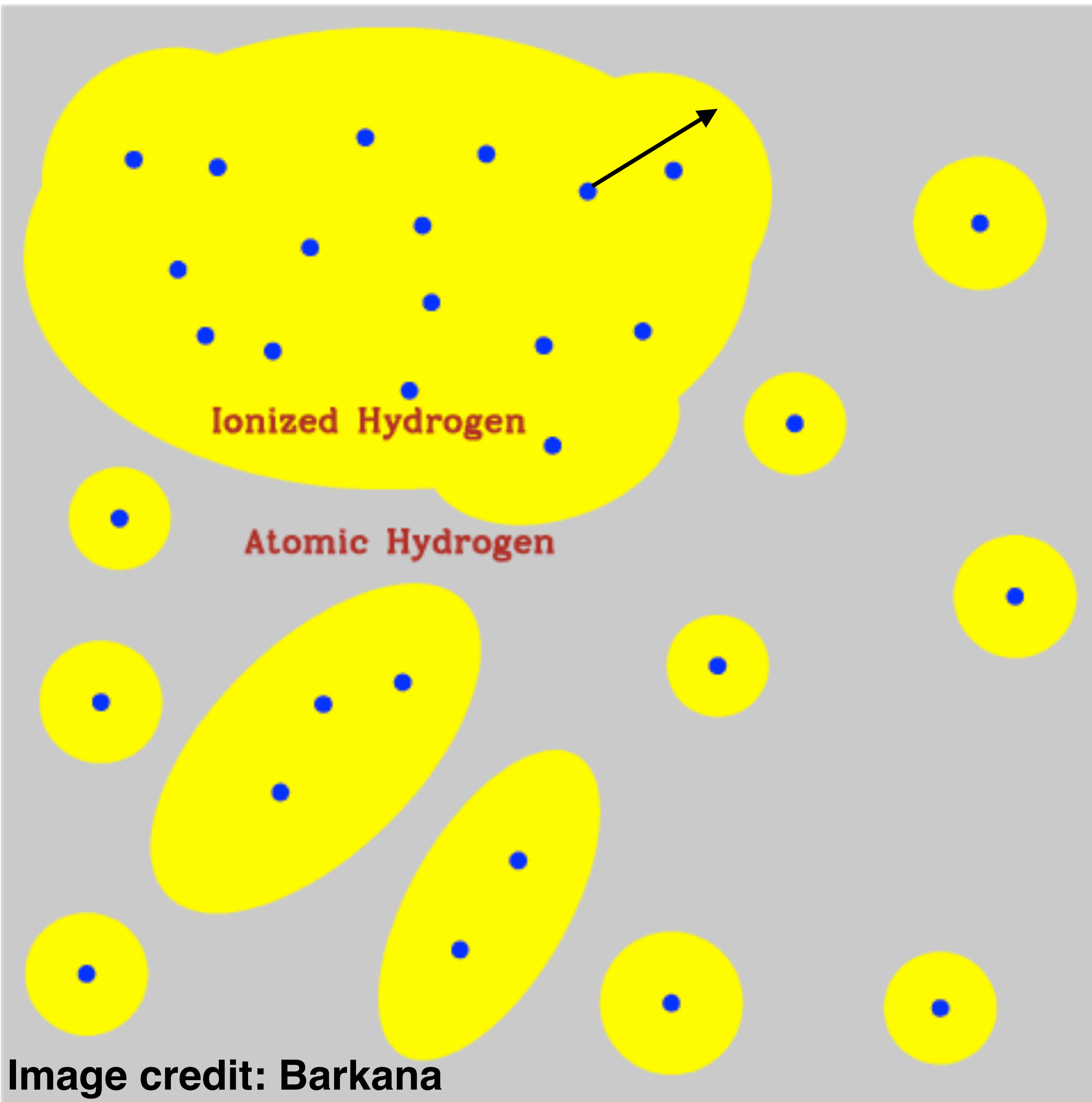

[OIII] luminosity is >12x that of [CII].

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.***

# Implications of Hard Radiation Fields: II. Impact on Lyman-alpha Escape

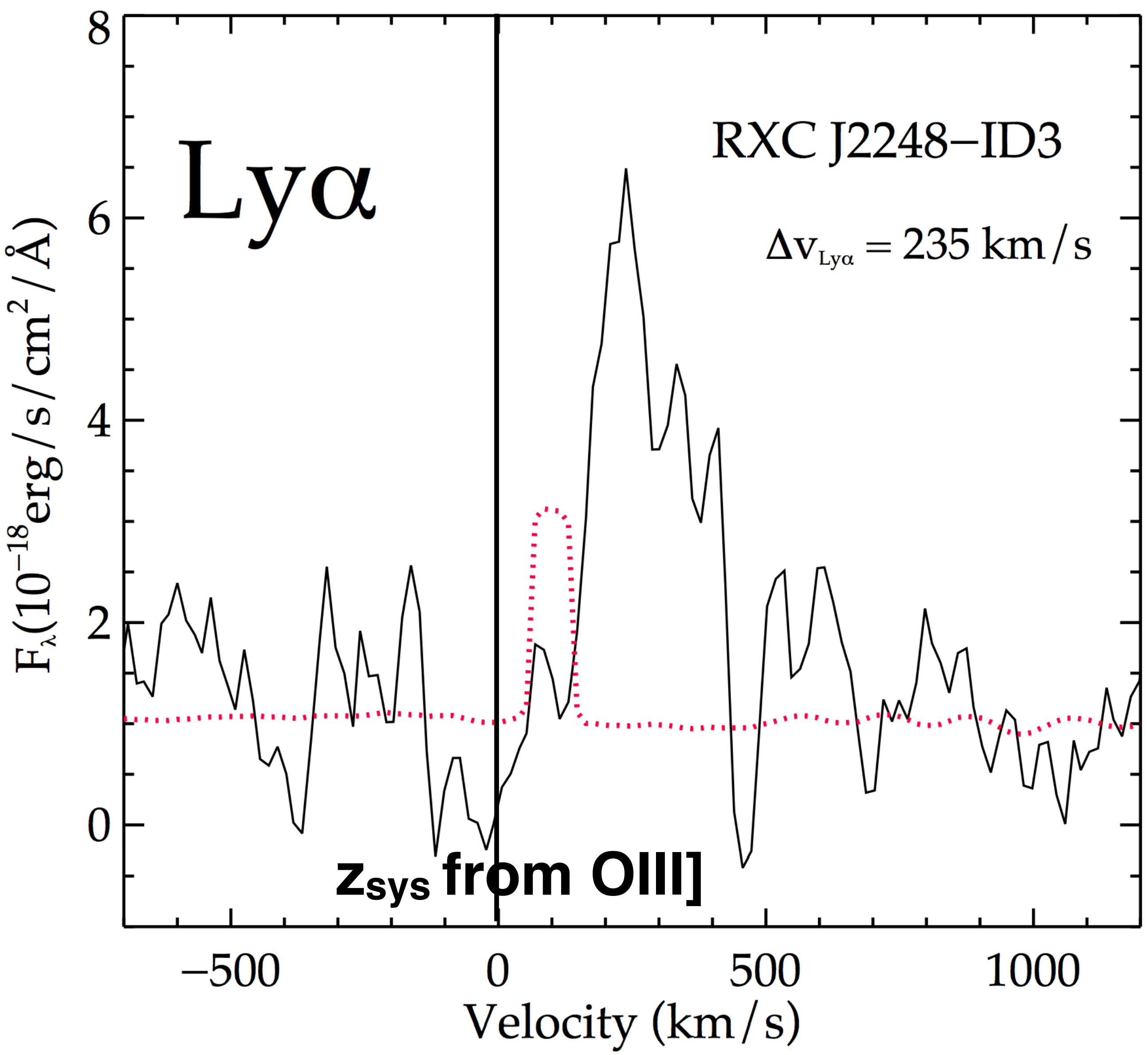



Transmission is boosted in most luminous galaxies by

(1) Location in largest ionized bubbles.

**(2) Hard ionizing spectra associated with extreme EW [OIII] emitters. Effective at ionizing surrounding HI?**

# Lyman-alpha Velocity Offset and Transmission through IGM



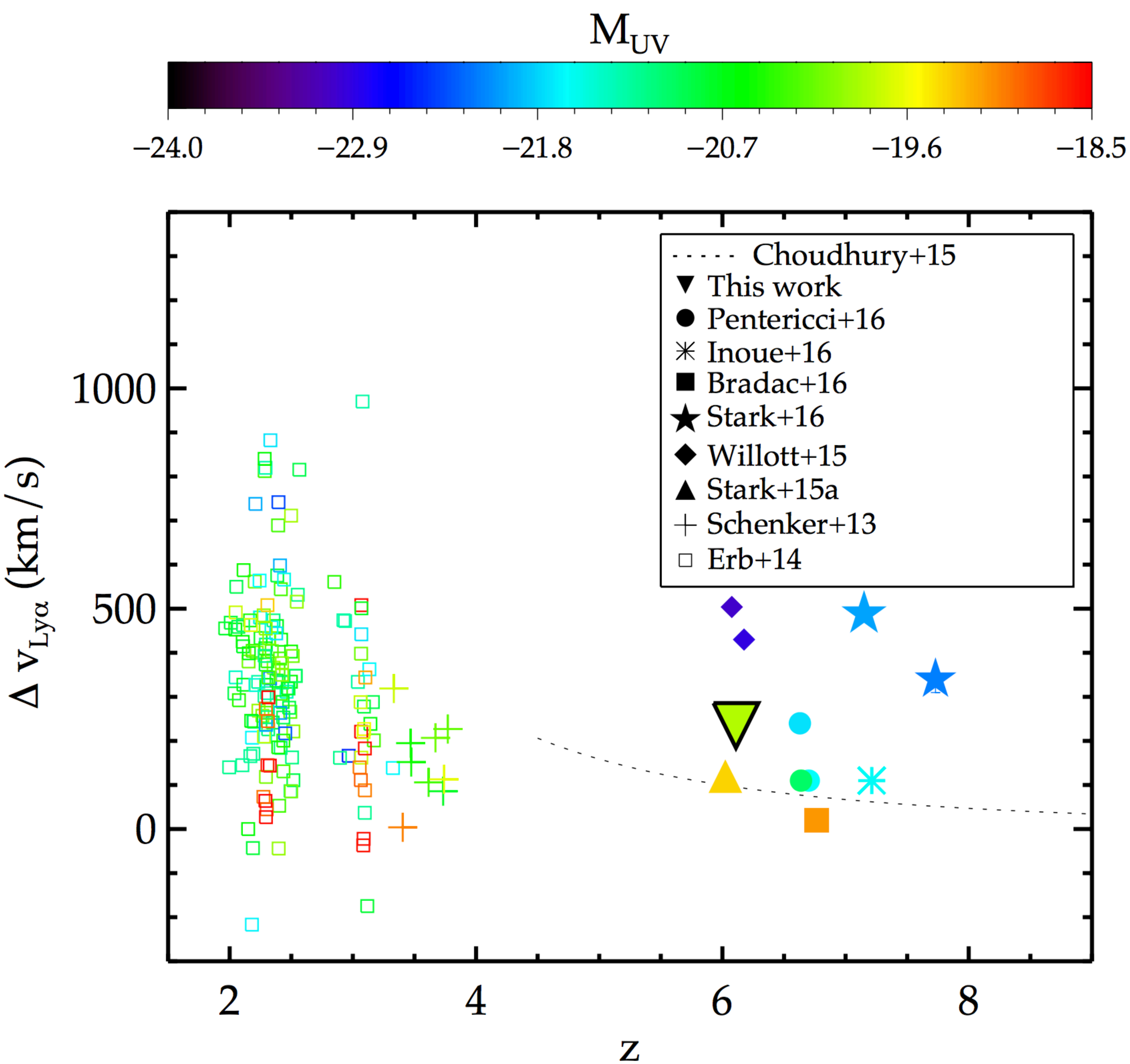

Lyman-alpha typically emerges from galaxy redshifted by several hundred km/s.

The further Ly$\alpha$ is redshifted from resonance (1215.67 Å) by time it reaches HI, the less likely it will be scattered by IGM.

**Large initial velocity offset = greater transmission of Lyman-alpha through IGM.**

# Velocity Offsets are Largest in Luminous Galaxies

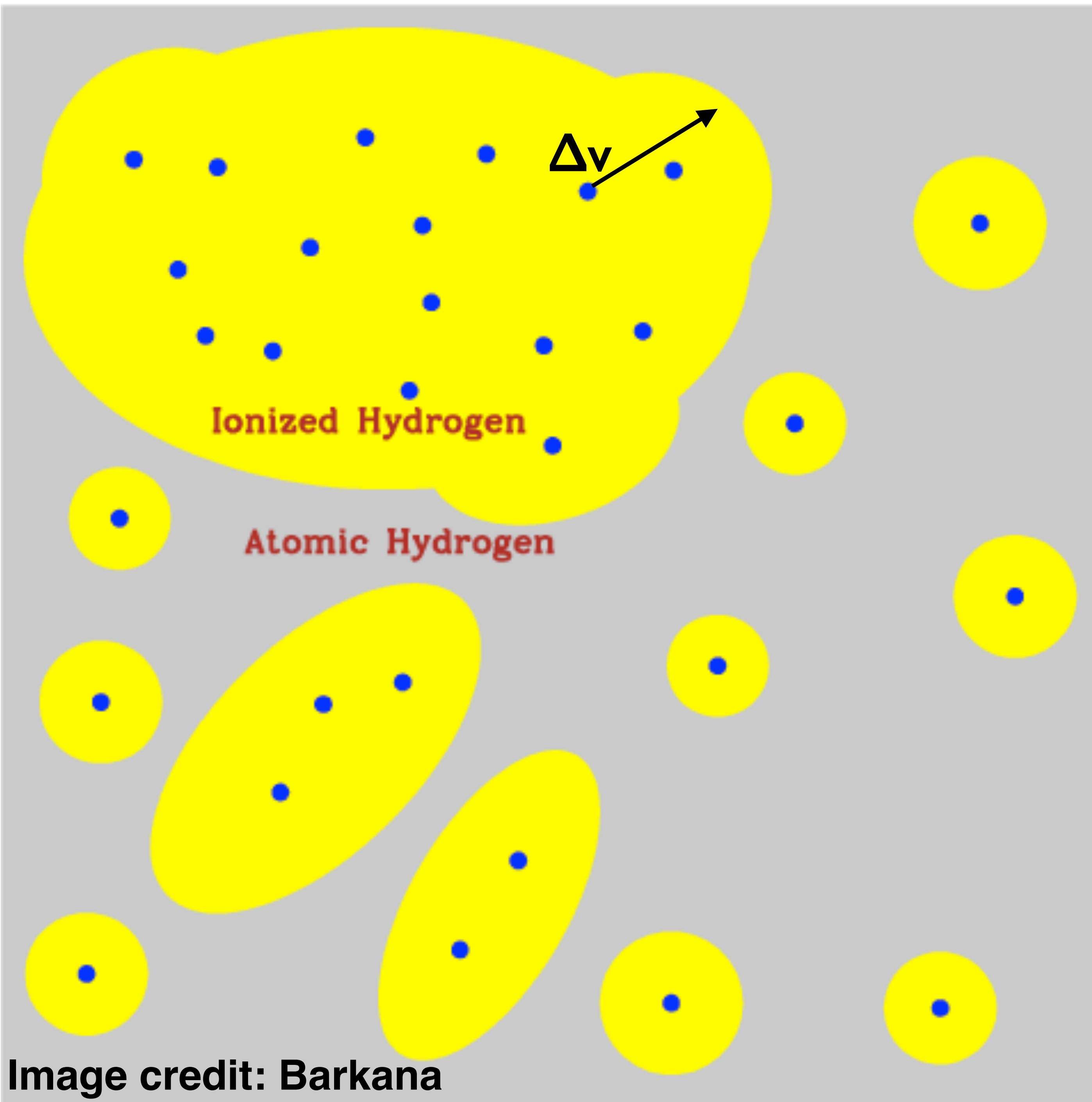
Mainali+16, submitted, arXiv:1611.07125




Large velocity offsets in luminous galaxies enhance Ly$\alpha$ transmission through partially neutral IGM.

# Lyman-alpha Escape from Young, UV Luminous z>7 Galaxies

Stark+16, arXiv:1606.01304




Transmission is boosted in most luminous galaxies by

(1) Location in largest ionized bubbles.

(2) Hard ionizing spectra associated with extreme EW [OIII] emitters. Effective at ionizing surrounding HI?

**(3) Large velocity offsets decrease attenuation from IGM.**

# Summary

- Ly$\alpha$ downturn at z>6, consistent with late reionization. New detections suggest Lyman-alpha more common in luminous galaxies.

- UV line (CIII], CIV, OIII]) detections suggest very hard radiation field is present in subset of z>7 galaxies.
    - Flux ratios point to metal poor stars rather than AGN as source of hard ionizing spectrum.
    - Consistent with metallicities in range 0.02 - 0.2 $Z_\odot$ for single star population synthesis models.
- Ly$\alpha$ enhanced in young, luminous galaxies for several possible reasons: 1) large ionized bubbles, 2) large velocity offsets and 3) hard radiation fields.

- Spectroscopic samples small: larger sample of bright galaxies required to tell if current conclusions are robust.