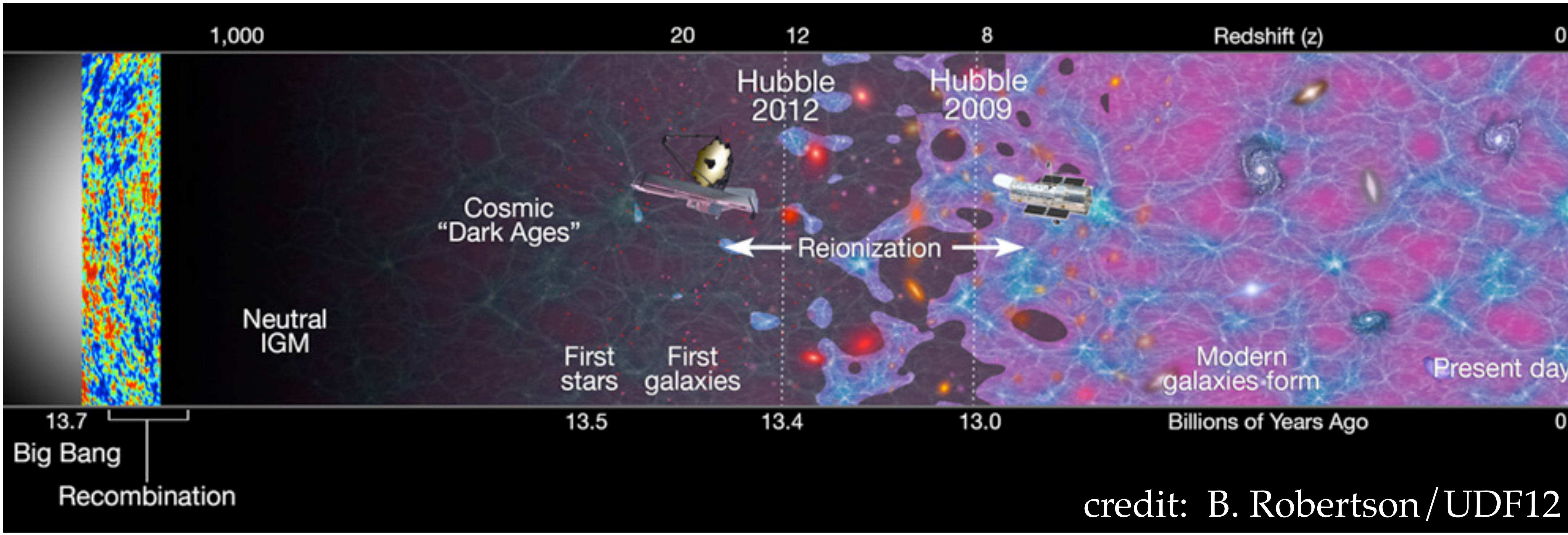
Spectroscopy of Lyman-alpha Emitters in the Reionization Era



credit: B. Robertson/UDF12

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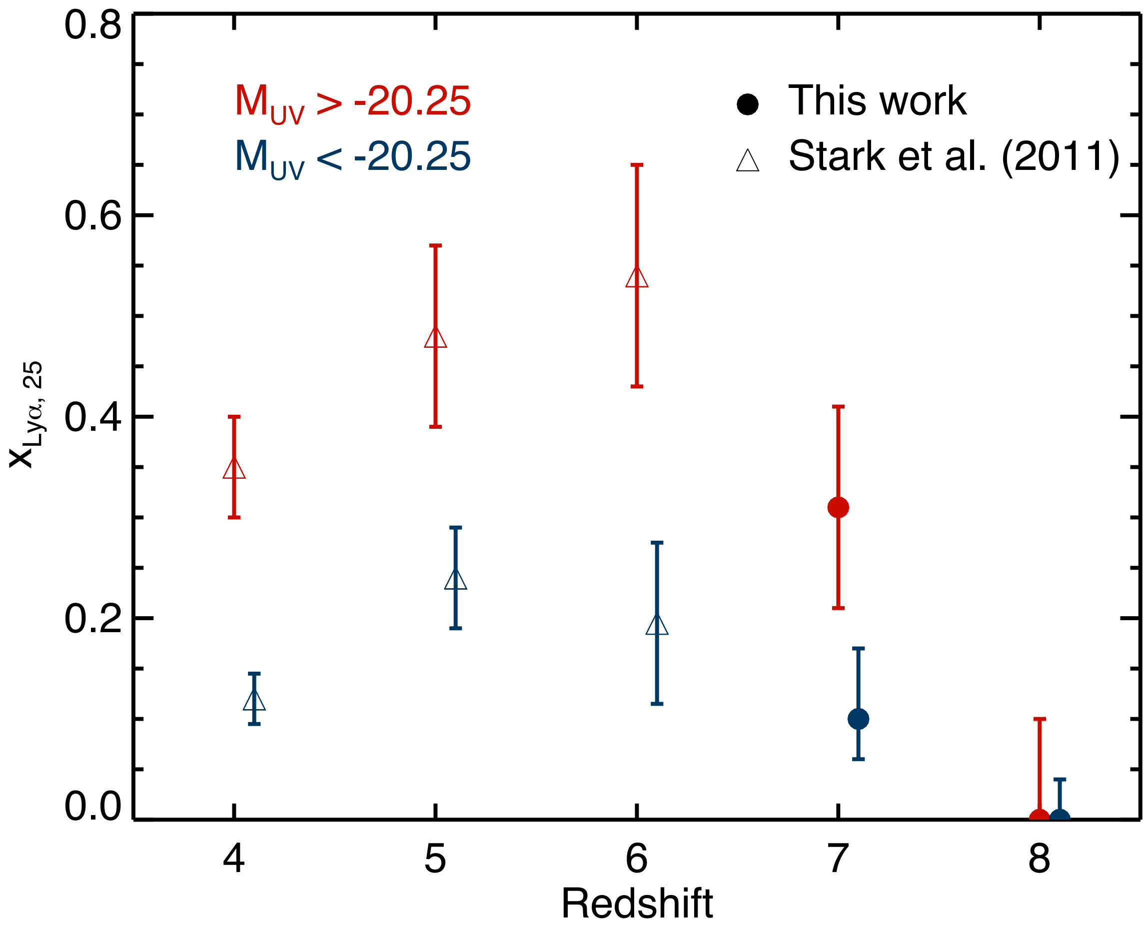
Stéphane Charlot (IAP), Jacopo Chevallard (IAP), Alba Vidal Garcia (IAP), Anna Feltre (CRAL/Lyon)
Johan Richard (CRAL/Lyon), Richard Ellis (UCL), Nicolas LaPorte (UCL)

Lyman-alpha Disappearance at z~7-8

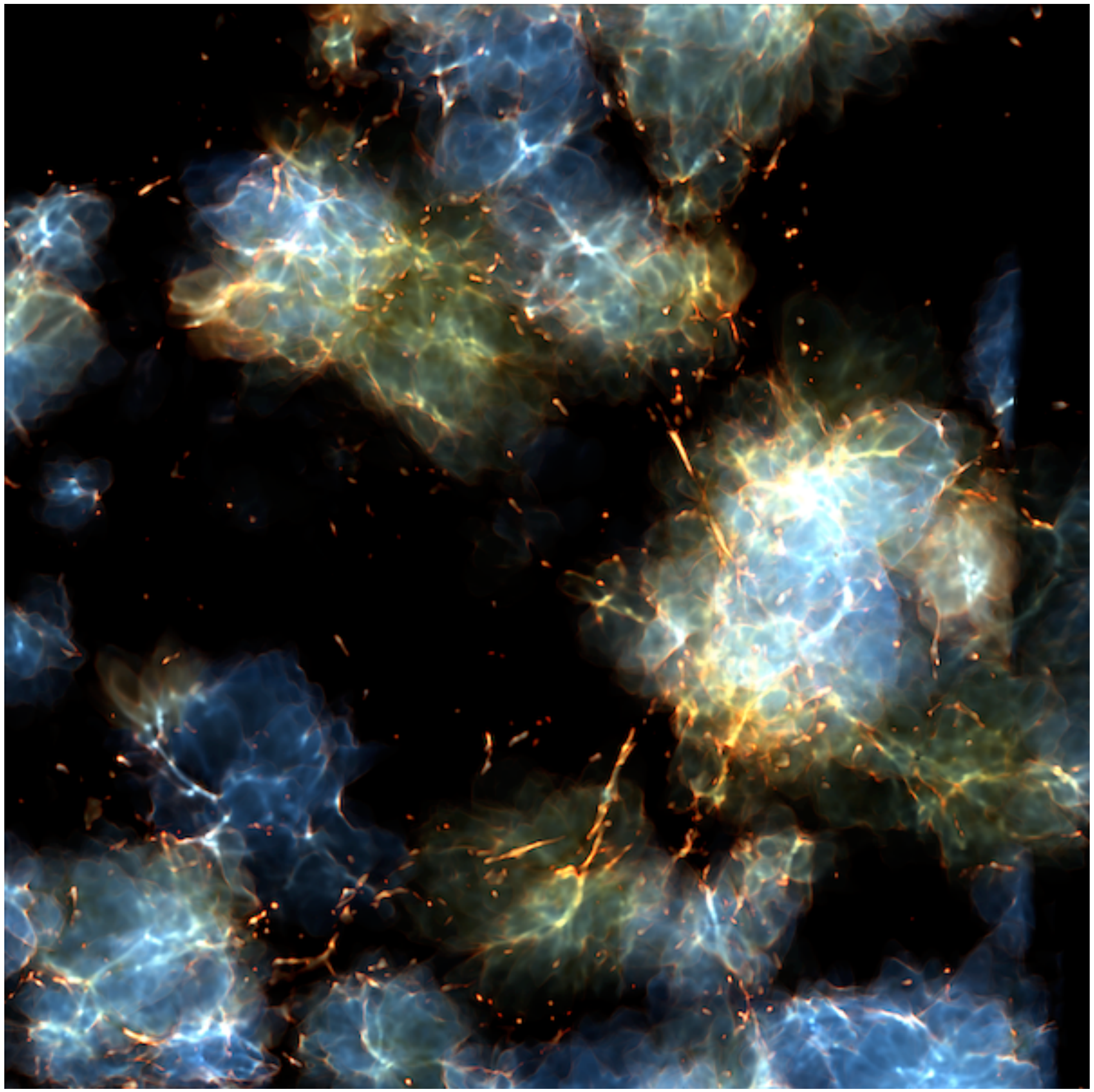
Stark 2016 ARAA, Schenker+2014



- Lyman-alpha emission is much less common among z>7 star forming galaxies than it is at z~5-6.
- Lyman-alpha emitter fractions are ~10% in UV-bright galaxies at 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, Caruana et al. 2014, Bian et al. 2014, Schmidt et al. 2015, Furusawa et al 2016).

Late Reionization Implied by Lyman-alpha



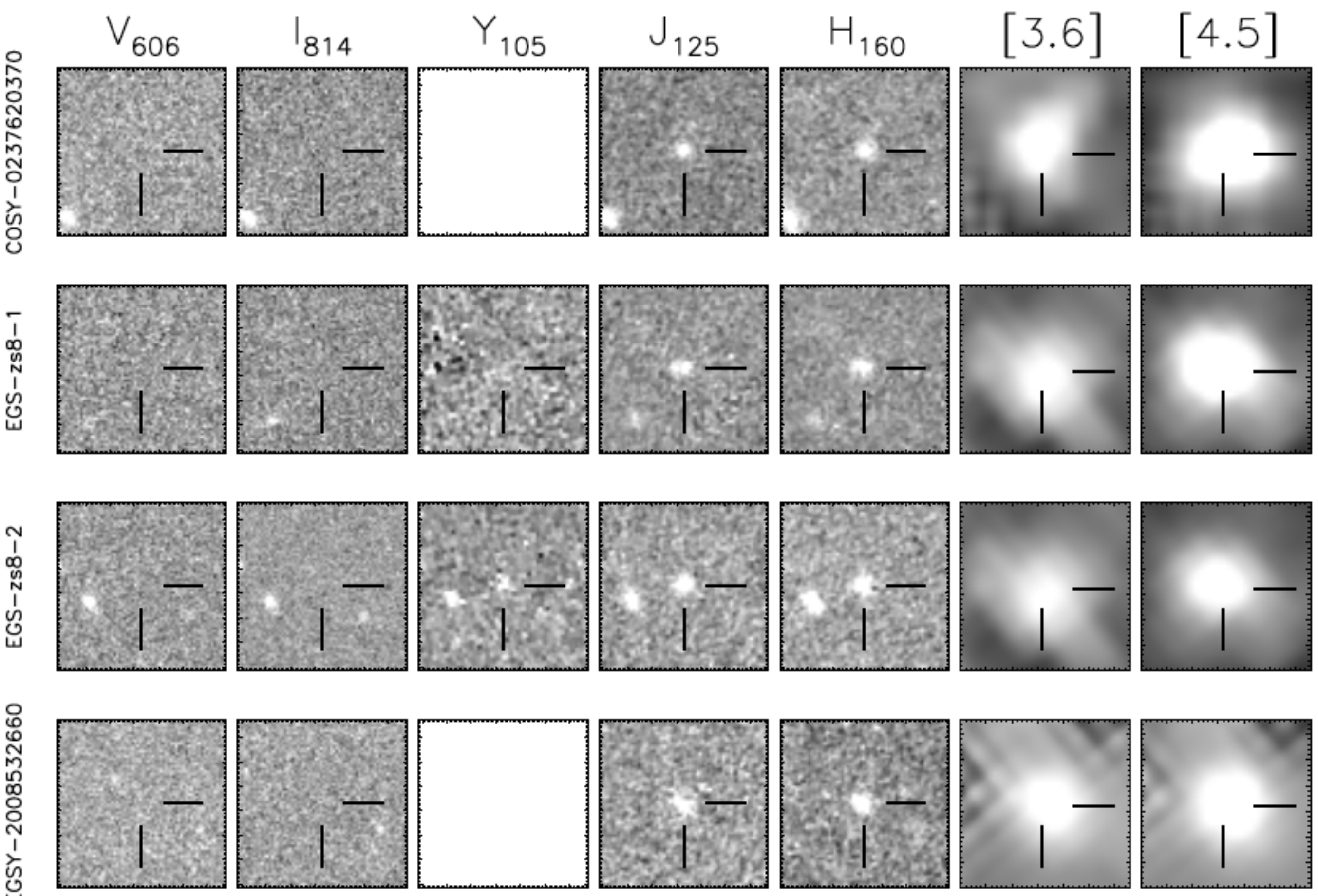
credit: Wise, Cen, and Abel

- Most models suggest neutral hydrogen must fill 40-60% of z~7 IGM to explain Lyman-alpha results (i.e., Mason+17).

- Lyman-alpha emitters we observe expected to trace early ionized bubbles in significantly neutral IGM.

Lyman-alpha Properties of Massive z~7-9 Galaxies with Extremely Large EW Optical Line Emission

Roberts-Borsani+16



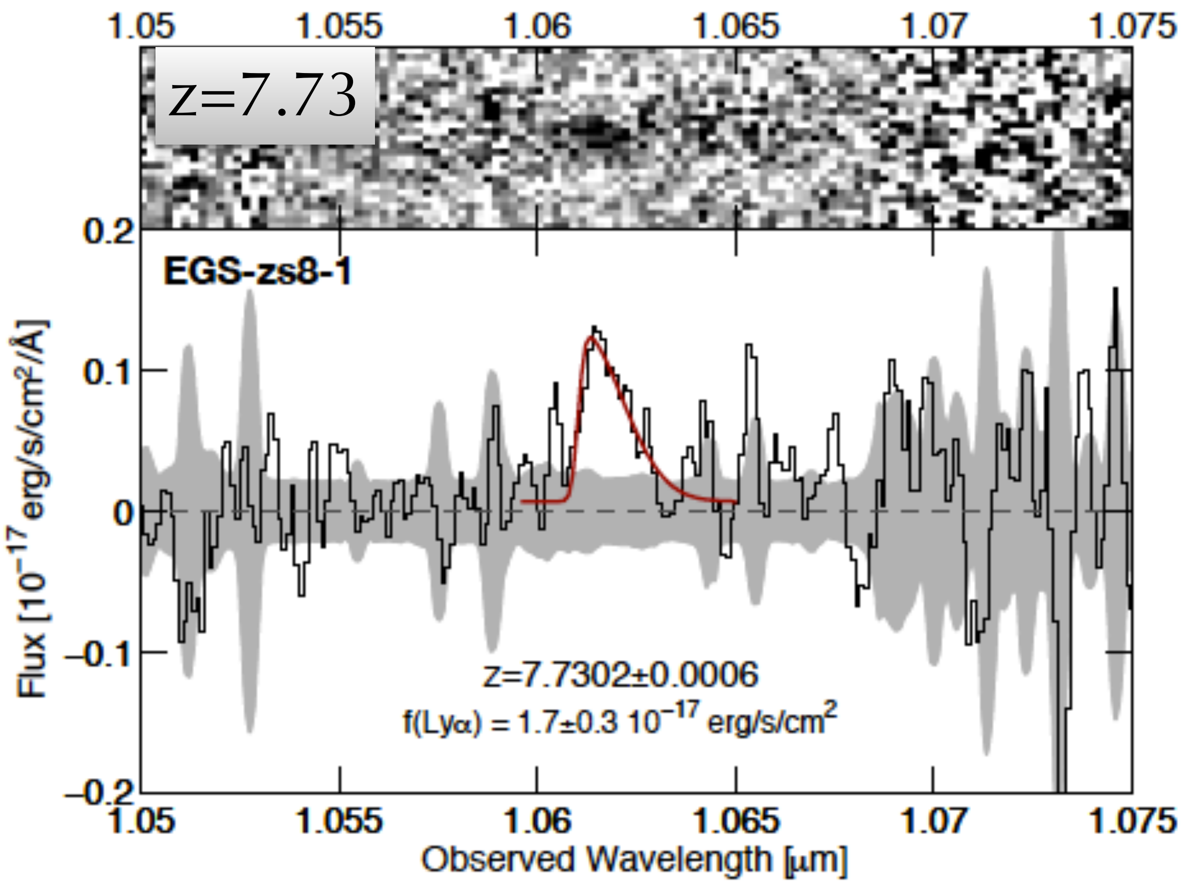
Four very bright (H~25) z~7-8 galaxies, stellar masses of 10^{10} $M_{\odot}$.

Selected to have extremely large EW [OIII]+Hβ.

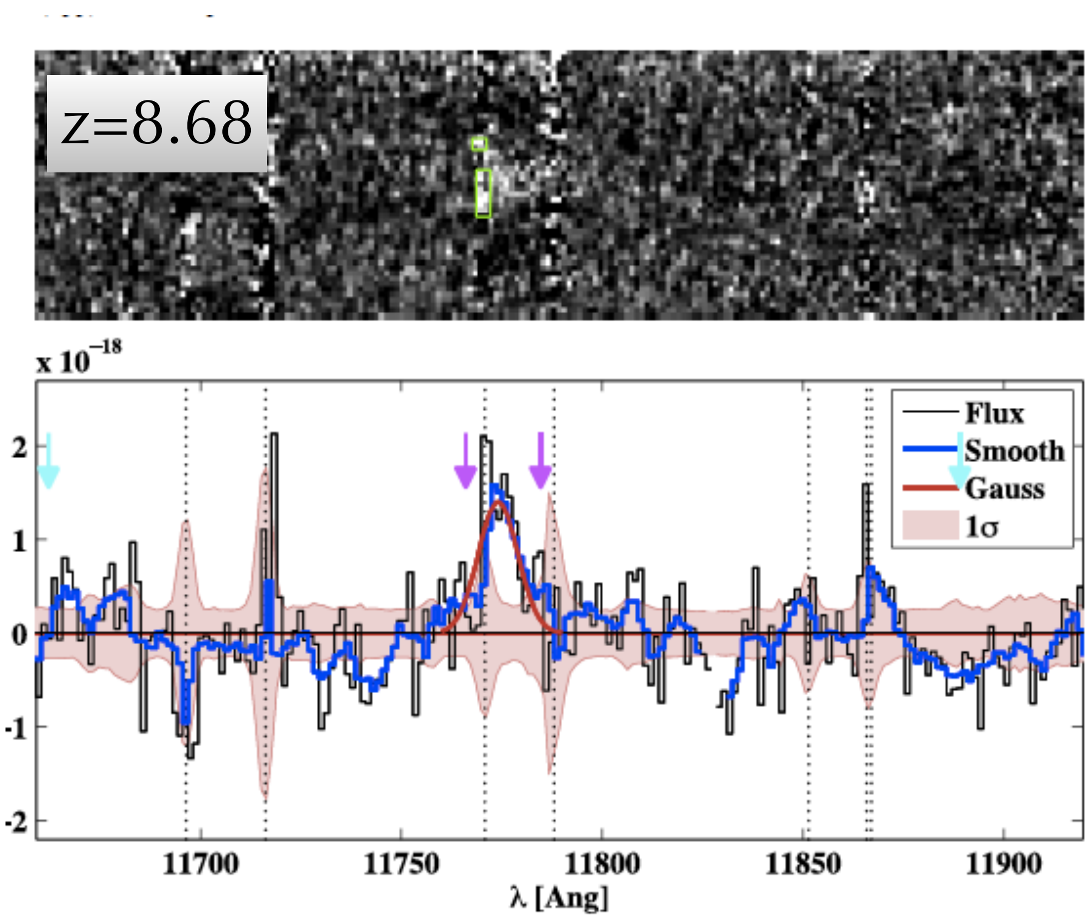
Ideal spectroscopic targets for Lyman-alpha visibility test!

Discovery of Lyman-alpha at z~8-9

Oesch+15



Zitrin+15

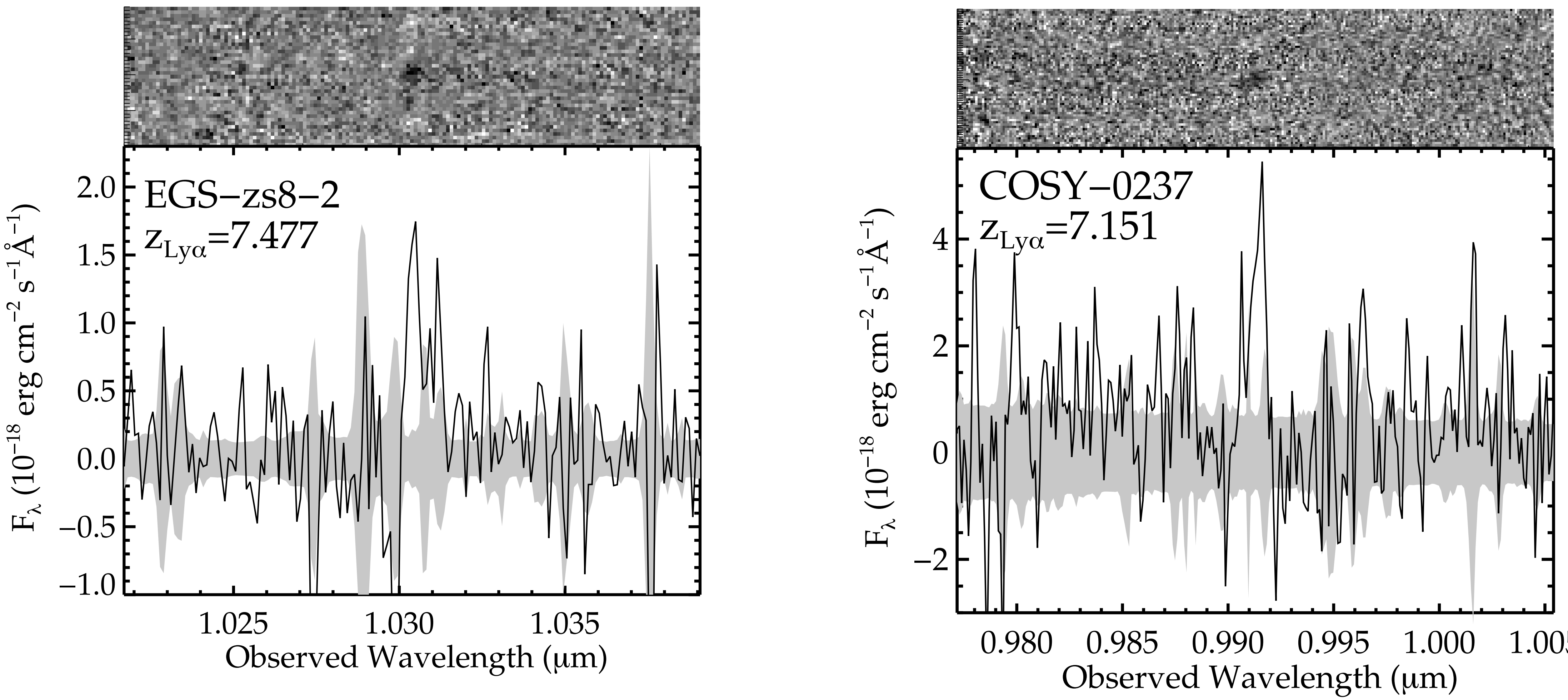


First two galaxies from this sample revealed record breaking Lyman-alpha detections:

- z=7.73 (Oesch et al. 2015)
- z=8.68 (Zitrin et al. 2015)

Large Lyman-alpha fraction in Strong [OIII] +Hβ Emitters at z~7-9

Stark+17



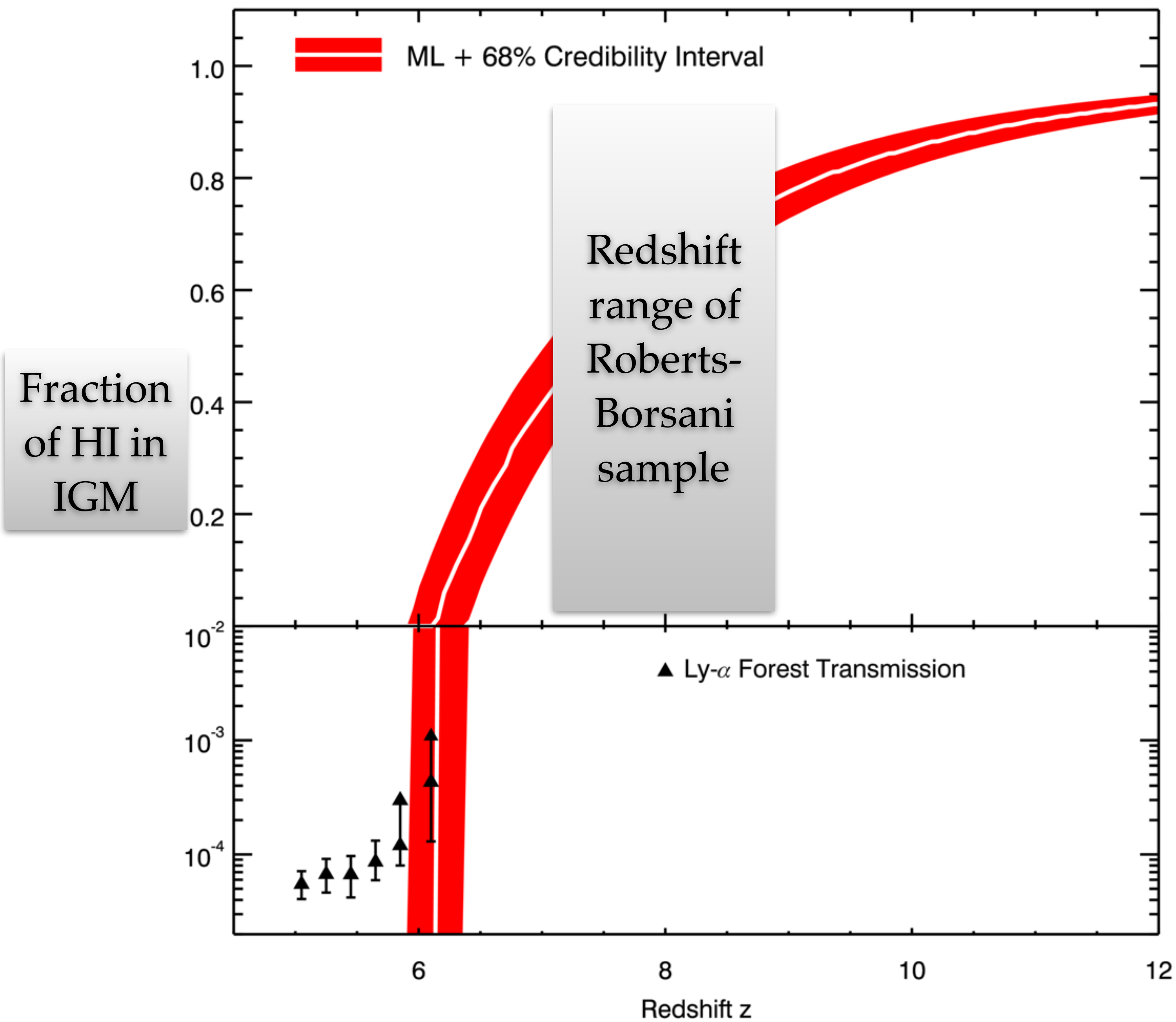
Next two objects also showed Lyman-alpha emission:

- z=7.48 (Roberts-Borsani+16, Stark+17)
- z=7.15 (Stark+17).

100% Lyman-alpha emission fraction in massive sample at z~7-9

What Regulates Detectability of Lyα Emission at z=8-9?

Robertson et al. 2015



Lyman-alpha fractions in luminous galaxies tend to be below 10% at z~8.

Why do we see a 100% Lyman-alpha fraction in this new sample while it is so strongly attenuated in most other systems?

Classical Explanation: Accelerated Reionization around Massive Galaxies

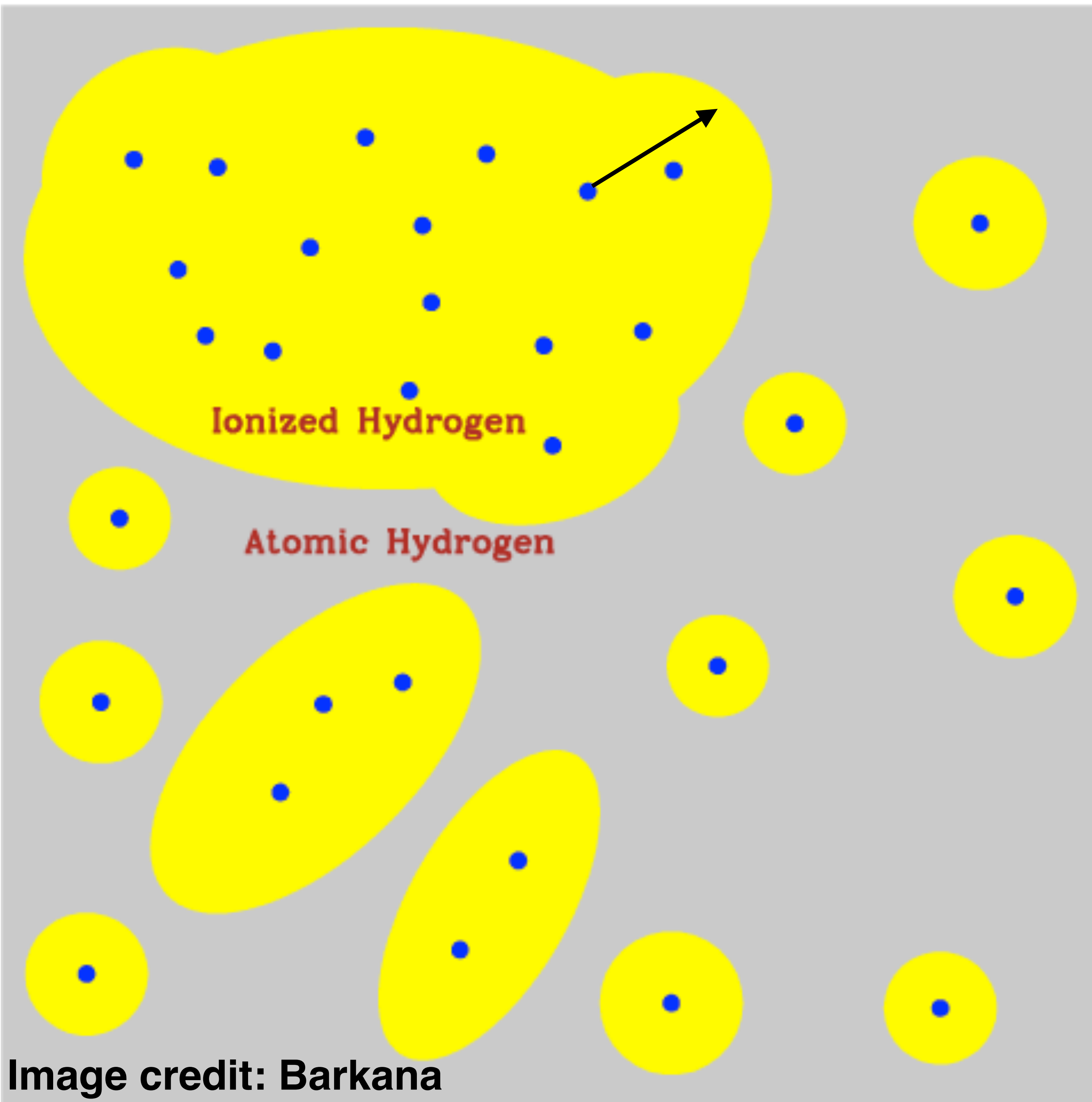
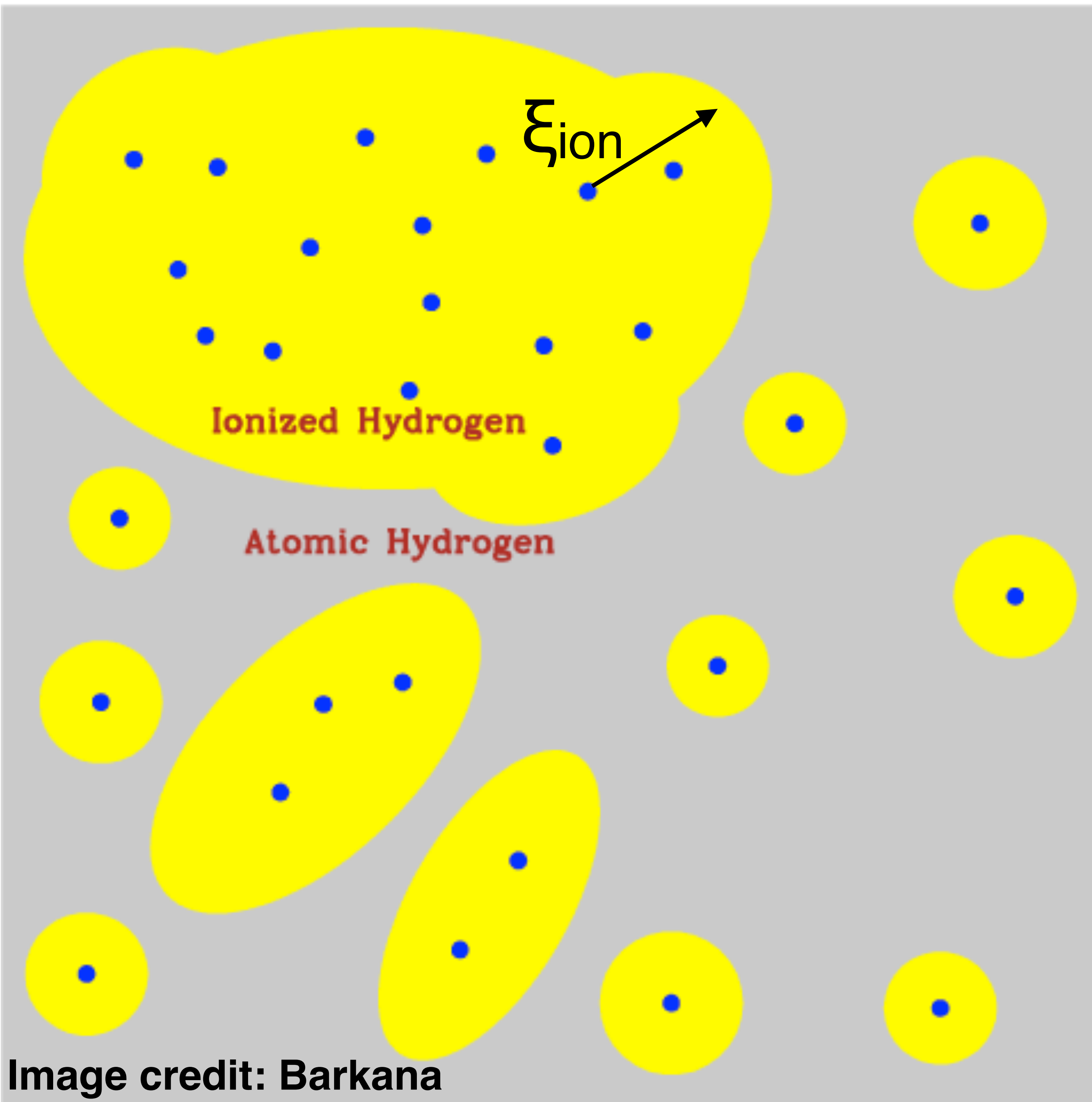


Image credit: Barkana

- Trace overdense regions that ionize their surroundings early.

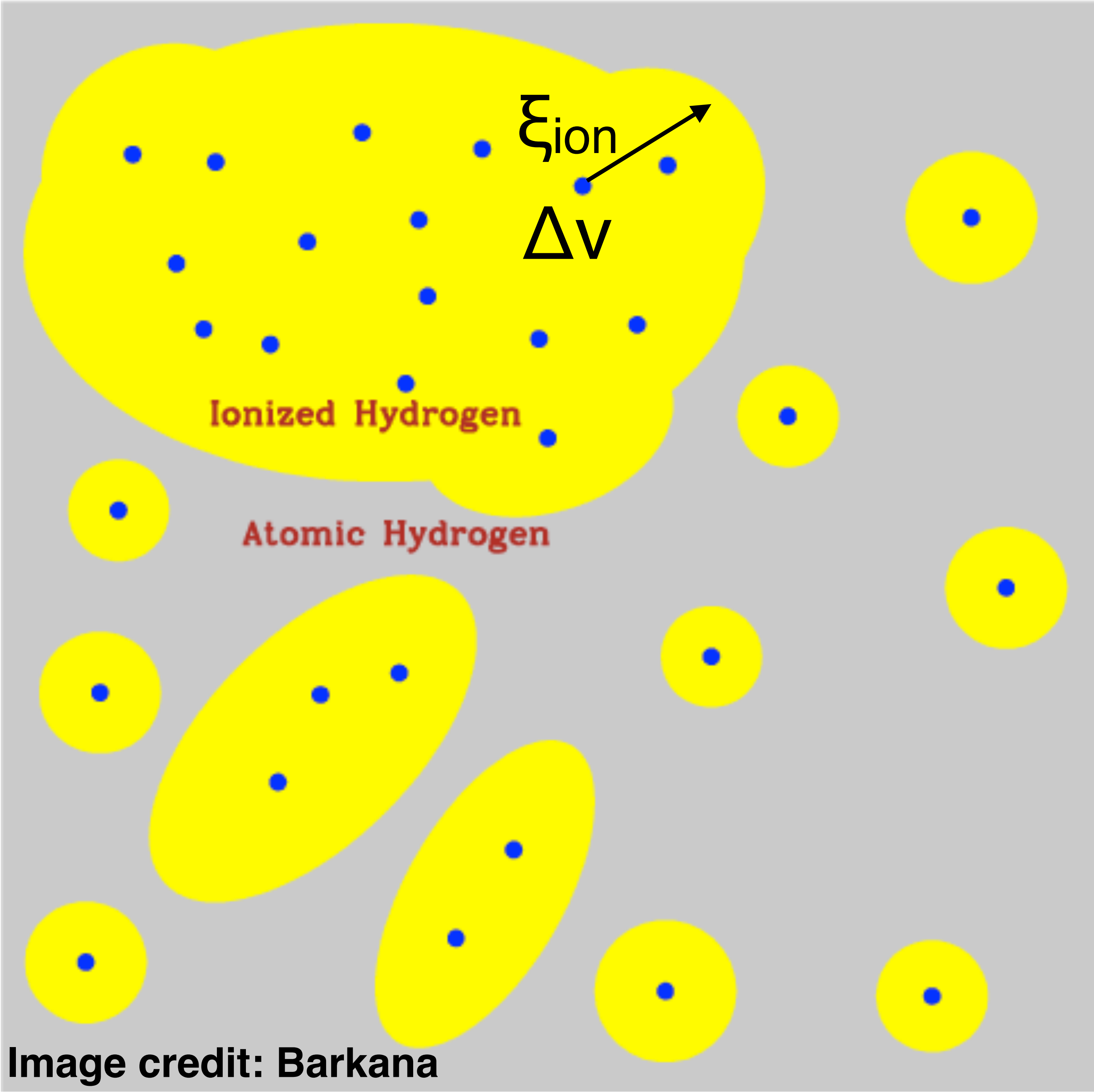
Additional Explanations May Be Required



Lyman-alpha emitters trace systems with hard ionizing spectra (AGN, very hot metal poor stars)?

- Enhanced production rate of Lyman continuum photons.
- Efficiently ionize/heat surroundings.

Additional Explanations May Be Required



Lyman-alpha emitters trace systems with hard ionizing spectra (AGN, very hot metal poor stars)?

- Enhanced production rate of Lyman continuum photons.
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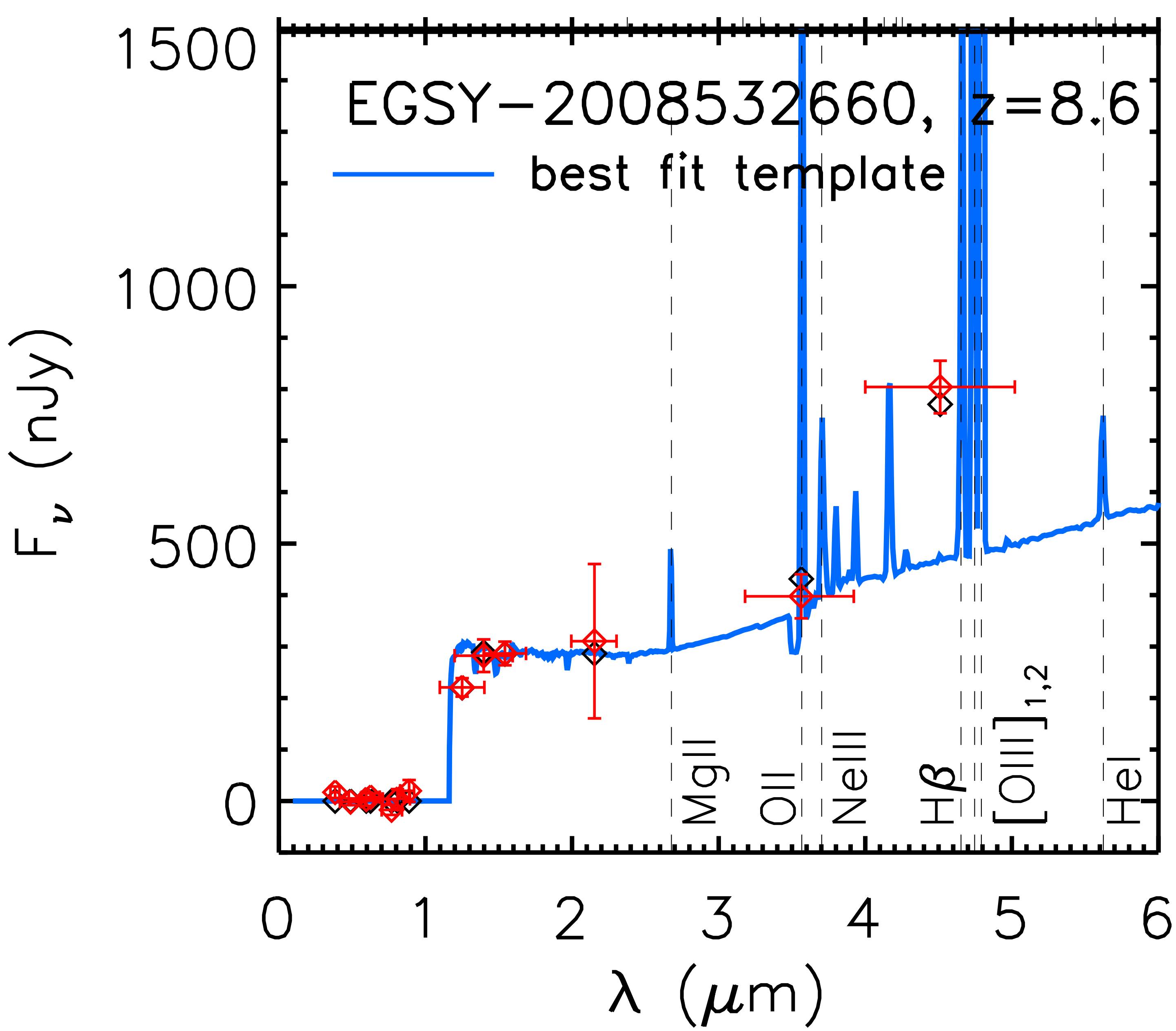
Massive sources may have larger velocity offsets.

- Reduced attenuation from IGM.

Lyman-alpha Emitters at z>7 Have Extreme Optical Line Emission

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

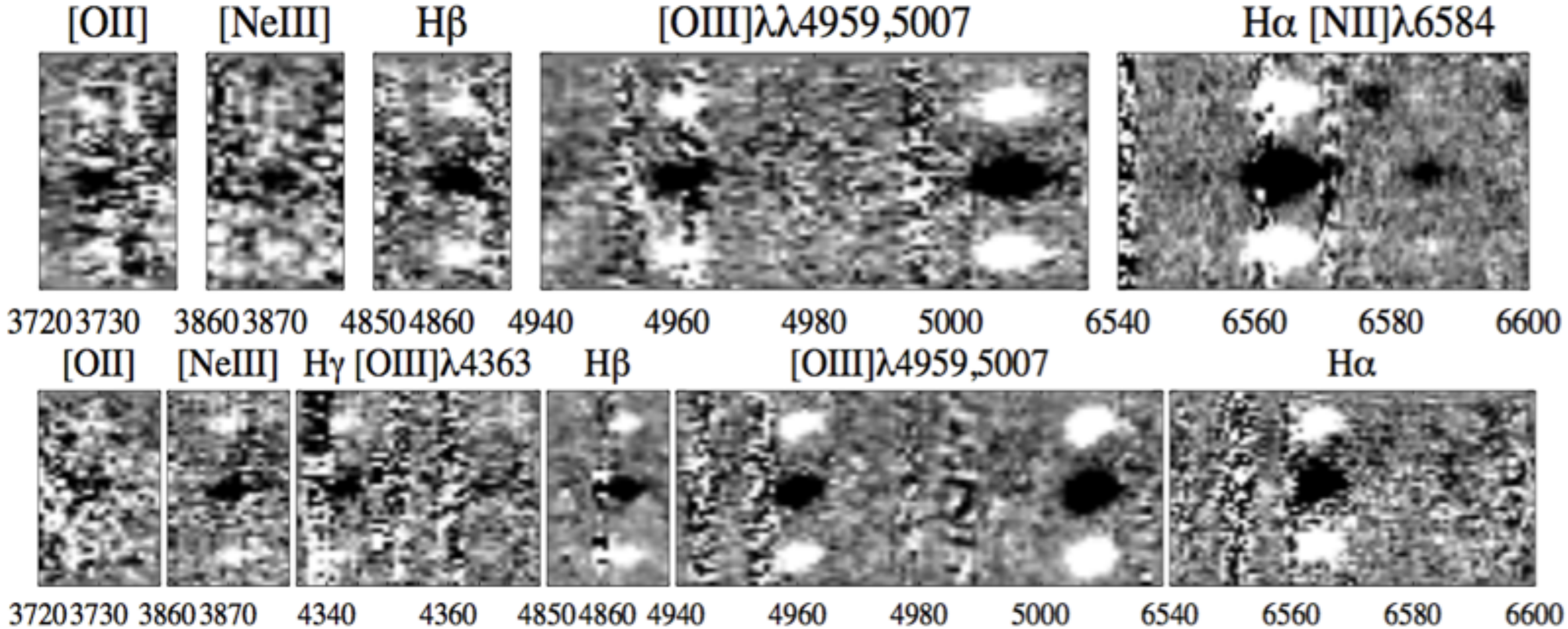


Inferred [OIII] equivalent widths of z>7 sources with Lyman-alpha tend to be ~2x larger than average.

Do these more extreme EW [OIII] emitters produce more LyC radiation?

Measuring the LyC Production Efficiency in z~2 galaxies with Extreme [OIII] Emission

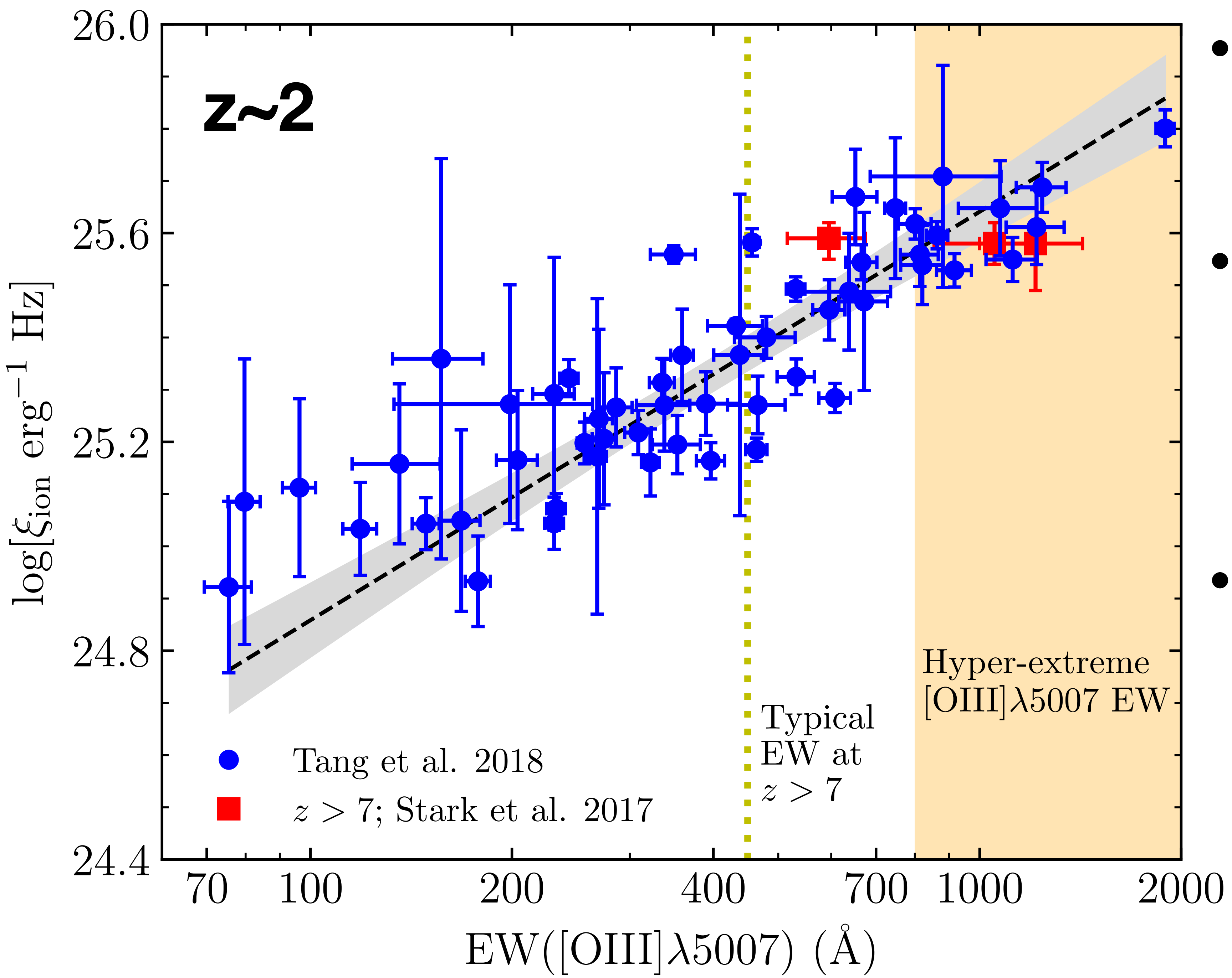
Tang+2018 (see Mengtao Tang's poster)



- Large near-IR spectroscopic survey of z~2 galaxies with similarly large [OIII] EW as z>7 Lyman-alpha emitters.
- Measure production efficiency of LyC photons (ξ_{ion}) as function of [OIII] EW.

Production Efficiency of Lyman Continuum Photons is Enhanced in EELGs at z~2

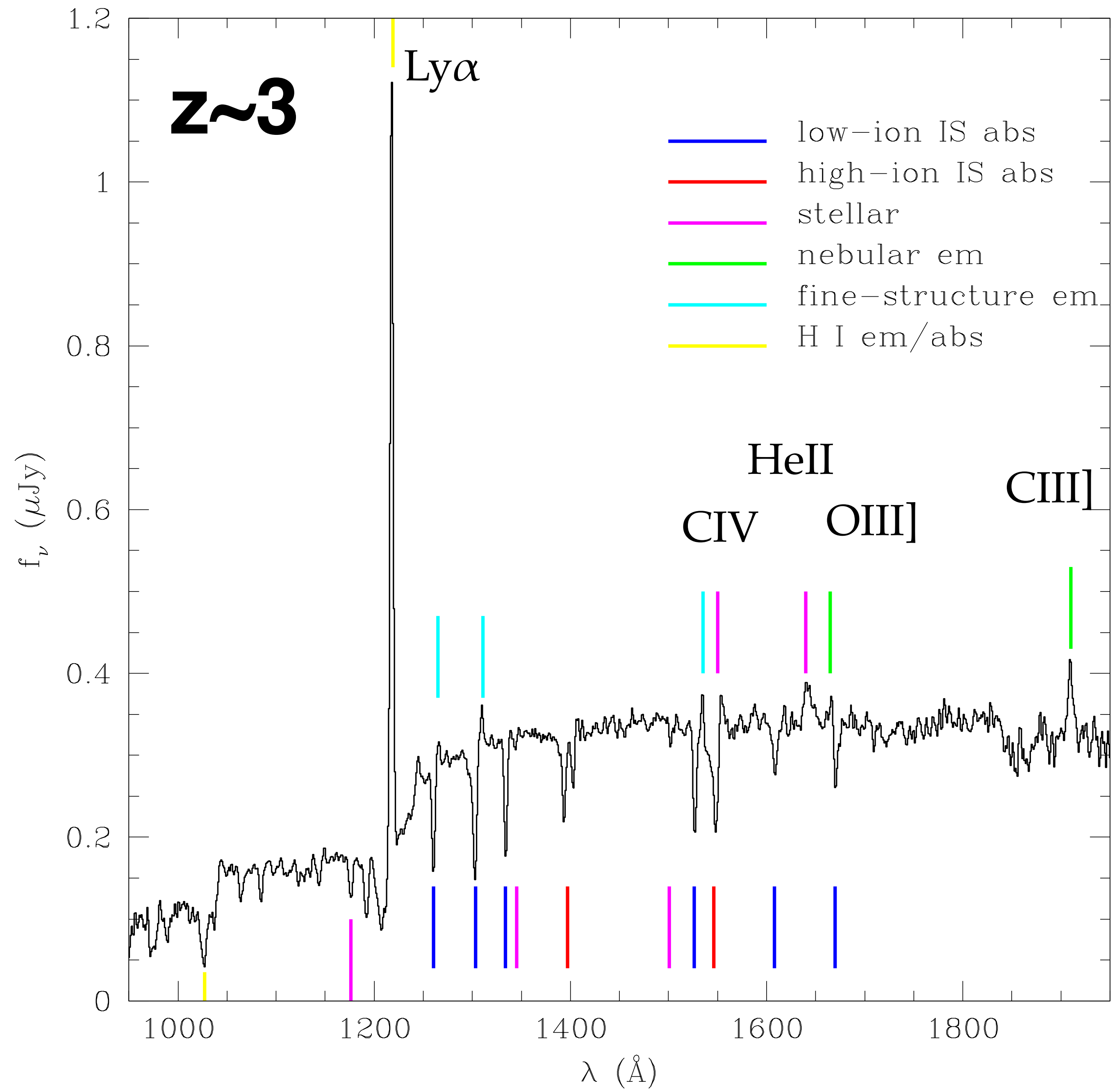
Tang+2018 (see Mengtao Tang's poster)



- Extreme [OIII] emitters at z~2 have largest ξ_{ion}.
- Produce more LyC radiation per UV luminosity, likely implying enhanced Ly**α** production rates.
- Largest EW [OIII] emitters are likely to be more easily detected in Ly**α**.

Can we learn more about radiation field of z>7 Lyman-alpha emitters?

Shapley et al. 2003



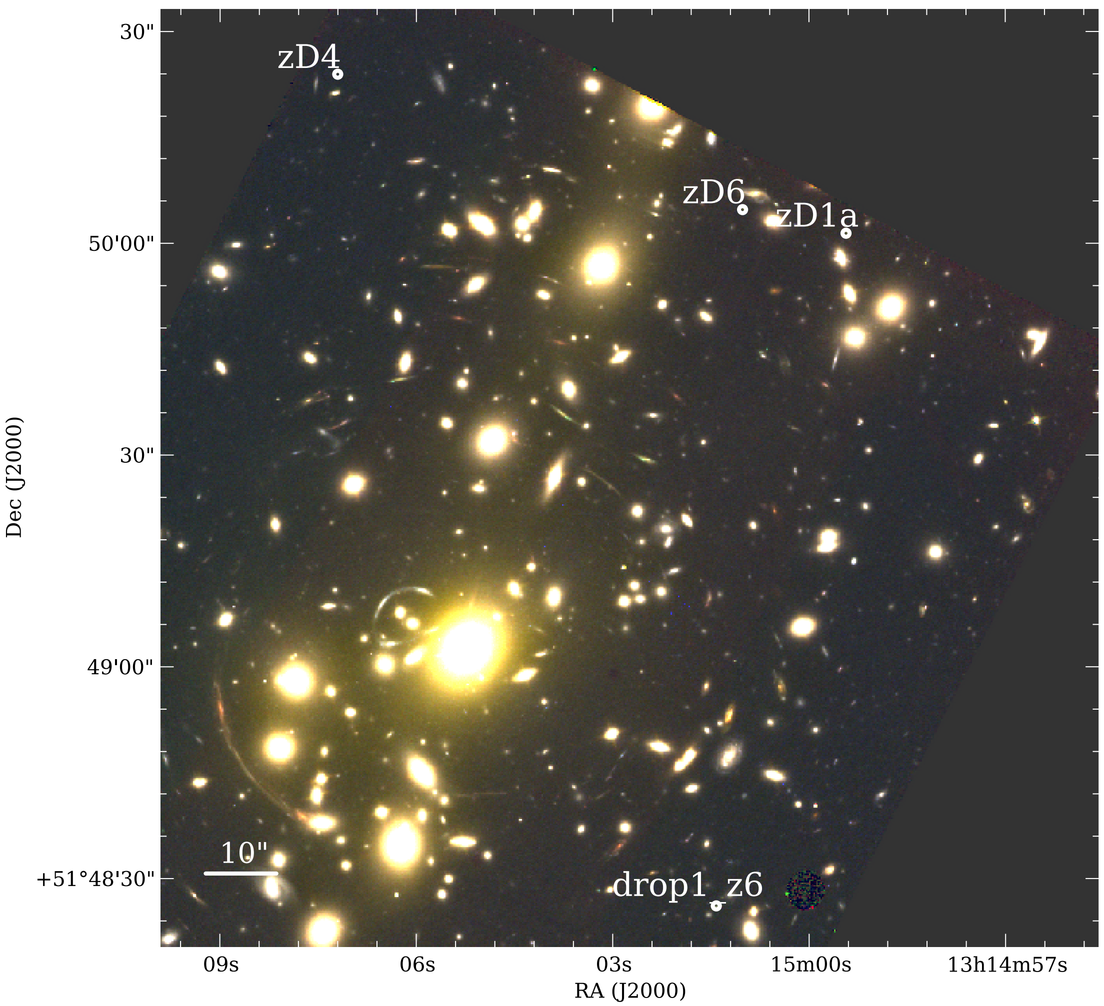
z~3 composite of ~900 LBGs

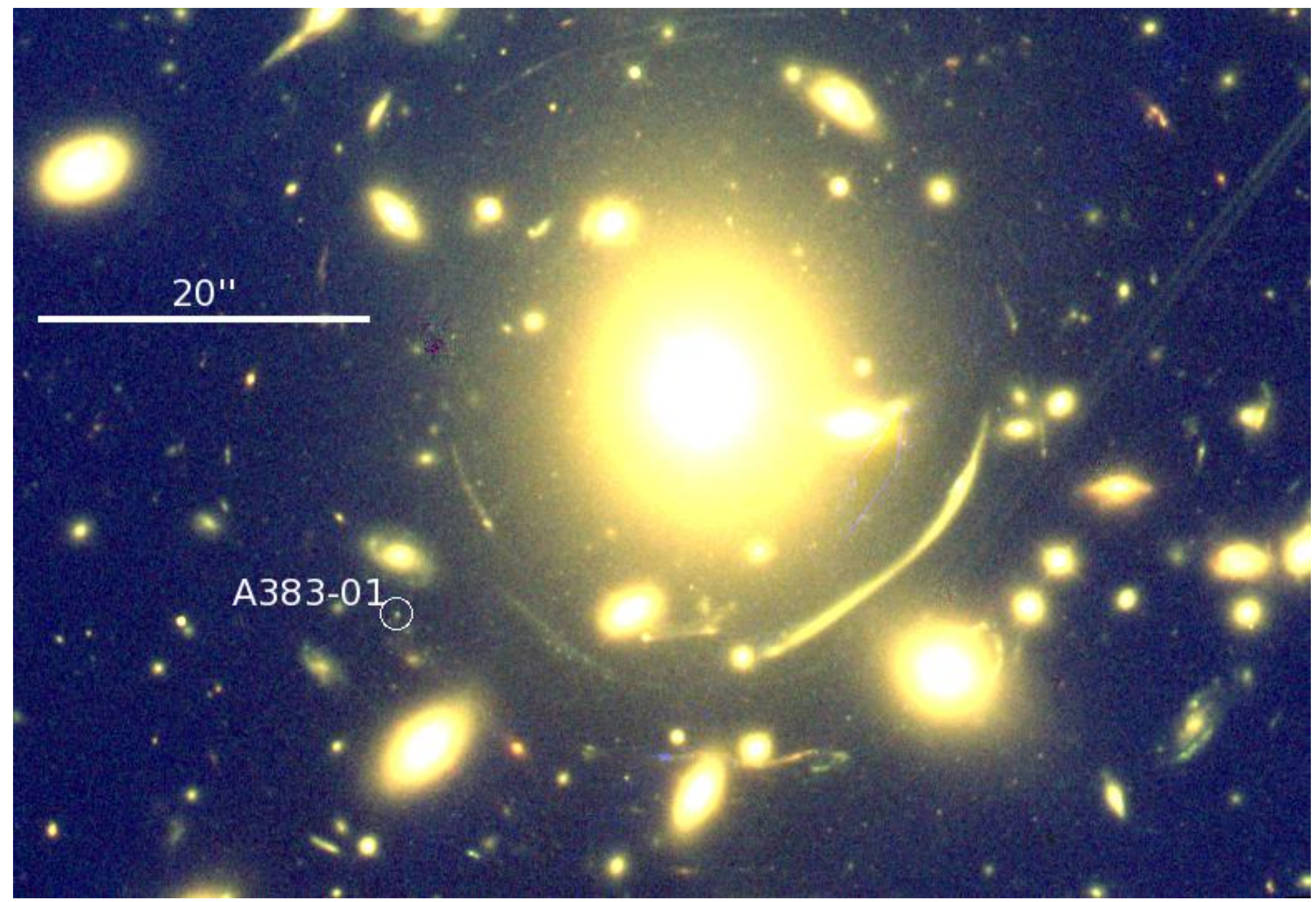
$W_{CIII]} = 1.7$ Å
$W_{HeII} = 1.3$ Å
$W_{OIII]\lambda1661+1666} = 0.2$ Å

- If galaxies similar to z~3, they will be undetectable (≲ 7x10^{-19} erg cm^{-2} s^{-1}) in z>7 galaxies.
- If radiation field more extreme, expect larger EW nebular emission, appearance of high ionization lines (NV, CIV, He II).

Characterizing the Far-UV Spectra of Reionization Era Galaxies

Stark et al. 2015a, 2015b, 2017, Mainali et al. 2017, 2018, Laporte+2017

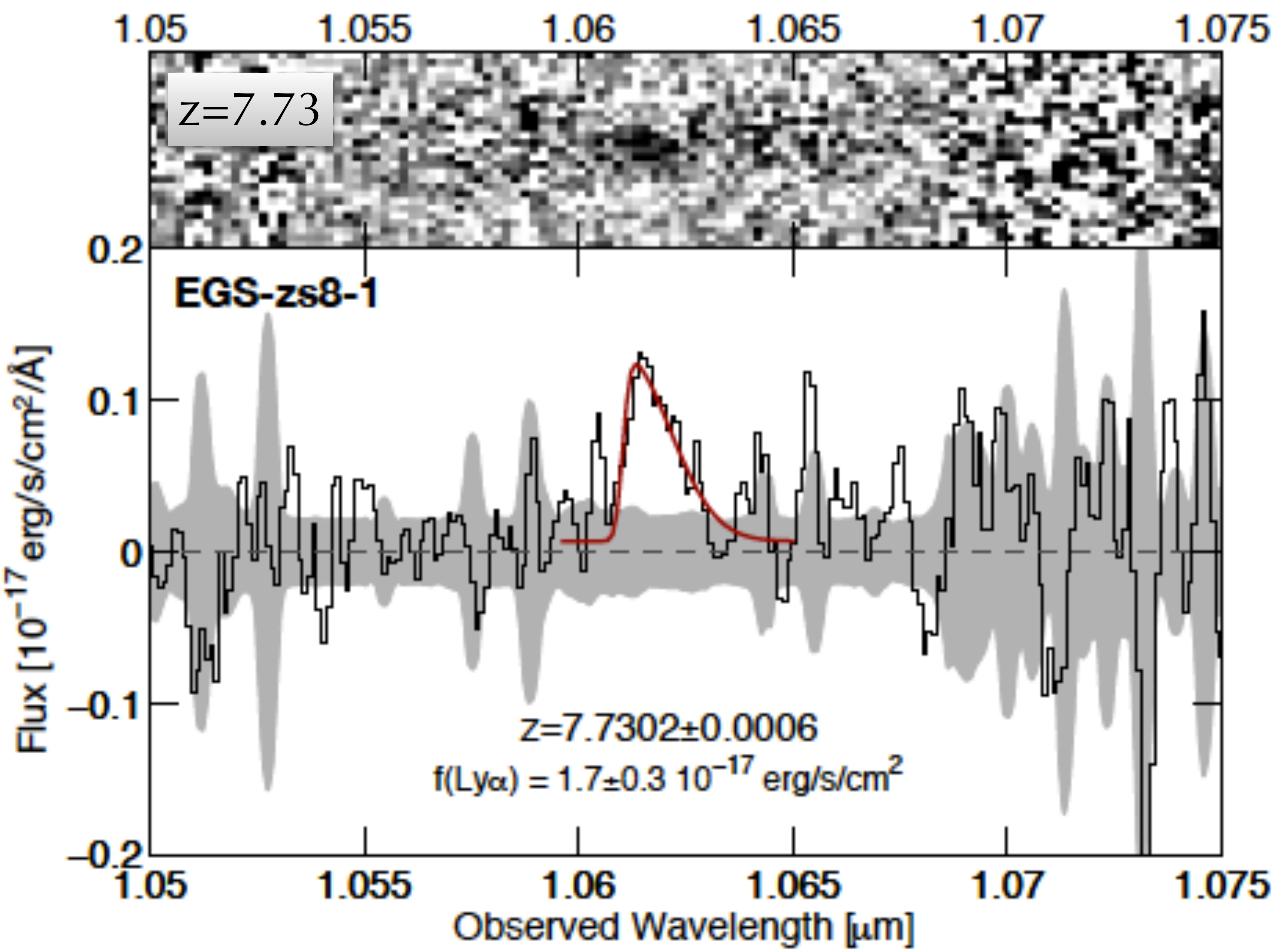




- Measure strength of far-UV lines in bright (24<H<26) galaxies at z~6-9.
- Test for presence of extreme radiation fields in z>6 systems with Lyman-alpha emission.

Massive Lyman-alpha Emitter at z=7.73

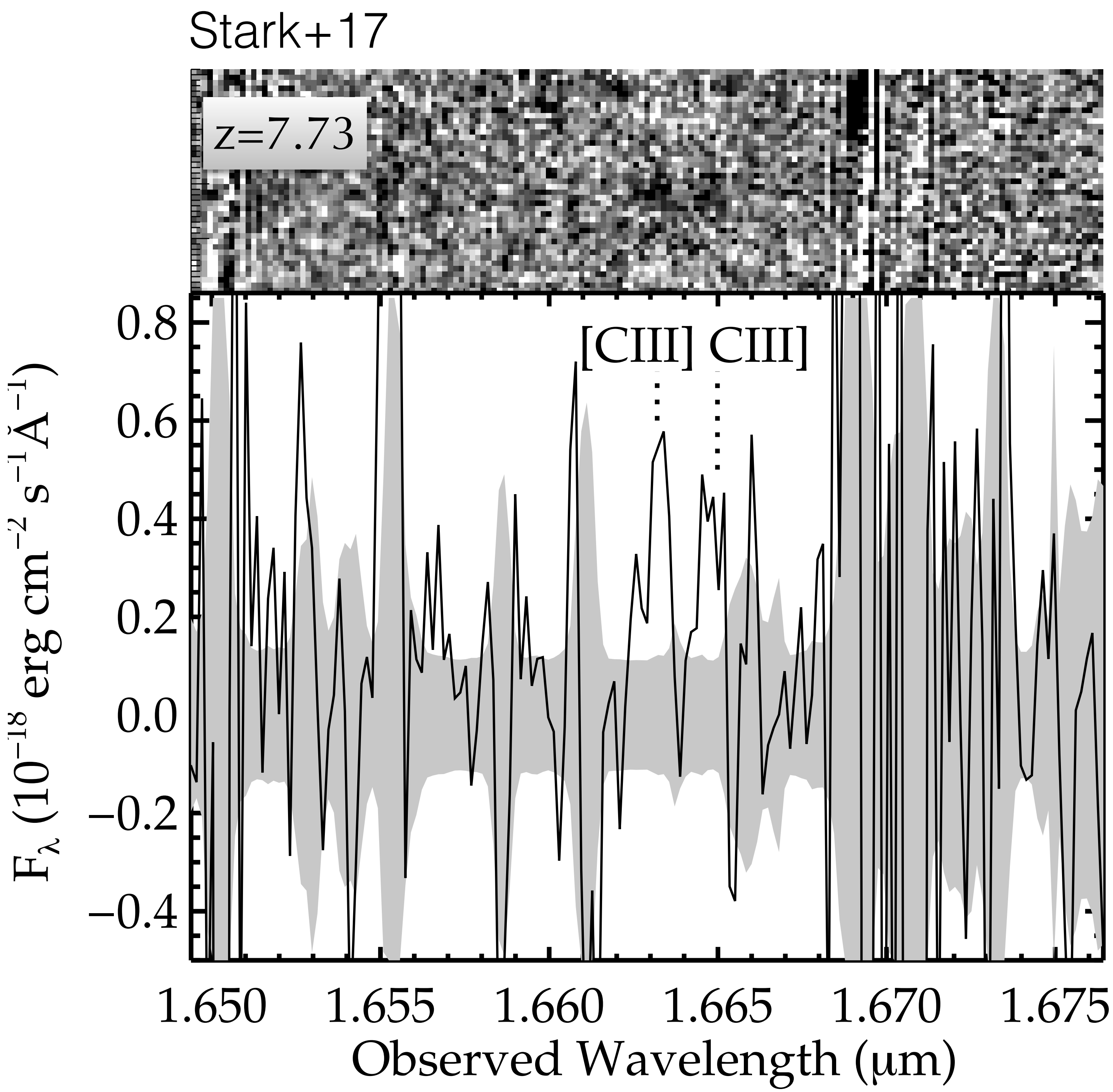
Oesch+15



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

Intense CIII] emission at z=7.73

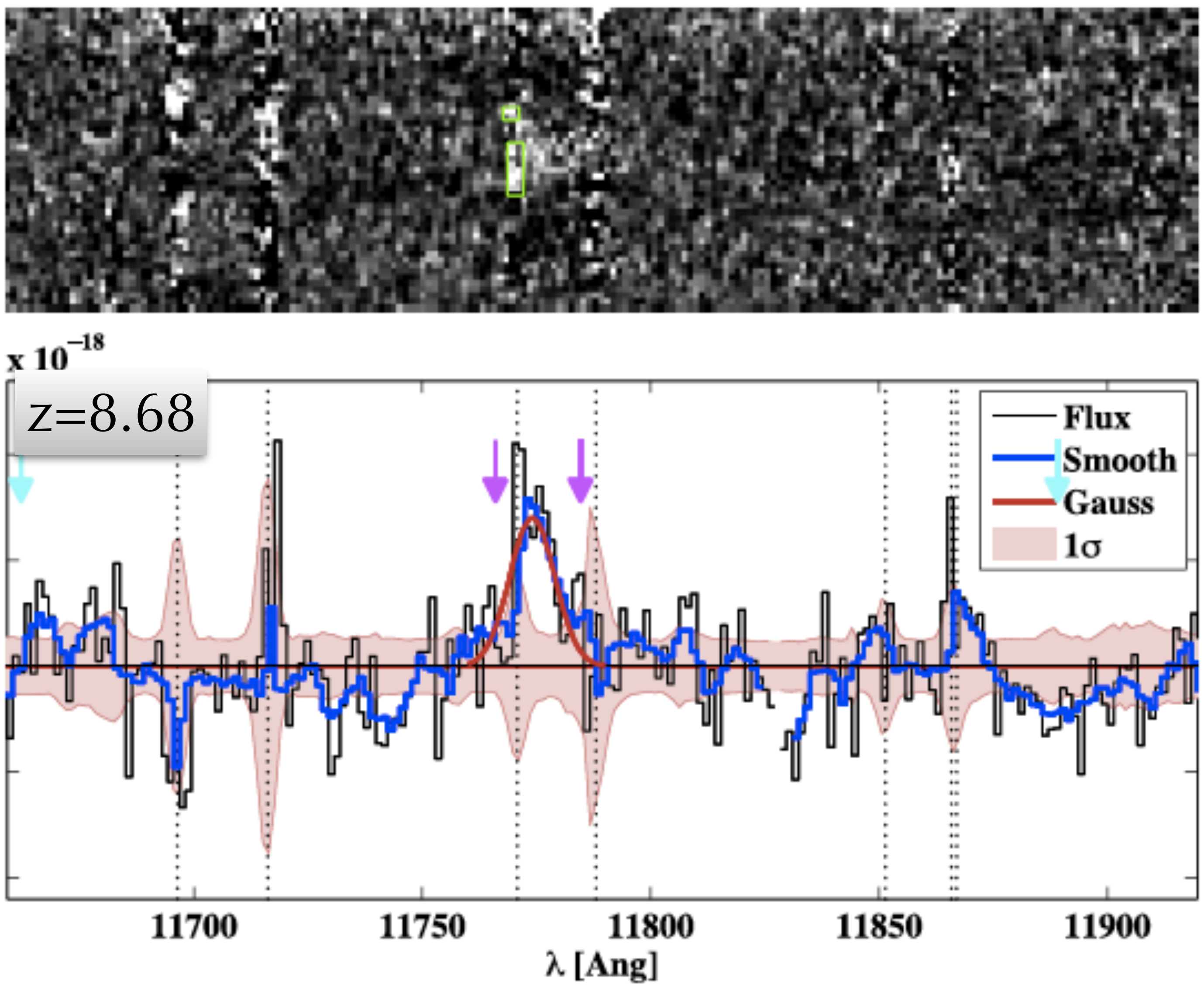


CIII] doublet detected with total EW~22Å.

- ~10x greater EW than in composite of z~1-3 galaxies (Shapley+03, Du+2016, 2018).
- Extreme radiation field, either from AGN (Nakajima+17) or metal poor stars (Stark+17).

Massive Lyman-alpha Emitter at z=8.68

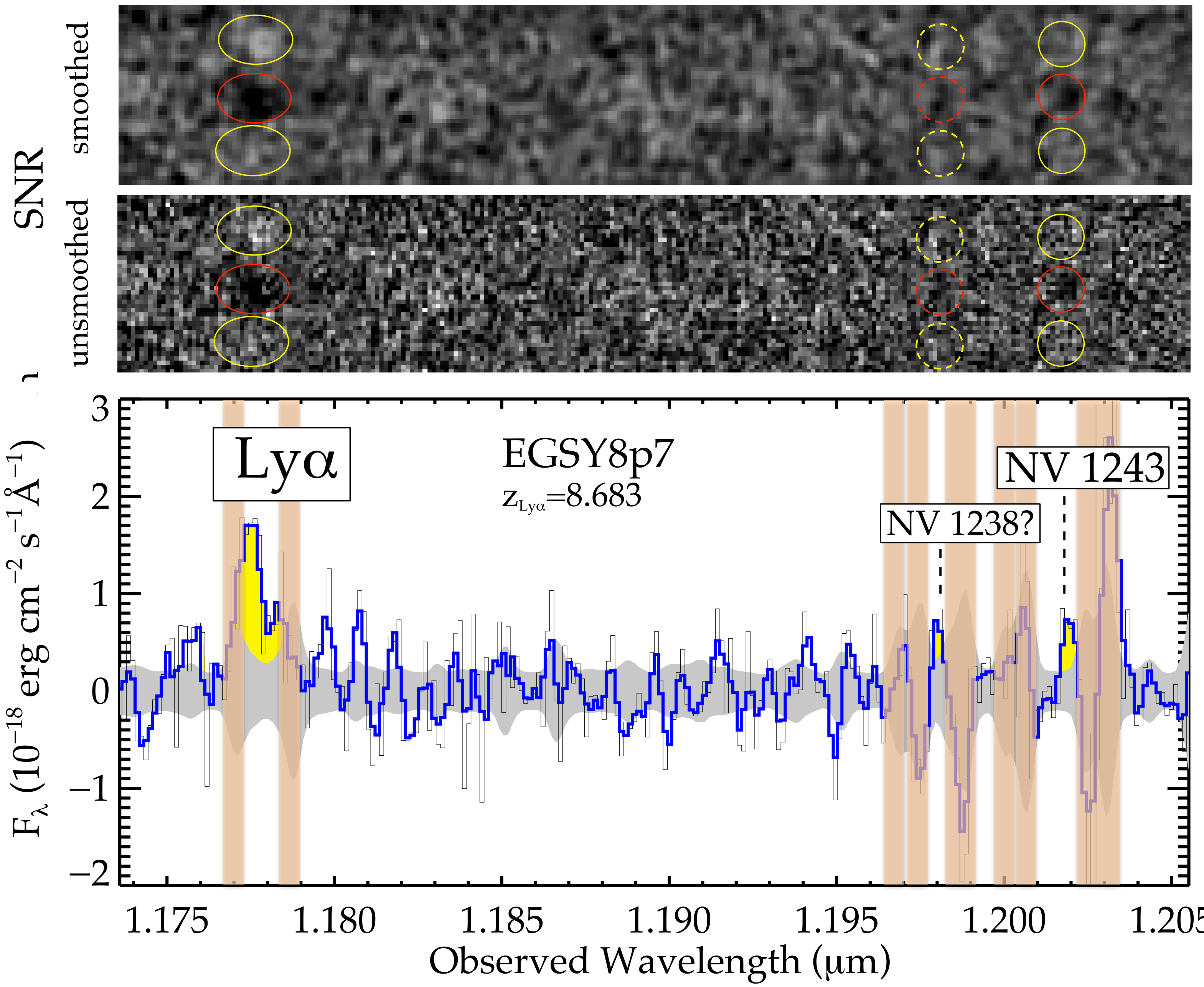
Zitrin+2015



- z=8.68 galaxy with strong [OIII] confirmed in Zitrin+15
  - H=25.3
  - $W_{Ly\alpha,0}$ = 28 Å
  - $W_{[OIII]+H\beta}$ ~ 895 Å

NV Emission in Lyman-alpha Emitter at z=8.68

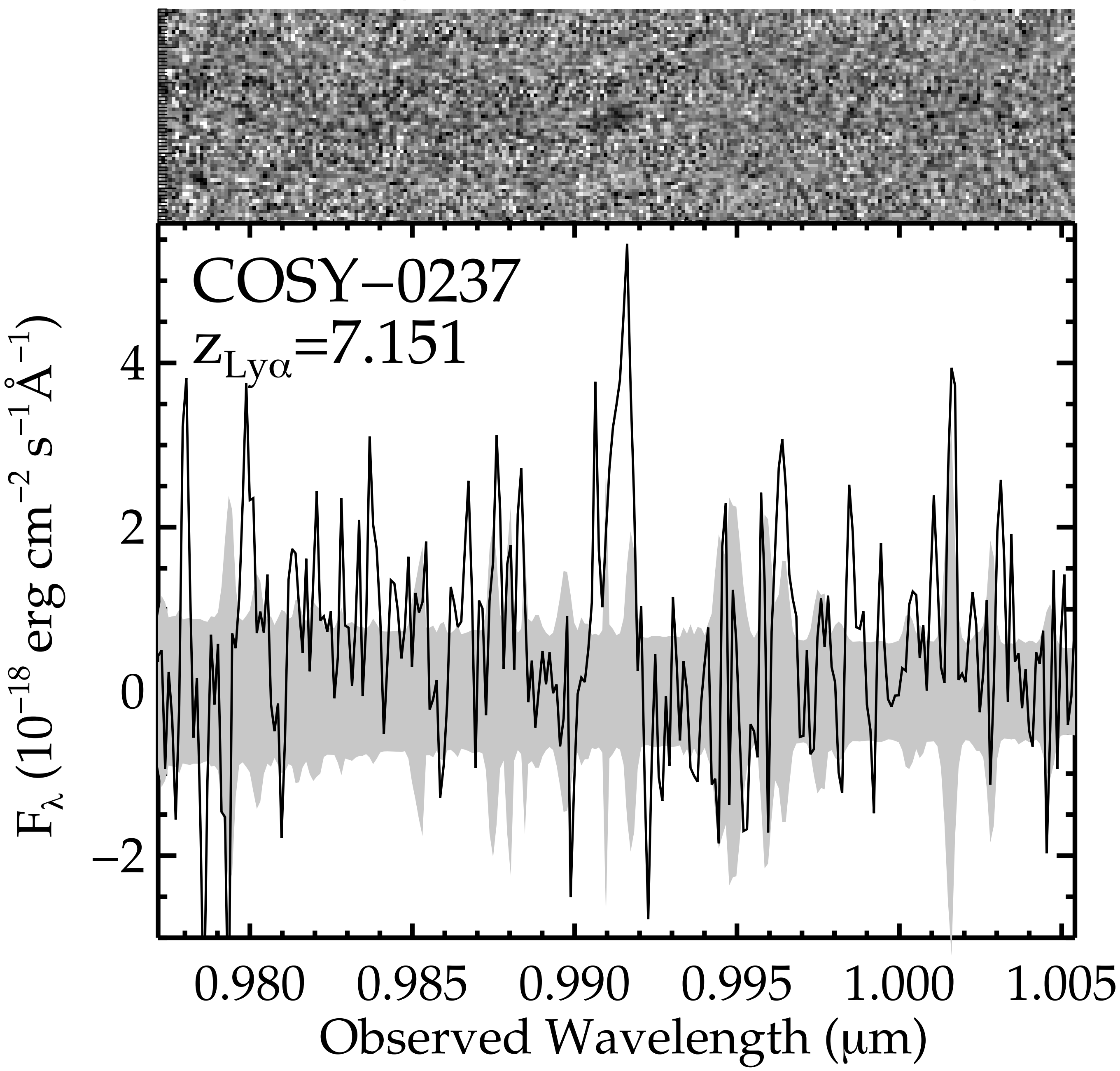
Mainali+18



- NV detected in Y-band spectrum, no CIV or OIII] in H-band spectrum.
- Requires >77eV photons, likely powered by AGN.

Massive z=7.154 Lyman-alpha Emitter

Stark+17 (see also Pentericci+17)

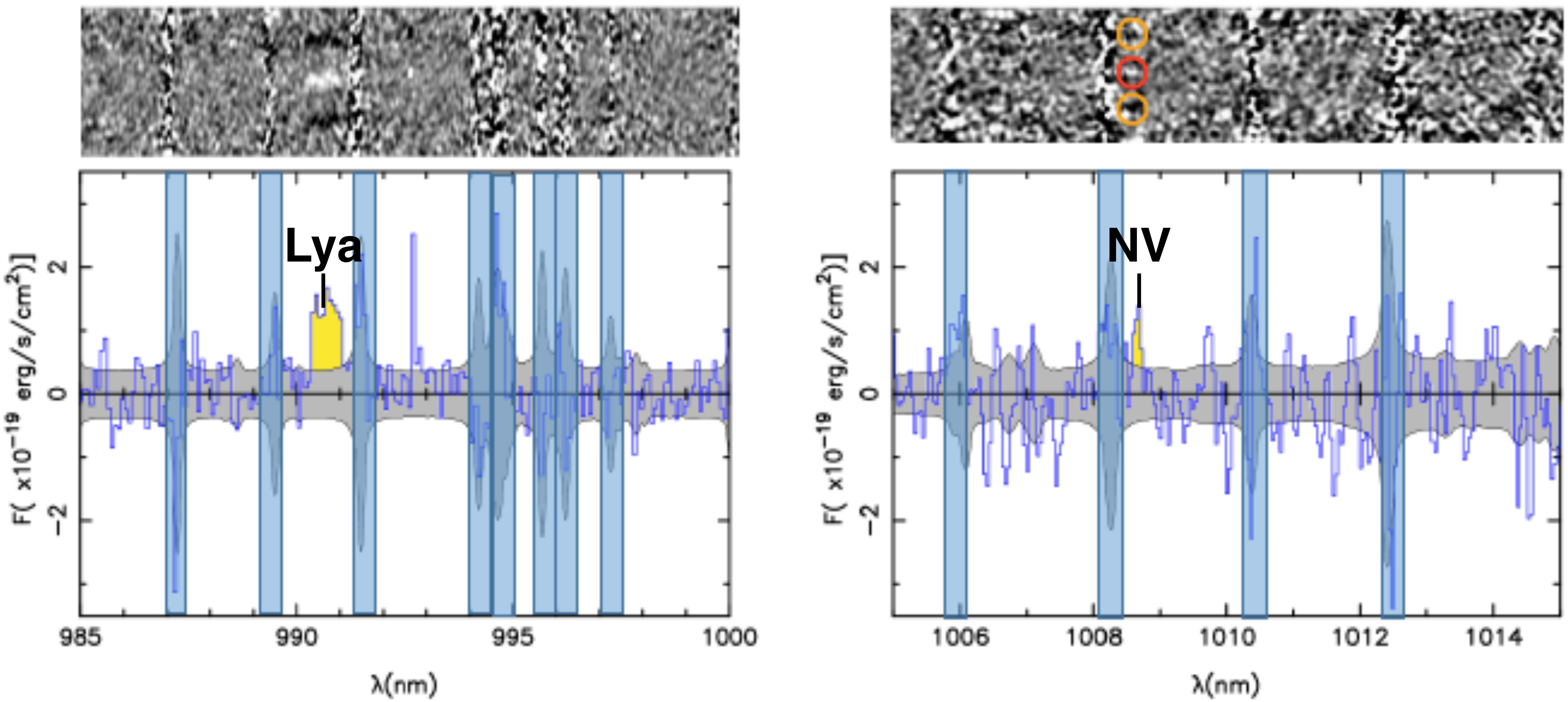


z=7.151 galaxy in COSMOS, confirmed in Stark+17

- H=25.1
- $W_{Ly\alpha,0}$ = 28 Å
- $W_{[OIII]+H\beta}$ ~ 1900 Å

Detection of NV and He II Emission

LaPorte +17

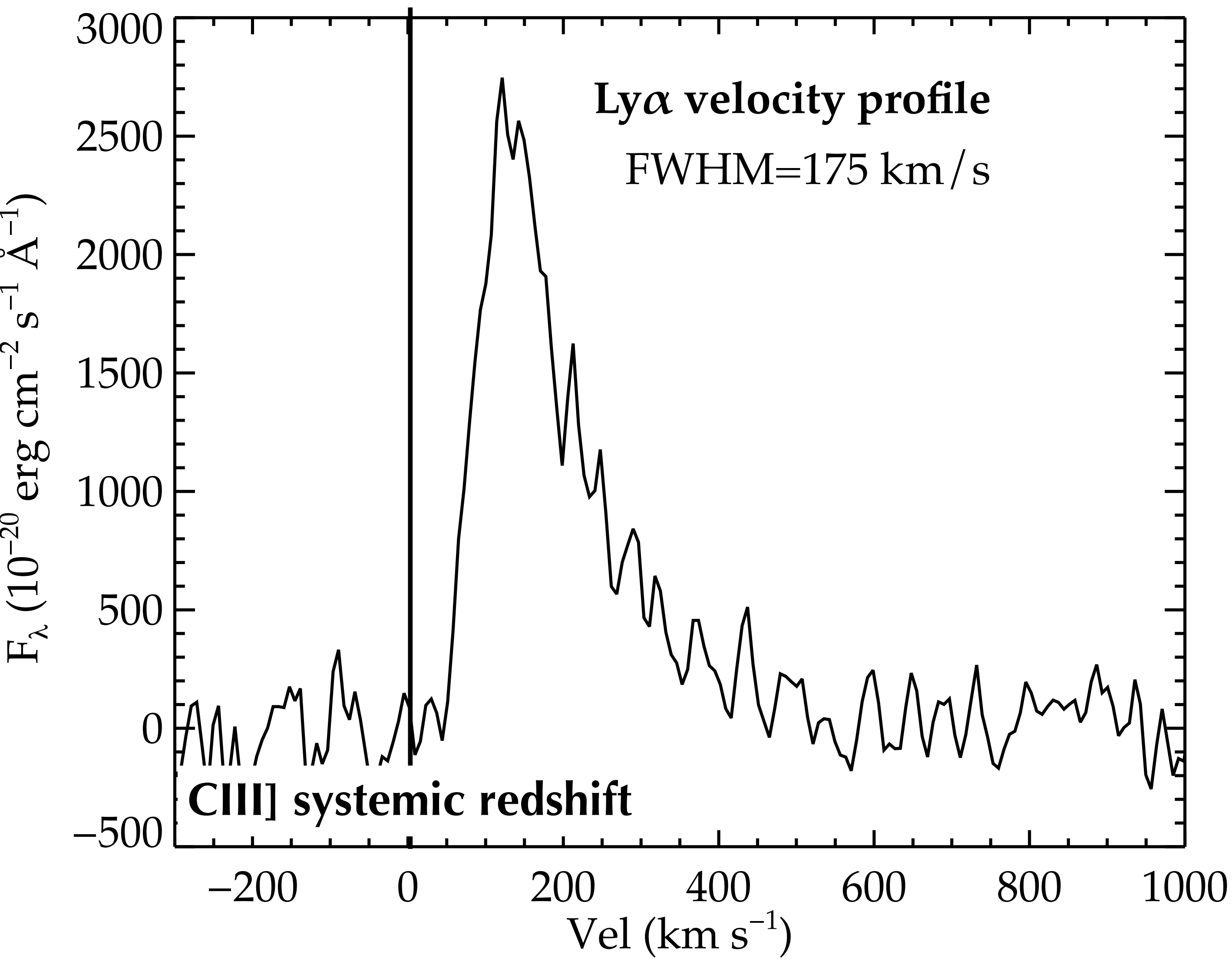


- Nebular NV and He II emission detected in 10 hr X-Shooter exposure. Another AGN?

Massive galaxies at z>7 with Lyman-alpha often have extreme radiation fields that may be effective at ionizing surrounding ISM/ CGM, contributing to visibility of strong Lyman-alpha.

Lyα Velocity Offsets at z>6

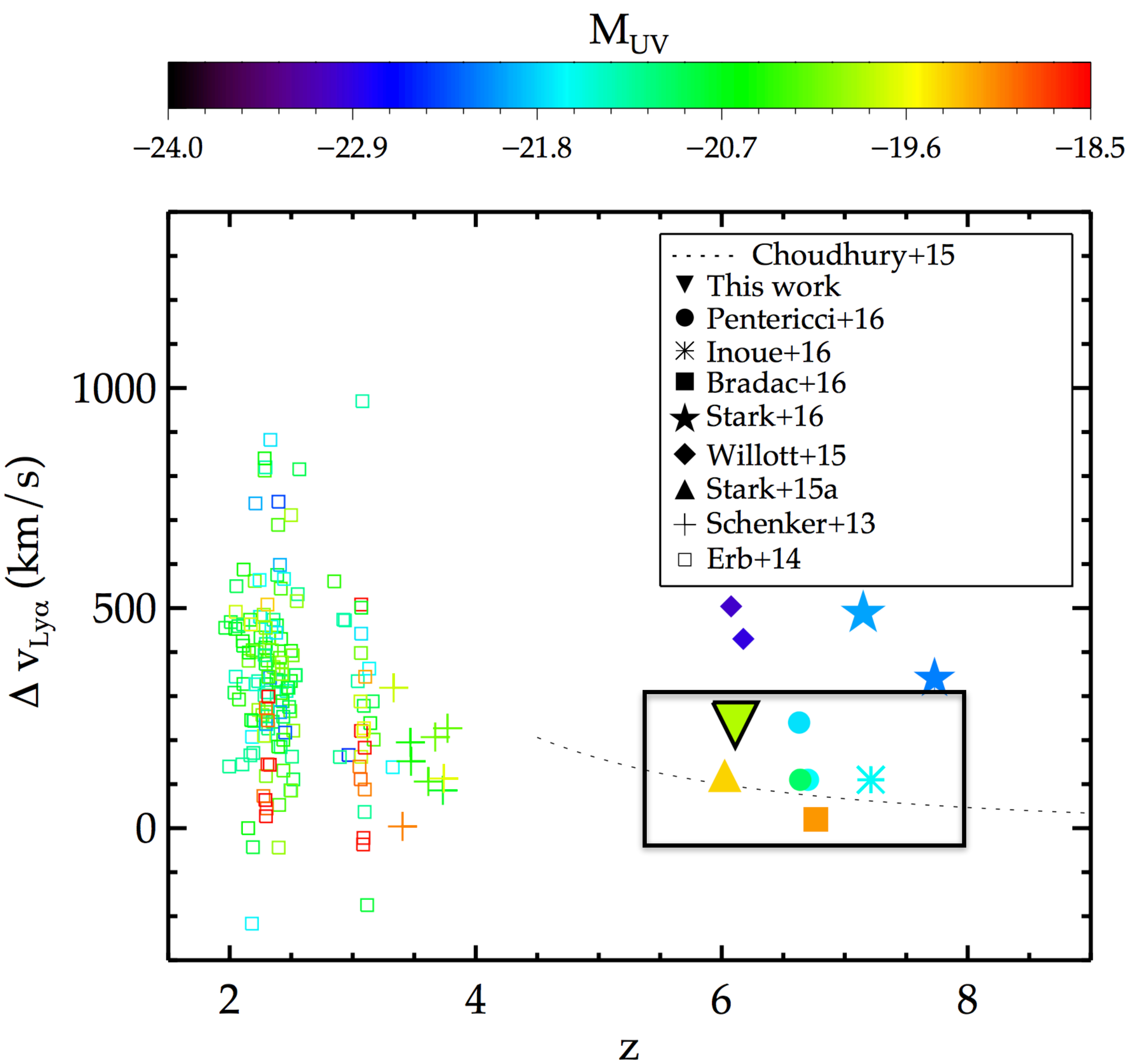
Stark et al. 2015a



- UV metal lines (CIII], OIII]) and far-IR lines ([CII], [OIII]) now providing systemic redshifts at z>6.

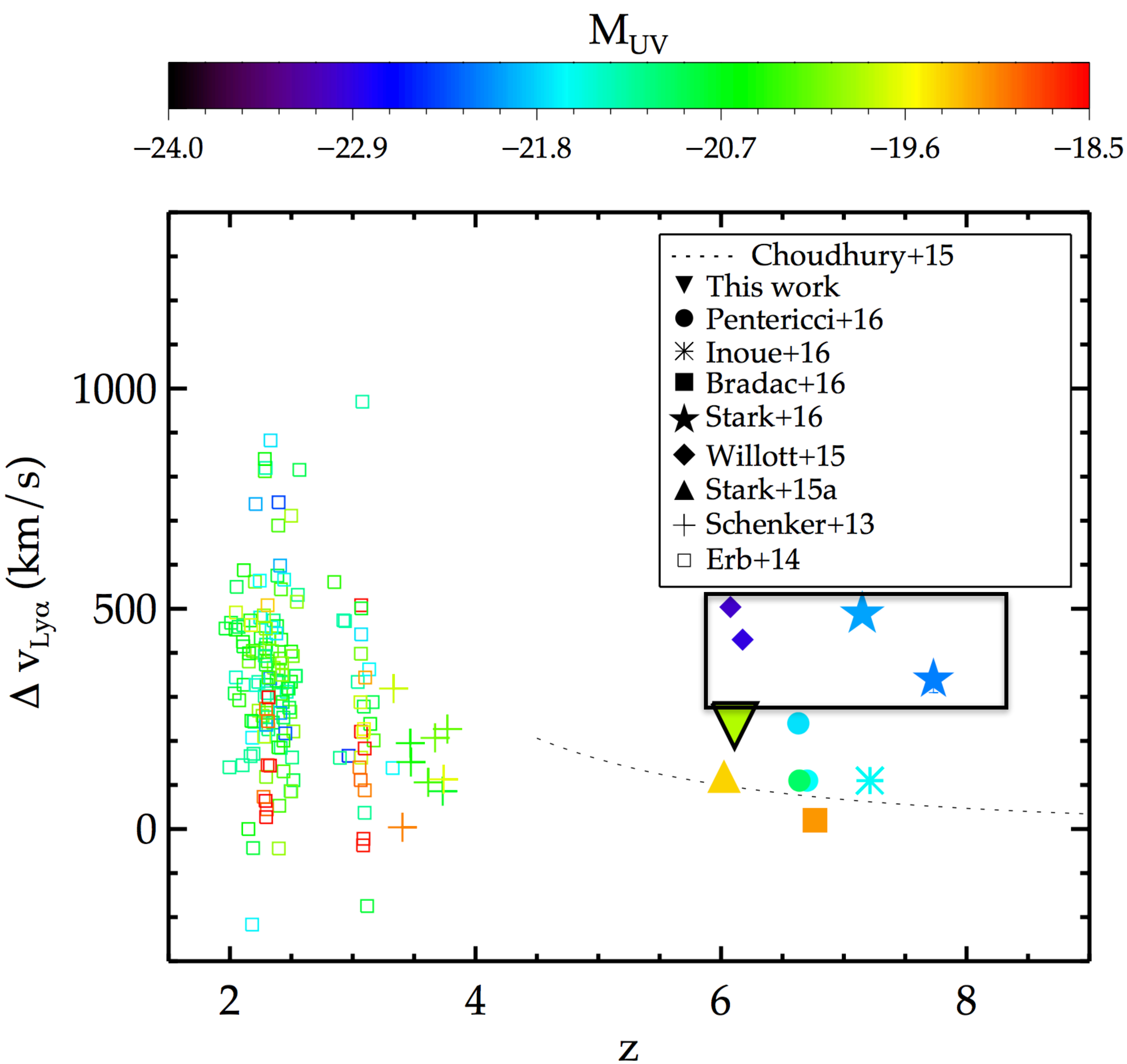
Lyα Velocity Offsets in Low Mass Galaxies

Mainali+17



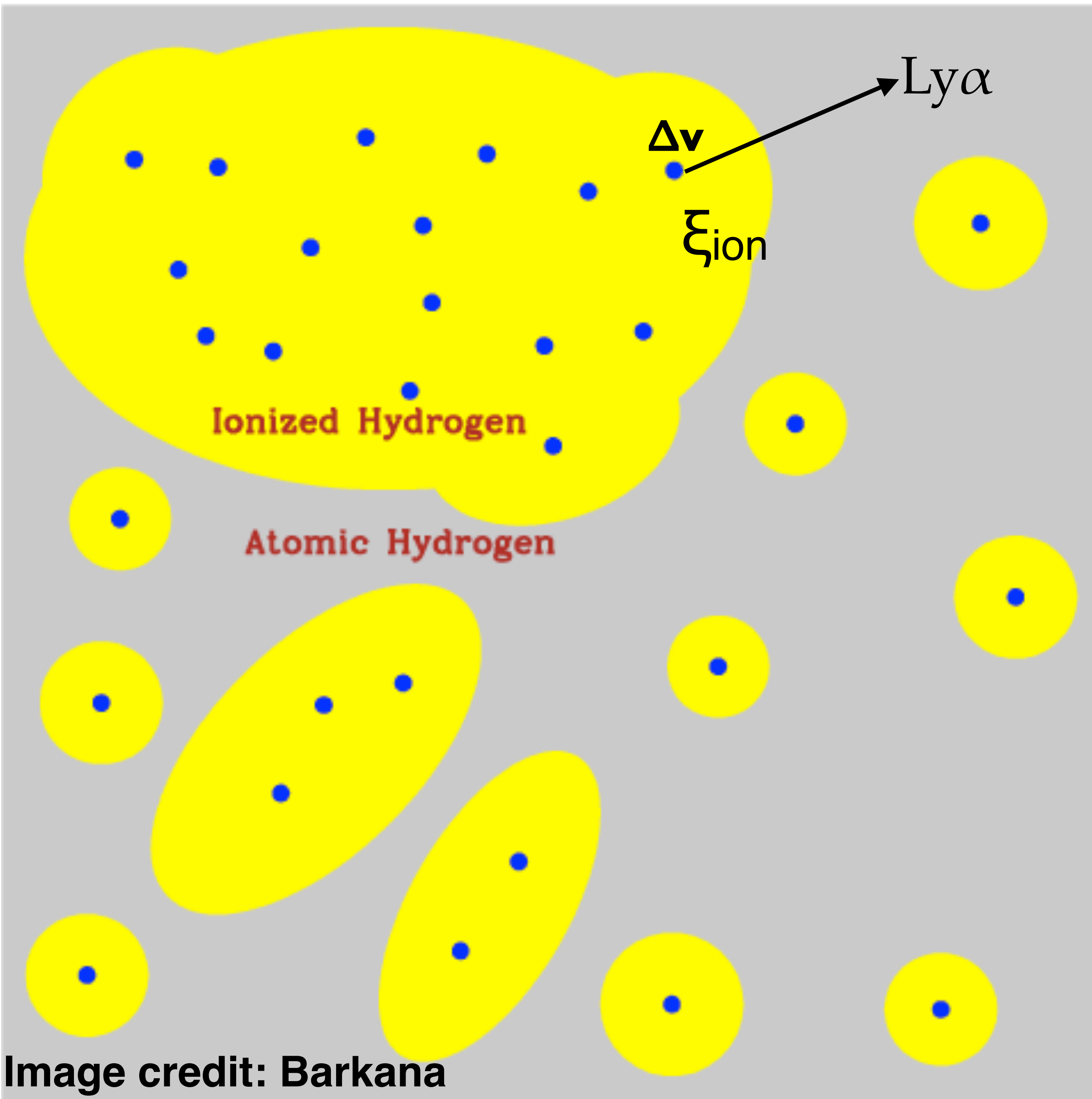
- Lyα velocity offsets small (<200 km/s) in low mass galaxies.
- Small velocity offsets in dwarf galaxies may lead to stronger IGM attenuation of Lyman-alpha than in systems with large offsets.

Lyman-alpha velocity offsets large in massive galaxies at z>6



- 2/4 Roberts-Borsani+16 z>7 LAEs have systemic redshift measurements.
- Ly**α** velocity offsets (and FWHM) much larger in these massive galaxies.
- Enhances transmission of Lyman-alpha through IGM.

Factors regulating Lyman-alpha visibility in massive galaxies at z>7



- Massive galaxies trace overdense regions with largest ionized bubbles.
- Extreme radiation fields: large Lyα output and enhanced transmission.
- Massive galaxies have large Lyman-alpha velocity offsets at z>7, boosting transmission.

Summary and Outlook

- Variations in galaxy properties (radiation field, velocity offsets) play significant role in Lyman-alpha visibility at z>7, and must be controlled for in inferences of X_{HI} .

- Rest-UV spectroscopy is already providing improved understanding of systematics (velocity offsets, LyC production rate) which are being included in inferences of X_{HI} (i.e., Mason+17).

- JWST will not only provide Lyα EW distributions at z>7, but it will deliver constraints on ξ_{ion} and Δv_{Lya}, improving mapping between Lyα and X_{HI}.