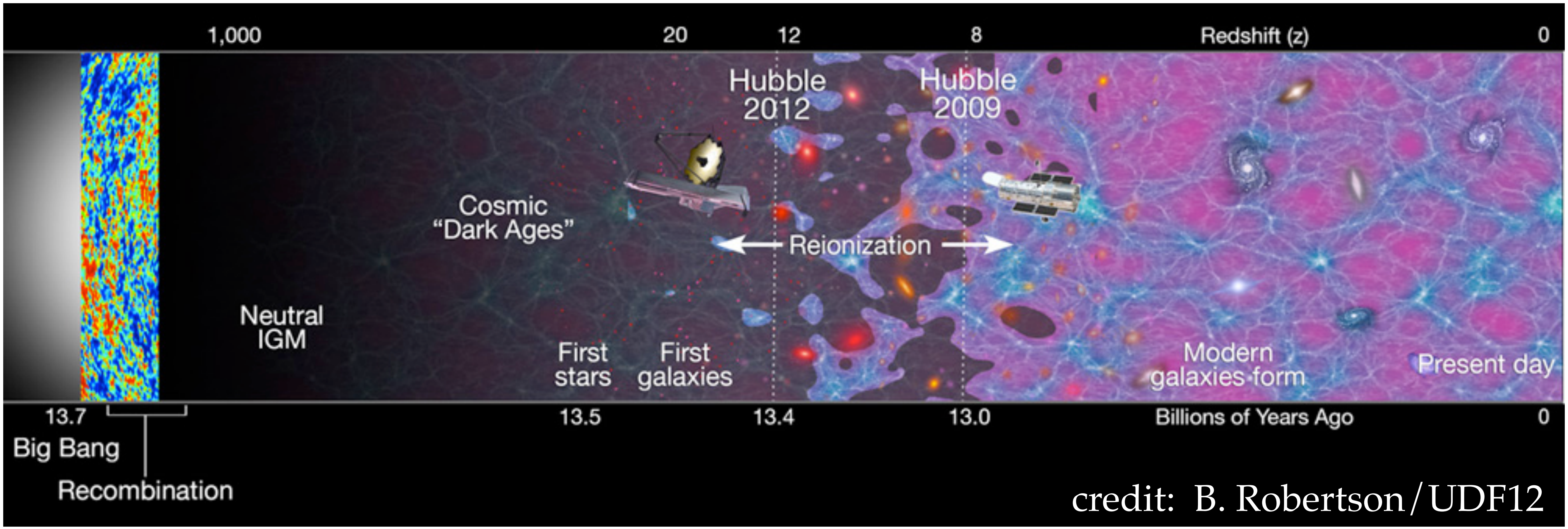
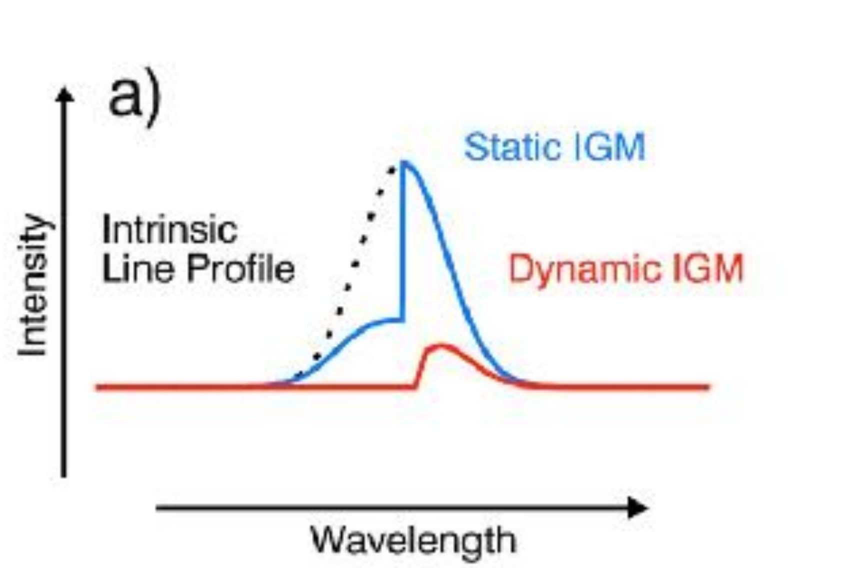
Spectroscopy of Galaxies in the Reionization Era



Dan Stark (University of Arizona)

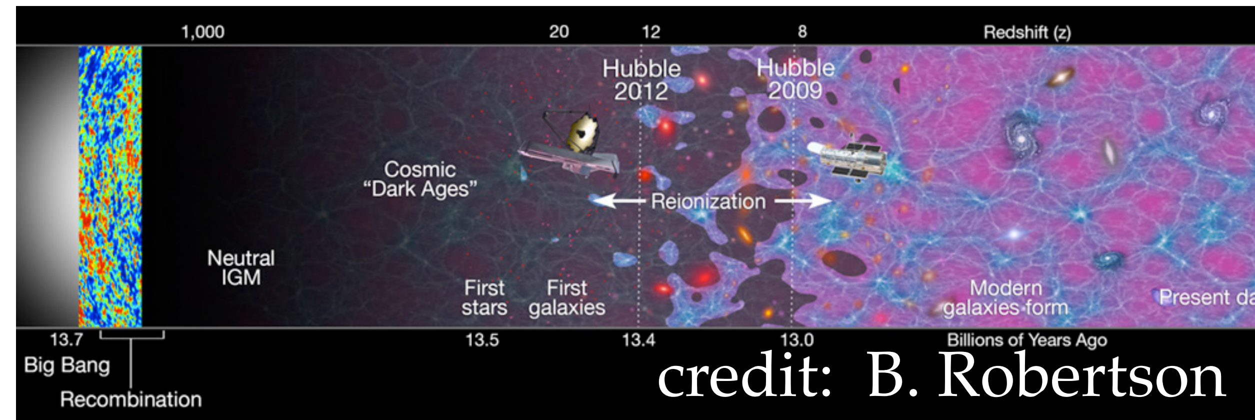
with Ramesh Mainali, Peter Senchyna, Mengtao Tang (Arizona),
Stéphane Charlot (IAP), Jacopo Chevallard (ESA), Alba Vidal Garcia (IAP), Anna Feltre (CRAL/Lyon)
Richard Ellis (ESO/UCL), Nicolas LaPorte (UCL), Brant Robertson (UCSC)

Lyα Emission in z>7 Galaxies

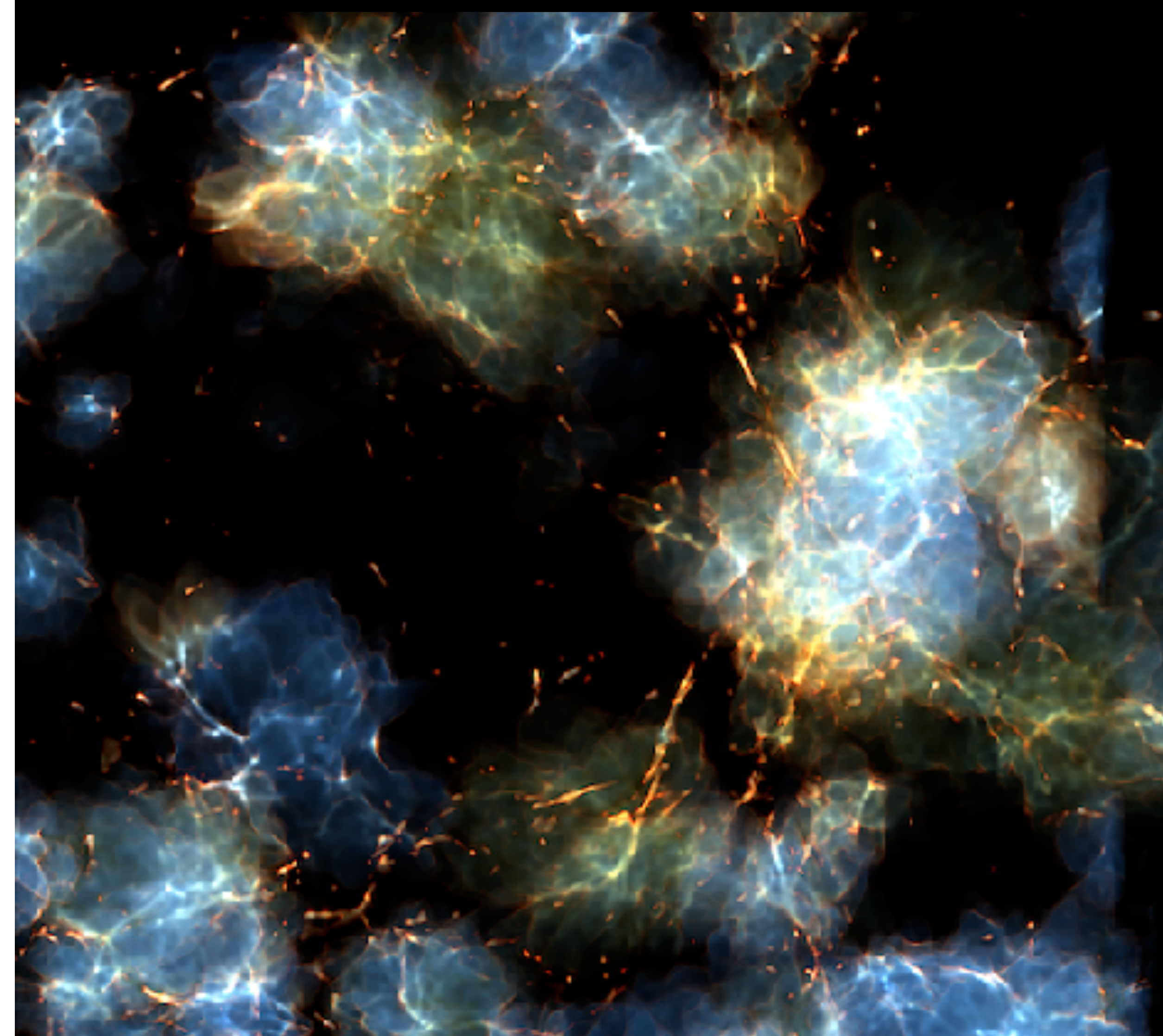


Partially neutral IGM will scatter Lyα from early galaxies.

Expect Lyα emission to be less common in UV-selected sample of galaxies in reionization era, providing probe of ionization state of IGM.



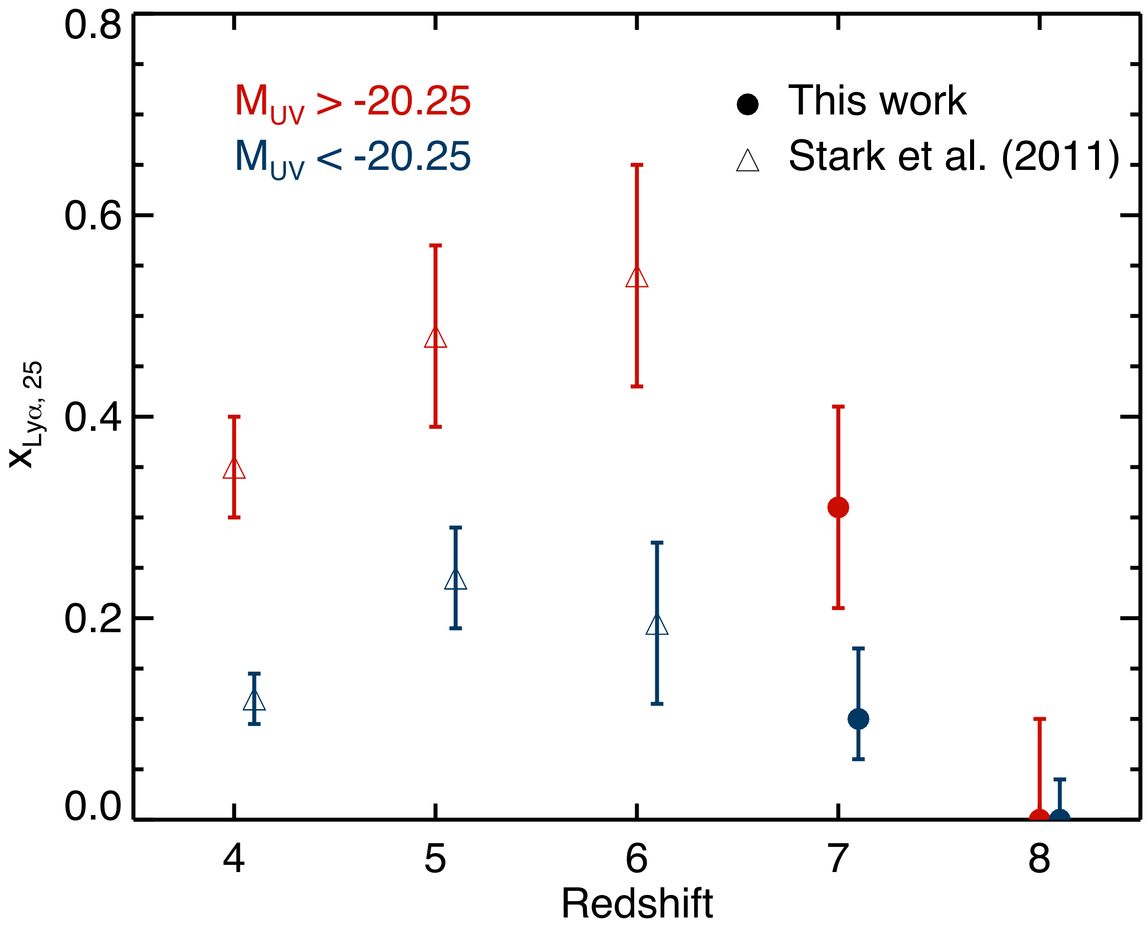
credit: B. Robertson



credit: Wise, Cen, and Abel

Lyman-alpha Disappearance at z~7-8

Schenker et al. 2014

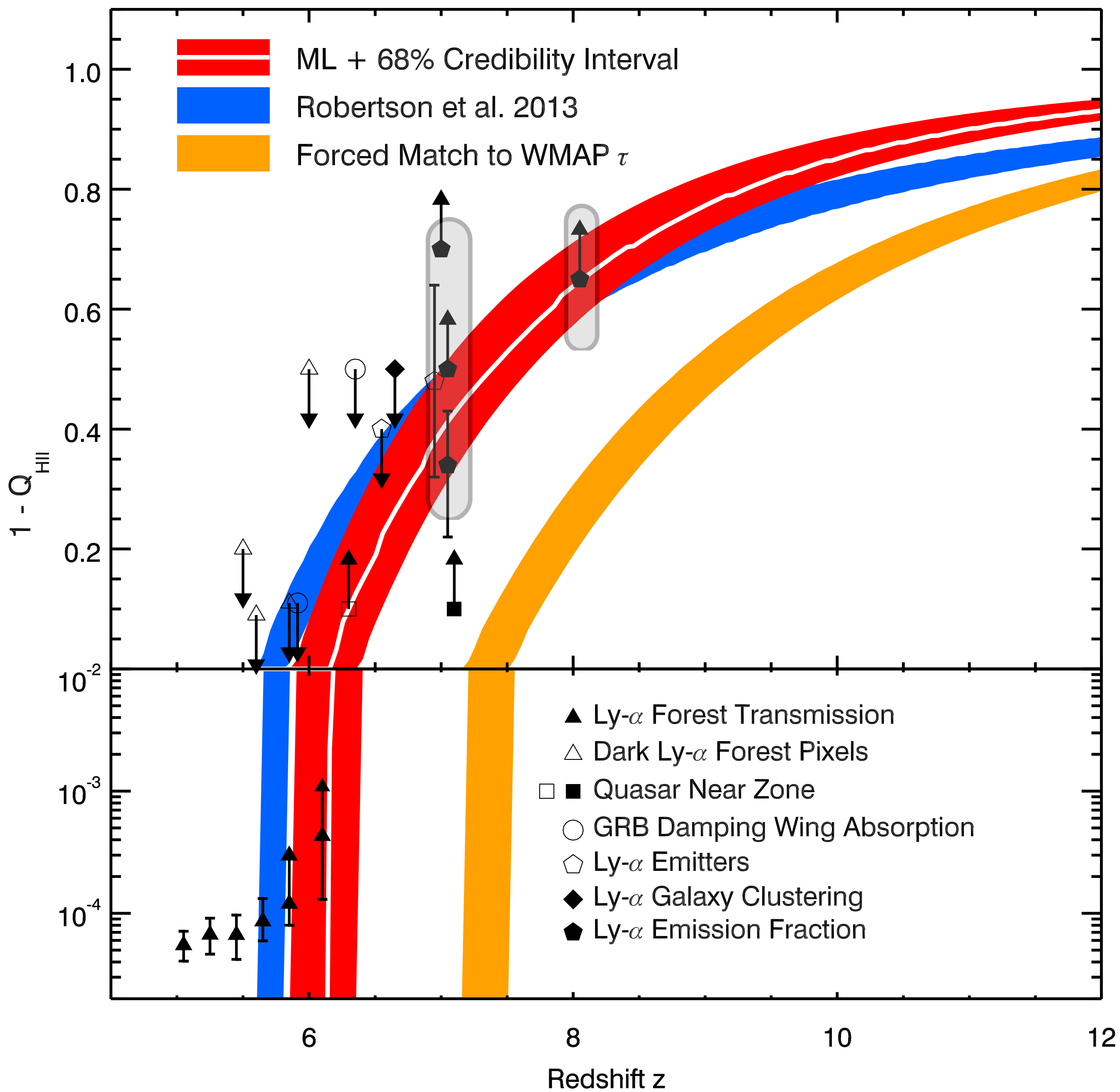


- Lyman-alpha emission is much less common among z>7 star forming galaxies than it is at z~5-6.
- Lyman-alpha emitter fractions are ~10% in UV-bright galaxies at z~7.

(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

Robertson et al. 2015

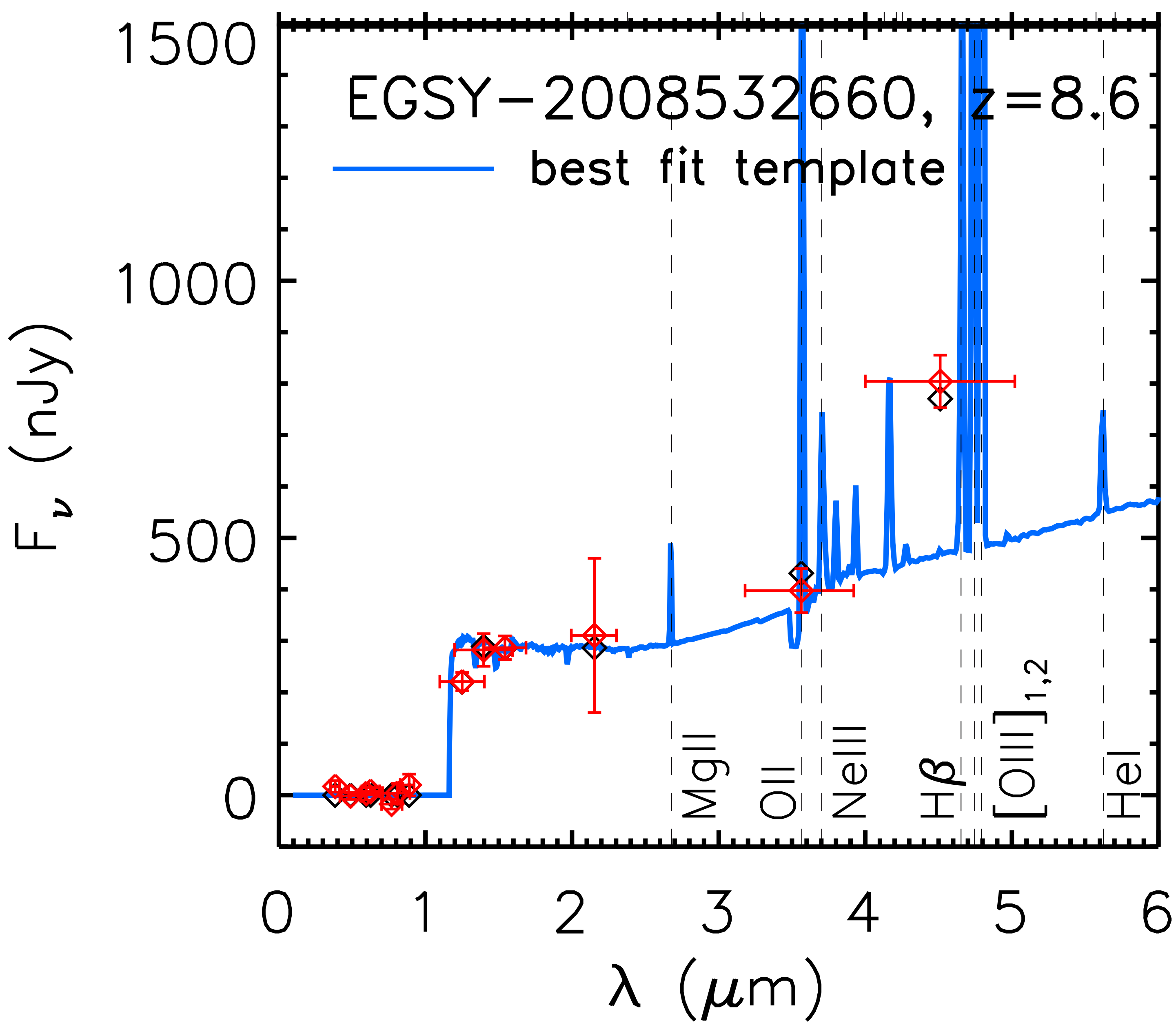


- Most models suggest neutral hydrogen must fill nearly 60% of z~7 IGM to explain Lyman-alpha results.

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

Sample of Massive z~7-9 Galaxies with Extremely Large EW Optical Line Emission

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



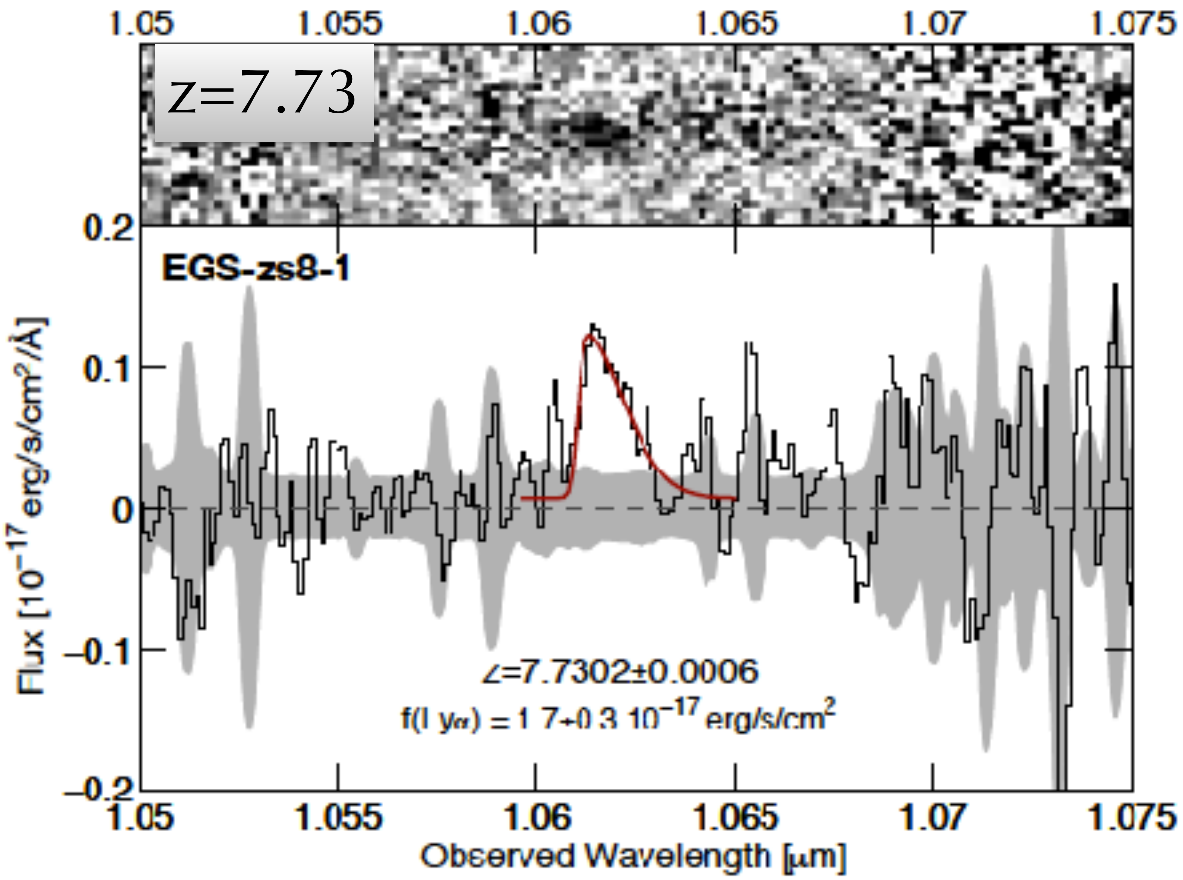
Four very bright (H~25) z~7-8 galaxies, stellar masses of 10^{10} $M_\odot$.

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

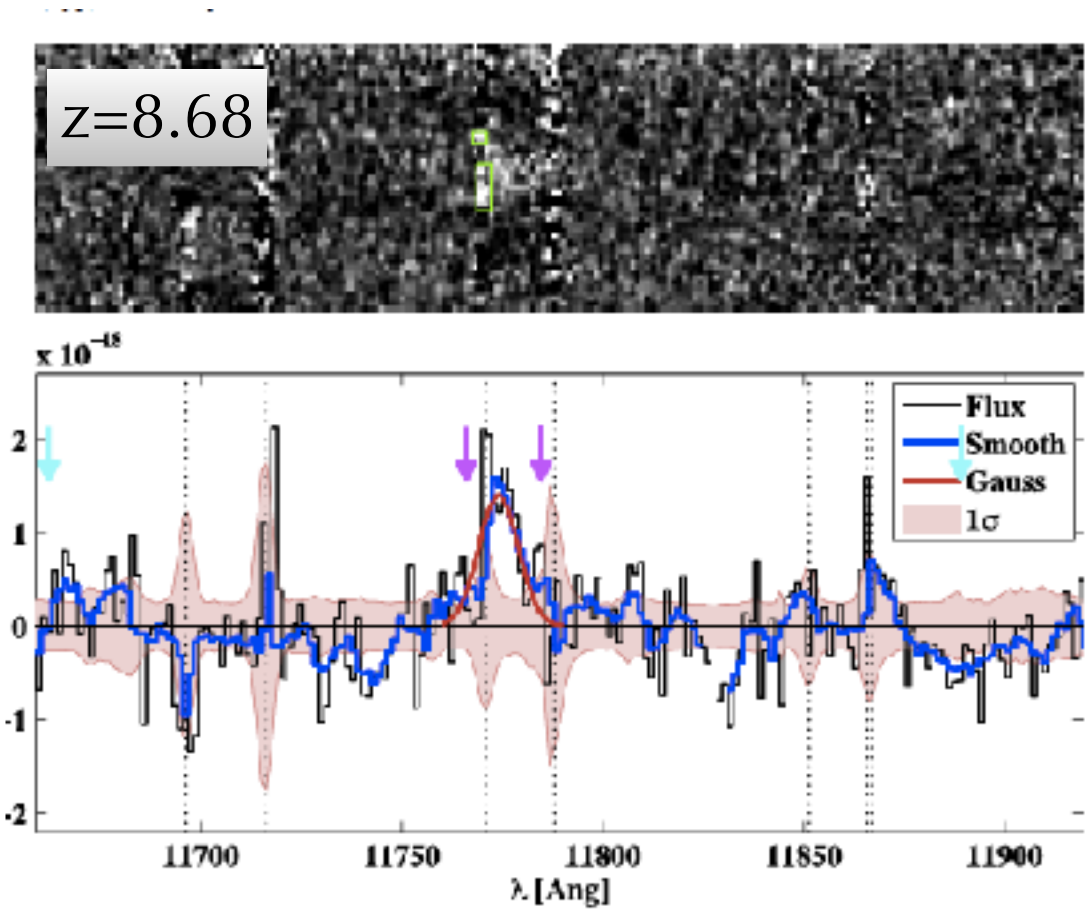
Very young stellar populations, with large ionizing output per unit 1500Å luminosity.

Discovery of Lyman-alpha at z~8-9

Oesch+15



Zitrin+15

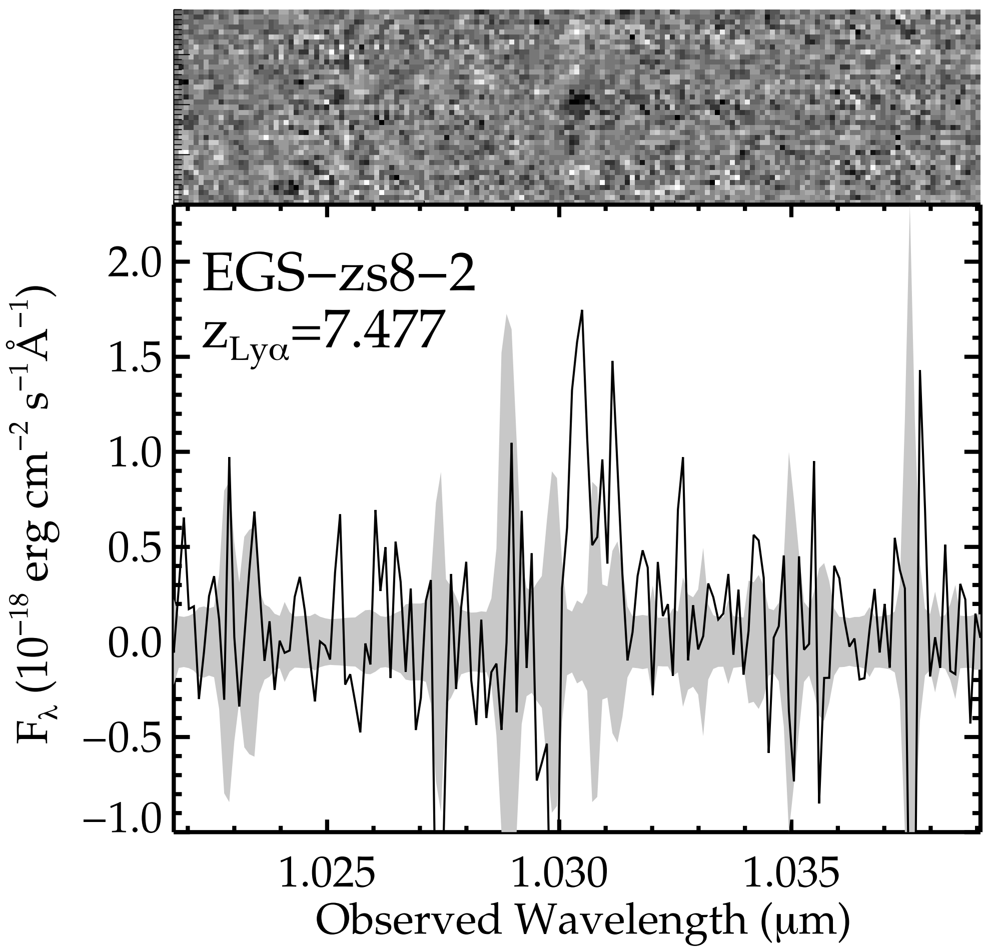


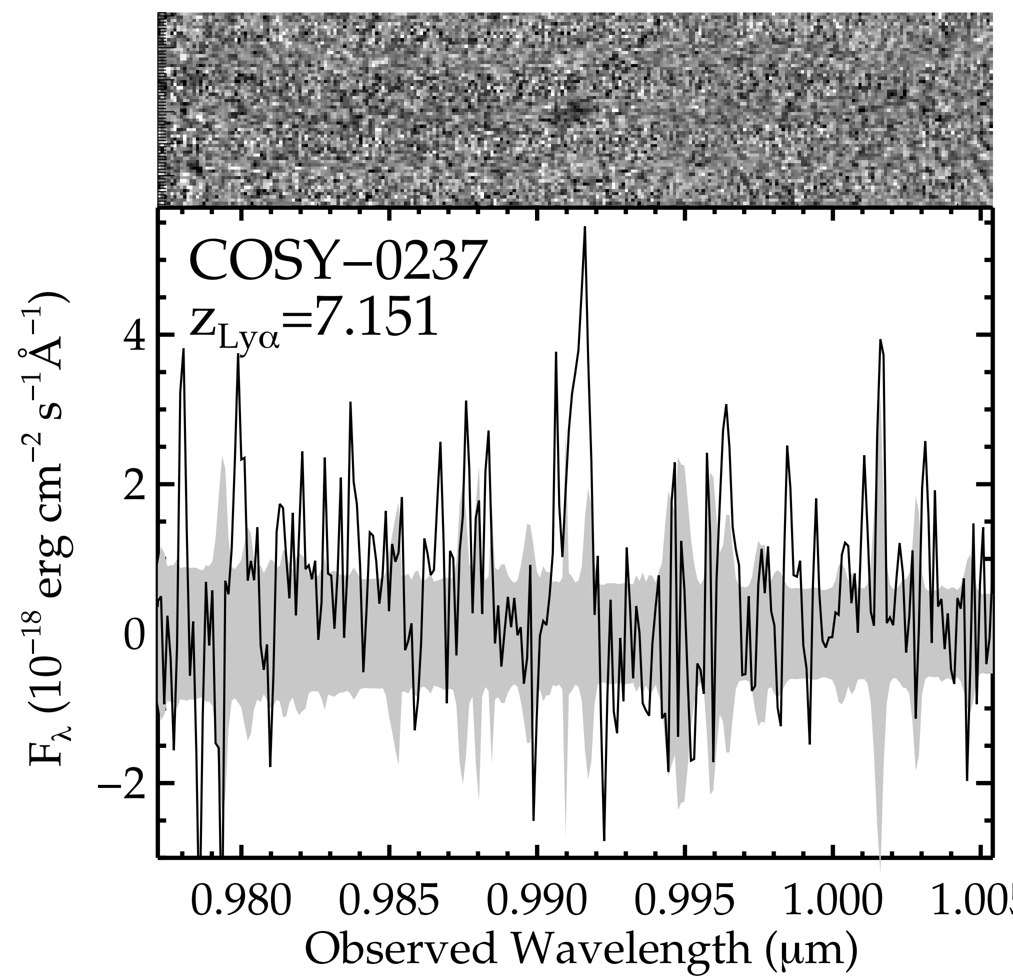
First two galaxies from this sample revealed record breaking Lyman-alpha detections:

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

100% Lyman-alpha fraction in Luminous [OIII]+Hβ Emitters at z~7-9

Stark+17





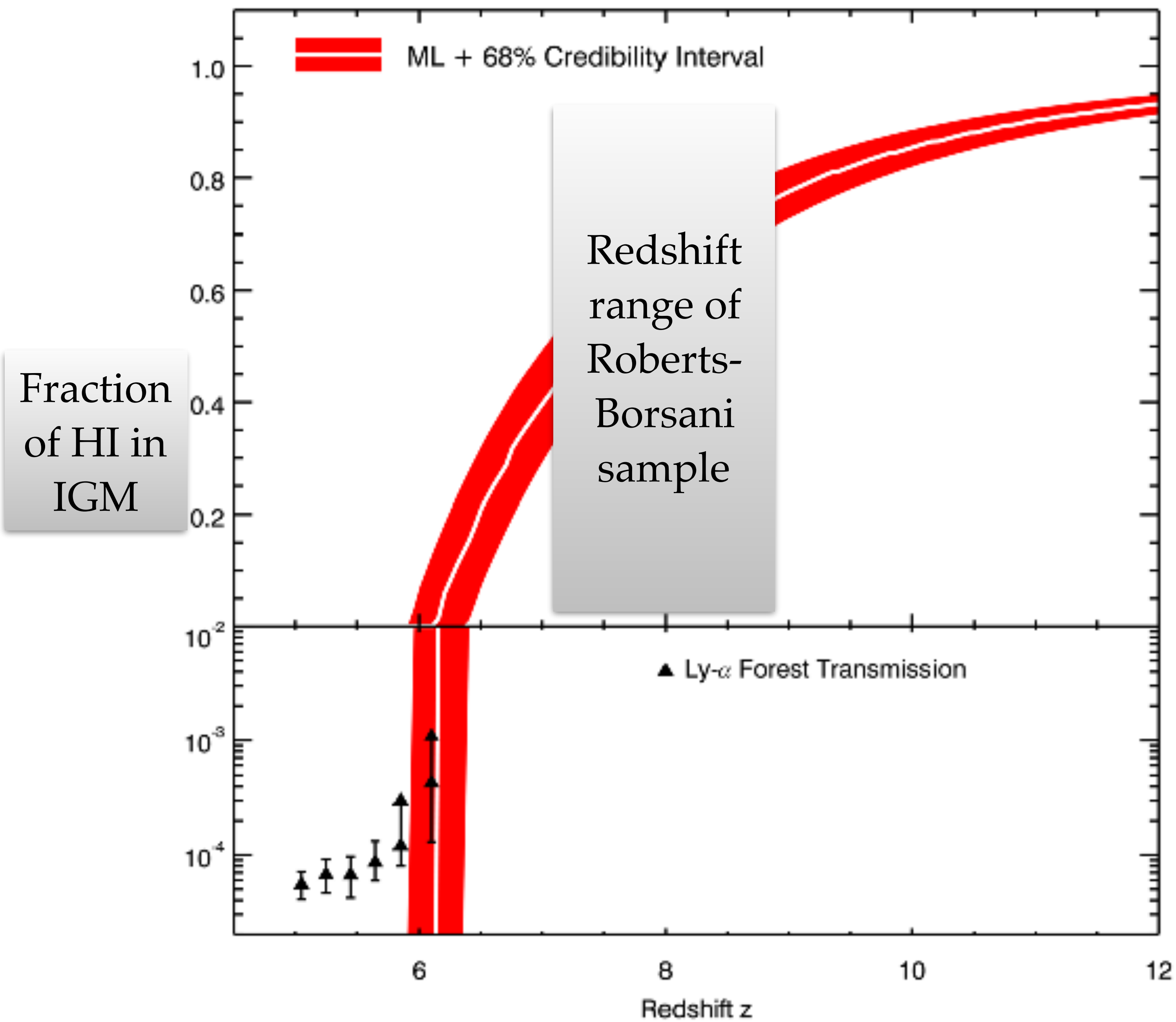
Next two objects also showed Lyman-alpha emission:

- 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?

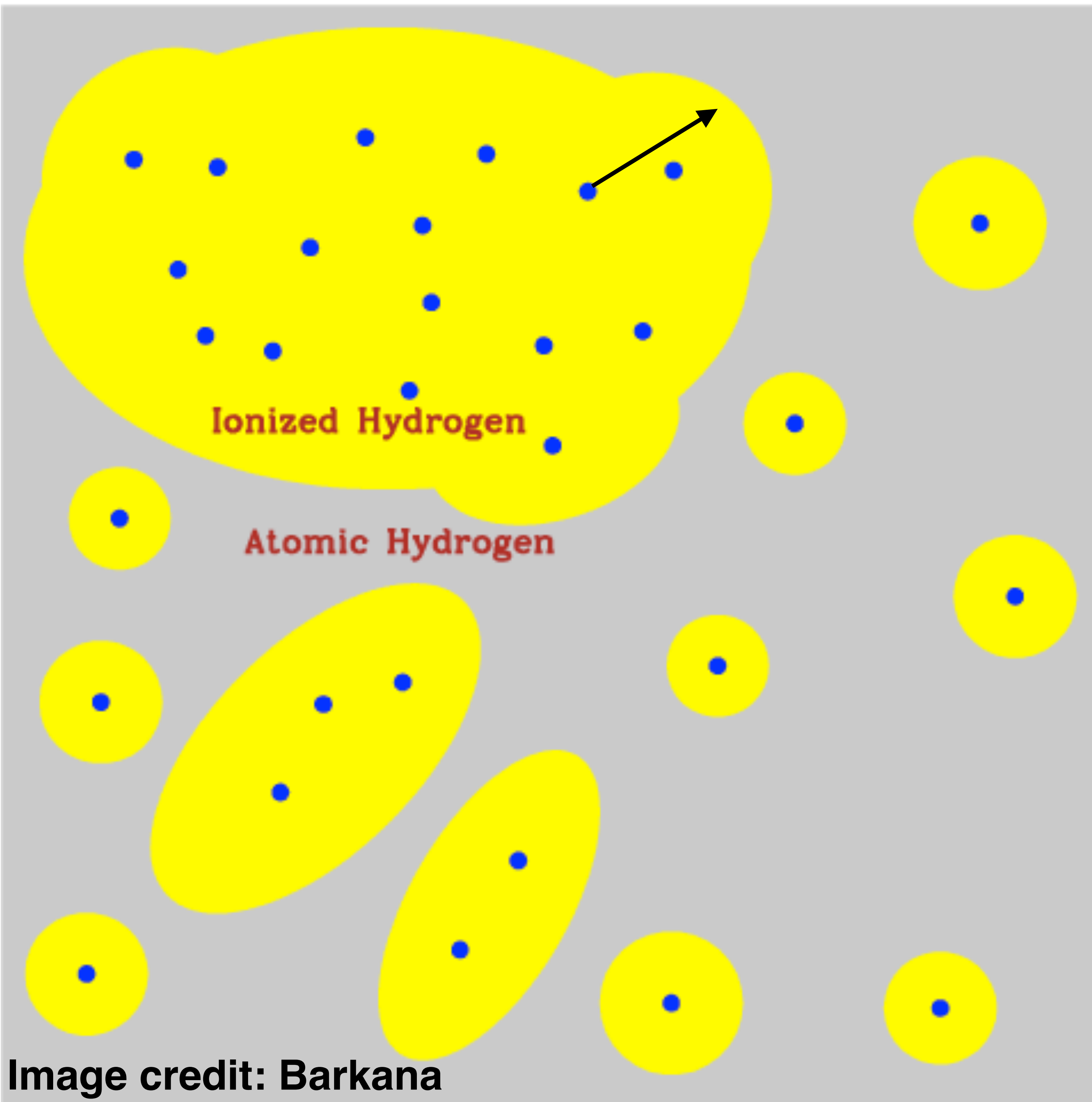
Robertson et al. 2015



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?

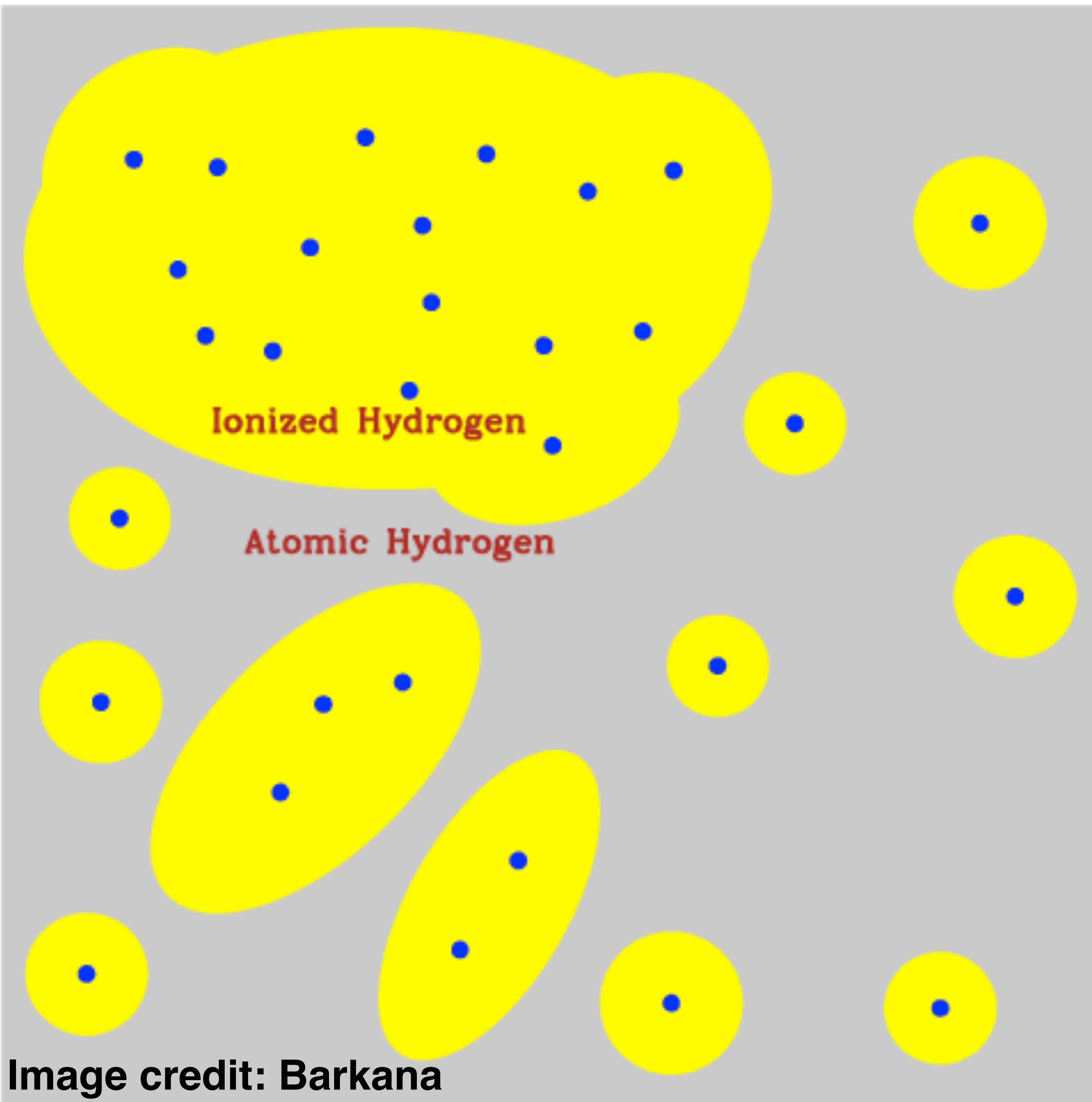
Explanation 1: Accelerated Reionization around the Most Luminous Galaxies?



Trace overdense regions that ionize their surroundings early?

- Two of the systems lie 9 Mpc from one another, perhaps in same ionized bubble?

Explanation 2: Rare galaxies with extreme radiation fields at z>7?

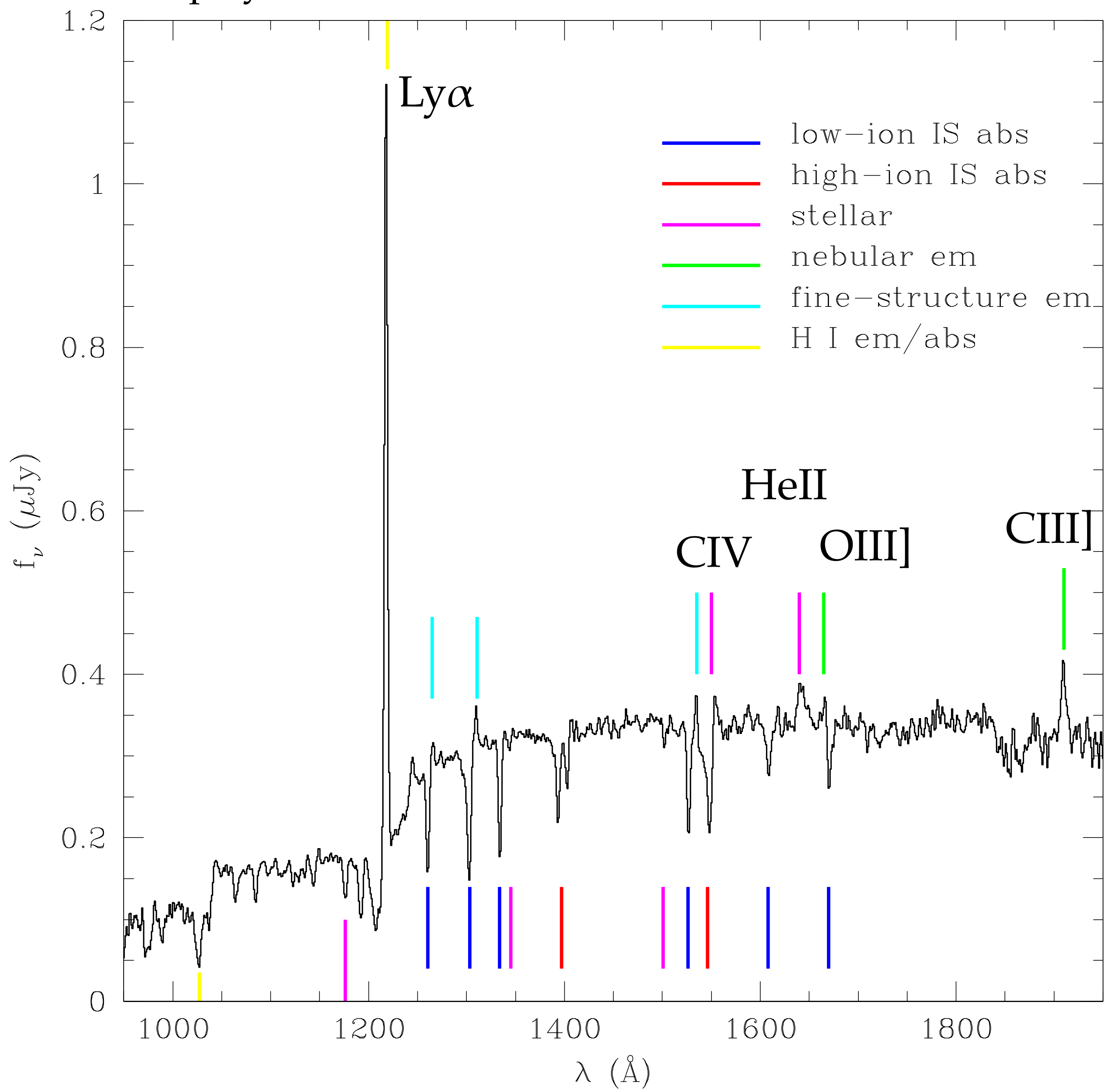


Lyman-alpha emitters trace systems with hard ionizing spectra (AGN, very hot metal poor stars)?

- Enhanced production rate of Lyman continuum photons.
- Efficiently ionize surrounding HI.

Rest-frame UV Nebular Emission Can Reveal Extreme Radiation Fields

Shapley et al. 2003



z~3 composite of ~900 LBGs

$W_{CIII]} = 1.7$ Å

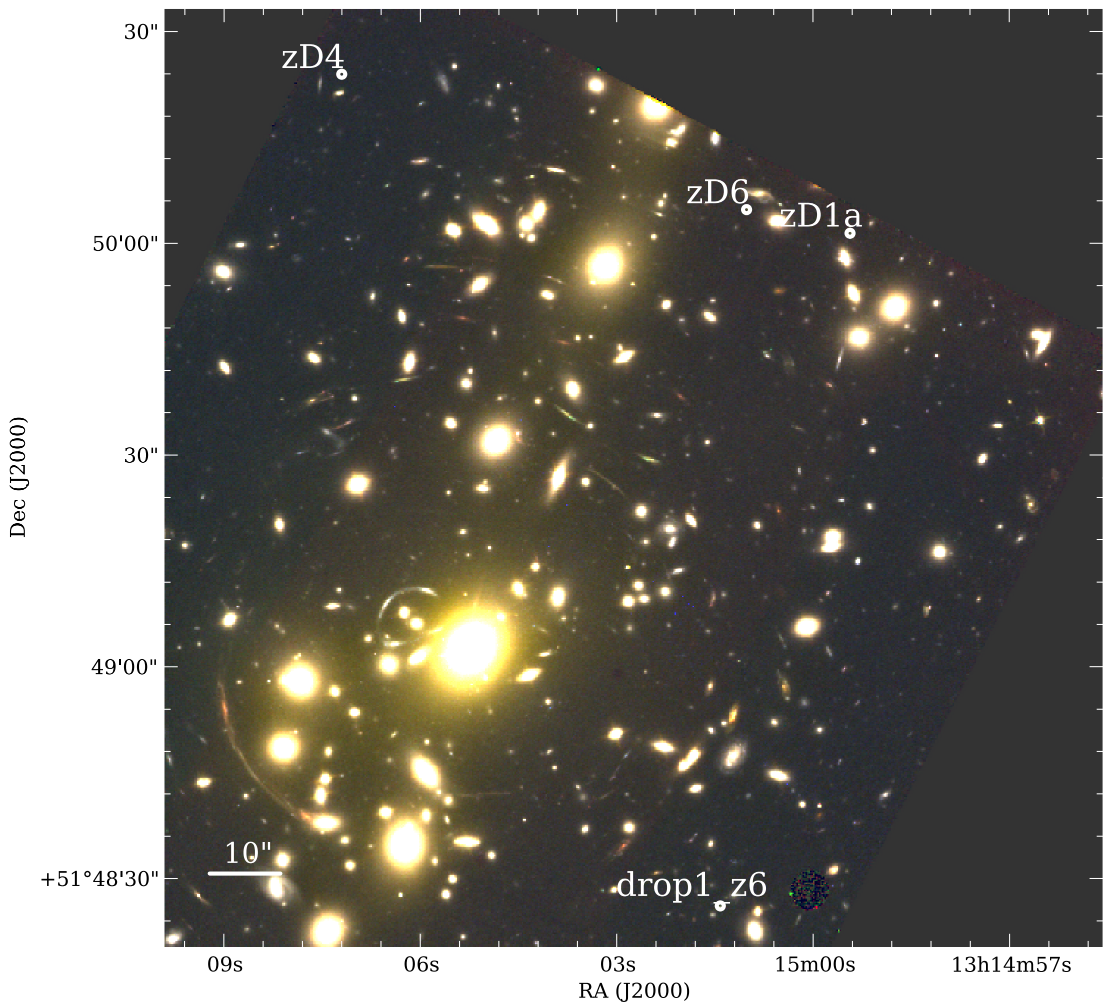
$W_{HeII} = 1.3$ Å

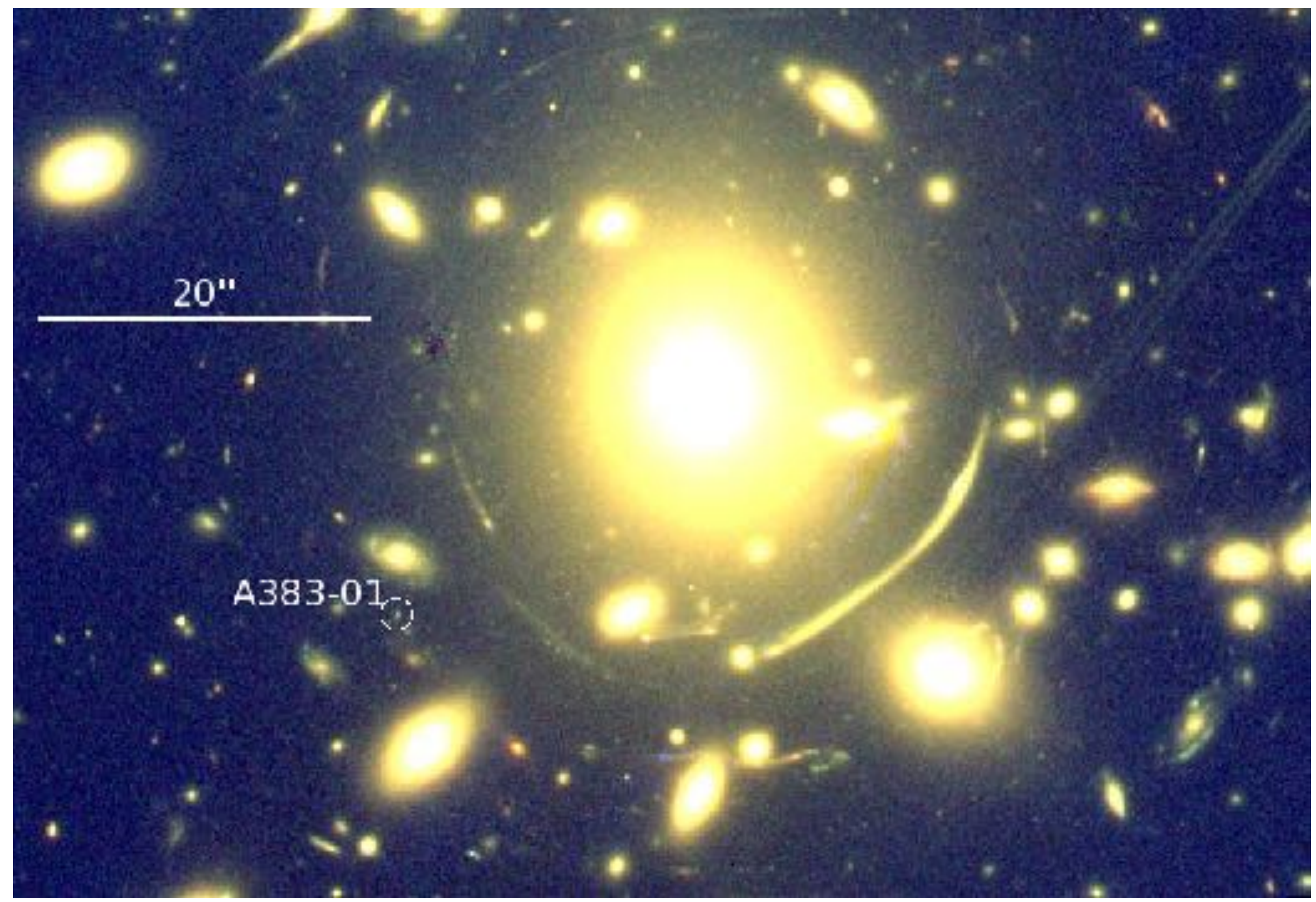
$W_{OIII]\lambda1661+1666} = 0.2$ Å

- If galaxies similar to z~3, they will be undetectable (≲ 7×10^{-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, Laporte+17

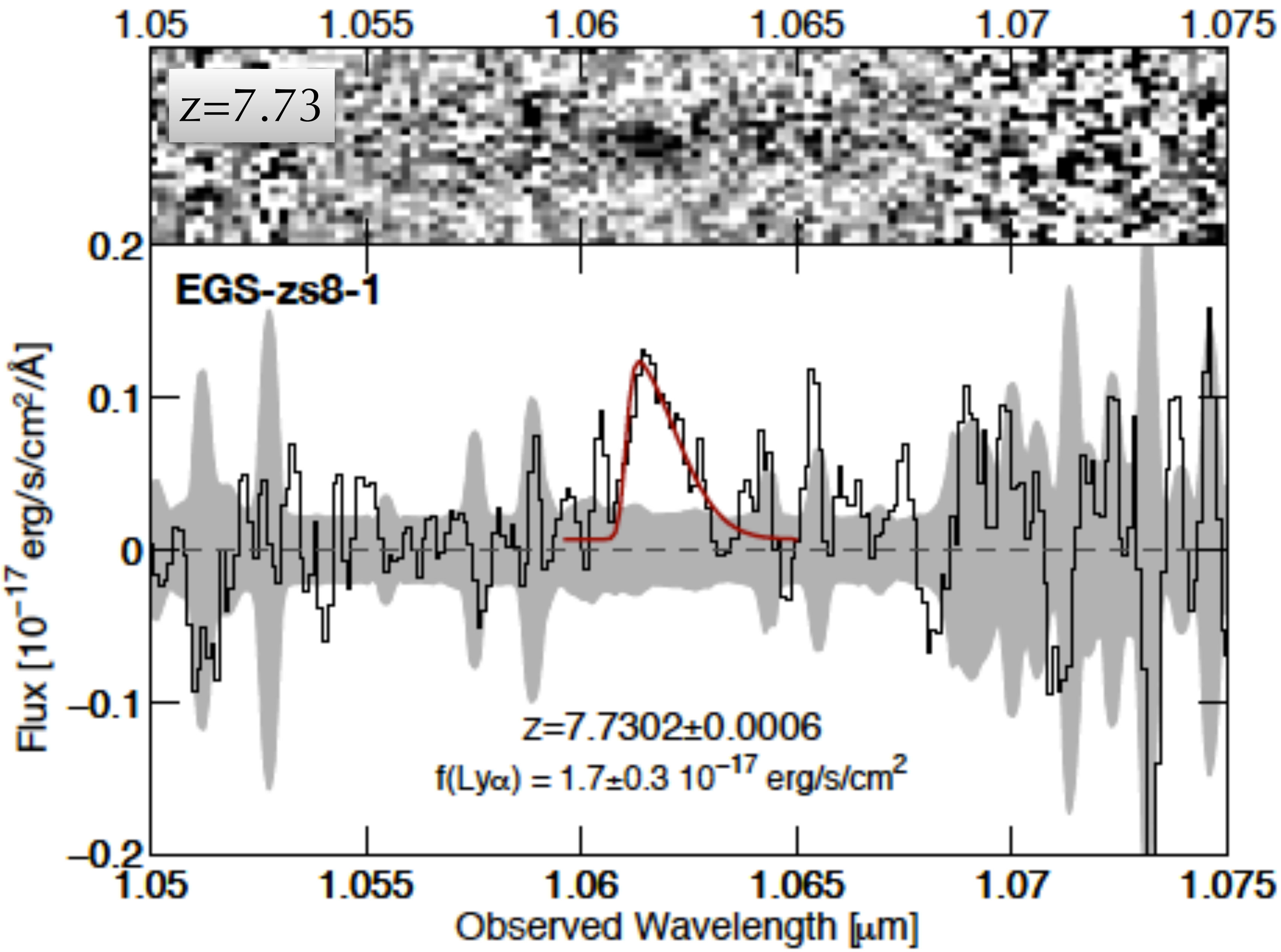




- Measure strength of far-UV lines in bright (24<H<26) galaxies at z~6-9.
- Test for presence of extreme radiation fields in z>6 systems.

Massive Lyman-alpha Emitter at z=7.73

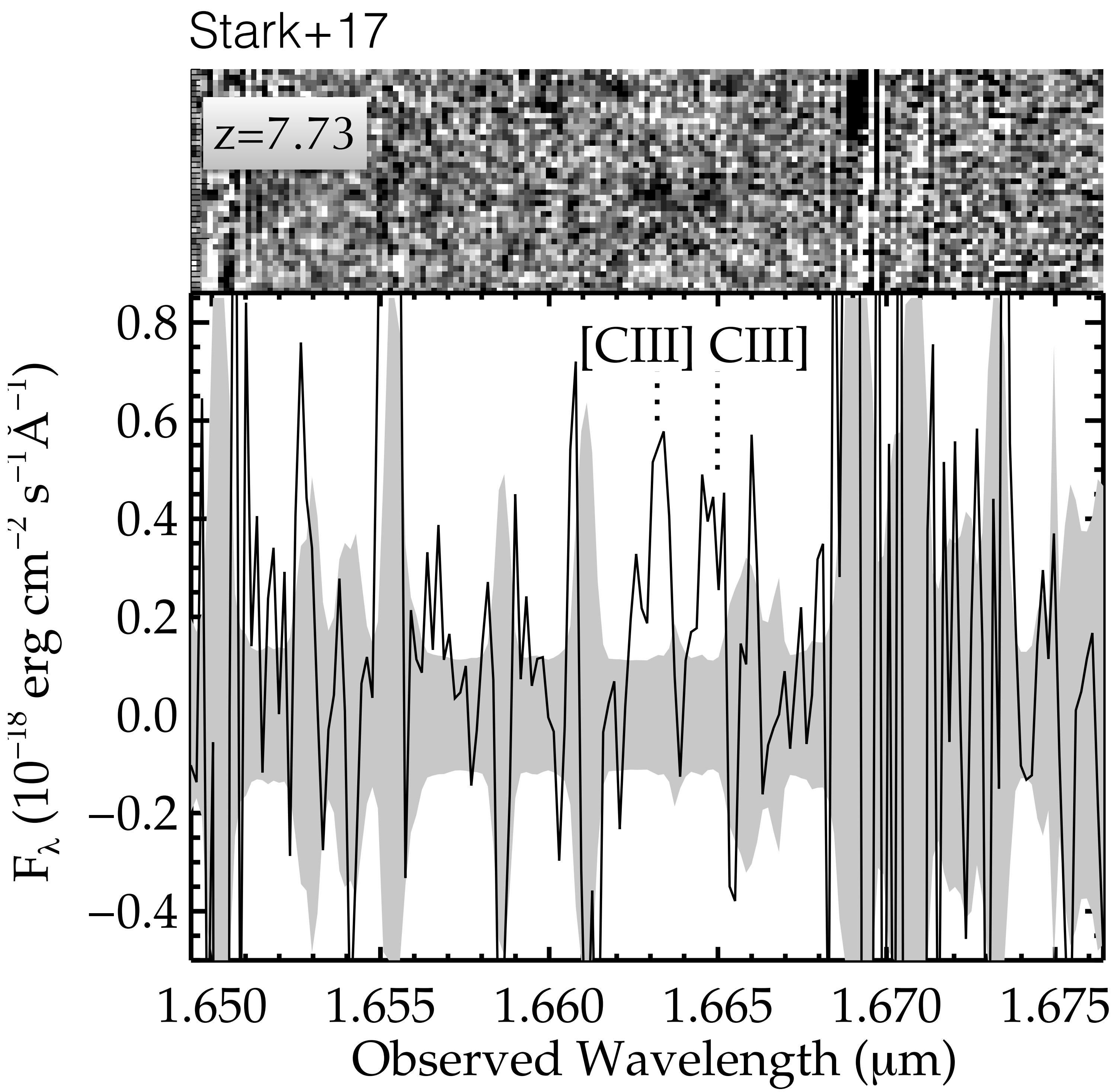
Oesch+15



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~8



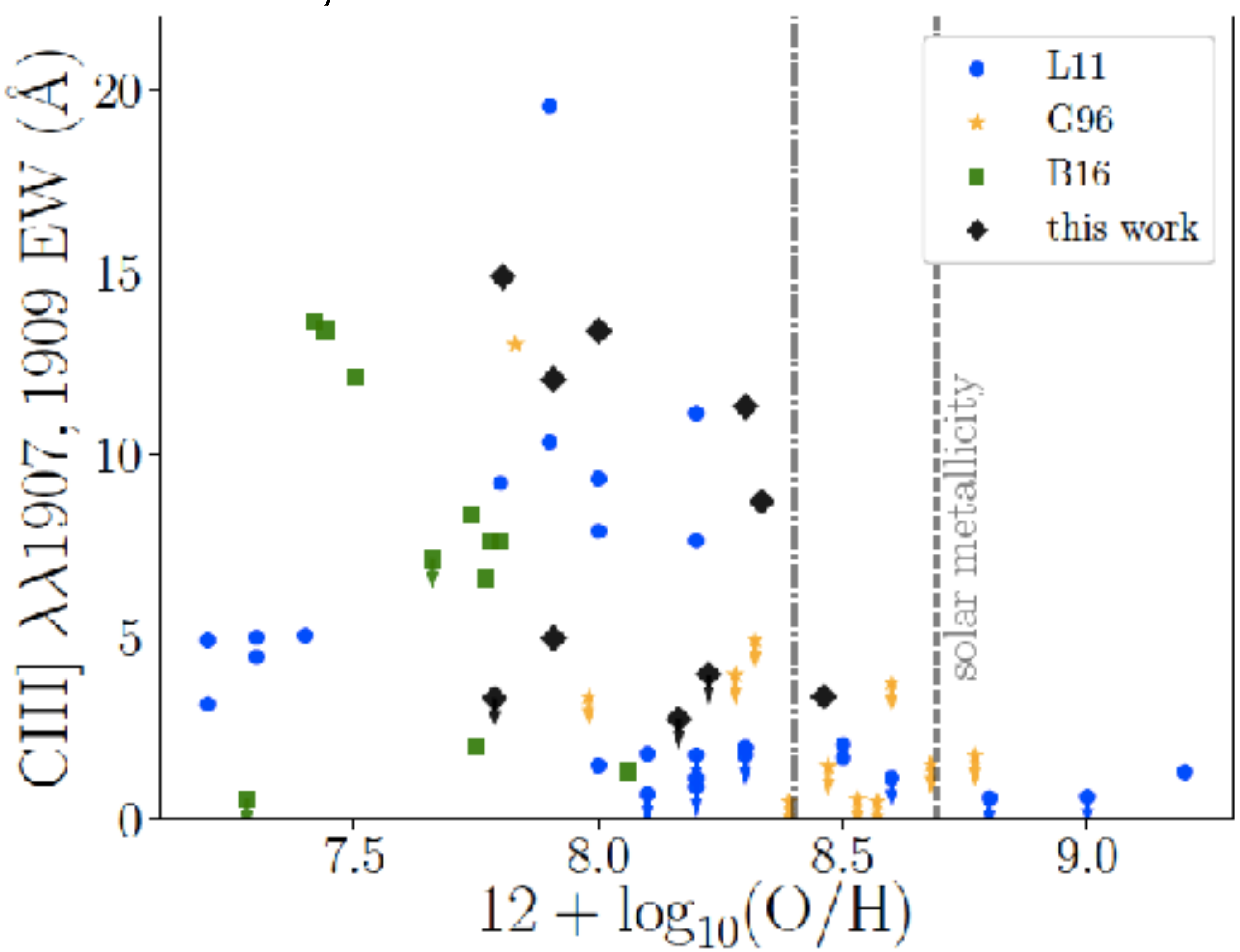
[CIII]1907,CIII]1909 detected in 3.5 hrs with MOSFIRE.

Total CIII] doublet equivalent width of 22Å.

- Among the largest robust CIII] EW detected at any redshift.
- ~10x greater EW than in composite of z~1-3 galaxies (Shapley+03, Du+2016).

Moderately low metallicity stars+gas in local CIII] emitters

Senchyna+17



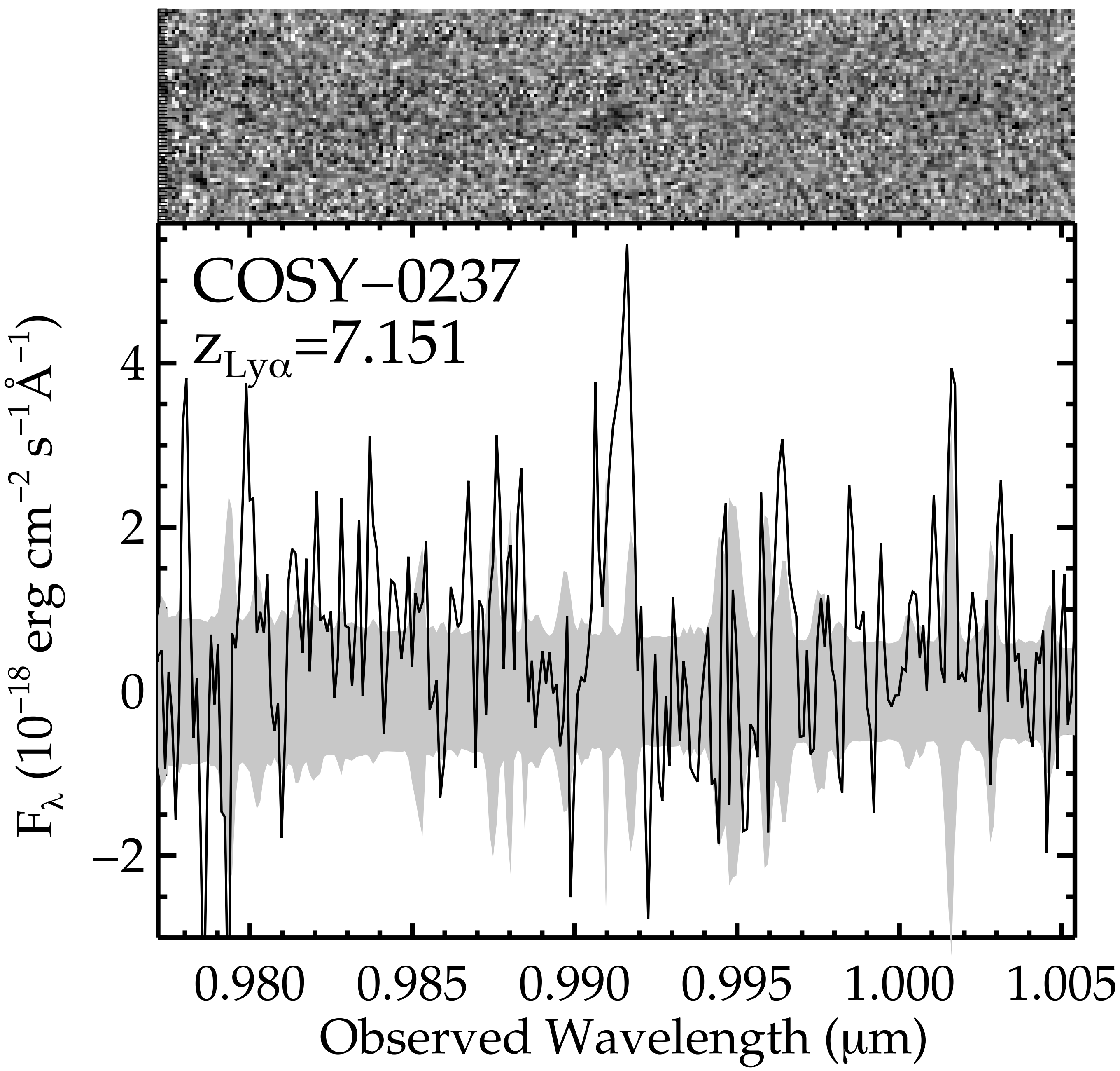
Local samples indicate CIII] requires moderately metallicities to reach large EW (10-20% $Z_{\odot}$)

Photoionization models suggest the z=7.73 galaxy has metallicity of ~10% $Z_{\odot}$, possibly AGN(?).

Extreme radiation field present, this system very different from similarly massive systems at lower redshift.

Massive z=7.154 Lyman-alpha Emitter

Stark+17

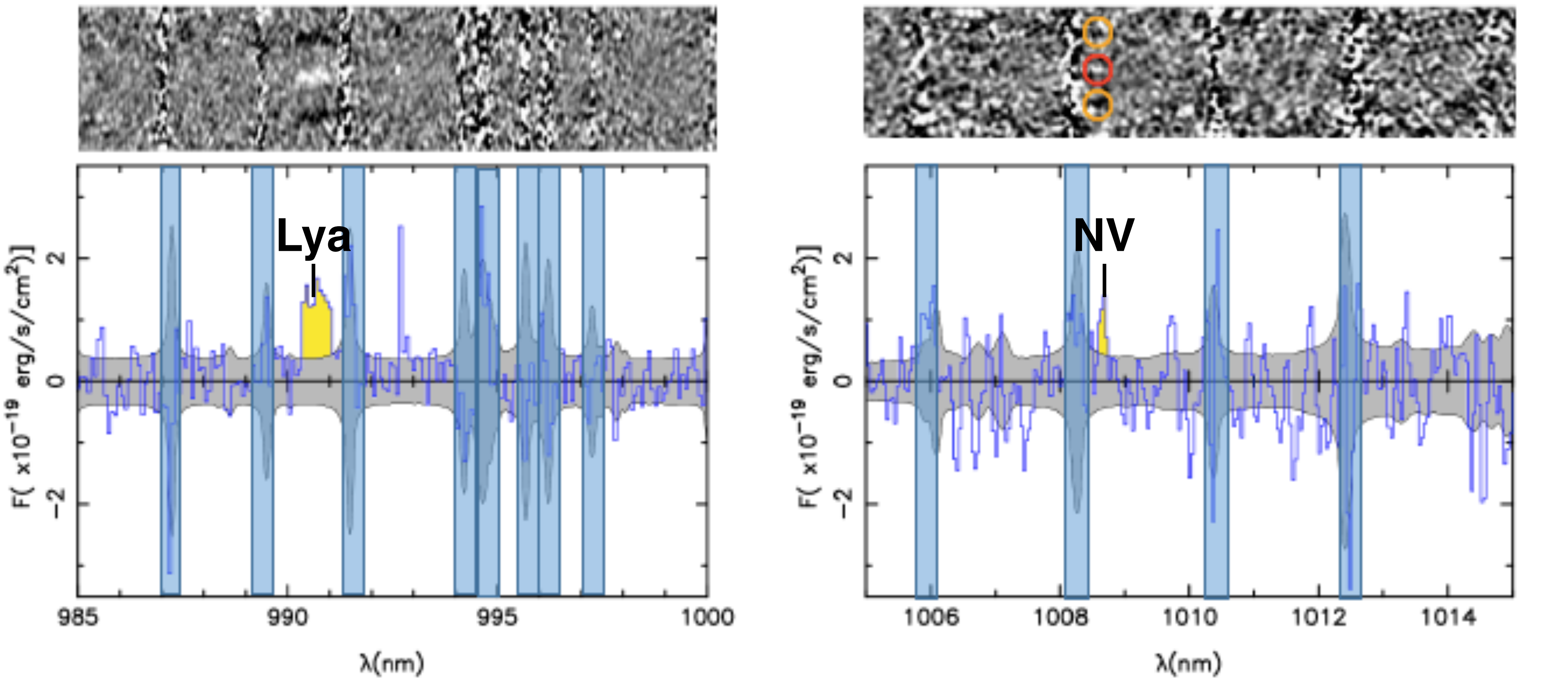


z=7.151 galaxy in COSMOS, confirmed in Stark+17

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

Detection of NV and He II Emission

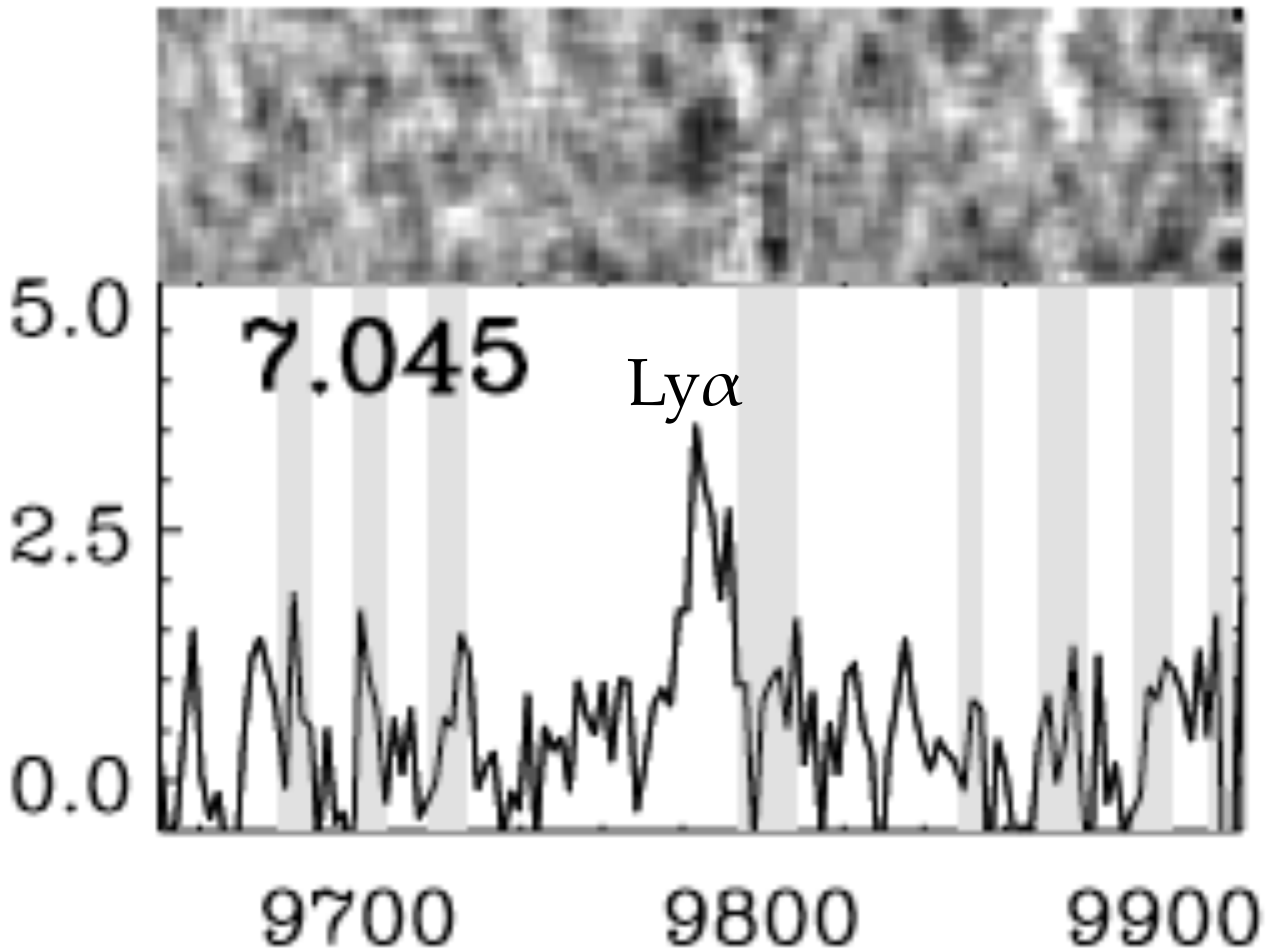
LaPorte +17



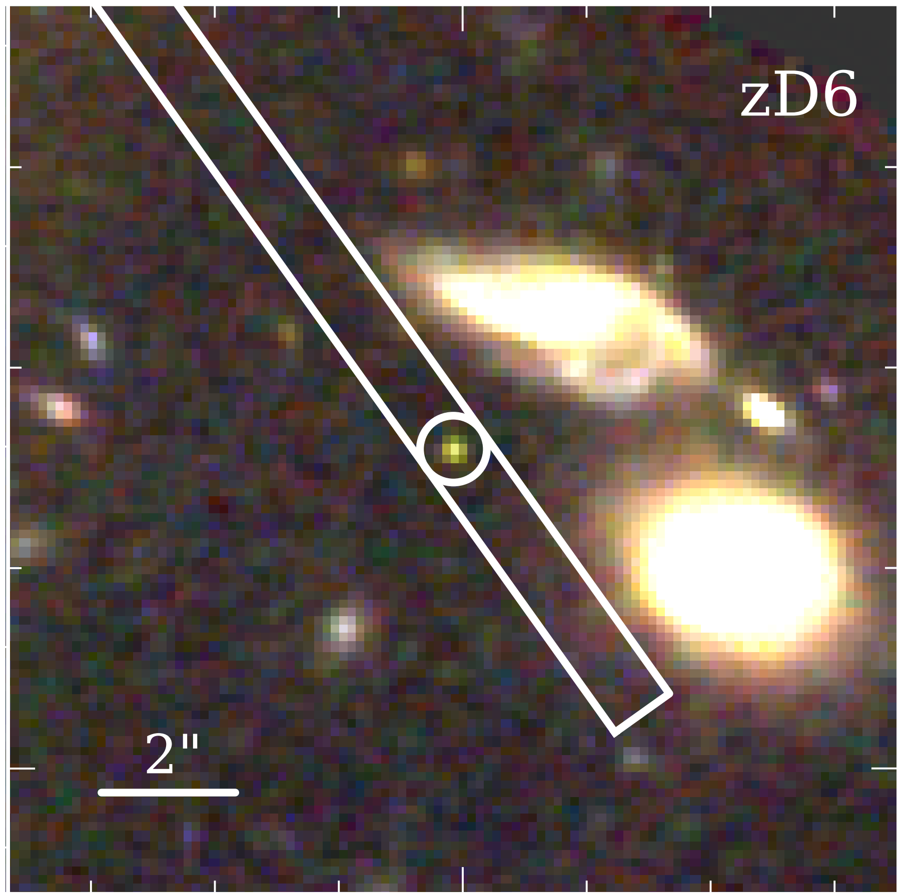
- Nebular NV and He II emission detected in 10 hr X-Shooter exposure. He II emission detected independently with MOSFIRE.
- Line ratios suggest this source powered by AGN.
- More evidence for extreme radiation fields among z>7 LAEs.

Low Luminosity z=7.045 Lyman-alpha Emitter

Schenker+12



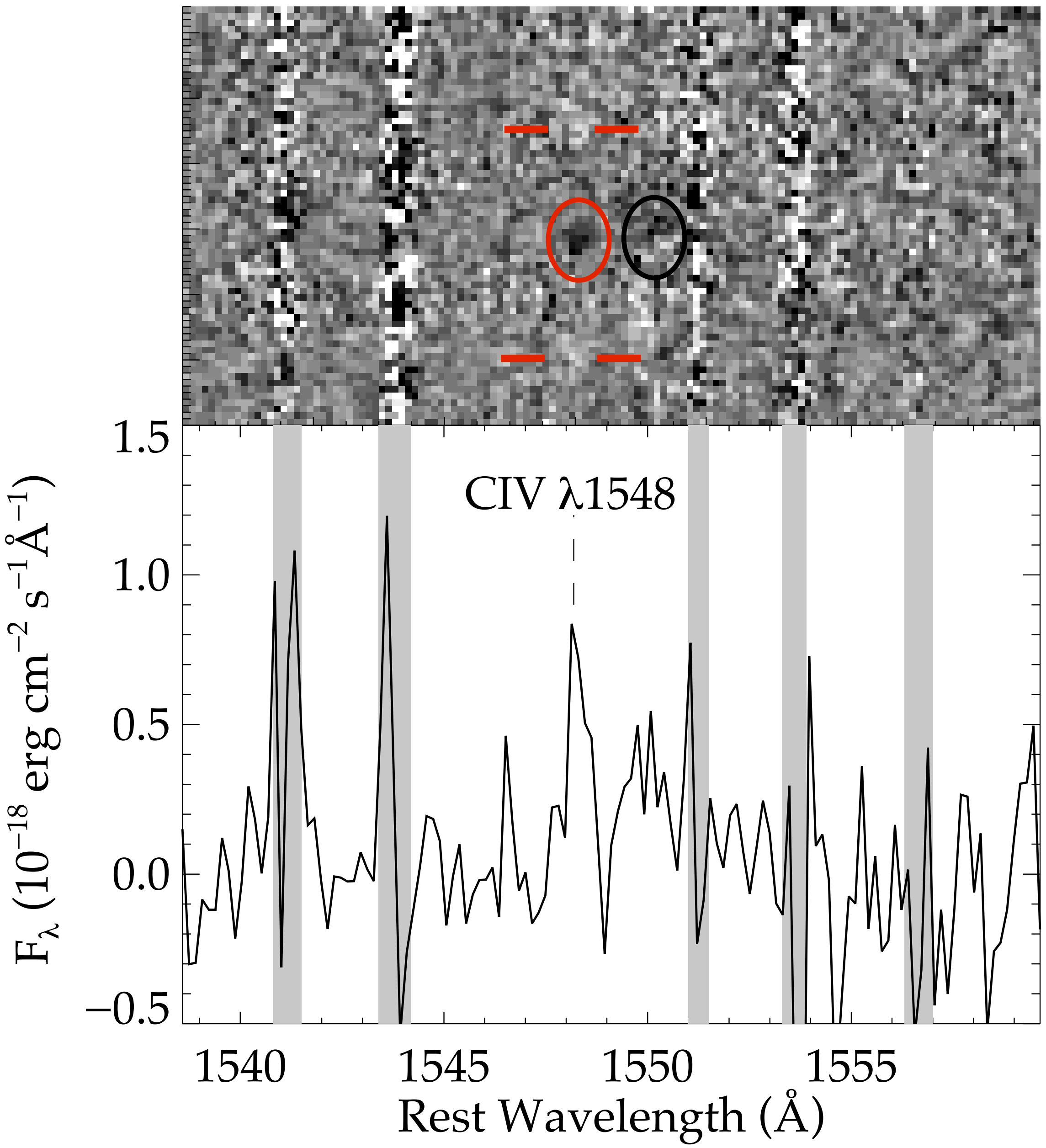
Stark+15b



- H=25.9, z=7.045 galaxy previously confirmed via Lyα (Schenker+12).
- Gravitationally-lensed, low mass Lyman-alpha emitter

Nebular CIV in z=7.045 Galaxy

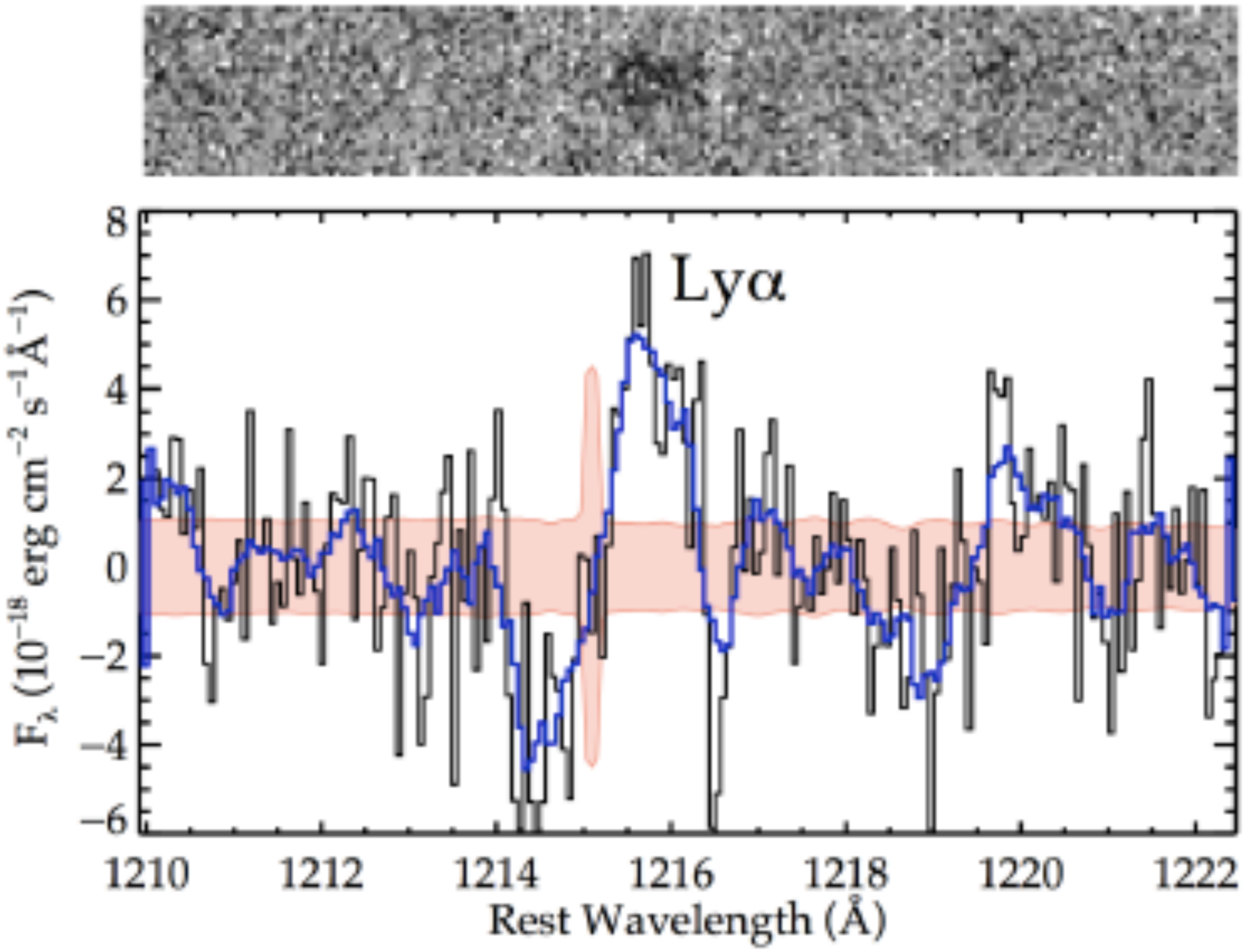
Stark+15b

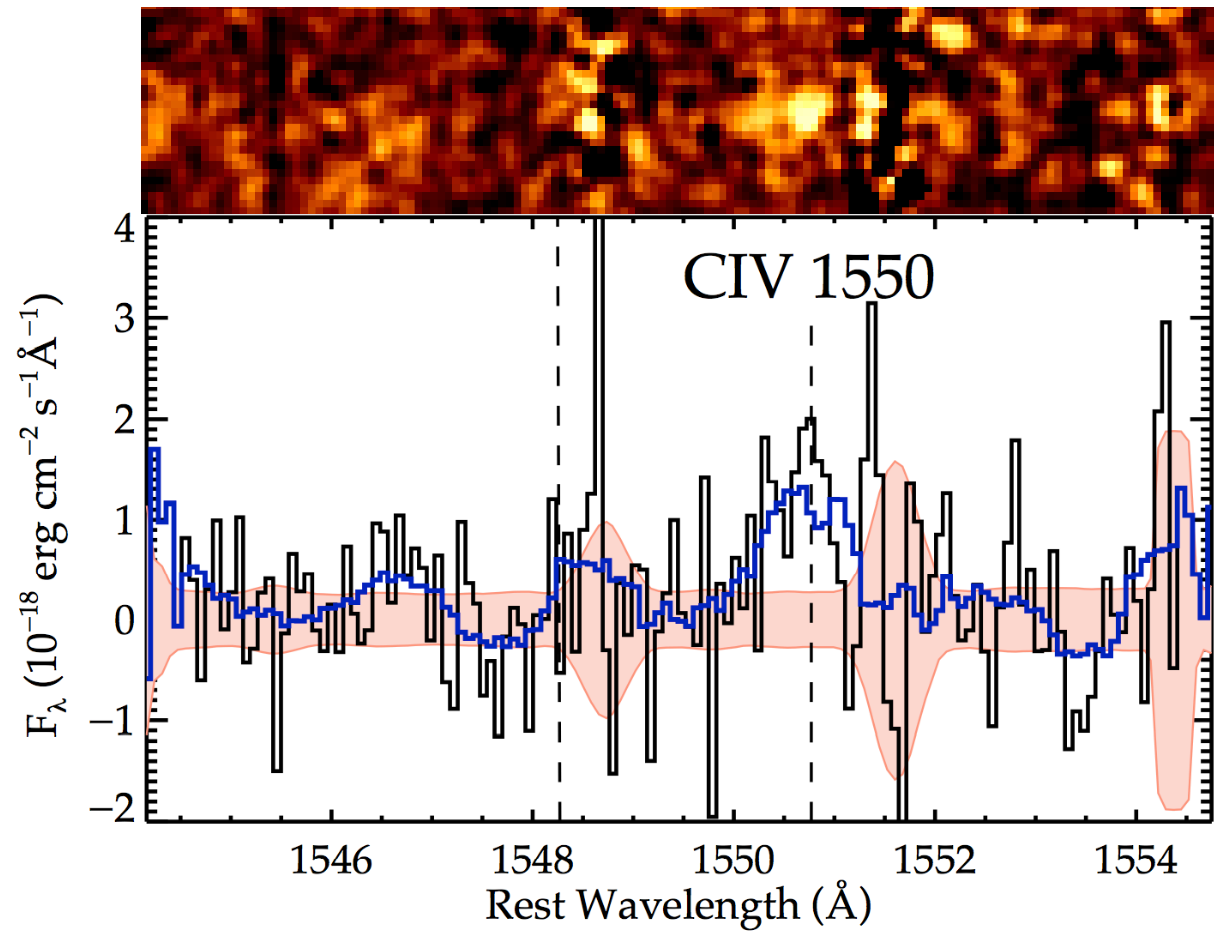


- Nebular CIV detected with rest-frame EW in excess of 20 Å. He II and NV absent.
- Requires hard ionizing spectrum with energetic radiation (>47.9 eV) capable of triply ionizing carbon.
- CIV is typically signature of active galactic nuclei.

CIV emission in a Second Lensed LAE at z>6

Mainali+17b



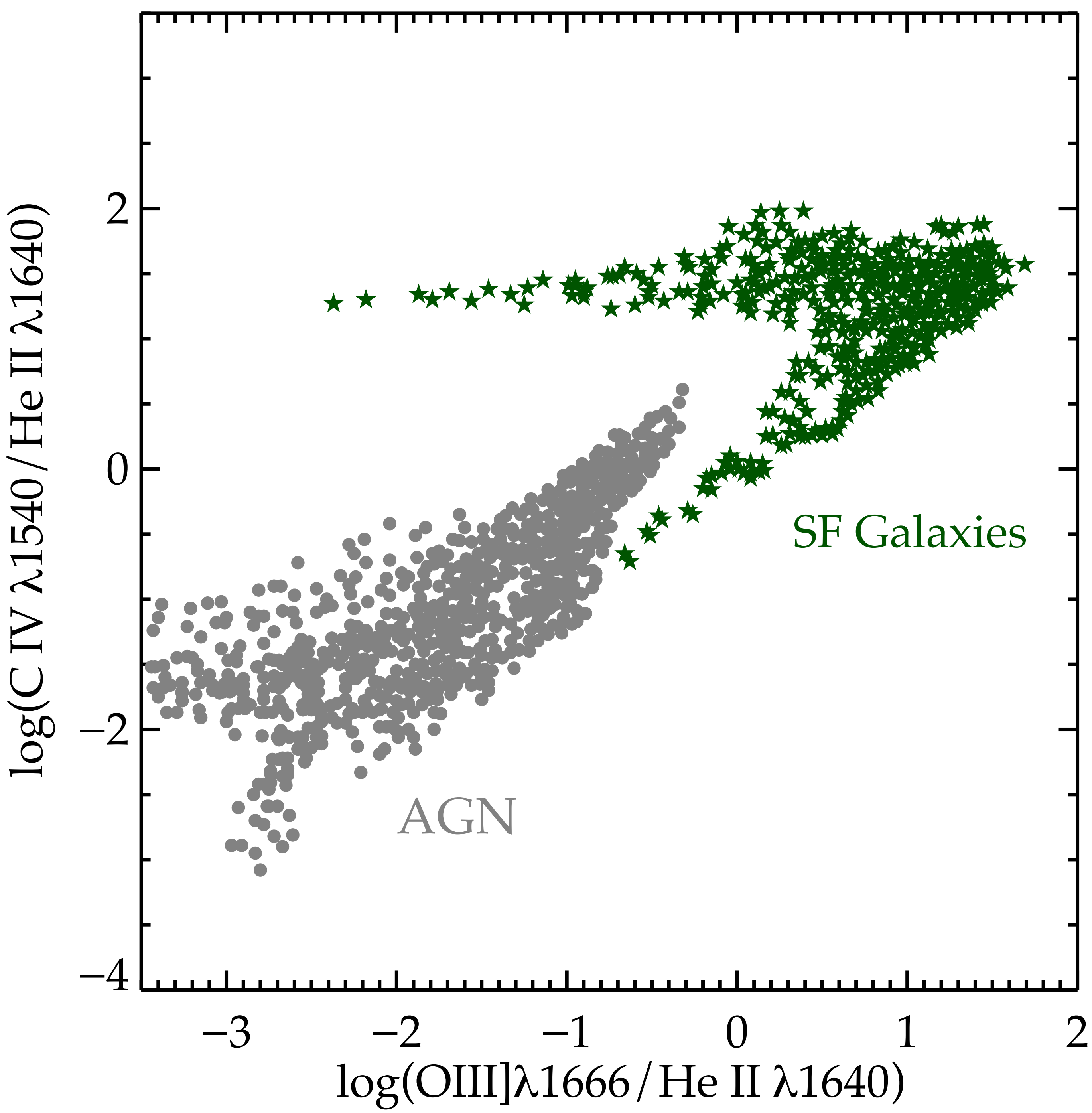


- CIV + OIII] detection in gravitationally lensed LAE at z=6.11, NV and He II not detected.

UV metal line detections reveal that z>7 LAEs definitely have extreme radiation fields that may help explain why we still see such strong Lyman-alpha in these early systems. Origin of radiation field unclear.

UV Line Ratios Sensitive to Powering Mechanism

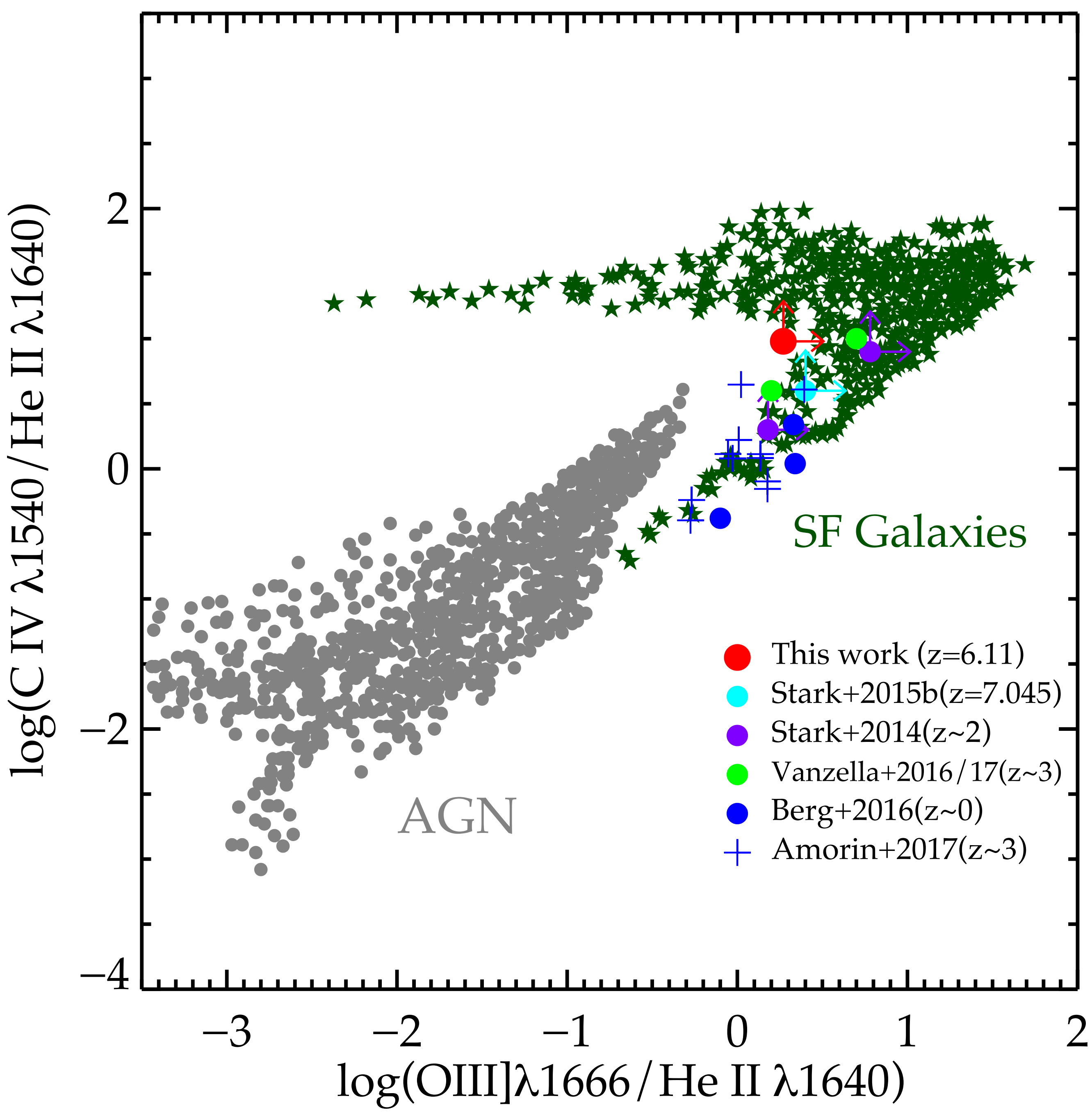
Mainali+17a (photoionization models from Feltre+16)



Star forming galaxies and AGN lie in distinct regions of UV line ratio diagrams.

Low Mass Nebular CIV Emitters Consistent with Hot Stars as Dominant Powering Mechanism

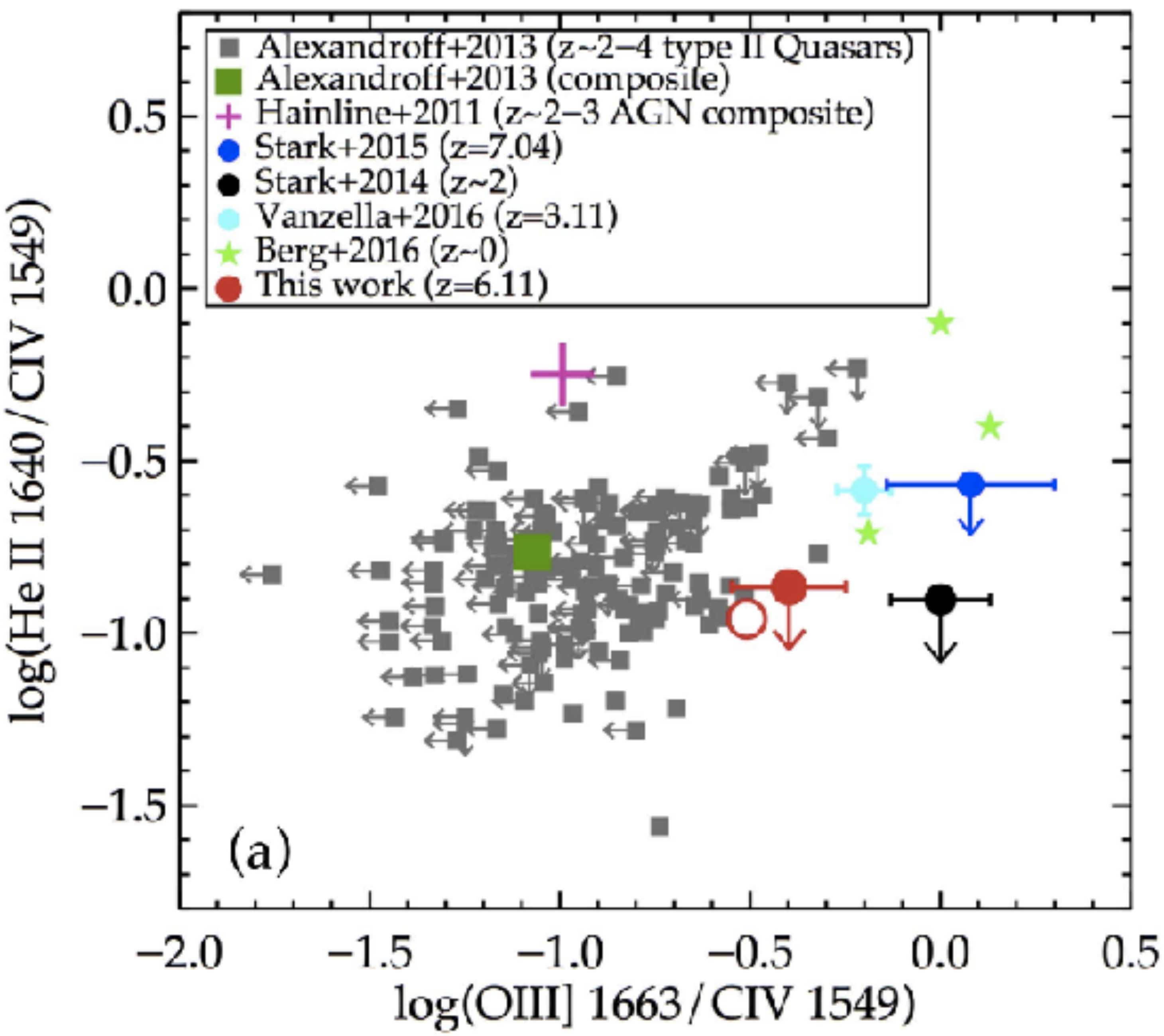
Mainali+17a



Lensed CIV emitters have OIII]/He II ratios consistent with low metallicity hot stars.

Low Mass Nebular CIV Emitters Consistent with Hot Stars as Dominant Powering Mechanism

Mainali+17a

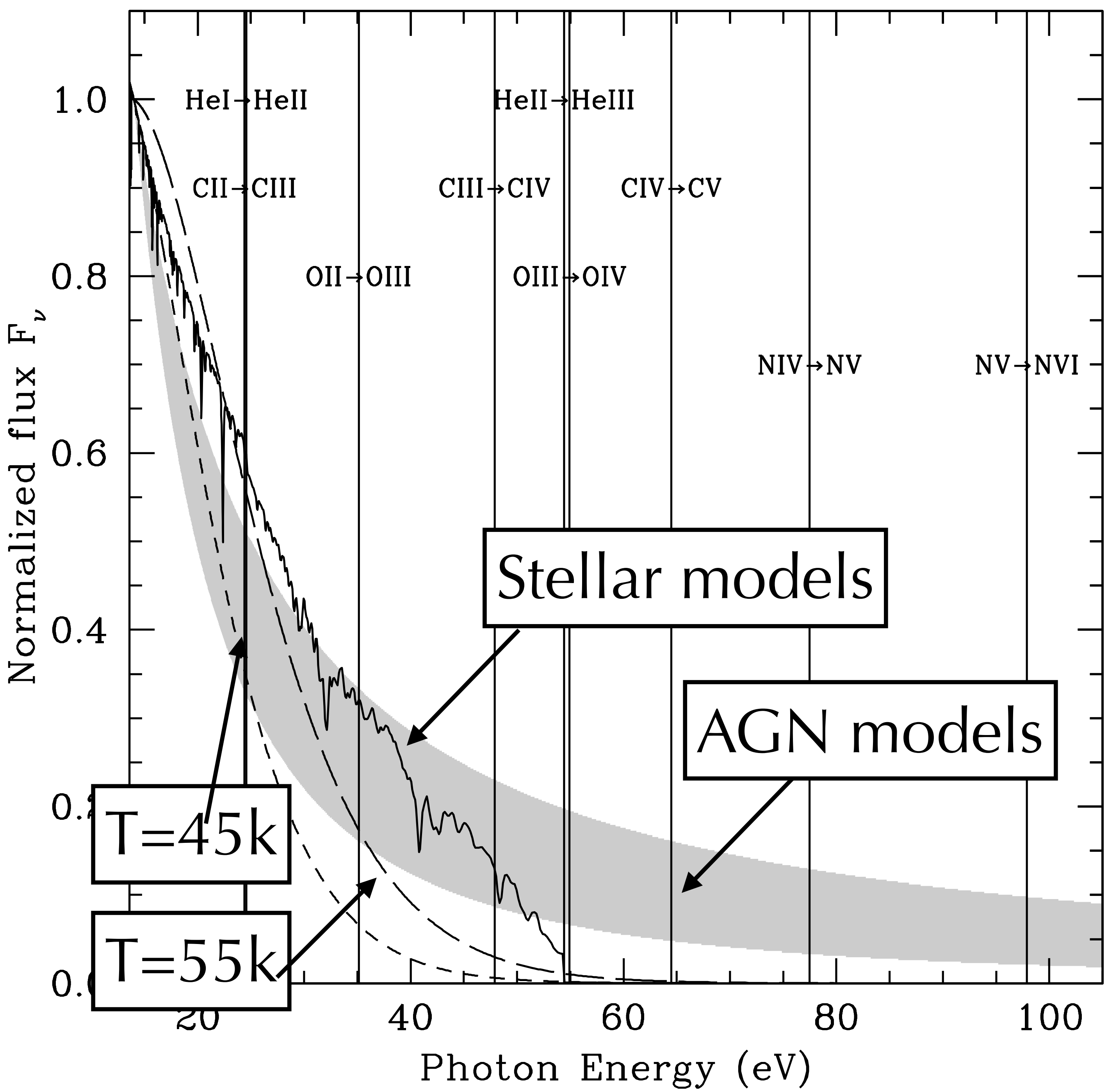


Lensed CIV emitters have OIII]/He II ratios consistent with low metallicity hot stars.

Lensed CIV emitters lie in different region of line ratio space from AGNs. Does not rule out some low level AGN contribution.

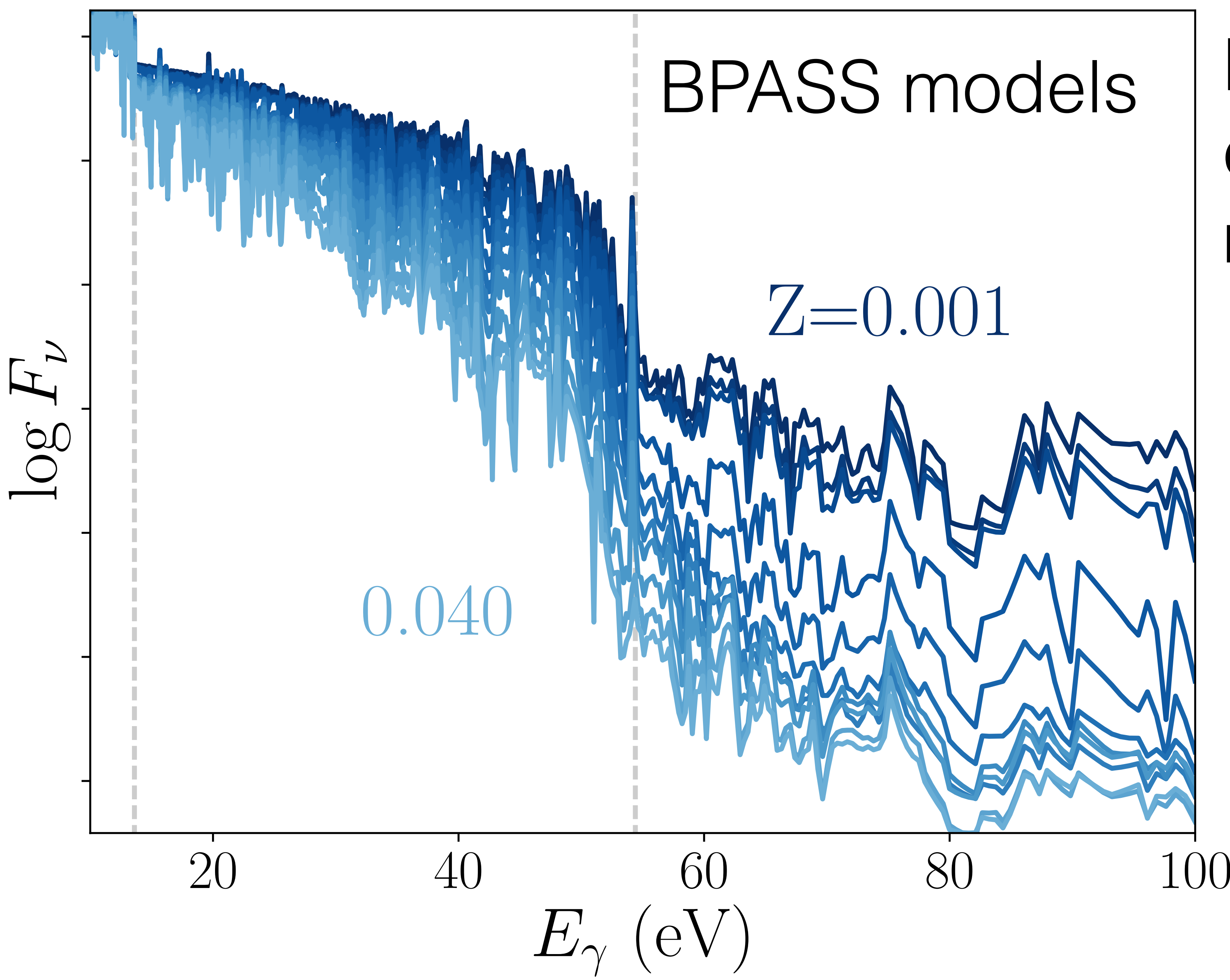
What Metallicity is Required to Explain CIV Emission?

Stark+15b



- For z=7.045 galaxy, single star synthesis models (CB17, Gutkin+16)+CLOUDY:
  12+log O/H =7.05
  log U = -1.35
- CIV emission typically requires <10% solar metallicity.
- Suggests z~7-8 studies are beginning to probe ultra low metallicities, a regime that is very poorly constrained.

Low Metallicity Stellar Populations



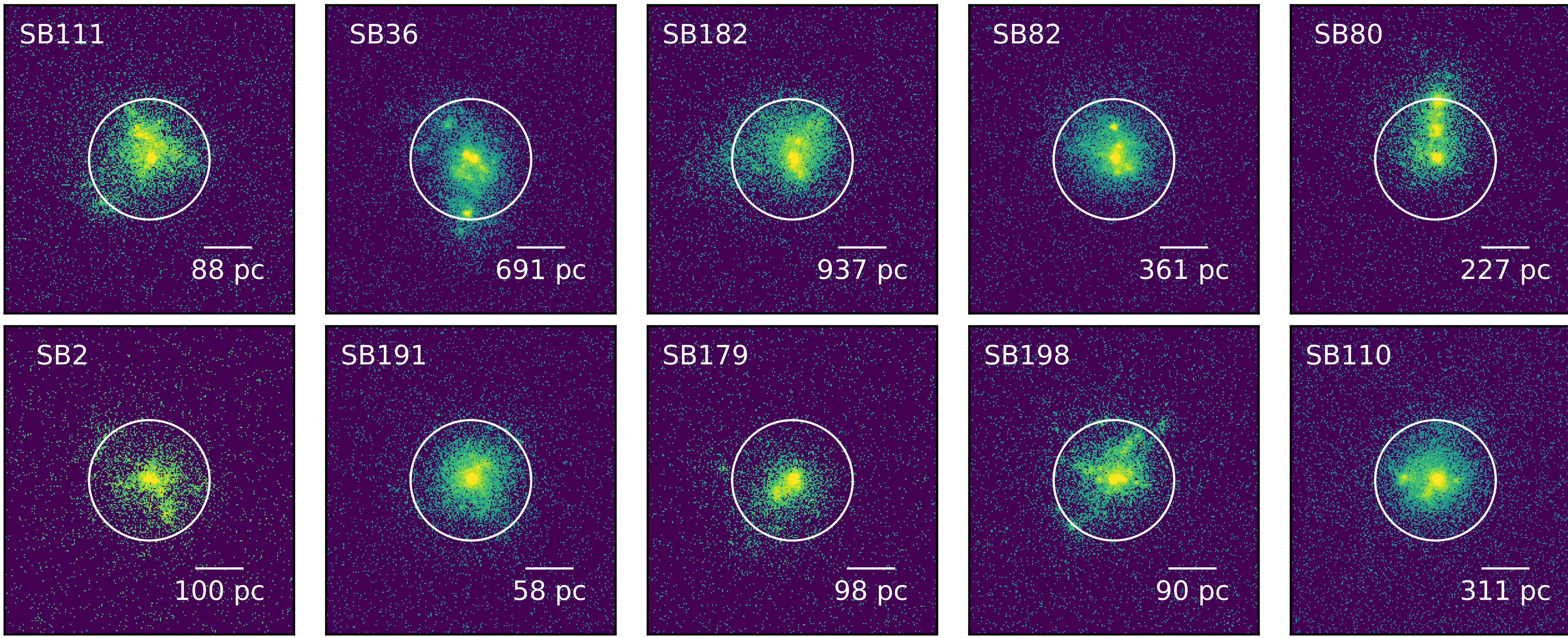
Hard ionizing spectrum expected at low metallicity.

But models very uncertain, depends on unknown physics:

- binary mass transfer
- rotational mixing at low Z
- stellar wind opacities at low Z
- contribution from X-ray binaries.

Characterizing Ionizing Spectrum of Nearby Metal Poor Galaxies with High S/N UV+Optical Spectra

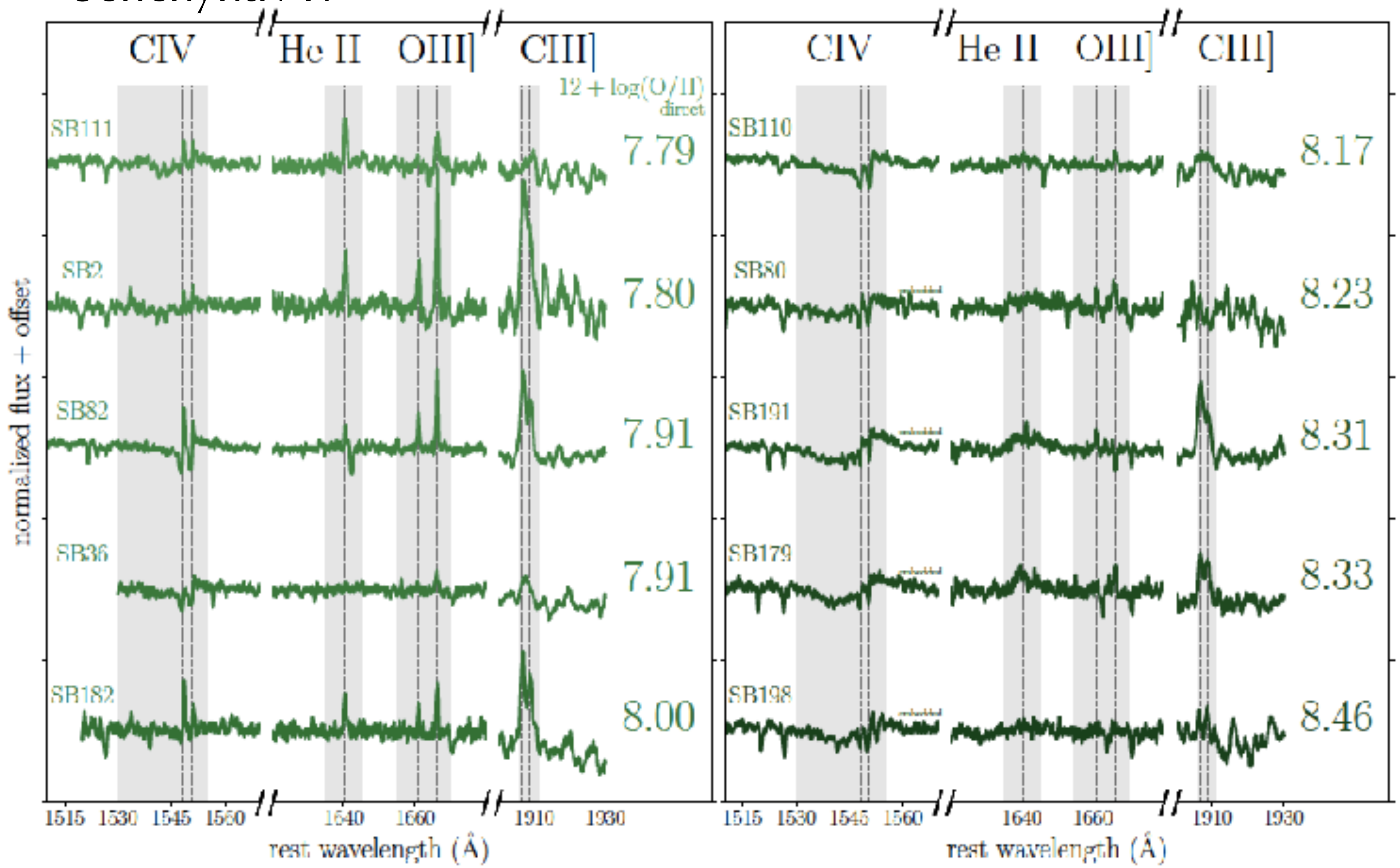
Senchyna+17



- HST Cycle 23-25 programs to obtain COS UV Spectra of metal poor galaxies
- Ongoing programs to obtain high S/N optical spectra with Keck and MMT.

HST/COS UV Spectra of Metal Poor Galaxies

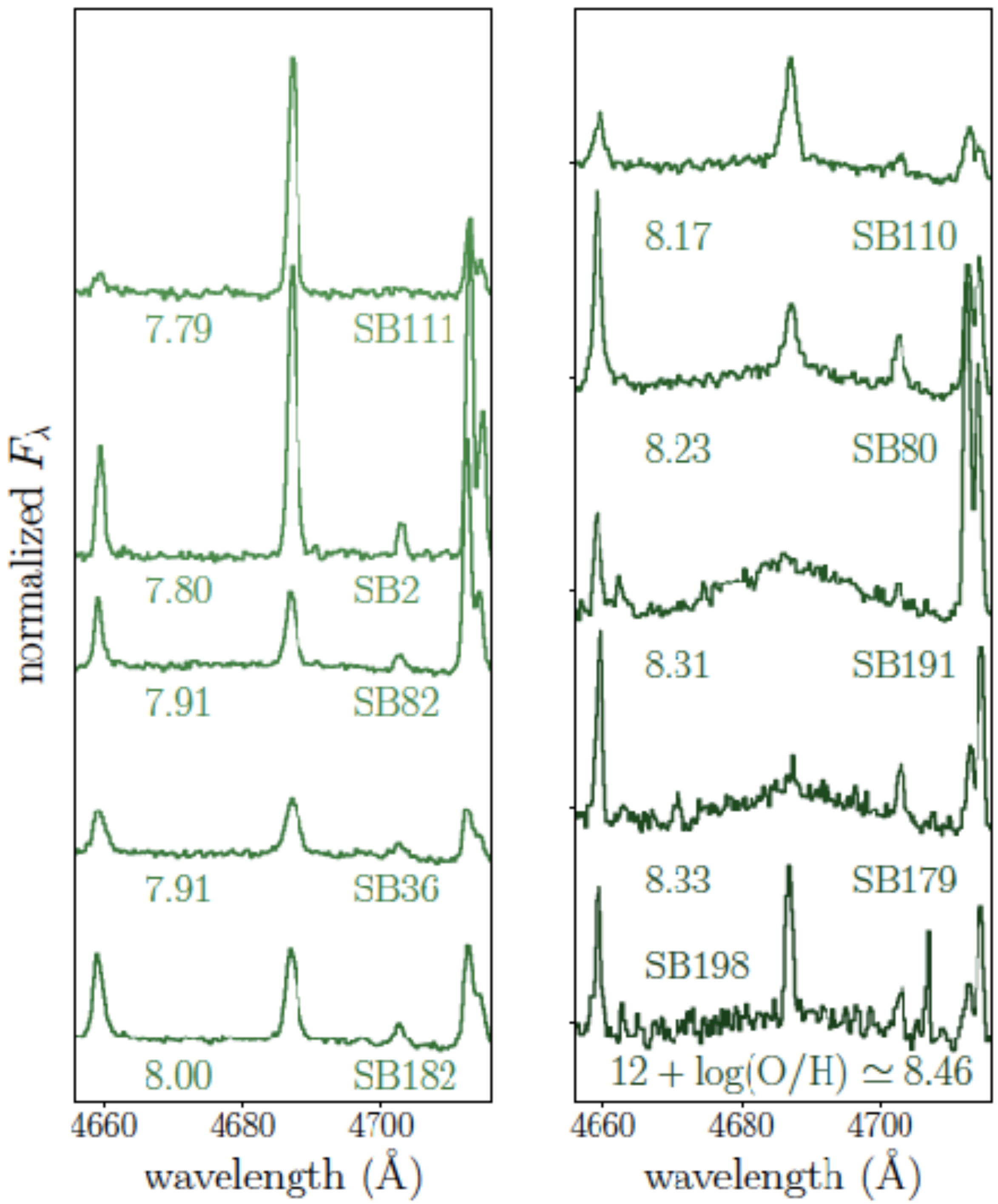
Senchyna+17



- High ionization lines (He II1640 and CIV1548,1550) begin to appear at low metallicities (<10% $Z_\odot$).

Nebular He II in Keck/ESI Optical Spectra

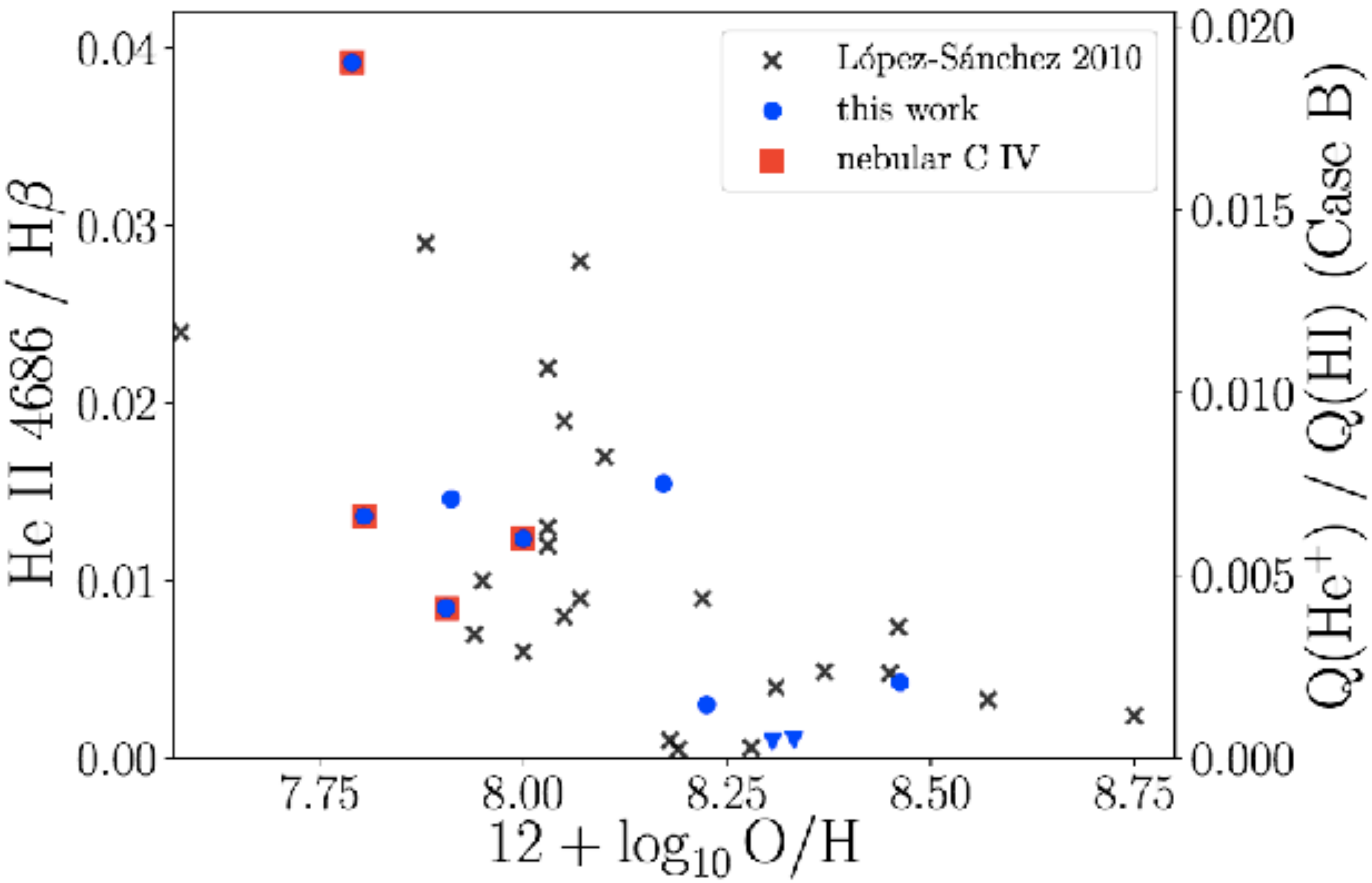
Senchyna+17



- Resolution sufficient to separate nebular and stellar wind components of He II 4686.
- Strong nebular He II 4686 limited to most metal poor systems.

Transition in Ionizing Spectrum at Low Metallicity

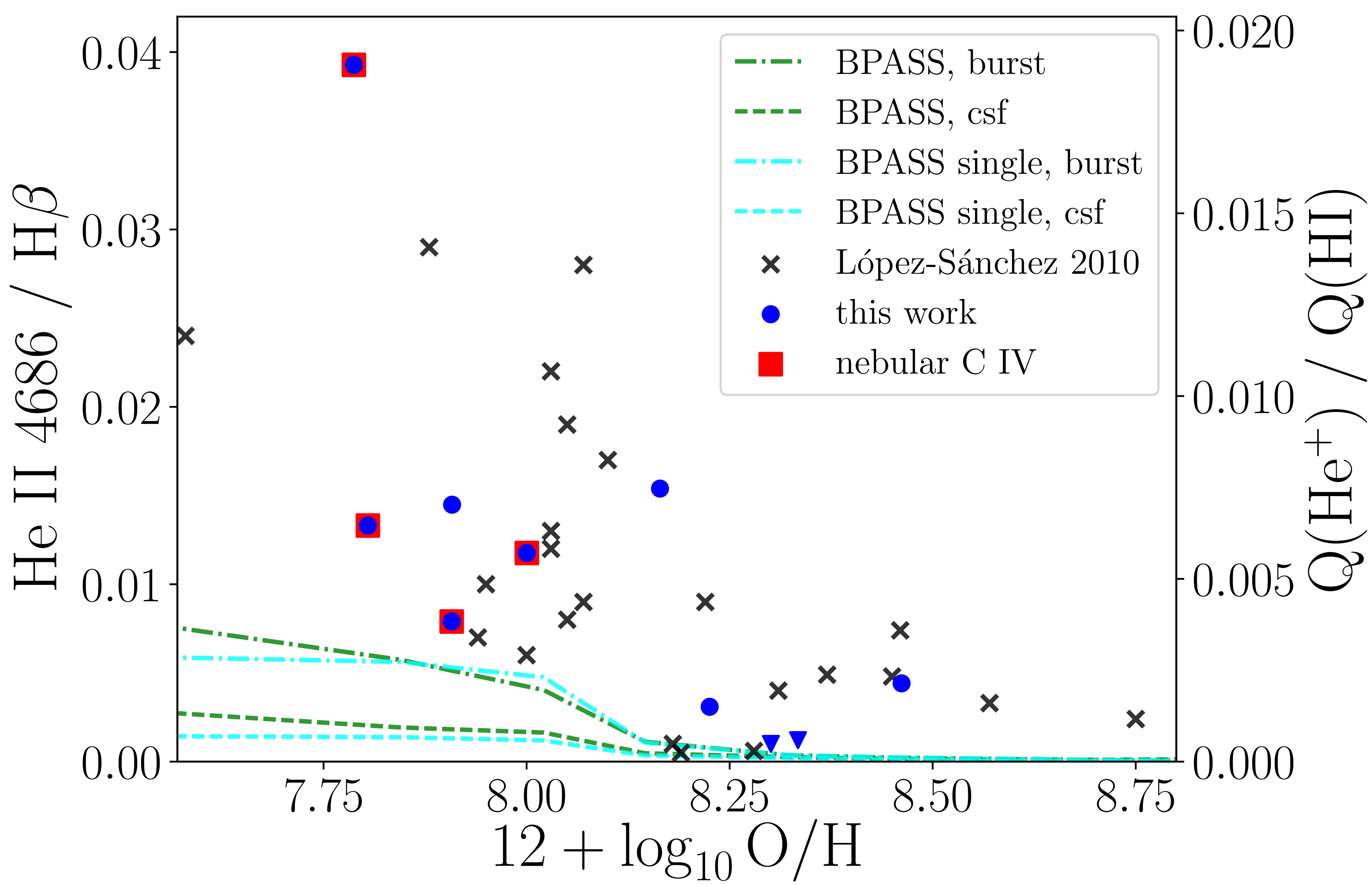
Senchyna+17



- Rapid increase in hard photons at lowest metallicities ($<0.2\ Z_{\odot}$).

Missing Sources of Energetic Radiation at Low Metallicity

Senchyna+17



- Rapid increase in hard photons at lowest metallicities (<0.2 $Z_\odot$).
- Stellar synthesis models do not match the data, suggesting models are missing sources of He^+-ionizing radiation.

- *Stripped binary products produce harder spectrum than thought?*
- *Rotational Mixing more efficient than predicted?*
- *Missing population of X-Ray binaries at low metallicities?*

Summary

- Lyα downturn at z>6, consistent with expectations for partially neutral IGM. New detections suggest Lyman-alpha more common in luminous galaxies with large EW optical line emission.

- UV line detections suggest very hard radiation field is present in LAEs at z>7, likely contributing to their visibility deep in reionization era.
    - Some systems appear to be AGN, others appear to be powered by low metallicity (<10% $Z_\odot$) hot stars.

- Metal poor galaxies have much harder ionizing spectra than predicted by binary stellar synthesis models. Origin of excess He^+-ionizing photons remains unclear.

- JWST will soon produce hundreds of line detections at z>7, leading to much-improved understanding of nature of early star forming systems and the reionization process.