New Insights into Early Galaxies and Reionization from JWST

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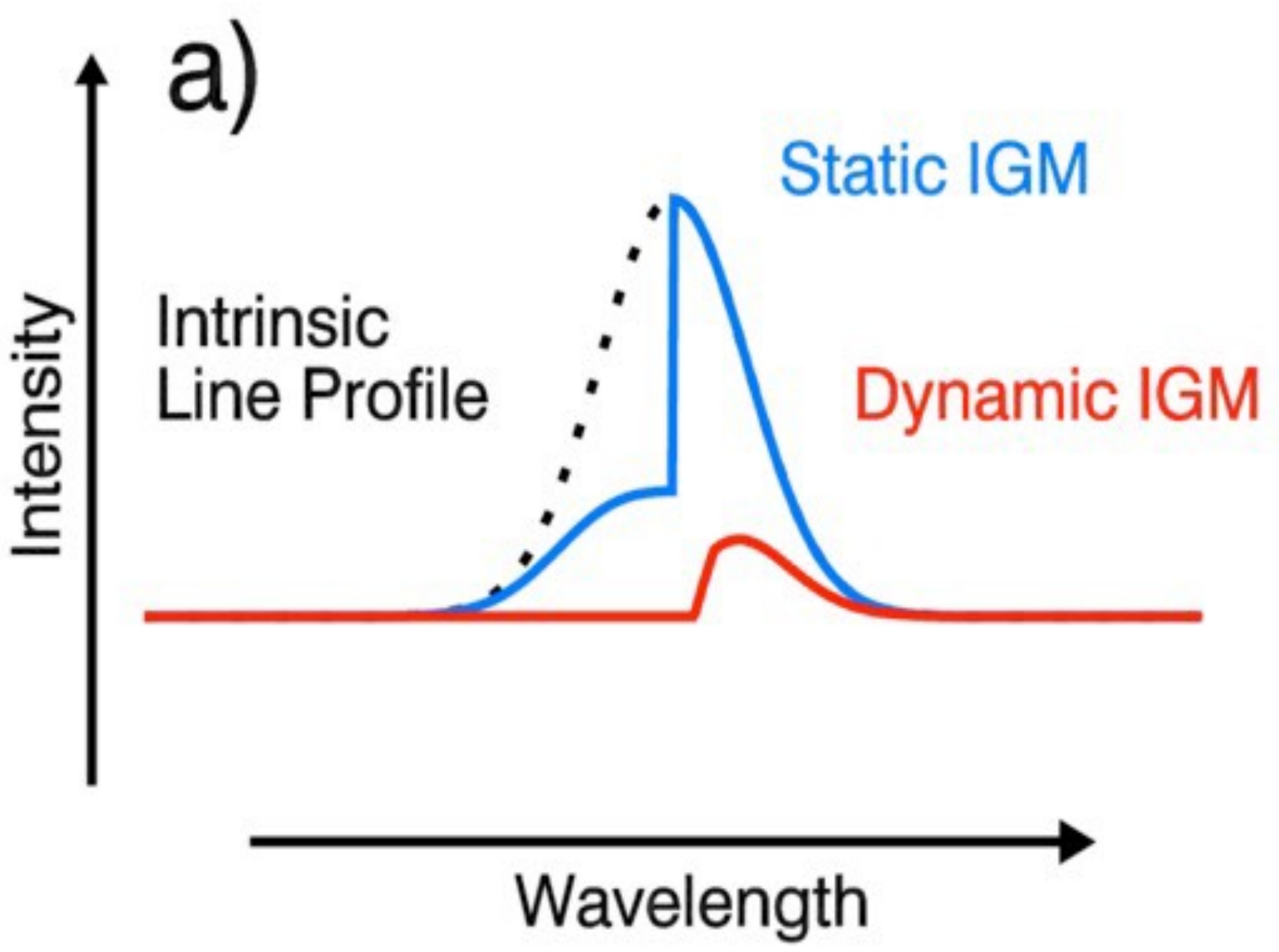
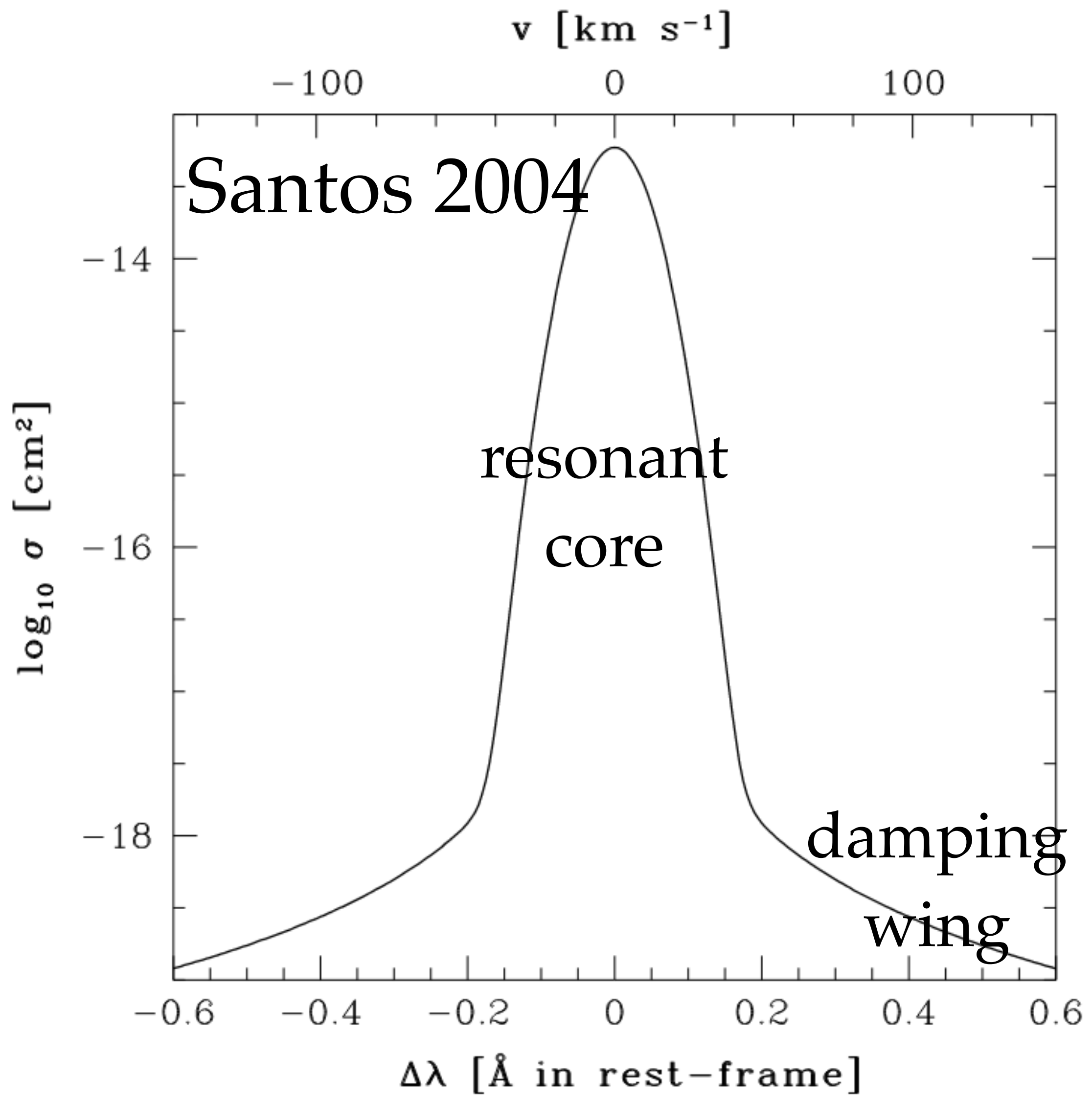
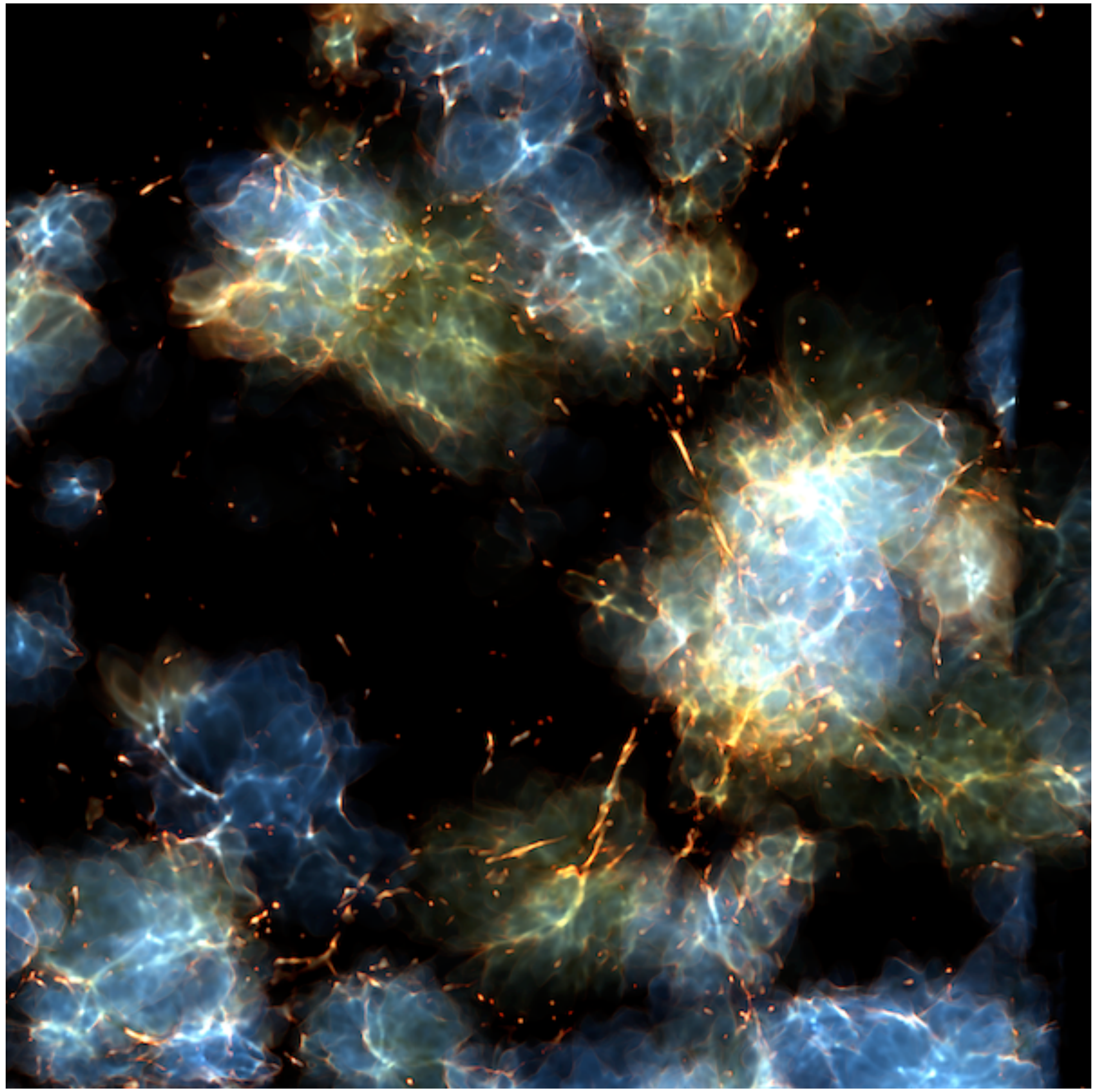
Cosmic Dawn at High Latitudes

June 25, 2024

Lyα Emission in Early Star Forming Galaxies







credit: Wise, Cen, and Abel

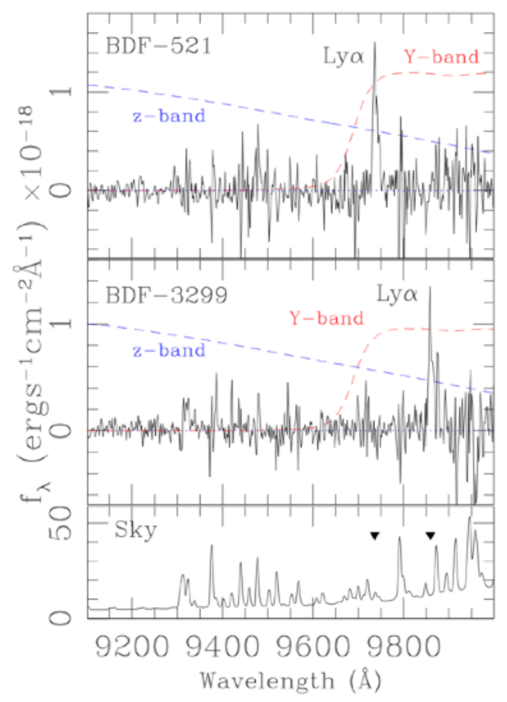
Neutral hydrogen (in galaxy and IGM) scatters Lyα, reducing observed flux in the line.

If IGM is partially neutral, it will attenuate Lyα in star forming galaxies.

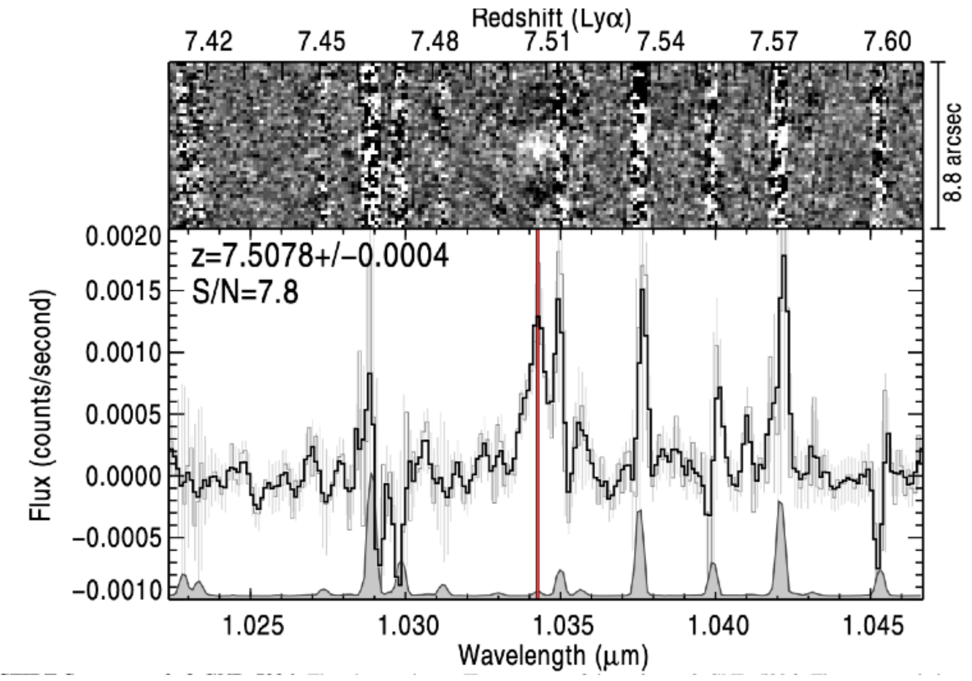
Fraction of star forming galaxies with strong Lyα emission (>25Å) will begin to decrease.

Searching for z>7 Lyα Emission: 2009-2022

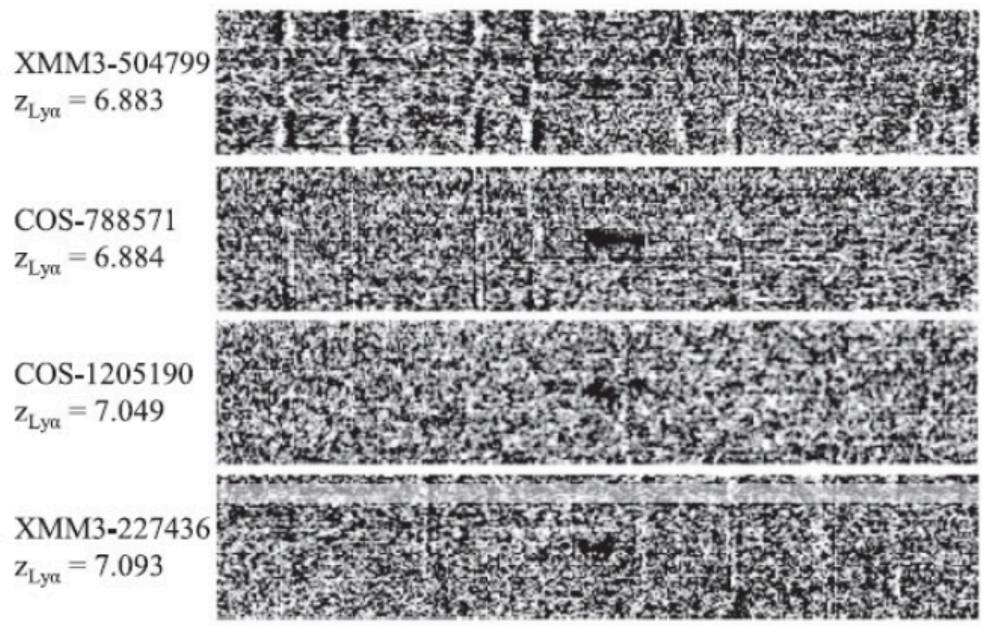
Vanzella+2011



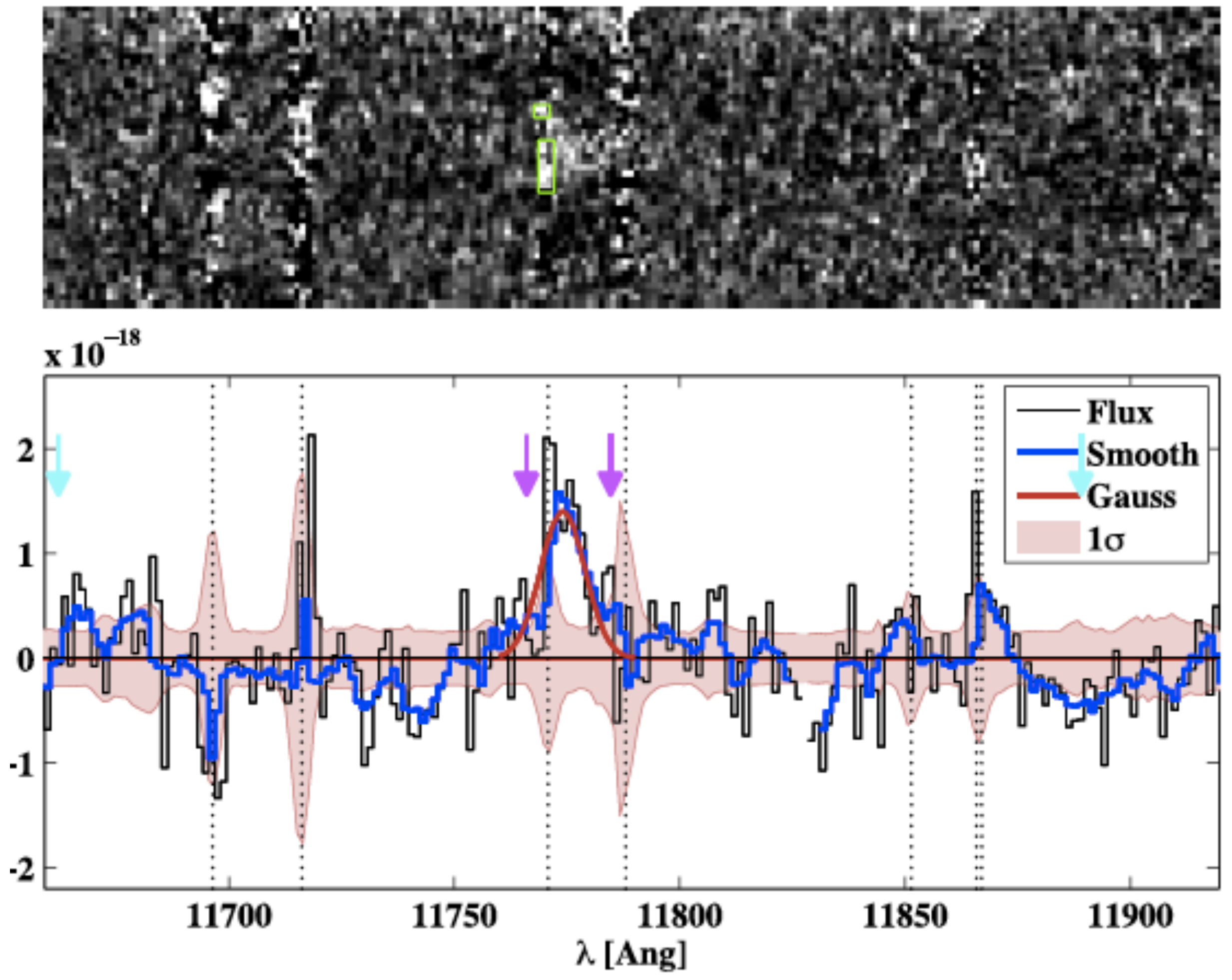
Finkelstein+2013



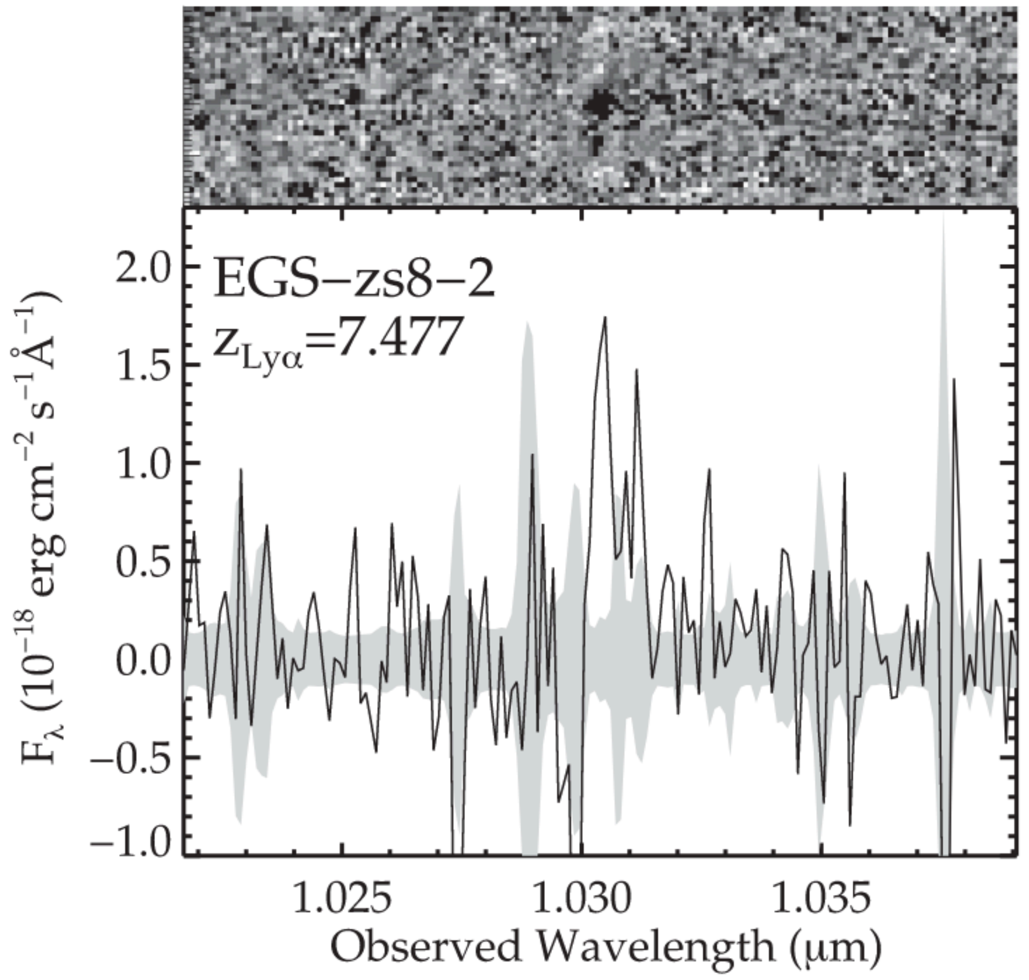
Endsley+2021b



Zitrin+2015



Roberts Borsani 2016, Stark+2017



- Large observational effort by community to characterize Ly**α** emission line EWs in continuum-selected galaxies over ~13 years.
- Small number of robust z>7 Ly**α** emitting galaxies detected after observing ~150 sources.

18 Ly**α** detections at 7<z<8

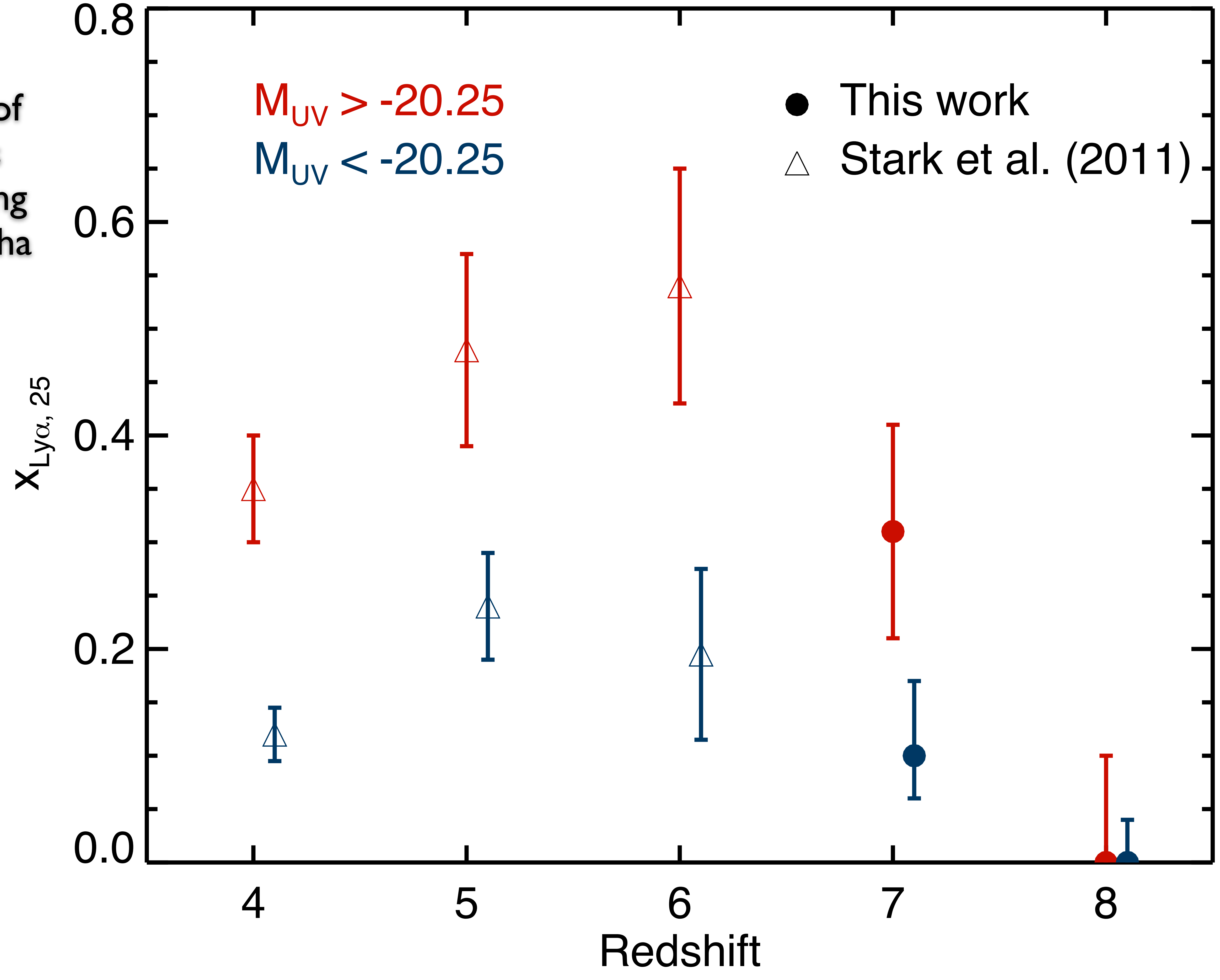
2 Ly**α** detections at 8<z<9

(see Vanzella+11,Ono+12, Schenker+12,Shibuya+12, Finkelstein+13,Oesch+15, Zitrin+15, Roberts Borsani+16, Song+16,Stark+17,Pentericci+18, Hoag+17,19, Tilvi+20, Endsley+22,Jung+19,20,22, Larson+22)

Disappearance of Lyα Emission: 2009-2022

Schenker+2014

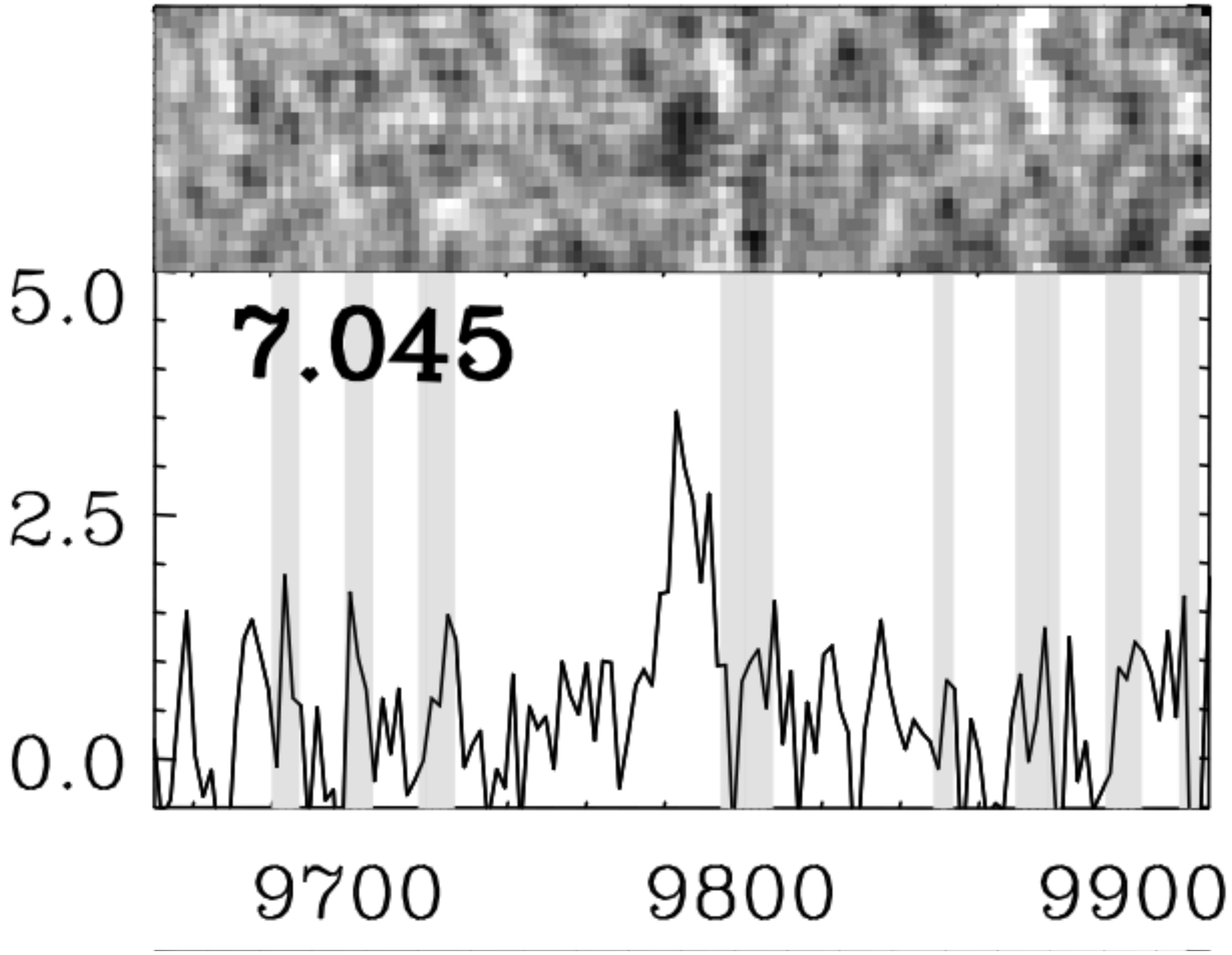
Fraction of Galaxies with Strong Lyman alpha



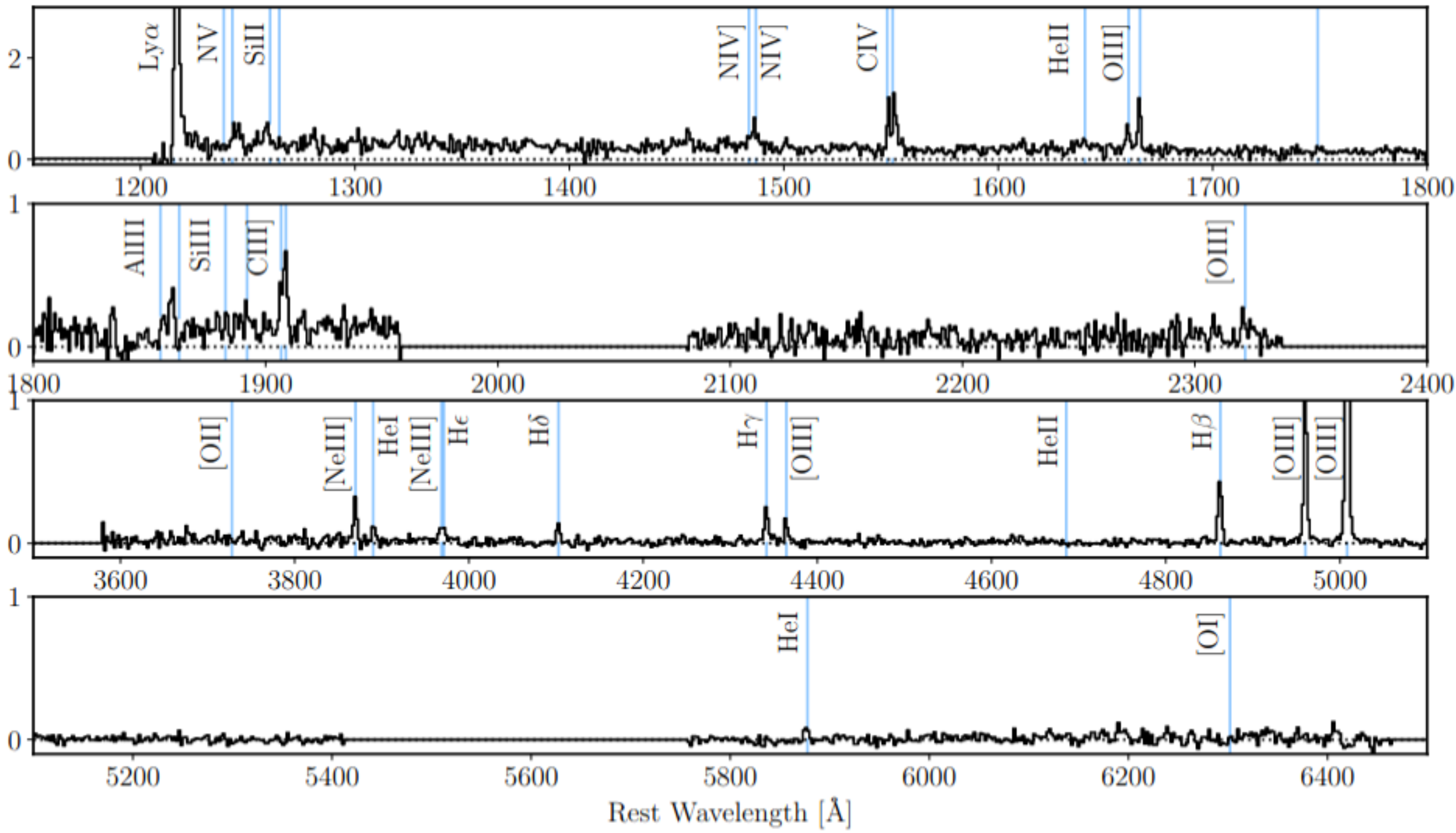
- Strong attenuation in Lyα emission in typical galaxies at z~7-8.
- As would be expected if IGM neutral fractions are quite large at z~7 (X_{HI}>0.5), consistent with other probes.

JWST Provides a New Window on Lyα emission (2022+)

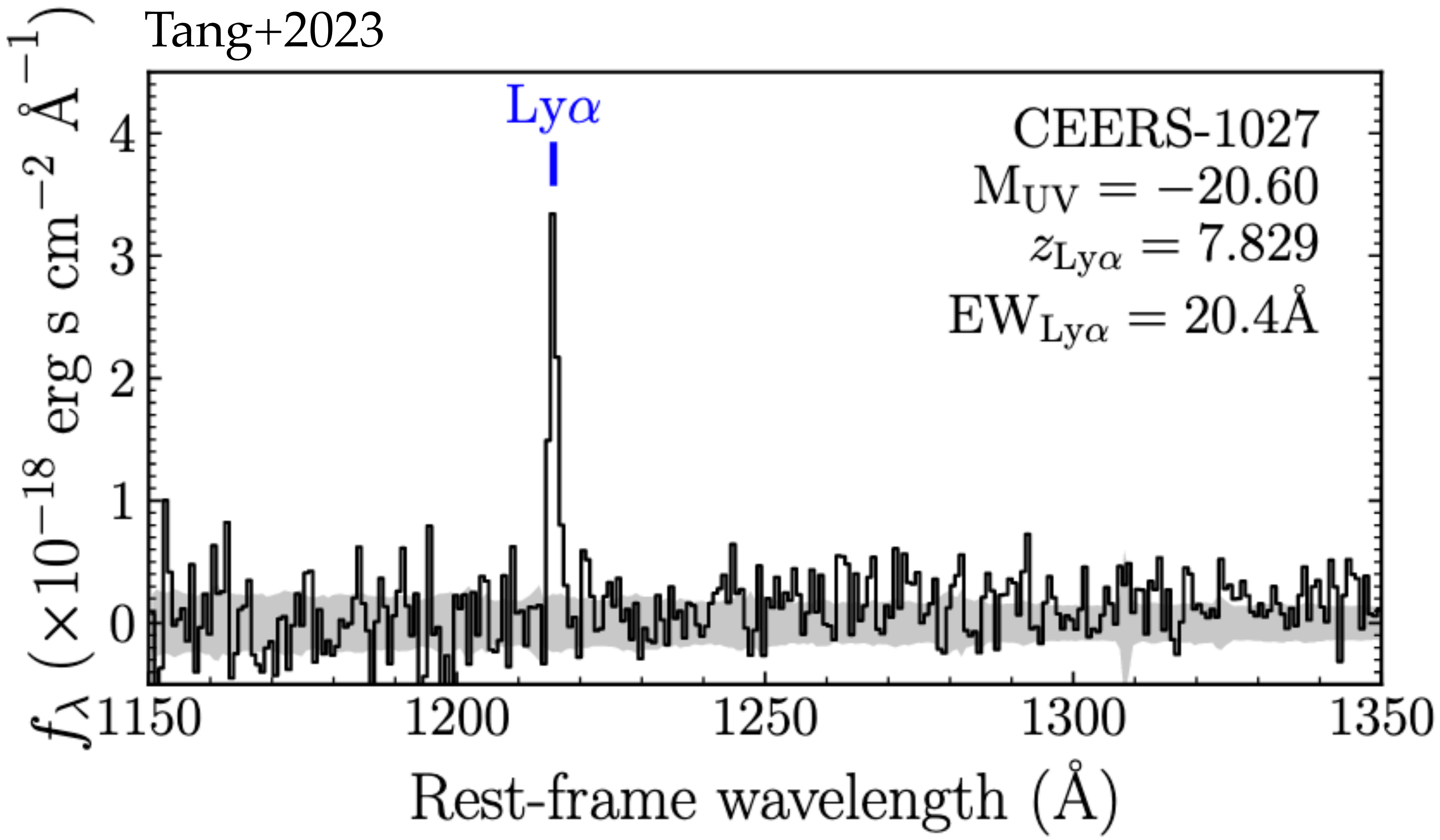
Schenker+2012

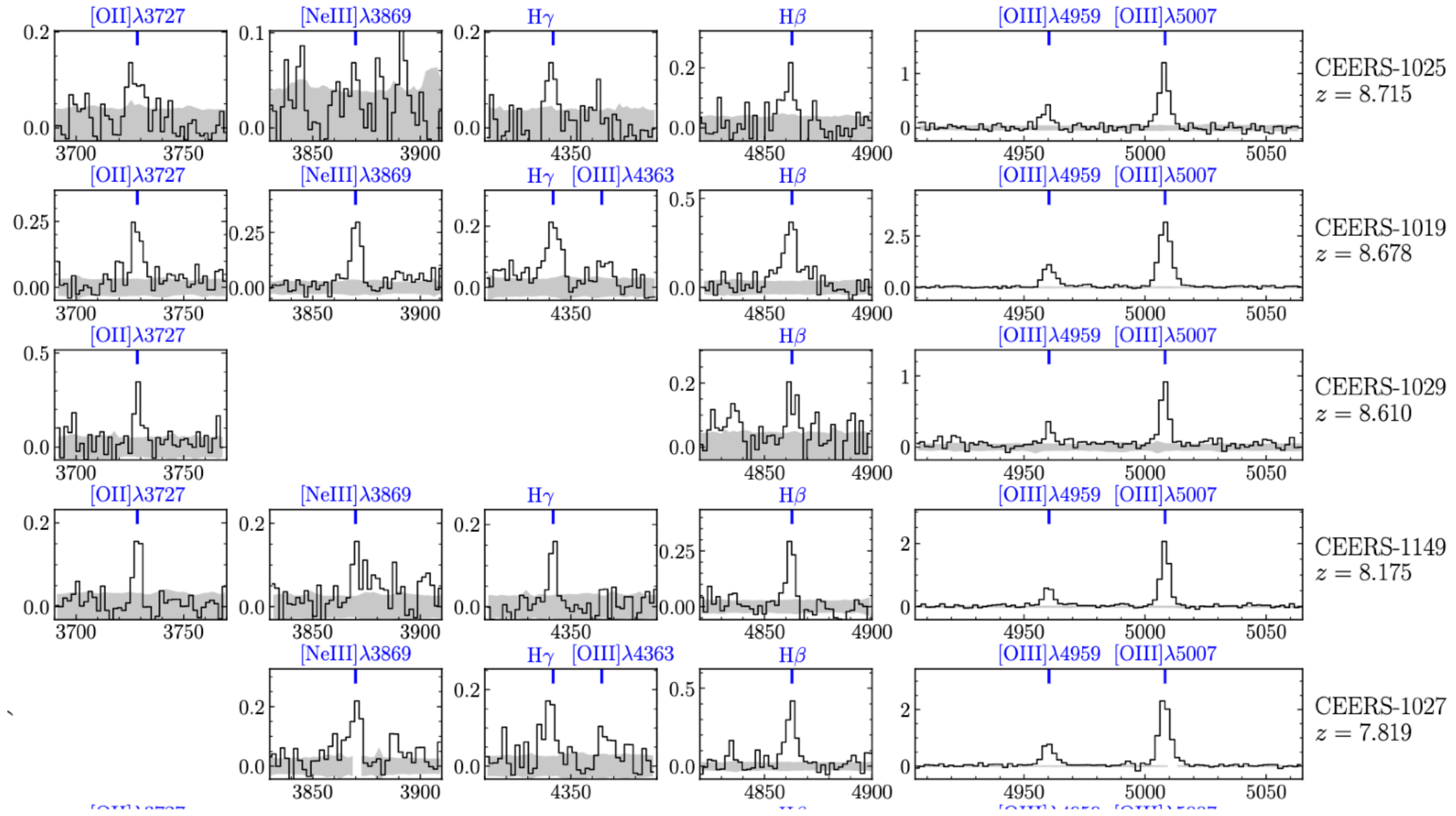


Topping+2024 in prep



JWST Provides a New Window on Lyα emission

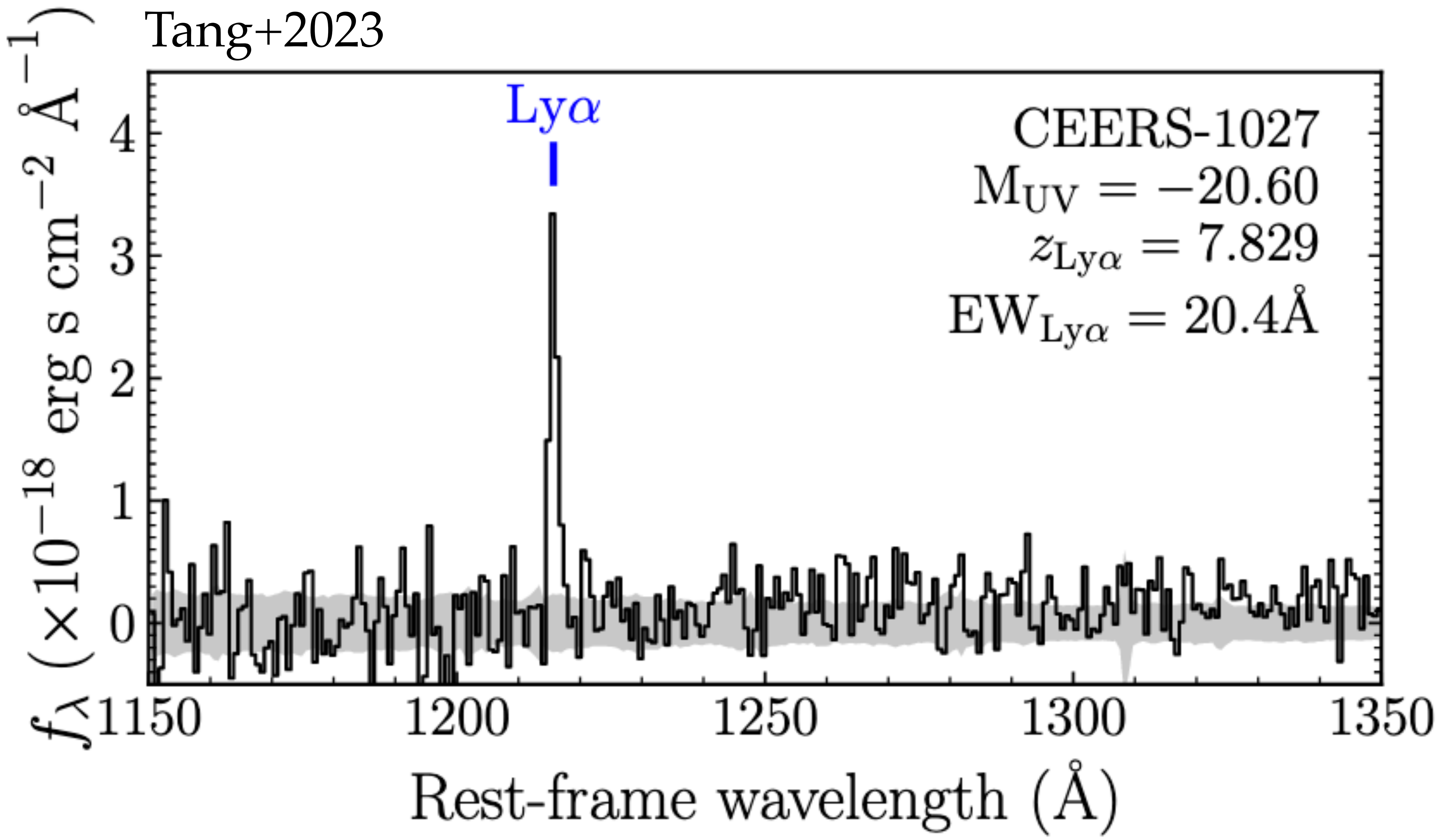


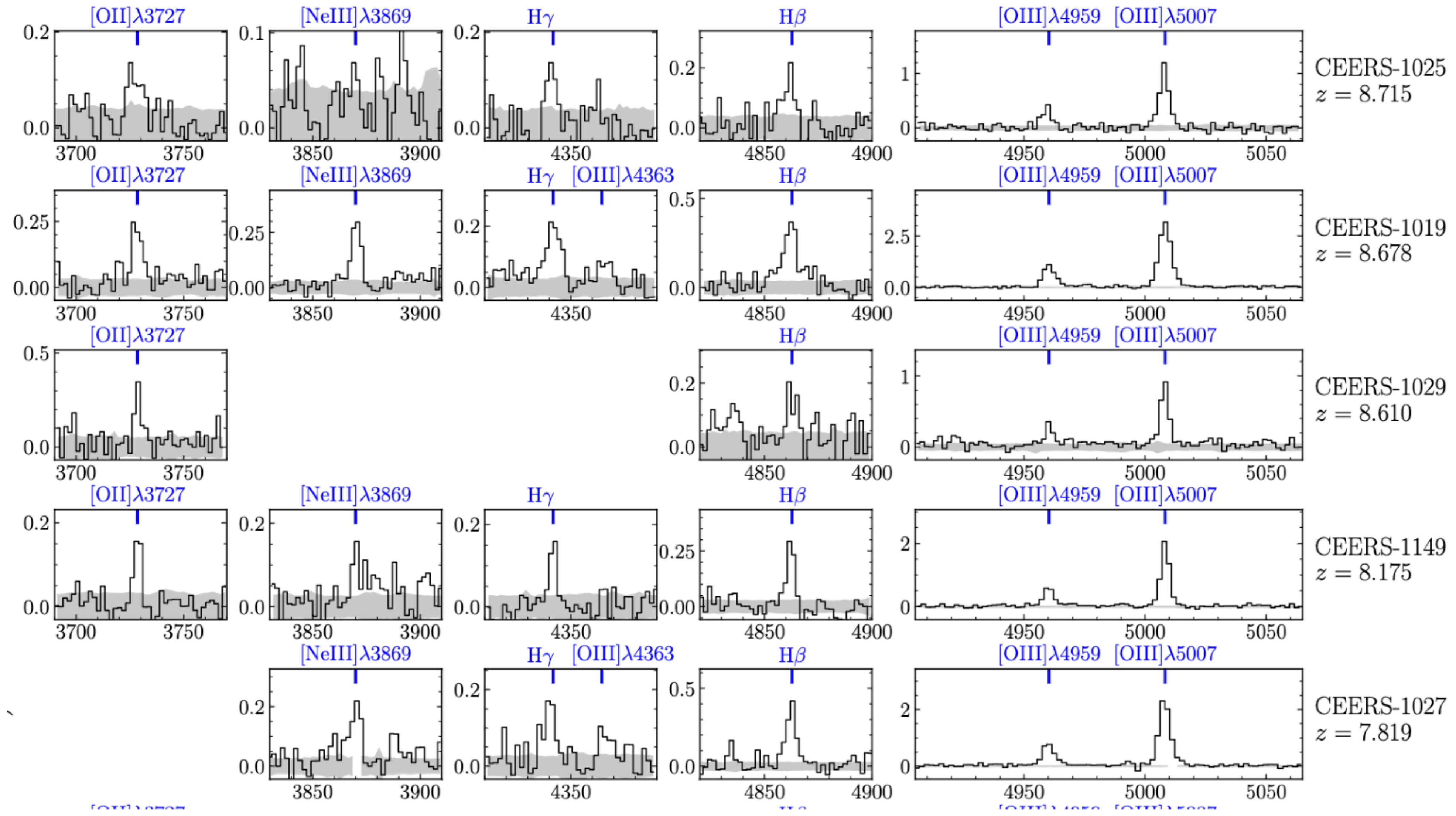


- JWST/NIRspec has ushered in new era for Lyα studies in reionization era.
- Detections in z>7 galaxies ~100x fainter (m~30) than what was possible from the ground.

JWST Provides a New Window on Lyα emission

Tang+2023



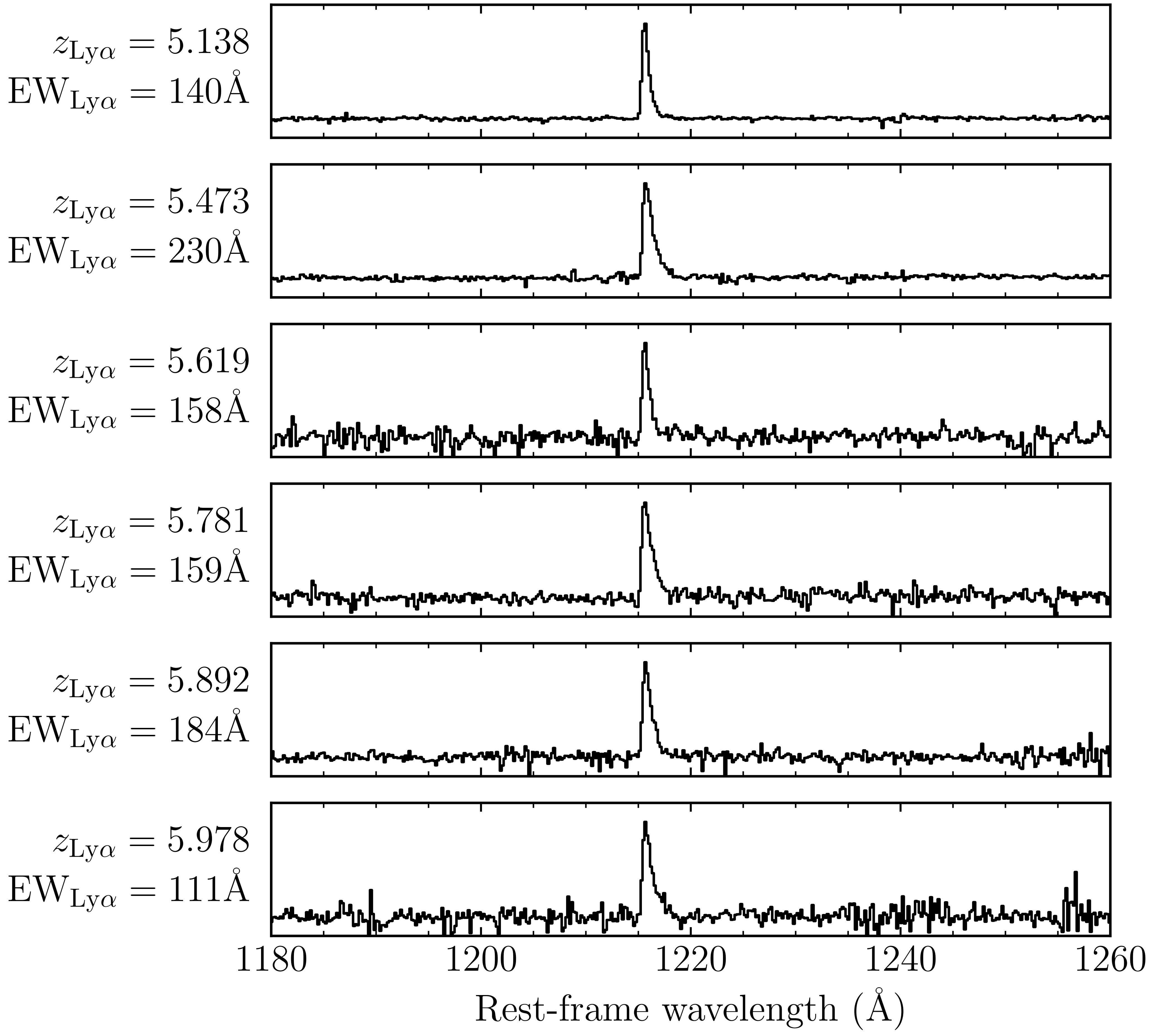


- JWST/NIRspec has ushered in new era for Lyα studies in reionization era.
- Detections in z>7 galaxies ~100x fainter (m~30) than what was possible from the ground.
- NIRSpec also provides rest-optical lines (i.e. Hβ, Hα).
- Allow *estimate* of **Lyα escape fraction*** and **velocity profiles** for individual galaxies at z>7.

  *under specific recombination assumptions (see Scarlata+24, McClymont+24)

First Step: Lyα Statistics in Baseline Sample at z~5-6

Tang+2024a (see also Lin et al. 2024, talk by Gonzalo Prieto-Lyon)



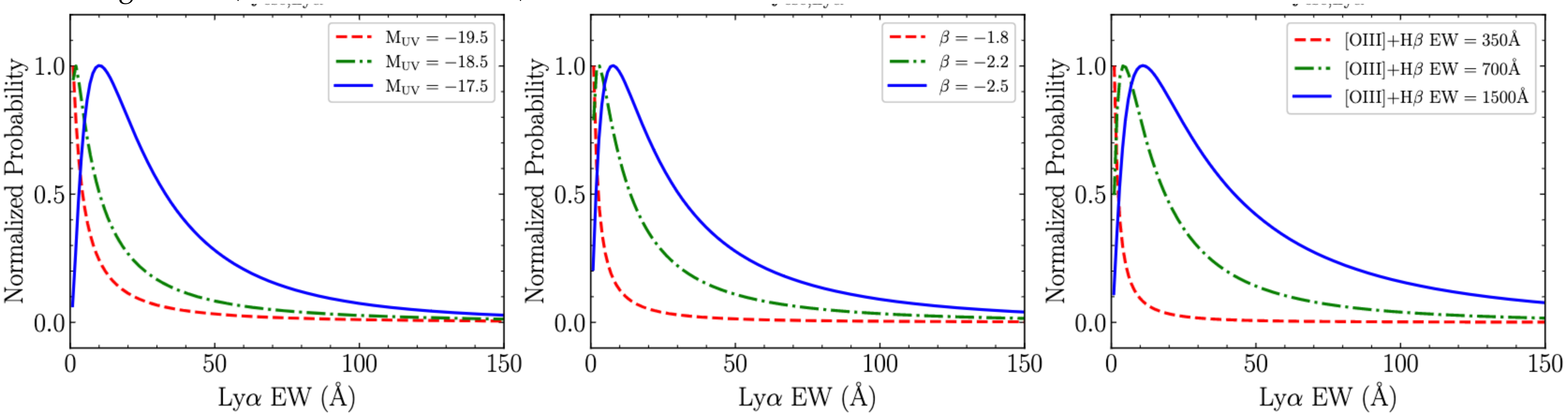
- To interpret Lyα detections at z~7-11, need statistical baseline of Lyα properties in final phase of reionization (z~5-6).

- JWST has made major progress — providing first Hα measurements (from FRESCO survey) for large samples of Lyα emitters identified with Keck and VLT.
    - Lyα escape fractions*
    - Lyα velocity profiles
    - Improved Lyα EWs
    - NIRCam SEDs (sSFR, [OIII]+Hβ EW, UV slope)

*under specific recombination assumptions (see Scarlata+24, McClymont+24)

Distribution of Lyα EW and $f_{esc,Ly\alpha}$ at z~5-6

Tang+2024a (see also Lin et al. 2024)



- New distributions of Lyα EW and $f_{esc,Ly\alpha,B}$ as function of JWST-derived galaxy properties.

Distribution of Lyα EW and $f_{esc,Ly\alpha}$ at z~5-6

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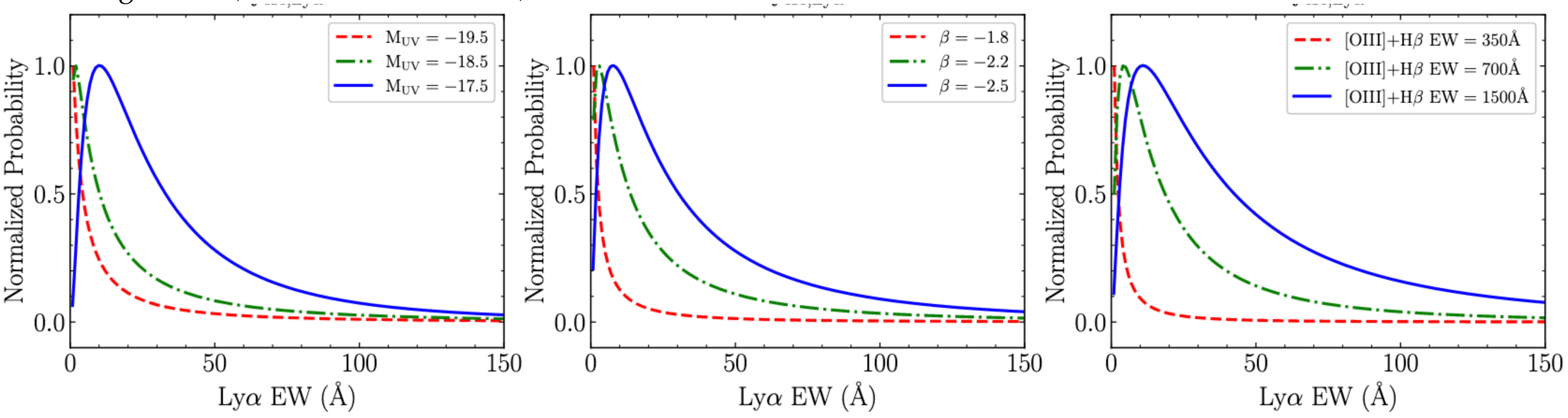
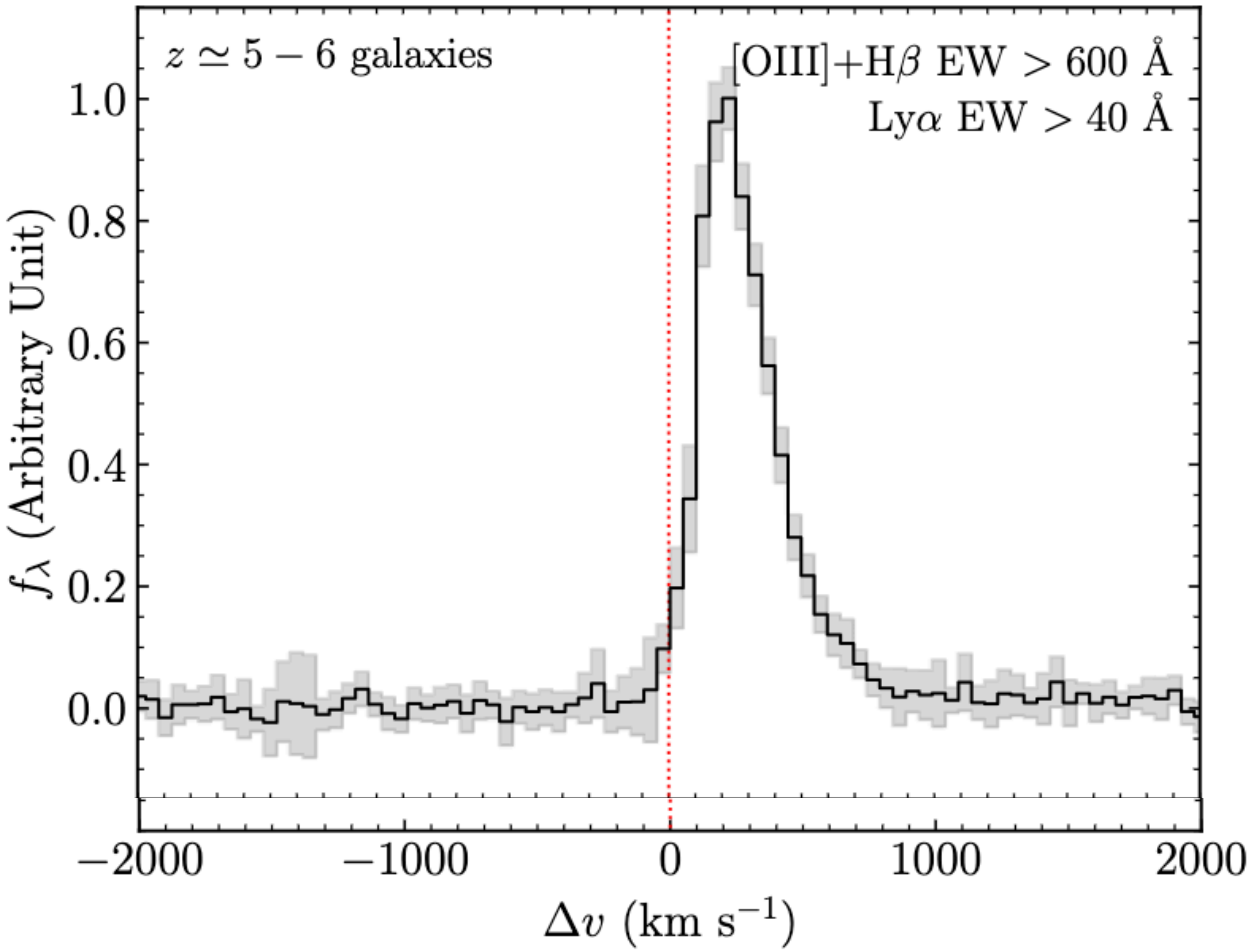
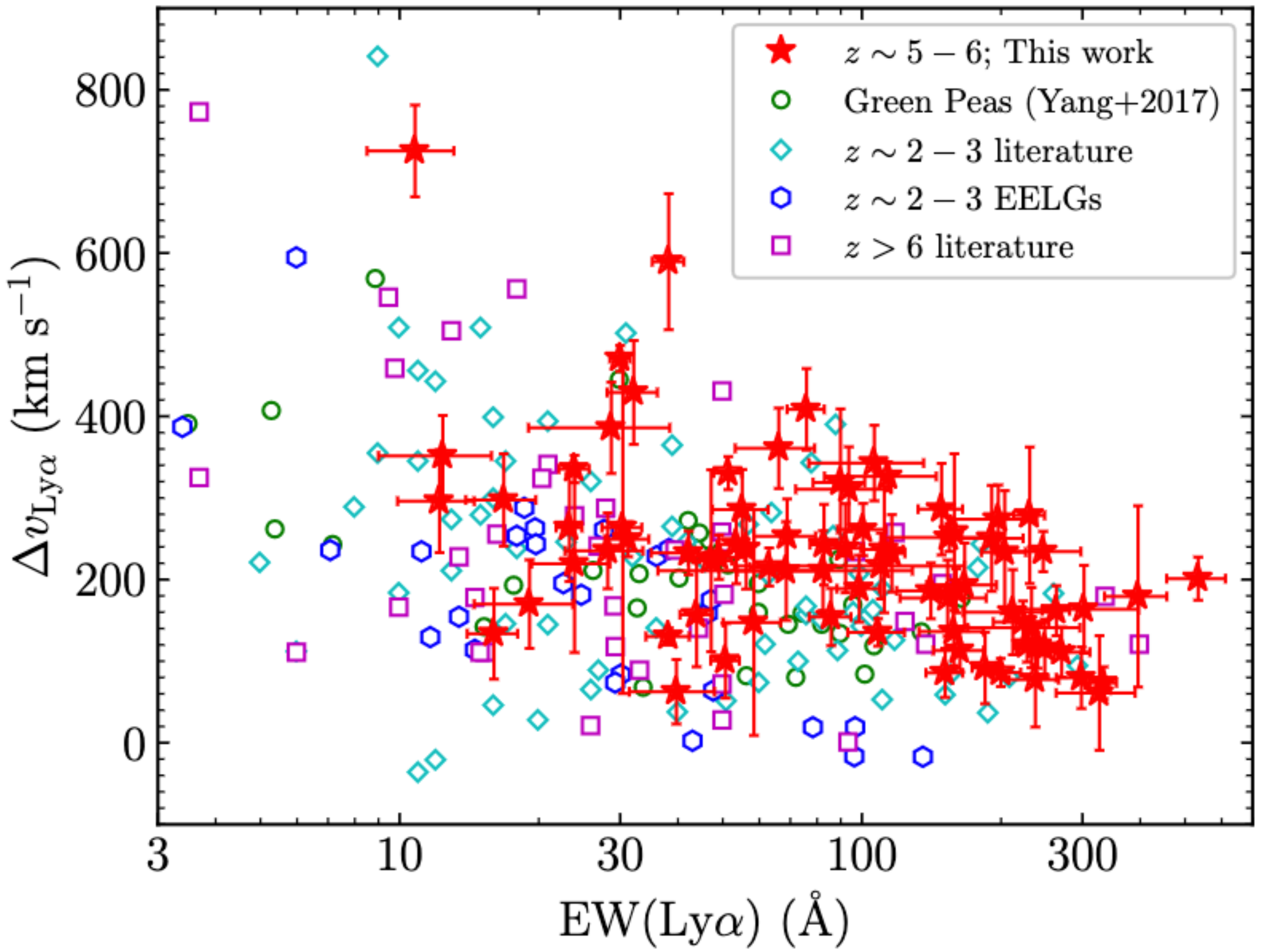


- New distributions of Lyα EW and $f_{esc,Ly\alpha,B}$ as function of JWST-derived galaxy properties.
- **Strong Lyα is reasonably common at z~5-6:** 38% of galaxies have EW > 25 Å.
- And 11% of galaxies have EW > 100 Å.

Velocity Profiles of Strong Lyα Emitting Galaxies

Tang+2024a (see also Cassata+20, Endsley+22)



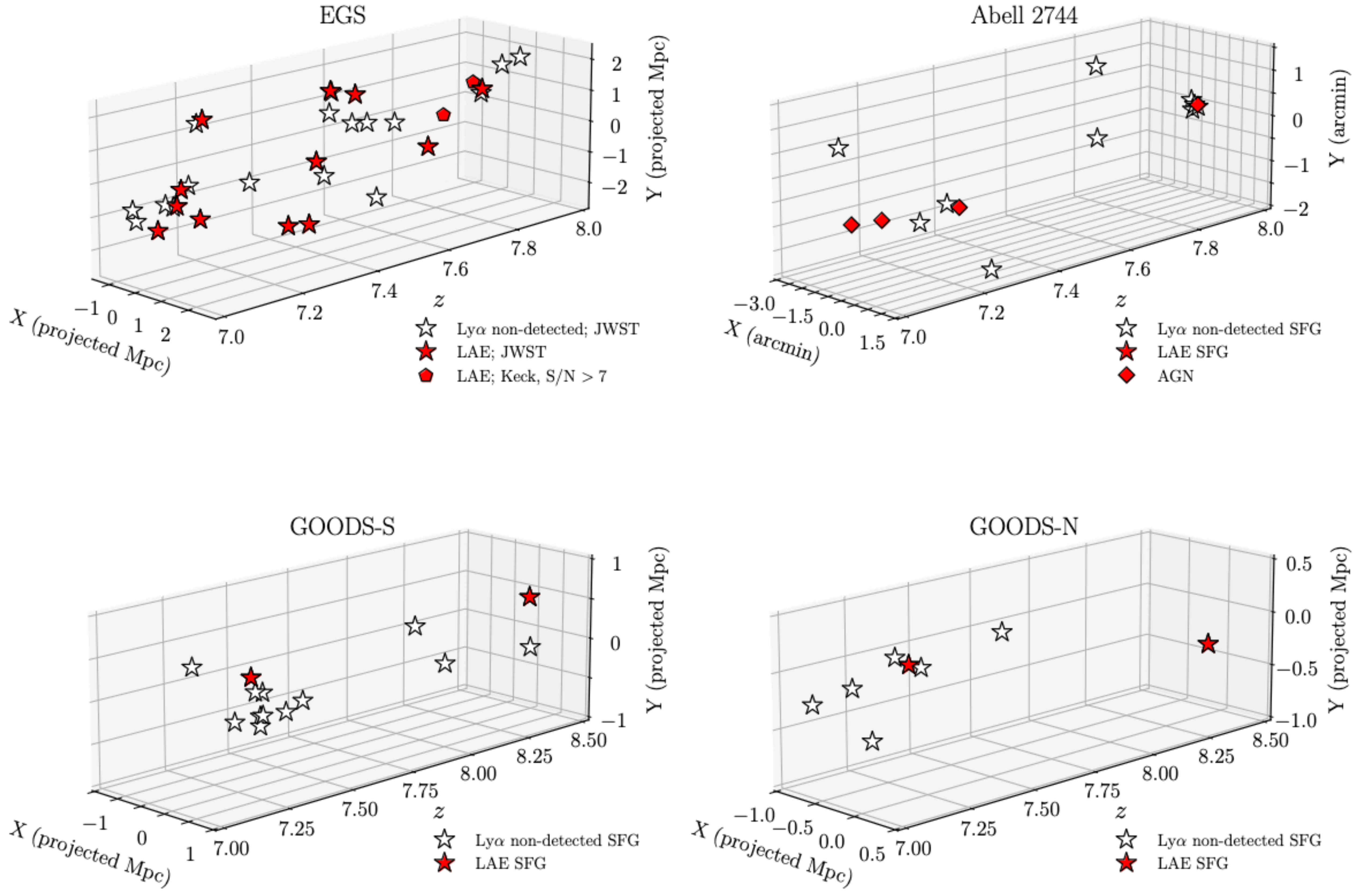


- Strongest Lyα emitters at z~5-6 typically have peak velocities of 150-400 km/s.
- Significant scattering in ISM/CGM, impact of IGM already apparent on Lyα profiles at z~5-6.

Current Status of Lyα Observations at $z>7$

Tang+2024c, in prep (see Tang+2023,Nakane+2024,Napolitano+2024, Jones+2024, Saxena+2023, Tang+2024ab, Chen+2024)

z=7-8



Large set of JWST spectra now publicly-available across 4 different fields.

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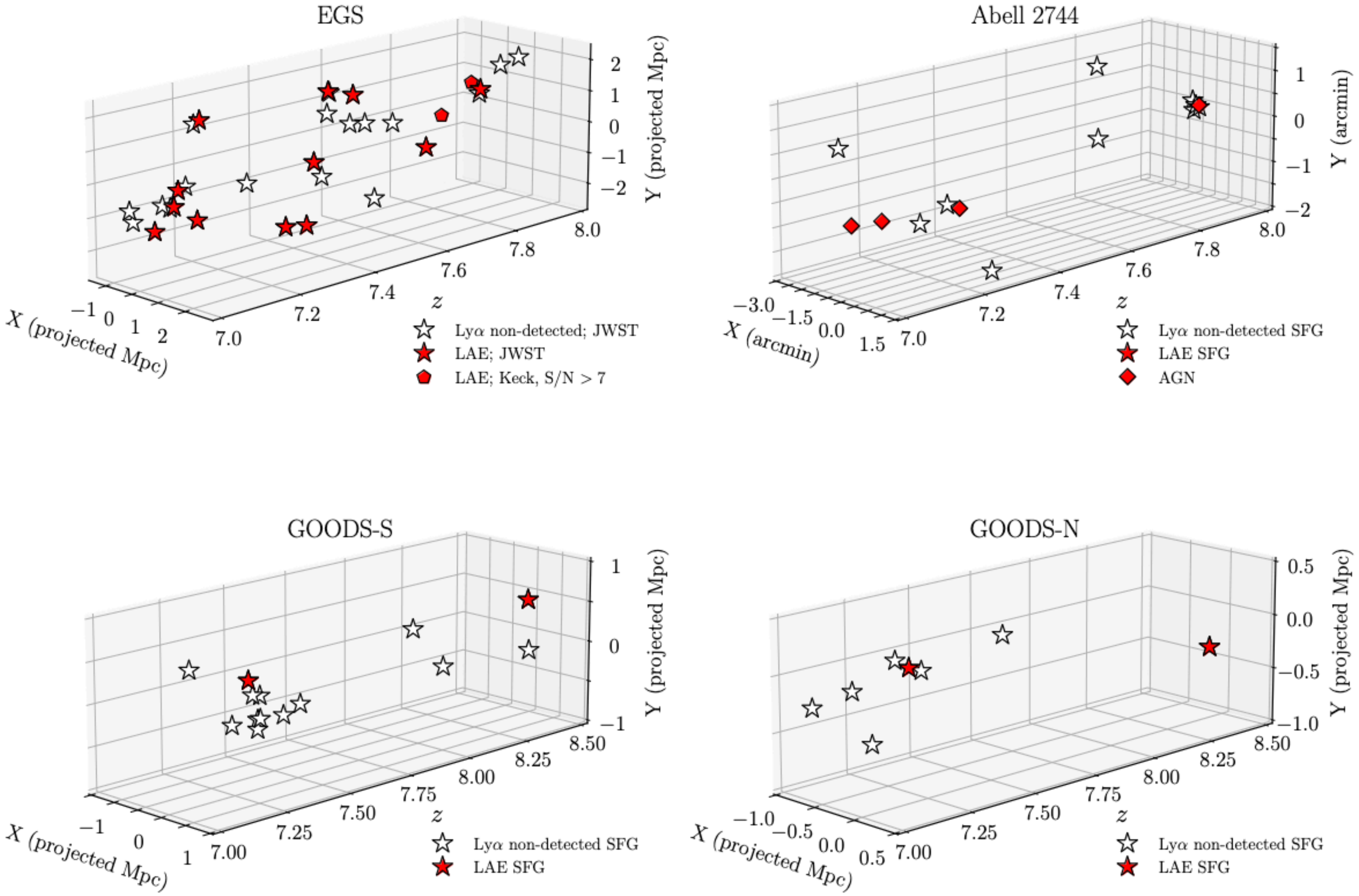


Large set of JWST spectra now publicly-available across 4 different fields.

z=7-8: 59 confirmed galaxies, with 14 showing Lyα

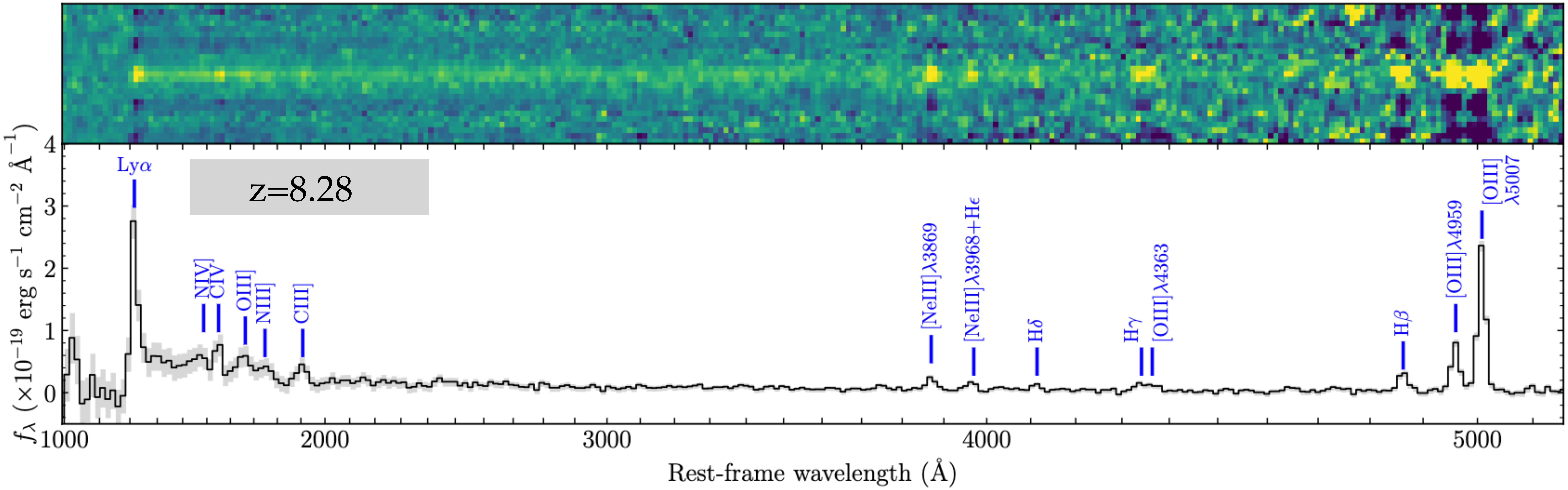
z=8-9: 19 confirmed galaxies, with 5 showing Lyα

z=9-12: 16 confirmed galaxies, with 1 showing Lyα.

*numbers from Tang+2024c (in prep), not including known broad-line AGN, or sources not yet in public archive.

Detections of Extremely Strong Lyα Emission at z~7-8.5

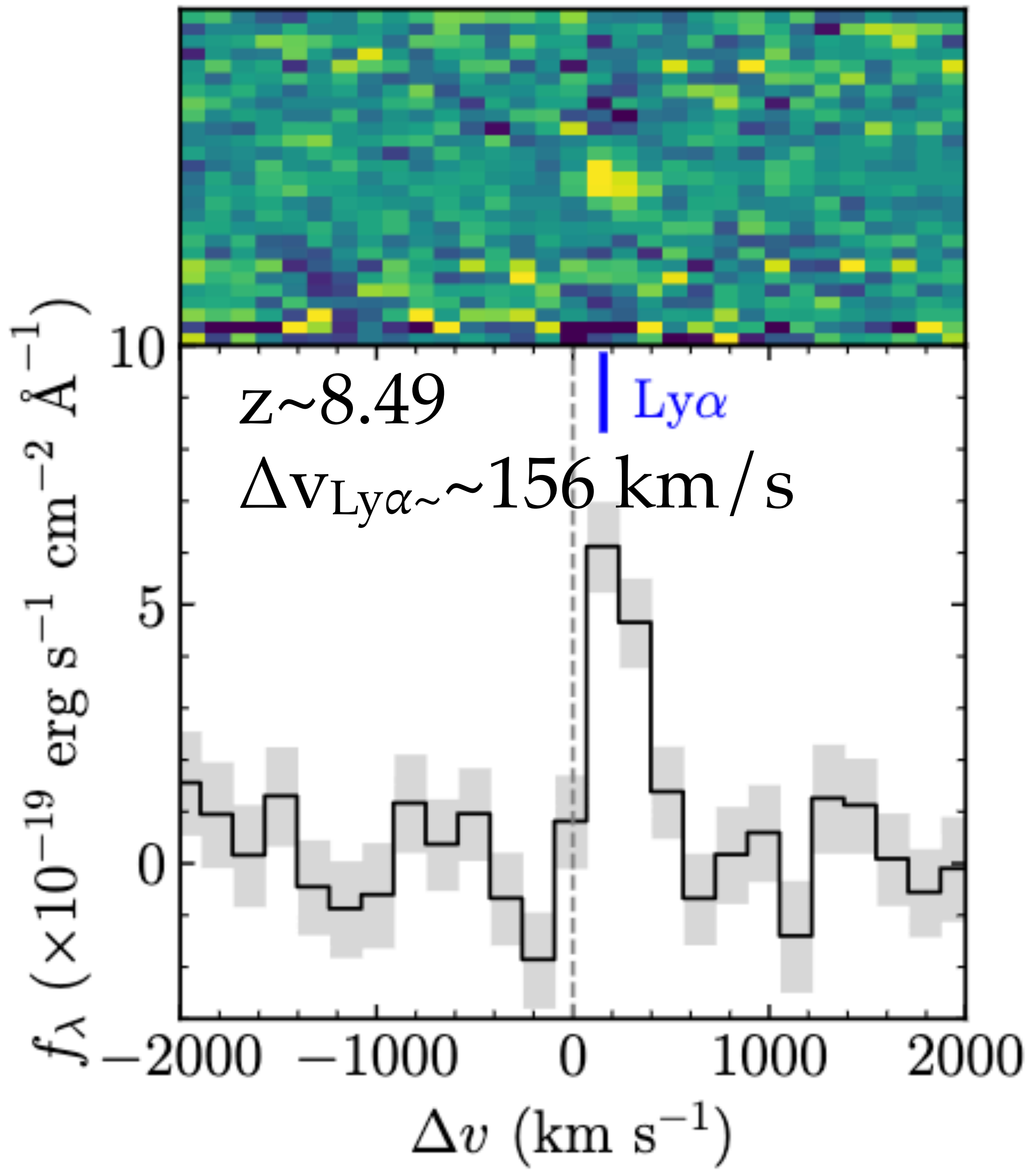
Tang 2024b, Witstok+2024

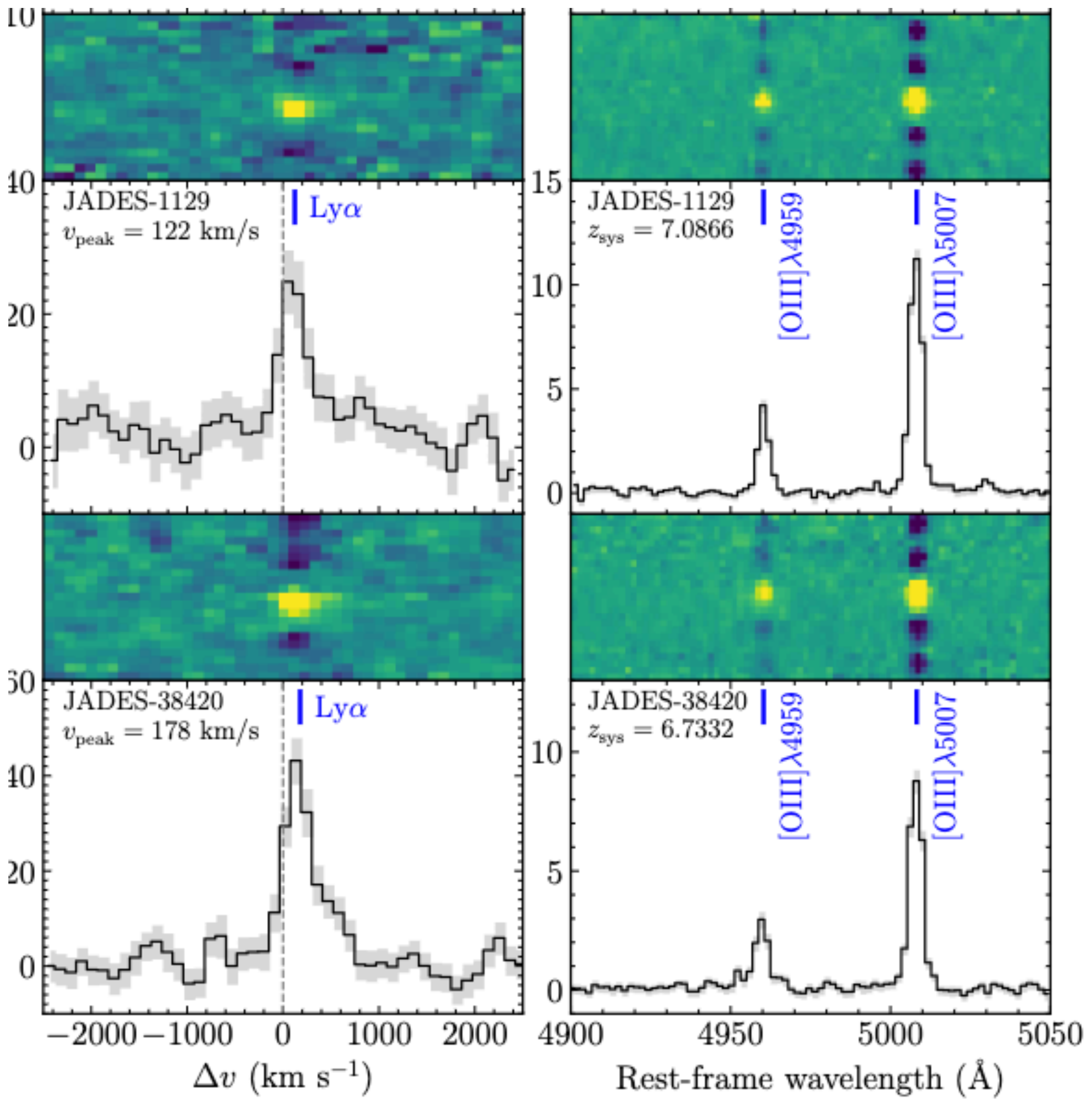


- Strong Lyα emitters (EW=137Å) being found at z~7-8.5, leaking a large fraction of line emission ($f_{esc,Ly\alpha,B}$=0.34).
- Low resolution (R=100) prism can identify very strong Lyα emitters, but struggles at lower S/N and cannot measure velocity profile.

Velocity Profiles of Lyα at z~7-11

Tang+2024a, Witstok+24

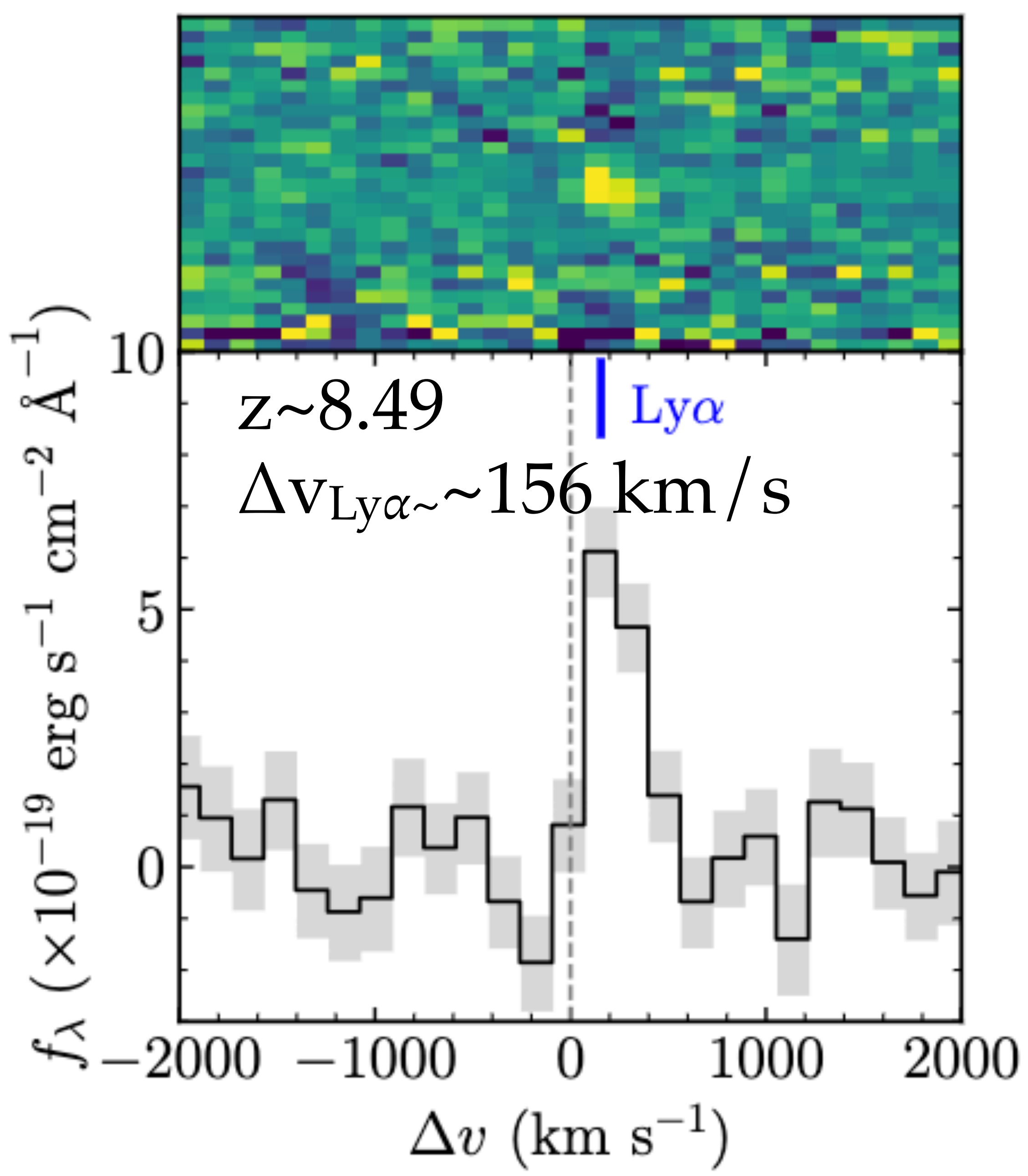


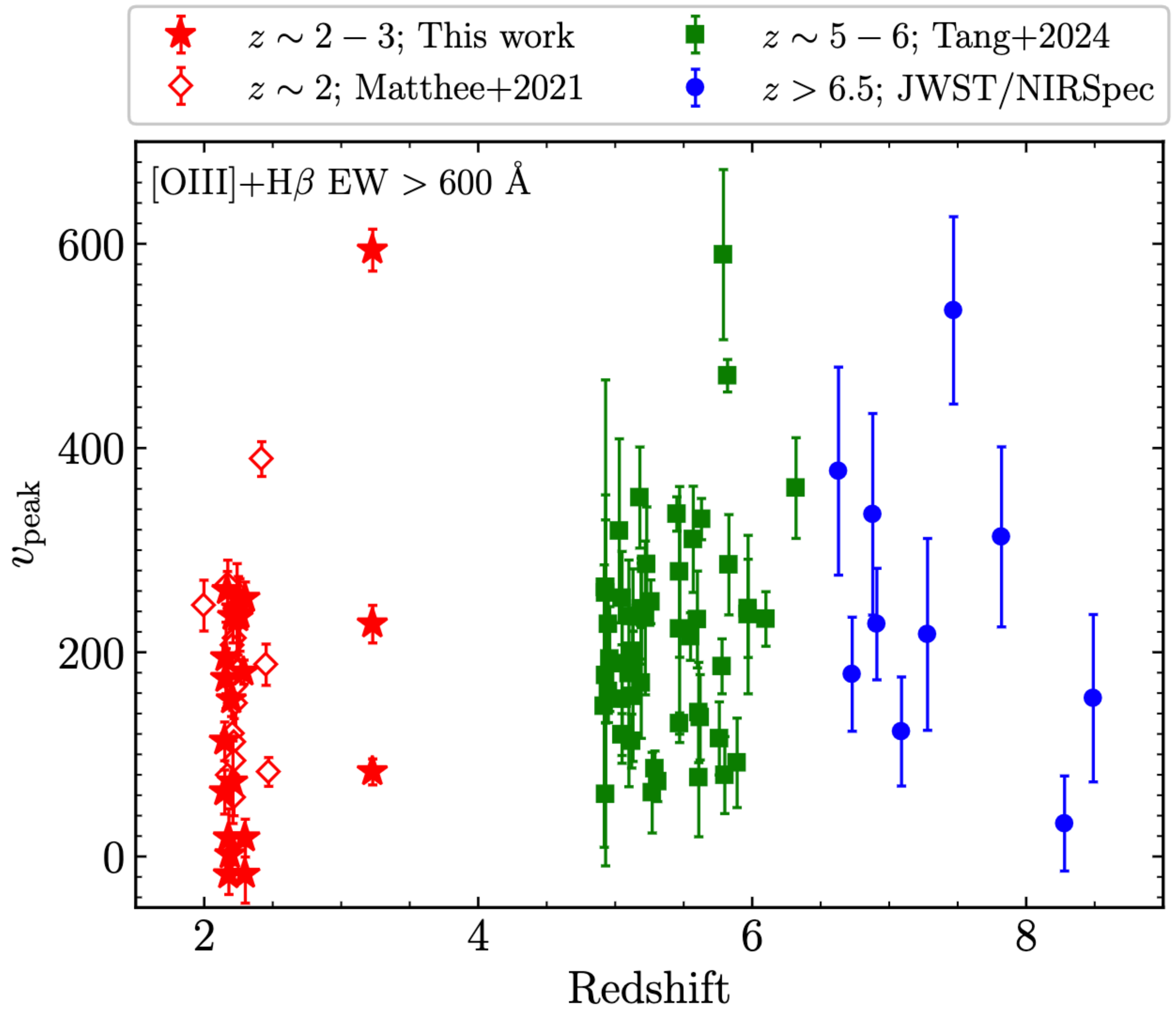


- With higher resolution NIRSpec gratings (R=1000,2700) we can actually measure velocity profiles of Lyα at z~7-11.

Velocity Profiles of Lyα at z~7-11

Tang+2024a, Witstok+24

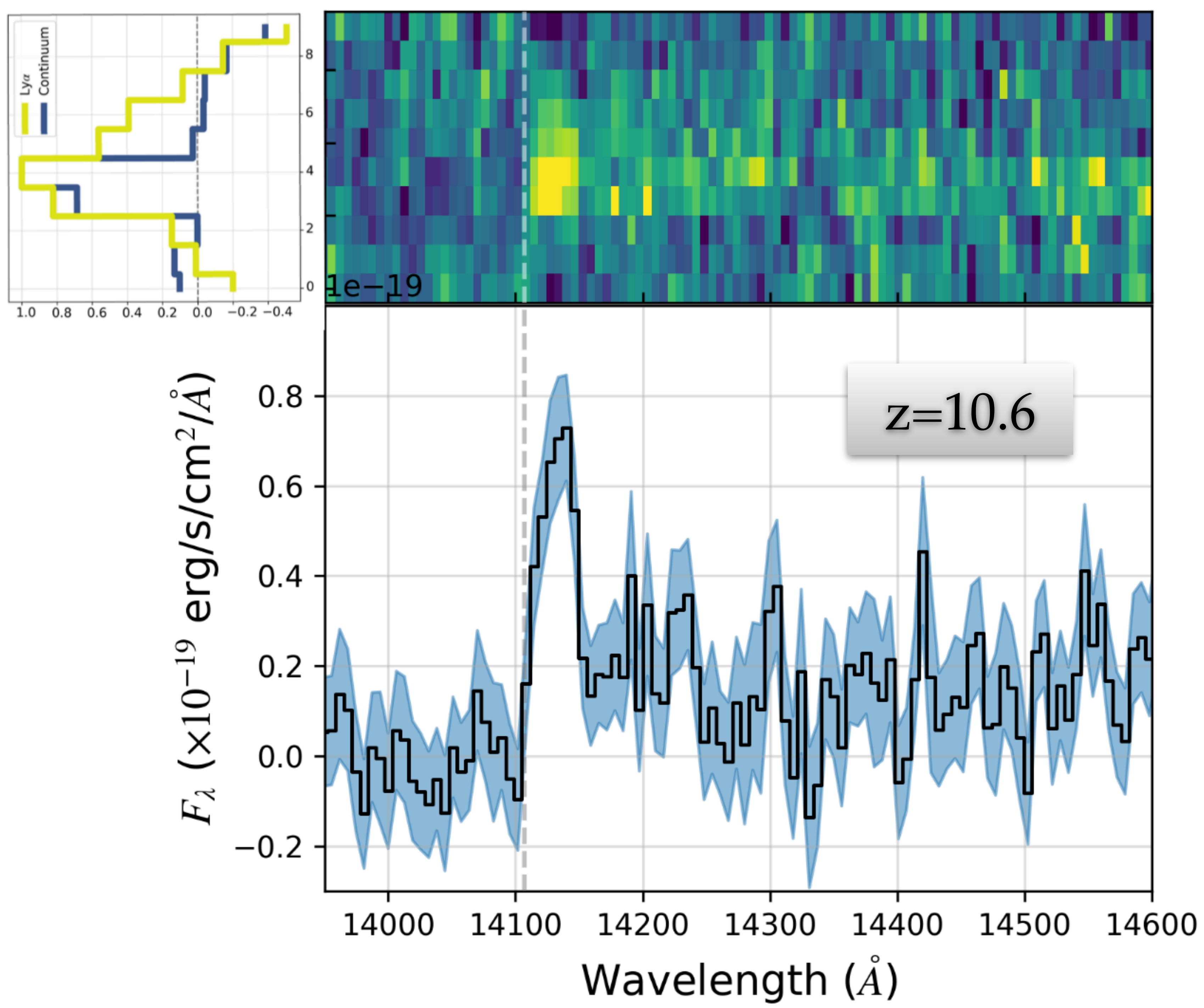




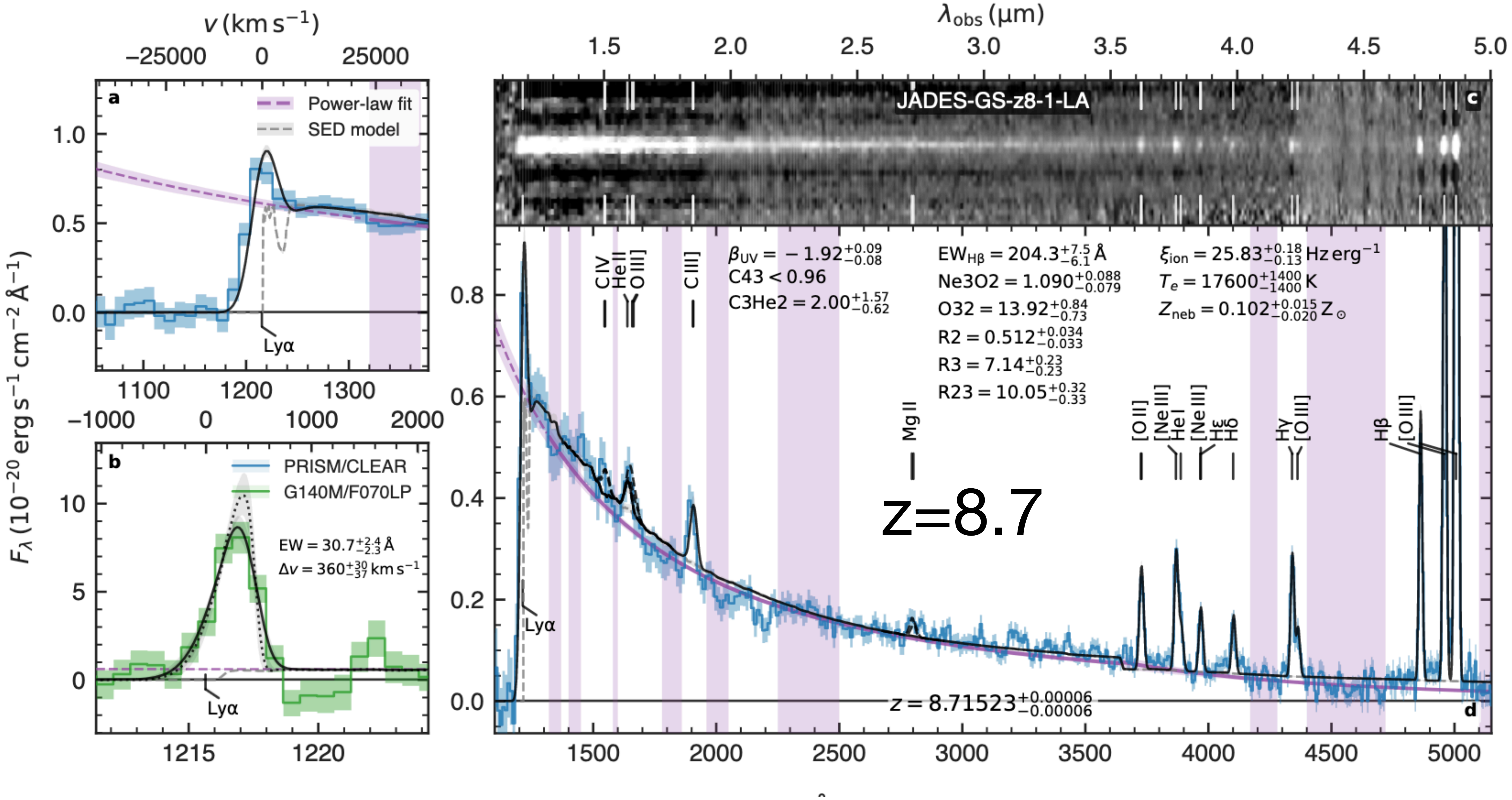
- With higher resolution NIRSpec gratings (R=1000,2700) we can actually measure velocity profiles of Lyα at z~7-11.
- 10 measurements at z>7 thus far, nearly all large peak offsets ($\Delta v_{Ly\alpha}$>150 km/s).

What about Lyα Detections at z>8.5?

Bunker+2023



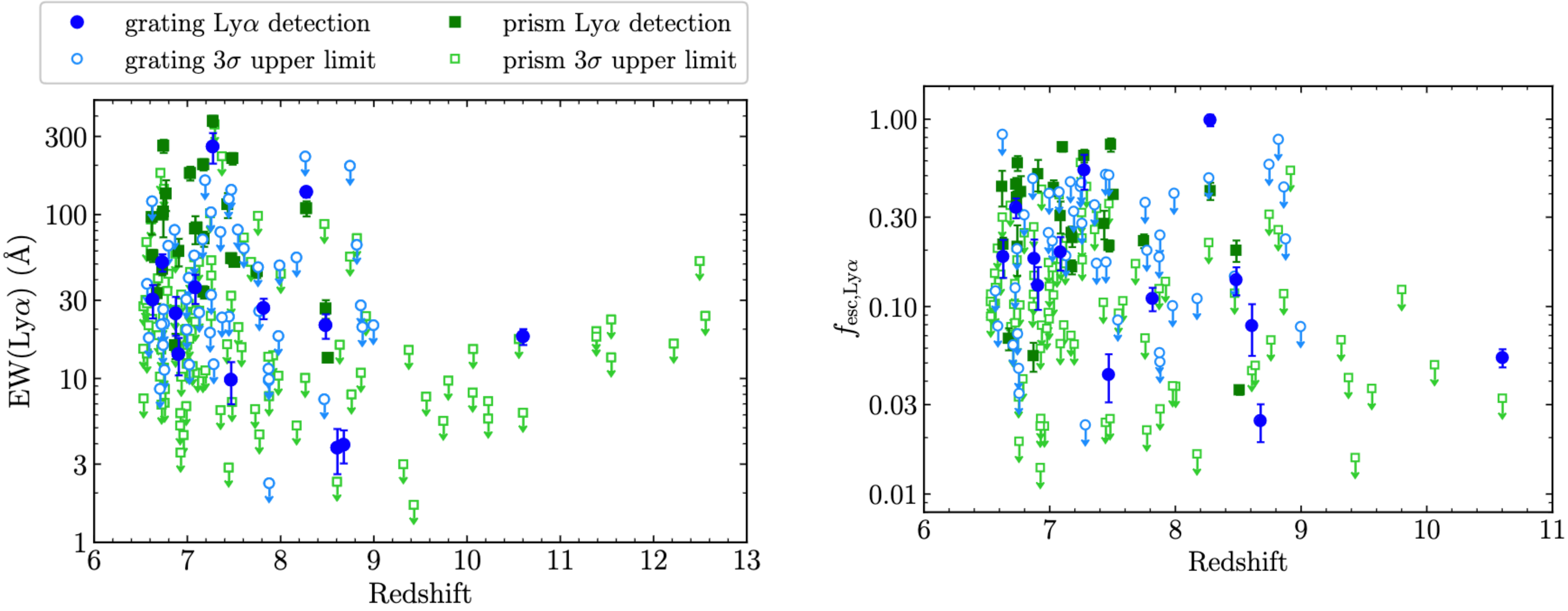
Witstok+2024



- Small number of detections (including GNz11 at z=10.6), but all with fairly weak line emission (< 30Å).

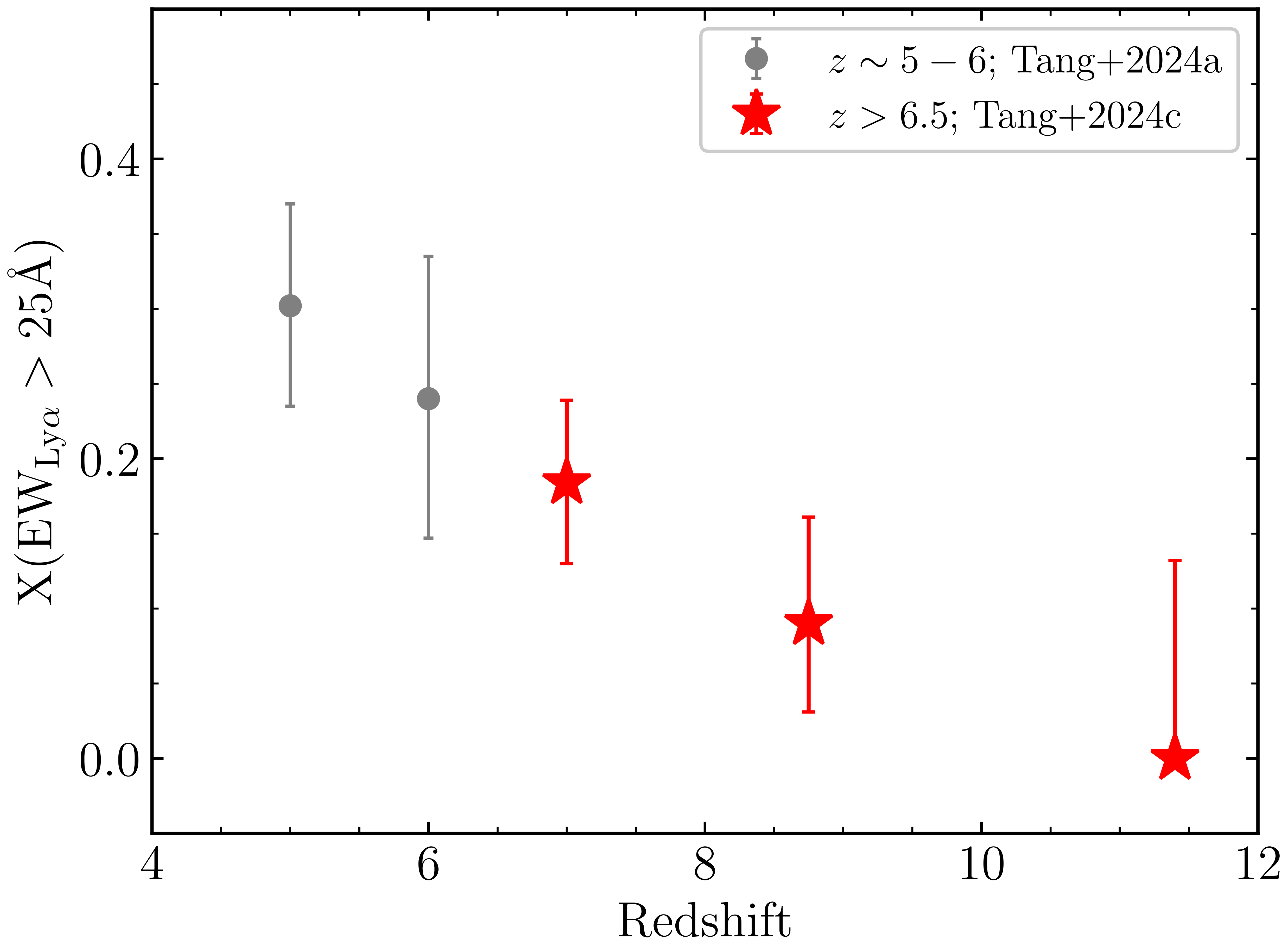
Current Status of Lyα Observations at z>7

Tang+2024c, in prep (see Tang+2023,Nakane+2024,Napolitano+2024, Jones+2024, Saxena+2023, Tang+2024ab, Chen+2024)



Quantifying Evolution of Lyα Emission

Tang+2024c, in prep (see Nakane+2024, Napolitano+2024, Jones+2024, Chen+2024)



- JWST is confirming attenuation in Lyα emission with much-improved reliability.

Quantifying Evolution of Lyα Emission

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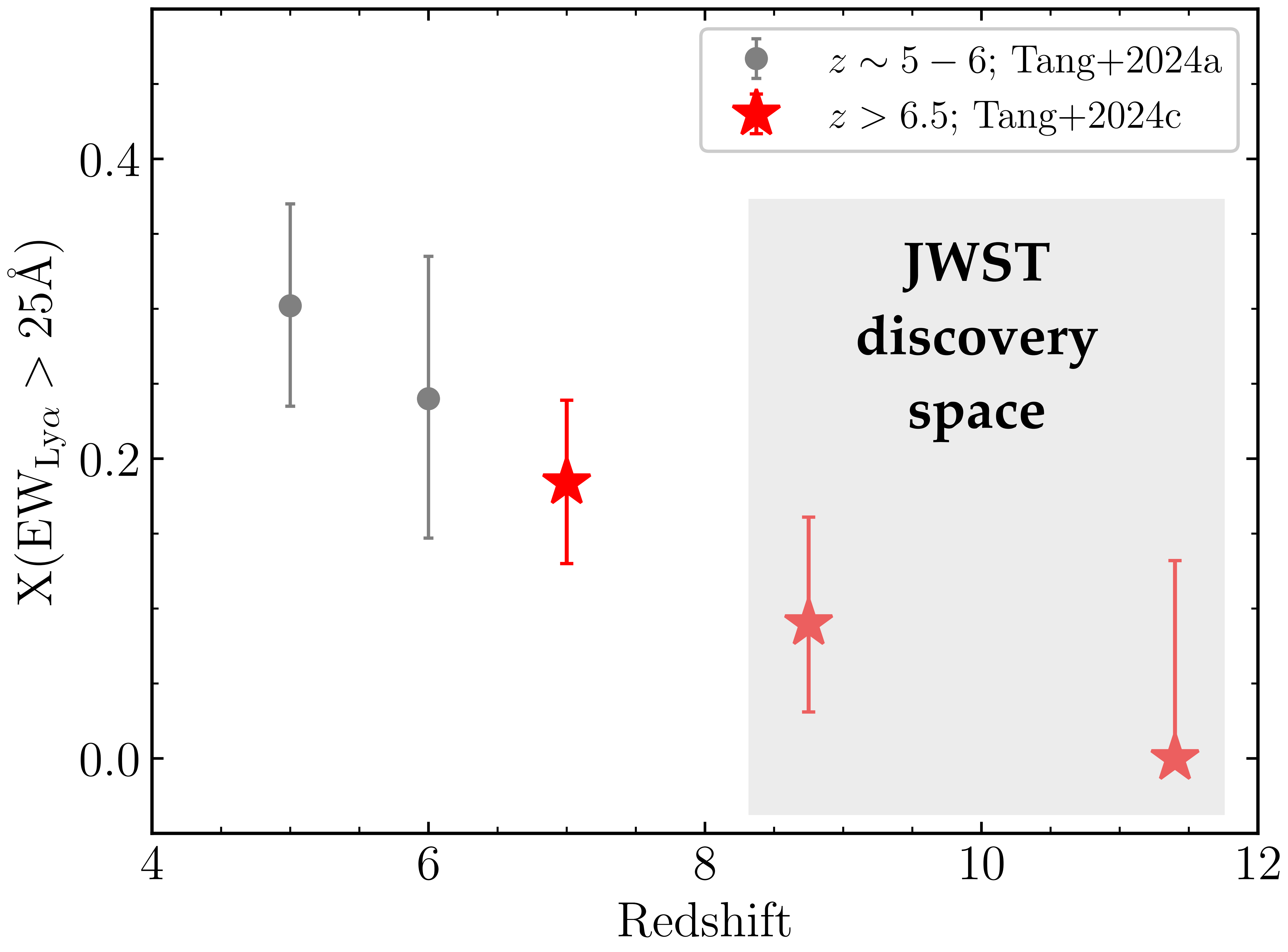
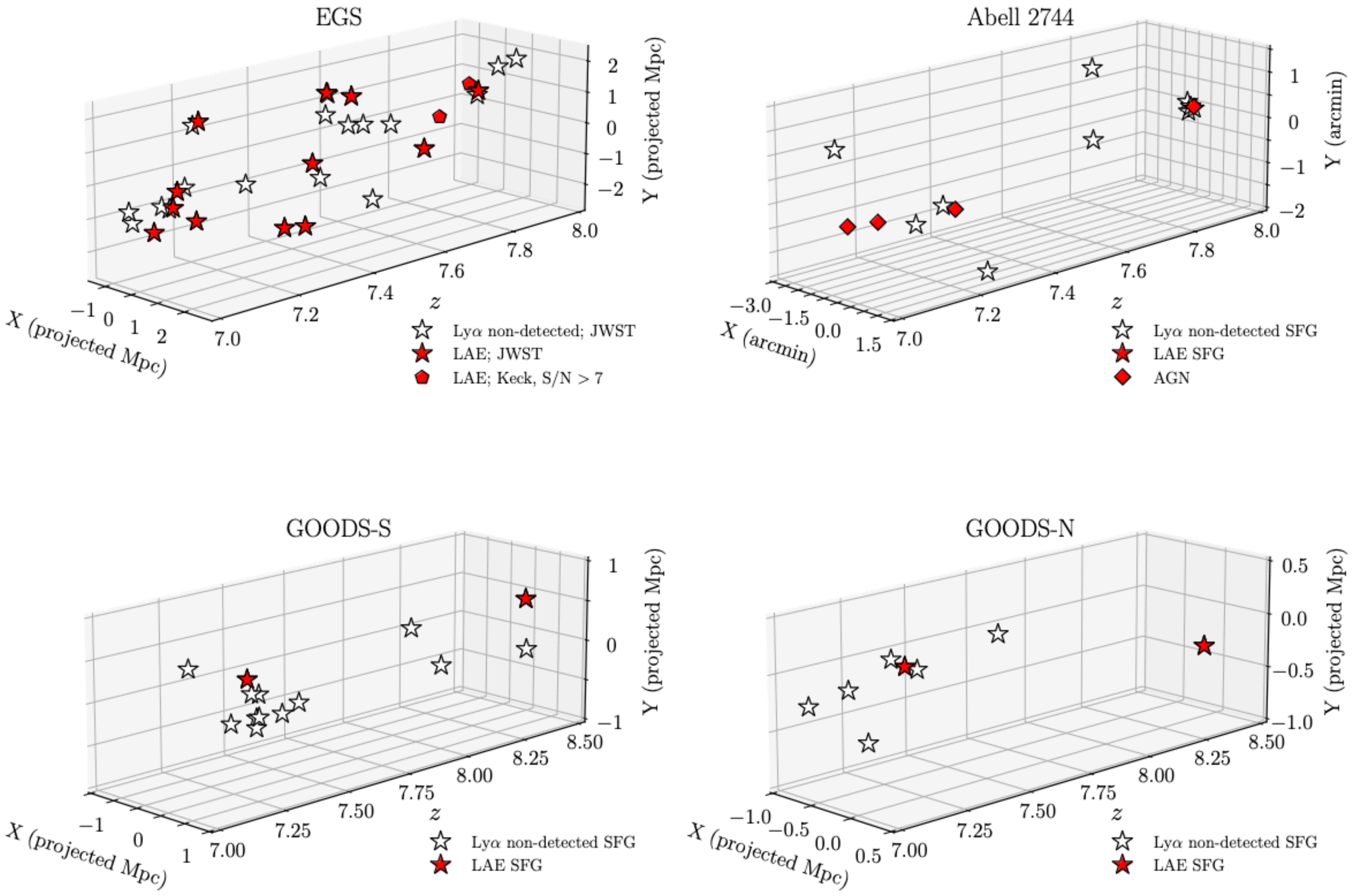


- JWST is confirming attenuation in Lyα emission with much-improved reliability.
- Already pushing Lyα visibility test to z~8-11 — significant improvements in statistics (and extension to z>12-15) will come soon.
- If we can improve mapping to x_{HI}, JWST will be able to probe very early reionization.

Lyman alpha Transmission in the CEERS/EGS Field

Tang+2024c

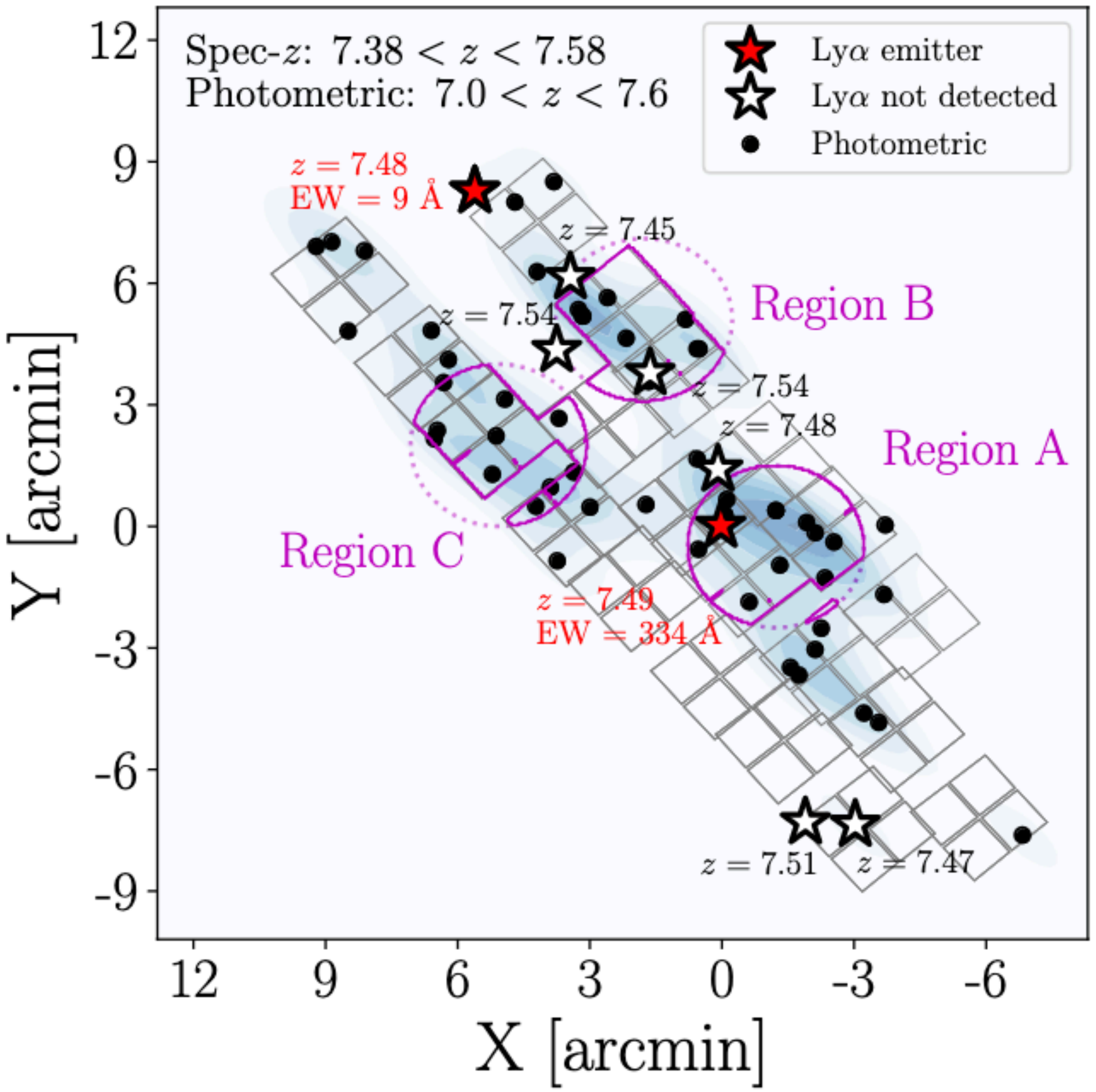


- If we look at four JWST deep fields, we see significant field to field variations in Lyα detections at z~7-8.
- One field (EGS, observed with CEERS) shows far more Lyα detections.

(see Nakane+2024, Napolitano+2024)

Lyman alpha Transmission in the CEERS/EGS Field

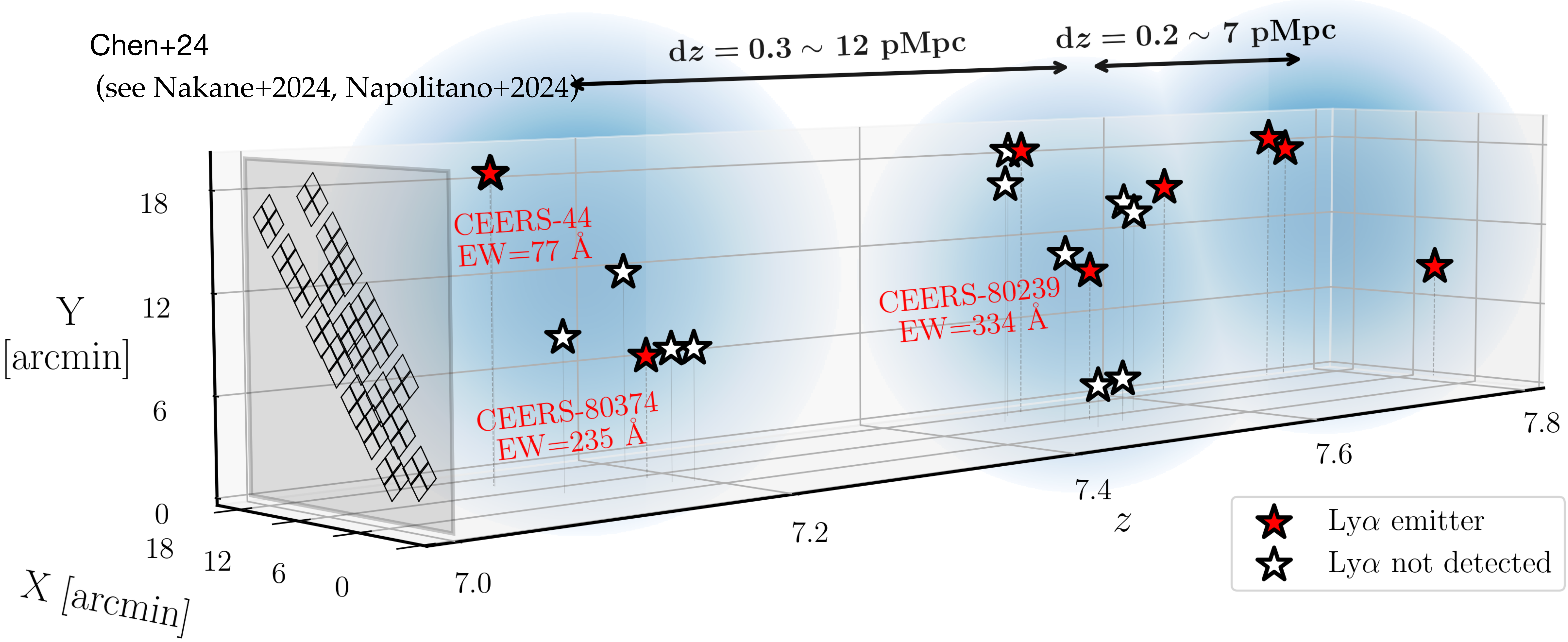
Chen+2024



- If we look at four JWST deep fields, we see significant field to field variations in Lyα detections at z~7-8.
- One field (EGS, observed with CEERS) shows far more Lyα detections.
- And shows evidence for a significant galaxy overdensity.

(see Nakane+2024, Napolitano+2024)

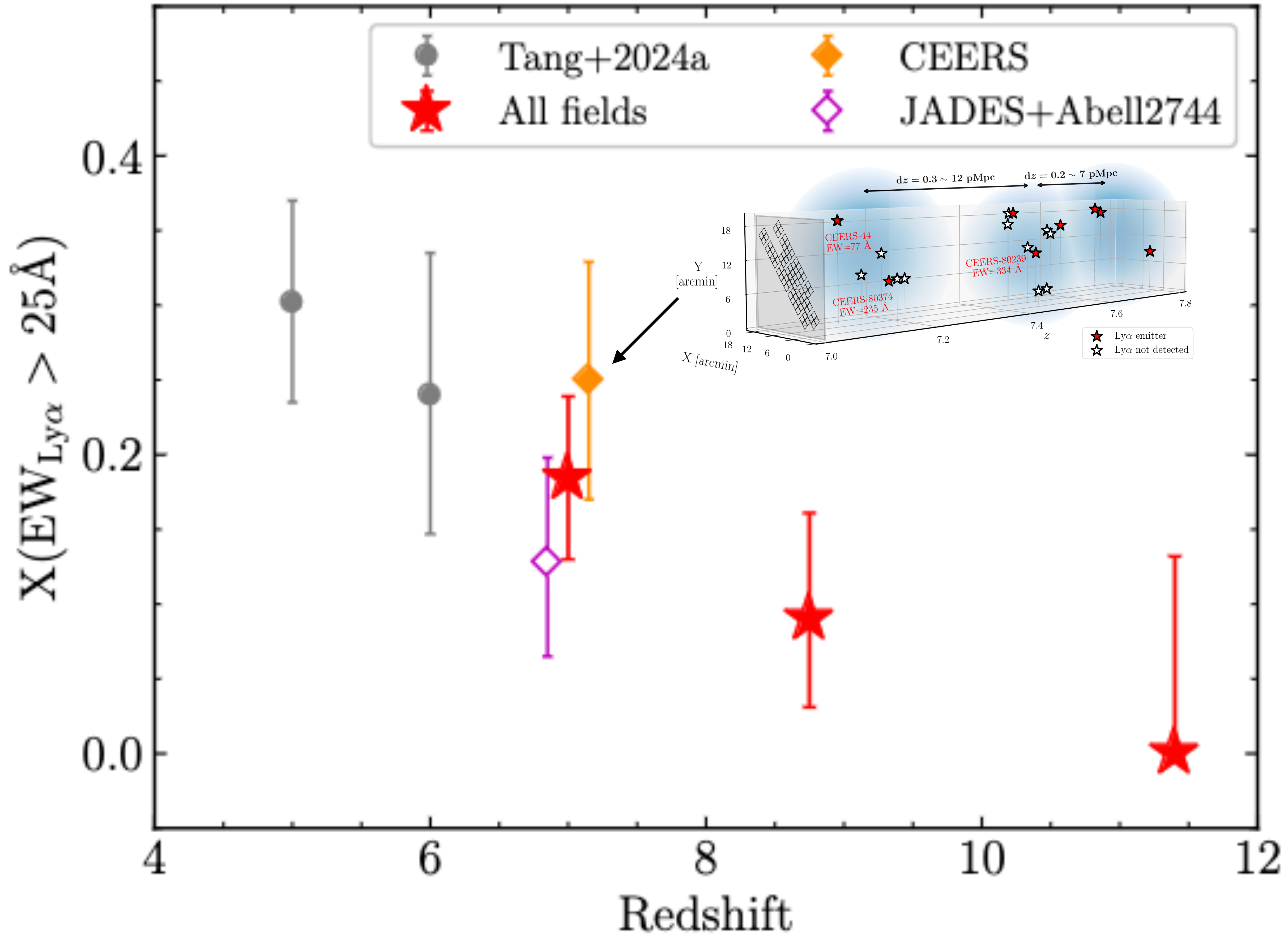
Strong Lyman alpha Emission in the CEERS/EGS Field



- Many of the Lyα lines in this field show extremely large EWs, potentially suggesting little attenuation from the IGM.
- We can derive Lyα EW distribution in this sightline.

Lyman alpha Transmission in the CEERS/EGS Field

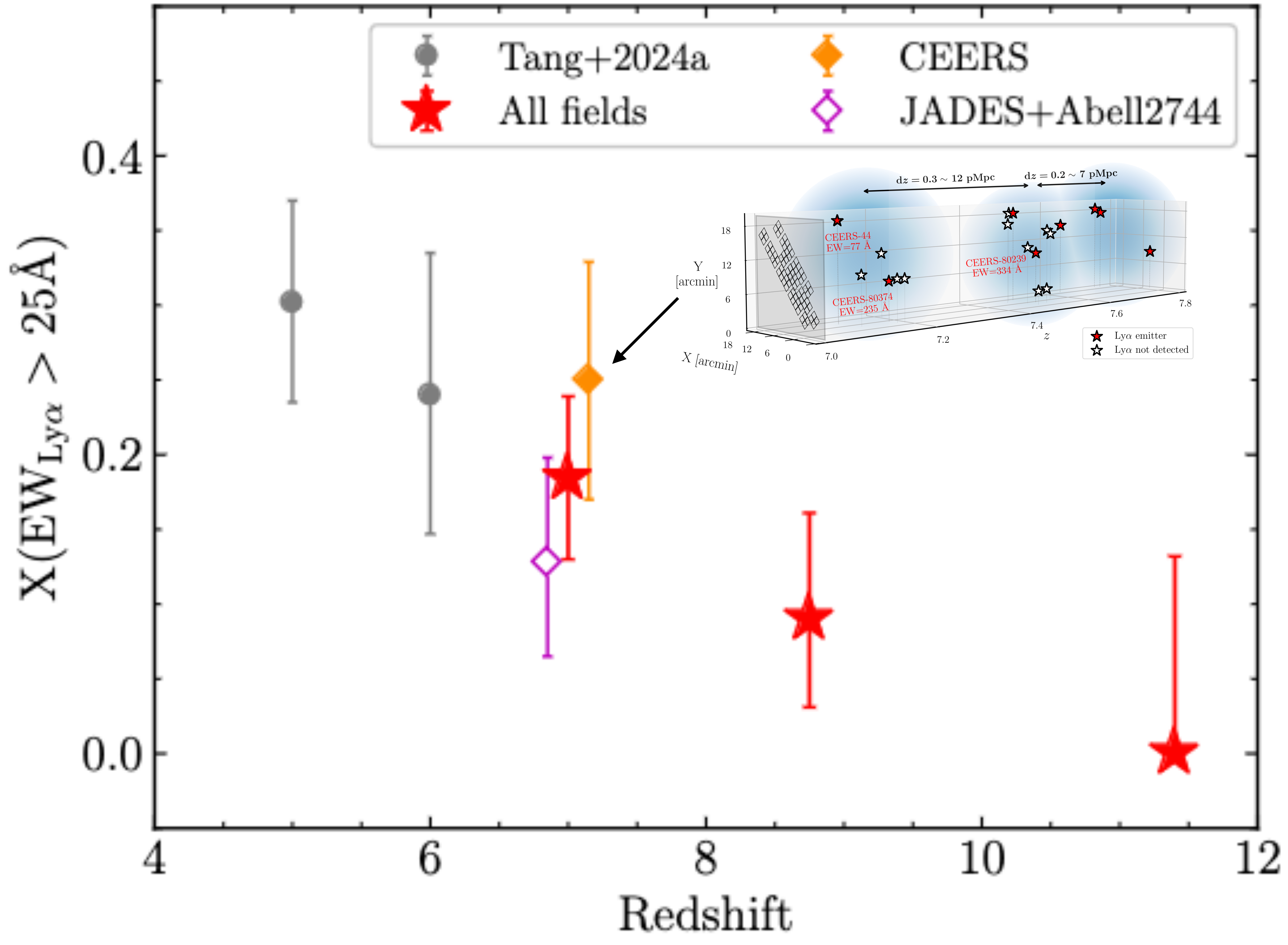
Tang+2024c (see Nakane+2024, Napolitano+2024)



- Lyα emitter fraction is in excess of that found in other JWST fields.

Lyman alpha Transmission in the CEERS/EGS Field

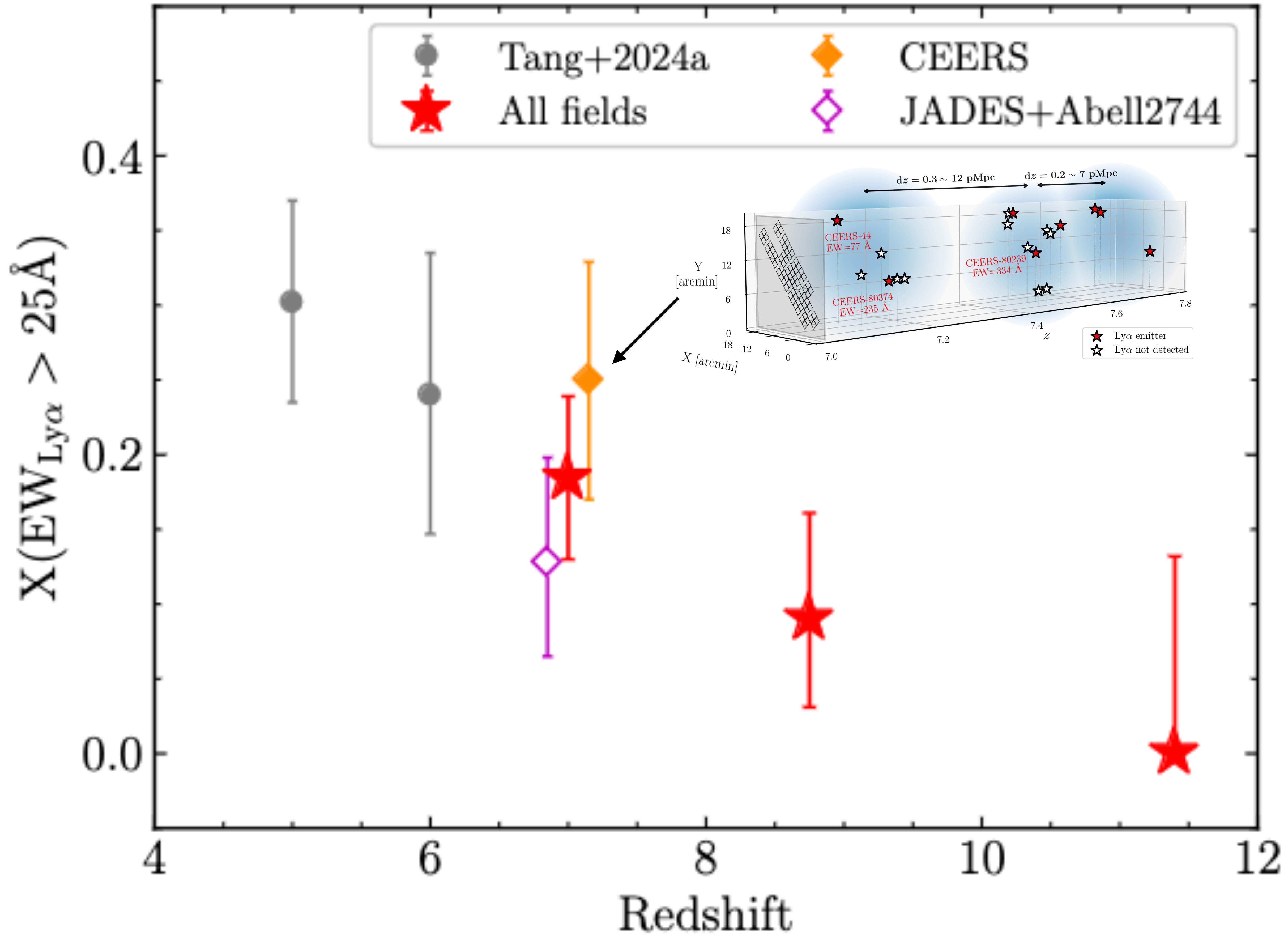
Tang+2024c (see Nakane+2024, Napolitano+2024)



- Lyα emitter fraction is in excess of that found in other JWST fields.
- And the Lyα emitter fraction in this z~7-8 region does not appear any lower than that at z~6.
- Excellent bubble candidate!

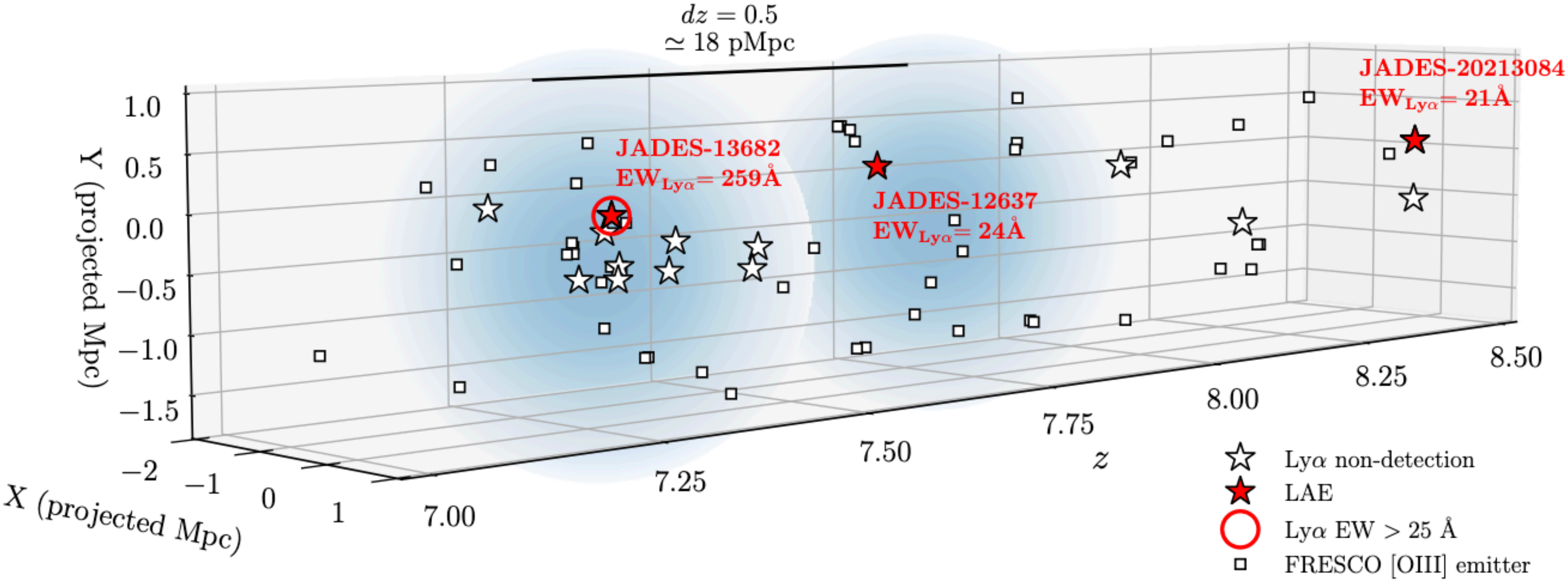
Lyman alpha Transmission in the CEERS/EGS Field

Tang+2024c (see Nakane+2024, Napolitano+2024)



- Lyα emitter fraction is in excess of that found in other JWST fields.
- And the Lyα emitter fraction in this z~7-8 region does not appear any lower than that at z~6.
- Excellent bubble candidate!
- Expect this field to be better characterized in near future, and more of these to be identified in years to come.

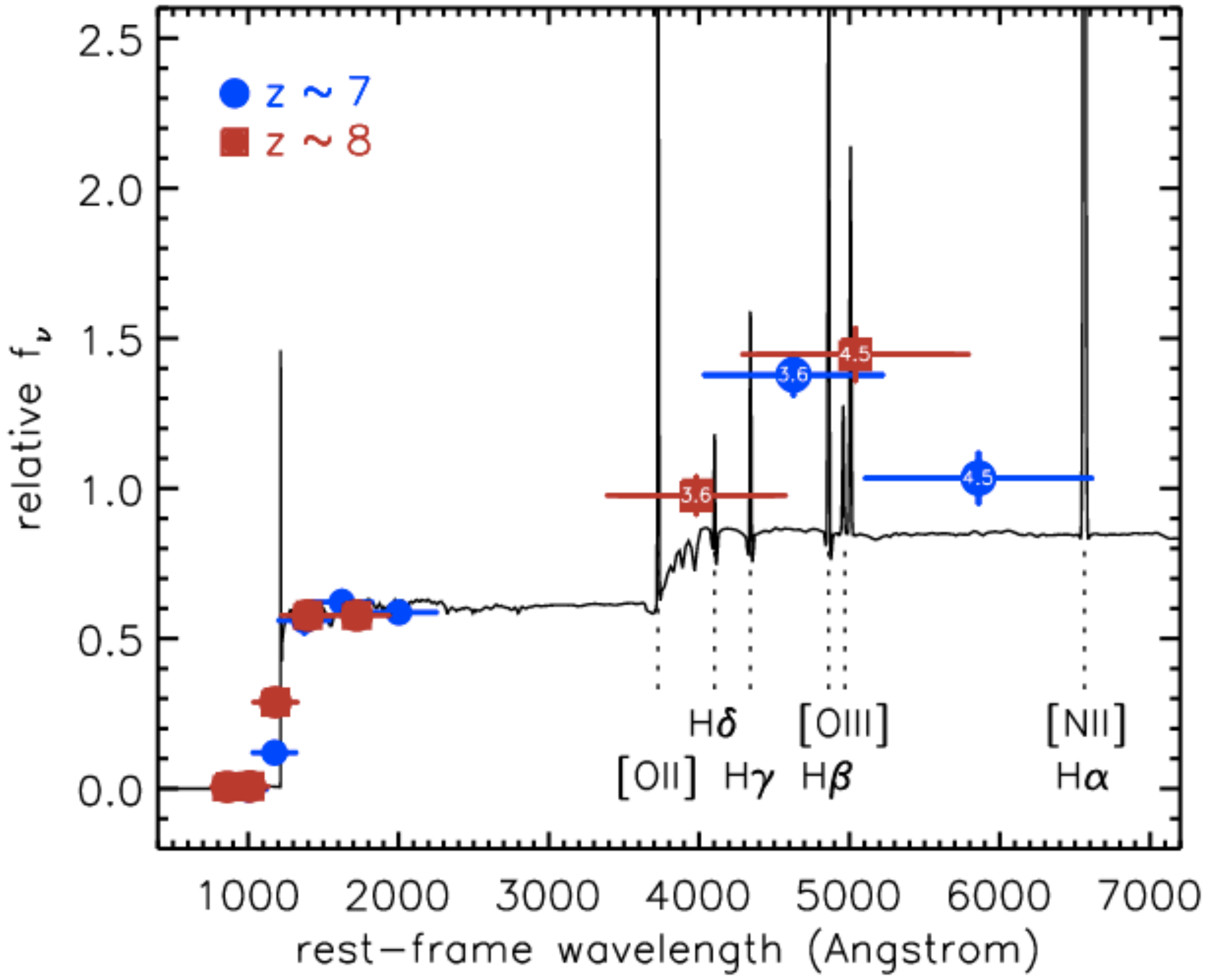
The Next Step: Map Galaxies around Lyα Emitters



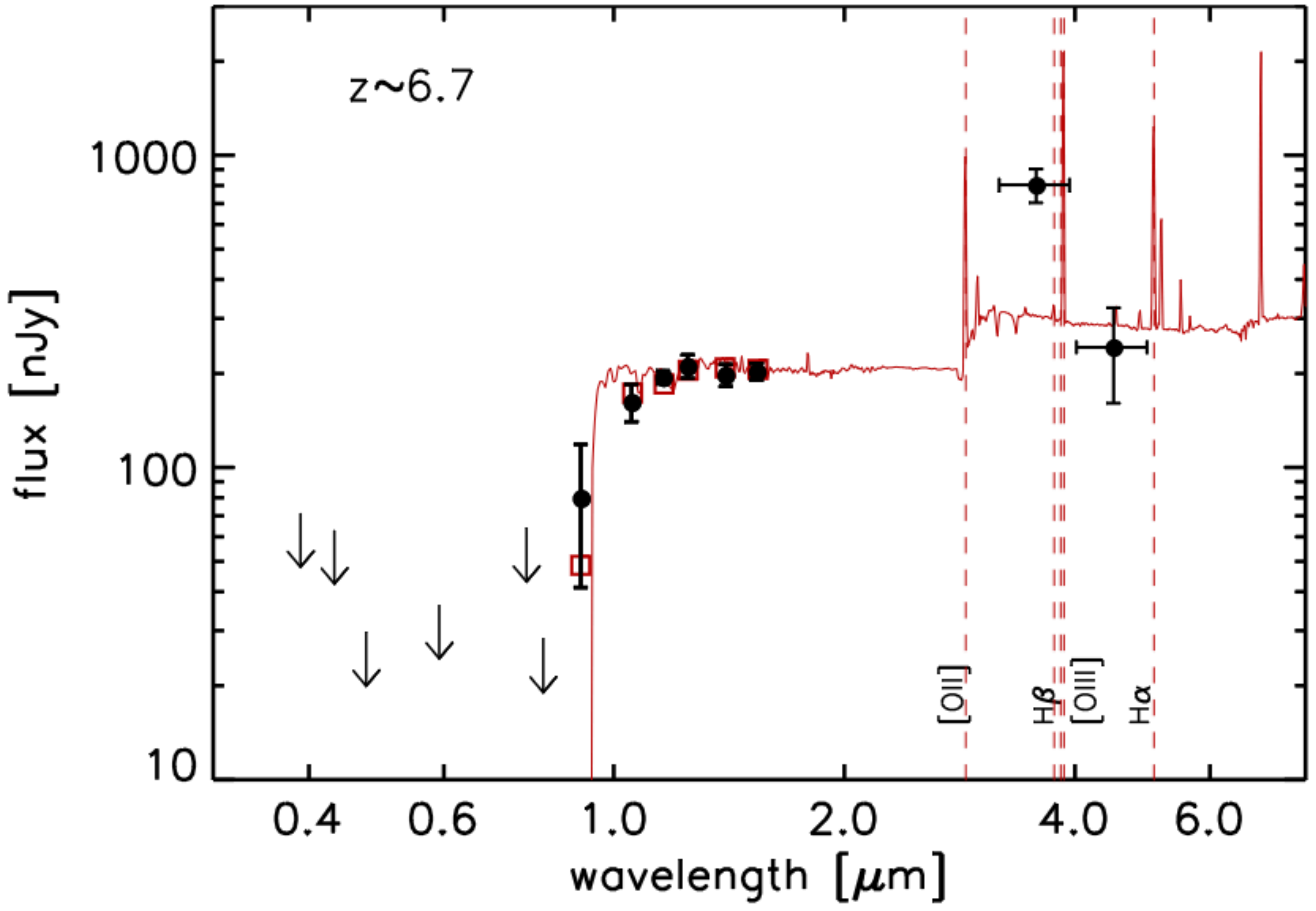
What are we learning about ionizing nature of galaxies?

Prior to JWST: Strong [OIII]+H-beta EW from Spitzer

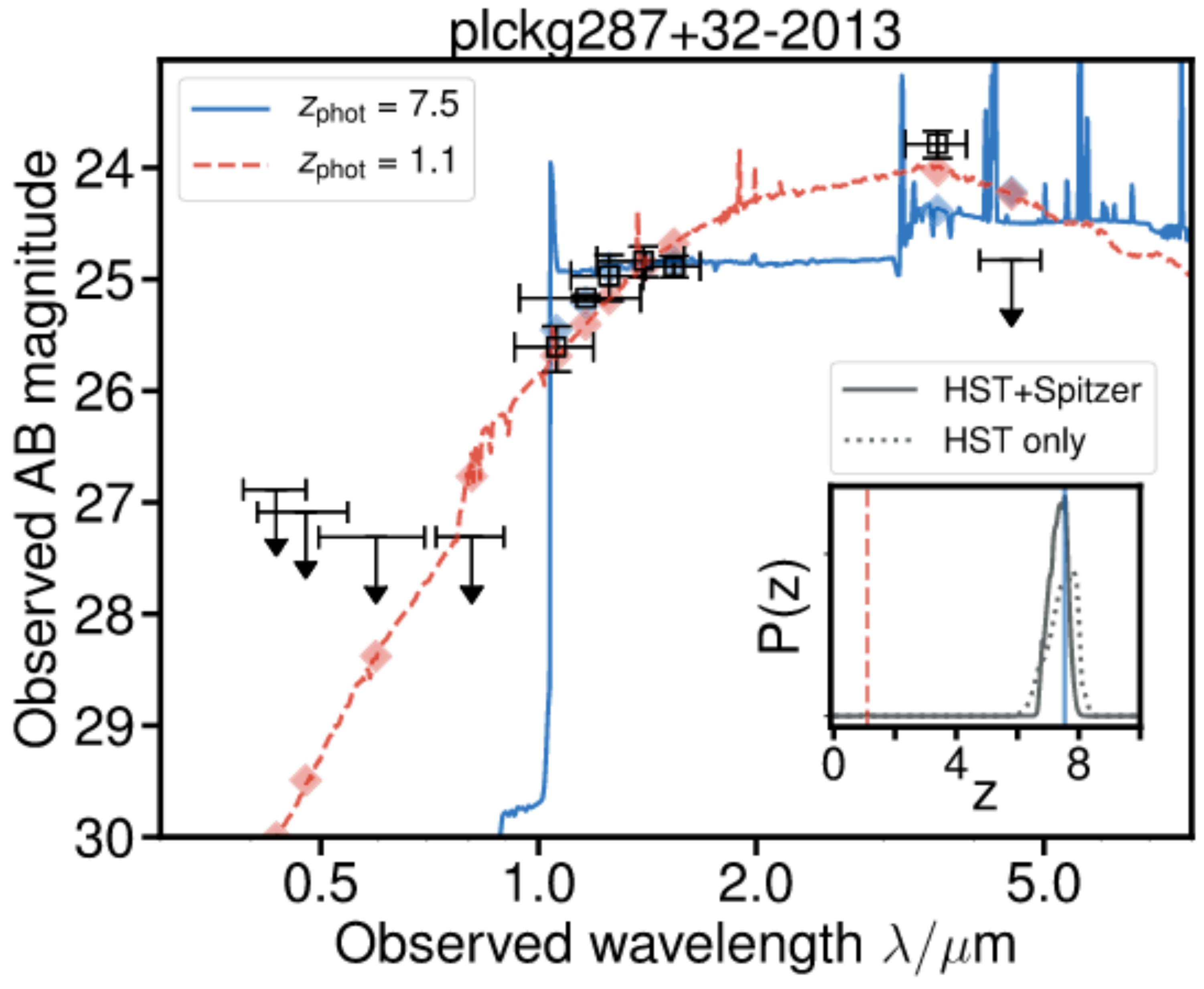
Labbé+2013



Smit+2014

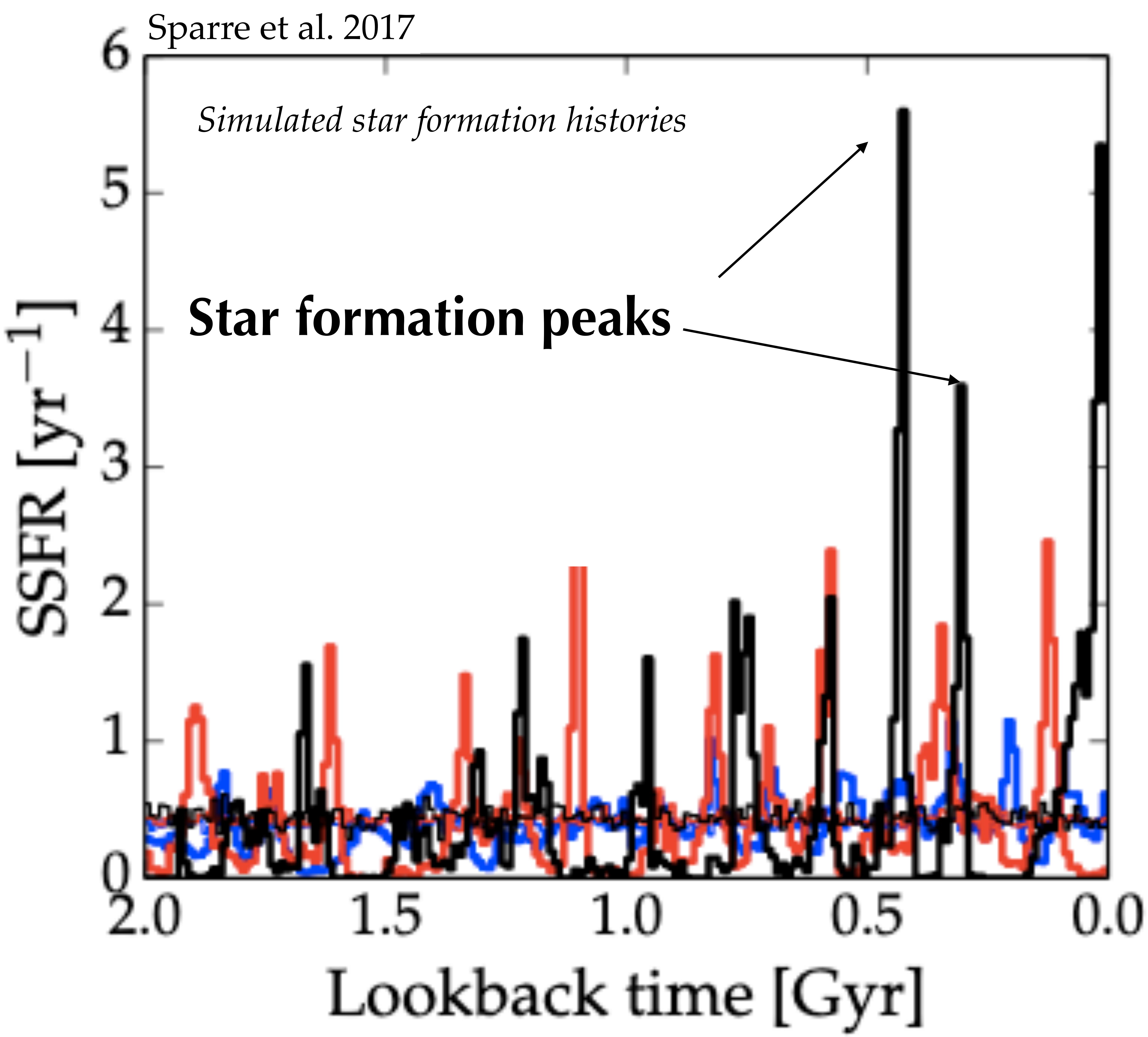


Strait+2021



- Spitzer flux excesses indicated strong [OIII] and H-beta emission at z>6 (EW>1000Å) — indicative of young stellar populations formed in a recent burst.

Prior to JWST: Strong [OIII]+H-beta EW from Spitzer

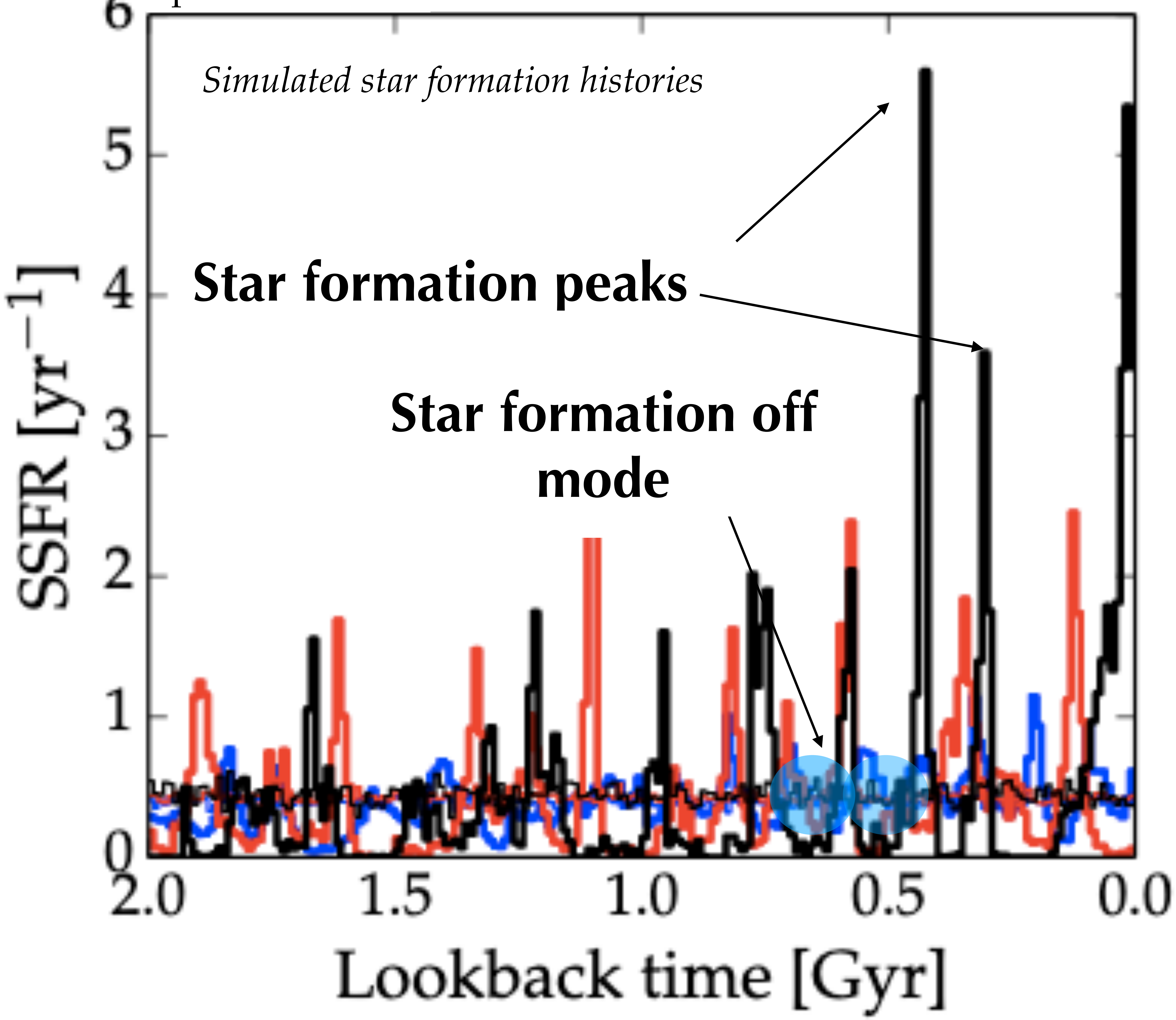


- When galaxies are observed in these burst phases (large [OIII]+H-beta EW), they are very efficient ionizing agents!

- Pre-JWST view: early galaxies have high ξ_{ion}
  (i.e., Stark+15,17, Bouwens+16,Tang+19, Endsley+21)

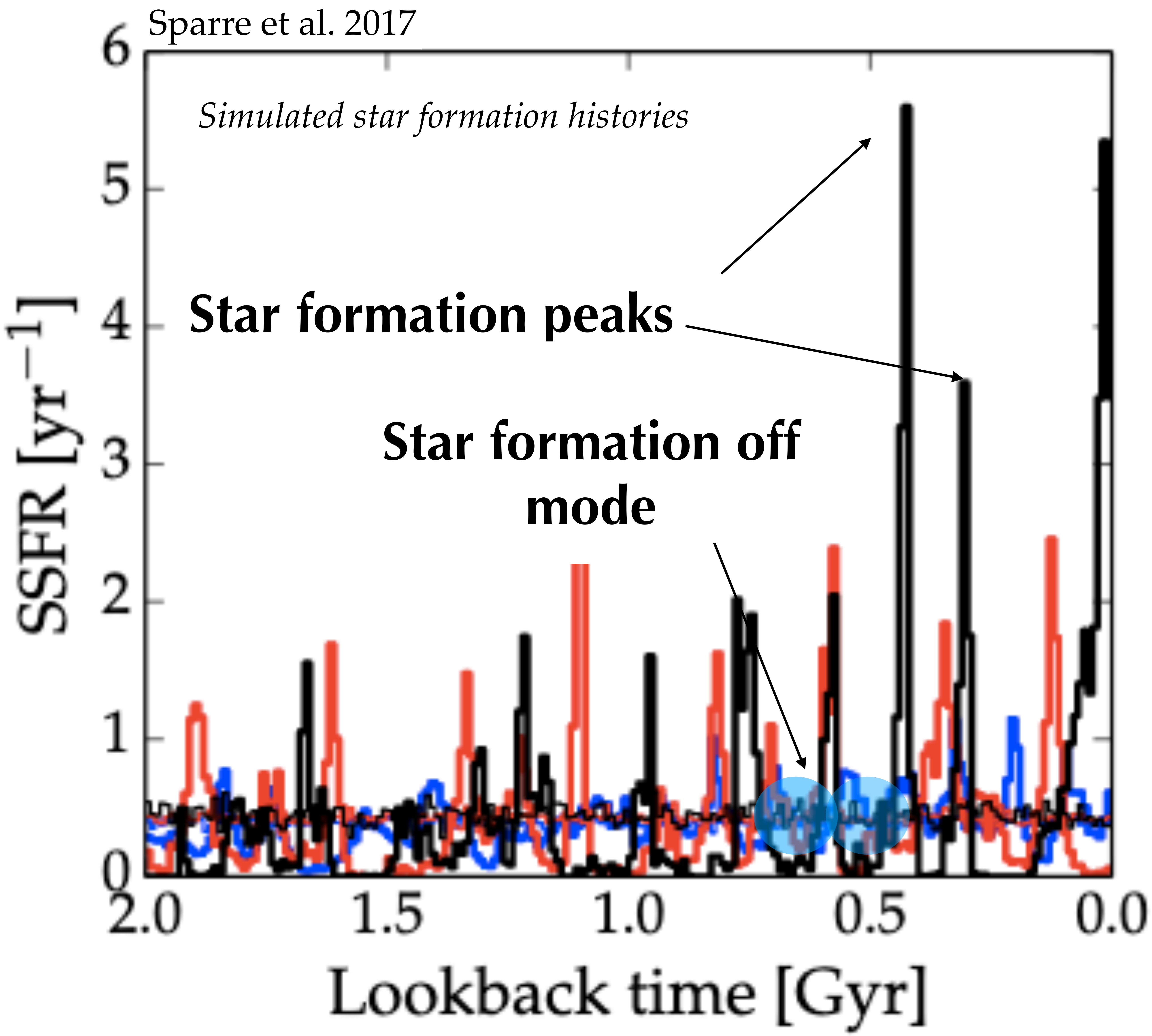
Prior to JWST: Strong [OIII]+H-beta EW from Spitzer

Sparre et al. 2017



- After burst, galaxies should grow fainter, emission lines should weaken — ξ_{ion} should decrease.
- Do we see evidence for **star formation off mode?**

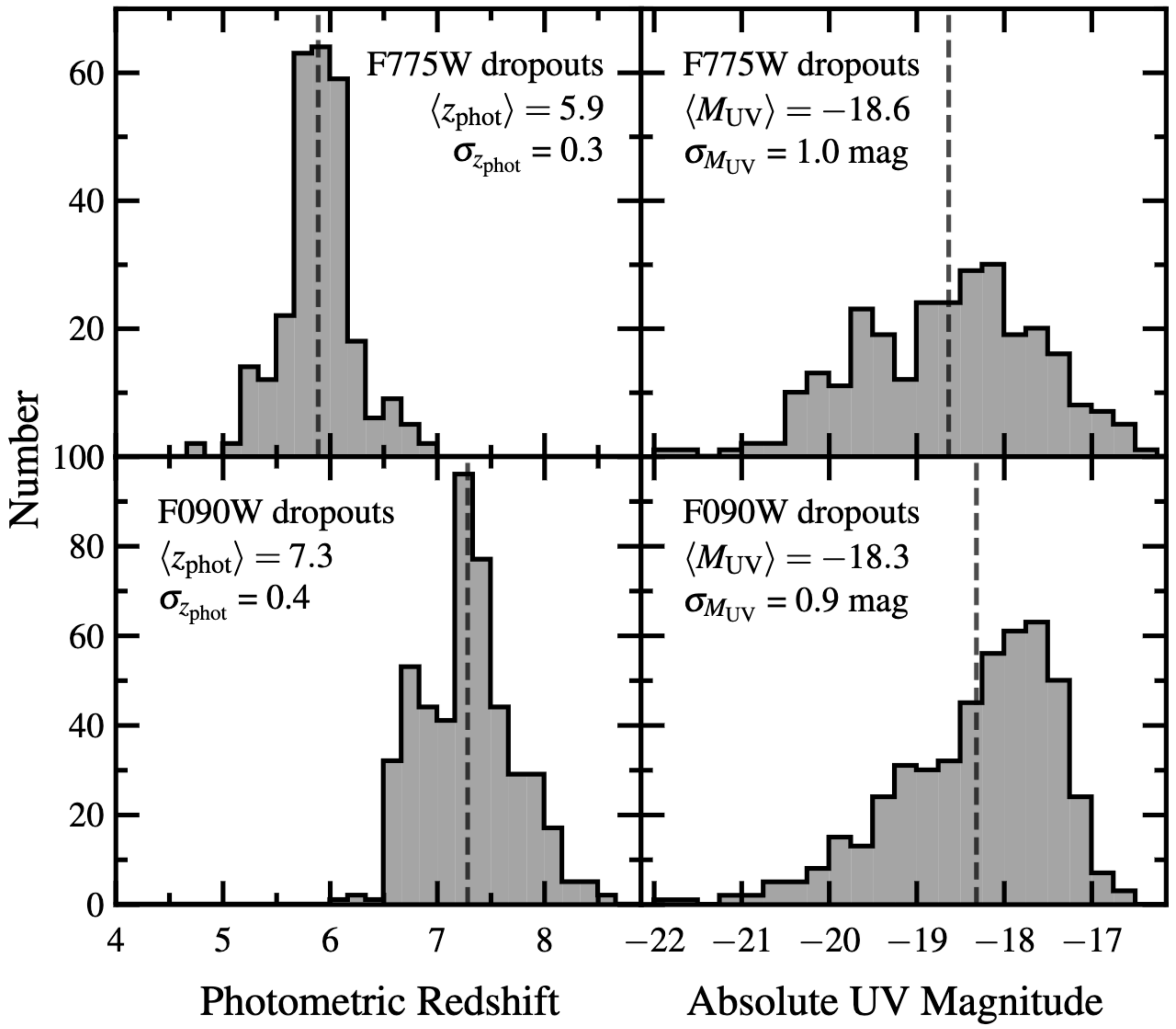
Prior to JWST: Strong [OIII]+H-beta EW from Spitzer

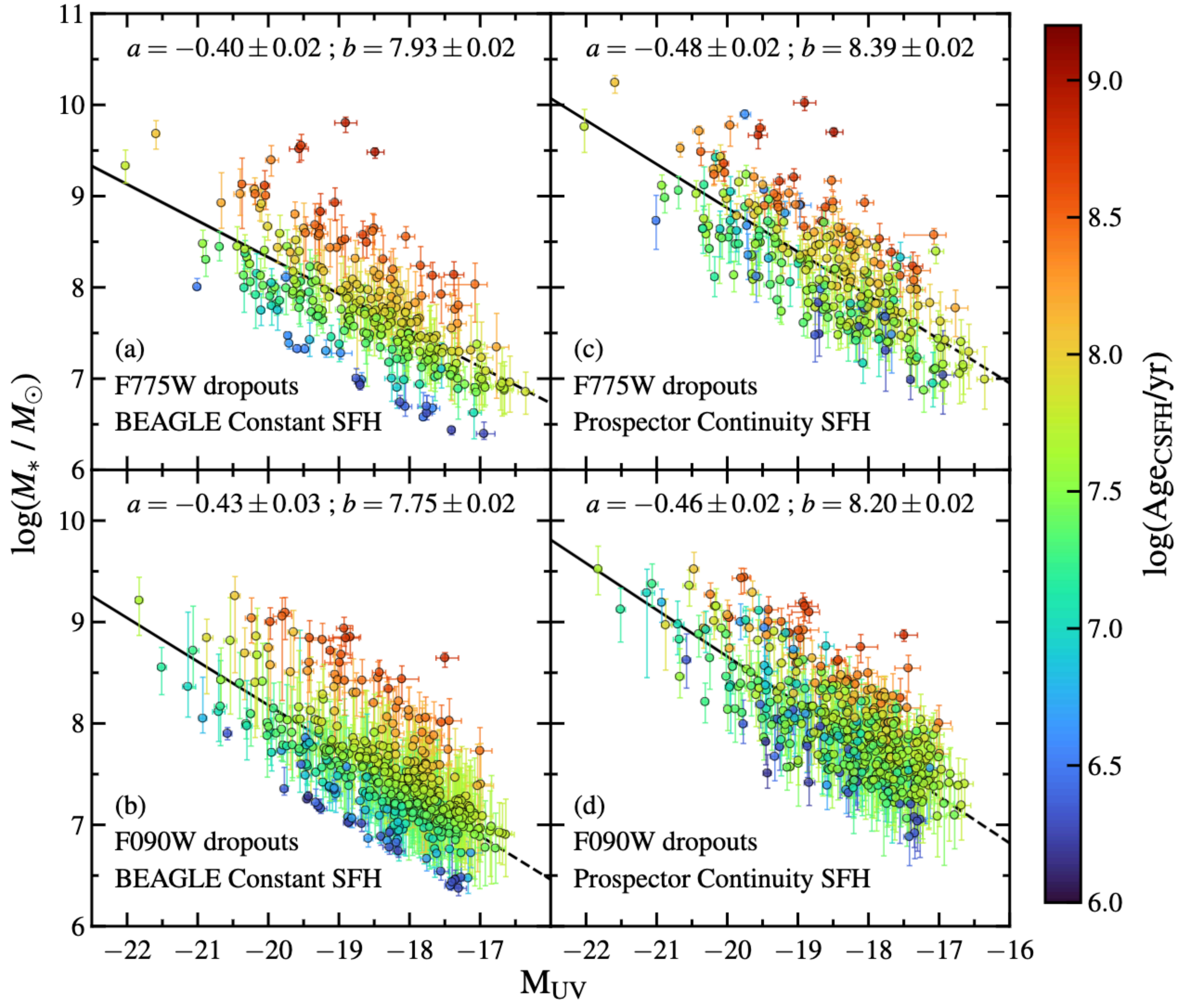


- After burst, galaxies should grow fainter, emission lines should weaken — ξ_{ion} should decrease.
- Do we see evidence for **star formation off mode?**
- This requires characterization of SEDs (and emission lines) of fainter (m~28-30) galaxies — very challenging before JWST.

NIRCam transforms Early Galaxy SED Characterization

Endsley+2023 (see also Furtak+23; Laporte+23; Leethochawalit+23; Morishita+Stiavelli+23; Whitler+23ab; Topping+23;

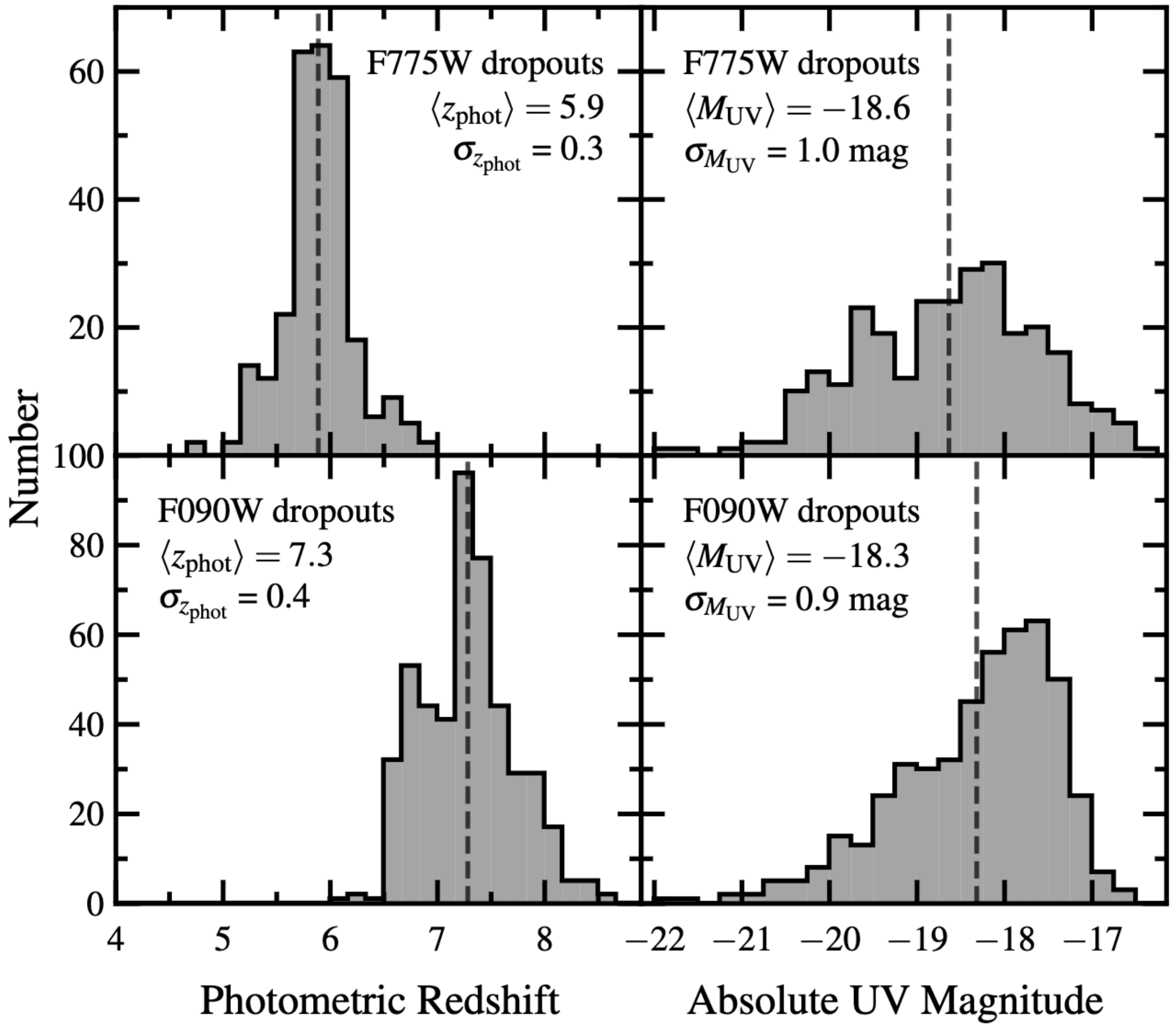


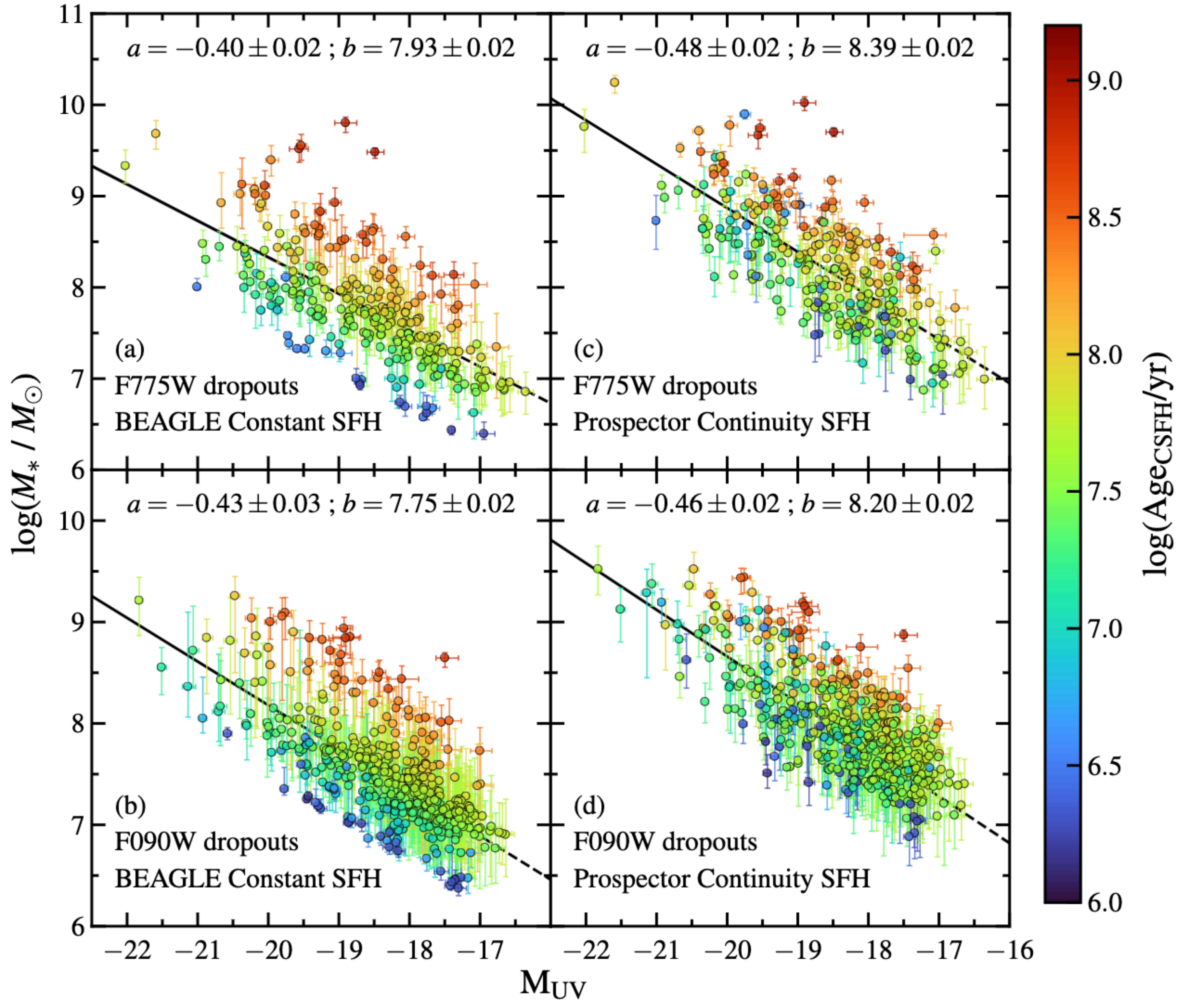


- SEDs of 756 galaxies at z~6-9 now reach down to m~30 (M_{UV}=-16)

NIRCam transforms Early Galaxy SED Characterization

Endsley+2023 (see also Furtak+23; Laporte+23; Leethochawalit+23; Morishita+Stiavelli+23; Whitler+23ab; Topping+23;

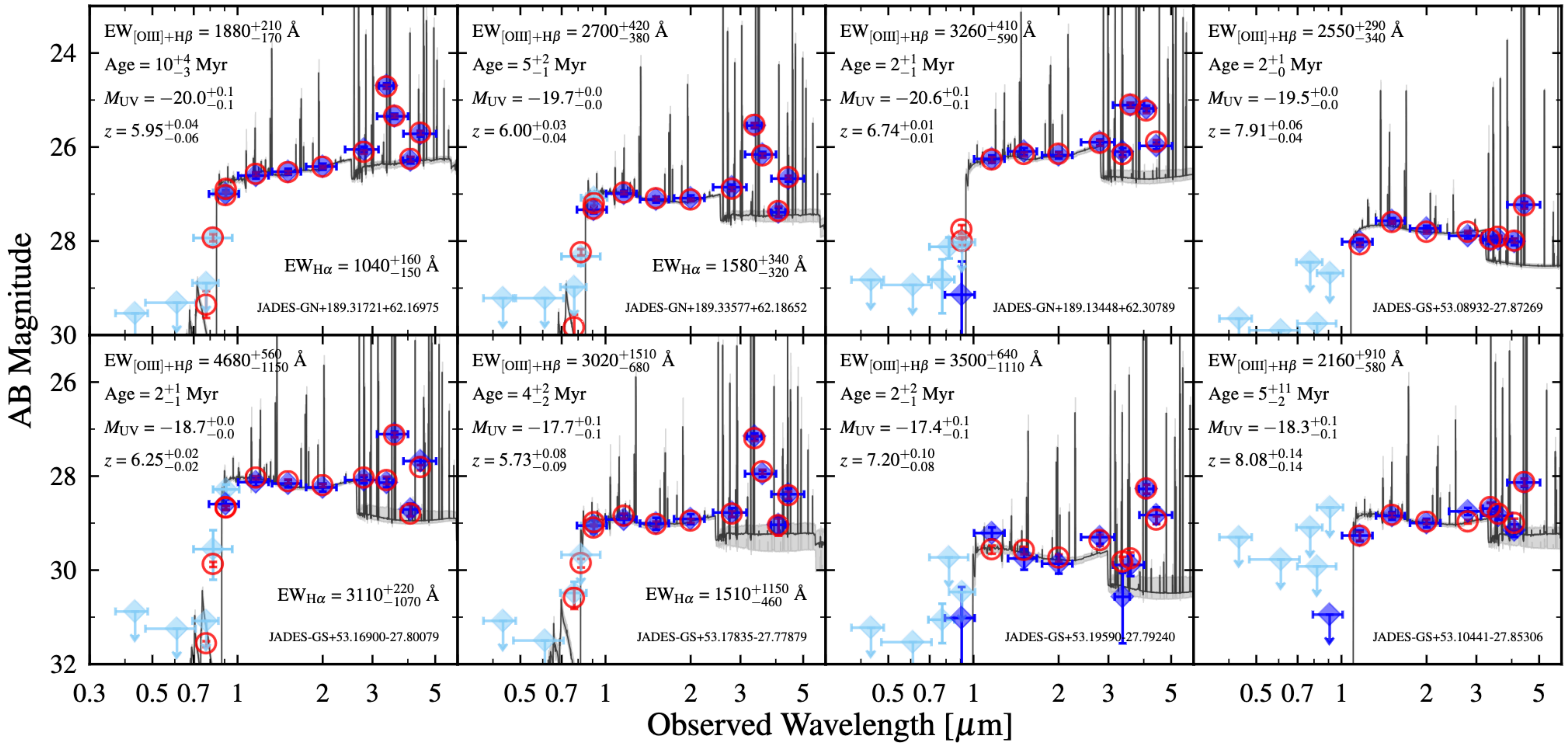




- SEDs of 756 galaxies at z~6-9 now reach down to m~30 (M_{UV}=-16)
- Do we find any evidence for the off mode populations? Or do all galaxies look like those from Spitzer shown on previous slides, dominated by young stellar populations?

NIRCam SEDs of Reionization-Era Galaxies

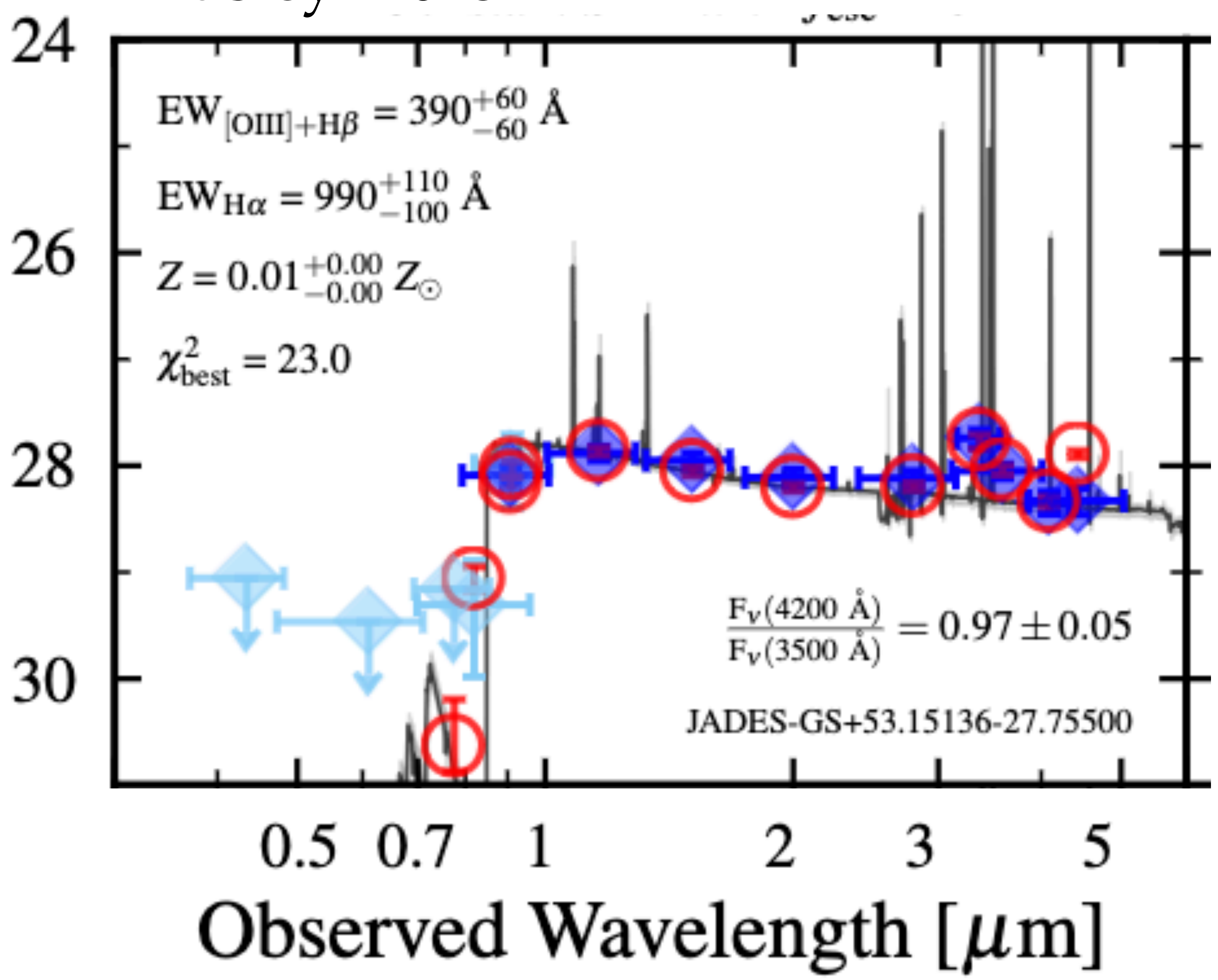
Endsley+2023 (see also Rinaldi+2023, Withers+2023, Bouwens+2023 + many spectroscopic papers)

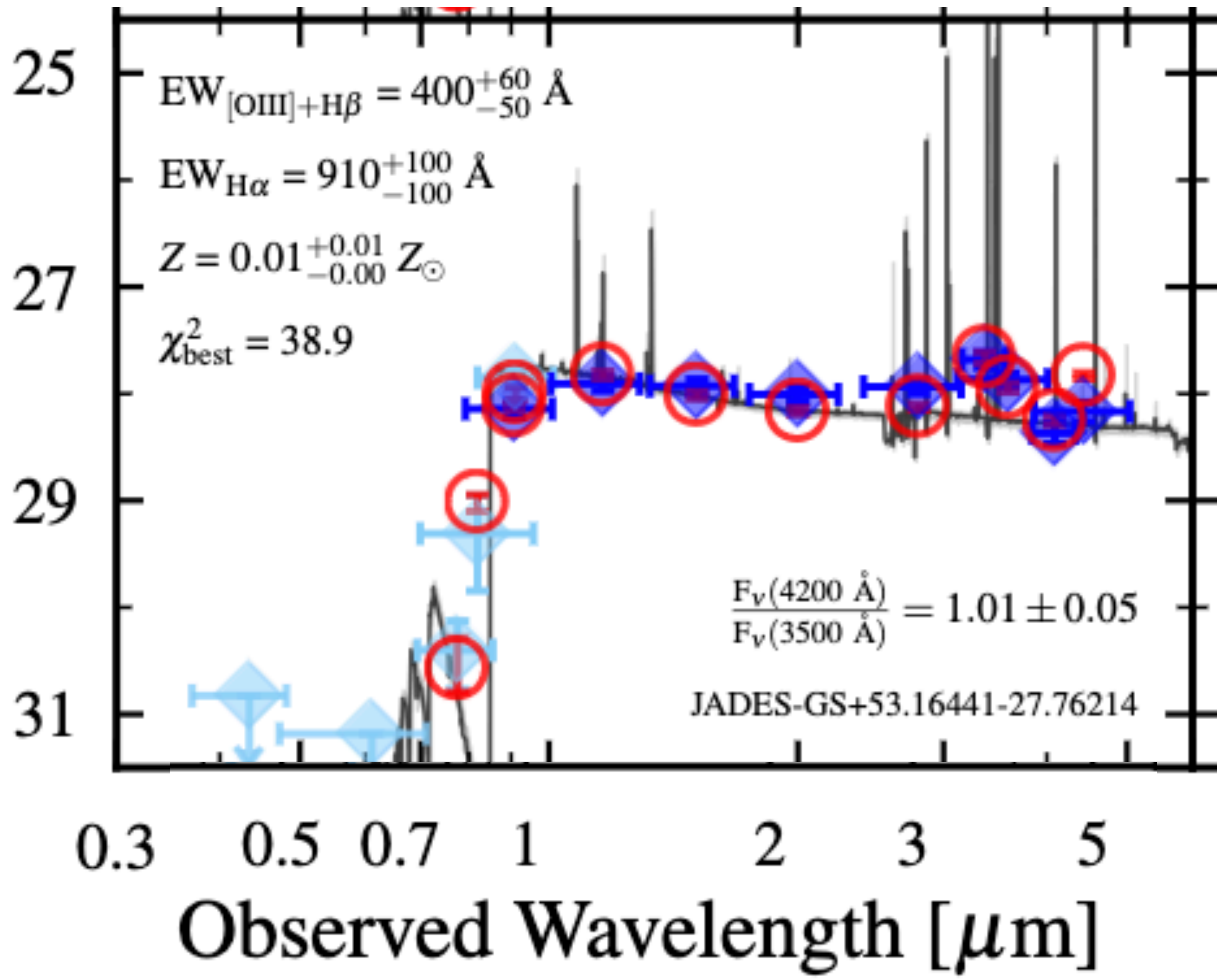


- Many faint z~6-9 galaxies show strong [OIII]+H-beta emission (>700Å).

Star formation off mode in faint reionization era galaxies

Endsley+2023

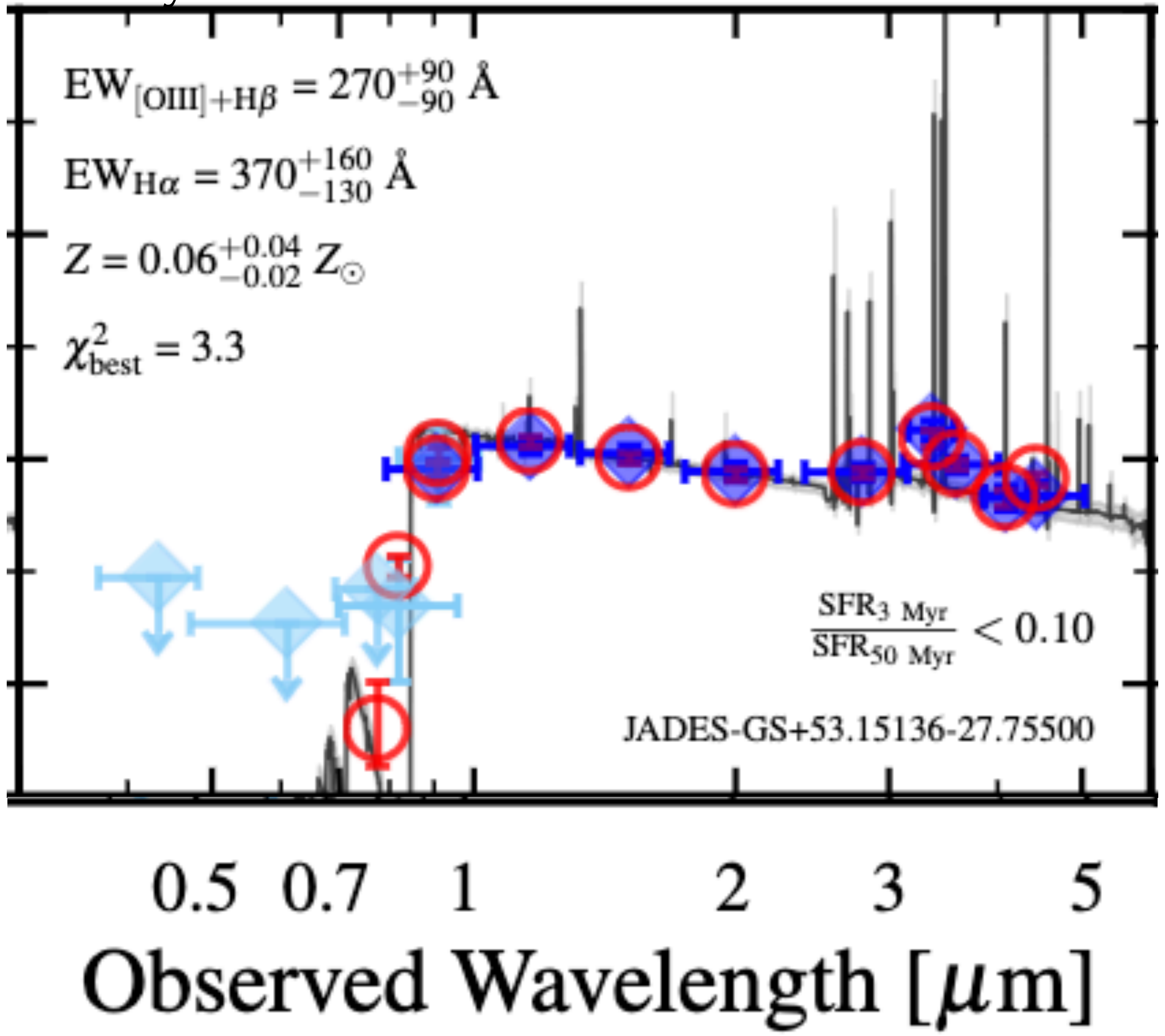


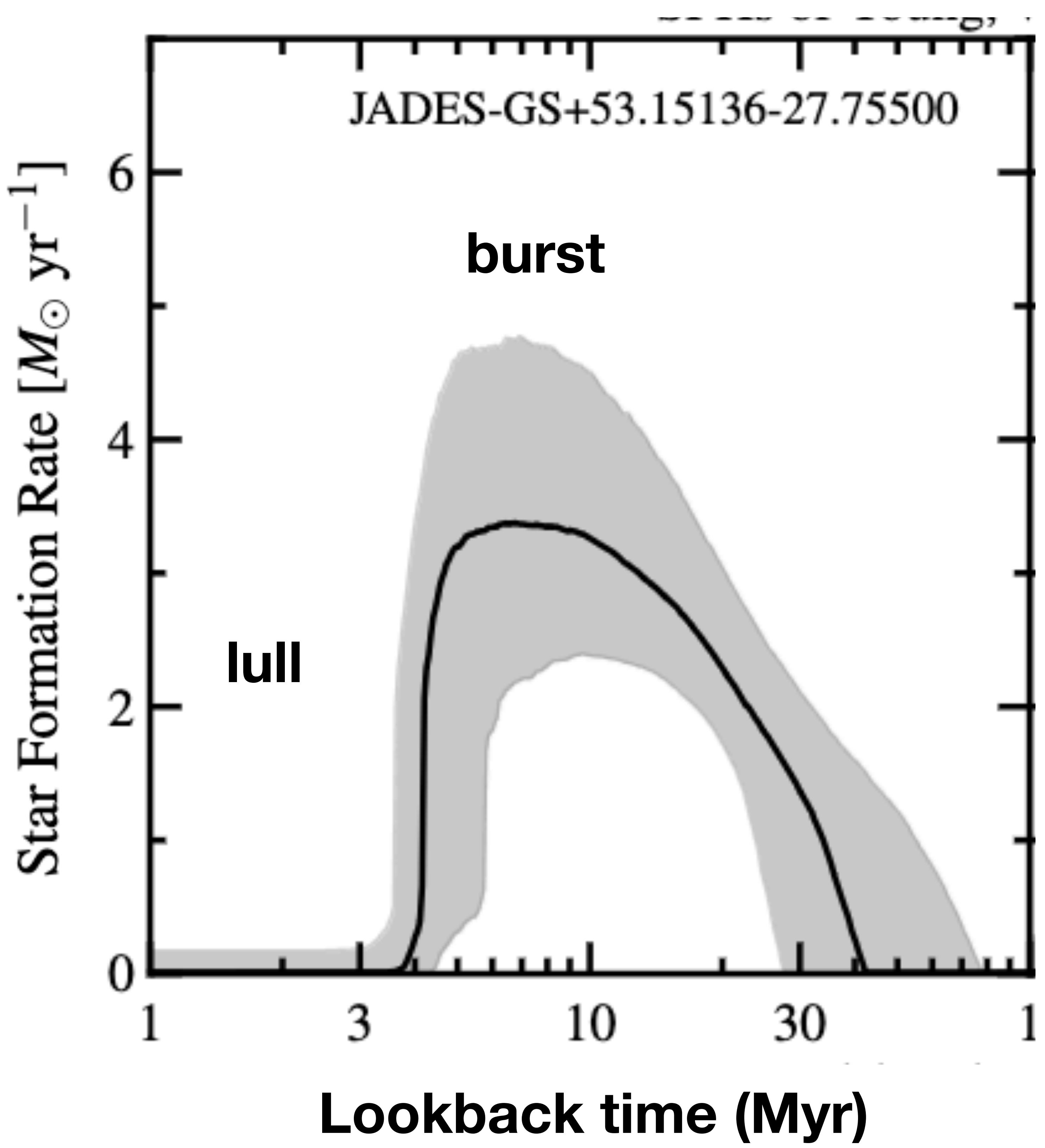


- We find a large subset of faint galaxies with **weaker H-alpha than expected given the young ages implied by UV and optical continuum.** Very challenging to explain with constant star formation models.

Star formation off mode in faint reionization era galaxies

Endsley+2023

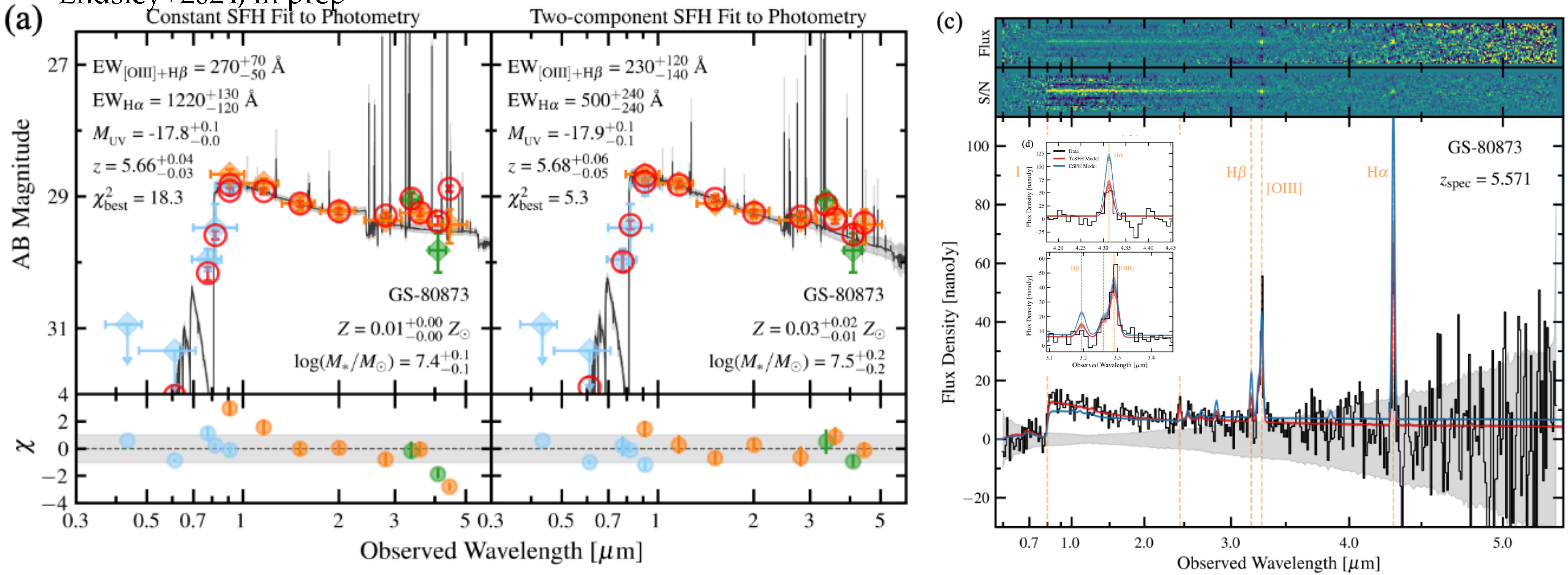




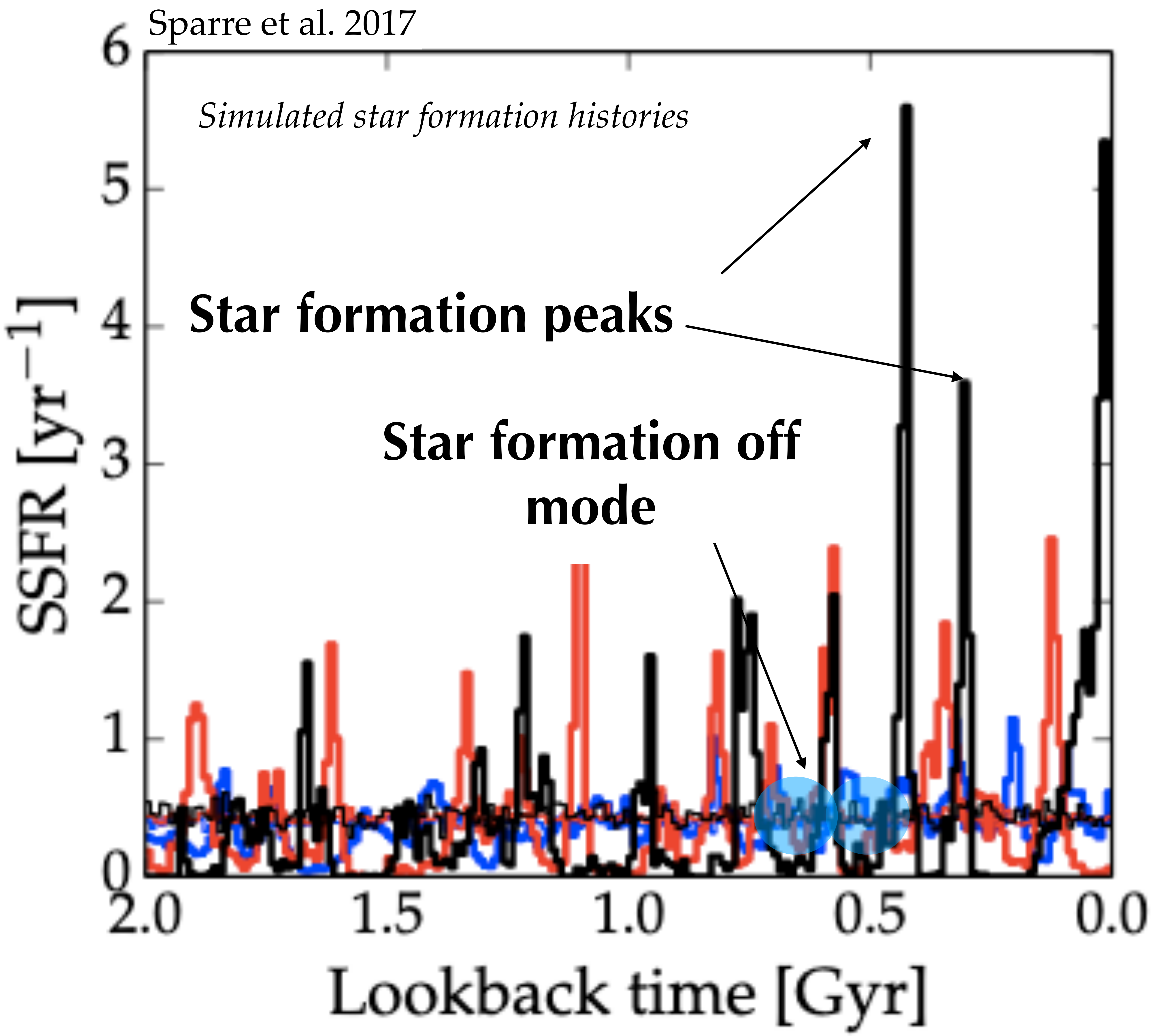
- We find a large subset of faint galaxies with **weaker H-alpha than expected given the young ages implied by UV and optical continuum.** Very challenging to explain with constant star formation models.
- But this is exactly what you would expect for an object entering an off-mode period.

JWST spectra are now providing confirmation of this population in the reionization era

Endsley+2024, in prep



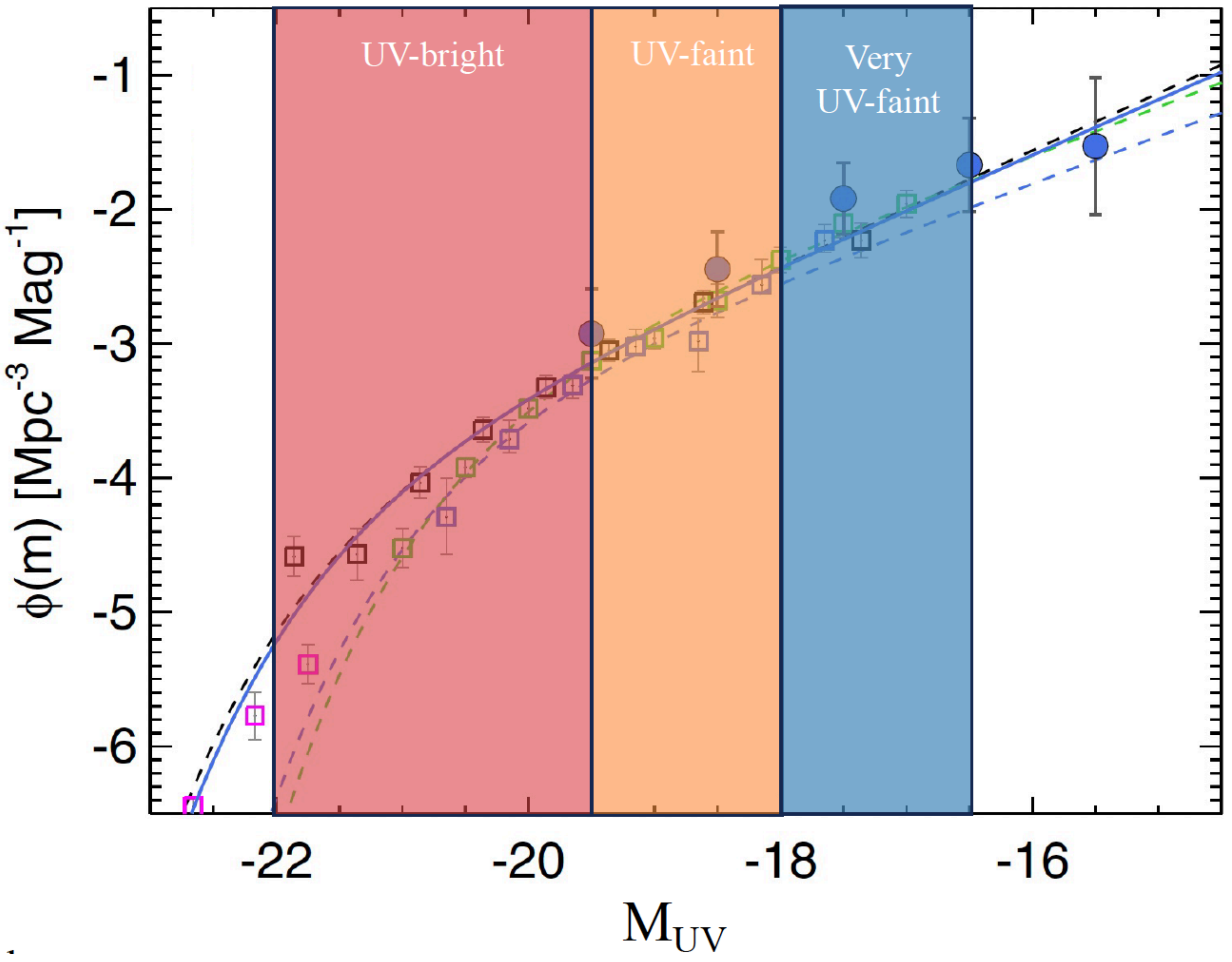
Bursty Star Formation in the Reionization Era



- JWST is confirming common presence of extreme emission line phase in early galaxies — these are **star formation peaks.**
- We also finding first evidence of the **off mode of star formation** — another key hallmark of bursty star formation histories.

Implications for Ionizing Photon Production

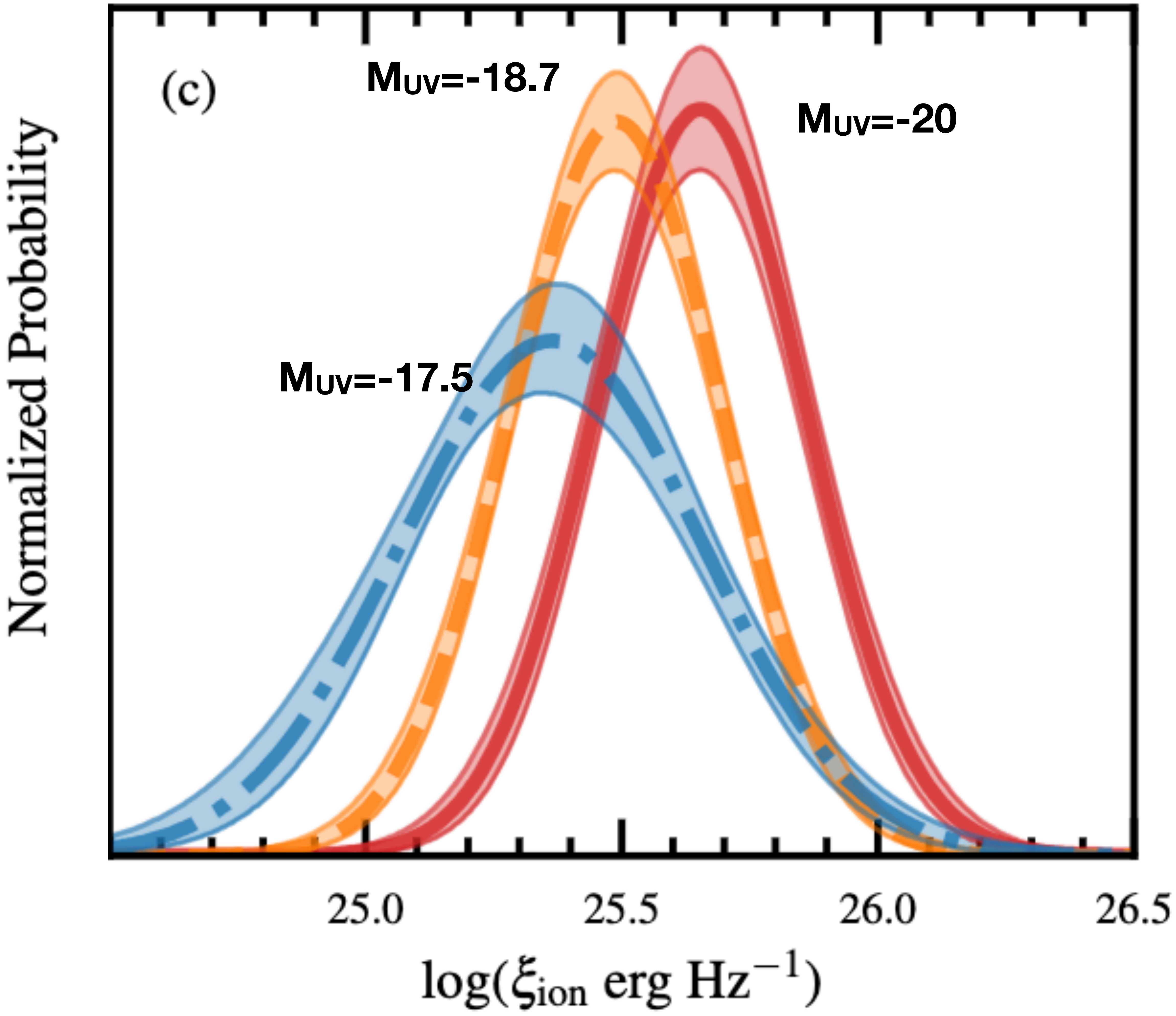
Endsley+2023



- Many galaxies emitting in UV continuum but with weak ionizing output.
- Large ionizing production efficiencies we saw with Spitzer are not the norm!

Implications for Ionizing Photon Production

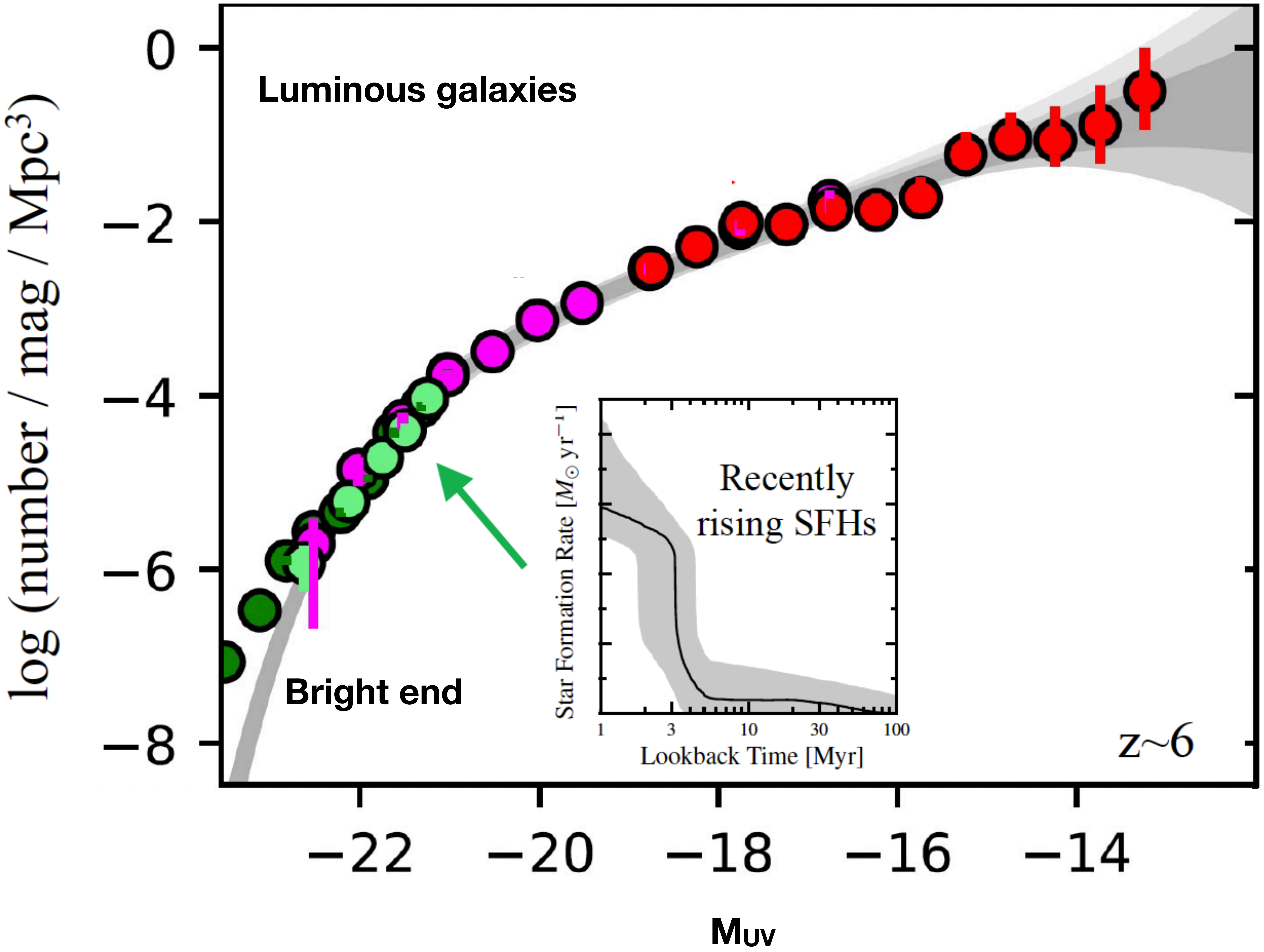
Endsley+2023



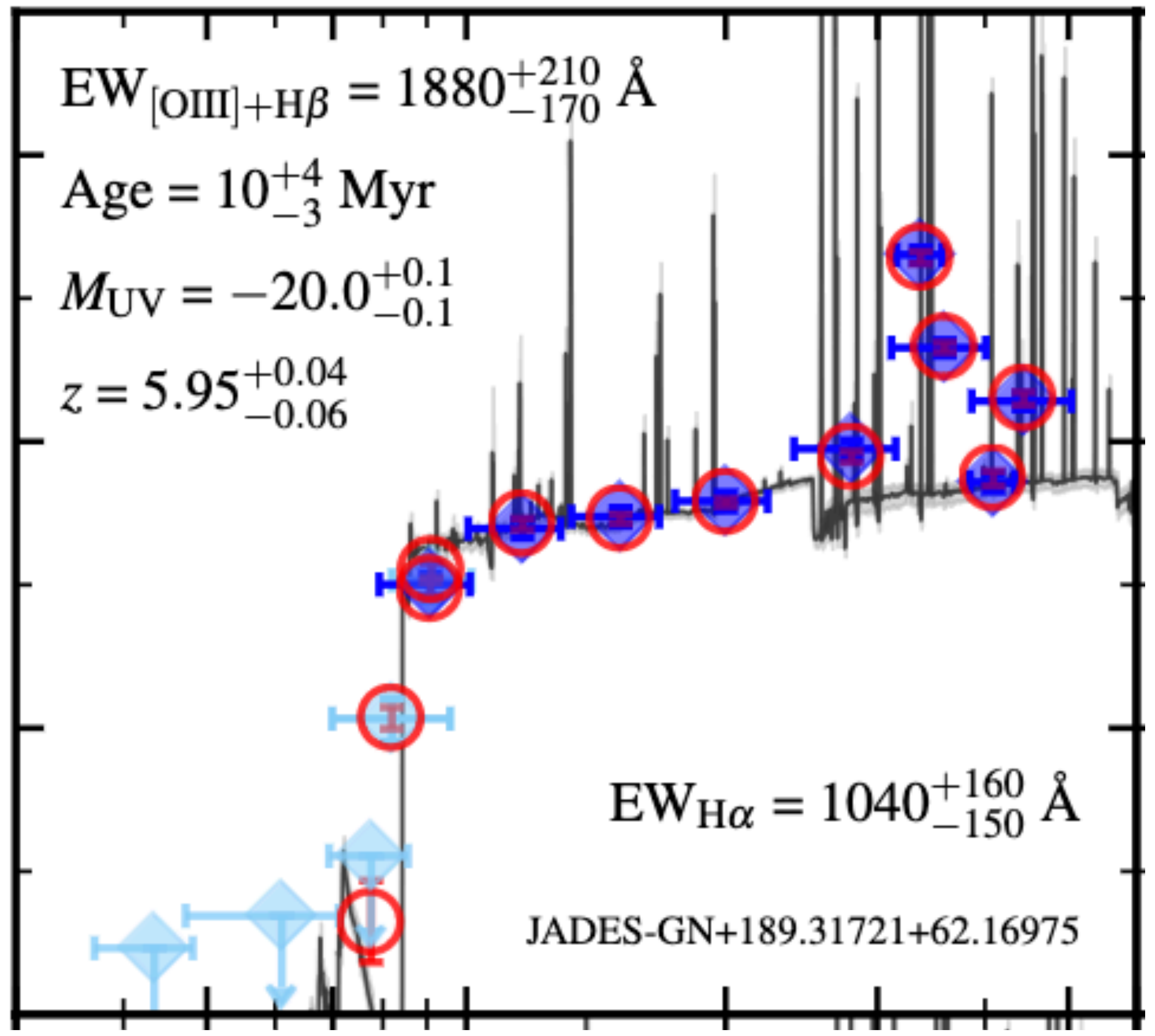
- Many galaxies emitting in UV continuum but with weak ionizing output.
- Large ionizing production efficiencies we saw with Spitzer are not the norm!
- Distribution of ionizing photon production efficiency has large dispersion, encompassing on and off modes of star formation.

We can quantify how the SEDs vary with UV luminosity

Adapted from Bouwens+22



- The **most UV luminous galaxies** are primarily comprised of galaxies having experienced a **recent upturn in star formation** — bumping up L_{UV}.



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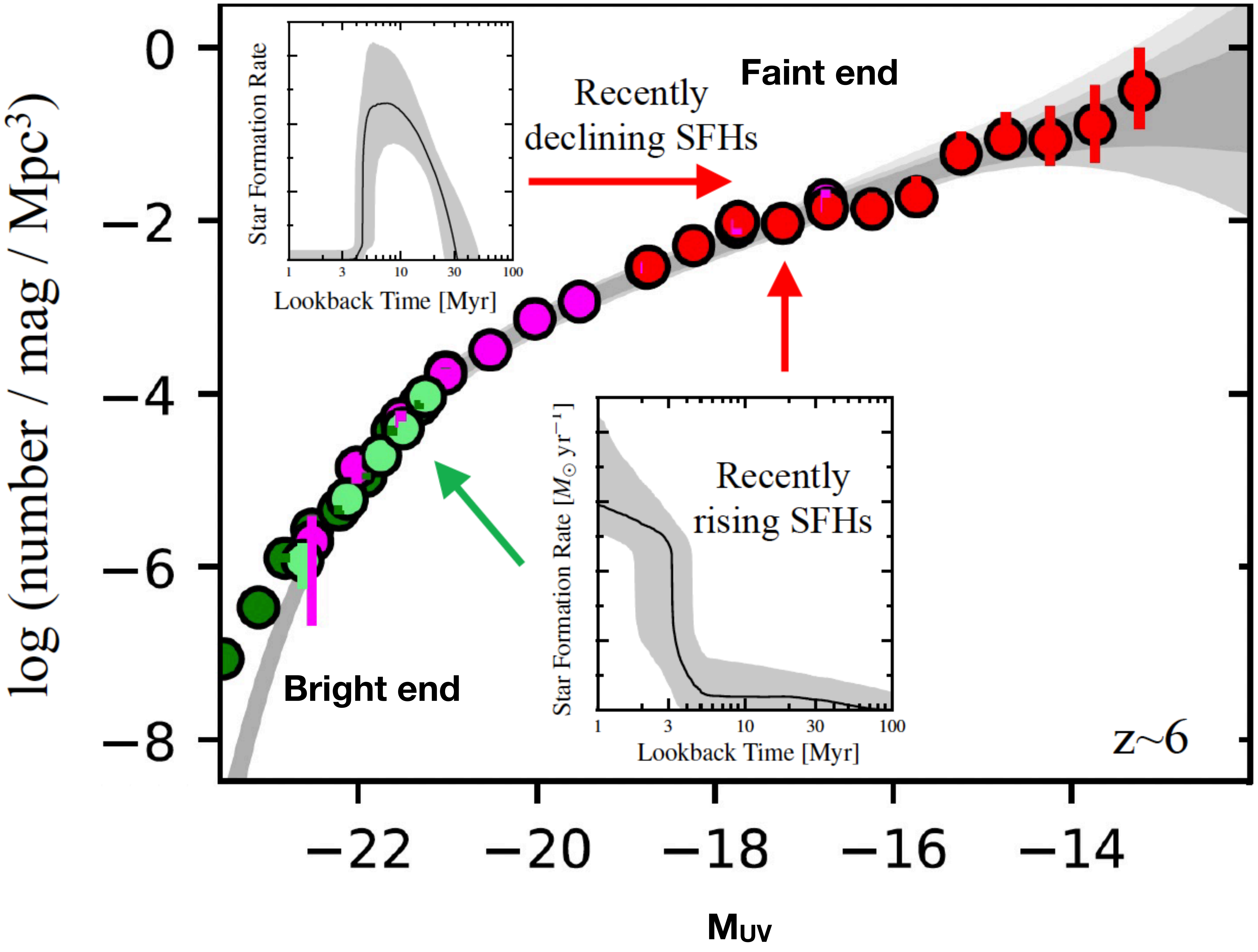
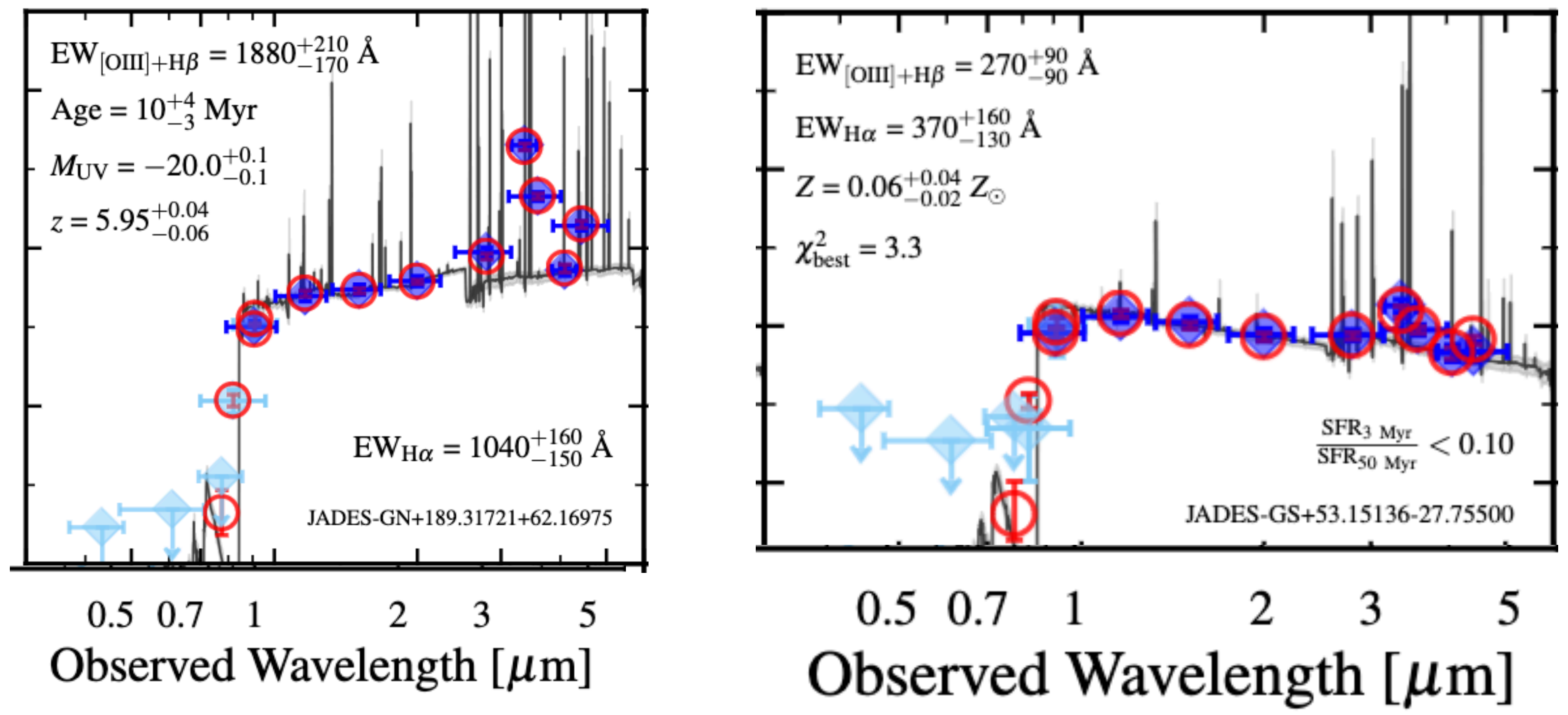


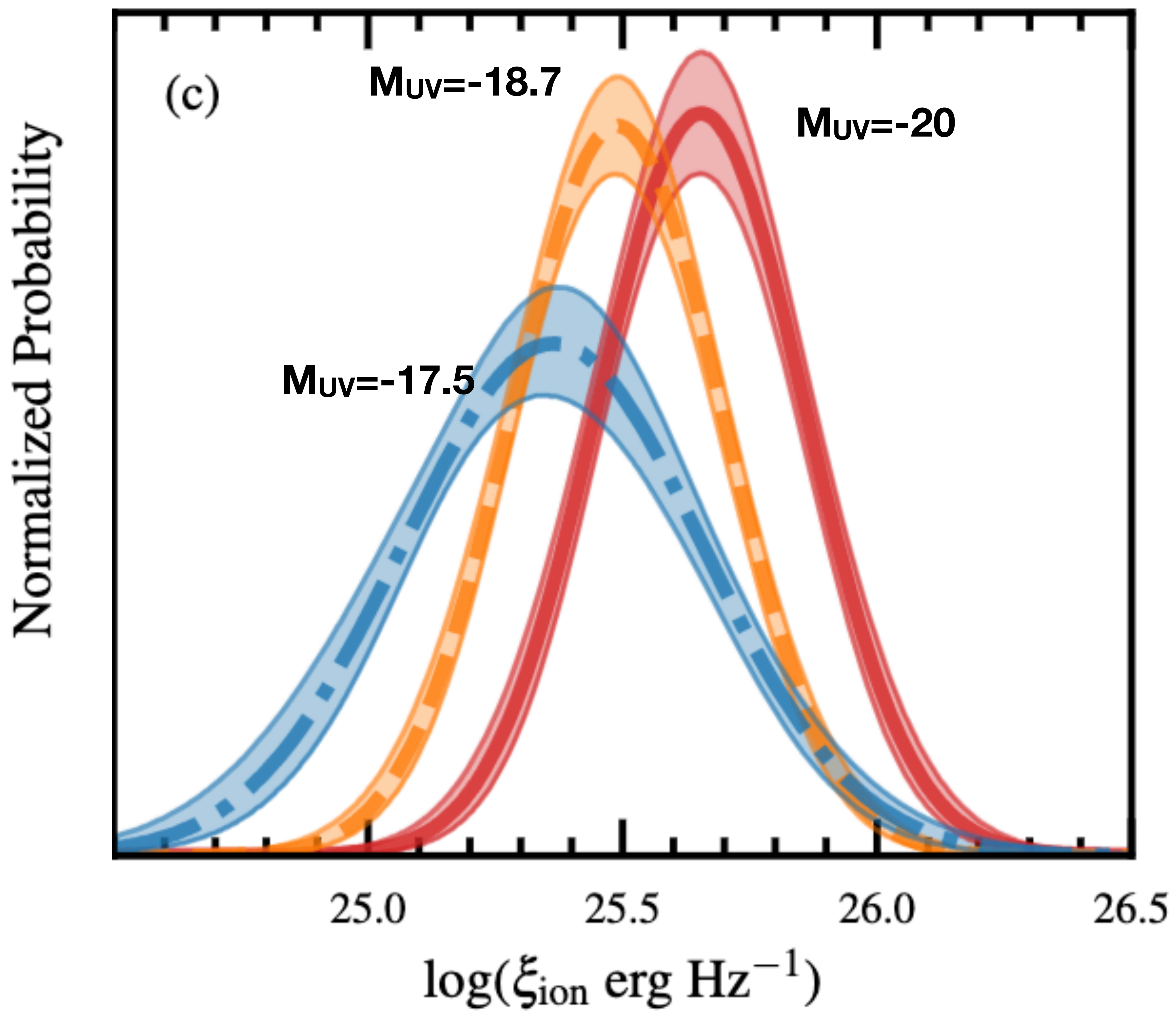
- The **most UV luminous galaxies** are primarily comprised of galaxies having experienced a **recent upturn in star formation** — bumping up L_{UV}.

- **UV faint galaxies** have more **equal mixture** of recently declining and rising SFHs.



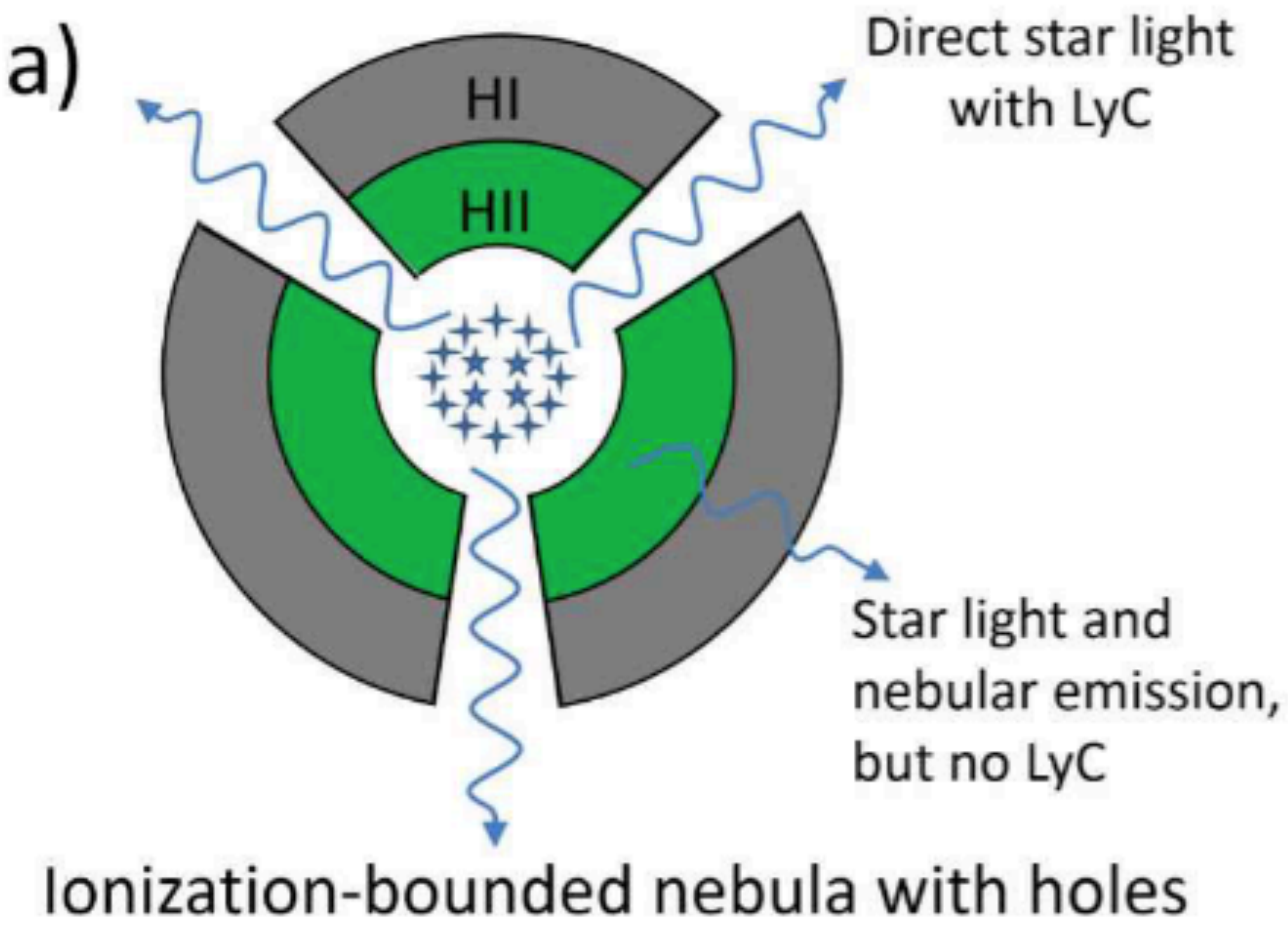
Implications for Ionizing Photon Production Efficiency

Endsley+2023



- Galaxies at the faint end of UV luminosity function are very abundant but **many have lower ionizing photon production efficiencies.**

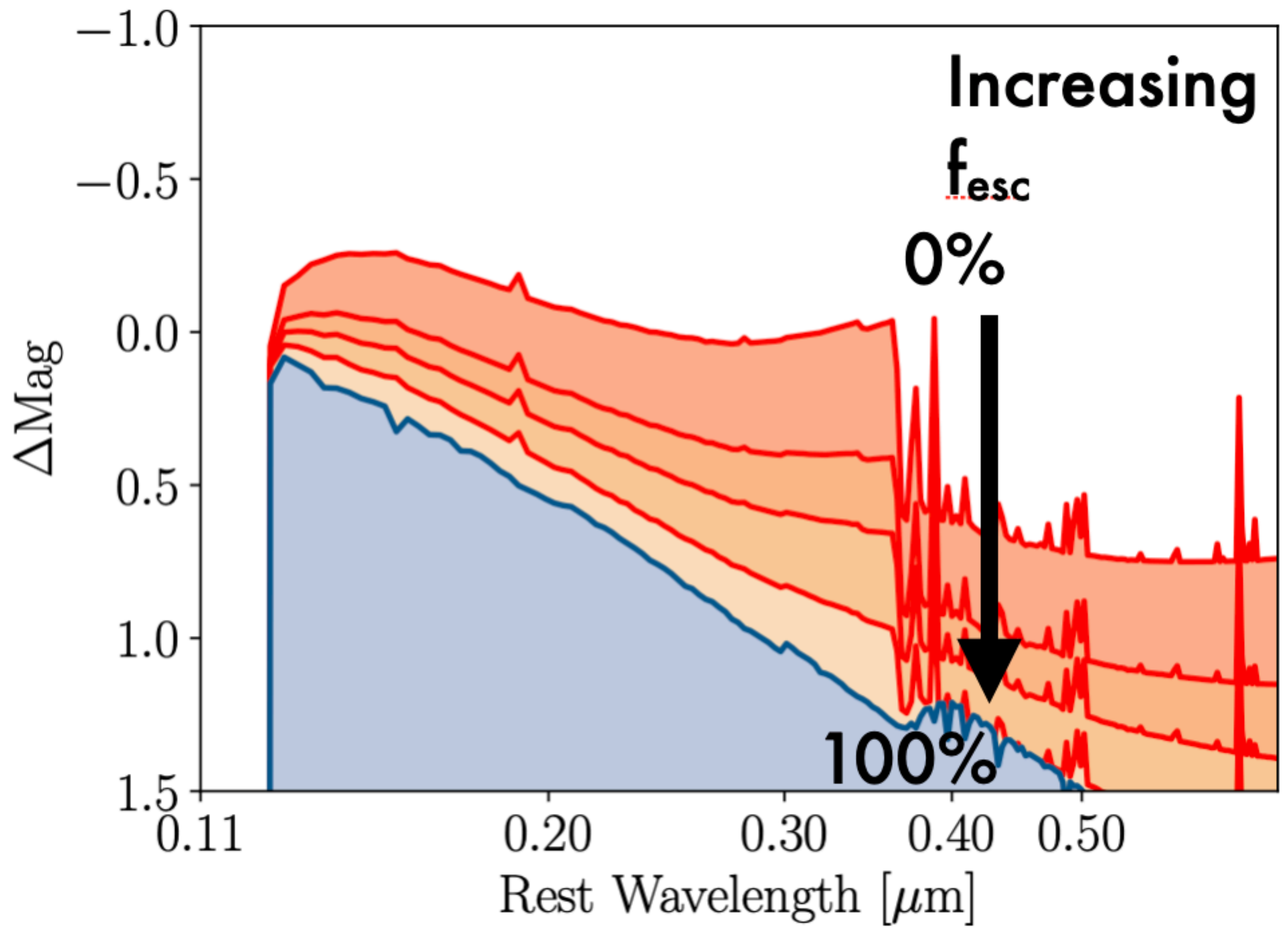
What about Ionizing Photon Escape?

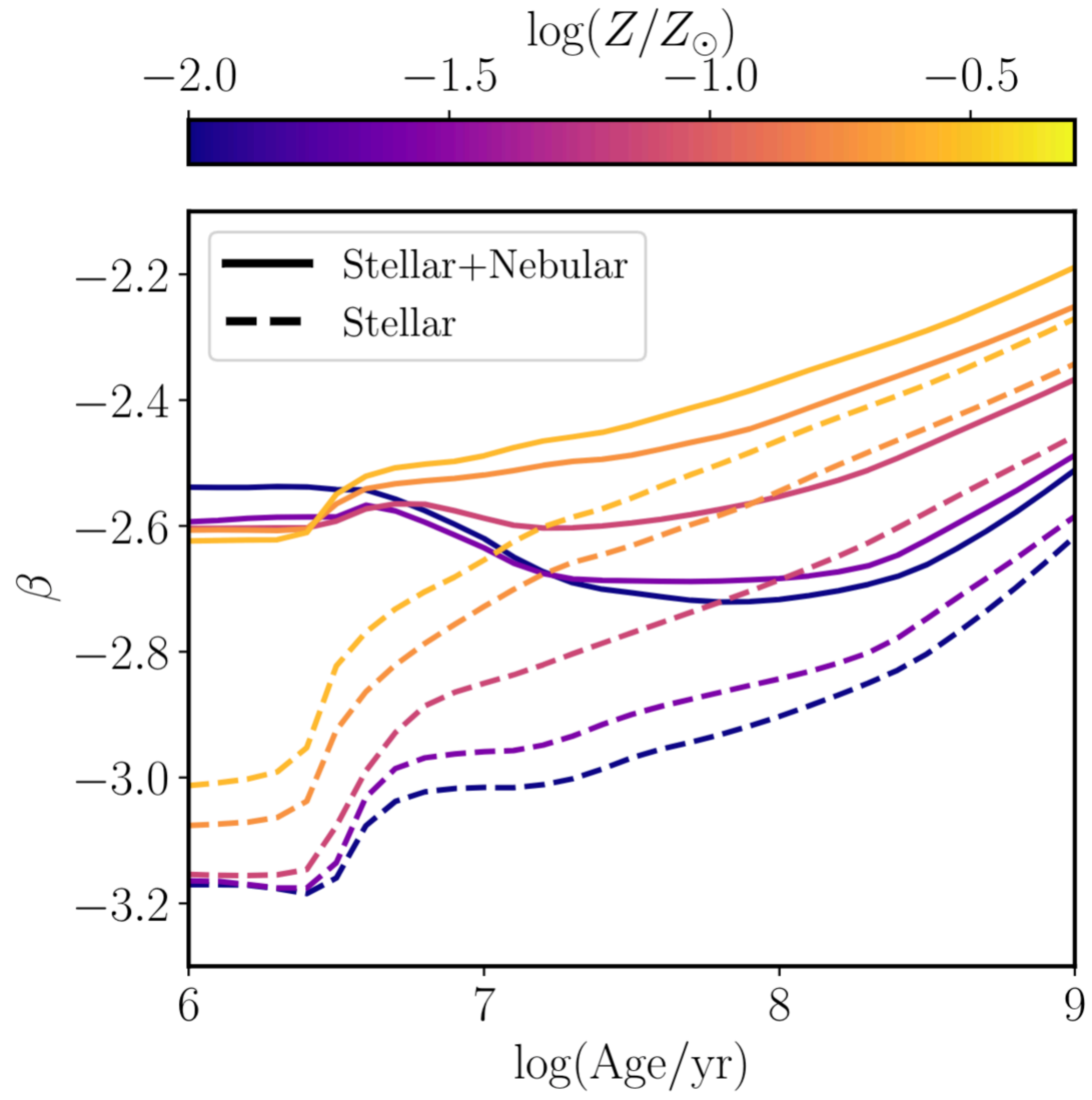


Zackrisson+2013

- The strong bursts we are finding at z>6 may be effective at clearing/ionizing channels through the CGM of early galaxies.
- May facilitate a large LyC escape fraction for brief window.
- Do we see any such examples at z>6?

Observational Signature of Large LyC escape fractions at z>6?

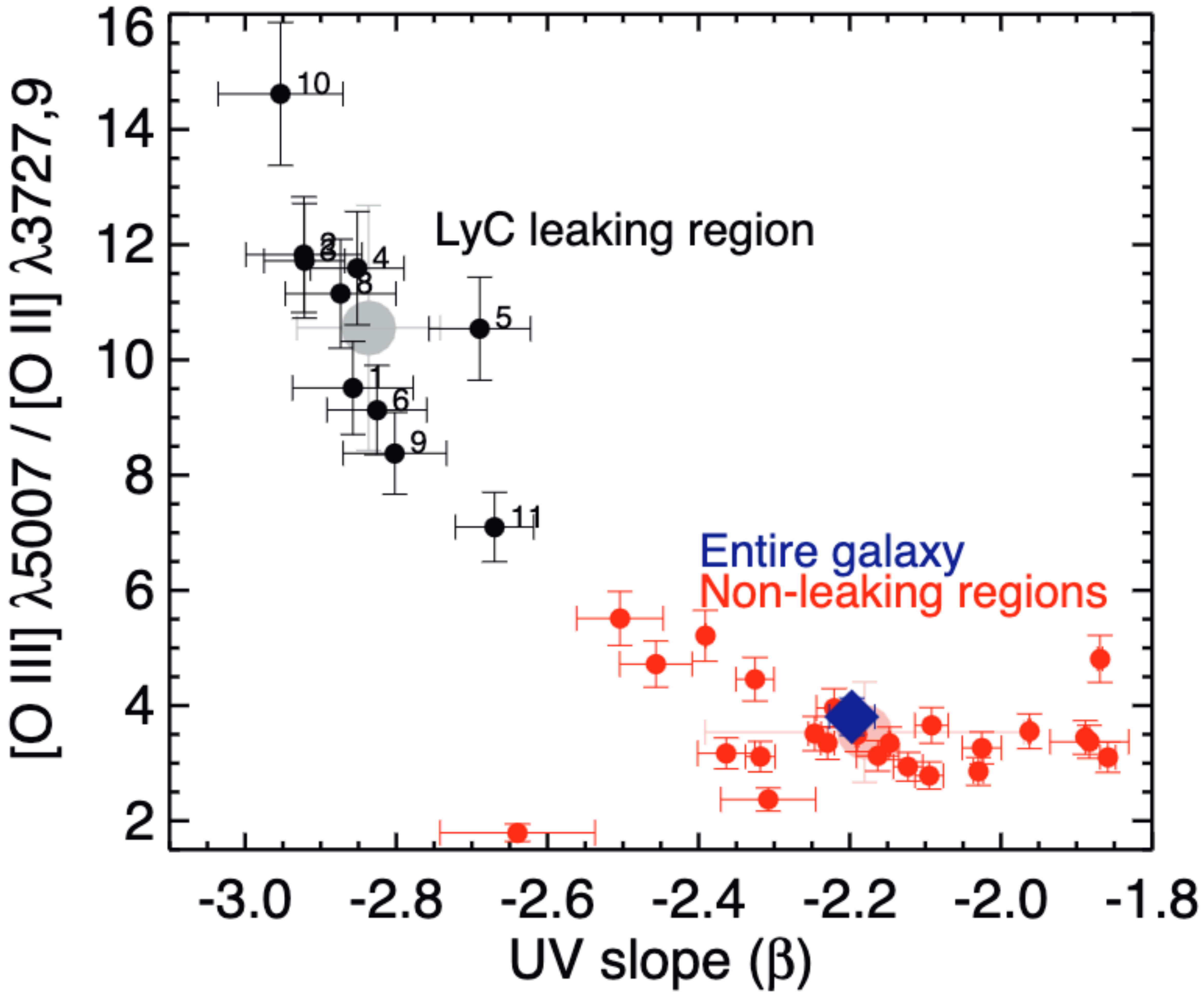




- If most ionizing photons escape HII regions ($f_{esc} > 0.5$), we significantly reduce nebular emission contribution to SED.
- Reduction of nebular continuum results in a much bluer SED, with β ~ -3 in cases.

Demonstration of Method in the Sunburst Arc

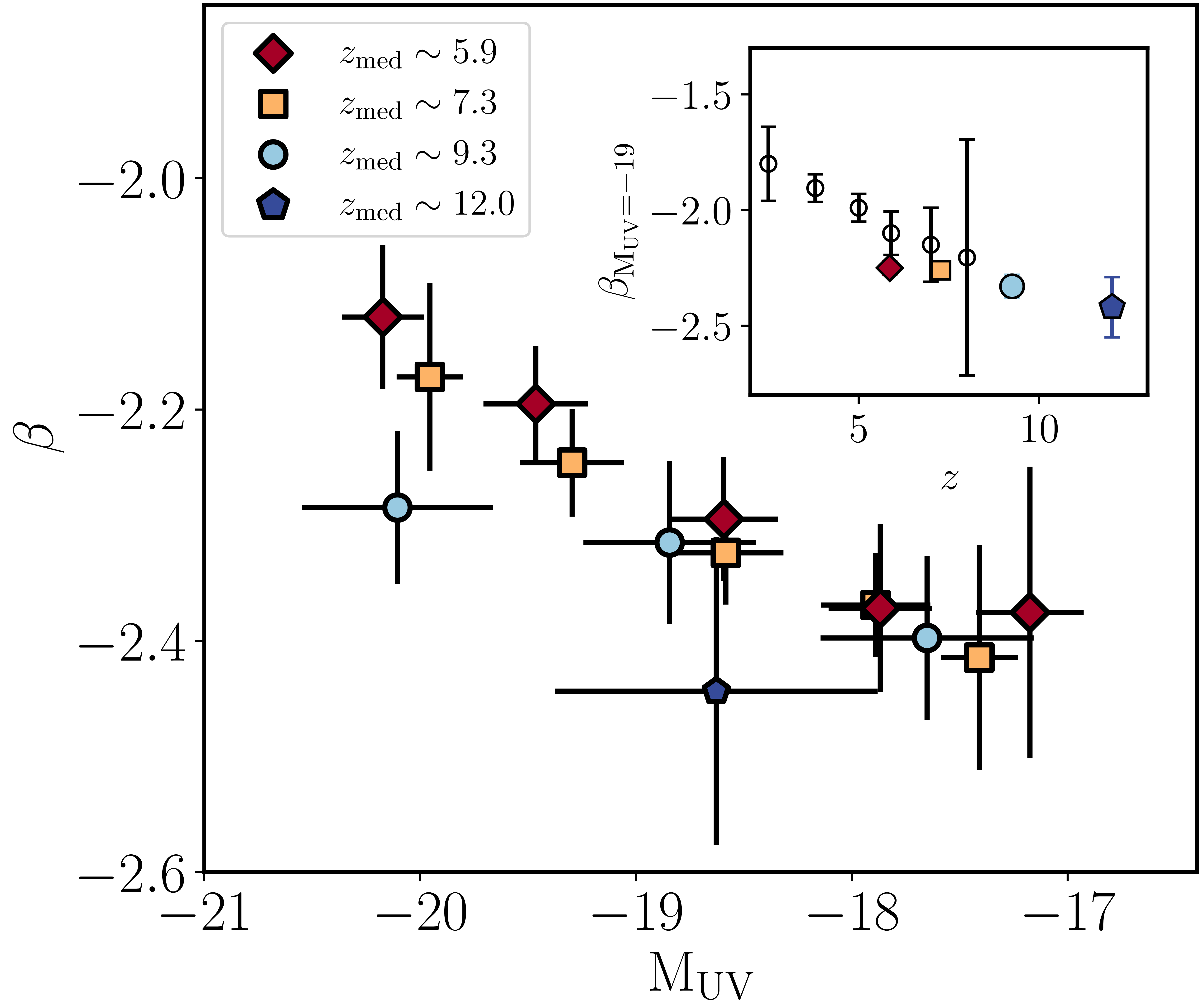
Kim+23



- This is exactly what is observed in the LyC leaking region of the Sunburst arc!
- Can we find examples at z>6?

Redshift Evolution of UV Slopes at z>9-14

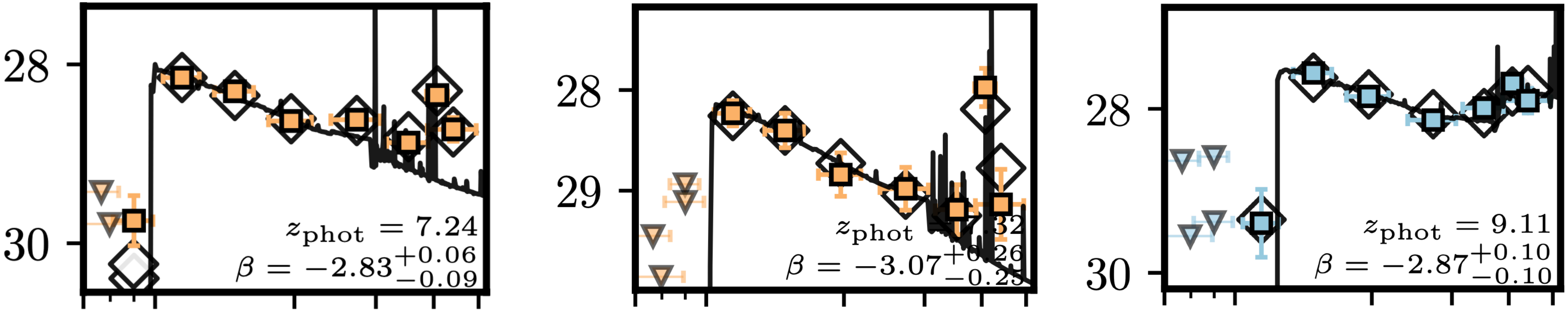
Topping et al. 2024, (see also Morales+24, Cullen+24)



- Galaxies are very blue at z>9, but average values (β~-2.5) do not require extremely large escape fractions.

The Discovery of Extremely Blue Galaxies

Topping et al. 2023



- 44 z~6-9 galaxies in JADES imaging of GOODS fields with robust UV slope measurements between β= -2.8 to -3 -- need f_{esc} > 0.5 to reproduce very blue UV colors.
- Similarly blue slopes found in other surveys (Morales+23, Cullen+23).

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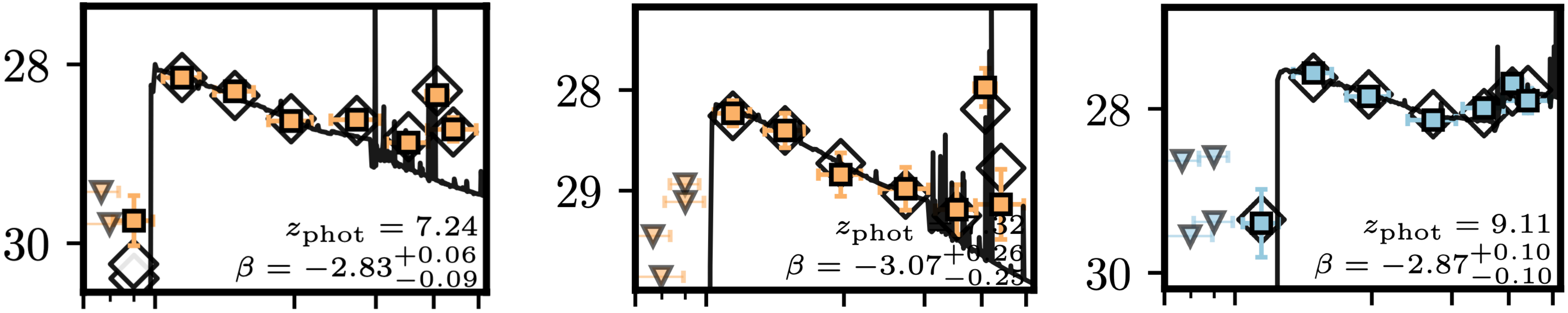

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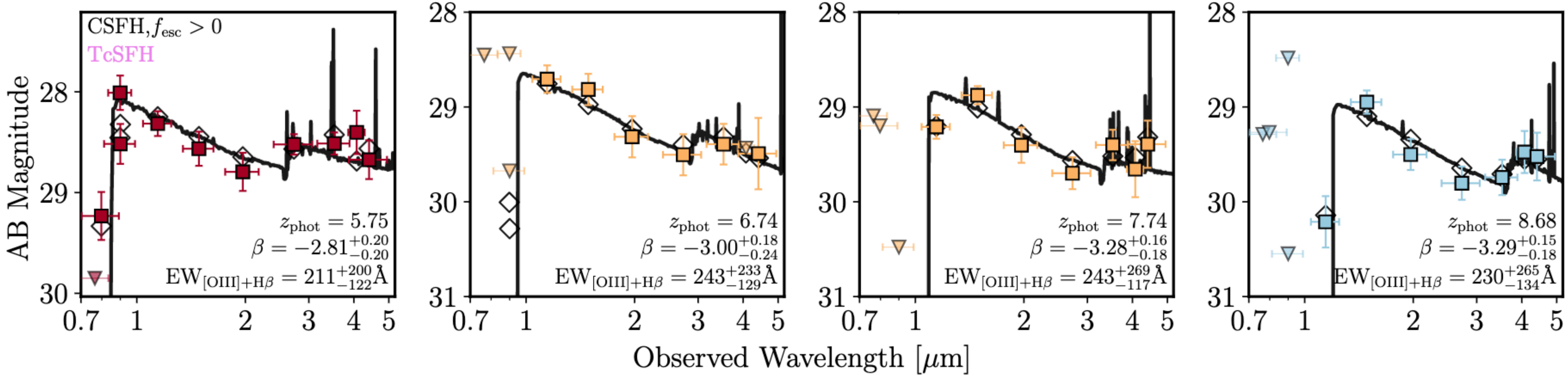
- Similarly blue slopes found in other surveys (Morales+23, Cullen+23).
- Photometric error can scatter sources to blue slopes, so need to only select robust systems.

Rest-Optical Properties of LyC Leaking Candidates

Topping+23



- If blue colors are driven by leakage, we should also see impact on emission lines.

Rest-Optical Properties of LyC Leaking Candidates

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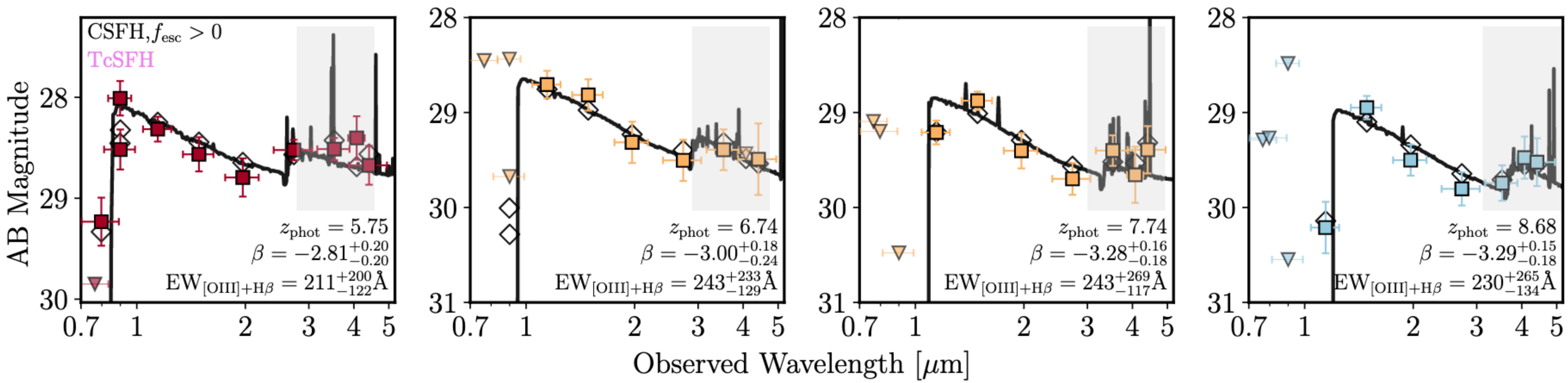
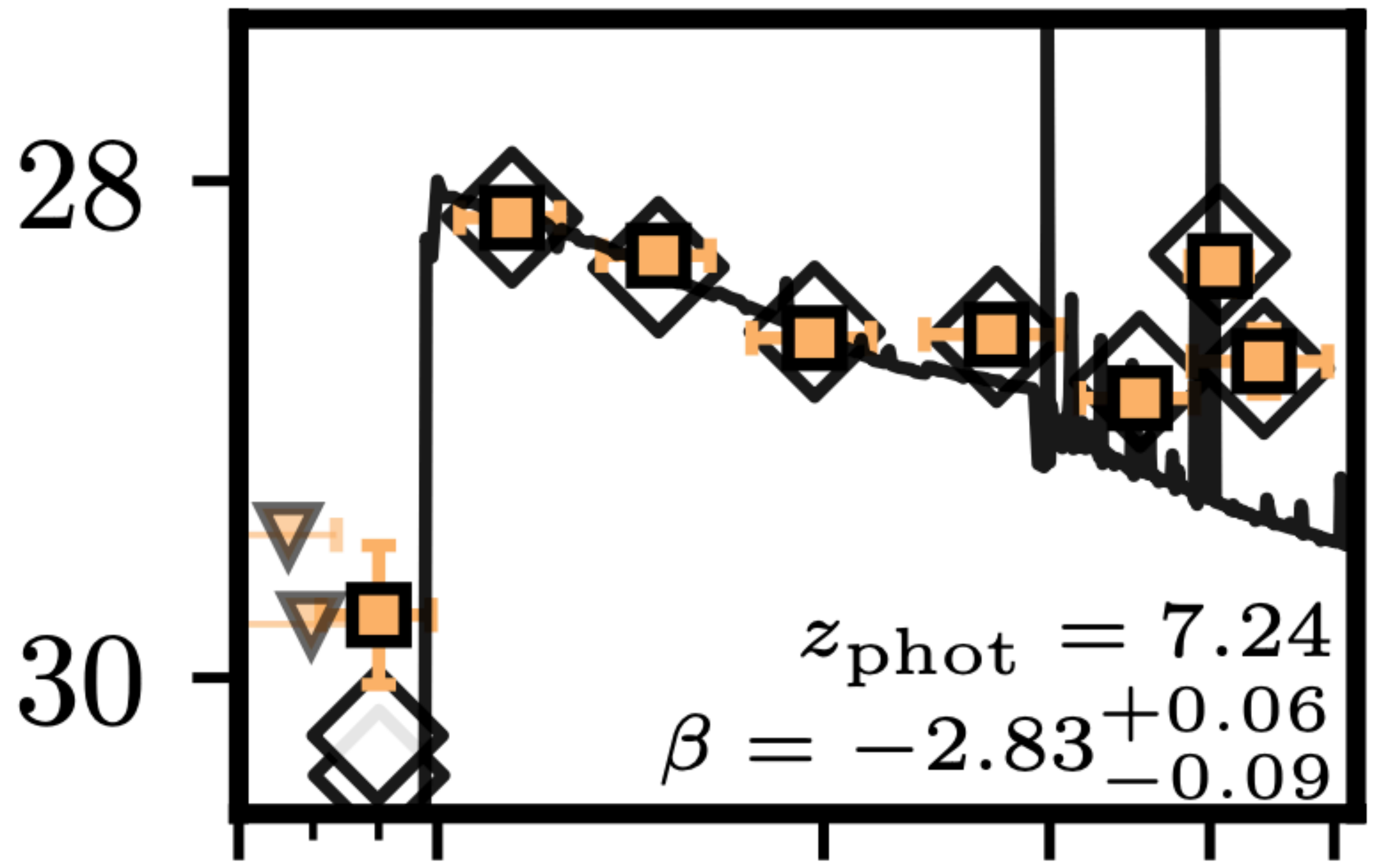


- If blue colors are driven by leakage, we should also see impact on emission lines.
- This is exactly what is seen with NIRCam medium bands — bluest galaxies have weaker emission lines.

Escape Fractions in the Reionization Era

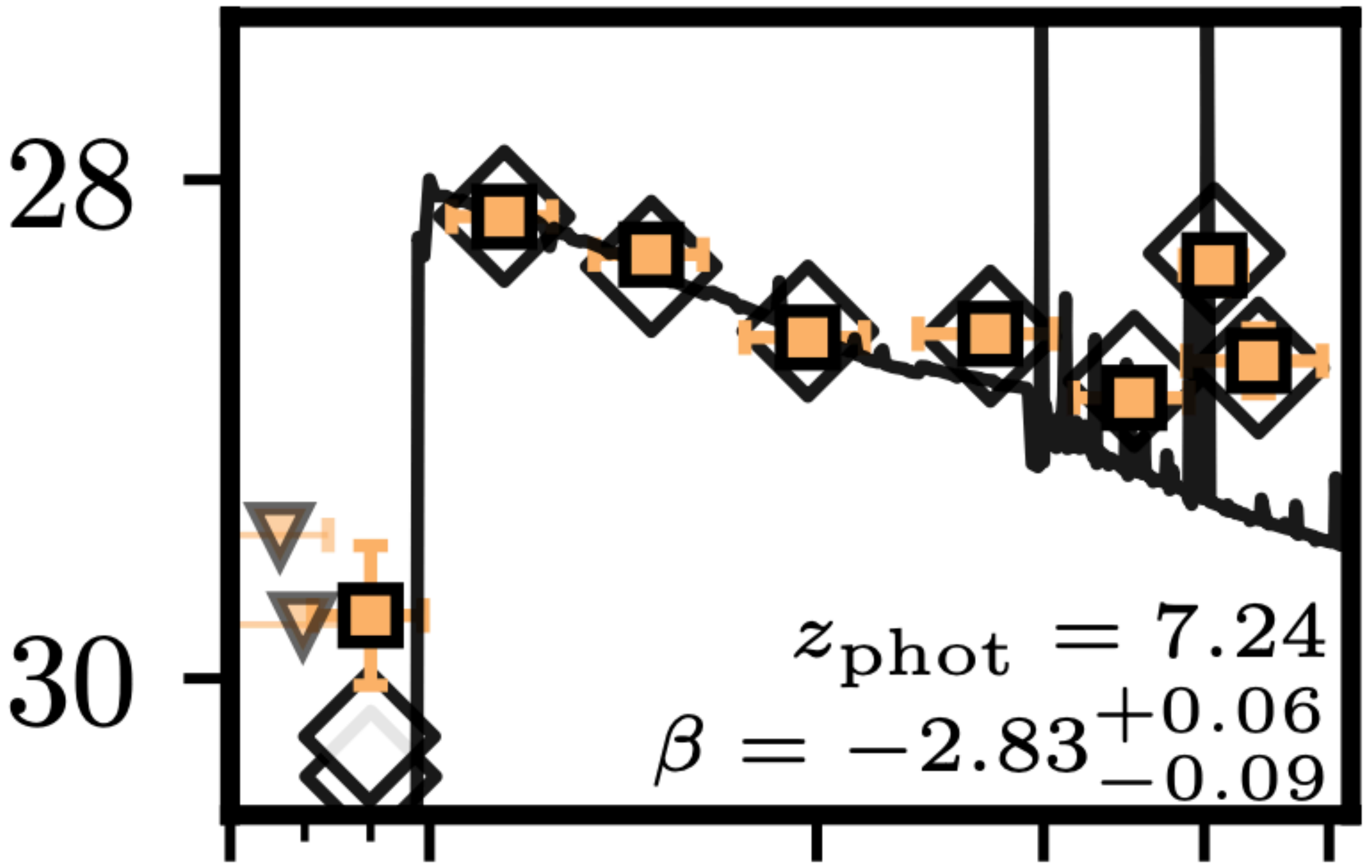
Topping et al. 2023



- These very blue sources may be examples of a brief phase when z>7 galaxies have extremely large escape fractions.

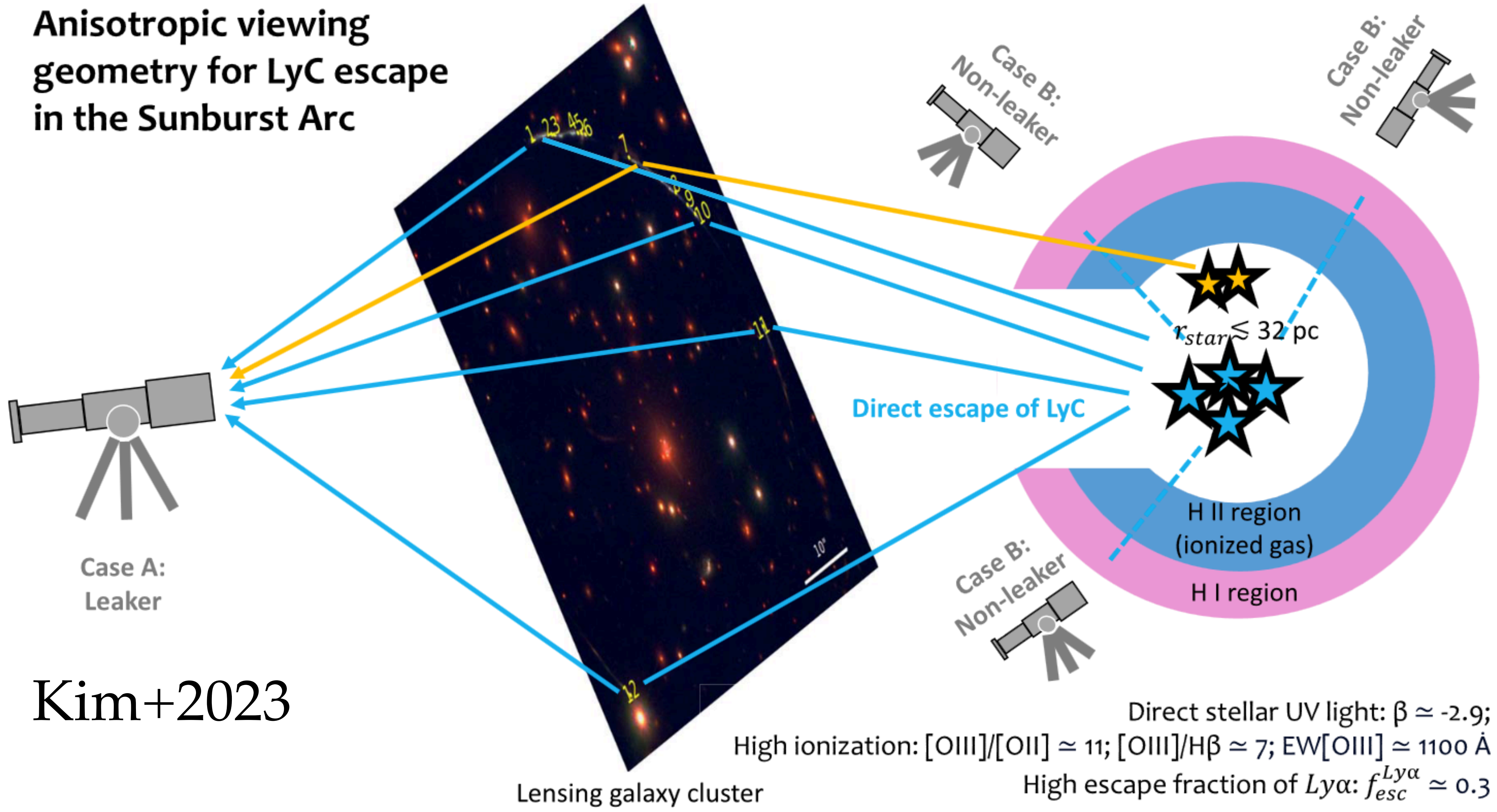
Escape Fractions in the Reionization Era

Topping et al. 2023



- These very blue sources may be examples of a brief phase when z>7 galaxies have extremely large escape fractions.

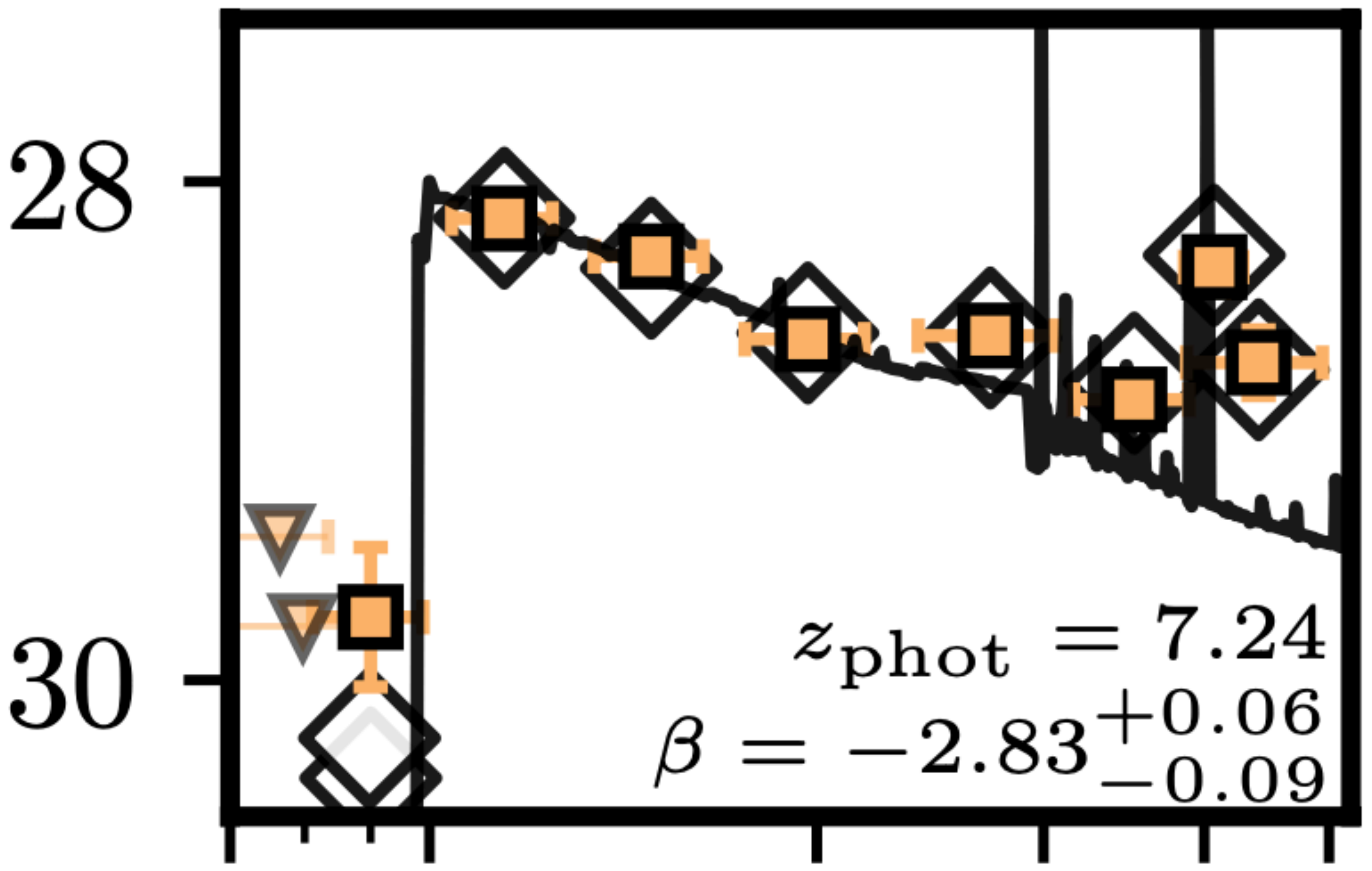
- Or sources where our viewing angle catches channel where neutral gas has been blown out / highly ionized, similar to Sunburst arc.



Kim+2023

Escape Fractions in the Reionization Era

Topping et al. 2023



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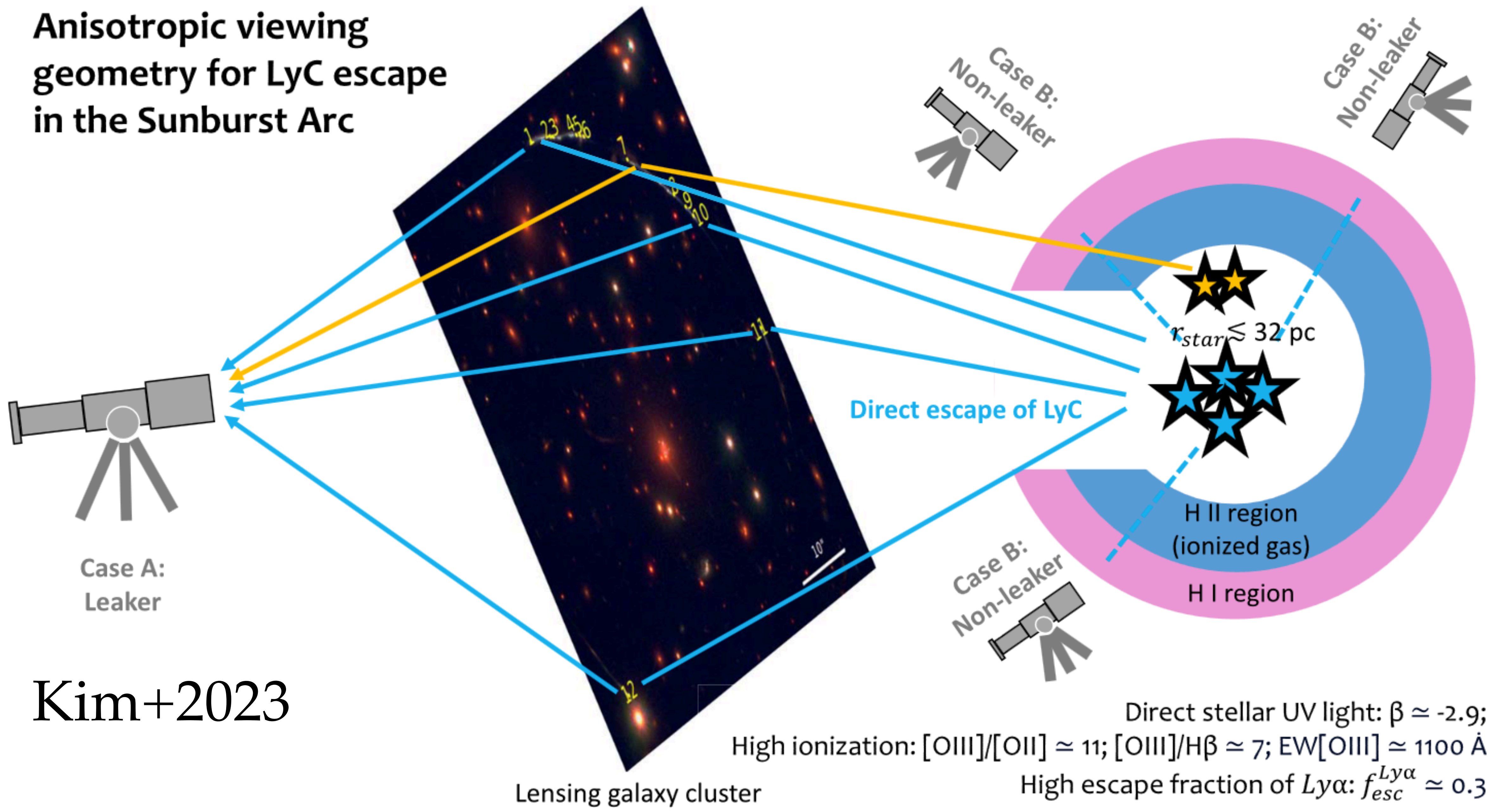


Kim+2023

- While these extreme objects are rare*, they may be an important phase of large LyC leakage — need follow-up spectroscopy to better characterize this population.

**see Mascia+23, Saxena+23 for discussion of fesc for broader population.*

Summary

- First Lyα samples at z>7 with JWST indicate transmission of line drops between z~5-6 and z>9, consistent with significant attenuation from IGM damping wing. Great potential to build on these studies to constrain early stages of reionization!

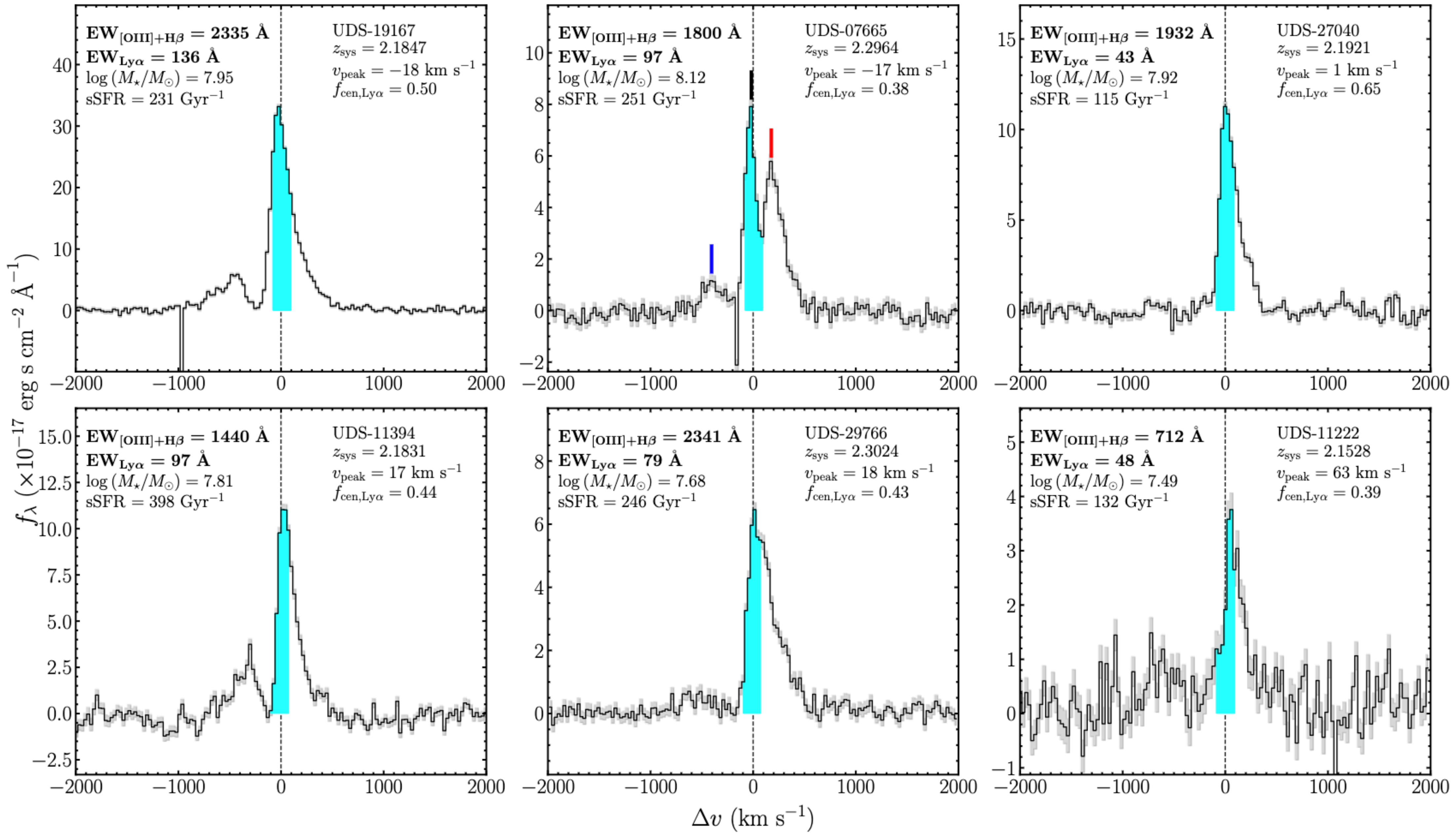
- Sensitivity of JWST spectroscopy is optimal for bubble characterization. Large ionized sightlines already potentially being identified at z~7-8.

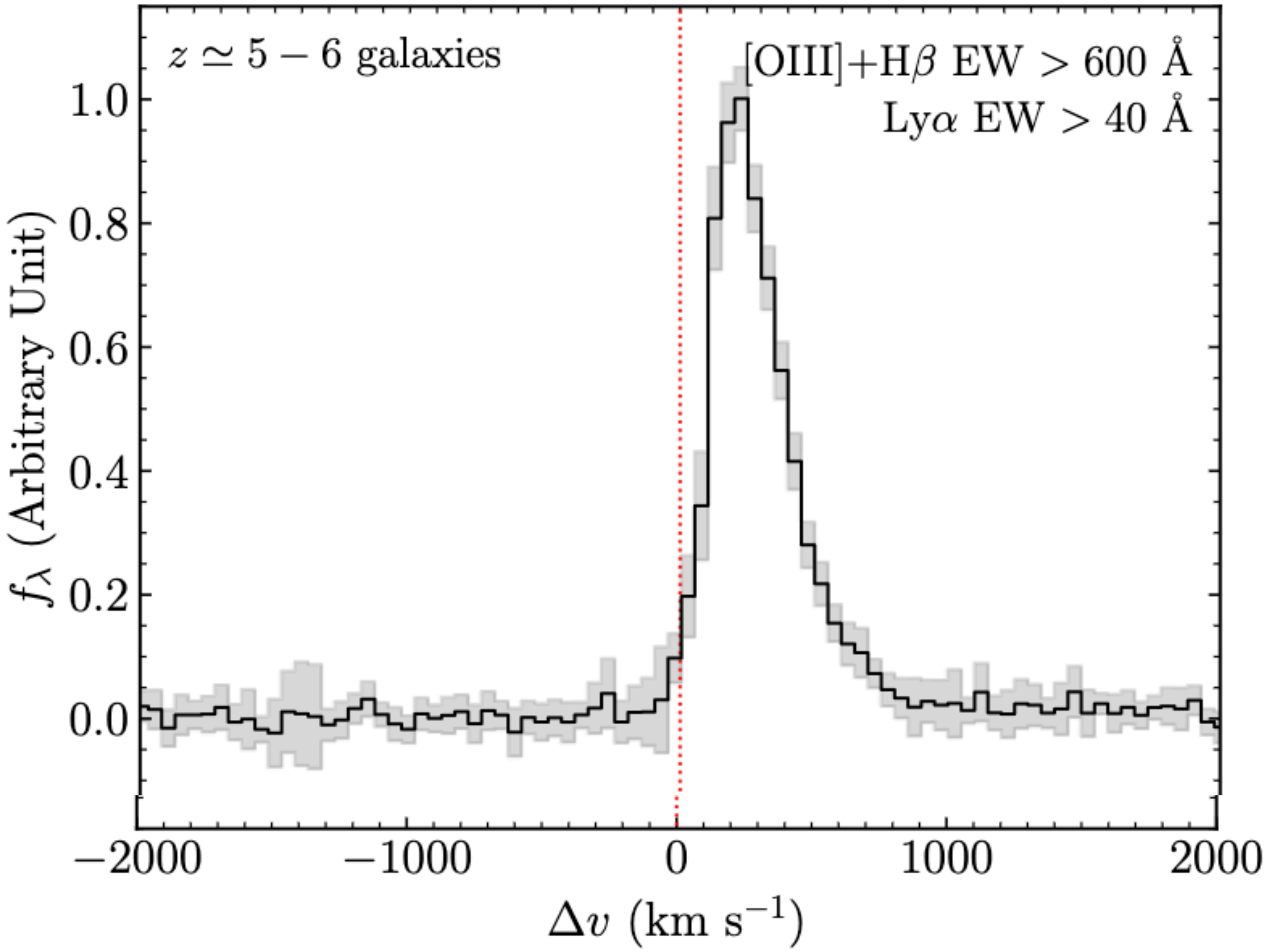
- Bursty star formation histories are apparent in z~6-9 SEDs. New population of weak emission line sources appear likely in off mode of star formation, following burst. Implies lower ionizing production efficiency than thought previously.

- Population of very blue (β~-3) sources discovered with NIRCam imaging. May be indicative of galaxies with large LyC leakage (>50%). Further spectroscopy is needed to better characterize this population.

Evolution in Velocity Profiles of Strong Lyα Emitters

Tang+2024b (see also Rivera-Thorsen+2017)

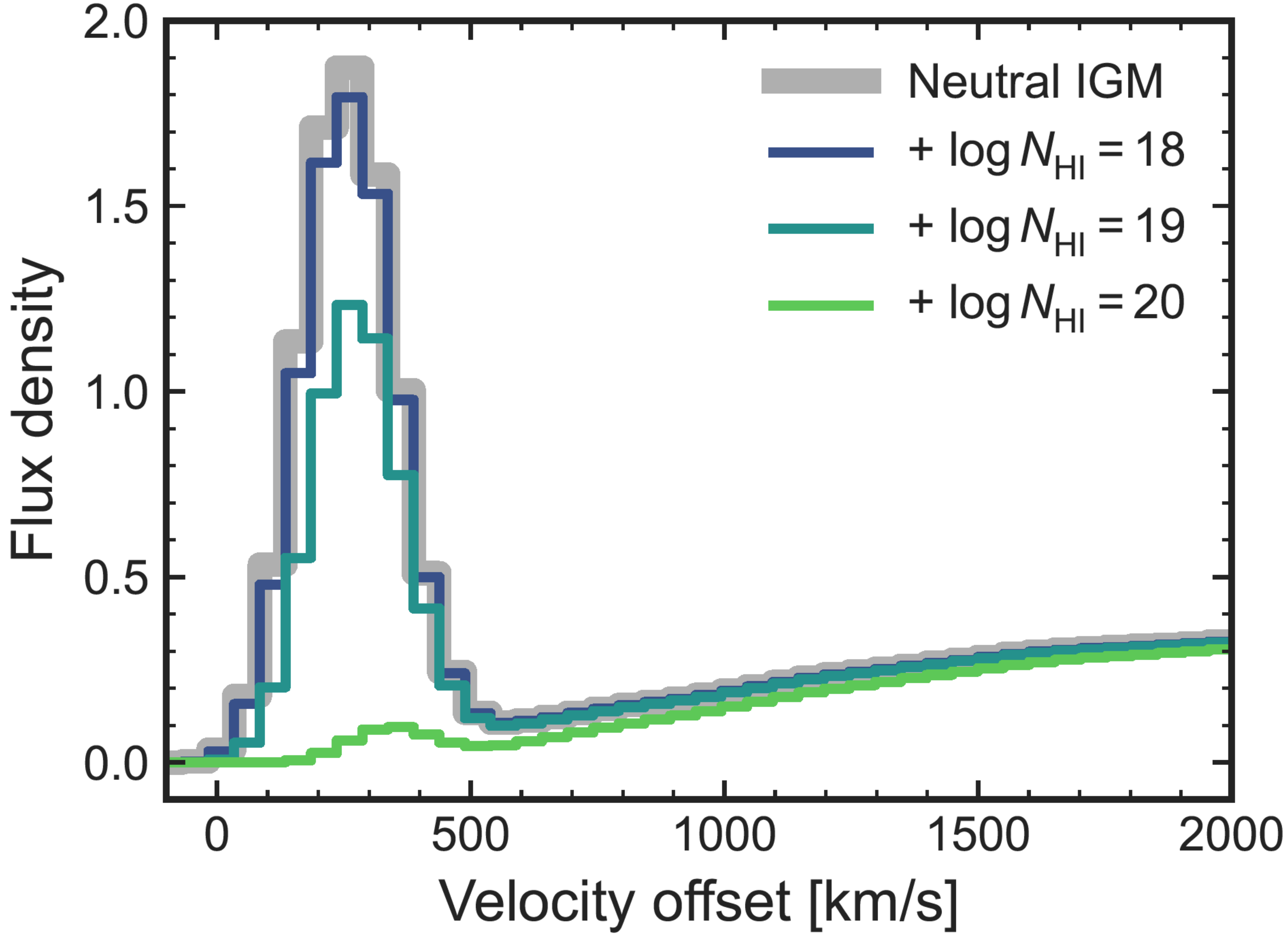




- Evolution in line profiles of strong Lyα emitting (large sSFR) galaxies at z>2 — *disappearance of blue-sided emission, and centrally-peaked profiles.*
- Consistent with attenuation from dense, ionized IGM at z~5 with potential additional contribution from damping wing at z~6 — impact of IGM already present in line profiles at z~6.

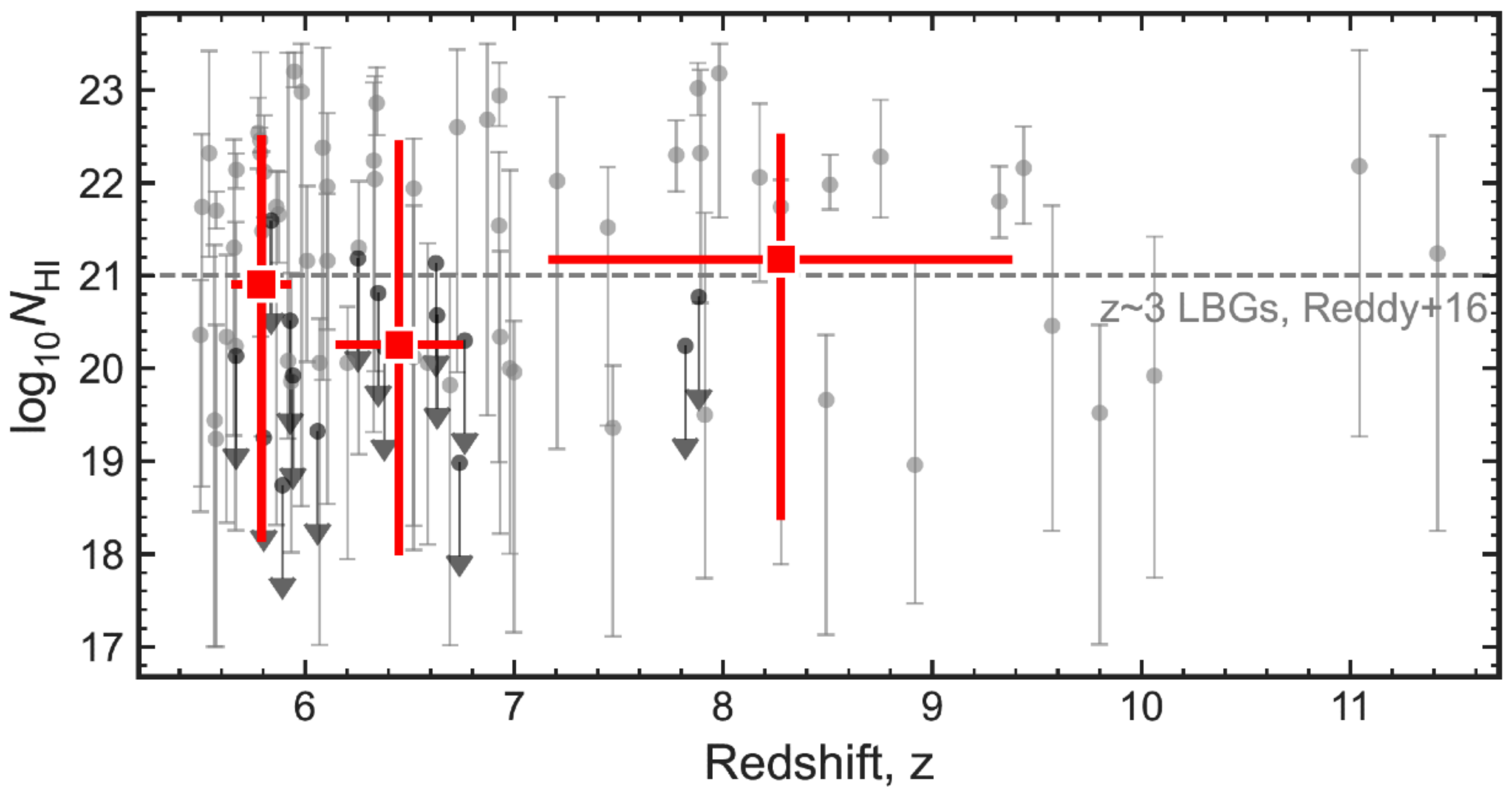
Quantifying Evolution of Lyα Emission

Mason+24 (in prep)



- Deep continuum spectra offer potential for investigation of role other factors (i.e. Lyman limit systems, DLAs) may be playing in attenuating Lyα emission.

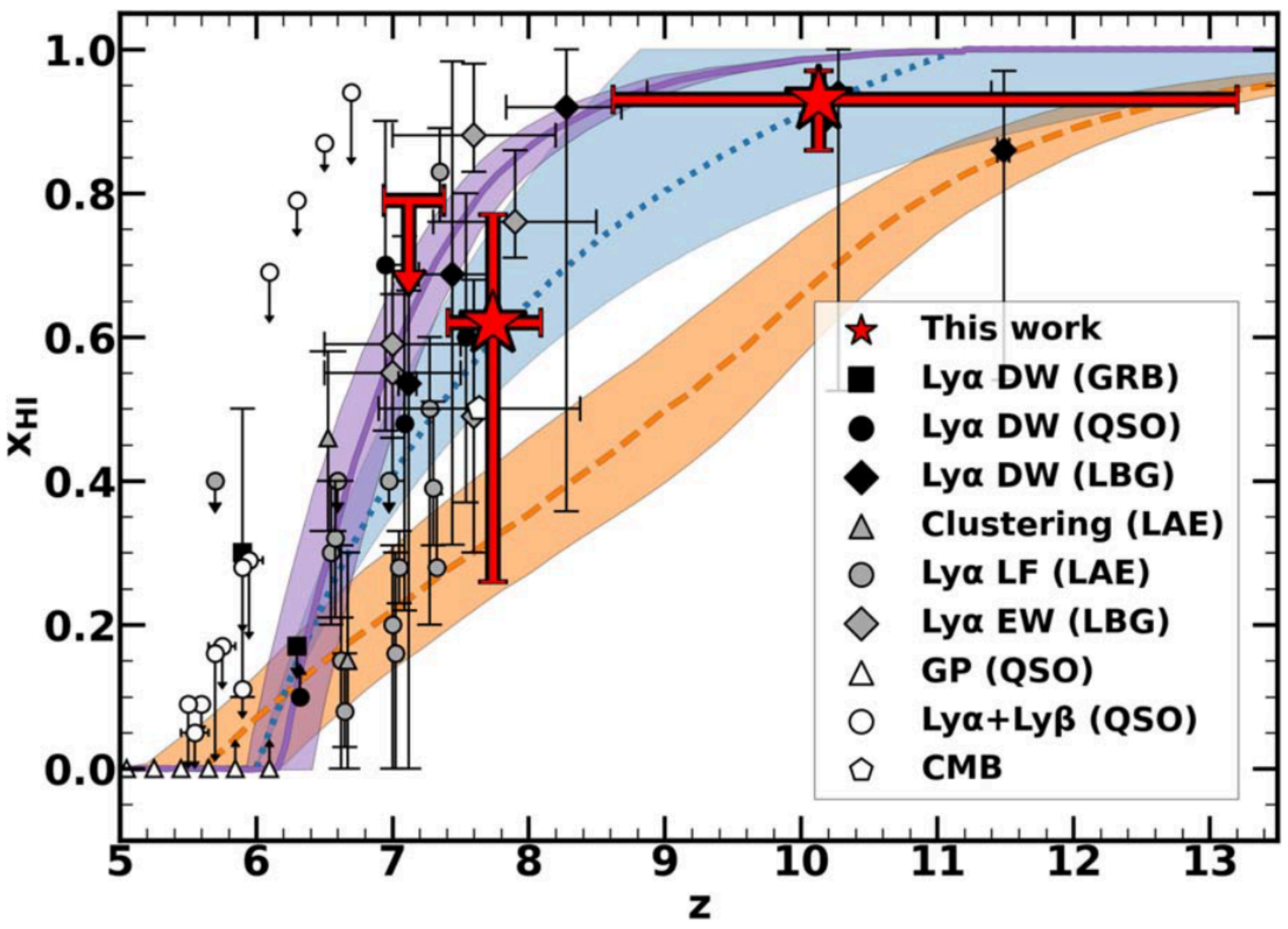
- Very important work, with potential to improve interpretation of Lyα downturn in future.



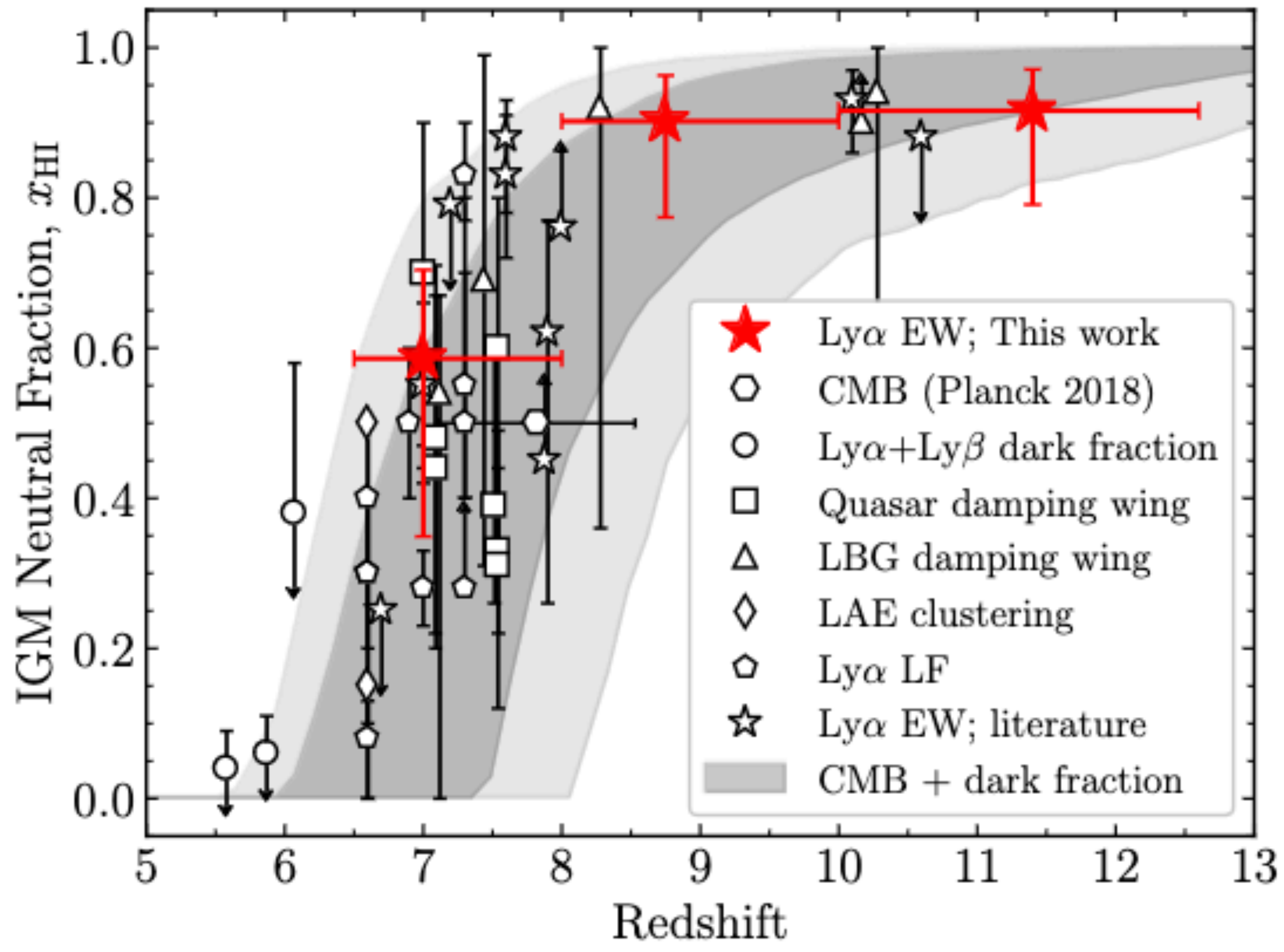
See Bolton & Becker 2013; Mesinger+2015; Kakiichi+2016; Weinberger+2018; Gangolli+2023; Davies+2023

Quantifying Evolution of Lyα Emission

Nakane+2024

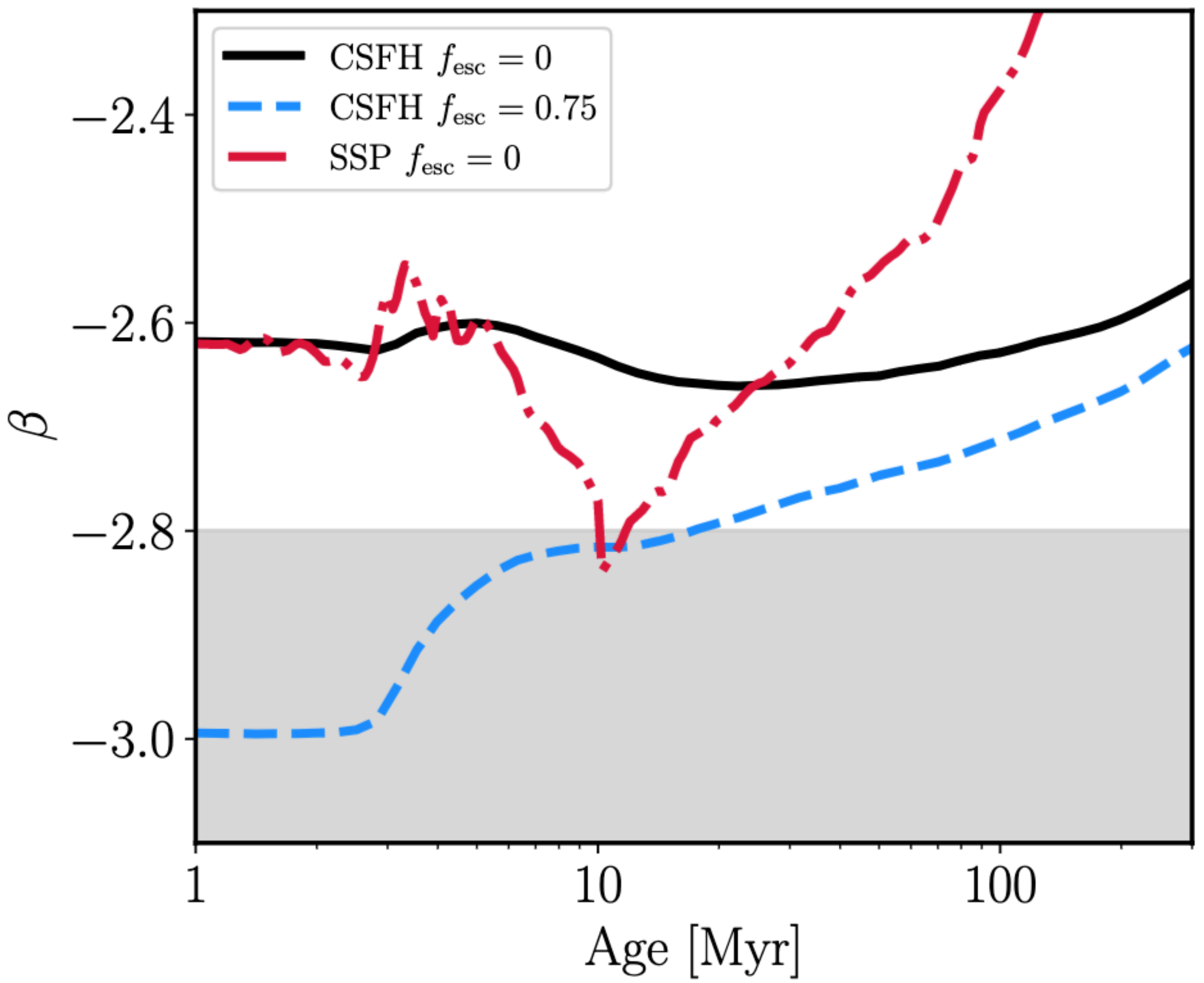


Tang+2024c



- If assume this is due to IGM damping wing, require large neutral fractions at z>7, consistent with earlier work.

- JWST will build on Lyα measurements at z>9, *providing one of our only probes on early star formation / reionization.*


CSFH $f_{\rm esc} = 0$
CSFH $f_{\rm esc} = 0.75$
SSP $f_{\rm esc} = 0$
-2.4
-2.6
-2.8
-3.0
β
1
10
100
Age [Myr]