Image Credit: Brant Robertson, S. Tacchella & JADES Collaboration

Early Galaxies and Cosmic Reionization: New Insights from JWST and Ground-Based Telescopes

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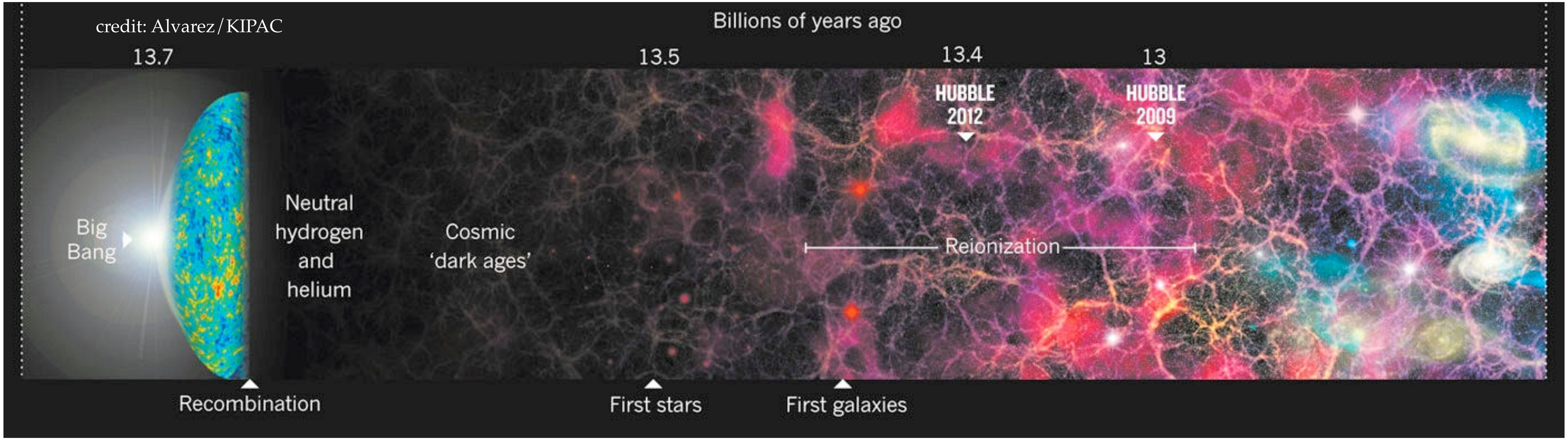
UC Berkeley Astronomy Colloquium

March 2, 2023

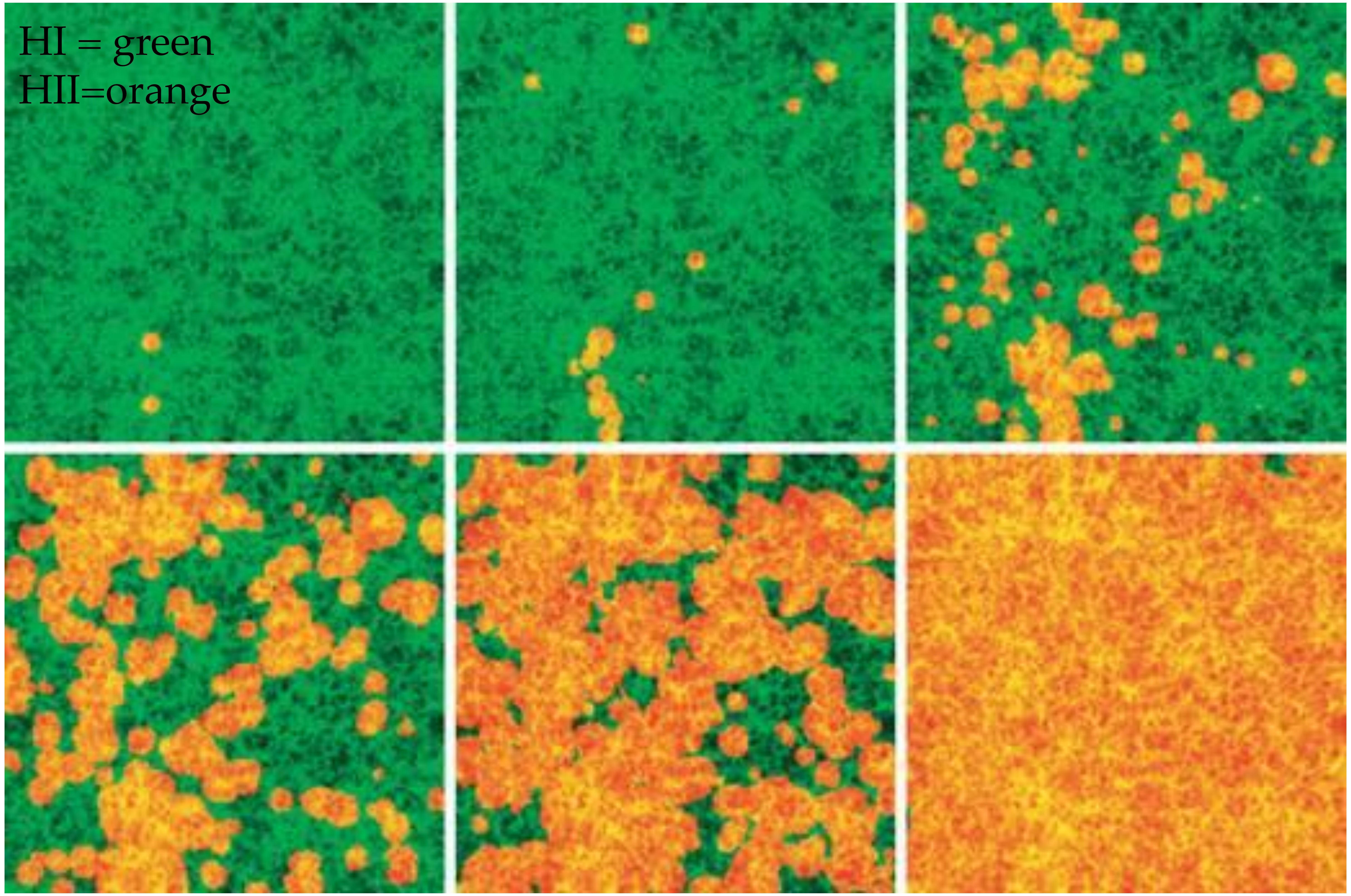
First Billion Years of Cosmic History



- Deep infrared imaging is rapidly pushing back cosmic frontier to z~9-15.
- Knowledge of when and how reionization happened promises insight into the first generation of stars/galaxies.
- Major science driver behind many current and future facilities (21-cm, [CII]+Ly**α** intensity mapping, TMT, Roman, JWST, ALMA).

From Cosmic Dawn to Reionization

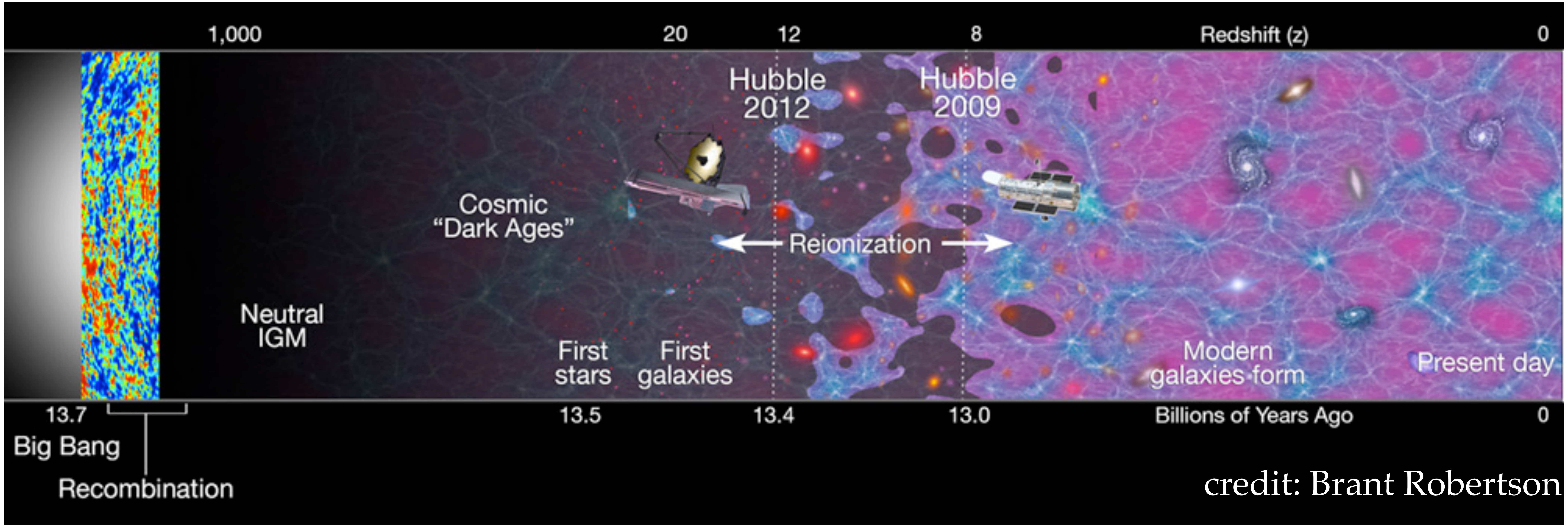
credit: Iliev et al.



- 1.First galaxies form stars in low mass halos.
- 2. Massive stars create small HII regions, beginning reionization.
- 3. Groups of small galaxies form in dense regions, leading to large bubbles.
- 4. Reionization complete once all bubbles have overlapped.

We are now beginning to directly observe this process!

What do we know about the timeline of reionization?



credit: Brant Robertson

- Completed by z~5-6, ~1 billion years after the Big Bang.
- Timescale of reionization regulates the optical depth to electron scattering ($\boldsymbol{\tau}_e$) faced by cosmic microwave background (CMB) photons.
- Measurement of $\boldsymbol{\tau}_e$ indicates reionization underway by z~9, 550 million years after the Big Bang.

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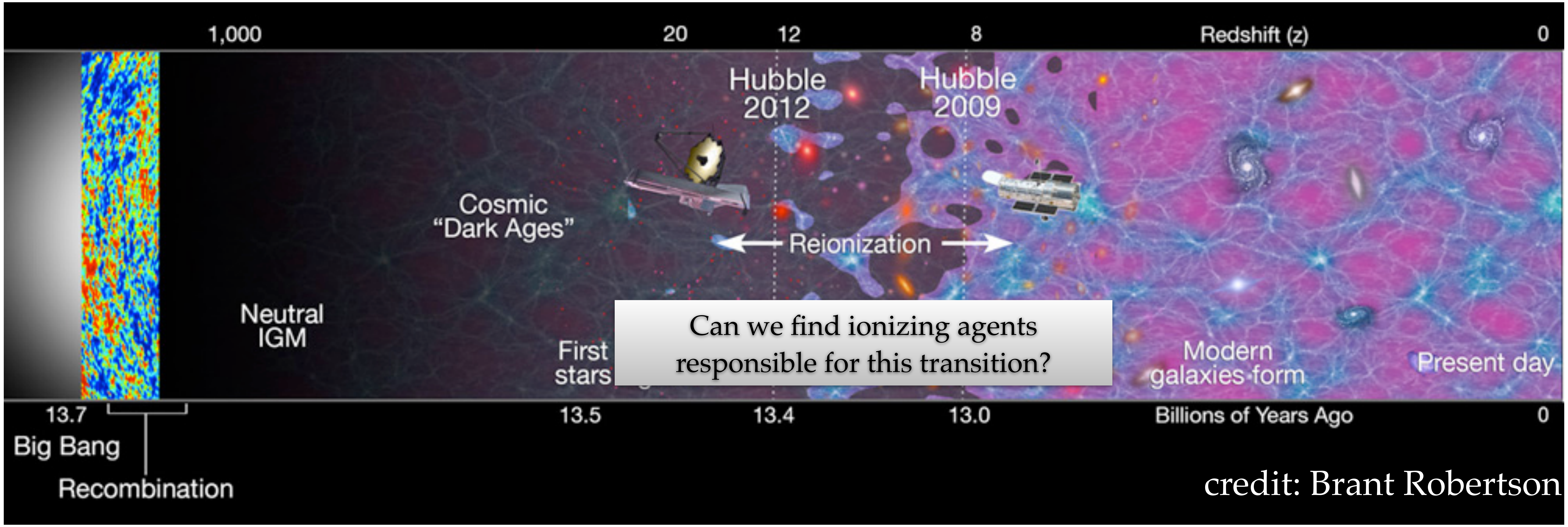

Can we find ionizing agents responsible for this transition?

credit: Brant Robertson

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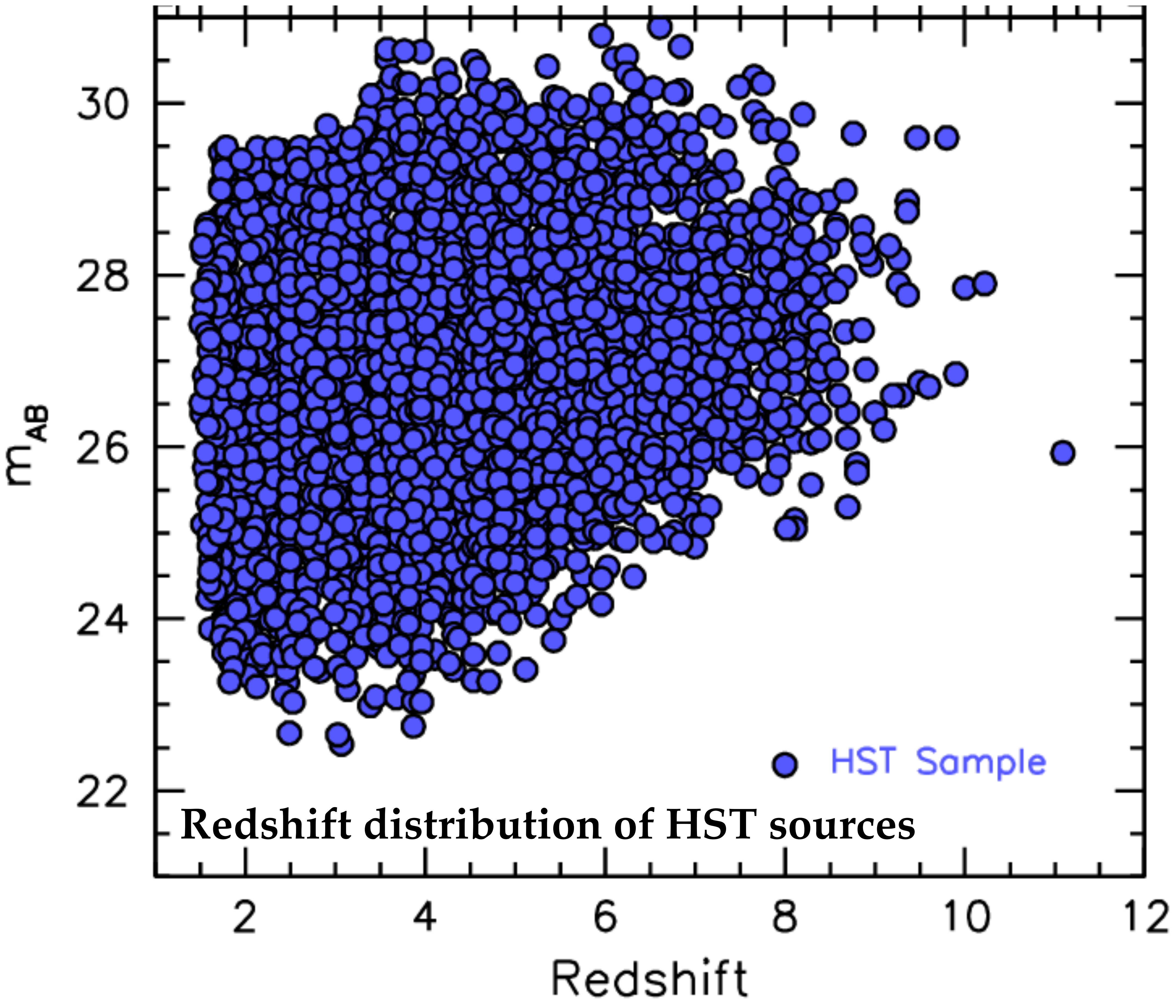
HST has Excelled in Discovery of Early Galaxies

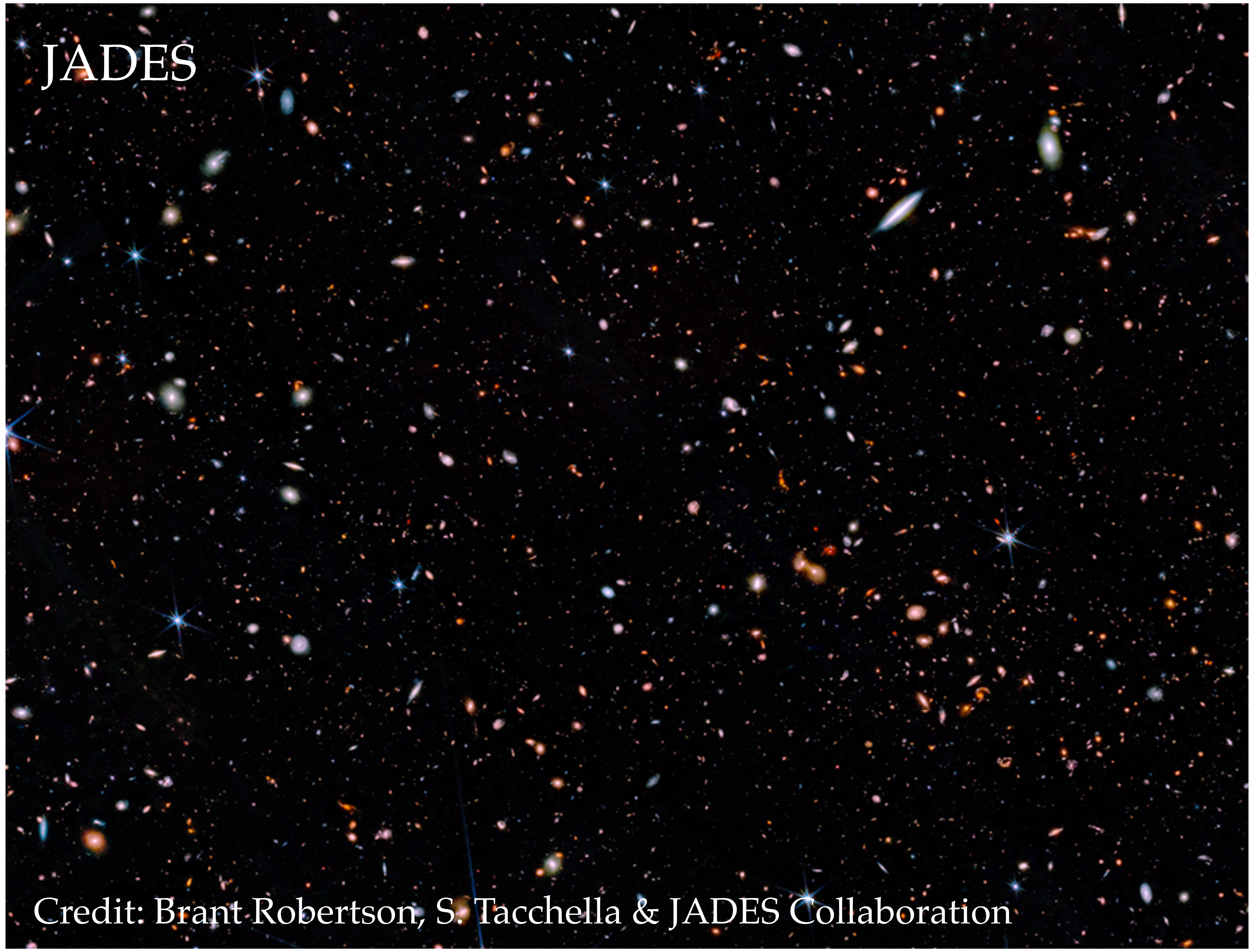
Bouwens et al. 2021


Redshift distribution of HST sources

- Large photometric samples at z~7-8 from HST WFC3/IR imaging.
    - 600 galaxies at z~7
    - 250 galaxies at z~8

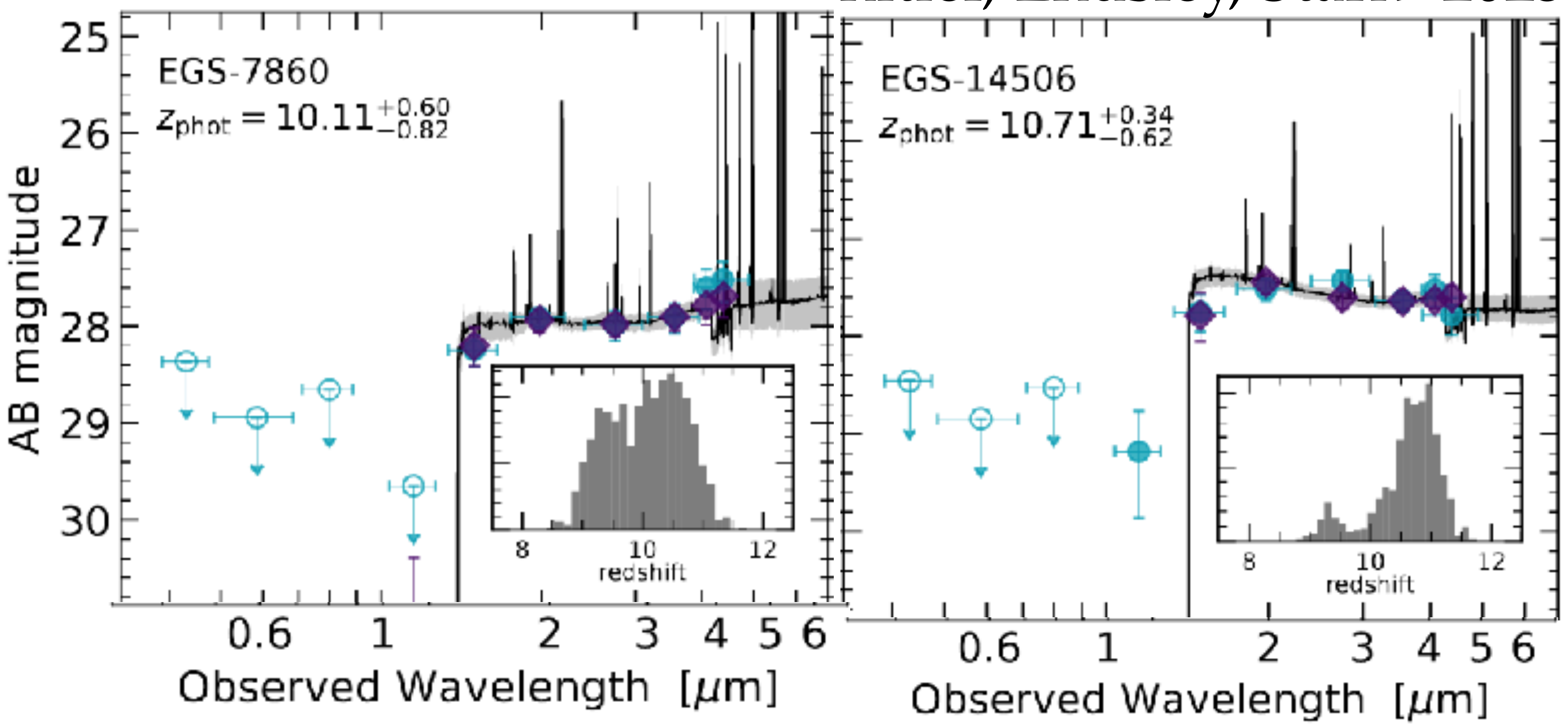
- Much smaller samples (~10) at z>9 from HST.

New Galaxy Samples at z~9-13 from JWST

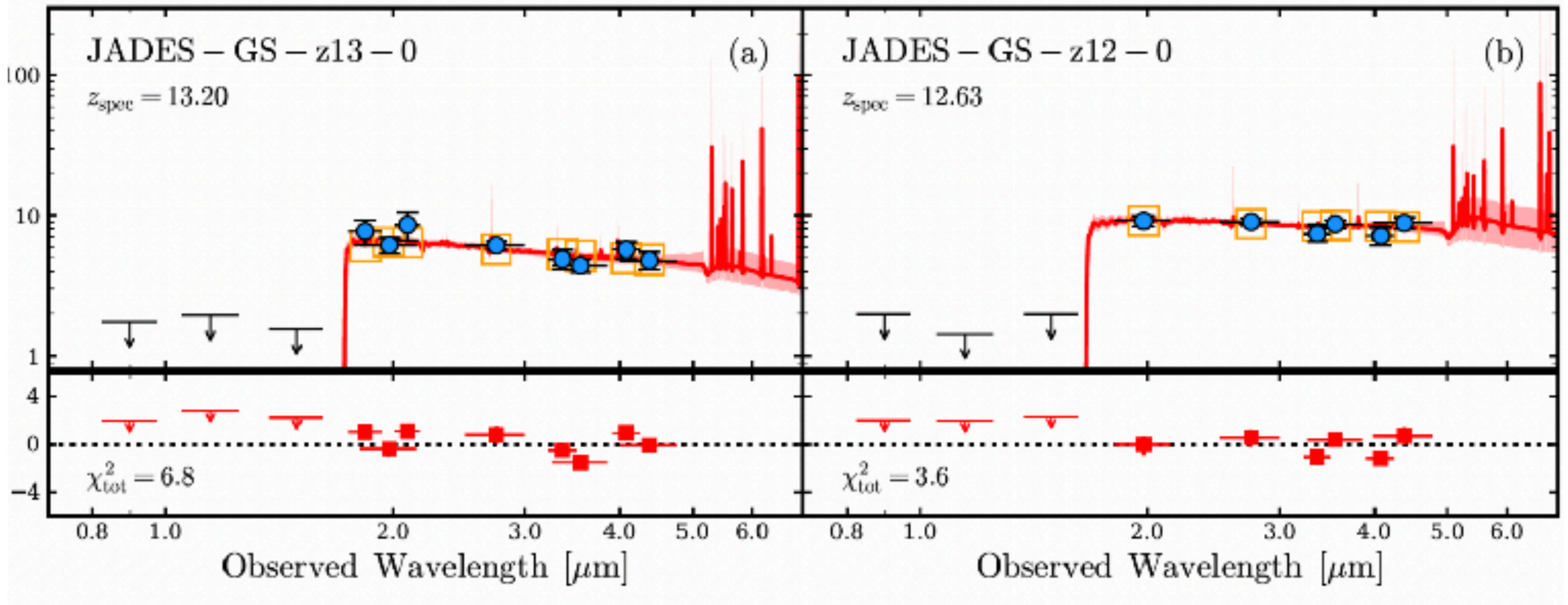


Credit: Brant Robertson, S. Tacchella & JADES Collaboration

Whitler, Endsley, Stark+2023



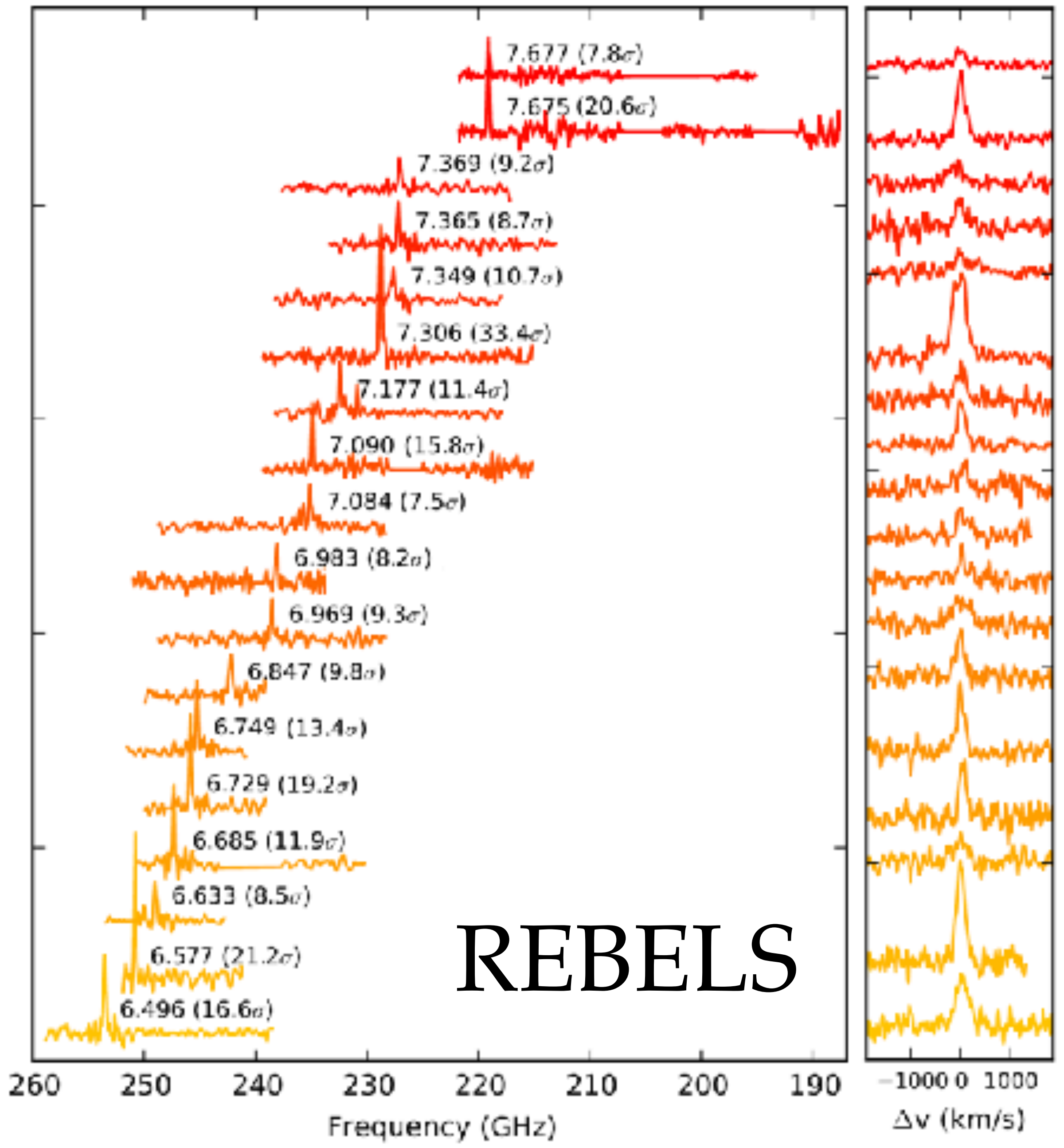
Robertson+2023



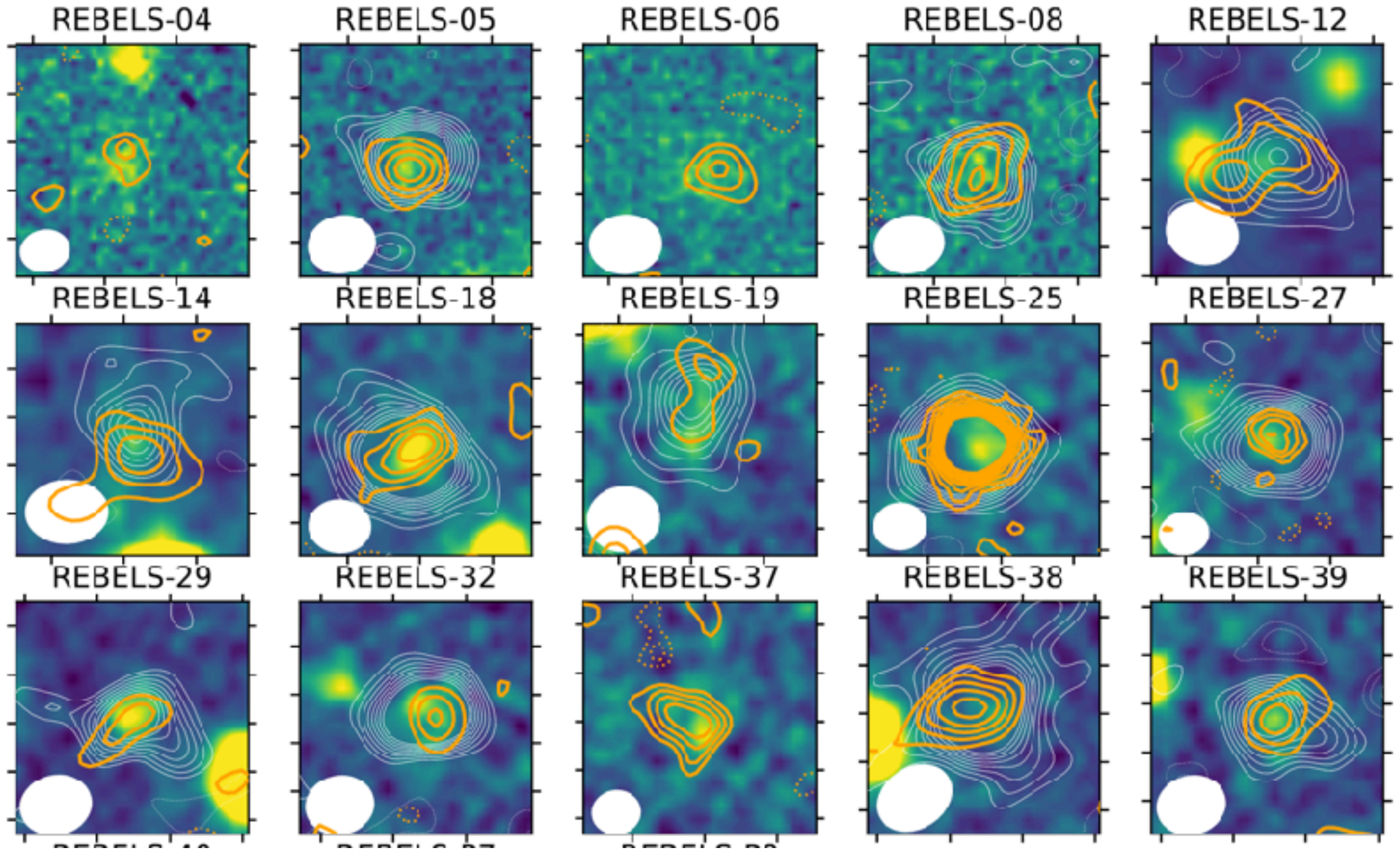
Deep JWST/NIRCam images have delivered the first large samples of z~9-15 galaxies, with a growing number now spectroscopically confirmed.

New Insight into Dust Obscuration from ALMA

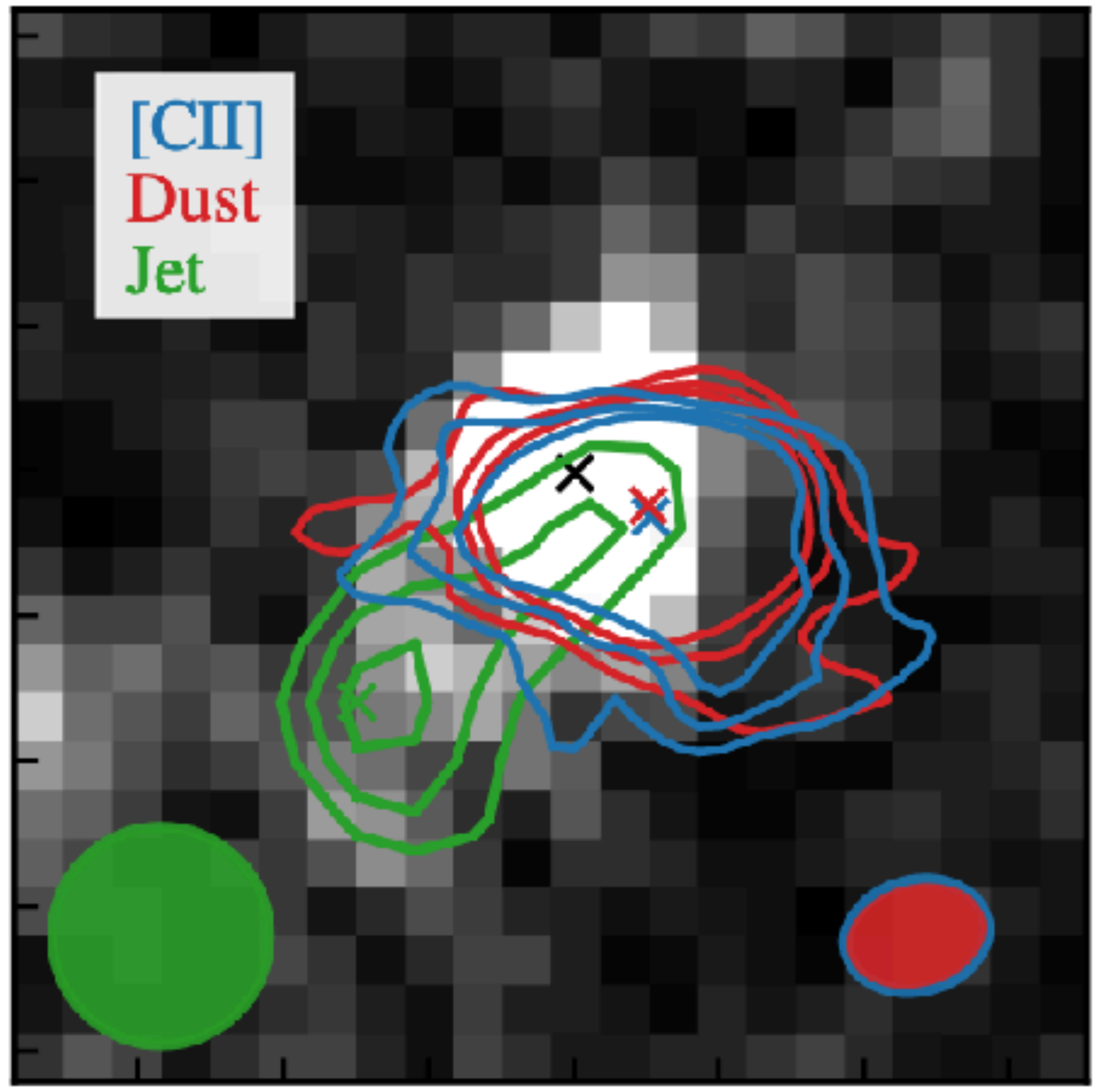
Bouwens+22



Inami+22



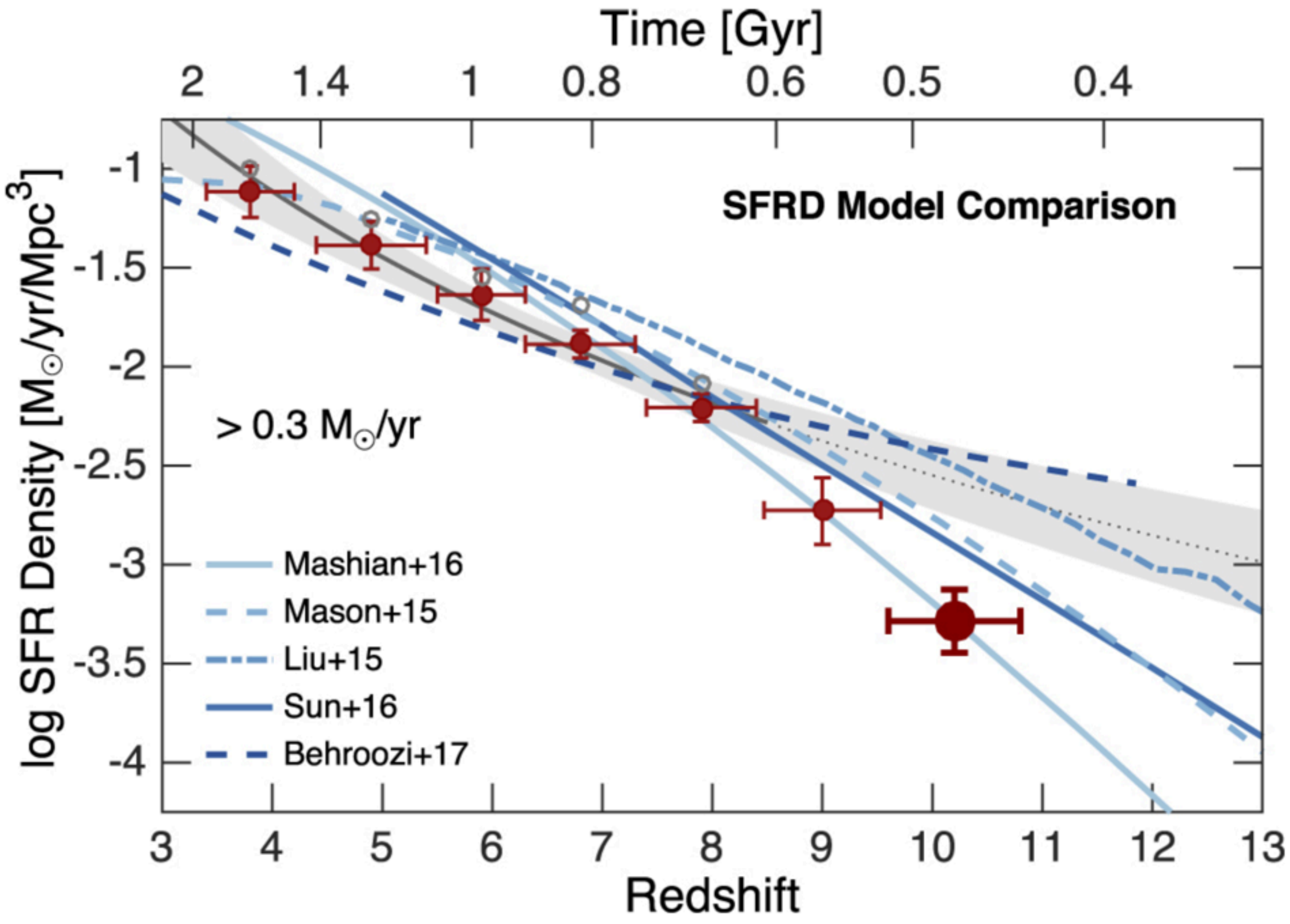
Endsley,Stark+2022d



ALMA beginning to contribute more to our understanding of early galaxies.

- Characterization of obscured star formation in typical UV-selected galaxies.
- Discovery of AGNs and heavily-obscured galaxies.

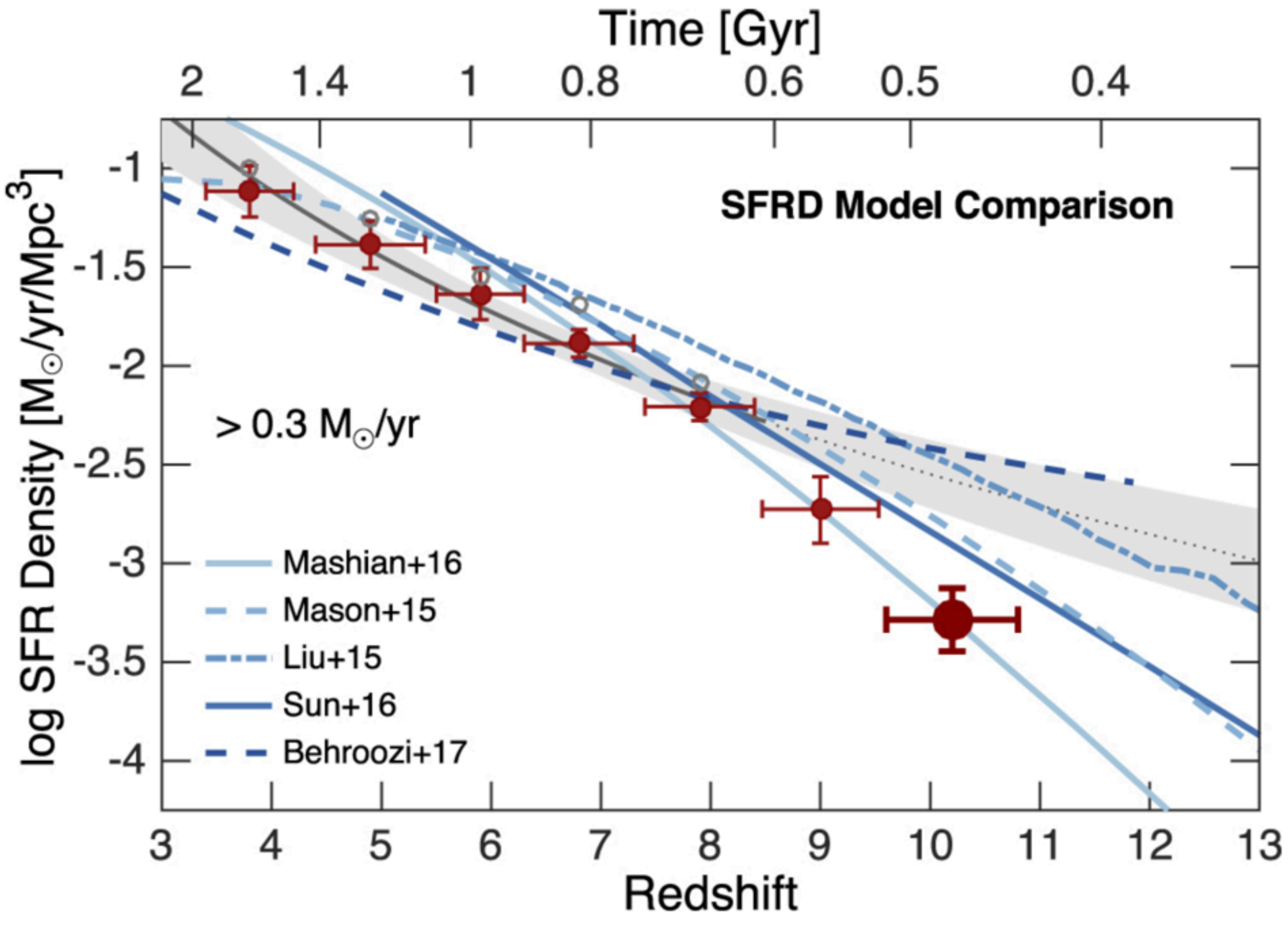
Census of Galaxies in Reionization Era



- SFR density smoothly declines toward higher redshift at z>6.
- HST suggests accelerated decline in SFR density at z>8.
- JWST has called this result into question, suggesting more gradual decline and more SFR at z>10 than we previously thought.

Robertson 2022, ARAA

Census of Galaxies in Reionization Era

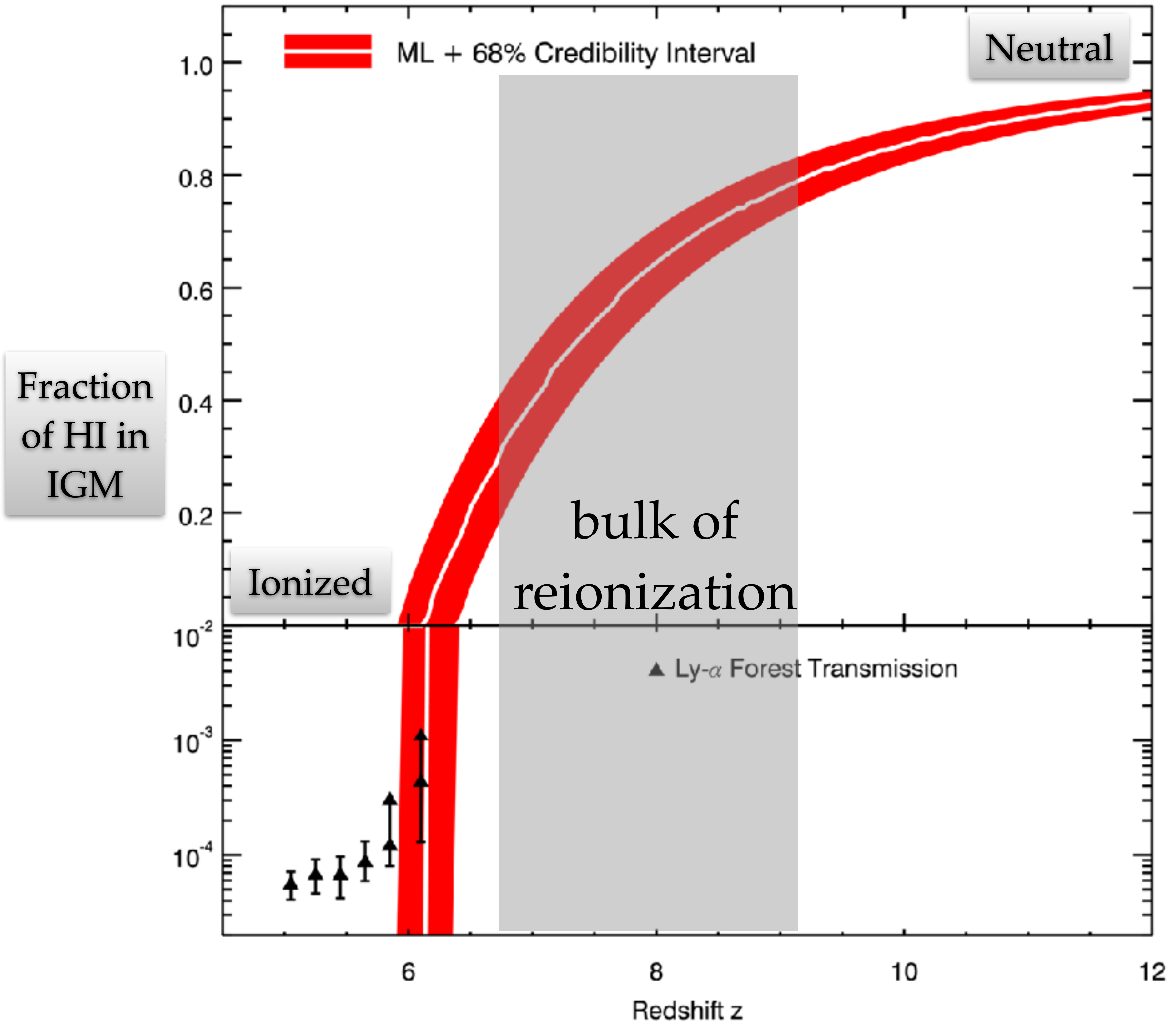


Robertson 2022, ARAA

- •SFR density smoothly declines toward higher redshift at z>6.
- •HST suggests accelerated decline in SFR density at z>8.
- •JWST has called this result into question, suggesting more gradual decline and more SFR at z>10 than we previously thought.
- •Nevertheless we see a drop off in UV photons at z>6. Motivates question: **can galaxies achieve reionization by z~6 given what we have learned about census?**

Late Reionization Histories are Expected

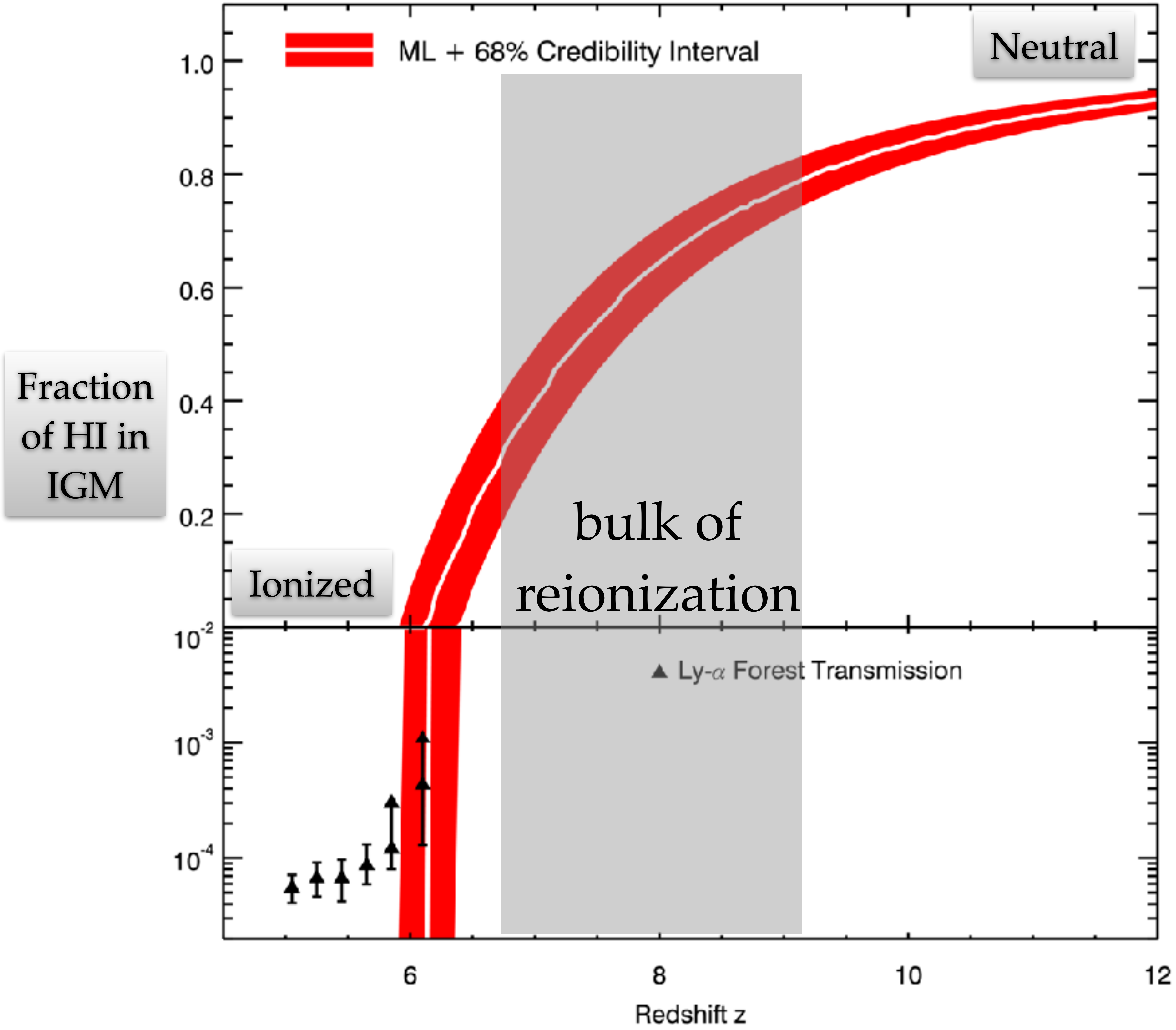
Robertson et al. 2015



- Galaxies can easily achieve reionization by z~6 for nominal source assumptions (i.e., ionizing efficiency of galaxies, lower luminosity bound on star formation).
- In this fiducial picture, bulk of reionization occurs relatively late at 6<z<9.

Measuring IGM Ionization State

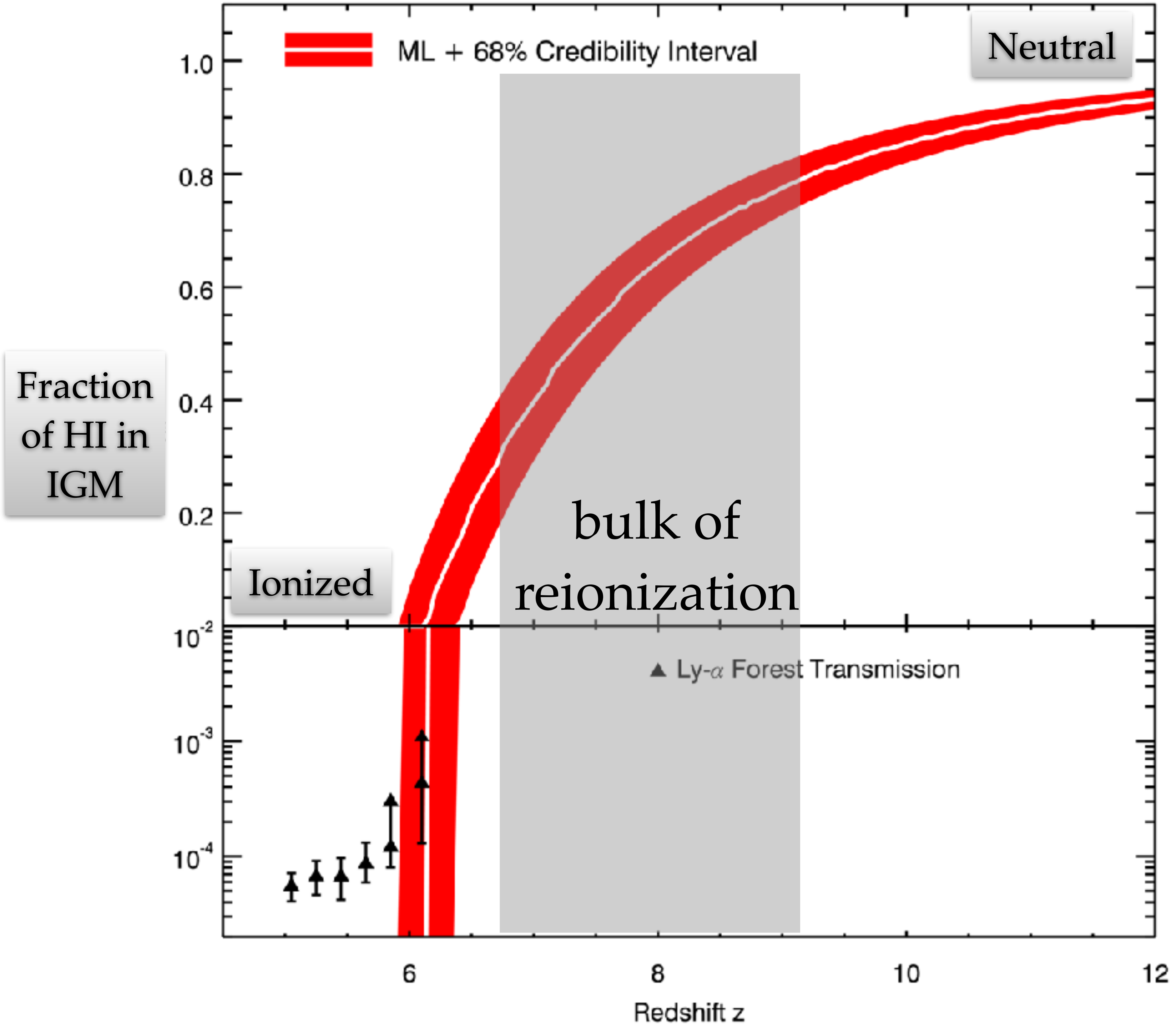
Robertson et al. 2015



- If this is correct, a significant fraction (~50%) of the IGM should be neutral at z~8, with closer to 80% neutral at z~10.

Measuring IGM Ionization State

Robertson et al. 2015



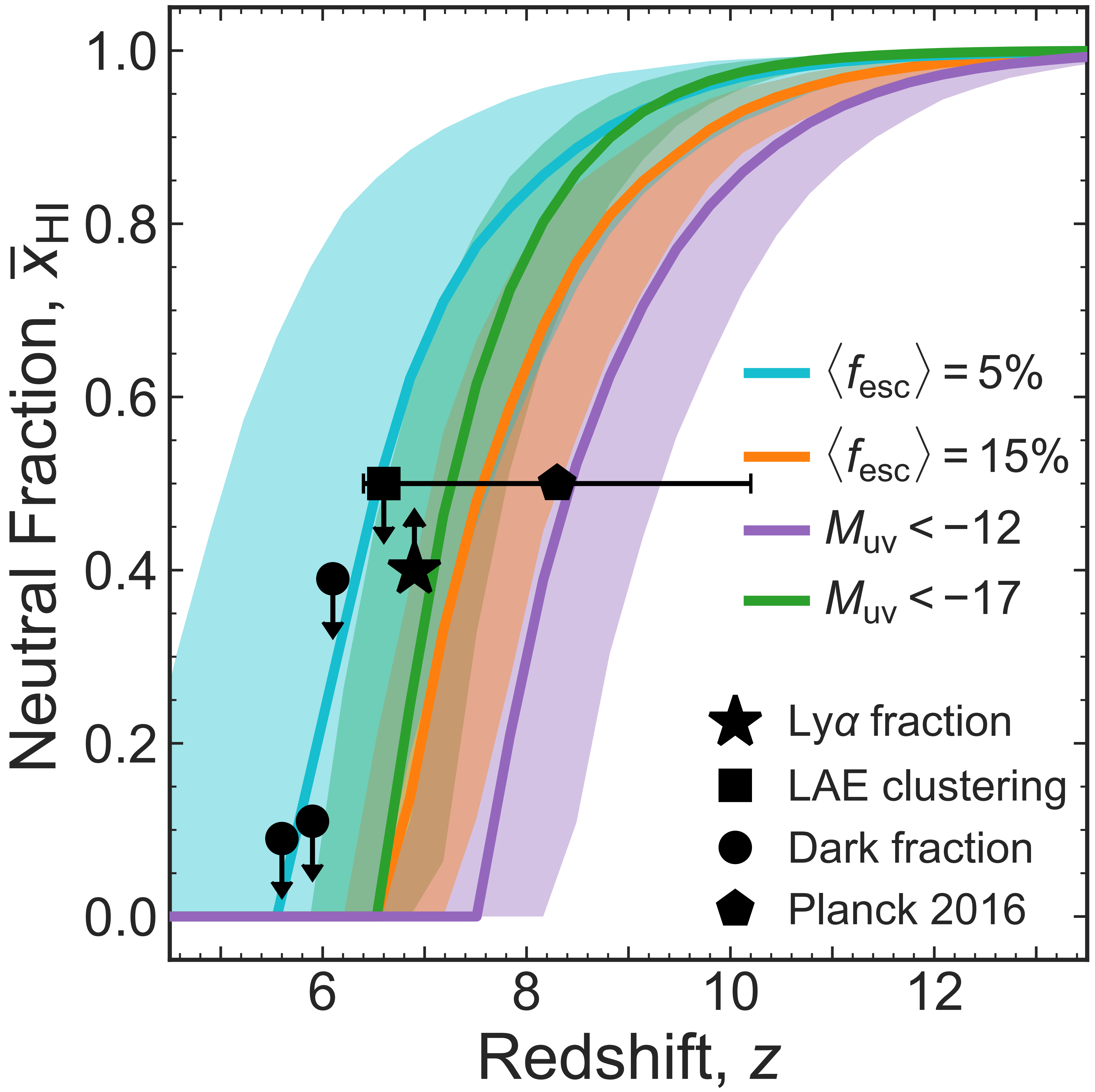
- If this is correct, a significant fraction (~50%) of the IGM should be neutral at z~8, with closer to 80% neutral at z~10.

- This needs to be tested, as reionization can occur differently for difference source assumptions (i.e., ionizing efficiency of galaxies, lower luminosity bound on star formation).

Measuring IGM Ionization State

Mason et al. 2015

Fraction of HI in IGM



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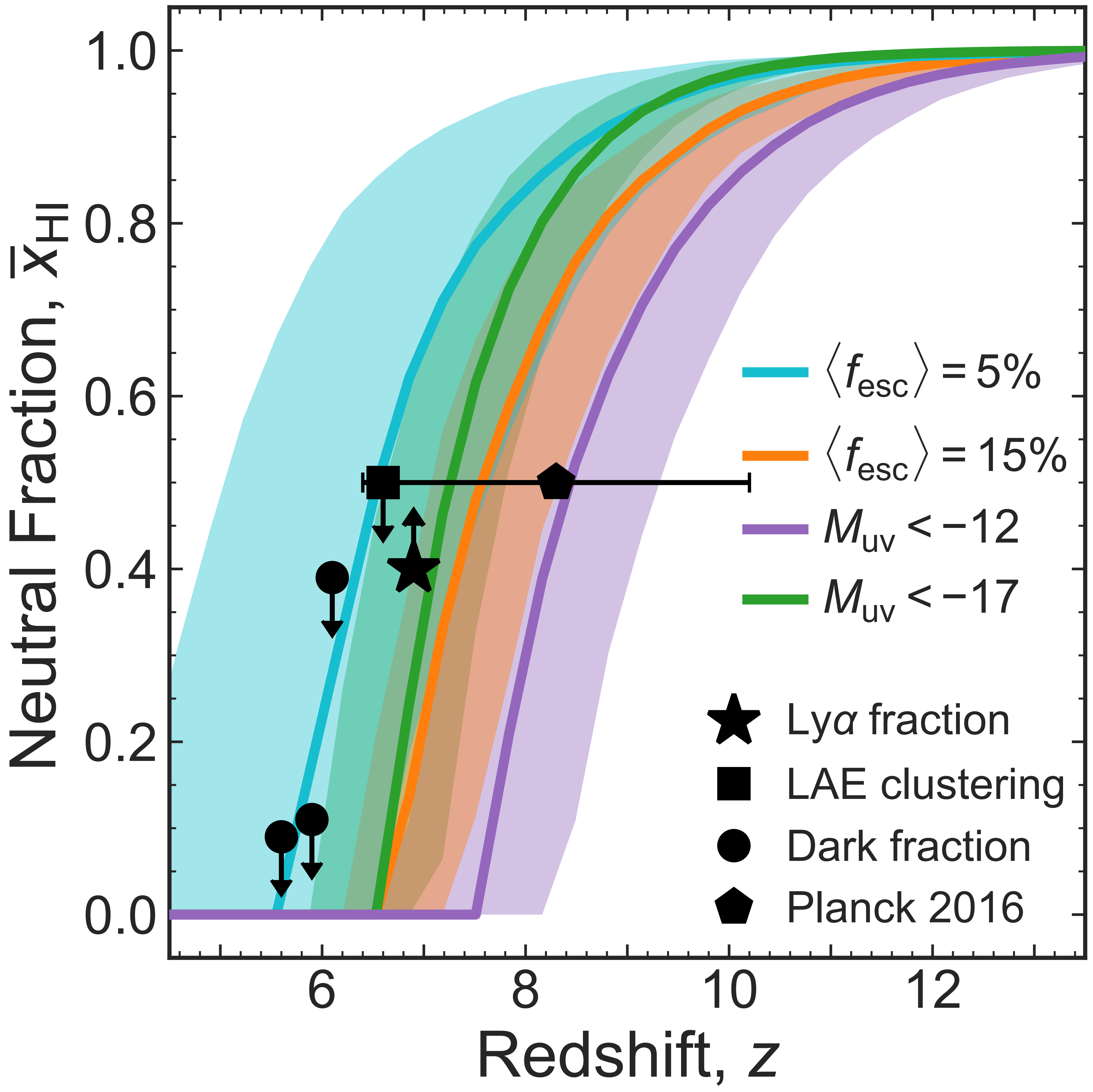
Measuring IGM Ionization State

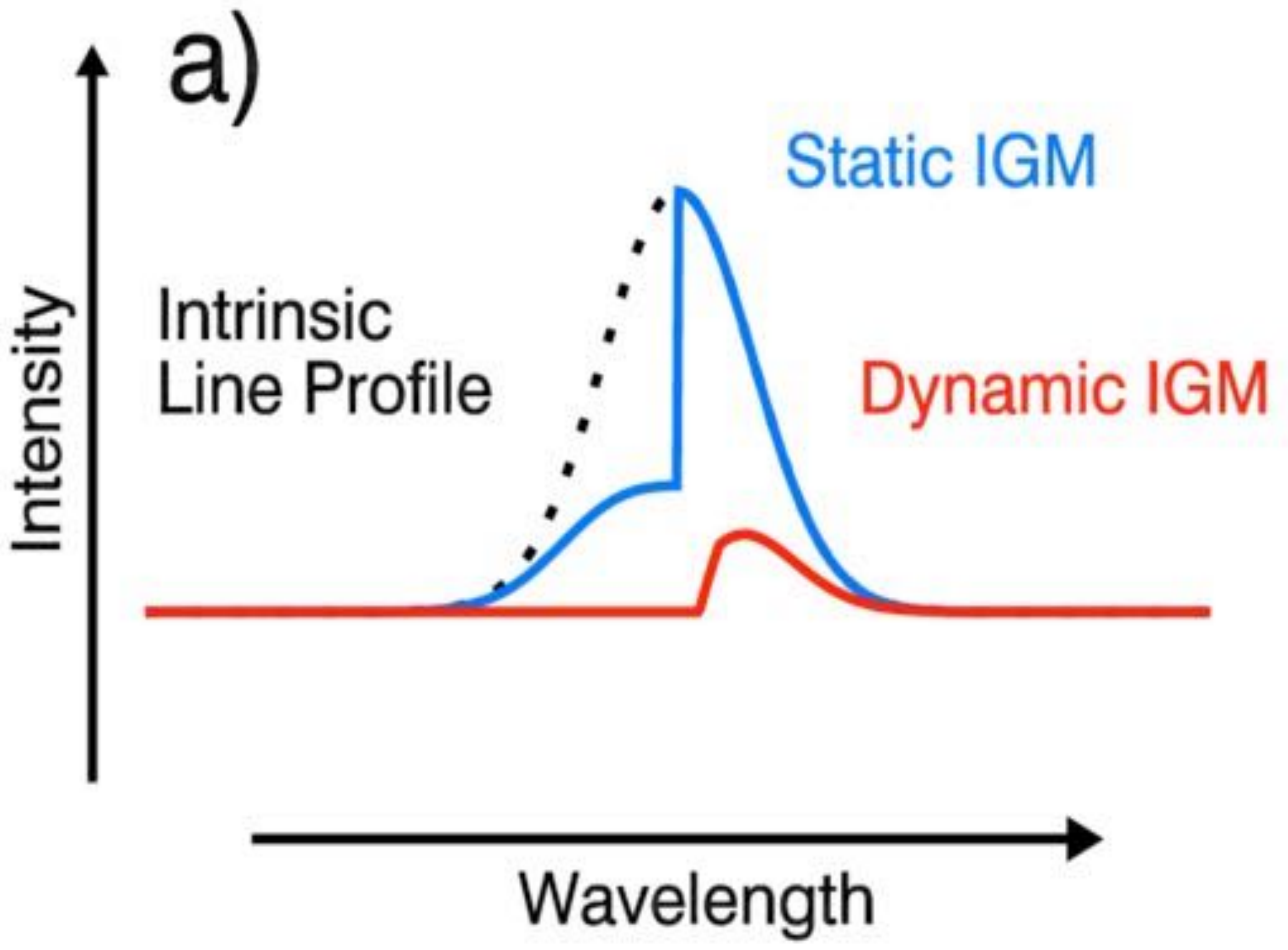
Mason et al. 2015

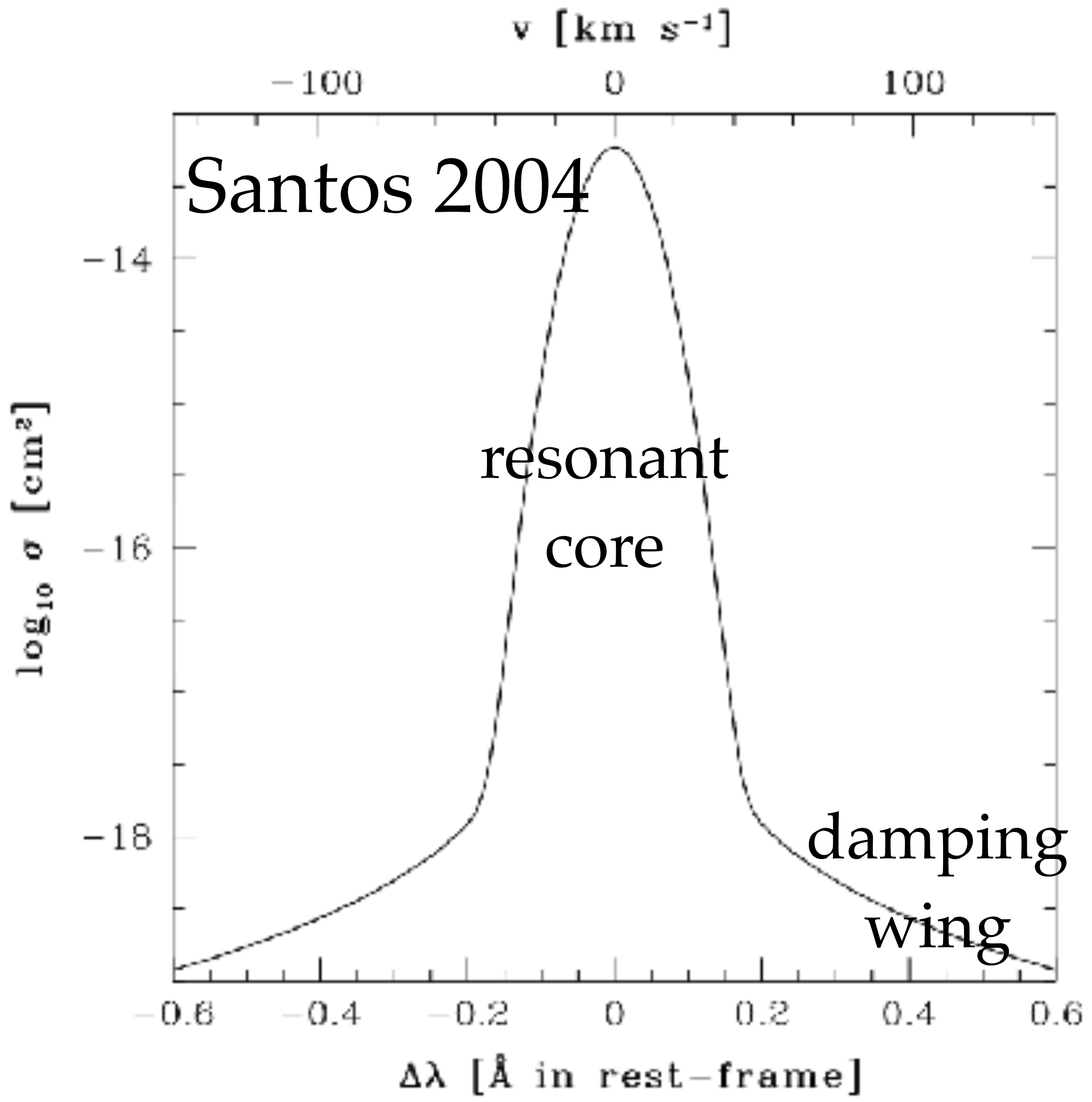


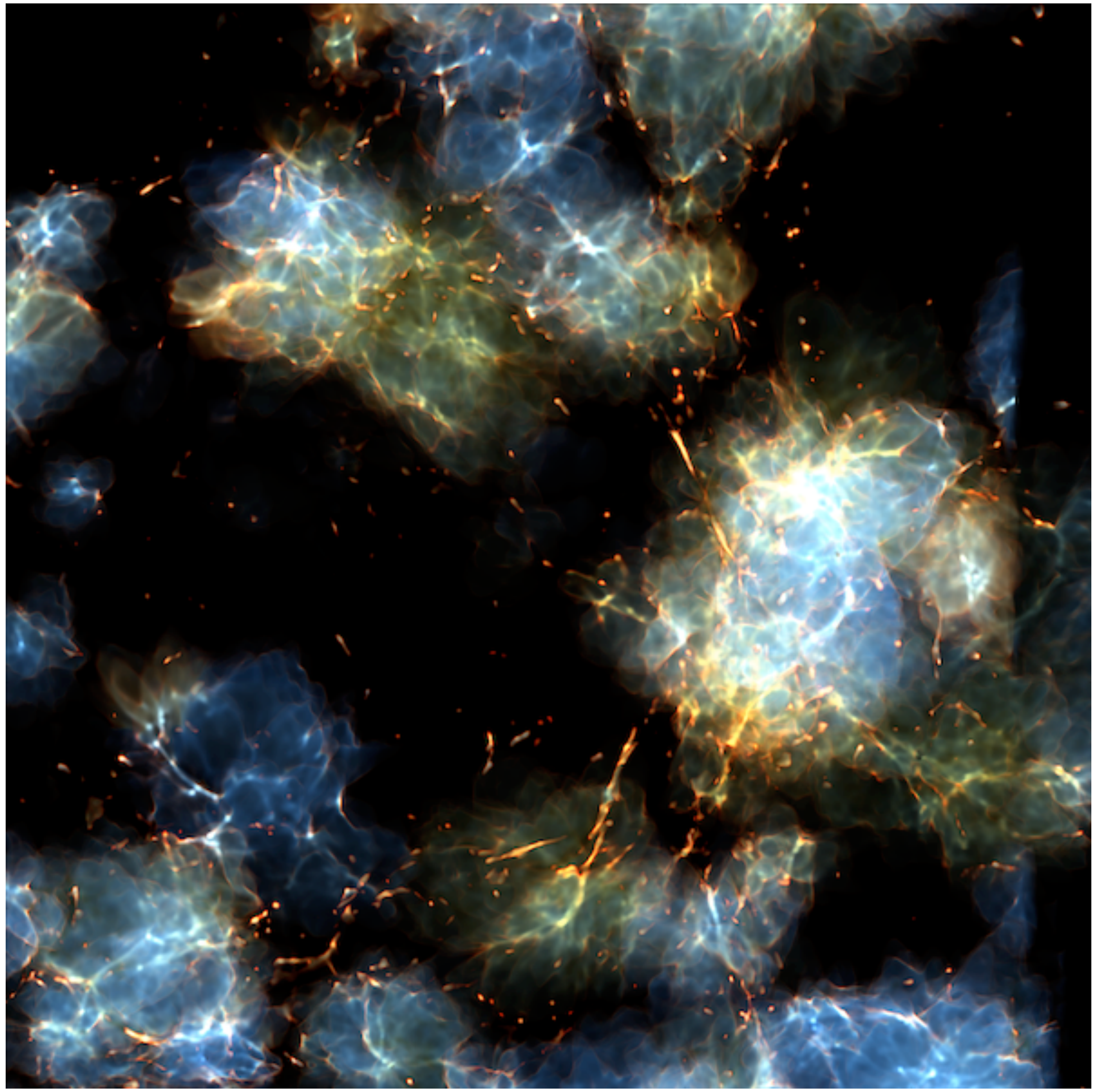
Fraction of HI in IGM

- If this is correct, a significant fraction (~50%) of the IGM should be neutral at z~8, with closer to 80% neutral at z~10.
- This needs to be tested, as reionization can occur differently for difference source assumptions (i.e., ionizing efficiency of galaxies, lower luminosity bound on star formation).
- And we are learning there may be more UV photons at z>10 than we previously thought.
- How can we probe the IGM ionization state at z~8-10?

Lyα Emission Provides a Path Forward




Santos 2004


credit: Wise, Cen, and Abel

Star forming galaxies emit Lyα emission line at 1215.67 Å

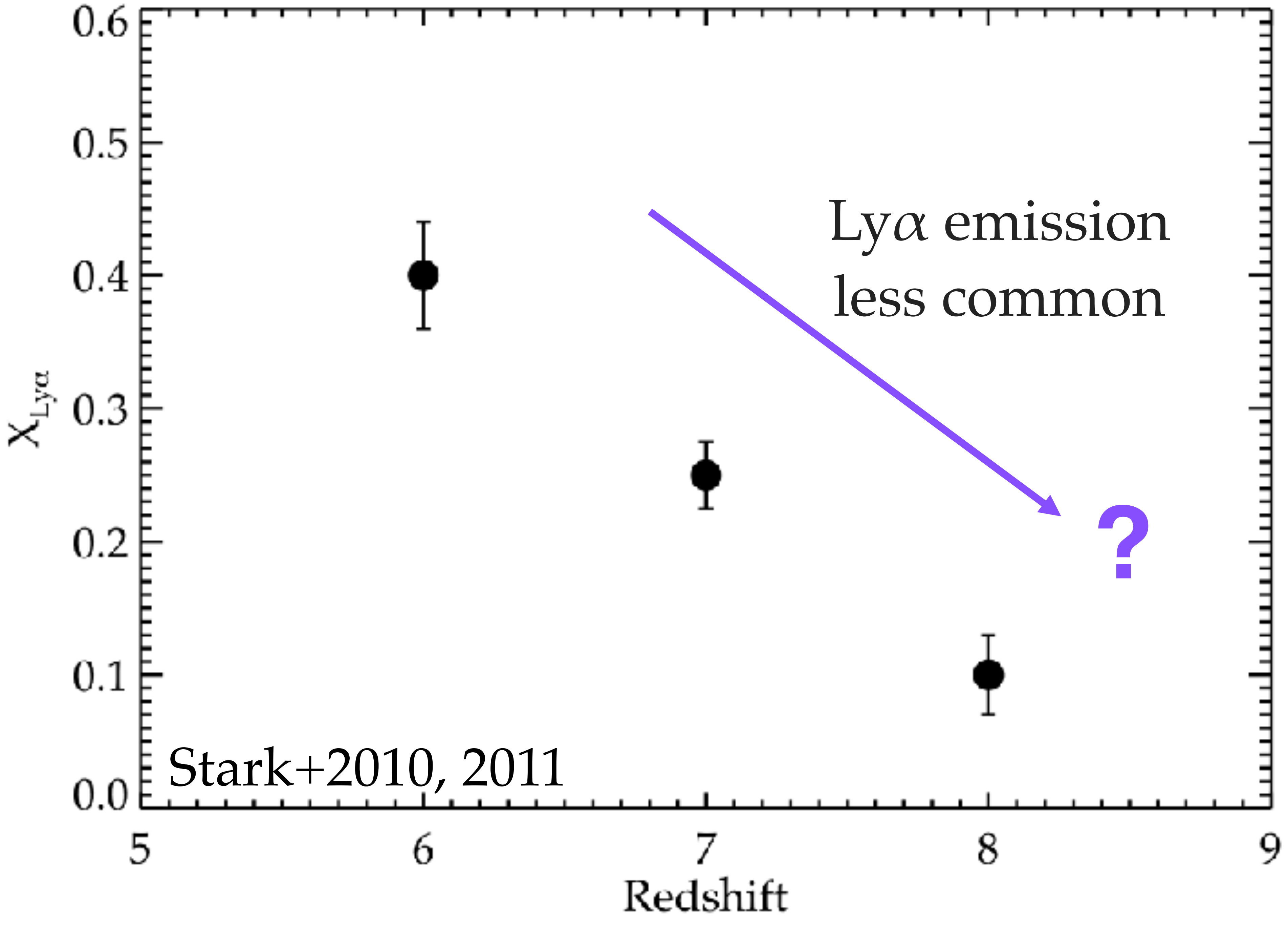
Neutral hydrogen (in galaxy and IGM) scatters Lyα, reducing observed flux in the line.

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

Lyα Fraction Test with Star Forming Galaxies

Fraction of star forming galaxies with Lyα emission above a fixed equivalent width threshold:

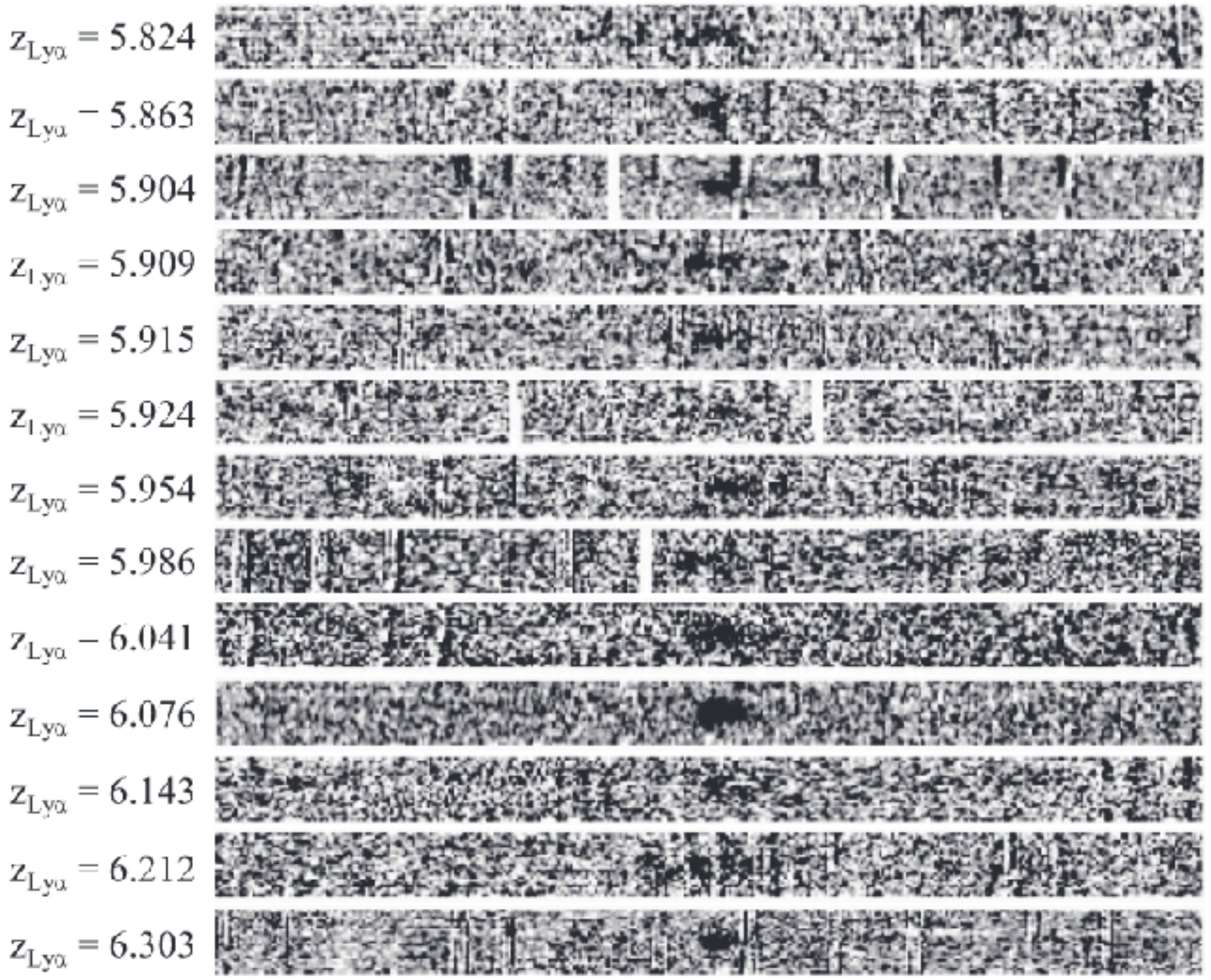
$$X_{Ly\alpha}(z) = \frac{N_{Ly\alpha}}{N_{tot}}$$

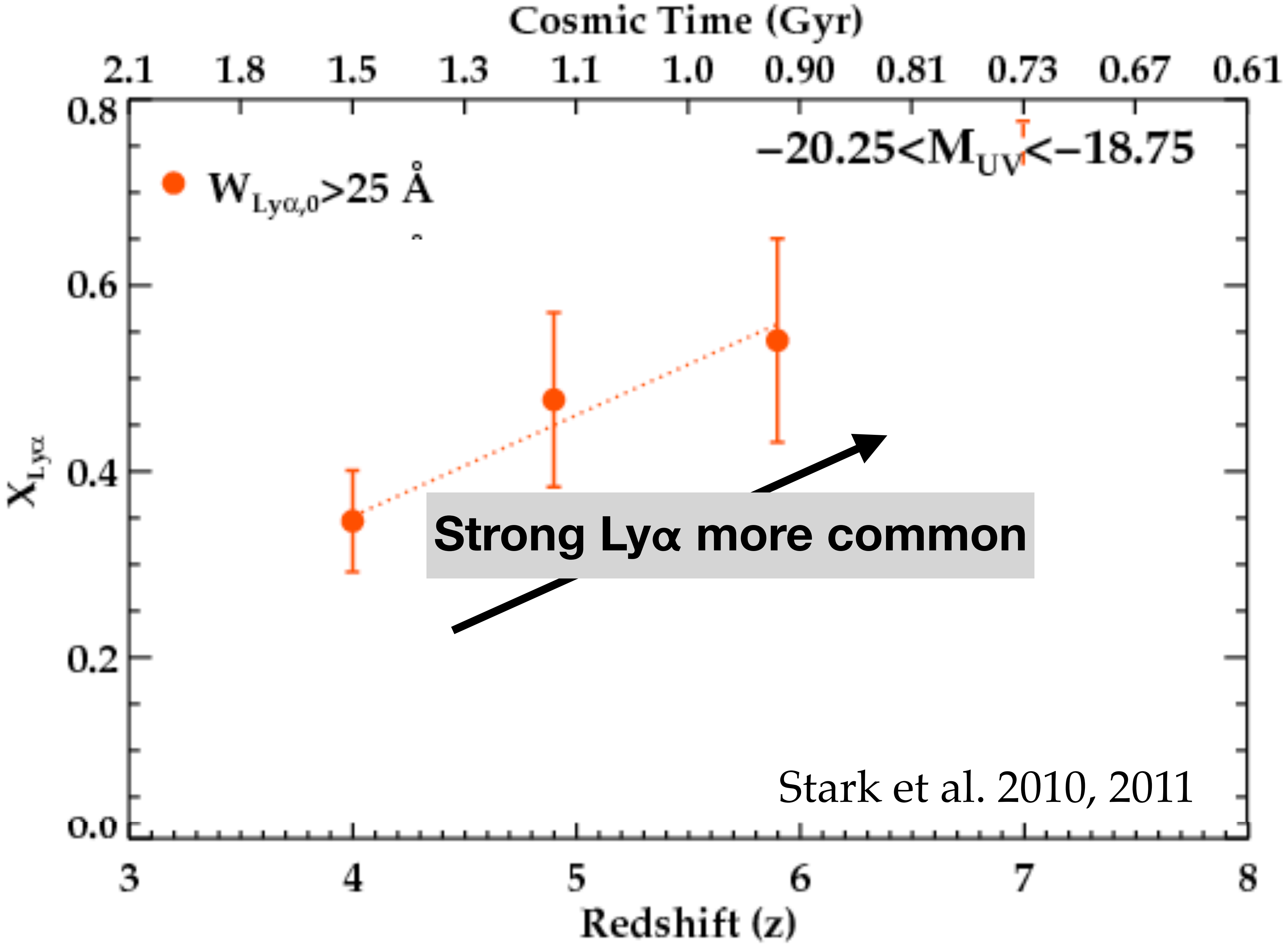


Stark+2010, 2011

Lyman-alpha Emission at z~6: A Baseline Measurement

Endsley, Stark+2021b





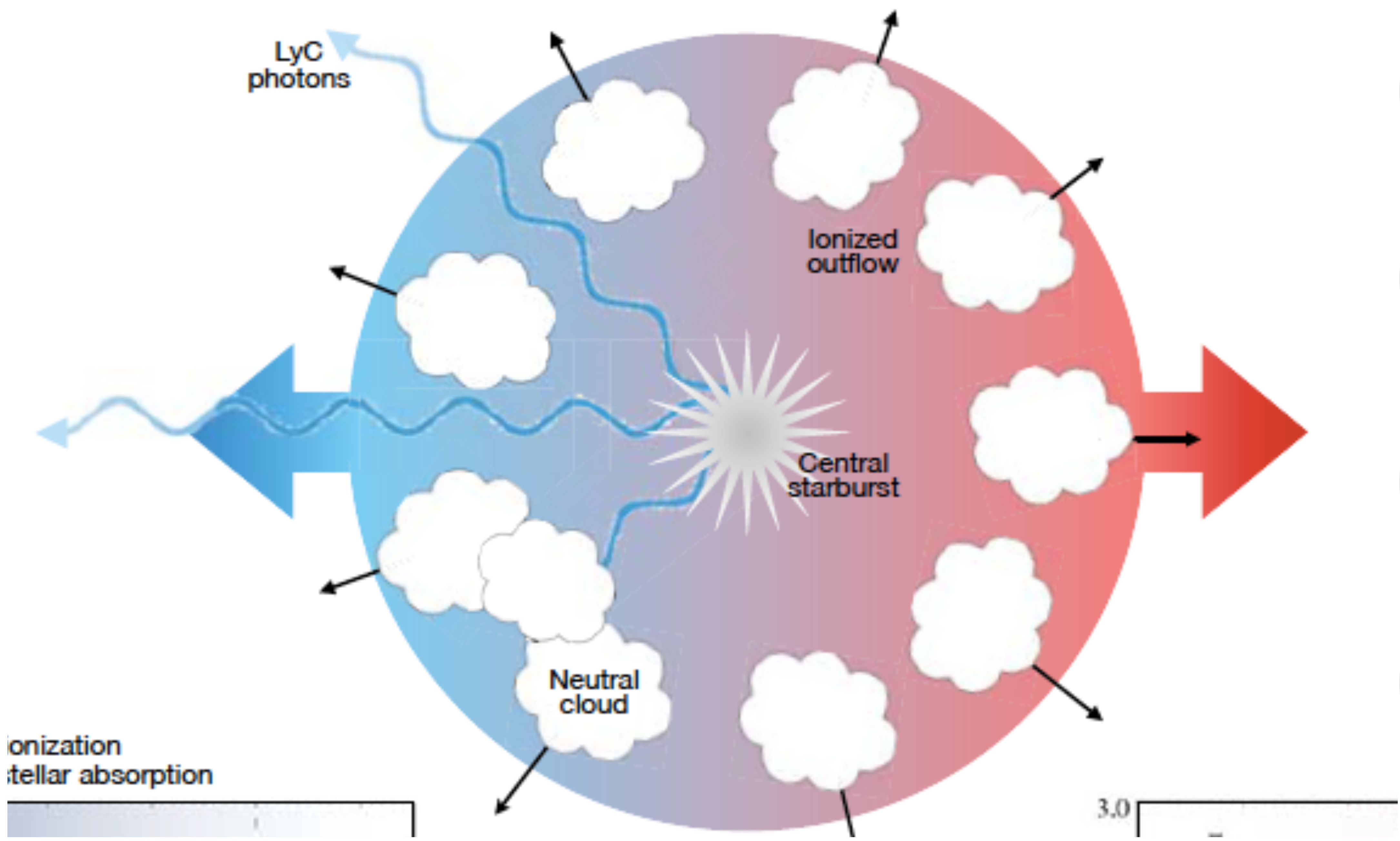
Strong Lyα more common

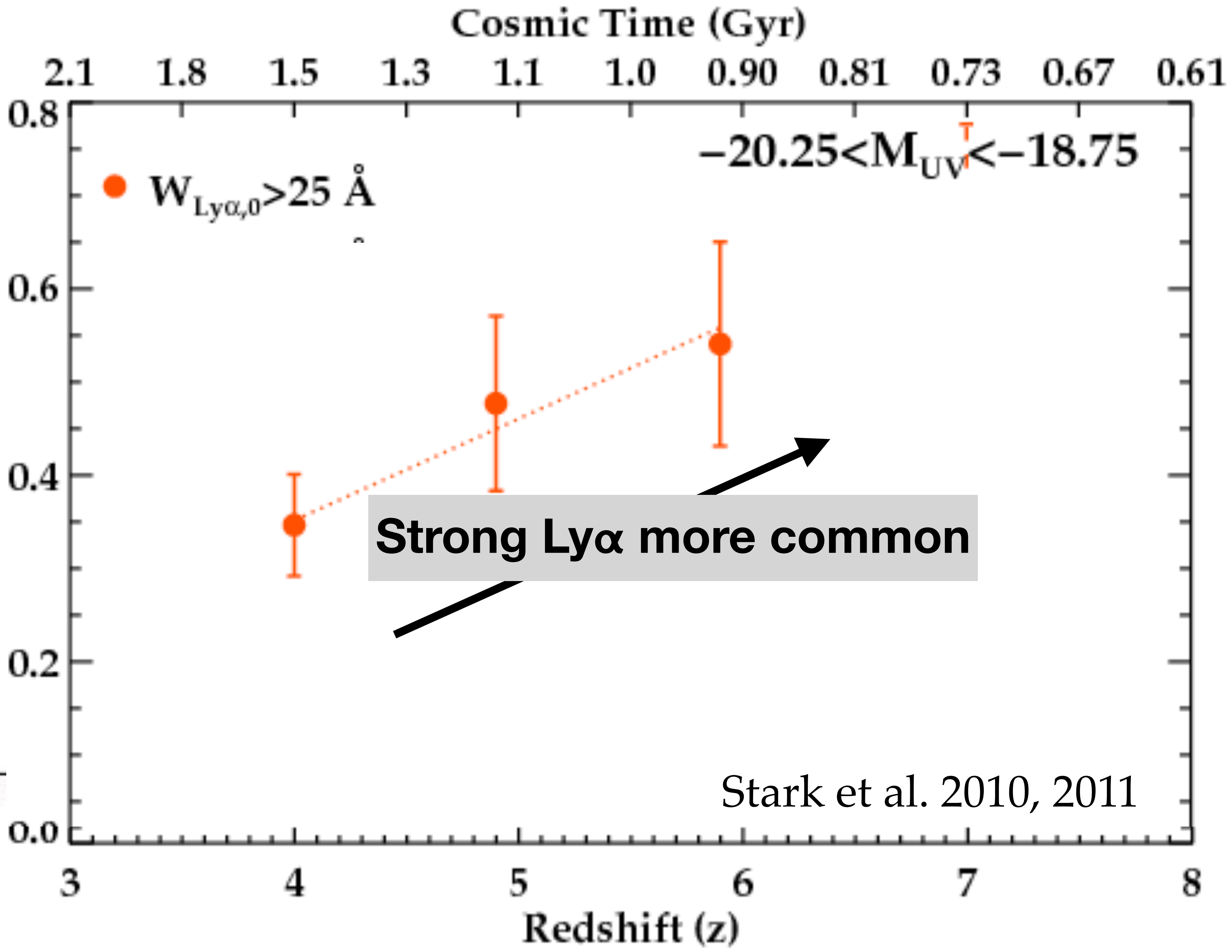
Stark et al. 2010, 2011

- Large EW Lyα emission seen in ~50% of low luminosity z~6 galaxies.

Lyman-alpha Emission at z~6: A Baseline Measurement

Erb 15





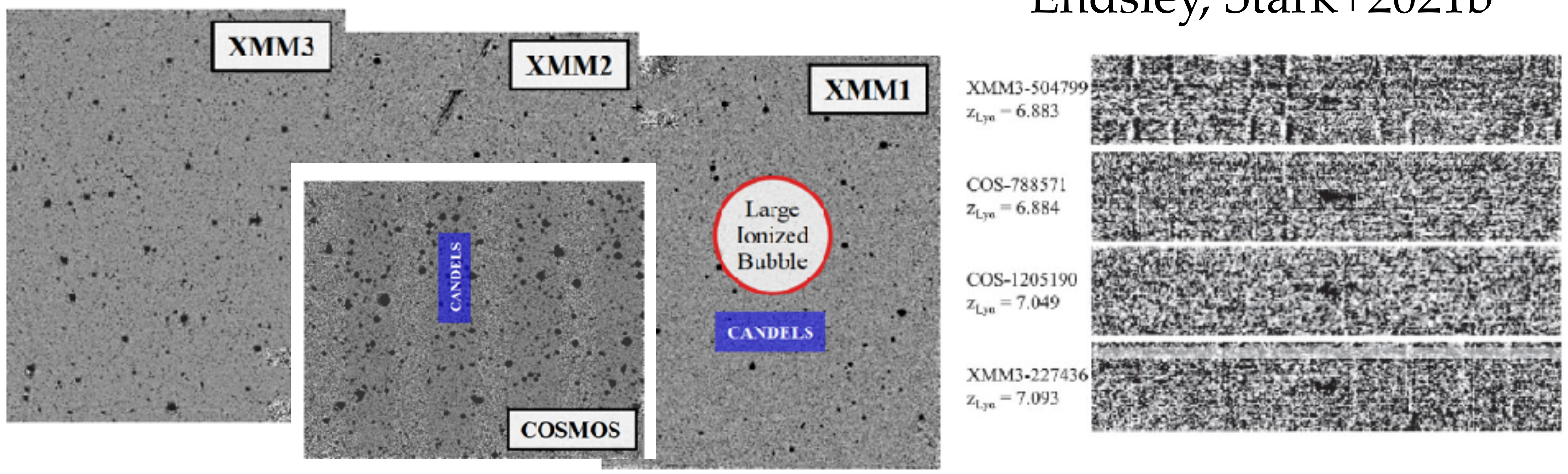
Strong Lyα more common

Stark et al. 2010, 2011

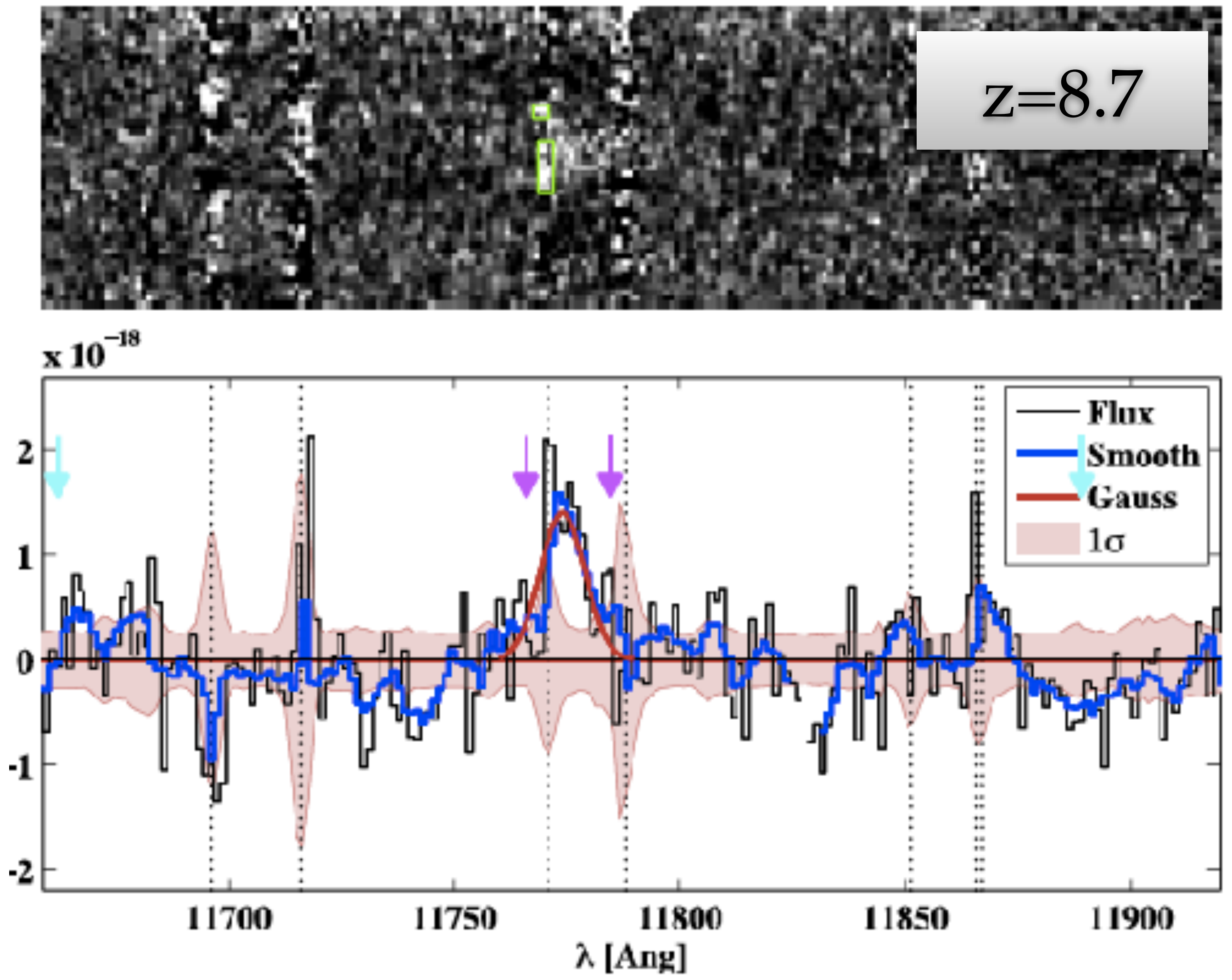
- Large EW Lyα emission seen in ~50% of low luminosity z~6 galaxies.
- **Why? Less dust and patchier neutral gas at z~6.**

Searching for z>7 Lyα Emission: 2009-2022

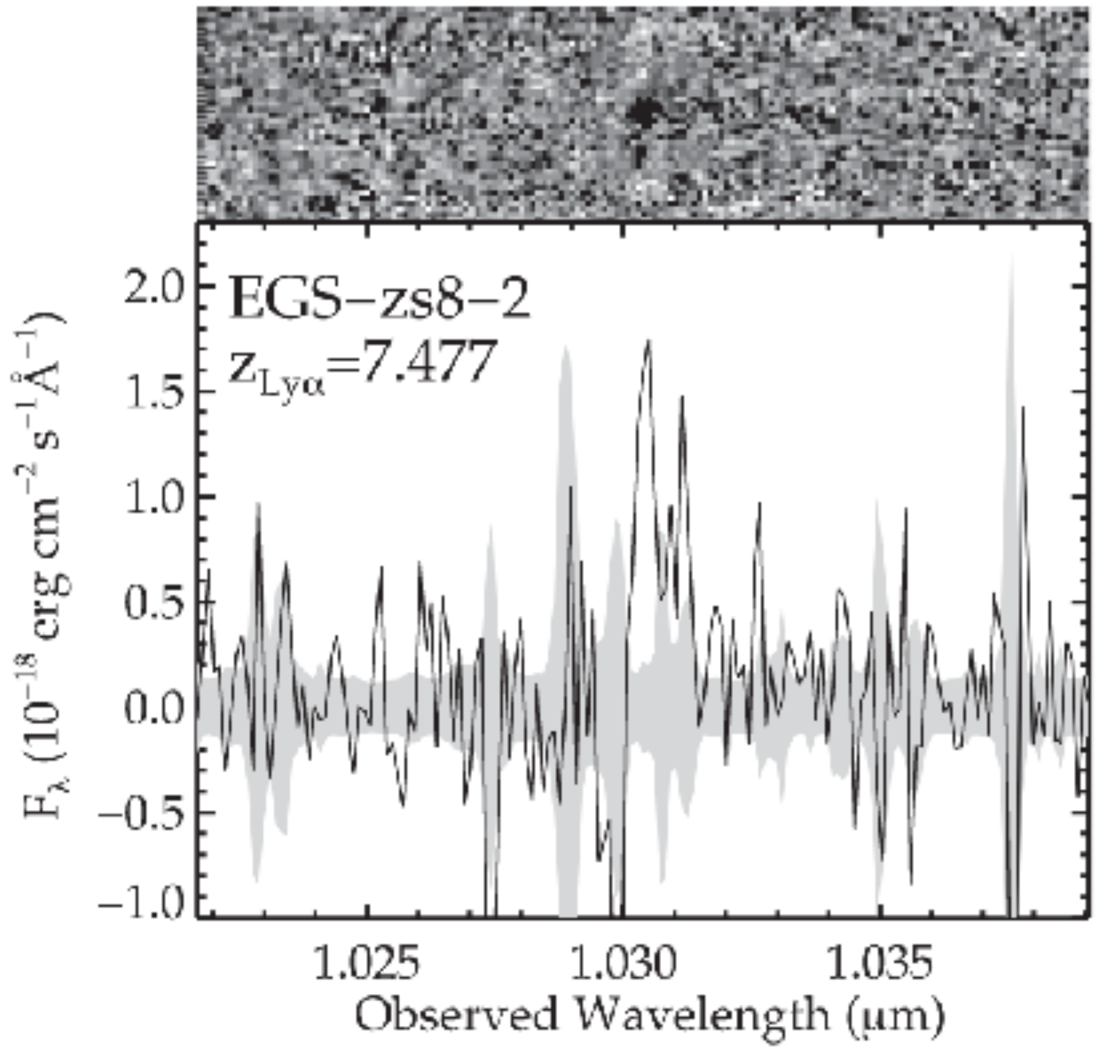
Endsley, Stark+2021b



Zitrin+2015



Stark+2017



- Large observational effort to characterize Lyα emission line EWs in continuum-selected galaxies over last 13+ years.

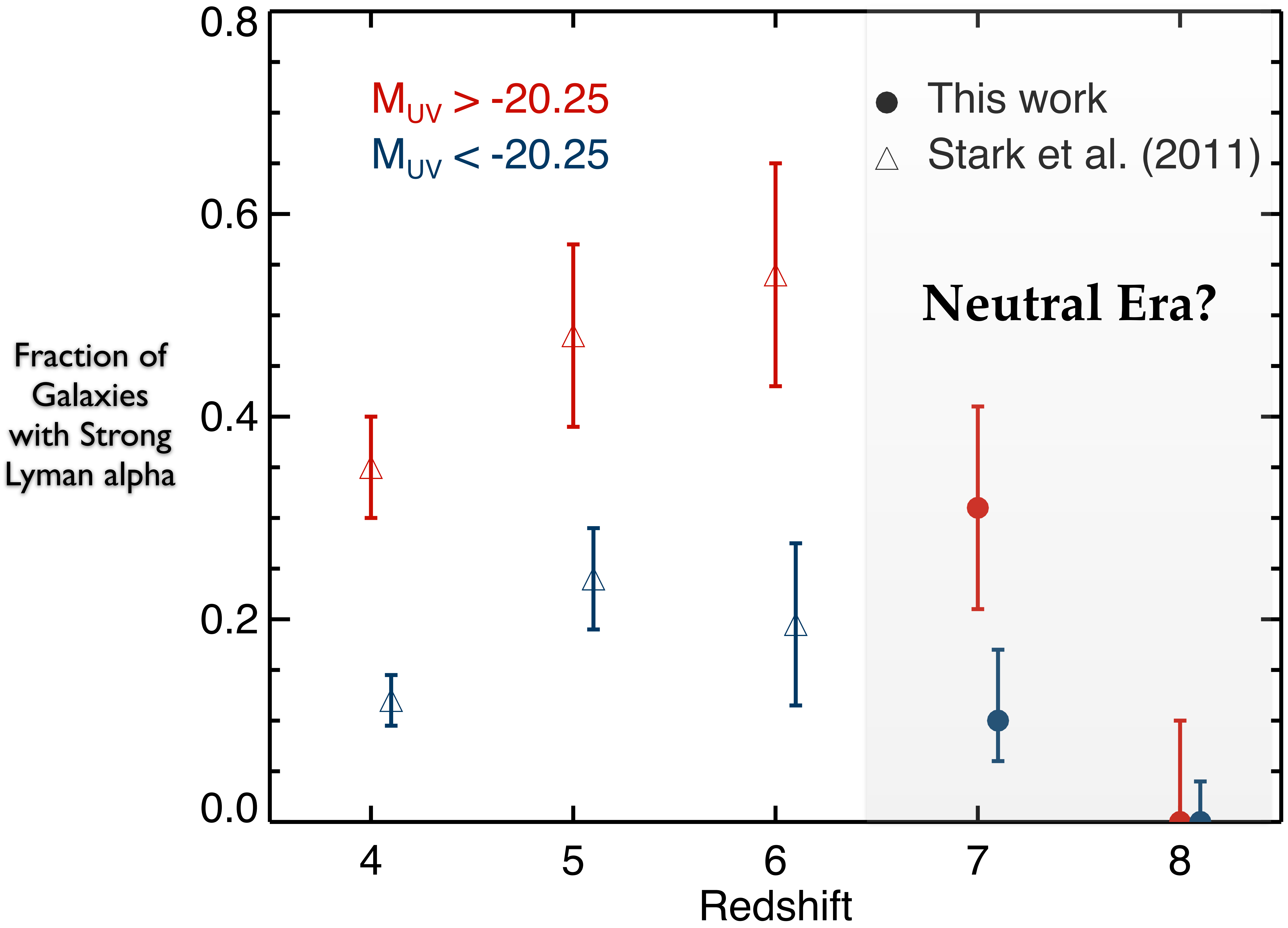
- Small number of z>7 Lyα emitting galaxies detected after observing ~300 sources.

  25 Lyα detections at 7<z<8

  2 Lyα detections at 8<z<9

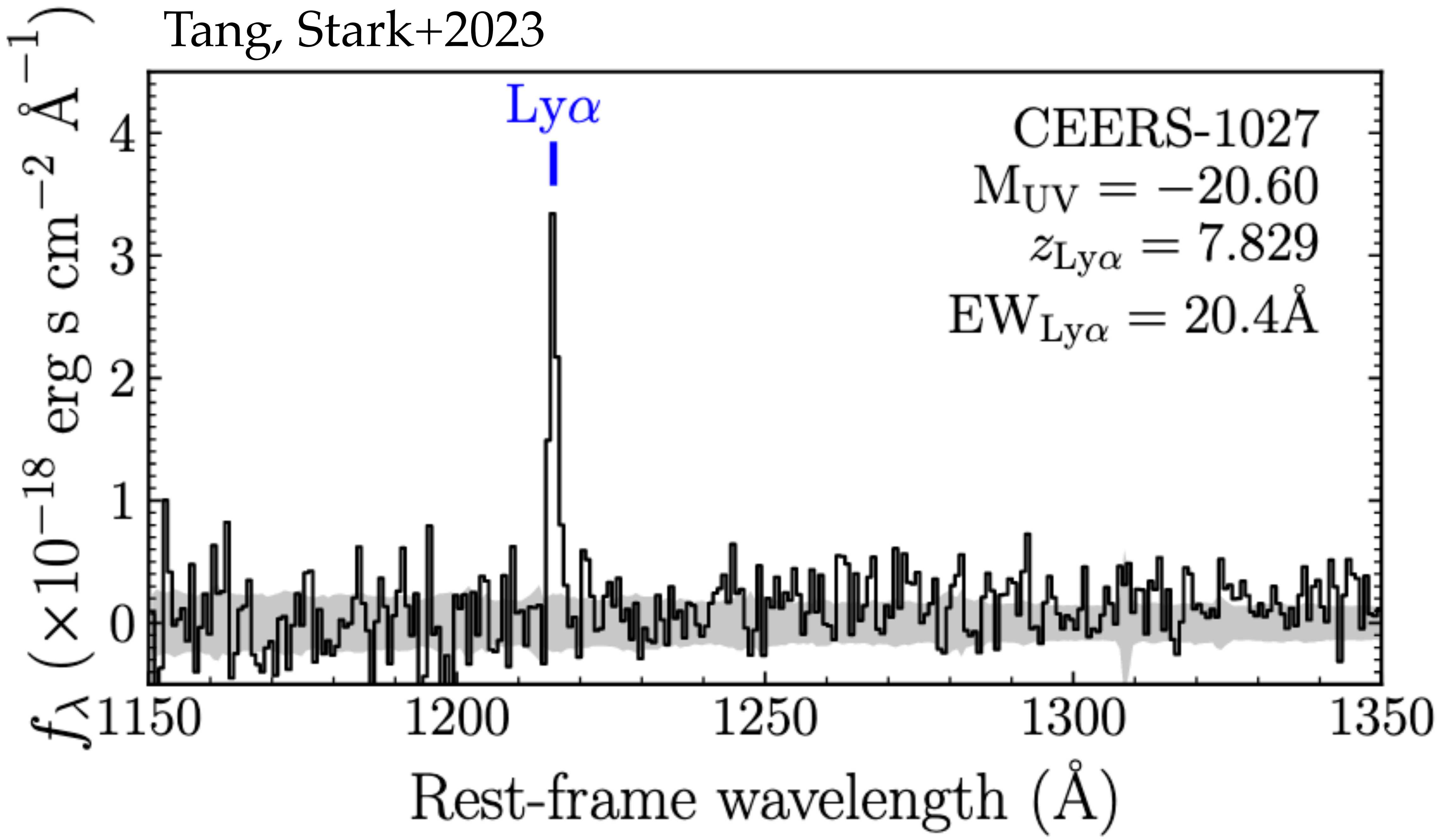
Lyα emission is Weak in $7<z<9$ Star Forming Galaxies

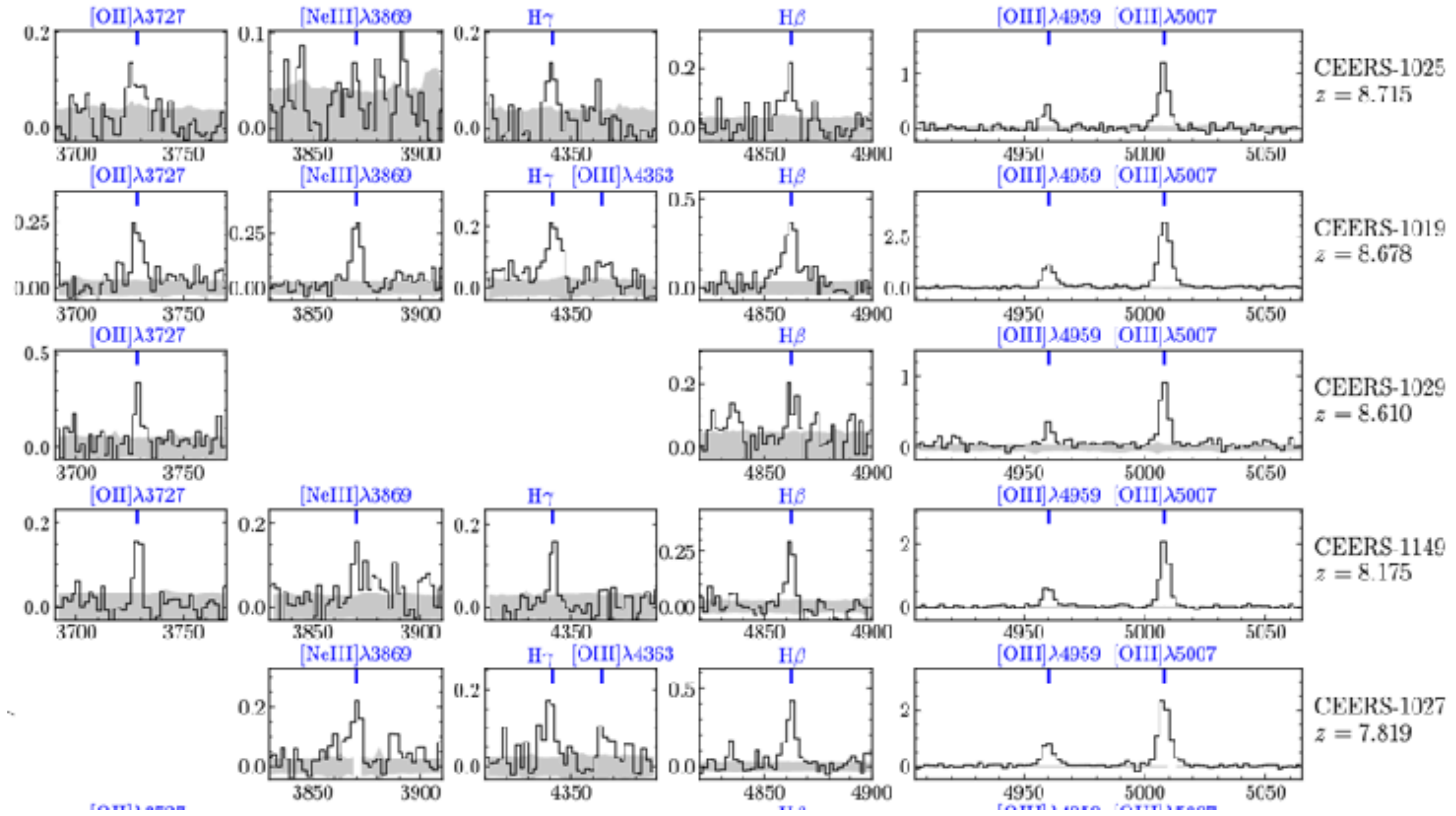
Schenker, Stark+2014



Strong Lyα emission (EW>25Å) is extremely rare in most z~7-8 galaxies, in contrast to what we saw at z~6.

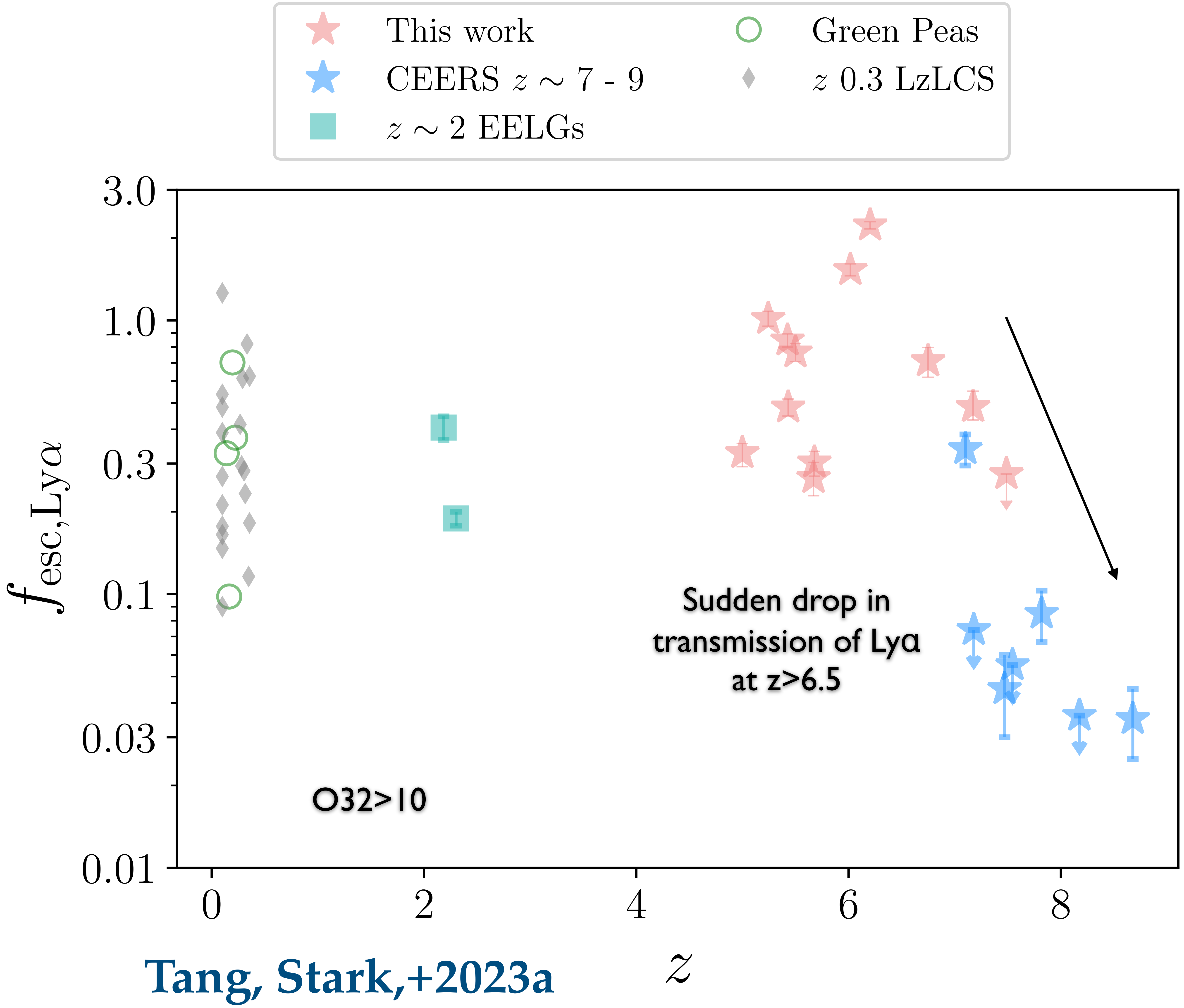
JWST Provides a New Window on Lyα emission


Tang, Stark+2023



- JWST/NIRspec is game-changer for Lyα, recently producing first detections at z>7.
- NIRSpec also provides rest-optical lines (i.e. H-beta), which allow us to predict intrinsic Lyα luminosity.
- This gives **escape fraction of Lyα** for individual galaxies at z>7.

JWST Provides a New Window on Lyα emission



Sudden drop in transmission of Lyα at z>6.5

O32>10

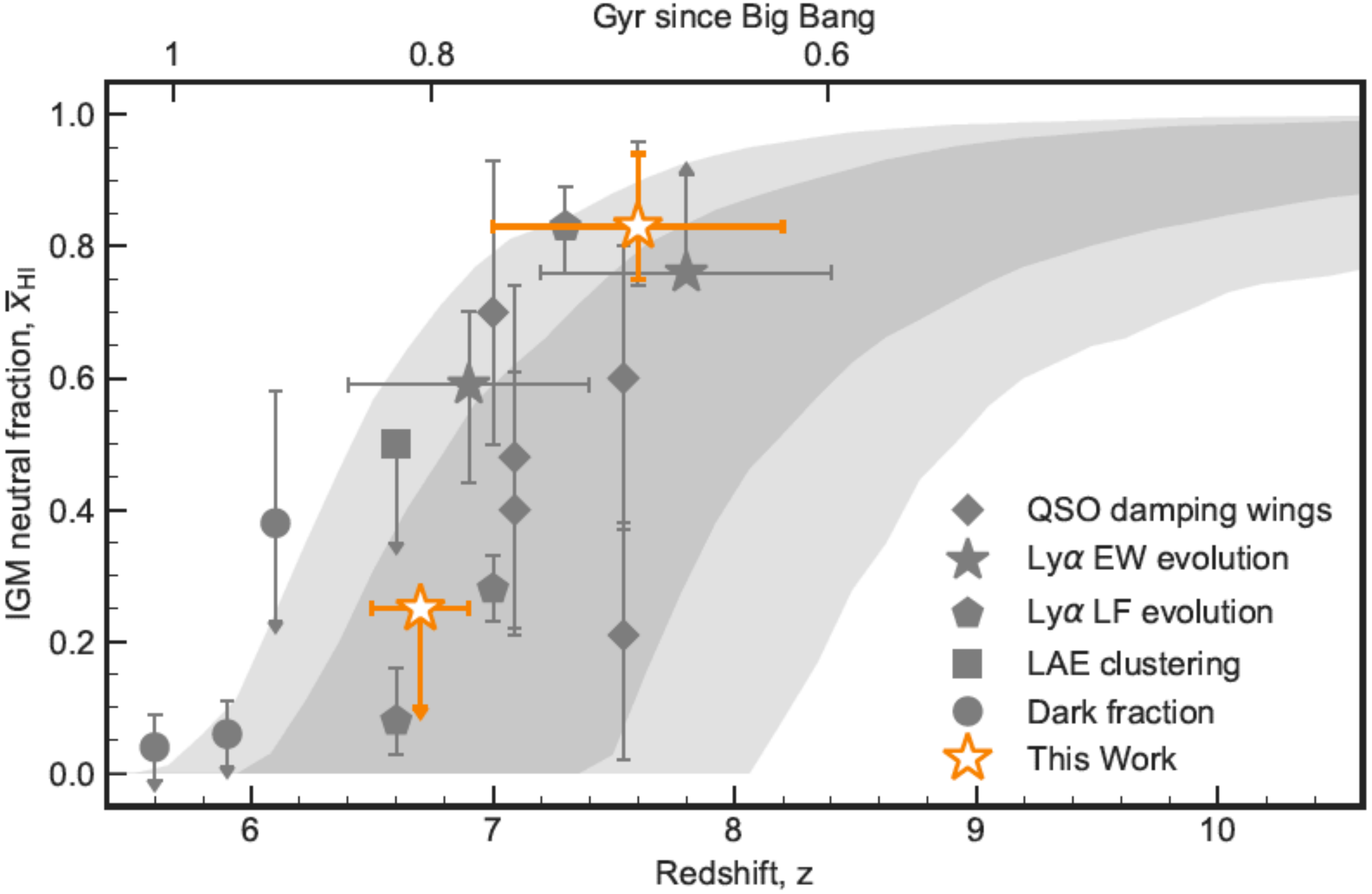
Tang, Stark,+2023a
Chen, Stark,+2023b

Results suggest that Lyα escape fraction drops rapidly in typical galaxies at z>6.5.

Something is **attenuating Lyα** in reionization-era galaxies.

Reionization Provides an Explanation

Bolan+2022



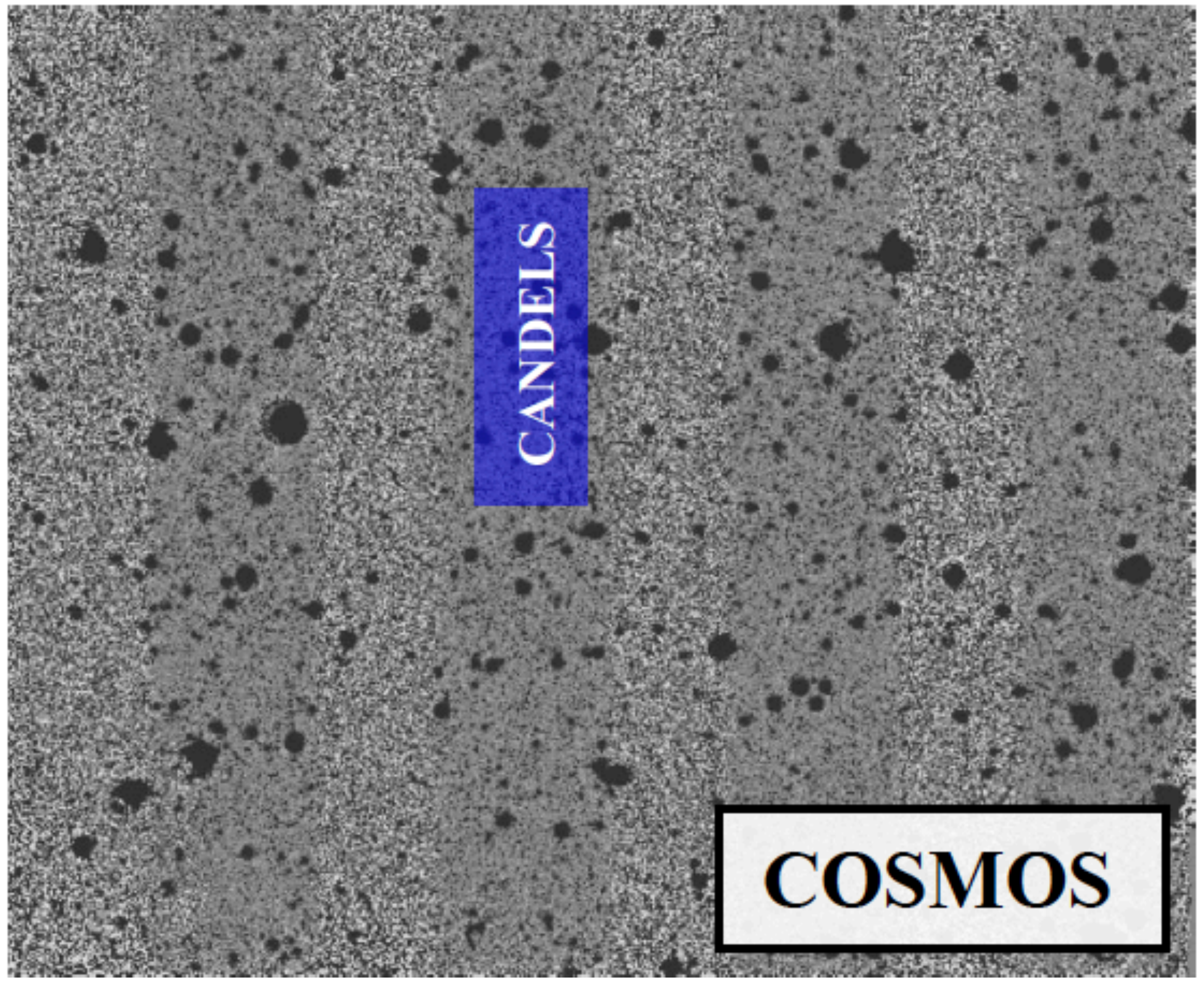
Lyα attenuation easily explained by scattering from HI in IGM.

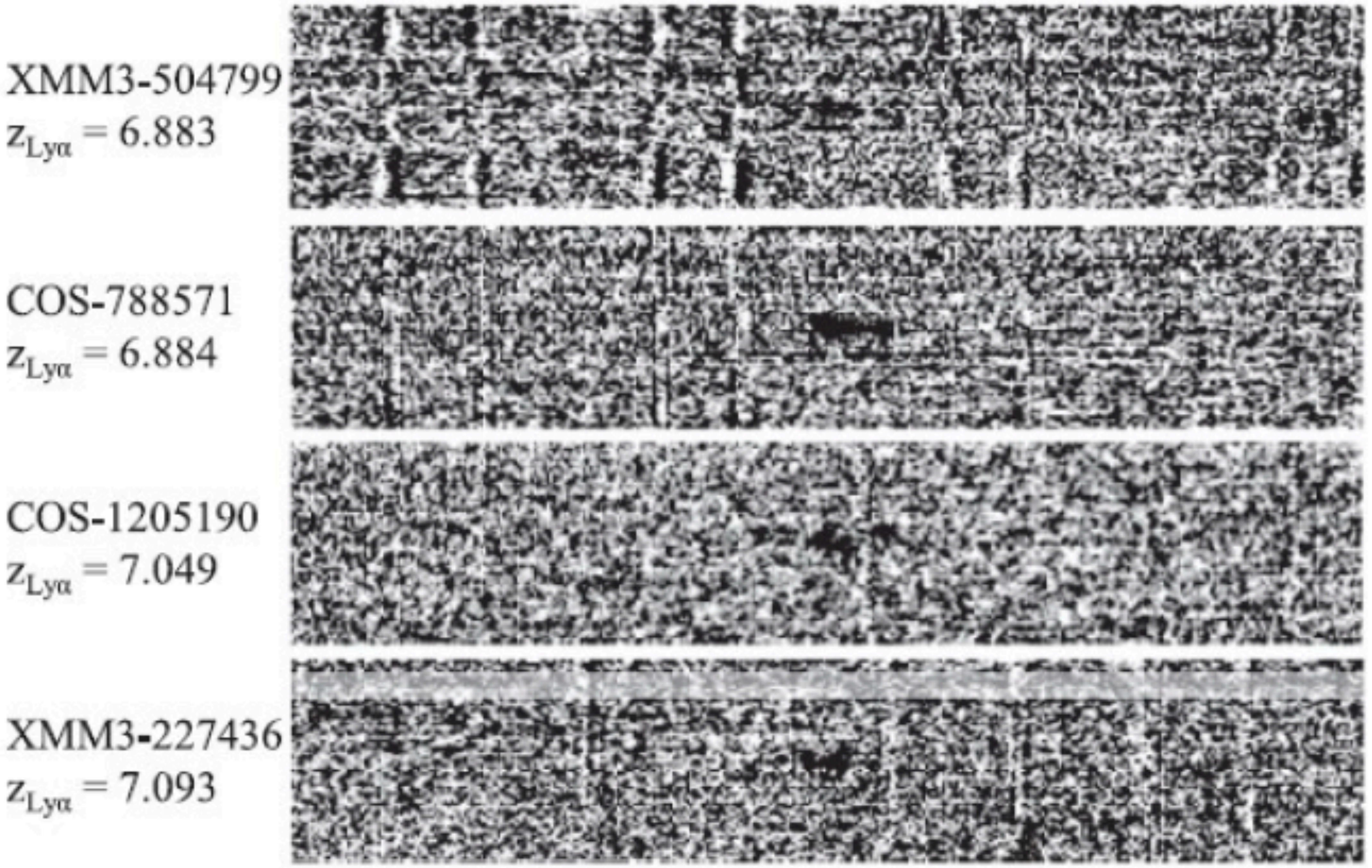
Need X_{HI}~0.5 at z~7 and X_{HI}~0.8 at z~8. Broadly consistent with expectations for late reionization model.

We are starting to see compelling evidence that IGM is still significantly neutral at z~7, 770 Myr after the Big Bang!

Lyα emission in Massive z~7 Galaxies

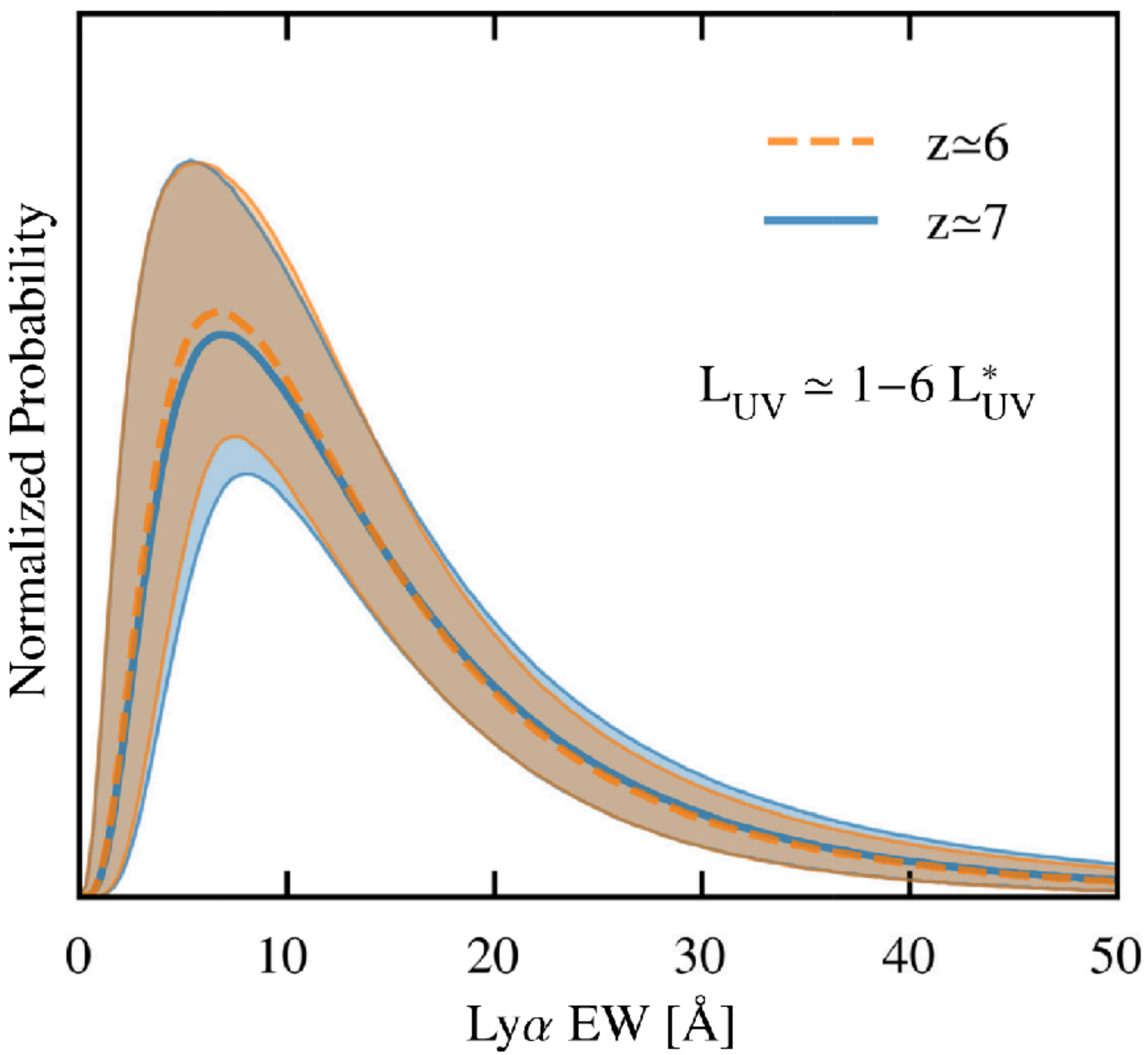
Endsley, Stark,+2021b





- In the last few years, attention has shifted to wide-area datasets, which allow Ly**α** fraction test to be extended to massive galaxies ($M^{*}>10^{9}\ M_{\odot}$).
- We have conducted a large Ly**α** survey of (7 deg^2) with MMT/Binospec.
- Lyman alpha detections are surprisingly common at z~7!

Lyα emission in Massive z~7 Galaxies

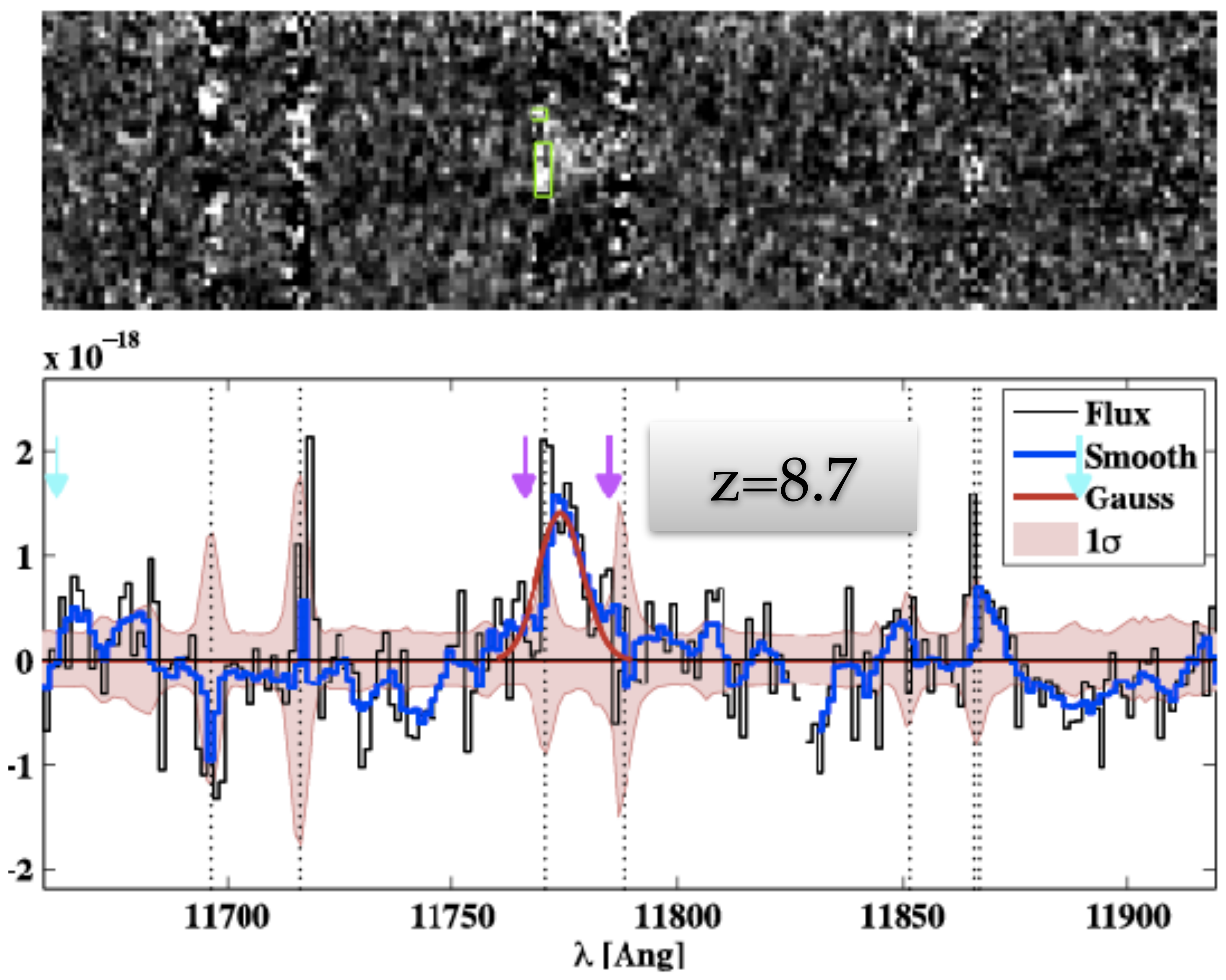

Endsley, Stark+2021b

- Distribution of z~7 Lyα line strengths in our survey is identical to that at z~6.

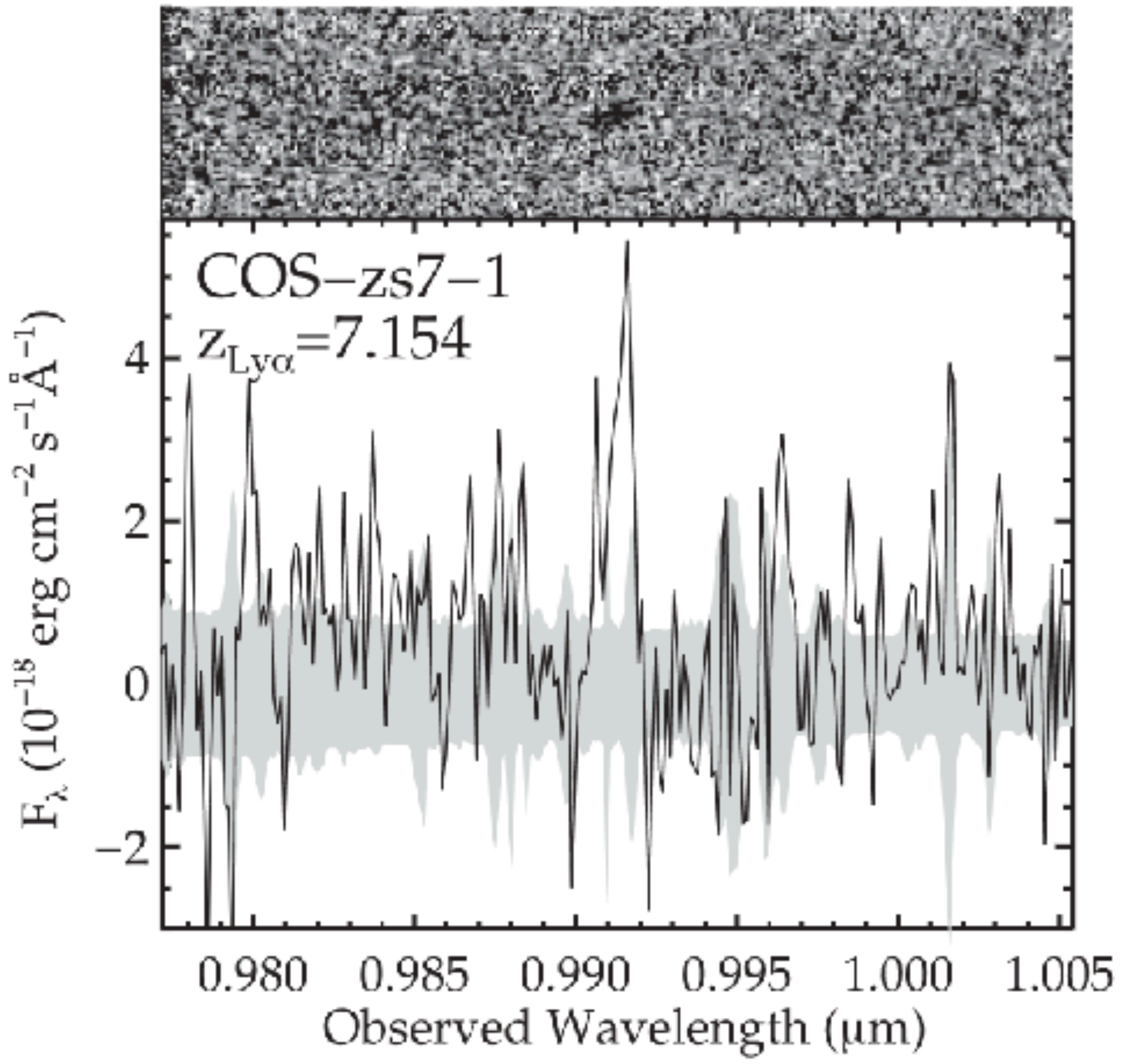
- Lyα emission does **not** disappear in massive z~7 galaxies.

Extension to Higher Redshifts with Keck

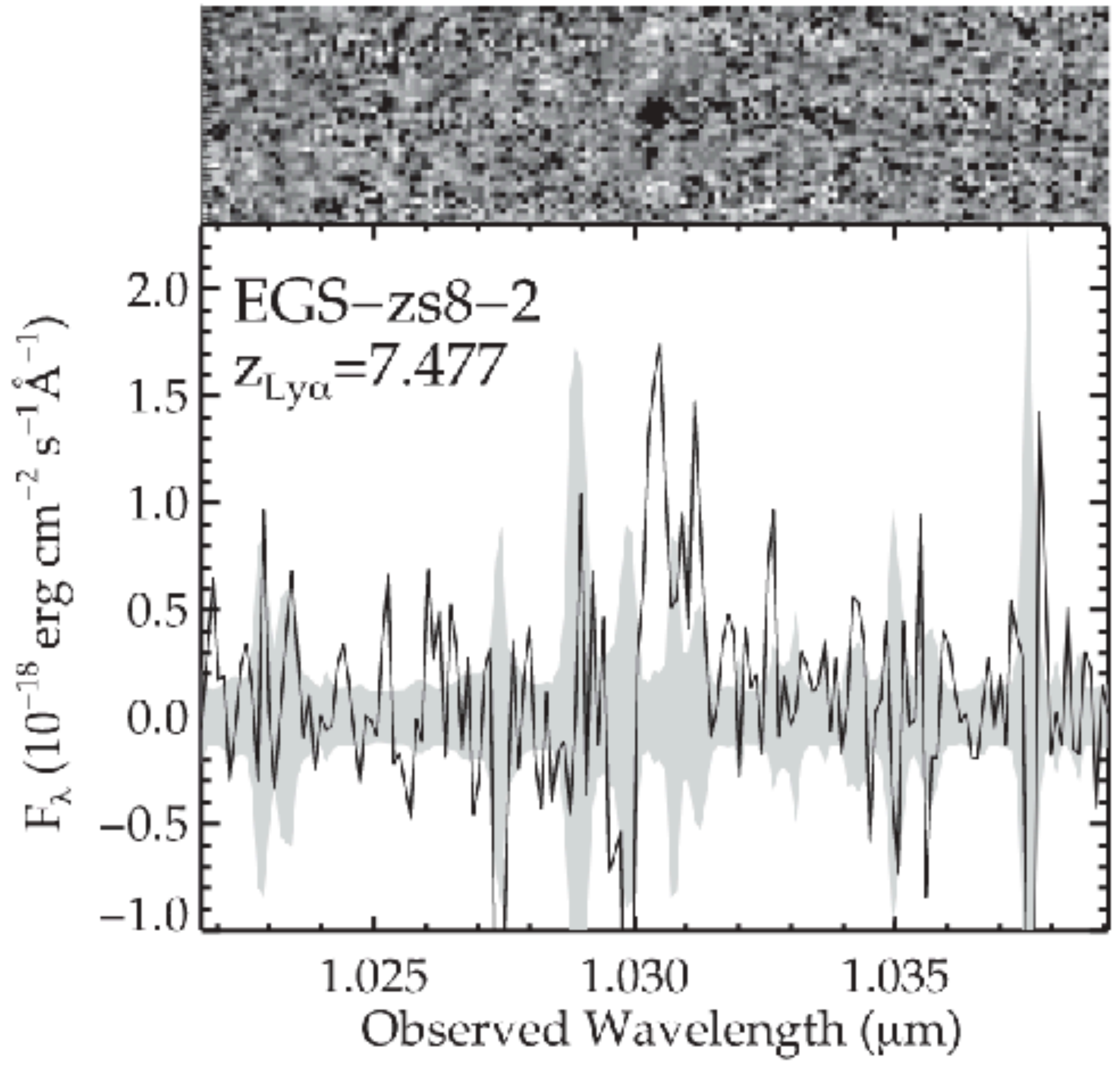
Zitrin+2015



Stark+2017



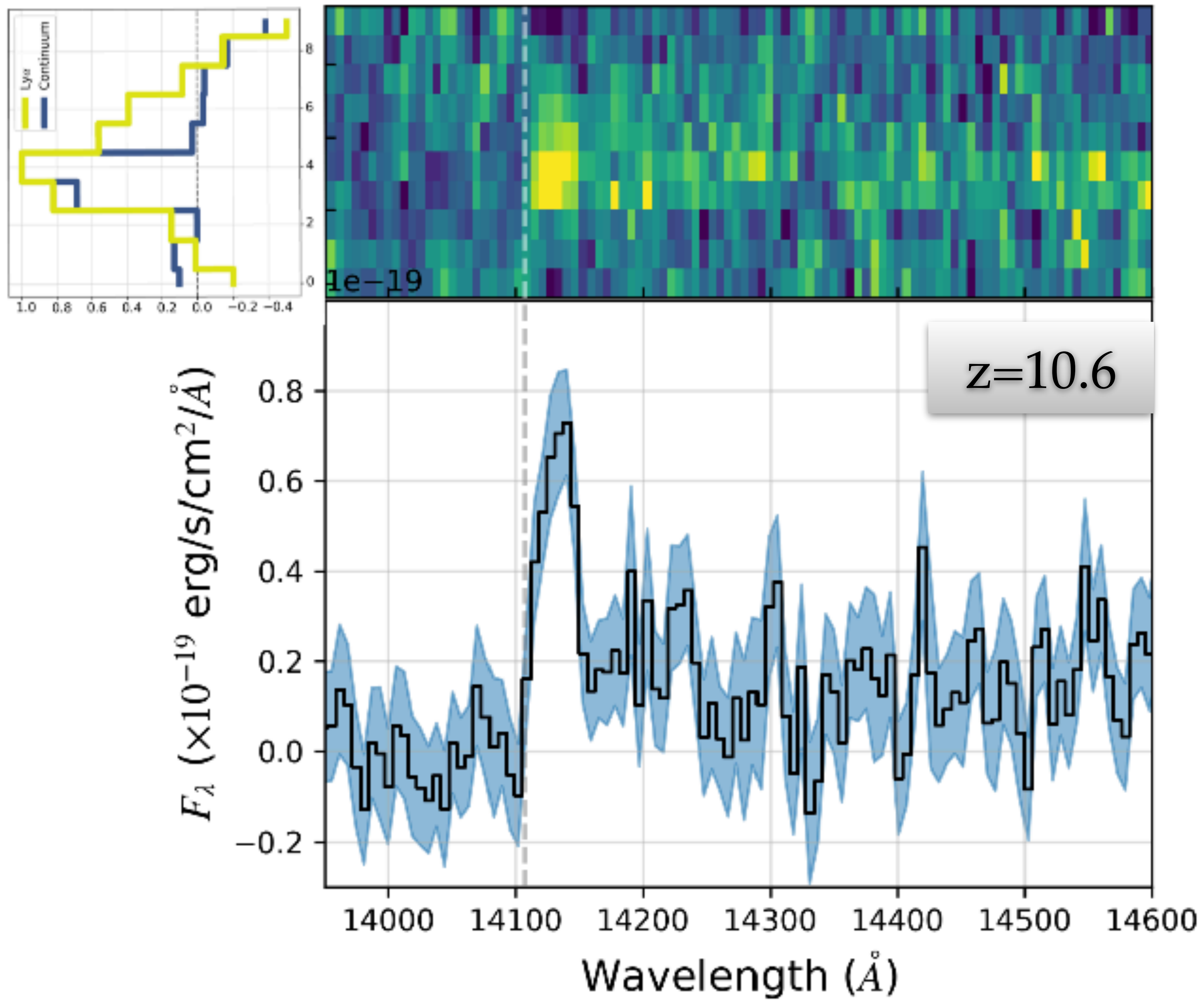
Stark+2017

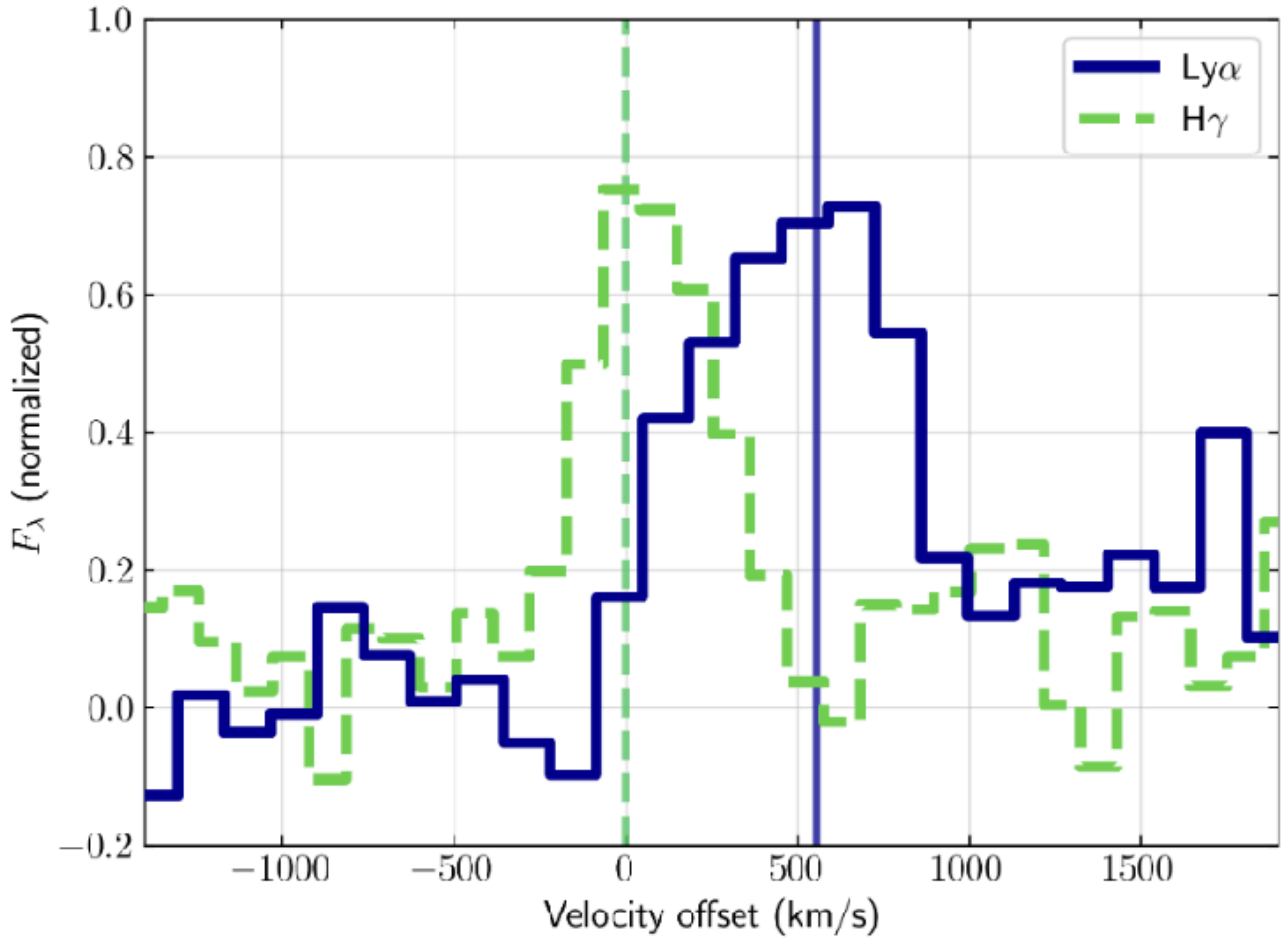


- Handful of similar Ly**α** detections in massive galaxies at z~7-9 with Keck (Oesch+2015, Zitrin+2015, Roberts Borsani+2016, Stark+2017)

Extension to Higher Redshifts with JWST

Bunker+2023

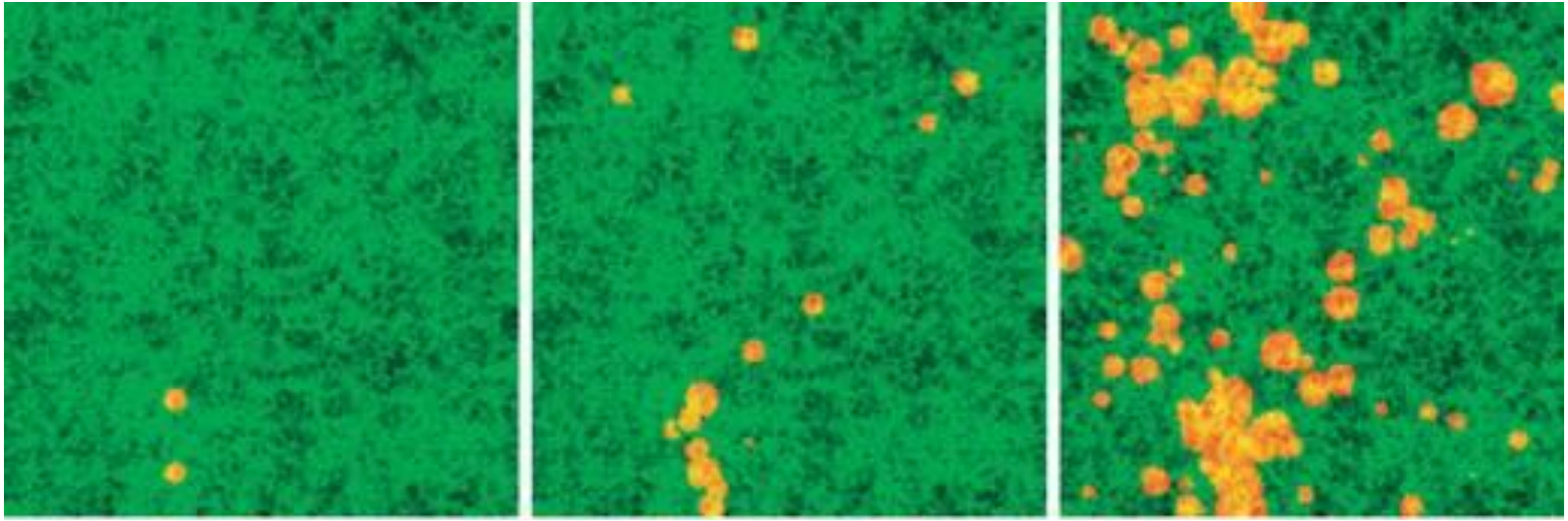




- NIRSpec detection of Lyα in bright, **massive galaxy at z~11** (GNz11; Oesch+16) in JADES survey (Bunker+2023, Tacchella+2023).
- Lyα transmission 430 Myr after Big Bang!

Lyα Transmission in the Reionization Era

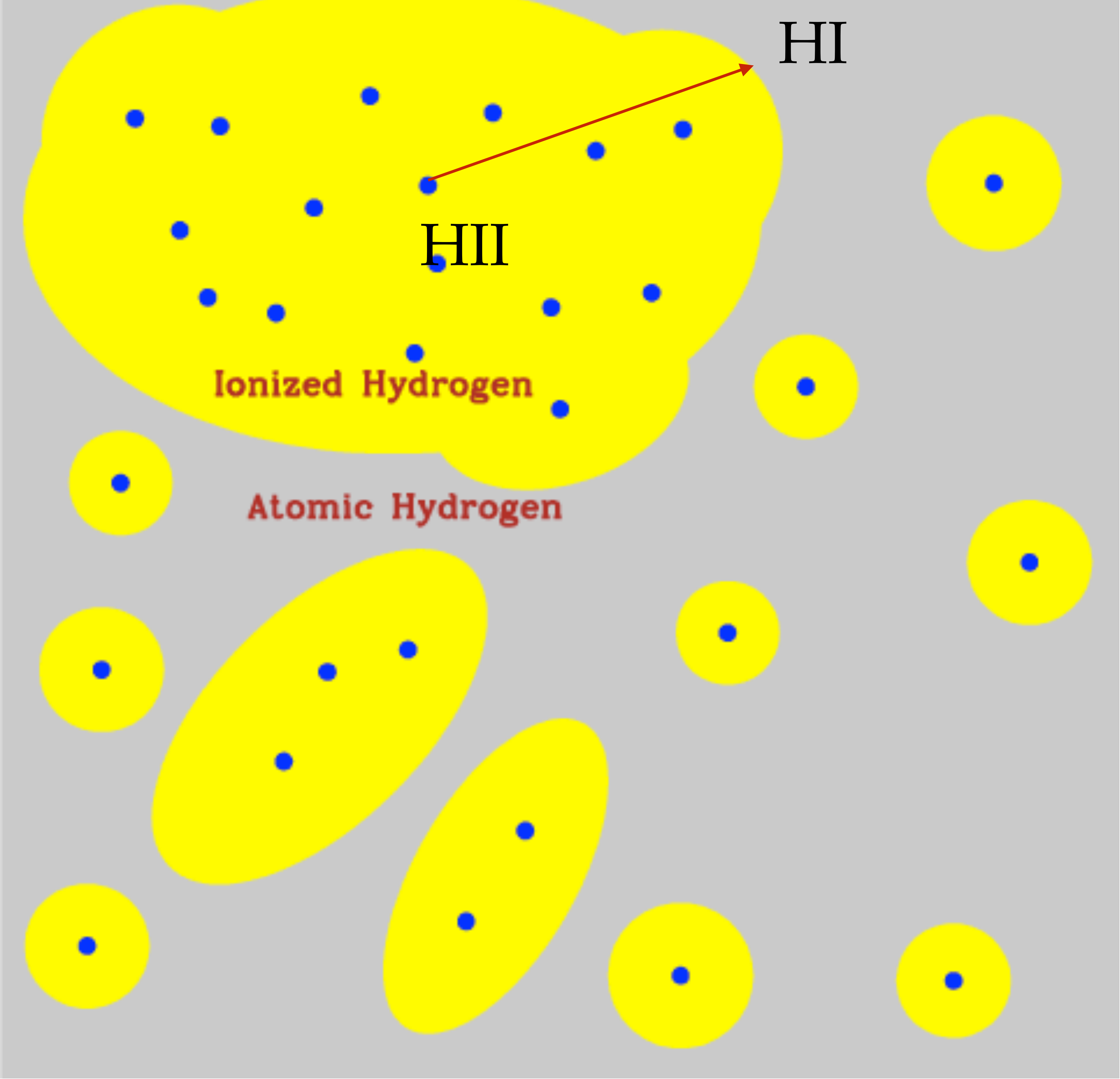
credit: Iliev et al.



Puzzling results! How can we see Lyman alpha so readily in some galaxies at z~7 to z~11 when IGM is significantly **neutral?**

Why do we see Lyman alpha in massive galaxies while it is so strongly attenuated in most lower mass galaxies?

Lyα Transmission in the Reionization Era



credit: Rennan Barkana

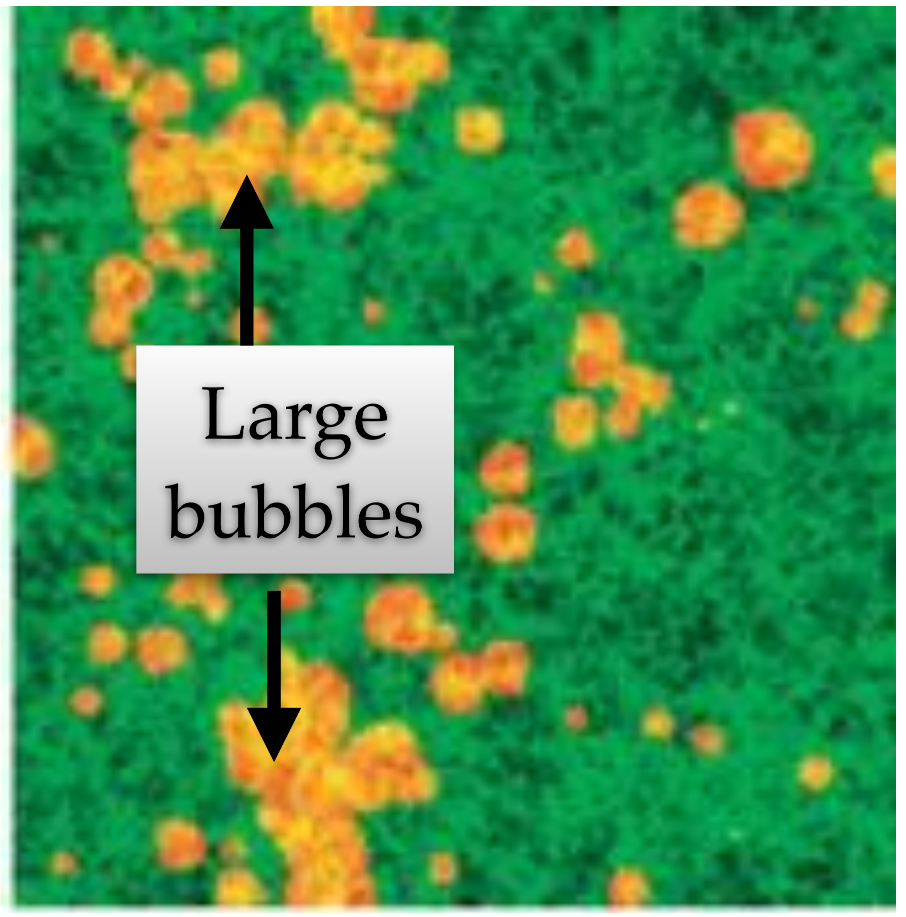
As Lyα photons travel outward from galaxy, they are cosmologically redshifted.

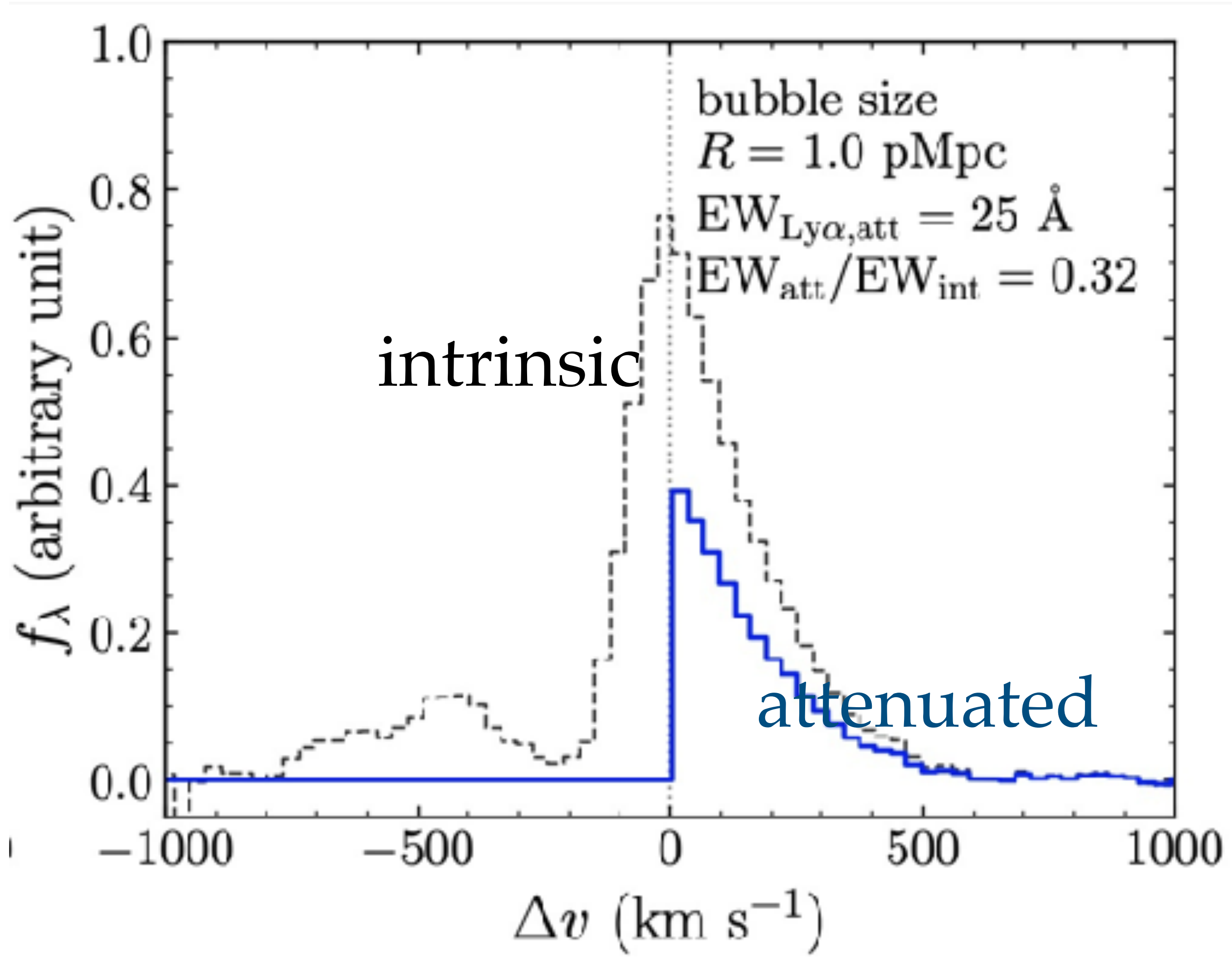
The more Lyα is able to redshift before reaching HI, the greater the transmission through the IGM.

Galaxies in large bubbles = more Lyα transmission through IGM.

We expect **Lyα emitters** to provide **signposts of ionized regions** of the universe.

How is Lyα Visible in Massive Galaxies out to z~11?





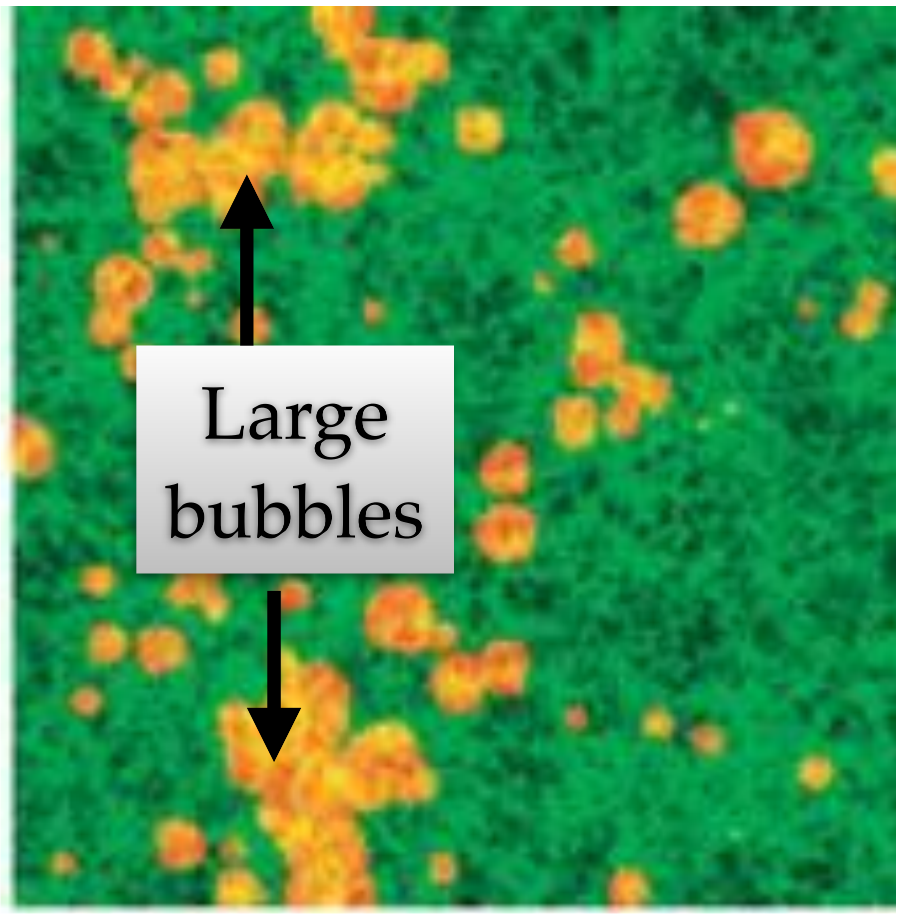
Tang, Stark+2023b

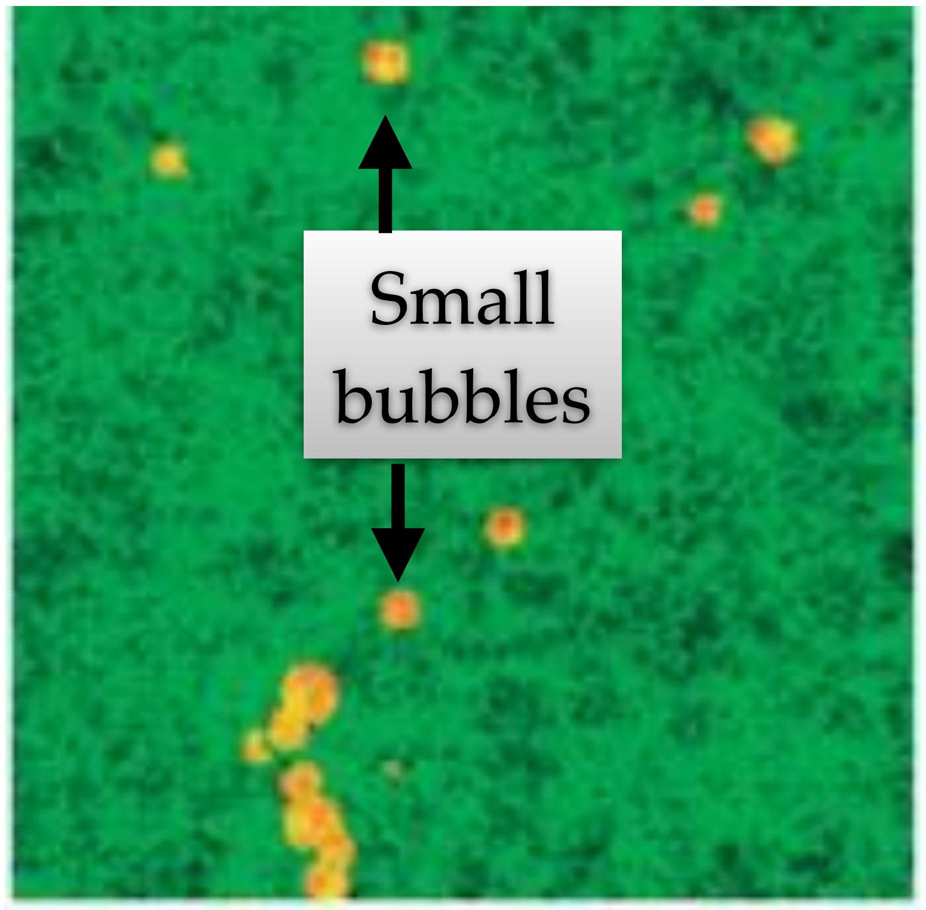
Transmission of Lyα facilitated by location of galaxy in ionized bubble.

Two possible scenarios:

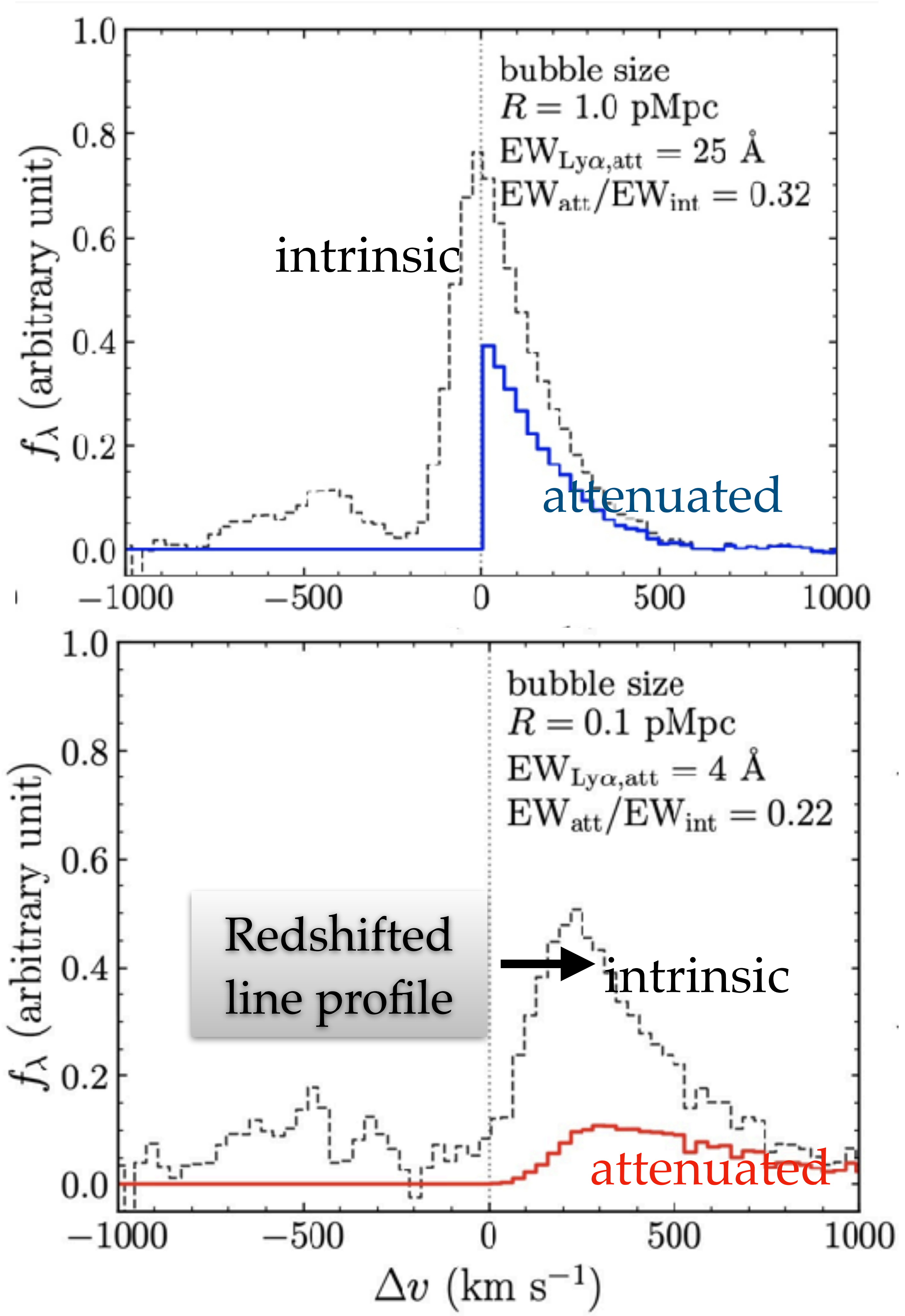
(1) **Massive galaxies tend to trace overdense** regions that have carved out **large ionized bubbles** (>1 physical Mpc) .

How is Lyα Visible in Massive Galaxies out to z~11?





Tang, Stark+2023b



Redshifted line profile

Transmission of Lyα facilitated by location of galaxy in ionized bubble.

Two possible scenarios:

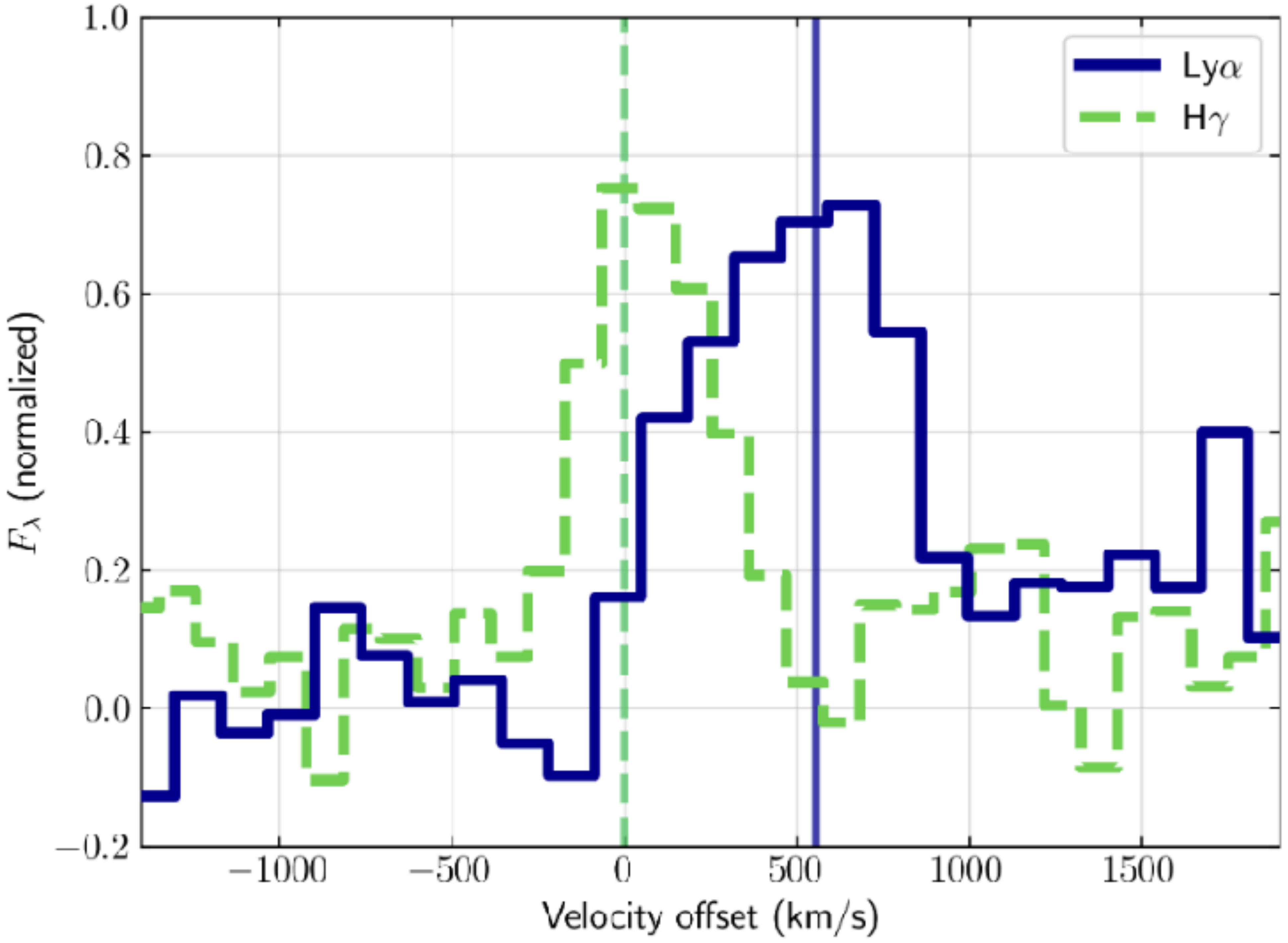
(1) **Massive galaxies tend to trace overdense** regions that have carved out **large ionized bubbles** (>1 physical Mpc) .

(2) Massive galaxies have carved out their own **small ionized bubbles** (~0.1 physical Mpc) .

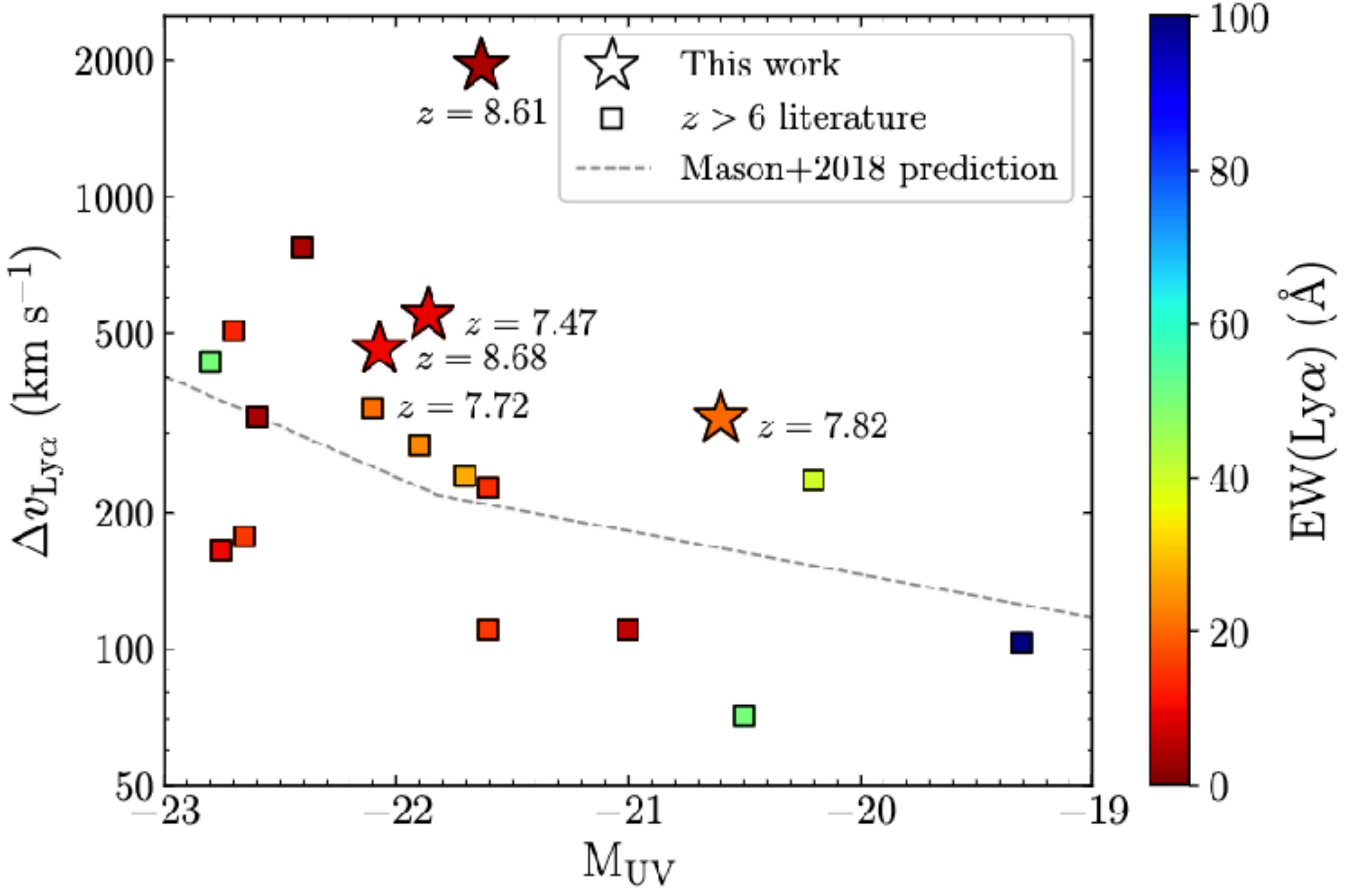
Transmission may be further assisted by outflows in galaxy — these **redshift** line profile (see left).

Progress from JWST/NIRSpec Spectra of Lyα Emitters

Bunker+2023 (see also Tacchella+2023)



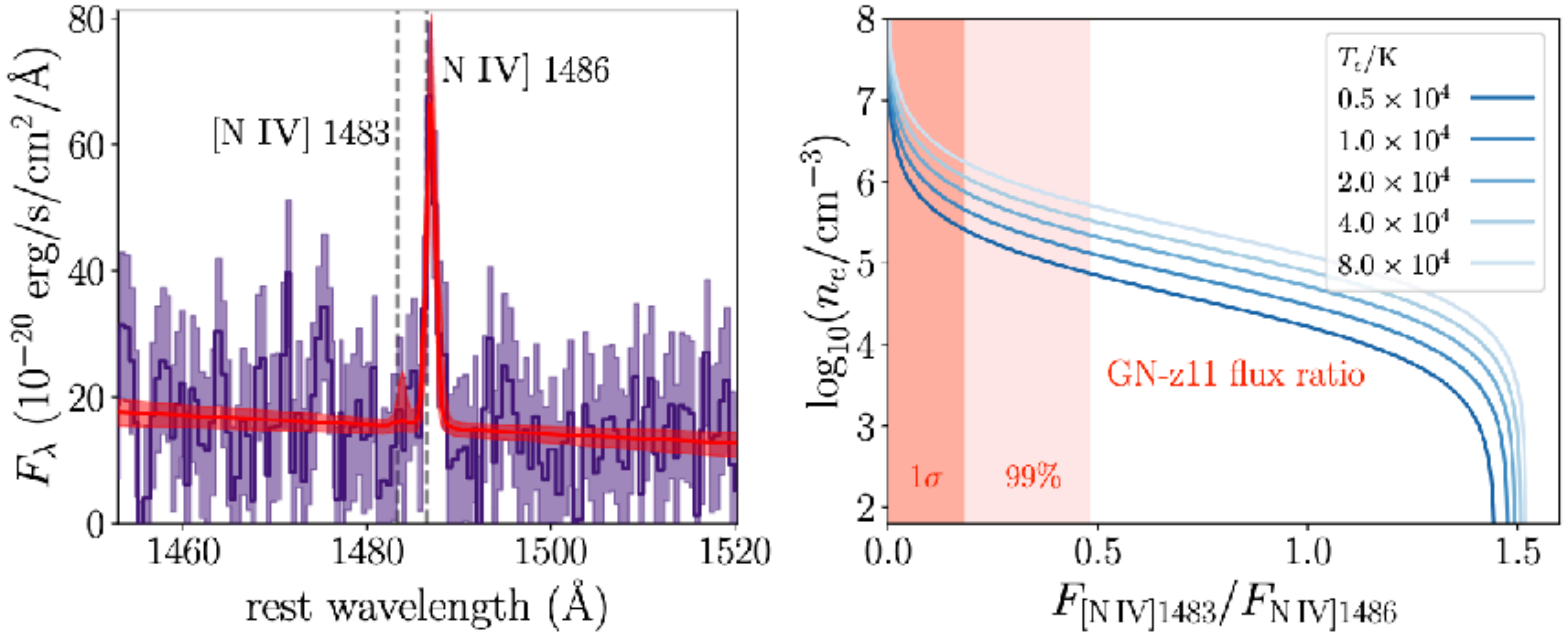
Tang, Stark+2023



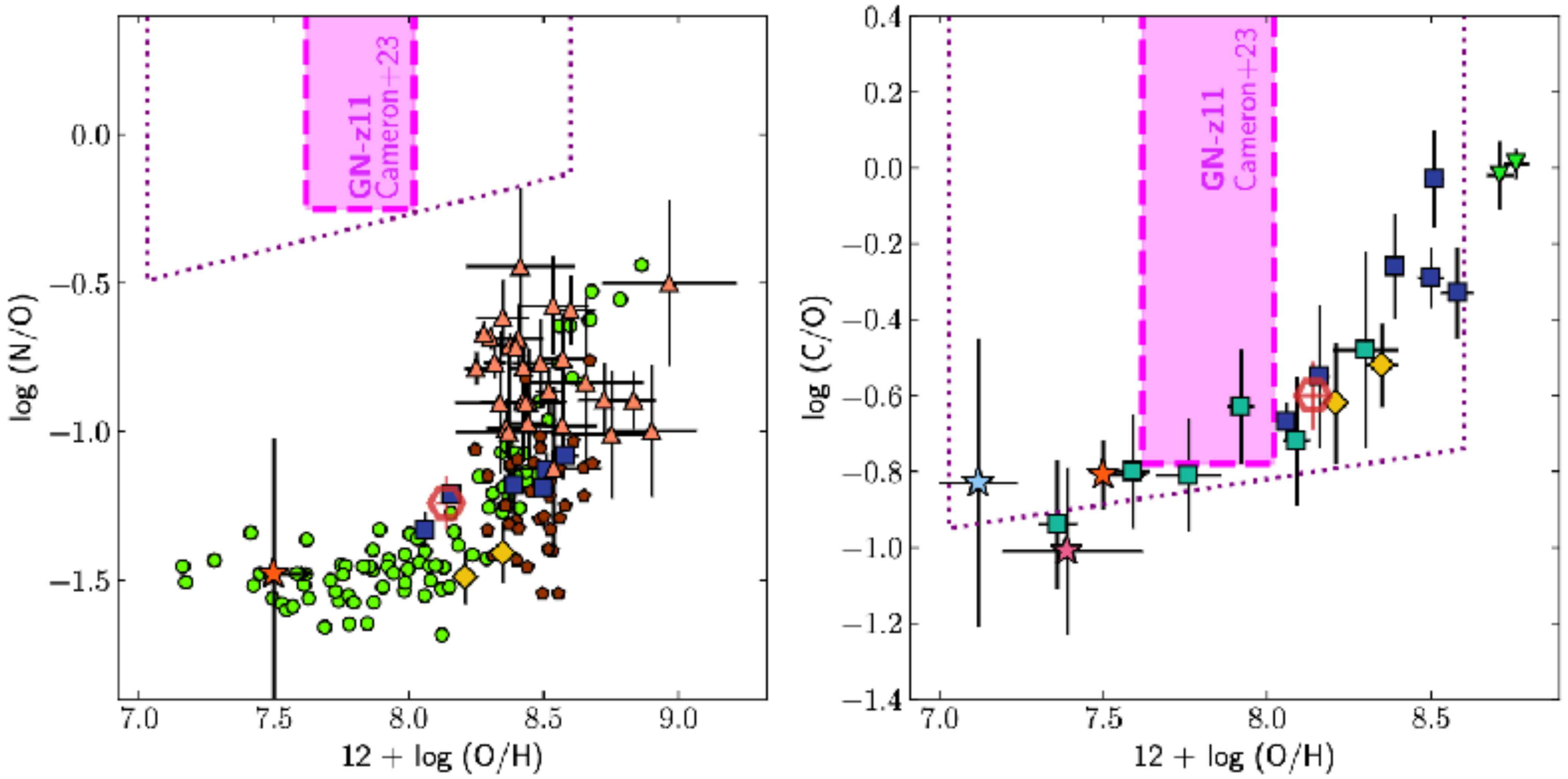
At z~8-11 we see that Lyα has large velocity shifts (>500 km/s) from systemic redshifts, as may be expected for small bubble picture.

Progress from JWST/NIRSpec Spectra of Lyα Emitters

Senchyna, Plat, Stark+2023



Cameron+2023

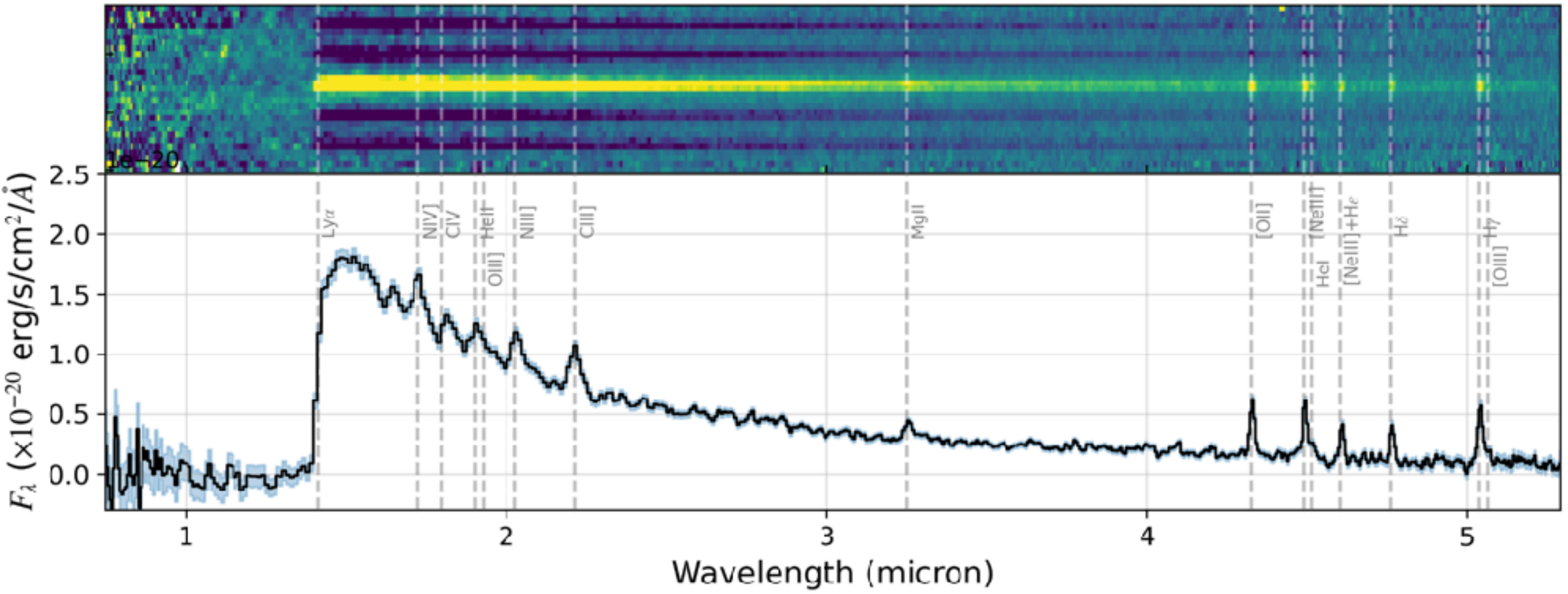


In the z~11 galaxy, we see Lyα is associated with a compact star forming complex ($\sim 10^8$ M$_\odot$ in 200 pc) with **extremely dense (>10^5 cm^{-3}) clouds of ionized gas** that are metal poor (~ 0.1 Z$_\odot$) yet **highly-enriched in nitrogen (super solar)** — *very peculiar abundance pattern with unknown origin!*

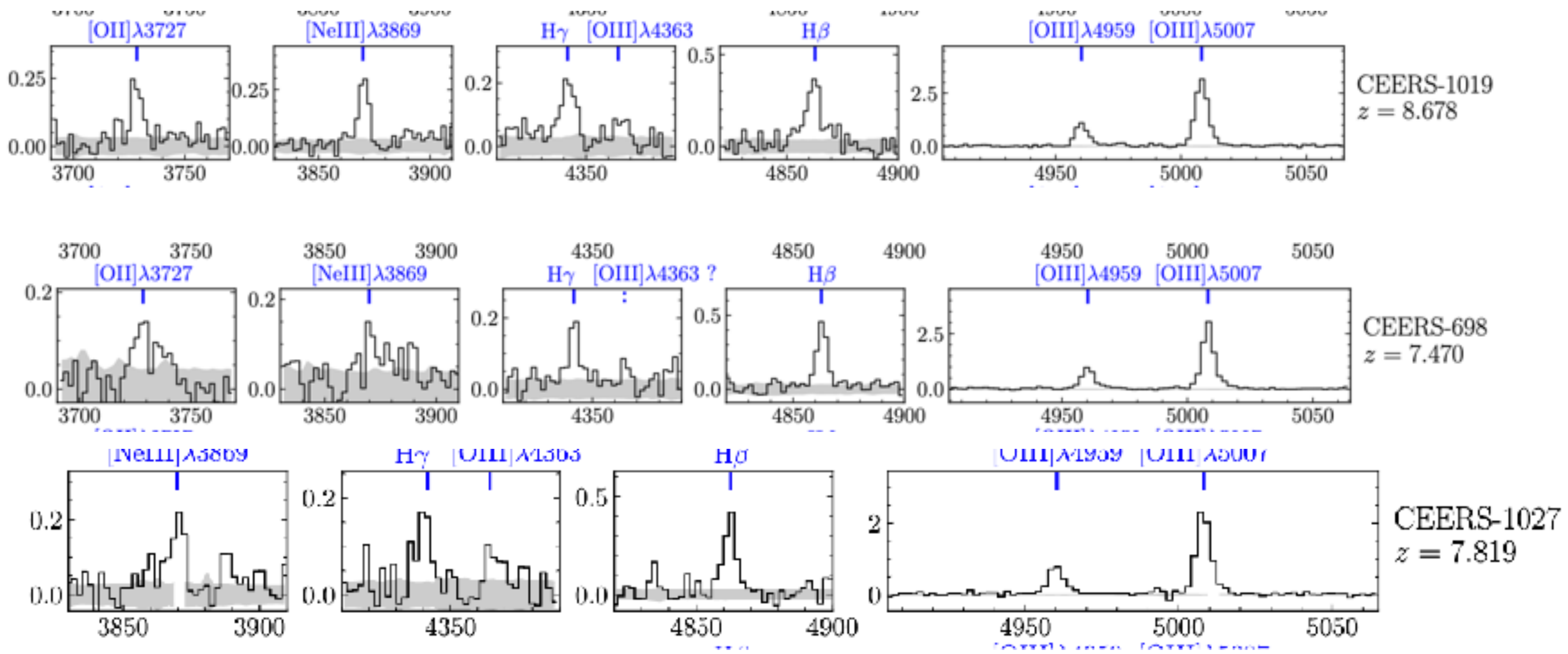
**see Pascale+2023 for a z~3 analog of this z=11 galaxy.

Progress from JWST/NIRSpec Spectra of Lyα Emitters

Bunker+2023



Tang, Stark+2023

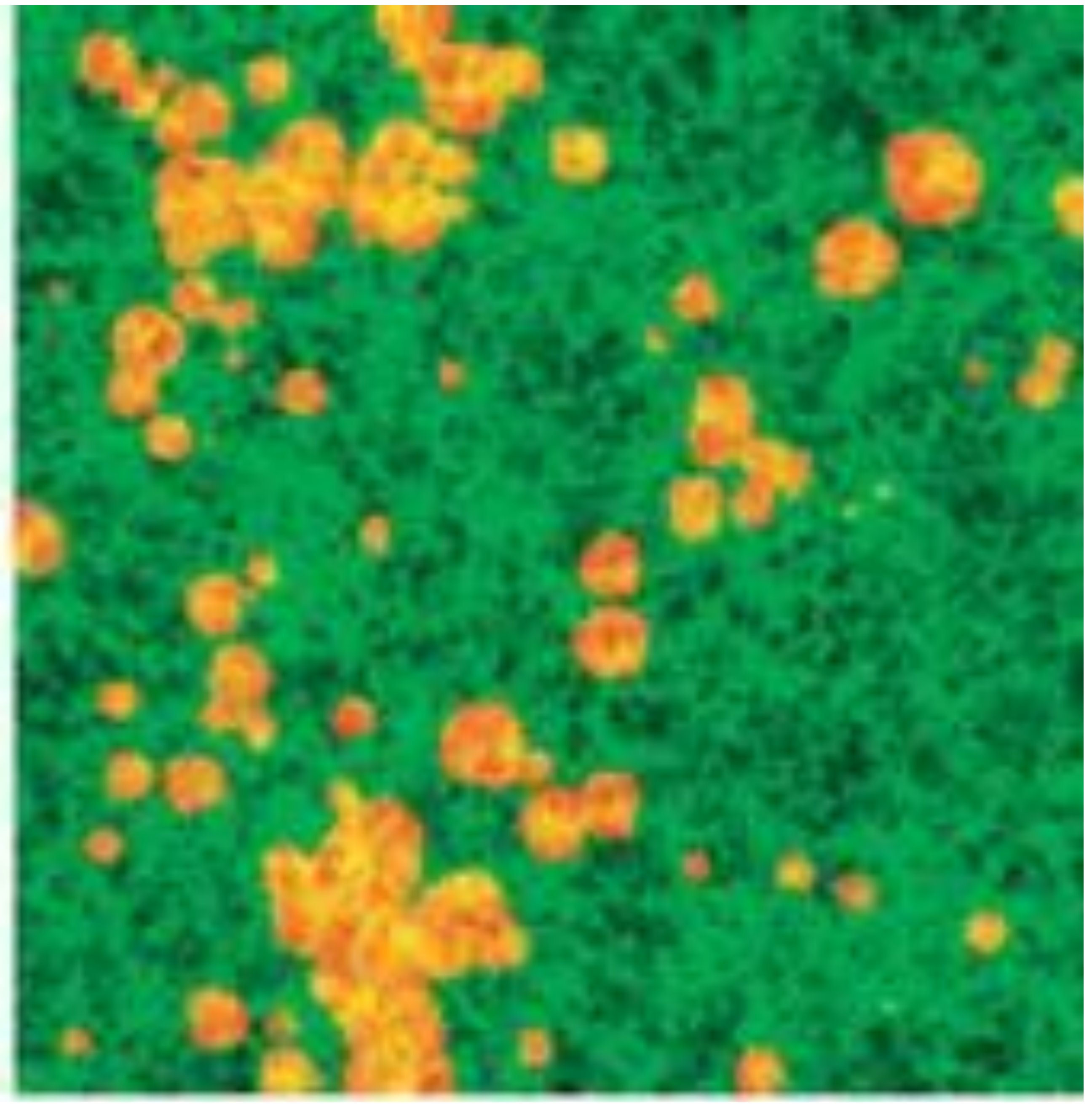


We are also finding that Lyα emitters have extreme emission line spectra (CIV, He II), indicating harder radiation fields than seen in typical sources.

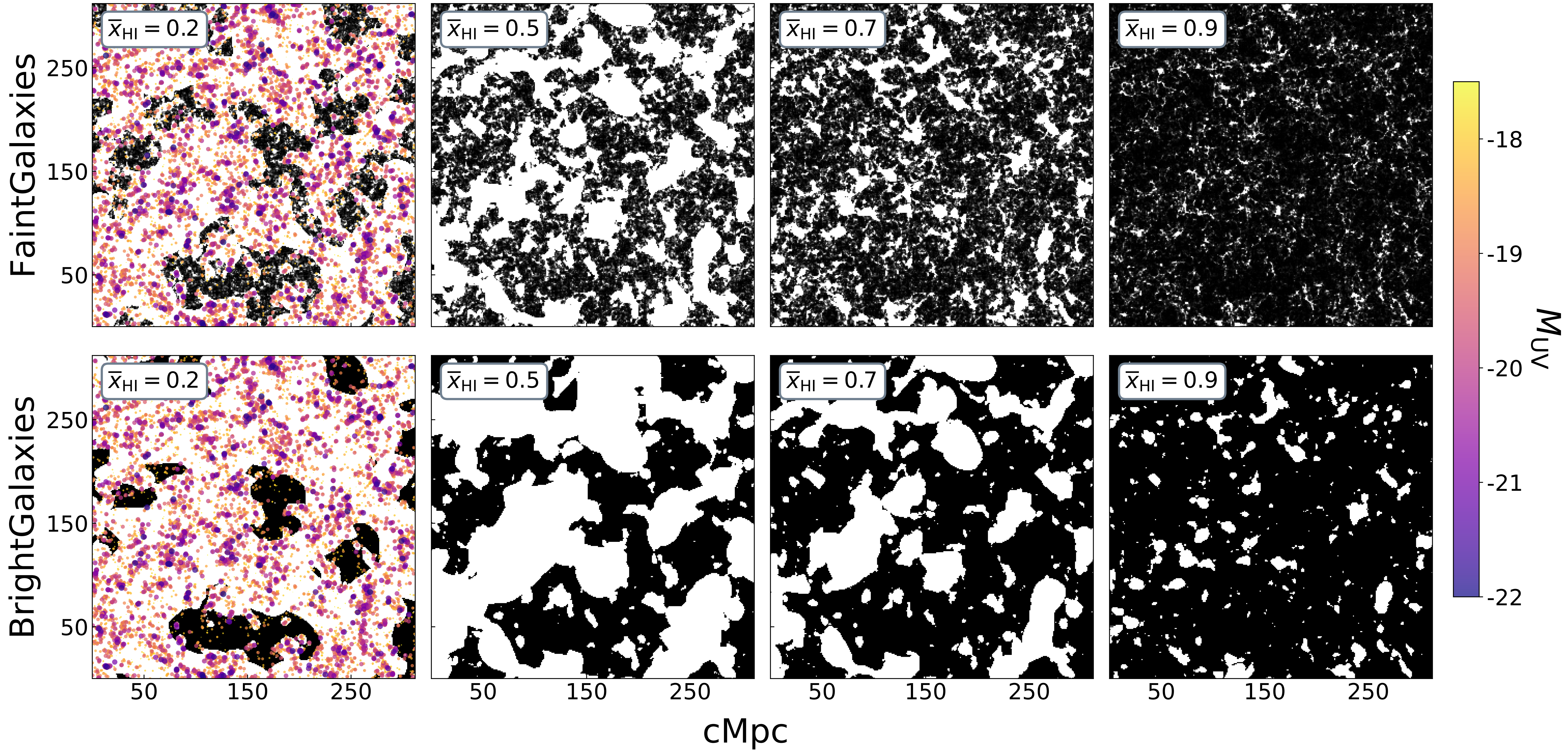
This suggests the Lyα emitters not only have enhanced transmission but also **enhanced production** -- likely contributing to line visibility in small bubbles.

Next Step: Identifying and Mapping Ionized Bubbles

credit: Iliev et al.

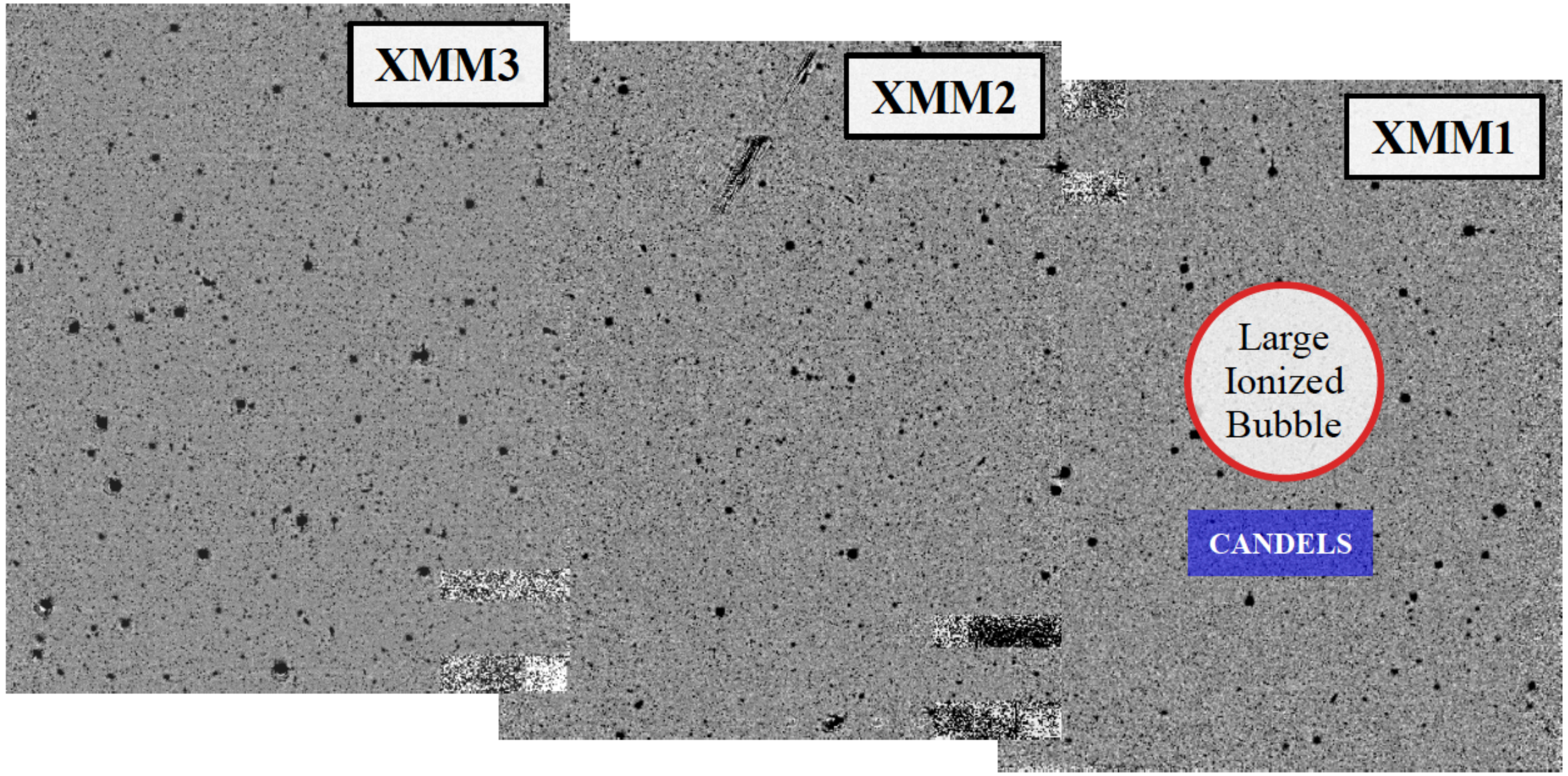


T. Lu, Mason+2023

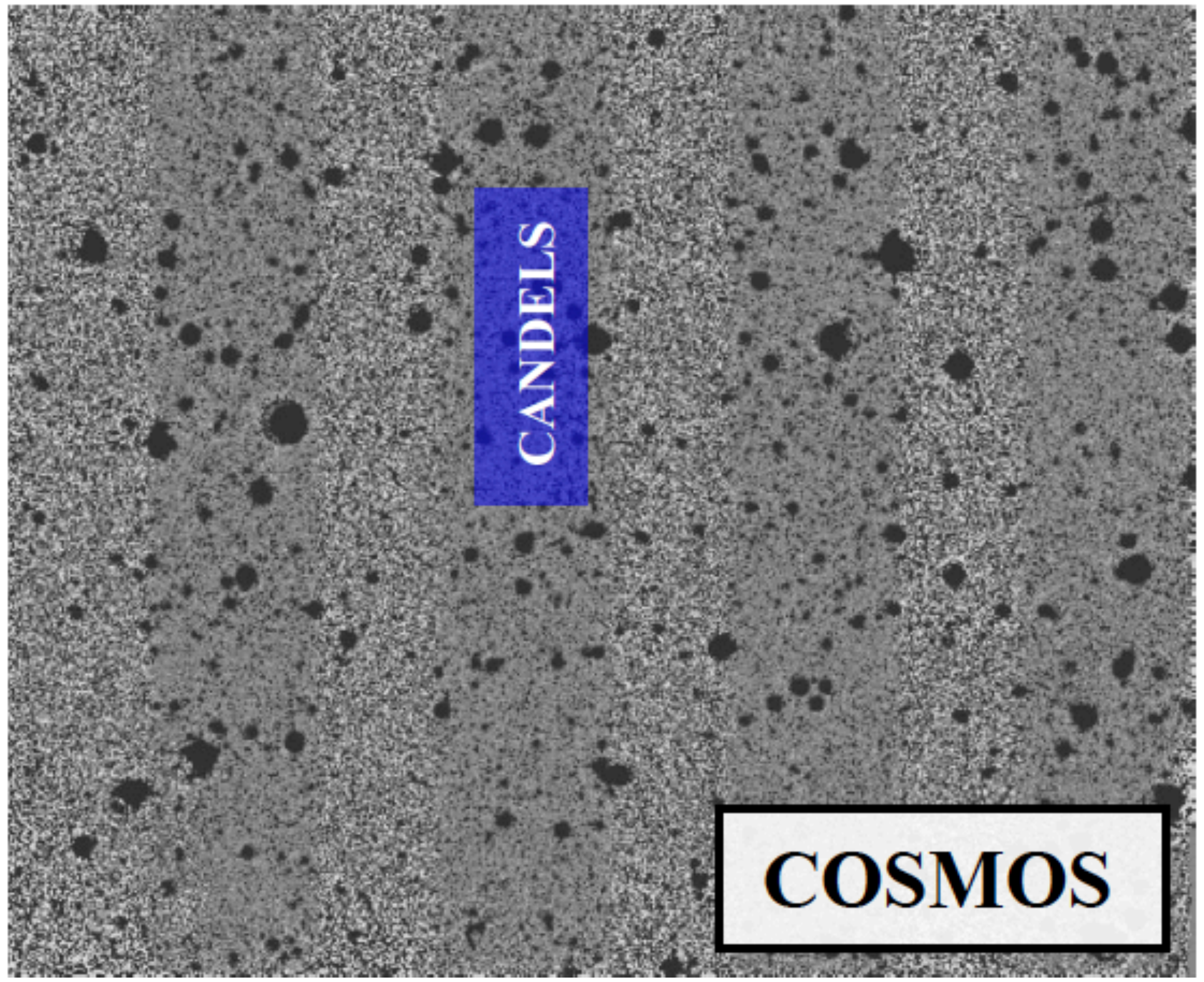


- We are finally assembling Lyα samples at z~7-11 that allow us to identify and map bubbles.
- This is next major phase in reionization studies (21cm, [CII] intensity mapping, Roman, Lyα).
- Promises insight into early (z>9-15) star formation, providing test of recent JWST results.
- Bubble sizes also sensitive to mass-scale of dominant ionizing sources.

Lyα emission bubble searches are just getting started

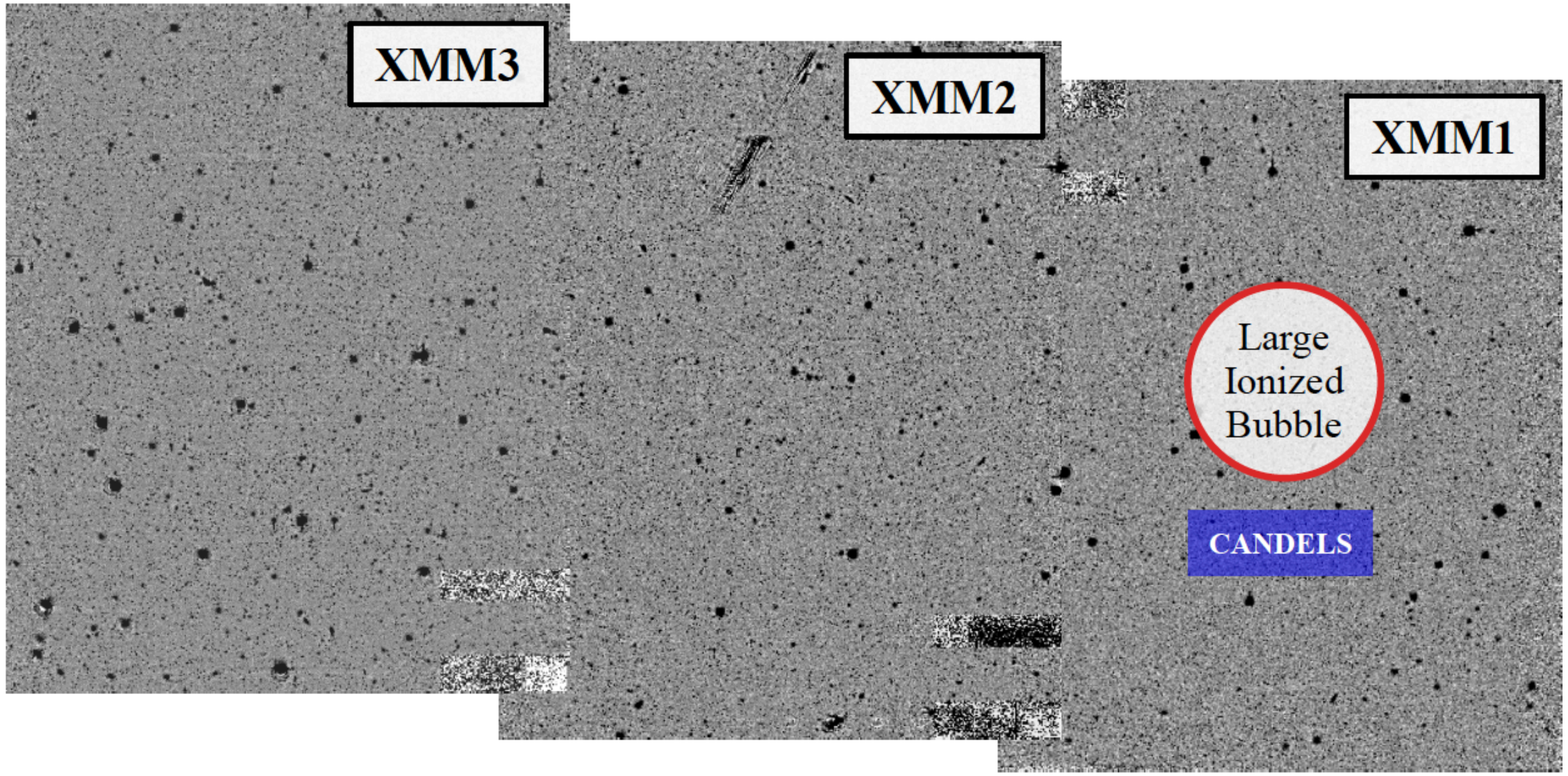


Endsley, Stark+2021b, 2022ab



- We have conducted Lyα survey across 7 deg^2 at z~7.
- Given what we know about IGM, there should be large bubbles in place!
- How do we find these bubbles?

Lyα emission bubble searches are just getting started



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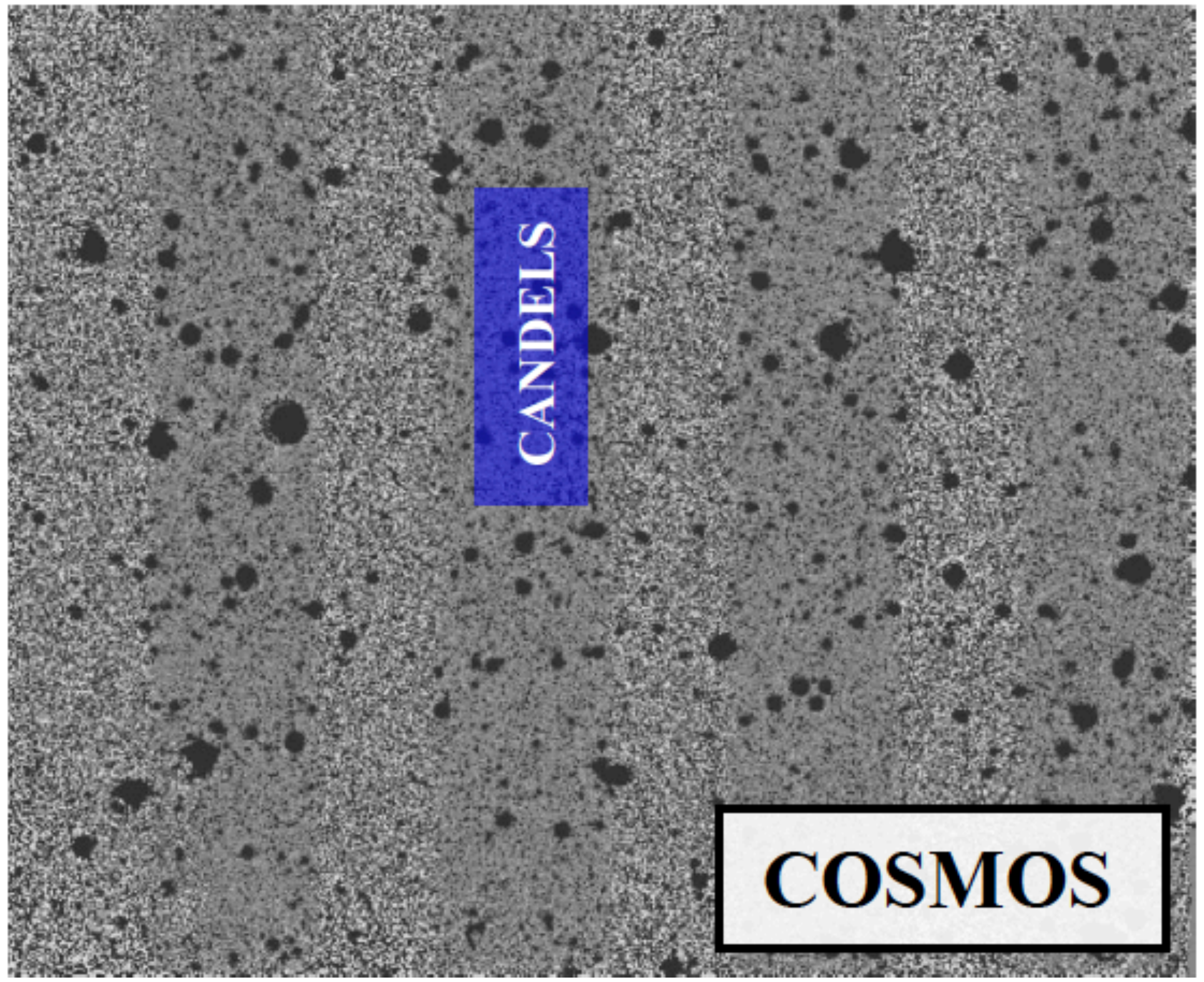
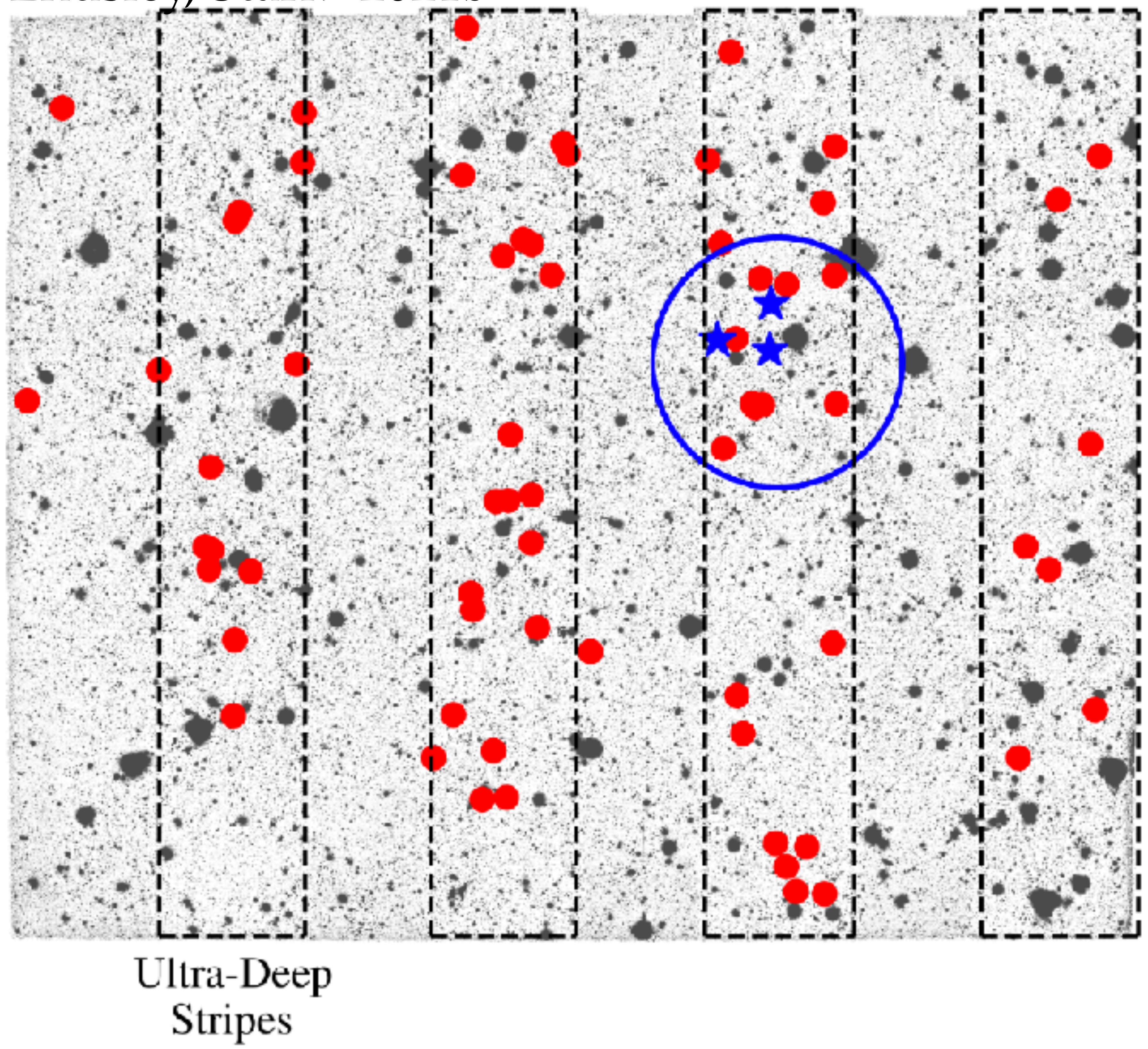


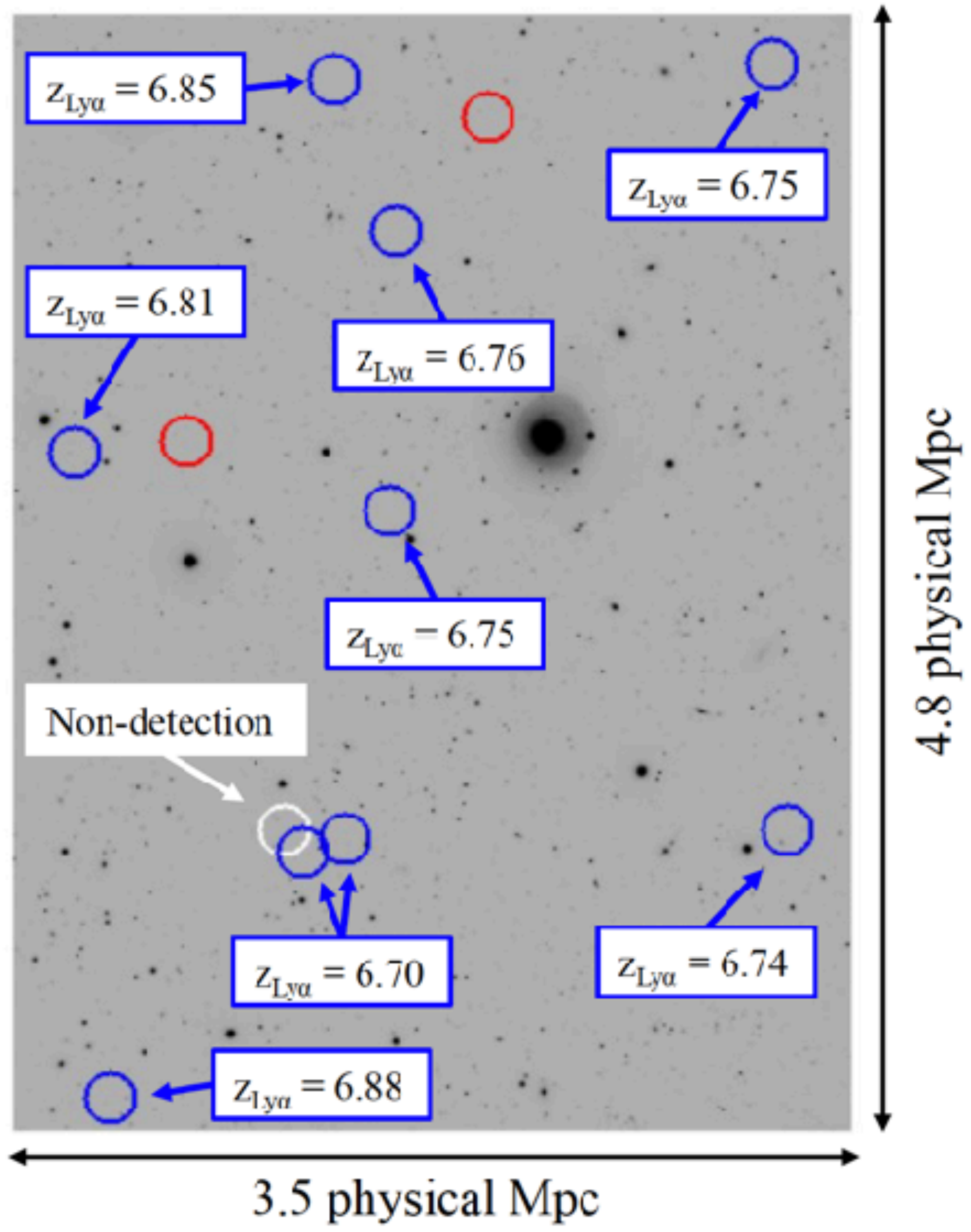
- We have conducted Lyα survey across 7 deg^2 at z~7.
- Given what we know about IGM, there should be large bubbles in place!
- We search for regions in our survey that satisfy three criteria
  - Overdensity of galaxies
  - Strong Lyα emission (excess relative to average)
  - Lyα profiles indicative of ionized sightlines (low velocity offsets).

Can we find z~7 ionized bubbles in our survey area?

Endsley, Stark+2021b



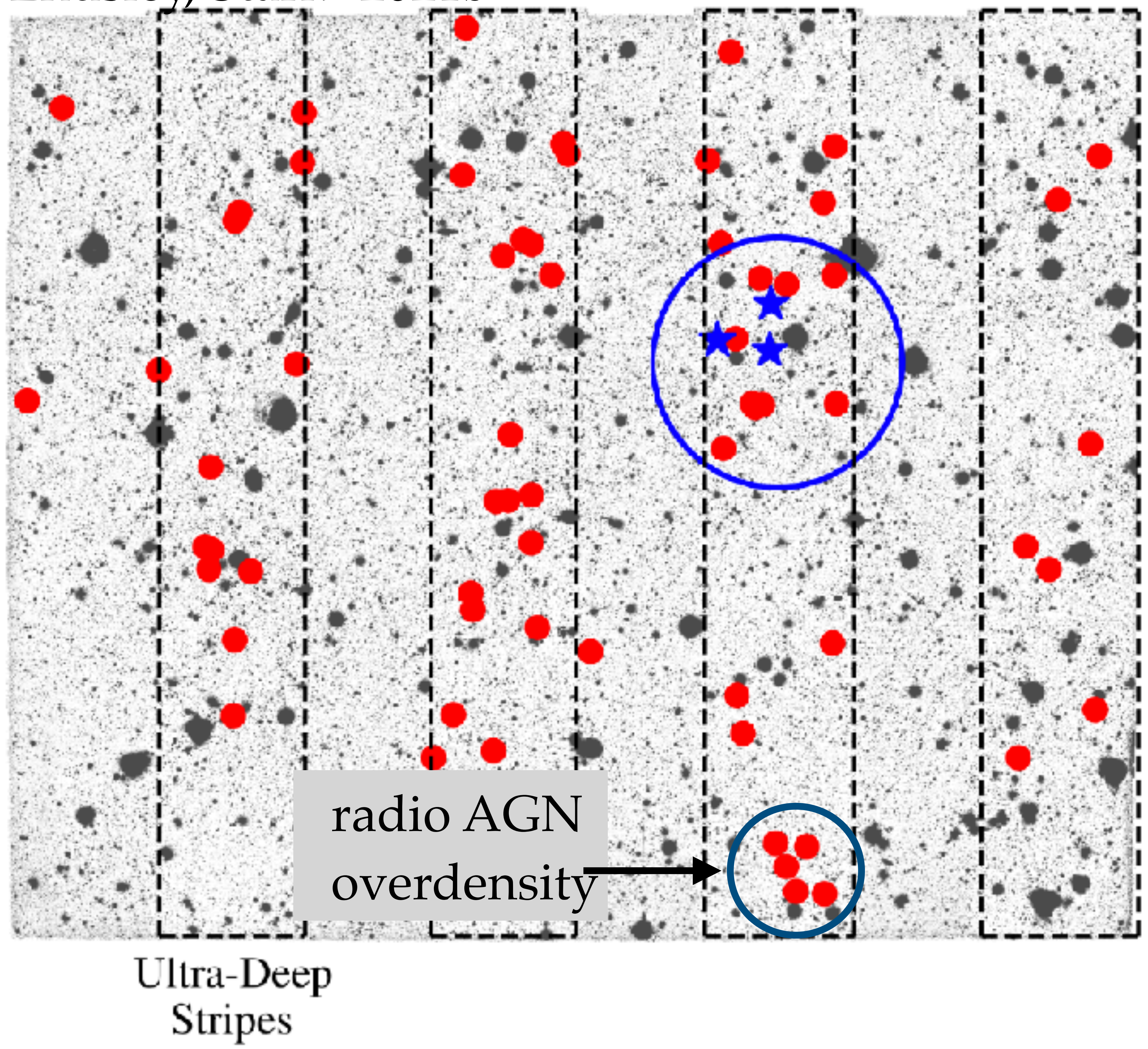
Endsley & Stark 2022a



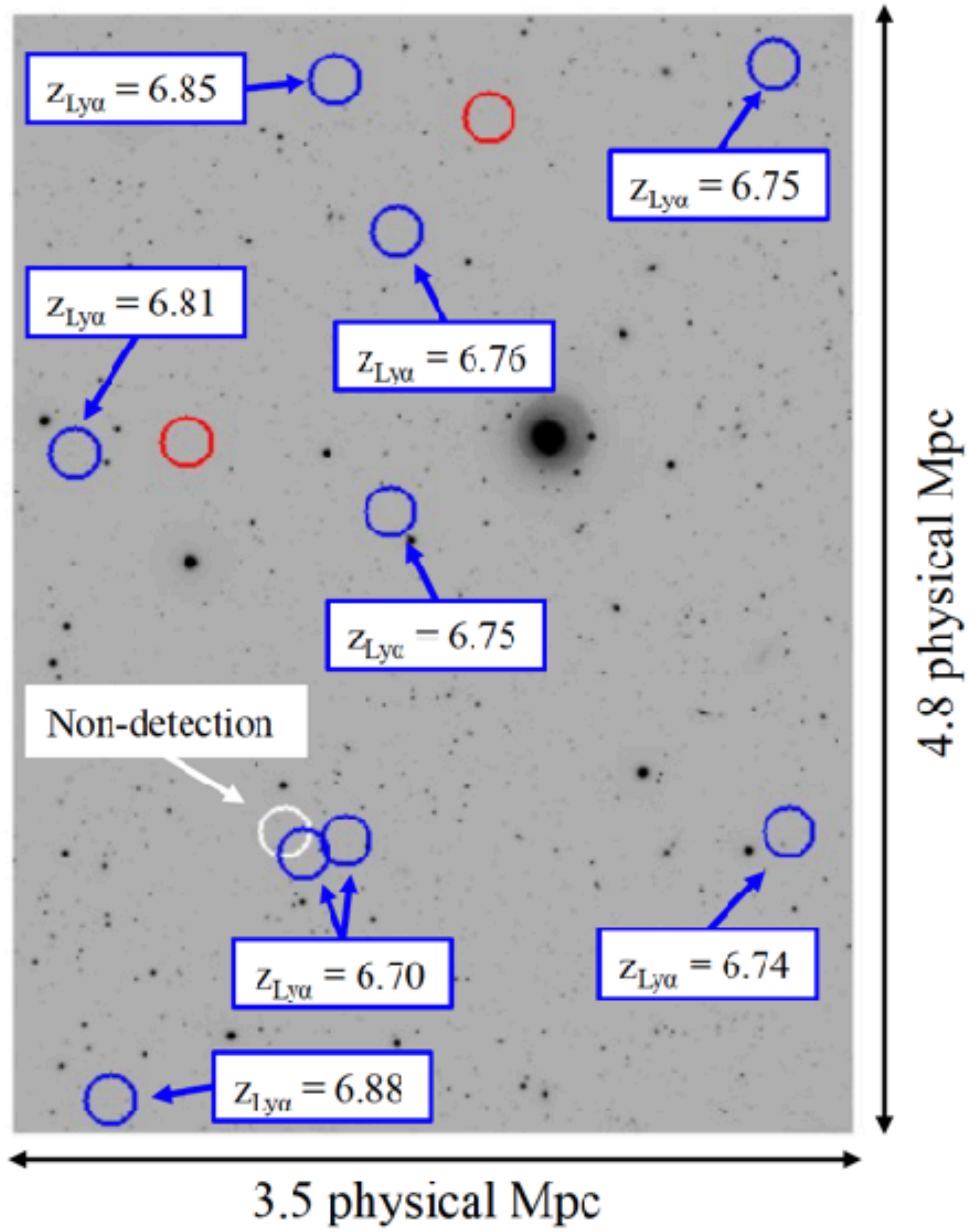
- Some sightlines show signatures of bubbles at z~7.
  - 5-10x overdensity on 10-15 arcmin scale
  - Enhanced Lyα transmission (90% success rate)
  - Line profiles indicative of ionized IGM.

Can we find z~7 ionized bubbles in our survey area?

Endsley, Stark+2021b



Endsley & Stark 2022a



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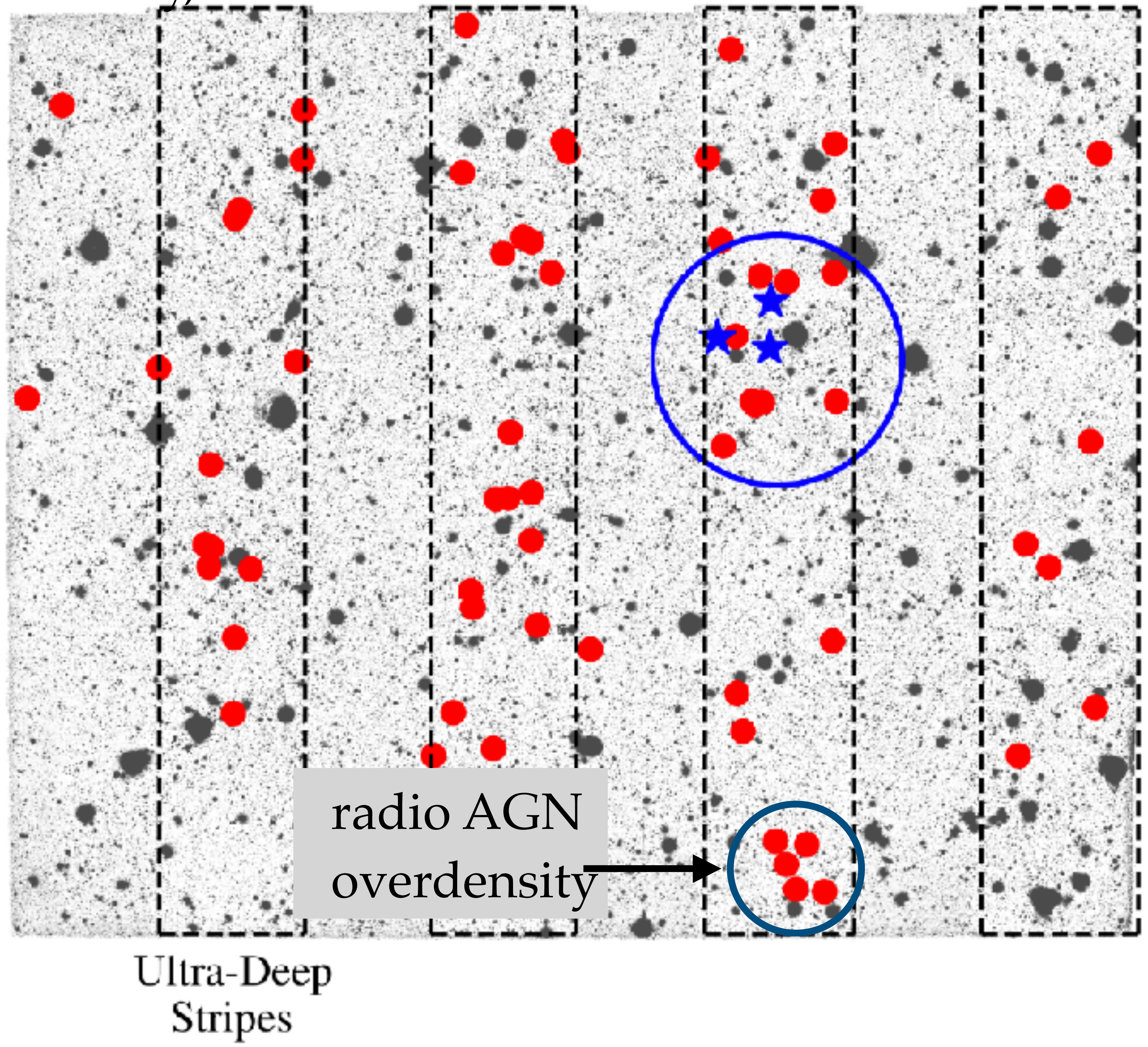
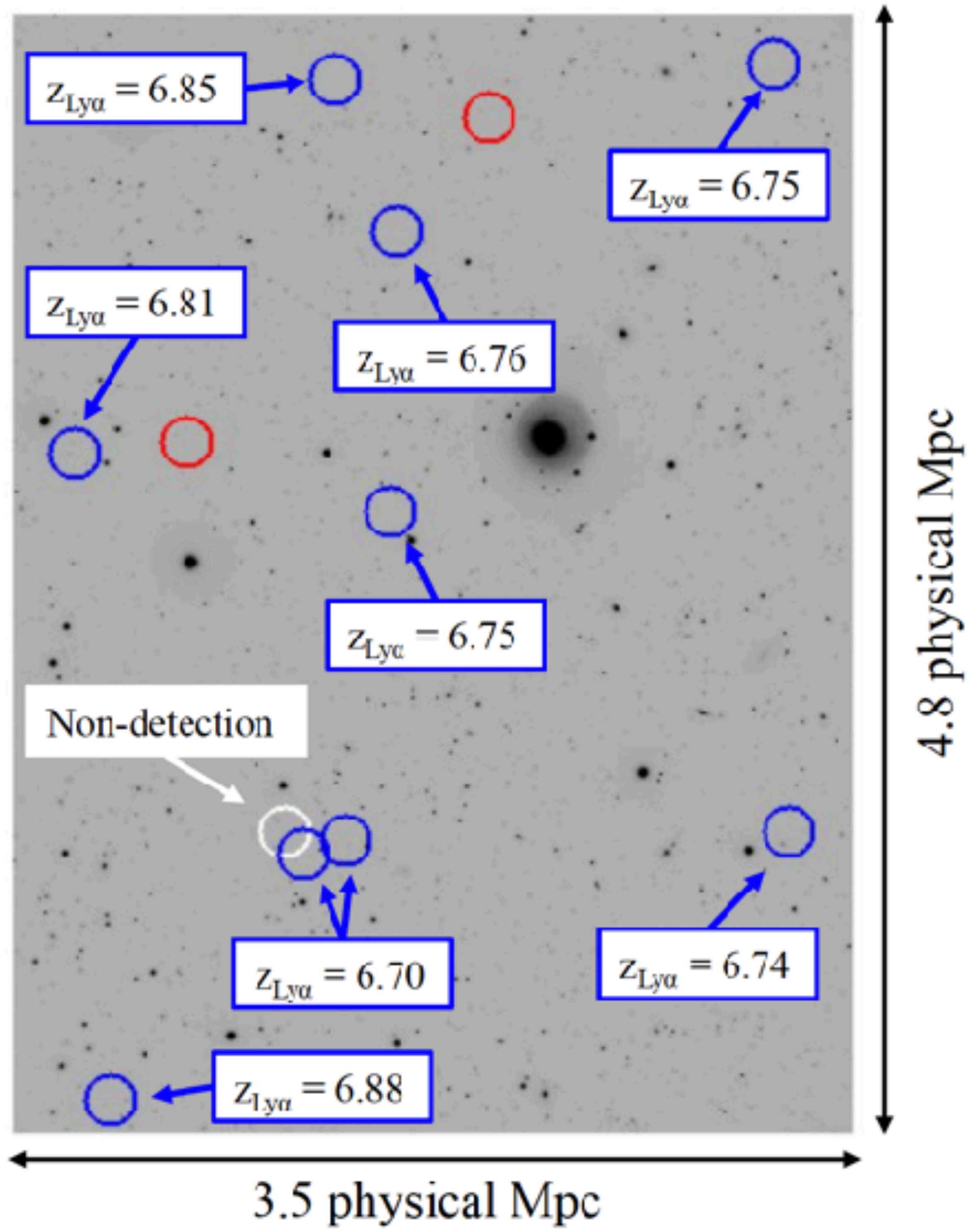
- Other overdensities do not!
  - Stronger overdensity on 3-5 arcmin scale
  - Surrounding radio AGN (Endsley, Stark+22c).
  - Very low Lyα success rate.

Can we find z~7 ionized bubbles in our survey area?

Endsley, Stark+2021b



Endsley & Stark 2022a



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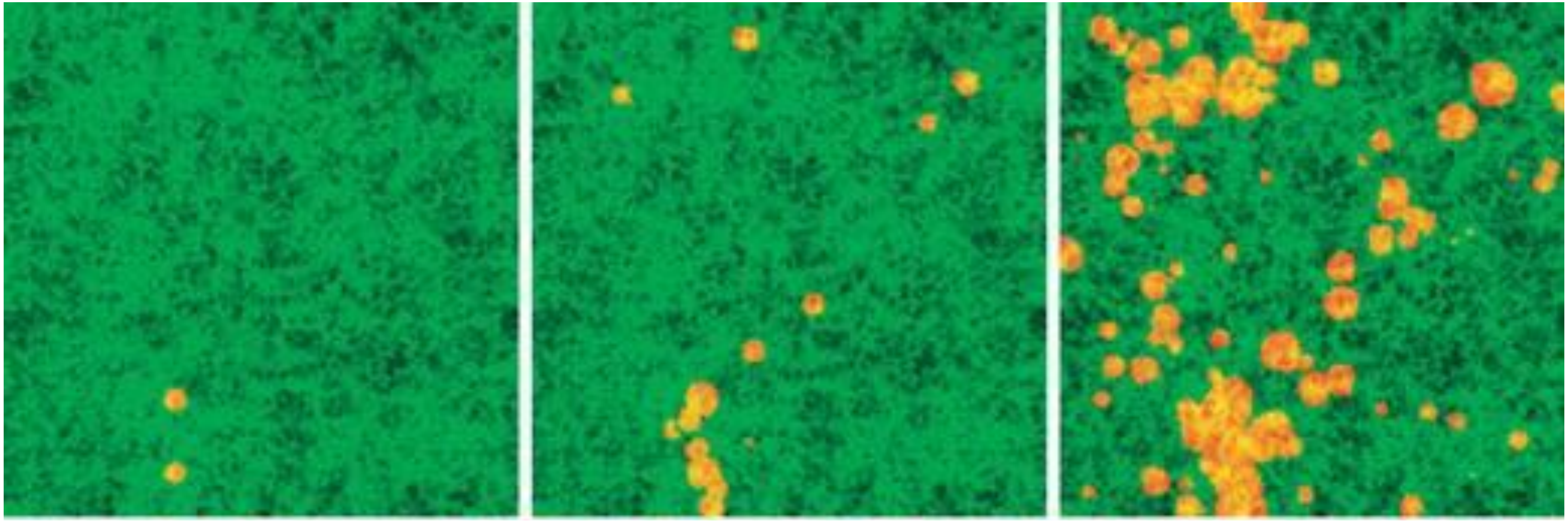
- Other overdensities do not!
  - Stronger overdensity on 3-5 arcmin scale
  - Surrounding radio AGN (Endsley, Stark+22c).
  - Very low Lyα success rate.
- Not yet clear why some overdensities are better at reionizing their surroundings.

Bubbles should be smaller at z~9

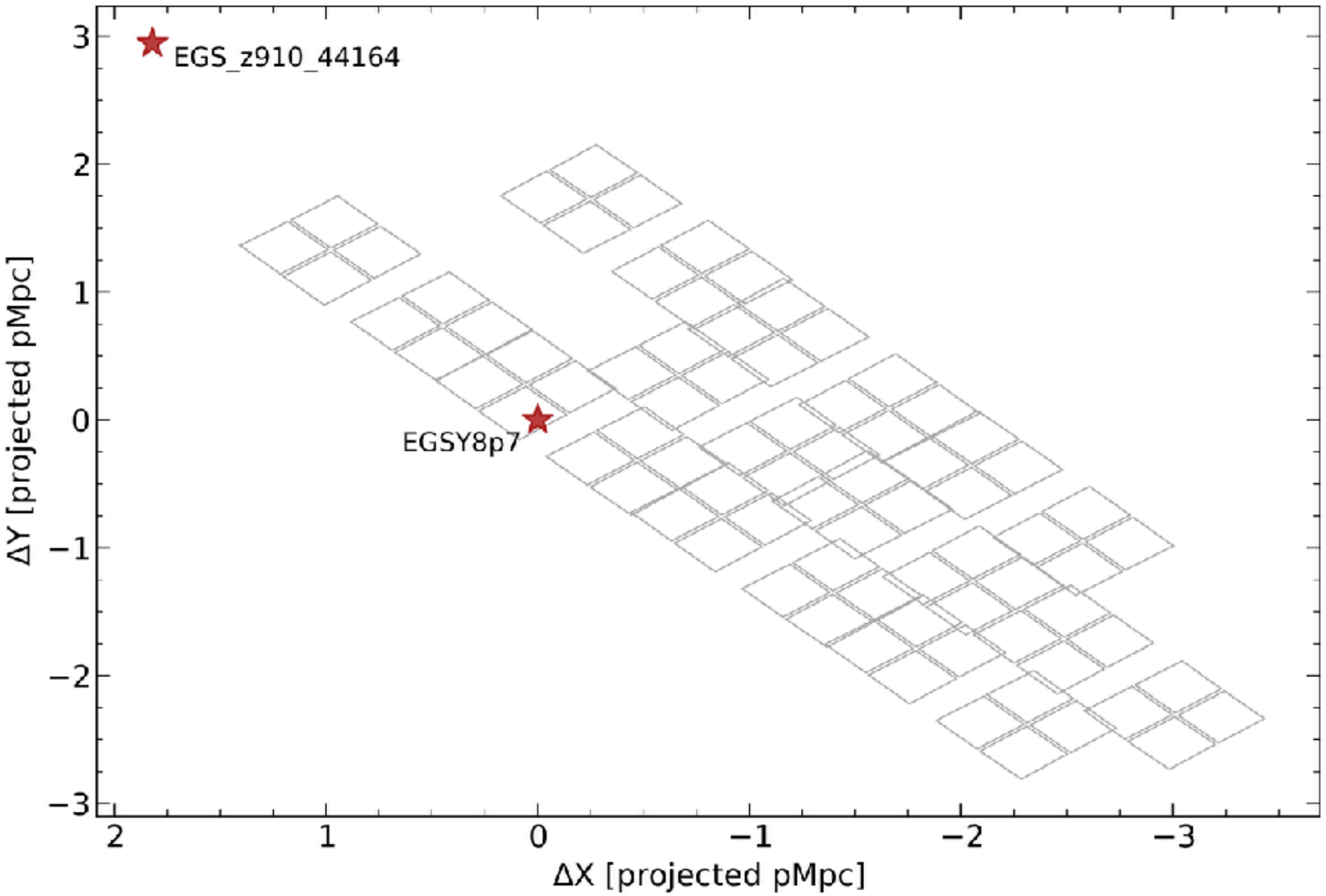
credit: Iliev et al.



- We expect vast majority of z~9 bubbles to be **smaller than 1 physical Mpc** given expected HI fraction in IGM.
- If we see larger bubbles at z~9, it may suggest more UV photons at z>10 than was thought previously, as has recently been suggested by JWST.

JWST is now extending bubble constraints to z~9

Whitler et al. 2023c, Tang et al. 2023a



- Two z~8.7 Lyα emitters have been identified with separation of ~5 physical Mpc — **signature of large bubble?**

- Is there also an overdensity?

Zitrin+2015, Roberts Borsani+2016, Larson+2022, Leonova+2022

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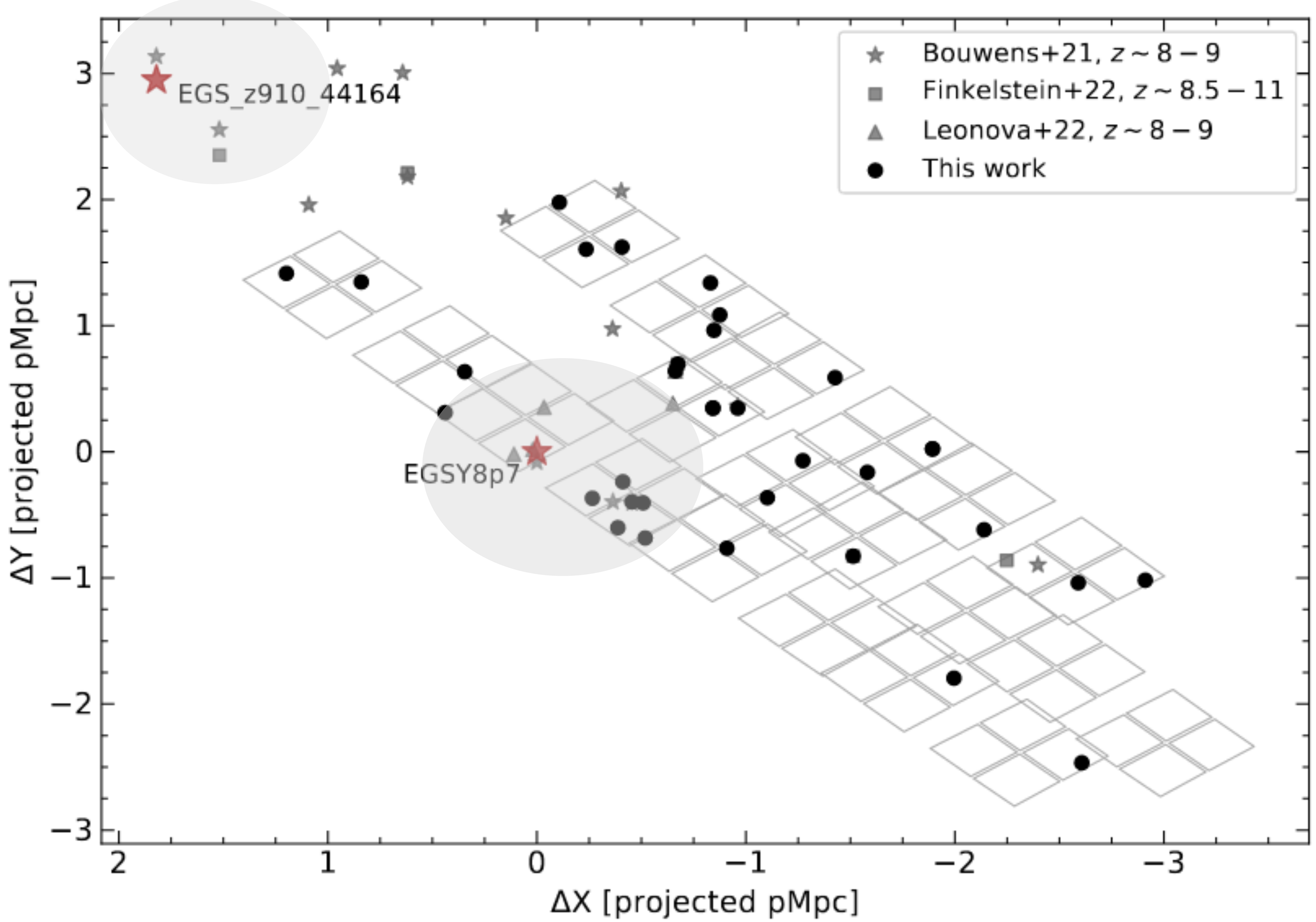
Whitler et al. 2023c, Tang et al. 2023a



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- NIRCam reveals strong 5x overdensity of galaxies in this field—*as would be required to carve out a large bubble.*

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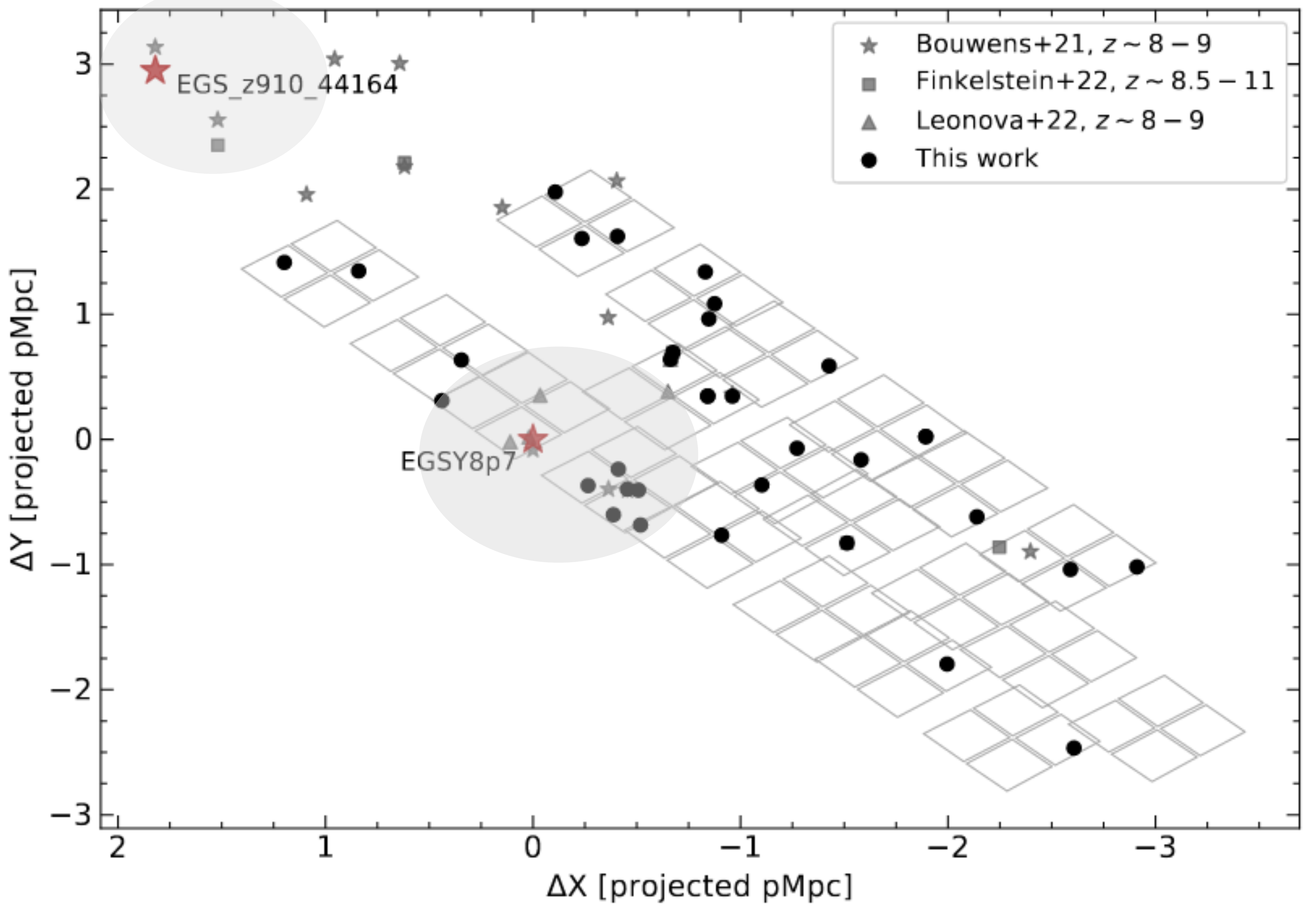

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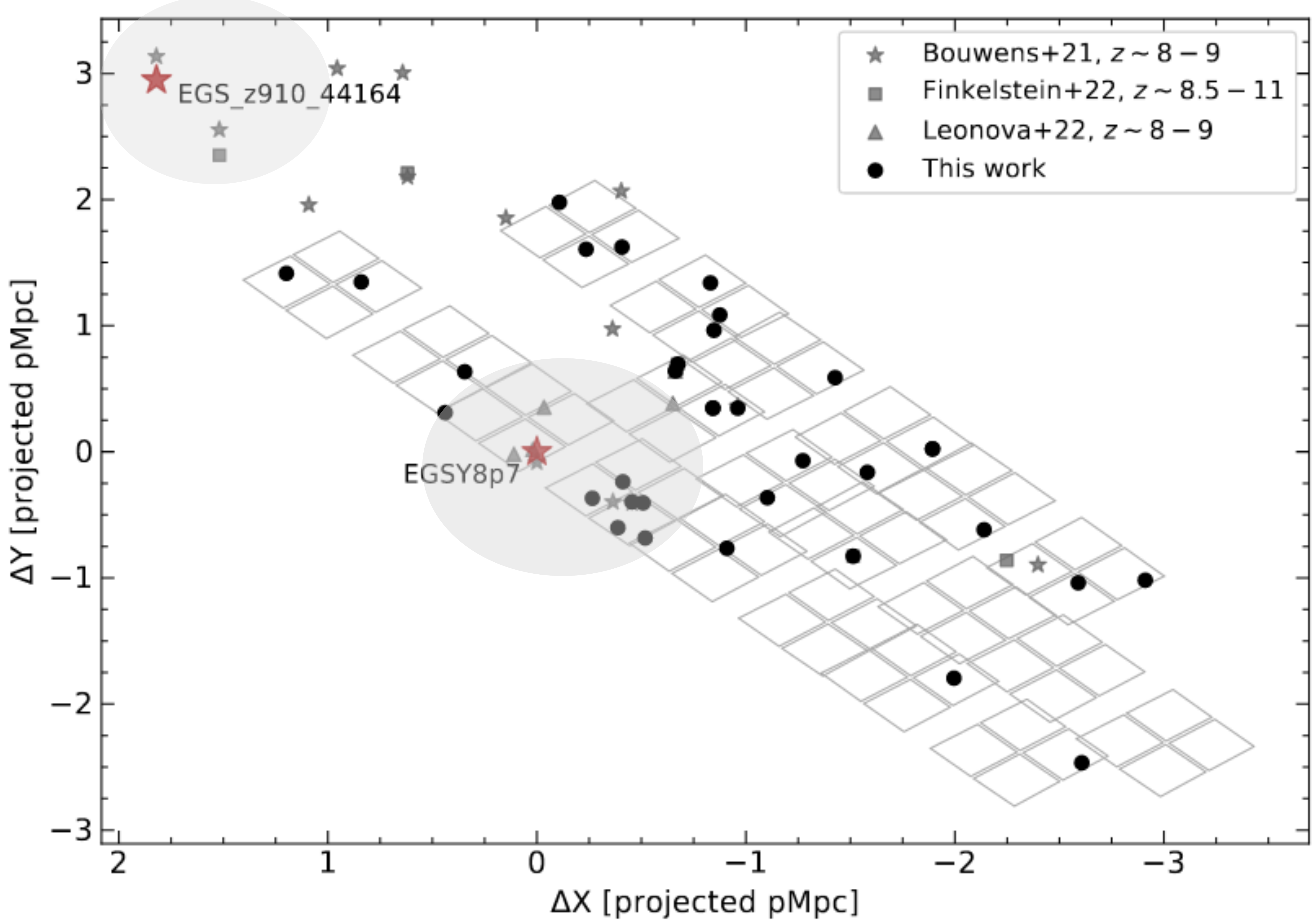
Whitler et al. 2023c, Tang et al. 2023a



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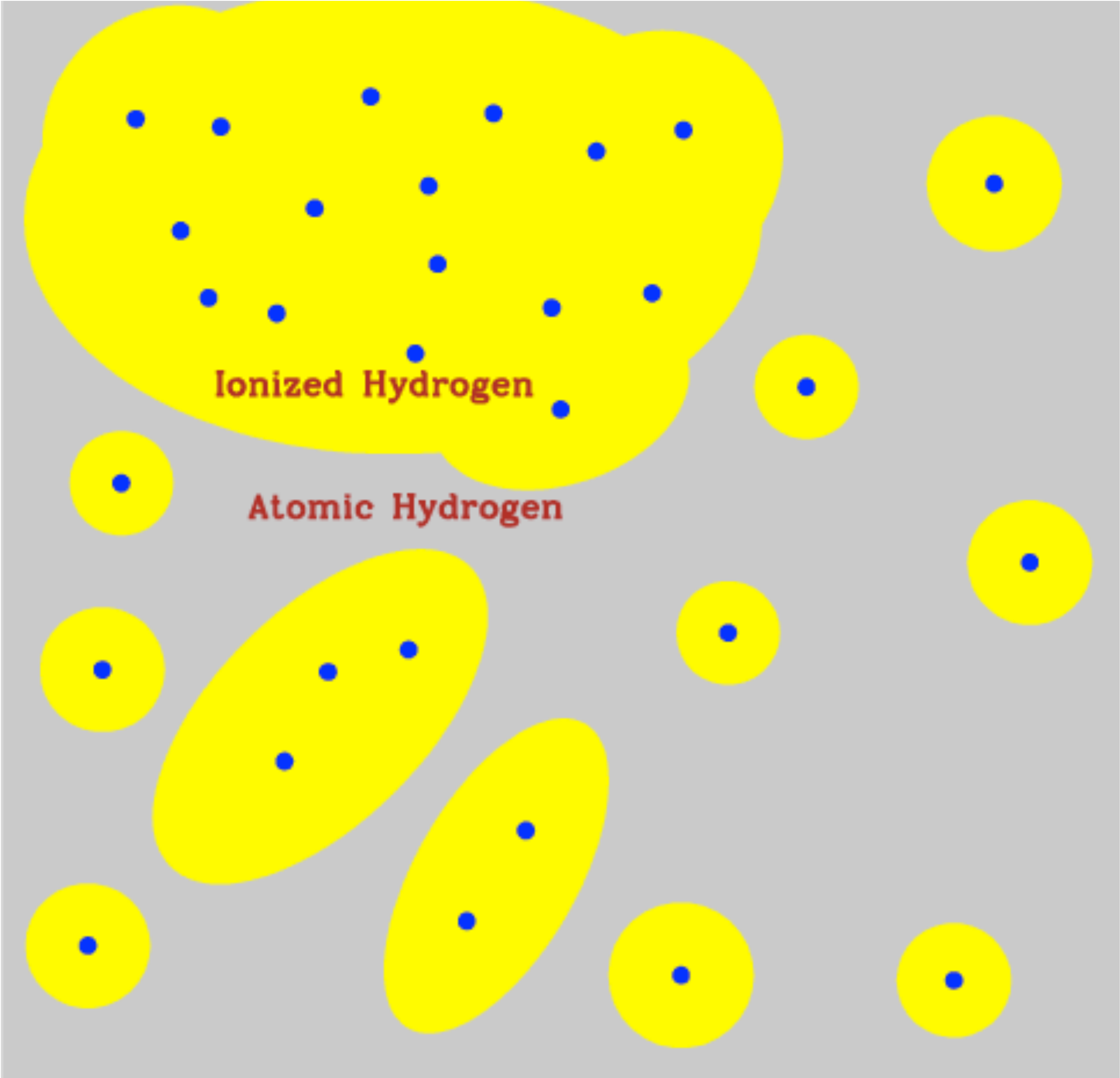
- May be first indications that bubbles are larger at z~9 than we expected.

- Deep Lyα spectroscopy targeting galaxies in overdensity will soon clarify full extent of the ionized region.

Zitrin+2015, Roberts Borsani+2016, Larson+2022, Leonova+2022

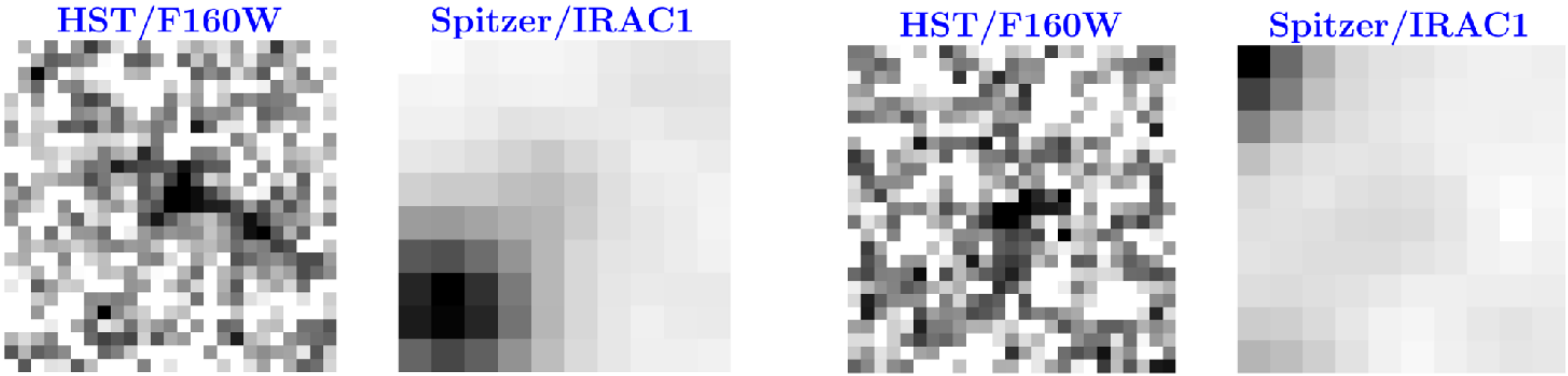
Star Formation History and Growth of Early Galaxies



credit: Rennan Barkana

- We have seen that large bubbles likely exist at z~7.
- To compute whether the galaxies within them could have created these bubbles, we need to know their **star formation timescales.**
    - If ages of stellar populations in z>6 galaxies are uniformly large, it would facilitate possibility of significant past ionizing photons for bubble growth.
- **What do we know about the stellar population ages of reionization era galaxies?**

Prior to JWST: Stellar Population Ages from HST+Spitzer

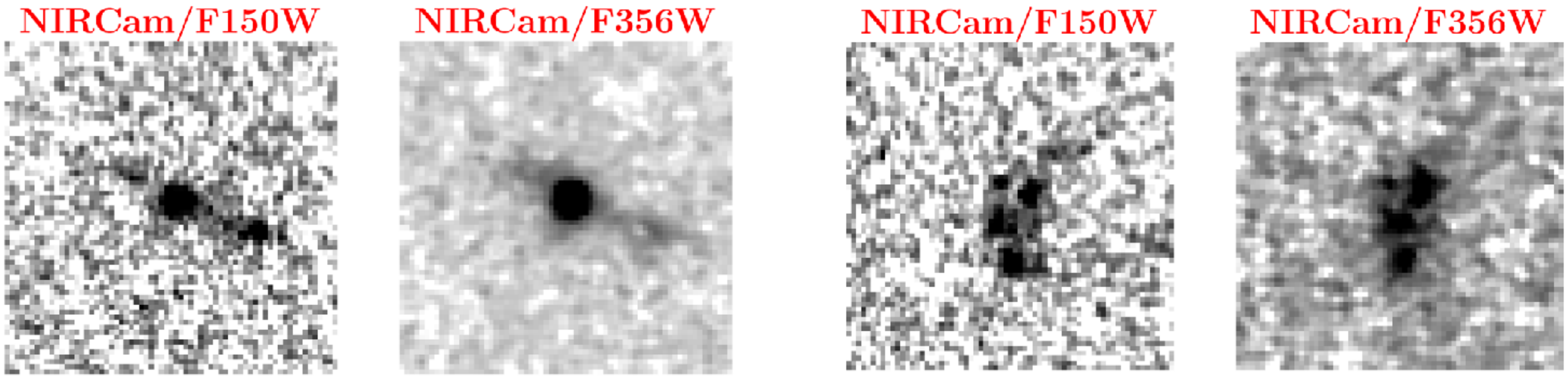


HST probed **rest-UV,** providing a measure of recently-formed O/B stars.

Spitzer probed **rest-optical,** revealing whether stellar population ages are old enough to have built up a substantial number of A stars.

Sensitivity/resolution of Spitzer clearly limiting for most z>6 galaxies!

JWST is a game-changer for star formation histories



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Sensitivity/resolution of Spitzer clearly limiting for most z>6 galaxies!

In contrast, NIRCam detects rest-UV to optical light with ease for z>6 galaxies.

How can we distinguish old and young stellar populations?

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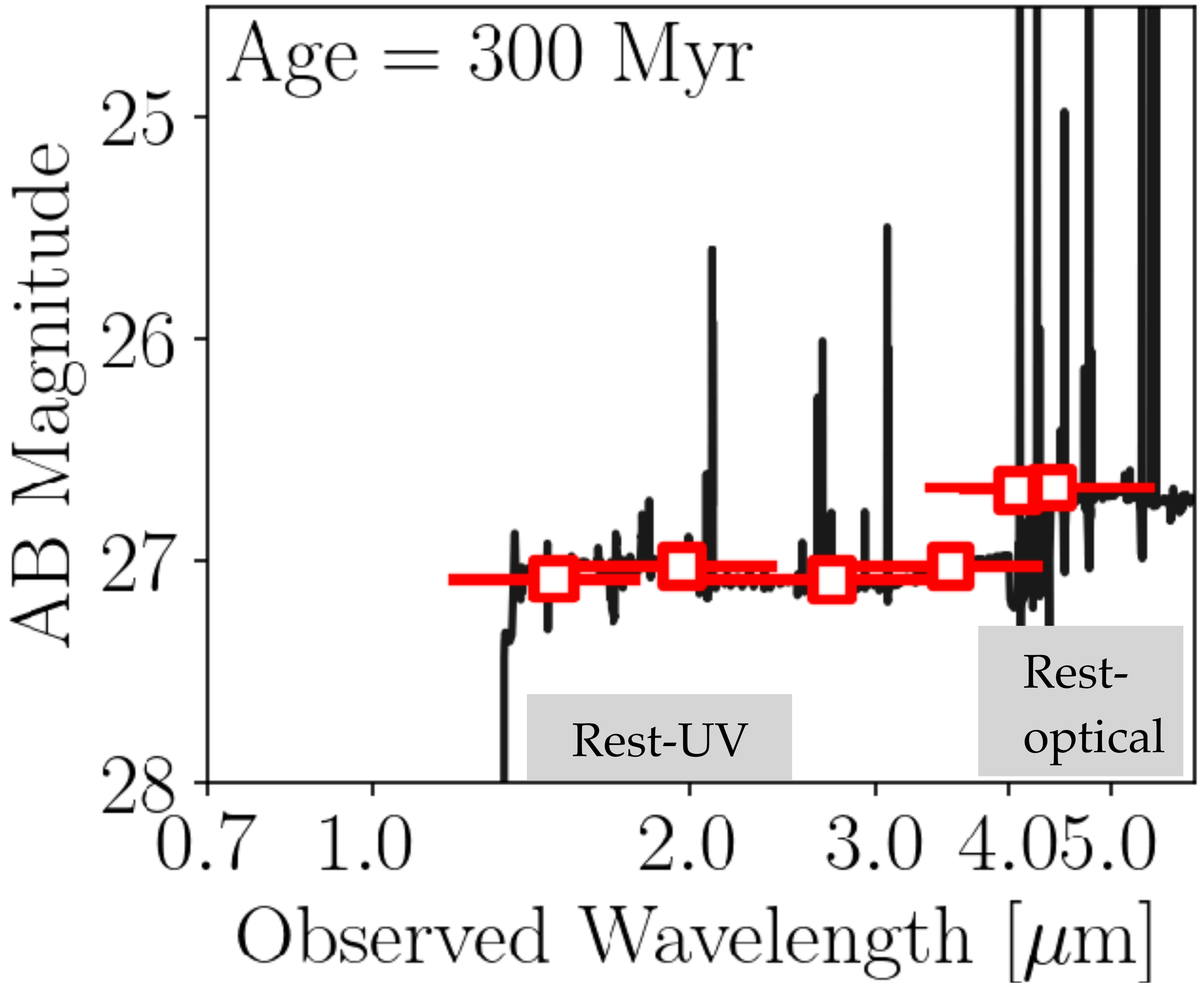
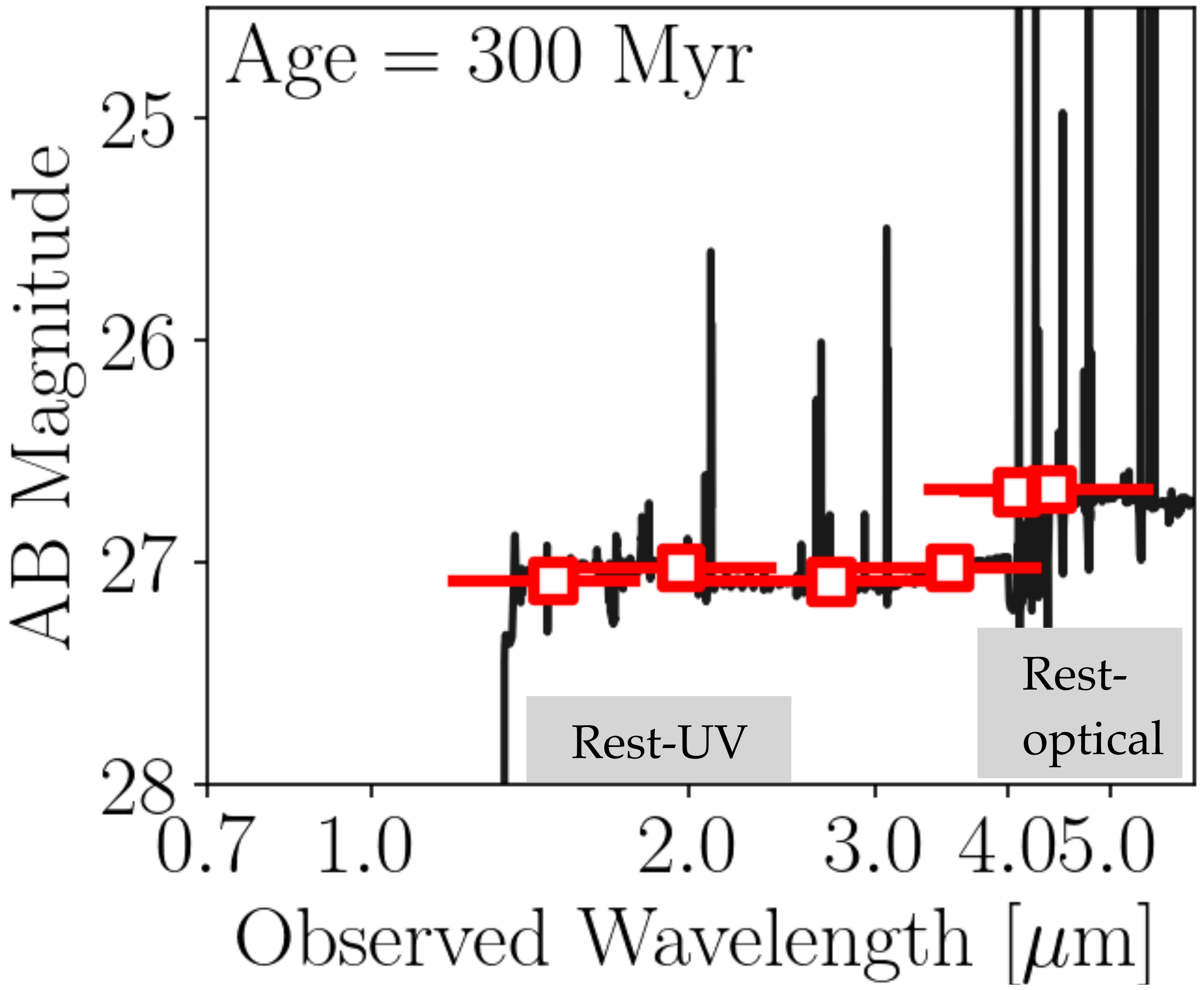
Old stellar population (CSFH t~300 Myr)



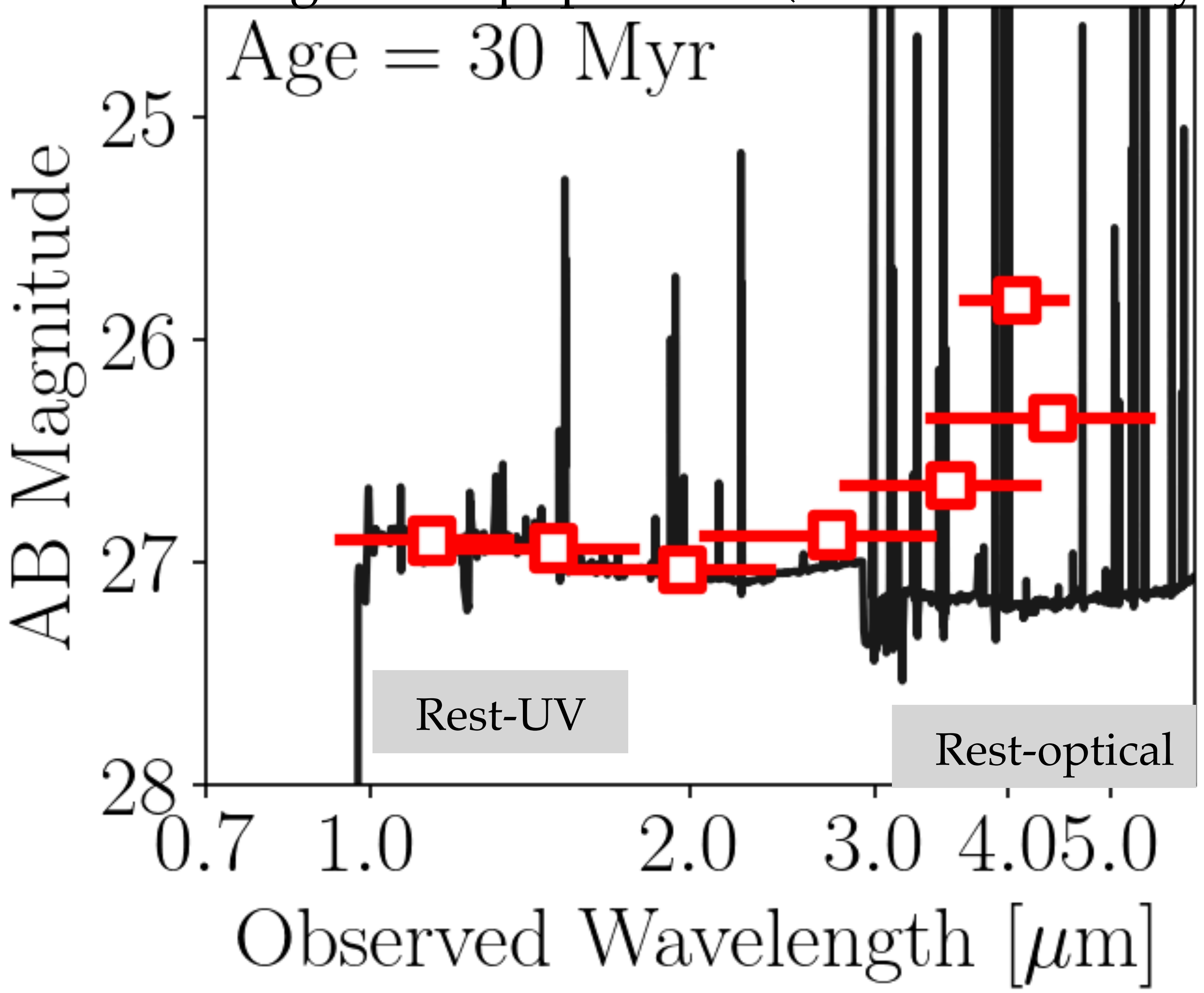
- **Balmer break:** rest-optical brighter than rest-UV owing to dominant A star population.

How can we distinguish old and young stellar populations?

Old stellar population (CSFH t~300 Myr)



Young stellar population (CSFH t~1-30 Myr)

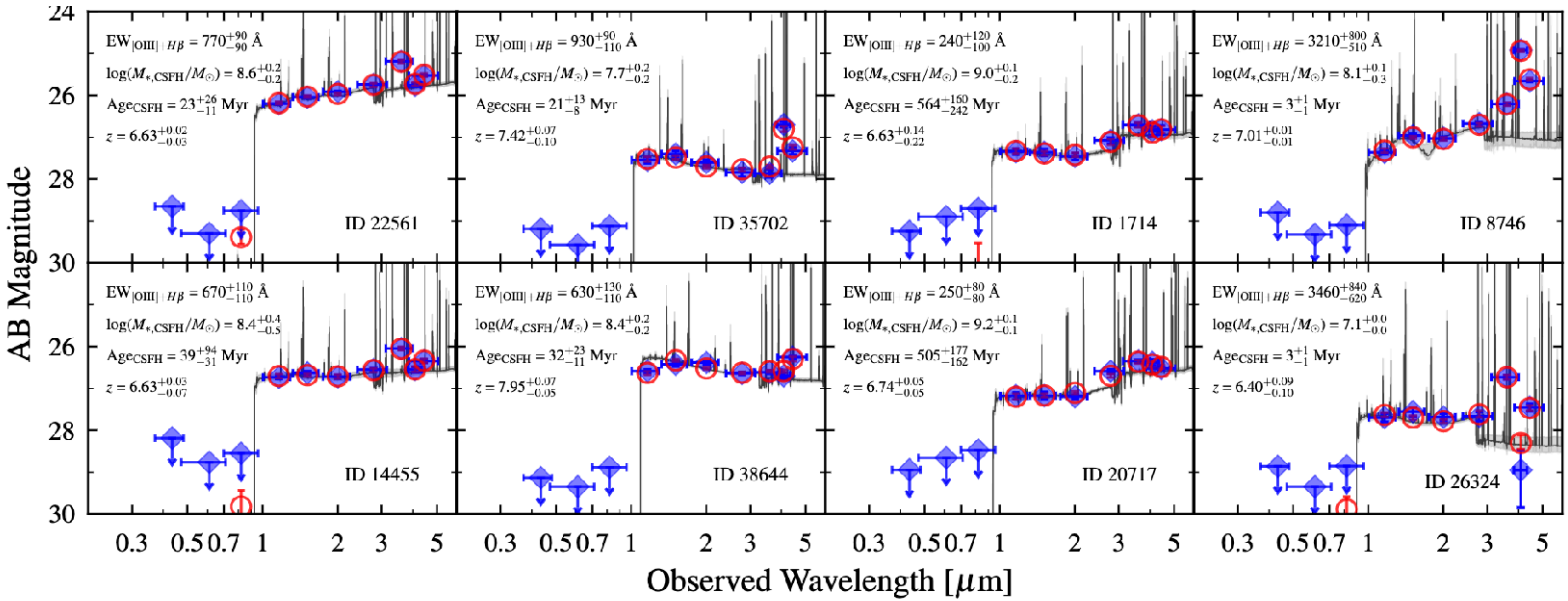


- **Balmer break:** rest-optical brighter than rest-UV owing to dominant A star population.

- No Balmer break, rest-UV as strong as optical.
- **[OIII] and Hα EW** are large, leading to large flux excesses in NIRCam filters they sit in.

NIRCam SEDs of z~6.5-8 Galaxies in CEERS

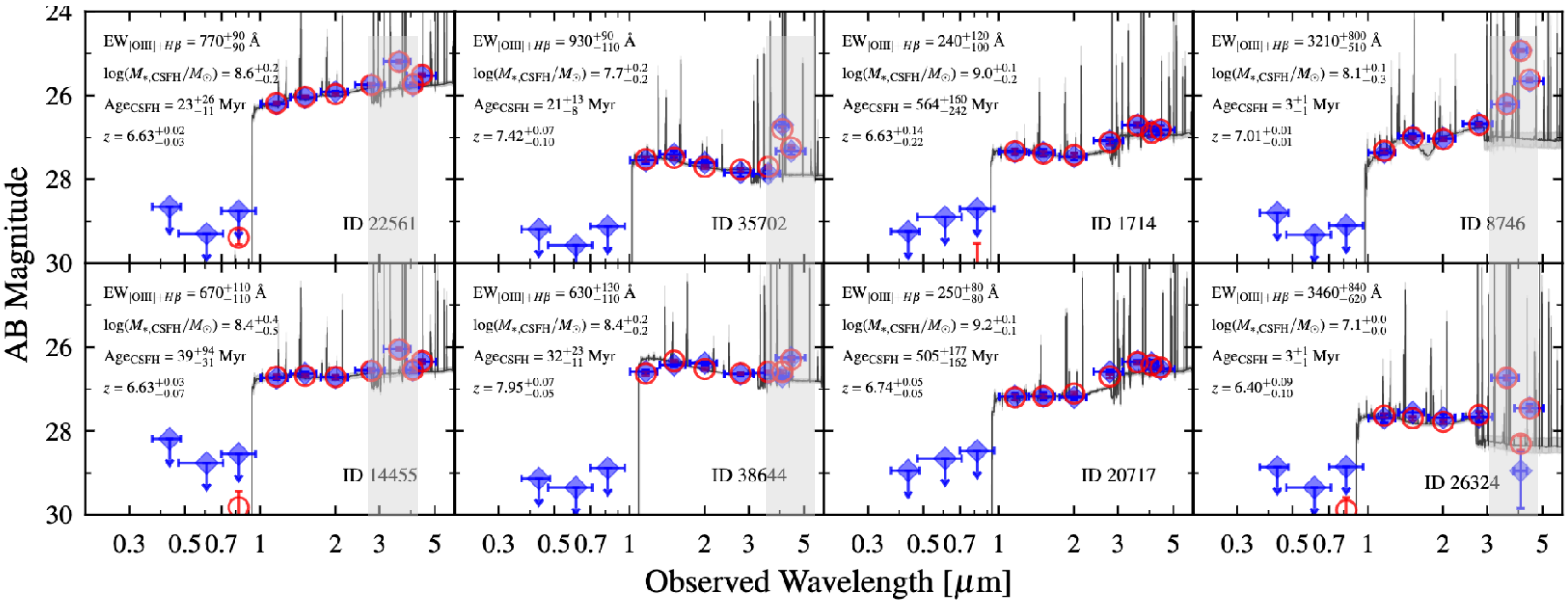
Endsley, Stark+2022d



- We characterized NIRCam SEDs of 118 z~6.5-8 galaxies in CEERS ERS imaging.
- Range of SED shapes present, with young and old stellar populations seen in early galaxies.

NIRCam SEDs of z~6.5-8 Galaxies in CEERS

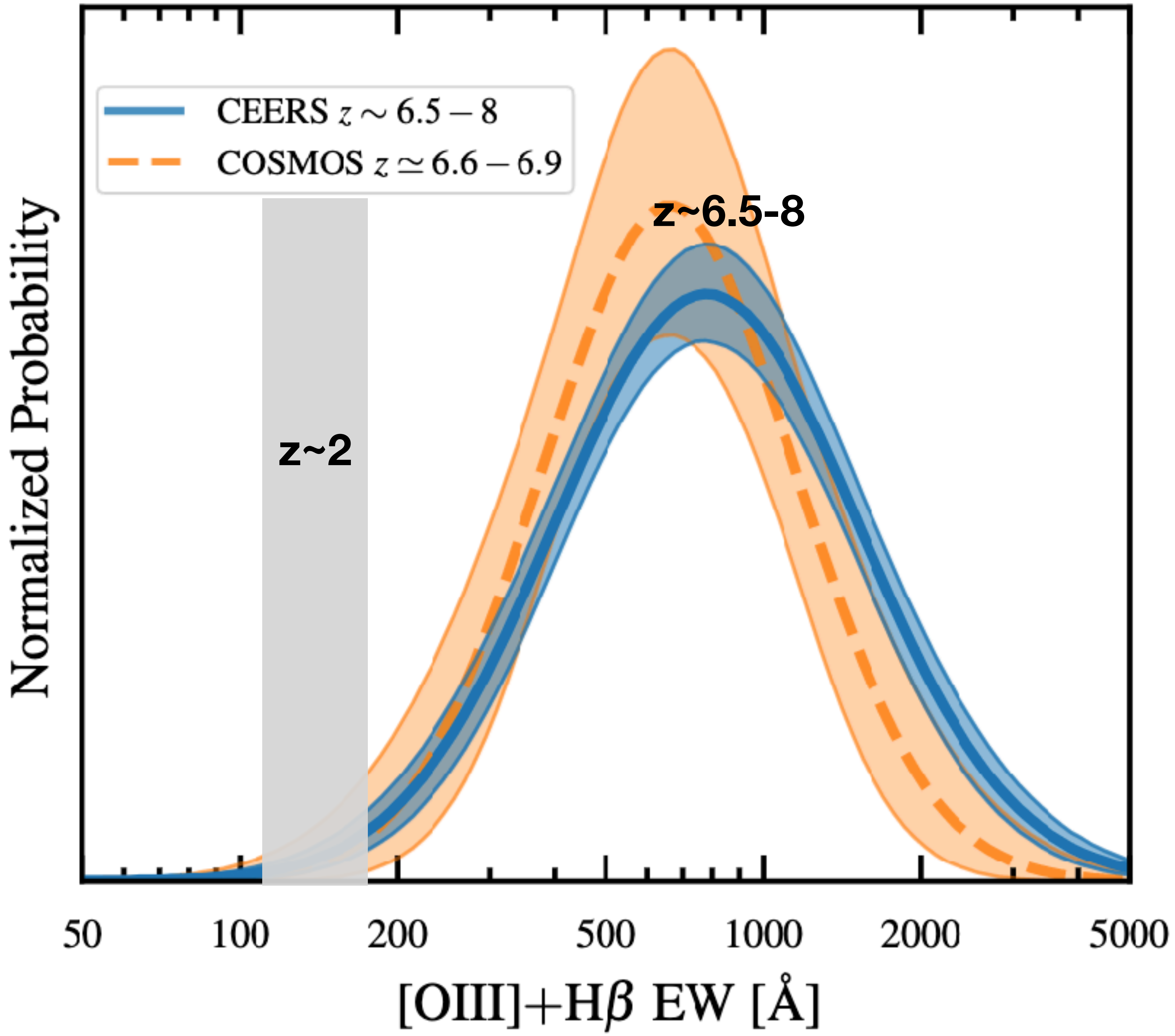
Endsley, Stark+2022d



- We characterized NIRCam SEDs of 118 z~6.5-8 galaxies in CEERS ERS imaging.
- Range of SED shapes present, with young and old stellar populations seen in early galaxies.
- But the majority show the signature of **large EW [OIII],** a sign of young stellar populations.

But the majority show very young stellar populations

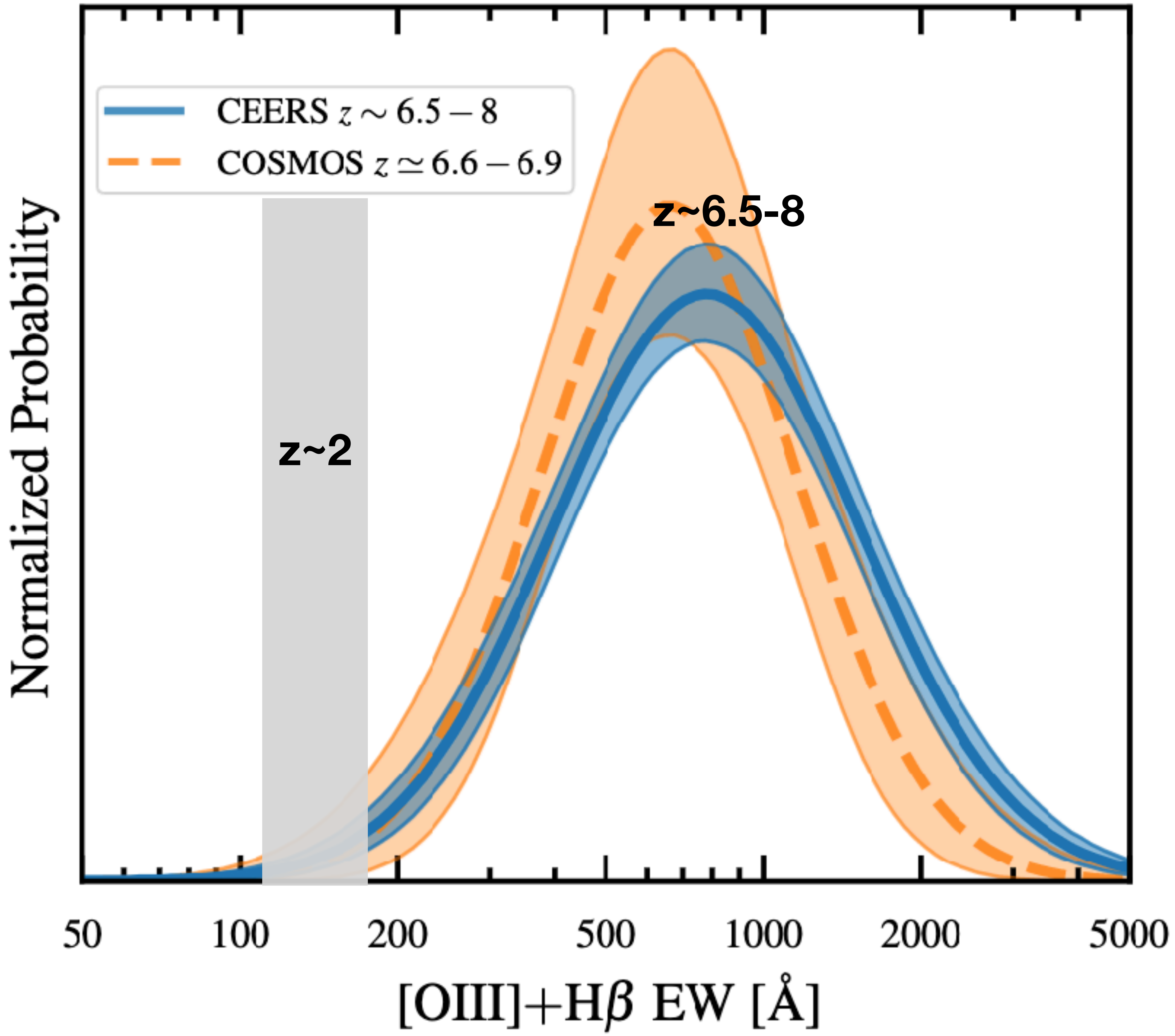
Endsley, Stark+ 2022d



- [OIII]+Hβ EW distribution has median (780Å) — almost never seen at z~2-3.
- Suggests very young stellar populations (~1-20 Myr of constant star formation) are dominating the entire SED at z~6.5-8.

But the majority show very young stellar populations

Endsley, Stark+ 2022d



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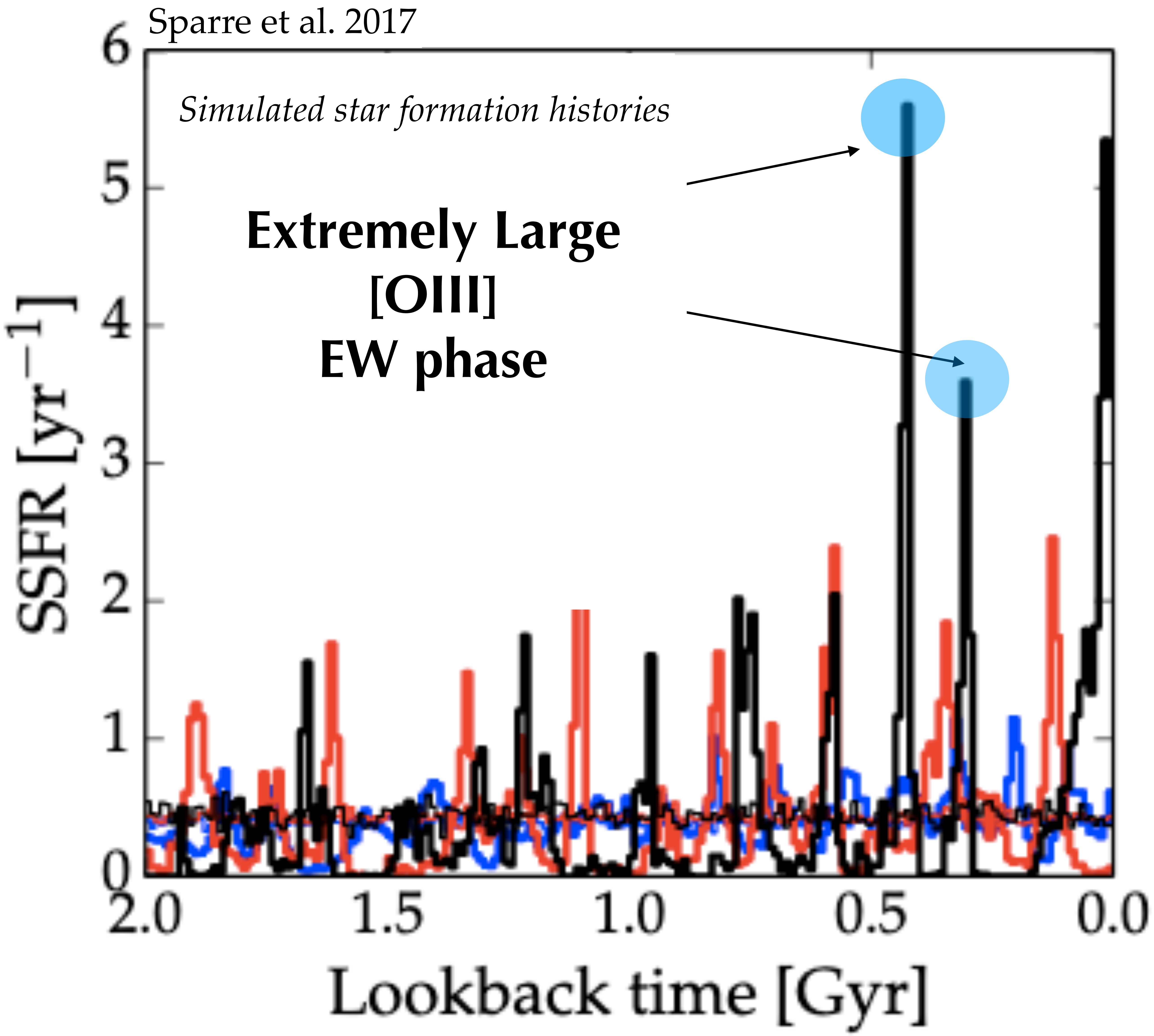
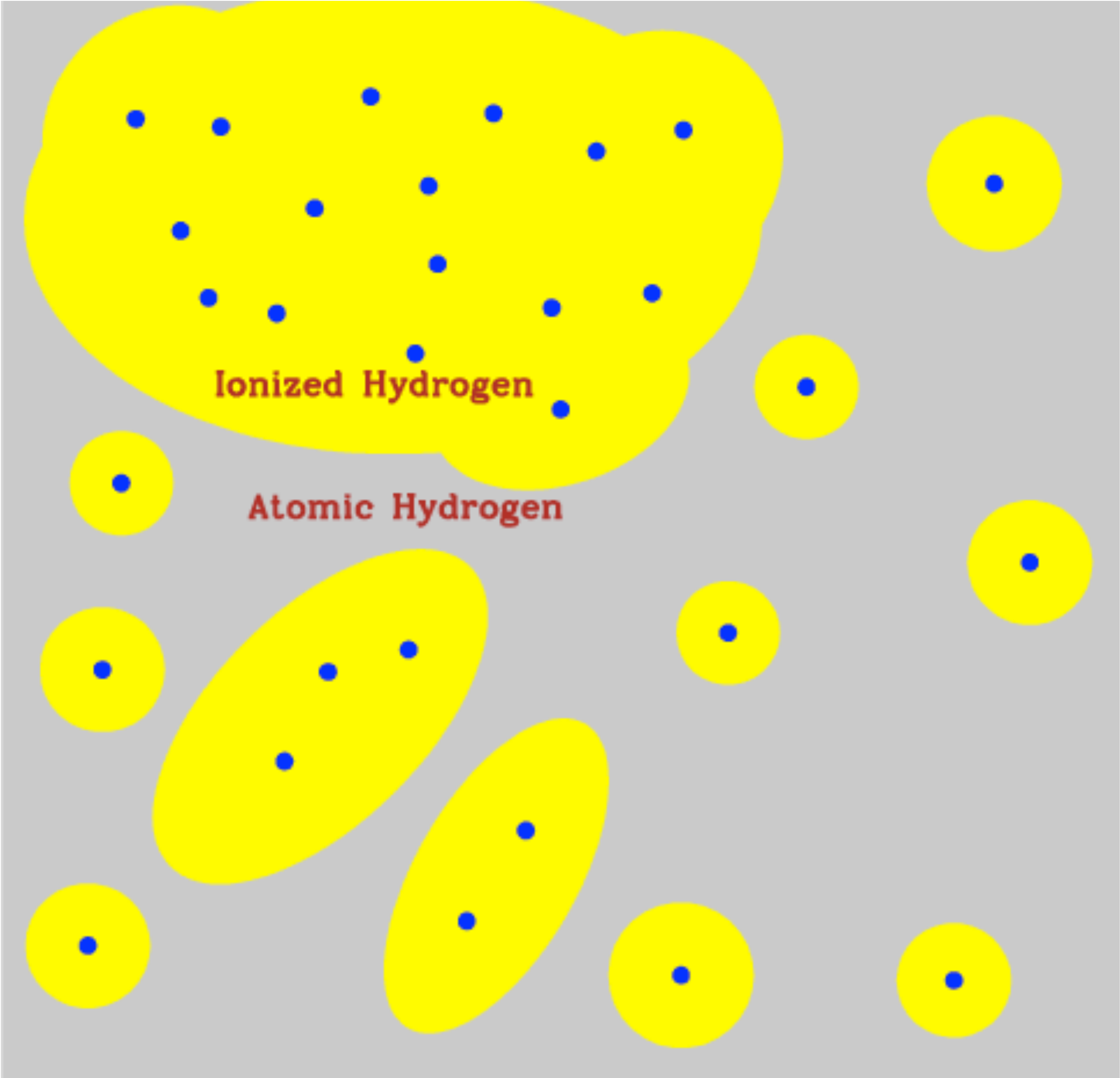
- Suggests very young stellar populations (~1-20 Myr of constant star formation) are dominating the entire SED at z~6.5-8.
- How do we explain such young ages being so common when universe is 700-900 Myr old?

How do we explain such young stellar populations?



- Very young SEDs are expected in galaxies that are in the midst of a recent upturn or burst of star formation.
- Evolution in SEDs suggests **shift toward very bursty star formation as we move from z~2 to z~7,** with some indications that bursts are more prominent at low masses (Endsley+22d).
- This has significant implications for how galaxies are able to achieve reionization!

Reionization with Bursty Star Formation



credit: Rennan Barkana

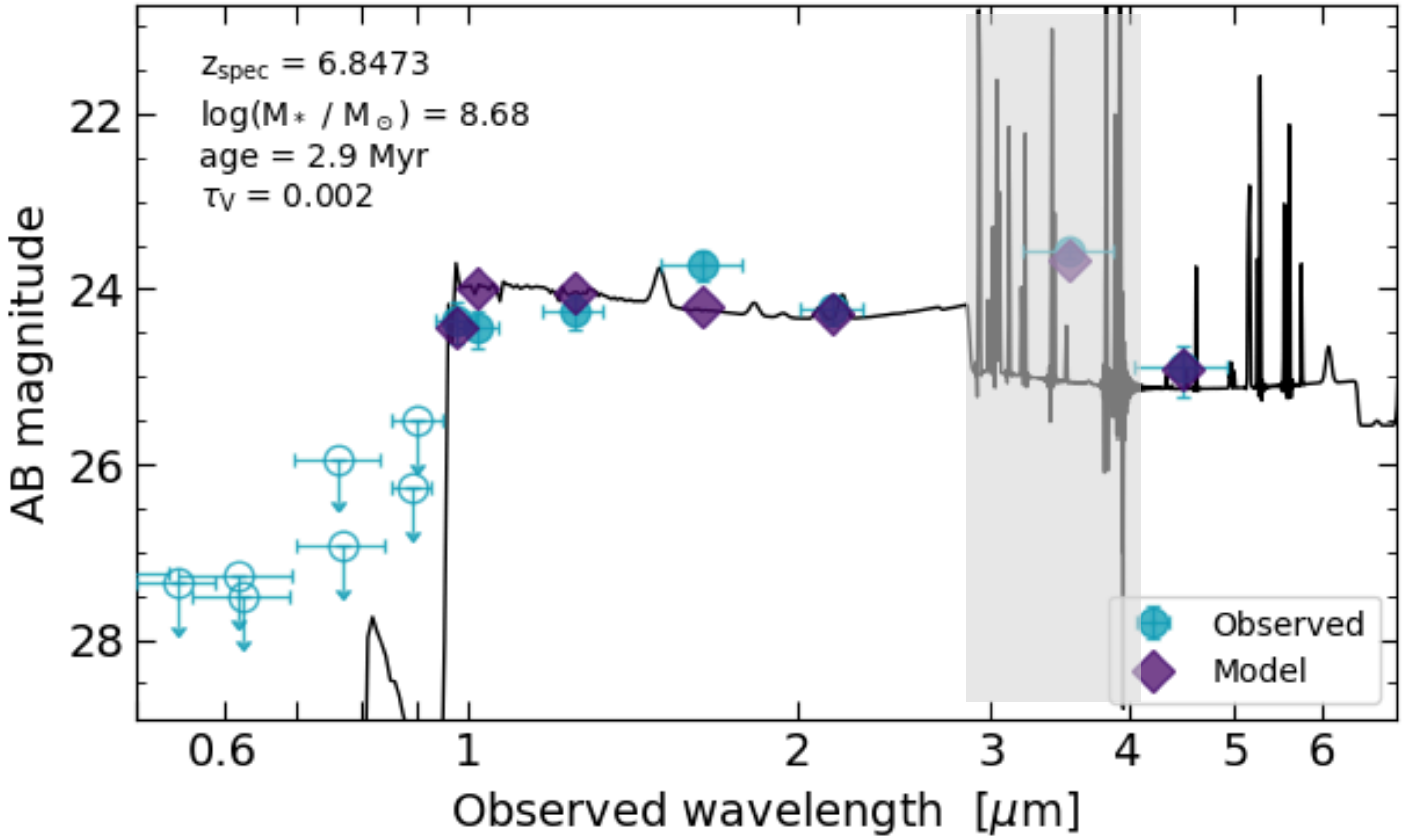
- How do galaxies build large bubbles if their star formation timescales are only a few Myr?

- Related question: were z~6.5-8 galaxies really not forming stars a few hundred Myr earlier at z>10?

- This motivates investigation of whether there could be significant star formation **before** the burst that we have missed.

Can we fit Old Stellar Populations in Bursty Galaxies?

Topping, Stark+2022, Whitler, Stark+2023b



- Consider REBELS-39, a large [OIII]+H-beta EW galaxy at z~7 with ALMA dust continuum and [CII] measurements (Bouwens+22, Topping+22).

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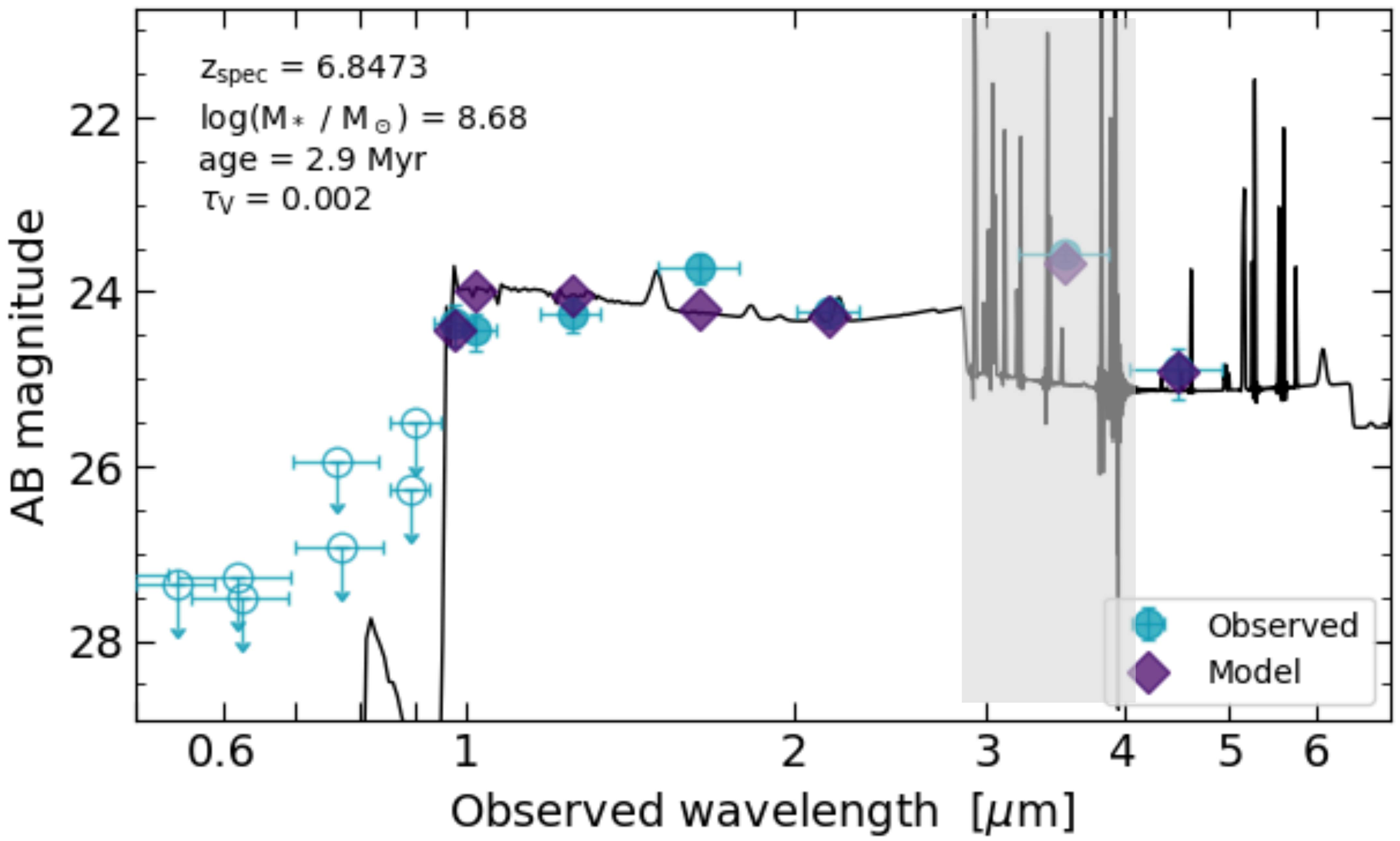
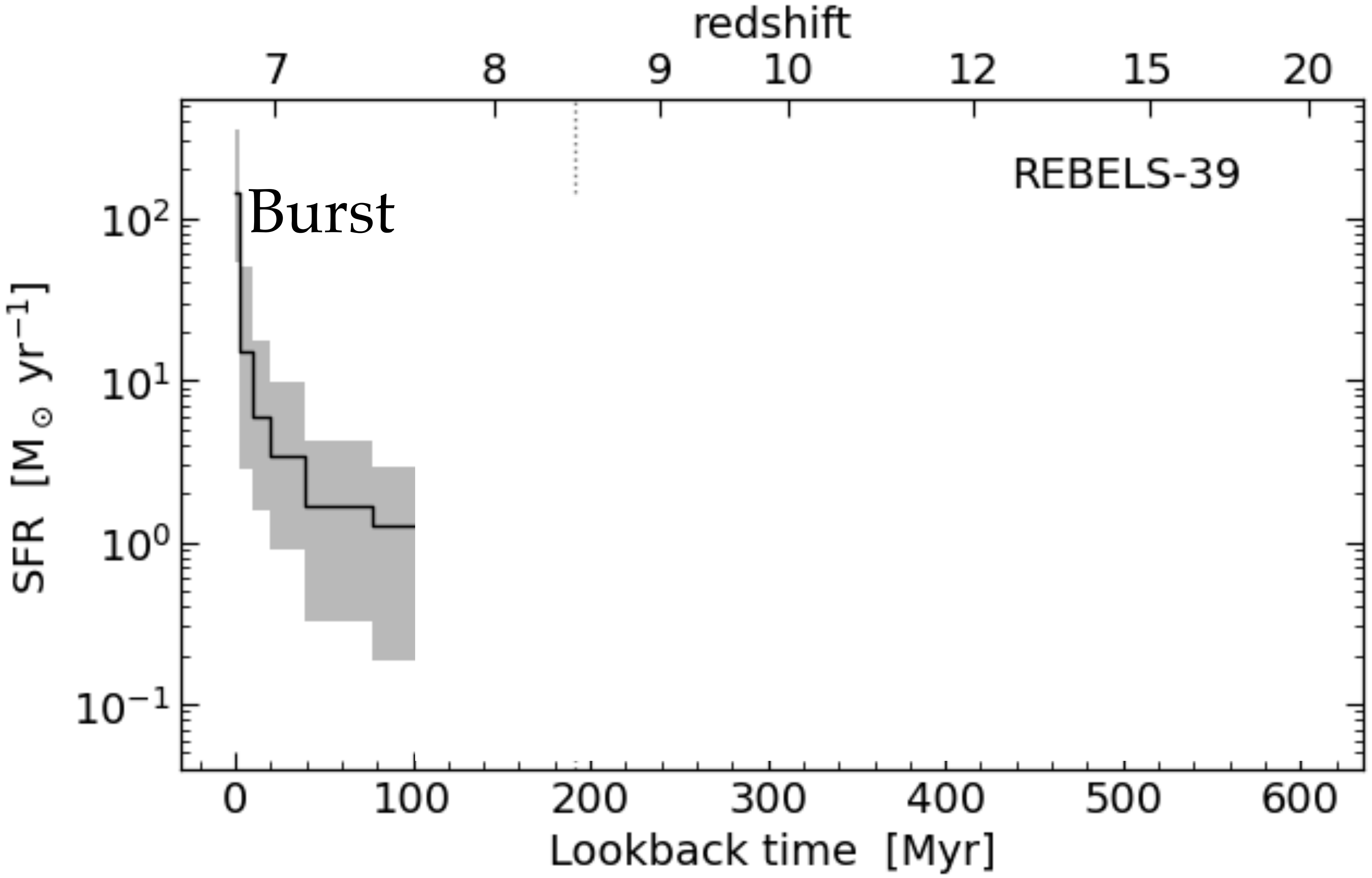
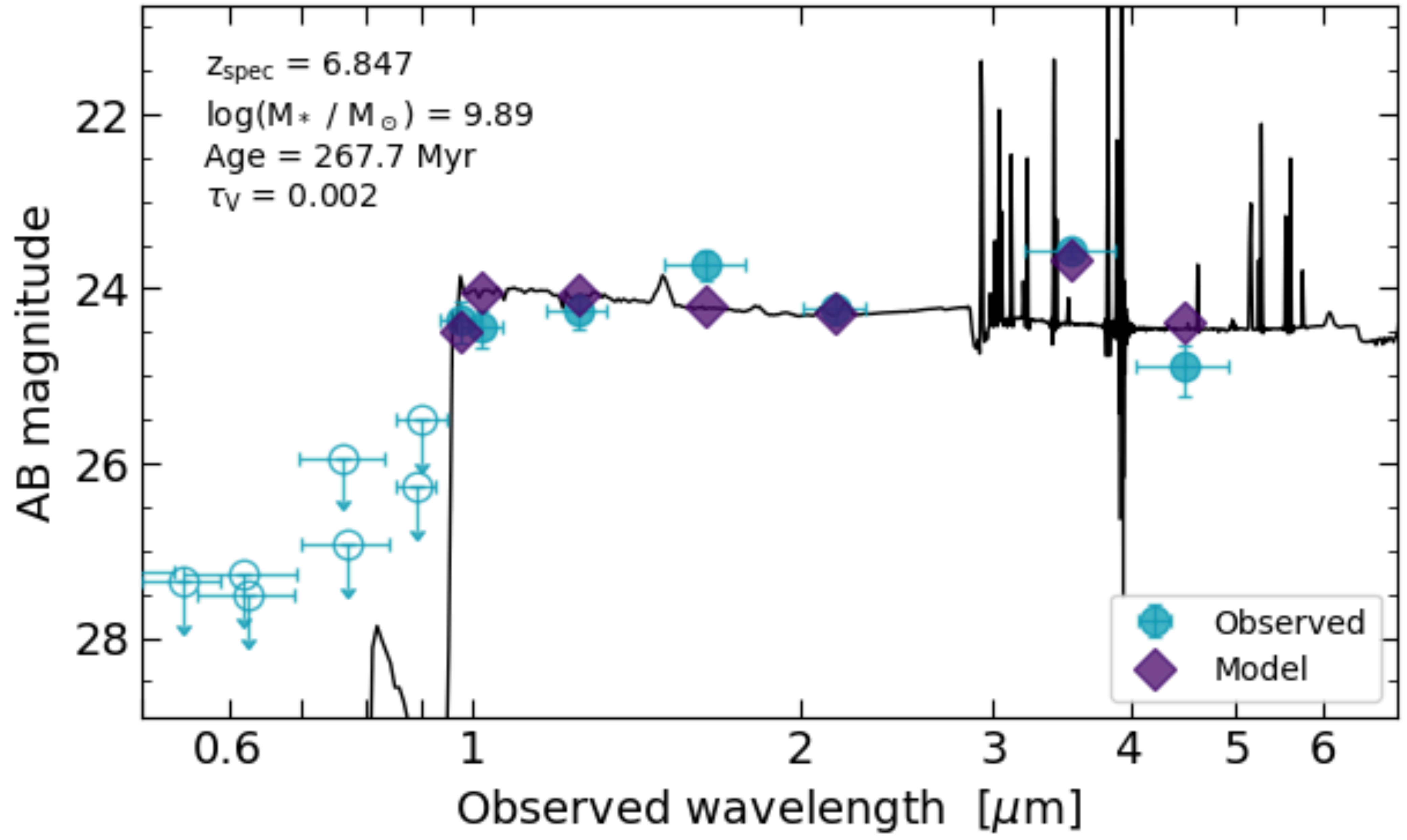


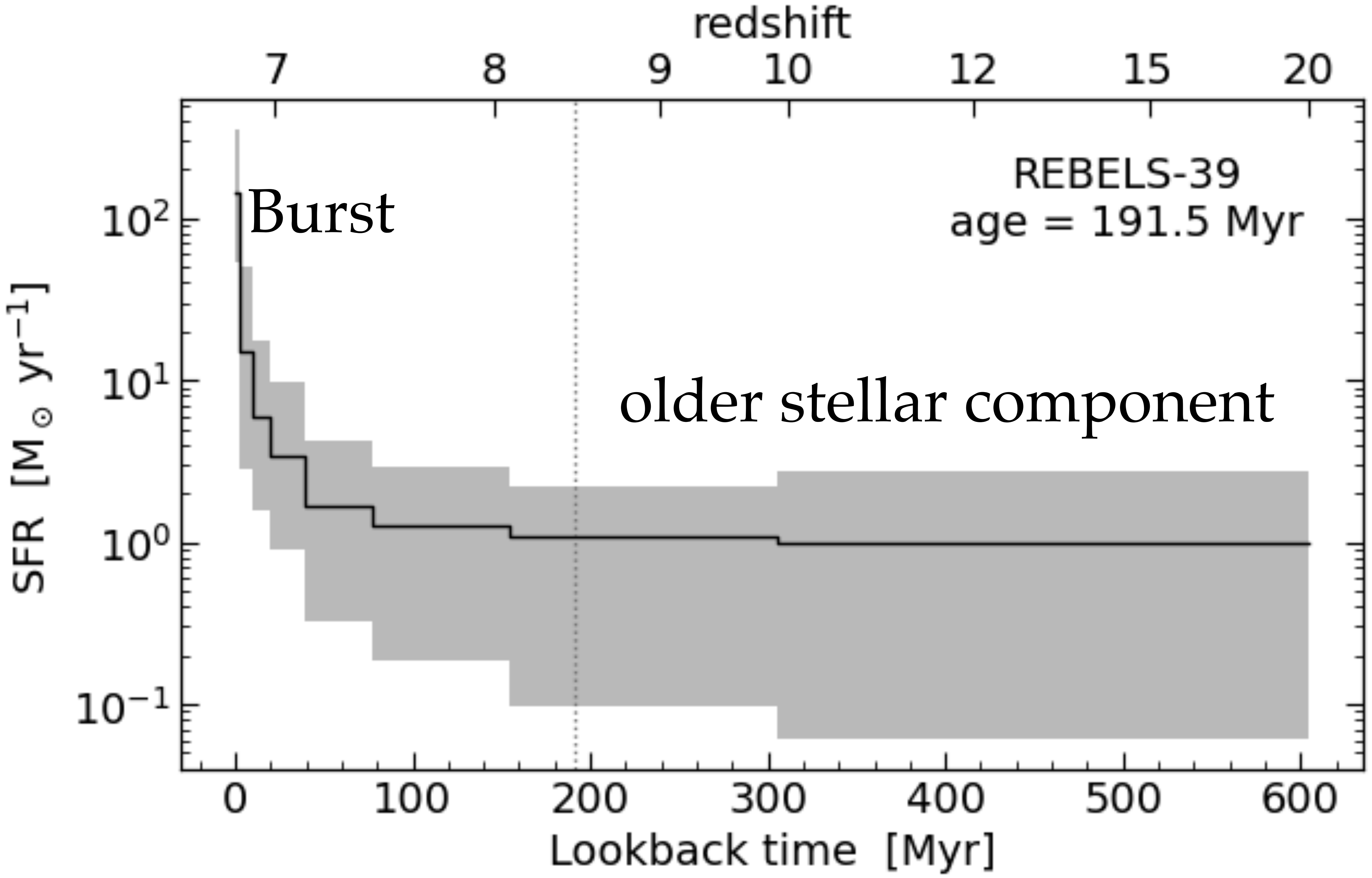


- Consider REBELS-39, a large [OIII]+H-beta EW galaxy at z~7 with ALMA dust continuum and [CII] measurements (Bouwens+22, Topping+22).
- Reproducing the [OIII]+H-beta EW requires very young stellar populations formed in a recent burst. Mass formed during the burst is very small (log $M^*/M_\odot$ ~ 8.68).

Can we fit Old Stellar Populations in Bursty Galaxies?

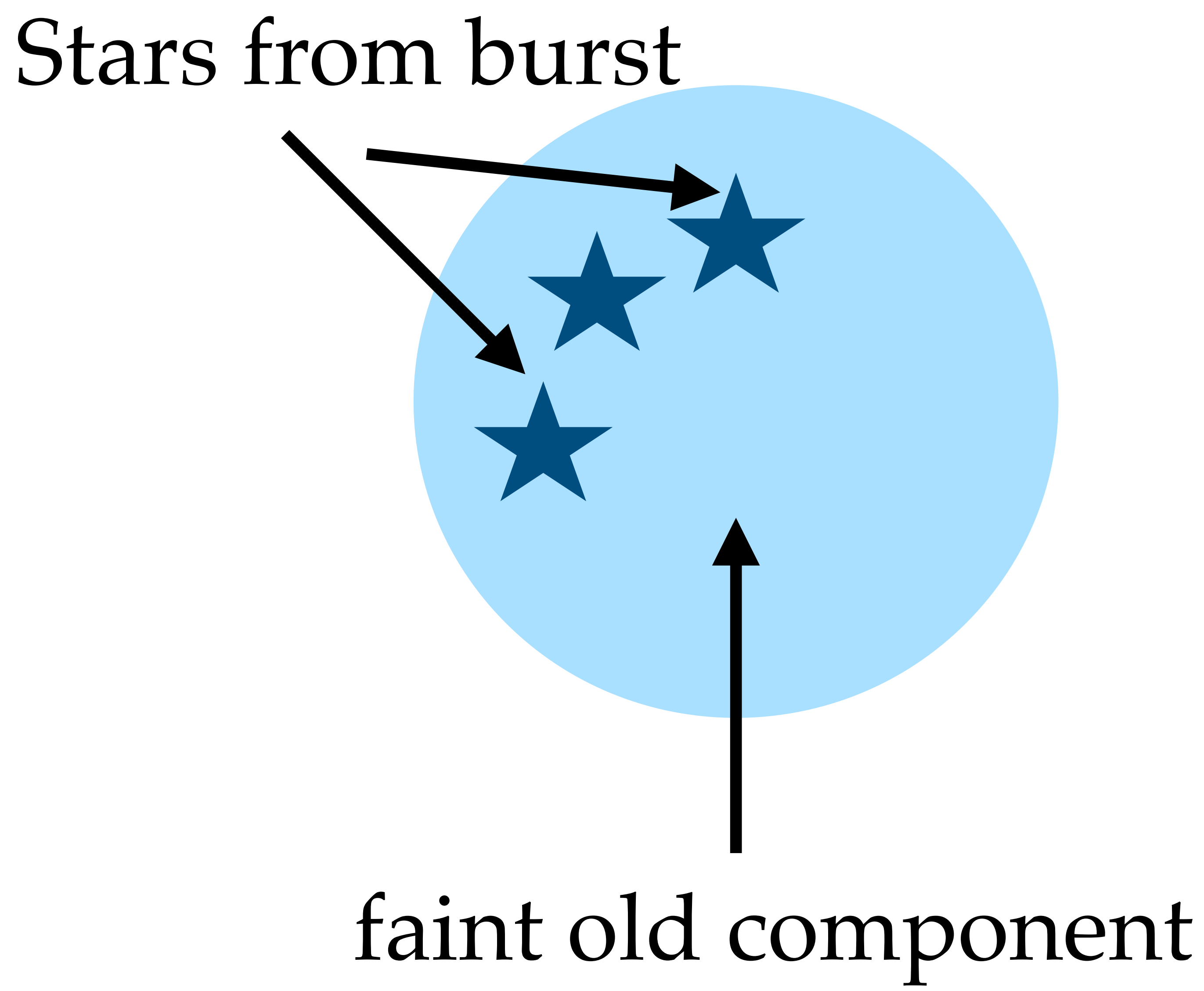
Topping, Stark+2022, Whitler, Stark+2023b





- But the SED of REBELS-39 can be fit equally well with an older stellar component — ***can increase the derived stellar mass (and age) by an order of magnitude*** (log M*/M$_\odot$ ~ 9.89).

The Outshining Problem in the Reionization Era



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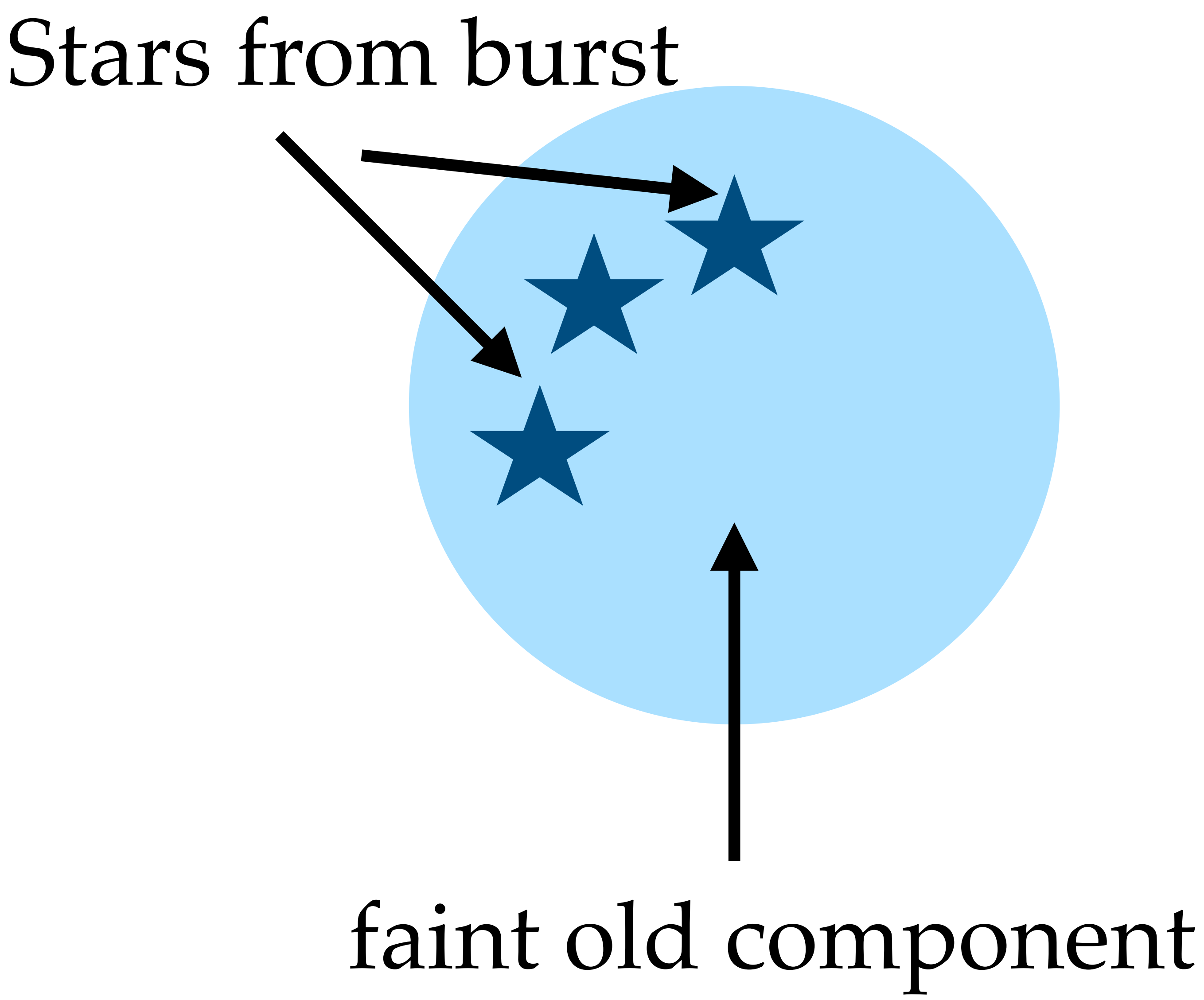
The Outshining Problem in the Reionization Era



- This is the classic outshining problem (i.e., Leja+2018).
- Our view in the UV and optical is dominated by the burst of star formation.
- We may be missing the light from the dominant older population — thereby dramatically underestimating total ages and masses (and integrated contribution to bubble growth).

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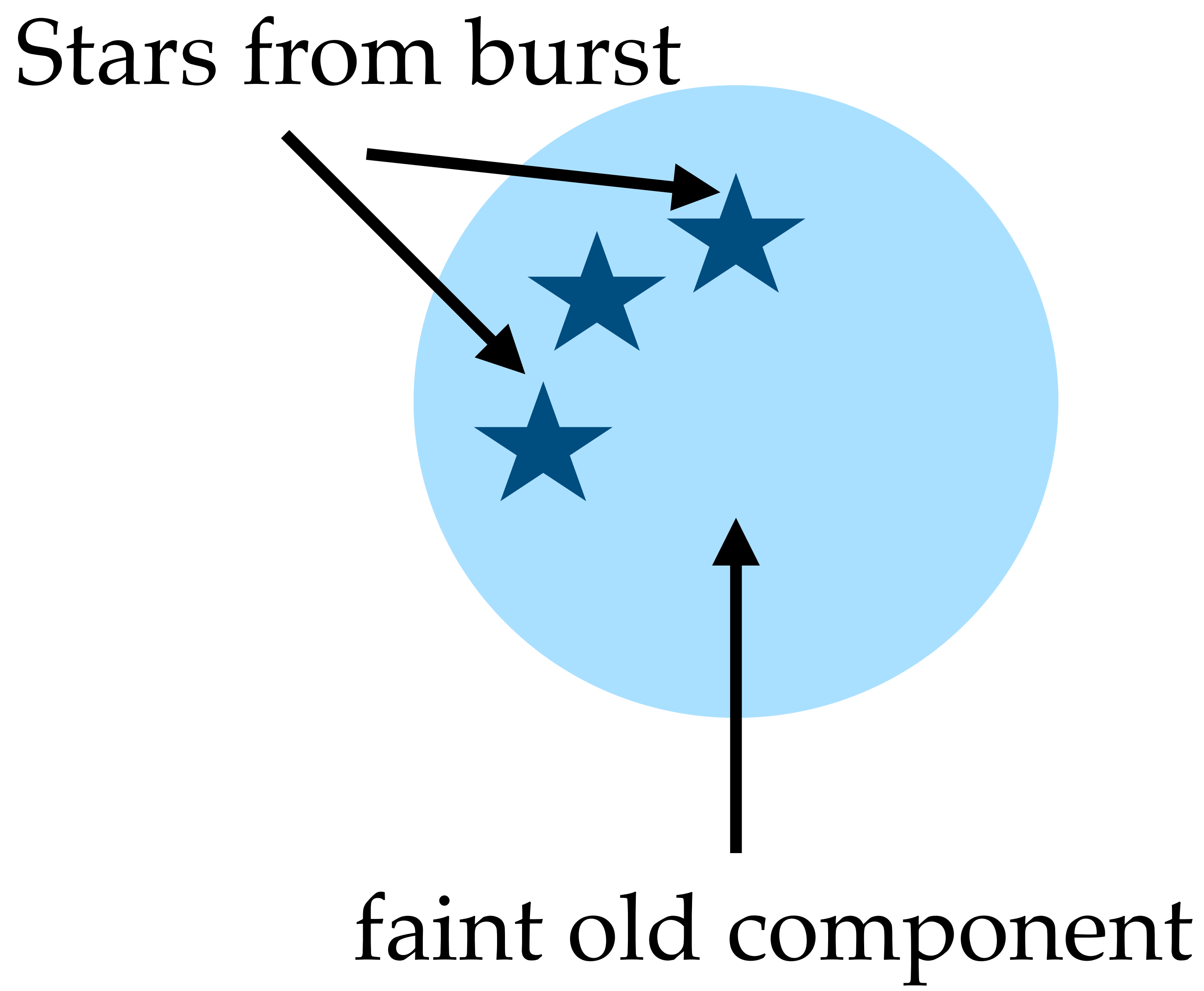

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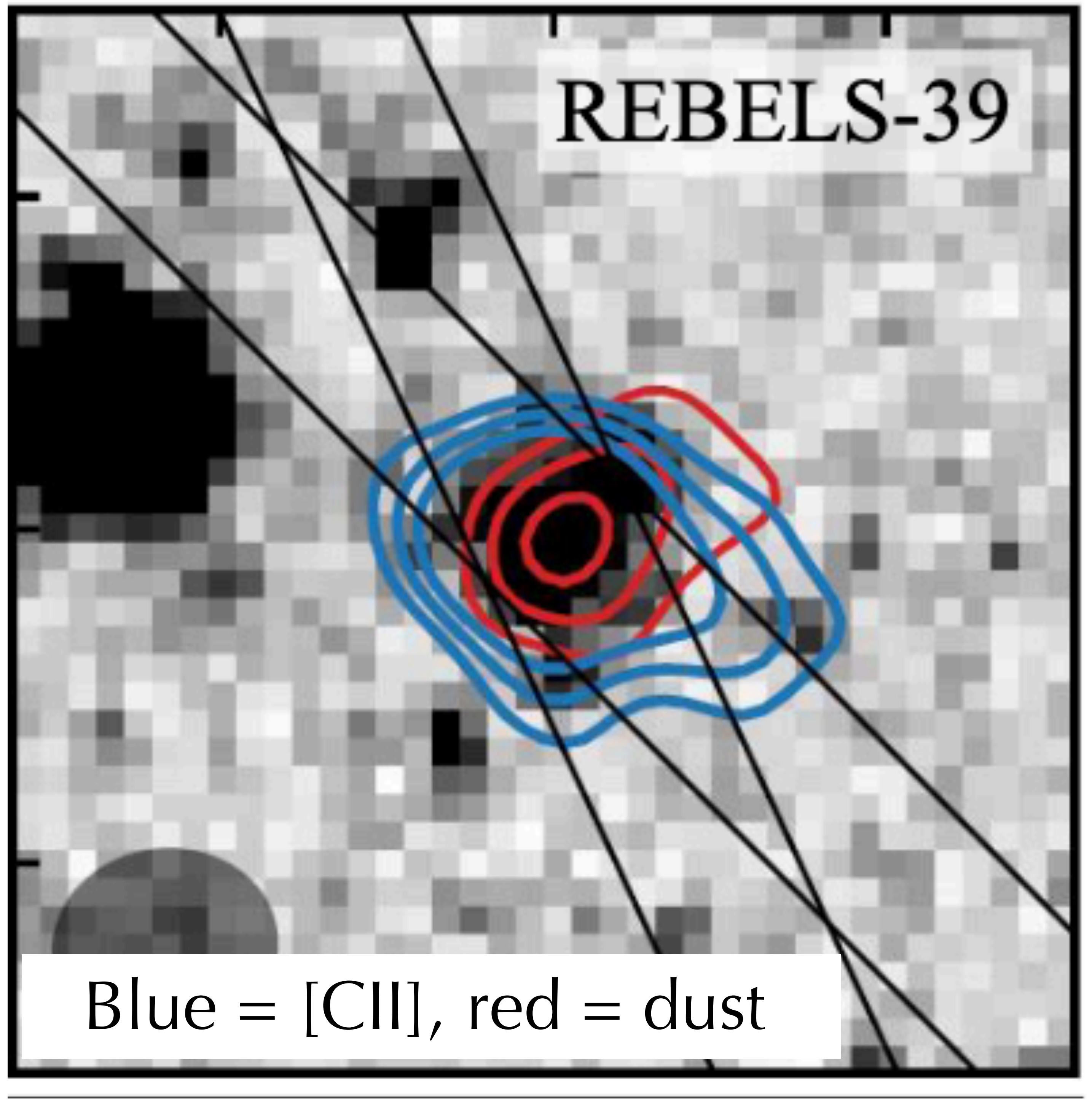
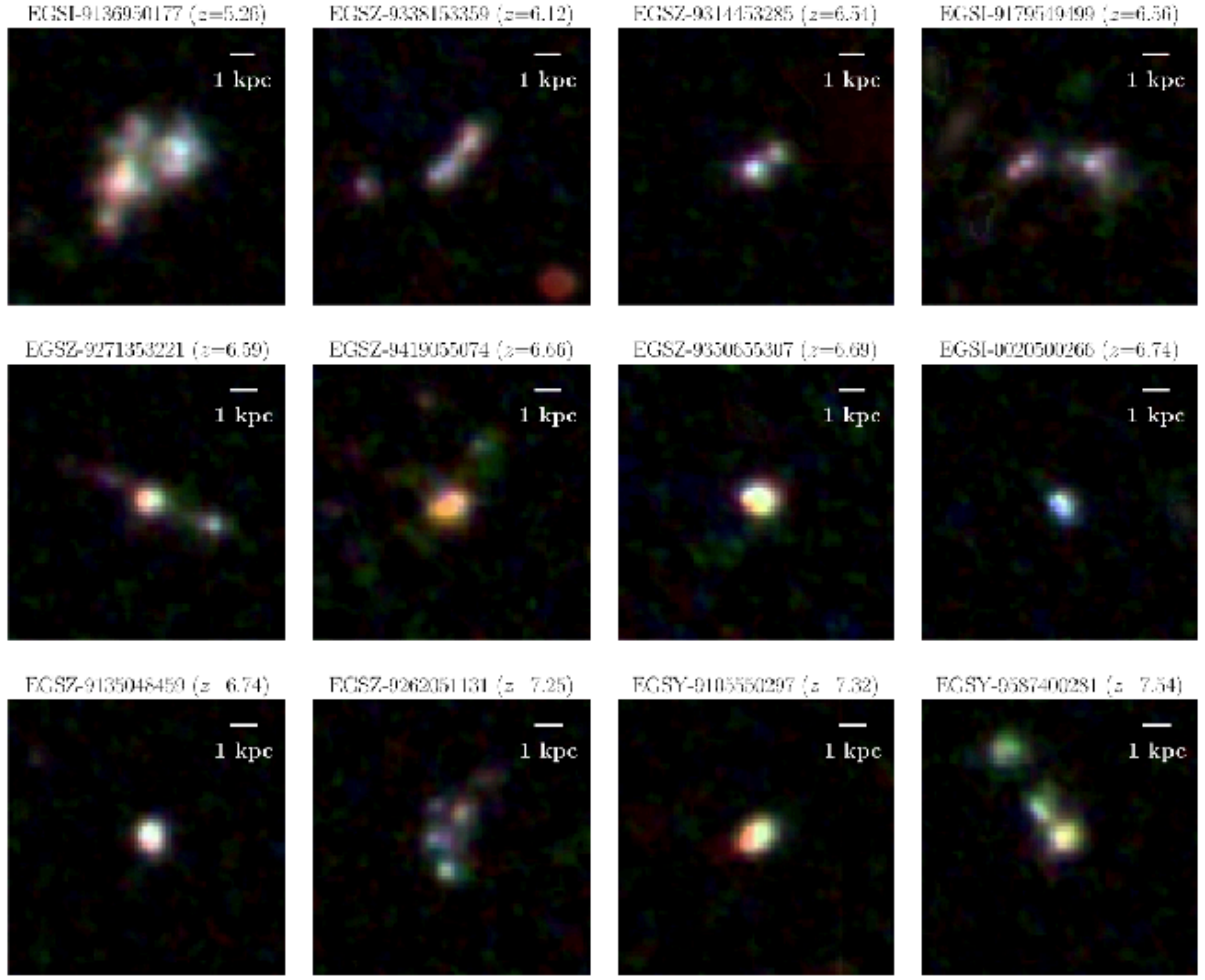
- Our view in the UV and optical is dominated by the burst of star formation.
- We may be missing the light from the dominant older population — thereby dramatically underestimating total ages and masses (and integrated contribution to bubble growth).
- One approach: move to longer wavelengths with MIRI where older component may come into view.
- Another approach: we may expect to resolve out the faint old component at longer wavelengths with JWST (old stars) or ALMA (ISM).

The Way Forward: Spatially Resolving Bursty Star Formation

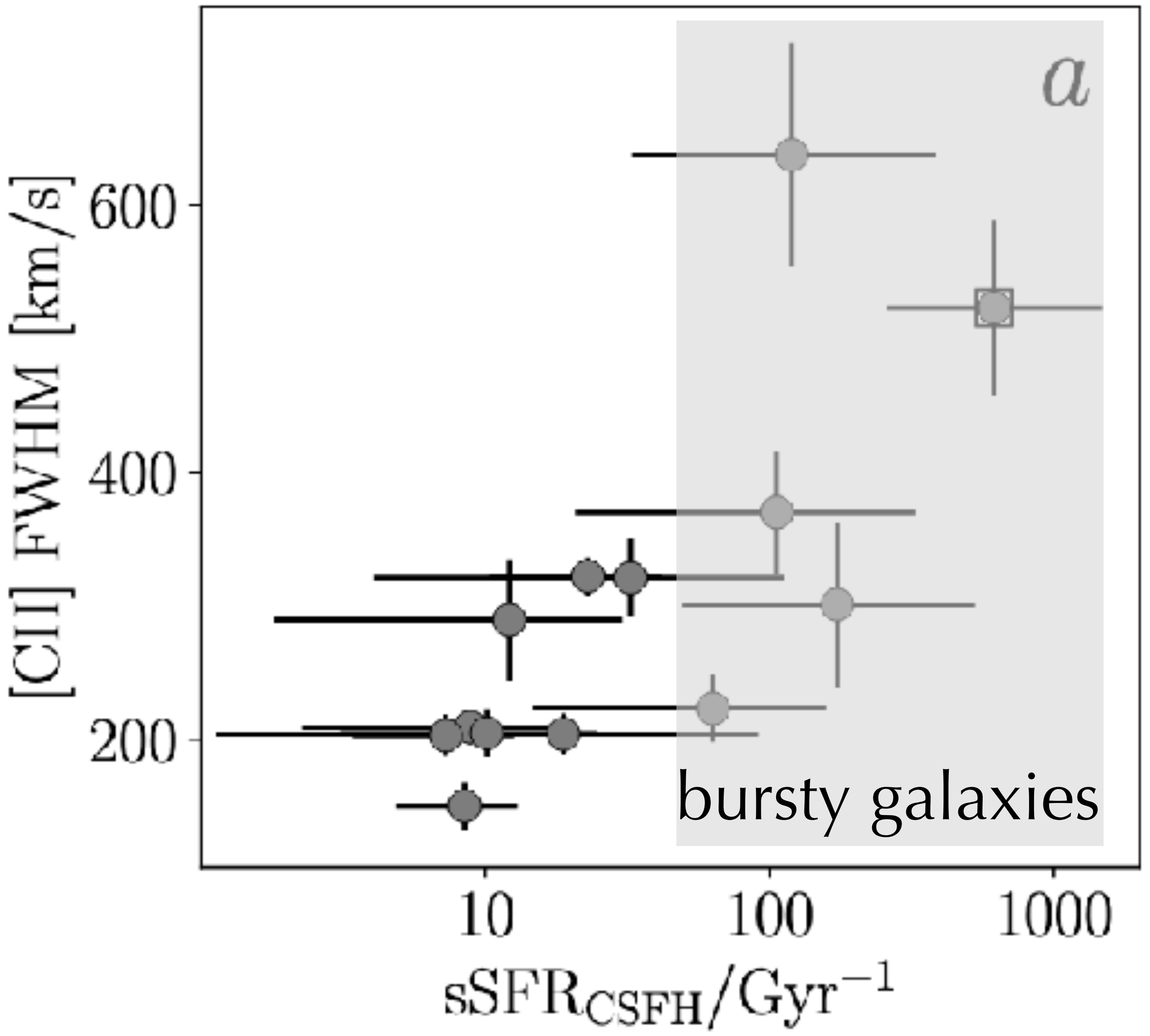
Endsley, Stark+2022e



Chen, Stark+2023a



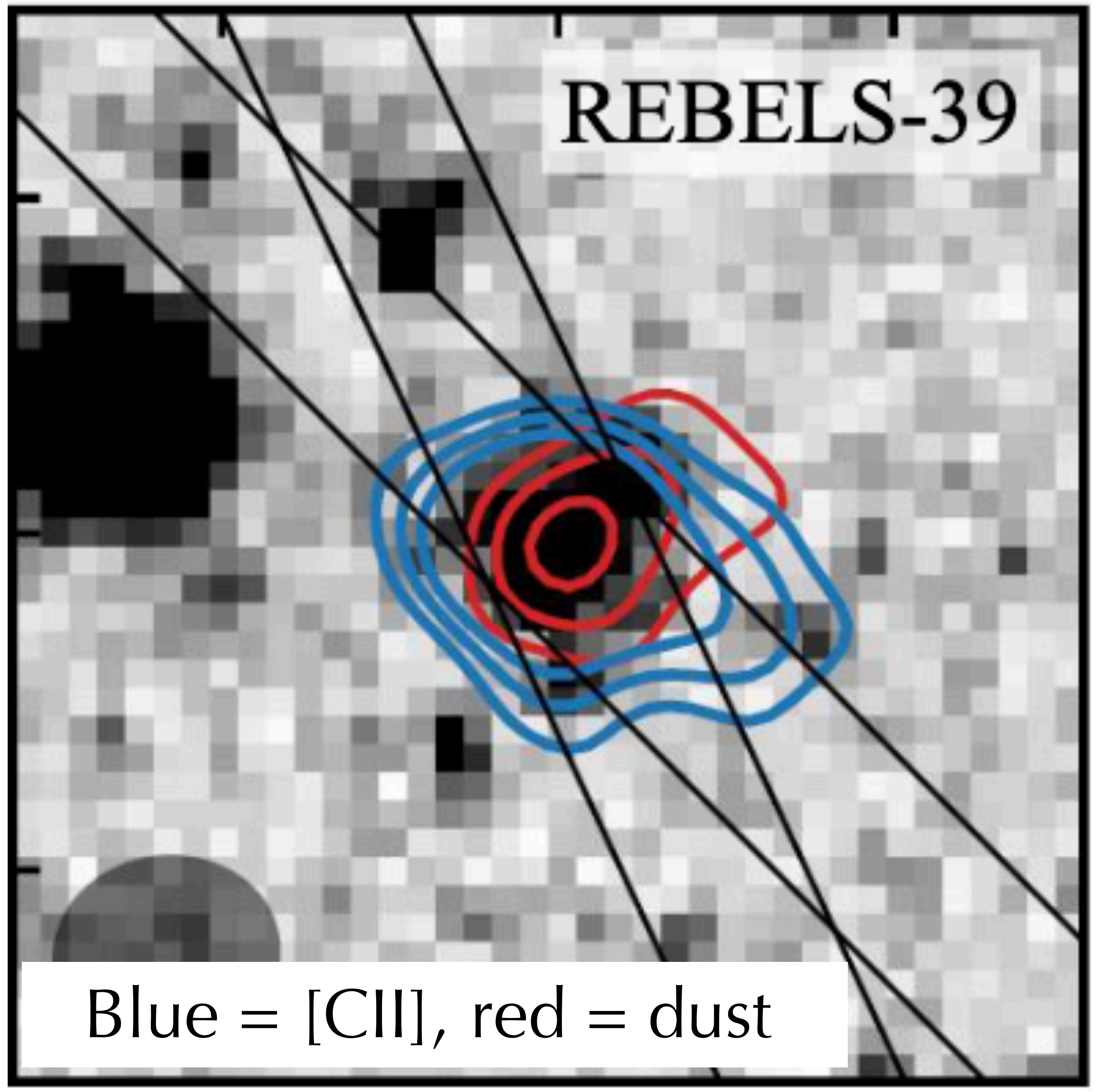
Topping, Stark+22a



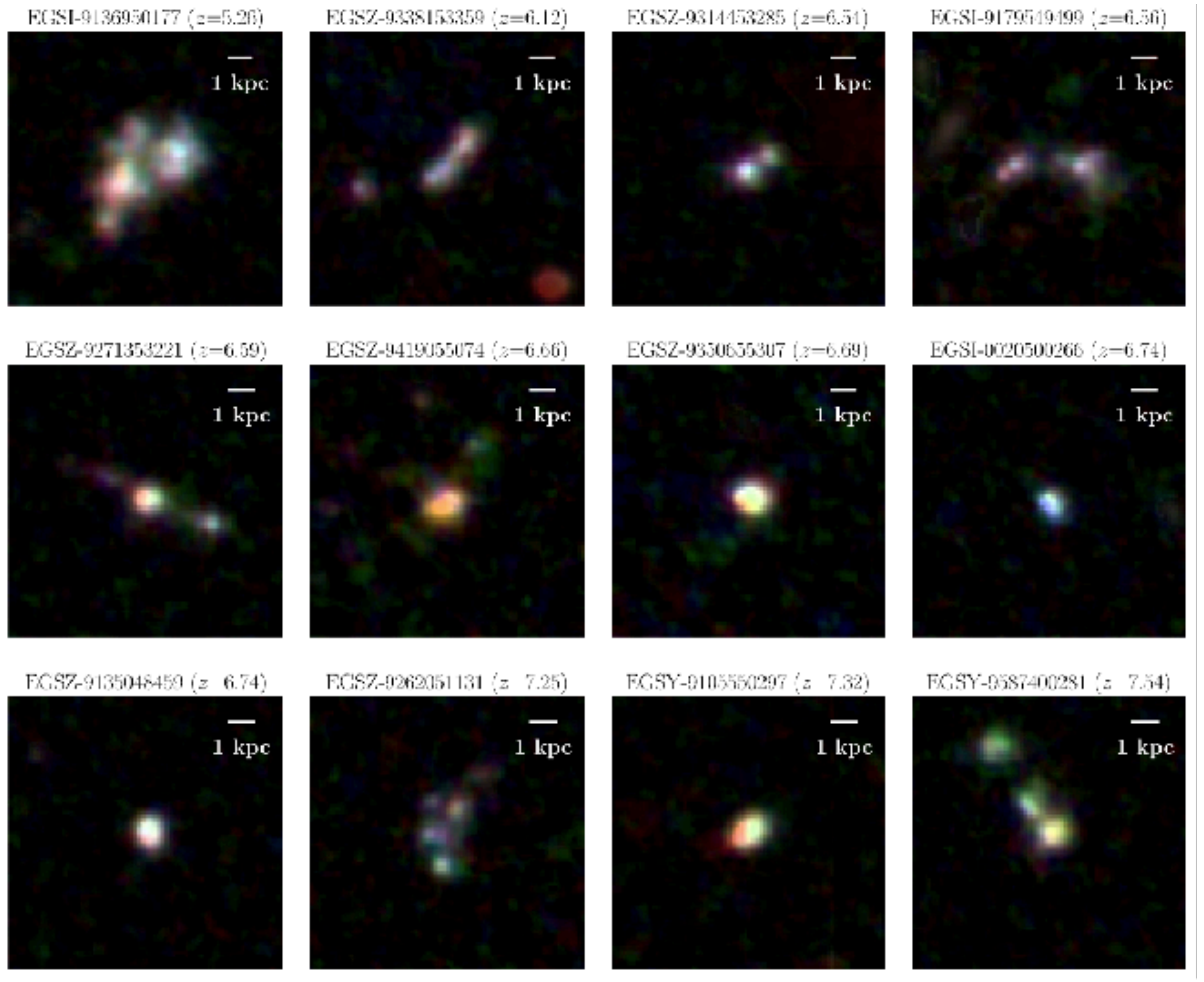
- ALMA and JWST are now providing maps of old/young stars and ISM reservoirs in bursts at z>6.

The Way Forward: Spatially Resolving Bursty Star Formation

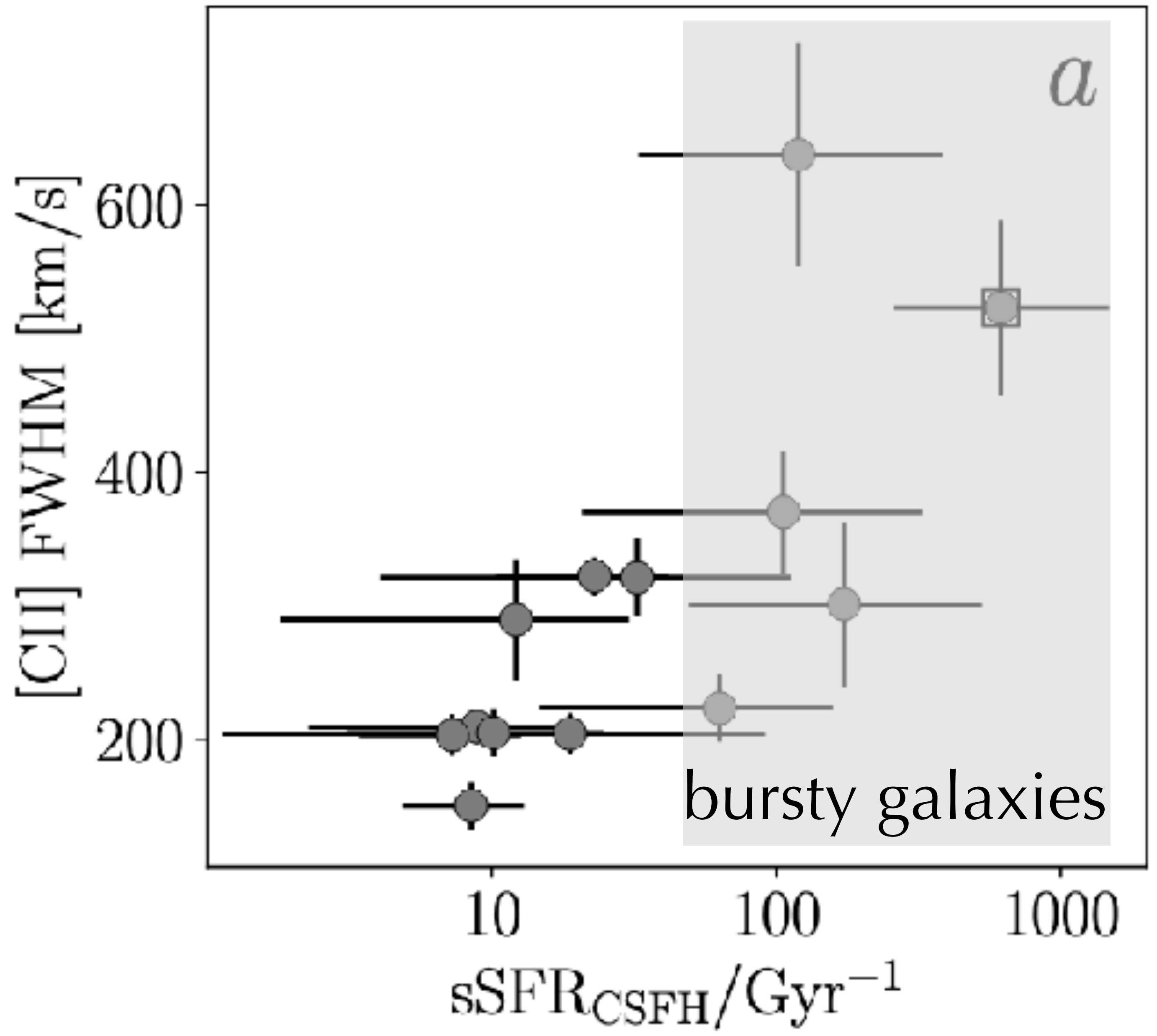
Endsley, Stark+2022e



Chen, Stark+2023a



Topping, Stark+22a



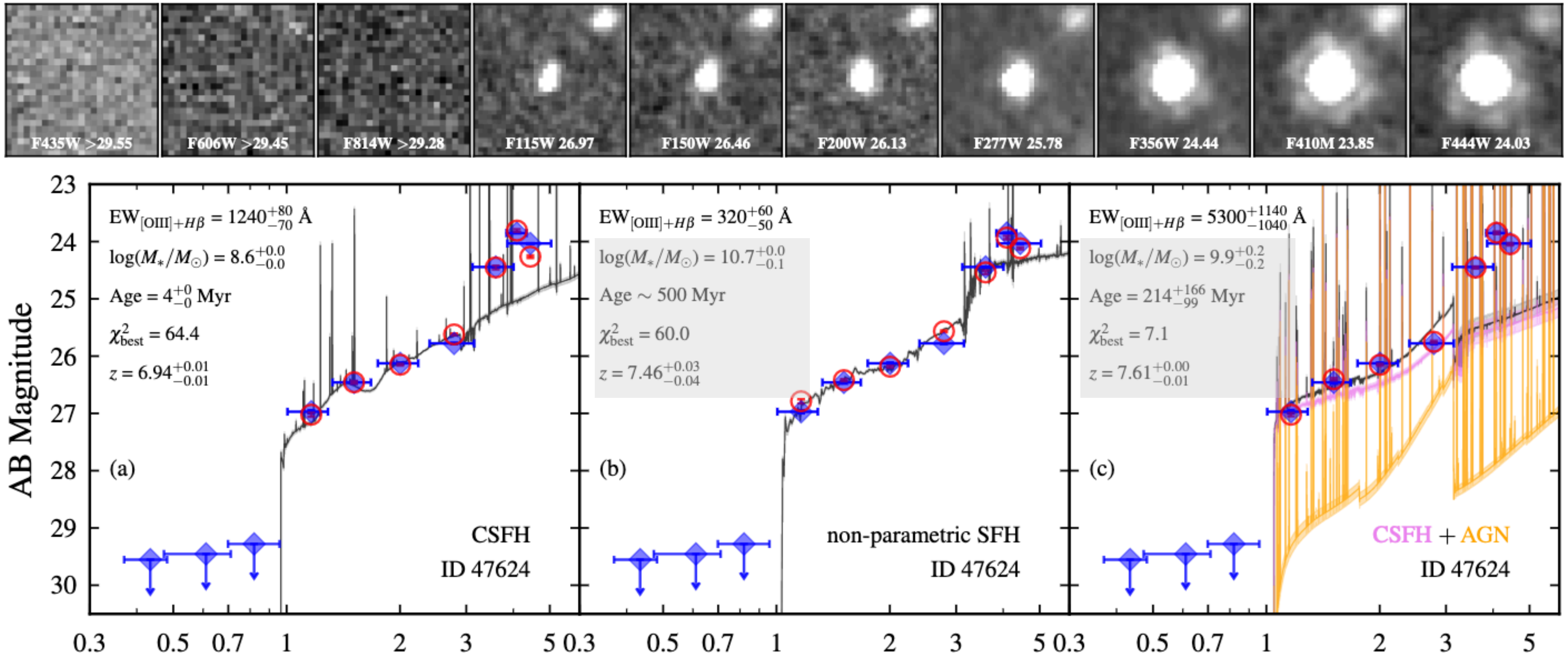
- ALMA and JWST are now providing maps of old/young stars and ISM reservoirs in bursts at z>6.
- Results suggest that young bursts sit in galaxies with very large ISM reservoirs, significant dust luminosities, and very large gravitational potentials: all consistent with galaxies being much more massive than previously thought (Topping+22).
- Leading to significant revisions in stellar masses and star formation timescales for bubble growth.

Summary

- New era of Lyα spectroscopy with JWST and wide-field ground-based spectrographs. Lyα detections now extending out to z~9-11, opening study of early stages of reionization.
- Large ionized bubble candidates are now being identified across wide fields, allowing the process of reionization to be directly studied on a local level.
- Potential signature of large ionized bubble at z~9, which would be unexpected given large neutral fraction thought to be in place at that redshift. If confirmed, may point to more early star formation at z>9 than previously thought.
- Reionization-era galaxies appear to have bursty star formation histories, leading to very young stellar population ages.
- These bursts reflect a distinct shift compared to star formation histories at z~2, with significant implications for how galaxies achieve reionization.
- New ALMA+JWST studies are needed to assess whether the burst outshines a dominant older stellar component, which would increase inferred mass+age by up to 10x.

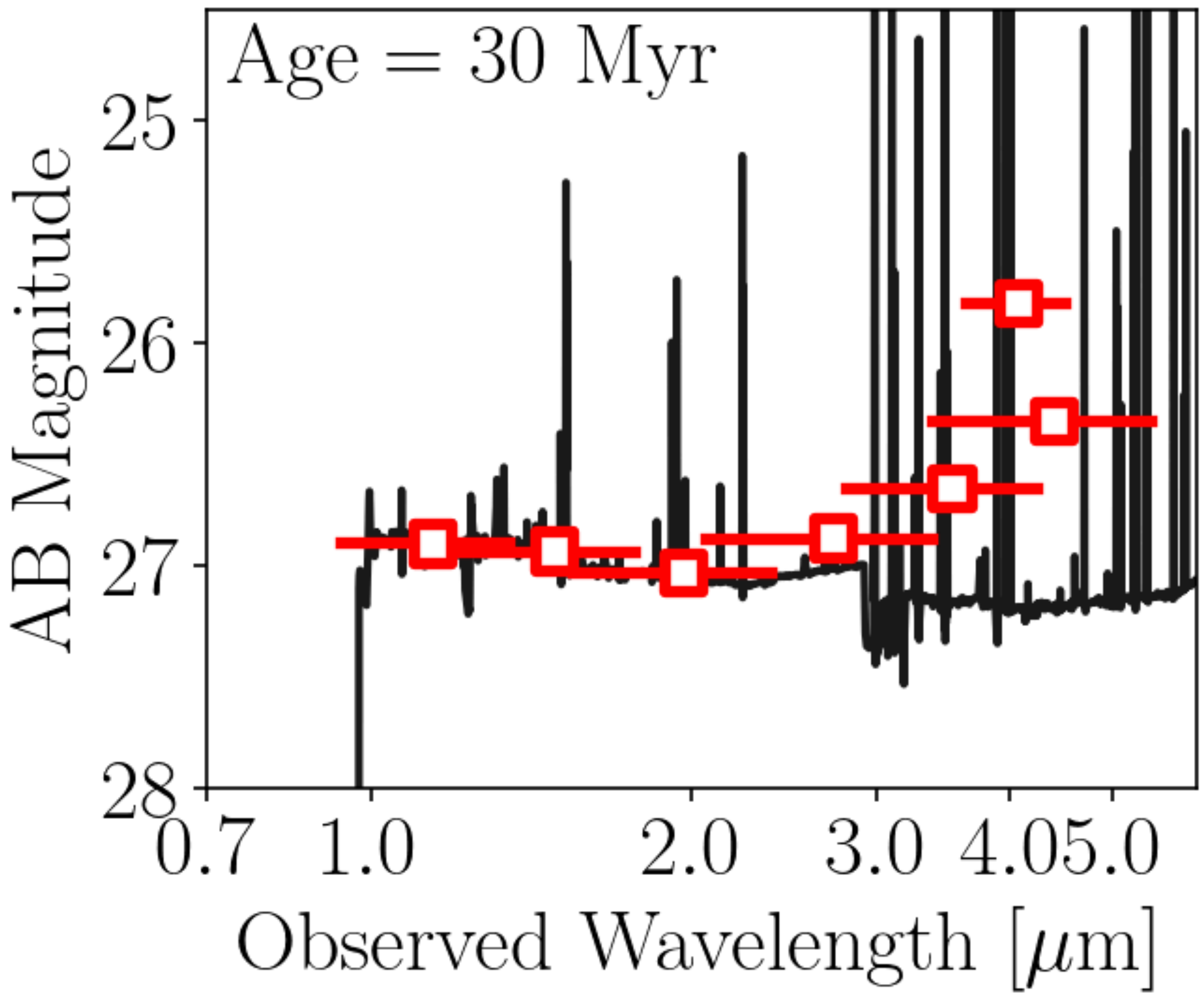
Massive Galaxies now appearing in JWST Datasets

Endsley, Stark+2022d



- Once old component accounted for, some galaxies potentially look *very* massive at $z>7$.
- New class of very compact (<150 pc) high mass galaxies with $\sim 10^{10}\,M_\odot$ in JWST imaging.
- Indicative of significant past star formation at $z\sim10$-15, with potential AGN signatures.

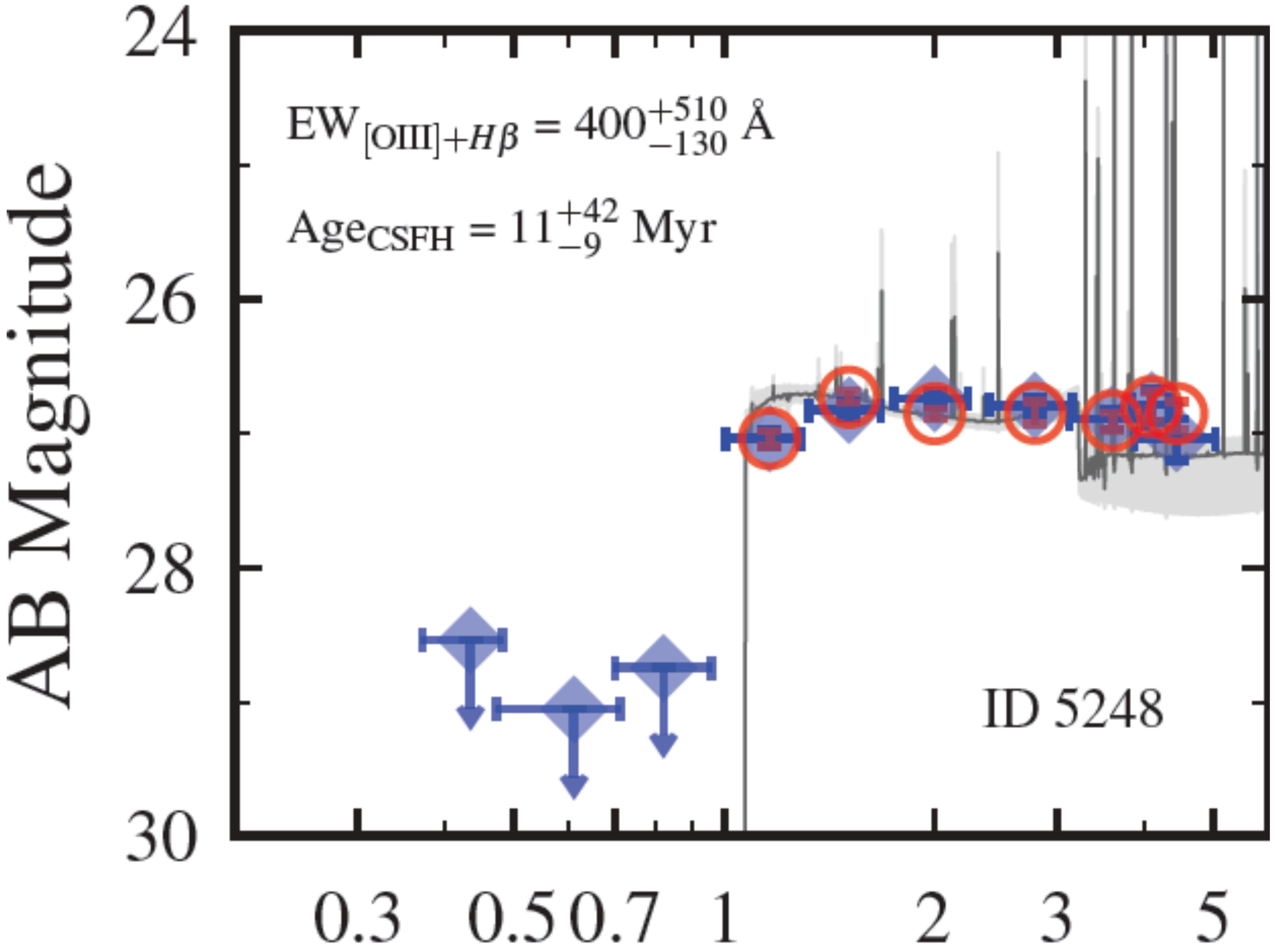
Surprise with JWST/NIRCam Imaging: Weak Emission Lines



The majority of NIRCam SEDs at z~6-8 have indications of strong emission lines.

Surprise with JWST/NIRCam Imaging: Weak Emission Lines

Endsley, Stark, et al. 2022d

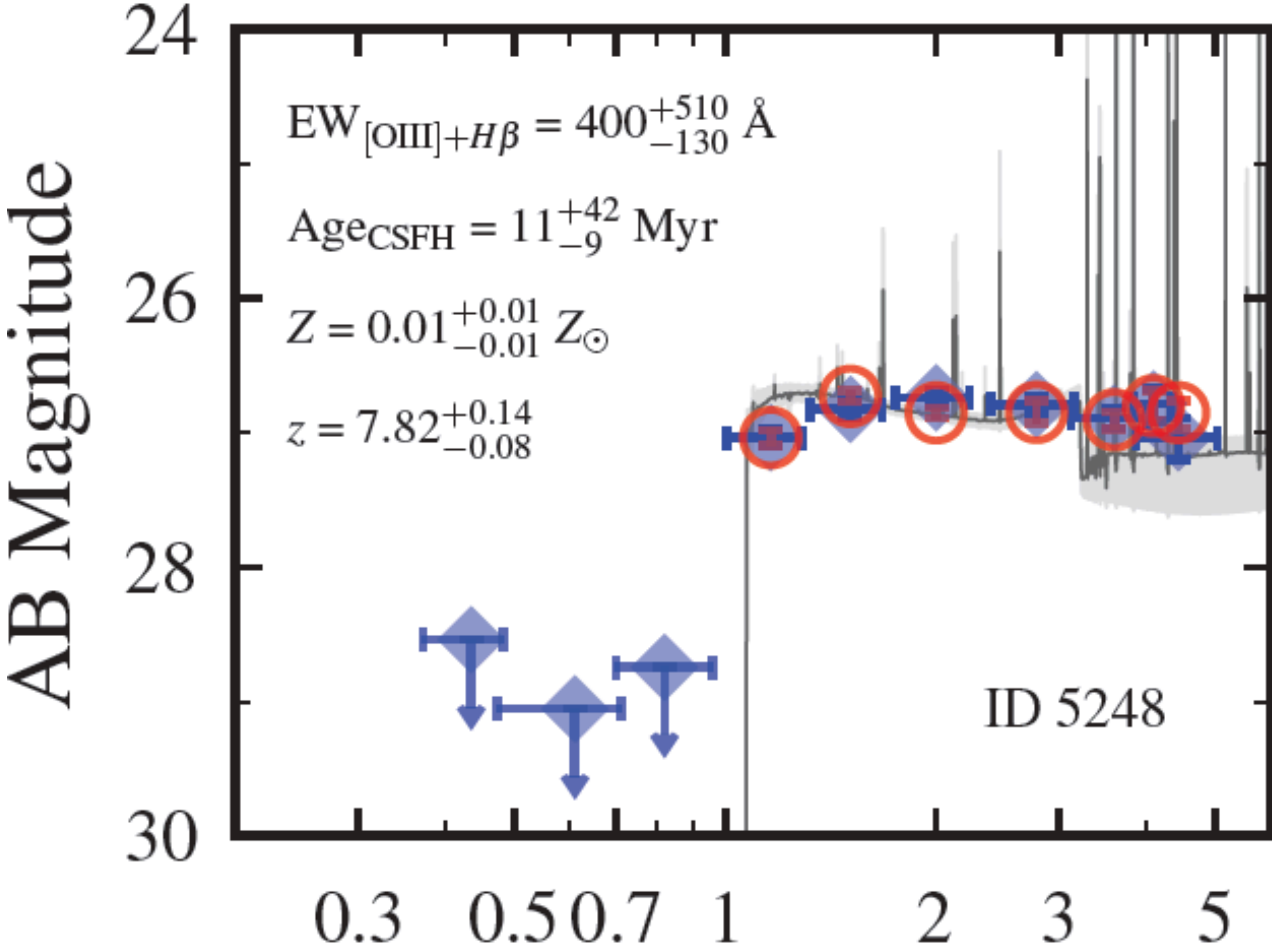


The majority of NIRCam SEDs at z~6-8 have indications of strong emission lines.

We have found a large fraction (~20%) of z~6-8 galaxies appear (i) young and (ii) have no indications of flux excesses associated with emission lines.

[OIII] must be weak!

Surprise with JWST/NIRCam Imaging: Weak Emission Lines

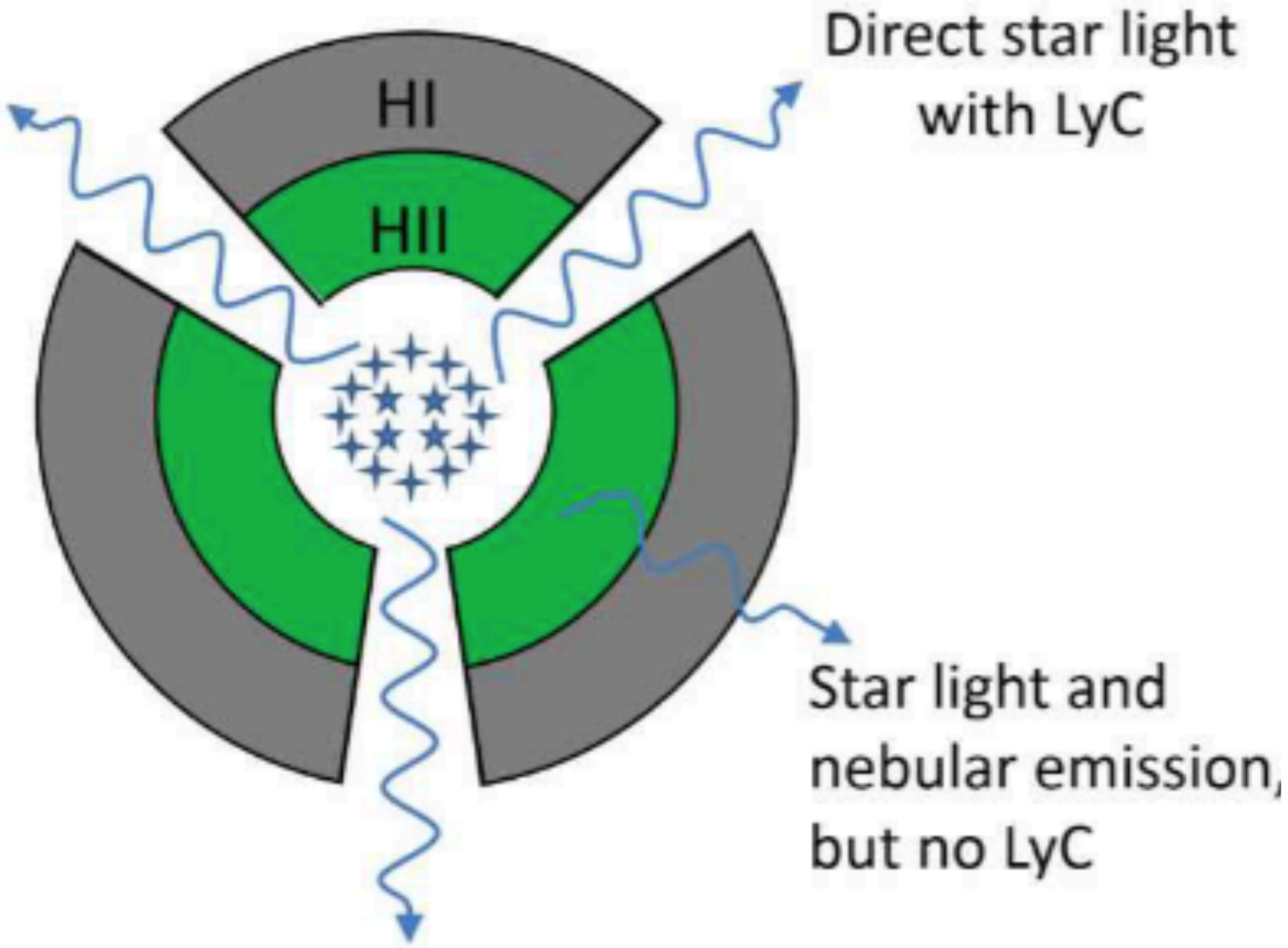


Endsley, Stark, et al. 2022d

Our fiducial models make [OIII] weak by going to extremely low gas-phase metallicities (~1% solar metallicity).

Signature of extremely low metallicities in dwarf galaxies?

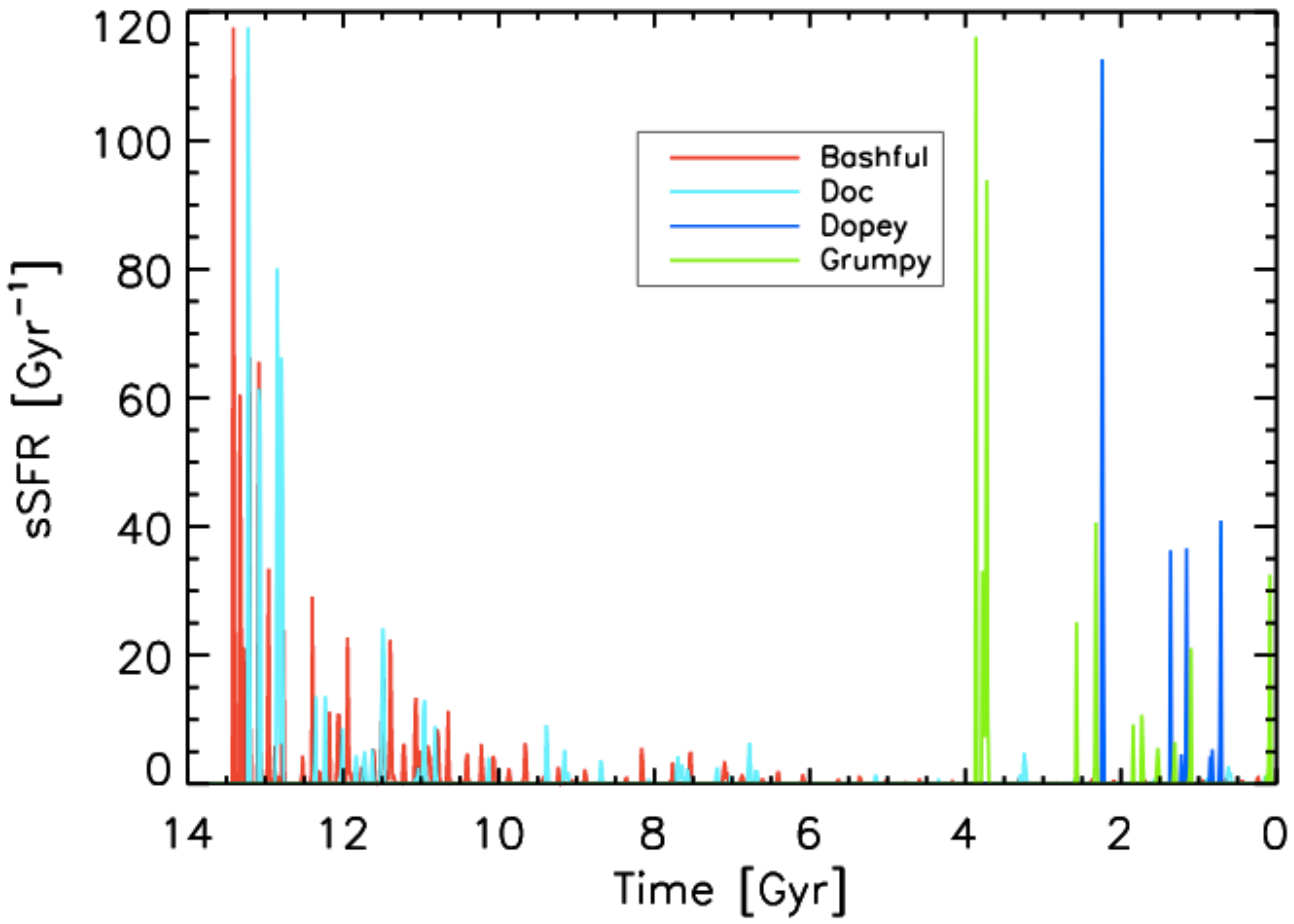
Surprise with JWST/NIRCam Imaging: Weak Emission Lines



There are **two other explanations** which could be contributing.

1. Ionizing photon escape without being absorbed, diminishing emission lines — would suggest very effective ionizing agents!

Surprise with JWST/NIRCam Imaging: Weak Emission Lines



Shen et al. 2014

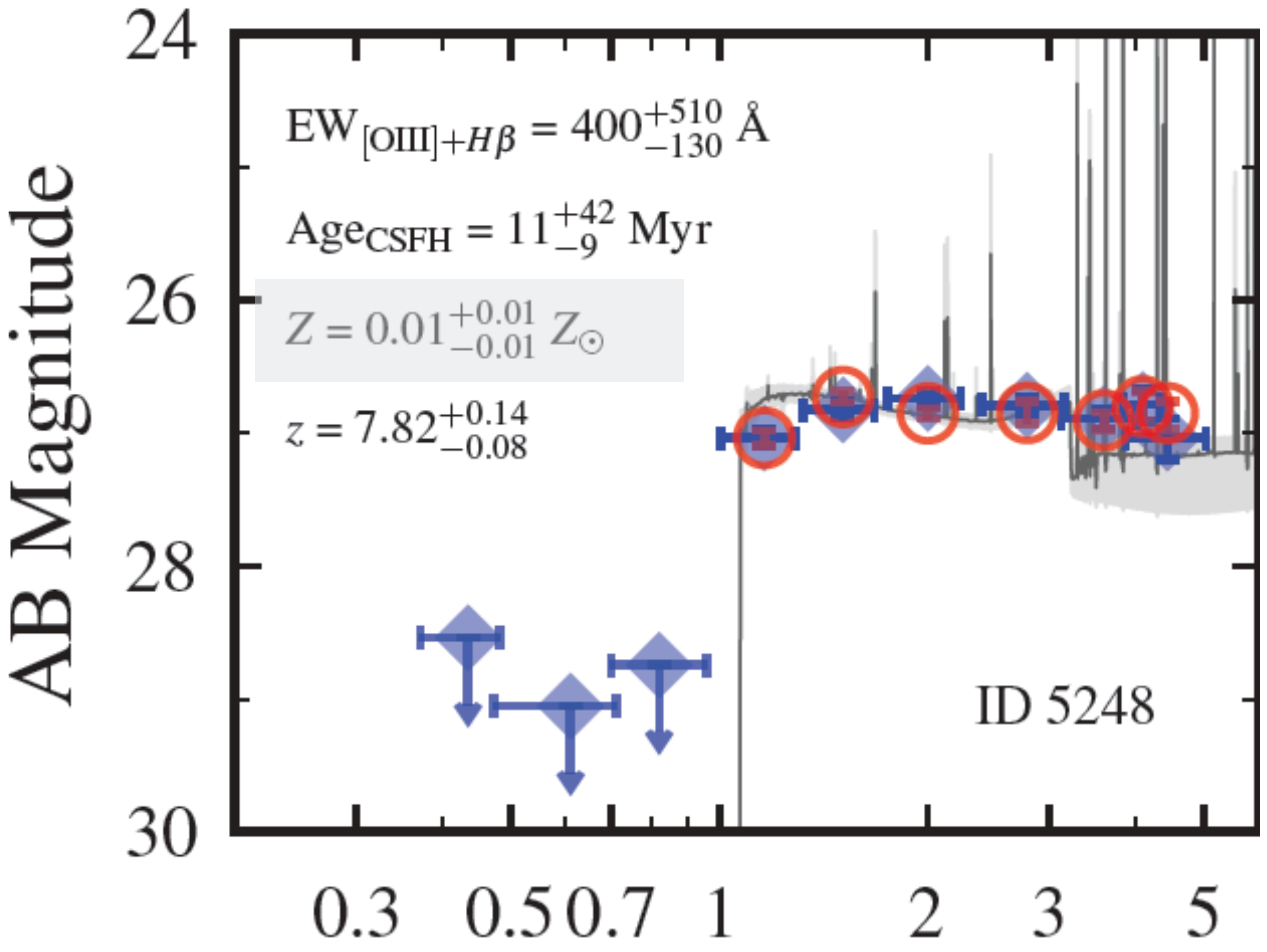
There are **two other explanations** which could be contributing.

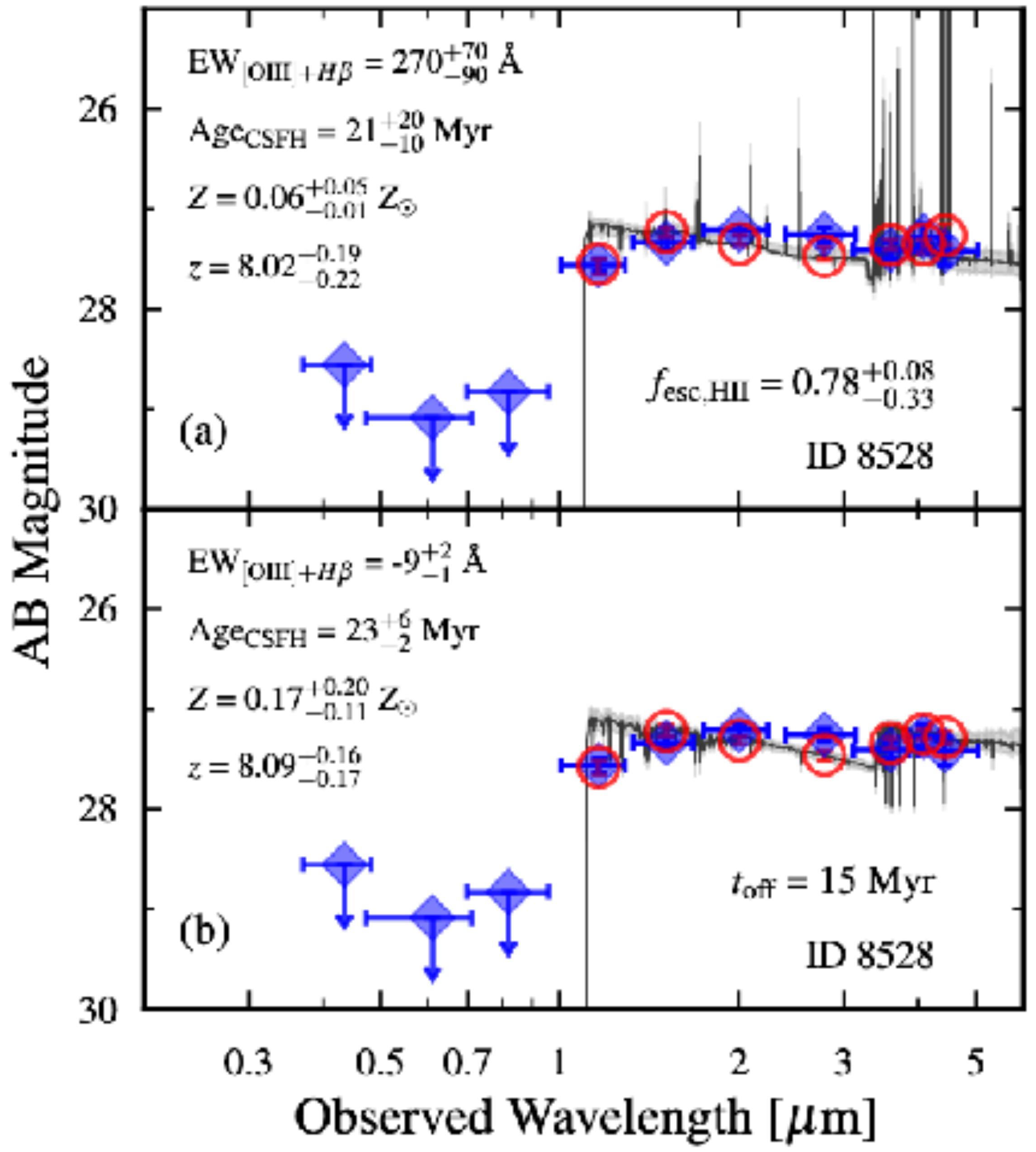
2. If bursty star formation is common, we expect to see galaxies in an "off mode" where they haven't form stars for ~10 Myr — no O stars, weak emission lines.

Further evidence for bursty star formation at z>6?

Surprise with JWST/NIRCam Imaging: Weak Emission Lines

Endsley, Stark, et al. 2022d





Each interpretation can fit the observed SED well with very different physics.

As these young, weak line sources represent 20% of the population at z~6-8, it is critical that we get to the bottom of this — spectroscopy can help distinguish!