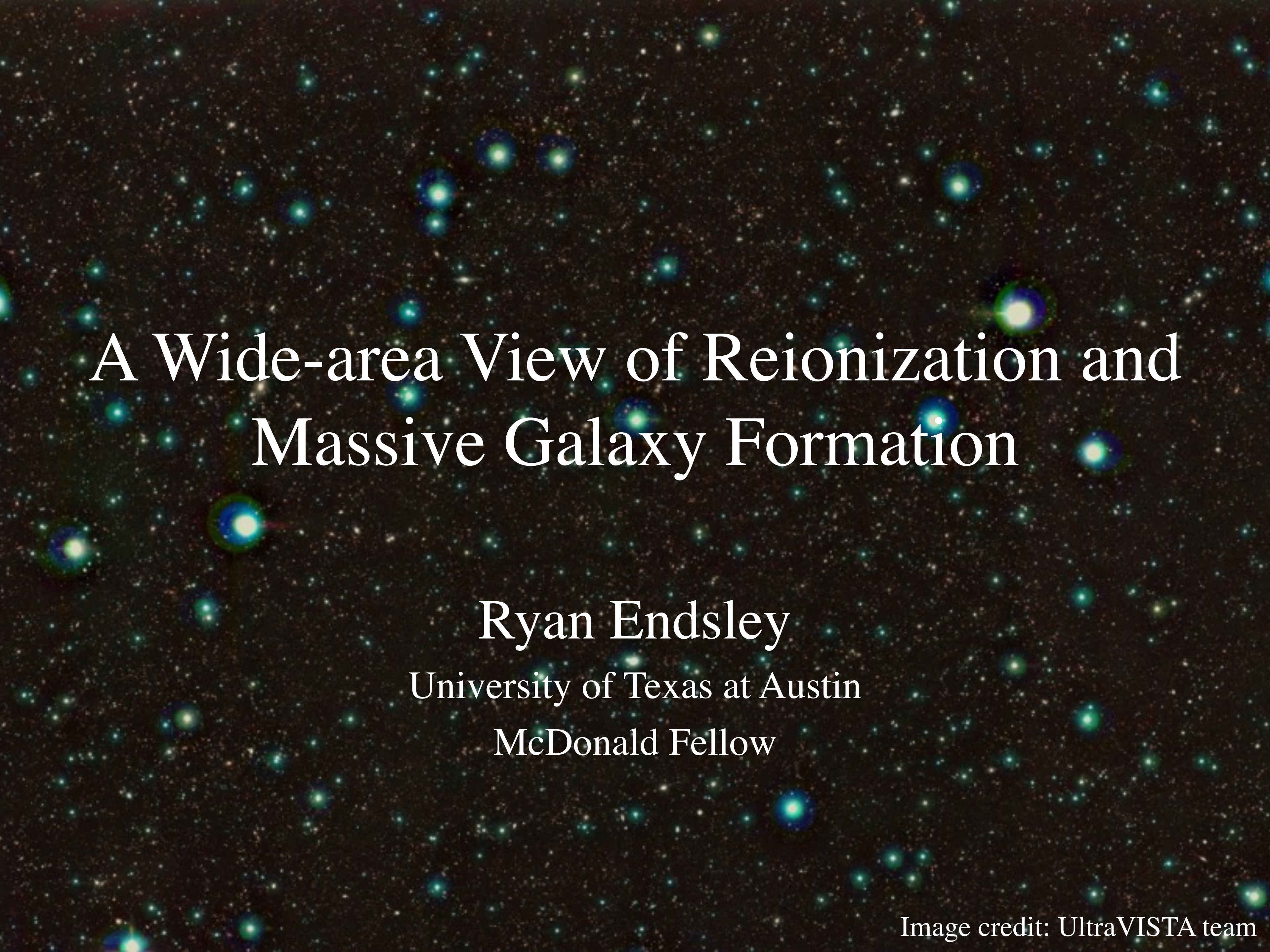


A Wide-area View of Reionization and Massive Galaxy Formation

Ryan Endsley

University of Texas at Austin

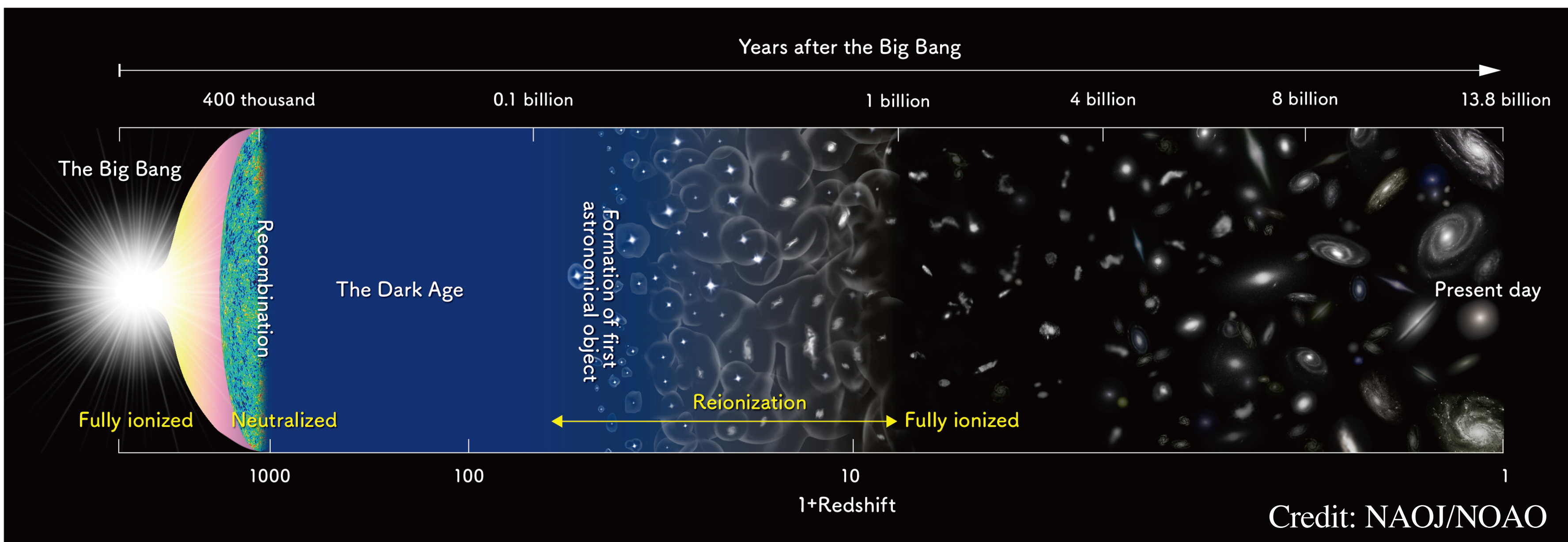
McDonald Fellow

Image credit: UltraVISTA team

Key Questions

1. How did reionization progress?
   - What was the size and spatial distribution of ionized bubbles as a function of redshift? In what environments did they form?

2. How did the most massive galaxies first assemble?
   - How quickly did they form stellar mass, dust, and supermassive black holes?



Key Questions

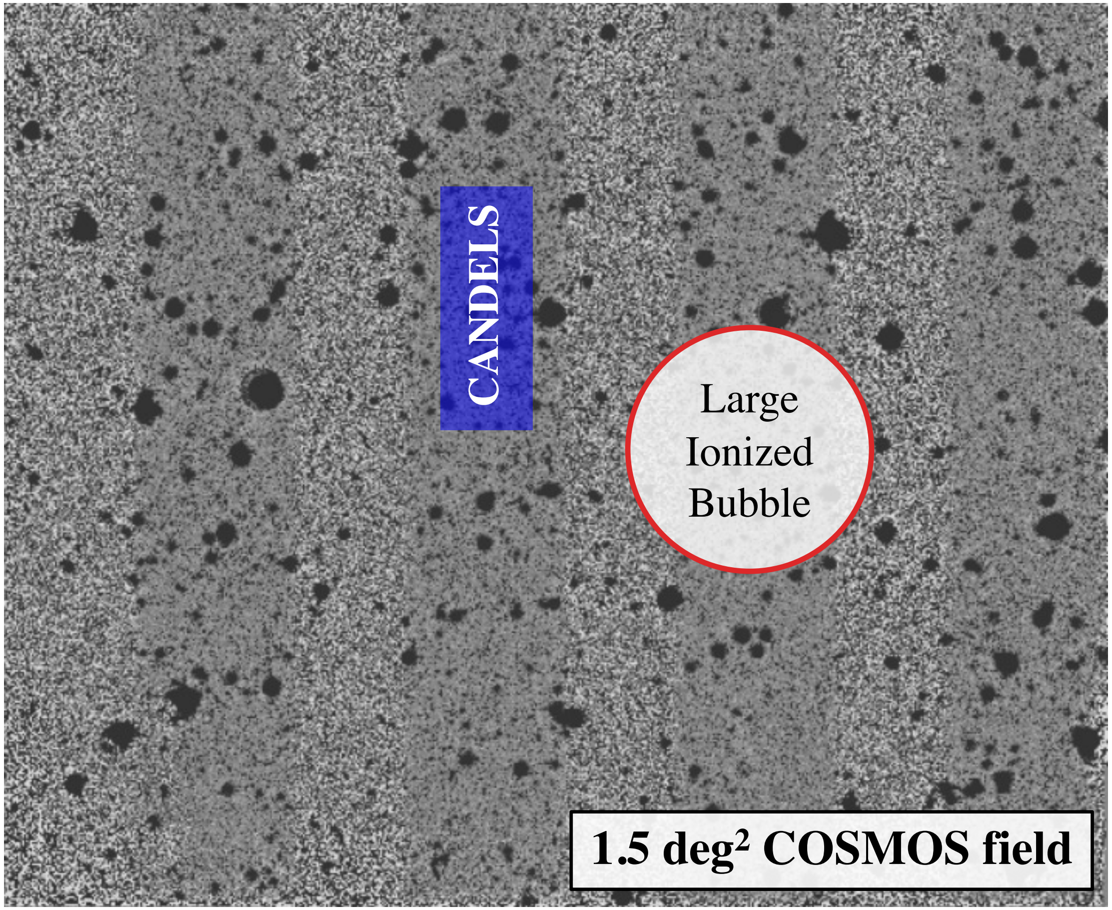
1. How did reionization progress?
    - What was the size and spatial distribution of ionized bubbles as a function of redshift?

<u>This Talk:</u>

Progress in answering these questions utilizing wide-area (>deg^2) data.

Unique Advantages of Wide Areas at z>6

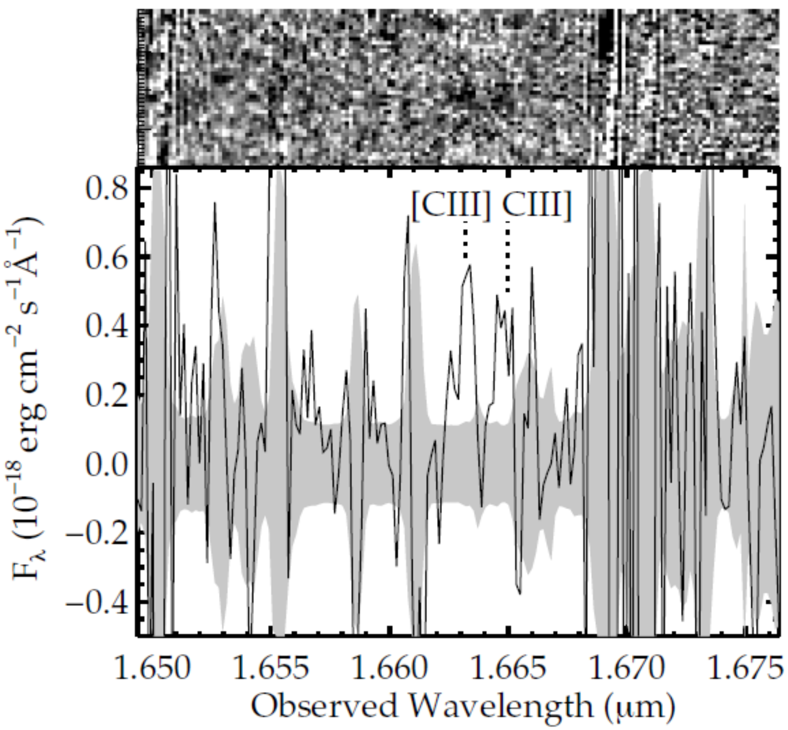
1. Statistically sample the largest ionized bubbles at z~7.
   - Largest z~7 bubbles expected to be ~15-30 arcmin in diameter (e.g. Lin+2016).

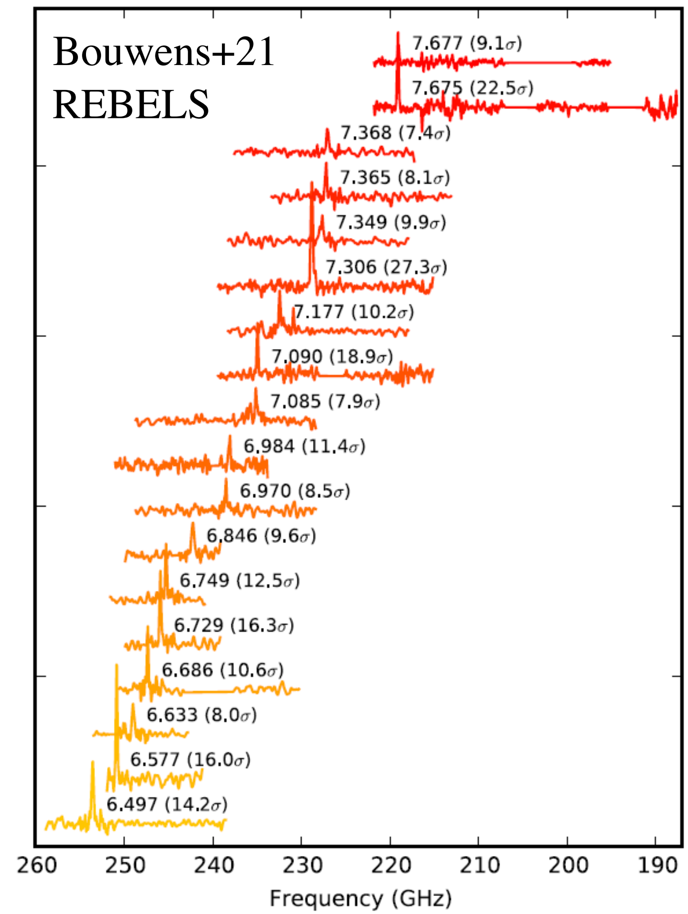


Unique Advantages of Wide Areas at z>6

2. Enables detailed characterization of brightest, most massive galaxies.
   - Emission lines accessible with existing facilities.

Stark+2017

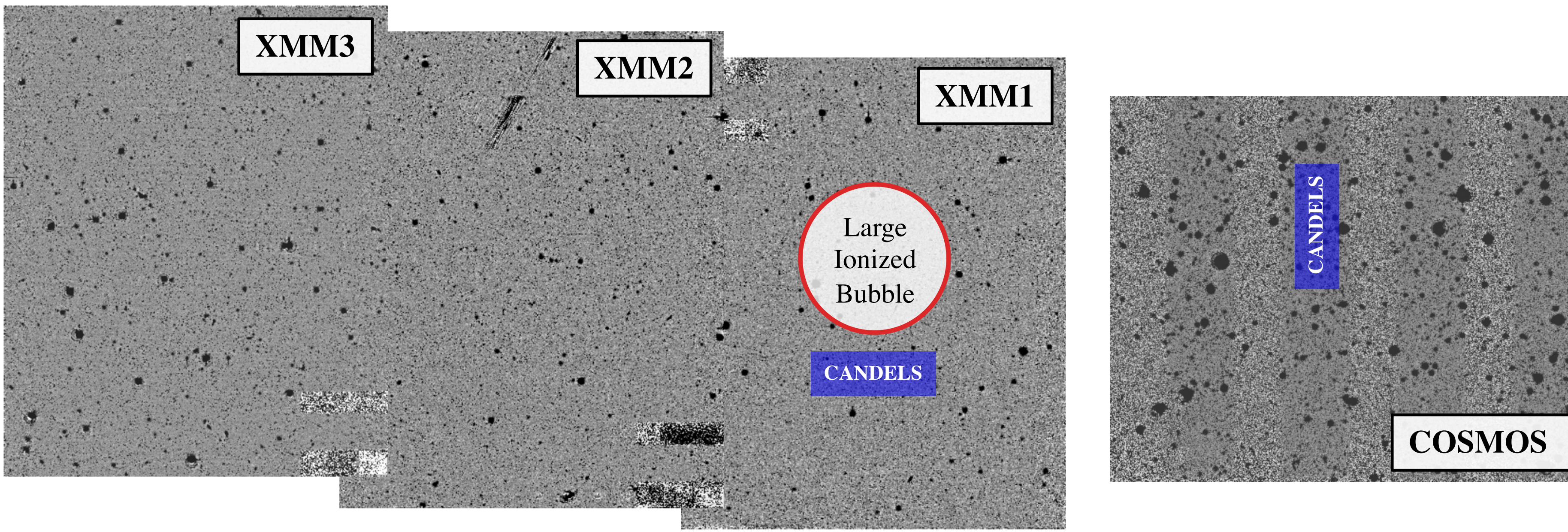




See also e.g. Bowler+17,18,22; Hashimoto+19,22; Inami+22; Schouws+21,22; Topping+22; Valentino+22

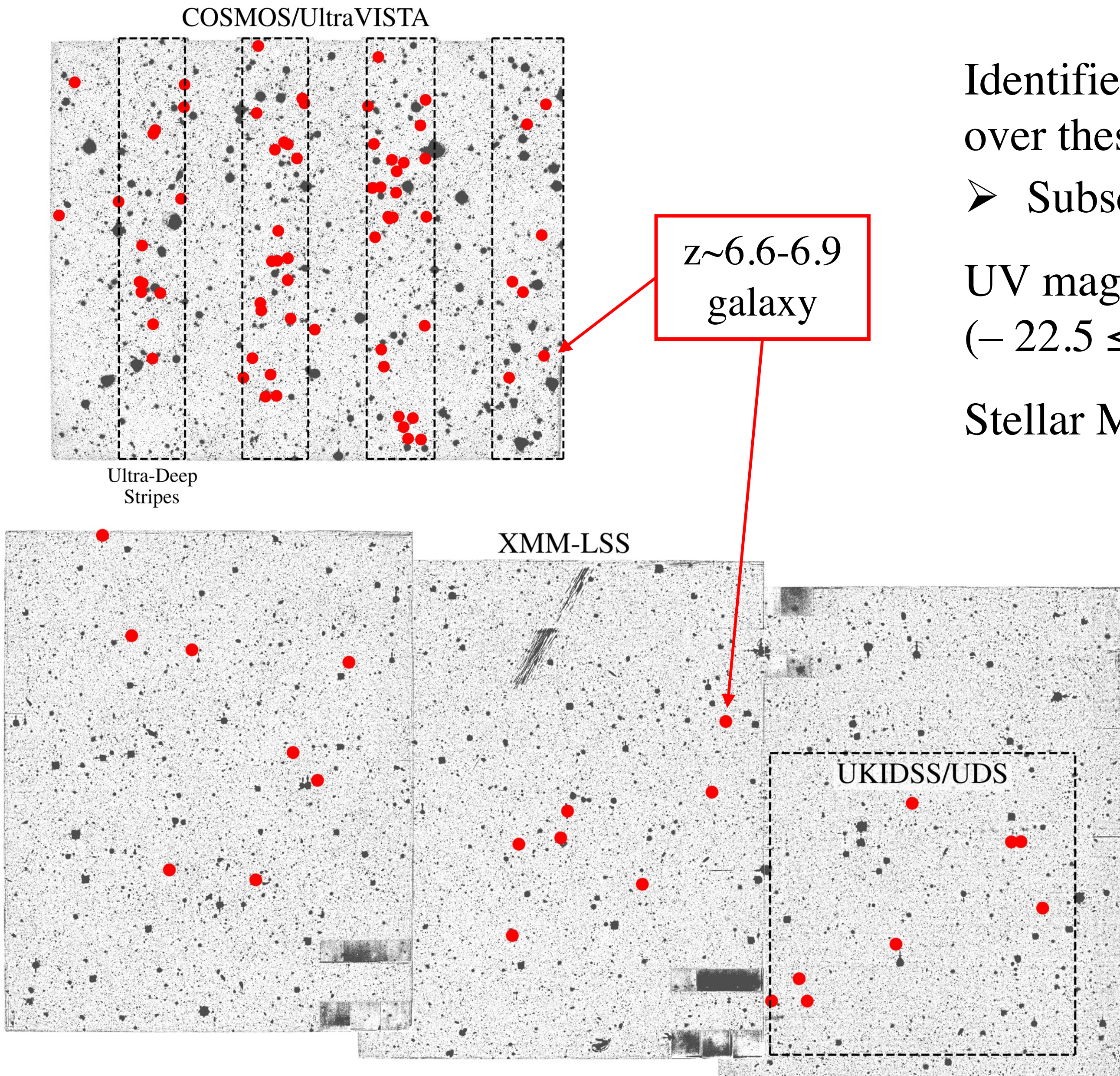
New Exploration of UV-luminous z~7 Galaxies over Wide-area Fields

Utilize 7 deg^2 of deep optical+near-infrared imaging to identify large numbers of UV-luminous Lyman-break galaxies at z~7.



- Volume is >30x larger than that of all deep HST fields.
- Allows us to statistically sample very large ionized bubbles at z~7.
- Able to characterize rare, massive galaxies in the early Universe.

Large Sample of UV-bright z~6.6-6.9 Galaxies



Identified >100 z~6.6-6.9 galaxies over these wide-area fields.

- Subset included in REBELS.

UV magnitude: $24.5 < J < 26.5$ ($-22.5 \leq M_{UV} \leq -20.5$)

Stellar Mass: $\sim 10^{8.5}$-10^{11} $M_{\odot}$

Endsley+21a, MNRAS, 500, 5229
Endsley+21b, MNRAS, 502, 6044
Endsley+22a, MNRAS, 511, 6042
Endsley+22b, MNRAS, 512, 4248
Endsley+22c, arXiv:2202.01219
Endsley+22d, arXiv:2206.00018

Unique Advantages of Wide Areas at z>6

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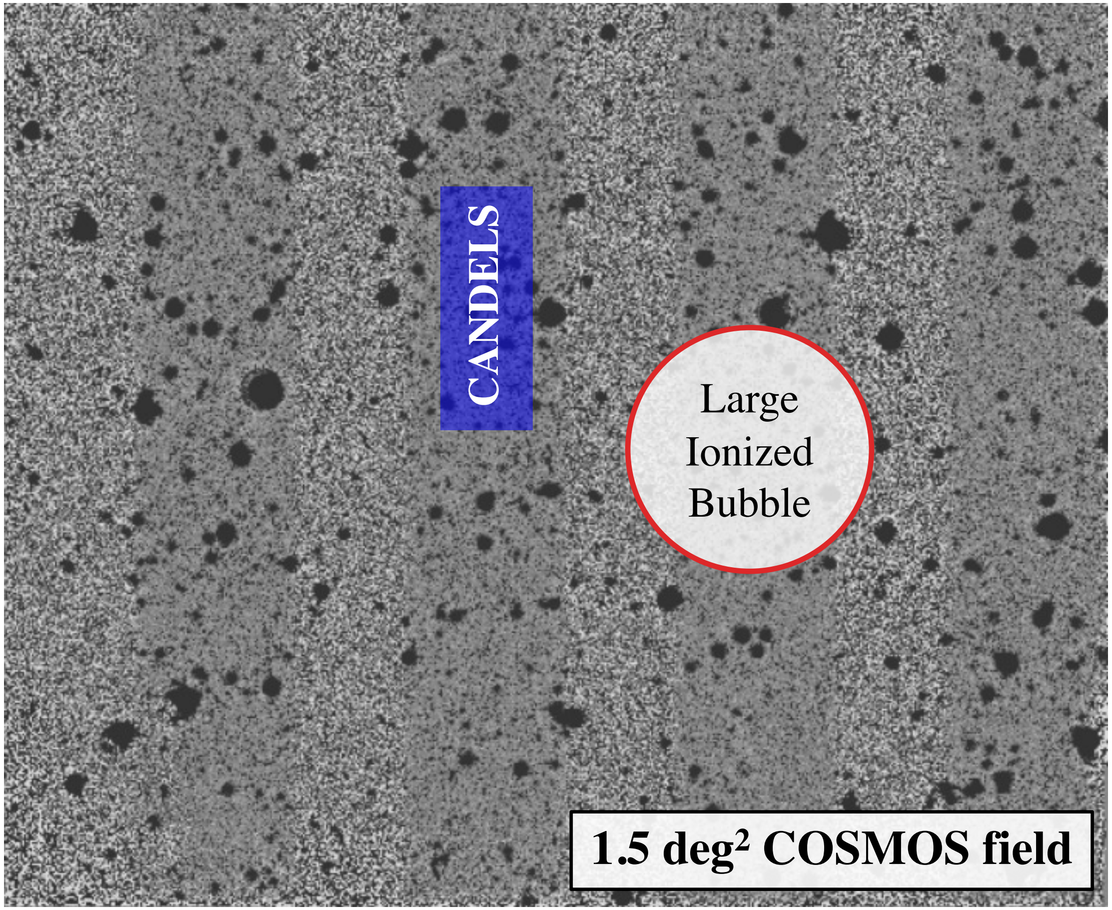


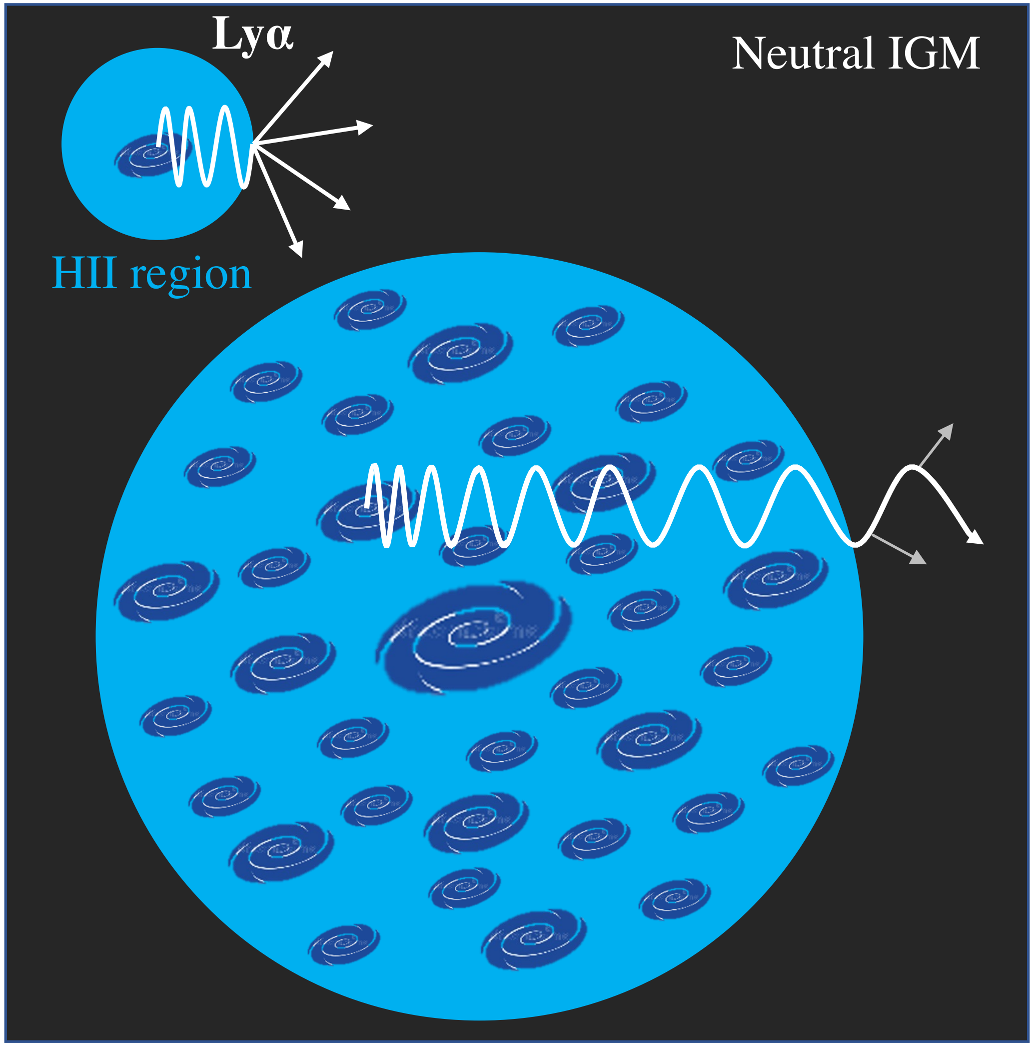
Identifying Large Ionized Bubbles with Lyman-alpha

Galaxies situated in small bubbles will show weak Lyα emission due to resonant scattering with HI.

- Low fraction of Lyα detections at $z \geq 7$ (~10%).

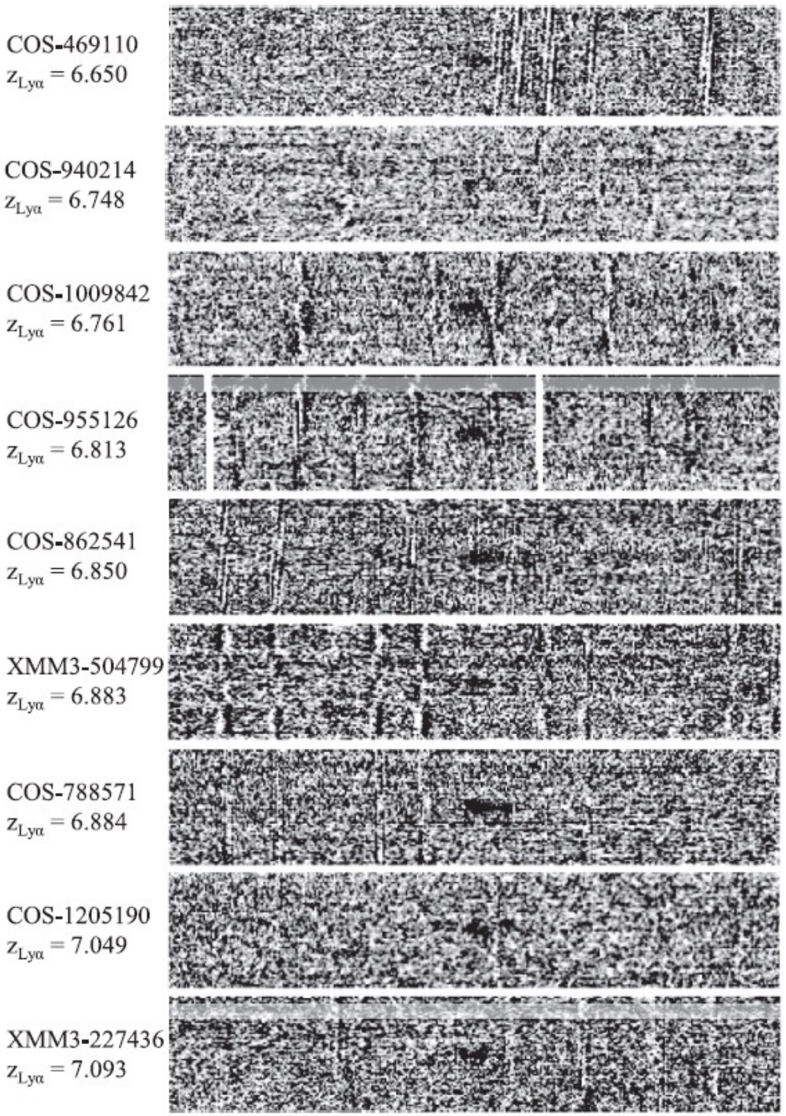
Large ionized bubbles boost Lyα transmission through neutral IGM

- Enhanced Lyα emission from $z \geq 7$ galaxies in a given volume indicates ionized bubble.



e.g., Miralda-Escude 1998, McQuinn+07, Jensen+14, Castellano+18

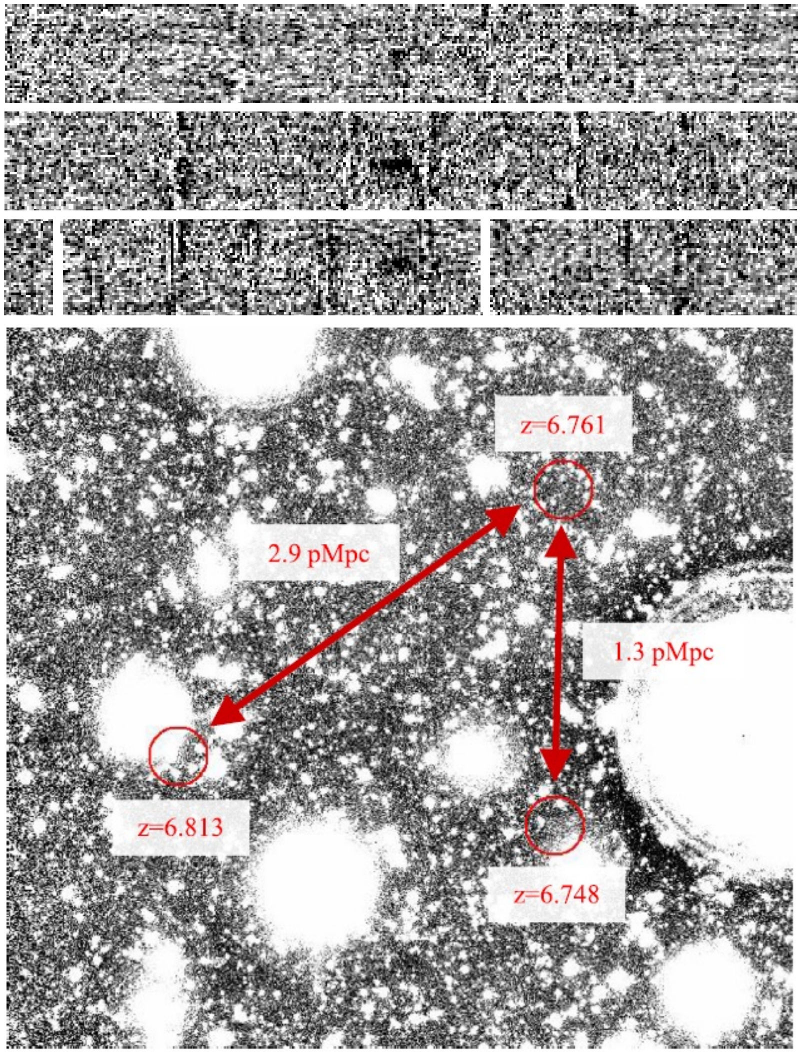
Wide-area z~7 Lyα Survey



Endsley+2021b, MNRAS, 502, 6044

- MMT/Binospec observations from 2018B-2021A (FoV = 240 arcmin^2).
- Observed 45 UV-bright z~6.6–6.9 Lyman-break galaxies to date.
  - 18 Lyα detections among this sample (40% detection rate).

Three Neighboring z=6.8 Lyα Emitters



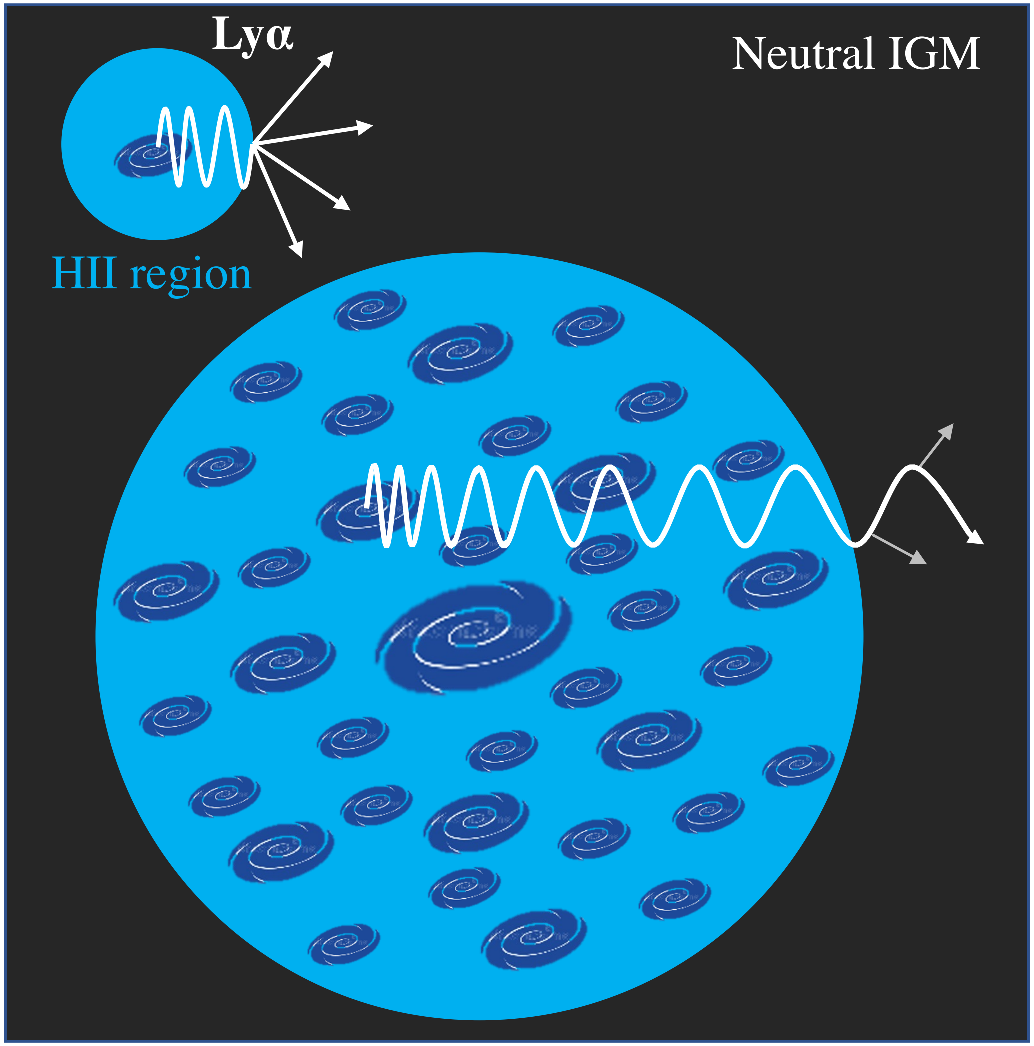
<u>Results from first data:</u>

Detected Lyα in three UV-luminous (L_{UV} = 1-2 L^*_{UV}) galaxies at z=6.8 separated by <5 arcmin and Δz=0.06.

- All contained within *R*=1.7 physical Mpc sphere.

Endsley+21b, MNRAS, 502, 6044

Discovery of Large Ionized Bubble at z~7?

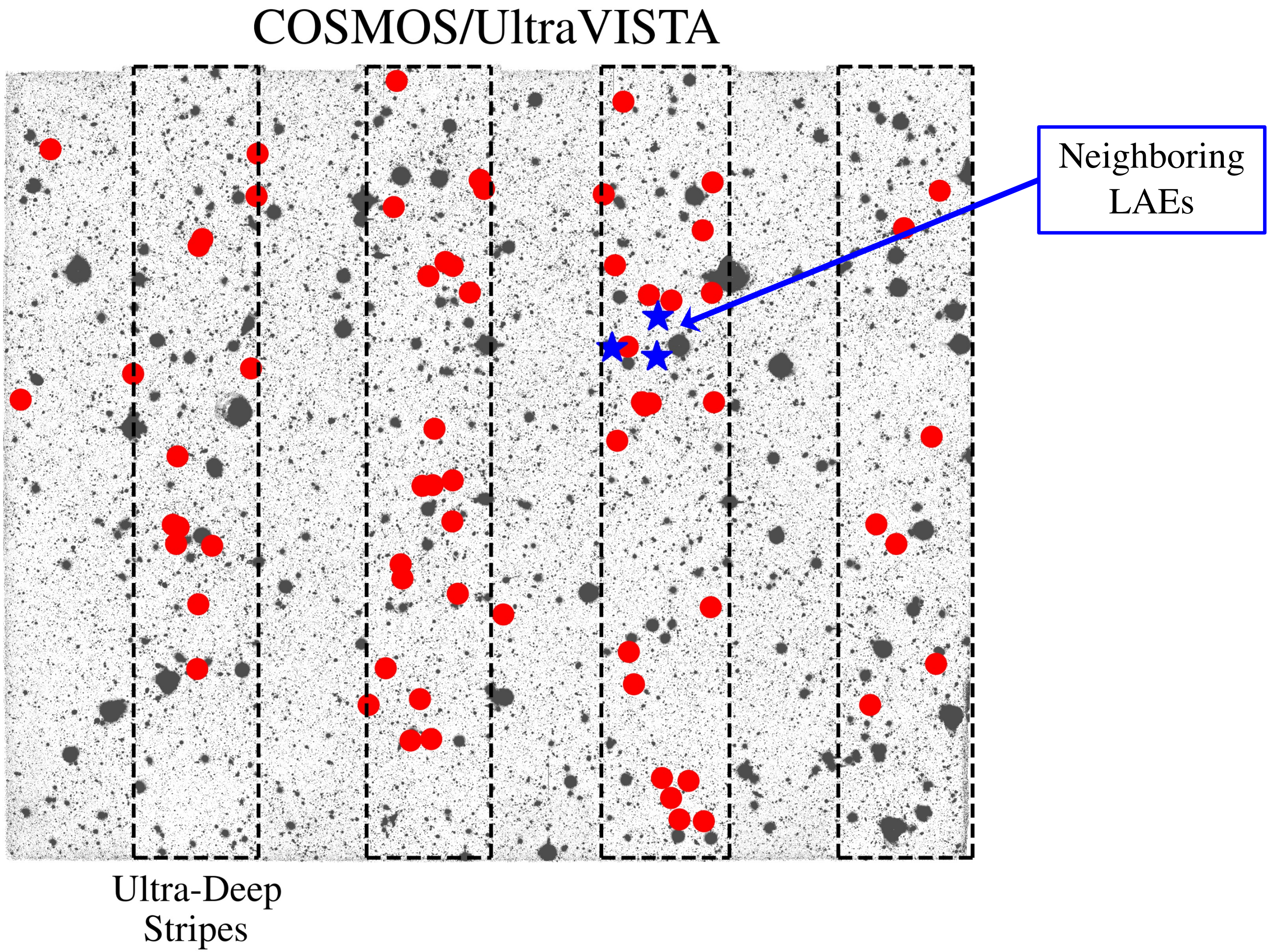


Perhaps these three neighboring LAEs trace a very large bubble.

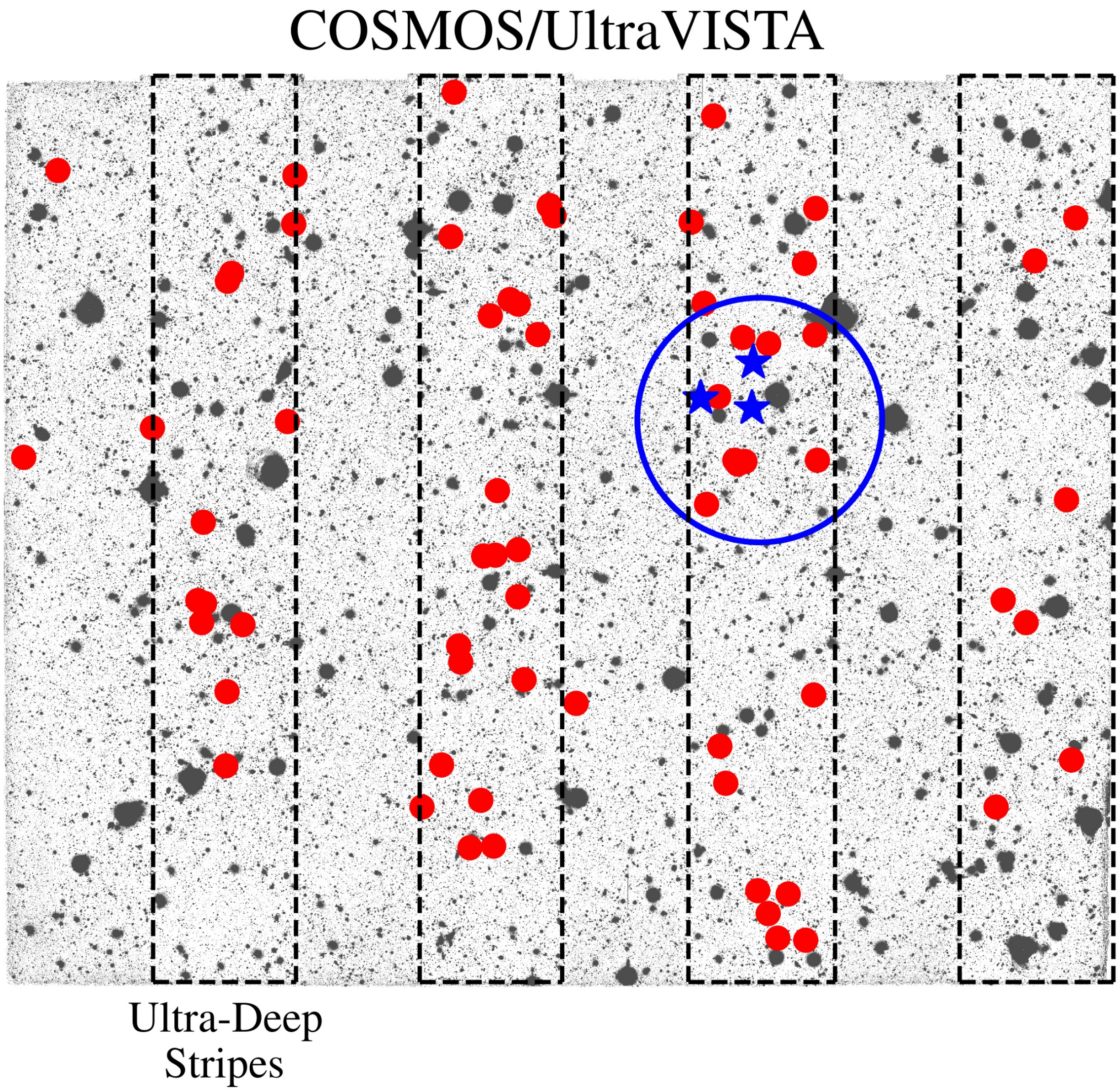
- If so, we would expect them to reside in a highly overdense region.

See also Castellano+18, Jung+20, Tilvi+20, Hu+21, Larson+22

A Strong Local Photometric Overdensity



A Strong Local Photometric Overdensity



Surface density of UV-bright galaxies suggest strong surrounding overdensity.

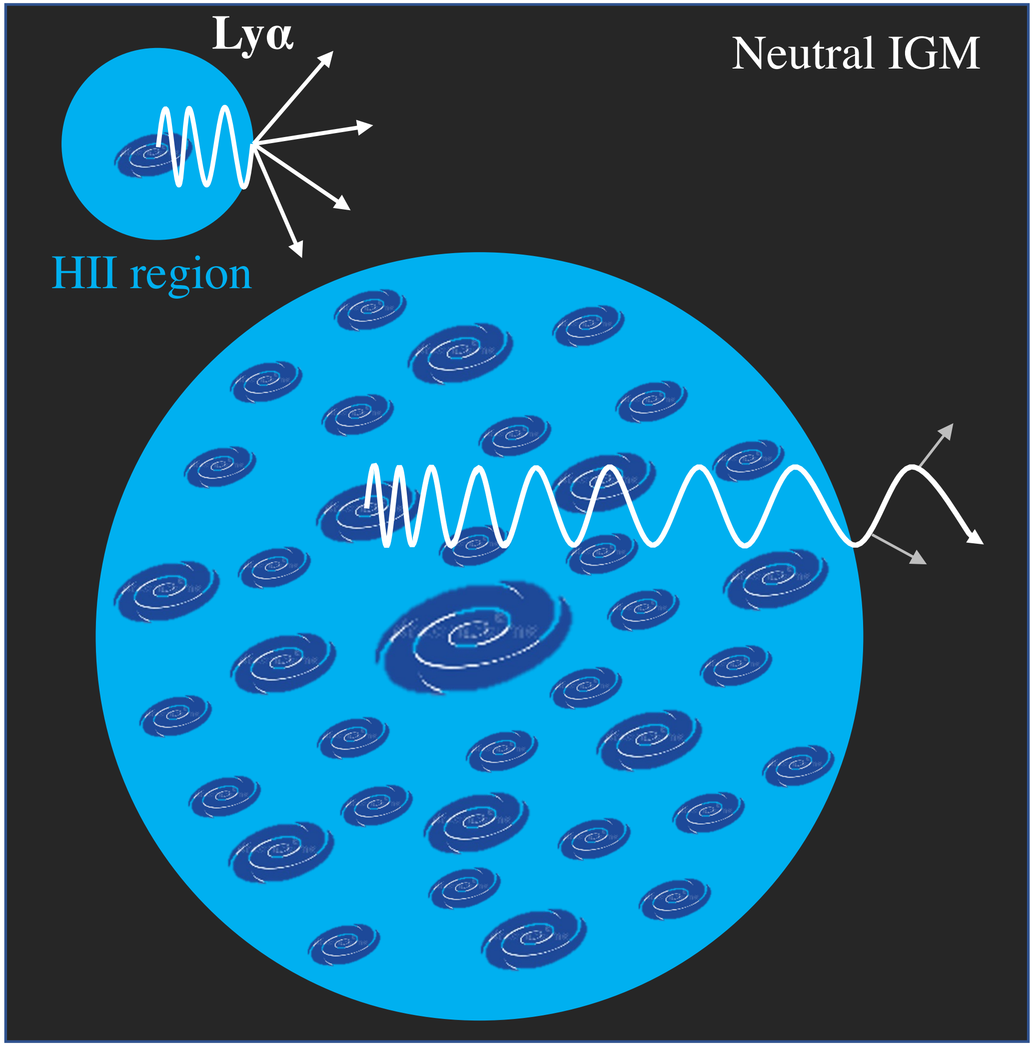
- ➢ N/<N> ≈ 3 on ~15 arcmin scales.

Overdensity Powering Large Ionized Bubble?

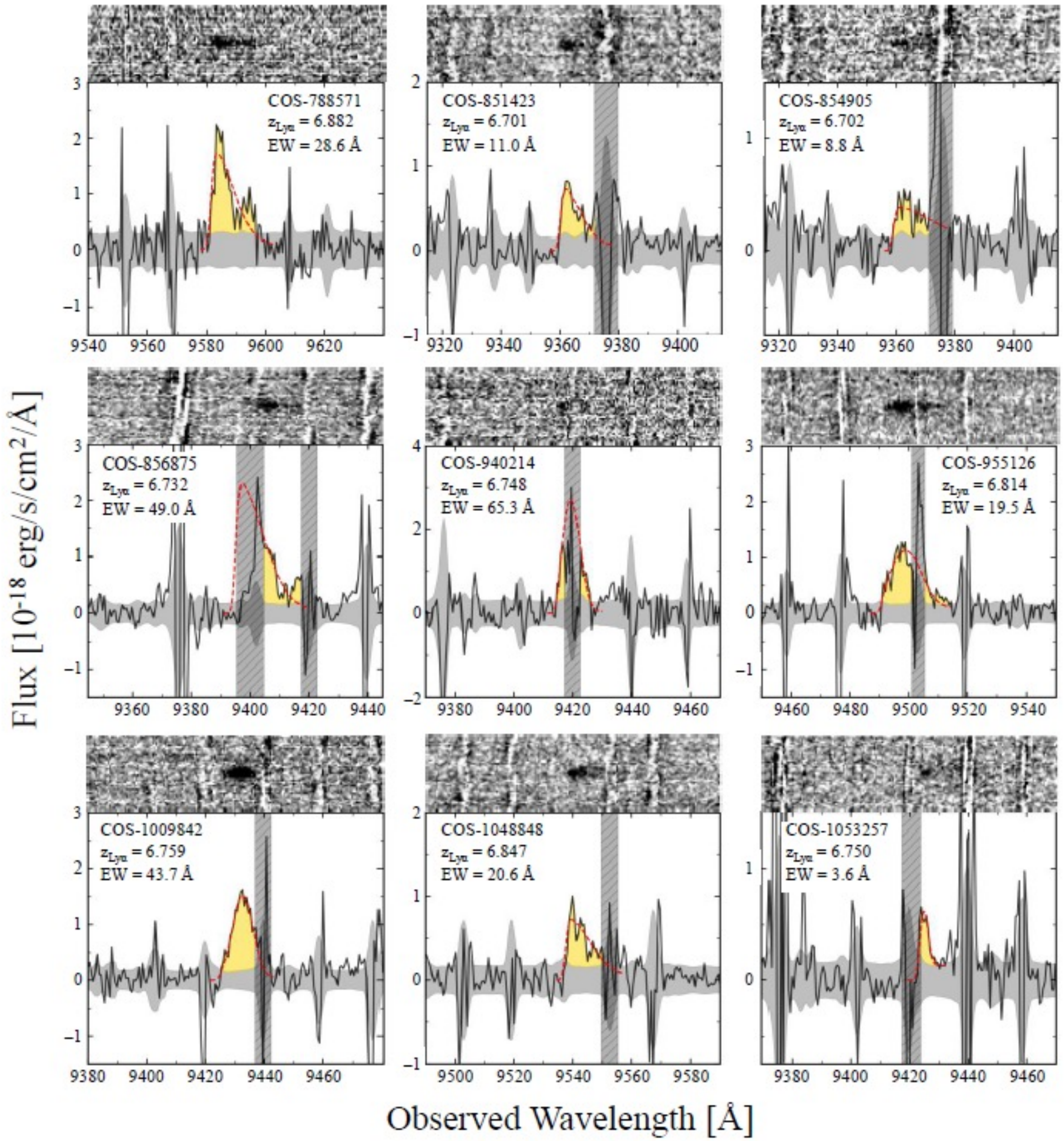
- Are the other Lyman-break galaxies physically associated with known Lyα emitters?
- Do other galaxies also show strong Lyα?

➢ Need to better characterize overdensity and Lyα emission over wider area.

Conducted ultra-deep (25 hour) Lyα follow-up of nearby galaxies.



Results of Spectroscopic Follow-up



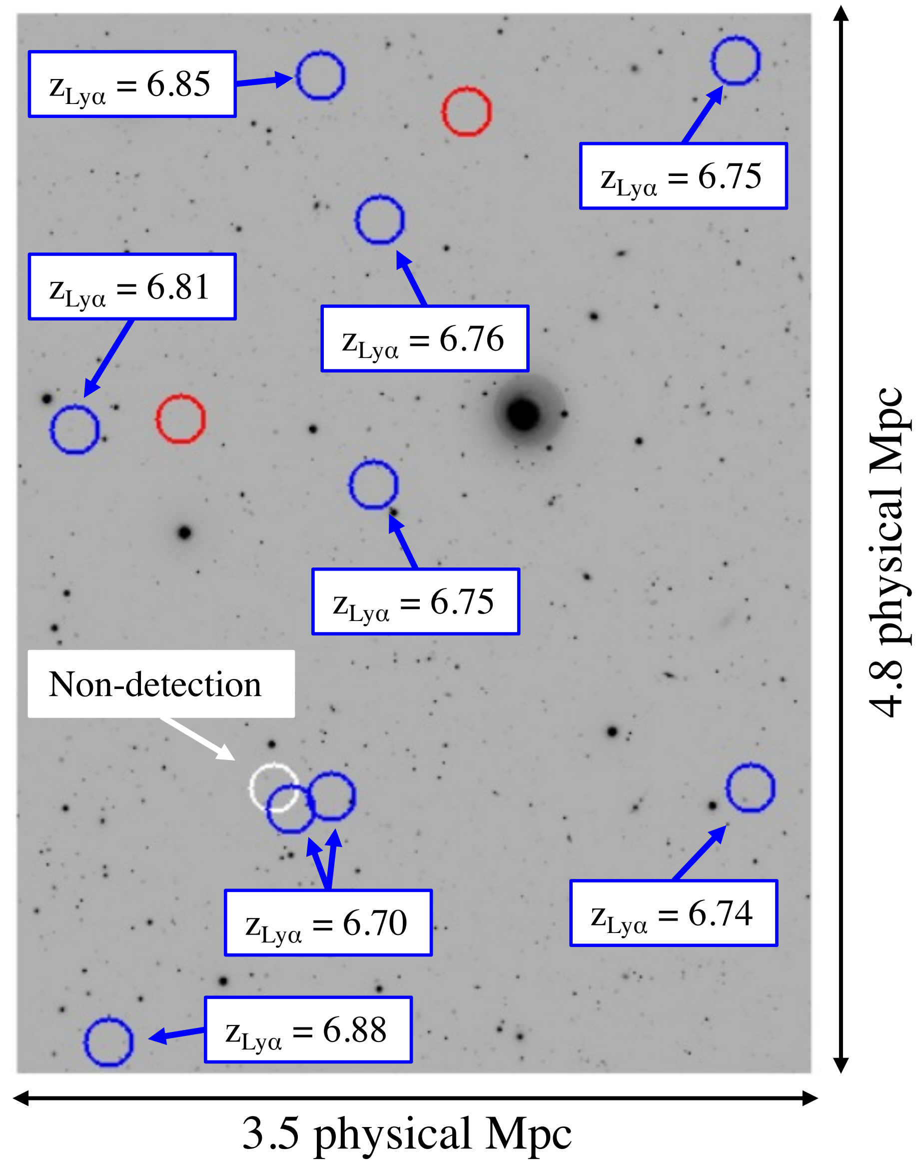
Detect Lyα in 9/10 targeted UV-luminous z~7 galaxies.

Endsley & Stark 2022, MNRAS, 511, 6042

A Large-scale Reionized Overdensity at z=6.8

Confident Lyα detections in 9/10 UV-luminous (L_{UV} = 1-4 L^*_{UV}) galaxies targeted in surrounding region.

- $z_{Ly\alpha}$ = 6.70-6.88.
- All sources contained within a 140 physical Mpc^3 volume (R=3.2 physical Mpc).
- At least 3x average number density, even when considering only spectroscopic confirmations.
- Lyα EWs enhanced by factor of ≈2.

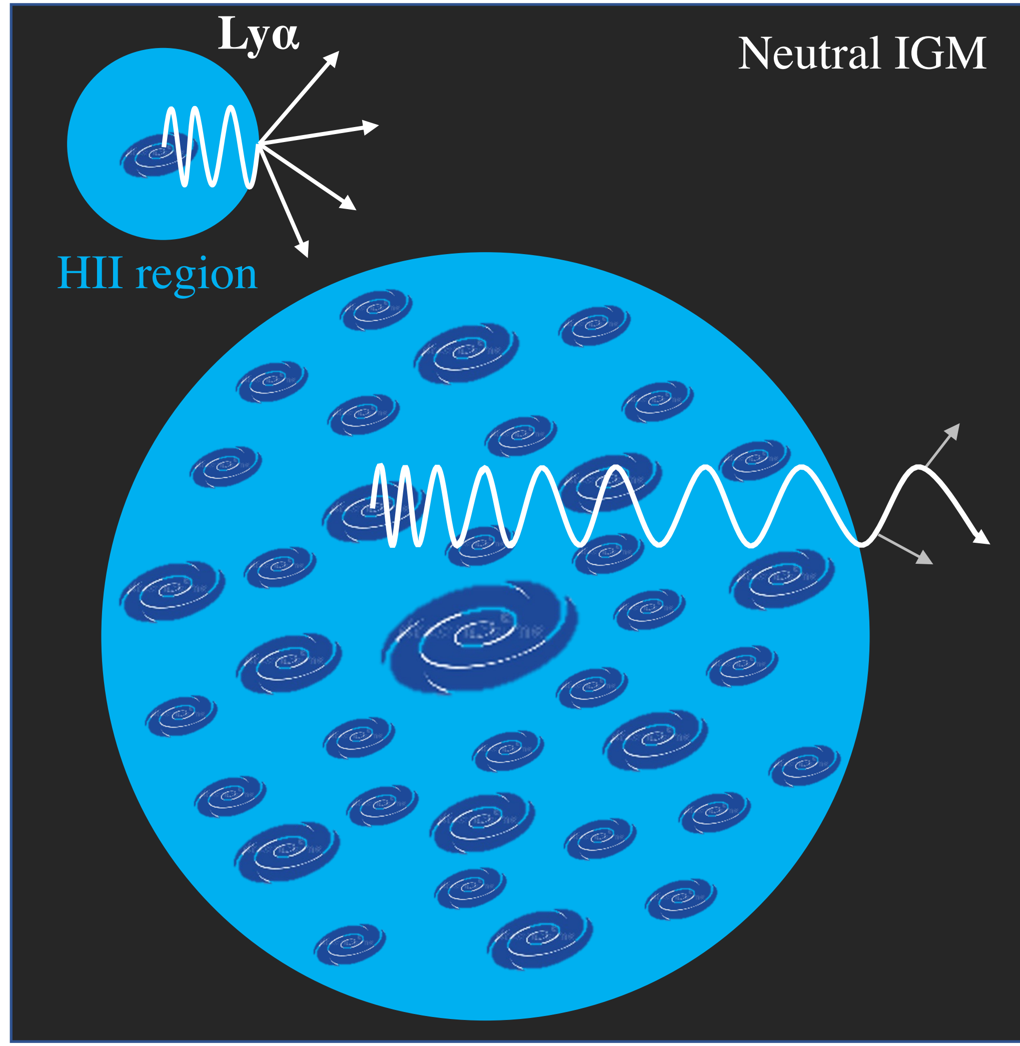


Endsley & Stark 2022, MNRAS, 511, 6042

A Large-scale Reionized Overdensity at z=6.8

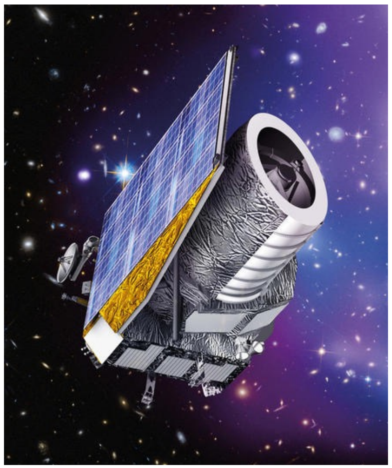
- Do the three Lyα emitters trace a more extended overdensity? ✓
- Do other galaxies in their vicinity show enhanced Lyα? ✓

➢ Suggests this z=6.8 volume likely hosts a very large (*R*≈3 physical Mpc) ionized bubble.



Endsley & Stark 2022, MNRAS, 511, 6042

Expanding Reionization Science to Wider Fields



Ultra-deep COSMOS

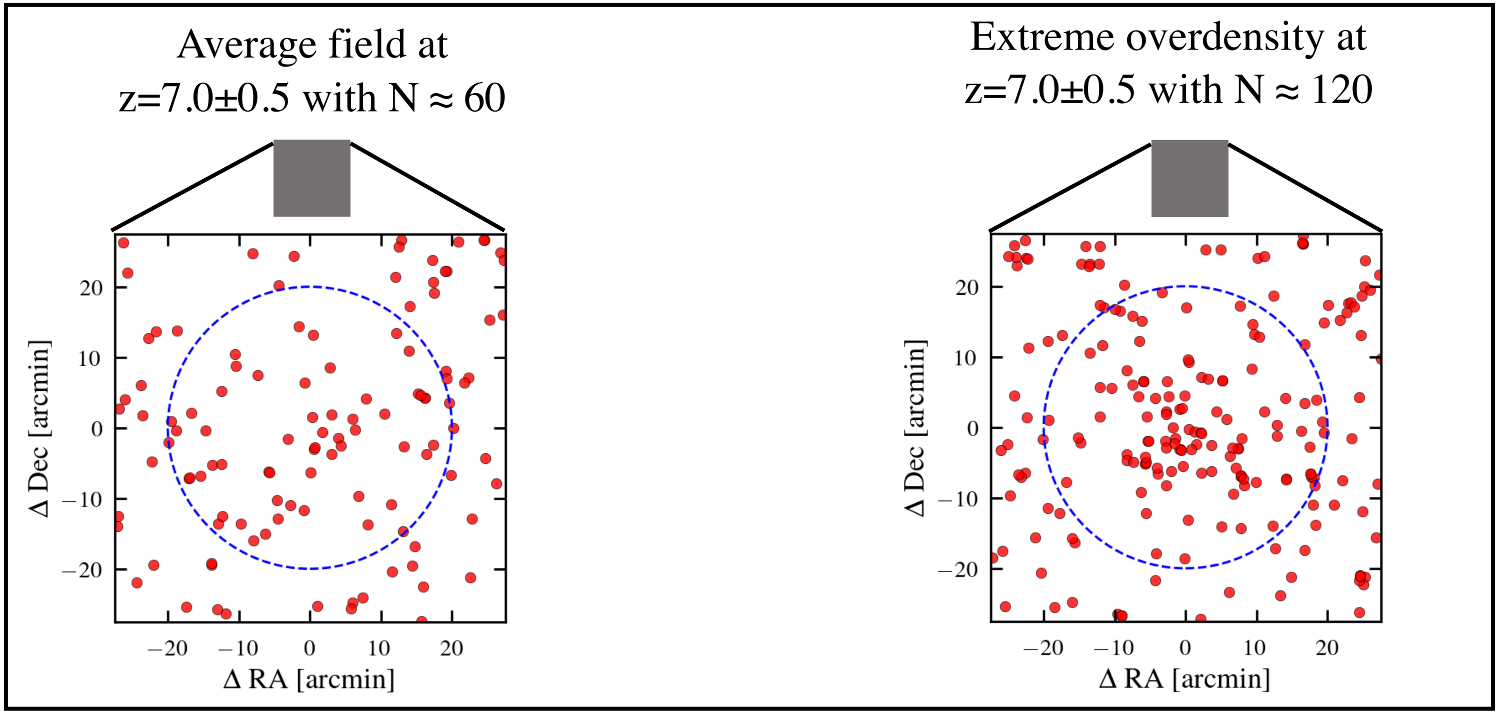
Euclid Deep Fields

~70x increase in area at comparable near-IR depth relative to ultra-deep COSMOS/UltraVISTA survey

The Euclid Deep Fields will enable the detection of thousands of $z \geq 7$ galaxies over 50 deg^2 (c.f. the 0.75 deg^2 area of ultra-deep COSMOS/UltraVISTA).

- ➢ Will greatly advance our ability to study ionized bubbles and their associated overdensities.

Identifying Extreme Overdensities with Euclid



With such large area, can precisely establish average z~7 galaxy surface density.

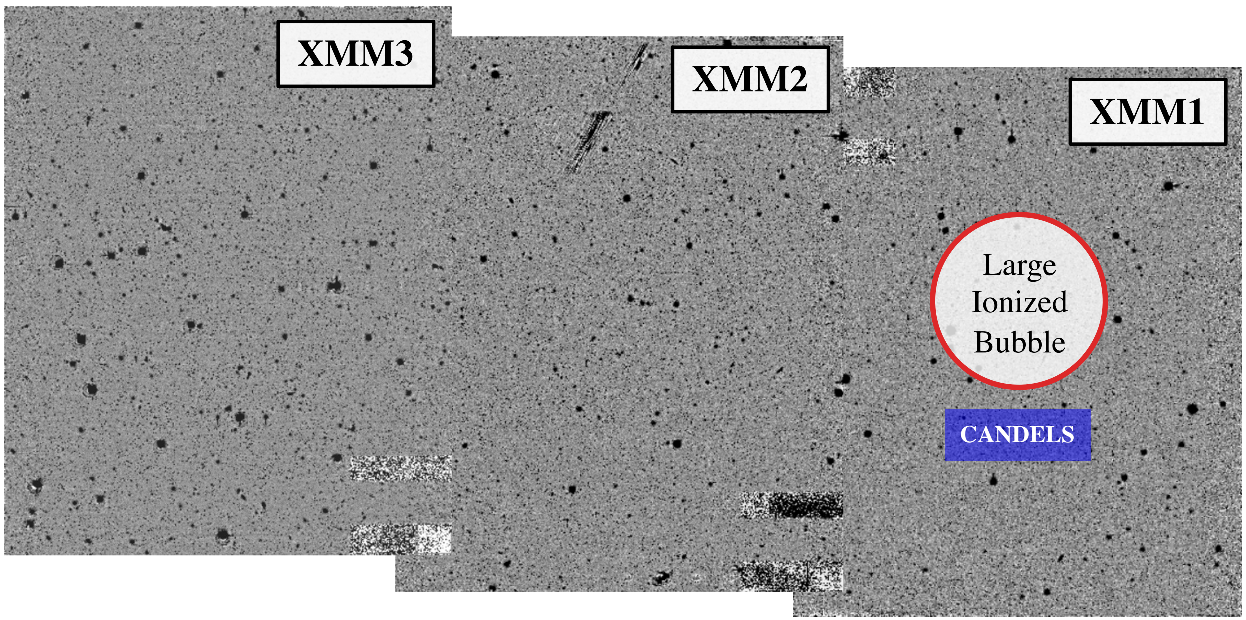
Predict Euclid Deep Fields will enable identification of wide-area regions (*R*~20 arcmin) with 2x the average z~7 surface density.

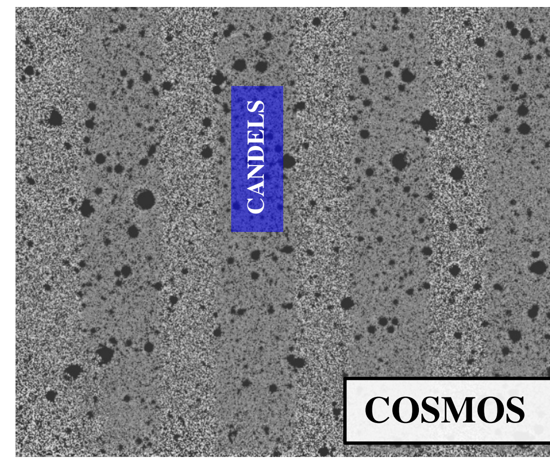
- Excellent regions for spectroscopic follow-up (e.g. MOONS) to characterize largest ionized bubbles (*R*~5–10 physical Mpc).

Utilizing predictions from UniverseMachine (Behroozi+19)

New Exploration of UV-luminous z~7 Galaxies over Wide-area Fields

Utilize 7 deg^2 of deep optical+near-infrared imaging to identify large numbers of UV-luminous Lyman-break galaxies at z~7.





- ➢ Volume is >30x larger than that of all deep HST fields.
- ➢ Allows us to statistically sample very large ionized bubbles at z~7.
- ➢ **Able to characterize rare, massive galaxies in the early Universe.**

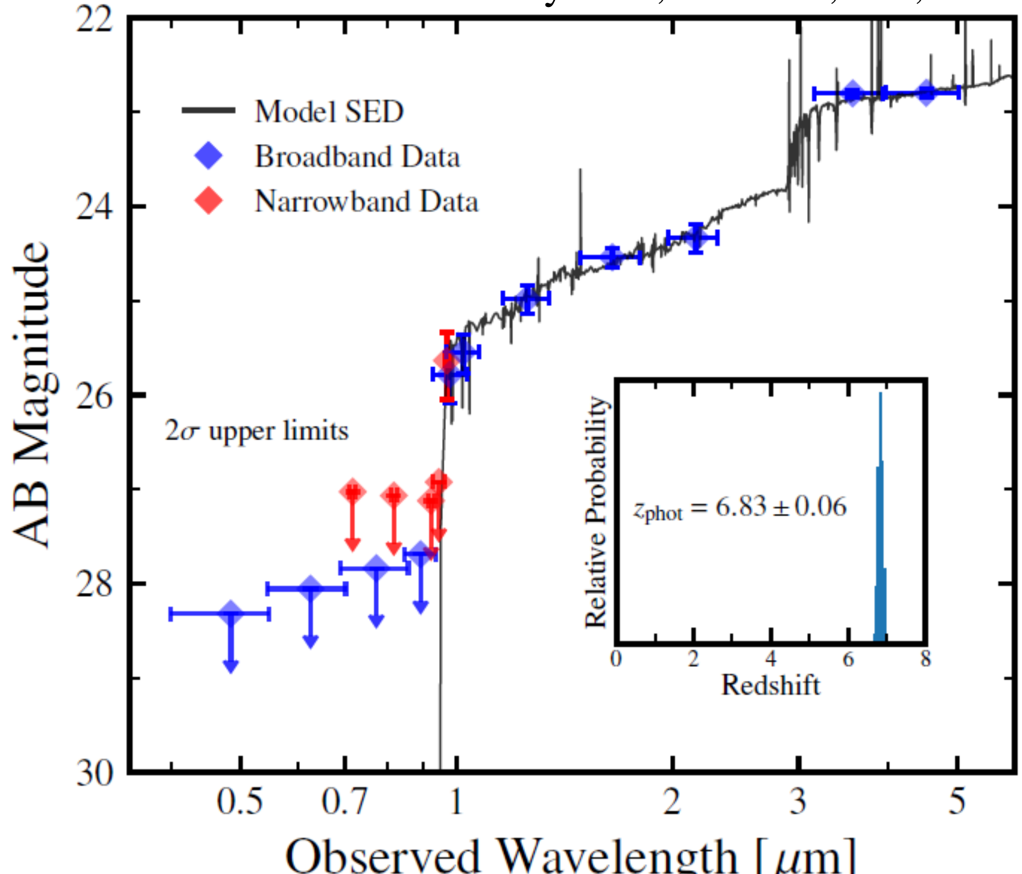
An Extremely Red, Massive z≈6.8 Galaxy

Identified a z≈6.8 galaxy in COSMOS with an extremely red UV slope and apparent strong Balmer Break.

- UV slope $\beta = -0.6$ versus typical $\beta \sim -2$
- Infer stellar mass $>10^{10}$ M_{sol}

Investigated rich multi-wavelength data sets in COSMOS to better understand source.

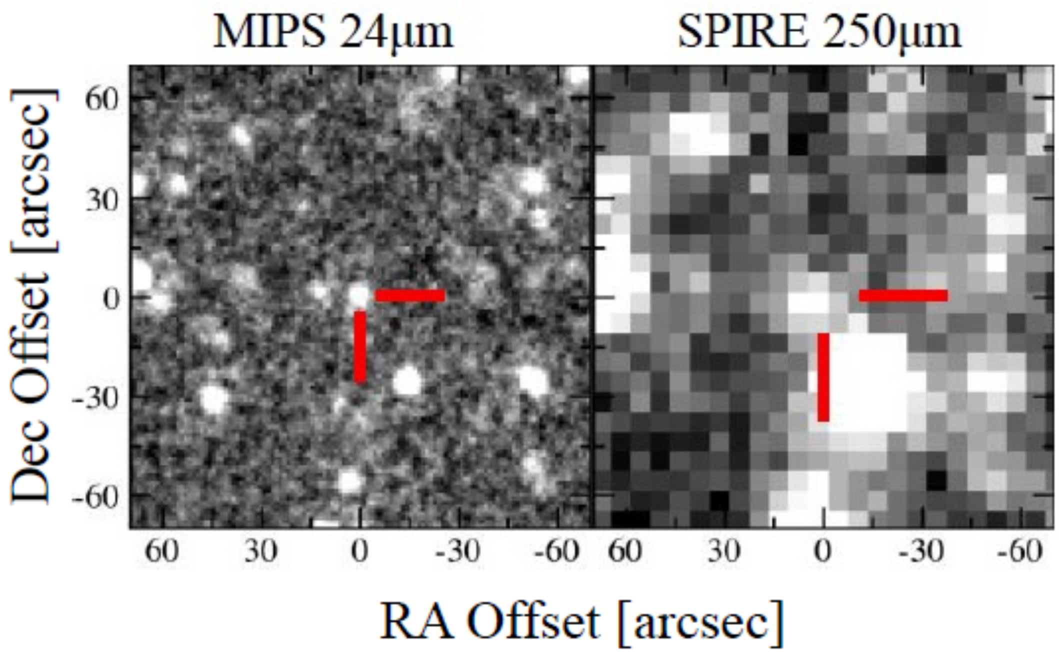
Endsley+22b, MNRAS, 512, 4248



Multi-wavelength Characterization

Detected in all six MIPS, PACS, and SPIRE bands (24–500 μm).

➢ Hot dust emission from an extremely luminous obscured AGN.

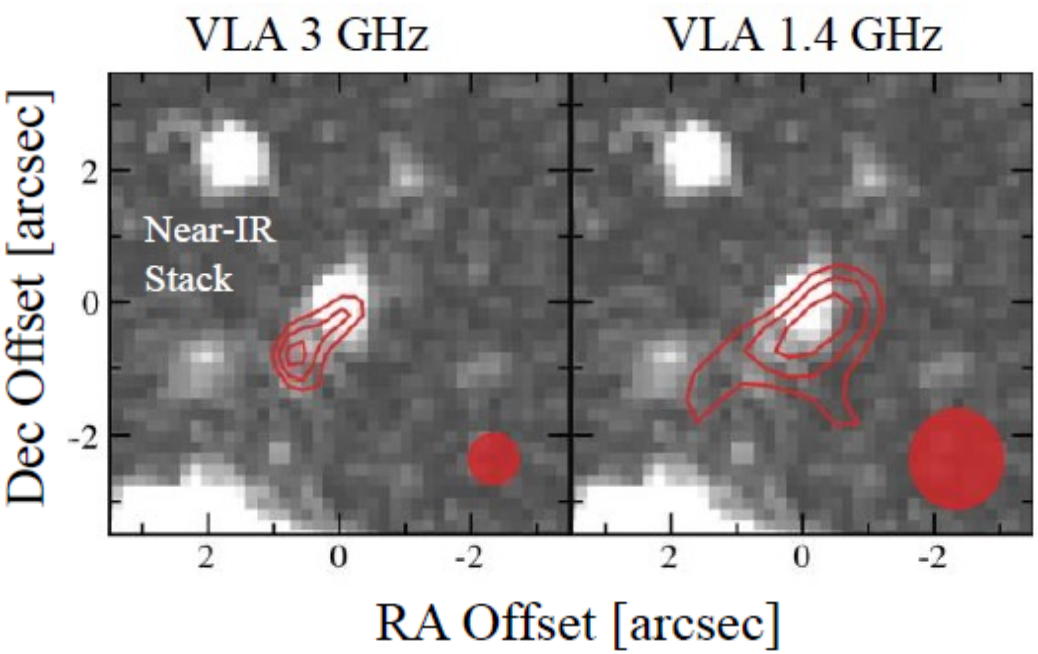


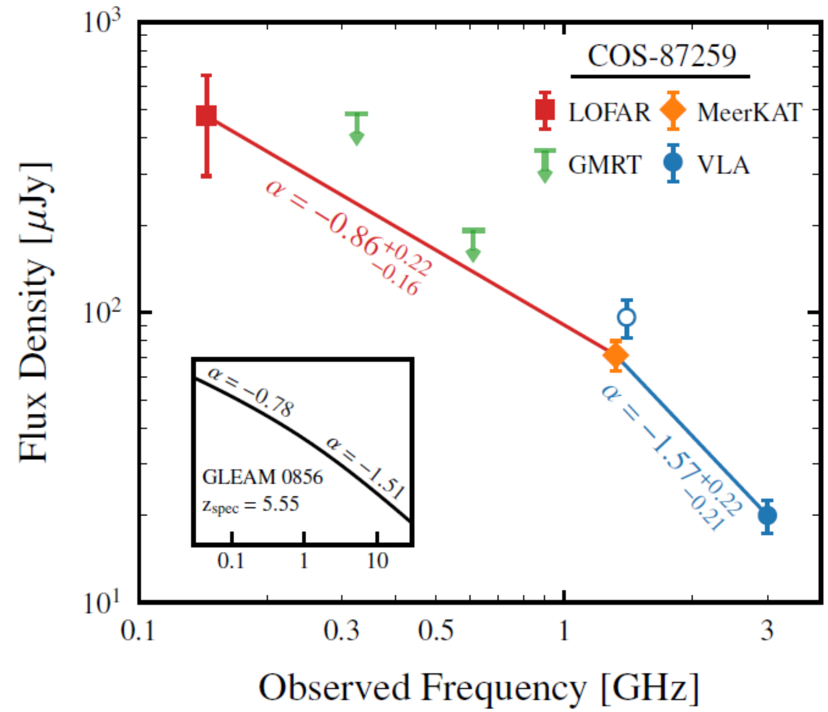
Endsley+22b, MNRAS, 512, 4248

Multi-wavelength Characterization

Detected in VLA, LOFAR, and MeerKAT (144 MHz – 3 GHz)

- Synchrotron emission from AGN jet.
- Shows strong turnover in radio slope as expected at very high redshifts.





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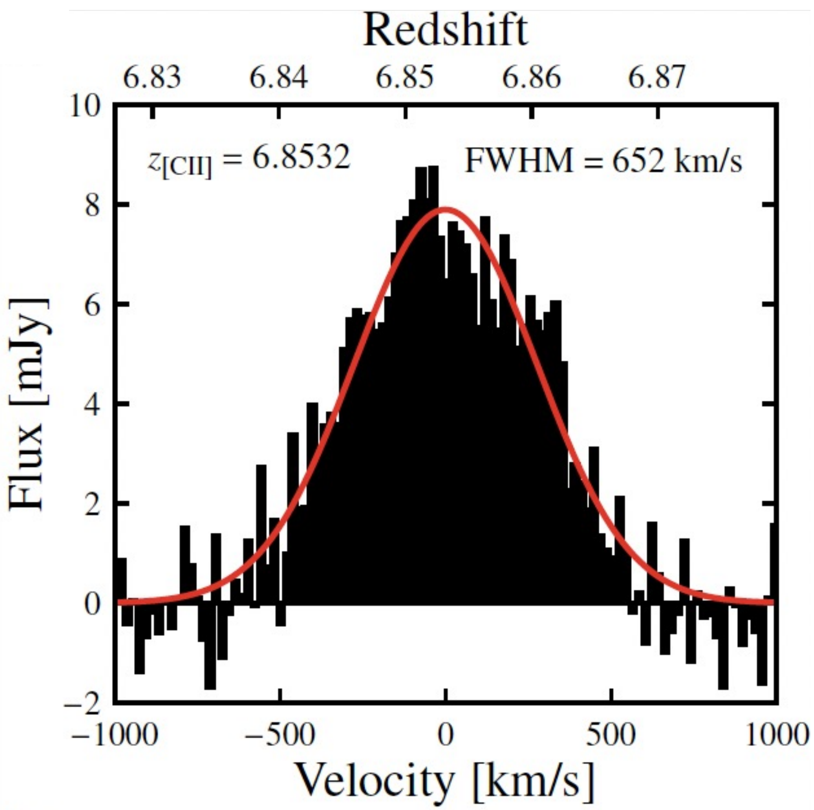
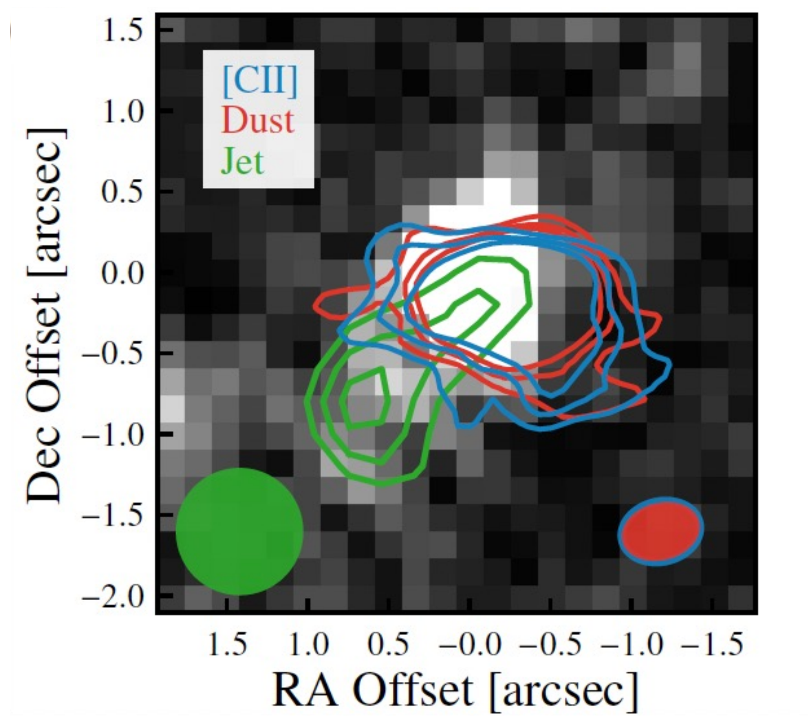
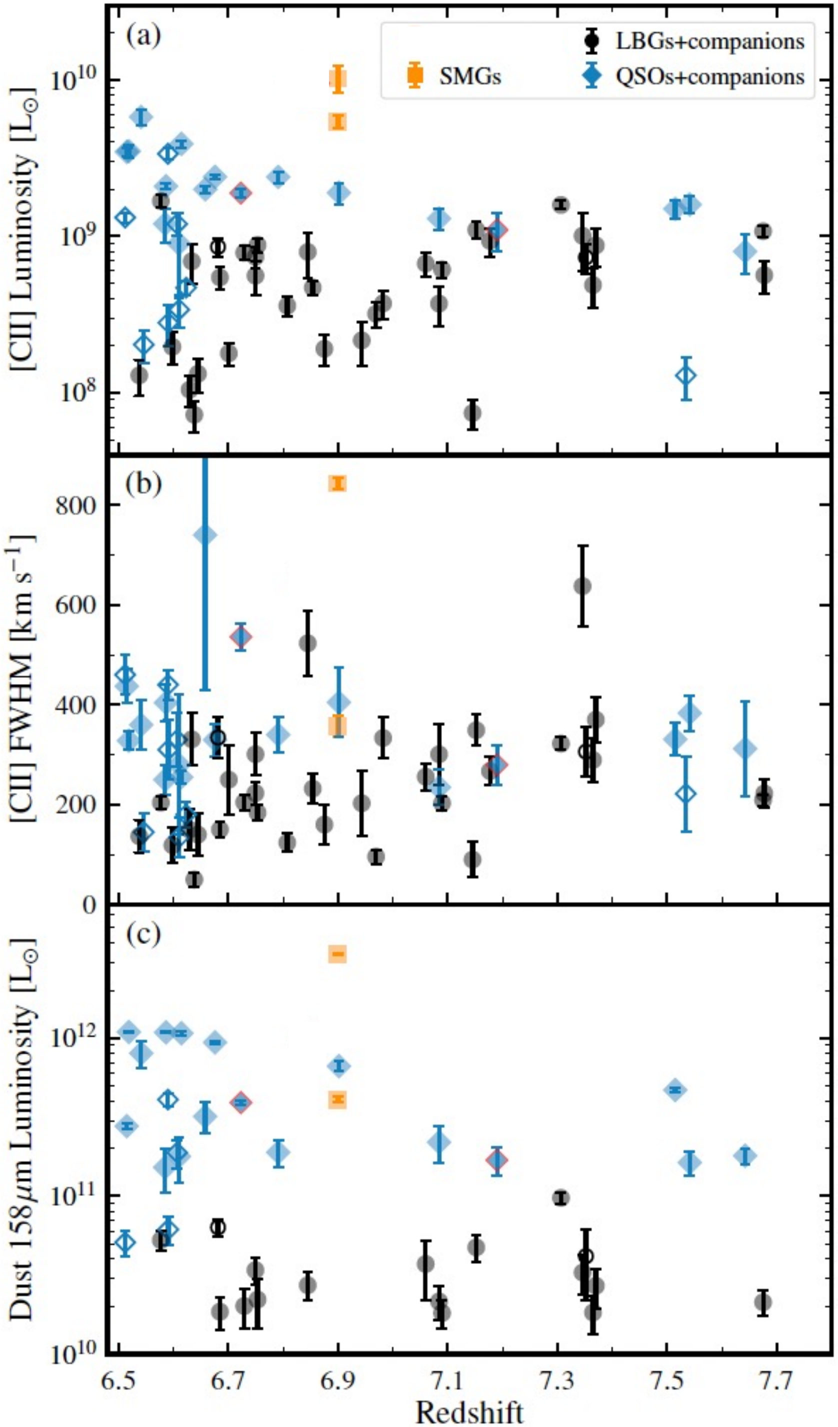
Cycle 8 ALMA Confirmation

Very strong [CII]158μm and underlying dust continuum detections.





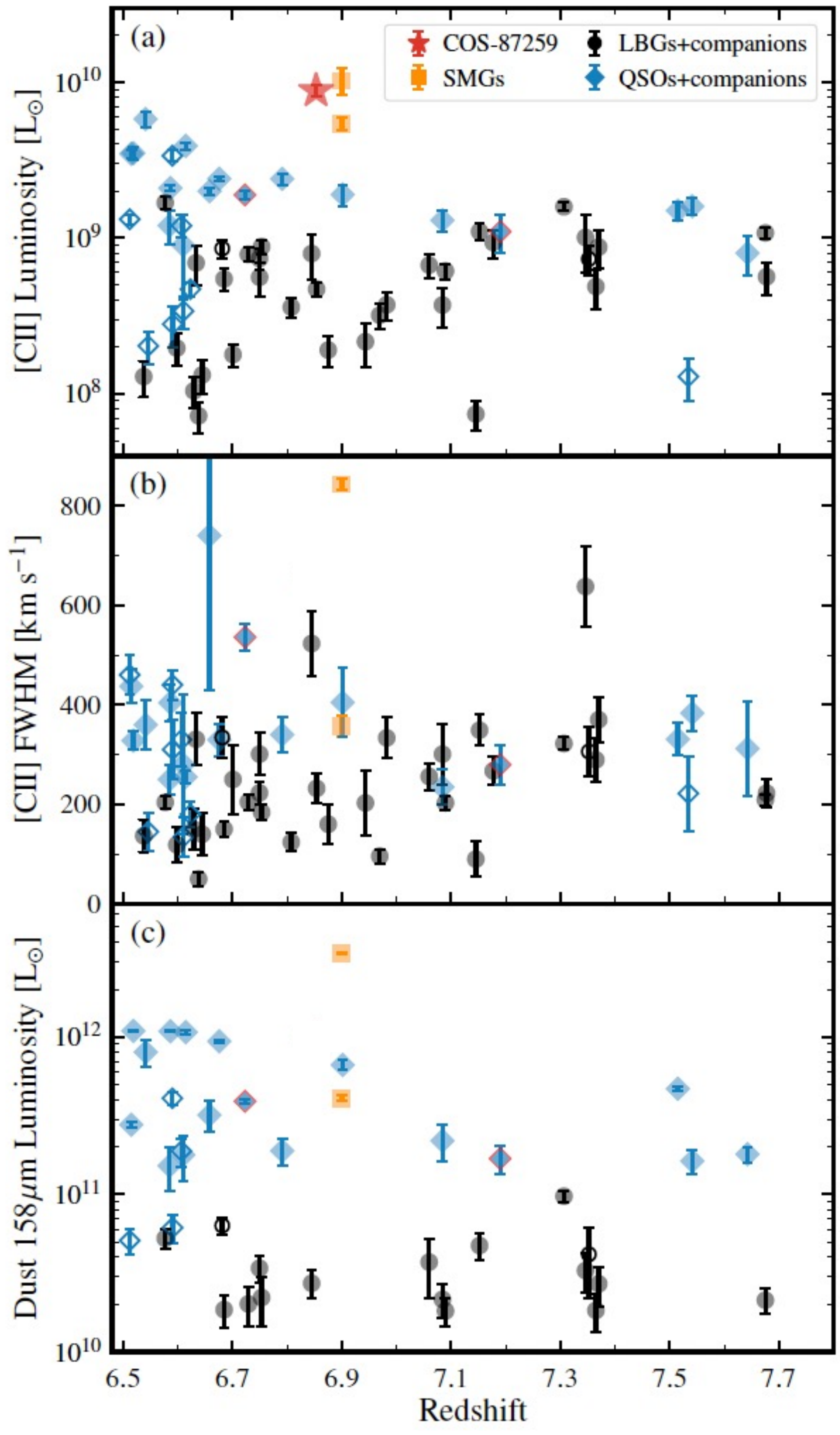
Endsley+22d: arXiv:2206.00018



Placing the far-IR measurements of COS-87259 in context of other z>6.5 objects:

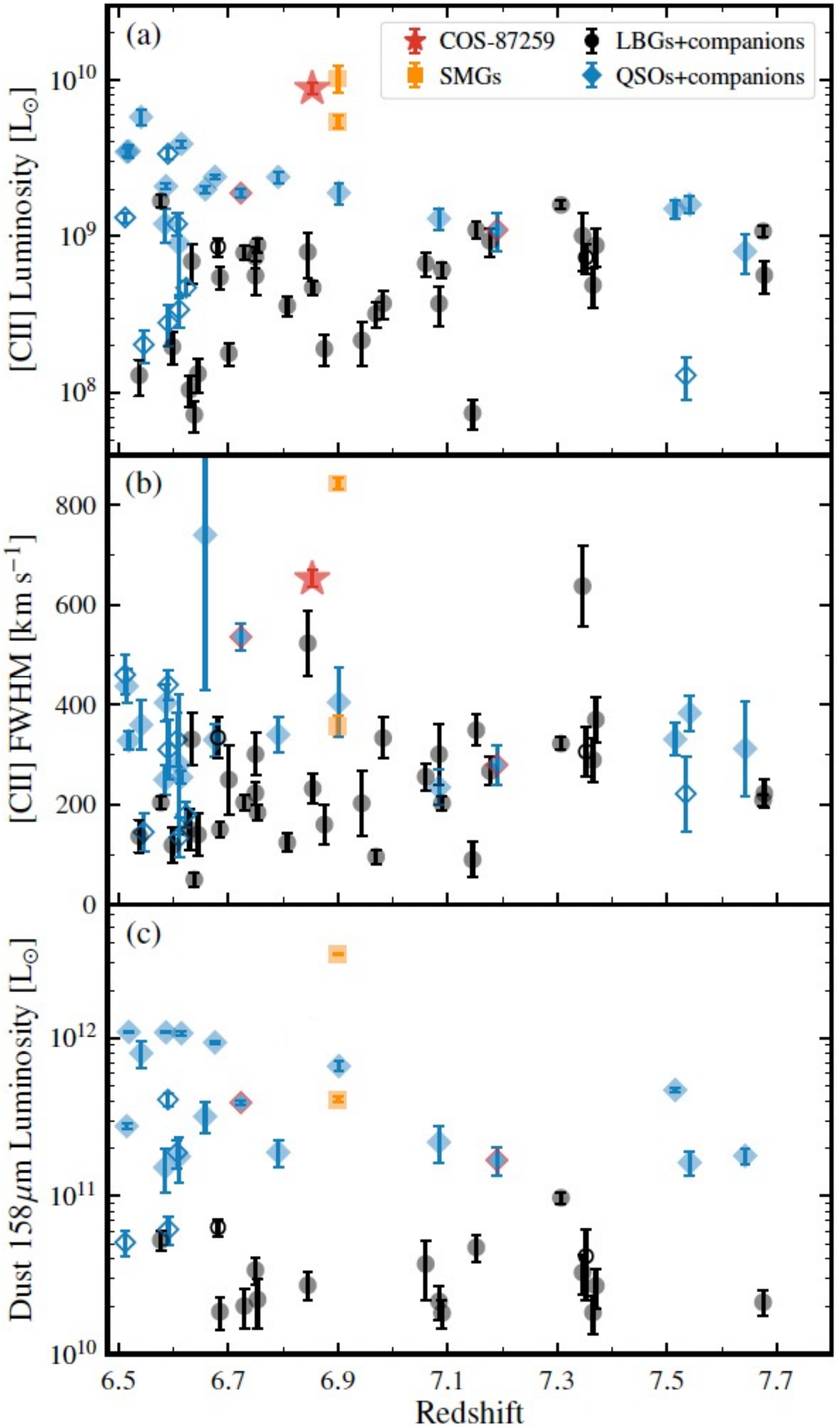
- Sub-mm galaxies
- Lyman-break galaxies
- Quasars

see Endsley+22d: arXiv:2206.00018



COS-87259 is one of the most [CII] luminous object known at z>6.5, comparable to SPT-0311 and the most luminous quasars.

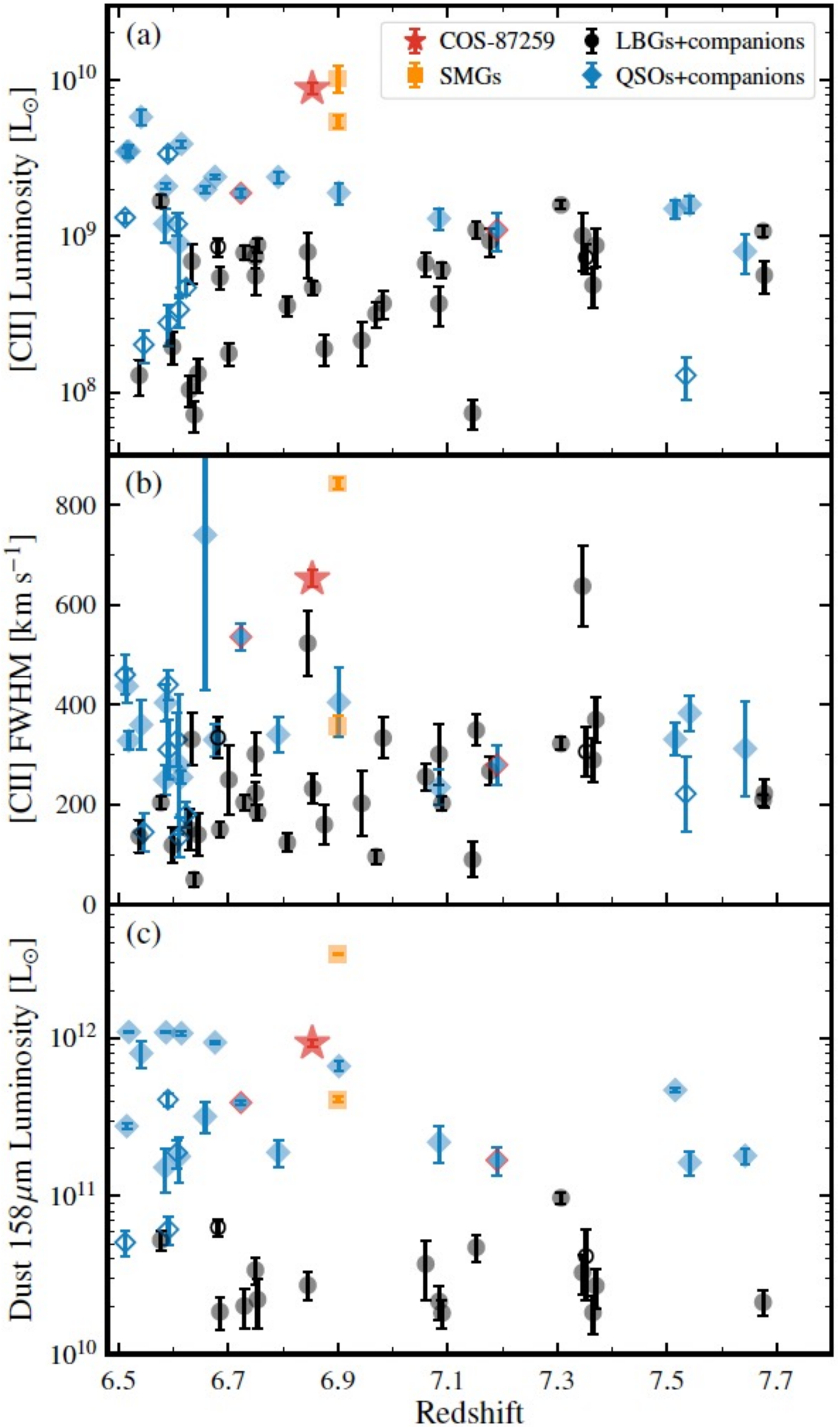
Endsley+22d: arXiv:2206.00018



COS-87259 is one of the most [CII] luminous object known at z>6.5, comparable to SPT-0311 and the most luminous quasars.

…exhibits one of the broadest [CII] lines known at z>6.5 (implies very large dynamical mass of ~10^{11} $M_\odot$).

Endsley+22d: arXiv:2206.00018



COS-87259 is one of the most [CII] luminous object known at z>6.5, comparable to SPT-0311 and the most luminous quasars.

…exhibits one of the broadest [CII] lines known at z>6.5.

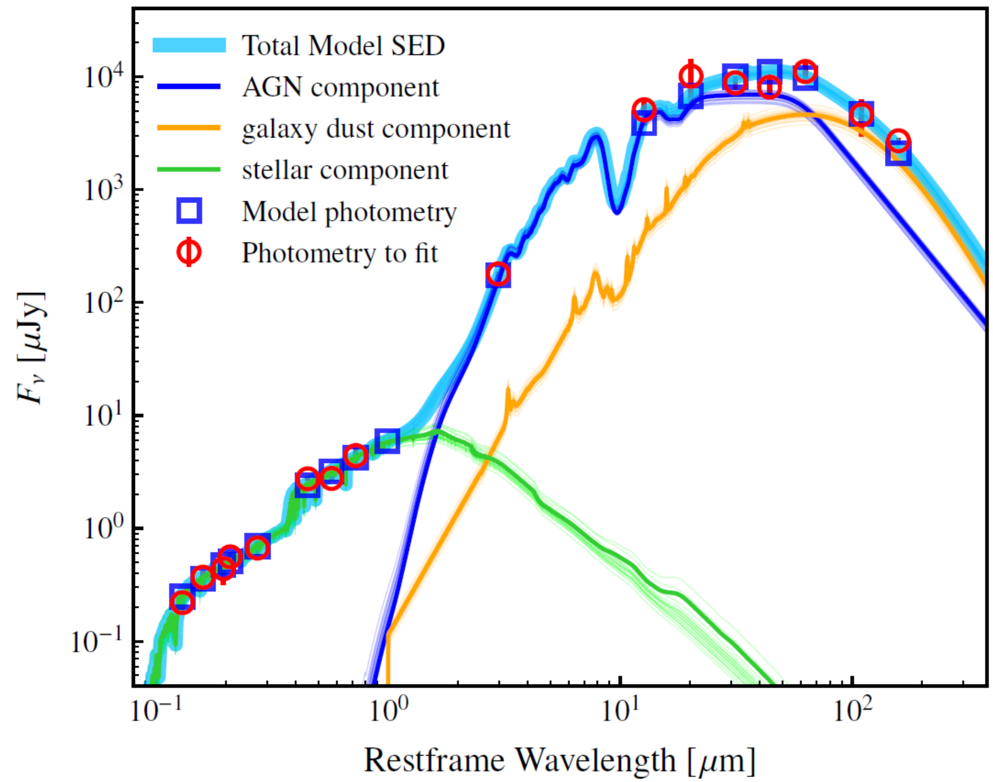
…shows a 158μm dust continuum luminosity comparable to the most luminous z>6.5 quasars.

Endsley+22d: arXiv:2206.00018

A New Sub-mm + Radio Galaxy at z=6.853

Full X-ray to radio SED implies:

- Stellar mass ≈10^{11} $M_\odot$.
- Intense obscured star formation (SFR_{IR} ~ 1300 $M_\odot$/yr).
- Radio-loud AGN ($L_{1.4GHz}$ = $10^{25.4}$ W/Hz).
- Effectively a highly-obscured z~7 quasar powered by a ≈billion solar mass black hole.
    - ➢ Unobscured M_{UV} ≈ –27: expect 1 per 3000 deg^{-2}



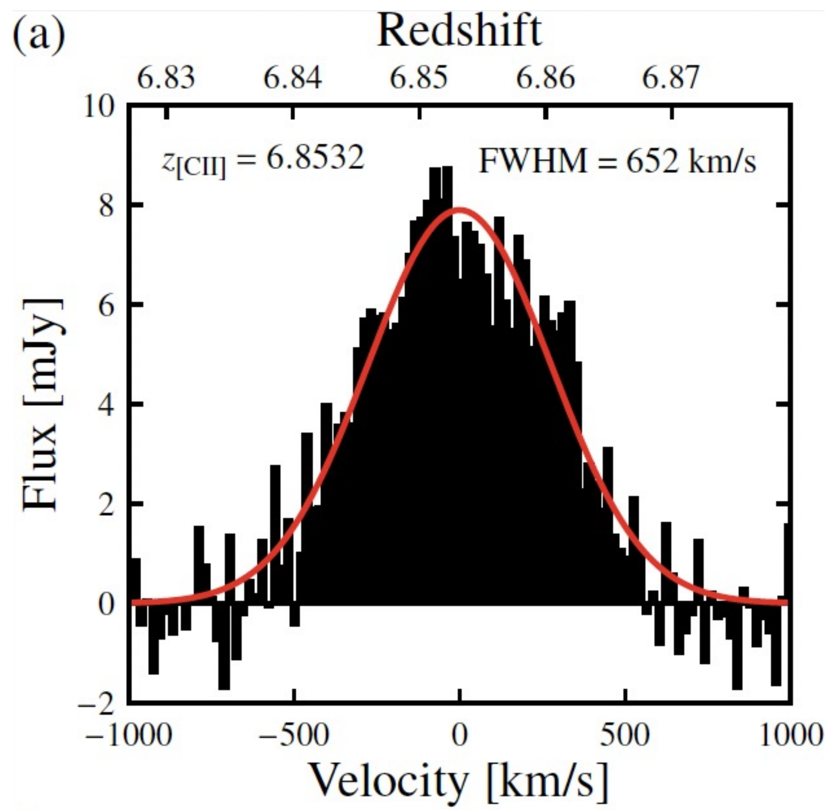
Endsley+22b, MNRAS, 512, 4248
Endsley+22d: arXiv:2206.00018

Implications for Early Evolution of Extremely Massive Galaxies and Supermassive Black Holes

COS-87259 is one of four $M_* > 10^{10}\ M_\odot$ z~6.6-6.9 galaxies identified in COSMOS.

May suggest that early very massive systems undergo intense bursts of obscured star formation activity relatively frequently.

Identification in 1.5 deg^2 COSMOS field may also suggest that the large majority of early supermassive black hole growth is heavily obscured.



Endsley+22b, MNRAS, 512, 4248
Endsley+22d: arXiv:2206.00018

Advancing our Understanding with Euclid

Deep Euclid photometry alone would deliver confident z~7 solution for COS-87259.

- ➢ Will soon better quantify abundance of UV-bright yet extremely red z>6 galaxies.
- ➢ Follow-up with e.g. ALMA and MIRI would constrain dust-obscured star formation activity and supermassive black hole growth (X-ray and radio complementary).