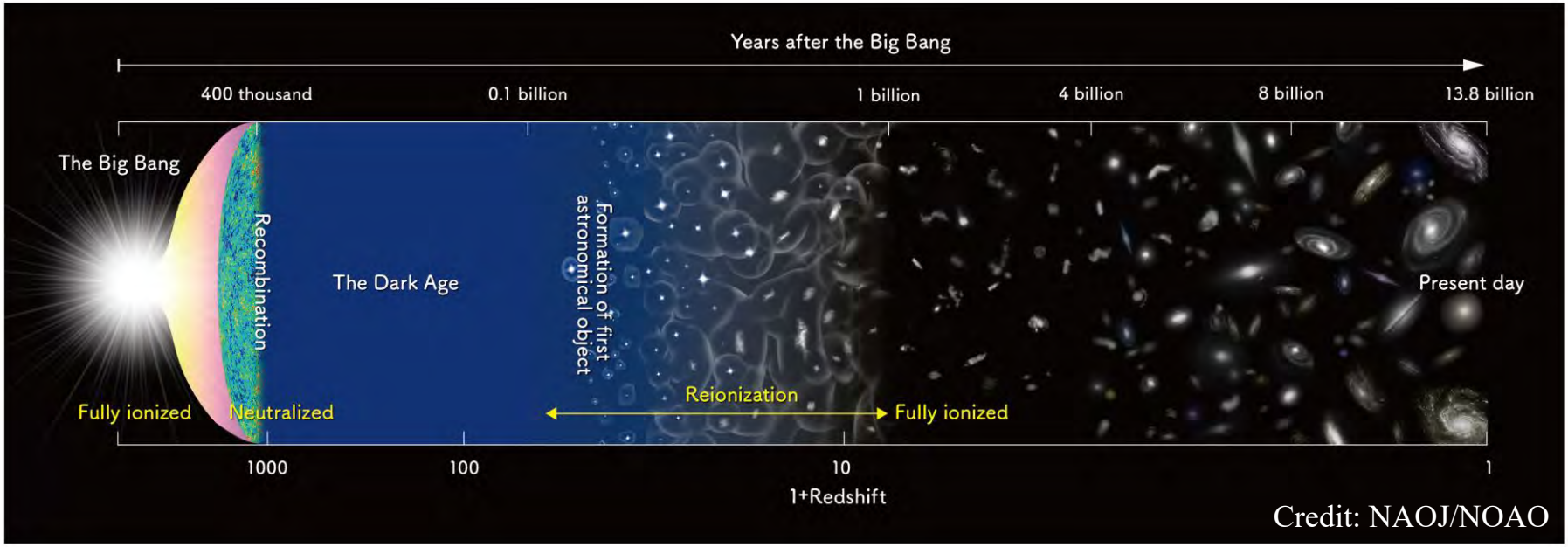
A Wide-area View on Reionization:

Identifying and Mapping the Largest Ionized Bubbles



Credit: NAOJ/NOAO

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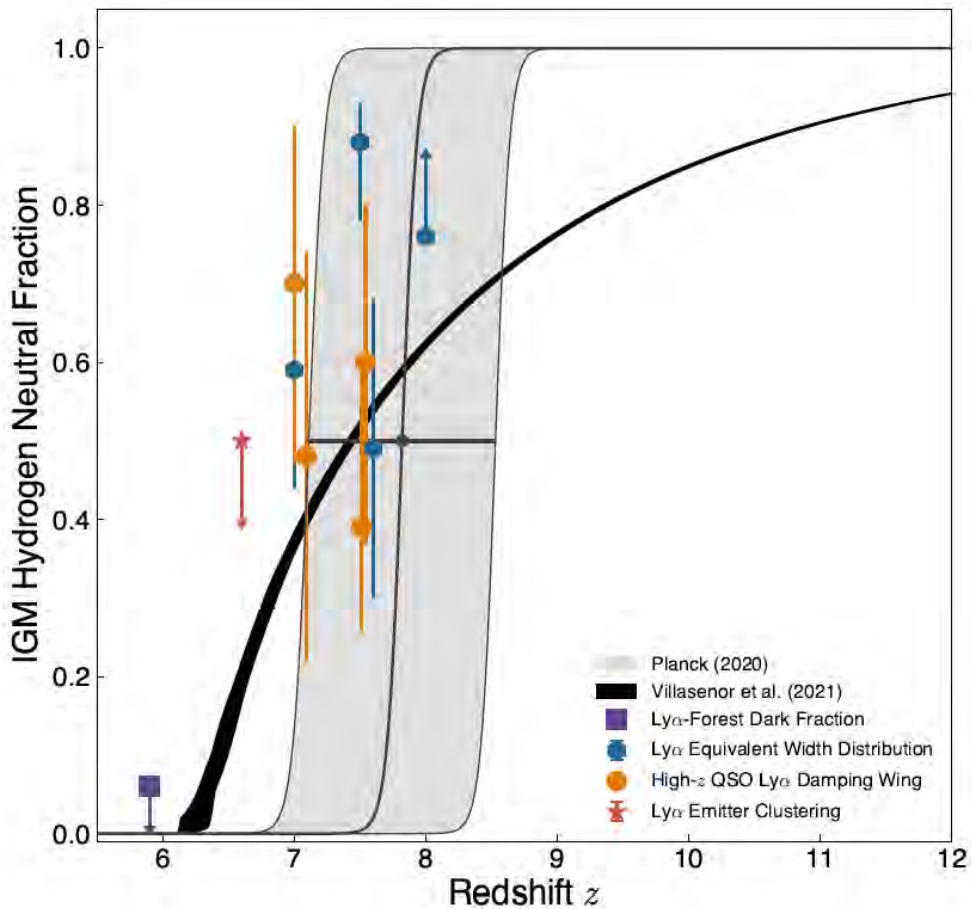
University of Arizona

PhD advisor: Dan Stark

Understanding the Process of Reionization

Robertson+21



When did reionization occur?

Substantial progress over the past decade from variety of studies.

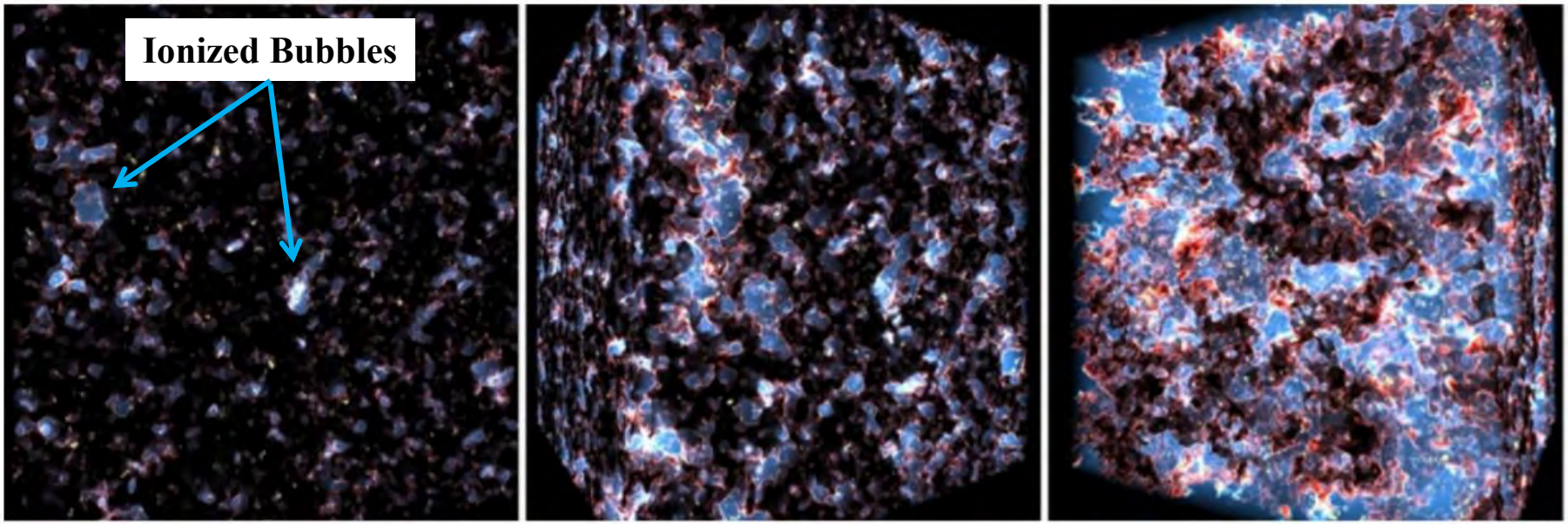
- IGM largely reionized by z=6 ($x_{HI} \leq 0.1$)
- Substantially neutral at z~7–8 ($x_{HI} \sim 0.5$)

e.g., McGreer+15, Zheng+17, Davies+18, Mason+18, Hoag+19, Jung+20, Planck Collaboration 2020, Yang+20, Wold+21

Understanding the Process of Reionization

How did reionization progress?

Early stage of reionization → Late stage of reionization



Alvarez+09

Several key questions remain unanswered. For example:

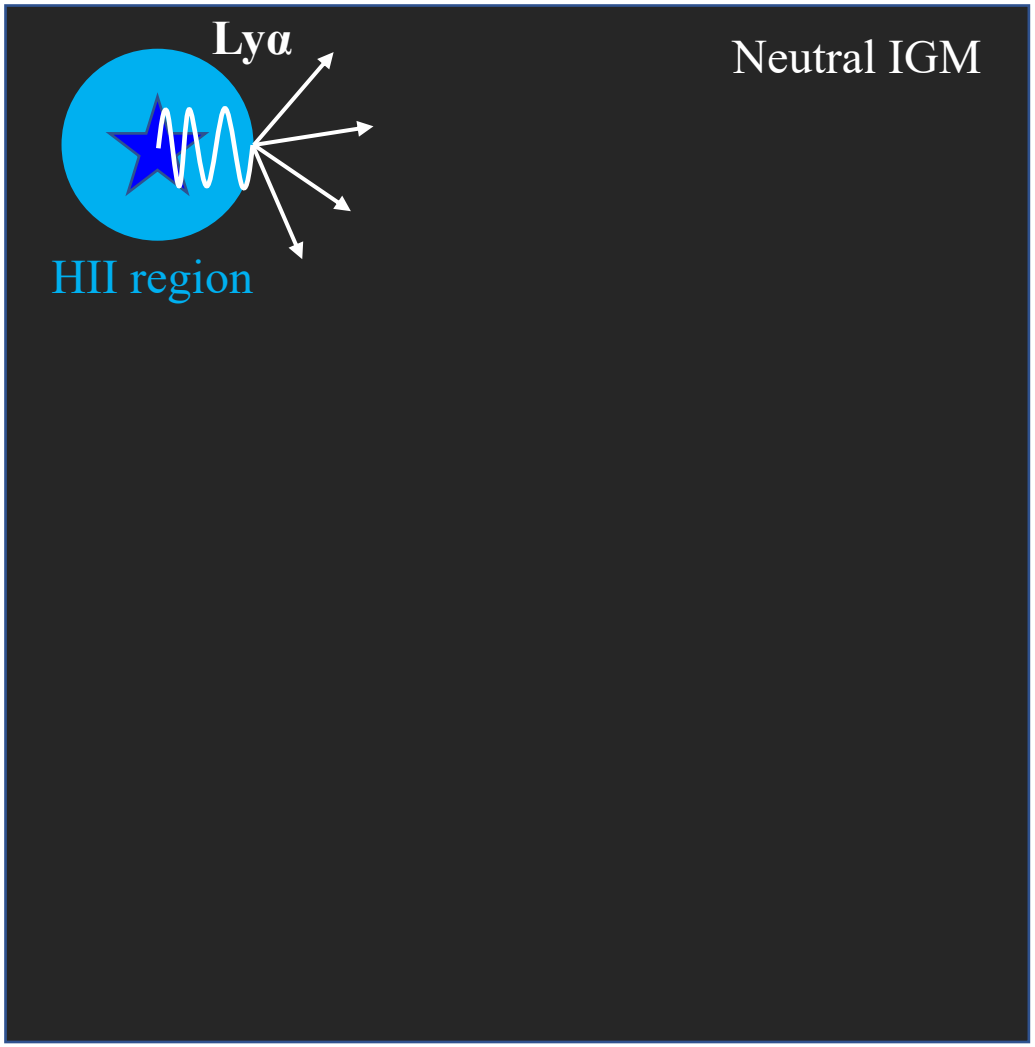
- What is the size and spatial distribution of ionized bubbles at a given redshift?
- What is the connection between bubble size and local galaxy overdensity?

Identifying Large Ionized Bubbles with Lyman-alpha

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≥7 (~10%).



e.g., Miralda-Escude 1998, Malhotra & Rhoads 2004, Mesinger & Furlanetto 2007

Identifying Large Ionized Bubbles with Lyman-alpha

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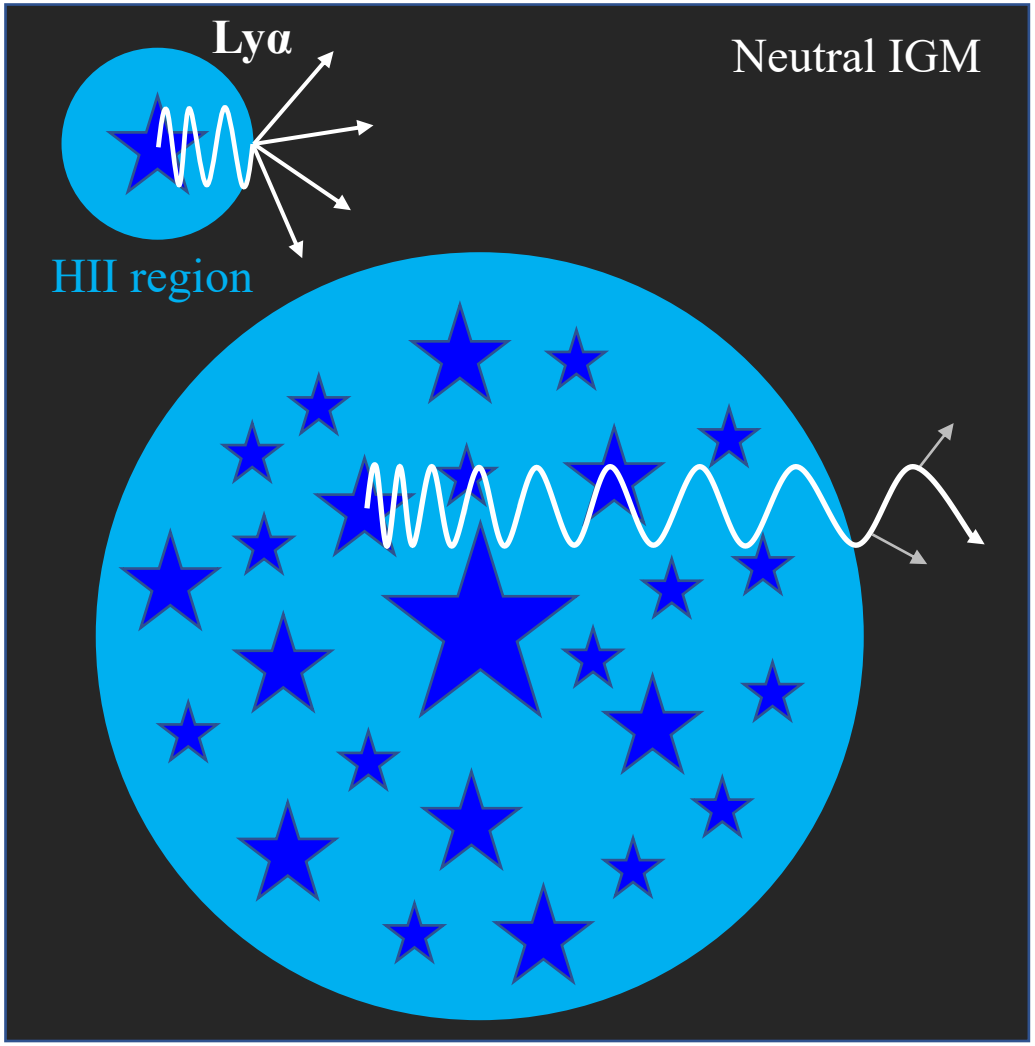
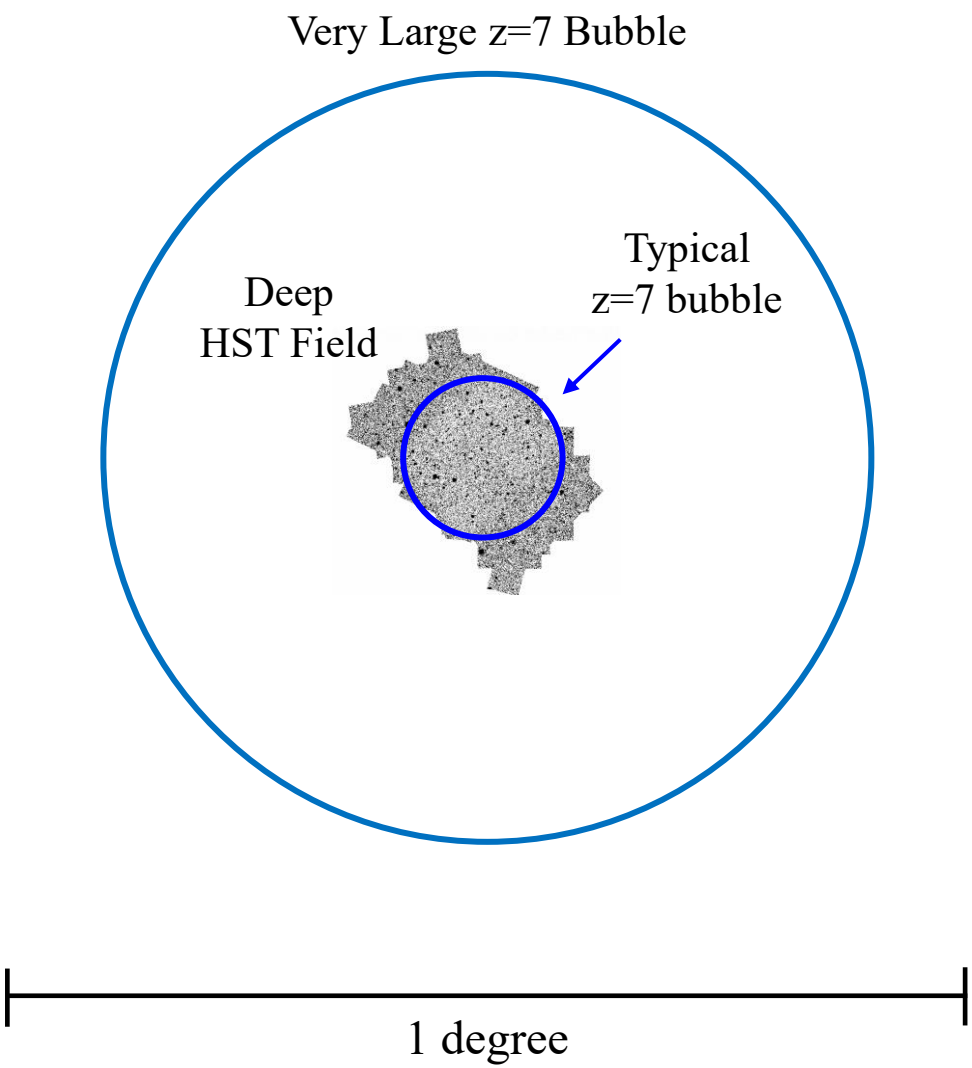
Large ionized bubbles boost Lyα transmission through IGM.

- Enhanced Lyα emission from z≥7 galaxies in a given volume indicates an ionized bubble.



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

The Need for Wide-Area Surveys



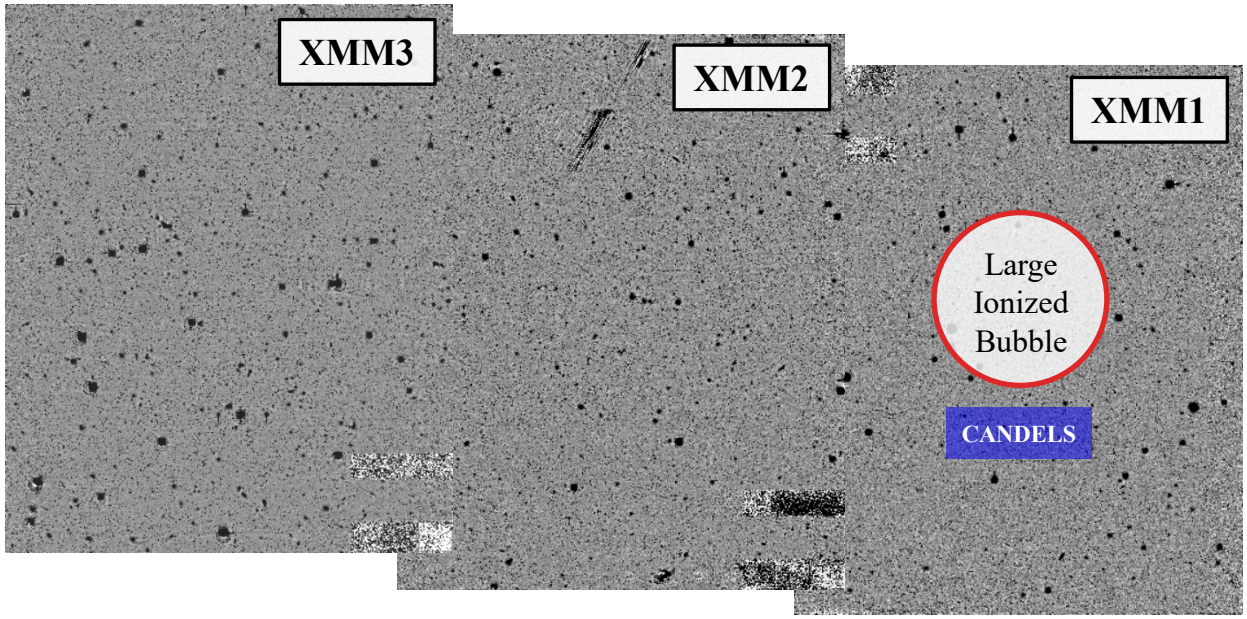
Typical bubbles at z=7 are expected to be ~10 arcmin in diameter. Largest bubbles predicted to be ~1 degree diameter.

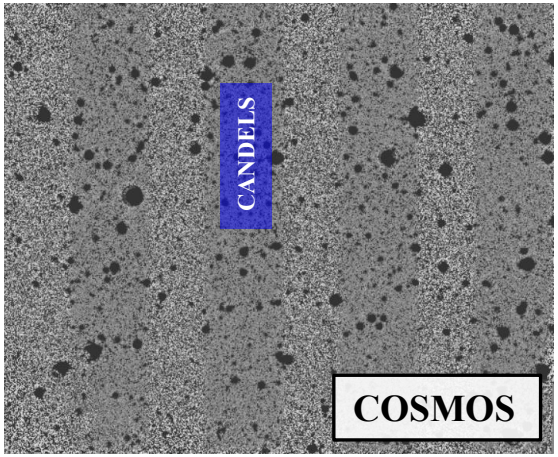
⇒ Need wide (~10+ deg^2) areas to sample representative range of ionized and neutral regions and simultaneously capture largest bubbles.

Bubble size estimates from Lin, Oh, & Furlanetto 2016

Wide-area z~7 Lyα Survey

MMT/Binospec Lyα survey of UV-bright (L_{UV} = 1-6 L^*_{UV}), massive z~7 Lyman-break galaxies identified across 7 deg^2 of ground-based imaging.





Survey Results:

- Identifying likely large (R~3 physical Mpc) bubbles at z~7 via enhanced Lyα emission.
- Quantifying galaxy overdensities in those regions.

Endsley+21a, MNRAS, 500, 5229
Endsley+21b, MNRAS, 502, 6044
Endsley+21c,d in prep

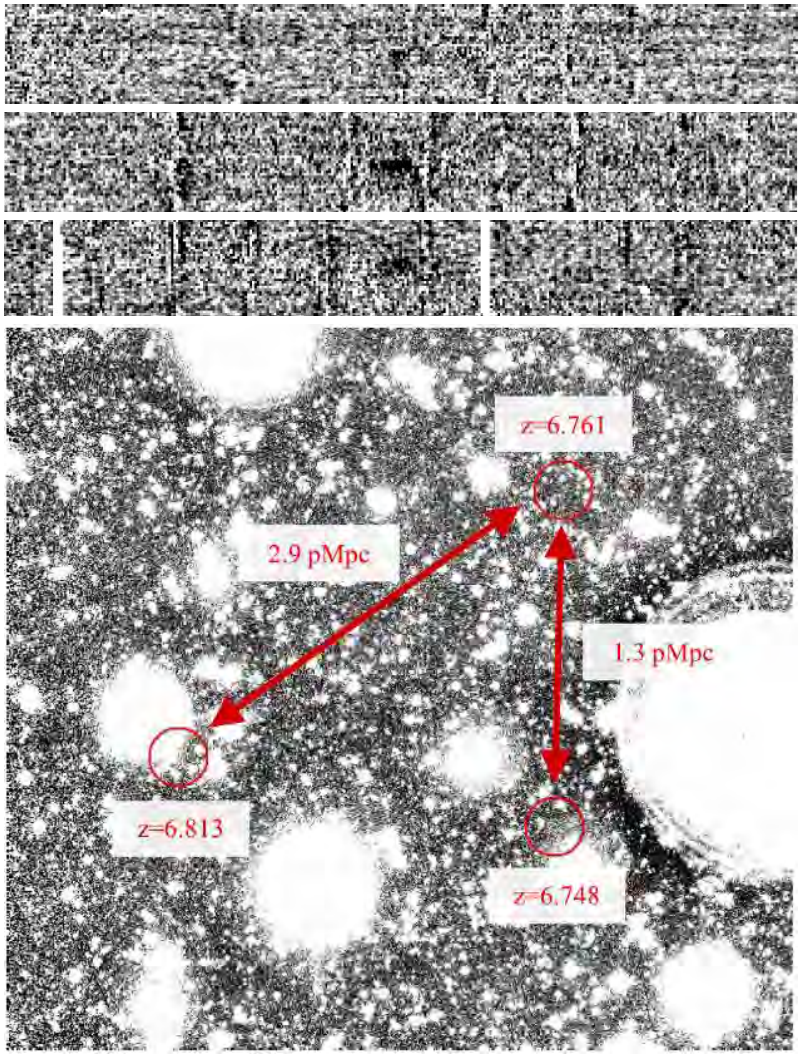
Three Extremely Close Massive Galaxies at z=6.8 with Lyα Detections

Detect 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.

Surface density of UV-luminous galaxies suggest substantial overdensity.

- N/<N> ≈ 4 on ~5 arcmin scales.



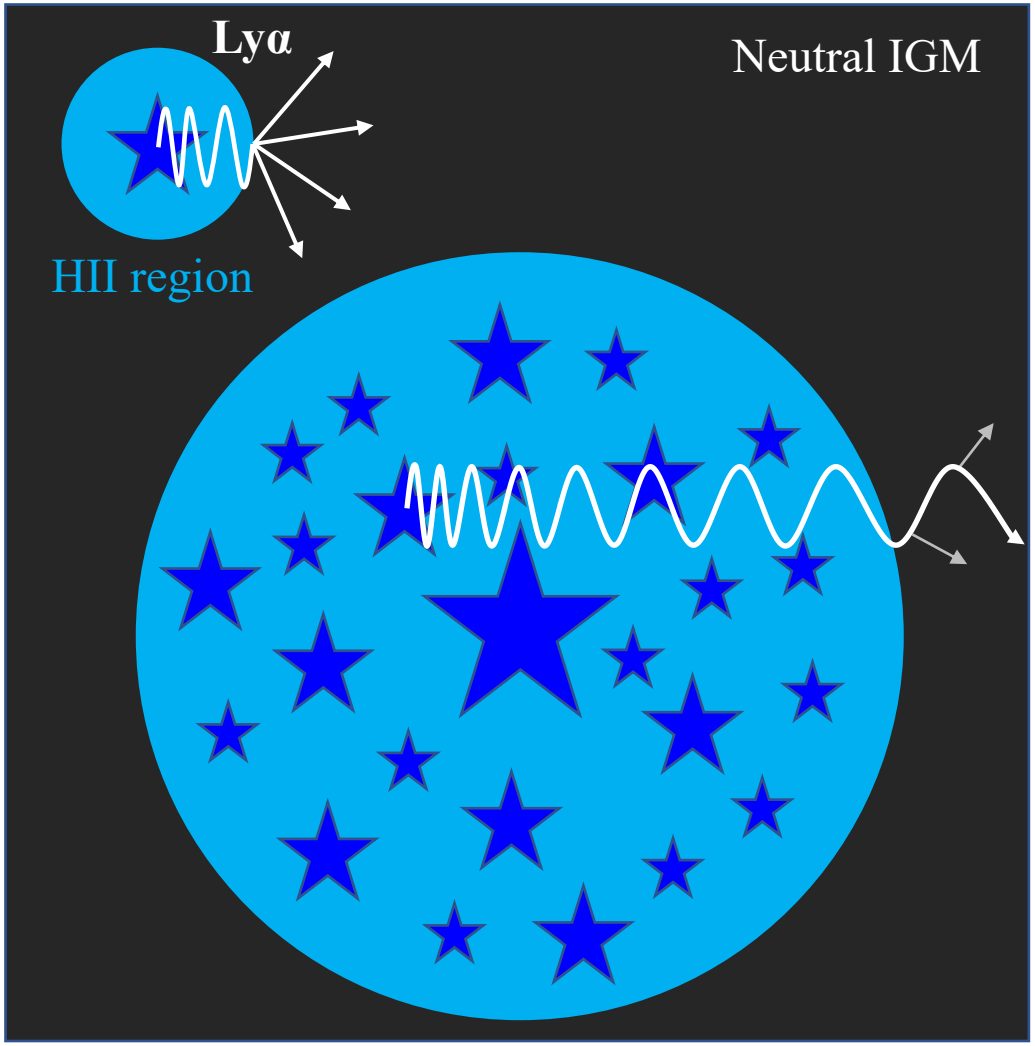
See also Castellano+18, Jung+20, Tilvi+20, Hu+21

Endsley+21b, MNRAS, 502, 6044

Overdensity Powering Large Ionized Bubble?

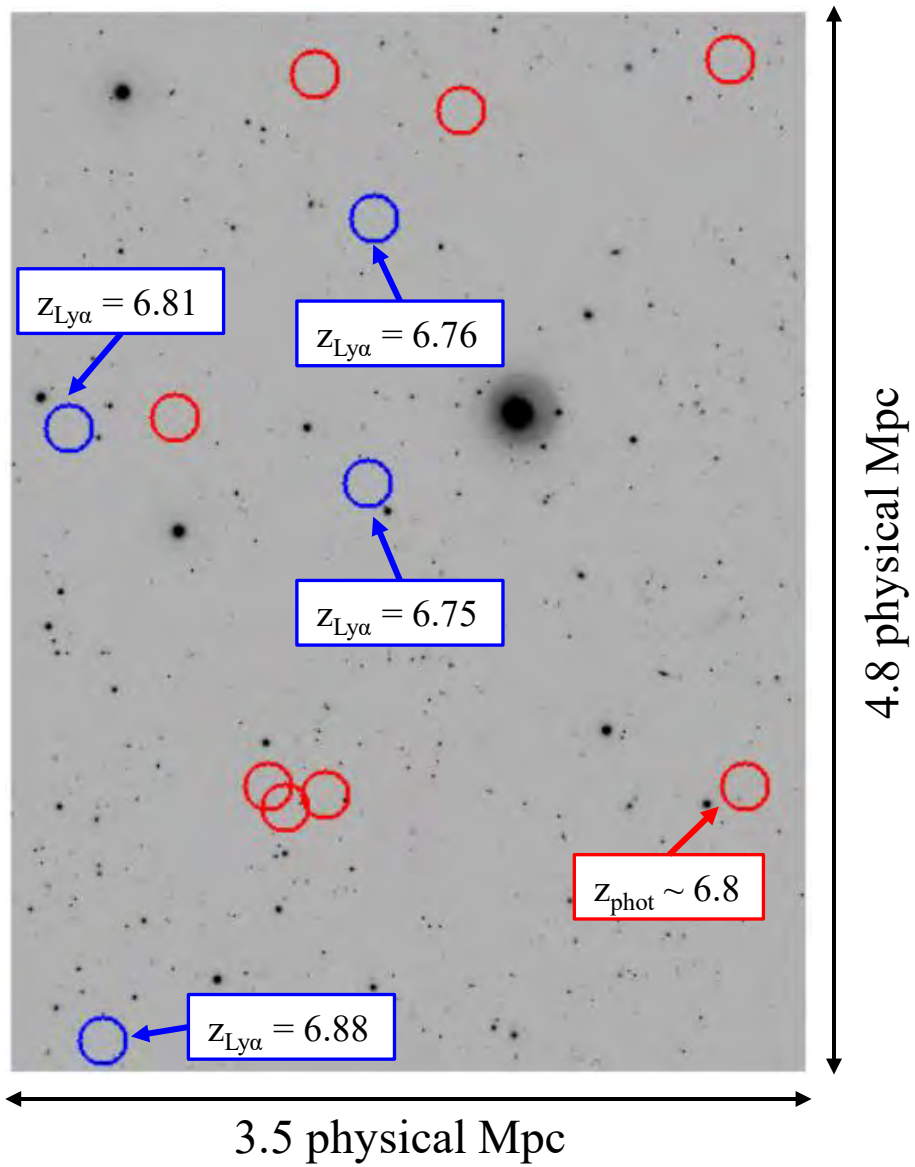
- Do the three Lyα emitters trace a more extended overdensity?
- Do other galaxies in their vicinity show enhanced Lyα?

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



Characterizing Wider Area

Identify 12 massive (L_{UV} = 1-4 L^*_{UV}) z~6.8 Lyman-break galaxy candidates in the surrounding 11 x 15 arcmin^2.



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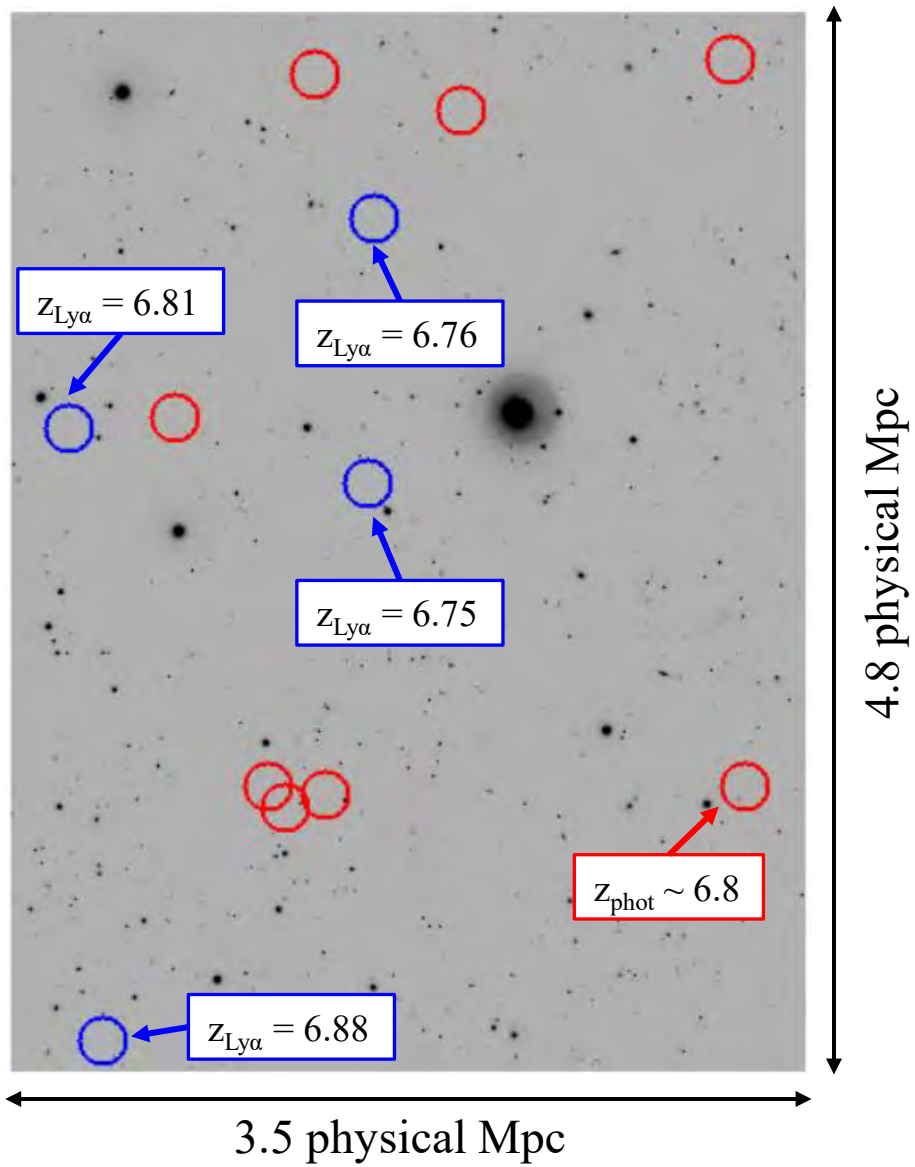


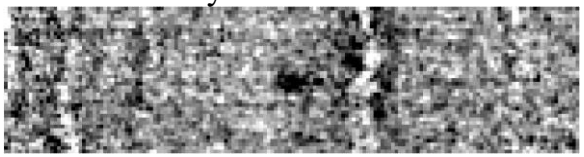
<u>Ultra-deep (~20 hr) Lyα follow-up:</u>

1) Quantify overdensity in this extended region.
2) Determine if local Lyα EW distribution is enhanced.
3) Better map extent of the ionized bubble.

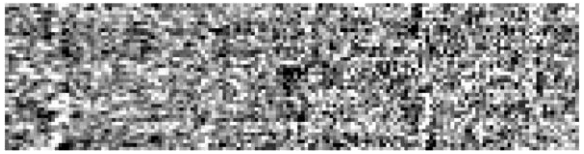
Results of Spectroscopic Follow-up

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

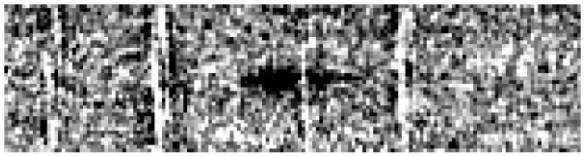
$z_{Ly\alpha} = 6.702$



$z_{Ly\alpha} = 6.746$



$z_{Ly\alpha} = 6.814$



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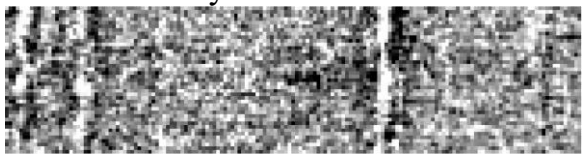
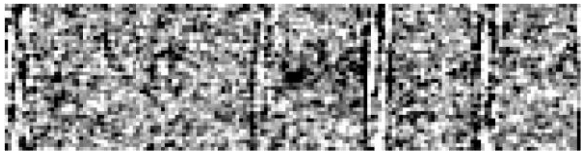
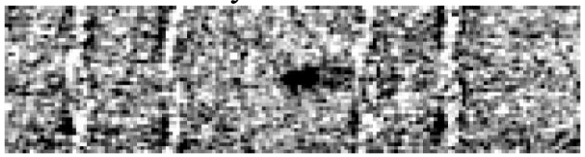


$z_{Ly\alpha} = 6.752$

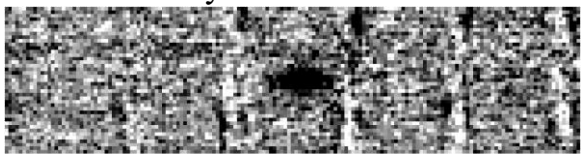


$z_{Ly\alpha} = 6.847$



$z_{Ly\alpha} = 6.736$

$z_{Ly\alpha} = 6.759$



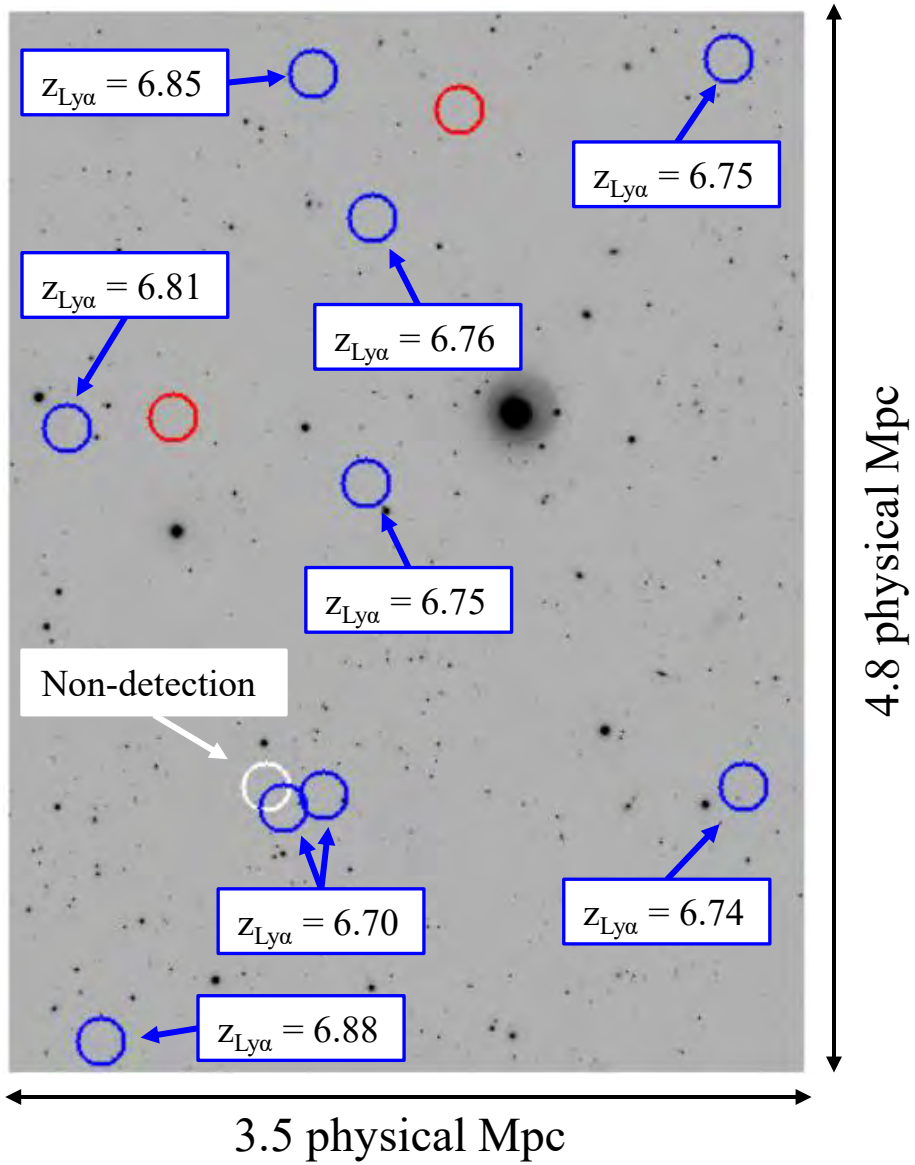
$z_{Ly\alpha} = 6.884$

Endsley+21c, in prep

A Large-scale Reionized Overdensity at z=6.8

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

- $z_{Ly\alpha}$ = 6.70-6.88.
- All sources contained within a 140 physical Mpc^3 volume (*R*=3.2 physical Mpc).



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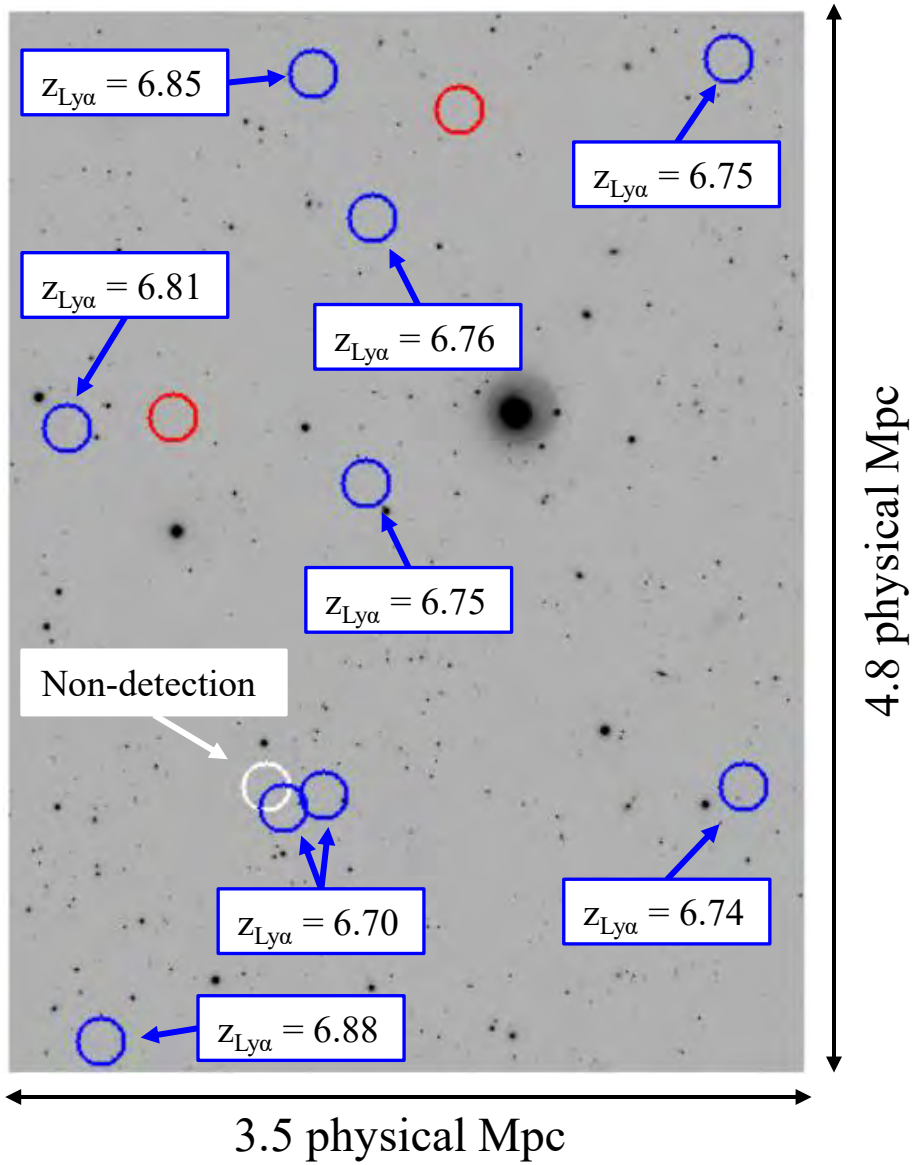
- $z_{Ly\alpha}$ = 6.70-6.88.
- All sources contained within a 140 physical Mpc^3 volume (*R*=3.2 physical Mpc).

- Large-scale overdensity of UV-bright (M_{UV} < -21) galaxies with N/<N> > 3.
- Lyα EWs enhanced by factor of ≈2.

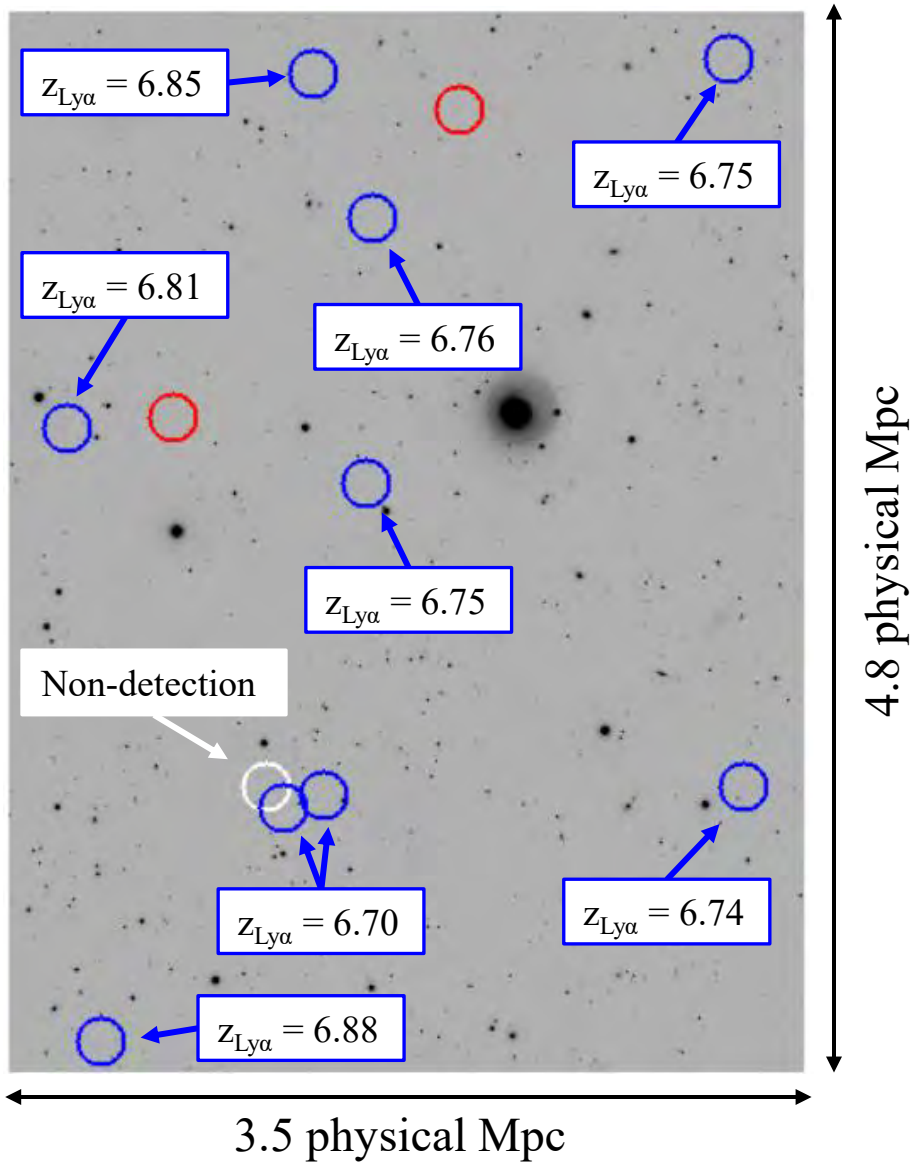


Endsley+21c, in prep

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? ✓

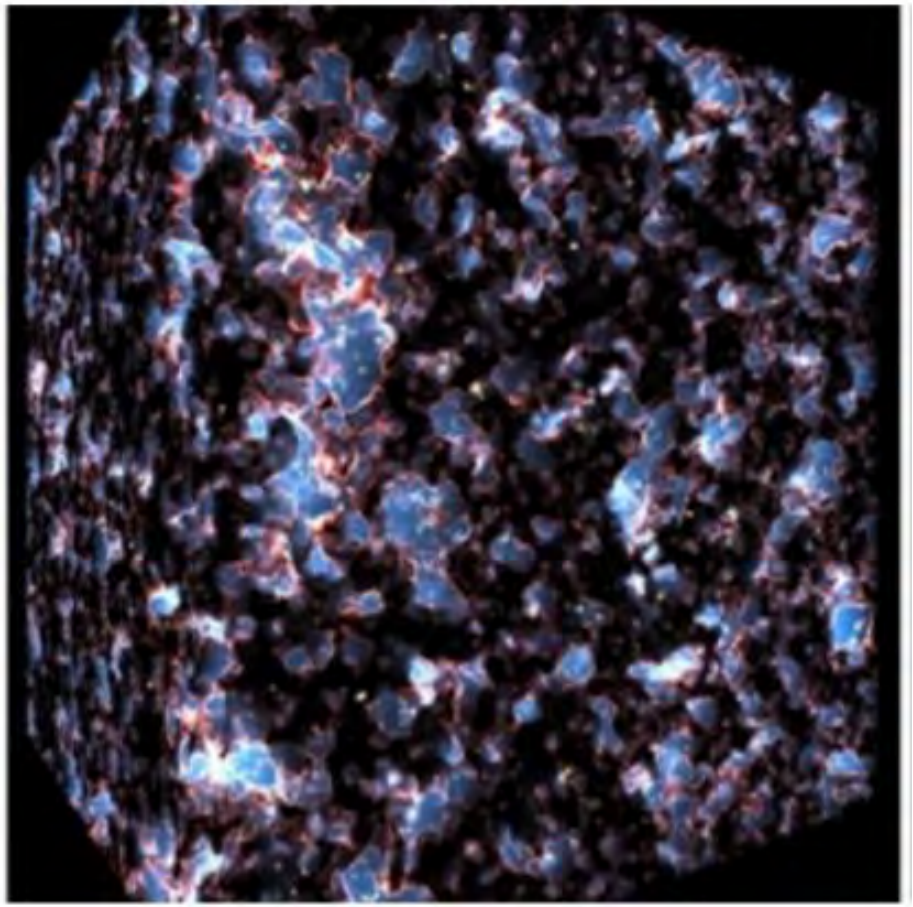
➢ Suggests this z=6.8 volume likely hosts a large (R≈3 physical Mpc) ionized bubble.



Endsley+21c, in prep

Moving Forward: Building a Picture of Reionization

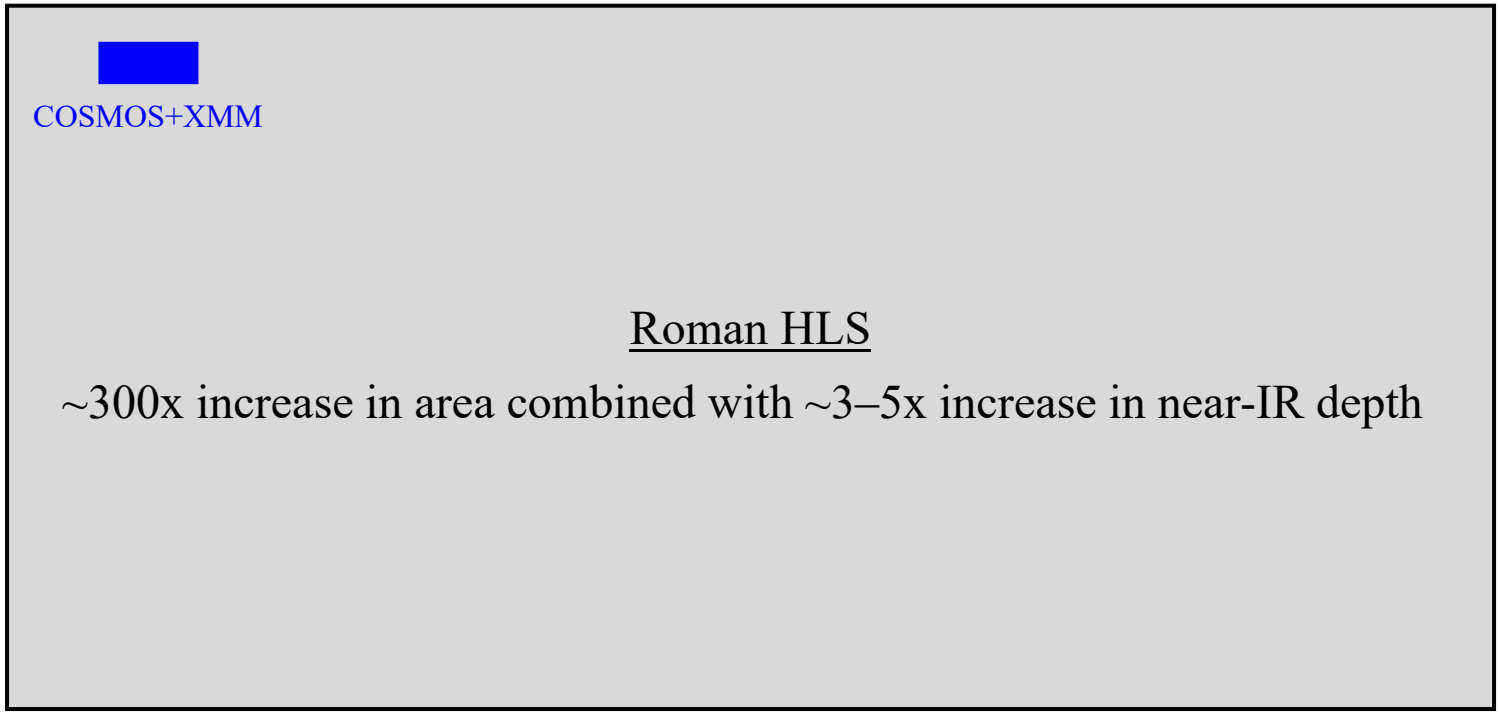
Alvarez+2009



Next step is to build deep, wide-area datasets to:

1. Statistically characterize the size and spatial distribution of ionized bubbles at $z \geq 7$.
2. Determine how bubble size correlates with overdensity.
3. Identify the largest ionized bubbles which trace the first sites of structure formation.

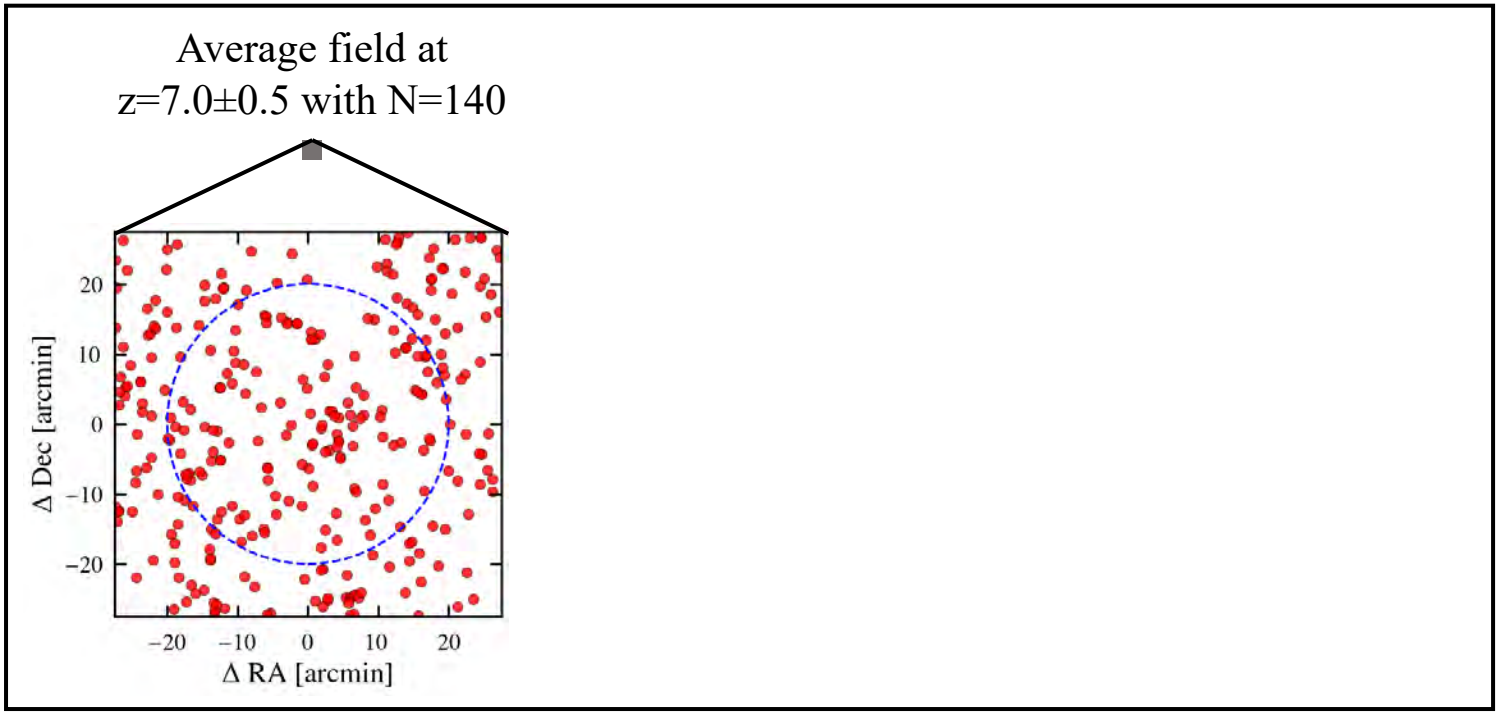
Revolutionizing Reionization Science with Roman



Roman HLS will enable the detection of millions of z≥7 galaxies over thousands of square degrees.

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

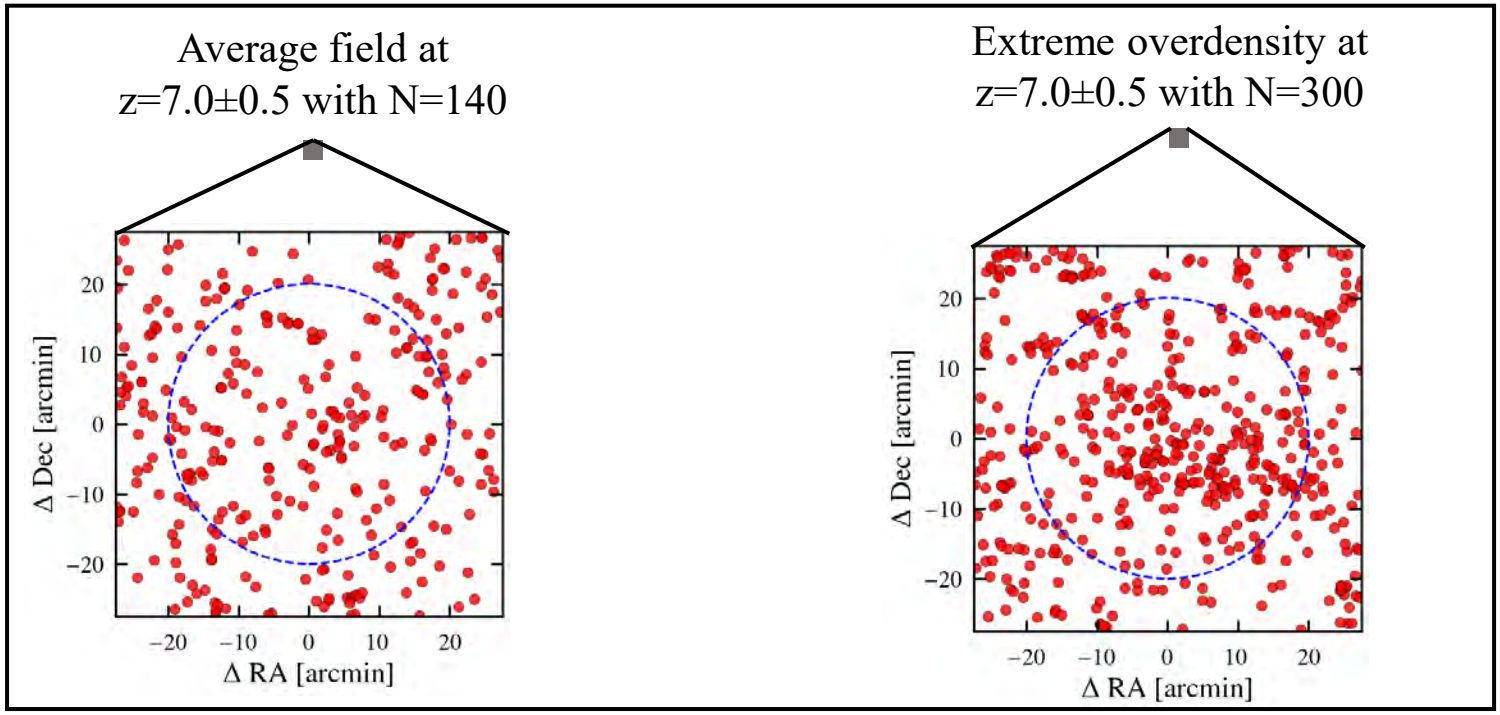
Identifying Extreme Overdensities with Roman



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

Survey realizations use MDPL dark matter simulation with UV luminosities assigned from Behroozi+19 empirical model.

Identifying Extreme Overdensities with Roman



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

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

- Excellent regions for spectroscopic follow-up to characterize largest ionized bubbles (R~5–10 physical Mpc) and interesting sites of structure formation.

Summary

- Key next step in studying reionization is characterizing the evolving ionized structures in the z>6 IGM.
  - Requires wide-area surveys to sample the largest ionized bubbles.

- We are conducting a 7 deg^2 Lyα survey at z~7 with MMT/Binospec.
  - Confirmed spectroscopic overdensity and enhanced Lyα visibility across large-scale (R≈3 physical Mpc) volume at z=6.8, suggesting presence of a large ionized bubble.

- Roman will greatly extend area and advance our ability to identify extreme z>6 overdensities.
  - Excellent regions for spectroscopic follow-up to characterize largest ionized bubbles (R~5–10 physical Mpc) and interesting sites of structure formation.