Unveiling the Reionization Process through Subaru Intensive Program (S25A-047QI)

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When Did Reionization Occur?

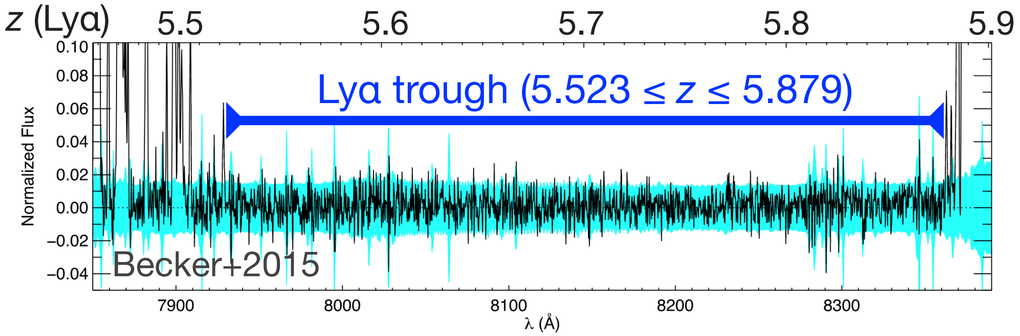
Cosmic Reionization

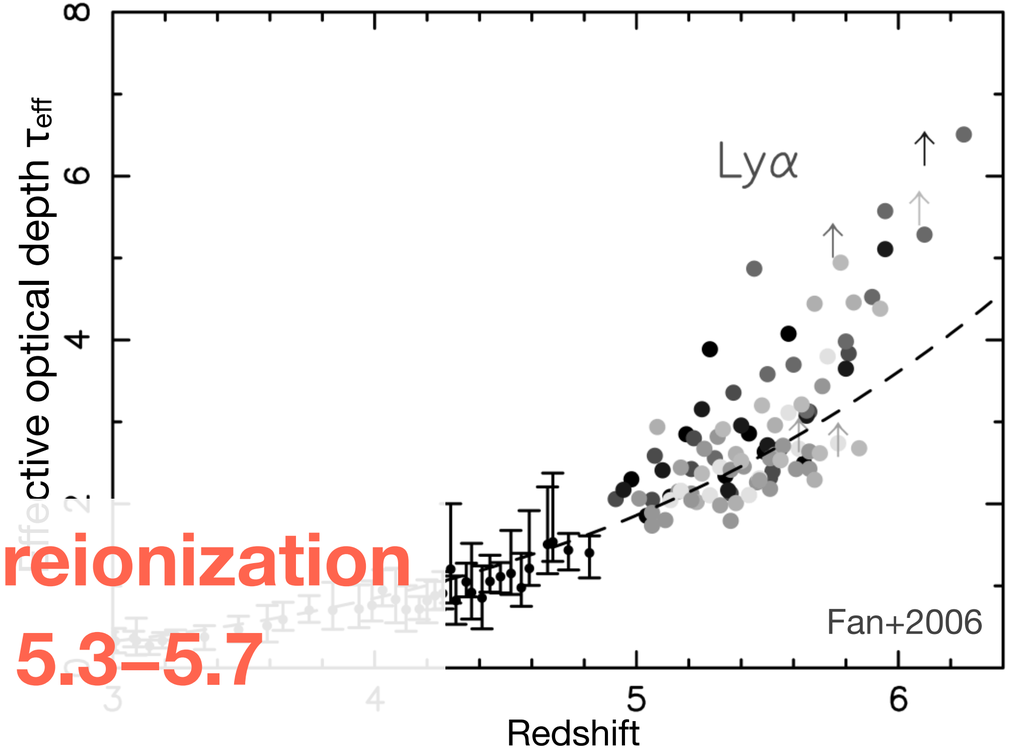
Traditional Picture

- Mainly occur at $z \sim 8$–7
- Finish by $z \sim 6$

Recent Findings at $z < 6$

- Long Lyα troughs
- Large scatter in $\tau_{\rm eff}$





☞ **Inhomogeneous reionization lasting until $z \sim 5.3$–5.7**

How Did Reionization Proceed?

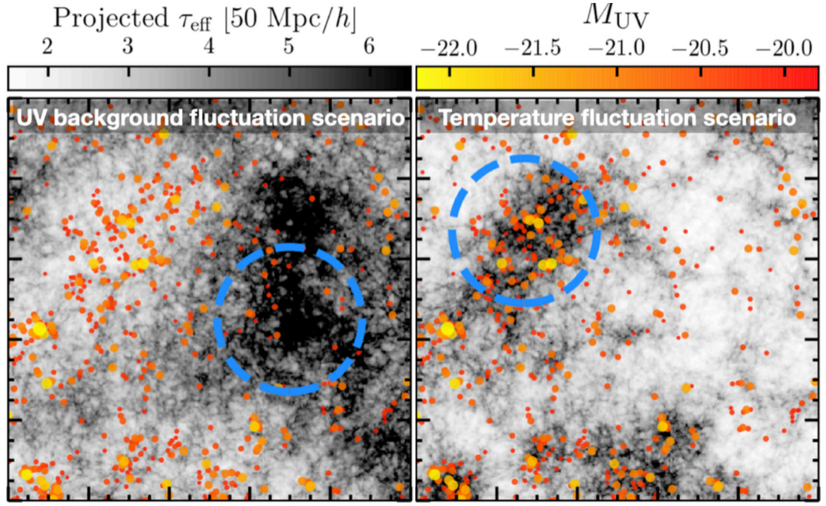
Are opaque IGM regions located in galaxy overdensities or underdensities?

$$\tau_{\rm eff} = -\ln\langle F_\lambda^{\rm obs}/F_\lambda^{\rm int}\rangle \propto \langle N_{\rm HI}\rangle \propto \Delta^2\ \Gamma^{-1}\ T^{-0.72}$$

Underlying density

UV background

IGM temperature

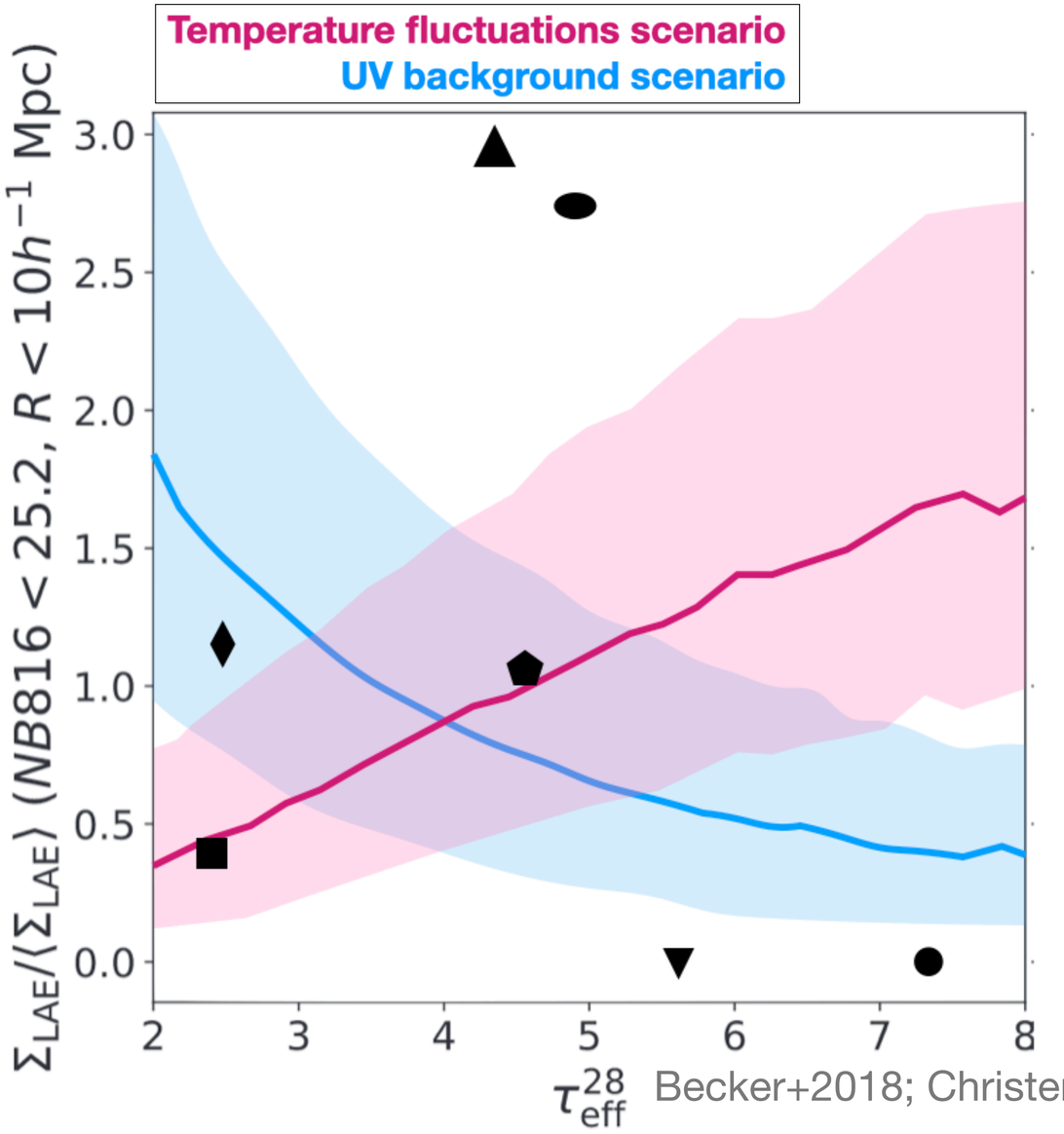


Grey Scale: IGM phase … more neutral in black
Dots: Galaxies

Scenarios	Fluctuation in what?	Predicted $\tau_{\rm eff}$ — $\delta_{\rm gal}$ relation
UV background	UVBG	High-$\tau_{\rm eff}$ ⇔ low $\delta_{\rm gal}$ (underdense) low-$\tau_{\rm eff}$ ⇔ high $\delta_{\rm gal}$ (overdense)
IGM temperature	IGM temp.	High-$\tau_{\rm eff}$ (hot IGM) ⇔ high $\delta_{\rm gal}$ (overdense) low-$\tau_{\rm eff}$ (cool IGM) ⇔ low $\delta_{\rm gal}$ (underdense)
Ultra-late reionization	UVBG, IGM temp.	High-$\tau_{\rm eff}$ ⇔ low $\delta_{\rm gal}$ (underdense) low-$\tau_{\rm eff}$ ⇔ wide variation

Scenarios. e.g., D'Aloisio+2015; Daves & Furlanetto 2016; Keating+2020;Fig. Davis＋2018

1. QSO Sightline LAE Mapping



Methodology

Measuring LAE overdensities around QSO sightline

Current status

7 QSO fields have been surveyed so far (in 4 publications).

Previous results are not yet conclusive.

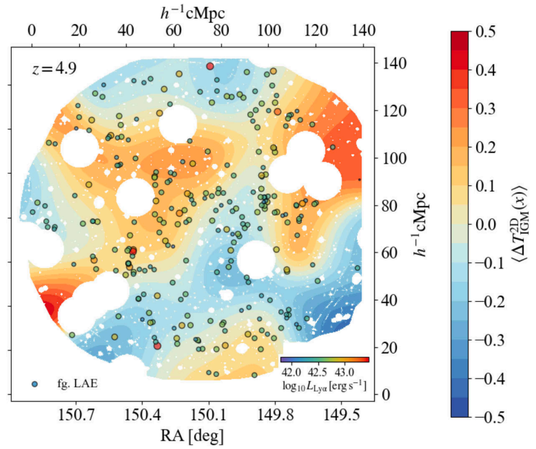
How to resolve the current tension

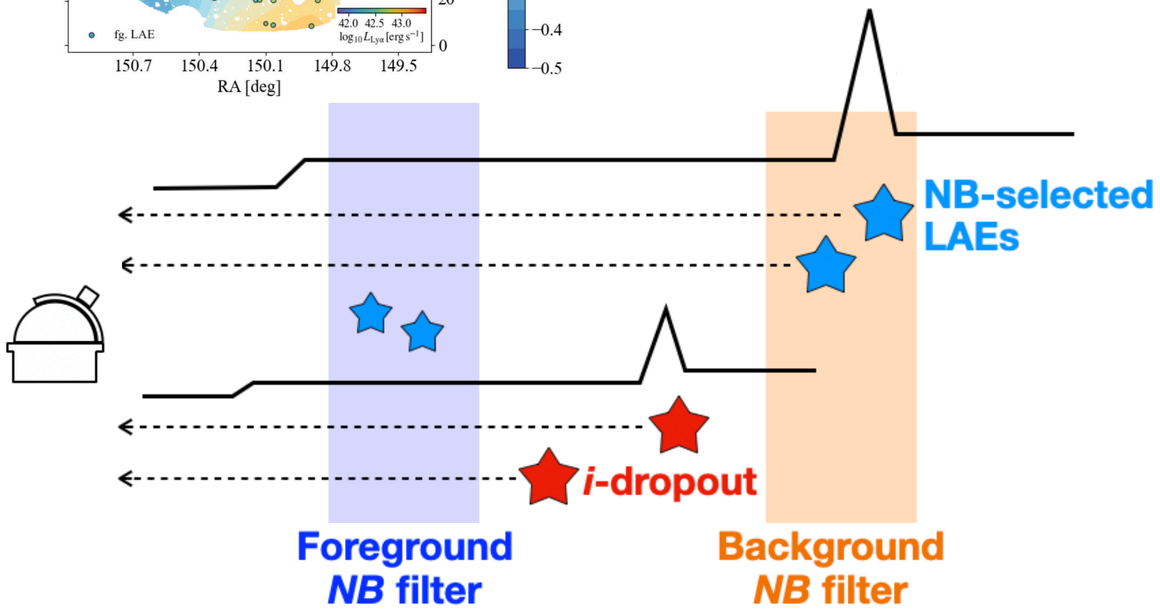
1) Increase the number of survey fields
2) Fill the parameter space: overdense in LAEs and/or lower HI optical depth (τ_{eff})
3) Apply the consistent methodology to all survey fields

Becker+2018; Christenson+2021, 2023; Ishimoto+2022; See also Kashino+2020 by drop-out

2. Photometric IGM Tomography Mapping

Photometric tomography map





Methodology

Quantifying the large-scale correlation between the IGM and galaxies using photometric images.

We can use many background sources across the HSC field of view.

Current status

No photometric IGM tomography map has yet been made for the $z > 5$ universe.

How to resolve the current challenges

1) Create IGM tomography maps during reionization
2) Increase survey fields for the tomography

See also Mawatari+2017; Kakiichi+2023

Objective of This Program

We aim to constrain the reionization scenarios with HSC observations

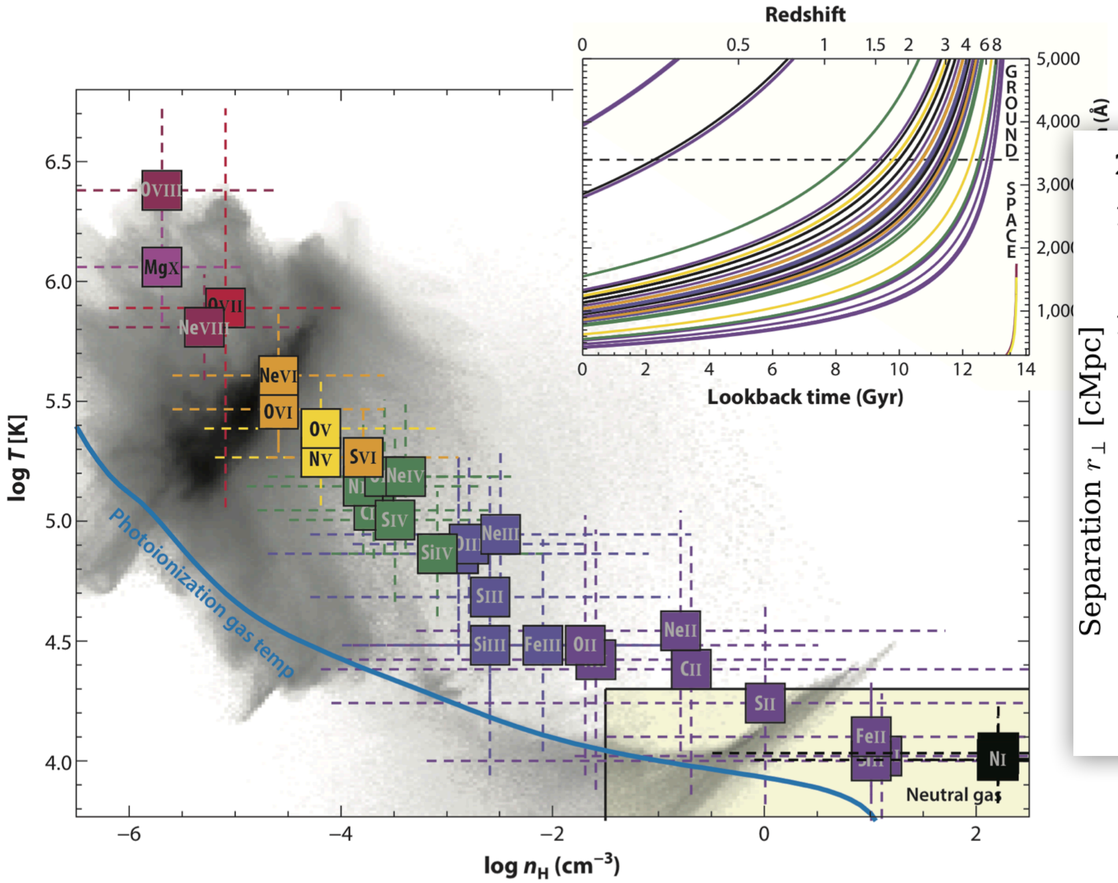
- ✓ Increasing the survey fields through the Intensive Program
- ✓ Applying two approaches: *QSO Sightline LAE Mapping* and *IGM Tomography*
- ✓ Following the basic observation strategy used in previous studies on *QSO Sightline LAE Mapping*.

☞ **Our project is unique in that**

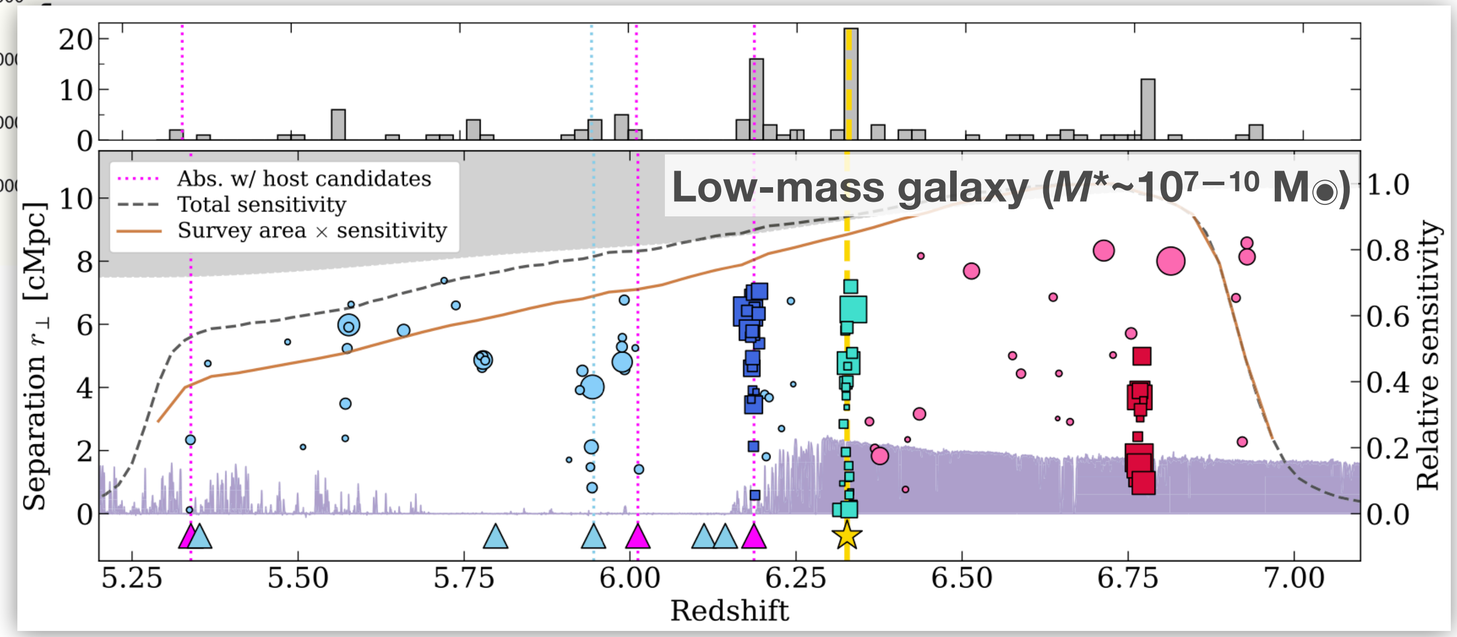
we are also using additional constraints from metal absorbers.

Why Do We Focus on Fields with Metal Absorbers?

Independent probe of the IGM phase



Tracer of galaxy overdensities



△: Redshift of metal absorber

e.g., Finlator+2013; Tumlinson+2017; Kashino+2023; Matthee+2023

Details of Our Intensive Program

- ✓ Observe **18** QSO sightline fields over **5** semesters (25A, 25B, 26A, 26B, 27B)
- ✓ Construct a dataset of **31** QSO fields in total
  - 6 from our pilot observations in 23B, 24A, 24B
  - 7 from the Subaru archival data used in the literature
- ✓ Include **10** QSO sightline fields without metal absorbers as a control sample
  - Overall results do not just depend on metal absorber regions.
  - We can test the impact on the conclusion w/o metal absorbers.

QSO sightline	Redshift for LAE Survey	QSO's Redshift
0140−1140	5.7	5.85
0142−3327	5.7	6.34
0142−3327	6.2	6.34
0226+0302	5.7	6.54
0226+0302	6.2	6.54
0402+2451	5.7	6.18
0411−0907	5.7	6.82
0439+1634	5.7	6.52
0559−1535	5.7	5.96
0923+0402	5.7	6.63
0923+0402	6.2	6.63
1030+0524	5.7	6.31
1535+1943	5.7	6.38
1558−0724	5.7	6.11
2132+1217	5.7	6.59
2132+1217	6.2	6.59
2310+1855	5.7	6.00
2315−0023	5.7	6.12
0100+2802	6.2	6.33
0411−0907	6.2	6.82
0439+1634	6.2	6.52
1030+0524	6.2	6.31
1120+9641	6.2	7.08
1148+5251	6.2	6.42
0148+0600	5.7	5.92
1137+3549	5.7	5.96
1250+3130	5.7	6.14
1306+0356	5.7	6.03
1602+4228	5.7	6.08
1630+4012	5.7	6.05
2356−0622	5.7	6.17

Summary

OBJECTIVE

Constrain the reionization scenario with HSC observations

STRATEGY

Observe 18 QSO sightline fields through Intensive Program (25A~27B)
Investigate the IGM and galaxies in the reionization using the largest dataset

CURRENT STATUS

Just end the first year — 63% requested data have been taken
Data reduction is underway

FURTHER GOALS BEYOND THE MAIN OBJECTIVE

Environmental studies toward metal absorber fields in the early universe
Detailed properties of galaxies in the large-scale structure using JWST data