Exploring the tail end of cosmic reionization with Subaru/HSC

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Aim

Reveal the origin of highly inhomogeneous reionization?

→ Large sightline variations in the HI optical depth at the end of reionization

❖ Introduction

Proposed scenarios for the origin of large optical depth fluctuations

❖ Testing the models — our observations

LBG surveys with HSC in the field of bright z>6 quasars

❖ First result

Evidence that an exceptional Lyα trough (i.e., highly opaque region) is associated to a galaxy underdensity.

→ Constraint on models
Gunn-Peterson test
Reionization almost ended until z~6

Effective optical depth
(averaged over ~70 cMpc, or Δz=0.15)

\[ \tau_{\text{eff}} = - \ln \left( \frac{F^{\text{obs}}_\lambda}{F^{\text{int}}_\lambda} \right) \]

Fit to z < 4.9
\[ \tau_{\text{GP}}^{\text{eff}} \propto (1 + z)^{4.3} \]

At z<5.5, almost completely ionized.
At z<6, \( f_{\text{HI}} \) increases,
marking the end of reionization.
Increasing scatter of $\tau_{\text{eff}}$

The scatter appears to rapidly grow up at $z \sim 5–5.5$, much beyond the range predicted with a uniform UV background.

→ need additional inhomogeneity in the neutral fraction
Increasing scatter of $\tau_{\text{eff}}$

The scatter appears to rapidly grow up at $z \sim 5–5.5$, much beyond the range predicted with a uniform UV background. **need additional inhomogeneity in the neutral fraction**
**Increasing scatter of $\tau_{\text{eff}}$**

The scatter appears to rapidly grow up at $z \sim 5-5.5$, much beyond the range predicted with a uniform UV background. What do the large optical depth variations mean?

![Graph showing increasing scatter of $\tau_{\text{eff}}$.](http://mnras.oxfordjournals.org/)
What do the large $\tau_{\text{eff}}$ variations mean?

In photoionization-recombination equilibrium, the optical depth $\tau_{\text{eff}}$ scales as

$$\tau_{\text{eff}} = -\ln \left( \frac{F_{\lambda}^{\text{obs}}}{F_{\lambda}^{\text{int}}} \right) \propto \left\langle N_{\text{HI}} \right\rangle \propto \Delta^2 \Gamma^{-1} T^{-0.72}$$

The large $\tau_{\text{eff}}$ fluctuations require additional fluctuations either in $\Gamma$ (UV background) or $T$ (IGM temperature).
Possible scenarios

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

UV background \[\rightarrow\] IGM temperature

<table>
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<tr>
<th>Model</th>
<th>Fluctuation in what?</th>
<th>Source of fluctuation</th>
<th>References</th>
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<td>fluctuating-(\lambda_{\text{mfp}})</td>
<td>(\Gamma)</td>
<td>Galaxy distribution and spatially-varying (\lambda_{\text{mfp}})</td>
<td>Davies &amp; Furlanetto ‘16</td>
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<tr>
<td>rare-source</td>
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<td>Significant contribution of rare bright sources, i.e., quasars</td>
<td>Chardin+15, 17</td>
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<td>fluctuating-(T_{\text{IGM}})</td>
<td>(T)</td>
<td>Time-lags of reionization b/w over- and underdensities</td>
<td>D’Aloisio+15</td>
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<td>Late-reionization</td>
<td>(\Gamma) (and (T))</td>
<td>Residual neutral islands ((x_{\text{HI}} \sim 1)) in reionization that ended at (z \sim 5.2)</td>
<td>Kulkurni+19, Keating+19</td>
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**Possible scenarios**

\[
\tau_{\text{eff}} = -\ln\left\langle \frac{F_{\lambda}^{\text{obs}}}{F_{\lambda}^{\text{int}}} \right\rangle \propto N_{\text{HI}} \propto \Delta^2 \Gamma^{-1} T^{-0.72}
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**UV background**

**IGM temperature**

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| fluctuating-$\lambda_{\text{mfp}}$ | $\Gamma$    | Galaxy distribution and spatially-varying $\lambda_{\text{mfp}}$                       | Negative correlation: $\text{high-}\tau_{\text{eff}} \Leftrightarrow \text{low-}\rho$  
                             |                                                                                     | $\text{low-}\tau_{\text{eff}} \Leftrightarrow \text{high-}\rho$                                                                 |
| rare-source      | $\Gamma$    | Significant contribution of rare bright sources, i.e., quasars                         | Not clear, but we should always find $>1$ quasars in $\text{high-}\tau_{\text{eff}}$ region, but no in $\text{low-}\tau_{\text{eff}}$ regions |
| fluctuating-$T_{\text{IGM}}$ | $T$         | Time-lags of reionization b/w over- and underdensities                                 | Positive correlation: $\text{high-}\tau_{\text{eff}} \Leftrightarrow \text{high-}\rho$  
                             |                                                                                     | $\text{low-}\tau_{\text{eff}} \Leftrightarrow \text{low-}\rho$                                                                 |
| Late-reionization | $\Gamma$ ($\text{and } T$) | Residual neutral islands ($x_{\text{HI}} \sim 1$) in reionization that ended at $z \sim 5.2$ | $\text{high-}\tau_{\text{eff}} \Rightarrow \text{low-}\rho$  
                             |                                                                                     | $\text{low-}\tau_{\text{eff}} \Rightarrow \text{wide variation in } \rho$                                                 |
Testing the models
Testing the models

Correlate **galaxy distribution** with **the HI optical depth** across 5.5<z<6.0.

**LAE/LBG surface density:** Over- or under-dense?

**Presence or absence of quasars within ~100 cMpc?**

**z>6 quasar:** Where we know $\tau_{\text{eff}}$

Those with extremely high- (opaque) or low- $\tau_{\text{eff}}$ (transparent) Ly$\alpha$ forest are good,

**HSC FoV matches perfectly to carry out this experiment.**
A surprisingly opaque and long trough

A remarkably **opaque** ($\tau_{\text{eff}} \geq 7$) and **long** (~160 cMpc) Ly$\alpha$ trough has been discovered at z=5.5–5.9 towards J0148+0600 (z=5.98)

→ Very good target field for distinguishing the models

Becker et al. (2015) (Figure taken from G. Becker’s slide, 2016)
Past result with HSC LAE survey

An LAE survey with HSC/NB816 (z=5.7) in the QSO J0148+0600 field ➔ the extremely high-τ_{eff} trough is associated with an LAE underdensity.

LAEs identified with NB816 fall into the center of the trough

Surface density map of ~800 LAEs

Becker et al. (2018)
Past result with HSC LAE survey

Caveats…

✓ Lyα may be suppressed in neutral/high-τ_{eff} regions.
✓ The full length of the trough is not covered.
✓ Only a single measurement.

Need complementary observations in more quasar fields.

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Becker et al. (2018)
LBG surveys with HSC in multiple quasar fields

✓ Good density tracers which are not impacted by local HI optical depth.
✓ Color (i-z) is sensitive to redshift ($\delta z \approx 0.25$, FWHM).
First result — QSO J0148+0600
**Result: LBG candidates**

The spatial distribution of 185 LBG candidates within 40 arcmin ➡ “deficit” at the quasar position

**Predicted $N(z)$**

covers the full length of the trough

Blue: J0148+0600 spectrum

$z_{QSO}=5.98$
Result: LBG surface density map

Σ_{LBG} is the lowest at the center among the independent r=8′ apertures across the field.
Test for the rare-source model:
No “obvious” bright quasars in the field

There is no obvious luminous ($z_{\text{PSF}} \leq 23$) quasars near the Ly\(\alpha\) trough. → consistent with the rare-source model (no quasars in high-$\tau_{\text{eff}}$ region)

- Point-like sources
  - $z_{\text{PSF}} \leq 23$

- Galactic M stars

But, it is challenging to distinguish quasars which are fainter and/or similar to stars in colors because of their similar light profile.
# Summary

An LBG underdensity is associated to an extremely opaque Lyα trough. This is a complementary confirmation of a pre-indication via an LAE survey.

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Stay tuned for further results!
Congratulations on the 20th anniversary of Subaru!