Islands of neutral hydrogen below redshift 5.5

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Figure from George Becker
At the same redshift, the Lyα forest looks very different along different sightlines.

Long troughs show some Lyβ transmission, so can’t be completely neutral.
Opaque sightlines are already seen below \( z = 5.5 \)

The scatter among sightlines is larger than expected for fluctuations in density

\[
\langle F \rangle = \exp(-\tau_{\text{eff}})
\]

measured in 50 Mpc/h segments

Bosman+18

see also Fan+06, Becker+15, Eilers+18
Can we learn something about reionization from this data?

from photoionization equilibrium:

$$n_{\text{HI}} \propto \frac{\alpha(T)n_en_{\text{HII}}}{\Gamma_{\text{HI}}} \propto \frac{T^{-0.7}\Delta^2}{\Gamma_{\text{HI}}}$$
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**Fluctuations in the UVB amplitude**

**Fluctuations in the mean free path?**

Davies+16

**Fluctuations in temperature**

**Due to patchy hydrogen reionization**

D’Aloisio+15
Let’s look in radiative transfer simulations that can model these temperature and UV fluctuations…
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Reionization ends at $z \sim 6$
Reionization ends below $z = 5.5$

We find that matching the mean flux requires a later reionization (ending at $z = 5.3$).
The increasing scatter in the effective optical depth above $z = 5.5$ is driven by large islands of neutral gas in the IGM at that redshift.
In this late reionization model, we can now produce distributions of Lyα opacities as broad as observed.
What about the large Lyα absorption troughs that are observed? Lyβ transmission seen, implying an ionized IGM

![Graph showing normalized flux vs. redshift](image-url)
What about the large Lyα absorption troughs that are observed? Lyβ transmission seen, implying an ionized IGM
What about the large Ly\(\alpha\) absorption troughs that are observed? Ly\(\beta\) transmission seen, implying an ionized IGM.
Small ionized bubbles within the neutral islands allow for transmission of Lyβ

HI fraction

Photoionization rate

Temperature

Redshift

log $f_{\text{HI}}$

$\log (I_{\text{HI}}/s^{-1})$

$\log (T/K)$
Searches for Lyman-α emitters around the trough can distinguish between different models for the large spatial fluctuations in the Lyman-α forest opacities.
In this model, the troughs are in the last regions to ionize (i.e., voids).

Find a deficit of LAEs around the most opaque sightlines as observed.
Observations of the Ly$\beta$ forest are also very useful for constraining the properties of the IGM.

Figure 4. Comparison of our Ly$\alpha$ and Ly$\beta$ opacity measurements shown as the red data points in different redshift bins, i.e. $5.5 < z < 5.7$ (left), $5.7 < z < 5.9$ (middle), and $5.9 < z < 6.1$ (right), to predictions from the Nyx hydrodynamical simulation post-processed in several different ways. The contours in the top panels show the prediction from simulations with uniform UVB and different slopes of the temperature-density relation of the IGM, whereas the middle and bottom panels show predictions from models with a fluctuating UVB or a fluctuating temperature field, respectively. Inner and outer contours show the 68th and 95th percentile of the distribution. The dotted contours show the respective distributions including $\pm 20\%$ continuum uncertainties (which we omitted in the top panels for better readability). The data points marked as diamonds correspond to the spectral bins shown in Fig. 2. Additionally, as noted before, we find a large increase in the scatter of the measurements, most notably at $z \sim 5.8$, compared to the predictions from the models. Note that in the two highest redshift bins in Fig. 5, the difference between the observed mean Ly$\beta$ forest optical depth and the reionization model with a fluctuating UVB is $\sim 1$, which corresponds to a factor of $\sim 2.5$ in the mean flux. Hence, systematic uncertainties...
A late reionization model is consistent with these Lyβ observations.
• Matching the mean flux in the Lyman-α forest requires an IGM that is still significantly neutral below redshift 6

• This model naturally reproduces the large spatial fluctuations in the opacity of the Lyman-α forest

• This model also explains the large observed Lyman-α absorption troughs and lack of Lyman-α emitters surrounding them, as well as recent observations of the Lyman-β forest