The Zeldovich Universe:
Genesis and Growth of the Cosmic Web
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Lyα Forest Tomography of the $z > 2$ Cosmic Web

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Abstract. The hydrogen Lyα forest is an important probe of the $z > 2$ Universe that is otherwise challenging to observe with galaxy redshift surveys, but this technique has traditionally been limited to 1D studies in front of bright quasars. However, by pushing to faint magnitudes ($g > 23$) with 8-10m large telescopes it becomes possible to exploit the high area density of high-redshift star-forming galaxies to create 3D tomographic maps of large-scale structure in the foreground. I describe the first pilot observations using this technique, as well discuss future surveys and the resulting science possibilities for galaxy evolution and cosmology.

Keywords. cosmology: observations — galaxies: high-redshift — intergalactic medium — quasars: absorption lines — surveys — techniques: spectroscopic

1. Introduction

For decades, the hydrogen Lyα forest absorption observed in the spectra of background quasars has been a crucial probe of the $z > 2$ universe. Since the realization in the mid-1990s that residual neutral hydrogen in the photoionized intergalactic medium (IGM) is a non-linear tracer of the overall matter density distribution in the large-scale cosmic web (the 'fluctuating Gunn-Peterson' paradigm Cen *et al.* 1994; Bi *et al.* 1995), the Lyα forest has enabled statistical studies of large-scale structure (LSS) at high redshifts.

The Lyα forest in each quasar spectrum is a one-dimensional probe of the foreground IGM, although a small number of close-pairs exist (e.g., D'Odorico *et al.* 2006). The area density of available quasars increase with limiting magnitude, and at faint magnitudes it becomes possible to study the 3D correlations of the Lyα forest across different lines-of-sight: the BOSS Lyα forest survey (Lee *et al.* 2013) has observed $g \leqslant 21.5$ quasars with an average area density of $15\,\mathrm{deg}^{-2}$, enabling measurement of the large-scale two-point Lyα forest correlation function in 3D (Slosar *et al.* 2011) and subsequently the detection of the $\approx 100\,h^{-1}$ Mpc baryon acoustic oscillation scale (Slosar *et al.* 2013; Delubac *et al.* 2014), which is useful as a cosmological distance measure.

Beyond clustering studies, it is also possible to directly interpolate separate Lyα forest sightlines to create a 3D map of the hydrogen absorption. This 'Lyα forest tomography' was conceptually first proposed by Pichon *et al.* (2001) (see also Caucci *et al.* 2008), although the first pilot observations were not conducted until recently (Lee *et al.* 2014b). In this article we will give a brief overview of this exciting new technique in terms of feasibility and initial pilot observations, as well as discuss future prospects.

2. Feasibility

In simplest terms, Lyα forest tomography simply interpolates between a set of Lyα forest spectra to create a map of the foreground IGM absorption. Therefore the typical transverse separation, $\langle d_\perp \rangle$, of the background sources must match the spatial scale of the desired map, ϵ_{3D}. At $z = 2.3$, the typical transverse separation of the BOSS Lyα forest sightlines is $\langle d_\perp \rangle \sim 20\,h^{-1}$ Mpc which is larger than most scales of interest, although there are efforts to create tomographic maps with BOSS (Cisewski *et al.* 2014).

The $\langle d_\perp \rangle$ is reduced by including fainter background sources, but the quasar luminosity function is relatively shallow (Palanque-Delabrouille *et al.* 2013) and even at $g \leqslant 24$, the typical sightline separation probed by quasars is $\langle d_\perp \rangle \sim 15\,h^{-1}$ Mpc. However, at $g \gtrsim 23$, star-forming galaxies (SFGs) begin to dominate the overall UV luminosity function (Reddy *et al.* 2008), allowing very dense grids to sample the foreground forest: at $g \leqslant [24, 25]$ the sightline separations are $\langle d_\perp \rangle \approx [4, 1]\,h^{-1}$ Mpc, respectively.

The question now turns to the requirements in terms of spectral resolution and signal-to-noise (S/N) in the data. If high-resolution ($R \sim 30,000$, S/N$\gtrsim 20$ per pixel) spectra are needed, then Lyα tomography will be a limited 'novelty' technique even with 30m class telescopes, due to the extreme exposure times (> 10hr) needed to obtain such data with $g \sim 24$ sources. Conversely, relatively noisy (S/N of a few) moderate-resolution spectra ($R \sim 200 - 1000$) are already achievable with existing 8-10m telescopes.

In Lee *et al.* (2014a), we studied this issue using both simulations and analytic calculations. In terms of spectral resolution, the desired reconstruction scale, ϵ_{3D}, must be resolved along the line-of-sight (LOS), therefore one needs merely $R \geqslant 1300(1\,h^{-1}\ \mathrm{Mpc}/\epsilon_{3D})\,[(1+z)/3.25]^{-1/2}$. As for the necessary S/N, the requirements depend on ϵ_{3D} as well as the desired map fidelity. Since there will always be reconstruction errors on scales approaching the skewer separation, $\langle d_\perp \rangle$, due to the finite transverse sampling ('aliasing'), the individual spectra do not need to oversample the absorption along the LOS. In simulated reconstructions using noisy mock data, we found that S/N $= 4$ per $\AA$ at a survey limit of $g = 24.2$ is sufficient to give tomographic maps that look similar to the 'true' simulated field on scales of $\epsilon_{3D} \approx 3.5\,h^{-1}$ Mpc. This is achievable with existing telescopes: e.g. with the VLT-VIMOS spectrograph (Le Fèvre *et al.* 2003) such data would require 6hr exposure times per pointing. The requirements do increase if we desire greater spatial resolutions: Lyα forest tomography resolving $\epsilon_{3D} \lesssim 1\,h^{-1}$ Mpc (i.e. $\lesssim$ 400kpc physical at $z \sim 2.5$) would require $g > 25$ background galaxies, which are accessible only with future 30m-class telescopes.

3. Pilot Observations

In March 2014, we obtained moderate-resolution ($R \approx 1000$) spectra of 24 SFGs at redshifts $2.3 \lesssim z \lesssim 3$, down to limiting magnitudes of $g \sim 24.7$, using the LRIS spectrograph on the Keck I telescope on Mauna Kea, Hawaii. These SFGs were all within a $5' \times 14'$ area of the COSMOS field (Scoville *et al.* 2007), resulting in an effective area density of ~ 1000 deg^{-2} or a nominal transverse separation of $\langle d_\perp \rangle \approx 2.3\,h^{-1}$ Mpc.

The data was taken with $\approx$ 2hr exposure times resulting in S/N $\sim 1.5 - 4$ per pixel. It may seem aggressive to use such noisy data, but our tomographic reconstruction uses a Wiener filtering algorithm (Wiener 1942) that incorporates noise-weighting. Another concern is the possible contamination by intrinsic SFG absorption lines, but studies of composite SFG spectra (Shapley *et al.* 2003; Berry *et al.* 2012) have revealed a relative lack of strong intrinsic absorption lines in the relevant $1040 - 1180\,\AA$ restframe region once the foreground Lyα forest fluctuations are averaged out by stacking. Moreover, UV spectroscopic observations of a small number of low-z SFGs (e.g. Heckman *et al.* 2011), in which the Lyα forest is negligible, have revealed a relatively flat 'continuum', with only 2-3 strong absorbers that are straightforward to mask. This is supported by the

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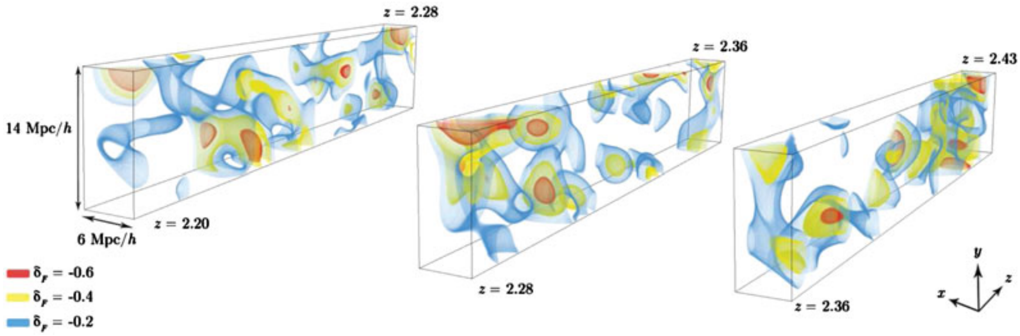

Figure 1. 3D visualization of the Lyα forest tomographic map obtained from the foreground absorption in 24 background SFG spectra, split into 3 different redshift segments for clarity. The color scale represents the relative Lyα absorption, such that lower values correspond to higher densities. Excerpted from Lee *et al.* (2014b).

high-resolution spectrum of the the lensed SFG cB158, which allowed Voigt-profile analysis of the absorbers in its Lyα forest region (Savaglio *et al.* 2002).

In Figure 1 we show the resulting 3D tomographic Lyα forest reconstruction (see Lee *et al.* 2014b), spanning $2.2 \leqslant z \leqslant 2.45$ with a spatial resolution of $\epsilon_{3D} \approx 3.5\,h^{-1}$ Mpc. The elongated map geometry is because bad weather limited us to a small transverse area, whereas each sightline probes a long pathlength $\sim 300\,h^{-1}$ Mpc along the LOS.

Despite the narrow geometry, one sees large coherent structures spanning $\gtrsim 10\,h^{-1}$ Mpc across the entire transverse dimension. These structures are contributed by multiple sightlines and are therefore unlikely to be due to random noise fluctuations nor intrinsic absorption (since the background SFG redshifts are not aligned). Simulated reconstructions on mock data with the exact same spatial sampling and S/N distribution yield a good recovery of LSS features on scales of a few Mpc, although there are distortions on smaller scales. We also compared the map with a small number of coeval galaxies with known spectroscopic redshifts (primarily from zCOSMOS, Lilly *et al.* 2007). In Lee *et al.* (2014b) we have shown that the galaxies live preferentially in lower-flux regions (i.e. overdensities), although this correlation is weakened somewhat by redshift errors on the coeval galaxies and tomographic reconstruction errors.

4. Science Applications & Future Prospects

Our pilot observations have established the feasibility of Lyα forest tomography, and motivates the COSMOS Lyman-Alpha Mapping and Tomography Observations (CLAMATO) survey, which aims to obtain ~ 1000 SFG spectra within $\sim 1\text{deg}^2$ of the COSMOS field, aimed at creating a tomographic reconstruction of the Lyα forest absorption at $\langle z \rangle \sim 2.3$ over a comoving volume equivalent to $\sim (100\,h^{-1}\ \text{Mpc})^3$.

This survey will require $\sim$ 15 nights of large-telescope time, and will have various science applications: **(I)** The large-scale morphology and topology of the cosmic web has never been studied at $z \gtrsim 1$, and the tomographic map will allow us to study this on scales of $\gtrsim 3-4\,h^{-1}$ Mpc. **(II)** Using Lyα forest absorption as a proxy for the underlying density field, we will be able to study the properties of $z \sim 2$ coeval galaxies as a function of their large-scale environment, yielding unique insights into this crucial era in galaxy formation and evolution. **(III)** Within the volume covered by the map, we expect to find ~ 10 progenitors of massive $M > 10^{14} M_\odot$ galaxy clusters. At $z \gtrsim 2$, these protoclusters are expected to manifest themselves as overdensities of a few on spanning $\sim 10\,h^{-1}$ Mpc

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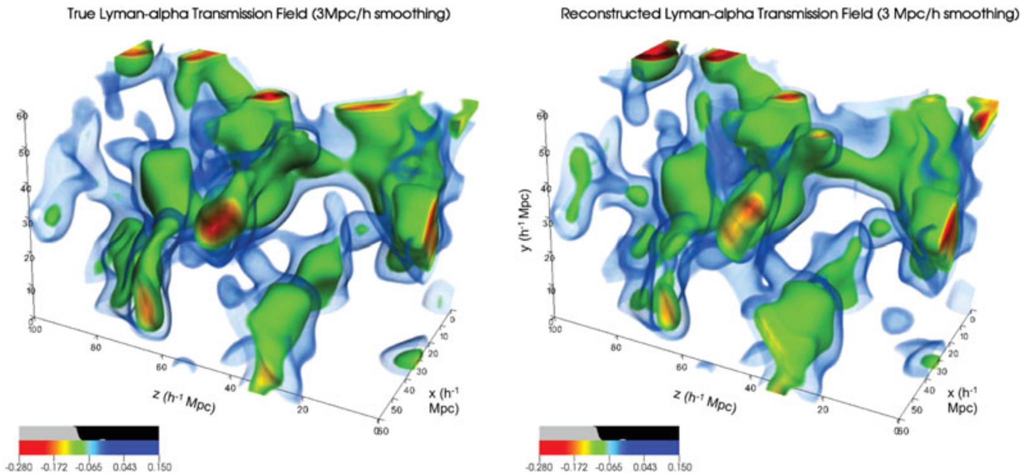

Figure 2. (Right) Tomographic reconstruction using realistic mock data simulating the 1 deg^2 CLAMATO survey, compared with the true 3D absorption field (left). Both fields have an effective smoothing of $\epsilon_{3D} = 3\,h^{-1}$ Mpc. The simulated survey data clearly recovers the LSS in the volume. Note that the z-dimension here is the LOS dimension, and in the real survey will span $\sim 2 - 3\times$ the distance shown here.

(c.f. Chiang *et al.* 2013), which should be easily detectable with Lyα forest tomography. Finally, **(IV)** the data will allow us to probe 3D small-scale Lyα forest clustering on scales of $\lesssim 10\,h^{-1}$ Mpc, complementary to the larger scales probed by the BOSS survey (Slosar *et al.* 2011). These measurements will be valuable in arriving at a comprehensive model of the Lyα forest absorption.

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