Second Data Release of the COSMOS Lyα Mapping and Tomography Observations: The First 3D Maps of the Detailed Cosmic Web at 2.05 < z < 2.55

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Received 2022 January 18; revised 2022 July 13; accepted 2022 August 3; published 2022 November 24

Abstract

We present the second data release of the COSMOS Lyα Mapping And Tomography Observations Survey conducted with the Low Resolution Imaging Spectrometer on the Keck I telescope. This project used Lyα forest absorption in the spectra of faint star-forming galaxies and quasars at z ~ 2–3 to trace neutral hydrogen in the intergalactic medium. In particular, we use 320 objects over a footprint of ~0.2 deg² to reconstruct the absorption field at 2.05 < z < 2.55 at ~2 h⁻¹ Mpc resolution. We apply a Wiener filtering technique to the observed data to reconstruct three-dimensional (3D) maps of the field over a volume of 4.1 × 10⁵ h⁻³ Mpc³. In addition to the filtered flux maps, for the first time we infer the underlying dark matter field through a forward-modeling framework from a joint likelihood of galaxy and Lyα forest data, finding clear examples of the detailed cosmic web consisting of cosmic voids, sheets, filaments, and nodes. In addition to traditional figures, we present a number of interactive 3D models to allow exploration of the data and qualitative comparisons to known galaxy surveys. We find that our inferred overdensities are consistent with those found from galaxy fields. We will make all our reduced spectra, extracted Lyα forest pixel data, and reconstructed tomographic maps publicly available upon publication.

Unified Astronomy Thesaurus concepts: Intergalactic medium (813); Extragalactic astronomy (506); Intergalactic filaments (811); Intergalactic gas (812); Voids (1779); High-redshift galaxy clusters (2007); Galaxy clusters (584); Lyman alpha forest (980); Spectroscopy (1558); Redshift surveys (1378); Surveys (1671); Hubble Space Telescope (761)

Supporting material: animation, machine-readable table

1. Introduction

The Lyα forest is a a collection of absorption features present in galaxy and quasar (quasi-stellar object, QSO) spectra caused by the presence of neutral hydrogen, H I, in the diffuse intergalactic medium (IGM) along the line of sight (Gunn & Peterson 1965). By interpreting the neutral hydrogen as a biased tracer of the underlying mass distribution, the Lyα forest has emerged over the past few decades as a key probe of large-scale structure for cosmological analysis (e.g., Croft et al. 1998; McDonald et al. 2006; Slosar et al. 2011; Busca et al. 2013). At high redshifts, z > 2.0, galaxy spectroscopic surveys become increasingly expensive while the IGM still has an appreciable neutral fraction (McQuinn 2016) and the rest frame Lyα (λ = 1215.67 Å) redshifts into the optical atmospheric window, making this an optimal redshift for Lyα forest observations.

Existing studies of the Lyα forest have focused on QSOs since they are the brightest ultraviolet (UV) sources at this redshift. Due to their comparatively low number densities, studies with QSOs have been primarily focused on one-dimensional (1D) line-of-sight analyses (e.g., Viel et al. 2005) or, in the case of the Baryon Oscillation Spectroscopic Survey (Eisenstein et al. 2011; Dawson et al. 2013) and Extended Baryon Oscillation Spectroscopic Survey (eBOSS; Alam et al. 2021), on correlations at scales of (d/δ) ~ 20 h⁻¹ Mpc. These separations are insufficient for resolving individual cosmic structures in the transverse direction but more than sufficient for the surveys’ main goal of measuring the baryon acoustic oscillation signal in the Lyα forest (Busca et al. 2013; Kirkby et al. 2013; Slosar et al. 2013; Font-Ribera et al. 2014;
Delubac et al. 2015; Bautista et al. 2017; du Mas des Bourboux et al. 2017).

Goingsignificantly fainter QSO sources only leads to marginal improvement in terms of target number densities and average line-of-sight separation due to the shallow slope of the QSO luminosity function (Siana et al. 2008; Palanque-Delabrouille et al. 2013, 2016). The number of potential lines of sight can increasendramatically by expanding surveys to include targeting UV-emitting star-forming galaxies at $z > 2$, known as Lyman break galaxies (LBGs; Steidel et al. 1996). It was shown in Lee et al. (2014b) that a $g = 24.5$ survey magnitude limit including LBGs would lead to $\sim 1500$ deg$^{-2}$ density of lines of sight, corresponding to $(d_z) \sim 2.5 h^{-1} \text{Mpc}$ at $z \sim 2.3$ versus $(d_z) \sim 7.5 h^{-1} \text{Mpc}$ using only QSOs. The properties of individual LBG spectra were futher characterized in Monzon et al. (2020).

With the increased density of lines of sight available, it becomes possible to create three-dimensional (3D) tomographic reconstructions of the underlying cosmic web. This approach was first discussed in Pichon et al. (2001) and Caucci et al. (2008), while the first pilot demonstration of tomographic Ly$\alpha$ forest observations was shown in Lee et al. (2014a). These early observations were later expanded in Lee et al. (2016) and the first data release (DR1) of the COSMOS Lyman Alpha Mapping and Tomography Observations (CLAMATO) survey (Lee et al. 2018). Results from the CLAMATO survey have been used to identify and catalog the highest-redshift cosmic voids (Krolewski et al. 2018). Along with these observations, there have been significant theoretical developments in using tomographic observations for identification and analysis of high-redshift protoclusters (Stark et al. 2015a, 2015b), voids (Krolewski et al. 2018), and cosmic web geometry (Lee & White 2016).

Since the release of the first CLAMATO results, the same Wiener filter (WF) reconstruction technique was applied to the Stripe 82 region of the eBOSS survey, creating a coarse tomographic map with $(d_z) \sim 13.0 h^{-1} \text{Mpc}$ over a large cosmic volume (Ravoux et al. 2020). The ongoing Ly$\alpha$ Tomography IMACS Survey (LATIS) survey will reach a comparable sight-line density as CLAMATO over a subset of the COSMOS and CFHTLS fields (Newman et al. 2020). The upcoming Subaru Prime Focus Spectrograph (Sugai et al. 2015) will have a significant IGM tomography component, which will enable 3D reconstructions over a substantial sky fraction ($\sim 15$ deg$^2$), representing an order of magnitude increase over the LATIS survey. In the future, there are proposed tomography programs for the Maunakea Spectroscopic Explorer (McConnachie et al. 2016), Thirty Meter Telescope Wide-Field Optical Spectrograph (Skidmore et al. 2015), and the European Extremely Large Telescope Multi-Object Spectrograph (Hammer et al. 2016), which would enable tomography at even higher special resolutions (Japelj et al. 2019), as well as surveys like WEAVE-QSO on the William Herschel Telescope (Pieri et al. 2016) that will cover significant sky area (over 400 deg$^2$) albeit at lower spatial resolution (Kraljic et al. 2022).

Along with the ongoing and proposed tomographic observational programs, there is significant theoretical interest in creating more accurate maps of the reconstructed Ly$\alpha$ forest flux (Li et al. 2021) and underlying dark matter density. Dynamic forward-modeling approaches can push reconstructions to smaller scales than the standard WF method (Horowitz et al. 2019) as well as allow joint reconstructions with overlapping galaxy observations (Horowitz et al. 2021). Additional science cases recently explored for IGM tomography include constraining galactic feedback models (Nagamine et al. 2021), mapping quasar light echos (Schmidt et al. 2019), and studying variations in the UV background (Tie et al. 2019; Monmose et al. 2021).

In this article, we present the second public data release of the CLAMATO survey (DR2). These observations were taken on the Low Resolution Imaging Spectrometer (LRIS: Oke et al. 1995; Steidel et al. 2004) on the Keck I telescope near the summit of Maunakea. These observations were taken over 20.5 nights and consisted of a total of 600 spectra, of which 320 were suitable for use in tomographic reconstructions. We describe the survey design in Section 2 and the data collected in Section 3. Our tomographic reconstruction techniques are described in Section 4, and results explored in Section 5.

In this paper, we assume a concordance flat ΛCDM cosmology, with $Ω_m = 0.31$, $Ω_\Lambda = 0.69$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. Survey Design and Target Selection

The CLAMATO survey covers the COSMOS field (Scoville et al. 2007), an extragalactic survey area which has excellent coverage from multiwavelength and spectroscopic observational efforts, while also having a large ($\sim 1$ deg$^2$) contiguous footprint well suited for studying large-scale structure. The new (post-2017) data presented within this paper follows the same target selection and observational details as the previous data release (Lee et al. 2018). In this section we provide an abbreviated description of our design with a focus on any differences from the previous iteration, and refer the reader to the earlier paper.

2.1. Source Catalogs

The CLAMATO survey, as shown in Figure 1, is designed to maximize the areal density and homogeneity of background sources in the COSMOS field (Scoville et al. 2007), which could probe the Ly$\alpha$ forest absorption at $z \sim 2–2.5$. To achieve this, we exploit the high-quality multiwavelength photometric redshifts (Ilbert et al. 2009; Laigle et al. 2016; Davidzon et al. 2017) available in the field, and also retarget spectroscopically confirmed objects in the zCOSMOS-Deep (Lilly et al. 2007) and VIMOS Ultra Deep Survey (VUDS; Le Fèvre et al. 2015) surveys.

As a first step, we assembled a raw master catalog containing all objects $g < 25.2$ within a redshift range that allows observations of the Ly$\alpha$ forest in the target volume, corresponding to objects with $2.0 < z < 3.5$. We began with a compilation of spectroscopic sources in the COSMOS field (M. Salvato et al. 2022, in preparation), which, at our redshifts of interests, are primarily from the zCOSMOS-Deep (Lilly et al. 2007) and VUDS (Le Fèvre et al. 2015) catalogs. This was then further supplemented with the MOSDEF spectroscopic survey (Kriek et al. 2015), ZFIRE spectroscopic survey (Nanayakkara et al. 2016), and 3D-HST grism redshift catalog (Momcheva et al. 2016).

16 http://clamato.lbl.gov

17 The spectra from these surveys have coarse spectral resolution $R \sim 200$, insufficient for our purposes.
We then further filled in our master catalog using objects with only photometric redshifts. This initially used the I-band-selected photometric redshift catalog from Ilbert et al. (2009), but prior to the 2017 observing season this was supplemented by near-IR (NIR) selected photometric redshifts (Laigle et al. 2016; Davidzon et al. 2017) that yield more accurate redshift estimates.

2.2. Selection Algorithm

The target-selection algorithm was carried out in two steps: initial prioritization of possible targets, followed by design of the individual slit-masks. Due to the spatial constraints of each LRIS slit-mask, only a subset of the possible targets could be manifested as slits.

For target prioritization, we fed the photometric/spectroscopic catalog described in Section 2.1 into an algorithm designed to homogeneously probe our target area at $z \sim 2.3$. In order to ensure sufficient spatial resolution within a finite volume at $z \sim 2.3$ along the line of sight, we ran our algorithm at two separate redshifts, $z_{\alpha} = 2.25$ and 2.45, and then merged the target lists. Our algorithm divides the survey footprint into square cells of our desired sight-line separation, 2.75 arcmin on each side. In each cell, we select candidate background sources that could theoretically probe the forest at $z_{\alpha}$ in the rest frame 1040 Å $< \lambda < 1216$ Å, i.e., between the Lyα and Lyβ transitions, corresponding to redshifts $(1 + z_{\alpha})1216/1195 < 1 < (1 + z_{bg})1216/1040 - 1$. We then give the highest priority to "bright" sources with $g < [24.2, 24.4]$ at $z_{\alpha} = [2.25, 2.45]$ which have confirmed spectroscopic redshifts, and down-prioritize objects with only photometric redshifts or at fainter magnitudes.

Due to slit-packing constraints, the algorithm deprioritizes relatively bright sources if another, brighter, high-confidence target is within the same cell, while fainter or photometric redshift targets might receive relatively high priority in the absence of other suitable background sources within its 2.75 arcmin cell. Due to the possibility that slit collisions from targets in other cells might clobber the highest-priority source within a given cell, the algorithm selected multiple sources per cell (with decreasing priority) where available. This procedure selected targets as faint as $g = 25.3$ in regions lacking brighter candidates, but such faint targets were assigned a commensurately low priority.

The initial selection of sources and their priority rankings from this algorithm were then fed into the AUTOSLIT3 software in order to design LRIS slit-masks. The initial slit assignment was automatically carried out by AUTOSLIT3 based on the priorities assigned by the initial target-selection algorithm, which we then manually refined to maximize the homogeneity of bright sources and the uniformity of redshift coverage within our desired 2 $\leq z_{\alpha} \leq 2.5$ redshift range. In each 7′ × 5′ LRIS slit-mask, we assigned ~20–25 science slits. Due to slit-packing constraints and the necessity of having at least four alignment stars within each slit-mask, this limited us to only ~80% of the high-priority targets within our desired redshift range.

We designed a uniform set of slit-masks to cover our entire survey footprint (Figure 2), but also supplemented these with additional slit-masks—designed and observed in subsequent observing seasons after the initial pass—to increase sight-line sampling in particular regions of interest (specifically the previously identified overdensities at $z \sim 2.5$; see Section 5), or to make up for shortfalls in sight-line density after the initial round of observations.

Over the 2019–2020 observing season, when it became apparent that further time allocations might not be forthcoming, we designed a row of slit-masks with horizontal orientations to try to ensure that the overall survey footprint would end up in a roughly rectangular shape. These horizontal slit-masks make up the bottom row of the survey footprint as seen in Figure 2.

3. Observations and Data Reduction

The CLAMATO observations were carried out using the LRIS spectrograph (Oke et al. 1995; Steidel et al. 2004) on the Keck I telescope at Maunakea, Hawai‘i. The observations described in this paper were carried out in 2014–2020 via a total time allocation of 20.5 nights, of which 18.5 nights were allocated by the University of California Time Allocation Committee (TAC) and 2 nights were from the Keck/Subaru exchange time given by the National Astronomical Observatory of Japan TAC. Out of this overall allocation, we achieved approximately 85 hrs of on-sky integration.

CLAMATO focused on the LRIS blue channel covering the range of 3700 Å $< \lambda < 4400$ Å, which corresponds to the rest frame Lyα at 2.1 $\leq z_{\alpha} \leq 2.6$. We used the 600-line grism blazed at 4000 Å in the blue channel which, with the 1″ slitwidth we used, has a spectral resolution of $R = \lambda / \Delta \lambda \approx 1100$. This corresponds to a FWHM of ~4 Å, which translates to a line-of-sight spatial resolution of 3 h$^{-1}$Mpc at $z \sim 2.3$, comparable to the separation between our lines of sight. We used the red channel to assist in redshift determination and object identification.

Observations were conducted with a mean seeing FWHM $\approx 0.7″$; in <0.8″ seeing we typically exposed for a total of 7200 s per typical survey slit-mask. In suboptimal seeing we increased exposures up to a total of 14,400 s in order to attain approximately homogenous minimal signal-to-noise ratio (S/N) over the sky. For survey slit-masks designed to plug gaps, we integrated up to 19,800 s to gain sufficient S/N on fainter background sources and to deal with poor seeing conditions during those observations. Individual exposures in the blue channel were typically 1800 s, while those in the red channel were only 860 s to mitigate for the effects of cosmic ray hits on the red channel’s thick, fully depleted CCDs (Rockosi et al. 2010).

The gathered data were reduced using the LowRedux routines from the XIDL software package. We performed initial flat-fielding, slit definition, and sky subtraction, and then coadded the two-dimensional (2D) images of the individual exposures. We then traced the 1D spectra, additionally coadding 1D spectra from different observing epochs which could not be coadded in 2D.

From the 32 unique slit-masks observed in the 2014–2020 CLAMATO campaign, we reduced and extracted 600 spectra from the blue channel, not including 19 spectra from unrelated “filler” programs. The resulting spectra were then visually inspected and compared with common line transitions and spectral templates (particularly the Shapley et al. 2003 composite LBG template) to determine their redshift and classification type. Each spectra was then assigned a confidence

\footnote{https://www2.keck.hawaii.edu/inst/lris/autoslit_WMKO.html}

\footnote{http://www.ucolick.org/~xavier/LowRedux}
flag with a ranking of 0–4, where 0 denotes no attempt at identification due to a corrupted spectra or little source flux, 1 is a rough best guess, 2 is a low-confidence redshift, 3 is an object with reasonable enough classification certainty to be used for scientific results, while 4 is a high-confidence redshift determined from multiple spectral features. Out of all the spectra, 393 spectra were determined to have confidence rating, of which 377 were at redshifts of $z > 2$ (Figure 3). The faintest object of this category was a $g = 25.29$ galaxy at $z = 2.568$, although this was a Ly$\alpha$ emitter that could not be used for IGM tomography. These high-redshift, high-confidence sources were classified into 359 galaxies (95.5%) and 18 broad-line quasars (4.5%). Both populations are suitable for Ly$\alpha$ forest absorption surveys, but require different continuum-fitting methods, as described in Lee et al. (2018). We show a full table of extracted sources in Table 1, while examples of the spectra are shown in Figure 4. Nearly all sources with an identified continuum were used for our end tomographic analysis; see Section 4.

4. Tomographic Reconstructions

In this section, we describe our methods for 3D tomographic reconstruction of the Ly$\alpha$ absorption seen in the spectra of our background selection. First, we describe the preprocessing of the reduced 1D spectra and setup of the tomographic reconstruction grid. Then, we describe the two methods we use for tomographic reconstruction: (i) WF of the transmitted Ly$\alpha$ flux, which was also used in our previous papers (e.g., Lee et al. 2014a, 2016, 2018), and (ii) a constrained realization method to estimate the underlying matter density field (Horowitz et al. 2019, 2021).

4.1. Data Preparation

We selected reduced spectra based on their continuum-to-noise ratio (CNR), defined as the value of the fitted continuum divided by the noise, within the Ly$\alpha$ forest absorption wavelengths for our tomographic analysis. We evaluated this ratio over three distinct absorption redshift windows: $2.05 < z_\alpha < 2.15$, $2.15 < z_\alpha < 2.35$, and $2.35 < z_\alpha < 2.55$. All high-redshift objects with estimated confidence $\geq 3$ and $\langle$CNR$\rangle \geq 1.2$ over any of these absorption windows were used in our tomographic reconstructions. This approach was fairly aggressive, selecting the vast majority of objects that had a confident redshift estimate (Figure 3), only excluding objects which had negligible continua. We show the sky positions of the selected lines of sight in Figure 5.
additional lines of sight in specific regions. The numbers in gray are the field numbers we assigned to the slit-masks.

Figure 2. Slits and footprints of the 32 Keck I/LRIS slit-masks observed in CLAMATO, overlaid on top of the deep Hubble Space Telescope ACS F814W mosaic of the COSMOS field (Koekemoer et al. 2007). The blue box indicates the footprint of the reconstructed tomographic map from the $2.15 < z < 2.55$ Ly\(\alpha\) forest absorption. Most of the slit-masks were designed to achieve a uniform survey layer (dark green), while several were “special” slit-masks (red) designed to obtain additional lines of sight in specific regions. The numbers in gray are the field numbers we assigned to the slit-masks.

Figure 3. Redshift distribution of well-identified ($\geq 3$ confidence rating) spectra from CLAMATO, shown as the black histogram with redshift bins of $\Delta(z) = 0.05$. The red histogram indicates background sources that were actually used to tomographically reconstruct the foreground Ly\(\alpha\) forest at $2.05 < z_\alpha < 2.55$. These plot axes leave out 11 objects at $z < 1.6$ and one object at $z > 3.2$. Note that the spike at $z \sim 2.45$ is due to previously identified large overdensity in this area (Casey et al. 2015; Diener et al. 2015; Chiang et al. 2015; Wang et al. 2016; Cucciati et al. 2018).

A total of 320 spectra from our observations fulfilled both the redshift criteria and S/N classification to contribute to our tomographic reconstruction of the Ly\(\alpha\) forest within the target redshift range $2.05 < z_\alpha < 2.55$ in our footprint. We show the distribution of the estimated Ly\(\alpha\) forest S/N in Figure 6 at different redshift ranges within our volume. We can model our S/N distribution with a power law with an index of $-2.7$, as done in Krolevski et al. (2017, 2018). Based on the sky positions of the lines of sight, the transverse footprint of the tomographic reconstruction spans a comoving region of $30'1 \times 24'8$ in the R.A. and decl. dimensions, respectively (see Figure 5), centered at $10^h 00^m 34.21 +02^d 17' 53.49$ (J2000). This angular size is equivalent to a comoving scale of $30 h^{-1}$ Mpc $\times 24 h^{-1}$ Mpc at $\langle z \rangle = 2.30$. The mean sight-line density is $\langle n_{\text{los}} \rangle = 856$ deg$^{-2}$ when averaged over the entire volume, equivalent to $\langle d_{\perp} \rangle = 2.35 h^{-1}$ Mpc at $z = 2.3$. At the two redshift extremes, $z = [2.05, 2.55]$, we find an effective sight-line density of $n_{\text{los}} = [617, 515]$ deg$^{-2}$, corresponding to an average transverse comoving separation of $\langle d_{\perp} \rangle = [2.73, 2.98] h^{-1}$ Mpc (see Figure 7). Toward the middle of our redshift range we have the highest effective sight-line density, peaking at $1075$ deg$^{-2}$ at $z_\alpha = 2.28$, equivalent to a transverse comoving separation of $\langle d_{\perp} \rangle = 2.07 h^{-1}$ Mpc. The overall sight-line densities in the current CLAMATO data is marginally worse than in DR1, as the boost from the known galaxy overdensities at $z \sim 2.5$ in DR1 has been diluted by the increased map area.

The Ly\(\alpha\) forest fluctuation at each pixel can be calculated from a given spectra with an estimated continuum, $C$. We divide the observed spectral flux density, $f$, by the mean Ly\(\alpha\) forest transmitted flux, $\langle F \rangle(z)$, multiplied by the estimated continuum value:

$$\delta_F = \frac{f}{C \langle F \rangle(z)} - 1.$$  

(1)

We adopt the Faucher-Giguère et al. (2008) values for $\langle F \rangle(z)$, which are based on a sample of 86 high-resolution, high-S/N quasar spectra with absorption features extending well over this redshift range.

The intrinsic continua, $C$, of a quasar source is estimated based on a principal component analysis (PCA)-based mean-flux regulation (MF-PCA; e.g., Lee et al. 2012, 2013). For each spectrum, a continuum template is fitted to determine the correct shape for the QSO emission lines. A linear function is further fitted within the Ly\(\alpha\) forest region.
We use the resulting flux pixel values, $\delta_F$, and associated noise uncertainties, $\sigma_N$, as inputs for our tomographic reconstructions. These extracted values are made publicly available and described in greater detail in the Appendix.

To perform our tomographic reconstructions, we define a Cartesian grid in our footprint (Figure 5). To simplify our analysis, we assume a fixed Hubble parameter, $H(z)$, throughout our volume evaluated at $z = 2.30$. This is equivalent to setting a fixed differential comoving distance $d\chi/dz$, allowing for a direct correspondence between redshift segment length, $\xi_z$, and comoving distance, $\delta_X$. Our angular footprint of $30'1 \times 24'8$ translates to a fixed comoving scale of $34 \, h^{-1} \text{Mpc} \times 28 \, h^{-1} \text{Mpc}$ at all redshifts in our map. Note that this will result in a slight variation of our smoothing kernel’s physical size from one side of our redshift range to the other. The alternative to this procedure would be use an evolving $H(z)$ over the volume, resulting in outward flared skewer positions relative to the comoving grid; this was found to have a negligible effect on the cosmic void analysis of Kroeko et al. (2017) while also breaking the one-to-one correspondence between $[x, y]$ and [R.A., decl.], complicating analysis of the maps.

The angular footprint of this grid is $\sim 30\%$ larger than Lee et al. (2018) and $4.5 \times$ larger than that in Lee et al. (2016).

\subsection{4.2. Wiener Filtering}

To construct maps using the Ly$\alpha$ forest flux alone, we use a WF scheme, as done in Lee et al. (2018). The basic algorithm is described in Pichon et al. (2001) and Caucci et al. (2008), and we use an implementation developed in Stark et al. (2015b).\footnote{Other methods for direct flux reconstruction also exist, including Cisewski et al. (2014) and Li et al. (2021), which could be applicable depending on the end use of the maps. For WF, we solve for the Ly$\alpha$ forest flux fields:}

$$
\delta_F^{\text{rec}} = C_{\text{MD}} \cdot (C_{\text{DD}} + N)^{-1} \cdot \delta_F,
$$

\footnote{https://github.com/caseywstark/dachshund}
where $C_{DD} + N$ and $C_{MD}$ are the data–data (with noise) and map–data covariances, respectively. We use a preconditioned conjugate gradient method to approximately solve the combination of matrix inversion and multiplication. For the noise covariance, we assume a diagonal form of

$\sigma_{\text{noise}}^2 = N_{ii} \delta_{i}$, which ignores subdominant errors from continuum misidentification and other correlated errors. We impose a noise floor of $\sigma_{\text{noise}} \geq 0.2$ in order to not overly weight a small subset of high-$S/N$ lines of sight.

We also assume a Gaussian data–data covariance of the form

$C_{DD} = C_{MD} = C(r_1, r_2)$, following Caucci et al. (2008), and

$$C(r_1, r_2) = \sigma_r^2 \exp \left[ -\frac{(\Delta r_1)^2}{2L_1^2} \right] \exp \left[ -\frac{(\Delta r_2)^2}{2L_2^2} \right],$$

where $\Delta r_1$ and $\Delta r_2$ are the distances between $r_1$ and $r_2$ along, and transverse to, the line of sight, respectively. We adopt

Figure 5. Points indicate the celestial positions of the Ly$\alpha$ forest lines of sight used to tomographically reconstruct the Ly$\alpha$ forest at $2.05 < z < 2.55$, with the blue rectangle showing the angular footprint adopted for the tomographic reconstruction; the pink dashed rectangle is the footprint from our previous data release (Lee et al. 2018). The different symbols denote coverage over different redshift ranges. Some background sources have the correct redshift to cover large ranges of our targeted foreground redshift range and are therefore indicated by multiple symbols. The top and right-hand axes denote the coordinates of our tomographic map grid in units of transverse comoving distances, evaluated at the mean redshift of our tomographic map.

Figure 6. Distribution of the median sight-line signal-to-noise ($S/N$) within the Ly$\alpha$ forest, evaluated at several redshift bins within our map volume. A small number of higher $S/N$ lines of sight have been left out by these plot axes. The dashed curve is a power law with an index of $-2.7$, which is a reasonable approximation for our $S/N$ distribution.

Figure 7. Effective area density of Ly$\alpha$ forest lines of sight over the redshift range of the CLAMATO tomographic reconstruction. The right axis labels the equivalent mean separation between lines of sight, $\langle d_\perp \rangle$, evaluated at $z = 2.3$. The peak sight-line density is $1056 \text{ deg}^{-2}$ at $z_\alpha = 2.28$, corresponding to $\langle d_\perp \rangle = 2.07 \text{ h}^{-1} \text{ Mpc}$. Note that this estimate does not take into account the pixel masks in the spectra.
transverse and line-of-sight correlation lengths of $L_\perp = 2.5 \, h^{-1} \, \text{Mpc}$ and $L_\parallel = 2.0 \, h^{-1} \, \text{Mpc}$, respectively, as well as a normalization of $\sigma_f^2 = 0.05$. This formulation of the covariance matrix and parameters was found in Stark et al. (2015b) to reasonably approximate the true covariance, have no explicit cosmological dependence, and provide accurate reconstructions on mock CLAMATO catalogs. The choices of $L_\perp$ and $L_\parallel$ are set by the average sight-line separation and the line-of-sight spectral smoothing, respectively.

From the input map data of 84,608 pixels, we perform a WF reconstruction using the Stark et al. (2015b) algorithm, which solves the matrix inversion using a preconditioned conjugation gradient solver with a stopping tolerance of $10^{-3}$. The runtime for the entire volume was approximately 1000 s using a single core of an Apple MacBook Pro laptop with a 2.9 GHz Intel Core i5 processor and 16 GB of RAM.

Our output grid is of size $68 \times 56 \times 876$ cells each $0.5 \, h^{-1} \, \text{Mpc}$ on a side with an effective smoothing scale of $\sim 2-3 \, h^{-1} \, \text{Mpc}$. The resulting map is publicly available for download as a binary file; see the Appendix for details.

### 4.3. Density Reconstructions and Cosmic Structure

In addition to the WF flux reconstructions, we also reconstruct the underlying matter density field using the Tomographic Absorption Reconstruction and Density Inference Scheme (TARDIS; Horowitz et al. 2019). This method iteratively solves for the initial density field, which gives rise to the observed structures through a forward-modeling framework. Unlike the WF reconstructions, this method solves for the underlying dark matter density fields instead of the Ly$_\alpha$ flux maps. This assumes an underlying $\Lambda$CDM cosmology and an analytical approximation to map from the evolved matter density to Ly$_\alpha$ forest optical depth. One can view this process as iteratively solving for an initial density field, $\delta_m^i$, given the following forward operating steps:

$$
\delta_m^i \rightarrow \frac{N - \text{Body}}{\text{FGPA}} (\delta_m^{\text{Body}}, \nu_m^{\text{FGPA}}) \rightarrow (\tau_{\text{real}}, \nu_m^{\text{RSD}}) \rightarrow \tau_{\text{red}},
$$

where from the end redshift space optical depth, $\tau_{\text{red}}$, we select matching lines of sight to the CLAMATO survey and iterate to find the density field that best matches the CLAMATO data. We assume the fluctuating Gunn–Peterson approximation, $\tau = A \exp(\delta_m^i)$, for the hydrodynamical mapping from the matter density to Ly$_\alpha$ flux, which was found to cause minimal decrease in cosmic structure recovery performance (Horowitz et al. 2021). For our N-body solver, we use a particle mesh scheme as described in Modi et al. (2021). This resulting $\tau_{\text{red}}$ field is compared along each line of sight with the true data with a Gaussian likelihood weighted by the inferred pixel noise. All steps of our forward operator are differentiable, allowing fast optimization using first-order-based methods. In this case we use a limited memory Broyden–Fletcher–Goldfarb–Shanno solver, which approximates the Hessian information via a truncated recursion relation from the previous update’s gradients.

In Horowitz et al. (2021), this framework was further extended to allow joint reconstruction of Ly$_\alpha$ forest tomography with an overlapping galaxy sample. This work found a synergistic reconstruction effect, where Ly$_\alpha$ forest absorption traced diffuse structures on large scales while galaxies were able to reconstruct the amplitudes of overdensities. As CLAMATO is located in the COSMOS field, there are a number of possible galaxy surveys which can be used for a joint reconstruction, including ZFIRE, zCOSMOS, MOSDEF, etc. However, large-scale structure reconstruction requires a well-defined radial selection function, which is difficult to determine in cases where the survey is designed to study a particular structure or galaxies of a certain subpopulation (see Ata et al. 2021 for a discussion). We therefore use zCOSMOS (Lilly et al. 2007) as the corresponding galaxy sample to combine with the Ly$_\alpha$ forest absorption, which comprises $\sim 45\%$ of all galaxies in the overlapping volume and has a well-characterized selection function that we take from Ata et al. (2021).

In practice it would be computationally difficult to reconstruct the full volume at once due to the elongated geometry. We divide the volume into four overlapping cubic subvolumes of $L = 128 \, h^{-1} \, \text{Mpc}$ each, with $15 \, h^{-1} \, \text{Mpc}$ overlap in the radial dimension. In addition we offset the data $10 \, h^{-1} \, \text{Mpc}$ into each reconstructed subvolume in order to minimize possible edge effects due to the simulation’s periodic boundary conditions. The reconstructed subvolumes are then pasted together with a linear weighted averaging in the overlapping regions. We have verified with mock catalogs that this pasting scheme does not introduce artifacts into the simulated volume or decrease reconstruction quality in the overlap. Our reconstruction with this method takes approximately 30 min on an NVIDIA Tesla V100 PCIe GPU card for the entire survey volume. We provide publicly our resulting reconstructed maps in numpy file format gridded in $1 \, h^{-3} \, \text{Mpc}$ cells.

As the reconstruction recovers directly the dark matter field in both real and redshift space, we can use these recovered fields for direct classification of the cosmic web environment. We use the pseudodeformation tensor as described in Lee & White (2016), Krolewski et al. (2017), and based on work in Hahn et al. (2007), Bond et al. (1996), Forero-Romero et al. (2009). The pseudodeformation tensor is defined as the Hessian of the gravitational potential, capturing the curvature information of the smoothed underlying density field. This tensor can be efficiently computed with known matter density in Fourier space, $\delta_\kappa$, as

$$
\tilde{D}_{ij} = \frac{k_i k_j}{k^2} \delta_\kappa.
$$

The eigenvectors of this tensor are related to the principle inflow or outflow directions depending on if the corresponding eigenvalue is positive or negative. The signature of the eigenvalues themselves can be used to classify the resulting cosmic structures as nodes, filaments, sheets, and voids (see Table 2).
5. Results

We show an example slice of our reconstructed map via both WF and via forward-model reconstruction in Figure 8. In addition to the reconstructed maps, we show a visualization of the cosmic structure as defined by the eigenvalues of the reconstructed matter deformation tensor, as well as coeval spectroscopically observed galaxies in the volume from different surveys. Each slab is projected over a thickness of $2 \, h^{-1} \text{Mpc}$, along R.A., with the $y$-axis of each plot representing change in decl. and the $z$-axis representing the redshift or line-of-sight dimension. For a clear comparison, we smooth all maps with a Gaussian kernel of $R = 2 \, h^{-1} \text{Mpc}$, the approximate average sight-line spacing of the survey. We have also created a number of 3D renderings of our reconstructed flux field, dark matter density field, and inferred cosmic structures. These are available both in movie form (Figure 9) as well as manipulable interactive figures (Figure 10).

There are a number of potential applications of these reconstructed maps to constrain IGM gas properties, galaxy formation and evolution, and cosmology. However, in this section we focus on a qualitative discussion of the structures recovered and will explore other applications in future work.

5.1. Large-scale Structure Features

All of the visualizations show a rich cosmic web environment, which is apparent in both the WF maps as well as the forward-modeled reconstructions. We see a close correspondence between the reconstructed flux maps and the underlying
galaxy surveys, with the significant caveat that all overlapping surveys have a nonuniform selection function along the line of sight and on the sky. Note that due to the varying selection functions and sky coverage of each survey, this galaxy sample is incomplete over our volume and it would be challenging to infer cosmic structures from galaxies alone (Horowitz et al. 2021).

Compared with Lee et al. (2018), the expanded footprint allows the reconstruction of a complete picture of the cosmic web. With a transverse length of 35 h^{-1} Mpc and 30 h^{-1} Mpc, we are able to completely capture filamentary structures spanning identified cosmic nodes within our survey area, as well as resolve sheet structures between filaments (see Figure 9). In addition to filamentary structures, as in Lee et al. (2018), we see apparent voids and (proto)clusters which have been previously discussed in past data releases in the same field (see Lee et al. 2015 and Kroekowski et al. 2017) but now with increased sky coverage. We see that DR2 completely includes a number of previously identified galaxy protoclusters including the z \approx 2.1 galaxy protocluster first identified through the ZFOURSE medium-band photometric redshift survey (Spitler et al. 2012) and later confirmed with NIR spectroscopy (Nanayakkara et al. 2016).

In addition, the previously identified z \approx 2.5 overdensity comprised of the z = 2.44 protocluster (Diener et al. 2015; Chiang et al. 2015), the z = 2.47 protocluster (Casey et al. 2015), and the X-ray-detected z = 2.51 cluster (Wang et al. 2016; Cucciati et al. 2018) all appear to form a massive interconnected structure (see Figures 9 and 10) extending from 2.44 < z < 2.52. While this structure was truncated by the survey geometry in Lee et al. (2018), it does not appear to extend significantly beyond our current survey volume. The VUDS galaxy survey has been used to infer the general shape of this structure (see Cucciati et al. 2018), and we find our inferred WF flux recovers a similar qualitative shape (see seventh panel of Figure 12). The exact correlation on small scales (\approx 1 h^{-1} Mpc) between galaxy density and Ly\alpha forest flux depends on the galaxy feedback model (Sorini et al. 2018). The late-time fate of these megastructures is of significant interest, with Wang et al. (2016) arguing that the z = 2.51 overdensity, in itself, might collapse into a 2 \times 10^{15} M_{\odot}. Using forward-modeling techniques (Horowitz et al. 2019, 2021; Ata et al. 2021) we will explore the late-time fate of these structures in future works (M. Ata et al. 2022, in preparation).

### 5.2. Comparison of TARDIS and Wiener Filter Reconstruction

TARDIS is a fundamentally different approach than WF reconstruction since the resulting density fields are constrained to evolve from gravitational evolution and the hydrodynamical properties are determined via the fluctuating Gunn–Peterson approximation; see Section 4.3. Substantial differences in the field reconstructed between these two methods could be an indication of strong deviations from simple analytical approximations for the IGM flux–density relationship due to strong feedback within cluster environments (see, e.g., Kooistra et al. 2022), or, for example, possible galaxy quenching in overdense environments (Newman et al. 2022). In the case of mock catalogs which include hydrodynamical effects, TARDIS has shown to be still highly accurate in classification of cosmic structures at the resolution available to the CLAMATO survey (Horowitz et al. 2021); see also Horowitz et al. (2019) for a discussion of TARDIS reconstruction versus WF in the absence of hydrodynamical effects.

In addition to the slice maps shown in Figure 12, we show the relationship between the inferred flux from TARDIS, calculated by performing a fluctuating Gunn–Peterson approximation (FGPA) transformation on the resulting density field and that inferred from the WF approach in Figure 11. We find the results are largely consistent, with a Pearson correlation coefficient of 0.86. Further propagating this analysis to cosmic structure as defined by the eigenvalues of the deformation tensor, we find a Pearson correlation coefficient of 0.83 between structures classified using the WF and TARDIS, indicating similar cosmic structure reconstruction. Further investigation into the causes of the differences between these maps will be the focus of future work.

### 5.3. Three-dimensional Visualizations

Figure 9 shows a 3D visualization of the CLAMATO-reconstructed cosmic web rendered using a self-developed...
software based on the Open Graphics Library (OpenGL) and the OpenGL Shading Language\textsuperscript{21} and implemented in C++. Because our tomographic map consists only of scalar values, we can apply direct volume rendering, where each density value is mapped to a particular color and opacity value via a transfer function. Then, a ray is generated for each image pixel and is sampled at regular intervals throughout the volume where the mapped RGBA values from the transfer function are composited in front-to-back order. For a smoother representation we use tricubic interpolation.

To highlight the cosmic structure classification, we use four Gaussians of nearly equal width to generate the transfer function. Sampling artifacts are reduced by making use of the pre-integration technique (Engel et al. 2001).

Finally, mesh and volume rendering are combined via two-pass rendering, where we first render the color and depth of the grid mesh into two textures.In the second pass, the depth texture is used while the rays are integrated to check for intersections with the mesh.

Figure 10 shows a 3D visualization of the CLAMATO tomographic map also using direct volume rendering. This time the transfer function consists of four very thin Gaussians to represent isodensity contours. The interactive online version (https://www2.mpia-hd.mpg.de/homes/tmueller/projects/clamato2020/clamato_vol.html) is based on WebGL/threejs. The isodensity values as well as the corresponding opacities can be modified via slider controls in the online interface.

6. Conclusion

In this paper, we have described the second data release of the CLAMATO survey, the first systematic attempt at implementing 3D Ly\(\alpha\) forest reconstruction on several-megaparsec scales using high area densities (\(\sim 1000 \text{ deg}^{-2}\)) of background LBG and quasar spectra. With Keck I LRIS observations of 23 multi-object slit-masks over \(\sim 0.2 \text{ deg}^{-2}\) in the COSMOS field, we obtained 393 spectra with confident redshifts, of which 320 spectra were suitable for use in tomographic reconstruction in the target redshift range, \(2.05 < z_{\alpha} < 2.55\) Ly\(\alpha\) forest. This set of lines of sight has an average transverse separation of only \((d_{\perp}) = 2.35 h^{-1} \text{ Mpc}\), allowing us to create a 3D tomographic map of the IGM and also infer the underlying dark matter density field. From this reconstructed map, we can identify for the first time the detailed cosmic web (including filaments and sheets) at high redshifts \(z \sim 2.4\). We have made all catalogs, pixel data, and reconstructed maps available to the general public along with various analytical code (see the Appendix). With the extended volume of DR2, we are currently performing multiple additional analyses in this volume, including studying galaxy properties as a function of IGM and cosmic environment, analysis of the protoclusters within the volume, intrinsic alignments of galaxies with cosmic structure, constraints on hydrodynamical properties of the IGM from the various reconstructed maps, and cross-correlations between the Ly\(\alpha\) forest and coeval galaxies.

Going forward, the analysis done with the CLAMATO survey will serve as a test for planned and ongoing surveys over a wider sky region. The high-redshift component of the Galaxy Evolution Survey with the Prime Focus Spectrograph (PFS) on the 8.2 m Subaru Telescope (Sugai et al. 2015) will perform an IGM tomographic analysis with similar sight-line densities and noise properties as the CLAMATO survey over a \(\sim 40 \times\) larger cosmic volume. Beyond PFS, there are various additional facilities in different stages of planning (e.g., the 11.25 m Maunakea Spectroscopic Explorer, M5E; McConnell et al. 2016), which will offer multiplex factors of several thousand over \(\sim 1 \text{ deg}^{2}\) fields of view, allowing IGM tomography over tens or hundreds of square degrees. While the cosmological constraining power of the current CLAMATO survey is limited, with the expanded footprint of PFS or M5E there are potential applications to detect the weak lensing of the Ly\(\alpha\) forest (Metcalf et al. 2018) as well as perform full 3D Ly\(\alpha\) forest power spectrum analysis (e.g., McDonald 2003; Font-Ribera et al. 2018).

B.H. is supported by the AI Accelerator program of the Schmidt Futures Foundation. K.G.L. acknowledges support from JSPS Kakenhi grant Nos. JP18H05868 and JP19K14755. M.A. was supported by JSPS Kakenhi grant No. JP21K13911. We are also grateful to the entire COSMOS collaboration for their assistance and helpful discussions. This work was supported by World Premier International Research Center Initiative (WPI), MEXT, Japan. The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors also wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawai’ian community. We are most fortunate to have the opportunity to conduct observations from this mountain.

\textsuperscript{21} OpenGL 4.6 Specification, https://www.khronos.org/opengl.
Appendix

Data Release

The second data release of the Keck-CLAMATO data is publicly available on Zenodo at doi:10.5281/zenodo.5842842. These include the reduced spectra, continuum-normalized Ly$\alpha$ forest pixels used as the input for the tomographic reconstruction, the tomographic map of the $2.05 < z < 2.55$ IGM, and the inferred density field and cosmic structure from TARDIS.

There are a total of 600 reduced spectra in the data release, available in FITS format with the following headings:

1. HDU0: Object spectral flux density, in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$.
2. HDU1: Noise standard deviation.
3. HDU2: Pixel wavelengths in angstroms.

On the data release web page, we will provide an ASCII catalog that contains the information in Table 1 as well as the file names for the spectra of each object. Note that the released spectrophotometry, especially in the red, might be unreliable.

We also will provide a binary file with the intermediate product of 84,608 concatenated Ly$\alpha$ forest pixels (Equation (1)) at $2.05 < z_{\alpha} < 2.55$ from the background sources that satisfy our redshift and S/N criteria. We will release the $\delta_f$ values and associated pixel noise as a function of the sky positions in $[x, y, z]$ on our tomographic map grid. The sky coordinates, $x$ and $y$, correspond to the transverse comoving distances in the R.A. and decl. directions, respectively. We choose an origin location of $[\alpha_0, \delta_0] = [9^h59^m47^s999, +02^d00^m00^s]$ (J2000) or $[\alpha_0, \delta_0] = [149^\circ9500, 2^\circ1500]$. The $z$ coordinate corresponds to the line-of-sight comoving distance relative to the origin redshift of $z_{\alpha} = 2.05$.

As mentioned in Section 4, we use a fixed conversion between redshift and the comoving distance in our volume. With our choice of cosmology, evaluated at $\langle z \rangle = 2.30$, we have $\chi = 3874.867$ h$^{-1}$ Mpc and $d\chi/dz = 871.627$ h$^{-1}$ Mpc. This intermediate binary file is the primary input used for the Wiener reconstruction and TARDIS algorithms to create the 3D tomographic maps.

The primary products are the binary files containing the IGM tomographic map, which spans comoving dimensions of $30$ h$^{-1}$ Mpc $\times 24$ h$^{-1}$ Mpc $\times 438$ h$^{-1}$ Mpc in the $[x, y, z]$ dimensions, respectively, with binning in units of 0.5 h$^{-1}$ Mpc. In addition, we make available our TARDIS reconstructions, which cover the same volume but with binning in units of 1.0 h$^{-1}$ Mpc. For both products we provide both the direct tomographic reconstruction of the data as well as a version which has been Gaussian smoothed with a $\sigma = 2$ h$^{-1}$ Mpc kernel; the latter is the version shown in the visualizations in Figures 9 and 10. We show slices of our various data products in Figure 12.
Figure 12. Wiener-filtered tomographic reconstructions of the Lyα forest absorption, $\delta_{\text{Ly} \alpha}$, at $2.05 < z_\alpha < 2.55$ from the current CLAMATO data (color map), shown after smoothing with an isotropic $R = 2 \, h^{-1} \text{Mpc}$ Gaussian kernel. Below the Wiener-filtered reconstruction, we show the inferred dark matter distribution from the TARDIS reconstruction and the inferred cosmic web classification, shown as a continuous color spectrum for the eigenvalues. Each color panel shows the field projected over a $2 \, h^{-1} \text{Mpc}$ decl. slice, the position of which is denoted by the shaded region in the subpanels to the left, which also show the sight-line positions on the sky as red dots. In the middle panel we show the overlapping galaxies within the slice: blue dots from MOSDEF, black dots from ZFIRE, pink dots from VUDS, orange dots from zCOSMOS-Deep, and red dots from CLAMATO. See Figure 8.
Figure 12. (Continued.)
Figure 12. (Continued.)
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The Astrophysical Journal Supplement Series, 263:27 (17pp), 2022 December Horowitz et al.