

EIGER VIII: First stars signatures in the connection between O I absorption and Galaxies in the Epoch of Reionization

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ABSTRACT

We investigate the association between galaxies and neutral O I absorption systems at $z \sim 6$, which trace metal-enriched gas during the epoch of reionization. We identify 40 galaxies across six quasar fields, residing in 15 overdensities within 300 kpc of the background sightlines. Five O I absorption systems are associated with five of these overdensities, yielding a covering fraction of $0.27^{+0.13}_{-0.10}$ within 300 kpc. The absorption occurs beyond typical virial radii, indicating that the gas traces extended overdensity environments rather than individual galaxy halos, unlike the $z \sim 0$ CGM which is largely bound to halos. These galaxy-associated absorbers account for $\sim 35\%$ of all O I systems seen in blind quasar surveys, implying the remainder arise in lower-mass galaxies below our detection threshold or in dense neutral IGM pockets. The CGM around these galaxies contains $\gtrsim 2 \times 10^6 M_{\odot}$ of oxygen, comparable to the ISM oxygen mass of the galaxies themselves, suggesting that the surrounding environment holds as much metal mass as the galaxies. All five galaxy-associated systems show significantly higher $\log(N_{\text{CII}}/N_{\text{OI}})$ ratios than absorbers lacking galaxy associations. Furthermore, relative abundance ratios ($[\text{Si}/\text{O}]$, $[\text{C}/\text{O}]$) reveal that four of the five exhibit enrichment patterns consistent with Population III nucleosynthesis. These rare systems offer a unique window into the role of first-generation stars in shaping the early metal enrichment of galaxies and their environments.

Keywords: Galaxy evolution (594) — High-redshift galaxies (734) — Circumgalactic medium (1879) — Intergalactic medium (813) — Emission line galaxies (459) — Quasar absorption line spectroscopy (1317)

1. INTRODUCTION

The first generations of stars formed shortly after the Epoch of Recombination within dark matter overdensities, producing the first significant quantities of metals and enriching the intergalactic medium (IGM) while reionizing hydrogen and helium (e.g., R. S. Klessen & S. C. O. Glover 2023). These metals and gas eventually coalesced into the first galaxies, which over cosmic time evolved into Milky Way-like systems today. Studying these young galaxies and their environments provides

critical insight into galaxy formation and evolution, constraining models of stellar feedback, gas accretion, and chemical enrichment (C.-A. Faucher-Giguère & S. P. Oh 2023; C. Peroux & D. Nelson 2024).

At low redshift, decades of observations using deep ground-based spectroscopy and HST data of background quasars and foreground galaxies have built a rich understanding of the circumgalactic medium (CGM) and its interplay with galaxies (e.g., J. Tumlinson et al. 2017). The CGM plays a crucial role in gas recycling, star formation regulation, and quenching; understanding its structure and composition informs galaxy growth models (Y. Peng et al. 2015; E. Zinger et al. 2020).

High-redshift studies, leveraging ground- and space-based NIR spectroscopy of quasars, reveal that the

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early Universe was already chemically enriched by the epoch of reionization (e.g., R. L. Davies et al. 2023a; T. J. Cooper et al. 2019; L. Christensen et al. 2023). Among tracers of neutral and low-ionization gas, O I has emerged as a key probe: surveys report an increase in O I number density at $z \gtrsim 5 - 6$ (G. D. Becker et al. 2019; L. Christensen et al. 2023; A. M. Sebastian et al. 2023), while higher-ionization species like C IV and Si IV decline, consistent with a softer and evolving UV background at the end of reionization (R. L. Davies et al. 2023a,b; V. D’Odorico et al. 2022; T. J. Cooper et al. 2019).

Historically, connecting absorption systems with their host galaxies was challenging due to the difficulty of obtaining deep, high-redshift galaxy spectroscopy. This has changed with the advent of JWST, providing unprecedented views of early galaxies and their impact on surrounding gas through surveys such as EIGER (D. Kashino et al. 2023) and ASPIRE (F. Wang et al. 2023). First systematic studies of cool, low-ionization CGM traced by Mg II around $z \sim 6$ galaxies suggest that high-redshift CGM differs significantly from its low-redshift counterpart: these galaxies typically have low masses, and strong stellar feedback can eject metals far beyond the halo’s gravitational potential (R. Bordoloi et al. 2024). Such pioneering studies now allow systematic investigations of the CGM in the early Universe.

The UV background during reionization was inhomogeneous and rapidly evolving (e.g., S. R. Furlanetto & S. P. Oh 2005; B. D. Oppenheimer et al. 2009; K. Finlator et al. 2013; G. D. Becker et al. 2015; S. E. I. Bosman et al. 2022), initially dominated by Population III stars (K. Nakajima & R. Maiolino 2022; K. Nakajima et al. 2025), then by early star-forming galaxies (L. Jiang et al. 2022; J. Matthee et al. 2022), with AGN contributing significantly by $z \sim 5$ (A. D’Aloisio et al. 2017; G. Kulkarni et al. 2019; C.-A. Faucher-Giguère 2020). Modeling indicates that pockets of Population III star formation may persist throughout the Epoch of Reionization (L. Tornatore et al. 2007; R. H. Mebane et al. 2018; J. L. Johnson & A. Aykotalp 2019; A. Venditti et al. 2023; O. Zier et al. 2025).

The large reservoir of neutral O I observed in quasar absorption lines at high redshift is typically self-shielded, providing robust estimates of chemical abundances. Studying the association of these absorbers with galaxies offers unique insight into the CGM of early galaxies, and into potential contributions from Population III stars to early chemical enrichment.

In this work, we study the cool, neutral CGM around galaxies at $z \sim 6$, traced by O I absorption from the EIGER survey (*Emission-line Galaxies and Intergalac-*

tic Gas in the Epoch of Reionization; D. Kashino et al. 2023). We focus on O I absorbers associated with [O III]₅₀₀₈-emitting galaxies at $5.875 < z < 6.378$ within 300 kpc of six background quasars. We quantify absorber incidence, column densities, and mass estimates, and analyze ionic abundances to probe chemical enrichment, including potential contributions from Population III stars.

This paper is organized as follows. Section 2 describes the observations; Section 3 details our methods for galaxy selection, redshift estimation, galaxy properties, defining galaxy overdensities, absorber measurements, and completeness; Section 4 presents the results, including the association of O I absorption with galaxies, the incidence of galaxy-associated O I absorbers, their chemical abundances, and physical interpretations; Section 5 summarizes our conclusions. Throughout, we adopt a Λ CDM cosmology with $H_0 = 67.66 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Planck Collaboration et al. 2020).

2. OBSERVATIONS

EIGER (Program ID 1243; PI: S. J. Lilly) is a large JWST Wide Field Slitless Spectroscopy (WFSS) program totaling 126.5 hours, conducting deep WFSS observations in six extragalactic fields, each centered on an ultra-luminous quasar at $z \geq 6$. These quasars have also been observed with deep optical and near-infrared (NIR) medium- and high-resolution spectroscopy with Magellan/FIRE, VLT/X-shooter, and Keck HIRES/MOSFIRE, providing over 100 hours of complementary NIR spectroscopy across the six sightlines. We refer the reader to A.-C. Eilers et al. (2023) and D. Ďurovčíková et al. (2025) for data reduction and details of the ground-based quasar spectroscopy. In addition, all fields are covered by deep JWST/NIRCam and HST imaging. A detailed description of the survey design, methodology and spectroscopic and photometric observation details are provided in D. Kashino et al. (2023), J. Matthee et al. (2023), and R. Bordoloi et al. (2024). In this work, we make use of the complete EIGER survey of $z \geq 5.9$ galaxies spanning all six extragalactic fields (D. Kashino et al. 2025).

We note that all six quasars were chosen with prior knowledge of metal absorption systems along their lines of sight, which could in principle bias any attempt to associate galaxies with those absorbers. In contrast, a galaxy-centric approach starts with quasar–galaxy pairs without prior knowledge of absorption and then builds statistics systematically (see e.g., R. Bordoloi et al. 2011; J. K. Werk et al. 2013; R. Bordoloi et al. 2014). However, once a blind, well-characterized galaxy survey is in place, the two approaches converge. This is con-

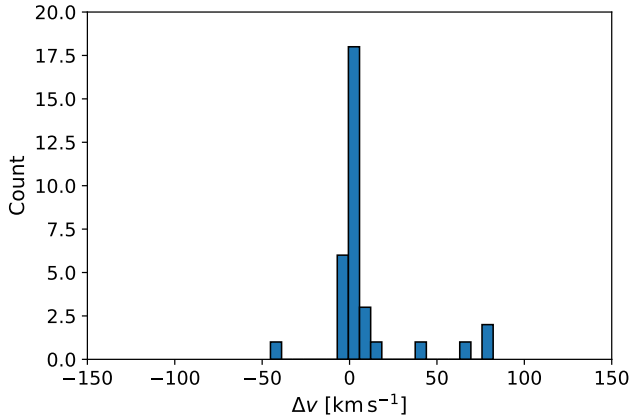


Figure 1. Redshift uncertainty distribution of the [O III] emitter EIGER galaxies. The histogram shows the difference in redshift between emission-line measurements from NIRCcam Grism Module A and Module B spectra, expressed in km s^{-1} . Individual redshifts were derived from Gaussian fits to the [O III] and H- β lines. The two modules yield consistent results with a mean offset and standard deviation of $\Delta z = 0.0028 \pm 0.0073$ ($\Delta v = 9.3 \pm 24 \text{ km s}^{-1}$).

ceptually similar to a program that combines quasar spectroscopy performed without prior absorber selection with a complete galaxy survey. This work employs deep blind galaxy searches in each of the EIGER fields, yielding an emission-line complete sample of spectroscopic galaxies (J. Matthee et al. 2022; R. Bordoloi et al. 2024) and a complete census of absorption lines along these sightlines (Section 3.5). By combining these two elements—a galaxy survey with quantified completeness and an absorption survey with well-defined sensitivity—we establish a robust framework for conducting a census of CGM absorption around galaxies. This combined approach has been successfully demonstrated at low redshifts (J. N. Burchett et al. 2019).

3. METHODS

In this section we describe how galaxy redshifts and properties are measured and how absorption lines are identified and measured.

3.1. Galaxy Redshifts

Since our focus is on galaxies at $z \sim 6$ near the quasar sightlines, we begin with the full EIGER catalog of [O III] emitters (D. Kashino et al. 2025), which contains 948 galaxies detected via [O III] emission within $5.33 \leq z \leq 6.97$. From this catalog we select galaxies that (1) lie in the foreground of each quasar ($z_{\text{gal}} < z_{\text{QSO}}$), (2) are within a projected impact parameter of 300 pkpc, and (3) have O I $\lambda 1302$ coverage in the quasar NIR spectra outside of the Gunn–Peterson trough. This yields a sample of 40 galaxies. Of these, 33 fall within

the central $\approx 4.6 \text{ arcmin}^2$ of the EIGER spectroscopic footprint (R. Bordoloi et al. 2024), observed with both JWST/NIRCcam reverse grism modules (A and B). Because the two modules disperse light in opposite directions, they provide independent moderate-resolution ($R \sim 1500$) spectra of the same target, enabling us to assess redshift measurement uncertainties.

Following the procedure in R. Bordoloi et al. (2024), we visually inspect each NIRCcam 2D spectrum using the custom Python API *zgui* (R. Bordoloi et al. 2025), extract 1D spectra from each module, and fit Gaussians to the [O III] $_{5008}$ emission line to determine redshifts. Redshifts from the two modules are consistent to a mean velocity offset of $\Delta v = 9.3 \text{ km s}^{-1}$ with a standard deviation of 24 km s^{-1} (Figure 1). We therefore adopt an average redshift uncertainty of $\approx 24 \text{ km s}^{-1}$ for the [O III] emitters, sufficient for associating metal absorption systems with their host galaxies. Hereafter, we focus on this sample of 40 galaxies.

3.2. Galaxy stellar mass, star-formation rate, halo mass

To estimate galaxy stellar masses and star-formation rates (SFRs), we follow the procedure of J. Matthee et al. (2022). We first measure the [O III] and H- β emission-line fluxes of each galaxy, and combine these with JWST/NIRCcam broad-band photometry (F115W, F200W, and F356W) to perform spectral energy distribution (SED) fitting at the galaxy redshift using the *Prospector* code (B. D. Johnson et al. 2021). We assume a G. Chabrier (2003) initial mass function (IMF), adopt MIST isochrones (J. Choi et al. 2016; A. Dotter 2016), a non-parametric star-formation history model (R. P. Naidu et al. 2024), and the dust attenuation curve of D. Calzetti et al. (2000). Galaxy SFRs are derived by averaging over the most recent 50 Myr of star-formation history from the *Prospector* posteriors.

Figure 2 (left) shows the impact parameter distribution of the 40 EIGER galaxies relative to the background quasars (black star symbols). The galaxies are randomly distributed with respect to the quasar sightlines. The right panel shows their stellar masses and SFRs, with symbols color-coded by galaxy redshift. Following R. Bordoloi et al. (2024), we estimate halo masses and virial radii (R_{vir}) using abundance matching from P. Behroozi et al. (2019). Uncertainties in R_{vir} are propagated from the 16th and 84th percentile stellar mass errors, giving a mean uncertainty of $\Delta R_{\text{vir}} = 1.8 \text{ kpc}$. The galaxies span stellar masses of $6.8 \leq \log(M_*/M_\odot) \leq 9.3$ and star-formation rates of $-1 \leq \log(\text{SFR}_{50}/M_\odot \text{ yr}^{-1}) \leq 1.5$, with all systems being star-forming by selection.

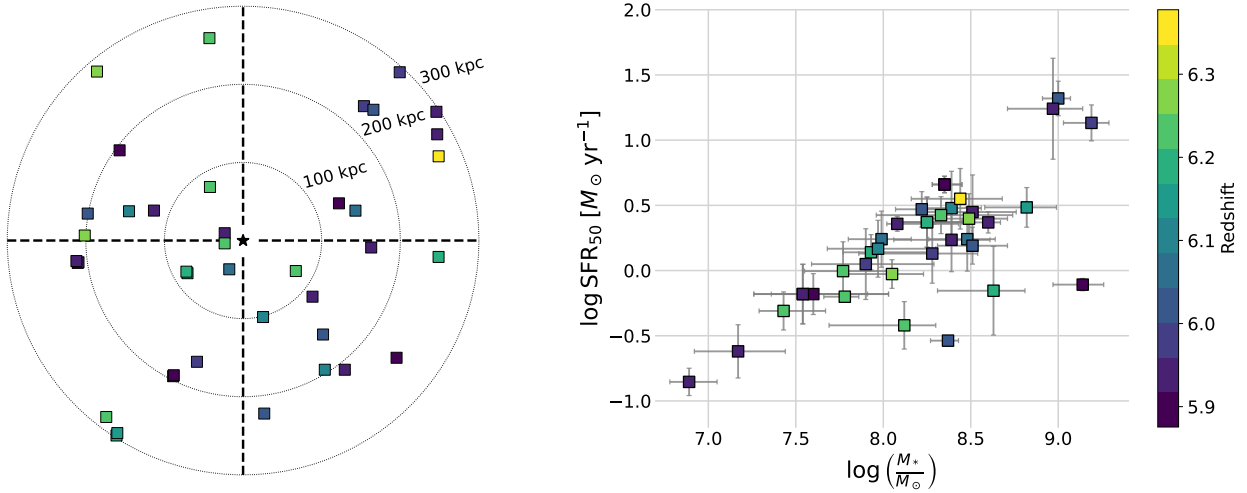


Figure 2. Properties of 40 spectroscopically confirmed galaxies at $5.9 \leq z \leq 6.4$ within 300 kpc of background quasars in the EIGER survey. Each square denotes a galaxy and is color-coded by redshift. *Left:* Angular positions and impact parameters relative to the background quasar (black star), with dashed concentric rings marking 100, 200, and 300 kpc at $z = 6$. *Right:* Stellar mass versus star-formation rate, averaged over the last 50 Myr. Error bars show the 16th–84th percentile uncertainties in stellar mass and SFR.

One galaxy ($z=5.910384$, galaxyID=15362, qsoID = J159) has an exceptionally high stellar mass of $\log(M_*/M_\odot) = 11.05$, beyond the calibrated range of the P. Behroozi et al. (2019) relation. This object exhibits a compact, point-like morphology and likely hosts an obscured AGN, placing it among the recently identified population of Little Red Dots (LRDs) (e.g., J. Matthee et al. 2024). We do not detect broad H- β for this object. However, this is not unexpected, as LRD can have H- α / H- β values as high as ~ 10 (M. Brooks et al. (2025), and Torralba et al., in prep). As robust AGN modeling at these redshifts is not yet established, we estimated its halo mass by linearly extrapolating the P. Behroozi et al. (2019) relation from the stable stellar mass regime. We explicitly note where this assumption may affect our results in the following sections.

3.3. Galaxy Overdensities

A significant fraction of $z \geq 6$ galaxies in the EIGER survey are not isolated but are found in overdense environments, either as mergers or members of “proto-groups” (see, e.g., D. Kashino et al. 2025). The EIGER [O III] galaxy catalog already merges individual [O III] emission clumps within $2''$ into a single system, even when they exhibit complex morphologies or merger signatures. To identify larger-scale overdensities, we therefore search for galaxies that lie at similar redshifts but are widely separated on the sky.

We identify overdensities around the 40 selected EIGER galaxies using a friends-of-friends algorithm (R. Bordoloi et al. 2025). Galaxies are grouped as an overdensity if they lie within 1 pMpc in projected separation and within $\pm 1000 \text{ km s}^{-1}$ in redshift space. A galaxy is considered part of an overdensity only if all members are “fully” connected, i.e., each galaxy in the overdensity satisfies these conditions with all other member. Around each detected O I absorption system, we further search for overdensities within $\pm 1500 \text{ km s}^{-1}$ of the absorber redshift, and merge these associations to ensure all clustered galaxies are treated as a single overdensity. This conservative approach ensures that we capture the full galaxy environment of O I absorbers. The 40 galaxies studied in this work are part of 15 distinct overdensities with each grouping containing 1 – 5 members. The typical velocity dispersion of these overdensities is 449.2 km s^{-1} . Throughout this work, we define the primary member of each overdensity as the galaxy with the smallest impact parameter to the background quasar sightline.

3.4. Absorption line detection and measurements

We follow the procedures outlined in R. Bordoloi et al. (2024) to identify and measure the strength of O I absorption systems around EIGER galaxies, and provide a brief summary here. We first use a custom Python-based 1D spectrum viewer to identify and tabulate all

intervening absorption lines in the EIGER quasar spectra. A semi-automated CGM absorption-line analysis pipeline is then used to perform the measurements. For each galaxy, we extract a $\pm 1500 \text{ km s}^{-1}$ spectral window centered on its systemic redshift, for all transitions of interest. In this work, we analyze slices around O I $\lambda 1302$, Si II $\lambda 1260$, Si II $\lambda 1304$, Si II $\lambda 1527$, C II $\lambda 1334$, Si IV $\lambda 1393$, Si IV $\lambda 1402$, C IV $\lambda 1548$, and C IV $\lambda 1550$. Each slice is locally continuum-normalized using an automated Legendre polynomial fit, with the polynomial order chosen via the Bayesian Information Criterion. The continuum fits and absorption features are visually inspected, and both rest-frame equivalent widths (W_r) and apparent optical depth (AOD) column densities are measured. We define a detection as any absorption system with $W_r \geq 3\sigma_w$, where σ_w is the 1σ uncertainty in W_r . We note that this uncertainty contains both the statistical uncertainty due to signal-to-noise ratio of the data and the continuum fitting uncertainty. Non-detections are reported as $2\sigma_w$ upper limits measured within $\pm 100 \text{ km s}^{-1}$ of the systemic redshift of the galaxy. For column density we report the 2σ uncertainty on AOD column density as upper limit on non-detections. When a transition is detected in multiple instruments, each spectrum is analyzed independently, and the inverse-variance-weighted mean is adopted as the final W_r . The details of this automated approach and full documentation of the APIs used can be found in R. Bordoloi et al. (2025).

For all detections, we perform Voigt profile fitting using the `rbvfit` package, which employs Markov Chain Monte Carlo (MCMC) sampling to simultaneously fit multiple absorption systems across different instruments (R. Bordoloi & J. Higginson 2025). This approach yields robust column densities, resolves the kinematic structure, and enables accurate modeling of blended lines. Additionally, since we obtain marginalized posterior distribution for the fitted parameters, the results yield accurate column density estimates even if doppler b parameter or velocity centroids are not well constrained in moderate resolution spectra (see discussion in R. Bordoloi et al. 2024). In our case, most of the O I Si II C II transitions are all covered by higher resolution HIRES spectroscopy and thus their properties are well constrained. `rbvfit` supports two MCMC samplers, `emcee` (D. Foreman-Mackey et al. 2013) and `zeus` (M. Karamanis et al. 2021; M. Karamanis & F. Beutler 2020), both of which are used in this work depending on the complexity of the fit. We typically adopt 50 walkers with initial perturbations of either 10^{-3} or 10^{-6} , and default chain lengths of 8000–20,000 steps, ensuring the total number of steps exceeds 50 times the autocorrela-

tion time. Additional steps are run as needed to achieve convergence. In each case, a flat prior is assumed with reasonable physical bounds.

Figure 3 shows an example of Voigt profile fits to O I $\lambda 1302$ and Si II $\lambda 1304$ lines simultaneously modeled across FIRE, X-shooter, and HIRES. We fit a two component Voigt profile with a mean velocity offset from the host galaxy of $v_{\text{offset}} = 157 \text{ km s}^{-1}$. This joint fitting maximizes information from all instruments while preserving the kinematic detail provided by higher-resolution data. Galaxy overdensities associated with this system are marked with green vertical ticks. This system has a total O I column density $\log N_{\text{OI}}/\text{cm}^{-2} = 13.46^{+0.11}_{-0.15}$. All other O I fits are presented in Figure 8. All absorption line measurements are presented in Table 1.

We note that an O I and Si II absorption system is detected along the J1030 quasar sightline at $z \sim 6.075$, blended with an intervening C IV absorber at $z \sim 4.948$ (Figure 8, top left panels; see also C. G. Díaz et al. 2021). The $z \sim 6.076$ system is confirmed by the independent detection of Si II, Mg II, C II, and Fe II absorption in FIRE and X-shooter data, and we simultaneously fit the C IV, O I, and Si II systems across three instruments. Although the proximity of the C IV doublet in wavelength space introduces an inherent degeneracy with the O I and Si II pair, high-resolution HIRES data reveal sufficient kinematic substructure to warrant an additional component at a mean velocity offset of $v_{\text{offset}} = -85.4 \text{ km s}^{-1}$. We interpret this component as O I, supported by the aforementioned coincident detections. To constrain the system, we use the secondary lines to fix the velocity centroid of the O I component and perform simultaneous Voigt profile fitting across all three instruments, including both C IV transitions and single-component O I and Si II models. The column density reported in this work corresponds to this singular O I component, and the system is marked with an asterisk in Table 1.

3.5. O I Absorption Detection Completeness

We quantify the completeness of O I absorption detection around each galaxy as follows. For each galaxy overdensity, we compute the detection sensitivity on a pixel-by-pixel basis following the general framework of e.g.; K. M. Lanzetta et al. (1987); M. L. Bernet et al. (2010); N. L. Mathes et al. (2017). Specifically, we use a continuum-normalized spectral slice of $\pm 1500 \text{ km s}^{-1}$ centered on the expected O I absorption at the redshift of each galaxy overdensity.

We define the completeness in O I absorption detection in a single instrument as

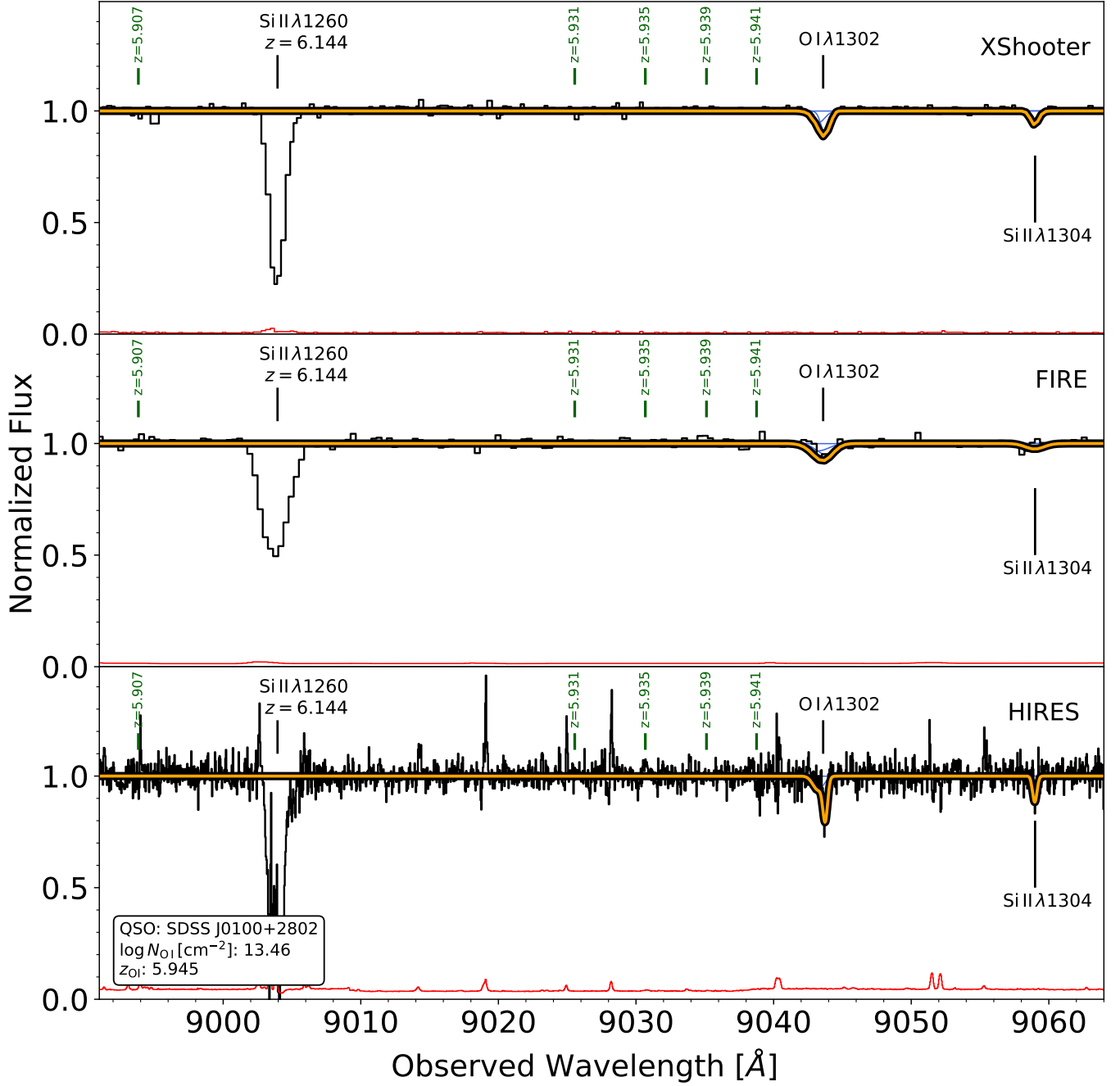


Figure 3. Voigt profile fits to O I and Si II absorption profiles at $z = 5.945$ toward the quasar SDSS J0100+2802. Shown are the flux (black), error spectrum (red), best-fit Voigt model (orange/black), and individual Voigt components (thin blue), using data from FIRE, X-Shooter, and HIRES. Vertical green lines mark galaxy members of the associated overdensity. Spectra from all instruments and all transitions are simultaneously fit using the `rbvfit` Bayesian absorption line fitter.

$$C_{\text{OD}}^1(z) = H(W_{\text{min}} - N_{\sigma} \frac{\sigma_{\text{EW}}(z)}{(1+z)}) \quad (1)$$

where H is the Heaviside step function and W_{min} is the equivalent-width cutoff at which completeness is defined. We adopt $W_{\text{min}} = 0.05 \text{ \AA}$ to facilitate comparison with the literature (see Section 4.2). N_{σ} is the detection threshold, which we set to $N_{\sigma} = 3$ by convention. The equivalent-width error, $\sigma_{\text{EW}}(z)$, is given by

$$\sigma_{\text{EW}}(z)^2 = \sum_j^{n_{\text{pix}}} \Delta\lambda_j^2 (\sigma_{I_j} / I_j^c)^2. \quad (2)$$

where $\Delta\lambda_j$ is the wavelength spacing between adjacent pixels (set by the spectrograph), and n_{pix} is the number of pixels over which the equivalent width is computed. In our case we adopt $n_{\text{pix, X-shooter}} = 10$, $n_{\text{pix, HIRES}} = 50$, and $n_{\text{pix, FIRE}} = 11$. We neglect continuum-fitting errors, so $\sigma_{\text{EW}}(z)$ reflects only statistical uncertainties from the spectra. Any chip gaps or sky lines are masked. σ_I and I^c are the flux uncertainty and continuum levels of the spectrum.

For galaxy overdensities observed with multiple spectrographs, we define the combined completeness as requiring detection in at least one instrument across the relevant wavelength range. For example, with three or more instruments available,

$$C_{\text{OD}}(z) = \bigvee_i C_{\text{OD}}^i(z), \quad (3)$$

where the logical OR ($\vee$) runs over all instruments $i \in \text{X-shooter, FIRE, HIRES}$. We then compute the mean completeness for each overdensity, and obtain the overall mean completeness, $\bar{C}$, by averaging over all overdensities weighted by their wavelength coverage. This yields a mean completeness of $\bar{C} = 91.4\%$ for O I absorption around galaxy overdensities in the EIGER survey for $W_{\text{min}} \geq 0.05 \text{ \AA}$.

4. RESULTS

In this section we present the variation of O I absorption around $z \sim 6$ galaxies, incidence of O I absorption per co-moving path length that is due to O I absorption around galaxies and the chemical abundance of these systems.

4.1. Variation of O I Absorption Around Galaxies

Since all 40 galaxies in our sample reside within 15 identified overdensities (Section 3.3), we investigate whether O I absorption is preferentially detected in these environments. For clarity, we show the primary galaxy in each overdensity (as defined in Section 3.3) when presenting the radial distribution of O I absorption. Out

of the 15 overdensities, 5 show associated O I absorption. Figure 4 presents the radial profiles around the primary galaxies in these systems. The marker size indicates the number of member galaxies in each overdensity, while the color encodes the velocity offset from the corresponding O I absorption. Panels (a) and (c) show impact parameter (R), and panels (b) and (d) show the same distribution normalized by the halo virial radius (R/R_{vir}).

Most of the O I detections occur within $R \lesssim 175 \text{ kpc}$ of the primary galaxy, corresponding to an incidence rate of $0.56_{-0.16}^{+0.15}$, estimated using 68% Wilson Score confidence intervals. Within 100 kpc, the incidence is $0.50_{-0.22}^{+0.22}$, increasing to $0.67_{-0.28}^{+0.20}$ for $R \leq 50 \text{ kpc}$. Conversely, at $R > 150 \text{ kpc}$ an incidence of $0.13_{-0.08}^{+0.16}$ is measured. Within 300 kpc of the primary galaxy, the overall incidence is $0.27_{-0.10}^{+0.13}$, with values of $0.17_{-0.08}^{+0.13}$ for $50 \leq R \leq 300 \text{ kpc}$ and $0.18_{-0.09}^{+0.14}$ for $100 \leq R \leq 300 \text{ kpc}$. These rates are substantially weaker than the incidence of strong Mg II absorption at $z \sim 6$ (R. Bordoloi et al. 2024), indicating that neutral oxygen preferentially traces a different phase of the circumgalactic environment.

Panels (b) and (d) reveal that O I absorbers are typically located at much larger R/R_{vir} than strong low-ionization tracers such as Mg II. This distinction suggests that O I absorption at $z \sim 6$ is not confined to the CGM of an individual galaxy but instead reflects the larger-scale gaseous environment of galaxy overdensities — what might be described as “cosmic ecosystems” rather than isolated halos. Figure 5 shows the 2D spatial distribution of galaxies around the five detected systems. The galaxies are randomly distributed around the absorbers, and we do not find correlations with stellar mass, star formation, or other galaxy properties.

Comparing the stellar mass distributions of overdensities with and without O I absorption, we find no statistically significant differences. The mean stellar mass of galaxies in overdensities with absorption is $\log(\langle M_{\star} \rangle / M_{\odot}) = 8.36$, compared to $\log(\langle M_{\star} \rangle / M_{\odot}) = 8.50$ for those without.

We emphasize that at $z \sim 6$, the large R/R_{vir} values of these halos imply that O I absorption typically arises at scales well beyond the typical CGM [$R/R_{\text{vir}} \lesssim 1$] (J. Tumlinson et al. 2017) probed by low-ionization lines at lower redshift. Unlike the low- z CGM, where metal absorbers are closely tied to the halo of a single massive galaxy, the O I absorbers studied here appear to be linked to extended networks of low-mass, young galaxies embedded in shared overdensities. Over cosmic time, these small systems and their diffuse gaseous environ-

ments are expected to merge and evolve into more massive systems, eventually forming Milky Way-like galaxies by $z = 0$. Thus, neutral O I at reionization is best understood not as a tracer of isolated galactic halos, but as a probe of the extended environments that connect galaxies, gas, and structure growth in the early universe.

Because O I absorption traces dense, neutral gas and requires only minimal ionization corrections, we can place a conservative lower limit on the total oxygen mass associated with the EIGER galaxies. These estimates are intended as simple, order-of-magnitude calculations to provide intuition about the amount of neutral oxygen relative to the observed galaxy properties. Following the formalism of R. Bordoloi et al. (2014), the oxygen mass contained in an annulus bounded by R_{in} and R_{out} is

$$M_{\text{O}} = \frac{1}{f_{\text{ion}}} f_c \pi (R_{\text{out}}^2 - R_{\text{in}}^2) \langle N_{\text{OI}} \rangle m_{\text{O}} \quad (4)$$

where R_{in} and R_{out} are the inner and outer radii of the annulus, f_c is the covering fraction (the incidence of O I detections in that bin), $\langle N_{\text{OI}} \rangle$ is the mean O I column density in the annulus, and $m_{\text{O}} = 16 m_p$ is the mass of an oxygen atom, with m_p being the mass of a proton. For a conservative lower limit we adopt $f_{\text{ion}} = 1$, where f_{ion} is the ionization fraction, (i.e., we assume that all of the oxygen mass is in the neutral phase). We justify this assumption as follows: O I is tightly coupled to H I through charge exchange, and in dense gas the required ionization correction is minor, even under strong radiation fields such as the Fermi Bubbles (R. Bordoloi et al. 2017; T. Ashley et al. 2022). Under a typical metagalactic UV background, it is generally less than 10% and does not significantly alter the inferred oxygen abundance. In addition, oxygen does not deplete onto dust grains, unlike Si or C. For these reasons, we consider the approximation $N_{\text{O},\text{total}} \approx N_{\text{OI}}$ to be valid for our analysis.

We compute masses in two radial bins 0–100 kpc and 100–300 kpc, respectively. The total oxygen mass within radius R_{max} is obtained by summing the masses of the constituent annuli. This yields a strict lower limit of $\gtrsim 2 \times 10^6 M_{\odot}$ on the total oxygen mass within $R_{\text{max}} = 300$ kpc.

We compare the inferred oxygen mass in the extended environment of our sample with the total oxygen content in the interstellar medium (ISM) of a typical $z \sim 6$ galaxy. In computing this quantity, we make the following assumptions. First, we assume that all galaxies in this work lie on the typical $z \sim 6$ mass-metallicity relation, derived by stacking [O III] emitter galaxies (J. Matthee et al. 2022), and we adopt the gas-phase metallicity from this relation for each galaxy.

Because direct measurements of the total H_2 and H I gas content are not available at these redshifts, we extrapolate the molecular gas fraction from L. J. Tacconi et al. (2018) to $z \sim 6$ and adopt a conservative H I gas fraction based on local observations (S. Huang et al. 2012). We note that high- z galaxies are likely more gas-rich than their local counterparts; therefore, the inferred ISM gas masses should be considered lower limits.

With these caveats in mind, we estimate the total ISM oxygen mass as

$$M_{\text{O,ISM}} \gtrsim X_{\text{O}} M_{\text{gas,total}}, \quad (5)$$

where we define $M_{\text{gas,total}} = M_{\text{H}_2} + M_{\text{HI}}$. Here, X_{O} is the gas-phase oxygen abundance derived from the mass-metallicity relation, and M_{H_2} and M_{HI} are the molecular and atomic gas masses derived as described above. For our galaxy sample, the mean stellar mass is $\log(M_{\star}/M_{\odot}) = 8.5$, corresponding to an ISM oxygen mass of $M_{\text{O,ISM}} \gtrsim 6.8 \times 10^5 M_{\odot}$. Remarkably, this indicates that the typical ISM oxygen content is comparable to the oxygen mass in the extended environment around these galaxies, implying that the circumgalactic or intergalactic medium at $z \sim 6$ contains a substantial reservoir of oxygen. While these estimates depend on several specific assumptions, the inferred ISM and CGM oxygen masses appear to be of similar magnitude.

At low redshift, both L^* and sub- L^* galaxies similarly exhibit substantial metal content in their circumgalactic medium (CGM), with the CGM containing at least as much metal as the ISM of their host galaxies (J. Tumlinson et al. 2011; R. Bordoloi et al. 2014). A key difference is that, whereas the low- z CGM is typically gravitationally bound to its host galaxy, at high redshift much of the gas exists in the extended environment of galaxy overdensities rather than being bound to individual galaxies (see also R. Bordoloi et al. 2024).

4.2. Expected Incidence of O I Absorbers

In this section we report the expected redshift-path incidence of O I absorbers around [O III] emitting galaxies detected in the EIGER survey. We define the number of O I absorbers associated with each galaxy overdensity per unit absorption distance above a detection threshold ($W_{\text{OI}} \geq 0.05 \text{ \AA}$) as

$$\frac{dN}{dX}(W_{\text{OI}} \geq 0.05 \text{ \AA}) = \left(\frac{c}{H_0} \right) f_c n_{\text{OD}} \pi R_{\text{max}}^2 \left(\frac{1}{\bar{C}} \right). \quad (6)$$

Here, $R_{\text{max}} = 300$ kpc is the survey radius adopted in this work, and $\bar{C}$ is the mean O I absorber detection completeness (see Section 3.5; 91.4% for $W_{\text{OI}} \geq 0.05 \text{ \AA}$). n_{OD} is defined as

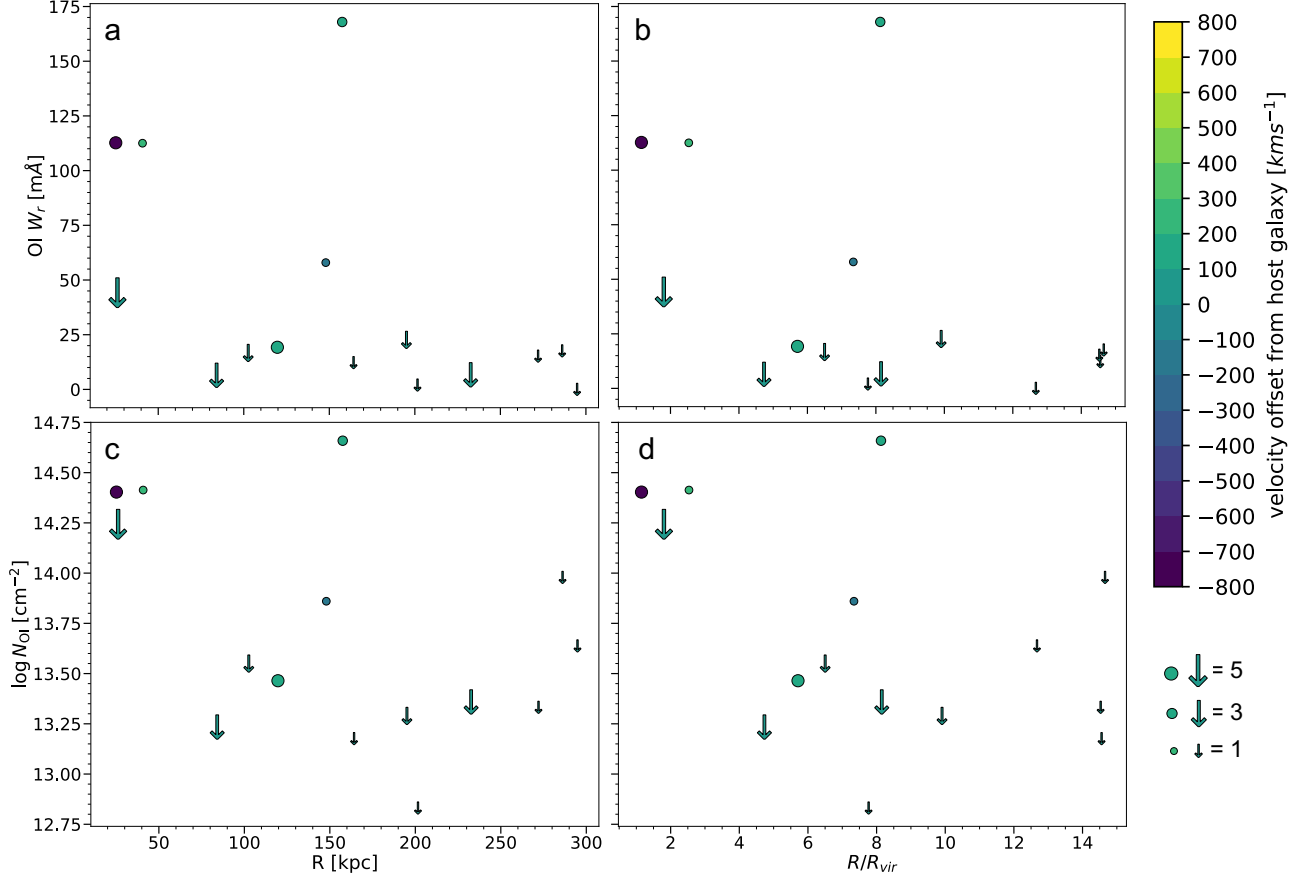


Figure 4. Radial absorption profiles of O I absorption at $z \sim 6$. Each point marks the impact parameter to the nearest galaxy in a galaxy overdensity, with all detected O I absorption arising in such environments. Overdensities with O I absorption are shown as circles, while non-detections (2σ limits) are indicated by downward arrows. Points are color-coded by the velocity offset between the galaxy redshift and the O I absorber, and their size scales with the number of members in the overdensity. The mean uncertainty on the virial radius is $\Delta R_{\text{vir}} = 1.81$ kpc. *Top panels:* Rest-frame equivalent width versus impact parameter (R , left) and normalized impact parameter (R/R_{vir} , right). *Bottom panels:* Same as above, but for O I column densities.

$$n_{\text{OD}} = \frac{n_{\text{gal}}}{\langle \text{overdensity size} \rangle}. \quad (7)$$

n_{gal} is the number density of [O III] emitting galaxies per unit comoving volume, estimated from the [O III] luminosity function at $z \sim 6$. And $\langle \text{overdensity size} \rangle$ is simply the mean number of galaxies in each galaxy overdensity empirically measured to be $\langle \text{overdensity size} \rangle = 2.67$. f_c is the O I absorption covering fraction within 300 kpc for $W_{\text{OI}} \geq 0.05$ Å ($f_c = 0.27^{+0.13}_{-0.10}$).

To estimate the number density of galaxies per unit comoving volume (n_{gal}), we integrate the $z \sim 6$ [O III] luminosity function derived from the EIGER survey, with a minimum luminosity of $L_{\text{min}} = 10^{42.2}$ ergs $^{-1}$ (J. Matthee et al. 2022):

$$n_{\text{gal}}(> L_{\text{min}}) = \int_{L_{\text{min}}}^{\infty} \Phi(L) dL, \quad (8)$$

where $\Phi(L)$ is the [O III] luminosity function defined as

$$\Phi(L) dL = \frac{\Phi^*}{L^*} \left(\frac{L}{L^*} \right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) dL. \quad (9)$$

Here, Φ^* is the characteristic number density, L^* is the characteristic luminosity, and α is the faint-end slope. We adopt $\Phi^* = 10^{-4.02}$ Mpc $^{-3}$, $L^* = 10^{43.33}$ ergs $^{-1}$, and $\alpha = -1.92$, values derived from detailed completeness calculations of the EIGER [O III]-emitting galaxies (Mackenzie et al., in prep). This results in $n_{\text{gal}} = 8.586 \times 10^{-4}$ Mpc $^{-3}$. Using these values in equation 6 yields $dN/dX = 0.12^{+0.06}_{-0.04}$, for O I absorption around galaxies at a mean galaxy redshift of 6.001.

All calculations in this section are performed with a detection threshold of $W_{\text{OI}} > 0.05$ Å, since the survey is highly complete down to this equivalent-width limit and because most of the literature surveys we compare against adopt the same threshold.

We emphasize that this approach differs from blind QSO absorption-line surveys (e.g., G. D. Becker et al.

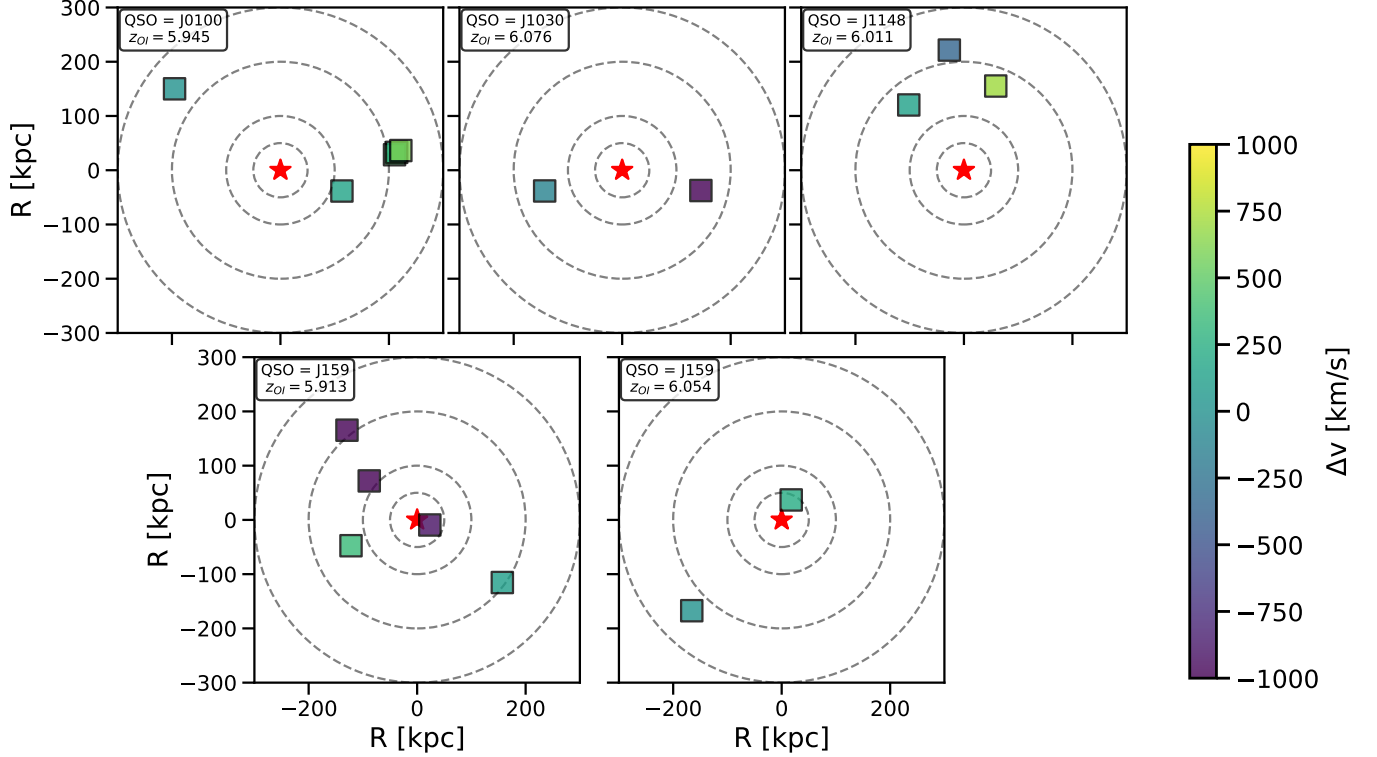


Figure 5. Galaxy overdensities around $z \sim 6$ O I absorbers in the EIGER survey. Each panel shows the background quasar (red star) at the center, with foreground galaxies associated with O I absorption marked as squares. Squares are color-coded by the velocity offset between the galaxy and the O I absorber. Only galaxies within 300 kpc of the quasar are shown, highlighting the overdensities nearest the absorbers. Dashed circles denote projected impact parameters of 50, 100, 200, and 300 pkpc from the quasar.

2006; A. M. Sebastian et al. 2023; L. Christensen et al. 2023), where all O I absorption-line systems along the full quasar redshift path are counted to compute dN/dX directly, under the assumption that the absorber cross-section is contributed by all galaxies. In contrast, our method begins by defining the absorber cross-section around galaxies and then estimating the corresponding contribution to dN/dX from the galaxies under study. Comparing these two approaches constrains the fraction of O I (or other metal) absorption systems that arise in the extended halos of galaxies. Figure 6 shows these literature measurements as colored circles, while the contribution to dN/dX around $z \sim 6$ galaxies is indicated by an orange square. To quantify the relative contribution of galaxy overdensities, we fit a single power law to all literature values at $z > 4$ (blue dashed line with shaded region). Comparing the dN/dX inferred from quasar absorption-line surveys at $z \sim 6$ to our measured value, we find that O I dN/dX around $z \sim 6$ EIGER galaxies accounts for $35\% \pm 16\%$ of all O I absorption-line systems detected in blind quasar surveys. This implies that [O III] emitting galaxies at $z \sim 6$ contribute

roughly one-third of the O I absorption systems at that epoch.

This in turn suggests that $\sim 65\%$ of the O I absorption systems detected along quasar sightlines at the epoch of reionization are not associated with [O III] emitter galaxy overdensities. Either the bulk of O I absorption resides in isolated pockets of neutral IGM gas outside extended galaxy halos, or it is contributed by even lower-luminosity, less massive galaxies ($\log M^*/M_\odot < 7.5$) that fall below the EIGER detection limits. Such systems may also be detected in galaxy halos that are oxygen-poor or lack strong [O III] emission features, since our galaxy identifications primarily rely on [O III] and H- β emission lines.

Simulations suggest that O I absorption should primarily arise in galactic halos rather than in the diffuse IGM, since metals are not widely distributed and ionization fronts propagate more quickly than metals (B. D. Oppenheimer et al. 2009; K. Finlator et al. 2013). Very low-mass proto-galaxies forming their first stars may blur the boundary between IGM and CGM, enriching their surroundings with metals, especially if their star formation is bursty and prolific. If sufficiently numerous,

Table 1. O I absorption lines and associated galaxy properties.

label	Quasar	z_{gal}^a	R	$\langle v \rangle^b$	$\#^c$	z_{OI}	$\log N_{\text{OI}}$	$\log N_{\text{Si II}}$	$\log N_{\text{C II}}$	$\log N_{\text{C IV}}$	$\log N_{\text{Si IV}}$
			[kpc]	[km s $^{-1}$]	galaxies		[cm $^{-2}$]	[cm $^{-2}$]	[cm $^{-2}$]	[cm $^{-2}$]	[cm $^{-2}$]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
a	J0100	5.941	119.6	157	5	5.945	$13.46^{+0.11}_{-0.15}$	$12.71^{+0.08}_{-0.07}$	$13.55^{+0.02}_{-0.02}$	$14.24^{+0.09}_{-0.09}$	$12.98^{+0.04}_{-0.04}$
b	J1148	6.008	157.5	130	3	6.011	$14.66^{+0.02}_{-0.02}$	$13.48^{+0.04}_{-0.05}$ *	$14.35^{+0.02}_{-0.02}$	$14.31^{+0.02}_{-0.02}$	$13.25^{+0.06}_{-0.06}$
c	J159	5.934	25.2	-920	5	5.913	$14.40^{+0.03}_{-0.03}$	$13.77^{+0.13}_{-0.09}$	$14.37^{+0.02}_{-0.02}$	—	—
d	J159	6.049	40.8	230	2	6.054	$14.41^{+0.04}_{-0.03}$	< 13.12	$14.29^{+0.04}_{-0.04}$	—	—
e	J1030	6.075	147.9	-131	2	6.076	$13.86^{+0.08}_{-0.08}$ **	$13.33^{+0.08}_{-0.09}$	$13.25^{+0.08}_{-0.08}$	—	—

^a Redshift of the primary member of the overdensity.

^b Velocity offset of O I relative to the primary member galaxy of the overdensity.

^c Number of galaxy members in the overdensity.

* For this system Si II λ 1304 was not present, so the value given here is derived from fitting Si II λ 1526.

** This system is blended; see discussion in Section 3.4.

NOTE—The galaxies listed are the primary member of groups with detections at the lowest impact parameter from the host quasar.

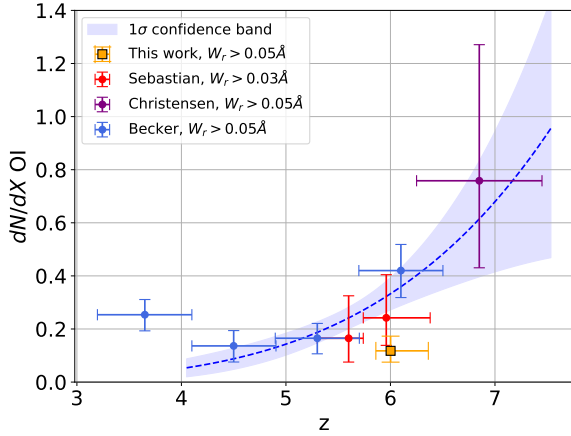


Figure 6. Incidence of O I absorbers per comoving path length, dN/dX . Values are derived from all O I absorption lines along high- z quasar sightlines. Literature measurements are shown from G. D. Becker et al. (2019) (blue circles), L. Christensen et al. (2023) (purple circles), and A. M. Sebastian et al. (2023) (red circles). The blue dashed line shows a power-law fit to the $z > 4$ literature data, with the shaded region marking the 1σ uncertainty. The orange square gives the inferred dN/dX when including only O I absorption associated with host galaxies (see Section 4.2), indicating that only $\sim 35\%$ of O I absorbers at $z \sim 6$ arise in galaxy environments.

such systems could contribute a non-negligible fraction of oxygen in the early Universe.

Recent observations support this possibility. K. Nakajima et al. (2025) reported a strongly lensed ($\mu = 98$) galaxy at $z \approx 6.6$ with a stellar mass upper limit of only $\sim 2700 M_{\odot}$ and a dynamical mass ~ 100 times larger. The source shows $[O III]_{5008}$ emission and may be dominated by Population III stars. This provides direct evidence of oxygen production in extremely low-mass systems. A population of such ultra-low mass dwarf galaxies could plausibly account for the $\sim 65\%$ of O I absorbers detected along quasar sightlines that are not associated with galaxies in our survey. Our sensitivity limit of $\log M_{*}/M_{\odot} \sim 7.5$ (J. Matthee et al. 2022) means such dwarfs remain undetected. However, these galaxies may lack a dense enough CGM to shield neutral O I from the UV background; thus, even if they produce oxygen, neutral O I may not survive (K. Finlator et al. 2013).

The simulations of K. Finlator et al. (2013) suggest that O I absorbers with $\log N > 14 \text{ cm}^{-2}$ are most likely associated with halos of mass $\sim 10^9 M_{\odot}$, where self-shielding is efficient. They further predict that only $\sim 13\%$ of all O I absorption systems should reside in halos of 10^{10} – $10^{11.5} M_{\odot}$, the mass range of galaxies probed in this work. By contrast, we measure a higher incidence of $\sim 35\%$, but qualitatively our results remain consistent with the idea that roughly two-thirds of O I absorbers are associated with undetected $\sim 10^9 M_{\odot}$ halos. Future observations targeting lower-luminosity galaxies and higher redshifts will be essential to test these predictions.

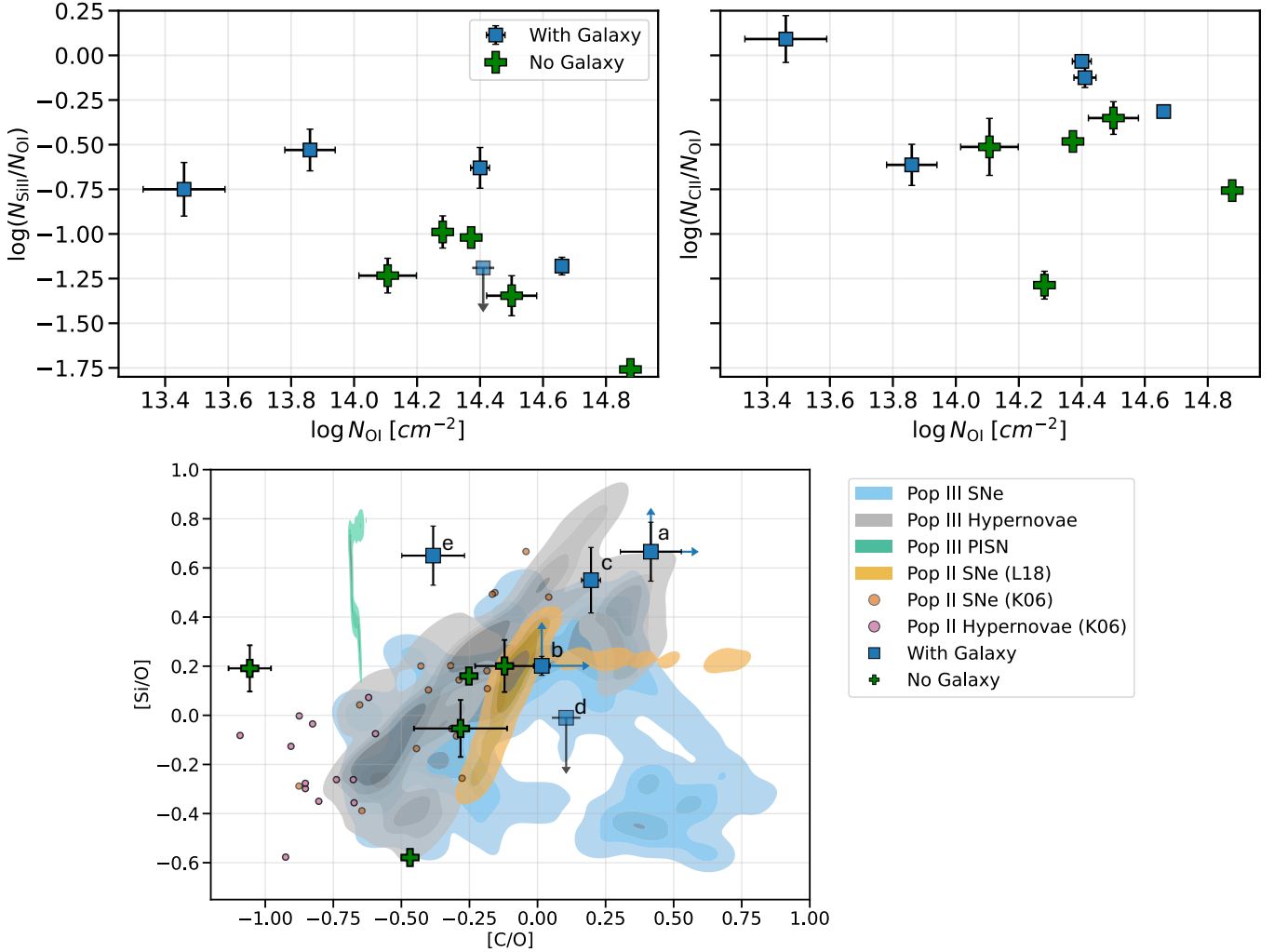


Figure 7. *Top panels:* Ion column density ratios of Si II to O I (left) and C II to O I (right) as a function of detected O I column densities, shown in logarithmic units. Absorbers associated with galaxy overdensities (blue squares) and those not associated with galaxy overdensities (green crosses) exhibit clear variations in their column density ratios. One sightline with no detected Si II absorption is indicated with a downward arrow, where a 2σ upper limit on the column density is assumed. *Bottom panel:* Relative abundance ratios $[\text{Si}/\text{O}]$ versus $[\text{C}/\text{O}]$ with respect to solar abundance. The background contours show the IMF-weighted abundance distributions from Population II and Population III supernova models. Orange and pink circles indicate abundance ratios predicted by low-metallicity Population II supernova models. The abundance ratios of several O I absorbers associated with galaxy overdensities are consistent with a significant contribution from Population III supernovae.

4.3. Metal Abundances in O I absorber population

In this section we examine the relative abundances and metal column density ratios of O I absorbers associated with galaxy overdensities, and compare them to O I absorbers without any associated galaxies. To enable a fair comparison, we restrict our analysis to the six quasar sightlines from the EIGER survey, and identify all O I absorption systems in the redshift range where an [O III]-emitting galaxy could be detected ($5.9 \leq z_{\text{OI}} \leq z_{\text{QSO}}$). We detect ten O I absorption systems in total, five of which have associated galaxy overdensities (Table 1), and five without any identified galaxy association.

We first compare the ionic column density ratios in these two populations. Figure 7 (top panels) shows the ratios of $N_{\text{SiII}}/N_{\text{OI}}$ and $N_{\text{CII}}/N_{\text{OI}}$ as functions of N_{OI} . Systems located near galaxy overdensities (blue squares) systematically show higher Si II/O I and C II/O I ratios compared to systems without associated overdensities (green crosses). This offset could reflect differences in metallicity, or alternatively the effects of ionization. However, since the majority of these O I systems lack detectable high-ionization transitions, it is reasonable to assume that neutral oxygen and singly ionized silicon and carbon dominate the elemental reservoirs (see also L. Christensen et al. 2023). In those cases, the

observed ionic ratios provide direct tracers of relative abundances. Two exceptions are found along the J0100 and J1148 sightlines, which do exhibit Si IV and C IV absorption; for these systems the degeneracy between chemical composition and ionization corrections cannot be resolved. It is plausible that on average, O I absorption found near galaxy overdensities have higher elemental abundance ratios as the non-galaxy associated absorbers either have significantly lower luminosity and less massive galaxies which would be expected to produce less metal, or there are truly no galaxies associated with this population.

We next compute the relative abundances $[\text{Si}/\text{O}]$ and $[\text{C}/\text{O}]$, presented in the bottom panel of Figure 7. These abundances are defined as

$$[\text{Si}/\text{O}] = \log_{10} \left(\frac{N_{\text{Si,tot}}}{N_{\text{OI}}} \right) - \log_{10} \left(\frac{\text{Si}}{\text{O}} \right)_{\odot}, \quad (10)$$

$$[\text{C}/\text{O}] = \log_{10} \left(\frac{N_{\text{C,tot}}}{N_{\text{OI}}} \right) - \log_{10} \left(\frac{\text{C}}{\text{O}} \right)_{\odot}, \quad (11)$$

where $N_{\text{Si,tot}}$ and $N_{\text{C,tot}}$ represent the summed ionic column densities. For systems with detected high-ionization absorption (C IV or Si IV), we include both low- and high-ionization states ($N_{\text{SiII}} + N_{\text{SiIV}}$ and $N_{\text{CII}} + N_{\text{CIV}}$), marking these measurements as lower limits (blue upward arrows in the figure) since additional undetected ionization states may be present. For systems without detected high-ionization transitions, we adopt N_{SiII} and N_{CII} as the dominant contributions. We assume $N_{\text{O,tot}} \approx N_{\text{OI}}$, as ionization corrections for O I are typically very small at high O I column densities (see Section 4.1 for discussion). We adopt solar reference abundances of $\log_{10}(\text{Si}/\text{O})_{\odot} = -1.18 \pm 0.05$ and $\log_{10}(\text{C}/\text{O})_{\odot} = -0.23 \pm 0.06$ (M. Asplund et al. 2021).

Figure 7 (bottom panel) reveals a striking separation between O I absorbers associated with galaxy overdensities (blue squares) and those without galaxy associations (green crosses). Systems near galaxies are found in the upper left of the $[\text{Si}/\text{O}]$ – $[\text{C}/\text{O}]$ diagram, with two cases exhibiting high-ionization absorption (lower abundance limits, blue arrows) which will offset them even farther from the locus of non-galaxy absorbers.

We place these abundance patterns in the context of chemical enrichment models from different stellar populations (see also L. Christensen et al. 2023). The contours and colored circles in Figure 7 highlight predicted $[\text{C}/\text{O}]$ and $[\text{Si}/\text{O}]$ yields from representative Population II and Population III supernova models, weighted by a Salpeter initial mass function (IMF). The weighting by number of stars predicted by an IMF is done to represent the typical observational relative abundance

distribution in these models. These are not exhaustive but span the dominant theoretical expectations.

Population III pair-instability SNe (PISNe; 140–260 $M_{\odot}$; light green contours) predict narrow $[\text{C}/\text{O}] \simeq -0.7$ and high $[\text{Si}/\text{O}]$ values, inconsistent with any of our observed systems. Such PISNe are also expected to produce substantial amounts of iron-peak elements, leading to elevated Fe/O ratios (J. Tumlinson et al. 2004). We will investigate Mg II and Fe II absorption associated with $z \sim 6$ galaxies in an upcoming work (Higginson et al., in prep.). Models of massive Pop III stars (10–100 $M_{\odot}$) produce both hypernovae (gray contours; $E > 10^{52}$ erg) and standard core-collapse SNe (light blue contours) (A. Heger & S. E. Woosley 2010), spanning a broader region overlapping some of our measurements. We also consider Pop II models: low-metallicity core-collapse SNe from M. Limongi & A. Chieffi (2018) (orange contours; Pop II SNe (L18)) occupy $-0.25 \lesssim [\text{C}/\text{O}] \lesssim 0.5$ and $-0.4 \lesssim [\text{Si}/\text{O}] \lesssim 0.4$, overlapping parts of the Pop III range, while the C. Kobayashi et al. (2006) yields (pink and orange circles for hypernovae and SNe, respectively) tend toward lower $[\text{Si}/\text{O}]$ and $[\text{C}/\text{O}]$.

Against these predictions, the contrast between the two absorber populations is clear. All non-galaxy O I systems (green crosses) fall at the lower left of the diagram, consistent with enrichment from both Pop II and/or Pop III SNe models. This regime also overlaps with ultra-metal-poor DLAs at $z \sim 3$ ($-0.5 \lesssim [\text{Si}/\text{O}] \lesssim 0$, $-0.5 \lesssim [\text{C}/\text{O}] \lesssim 0$; R. Cooke et al. 2011; R. J. Cooke et al. 2017). By contrast, three of the five galaxy-associated absorbers lie well outside the locus of Pop II predictions. These systems are best explained if Pop III enrichment played a major role.

The absorber toward J159 at $z = 5.91$ shows $[\text{C}/\text{O}] = 0.20$, $[\text{Si}/\text{O}] = 0.55$ (labeled *c*), and no evidence of high-ionization absorption. These abundance ratios are best explained by contributions from Pop III SNe or hypernovae. The absorber toward J1030 at $z = 6.07$ ($[\text{C}/\text{O}] = -0.38$, $[\text{Si}/\text{O}] = 0.65$, labeled *e*) also show no high-ionization absorption. The relative abundances in these two predominantly neutral systems are therefore quite robust. Interestingly, the J1030 system is not reproduced by any single Pop II or Pop III model, suggesting that it may have experienced multiple enrichment episodes, producing unusually high $[\text{Si}/\text{O}]$ coupled with low $[\text{C}/\text{O}]$.

Two cases require special mention. The absorber toward J0100 at $z = 5.94$ shows $[\text{C}/\text{O}] \geq 0.42$ and $[\text{Si}/\text{O}] \geq 0.67$ (labeled *a*), with strong C IV and Si IV absorption. Since these are lower limits, ionization corrections (for carbon and silicon) would push this system further

upward, strengthening the case for Pop III contributions. This observation is best explained by contribution from Pop III hypernovae models. The J1148 absorber at $z = 6.01$ shows $[\text{C}/\text{O}] \geq 0.02$ and $[\text{Si}/\text{O}] \geq 0.20$ (labeled *b*), again with high-ionization lines; correcting for ionization would shift it diagonally upward in the diagram. Taken together, four of the five galaxy-associated absorbers show relative abundances that cannot be explained by Pop II models alone, pointing instead to significant enrichment from Pop III supernovae or hypernovae.

Thus, most galaxy-associated O I systems carry signatures of Pop III enrichment. These results suggest that O I systems tracing galaxy overdensities at $z \sim 6$ carry chemical signatures of Population III enrichment, likely from multiple supernova events rather than a single explosion. The elevated $[\text{Si}/\text{O}]$ and $[\text{C}/\text{O}]$ ratios in these environments imply that [O III]-emitting galaxies at this epoch may retain significant Pop III contributions, and that metal-line absorbers around such overdensities provide a powerful probe of the first generations of stars.

5. CONCLUSION

We have conducted a survey of neutral O I absorption systems associated with galaxies during the Epoch of Reionization in the EIGER survey, using six high-redshift quasars as background sightlines. Our study focuses on the distribution of neutral oxygen around [O III]₅₀₀₈-emitting galaxies within 300 kpc and their connection to galaxy overdensities. The main results are as follows:

- Five O I absorbers are detected among 15 galaxy overdensities, spanning $z = 5.91\text{--}6.16$ with a mean redshift $\langle z \rangle = 6.001$.
- The O I covering fraction within 300 kpc of the closest galaxy is $0.27^{+0.13}_{-0.10}$, with $0.67^{+0.20}_{-0.28}$ for $R \leq 50$ kpc and $0.17^{+0.13}_{-0.08}$ for $50 \leq R \leq 300$ kpc.
- We find $\gtrsim 2 \times 10^6 M_\odot$ of oxygen within 300 kpc, a mass comparable to the ISM oxygen content of $z \sim 6$ galaxies — under assumptions required to estimate these masses — suggesting that the circumgalactic environment already holds metal reservoirs rivaling those inside galaxies.
- O I absorbers are detected as far as $\sim 8 R/R_{\text{vir}}$ from galaxies, in sharp contrast to low-ionization tracers such as Mg II, which are typically confined within $\lesssim R/R_{\text{vir}}$.
- The incidence of galaxy-associated O I absorbers is $\frac{dN}{dX} = 0.12^{+0.06}_{-0.04}$. Comparison with blind quasar

absorption-line surveys indicates that these systems represent only $\sim 35\%$ of all O I absorbers at $z \sim 6$, implying that the majority likely arise in lower-mass galaxies below current detection limits or in dense neutral IGM pockets that survived reionization.

- Relative abundance and ionization ratios ($[\text{Si}/\text{O}]$, $[\text{C}/\text{O}]$) show that galaxy-associated O I systems are chemically enriched, with signatures in several systems consistent with contributions from Population III stars.

Overall, these results indicate that neutral O I at $z \sim 6$ primarily traces extended overdensity environments rather than the CGM of individual halos. Moreover, the chemical abundance patterns of galaxy-associated O I systems suggest contributions from Population III stars, likely arising from multiple supernova events rather than a single explosion. The elevated $[\text{Si}/\text{O}]$ and $[\text{C}/\text{O}]$ ratios imply that [O III]-emitting galaxies at this epoch may retain significant Pop III enrichment. Consequently, metal-line absorbers around such overdensities offer a powerful probe of the first generations of stars, providing insight into early chemical enrichment and the role of primordial stellar populations in shaping galaxy evolution during the Epoch of Reionization.

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Software: astropy (Astropy Collaboration et al. 2013, 2018, 2022), rbcodes (R. Bordoloi et al. 2025), rbvfit (R. Bordoloi & J. Higginson 2025).

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6. APPENDIX

In this appendix we present the four of the five O I and Si II absorption lines associated with galaxy overdensities at $z \sim 6$ presented in this work. The corresponding Voigt profiles and the total O I column density of the systems are noted. Associated galaxies are marked as green ticks. The fifth system is presented in Figure 3.

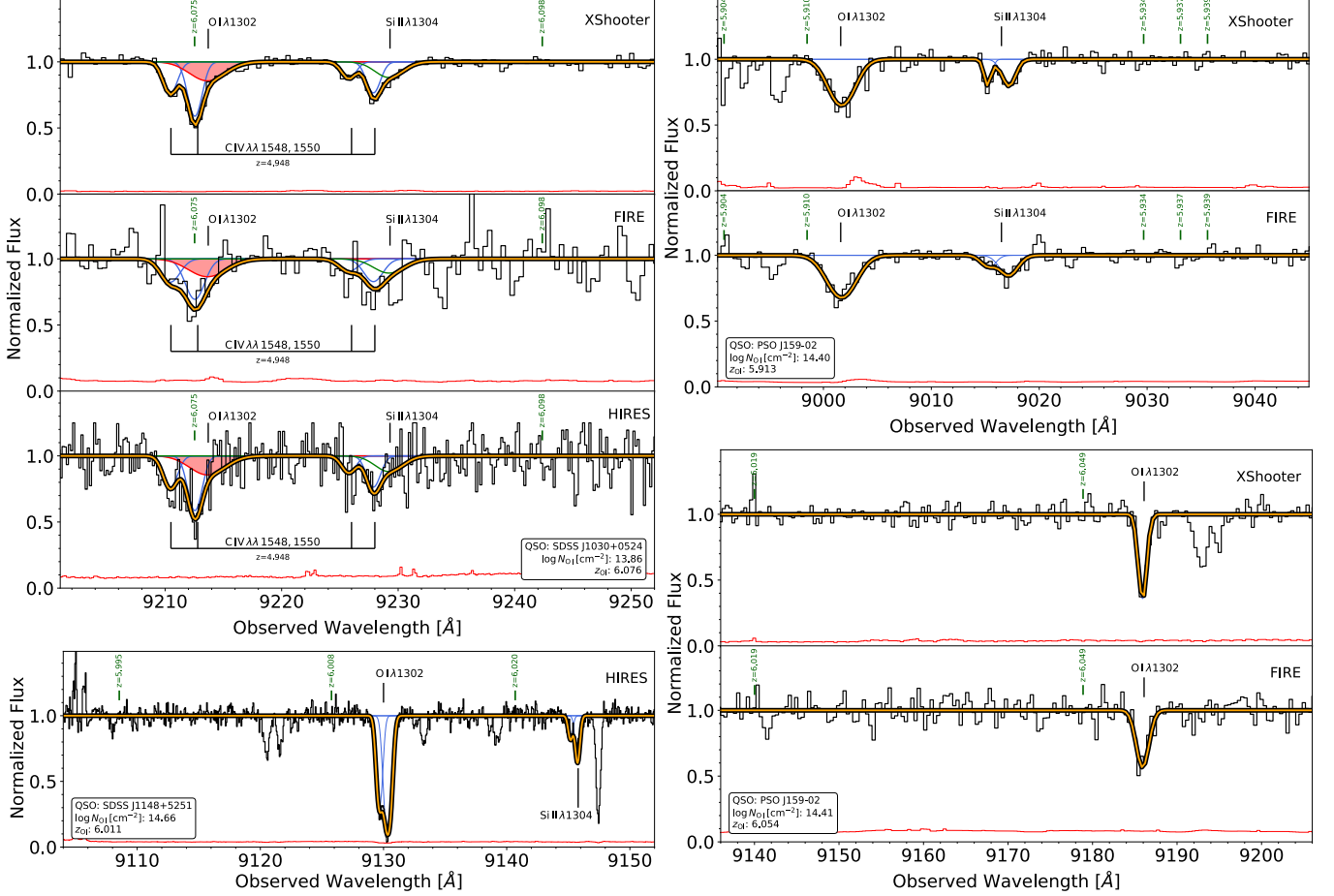


Figure 8. Voigt profile fits: Flux (black), error (red), most likely Voigt fit (orange and black). The individual Voigt component fits are shown for all instruments available for the quasar sightline. Lines and text present to specify the velocity centroids for each element. The vertical green lines indicate the galaxy members of the overdensity. *Top left:* A Voigt profile fit for O I and Si II $\lambda 1304$ at $z = 6.075$, and C IV $\lambda\lambda 1548, 1550$ at $z = 4.9484$ around the quasar SDSS J1030+0524. The HIRES data has been re-binned and clipped for aesthetic purposes. The colors represent different transitions: blue for C IV, green for Si II, and red for O I, with O I being filled in red. *Top right:* A Voigt profile fit for O I and Si II $\lambda 1304$ at $z = 6.011$ around the quasar SDSS J1148+5251. *Bottom left:* A Voigt profile fit for O I and Si II $\lambda 1304$ at $z = 5.913$ around the quasar PSO J159-02. *Bottom right:* A Voigt profile fit for O I at $z = 6.054$ around the quasar PSO J159-02.