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Measurements of Quasar Proximity Zones with the Ly α Forest of DESI Y1 Quasars

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Abstract

The intergalactic medium (IGM) around a quasar is shaped by its dense environment and by its excess ionizing radiation, which form a “quasar proximity zone” whose size and anisotropy depend on the quasar’s halo mass, luminosity, age, and radiation geometry. Using over 10,000 quasar pairs from the Dark Energy Spectroscopic Instrument (DESI) Year 1 data, with projected comoving separations $r_{\perp} < 2h^{-1}$ Mpc, we investigate how the proximity zone of foreground quasars at $z \sim 2\text{--}3.5$ affects Ly α absorption in their background quasars. The large DESI sample enables unprecedented precision in measuring this “transverse proximity” effect, allowing a detailed investigation of the signal’s dependence on the projected separation of quasar pairs and the luminosity of the foreground quasar. We find that enhanced gas clustering near quasars dominates over their ionizing effect, leading to stronger absorption on neighboring sightlines. Under the assumption that quasar ionizing luminosity is isotropic and steady, we infer the IGM overdensity profile in the vicinity of quasars, finding overdensities as high as $\Delta \sim 10$ at comoving distance $\sim 1h^{-1}$ Mpc from the most luminous systems. Surprisingly, however, we find no

significant dependence of the proximity profile on the luminosity of the foreground quasar. This lack of luminosity dependence could reflect a cancellation between higher ionizing flux and higher gas overdensity, or it could indicate that quasar emission is highly time-variable or anisotropic, so that the observed luminosity does not trace the ionizing flux on nearby sightlines.

Unified Astronomy Thesaurus concepts: Quasars (1319); Lyman alpha forest (980); Intergalactic medium (813); Galaxy environments (2029); Redshift surveys (1378)

1. Introduction

Active galactic nuclei (AGNs) play a crucial role in understanding the coevolution of galaxies and their central supermassive black holes (e.g., J. Kormendy & L. C. Ho 2013). In particular, quasars—an extremely luminous phase of AGNs—emit intense radiation that can significantly influence both the intergalactic medium (IGM) and nearby galaxies (e.g., A. A. Meiksin 2009). This connection allows us to use the large-scale ($\gtrsim 1$ Mpc) impact of quasar radiation as a probe of the compact central regions ($\lesssim 10$ pc) that host the AGNs and their central supermassive black holes. Quasars thus serve as a powerful observational tool to investigate the interplay between black hole activity and galaxy-scale environments across cosmic time.

Among the observational signatures of quasars, two aspects are particularly informative for probing the small-scale physics of AGNs: the *timescale* of their emission and its *spatial anisotropy*. First, quasar lifetimes remain highly uncertain, with current population-averaged estimates ranging from 10^5 to 10^8 yr (e.g., A.-C. Eilers et al. 2021). In contrast, the recent discovery of changing-look quasars—objects that exhibit dramatic spectral transitions over just a few years—suggests that at least some quasars may vary an enormous amount on surprisingly short timescales (e.g., C. L. MacLeod et al. 2016). Understanding the relationship between these two vastly different timescales offers a unique window into the physical conditions of the accretion disk and its immediate surroundings. Second, the AGN unification model predicts that quasar radiation is anisotropic, due to a dusty torus that obscures the central engine depending on the viewing angle (e.g., H. Netzer 2015). This anisotropy has been confirmed through comparisons of Ly α absorption in the longitudinal and transverse directions relative to quasars (e.g., J. X. Prochaska et al. 2013). The geometry and orientation of this obscuring structure determine whether a quasar appears as type 1 (unobscured) or type 2 (obscured), thereby providing direct insight into the nuclear and parsec scales.

The impact of quasar ionizing radiation on the surrounding IGM, known as the quasar proximity effect (S. Bajtlik et al. 1988), has been widely used to probe quasar activity in a model-independent way (see, e.g., T. M. Schmidt et al. 2019 for a review). Since the size of the ionized region depends on the quasar’s age and the propagation speed of the ionization front, measurements of the proximity effect can constrain quasar lifetimes without relying on assumptions about their demographics (e.g., luminosity function or host halo mass). Two forms of this effect have been studied: the line-of-sight proximity effect (LPE), observed as a reduction in Ly α forest absorption in the quasar’s own spectrum (R. F. Carswell et al. 1982; S. Bajtlik et al. 1988), and the transverse proximity effect (TPE), identified by Ly α absorption features along background sightlines passing near foreground quasars (A. P. S. Crotts 1989; A. Dobrzycki & J. Bechtold 1991; K. L. Adelberger 2004).

Recent studies of the quasar proximity effect have focused on the LPE at high redshifts ($z \gtrsim 5$), in the context of cosmic reionization or the formation of supermassive black holes (for a recent summary, see S. Onorato et al. 2025). At these redshifts, the LPE is often discussed under the name “near zone,” here taken to include cases in which the observed high-transmission region blueward of Ly α is set by a quasar’s H II ionization front propagating into a substantially neutral IGM (e.g., X. Fan et al. 2006b; J. S. Bolton & M. G. Haehnelt 2007). One key reason for this focus is that the high neutral hydrogen fraction at that epoch makes it easier to detect the ionizing impact of quasars on the surrounding IGM. In addition, for such high-redshift quasars, obtaining background spectra at small angular separations is observationally challenging, making the LPE a more accessible approach. Nonetheless, a recent JWST study has demonstrated the feasibility of detecting the TPE even at $z \sim 6.3$, where Ly α tomography of 12 background galaxies revealed a quasar “light echo” and provided new constraints on the geometry of its ionization cone and on the timescale of the quasar’s UV radiation (A.-C. Eilers et al. 2025).

At redshifts $2 \lesssim z \lesssim 4$, the TPE becomes more accessible, as background spectra are more readily available. Moreover, while the LPE provides only lower limits on quasar age in this redshift range due to the short ionization timescale, the TPE offers a complementary advantage: it enables us to probe much longer timescales, since it is sensitive to radiation emitted in the past (for theoretical context, see R. Hada et al. 2024). This redshift range encompasses the cosmic peak of quasar activity. Understanding quasar physics during this active phase provides essential clues to the coevolution of galaxies and black holes, including the connection between galaxy morphology, star formation rates, and AGN feedback processes.

Several studies have investigated the TPE at moderate redshifts ($2 \lesssim z \lesssim 4$) using quasar pair samples to probe quasar radiation properties. R. A. C. Croft (2004) predicted decreased Ly α absorption near foreground quasars using simulations, but instead found enhanced absorption, suggesting short episodic lifetimes or anisotropic emission. The Quasars Probing Quasars survey similarly reported excess neutral hydrogen (H I) absorption and a high covering fraction of optically thick systems around $z \sim 2$ quasars (e.g., J. X. Prochaska et al. 2013), consistent with dense environments and obscured radiation. In contrast, D. Kirkman & D. Tytler (2008) found no TPE signal in over 100 quasar pairs, inferring lifetimes shorter than ~ 1 Myr.

TPE has also been explored using He II Ly α absorption at similar redshifts (e.g., T. M. Schmidt et al. 2017, 2018). Due to the much higher Ly α opacity of He II compared to H I in this redshift range, variations in absorption can be more dramatic, analogous to the H I Ly α forest at higher redshifts. However, these studies face challenges such as the limited number of available He II sightlines, which number only a few dozen (e.g., T. M. Schmidt et al. 2019), and the inhomogeneous

ionization state of He II in the IGM around $z \sim 3$, which complicate the interpretation. While these results highlight the potential of TPE as a probe of quasar variability and geometry, the observational outcomes remain inconclusive, reflecting a complex interplay between episodic activity, anisotropic emission, and the properties of the surrounding environment, including local gas density.

The influence of quasar ionizing radiation on the local intergalactic environment has been studied in large-scale structure (LSS) analyses, where cross-correlations between quasars and the Ly α forest aim to probe the underlying matter density distribution. This radiative contribution was thoroughly explored by A. Font-Ribera et al. (2013), and nonzero signals have since been measured in spectroscopic surveys (e.g., H. du Mas des Bourboux et al. 2020). In particular, recent analyses of the Dark Energy Spectroscopic Instrument (DESI; DESI Collaboration et al. 2016a, 2016b) data have reported nonzero TPE amplitudes under the simplifying assumption of isotropic quasar emission, which makes the modeling more tractable. In these analyses, the effect is captured by a single free parameter, ξ_0^{TP} , which scales the additional term introduced to represent the TPE. Reported values are $\xi_0^{\text{TP}} = 0.395 \pm 0.051$ and 0.453 ± 0.046 for DR1 (A. G. Adame et al. 2025a) and DR2 (DESI Collaboration et al. 2025b), respectively. These results underscore the importance of accurately modeling both the radiation from quasars and their local environments when interpreting measurements of Ly α forest clustering.

Independent efforts using the LPE have also aimed to characterize the dense environments around quasars. Several studies have analyzed the distribution of Ly α optical depth in proximity zones and shown that the observed reduction in absorption is weaker than expected from ionizing radiation alone, which suggests the presence of significant overdensities. For example, E. Rollinde et al. (2005) and R. Guimarães et al. (2007) applied optical depth statistics to high-resolution quasar spectra at $z \sim 2-4$ and found mean overdensities of a factor of $\sim 2-5$ within $\sim 10h^{-1}$ Mpc. These results support the picture in which quasars reside in highly biased regions that are likely to evolve into massive galaxy clusters. Furthermore, C.-A. Faucher-Giguère et al. (2008) demonstrated that the LPE signal in cosmological simulations depends on the mass of quasar host halos due to both local overdensities and gas infall. They showed that neglecting these effects can bias the inferred ionizing background by up to a factor of ~ 2.5 at $z = 3$, and they proposed that proximity effect measurements can be inverted to estimate the mass of quasar host halos.

A recent study by P. Jalan et al. (2019) utilized a large sample of 181 projected quasar pairs from the Sloan Digital Sky Survey (SDSS) DR12 to investigate the quasar proximity effect in both the longitudinal and transverse directions. Their work demonstrated the power of using quasar pairs from wide-area spectroscopic surveys to statistically probe quasar environments and radiation geometry. In this study, we focus on the TPE using the DESI Year 1 (Y1) data publicly available as part of the first data release (DR1, DESI Collaboration et al. 2026), which provides an unprecedentedly large sample of quasar pairs. Specifically, the DESI DR1 catalog includes 531,000 quasars at $z > 2.1$ for studies of the Ly α forest, nearly triple the 184,101 quasars with $z > 2.15$ available in SDSS DR12 (I. Pâris et al. 2017). Leveraging this sample size, we investigate the redshift, luminosity, and transverse-distance

dependence of the TPE by constructing subsamples, allowing us to examine the physical nature of quasar radiation and its impact on the surrounding IGM in greater detail. Our full sample includes more than 10,000 quasar pairs with transverse separations $r_{\perp} < 2h^{-1}$ Mpc (comoving).

The structure of this paper is as follows. In Section 2, we describe the data used in this study, including the DESI Y1 quasar sample, the extraction of the Ly α forest absorption spectra, and the construction of quasar pair and control samples. Section 3 presents our measurements of the stacked Ly α transmission near quasars, based on three types of subsamples constructed by redshift, luminosity, and transverse separation. In Section 4, we interpret the observed signals by modeling the H I optical depth in the proximity region, estimate the impact of quasar radiation and gas overdensity, and test for anisotropy in quasar emission. Finally, we summarize our findings in Section 5. Throughout this paper, we assume a flat Λ CDM cosmology consistent with the best-fit parameters from the Planck 2018 results (Planck Collaboration et al. 2020), with $H_0 = 67.32 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m = 0.3158$. We use comoving distances unless otherwise noted.

2. Data

We use quasar spectra obtained during the first year of the DESI main survey, which ran from 2021 May 14 to 2022 June 14. These data were obtained with extensive new instrumentation that was designed to observe 5000 spectra in a single observation (DESI Collaboration et al. 2022). The instrumentation includes a new, 3 deg² prime focus corrector (T. N. Miller et al. 2024), a focal-plane system with robotic fiber positioners (J. H. Silber et al. 2023), and 5000 fiber optic cables that direct light (C. Poppett et al. 2024) into ten bench-mounted spectrographs. Each of the ten spectrographs has three channels that together span from 3600 to 9800 Å and have a spectral resolution that ranges from 2000 to 5000. The DESI spectroscopic pipeline is described by J. Guy et al. (2023) and the nightly survey operations is described by E. F. Schlafly et al. (2023). The processed products were released as the DESI Year 1 dataset in the first public data release (DESI DR1; DESI Collaboration et al. 2026), forming the foundation for subsequent scientific analyses, including the first cosmological constraints from clustering measurements with DESI (A. G. Adame et al. 2025b).

2.1. Quasar Catalog

The target selection, validation, and classification of DESI quasars are described by E. Chaussidon et al. (2023). In particular, quasar classification and redshift determination follow a multistep procedure to ensure high completeness and accuracy. The primary tool is the template-fitting code *Redrock*³⁹ (S. Bailey et al. 2025 in preparation), which fits templates based on principal component analysis for stars, galaxies, and quasars across a wide redshift range and assigns the most likely class and redshift by minimizing χ^2 . To further improve completeness and redshift accuracy, two “afterburners” were introduced (for details, see D. M. Alexander et al. 2023): one that searches for broad Mg II emission in spectra not initially classified as quasars, and

³⁹ <https://github.com/desihub/redrock/>

QuasarNET⁴⁰ (N. Busca & C. Balland 2018; J. Farr et al. 2020), a deep convolutional neural network trained to identify quasar emission features and provide redshift estimates. For analysis of the Ly α forest, we further adopt updated redshifts based on improved high- z quasar templates, which mitigate biases identified in the original catalog (A. Brodzeller et al. 2023; A. Bault et al. 2025). For quasar luminosities, we utilize the monochromatic luminosity at 1500Å in the rest frame measured by fastspecfit⁴¹ (J. Moustakas et al. 2023).

2.2. Ly α Forest

The Ly α forest catalog, a subset of the quasar spectra, is described by C. Ramírez-Pérez et al. (2024) and A. G. Adame et al. (2025a). Here, we summarize its main characteristics and properties. There are two different catalogs that correspond to two different ranges of rest-frame wavelength of the quasar spectra, Region “A” (1040–1205 Å) and Region “B” (920–1020 Å). In the following analysis, we focus on the Region A catalog, which is not affected by other Lyman series lines. Note that we use only data from the blue channel (one of the three spectrograph channels), and the observed wavelength coverage is limited to 3600–5772 Å. Combined with the above cut in rest-frame wavelength, this corresponds to a quasar redshift range of $z = 2.1$ – 4.4 for Region A.

Furthermore, various masks are applied to remove bad pixels caused by cosmic rays or CCD defects, as well as to mitigate galactic absorption, residual sky lines, and the effects of damped Ly α systems (DLAs) and broad absorption line (BAL) features. Briefly, DLAs are identified using both convolutional neural network and Gaussian process-based finders, and regions around DLAs detected by both algorithms with probability $>50\%$ are masked. To ensure purity, the DLA catalog only includes DLAs identified in spectra with mean Ly α -forest signal-to-noise ratio $S/N > 3$. In our selection of Ly α forests or quasar pairs, we do not impose such an S/N cut. Since the DLA-masked pixels are only a small fraction ($\sim 5\%$; e.g., Figure 3 of C. Ramírez-Pérez et al. 2024) in the DESI Ly α forest catalogs, their overall impact on the measured transmission is small. BAL features are identified using the DESI DR1 BAL catalog, which is based on the absorptivity index and balnicity index criteria; the corresponding absorption troughs are masked, while the rest of the Ly α forest region in those spectra is retained. After discarding forests that do not have 150 valid pixels (too short) or do not have a valid continuum fit (negative continuum), we finally have 428,403 Ly α forests (Region A).

The catalog provides the density fluctuation and the associated weight for each forest pixel. The density fluctuation is measured by the DESI Ly α analysis pipeline, PICCA⁴² (H. du Mas des Bourboux et al. 2020), and defined by the transmitted flux:

$$\delta_q(\lambda) = \frac{f_q(\lambda)}{\bar{F}(\lambda)C_q(\lambda)} - 1, \quad (1)$$

where $f_q(\lambda)$ is the observed flux, $\bar{F}(\lambda)$ is the mean transmission, and $C_q(\lambda)$ is the unabsorbed continuum of the quasar spectrum. The subscript q references an individual

quasar, while $\bar{F}$ is an average over all quasars. We estimate the mean expected flux $\bar{F}(\lambda)C_q(\lambda)$ by a continuum fitting procedure, described in detail by C. Ramírez-Pérez et al. (2024). The main assumption behind this procedure is that $\bar{F}(\lambda)C_q(\lambda)$ for each forest can be expressed as a universal function of the quasar continuum, $\bar{C}(\lambda_{\text{rf}})$, adjusted by a linear polynomial in $\Lambda \equiv \log \lambda$. In addition to its fitting parameters, the total variance of f_q , σ_q^2 , is determined through likelihood maximization in the following form:

$$\sigma_q^2(\lambda) = \eta_{\text{pip}}(\lambda)\sigma_{\text{pip},q}^2(\lambda) + \sigma_{\text{LSS}}^2(\lambda)(\bar{F}C_q)^2(\lambda), \quad (2)$$

where the first term represents the pipeline noise, $\sigma_{\text{pip},q}^2$, modulated by a function η_{pip} , while the second term corresponds to the intrinsic variance of the Ly α forest, given by $(\bar{F}C_q)^2$ scaled by a universal function σ_{LSS}^2 . The weight associated with the transmitted flux (Equation (1)) is then given as the inverse of the variance,

$$w_q(\lambda) = \frac{1}{\eta_{\text{pip}}(\lambda)\tilde{\sigma}_{\text{pip},q}^2(\lambda) + \eta_{\text{LSS}}\sigma_{\text{LSS}}^2(\lambda)}, \quad (3)$$

where $\tilde{\sigma}_{\text{pip},q} = \sigma_{\text{pip},q}/\bar{F}C_q$. An additional scaling parameter, η_{LSS} , was introduced to optimize the measurement of correlation function (C. Ramírez-Pérez et al. 2024), modulating the contribution of the intrinsic variance, and was fixed at a value of 7.5 for this catalog.⁴³ Since the above expression for the weight corresponds to $(\bar{F}C_q)^2/\sigma_q^2$, apart from the factor η_{LSS} , we evaluate S/N for each pixel by relating its weight to the squared S/N as $w_q(\lambda) = (S/N)^2(\lambda)$.

2.3. Quasar Pairs

Since we are interested in Ly α absorption in the vicinity of quasars, we first construct a catalog of closely separated quasar pairs on the sky from the Ly α forest catalog. The steps are as follows.

1. Consider quasar pairs, consisting of a foreground and a background quasar, selected from a total of 428,403 quasars that constitute the Ly α forest catalog, and apply a cut based on the transverse distance between the foreground quasar (at redshift $z_{f/g}$) and the line of sight to the background quasar, requiring

$$D_M(z_{f/g})\sin\theta_{\text{sep}} < 2h^{-1} \text{ Mpc}, \quad (4)$$

where $D_M(z)$ is the angular (transverse) comoving distance at a redshift z and θ_{sep} is the separation angle between the quasar pairs. We restrict our analysis to transverse comoving distances $< 2h^{-1}$ Mpc because, for typical quasar luminosities in our sample, the photoionization rate from the foreground quasar falls below the metagalactic UV background (UVB) at larger separations, making the TPE undetectable beyond this

⁴⁰ <https://github.com/ngbusca/QuasarNET>

⁴¹ <https://github.com/deshub/fastpecfit>

⁴² <https://github.com/igmhub/picca/>

⁴³ The value of $\eta_{\text{LSS}} = 7.5$ was determined to optimize the precision of the auto- and cross-correlation of the density fluctuation (δ_q , Equation (1)), rather than that of the transmitted flux (f_q/C_q), which is the focus of this paper. Nevertheless, we expect this choice to have no significant impact on our qualitative error estimation, as the gain in precision for cross-correlation is only 10% compared to the case with $\eta_{\text{LSS}} = 1.0$ (C. Ramírez-Pérez et al. 2024).

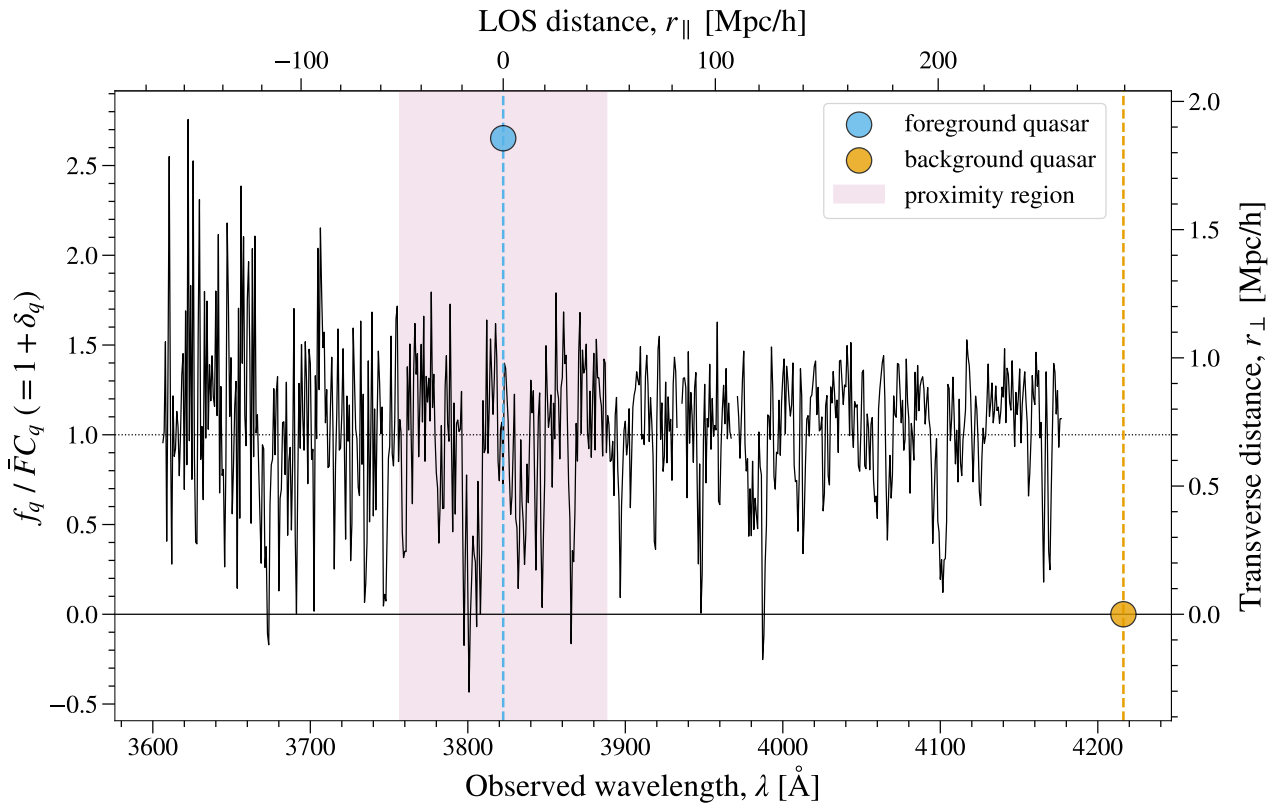


Figure 1. Spectrum of the Ly α forest of a background quasar that has a minimum projected separation of $1.86h^{-1}$ Mpc from a foreground quasar. The sky blue and orange circles indicate the spatial positions of the foreground and background quasars, respectively. The dashed vertical lines mark the Ly α wavelengths of these quasars. The pink shaded region represents the proximity region, defined as a comoving line-of-sight separation of $\pm 50h^{-1}$ Mpc relative to the foreground quasar. The foreground quasar is at $z = 2.14$ (TargetID = 39627480138519001) and the background quasar is at $z = 2.47$ (TargetID = 39627480138519447).

scale (see Section 4.1.2 for details).—remaining pairs: 25,210

2. Require that the quasar proximity region, within $\pm 50h^{-1}$ Mpc of foreground quasar along the line of sight,⁴⁴ is fully covered by both the observed wavelength (i.e., 3600–5772 Å) and the Ly α forest region in the background quasar spectrum (i.e., the rest-frame wavelength range of 1040–1205 Å).—remaining pairs: 10,942
3. Remove pairs in which the foreground quasar does not have a well-measured luminosity.—remaining pairs: 10,919
4. For pixels in the background quasar spectrum within the proximity region of its foreground quasar, consider the fraction of well-defined pixels (e.g., not masked) and the mean S/N averaged over those pixels, given by $\langle (S/N)^2 \rangle_{\text{prox}} = \langle w_q \rangle_{\text{prox}}$, and then remove pairs with more than half of the pixels being ill-defined and/or with extremely low S/N, $\langle (S/N)^2 \rangle_{\text{prox}} < 0.02$.—remaining pairs: 10,263

Figure 1 presents an example of the selected quasar pairs, illustrating the spatial positions of the foreground and background quasars, as well as the normalized Ly α flux, $f_q / FC_q (= 1 + \delta_q)$, of the background quasar spectrum passing

through the proximity region of the foreground quasar. Notably, the number of quasar pairs in our sample is nearly 50 times larger than that in the P. Jalan et al. (2019) analysis based on the SDSS DR12 quasar catalog. While the number of quasars available for Ly α forest analyses increased by only a factor of ~ 3 , this would translate into an expected ~ 10 -fold increase in pair counts, still far below the factor of 50 actually achieved. This additional enhancement arises mainly because they also investigated the LPE and therefore conservatively restricted their quasars to $z > 2.57$ in order to ensure spectral coverage of the Ly α absorption region.

2.4. Control Sample

The Ly α forests observed toward the background quasars in our 10,263 close pairs are expected to be influenced by radiation from their foreground quasars. To investigate variations in quasar proximity regions, we require a reference sample catalog for comparison with the background quasar spectra. Taking advantage of the large DESI dataset, we construct the control sample catalog from the same Ly α forest catalog, partially following the procedure adopted by P. Jalan et al. (2019),⁴⁵ in which the control sample was selected to match the redshift and S/N of the background quasar spectra.

First, we divide the 428,403 quasars in the Ly α forest catalog into 50 redshift bins, each containing an equal number of quasars. For each quasar pair, we then randomly select 10

⁴⁴ Although the term *quasar proximity region* generally refers to the region around a quasar where its ionizing radiation dominates over the UV background, here we adopt a fixed $\pm 50h^{-1}$ Mpc window purely for convenience in stacking. This choice also encompasses the broad Si III 1206.5 Å absorption feature (around $-30 \lesssim r_{\parallel} \lesssim -10h^{-1}$ Mpc), clearly seen for the closest transverse sightlines (Figure 2).

⁴⁵ They adopted a smaller proximity region ($\sim 40h^{-1}$ Mpc at $z \sim 3$) and a relaxed S/N matching criterion of 0.15 in Equation (5), requiring 25 control sample quasars per foreground quasar.

quasars from the same redshift bin as the background quasar without repetition, ensuring the following condition:

$$\left| \frac{[S/N]_{cs} - [S/N]_{b/g}}{[S/N]_{b/g}} \right| < 0.1, \quad (5)$$

where $[S/N] \equiv \sqrt{\langle (S/N)^2 \rangle_{\text{prox}}} = \sqrt{\langle w_q \rangle_{\text{prox}}}$ is the mean S/N averaged over pixels within the proximity region of the foreground quasar. The subscripts “b/g” and “cs” refer to the background quasar and a candidate quasar to be selected as a control sample, respectively. Note that when computing $[S/N]_{cs}$, we exclude quasar spectra in which all pixels within the proximity region are ill-defined.

3. Results

In this section, we first introduce three types of subsample catalogs and then present the measurements of Ly α transmission in the quasar proximity for each. Before presenting the results, we define the line-of-sight and transverse distances of pixels in background quasars at z_{pix} relative to the positions of their foreground quasars:

$$\begin{aligned} r_{\parallel} &= D_C(z_{\text{pix}}) - D_C(z_{f/g}) \cos \theta_{\text{sep}} \\ r_{\perp} &= D_M(z_{f/g}) \sin \theta_{\text{sep}}, \end{aligned} \quad (6)$$

where D_C and D_M are the comoving distance and the angular (transverse) comoving distance, respectively, and θ_{sep} is the separation angle between the quasar pairs. Note that, by definition, all pixels in the same background quasar spectrum share the same transverse distance.⁴⁶

3.1. Subsamples

In the following analysis, we consider three different subsample catalogs based on the transverse distance of the background quasar sightline, the foreground quasar redshift, and the foreground quasar luminosity. The transverse distance of a background quasar sightline directly reflects its susceptibility to the influence of its foreground quasar environment. We divide the quasar pairs into three bins of equal width based on the transverse distance, covering the range $0\text{--}2h^{-1}\text{Mpc}$. Figure 2(a1) shows the subsample distribution and illustrates the number of samples scaling with the transverse distance, as expected. We also consider a subsample binned by the foreground quasar redshifts to investigate the redshift evolution of the proximity region. Figure 2(b1) shows the distribution of this subsample, which is divided into three bins containing an equal number of quasars. One of the main interests here is to understand the relationship between variations of Ly α absorption in the foreground quasar proximity region and their ionizing radiation flux. Figure 2(c1) represents three bins based on the monochromatic luminosity at rest-frame $1500\text{ \AA}$ of foreground quasars, $\nu L_{\nu}|_{1500\text{ \AA}}$. Since luminosity and redshift are generally correlated, we divide the sample in a way that preserves similar redshift distributions across luminosity subsamples. Specifically, we first sort the foreground quasars by redshift

and divide them into 30 redshift bins. Within each bin, we then divide the quasars into three equal-sized subsamples based on their luminosity. This procedure ensures that the redshift distribution is nearly identical across the luminosity subsamples, although it results in some overlap in luminosity between the bins. This allows us to isolate the dependence on luminosity more clearly without contamination from redshift evolution effects. We summarize in Table 1 the parameter ranges used to define the subsamples based on transverse distance, redshift, and luminosity. We have verified that, as expected, the transverse-distance subsamples have similar distributions in luminosity and redshift, the redshift subsamples have comparable distributions in transverse distance, and the luminosity subsamples also show similar distributions in transverse distance. These results indicate that, apart from the known correlation between redshift and luminosity, no significant correlations are present among these quantities, and they are not expected to bias the comparison among the subsamples.

3.2. Ly α Transmission

Following previous studies (D. Kirkman & D. Tytler 2008; P. Jalan et al. 2019), we focus on the (normalized) transmitted flux, defined as the ratio of the observed flux to the unabsorbed continuum flux, f_q/C_q , to investigate variations in Ly α absorption within the quasar proximity region. Since our continuum fitting procedure yields the mean expected flux, $\bar{F}C_q$, for each quasar spectrum, we need to estimate the mean transmission, $\bar{F}$, in order to compute the transmitted flux.

W. Turner et al. (2024) developed a convolutional neural network that predicts the unabsorbed quasar continuum based on the red side of the Ly α emission line, referred to as the Ly α Continuum Analysis Network (LyCAN). They applied LyCAN to a high-S/N subset of the DESI Y1 quasars ($2.1 < z < 4.2$) to predict their unabsorbed continua and then measured the effective Ly α optical depth, which they modeled as

$$\tau_{\text{eff}}(z) = \tau_0(1+z)^\gamma, \quad (7)$$

with best-fit parameters $\tau_0 = (2.46 \pm 0.14) \times 10^{-3}$ and $\gamma = 3.62 \pm 0.04$. In the following, we use these best-fit values to compute the mean transmission as $\bar{F}(z) = \exp[-\tau_{\text{eff}}(z)]$.

Our proximity measurements are evaluated relative to a redshift- and S/N-matched control sample constructed from the same Ly α forest catalog (Section 2.4). This design mitigates continuum systematics shared between the proximity and control samples; in particular, smooth multiplicative continuum errors that vary slowly with wavelength should similarly impact the proximity and control samples. The continuum fitting is also performed on the scale of entire Ly α forest skewers (typically several hundred $h^{-1}\text{Mpc}$), which is much larger than the proximity region adopted here (e.g., Figure 1). We therefore do not expect these smooth continuum systematics to generate localized features confined to the proximity region that could mimic the differential trends among our subsamples.

Solid lines in the right panels of Figure 2 represent the stacked Ly α transmission, f_q/C_q , for background quasars in each subsample bin as a function of the line-of-sight separation from the foreground quasars, with a bin width of $3h^{-1}\text{Mpc}$. We also show the stacked Ly α transmission for the corresponding control samples as dashed lines for reference.

⁴⁶ The conventional definition of distance used in Ly α forest auto- and cross-correlation analyses takes a different form (e.g., see Equation (3.1) of A. G. Adame et al. 2025a), as it focuses on the correlation between pixels (or quasar positions) rather than between sightlines and quasar positions, which is more suitable for our context here.

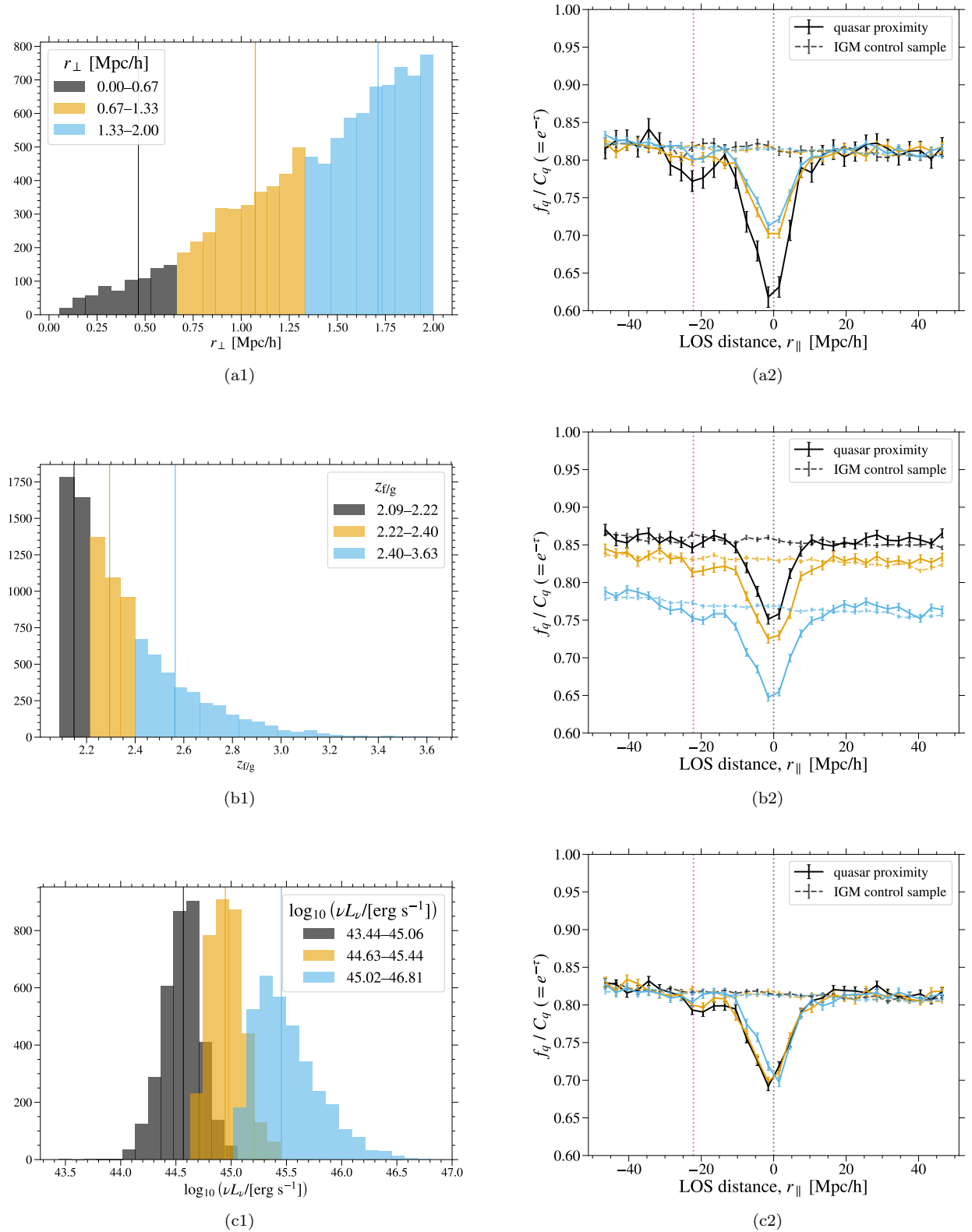


Figure 2. Distributions and stacked Ly α transmissions for three subsamples divided by transverse distance (top), redshift (middle), and luminosity (bottom). Left: histograms of each subsample, with solid vertical lines showing the median values. Right: stacked Ly α transmissions around foreground quasars (solid) and corresponding control samples (dashed) as a function of line-of-sight separation from the foreground quasars (black dotted line). The pink dotted line marks the Si III absorption at 1206.5 Å. Redshift and luminosity subsamples include all transverse separations $r_{\perp} = 0$ – $2h^{-1}$ Mpc, and luminosity bins are selected to have similar redshift distributions.

Each color corresponds to the one shown in the left panel. The error bars indicate the standard error of the mean in each pixel bin. We note that the errors in the control samples are smaller

than those in the background quasars by approximately a factor of $1/\sqrt{10}$, which is expected since each quasar pair is assigned 10 quasar pairs from the control sample. We

Table 1
Parameter Ranges for Subsamples of 10,263 Quasar Pairs Defined by
Transverse Distance, Redshift, and Luminosity

Parameter	Bin	Range
Transverse distance $r_{\perp}$ [Mpc h^{-1}]	Low	0.00–0.67
	Mid	0.67–1.33
	High	1.33–2.00
Redshift $z_{t/g}$	Low	2.09–2.22
	Mid	2.22–2.40
	High	2.40–3.63
Luminosity $\log_{10}\left(\frac{\nu L_{\nu} _{1500\text{ Å}}}{[\text{erg s}^{-1}]}\right)$	Low	43.44–45.06
	Mid	44.63–45.44
	High	45.02–46.81

emphasize that even after dividing the sample into subsamples, the error bars remain small enough to allow for meaningful comparisons between different subsample bins.

Transverse-distance subsample. Let us first examine the results for the transverse-distance subsample in Figure 2(a2). We can clearly see that Ly α absorption in the background quasar spectra is enhanced around the foreground quasars, with a stronger signature for sightlines closer to the foreground quasars. The difference between $r_{\perp} = (0.00\text{--}0.67)h^{-1}$ Mpc and $r_{\perp} = (0.67\text{--}1.33)h^{-1}$ Mpc is more marked than the difference between $r_{\perp} = (0.67\text{--}1.33)h^{-1}$ Mpc and $r_{\perp} = (1.33\text{--}2.00)h^{-1}$ Mpc. On the other hand, the Ly α transmissions for the control samples in the three subsample bins are consistent with each other, as expected. We note that the differences in error sizes reflect variations in the number of quasar pairs in each subsample bin. The excess absorption in proximate quasar pairs suggests that the clustering of H I in the dense environment around foreground quasars has a greater impact on Ly α absorption than their ionizing radiation. We also find a small dip at $r_{\parallel} \simeq -20h^{-1}$ Mpc, particularly in the innermost bin (black solid line), which aligns with the expected position of Si III absorption at the rest-frame wavelength of 1206.5 Å (vertical pink dotted line).

Redshift subsample. Figure 2(b2) illustrates the redshift dependence of Ly α transmission in the quasar proximity region. We do not find a clear difference between the foreground quasar redshift bins, apart from variations in the mean transmission, $\bar{F}(z)$. The transmission of the control samples exhibits a slight gradient from left to right (i.e., from the near side to the far side), likely reflecting the same redshift evolution of $\bar{F}(z)$ mentioned above. This trend is not unique to the redshift subsamples but is also observed in the other two subsample categories.

Luminosity subsample. In Figure 2(c2), we present the results for the luminosity subsamples. Interestingly, we do not find any dependence of the Ly α transmission on the foreground quasar luminosity, even though the luminosity in the bins differs by nearly an order of magnitude. We will further investigate this feature in the following sections. The only exception is that the position of the dip in the transmission at $r_{\parallel} \simeq 0$ for the highest luminosity bin is slightly shifted with respect to the other two subsamples toward the far side (i.e., by approximately one bin width, $3h^{-1}$ Mpc) compared to those for the other two bins. In the context of the Ly α forest–quasar cross-correlation, this offset is commonly parameterized as a free parameter, $\Delta r_{\parallel}$,

representing a small systematic bias in the quasar redshift estimates. The baryon acoustic oscillation analysis using the same DESI Y1 Ly α forest data as in this paper found a best-fit value of $\Delta r_{\parallel} = 0.077^{+0.061}_{-0.062} h^{-1}$ Mpc from the cross-correlation alone (A. Brodzeller et al. 2023; A. G. Adame et al. 2025a; A. Bault et al. 2025). The results here suggest that the bias could depend on luminosity.

A plausible explanation for such a luminosity-dependent shift is the well-known blueshift of the high-ionization C IV emission line in luminous quasars (e.g., C. M. Gaskell 1982; D. E. Vanden Berk et al. 2001; M. J. Temple et al. 2023), which can lead to an underestimation of their systemic redshift and hence produce an apparent displacement of associated absorption features toward the far side. The typical magnitude of this blueshift corresponds to a few hundred up to $\sim 1000 \text{ km s}^{-1}$ (i.e., of order $10h^{-1}$ Mpc at $z \sim 2.5$). In practice, however, Redrock, the DESI redshift pipeline, determines redshifts by fitting the full quasar spectrum with multiple emission features, so the effect is not a direct one-to-one shift from C IV alone, but rather contributes to a residual systematic uncertainty in the estimated quasar redshifts. The observed offset of $\sim 3h^{-1}$ Mpc is well within the expected scale of such blueshift-induced biases, suggesting that the contribution from C IV systematics provides a reasonable explanation. The transmission spectra shown in the right panels also appear to show an asymmetric profile, such that the transmission is higher on the far side ($r_{\parallel} > 0$) than the near side of the foreground quasar. We return to this point in Section 4.3.

4. Interpretation

Following the results on the Ly α transmission presented in the previous section, we further investigate the properties of H I absorption in the quasar proximity region, with a particular focus on the impact of quasar radiation.

4.1. Optical Depth and Quasar Radiation

As discussed in Section 3.2, our measurements of Ly α transmission suggest that the effect of H I gas clustering in the dense environments around quasars dominates over the extra ionization caused by their radiation. We now proceed to investigate these two contributions more quantitatively. To connect the overdensity and ionization state of H I gas clouds to our measurements, we focus on the optical depth,

$$\tau = -\ln(f_q/C_q), \quad (8)$$

which is proportional to the neutral hydrogen number density. We adopt the notation τ_{prx} for the optical depth measured from the background quasars, which probe the proximity regions of their corresponding foreground quasars, and τ_{IGM} for the optical depth measured from the control samples, which represent the average IGM. Following previous studies (e.g., E. Rollinde et al. 2005; C.-A. Faucher-Giguère et al. 2008), we introduce a simple relation between τ_{prx} and τ_{IGM} , expressed in terms of the density contrast of H I gas clouds and the ionizing photon flux from foreground quasars.

4.1.1. A Simple Model for Optical Depth

In the redshift range $z = 2\text{--}3.5$ relevant to our foreground quasars, the neutral hydrogen fraction in the IGM is known to

be extremely low—for instance, $x_{\text{HI}} \lesssim 3 \times 10^{-5}$ at $z < 6$ (M. McQuinn 2016). Moreover, theoretical considerations by J. Schaye (2001) indicate that typical Ly α forest absorbers have neutral hydrogen column densities of $N_{\text{HI}} \lesssim 10^{14} \text{ cm}^{-2}$ at $z < 5$, significantly below the Lyman limit of $\sim 10^{17} \text{ cm}^{-2}$, above which the gas becomes optically thick to ionizing photons. This implies that the IGM is largely transparent to ionizing radiation in most regions. In our analysis, this assumption is further justified as we exclude systems with high column densities, such as DLAs, by applying appropriate masks in the construction of the Ly α forest catalog.⁴⁷ In such a highly ionized and optically thin environment, assuming photoionization equilibrium, the following relation holds:

$$\Gamma_{\text{tot}} n_{\text{HI}} = \alpha_A(T) n_e n_{\text{HII}} \propto \alpha_A(T) \Delta^2, \quad (9)$$

where n_{HI} , n_{HII} , and n_e are the number densities of neutral hydrogen, ionized hydrogen, and electrons, respectively. The total hydrogen number density is given by $n_{\text{H}} = n_{\text{HI}} + n_{\text{HII}}$, and Δ denotes the gas overdensity, which is approximately equal to the hydrogen overdensity, $\rho_{\text{H}}/\bar{\rho}_{\text{H}}$. Γ_{tot} is the total photoionization rate, and $\alpha_A(T)$ is the case-A recombination coefficient for optically thin gas at temperature T , which is well approximated by the fitting formula $\alpha_A(T) \simeq 4.13 \times 10^{-13} (T/10^4 \text{ K})^{-0.71} \text{ cm}^3 \text{ s}^{-1}$ (B. T. Draine 2011). Note that we used $n_{\text{HII}} \simeq n_{\text{H}}$ and $n_e \simeq n_{\text{H}} + 2n_{\text{He}} \propto n_{\text{H}}$, where n_{He} is the total helium number density, valid under the assumption of fully ionized hydrogen and helium gas. In our case, we can reasonably assume that the proportionality constant in Equation (9) is independent of local physical conditions, such as gas temperature or overdensity, as long as the contribution of helium to the electron number density is spatially uniform.⁴⁸

According to Equation (9), both optical depths, τ_{IGM} and τ_{prx} , can be related to the photoionization rate and gas overdensity. In the IGM control samples, both quantities follow simple assumptions: photoionization is driven solely by the uniform UVB (Γ_{UVB}), and the gas overdensity is unity on average across many sightlines, as defined by our continuum fitting procedure. Under these conditions, the optical depth is given by $\tau_{\text{IGM}} \propto C_{\text{HII}} \alpha_A(T) / \Gamma_{\text{UVB}}$, where $C_{\text{HII}} \equiv \langle n_{\text{HII}}^2 \rangle / \langle n_{\text{HII}} \rangle^2$ is the clumping factor that accounts for small-scale inhomogeneities in the ionized hydrogen density. In contrast, in quasar proximity regions, where the total photoionization rate includes a local contribution from foreground quasars (Γ_q), the HI optical depth is $\tau_{\text{prx}} \propto C_{\text{HII}} \alpha_A(T) \Delta^2 / (\Gamma_{\text{UVB}} + \Gamma_q)$. In this case, Δ remains significantly different from unity even after stacking quasar pairs, reflecting the typically overdense environments surrounding quasars. Note that although we assume the clumping factor to be the same in the IGM and in quasar proximity regions, it has been shown that local clumping factors can vary with the local gas overdensity (e.g., A. A. Kaurov & N. Y. Gnedin 2015). In

this case, we would need to consider the variation of the clumping factor in proximity regions separately from the gas overdensity. However, for simplicity, we neglect such variation in this study.

Assuming a simple temperature–density relation, $T \propto \Delta^{\gamma-1}$, and using the above fitting formula for the recombination coefficient, the ratio of the two optical depths can be written as

$$\frac{\tau_{\text{prx}}}{\tau_{\text{IGM}}} = \frac{\Delta^{2-0.71(\gamma-1)}}{(\Gamma_{\text{UVB}} + \Gamma_q) / \Gamma_{\text{UVB}}}. \quad (10)$$

G. C. Rudie et al. (2012) analyzed a sample of more than 5000 HI absorbers in the IGM over the redshift range $2.0 < z < 2.8$ and inferred a power-law index of $\gamma - 1 = 0.46 \pm 0.05$ for the temperature–density relation at a mean redshift of $\bar{z} = 2.4$. In the following analysis, we adopt this value for γ . The most important source of inaccuracy in Equation (10) is that τ_{prx} is measured from the flux averaged over a DESI resolution element, and averaging flux is not the same as averaging optical depth because of the nonlinear relation between them. Similarly, τ_{IGM} is defined from the mean transmitted flux of the IGM rather than an average of optical depth. Thus, Equation (10) only applies strictly in the limit that all optical depths are $\tau \ll 1$. Nevertheless, it provides a useful approximate tool for interpreting our measurements in terms of density profiles around quasars, as a prelude to full forward modeling from IGM simulations.

4.1.2. Quasar Ionization

Throughout this work, we adopt a UVB ionization rate of $\Gamma_{\text{UVB}} = 9 \times 10^{-13} \text{ s}^{-1}$ over the redshift range $2 \lesssim z \lesssim 3$ (F. Haardt & P. Madau 2012). On the other hand, since the luminosities of the foreground quasars are known, we can estimate the photoionization rate at each pixel along the background quasar spectra, Γ_q . To do this, we extrapolate the quasar ionizing photon flux from the luminosity measured at rest-frame 1500 Å, $L_{\nu}|_{1500 \text{ Å}}$. Assuming typical values for the spectral slope of the quasar continuum (E. Lusso et al. 2015),

$$\alpha = \begin{cases} -0.61 & (\nu < \nu_{\text{LL}}) \\ -1.70 & (\nu > \nu_{\text{LL}}), \end{cases} \quad (11)$$

the quasar luminosity density, $L_q(\nu_q)$ (in $\text{erg s}^{-1} \text{ Hz}^{-1}$), can be expressed as

$$L_q(\nu_q) = L_{q,\nu}|_{1500 \text{ Å}} \left(\frac{\nu_{\text{LL}}}{\nu|_{1500 \text{ Å}}} \right)^{-0.61} \left(\frac{\nu_q}{\nu_{\text{LL}}} \right)^{\alpha}, \quad (12)$$

where ν_q is the rest-frame frequency at the quasar’s position, and ν_{LL} is the Lyman limit frequency. Assuming isotropic emission, the quasar flux per unit frequency at a pixel in the background quasar spectrum, denoted as $F_q(\nu)$ (in $\text{erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$), is given by

$$F_q(\nu) = (1 + z_{\text{rel}}) \frac{L_q((1 + z_{\text{rel}})\nu)}{4\pi d_{L,\text{rel}}^2}. \quad (13)$$

Here, z_{rel} is the relative redshift between the foreground quasar and the pixel, defined by $1 + z_{\text{rel}} = a(\eta_{\text{pix}})/a(\eta_{\text{emi}})$, where η_{emi} denotes the conformal time when the ionizing photons were emitted from the foreground quasar. The conformal time η_{pix} corresponds to the comoving distance χ_{pix} to the pixel and is

⁴⁷ If DLAs were statistically more abundant in the vicinity of foreground quasars, our masking procedure could lead to an underestimation of the neutral hydrogen content. In addition, while residual contamination from undetected DLAs may remain, we do not explicitly model this effect in our analysis.

⁴⁸ While the reionization of neutral helium (He I), which likely proceeded similarly to that of neutral hydrogen, had already completed by the relevant redshifts (e.g., X. Fan et al. 2006a), He II reionization is thought to occur around $z \gtrsim 3$ (e.g., B. Ciardi & A. Ferrara 2005; M. McQuinn et al. 2009; L. Yang et al. 2023). Nevertheless, incomplete knowledge of the He II reionization state within local IGM gas can introduce up to an 8% uncertainty in the estimate of the electron number density (e.g., F. Haardt & P. Madau 2012).

given by $\eta_{\text{pix}} = \eta_0 - \chi_{\text{pix}}$, with η_0 being the conformal time at the present epoch. The relative luminosity distance is denoted by $d_{L,\text{rel}}$ and calculated accordingly (see R. Hada et al. 2024 for more details).

We now briefly discuss the comoving separation between the foreground quasar and the pixel, $\chi_{q\text{-pix}} = \eta_{\text{pix}} - \eta_{\text{emi}}$. In practice, quasars have finite lifetimes, meaning there is a maximum distance up to which their radiation can reach. This sets a lower bound on η_{emi} and consequently an upper bound on $\chi_{q\text{-pix}}$. Ideally, we should assess whether each pixel lies within the illuminated region, and set the quasar flux to zero for those beyond it. However, for simplicity, we assume that all foreground quasars have infinite lifetimes and that all pixels of background quasars are exposed to the quasar radiation. We note that this assumption is intentionally simplified, as quasars are expected to have finite lifetimes and anisotropic emission. These effects are discussed in Section 4.3.

Finally, the ionization rate contributed by the foreground quasar can be written as

$$\Gamma_q = \int_{\nu_{\text{LL}}}^{\infty} d\nu \frac{F_q(\nu)}{h\nu} \sigma_{\text{ion}}(\nu) \quad (14)$$

where $\sigma_{\text{ion}}(\nu)$ represents the photoionization cross section for H I atoms, given by

$$\sigma_{\text{ion}} = \sigma_{\nu_{\text{LL}}} \left(\frac{\nu}{\nu_{\text{LL}}} \right)^{-3}, \quad (15)$$

with $\sigma_{\nu_{\text{LL}}} = 6.3 \times 10^{-18} \text{ cm}^2$ being the cross section at the Lyman limit (D. E. Osterbrock & G. J. Ferland 2005; B. T. Draine 2011).

As expected from its definition, the ionization rate Γ_q scales with the quasar luminosity and inversely with the square of the distance to the pixels. To illustrate this behavior, in Figure 3, we present the ionization rates along the background quasar sightlines for three quasar pairs, each representing a different combination of low- and high-luminosity foreground quasars, as well as small and large separations. The black curve shows a pair with a luminous foreground quasar and a large separation, illustrating that the ionization rate from the foreground quasar exceeds that of the UVB around the proximity region. The orange curve presents the opposite case, featuring a faint foreground quasar with a small separation, where the peak ionization rate is comparable but the region of excess Γ_q is much narrower. In sky blue, we show the remaining case of a faint foreground quasar with a large separation, where $\Gamma_q \simeq \Gamma_{\text{UVB}}$ even at the peak. This comparison highlights that, for typical luminosities in our sample ($\log(\nu L_{\nu}|_{1500 \text{ \AA}} / [\text{erg s}^{-1}]) \sim 45$), the quasar photoionization rate falls below the UVB level beyond $\sim 2h^{-1} \text{ Mpc}$, consistent with our choice to limit the analysis to these separations (see Section 2.3).

4.1.3. Observed Optical Depth

Based on the discussion above, we now compare our measurements with the model prediction for the Ly α optical depth. In Figure 4, the solid lines show the ratio of the observed optical depths, $\tau_{\text{prx}}/\tau_{\text{IGM}}$, for the three luminosity subsamples defined in Figure 2. The dashed lines in the figure indicate the expected contribution from quasar ionizing radiation alone, corresponding to the case where the

overdensity is set to $\Delta = 1$ in Equation (10):

$$\left[\frac{\tau_{\text{prx}}}{\tau_{\text{IGM}}} \right]_{\text{rad}} \equiv \frac{\tau_{\text{prx}}}{\tau_{\text{IGM}}} \bigg|_{\Delta=1} = \frac{\Gamma_{\text{UVB}}}{\Gamma_{\text{UVB}} + \Gamma_q}, \quad (16)$$

where, for each quasar pair, Γ_q is calculated based on the luminosity of the foreground quasar and the positions of pixels along the background quasar spectrum, following the equations presented in Section 4.1.2. This prediction implicitly assumes isotropic and steady emission from the foreground quasar.

We estimated the mean and its uncertainty in each line-of-sight separation bin (with a width of $3h^{-1} \text{ Mpc}$) using bootstrapping, for both the observed optical depth ratio and its expected contribution from quasar radiation. Specifically, we generated 100 bootstrap samples by randomly resampling quasar pairs with replacement, and computed the mean and standard error of the optical depth ratio from these resampled datasets. We compare the error estimation methods for the transmission of the Ly α forest—standard deviation versus bootstrapping—in the Appendix, and find that our bootstrapping approach provides sufficient precision for comparing different subsamples and for comparing the data with model predictions, given that high-precision error estimation is not required. We estimate the mean and its uncertainty for all subsequent measurements using the bootstrap method described above.

As expected from the results on Ly α transmission, we find no significant differences in the observed optical depths among the luminosity subsamples, except for a shift in the peak position. The enhanced optical depth near foreground quasars suggests that the clustering of H I absorbers in dense environments has a greater impact than the quasar radiation. Consistent with this picture, previous TPE studies also reported excess H I absorption around quasars, pointing to overdense environments (e.g., J. X. Prochaska et al. 2013; P. Jalan et al. 2019). On the other hand, the expected contribution from quasar radiation is substantial enough to alter the optical depth ratio and shows a clear dependence on quasar luminosity. Similar effects were anticipated in simulations by R. A. C. Croft (2004), who showed that finite lifetimes and light-cone effects can shape quasar light echoes and modify the Ly α forest absorption, highlighting the sensitivity of the proximity effect to quasar radiation models. The shift in the peak position corresponds directly to the displacement of the dip in the Ly α transmission. While a luminosity-dependent C IV blueshift provides a plausible explanation, we will also discuss in Section 4.3 alternative mechanisms that could produce such an offset.

The contribution from quasar radiation should be regarded as an upper limit, due to several simplifying assumptions we have made. First, as noted below Equation (10), the optical depth of high-column-density absorbers may be underestimated due to the finite pixel size, which can obscure the full extent of the quasar ionization effect. P. Jalan et al. (2019) used synthetic spectra generated from hydrodynamical simulations of the IGM to demonstrate that the observationally inferred Γ_q tends to underestimate the true value. In addition, Lyman limit systems (LLSs), along with H I gas clouds, are known to cluster in the dense environments around quasars (e.g., J. X. Prochaska et al. 2013), which can further attenuate the quasar ionizing flux reaching the pixels. Nevertheless, it remains important to consider how to reconcile the lack of

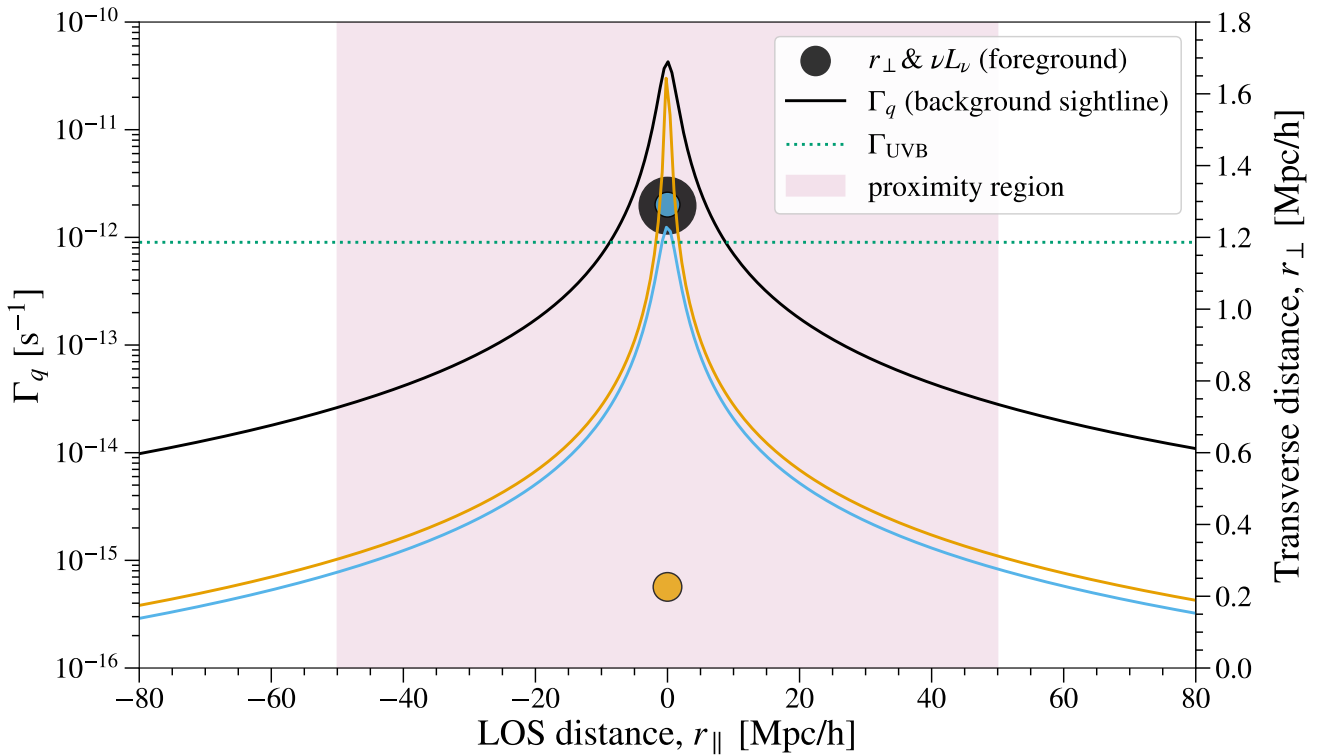


Figure 3. Ionization rates due to three foreground quasars at $z \simeq 2.2$ (circle) on their background quasar sightlines (solid line), compared with the UVB ionization rate (green dotted line). This is similar to Figure 1, but with circle size reflecting the luminosity of the foreground quasar: $\log(\nu L_{\nu}|_{1500 \text{ \AA}} / [\text{erg s}^{-1}]) = 46.39$ (black), 44.98 (orange), and 44.86 (sky blue).

luminosity dependence in the observed optical depth with the clear luminosity dependence predicted for the contribution from quasar ionization.

4.2. Gas Overdensity Profile

The contribution predicted from quasar ionization alone is given by Equation (10) with $\Delta = 1$ and we interpret the difference between the predicted and measured values (dashed and solid lines in Figure 4) as arising from the gas overdensity. In other words, by substituting the measured optical depth ratio into the left-hand side of Equation (10), we can estimate the average value of Δ as a function of distance.

Figure 5 shows the gas overdensity profiles for the luminosity subsamples, plotted as a function of line-of-sight separation $r_{\parallel}$ (left; bin width $3h^{-1}$ Mpc) and three-dimensional distance $r_{3D} = (r_{\parallel}^2 + r_{\perp}^2)^{1/2}$ (right; bin width $0.33h^{-1}$ Mpc).⁴⁹ Solid and dashed lines indicate the overdensity profiles with and without the contribution from quasar radiation, respectively. In the absence of quasar ionization ($\Gamma_q = 0$), the three dashed profiles overlap, consistent with the expectation that the overdensity is described by a simple power-law function of the optical depth ratio, independent of luminosity. By contrast, the separation of the solid lines demonstrates the luminosity dependence of the quasar ionization rate.

We find that the gas overdensity is systematically higher around more luminous foreground quasars, and the dense environments are particularly prominent at scales

$r_{3D} \lesssim 10h^{-1}$ Mpc. Similar conclusions have been drawn from LPE studies at redshifts $z = 2-4$, which analyzed the optical depth distribution along quasar sightlines. For example, E. Rollinde et al. (2005) inferred overdensities of order a few within $\sim 10h^{-1}$ Mpc to explain the observed LPE, while R. Guimarães et al. (2007) reported overdensities up to ~ 5 (or ~ 2) within $\sim 3h^{-1}$ (or $10h^{-1}$) Mpc, and further noted a positive correlation between quasar luminosity and overdensity. These findings are qualitatively consistent with our TPE analysis, although they are based on different sightline geometries.

Based on this result, one possible interpretation for the lack of luminosity dependence in the optical depth is that more luminous quasars reside in denser environments, and that the environmental dependence cancels out the effect of increased quasar ionizing radiation. However, such an almost exact cancellation appears coincidental. Moreover, previous measurements of quasar clustering in redshift surveys suggest that quasar clustering does not depend on luminosity (S. M. Croom et al. 2005; S. Eftekharzadeh et al. 2015; P. Laurent et al. 2017), or at most depends only weakly (Y. Shen et al. 2013), which in turn implies that quasars of different luminosity reside in halos of similar mass and environment. These tests of luminosity dependence are anchored by relatively luminous quasars, e.g., the BOSS luminosity-binned analysis (S. Eftekharzadeh et al. 2015), whose faint-end limit ($L_{\text{bol}} \geq 3.2 \times 10^{45} \text{ erg s}^{-1}$) roughly corresponds to $\log_{10}(\nu L_{\nu}|_{1500 \text{ \AA}} / \text{erg s}^{-1}) \gtrsim 44.9$, and this luminosity regime still overlaps our middle and high luminosity bins (Figure 2; Table 1). This apparent inconsistency motivates us to consider alternative explanations for the lack of luminosity dependence, focusing on aspects related to quasar emission itself. We explore these possibilities in the following subsection.

⁴⁹ A finer bin width of $0.33h^{-1}$ Mpc was adopted for r_{3D} , since the original $3h^{-1}$ Mpc bin (used for $r_{\parallel}$) would be too coarse relative to the $0.67h^{-1}$ Mpc bin size used in defining the transverse-distance subsamples, making it difficult to compare results across different transverse-distance bins.

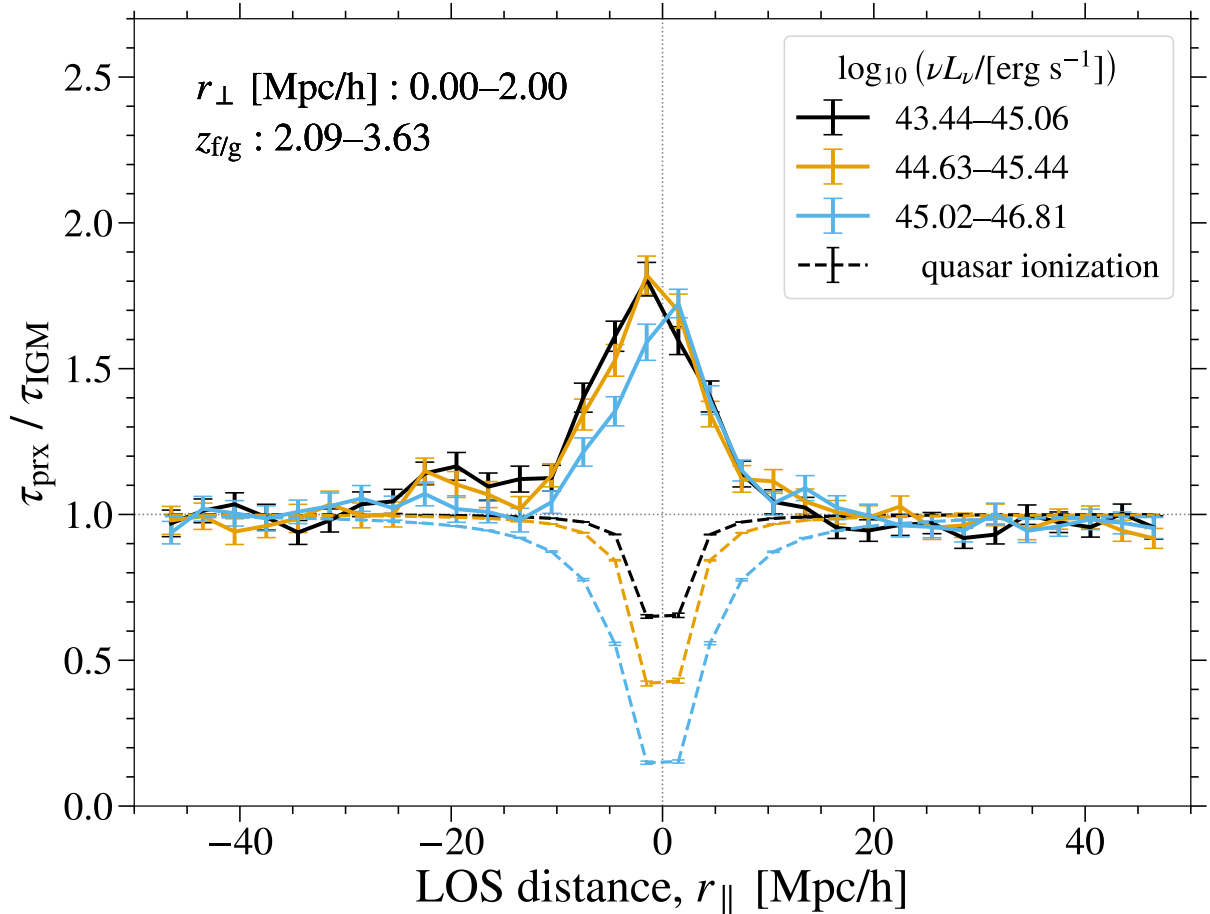


Figure 4. Luminosity dependence of Ly α optical depth variations in quasar proximity regions (solid lines). For comparison, we also show the expected contribution from quasar ionizing radiation alone (dashed lines), corresponding to the case where the overdensity is fixed at $\Delta = 1$ in Equation (10). Line colors and vertical lines are the same as in Figure 2.

4.3. Quasar Emission: Variation, Lifetime, and Geometry

So far, we have assumed quasars to remain constantly luminous, shine indefinitely, and emit radiation isotropically, for simplicity. In reality, however, their luminosity can evolve over time, their lifetimes are finite, and their emission may be anisotropic. In this section, we consider how these factors affect our interpretation.

First, one plausible explanation for the lack of luminosity dependence in the Ly α optical depth involves the time evolution of quasar luminosity. The absence of strong luminosity-dependent clustering implies that quasars of different luminosities reside in halos of similar mass, which suggests that quasar luminosity may not be tightly coupled to halo mass. This scenario can be understood if individual quasars undergo substantial luminosity variation, such that the most luminous quasars represent short-lived, high-luminosity phases within longer episodic lifetimes. If the duration of these luminous episodes is shorter than the light-crossing time across the transverse separation, then the observed luminosity along the line of sight may not reflect the ionizing flux seen by the transverse sightlines. In this case, the effective ionizing radiation in the transverse direction could be decoupled from the observed luminosity, naturally accounting for the lack of luminosity dependence. This interpretation does not conflict with the luminosity dependence often discussed for the LPE;

in particular, that luminosity scaling has been explicitly used in UVB measurements (e.g., A. Dall’Aglio et al. 2008; A. A. Meiksin 2009). A similar idea is proposed by A. Lidz et al. (2006), who suggest that quasars spend significantly more time in low-luminosity states than in high-luminosity ones, thereby biasing instantaneous luminosity measurements.

Furthermore, the quasar proximity zone has a characteristic apparent boundary that is asymmetric with respect to the quasar, resulting from the effect of light-travel time. It extends farther on the near side than on the far side, and the overall size grows as the quasar ages (see, for example, the figures of Q. Yu 2005; T. M. Schmidt et al. 2019; R. Hada et al. 2024, for visualization). Based on this fact, we can propose an alternative explanation for the shift in the dip position of the transmission (or the peak position of the optical depth). Specifically, the contribution of quasar ionization is more significant on the near side of luminous quasars, leading to the suppression of the optical depth for the most luminous quasar subsample (sky blue solid line in Figure 4) on the near side ($r_{\parallel} < 0$).

Finally, the unified model of AGNs (e.g., R. Antonucci 1993; H. Netzer 2015) suggests that quasar radiation is emitted through bipolar cones, a scenario supported by several observational studies (e.g., M. Weidinger et al. 2004; J. F. Hennawi & J. X. Prochaska 2007; J. X. Prochaska et al. 2013). In particular, P. Jalan et al. (2019) compared the

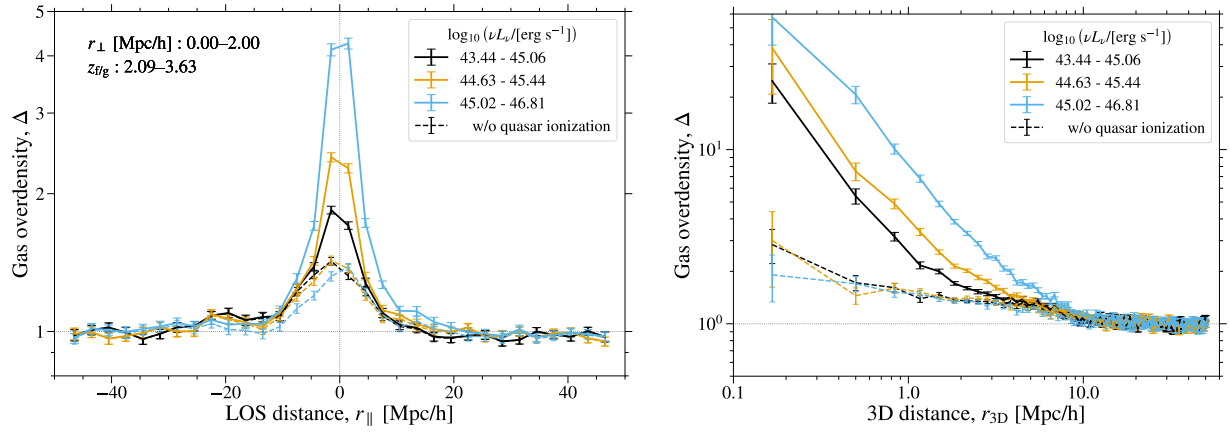


Figure 5. Inferred gas overdensity profiles around quasars for the luminosity subsamples, shown as a function of line-of-sight separation $r_{||}$ (left panel) and 3D distance r_{3D} (right panel). The overdensities are derived from the $\tau_{\text{prx}}/\tau_{\text{IGM}}$ profiles in Figure 4 using Equation (10), with (solid lines) and without (dashed lines) including the contribution from quasar ionizing radiation. Line colors and vertical lines are the same as in Figure 2.

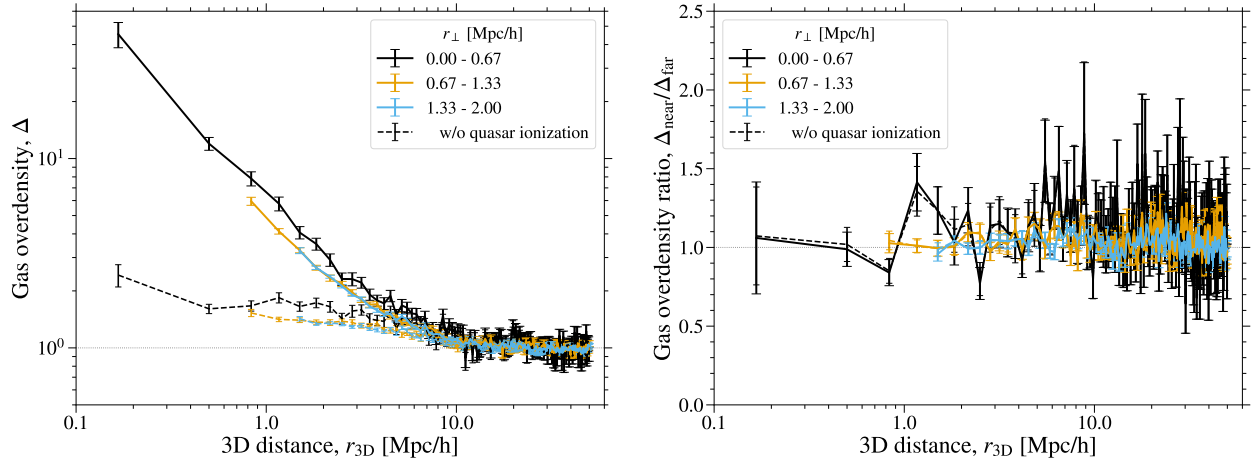


Figure 6. Inferred gas overdensity profiles around quasars for the transverse-distance subsamples (left panel), and the ratio of overdensities between the near side ($r_{||} < 0$) and the far side ($r_{||} > 0$) based on those profiles (right panel). The overdensities are derived from the $\tau_{\text{prx}}/\tau_{\text{IGM}}$ profiles for the transverse-distance subsamples using Equation (10), with (solid lines) and without (dashed lines) including the contribution from quasar ionizing radiation. Line colors are the same as in Figure 2.

LPE and TPE, and showed that the transverse illumination is less than $\sim 30\%$ of that along the line of sight, reinforcing the case for anisotropic obscuration. The $\text{Ly}\alpha$ optical depth profiles in Figure 4 assume isotropic emission. If, instead, quasars emit ionizing radiation anisotropically through bipolar cones, this assumption would lead to an overestimate of the ionizing flux reaching the transverse sightlines. In such a scenario, the lack of luminosity dependence can be naturally explained by the reduced or absent ionizing flux in directions perpendicular to the radiation cones. Consequently, the contribution of quasar ionization shown in the same figure (dashed lines) likely exceeds the actual effect, potentially exaggerating the apparent difference between luminosity subsamples. In fact, if the transverse sightlines lie outside the radiation cones, the inferred gas overdensity profiles—after removing the overestimated radiation contribution (e.g., setting $\Gamma_q = 0$)—become consistent across luminosity bins (dashed lines in the right panel of Figure 5), as the overdensity profile then depends solely on the optical depth. This scenario also helps resolve the apparent inconsistency with the lack of luminosity dependence in quasar clustering.

While the discussion so far has focused on how quasar emission properties may explain the lack of luminosity dependence in the $\text{Ly}\alpha$ optical depth, it is also instructive to examine the dependence on transverse distance. Both finite quasar lifetimes and anisotropic emission can imprint characteristic spatial signatures on the three-dimensional distribution of $\text{Ly}\alpha$ optical depth around quasars.

The left panel of Figure 6 shows the inferred gas overdensity profiles for the transverse-distance subsamples, plotted as a function of three-dimensional separation r_{3D} with a bin width of $0.33h^{-1}\text{Mpc}$. These overdensities are derived from the $\tau_{\text{prx}}/\tau_{\text{IGM}}$ profiles using Equation (10), with (solid lines) and without (dashed lines) the contribution of quasar ionizing radiation. Across most scales, all three subsamples agree well with one another in cases both with and without radiation contribution, except that the innermost subsample (black line) shows a marginally higher overdensity at $r_{3D} \sim (1-5)h^{-1}\text{Mpc}$. If both the gas overdensity and quasar emission are isotropic, the three subsamples would be expected to yield identical profiles when binned by r_{3D} . In this sense, the overall consistency suggests either that (1) quasar emission is isotropic (corresponding to solid lines), or

(2) the ionizing radiation cones have narrow opening angles such that their contribution to transverse sightlines is minimal (corresponding to dashed lines). However, the possibility of intermediate opening angles cannot be firmly excluded, as the stacking is performed over quasars whose emission axes are randomly oriented.

The right panels of Figure 2 all suggest some asymmetry in the transmission spectra relative to the location of the foreground quasar, such that there is more transmission on the far side than the near side. This asymmetry could be produced by a decrease in the neutral gas fraction on the far side relative to the near side, which is in the opposite sense of what would be expected from a finite lifetime. However, it is worth noting that residual uncertainties in quasar redshifts can also contribute to such apparent asymmetries: while the systematic bias has been corrected in DESI DR1 (A. Bault et al. 2025), scatter remains and may lead to asymmetric distributions when stacking large samples.

To further investigate potential anisotropies in the quasar emission or environmental asymmetries, we examine the near-side versus far-side variation in the same transverse subsamples. The right panel of Figure 6 displays the ratio of the same profiles between pixels on the near side ($r_{\parallel} < 0$) and far side ($r_{\parallel} > 0$) relative to the foreground quasars. The ratios for all subsamples are consistent with unity, and no significant deviations are observed. In other words, while the asymmetry is visually noticeable in the transmission spectra, it is not statistically significant when quantified through the near–far ratio. A formal two-sample Kolmogorov–Smirnov test would provide one way to check this more rigorously, but the current results already suggest that any anisotropy or finite-lifetime signatures are weak compared to the statistical uncertainties or washed out in the stacked sample.

In particular, a significant contribution from finite quasar lifetimes would likely induce an asymmetric signal because the near and far sides correspond to different light-travel delays relative to the foreground quasar. This effect is expected to be strongest when the quasar lifetime is shorter than, or comparable to, the characteristic light-travel time to the transverse sightlines. The observed symmetry thus implies that, if the ionizing radiation is effectively isotropic, the quasar lifetime must be sufficiently long for the radiation to reach both sides of the foreground quasar, yielding an apparent near–far symmetry. In this context, a characteristic scale is the transverse distance within which quasar ionization dominates over the UV background, i.e., where $\Gamma_q > \Gamma_{\text{UVB}}$, or equivalently where $[\tau_{\text{prx}}/\tau_{\text{IGM}}]_{\text{rad}} < 0.5$. In Figure 4, for the middle luminosity bin, this criterion is satisfied only for the innermost transverse bin, with center $r_{\perp} = 1.5h^{-1}$ Mpc. Under this simple isotropic interpretation, the corresponding rest-frame light-travel time, of order a few Myr, can therefore be regarded as an illustrative lower-limit scale for the quasar lifetime. In an earlier study based on a much smaller sample of quasar pairs, D. Kirkman & D. Tytler (2008) found no clear evidence for the transverse proximity effect in over 100 quasar pairs, and even reported enhanced absorption behind the foreground quasars, which they interpreted as evidence for a Myr-scale episodic lifetime.

On the other hand, strongly anisotropic emission would reduce such lifetime constraints, since regions outside the cones may never be illuminated. Moreover, if the ionizing radiation is emitted through bipolar cones, the lack of near–far

asymmetry could indicate that the orientation of the emission axes is randomly distributed and sufficiently averaged out in the stacking. This interpretation aligns with the earlier result that the transverse subsamples exhibit only marginal differences in the overdensity profiles, supporting the idea that quasar emission is either narrowly beamed or appears isotropic due to random orientations of the emission axes.

Another possibility is that the slightly enhanced overdensity seen in the innermost transverse subsample at $r_{3D} \sim (1-5)h^{-1}$ Mpc may arise from redshift-space distortions (RSD), particularly the Fingers-of-God (FoG) effect. Although FoG primarily affects the line-of-sight direction, the innermost $r_{\perp}$ bin corresponds to scales comparable to typical halo sizes, where RSD can have a stronger influence. At fixed r_{3D} , sightlines with smaller transverse separations are more susceptible to line-of-sight velocity dispersion, which could artificially boost the inferred gas overdensity in these regions. This effect may offer an alternative explanation that is consistent with the modest excess seen only in the innermost bin and not accompanied by any significant near–far asymmetry.

5. Summary

In this work, we have carried out a large-sample study of the TPE using more than 10,000 quasar pairs from the DESI Year 1 data. By analyzing the Ly α absorption in the vicinity of foreground quasars, we examined how quasar radiation and environmental effects shape the surrounding IGM. Our analysis combined statistical measurements of transmission and optical depth profiles with model predictions of quasar ionization, allowing us to extract information on both gas overdensities and quasar emission properties. Our main findings are as follows.

1. Dense environments dominate radiation. The observed optical depth near quasars is enhanced relative to the IGM average, consistent with strong clustering of H I absorbers. This interpretation is supported by the inferred gas overdensity profiles, which remain high at scales $\lesssim 10h^{-1}$ Mpc, especially around luminous quasars.
2. Luminosity subsamples—no clear dependence. The measured Ly α optical depth shows no clear dependence on foreground quasar luminosity. This lack of luminosity dependence could arise from an almost coincidental balance between higher ionizing flux and higher gas overdensity. Explaining it purely by environment, however, would require strong luminosity-dependent clustering, in conflict with clustering studies. Alternatively, it may reflect emission that is time-variable or anisotropic such that the ionizing radiation emitted toward us does not represent that in other directions.
3. Transverse-distance subsamples—apparent isotropy. The stacked transverse-distance subsamples yield nearly identical overdensity profiles. This apparent isotropy may reflect either intrinsically isotropic emission or moderate-angle cones averaged out by random orientations. Alternatively, strongly anisotropic emission with narrow cones could simply miss most transverse sightlines.
4. Constraints from near–far symmetry. The near–far ratio shows no significant difference, implying that if emission is isotropic, quasar lifetimes must be long enough for

radiation to reach both sides (suggesting an illustrative lower-limit scale of order a few Myr for the quasar lifetime). The lack of asymmetry is also consistent with anisotropic emission, either with narrow cones that miss the transverse sightlines or with moderate cones whose orientations average out in the stacked sample.

5. Comparison with previous TPE studies. Earlier work at $z = 2-4$ (e.g., R. A. C. Croft 2004; D. Kirkman & D. Tytler 2008; J. X. Prochaska et al. 2013; P. Jalan et al. 2019) similarly reported excess H I absorption in the transverse direction, often interpreted as signatures of dense environments and/or anisotropic quasar emission. Our results provide a consistent picture with these smaller-sample studies, now confirmed with unprecedented statistical power.

A key challenge is to disentangle the combined effects of quasar emission properties (e.g., variation, lifetime, and geometry) and overdense environments. Y. Lu & Q. Yu (2011) demonstrated that apparently contradictory lifetime estimates from previous measurements of the proximity effect may be reconciled when density enhancements and obscuration are modeled simultaneously. More recently, R. A. C. Croft et al. (2025) developed a halo-model framework of the quasar proximity effect, calibrated and tested with hydrodynamic simulations, which can connect the proximity effect to both quasar host halo mass and the UVB on large scales. These studies highlight the importance of forward modeling with radiative transfer and realistic environments to fully exploit the statistical power of DESI.

Ongoing observations with DESI will significantly increase the size and quality of the dataset that may be used for future studies of the quasar proximity effect. The DESI collaboration is in the midst of analyzing the data that will form its second data release, which includes over 820,000 spectra that include the Ly α forest (DESI Collaboration et al. 2025b), and which have already been used to study the expansion history (DESI Collaboration et al. 2025a). These new observations will increase the total number of quasars, increase the S/N of existing spectra, and increase the number of close pairs. These improvements will also facilitate more targeted tests of environmental absorption, for example by repeating the stacking analysis after splitting the sample by the presence/absence of LLSs at the foreground-quasar redshift once a robust DESI-based LLS catalog becomes available.

At higher redshifts, recent work has begun to map quasar light echoes and anisotropy directly. For example, A.-C. Eilers et al. (2025) used JWST spectroscopy of background galaxies for a foreground quasar at $z \sim 6$ to reveal the first tomographic detection of its light echo, constraining the orientation and lifetime of a luminous quasar. At lower redshift, T. Misawa et al. (2022) examined the transverse proximity effect around BAL quasars, which are thought to be viewed from near the equatorial plane of the AGN torus and thus provide a probe of transverse emission. Their small sample did not show statistically significant differences from non-BAL quasars. In future DESI analyses, it will be interesting to compare the transverse proximity effect around BAL and non-BAL quasars, which could provide further insights into the anisotropy of quasar emission. External estimates of the obscured quasar fraction from X-ray or mid-infrared observations may also provide an independent consistency check on anisotropic-emission interpretations and potentially an

additional constraint on the opening angle, since in a simple geometric picture a larger obscured fraction corresponds to a smaller unobscured solid angle. Together, these studies show how anisotropy, obscuration, and finite lifetimes can be probed across cosmic time, and they provide complementary perspectives to the DESI measurements at $z \sim 2-3$.

A powerful next step is to combine measurements of the transverse and line-of-sight proximity effects. As demonstrated by P. Jalan et al. (2019), joint analyses of the TPE and LPE provide decisive constraints on anisotropy. A major challenge for LPE studies is accurate continuum fitting in the Ly α forest region, since the measurement relies on the immediate blue side of the quasar's Ly α emission line. Recently, W. Turner et al. (2024) introduced LyCAN, a convolutional neural network trained on synthetic spectra derived from Hubble Space Telescope/Cosmic Origins Spectrograph data together with DESI mock spectra, which predicts the unabsorbed continuum in the forest region using only the red side of the Ly α emission line. This approach achieves errors of only a few percent, making it especially promising for combining TPE and LPE measurements.

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The authors are honored to be permitted to conduct scientific research on I'oligam Du'ag (Kitt Peak), a mountain with particular significance to the Tohono O'odham Nation.

Data Availability

The numerical data underlying the figures presented in this paper, together with the quasar-pair catalog used in the

analysis, are publicly available on Zenodo at DOI: [10.5281/zenodo.19281859](https://doi.org/10.5281/zenodo.19281859). The parent quasar and Ly α -forest data products are based on the public DESI DR1 data release.

Facility: Mayall (DESI).

Software: NumPy (C. R. Harris et al. 2020), Scipy (P. Virtanen et al. 2020), Matplotlib (J. D. Hunter 2007), Astropy (Astropy Collaboration et al. 2013, 2018, 2022), healpy (A. Zonca et al. 2019), Statsmodels (S. Seabold & J. Perktold 2010), Numba (S. K. Lam et al. 2015), CAMB (A. Lewis et al. 2000).

Appendix

Comparison of Error Estimation Methods

In this paper, we adopted two different approaches to estimate the uncertainties in our measurements: the standard deviation for Ly α transmission and bootstrapping for other observables such as Ly α optical depth and gas overdensity. Here, we assess the consistency between these two methods (see the main text for details). Figure 7 shows the mean uncertainties of Ly α transmission, $\sigma_\mu(f_q/C_q)$, computed for the entire sample of 10,942 background quasars (solid lines) and the control samples (dashed lines) using both the standard deviation and bootstrap resampling with $N = 100$.

The two methods yield consistent results across most distances, with only a small deviation around $r_{\parallel} = 0$. This confirms that our bootstrap approach provides sufficient precision for comparing different subsamples and for confronting the data with model predictions. Given that high-precision error estimation is not critical for our main scientific goals, we adopt the bootstrap method to estimate the mean and its uncertainty for all subsequent measurements in this study.

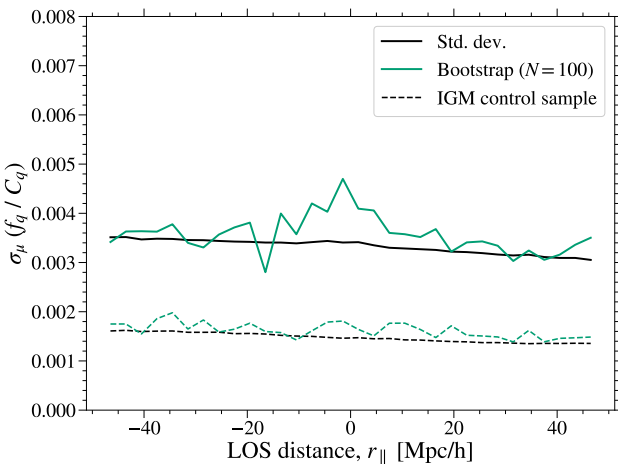


Figure 7. Comparison of Ly α transmission uncertainties estimated using two methods: the standard deviation across the entire sample (black) and bootstrap resampling with $N = 100$ (green). Results are shown for both background quasars (solid lines) and the control samples (dashed lines).

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