

Cosmic Chance Superpositions: Largest Catalog of Quasar-galaxy Pairs at a Projected Separation of $D \lesssim 20$ kpc

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Abstract

We present the largest catalogue to date of Galaxies On Top Of Quasars (GOTOQs)—systems where the sight line to a background quasar passes directly through or very close to a foreground galaxy. Using ~ 1.1 million quasar spectra from the SDSS-DR16 and DESI Early Data Release, we identify 1345 unique GOTOQs over $0.0045 \leq z \leq 1.09$, more than quadrupling the number previously known. The catalogue combines both absorption-agnostic and absorption-selected searches, enabling a robust characterisation of gas in galaxies at projected separations of $D \lesssim 20$ kpc. The GOTOQ emission-line ratios indicate that their host galaxies are predominantly normal, star-forming disks with typical dust extinctions of $A_V \simeq 0.5$ mag. We measure the Mg II covering fraction at $D \lesssim 20$ kpc and find it to be remarkably high, $f_c = 98.2^{+1.3}_{-4.5}\%$, indicating that these systems trace gas-rich, metal-enriched regions at the disk-halo interface. The median colour excess towards the quasar line of sight of $E(B - V) = 0.087$ is significantly higher than that of typical Mg II absorbers, underscoring the dust-rich nature of GOTOQ sight lines. From a high signal-to-noise composite spectrum, we report the first statistical detection of the diffuse interstellar band at $\lambda 4428$ ($W_r = 0.055 \pm 0.011$ Å) and at $\lambda 5780$ ($W_r = 0.051 \pm 0.012$ Å), revealing the presence of complex organic molecules at the disk-halo interface. This catalogue provides a powerful reference sample for future multiwavelength studies of gas flows, cold gas, and dust evolution in the inner circumgalactic medium.

Unified Astronomy Thesaurus concepts: Quasar absorption line spectroscopy (1317); Quasar-galaxy pairs (1316); Galaxy evolution (594); Circumgalactic medium (1879); Interstellar medium (847); Interstellar dust (836); Catalogs (205)

1. Introduction

Galaxy evolution is governed by a complex interplay between gas accretion, star formation, black hole formation and growth, and a range of feedback processes. A key component in this evolutionary cycle is the circumgalactic medium (CGM), a diffuse halo of gas that surrounds galaxies and typically extends to hundreds of kiloparsecs (e.g., J. Tumlinson et al. 2017; C. Péroux & J. C. Howk 2020), far beyond the stellar body. Acting as both a reservoir and a conduit for baryons, the CGM regulates galaxy growth through the exchange of materials between galaxies and their larger-scale environments.

Owing to its low density, the CGM is most effectively studied through quasar absorption line spectroscopy, which provides sensitive, pencil-beam probes of gas over a wide range of physical conditions and redshifts. Although recent advances in integral field unit (IFU) spectroscopy using instruments such as the Multi Unit Spectroscopic Explorer (MUSE) and the Keck Cosmic Web Imager (KCWI) have enabled direct imaging of the CGM in emission (see, for example, J. Chisholm et al. 2020; E. Banerjee et al. 2025), quasar absorption lines remain the most powerful and statistically efficient tool for characterizing the CGM, particularly at high redshifts.

Among the various absorption tracers, Mg II has been widely used to study the CGM of low-redshift galaxies ($z < 1$) from ground-based spectrographs. Over the past two decades, systematic surveys combined with IFU follow-up studies (e.g., N. Bouché et al. 2012; B. F. Lundgren et al. 2012; N. M. Nielsen et al. 2013; I. Schroetter et al. 2019; R. Dutta et al. 2020; Y.-H. Huang et al. 2021; B. F. Lundgren et al. 2021; L. K. Guha et al. 2022, 2024) have established robust connections between Mg II absorbers and their host galaxies or galaxy groups across a broad range of impact parameters (D). However, the majority of these investigations are biased toward large separations, typically $D \gtrsim 30$ kpc, leaving a significant gap in our understanding of the inner CGM at $D \lesssim 20$ kpc (see, however, G. G. Kacprzak et al. 2013; L. K. Guha & R. Srianand 2023, 2024).

Establishing a direct connection between star formation in galaxies and the circumgalactic gas, especially at large impact parameters, remains challenging. On the other hand, examining star-forming galaxies through background quasar sight lines at very low impact parameters—within regions affected by galactic winds over characteristic star formation timescales—can offer significant insights into the role of large-scale gas flows in shaping CGM conditions. For example, an outflow moving at 200 km s^{-1} can influence a region up to approximately 20 kpc around galaxies within about 100 Myr, a timescale comparable to that of a typical starburst episode (K. B. W. McQuinn et al. 2009).

A quasar line of sight passing near the center of an intervening galaxy (i.e., at $D \lesssim 20$ kpc) is likely to probe the gaseous disk or disk-halo interface of a galaxy, providing the



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optimal means to link large-scale gas flows with galaxy evolution. Investigating gas flows at these scales is essential for understanding the mechanisms that sustain or quench star formation in galaxies. The most effective strategy for identifying such quasar-galaxy pairs is to search for nebular emission lines from the intervening galaxy in the spectrum of the background quasar. This method has proven highly efficient for identifying host galaxies of Mg II absorption systems situated at very small angular separations—typically at subarcsec separations (P. Noterdaeme et al. 2010; D. G. York et al. 2012; L. A. Straka et al. 2015; R. Joshi et al. 2017, 2018; V. P. Kulkarni et al. 2022; K. H. R. Rubin et al. 2022). Such systems are referred to as Galaxies On Top of Quasars (GOTOQs; D. G. York et al. 2012).

Past studies utilize one of the two primary methods to search for GOTOQs: absorption agnostic and absorption selected. The absorption-agnostic method involves detecting multiple strong nebular emission lines from an intervening galaxy in the spectrum of a background quasar without any prior knowledge of the presence of absorption lines toward the quasar line of sight (see, for example, P. Noterdaeme et al. 2010; L. A. Straka et al. 2013). This method is particularly effective at lower redshifts ($z \lesssim 0.4$) because all the strong nebular emission lines in the rest-frame optical wavelengths (e.g., [O II] $\lambda\lambda$ 3727, 3729, [O III] λ 5008, and H α λ 6564) can be observed using ground-based spectrographs. However, at higher redshifts ($z \gtrsim 0.4$), the H α line gets redshifted beyond the observable range of these spectrographs, reducing the efficiency of the technique. Using this approach, L. A. Straka et al. (2015) compiled a total of 103 such systems from the Sloan Digital Sky Survey (SDSS) DR7, covering the redshift range of $0 < z < 0.84$.

In the absorption-selected method, one starts from systems identified based on the presence of intervening metal absorption (e.g., Mg II $\lambda\lambda$ 2796, 2803) in the quasar spectrum and searches for the presence of associated nebular emissions at the absorption redshift. This method is particularly efficient for identifying GOTOQs at higher redshifts, $z \gtrsim 0.4$. Starting from the SDSS DR12 Fe II/ Mg II metal absorber catalog (G. Zhu & B. Ménard 2013), R. Joshi et al. (2017) have identified a total of 198 GOTOQs over the redshift range of $0.3 < z < 1.1$. As a result, approximately 300 unique GOTOQs are currently known in the literature, based on earlier SDSS data releases.

Although detecting these galaxies in H I 21 cm emission at $z \gtrsim 0.2$ is challenging, owing to their distinctive geometrical configuration where the line of sight to a background quasar passes either through or very close to the star-forming disk of a foreground galaxy, GOTOQs provide an exceptional opportunity to study the cold gas in the disk and their kinematics through H I 21 cm absorption if the background quasar happens to be radio-loud. A recent survey on GOTOQs by L. K. Guha et al. (2025) reported a staggering $\approx 90\%$ detection rate of H I 21 cm absorption, which is significantly higher than that obtained from searches based on metal lines or damped Ly α absorbers, thereby highlighting the efficiency of GOTOQs in tracing cold gas reservoirs. As seen in the Galactic interstellar medium (ISM), GOTOQs also show a correlation between the line-of-sight reddening and the H I 21 cm absorption line optical depth.

Moreover, GOTOQs serve as valuable laboratories for investigating large-scale gas flows and the cycling of material

through galactic fountains (see, e.g., K. H. R. Rubin et al. 2022) by combining quasar absorption lines with down-the-barrel absorption from galaxies. Observational studies have revealed a possible bimodal azimuthal dependence of metal-line absorption around galaxies, with gas accretion and outflows occurring preferentially along the major and minor axes, respectively (e.g., G. G. Kacprzak et al. 2012). However, other studies (e.g., S. K. Pointon et al. 2019) have found no such orientation dependence in the CGM metallicity, possibly due to gas mixing that “washes out” the bimodality. A well-curated and statistically significant sample of GOTOQs can settle this debate, as the effects of gas mixing are expected to be minimal at the small impact parameters probed by these systems.

In this study, we revisit the search for GOTOQs using the latest data from SDSS-DR16 (R. Ahumada et al. 2020) and the Early Data Release (EDR) of the Dark Energy Spectroscopic Instrument (DESI-EDR; DESI Collaboration et al. 2023). This effort has resulted in the compilation of the largest sample of GOTOQs to date, increasing the number known in the literature by more than a factor of four. Building a large sample of GOTOQs is particularly important for probing the CGM at very low impact parameters, a regime that is rarely sampled in conventional CGM surveys. However, the detection of GOTOQs depends on several factors—(i) fiber diameter, (ii) the signal-to-noise ratio (SNR) and free spectral range of the observed spectrum, (iii) the criteria adopted for identifying detections, and (iv) the relative brightness of the galaxies and quasars—making it difficult to uniquely quantify the selection function (see, e.g., P. Noterdaeme et al. 2010). Consequently, while the catalog is extremely valuable for follow-up studies, it must be used with caution when drawing statistical or physical inferences. This paper is organized as follows. In Section 2, we describe the methods used to identify GOTOQs and provide details of the sample. In Section 3, we present our analysis of the GOTOQs along with the key results. Section 4 summarizes the main findings and discusses their implications. Throughout this work, we adopt a flat Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m = 0.3$.

2. The GOTOQ Sample

Our search for GOTOQs involves both the methods invoked in the literature—absorption-agnostic as well as absorption-selected searches. In the following, we briefly describe the methods employed to search for GOTOQs.

2.1. Absorption-agnostic Searches of GOTOQs

To search for GOTOQs without any prior knowledge of the presence of any absorption toward the quasar line of sight, we start with a quasar spectrum. As the principal component analysis-based continuum of the quasar spectrum provided in SDSS is not always adequate for the analysis presented here, we first perform an automated fitting of the quasar continuum spectra, using QSmooth (D. Āurovčíková et al. 2020) to obtain a continuum-subtracted quasar spectrum. In brief, QSmooth processes the spectrum by initially computing a running median to capture the continuum and broad emission lines. Subsequently, a peak-finding algorithm identifies peaks above this median. These peaks are then interpolated to create an upper envelope of the spectrum, which is then subtracted. The method then applies RANSAC regression (M. A. Fischler & R. C. Bolles 1981) to the residuals to eliminate absorption

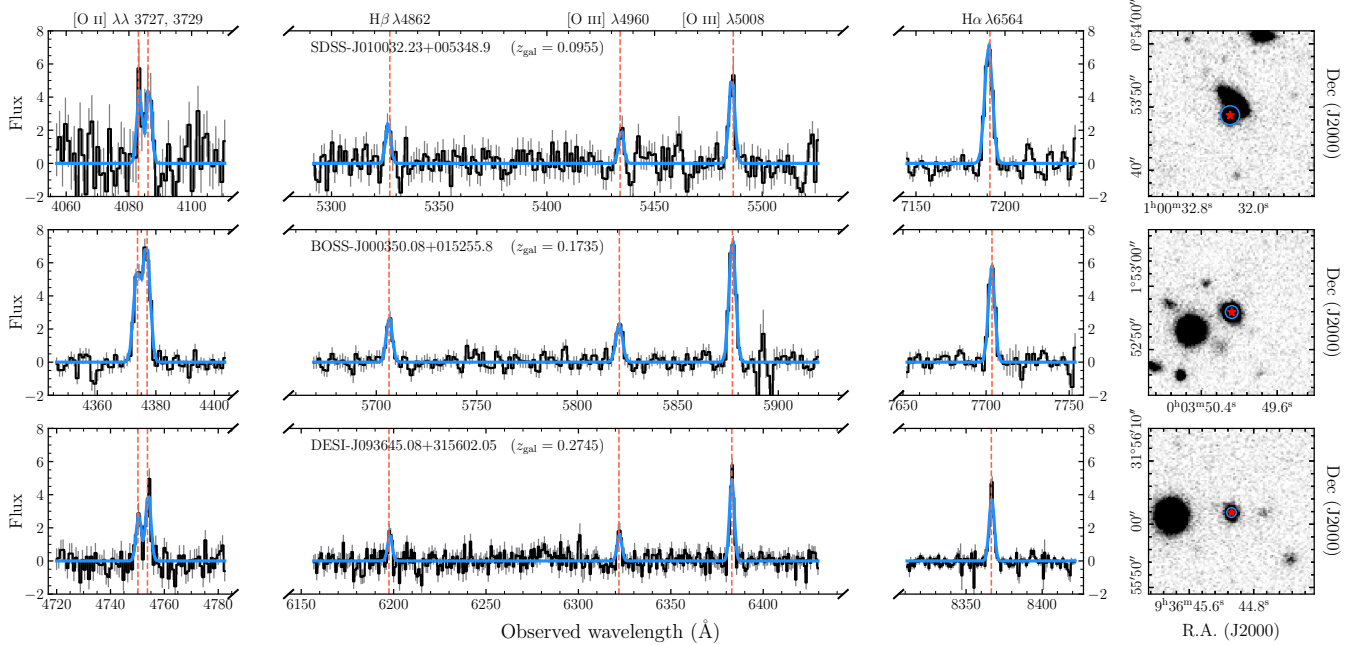


Figure 1. Examples of absorption-agnostic GOTOQs. Each row represents a different quasar observed with SDSS, BOSS, and DESI spectrographs, respectively, from top to bottom. In each horizontal panel: the left plot displays the nebular emission lines detected in the continuum-subtracted quasar spectra, with the solid blue line representing the Gaussian fits to the nebular emission lines, and the right plot shows a composite *griz* band DESI-LIS image of the quasar field, with the quasar marked by a red star and the observing fiber outlined by a blue circle. Flux scales in the left panels are in units of 10^{-17} ergs s^{-1} cm^{-2} $\text{\AA}^{-1}$.

features. The inliers are interpolated and smoothed using a running median, ultimately producing an adequate quasar continuum. We then subtract this continuum to obtain the continuum-subtracted quasar spectrum.

To search for nebular emission lines from a foreground galaxy superimposed on the continuum-subtracted quasar spectrum, we first mask ± 3000 km s^{-1} around the prominent quasar emission lines to ensure that the identified emission features are not due to the quasar itself. Subsequently, we smooth the continuum-subtracted quasar spectrum by 3 pixels to enhance the prominence of any potential emission lines from the foreground galaxy. A peak-finding algorithm is then applied to the smoothed spectrum to identify emission features at 2σ significance and calculate the wavelength ratios for all possible pairs of these features. We then assess how many of these ratios are consistent within a rest-frame velocity offset of 100 km s^{-1} with the wavelength ratios of known strong nebular emission lines ([O II] $\lambda 3728$, H β $\lambda 4862$, [O III] $\lambda 4960$, [O III] $\lambda 5008$, and H α $\lambda 6564$). If there are at least three emission-line pairs that match these wavelength ratios, we classify the quasar spectrum as a potential GOTOQ candidate. Finally, each GOTOQ candidate is visually inspected and confirmed to contain at least three nebular emission lines, each detected with a significance greater than or equal to 3σ , to verify the presence of a foreground galaxy on top of the quasar. Although, in principle, our search method enables the detection of GOTOQs over the full redshift range of $z < z_{qso}$, we restrict our analysis to $z < 1$ to ensure that the [O III] $\lambda 5008$ line remains within the observable spectral window, thereby guaranteeing coverage of at least three prominent emission lines.

To search for GOTOQs, we apply our search pipeline to the quasar spectra available in the SDSS-DR16 and DESI-EDR surveys. The SDSS-DR16 quasar catalog (B. W. Lyke et al. 2020) includes approximately 0.75 million unique quasars,

encompassing nearly 1 million observed spectra across various epochs. The DESI-EDR survey, on the other hand, covering only 2% of the DESI sky, contains about 95,000 quasar spectra. Therefore, we search for GOTOQs in almost 1.1 million quasar spectra toward more than 0.8 million quasars. Our search identified 681 GOTOQs from SDSS-DR16 and 56 GOTOQs from the DESI-EDR survey. With six overlaps, the combined sample comprises 731 unique GOTOQs spanning the redshift range of $0.0045 \leq z \leq 0.9782$ with a median value of 0.33. In Figure 1, we show three examples of absorption-agnostic GOTOQs. Each row in this figure represents a different quasar observed with SDSS (fiber diameter of 3"), BOSS (fiber diameter of 2"), and DESI (fiber diameter of 1.5") spectrographs, respectively, from top to bottom. In each horizontal panel, the left plot displays the nebular emission lines detected in the continuum-subtracted quasar spectra and the right plot shows a composite *griz* band DESI Legacy Imaging Survey (LIS) image of the quasar field, with the quasar marked by a red star and the observing fiber outlined by a blue circle.

2.2. Absorption-selected Searches of GOTOQs

The efficiency of the absorption-agnostic searches reduces beyond $z \gtrsim 0.4$ as H α , the most prominent nebular emission line in the optical band, gets redshifted beyond the observable window of ground-based spectrographs. In addition, a significant fraction of the spectral region containing the H β and [O III] emission lines for systems at $z > 0.4$ is affected by atmospheric absorption and strong sky-line residuals. Fortunately, at $z > 0.4$, Mg II $\lambda\lambda 2796, 2803$ gets redshifted within the observable window of ground-based telescopes. The Mg II $\lambda\lambda 2796, 2803$ absorption lines found in the spectra of background quasars, originating from the halos of foreground galaxies, are excellent tracers of cold gas ($T \sim 10^4$ K) with a

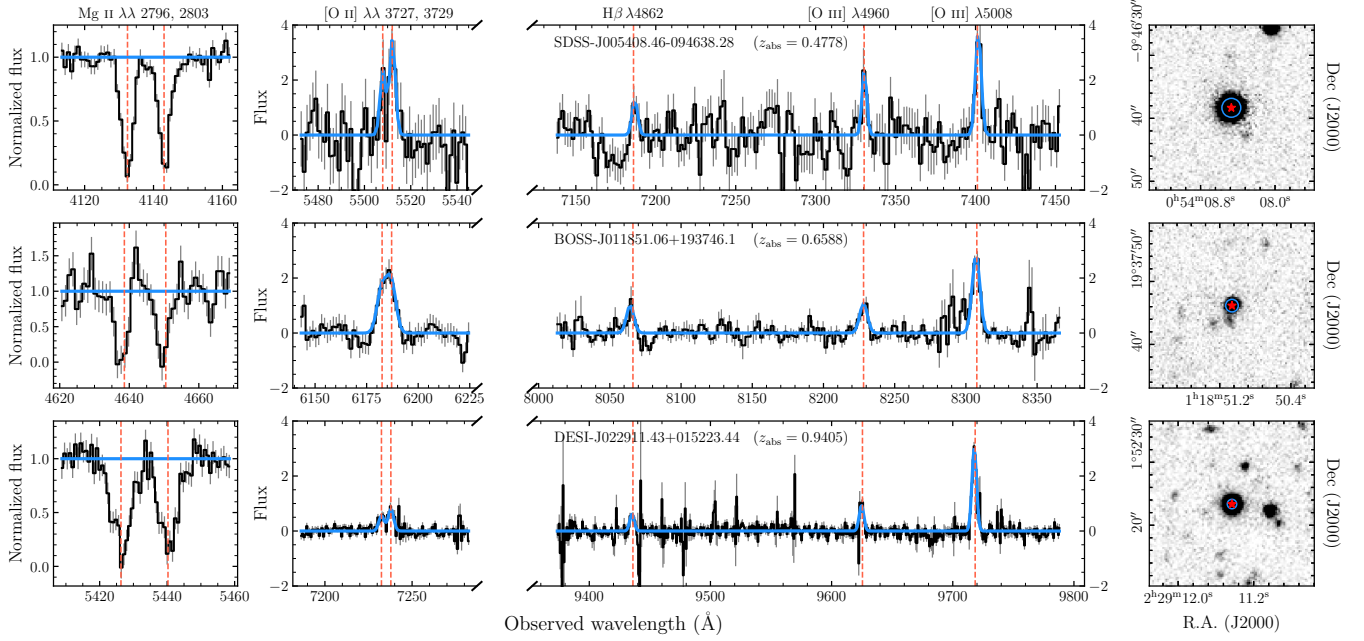


Figure 2. Examples of absorption-selected GOTOQs. Each row represents a different quasar observed with SDSS, BOSS, and DESI spectrographs, respectively, from top to bottom. In each horizontal panel: the left plot displays the intervening Mg II absorption in a continuum-normalized spectrum; the middle plot highlights the nebular emission lines detected in the continuum-subtracted quasar spectra, corresponding to the Mg II absorption with the solid blue line representing the Gaussian fits to the nebular emission lines; the right plot shows a composite *griz* band DESI-LIS image of the quasar field, with the quasar marked by a red star and the observing fiber outlined by a blue circle. Flux scales in the middle panels are in units of 10^{-17} ergs s^{-1} cm^{-2} $\text{\AA}^{-1}$.

near-unity covering fraction within $D \lesssim 10$ kpc of star-forming galaxies (A. Anand et al. 2021).

To search for GOTOQs using this method, we begin with a quasar spectrum that contains an intervening Mg II absorption. We then obtain the continuum-subtracted spectrum as described in the first part of Section 2.1. In this spectrum, we look for [O II], [O III], and $H\beta$ nebular emission lines associated with Mg II absorptions within ± 500 km s^{-1} based on the following criteria: either the [O II] $\lambda\lambda 3726, 3729$ emission is detected with at least 4σ significance, or the [O III] $\lambda\lambda 4960, 5008$ doublets are individually detected with at least 3σ significance, or both the [O II] $\lambda\lambda 3726, 3729$ and [O III] $\lambda 5008$ lines are individually detected with at least 3σ significance. Finally, the spectrum of each selected candidate is visually inspected to confirm it as a GOTOQ system. While our method theoretically allows for the search for GOTOQs over the redshift range of $0.4 \lesssim z \lesssim 1.7$, ensuring that both Mg II absorption and the associated [O II] emission fall within the observable window of the SDSS and DESI spectrographs, we follow R. Joshi et al. (2017) and restrict our searches to $0.36 \leq z \leq 1.1$. This limitation is due to the presence of strong skylines and fringing at higher wavelengths, which are likely to result in a high fraction of false positives.

In the publicly available SDSS Mg II absorption catalogs (A. Anand et al. 2021; G. Zhu & B. Ménard 2013) up to DR16, we search for Mg II absorbers within the redshift range of $z_{\text{abs}} \leq 1.1$. To minimize false detections, we include only those systems where Mg II $\lambda 2796$ lines are detected with a significance of at least 2σ . This criterion results in approximately 88,000 unique Mg II absorption systems toward about 75,000 quasars. Similarly, using the same criterion, the DESI-EDR Mg II absorption catalog (L. Napolitano et al. 2023) yields approximately 6200 Mg II absorption systems toward about 5500 quasars. Therefore, we search for nebular emissions associated with about 94,200 Mg II absorption systems toward

about 80,500 quasars. This resulted in 651 GOTOQs in SDSS and 97 GOTOQs in DESI-EDR. With 15 overlaps, there are 733 unique GOTOQs identified based on the presence of Mg II absorption toward the quasar line of sight spanning the redshift range of $0.3626 \leq z \leq 1.0866$ with a median value of 0.73. For about 85% of the cases, the GOTOQs are selected purely based on the [O II] emission line. In Figure 2, we show three examples of absorption-selected GOTOQs. In this figure, each row represents a different quasar observed with SDSS, BOSS, and DESI spectrographs, respectively, from top to bottom. In each horizontal panel, the left plot displays the intervening Mg II absorption in a continuum-normalized spectrum, the middle plot highlights the nebular emission lines detected in the continuum-subtracted quasar spectra, corresponding to the Mg II absorption, and the right plot shows a composite *griz* band DESI-LIS image of the quasar field, with the quasar marked by a red star and the observing fiber outlined by a blue circle.

2.3. Final Combined Sample

By merging our absorption-agnostic and absorption-selected searches, we identified 119 overlapping cases. Consequently, our final sample includes 1345 unique GOTOQs within the redshift range of $0.0045 \leq z \leq 1.0866$, with a median redshift of 0.54, sourced from the SDSS-DR16 and DESI-EDR surveys, with a typical redshift uncertainty of 70 km s^{-1} . This constitutes by far the largest sample of GOTOQs ever compiled, more than quadrupling the number of previously known GOTOQs. In Figure 3, we show the redshift distribution of the absorption-agnostic (blue histogram) and absorption-selected (green histogram) GOTOQs. The distribution for the combined sample is depicted in gray. It is evident from the figure that absorption-agnostic searches are more effective at identifying low-redshift GOTOQs ($z \lesssim 0.4$), whereas absorption-selected searches dominate the discovery

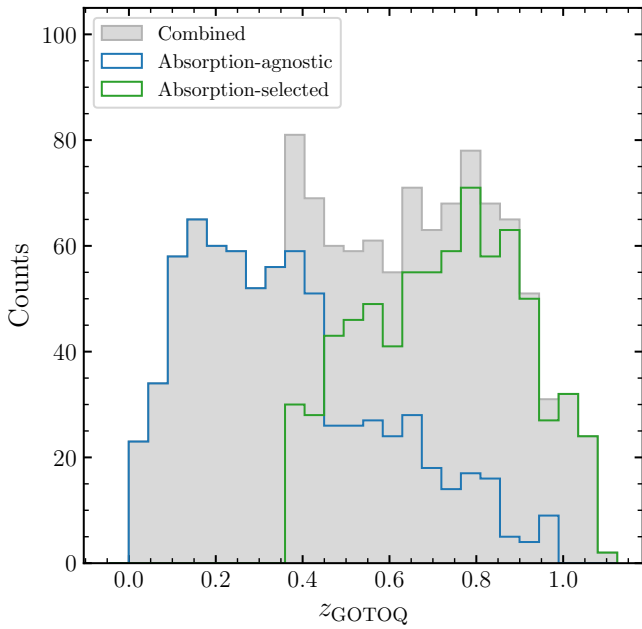


Figure 3. The redshift distribution of the absorption-agnostic (blue histogram) and absorption-selected (green histogram) GOTOQs. The distribution for the combined sample is depicted in gray.

Table 1
Summary of the Final Combined GOTOQ Sample

Survey	N_{GOTOQs}	z Range	$L_{[\text{O II}]}$ Range (erg s^{-1})
(1)	(2)	(3)	(4)
DESI-EDR	140	0.0595–1.0849	7.90×10^{38} – 4.74×10^{41}
BOSS	1016	0.0045–1.0866	7.11×10^{36} – 1.89×10^{42}
SDSS	289	0.0206–1.0628	2.48×10^{38} – 2.06×10^{42}

Note. Column (1) lists the survey or instrument from which the GOTOQs were identified, column (2) gives the number of GOTOQs contributed by each survey, column (3) provides the corresponding redshift range of the GOTOQs, and column (4) lists the range of fiber-measured [O II] emission-line luminosities for the GOTOQs.

of higher-redshift systems ($0.4 \lesssim z \lesssim 1$). As discussed earlier, this is partly due to the stringent criteria adopted in our absorption-agnostic search, as well as contamination from atmospheric absorption and sky-line residuals.

Table 1 summarizes the number of GOTOQs identified from each spectrograph and their corresponding sample properties. We identify 140 GOTOQs from DESI-EDR, while the BOSS and SDSS spectrographs contribute 1016 and 289 GOTOQs, respectively. Since 82 systems are detected in both the BOSS and SDSS spectroscopic datasets, the combined SDSS-DR16 sample comprises 1223 unique GOTOQs. Furthermore, 18 of these systems are also present in DESI-EDR. After accounting for these duplicates, our final catalog contains a total of 1345 unique GOTOQs.

3. Analysis and Results

For each identified GOTOQ, we estimate the emission-line parameters by fitting the detected nebular lines using Gaussian profiles. Since the [O II] doublet is often unresolved in low-resolution spectrographs like SDSS, we model the [O II] emission with a double Gaussian, tying the redshifts and line

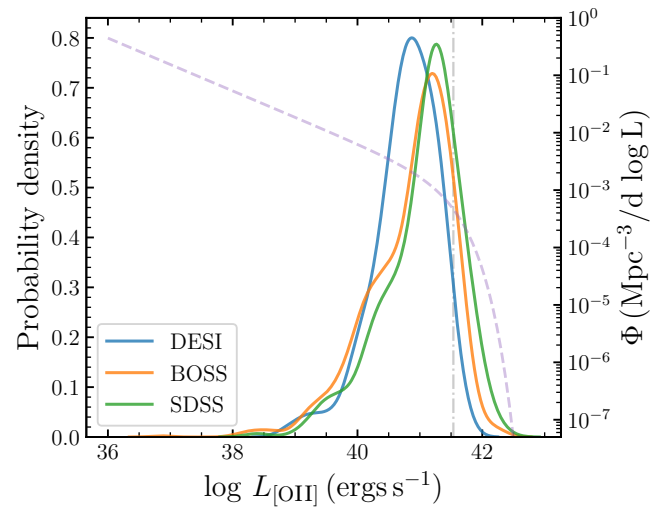


Figure 4. The kernel density estimations of [O II] line luminosities (considering only detections and excluding upper limits) for the GOTOQs in our sample are shown from DESI (blue), BOSS (orange), and SDSS (green). For comparison, the [O II] luminosity function of field galaxies at the median redshift of our GOTOQ sample, $z = 0.54$, is shown as a dashed purple curve. The brown vertical dotted-dashed line marks the characteristic [O II] luminosity ($L_{[\text{O II}]}$) at $z = 0.54$ (J. Comparat et al. 2016).

widths while allowing the line ratio to vary within the range of 0.34–1.5 (D. E. Osterbrock & G. J. Ferland 2006). The $\text{H}\beta$ $\lambda 4862$, [O III] $\lambda \lambda 4960, 5008$, and $\text{H}\alpha$ $\lambda 6564$ lines are each modeled with a single Gaussian. In Figures 1 and 2, we also present the best-fitting Gaussian profiles (shown in blue) for the nebular emission lines from foreground galaxies present on top of the background quasar spectra. The integrated fluxes for the nebular lines are then measured based on the fitted Gaussian parameters. In the following, we examine the emission-line properties of GOTOQs and compare them with those derived from absorption lines, as well as with the properties of field galaxies.

3.1. The [O II] Line Luminosity: Fiber Effects

In Figure 4, we show the distribution of the measured [O II] line luminosities captured within the fiber (considering only detections and excluding upper limits) for the GOTOQs in our combined sample from DESI (blue), BOSS (orange), and SDSS (green). For comparison, the [O II] luminosity function of field galaxies at the median redshift of our GOTOQ sample, $z = 0.54$, is shown as a dashed purple curve. The brown vertical dotted-dashed line marks the characteristic [O II] luminosity at $z = 0.54$ (J. Comparat et al. 2016). The [O II] line luminosity for the clear detections in the final combined sample of GOTOQs varies from $7.11 \times 10^{36} \text{ erg s}^{-1}$ to $2.06 \times 10^{42} \text{ erg s}^{-1}$ with a median value of $1.04 \times 10^{41} \text{ erg s}^{-1}$. In cases where the same GOTOQ was observed with multiple spectrographs, we include the measured line luminosities from all instruments. If a GOTOQ was observed multiple times with the same spectrograph, we consider the [O II] line luminosity from the co-added spectra. However, line luminosities of GOTOQs in general are severely affected by fiber effects and dust attenuation, and thus what we measure should be considered as the lower limits.

To illustrate the effects of fiber size, Figure 5 shows the [O II] line luminosities of the GOTOQs as a function of redshift. Regardless of fiber size, a strong correlation is

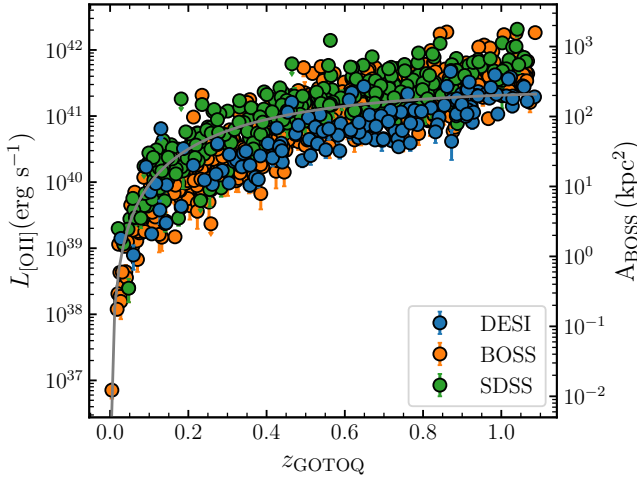


Figure 5. The [O II] line luminosities of the GOTOQs captured within the fibers of DESI (blue), SDSS (green), and BOSS (orange) spectrographs are plotted against their redshift. The solid gray line corresponds to the physical area a BOSS fiber covers as a function of redshift.

observed between the measured [O II] luminosities and the redshifts of the GOTOQs. A Kendall τ rank correlation test, including upper limits (T. Isobe et al. 1986), yields a correlation coefficient of $\tau_r = 0.677$ with a p -value of essentially zero, indicating a statistically strong and significant trend. However, this apparent evolution in the [O II] line luminosity is not intrinsic, but rather a consequence of the increasing projected area of the fiber with redshift (in addition to the typical trend expected for a flux-limited sample). The solid gray line in Figure 5 illustrates this evolution, showing that the increase in [O II] luminosity basically tracks the growth of the projected area within the fiber.

3.2. Nebular Line Ratios

While the measured line luminosities of the GOTOQs are severely affected by the fiber effects, nebular line ratios, in principle, characterize the GOTOQs better as the line ratios are expected to be least affected by the fiber effects.

3.2.1. $H\alpha/H\beta$ Line Ratio

The $H\alpha/H\beta$ line ratio is sensitive to dust and serves as a diagnostic of dust attenuation in the ISM (particularly in newly star-forming regions) of galaxies. In the absence of dust, this ratio is expected to be approximately 2.86. However, in the presence of dust, a lower $H\beta/H\alpha$ is observed as the dust attenuates the $H\beta$ line more than the $H\alpha$ line—a phenomenon known as the Balmer decrement (D. E. Osterbrock & G. J. Ferland 2006). In Figure 6, we present the redshift evolution of the $H\alpha/H\beta$ line ratios for the GOTOQs in our sample where the $H\alpha$ line is covered, i.e., $z \lesssim 0.5$. A Kendall τ rank correlation test between z_{GOTOQ} and the $H\alpha/H\beta$ ratio, accounting for both upper and lower limits, yields a correlation coefficient of $\tau_r = 0.02$ with a p -value of 0.58, indicating no redshift evolution of the ratio over the redshift range of $0 < z \lesssim 0.5$. Excluding the lower and the upper limits, the median value of the $H\alpha/H\beta$ line ratio for the GOTOQs is $3.33^{+1.57}_{-1.09}$, with the errors corresponding to the 34th percentiles from the median. Assuming the D. Calzetti et al. (2000) extinction curve, this corresponds to the median dust extinction coefficient of $A_V \approx 0.53^{+1.33}_{-1.38}$ mag.

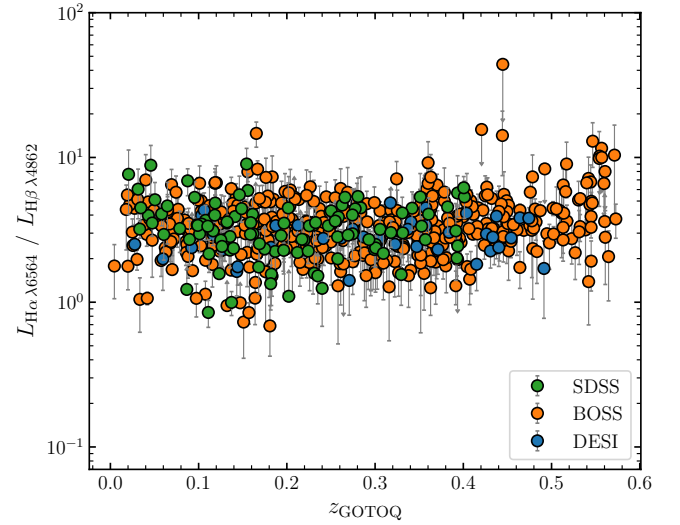


Figure 6. The redshift evolution of the $H\alpha/H\beta$ line ratios for the GOTOQs in our sample, where the $H\alpha$ line is covered.

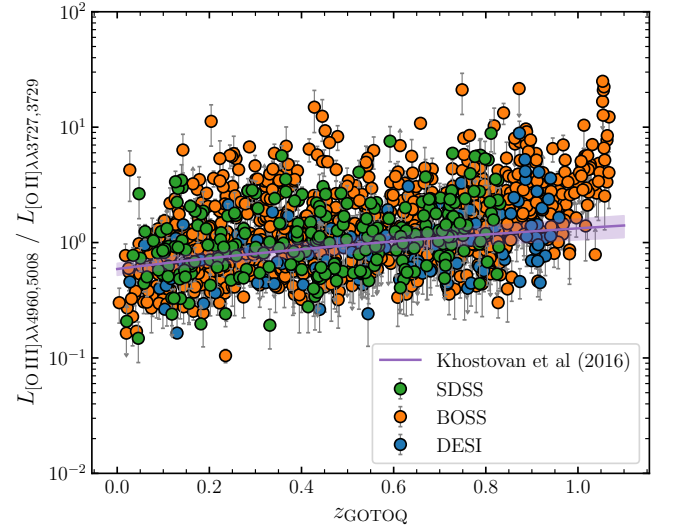


Figure 7. The [O III]/[O II] line ratios for the GOTOQs in our sample. The green, orange, and blue points correspond to the GOTOQs detected with SDSS, BOSS, and DESI spectrographs, respectively. The redshift evolution of the [O III]/[O II] ratio for the field galaxies, as modeled by a power-law fit from A. A. Khostovan et al. (2016), is represented by the solid magenta line, with the shaded region indicating the 1σ uncertainty.

3.2.2. [O III]/[O II] Line Ratio

The [O III]/[O II] line ratio is sensitive to the hardness of the ionizing radiation field. Observational studies have consistently reported an increase in this ratio for star-forming galaxies over the redshift range of $z = 0-5$. This trend suggests that high-redshift galaxies typically exhibit higher ionization parameters, lower metallicities, harder stellar ionizing spectra, and elevated electron densities compared to their local counterparts (L. J. Kewley & M. A. Dopita 2002).

In Figure 7, we show the [O III] $\lambda\lambda 4960, 5008$ / [O II] $\lambda\lambda 3727, 3729$ line ratios of the GOTOQs in our sample as a function of redshift. Since [O III] $\lambda 4960$ emission is not detected most of the time, we scale the [O III] $\lambda 5008$ luminosity by a factor of 4/3, since the $\lambda 5008$ line is expected to be three times stronger than the $\lambda 4960$ line (M. E. Galavis et al. 1997). The green, orange, and blue points indicate

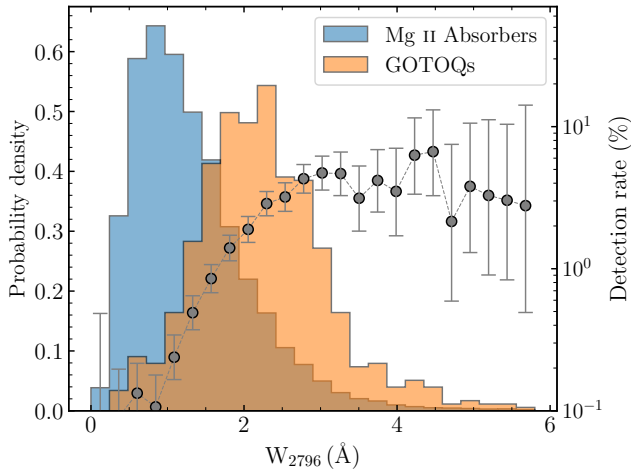


Figure 8. Normalized rest-frame equivalent width distributions of Mg II absorption systems from the SDSS and DESI-EDR catalogs (blue), compared with those for the GOTOQs (orange). The absorption-selected GOTOQs were specifically searched for corresponding systems in these catalogs, and the gray circles correspond to the fraction of GOTOQs in each REW bin. The error bars on the detection rates correspond to the 95% Wilson confidence intervals.

GOTOQs detected with SDSS, BOSS, and DESI spectra, respectively. For comparison, the redshift evolution of the [O III]/[O II] ratio for field galaxies, modeled with a power-law fit by A. A. Khostovan et al. (2016), is shown as the solid magenta line, with the shaded region marking the 1σ uncertainty. The similarity between the GOTOQ measurements and the field-galaxy trend demonstrates that GOTOQs predominantly select normal star-forming field galaxies, rather than a distinct or unusual population. It is worth noting that, unlike in Figure 5, where the measured line luminosities at a given redshift are systematically higher for larger fibers and there is minimal overlap between the SDSS and DESI measurements, Figures 6 and 7 show that the line ratios span overlapping regions across different spectrographs. This indicates that, in contrast to absolute line luminosities, line ratios are largely insensitive to fiber size effects.

3.3. Absorption-selected GOTOQs: The W_{2796} Distribution

The Mg II $\lambda 2796$ rest-frame equivalent widths (W_{2796}) of the GOTOQs in our absorption-selected sample range from 0.31 to 5.90 Å, with a median value of 2.16 Å. In comparison, the Mg II absorption systems compiled from SDSS-DR16 and DESI-EDR, over the parent sample from which the absorption-selected searches for GOTOQs were performed, have a median W_{2796} of 1.16 Å. Figure 8 presents the normalized distributions of W_{2796} , showing the SDSS and DESI-EDR absorbers in blue and the GOTOQs in orange. It is evident from the figure that the W_{2796} distribution tends to be systematically higher when nebular emission lines are detected. A Kolmogorov–Smirnov test between the W_{2796} of the absorption-selected GOTOQs and the parent Mg II absorber population confirms that the two are statistically distinct (with a p -value of almost zero). We confirm this result even when we consider SDSS or DESI-EDR systems separately. This is in line with the earlier finding of R. Joshi et al. (2017), who showed the distribution of W_{2796} in GOTOQs is consistent with what has been seen for Milky Way sight lines.

3.3.1. GOTOQ Detection Rate As a Function of W_{2796}

Figure 8 also shows the detection rate of nebular emission as a function of W_{2796} (gray circles). The GOTOQ detection fraction increases steadily up to $W_{2796} \approx 3$ Å, where it reaches a peak of roughly 5%, and then remains nearly flat at larger equivalent widths. If one were to rely solely on the empirical anticorrelation between W_{2796} and impact parameter (H.-W. Chen et al. 2010), values of $W_{2796} > 3$ Å would typically correspond to $D \leq 5$ kpc. In such cases, the [O II] emission from the host galaxy should fall well within the spectroscopic fiber. The persistently low detection rate of [O II] emission, even among systems with very strong Mg II absorption, therefore likely reflects several contributing factors: (i) significant scatter in the W_{2796} – D relation, as many high- W_{2796} systems may arise in nonisolated or group environments (see L. K. Guha et al. 2022, 2024); (ii) a nonnegligible contribution from passive galaxies that exhibit large W_{2796} but weak or no nebular emission; and (iii) observational biases that hinder the detection of faint emission lines superimposed on quasar continua, as discussed by P. Noterdaeme et al. (2010). We return to the W_{2796} – D relation for our GOTOQ sample in Section 3.4.

3.3.2. Correlation between W_{2796} and $L_{[\text{O II}]}$

We now turn to the correlation between the [O II] line luminosity of the absorption-selected GOTOQs and the W_{2796} measured along the quasar sight line. A strong correlation between these two quantities has previously been reported in stacking analyses of Mg II absorption systems (P. Noterdaeme et al. 2010; B. Ménard et al. 2011). R. Joshi et al. (2017) demonstrated that such a correlation could arise from the nebular emission-line detection rate being dependent on W_{2796} and not necessarily due to a physical connection between star formation rate (as probed by [O II] line) and gas flows (as probed by W_{2796}). They found a large scatter in $L_{[\text{O II}]}$ for a given W_{2796} and vice versa and reported a weak 3σ correlation between the two quantities.

In Figure 9, we plot the [O II] line luminosities of the GOTOQs against the rest-frame equivalent widths of the Mg II $\lambda 2796$ line, with points color coded by spectrograph. At fixed W_{2796} , the observed $L_{[\text{O II}]}$ spans a wide range, and conversely a given $L_{[\text{O II}]}$ corresponds to a broad distribution of W_{2796} . Owing to fiber losses, the [O II] luminosities measured from SDSS and DESI spectra show little overlap, illustrating how aperture effects can strongly bias the observed luminosity distribution. Despite this, among the direct detections we find a weak but statistically significant positive correlation between $L_{[\text{O II}]}$ and W_{2796} , with a Spearman rank coefficient of $r_s = 0.25$ and a near-zero p -value. The trend is largely driven by the scarcity of low [O II]-luminosity systems at high equivalent widths. While this could very well be driven by fiber-related effects, if true, this correlation can provide important physical insight.

For example, since W_{2796} primarily traces the number of absorbing components and their velocity dispersion rather than column density, it is natural to speculate that the largest equivalent widths arise in systems hosting star formation-driven outflows, whose strength correlates with nebular emission-line luminosity. However, recent work by A. Fernández-Figueroa et al. (2025), comparing down-the-barrel absorption with quasar sight lines in strong Mg II absorbers, suggests that a significant

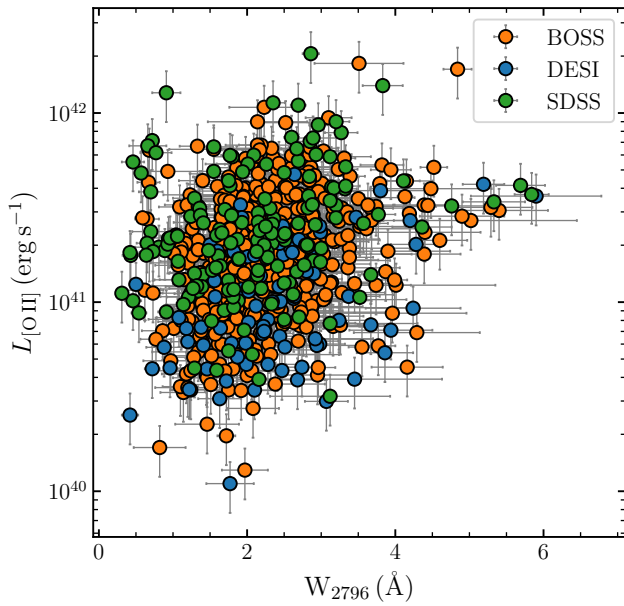


Figure 9. The [O II] line luminosity of the GOTOQs vs. the rest-frame equivalent width of the Mg II $\lambda 2796$ line for the absorption-selected sample. The blue, green, and orange points correspond to the GOTOQs observed with DESI, SDSS, and BOSS spectrographs, respectively.

fraction of the absorbing components may instead be associated with infalling gas. Such inflow signatures are rarely seen in field galaxies (e.g., K. H. R. Rubin et al. 2014). A larger, statistically uniform sample of strong Mg II absorbers with both emission—and absorption line information will therefore be required to disentangle the relative roles of inflows and outflows in producing large W_{2796} values.

An alternative explanation could arise from the strong anticorrelation between W_{2796} and impact parameter (D) seen in the general Mg II absorber population (coupled with the fiber loss issues discussed above): high- W_{2796} systems would, on average, have smaller D and therefore suffer less fiber loss, leading to a correlation between W_{2796} and $L_{[O II]}$. In the following section, however, we demonstrate that this W_{2796} – D anticorrelation flattens out for GOTOQs, implying that the observed W_{2796} – $L_{[O II]}$ correlation may not be driven solely by impact parameter effects.

3.4. Absorption-selected GOTOQs: W_{2796} versus Impact Parameters

Through spectroscopic follow-up of GOTOQs, L. K. Guha & R. Srianand (2024) demonstrated that, in many cases, the impact parameters of GOTOQs can be reliably determined directly from broadband photometry. They showed that GOTOQs with extended photometric counterparts (see Figure 1 of L. K. Guha & R. Srianand 2023) whose photometric redshifts agree within 2σ of the Mg II absorption redshifts are indeed the galaxies responsible for the absorption. Using this approach, impact parameters were determined for 74 GOTOQs (L. K. Guha & R. Srianand 2023) out of a parent sample of 198 compiled by R. Joshi et al. (2017). In this work, we adopt the same method to identify foreground galaxies and measure their impact parameters.

Based on visual inspection of the absorption-selected GOTOQs in our absorption-centric sample using DESI-LIS

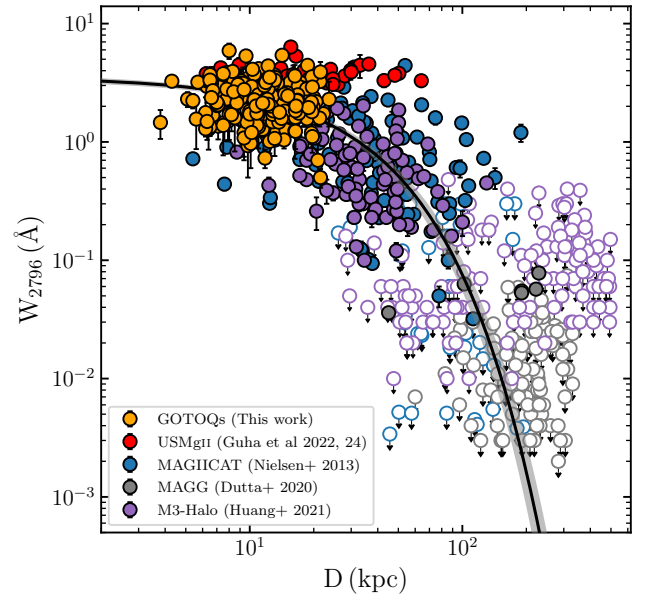


Figure 10. W_{2796} – D anticorrelation for isolated galaxies. Orange points show the GOTOQs with photometric extensions from this work, red points represent the USMgII absorbers (L. K. Guha et al. 2022, 2024), blue points are from the MAGIICAT survey (N. M. Nielsen et al. 2013), gray points are from the MAGG survey (R. Dutta et al. 2020), and the purple points are from Y.-H. Huang et al. (2021). Filled circles denote detections, while open circles indicate upper limits in W_{2796} from nondetections. The best-fit log-linear relation is shown as a solid black line, with the shaded gray band representing the 1σ uncertainty. The GOTOQ sample densely populates the previously sparsely sampled regime at $D \lesssim 20$ kpc.

images, we identified the foreground galaxies and measured their impact parameters from photometric redshifts for 267 systems, corresponding to about 36.5% of the sample. This identification rate is broadly consistent across the different spectroscopic datasets and does not vary significantly between the SDSS, BOSS, and DESI subsamples. The derived impact parameters range from 3.8 to 23.6 kpc, with a median value of 11.6 kpc. A Spearman rank correlation test between W_{2796} and D for the GOTOQs yields a rank correlation coefficient of $r_s = -0.05$ with a p -value of 0.43, indicating no significant (anti-)correlation. This confirms the flattening of W_{2796} at small D , as reported in previous studies (G. G. Kacprzak et al. 2013; L. K. Guha & R. Srianand 2023).

In Figure 10, orange points represent the GOTOQs with photometric extensions from this work, red points correspond to the USMgII absorbers (L. K. Guha et al. 2022, 2024), blue points are from the MAGIICAT survey (N. M. Nielsen et al. 2013), gray points are from the MAGG survey (R. Dutta et al. 2020), and the purple points are from Y.-H. Huang et al. (2021). Filled circles denote detections, while open circles represent 3σ upper limits from nondetections.

The observed W_{2796} – D anticorrelation has traditionally been characterized using either a power-law relation (e.g., Y.-H. Huang et al. 2021) or a log-linear fit (e.g., N. M. Nielsen et al. 2013). However, studies focusing on low-impact parameter systems (G. G. Kacprzak et al. 2013) and exceptionally strong absorbers such as USMgII systems (L. K. Guha et al. 2022, 2024) have shown that this anticorrelation flattens at small impact parameters ($D \lesssim 20$ kpc). Moreover, L. K. Guha et al. (2024) demonstrated through a nonparametric rank correlation analysis that the anticorrelation effectively disappears for absorbers with $W_{2796} > 1.5$ Å. Given that GOTOQs predominantly probe very

small impact parameters and are associated with strong Mg II absorption, these systems lie precisely in the regime where the conventional W_{2796} - D anticorrelation is expected to weaken or vanish. Consistent with this picture, our nonparametric rank correlation analysis does not reveal any statistically significant anticorrelation. We therefore adopt a log-linear parameterization rather than a single power-law model. Unlike a power-law fit, which inherently enforces a strong monotonic decline even at small impact parameters, the log-linear form provides a more physically motivated description of the behavior observed in this regime.

We perform a log-linear fit between W_{2796} and D for the GOTOQs, incorporating upper limits following the prescription of K. H. R. Rubin et al. (2018) and R. Dutta et al. (2020). The likelihood function is defined as the product of the likelihoods for detections and nondetections,

$$\mathcal{L}(W) = \left(\prod_{i=1}^n \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp \left\{ -\frac{1}{2} \left[\frac{W_i - W(D_i)}{\sigma_i} \right]^2 \right\} \right) \times \left(\prod_{i=1}^m \int_{-\infty}^{W_i} \frac{dW'}{\sqrt{2\pi\sigma_i^2}} \exp \left\{ -\frac{1}{2} \left[\frac{W' - W(D_i)}{\sigma_i} \right]^2 \right\} \right),$$

where W_i and D_i are the W_{2796} and impact parameter of the i th measurement, respectively. The total error term is defined as $\sigma_i = \sqrt{\sigma_{\text{int}}^2 + \sigma_{\text{mi}}^2}$, accounting for both the intrinsic scatter, σ_{int} , and the measurement uncertainty, σ_{mi} . $W(D_i)$ denotes the model-predicted W_{2796} at D_i .

The resulting best-fit relation is

$$\log(W_{2796}/\text{\AA}) = (-0.017 \pm 0.002)(D \text{ kpc}^{-1}) + (0.547 \pm 0.019), \quad (1)$$

with an intrinsic scatter of $\sigma_{\text{int}} = 0.965 \pm 0.037 \text{ \AA}$. The best-fit log-linear relation is shown as a solid black line in Figure 10, with the shaded gray region representing the 1σ uncertainty.

In summary, the GOTOQ sample densely populates the previously sparsely sampled regime at $D \lesssim 20$ kpc, providing an unprecedented view of the behavior of Mg II absorption at small Galactocentric distances. The observed flattening of the canonical W_{2796} - D anticorrelation in this regime indicates that the cool, metal-enriched gas traced by Mg II becomes increasingly saturated toward the inner halo. This smooth transition from the outer CGM to extra-planar gas, and ultimately the ISM, suggests a continuous distribution of cold gas across these regions, rather than a sharp boundary. Our results therefore point to a coherent multiphase gas structure extending from the extended halo down to the disk-halo interface, with GOTOQs uniquely revealing this continuity at kiloparsec scales.

3.5. Absorption-agnostic GOTOQs: Mg II Gas Covering Fractions at $D \lesssim 20$ kpc

The Mg II covering fraction (f_c) is defined as the ratio of sight lines exhibiting Mg II absorption above a specified rest-equivalent width (REW) threshold to the total number of sight lines. As expected, the covering fraction of cold gas traced by Mg II decreases rapidly with increasing impact parameter for isolated galaxies (R. Dutta et al. 2020; A. Anand et al. 2021; M. Cherrey et al. 2025), starting from ~ 20 kpc. Directly probing the Mg II covering fraction at smaller separations

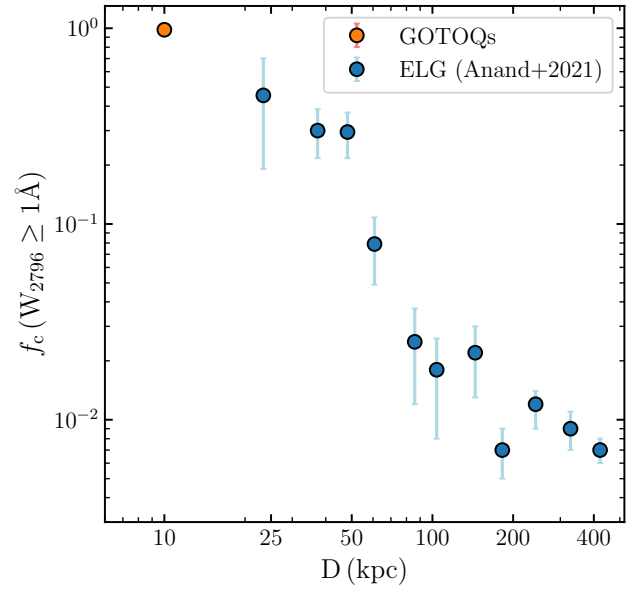


Figure 11. Mg II gas covering fraction around the ELGs as a function of the distances. Orange point corresponds to the GOTOQs, whereas the blue points are taken from A. Anand et al. (2021).

($D < 20$ kpc) has been challenging, since most quasar-galaxy pairs at such small angular separations have historically been identified through the very absorption features they are used to study. This limitation arises primarily because the bright background quasars often outshine their comparatively faint foreground galaxies, making independent identification difficult.

With our absorption-agnostic sample, we are now able to constrain, for the first time, the Mg II covering fraction below $D \lesssim 20$ kpc. Since the GOTOQs with photometric extensions have a median impact parameter of 11.6 kpc, and those without detectable extensions are likely to lie at even smaller separations, we treat our sample as probing the Mg II gas covering fraction over $0 < D \lesssim 20$ kpc, with an effective median separation of ≈ 10 kpc. To achieve this, we identified quasar sight lines in which the Mg II $\lambda 2796$ transition lies within the spectral coverage and for which a Mg II absorption line with an REW of 1 Å would be detectable at a significance of at least 3σ , given the observed signal-to-noise (SNR). This selection yielded 113 quasar sight lines. Mg II absorption was detected with $W_{2796} \geq 1 \text{ \AA}$ in all but two cases (SDSS J220312.24+183446.4 with $z_{\text{gal}} = 0.6583$ where no Mg II absorption (3σ upper limit of $W_{2796} \leq 0.6 \text{ \AA}$) is detected, and SDSS J104223.54+092708.2 with $z_{\text{gal}} = 0.5922$ where $W_{2796} = 0.59 \pm 0.15 \text{ \AA}$), resulting in an estimated Mg II gas covering fraction of $f_c = 98.2^{+1.3}_{-4.5}\%$ (95% Wilson confidence interval) for the REW threshold of 1 Å and $D < 20$ kpc. In Figure 11, we show the Mg II gas covering fraction with an REW threshold of 1 Å around the emission-line galaxies (ELGs) as a function of the projected physical distances. The orange point corresponds to the GOTOQs, whereas the blue points are taken from A. Anand et al. (2021), who studied Mg II gas covering fraction by cross-correlating $\approx 200,000$ ELGs and the Mg II absorption systems present in the background quasar spectra from the SDSS-DR16 over the redshift range of $0.5 < z < 1.0$.

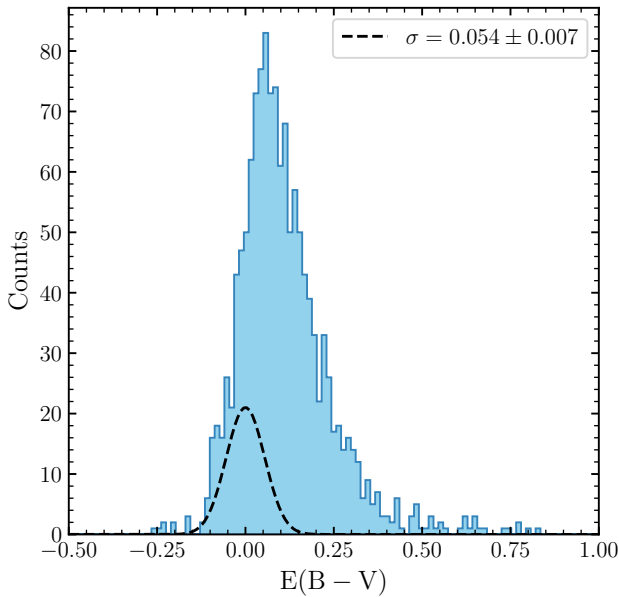


Figure 12. Histogram of the line-of-sight reddening of background quasars caused by the foreground galaxies, assuming an SMC-like extinction curve. The presence of negative $E(B - V)$ values indicates possible systematic uncertainties of approximately 0.05 mag arising from quasar-to-quasar SED variations. This uncertainty is illustrated by the dashed black Gaussian curve centered at $E(B - V) = 0$, with a width of $\sigma = 0.054$.

3.6. Line-of-sight Reddening

It is well established that dust associated with foreground galaxies along the quasar line of sight can cause the quasar to appear redder. Quantifying this reddening is essential, as such dust-induced bias can influence quasar number counts and their selection in spectroscopic surveys.

We estimate the line-of-sight reddening of background quasars due to the intervening galaxies in the GOTOQ sample assuming the Small Magellanic Cloud (SMC) extinction law (K. D. Gordon et al. 2003) and an average rest-frame spectral energy distribution (SED) of quasars given in J. Selsing et al. (2016). The SMC extinction curve differs markedly from those of the Large Magellanic Cloud (LMC) and the Milky Way, notably lacking the 2175 Å absorption feature. Since this feature can be observed only for GOTOQs at redshifts $z \gtrsim 0.8$, and the majority of our sample lies below this threshold, we adopted the SMC-like extinction curve. Thus, the choice of extinction law has negligible impact on the derived results, as LMC, Milky Way, and SMC extinction curves are similar in the rest wavelength range of interest here. We model the optical spectra of the background quasars using the composite quasar template redshifted to the quasar’s rest frame. The SMC extinction curve was then applied at the redshift of the intervening galaxies, with the V -band extinction (A_V) as the only free parameter, along with a multiplicative scaling factor, following the procedure outlined by R. Srianand et al. (2008). The resultant color excess $E(B - V)$ toward the GOTOQ sight lines ranges from -0.261 to 1.091 with a median value of 0.087 mag (corresponding to a median of $A_V = 0.238$, assuming $R_V = 2.74$).

A histogram of the obtained color excess toward the line of sight of all the GOTOQs in our sample is shown in Figure 12. The presence of negative $E(B - V)$ values indicates possible systematic uncertainties of approximately 0.05 mag arising from quasar-to-quasar SED variations. This uncertainty is

illustrated by the dashed black Gaussian curve centered at $E(B - V) = 0$, with a width of $\sigma \approx 0.05$ mag. Note that the median $E(B - V)$ derived from continuum fitting of the background quasars is substantially smaller than the value inferred from the Balmer decrement (median $A_V \approx 0.53$; see Section 3.2.1). This indicates that, even at low impact parameters, extinction produced by the CGM dust is far less than the dust extinction associated with the star-forming regions traced by the Balmer lines (see Section 3.2.1).

Next, we compare the dust extinction due to the GOTOQs and that due to typical intervening galaxies probed by the Mg II and Ca II absorption systems as well as H I 21 cm absorbers. Previous studies have established a strong correlation between color excess and absorber strength, with $E(B - V)$ increasing with W_{2796} (B. Ménard et al. 2008), empirically described by $E(B - V) = (8.0 \pm 3.0) \times 10^{-4} W_{2796}^{(3.48 \pm 0.30)}$ (J. M. Budzynski & P. C. Hewett 2011). For the median equivalent width of $W_{2796} = 2.15 \text{ Å}$ in our absorption-selected sample, the expected reddening is $E(B - V) \approx 0.012$ mag. In contrast, the GOTOQs sight lines exhibit substantially higher reddening than typical Mg II absorbers, likely because these quasars probe the dusty regions within or near the star-forming disks of their foreground galaxies. The Ca II absorbers, on the other hand, are known to comprise two distinct populations—strong ($W_{3935} \geq 0.7 \text{ Å}$) and weak ($W_{3935} < 0.7 \text{ Å}$). The stronger systems are generally associated with smaller impact parameters and greater dust content (V. Wild et al. 2006). The average reddening for strong Ca II absorbers, $E(B - V) \approx 0.099$, is comparable to that measured for the GOTOQs. Furthermore, L. K. Guha et al. (2025) recently reported a strong correlation between the integrated H I 21 cm optical depth and line-of-sight reddening for GOTOQs, consistent with the trend observed in Galactic sight lines. Based on this relation and assuming a spin temperature of 100 K, GOTOQs in our sample are expected to be damped Ly α absorbers ($N_{\text{HI}} \geq 2 \times 10^{20} \text{ cm}^{-2}$; see also V. P. Kulkarni et al. 2022), indicating that these systems are excellent probes of cold atomic and molecular gas and can provide valuable insights into their cosmic evolution.

We next examine the redshift evolution of the line-of-sight reddening toward the background quasars in the GOTOQ sample. The blue points in Figure 13 show the color excess, $E(B - V)$, measured along each quasar sight line as a function of the redshift of the corresponding foreground galaxy. The orange points represent the median $E(B - V)$ values computed in redshift bins of width $\Delta z = 0.22$, with the vertical error bars indicating the 16th–84th percentile range within each bin. Although the individual measurements exhibit considerable scatter around the median trend, the binned data reveal a clear albeit mild redshift dependence, with the average line-of-sight reddening decreasing at higher redshifts. A Spearman rank correlation test between $E(B - V)$ and z_{GOTOQs} yields a negative correlation ($r_s = -0.18$) with a near-zero p -value, confirming the statistical significance of this trend. This behavior is consistent with that observed for the intervening Mg II absorbers as the dust builds up in galaxies with time (L. Napolitano et al. 2025).

3.7. Composite GOTOQs Spectrum: Detection of Diffuse Interstellar Bands

Diffuse interstellar bands (DIBs) are generally weak optical or near-infrared absorption features that are widely attributed to large carbonaceous molecules or molecular ions. In Galactic

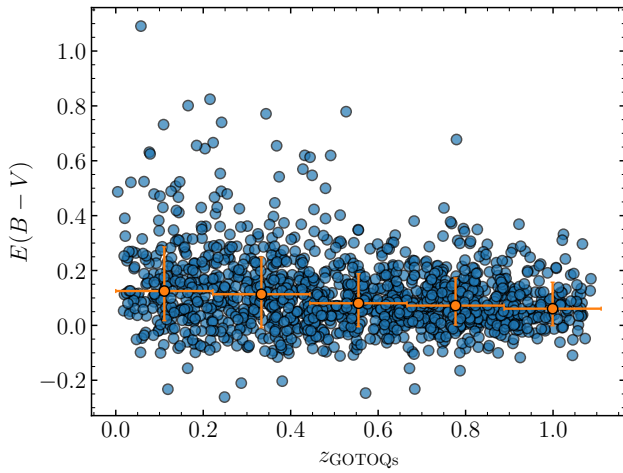


Figure 13. Redshift evolution of the line-of-sight reddening toward quasars caused by the foreground galaxies in the GOTOQ sample. The orange points indicate the median $E(B - V)$ values computed in redshift bins of width $\Delta z = 0.22$, while the error bars represent the 16th–84th percentile range within each bin.

sight lines, their strengths show a correlation, albeit with significant scatter, with the dust column density commonly expressed through the color excess, $E(B - V)$. Some of the strongest bands, particularly the broad $\lambda 4428$ feature, have long been used as empirical tracers of diffuse, dust-rich gas (G. H. Herbig 1995; J. Kos & T. Zwitter 2013). The $\lambda 4428$ band is both strong and broad, which makes it relatively easy to detect in high signal-to-noise spectra of reddened stars, although its width introduces uncertainties in the measurement of its centroid and profile.

Searches for DIBs beyond the Milky Way have revealed that several bands are present in nearby galaxies such as the LMC, SMC, M31, and M33 (P. Ehrenfreund et al. 2002; M. A. Cordiner et al. 2008a, 2008b; J. T. van Loon et al. 2013). Their strengths are broadly consistent with Galactic relations once environmental factors and metallicity are taken into account (M. A. Cordiner et al. 2008a, 2008b). These extragalactic detections demonstrate that DIB carriers can survive outside the Milky Way, and that variations in ultraviolet radiation fields, metallicity, and grain processing influence the band strength per unit extinction. Extending DIB studies to more diffuse environments, such as the CGM using intervening quasar absorbers, has yielded only a few positive detections. A limited number of intervening systems show identifiable DIBs, including a $\lambda 4428$ feature detected in the damped $\text{Ly}\alpha$ absorber toward AO 0235+164 at $z \approx 0.524$ (V. T. Junkkarinen et al. 2004), a $\lambda 6284$ feature detected toward SDSS J163956.35+112758.7 at $z \approx 0.079$ and associated with a strong H I 21 cm absorber (R. Srianand et al. 2013), and the $\lambda 5780$ band observed in a Ca II selected quasar sight line (S. L. Ellison et al. 2008). These detections typically require high signal-to-noise, targeted spectroscopy and are associated with sight lines characterized by high neutral hydrogen columns and significant dust content, conditions more typical of the ISM than of diffuse halo gas.

More recently, large statistical searches using composite spectra of Mg II selected CGM sight lines have placed stringent limits on the presence of DIBs in halo environments. C.-Y. Chang & T.-W. Lan (2025) analyzed approximately 60,000 Mg II absorber spectra from SDSS to probe the DIB $\lambda 4428$ at milli-angstrom precision and found no significant

detection. Their composite spectra set upper limits at the few-milli-angstrom level, inconsistent with a simple extrapolation of the Galactic equivalent width–reddening relation into typical CGM dust columns. Overall, the literature indicates that DIB carriers are widespread in the ISM of galaxies and detectable in several extragalactic ISM sight lines, but are largely absent or severely suppressed in Mg II traced CGM gas.

We now investigate whether DIBs can be detected in the GOTOQ sample. Because DIB absorption features are intrinsically weak, spectra with very high SNRs are required for a reliable detection. To improve the sensitivity, we construct a composite spectrum of the GOTOQs. Each quasar spectrum is first continuum-normalized and then shifted to the rest frame of the corresponding foreground galaxy. The spectra are subsequently resampled onto a common wavelength grid with a spacing of 1 Å, and the median flux is computed at each wavelength bin to obtain the composite GOTOQ spectrum. The uncertainty in the composite median spectrum is estimated using 200 bootstrap realizations, each generated by randomly replacing 20% of the input quasar spectra. The standard deviation of the resulting flux values at each wavelength bin is adopted as the 1σ error. The number of quasars contributing to the stack at any given wavelength varies depending on the absorber redshift, the quasar redshift (since regions blueward of the $\text{Ly}\alpha$ emission line are excluded), and the observed spectral coverage of the spectra.

Figure 14 presents the composite spectra in the regions around the expected DIB $\lambda 4428$ (left panel) and DIB $\lambda 5780$ features (right panel), with the corresponding 1σ uncertainties displayed in gray. Around the DIB $\lambda 4428$ region, approximately 1336 quasar sight lines contribute to the stacked spectrum, whereas the DIB $\lambda 5780$ region is constructed from about 960 quasar sight lines owing to the more limited spectral coverage at longer rest-frame wavelengths. In both cases, a broad depression in the composite flux is evident near the expected wavelength of the DIBs. The solid red curves show the best-fitting Gaussian profiles to these absorption features. The resulting rest-frame equivalent width of the DIB $\lambda 4428$ is 0.055 ± 0.011 Å, corresponding to a detection significance of approximately 5σ . We detect the DIB $\lambda 4428$ feature (albeit at a slightly lower significance) even after dividing the sample into two subsamples about the median $E(B - V)$ derived from the SED fitting. We also find that the absorption lines of ions such as Zn II, Mn II, Na I, and Ca II are significantly stronger in the high- $E(B - V)$ subsample (e.g., the Ca II REW is 0.43 ± 0.05 Å compared to 0.25 ± 0.05 Å in the low- $E(B - V)$ subsample), consistent with the expected correlation between $E(B - V)$ and metallicity (E. Dwek 1998). We detect the DIB $\lambda 5780$ feature at a significance of approximately 4σ (right panel of Figure 14), with a rest-frame equivalent width of 0.051 ± 0.012 Å. The independent detection of this second prominent DIB provides additional support for the reality of the DIB $\lambda 4428$ detection. No statistically significant detections are found for any other DIB features in the stacked spectra.

In the Milky Way, the strength of the $\lambda 4428$ DIB correlates with line-of-sight reddening, and T.-W. Lan et al. (2015) quantify this relation as $W_r(\text{Å}) = (1.22 \pm 0.04) E(B - V)^{0.89 \pm 0.02}$. For the median reddening of our GOTOQ sample, $E(B - V) = 0.087$, the expected equivalent width is $W_r \approx 0.139 \pm 0.008$ Å, more than twice the value measured from the stacked GOTOQ spectrum. This suggests that either the disk-halo interface probed by the

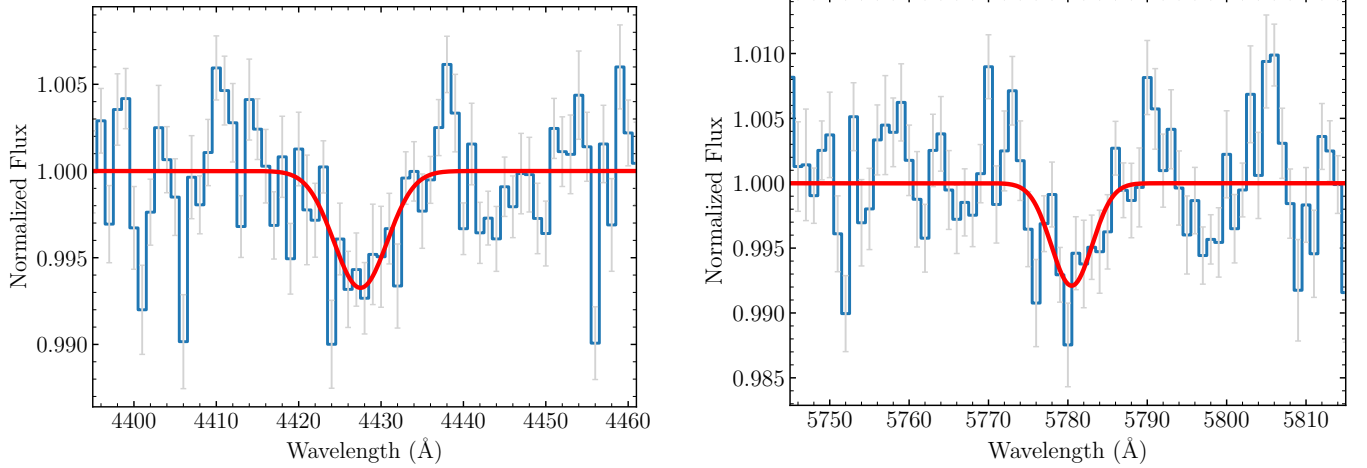


Figure 14. Detection of the DIB $\lambda 4428$ (left panel) and DIB $\lambda 5780$ (right panel) features in the continuum-normalized, median-stacked spectrum (blue) of the GOTOQs in our sample. The solid red curve represents the Gaussian fit to the absorption feature observed in the stacked spectrum.

GOTOQs contains fewer DIB carriers than the Milky Way for a given $E(B - V)$ value, or the carriers are destroyed or ionized in the harsher halo conditions characterized by low densities and stronger radiation fields. Detailed individual spectroscopic detection of DIBs in a follow-up study of a subsample of GOTOQs may shed light on this issue.

4. Discussion and Summary

With the identification of 1345 unique GOTOQs from the SDSS-DR16 and DESI-EDR datasets, we have compiled the largest catalog of quasar-galaxy pairs at projected separations of $D \lesssim 20$ kpc to date, resulting in almost a fivefold increase over previous samples (L. A. Straka et al. 2013; R. Joshi et al. 2017). This unprecedented dataset provides a valuable resource for investigating the gas, dust, and star-forming properties of galaxies probed essentially through their own disks or inner halos.

4.1. Nature of GOTOQs and Their Host Galaxies

The emission-line properties of GOTOQs indicate that they trace predominantly normal, star-forming galaxies. The measured $[\text{O III}]/[\text{O II}]$ ratios follow the same redshift evolution as field galaxies (see Figure 7; A. A. Khostovan et al. 2016), while the median Balmer decrement of $H\alpha/H\beta = 3.33$ implies a dust extinction of $A_V \approx 0.5$ mag assuming the D. Calzetti et al. (2000) extinction curve (see Figure 6). The absence of any significant redshift trend in the Balmer decrement up to $z \approx 0.5$ suggests that the dust attenuation properties of such galaxies remain broadly unchanged over this epoch. The $[\text{O II}]$ luminosities, although affected by fiber aperture effects, span $7 \times 10^{36} - 2 \times 10^{42}$ erg s $^{-1}$, consistent with sub- $L_{[\text{O II}]}$ galaxies at comparable redshifts (J. Comparat et al. 2016, see Figure 4). These findings confirm that GOTOQs preferentially select main-sequence star-forming systems rather than active galactic nucleus-dominated or extreme ELGs. The systematic increase of $L_{[\text{O II}]}$ with redshift primarily reflects the increasing physical area subtended by the spectroscopic fibers rather than intrinsic evolution, as demonstrated by the scaling with projected fiber area (see Figure 5).

4.2. Gas Content and Covering Fractions

Our absorption-agnostic sample provides a direct measurement of the cold gas covering fraction at the smallest Galactocentric radii of star-forming galaxies. For impact parameters $D < 20$ kpc, the Mg II $\lambda 2796$ covering fraction above an REW threshold of $1 \text{ \AA}$ is $f_c = 98.2^{+1.3}_{-4.5}\%$, substantially higher than the values reported at larger separations (R. Dutta et al. 2020; A. Anand et al. 2021). This is consistent with the earlier findings that the occurrence of H I 21 cm absorption and damped Ly α absorbers in GOTOQs is very high (V. P. Kulkarni et al. 2022; L. K. Guha et al. 2025). All this confirms that the inner few tens of kiloparsecs around star-forming galaxies are almost completely filled with cool, metal-enriched gas.

The GOTOQs preferentially host strong Mg II absorbers with median $W_{2796} = 2.15 \text{ \AA}$, nearly twice that of the parent Mg II population (see Figure 8). A positive correlation is observed between $L_{[\text{O II}]}$ and W_{2796} (see Figure 9), consistent with previous stacking analyses (B. Ménard et al. 2011). Although part of this trend may arise from reduced fiber losses at smaller impact parameters, it may as well be driven by an intrinsic link between star formation-driven outflows and the enriched gaseous halos. Detailed investigation of the velocity distribution of absorbing gas with respect to the systemic redshift and down-the-barrel absorption toward the galaxies is needed to establish such a picture.

Using photometric identifications of host galaxies, we confirm that the canonical anticorrelation between W_{2796} and impact parameter flattens for $D \lesssim 20$ kpc, implying that the Mg II transition becomes saturated in the dense disk-halo interface (see Figure 10). Such a flattening has also been observed in smaller samples (G. G. Kacprzak et al. 2013; L. K. Guha & R. Srianand 2023).

4.3. Dust Reddening and the Interstellar Environment

The median color excess toward the background quasars, $E(B - V) = 0.087$, is significantly higher than the typical reddening in randomly selected Mg II absorbers (B. Ménard et al. 2008; J. M. Budzynski & P. C. Hewett 2011). This confirms that GOTOQs probe the dusty, metal-rich interstellar regions of their host galaxies rather than diffuse halo gas. The

derived reddening is comparable to that of strong Ca II absorbers (V. Wild & P. C. Hewett 2005), supporting the notion that GOTOQs trace similar environments with high neutral-gas fractions. A statistically significant negative correlation between $E(B - V)$ and redshift suggests a gradual decline in dust content with cosmic time (see Figure 13), consistent with trends seen in intervening absorbers (L. Napolitano et al. 2025).

The reddening measured using the SED fitting (i.e., $A_V \approx 0.23$) is smaller than that obtained using the Balmer decrement (i.e., $A_V \approx 0.5$). This is consistent with what has been seen in the case of star-forming galaxies (for example, D. Calzetti et al. 2000), where nebular emission (and light from young massive stars) suffers more extinction compared to the light from old and relatively less massive stars. This is interpreted as young stars still being embedded in parent molecular clouds (for about the first 100 million yr) and hence suffering more reddening. In our case, the quasar line of sight may be probing even less dusty regions compared to the typical ISM gas. Thus, the relatively smaller extinction seen toward these quasars may not be surprising.

4.4. DIBs in GOTOQs

The composite spectrum of 1336 GOTOQs reveals a statistically significant detection of the broad DIB $\lambda 4428$ feature. As shown in the left panel of Figure 14, the stacked spectrum displays a wide, shallow depression at the expected wavelength, with a best-fitting profile yielding a rest-frame equivalent width of $0.055 \pm 0.011 \text{ \AA}$ (5σ detection). This constitutes the first statistical detection of the $\lambda 4428$ band in quasar-galaxy pairs at such small impact parameters, demonstrating that the carriers of DIBs survive in the inner halo and disk-halo interface of these galaxies. This detection is supported by the presence of absorption at the expected wavelength of the DIB $\lambda 5780$ feature at the $\sim 4\sigma$ level.

In the Milky Way, the strength of the $\lambda 4428$ band scales with line-of-sight reddening. However, this relation yields an expected DIB absorption strength more than twice the value measured from the GOTOQ composite spectrum. This shortfall indicates that the disk-halo interface probed by GOTOQs contains fewer DIB carriers per unit dust than typical Milky Way diffuse sight lines. Possible explanations include destruction or ionization of the carriers in the lower-density, more strongly irradiated halo environment, reduced formation efficiency in lower-metallicity gas, or differences in dust composition relative to the Galactic ISM. Despite this suppression, the clear detection of the $\lambda 4428$ band demonstrates that GOTOQs trace dust-rich, molecule-bearing gas and opens a new pathway to studying organic chemistry beyond the Milky Way. It also highlights the sensitivity of DIB carriers to environmental conditions in the inner CGM.

4.5. Implications and Future Prospects

The GOTOQ sample offers unique opportunities for follow-up studies of the multiphase interstellar and circumgalactic media:

1. *Cold gas and molecular follow-up.* The high Mg II covering fraction and strong dust extinction imply excellent prospects for HI 21 cm and molecular (e.g., OH, CO) absorption searches with the upgraded Giant Metrewave Telescope, MeerKAT (Karoo Array Telescope) and future

Square Kilometer Array pathfinders (see L. K. Guha et al. 2025).

2. *Orientation and feedback diagnostics.* High-resolution imaging (with, e.g., Hubble Space Telescope and JWST) can be used to relate absorber properties to disk inclination and azimuthal orientation, distinguishing inflow and outflow geometries (G. G. Kacprzak et al. 2012; K. H. R. Rubin et al. 2022).
3. *Dust and molecule evolution.* Combining optical extinction, DIB strengths, and HI 21 cm optical depths will allow constraints on dust-to-gas ratios and the chemistry of complex molecules across cosmic time.
4. *Emission-absorption synergy.* Spatially resolved IFU spectroscopy (with, e.g., MUSE, KCWI) can recover total star formation rates and metallicities of GOTOQ hosts, enabling joint studies of emission-line diagnostics and absorption line kinematics.

In summary, the present GOTOQ catalog constitutes the largest and most complete census of quasar-galaxy pairs at $D \lesssim 20$ kpc. GOTOQs provide direct, dust-biased probes of the inner CGM and the interstellar disks of galaxies. Their high Mg II covering fraction, strong dust reddening, and detection of DIBs demonstrate that they are exceptional laboratories for studying the cold, dusty, and molecular phases of gas at intermediate redshifts. The GOTOQ sample thus lays the foundation for future multiwavelength investigations of gas flows, feedback, and dust evolution in galaxies.

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Software. This work made use of the following software packages: NumPy (C. R. Harris et al. 2020), SciPy (P. Virtanen et al. 2020), Matplotlib (J. D. Hunter 2007), astropy (Astropy Collaboration et al. 2018), dust_extinction (K. D. Gordon 2024), pymccorrelation (G. C. Privon et al. 2020), and SpecTres (A. C. Carnall 2017).

Data Availability

The data used in this study are publicly available from the SDSS³ and DESI⁴ surveys. The catalog will be made available to interested readers upon reasonable request to the authors following publication of the paper.

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⁴ <https://data.desi.lbl.gov/doc/releases/edr/>

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