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Ilane Schroetter, Nicolas Bouché, Johannes Zabl, Hadi Rahmani, Martin Wendt, et al.. MusE GAs FLOW and Wind (MEGAFLOW) VI. A study of C iv and Mg ii absorbing gas surrounding [O ii] emitting galaxies. Monthly Notices of the Royal Astronomical Society, 2021, 506 (1), pp.1355-1363. 10.1093/mnras/stab1447 . hal-03086166

HAL Id: hal-03086166

<https://hal.science/hal-03086166>

Submitted on 26 Nov 2021

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MusE GAs Flow and Wind (MEGAFLOW) VI. A study of C IV and Mg II absorbing gas surrounding [O II] emitting galaxies [★]

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July 2, 2021

ABSTRACT

Using the MEGAFLOW survey, which consists of a combination of MUSE and UVES observations of 22 quasar fields selected to contain strong Mg II absorbers, we measure the covering fractions of C IV and Mg II as a function of impact parameter b using a novel Bayesian logistic regression method on unbinned data, appropriate for small samples. We also analyse how the C IV and Mg II covering fractions evolve with redshift. In the MUSE data, we found 215 $z = 1 - 1.5$ [O II] emitters with fluxes $> 10^{-17}$ erg s⁻¹ cm⁻² and within 250 kpc of quasar sight-lines. Over this redshift path $z = 1 - 1.5$, we have 19 (32) C IV (Mg II) absorption systems with rest-frame equivalent width (REW) $W_r > 0.05 \text{ \AA}$ associated with at least one [O II] emitter. The covering fractions of $z \approx 1.2$ C IV (Mg II) absorbers with mean $W_r \approx 0.7 \text{ \AA}$ (1.0 \AA), exceeds 50% within 23^{+62}_{-16} (46^{+18}_{-13}) kpc. Together with published studies, our results suggest that the covering fraction of C IV (Mg II) becomes larger (smaller) with time, respectively. For absorption systems that have C IV but not Mg II, we find in 73% of the cases no [O II] counterpart. This may indicate that C IV comes from the intergalactic medium (IGM), i.e. beyond 250 kpc, or that it is associated with lower-mass or quiescent galaxies.

Key words: galaxies: evolution — galaxies: formation — galaxies: intergalactic medium — quasars: absorption lines

1 INTRODUCTION

The surroundings of galaxies, the intergalactic medium (IGM) or the very close environment around galaxies: the circum-galactic medium (CGM), are known to be filled with gas in various phases. This CGM is composed of both ionized and neutral gas. For instance, Mg II is probing the cool ionized $T \sim 10^4$ K temperature gas whereas C IV probes warm $T \sim 10^5$ K gas (see the CGM review of Tumlinson et al. 2017). Because the gas usually has low density compared to the gas in galaxies, it is very difficult to observe di-

rectly. Understanding the origin of the gas surrounding galaxies is one of the keys to drawing a precise picture of how galaxies form and evolve.

In order to study the structure of the gas surrounding galaxies, the covering fraction (f_c) as a function of impact parameter is a key diagnostic tool. Indeed, in numerical simulations, column density profiles (e.g. Hummels et al. 2013) and covering fractions f_c (e.g. Bordoloi et al. 2014; Liang et al. 2016; Li et al. 2021) of low and high ionization elements are sensitive to feedback implementations and to added physical processes such as cosmic rays (CRs). Low ionization Mg II ($\lambda\lambda 2796, 2803$) is a useful probe of the cool ($T \sim 10^4$ K) CGM because it is a doublet accessible over a wide range of redshifts with optical spectrographs. Since the pioneering work of Bergeron & Stasinska (1986) and Steidel & Sargent (1992), numerous groups have constrained the covering fraction $f_{c, \text{Mg II}}$ with ever increasing samples (e.g. Chen et al. 2010; Nielsen et al.

[★] Based on observations made with ESO Telescopes at the La Silla Paranal Observatory under programme IDs 094.A-0211, 095.A-0365, 096.A-0609, 096.A-0164, 097.A-0138, 097.A-0144, 098.A-0216, 098.A-0310, 099.A-0059, 293.A-5038

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2013b; Dutta et al. 2020; Huang et al. 2021) and perhaps the largest sample is Lan (2020) who used 15,000 galaxy-quasar pairs.

However, concerning C IV ($\lambda\lambda 1548, 1550$), studies of $f_c(\text{C IV})$ are often limited to relatively small samples because of the UV coverage required or the need to find the host galaxies at $z > 2$ (e.g. Fox et al. 2007; Fox & Richter 2016). Among the earlier C IV studies, there is the $z < 1$ Chen et al. (2001) study. Since the availability of the Cosmic Origin Spectrograph (COS) onboard the *Hubble* Space Telescope, we note the $z < 0.1$ work of Bordoloi et al. (2014) and Burchett et al. (2016) on COS quasar sight-lines. In addition, there are other constraints on the C IV CGM with quasar-quasar pairs (Prochaska et al. 2014; Landoni et al. 2016), with lensed quasars (Rauch et al. 2001) and with statistical clustering (e.g. Schaye et al. 2003; Turner et al. 2014) which can be compared to hydrodynamical simulations (e.g. Turner et al. 2017). While these agree that the C IV gas is mainly located outside their host galaxies, there is a lack of consensus on the origin and properties of this highly ionized gas. As a result the origin of this highly ionized gas, C IV, and its distribution around galaxies, is thus still debated.

In this paper, we aim to address the question of how C IV is located around galaxies compared to Mg II by searching for C IV absorption systems and their possible galaxy counterparts by studying the C IV and Mg II covering fractions using the MEGAFLOW survey (Schroetter et al. 2016, 2019; Zabl et al. 2019, 2020). The C IV and Mg II covering fractions are obtained from a novel Bayesian logistic fit to the unbinned data. This method is designed to go beyond the limitations of using binned statistics and the Bayesian fit provides a built-in robustness to outliers.

The paper is organized as follows. We present in § 2 the data and the independent detection of absorption systems and star-forming galaxies. We then combine those detections in order to identify possible galaxy counterparts to the absorbers. In § 3 we focus on constraining covering fractions of C IV and Mg II, we present our results in § 4 and our conclusions in § 5. Throughout, we use a 737 cosmology ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$) and a Chabrier (2003) stellar Initial Mass Function (IMF). All wavelengths and redshifts are in vacuum and are corrected to a heliocentric velocity standard. All distances are physical. All stated errors are 2σ , unless otherwise noted.

2 MUSE AND UVES OBSERVATIONS

The data we use in this study are part of a MUSE GTO program aiming to study gas flows around galaxies using background quasars. This MusE GAs FLOW and Wind (MEGAFLOW) program combines MUSE (Bacon et al. 2010) and UVES (Dekker et al. 2000) observations of 22 quasar fields and is described in Schroetter et al. (2016); Zabl et al. (2019); Schroetter et al. (2019). The quasar fields were selected based on the presence of at least 3 strong ($W_r^{12796} > 0.5\text{--}0.8\text{\AA}$) Mg II absorptions in SDSS spectra and observed with MUSE with on average 3 hours of exposure time each. The observations and data reduction are described in Schroetter et al. (2019) and Zabl et al. (2019).

For each field, UVES follow up observations of the quasar have been carried out. In this section, we present, first, the detection of [O II] emitters throughout all the 22 MUSE fields, and then the detection of C IV and Mg II absorption systems in the UVES spectra. We will combine those two samples in order to search for absorber counterparts to [O II] emitters.

2.1 Galaxy detection in all MUSE fields from $z \geq 1.0$

The MUSE wavelength range spans from ≈ 4700 to $\approx 9300 \text{ \AA}$, at a spectral resolution of $R \approx 2000$ (or 150 km s^{-1}). This wavelength range allows for the detection of [O II] emitters from redshifts $0.3 \leq z \leq 1.5$.

In order to find star-forming galaxies potentially associated with C IV or Mg II absorbers, we searched for [O II] emitters in our MUSE fields, independently of any absorption systems, but to ensure overlapping redshift ranges between C IV and Mg II in UVES quasar spectra, we restricted the search for [O II] emitters at redshifts 1.0–1.5, i.e. in the 7400–9300 \AA MUSE wavelength range. For this, we used narrow band images with the continuum subtracted throughout the cube wavelength range. In the 22 MEGAFLOW fields, we found 215 [O II] emitters and visually inspected each galaxy, making sure the [O II] emission doublet was clearly identified down to a flux detection limit of $10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2}$. In a forthcoming paper (Bouché et al. in prep.), we will characterize and present the detection completeness for the MEGAFLOW survey using a combination of automatic and visual inspection sources detection. Preliminary results based on inserting fake [O II] emitters with realistic sizes and kinematic properties give a 50% completeness level at $\approx 8.0 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$ (corresponding to a SFR of $\approx 0.3 M_\odot \text{ yr}^{-1}$ at $z = 1.0$) for a typical depth of 3 hr in the red part of the MUSE wavelength range away from skylines.

2.2 C IV and Mg II absorption systems

Using the MEGAFLOW UVES quasar spectra, we searched for C IV and Mg II systems at $z = 1\text{--}1.55$, i.e. in the redshift range where both C IV and Mg II are covered in the UVES spectra and where [O II] can be detected in the MUSE wavelength range, down to a rest-frame equivalent width (REW) W_r of $\sim 0.1 \text{ \AA}$. The detection limit for each field is based on the signal to noise ratio and we find an overall equivalent width limit $\text{EW}_{\text{lim}} \approx 0.1 \text{ \AA}$ for both C IV and Mg II in the observed frame. Since all the absorption systems have $z > 1$, the rest EW_{lim} is thus divided by $1+z$, leading to $\text{REW}_{\text{lim}} = 0.05 \text{ \AA}$. Examples of absorption and emission systems are shown in Figure 2. This Figure shows a selected sample of C IV, Mg II and [O II] systems detected at high, medium and low SNR. We emphasize here that each panel of this Figure is an independent system (different field, redshift or position).

We visually searched all the 22 QSO's UVES spectra for C IV systems. UVES allows for C IV absorption detection for redshift $z > 1.0$ with a spectral resolution of $R \approx 38000$ ¹. The UVES spectral coverage is continuous over the redshift range of $1.0 < z < 1.55$. Two of the authors performed this search independently and cross-checked the findings. In short, what we call a "confident C IV system" is a system having clear C IV ($\lambda\lambda 1548, 1550$) absorption. Both doublet components had to have the same overall shape. Figure 1 shows the redshifts of all the C IV systems for each quasar sight-line.

In the 22 UVES spectra, we find a total of 41 C IV absorption systems with redshifts between 1.0 and 1.55, for which we also have Mg II coverage. Out of the 22 quasar fields, we only find C IV absorption systems in 13 of them. The 9 remaining fields either do not have UVES wavelength coverage (for 6 of them) or the quasars

¹ With a slit width of $1.2''$ and a CCD readout with 2x2 binning. UVES observation settings and data quality are detailed in Zabl et al. (2019) and Schroetter et al. (2019).

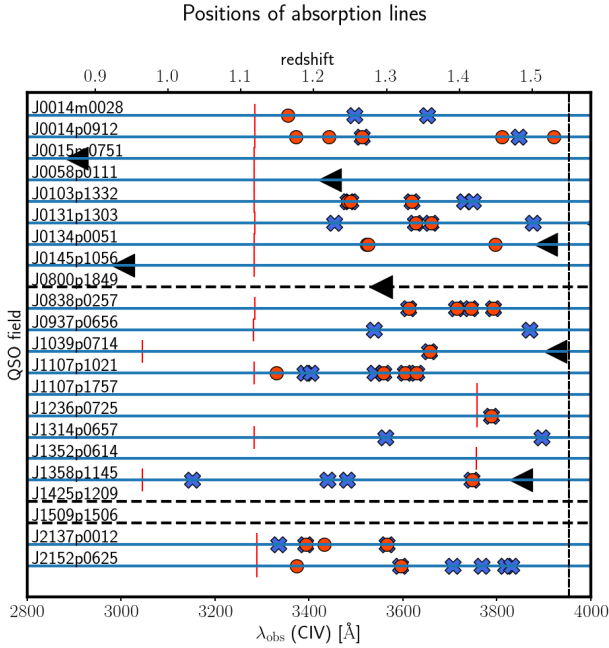


Figure 1. Observed wavelengths of C IV systems in each MEGAFLOW QSO UVES spectra. The top x -axis represents the corresponding redshift. The blue crosses represent the detected C IV absorption system. The red circles represent the expected $\lambda_{\text{obs}}(\text{C IV})$ for systems with detected Mg II. The red vertical lines represent the UVES lowest wavelength coverage and the black vertical line the $z = 1.55$ redshift limit. The 3 horizontal black dashed lines are the fields for which the lowest UVES wavelength is above 4000 Å where C IV is not covered at $z \approx 1-1.5$. The left black triangles show the quasar redshift positions with $z_{\text{QSO}} < 1.5$.

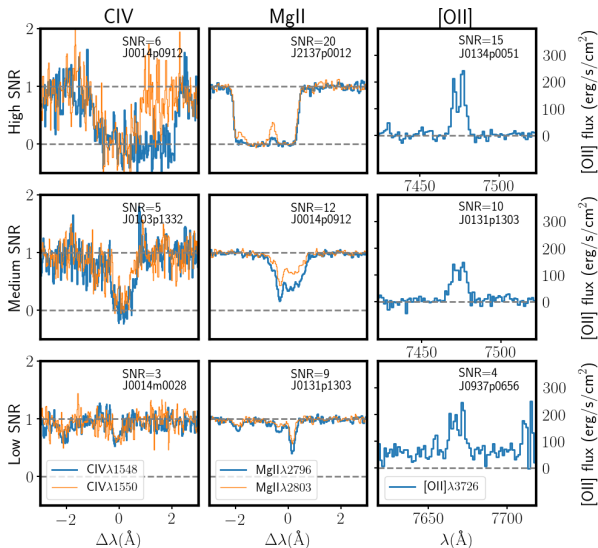


Figure 2. Examples of C IV (left) and Mg II (middle) absorption systems as well as [O II] (right) emission for high, medium and low Signal to Noise Ratio (SNR) in the top, middle and bottom rows, respectively. Each panel is independent and they were chosen arbitrary for examples purpose. Each SNR is shown for each panel as well as each field name. The x -axis for [O II] emission (right column) corresponds to observed wavelength.

have lower redshift than 1.55 (for 3 of them). It is worth mentioning that within our selected wavelength coverage from redshifts 1 to 1.55 (from ≈ 3100 Å to ≈ 4000 Å), our UVES data do not have any spectral gap.

For those 41 C IV absorption systems, we also searched for Mg II absorption lines. We find that out of the 41 C IV systems, 18 have Mg II absorption (see blue and hatched systems in Figure 3). We emphasize the fact that the MEGAFLOW survey was built based on Mg II absorption lines detected in quasar spectra from SDSS. Hence, we keep in mind that the numbers we give in this paper may be biased towards more Mg II absorption systems and that the MEGAFLOW selection may also increase the number of expected C IV systems. However, since this survey has the advantage of having high-resolution quasar spectra for each of the MUSE fields, we begin with this biased sample before building larger ones.

In order to complete our analysis and for the purpose of the covering fraction study later in this paper, we also searched for all Mg II absorption systems in each of our UVES data, regardless of the presence of C IV absorbers. We first searched for any Mg II absorption system with redshift between 1.0 and 1.55. We found 52 Mg II systems in total to begin with. Then, we rejected the ones for which we cannot observe C IV absorption due to the UVES wavelength coverage, resulting in 30 Mg II systems where the C IV feature is covered. Out of these 30, we detected C IV in 18 systems. The distribution of REW for all the Mg II systems is represented in Figure 4. Comparing the REW distribution of systems which have only C IV and the ones with the presence of Mg II (hashed histogram on Figure 4), we find that we are in good agreement with the study of Steidel & Sargent (1992) where they found that C IV-only systems are peaked towards lower REW. This difference could come from the fact that C IV may be more diffuse than Mg II around galaxies.

Table 1 summarizes all the different absorption systems for which both absorption lines (C IV and Mg II) can be detected. Table 1 lists the absorption system redshift with the corresponding REW of C IV ($\lambda\lambda 1548, 1550$) and Mg II ($\lambda\lambda 2796, 2803$) (if detected) absorption lines. We note that each C IV or Mg II doublet is resolved and each corresponding limit was applied to each individual doublet member. Table 2 shows Mg II absorption system properties for which C IV is not covered in UVES.

Having independently detected the absorption systems in UVES spectra and the [O II] emitters in MUSE, we next try to match galaxies to absorption systems.

2.3 Absorber counterparts

We now look for galaxies which possibly correspond to the C IV absorption systems. For each detected galaxy, we measured the velocity difference² between C IV absorption and [O II] emission. For the purpose of this work, a galaxy was considered to be a counterpart if $|\Delta v| < 500$ km s⁻¹.³ With this criterion, we find 39 counterpart galaxies for 19 C IV absorption systems, out to 250 kpc from the quasar. Out of those 19 systems, 13 ($\approx 70\%$) have Mg II absorption lines.

One of the most interesting results is that out of all the 22 systems with only C IV absorption detected (not Mg II), we detect counterparts for only 6 systems. This means that we do not detect

² The velocity difference between the absorber redshift and the galaxy systemic redshift.

³ We also searched for systems with $\Delta v < 1000$ km s⁻¹ but found no more associations.

Table 1. Absorption system properties (both C iv and Mg II covered).

Field name (1)	z_{abs} (2)	$W_r^{\lambda 1548}$ (3)	$W_r^{\lambda 1550}$ (4)	$W_r^{\lambda 2796}$ (5)	$W_r^{\lambda 2802}$ (6)	N_c (7)
J0014m0028	1.16444	≤ 0.05	≤ 0.05	0.3251	0.2721	0
...	1.25638	0.6108	0.3913	≤ 0.05	≤ 0.05	0
...	1.35566	0.0655	0.0762	≤ 0.05	≤ 0.05	0
J0014p0912	1.17550	≤ 0.05	≤ 0.05	0.9277	0.8453	0
...	1.22115	≤ 0.05	≤ 0.05	1.2521	0.9717	5
...	1.26575	1.5459	0.9266	0.3772	0.1909	0
...	1.45844	≤ 0.05	≤ 0.05	0.2831	0.1541	0
...	1.48212	0.1778	0.3613	≤ 0.05	≤ 0.05	0
J0103p1332	1.24646	0.5493	0.5053	0.2369	0.1577	0
...	1.25029	0.5005	0.1065	≤ 0.05	≤ 0.05	0
...	1.33451	0.4467	0.3516	0.3347	0.2231	0
...	1.34053	≤ 0.05	≤ 0.05	0.1687	0.1107	1
...	1.36112	≤ 0.05	≤ 0.05	0.3727	0.2989	2
...	1.40648	0.3491	0.2141	≤ 0.05	≤ 0.05	0
...	1.41847	0.9428	0.6973	≤ 0.05	≤ 0.05	0
J0131p1303	1.22845	0.2819	0.2384	≤ 0.05	≤ 0.05	0
...	1.33945	0.7591	0.5660	0.1567	0.1024	1
...	1.36075	0.3734	0.3213	0.3582	0.2862	2
...	1.50130	0.0947	0.0695	≤ 0.05	≤ 0.05	0
J0134p0051	1.27246	≤ 0.05	≤ 0.05	0.3312	0.2847	0
...	1.27411	≤ 0.05	≤ 0.05	0.3500	0.2266	0
...	1.44917	≤ 0.05	≤ 0.05	0.4287	0.2362	1
J0838p0257	1.33042	1.4164	1.1392	1.5306	1.2020	1
...	1.39601	0.5442	0.5272	0.0598	0.0228	1
...	1.41490	0.7320	0.3133	0.8686	0.6654	2
...	1.44629	1.4876	1.2233	0.7595	0.5980	0
J0937p0656	1.28260	1.0395	0.7001	≤ 0.05	≤ 0.05	0
...	1.49647	1.0355	1.0112	≤ 0.05	≤ 0.05	0
J1039p0714	1.35888	1.1127	1.0100	2.4970	2.2989	3
J1107p1021	1.14907	≤ 0.05	≤ 0.05	0.7981	0.515	0
...	1.18750	0.2123	0.1948	≤ 0.05	≤ 0.05	2
...	1.19557	0.4752	0.1473	≤ 0.05	≤ 0.05	0
...	1.28363	0.2810	0.1408	≤ 0.05	≤ 0.05	2
...	1.29562	2.1644	1.9257	0.5323	0.2984	6
...	1.32523	1.6618	1.4281	2.7651	2.6038	3
...	1.34105	1.2897	1.0869	0.1009	0.0524	3
J1236p0725	1.44338	0.4736	0.3960	1.7089	1.5374	0
J1314p0657	1.29867	0.2399	0.1287	≤ 0.05	≤ 0.05	0
...	1.51345	0.1353	0.1080	≤ 0.05	≤ 0.05	0
J1358p1145	1.03320	1.1543	0.9007	≤ 0.05	≤ 0.05	1
...	1.21902	0.1625	0.1520	≤ 0.05	≤ 0.05	2
...	1.24627	0.0615	0.0350	≤ 0.05	≤ 0.05	0
...	1.41709	0.9830	0.7056	2.5651	2.3938	1
J2137p0012	1.15191	0.2559	0.1254	≤ 0.05	≤ 0.05	0
...	1.18860	0.6404	0.4889	0.2686	0.1671	2
...	1.21472	≤ 0.05	≤ 0.05	1.1219	1.0573	4
...	1.30023	0.4736	0.1542	0.0731	0.0590	1
J2152p0625	1.17651	≤ 0.05	≤ 0.05	0.496	0.3924	0
...	1.31870	1.3851	0.9527	1.3841	1.1038	2
...	1.39149	0.8075	0.7151	≤ 0.05	≤ 0.05	1
...	1.43101	1.0550	0.9595	0.9884 [†]	≤ 0.05	3
...	1.46349	0.4458	0.1634	≤ 0.05	≤ 0.05	0
...	1.47132	0.5880	0.4002	≤ 0.05	≤ 0.05	0

1: Field name; 2: Absorption system redshift; 3: C iv ($\lambda 1548$) REW (\AA); 4: C iv ($\lambda 1550$) REW (\AA); 5: Mg II ($\lambda 2796$) REW (\AA); 6: Mg II ($\lambda 2802$) REW (\AA); 7: Number of detected counterparts. Typical EW $1-\sigma$ errors are 0.01\AA . †: this system is not considered as a detection since we do not detect the $\lambda 2802$ component which falls in the UVES coverage gap.

Table 2. Mg II absorption system properties (C iv not covered).

Field name (1)	z_{abs} (2)	$W_r^{\lambda 2796}$ (3)	$W_r^{\lambda 2802}$ (4)	N_c (5)
J0014m0028	1.05265	2.1232	1.7896	1
J0058p0111	1.06528	1.5822	1.3268	0
J0103p1332	1.04836	2.9956	2.7317	2
J0134p0051	1.07010	0.1906	0.0534	2
J0131p1303	1.01045	1.3197	0.9514	2
...	1.10436	1.0906	0.8421	2
J0800p1849	1.12153	0.5252	0.5156	0
J0838p0257	1.09958	0.1474	0.0538	1
J1107p1021	1.01464	0.6477	0.5716	0
...	1.01643	1.1665	1.0339	4
...	1.04815	0.4274	0.3120	1
J1107p1757	1.04801	2.1392	1.6854	0
...	1.06296	3.2741	2.6220	1
...	1.16320	1.5809	1.4023	1
...	1.32678	0.7279	0.5251	0
...	1.33079	0.9160	0.7724	2
J1236p0725	1.33128	0.3908	0.2291	3
J1352p0614	1.13736	1.4189	1.0794	0
...	1.20049	1.0326	0.9159	0
J1509p1506	1.04659	1.5000	1.3575	0
J2137p0012	1.04423	0.8518	0.8741	2
J2152p0625	1.05366	0.5688	0.4714	2

1: Field name; 2: Absorption system redshift; 3: Mg II ($\lambda 2796$) REW (\AA); 4: Mg II ($\lambda 2802$) REW (\AA); 5: Number of detected counterparts. Typical EW $1-\sigma$ errors are 0.01\AA .

any counterpart for $\approx 73\%$ of those "C iv only" systems. This result suggests that the C iv gas is probably located in the IGM rather than in the CGM or that C iv is associated with galaxies with lower SFR than Mg II, i.e. with $\text{SFR} \lesssim 0.3 M_{\odot} \text{ yr}^{-1}$. As already argued by [Rahmani et al. \(2018\)](#), a system having both C iv and Mg II absorption lines appears to have a higher chance of a counterpart detection, compared to a system with only C iv absorption. Here we can confirm this statement as 70% of our systems for which we find at least 1 counterpart have both C iv and Mg II absorption lines.

Using the same criterion to identify counterparts of the 52 detected Mg II systems, we find at least one galaxy counterpart for 32⁴ systems ($\approx 63\%$ ⁵), within 250 kpc from the quasar. In both Table 1 and 2, the last column shows the number of galaxy counterpart detected for each system.

⁴ Note that 21 of those 32 systems were part of the original MEGAFLOW selection.

⁵ Note that this is the detection rate for $z > 1$ galaxies, compared to the $\approx 70\%$ detection of the whole MEGAFLOW survey for redshifts $0.4 < z < 1.5$.

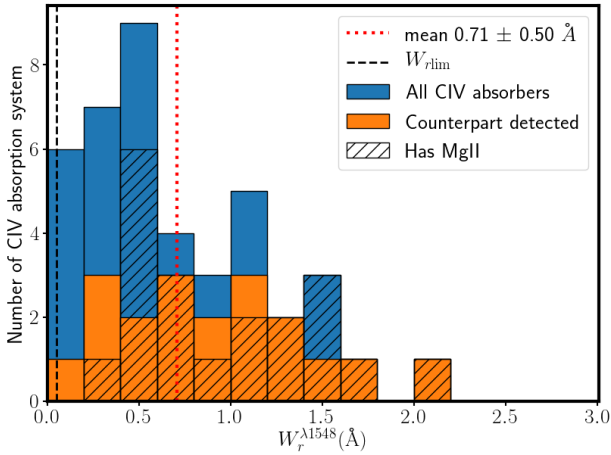


Figure 3. Histogram showing number of C IV absorption systems as a function of their REW for all the C IV absorbers (in blue), the ones with galaxy counterparts detected (in orange) and the number of absorbers for which we also detect Mg II absorption lines (hatched). The REW detection limit is shown by the black dashed vertical line

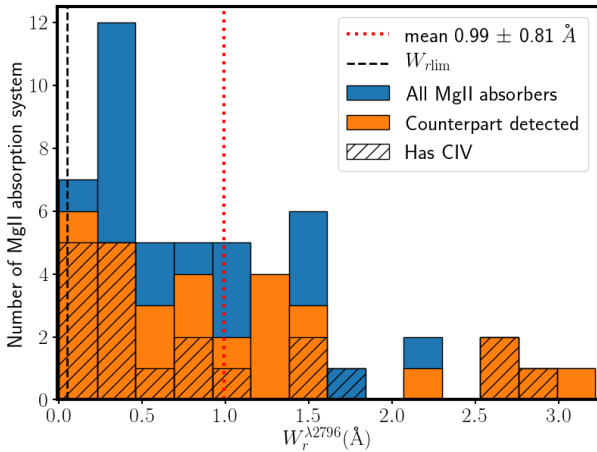


Figure 4. $W_r^{\lambda 2796}$ distribution for all detected Mg II absorption systems.

3 MEASURING COVERING FRACTIONS

With our sample of [O II] galaxies, we investigate the covering fractions of C IV and Mg II at redshifts $1.0 < z < 1.5$. The covering fraction f_c describes the probability of having an absorber detected (1) or not (0) at a distance r from a galaxy, which is inherently dichotomous. f_c can be estimated from the ratio between the number of galaxies at a given impact parameter $r \pm \Delta r$ which have an absorber detected (above some detection limit) to the total number of galaxies N_{tot} at that impact parameter with or without a detected absorber. If ‘D’ (‘U’) represent the detected (undetected) absorbers, respectively, $f_c(r) \equiv D/D + U$. In the notation of [Bordoloi et al. \(2014\)](#), D is $N_{W_r > W_{r,\text{lim}}}(r)$, and f_c is

$$f_c(r) \equiv \frac{N_{W_r > W_{r,\text{lim}}}(r)}{N_{\text{tot}}(r)} \quad (1)$$

In general, the probability p for an absorber to be detected (i.e., $Y = 1$) can be described by any continuous function $p = L(t)$. Here, we use a logistic function⁶ for the probability p to detect an

absorber. The logistic function yields a continuous transition of p from 0 to 1:

$$p(Y = 1) = \frac{1}{1 + \exp(-t)} \equiv L(t) \quad (2)$$

where t is usually taken to be a linear combination of the independent variables, X_n , i.e., $t = \alpha + \beta_1 X_1 + \dots + \beta_n X_n$.⁷ Here, the independent variables will be impact parameter r and redshift z .

It is customary to determine $f_c(r)$ in radial bins, by binning the data. However, this technique requires samples with large number of galaxies in each bin and thus can lead to large statistical uncertainties when the data do not populate each bin equally. Here, we use a novel unbinned approach to fit the probability function p directly using a logistic function in a Bayesian framework. As discussed in [Hosmer & Lemeshow \(2000\)](#), this is commonly used to examine the possible relationship between a dichotomous variable (here whether the absorption are detected in the quasar spectra) and independent variables (X_n , such as impact parameter, redshift, etc.). This technique has several advantages, namely it uses all the information contained in the data even in bins where there would be few galaxies. The Bayesian framework is natural for this problem and provides also a more robust fitting procedure against outliers which could skew the mean of a particular bin.

A series outcomes O can be generated by the Bernoulli distribution $\text{Bern}(p)$, since the observables are dichotomous, with values at 0 or 1, for undetected and detected systems, respectively. In summary, the model is

$$t = f(X_i; \theta) \quad (3)$$

$$p = L(t) \quad (4)$$

$$O \sim \text{Bern}(p) \quad (5)$$

where $L(t)$ is given by Eq. 2, $f(X_i; \theta)$ linearly combines the data and map it to $L(t)$, X_i are the independent variables, θ are the model parameters, and O are the simulated observables which can be compared to the observed data Y_i .

For the model function t , we choose a simple linear function f of impact parameter b ,

$$f(b; \theta) = A(\log b - C) \quad (6)$$

where A describes the slope of the covering fraction and C the zero-point at 50% covering fraction $f_c = 0.5$, since $L(0) = 0.5$. One could add a redshift dependent zero-point

$$f(b, z; \theta) = A(\log b - \text{ZP}(z)) \quad (7)$$

where $\text{ZP}(z) = B \log(1 + z) + C$. This second model is discussed/shown in § 4.

We used a Markov Chain Monte Carlo (MCMC) algorithm to estimate the best fitting parameters θ for our model. Because traditional MCMC algorithms are somewhat sensitive to the step size and the desired number of steps, in what follows we use the No-U Turn Sampler (NUTS) of [Hoffman & Gelman \(2014\)](#) implemented in PyMC3 ([Salvatier et al. 2016](#)), a self-tuning variant of Hamiltonian Monte Carlo (HMC). We typically used 2 MCMC chains per run and 4,500 iterations per chain.

We stress that the purpose of this exercise is to demonstrate the viability of our new technique for determining the covering fractions of metal lines in the regime of small number statistics.

⁶ See [Wilde et al. \(2020\)](#) for another physical parameterisation.

⁷ This assumes that all variables are independent of one another, but covariance terms can be included.

4 RESULTS

4.1 Mg II covering fraction

The distribution of Mg II REWs for all detected absorbers is shown in Fig. 4. The Mg II systems have REWs of [0.1–2.5 Å] with a mean of $W_r^{2796} = 0.99 \pm 0.8 \text{ \AA}$. As discussed in Appendix A2, the mean REW (W_r^{12796}) of our sample is biased towards high W_r^{12796} compared to random field Mg II absorbers due to the MEGAFLOW survey selection criteria (§ 2). The mean value for absorbers in the original MEGAFLOW selection is $\langle W_r^{12796} \rangle = 1.41 \text{ \AA}$.

Fig. 5(bottom) shows the Mg II covering fraction f_c as a function of impact parameter b . The solid line represents a logistic fit with our model (Eq. 7) to the unbinned data (black ticks) with the 95% confidence interval (grey area) derived from the Markov chain. The 50% covering fraction $f_c(50\%)$ occurs at $\log b/\text{kpc} = 1.66 \pm 0.15 (2\sigma)$, corresponding to $46_{-13}^{+18} \text{ kpc}$. For comparison, the filled squares with error bars represent the binned data. These error bars are 1σ confidence intervals computed for proportion of a binomial distribution (Wilson 1927; Cameron 2011). Comparing these 1σ errors on the binned data to the 95% confidence interval to the unbinned data, this figure shows the benefit of a parametric fit to the unbinned data. The fitted parameters for the Mg II covering fractions are listed in Table 3 with (Eq. 7) and without the redshift evolution term (Eq. 6).

Fig. 5(top) shows the redshift evolution determined from our model fit (Eq. 7). The solid line shows that $f_c(50\%)$ evolves as $(1+z)^B$ with $B = 1.96_{-2.68}^{+2.32} (2\sigma)$. The dotted-dashed line represents the redshift evolution of dark-matter halos $R_{\text{vir}} \propto H(z)^{-1}$ (e.g. Mo et al. 1998) of a given mass. Comparing the dotted-dashed line to the redshift evolution of f_c , one sees that the Mg II halo is becoming proportionally smaller.

Our results are broadly in agreement with the study of Nielsen et al. (2013a) (grey triangles) which used a sample of 182 galaxies towards 134 quasar sight-lines over a wide redshift range of $0.07 \leq z \leq 1.12$. Among other literature results of Mg II covering fractions, Lan (2020) stands out with a sample of 15,000 Mg II-galaxy pairs in SDSS with $W_r^{2796} > 0.4 \text{ \AA}$ (albeit with photometric redshifts). Their f_c as a function of radius (redshift) is shown with the dotted line in the bottom (top) panel of Fig. 5, respectively. In spite of our much smaller sample, our results are in good agreement with theirs. The dotted line in Fig. 5(bottom) from Lan (2020) has been calculated for absorbers with $W_r^{2796} \geq 1 \text{ \AA}$ ⁸, at $z = 1.2$, for star-forming galaxies with $\log(M_*/M_\odot) = 10.0$ assuming a $R_{\text{vir}} \approx 200\text{--}250 \text{ kpc}$ from their Eqs 7–9. The dotted line in Fig. 5(top) has been calculated by solving numerically for the redshift evolution of f_c in Lan (2020). Overall, our results, from a much smaller sample, are very similar to those of Lan (2020) who used 15,000 pairs.

It is interesting to compare the halo mass for Mg II absorbers corresponding to $R_{\text{vir}} \approx 200\text{--}250 \text{ kpc}$, namely $\log M_h/M_\odot \approx 12.6$, to the mass scale obtained by Bouché et al. (2006) from a clustering analysis of 2,500 $z = 0.5$ absorbers (see also Gauthier et al. 2009; Lundgren et al. 2009, 2011): $\log M_h/M_\odot \approx 12.5 \pm 0.4$ for their absorbers with $0.3 < W_r^{2796} < 1.15$. The covering fraction could also be weakly dependent on stellar mass (e.g. Chen et al. 2010; Nielsen et al. 2013a; Lan 2020), but we reserve such an analysis to a forthcoming paper on the full MEGAFLOW sample. Nonetheless, these

results are a demonstration of the power of our fitting technique on unbinned data.

4.2 C IV covering fraction

In this section, we use the galaxies for which C IV could be detected from our UVES coverage. This lowers the number of [O II] emitters from 215 to 141. From a total of 141 [O II] emitters in the MUSE data with redshift > 1.0 , after looking at the redshift differences between each emitter and C IV absorption systems, we found 39 galaxy counterparts corresponding to 19 C IV absorption systems. Incidentally, 70% (13 out of 19) of those systems have detectable Mg II absorption lines as well⁹.

Fig. 6(bottom) shows the covering fraction as a function of impact parameter b from our logistic fit (Eq. 7) to the unbinned data (black ticks). The 50% covering fraction occurs at $\log b/\text{kpc} = 1.36 \pm 0.57 (2\sigma)$, i.e. $23_{-16}^{+62} \text{ kpc}$. For comparison, the filled squares with error bars represent the binned data. These error bars are 1σ confidence intervals as in § 4.1. Our $f_c(\text{C IV})$ appears to be in good agreement with the Bordoloi et al. (2014) study (solid triangles), which used a sample of 43 low-mass $z \leq 0.1$ galaxies around sight-lines with C IV W_r^{1548} greater than $\sim 0.1 \text{ \AA}$.

The top panel of Fig. 6 shows the fitted redshift evolution with the 95% predictive interval. The solid line represent the fitted $(1+z)^B$ evolution with $B = -0.7_{-4.0}^{+3.9} (2\sigma)$, i.e. consistent with no evolution. The tick marks show the location of the unbinned data. The fitted parameters for the C IV covering fractions are listed in Table 3 with (Eq. 7) and without the redshift evolution term (Eq. 6). The solid triangle in this figure represent the C IV covering fraction $f_c(50\%)$ from the study of Bordoloi et al. (2014) at $z = 0.1$. This data point is obtained after applying our methodology to their 44 data points which yielded a size of $\log b/\text{kpc} = 1.71 \pm 0.26 (2\sigma)$ for the 50% covering, i.e. $51_{-23}^{+42} \text{ kpc}$.

5 DISCUSSION AND CONCLUSIONS

This study was divided into two parts: (i) the independent detection of absorption systems in MEGAFLOW UVES and [O II] emitters in MEGAFLOW MUSE with the identification of galaxy counterparts to the absorbers; (ii) measurement of the covering fractions of C IV and Mg II.

We adopted an innovative Bayesian logistic regression and have shown its ability (§ 3) to determine the covering fractions of absorption lines (such as Mg II, C IV) with limited samples. This approach allows one to fit a parametric model directly to unbinned binary data (1/0) where 1 represents an absorption detection and 0 its absence. The advantage of our method is that it does not suffer from the limitations inherent when using binned data.

Using the MEGAFLOW UVES quasar spectra, we searched for C IV, Mg II systems at $z = 1\text{--}1.5$, i.e. in the redshift range where both C IV and Mg II are covered by UVES and where [O II] could be detected in the MUSE wavelength coverage, down to a rest-frame equivalent width of 0.05 \AA . We detected a total of 52 Mg II absorption systems and 41 C IV absorption systems independently, having large mean REWs of 0.99 and 0.71 \AA respectively. 50% and 60% of the 41 C IV and 32 Mg II systems¹⁰, respectively, have absorption by both ions.

⁸ Lan (2020) does not provide a fit for $W_r^{2796} > 0.4 \text{ \AA}$ absorbers, but the equivalent width dependence seems small compared to the other parameters.

⁹ MEGAFLOW was not designed around C IV absorption system, this 70% might be indirectly biased by our Mg II selection.

¹⁰ The 32 Mg II systems are the ones with C IV coverage.

	Fitted parameters			log f_c (50%)	Model
	A [95%]	B [95%]	C [95%]		
Mg II	-4.2 [-5.7;-2.9]	2.0 [-0.7; 4.3]	1.0 [0.2; 1.9]	1.67±0.15	Eq. 7
Mg II	-4.7 [-6.3;-3.2]	–	1.6 [1.5;1.8]	1.66±0.15	Eq. 6
C IV	-2.8 [-4.5;-1.2]	-0.7 [-4.7;3.2]	1.6 [0.3;2.8]	1.36±0.57	Eq. 7
C IV	-3.0 [-4.6;-1.6]	–	1.4 [0.9;1.7]	1.44±0.39	Eq. 6

Table 3. Fitted parameters (A , B , C) for f_c for Mg II and C IV in relation to Eqs. 6-7 along with their 95% confidence interval. The log f_c column shows the distance at which f_c reaches 50% at $z = 1.2$.

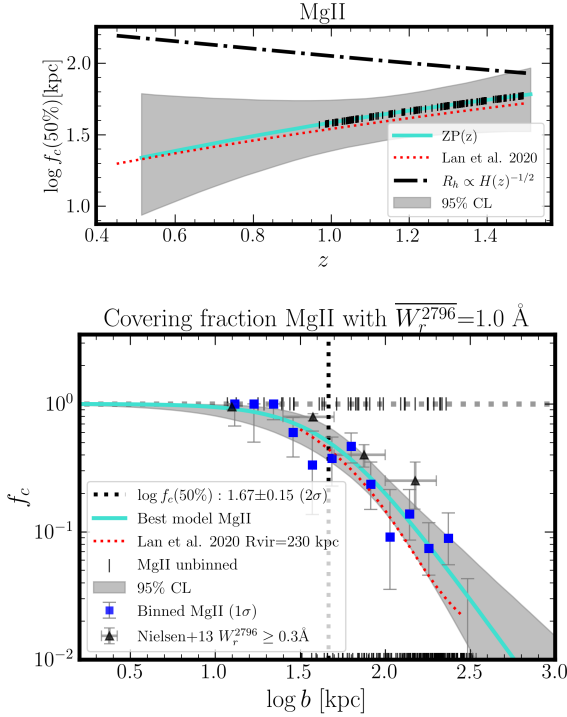


Figure 5. *Bottom:* Mg II covering fraction f_c as a function of impact parameter b . The fit to the *unbinned* data (black ticks) is shown (for $z = 1.2$) with the solid blue line and its 2σ confidence region is shown by the shaded region. The 50% covering fraction is found to be at $\log b/\text{kpc} \approx 1.7$ or $b \approx 50$ kpc. The dotted red line represents the fit found by Lan (2020) for $z = 1.2$, $\log(M_*/M_\odot) = 10$ and $R_{\text{vir}} = 250$ kpc. The solid black (green) triangles represent the Nielsen et al. (2013a) (Huang et al. 2021) results, respectively, both at $z \sim 0.5$. The solid blue squares with error bars show the binned data with 1σ confidence intervals for binomial proportions (see text). The error bars are shown only with at least 2 galaxies contributing. *Top:* The redshift evolution of the 50% covering fraction with the 2σ predictive interval shown in grey. The redshift evolution found by Lan (2020) is shown with the dotted red line. The dotted-dashed line shows the expected redshift evolution of halo sizes (e.g. Mo et al. 1998).

Using the 22 MEGAFLOW MUSE fields, we searched for [O II] emitters at redshift $z = 1.0$ – 1.5 and found a total of 215 emitters down to a flux limit of $\approx 10^{-17}$ erg s $^{-1}$ cm $^{-2}$ (Schroetter et al. 2016, 2019; Zabl et al. 2019). For each of these 215 [O II] galaxies, we searched in our catalog of C IV systems with REW > 0.05 Å for matches within 500 km s $^{-1}$ and $b < 250$ kpc. We found 39 galaxies associated with 19 C IV systems. For each galaxy, we also searched for corresponding Mg II systems and found 67 galaxies associated with 32 Mg II systems.

We find that 70% of the systems for which we detect at least

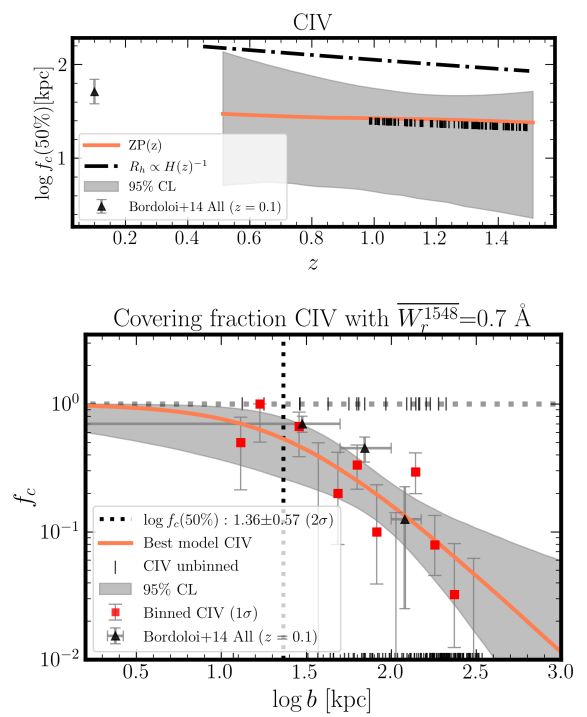


Figure 6. *Bottom:* C IV covering fraction f_c as a function of impact parameter b . The fit to the *unbinned* data (black ticks) is shown (for $z = 1.2$) with the solid orange line and its 95% (2σ) confidence region is shown by the shaded region. The black triangles represent the Bordoloi et al. (2014) $z = 0$ results. The solid red squares with error bars show the binned data with 1σ confidence intervals for binomial proportions (see text). The 50% covering fraction is found to be at $\log b/\text{kpc} \approx 1.4$ or $b \approx 25$ kpc. *Top:* The redshift evolution of the 50% covering fraction with the 2σ predictive interval shown in grey. The dotted-dashed line shows the expected redshift evolution of halo sizes (e.g. Mo et al. 1998).

one galaxy counterpart have both C IV and Mg II absorption lines. Globally, these results point towards a physical picture where Mg II and C IV (with mean REWs of ≈ 1 Å) are associated with individual $L_*/\text{sub-}L_*$ galaxies. We also find that 73% of the ‘only C IV’ systems do not appear to have any galaxy counterpart in our MUSE fields. This suggests that C IV-only gas is more likely to be part of the IGM, i.e. beyond 250 kpc rather than of the CGM, or that C IV is preferentially associated with very low mass galaxies (with $\text{SFR} \lesssim 0.3 M_\odot \text{ yr}^{-1}$).

Then, using the closest associated galaxies in our small sample of 19 (32) C IV (Mg II) absorber-galaxy pairs, we studied the covering fraction and its redshift evolution using a logistic regression to the unbinned data in a Bayesian framework (§ 3). For Mg II, we find that $f_c(r)$ reaches 50% at $r_{50} \approx 50$ kpc (46_{-13}^{+18} ; 2σ) (Fig. 5 bottom

panel). Whereas for C iv, we find that the size of the warm C iv halo is somewhat smaller with $r_{50} \approx 25$ kpc (23_{-16}^{+62} ; 2σ) (Fig. 6 bottom panel). However, given the current sample size, this difference is not significant at 2σ .

Regarding the redshift evolution of $f_c(r, z)$ for strong Mg II absorbers with mean $W_r \approx 1 \text{ \AA}$ (Fig. 5 top panel), we found that $f_c(50\%)$ evolves as $(1+z)^B$ with $B = 1.96_{-2.68}^{+2.32}$. Although the uncertainty of B is large due to our small sample size, such that the relation is consistent with no redshift evolution, the best-fit B value agrees with that derived by Lan (2020) $\propto (1+z)^2$ with a sample of 15,000 pairs. Therefore, the two results combined support a physical picture where the size of Mg II gas/halo decreases over time. We note that whether this redshift index B is ~ 0 or 2 , it appears that the Mg II gas/halo is becoming smaller with time *relative* to the dark-matter halo.

Regarding the redshift evolution of $f_c(r, z)$ for C iv absorbers (Fig. 6 top panel), our data over $z \sim 1 - 1.5$ do not show significant redshift evolution. However, extending the redshift baseline to $z \sim 0.1$ by including the Bordoloi et al. (2014) data reveals that the C iv covering fraction may in fact increase over time and possibly co-evolve with the dark-matter halo evolution (dotted-dashed line in top panel). This would indicate that the warm CGM probed by C iv is growing with the halo size. This co-evolution is expected under a scenario where the warm gas is in hydrostatic equilibrium with the halo.

With the final MEGAFLOW survey and upcoming larger surveys, it will be possible to address this redshift evolution and the potential dependence of covering fraction on azimuthal angle and/or EWs, thus yielding a better understanding of the CGM.

ACKNOWLEDGMENTS

We thank the referee for his/her in depth comments which led to an improved paper. This work received funding from the grants 3DGasFlows (ANR-17-CE31-0017), and the OCEVU Labex (ANR-11-LABX-0060) from the French National Research Agency (ANR).

Software: This work made use of the following open-source software: NUMPY (Van Der Walt et al. 2011), SCIPY (Jones et al. 2001), MATPLOTLIB (Hunter 2007), and PYMC3 (Salvatier et al. 2016). SM is supported by the Alexander von Humboldt-Stiftung via the Experienced Researchers fellowship.

DATA AVAILABILITY

The data underlying this article are available in the ESO archive (<http://archive.eso.org>). The reduced data will be shared on reasonable request to the corresponding author.

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APPENDIX A:

A1 Additional Material

Fig. A1 shows two dimensional covering fraction of Mg II as a function of impact parameter $\log b$ and redshift $\log 1+z$ using the logistic regression described in § 3 (Eq. 7). The fitted covering fraction is represented by the background color from low to high covering fractions represented as blue and red respectively. Similarly, Fig. A2 shows two dimensional covering fraction of C iv.

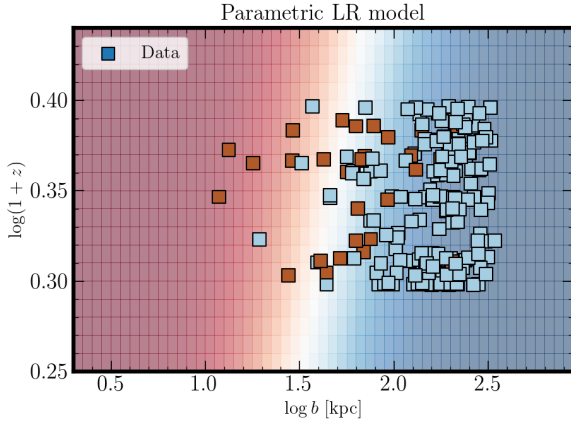


Figure A1. Two dimensional covering fraction of Mg II as a function of impact parameter $\log b$ and redshift $\log(1+z)$. The unbinned data is shown as blue (red) squares representing the undetected (detected) systems, respectively. The Mg II covering fraction from the logistic fit is represented by the background color with low (high) covering fractions represented as blue (red) respectively.

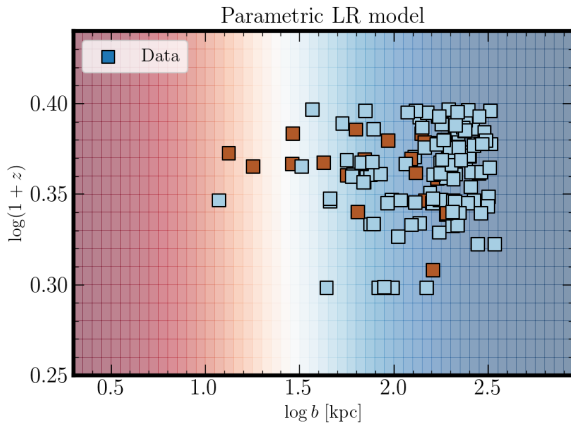


Figure A2. Two dimensional covering fraction of C IV as in Fig. A1.

A2 Strong absorbers distribution

In Figure A3, we compare the distribution of W_r^{12796} with literature samples. Our sample (in red and grey) has an overabundance of strong absorbers compared to other Mg II surveys due to the MEGAFLOW selection of multiple strong Mg II absorbers in quasar spectra. However, the lower REW population ($\log(W_r^{12796}) \leq -0.5$) of MEGAFLOW absorbers found in this study, which are not pre-selected, are in agreement with other studies.

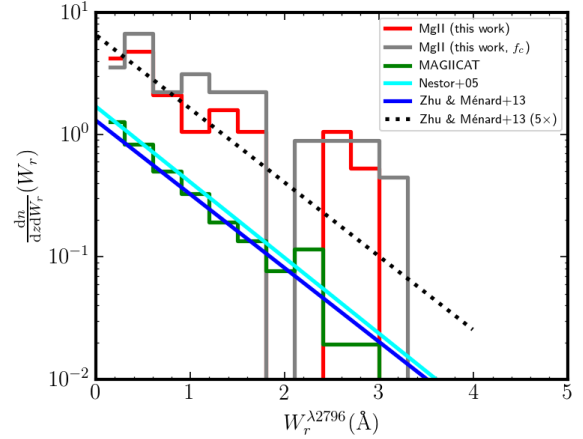


Figure A3. Rest-frame W_r^{12796} distribution of the 32 Mg II systems with C IV (red histogram) and the 52 Mg II systems (grey histogram) using in Fig. 5. The cyan (blue) curve represent the W_r distribution from Nestor et al. (2005) (Zhu & Ménard 2013) at $z = 1.2$, respectively. For comparison, the MAGICAT data is shown with the green histogram (Nielsen et al. 2013b).