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**Author:** Segers, Marijke  
**Title:** Galaxy formation traced by heavy element pollution  
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Neutral hydrogen and metal-line absorption around $z < 1$ star-forming galaxies detected with MUSE

We study the abundance of neutral hydrogen and the metal ions O\textsc{vi} and C\textsc{iii} in the circum-galactic medium (CGM) of 208 galaxies at $z < 1$, that are detected with the Multi Unit Spectroscopic Explorer in the fields centred on 16 bright quasars with archival Cosmic Origins Spectrograph spectra. The, predominantly low-mass (median stellar mass of $M_\star = 10^{8.9} \, M_\odot$ and median star formation rate of $SFR = 0.21 \, M_\odot \, yr^{-1}$), galaxies are selected blindly – without prior knowledge of the absorption data – by their continuum emission, and we measure their redshifts from their emission (or absorption) lines. Using the pixel optical depth technique, we find that the strength of the median H\textsc{i} and metal-line absorption decreases with increasing line-of-sight (LOS) velocity ($v_{\text{LOS}}$) and projected distance (both in physical units, $d_{\text{trans}}$, and as a fraction of the halo virial radius, $d_{\text{trans}}/R_{\text{vir}}$) from the galaxies. Along the LOS direction, the absorption signals start to deviate from the approximately flat trend at small $v_{\text{LOS}}$ at $v_{\text{drop}} \approx 50 \, \text{km/s}$ for H\textsc{i} and at $v_{\text{drop}} \approx 80 \, \text{km/s}$ for the metal ions. For H\textsc{i} and O\textsc{vi}, we find a significant ($>95\%$ confidence) absorption enhancement, with respect to the detection limit, out to $v_{\text{LOS}} \approx 260 \, \text{km/s}$ ($\approx 3.2 \, \text{pMpc}$ in the case of pure Hubble flow) and $v_{\text{LOS}} \approx 115 \, \text{km/s}$ ($\approx 1.3 \, \text{pMpc}$), respectively, in the LOS direction, and out to $d_{\text{trans}} \approx 300 \, \text{pkpc}$ (which is the maximum distance we can probe) in the transverse direction. In normalized units, the transverse extent of the H\textsc{i} and O\textsc{vi} signals is equal to at least four times the halo virial radius. For C\textsc{iii}, the signal extends to $v_{\text{LOS}} \approx 115 \, \text{km/s}$ ($\approx 1.3 \, \text{pMpc}; \, >68\%$ confidence) and $d_{\text{trans}} \approx 120 \, \text{pkpc}$ ($>95\%$ confidence). We do not find evidence for significant evolution of the H\textsc{i} optical depth over the range $0.30 < z < 0.48$, and of the O\textsc{vi} optical depth over the range $0.38 < z < 0.74$, where an unbiased assessment of the redshift dependence is possible. At fixed $v_{\text{LOS}}$ and $d_{\text{trans}}$, the O\textsc{vi} absorption strength within $v_{\text{LOS}} = 100 \, \text{km/s}$ increases with increasing galaxy stellar mass and star formation rate (SFR), and weakly decreases with increasing specific SFR. It also increases with increasing stellar mass at fixed $d_{\text{trans}}/R_{\text{vir}}$. However, the dependence of the signal (both its strength and extent along the LOS direction) on stellar mass is only evident when comparing the $M_\star < 10^{8.5} \, M_\odot$ and $M_\star > 10^{8.5} \, M_\odot$ stellar mass regimes, while the signal exhibits no mass dependence for $M_\star > 10^{8.5} \, M_\odot$. This likely
Absorption around $z < 1$ MUSE galaxies reflects the decreasing ability of galactic winds to drive out metals into the CGM in higher mass galaxies.

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*In preparation*
5.1 Introduction

Galaxies enrich their circumgalactic medium (CGM) with a range of metal species like carbon, oxygen and silicon. While metals are synthesised in stars, residing in the dense parts of the galaxies, they can travel out to large distances, enriching the diffuse gas around galaxies and in the intergalactic medium (IGM), as they are expelled by galaxy-scale outflows. These outflows are believed to be driven by feedback processes resulting from star formation or due to active galactic nuclei (AGN). The ubiquity of galactic winds in star-forming galaxies at $0.5 \lesssim z \lesssim 3$, as implied by observations (e.g. Pettini et al., 2001; Steidel et al., 2010; Weiner et al., 2009; Rubin et al., 2014), supports this picture. Furthermore, various theoretical studies employing hydrodynamical simulations of galaxy formation have emphasised the importance of galactic winds for enriching the CGM and IGM to the observed levels (e.g. Aguirre et al., 2001b,a; Oppenheimer & Davé, 2006; Cen & Chisari, 2011; Wiersma et al., 2011).

Observing the CGM by probing different metal ionization states provides information about the composition, density, temperature and kinematics of the gas around galaxies, and therefore about the galaxies themselves: it gives insight into their star formation history and the processes through which they interact with their surroundings. However, as the gas in the CGM and IGM is generally too diffuse to be detected in emission, a common approach is to observe it in absorption against the light from a bright quasi-stellar object (QSO). This technique has been used to study a wide range of ion transitions at both low and high redshift, in particular Mg\textsc{ii} (e.g. Petitjean & Bergeron, 1990; Bowen et al., 1995; Chen et al., 2010; Nielsen et al., 2013), C\textsc{iv} (e.g. Chen et al., 2001; Schaye et al., 2003; Cooke et al., 2013; Bordoloi et al., 2014; Liang & Chen, 2014) and O\textsc{vi} (e.g. Carswell et al., 2002; Danforth & Shull, 2005; Aguirre et al., 2008; Wakker & Savage, 2009; Prochaska et al., 2011; Turner et al., 2014), as well as neutral hydrogen (H\textsc{i}; e.g. Wakker & Savage, 2009; Rakic et al., 2012; Rudie et al., 2012; Tumlinson et al., 2013).

A crucial step in the interpretation of CGM observations within the framework of galaxy formation, is to connect the absorption features from the QSO spectra to the galaxies that are associated with the absorbing gas. For a sample of absorption systems (i.e. the absorber-centred approach; see e.g. Stocke et al., 2006; Burchett et al., 2016), this is generally done by selecting the galaxy that is ‘closest’ to each absorber, considering both its projected distance to the QSO sightline and its velocity offset along the line-of-sight (LOS). The galaxy association is, however, not unambiguous, as multiple galaxies might be similarly close and it is not obvious whether the absolute distance or the distance relative to the galaxy size should be considered. Furthermore, the association is complicated by the possibility that the true galaxy giving rise to the absorption is too faint to be detected with the instrument that is used. For example, Rahmati & Schaye (2014) found that this could explain the low success rate of observational searches for galaxy counterparts of optically thick H\textsc{i} absorbers. The alternative approach of connecting galaxies and absorbers is to select the absorber that is closest to each galaxy (i.e. the galaxy-centred approach; see e.g. Bowen et al., 1995; Rakic et al., 2012; Tumlinson et al.,
individual galaxies rather than with galaxy voids. The studies by these results, they argued that O\textsubscript{L} incidence rate beyond that. For C\textsubscript{⇒} ≈ (corresponding to species, as it is observed with near-unity covering fractions out to distances of low-ionization species trace cold (detected some O\textsubscript{L} Halos survey, only probes distances up to 200 pkpc, or
\[R_{\text{vir}}\] of 800 proper kpc (pkpc), with the maximum distance reducing to 400 pkpc in regions that are complete down to galaxy luminosities of \(L = 0.1L^\ast\). They also derived a median distance of 625 pkpc from the O\textsubscript{L} absorber to the nearest \(L > L^\ast\) galaxy, and a distance of 335 pkpc to the nearest \(L > 0.1L^\ast\) galaxy. Based on these results, they argued that O\textsubscript{L}-bearing gas is predominantly associated with individual galaxies rather than with galaxy voids. The studies by Wakker & Savage (2009) and Prochaska et al. (2011) found similar distances from O\textsubscript{L} absorbers to the nearest 0.1L\ast and L\ast galaxies.

Various studies of metal absorbers and their relation to galaxies have found that they generally reside at relatively small distances to galaxies (i.e. close enough to be considered part of their CGM), as opposed to weak H\textsc{i} absorbers appearing as Ly\textalpha forest absorbers, which are believed to trace the filamentary large-scale structure of the Universe (e.g. Cen et al., 1994; Davé et al., 1999; Schaye, 2001). Stocke et al. (2006) found that for each of the \(z < 0.15\) O\textsubscript{L} absorbers in their sample, a galaxy resides within a 3D distance (corrected for increased distances along the LOS) of 800 proper kpc (pkpc), with the maximum distance reducing to 400 pkpc for their sample), and to have a steeply declining incidence rate beyond that. For C\textsubscript{⇒}, similar results have been obtained by Chen et al. (2001) and Bordoloi et al. (2014, probing \(\leq 0.1L^\ast\) galaxies), while the typical extent of Mg\textsubscript{II}-bearing gas seems to be lower (e.g. Bowen et al., 1995; Chen et al., 2010). In contrast, O\textsubscript{L} is found to be somewhat more extended than the low ionization species, as it is observed with near-unity covering fractions out to distances of \(\approx 200\) pkpc, or \(\approx 1 – 2R_{\text{vir}}\), around (sub-)\(L^\ast\) galaxies (e.g. Prochaska et al., 2011; Tumlinson et al., 2011; Johnson et al., 2015, where the second study, the COS-Halos survey, only probes distances up to 150 pkpc). Johnson et al. (2015) even detected some O\textsubscript{L} out to a distance of \(3R_{\text{vir}}\). Furthermore, while it is known that low-ionization species trace cold (\(T \sim 10^4\) K), photoionized gas, the origin of the gas traced by O\textsubscript{L} is still a topic of debate: observations seem to suggest that O\textsubscript{L} can arise in both photoionized and collisionally ionized gas (see e.g. Carswell et al., 2002; Thom & Chen, 2008; Savage et al., 2014; Stocke et al., 2014).

In this work, we study the abundance of H\textsc{i}, O\textsubscript{L} and C\textsubscript{II}, where we mainly focus on O\textsubscript{L}, in the CGM of \(z < 1\) galaxies detected using the Multi Unit Spectro-
scopic Explorer (MUSE; Bacon et al., 2010) on the Very Large Telescope (VLT). We detect these galaxies by their Hα (\(z_{\text{em}} \lesssim 0.4\)), \(\text{O} \text{II}\) (\(z_{\text{em}} \gtrsim 0.25\)), \(\text{O} \text{III}\) (\(z_{\text{em}} \lesssim 0.85\)) or Hβ (\(z_{\text{em}} \lesssim 0.9\)) emission in the fields centred on 16 sightlines towards bright QSOs (\(z_{\text{QSO}} = 0.4 - 1.5\)) that have been observed with the Cosmic Origins Spectrograph (COS; Green et al., 2012) on board the Hubble Space Telescope (HST). This enables us to probe the galaxy CGM in absorption out to projected distances of \(\approx 300\) pkpc. This study is part of the MUSE Quasar-field Blind Emitter Survey (MUSE-QuBES), which aims to study the CGM of star-forming galaxies in absorption by conducting a search for line-emitting galaxies in the fields near QSO sightlines for which high-quality spectra are available. The survey is blind in the sense that the QSOs were not selected based on the presence of any particular absorbers or nearby galaxies. Complementary to the sample of 16 low-redshift QSO fields, MUSE-QuBES also targets 8 high-redshift QSO fields (with QSOs at \(z_{\text{QSO}} = 3.6 - 4.0\)), to study the CGM of Lyα-emitting galaxies at \(3 < z < 4\) (Muzahid et al., in prep.).

The fact that MUSE is an Integral Field Spectrograph (IFS) enables us to compile a sample of a few hundred galaxies around QSO sightlines very efficiently: while non-IFS studies need to carry out spectroscopic follow-up observations to accurately determine the redshifts of the galaxies after detecting them through imaging, we can detect the galaxies and measure their redshifts both at the same time. While the galaxies do not necessarily have to be continuum sources to be able to detect them with MUSE and determine their redshifts, we do focus our current study on continuum-detected galaxies only. In the future, we will extend the sample by also including purely line-emitting galaxies.

Our deep MUSE observations – ranging from two to ten hours of exposure time per field – of a relatively small survey volume yield a sample of predominantly low-mass (i.e. with stellar masses of \(M_* < 10^{10}\) M\(_\odot\)) galaxies. As measured in the Cousins R band, the median luminosity of the sample is \(\approx 0.09L^*\). Sub-\(L^*\) galaxies are interesting targets for studies of CGM metals, as the majority of the OVI absorbers is likely to be associated with galaxies with luminosities significantly below \(L^*\) (e.g. Stocke et al., 2006; Wakker & Savage, 2009; Prochaska et al., 2011) (even though the OVI abundance around individual galaxies likely peaks for \(L \approx L^*\) galaxies; Oppenheimer et al., 2016). By comparing the observed rate of incidence of OVI absorbers with the occurrence of low-redshift galaxies, Tumlinson & Fang (2005) inferred that \(L \gtrsim L^*\) galaxies alone cannot account for the observed population of OVI absorbers, unless their surroundings are enriched out to unrealistically large distances. The theoretical study by Wiersma et al. (2010) also emphasised the role of low-mass galaxies in the enrichment of the IGM, predicting that more than half of the IGM metal mass at \(z = 0\) is contributed by \(M_* < 10^9\) M\(_\odot\) galaxies, while Booth et al. (2012) inferred from observations of CIV that the low-density IGM at \(z = 3\) was primarily enriched by galaxies residing in \(M_{\text{vir}} < 10^{10}\) M\(_\odot\) haloes.

In this work, we study the CGM abundance of H\(_i\), OVI and CII by measuring the median pixel optical depth in the QSO spectra as a function of LOS velocity and projected distance to the galaxies. We study the extent of the absorption signal in both the LOS and projected directions, and we investigate how the absorption strength of H\(_i\) and OVI evolves over the redshift range probed. We also explore the dependence of the OVI absorption strength on galaxy stellar mass and star for-
Absorption around $z < 1$ MUSE galaxies

A study of the O\textsc{vi} covering fraction around MUSE galaxies as a function of O\textsc{vi} column density, and how it depends on the different galaxy properties, will be presented in Straka et al. (in prep.).

This work is organized as follows. In Section 5.2, we give an overview of the sample of QSO targets and the MUSE observations. We also explain how we identify galaxies and measure their redshifts and other properties. In Section 5.3, we describe the characteristics of the COS spectra, the optical depth recovery performed on the spectra and the construction of the median optical depth profiles. We present our results in Section 5.4: we show the H\textsc{i}, O\textsc{vi} and C\textsc{iii} absorption strength as a function of LOS velocity and transverse distance (Section 5.4.1), and its dependence on galaxy redshift (H\textsc{i} and O\textsc{vi}; Section 5.4.2), stellar mass (O\textsc{vi}; Section 5.4.3) and SFR (O\textsc{vi}; Section 5.4.4). We summarise our conclusions in Section 5.5. Throughout this work, we adopt a cold dark matter cosmology with parameters $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

5.2 Galaxy sample

We carry out a blind spectroscopic redshift survey in the fields centred on 16 QSOs using the MUSE instrument, which is mounted on the VLT. In this section, we first describe our criteria for selecting the QSO targets. Then, we describe the MUSE observations, carried out as part of the MUSE Guaranteed Time Observations, and the method we use to detect galaxies and determine their redshifts. We also explain how we obtain an estimate of the galaxy stellar mass and SFR.

5.2.1 QSO sample selection

All QSO targets have high-quality absorption spectra from HST/COS, with coverage in both the G130M and G160M gratings. The QSOs are sufficiently luminous, with a $V$-band magnitude of $m_V \leq 18$, to have a relatively high signal-to-noise ratio (S/N) over the majority of the COS wavelength range. Their redshifts are chosen to be both high enough ($z_{\text{QSO}} > 0.4$) so that the full range for which H\textsc{ii} emission is observable with MUSE can be studied in absorption (i.e. $z < z_{\text{QSO}}$), and low enough ($z_{\text{QSO}} < 1.5$) to limit the amount of blended absorption in the spectra. The maximum redshift of 1.5 corresponds to the maximum redshift at which O\textsc{ii} emission can be detected with MUSE. Furthermore, to be able to observe the targets from Paranal Observatory, we only select QSOs with a declination below $+30^\circ$. The properties of our final sample of 16 QSOs are summarized in Table 5.1.

5.2.2 MUSE observations

The MUSE observations of the 16 QSO fields were conducted between September 2014 and September 2016 (ESO programmes 094.A-0131, 095.A-0200, 096.A-0222 and 097.A-0089). The total amount of exposure time is 60.75 h, where all fields have been observed for at least 2 h and 4 fields have been observed for 8–10 h. An overview of the exposure time per field is given in Table 5.2. Each observation block of 1 h was split into $4 \times 900$ s exposures, which were rotated by $90^\circ$ and offset...
Table 5.1: Sample of QSO targets. From left to right, the columns show the QSO name, right ascension (J2000), declination (J2000), redshift, $V$-band magnitude, exposure time ($t_{exp}$) with the COS/G130M grating, $S/N$ per resolution element at $\lambda = 1250$ Å, exposure time with the COS/G160M grating, $S/N$ per resolution element at $\lambda = 1650$ Å and the HST programme ID of the COS observations.

<table>
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<th>QSO name</th>
<th>RA</th>
<th>Dec.</th>
<th>$z_{QSO}$</th>
<th>$m_V$</th>
<th>$t_{exp}$ [h]</th>
<th>$S/N$</th>
<th>$t_{exp}$ [h]</th>
<th>$S/N$</th>
<th>PID</th>
</tr>
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<td>-52 58 49</td>
<td>0.425</td>
<td>16.4</td>
<td>2.3</td>
<td>14.5</td>
<td>2.5</td>
<td>5.8</td>
<td>11520</td>
</tr>
<tr>
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<td>-45 06 12</td>
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<td>1.6</td>
<td>17.2</td>
<td>11541</td>
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<td>21.6</td>
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</tr>
<tr>
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*aThis is the $S/N$ at $\lambda = 1350$ Å. Due to a Lyman-limit system at $z = 0.390$, there is no flux at $\lambda < 1280$ Å.
Table 5.2: Overview of the MUSE observations. From left to right, the columns show the QSO name, exposure time, effective seeing measured at $\lambda = 7000$ Å and number of galaxies per QSO field included in our galaxy catalogue.

<table>
<thead>
<tr>
<th>QSO name</th>
<th>$t_{\text{exp}}$ [h]</th>
<th>Seeing [$''$]</th>
<th>Number of galaxies</th>
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by a small $\approx 1 - 5''$ shift from each other. The effective seeing per field, corresponding to the full width at half maximum (FWHM) of a 2D Gaussian profile fitted to a point source at $\lambda = 7000$ Å in the reduced and combined data cube, varies between 0.54'' and 1.20'', but is typically 0.7 – 0.8'' (see Table 5.2).

With the MUSE field-of-view (FoV) of $1' \times 1'$ centred on the QSO, we are able to observe a region of $480 \times 480$ pkpc around the QSO at $z \approx 1$ ($110 \times 110$ pkpc at $z \approx 0.1$). The field is spatially sampled by a grid of 0.2''×0.2'' pixels. All observations were carried out using the standard wavelength range of 4750–9300 Å, sampled by 1.25 Å spectral pixels. The spectral resolution ranges from $R \approx 1800$ at $\lambda = 5000$ Å to $R \approx 3500$ at $\lambda = 9000$ Å, corresponding to a FWHM of 167 km/s to 86 km/s.

Data reduction

The data reduction is performed using the standard MUSE data reduction pipeline (v1.2; Weilbacher et al., 2012, in prep.), adopting the default set of parameters. First, a number of basic reduction steps – like bias subtraction, flat-fielding, illumination correction and wavelength calibration – is carried out for each individual science exposure, where the calibration frames are used that were taken closest in time to the respective science frames. We then perform an initial sky subtraction, using the appropriate line spread function (LSF) calibration frames, and construct a 2D white-light image for each exposure by collapsing the corresponding data cube along the wavelength direction. Note that this initial sky subtraction is only done to facilitate the detection of continuum sources in the exposure white-light images, which are used to determine the dithering offset between the exposures: the actual
sky subtraction on the data used for our science is performed using **CubeSharp** (as described below). Based on the spatial positions of the point sources (preferably two or more stars, otherwise the QSO and a star) detected in the white-light images, we calculate the offset of each exposure with respect to a reference frame, which we choose to be the first exposure of the field. These offsets are then used to realign the calibrated, non-sky subtracted science frames to the same coordinate system, so that they can be combined after the final data reduction steps without shifting them.

We perform a few additional reduction procedures using the **CubExtractor** package (Cantalupo et al., in prep.). These are described by Borisova et al. (2016), and we will only briefly outline the main steps. For each exposure, the **CubeFix** routine applies a flat-fielding correction to the individual slices (‘spatial segments’) of the Integral Field Unit (IFU) and to the individual IFU channels (‘wavelength segments’). It utilises the sky continuum and sky lines as spatially uniform sources to normalize each of the slices per channel to the same median flux value, and it then normalizes each of the channels to the same median flux value. Masks are created to cover any gaps in between the IFU slices and slice edges that have significant flat-fielding residuals. Next, the **CubeSharp** routine is used to perform a sky subtraction, which is uses the shape of the sky LSF obtained from the data itself and is flux-conserving by design. The data cubes from the individual exposures are then combined (by taking a $3\sigma$-clipped mean for each spatial pixel) and converted into one white-light image. After the bright continuum objects in the field have been identified using the **CubEx** routine, the procedures with **CubeFix** and **CubeSharp** as outlined above are repeated, this time with the bright objects masked out. This improves the flat-fielding of the IFU slices and channels. After the second round of sky subtraction, the exposure files are combined into the final data cube for the QSO field.

The wavelengths in the MUSE data cubes are given in air. However, all redshifts given in this work correspond to vacuum redshifts, as we apply the appropriate corrections while building the galaxy catalogue.

### 5.2.3 Galaxy identification

We compile a sample of galaxies in the 16 QSO fields by detecting them in the MUSE data through their continuum emission, and measuring their redshifts from their emission-line (or absorption-line) features. For each QSO field, we construct a white-light image from the final MUSE data cube. We run the **Source Extractor** (**SExtractor**; Bertin & Arnouts, 1996) package on each image, using a detection threshold of $1\sigma$ per pixel (**DETECT_THRESH = 1**) and requiring a minimum number of neighbouring pixels above the threshold of $3$ (**DETECT_MINAREA = 3**). This yields a sample of 2299 continuum-detected objects.

We then use a modified version of the application **Marz** (Hinton et al., 2016) to identify galaxies and determine their redshifts based on their spectral features. For every object, we extract a 1D spectrum from the MUSE data cube using a segmentation map from **SExtractor**, where we sum the flux, weighted by the variance, from all pixels associated to the object that are $0.5\sigma$ above the background in the white-light image. This spectrum is loaded into the interactive **Marz** interface to
Table 5.3: Adopted rest-frame wavelengths of absorption-line species studied in the COS spectra (upper part) and emission-line features used to measure galaxy redshifts from the MUSE data (lower part). In case of a line doublet, the wavelengths of both components are given.

<table>
<thead>
<tr>
<th>Name</th>
<th>Rest-frame wavelength [Å]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorption</td>
<td></td>
</tr>
<tr>
<td>C\text{\textsc{iii}}</td>
<td>977.02</td>
</tr>
<tr>
<td>O\text{\textsc{vi}}</td>
<td>1031.93, 1037.62</td>
</tr>
<tr>
<td>H\text{\textsc{i}} Ly\text{\alpha}</td>
<td>1215.67</td>
</tr>
<tr>
<td>Emission</td>
<td></td>
</tr>
<tr>
<td>O\text{\textsc{ii}}</td>
<td>3727.09, 3729.88</td>
</tr>
<tr>
<td>H\beta</td>
<td>4862.69</td>
</tr>
<tr>
<td>O\text{\textsc{iii}}</td>
<td>4960.30, 5008.24</td>
</tr>
<tr>
<td>H\alpha</td>
<td>6564.61</td>
</tr>
</tbody>
</table>

Figure 5.1: Redshift ranges where absorption-line (blue) and emission-line (green) species can be observed, based on the wavelength coverage of COS and MUSE, respectively. The top panel shows the number of QSO sightlines covering each redshift interval (i.e. the number of QSOs with $z_{\text{QSO}} > z$ at each $z$). We select galaxies below a redshift of $z = 0.91$ (vertical dashed line), where their CGM can be studied in absorption.
classify the object as a galaxy or a star (or an instrumental artifact), based on an automated matching algorithm. In brief, the observed spectrum is compared to a number of template spectra and, in the case of a galaxy, aligned to measure the redshift. Instead of the standard set of templates, we use a set of 23 stellar spectra, ranging from O stars to white dwarfs, and a set of 20 representative galaxy spectra, which were taken from MUSE observations of the Hubble Ultra Deep Field (Bacon et al., in press; Paalvast et al., in prep.). These galaxy templates cover a range of galaxy types (late-type, early-type, transitional), a range of emitter types (as it depends on the redshift which lines are visible in the optical), and allow a weak or strong continuum relative to the emission lines. Marz selects the best-fitting template by performing a cross-correlation, but the user is allowed to select a different template based on visual inspection. The objects classified as galaxies are then automatically assigned a redshift, which we manually assign a quality flag ($QOP$) indicating its reliability.

The most prominent emission lines that are used for the redshift determination are $\text{H} \alpha$, $\text{H} \beta$, $\text{O} \text{ii}$, and $\text{O} \text{iii}$. Their adopted rest-frame wavelengths\(^1\) are summarized in the bottom part of Table 5.3 and their observable redshift range, given the wavelength coverage of MUSE, is shown in the bottom panel of Fig. 5.1. In addition, some galaxies (about 20% of the final sample) show interstellar absorption lines, of which the calcium II H and K lines (at 3968.47 Å and 3933.66 Å, respectively) are the most prominent ones. When available, these are also used for the redshift determination.

Out of the 2299 objects detected in the white-light images, we can estimate the redshift of 868 galaxies. In this work, we only use the galaxies with the highest quality flag, $QOP = 3$, for which the redshift estimate is based on multiple spectral features – either two or more emission lines or multiple absorption lines (at least the Ca ii H and K lines). This corresponds to $\approx 44\%$ of the 868 galaxies. The flags $QOP = 1$ and $QOP = 2$ refer to galaxies with redshift estimates based on only one spectral feature, where its identification is based on the line shape or the absence of other lines, or to galaxies with a noisy spectrum or weak spectral features, that make the redshift estimate less robust. We will refer to the galaxy redshift as $z_{\text{em}}$, since for the majority of the galaxies the redshift is derived from their emission lines.

As the redshifts resulting from the galaxy template match by Marz can be uncertain by $\sim 10^2$ km/s, we use a modified version of the code Platefit (Tremonti et al., 2004; Brinchmann et al., 2004) to further refine the redshifts. This routine constrains the local continuum and fits (positive and negative) Gaussian profiles to a large set of emission and absorption lines. Doublet features like $\text{O} \text{ii}$ are fit with a double Gaussian profile. In this version of Platefit, the redshifts of both the Balmer lines and the forbidden lines are tied together, allowing common shifts up to $\pm 300$ km/s with respect to the original value from Marz. The routine therefore enables us to refine the redshift estimates, but also to measure the flux in various emission lines, which we will use to obtain an estimate of the SFR (see Section 5.2.4). We note that we apply two corrections to the error estimates on the line fluxes re-

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\(^1\)Note that these wavelengths are given in vacuum. Even though the original MUSE data cube contains wavelengths in air, Marz corrects for this by converting the wavelengths to vacuum before determining the redshift.
Absorption around $z < 1$ MUSE galaxies turned by Platefit. As will be described by Bacon et al. (in press), to take into account the correlation between adjacent pixels, the noise estimate per pixel (and therefore the error on the line flux) needs to be multiplied by a factor of $1/0.60$, so that it reflects the true pixel-to-pixel standard deviation. Furthermore, to correct for the fact that Platefit does not automatically include all sources of error – such as the uncertainty in the continuum subtraction – in its estimate of the error on the line flux, we multiply the errors by a factor of 2.2 for OII and the Balmer lines and by a factor of 1.3 for forbidden lines (following Brinchmann et al., 2008). Hence, we adopt line flux errors that are 3.7 times larger than the original values from Platefit in the case of OII and the Balmer lines, and errors that are 2.2 times larger in the case of OIII. These errors are used to assess the significance ($S/N$) of the emission lines.

Having refined our redshift estimates, we apply the following selection cuts to the galaxy sample. As we aim to study the CGM of the galaxies in absorption, we only select galaxies at $z_{\text{em}} < 0.91$, which corresponds to the redshift range in which the H\textsc{i} Ly\alpha, OVI or C\textsc{ii} absorption lines are observable with COS (as indicated in blue in Fig. 5.1). The upper bound of 0.91 on the redshift includes a velocity range up to $\approx 10,000$ km/s redwards of the maximum C\textsc{iii} redshift covered by COS, corresponding to the velocity range in which we plot the absorption signal (see Section 5.4). This yields a sample of 233 galaxies. Furthermore, for the 7 QSO fields with $z_{\text{QSO}} < 0.91$, we only select galaxies that are at redshifts at least 3000 km/s bluewards of the redshift of the QSO, in order to avoid QSO proximity effects. Our final galaxy catalogue includes 208 galaxies, with a median redshift of $z_{\text{em}} = 0.52$. For each QSO field, the number of galaxies included in the catalogue is listed in the fourth column of Table 5.2. Note that for one QSO field, HE 0435-5304, we do not detect any galaxies below the QSO redshift (neither with $QOP = 3$, nor with $QOP = 1$ or $QOP = 2$). Hence, we will not consider this field in our absorption analysis.

Fig. 5.2 shows the projected proper distance from the galaxy to the QSO sightline, referred to as the galaxy impact parameter, as a function of the galaxy redshift. The impact parameters range from 11 to 304 pkpc (with a median of 141 pkpc), limited at the low end by the extent of the QSO point spread function (PSF; which we aim to improve in future work) and at the high end by the size of the MUSE FoV. In units of the halo virial radius, which we define as the radius at which the mean enclosed density is 200 times the critical density of the Universe (see Section 5.2.4 for its derivation), the impact parameters range from 0.062$R_{\text{vir}}$ to 5.2$R_{\text{vir}}$ and have a median of 1.6$R_{\text{vir}}$. Fig. 5.3 shows the distribution of ‘normalized’ impact parameters, and how they vary as a function of the galaxy redshift.

To assess the type of emission exhibited by the galaxies in our sample, we show in Fig. 5.4 the galaxy redshift distribution split by emitter type. The red histograms include all galaxies for which the indicated emission line has $S/N > 3$. Hence, some galaxies occur in multiple panels. For 69 out of the 208 galaxies, H\alpha is detected with $S/N > 3$. This number is relatively low, as H\alpha is only observable with MUSE.

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2We note that the adopted velocity limit of 3000 km/s is, in this case, equivalent to a limit of 6000 km/s, as the 7 QSO fields with $z_{\text{QSO}} < 0.91$ do not contain galaxies with redshifts between 6000 km/s and 3000 km/s below the QSO redshift.
5.2 Galaxy sample

Figure 5.2: Galaxy impact parameter as a function of galaxy redshift for our final sample of 208 galaxies detected with MUSE. The histograms at the top and on the right show the individual distributions of redshift and impact parameter, respectively.

Figure 5.3: Galaxy impact parameter, in units of the halo virial radius, as a function of galaxy redshift for the total sample of 208 galaxies. The histograms at the top and on the right show the individual distributions of redshift and normalized impact parameter, respectively.
Absorption around $z < 1$ MUSE galaxies

Figure 5.4: The galaxy redshift distribution split by emitter type. The red (black) histogram in each panel includes galaxies for which the respective emission line has $S/N > 3$ (has $S/N > 3$ and a higher $S/N$ than the other lines), where the total number of galaxies included is indicated by the first (second) number in the legend. Hence, while for the red histograms a single galaxy can occur in multiple panels, for the black histograms each galaxy occurs only once. All but 8 galaxies exhibit at least one of the H$\alpha$, H$\beta$, O$\text{II}$ or O$\text{III}$ lines with $S/N > 3$, where for the majority of the galaxies O$\text{III}$ has the highest $S/N$.

at $z_{\text{em}} < 0.42$: if we focus solely on that redshift range, then we find that $\approx 91\%$ of the galaxies has significant (i.e. $S/N > 3$) H$\alpha$ emission. The H$\beta$ and O$\text{II}$ lines, which are observable over most of the redshift range (O$\text{II}$ at $z_{\text{em}} > 0.27$), are significantly detected for approximately 70% of the galaxies, while O$\text{III}$ is significantly detected for $\approx 91\%$ of the galaxies. For the majority of the galaxies, O$\text{III}$ is also the line that exhibits the highest $S/N$ (compared to the other three lines), as illustrated by the black, dashed histograms. Only at the low- and high-redshift ends of the distribution, a significant fraction of the galaxies exhibits the highest $S/N$ in the H$\alpha$ and O$\text{II}$ emission lines, respectively. Overall, we find that only 8 galaxies in our sample do not show any emission with $S/N > 3$ in either H$\alpha$, H$\beta$, O$\text{II}$ or O$\text{III}$. One of these, however, shows O$\text{III}$ emission with $S/N = 2.5$, where both O$\text{III}$ components with rest-frame wavelengths 5008 Å and 4960 Å are visible in the spectrum, and H$\beta$ and O$\text{II}$ emission with $S/N \approx 0.7$. We therefore consider its identification to be robust. For the other 7 galaxies, their identification and redshift measurement is solely based on interstellar absorption lines, where in all cases the spectrum exhibits strong absorption in at least the Ca$\text{II}$ H and K lines.

In future work, we will expand the catalogue with a sample of purely line-emitting galaxies. This requires the detection of emission-lines sources in 3D, as these sources do not have counterparts in the white-light image. There are a number of tools available, like CubEx (Cantalupo et al., in prep.) and LSDCat (Herenz & Wisotzki, 2017), that are specifically designed for MUSE data. The CubEx detection algorithm is based on finding and connecting 3D pixels above a certain $S/N$ threshold. In this case, great emphasis is placed on the identification afterwards in
5.2 Galaxy sample

Figure 5.5: Galaxy stellar mass as a function of Cousins R broadband magnitude. The histograms at the top and on the right show the individual distributions of R-band magnitude and stellar mass, respectively. The galaxies exhibit a positive correlation between the stellar mass and the brightness in the R-band: the best-fitting relation (equation 5.1) is shown by the black, dashed line.

constructing a sample of objects that are physically real. The LSDCat package instead takes a matched filtering approach, where the data cube is first convolved with the expected 3D signal of a compact emission line before 3D pixels above a certain S/N threshold are detected and grouped into objects.

5.2.4 Derivation of galaxy properties

Stellar mass and R-band magnitude

To estimate the stellar masses of the galaxies, we use the FAST code (v1.0; Kriek et al., 2009), which fits stellar population synthesis (SPS) templates to a set of photometric flux values. Since for the majority of the QSO fields, there is not sufficient ancillary photometric data available, we calculate for every galaxy the flux in a number of pseudo filters from the MUSE data. We use a set of 11 adjacent boxcar filters, with a width of 400 Å each and spanning the wavelength range from 4800 Å to 9200 Å. We calculate the filter flux by convolving the 1D galaxy spectrum – the same one as used for the redshift determination with MARZ – with a boxcar function centred at $\lambda = 5000, 5400, \ldots$ Å. As the models only fit the continuum, we mask bright emission lines by excluding a velocity range of $\pm 200$ km/s around emission lines detected with S/N $> 1$ (and $\pm 500$ km/s around lines with S/N $> 3$) and interpolating the continuum, after smoothing it by a low-order spline function, across the gaps. Since the CUBE SHARP algorithm used for the sky subtraction is designed to conserve the continuum flux, the boxcar filter fluxes are not affected by any sky

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Some of the QSO fields do have HST imaging, but in a limited number of filters.
Figure 5.6: Galaxy stellar mass (top panel), SFR (middle panel) and specific SFR ($= SFR/M_{\star}$; bottom panel) as a function of emission redshift. While the top panel shows the full sample, the middle and bottom panels only show galaxies for which we could obtain an estimate of the SFR, derived from the H$\alpha$ (purple diamonds), H$\beta$ (blue triangles) or OII (green squares) emission-line flux. The black symbols indicate upper limits. The grey shading indicates the redshift range in which we study the dependence of the OVI absorption strength on various galaxy properties, which we select in order to reduce the correlation between the absorption strength and properties other than the one under consideration (see Section 5.4.1 for details).
line residuals. FAST then uses $\chi^2$ minimalization to determine the best-fitting spectrum from a grid of SPS template spectra. We use the SPS models from Bruzual & Charlot (2003), assuming a Chabrier (2003) stellar initial mass function (IMF) from $0.1 - 100\,M_\odot$, an exponentially declining star formation history with characteristic timescale $\tau$ and a Calzetti et al. (2000) dust law. The grid of model spectra is constructed for $\tau$ varying between $10^{8.5}$ yr and $10^{11}$ yr in steps of 0.5 dex, the age of the stellar population varying between $10^7$ yr and $10^{10}$ yr in steps of 0.2 dex, the visual extinction varying between $A_V = 0$ mag and $A_V = 3$ mag in steps of 0.1 mag and adopting values for the metallicity of $Z = 0.004, 0.008, 0.02, 0.05$ (where $Z$ refers to the mass fraction of metals).

The histogram on the right side of Fig. 5.5 shows the distribution of best-fitting stellar masses for the total sample of 208 galaxies, while the upper panel of Fig. 5.6 shows the stellar mass as a function of redshift. The sample has a median stellar mass of $M_* = 10^{8.9}\,M_\odot$, with a standard deviation of 0.9 dex. Hence, the majority of the galaxies have a stellar mass $< 0.1M_\star$, where $M_\star \approx 10^{10.7-11.0}\,M_\odot$ is the characteristic turnover mass of the galaxy stellar mass function at $z < 1$ (see e.g. Baldry et al., 2012; Moustakas et al., 2013; Muzzin et al., 2013). The galaxies in the sample have much lower masses than the galaxy used in other quasar absorption-line studies such as the COS-Halos survey (Tumlinson et al., 2013; Werk et al., 2013). Even compared to the $z < 1$ CGM studies by Bordoloi et al. (2014, i.e. the COS-Dwarfs survey) and Liang & Chen (2014), which are specifically focused on low-mass galaxies, our sample contains a factor of $\approx 2 - 10$ more galaxies with $M_* < 10^9\,M_\odot$. The typical mass of our galaxy sample is also significantly lower than the mass of the Lyman Break Galaxies studied in the Keck Baryonic Structure Survey (KBSS) at $z \sim 2 - 3$ (Rudie et al., 2012; Turner et al., 2014), which have $M_* \sim 10^{10}\,M_\odot$.

The stellar mass of the galaxies is positively correlated with their brightness, as measured with the Cousins $R$ broadband magnitude $M_R$ (as shown in Fig. 5.5). We calculate $M_R$ by constructing a pseudo-broadband image from the MUSE data cube using the Cousins $R$ filter transmission curve, and running SExtractor with the same parameters as on the white-light image. The magnitude zeropoint is derived from the magnitudes of objects in the fields that have a known brightness. We apply a K-correction to each galaxy magnitude, assuming an Sab galaxy type. We find that the best-fitting relation between $M_*$ and $M_R$ is

$$\log_{10} \frac{M_*}{M_\odot} = -0.43 \log_{10} M_R + 0.77,$$

(5.1)

where the values of the two free parameters have been obtained using least square fitting. This relation is shown by the black, dashed line in Fig. 5.5.

For each galaxy, we estimate the halo mass and halo virial radius, defined as the mass and radius of a spherical region within which the mean density is equal to 200 times the critical density of the Universe, from its stellar mass and redshift, using the abundance matching relation from Moster et al. (2013). The sample has a median halo mass of $M_{\text{vir}} = 10^{11.1}\,M_\odot$ (with a standard deviation of 0.6 dex) and a median virial radius of $R_{\text{vir}} = 86\,\text{pkpc}$ (with a standard deviation of 0.2 dex). We note that for satellite galaxies the Moster et al. (2013) relation is actually not applicable. For satellites, the halo mass derived from abundance matching is a poor estimate of the
Absorption around $z < 1$ MUSE galaxies

Figure 5.7: The distribution of SFRs for the 185 out of 208 galaxies with an estimate of their SFR, from either the H$\alpha$ (purple; top panel), H$\beta$ (blue; middle panel) or O$\text{II}$ (green; bottom panel) emission-line flux. The total distribution (dashed) and distribution of upper limits (dotted) are shown in black (all panels). Galaxies with H$\alpha$-based SFR estimates mainly populate the low end of the distribution, as they are restricted to low redshifts ($z_{em} < 0.42$), while galaxies with H$\beta$-based SFRs (by construction) mainly populate the high end.

We use the emission-line fluxes of the Balmer lines and O$\text{II}$ to derive an estimate of the SFR of the galaxies. For galaxies at $z_{em} \lesssim 0.4$, we can estimate the SFR from the luminosity of the H$\alpha$ line ($L_{H\alpha}$), using the relation from Kennicutt (1998),

$$\frac{SFR}{M_{\odot} \text{ yr}^{-1}} = 4.8 \times 10^{-42} \frac{L_{H\alpha}}{\text{erg s}^{-1}}. \quad (5.2)$$

We have decreased the amplitude of the relation by a factor of 1.65 with respect to the original value used by Kennicutt (1998), to account for the fact that we adopt a Chabrier IMF rather than a Salpeter (1955) IMF. We require the H$\alpha$ emission line to be detected with at least $S/N = 3$. Otherwise, we use SFR estimators based on H$\beta$ or O$\text{II}$ (see below).

We correct the H$\alpha$ emission-line flux for dust extinction by using the flux ratio of the H$\alpha$ and H$\beta$ Balmer lines. By comparing H$\alpha$/H$\beta$ to its intrinsic value of 2.85, which corresponds to Case B recombination at a temperature of $T \sim 10^4$ K and electron densities of $n_e \sim 10^2 - 10^4$ cm$^{-3}$ (Osterbrock & Ferland, 2006), we derive

current current halo mass, but will be closer the maximum past halo mass (typically reached at the time of infall on to a larger halo), as the mass, especially in the outer regions, is reduced due to tidal stripping. Hence, for $\approx 50\%$ of the galaxies, which have a neighbouring galaxy within the MUSE FoV that resides within a LOS velocity difference of $|\Delta v| = 300$ km/s, we are likely to underestimate the halo mass.

Star formation rate

We correct the H$\alpha$ emission-line flux for dust extinction by using the flux ratio of the H$\alpha$ and H$\beta$ Balmer lines. By comparing H$\alpha$/H$\beta$ to its intrinsic value of 2.85, which corresponds to Case B recombination at a temperature of $T \sim 10^4$ K and electron densities of $n_e \sim 10^2 - 10^4$ cm$^{-3}$ (Osterbrock & Ferland, 2006), we derive
5.2 Galaxy sample

![Graph showing the size of the dust correction as a function of the uncorrected SFR for the 115 galaxies for which the Hα flux (purple) or the Hβ flux (blue) could be corrected for dust extinction (using the Hα/Hβ and Hβ/Hγ ratios, respectively). The largest dust corrections are generally associated with the galaxies with the highest uncorrected SFRs.](image)

**Figure 5.8:** The size of the dust correction as a function of the uncorrected SFR for the 115 galaxies for which the Hα flux (purple) or the Hβ flux (blue) could be corrected for dust extinction (using the Hα/Hβ and Hβ/Hγ ratios, respectively). The largest dust corrections are generally associated with the galaxies with the highest uncorrected SFRs.

a correction for the Hα flux, assuming a Cardelli et al. (1989) reddening curve. As for Hα, we require the Hβ line to be detected with at least S/N = 3 for performing the dust correction. Otherwise, the SFR is calculated using the uncorrected Hα flux.

If Hα is not detected with S/N > 3, for example if it falls in a spectral region with significant sky line residuals or if the galaxy redshift is too high for Hα to be detected with MUSE, we use Hβ to calculate the SFR, under the condition that we can correct the line flux for dust extinction using the Hβ/Hγ ratio. This requires that both Hβ and Hγ are detected with S/N > 3. We then convert the corrected Hβ flux into an estimate of the SFR using equation (5.2), making use of the known intrinsic ratio between the Hα and Hβ flux.

Finally, if the SFR cannot be estimated from the Hα line or the dust-corrected Hβ line, we estimate it from the OII luminosity ($L_{OII}$) using the relation from Kewley et al. (2004),

$$\frac{SFR}{M_\odot \text{yr}^{-1}} = 4.0 \times 10^{-42} \frac{L_{OII}}{\text{erg s}^{-1}}, \quad (5.3)$$

which has been adjusted from a Salpeter to a Chabrier IMF. We note that this relation does not take into account the metallicity variation between galaxies. As before, we require S/N > 3 for the total emission-line flux of the OII doublet.

For the galaxies with an OII-based SFR, we do not perform a dust correction. These galaxies lack S/N = 3 detections of Hβ and Hγ (otherwise we would have derived the SFR from Hβ), so that this would require using Hδ or higher-order Balmer lines (the use of Hβ and Hγ is not possible for this subset of galaxies). Not only is the emission component of Hδ expected to be a factor of $\approx 11$ ($\approx 4$) weaker than that of Hα (Hβ), but the Balmer absorption originating from stellar
absorption around $z < 1$ MUSE galaxies in the atmospheres is also strongest at the H$\delta$ line. This causes H$\delta$ to be rarely detected with a high significance. Furthermore, the intrinsic weakness of the line makes the fit to the absorption component performed by PLATEFIT highly uncertain.

For galaxies without $S/N > 3$ detections of H$\alpha$, H$\beta$ (in combination with H$\gamma$) or O$\alpha$, which corresponds to $\approx 11\%$ of the sample, we are not able to obtain a reliable estimate of the SFR. For these galaxies, we use the PLATEFIT error on the H$\alpha$ (for $z_{\text{em}} < 0.42$) or O$\alpha$ (for $z_{\text{em}} > 0.42$) line flux to derive a 3$\sigma$ upper limit on the SFR. For one galaxy (at $z_{\text{em}} = 0.51$, with the redshift estimated from the Ca$\alpha$ H and K lines), the PLATEFIT fit in the emission-line regions failed and therefore did not return a reliable estimate of the O$\alpha$ line flux error. In this case, we derive a 3$\sigma$ upper limit on the SFR by calculating the 3$\sigma$ upper limit on the flux in the object spectrum in a 20 $\angstrom$ region around the O$\alpha$ wavelength (and converting using equation 5.3).

We exclude the galaxies with SFR upper limits from the sample when we explore the CGM O$\alpha$ absorption for different galaxy samples split according to their SFR. However, we confirm that if we do include them, either by considering the 3$\sigma$ upper limits on the SFR as the actual values or by including them in the sample containing the lowest SFRs, our conclusions remain unchanged. For the rest of the absorption analysis presented in this work, we do include the whole sample of galaxies.

Fig. 5.7 shows the distribution of the SFRs (total: black, dashed; excluding upper limits), which for 69 galaxies has been obtained from the H$\alpha$ flux (purple), for 58 from the H$\beta$ flux (blue), and for 58 from the O$\alpha$ flux (green). The distribution of upper limits is shown by the black, dotted line. While the H$\alpha$ sample mainly populates the lower end of the SFR distribution (median SFR $= 0.069 \, M_\odot \, yr^{-1}$), due to their restriction to $z < 0.42$, the H$\beta$ sample by construction mainly populates the upper end of the distribution (median SFR $= 1.3 \, M_\odot \, yr^{-1}$). The median of the O$\alpha$ sample, SFR $= 0.21 \, M_\odot \, yr^{-1}$, is close to the median of the total sample, SFR $= 0.14 \, M_\odot \, yr^{-1}$. Together, these samples exhibit a common trend of SFR increasing with increasing redshift, as shown in the middle panel of Fig. 5.6. The specific SFR ($sSFR = SFR/M_\star$) is approximately constant as a function of redshift (bottom panel). The upper limits on the SFR and $sSFR$, as derived from the upper limit on the H$\alpha$ or O$\alpha$ flux, are shown in black in this figure.

Fig. 5.8 shows the size of the dust correction as a function of the uncorrected SFR, for the 115 galaxies for which we could perform a dust correction using either the H$\alpha$/H$\beta$ (purple) or the H$\beta$/H$\gamma$ (blue) ratio. The median dust correction is 0.14 dex, with a median of 0.14 dex for the H$\alpha$/H$\beta$-based corrections and 0.20 dex for the H$\beta$/H$\gamma$-based corrections. The largest dust corrections are applied to the highest (uncorrected) SFRs, with corrections of up to 1.6 dex. For 35 galaxies we find a Balmer line ratio that is smaller than the intrinsic one, possibly as a result of uncertainties in the line fluxes. As this would correspond to a ‘negative’ dust correction, which would be unphysical, we assume the dust correction in these cases to be zero.

For a fraction of the galaxies in our sample, the emission spectrum is expected to be dominated by an AGN component. In that case, the H$\alpha$, H$\beta$ or O$\alpha$ emission-line flux is a poor indicator of the SFR. Kauffmann et al. (2003) showed that typically a few per cent of the galaxies with $M_\star = 10^{10-11} \, M_\odot$ shows signs of optical AGN activity, but that this percentage is likely to decrease towards lower stellar masses.
For the 26 galaxies for which we detect O\textsubscript{III} λ5007, H\textbeta, N\textsubscript{II} λ5583 and H\textalpha with S/N > 3, we estimate their locations in the Baldwin, Phillips, & Terlevich (BPT; 1981) diagram based on the O\textsubscript{III} λ5007/H\textbeta and N\textsubscript{II} λ6583/H\textalpha emission-line ratios. However, we find no galaxies that satisfy the AGN classification, either according to the criterion from Kewley et al. (2001) or the criterion from Kauffmann et al. (2003). The individual line flux ratios span ranges of O\textsubscript{III} λ5007/H\textbeta = 0.4 – 6.2 and N\textsubscript{II} λ6583/H\textalpha = 0.02 – 0.35. As we could only derive the BPT classification for \approx 13% of the galaxies, we do not rule out that some fraction of the rest of the sample harbours optical AGN.

Uncertainties on galaxy properties

We note that estimating the statistical and systematic uncertainties on the stellar masses, SFRs and dust corrections is still work in progress. Once we have derived the errors on the boxcar filter fluxes, we can obtain the statistical uncertainties on the stellar masses from FAST, which performs a Monte Carlo simulation by running the fitting procedure 500 times while varying the input flux values according to their errors. Comparing our derived stellar masses with already published values in the fields overlapping with other surveys, can give us an idea of the systematic errors on the stellar masses. Statistical uncertainties on the SFRs and dust corrections can be derived similarly to those on the stellar masses, by using Monte Carlo methods to propagate the errors on the emission-line fluxes. Comparing the SFRs using different tracers for the galaxies that either have both significant H\textalpha and O\textsubscript{II} or both H\textbeta and O\textsubscript{II} emission lines, will give an indication of the systematic errors on the SFRs. In future work, we also aim to explore the effect of neglecting the dust corrections for galaxies for which we found these corrections to be ‘negative’.

5.3 Absorption data analysis

We study the abundances of H\textsc{i}, C\textsc{iii} and O\textsc{vi} in the CGM of the galaxies found in our blind search with MUSE, by analysing the absorption signal in the QSO spectra. Instead of identifying and fitting absorption lines associated with individual galaxies, we take a statistical approach by measuring the median pixel optical depth for a sample of galaxies as a function of distance to those galaxies. This method was earlier applied to the CGM of z \sim 2 star-forming galaxies by Rakic et al. (2012) for H\textsc{i} and by Turner et al. (2014) for H\textsc{i} and metals. The method is independent of the specific identification of galaxy-absorber pairs and the details of modelling the absorption systems, and thus provides a simple and objective way of studying the ion abundance around the ‘average’ galaxy. In this section, we first describe the properties of the COS spectra and their analysis using the pixel optical depth method. Then, we explain how we construct galaxy-centred profiles of the median optical depth as a function of velocity along the LOS for a given sample of galaxies.
5.3.1 COS spectra

We obtain the 16 HST/COS spectra in reduced form from the HST Spectroscopic Legacy Archive\(^4\). This archive provides science-grade reduced spectra combining all COS data that is available for each target. The reduction pipeline uses the individual exposure files that were processed by CALCOS (v3.1.1), aligns them in velocity space and coadds the count rates per pixel. The velocity alignment is done by cross-correlating the positions of strong Galactic absorption lines (e.g. Si\(_{ii}\), C\(_{ii}\) and Al\(_{ii}\)), thereby correcting for the small offsets in the wavelength solution between individual exposures. We take the separate coadded spectra of the medium-resolution (\(R \approx 18,000\), FWHM \(\approx 16\) km/s) G130M and G160M gratings and splice them together at the wavelength in the overlap region where the S/N per pixel becomes equal (typically around \(\lambda = 1425\) Å). The final spectrum covers a wavelength range from \(\approx 1150\) Å to \(\approx 1800\) Å. The uncertainty in the COS wavelength calibration (even after aligning the individual exposures) is estimated to be \(\approx 20–30\) km/s (e.g. Savage et al., 2011; Tumlinson et al., 2011; Wakker et al., 2015), due to both velocity shifts that vary with wavelength and the uncertainty in the zero-point velocity. For our analysis, we keep the original pixel scale: hence, the final spectrum has a dispersion of 0.010 Å per pixel in the G130M part and 0.012 Å per pixel in the G130M part. Due to differences in the total exposure time and the brightness of the QSO, the spectra show a large variation in S/N. Typically, S/N \(\approx 15–35\) per resolution element at \(\lambda = 1250\) Å in G130M and S/N \(\approx 10–20\) per resolution element at \(\lambda = 1650\) Å in G160M (see Table 5.1). We normalize each spectrum by the unabsorbed quasar continuum, which we estimate by fitting smooth low-order polynomials through a manually selected set of points in regions without absorption.

5.3.2 Pixel optical depth recovery

We measure the strength of H\(_{i}\) and metal absorption in the COS spectra using the pixel optical depth method, applying the routine Podpy\(^5\) developed by Turner et al. (2014), which is based on the method from Aguirre et al. (2002) and earlier works (Cowie & Songaila, 1998; Ellison et al., 2000; Schaye et al., 2000). Here, we only highlight the most important aspects of the method and refer the reader to Appendix A of Turner et al. (2014) for a more detailed description. Note that while the pixel optical depth method was originally developed to study absorption in Keck/HIRES and VLT/UVES spectra at \(z > 2\), we apply the method to COS spectra to study absorption at \(z < 1\). Since the density of Lyman series lines (which are a source of contamination for other transitions) is much lower at low than at high redshifts, we do not restrict our analysis to the absorption overlapping with the QSO Ly\(_{\alpha}\) forest (or the Ly\(_{\beta}\) forest in the case of O\(_{vi}\)) as in previous works. Furthermore, since COS spectra have significantly lower S/N than HIRES or UVES spectra, we run Podpy with the significance parameter set to \(N_{\sigma} = 1\) (rather than \(N_{\sigma} = 3\)).

\(^4\)http://archive.stsci.edu/hst/spectral_legacy
\(^5\)This code is available at http://github.com/turnerm/podpy.
For each pixel, we obtain the optical depth $\tau$ from the continuum-normalized flux $F$ as

$$\tau = -\ln(F), \quad (5.4)$$

where we set the optical depth to $\tau = 10^{-6}$ for $F > 1$. We will denote the optical depth of an ion species $Z$ with rest-frame wavelength $\lambda_0$ (using the strongest transition in the case of a multiplet) at pixel wavelength $\lambda = \lambda_0(1 + z)$ by $\tau_Z(z)$. To infer an estimate of the ‘true’ optical depth from the observed spectrum, which is affected by noise, saturation and contamination, a number of corrections is applied. For H$\text{I}$, saturated absorption in the Ly$\alpha$ transition, where saturation is defined as $F(\lambda) < N_\sigma \sigma(\lambda)$, with $\sigma(\lambda)$ the continuum-normalized noise array, is corrected using the optical depth of the higher-order Lyman transitions (i.e. Ly$\beta$ and higher): we take the minimum optical depth, scaled to that of Ly$\alpha$, of 16 higher-order pixels at the corresponding $z$, selecting only those pixels that are significantly offset from the continuum (by $> N_\sigma \sigma(\lambda)$) and that are not saturated themselves. If a correction is not possible, we set the Ly$\alpha$ optical depth to $10^4$, so that the pixel does not affect the measured median. Furthermore, we use the higher-order transitions to identify any Ly$\alpha$ pixels (saturated or non-saturated) that are contaminated by metal absorption, by comparing the observed optical depth at each transition to the one expected based on Ly$\alpha$. We discard the contaminated pixels from the analysis.

For metal ions, we correct for contamination by H$\text{I}$ absorption by subtracting the optical depth contributions from 5 higher-order Lyman transitions\(^6\), scaled from the recovered Ly$\alpha$ optical depth. For example, correcting C$\text{iii}$ absorption at $z_{\text{C}^{\text{iii}}}$ for contamination from H$\text{I}$ Ly$\beta$ involves using the recovered H$\text{I}$ Ly$\alpha$ optical depth at

$$z_{\text{H}^{\text{I}}} = \frac{\lambda_{0,\text{C}^{\text{iii}}}}{\lambda_{0,\text{Ly}^{\beta}}} (1 + z_{\text{C}^{\text{iii}}}) - 1, \quad (5.5)$$

where $\lambda_{0,\text{C}^{\text{iii}}} = 977.02$ Å and $\lambda_{0,\text{Ly}^{\beta}} = 1025.72$ Å. Note that due to the limited wavelength range covered by COS, we can only correct for H$\text{I}$ contamination at $z_{\text{H}^{\text{I}}} < 0.48$, which for O$\text{vi}$ and C$\text{iii}$ corresponds to redshifts of $z_{\text{O}^{\text{vi}}} < 0.47$ and $z_{\text{C}^{\text{iii}}} < 0.55$, respectively. In the case of saturated metal pixels, we either do not apply an H$\text{I}$ contamination correction, or we discard the pixels entirely, if the saturated absorption can be fully attributed to overlapping higher-order H$\text{I}$ components.

Finally, for O$\text{vi}$, we make use of the information from the two doublet transitions to further refine the correction for contamination. After performing the H$\text{I}$ subtraction for both doublet components, we take $\tau_{\text{O}^{\text{vi}}}$ to be the minimum optical depth of the two components, where the optical depth of the weaker component has been scaled to that of the stronger one. However, in the presence of noise taking the minimum at each pixel will cause the optical depths to be biased low. We therefore only use the scaled optical depth from the weaker component as the final recovered optical depth if it is significantly lower (i.e. taking into account the $N_\sigma \sigma(\lambda)$ noise level at the wavelengths of both transitions) than that of the stronger component.

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\(^6\)Before submitting this work for publication, we will explore the impact of using a lower or higher number of Lyman transitions for the contamination correction.
5.3.3 Construction of median optical depth profiles

Using the recovered pixel optical depth spectra, we measure the strength of the CGM absorption signal for a given sample of galaxies as follows. We construct profiles of the median pixel optical depth as a function of the absolute LOS velocity, $v_{\text{LOS}}$, from the galaxies. We make the profiles by binning the spectral pixels according to their velocity separation from each galaxy redshift $z_{\text{em}}$, and calculating the median log optical depth per $v_{\text{LOS}}$ interval. For example, for $v_{\text{LOS}} = [v_1, v_2]$, we select all pixels corresponding to ion redshifts $z_Z = \lambda/\lambda_0 - 1$ in the range

$$\frac{v_1}{c} (1 + z_{\text{em}}) < z_Z < \frac{v_2}{c} (1 + z_{\text{em}}) + z_{\text{em}},$$

(5.6)

where $c$ is the speed of light.$^7$ Note that we combine the selected pixels from all galaxies in the sample before taking the median. However, to avoid contamination from unrelated absorption and QSO proximity effects, we exclude the pixels from the following regions:

- Redshifts less than 3000 km/s below the QSO redshift, $z > z_{\text{QSO}} - \frac{3000 \text{ km/s}}{c} (1 + z_{\text{QSO}})$;
- Wavelengths contaminated by H$\text{I}$ Ly$\alpha$ emission and absorption damping wings from the Milky Way, $1212 \text{ Å} < \lambda < 1220 \text{ Å}$;
- Wavelengths contaminated by O$\text{I}$ emission from the Milky Way, $1301 \text{ Å} < \lambda < 1307 \text{ Å}$;
- The region at $\lambda < 1280$ Å in the TEX 0206-048 spectrum and at $\lambda < 1220$ Å in the Q 1354+048 spectrum, where (most of) the flux is absorbed due to Lyman-limit systems at $z = 0.390$ and at $z = 0.329$, respectively.

While including all galaxies identified in the MUSE fields yields the LOS absorption profile for our total sample (Section 5.4.1), computing the absorption profiles for different subsamples of galaxies enables us to study the dependence of the absorption strength on various galaxy properties. In Sections 5.4.1 and 5.4.1, we divide the sample according to the galaxy impact parameter to study the H$\text{I}$, O$\text{VI}$ and C$\text{III}$ absorption strength as a function of (normalized) transverse distance from the galaxies. We also explore the dependence of the H$\text{I}$ and O$\text{VI}$ absorption strength on galaxy redshift (Section 5.4.2), and the dependence of the O$\text{VI}$ absorption strength on galaxy stellar mass and SFR (Sections 5.4.3 and 5.4.4).

5.4 Results

In this section, we present the results of our measurements of the H$\text{I}$, O$\text{VI}$ and C$\text{III}$ abundances around the galaxies blindly selected with MUSE. The wavelength coverage of COS enables us to measure the absorption strength of H$\text{I}$ Ly$\alpha$ out to redshifts $v \sim 10,000$ km/s, the assumption of $v \ll c$ underlying the equation (5.6) is no longer valid and we should use the more general formula for relativistic velocities. We will address this issue for our future publication.

$^7$We acknowledge the fact that for $v \sim 10,000$ km/s, the assumption of $v \ll c$ underlyi


5.4 Results

of 0.48, while the absorption of OⅥ and CⅢ is observable at $0.10 < z < 0.74$ and $0.16 < z < 0.84$, respectively. These redshift ranges are indicated by the blue bars in Fig. 5.1. In addition to OⅥ and CⅢ, we also examined the absorption of the metal ion transitions SiⅡ (1260.42 Å; $z < 0.43$), CⅡ (1334.53 Å; $z < 0.35$), SiⅢ (z < 0.49), SiⅣ (z < 0.29), CⅣ (z < 0.16) and NⅤ (z < 0.45), but except for NⅤ, we found no significant absorption signal (see Appendix 5.A).

5.4.1 Full sample

Dependence on LOS velocity

Fig. 5.9 shows the absorption strength of HI, OⅥ and CⅢ for the full sample of galaxies (squares). In the left-hand panels, we plot the median $\log_{10} \tau_Z$ as a function of LOS velocity from the galaxies. The axis at the top indicates the corresponding absolute LOS Hubble distance in the case of pure Hubble flow,

$$d_{\text{LOS}} = \frac{v_{\text{LOS}}}{H(z)},$$

where $H(z)$ is the Hubble parameter at redshift $z$. We assume $z = 0.5$, which is close to the median redshift of the sample. For both HI and the metal ions, the strength of the absorption (red squares) decreases as the LOS velocity from the galaxies increases. We find that the absorption remains enhanced with respect to the absorption in random regions (red, dashed lines) out to $v_{\text{LOS}} \sim 100$ km/s ($d_{\text{LOS}} \sim 1$ pMpc).

The optical depth of random regions, which can be considered as the detection limit ($\tau_{\text{lim}}$), is calculated as the median $\log_{10} \tau_Z$ of all pixels at $15,000 < v_{\text{LOS}} < 25,000$ km/s from the galaxies contributing to the corresponding absorption profile, which are 106, 171 and 200 galaxies in total for HI, OⅥ and CⅢ, respectively. In this way, $\tau_{\text{lim}}$ is estimated from regions that are sufficiently far away from the targeted galaxies, but still mimic the specific redshift distribution of the galaxy sample. This is necessary because the sampling of redshift space in our survey is non-uniform, as a result of the differences in the redshift path length below $z_{\text{QSO}}$ and the exposure time of the MUSE observation between different QSO targets.

We estimate the uncertainties in the median optical depth values by dividing the total absorption distance, $\Delta X$ (Bahcall & Peebles, 1969), of the 15 QSO spectra into chunks and bootstrap resampling the chunks 1000 times. For ion Z, the absorption distance per QSO spectrum is given by

$$\Delta X_Z = \int_{z_{\text{min}}}^{z_{\text{max}}} \frac{(1 + z)^2}{\sqrt{\Omega_M(1 + z)^3 + \Omega_A}} \, dz,$$

with integration limits $z_{\text{min}} = \max(zz_{\text{min}}, 0)$ and $z_{\text{max}} = \min(zz_{\text{max}}, z_{\text{QSO}})$, where $zz_{\text{min}}$ and $zz_{\text{max}}$ are the minimum and maximum ion redshifts covered by COS.

\(^8\)Note that since we consider absorption up to $v_{\text{LOS}} = 10,000$ km/s from the galaxy redshift, galaxies above or below the ion redshift range covered by COS can contribute to the absorption profile (as long as they are at least 3000 km/s below the redshift of the QSO).
Figure 5.9: The median pixel optical depth of H\textsc{i} (top), O\textsc{vi} (middle) and C\textsc{iii} (bottom) as a function of LOS velocity (left) and transverse distance (right). While the squares show the absorption signal for the full sample of galaxies, the circles (which, for clarity, have been offset horizontally by 0.02 dex and 0.006 dex in the left- and right-hand panels, respectively) show the signal for galaxies in a restricted redshift range. Along the LOS direction, the median log_{10} \tau_{Z} is calculated in 20 logarithmic bins between v_{LOS} = 3 km/s and v_{LOS} = 10,000 km/s, where the corresponding absolute LOS Hubble distance, assuming z = 0.5 and pure Hubble flow, is indicated at the top. The horizontal dashed lines show the detection limit, calculated as the median log_{10} \tau_{Z} at 15,000 < v_{LOS} < 25,000 km/s from the galaxies contributing to the profile of the respective colour. Along the transverse direction, the median log_{10} \tau_{Z} is calculated, using only pixels at v_{LOS} = 100 km/s, in 5 logarithmic bins between d_{trans} = 30 pkpc and d_{trans} = 300 pkpc, where we only show bins containing at least three galaxies. The points are colour-coded by the median galaxy stellar mass in each bin. The detection limit is calculated separately for each transverse distance bin, and shown by the light-coloured symbols connected by dashed lines. In all panels, the error bars (and shaded regions) show the 1\sigma confidence interval on the median optical depth.
The total ion absorption distances covered by the 15 QSO spectra are $\Delta X_{\text{H} \text{i}} = 10.6$, $\Delta X_{\text{O} \text{vi}} = 14.9$ and $\Delta X_{\text{C} \text{iii}} = 15.8$. We divide these into $N_{\text{chunk}} = 353, 497$ and 528 chunks, respectively, in order to have a chunk size of $\Delta X \approx 0.03$, which is about 3 times larger than the velocity extent of the largest galaxy group$^9$ identified in our fields. This ensures that different chunks are independent. In each bootstrap realization, we select $N_{\text{chunk}}$ chunks with replacement, take the galaxies with redshifts within the selected chunks, and calculate the median absorption optical depth per $v_{\text{LOS}}$ interval. The error bars on the points and the shaded regions on the dashed lines in Fig. 5.9 indicate the 16th to 84th percentile ranges of the resulting distributions.

To assess the significance of the enhancement in the absorption with respect to the detection limit, we calculate the fraction, $f_{\text{high}}$, of bootstrap realizations for which $\tau_{\text{lim}}^j > \tau_{\text{Z}}^j$, where $i$ denotes the $i$th bootstrap iteration. We refer to $1 - 2f_{\text{high}}$ as the confidence level of the absorption enhancement. For H$\text{i}$ and O$\text{vi}$, we find a confidence level of $> 95\%$ (2$\sigma$)$^{10}$ out to $v_{\text{LOS}} = 260$ km/s and $v_{\text{LOS}} = 115$ km/s$^{11}$, respectively. These LOS velocities correspond to LOS Hubble distances of $d_{\text{LOS}} = 3.2$ pMpc and $d_{\text{LOS}} = 1.3$ pMpc at the median redshifts of the galaxies contributing to the absorption, $z_{\text{med}}^\text{H} \text{i} = 0.36$ and $z_{\text{med}}^\text{O} \text{vi} = 0.45$. For C$\text{iii}$, the dynamic range of optical depths is smaller, and we find a $> 68\%$ (1$\sigma$) confidence level out to $v_{\text{LOS}} = 115$ km/s ($d_{\text{LOS}} = 1.3$ pMpc at $z_{\text{med}}^\text{C} \text{iii} = 0.53$).

Studies of the optical depth around galaxies from the KBSS (H$\text{i}$: Rakic et al. 2012; H$\text{i}$ and metal ions: Turner et al. 2014) have suggested that the extent of the absorption signal along the LOS direction depends on the peculiar velocities of the absorbing gas, related to infall, outflows or virial motions, rather than errors in the galaxy redshifts. Using mock spectra generated from the EAGLE simulations (Schaye et al., 2015; Crain et al., 2015), Turner et al. (2017) showed that this is indeed the case: while the presence of redshift errors somewhat reduces the optical depth profile at small LOS velocities, the velocity extent of the absorption enhancement is governed by peculiar velocities. Furthermore, Turner et al. (2017) explored the radial velocities of the gas traced by H$\text{i}$ (and metal ions C$\text{iv}$ and Si$\text{iv}$) and showed that this gas is mostly infalling, where the gas velocities are sensitive to the host halo mass (and insensitive to changes in the strength of the stellar feedback). This suggests that the velocity scale of the drop in the optical depth profile is related to the typical velocity of infalling gas, which is likely close to the circular velocity ($v_{\text{circ}}$) of the halo. For our sample, the median circular velocity is $v_{\text{circ}} = 81$ km/s. While this is a factor of $\approx 2 - 4$ smaller than the maximum LOS velocity extent of the detected enhancement in the H$\text{i}$ and O$\text{vi}$ absorption, we note that our sample contains a range of stellar masses (with a standard deviation of 0.9 dex about the

$^9$We define a galaxy group as a set of galaxies that have, when ordered by redshift, a velocity difference of less than 300 km/s between subsequent galaxies. We do not impose a constraint on their transverse distance separation, as the size of the MUSE FoV is $\leq 500$ pkpc.

$^{10}$To indicate the significance and extent of the absorption enhancement, we choose the 95% and 68% confidence levels as characteristic values. However, at LOS velocities (and transverse distances) smaller than the indicated maximum extent, the confidence levels for H$\text{i}$ and O$\text{vi}$ reach 100%.

$^{11}$There is also a significant offset of $\tau_{\text{O} \text{vi}}$ from $\tau_{\text{lim}}$ at $v_{\text{LOS}} \approx 1600$ km/s. However, we attribute this to a combination of residual contamination from H$\text{i}$ Ly$\beta$ and the weak O$\text{vi}$ doublet component (despite the corrections performed during the optical depth recovery).
Absorption around $z < 1$ MUSE galaxies

median), which are also associated to a range of host halo masses, even at a fixed stellar mass. Since a 10 times higher halo mass corresponds to a 2.2 times higher circular velocity, the contribution from the most massive halos in the sample likely extends the absorption signal to $v_{\text{LOS}} \gg 81 \text{ km/s}$. We do note that $v \approx 80 \text{ km/s}$ seems to be similar to the velocity scale at which the optical depth profiles start to fall off from the roughly flat trend at small $v_{\text{LOS}}$ towards the detection limit. For H$\text{i}$ and O$\text{vi}$, we estimate the velocity scales of the drop to be $v_{\text{drop}} \approx 50 \text{ km/s}$ and $v_{\text{drop}} \approx 80 \text{ km/s}$, respectively. For C$\text{iii}$, it is difficult to see, but the profile shape seems to be consistent with that of O$\text{vi}$. Fitting, for example, a sigmoid function to the profiles would yield a more accurate estimate of the typical drop-off velocity, which we plan to do in the future.

In the case of the KBSS, the redshift errors were $\approx 2 - 10$ times smaller than the typical halo circular velocity of the survey. For our study, we also need to verify that the redshift errors are sufficiently small that they do not dominate the shape of the absorption signal in Fig. 5.9. Based on MUSE observations of the Hubble Ultra Deep Field (which are somewhat deeper than our observations: nine $1' \times 1'$ fields with $t_{\text{exp}} = 10 \text{ h}$ and one $1' \times 1'$ field with $t_{\text{exp}} = 30 \text{ h}$), the error on spectroscopic redshifts from MUSE is estimated to be $\sigma_{\text{error}} \approx 40 \text{ km/s}$ (Inami et al., in press). We confirm that adding random velocity offsets, assuming a Gaussian distribution with a width of 40 km/s, to the galaxy redshifts (adopting the approach from Appendix A of Rakic et al. (2012)), does not have a significant effect on the H$\text{i}$ and O$\text{vi}$ optical depths.

Dependence on transverse distance

In the right-hand panels of Fig. 5.9, we show the median optical depth as a function of transverse distance ($d_{\text{trans}}$; i.e. projected distance on the sky) from the galaxies, where we only include pixels at $v_{\text{LOS}} < 100 \text{ km/s}$, in order to maximize the strength of the signal. As in the left-hand panels, the squares show the results for the total sample. In contrast to the absorption profile along the LOS direction, different transverse distance intervals contain different galaxies (according to their impact parameter to the QSO sightline), which makes each point independent. The confidence interval on the median $\log_{10} \tau_Z$, as well as $\tau_{\text{lim}}$ and corresponding confidence interval (now indicated by light-coloured symbols), is therefore calculated separately for each $d_{\text{trans}}$ bin.

In general, for $d_{\text{trans}} > 50 \text{ pkpc}$, the median H$\text{i}$, O$\text{vi}$ and C$\text{iii}$ optical depths decrease as the transverse distance from the galaxies increases. A slight drop in all three profiles is seen at $d_{\text{trans}} \approx 120 \text{ pkpc}$. Assessing the confidence level of the absorption enhancement with respect to the detection limit, we find enhanced H$\text{i}$ and O$\text{vi}$ absorption at $> 95\%$ confidence out to the largest transverse distance probed, $d_{\text{trans}} = 300 \text{ pkpc}$\textsuperscript{12}. This is roughly three times the size of the estimated median virial radius of our sample, and comparable to the estimated virial radius of the

\textsuperscript{12}For the innermost $d_{\text{trans}}$ bin of the O$\text{vi}$ profile (containing 3 galaxies, all at $0.15 < z_{\text{em}} < 0.35$), $\log_{10} \tau_Z = -6$, the artificial minimum employed by the pixel optical depth method. This is potentially due to the H$\text{i}$ contamination correction (which is especially important at low redshift), which assigns pixels $\log_{10} \tau_Z = -6$ if the the absorption can be fully accounted for by H$\text{i}$. 
most massive galaxies in the sample. For C\textsubscript{iii}, we find a > 95% confidence level out to \(d_{\text{trans}} = 120\) pkpc, while the \(120 < d_{\text{trans}} < 190\) pkpc bin has a confidence level of 84%.

The size of the MUSE FoV complicates a comparison of the extent of the absorption signal along the LOS and transverse directions, as was done for the KBSS. Studying the 2D distribution of optical depths, Rakic et al. (2012) and Turner et al. (2014) reported a significant elongation of the HI and metal absorption along the LOS direction on scales of \(\sim 0.1 - 1\) pMpc (\(\approx 20 - 200\) km/s), as result of gas peculiar velocities smearing the signal along the LOS but not in the transverse direction. While we cannot conclude definitively that the small-scale elongation along the LOS direction is also present in our data (except for C\textsubscript{iii} perhaps), we do conclude that the median HI and O\textsc{vi} optical depth as a function of transverse distance starts to decrease at a distance that is \(\sim 10\) smaller than the scale at which the optical depths fall off along the LOS direction.

**Dependence on normalized transverse distance**

As our sample contains a wide range of stellar masses, it might be more appropriate to consider the optical depth as a function of \(d_{\text{trans}}/R_{\text{vir}}\), the transverse distance normalized by the virial radius, instead of \(d_{\text{trans}}\): this likely gives a better indication of how the absorption strength varies from the inner to the outer halo. Hence, in Fig. 5.10, we show the median HI, O\textsc{vi} and C\textsubscript{iii} optical depth profiles in the transverse direction (squares), as in the right-hand column of Fig. 5.9, but now by binning the galaxies according to their impact parameter in units of the halo virial radius. We only show bins that contain at least three galaxies, which excludes the innermost bin (\(0.2 < d_{\text{trans}}/R_{\text{vir}} < 0.4\)) for O\textsc{vi} and C\textsubscript{iii}.

The median absorption strength (of both HI and the metal ions) generally decreases as a function of \(d_{\text{trans}}/R_{\text{vir}}\), although the median O\textsc{vi} optical depth seems to decrease for \(d_{\text{trans}}/R_{\text{vir}} < 0.7\). For all three profiles, a tentative drop, comparable to the twice the size of the estimated error on the median optical depth, is seen at \(d_{\text{trans}}/R_{\text{vir}} \approx 1.2\). We find that that for HI and O\textsc{vi}, the absorption is significantly enhanced (with > 95% confidence) with respect to \(\tau_{\text{lim}}\) over the whole range plotted, hence out to at least \(d_{\text{trans}}/R_{\text{vir}} = 4.0\). For C\textsubscript{iii}, we only find a > 95% confidence level at \(0.7 < d_{\text{trans}}/R_{\text{vir}} = 1.2\), as the bin at \(0.4 < d_{\text{trans}}/R_{\text{vir}} = 0.7\) has a confidence level of 94%.

**Imposing a minimum emitter redshift**

So far, we have presented the results for the full sample of galaxies. As we showed in Sections 5.2.3 and 5.2.4, these galaxies span a wide range of redshifts, stellar masses and SFRs. When we explore the dependence of the strength of the absorption signal on these galaxy properties (in Sections 5.4.2, 5.4.3 and 5.4.4), ideally we would keep all other properties constant while varying the property of interest. However, due to correlations between galaxy characteristics, which have a physical origin or are the result of observational bias (or a combination of both), this condition is not automatically satisfied: Fig. 5.2 shows that our sample lacks high-impact parameter galaxies at low redshift (due to the limiting physical size of the
Figure 5.10: As in the right-hand column of Fig. 5.9, but showing the median pixel optical depths as a function of transverse distance normalized by the virial radius. We calculate the median \( \log_{10} \tau_Z \) and \( \tau_{\text{lim}} \) in 5 logarithmic bins between \( d_{\text{trans}}/R_{\text{vir}} = 0.2 \) and \( d_{\text{trans}}/R_{\text{vir}} = 4.0 \). For clarity, the points are offset horizontally from each other by 0.0075 dex. For both \( \text{H}^\text{i} \) and the metal ions, the absorption strength generally decreases as a function of \( d_{\text{trans}}/R_{\text{vir}} \) and shows a tentative drop at \( d_{\text{trans}}/R_{\text{vir}} \approx 1.2 \). For \( \text{H}^\text{i} \) and \( \text{OVI} \), the absorption is enhanced with respect to \( \tau_{\text{lim}} > 95\% \) (2\( \sigma \)) confidence out to \( d_{\text{trans}}/R_{\text{vir}} = 4.0 \). For \( \text{CIII} \), we only find a > 95\% confidence level at \( 0.7 < d_{\text{trans}}/R_{\text{vir}} = 1.2 \).
5.4 Results

MUSE FoV), and low-impact parameter galaxies at all but the lowest redshifts (due to the increasing physical size of the QSO PSF with increasing redshift). This causes galaxies at smaller impact parameters to have, on average, lower redshifts. Furthermore, stellar mass and SFR exhibit positive correlations with redshift (see Fig. 5.6), as well as with each other. When these correlations are not taken into account, a correlation between the absorption strength and the value of one property might be incorrectly interpreted as a causal relation, while the correlation is actually driven by a second property.

In the following sections, we therefore apply selection cuts to the galaxy redshifts, which largely remove the correlations of impact parameter, stellar mass and SFR with redshift, and thereby also the correlation of stellar mass and SFR with impact parameter. In Appendix 5.B, we additionally apply cuts on the stellar mass and SFR, in order to isolate the effects of varying these two properties independently. We always try to find a balance between the strictness of the cut and the number of selected galaxies, in order to maintain a reasonable sample size for each comparison. However, before we turn to an investigation of the impact of galaxy redshift, stellar mass and SFR on the absorption signal, we first revisit the relation between absorption strength and (normalized) impact parameter presented in Sections 5.4.1 and 5.4.1.

While for the full sample (squares in the right-hand panels of Fig. 5.9), the median optical depths of H\textsc{i}, O\textsc{vi} and C\textsc{iii} at $d_{\text{trans}} > 50$ pkpc generally decrease with increasing transverse distance from the galaxies, this trend is not independent of redshift. The median redshift of the galaxies contributing to the signal in each impact parameter bin increases from $\approx 0.2 - 0.3$ at $d_{\text{trans}} < 75$ pkpc to $\approx 0.6$ at $d_{\text{trans}} > 190$ pkpc in the case of O\textsc{vi} and C\textsc{iii}, and to $\approx 0.4$ in the case of H\textsc{i}. For O\textsc{vi} and C\textsc{iii}, this is reflected by the (slight) increase in $\tau_{\text{lim}}$, which is higher at higher redshifts. Even though we show in Section 5.4.2 that we do not find evidence for significant evolution of the absorption signal, the correlation between redshift and stellar mass causes also the median stellar mass of the galaxies to increase with impact parameter. As indicated by the colour coding, the median stellar mass increases from $M_\ast = 10^{8.4-8.5} M_\odot$ at $d_{\text{trans}} < 75$ pkpc to $M_\ast = 10^{9.4} M_\odot$ at $d_{\text{trans}} > 190$ pkpc (to $M_\ast = 10^{9.6} M_\odot$ in the case of H\textsc{i}). Furthermore, the median SFR of the galaxies increases by a factor of $\approx 3 - 5$ from small to large impact parameters. The effect is particularly evident for O\textsc{vi}: the optical depth within $d_{\text{trans}} \approx 50$ pkpc seems to be significantly lower than at $d_{\text{trans}} \gtrsim 50$ pkpc, where we note that the difference in $\tau_{\text{lim}}$ has only a minor effect.

In order to minimize the effect of any stellar mass or SFR dependence on the signal, we impose a minimum redshift cut on the galaxy sample. Based on visual inspection, we find that a cut of $z_{\text{em}} > 0.30$ for H\textsc{i} and a cut of $z_{\text{em}} > 0.38$ for O\textsc{vi} and C\textsc{iii} eliminates most of the correlation of impact parameter with redshift (see Fig. 5.2), and of stellar mass and SFR with redshift (see Fig. 5.6, where the shaded area marks the redshift range selected for O\textsc{vi}), while still maintaining a reasonable sample size\textsuperscript{13}. As a result, when we apply these redshift cuts, the median stellar mass of the galaxies is also approximately constant across the impact parameter range.

\textsuperscript{13}We adopt a lower redshift cut of $z_{\text{em}} < 0.30$ for H\textsc{i}, as it is only observable at $z < 0.48$. 
The resulting median \( \log_{10} \tau_{\text{Z}} \) as a function of transverse distance is shown by the circles in the right-hand column of Fig. 5.9. Note that the innermost bin is not shown, as there are no galaxies at those impact parameters above the imposed redshift cut. We also show the median \( \log_{10} \tau_{\text{Z}} \) as a function of LOS velocity (left-hand panels), where we include all galaxies in the selected subsamples (73 galaxies for \( \text{H} \), 116 for \( \text{OVI} \) and 150 for \( \text{CIII} \)): the result for \( \text{H} \) is similar to that of the full sample, while the \( \text{OVI} \) and \( \text{CIII} \) optical depths are somewhat higher than for the full sample. This is caused by an increase of the \( \text{OVI} \) and \( \text{CIII} \) optical depths within \( d_{\text{trans}} \approx 120 \) pkpc\(^{14} \), which also results in a more steeply decreasing trend with increasing \( d_{\text{trans}} \). The roughly constant \( \tau_{\lim} \) as a function of transverse distance is consistent with the fact that these different \( d_{\text{trans}} \) bins exhibit similar redshift distributions. Interestingly, the optical depth profile of \( \text{H} \) (as well as \( \tau_{\lim} \)) for the \( z_{\text{em}} > 0.30 \) subsample is similar to that of the full sample, even though the median redshift, stellar mass and SFR increase with \( d_{\text{trans}} \) for the latter. This is perhaps due to the less stringent redshift cut imposed on \( \text{H} \) than on the metals, or due to a lack of correlation between absorption strength and stellar mass.

Similarly to Fig. 5.9, the median redshift of the galaxies in each \( d_{\text{trans}}/R_{\text{vir}} \) bin in Fig. 5.10 increases from \( \approx 0.2 - 0.3 \) at \( d_{\text{trans}}/R_{\text{vir}} \approx 0.2 \) to \( \approx 0.6 \) at \( d_{\text{trans}}/R_{\text{vir}} \approx 4.0 \) (and to \( \approx 0.4 \) in the case of \( \text{H} \)). After imposing the minimum redshift cuts, the trend of increasing \( \tau_{\lim} \) with increasing \( d_{\text{trans}}/R_{\text{vir}} \) becomes shallower (in the case of \( \text{OVI} \)) and the trends of decreasing \( \text{OVI} \) and \( \text{CIII} \) optical depths become steeper. Unlike in Fig. 5.9, however, the redshift cut does not eliminate the correlation between stellar mass and \( d_{\text{trans}}/R_{\text{vir}}^{15} \). The finding that the optical depths decrease more steeply with \( d_{\text{trans}}/R_{\text{vir}} \) than with \( d_{\text{trans}} \) may be caused by a slight enhancement of the variation in median stellar mass from low to high normalized impact parameters. For the full sample, the median stellar mass decreases from \( M_{*} = 10^{9.4} \) \( M_{\odot} \) at \( d_{\text{trans}}/R_{\text{vir}} < 1.2 \) to \( M_{*} = 10^{8.2} \) \( M_{\odot} \) at \( d_{\text{trans}}/R_{\text{vir}} \approx 4.0 \) (in the case of \( \text{OVI} \) and \( \text{CIII} \)); for \( \text{H} \), the trend is non-monotonic). For the subsamples with the restricted redshift range (shown by the circles), the median stellar mass at small \( d_{\text{trans}}/R_{\text{vir}} \) is even higher (by \( \approx 0.2 \) dex), as excluding low-redshift galaxies removes galaxies with low stellar masses at low \( d_{\text{trans}}/R_{\text{vir}} \). Hence, the fact that the optical depths in Fig. 5.10 decrease as a function of \( d_{\text{trans}}/R_{\text{vir}} \), could be due to a combination of a decrease in stellar mass and an increase in \( d_{\text{trans}} \).

### 5.4.2 Dependence on redshift

As the cumulative mass in metals produced by stars grows with time, one might expect that the metal ion abundance in the CGM of individual galaxies is an increasing function of decreasing redshift. However, the CGM abundance of metal ions does not only depend on the level of enrichment, which itself depends on factors like the current and past efficiency of galactic winds in driving out metals, but

\(^{14}\)Note that the increase in the median \( \log_{10} \tau_{\text{Z}} \) cannot be attributed solely to an increase in \( \tau_{\lim} \). In fact, (linearly) normalizing the optical depths from the subsample and the total sample to a common \( \tau_{\lim} \), has negligible effect on the optical depths at \( v_{\text{LOS}} < 100 \) km/s and at all \( d_{\text{trans}} \).

\(^{15}\)We acknowledge that for this reason, the application of the redshift cut has no advantage. For our future publication, we therefore plan to include the full galaxy sample when considering optical depth profiles as a function of \( d_{\text{trans}}/R_{\text{vir}} \).
Figure 5.11: The dependence on galaxy redshift of the median O\textsc{vi} optical depth as a function of LOS velocity (left) and normalized transverse distance (using only pixels at $v_{LOS} < 100$ km/s; right). The grey triangles, blue circles and red circles show the median $\log_{10} \tau_{OVI}$ (binned as in Figs. 5.9 and 5.10) for galaxies at $z_{em} < 0.38$, $0.38 < z_{em} < 0.56$ and $z_{em} > 0.56$, respectively, where the optical depths have been linearly shifted to the same $\tau_{lim}$ (horizontal dashed line). The median redshift of each sample is indicated in the legend. We only show $d_{trans}/R_{vir}$ bins containing at least three galaxies. For clarity, the points are offset horizontally from each other by 0.02 dex and 0.075 dex in the left- and right-hand panels, respectively. The velocity axis shows the absolute LOS Hubble distance at $z = 0.5$. We find no evidence for significant evolution of the O\textsc{vi} optical depth over the range $0.38 < z < 0.74$. For the galaxies below the $z_{em} = 0.38$ redshift cut (see Section 5.4.1), the lower optical depth at small LOS velocities and transverse distances might also be due to the lower stellar masses and SFRs compared to the galaxies at $z_{em} > 0.38$. 
Absorption around $z < 1$ MUSE galaxies

is also highly sensitive to the ionization state of the gas. It is therefore not straightforward to predict how a certain population of absorbers, in the Universe in general or around galaxies of a given mass, evolves as a function of redshift. Considering only the expansion of the Universe and assuming that we probe gas at a fixed overdensity and temperature across redshifts, we would expect the optical depth to scale with redshift as $\tau \propto (1+z)^3$ (where $n_Z$ is the ion number density). However, Chen (2012) compared the strength and transverse spatial extent of the H$\text{I}$, Mg$\text{II}$ and C$\text{IV}$ absorption around galaxies with a similar stellar mass between $z \approx 2.2$ and $z \approx 0$ and found no significant evolution. Furthermore, Wakker & Savage (2009) showed that the incidence of H$\text{I}$ and O$\text{VI}$ absorbers as a function of the minimum absorption equivalent width does not significantly evolve from $z = 0.5$ to $z = 0$.

Even though the ion redshift ranges covered by COS are relatively small, we explore how the absorption enhancement depends on galaxy redshift. We compare the median $\log_{10} \tau_Z$ as a function of LOS velocity and transverse distance (normalized by $R_{\text{vir}}$) between different subsamples of galaxies selected according to their redshifts. Since the small dynamic range of the C$\text{III}$ optical depths complicates an assessment of the absorption signal for galaxy samples smaller than the full sample, we will focus on H$\text{I}$ and O$\text{VI}$. In Sections 5.4.3 and 5.4.4, we will focus solely on O$\text{VI}$, and present the results for H$\text{I}$ in Appendix 5.C.

Fig. 5.11 shows the median optical depth profiles of O$\text{VI}$ for three galaxy redshift samples: $z_{\text{em}} < 0.38$ (57 galaxies; grey triangles), $0.38 < z_{\text{em}} < 0.56$ (62 galaxies; blue circles) and $z_{\text{em}} > 0.56$ (52 galaxies; red circles). For each sample in the left-hand panel and each $d_{\text{trans}}/R_{\text{vir}}$ bin (which we only show if it contains three or more

Figure 5.12: As Fig. 5.11, but showing the dependence on galaxy redshift for the median H$\text{I}$ optical depth, with the galaxy sample split into $z_{\text{em}} < 0.30$ (grey triangles), $0.30 < z_{\text{em}} < 0.40$ (blue circles) and $z_{\text{em}} > 0.40$ (red circles). We do not find evidence for significant evolution of the H$\text{I}$ optical depth over the range $0.30 < z < 0.48$. Probing evolution down to $z \approx 0$ is difficult, as the typical impact parameter, stellar mass and SFR of the galaxies are lower at $z_{\text{em}} < 0.30$ than at $z_{\text{em}} > 0.30$. 

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**Figure 5.12:** As Fig. 5.11, but showing the dependence on galaxy redshift for the median H$\text{I}$ optical depth, with the galaxy sample split into $z_{\text{em}} < 0.30$ (grey triangles), $0.30 < z_{\text{em}} < 0.40$ (blue circles) and $z_{\text{em}} > 0.40$ (red circles). We do not find evidence for significant evolution of the H$\text{I}$ optical depth over the range $0.30 < z < 0.48$. Probing evolution down to $z \approx 0$ is difficult, as the typical impact parameter, stellar mass and SFR of the galaxies are lower at $z_{\text{em}} < 0.30$ than at $z_{\text{em}} > 0.30$. Even though the ion redshift ranges covered by COS are relatively small, we explore how the absorption enhancement depends on galaxy redshift. We compare the median $\log_{10} \tau_Z$ as a function of LOS velocity and transverse distance (normalized by $R_{\text{vir}}$) between different subsamples of galaxies selected according to their redshifts. Since the small dynamic range of the C$\text{III}$ optical depths complicates an assessment of the absorption signal for galaxy samples smaller than the full sample, we will focus on H$\text{I}$ and O$\text{VI}$. In Sections 5.4.3 and 5.4.4, we will focus solely on O$\text{VI}$, and present the results for H$\text{I}$ in Appendix 5.C.

Fig. 5.11 shows the median optical depth profiles of O$\text{VI}$ for three galaxy redshift samples: $z_{\text{em}} < 0.38$ (57 galaxies; grey triangles), $0.38 < z_{\text{em}} < 0.56$ (62 galaxies; blue circles) and $z_{\text{em}} > 0.56$ (52 galaxies; red circles). For each sample in the left-hand panel and each $d_{\text{trans}}/R_{\text{vir}}$ bin (which we only show if it contains three or more
galaxies) in the right-hand panel, \( \tau_{\text{lim}} \) is, by construction, estimated from regions that follow the same redshift distribution as the galaxies: as a result, \( \tau_{\text{lim}} \) depends on the typical galaxy redshift of the bin or sample. To enable a straightforward comparison between the different samples, we convert all optical depth values to a common \( \tau_{\text{lim}}^{\text{norm}} \), by linearly adding the difference \( (\tau_{\text{lim}}^{\text{norm}} - \tau_{\text{lim}}) \) to \( \tau_{Z} \). We choose \( \tau_{\text{lim}} \) to be the highest \( \tau_{\text{lim}} \) (where we take all \( d_{\text{trans}}/R_{\text{vir}} \) bins together) of the three samples in the comparison.

As discussed in Section 5.4.1, due to correlations between galaxy properties like redshift and stellar mass, only the samples above the \( z_{\text{em}} = 0.38 \) redshift cut provide an approximately unbiased comparison between redshift regimes. The \( 0.38 < z_{\text{em}} < 0.56 \) and \( z_{\text{em}} > 0.56 \) samples have median redshifts of 0.47 and 0.66, respectively, and have similar median impact parameters (\( \approx 150 \) pkpc and, in units of the virial radius, \( \approx 1.7 R_{\text{vir}} \)) and stellar masses (\( M_{\ast} \approx 10^{9.0} M_{\odot} \)). However, the median SFR of the samples do differ by \( \approx 0.4 \) dex (where we, to calculate the median, consider the SFR upper limits as actual values). Comparing the optical depth profiles of the two samples (see Fig. 5.11), we find no evidence for significant evolution of the O\,I optical depth over the redshift range \( 0.38 < z < 0.74 \). Along the LOS direction, the strength and extent of the absorption enhancement with respect to the detection limit are consistent within the error bars, and in the transverse direction, we only find a significant difference between the redshift samples for \( 1.2 < d_{\text{trans}}/R_{\text{vir}} < 2.2 \). Note that the halo circular velocity does scale with redshift as \( (1 + z)^{1/2} \) for a fixed halo mass, but that the redshift range is too small for this to have a significant effect on the scale at which the optical depths fall off as a function of \( v_{\text{LOS}} \).

We do include the optical depth profile for the \( z_{\text{em}} < 0.38 \) sample in Fig. 5.11. However, while the galaxies in this sample have a median redshift of 0.29, they also have significantly lower impact parameters (with a median of \( \approx 79 \) pkpc) than the galaxies at \( z_{\text{em}} > 0.38 \) (with a median of \( \approx 150 \) pkpc), and a median stellar mass that is lower by \( \approx 0.5 \) dex. The median \( R_{\text{vir}} \)-normalized impact parameter is lower by \( \lesssim 0.2 \) dex. Hence, the fact that the \( z_{\text{em}} < 0.38 \) sample shows somewhat lower optical depths for \( v_{\text{LOS}} < 100 \) km/s and \( d_{\text{trans}}/R_{\text{vir}} < 2.2 \) cannot be unambiguously explained as evolution of the O\,I optical depth with redshift. The reduction at \( z < 0.38 \) may well be due to the lower stellar masses and SFRs of the galaxies, as we find that the absorption strength is positively correlated with both of these quantities (see Sections 5.4.3 and 5.4.4), thereby also compensating for the increase of the optical depth at smaller impact parameter.

For HI, the median optical depth profiles for three galaxy redshift samples are shown in Fig. 5.12, where we adopt redshift ranges of \( z_{\text{em}} < 0.30 \) (33 galaxies; grey triangles), \( 0.30 < z_{\text{em}} < 0.40 \) (35 galaxies; blue circles) and \( z_{\text{em}} > 0.40 \) (38 galaxies; red circles). The two samples above the redshift cut of \( z_{\text{em}} > 0.30 \) have similar median stellar masses of \( M_{\ast} \approx 10^{8.9} M_{\odot} \). However, the median impact parameter and median SFR are still somewhat lower for the \( 0.30 < z_{\text{em}} < 0.40 \) sample (i.e. \( \approx 115 \) pkpc and \( SFR \approx 0.1 M_{\odot} \) yr\(^{-1} \), respectively) than for the \( z_{\text{em}} > 0.40 \) sample (\( \approx 146 \) pkpc and \( SFR \approx 0.2 M_{\odot} \) yr\(^{-1} \)), where these two differences would affect the absorption signal in opposite ways. Comparing the optical depth profiles for the

\[ \text{We have checked that if we divide the } 0.38 < z < 0.74 \text{ range up into three instead of two subsamples, we reach the same conclusion.} \]
two samples, we do not find evidence for evolution in the H\textsc{i} optical depth over the range $0.30 < z < 0.48$.

As expected, a comparison of the H\textsc{i} optical depth between galaxies at $z_{\text{em}} < 0.30$ and at $z_{\text{em}} > 0.30$ is even less straightforward. The $z_{\text{em}} < 0.30$ sample has a median impact parameter of $\approx 70$ pkpc, and a median stellar mass and median SFR that are lower by $\approx 1.0$ dex and $\approx 0.5 - 0.8$ dex, respectively, than those of the $z_{\text{em}} > 0.30$ samples. Hence, the fact that we find the H\textsc{i} optical depths at $z < 0.30$ and $z > 0.30$ to be consistent within the error bars is likely because the dependence of the absorption strength on impact parameter compensates for the dependence on stellar mass and SFR.

### 5.4.3 Dependence on stellar mass

While the extent of the absorption signal along the LOS direction depends on the typical halo circular velocity, and therefore the halo mass, of the galaxies in the
sample, we also expect the strength of the metal absorption to depend on the mass of the galaxies and their host haloes (e.g. Rakic et al., 2013; Turner et al., 2017). On the one hand, more massive galaxies have higher metallicities (both in the gas-phase and in stars; e.g. Tremonti et al., 2004; Gallazzi et al., 2005; Zahid et al., 2014a), and a fraction of this metal-enriched gas is released into the CGM, as stellar (or AGN) feedback ejects material from the galactic disc in galactic winds (e.g. Aguirre et al., 2001b; Oppenheimer & Davé, 2006; Shen et al., 2012). On the other hand, the ion abundances as observed in absorption are strongly dependent on the ionization state of the gas. For example, Oppenheimer et al. (2016) showed that the virial temperature ($T_{\text{vir}}$) of the halo is a major factor in determining the column density of OVI in the CGM. For galaxies with a luminosity somewhat below $L^*$ ($M_{\text{vir}} \lesssim 10^{12.0} \, M_\odot$), more massive galaxies exhibit larger CGM column densities of OVI, as their virial temperature is closer to the temperature at which the OVI ion fraction peaks in collisional ionization equilibrium (i.e. $T_{\text{peak}} \sim 10^{5.5} \, K$). Furthermore, while for haloes with $T_{\text{vir}} \ll T_{\text{peak}}$ OVI arises predominantly from photoionized gas, their CGM still contains less OVI than that of $L^*$ haloes, as the total mass of oxygen is lower.

In this section, we investigate how the median OVI optical depth as a function of LOS velocity and normalized transverse distance depends on the mass of the galaxies. We divide the galaxy sample into three subsamples of roughly equal size, where the restriction to $z_{\text{em}} > 0.38$ ensures that the distribution of galaxies in impact parameter (and redshift) space is approximately uniform. Fig. 5.13 shows the resulting absorption profiles for the three galaxy mass samples, $M_* < 10^{8.5} \, M_\odot$ (36 galaxies; blue), $10^{8.5} < M_* < 10^{9.5} \, M_\odot$ (47 galaxies; yellow) and $M_* > 10^{9.5} \, M_\odot$ (31 galaxies; red), which have median stellar masses of $M_* = 10^{8.2}, 10^{9.1}, 10^{10.1} \, M_\odot$, respectively. According to the abundance matching relation from Moster et al. (2013) (assuming $z = 0.5$), these correspond to halo masses of $M_{\text{vir}} = 10^{10.8}, 10^{11.2}$ and $10^{11.8} \, M_\odot$, and hence halo circular velocities of $v_{\text{circ}} = 63.85$ and 135 km/s. Unavoidably, lower mass galaxies are probed at larger fractions of their virial radius than higher mass galaxies: the three galaxy mass samples correspond to median $d_{\text{trans}}/R_{\text{vir}}$ values of 2.6, 1.7 and 1.2.

Along the LOS direction (left-hand panel), the optical depths within $v_{\text{LOS}} \sim 100 \, \text{km/s}$ are significantly lower for the $M_* < 10^{8.5} \, M_\odot$ galaxies than for the higher mass galaxies. Since the three galaxy mass samples exhibit similar impact parameter distributions (due to the $z_{\text{em}} > 0.38$ cut), this is a trend at fixed $d_{\text{trans}}$. At fixed $d_{\text{trans}}/R_{\text{vir}}$ (right-hand panel), the OVI optical depths seem consistent between the $M_* < 10^{8.5} \, M_\odot$ and $M_* > 10^{8.5} \, M_\odot$ mass regimes. However, while the difference is not significant for the $1.2 < d_{\text{trans}}/R_{\text{vir}} < 2.2$ and $2.2 < d_{\text{trans}}/R_{\text{vir}} > 4.0$ bins individually, we do find a significant difference for the two bins combined. We calculate the confidence level of this difference in a similar way to the confidence level of the absorption enhancement described in Section 5.4.1. For each $d_{\text{trans}}/R_{\text{vir}}$ bin, we calculate the fraction $f_{\text{high}}$ of bootstrap realizations for which $\tau_{Z, \text{sample}1}^{i} > \tau_{Z, \text{sample}2}^{i}$, where in this case $\tau_{Z, \text{sample}1}$ and $\tau_{Z, \text{sample}2}$ refer to the median optical depths of the $M_* < 10^{8.5} \, M_\odot$ and $10^{8.5} < M_* < 10^{9.5} \, M_\odot$ samples at the $i$th bootstrap iteration (after linearly shifting them to the same $\tau_{\text{lim}}$). The optical depth for the $M_* < 10^{8.5} \, M_\odot$
sample is then lower than for the $10^{8.5} < M_* < 10^{9.5} \, M_\odot$ sample with a confidence level of $1 - 4 \times \frac{d_{\text{bin1}}}{d_{\text{bin2}}} \approx 98\%$ for the $1.2 < d_{\text{trans}}/R_{\text{vir}} < 2.2$ (‘bin1’) and $2.2 < d_{\text{trans}}/R_{\text{vir}} < 4.0$ (‘bin2’) bins combined. Furthermore, the fact that the LOS profile of the $M_* < 10^{8.5} \, M_\odot$ galaxies falls off at a lower LOS velocity is consistent with their lower halo $v_{\text{circ}}$, but can also be partly due to the gas dynamics in the outer halo (i.e. at higher fractions of the virial radius) being less sensitive to peculiar velocities.

In contrast, for the $10^{8.5} < M_* < 10^{9.5} \, M_\odot$ and $M_* > 10^{9.5} \, M_\odot$ samples, the OVI optical depths (in the LOS and transverse directions) agree within the error bars, despite the 1.0 dex difference in median stellar mass and the 0.6 dex difference in corresponding halo mass. This suggests that the OVI optical depth in this mass regime is insensitive to stellar mass, both at fixed $d_{\text{trans}}$ and at fixed $d_{\text{trans}}/R_{\text{vir}}$. Even for the three bins at $0.4 < d_{\text{trans}}/R_{\text{vir}} < 2.2$ combined, we find no significant difference between the mass samples. Also, there seems to be no significant difference in the LOS velocity scale at which the LOS profiles fall off, even though the samples have a different median halo $v_{\text{circ}}$ (and a different median $R_{\text{vir}}$-normalized impact parameter). We do note, however, that a $\approx 0.2$ dex difference in the velocity scale of the drop (corresponding to the difference in the median $v_{\text{circ}}$) is not ruled out considering the size of the error bars$^{18}$ at $v_{\text{LOS}} \approx 100 - 300 \, \text{km/s}$.

One possible explanation for the lack of mass dependence of the LOS profiles at $M_* > 10^{8.5} \, M_\odot$ is that the highest mass bin contains galaxies both above and below $M_* < 10^{10.5} \, M_\odot$, which corresponds to a halo mass scale of $M_{\text{vir}} < 10^{12} \, M_\odot$. Oppenheimer et al. (2016) showed that, while the OVI column density around galaxies with $M_{\text{vir}} < 10^{12} \, M_\odot$ increases with halo mass, the OVI content of $M_{\text{vir}} > 10^{12} \, M_\odot$ haloes decreases with mass, as their higher virial temperatures increasingly suppress the ion fraction of OVI. However, when we recompute the optical depths for the $M_* > 10^{9.5} \, M_\odot$ sample, where we exclude the 6 galaxies with $M_* > 10^{10.5} \, M_\odot$, we find no significant increase. Hence, the lack of mass dependence is not the result of averaging the absorption strength from haloes with a high and low OVI content.

Furthermore, given that the strength of the absorption signal exhibits a positive correlation with galaxy SFR (see Section 5.4.4), we need to confirm that the difference in absorption strength at fixed $d_{\text{trans}}$ between galaxies with $M_* < 10^{8.5} \, M_\odot$ and galaxies with $M_* > 10^{8.5} \, M_\odot$ is not solely driven by the different SFR distributions exhibited by the different galaxy mass samples. While the $10^{8.5} < M_* < 10^{9.5} \, M_\odot$ and $M_* > 10^{9.5} \, M_\odot$ samples have median SFRs of $\approx 0.4 \, M_\odot \, \text{yr}^{-1}$ and $\approx 0.7 \, M_\odot \, \text{yr}^{-1}$, respectively, the $M_* < 10^{8.5} \, M_\odot$ sample has a much lower median SFR of $\approx 0.09 \, M_\odot \, \text{yr}^{-1}$. This accounts for at least part of the difference between the absorption strength for $M_* < 10^{8.5} \, M_\odot$ and higher stellar mass. However, we show in Appendix 5.B that both stellar mass (comparing galaxies with $10^{8.0} < M_* < 10^{9.0} \, M_\odot$ and $10^{9.0} < M_* < 10^{10.0} \, M_\odot$) and SFR also independently correlate positively with the strength of the absorption signal along the LOS direction. We demonstrate this by varying one property, while restricting the galaxies to a narrow range.

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$^{17}$We consider a difference with a confidence level $> 95\%$ to be significant.

$^{18}$Even though the points representing consecutive LOS velocity bins (unlike the transverse distance bins) are not independent from each other, the error bars do reflect the true optical depth confidence intervals, as they are derived by bootstrapping independent chunks of absorption distance.
5.4 Results

Another factor that might play a role in the comparison of galaxy mass samples, is the possible occurrence of galaxies in groups. A fraction of the galaxies at low stellar masses will be satellites of more massive galaxies, while at the high-mass end some galaxies will also be part of larger structures, where multiple galaxies are contained within the same group-scale dark matter halo. In both cases, the halo mass inferred from the galaxy stellar mass through abundance matching is not representative of the mass of the group halo. Observations of circumgalactic O\textsc{vi} in group environments suggest that the O\textsc{vi} column density (or equivalent width) and covering fraction are lower for groups than for isolated galaxies (e.g. Wakker & Savage, 2009; Pointon et al., 2017). This is likely due to the higher virial temperature of the group-scale halo, which causes less oxygen to reside in O\textsc{vi}, and more in higher states (O\textsc{vi} absorption in group environments is generally broad; see e.g. Stocke et al., 2014, 2017).

To assess the importance of this environmental dependence for the results presented in this section, we repeat the comparison of the O\textsc{vi} absorption signal between different stellar mass samples, using only galaxies without any neighbouring galaxies (within the MUSE FoV) within a LOS velocity difference of $|\Delta v| = 300$ km/s. To be conservative, we consider all galaxies identified at $z < z_{QSO}$ – not just the ones with the highest-quality redshift assignment, to which we limit our absorption analysis – as potential neighbours. Furthermore, we consider galaxies with all masses, not just the ones with higher masses, as potential neighbours, which makes our approach even more conservative. From low to high stellar mass, this removes 16, 26 and 20 non-isolated galaxies from the samples shown in Fig. 5.13. We find that the O\textsc{vi} absorption profiles for isolated galaxies, when we split them according to their stellar mass as in Fig. 5.13, are consistent with those for all (isolated and non-isolated) galaxies. Hence, we find that the effects of the group environment do not impact our conclusions about the dependence of the CGM O\textsc{vi} content on galaxy stellar mass. However, we note that when we split the galaxy sample according to the number of neighbours of each galaxy (irrespective of their stellar mass), we do find significantly lower O\textsc{vi} absorption around galaxies with three or more neighbours than around galaxies with two or fewer neighbours. We will explore the O\textsc{vi} content of groups identified in our MUSE fields in more detail in a forthcoming paper.

We conclude that the lack of a galaxy mass dependence in the O\textsc{vi} absorption signal along the LOS direction for $M_* > 10^{8.5}$ $M_\odot$ galaxies is not due to a significant contribution from $T_{\text{vir}} \gg 10^{5.5}$ K haloes to the highest-mass galaxy sample or due to the suppression of O\textsc{vi} in group environments. It can also not be attributed solely to the dependence of O\textsc{vi} absorption on SFR. The inferred mass trend is therefore likely related to a reduced efficiency of galactic winds in expelling metals from the disc into the CGM in higher mass galaxies (as the ionization conditions do seem more favourable around higher mass galaxies in this mass regime; Oppenheimer et al., 2016). As a result, the difference in the enrichment level of the CGM between $M_* \sim 10^9$ $M_\odot$ and $M_* \sim 10^{10}$ $M_\odot$ galaxies is smaller – and too small for us to observe a difference in the optical depth – than between $M_* \sim 10^8$ $M_\odot$ and $M_* \sim 10^9$ $M_\odot$ galaxies, even though the metallicity of the galaxy itself does increase with increasing
stellar mass (see e.g. Tremonti et al., 2004; Zahid et al., 2014a, who probe the relation between stellar mass and gas-phase metallicity down to $M_\ast \sim 10^{8.5-9} \, M_\odot$).

### 5.4.4 Dependence on (specific) star formation rate

The discovery of a correlation between the OVI column density around a sample of $L \approx L^*$ galaxies and their sSFR by Tumlinson et al. (2011) suggested that there is a connection between the enrichment of the CGM and the star formation activity of the host galaxy. Other studies have also shown that the rate of incidence of OVI and other metal ions is higher around star-forming galaxies than around quiescent ones (e.g. Chen & Mulchaey, 2009; Borthakur et al., 2013; Werk et al., 2013; Bordoloi et al., 2014). Such a connection between the CGM metal content and star formation may arise naturally if stellar feedback is responsible for enriching the CGM by driving metal-enriched galactic winds. However, due to the time delay between the actual star formation event – if star formation is bursty – and the metals reaching distances comparable to the virial radius of the galaxy, and due to fact that metals may remain in the CGM even after the SFR of the host decreases, the correlation between the CGM metal content and the instantaneous SFR is not expected to be tight. Indeed, the simulations of Oppenheimer et al. (2016) suggest that the correlation between sSFR and OVI column density is indirect: passive galaxies reside in
5.4 Results

![Graph showing the dependence of the median O VI optical depth on the specific SFR of the galaxies.](image)

**Figure 5.15:** As Fig. 5.13, but showing the dependence of the median OVI optical depth on the specific SFR of the galaxies. We compare samples of galaxies with $SFR/M_* < 10^{-9.7}$ yr$^{-1}$ (red), $10^{-9.7} < SFR/M_* < 10^{-9.2}$ yr$^{-1}$ (yellow) and $SFR/M_* > 10^{-9.2}$ yr$^{-1}$ (blue), with redshifts constrained to $z_{em} > 0.38$. We only consider galaxies for which we could determine the SFR. As a function of LOS velocity, the OVI optical depths for the $SFR/M_* > 10^{-9.2}$ yr$^{-1}$ sample are lower than for the lower sSFR samples, consistent with lower median stellar mass ($M_* = 10^{8.4} M_\odot$). As a function of $d_{trans}/R_{vir}$, there is no significant difference between the $SFR/M_* > 10^{-9.2}$ yr$^{-1}$ sample and the lower sSFR samples. However, we find a significantly higher optical depth for the $10^{-9.7} < SFR/M_* < 10^{-9.2}$ yr$^{-1}$ sample than for the $SFR/M_* < 10^{-9.7}$ yr$^{-1}$ sample at $0.7 < d_{trans}/R_{vir} < 1.2$ or for the bins at $0.7 < d_{trans}/R_{vir} < 4.0$ combined.
haloes with virial temperatures that are too high for O\textsc{v i}.

In this section, we study the dependence of the O\textsc{v i} absorption strength on the SFR and sSFR of the galaxies. Our sample contains predominantly star-forming galaxies; only two galaxies at $z_{\text{em}} > 0.38$ and within the O\textsc{v i} redshift range have $\text{SFR}/M_\ast < 10^{-11} \text{ yr}^{-1}$ (and three have an upper limit below this value). Although we do include these galaxies in the analysis, our assessment of how the CGM O\textsc{v i} content depends on the star formation activity of the galaxies is mainly focussed on the star-forming population. Fig. 5.14 shows the median O\textsc{v i} optical depth as a function of LOS velocity and $R_{\text{vir}}$-normalized transverse distance for three galaxy samples divided by SFR: $\text{SFR} < 0.1 \, M_\odot \, \text{yr}^{-1}$ (21 galaxies; red), $0.1 < \text{SFR} < 1.0 \, M_\odot \, \text{yr}^{-1}$ (45 galaxies; yellow) and $\text{SFR} > 1.0 \, M_\odot \, \text{yr}^{-1}$ (30 galaxies; blue). These samples have median SFRs of $\text{SFR} = 0.048, 0.26, 2.0 \, M_\odot \, \text{yr}^{-1}$. As before, we only use galaxies with $z_{\text{em}} > 0.38$. Furthermore, in this section we only consider galaxies for which we could obtain a reliable estimate of the SFR (as described in Section 5.2.4), excluding those galaxies with only an upper limit on the SFR. However, we have checked that if we do include the galaxies with SFR upper limits, either considering the limits as the actual values or including them all in the lowest SFR sample, the significance of the correlation between absorption strength and SFR slightly decreases (despite the higher number of galaxies), but that our conclusions remain unaffected.

Fig. 5.14 shows that along the LOS direction (left-hand panel), the median O\textsc{v i} optical depths increase (especially within $v_{\text{LOS}} \approx 100 \, \text{km/s}$) and fall off at a larger LOS velocity as the SFR of the galaxies increases. However, based on the median stellar masses of $M_\ast = 10^{8.2}, 10^{8.9}, 10^{9.4} \, M_\odot$ (corresponding to the $\text{SFR} < 0.1 \, M_\odot \, \text{yr}^{-1}$, $0.1 < \text{SFR} < 1.0 \, M_\odot \, \text{yr}^{-1}$ and $\text{SFR} > 1.0 \, M_\odot \, \text{yr}^{-1}$ samples, respectively), we expect differences of only $\approx 0.1$ dex in the halo circular velocity. For the $\text{SFR} > 1.0 \, M_\odot \, \text{yr}^{-1}$ sample in particular, the velocity scales of the drop and the maximum extent seem to differ by more than 0.1 dex from the other SFR samples.

While the impact parameters of the galaxies in the three samples are similar, the high-SFR galaxies are probed at slightly smaller fractions of their virial radii due to their slightly higher stellar masses. The median $d_{\text{trans}}/R_{\text{vir}}$ in decreases by $\approx 0.1$ dex from the low to intermediate and from intermediate to high SFRs. To confirm that the result in the left-hand panel of Fig. 5.14 is not solely due to the dependence of the O\textsc{v i} absorption strength on stellar mass and $d_{\text{trans}}/R_{\text{vir}}$, we show in Appendix 5.B that, even at fixed stellar mass (and hence fixed $d_{\text{trans}}/R_{\text{vir}}$), the absorption strength at small LOS velocities is higher at higher SFR.

However, the SFR dependence is too weak to cause a significant trend when we split the sample up into $d_{\text{trans}}/R_{\text{vir}}$ bins (right-hand panel of Fig. 5.14). Only for the $1.2 < d_{\text{trans}}/R_{\text{vir}} < 2.2$ bin, which does contain the highest number of galaxies, is the O\textsc{v i} optical depth lower for the $\text{SFR} < 0.1 \, M_\odot \, \text{yr}^{-1}$ sample than for the $\text{SFR} > 1.0 \, M_\odot \, \text{yr}^{-1}$ sample, although the difference is comparable to the size of the errors. For the three bins at $0.7 < d_{\text{trans}}/R_{\text{vir}} < 4.0$ combined, we find a confidence level for the difference of 93%, which is just below our significance threshold. The $0.1 < \text{SFR} < 1.0 \, M_\odot \, \text{yr}^{-1}$ sample is consistent with both of the other samples (for the $d_{\text{trans}}/R_{\text{vir}}$ bins individually or combined).

Following Werk et al. (2016), we have also computed the O\textsc{v i} optical depth profiles for three different samples of $\text{SFR}/d_{\text{trans}}^2$, which may be a measure of the
amount of ionizing radiation originating from ongoing star formation in the galaxy. We note, however, that this neglects the dependence of the \OVI abundance on the ionization state of the gas. Taking into account the dependence on the ionization parameter, we would expect \OVI to scale with $\text{SFR}/d_{\text{trans}}^2/\rho$, where $\rho$ is the gas mass density, which decreases as a function of radial distance from the galaxy. Although we do not show it here, we find that the difference between the profiles is somewhat more distinct than for the different SFR samples. Within $v_{\text{LOS}} \sim 100$ km/s, the optical depths along the LOS direction increase by $\approx 0.2$ dex as the median $\text{SFR}/d_{\text{trans}}^2$ of the sample increases by $\approx 1.0$ dex, where we do note that the $\text{SFR}/d_{\text{trans}}^2$ values probed here ($10^{-6.0} \leq \text{SFR}/d_{\text{trans}}^2 \leq 10^{-3.5} \, M_\odot \text{ yr}^{-1} \text{ kpc}^{-2}$) are much lower than those considered by Werk et al. (2016). While this might hint at a significant impact of local ionizing radiation on the metal ion fractions in the CGM, it is also possible that the correlation between the \OVI absorption strength and $\text{SFR}/d_{\text{trans}}^2$ arises from a combination of the positive correlation of absorption strength with SFR and the negative correlation with impact parameter.

Finally, in Fig. 5.15 we show the dependence of the \OVI optical depth on sSFR, which is related to the gas fraction ($= M_{\text{gas}}/(M_{\text{gas}}+M_*)$, where $M_{\text{gas}}$ is the mass of gas in the interstellar medium) of the galaxy. We choose the boundaries of the samples so as to have three samples of roughly equal size: $\text{SFR}/M_* < 10^{-9.7}$ yr$^{-1}$ (33 galaxies; red), $10^{-9.7} < \text{SFR}/M_* < 10^{-9.2}$ yr$^{-1}$ (31 galaxies; yellow) and $\text{SFR}/M_* > 10^{-9.2}$ yr$^{-1}$ (32 galaxies; blue), which have median sSFRs of $\text{SFR}/M_* = -10.0, -9.4, -8.8$ yr$^{-1}$. Along the LOS direction (left-hand panel), the optical depth profile for the $\text{SFR}/M_* < 10^{-9.7}$ yr$^{-1}$ sample (median $M_* = 10^{9.5} M_\odot$ and median SFR = 0.17 $M_\odot$ yr$^{-1}$) is similar to the $10^{-9.7} < \text{SFR}/M_* < 10^{-9.2}$ yr$^{-1}$ sample (median $M_* = 10^{8.9} M_\odot$ and median SFR = 0.27 $M_\odot$ yr$^{-1}$). These sSFR samples contain predominantly galaxies in the mass regime where the \OVI optical depth is insensitive to stellar mass. Furthermore, the $\approx 2$ times higher SFR for the $10^{-9.7} < \text{SFR}/M_* < 10^{-9.2}$ yr$^{-1}$ sample may cancel out any mass dependence.

The optical depths for the $\text{SFR}/M_* > 10^{-9.2}$ yr$^{-1}$ sample (median $M_* = 10^{8.4} M_\odot$ and median SFR = 0.85 $M_\odot$ yr$^{-1}$) are lower than for the other samples and fall off at a lower LOS velocity. This indicates that the effect of a lower stellar mass more than compensates for the effect of a higher SFR, which is also consistent with the different profile shape. As a function of $d_{\text{trans}}/R_{\text{vir}}$ (right-hand panel), the sSFR samples show similar \OVI optical depths on the scales where all three samples can be compared ($1.2 < d_{\text{trans}}/R_{\text{vir}} < 4.0$). Even for the $1.2 < d_{\text{trans}}/R_{\text{vir}} < 2.2$ and $2.2 < d_{\text{trans}}/R_{\text{vir}} < 4.0$ bins combined, the differences between the $\text{SFR}/M_* > 10^{-9.2}$ yr$^{-1}$ sample and the other samples are not significant. However, at $0.7 < d_{\text{trans}}/R_{\text{vir}} < 1.2$, where the $\text{SFR}/M_* > 10^{-9.2}$ yr$^{-1}$ sample does not have sufficient galaxies, the optical depth is significantly higher for the $10^{-9.7} < \text{SFR}/M_* < 10^{-9.2}$ yr$^{-1}$ sample than for the $\text{SFR}/M_* < 10^{-9.7}$ yr$^{-1}$ sample. Combining the results from the three bins at $0.7 < d_{\text{trans}}/R_{\text{vir}} < 4.0$, we find a higher optical depth for the $10^{-9.7} < \text{SFR}/M_* < 10^{-9.2}$ yr$^{-1}$ sample at 96% confidence.
5.5 Conclusions

We have studied the H\textsc{i}, O\textsc{vi} and C\textsc{iii} abundances in the CGM of 208 galaxies at $z_{\text{em}} < 0.91$, which were blindly selected with MUSE in the fields centred on 15 QSOs – plus one field where we found no galaxies – with high-quality COS quasar spectra. We compiled the sample of galaxies by detecting them through their continuum emission, and measuring their redshifts from their emission lines – mainly H\textsc{a}, H\textsc{b}, O\textsc{ii} and O\textsc{iii} – and, in a few cases, from their absorption lines. For this study, we only selected the galaxies with redshift estimates based on multiple spectral features. Our sample has a median stellar mass of $10^{8.9}$ M$_\odot$ and a median SFR of 0.21 M$_\odot$ yr$^{-1}$. Hence, the typical galaxy mass is much lower than for other (low- and high-redshift) quasar absorption-line studies. We studied the CGM of the galaxies in absorption by calculating the median pixel optical depth, employing the pixel optical depth method to partially correct for the effects of noise, saturation and contamination, as a function of LOS velocity and transverse distance (up to impact parameters of 300 pkpc or four times the halo virial radius). We investigated the extent of the absorption signal in both of these directions, and explored the dependence of the absorption strength, where we mainly focused on O\textsc{vi}, on galaxy redshift, stellar mass, SFR and sSFR. Our main results can be summarized as follows.

1. Along the LOS direction, the median H\textsc{i}, O\textsc{vi} and C\textsc{iii} optical depths generally decrease with increasing LOS velocity from the galaxies. The characteristic scale at which the optical depth starts to deviate from the approximately flat trend at small $v_{\text{LOS}}$ is $v_{\text{drop}} = 50$ km/s for H\textsc{i} and $v_{\text{drop}} \approx 80$ km/s for O\textsc{vi} and C\textsc{iii}.

2. We find a significant enhancement of the H\textsc{i} and O\textsc{vi} absorption, with respect to the detection limit, with $> 95\%$ confidence out to LOS velocities of $v_{\text{LOS}} \approx 260$ km/s ($d_{\text{LOS}} \approx 3.2$ pMpc in the case of pure Hubble flow) and $v_{\text{LOS}} \approx 115$ km/s ($d_{\text{LOS}} \approx 1.3$ pMpc), respectively. At small LOS velocities, the median optical depth reaches values up to $\approx 1.3$ dex above $\tau_{\text{lim}}$ in the case of H\textsc{i}, and up to $\approx 0.8$ dex above $\tau_{\text{lim}}$ in the case of O\textsc{vi}, where $\tau_{\text{lim}}$ is the median optical depth far from the galaxies. For C\textsc{iii}, we find enhanced absorption with $> 68\%$ confidence out to $v_{\text{LOS}} \approx 115$ km/s ($d_{\text{LOS}} \approx 1.3$ pMpc), with the median optical depth reaching values up to $\approx 0.2$ dex above $\tau_{\text{lim}}$ (Fig. 5.9, left-hand panels).

3. In the direction projected on the sky, the median H\textsc{i}, O\textsc{vi} and C\textsc{iii} optical depths decrease as a function of both transverse distance and transverse distance divided by the halo virial radius. A tentative drop in the optical depths profiles, comparable to twice the size of the estimated error on the median optical depth, is seen at $d_{\text{trans}} \approx 120$ pkpc and $d_{\text{trans}}/R_{\text{vir}} \approx 1.2$.

4. For H\textsc{i} and O\textsc{vi}, the absorption is enhanced with $> 95\%$ confidence over the whole transverse distance range probed (i.e. up to $d_{\text{trans}} = 300$ pkpc). For C\textsc{iii}, the absorption is enhanced with $> 95\%$ confidence out to $d_{\text{trans}} \approx 120$ pkpc.
These scales are ~ 10 times smaller than the extent of the absorption enhancement along the LOS direction, which can be attributed to gas peculiar velocities smearing the absorption signal along the LOS but not in the transverse direction (Fig. 5.9, right-hand panels). When considering transverse distances in units of the halo virial radius, we find the H\textsc{i} and O\textsc{vi} absorption to be enhanced with > 95% confidence out to $d_{\text{trans}}/R_{\text{vir}} = 4.0$. For C\textsc{iii}, we find a confidence level of > 95% only at $0.7 < d_{\text{trans}}/R_{\text{vir}} = 1.2$ (Fig. 5.10).

5. We emphasize that, to enable an approximately unbiased assessment of the dependence of the absorption signal on a particular galaxy property, it is necessary to eliminate any secondary correlations – due to observational bias or with a physical origin – with other galaxy properties as much as possible. This avoids misinterpreting the effects of different galaxy properties on the absorption signal. We find that imposing a minimum galaxy redshift of $z_{\text{em}} > 0.38$ (and $z_{\text{em}} > 0.30$ in the case of H\textsc{i}) largely removes the correlations of impact parameter, stellar mass and SFR with redshift, and thereby also the correlations of stellar mass and SFR with impact parameter, while still yielding a reasonable sample size (i.e. 73 galaxies for H\textsc{i}, 116 for O\textsc{vi} and 150 for C\textsc{iii}).

6. Comparing the LOS and transverse absorption profiles for different galaxy samples split according to their redshifts, we find no evidence for significant evolution of the H\textsc{i} and O\textsc{vi} optical depth over the ranges $0.30 < z < 0.48$ and $0.38 < z < 0.74$, respectively. At lower redshifts, an unbiased comparison is impossible, as the typical impact parameter, stellar mass and SFR of the galaxies in the sample is also significantly lower (Figs. 5.11 and 5.12).

7. We find that the O\textsc{vi} absorption strength as a function of LOS velocity is significantly higher, and falls off at a higher LOS velocity, for galaxies with $M_* > 10^{8.5} M_\odot$ than for galaxies with $M_* < 10^{8.5} M_\odot$ (Fig. 5.13, left-hand panel). This is a comparison at fixed $d_{\text{trans}}$, as we eliminate the correlation between impact parameter and stellar mass, but the median $d_{\text{trans}}/R_{\text{vir}}$ does decrease from low to high stellar mass. At fixed $d_{\text{trans}}/R_{\text{vir}}$, we also find a significantly lower O\textsc{vi} optical depth for $M_* < 10^{8.5} M_\odot$ galaxies than for higher mass galaxies (Fig. 5.13, right-hand panel). In contrast, for galaxies at $M_* > 10^{8.5} M_\odot$, the O\textsc{vi} LOS and transverse profiles do not exhibit a clear dependence on stellar mass, which can be explained if the total CGM metal abundance no longer increases with increasing galaxy mass in this mass regime (due to the lower efficiency of galactic winds in driving out metals), as the ionization conditions for O\textsc{vi} do seem more favourable in higher mass galaxies at these mass scales. We have checked that this lack of a stellar mass dependence is not due to the suppression of the O\textsc{vi} abundance in galaxy groups. We have also confirmed that the O\textsc{vi} absorption strength along the LOS direction exhibits positive correlations with both stellar mass and SFR when these are varied independently; hence, any trend of the signal with stellar mass is not solely driven by the correlation with SFR (Fig. 5.18).

8. Using only the galaxies with a reliable estimate of the SFR ($\approx 89\%$ of the sample), we find that the median O\textsc{vi} optical depth increases with increasing SFR
and weakly decreases with increasing sSFR, but only when we consider the optical depth as a function of LOS velocity (Figs. 5.14 and 5.15). The SFR dependence is too weak to show an effect across all $d_{\text{trans}}/R_{\text{vir}}$ bins. The trend of decreasing O\textsc{vi} optical depth with increasing sSFR is only evident when comparing the SFR/M$_{\ast}$ > 10$^{-9.2}$ yr$^{-1}$ sample with the two SFR/M$_{\ast}$ < 10$^{-9.2}$ yr$^{-1}$ samples, which is consistent with the fact that the median stellar masses of the samples in these two sSFR regimes are lower and higher than M$_{*}$ = 10$^{8.5}$ M$_{\odot}$, respectively. In contrast, for SFR/M$_{\ast}$ < 10$^{-9.2}$ yr$^{-1}$, the median O\textsc{vi} optical depth (weakly) increases with sSFR, but only when considered at fixed $d_{\text{trans}}/R_{\text{vir}}$.

5.A Optical depth profiles of other metal ions

Fig. 5.16 shows the median pixel optical depth, $\log_{10} \tau_Z$, as a function of LOS velocity for the following ions: Si\textsc{iii} 1260.42 Å ($z < 0.43$), C\textsc{ii} 1334.53 Å ($z < 0.35$), Si\textsc{iii} ($z < 0.49$), Si\textsc{iv} ($z < 0.29$), C\textsc{iv} ($z < 0.16$) and N\textsc{v} ($z < 0.45$). As described in Section 5.3.2, the optical depths have been corrected for H\textsc{i} contamination and, in the case of a doublet transition, corrected for further contamination by taking the doublet minimum. For Si\textsc{ii} and C\textsc{ii}, which are multiplets, we only apply the H\textsc{i} contamination correction and show the absorption in the strongest transition.

Only N\textsc{v} shows a significant absorption enhancement with respect to the detection limit within $v_{\text{LOS}}$ ∼ 100 km/s, although for the individual points the confidence levels of the enhancement vary from less than 50% to 97%. In the transverse direction (Fig. 5.17), we find an enhancement at 100% confidence for 0.2 < $d_{\text{trans}}/R_{\text{vir}}$ < 0.4 and at 88% confidence for 0.7 < $d_{\text{trans}}/R_{\text{vir}}$ < 1.2. For none of the other ions, is the absorption significantly enhanced. Especially in the case of C\textsc{iv}, this can be partly attributed to the limited sample size, as C\textsc{iv} is only observable with COS at $z < 0.16$.

5.B Varying the stellar mass and star formation rate independently

We investigate how the O\textsc{vi} absorption strength as a function of LOS velocity depends on galaxy stellar mass and SFR, when we vary one property independently from the other. The lower-left panel of Fig. 5.18 shows the median O\textsc{vi} optical depth profile along the LOS direction for a sample of galaxies with 10$^{8.0}$ < M$_{\ast}$ < 10$^{9.0}$ M$_{\odot}$ (23 galaxies; blue) and a sample with 10$^{9.0}$ < M$_{\ast}$ < 10$^{10.0}$ M$_{\odot}$ (15 galaxies; red), which have all been selected to have a SFR in the range 0.1 < SFR < 1.0 M$_{\odot}$ yr$^{-1}$ (as illustrated in the upper-left panel). As in Sections 5.4.3 and 5.4.4, we restrict the galaxy redshifts to $z_{\text{em}} > 0.38$, in order to eliminate any correlation between stellar mass and impact parameter. The median $d_{\text{trans}}/R_{\text{vir}}$ does decrease with increasing stellar mass (from 1.9 to 1.5), but we aim to perform a comparison at fixed $d_{\text{trans}}$ to mimic the investigation of the stellar mass dependence (left-hand panel of Fig. 5.13) in a restricted SFR range. The optical depth profile of the high mass sample reaches up to higher values at small LOS velocities, and falls off at a larger LOS velocity.
5.B Varying the stellar mass and star formation rate independently

Figure 5.16: The median pixel optical depth of, from top left to bottom right, Si\textsc{ii} 1260.42 Å (z < 0.43), C\textsc{ii} 1334.53 Å (z < 0.35), Si\textsc{iii} (z < 0.49), Si\textsc{iv} (z < 0.29), C\textsc{iv} (z < 0.16) and N\textsc{v} (z < 0.45) as a function of LOS velocity. The corresponding absolute LOS Hubble distance, assuming \( z = 0.5 \), is shown at the top. In the top right of each panel, we indicate the number of galaxies contributing to the profile. We do not apply a redshift cut. Only N\textsc{v} shows a significant enhancement of the absorption signal with respect to the detection limit (horizontal dashed line) for \( v_{\text{LOS}} \lesssim 100 \) km/s. The other ions show no significant absorption enhancement.
Figure 5.17: The median NV optical depth as a function of transverse distance normalized by the virial radius. For each $d_{\text{trans}}/R_{\text{vir}}$ bin, we calculate the median log$_{10} \tau_{\text{NV}}$ using only pixels at $v_{\text{LOS}} < 100$ km/s and we linearly shift the optical depths to the same $\tau_{\text{lim}}$ as in the bottom right panel of Fig. 5.16 (horizontal dashed line). We only show $d_{\text{trans}}/R_{\text{vir}}$ bins containing at least three galaxies. We find an enhancement of the NV absorption signal at 100% confidence for $0.2 < d_{\text{trans}}/R_{\text{vir}} < 0.4$ and at 88% confidence for $0.7 < d_{\text{trans}}/R_{\text{vir}} < 1.2$.

scale, which is consistent with what is expected for more massive haloes. Hence, even at fixed SFR, the optical depth profile exhibits a clear dependence on galaxy stellar mass.

In the right-hand panels of Fig. 5.18, we show a comparison of the median OVI optical depth profile between galaxies with $0.03 < SFR < 0.3 \text{ M}_\odot \text{ yr}^{-1}$ (20 galaxies; yellow) and galaxies with $0.3 < SFR < 3.0 \text{ M}_\odot \text{ yr}^{-1}$ (20 galaxies; green), which are selected from a narrow range in stellar mass ($10^{8.5} < M_* < 10^{9.5} \text{ M}_\odot$). As the two samples exhibit similar impact parameter and stellar mass distributions, the galaxies are also probed at similar fractions of their virial radius (i.e. at similar $d_{\text{trans}}/R_{\text{vir}}$, where both sample have a median of $\approx 1.7$). While the optical depth profiles of both samples fall off at a similar LOS velocity, reflecting the similar halo mass distributions of the two samples, the optical depths at small LOS velocities are significantly higher for the high-SFR sample than for the low-SFR sample. We therefore confirm that the OVI absorption strength correlates positively with the SFR of the galaxies, even at fixed galaxy stellar mass.

5.C Dependence of the H\textsc{i} optical depth on stellar mass and star formation rate

Fig. 5.19 shows how the median H\textsc{i} optical depth as a function of $v_{\text{LOS}}$ and $d_{\text{trans}}/R_{\text{vir}}$ depends on galaxy stellar mass. As, compared with OVI, H\textsc{i} is observable over a smaller redshift range, we split the galaxy sample into two instead of three stellar
Dependence of the H\textsubscript{i} optical depth on stellar mass and star formation rate

Figure 5.18: The dependence of the median O\textsubscript{VI} optical depth as a function of LOS velocity on galaxy stellar mass (left-hand panels) and SFR (right-hand panels) for galaxies with $z_{\text{em}} > 0.38$. As shown in the upper panels, we select galaxies from a narrow range in SFR when we vary the stellar mass ($10^8.0 < M_\ast < 10^{9.0} \, M_\odot$: blue; $10^{9.0} < M_\ast < 10^{10.0} \, M_\odot$: red), and we select galaxies from a narrow range in stellar mass when we vary the SFR ($0.03 < SFR < 0.3 \, M_\odot \, yr^{-1}$: yellow; $0.3 < SFR < 3.0 \, M_\odot \, yr^{-1}$: green). The legends indicate the median stellar mass and SFR of each sample in the left- and right-hand panels, respectively. In both of the lower panels, the points are offset horizontally from each other by 0.02 dex, and have been linearly shifted to the same $\tau_{\text{lim}}$ (horizontal dashed line). The velocity axis indicates the absolute LOS Hubble distance at $z = 0.5$. We conclude that both stellar mass and SFR independently exhibit positive correlations with the O\textsubscript{VI} absorption strength.
Figure 5.19: The dependence on galaxy stellar mass of the median H\textsc{i} optical depth as a function of LOS velocity (left) and normalized transverse distance (using only pixels at $v_{\text{LOS}} < 100$ km/s; right). We compare samples of galaxies with $M_\ast < 10^{9.0} \, M_\odot$ (blue) and $M_\ast > 10^{9.0} \, M_\odot$ (red), with redshifts constrained to $z_{\text{em}} > 0.30$. The median stellar mass of each sample is indicated in the legend. The median log_{10} $\tau_{\text{HI}}$ values for each sample and $d_{\text{trans}}/R_{\text{vir}}$ bin have been linearly shifted to the same $\tau_{\text{lim}}$ (horizontal dashed line). We only show $d_{\text{trans}}/R_{\text{vir}}$ bins containing at least three galaxies. For clarity, the points are offset horizontally from each other by 0.02 dex and 0.075 dex in the left- and right-hand panels, respectively. The velocity axis shows the absolute LOS Hubble distance at $z = 0.5$. We do not find a significant dependence of the median H\textsc{i} optical depth on stellar mass.
Figure 5.20: As Fig. 5.19, but showing the dependence of the median H\textsc{i} optical depth on galaxy SFR. We compare samples of galaxies with $SFR < 0.3 \, M_\odot \, yr^{-1}$ (red) and $SFR > 0.3 \, M_\odot \, yr^{-1}$ (blue), with redshifts constrained to $z_{\text{em}} > 0.30$. We only consider galaxies for which we could determine their SFR. Along the LOS direction, the H\textsc{i} optical depth seems to be significantly higher for the high-SFR sample than for the low-SFR sample. A similar dependence on SFR in the transverse direction is only shown by the $1.2 < d_{\text{trans}}/R_{\text{vir}} < 2.2$ distance bin.

Figure 5.21: As Fig. 5.19, but showing the dependence of the median H\textsc{i} optical depth on the specific SFR of the galaxies. We compare samples of galaxies with $SFR/M_\star < 10^{-9.5} \, yr^{-1}$ (red) and $SFR/M_\star > 10^{-9.5} \, yr^{-1}$ (blue), with redshifts constrained to $z_{\text{em}} > 0.30$. We only consider galaxies for which we could determine their SFR. Except for the significant increase of the H\textsc{i} absorption strength with increasing sSFR shown at $1.2 < d_{\text{trans}}/R_{\text{vir}} < 2.2$, we do not find evidence for a dependence of the absorption signal on sSFR.
mass samples, so as to maintain reasonable sample sizes. We split the sample in the middle of the bins used for Ovi, yielding $M_\ast < 10^{9.0} M_\odot$ (42 galaxies; blue) and $M_\ast > 10^{9.0} M_\odot$ (31 galaxies; red). These samples have median stellar masses of $M_\ast = 10^{8.3}, 10^{9.5} M_\odot$ and median SFRs of $SFR = 0.087, 0.31 M_\odot$ yr$^{-1}$.

While the imposed redshift cut of $z_{em} > 0.30$ ensures that the samples have similar impact parameter and redshift distributions, lower mass galaxies are typically probed at a higher fraction of their virial radius. The median $d_{\text{trans}}/R_{\text{vir}}$ values corresponding to the low- and high-mass samples are 1.7 and 1.1, respectively. However, despite the 1.2 dex difference in median stellar mass and the 0.19 dex difference in median $d_{\text{trans}}/R_{\text{vir}}$, we do not find a significant dependence of the H$\iota$ absorption signal on stellar mass, neither at fixed $v_{\text{LOS}}$ (left-hand panel) nor at fixed $d_{\text{trans}}/R_{\text{vir}}$ (right-hand panel).

Interestingly, we do find a significant dependence of the median H$\iota$ optical depth as a function of LOS velocity on SFR. This is shown in Fig. 5.20. We split the total sample in two, creating samples with $SFR < 0.3 M_\odot$ yr$^{-1}$ (46 galaxies; red) and $SFR > 0.3 M_\odot$ yr$^{-1}$ (22 galaxies; blue), where we only use galaxies for which we could determine the SFR. We find a higher H$\iota$ absorption signal out to $v_{\text{LOS}} \approx 300$ km/s for the high-SFR sample than for the low-SFR sample. The median SFRs of the two samples are $SFR = 0.10, 1.5 M_\odot$ yr$^{-1}$ and the median stellar masses ($d_{\text{trans}}/R_{\text{vir}}$ values) are $M_\ast = 10^{8.5}, 10^{9.4} M_\odot$ ($d_{\text{trans}}/R_{\text{vir}} = 1.5, 1.1$). In the transverse direction, only the $1.2 < d_{\text{trans}}/R_{\text{vir}} < 2.2$ shows a (barely significant) difference between the low- and high-SFR samples.

However, the H$\iota$ absorption signal does not exhibit a significant dependence on the specific SFR. This is shown in Fig. 5.21, where we split the total sample into galaxies with $SFR/M_\ast < 10^{-9.5}$ yr$^{-1}$ (32 galaxies; red) and $SFR/M_\ast > 10^{-9.5}$ yr$^{-1}$ (36 galaxies; blue). The median sSFRs of the two samples are $SFR/M_\ast = 10^{-9.9}, 10^{-9.1}$ yr$^{-1}$. The median stellar mass and SFR of the high-sSFR sample are 0.8 dex lower and 0.4 dex higher, respectively, than those for the low-sSFR sample. At $1.2 < d_{\text{trans}}/R_{\text{vir}} < 2.2$, we do find a significant increase of the H$\iota$ absorption strength with increasing sSFR, which would be consistent with its dependence on the SFR. However, the median optical depth at $0.7 < d_{\text{trans}}/R_{\text{vir}} < 1.2$ suggests (although with a low significance) opposite trend.

The results presented in this section stand in contrast with the clear dependence of the Ovi optical depth on both SFR and stellar mass (at fixed $v_{\text{LOS}}$ and $d_{\text{trans}}$). For metal ion species, a strong dependence of the CGM abundance on SFR might be interpreted as the result of a connection between the enrichment of the CGM and the star formation activity of the host galaxy, considering that stellar feedback can drive galactic winds. Furthermore, more massive galaxies have had more time to increase the metal content of the CGM. However, for H$\iota$, the higher abundance around higher SFR galaxies with a similar stellar mass can also be due an enhanced infalling gas component. Hence, the results for H$\iota$ are not in contradiction with such an interpretation of our findings for Ovi.