

# Probing the intra-group medium of a $z = 0.28$ galaxy group

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## ABSTRACT

We present new MUSE observations of a galaxy group probed by a background quasar. The quasar sightline passes between multiple  $z = 0.28$  galaxies, whilst showing at the same redshift low-ionized metal line species, including Ca II, Mg I, Mg II and Fe II. Based on the galaxy redshifts measured from the MUSE data, we estimate the galaxies to be part of a small galaxy group with a halo mass of  $\approx 6 \times 10^{12} M_{\odot}$ . We use the MUSE data to reveal the two-dimensional dynamical properties of the gas and stars in the group galaxies, and relate these to the absorber kinematics. With these data, we consider a number of scenarios for the nature of the gas probed by the sightline absorbers: a corotating gas halo associated with a single galaxy within the group; outflowing material from a single group member powered by recent star-formation; and cool dense gas associated with an intra-group medium. We find that the dynamics, galaxy impact parameters, star formation rates and the absorber strength suggest that the cool gas cannot be clearly associated with any single galaxy within the group. Instead, we find that the observations are consistent with a superposition of cool gas clouds originating with the observed galaxies as they fall into the group potential, and are now likely in the process of forming the intra-group medium.

**Key words:** galaxies: groups: general – galaxies: kinematics and dynamics – quasars: absorption lines.

## 1 INTRODUCTION

The interplay between galaxies and the gaseous media that surround them is a crucial element in the study of galaxy formation, providing insights into both the infall of material on to galaxies and the extent and impact of galactic outflows. Observing the baryonic material surrounding galaxies is primarily performed (at least beyond modest redshifts) using absorption line studies, either in the line of sight to background Quasi-stellar objects (QSOs) or galaxies. Much work has been performed on both the small scales, linking absorption systems to individual galaxies (e.g. Kacprzak et al. 2011; Bouché et al. 2012, 2013; Kacprzak, Churchill & Nielsen 2012; Nielsen, Churchill & Kacprzak 2013b; Péroux et al. 2013; Stocke et al. 2013; Tumlinson et al. 2013; Werk et al. 2014; Fumagalli et al. 2015; Nielsen et al. 2015, 2016); and on statistical scales: analysing

the large-scale distribution of gas around galaxies (e.g. Adelberger et al. 2003, 2005; Morris & Jannuzi 2006; Ryan-Weber 2006; Chen & Mulchaey 2009; Shone et al. 2010; Crighton et al. 2011; Rakic et al. 2012; Rudie et al. 2012; Tejos et al. 2014; Tummuangpak et al. 2014; Turner et al. 2014, 2015; Bielby et al. 2016; Finn et al. 2016).

An important, but poorly constrained, element in connecting absorbers with individual galaxies, however, is the galaxies' place in the large-scale structure of the Universe. Many studies focus on so-called field galaxies with little or no quantification of the nearby galaxy population. Moreover, much of the star-forming galaxy population resides in groups, and this element is rarely considered in the analysis of absorption line systems, especially at high redshift. Absorbers are often treated as part of a distinct galaxy halo, whereas in reality, the distribution of gas around galaxies is more complex and it may not be clear or reasonable to constrain where the halo of one galaxy finishes and the next begins (e.g. Yun, Ho & Lo 1994; Morris, Jannuzi & Weymann 2002).

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In terms of absorption of background light by gas within galaxy groups, Morris & van den Bergh (1994) suggested that a significant fraction of H I absorption systems (with column densities above of  $\sim 10^{13}$  cm $^{-2}$ ) are the result of gaseous pressure-confined tidal debris, finding comparable space densities between low-column density H I absorbers and galaxy groups in the local Universe. Such absorption studies are complemented by H I emission maps of nearby galaxies and small groups (e.g. Hoffman et al. 1999), which show significant clumps of H I gas apparently tidally or ram-pressure-stripped from the surrounding galaxies.

Further work has been performed analysing the place of H I gas (over a range of column densities) within the large-scale structure, with Penton, Stocke & Shull (2002), for example, looking at the relationship between Ly $\alpha$  absorbers and voids and superclusters. Through a clustering analysis, they reported that Ly $\alpha$  absorbers (with column densities of  $10^{13.2}$ – $10^{15.4}$  cm $^{-2}$ ) cluster with galaxies, but more weakly than galaxies cluster with each other. As such, Penton et al. (2002) conclude that such Ly  $\alpha$  absorption systems are primarily associated with the large-scale structures of galaxies, i.e. filaments and groups, rather than individual galaxies (see also Tejos et al. 2014).

Continuing such considerations of the relationship between absorbers and the large-scale structure, Crighton et al. (2010) found evidence that galaxy groups trace Mpc-scale structures that appear in both H I gas and galaxies based on the study of a triplet of closely separated QSO sightlines. Additionally, Tejos et al. (2012) found peaks in the Ly  $\alpha$  absorbers distribution around the edges of large voids, i.e. tracing the filamentary structures enclosing such voids (a topic further developed in Tejos et al. 2016).

Consistent with the column densities of H I emission maps discussed above, Chen & Prochaska (2000) presented the detection of a Lyman limit system (LLS) apparently associated with a pair of galaxies at  $z = 0.167$ . Significantly, the reported LLS corresponded in velocity space to an O VI absorption system, which the authors claimed as tracing warm gas within the intra-group medium of this small galaxy group. Given that this detection of O VI absorption fits with the gas temperatures expected for the intra-group medium of typical galaxy groups (i.e.  $T \sim 10^5$  K), much interest has since been placed in tracing the potentially huge reservoirs of gas within galaxy groups using such absorption systems. Indeed, Prochaska et al. (2006) find O VI absorption arises in a diverse set of galactic environments including the haloes of individual galaxies, galaxy groups, filamentary-like structures, and also regions devoid of luminous galaxies, albeit based on a relatively small sample of galaxies and absorbers. Similarly, Chen & Mulchaey (2009) find that tidal debris in groups/galaxy pairs may be principally responsible for observed O VI absorbers (although this is somewhat in contrast to other findings; e.g. Tumlinson et al. 2011).

Stocke et al. (2014) presented a study of absorber measurements in quasar sightlines, observed with *Hubble Space Telescope* (HST)/COS, passing through 14 galaxy groups. Their far-UV spectra produced 14 warm ( $T \geq 10^5$  K) absorption systems consisting of broad Ly  $\alpha$  and broad O VI absorption, which were each found to be coincident with spiral-rich groups or cluster outskirts. Their analysis tentatively favours the absorbers to be associated with the intra-group/cluster medium rather than the haloes of individual galaxies, albeit with some systematic uncertainties. Supporting this finding, Johnson, Chen & Mulchaey (2015) analyse the effect of environment on their analyses of O VI, finding that galaxies with nearby neighbours exhibit a modest increase in O VI covering fraction compared to isolated galaxies, which suggest that environmental effects play a role in distributing heavy elements beyond

the enriched gaseous haloes of individual galaxies, whilst Pachat et al. (2016) identify O VI and broad Ly  $\alpha$  absorbers associated with  $z = 0.4$  galaxy group.

However, although there has been much focus on O VI as a tracer of intra-group gas, in reality, the intra-group medium is likely a complex mix of phases incorporating cool gas, potentially in clumpy structures or clouds, as well as the warmer gas phases (Stern et al. 2016). Mg II as a doublet observed at optical wavelengths represents an excellent tracer of cool gas, and as such, it is an important and complementary diagnostic to add to the O VI studies discussed above. Only a small number of Mg II-galaxy group associations have been reported in detail, however, Whiting, Webster & Francis (2006) detected Mg II absorption coincident with a galaxy group at  $z = 0.666$ ; Kacprzak, Murphy & Churchill (2010) reported a strong Mg II absorber ( $W_r(2796) = 1.8$  Å) coincident with a galaxy group with five observed members at  $z = 0.313$ ; and Gauthier (2013) investigated a large equivalent width (EW) Mg II absorber detected in close proximity to a galaxy group at  $z \sim 0.5$ . The latter study concluded that the absorption system is most likely associated with the intra-group medium, with the authors favouring a scenario whereby the absorption originates in tidal debris. To give a sense of the number of potential Mg II absorber-galaxy group associations, we note that from a sample of  $\sim 200$  Mg II absorbers and nearby galaxies, Nielsen et al. (2013a) found that  $\approx 40$  appeared to be associated with group galaxies or were ambiguous in what galaxy they may be associated with. However, due to the complexity of disentangling the relationship between absorbers found in a group environment and the group galaxies, most studies have taken the approach of either removing the group absorbers from their analysis (e.g. Churchill et al. 2013; Nielsen et al. 2013b, 2015) or simply taking the group galaxy with the smallest impact parameter (e.g. Schroetter et al. 2016) as the absorber ‘host’.

Here, we present serendipitous MUSE observations of a galaxy group observed at  $z = 0.2825$  in the foreground of a bright  $z = 1.71$  quasar and coincident with significant metal line absorption features. MUSE represents an excellent probe of galaxy-group structures around QSO sightlines, providing as it does a blind survey over an area of 1 arcmin  $\times$  1 arcmin (e.g. Fumagalli et al. 2016; Péroux et al. 2017). Our observations are nominally part of the QSO Sightline and Galaxy Evolution survey, which aims to provide deep galaxy data around HST/STIS observed QSO sightlines, primarily using the Wide Field Camera 3 (WFC3) G141 grism (HST programme 14594, PI: R. Bielby). In Section 2 of this paper, we present our MUSE observations and give an overview of the available ancillary galaxy data and the sightline spectral data. In Section 3, we present an analysis of the galaxy and group properties alongside an analysis of the sightline absorbers. In Section 4, we discuss the relationship between the group galaxies and the absorbers and the implications for the nature of the group environment. We present our conclusions in Section 5. We assume a Planck 2013 cosmology (Planck Collaboration XVI 2014) throughout. All quoted distances are in proper coordinates unless stated otherwise.

## 2 OBSERVATIONS

### 2.1 Muse observations

#### 2.1.1 Overview

The MUSE instrument provides integral field spectroscopy of a contiguous square field of view with a width of 1 arcmin. MUSE provides a spatial pixel scale of 0.2 arcmin pixel $^{-1}$ , whilst the

spectral resolution gives a resolution element of  $\Delta\lambda \approx 3 \text{ \AA}$ . This is over a wavelength range of  $4800 < \lambda < 9300 \text{ \AA}$  (in the nominal mode used here).

The MUSE data presented here were taken as part of European Southern Observatory (ESO) project 094.B-0304(A) aimed at identifying galaxy counterparts to a sub-DLA system in the HE0515-4414 sightline at  $z = 1.15$ . Out of five intended 1 h observing blocks, only two were attempted during the allotted semester, with the first being out of the condition constraints (due to poor seeing) and the second being aborted due to high wind. Here we present results from the successfully taken observing block, albeit at poorer seeing than required for the original science goals.

The data were observed on 2015 February 6 with two integrations, the first of duration 1458 s and the second of duration 548 s (cut short due to worsening conditions). Given the increasingly poor atmospheric conditions for the second exposure, we solely use the first, uninterrupted, exposure for all the analysis that follows.

### 2.1.2 MUSE data reduction

The MUSE data reduction was performed using a combination of recipes from the ESO MUSE pipeline (v1.2.1; Weilbacher et al. 2014), the CUBEXTRACTOR package (CUBEX, version 1.5; Cantalupo, in preparation) and in-house PYTHON codes.

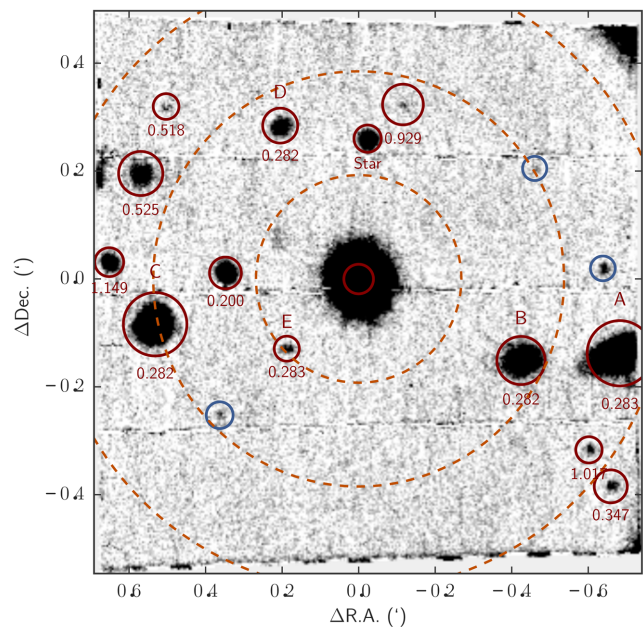
We created the master bias, master flat and a wavelength solution using the MUSE pipeline. The illumination correction was then calculated using the adjacently taken flat-field. These calibrations were applied to the science exposures and the standard stars used for spectro-photometric flux calibration. The individual exposures were transformed into data cubes with a common reference grid (voxels of  $1.25 \text{ \AA}$  in the spectral direction and  $0.2 \text{ arcsec}$  in the spatial direction) and barycentric corrections were applied.

A two-stage optimization of the data was then performed using the CUBEX package. We first applied a flat-field correction and sky-subtraction using the CUBEFIX and CUBESHARP routines within CUBEX (e.g. Borisova et al. 2016) and from the resultant cubes created collapsed white-light images. Using these images, we identified sources and created source masks and then re-ran the CUBEX flat-field correction and sky-subtraction with these source masks applied.

For the analysis presented in this paper, the wavelength axis was transformed from air to vacuum (matching the QSO sightline spectra described later). Our final white-light image (i.e. produced from collapsing the cube along the wavelength direction) is shown in Fig. 1. The narrow horizontal bands visible in the image are the result of the boundaries between the four banks of individual detector elements in the MUSE instrument. The data cube has seeing of  $1.2 \text{ arcsec}$  and  $3\sigma$  depth of  $f_{3\sigma} = 16 \times 10^{-18} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$  (based on a 3D aperture with full width at half-maximum of  $1.2 \text{ arcsec}$  and  $3.0 \text{ \AA}$  in the spatial and spectral directions, respectively).

### 2.1.3 Galaxy identification

In order to identify sources within the final cube, we ran SEXTRACTOR (Bertin & Arnouts 1996) on the white-light image. We removed clearly spurious objects via visual inspection (e.g. caused by noise spikes, chip defects, imperfections in the background subtraction around chip edges) from the resulting catalogue and proceeded to extract spectra and identify individual objects within the field. The primary features used to visually identify object redshifts, given the wavelength range and redshifts covered, were [O II]  $3727 \text{ \AA}$ , Ca K  $3933 \text{ \AA}$  and H  $3869 \text{ \AA}$  absorption, H $\beta$   $4861 \text{ \AA}$ , [O



**Figure 1.** White image of the MUSE cube centred on the bright  $z = 1.7$  quasar HE0515-4414. The axes show the offset from the central quasar in arcminutes. Detected sources in the MUSE data are circles, whilst those with identified redshifts are labelled. The background quasar lies between five identified foreground galaxies forming a galaxy group at  $z = 0.2825$ . The dashed concentric rings centred on the QSO show impact parameters of  $b = 50, 100$  and  $150 \text{ kpc}$  (at  $z = 0.28$ ).

III]  $4959 \text{ \AA}$ , [O III]  $5007 \text{ \AA}$ , H $\alpha$   $6562 \text{ \AA}$  and [N II]  $6583 \text{ \AA}$ . Redshifts were obtained for galaxies showing nebular emission by fitting the [O II], H $\beta$ , [O III], and H $\alpha$  lines individually with a Gaussian (or double Gaussian in the case of [O II]) and taking the average. For passive galaxies with little or no nebular emission, we simultaneously fit the Ca H and K absorption lines, again with Gaussian profiles. With this initial solution, we then fit the absorption line galaxy spectra using the penalized pixel-fitting code described by Cappellari & Emsellem (2004) and Cappellari (2017) in conjunction with the spectral templates of Sánchez-Blázquez et al. (2006). Redshift uncertainties are derived using Monte Carlo realizations of the data incorporating the measured noise on the galaxy spectra and are given alongside the estimated redshifts in Table 1.

The resultant galaxy identifications are shown in Fig. 1, where each identified source is circled and (where one was successfully obtained) its redshift is given. The sources are also listed in Table 1.

### 2.2 QSO sightline

In this work, we use archival UVES spectra of the HE05015-4414 QSO, taken from the ESO archive (ESO programmes 66.A-0212, 076.B-0055 and 082.A-0078). These data were reduced, calibrated and combined as described by Kotuš et al. (2017). The data cover the wavelength range of  $3050 < \lambda < 3910 \text{ \AA}$ , with a total integration time of  $\approx 78\,000 \text{ s}$  and a resolution of  $R \approx 60\,000$ . After correcting the reduced spectra for helio-centric velocity offsets and converting wavelengths from air to vacuum, we combine the individual exposures using a weighted mean taking into account the pipeline error estimates. The combined spectrum has a median signal to noise of  $S/N = 63$ .

We also note that the quasar was observed using CASPEC by de la Varga et al. (2000) in 1996 October and 1997 November.

**Table 1.** Catalogue of objects identified in the MUSE data centred on the bright QSO HE0515-4414.

ID	RA (J2000)	Dec.	$R_e$ (arcsec)	Redshift	Class	$R$ (mag)	$M_B$ (mag)	$M_R$ (mag)
J051709-441111	79.287 842	-44.186 323	0.56	–	–	23.41	–	–
J051706-441043	79.274 123	-44.178 698	0.50	–	–	24.12	–	–
J051705-441054	79.271 154	-44.181 787	0.52	–	–	22.45	–	–
J051708-441040	79.281 399	-44.177 778	0.57	–	M-star	20.18	–	–
J051709-441055	79.287 592	-44.181 929	0.66	$0.199\ 68 \pm 0.000\ 13$	Em	20.12	-19.70	-20.00
J051708-441039	79.285 206	-44.177 375	0.73	$0.282\ 10 \pm 0.000\ 22$	Em	20.82	-19.81	-20.27
MRSS252-053745	79.290 654	-44.183 513	1.32	$0.282\ 25 \pm 0.000\ 07$	Em	18.73	-22.02	-22.26
MRSS252-054266	79.274 720	-44.184 633	1.00	$0.282\ 50 \pm 0.000\ 06$	Ab	19.07	-21.44	-22.03
MRSS252-054422	79.270 413	-44.184 410	1.36	$0.282\ 59 \pm 0.000\ 06$	Ab	18.72	-21.83	-22.47
J051708-441103	79.284 920	-44.184 267	0.52	$0.283\ 47 \pm 0.000\ 33$	Em	22.74	-18.13	-17.94
J051705-441119	79.270 810	-44.188 522	0.69	$0.347\ 36 \pm 0.000\ 16$	Em	22.58	-18.74	-19.06
J051710-441036	79.290 177	-44.176 785	0.54	$0.518\ 49 \pm 0.000\ 26$	Em	23.47	-19.20	–
J051710-441044	79.291 282	-44.178 854	0.92	$0.524\ 81 \pm 0.000\ 11$	Ab	20.36	-22.34	–
J051707-441036	79.279 861	-44.176 723	0.85	$0.928\ 88 \pm 0.000\ 40$	Em	23.84	-20.59	–
J051705-441115	79.271 760	-44.187 394	0.55	$1.017\ 40 \pm 0.000\ 78$	Em	23.01	-21.88	–
J051710-441054	79.292 655	-44.181 594	0.60	$1.149\ 20 \pm 0.000\ 62$	Em	20.67	-24.39	–
HE0515-4414	79.281 790	-44.182 116	0.62	$1.717\ 57 \pm 0.002\ 11$	QSO	14.65	–	–

These observations cover the spectral range of 3530–8570 Å with  $R \sim 21\ 000$ – $29\ 000$ , and have a typical signal-to-noise ratio of  $\approx 40$ . de la Varga et al. (2000) performed a Voigt profile (VP) analysis of absorbers along the line of sight, which we refer to in our analysis. We update the CASPEC analysis using the above UVES data (see Section 3.3), which has both higher resolution and signal to noise.

## 2.3 Ancillary data

### 2.3.1 FORS1 V-band imaging

As part of a polarimetry study of absorption lines in the QSO spectrum (ESO programme 072.B-0699), 15-s FORS1 V-band imaging was taken as part of the target acquisition. We reduced this data, performing bias subtraction and flat-fielding with the nightly calibrations. The acquisition frames consist of  $3\text{ s} \times 5\text{ s}$  exposures taken on 2003 December 16 and 28 and cover an area of  $6.9\text{ arcmin} \times 6.8\text{ arcmin}$  centred on the QSO.

Our stack of the three sub-exposures shows a seeing level of 1.3 arcsec with a  $3\sigma$  magnitude limit of  $V = 21.5$  (based on a 0.6 arcsec diameter detection aperture). This stacked image is shown in Fig. 2.

### 2.3.2 Sky survey data

In order to evaluate the wider area around our observations, we use data from the Automatic Plate Measuring machine Galaxy Survey (APM; Maddox et al. 1990) and the Muenster Red Sky Survey (MRSS; Ungruhe, Seitter & Duerbeck 2003). The APM survey is complete to  $B_j \leq 20.5$  (90 per cent completeness limit).

The MRSS data are complete to  $R = 19.0$  mag for extended sources at the 80 per cent level (cf. fig. 4.4 of Ungruhe et al. 2003). Star/galaxy separation has been performed on the MRSS sources by Ungruhe et al. (2003) based on a combination of effective radius, apparent magnitude and central intensity, and in this work, we use only sources classed as galaxies in MRSS. Galaxies detected by MRSS with  $R < 19.5$  mag (i.e. to  $\approx 50$  per cent completeness) are highlighted by squares in Fig. 2.

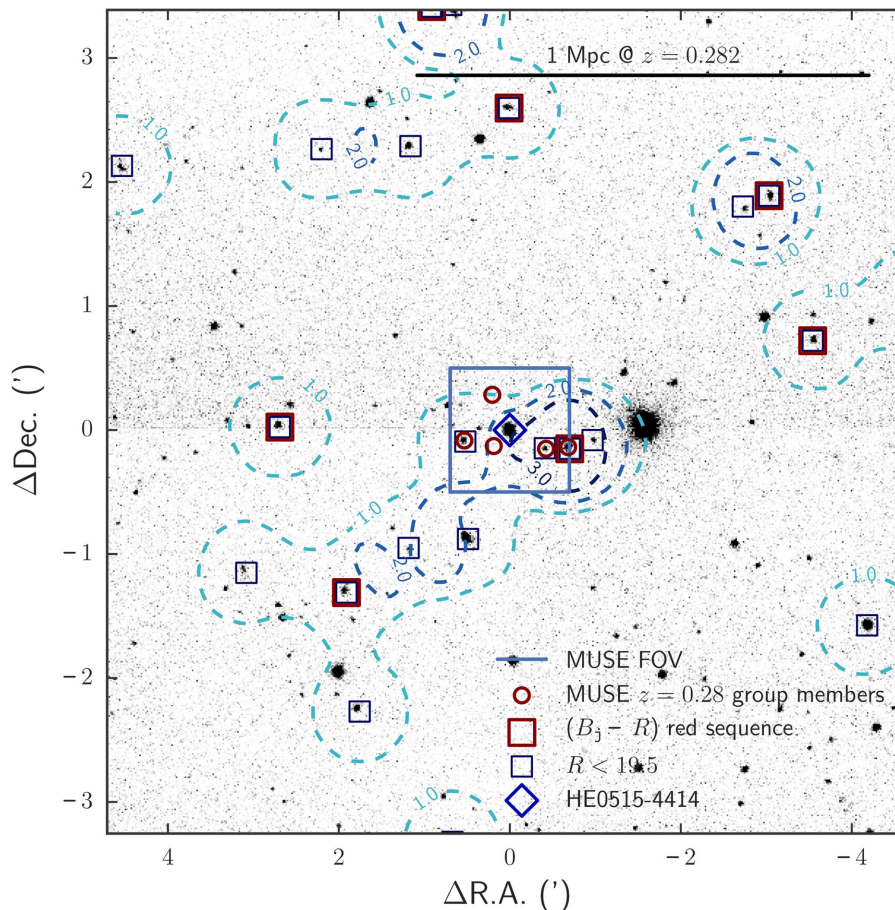
## 3 A GALAXY GROUP AT A REDSHIFT OF 0.2825

### 3.1 Galaxy group

From our MUSE observations, we find five galaxies within a tight redshift range of  $z = 0.2825 \pm 0.0006$  and separated by  $\lesssim 0.9$  arcmin ( $\lesssim 300$  kpc). The MUSE spectra for these five galaxies, covering prominent spectral features, are shown in Fig. 3. We denote the five group members as galaxies A–E as indicated in Fig. 1 and Table 2.

Given the  $z = 0.28$  galaxies observed with MUSE are spread across the full range of RA covered by the MUSE data, it is reasonable to expect that further associated galaxies are present outside of the field of view. Indeed, from the MUSE data alone, it is not absolutely clear whether this is a galaxy group or the outskirts of a cluster. We therefore turn to the ancillary data around this field to clarify the nature of the observed  $z = 0.28$  structure. If the structure is a cluster, we would of course expect to see a large number of galaxies within scales of  $\lesssim 1$  Mpc with comparable colours to the passive members identified in the MUSE observations.

First, a visual inspection of the FORS V-band imaging, shown in Fig. 2, shows no obvious evidence of a strong cluster-like overdensity (i.e. many galaxies across scales of  $\gtrsim 1$  Mpc or  $\gtrsim 3.8$  arcmin at  $z = 0.28$ ) around the confirmed  $z = 0.28$  galaxies (marked with circles). Following Matsuda et al. (2011) and Farina et al. (2016), we quantify the galaxy density field by mapping the density distribution from the MRSS catalogue with a magnitude cut of  $R < 19.5$  (corresponding to  $\approx 50$  per cent completeness limit of the MRSS data and equivalent to  $\approx 1.8L^*$  at  $z = 0.28$ ). Galaxies brighter than this limit are indicated by squares in Fig. 2. We use a cell size of radius 0.5 arcmin, equivalent to  $\approx 150$  kpc at  $z = 0.28$ . The resultant density map is shown by the contours in Fig. 2, with the labels giving the galaxy density in units of  $\text{arcmin}^{-2}$ . The average galaxy density at  $R < 19.5$  across the area is  $0.26 \pm 0.07\ \text{arcmin}^{-2}$ , whilst the peak density within the galaxy group region is  $3.0 \pm 1.7\ \text{arcmin}^{-2}$ . The peak is centred in the proximity of MRSS252-054422 (galaxy A), whilst we note that a potentially filamentary structure extends  $\approx 3$ – $4$  arcmin to the south-east. Being outside the MUSE field of view, we have no way of distinguishing whether this extension consists of  $z = 0.28$  galaxies or is simply a projection effect.



**Figure 2.** FORS1 V-band image of the region around the QSO HE0515-4414. The field of view of the MUSE data presented in this paper is shown by the 1 arcmin width square at the centre of the image. Sources identified within the MUSE data at  $z \approx 0.28$  are marked with circles, whilst the quasar is marked with a diamond. Objects identified with  $(B_j - R)$  colours consistent with being passive at  $z \approx 0.28$  are marked with large red squares and the smaller blue squares denote galaxies detected in the MRSS with  $R < 19.5$ . The brightest  $z = 0.2825$  group member, MRSS 252-054422 (galaxy A), is marked by both a circle and the squares, falling as it does in all three categories. The dashed contours show the derived density map, with the highest density region in the field of view found to be centred on MRSS 252-054422.

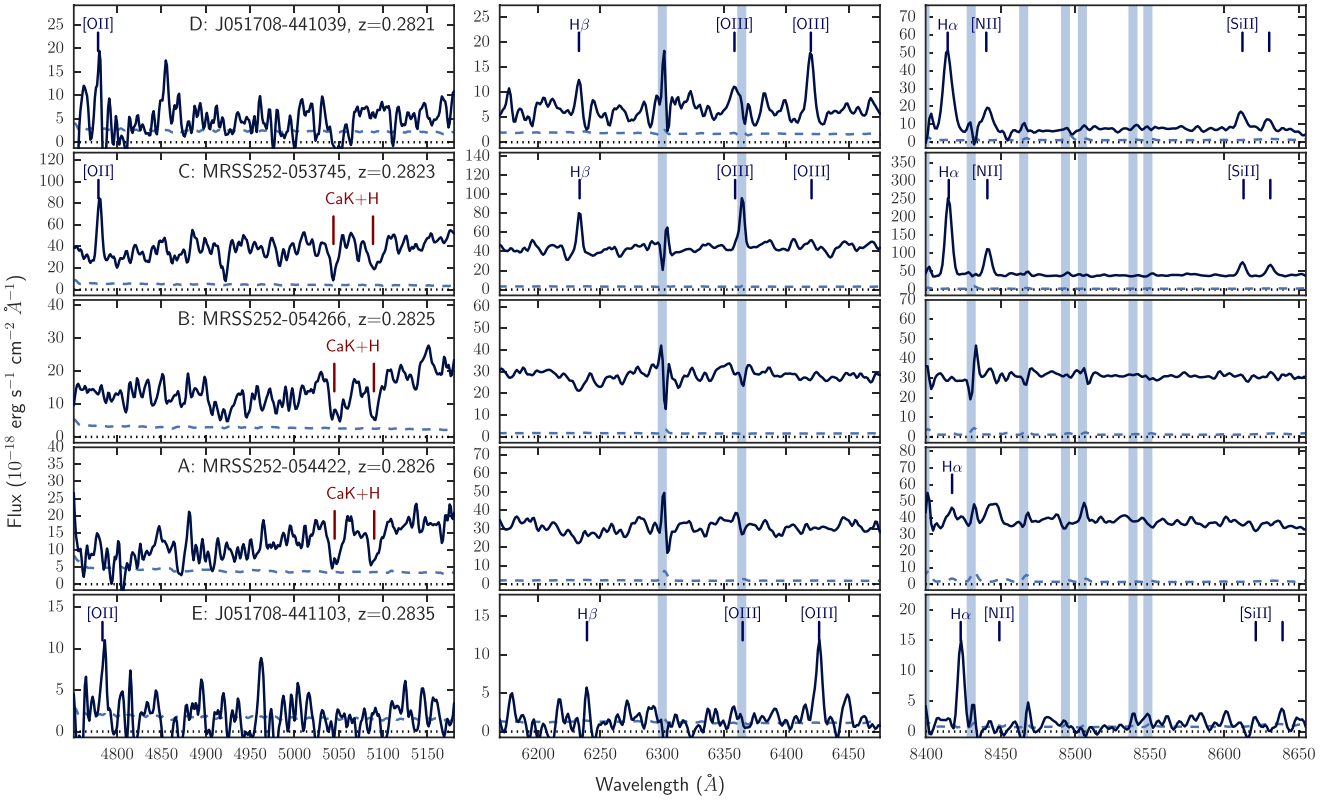
As a further check, in Fig. 4, we show the  $(B_j - R)$  versus  $R$  colour–magnitude diagram for galaxies detected by both the APM Galaxy Survey and MRSS (small circles). Galaxy A (non-SF,  $R = 18.2$  mag) and MRSS 252-053745 (galaxy C, SF,  $R = 18.9$  mag) from our observations are both detected in the APM Galaxy Survey and the MRSS, and are each highlighted with a large circle. MRSS 252-054266 (galaxy B,  $R = 19.1$  mag) is not detected in the  $B_j \leq 20.5$  complete galaxy sample from the APM Galaxy Survey used here. The shaded region in Fig. 4 shows the area of the colour–magnitude space lying beyond the  $B_j = 20.5$  magnitude limit.

At  $z = 0.28$ , the  $4000 \text{ \AA}$  break falls directly between these two bands, giving rise to a large  $(B_j - R)$  colour and making these bands ideal for detecting passive galaxies. Based on the  $(B_j - R)$  colour of galaxy A, we show a  $z = 0.28$   $(B_j - R)$  versus  $R$  red sequence model (e.g. Bielby et al. 2010), based on which we identify candidate  $z = 0.28$  passive galaxies surrounding the MUSE observations (we note that this model is consistent with the passive galaxy B not being detected in the APM  $B_j \leq 20.5$  galaxy sample). Galaxies lying within  $\Delta(B_j - R) \leq 0.2$  of the model red sequence are denoted by red circles and are marked in Fig. 2 by squares. The candidate red sequence galaxies are widely spread over scales of  $\sim 4$  arcmin ( $\sim 1.3$  Mpc at  $z = 0.28$ ) and do not form any visible clump con-

sistent with a significantly larger structure around the  $z = 0.28$  galaxies.

Based on the five group members with MUSE redshifts, we estimate the group redshift and velocity dispersion to be  $z_{\text{group}} = 0.2825 \pm 0.0002$  and  $\sigma_r = 114^{+49}_{-35} \text{ km s}^{-1}$ , respectively (Danese, de Zotti & di Tullio 1980). Taking this velocity dispersion and assuming the group to be virialized results in a mass estimate of  $M_h = 6.4^{+4.2}_{-4.1} \times 10^{12} M_{\odot}$ , with an estimated virial radius of  $R_h = 340 \pm 210$  kpc (comoving, Ramella, Geller & Huchra 1989). These estimates are consistent with the observed galaxies being part of a relatively low-mass group (e.g. Ramella et al. 1989; Zabludoff & Mulchaey 1998), although given the limited view of this group of galaxies and the small number of member galaxies observed, the estimated virial mass and radius represent lower limits (assuming the structure is, in fact, virialized).

Combining the above estimates with the lack of a cluster-scale structure in Fig. 2, the MUSE observations and the QSO sight-line appear to be probing the central regions of a galaxy group at  $z = 0.2825$  and we can reasonably exclude the possibility of this being the outskirts (or the core) of a galaxy cluster. We note that this is not absolutely conclusive, however, in terms of the large-scale structure surrounding the MUSE field of view. Planned Integral Field Unit (IFU) future observations with Very Large



**Figure 3.** Extracted MUSE-observed frame spectra for the five  $z = 0.28$  group galaxies. The left-hand panel in each row is centred on the wavelength range of [O II] and Ca H K, the centre panel on the wavelength range of H $\beta$  and [O III] and the right-hand panel covers H $\alpha$ , [N II] and Si II emission. The solid curve in each panel shows the measured flux, whilst the dashed line shows the estimated uncertainty on that flux. The positions of key spectral features are marked. The vertical shaded regions in the central column of plots show the position of prominent atmospheric emission lines (Osterbrock et al. 1996).

**Table 2.** Group galaxy properties.

ID	$b$ (kpc)	$f(\text{H}\alpha)$ ( $10^{-18}\text{erg s}^{-1}\text{cm}^2$ )	SFR ( $M_{\odot}\text{ yr}^{-1}$ )	PA ( $^{\circ}$ )		$V_{\text{max}}$ ( $\text{km s}^{-1}$ )		$\sigma_v$ ( $\text{km s}^{-1}$ )		
				Gas	Stellar	Gas	Stellar	Gas	Stellar	
MRSS 252-054422	(A)	132	$54.7 \pm 2.8$	$0.169 \pm 0.009$	–	$159 \pm 7$	–	$135 \pm 32$	–	$158 \pm 7$
MRSS 252-054266	(B)	88	$<5.0$	$<0.015$	–	$102 \pm 10$	–	$85 \pm 23$	–	$160 \pm 10$
MRSS 252-053745	(C)	101	$1077 \pm 11$	$3.236 \pm 0.032$	$35 \pm 8$	$51 \pm 55$	$23 \pm 5$	$32 \pm 37$	$34 \pm 2$	$91 \pm 22$
J051708-441039	(D)	83	$314.2 \pm 9.4$	$0.943 \pm 0.028$	$116 \pm 22$	–	$38 \pm 12$	–	$68 \pm 5$	–
J051708-441103	(E)	49	$68.4 \pm 3.2$	$0.208 \pm 0.010$	–	–	–	–	–	–

Telescope/ $K$ -band Multi-Object Spectrograph and grism observations with *HST*/WFC3 will clarify this conclusion.

### 3.2 Group galaxy properties

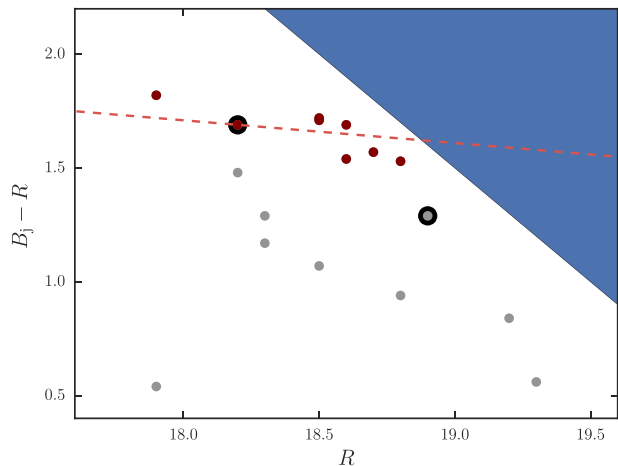
For each of the member group galaxies, we calculate the total H $\alpha$  flux and from this estimate the integrated star formation rate (SFR). Assuming a Kroupa 2003 initial mass function (Kroupa & Weidner 2003), the SFRs are estimated with  $C_{\text{H}\alpha} = 5.5 \times 10^{42} M_{\odot} \text{ yr}^{-1} \text{ erg}^{-1} \text{ s}$  (Hao et al. 2011; Murphy et al. 2011), whereby  $\text{SFR}_{\text{H}\alpha} = C_{\text{H}\alpha} L_{\text{H}\alpha}$ . We then correct the SFR estimates for intrinsic absorption assuming  $A_V = 1.0$ . The resulting corrected SFRs are presented in Table 2, alongside the impact parameter (given in proper coordinates) and the galaxy dynamical information derived in the sections that follow. For the two ‘passive’ galaxies in the group, we place an upper limit on the SFR of  $<0.015 M_{\odot} \text{ yr}^{-1}$  for MRSS 252-054266, whilst MRSS 252-054422

(i.e. our assumed brightest group member) shows low levels of star formation based on the detection of relatively weak H $\alpha$  emission.

### 3.3 Absorption features at the group redshift

From the optical CASPEC data of HE0515-4414, de la Varga et al. (2000) found absorption lines for Al I, Ca II, Fe I, Fe II, Mn II and Mg II at  $z = 0.281\text{--}0.282$ . Based on their Mn II column density and assuming Mn abundance relative to H of 1/10 solar, de la Varga et al. (2000) estimate an H I column density of  $N(\text{H I}) \approx 10^{19.9} \text{ cm}^{-2}$ .

The metal lines listed above are all covered by available UVES spectra, which we have used to re-analyse the absorber properties. There are five components for which we measure individual column densities and  $1\sigma$  errors using the apparent optical depth method. We note that Fe II is blended with forest absorption, so  $N_{\text{Fe II}}$  is instead estimated from VP fitting. The column densities, the values of  $\lambda_{\text{min}}$  and  $\lambda_{\text{max}}$ , and the velocities relative to  $z = 0.2825$  are given in



**Figure 4.**  $(B_j - R)$  versus  $R$  colour–magnitude data points (small circles) for all galaxies detected in both MRSS  $R$  band and APM  $B_j$  band within 5 arcmin of the QSO HE0515-4414. The two ringed points denote galaxies identified at  $z = 0.28$  from our MUSE data (i.e. galaxy A at  $R = 18.2$  and galaxy C at  $R = 18.9$ ). The dashed line shows a model red sequence based on the  $(B_j - R)$  colour of galaxy A (MRSS 252-054422). Galaxies conforming with this model within  $\pm 0.2$  mag are shown in red and are highlighted by square boxes in Fig. 2. The shaded region shows the limit of the APM  $B_j$  data.

Table 3. The minimum ( $\lambda_{\min}$ ) and maximum ( $\lambda_{\max}$ ) wavelengths indicate the ranges used for the above measurements. The estimated errors on the column densities include zero-level and continuum uncertainties. We plot the continuum normalized flux profiles from the UVES data for the available Fe II, Mn II and Mg II lines in Fig. 5 (black lines). Fig. 5 also shows the total VP fit (red curve), the individual component VP fits (grey curves – where not obscured by the total VP fit), and the regions used to estimate the column densities given in Table 3 (grey shaded areas). From the UVES data, we find that the total rest EW of the Mg II absorption is  $W_r(2796) = 0.73 \pm 0.02 \text{ \AA}$ .

At the group redshift, the STIS E230M spectra cover a rest-frame wavelength range of  $\lambda \approx 1770\text{--}2430 \text{ \AA}$ , providing coverage of the common transitions of Si II, Fe II and Al III. Indeed, we find multiple Fe II absorption lines at  $z = 0.28138$  and  $0.28177$ , plus Si II  $1808 \text{ \AA}$  at  $z = 0.28135$ .

### 3.4 Galaxy velocity fields

The co-incidence of the absorbers and group galaxies may be the result of a range of possible connections. The absorbers may be tracing gas that could be physically attributed (i.e. bound) to the halo of a single galaxy; they could be probing gas within a shared intra-group medium and not bound to any single galaxy; or they may be attributable to outflowing gas clouds, driven by ongoing or recent star formation. To help disentangle these possibilities, it is useful to derive information on the dynamics of both gas and stars within the galaxy discs in the proximity of the absorbing gas.

The MUSE data presented here offer the opportunity to do exactly that, and in this section, we present the results of analyses of both the gas and stellar dynamics of the group galaxies.

#### 3.4.1 Gas dynamics

We measure the gas dynamics for the group member galaxies using the observed H $\alpha$  emission. This is observed in four of the detected galaxies, however, J051708-441103 (galaxy E) is not resolved sufficiently (given the measured half-light radius of  $R_e = 0.52$ , consistent with a point source under the seeing conditions) and the H $\alpha$  emission detected in galaxy A does not possess a high enough SNR to enable a meaningful 2D velocity analysis to be made. As such, we present the gas velocity fields for galaxy C (MRSS 252-053745) and galaxy D (J051708-441039).

For each galaxy, we fit the H $\alpha$  emission in all spatial IFU pixels with an integrated H $\alpha$  flux of SNR  $> 2$ . The fit is performed with a Gaussian function, from which we calculate the velocity offset ( $\Delta v$ ) and line-of-sight velocity dispersion ( $\sigma_v$ ) in each pixel. The resulting maps are shown in Fig. 6, with  $\Delta v$  shown by the colour maps in the left-hand column and  $\sigma_v$  shown by the colour maps in the right-hand column. In both columns, the contours show the  $2\sigma$ ,  $4\sigma$ , and  $8\sigma$  SNR levels of the integrated H $\alpha$  flux. From these maps, we estimate the position angles for the two galaxies using FIT\_KINEMATIC\_PA (Krajinović et al. 2006). Using the derived position angles, we then calculate rotation curves for each galaxy, which are shown by the circular points in the lower two panels of Fig. 7.

The calculated positional angles, maximal velocity offsets ( $V_{\max}$ ) and mean velocity dispersions ( $\sigma_v$ ) derived from the gas kinematics for these two galaxies are listed in Table 2. The estimated inclination angles for galaxies C and D are  $i = 24.9 \pm 3.2$  and  $75.7 \pm 10.1$  respectively.

#### 3.4.2 Stellar dynamics

We measure the galaxy velocity fields for our three highest S/N galaxies (i.e. galaxies A–C) using the PPF Python code (Cappellari & Emsellem 2004). For the template fitting, we use the Vazdekis (1999) single stellar population (SSP) library, fitting to our observed spectra over a rest-frame wavelength range of  $4800 \text{ \AA} < \lambda < 5465 \text{ \AA}$ .

The results of the template velocity fitting with PPF are shown in Fig. 8, where the left-hand column shows the velocity field for each galaxy and the right-hand column shows the velocity dispersion. In each of the velocity field panels, the direction to the QSO sightline is shown by the arrow. In all panels, the contour curves show the  $3\sigma$  (pale grey),  $6\sigma$  (dark grey) and  $9\sigma$  (black) S/N levels from the collapsed continuum image. Again, the calculated positional angles, maximal velocity offsets ( $V_{\max}$ ) and mean velocity dispersions ( $\sigma_v$ ) are given in Table 2.

Clear rotational dynamics are seen in the stellar population for both of the passive galaxies (i.e. galaxies A and B). We note that the sides of the two galaxies nearest to each other are both blueshifted, such that the two galaxies are rotating in the opposite direction to each other. Again, the rotation curves for these galaxies are shown in Fig. 7 (red stars in the top two panels), showing the clear rotational dynamics detected in the MUSE data.

The rotation in the stellar component of galaxy C is less clear, although we note that the blueshifted component in the south-west of the galaxy is consistent with the blueshifted component seen in the gas dynamics in the previous section. This is evident in the rotation curve shown in Fig. 7, where the red stars show the stellar rotation curve and the blue circles show the gas dynamics. The stellar rotation curve is much noisier than the gas dynamics, but does at least show agreement in terms of polarity of the rotation.

**Table 3.** Properties of the absorbers detected in the UVES spectrum close to the galaxy redshifts. The upper and lower limits on a number of the ion column densities are given at the  $3\sigma$  level.

Atom	Ion	$\lambda_{\text{rest}}$ (Å)	$v_{\text{min}}$ (km s <sup>-1</sup> )	$v_{\text{max}}$ (km s <sup>-1</sup> )	$\lambda_{\text{min}}$ (Å)	$\lambda_{\text{max}}$ (Å)	$\log N$ (cm <sup>-2</sup> )
Ca	II	3969.590	-272.0	-255.0	5086.383	5086.670	10.55 <sup>+0.19</sup> <sub>-0.30</sub>
Fe	II	2600.172	-	-	-	-	12.16 ± 0.05
Mg	I	2852.963	-273.8	-230.9	3655.585	3656.108	10.85 <sup>+0.13</sup> <sub>-0.17</sub>
Mg	II	2796.354	-316.9	-224.6	3582.535	3583.638	> 13.08
Mn	II	2606.462	-279.1	-221.9	3339.677	3340.314	< 11.86
Na	I	5891.583	-280.0	-226.7	7548.903	7550.245	< 10.77
Ti	II	3384.730	-281.5	-236.1	4336.842	4337.500	< 10.99
Ca	II	3969.590	-175.8	-156.3	5088.015	5088.346	10.71 <sup>+0.17</sup> <sub>-0.19</sub>
Fe	II	2600.172	-180.1	-154.1	3332.719	3333.008	12.94 <sup>+0.03</sup> <sub>-0.02</sub>
Mg	I	2852.963	-180.2	-152.9	3656.727	3657.060	11.25 <sup>+0.04</sup> <sub>-0.04</sub>
Mg	II	2796.354	-184.3	-154.5	3584.120	3584.477	> 13.12
Mn	II	2576.877	-178.3	-153.6	3302.880	3303.152	< 11.65
Na	I	5891.583	-181.2	-155.2	7551.391	7552.046	< 10.74
Ti	II	3384.730	-180.1	-155.5	4338.309	4338.666	< 10.74
Ca	II	3969.590	-152.4	-134.2	5088.412	5088.721	< 10.32
Fe	II	2600.172	-154.1	-137.1	3333.008	3333.196	11.83 <sup>+0.04</sup> <sub>-0.04</sub>
Mg	I	2852.963	-151.7	-133.5	3657.075	3657.297	< 10.29
Mg	II	2796.354	-154.5	-136.2	3584.477	3584.695	12.17 <sup>+0.03</sup> <sub>-0.02</sub>
Mn	II	2576.877	-154.9	-136.7	3303.138	3303.338	< 11.59
Na	I	5891.583	-152.5	-138.2	7552.112	7552.472	< 10.31
Ti	II	3384.730	-152.9	-136.0	4338.704	4338.948	< 10.71
Ca	II	3969.590	-130.2	-105.6	5088.788	5089.207	< 10.41
Fe	II	2600.172	-125.5	-108.5	3333.326	3333.514	11.83 <sup>+0.05</sup> <sub>-0.05</sub>
Mg	I	2852.963	-124.4	-110.0	3657.408	3657.583	10.97 <sup>+0.04</sup> <sub>-0.04</sub>
Mg	II	2796.354	-128.5	-109.0	3584.788	3585.021	> 12.59
Mn	II	2576.877	-125.0	-111.9	3303.467	3303.611	< 11.33
Na	I	5891.583	-131.7	-109.7	7552.636	7553.192	< 10.56
Ti	II	3384.730	-132.1	-111.3	4339.005	4339.306	< 10.63
Ca	II	3969.590	-112.0	-88.7	5089.097	5089.494	< 10.54
Fe	II	2600.172	-108.5	-93.0	3333.514	3333.687	11.85 <sup>+0.04</sup> <sub>-0.04</sub>
Mg	I	2852.963	-110.0	-91.8	3657.583	3657.805	10.61 <sup>+0.10</sup> <sub>-0.12</sub>
Mg	II	2796.354	-109.0	-89.5	3585.021	3585.254	12.14 <sup>+0.03</sup> <sub>-0.02</sub>
Mn	II	2576.877	-111.9	-97.7	3303.611	3303.768	< 11.46
Na	I	5891.583	-109.7	-86.3	7553.192	7553.782	< 10.55
Ti	II	3384.730	-111.3	-89.2	4339.306	4339.626	< 10.51

## 4 DISCUSSION

The MUSE data on this group/QSO sightline combination provides a wealth of information on the group members. In particular, the galaxy velocity maps provide an opportunity to disentangle the relationship between the absorbers and the galaxies. We now explore a number of possibilities for what the structure is that the absorbing gas is tracing: the corotating halo of one of the group galaxies, an outflow from one of the group galaxies and material within a wider group medium.

Before considering the possibilities associated with the absorber probing halo gas of one of the absorbed galaxies, we first need to evaluate the possibility of there being an undetected galaxy, either hidden by the QSO light or below the detection threshold of the data, which the absorbers could instead be associated with.

To evaluate the potential for a star-forming galaxy directly in the line of sight of the QSO, we perform a subtraction of the QSO continuum (incorporating the point spread function on the QSO) within  $\pm 1000$  km s<sup>-1</sup> of the galaxy group redshift. We find no evidence for any line emission in this window, placing an upper limit on any H $\alpha$  emission at  $z = 0.2825$  coincident with the QSO

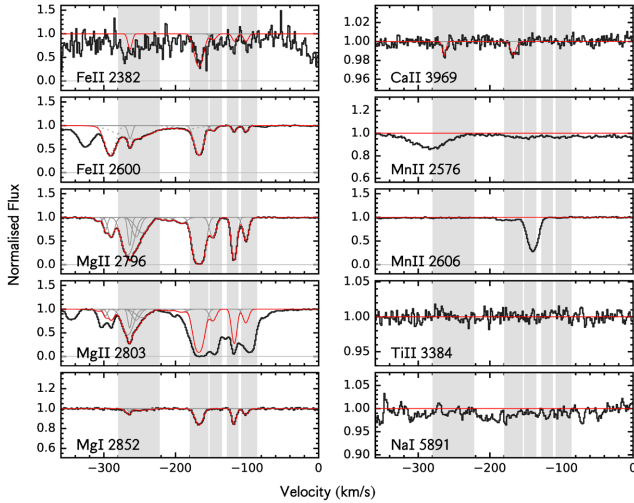
sightline of  $f(\text{H}\alpha) \leq 8.4 \times 10^{-18}$  erg cm<sup>-2</sup> s<sup>-1</sup> Å<sup>-1</sup>. We note also that should there be a coincident system in the line of sight, statistically we might expect a much larger Mg II absorber EW than observed.

### 4.1 Co-rotating disc/halo

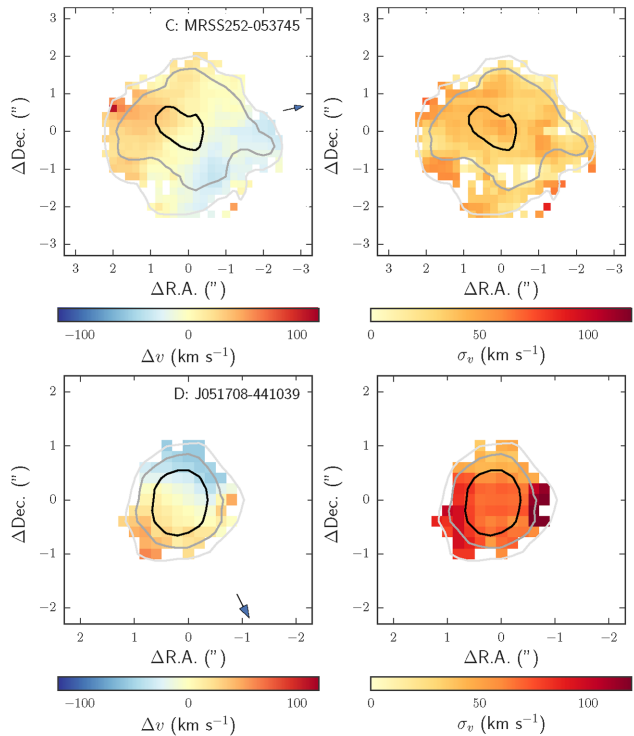
Perhaps the simplest physical model for the nature of the sightline absorbers in relation to the galaxy population is that they inhabit a gaseous halo corotating with a single host galaxy (e.g. Steidel et al. 2002; Churchill, Kacprzak & Steidel 2005). In this simple model, it may be expected that the absorbers possess a velocity offset consistent with extrapolating the velocity curve of the host galaxy out to the distance of the absorbers (e.g. Churchill & Vogt 2001; Steidel et al. 2002; Churchill et al. 2005).

Such a configuration is predicted to result from infall of material from the IGM on to galaxy haloes (e.g. Stewart et al. 2011, 2013), and so cool absorber species such as Mg II are predicted to be tracers of infalling material (e.g. Barnes, Garel & Kacprzak 2014). Recent observations have shown evidence for such corotating material potentially resulting from infall on to galaxy haloes with, for example,

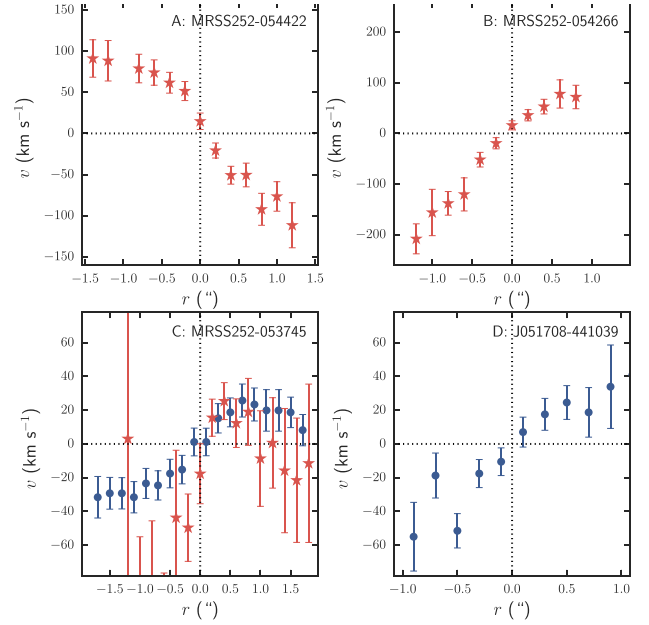




**Figure 5.** The UVES spectra (black line) and fitted profiles (red line) for the transitions given in Table 3. The velocity scale along the horizontal axis gives the offset from the estimated group centre (where galaxies C and D lie at velocities of  $\approx -50$  to  $100$  km s $^{-1}$  and galaxies A, B and E lie at  $\gtrsim 0$  km s $^{-1}$ ). Individual VP components are shown by the grey curves. The five shaded grey areas in each plot show the regions used to estimate the column densities given in Table 3 (we do not attempt to estimate column densities for lines outside these regions due to blending issues).



**Figure 6.** The H $\alpha$  emission velocity field (left-hand column) and velocity dispersion (right-hand column) of the two brightest H $\alpha$  emitters in our sample: galaxy C (MRSS 252-053745, top panel) and galaxy D (J051708+441039, bottom panel). In each case, the colour map shows the velocity measurement, whilst the contours show the  $3\sigma$ ,  $6\sigma$  and  $9\sigma$  S/N levels from the collapsed H $\alpha$  emission image. The direction to the QSO sightline is given by the arrow in each of the left-hand panels.



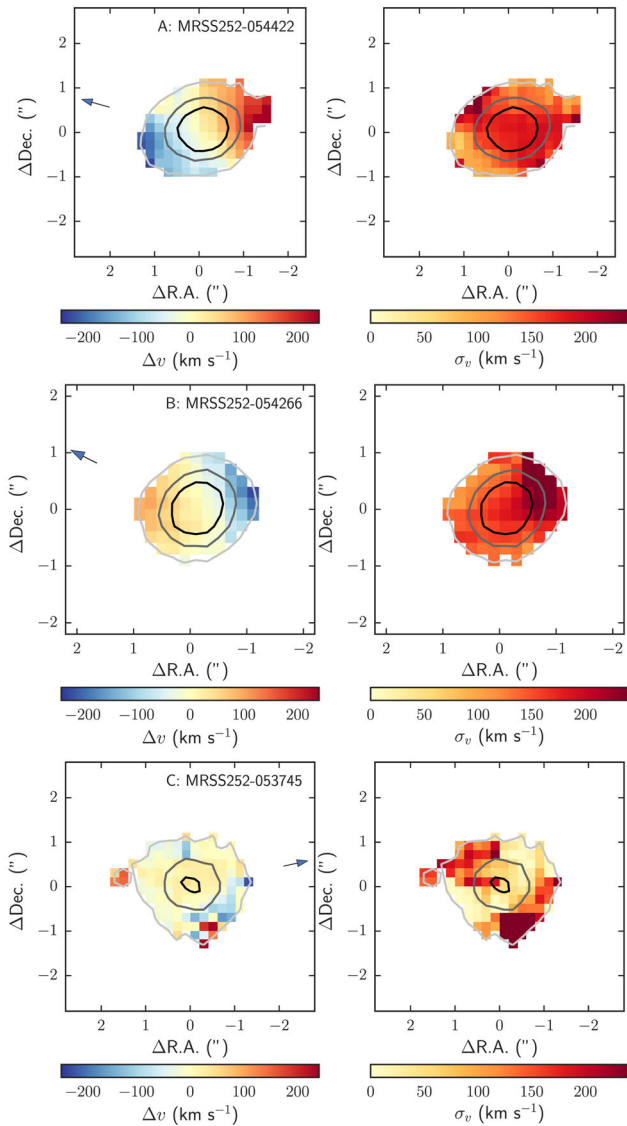
**Figure 7.** Rotation curves derived from the gas dynamics (traced via H $\alpha$  emission, blue circles) and stellar dynamics (traced by SSPs, red stars).

Diamond-Stanic et al. (2016) and Bouché et al. (2016) presenting absorption line studies in the proximity of a star-forming galaxy at  $z \sim 0.4$  and another at  $z \sim 1$ , respectively. Such corotating halo detections have exclusively been claimed for isolated galaxies thus far. Although some potential detections of infall on to groups has been presented (Gialalisco et al. 2011; Cucciati et al. 2014), these observations are at high redshift ( $z \sim 2-3$ ) and are posited as evidence for filamentary (i.e. cold-flow) accretion (which is predicted to dominate gas accretion processes at  $z \gtrsim 2$ ; e.g. Dekel et al. 2009; Fumagalli et al. 2011; Kimm et al. 2011; van de Voort et al. 2011; Goerdt et al. 2012).

The most closely associated galaxy in our sample to the Mg II absorbers, in terms of on-sky separation, is galaxy E, with  $b = 49$  kpc and  $M_B = -18.13$ . It is also the most separated in velocity space with  $\Delta v \approx 300-500$  km s $^{-1}$ . Galaxy E has no velocity information from the MUSE data, given its relatively low surface brightness. Chen et al. (2010) investigate what they refer to as extended Mg II absorbing haloes using a large sample of Mg II absorber–galaxy pairs. They plot the Mg II EW,  $W_r(2796)$ , of absorption lines as a function of a combination of nearest galaxy distance,  $b$ , and absolute magnitude,  $M_B$ , finding evidence of a correlation. Using the impact parameter and brightness of galaxy E with the relation derived by Chen et al. (2010) (measured for Mg II absorbers at a median redshift of  $\langle z \rangle = 0.2357$ ) predicts an Mg II EW of  $\log W_r(2796) = -1.04 \pm 0.37$  (assuming  $M_B^* = -20.3$ ; Faber et al. 2007). This falls significantly below the observed total rest EW of the Mg II absorption ( $\log W_r(2796) = -0.137 \pm 0.012$ ), with the observation lying above the relation by  $2.7\sigma$  (Chen et al. 2010).

Galaxy E would seem an unusual Mg II ‘host’ galaxy then, given its outlier status in the relationship presented by Chen et al. (2010). Given the close proximity of the four further  $z = 0.28$  galaxies, and the relatively large velocity offset between galaxy E and the absorber system, we now consider the dynamics of the four brighter galaxies detected close to the sightline.

Galaxy D has the smallest offset in velocity space to the absorber group and lies at only  $b = 83$  kpc from the sightline. From the



**Figure 8.** The stellar absorption velocity field (left-hand column) and velocity dispersion (right-hand column) of the three brightest and most extended  $z = 0.28$  galaxies: galaxy B (MRSS 252-054266, top panel) galaxy A (MRSS 252-054422, middle panel) and galaxy C (MRSS 252-053745, bottom panel). In each case, the colour map shows the velocity measurement, whilst the contours show the  $3\sigma$ ,  $6\sigma$  and  $9\sigma$  S/N levels from the collapsed continuum image (over the wavelength range covered in the fitting procedure). The direction to the QSO sightline is given by the arrow in each of the left-hand panels.

interstellar medium gas kinematics, we find that the absorbers are on the redshifted side of the galaxy, however, they lie blueshifted from the galaxy redshift ( $-10 \lesssim \Delta v \lesssim -200 \text{ km s}^{-1}$ ). They are thus offset in velocity in the opposite direction to the galaxy disc rotation.

The remaining three galaxies lie at impact parameters of  $\gtrsim 100 \text{ kpc}$  from the sightline, which, based on the correlation of Chen et al. (2010), implies that these galaxies are unlikely to host a  $\log W_r(2796) = -0.137$  absorber in such a discrete single halo model. For example, an equivalent width of  $\log W_r(2796) = -0.60 \pm 0.34$  is predicted based on the impact parameter and luminosity of galaxy C, significantly lower than observed.

Briefly considering the dynamics of these three galaxies, however, we note that for B, the absorbers lie  $\approx -100 \text{ km s}^{-1}$  (i.e. blueswards) of the galaxy, but are closest to the redshifted side of the galaxy; for C, the sightline is aligned with the blueshifted ( $\Delta v \approx -30 \text{ km s}^{-1}$ ) side of the galaxy with the absorber components covering a velocity range of  $-30 \lesssim \Delta v \lesssim -220 \text{ km s}^{-1}$  relative to the intrinsic galaxy redshift; and for A, the absorbers are offset by  $\Delta v \gtrsim -100 \text{ km s}^{-1}$  and lie on the blueshifted side ( $\approx -120 \text{ km s}^{-1}$ ) of the galaxy. The absorbers are thus aligned in velocity space with both the rotational kinematics of galaxies C and A, but anti-aligned for galaxy B.

Although we find kinematic alignment of the absorbers with the galactic rotation in the cases of both galaxy A and galaxy C, the high EW makes such a scenario unlikely. In addition, given the comparable impact parameters (101 kpc versus 132 kpc) of these two galaxies, it is difficult to justify a gravitational association between the absorption system and just one of the galaxies. We conclude then that the observations do not favour a single galaxy-absorber pair with a co-rotational configuration.

In summary, such a disc co-rotation model is an unlikely configuration for this system, given the data available.

## 4.2 Outflows

Alternatively, there is a broad range of work suggesting that Mg II absorbers may be evidence of outflowing material (e.g. Kacprzak & Churchill 2011). In the system observed here, this possibility is supported by the fact that the absorbing material is entirely blueshifted from the observed galaxies. Absorber strength also provides some indication of whether the absorber system is consistent with tracing an outflow and it has been shown in systems where outflows are observed directly (and probed by the sightline of a background source) that they are almost exclusively associated with  $W_r(2796) \gtrsim 1 \text{ \AA}$  absorption systems. Considering the Mg II system presented here, the EW of  $W_r(2796) = 0.73 \pm 0.02 \text{ \AA}$  places it as a borderline candidate for outflowing material by this criterion.

The galaxy dynamical structure is often invoked in differentiating between the outflowing and infalling scenarios, primarily using the position angle as the defining parameter. The criteria used by number of authors (e.g. Bouché et al. 2012; Bordoloi et al. 2014a,b; Kacprzak et al. 2014; Schroetter et al. 2016) applies the logic that if an absorber is aligned with the minor axis of a star-forming galaxy (i.e. the azimuthal angle to the absorber is  $\alpha \gtrsim 45^\circ$ ), it is assumed to be tracing infalling material; whilst if an absorber is aligned with the major axis of a star-forming galaxy (i.e.  $\alpha \lesssim 45^\circ$ ). However, the results of Bordoloi et al. (2011) show evidence for any azimuthal angle dependence of Mg II absorber properties vanishing beyond impact parameters of  $b \gtrsim 50 \text{ kpc}$ .

All our detected galaxies lie at impact parameters beyond where any azimuthal angle dependency is observed. Additionally, the nearest detected galaxy (E) in our sample is not detected with sufficient signal to noise to afford a dynamical analysis anyway. We note that the absorption system does lie significantly blueshifted, at  $\approx 250\text{--}550 \text{ km s}^{-1}$ , from galaxy E lending itself well to an outflow scenario for the absorber, however. We measure an SFR of  $0.208 \pm 0.010 M_\odot \text{ yr}^{-1}$  for this source based on its measured H $\alpha$  flux. Looking to statistical studies of outflows traced by Mg II, Rubin et al. (2010) find in their sample that galaxies with SFR  $\lesssim 4 M_\odot \text{ yr}^{-1}$  show associated Mg II absorption EWs of  $W < 0.44 \text{ \AA}$  (although they do measure Mg II EWs of  $W \approx 1 \text{ \AA}$  in galaxies with SFRs as low as  $\approx 1 M_\odot \text{ yr}^{-1}$ ). These SFRs are significantly higher than that observed for galaxy E, and we conclude that short of a

previous strong starburst episode, galaxy E is incapable of powering outflows giving rise to strong EW absorbers.

The two most strongly star-forming galaxies in the sample, galaxies C ( $b = 101$  kpc) and D ( $b = 83$  kpc), lie at approximately the same velocity as the strongest of the Mg II absorption, with the absorption complex extending  $\sim 100$ – $150$  km s $^{-1}$  bluewards of the galaxy velocities (see Fig. 9). With an SFR of  $3.2 M_{\odot} \text{ yr}^{-1}$ , galaxy C would be the most likely of the two to power an outflow, however, given the large impact parameter of  $b \approx 100$  kpc, it is unlikely that the sightline absorber is close enough to be probing such an outflow.

With impact parameters of  $b \gtrsim 90$  kpc and low or negligible SFR, the two passive galaxies (i.e. A and B) appear unlikely sources for outflowing material. Finally, given the flux limits of our observations, it is unlikely that a galaxy below our detection threshold would be undergoing powerful enough star formation to be powering such a wind.

In conclusion, if the absorber system is tracing outflowing gas, it is most likely associated with galaxy C. This galaxy has the highest SFR of our sample, whilst being the third nearest galaxy to the sightline given our detection limits. We note that one would be unlikely to conclude that this was outflowing gas based on assuming the absorber to be associated with the closest galaxy on the sky within  $\approx \pm 500$  km s $^{-1}$ , given galaxy E's low SFR.

### 4.3 Intra-group material

From Fig. 9, it may seem unphysical to simply associate one or all of the sightline absorbers with a single galaxy within the group. All five galaxies found at  $z = 0.28$  lie within 200 kpc of the sightline, within the scales usually cited as typical for the CGM or halo of an  $L^*$  galaxy (e.g. Tumlinson et al. 2013). Given the proximity of the galaxies to each other and to the position of the sightline between these galaxies, perhaps the most reasonable (and physical) explanation of the gas probed by the absorbers is as an intra-group medium consisting of the merged (or merging) haloes of some combination of the identified galaxies. Indeed, in this case, it seems more appropriate to consider the absorber impact parameter in terms of group-centre distance as opposed to galaxy distance, and in this case, we find  $b_{\text{Gr}} \approx 110$  kpc, assuming that the passive pair of galaxies forms the group centre. In terms of a group virial scale, this is equivalent to  $\approx 0.32 R_{\text{h}}$ .

It is interesting to consider this system in the context of H I maps of the distribution of gas in the M81 group. Yun et al. (1994) presented the first high-resolution map of H I gas in the proximity of M81, M82 and NGC3077, showing a complex distribution of high-column density gas bridges ranging within velocities of  $\Delta v = \pm 100$  km s $^{-1}$  of M81 and extending over on-sky distances of  $\approx 100$  kpc. The distribution of gas in the M81 group is highly indicative of tidally disrupted material that could be considered to be both an extension of the individual galaxies and the mixing of material to form an intra-group medium. The evidence for tidally disrupted material in the case presented here, however, is minimal, given the lack of any observed disruption to the groups galaxies.

The mixing of gas to form an intra-group medium could source material via two other possible scenarios: (a) the gas is in the process of being accreted into the group halo, and b) the absorption represents multiple gas systems that are being accreted alongside their original parent galaxies to form the intra-group medium. Supporting the latter of these cases are the results and superposition model of Bordoloi et al. (2011). Comparing samples of nominally isolated galaxies and group galaxies, they find an enhancement in the total Mg II EW as measured within galaxy groups when com-

pared to field galaxies. The authors model this with a superposition of the predicted EWs for the individual group galaxies, finding that these linearly add up to the measured group galaxy EWs. From fig. 6 in Bordoloi et al. (2011), we find that at  $b_{\text{Gr}} \approx 110$  kpc, their average group model predicts  $W_r \approx 0.2$  Å. However, performing the superposition summation with the five detected group galaxies, we find a predicted EW of  $W_r = 0.79 \pm 0.07$  Å, consistent with the measured value. It is highly plausible then that the absorption represents the projected overlap of halo gas from the individual galaxies and that the gas is being or has been accreted into the group environment alongside the group galaxies. This would suggest that the detected gas is at some stage in the process of forming the intra-group medium for this group.

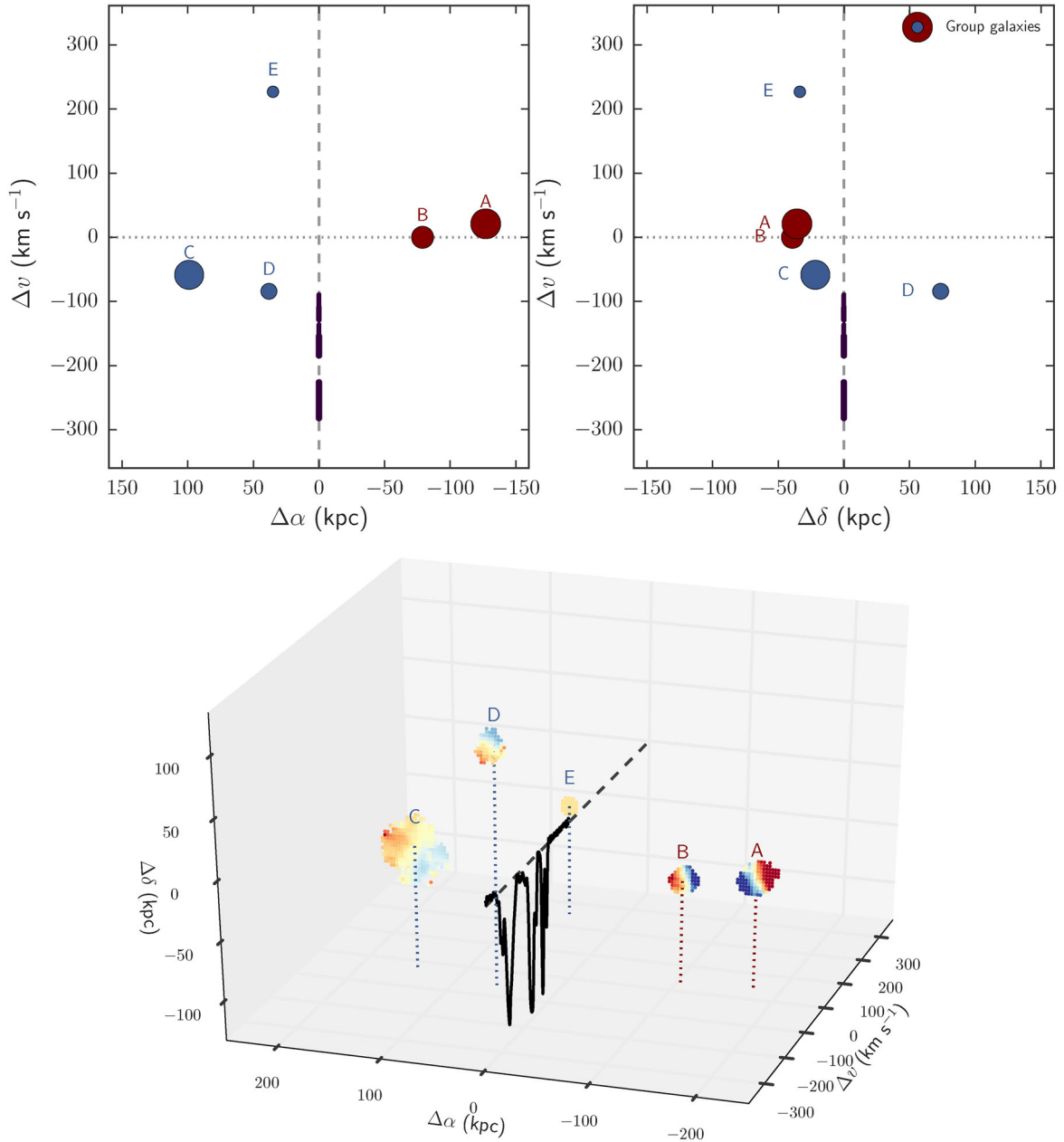
Looking at comparable studies of cool gas in the proximity of galaxy group systems, Whiting et al. (2006) and Kacprzak et al. (2010) studied two separate groups of five galaxies (at  $z = 0.666$  and  $0.313$ , respectively). Both groups contain four galaxies within an impact parameter of 100 kpc of associated Mg II absorbers. We derive a Mg II EW of  $W_r(2796) = 2.2 \pm 0.2$  Å for the  $z = 0.666$  absorber based on UVES data of the background QSO reduced as part of the VLT LBG Redshift Survey (Crighton et al. 2011), whilst Kacprzak et al. (2010) quote  $W_r(2796) = 1.8$  Å for the  $z = 0.313$  absorber.

Whiting et al. (2006) conclude that it is difficult to associate a given galaxy with the absorption system and that debris produced by interactions may be producing the absorption. Kacprzak et al. (2010) reach a similar conclusion, finding that three of the group galaxies exhibit perturbed morphologies and extended optical streams (extending up to  $\sim 25$  kpc) in *HST* data. This work further supports these previous studies, adding 2D dynamical data on an independent group-absorber system. Additionally, the present system is of a significantly lower Mg II equivalent width, showing that such absorbers found associated with group systems may probe a wide range of absorber column densities. This likely reflects the wide range of substructures present in group systems and also in the haloes of individual galaxies. Turning to the Local Group, we note that neither our own, nor the previous two works mentioned would have detected a significant fraction of the dwarf galaxy population observed in both the Milky Way and Andromeda haloes (e.g. Collins et al. 2016; Martin et al. 2016). Such dwarf galaxy and tidal structure is observed to distances of  $\gtrsim 150$  kpc from both Milky Way and Andromeda (e.g. McConnachie et al. 2009; Collins et al. 2016; Küpper et al. 2017). Indeed, it is clear that 'isolated' galaxies identified in the bulk of studies will also contain a vast range of substructures (in the form of undetected dwarf galaxies and tidally stripped material), which is undetected, hiding a complex halo environment.

## 5 SUMMARY AND CONCLUSIONS

We have presented MUSE observations of a galaxy group, which is itself intersected by a background QSO sightline containing multiple metal absorption lines coincident in velocity space with the galaxy group.

The MUSE observations used here were of a short exposure time and taken in relatively poor conditions, but we have shown that a considerable amount of useful information may still be gleaned from it. Indeed, based on these observations of a single galaxy group, it is clear that by repeating this work on multiple sightlines intersecting galaxy groups, we may statistically probe the group environment and disentangle the complex relationship between absorbers in the line of sight of distant quasars and the large-scale structure as traced



**Figure 9.** Top panels: the distribution of group galaxies (circles) around the QSO sightline in velocity space and impact parameter projected in RA (left-hand panel) and Dec. (right-hand panel). Passive galaxies are shown in red and star-forming galaxies are shown in blue, whilst the size of points is proportional to the measured galaxy half-light radius. The dashed line indicates the QSO sightline, whilst the solid sections along this line show the velocity space covered by the Mg II absorbers listed in Table 3. Lower panels: the same galaxies shown in 3D projection around the sightline. For galaxies A–D, the measured galactic kinematics are shown (magnified by a factor of 3 in  $\Delta\alpha$  and  $\Delta\delta$ ) by the colour gradients. Dotted vertical lines are plotted to give a sense of the distribution, with the lower point of each line positioned on the  $\Delta\alpha$ – $\Delta v$  axis plane. The dashed line shows the position of the QSO sightline, whilst we show the normalized UVES spectrum (scaled in velocity space to Mg II 2796 Å) for illustration purposes.

by the galaxy population in a highly efficient manner. Indeed, by comparing to existing dynamical+QSO absorption line studies of ‘isolated’ galaxies (e.g. Kacprzak et al. 2011; Nielsen et al. 2015), differences between the halo gas of individual galaxies and that of galaxy groups may be investigated.

Taking the nearest galaxy in impact parameter ( $b = 49$  kpc) to the detected absorber system presents no obvious simple connection between the two. The velocity offset between the two would seem to be inconsistent with a corotating disc/halo model, especially given the low luminosity (and likely low mass) of the galaxy. An outflow

model associated with this nearest galaxy also appears unlikely given the low luminosity and low SFR of the galaxy. The most plausible association in terms of an outflow model would be with the most highly star-forming galaxy detected in the galaxy group, however, the galaxy impact parameter of  $\approx 101$  kpc would make this scenario seem extremely unlikely.

We find instead that the scenario most favoured by the data is that the absorber traces cool gas in the intra-group medium. The gas appears most likely to be multiple cool gas components potentially accreting into the group halo alongside individual group galaxies

and currently existing at some stage in the process of mixing to form an intra-group medium, i.e. the cool gas components most likely originated in the original galaxy CGMs (via previous outflow or accretion) and are now entering the group environment alongside those parent galaxies.

Combining our analysis with previous detections of Mg II absorbing gas likely associated with galaxy groups (i.e. Whiting et al. 2006; Kacprzak et al. 2010; Gauthier 2013) provides a sample of four Mg II absorber–group associations. From this sample, we find a range of Mg II EWs of  $W_r(2796) \sim 0.7\text{--}4.2 \text{ \AA}$ . A range of other low-ionization absorption species are detected at the Mg II absorber redshift in our own and other absorber–group associations including Ca II, Fe II, Mg I, Mn II, Na I and Ti II.

In summary, we find that the association between galaxies and low-ionization absorbers can be an extremely complex one in which simply taking the nearest detected galaxy can be misleading, whilst we argue that discarding absorber–galaxy pairs found in group environments from analyses can exclude a large fraction of astrophysically interesting systems. Galaxy group systems are inherently complex, especially when considering the baryon content and structure, but contain a necessarily high fraction of the overall baryonic content of the Universe. Probing the gas in such systems via absorption line studies is thus important for understanding the broader topic of galaxy evolution and the role baryons play in this.

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## APPENDIX: OTHER SYSTEMS IN THE SIGHTLINE

Although our focus here is the low-redshift galaxy group, we also note that the MUSE data provides redshifts for one lower and six higher redshift galaxies. We briefly note here the associations within  $\Delta v \sim 300 \text{ km s}^{-1}$  between these galaxies and sightline absorption systems.

The E230M STIS data cover a Ly  $\alpha$  redshift range of  $0.87 < z < 1.56$  and the detected galaxies that fall within the range are J051707-441036, J051705-441115 and J051710-441054.

J051707-441036 corresponds to two Ly  $\alpha$  lines within  $\lesssim 300\text{--}400 \text{ km s}^{-1}$  with column densities of  $N_{\text{HI}} = 10^{13.3} \text{ cm}^{-2}$  and  $10^{15.1} \text{ cm}^{-2}$  (Janknecht et al. 2006). Also, a  $N_{\text{CIV}} \approx 10^{14} \text{ cm}^{-2}$  C IV system lies within only a few  $\text{km s}^{-1}$  of the galaxy redshift (Cooksey et al. 2010).

J051705-441115 ( $z = 1.0183$ ) lies within  $\Delta v \lesssim 350 \text{ km s}^{-1}$  of five low column density ( $N_{\text{HI}} = 10^{12}\text{--}10^{13} \text{ cm}^{-2}$ ) Ly  $\alpha$  absorbers (Janknecht et al. 2006).

The original subject of the MUSE proposal was a sub-DLA at  $z \approx 1.15$  ( $N_{\text{HI}} = 10^{19.8} \text{ cm}^{-2}$ ; Janknecht et al. 2006) and this lies within  $\approx 200 \text{ km s}^{-1}$  of J051710-441054. We note that this galaxy is only weakly detected in our data, however, and requires further observations to ascertain a reliable redshift.

The remaining galaxies in our sample correspond to redshifts that have so far not been probed in Ly  $\alpha$  for the background QSO. We therefore list any known metal lines at the galaxy redshifts.

J051710-441054 at  $z = 0.5181$  is found to lie within  $\Delta v \approx 100 \text{ km s}^{-1}$  of an  $N_{\text{CIV}} > 10^{14.5} \text{ cm}^{-2}$  C IV system (Cooksey et al. 2010). J051710-441044 corresponds to an  $N_{\text{CIV}} \approx 10^{13.5} \text{ cm}^{-2}$  and an  $N_{\text{CIV}} > 10^{14} \text{ cm}^{-2}$  at  $\Delta v \approx 60$  and  $200 \text{ km s}^{-1}$ , respectively (Cooksey et al. 2010).

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