Discovery of a rich proto-cluster at $z = 2.9$ and associated diffuse cold gas in the VIMOS Ultra-Deep Survey (VUDS)*

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ABSTRACT

High-density environments are crucial places where to study the link between hierarchical structure formation and stellar mass growth in galaxies. In this work, we characterise a massive proto-cluster at $z = 2.895$ that we found in the COSMOS field using the spectroscopic sample of the VIMOS Ultra-Deep Survey (VUDS). This is one of the rare structures at $z > 3$ not identified around an AGN or a radio galaxy, thus it represents an ideal laboratory to investigate the formation of galaxies in dense environments. The structure comprises 12 galaxies with secure spectroscopic redshift in an area of $\sim 7 \times 8'$, in a total $z$ range of $\Delta z = 0.016$. The measured galaxy number overdensity is $\delta_g = 12 \pm 2$. This overdensity has total mass of $M \sim 8.1 \times 10^{14} M_\odot$ in a volume of $13 \times 15 \times 17$ Mpc$^3$. Simulations indicate that such an overdensity at $z \sim 2.9$ is a proto-cluster, that will collapse in a cluster of total mass $M_{z=0} \sim 2.5 \times 10^{15} M_\odot$ at $z = 0$, i.e. a massive cluster in the local Universe. We analyse the properties of the galaxies within the overdensity, and we compare them with a control sample at the same redshift but outside the overdensity. We could not find any statistically significant difference between the properties (stellar mass, SFR, sSFR, NUV-r, r-K) of the galaxies inside and outside the overdensity. The stacked spectrum of galaxies in the background of the overdensity shows a significant absorption feature at the wavelength of Ly$\alpha$ redshifted at $z = 2.895$ ($\lambda = 4736$Å), with a rest frame EW of $10 \pm 2$ Å. Stacking only background galaxies without intervening sources at $z = 2.9$ along their line of sight, we find that this absorption feature has a rest frame EW of $10.8 \pm 3.7$ Å, with a detection S/N of $\sim 4$. We verify that this measurement is not likely to be due to noise fluctuations. These EW values imply a high column density $\langle N(\text{HI}) \rangle \sim 3 \times 10^{19}$ cm$^{-2}$, consistent with a scenario where such absorption is due to intervening cold streams of gas, that are falling into the halo potential wells of the proto-cluster galaxies.

Key words. Galaxies: high redshift - Cosmology: observations - Cosmology: Large-scale structure of Universe

1. Introduction

The detection and study of (proto) clusters at high redshift is an important input to cosmological models and these high-density environments are crucial places where to study the link between hierarchical structure formation and stellar mass growth in galaxies at early times. The earlier is the epoch when an overdensity is detected, the more powerful are the constraints on models of galaxy formation and evolution because of the shorter cosmic time over which physical processes have been able to work. Specifically, in high-redshift ($z \geq 1.5 - 2$) (proto) clusters the study of how environment affects the formation and evolution of galaxies is particularly effective, as galaxies had their peak of star formation at such redshifts (Madau et al. 1996, Cucciati et al. 2012).

However, the sample of high redshift ($z \geq 1.5$) structures detected so far is still limited, and it is very heterogeneous, spanning from relaxed to unrelaxed systems. Many detection techniques have been used, based on different (and sometimes apparently contradicting) assumptions. For instance, the evolution of galaxies in clusters appears to be accelerated relative to that in low-density regions (e.g. Steidel et al. 2005). As a result, while the average SFR of a galaxy decreases with increasing local galaxy density in the low-redshift Universe, this trend should reverse at earlier times, with the SFR increasing with increasing galaxy density (Cucciati et al. 2006, Elbaz et al. 2007). Indeed, some (proto) clusters have been identified at high redshift as overdensities of star-forming galaxies (Capak et al. 2011), such as Ly$\alpha$ emitters (Steidel et al. 2003, Ouchi et al. 2003, 2005, Lemaux et al. 2009) and H$\alpha$ emitters (Hatch et al. 2011). At the same time, in some high-$z$ overdensities an excess of massive red galaxies has also been observed (e.g. Kodama et al. 2007, Spilker et al. 2012), and other dense structures have been identified via a red-sequence method (e.g. Andreon et al. 2009) or via an excess of IR luminous galaxies (e.g. Gobat et al. 2011, Stanford et al. 2012) or LBGs (e.g. Toshikawa et al. 2012).

High-$z$ overdensities have been also identified using other observational signatures, for instance using the Sunyaev-Zeldovich effect (Sunyaev & Zeldovich 1972, 1980) like e.g. Foley et al. 2011, or searching for diffuse X-ray emission (e.g. Article number, page 1 of 15
Fassbender et al. 2011), or looking for photometric redshift overdensities in deep multi-band surveys (Castellano et al. 2007, Salimbeni et al. 2009, Scoville et al. 2013, Chiappini et al. 2014). Moreover, assuming a synchronised growth of galaxies with that of their super-massive black holes, high redshift proto-structures have been searched for around AGNs (e.g. Miley et al. 2004) and radio galaxies (e.g. Pentericci et al. 2000, Matsuda et al. 2009, Galametz et al. 2013), even if an excess of galaxies around high-$z$ QSOs has not always been found (see e.g. Decarli et al. 2012). However, this approach could introduce unknown selection effects, for example due to the influence of powerful radio galaxies on the surrounding environment. The study of proto-structures selected only on the basis of the redshift distribution of its members is more likely to offer an unbiased view of high density environments at high redshift and allow a comparison with the habitof of radio galaxies and quasars. Nevertheless it is necessary to obtain spectroscopic redshifts of member galaxies, which is a costly observational task at high redshifts. Spectroscopic surveys conducted with visible wavelength spectrographs will observe the UV rest frame light of galaxies at redshifts $z > 2$, and therefore be mostly sensitive to star-forming galaxies.

Although the sample of (proto) clusters at $z > 1.5$ is increasing in number, it is an heterogeneous data set. This inhomogeneity prevents from using it to assess the abundance of clusters at such redshifts, which could be used to constrain cosmological parameters (e.g. Borgani et al. 1999, Ettori et al. 2009). Chiappini et al. 2013 recently made an attempt to find a common parameter to group and analyse the known overdensities at high $z$. Namely they studied, using simulations, the probability of given overdensities at $z = 2 - 5$ to collapse in bound clusters at $z = 0$, and, in case of collapse, the mass at $z = 0$ ($M_{z=0}$) of such clusters. They also give prescriptions to compute $M_{z=0}$ using the overdensity of the proto-cluster within a given volume. Following their own prescriptions, in a second work (Chiappini et al. 2014) they perform a homogeneous search for overdensities using the photometric redshifts in the COSMOS field. We will come back to their analysis in the following Sections.

The discovery and study of an overdensity at high $z$ also naturally addresses how a dense environment affects galaxy formation and evolution. Galaxies can build their stellar masses via abrupt processes like mergers, which in some cases produce an increase in mass up to a factor of two or so, or via more continuous processes based on in-situ star formation. At the same time, other physical processes are likely to work to quench star formation (like AGN and SNe feedback), and some of these processes are particularly effective in high density environments, where the gas reservoirs in galaxies can be stripped during interactions with the intra-cluster medium (ICM).

The relative role of all these processes as a function of cosmic time is still matter of debate. In the recent years, many observational studies have focused on the analysis of merger rate. If at $z < 1$ the evolution of merger rate is quite well constrained for both major and minor mergers (i.e. with a luminosity/mass ratio greater or less that $\sim 1/4$, see e.g. de Ravel et al. 2009 and López-Sanjuan et al. 2011), at $z > 1$ observational results do still show a large scatter (see e.g. López-Sanjuan et al. 2013 and Tasca et al. 2013 for the most recent studies). On the side of stellar mass growth via smooth star formation, some theoretical models support a scenario where massive ($M_{\text{baryon}} \sim 10^{11} M_{\odot}$) galaxies at $z \sim 2 - 3$ are efficiently fed by narrow, cold (e.g. $T \sim 10^5$ K), intense, partly clumpy, gaseous streams that penetrate through the shock-heated halo gas into the inner galaxy with rates of the order of 100 $M_{\odot}$yr$^{-1}$. These streams can grow a dense, unstable, turbulent disc with a bulge, and trigger rapid star formation (e.g. Keréš et al. 2005, Dekel et al. 2009). Observational evidence of gas accretion is still limited (Giavalisco et al. 2011, Bouché et al. 2013), and further studies are needed to support this scenario. Simulations (Kimm et al. 2011) show that the covering fraction of dense cold gas is larger in more massive haloes, suggesting that the best environment to test the cold flow accretion scenario are high redshift over-dense regions.

In this paper, we present the discovery of an overdensity at $z \sim 2.9$ in the COSMOS field, detected in the deep spectroscopic survey VUDS. In Sect. 2 we describe our data. In Sect. 3 we describe the overdensity and compute the total mass that it comprises, and also its possible evolution to $z = 0$. Sect. 4 shows the search for diffuse cold gas in the overdensity, as inferred by absorption lines in the spectra of background galaxies. In Sect. 5 we analyse the global properties of the galaxies in the overdensity, and contrast them to a sample of galaxies outside the structure at a similar redshift. Finally, in Sect. 6 we discuss our results and summarise them in Sect. 7.

We adopt a flat $\Lambda$CDM cosmology with $\Omega_{m} = 0.27$, $\Omega_{\Lambda} = 0.73$, and $H_{0} = 70$ km s$^{-1}$ Mpc$^{-1}$. Magnitudes are expressed in the AB system.

### 2. Data

The VUDS survey is fully described in Le Fèvre et al. (2014, submitted). In summary, VUDS is a spectroscopic survey using VIMOS on the ESO-VLT (Le Fèvre et al. 2003), targeting $z > 2$ galaxies in one square degree in 3 fields: COSMOS, ECDFS and VVDS-2h. Spectroscopic targets have been mainly selected to have photometric redshifts $z_{p} > 2.3$. Photometric redshifts are measured with the code Le Phare (Arnouts et al. 1999, Ilbert et al. 2006) using the multi-wavelength photometry available in the survey fields, and have an accuracy of $\sigma_{z_{p}} \approx 0.04(1+z)$ for magnitudes $i_{AB} \leq 25$ in the COSMOS field (see Ilbert et al. 2013).

The VIMOS spectra have been observed with 14 integrations with the LRBLUE (R=230) and LRRED (R=230) grisms, covering a combined wavelength range $3600 < \lambda < 9350$ Å. The redshift accuracy with this setup is $\sigma_{\Delta z} = 0.0005(1+z)$ (Le Fèvre et al. 2013), corresponding to $\sim 150$ km s$^{-1}$. Data reduction, redshift measurement and assessment of the reliability of measured redshift are described in Le Fèvre et al. (2014, submitted). A reliability flag has been assigned to each measured redshift, namely flag $=1,2,3,4,9$, with a probability to be right of $\sim 80, 98, 100, 80\%$, respectively.

In addition to the VIMOS spectroscopic data, a large set of imaging data is available in the three fields. In particular, the COSMOS field (Scoville et al. 2007) has a full coverage with the HST-ACS F814W filter (Koekemoer et al. 2007) and includes, among other data, BVriz photometry from Subaru (Capak et al. 2007, Taniguchi et al. 2007), and the more recent YJHK photometry from the UltraVista survey (McCracken et al. 2013).

Absolute magnitudes and stellar masses for the spectroscopic sample and for the photometric parent catalogue have been computed using the code Le Phare as described in Ilbert et al. (2013), using the measured spectroscopic redshift when available. The method is based on a spectral energy distribution (SED) fitting technique. Absolute magnitude computations are optimised using the full information given by the multi-band photometric data described above, with a method that minimises the dependency on the templates chosen to fit the observed colours (see 1

1 http://www.cfht.hawaii.edu/~arnouts/LEPHARE/lephare.html
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Fig. 1. Top: RA-Dec distribution of VUDS galaxies in the COSMOS field (dark dots). Red filled circles: VUDS galaxies within $2.8858 \leq z \leq 2.9018$ in the VIMOS quadrant where the structure has been found (P2Q1). Orange open diamonds: other VUDS galaxies within $2.8858 \leq z \leq 2.9018$ but outside P2Q1. The blue rectangles show the VIMOS footprint. Bottom: like the top panel, but zoomed-in in the region of P2Q1. Green open circles are VUDS galaxies at $z \geq 3$, and blue open circles are ‘free-line-of-sight’ VUDS galaxies at $z \geq 3$ (see text for details).

Appendix A.1 in Ilbert et al. 2005. We used a template set that comprises Bruzual & Charlot (2003) templates. We assume the Calzetti et al. (2000) extinction law, and include emission line contributions as described in Ilbert et al. (2009). We used both delayed star formation histories (SFH) and exponentially declining SFHs, with nine possible $\tau$ values ranging from 0.1 Gyr to 30 Gyr.

3. The spectroscopic overdensity

Using the VUDS spectroscopic data, we discovered a galaxy overdensity in the COSMOS field at $z = 2.895$. It comprises 12 galaxies with reliable spectroscopic redshifts (1 galaxy with flag=2, 11 galaxies with flag 3 or 4) in a very narrow redshift bin ($\Delta z = 0.016$, namely $2.8858 \leq z \leq 2.9018$) in a region covered by a single VIMOS quadrant. The RA-Dec distribution of the VUDS galaxies in the COSMOS field, and in particular of those at $2.8858 \leq z \leq 2.9018$ is shown in the top panel of Fig. 1. The blue rectangles in the panel represent the VIMOS footprint, made by four quadrants. Namely, 11 out of 12 galaxies have been detected in quadrant Q1 of the pointing F51P002 (P2Q1 from now on), and 1 in the adjacent quadrant F51P005 Q4 (same RA as P2Q1 but at higher Dec). The two quadrants overlap, hence this 12th galaxy is within the area covered by P2Q1. From now on, we will consider this galaxy as part of P2Q1. One VIMOS quadrant covers a region of $\sim 7' \times 8'$, that corresponds, at $z \sim 2.9$, to $\sim 13 \times 15$ Mpc$^2$ comoving, or $\sim 3.4 \times 3.9$ Mpc$^2$ physical.

Fig. 2 shows the VUDS redshift distribution in the COSMOS field and the one in P2Q1, both made using only reliable redshifts (flag=2, 3, 4 and 9), in redshift bins of $\Delta z = 0.01$. There is an evident peak of 10 galaxies in P2Q1 at $z = 2.895$, with two other galaxies in the two adjacent redshift bins, for a total of 12 galaxies in $\Delta z = 0.016$. In all the quadrants in the three VUDS fields, in the range $2.5 < z < 3.3$ the median number of spectroscopic galaxies with reliable redshifts falling in such narrow $z$ bins is 0. In only 1.5% of the cases these narrow bins comprise more than 3 galaxies, and always less than 7, with the exception of the structure described in this paper (the few cases with 5-6 spectroscopic galaxies within $\Delta z = 0.016$ will be inspected in details in a future work). Using the 12 galaxies in the overdensity, we measured a velocity dispersion along the line of sight of $\sigma_{\text{los}} = 299 \pm 70$ km s$^{-1}$, but we can not assume that the galaxy velocities in our overdensity follow a Gaussian distribution. A more appropriate estimator to measure the dispersion of a non-Gaussian (or contaminated Gaussian) distribution is the “biweight method”, that has been proven to be very robust also in case of small number statistics (see case C in Beers et al. 1990, and references therein). With this method we estimate $\sigma_{\text{los}} = 270 \pm 80$ km s$^{-1}$. We will retain this second estimation as the velocity dispersion of the galaxies in the overdensity.

Fig. 2. VUDS redshift distribution in the COSMOS field (black) and in the quadrant of the structure (red), in redshift bins of $\Delta z = 0.01$.
We remark that we did not find any broad line AGN among the 12 VUDS galaxies. In the Chandra-COSMOS (Elvis et al. 2009) and XMM-COSMOS (Cappelluti et al. 2007) catalogues, it has not been detected any extended nor point-like source matching with the galaxies in the structure (Cappelluti, private communication), and we found only one match with the sources in the Herschel PEP (Lutz et al. 2011) catalogue.

We also explored whether the overdensity discovered in the VUDS spectroscopy survey is detectable using photometric redshifts, i.e. in the RA-Dec-zP space. To do this, we applied both the Voronoi Tessellation algorithm (Voronoi 1908) and the DEDICA algorithm (Bardelli et al. 1998). The two methods give equivalent results and therefore we discuss only the DEDICA results. DEDICA is an algorithm based on an Adaptive Kernel Method estimate of the density field, also estimating the significance of the detected structures. We use the VUDS photometric parent catalogues, with the most recent photometric redshifts obtained using also the YJHK bands of the UltraVista survey. In order to maximise the signal, we limit the analysis of the photometric redshift catalogue to the i-band range [24 - 25] (the same range that comprises the 12 spectroscopic galaxies in the overdensity) and to the redshift range [2.72 - 3.19]. The choice of this redshift range is due to the mean difference between the photometric (zP) and spectroscopic redshift (z) of the 12 galaxies in the overdensity. We found (zP - z) = 0.06 ± 0.12. To chose the redshift range for the photometric redshifts, first we applied this shift of 0.06 to the redshift of the structure, then we considered a range of ±1σ = ±0.12 around this redshift. After running the algorithm on this photometric data set, we found no significant overdensities (at 90%) in the region of our structure. We obtained the same result by increasing the photometric redshift range up to ±2σ, and also without applying the shift.

We verified with a simple model whether our spectroscopic overdensity, given its characteristics, would be detectable in the parent photometric catalogue using photometric redshifts as described above. We assume a sampling rate of ~ 25% in P2Q1 for the spectroscopic galaxies in the i-band range [24 - 25] (see the following section). This would give us ~ 50 galaxy members in the overdensity in the full parent photometric catalogue. We model the z of these 50 galaxies to be distributed with σz = 270 ± 80 km s⁻¹ centre on z = 2.895. To this z distribution, we add a random photometric error extracted from a Gaussian distribution with σ = 0.12 (found above). We repeated this computation 1000 times, and each time we counted the number of galaxies within the redshift range [2.72 - 3.19], and computed the overdensity δ with respect to all the galaxies in the photometric catalogue in the same redshift range (and with i-band magnitude in the range [24 - 25]). We found δ = 0.62 ± 0.1, i.e. ~ 20 times lower than the value we find using spectroscopic redshift (see next section). We conclude that, given the characteristics of the spectroscopic overdensity (number of member galaxies and measured velocity dispersion), it is unlikely to detect it using photometric redshifts with a typical error as the ones we used. In the recent works by Scoville et al. (2013) and Chiang et al. (2014), who identify overdensities in the COSMOS field using photometric redshifts, no overdensity at the position of P2Q1 at z ~ 2.9 is detected, but they both find a very close overdensity (lower RA, roughly the same Dec) at about the same redshift.

3.1. The galaxy density contrast

An approximate estimate of the overdensity of this structure can be derived in the following way. Given the number of galaxies at z ~ 2.9 in the VUDS area in the COSMOS field, and the ratio between such area and the area of one quadrant, the expected number of galaxies in a redshift bin Δz = 0.016 in one quadrant is ~ 0.71. Thus, the estimated galaxy overdensity in this quadrant is δ = (12 - 0.71)/0.71 ≈ 16. To compute the uncertainty on δ, given by the uncertainty in the counts in the field, we performed the same computation via bootstrapping, selecting randomly 31 quadrants (with repetitions allowed) for 5000 times, and each time computing the estimated overdensity with respect to the counts in the 31 selected quadrants. In this way, we obtain δ = 14 ± 2. Finally, we performed again this computation, but weighting galaxies by the spectroscopic success rate (SSR) in each quadrant to take into account the varying success rate in measuring the redshifts. With this weighting scheme, we obtain δ = 12 ± 2. We assume this value as our best estimate for the galaxy overdensity. It is reasonable that, applying the quadrantal-dependent weights, we obtain a lower overdensity than not applying them, as P2Q1 has a spectroscopic success rate slightly higher than the mean.

The redshift bin Δz = 0.016 that comprises our 12 galaxies is quite small compared to the one enclosing other overdensities at this redshift (see e.g. the summary table in Chiang et al. 2013 where the smallest Δz is ~ 0.03). We verified that our value is not an effect of the low sampling rate of our survey, and that it corresponds to the expected maximum extension in redshift for galaxies at z = 2.9 distributed with σz = 270 km s⁻¹. Specifically, we proceeded by computing a rough estimate of the total galaxy sampling rate in P2Q1, estimated as the number of reliable redshifts over the total number of objects in the photometric catalogue. To compute the sampling rate we considered, in both the spectroscopic and photometric catalogues, only galaxies with i ≤ 25, that is the faintest i-band magnitude reached by the galaxies in the overdensity, and only galaxies with z ≥ 2.5 (zP or z, according to the catalogue). The result is a sampling rate of ~ 25% (we refer the reader to Le Fèvre et al. 2014, submitted, for more details on the VUDS sampling rate). This means that we would expect ~ 12 × 4 = 48 galaxies in the overdensity. From a Gaussian distribution with σ = 270 km s⁻¹, we selected 48 galaxies, converted their velocity in redshift (assuming the peak of the distribution is at z = 2.895) and computed the maximum range spanned in redshift (Δzmax). We repeated this computation 1000 times. We averaged Δzmax over the 1000 extractions and obtained a mean value of 0.015. This indicates that the redshift bin of Δz = 0.016 that we use for our analysis is consistent with the total extent in redshift of the global population (down to i = 25) of this overdensity, in the assumption of σz = 270 km s⁻¹. The redshift range 2.8858-2.9018 corresponds to ~ 17 Mpc comoving. From now on, we will set the volume (in redshift space) enclosing the overdensity as ~ 13 × 15 × 17 = 3340 Mpc³.

3.2. The overdensity total mass

In this Section, we estimate the total mass contained in the volume occupied by the overdensity. Assuming this overdensity will collapse in a cluster (see below for details), we also estimate the mass enclosed within the peak of the overdensity.

\[ M_{\text{enclosed}} = \frac{4}{3} \pi R^3 \delta \rho \]
total mass that this cluster should have at \( z = 0 \). We stress that we took particular attention in determining the volume in which to compute the overdensity, especially in the selection of the most appropriate \( \Delta \) (see the previous Section). This accurate choice makes the following computations more robust, at least for what concerns the observed quantities to be used. The results of this Section will be discussed in Sect. 6.

3.2.1. The total mass at \( z = 2.9 \)

We estimate the total mass contained in the volume occupied by the overdensity, following Steidel et al. (1998). We used the relation

\[
M = \rho_m V_{\text{true}}(1 + \delta_m),
\]

where \( \rho_m \) is the mean density, \( \delta_m \) is the matter overdensity in our proto-cluster and \( V_{\text{true}} \), the volume in real space that encloses the proto-cluster. We computed \( V_{\text{true}} \) and \( \delta_m \) as follows. First, we use the relation between \( \delta_m \) and the galaxy overdensity \( \delta_g \):

\[
1 + b \delta_m = C(1 + \delta_g),
\]

where \( \delta_g = 12 \), and \( b \) is the bias factor. We assume \( b = 2.59, \) as derived in Bielby et al. (2013) at \( z \sim 3 \) for galaxies similar to ours. The factor \( C \), defined as \( C = V_{\text{app}}/V_{\text{true}} \), takes into account the redshift space distortions due to peculiar velocities and the growth of perturbations. \( V_{\text{app}} \) is the volume in redshift space that encloses the proto-cluster. Assuming that the matter peak under study is undergoing an isotropic collapse, we have the simplified expression

\[
C = 1 + f - f(1 + \delta_m)^{1/3}.
\]

Here we use \( f(z) = \Omega_m(z)/0.6 \). Solving the system of Eq. 2 and 3 we find \( \delta_m = 2.65 \) and \( C = 0.60 \). Using these values and \( V_{\text{true}} = V_{\text{app}}/C = 3340/0.6 \text{ Mpc}^3 \) in Eq. 1 we obtain \( M \sim 8.1 \times 10^{14} M_\odot \). A lower limit for the uncertainty on this value is around \( \sim 30\% \), computed by propagating the Poissonian error on the galaxy counts in the structure and in the field (used to compute the mean galaxy density). One should ideally include at least also the error on the galaxy bias, but this crude estimate is enough for the purpose of this work. The same \( \sim 30\% \) uncertainty is valid, with the same caveat, for all the mass estimations below. We can also compute a lower limit for the volume enclosed by the overdensity, using a depth along the line of sight that takes into account the typical error in the \( z_s \) measurement (see Sec. 3). The resulting volume is \( \sim 88\% \) of the nominal one, giving \( M \sim 7.1 \times 10^{14} M_\odot \).

3.2.2. The expected mass at \( z = 0 \)

We estimated the present day mass \( M_{z=0} \) of the cluster descending from our structure, as suggested in Chiang et al. (2013). As discussed by the authors, the computation of \( M_{z=0} \) allows us to have a uniform parameter to classify the proto-clusters/structures found at higher redshift, that currently constitute a rather heterogeneous sample. Chiang et al. (2013) use the Millennium Run (Springel et al. 2005) as N-body dark matter simulation, with the semi-analytical model of galaxy formation and evolution by Guo et al. (2011). They study the typical characteristics (dimension, galaxy and matter overdensity) of proto-clusters at \( z \geq 2 \), in relation to the total mass that these structures would have at \( z = 0 \) \( (M_{z=0}) \), and they characterise their growth in size and mass with cosmic time. To quantify the spatial extent and the size of the structures, they define an effective radius \( R_e \) of proto-clusters. \( R_e \) is defined as the second moment of the member halo positions weighted by halo mass. Namely, they found that

\[
M_{z=0} = C_e(1 + \delta_{m,e}) \rho_m V_e,
\]

where \( V_e = (2R_e)^3 \) is the effective volume, and \( \delta_{m,e} \) is the total matter overdensity computed within \( V_e \). The quantities \( R_e, \rho \) and \( \delta_{m,e} \) are estimated at the redshift of the proto-cluster of interest (they studied \( z = 2, 3, 4, 5 \) ), \( C_e \) is a correction factor of \( \sim 2.5 \), due to the fact that they found that, irrespectively of \( M_{z=0} \) and redshift (in the range that they explored, i.e. \( 2 \leq z \leq 5 \) ), \( V_e \) encloses \( \sim 40\% \) of \( M_{z=0} \). They do not need any factor to correct for redshift space distortions, as they work in real space.

We computed \( R_e \) using the galaxies of our structure (instead of using halos), weighting them by their stellar mass (under the assumption that there is a constant ratio between the mass of the galaxies and the mass of the hosting halos). We find a two-dimensional \( R_e \) of \( \sim 5.7 \) comoving Mpc, that is a 3D \( R_e \) of \( \sim \sqrt[3]{27/4} R_e \sim 7 \text{ Mpc} \). Our \( V_e \) would then be not too different from the volume used above to compute \( \delta_g \) \( (13 \times 15 \times 17 \text{ Mpc}) \). Moreover, our \( V_e \) is comparable to the one used by Chiang et al. (2013) for their analysis \( (15^3 \text{ Mpc})^3 \).

In our computation, the main difference with Chiang et al. (2013) is that our \( V_e \) is in redshift space, while their analysis is in real space. This implies that, before applying their results to our data, we have first to transform an apparent volume \( (V_{\text{app}}) \) into a true volume \( (V_{\text{true}}) \) via the correction factor \( C \), as done above following Steidel et al. (1998). In Chiang et al. (2013), \( V_e \) is in redshift space, so we should compute our \( \delta_g \) in an apparent volume corresponding to \( V_{\text{app}} = C V_{\text{true}} = 0.60 V_{\text{true}} \), i.e. in a volume that is shrunk by a factor 1.0/0.6 = 1.66 with respect to \( V_e \). The choice of this smaller volume it is about equivalent to computing \( \delta_g \) in the same RA-Dec area defined by \( R_e \), but in a redshift slice of \( \Delta z = 0.01 \) instead of \( \Delta z = 0.016 \). Using \( \Delta z \approx 0.01 \), we measure \( \delta_g \sim 17 \). We remark that in this case \( \delta_g \) is measured within an apparent volume that in real space would correspond exactly to \( V_e \), so in this case we derive \( \delta_m \) using \( b \delta_m = \delta_g \), i.e. like in Eq. 2 but without the factor \( C \). Using \( b = 2.59 \) as above, we obtain \( \delta_m = 6.56 \). Using this new \( \delta_m \) and \( V_{\text{app}}/C = V_e = 3340 \text{ Mpc}^3 \), we obtain \( M_{z=0} \sim 2.5 \times 10^{15} M_\odot \), with an error of at least \( \sim 30\% \) as discussed in Sect. 3.2.1.

We remark that, according to Chiang et al. (2013), a structure with \( \delta_g \approx 12-17 \) like ours at \( z \sim 2.9 \) has \( 100\% \) probability to evolve into a galaxy cluster at \( z = 0 \).

3.3. Comparison with the Millennium Simulation

The contrast between the relatively small \( \sigma_{\text{los}} \sim 270 \text{ km s}^{-1} \), measured at \( z \sim 2.9 \) and the estimated \( M_{z=0} \sim 2.5 \times 10^{15} M_\odot \) is apparently striking, but Eke et al. (1998) showed that the velocity dispersion of a cluster increases as time goes by, especially at \( z < 1 \), and this consideration relaxes the apparent inconsistency between \( \sigma_{\text{los}} \) at \( z = 2.9 \) and \( M_{z=0} \). Nevertheless, the expected velocity

\(^4\) If we use the scaling relations derived from the virial theorem to compute the total mass at \( z \sim 2.9 \) of our overdensity, we obtain a total mass of \( M \sim 2 \times 10^{13} M_\odot \) (following for instance Eke et al. 1998), much smaller that the total mass obtained following Steidel et al. (1998) in Sect. 3.2.1. Of course, the use of these scaling relations would imply the assumption that the overdensity is virialised, which is most probably not the case.
In this plot, each point represents a proto-cluster at $z \sim 2.9$ in the Millennium light-cones (see Sect. 3.3 for details). For each proto-cluster, we computed the median of the total mass at $z = 0$ of the cluster into which the proto-cluster will collapse. The green cross represents our overdensity; its dispersion at $z \sim 2.9$ for a cluster with $M_{\text{sim}} \sim 10^{15} M_\odot$ is around 400 km s$^{-1}$, that is larger than our findings. 

Eke et al. (1998) used N-body hydrodynamical simulations of clusters formation and evolution. To better compare our results with simulations, i.e. to study the galaxy distribution of proto-cluster members in redshift space at $z = 2.9$, we use galaxy mock catalogues suited to fit at least the basic observational characteristics of VUDS. In this section, with 'proto-cluster' we mean the set of galaxies that, according to the merger tree of their members at $z = 0$, we use only the clusters for which the median $\Delta_{\text{max}}$ and $\sigma_{\text{los}}$ values are those computed at the beginning of Sect. 3. 

We remark that we did not apply any algorithm to identify clusters, but we simply used the ID provided in the Millennium Database to identify them (namely, their 'Friend-of-Friend' halo ID). The Millennium Database provides, for each cluster, its total mass and its 1D velocity dispersion. We will call this mass $M_{\text{sim}}$ and the 1D velocity dispersion $\sigma_{\text{los}}$. We considered for this study only clusters with $M_{0,\text{sim}} \geq 10^{13.5} M_\odot$. The highest $M_{0,\text{sim}}$ reached in the used light-cones is $M_{0,\text{sim}} \sim 1.2 \times 10^{15} M_\odot$.

For each cluster, we counted its corresponding galaxies at $z \sim 2.9$ ($N_{\text{gal}} = 25$) and measured their median RA and Dec position and their angular 2D distance from the median point. We retain for each cluster the maximum value of $R$ ($R_{\text{max}}$) and the $R_{\text{rms}}$ value with the biweight method (see text for details); red symbols represent the median values of the orange points, in bin of 0.2 in $\log(M/M_\odot)$, and their bars show the 25% and 75% of the distribution. In both panels, the green cross is our overdensity. Its $\Delta_{\text{max}}$ and $\sigma_{\text{los}}$ values are those computed at the beginning of Sect. 3. 

To avoid boundary effects on the computation of $R_{\text{max}}$ and $R_{\text{rms}}$, we use only the clusters for which the median RA and Dec of members at $z \sim 2.9$ is far at least 20 arcmin from the light-cones boundaries.
The quantities \( R_{\text{max}} \) and \( R_{\text{rms}} \) are shown in Fig. 3 as function of \( M_{\text{0,lim}} \), with the values for our overdensity plotted with a green cross. The \( R_{\text{max}} \) value of our overdensity (5 arcmin) has been computed using only the galaxies in P2Q1. Because of this, the value should be considered a lower limit. It is not possible to measure the real \( R_{\text{max}} \), as we cannot know if the galaxies in the overall COSMOS field in the same \( \Delta z \) as the overdensity (orange diamonds in the top panel of Fig. 4 spanning the entire RA-Dec range of the field) will collapse in one single cluster at \( z = 0 \), as their density outside P2Q1 is consistent with the field. On the contrary, thanks to our analysis of the Millennium Simulation we expect that its \( R_{\text{max}} \) should be around 10-12 arcmin (see top panel of Fig. 5), giving its \( M_{\text{0,lim}} \). As a consequence, to derive the \( R_{\text{rms}} \) of our structure we used all the galaxies within a radius of 12 arcmin from the median RA and Dec of the galaxies in the structure (very close to the centre of quadrant P2Q1).

The top panel of Fig. 4 shows the velocity dispersion along the line of sight (\( \sigma_{\text{los}} \)) as a function of the total cluster mass at \( z = 0 \). Black and orange symbols represent the clusters in the simulation. Namely, black points represent \( \sigma_{\text{los}} \) while the orange points are \( \sigma_{\text{los}} \) computed using the redshift of the galaxies at \( z \sim 2.9 \), using the biweight method. Comparing black and orange points, it is evident that \( \sigma_{\text{los}} \) increases as time goes by (as already shown in simulated clusters e.g. by Eke et al. 1998). The panel also shows that the measured velocity dispersion of our structure is below the typical \( \sigma_{\text{los}} \) of proto-clusters in the simulation. In the plot, the values of \( \sigma_{\text{los}} \) at \( z \sim 2.9 \) are computed with the biweight method using all the available galaxies. For the richest proto-clusters (\( N_{\text{gal}} \gtrsim 30 \)), we also measured the same \( \sigma_{\text{los}} \) but using only 12 galaxies (like in our structure). We repeated this computation 1000 times per proto-cluster, and we verified that the median of the distribution of such 1000 \( \sigma_{\text{los}} \) is always very close to the \( \sigma_{\text{los}} \) computed using all the available galaxies, with a maximum difference of \( \sim 20 \text{ km s}^{-1} \).

The bottom panel of Fig. 4 is similar to the top panel in Fig. 3 but on the \( y \)-axis we plot \( \Delta z_{\text{max}} \), i.e. the maximum range in redshift covered by the galaxies at \( z \sim 2.9 \). This plot is particularly useful to determine which is the more suited redshift interval in which ‘proto-clusters’ should be searched for at \( z \sim 3 \). This figure suggests that searches for proto-clusters at \( z \sim 3 \) should be done in redshift bins of \( \Delta z \lesssim 0.02 \) (although this result is based on low statistics), to which the typical redshift measurement error of the given survey should be added in quadrature. In the case of VUDS, the redshift measurement error is small compared to \( \Delta z \sim 0.02 \) (\( \sigma_{\text{z}} = 0.0005(1+z) \), see Sect. 2), so its effect is negligible.

4. Searching for diffuse cold gas

In this Section we describe our search for the presence of (diffuse) cold gas within the proto-cluster. It has already been suggested that galaxies could be fed by cold gas streams. The detection and study of such gas, in the form of flows, blobs or diffuse nebulas, would add precious pieces to the puzzle of galaxy evolution. Here, we try to give constraints on the presence of this gas examining the absorption features in the spectra of galaxies in the background of our structure, as already done e.g. in Giavalisco et al. (2011) for an overdensity at \( z = 1.6 \). We will discuss our results in Sect. 6.

We inspected the spectra of the galaxies in the background of the structure, searching for an absorption feature at the wavelength of the Ly\( \alpha \) at \( z = 2.895 \), i.e. \( \lambda = 4736\,\text{Å} \). Our aim is to verify the presence of gas in the halo of the galaxies in the overdensity or diffuse gas in the IGM of the overdensity itself.

These background galaxies are selected to be at \( 3 \leq z \leq 4.15 \), with secure \( z_{\text{s}} \) (flag=2, 3, 4, 9), and observed in the same V-MOS quadrant as the structure. The lower limit in \( z_{\text{s}} \) is required to distinguish the possible absorption by Ly\( \alpha \) at \( z = 2.895 \) from the intrinsic absorption of the Ly\( \alpha \) in the given background galaxy. The upper \( z_{\text{s}} \) limit exclude galaxies for which the line at \( \lambda = 4736\,\text{Å} \) (observed) falls blue-ward of the Lyman limit at \( 912\,\text{Å} \) (rest frame). For such galaxies, we would not have signal in the wavelength range of interest. With this selection, we found 36 background galaxies, amongst which 18, 12, and 6 with flag =2, 3, and 4 respectively. We also found one broad line AGN with a secure redshift, that we do not use in our analysis.

The top panel of Fig. 6 shows the mean and median stacked spectrum of all the 36 background galaxies, at observed wavelengths. We compute the stacked spectrum in the following way. We interpolate each input spectrum on the same grid with a pixel scale of 5.3Å/pixel (i.e. the dispersion of the blue grism used for the observations). Even if the pixel scale is the same as in each single spectrum, each of the spectra is interpolated on this pixel scale before co-adding, and the flux rescaled to preserve the total flux after rescaling. For each of the spectra, we compute the median sky level, and we consider as ‘good pixels’ those for which the sky flux is within 120% of the median sky level. In this way, in each spectrum, we exclude from the analysis the regions contaminated by strong sky lines. For each grid pixel at \( \lambda_j \), the flux \( f_j \) in the co-added spectrum is computed as the median (or mean) of the fluxes at \( \lambda_j \) of the input spectra, where only spectra for which the pixel at \( \lambda_j \) is a good pixel were considered. For each \( \lambda_j \), we retain the information on the number of spectra that have been used for the stacking (\( N_{\text{sin}} \)). The stacked spectrum is then smoothed on a scale comparable to the resolution of VUDS spectra at the line of interest. Given \( R=230 \) (see Sect. 2), we obtain a resolution element of \( \Delta \lambda \sim 25\,\text{Å} \) at \( \lambda = 4736\,\text{Å} \). Spectra are not normalised nor weighted before stacking.

In the spectra showed in Fig. 6 we do see an absorption feature at \( \lambda = 4736\,\text{Å} \). In the median spectrum, this absorption feature has a rest frame FWHM \( \sim 9\,\text{Å} \) (not deconvolved with instrumental resolution), and rest frame EW \( \sim 4 \pm 1.4\,\text{Å} \), i.e. a measurement S/N of \( \sim 3 \). Its detection S/N is \( \sim 3.3 \). The error on the EW has been computed in a similar way as in Tresse et al. (1999). For the mean spectrum we obtain very similar values (see Table I). If we stack only the background galaxies with redshift flag=3 and 4 (mid panel in Fig. 6), we find slightly larger EW in both the mean and median spectrum, but the values are compatible with the ones obtained by stacking all galaxies (see Table I).

Given that this feature is detected in both the mean and median spectrum with a reasonable S/N, this suggests that it is a common feature in the sample of background galaxies, and it is not due to a minority of the spectra. This absorption feature is also visible (by eye) in some of the single spectra. Clearly, the origin of this absorption could be due to the presence of an intervening galaxy in the structure, and not to diffuse gas. For instance, inspecting the HST image of the galaxy where the absorption line at \( \lambda = 4736\,\text{Å} \) is the most evident, we notice that there are two faint objects close to the galaxy without any spectroscopic nor photometric redshift, one of the two possibly belonging to the galaxy itself. In such a case it is not possible to say if the absorption at \( \lambda = 4736\,\text{Å} \) is due to diffuse gas at \( z \sim 2.895 \) or to one of the two faint objects, that could be at \( z \sim 2.895 \).
Fig. 5. HST-ACS images from the HST-COSMOS survey (Koekemoer et al. 2007), centred on the six ‘free-line-of-sight’ background galaxies (see text for details). The red circle has a radius of 6.4″, corresponding to 50 kpc (physical) at $z = 2.9$. All the other visible sources within the circle are spectroscopic galaxies with $z_s < 2.8761$ or $z_s > 2.9133$ or photometric galaxies with $z_p < 2.895 - 0.17$ or $z_p > 2.895 + 0.17$. All the other visible sources within the circle are spectroscopic galaxies with $z_s < 2.8761$ or $z_s > 2.9133$ or photometric galaxies with $z_p < 2.895 - 0.17$ or $z_p > 2.895 + 0.17$.

Table 1. EW measurements for the absorption feature at $\lambda = 4736$ Å, for different samples of background galaxies (all background galaxies, background galaxies with redshift flag $= 3$ and 4, and ‘free-line-of-sight’ background galaxies). The EW is rest-frame, and expressed in Å. Its error is computed in a similar way as in Tresse et al. (1999). We also quote the measurement $S/N$, i.e. the ratio of the EW over its error, that indicates how well the EW has been measured, and the detection $S/N$, that indicates how well the line is globally detected above the continuum noise. All these quantities are computed for both the mean and median smoothed stacked spectrum.

| Sample                        | $N_{gal}$ | Mean | Median |
|-------------------------------|----------|------|--------|
| Bkg galaxies, flag=2,3,4      | 36       | 4.0  | 3.9    |
| Bkg galaxies, flag=3,4        | 18       | 5.1  | 6      |
| Bkg ‘free-line-of-sight’      | 6        | 10   | 10.8   |

To have a better handle on the possibility of detecting diffuse gas, we removed this and similar cases from our background sample in the following way. We looked in a radius of 50 kpc (physical) around each background galaxy and we removed from our analysis the given background galaxy if in that radius i) there was another VUDS galaxy with $2.8761 \leq z_s \leq 2.9133$; ii) there was a galaxy with $z_p$ (primary or secondary peak) in the range $z = 2.895 \pm 0.17$; iii) there was one or more unidentified sources (not included in our photometric catalogue) in the HST images. A possible absorption found in a background galaxy at $\lambda = 4736$ Å, even if due to gas at $z \sim 2.895$, would not be resolved from an absorption line due to a foreground galaxy in the range $2.8761 \leq z_s \leq 2.9133$ (given the resolution of the grism), and this consideration gives us the restriction on spectroscopic galaxies assumed in point i). For what concerns galaxies with only $z_p$ (point ii), we computed the distribution of $z_s - z_p$ for galaxies with $2.5 < z_s < 3.5$, we fitted it with a Gaussian function and found $\sigma \sim 0.17$, that we used as the redshift interval assumed in point ii).

After removing the background galaxies satisfying the three above-mentioned criteria, we are left with 6 ‘free-line-of-sight’ background galaxies. They are in the range $3.1 \leq z_s \leq 4.1$, and are distributed quite uniformly in RA-Dec, covering half of the entire sky area of the structure (see bottom panel of Fig. 1). Fig. 5 shows the HST images centred on these six galaxies. Their median and mean coadded spectra are shown in the bottom panel of Fig. 6. In the median spectrum, the absorption line at $\lambda = 4736$ Å has a flux detection $S/N$ of about 4 and a rest frame EW $\sim 11 \pm 4$ Å, i.e. an EW measurement $S/N$ of $\sim 3$. The rest frame FWHM is $\sim 10$ Å.
In the stacked spectrum of the six ‘free-line-of-sight’ galaxies there are no other absorption features with a meaningful EW corresponding to typical lines at \( z = 2.9 \), but one. This exception is the (blended) doublet Si IV \( \lambda \lambda 1393, 1402 \), with a rest frame EW of \( 5.5 \pm 1.5 \) Å. This absorption feature is also visible in the two other panels of Fig. 6 but with a lower EW (\( \sim 3 \pm 1 \) Å). We estimate also the EW of the blend Si IV \( \lambda \lambda 1390, 1304 \) and C II \( \lambda 1334 \) in the coadded spectrum of galaxies with redshift flag=3 and 4, and we find EW \( \sim 3 \pm 1 \) and EW \( \sim 2 \pm 1 \) Å respectively. Nevertheless, the lines are blended, and they become even less evident when coadding also flag 2 and 9.

We verified that the absorption line at \( \lambda = 4736 \) Å in the observed frame coadded spectrum of the six ‘free-line-of-sight’ galaxies is not a spurious effect of the noise of the coadded spectra. We did this by comparing its EW with the EW of all the possible absorption features (real or not) in 1000 stacked spectra, obtained by stacking 6 galaxies chosen randomly among all the VUDS galaxies in the COSMOS field, with redshift quality flag equal to 2, 3, 4 and 9, and with \( z \geq 3 \) (the result of this test do not change when the sets of 6 galaxies are built considered only galaxies in the same redshift range as the six galaxies with a free line of sight, i.e. \( 3.14 \leq z \leq 4.12 \)).

Appendix A describes in details how we computed the distribution of the observed-frame EWs of all the absorption features in these 1000 stacked spectra. We find that the 25th, 50th and 75th percentile of this distribution correspond to 3.6, 7.3 and 12.6 Å. The observed frame EW of the absorption line in the median stacked spectrum of our 6 galaxies is 42 Å. This value corresponds to the 99th percentile of the distribution of all the absorption features in the 1000 stacked spectra. This result suggests that our measurement is unlikely to be due to noise fluctuations. Moreover, in this analysis we did not make any use of the additional information that the detected absorption line at \( \lambda = 4736 \) Å is exactly at the wavelength corresponding to \( \text{Ly} \alpha \) absorption at the redshift of the structure. This fact reduces even further the likelihood for this line to be spurious. The physical interpretation of this significant feature will be discussed in Sect. 6.2.

5. Galaxy properties

In this Section we analyse the properties of the galaxies within the overdensity, and we compare them with a control sample at the same redshift but outside the overdensity. For this analysis, we use the 11 galaxies in the overdensity with redshift quality flag=3 and 4. The control sample comprises all the VUDS galaxies with flag=3 and 4 in the range \( 2.8 < z < 3.0 \), outside the structure. This sample includes 151 galaxies. In the following analysis, we include all the galaxies in the two samples, irrespectively of their stellar mass (\( M \)). We verified that the results do not change if we use only galaxies above a given mass limit, common to the two samples (i.e., \( \log(M/M_\odot) \geq 9.5 \)).

We remark that a more detailed analysis is deferred to a future work, when the VUDS selection function (Tasca et al, in prep.) will be fully assessed. A robust computation of the selection function will allow us to determine whether we are missing specific population(s) due to the VUDS observational strategy. We also stress that, given the low statistics (11 galaxies in the overdensity), the comparison of the galaxies in the overdensity with any control sample is prone to large uncertainties. This kind of analysis is better performed with larger samples of galaxies (possibly residing in homogeneous environments), but the analysis presented here has the advantage of being one of the few attempted at these high redshifts.

5.1. Stellar mass, star formation and colours

Fig. 7 shows the distribution of stellar masses (\( M \)) and star formation rate (SFR) for the two samples. Both \( M \) and SFR are computed via SED fitting (see Sect. 2). The stellar mass distribution of the galaxies in the structure seems to peak at smaller masses, and its SFR distribution seems to be narrower than the one of the control sample, but in both cases the two distributions are consistent, on the basis of a KS test, with being drawn from the same \( M \) and SFR distributions.

The top panel of Fig. 8 shows the \((NUV - r) \) vs \((r - K)\) rest frame colours. This plot is particularly useful to distinguish between active and passive galaxies, being able to distinguish dusty active galaxies from truly red and passive ones (see e.g. Williams et al. 2009, Arnouts et al. 2013). Namely, the \( NUV - r \) colour is sensitive to specific star formation (sSFR: the higher the sSFR the bluer the colour), because \( NUV \) traces recent star formation and \( r \) the old stellar populations. Dust attenuation can alter the \( NUV - r \) colour, moving dusty star forming galaxies toward redder colours. The \( r - K \) colour does not vary much for different stellar populations, but is strongly sensitive to dust attenuation (see e.g. Fig. 3 in Arnouts et al. 2013). Using both colours, it is possible to partially disentangle red passive galaxies from dusty active ones. The top panel of Fig. 8 shows that possibly the galaxies in the structure are less attenuated by dust, but, given the low statistics, the difference in the \( r - K \) distribution between the two samples is not significant on the basis of a KS test. We remark that the locus of passive galaxies defined in Arnouts et al. (2013) is \((NUV - r) > 3.75 \) and \((NUV - r) > 1.37 \times (r - K) + 3.2\), i.e. it comprises \( NUV - r \) colours much redder than we find in our sample.

The bottom panel of Fig. 8 shows the sSFR versus the stellar mass. Also in this case, the galaxies in the structure seem not to have very different properties from those in the control sample. At most, they could show a less scattered relation between sSFR and \( M \), and basically this is the same as shown by the SFR histograms in Fig. 7, where the SFR of the galaxies in the structure spans a narrower range than the one in the field.

We also analysed how galaxies are distributed in the plane \( J - K \) vs \( K \) (observed magnitudes). The filters \( J \) and \( K \) bracket the D4000 Å break at \( z \sim 3 \), so the \( J - K \) colour can be used to identify passive galaxies (see e.g. Hatch et al. 2011). We found that galaxies within and outside the structure are distributed very similarly in the \( J - K \) vs \( K \) plane. The reddest galaxies do not belong to the overdensity, but to the field, and they do not seem to reside preferentially in the proximity of the overdensity. Considering the two reddest spectroscopic galaxies in the structure, that have a very similar \( J - K \), one is located in the middle of P2Q1, the other one close to its boundary.

5.2. Stacked spectra

Fig. 9 shows the stacked spectra of the two subsamples of galaxies, i.e. the 11 galaxies in the overdensity (top panel) and the 151 galaxies in the control sample (bottom panel). Spectra are stacked as in Sect. 4 but in this case they have been blue-shifted to rest frame wavelength before stacking and the stacked spectrum is smoothed with a Gaussian filter with \( r \) equal to one pixel.

The two spectra show some differences. First, the median stacked spectrum of the control sample shows some Ly\( \alpha \) in emis-

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in the overdensity, given that the number of galaxies with Ly{\alpha} in emission in the structure is compatible, at 2\sigma level, with being more than 50%.

In the control sample coadded spectrum all the ISM absorption lines are visible: Si II \(\lambda 1260\), the blend OI - Si II \(\lambda\lambda 1302, 1304\), C II \(\lambda 1334\), and the doublet Si IV \(\lambda\lambda 1393, 1402\) (resolved), Si II \(\lambda 1526\), the doublet C IV \(\lambda\lambda 1548, 1550\), Fe II \(\lambda 1608\) and Al II \(\lambda 1670\). Despite the higher noise, all these lines are visible also in the coadded spectrum of the overdensity galaxies, with the exception of Fe II \(\lambda 1608\). The fact that we do not see a clear Fe II \(\lambda 1608\) absorption is probably due to the fact that it falls in a region where the observed frame spectrum is contaminated sky lines: the 11 galaxies in the structure are almost at the same redshift, so the observed frame skylines in the 11 spectra fall always in the same rest frame wavelength. This does not happen for the galaxies in the control sample, that span a larger extent in redshift. These differences (and their significance) will be studied in more details in a future work.

6. Discussion

The overdensity that we found at \(z \sim 2.9\) in the VUDS sample in the COSMOS field has two main characteristics that make it an extremely interesting case study: the large value of the galaxy overdensity, and the evidence of the presence of cold gas in the IGM. In this Section we discuss in more details these two points.

6.1. The overdensity

In Sect. 3 we estimated a galaxy overdensity of \(\delta_g = 12 \pm 2\). Such an overdensity is much higher than the typical \(\delta_g\) found in the literature at similar redshift (e.g., \(\delta_g \sim 6\) at \(z \approx 3.09\) in Steidel et al. 2000, \(\delta_g = 2.3\) at \(z = 3.13\) in Venemans et al. 2007, see also Table 5 in Chiang et al. 2013 for a more complete list, and their more recent work shown in Chiang et al. 2014). Overdensities with \(\delta_g\) similar to ours have been found, but they are very rare, and they seem to span a wide redshift range (e.g., \(\delta_g \sim 8.3\) at \(z = 1.6\) in Kurk et al. 2009, \(\delta_g \sim 16\) at \(z \sim 6\) in Toshikawa et al. 2012). We refer the reader also to Lemaux et al. (2014, submitted), where we study a spectroscopic overdensity of \(\delta_g = 13.3 \pm 6.6\) found at \(z = 3.3\) in the VVDS field using VUDS observations.

The study of such over-dense regions is particularly important as these structures are more likely to become clusters than lower density structures (Chiang et al. 2013). This allows us to study how mass assembles along cosmic time. In our case, the high \(\delta_g\) value is primarily due to the narrow \(z\) range (\(\Delta z = 0.016\)) in which the spectroscopic members reside compared with much larger redshift slices in which other overdensities have been found.

The large \(\delta_g\) means a large total mass (given the typical bias between galaxies and matter at \(z = 2.9\)). Specifically, we find that the total mass associated to the structure at \(z = 2.9\) is \(\sim (8.1 \pm 2.4) \times 10^{14} M_\odot\), that makes our overdensity one of the most massive found in the literature at high redshift. Following Chiang et al. (2013), we estimate that this structure will collapse in a cluster with \(M_{\text{crit}} \sim (2.5 \pm 0.8) \times 10^{15} M_\odot\) at \(z = 0\). For both masses, the uncertainty represents \(\sim 30\%\) of the nominal value (see Sect. 3.2). We verify how rare these structures might be, and how many we should expect to find in the volume explored by VUDS in the COSMOS field. Considering the...
Fig. 7. Top. Distribution of galaxies stellar masses in the control sample (black solid line) and in the structure (red dashed line). Bottom. Same as in the top panel, but for the distribution of SFR.

As the two masses are not directly comparable. The mass measured at \( z = 0 \) is the mass bound in the cluster, while at \( z \sim 2.9 \) we measure the total mass that will collapse in that cluster, and that at \( z \sim 2.9 \) is not necessarily bound in one single structure. The two masses should differ only by the factor \( C_e \) described by Chiang et al. (2013), that links the total mass at \( z \sim 2.9 \) enclosed in a given volume with the final bound mass at \( z = 0 \). The most evident evolution from the overdensity at \( z \sim 2.9 \) and its descendant cluster at \( z = 0 \) is an evolution in overdensity, and not in total mass.

A different discussion has to be devoted to the measured velocity dispersion. We measured \( \sigma_{\text{los}} = 270 \pm 80 \) km s\(^{-1}\) with the biweight method, a method which is quite effective in measuring a dispersion of a contaminated Gaussian distribution. Indeed, it...
is not known which should be the shape of the velocity distribution of galaxies in a proto-cluster, if such structure is not already relaxed. We inspected the shape of the velocity distribution of the galaxies in the proto-clusters at $z = 2.9$ in the galaxy mock catalogues that we used in Sect. 5.3 focusing our attention on the proto-clusters that will collapse in clusters with $M_{\text{vir}} \geq 10^{15} M_\odot$. We found that these velocity distributions can have a broad range of shapes, from Gaussian, to contaminated Gaussian, to almost flat distributions. Indeed, if our measured $\sigma_{\text{los}}$ is lower than the expected one (see Eke et al. 1998), there are cases in the literature where the measured $\sigma_{\text{los}}$ is too large with respect to expectations (see e.g. Toshikawa et al. 2012). We suggest that the important piece of information that we can retrieve from simulations is the maximum span in redshift space that the member galaxies can encompass, rather than their velocity dispersion. The first one is needed to tune the search for high-$\z$ overdensities, while the second one might be less meaningful, depending on the evolutionary state of the proto-cluster under analysis.

6.2. The diffuse gas
The stacked spectrum of the background galaxies at $z > 3.0$ shows an absorption consistent with Ly$\alpha$ at $z = 2.895 (\sim 4736 \AA)$. Its rest frame EW is $\sim 4 - 10 \AA$ according to the sample used for the stacking (see Table 1). These EWs correspond to N(HI) $\sim 3 - 20 \times 10^{13} \text{cm}^{-2}$ (with large uncertainties, and assuming a constant gas density over the transverse dimension of the structure). The angular size of the structure would imply a total mass of HI of a few $10^{12} - 10^{13} M_\odot$ if the absorption were due to diffuse gas.

Several hypotheses can be suggested on the very nature of this absorption feature. The debate is open in the literature about the detectability of the signature of physical processes that could give rise to such feature. The first hypothesis, already introduced above for the computation for the total HI mass, is that the Ly$\alpha$ in absorption is related to the diffuse gas (IGM) within the overdensity. This could be especially the case for the six ‘free-line-of-sight’ galaxies, as they are $> 50 \text{kpc}$ (physical) away from all the identified sources in the structure.

The high column density that we infer could support a second hypothesis that the absorption is due to intervening cold streams of gas, which are falling into the potential well of the galaxies in the overdensity. This high column density is shown, for instance, in Goerdt et al. (2012). They use hydrodynamical simulations at $z \sim 3$ to create and trace such streams in the circumgalactic medium via Ly$\alpha$ absorption manifest in the spectra of background galaxies. In particular, their Fig. 15 shows that the projected HI column density of such absorption features can reach up to a few $10^{20} \text{cm}^{-2}$ at a distance of more than 50 kpc from the galaxy that is fed by cold streams. This N(HI) value is consistent with the N(HI) of the absorption line that we find in the stacked spectrum of the ‘free-line-of-sight’ background galaxies. Similarly, they show in their Fig. 20 that the Ly$\alpha$ rest frame EW can easily reach values of EW $\sim 4 - 5 \AA$ along the line of sight of the cold flows up to 60 – 80 kpc from the centre of the galaxy.

The fraction of the area (or ‘covering factor’) around a galaxy that is covered by these cold streams with high enough density to produce a detectable absorption line is very low. For EW(Ly$\alpha$) $\sim 4 - 5 \AA$, Goerdt et al. (2012) show that the covering factor is typically of the order of few percent. Given these results on the covering factor, the fact that we see such a strong absorption not only in the mean stacked spectrum but also in the median, strongly suggests that the absorption is due to a more widely extended source rather than to cold streams. On the other hand, the fact that we are studying an over-dense region would likely give rise to denser and/or more widely distributed filaments (see e.g. Kimm et al. 2011, who find that the covering fraction of filaments is larger in more massive halos).

Very similar results on simulated cold streams extension, N(HI) and covering factor are shown in Fumagalli et al. (2011) (see e.g. their Fig 6). They also show that such cold flows are generally metal poor (as also shown in Goerdt et al. 2012 and Kimm et al. 2011). They suggest that any observational detection of metal lines is more probably due to outflows rather than infalls. We do not find any other significant absorption lines in the coadded spectrum of the ‘free-line-of-sight’ background galaxies except for the Si IV $\lambda\lambda 1393, 1402$ (blended) doublet, with a rest frame EW of $5.5 \pm 1.5 \AA$ (EW = $3 \pm 1 \AA$ for the total sample of background galaxies). Such an EW could, however, be due to the fact that this is a not resolved doublet. This detection, that does not directly support the infall scenario, will deserve further analysis.

7. Summary and conclusions
In this work, we characterise a massive proto-cluster at $z = 2.895$ that we found in the COSMOS field using the spectroscopic sample of the VUDS survey. Our results can be summarised as follows:

![Fig. 9. Top: coadded spectrum of the 11 galaxies in the structure with redshift quality flag 3 and 4. Bottom: coadded spectrum of the 151 galaxies in the control sample with redshift quality flag 3 and 4. Line and colour codes are as in Fig. 6](image-url)
- The overdensity comprises 12 galaxies with secure spectroscopic redshift in an area of ~ 7′ × 8′, in a total redshift range of Δz = 0.016. The measured galaxy overdensity is δg = 12 ± 2. According to simulations (Chiang et al. 2013), such a structure with δg = 12 at z = 2.9 has 100% probability to evolve into a galaxy cluster at z = 0.

- We estimated that this overdensity has total mass of M ≈ 8.1 × 10^{13} M_⊙ in a volume 13 × 15 × 17 Mpc^3. According to Chiang et al. (2013), such overdensity should collapse into a cluster of total mass M_{z=0} ≈ 2.5 × 10^{15} M_⊙ at z = 0. In the volume surveyed by VUDS at 2 < z < 3.5 in the COSMOS field, we should have expected 0.12-0.3 proto-cluster of this kind.

- The velocity dispersion of the 12 members is σ_{los} = 270 ± 80 km s^{-1}. We verified, using light-cones extracted from the Millennium Simulation, that this is lower (but consistent within 2σ) than the typical velocity dispersion of the galaxies belonging to the same kind of proto-clusters at this redshift. This low value is consistent with the increase of σ_{los} as time goes by (Eke et al. 1999).

- In the light-cones that we examined, the typical span in redshift of the galaxies belonging to proto-clusters at z ~ 2.9, that will collapse into massive clusters at z = 0, is Δz ≈ 0.02. This value is much smaller than the redshift bin often used to search for proto-clusters at this redshift.

- The stacked spectra of the galaxies in the background of the overdensity show a significant absorption feature at the observed wavelength corresponding to the Lyα at the redshift of the structure (λ = 4736 Å). We find that this absorption feature has a rest frame EW of 10.8 ± 3.7 Å, with a detection S/N of ~ 4, when stacking only background galaxies without intervening sources at z ~ 2.9 along their line of sight. We verified that this measurement is likely not due to noise fluctuations. Considering also the lower (but consistent) EW found using different samples of background galaxies (see Table 1), such an EW range corresponds to a column density N(HI) of the order of 3 × 10^{19} cm^{-2}.

- We analysed the properties of the galaxies within the overdensity, and we compared them with a control sample at approximately the same redshift outside the overdensity. Although the galaxies within the overdensity seem to be on average less massive and less dusty, we could not find any statistically significant difference between the properties (stellar mass, SFR, sSFR, NUV-r, r-K) of the galaxies inside and outside the overdensity, but this result might be due to the low statistics.

Simulations (Chiang et al. 2013) indicate that such an overdensity at z ~ 2.9 is indeed a proto-cluster that, given the measured galaxy overdensity, will collapse to a (massive) cluster at z = 0. For this reason, the detailed analysis of this proto-cluster represents a fundamental piece in the comprehension of galaxy formation and evolution.

For what concerns the properties of the galaxies within the proto-cluster, we plan to perform a more detailed study when the VUDS selection function is assessed. A well defined selection function will allow us to robustly quantify the average properties of the galaxies in such a dense environment and to compare them with the galaxies in the field at the same z and with other overdensities found in the literature (like, e.g., Lemaux et al., 2014, submitted). The synergy of spectroscopy and multi-band photometry in next generation surveys like Euclid will allow to identify several proto-cluster structures thanks to combination of depth and large surveyed areas. In this respect, current surveys such as VUDS, are essential to characterise the global properties of these structures and use them to predict their observability and optimal detection with future surveys.

On the side of the detection of cold gas, the EW of the absorption line corresponding to the Lyα at z ~ 2.9 implies a high column density (N(HI) ~ 10^{20} cm^{-2}). This N(HI) value would be compatible with the scenario where the absorption is due to intervening cold streams of gas, that are falling (and feeding) into the halo potential well of the galaxies in the proto-cluster (Fumagalli et al. 2011, Goerdt et al. 2012). In contrast, the stacked spectrum of the galaxies in the proto-cluster background also shows an absorption line corresponding to Ly α at 11393, 1402 (blended) doublet at the redshift of the proto-cluster, detection which is not in agreement with the fact that the cold flows are predicted to be metal poor. Surely, the scenario of gas accretion by cold gas stream needs to be more robustly assessed from additional observational evidence. An exciting prospect is looking for Lyα emission produced by gravitational energy released by cold gas flowing into the potential wells of galaxies (see e.g., Goerdt et al. 2010).

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In our analysis, we keep only the EWs \(\lambda_+\) for the definition of \(\lambda_c\). If the flux \(f_i\) at \(\lambda_+\) is below the continuum, we compute the \(f_i\) at \(\lambda_+\). If \(f_i\) is above \(\lambda_+\), there is an absorption line at that position, so we move to the next \(\lambda_+\). If \(f_i\) is below \(\lambda_+\), we compute the \(f_i\) of the possible line centred at \(\lambda_+\), considering as ‘line’ the spectrum in the range \(\lambda_+ - 30 < \lambda < \lambda_+ + 30\). 

The output of this procedure is a value of \(\text{EW}_i\) for each \(\lambda_+\). We implemented an automatic procedure to measure in a homogeneous way the EW of all the absorption features (real or not) in the 100 stacked spectra mentioned at the end of Sect. 4. Specifically, we perform the following analysis at each pixel (at position \(\lambda_+\)) of the stacked spectrum. We define the continuum \(f_c\) around \(\lambda_+\) as the mean value of the flux of the coadded spectrum in the two intervals \(\lambda_+ - 80 < \lambda < \lambda_+ - 280\) Å and \(\lambda + 80 < \lambda < \lambda_+ + 280\) Å. To compute the mean, we use only the pixels where \(f_i,\lambda_+\) is above the continuum. Our automatic procedure will be below the continuum for \(\lambda_+\) is above \(\lambda_+\) at \(\lambda_+\), there is no absorption feature and negative for emission features. 

In our analysis, we keep only the \(\text{EW}_i\) that satisfy the following requirements:

- \(\text{EW}_i\) must be positive.
- The continuum around the line must be entirely included in the observed spectrum, so we need \((\lambda_+ - 280) > 36000\) Å and \((\lambda + 280) < 9350\) Å.
- The flux at \(\lambda_+\) must be on the local maximum, i.e. \(f_i < f_{i-1}\) and \(f_i < f_{i+1}\). In the majority of cases, \(f_i\) is less than \(f_{i-1}\) only because of noise fluctuations around the continuum, and most probably \(f_{i-1}\) and \(f_{i+1}\) will be above the continuum. 

We want to keep all these cases. In the case of absorption features larger than one pixel and centred at a given \(\lambda_+\), \(f_i\) will be below the continuum for \(\lambda_+\) included in a given range \([\lambda_c - L, \lambda_c + L]\), where \(2L\) is the width of the absorption feature at the level of the continuum. Our automatic procedure
computes the EW centred at all possible \( \lambda_i \) included in this range and the output is a series of positive EWs with (most probably) a (local) maximum EW at \( \lambda_c \). We retain only EWs \( f_i \) values where \( f_i \) is a local minimum, thus normally we keep the largest possible EW for each absorption feature.

- \( N_{s,i} \) in the entire range \( \lambda_i - 30 < \lambda < \lambda_i + 30 \text{ Å} \) must be \( \geq 5 \).
- The continuum flux \( f_{c,i} \) must be computed in a range of at least 100 Å. As described above, \( f_{c,i} \) is measured using two intervals of \( \sim 200 \text{ Å} \) each, but using only the fluxes \( f_i \) where \( N_{s,i} \geq 4 \). In some case, this threshold shrinks the wavelength range on which \( f_{c,i} \) is computed, especially at \( \lambda > 6000 \), where the sky level in VUDS spectra is on average quite high due to fringing.

- The continuum measured on the left \( (f_{l,c},i) \) and on the right \( (f_{r,c},i) \) of \( \lambda_i \) must be similar. Namely, \( \max(f_{l,c}/f_{r,c}, f_{r,c}/f_{l,c}) \leq 1.5 \). In this way we avoid absorption features too close to a break in the continuum, a situation difficult to be treated properly when measuring EW automatically for all features, without knowing a-priori their position and the shape of the continuum around them.

The EW distribution used for the analysis at the end of Sec. 4 is computed using all the EWs in the 1000 coadded spectra that satisfy the conditions listed above. We verified that these conditions are also satisfied by the absorption line at \( \lambda = 4736 \text{ Å} \) in the stacked spectra shown in Fig. 6.