The VIMOS Ultra Deep Survey: 10 000 Galaxies to Study the Early Phases of Galaxy Assembly at 2 < *z* < 6+

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The VIMOS Ultra Deep Survey (VUDS) aims to study the early phases of galaxy assembly from a large, well-defined sample of ~ 10 000 galaxies with spectra obtained from very deep VIMOS observations. This sample is by far the largest to date, with spectroscopic redshifts covering a redshift range 2 < *z* < ~ 6 and it enables a range of fundamental studies to better understand the first major steps in galaxy evolution. The first results from the VUDS survey are summarised, including the discovery of a galaxy protocluster at *z* = 3.3.

Over the past 20 years our view of galaxy formation and evolution has dramatically improved. Observational cosmology has reached an unprecedented level of precision, and we have in hand a plausible scenario to explain the time evolution of galaxies over more than 13 billion years, resting on the hierarchical assembly of dark matter halos in a Lambda Cold Dark Matter (ΛCDM) cosmology, and supported by detailed numerical simulations.

However, the observational evidence sustaining a robust picture of galaxy formation and evolution is still limited at redshifts beyond *z* ~ 1–3, and much remains to be learned about the critical time when the progenitors of today's galaxies were assembling. Our current observational knowledge rests solely on the ability to find all distant galaxies, as this provides the basic input to derive volume-averaged quantities of cosmological value. A primary key question arises, and is one of the basic quests throughout the history of extragalactic astronomy: are we properly counting galaxies of all types in order to be able to derive a complete census of stars, gas and black holes at any epoch?

The peak of the star formation rate in the Universe seems to have happened at a redshift *z* ~ 1.5; but do we understand what the star formation history was at earlier times? Evolved passive/quiescent galaxies are already observed at *z* ~ 2, some of them very compact; but when they were formed, what their progenitors were, and what the history of mass buildup at earlier times was, are largely unexplored questions. When did the progenitors of the massive clusters of galaxies identified at redshifts *z* ~ 1–2 assemble? How were galaxies distributed in space, and what was the impact of the local environment during the first phases of galaxy assembly? Are galaxies building up their mass with time from cold gas accretion or through mergers, or both? What are the consequences of the coevolution of supermassive black holes and galaxies? At which epochs are these different processes playing a dominant role?

The importance of large statistically representative surveys

Large statistically representative surveys of the Universe at different epochs constitute a fundamental tool in this quest. To measure a quantity (e.g., volume density) at better than 5σ, one needs at least 25 independent measurements (assuming Poisson statistics). For a multivariate quantity, the required sample size multiplies by each variable. Taking a classical example, measuring the luminosity function in the ten luminosity bins necessary to constrain the three parameters of a Schechter function (ϕ^*,

L^*, α) takes about 250 galaxies at each redshift. To study the multivariate dependence for five different galaxy types and over a range of three different environments, one therefore needs 3750 galaxies, or about 10 000 galaxies to cover three redshift ranges. Another key element is the need to mitigate the effects of cosmic variance by observing large (and possibly unconnected) volumes. It is only on field sizes of order of one square degree that cosmic variance can be reduced to below 10% for galaxies with a typical mass M^* at $z \sim 3$ (Moster et al., 2011).

In addition to these simple statistical arguments, the selection function of a survey is of paramount importance: the pre-selection of galaxies in any survey will preset which questions can be investigated by a particular survey. The ultimate goal is for representative surveys. This requires that we make a census of all galaxy types at a given epoch, imposing as few as possible of our priors when exploring the high-redshift Universe. This is obviously a difficult concept, as we do not know *a priori* what we are attempting to measure. With all this in mind, exploratory investigations with a few tens, or even a few hundreds of objects, in small fields must be followed up by systematic surveys strictly guided by the above principles.

VUDS: The VIMOS Ultra-Deep Survey

The high-redshift galaxy population has been extensively studied with spectroscopic surveys, reaching ~ 10^5 redshifts at $z \sim 1$. Such surveys at the VLT include: the VIMOS Very Deep Survey (VVDS; Le Fèvre et al., 2005; 2013); zCOSMOS (Lilly et al., 2007); and VIPERS (Guzzo et al., 2013; 2014). However, at redshifts $z > 2$ spectroscopic samples are much more limited: a few thousand Lyman-break galaxies (LBGs) at $z \sim 3$ (Steidel et al., 2003; Bielby et al., 2011), about 800 galaxies selected for their *i*-band luminosity or Lyman-α flux (VVDS; Le Fèvre et al., 2013; and the article on p. 33), Lyman-α emitters in narrow redshift ranges (e.g., Ouchi et al., 2008), and other targeted populations (e.g., Stark et al. 2010; Vanzella et al., 2009). It is worth noting that the majority of today's most referenced studies at redshifts $z > \sim 3.5$ are conducted on the basis of colour-selected samples and photometric redshifts, but on samples containing relatively few objects (e.g., Bouwens et al., 2007) and with significant uncertainties associated to their exact redshifts and the catastrophic failure rate. Further, the spectroscopic samples at these redshifts reach only a few hundred galaxies altogether.

To improve our understanding of the population at $z > 2$, we are conducting the VIMOS Ultra-Deep Survey, based on ESO Large Programme 185.A-0791 with 640 hours awarded. The key features of VUDS are: (i) the large sample, with about 10 000 galaxies observed with multi-slit spectroscopy; (ii) the 1 square degree field coverage in three separate fields (COSMOS, Extended Chandra Deep Field-South [ECDFS], VVDS-02h), currently unprecedented at this depth; (iii) the large wavelength coverage 3650 Å $\leq \lambda \leq$ 9350 Å; and (iv) the long exposure times of 14 hours. All these aspects make for a unique survey, the largest at these redshifts to date.

The primary target selection criterion for VUDS is photometric redshifts of $z \geq 2.4$, computed from the multi-wavelength data using Le Phare (e.g., Ilbert et al. 2013). This is definitely using more information than basic colour–colour selection (such as *BzK* or LBG-like *ugr* or *gri* selection), and is therefore expected to be more complete and more robust against photometric errors. However, photometric redshifts have associated degeneracies and catastrophic failure modes, so we have elected to be inclusive rather than exclusive by selecting galaxies for which either of the primary or secondary peaks of the photometric redshift probability distribution function is at $z \geq 2.4$. To be as inclusive as possible in our target selection strategy, we have supplemented this primary selection by targets satisfying various other photometric criteria if not selected by the primary selection, including those galaxies in the right location of the LBG *ugr*, *gri* and *riz* colour–colour diagrams, as well as galaxies showing a continuum break at any wavelength redder than the *r*-band with bluer colours compatible with intergalactic medium (IGM) extinction at high redshift.

VUDS observations and data processing are quite challenging. Never before had anyone assembled such a large sample of very faint galaxies for these redshifts. The first important input was to assemble reference multi-wavelength catalogues covering at least from the *u*-band to the *K*-band, and the spectroscopic redshifts needed to calibrate the photometric redshifts. We have selected three of the best fields where these conditions are met: the COSMOS field with extensive deep multi-band data including Hubble Space Telescope (HST) imaging (Scoville et al., 2007) and the recent addition of the UltraVista photometry (see, e.g., Ilbert et al., 2013), as well as extensive spectroscopy (with VIMOS on the VLT and the Keck Telescope); the ECDFS (see Cardamone et al. [2010] for the photometry and Le Fèvre et al. [2013] and references therein for the spectroscopy); and the VVDS 0226-04 field with deep Canada-France-Hawaii Telescope Legacy Survey [CFHTLS] and WIRcam Deep Survey [WIRDS] photometry and extensive spectroscopy from the VVDS Deep and Ultra Deep surveys (Le Fèvre et al., 2005; 2013; and references therein).

VIMOS slit masks have been designed implementing several levels of target priority using the VIMOS Mask Preparation Software (VMMPS) software. In particular shorter slits, as discussed in Scodeggio et al. (2009), were employed, which enable about 600 objects to be observed simultaneously. A total of 16 VIMOS pointings have been observed, each with 14 hours of integration in both of the LRBLUE and LRRED gratings, with a spectral resolution $R \sim 230$. The large wavelength range 3650 Å $< \lambda <$ 9350 Å is a key factor in minimising any redshift desert (Le Fèvre et al., 2014a). Observations for each pointing consist of 13 different observing blocks and a total of 40 individual ~ 20-minute exposures, executed in service mode by the Paranal staff. The data processing is performed within the VIMOS Interactive Pipeline and Graphical Interface environment (VIPGI; Scodeggio et al., 2005), optimised to take into account the large number of individual exposures to be combined, and for joining the blue and red spectra.

Spectra and redshift measurements

The next critical step is to measure redshifts. We follow the methodology initiated with the Canada France Redshift Survey (CFRS) and further iterated with the VVDS: independent measurements are performed by two team members using the EZ software (Garilli et al., 2010), who then compare their measurements to assign a final redshift. As part of this process a reliability flag is assigned to each redshift, giving the probability that a redshift is correct. The team expertise has grown steadily as more spectra have been measured, but we realised that some measurements needed to be revised because the measurers were assigning wrong redshifts to spectra with which they were previously unfamiliar, the most common being M-stars *vs*. redshift $z \sim 5$ galaxies, or Lyman-α vs. [O II] 3727 Å emission. We therefore decided to setup a "Tiger team" in charge of reviewing all redshifts, again with two reviewers (and independent of the first two). As a result about 10% of the measurements or flags were changed through this process. In the end about 80% of the target sample received a redshift measurement, an impressive result given that observations reach beyond i_{AB} = 25–25.5 mag. A paper presenting a complete survey description has been submitted (Le Fèvre et al., 2014b).

First results

We present examples of the VUDS spectra in Figure 1, and average spectra in several redshift ranges in Figure 2. The average signal-to-noise (S/N) of the spectra is about five in the continuum in the magnitude bin i_{AB} = 24–25 mag. It is very illustrative and striking to display all VUDS spectra between redshift 2 and redshift ~ 6 in a single image, as shown in Figure 3. The most prominent feature is the hydrogen Lyman-α line at 1215 Å, which enters the VIMOS spectral domain at 3650 Å for $z = 2$ and is redshifted to 8500 Å at $z = 6$; it is observed in emission or in absorption (or both). On the red side of Lyman-α a wealth of photospheric and interstellar medium (ISM) lines are readily seen at all redshifts, including Si II, Si IV, O I, C II, C III], C IV, He II, Al II, Al III and Fe II. On the blue side, one can iden-

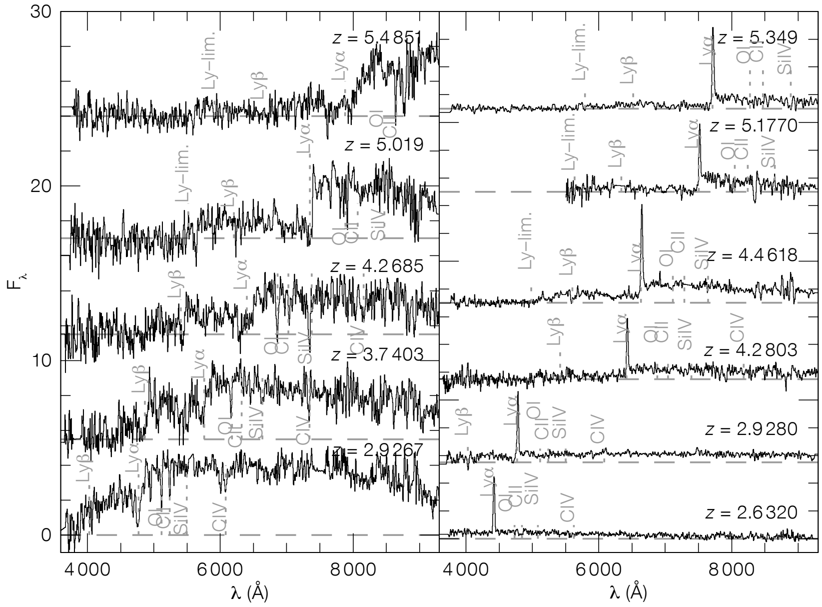
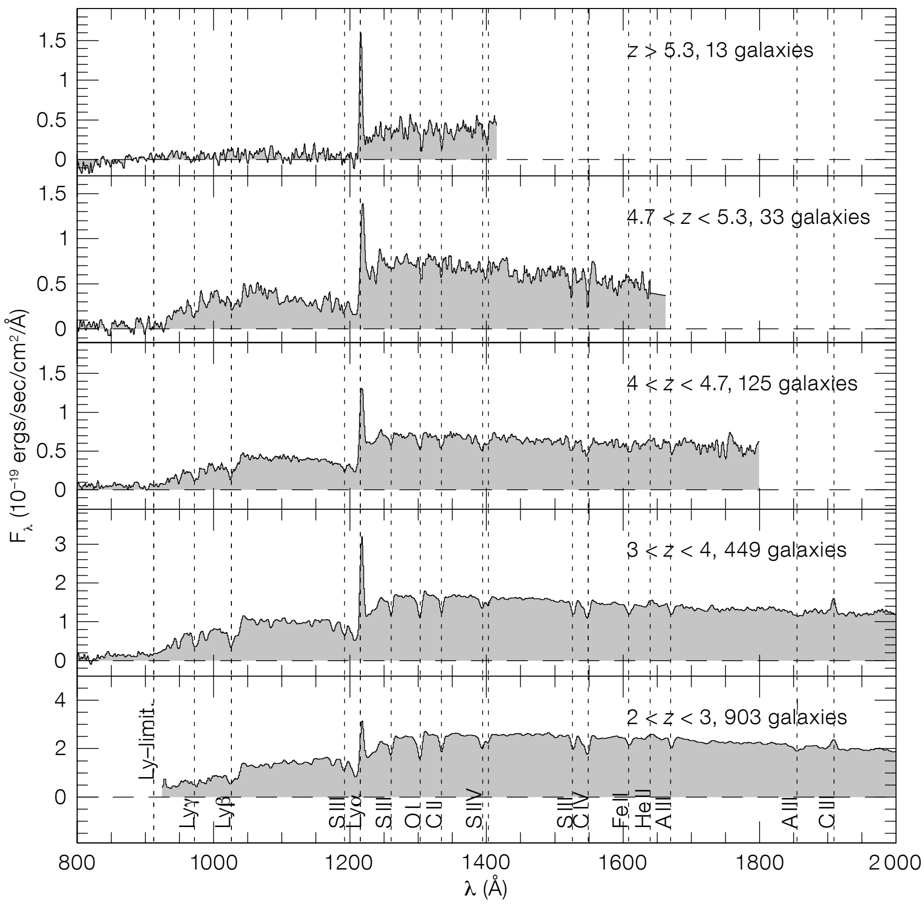


Figure 1. (Above) Examples of VUDS spectra obtained with VIMOS are displayed, covering the redshift range 2.6 to 5. Galaxies with Lyα in absorption are shown in the left panels, those with Lyα in emission in the right panels.

Figure 2. (Below) Average spectra of VUDS galaxies in five redshift ranges from $z \sim 2$ to $z \sim 6$ are shown.



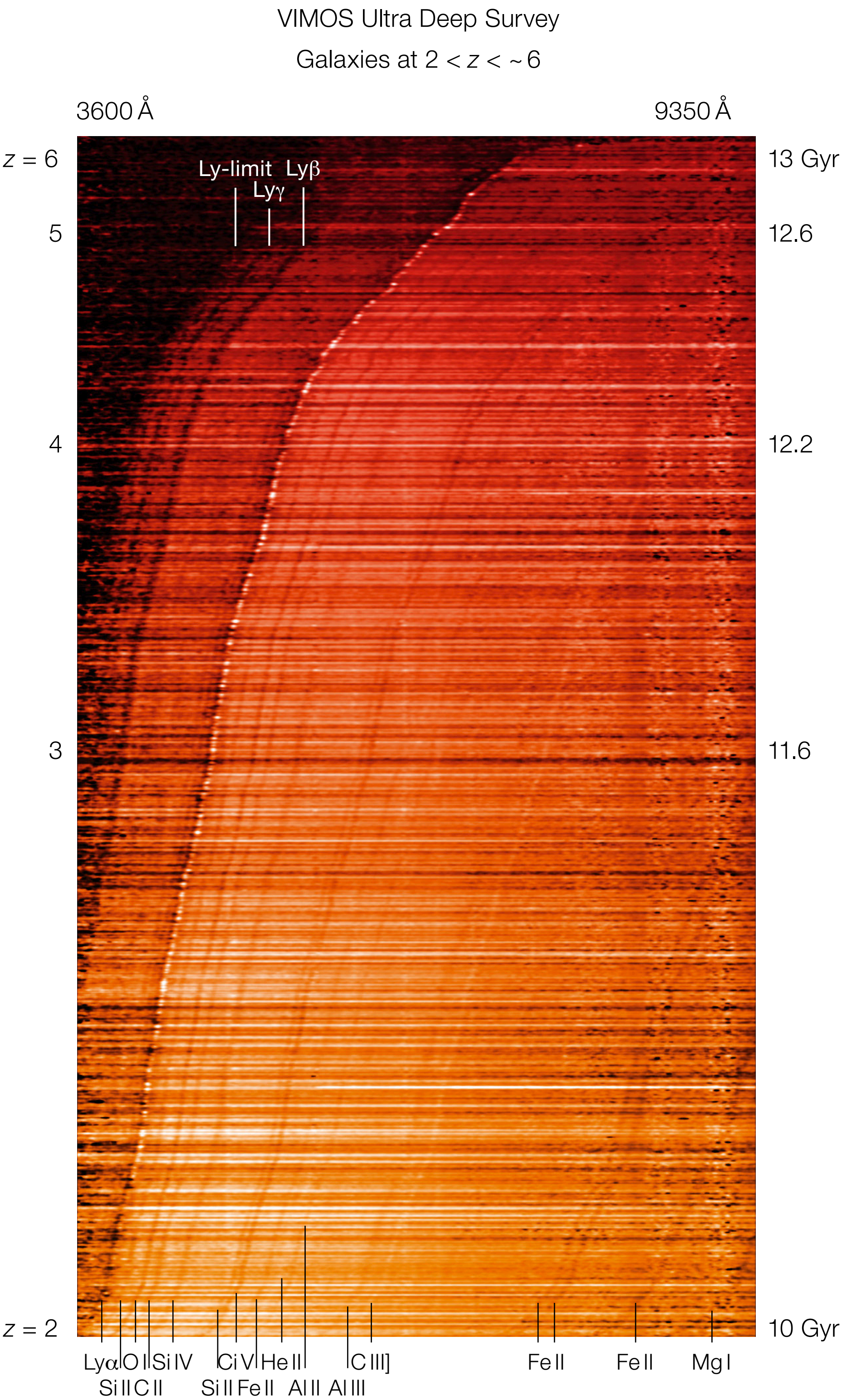


Figure 3. Stacked display of VUDS spectra between redshift 2 and ~ 6 (left-hand axis), covering between ~ 10 and 13 billion years back into the history of the Universe (right-hand axis). Prominent absorption and emission lines and the Lyman limit are indicated.

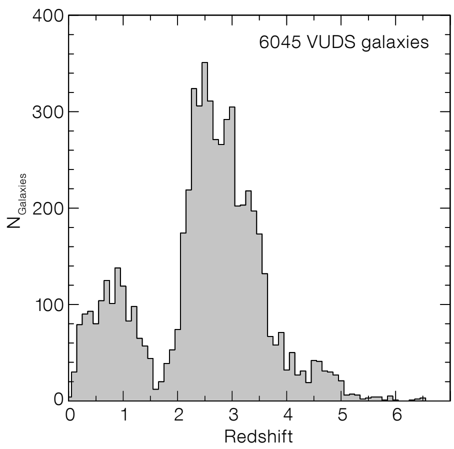


Figure 4. The redshift distribution of the current VUDS sample of 6045 galaxies is shown.

tify at the higher redshifts the hydrogen Lyman-β and Lyman-γ absorptions, and the Lyman limit at 912 Å.

The current redshift distribution of the VUDS sample is presented in Figure 4. The main sample is at $z > 2$, peaks at $z \sim 3$–4, and extends beyond $z = 6$, providing an unprecedented continuous redshift coverage at these early epochs (10–13 Gyr lookback time). Targets at $z < 2$ originate either from galaxies for which the photo-z pre-selection was ambiguous (e.g., through the degeneracy between the 4000 Å and 1215 Å continuum breaks when computing photometric redshifts, leading to a secondary peak at high redshift), and from a random sample selected down to $i_{AB} \leq 25$ mag added to the slit masks when space was available after the primary target selection. It quickly appeared that galaxies at $z \sim 3$ are quite often involved in major merging events. As reported in Tasca et al. (2014), the major pair fraction is about 20% at these redshifts, and these pairs should have merged into a more massive galaxy with approximately twice the mass by the peak of star formation rate at $z \sim 1.5$, indicating that merging is an important contributor to stellar mass assembly.

Several large overdensities have been unambiguously identified, particularly at redshifts 2.9 and 3.3 and could be protostructures, the high-redshift analogues to the rich clusters found at $z \sim 1$ and below (Cucciati et al., 2014; Lemaux et al., 2014). The properties of galaxies in

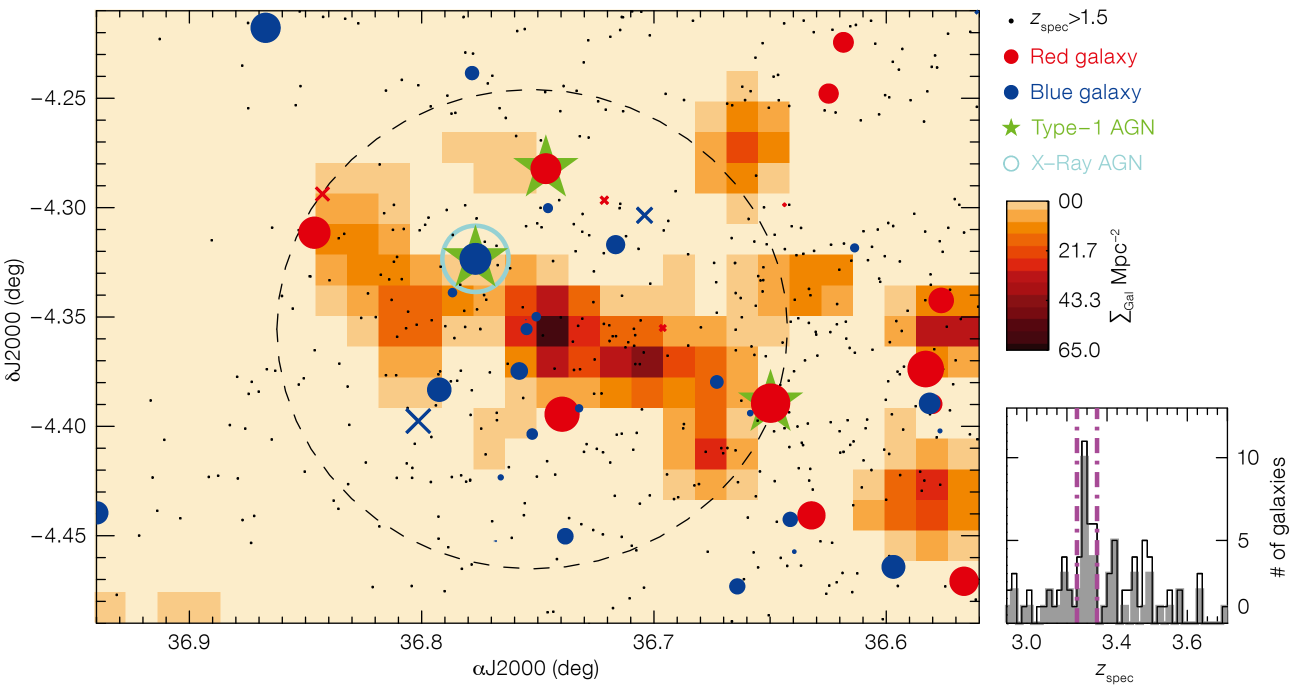


Figure 5. A rich $z = 3.3$ proto-cluster identified from the VUDS survey in the VVDS-02h/CFHTLS-D1 field is shown. The redshift distribution of the cluster members is shown in the lower right. The most reliable spectroscopic redshifts are represented as filled circles, the others as crosses. Red symbols indicate galaxies which appear at the expected location of the colour–magnitude red sequence observed in clusters at $z \sim 1$, assuming passive evolution from $z \sim 3.3$; blue symbols represent active star-forming galaxies. Three Type-I active galactic nuclei (AGN) are identified from broad emission lines in their spectra and are shown as stars; one of them is an X-ray source identified by XMM (circled blue). Other galaxies with spectroscopic redshifts $z > 1.5$ from VVDS and VUDS are indicated as small black dots. The surface density of all galaxies with photometric redshifts consistent with being in the structure is indicated by the colour-coded pixel map, and the dashed circle has a 3 h^{-1} Mpc radius.

these structures have been compared to field galaxies to try and identify signatures of the environment. In Figure 5 we show the strong overdensity in redshift and projected distribution for the $z = 3.3$ proto-cluster identified in the VVDS-02h/CFHTLS-D1 field. We found 27 cluster members identified with spectroscopic redshifts between 3.27 and 3.35. This proto-cluster is the richest identified so far at these redshifts.

The brightest and more massive galaxies at $z \sim 4$ show a diversity of properties, and we single out the more compact ones as the possible progenitors of the compact passive galaxies identified at $z \sim 2$ (Tasca et al., in prep). We follow the evolution of the fraction of strong Lyman-α emitters and find that it is increasing by a factor two from $z \sim 2$ to $z \sim 6$, providing an important reference on the post-reionisation era, necessary to understand what the main ionising sources in the early Universe are (Cassata et al., 2014). The knowledge of the redshift, combined with very deep *U*-band imaging data enables an accurate estimate of the Lyman escape fraction (Grazian et al., in prep.). Interestingly this survey turns up some of the faintest low-mass galaxies at $z \sim 1$ (Amorin et al., 2010). Several other investigations on the VUDS dataset are ongoing.

Next steps

With the observations recently completed, we are now processing the last data to assemble the final VUDS sample. Analyses requiring the full sample will then be carried out.

The VUDS survey provides an unprecedented sample of ~ 10 000 galaxies with spectra in one square degree to study early galaxy formation and evolution in the key redshift range $2 < z \sim 6+$. Analysis of the current data demonstrates that this sample is ideally suited to establish the volume-averaged properties of a complete sample of star-forming galaxies, which are the progenitors of the galaxy populations observed at later epochs. As a legacy, we will produce staged public releases of this survey.

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