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The VIMOS Public Extragalactic Redshift Survey (VIPERS): Science Highlights and Final Data Release

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The VIMOS Public Extragalactic Redshift Survey (VIPERS) released its final set of nearly 90 000 galaxy redshifts in November 2016, together with a series of science papers that range from the detailed evolution of galaxies over the past 8 Gyr to the growth rate and the power spectrum of cosmological structures measured at about half the Hubble time. These are the results of a map of the distribution of galaxies and their properties which is unprecedented in its combination of large volume and detailed sampling at $0.5 < z < 1.2$. In this article, the survey design and data properties are briefly summarised and an overview of the key scientific results published so far is provided. The VIPERS data, obtained within the framework of an ESO Large Programme over the equivalent of just under 55 nights at the Very Large Telescope, will remain the largest legacy of the VIMOS spectrograph and its still unsurpassed ability to reach target densities close to 10 000 spectra per square degree.

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Introduction

Galaxy redshift surveys represent one main pillar of the current "standard" Λ Cold Dark Matter (CDM) cosmological model, in combination with observations of distant supernovae and the Cosmic Microwave Background (see for example Planck Collaboration, 2016). The amplitude of galaxy clustering on different scales is a probe of both the initial conditions and the physical processes that governed the growth of cosmic fluctuations since the Big Bang. Surveys like the 2dF Galaxy Redshift Survey (Colless et al., 2001) and the Sloan Digital Sky Survey (SDSS) led this effort at the turn of the millennium. The SDSS in particular, in its subsequent incarnations the Luminous Red Galaxy (LRG) survey (Eisenstein et al., 2011) and, more recently, the Baryon Oscillation Spectroscopic Survey (BOSS: Alam et al., 2015), progressively increased the cosmological yield by maximising the sampled volume at the expense of restriction to specific, sparse sub-populations of galaxies. It was the original SDSS main sample of 10^6 objects with measured redshifts, however, that also allowed the properties of galaxies and their scaling relationships to be defined with exquisite accuracy, thanks to its broad selection function, good resolution spectra and multi-band imaging (York et al., 2003).

The VIPERS project was started in 2008 (Period 82), with the goal of extending such precise measurements of both structure and galaxy properties to redshifts approaching unity. VIPERS was built upon the experience of earlier VIsible Multi-Object Spectrograph (VIMOS) surveys, such as the VIMOS Very Deep Survey (VVDS: Le Fèvre et al., 2005) and *z*COSMOS (Lilly et al., 2009), pushing the data size, reduction techniques and management infrastructure to an even higher level (see Garilli et al., 2012 and Guzzo et al., 2014).

The VIPERS project

The way to achieve this goal has been to measure redshifts for galaxies with $i_{AB} < 22.5$ mag., further limited to redshift $z > 0.5$ through a robust *ugri* colour preselection. This nearly doubled the density of galaxies at $0.5 < z < 1.2$, compared to the pure magnitude-limited sample and was made possible by the accurate five-band photometry provided by the Canada France Hawaii Telescope Legacy Survey (CFHTLS) Wide data[1], on which VIPERS is based. The goal was to focus the effort at high redshifts by excluding the galaxies in the low-redshift volume that would not be competitive with the wide-angle samples already available. With an average sampling of 47 %, the VIPERS strategy has in fact yielded a spatial density close to $10^{-2}\ h^3$ Mpc^{-3} (where *h* is the normalised Hubble constant) at the peak of the survey selection function.

A volume comparable to that of the 2dF Galaxy Redshift Survey, i.e., close to $5 \times 10^7\ h^{-3}$ Mpc^3, was secured by tiling an overall footprint of 23.5 square degrees with a mosaic of 288 VIMOS pointings over the W1 and W4 CFHTLS fields (192 and 96 pointings, respectively), which are shown in Figure 1. 372 hours of multi-object spectroscopy (MOS) observations (45 min exposure per field), and 68.5 hours of pre-imaging were invested on VLT Unit Telescope 3 (Melipal), corresponding to a total of about 55 night-equivalents.

Working at low resolution between 5500 and 9500 Å with the LR-Red grism (resolution, $R = 210$) resulted in a typical redshift root mean square (rms) error of $s_z = 0.00054\ (1 + z)$. This value has been directly estimated from about 3000 double measurements available in the final sample (Scodeggio et al., 2017). A few examples of VIPERS spectra are presented in Figure 2.

The final Public Data Release 2 (PDR-2) includes 86 775 measured redshifts for galaxies in the statistical VIPERS target

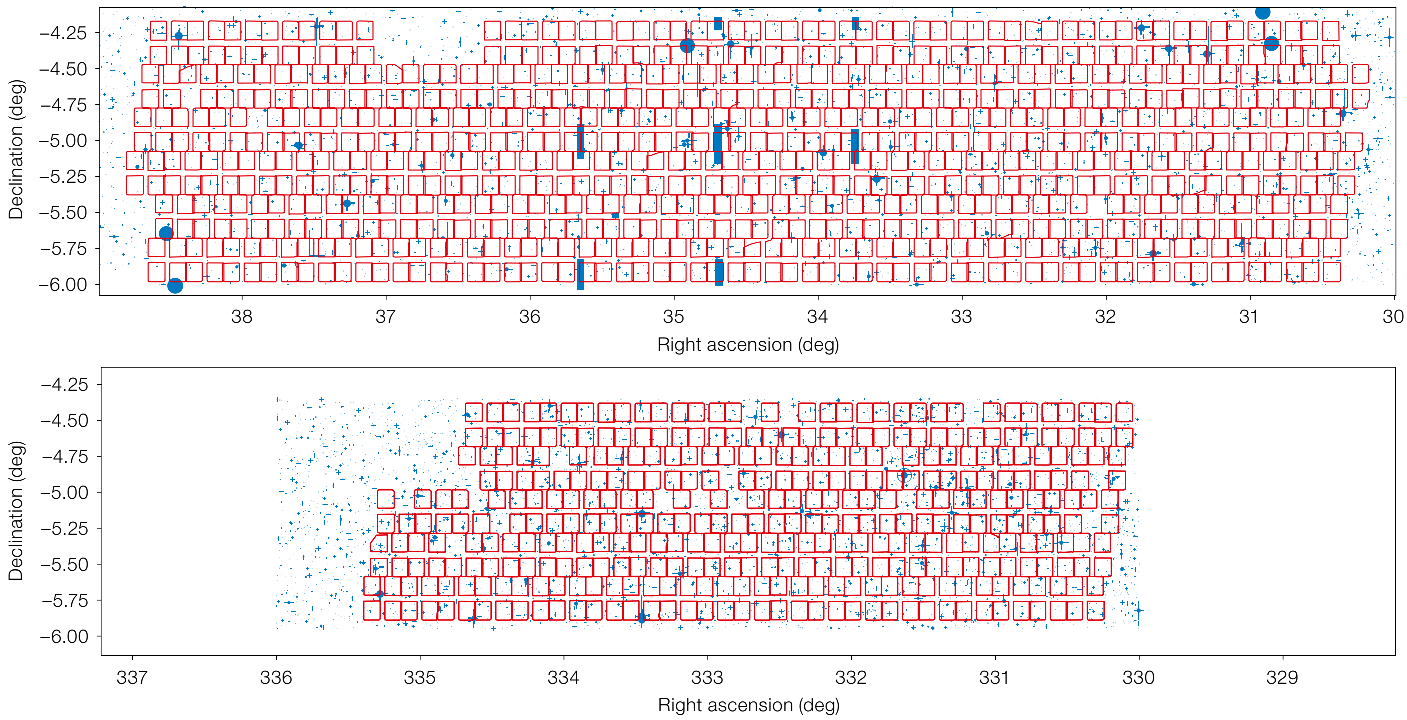

Figure 1. (Above) Layout of the 288 VIMOS pointings comprising the VIPERS survey, over the W1 (upper) and W4 (lower) fields of the CFHTLS photometric survey. From Scodeggio et al. (2017).

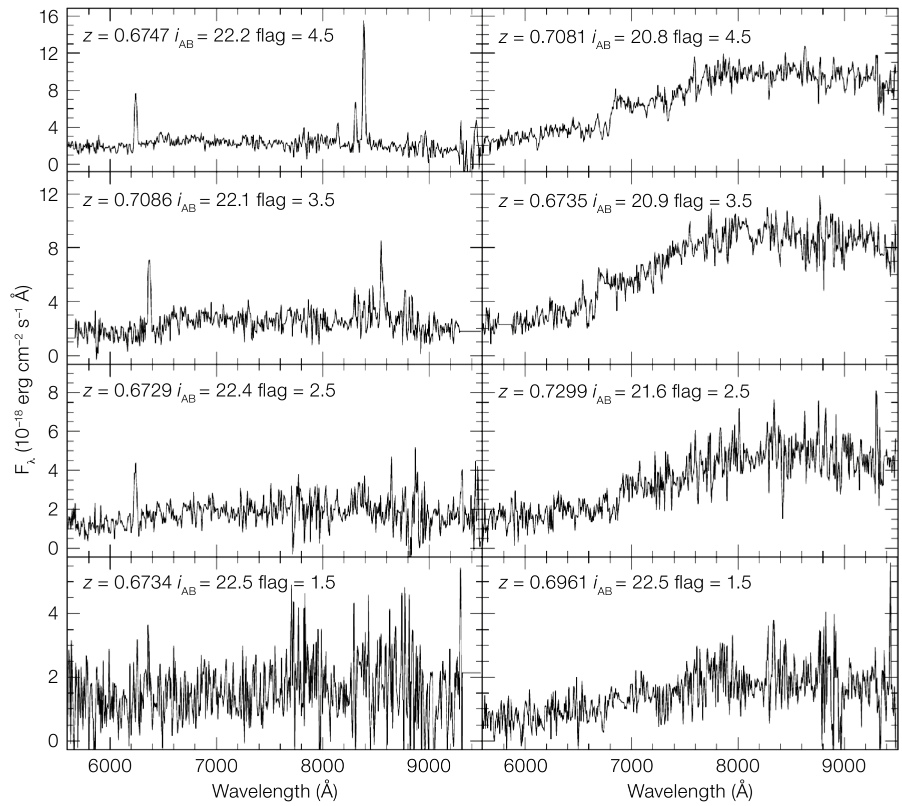

Figure 2. Examples of VIPERS spectra at z around 0.7, i.e. near the peak of the VIPERS redshift distribution. For different values of the redshift quality flags, examples of both a late-type and an early-type galaxy spectrum are shown. Note that objects with flag < 2 (bottom row) are not part of the statistical sample of highly reliable redshifts, as discussed in the text. The decimal part of the flag (0.5) indicates agreement with the photometric redshift. From Scodeggio et al. (2017).

sample. Of these, 78 586 (90.6 %) have been validated as highly reliable (confidence level > 96 %) and represent the sample to be used for statistical investigations. 2247 targets turned out to be stars, a very low residual contamination (2.5 %) that confirms the quality of the original star-galaxy separation (see appendix in Guzzo et al., 2014). More details of the PDR-2 sample can be found in Scodeggio et al. (2017); the survey construction and first data release were presented in Guzzo et al. (2014) and Garilli et al. (2014), respectively. The PDR-2 data are available both in the ESO Science Archive and, together with other complementary information, from the VIPERS website[2].

The combination of sampling and volume provided by VIPERS at these redshifts can be appreciated from the cone diagrams in Figure 3 and represents a unique feature among redshift surveys of the $z > 0.5$ Universe. In the same figure, galaxy positions are marked by circles of different size and colour, reflecting the actual luminosity and ultraviolet rest-frame

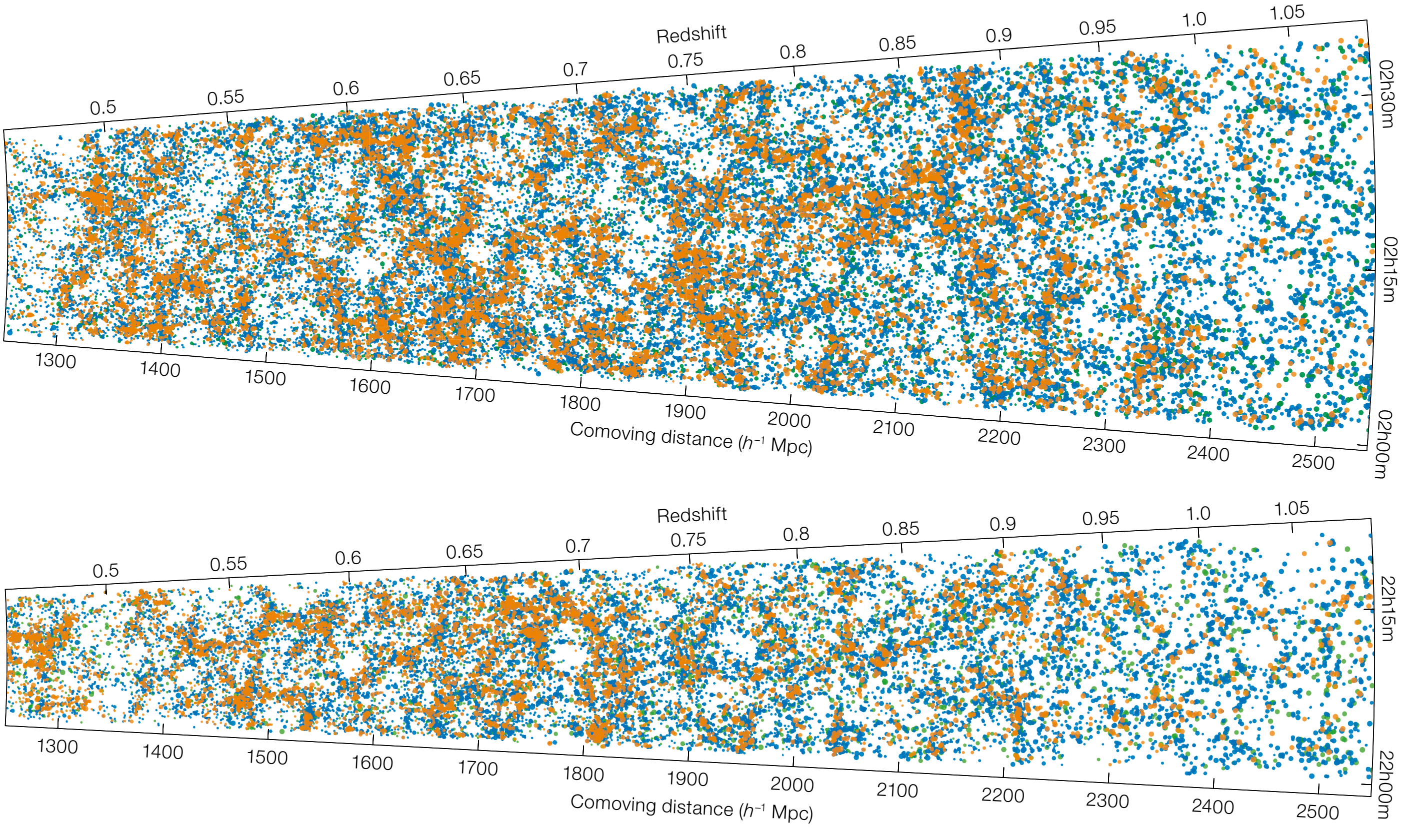

Figure 3. The detailed picture of the large-scale structure of the Universe at $0.45 < z < 1.1$, delivered by the VIPERS survey over the W1 and W4 CFHTLS fields (upper and lower, respectively). The opening angle corresponds to Right Ascension and the data are projected over ~ 2 degrees in declination. The size of each dot is proportional to the galaxy *B*-band luminosity and the dot colours reflect the intrinsic *U*-*B* colour of each galaxy. From Scodeggio et al. (2017).

colours of the galaxies, respectively, providing evidence of some of the unique information yielded by the VIPERS data. A first characterisation of such filamentary structure and its relation to galaxy properties is presented in Malavasi et al. (2017).

Straddling local surveys and Planck: a consistency test of the ΛCDM model

Figure 4 shows the estimate of the power spectrum of the galaxy distribution, $P(k)$, from four independent sub-samples of the VIPERS PDR-2 data over the redshift range $0.6 < z < 1.1$. At about half the Hubble time, this is the highest redshift where such a measure has been produced, straddling Planck and local measurements. This classic statistic contains information about the mean total density of matter in the Universe and the baryonic-to-dark matter fraction. The estimated posterior distribution of these quantities, obtained through a combined likelihood analysis of the four $P(k)$ estimates, is shown in Figure 5, compared to results from other surveys. Such a comparison provides an important test of the validity of the ΛCDM model. The position of the first acoustic peak measured by Planck constrains the combination $\Omega_M h^3$, while the galaxy power spectrum on large scales probes $\Omega_M h$. Therefore, although the error bars are currently large, the galaxy power spectrum measurements can help to resolve the tension between estimates of the Hubble constant made in the local Universe and at the last scattering surface.

Measuring the growth rate of structure with redshift-space distortions

Measurements of the growth rate of structure constitute a key observation to detect possible deviations from General Relativity (GR). A modification of the laws of gravity on large scales may represent an alternative to dark energy as an explanation of the apparent acceleration of cosmic expansion. Galaxy peculiar velocities that trace this growth manifest themselves by corrupting our redshift measurements: they add a Doppler component along the line of sight that distorts galaxy maps and the derived clustering measurements. Such redshift-space distortions (RSD: Kaiser, 1987; Peacock et al., 2001) produce a detectable anisotropy in the measured power spectrum, or its Fourier counterpart the two-point correlation function. This function can be estimated as a 2D map, $x(r_p,\pi)$, in which the distortion affects only the radial direction, i.e. the π axis, in Figure 6.

This figure shows a measurement based on the full VIPERS sample, which has been split into two redshift bins. The effect of RSD is evident in the flattening of $x(r_p,\pi)$ along the line of sight direction. This flattening is proportional to the growth rate of cosmic structure $f(z)$, which can be extracted through model fits and is characterised by gravity theory. In GR

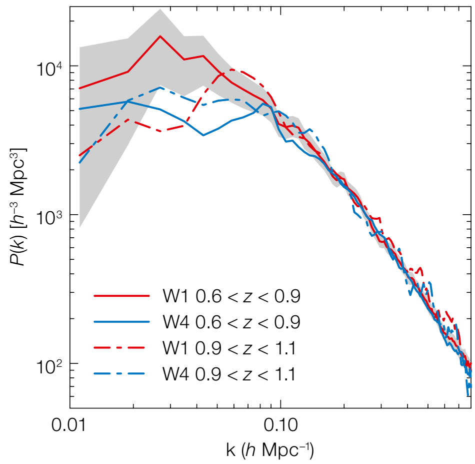

Figure 4. Estimates of the redshift-space power spectrum of the galaxy distribution $P(k)$ from four independent VIPERS subsamples (two redshift bins in each of W1 and W4 fields). A representative error corridor (shaded) is shown for one of the samples, and was obtained from the dispersion of a corresponding set of 150 mock catalogues. From Rota et al. (2017).

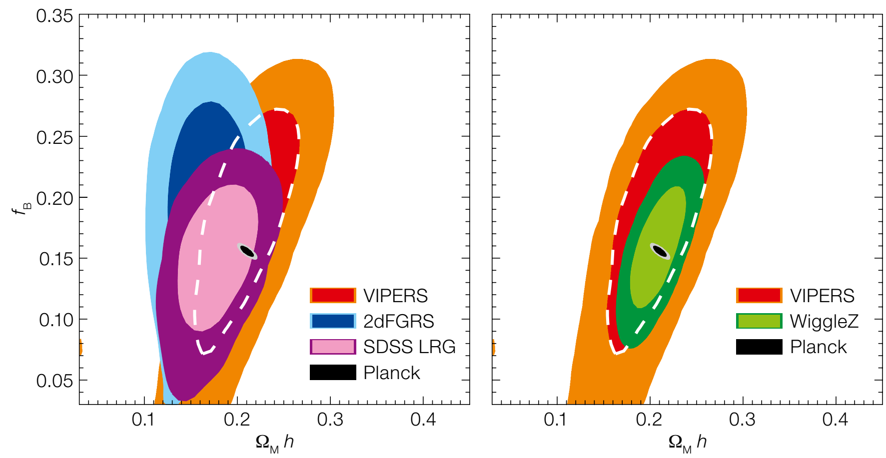

Figure 5. VIPERS constraints on the baryonic fraction f_B and the matter density parameter times the Hubble parameter $\Omega_M\,h$, obtained from a fit of a ΛCDM model with flat prior to the measured VIPERS power spectra. These are compared to similar measurements from other galaxy surveys and those from Planck observations. The left panel shows low-redshift constraints from the 2dFGRS at $z = 0.2$ and the SDSS LRG at $z = 0.35$. The right panel instead compares VIPERS to WiggleZ results at comparable redshift. See Rota et al. (2017) for details and references to the literature data.

we expect a growth rate $f(z) = [\Omega_M(z)]^{0.55}$. A more precise measurement of this quantity at z approaching unity was one of the original motivations for the VIPERS survey, following the early proof of concept from the VVDS-Wide data and its implications for the understanding of cosmic acceleration (Guzzo et al., 2008).

A first VIPERS estimate of the cosmic growth rate from RSD was obtained from the PDR-1 data (de la Torre et al., 2013).

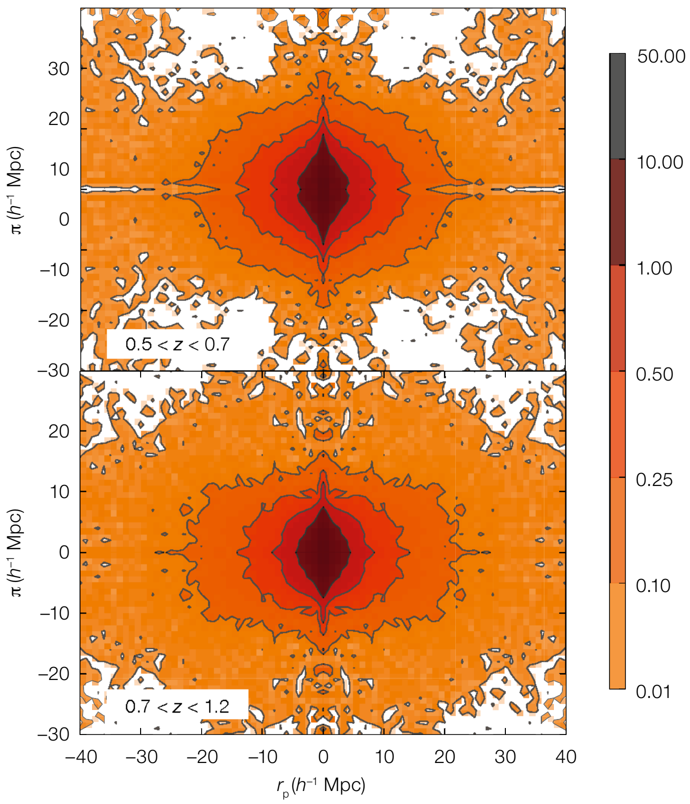

Figure 6. The redshift-space two-point correlation function $x(r_p,\pi)$ computed from the final VIPERS catalogue within two redshift bins, $0.5 < z < 0.7$ (upper) and $0.7 < z < 1.2$ (lower). The large-scale deviations from circular symmetry (i.e., oval shape) are the fingerprint of peculiar motions produced by the growth of cosmic structures. From de la Torre et al. (2017) and Pezzotta et al. (2017).

The richness of information and the broad selection function of VIPERS allow us to extend this result with the full data release by applying different estimation techniques to improve the systematics inherent in the analytic models (for example, de la Torre & Guzzo, 2012). Using the PDR-2 data, therefore, a series of RSD investigations using a variety of methods has been planned, some of which are still being completed. Pezzotta et al. (2017) present the measurement on the full sample with a focus on the required non-linear corrections and investigate in detail the systematic effects present in the VIPERS data.

In de la Torre et al. (2017), these investigations have been supplemented by measurements of galaxy-galaxy lensing performed on the parent photometric sample, the CFHTLS, allowing the growth rate of structure to be separated from the amplitude of matter fluctuations. While the RSD in the galaxy correlation function tell us how large-scale structures are collapsing, we are also looking at how the cosmic voids are expanding. A first catalogue of voids was built from PDR-1 (Micheletti et al., 2014) and then updated to PDR-2 in Hawken et al. (2017), where the void-galaxy cross-correlation has been fitted with a model to give a complementary measure of the growth of structure from the lowest density environments.

These different VIPERS estimates are shown in Figure 7, compared to similar measurements from the literature. The scatter in the different VIPERS values provides a direct indication of the level of systematic errors in the different techniques.

Two further RSD measurements using different galaxy tracers/techniques are in preparation. Both works aim at reducing the complex non-linear signal in the data, while keeping the modeling as simple as possible. The first shows that use of the luminous blue galaxies as tracers of RSD can sensibly reduce the impact of non-linearities (Mohammad et al., in preparation). In the second (Wilson et al., in preparation), the so-called "clipping" technique is used to linearise the density field before computing $P(k)$ and estimating redshift distortions.

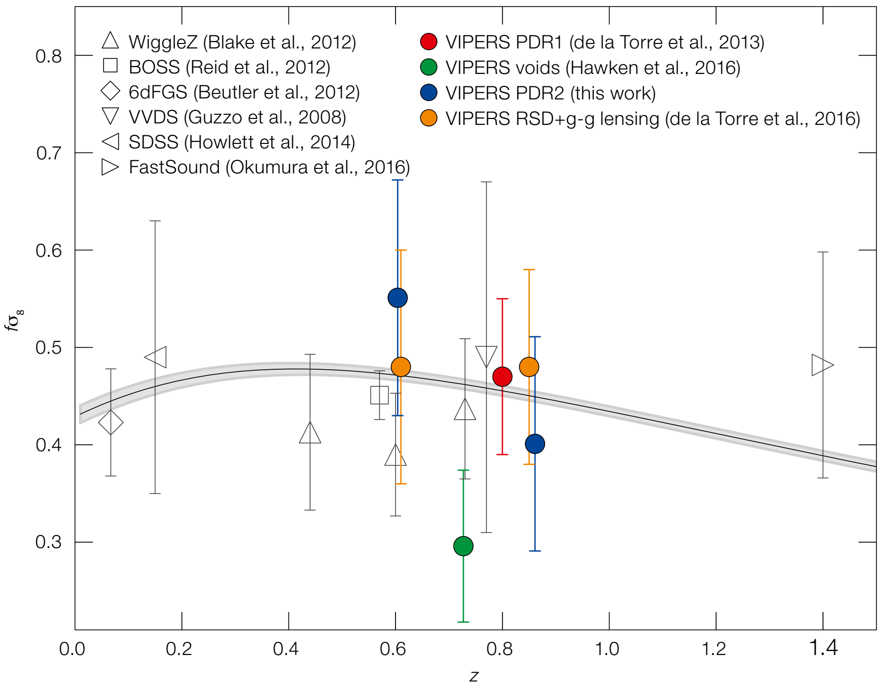

Figure 7. Published estimates of the growth rate of structure from redshift space distortions (RSD) in the VIPERS PDR-2 data, as summarised in Pezzotta et al. (2017). In addition to developing an improved modeling in this paper, RSD have been combined with galaxy-galaxy lensing (de la Torre et al. 2017) and also extracted in a completely independent way using galaxy outflows in cosmic voids (Hawken et al. 2017). These VIPERS measurements are compared to the earlier PDR-1 estimate and to a collection of similar results from the literature (see the journal paper for references). Two further analyses of RSD are currently in preparation (see text). The growth rate f is plotted in its conventional combination with the amplitude of clustering, $f\sigma_8$.

A detailed movie of galaxy transformations over the past 9 Gyr

The description of the physical properties of VIPERS galaxies is significantly enhanced by the availability of a series of ancillary photometric observations that complement the five high-quality bands of the CFHTLS. These include two ultraviolet bands (from the Galaxy Evolution Explorer [GALEX] satellite) and the near-infrared *K*-band (from the CFHT Wide-field InfraRed CAMera [WIRCAM]), which comprise the so-called VIPERS Multi-Lambda Survey (Moutard et al., 2016). These data are combined to perform reliable spectral energy distribution (SED) fits and, in turn, estimate luminosities, colours and stellar masses.

All these quantities, coupled to spectral information (like the amplitude of the 4000 Å break) and structural parameters from a morphological analysis (Krywult et al., 2017), have allowed us to look at the evolution of classic relationships observed at $z \sim 0$. In Haines et al. (2017), VIPERS and the SDSS have been combined to trace the evolution in redshift of the bimodality of galaxy properties, producing an unprecedentedly clear and coherent picture. This is visible in Figure 8 for the D4000 index, revealing the developing bimodality of galaxies into those whose optical light is still dominated by young stars (D4000 ~ 1.2; the blue cloud population) and the red sequence of old, passive galaxies (D4000 ~ 1.9). This figure shows the assembly of the red sequence, extending to ever lower masses, but also the decline of the blue cloud, its high-mass limit remarkably dropping by a factor of around 3 from $z \sim 1$ to today.

Important extra value has been added to VIPERS by the morphological analysis of the CFHTLS images, which allowed us to obtain reliable Sérsic indexes and effective radii for the majority of the objects in the catalogue (Krywult et al., 2017). Benefiting from this crucial information, in Gargiulo et al. (2017) we studied the evolution of the number density of massive (> 10^{11} $M_\odot$) passive galaxies (MPGs) and their stellar population ages, separating objects by surface stellar mass density. With an unprecedented sample of about 2000 such galaxies, VIPERS provides a novel picture of how the current population of massive red galaxies could have been formed (Figure 9). What emerges is that while compact objects in this class seem to be there from previous epochs and their number density does not change as a function of cosmic time, the less compact ones (left panel, green points) show instead a significant increase.

What is most interesting is that this observed increase quantitatively matches the parallel disappearance of star-forming objects within the same mass range, consistent with a scenario in which the least compact passive galaxies replace the massive star-forming ones, whose number density drops five-fold from $z = 1.0$ to $z = 0.5$, as shown in Figure 10 (from Haines et al., 2017). VIPERS provides statistically definitive evidence for the decline of this blue massive population between $z = 1$ and $z = 0.5$, consistent with the value measured at $z \sim 0$ from the SDSS. Comparison with the zCOSMOS-20K bright sample (Lilly et al. [2009] re-analysed by us in this work;

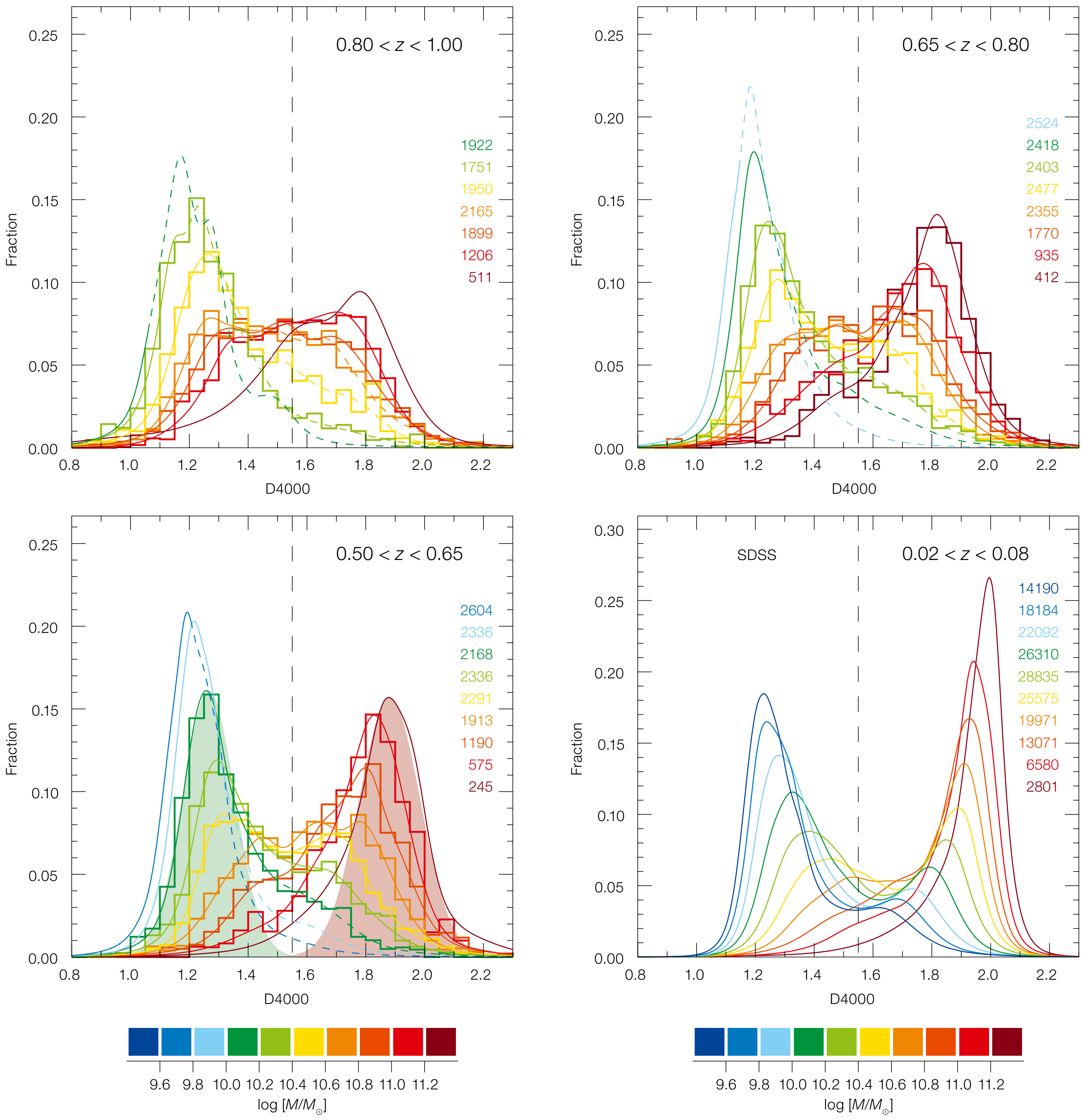

Figure 8. The evolution from $z = 1$ of the bimodal distribution of the 4000 Å break amplitude (D4000), for galaxies in four redshift ranges with different stellar masses (see colour bar), as traced by combining VIPERS with the local SDSS DR7 data. The *y*-axis scale indicates the fraction of galaxies within bins of width 0.05 in D4000. The coloured numbers down the right-hand side indicate the number of galaxies in each stellar mass bin. From Haines et al. (2017) where further details can be found.

purple points) clearly demonstrates that the gain in our understanding of these rare, massive galaxies is due to the much larger volumes covered by VIPERS (Haines et al., 2017).

These works, together with the earlier studies of the colour-magnitude diagram (Fritz et al., 2014) and the stellar mass function (Davidzon et al., 2013), give a remarkably consistent picture of how galaxies migrate from the blue to the red sequences in the colour-magnitude diagram as a function of redshift. The measurements suggest that dry mergers are not the main mechanism to produce

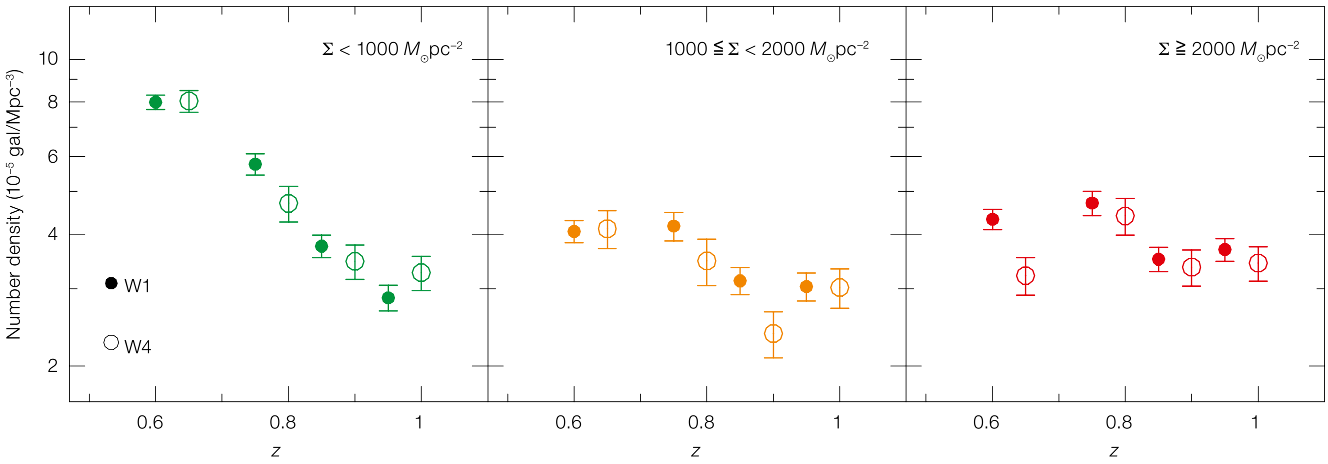

Figure 9. (Above) The evolution of the number density of massive ($M > 10^{11}$ $M_\odot$) passive galaxies split into different classes of mass surface density. VIPERS shows that the abundance of the most compact of such galaxies (right panel) does not change with cosmic time, while the least compact of these objects do increase in number. The solid and open circles are for the W1 and W4 fields respectively, demonstrating the robustness of the observed trend, a consequence of the large survey volume, allowing samples of rare populations with unprecedented statistics. From Gargiulo et al. (2017).

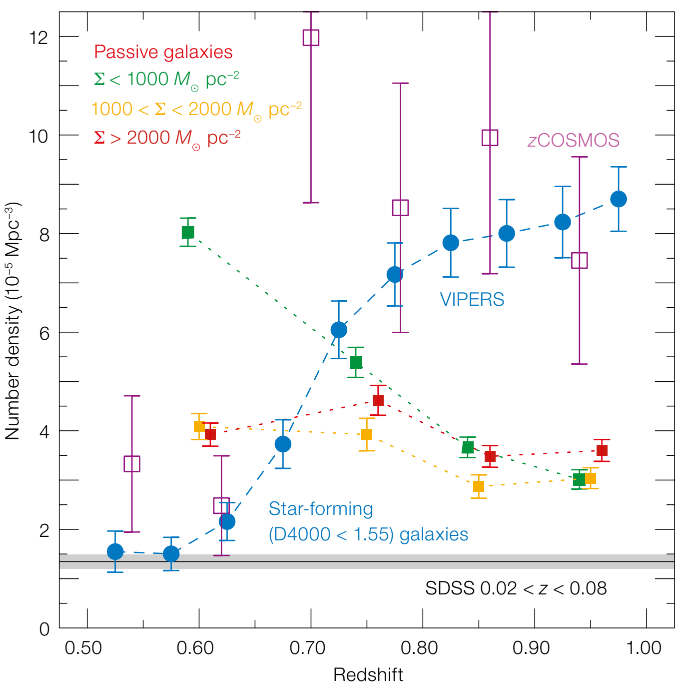

Figure 10. (Left) Same as Figure 9 but now for the evolution of the whole population of massive galaxies ($M_* > 10^{11}$ $M_\odot$), including star-forming objects (blue points). These are compared to passive objects, again split as a function of mass surface density. The least compact passive galaxies appear to replace the massive star-forming ones, whose number density drops five-fold from $z = 1.0$ to $z = 0.5$; see text for details. From Haines et al. (2017).

the population of massive passive galaxies seen at low redshifts. This scenario is supplemented by a parallel study of the star formation history of massive galaxies (Siudek et al., 2016), while in another work in preparation we are trying to derive constraints on the quenching mechanism (Manzoni et al., in preparation). At the same time, the fraction of star-forming *vs.* passive galaxies is quantified as a function of local density (Cucciati et al., 2017), revealing that it is higher in low-density regions and for the most massive galaxies at redshift approaching unity.

Conclusions

Redshift surveys remain at the forefront of cosmological research in the 21st century. Huge cosmology-focused surveys, such as Euclid[3] and the Dark Energy Spectroscopic Instrument (DESI[4]), are being prepared with the goal of collecting tens of millions of redshifts in the distant Universe. Such projects will typically deliver low signal-to-noise (SNR) spectra with limited information, often targeting specific sub-populations of galaxies. This implies that complementary spectroscopic surveys with broader scope and selection functions will be necessary to assess to high statistical precision the evolution of the physical properties of the full population (see for example the report of the ESO Working Group on the Future of Multi-Object Spectroscopy, Ellis et al., 2017). These surveys will be similar in spirit to VIPERS, involving a detailed sampling of large-scale structure over large volumes to determine accurate information on galaxy properties, possibly enhanced by higher spectral resolution.

VIPERS has opened the way to such accurate statistical studies at $z > 0.5$, refining the scaling relationships that were only hinted at so far, owing to the limited size of deep samples, and enabling novel ways to look at the data, self-consistently modelling the galaxy properties and the underlying density field through a Bayesian approach (Granett et al., 2015). This is a necessary path, if the goal is to understand the full growth history of galaxies and the cosmic web they inhabit, providing the crucial link between the cosmological dark-matter skeleton and the objects we use to trace it.

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Links

[1] CFHTLS: http://www.cfht.hawaii.edu/Science/CFHLS
[2] VIPERS web site: http://vipers.inaf.it
[3] Euclid satellite mission: http://sci.esa.int/euclid/
[4] DESI: http://desi.lbl.gov/

ESO/CFHT

A small region (42 × 41 arcminutes) of the Canada France Hawaii Telescope Legacy Survey W1 field, which was covered by VIPERS, centred at 2 h 27 m, −4° 24′, in a *u*-, *r*- and *z*-band colour composite. See Release eso1212.