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VIPERS: Unveiling the Combined Evolution of Galaxies and Large Scale Structure at $0.5 \le z \le 1.2$

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Abstract. The VIMOS Public Extragalactic Redshift Survey (VIPERS) is the largest redshift survey ever conducted with the ESO telescopes. It has used the Very Large Telescope to collect nearly 100,000 redshifts from the general galaxy population at $0.5 \le z \le 1.2$. With a combination of volume and sampling density that is unique for these redshifts, VIPERS allows statistical measurements of galaxy clustering and related cosmological quantities to be obtained on an equal footing with classic results from local redshift surveys. At the same time, the broad selection function and ancillary photometric data provide detailed information on the physical properties of the galaxy population and their relation to large-scale structure. This talk presents an overview of the results obtained so far, mostly based on the $\sim 55,000$ galaxies forming the first public data release (PDR-1).

1. VIPERS design and motivation

VIPERS - the VIMOS Public Extragalactic Redshift Survey - was conceived with a focus on galaxy clustering and the growth rate of structures at $z \sim 0.5 - 1.2$, but enabling at the same time broader studies of the statistical properties of galaxies and their evolution, similarly to 2dFGRS and SDSS at $z \sim 0.1$. Such an ambitious aim was achievable thanks to the unique capabilities of the VIMOS multi-object spectrograph at the ESO VLT together with a well planned survey strategy and a successful Large Program at ESO, with a total allocated telescope time of ~ 440 hours.

Galaxy targets were selected from the W1 and W4 fields of the Canada–France–Hawaii Telescope Legacy Survey Wide catalog (CFHTLS–Wide), which provides high-quality photometry in five bands (*ugriz*).[1] The survey area is tiled with a mosaic of 288 VIMOS pointings, producing the geometry shown schematically in Fig. 1. The target sample is magnitude-limited to $i_{AB} = 22.5$, and further constrained to $z > 0.5$ through a thoroughly-tested *ugri* color pre-selection (see Guzzo et al. 2014, Garilli et al. 2014). Discarding the $z < 0.5$ population allows to nearly double the sampling density within the high-redshift volume of interest, reaching an average sampling of the parent population of $\sim 40\%$ over a volume of $\sim 5 \times 10^7\ h^{-3}$ Mpc^3.

As of May 2015, more than 90,000 redshifts have been validated and made ready for the final investigations. These include among their main goals:

[1] http://terapix.iap.fr/rubrique.php?id_rubrique=252

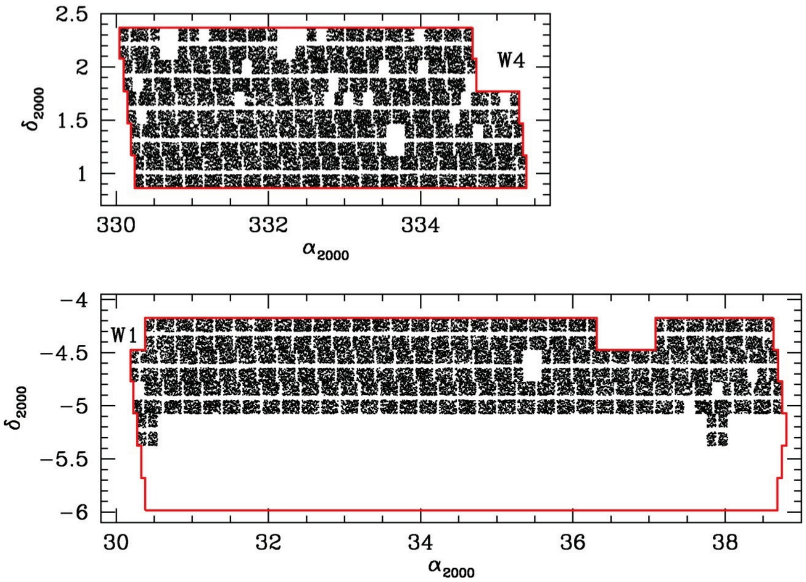

Figure 1. The (red) outline displays the mosaic of 288 VIMOS pointings that cover the VIPERS survey area. At the date of writing this paper (May 2015) all fields have been observed, reduced and validated. Black areas show the subset of spectroscopically observed pointings available to the whole community in PDR-1.

- To measure precisely galaxy clustering up to scales $\sim 100\,h^{-1}$ Mpc at $z \sim 1$, and obtain cosmological constraints from the power spectrum and correlation function at an epoch when the Universe was about half its current age.
- To measure the growth of structure through Redshift Space Distortions out to $z \sim 1$, possibly using different populations of tracers, as allowed by the broad selection function.
- To characterize the density field at such redshifts, tracing the evolution and non-linearity of galaxy bias and identifying non-linear structures as groups and clusters.
- To measure precisely statistical properties of the galaxy population (luminosity, color, spectral energy distribution, stellar mass) and their relationship with large-scale structure.

The simplest, yet striking result of VIPERS can be appreciated in the the map of the galaxy distribution from the first epoch data release (PDR-1), shown in Fig. 2. The comparison of the two VIPERS wedges to the data of the local Universe evidences the remarkable combination of volume and dynamical range (in terms of scales sampled), which is a unique achievement of VIPERS at these redshifts. The two slices are about 2 degrees thick and display with great detail the cellular structure with which we have become familiar from local surveys and numerical simulations, but at an epoch when the Universe was about half its current age and for which no such detailed and extended map existed so far.

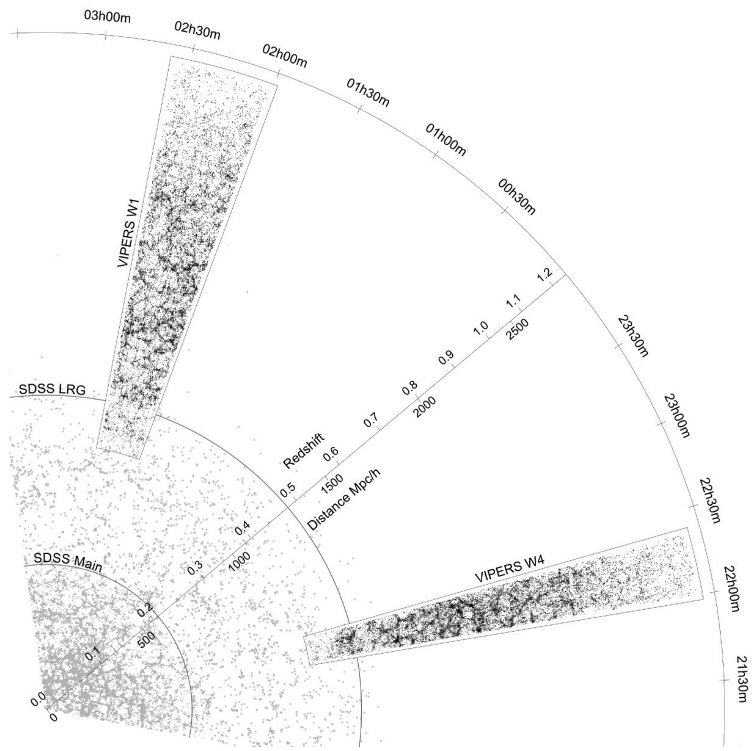

Figure 2. The large-scale distribution of galaxies within the two VIPERS survey volumes, integrated over the declination direction (1.84 and 1.54 degrees thick, respectively for W1 and W4). The new data are matched to the SDSS main and LRG samples at lower redshift (for which a 4-degree-thick slice is shown). Note how VIPERS pushes into a new epoch, with detailed sampling on all scales, similarly to SDSS Main below $z \sim 0.2$. Conversely, sparse samples like the SDSS LRG are excellent statistical probes of the largest scales, but (by design) fail to register the details of the underlying non-linear structure.

2. Redshift-space clustering and the growth of structure

One of the original goals of VIPERS is measurement of the amplitude and anisotropy of the redshift-space two-point correlation function at redshift approaching unity. The projected function $w_p(r_p)$ from the PDR-1 catalog is shown in the left panel of Fig. 3 (de la Torre et al. 2013), where the fingerprint of RSD is evident in the flattening of $\xi(r_p, \pi)$ along the line-of-sight direction. As we discuss in detail in that paper, crucial for this measurement is an accurate knowledge of several ancillary pieces of information from the survey, such as the photometric and spectroscopic angular selection masks, the target sampling rate and the spectroscopic success rate. These allow us to assign a weight to every observed galaxy in the survey to correct for the overall incompleteness introduced by the different observational limitations.

Modeling $\xi(r_p, \pi)$, we have obtained a first estimate of the mean growth rate of structure at an effective redshift $z = 0.8$, $f\sigma_8 = 0.47 \pm 0.08$ (de la Torre et al. 2013). Our measurement, conventionally expressed as the product of the growth rate f with

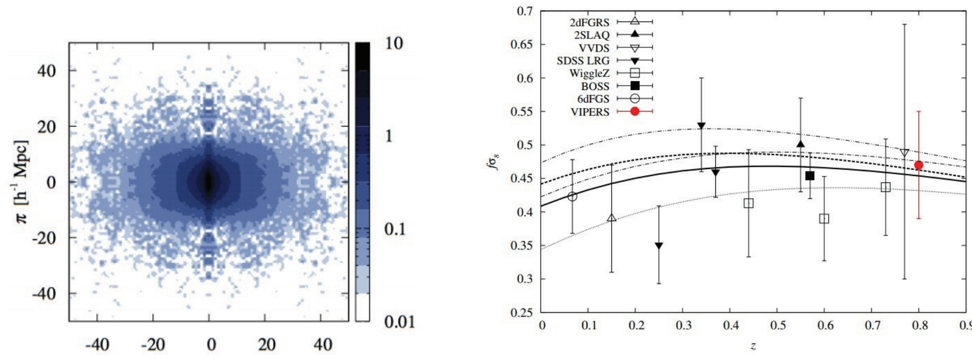

Figure 3. Left panel: $\xi(r_p, \pi)$ showing the well-defined signature of linear redshift distortions, i.e. the oval shape of the contours. Right panel: The growth rate of structure at $z \sim 0.8$ expressed as the product $f\sigma_8$ and compared to a compilation of recent measurements. Both results have been obtained from VIPERS PDR-1 data, see de la Torre et al. (2013) for a detailed discussion.

the *rms* amplitude of matter fluctuations, σ_8, is compared to a selection of literature results and models in right panel of Fig. 3, where the models have been self-consistently normalized to the Planck estimate of σ_8. The VIPERS value is in agreement with the predictions of general relativity within the current error bars.

A full review of the main VIPERS cosmological results may be found in Guzzo et al. (2015), and include an estimate of evolution and non-linearity of galaxy bias up to $z \sim 1$ (Di Porto et al. 2015), an analysis of the dependence of galaxy clustering on the luminosity and stellar mass (Marulli et al., 2013), measurements of two-, three- and four-point correlation functions and the normalized skewness S_{3g} and kurtosis S_{4g} (Cappi et al., 2015).

3. Galaxy evolution within the cosmic web: voids, filaments and groups

We estimated the galaxy stellar mass function at several epochs between $z \sim 0.5$ and 1.3, with special emphasis on its high-mass tail, which using VIPERS PDR-1 includes already a significant number of galaxies that are usually too rare to detect with any of the past spectroscopic surveys (Davidzon et al. 2013). Our results show that at the epochs sampled by VIPERS, massive galaxies had already assembled most of their stellar mass.

When applying a photometric classification in the $(U-V)$ rest-frame color to compute the mass function of blue and red galaxies, we find evidence for the evolution of their contribution to the total number density budget: the transition mass above which red galaxies dominate is found to be about $10^{10.4} M_\odot$ at $z \sim 0.55$ and evolves proportional to $(1 + z)^3$. Interestingly in the highest mass bin, while red galaxies show only a mild evolution with redshift, when compared to objects at lower masses, there seems to be an indication of the presence of a population of similarly massive blue galaxies, which are no longer detectable below z = 0.7 (Davidzon et al., 2013). A complementary

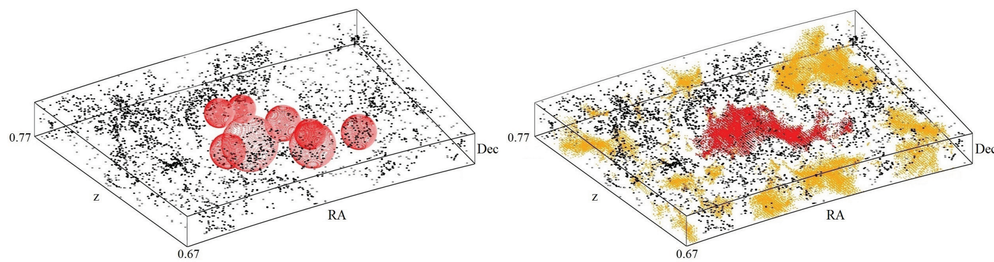

Figure 4. The left-hand panel shows a region of the VIPERS PDR-1 W1 volume, including the largest maximal sphere in the VIPERS voids catalog, possessing a radius of 31 h^{-1} Mpc, together with other six maximal spheres. The right-hand panel shows in dark gray (red) the centers of the overlapping significant spheres that make up the void, while other void regions within this volume of the survey are shown in light gray (orange). The gray and black *points* in both panels are the isolated and un-isolated galaxies, respectively (see Micheletti et al. 2014 for details).

and thorough study of the evolution of the Color-Magnitude diagram and the galaxy luminosity function over the same range is presented in Fritz et al. (2014).

In parallel, voids have been identified in VIPERS PDR-1 data over the range $0.55 < z < 0.9$, using a search method based upon the identification of empty spheres that fit between galaxies, as shown in Fig. 4. This is a novel search at such redshifts and allows us to characterize cosmic voids despite the presence of complex survey boundaries and internal gaps. The void size distribution and the void-galaxy correlation function are found to agree well with the equivalent functions in Λ-CDM mock catalogs. Details can be found in Micheletti et al. (2014). The anisotropy of the void-galaxy cross correlation function indicates that galaxies are outflowing from voids. Modeling this effect can help to constrain the growth rate of structure and is the subject of ongoing analysis.

Now that the survey has been completed and the final data-set of more that 90,000 redshifts is being made ready for the analysis, we will finalize the voids catalog and progress to identify groups - using well known FoF and Voronoi algorithms - and filaments in the whole survey. VIPERS survey large volume will enable us to detect rich groups up to $z \sim 1$, while we plan to use a novel technique based on the algorithm Disperse (Sousbie 2011) to identify filamentary structures connecting denser regions in the Universe.

Thanks to VIPERS we will be able to trace the detailed grand-design of cosmic structures on scales yet unexplored with such sharp spectroscopic resolution, and to link statistical properties of galaxies with their precise location within the cosmic web.

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Pollo, S. Rota, H. Schlagenhaufer, M. Scodeggio, A. Solarz, L. A. M. Tasca, R. Tojeiro, D. Vergani, M. Wolk, G. Zamorani, A. Zanichelli (see `http://vipers.inaf.it`).

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