VIPERS: in search for the solution of the riddle of dark energy (and many others)

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We present the "VIMOS Public Extragalactic Redshift Survey" (VIPERS). We discuss the present status of the survey, the data which are already open to the public, and review first scientific results of the project.

1 Introduction

The "VIMOS Public Extragalactic Redshift Survey" (VIPERS) is an ongoing ESO Large Program. Its main goal is to provide a detailed map of the the spatial distribution of galaxies over a very large volume of the $z \sim 1$ Universe. VIPERS makes use of the multispectrograph VIMOS, which is installed at Melipal - one of the Very Large Telescope (VLT) units on Mount Paranal in Chile. VIPERS is aiming at measuring 100,000 redshifts for galaxies in the redshift range $0.5 < z < 1.2$ and red magnitude range $17.5 < I_{AB} < 22.5$. The survey at the end will cover an area of 24 square degrees on the sky, in only two separate fields. These fields are located inside two fields of the Canada-France-Hawaii Telescope Legacy Survey Wide catalogue (CFHTLS-Wide) which allowed to base the selection of the galaxy target sample on the 5-band CFHTLS photometric data.

The pre-selection was first based on the combination of the measurement of the object's apparent size and the Spectral Energy Distribution (SED) fitting to eliminate stars, and then on a robust color-based pre-selection in order to eliminate low-z galaxies. A resultant sample proved to be 98% complete at $z > 0.6$, with a contamination of 5% of low-redshift interlopers and 3.22% stars. A small number of AGN candidates was also added to the target sample. This pre-selection allowed for a very high - above 40% - target sampling rate of the resultant catalogue (Guzzo et al., 2014, see also http://vipers.inaf.it).

At redshift $z \sim 1$, a large covered area together with a high sampling rate make VIPERS unique among galaxy surveys. When completed, it will probe a volume of $5 * 10^7\ h^{-3}$ Mpc^3 (assuming Hubble constant $H_0 = 100h$ km/s/Mpc) which will make VIPERS a statistically worthy equivalent of the local ($z \leq 0.2$) galaxy surveys.

The main scientific goal of VIPERS is the establishment of cosmological parameters and measurements of the large-scale structure at an epoch when the Universe was about half of its today's age. At the same time, the survey will allow to measure physical properties of galaxies with unprecedented statistical accuracy at these redshifts, and relate galaxy evolution with the evolution of the cosmic structure itself.

Until now, more than 70,000 targets were observed, more than 75% of the planned area covered by observations, and more than 66,00 redshifts measured (the difference is related to the fact that for a small percentage of spectra a sufficiently secure redshift measurement is not possible). Further observations are on-going. In the beginning of 2013 the first scientific results, based on more than a half of planned final data, were published. The submission of the scientific articles was followed by the public release of the redshifts used to obtained these results.

2 Publicly released data: VIPERS PD-1

On 4 October 2013 the VIPERS team publicly released the first spectroscopic measurements for 57,204 objects, including 54,756 galaxies and 2,448 stars. The related data files, separately for fields W1 and W4, can be freely downloaded from the following link: http://vipers.inaf.it/rel-pdr1.html. They are accompanied by the survey masks and weights, as well as photometric ancillary data from the CFHTLS, which are necessary, e.g., for clustering measurements. A map of cone W1 and redshift histograms of the released data from both fields are presented in Figure 1. The public release of the related spectra is foreseen in 2014. Detailed information on the data can be found in Garilli et al. (2014) and Guzzo et al. (2014).

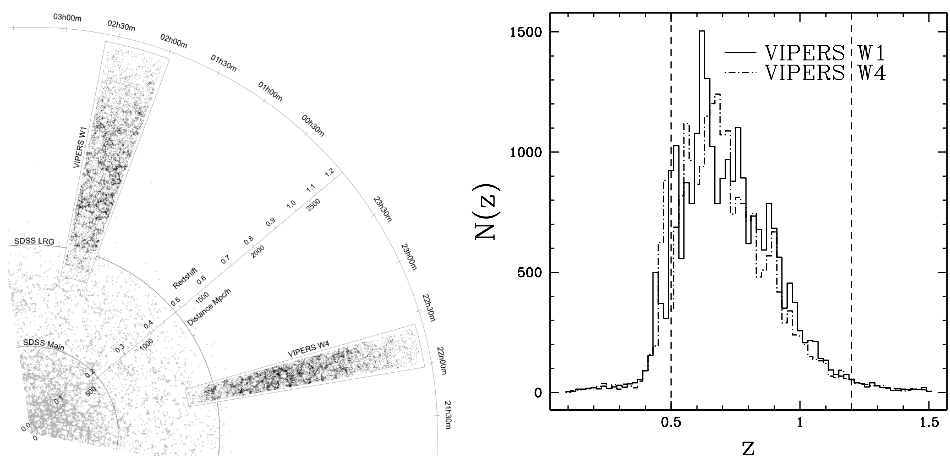

Fig. 1: Left: Depth (in redshift and comoving distance, computed for the ΛCDM model with the value of $\Omega_{\Lambda,0} = 0.7$) of VIPERS cones in both fields: W1 and W2, compared to the SDSS (from VIPERS public materials). Right: Redshift histogram for galaxies with reliable redshift measurements for both VIPERS fields.

3 Epoch 1 Results

3.1 Source classification

Dealing with huge databases of present-day sky surveys, we encounter a number of statistical problems. One of them is the classification of sources and selection of certain classes of objects based on the existing, usually incomplete, information. As the first attempt to deal "blindly" with VIPERS data Marchetti et al. (2013) applied the principal component analysis (PCA) to classify and repair galaxy spectra.

Małek et al. (2013) applied the support vector machine (SVM) based method to design a classifier able to distinguish galaxies, active galactic nuclei (AGNs) and stars from the photometric data only. As explained above, the pre-selection techniques used in VIPERS are effective but not perfect: a certain number of stars escapes a pre-selection, and the distinction between AGNs, stars, and galaxies always poses a tricky problem. As demonstrated in the left panel of Figure 2, all these classes overlap in a large part in classical color-color diagrams. SVM-based classifier operates in a multi-color (in general, multi-parameter space) and allows to draw a hyperplane dividing all three populations in these multidimensional space. Małek et al. (2013) has demonstrated a very good performance of the so-obtained classifier; as shown in the right panel of Figure 2, a classifier using optical colors only has a performance above 90% in selecting galaxies brighter than $i' \sim 21$ and above 85% for fainter ones; the performance of the classifier can be significantly (above 95%) enhanced by adding near-infrared data to the color space.

This kind of classifiers can be used for pre-selecting targets for the future, yet larger and more complex surveys. After fine-tuning, they can also be used for selecting certain classes of sources, e.g. narrow-line AGNs, from VIPERS (or other surveys) for the subsequent more detailed analysis (Małek et al. 2014, in prep.).

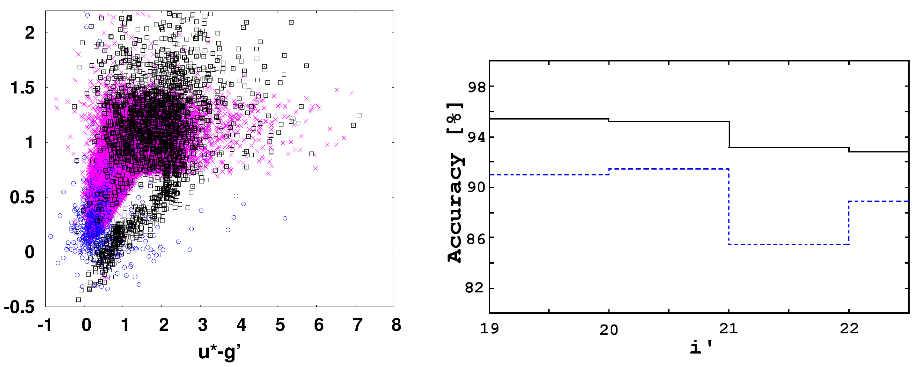

Fig. 2: Left: Representative color–color plot for VIPERS galaxies (pink x-es), AGNs (blue circles) and stars (open black squares) with redshift security level $\geq$ 99%, and with the apparent magnitude $19 < i' < 22.5$. Right: Accuracy of optical (blue dashed line) and optical+NIR (black solid line) SVM-based classifiers for VIPERS galaxies, as a function of i' apparent magnitude. See Małek et al. (2013) for details.

3.2 Galaxy clustering and what is behind

The central topic of VIPERS science is the determination of cosmological parameters and the recovery of the cosmic large scale structure at $z \sim 1$. The structure emerging from the first-epoch observations, presented in Figure 3, looks strikingly similar to today's one: there are clear overdensities (i.e. clusters and groups of galaxies), voids, walls and filaments in between. Moreover, the location of galaxies in this cosmic web is strongly correlated with their rest-frame colors: very similarly to what is observed in the local Universe, red galaxies are located in the "nodes" of the cosmic net - the strongest overdensities, while the blue objects are mostly field galaxies. The intermediate green population is located in the areas of the intermediate densities.

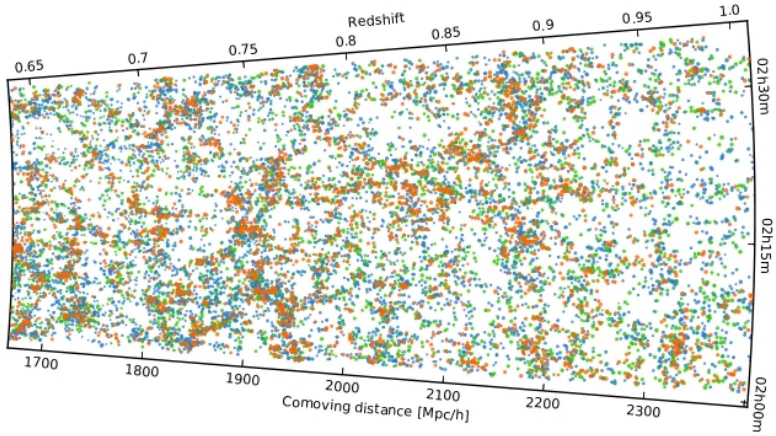

Fig. 3: VIPERS galaxies in the field W1 and their "physical" colors: blue star-forming galaxies are marked in blue, red passive galaxies – in red, and the intermediate green valley population is marked by green dots (VIPERS public materials).

This picture seen "by eye" can be, however, deceptive. The comparison between today's large scale structure and those revealed by VIPERS, which can allow for cosmological conclusions, requires deeper statistical analysis and taking into account all the observational biases and incompletnesses, including geometrical biases (related to the photometric and spectroscopic masks, as well as the target selection procedure which leaves a pattern of spectroscopic slits in the data), color-based selection, effects of apparent magnitude limits (which turn into different rest-frame magnitude limits for different z) and so on. These effects superimpose on the actual physical effects: the evolution of the large scale structure on one side, and the evolution of galaxies themselves on the other side. Since we try to probe the evolution of the large scale structure probing the evolving - in the environmentally dependent way - population of galaxies, the problem becomes multifold.

Taking these biases into account, de la Torre et al. (2013) provided a first measurement of the galaxy clustering and redshift space distortions from VIPERS, and recovered from them growth rate of structure at $z = 0.8$: $f_{\sigma_8} = 0.47 \pm 0.08$. This value is consistent with the predictions of standard cosmological models based on Einstein gravity; the standard cosmological constant Λ remains the most likely interpretation of the accelerated expansion of the Universe. However, this measurement alone does not yet discriminate between different gravity models and does not rule out all the alternatives. More accurate theoretical modelling of the redshift space distortions will be necessary to reduce the uncertainties.

Marulli et al. (2013) measured the two-point correlation function for VIPERS galaxies as a function of the B-band absolute magnitude, stellar mass, and redshift. It was confirmed that the relation between the luminosity and stellar mass in $z \sim 1$

galaxies is in fact quite complex; some of the differences between clustering properties of luminosity-selected and mass-selected populations might be related to processes occurring in galaxies mostly at high z.

An interesting attempt to constrain the cosmological model through a measurement of the galaxy clustering ratio $\eta_{g,R}$ was presented by Bel et al. (2014). Combining two measurements at $z \sim 0.3$ and $z \sim 0.9$ allowed for a very precise estimate of the density parameter $\Omega_{m,0} = 0.274 \pm 0.017$, well consistent with other other cosmological probes, but obtained by an independent method.

Another way to probe large scale structure properties is the direct measurement of the galaxy density field. Cucciati et al. (2014) tested seven different methods to recover the VIPERS density field and concluded that the performance of all these methods is similar. Results do not differ significantly, and methods with the smallest random errors can be more affected by systematic errors than others and vice versa. Thus, it is not possible to chose the clearly best method. However, in spite of systematic effects, it should be possible to reconstruct the lowest and highest density environments on scales $\sim 5h^{-1}$ Mpc at redshifts and volumes covered by the VIPERS.

3.3 Galaxy properties and their evolution

The reliability of the large scale structure measurements at high z strongly depends on how well we understand the evolution of galaxy properties and its environemental dependence. Using VIPERS data, Davidzon et al. (2013) presented the evolution of the galaxy stellar mass function from $z = 1.3$ to $z = 0.5$, finding that high mass red galaxies evolve more slowly with redshift, when compared to lower mass red galaxies. Additionally, a population of similarly massive blue galaxies was found, and such galaxies are no longer detectable below $z = 0.7$. These results may suggest a mass-dependent quenching of star formation in galaxies at $z \sim 1$.

Fritz et al. (2014) analysed the evolution of the colour–magnitude relation and luminosity function in VIPERS and found that most massive red galaxies have apparently experienced a sharp quenching of star formation at $z \sim 1$, and merging played only a limited role in their evolution. In contrast, less massive red galaxies experienced a mix of the truncation of star formation and minor mergers which together led to the formation of low- and intermediate-mass red galaxies observed at later epochs.

In the local Universe, galaxies are classified primarily according to their shapes (elliptical vs spiral galaxies). Moving to higher z, determination of galaxy morphologies from images becomes more difficult and most classifications rely rather on galaxy colors. Krywult et al. 2014 (in prep.; see also Krywult et al. 2014, in this issue) used CFHTLS images of VIPERS $z \sim 1$ galaxies to fit their Sérsic profiles and select spheroidal, disk-like and immediate populations using the Sérsic index n. So-defined galaxy types are well consistent with color-based types, and preliminary results indicate that the sizes and shapes of the red population evolved after $z \sim 1$ much less than those of the blue population, and that the strength of this effect depends on galaxy sizes and stellar masses.

Next works should allow to reveal the links between the evolution of the galaxies and cosmic structure with an even greater accuracy.

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