VIPERS: How luminous galaxies trace the dark Universe?

Agnieszka Pollo[1·2], Katarzyna Małek[1], Janusz Krywult[3], Małgorzata Siudek[1·4], Anna Durkalec[1], Tobiasz Górecki[2], Aleksandra Solarz[1·4], Tomasz Krakowski[1], Aleksandra Nadkańska[2] and The VIPERS Team[5]

1. National Center for Nuclear Research, A. Sołtana 7, 05–400 Otwock, Poland
2. Astronomical Observatory of the Jagiellonian University, Orla 171, 30–001 Kraków, Poland
3. Institute of Physics, Jan Kochanowski University, Świetokrzyska 15, 25–406 Kielce, Poland
4. Center for Theoretical Physics, Polish Academy of Sciences, Al. Lotników 32/46, 02–668 Warszawa, Poland
5. The VIPERS Team coauthors are presented at the end of this proceedings

I summarize the most recent results of the VIMOS Public Extragalactic Redshift Survey (VIPERS). What do they tell us about the properties and history of the cosmic structure woven from dark matter and even more elusive dark energy? How different were galaxies 8 bln years ago in comparison to their descendants we find in the Local Universe? And, finally, how is the evolution of these galaxies related to their position in the large scale structure?

1 Introduction

The VIMOS Public Extragalactic Redshift Survey (VIPERS) was a European Southern Observatory Large Programme. It was designed to provide a detailed map of the spatial distribution of galaxies in the Universe when it was around a half of its present age, in a volume comparable to the local state-of-the-art surveys like SDSS and 2dF. VIPERS spectroscopic observations were carried out by the multispectrograph VIMOS, installed at Melipal - one of the Very Large Telescope (VLT) units on Mount Paranal in Chile. The survey has covered an area of 24 square degrees on the sky, in two separate fields located inside two fields of the Canada-France-Hawaii Telescope Legacy Survey Wide catalogue (CFHTLS-Wide). This allowed to use 5-band CFHTLS photometric data for the selection of spectroscopic targets for VIMOS in the redshift range $0.5 < z < 1.2$, which proved to be very effective.

The observations lasted from 2008 until 2015. At the end of 2016 the second data release (PDR-2) of the VIPERS was presented to the scientific community. It included spectroscopic measurements for 91,507 objects, together with the survey masks, statistical weights and photometric ancillary information from the VIPERS multi-lambda survey (Moutard et al., 2016a,b). 89,022 of these objects are the main survey targets. The catalogs are provided either through an easy-to-use Web interface[1], which allows to select specific objects or sub-samples of the data, either from the ESO Phase-3 archive, or as tar files, available from the webside[2] along with the mask files characterizing the survey selection function. The data were thoroughly described by Scodeggio et al. (2017), and a general information about the survey can be found in Guzzo et al. (2014) and Garilli et al. (2014).

[1]http://vipers.inaf.it:8080/
[2]http://vipers.inaf.it/rel-pdr2.html

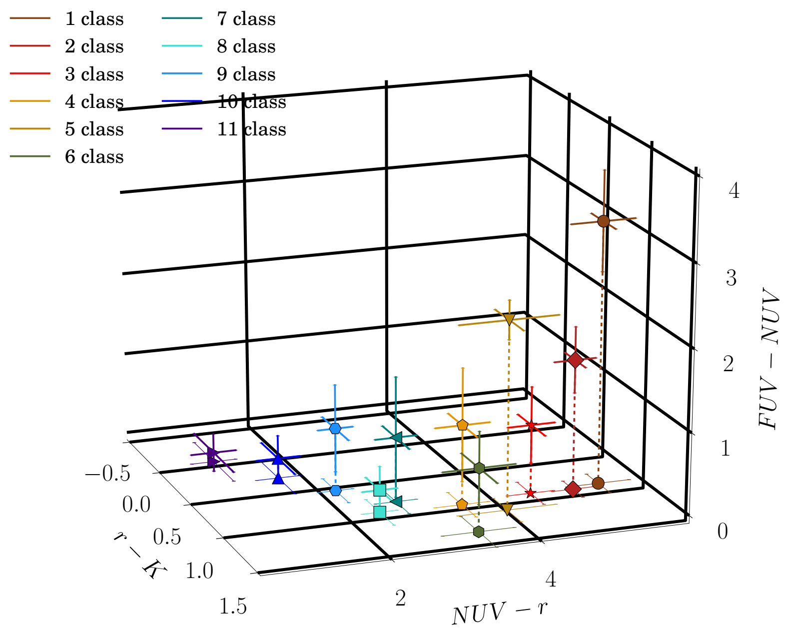

Fig. 1: New detailed galaxy classification in the multiparameter space of rest-frame magnitudes (Siudek et al., 2018a).

2 Large scale structure of the Universe at $z \sim 1$

The main scientific goal of VIPERS was to estimate cosmological parameters, with a high statistical significance, based on the galaxy distribution in an epoch when the Universe was just starting its accelerated expansion caused by dark energy. In both VIPERS fields we can see, indeed, an impressive view of large scale structure at $z \sim 1$. At the first glance, it is stunningly similar to the structure we can see in the local surveys. The cosmic web is already then made of nodes, voids (Micheletti et al., 2014) and filaments (Malavasi et al., 2017), and different types of galaxies already then trace all these cosmic environments in a different way. However, the detailed analysis of all these structures revealed differences with respect to the present-day Universe.

One simple but nevertheless important question is about how uniform the Universe really is at $z \sim 1$. While homogeneity and isotropy of the Universe are basic assumptions of the whole family of the *standard* Friedmann cosmological models, confirmed by observations of the Local Universe and cosmic microwave background radiation, they still need to be verified at higher redshifts. We found that measurements of the galaxy correlation function in both VIPERS fields agree with a great precision, thus providing an evidence that the Universe is uniform also at very large scales (de la Torre et al., 2013). VIPERS measurements demonstrated that the ΛCDM model gives a good match to cosmic structure at all redshifts currently accessible to observations (Bel et al., 2014; Rota et al., 2017).

Bias of galaxies with respect to the underlying dark matter field can be well described as linear, and it is slowly rising with redshift and galaxy luminosity, as expected from the hierarchical model of the structure formation. However, a non-conclusive evidence for a non-zero non-linear bias term was also found (Marulli et al., 2013; Cappi et al., 2015; Di Porto et al., 2016; Moresco et al., 2017).

Among the main questions addressed to the VIPERS was the one about the nature and properties of *dark energy* through the measurement of the evolution of growth rate of the large scale structure, which is expected to differ slightly not only in different cosmological models, but also for different models of the dark energy.

The growth rate is estimated based on so-called redshift-space distortions of the correlation function, which are introduced by proper motions of galaxies. These measurements were performed making use of several different methods, and the measured values are in agreement with the predictions of General Relativity (de la Torre et al., 2013; Pezzotta et al., 2017; Hawken et al., 2017). However, it also became clear that we still need both: larger datasets and further developments in theory linking statistical properties of the large scale density and velocity fields to obtain a conclusive answer about the properties of dark matter.

3 Galaxy evolution from $z \sim 1$

How do different populations of galaxies evolve in this hierarchically evolving large scale structure and how much did the galaxy population change between $z \sim 1$ and now? Today's most massive and most luminous galaxies are red and passive, and usually elliptical; we know that at some point in the past they must have been star forming - i.e. active and blue. What were their shapes at that time?

VIPERS data have shown clearly that at $z \sim 1$ the distribution of galaxy colors is already bimodal - populations of passive red and star forming blue galaxies are already well established (Fritz et al., 2014). Krywult et al. (2017b) demonstrated that for the whole redshift and galaxy stellar mass range covered by VIPERS this color bimodality is already well correlated with galaxy morphological structure. In the other words, already at $z \sim 1$ red passive galaxies were mostly spheroidal and blue galaxies had disky shapes, as it is observed in the Local Universe (see also Krywult et al., 2017a, in this volume).

The statistical power of VIPERS data allows us for a yet deeper look into the properties of different types of galaxies at $z \sim 1$, including a significant number of galaxies that are too rare to be detected by any of the past spectroscopic surveys.

Siudek et al. (2017) analyzed properties of an unprecedented sample of 3991 passive galaxies extracted from the VIPERS data and found that high-mass passive red galaxies formed their stars at $z \sim 1.7$, while their low-mass counterparts formed their main stellar populations much more recently, at $z \sim 1$, thus reinforcing the downsizing scenario (Cowie et al., 1996). Measurements by Gargiulo et al. (2017) further strengthened the scenario in which the population of massive and passive galaxies is being built up over the cosmic time by continuous addition of less dense galaxies.

Davidzon et al. (2013) measured with unprecedented detail the high mass end of the galaxy mass function and found that in the epoch observed by VIPERS massive galaxies had already assembled most of their stellar mass. However, they also found a population of massive blue galaxies at $z \sim 1$, which are no longer detectable below $z = 0.7$. This sharp drop of the number density of massive blue-cloud galaxies by a factor five between $z \sim 0.8$ and $z \sim 0.5$ matches the increase in the numbers of massive and passive galaxies seen over this period. Haines et al. (2017) found that galaxy star forming potential can be related to its size-mass relation - larger galaxies can continue to form stars to higher stellar masses than smaller galaxies. As blue-cloud galaxies are approaching this high-mass limit, they enter the *quenching zone*, and, in parallel, start to change their structure building a larger bulge. Thus, as the blue-cloud galaxies that are being quenched at $z \sim 0.8$ lie along the same size-mass relation as present day quiescent galaxies, they are most likely the progenitors of today's lenticular galaxies.

Małek et al. (2013) used the support vector machine (SVM) based method to distinguish galaxies, quasars and stars from the CFHTLS data, with the VIPERS used as a training sample. In our recent work (Siudek et al., 2018a,b) we apply a new machine learning unsupervised method to obtain a much finer classification of high-z galaxies. The resultant 11 galaxy types in an exemplary six-dimensional subspace of a 13-dimensional parameter space used for classification are presented in Fig. 1 (see also Krakowski et al., 2017, in this volume).

4 How do galaxies evolve in the cosmic web?

Now the most intriguing question is - how both these components of the Universe, dark matter woven cosmic web and luminous galaxies which trace it, co-evolve? How local environment and position in a cosmic web affects the fate of a single galaxy and how is it reflected in a way different galaxies trace the distribution of the dark matter?

In Local Universe galaxy properties are strongly correlated with their local environment: red passive galaxies usually reside in galaxy clusters, star forming spiral galaxies are more often field galaxies. VIPERS have shown that - broadly speaking - this segregation is already well established at $z \sim 1$ (Guzzo et al., 2014). The details of this relation may be the key to our understanding of how environmental effects shape galaxy evolution.

One possible approach is tracing the dependence of galaxy properties on local galaxy densities. Cucciati et al. (2017) found that, similarly to what is seen locally, up to $z \sim 1$ more massive galaxies reside in higher-density environments. The fraction of star-forming over passive galaxies is higher in low-density regions, but with decreasing significance going from lower to higher masses. But again, an enhancement of massive galaxies and a hint of a flatter slope is seen at redshift $z < 0.8$ Davidzon et al. (2016).

Malavasi et al. (2017) found a significant segregation of galaxies in filaments, with the most massive or quiescent galaxies being closer to the filament axes than less massive or star forming active galaxies. This emphasizes the role of the large-scale cosmic environment and cosmic flows in shaping galaxy properties already at $z \sim 1$.

All this work is only a starting point of an intriguing journey to disclose the relations between galaxy and large scale structure evolution over all cosmic epochs.

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[2]The VIPERS Team coauthors: U. Abbas[5], C. Adami[6], S. Arnouts[7], J. Bel[8], M. Bolzonella[9], D. Bottini[18], E. Branchini[10,11,12], A. Cappi[9,13], J. Coupon[14], O. Cucciati[15,9], I. Davidzon[6,9], G. De Lucia[16], S. de la Torre[6], P. Franzetti[18], B. Garilli[18], B. R. Granett[8], L. Guzzo[8,17], O. Ilbert[6], A. Iovino[8], V. Le Brun[6], O. Le Fèvre[6], D. Maccagni[18], F. Marulli[15,19,9], H. J. McCracken[20], M. Polletta[18], L. A. .M. Tasca[6], R. Tojeiro[23], D. Vergani[24,9], A. Zanichelli[25], A. Burden[23], C. Di Porto[9], A. Marchetti[26,8], C. Marinoni[27,12,28], L. Moscardini[15,19,9], J. A. Peacock[29], M. Scodeggio[18], G. Zamorani[9], T.T. Takeuchi[30] [5] INAF - Osservatorio Astronomico di Torino, 10025 Pino Torinese, Italy, [6] Aix Marseille Universit'e, CNRS, LAM (Laboratoire d'Astrophysique

de Marseille) UMR 7326, 13388, Marseille, France; [7] Canada-France-Hawaii Telescope, 65–1238 Mamalahoa Highway, Kamuela, HI 96743, USA, [8] INAF - Osservatorio Astronomico di Brera, Via Brera 28, 20122 Milano, via E. Bianchi 46, 23807 Merate, Italy, [9] INAF - Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127, Bologna, Italy, [10] Dipartimento di Matematica e Fisica, Università degli Studi Roma Tre, via della Vasca Navale 84, 00146 Roma, Italy, [11] INFN, Sezione di Roma Tre, via della Vasca Navale 84, I-00146 Roma, Italy, [12] INAF - Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monte Porzio Catone (RM), Italy, [13] Laboratoire Lagrange, UMR7293, Université de Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur, 06300 Nice, France, [14] Astronomical Observatory of the University of Geneva, ch. d'Ecogia 16, 1290 Versoix, Switzerland, [15] Dipartimento di Fisica e Astronomia - Alma Mater Studiorum Università di Bologna, viale Berti Pichat 6/2, I-40127 Bologna, Italy, [16] INAF - Osservatorio Astronomico di Trieste, via G. B. Tiepolo 11, 34143 Trieste, Italy, [17] Dipartimento di Fisica, Università di Milano-Bicocca, P.zza della Scienza 3, I-20126 Milano, Italy, [30] INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica Milano, via Bassini 15, 20133 Milano, Italy, [19] INFN, Sezione di Bologna, viale Berti Pichat 6/2, I-40127 Bologna, Italy, [20] Institute d'Astrophysique de Paris, UMR7095 CNRS, Université Pierre et Marie Curie, 98 bis Boulevard Arago, 75014 Paris, France, [21] Universitätssternwarte München, Ludwig-Maximillians Universität, Scheinerstr. 1, D-81679 München, Germany, [22] Max-Planck-Institut für Extraterrestrische Physik, D-84571 Garching b. München, Germany, [23] Institute of Cosmology and Gravitation, Dennis Sciama Building, University of Portsmouth, Burnaby Road, Portsmouth, PO1 3FX, [24] INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica Bologna, via Gobetti 101, I-40129 Bologna, Italy, [25] INAF - Istituto di Radioastronomia, via Gobetti 101, I-40129, Bologna, Italy, [26] Università degli Studi di Milano, via G. Celoria 16, 20130 Milano, Ital, [27] Aix Marseille Université, CNRS, CPT, UMR 7332, 13288 Marseille, France, [28] Université de Toulon, CNRS, CPT, UMR 7332, 83957 La Garde, France, [29] SUPA, Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK [30] Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan.