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OPTICAL GALAXY REDSHIFT SURVEYS

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Abstract. Galaxy redshift surveys are a major tool to address the most challenging cosmological problems of contemporary cosmology, like the nature of dark energy and properties of dark matter. These surveys, besides their interest for cosmology, are useful for a much larger variety of scientific applications, from the study of small bodies in the solar system, to properties of tidal streams in the Milky Way halo, galaxy clusters, and galaxy formation and evolution. Here I briefly discuss what is a redshift survey and how it can be used to attack astrophysical and cosmological problems. I finish with a brief description of two new surveys: the Javalambre Physics of the Accelerating Universe Astrophysical Survey (JPAS) and the Subaru Prime Focus Spectrograph (PFS) survey.

Keywords: Cosmology: observations, Galaxies: general, Galaxies: evolution

1 Introduction

Galaxy redshift surveys on large areas of the sky are nowadays the astrophysical equivalent of large high-energy physics collaborations, like those built around the Large Hadron Collider at CERN to probe the realm of elementary particles. They aim to build 3-D maps of the galaxy distribution, since many astrophysical and cosmological process let their imprint in the spatial structure traced by galaxies.

Here I briefly review what galaxy redshift surveys are and what science they can address. I conclude presenting the main characteristics of two new surveys: JPAS, conducted by a Spanish-Brazilian collaboration from 2014 on, and PFS, a survey based in a new massively-multiplexed fiber-fed optical and near-infrared spectrograph under construction for the Subaru telescope and with first light predicted for late 2017.

2 The large scale structure

The knowledge of the galaxy distribution at the largest scales is a major achievement of redshift surveys like the 2dF Galaxy Redshift Survey (Colless et al. 2001) and the Sloan Digital Sky Survey (e.g., Abazajian et al. 2005). They have demonstrated that galaxies are distributed in a network of filaments and walls with galaxy clusters at their intersection. This network also contains large voids embedded, with diameters of a few tens Mpc (e.g., Costa-Duarte, Sodré & Durret 2011).

But galaxies are just the visible tracers of the dominant mass component of the universe: cold dark matter. Cold means that the velocity of the dark matter particles is non-relativistic when they were formed, just after the Big Bang. A major reason for the CDM paradigm is the strong resemblance between the observed galaxy distribution with the large scale distribution of dark matter established by numerical N-body simulations (e.g., Springel, Frenk & White 2006). Indeed, the type of dark matter has a profound effect on the appearance of the large scales (e.g., Ostriker & Steinhardt 2003). Cold particles allow the collapse of very small structures, whereas if the universe was dominated by hot dark matter (e.g., massive neutrinos), only large objects, like superclusters and clusters, would be initially formed, and galaxies would appear later through the fragmentation of large objects.

The difference between the expected appearance of the universe in its largest scales predicted by different models actually shows how powerful is the study of galaxy distribution for unveiling some of the universe deepest mysteries.

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Galaxy redshift surveys are an important tool of contemporary astrophysics and observational cosmology. Their objective is to map the universe as traced by galaxies, obtaining a 3-D map of the galaxy distribution. The reason is that the cosmological parameters are imprinted in these 3-D maps, and their analysis is considered the most powerful way to address the nature of dark energy and other problems (Albrecht et al. 2006).

To make these 3-D maps we need to determine the cosmological distances of galaxies. This is usually done by measuring their spectral deviation z. For a given (homogeneous and isotropic) cosmological model, distances are a function of z, only.

The overall, uniform, expansion of the universe is known as the Hubble flow. But z is also affected by the peculiar velocities, the movements produced by the gravitational interaction between a galaxy and its neighbors, affecting the distance estimation of nearby galaxies. It is worth mentioning that galaxies are a biased tracer of dark matter, and studies of the peculiar velocity field (e.g., through redshift space distortions; Lahav & Suto 2004) are a powerful way to measure this bias.

There are two ways to obtain z: spectroscopy and photometry. In the first case, the measured spectrum allows the measurement of the spectral deviation of a galaxy with high accuracy (rms error $\sigma_z \sim 3 \times 10^{-4}$). In the case of photometric redshifts, the fluxes in a few filters (5 for SDSS) are used as proxies for the galaxy spectrum, and typical errors are much larger (e.g., $\sigma_z \sim 0.02(1+z)$ for SDSS/DR7; O'Mill et al. 2012). Each method has its pros and cons: photometric redshifts are much cheaper in terms of telescope time and consequently photometric surveys can go wider and deeper than spectroscopic surveys. Spectroscopic surveys, on the other side, besides their accuracy and superiority for several cosmological applications (e.g., measurement of redshift space distortions, radial baryon accoustic oscillations), also provide detailed galaxy SEDs, very useful for evaluating galaxy properties.

3 Cosmology with large scale probes

The prime objective of most galaxy redshift surveys is to investigate the nature of dark energy, mainly by constraining its equation of state, $p_{DE} = w\rho_{DE}c^2$. The value $w = -1$ corresponds to a cosmological constant, which provides a good fit to the current data (Komatsu et al. 2011). But is this indeed a good model for the behavior of dark energy or does its properties vary with redshift?

There are several probes to address dark energy properties, either based on distance-redshift relations or on the growth rate of cosmic structures. Indeed, the existence of dark energy was established though the luminosity distance-redshift relation of type Ia supernovae. Other canonical probes include the baryon acoustic oscillations (BAOs), cosmic shear, and the abundance of galaxy clusters. These probes, when combined with information obtained from the analysis of the temperature fluctuations of the cosmic microwave background (CMB), are able to impose stringent constraints on cosmological parameters (Eisenstein, Hu & Tegmark 1999).

Baryon acoustic oscillations (BAOs) are acoustic waves produced during the radiative era by the interaction of the photon-baryon plasma with dark matter. These waves stop propagating at recombination, when the rate of Compton scattering between electrons and photons becomes too low, and have their size frozen and equal to the size of the sound horizon at that epoch, $l_{BAO} \sim 150h^{-1}$ Mpc (Eisenstein & Hu 1998). Since BAOs are associated with a density enhancement, they increase the probability of finding a galaxy at l_{BAO} of other galaxies, and can be observed as a small excess ($\sim 1\%$) in the galaxy correlation function (e.g., Percival et al. 2010). Analysis of SDSS luminous red galaxies with an algorithm that takes in to account the effects of the peculiar velocity field (Padmanabhan et al. 2012) provides a 2% accuracy in l_{BAO} in the local universe, $z = 0.35$. The measurement of this scale as a function of z is a powerful cosmological probe and a major objective of future surveys. It is worth mentioning that the BAO features can be measured either in the transverse or radial directions and that each of these measurements bring different cosmological information: radial BAO is directly sensitive to the Hubble parameter $H(z)$, whereas transverse BAO is a probe of the distance-redshift relation. Photometric redshift surveys are more sensitive to transverse BAOs, since photometric redshift errors tend to blur the radial information.

In a ΛCDM universe structures grow from small density fluctuations due to their gravitational attraction. The largest virialized (or quasi) structures formed are the galaxy clusters and it is assumed that their material composition is representative of the universe as a whole. The number of clusters in a given redshift and the cluster spatial correlations are strong functions of the cosmological parameters, and the cluster mass function- the number of clusters at a given redshift with mass in a certain interval- is then a powerful cosmological probe, since it depends directly on the element of volume and on the growth of structures. Massive clusters can be found in the galaxy distribution through a variety of techniques (e.g., Wen, Han & Liu 2012). An important difficulty with this approach is the estimation of cluster masses from the photometric information (richness and/or luminosity) available in these surveys. This can be overcomed through multiwavelength observations (e.g., X-rays) and/or self-calibration of the mass function (Lima & Hu 2007) in combination with external mass inferences. Nevertheless, the results obtained up to now are consistent and highly complementary to those obtained by other probes (e.g., Vikhlinin et al. 2009).

Density fluctuations can also be studied through gravitational lensing. The ellipticities of background galaxies change as their light travels towards the observer due to the gravitational deflection by the mass distribution along the line of sight. These optical distortions are highly correlated and are the signature of cosmic shear. The study of the cosmic shear as a function of redshift is called lensing tomography and is sensitive to cosmic expansion through both geometry and the growth rate of structures (e.g., Hu 2002).

Gravity affects both the overall expansion and the formation and evolution of structures, but in completely different ways, what allows to use observations of the 3-D galaxy distribution to test the gravitational theory in cosmological scales. Recently, the combination of cosmic shear, galaxy clustering and structure growth rate allowed the comparison between general relativity and modified gravity theories, suggesting that general relativity is a better descriptor of the behavior of gravitation theory in large scales than some versions of alternative gravity theories (Reyes et al. 2010).

Massive neutrinos also let their imprint on the galaxy distribution. They are a kind of hot dark matter, since they were relativistic when formed. Consequently, they escape from density fluctuations and, since they carry mass, they dissipate small density fluctuations. This process, called "free streaming", produces a cut-off in the number density of small fluctuations that can be detected in the power spectrum of the galaxy distribution and, in combination with other probes, provides strong constraints on the sum of the mass of neutrinos species. For example, analysis of the Canada-France-Hawaii Telescope Legacy Survey Wide Fields combined with WMAP7 data and a prior on the Hubble constant gives a very stringent upper limit on the sum of mass of neutrino species equal to 0.29 eV (Xia et al. 2012).

Another major scientific contribution from large scale redshift surveys is on our knowledge on how galaxies form and evolve. The reason is that the spectra or colors collected are useful to investigate the stellar populations and other galaxy properties (Cid Fernandes et al. 2005). Thanks mainly to SDSS photometric and spectroscopic surveys, much is known about the galaxy populations (e.g., stellar mass, luminosity, size, stellar populations, mean stellar ages and metallicities) and their relation with the environment, but big uncertainties remain. With CDM we expect that structures grow hierarchically, with merger of structures producing larger structures. But how does it work? Why the star formation rate start decreasing since $z \sim 1 - 2$? How massive black holes interact with their host galaxy? In the case of Milk Way, SDSS lead to the discovery of many satellite galaxies (e.g., Belokurov et al. 2010) and tidal tails, which are snapshots of merging activity. We hope that most of these questions will be addressed by surveys like those we describe in the next section.

4 JPAS and PFS

The Javalambre Physics of the Accelerating Universe Astrophysical Survey (JPAS) is a collaboration between Spain and Brazil aiming to conduct a survey on ∼ 8000 square degrees with 54 narrow band filters and two broad band filters over the range ∼ 3500Å to ∼ 10000Å, with photometric depth $I < 22.5$. This innovative filter system actually provides a low resolution spectrum at each pixel on the sky and was designed to produce photometric redshifts with accuracy $\sim 0.003(1 + z)$, about ten times better than that possible with SDSS (Benitez et al. 2009). This survey should start in 2014 and its main part should be concluded by 2018. The survey will be conducted from the Javalambre Astrophysical Observatory (JAO), which is being built on Pico del Buitre, near the city of Teruel, in Spain. The Sierra de Javalambre is amongst the darkest regions in Europe and has an excellent seeing, with a median of 0.71 arcsec (Moles et al. 2010). The main telescope, T250, has diameter of 2.5m and a very large field of view, ∼5 square degrees. It will be equipped with a 1.2 Gigapixel camera which will be a mosaic of 14 10k x 10 k CCDs, with the 56 filters mounted in 4 trays. OAJ will also have a smaller telescope, T80, with diameter of 80cm and equipped with a 2 square degree camera for calibration of the photometric system of the survey.

The JPAS expected accuracy in photometric redshifts is enough to allow measuring BAO features also in the radial direction, what makes this photometric survey very competitive, with a DETF figure of merit above 100. We plan to measure the BAO scale above that allowed by galaxies ($z \sim 1.3$) by using quasars (Abramo et al. 2012); these probes have number densities large enough to allow measuring BAOs up to $z \sim 3 - 4$. Besides cosmology, JPAS will provide scientific results in many other areas: small bodies in the solar system, Galaxy archeology, galaxy evolution, quasars, clusters of galaxies. An absolutely unique aspect of JPAS is that it will allow us for the first time to do an all-sky IFU (for integral field unit) science, since JPAS will measure a low resolution spectrum at each pixel on the sky. This opens immense opportunities for studies on galaxy structure and evolution. But, besides these very competitive scientific perspectives we are pursuing, maybe the most compelling results of JPAS are still unknown, as always happens when new windows are open.

The Prime Focus Spectrograph (PFS) survey will be carried on from the Subaru Telescope by using a new optical to near-infrared spectrograph equipped with 2400 optical fibers and which is under construction by an international collaboration under the leadership of Kavli IPMU (Ellis et al. 2012). The survey will be conducted as a Subaru Strategic Program of ∼300 nights and aims to constrain the nature of dark energy in the redshift range $0.8 < z < 2.4$ by measuring accurate (3%) cosmological distances through BAOs, as well as using redshift space distortions to constrain the structure growth factor to 6% precision. The survey will also complement the goals of Gaia mission by the measurement of velocities and metallicities for $\sim 10^6$ Milky Way stars, and will also target red giant branch stars in M31. The survey will also probe galaxy evolution at large redshift through the observation of galaxies, quasars, Lyman break galaxies and Lyman-α emitters, quantifying galaxy evolution from $z = 0$ to close the reionization epoch. PFS will be probably, the most powerful spectrograph during the Euclid era.

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