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Understanding cosmic acceleration with galaxy redshift surveys

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Abstract. Our increased efficiency in performing massive redshift surveys of galaxies well beyond the local Universe (i.e. $z \gg 0.1$) is opening up new possibilities to understanding the observed acceleration of cosmic expansion, the greatest mystery in modern cosmology. Redshift surveys can measure both the expansion history $H(z)$ and the evolution of the growth rate of structure $f(z)$. Coupling these two measurements one can distinguish wether cosmic acceleration is due to a new form of "dark energy" in the cosmic budget, or rather requires a modification of General Relativity. These two radically alternative scenarios are degenerate when considering $H(z)$ alone, as yielded, e.g., by the Hubble diagram of Type Ia supernovae. While redshift surveys have the ability to measure $H(z)$ through *Baryonic Acoustic Oscillations* in the galaxy power spectrum, they can at the same time probe $f(z)$ using the *redshift-space distortions* introduced in the observed clustering pattern by galaxy peculiar motions. In this short review paper I will mostly concentrate on the latter measurement, whose potential importance in this context has been recently highlighted (Guzzo et al. 2008). Current estimates are consistent with the simplest cosmological-constant scenario, but error bars are still too large to rule out alternative models. Extensive simulations show that with the next-generation deep surveys with $N > 100,000$ redshifts over large (> 20 deg^2) areas, redshift distortions can be one of the key tools for understanding the physical origin of cosmic acceleration.

Key words. Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters – Galaxy: abundances – Cosmology: observations

1. Introduction

Observations indicate that we live in a low-density, expanding Universe with spatially flat geometry, that, quite surprisingly, appears to have recently entered a phase of accelerated expansion. This latter conclusion emerges naturally when interpreting the observed Hubble diagram of distant Type Ia supernovae within the standard Friedmann-Lemaitre-Robertson-Walker (FLRW) cosmology (Riess et al. 1998; Perlmutter et al. 1999). Formally, this requires adding an extra mass-energy contribution in the Friedmann equation in the form of a fluid with equation of state $w = -1$. This corresponds to having a *cosmological constant* in the equations of General Relativity (GR), i.e. the term originally introduced by Einstein to obtain a static solution. A constant, vacuum-like equation of state $w = -1$, however, has a few disturbing features, as

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e.g. that of making the current epoch a special one in which the contributions from matter and cosmological constant are comparable. Among possible remedies, scenarios with evolving "dark energy" density related to a cosmological scalar field, have been proposed (see e.g. Turner & Huterer 2007, for a review). Both the cosmological constant and these more sophisticated variants can be seen as modifications of the source term in the right-hand side of Einstein field equations, i.e. adding extra contributions to the stress-energy tensor. Alternatively, however, one could assume that it is the theory of gravity that needs to be revised and thus modify the left-hand side of the equation. In this case, the "observed" acceleration could just be a cosmic mirage, simply evidencing our still limited knowledge of the laws of Nature (see Copeland et al. 2006, for a comprehensive review of these variants).

These two classes of solutions, dark energy vs modified gravity, cannot be distinguished by measuring only the expansion history $H(z)$ or equivalently the equation of state $w(z)$ for the extra component. The linear growth of density inhomogeneities provides us with a way to break this degeneracy. We can characterize the way matter is assembled by gravity in the expanding Universe through the *growth rate* $f = d\ln D/d\ln a$, where $D(t)$ is the time-dependent part of the solution of the linear growth equation (Heath 1977) and $a = (1+z)^{-1}$ is the cosmic scale factor. Models with the same expansion history $H(z)$, but based on a different gravity theory predict a different $f(z)$, which is therefore a sensitive probe of the physics originating cosmic acceleration. A convenient approximation for $f(z)$ for a broad range of models is given by the form $f(z) \simeq [\Omega_m(z)]^\gamma$, with γ depending on the gravity theory (Wang & Steinhardt 1998; Linder 2005). GR-based Friedmann models have $\gamma = 0.55$, while for example in the DGP "braneworld" theory, an extra-dimensional modification of gravity, one has $\gamma = 0.68$ (e.g. Lue et al. 2004).

2. Redshift surveys as probes of cosmic acceleration

Galaxy redshift surveys allow us to measure the expansion history $H(z)$ thanks to the presence of *Baryonic Acoustic Oscillations* (BAO) in the galaxy power spectrum (Eisenstein et al. 2005; Blake & Glazebrook 2003; Seo & Eisenstein 2003). BAOs are related to the characteristic scale determined by the comoving sound horizon at recombination. This is accurately measured by Cosmic Microwave Bakground anisotropies (Spergel et al. 2007) and can be compared as a standard rod to the observed BAO scale at different redshifts. This yields a measurement of $H(z)$ in the radial direction, and of the comoving angular diameter distance $D_A(z) = r(z)/(1+z)$ in the transverse direction. In the latter expression $r(z)$ is the comoving distance to redshift z. Given the limited space here, I will not review current measurements and future perspectives for BAOs measurements, but instead concentrate on some more recent, complementary developments on the measurement of the growth rate from redshift space distortions.

2.1. Redshift-space distortions and the growth of structure

In a paper based on the data from the VVDS-Wide survey (Guzzo et al. 2007, 2008), we showed how *redshift-space distortions* in deep, large redshift surveys represent a promising way to test the physics of dark energy through measurements of $f(z)$ at different cosmic epochs. This work stimulated renewed interest in the almost neglected field of galaxy peculiar velocities, with a few recent papers either presenting more detailed (e.g. Fisher-matrix based) theoretical investigations (Wang 2008; Linder 2008), or comparing modified gravity models to more extended collections of growth rate measurements (Nesseris & Perivolaropulos 2008; Acquaviva et al. 2008). Galaxy peculiar motions are a direct consequence of the growth of structure. When redshifts are used to measure galaxy distances, the contribution from pecu-

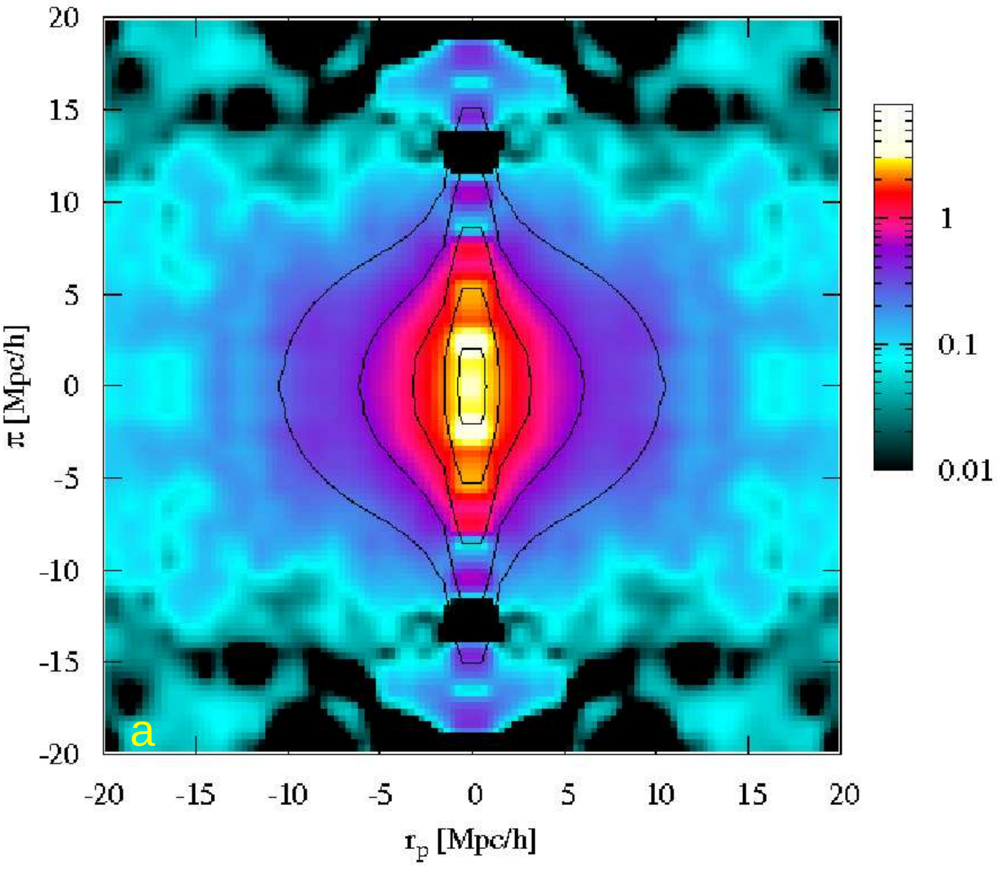

Fig. 1. $\xi(r_p, \pi)$ at $< z > \simeq 0.77$ from the VVDS-Wide survey, replicated over four quadrants to enhance deviations from circular symmetry. Colors correspond to the level of correlation as a function of the transverse (r_p) and radial (π) separation of galaxy pairs. The effect of galaxy infall due to the growth of large-scale structure is proportional to the flattening of the purple-blue large-scale levels, with the solid contours corresponding to the best-fitting distortion model with $\beta = 0.70$ and $\sigma_{12} = 412$ km s^{-1} (see Guzzo et al. 2008, for details).

liar velocities introduces a measurable distortion in the clustering pattern, which is proportional to $f(z)$. This can be measured by modeling the anisotropy of the redshift-space two-point correlation function $\xi(r_p, \pi)$. The anisotropy of $\xi(r_p, \pi)$ at large r_p's is quantified by the "compression parameter" β (see Hamilton 1998, for a review), which is directly related to the growth rate as $f(z) = \beta(z) b_L(z)$. The *bias factor* b_L appearing here, is the ratio of the clustering amplitude of the galaxies used in the measurement, to that of the underlying matter (Kaiser 1984). Estimating b_L is thus an important ingredient of this procedure to measure $f(z)$. This can be done either directly from the redshift surveys data using higher-order clustering (Verde et al. 2002), or using the information from CMB anisotropy observations (Guzzo et al. 2008).

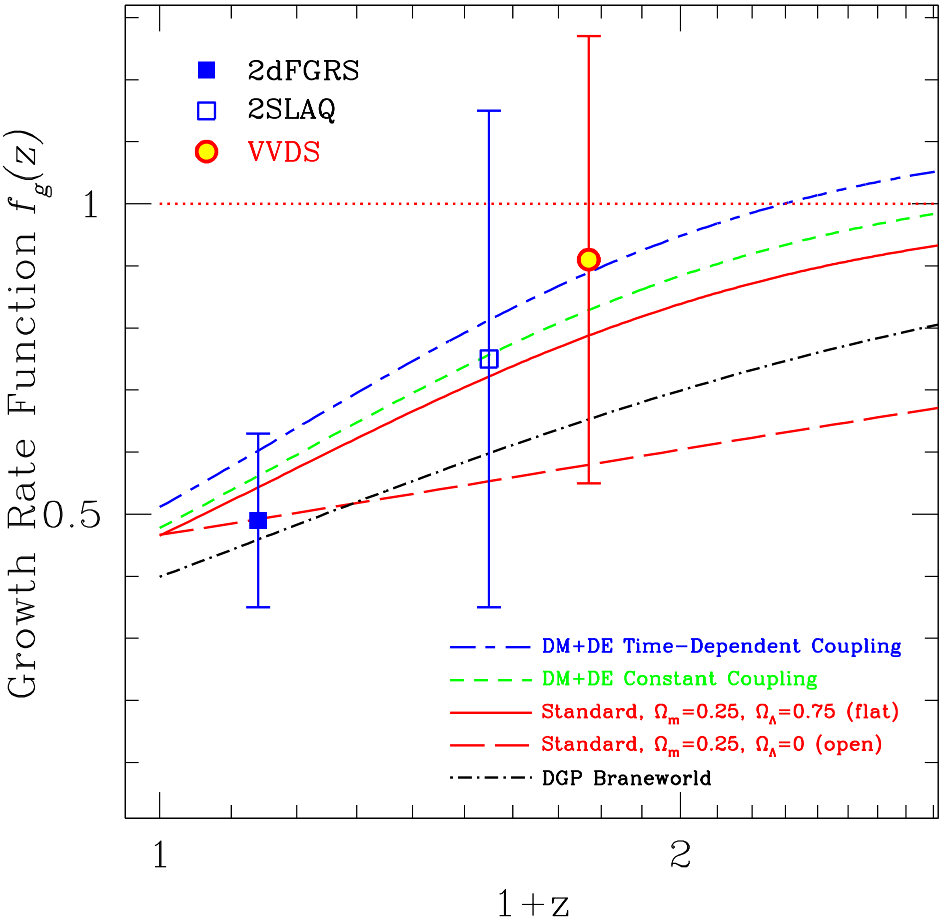

Fig. 2. Estimates of the growth rate $f = \beta b_L$ compared to predictions from theoretical models: the standard cosmological constant (ΛCDM) model ($w = -1$) (solid line); an open $\Omega_\Lambda = 0$ model with the same Ω_m (long-dashed line, for both cases $f(z) \simeq \Omega(z)^{0.55}$); two models in which dark energy is coupled to dark matter (Amendola 2000) (upper dashed curves) ; the DGP braneworld model, an extra-dimensional modification of the gravitation theory (Dvali et al. 2000) for which $f(z) \simeq \Omega(z)^{0.68}$ (dot-dashed curve).

In the local Universe ($z \simeq 0.15$) the 2dF galaxy redshift survey has measured $\beta = 0.49 \pm 0.09$ (Hawkins et al. 2003) for galaxies with $b_L = 1.0 \pm 0.1$ (Verde et al. 2002). This represents an important local constraint on the growth rate, corresponding to $f(z = 0.15) = 0.49 \pm 0.14$.

3. Measuring $f(z)$ at $z \sim 1$ with the VVDS-Wide survey

The VIMOS-VLT Deep Survey (VVDS) was designed to probe the combined evolution of galaxies and large scale structure to $z \sim 2$ using the VIMOS spectrograph at the ESO VLT. It measured so far ∼ 40000 spectra

(Le Févre et al. 2005; Garilli et al. 2008) over its *Deep* (0.5 deg^2 to $I_{AB} < 24$) and *Wide* ($\sim$ 8 deg^2 to $I_{AB} < 22.5$) parts. A sub-sample of 5895 galaxies with $0.6 < z < 1.2$ (volume $V = 6.35 \times 10^6$ h^{-3} Mpc^3) in the 4-deg^2 *F22* field of VVDS-*Wide* has been used to extract a measurement of β at an effective redshift $z = 0.77$ (Guzzo et al. 2008). $\xi(r_p, \pi)$ has been fit with a distortion model including both linear and non-linear distortions, described respectively by two parameters, the compression β and the *rms* pairwise dispersion σ_{12}. Fig. 1 shows the observed $\xi(r_p, \pi)$, measured using standard techniques (Landy & Szalay 1993), with superimposed the best-fit model contours, corresponding to $\beta = 0.70 \pm 0.26$ and $\sigma_{12} = 412 \pm 70$ km s^{-1}. Error bars are obtained from 100 fully realistic mock realizations of the survey (Pierleoni et al. 2008; De Lucia & Blaizot 2006), which have also been used to explore and minimize the variety of systematic effects that can affect the measurement of β. Using the amplitude of mass fluctuations provided by the power spectrum of CMB anisotropies (Spergel et al. 2007) and the PDF reconstruction method (Marinoni et al. 2005), we then obtain for the effective redshift of the survey a linear bias $b_L = 1.3 \pm 0.1$ (see Guzzo et al. 2008, for details), and a growth rate $f(z = 0.77) = 0.91 \pm 0.36$. This value is compared in Fig. 2 to model predictions, together with measurements from the 2dFGRS (Hawkins et al. 2003) and 2SLAQ surveys (Ross et al. 2007). Given the size of the error bars, deviations from the standard cosmological-constant model cannot yet be detected. Interestingly, however, in the framework of General Relativity, the two high-redshift measurements seem already to disfavor an $\Omega_\Lambda = 0$ model, providing a marginal independent indication for the need of a cosmological constant.

4. Future prospects for cosmological redshift surveys

Only $\sim$ 6000 redshifts have been used to obtain the result just discussed; there are thus ample margins for improvement with future, larger surveys. This includes the estimates of both β and of the linear bias. In Guzzo et al. (2008) we have used a large set of simulations to forecast the gain in accuracy that can be expected from future surveys. The error on β scales with the mean density $\langle n \rangle$ and the volume of the survey V, as $\sigma_\beta \propto (\langle n \rangle^{0.44} V^{0.5})^{-1}$ (i.e. nearly as the inverse square root of the total number of objects). In addition, it also decays nearly linearly with the bias value of the kind of galaxies used, with more biased (i.e. more clustered) galaxies providing a more accurate measurement.

Using these results, one can see that going below a 10% uncertainty on β is already within reach of current instrumentation. For example, an extended version of VVDS-Wide using VIMOS at the VLT, with similar depth but measuring over 100,000 redshifts over 20-30 deg^2 would produce, at $< z > \sim 0.8$, a sample comparable in volume and number of objects to the low-redshift 2dFGRS. An incarnation of this concept, named VIPERS (VIMOS Public Extragalactic Redshift Survey), has been recently accepted by ESO and is going to start in the fall of 2008. The goal of this new project is not only to perform key measurements of the growth rate in two redshifts bins, but also to extend a number of investigations that have just been sketched, at these redshifts, by surveys the VVDS. These include, for example, the detailed study of small-scale clustering as a function of galaxy properties at $z \sim 1$ and its description in terms of Halo Occupation Distribution models (Pollo et al. 2000; Meneux et al. 2008).

For the more distant future (2017), the ESA EUCLID mission, resulting from the merging of the original DUNE (Refregier et al. 2008) and SPACE (Cimatti et al. 2008) concepts proposed for the Cosmic Vision framework, promises to be the definitive experiment to map the structure of the dark and visible Universe and solve the mystery of cosmic acceleration. EUCLID plans to survey 20,000 deg^2 of extragalactic sky both in imaging (optical and infrared) and spectroscopy (200 million redshifts), to measure simultaneously $H(z)$ and $f(z)$ to percent accuracy in several redshift bins to $z \sim 2$, through a combination of dark-energy probes including Baryonic

Acoustic Oscillations, weak gravitational lensing and redshift-space distortions.

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