TESTING DARK ENERGY VS. MODIFIED GRAVITY WITH REDSHIFT-SPACE DISTORTIONS

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Measurements of the growth rate of structure f at different redshifts can discriminate the origin of cosmic acceleration. Coupled to estimates of the expansion rate $H(z)$ as provided by Type Ia supernovae or Baryonic Acoustic Oscillations, they can distinguish whether this is due to the presence of "dark energy" or could possibly be the result of a different theory of gravity. These two radically alternative scenarios are degenerate when considering $H(z)$ alone. We have recently pointed out [1] that measurements of redshift-space distortions in the clustering pattern of galaxies at different epochs represent a very promising technique to trace $f(z)$ back in time. We have measured the distortion parameter β at $z \sim 0.8$ using the currently largest field of the VVDS-Wide survey, that includes more than 10,000 galaxy redshifts to $I_{AB} = 22.5$ over 4 deg^2. We obtain $\beta = 0.70 \pm 0.26$, corresponding to a growth rate $f = \beta b_L = 0.91 \pm 0.36$ (where b_L is the galaxy linear bias parameter). This value is close to that of 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 will become one of the important tools for understanding the physical origin of cosmic acceleration.

1 Cosmic acceleration and the growth of structure

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 [2,3]. 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

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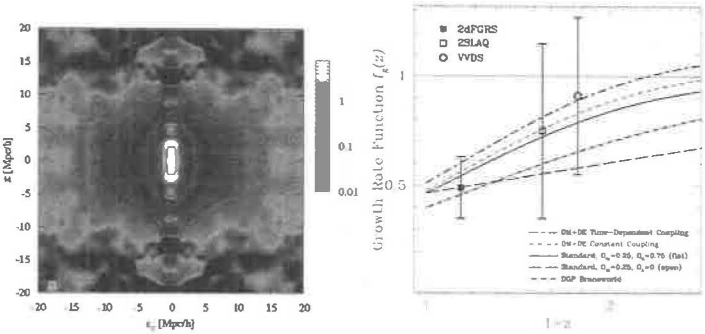

Figure 1: **Left panel**: $\xi(r_p, \pi)$ at $< z >\simeq 0.77$ from the VVDS-Wide survey, replicated over four quadrants to enhance deviations from circular symmetry. Colors correspond to the level of correlation as a function of the transverse (r_p) and radial (π) separation of galaxy pairs. The effect 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 ref. 1 for details). **Right panel**: 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[29] (upper dashed curves) ; the DGP braneworld model, an extra-dimensional modification of the gravitation theory[30] for which $f(z) \simeq \Omega(z)^{0.68}$ (dot-dashed curve).

$w = -1$ has a few disturbing features, as e.g. that of making the current epoch a special one in which the contributions from matter and cosmological constant are comparable. As a remedy, scenarios with evolving "dark energy" density have been proposed (see e.g. [1] 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 in the stress-energy tensor. Alternatively, one can however assume that it is the theory of gravity that needs to be revised and thus modify the left-hand side of the equation. This could imply that the "observed" acceleration is just a cosmic mirage, simply evidencing our still limited knowledge of the laws of Nature (see [5] 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 $w(z)$ 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 [6] and $a = (1+z)^{-1}$ is the cosmic scale factor. It is found that a simple form $f(z) \simeq [\Omega_m(z)]^\gamma$ gives an accurate description for a wide range of models [7,8], with γ depending on the gravity theory (e.g. [14]). $f(z)$ is sensitive to the physics responsible for the cosmic acceleration: scenarios with the same expansion history $H(z)$, but based on a different gravity theory will predict a different $f(z)$.

In a recent paper [9,1], we showed that measurements of *redshift-space distortions* at different cosmic epochs represent a very promising way to test dark energy through $f(z)$. This work has stimulated renewed interest in galaxy peculiar velocities and redshift distortions. A few papers appeared recently (even before our paper was published, following presentations and discussions at meetings), either presenting more detailed (e.g. Fisher-matrix based) theoretical investigations [10,11], or comparing modified gravity models to more extended collections of growth rate measurements from redshift distortions [12,13]. Galaxy peculiar motions are a direct consequence of the growth of structure. When redshifts are used to measure galaxy distances, the contribution from peculiar velocities introduces a measurable distortion in the clustering pattern, which is proportional to $f(z)$. This can be measured by modelling 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 [15] 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. Estimating b_L is thus an important ingredient of this procedure. This can be done either directly from the redshift surveys data using higher-order clustering [16], or using the information from CMB anisotropy observations [1]. Locally ($z \simeq 0.15$) the 2dF galaxy redshift survey has measured $\beta = 0.49 \pm 0.09$ [17] for galaxies with $b_L = 1.0 \pm 0.1$ [16]. This represents an important local constraint on the growth rate, corresponding to $f(z = 0.15) = 0.49 \pm 0.14$.

2 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 $\sim$ 40000 spectra [18,19] over its *Deep* (0.5 deg^2 to $I_{AB} < 24$) and *Wide* ($\sim$ 8 deg^2 to $I_{AB} < 22.5$) parts. We have used 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* to measure β at an effective redshift $z = 0.77$ (ref. 1). We have fitted $\xi(r_p, \pi)$ with a distortion model including both linear and non-linear distortions. These contributions are described respectively by two parameters, the compression β and the *rms* pairwise dispersion σ_{12}. Fig. 1 (left) shows $\xi(r_p, \pi)$ estimated using standard methods [20], 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 were obtained from 100 fully realistic mock realizations of the survey [21,22]. Using the amplitude of mass fluctuations provided by the power spectrum of CMB anisotropies [23] and the PDF reconstruction method [24], we obtain for the effective redshift of the survey a linear bias $b_L = 1.3 \pm 0.1$ (see [1] for details), and a growth rate $f(z = 0.77) = 0.91 \pm 0.36$. This value is compared in Fig. 1 (right) to model predictions, together with measurements from the 2dFGRS [17] and 2SLAQ surveys [25]. Given the size of the error bars, deviations from the standard cosmological-constant model cannot yet be detected. Interestingly, in the framework of General Relativity, the two high-redshift measurements seem already to disfavour an $\Omega_\Lambda = 0$ model, providing an independent indication for the need of a cosmological constant.

3 Future prospects for cosmological redshift surveys

Only $\sim$ 6000 redshifts have been used to obtain the result just discussed: this suggests that there are ample margins for improvement with future, larger surveys. This includes both the estimate of β and of the linear bias. In [1] we have used a large set of simulations to forecast the gain in accuracy that can be expected from future surveys. We have established that 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 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. Such a survey has been recently proposed to ESO. Its realization would represent the basis not only for a key measurement of the growth rate, but also for a number of front-ranked investigations that have just been sketched, at this redshift, by surveys like the VVDS. As a by-product, these redshifts will also be precious for calibrating photometric redshifts from the huge imaging surveys that are just starting, as e.g. Pan-STARRS.

For the more distant future (2017), the ESA *EUCLID* mission, resulting from the merge of the original *DUNE*[27] and *SPACE*[28] 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 plan 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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