

Dark Energy and the Seeds of Galaxy Formation

1 Overview

Massive redshift surveys at $z \sim 1$ and $z \sim 3$ comprising $\sim 10^6$ galaxies over 10^2 - 10^3 deg² have the potential to measure the equation of state of the universe and its evolution, and also probe the density fluctuations that formed the seeds for the formation of galaxies and clusters. Such surveys are therefore probes of new physics: the source and nature of the dark energy that drives the accelerating expansion of the universe, and the origin of the primordial density enhancements that grew to form galaxies. The constraints on the cosmic equation of state are complementary to those that will be derived from next generation facilities observing the cosmic microwave background (Planck), distant supernovae (SNAP) and gravitational lensing (PANSTARRS and LSST). The measurements of the primordial fluctuations on galaxy scales are beyond the physical limits achievable with any future CMB measurements. The science case for these studies is extremely strong, but a 30m with a relatively small field of view faces stiff competition from an 8-10m telescope with a very wide field of view and a high-multiplex spectrograph (such as the proposed KAOS facility on Gemini).

2 Dark Energy and the Cosmic Equation of State

With the advent of the recent results from distant supernovae (Riess et al. 1998, Perlmutter et al. 1999), large redshift surveys at low redshift (Percival et al. 2001) and the WMAP measurements of the CMB anisotropies (Spergel et al. 2003) we now have quite precise measurements for the major cosmological parameters, with each of the three sets of results making an important contribution to breaking the various degeneracies. However we are left with two glaring gaps in our cosmological model: we do not know the nature of either of the two dominant components of the universe, the dark matter and the dark energy. With recent large-scale structure results ruling out neutrinos (or other hot or warm dark matter) as significant contributors to the total matter density (Elgaroy et al. 2002), it may now be the turn of direct dark matter searches to make the next major breakthrough in understanding the dark matter. However redshift surveys of large-scale structure can still make very important contributions to understanding the even more mysterious dark energy, with the potential to push physics beyond the current standard model.

The observations of distant supernovae were the first to show that the universe is currently accelerating, implying the existence of an unknown energy component acting with *negative* pressure. This discovery poses a tremendous challenge to theoretical physics, since the natural scale for the dark energy is far larger than the observed value. One venerable candidate for the dark energy is the cosmological constant, but several more dynamic possibilities have been proposed. These include quintessence (Ratra & Peebles 1998; Frieman et al. 1995; Caldwell et al. 1998), tracking scenarios (Wetterich 2002), *k*-essence (Armendariz-Picon et al. 2000), 'Cardassian Expansion' (Freese & Lewis 2002), a unification of dark energy and dark matter known as a Chaplygin gas (Bilic et al. 2002), and the alteration of gravity due to leakage into extra dimensions (Deffayet et al. 2002). All of these require exotic new physics and can be constrained by observations of the accelerating universe. Astronomical observations may therefore provide one of the few experimental handles on quantum gravity and string theory.

The characterisation of the acceleration of the universe and its physical origin is therefore *the* major frontier of cosmology. Dark energy makes its presence known by altering distance measures in cosmology, including the evolution of the Hubble parameter with time, and the growth of structure. Precision measures of distance, Hubble parameter, or object counts across

a range of redshifts all yield measures of the equation of state. It is common to parameterise the effect of the dark energy on the acceleration of the universe by the ratio between its pressure P and energy density ρ . We write the equation of state as $w=P/\rho$, where w can in principle be a function of time (Turner & White 1997). The cosmological constant has $w=-1$ at all redshifts, whereas other scenarios give different values that generally evolve with redshift. Note that in what follows we are assuming a flat Λ CDM cosmology with $\Omega_M=0.3$ and $h=0.7$.

3 Current status and prospects for the next decade

Current observations of CMB anisotropies, galaxy redshift surveys, and supernovae distances constraints together require $w<-0.7$ at the current epoch, assuming a constant w (Perlmutter et al. 1999; Percival et al. 2002; Spergel et al. 2003). This is a remarkable constraint given that it is only 5 years since the acceleration of the universe was first established. However the challenge for observational cosmology now is to determine w with precision of order 1% and also to determine its variation with time. Methods to achieve these goals are now being developed, but the observational problem is very challenging because of the subtlety of the differences in observables that are created by variations in w .

One major advance will come with the Planck satellite, due to be launched in 2007, which will provide an order of magnitude improvement in CMB measurements over *WMAP*. Another will be the *SNAP* satellite, which could launch as soon as 2008 and would provide a similar improvement in supernova cosmology. On a similar time-scale, the PANSTARRS telescopes could be carrying out deep, wide-field imaging surveys for weak-lensing mass reconstructions and cluster finding, which provide other routes to constraining the equation of state. Weak lensing provides another possible precision route to cosmology.

4 Key measurements

Massive redshift surveys of galaxies at $z>0.5$ offer an independent, high-precision route to measuring the equation of state. This is because the large-scale structure contains a preferred scale, imprinted at the epoch of reionization, that manifests itself as a series of acoustic oscillations in the power spectrum. This scale is the sound horizon, the distance that a sound wave can travel in the plasma filling the universe in the interval between the Big Bang and the epoch of recombination. The sound horizon depends only on properties of the early universe and can be precisely measured from the CMB anisotropies. *WMAP* gives a 3% measurement of the sound horizon (Spergel et al. 2003), and future CMB data should improve this to better than 1%. Hence, this scale is effectively a cosmological standard ruler (Eisenstein et al. 1998). By measuring the apparent size of the acoustic oscillations along and across the line of sight, one can measure the Hubble parameter $H(z)$ and the angular diameter distance $D_A(z)$ as a function of redshift. Such measurements would produce a precise value for the equation of state parameter at high redshifts and an estimate for its rate of evolution. This approach would give results with a precision comparable to the SNe observations obtained by *SNAP*, but using a completely independent method with well-understood uncertainties. In addition, the redshift survey approach offers the unique opportunity to pursue the dark energy to $z\sim 3$. Although a cosmological constant (i.e. $w=-1$) model predicts that the dark energy has tiny effects at $z>1.5$, some of the more dynamic (and physically exciting) models predict detectable effects at $z\sim 3$.

An obstacle to the detection of this signal in the galaxy distribution is that the gravitational evolution of structure works to erase the primordial record in the clustering patterns on smaller scales. This occurs when perturbations on a given scale become of order unity in amplitude, leading to non-linear coupling between Fourier modes. Today, this veil of non-linearity extends to wavelengths as large as 80 Mpc, enough to wipe out all but the first of the acoustic

oscillations (Meiksen et al. 1999). At higher redshifts, the process is less advanced, and the primordial signals can be recovered on smaller scales, including the full series of acoustic oscillations. For example, at $z=3$, it should be possible to recover primordial information on scales down to ~ 10 Mpc, which is at least a factor of two smaller than can be measured from the anisotropies in the CMB. Because non-linear clustering erases primordial small-scale structure, direct measurements of the primordial fluctuations on scales of 10-40 Mpc are *only* possible at high redshifts. The detailed nature of the fluctuations on these scales, which are critical to the formation of galaxies and clusters, is essentially unknown at present. Although signatures beyond the acoustic oscillations are speculative, we might find other modulations or non-Gaussianities that could provide a window onto the inflationary generation of cosmic structure and a vital modification of our assumptions about structure formation.

5 Baseline program

In a galaxy redshift survey, the fundamental observables are the angular separations and redshifts of the galaxies, and a cosmological model is required to translate these angles and redshifts into physical distances. If we observe a standard ruler at a particular redshift, then alterations in the dark energy model will distort the radial and transverse apparent size of the ruler. Since we know the true size, we can use the radial clustering signal to recover the Hubble parameter $H(z)$ and the transverse clustering signal to recover the distance $D_A(z)$. Changing w has only a small impact on cosmology, so that one must measure the distances to $\sim 1\%$ at $z\sim 1$ to distinguish these models.

Given this requirement, it is possible to calculate the necessary size of the redshift survey, using the approximate formula given by Tegmark (1997) to estimate the statistical errors on the power spectrum resulting from a particular survey design. As we are interested in the higher acoustic peaks, which occur at wavenumbers $k\sim 0.1-0.2$ Mpc^{-1} , this formula indicates that we should be using galaxies with a co-moving density around $10^{-4}-10^{-3}$ Mpc^{-3} . This is considerably lower than the density of L^* galaxies. A slightly higher density offers additional advantages and can be achieved by only going a little fainter, since this moves us rapidly up the luminosity function

At $z\sim 3$, the Lyman break galaxies provide suitable targets. If we aim for a number density of $\sim 10^{-3}$ Mpc^{-3} , then for a survey over the redshift range between $z=2.5$ and $z=3.5$ (for which the co-moving volume is 3265 Mpc^3 per arcmin²), this corresponds to ~ 3 galaxies arcmin⁻² which is

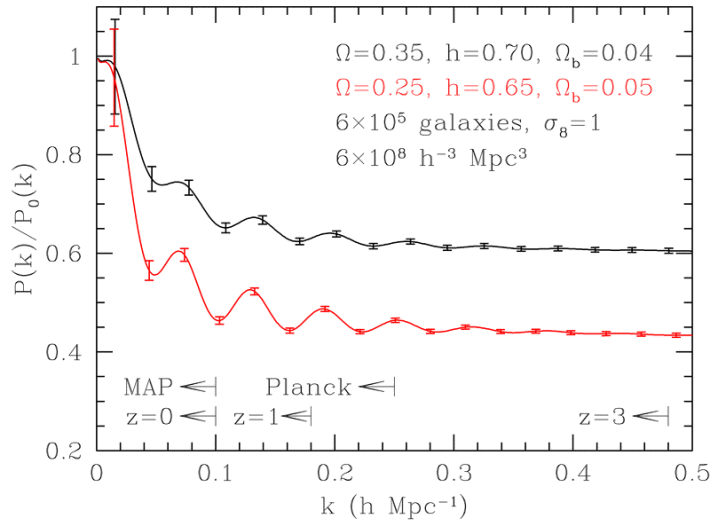


Figure 1. Simulated power spectrum and errors for the fiducial $2.5 < z < 3.5$ survey over 150 deg^2 of 6×10^5 LBGs with a co-moving density of $3 \times 10^{-3} \text{ Mpc}^{-3}$ (Eisenstein, 2002; Seo & Eisenstein 2003). Two cosmologies with different baryon fractions (both consistent with BBN and WMAP) are shown. The power spectra are divided by a zero-baryon model with the same cosmology to show the acoustic oscillations. The arrows at the bottom show the linear regime accessed by WMAP, Planck and galaxy surveys at different redshifts; note that a $z\sim 3$ galaxy survey probes the linear regime on small scales that are inaccessible to CMB observations.

obtained at a limiting magnitude of $R \approx 24$ (Steidel et al. 1996, 1999). We adopt as a fiducial survey one with 6×10^5 galaxies covering 150 deg^2 (this size being chosen to yield clear detections of the first three acoustic peaks). Figure 1 shows the power spectra recovered from the $z \sim 3$ fiducial survey, together with the estimated errors. This survey measures the power spectrum out to wavenumber $k \approx 0.4 \text{ Mpc}^{-1}$ (i.e. scales down to $\sim 15 \text{ Mpc}$), whereas Planck will only measure down to scales twice as large.

At $z \sim 1$, the choice of galaxy is less obvious, as one could use either giant ellipticals or luminous star-forming galaxies. In either case, we aim for a slightly lower number density, $2 \times 10^{-4} \text{ Mpc}^{-3}$ (since we are forced to $k < 0.15 \text{ Mpc}^{-1}$ by non-linear clustering at $z=1$, and so do not need to sample the smaller scales). From $z = 0.5$ to $z = 1.3$, there is a co-moving volume of 1574 Mpc^3 per arcmin^2 , so this leads to a surface density of ~ 0.8 galaxies arcmin^{-2} which is obtained at $R \approx 23$. We adopt a fiducial survey size of 1000 deg^2 (a similar volume to the SDSS luminous red galaxy sample), and this corresponds to 9×10^5 galaxies. This survey would only measure the power spectrum for wavenumbers less than $k \approx 0.15 \text{ Mpc}^{-1}$ (since on smaller scales non-linear clustering erases the acoustic oscillations).

Figure 2 shows the fractional errors that these surveys would yield in measuring the Hubble parameter $H(z)$ and the angular diameter distance $D_A(z)$ at different redshifts. Figure 3 then compares the resulting constraints on the mean value of the equation of state parameter (w_0) and its rate of change (w_1) with the constraints obtained using the SNAP mission (assuming best-case estimates for the systematic errors in the SNe distance estimates). For the case of a cosmological constant ($w_0 = -1$, $w_1 = 0$), SNAP provides tighter constraints, with a 1σ uncertainty on w_0 of 0.23 compared to 0.28 from the redshift surveys. However for the more physically interesting case where $w_0 \neq -1$, $w_1 \neq 0$, the redshift surveys have slightly better performance, with a 1σ uncertainty of 0.08 compared to SNAP's 0.12.

6 Need for a 20-30m telescope

Large redshift surveys such as those described above can provide accurate measurements of the dynamics of the late-time universe by using the acoustic peaks in the galaxy power spectra as a standard ruler. The level of precision is competitive with that of the SNAP satellite, and the systematic errors are completely unrelated. The results have the potential to overthrow the standard model of physics.

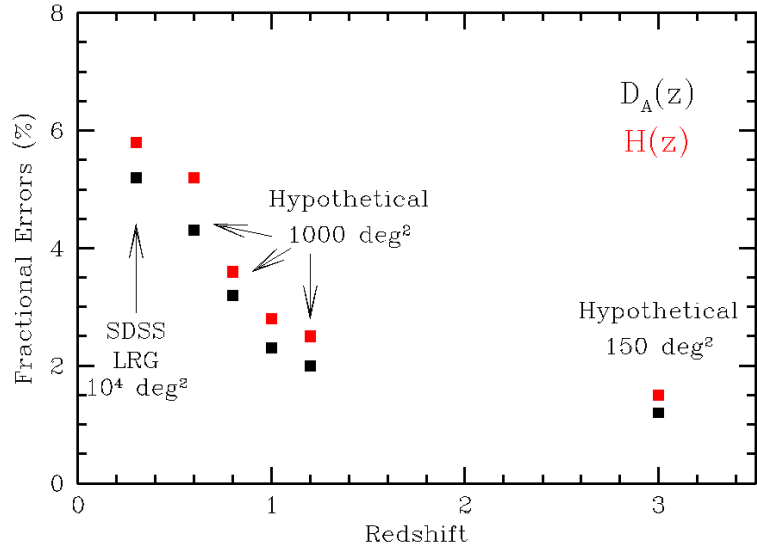


Figure 2. The 1σ errors on the Hubble parameter $H(z)$ and the angular diameter distance $D_A(z)$ for the two fiducial surveys at $z \sim 1$ and $z \sim 3$ (note that the $z \sim 1$ survey has been split into four redshift ranges), and for the SDSS Luminous Red Galaxy survey at $z \sim 3$ (Seo & Eisenstein 2003; see also Blake & Glazebrook 2003).

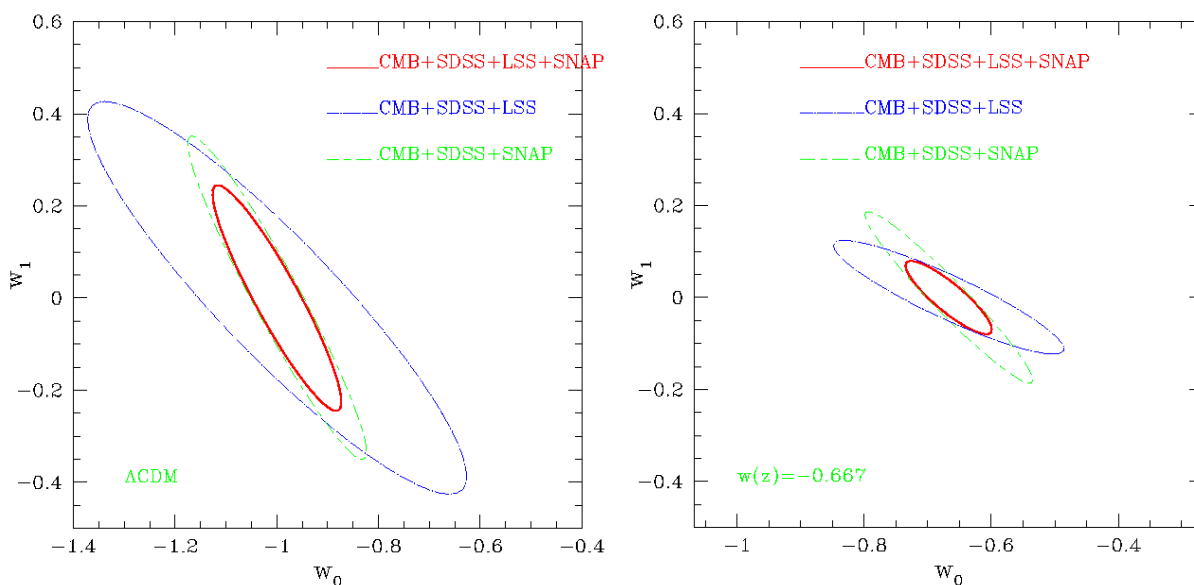


Figure 3. Constraints on w_0 and w_1 from a combination of the surveys in Fig.2, the Planck CMB data and the SNAP data (Seo & Eisenstein 2003). In the left panel the model is a flat Λ CDM cosmology with $\Omega_M=0.35$, $\Omega_b=0.05$ and $h=0.65$; in the right panel the model has the same parameters but dark energy with $w_0=-2/3$, $w_1=0$. Because the dark energy is more important at high redshift in this model, the $z\sim 3$ survey provides a stronger constraint and the galaxy surveys compare favourably with SNAP.

The massive redshift surveys over wide areas at faint magnitude limits that are required to achieve these results are very demanding. Although they could in principle be carried out with current multi-object spectrographs on existing 8-10m telescopes, in practice this approach would be far too time-consuming. For example, the fiducial $z\sim 1$ survey over 1000 deg^2 down to $R\approx 23$ would require about 5 years on an 8m telescope with a 20 arcmin field; the fiducial $z\sim 3$ survey over 150 deg^2 down to $R\approx 24$ would require about 2.5 years. This performance is readily surpassed by a 30m with a 15 arcmin field, which could do the $z\sim 1$ survey in about 230 nights, and the $z\sim 3$ survey in about 120 nights.

However an 8-10m telescope with a very wide field would be better still. For example, the KAOS facility proposed for Gemini has an 80 arcmin field and 4000 fibres could perform the $z\sim 1$ survey in 115 nights and the $z\sim 3$ survey in 60 nights. A 30m telescope with reasonably high multiplex and a field of view

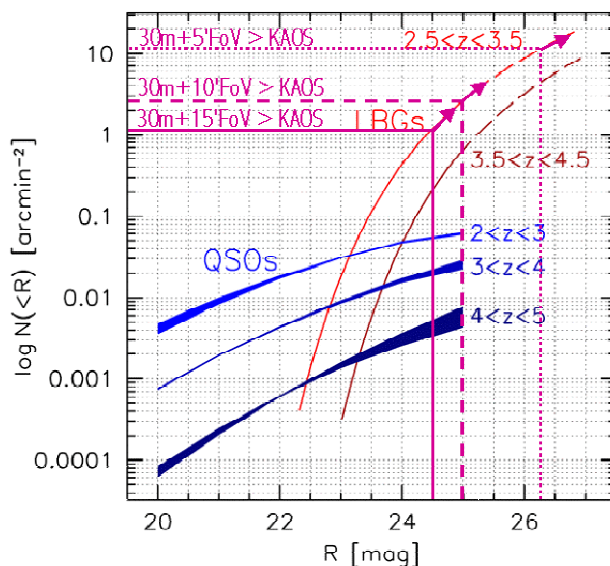


Figure 4. The surface densities at which a 30m with a 15, 10 or 5 arcmin field of view outperforms KAOS, and the corresponding magnitude limits at which these source density of Lyman break galaxies are found. A 30m needs a field greater than 21 arcmin to be superior to KAOS at all source densities.

of 15/10/5 arcmin will only out-perform KAOS on large-area surveys if the source density becomes greater than 1.3/2.8/11 deg⁻² (corresponding to the number of LBGs brighter than $R \approx 24.5/25.0/26.2$; see Fig.4); it will only out-perform KAOS at all source densities if it has a field of view greater than 21 arcmin.

If KAOS, or some similar facility, is implemented on an 8-10m telescope in the next decade, then a 30m telescope is not likely to be competitive for large-area surveys for cosmology and large-scale structure unless it has a wide (>20 arcmin) natural-seeing field of view.

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