Cosmology with the SKA

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We argue that the Square Kilometre Array has the potential to make both redshift (HI) surveys and radio continuum surveys that will *revolutionize* cosmological studies, provided that it has sufficient instantaneous field-of-view that these surveys can cover a hemisphere ($f_{\rm sky} \sim 0.5$) in a timescale ~ 1 yr. Adopting this assumption, we focus on two key experiments which will yield fundamental new measurements in cosmology, characterizing the properties of the mysterious dark energy which dominates the dynamics of today's Universe. Experiment I will map out $\sim 10^9 (f_{\rm sky}/0.5)$ HI galaxies to redshift $z \approx 1.5$, providing the premier measurement of the clustering power spectrum of galaxies: accurately delineating the acoustic oscillations and the 'turnover'. Experiment II will quantify the cosmic shear distortion of $\sim 10^{10} (f_{\rm sky}/0.5)$ radio continuum sources, determining a precise power spectrum of the dark matter, and its growth as a function of cosmic epoch. We contrast the performance of the SKA in precision cosmology with that of other facilities which will, probably or possibly, be available on a similar timescale. We conclude that data from the SKA will yield transformational science as the direct result of four key features: (i) the immense cosmic volumes probed, exceeding future optical redshift surveys by more than an order of magnitude; (ii) well-controlled systematic effects such as the narrow 'k-space window function' for Experiment I and the accurately-known 'point-spread function' (synthesized beam) for Experiment II; (iii) the ability to measure with high precision large-scale modes in the clustering power spectra, for which nuisance effects such as non-linear structure growth, peculiar velocities and 'galaxy bias' are minimised; and (iv) different degeneracies between key parameters to those which are inherent in the Cosmic Microwave Background.

1. Background

Over the last few years we have entered an 'era of precision cosmology' in which rough estimates of many of the key cosmological parameters have been replaced by what can reasonably be described as 'measurements' (parameters known to better than ~ 10 per cent accuracy). Remarkable progress in observations of the temperature fluctuations in the Cosmic Microwave Background (CMB) has been central to this scientific transformation (e.g. the recent results from the WMAP satellite, Spergel et al. 2003).

The current standard cosmological model ('ΛCDM') assumes that the Universe is composed of baryons, cold dark matter (CDM) and Einstein's cosmological constant Λ. The present-day densities of baryons, (baryons + CDM) and Λ, as a fraction of the critical density, are denoted by $\Omega_{\rm b}$, $\Omega_{\rm m}$ and Ω_Λ, respectively. The local rate of cosmic expansion is described by the Hubble parameter $h = H_0/(100\,{\rm km\,s^{-1}\,Mpc^{-1}})$. Structures in the Universe are assumed to grow by gravitational amplification of a primordial 'power spectrum of fluctuations' created by inflation, which is taken to be a 'scale free' power law $P_{\rm prim}(k) \propto k^{\,n_{\rm scalar}}$.[1]

Within this framework, we begin by reviewing what the CMB tells us about the cosmological model. The basic CMB observable is the angular power spectrum of temperature fluctuations, which consists of a series of 'acoustic peaks'. We note that the physics of the CMB fluctuations (i.e.

[1] A power law function is 'scale free' because it contains no preferred length scale. The power law index $n_{\rm scalar} = 1$ is described as 'scale invariant' because in this case, the matter distribution has the same degree of inhomogeneity on every resolution scale (is 'self-similar'). Inflationary theories of the early Universe predict that this should be approximately true.

the photon-baryon fluid driven by the dark matter potential wells) depends entirely on the physical densities of matter and of baryons, $\Omega_{\rm m}h^2$ and $\Omega_{\rm b}h^2$.[2] However, the *projection* of the anisotropy spectrum onto the sky (i.e. the angular locations of the acoustic peaks) also involves the angular diameter distance to the last-scattering surface.

- The angular location θ_A of the first 'acoustic peak' of the temperature power spectrum turns out to be relatively insensitive to all parameters apart from the *curvature of the Universe*. The global geometry is *close to* spatially flat, although positive spatial curvatures ($\Omega_k \approx -0.05$) and hence closed-Universe models remain consistent with all available data (Efstathiou 2003). It is important to note that exact spatial flatness, typically assumed, remains a theoretical prior which demands observational confirmation.

- The *physical matter density* ($\Omega_{\rm m}h^2 \approx 0.14$) is set by the ratio of the first acoustic peak height to the large-scale amplitude of the temperature power spectrum.

- The *physical baryon density* ($\Omega_{\rm b}h^2 \approx 0.024$) is fixed by the relative heights of the first and second acoustic peaks (and is nicely in accord with the value derived from nucleosynthesis-based arguments).

- The values of $\Omega_{\rm m}h^2$ and $\Omega_{\rm b}h^2$ together determine the *sound horizon s* at recombination, the characteristic physical scale fixing the spatial position of the first acoustic peak. Using the angular location θ_A of this peak, we can derive the angular diameter distance $D_A = s/\theta_A$ to the surface of last scattering (whose redshift $z \approx 1100$ is known from thermal physics). *Assuming a flat Universe and the* ΛCDM *model*, $D_A(z = 1100)$ depends on a combination of $\Omega_{\rm m}$ and h. Together with the value of $\Omega_{\rm m}h^2$ known from the first peak height, this breaks the degeneracy between $\Omega_{\rm m}$ and h, yielding $\Omega_{\rm m} \approx 0.3$ and $h \approx 0.7$.

- The overall normalization of the temperature power spectrum (i.e. the fluctuation strength at $z = 1100$) can be related to the *amplitude of mass fluctuations at redshift zero*, conventionally defined as the rms mass perturbation in spheres of radius $8\,h^{-1}$ Mpc assuming linear evolution[3] (and denoted σ_8). In a ΛCDM model, if the matter densities and Hubble constant are known, then this quantity is still degenerate with the *optical depth to the last-scattering surface* (τ). The detection of polarization in the CMB by the WMAP experiment begins to break this degeneracy by obtaining the value $\tau \approx 0.17$ (hence $\sigma_8 \approx 0.9$).

- Changing the slope of the primordial power spectrum of mass fluctuations ($n_{\rm scalar}$) induces a broad-band tilt in the CMB temperature power spectrum, that may be quantified by e.g. the ratio of the first and third acoustic peaks (note that the quantity $\Omega_{\rm b}h^2$ only controls the ratio of odd-to-even peak heights). Current data favours a roughly scale-invariant primordial fluctuation spectrum ($n_{\rm scalar} \approx 1$).

In summary, according to this crude argument, the CMB yields six independent quantities (assuming polarization measurements). For a flat ΛCDM model, the WMAP experiment alone measured values of ($\Omega_{\rm m}$, $\Omega_{\rm b}$, h, σ_8, τ, $n_{\rm scalar}$) to $5-10$ per cent accuracy (see Spergel et al. 2003).

Similar values for some of these parameters are yielded by several independent, non-CMB techniques, for example:

[2]The factor h^2 arises because these physical densities are proportional to the critical density of the Universe, which scales as H_0^2. The existence today of non-zero curvature or of a cosmological constant Λ is insignificant at recombination.

[3]When the amplitudes of density fluctuations are small (when the overdensity $\delta \ll 1$), the equations of structure formation may be *linearized* using perturbation theory. Gravitational growth is said to be in the *linear regime* and may be solved analytically with relative ease. Eventually, the fluctuation amplitudes will become too high and linear theory will break down.

- Observations of Cepheid variables and secondary distance indicators to measure h (Freedman et al. 2001).
- Searches for high-redshift supernovae to measure Ω_Λ (Riess et al. 1998; Perlmutter et al. 1999).
- Measurements of the abundance of rich clusters to determine σ_8 (e.g. Bahcall & Bode 2003).
- Measurement of the amplitude of cosmic shear (weak lensing due to large-scale structure) to constrain σ_8 (e.g. Brown et al. 2003; Hoekstra, Yee & Gladders 2002; Jarvis et al. 2003; Bacon et al. 2003; Pen et al. 2003).

The consistency of these results with those obtained from the CMB demonstrates that – if the standard cosmological picture is correct – these methods are not obviously compromised by systematic errors *at the current level of accuracy*. The next-generation CMB experiment, the Planck satellite, is planned to launch in 2007 and will further refine CMB measurements of these six parameters and second-order effects via (i) drastically-improved sensitivity on small scales and (ii) an enhanced polarization capability.[4]

However, if we wish to relax any of the assumptions of our most basic (flat ΛCDM) model then, as we will describe, the degeneracies inherent in the CMB become insuperable and *extra information* is required (Efstathiou & Bond 1999; Bridle et al. 2003). Just such a course of action is demanded by today's most pressing cosmological questions:

- Is the current rate of cosmic expansion accelerating, as suggested by recent supernova measurements?
- If so, does Einstein's cosmological constant (vacuum energy) exist, despite our inability to understand its value theoretically? Or, is the accelerating expansion driven by a different form of *dark energy*, such as 'quintessence'? What are the properties of this dark energy?
- Can competing models of inflation be discriminated by accurate measurements of the shape of the primordial power spectrum (e.g. by a 'running spectral index' instead of $n_{\rm scalar}$)?
- Can the tensor (gravitational wave) component be isolated?
- Is the Universe exactly flat or does it possess a small spatial curvature Ω_k?

In this paper we focus our discussion upon the quest to characterize the mysterious dark energy, which drives the accelerating cosmic expansion and contributes the majority of the present-day energy density of the Universe. As an explanation of the dark energy, Einstein's cosmological constant Λ is consistent with current observations but poses *tremendous theoretical challenges*. The 'natural' (quantum-mechanical) value of Λ is a factor 10^{120} higher than that measured by astronomers. This severe difficulty has motivated the development of alternative models, many featuring a *dynamic* component of dark energy whose properties evolve with time, such as *quintessence*. These competing models are essentially untested and require experiments able to measure the properties of dark energy as a function of cosmic epoch. The dark energy model is commonly characterized by its *equation-of-state* $w(z) = P/\rho$ relating its pressure P to its energy density ρ (in units where the speed-of-light $c = 1$). For Einstein's cosmological constant, $w(z) = -1$.

The resolution of this problem is the current cosmological frontier, and has been widely identified as having profound importance for physics as a whole. Needless to say, if there were a paradigm shift in the next decade that alleviated the dark energy problem, then the SKA experiments described below would be even more important in confirming and better understanding the new cosmological model.

Can the CMB inform us about dark energy? Although in the standard (ΛCDM) model dark

[4]See `http://www.astro.esa.estec.nl/~Planck`. The temperature power spectrum measured by WMAP is already 'cosmic variance limited' (i.e. cannot be improved) on large scales up to and including the first acoustic peak.

energy has a negligible effect at recombination, the CMB is in fact sensitive to the equation-of-state of dark energy because the angular positioning of the acoustic peaks depends on the angular diameter distance to $z = 1100$, which is affected by $w(z)$ (Huey et al. 1999). However, the efficacy of this probe of $w(z)$ is limited because:

- Using CMB data alone, there is an immediate degeneracy between $w(z)$ and $\Omega_{\rm m}$ to produce the same value of $D_A(z = 1100)$.
- Even given accurate external information about $\Omega_{\rm m}$ and h, the quantity $D_A(z = 1100)$ can still only constrain a weighted average of $w(z)$, i.e. *one degree of freedom*.
- The precision with which this one degree of freedom can be measured is further limited because $w(z)$ only influences dynamics at low redshift, thus its influence upon $D_A(z = 1100)$ is small.
- This lack of sensitivity implies that we can make small adjustments to the value of the sound horizon s at fixed $\Omega_{\rm m}$ by changing the mix of baryons and CDM (i.e. $\Omega_{\rm b}$) to leave unchanged the angular locations of the CMB acoustic peaks, which depend on $s/D_A(z = 1100)$.

This difficulty in measuring a non-Einstein dark energy equation-of-state $w(z)$ using the CMB alone, even if assumed to be a constant $w_{\rm cons} \neq -1$, is illustrated by Figure 1, in which we simulate the degeneracy between $\Omega_{\rm m}$ and $w_{\rm cons}$ *after Planck data has been analyzed*. Even with the addition of a very accurate independent measurement of h, there remains a ± 0.1 scatter in the value of $w_{\rm cons}$. We note that changing $w_{\rm cons}$ from -1 to -1.1 alters the value of $D_A(z = 1100)$ by less than 1%. This is because the co-moving distance to a given redshift is determined by the integral

$$x(z) = \int_0^z \frac{dx}{dz'}\,dz' = \int_0^z \frac{c}{H(z')}\,dz'$$
$$= \int_0^z \frac{(c/H_0)\,dz'}{\sqrt{\Omega_{\rm m}(1+z')^3 + (1-\Omega_{\rm m})(1+z')^{3(1+w_{\rm cons})}}}$$

to which dark energy only contributes at very low redshifts ($z \lesssim 1$). For fixed $\Omega_{\rm m}$ and h, the sound horizon can be changed by a similar fraction by varying $\Omega_{\rm b} h^2$ within its uncertainty range after the Planck experiment.

The prospects for using the CMB to map out any variations in the dark energy equation-of-state with cosmic time, the key observation required to discriminate quintessence cosmologies, are even worse. Even if the exact value of $\Omega_{\rm m}$ were known, the CMB primary anisotropies only measure a weighted average of $w(z)$ (Saini, Padmanabhan & Bridle 2003). For example, in a simple model $w(z) = w_0 + w_1 z$, we can always scale w_1 with w_0 in such a way to keep $D_A(z = 1100)$ fixed and leave the power spectrum of the primary anisotropies invariant (although there will be *second-order* changes, such as Sunyaev-Zeldovich decrements due to galaxy clusters, and the late-time Integrated Sachs-Wolfe effect).

We conclude that, due to degeneracies intrinsic to the CMB, the outstanding questions of the era of precision cosmology *demand* additional experiments of comparable power, with different inherent parameter degeneracies. As discussed above, the CMB can only weakly constrain the dark energy model. An accurate measurement of $w(z)$ requires *extremely precise* cosmological data at lower redshifts, where dark energy significantly affects the dynamics of the Universe; for example, per-cent level determinations of the distances to redshift slices at $z \sim 1$.[5] What cosmological probes can provide such precision?

- Observations of distant Type Ia supernovae as 'standard candles' track the luminosity distance as a function of redshift and provide an 'orthogonal constraint' to the CMB. Supernova surveys will be a powerful probe of the dark energy model, but we argue that *it is not yet proven* that the experimental systematics can be controlled to sufficient precision to disentangle the effects of dark

[5] Beyond $z \approx 1.5$, dark energy is expected to have a negligible effect on dynamics. This assertion should be tested; but if true, distance determinations to $z \approx 3$ have limited power for constraining $w(z)$, and measurements of the Hubble constant at $z \approx 3$ have no such power.

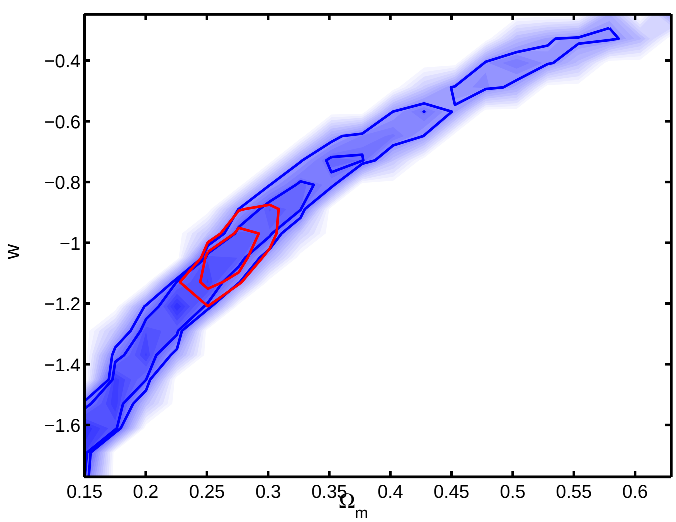

Figure 1. Simulated joint constraints $(68\%, 95\%)$ on the matter density $\Omega_{\rm m}$ and a constant dark energy equation-of-state $w(z) = w_{\rm cons}$, resulting from Planck observations of the CMB. We use TT, TE and EE simulated Planck data and only retain points with $\ell > 50$ to account for uncertainty in any dark energy perturbations, which may manifest themselves on very large scales and are strongly dependent on the exact dark energy model. The strong degeneracy in the $(\Omega_{\rm m}, w_{\rm cons})$ plane arises because the CMB power spectra are approximately invariant for fixed values of (1) $\Omega_{\rm m}h^2$ and (2) the angular diameter distance to the last-scattering surface, $D_A(z = 1100)$, which fixes the angular location of the first acoustic peak. $D_A(z = 1100)$ may be held constant by varying $\Omega_{\rm m}$ simultaneously with $w_{\rm cons}$; the combination $\Omega_{\rm m}h^2$ is kept fixed by also varying h. The inclusion of an additional tight Gaussian prior on the Hubble parameter $(h = 0.72 \pm 0.02)$ breaks the main degeneracy, resulting in the tighter inner contours. However, there remains a *secondary degeneracy* between the value of $w_{\rm cons}$ and the physical baryon density $\Omega_{\rm b}h^2$. This latter quantity can be varied to change the size of the sound horizon and compensate for changes in $D_A(z = 1100)$ due to $w_{\rm cons}$, keeping the angular peak locations fixed. The result is that, even if $\Omega_{\rm m}$ and h are known precisely, Planck data cannot determine $w_{\rm cons}$ to a precision better than ± 0.1.

energy at the required accuracy (see Section 5).

- Redshift surveys of $10^5 - 10^6$ galaxies in the local Universe provide an independent measure of $\Omega_m h$ via the shape of the galaxy power spectrum (if $n_{\rm scalar}$, Ω_b, the neutrino masses and any running spectral index are known). We argue that the efficacy of this cosmological probe is fundamentally limited by uncertainties regarding galaxy bias. In any case, Figure 1 demonstrates that the CMB cannot produce a very accurate measurement of dark energy even with the addition of extra data fixing Ω_m and/or h.

In our opinion, the critical additional information required to answer the profound questions posed in this Section will be provided by experiments measuring:

- Acoustic oscillatory features in the clustering power spectrum (Experiment I, Section 3.2).
- Weak gravitational lensing by large-scale structure, otherwise known as 'cosmic shear' (Experiment II, Section 4).

In this paper we argue that radio surveys with the SKA will provide the ultimate databases for these experiments, assuming that the telescope is designed with a wide enough field-of-view.

2. Assumptions of this paper

2.1. SKA capabilities

We adopt in this paper the SKA capabilities given by the current 'Strawman Science Requirements' (Jones 2004) with one key exception: the instantaneous (1.4 GHz) field-of-view (FOV) must exceed the Strawman value ($FOV \sim 1$ deg^2) by more than an order of magnitude for our proposed experiments.

Abdalla & Rawlings (2004; hereafter AR04) have considered this requirement in more detail, concluding that FOV and β (the ratio of the instantaneous bandwidth to the frequency range $0.5 - 1.4$ GHz required by Experiment I) must obey the relation $(\beta/0.25) \times FOV > 40$ deg^2 for the survey to have a reasonable (~ 1 yr) duration. We emphasise that FOV is the field-of-view obtained at 1.4 GHz (HI at $z = 0$) and that the calculations of AR04 assume that this field-of-view scales with redshift ($\propto \nu^{-2}$ for the purposes of this study, where ν is the frequency of redshifted HI). AR04 also note the necessity for at least half the collecting area to reside in a core of diameter ~ 5 km for Experiment I, and that Experiment II requires significant collecting area in the longer baselines to deliver the sharp angular resolution (at 1.4 GHz) necessary for measuring cosmic shear. Both of these requirements are already in the 'Strawman' design.

Using these SKA specifications, and assuming that the field of view (in units of deg^2) scales as ν^{-2}, the effective sensitivity of a 'tiled' survey[6] is sufficient to detect an $M^\star_{\rm HI} \approx 6 \times 10^9\,{\rm M}_\odot$ galaxy with a signal-to-noise ratio of 5 out to redshift $z \sim 1.5$ (assuming no evolution in the break of the HI mass function; see Sec. 2 of Rawlings et al., this volume).

In this paper we have not attempted to model those aspects of our proposed surveys which will be very dependent on the precise SKA design, such as how the *usable FOV* scales with wavelength for Experiment I, or what dynamic range is achievable for Experiment II; we note that in practice these limitations might be extremely significant. We will also ignore restrictions on 'all-sky' surveys due to finite processing resources which – even given likely technological advances over the coming decade – may still prove important, given the huge datasets that will be generated.

2.2. Other assumptions

For the remainder of this paper we assume, unless stated otherwise, a fiducial model consisting of a spatially-flat ($\Omega_k = 0$) Universe with cosmological parameters $h = 0.7$, $\Omega_m = 0.3$, $\Omega_b/\Omega_m = 0.15$, $\sigma_8 = 1$ and $n_{\rm scalar} = 1$ (broadly consistent with the recent WMAP results, Spergel et al. 2003). We adopt a fiducial dark energy model characterized by an equation-of-state $w(z) =$

[6] In which pointings just overlap at 1.4 GHz, and each receives a 4-hour integration so that the effective exposure time scales as $(\nu/1.4\ {\rm GHz})^{-2}$.

$w_0 + w_1 z$ where $(w_0, w_1) = (-0.9, 0)$, in order to illustrate the accuracy with which the SKA will be able to discriminate a general dark energy model from a cosmological constant model, for which $(w_0, w_1) = (-1, 0)$. Unless stated otherwise, we neglect contributions from tensors (primordial gravitational waves) and massive neutrinos. We assume that structure in the Universe is seeded by adiabatic Gaussian fluctuations.[7]

3. Experiment I: HI emission line surveys

The SKA will enable revolutionary progress in the field of large-scale structure. In particular, it will map out the cosmic distribution of neutral hydrogen by detecting the HI 21cm transition at cosmological distances that are almost entirely inaccessible to current instrumentation. Once an HI emission galaxy has been located on the sky, the observed wavelength of the emission line automatically provides an accurate redshift, locating the object's position in the three-dimensional cosmic web.

We simulated the co-moving space densities of HI-emitting galaxies as a function of redshift by extrapolating the observed local HI mass function using model 'C' of AR04. We note that, although an integral property of the HI mass function is constrained by observations of damped-Lyα systems, considerable uncertainty remains concerning the redshift-evolution of its break. However, reasonable models indicate that the SKA, if designed with a sufficiently wide field-of-view, can survey the entire visible sky in a year of operation, locating $\sim 10^9$ HI emission galaxies over a volume stretching to redshift $z \approx 1.5$ *with sufficient number density that clustering statistics are limited by cosmic variance, not by shot noise.* In this case, the precision with which the galaxy clustering pattern can be measured is limited entirely by the cosmic volume mapped: the SKA becomes the premier large-scale structure machine. In comparison, planned next-generation optical redshift surveys (e.g. the proposed KAOS spectrograph; `http://www.noao.edu/kaos`) will only cover $\sim$ 1000 deg^2 at $z \sim 1$, whereas all-sky photometric redshift surveys (e.g. Pan-STARRS; `http://panstarrs.ifa.hawaii.edu`) inevitably result in a serious degradation of radial power spectrum modes due to the relatively large redshift error.[8]

3.1. Galaxy power spectrum

The resulting HI redshift survey yields an improvement in power spectrum precision of between one and two orders of magnitude compared to the current state-of-the-art (Figure 2), delineating features such as the *acoustic oscillations* (see Section 3.2). In addition, the SKA clustering map traces *clustering modes on large scales beyond the power spectrum turnover* (i.e. on scales $k < 0.02\,h$ Mpc^{-1}) that are entirely inaccessible to local redshift surveys; together with extra small-scale modes (to $k \approx 0.2\,h$ Mpc^{-1}) that are hidden by non-linear clustering at redshift zero.

What cosmological information can we glean? The galaxy clustering pattern encodes a wealth of data about the underlying constituents of the Universe and the basic gravitational processes governing the formation of structure. In particular, the shape of the power spectrum depends on a combination of cosmological parameters. In Figure 3 we demonstrate that parameter constraints resulting from the SKA power spectrum vastly improve upon those obtained using the Sloan Digital Sky Survey (SDSS). Note in particular that, since the acoustic oscillations are detected in the SKA power spectrum (see Section 3.2), the baryon fraction is strongly constrained, whereas the SDSS contours are compatible with zero baryons.

The precise determination of the power spectrum on large scales can be compared with the predictions of *inflationary models*, testing for effects such as departures of the primordial power spectrum $P_{\rm prim}(k)$ from a pure power-law. The narrow window function in k-space (resulting

[7] An SKA redshift survey would provide a useful probe of non-Gaussianity by detecting large numbers of superclusters, which correspond to high-peak fluctuations in the primordial density field evolving into the quasi-linear regime.

[8] Even with a very optimistic redshift error $\Delta z = 0.02$, a photometric redshift survey must cover ≈ 10 times the area of a spectroscopic experiment to map out the same number of Fourier modes in the linear regime (Blake & Glazebrook 2003).

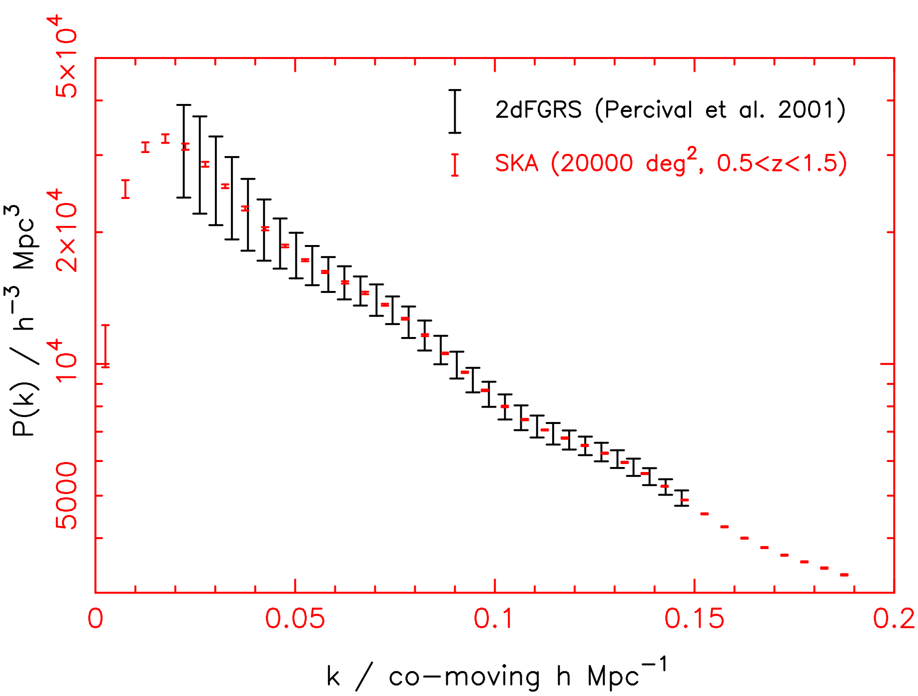

Figure 2. Simulated measurement of the galaxy clustering power spectrum by a 1-year SKA survey, compared to the 2dFGRS 100k data release (Percival et al. 2001). The measurements have been normalized to the same underlying power spectrum model, keeping the (1σ) fractional errors in each k-bin the same. For the SKA data, we assume that the redshift evolution of clustering may be divided out so that results from different redshift slices can be combined. We note that the 2dFGRS $P(k)$ data points are *heavily correlated* in this binning, whereas the SKA survey possesses a much narrower 'k-space window function' owing to the vastly greater cosmic volume probed, implying that the resulting $P(k)$ measurements are barely correlated. The SKA clustering data delineates the power spectrum turnover on large scales ($k < 0.02\,h$ Mpc^{-1}) and the acoustic oscillations (Section 3.2), as a direct result of mapping a vastly greater cosmic volume V. The error in a power spectrum measurement in the cosmic-variance-limited regime scales as $1/\sqrt{V}$, and $V_{\rm SKA} \approx 500\,V_{\rm 2dF}$.

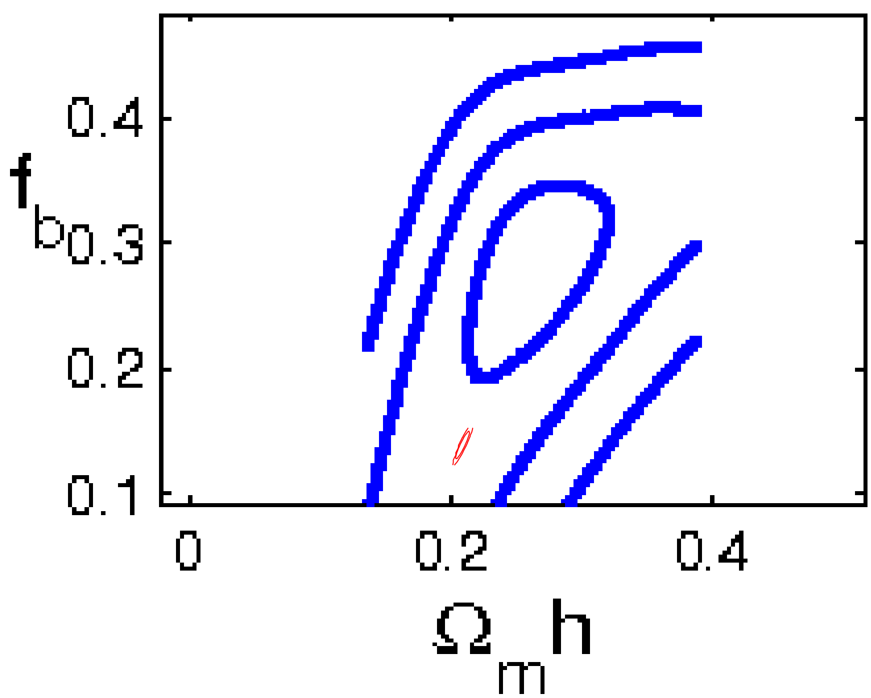

Figure 3. Joint constraints on the cosmological parameters ($\Omega_{\rm m}h, f_{\rm b} = \Omega_{\rm b}/\Omega_{\rm m}$) resulting from fitting linear theory models (calculated using the CAMB software; Lewis, Challinor & Lasenby 2000) to the shape of the SKA galaxy power spectrum (assuming a linear galaxy biasing scheme). Contours are shown for the analyzed Sloan Digital Sky Survey (SDSS) data (Pope et al. 2004; $1\sigma, 2\sigma, 3\sigma$) and for a simulated SKA HI emission-line survey (inner contour; 2σ). We only use SKA clustering data in the linear regime (with $k < 0.2\,h$ Mpc^{-1}). In order to match the assumptions of the SDSS contours, we fix $n_{\rm scalar} = 1$ and marginalize over only the Hubble constant. Whilst the SKA produces an exquisite delineation of the power spectrum, we argue that this Figure *may be wildly optimistic* because the bias model cannot be assumed to be linear at the required level of precision.

from the vast cosmic volume probed by the SKA) implies that any *sharp features* in $P_{\rm prim}(k)$ are *not smoothed out* and may be detected in a manner not possible using the CMB. It has been suggested that the intriguing outliers in the CMB temperature power spectrum measured by the WMAP satellite (at $\ell \sim 30$ and $\ell \sim 200$) could be due to unknown physics on scales smaller than the Planck length, which are imprinted during inflation (e.g. Martin & Ringeval 2004). The SKA would delineate any such effects. Furthermore, comparison with large-scale CMB modes can yield information about any *tensor contribution* to the CMB anisotropies, arising from gravity waves in the early Universe.[9] This is a second potential means, together with pulsar observations, by which the SKA can be used as a gravitational wave detector.

However, we wish to argue that the applications of the SKA large-scale structure measurements discussed above are *potentially flawed* (and at best severely complicated) by our lack of knowledge of the *detailed biasing scheme* linking the observed galaxy distribution to the underlying pattern of dark matter fluctuations produced by theoretical models (e.g. Coles 2004). In general, galaxy biasing is almost certainly stochastic, scale-dependent, non-local and non-linear (Dekel & Lahav 1999): the assumption of a simple linear bias, implicit in Figure 3, is likely to be inadequate when confronted with sub-percent precision power spectrum data.

3.2. Acoustic oscillations

Given the likely complexities of galaxy bias, we seek cosmological experiments that are less sensitive to the biasing model. The power spectrum of galaxies on large scales ($\gtrsim 30$ Mpc) should contain a series of small-amplitude *acoustic oscillations* of identical physical origin to those seen in the CMB.[10] These features result from oscillations of the photon-baryon fluid before recombination, and encode a characteristic scale – the *sound horizon at recombination* – accurately determined by CMB observations as described in Section 1. This scale can act as a *standard ruler* (Eisenstein 2002). Its recovery from a galaxy redshift survey depends on the assumed cosmological parameters, particularly the dark energy model, and thus constrains that model over a range of redshifts (Blake & Glazebrook 2003; Seo & Eisenstein 2003).

The application of this cosmological test does not depend on the overall shape of the power spectrum, which can be divided out using a smooth fit, but only on the residual oscillatory signature of the acoustic peaks. Hence the method is insensitive to smooth broad-band tilts in $P(k)$ induced by such effects as a running spectral index, redshift-space distortions, and complex biasing schemes (e.g. based on haloes; Seljak 2000). It would be very surprising if the biasing scheme introduced *oscillatory features* in k-space liable to obscure the distinctive acoustic peaks and troughs. In the absence of major systematic effects, constraints on the dark energy model are limited almost entirely by how much cosmic volume one can survey, rendering this an ideal experiment for the SKA, which can map the HI galaxy distribution out to $z \approx 1.5$ (where three acoustic peaks lie in the linear regime).

In Figure 4 we display simulated power spectra for a survey covering $20,000$ deg^2, divided into redshift slices. If the observer applies the wrong dark energy model when converting HI redshifts to cosmic distances, then the peaks and troughs in the recovered $P(k)$ lie in the wrong places: the experiment becomes a powerful probe of dark energy.

The standard ruler provided by the acoustic oscillations may be applied separately to the tangential and radial components of the power spectrum, resulting in independent measurements of the co-ordinate distance $x(z)$ to each redshift slice and its rate of change $x'(z) \equiv dx/dz$, respec-

[9] Assuming that such a tensor contribution may be disentangled from any large-scale effects due to clustering of dark energy, galaxy bias, and the potential presence of 'isocurvature' density fluctuations in the early Universe (in addition to the usual adiabatic perturbations).

[10] The acoustic oscillations imprinted in the matter power spectrum possess significantly lower amplitude than those found in the CMB power spectrum, because the baryonic component of the matter distribution, which contains the oscillatory imprint, is sub-dominant to the CDM component.

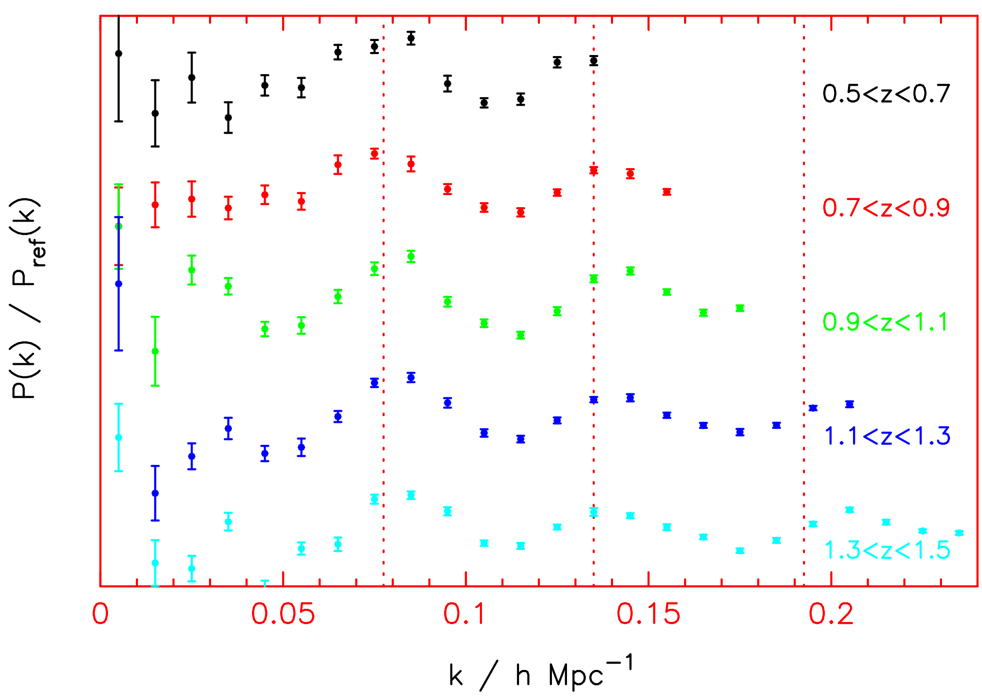

Figure 4. Simulated galaxy power spectra for an SKA survey of 20,000 deg^2, analyzed in redshift slices of width $\Delta z = 0.2$. Each power spectrum is divided by a smooth polynomial fit, revealing the sinusoidal imprint of acoustic oscillations, and is shifted along the y-axis for clarity. As redshift increases, the linear regime extends to smaller physical scales (larger values of k), unveiling more peaks. The acoustic oscillation 'wavelength' may be used as a standard ruler. This is illustrated by the Figure: the true dark energy model is $w = -1$, but the observer has incorrectly assumed $w = -0.8$ when constructing the power spectra, and consequently the recovered acoustic scale disagrees with that observed in the CMB (represented by the vertical dotted lines).

tively.[11] We fitted these simulated measurements of $x(z)$ and $x'(z)$ over a series of redshift slices, assuming a dark energy model $w(z) = w_0 + w_1 z$. Figure 5 illustrates the accuracy of recovery of (w_0, w_1) assuming a fiducial cosmology $(-0.9, 0)$, demonstrating that in this case we can dismiss a cosmological constant model $(-1, 0)$ with high significance. The accuracy of our prior knowledge of Ω_m and h affects the tightness of the dark energy constraints. These parameters must be known to standard deviations $\sigma(\Omega_m) = 0.01$ and $\sigma(h) = 0.01$ if these uncertainties are not to dominate the overall error in (w_0, w_1). These demands are not unrealistic on the SKA timescale: SKA observations of masers in the vicinity of black holes will determine h to $\sim 1\%$ accuracy (Greenhill, these proceedings) and CMB data from the Planck satellite will fix $\Omega_m h^2$ to a similar precision (Balbi et al. 2003).

Given that the SKA will be unavailable until ~ 2020, what other projects plan to survey the acoustic peaks? Two leading contenders are the multi-object near-infrared/optical spectrographs FMOS and KAOS, due to commence operation later this decade at the Subaru and Gemini telescopes, respectively.[12] These projects may perform redshift surveys of a few hundred deg^2, deriving constraints on (w_0, w_1) that are several times poorer than the $20,000$ deg^2 SKA survey presented above (the error bars roughly scale as $1/\sqrt{f_{\rm sky}}$). In radio wavebands, SKA prototypes may be developed such as the HYFAR proposal (Bunton et al. 2003). The speed of surveying $z = 1$ HI emission galaxies for such a prototype would lag the SKA by roughly an order of magnitude; furthermore, the bandwidth may be significantly smaller than that envisaged for the SKA.

In summary: even if these precursor experiments succeed in detecting a deviation from Einstein's cosmological constant, the SKA will still be required for a precise delineation of the new model. The key advantage offered by a radio telescope is that it may be designed with a field of view exceeding an optical spectrograph by a factor of 100: the SKA can survey *all the available volume* by studying the whole visible sky. Moreover, SKA sensitivity is necessary and sufficient for detecting tracers of this volume out to $z = 1.5$.

4. Experiment II: radio continuum surveys for cosmic shear

Light rays follow geodesics, which bend in the presence of matter. It follows that a coherent shape distortion is imprinted in the distribution of distant background galaxies by mass fluctuations in the intervening cosmic web: there is a small tendency for galaxies to be tangentially aligned. This pattern of *cosmic shear* encodes a vast body of information and, in principle, is a remarkably powerful cosmological probe. The shear pattern is directly sensitive to the mass distribution predicted by the underlying theory, and does not depend on the complex details of how galaxy light traces mass. Furthermore, cosmic shear may be used to measure dark energy: which controls both the *angular diameter distances* intrinsic to the lens equation (e.g. the source-lens distance) and the *redshift evolution of the mass fluctuations* producing the lensing.

A successful cosmic shear survey has three leading design requirements: very high image quality for reliable shape measurements, a high source surface density ($\gtrsim 100$ arcmin^{-2}) to limit statistical noise, and a wide survey area to reduce cosmic variance. Each of these demands is delivered superbly by an SKA radio continuum survey (Schneider 1999).

The leading systematic for ground-based optical cosmic shear experiments is the difficulty in quantifying systematic variations in the point-spread function, due to inevitable changes in the atmospheric seeing and telescope properties with position and time. The psf determination is accomplished by observing stars in the field (of

[11] The actual quantities determined by the experiment are the ratio of x and x' to the sound horizon s at recombination (which determines the characteristic spatial scale of the acoustic oscillations). The value of s is determined by CMB observations, via $\Omega_{\rm m} h^2$ and $\Omega_{\rm b} h^2$, but is affected to some extent by uncertainities in $\Omega_{\rm m}$ and h (Figure 5). The tangential component of $P(k)$ measured in a survey slice at redshift z determines $x(z)$ because this latter quantity governs the tangential scale of the recovered galaxy distribution in that redshift slice: displacements Δr are determined by $\Delta r = x\,\Delta\theta$. The value of $x'(z)$ fixes the radial scale of the recovered distribution: $\Delta r = (dx/dz)\,\Delta z$.

[12] KAOS is still unfunded.

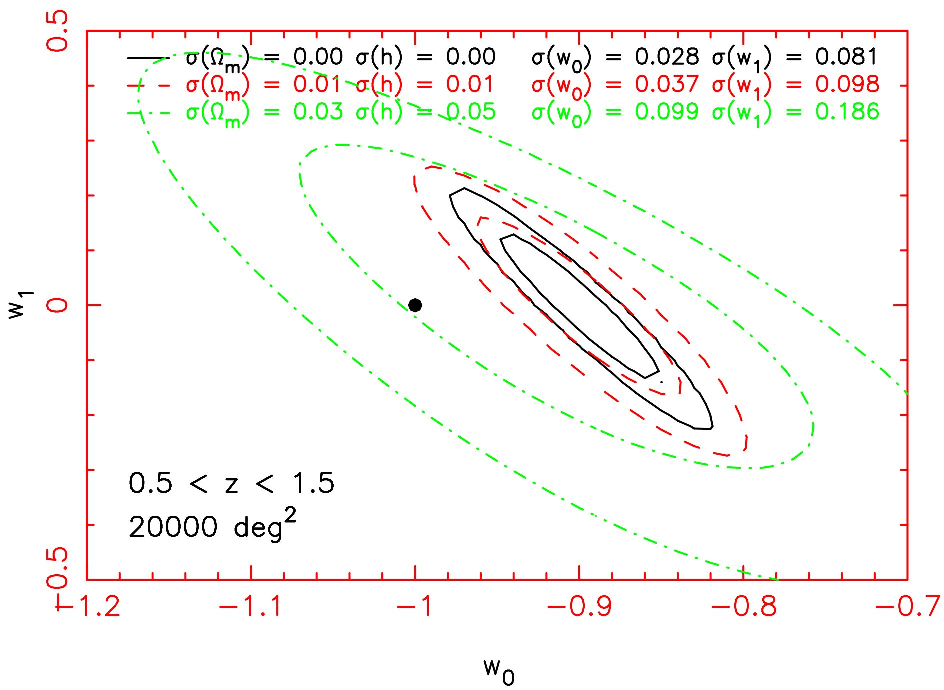

Figure 5. Constraints on a dark energy model $w(z) = w_0 + w_1 z$ achievable by an SKA survey of the acoustic peaks, illustrated by sets of $(68\%, 95\%)$ contours corresponding to different assumed priors. The solid contours correspond to perfect knowledge $\Omega_m = 0.3$ and $h = 0.7$. For the dashed contours we impose Gaussian priors with standard deviations $\sigma(\Omega_m) = 0.01$ and $\sigma(h) = 0.01$, which are not unrealistic in the SKA epoch. In each of these two cases we are able to distinguish a fiducial model $(w_0, w_1) = (-0.9, 0)$ from a cosmological constant (marked by the solid circle). Weaker Gaussian priors $\sigma(\Omega_m) = 0.03$ and $\sigma(h) = 0.05$ (the dot-dashed contours) are inadequate for this purpose. Note that there remains a residual degeneracy in the (w_0, w_1) plane because at a given redshift, approximately the same cosmology can be obtained by increasing w_0 and decreasing w_1. This degeneracy is partially broken by measurements across a range of redshift slices (and by the independent determinations of x and x' for each redshift).

which there are a limited number density). In comparison, the point-spread function of a radio telescope is well-determined and stable (being simply derived from the interferometer baseline distribution, i.e. the synthesized beam). In addition, the planned SKA angular resolution (≈ 0.05 arcsec at 1.4 GHz) vastly improves upon that obtainable over wide fields from the ground.

Space-based optical cosmic shear surveys should also exist by the time the SKA is available. However, the planned area for these surveys is ≈ 300 deg^2 (a SNAP-like experiment; Massey et al. 2004), which will be dwarfed by an SKA all-sky continuum survey. The fraction of sky $f_{\rm sky}$ mapped is directly related to the precision of the shear power spectrum measurement via a factor $1/\sqrt{f_{\rm sky}}$.

An SKA continuum survey will achieve sensitivities of ~ 30 nJy in a 4-hour pointing, far exceeding depths attained by contemporary radio surveys. In order to simulate the results of an SKA cosmic shear experiment, we must assume a model for the radio source populations at these unprecedented flux densities. We generated this model from a combination of two populations: starburst galaxies and quiescent spiral disks (we ignore for now the Active Galactic Nuclei which dominate at the highest flux densities but which have too low surface density to contribute significantly to the weak lensing signal at SKA sensitivities). We extrapolated local radio luminosity functions for these two populations (Sadler et al. 2002) as a function of redshift using a Press-Schechter-based approach, and folded in a prescription for the physical sizes of each population. Full details of these models will be published elsewhere (Abdalla et al., in prep.).

Using these population models, we simulated radio skies as a function of SKA integration time and angular resolution. Following the method of Massey et al. (2004), we then employed standard shape-estimation software (Kaiser, Squires & Broadhurst 1995) to recover the shear dispersion per galaxy arising from intrinsic shapes and from measurement errors (σ_γ) together with the surface density of 'usable galaxies' (n_g) after cuts for objects that are unresolved or faint. The values achieved, $\sigma_\gamma \approx 0.2$ and $n_g \sim 500$ arcmin^{-2}, are comparable to space-based optical surveys (Massey et al. 2004) whilst covering a survey area 100 times larger. Figure 6 illustrates the measurement accuracy of the *cosmic shear angular power spectrum* using these data.[13]

The resulting measurements of the dark energy model can be estimated using the Fisher matrix methodology (e.g. Refregier et al. 2004). Figure 7 illustrates joint constraints on (w_0, w_1) using the shear power spectrum up to $\ell = 10^5$. The analysis requires models for both the *source redshift distribution* (which can be readily inferred from a deep HI emission-line survey of a sub-area of the sky) and the *linear theory mass power spectrum* (e.g. calculated using CMBFAST; Seljak & Zaldarriaga 1996) corrected for non-linear effects in accordance with the prescription of e.g. Smith et al. (2003).

The power of this experiment may be increased by splitting the lensed galaxies into two broad redshift bins (Refregier et al. 2004). This is readily, if roughly, accomplished by separating the radio continuum sources into two groups determined by detection (or absence) in the HI emission-line survey of Experiment I.

We note that a cosmic shear survey does not necessarily require exquisitely-measured galaxy shapes, because there is an irreducible scatter resulting from the unknown ellipticity of each galaxy *before* shear.[14] Instead, the 0.05-arcsec SKA resolution is required to (1) resolve starburst galaxy disks at high redshift and (2) eliminate radio source confusion. A potential residual systematic error may lie in *intrinsic alignments* of galaxy disks (owing to structure formation processes) which may masquerade as coherent shear signal. For example, some starburst galaxies may exist in pairs, forming merging disk systems. Taking an extremely cautious approach, we assume for now that starburst galaxies would not be used in the cosmic shear analysis. This reduces the surface density by a factor of two, but the SKA still yields a vast improvement in dark energy con-

[13] We note that it is also possible to analyze a radio cosmic shear survey directly in the *uv*-plane (Chang & Refregier 2002).

[14] In the ideal cosmic shear experiment, the unsheared objects would all be circular.

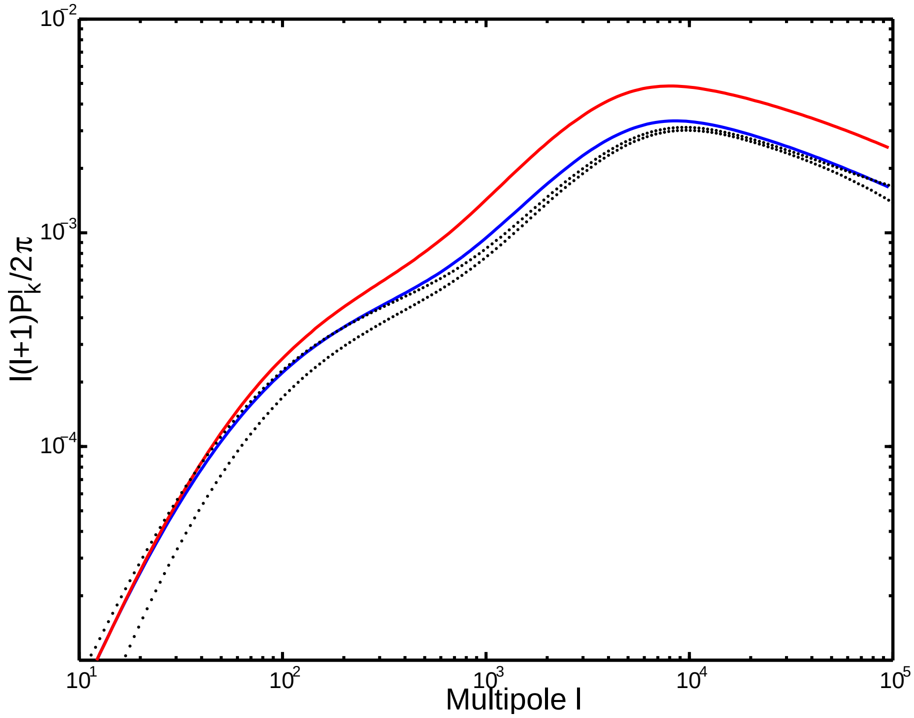

Figure 6. The cosmic shear angular power spectrum measured from a simulated SKA radio continuum survey. The upper (red) curve is for a model with $\Omega_{\rm m} = 0.25$ and $w_{\rm cons} = -0.9$; the lower (blue) curve is for $\Omega_{\rm m} = 0.3$ and $w_{\rm cons} = -1$; the dotted lines show the $\pm 1\sigma$ range for $\Omega_{\rm m} = 0.3$ and $w_{\rm cons} = -0.9$. We assume that the survey contains a surface density of usable galaxies $n_g = 200$ arcmin^{-2} and covers one hemisphere ($f_{\rm sky} = 0.5$).

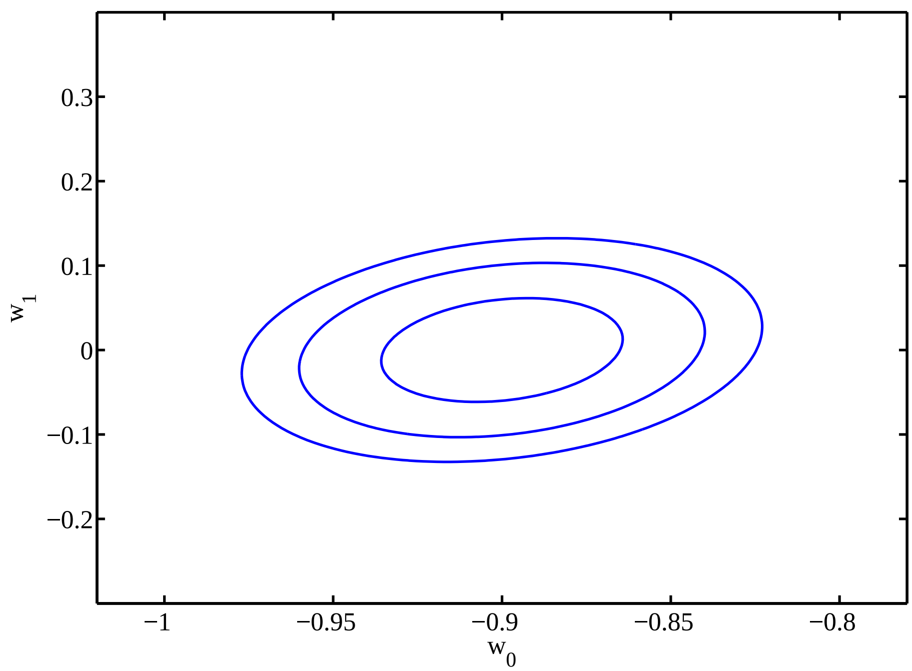

Figure 7. (68%, 95%, 99%) likelihood contours for a dark energy model $w(z) = w_0 + w_1 z$ from an SKA cosmic shear survey over a hemisphere, assuming 200 usable galaxies per square arcminute. We marginalize over the other cosmological parameters ($\Omega_{\rm m}$, $\Omega_{\rm b}$, h, n_s). These contours are conservative because no redshift information per galaxy has been included.

straints compared to future space-based surveys.

The shear angular power spectrum is the most basic lensing experiment; we note that the *bi-spectrum* (three-point statistic) promises comparable, statistically-independent constraining power on small scales (Takada & Jain 2004). A third independent approach is to target *the most massive clusters* around which the imprint of cosmic shear is most significant. Deep HI follow-up can yield full background source redshift information, allowing us to cross-correlate the cosmic shear signal in redshift slices behind the massive lens, yielding a purely geometric probe of cosmic distances ('cross-correlation cosmography', e.g. Jain & Taylor 2003). This method provides a probe of the angular diameter distance as a function of redshift independent of the acoustic oscillations in the clustering power spectrum. However, a potential systematic error is introduced by the presence of additional projected masses along the line-of-sight.

5. The SKA as the Dark Energy Machine

The current frontier of cosmological research is the characterization of the properties of the 'dark energy' that dominates the energy density of today's Universe and drives its accelerating expansion. In this paper we have focussed on two key experiments – acoustic oscillations (Experiment I) and cosmic shear (Experiment II) – by which a wide-field SKA can generate measurements of the dark energy model that are significantly more accurate than any competition by ~ 2020. Even if precursor surveys detect evidence for a deviation from Einstein's cosmological constant, the SKA will be required for a precise delineation of the new model.

In Figure 8 we compare overall SKA measurements of a dark energy model $w(z) = w_0 + w_1 z$ with (arguably) the most promising competitor: the (currently unfunded) satellite mission SNAP, planned to launch in ~ 2014, whose basic goal is to locate approximately two thousand supernovae to $z \approx 1.7$ (`http://snap.lbl.gov`; Aldering et al. 2004).[15]

Observations of distant Type Ia supernovae as 'standard candles' provided the first clear evidence for the accelerating expansion of the Universe (Riess et al. 1998; Perlmutter et al. 1999). Future high-redshift supernova searches will be a powerful probe of the dark energy model. However, we argue that *it is not yet proven* that the dimming effect of cosmic acceleration can be distinguished from other systematic effects *with sufficient precision* to render this cosmological probe as reliable as Experiments I and II above. Such systematic effects include changes in the intrinsic properties of supernovae with galactic environment (e.g. metallicity), dust extinction from both the host galaxy and the Milky Way[16], and the difficulties of photometric calibration (supernova K-corrections, together with the inadequacy of local 'standard stars' such as Vega for providing sub-percent-level flux calibration).

Many other probes of dark energy have been suggested in the literature (see e.g. Gurvits, this volume). We argue that, whilst these probes will provide important cross-checks of the cosmological model, none can yield the raw precision or control of systematic errors afforded by our Experiments I and II. For example, using SKA (or other) data we can perform *number counts of haloes* as a function of circular velocity and redshift to infer the cosmological volume element (Newman & Davis 2000). But this experiment requires an accurate theoretical prediction of the number density distribution with circular velocity (i.e. a precise understanding of baryons) together with precisely-measured rotation curves at high redshift. Alternatively, *number counts of galaxy clusters* can be utilized (e.g. Weller, Battye & Kneissl 2002). The main systematic difficulty here is connecting the cluster observable (e.g. X-ray luminosity or SZ decrement) to the halo mass (upon which the cluster abundance is exponen-

[15] We note that the planned SNAP mission also includes a weak lensing component that will yield outstanding space-based image fidelity. However, as noted in Section 4, an SKA cosmic shear survey can cover a area ~ 100 times greater with comparable resolution.

[16] The recent measurement of several supernovae at $z > 1$ by the Hubble Space Telescope (Riess et al. 2004) has assuaged this doubt to some extent by detecting a transition with increasing redshift from accelerating to decelerating expansion, which would not occur if the inferred acceleration was an artefact of dust extinction.

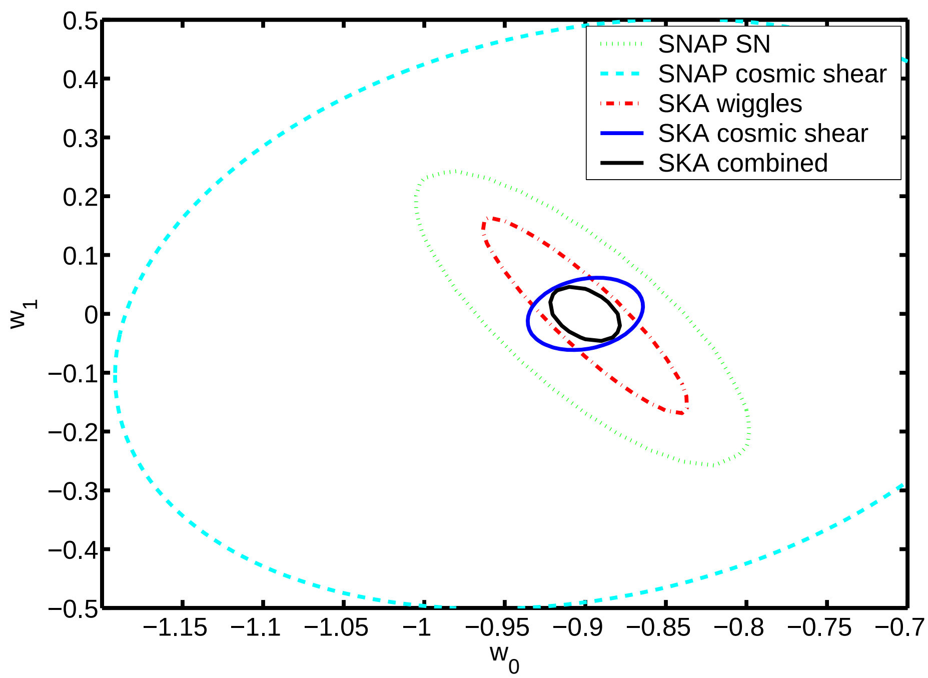

Figure 8. Comparison of constraints on the dark energy equation-of-state, parameterized as $w(z) = w_0 + w_1 z$, obtained by the proposed satellite mission SNAP (using both the supernova and cosmic shear experiments) and the SKA (via acoustic oscillations and cosmic shear). The contours represent '$\pm 1\sigma$' confidence intervals. A Gaussian prior upon the matter density, $\sigma(\Omega_{\rm m}) = 0.01$, was consistently applied to the supernova and acoustic peaks analyses. For the latter we also assume a prior $\sigma(h) = 0.01$ for the Hubble parameter, which could be obtained by measuring masers using the SKA. We assumed that the SNAP supernova component produces measurements of the luminosity distance to an accuracy of 1.4% in each of 50 redshift bins between $z = 0.1$ and $z = 2$. The cosmic shear contours for both SNAP and SKA are conservative because the sample has not been split into two or more bands in redshift. This analysis method was shown by Refregier et al. (2003) to improve significantly the constraints from SNAP cosmic shear, and would have a similar effect on the SKA measurements.

tially sensitive). The frequency of *strong gravitational lensing* (the number of lensing arcs in the vicinity of massive haloes) is also sensitive to dark energy (Bartelmann et al. 2003), but in manner very dependent on accurate simulations (see also Koopmans, Browne & Jackson, this volume)DW. We argue that these various experiments will provide insight into the complex processes of structure formation, rather than into the underlying cosmological model.

Finally, if matter *does not* dominate the dynamics of the Universe, then gravitational potential wells begin to 'decay', inducing a net shift in the energies of CMB photons passing through these wells. This phenomenon is known as the *late-time Integrated Sachs Wolfe (ISW) effect*. Its influence on the CMB power spectrum is restricted to large scales ($\ell < 10$) where it is clouded by cosmic variance. However, its presence induces a correlation between CMB anisotropies and the low-redshift matter distribution, which has been detected using *current* radio surveys (e.g. Boughn & Crittenden 2002) and could be probed further with the SKA. Measurement of the late ISW effect is an important confirmation of the dark energy model, and is sensitive not just to the evolution of dark energy, but also to its clustering properties (e.g. Weller & Lewis 2003; Bean & Dore 2003).

We conclude that, owing to its capacity to undertake cosmic surveys on an unprecedented scale, the SKA will become the paramount tool for answering the key questions of the era of precision cosmology. The SKA can perform clean and powerful experiments to characterize dark energy, mapping the acoustic oscillations in the clustering power spectrum and the patterns of cosmic shear distortion in the radio sky. Furthermore, SKA data can enlighten other pressing cosmological questions, pursuing tests of inflationary theories and measuring spatial flatness with unprecedented precision.

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Acknowledgments

CB acknowledges Karl Glazebrook for a valuable collaboration developing simulations of acoustic oscillations. FA and SB thank Phil Marshall and Richard Massey for useful discussions about cosmic shear. CB thanks the SKA Project Office for financial support. FA thanks PPARC for a Gemini Research Studentship and the SKA Project Office for financial support. SB acknowledges the support of the Royal Society. SR thanks PPARC for a Senior Research Fellowship and the ATNF for financial support.