Cosmology Science Assessment Workshop Summary

February 2014

Overview

SKA Phase 1 will be a cosmology machine with unprecedented power to probe the largest scales of the dark Universe. All sky (3pi) surveys in HI (intensity mapping and threshold) and in continuum can deliver constraints competitive with the future 'benchmark' experiment Euclid on key probes of dark energy, such as the Baryon Acoustic Oscillations and Redshift-Space Distortions. It will also provide unprecedented constraints on key parameters such as the curvature of the Universe and primordial non-Gaussianity. With different systematics from the optical, SKA1 provides a valuable consistency check of optical surveys. By also checking for consistency with the CMB, SKA1 has the potential for discovery of new features of the Universe. SKA1 will pave the way for the billion galaxy survey and for revolutionary weak lensing surveys that will be delivered by SKA2.

HI intensity mapping survey

Most of the interesting cosmological signal is on large scales (> 0.5 deg, including the BAO) so that we can relax the resolution requirements and just map the intensity fluctuations from the HI emission on the sky without the need for a threshold survey. A single SKA dish has the capability to do such a survey. Combining the information from all the SKA dishes (just the auto-correlation) will reduce the survey time by a large factor. The interferometer data itself can be used in the calibration of the gains for the dish survey. Moreover, the interferometer can provide extra information on small scales which can be used to constrain other physics such as neutrino mass.

A dish survey with SKA1-MID and 10,000 hours observing time can provide constraints on the Hubble rate and angular diameter distance at the percent level and make measurements of the dark energy equation of state, the growth index and neutrino mass, comparable with Euclid. Moreover, since it will be able to probe higher redshifts and extremely large scales, it can provide unprecedented measurements on the curvature of the Universe and primordial non-Gaussianity. Taking into account SKA1-SUR as well as the interferometer information from SKA1-MID will further improve on these measurements. (Bull et al. 2014.)

These measurements will require accurate foreground subtraction. Detailed simulations have shown that the simple application of current foreground subtractions keeps the BAO information unchanged with intensity mapping surveys (Wolz et al. 2014). More advanced methods will enhance the results. Comparison of the intensity mapping power spectrum with the direct galaxy power spectrum will impose other constraints and further reduce the foreground problem.

Requirements: For the dish survey, the first level requirement is that the auto-correlation data be provided together with the calibration information from the interferometer. Given that we are talking about 254 single-dish information and frequency resolutions of ~ 0.1 MHz, analysing this data is easily within reach of even today's computing. Polarization calibration to reduce leakage is an important factor but this is a requirement for many other projects (exact level needs to be checked). Other issues related with temperature stability can be important if there is room for improvement. Note that we are only interested in the *fluctuations* of the diffuse signal across the sky. Being able to probe frequencies below 600 MHz (z>1.4), ideally 350 - 1000 MHz, is crucial in order to probe the Universe before dark energy domination and the large scale modes only available at z>2. For the interferometer, probing BAO requires baselines < 100m. One option to increase the number of baselines between 15m and 100m without a major impact on the overall baseline configuration, would be to rearrange the dishes within the inner core into clusters of ~10 dishes each, packed together within a 100m diameter.

HI threshold survey

SKA1 can detect tens of millions of galaxies out to z~0.7. Although this is not competitive with Euclid for BAO and the power spectrum (smaller redshift range), it does provide better redshift space distortions than Euclid (since the number density of galaxies probed will be much higher). SKA1 will also have different systematics on large scales, allowing for important cross-checks with Euclid. The SKA1 threshold survey will pave the way for the deeper 'billion galaxy' survey on SKA2.

The SKA1 threshold survey can help reduce systematics in the intensity mapping survey on large scales, helping foreground subtraction and reducing errors on non-Gaussianity. Smaller area threshold surveys can be used to provide high redshift measurements of the power spectrum. They will also be important for the continuum surveys – improving knowledge of the redshift distribution of galaxies in the continuum survey via cross correlation.

Continuum survey with no morphological information

Several experiments can be carried out with a 3pi steradian continuum survey at relatively poor resolution, i.e. around 2 arcsec, to ensure that the survey is not source confusion limited. A combination of three probes - the angular power spectrum, the integrated Sachs-Wolfe effect (ISW; cross-correlation with the CMB), and the cosmic magnification signal - can provide relatively strong constraints on how gravity works on the very largest scales, and probe departures from General Relativity (Raccanelli et al. 2012). If the radio continuum data is cross-matched with relatively shallow optical data, this significantly improves the constraints on dark energy. It also turns the cross-correlation with the ISW into a powerful probe of non-Gaussianity, matching Planck but with the key difference that it provides a probe at a redshift of order unity. (Camera et al. 2013, Raccanelli et al. 2014.) Simulations are being developed to study the effect of systematics in the relative flux calibration on the potential of SKA to measure the very large scale features at high statistical significance.

One of the main uncertainties of this work is in the evolution of bias of radio sources. Weak lensing maps of the CMB from Planck can be used to determine the bias of the radio source populations. Continuum surveys over the CMB lensing map regions would thus be of direct benefit for investigating the cosmological model with radio surveys.

At the largest angular scales, the interpretation of the CMB dipole as kinematic (i.e. due to our motion through the Universe) leads to the prediction of a corresponding kinematic cosmic radio dipole. A good understanding of both dipoles is key to define comoving observers and probe isotropy of the Universe. First attempts to measure the cosmic radio dipole find it to point to a direction consistent with the CMB dipole, but with an amplitude 4 times greater (both from NVSS and from WENSS). All sky surveys from SKA1 will be able to pin point the cosmic radio dipole to better than a few degrees and to measure its amplitude with high precision. At the same time they can map the local large-scale structure over all the sky and thus improve our understanding of bulk flows. SKA2 surveys might be able to match the precision of the current CMB dipole measurement.

Continuum survey with morphological information – huge gains

If SKA1 can conduct the all sky continuum survey with ~0.5 arcsec resolution rather than 2arcsec, then there are huge gains for cosmology.

Radio weak lensing surveys

Over the last two decades, weak gravitational lensing has emerged as a key cosmological probe of the dark sector and of gravity. Lensing is a key science driver for current and forthcoming large surveys and telescopes, including the Kilo-Degree Survey, the Dark Energy Survey, the Large Synoptic Survey Telescope and Euclid. The SKA offers a unique approach to performing precision weak lensing. This is due to a number of compelling potential advantages of radio-based lensing measurements. Of particular note are the following:

- Radio interferometer telescopes in principle have stable and deterministic beams. Problems associated with image distortions induced by the telescope (which are a key instrumental systematic in optical lensing surveys) will be predictable, and therefore calibratable, to a large extent.
- Cross-correlation of galaxy shapes as observed in overlapping optical and radio surveys (e.g. SKA, Euclid and LSST) would provide a powerful route to minimising instrumental systematic effects, which are expected to be the dominant error in the next generation of lensing measurements. In cross-correlations between radio and optical, systematic effects would not be correlated between the telescopes.
- Radio polarization observations and/or HI rotational velocity measurements can be used to estimate and remove the effects of intrinsic galaxy alignments, the key astrophysical systematic effect that limits weak lensing at all wavelengths.
- The ability to split up the radio continuum signal as a function of frequency, coupled with the fact that galaxies exhibit smoothly varying spectra in the radio band, mean that radio based lensing measurements will be much less susceptible to the 'colour gradient' bias that afflicts optical lensing analyses.

The SKA has a unique ability to probe the very largest scales in the Universe. An ultra-wide SKA1 weak lensing survey with 2 years of on-sky observing, and covering 3pi steradians, would provide highly competitive constraints on the evolution on the matter power spectrum in the purely linear regime. Alternatively, a two-year survey concentrated over a few thousand square degrees (e.g. the DES survey area) would probe the source galaxy population to higher redshift ($z > 1.2$) than typically reached by optical lensing surveys (e.g. DES median $z\sim0.6$). The addition of this high redshift information would enhance studies of structure growth by adding additional high-redshift bins to a tomographic cosmic shear analysis. This would in turn result in improved constraints on dark energy parameters.

In order to realize the potential of SKA1 for weak lensing, careful consideration of a number of technical issues is required. In particular, work is currently ongoing to address the following issues:

- Trade-off between resolution and sensitivity: the ideal weak lensing SKA antenna configuration would maximize sensitivity at the resolution required to accurately characterize the shapes of star-forming galaxies at $z\sim1$ to 2. Current observations suggest a required resolution of ~0.5 arcsec (and pixel scale of ~0.2"). Slight modifications to the SKA1 Baseline Design for SKA-MID would ensure that the telescope maintains near-maximum sensitivity at this resolution. The Cosmology

SWG has MeqTrees-based simulations of a shear measurement pipeline which can assess measurement fidelity for different proposed SKA measurement sets.

- The potential impact of ionospheric distortions at low frequency needs to be examined further. Source number densities increase with decreasing frequency, suggesting that one should aim to achieve the optimal combination of sensitivity and resolution at lower frequency. However, at low frequency ionospheric distortions will introduce a blurring of the sky signal (akin to the seeing effect in optical telescopes) which will inhibit accurate shape measurements.
- The use of radio polarization measurements to remove intrinsic alignments will require careful correction for the effects of Faraday rotation of the observed polarization angles. Further work is also needed to understand the impact of de-polarization effects within the source galaxies themselves.

Even if SKA1 is not able to compete with optical/IR weak lensing surveys, it will provide the essential groundwork for SKA2, which will take weak lensing to an entirely new level, beyond the capabilities of optical/IR surveys.

Large-scale effects – beating cosmic variance

Morphological information on the radio sources also provides a powerful method of probing large-scale effects, in particular, non-Gaussianity. This is due to the fact that sources that trace the underlying dark matter density field with a different bias parameter can be used to overcome cosmic variance, something which is particularly important for large-scale probes. The different source populations that comprise the radio surveys, e.g. FRII, FRI, radio-quiet AGN, star-forming and starburst galaxies, reside in dark matter haloes spanning a large mass range, thus with different biases. If some of these sources can be distinguished on morphological grounds (e.g. FRI and FRII) then the constraints on primordial non-Gaussianity with a 1μJy rms 3pi survey can outperform Planck by a factor of several (Ferramacho et al. 2014).

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