PROCEEDINGS OF SCIENCE

The role of HI and continuum radio surveys in cosmology

Mario G. Santos*
Department of Physics, University of Western Cape, Cape Town 7535, South Africa
SKA South Africa, The Park, Park Road, Cape Town 7405, South Africa
CENTRA, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal
E-mail: mariogrs@gmail.com

The new frontier of cosmology will be led by three-dimensional surveys of the large-scale structure of the Universe. Based on its all-sky surveys and redshift depth, the SKA is destined to revolutionize cosmology, in combination with future optical/ infrared surveys such as Euclid and LSST. In the first phase of deployment (SKA1), large HI intensity mapping and continuum surveys are forecast to be at the forefront on the major questions of cosmology. It will not only deliver precision cosmology but also probe the foundations of the standard model and open the door to new discoveries on large-scale features of the Universe. In here I review the proposed surveys for SKA1 given the latest specifications and discuss some of the difficulties we will have to overcome.

EXTRA-RADSUR2015 (+)
20–23 October 2015
Bologna, Italy

(+) This conference has been organized with the support of the Ministry of Foreign Affairs and International Cooperation, Directorate General for the Country Promotion (Bilateral Grant Agreement ZA14GR02 - Mapping the Universe on the Pathway to SKA)

*Speaker.

PoS(EXTRA-RADSUR2015)030

1. Introduction

It is often said that cosmology has entered a new era of precision. In particular, the cosmic microwave background (CMB) has been one of the main observational tools for cosmology in recent years. Although basically only giving 2-dimensional information, we were able to constrain the standard cosmological model with great accuracy (Planck Collaboration 2013). This "high precision cosmology" is particularly true for the “vanilla" model with 6 parameters. More parameters or non-standard models can lead to degeneracies and limit the constraining power of the CMB (for instance the w_0/w_a non-flat model). The next step towards precision cosmology and exploring novel models will need to use extra information. In particular, due to its huge information content, measurements of the 3-dimensional large-scale structure of the Universe across cosmic time will be an invaluable tool. One of the most accessible methods to probe this is through large galaxy surveys to trace the underlying dark matter distribution. Several surveys are now under way or in preparation, such as DES, eBOSS, DESI, 4MOST, LSST, and the Euclid satellite. These surveys are based on imaging of a large number of galaxies at optical or near-infrared wavelengths combined with redshift information to provide a 3-dimensional position of the galaxies.

The new generation of radio telescopes now under construction will provide several surveys of the large scale structure of the Universe, capable of giving new insights into some of the big questions in Cosmology:

- Why is the expansion of the Universe accelerating? (Dark energy? Modified gravity?)
- What is the nature of the primordial Universe? (Inflation? Is the primordial spectrum of perturbations non-Gaussian?)
- Does the General Theory of Relativity really applies to cosmological scales, or does it need modification?
- Is the Universe really isotropic and homogeneous? Is the Universe really flat?

This can be probed by relying on three main surveys in the radio: i) a continuum radio galaxy survey; ii) an HI galaxy survey and iii) an HI intensity mapping survey. This is particularly true for the Square Kilometre Array (SKA), a planned general-purpose array split over two main sites in South Africa and Australia. The first phase of construction, due to finish around 2023, will consist of two sub-arrays: SKA1-LOW, a low-frequency aperture array operating below 350 MHz; and SKA1-MID, a conventional mid-frequency array of 130 dishes equipped with low noise receivers covering the 350 MHz - 14 GHz range. This will be further extended with the 64 MeerKAT dishes currently being built in South Africa. A second phase, scheduled for completion around 2030, will improve the overall sensitivity by a factor of 10. The SKA will revolutionise cosmology and in this proceeding, I will review what can be achieved with the surveys above.

2. Cosmology with radio continuum surveys

The next generation of radio telescopes will provide exquisite cosmological measurements through the use of very large continuum sky surveys at low redshifts. Contrary to line surveys, requiring high resolution in frequency, these surveys will be obtained through the integration of a continuous interval in frequency (~300 MHz), providing high sensitivity and the detection of a large number of radio-galaxies ($> 10^8$ with SKA1). However, unlike the wide-field optical surveys, radio continuum emission is unaffected by dust, and in the age of the SKA, the star-forming galaxies, as well as the AGN, can be detected to high redshifts. Since galaxies are biased tracers of the underlying dark matter distribution, these wide-field surveys will allow to probe the large-scale structure of the Universe and provide enough statistics for stringent constraints on Cosmology.

The largest existing radio survey to date is the NRAO VLA Sky Survey (NVSS), whose release paper (Condon et al. 1998) is one of the most cited in Astronomy. Although some cosmological studies were done using this survey, very little was achieved in terms of setting competitive constraints on parameters of the cosmological model, mainly due to the low sensitivity of the survey. On the other hand, future surveys such as the Westerbork Observations of the Deep APERTIF Northern Sky (WODAN) and the Evolutionary Map of the Universe (EMU) using ASKAP, will reach much higher sensitivity (10 μJy/beam) over the entire visible sky. EMU will cover the same area (75% of the southern sky) as NVSS, but will be about 30 times more sensitive, and will have an angular resolution (~10 arcsec) five times better. MeerKAT also has the potential to do such large continuum surveys with improved resolution.

2.1 Cosmology with the angular power spectrum

In the the absence of redshift information, the most straightforward experiment is to measure the angular correlation function or power spectrum of the radio sources (e.g. 2-point correlation of the galaxy number counts across the sky). Raccanelli et al. (2012) showed that a measurement of the angular power spectrum, in combination with the CMB and supernovae Ia, can be a very useful tool to determine both the dark energy equation of state and departures from general relativity, even with the precursor surveys within reach of ASKAP, LOFAR and MeerKAT. Moreover, in Camera et al. (2012) it was shown that the cross-id with shallow, low redshift surveys with photometric and spectroscopic information allows a rough binning of the radio data, providing very competitive constraints on the evolution of dark energy.

However, to make radio surveys competitive with the largest surveys at other wavelengths, we need the combination of source density, sky area and morphological characterisation that is only feasible with the SKA. A radio continuum survey on SKA-MID with $\sim$25,000 deg^2 will detect $\sim 10^8$ galaxies out to $z \sim 5$ in SKA1 and more than $\sim 10^9$ galaxies in SKA2. Recently, Ferramacho et al. (2014) demonstrated that even without redshift information for the individual sources, or a subset of sources, the wide-area radio continuum surveys with SKA1 can play a unique role in constraining the level of non-Gaussianity. Utilising the multi-tracer technique (Seljak 2009) they showed that the different populations of radio sources, which trace the underlying dark matter distribution with vastly different biases, can constrain the local non-Gaussian parameter f_{NL} with uncertainty $\sigma_{f_{NL}} = 3.6$ for a galaxy detection flux limit of 10μJy and $\sigma_{f_{NL}} = 2.2$ for 1μJy (see Figure 1). The former survey is within reach of SKA1, but requires good resolution in order to morphologically distinguish the different classes of radio source, i.e. FRI/FRII from star-forming galaxies and radio-quiet quasars. As shown in Makhathini et al. (2015) this sort of classification is possible to very high redshifts with SKA1-MID. Therefore radio surveys with SKA1-MID, without

PoS(EXTRA-RADSUR2015)030

any additional data, have the potential to constrain primordial non-Gaussianity to a factor of ~ 2 better than the present constraints obtained with Planck.

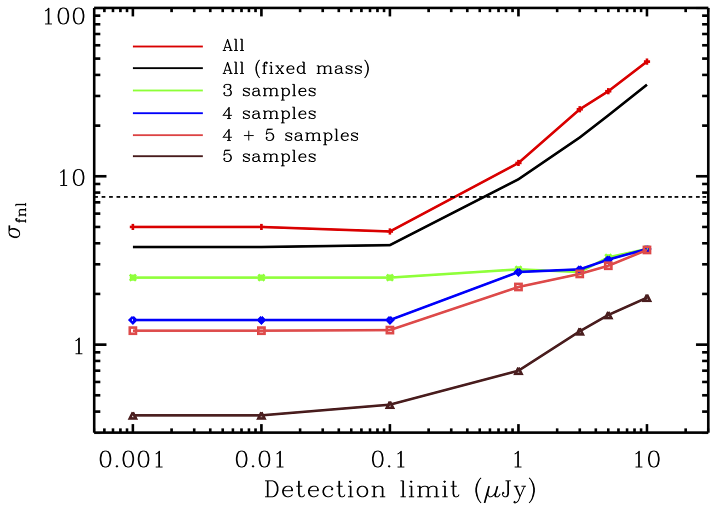

Figure 1: Constraints on fNL obtained with the multi-tracer method as a function of the flux-density threshold used to detect galaxies. The various populations considered are FR-I and FR-II radio galaxies, radio-quiet quasars, star-forming galaxies and starburst galaxies, with different biases, as described in both Wilman et al. (2008) and Ferramacho et al. (2014). The horizontal line represents the best constraint obtained by the Planck collaboration. See Ferramacho et al. (2014) for more details.

2.2 Probing the Cosmological Principle

The concordance model, as well as dynamical dark energy and modified gravity models, are all based on the fundamental assumption that the Universe is statistically isotropic and homogeneous – the 'Cosmological Principle'. This principle should be interrogated by carefully designed observational tests. One critical feature of the standard assumption is that the dipole in the CMB – accurately measured by Planck – should match the dipole in the LSS, since both are predicted to originate from our motion relative to the common radiation/matter frame in the background. SKA all-sky surveys will allow the measurement of the cosmic radio dipole almost as precisely as the CMB dipole. SKA1 will constrain the cosmic radio dipole direction with an accuracy better than 5 degrees (Figure 2), and SKA2 within a degree (at 99 per cent C.L.). Compared to todays best estimate based on NVSS data, this will be an improvement of a factor of 100 in the accuracy of the cosmic radio dipole direction for SKA1. This measurement could firmly establish or refute the commonly adopted assumption that the CMB and the overall large-scale structure frames agree. Moreover, the CMB exhibits unexpected features at the largest angular scales, among them a lack of angular correlation, alignments between the dipole, quadrupole and octopole, hemispherical asymmetry, a dipolar power modulation, and parity asymmetries (Planck Collaboration et al. 2014; Copi et al. 2015a,b). Understanding the statistical significance of these anomalies is crucial, as a lack of statistical isotropy or Gaussianity could rule out the standard cosmological model. The angular two-point correlation at angles > 60 degrees from SKA continuum surveys, as well as the reconstruction and cross-correlation of low multipoles will offer further insight into these puzzles (Schwarz et al. 2014).

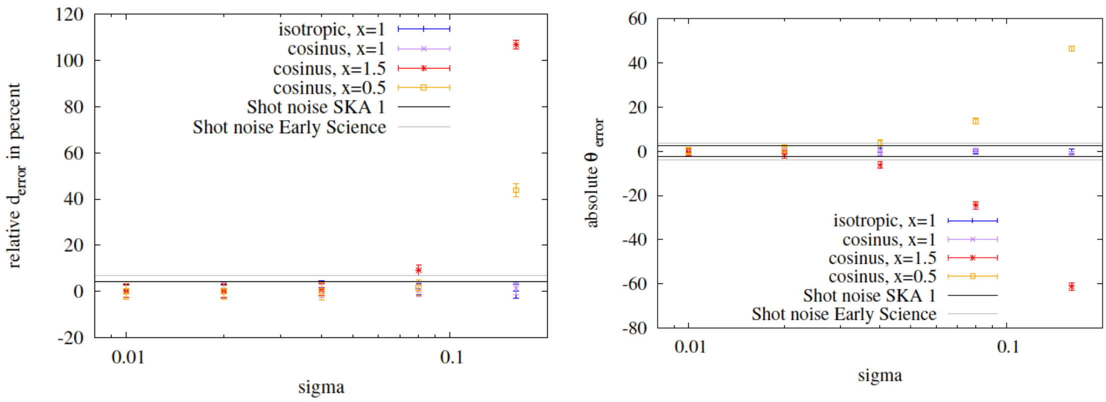

Figure 2: Left: Accuracy (in per cent) of the measurement of the dipole amplitude as function of fractional error on flux density calibration on individual point sources (sigma). All points are based on 100 simulations. Right: Accuracy (in degrees) of the measurement of the dipole direction. The horizontal lines denote the error due to shot noise for a dipole estimate based on 8×10^7 sources (SKA Early Science) and 2×10^8 sources (SKA1). See Schwarz et al. (2014) for further details.

3. Cosmology with HI intensity mapping surveys

Although radio continuum surveys can provide important constraints on cosmological parameters as discussed above, they still lack redshift information from the radio that would provide further improvements on the constraints, in particular for the dark energy evolution. A solution is to use the hydrogen 21cm line to provide the redshift information. Telescopes probing the sky between a rest frequency of 1420 MHz and 250 MHz would be able to detect galaxies up to redshift 5. The problem is that this emission line is usually quite weak: at $z = 1.5$, most galaxies with a HI mass of $10^9\,M_\odot$ will be observed with a flux density of $\sim 1\,\mu$Jy using the HI line.

In order to obtain “game changing" cosmological constraints, experiments with sensitivities better than $10\,\mu$Jy over 10 kHz channels will then be required to provide enough galaxies to beat shot noise and become cosmic variance dominated (Santos et al. 2014b). “Near term" radio telescopes such as ASKAP and MeerKAT should be able to achieve such sensitivities but only on deep single pointings. SKA1 on the other hand, should be able to detect about 10^7 galaxies over a 5,000 deg^2 survey. However, even with this number, "cosmological grade" constraints will only be feasible up to $z \sim 0.6$ (Yahya et al. 2015). It will require a much more powerful telescope such as SKA Phase 2, to integrate down to the required sensitivity over the required sky area and redshift range in a reasonable amount of time (Abdalla et al. 2014). This would imply that one would need to wait until then to use radio telescopes for cosmology.

Galaxy surveys are threshold surveys in that they set a minimum flux above which galaxies can be individually detected. Instead we could consider measuring the integrated 21cm emission of several galaxies in one angular pixel on the sky and for a given frequency resolution. For a reasonably large 3d pixel we expect to have several HI galaxies in each pixel so that their combined emission will provide a larger signal. Moreover we can use statistical techniques, similar to those that have been applied for instance to CMB experiments, to measure quantities in the low signal to noise regime. By not requiring the detection of individual galaxies, the specification requirements imposed on the telescope will be much less demanding. This way, the intensity mapping technique transfers the problem to one of foreground cleaning: how to develop cleaning methods to remove everything that is not the HI signal at a given frequency (Alonso et al. 2014, 2015; Wolz et al. 2014). This in turn also impacts on the calibration requirements of the instrument. For more details, see Santos et al. (2014a).

3.1 The HI signal

After reionization, most neutral hydrogen will be found in dense systems inside galaxies, e.g. Damped Lyman-alpha Absorbers (DLAs). In terms of the brightness temperature, the average signal over the sky can be written as:

$$\overline{T}_b(z) \approx 566h \left(\frac{H_0}{H(z)}\right) \left(\frac{\Omega_{\rm HI}(z)}{0.003}\right) (1+z)^2 \; \mu{\rm K}, \tag{3.1}$$

where the neutral hydrogen density fraction is given by

$$\Omega_{\rm HI}(z) \equiv (1+z)^{-3} \rho_{\rm HI}(z)/\rho_{c,0}, \tag{3.2}$$

$\rho_{\rm HI}(z)$ is the proper HI density and $\rho_{c,0}$ the critical density of the Universe at redshift zero. Figure 3 shows constraints on $\Omega_{\rm HI}(z)$ from different experiments. For a recent summary of observed trends we refer to Padmanabhan et al. (2014).

Assuming the signal is linear with respect to the underlying dark matter fluctuations, the total brightness temperature at a given position on the sky and frequency will be

$$T_b(\nu,\Omega) \approx \overline{T}_b(z) \left[1 + b_{\rm HI}\delta_m(z) - \frac{1}{H(z)}\frac{dv}{ds}\right]. \tag{3.3}$$

The signal will then be completely specified once we find a prescription for the HI density and bias function ($b_{\rm HI}$). This can be obtained by making use of the halo mass function, $\frac{dn}{dM}$ and halo bias, while relying on a model for the amount of HI mass in a dark matter halo of mass M, e.g. $M_{\rm HI}(M)$. For the mass function, we decided to consider a simple power law:

$$M_{\rm HI}(M) = AM^{\alpha}, \tag{3.4}$$

which is independent of redshift. We found that a value of $\alpha \sim 0.6$ fits both the low z and high z data reasonably well. This can be seen in figure 3 (left), that shows the $\Omega_{\rm HI}(z)$ measurements and the evolution obtained from this model (solid line). The constant A is normalised to the results from Switzer et al. (2013) at $z \sim 0.8$. The right panel shows the redshift evolution for both the linear and power law model of the temperature multiplied by the bias, which is the figure of merit for the strength of the power spectrum used in the forecasts.

3.2 Current and planned experiments

First attempts at using intensity mapping have been promising, but have highlighted the challenge of calibration and foreground subtraction. The Effelsberg-Bonn survey (Kerp et al. 2011) has

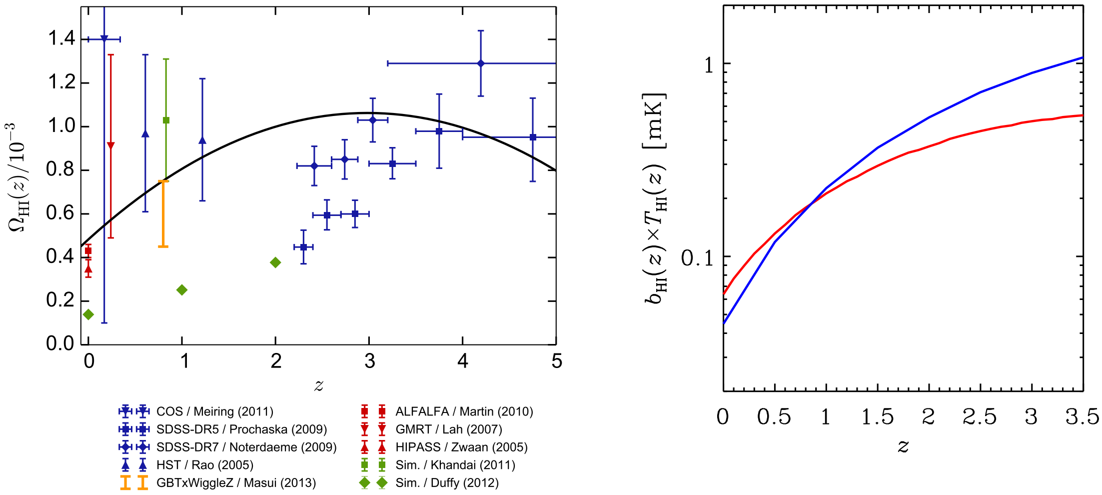

Figure 3: Left: Current constraints on the HI density fraction as a function of redshift, partially based on the compilation in Duffy et al. (2012). DLA observations are shown in blue, cross-correlations in orange, other observations in red, and simulations in green. The thick black line shows $\Omega_{\rm HI}(z)$ from the fiducial model power law used throughout this chapter. Right: Evolution of the brightness temperature times bias with redshift for the linear (red curve) and our fiducial power-law model (blue).

produced a data cube covering redshifts out to $z = 0.07$, while the Green Bank Telescope (GBT) has produced the first (tentative) detection of the cosmological signal through IM by cross-correlating with the WiggleZ redshift survey (Chang et al. 2010; Switzer et al. 2013; Masui et al. 2013). As probes to constrain cosmological parameters these measurements are, as yet, ineffective, but they do point the way to a promising future.

We can basically divide the intensity mapping experiments into two types: single dish surveys and interferometers. In single dish surveys (e.g. using auto-correlations) each pointing of the telescope gives us one single pixel on the sky (though more dishes or feeds can be used to increase the field of view). This has the advantage of giving us the large scale modes by scanning the sky. Since brightness temperature is independent of dish size we can achieve the same sensitivity with a smaller dish although that will in turn limit the angular resolution of the experiment (a 30 arc min resolution at $z \sim 1$ would require a dish of about 50 m in diameter). One example is the GBT telescope as described above. BINGO (Battye et al. 2013) is a proposed 40m multi-receiver single-dish telescope to be situated in South America and aimed at detecting the HI signal at $z \sim 0.3$.

Interferometers basically measure the Fourier transform modes of the sky. They have the advantage of easily providing high angular resolution as well being less sensitive to systematics that can plague the auto-correlation power. On the other hand, the minimum angular scale they can probe is set by their shortest baseline which can be a problem when probing the BAO scales. One example of a purpose built interferometer for intensity mapping is CHIME, a proposed array, aimed at detecting BAO at $z \sim 1$, made up of 20×100m cylinders, based in British Columbia, Canada. TIANLAI, set in China, follows a similar approach. A different setup is used in HIRAX, to be set in South Africa: an interferometer with about 1,000 highly packed 6m dishes.

The next generation of large dish arrays can also potentially be exploited for HI intensity mapping measurements. Such is the case of MeerKAT and ASKAP. However, these interferometers do not provide enough baselines on the scales of interest (5m to 80m) so that their sensitivity to BAO will be small. The option is to use instead the auto-correlation information from each dish, e.g. make a survey using the array in single dish mode. The large number of dishes available with these telescopes will guarantee a large survey speed for probing the HI signal. The great example of this approach will be SKA1, the first phase of the SKA telescope, to be built in 2018. An HI intensity mapping survey will turn SKA phase 1 into a state of the art cosmological probe. In particular, the huge volume available with such a survey will surpass any other large experiment such as Euclid or LSST. In the following sections I will summarise what can be achieved with SKA1, assuming 133 15m dishes plus 64 13.5m MeerKAT dishes, a band 2 from 950 MHz to 1420 MHz ($0 < z < 0.5$) and a band 1 from 350 MHz to 1050 MHz ($0.35 < z < 3.06$) and a survey size of 25,000 deg^2 over 10,000 hours.

3.3 High precision cosmology with an SKA1-MID HI intensity mapping survey

Surveys of large-scale structure are a rich source of information about the geometry and expansion history of the Universe. The baryon acoustic oscillations (BAO) are a preferred clustering scale imprinted in the galaxy distribution, originating from the time when photons and baryonic matter were coupled together in the early Universe. By using them as a statistical 'standard ruler', one can obtain constraints on the expansion rate, $H(z)$, and (angular) distance-redshift relation, $D_A(z)$, as functions of redshift, as has been done successfully with recent large galaxy redshift surveys such as BOSS and WiggleZ. Measuring these functions is vital for testing theories of dark energy which seek to explain the apparent acceleration of the cosmic expansion, as they constrain its equation of state, $w = P/\rho$, and thus its physical properties. Shedding light on the behaviour of dark energy – especially whether w deviates from -1 and whether it varies in time – is one of the foremost problems in cosmology.

Intensity mapping (IM) has a few major advantages over conventional galaxy surveys for this task. IM surveys can map a substantial fraction of the sky with low angular resolution in a short period of time. Combined with the wide bandwidths of modern radio receivers, this makes it possible to cover extremely large survey volumes and redshift ranges in a relatively short time, helping to beat down sample variance. Figure 4 (left) summarises the expected constraints from the SKA HI IM surveys for the BAO scale at $k \sim 0.074$ Mpc^{-1}. Although the real power of the SKA1 IM survey will be on very large scales, we see that even at BAO scales, SKA1-MID present constraints not far from Euclid while only using a ~ 2 year survey (the full Euclid requires about 5 years). In fact, as shown in Bull (2016), the high sensitivity of the SKA1 survey at low redshifts will allow it to surpass contemporary spectroscopic galaxy surveys such as DESI and Euclid in terms of constraints on modified gravity parameters. This is aided by the ability of an SKA1 IM survey to achieve sub-1% measurements of $f\sigma_8$, where $f(z)$ is the linear growth rate, which can be measured from the degree of anisotropy of the redshift-space correlation function (or power spectrum). The growth rate is directly related to the strength of gravity, and so is an extremely useful tool for probing possible deviations from general relativity that have been invoked as an alternative to dark energy to explain cosmic acceleration (see Figure 4 - right).

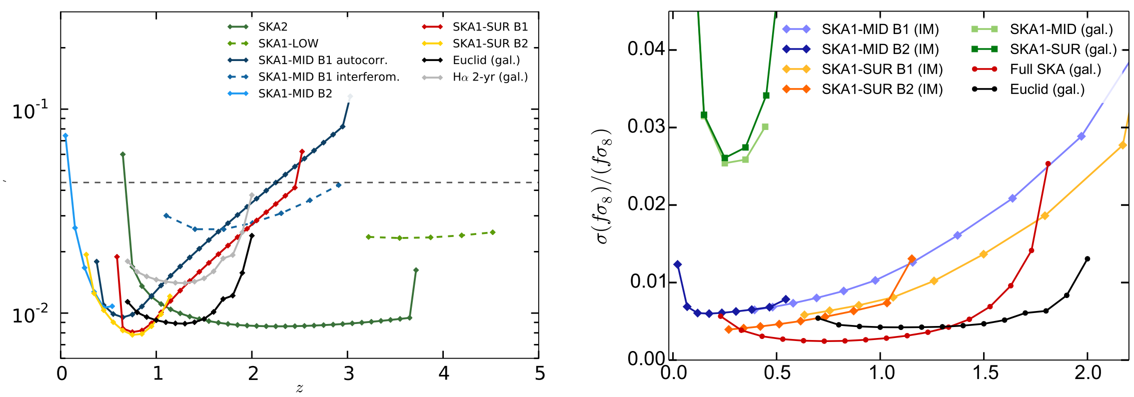

Figure 4: *Left:* Constraints (noise over signal) from SKA HI IM surveys for BAO scales ($k \sim 0.074$ Mpc^{-1}) as a function of redshift. Dashed line shows the BAO detection threshold. The lower green curve shows what would be expected from a SKA2 IM survey (in interferometer mode) optimised for high-z. The grey curve shows what can be expected for a two-year H_α galaxy survey with similar depth as Euclid but over a smaller sky area. *Right:* Predicted constraints from SKA on the unparameterized growth function $f\sigma_8$ from the SKA1 (galaxy and IM) and the SKA2 galaxy survey, compared with predicted constraints coming from the Euclid galaxy survey. Both constraints include Planck+BOSS priors.

3.4 Probing very large scales with a SKA1 HI intensity mapping survey

The study of the Universe on ultra-large scales is one of the major science cases for the SKA. On ultra-large cosmic scales, two key effects become significant: primordial non-Gaussianity and relativistic corrections to cosmological observables. Moreover, if late-time acceleration is driven not by dark energy but by modifications to general relativity, then such modifications should become apparent near and above the horizon scale. As a result, the SKA is forecast to deliver transformational constraints on non-Gaussianity and to probe gravity on super-horizon scales for the first time. Figure 5 (left) summarises the expected constraints from the SKA HI IM surveys for a very large scale, past the equality peak at $k \sim 0.01$ Mpc^{-1}. We see the huge constraining power of these surveys (see Camera et al. 2015 for a more in depth discussion).

In Camera et al. (2013), an analysis is given of the constraining power of IM surveys over non-Gaussianity, showing that errors on $f_{\rm NL}$ can be taken down towards $\sigma_{f_{\rm NL}} \lesssim 3$ with SKA1, which is more than three times better than the current constraint from Planck. In terms of testing Einstein's theory of general relativity on horizon scales, one of the most interesting effects is the correction to the standard Newtonian approximation for the observed galaxy overdensity. It turns out that these relativistic corrections are very hard to detect using IM (although the same is true for other single tracers) due to cosmic variance. The way forward is the use of the multi-tracer technique. By combining an HI IM survey from SKA1 with a galaxy survey such as from Euclid or LSST, it is possible to obtain exquisite constraints on these large scale relativistic corrections as well as primordial non-Gaussianity (Fonseca et al. 2015) (Figure 5 - right). Moreover, these novel cross-correlation between different surveys will give a better handle on systematics and foreground issues.

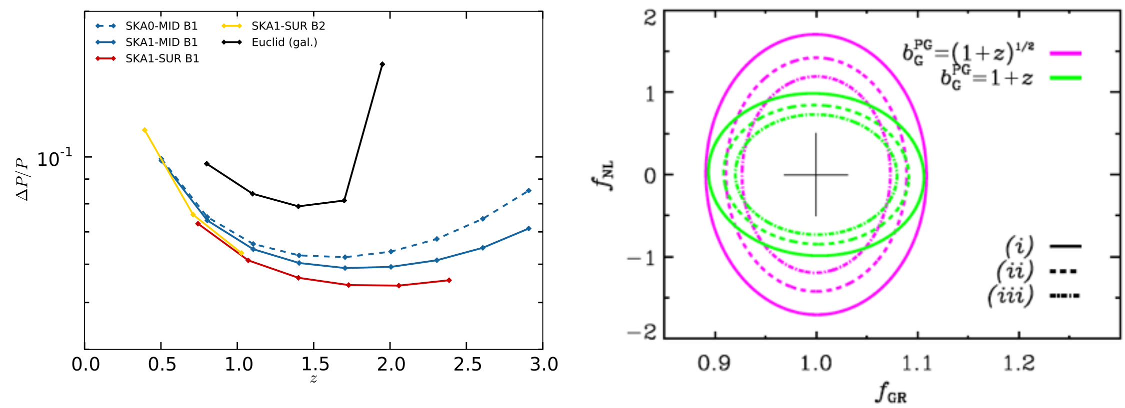

Figure 5: *Left:* Constraints (noise over signal) from SKA HI IM surveys for large scales, past the equality peak ($k \sim 0.01$ Mpc^{-1}) as a function of redshift. A value below 1 would imply a detection. Dashed line indicates what can be achieved with SKA0 (50% of SKA1) which is quite similar to SKA1. *Right:* Joint constrains on primordial non-Gaussianity and relativistic corrections by combining an HI IM survey with a LSST type survey using the multi-tracer technique and assuming two different types of galaxy bias.

4. Conclusions

The combination of several probes available with radio telescopes will provide unprecedented constraints on cosmological parameters and a handle on systematics. In particular, SKA1 will allow to perform several surveys capable of testing different aspects of the cosmological paradigm. Large continuum surveys will probe the isotropy of the Universe and the cosmic dipole, as well as "standard" cosmology (specially when combined with other optical surveys). Moreover, HI intensity mapping is set to become a leading cosmology probe during this decade. One of the key instruments that can be used for this purpose is phase I of the SKA. A large sky survey with this telescope (in total power array) should be able to provide stringent constraints on the nature of dark energy, modified gravity models and the curvature of the Universe. Moreover, it will open up the possibility to probe BAO at high redshifts as well as ultra-large scales, beyond the horizon size, which can be used to constrain effects such as primordial non-Gaussianity or potential deviations from large-scale homogeneity and isotropy. The combination of this signal with galaxy surveys using the multi-tracer technique will provide revolutionary constraints on non-Gaussianity and relativistic corrections on large scales.

Several challenges will have to be overcome, however, if we want to use IM for cosmological purposes. In particular, cleaning of the huge foreground contamination, removal of any systematic effects and calibration of the system. Foreground cleaning methods have already been tested with relative success taking advantage of the foreground smoothness across frequency but novel methods need to be explored in order to deal with more complex foregrounds. Other contaminants, such as some instrumental noise bias that shows up in the auto-correlation signal, can in principle be dealt with the same methods. Ultimately, we should deal with the cleaning of the signal and the map making at the same time. This will require even more sophisticated statistical analysis methods and it will be crucial to take on such an enterprise in the next few years in order to take full advantage of this novel observational window for cosmology.

Acknowledgements. MGS acknowledges support by the South African Square Kilometre Array Project, the National Research Foundation and FCT grant PTDC/FIS-AST/2194/2012. MGS also acknowledges support from the Ministry of Foreign Affairs and International Cooperation, Directorate General for the Country Promotion (Bilateral Grant Agreement ZA14GR02 - Mapping the Universe on the Pathway to SKA)

References

Abdalla, F. B., Bull, P., Camera, S., et al. 2014, in Advancing Astrophysics with the Square Kilometre Array, PoS (AASKA14) 017

Alonso, D., Bull, P., Ferreira, P. G., & Santos, M. G. 2015, MNRAS, 447, 400

Alonso, D., Ferreira, P. G., & Santos, M. G. 2014, MNRAS, 444, 3183

Battye, R. A., Browne, I. W. A., Dickinson, C., Heron, G., Maffei, B., & Pourtsidou, A. 2013, MNRAS, 434, 1239

Bull, P. 2016, ApJ, 817, 26

Camera, S., Raccanelli, A., Bull, P., Bertacca, D., Chen, X., Ferreira, P., Kunz, M., Maartens, R., Mao, Y., Santos, M., Shapiro, P. R., Viel, M., & Xu, Y. 2015, Advancing Astrophysics with the Square Kilometre Array (AASKA14), 25

Camera, S., Santos, M. G., Bacon, D. J., Jarvis, M. J., McAlpine, K., Norris, R. P., Raccanelli, A., & Röttgering, H. 2012, MNRAS, 427, 2079

Camera, S., Santos, M. G., Ferreira, P. G., & Ferramacho, L. 2013, Phys.Rev.Lett., 111, 171302

Chang, T.-C., Pen, U.-L., Bandura, K., & Peterson, J. B. 2010, Nature, 466, 463

Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693

Copi, C. J., Huterer, D., Schwarz, D. J., & Starkman, G. D. 2015a, MNRAS, 451, 2978

—. 2015b, MNRAS, 449, 3458

Duffy, A. R., Kay, S. T., Battye, R. A., et al. 2012, MNRAS, 420, 2799

Ferramacho, L. D., Santos, M. G., Jarvis, M. J., & Camera, S. 2014, MNRAS, 442, 2511

Fonseca, J., Camera, S., Santos, M. G., & Maartens, R. 2015, ApJ, 812, L22

Kerp, J., Winkel, B., Ben Bekhti, N., Flöer, L., & Kalberla, P. M. W. 2011, Astronomische Nachrichten, 332, 637

Makhathini, S., Jarvis, M., Smirnov, O., & Heywood, I. 2015, Advancing Astrophysics with the Square Kilometre Array (AASKA14), 81

Masui, K. W. et al. 2013, Ap. J. L., 763, L20

Padmanabhan, H., Choudhury, T. R., & Refregier, A. 2014, ArXiv e-prints

Planck Collaboration. 2013, ArXiv e-prints

Planck Collaboration, Ade, P. A. R., Aghanim, N., Armitage-Caplan, C., Arnaud, M., Ashdown, M., Atrio-Barandela, F., Aumont, J., Baccigalupi, C., Banday, A. J., & et al. 2014, A & A, 571, A23

Raccanelli, A., Zhao, G.-B., Bacon, D. J., Jarvis, M. J., Percival, W. J., Norris, R. P., Röttgering, H., Abdalla, F. B., Cress, C. M., Kubwimana, J.-C., Lindsay, S., Nichol, R. C., Santos, M. G., & Schwarz, D. J. 2012, MNRAS, 424, 801

Santos, M. G., Bull, P., Alonso, D., et al. 2014a, in Advancing Astrophysics with the Square Kilometre Array, PoS (AASKA14) 019

Santos, M. G. et al. 2014b, in Advancing Astrophysics with the Square Kilometre Array, PoS (AASKA14) 021

Schwarz, D., Bacon, D., Chen, S., et al. 2014, in Advancing Astrophysics with the Square Kilometre Array, PoS (AASKA14) 035

Seljak, U. 2009, Physical Review Letters, 102, 021302

Switzer, E. R., Masui, K. W., Bandura, K., Calin, L.-M., Chang, T.-C., Chen, X.-L., Li, Y.-C., Liao, Y.-W., Natarajan, A., Pen, U.-L., Peterson, J. B., Shaw, J. R., & Voytek, T. C. 2013, MNRAS, 434, L46

Wilman, R. J., Miller, L., Jarvis, M. J., Mauch, T., Levrier, F., Abdalla, F. B., Rawlings, S., Klöckner, H.-R., Obreschkow, D., Olteanu, D., & Young, S. 2008, MNRAS, 388, 1335

Wolz, L. et al. 2014, in Advancing Astrophysics with the Square Kilometre Array, PoS (AASKA14) 032

Yahya, S., Bull, P., Santos, M. G., Silva, M., Maartens, R., Okouma, P., & Bassett, B. 2015, MNRAS, 450, 2251

PoS(EXTRA-RADSUR2015)030