Cosmology on the largest scales with intensity mapping

2014 J. Phys.: Conf. Ser. 566 012004

(http://iopscience.iop.org/1742-6596/566/1/012004)

Journal of Physics: Conference Series **566** (2014) 012004 doi:10.1088/1742-6596/566/1/012004

Cosmology on the largest scales with intensity mapping

Stefano Camera[1], Mário G Santos[2,3,1], Pedro G. Ferreira[4] and Roy Maartens[2,5]

[1] CENTRA, Instituto Superior Técnico, Universidade de Lisboa, Avenida Rovisco Pais 1, 1049-001 Lisboa, Portugal

[2] Department of Physics, University of the Western Cape, Bellville 7535, South Africa

[3] SKA SA, 3rd Floor, The Park, Park Road, Pinelands, 7405, South Africa

[4] Astrophysics, University of Oxford, Dennis Wilkinson Building, Keble Road, Oxford OX1 3RH, UK

[5] Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Portsmouth P01 3FX, UK

E-mail: stefano.camera@tecnico.ulisboa.pt

Abstract. We review the state of the art of the study of the cosmic structure on ultra-large scales as is forecast to be achievable by the oncoming generation of intensity mapping experiments. We focus on intensity maps of the redshifted 21 cm line radiation of neutral hydrogen (HI) in the post-reionisation Universe. Such measurements will be performed by future radio telescopes such as for instance the Square Kilometre Array and will allow for surveying the biggest volume ever of cosmic structure. After having shown why it is valuable to scrutinise such extremely large cosmic scales – they will supply crucial information about the physical processes at play at early times – we concentrate on primordial non-Gaussianity as a working example. We illustrate that HI intensity mapping experiments can place tight bounds on different inflationary scenarios via constraining the non-Gaussianity parameter, $f_{\rm NL}$, with an error close to 1.

1. Introduction

The study of the largest cosmological scales and of the peculiar phenomena there occurring has recently seen a renewed interest. This has been mostly driven by the forthcoming generation of experiments which will scrutinise the cosmic large-scale structure with unprecedented accuracy over the biggest volume ever surveyed. However, if on the one hand such a new, unexplored landscape is a rich source of information valuable to strengthen our understanding of the Universe, on the other hand it is utterly difficult, technically speaking, to access those extremely large scales.

Following References [1, 2], we here review the state of the art concerning the effort put for reaching those ultra-large scales as well as the most important achievable scientific outcomes. More specifically, we shall briefly present the most interesting effects which may occur on the largest cosmic scales, such as deviations from the Newtonian prediction which can either further confirm general relativity or hint at a modified behaviour of gravity, or non-standard halo clustering due to a possible amount of non-Gaussianity in the statistical distribution of primordial density fluctuations. Hence, we shall focus on primordial non-Gaussianity and show what we could attain with one of the envisaged techniques, namely the so-called intensity mapping.

Surveying the large-scale cosmic structure by means of intensity maps of a particular line, such as for instance the redshifted 21 cm line of neutral hydrogen (HI), is a newly proposed technique (see [3] and references therein). It is still in its infancy but promises to obtain great results, being by the way pretty cheap compared to usual galaxy surveys. Instead of making a catalogue of HI emitting galaxies as detected above a certain flux threshold, an intensity mapping experiment effectively makes a map of large-scale fluctuations in 21 cm temperature by measuring the integrated emission in one big pixel. By doing so, it bypasses the need of resolving individual galaxies, thus being much similar to a map of the cosmic microwave background (CMB) radiation. Thanks to the high frequency (and thus redshift) resolution of oncoming radio telescopes, this intensity mapping methodology renders it possible to survey efficiently extremely large volumes.

2. Ultra-large scale effects

The investigation of the cosmic structure on the largest scales presents many advantages and can greatly improve our confidence in the theoretical model we employ to understand the Universe and its evolution. For a start, the modes related to the largest separations are well described by linear theory. Therefore, we do not have to rely on approximations coming from numerical simulations to take non-linear effects properly into account. This is a major gain, for numerical simulations are time consuming and they always imply a certain degree of ad hoc implementation [4, 5]. Closely related to this is the fact that on smaller scales, not only the growth of perturbations becomes non-linear, but also baryonic effects begin to play a more and more relevant rôle. Unfortunately though, the interplay of non-gravitational physical processes occurring on small scales – energy exchanges, radiative cooling, gas accretion to name a few – is very resilient to theoretical modelling (see e.g. [6]).

Having now clear in mind the pros of pursuing cosmology on ultra-large scale, let us briefly describe two of the most important effects that will be in principle detectable, namely general relativistic corrections to cosmological observables and primordial non-Gaussianity.

2.1. Testing gravity on the largest scales

The vast majority of the predictions hitherto employed to analyse experimental data coming from surveys of the large-scale structure have relied on Newtonian or quasi-Newtonian approximations. This has proven to be fairly adequate for past and present surveys, since their interest is galaxy clustering well below the horizon scale. Often, so-called redshift-space distortions are also included in the analysis, and the contribution of weak lensing convergence and magnification to matter over-densities are sometimes considered too. However, there are much more effects, usually subdominant with respect to number density fluctuations and redshift-space distortions, but whose magnitude tends to increase as we go to larger scales. Specifically, the full relativistic analysis includes terms that are suppressed on sub-horizon scales, viz. velocity (or Doppler) terms, Sachs-Wolfe and integrated Sachs-Wolfe type terms, and time-delay contributions [7–9]. One the one hand, this implies that future wide and deep surveys will need to employ an accurate, precise modelling accounting not only for redshift-space distortions and weak lensing effects, but for all geometric and relativistic corrections. On the other hand, this also means that a clear detection of such relativistic corrections will signify a further confirmation of the goodness of Einstein's general relativity – even on scales farthest from those where it has been tested so far.

However, the largest cosmic scales might as well represent the very ground where Einsteinian predictions fail. Indeed, the last decade has seen a great endeavour by the cosmologists' community in the search for explanations of the observed late-time cosmic acceleration alternative to the standard cosmological constant hypothesis. The main idea inspiring such an effort is that behind the Universe's accelerated expansion there may be not some exotic component – for instance dark energy – which we never directly detected but nonetheless accounts for more than 70% of the total energy budget, bur rather a modification to the gravity law occurring on cosmological scales. (We refer the reader to Clifton et al. [10] for an exhaustive review on cosmology in modified gravity theories.) Since the accelerated expansion of the cosmos is a late-time phenomenon, it is natural to look for hints concerning the physical nature of the underlying mechanism on very large scales. Clearly, the detection of a modified gravity signature will be such an enormous breakthrough that it appears worth scrutinising the ultra-large scales.

2.2. Primordial non-Gaussianity

The standard inflationary scenario predicts almost Gaussian primordial fluctuations which successively grow by gravitational accretion to form the large-scale structure we observe today (e.g. [11]). However, inflation is rather a paradigm than an established theory and at the present day there is no such 'standard model' universally agreed upon. Quite on the contrary, many viable scenarios have been proposed, and a deeper understanding of the mechanism which drove inflation represents one of the cardinal goals of contemporary cosmology. To this aim, the study of primordial non-Gaussianity stands as a major tool at our disposal. Indeed, if the distribution of primordial density perturbations is not Gaussian, it cannot be fully described by a power spectrum; we rather need higher-order moments such as the bispectrum. In particular, different models of inflation give rise to different bispectrum shapes. Thence, it is in principle possible to discriminate amongst different inflationary models by measuring a particular shape of non-Gaussianity.

For instance, standard single-field inflation generates negligibly small deviations from Gaussianity. They are called of the local shape, where one of the three bispectrum wavenumbers has got a much smaller magnitude than the other two. Local-shape non-Gaussianity can also be generated when an additional light scalar field other than the inflaton contributes to the observed curvature perturbations, e.g. in curvaton models [12] or in multi-field models [13]. Besides, there are inflationary models with a non-standard inflaton kinetic term which contains higher-order derivatives of the field itself [14]. Their primordial bispectrum is maximised for configurations where the three wavevectors have approximately the same amplitude and falls under the name of equilateral-type primordial non-Gaussianity [15]. Eventually, we have also so-called squashed configurations [16] or shapes of the bispectrum which are nearly orthogonal to both the local and equilateral forms [17].

The method par excellence hitherto employed to constrain primordial non-Gaussianity has relied on measuring the CMB temperature anisotropy bispectrum [18]. However, primordial non-Gaussianity also induces an additional scale and redshift dependence in a biased tracer of the underlying matter distribution [19, 20]. For example, the modification $\Delta b_X(z,k)$ to the Gaussian large-scale bias b_X^G of a biased tracer X induced by local non-Gaussianity reads $\Delta b_X(z,k) = 3[b_X^G(z) - 1]\Omega_m {H_0}^2\delta_c/[k^2T(k)D_+(z)]f_{\rm NL}$, where Ω_m is the total mass fraction in units of the critical density, H_0 the Hubble constant, δ_c the critical value of the matter over-density at collapse, $T(k)$ the transfer function, $D_+(z)$ the linear growth factor of density perturbations normalised to unity today and $f_{\rm NL}$ parameterises the quadratic correction to the linear Gaussian term in Bardeen's gauge invariant potential [21, 22]. Attempts at detecting this effect with galaxy surveys already led to promising results (e.g. [23]). In what follows, we shall exploit this peculiar behaviour to forecast constraints on primordial non-Gaussianity with HI intensity mapping.

3. HI intensity mapping

Late-time cosmology with HI intensity mapping is based on the assumption that, after reionisation, most of HI in the cosmos is confined within galaxies. Thus, a map of its 21 cm line emission is a proxy of the underlying clustered distribution of galactic haloes. The idea is that radio telescopes measure flux density. In the Rayleigh-Jeans limit, this can be converted into an effective brightness temperature – in turn split into a homogeneous and a fluctuating part, $T_b = \overline{T}_b(1 + \delta_{\rm HI})$, where $\delta_{\rm HI}$ are the perturbations in the large-scale HI distribution. By investigating the statistical properties of such HI over-densities in the Universe, we can thus reconstruct the fluctuations of underlying matter density field, much in the same way as it is done with the power spectrum or the correlation function of usual galaxy surveys.

There are two other main ingredients for constructing the power spectrum of HI density fluctuations, namely its bias, $b_{\rm HI}$, and the total HI density fraction, $\Omega_{\rm HI}$. The former depends upon the size of host dark matter haloes. Such dependence can be modelled by using the halo mass function with an appropriate lower mass cutoff (see e.g. [24–26] for more discussions). Despite the considerable disagreement between various HI bias models, we have got at least one robust measurement of the combined quantity $\Omega_{\rm HI}b_{\rm HI} = (4.3 \pm 1.1) \times 10^{-4}$ at the 68% confidence level at $z = 0.8$ [25]. This constraint can be used to gauge a semi-analytical derivation of b_{HI} and Ω_{HI} [27, 28]. Firstly, we need to specify the amount of HI within a halo of mass M at redshift z, $M_{\mathrm{HI}}(M, z)$. The most straightforward ansatz is a direct proportionality with respect to the halo mass, which can be then fitted against the available data. Thence, we can calculate Ω_{HI}, the HI bias and HI brightness temperature in a consistent manner.

The principal advantage of HI intensity mapping experiments in the task of surveying the cosmic structure on the largest scales is that they are sensitive to structures at a redshift range which is difficult to span for conventional galaxy surveys [29]. Indeed, for them it is hard to achieve the required sensitivity at high redshift over vast areas of the sky. Moreover, the problem of a poor sampling, usually referred to as cosmic variance, can greatly spoil the results. However, by not requiring galaxy detections, the intensity mapping technique transfers the problem to the issues of calibration and foreground removal, viz. the need for cleaning methods for removing everything but the HI signal we are interested in [30].

4. Forecasts for future surveys

Now, we show forecast constraints on the primordial non-Gaussianity parameter, f_{NL}, as achievable by viable future experiments. If we work with Fourier-Bessel transforms on the celestial sphere, the HI angular power spectrum is $C_\ell^{\mathrm{HI}}(\nu_i, \nu_j)$, where ν_i is the frequency of ith shell. To calculate this quantity, we use the CAMB_sources code [9], and include the redshift space distortion but discard subdominant terms. We refer to Camera et al. [1] for other assumptions and the experimental set up. Fig. 1 from Ref. [1] depicts the main results. We plot $\sigma_{f_{\mathrm{NL}}}$ contours in the plane of surveyed area and total observation time, with abscissas covering from a $15 \times 15\,\mathrm{deg}^2$ survey to 2π. The three top panels, where the y-axis is observation time t_{TOT} multiplied by the number of dishes N_d, illustrates the case for a dish survey with three distinct maximum angular modes, corresponding to dish diameters of 5, 15 and 80 metres at redshift ~ 3. For higher angular resolution, interferometers may be a better option. The lower panels of Fig. 1 show $\sigma_{f_{\mathrm{NL}}}$ for 1, 10 and 100 pointings at a resolution of $\ell_{\max} \simeq 300$, as set by choosing $D_a \sim 80\,\mathrm{m}$ as the diameter for the array. For interferometers, the main design parameter is the field of view, which fixes $\ell_{\min}$, and for a 'dense array' it is related to the number of elements. Given that the maximum angular scale is set by the field of view, by pointing several times we simply diminish the variance by N_p, though the noise increases too, because $t_{\mathrm{obs}} \to t_{\mathrm{obs}}/N_p$.

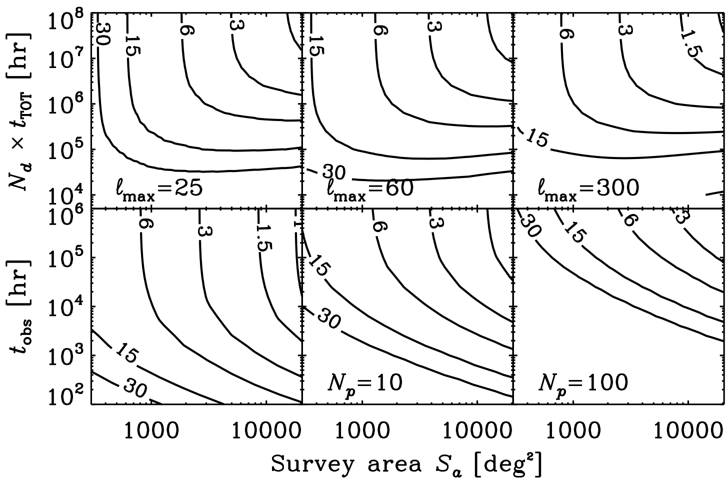

Figure 1. Forecast 68.3% error contours on f_{NL} as a function of surveyed area and total observation time, for a dish survey with N_d dishes (upper panels) and an interferometer making N_p pointings (lower panels). Courtesy of [1].

Several dish survey telescopes under development should be able to probe this HI intensity signal and thus constrain primordial non-Gaussianity. One of the major candidate is the Square Kilometre Array (SKA) phase 1, which will probe down to $\sim 350\,\mathrm{MHz}$, thus allowing us to push below *Planck* constraints. In terms of designing a new system from scratch, something like $10,000$ small dishes between $2 - 4\,\mathrm{m}$

diameter, working at ~ 400 MHz, would be a good and cheap possibility to target the $f_{\rm NL} \sim 1$ region. For interferometric surveys, none of the planned telescopes are compact enough to deliver the required sensitivity on large scales. This means we would need in principle to wait for the full SKA, with the proposed 'aperture array' system working below 1 GHz, thus reaching the $\sigma_{f_{\rm NL}} \lesssim 1$ limit. However, the full SKA is designed to achieve much higher angular resolution than what is needed for our purposes and a smaller array with 80 m or less in diameter would be an interesting, near term, alternative, capable of reaching $\sigma_{f_{\rm NL}} \sim 1$.

5. Conclusions

Here, we have succinctly reviewed the current theoretical and experimental endeavour to the aim of accessing the largest cosmological scales. We have shown why such extremely large scales contain a wealth of information capable to deepen our understanding of the physical mechanism driving the early Universe inflation and of the law of gravity itself. We have presented the HI intensity mapping technique as a valuable tool to access ultra-large scales – hardly reachable with enough sensitivity for conventional galaxy surveys. As a figure of merit, we have focussed on primordial non-Gaussianity as an emblematic large-scale effect and have shown how forthcoming HI intensity mapping experiments will enable us to constrain $f_{\rm NL}$ to a degree of accuracy much higher than the current most stringent constraints achieved by the Planck CMB experiment.

Acknowledgments

SC wishes to thank his collaborators for allowing him to show results from common projects. SC is funded by FCT-Portugal under Post-Doctoral Grant No. SFRH/BPD/80274/2011.

References

[1] Camera S, Santos M G, Ferreira P G and Ferramacho L 2013 *Phys. Rev. Lett.* **111** 171302 (*Preprint* 1305.6928)
[2] Camera S *et al.* 2014 *Advancing Astrophysics with the Square Kilometre Array*
[3] Santos M G *et al.* 2014 *Advancing Astrophysics with the Square Kilometre Array*
[4] Bertschinger E 1998 *Ann.Rev.Astron.Astrophys.* **36** 599–654
[5] Dolag K, Borgani S, Schindler S, Diaferio A and Bykov A M 2008 *Space Science Reviews* **134** 229–268
[6] Van Daalen M P, Schaye J, Booth C M and Dalla Vecchia C 2011 *Mon. Not. Roy. Astron. Soc.* **415** 3649–3665
[7] Yoo J 2010 *Phys. Rev.* **D82** 083508 (*Preprint* 1009.3021)
[8] Bonvin C and Durrer R 2011 *Phys. Rev.* **D84** 063505 (*Preprint* 1105.5280)
[9] Challinor A and Lewis A 2011 *Phys. Rev.* **D84** 043516 (*Preprint* 1105.5292)
[10] Clifton T, Ferreira P G, Padilla A and Skordis C 2012 *Phys. Rept.* **513** 1–189 (*Preprint* 1106.2476)
[11] Bartolo N, Komatsu E, Matarrese S and Riotto A 2004 *Phys. Rept.* **402** 103–266 (*Preprint* astro-ph/0406398)
[12] Sasaki M, Valiviita J and Wands D 2006 *Phys. Rev.* **D74** 103003 (*Preprint* astro-ph/0607627)
[13] Bartolo N, Matarrese S and Riotto A 2002 *Phys. Rev.* **D65** 103505 (*Preprint* hep-ph/0112261)
[14] Arkani-Hamed N, Creminelli P, Mukohyama S and Zaldarriaga M 2004 *JCAP* **0404** 001 (*Preprint* hep-th/0312100)
[15] Creminelli P, Senatore L, Zaldarriaga M and Tegmark M 2007 *JCAP* **0703** 005 (*Preprint* astro-ph/0610600)
[16] Chen X, Huang M x, Kachru S and Shiu G 2007 *JCAP* **0701** 002 (*Preprint* hep-th/0605045)
[17] Senatore L, Smith K M and Zaldarriaga M 2010 *JCAP* **1001** 028 (*Preprint* 0905.3746)
[18] Ade P *et al.* (Planck Collaboration) 2013 (*Preprint* 1303.5084)
[19] Dalal N, Dore O, Huterer D and Shirokov A 2008 *Phys. Rev.* **D77** 123514 (*Preprint* 0710.4560)
[20] Matarrese S and Verde L 2008 *Astrophys. J.* **677** L77–L80 (*Preprint* 0801.4826)
[21] Verde L, Wang L M, Heavens A and Kamionkowski M 2000 *Mon. Not. Roy. Astron. Soc.* **313** L141–L147
[22] Komatsu E and Spergel D N 2001 *Phys. Rev.* **D63** 063002 (*Preprint* astro-ph/0005036)
[23] Giannantonio T, Ross A J, Percival W J, Crittenden R, Bacher D *et al.* 2014 *Phys. Rev.* **D89** 023511 (*Preprint* 1303.1349)
[24] Bagla J, Khandai N and Datta K K 2010 *Mon. Not. Roy. Astron. Soc.* **407** 567 (*Preprint* 0908.3796)
[25] Switzer E R, Masui K W, Bandura K *et al.* 2013 *Mon. Not. Roy. Astron. Soc.* **434** L46–L50
[26] Jarvis M J, Bhatnagar S, Bruggen M, Ferrari C, Heywood I *et al.* 2014 (*Preprint* 1401.4018)
[27] Gong Y, Chen X, Silva M, Cooray A and Santos M G 2011 *Astrophys. J.* **740** L20 (*Preprint* 1108.0947)
[28] Bull P, Ferreira P G, Patel P and Santos M G 2014 (*Preprint* 1405.1452)
[29] Seo H J, Dodelson S, Marriner J, Mcginnis D, Stebbins A *et al.* 2010 *Astrophys.J.* **721** 164–173 (*Preprint* 0910.5007)
[30] Alonso D, Ferreira P G and Santos M G 2014 (*Preprint* 1405.1751)