The Multi-Tracer Technique To Detect Horizon-Scale Effects

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The opportunity of measuring various effects occurring on the largest cosmic scales have recently drawn an increasing attention, thanks also to the strong effort that will lead to next-generation cosmological experiments such as the *Euclid* satellite, the Large Synoptic Survey Telescope, and the Square Kilometre Array. Such experiments will probe enormous volumes of the Universe, allowing us to have a glimpse at scales near and beyond the cosmological horizon. The study of perturbations on those scales is extremely interesting, because their evolution is fully linear, and we can safely neglect baryonic effects occurring on much smaller scales. Through probes of ultra-large scales we can learn a lot about gravity, inflation and the early Universe. Unfortunately, measurements of such long-wavelength modes are hampered by the poor statistical sampling usually referred to as 'cosmic variance'. Here, we shall briefly review the so-called 'multi-tracer' technique, which will enables us to overcome cosmic variance by comparing the relative clustering of different tracers of the underlying cosmic structure. We shall discuss the most recent results and also illustrate how an incorrect treatment of horizon-scale effects may lead to a seriously biased reconstruction of cosmological parameters.

1 Horizon-Scale Cosmology

Constraints on properties and evolution of density fluctuations on extremely large scales, near and beyond the Hubble horizon $H^{-1}(z)$, will greatly improve our understanding of gravity, inflation and the physics of the early Universe [see e.g. 1, 2]. Hitherto, the study of the physics occurring on those scales has remained confined in a rather small niche, mostly because of the impossibility of performing measurements that could corroborate theoretical findings. However, the next decade will see a revolution in this respect, mostly thanks to forthcoming observational campaigns like the European Space Agency's flagship, the *Euclid* satellite [3, 4],[a] and the Large Synoptic Survey Telescope (LSST),[b] at optical/near-infrared wavelengths, or the various surveys envisaged for the Square Kilometre Array [5, 6, 7, 8],[c] at radio frequencies.

[a] `http://www.euclid-ec.org`
[b] `http://www.lsst.org`
[c] `https://www.skatelescope.org`

1.1 Relativistic Corrections

A crucial point that has to be emphasised is that, when we observe galaxies, we do not really have access to a Universe 'cube', but we rather see sources on the past light-cone. This means that we cannot simply perform a three-dimensional Fourier analysis of source number counts to get the power spectrum of density fluctuations. Instead, the correct procedure is to take such light-cone projection effects into account via e.g. full-sky angular power spectrum tomography or spherical Bessel-Fourier decomposition [9, 10, 11]. (Similar considerations can be made concerning redshift-space analyses [e.g. 12].) This procedure leads to general relativistic (GR) corrections to the standard linear power spectrum. The observed galaxy number counts contain not only the well-known Kaiser redshift-space distortions (RSDs), but also further GR contributions from gravitational redshift, lensing convergence, Doppler terms, Sach-Wolfe (SW) and integrated SW (ISW) terms, and a time-delay term.

On sub-Hubble scales, terms other than RSDs and lensing are typically negligible. However, on scales near and beyond the horizon, the other purely GR terms become increasingly important. This is one of the reasons why cosmology on horizon scales is so promising to deepen our knowledge of gravity. On the one hand, if we measure such purely GR effects, we will have a further confirmation of the validity of Einstein's theory of gravity in a régime extremely far from where we have accurate tests of it. On the other hand, deviations from the GR prediction on ultra-large scales will be a strong hint in favour of an explanation of the present-day cosmic acceleration in terms of modified gravity effects [see e.g. 13].

1.2 Primordial Non-Gaussianity

A small amount of non-Gaussianity in the primordial distribution of density fluctuations is predicted in many scenarios of inflation [e.g. 14]. We can parameterise through an overall amplitude, $f_{\rm NL}$, such primordial non-Gaussianity (PNG) in Bardeen's gauge invariant potential Φ, as the sum of a linear Gaussian term ϕ and a quadratic correction [15], namely $\Phi = \phi + f_{\rm NL}(\phi^2 - \langle\phi^2\rangle)$. A non-Gaussian distribution of primordial density perturbations cannot be fully described by a power spectrum. In this case, we also need higher-order moments such as the bispectrum, andc. In particular, different models of inflation give rise to different bispectrum shapes, thus making the study of PNG valuable for obtaining a deeper knowledge of the physics of inflation.

So far, the best way to probe PNG has relied upon measurements of the cosmic microwave background (CMB) temperature anisotropy bispectrum [see 16, for the most recent results]. However, it has been demonstrated that PNG also induces an additional, peculiar scale and redshift dependence in a biased tracer of the underlying matter distribution [e.g. 17]. For the sake of simplicity, we shall limit ourselves to the most well-studied type of PNG, which is referred to as 'local' type. The modification $\Delta b(z,k)$ it causes to the Gaussian large-scale bias b of a biased tracer is $\Delta b(z,k) \propto 3[b(z)-1]f_{\rm NL}/[k^2T(k)D(z)]$, where $b(z)$ is assumed scale-independent, $T(k)$ is the transfer function, $D(z)$ is the linear growth factor of density perturbations (normalised to unity today), and the proportionality depends on other standard cosmological parameters. Clearly, the effect of local-type PNG on the power spectrum grows on large scales because of the k^{-2} term.

2 Accessing the Largest Scales

Until recently, measurements of horizon-scale effects have been out of reach even for the most advanced cosmological experiments. On the one hand, the CMB is, practically speaking, a single slice in redshift. This implies that the reconstructed power spectrum of its temperature (or polarisation) anisotropies is a two-dimensional quantity, with much fewer large-scale modes than any three-dimensional probe [see also 18]. On the other hand, the matter power spectrum reconstructed from spectroscopic surveys [e.g. 19] relies on computing correlations between three-dimensional positions of a large number of galaxies. However, it is hard to reach high-significance detections both over large areas of the sky and at high redshifts. Hence, state-of-the-art spectroscopic surveys reach at most modes $k_{\rm min} \simeq 0.01h\,{\rm Mpc}^{-1}$, making it unfeasible to put constraints on large-scale effects such as PNG that are competitive with those from the CMB. Prospects for next-generation surveys like *Euclid* or the SKA look certainly better [e.g. 20, 21], but probably not enough to put a final word on PNG.

A newly proposed, promising approach is represented by mapping the intensity of the unresolved neutral hydrogen (HI), which is expected mostly to reside in galaxies after the end of reionisation [e.g. 7].[d] Such 'intensity mapping' will allow us to obtain CMB-like maps of the HI distribution over the redshift range $0 \lesssim z \lesssim 4$, highly valuable for PNG and GR effects [22, 23].

2.1 The Multi-Tracer Technique

The multi-tracer (MT) technique is a different approach to the problem of accessing the largest cosmic scales [24]. Instead of observing larger and larger volumes to lessen the repercussions of cosmic variance, we try to bypass it directly. MT involves a comparison between the relative clustering of different tracers of the underlying cosmic structure. It is based on the fact that on large, linear scales, the dark matter haloes are biased but not stochastic tracers of dark matter. (In other words, on large scales the stochastic quantity is the distribution of matter fluctuations itself, whereas the bias is deterministic.) Then, if what we are interested in is measuring quantities that have a peculiar impact on the clustering of biased tracers of the cosmic structure, by comparing various tracers with different biases we have in a sense access to different realisation of the bias field [see 25, for a comprehensive discussion].

In Fig. 1 we illustrate the great potential of the MT technique by showing the forecast marginal errors on $f_{\rm GR}$ (solid) and $f_{\rm NL}$ (dashed) as a function of the noise level for two single-tracer surveys: a phase 1 SKA HI intensity mapping survey (IM, blue); and a *Euclid*-like photometric galaxy survey (PG, red); as well as their combined MT analysis (black) [see 26, for details]. Here, $f_{\rm GR}$ is a fudge factor parameterising all the terms in the angular power spectrum of number counts other than standard Newtonian fluctuations and RSDs. We multiply the noise of both intensity mapping and galaxy number counts by an overall amplitude and let it vary from 0 to 1, where 0 means a noiseless experiment and 1 is the real setting. It is straightforward to see that, as we remove noise, single tracers soon reach the cosmic variance limited plateau, while MT keeps improving.

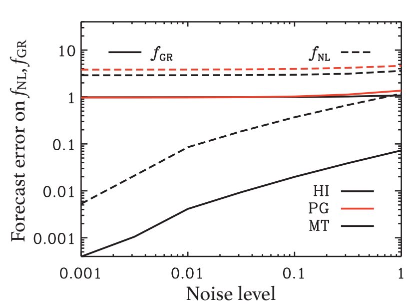

Figure 1 – Forecast 1σ marginal error on $f_{\rm GR}$ (solid) and $f_{\rm NL}$ (dashed) vs noise level for SKA phase 1 intensity mapping (blue), *Euclid*-like photo-z galaxies (red) and MT (black) [from 26].

[d] See also: M.G. Santos; R. Battye; S. Harper; and L. Olivari in this volume 'Moriond 2016 – Cosmology'.

3 Ultra-Large Scales Matter

Lastly, we show that, albeit horizon-scale effects such as GR corrections or PNG are largely sub-dominant with respect to the standard terms included in a power spectrum analysis, it will be very important for next-generation cosmological experiments to include them in their analysis pipeline, if we do not want to bias the reconstruction of cosmological parameters. First, we can note that the large scales where PNG is stronger are the very same on which GR corrections become significant. Therefore, one needs to incorporate the GR corrections in theoretical analysis in order to make accurate (and non-biased) predictions and estimates of PNG. To illustrate this, the left panel of Fig. 2 show with a dashed, blue ellipse the 1σ confidence region forecast for an SKA HI galaxy survey on the estimation of $f_{\rm NL}$ (on abscissas, the amplitude of the primordial power spectrum, A_s) [27]. Here, the true input value for the parameters is indicated by the red dot, and GR corrections have been thoroughly neglected in the analysis (i.e. $f_{\rm GR} = 0$). In other words, an incorrect treatment of GR corrections will lead to a spurious measurement of PNG due to the fact that the two signals have a similar impact on the power spectrum on large scales.

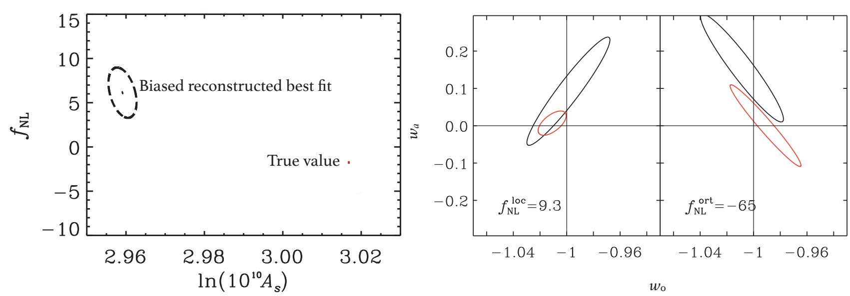

Figure 2 – Biased 1σ error contours on cosmological parameters due to incorrect modelling of horizon-scale effects. *Leftmost panel:* Spurious estimation of $f_{\rm NL}$ by an SKA HI galaxy survey caused by neglecting GR corrections in the analysis [from 27]. *Rightmost panel:* Spurious estimation of dynamical dark energy by a *Euclid*-like spectroscopic galaxy survey cause by not accounting for non-zero local-type (left panel) or orthogonal-type (right panel) PNG, with (red) and without (black) priors from *Planck* [from 28].

The right panel of Fig. 2 considers a similar scenario, but in this case the experimental set up is a *Euclid*-like spectroscopic galaxy survey, on the axes are the dark energy equation-of-state parameters $\{w_0, w_a\}$, and the horizon-scale effect that has been neglected to the purpose of showing its impact is PNG [see 28, for more details]. In particular, the left panel refers to local-type PNG, whilst the right panel is for PNG of the orthogonal-type. The central crosses indicate the fiducial value in the concordance ΛCDM model. It is important to note that the fiducial values for $f_{\rm NL}$ quoted in the plot are well within $1-2\sigma$ bounds from *Planck* [16]. Black ellipses are obtained with *Euclid*-like data alone, whereas red contours include priors from *Planck*. Clearly, the bias on the estimated value of $\{w_0, w_a\}$ is much smaller than in the previous case. However, let us emphasise that dark energy is not significant on ultra-large scales only. This means that even for measuring standard cosmological parameters—more, parameters that are the most targeted by forthcoming surveys—it is of primary importance to account for horizon-scale effects correctly, either we will get very accurate but biased results that may undermine the quality of envisaged scientific products of future cosmological experiments.

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