The Zeldovich Universe:
Genesis and Growth of the Cosmic Web
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The impact of superstructures in the Cosmic Microwave Background

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Abstract. In 2008, Granett *et al.* claimed a direct detection of the integrated Sachs-Wolfe (iSW) effect, through the stacking of CMB patches at the positions of identified superstructures. Additionally, the high amplitude of their measured signal was reported to be at odds with predictions from the standard model of cosmology. However, a closer inspection of these results prompts multiple questions, more specifically about the amplitude and significance of the expected signal. We propose here an original theoretical prediction of the iSW effect produced by such superstructures. We use simulations based on GR and the LTB metric to reproduce cosmic structures and predict their exact theoretical iSW effect on the CMB. The amplitudes predicted with this method are consistent with the signal measured when properly accounting the contribution of the non-negligible (and fortuitous) primordial CMB fluctuations to the total signal. It also highlights the tricky nature of stacking measurements and their interpretation.

Keywords. cosmic microwave background, large-scale structure of universe, dark energy

1. Introduction

Dark Energy (DE) is one of the great mysteries of modern cosmology. The integrated Sachs-Wolfe effect (iSW) is an original probe of DE, linked to the large-scale structure of the Universe and the cosmic microwave background (CMB). Indeed, one of the effects of the accelerated expansion is the stretching of gravitational potentials, therefore changing the frequency of the CMB photons that travel through them. This effect is integrated along the whole line of sight of the CMB photons and shifts their temperature by an amount defined by :

$$\delta_T^{\rm iSW} = 2 \int \dot{\Phi} dt \qquad\qquad (\Phi = \text{grav.potential}).$$

Consequently, the iSW effect has a direct but weak impact on the largest scales of the power spectrum of the CMB temperature fluctuations (Kofman & Starobinskii 1985). Since cosmic variance prevents a CMB-only detection of this iSW signal at those low multipoles, the use of external data is therefore required. The conventional approach is to correlate the CMB with a tracer of the matter distribution – usually galaxy surveys. This approach has been attempted numerous times (see Dupé *et al.*2011 for a review), these have yet to give a definitive and unambiguous detection of the iSW effect. This situation is mainly a consequence of the shortcomings of current surveys, not deep enough and/or with too small a sky coverage and therefore not optimised for iSW studies (see Douspis *et al.*2008 for a detailed discussion on the optimisation of such surveys).

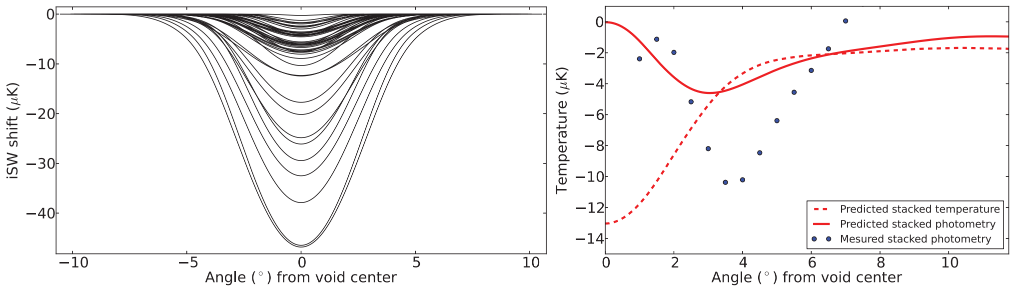

Figure 1. *Left panel:* Predicted temperature profiles of the iSW shift induced by the 50 Granett *et al.* voids. The amplitude of about 10 of these voids clearly stands out from the rest and makes up for most of the predicted signal. *Right panel:* Predicted temperature (dashed red curve) and photometry (solid red) profiles from the stacked iSW signal of the 50 Granett *et al.* voids. The blue points correspond to the real photometry profile measured in the CMB data.

Another approach to the iSW detection is to focus on the individual objects expected to leave the biggest imprint in the CMB, i.e. the largest superstructures in the Universe. While their individual imprint is buried under the primordial CMB fluctuations, we can average patches of the CMB at the locations of many superstructures in order to cancel the random CMB fluctuations while enhancing the iSW signal. In their pioneering work, Granett *et al.* (2008) claimed a $4\,\sigma$ detection of the iSW effect by stacking CMB patches at the positions of 100 superstructures, identified in the DR4 release of the LRGs sample of the SDSS. However, the measured amplitude was reported to be at odds with ΛCDM predictions (e.g. Cai *et al.*2013), while some peculiar features were also noted in the signal (Ilić *et al.*2013) such as the large hot ring around the cold signal from voids.

2. Simulating a superstructure and its impact on the CMB

The use of a stacking approach for the iSW detection raises a number of questions, especially concerning the nature and amplitude of the expected signal. To answer them, we developed an original theoretical prediction of the iSW effect produced by superstructures. The procedure we created is twofold : first, we modelled a structure and its evolution using the Lemaître-Tolman-Bondi (LTB) metric, the most general metric with a spherical symmetry. Using the data from the Granett *et al.* catalogue, we focused on reproducing their 50 voids (size, redshift, etc.) and we derived their evolution history. Secondly, we then computed the exact theoretical iSW effect of these structures on the CMB by solving geodesic equations for photons crossing through the previously computed LTB metric.

As expected, the iSW effect produced by the majority of these voids is indeed small (less than 10μK for the decrement in the temperature of CMB photons) as we can see in the left panel of Fig. 1. However, using my simulations we show here that about one fifth of the Granett *et al.* voids (and, as intuited, the largest ones) create a signal large enough to greatly increase the mean amplitude of the shift. Going further, we were also able to reconstruct the theoretical iSW map associated with these 50 voids, i.e. the temperature shift due to the iSW effect associated to each point in the sky accounting for all the voids present on the corresponding line of sight. Similarly to the analysis of real data, we can perform the stacking procedure on this iSW map, and obtain the expected temperature and photometry signal from these voids (see the right panel of Fig. 1). At a scale of 4 degrees the predicted photometry signal reaches approximatively -4μK, whereas the measured signal peaks at about -10μK at the same scale.

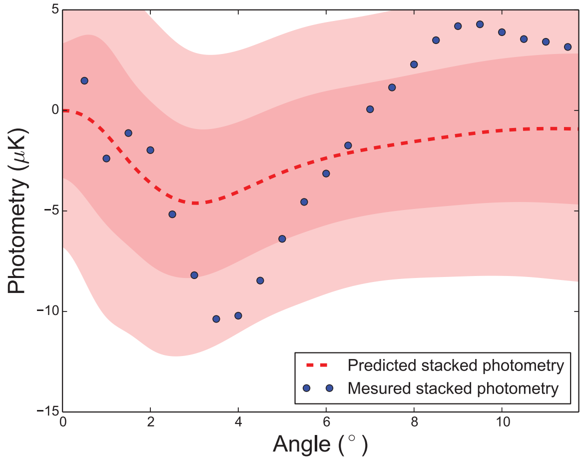

Figure 2. Predicted (dashed red) and measured (blue points) photometry profiles from the stacked iSW signal of the 50 Granett *et al.* voids. From dark to light red, the areas correspond to the $1\,\sigma$ and $2\,\sigma$ levels of the expected photometry profile.

However, this result only shows that the iSW effect of the 50 supervoids cannot solely account for the entirety of the signal measured by stacking. Indeed, it does not invalidate the hypothesis of the presence of an iSW signal in the measurement, that would be mixed with and contaminated by a larger, fortuitous signal coming from the primordial fluctuations of the CMB.

To assess the likelihood of such a scenario and its compatibility with the data, we generated a few thousands Gaussian realisations of the CMB (with the current best-fit cosmological parameters as determined by the *Planck* mission) to which we added our predicted iSW map of the 50 voids. For each of the resulting map, we applied the same stacking procedure as the one used on the real CMB data and obtained the temperature and photometry profiles of the corresponding stacked image.

With the resulting collection of profiles, we estimated that the photometry of the measured stacking signal at 4 degrees stands out at a $1.7\,\sigma$ level compared to its expected value (see Fig. 2). Furthermore, we were also able to compute the reduced χ^2 of the whole photometry profile, which we found to be close to one. Contrary to claims in the literature, it appears here that the signal measured through the stacking procedure is compatible with ΛCDM predictions. The high reported amplitude and the observed peculiarity of the photometry profile seem to be merely due to random (and not particularly rare) fluctuations from the primordial part of the CMB. The measurement from Granett *et al.* (2008) is therefore compatible with the expected iSW from such structures and does not present any significant discrepancy with respect to the ΛCDM paradigm.

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