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Cross-correlation between cosmological and astrophysical datasets: the Planck and Herschel case

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Abstract. We present the first measurement of the correlation between the map of the CMB lensing potential derived from the Planck nominal mission data and $z \gtrsim 1.5$ galaxies detected by *Herschel*-ATLAS (H-ATLAS) survey covering about 550 deg^2. We detect the cross-power spectrum with a significance of $\sim 8.5\sigma$, ruling out the absence of correlation at 9σ. We check detection with a number of null tests. The amplitude of cross-correlation and the galaxy bias are estimated using joint analysis of the cross-power spectrum and the galaxy survey auto-spectrum, which allows to break degeneracy between these parameters. The estimated galaxy bias is consistent with previous estimates of the bias for the H-ATLAS data, while the cross-correlation amplitude is higher than expected for a ΛCDM model. The content of this work is to appear in a forthcoming paper Bianchini, *et al.* (2014).

Keywords. cosmology: cosmic microwave background, gravitational lensing, galaxies: high-redshift, methods: data analysis

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1. Introduction

Cosmological observations carried out in the last two decades have led to the establishment of the standard cosmological model. In this framework observed galaxies form in matter overdensities which are the result of the growth, driven by gravitational instabilities in an expanding Universe, of primordial inhomogeneities generated during an inflationary epoch. A picture of primordial inhomogeneities and the Universe at the beginning of its evolution is provided by observations of the cosmic microwave background (CMB) anisotropy at redshift $z \sim 1100$.

However as CMB photons travel from last scattering surface to the observer, they are gravitationally deflected on the arcminute scale by the intervening matter. The effect of the cosmic web is to induce a small but coherent (on the degree scale) deflections of the observed CMB temperature and polarization anisotropies; as a consequence, these deflections change the statistics of small scale unlensed CMB fluctuations by introducing a correlation between different Fourier modes.

In recent years CMB lensing has been measured in a number of CMB experiments. The first detections were made via cross-correlations with large scale structure probed by galaxy surveys. The higher sensitivity and resolution of recent CMB experiments, such as ACT, SPT and Planck, made possible to detect lensing using CMB data alone.

As already mentioned, the CMB lensing potential is an integrated measure of the matter distribution in the universe, up to the last scattering surface while the galaxies constitute signposts of nonlinear, virialized dark matter structures. In the standard, hierarchical paradigm for structure formation, nonlinear objects are preferentially formed on the peaks of the underlying linear density field, thus a cross-correlation between these two cosmic fields is expected; by measuring this cross-correlation we can determine the linear galaxy bias factor b that relates galaxies δ_g and matter δ fractional overdensities as $\delta_g = b\delta$.

In this work we present the first investigation of the cross correlation between the CMB lensing potential measured by Planck and Herschel-selected galaxies with estimated redshifts $z \gtrsim 1.5$. We adopt the fiducial flat ΛCDM cosmology with best-fit Planck cosmological parameters as provided by the Planck team in Planck Collaboration XVI (2013) (combination of Planck+WP+ highL+lensing datasets).

2. Modeling the expected signal

Both the strength of CMB lensing (encoded in the convergence field κ) and galaxy density fluctuations in a given direction of the sky depend on the projected dark matter density in that direction, so that these fields can be written as

$$X(\hat{\mathbf{n}}) = \int_0^{z_*} dz\, W^X(z)\delta(\chi(z)\hat{\mathbf{n}}, z), \tag{2.1}$$

where $X = \kappa, g$ and $W^X(z)$ is the kernel related to a given field.

The lensing kernel W^κ is

$$W^\kappa(z) = \frac{3\Omega_m}{2c}\frac{H_0^2}{H(z)}(1+z)\chi(z)\frac{\chi_* - \chi(z)}{\chi_*}. \tag{2.2}$$

In this equation, $\chi(z)$ is the comoving distance to redshift z, χ_* is the comoving distance to the last scattering surface at $z_* \simeq 1090$, $H(z)$ is the Hubble factor at redshift z, c is the speed of light, $\Psi(\chi(z)\hat{\mathbf{n}}, z)$ is the 3D gravitational potential at a point on the photon path given by $\chi(z)\hat{\mathbf{n}}$, Ω_m and H_0 are the present-day values of matter density and Hubble parameter respectively.

The galaxy kernel is

$$W^g(z) = \frac{b(z)\frac{dN}{dz}}{\left(\int dz'\, \frac{dN}{dz'}\right)} + \frac{3\Omega_m}{2c}\frac{H_0^2}{H(z)}(1+z)\chi(z)\int_z^{z_*} dz' \left(1 - \frac{\chi(z)}{\chi(z')}\right)(\alpha(z') - 1)\frac{dN}{dz'}. \tag{2.3}$$

The galaxy overdensity kernel is the sum of two terms: the first one is given by the product of the linear bias $b(z)$ by the redshift distribution dN/dz, while the second one takes into account the effect of gravitational magnification on the observed density of foreground sources. This effect depends on the slope, $\alpha(z)$, of their integral counts ($N(> F) \propto F^{-\alpha}$) below the adopted flux density limit.

Since the relevant angular scales are smaller than 1 radian (multipoles $\ell \gtrsim 100$) the theoretical angular cross-correlation can be computed using the Limber approximation:

$$C_\ell^{\kappa g} = \int_0^{z_*} \frac{dz}{c}\frac{H(z)}{\chi^2(z)} W^\kappa(z) W^g(z) P\left(k = \frac{\ell}{\chi(z)}, z\right), \tag{2.4}$$

where $P(k, z)$ is the matter power spectrum evaluated at wavenumber k and redshift z. The strength of the cross-correlation signal is determined by the overlap of the two kernels which are shown in Fig. 1 (left panel) using the H-ATLAS redshift distribution for W^g. The mean redshift probed by this cross-correlation is $\langle z\rangle \simeq 2$.

3. Datasets

We use the publicly released Planck CMB lensing potential map derived from a minimum variance combination of the 143 and 217 GHz temperature anisotropy maps only

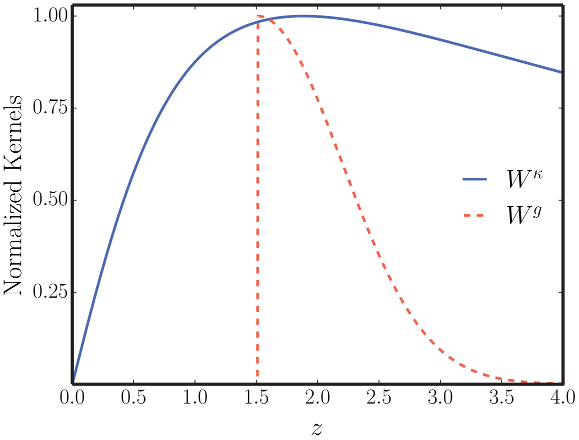

Figure 1. *Left panel*: estimated redshift distribution of the full sample of H-ATLAS galaxies (dashed line) compared with the CMB lensing kernel W^κ (solid line). Both kernels are normalized to a unit maximum. *Right panel*: the CMB convergence - galaxy density cross-spectrum as measured from Planck and Herschel data with best-fit theory lines (see text).

(Planck Collaboration XVII (2013)). To avoid biases in the estimation of the power spectrum for small patches of the sky due to the leakage of the large scale power to small scales, we converted to ϕ map to a κ map.

We have selected our galaxy sample from the catalogue of sources detected in the H-ATLAS fields, covering altogether $\sim$ 550 deg^2 with PACS and SPIRE instruments between 100 and 500 μm. The survey area is divided into five fields: three equatorial fields (GAMA fields, G09, G12 and G15), the North Galactic Pole (NGP) block and the South Galactic Pole (SGP) block.

The $z \lesssim 1$ galaxies detected by the H-ATLAS survey are mostly late-type and starburst galaxies with moderate star formation rates and relatively weak clustering. High-z galaxies are forming stars at high rates ($\geqslant$ few hundred $M_\odot$ yr^{-1}) and are much more strongly clustered, implying that they are tracers of large scale over-densities. Their properties are consistent with them being the progenitors of local massive elliptical galaxies (Lapi, *et al.*(2011)). We aim at correlating high-z H-ATLAS galaxies with the *Planck* CMB lensing map.

To select the high$-z$ population we adopt the criteria developed by Gonzalez-Nuevo, *et al.*(2012): (i) $S_{250\,\mu m} > 35$ mJy; (ii) $S_{350\,\mu m}/S_{250\,\mu m} > 0.6$ and $S_{500\,\mu m}/S_{350\,\mu m} > 0.4$; (iii) $3\,\sigma$ detection at $350\,\mu$m; (iv) photometric redshift $z_{\rm phot} > 1.5$, estimated following Lapi, *et al.*(2011) who showed that the uncertainty is $|z_{\rm phot} - z|/(1+z) \leqslant 20\%$. Our final sample comprises a total of 99823 sources.

4. Methods and Results

We estimate the angular power spectra using a pseudo-C_ℓ estimator, based on MASTER algorithm, using a sky mask leaving out only the regions covered by the H-ATLAS survey. We choose to measure the signal in seven linearly spaced bins of width $\Delta\ell = 100$ in the $100 \leqslant \ell \leqslant 800$ range.

In order to validate the pipeline developed and check that the measured cross- and auto-power spectra estimates are unbiased, we created 500 simulated maps of the CMB convergence field and the galaxy overdensity field with the statistical properties consistent with observations. The analysis pipeline recovers the input power spectra within measured errors. We also verify our pipeline by cross correlating our 500 simulated CMB lensing maps (containing both signal and noise) with the real H-ATLAS galaxy density map and our 500 simulated galaxy maps constructed using $b = 3$ with the true *Planck* CMB convergence map: in both cases no significant signal is detected.

The recovered cross-spectrum is shown in Fig. 1 (right panel). The error bars are estimated cross-correlating 500 Monte Carlo realizations of simulated CMB convergence maps (containing both signal and noise) with the true H-ATLAS galaxy density map. We evaluate the χ^2 of null hypothesis as $\chi^2_{\rm null} = \hat{\mathbf{C}}_L\, {\rm Cov}^{-1}_{\rm LL'}\, \hat{\mathbf{C}}_{\rm L'}$, rejecting no correlation hypothesis with 9σ significance. If all of the signal is indeed due to cosmological origin, the significance of the detection can be evaluated as $\Delta\chi^2 = \sqrt{\chi^2_{\rm null} - \chi^2_{\rm best}} \simeq 8.5\sigma$, where $\chi^2_{\rm best}$ is the chi-squared value of best-fit theoretical spectrum.

We introduce an additional parameter, A, that scales the expected amplitude of the cross-power spectrum, $C_\ell^{\kappa g}$. The best values of the parameters (amplitude A and bias b) have been obtained fitting the function $C_\ell^{\kappa g}$, multiplied by $A \times b$, to the observed cross-power spectrum. The obvious degeneracy between the amplitude A and the bias parameter b can be broken fitting simultaneously also the galaxy auto-correlation that scales as b^2. The best-fit values obtained using only the cross-spectrum data are $b = 5.12^{+3.89}_{-2.86}$ and $A = 1.15^{+1.39}_{-0.52}$ while adding the galaxy auto-spectrum data we are able to break the degeneracy: $b = 2.80^{+0.12}_{-0.11}$ and $A = 2.08^{+0.23}_{-0.23}$.

The amplitude is higher than expected from the standard model and found by cross-correlation analyses with other tracers of the large-scale structure. This tension may be due to magnification bias due to weak gravitational lensing: recent work by Gonzalez-Nuevo, *et al.*(2014) has shown that this effect is substantial for high-z H-ATLAS sources selected with the same criteria as the present sample (the number counts are steep and the slope is $\alpha = 3 \div 5$). The consequence of such effect is to enhance the expected $C_\ell^{\kappa g}$ amplitude, hence decreasing the tension. Nevertheless, even for $\alpha = 5$ the data require $A > 1$. Another systematic effect that can bias our measurement of the CMB convergence-galaxy cross-correlation is the leakage of CIB emission into the lensing map through the temperature maps, as it correlates strongly with the CMB lensing signal. Work is in progress to address these issues.

5. Conclusions

We have presented the first measurement of the correlation between the lensing potential derived from the Planck data and a high$-z$ ($z \gtrsim 1.5$) galaxy catalogue from the H-ATLAS survey, the highest z sample for which the correlation between Planck CMB lensing and tracers of large-scale structure has been investigated so far. We rule out the absence of cross-correlation signal with a significance of 9σ. A joint analysis of the cross-power spectrum and of the auto-power spectrum of the galaxy density contrast yielded a galaxy bias parameter consistent with earlier estimates for H-ATLAS galaxies at similar redshifts (Xia, *et al.*(2012)), although reporting an higher amplitude than expected.

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