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VOIDS LENSING OF THE CMB AT HIGH RESOLUTION

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ABSTRACT

Recently, cosmic voids have been recognized as a powerful cosmological probe. A number of studies have focused on the effects of the gravitational lensing by voids on the temperature (and in some cases polarization) anisotropy of the Cosmic Microwave Background (CMB) background at relatively large to medium scales, $l \sim 1000$. Many of these studies attempt to explain the unusually large cold spot in CMB temperature maps and dynamical evidence of dark energy via detections of late-time integrated Sachs Wolfe (ISW) effect. Here, the effects of lensing by voids on the CMB temperature anisotropy at small scales, up to $l = 3000$, will be investigated.

This work is carried out in the light of the benefits of adding large catalogues of cosmic voids, to be identified by future large galaxy surveys such as EUCLID and LSST, to the analysis of CMB data such as those from Planck mission. Our numerical simulation utilizes two methods, namely, the small-deflection-angle approximation and full ray-tracing analysis. Using the fitted void density profiles and radius (R_V) distribution available in the literature from N-body simulations, we simulated the secondary temperature anisotropy (lensing) of CMB photons induced by voids along a line of sight from redshift 0 to 2. Each line of sight contains approximately 1000 voids of effective radius $R_{V,eff} = 35\ h^{-1}$Mpc with randomly distributed radial and projected positions. Both methods are used to generate temperature maps. The two methods will be compared for their accuracy and efficiency in the implementation of theoretical modeling.

Key words: Cosmic void: CMB: Weak lensing:

1. INTRODUCTION

Recent observations of the cosmic microwave background (CMB) (Hinshaw, G. et al. , 2013; Planck collab , 2014) have shown that our Universe is highly Gaussian with a nearly scale-invariant power spectrum. It is strong evidence of a homogeneous and isotropic universe on large scales. This picture of the universe is known as the inflationary ΛCDM model (see e.g. Carroll, S. M. et al. , 1992). However, on small scales, the universe has been observed to be inhomogeneous with local clumps of over-dense (clusters) or under-dense (voids) regions.

The CMB radiation has been traveling towards us from the last scattering surface, passing through intervening clusters and voids along the line-of-sight. The trajectories of CMB photon are bent towards gravitating matter by gravitational lensing (Bartelmann, M. & Schneider, P. , 2001). In this work, we study the cosmic void gravitational lensing effect on the CMB anisotropy temperature, and predict what high resolution CMB observations will reveal. Furthermore, the integrated Sachs Wolfe (ISW) effect will be included in the research. Finally, lensing and ISW effects on the CMB will be distinguished for the study of dark energy dynamics.

2. THEORY

2.1. CMB Flat Sky Approximation

The lensed CMB temperature anisotropy in the direction $\hat{n}$ on the sky, $\tilde{\Theta}(\hat{n})$, is equivalent to an unlensed anisotropy $\Theta(\hat{n} + \alpha)$ where α is deflection angle (Lewis, A. & Challinor, A. , 2006) caused by a source with gravitational lensing potential $\alpha(\hat{n}) \equiv \nabla\psi(\hat{n})$. Since α is very small we can used Taylor's expansion to approximate

$$\tilde{\Theta}(\hat{n}) = \Theta(\hat{n}) + \alpha_i \partial^i \Theta(\hat{n}) + \frac{1}{2}\alpha_i \alpha_j \partial^i \partial^j \Theta(\hat{n}) + O(\alpha^3) \quad (1)$$

summed over i and j.

2.2. Void Profile

Recently, the simulations of Hamaus, N. et al. (2014) have shown that on average a void profile is spherically

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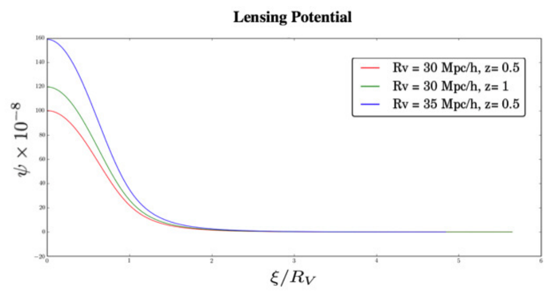

Figure 1. The lensing potential as a function of impact parameter, ξ (in units of R_V). The potential is spherically symmetric and similar to a Gaussian function.

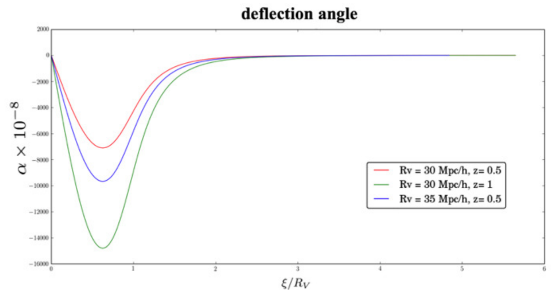

Figure 2. The deflection angles as a function of ξ.

symmetric and can be described by

$$\rho_V(r)/\langle\rho\rangle_M = 1 + \rho_c \frac{1-(r/R_s)^\gamma}{1+(r/R_V)^\beta}, \tag{2}$$

where$\langle\rho\rangle_M$ is the mean cosmic matter density and R_V is the characteristic void radius. R_S is the radius scale where $\rho_V = \langle\rho\rangle_M$. In this calculation our parameters are $R_S/R_V = 0.934$, $\gamma = 2.13$, $\beta = 9.24$ and $\delta_c =$ -0.768 for R_V within 20 - 50 Mpc h^{-1}.

3. METHOD

3.1. Lensing Potential Calculation

he lensing potential can be considered as the projection of a Newtonian gravitational potential along the line of sight divided by the speed of light squared. Following this approach, the lensing potential satisfies the two - dimensional Poisson equation,

$$\nabla^2_\theta \psi(\theta) = \frac{8\pi G}{c^2} \frac{D_d D_{ds}}{D_s} \Sigma(D_d\theta) \tag{3}$$

The projected mass density $\Sigma(D_d\theta)$ is evaluated by integrating the density $\rho(D_d\theta, \chi)$ along a line of sight χ

$$\Sigma(D_d\theta) = \int \rho(D_d\theta, \chi) d\chi. \tag{4}$$

Where D_d is the angular diameter distance between the observer and lens plane, D_s is the distance between the observer and the source image plane and D_{ds} is for the lens plane and source plane. Notice that the lensing potential is dimensionless and $\xi = D_d\theta$ is the impact parameter.

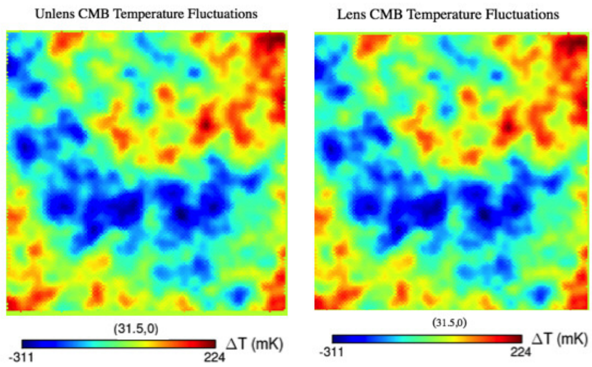

Figure 3. The un-lensed (left) and lensed (right) CMB maps. The effect is very weak, suggesting that high resolution observations are required to detect CMB-void lensing.

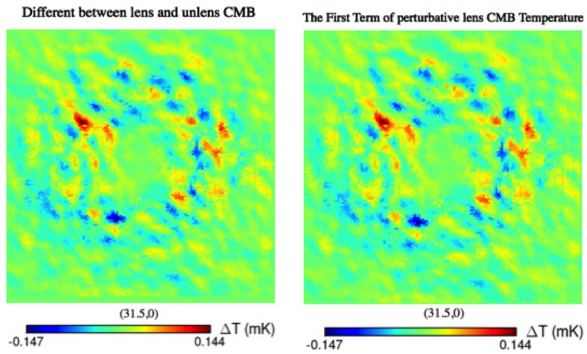

Figure 4. The plots show the lensing contribution (Eq. 1) to the CMB temperature anisotropy (left) and when only the first-order term is considered (right).

4. RESULTS AND DISCUSSION

The simulation results show that the lensing potential is spherically symmetric and very similar to a Gaussian function as illustrated by Fig. 1. Fig. 3 (left) shows a CMB map generated by HEALPix software (Górski et al., 2005) using Planck collab (2014) cosmological parameters. The right panel shows a CMB map lensed by 1000 voids with $R_{\rm V,eff}$= 35 Mpc h^{-1} from $z = 0 - 1$.

The approximation of the secondary CMB temperature is dominated by the first-order approximation, which is illustrated in Fig. 4. The ray-tracing results are not included in this paper. A comparison analysis between the flat-sky approximation and the ray tracing method as well as ISW effect and weak lensing will be reported in future papers.

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