CMB Weak Lensing by Dark Matter Halos

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In this paper, I summarize and discuss the results of Madhavacheril, *et al.*, who use new data from the Atacama Cosmology Telescope Polarimeter (ACTPol) in conjunction with the positions of constant mass (CMASS) galaxies chosen from the SDSS-III/BOSS survey to detect the presence of dark matter halos on a smaller scale (clusters and massive galaxies) than ever before with a signal significance of 3.2σ [1]. In addition to concisely summarizing their processes and findings, I provide some physics and technical background and explain the significance of their work and possible future work in the context of modern cosmological theory.

I. INTRODUCTION

The cosmic microwave background (CMB) is very nearly a perfect blackbody at 2.725 K, but there are anisotropies at $\mathcal{O}(10^{-5})$ in the temperature *and* polarization fields [2, p. 5,6]. Variations in the polarization, like variations in the temperature field, are a result of oscillations within the photon-baryon fluid on the last scattering surface. Because this "surface" has some thickness, quadrupoles have time to arise and scatter off of a surface which has temperature fluctuations which in turn can give rise to a polarization field which possesses many of the same statistical characteristics of the temperature field. For simplicity, from this point on, I will only deal with the temperature field since the ACTPol is calibrated to the WMAP temperature in the Madhavacheril, *et al.* analysis anyway.

Because the CMB has relatively well-known statistical characteristics and it fills up the entire sky, it is perfectly well-suited to study the distribution of intervening matter [1, p. 1,2]. Studying the lensing of the CMB can allow one to test different models of large-scale matter distribution and constrain several cosmological parameters. In particular it allows a more detailed study of inflation and curvature [1, 2, p. 1,2], and it may be able to corroborate other findings on neutrino mass [2, p. 77-8]. It may also allow a more complete understanding of the nature of dark matter.

Madhavacheril, *et. al.* use data from ACTPol to construct a convergence map which they then compare with the positions of a subset of CMASS galaxies found from a recent data release from the Sloan Digital Sky Survey (SDSS-III/BOSS). The significance of their result is 3.2σ [1, p. 2].

II. DISCUSSION

Madhavacheril, *et. al.* select only nighttime ACTPol data because of its lower noise and filter the data by subtracting significant point sources while taking into account beam convolutions and each point's respective flux. As previously discussed, the data is then calibrated to the WMAP temperature profile [1, p. 2]. They attain optical/photometric data on a subset of CMASS galaxies from SDSS-III/BOSS. These galaxies have redshifts $z \in [0.4, 0.7]$ with $\overline{z} = 0.54$ and are therefore also volume limited (according to Hubble's law). For each CMASS source, a temperature "stamp" is created from ACTPol. These "stamps" are then beam deconvolved, apodized, and further filtered to remove unwanted optical effects [1, p. 3]. An appropriate understanding of lensing and some of the underlying physics can allow one to understand how weak lensing would alter the CMB.

Lensing can be understood even through Newtonian mechanics, where α is the angle of deflection, ϕ is the deflection potential, and R_0 is the distance at closest approach.

$$\alpha = \frac{2\Phi(R_0)}{c^2} = \nabla\phi \quad (1)$$

$$\alpha = \frac{2GM}{c^2 R_0} * 2 \quad (2)$$

The factor of 2 in equation (2) is a relativistic correction [2, p. 6-7]. An unlensed CMB temperature map, $\tilde{T}(\hat{n})$, is lensed to $T(\hat{n})$ based on α or $\nabla\phi$.

$$T(\hat{n}) = \tilde{T}(\hat{n} + \nabla\phi) \quad (3)$$

$$\kappa = \frac{-\nabla^2\phi}{2} \quad (4)$$

Here, κ is the convergence [1, 2]. The derivation of the relativistic result is too involved for our purposes. On the scale under consideration ($< 100'$), $\tilde{T} \approx \nabla\phi \cdot \nabla T$ [1, 2]. Therefore, to find a convergence map in the small angle limit, we need only consider the large-scale background temperature gradient, ∇T, and small scale variations, $\nabla\phi$.

This is an interesting method! By assuming that the unlensed CMB temperature map is best approximated by the large-scale gradient (because lensing most likely "smooths" out small scale variations in the CMB), one can then find the angle deflection field by merely identifying deflections that lie in the same direction [1, 2, p. 69]. To summarize the process, one finds a small-scale fluctuations map, a large-scale fluctuations map, takes their product, and then determines the divergence of said product. This gives the convergence, κ.

The convergence "stamps" are subsequently normalized and low-pass filtered to ignore things on a scale smaller than the telescope could measure. The data are averaged or "stacked" and normalized again. Modhavacheril, *et. al.* simulate 50 ACTPol "stamps" per original window and using these simulations, calculate a covariance matrix for each stamp. This process is also repeated for combined or stacked stamps [1, p. 4]. There's a very strong signal within the approximate Virial radius. See figures 1 and 2.

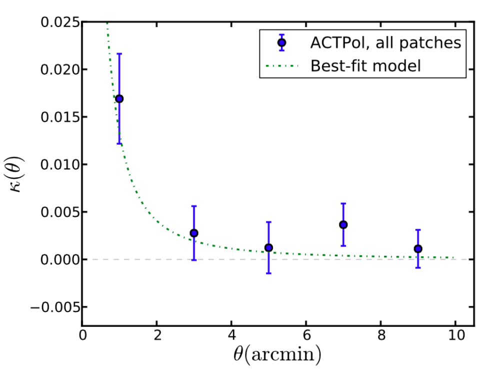

FIG. 1: This is an azimuth-averaged plot of convergence as a function of angle from the center of a CMASS object. Notice in particular the peak at $\theta \approx 7'$. At $z = 0.6$ & halo mass $= 10^{13} M_\odot$, the Virial Radius is approximately $1.5'$. From Madhavacheril, *et. al.* p. 5 [1].

The κ measurement was above what the random-position null hypothesis described above predicted by 3.8σ [1, p. 4,5]. A precise determination of the significance of the measurements depends on the width of the profile among other factors, but regardless of the particular methods used in the error analysis, the results are undoubtably statistically significant. A null test (see fig. 3)

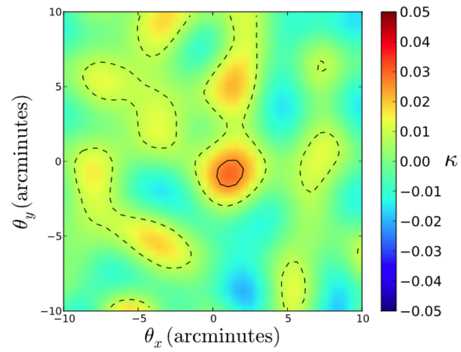

FIG. 2: This is a plot of κ in one of the previously described tiles around a CMASS object. The solid line line which represents a result of 3σ clearly indicates the presence of a large central mass while it seems unclear what the dotted line, 1σ, seems to indicate if anything. From Madhavacheril, *et. al.* p. 5 [1].

where a random part of the sky is studied, reinforces this conclusion. Sunyaey-Zeldovich (SZ) radiation may also be introducing some systematic error. The SZ effect is a result of inverse Compton scattering between very energetic electrons and low-energy photons from the CMB; it increases the frequency of the measured CMB and its effect on the structure of the CMB is poorly understood [2]. Nevertheless, Madhavacheril, *et. al.* suggest that this effect should be negligible [1, p. 6,7].

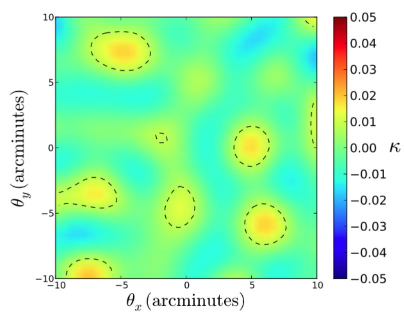

FIG. 3: This is a 2-D plot of κ in a null test, which uses a random position as opposed to the position of a CMASS object. From Madhavacheril *et. al.* p.6 [1].

III. SUMMARY

From these data, it is determined that one can indeed find large scale mass distributions only given the measured CMB temperature or polarization. Because of improved instrument precision, scientists are able to detect matter through lensing on increasingly smaller scales. Further analysis could better constrain fundamental cosmological parameters. The curvature of the universe influences CMB temperature and polarization power spectra in a predictable way (which can be determined using general relativity). In order to continue to use these new methods on increasingly tiny scales, the influence of the SZ effect must be studied further. A more accurate determination of lensing potentials can also improve constraints on neutrino masses and dark energy among other things [2, p. 70-80].

In addition to the arXiv sources, I made great use of: [6], which provides information about the BOSS target selection from SDSS data and the Princeton ACT website, [7]. The Wikipedia articles on weak lensing and the SZ effect provide excellent background ([8] and [9] respectively).

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