THE SIGNATURE OF THE WARM-HOT INTERGALACTIC MEDIUM IN WMAP AND THE FORTHCOMING PLANCK DATA

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ABSTRACT

We compute the cross-correlation between the Warm-Hot Intergalactic Medium and maps of cosmic microwave background temperature anisotropies using a log-normal probability density function to describe the weakly nonlinear matter density field. We search for this contribution in the data measured by the Wilkinson Microwave Anisotropy Probe. We use a template of projected matter density reconstructed from the Two-Micron All-Sky Redshift Survey as a tracer of the electron distribution. The spatial distribution of filaments is modeled using the recently developed Augmented Lagrangian Perturbation Theory. On the scales considered here, the reconstructed density field is very well described by the assumed log-normal distribution function. We predict that the cross-correlation will have an amplitude of 0.03–0.3 \( \mu \)K. The measured value is close to 1.5 \( \mu \)K, compatible with random alignments between structure in the template and in the temperature anisotropy data. Using the W1 Differencing Assembly to remove this systematic gives a residual correlation dominated by Galactic foregrounds. Planck could detect the Warm-Hot Medium if it is well traced by the density field reconstructed from galaxy surveys. The 217 GHz channel will allow to eliminate spurious contributions and its large frequency coverage can show the sign change from the Rayleigh–Jeans to the Wien part of the spectrum, characteristic of the thermal Sunyaev–Zel’dovich effect.

Key words: cosmic background radiation – cosmology: observations – cosmology: theory – intergalactic medium

Online-only material: color figures

1. INTRODUCTION

The baryon budget in the local universe shows a deficit relative to the predicted density synthesized in the big bang (Fukugita et al. 1998; Fukugita & Peebles 2004). Galaxies and clusters contain about 10% of the total number of baryons and an extra 5% could be in the form of circumgalactic medium (CGM) around galaxies, although the results of Gupta et al. (2012) of a large-scale massive hot gaseous halo around the Galaxy have been disputed by Wang & Yao (2012). Of the remaining 85%–90%, only half has been accounted for in the low-redshift intergalactic medium (IGM; Danforth & Shull 2008). Hydrodynamical simulations predict that the rest could reside within mildly nonlinear structures with temperatures 0.01–1 KeV, called Warm-Hot Intergalactic Medium (WHIM). The baryon fraction in this medium could be 40% (Cen & Ostriker 1999; Davé et al. 1999, 2001; Smith et al. 2011). In the X-ray, the WHIM signature has been searched for both in emission and in absorption. Soltan (2006) looked for the extended soft X-ray emission around field galaxies but his task was complicated by the need to subtract all systematic effects that could mimic the diffuse signal. The recent observational effort has concentrated in searching for absorption lines due to highly ionized heavy elements from the far-ultraviolet to the soft X-ray (see Shull et al. 2012 for a review). Alternatively, as the WHIM is highly ionized, in Atrio-Barandela & Mücke (2006) and Atrio-Barandela et al. (2008) we suggested that it would generate measurable temperature anisotropies on the cosmic microwave background (CMB) due to the thermal and kinematic Sunyaev–Zeld’ovich effect (TSZ and KSZ, respectively; Sunyaev & Zel’dovich 1970, 1972). Our expectations were confirmed by Hallman et al. (2007) who found, using numerical simulations, that after the contribution of resolved clusters is removed, about one-third of the SZ flux from unresolved sources would be generated by unbound gas. More recently, Lieu & Duan (2013) suggested that the line-of-sight column density of the ionized baryons in the local universe could be determined by monitoring quasar light curves.

Our model assumes that the undetected baryon phase, in the form of filaments of hot and low density IGM, is well described by a log-normal probability distribution function. The filamentary structure of the intercluster medium has been recently confirmed using observations on interacting clusters. A joint analysis of ROSAT X-ray and Planck CMB data has provided the first detection of hot and diffuse intercluster gas, extending beyond the virial region of the cluster pair A399–A401 (Planck Collaboration 2013). If the WHIM can be traced with templates constructed from the matter distribution, then cross-correlating those templates with CMB maps could provide further evidence of the existence of the WHIM or provide strong constraints on its spatial distribution. Based on our log-normal model, in this article we compute the cross-correlation between CMB data with a template that traces the WHIM distribution. If galaxies from the Two-Micron All-Sky Redshift Survey (2MRS) are good tracers of intergalactic gas, we can predict theoretically the amplitude of the TSZ component due to the WHIM. We compare our prediction with the cross-correlation derived from Wilkinson Microwave Anisotropy Probe (WMAP) data (Jarosik et al. 2011). We show that the cross-correlation of galaxy templates and CMB data is dominated by random alignments. The differences between channels are due to Galactic foreground residuals and instrumental noise. Planck could provide the first detection of the WHIM with our method by using the 217 GHz channel to remove systematics. In Section 2 we briefly describe our model; in Section 3 we describe the construction of the matter
templates, show that they are well described by our log-normal formalism, and compute the theoretically expected amplitude of the cross-correlation; in Section 4 we particularize our methods to a matter reconstruction of the 2MRS catalog and WMAP data and discuss the prospects of a successful detection using the forthcoming Planck data; finally, in Section 5 we present our main conclusions.

2. A LOG-NORMAL MODEL OF THE WARM-HOT INTERGALACTIC MEDIUM

In our model, baryons in the WHIM are distributed like a log-normal random field. The log-normal distribution was introduced by Coles & Jones (1991) to describe the nonlinear distribution of matter in the universe. In this approximation, the number density of baryons \( n_B(x, z) \) is given by (Choudhury et al. 2001; Atrio-Barandela & Mück 2006)

\[
n_B(x, z) = n_0(z)e^{\delta_B(x, z) - \Delta^2_B(z)/2},
\]

where \( x \) denotes the spatial position at redshift \( z \) and \( |x(z)| \) is the proper distance, \( \Delta^2_B(z) = (\delta_B^2(x, z), z) \), with \( \delta_B(x, z) \) the baryon (linear) density contrast, \( n_0(z) = \rho_B(1+z)^3/\mu_B m_p \) with \( \rho_B \), \( m_p \) \( m_B \) the baryon density and the proton mass, respectively; finally, \( \mu_B = 4/(8+5Y) \) is the mean molecular weight of the IGM and \( Y = 0.24 \) is the helium weight fraction. The log-normal distribution has been found to describe very well the matter statistics at scales larger than \( 7 h^{-1} \) Mpc based on the improved Wiener density reconstruction from the Sloan Digital Sky Survey (see Kitaura et al. 2009). The linear baryon power spectrum is related to the DM power spectrum by (Fang et al. 1993)

\[
P_B^{(3)}(k, z) = \frac{P_{DM}^{(3)}(k, z)}{[1 + k^2L^2_{cut}]} ,
\]

where the cutoff length is the scale below which baryon density perturbations are smoothed due to physical effects like Jeans dissipation or shock heating (Klar & Mück 2010); in the WHIM, shock heating is assumed to be the dominant effect. At any given redshift the comoving scale \( L_{cut} \) is determined by the condition that the linear velocity perturbation \( v(x, z) \) is equal to or larger than the sound speed \( c_s = (k_B T_{IGM}(z)/m_B)^{1/2} \) at each redshift. Here \( m_p \) is the proton mass and \( T_{IGM} \) is the mean IGM temperature. At redshifts \( z \lesssim 3 \), \( T_{IGM} = 10^{5.6}-10^{6} K \) and its variation with redshift is small (Tittley & Meiksin 2007). In addition, \( L_{cut} \approx L_0(1+z)^{1/2} \), with \( L_0 \) a constant and if \( T \approx 10^{6} K \) at present then \( L_0 \approx 1.7 h^{-1} \) Mpc. Hereafter, \( L_0 \) will be parameterized by \( T_{IGM} \) (see Suarez-Velásquez 2013 for details).

The number density of electrons \( n_e \) in the IGM can be obtained by assuming equilibrium between recombination and photoionization and collisional ionization. At temperatures in the range \( 10^5\text{--}10^7 K \) and density contrasts \( \delta \lesssim 100 \), the gas can be considered fully ionized. The two-point correlation function of the spatial variations of the electron pressure is given by

\[
C(\theta) = \int_0^{\xi_1} \int_0^{\xi_2} \langle S_1(\hat{x}, z)S_2(\hat{x}', z') \rangle dz dz',
\]

where the integration is along lines of sight separated by an angle \( \theta \). The TSZ WHIM temperature anisotropy is \( \Delta T = x_e G(v) \), with \( x_e = k_{e} \sigma_T / m_e c^2 \int T_e n_e dl \) the Comptonization parameter along the line of sight, \( n_e \) and \( T_e \) the electron density and electron temperature, \( m_e c^2 \) the electron annihilation temperature, \( k \) the Boltzmann constant, \( \sigma_T \) the Thomson cross section, \( G(v) = (x \ coth(x/2) - 4) / \xi \) with \( \xi = hv/K_0 \) the reduced frequency, \( K_0 \) the CMB temperature, \( dl \) the line element along the line of sight, and \( dz \) its corresponding redshift interval. Then if \( S_1 = S_2 = k_{e} \sigma_T / m_e c^2 n_e T_e (dl/dz) \), from Equation (3) we can obtain the contribution of the WHIM to the power spectrum of CMB temperature anisotropies as

\[
C_\ell = 2\pi \int_{-1}^{1} C(\theta) P_\ell(\cos \theta) d\cos \theta ,
\]

where \( P_\ell \) is the Legendre polynomial of multipole \( \ell \). In Atrio-Barandela & Mück (2006) we modeled the gas as a polytrope. The amplitude of the resulting power spectrum was strongly dependent on the polytropic index; for some model parameters, it would be larger than \( 100(\mu K)^2 \). Recently, Suarez-Velásquez et al. (2013) have refined the model for the shock-heated IGM by deriving the relation \( T_e \) versus \( n_e \) from a fit to the phase diagrams obtained in various hydrodynamical simulations. The fit \( \log_{10} T_e = 8 - 2(\log_{10}(4 + x^4))^{-1} \) with \( b = \alpha + x^{-1} \) and \( x = n_e/\bar{n}_B \) the electron density in units of the mean baryon density reproduces well the phase diagram in Kang et al. (2005). Then, the model is parameterized by the IGM temperature and equation of state with parameters in the range \( T_{IGM} = 10^{5.6}, 10^{6} K \) and \( \alpha = [1, 4] \). For this parameterization, temperature anisotropies grow with increasing electron temperature and decreasing cutoff length \( L_0 \).

3. CROSS-CORRELATION OF MATTER DENSITY TEMPLATES AND CMB MAPS

The search of the WHIM contribution to the temperature anisotropies of the CMB was pioneered by Hernández-Monteagudo et al. (2004). We correlated the first year of WMAP 1 yr with templates of projected matter density constructed from the Two Micron All Sky Survey (2MASS) galaxy catalog; all significant TSZ contributions were originated by clusters of galaxies and no evidence of the WHIM was found. A second approach was tried by Génova-Santos et al. (2009, 2013), who used a Monte Carlo Markov Chain to find the contribution in the CMB power spectrum but the evidence was not statistically significant. In this article we revisit the cross-correlation approach using templates of the density field reconstructed from 2MRS by Kitaura et al. (2012). The reconstruction technique is based on a Bayesian Networks Machine Learning algorithm (the kigen code) which self-consistently samples the initial density fluctuations compatible with the observed galaxy distribution and a structure formation model given by second-order Lagrangian perturbation theory (2LPT). We have used the Augmented Lagrangian Perturbation Theory (ALPT; Kitaura & Hess 2013) to perform constrained simulations from the initial conditions found with kigen. It improves previous approximations at all scales by combining 2LPT with the spherical collapse model and shows a higher correlation with the N-body solution than previous methods. This approach enables us to find nonlinear structures like filaments in the cosmic web to great accuracy. The number of solutions compatible with the observations of a galaxy sample is degenerate due to shell crossing and redshift distortions and the method provides an ensemble of reconstructions useful to estimate the uncertainties associated with the technique and intrinsic to the data (see Kitaura 2012 for details). Work to perform self-consistent reconstructions implementing ALPT within the kigen code is in progress (S. Hess et al. 2013, in preparation).
The reconstruction of the matter density field requires evaluation of fast Fourier transforms and, therefore, it is carried out on a cubic box. Cubic boxes of side $160 \, h^{-1} \, \text{Mpc}$ and $180 \, h^{-1} \, \text{Mpc}$ were used to check that the impact of boundary effects in the density field is negligible on spheres of radius up to $80 \, h^{-1} \, \text{Mpc}$. To consider even larger volumes one would be required to model the “Kaiser Rocket effect” in the selection function (Branchini et al. 2012) which is beyond the scope of this work. One such reconstruction, denoted by $M$, is represented in Figure 1(a). The matter distribution shows well-defined filaments, characteristic for the mildly nonlinear regime. The sky is represented using Healpix (Gorski et al. 2005) with resolution.
in Figure 1(a) that are compatible with 2MRS (solid blue line) and the rms dispersion around the mean (shaded area). The dashed (green) line is the power spectrum of the density of 2MASS projected galaxies corrected by the selection function and the solid (red) line is the spectrum of baryon distribution given by our log-normal model. All power spectra were normalized to zero mean and unit variance. In the inset we represent the low-order multipoles in a log-scale; the amplitude of the power spectrum of galaxies has been multiplied by a factor 20 to facilitate the comparison.

(A color version of this figure is available in the online journal.)

\[ N_{\text{side}} = 128, \text{ which corresponds to an angular resolution of } 27.5'. \]

We used a linear scale saturated at 500 galaxies per pixel for better visualization. In Figure 1(b) we represent the difference between two reconstructions. While the cosmic web displayed in all reconstructions is very similar, the extension around very massive structures and the exact location of filaments differ from one reconstruction to another. For example, the uncertainty on the position of Coma is 2–3 \( h^{-1} \) Mpc, less than 5% of its distance to the Local Group. Filaments that are slightly displaced appear in the difference map to be running side by side. The ensemble of constrained simulations can be used to compute the mean and standard deviation of the density field in each cell, giving an estimate of the uncertainty in the position of the density peaks and filaments. For illustration purposes, in Figure 1(c) we represent the W1 Differencing Assembly (DA) of WMAP 7 yr data. The galactic and point-source contaminations are masked using the extended temperature analysis WMAP mask KQ75. The data are normalized to zero mean and unit variance outside the mask.

In Figure 2 we represent the mean power spectra of 24 different template reconstructions of the matter distribution as in Figure 1(a) that are compatible with 2MRS (solid blue line) and the rms dispersion around the mean (shaded area). The dot-dashed (green) line represents the power spectrum of the projected density of 2MASS galaxies used in this reconstruction, corrected by inverse weighting with the selection function. To avoid the instabilities due to small divisors, 37 pixels with number density of galaxies equal to or larger than \( 10^3 \) galaxies were eliminated. All templates were normalized to zero mean and unit variance. Since the projected distribution of galaxies is close to a Poisson point process, the power spectrum of 2MASS galaxies is roughly constant and very different, at high multipoles, from the spectrum of the reconstructed matter density field. At those scales, the matter distribution is smoother and the power falls. The solid red line represents the power spectrum of the baryon density distribution computed by taking \( S_1 = S_2 = n_e \) in Equation (3), with a cutoff length of \( L_0 \approx 1.13 h^{-1} \) Mpc. We found that the best fit to the power spectrum of the reconstructed template was obtained when the integration in Equation (3) was restricted to the interval 60–120 \( h^{-1} \) Mpc, while the template of Figure 1(a) reproduces the local volume out to 80 \( h^{-1} \) Mpc. This discrepancy is only apparent. Even if the template has been reconstructed up to 80 \( h^{-1} \) Mpc, it does include higher modes since the method uses a 160 \( h^{-1} \) Mpc box. Second, we have to take into account sampling variance; the local universe lacks power up to 30 \( h^{-1} \) Mpc (see, e.g., Courtois et al. 2012). Spikes and oscillations in the spectra reflect the sample variance associated with observing a single universe. While the distribution of the WHIM and matter is different from that of galaxies at small scales, they coincide at large scales, as it could be expected if galaxies traces the overall matter distribution.

In the inset we represent in a logarithmic scale the power spectrum at low multipoles to show that the reconstructed matter density field and the galaxy distribution on those scales are very similar. Lines follow the same convention as in the main plot. To facilitate the comparison, the power spectrum of galaxies in this inset was multiplied by a factor of 20 to bring its amplitude closer to that of the power spectrum of the reconstructed matter density templates.

Except at very large scales, where the power spectrum is dominated by a few modes and sample variance is large, the templates of the reconstructed matter density field agree with the log-normal model at all angular scales. This agreement demonstrates that templates like the one shown in Figure 1(a) are very well described by our log-normal model, but it does not prove that the WHIM is stored in filaments. It only indicates that we can use the log-normal model to predict the value of observable quantities that can be later compared with the data. For this purpose, electron overdensities will be normalized to unit variance so the cross-correlation is given in units of temperature. For the template of Figure 1(a) and for model parameters in the fiducial ranges \( T_{\text{IGM}} = [10^{5.6}, 10^6] K \) and \( \alpha = [1, 4] \) the correlation at the origin is 0.03–0.3 \( \mu K \). For a different parameterization that fits the Cen & Ostriker (2006) phase diagram, the amplitude would be 0.01 \( \mu K \), slightly lower.

Contributions coming from gas in clusters or in the CGM are not included in our formalism. First, the log-normal model is restricted to overdensities \( \delta \leq 100 \), while in clusters and in the CGM, \( \delta \sim 500–1000 \) (Fukugita & Peebles 2004). Second, the distribution of galaxies or clusters is not well described by our log-normal model. For instance, the CGM would induce anisotropies with the spatial distribution of galaxies and not templates that, as Figure 2 shows, are very different.

If template \( M \) is a good tracer of the gas in filaments, cross-correlation with CMB data will give us an estimate of the CMB temperature anisotropies generated by the WHIM measured, for example, by WMAP. Since the reconstruction is not unique, we need to quantify the uncertainty introduced by using a template that does not exactly describe the distribution of baryons. To speed up the calculation we degraded all our templates to a resolution of \( \sim 1.8' \), corresponding to Healpix \( N_{\text{side}} = 32 \). At this resolution, at separation of \( 1' \) the correlation function is between first neighbors, at \( 2' \) between second neighbors, etc. In Figure 3 we represent the cross-correlation of the template \( M \) with the 24 different reconstructions of the matter density field from 2MRS. The solid (black) line represents the autocorrelation function of \( M \); the dashed (blue) line represents the mean of the cross-correlation of \( M \) with the 23 other different reconstructions and the shaded area is the rms dispersion about the mean. At the origin, the autocorrelation function and the mean of the cross-correlations differ by 20%. Outside the origin, the
The autocorrelation is similar to the mean and very well within the 1σ error bar, indicating that the uncertainty on the position of the density peaks in the matter reconstruction of the 2MRS catalog is \( \sim 2^{\circ} \). Figure 3 is very illustrative of the accuracy of our method. Using resolution \( N_{\text{side}} = 32 \) instead of \( N_{\text{side}} = 128 \) we lose information about the correlation on scales \( 0.5^{\circ} \)–\( 2^{\circ} \), but on those scales the reconstruction of the density field is uncertain (see Figure 1(b)). If we use a reconstruction of the density field that is not fully coincident with the true distribution of baryons in the local universe, we can expect to underestimate the true correlation function by 20% but the effect is negligible outside the origin. Then, by restricting our analysis to Healpix resolution \( N_{\text{side}} = 32 \), not only is the computation faster, we also average over the uncertainties on our template that only contribute to the correlation with a 20% uncertainty at zero lag. With this resolution there are no differences between the data and the former were used.

4. APPLICATION TO WMAP DATA

Since the log-normal model describes reasonably well the power spectrum of the matter density then cross-correlation of a matter template \( M \) with WMAP 7 yr data would determine the fraction of gas traced by the matter. In Figure 4(a) we represent the cross-correlation of \( M \) with the eight DAs of WMAP 7 yr data. From top to bottom: solid (blue), dashed (green), and dot-dashed (red) lines correspond to the \( Q \), \( V \), and \( W \) channels. The contribution of galactic foregrounds and point sources were removed using the KQ75 mask that eliminates 27% of the sky (see Figure 1(c)). The matter density template \( M \) was normalized to zero mean and unit variance outside the mask. The symmetric solid (black) lines represent the rms deviation of the cross-correlations of \( M \) with 1000 different random realizations of WMAP data that include cosmological CMB signal and noise, but no foreground residuals. The amplitude of the cross-correlation at the origin, \( \sim 1.5 \mu K \), is much larger than the expected amplitude of 0.03–0.3 \( \mu K \) and it is compatible with being due to random alignments between structures in the CMB data and in the template. The differences between the eight DA are due to the WHIM, noise, and foreground residuals. Subtracting the correlation of \( M \) and \( W \) to the correlation of \( M \) with the other seven DAs removes the contribution due to random alignments and yet, due to the frequency variation of the TSZ signal from 40 to 90 GHz, it leaves 14%–18% of the original TSZ signal in the \( Q \) and \( V \) bands, respectively. If in Figure 4(a) the differences were dominated by TSZ, then the quantity \( \langle (T - W) M \rangle = [C_{W,M} - C_{W1,M}]/[C_{(V) M} - C_{(W1) M}] \) would give the correlation of the template with the map of the Comptonization parameter, \( y_e \)-map. In Figure 4(b) we plot the \( \langle M (y_e \text{-map}) \rangle \) correlation for WMAP. The solid (blue) and dashed (green) lines correspond to the \( Q \) and \( V \) channels, respectively. The differences between the \( W2 \), \( W3 \), \( W4 \) and \( W1 \) would remove not only the intrinsic CMB, but also the foreground and WHIM signals. The rms variation of the subtracted correlations of the \( W \) channel provides a simple estimate of the error bar due to the instrumental noise, but does not account for foreground residuals and sampling variance contributions due to the variation of the number of pairs with separation angle. The error bars are represented in Figure 4(b) by the symmetrical solid (black) lines. The correlations \( \langle Q1,2 - W1 \rangle M \) and \( \langle V1,2 - W1 \rangle M \) are similar and well outside the error bar, but this is not evidence of WHIM. In fact, the \( \langle M (y_e \text{-map}) \rangle \) correlation should be positive at the origin, not negative. We verify that this residual correlation is due to foregrounds by masking all CMB data with \( |b| \leq 30^{\circ} \). The results are presented in Figure 4(c). Lines follow the same convention as in panel (b). By restricting the correlation to the polar caps, \( \langle Q1,2 - W1 \rangle M \) decreased by 30% while \( \langle V1,2 - W1 \rangle M \) became positive, with an amplitude of 0.4 \( \mu K \) at the origin, compatible with noise. Compared with Figure 4(b), the correlation of the \( Q \) and \( V \) bands is very different, reflecting the differences in the foreground residuals between the \( Q \)–\( W1 \) and the \( V \)–\( W1 \) maps and an increased sample variance as the fraction of the sky removed was larger.

The previous results indicate that WMAP is not well suited to separate the TSZ contribution from that of the other components. In this respect, Planck is a much better instrument. To forecast its performance, we simulated six Planck channels with frequencies in the range 44–353 GHz. The simulated maps were constrained to reproduce WMAP data for multipoles \( \ell \leq 256 \). The maps were downgraded to resolution \( N_{\text{side}} = 32 \) so differences in beamwidth and beam asymmetries have an unmeasurable effect. The simulated data contain CMB and homogeneous white noise but did not contain foregrounds, foreground residuals or \( (1/f) \) noise. At each frequency we added a WHIM component following the matter distribution in \( M \) assuming \( T_e \propto n_e \) with a mean Comptonization parameter \( \langle y_e \text{-map} \rangle = 0.1 \mu K \). In the frequency range considered, the amplitude of the TSZ effect varies from \(-1.9 \) at 44 GHz to \( 2.2 \) at 353 GHz and passes through the TSZ null at 217 GHz. This channel was later used to subtract the correlation of \( M \) with the CMB data due to random alignments. In Figure 4(d) we plot the results (solid black line), which are very close to each other and close to the theoretical expectation, represented by the dashed (blue) line. The differences between the theoretical curve and the simulated data are due to masking and pixelization. If foreground and noise inhomogeneities are not important and the template traces the gas distribution, Planck will measure the WHIM TSZ correlation very accurately.

Together with the uncertainties in the reconstruction of the density field, there are additional uncertainties associated with how well the galaxy template traces the electron pressure. The WHIM could be made of clumps, with typical sizes \( 100 h^{-1} \) kpc...
like the CGM. At $60 \, h^{-1} \, \text{Mpc}$, a clump of this size would subtend $6^\circ$. The 217 and 343 GHz Planck channels have the largest resolution of the instrument, $5^\circ$; then, in Planck data we can neglect the effect of gas inhomogeneities at scales below $100 \, h^{-1} \, \text{Kpc}$. Also, in our analysis we have assumed a smooth distribution of baryons and temperatures within the filaments. As an average of the different Kang et al. (2005) models we assumed the temperature scaling as $T_e \propto n_e$ so the electron pressure in the template scaled as $n_e T_e \propto n_e^2$. The simulations of individual filaments carried out in Klar & Mücket (2010, 2012) have characterized the state of the gas and its evolution inside the filament in terms of the length of the initial perturbation. Their simulations indicated the existence of multiple phases and temperatures in the WHIM. To estimate the uncertainty associated with an inhomogeneous distribution of gas and temperature within filaments, we repeat our simulations but added to the CMB data a TSZ contribution with two different temperature scalings in the range $\delta \in [1, 100]$: (1) an isothermal gas $T \sim \text{const}$ and (2) a clumpier temperature distribution, $T_e \propto n_e^2$. In both cases, the mean amplitude of the $y_\nu$-map was $0.1 \, \mu\text{K}$. These temperature–density relations can be considered extreme cases of the temperature variation in the IGM. Next, we cross correlate the CMB data with our template $M$, where the electron pressure scales like $n_e T_e \propto n_e^2$. The resulting correlations are represented by dot-dashed (red and violet) lines in Figure 4(d). The comparison of these cross-correlations with our previous result shows that, at $N_{\text{side}} = 32$ resolution, the shapes are similar and only differ by $\sim 5\%$–$10\%$ in the amplitude at the origin. In summary, the uncertainty on the cross-correlation of template and CMB data due to (1) how the template traces the gas distribution and (2) how the electron pressure scales with density within the template add at most an uncertainty of $30\%$ at the origin, being almost negligible on scales above $2^\circ$.

The final error bar will certainly have non-zero contributions from foreground residuals, whose distribution and amplitude change with frequency, and instrumental $(1/f)$ noise that will complicate the detection. However, first and foremost, the TSZ has a distinctive signature, different from that of any other foreground. It changes sign from the Rayleigh–Jeans to the Wien part of the spectrum. This change of sign will also be present in the correlation function, and could be sufficient to detect the effect. Second, foreground residuals are probably largest close to the galactic plane, so computing the cross-correlation at different galactic latitudes could help to disentangle the different contributions, as for WMAP data. Third, in our Planck simulations, the template contributes with just $0.1 \, \mu\text{K}$. According to our model, this is a reasonable expectation for a large fraction of the parameter space. Naturally, the contribution due a larger volume will be higher so templates constructed from deeper galaxy surveys would give statistically more significant detections.
5. CONCLUSIONS

We have computed the amplitude of the correlation between the WHIM with CMB data. We have shown that templates of projected matter density that describe the weakly nonlinear regime are well represented by our log-normal model. This permits us to predict that the amplitude of the cross-correlation of the WHIM with CMB data is 0.03–0.3 μK depending on model parameters. Assuming that the reconstructed matter density templates trace the electron distribution, we computed the cross-correlation of the matter density field within a volume of $160 h^{-1}$ Mpc reconstructed using the 2MRS galaxy survey. The cross-correlation with WMAP data showed it to be dominated by random alignments of CMB structures and galaxy filaments. The differences between DAs could be due to the WHIM signal, but also to noise and foreground residuals. We checked that foreground residuals are the most likely source of the correlation, but also to noise and foreground residuals. We checked that foreground residuals are the most likely source of the correlation by showing the results varied significantly when removing data with $|b| \leq 30^\circ$.

Using 2MASS galaxies and WMAP data, Lavaux et al. (2013) described evidence that baryons are distributed in galactic coronae. This result is in apparent contradiction with Hernández-Monteagudo et al. (2004) where cross-correlation of WMAP 1 yr data with templates of projected galaxy density showed no evidence of ionized gas outside known clusters of galaxies and, to some degree, with the results presented here. Even if our matter density templates are different from a pure galaxy template their power spectra overlap (see Figure 2) and any signal traced by galaxies must also be traced at some level by our templates. In addition, the contribution due to random alignments, which we have shown to be dominant for WMAP, was not quantified. Due to the difference in methodology, our results are not fully comparable and consistency between both methods will increase the statistical significance of any detection.

Planck, with its large frequency coverage and high resolution, is a more adequate instrument than WMAP to search for the WHIM contribution. First, the 217 GHz channel is very close to the TSZ null, allowing us to remove spurious correlations that dominates the signal. Second, the instrument contains measurements on the Rayleigh–Jeans and Wien part of the spectrum. If the correlation is due to the WHIM, it will vary with frequency and change sign. Reconstructions of the matter density field using deeper surveys like the Sloan Digital Sky Survey will allow us to probe the baryon distribution to higher depths, enhancing the signal. Alternatively, the reconstructed density field allows to select filaments aligned with the line of sight, where the optical depth of the WHIM would be larger. The higher resolution of Planck could facilitate the identification of the WHIM signal in those regions and clarify its spatial distribution, whether it is distributed as a network of filaments or is stored in the galactic corona.

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