ONE THOUSAND AND ONE CLUSTERS: MEASURING THE BULK FLOW WITH THE PLANCK ESZ AND X-RAY-SELECTED GALAXY CLUSTER CATALOGS

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ABSTRACT

We present our measurement of the “bulk flow” using the kinetic Sunyaev–Zel'dovich (kSZ) effect in the Wilkinson Microwave Anisotropy Probe (WMAP) seven-year data. As the tracer of peculiar velocities, we use Planck Early Sunyaev–Zel'dovich Detected Cluster Catalog and a compilation of X-ray-detected galaxy cluster catalogs based on ROSAT All-Sky Survey. We build a full-sky kSZ template and fit it to the WMAP data in W band. Using a Wiener filter we maximize the signal-to-noise ratio of the kSZ cluster signal in the data. We find no significant detection of the bulk flow, and our results are consistent with the ΛCDM prediction.

Key words: cosmic background radiation – galaxies: clusters: general – large-scale structure of universe

Online-only material: color figures

1. INTRODUCTION

Since the first claimed detection of large-scale streaming by Rubin et al. (1976) in Sc galaxies, the issue of coherent departures from uniform Hubble flow has been the source of much debate. The inflationary model predicts that the coherent, large-scale peculiar motion of matter caused by gravitational potentials, also called “bulk flow,” is negligible in a ΛCDM universe (Strauss & Willick 1995). This prediction has been tested in the last few decades and it has been the theme of much of the work in peculiar velocities. A known flow at small scales (∼60 Mpc h⁻¹) is the motion of the Local Group toward a mass concentration of about 10¹⁰ M☉ known as the Great Attractor. This is closely associated and aligned with the observed cosmic microwave background (CMB) dipole (Kogut et al. 1993; Jarosik et al. 2011). On large scales, Lauer & Postman (1994) found a non-zero bulk flow at 80 h⁻¹ < R < 110 h⁻¹ Mpc by using a full-sky peculiar velocity survey consisting of 119 Abel clusters, but a re-analysis of the data led to a reduced bulk flow in a different direction (Hudson & Ebeling 1997). At the same time, Riess et al. (1997) used Type Ia supernovae (SNIa) data and found no evidence of a bulk flow at similar scales. More recently, Colin et al. (2011) did similar analysis using SNIa data and found a bulk flow that contradicts the ΛCDM prediction at low redshift (z < 0.06), but is consistent with ΛCDM at higher redshifts. Feldman et al. (2010) used a compilation of peculiar velocity surveys and found a non-zero bulk flow at R ≃ 100 h⁻¹ Mpc. Most recently, Nusser & Davis (2011) and Davis et al. (2011), using Tully–Fisher data, found no deviations from the Hubble flow out to ∼ 100 h⁻¹ Mpc. Using the Two Micron All Sky Survey redshift survey, Lavaux et al. (2010) and Nusser et al. (2011) obtained consistent results with the ΛCDM prediction of no significant bulk flow.

All methods based on galaxy data are limited by our ability to accurately observe and measure at large distances. This limits the reach of these methods to scales of ∼100 Mpc. An independent measurement method on substantially larger scales can clarify the situation. In this sense, the best available probe to study the bulk flow is the kinetic Sunyaev–Zeldovich (kSZ: Sunyaev & Zeldovich 1980) effect due to the coherent motion of clusters of galaxies with respect to the rest frame of the CMB radiation (Haehnelt & Tegmark 1996). Peculiar velocities of the electrons in the hot intracluster gas lead to a Doppler shift of scattered photons. The shift is proportional to the product of the line-of-sight component of the peculiar velocity and the electron density integrated along the line of sight through the cluster. A coherent flow causes an overall dipole observable through variation across the optical depths of clusters. This is a unique pattern that can be exploited in measuring the bulk flow.

Most recently, Kashlinsky et al. (2008) found a net dipole moment in the kSZ component measured in Wilkinson Microwave Anisotropy Probe (WMAP) data that was consistent with a non-zero bulk motion at scales of R ∼ 575 h⁻¹ Mpc. Keisler (2009) repeated their analysis and found a negligible bulk flow in contradiction to the findings of Kashlinsky et al. (2008). Osborne et al. (2011) did an independent analysis of the kSZ in WMAP data and again found no significant velocity dipole. Although a lot of work has been done on this subject, the above summary clearly shows that there is no consensus on the existence of the bulk flow, its magnitude, depth, or direction. In this paper we use two different sets of cluster catalogs, based on SZ and X-ray detection of the clusters, to independently measure the bulk flow. Explaining the bulk flow within the framework of the ΛCDM model is difficult. Several theoretical models have been proposed to explain the possible existence of a large bulk flow at large scales in the framework of a DGP model (Wyman & Khoury 2010) or by using other modified gravity models (Afshordi et al. 2009; Khoury & Wyman 2009).

The rest of this paper is organized as follows: In Section 2, we briefly describe the data sets used for this analysis. In Section 3, we explain the details of the algorithm we use in constructing the full-sky kSZ templates, filtering, template fitting, and error estimation. We present the results in Section 4 and discuss its implications and systematics in Section 5. Throughout this paper, we use the best-fit ΛCDM model of WMAP7 (Larson et al. 2011) for the cosmological parameters.

2. DATA

Our analysis uses two types of data sets: a data map and a cluster catalog. We use WMAP data with the highest resolution full-sky map to date. We use two independent catalogs of galaxy clusters as velocity tracers; an SZ-selected catalog and an X-ray-selected catalog. Below we explain each of these data sets in more detail.
2.1 CMB Data

We use co-added inverse-noise-weighted data from seven single-year maps observed by WMAP at 94 GHz (W band). The maps are foreground cleaned (using the foreground template model discussed in Hinshaw et al. 2009) and are at HEALPix3 resolution 9 ($N_{side} = 512$). The WMAP data are signal dominated on large scales, $l < 548$ (Larson et al. 2011), and the detector noise dominates at smaller scales. The noise in WMAP data is a non-uniform (anisotropic) white noise that varies from pixel to pixel in the map. Pixel noise in each map is determined by $N_{obs}$ with the expression

$$\sigma = \sigma_0 / \sqrt{N_{obs}},$$

where $\sigma_0$ is the noise for each differencing assembly and can be found on the WMAP data products Web site on LAMBDA.4 $N_{obs}$ is the number of observations at each map pixel which is directly proportional to the statistical weight, i.e., regions with larger number of observations have lower noise variances. $N_{obs}$ is included in the maps available from the LAMBDA Web site.

In all of our analysis we use pixel masks to exclude foreground-contaminated regions of the sky from the analysis. We use a galactic mask which masks 19.30% of the sky. We do not mask point sources.

2.2 Cluster Catalogs: RASS X-Ray Catalogs

We use two sets of catalogs for the clusters of galaxies: three X-ray catalogs and one SZ catalog. There are 870 clusters in the X-ray catalogs and 189 clusters in the SZ catalog. The Clusters in the Zone of Avoidance (CIZA) cluster catalog is an X-ray survey that identified clusters in the region where the magnitude of the galactic latitude is less than or equal to 20°. CIZA used X-ray data from ROSAT All-Sky Survey (RASS) for its initial cluster candidate selection, and accepted or rejected candidate clusters according to optical and near-infra-red (NIR) observations. There are 73 and 57 clusters in the CIZA, CIZAII surveys, and the median redshift of these clusters are 0.07 and 0.125, respectively (Ebeling et al. 2002; Kocevski et al. 2007).

The ROSAT BCS (ROSAT Brightest Cluster Sample; Ebeling et al. 1998) contains the brighter sources of the Northern ROSAT All-Sky galaxy cluster survey. There are 206 galaxy clusters in this sample with the median redshift of 0.09. The Extended ROSAT Brightest Cluster Sample (eBCS) compiled from RASS data, also identified clusters in the northern hemisphere with galactic latitudes of magnitude greater than or equal to 20°; it is estimated to be 75% complete. Total fluxes of clusters in this catalog are between $2.8 \times 10^{-12}$ and $4.4 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ (0.1–2.4 keV). We have the locations of 107 clusters from the eBCS catalog, and the median redshift of these clusters is 0.13. (Ebeling et al. 2000). The third X-ray cluster catalog we use is the ROSAT-ESO Flux Limited X-Ray (REFLEX) cluster catalog which covers 4.24 sr in the southern sky. The sample is limited to clusters with an X-ray flux above $3 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ (0.1–2.4 keV), and it is estimated to be more than 90% complete. We have the locations of 447 clusters identified by REFLEX, and the median redshift of these clusters is 0.09 (Bohringer et al. 2004). There is a total of 890 clusters in the combined catalogs. Removing 20 repeated entries, we have 870 clusters in the combined X-ray-selected cluster catalog. The smallest clusters in the low-mass end of the catalog only contribute to the uncertainties because their amplitudes are too small.

2.3 Cluster Catalogs: Planck ESZ

Planck is mapping the whole sky at a few arcminute resolution and will eventually produce an SZ-detected cluster catalog of a few thousand galaxy clusters. What is currently available, hereafter Planck Early Sunyaev–Zel’dovich (Planck ESZ) catalog, is an isotropic all-sky catalog and has 189 clusters with a median redshift of 0.154 (Planck early results, Planck Collaboration VIII 2011). Three clusters from this catalog are masked when we use the galactic mask in our analysis.

Figure 1 shows the spatial distribution of the clusters of galaxies in the SZ and combined X-ray catalogs discussed above. It also compares the stacked cluster profiles in the two sets of catalogs we use in our analysis. The stacked profile is smaller in the X-ray sample because the clusters in the RASS catalogs have a smaller mass threshold than those in the Planck ESZ catalog.

3. Generating and Fitting Full-Sky kSZ Templates

We generate a full-sky kSZ template due to a bulk flow and measure the components of the bulk flow velocities by fitting the template to the data in real space. The kSZ template is built using an indicator of the mass of the cluster. We do not have a direct mass estimate in the catalogs, so we use scaling relations to derive the masses based on other properties of the clusters, in particular their luminosities and their integrated Compton-Y factors depending on the catalog.

3.1 Cluster Parameters: X-Ray Catalogs

In each of the X-ray catalogs, we have the luminosity of each cluster, and we use the luminosity to find the virial mass and radius for each cluster. To do so, we first find $M_{500} = 4\pi/3 [500 \rho_c(z)] R_{500}^3$, the mass of the cluster contained within $R_{500}$, the radius within which the mean overdensity of the cluster is 500 times the critical density of the universe, $\rho_c(z) = 2.775 \times 10^{11} E^2(z) M_{\odot} \text{Mpc}^{-3}$. We use the scaling relation of Vikhlinin et al. (2009) to compute $M_{500}$ from the X-ray luminosities

$$\ln L_X = (47.392 \pm 0.085) + (1.61 \pm 0.14) \ln M_{500} + (1.850 \pm 0.42) \ln E(z) - 0.39 \ln (h/0.72) \pm (0.396 \pm 0.039),$$

where $L_X$ is the X-ray luminosity in units erg s$^{-1}$, $M_{500}$ is in units of $M_\odot$, and $E(z) = [\Omega_m(1 + z)^3 + \Omega_k]^{1/2}$ is the expansion history of the universe (Vikhlinin et al. 2009). From $M_{500}$ we simultaneously calculate the virial mass, $M_{\text{vir}}$, i.e., mass enclosed within the virial radius, $R_{\text{vir}}$, and the concentration parameter, $c$, using the system of equations

$$M_{\text{vir}} = \frac{4\pi}{3} [\Delta_c(z) \rho_c(z)] R_{\text{vir}}^3,$$

$$M_{500} = M_{\text{vir}} \frac{m(c R_{500}/R_{\text{vir}})}{m(c)}$$

$$c = \frac{5.72}{(1 + z)^{0.71}} \left( \frac{M_{\text{vir}}}{10^{14} h^{-1} M_\odot} \right)^{-0.081},$$

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where \( m(x) = \ln(1 + x) - x/(1 + x) \), \( c \) is taken from Duffy et al. (2008) based on the \( N \)-body simulations with the WMAP five-year cosmological parameters, \( \Delta_c(z) \) is a function of \( \Omega_m \) and \( \Omega_{\Lambda} \) (Bryan & Norman 1998)

\[
\Delta_c(z) = 18\pi^2 + 82[\Omega(z) - 1] - 39[\Omega(z) - 1]^2, \tag{4}
\]

and \( \Omega(z) = \Omega_m (1 + z)^3/E^2(z) \). For reference, \( 2R_{500} \) approximates \( R_{\text{vir}} \) (Komatsu et al. 2011). We use the concentration parameter to define the scaling radius, namely,

\[
r_s = \frac{R_{\text{vir}}}{c}. \tag{5}
\]

We numerically solve the system of equations (3) using FuncDesigner library for Python.\(^5\)

### 3.2. Cluster Parameters: SZ Catalog

Planck ESZ contains the integrated Compton-\( Y \) (\( Y = \int y d\Omega \)) at the cluster position and within \( 5R_{500} \). The magnitude of the SZ effect, known as the Compton parameter \( y \), depends only on the clusters characteristics, electronic temperature \( T_e \), and density \( n_e \), as

\[
y = \frac{k_B \sigma_T}{m_e c^2} \int T_e n_e dl, \tag{6}
\]

where \( k_B \) is the Boltzmann constant, \( \sigma_T \) is the Thomson cross section, \( m_e c^2 \) is the rest mass of an electron, and the integral is taken along the line of sight and over the area of the cluster in question. To find \( M_{500} \), we use the scaling relation \( Y_{R_{500}} = 0.55 Y_{5R_{500}} \) which gives the integrated Compton-\( Y \) at X-ray position and within \( 5R_{500} \). Furthermore, we use the scaling relation

\[
Y_{R_{500}} \left( \frac{E(z)}{\Omega_{\Lambda}} \right)^{1/3} = 10^A \left( \frac{M_{500}}{10^{14} M_\odot} \right)^B, \tag{7}
\]

where \( A = -4.213 \) and \( B = 1.72 \) (Planck early results, Planck Collaboration XXI 2011). Then we use the system of equations (3) to find \( M_{\text{vir}} \) and \( R_{\text{vir}} \).

### 3.3. Cluster Profiles

We use a \( \beta \)-model for the cluster profiles. In this model, the number density of electrons in a cluster is given by

\[
n_e(r) = n_{e0} \left( 1 + \frac{r^2}{r_s^2} \right)^{-3\beta/2}, \tag{8}
\]
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3.4. Template Fitting

The optical depth templates explained above are used to create kSZ templates for unit velocities in the x-, y-, and z-directions, [1, 0, 0] km s\(^{-1}\), [0, 1, 0] km s\(^{-1}\), and [0, 0, 1] km s\(^{-1}\), respectively, by multiplying each pixel by \(-\Delta T_{\text{CMB}} \hat{n} \cdot \mathbf{v} / c\), where \(\hat{n}\) is the vector pointing to the pixel in question and \(T_{\text{CMB}}\) is the temperature of the CMB. We also use a template for the thermal component of the SZ (tSZ) signal (Sunyaev & Zeldovich 1972) in our analysis

\[
\Delta T^{\text{tSZ}} = \left( \frac{x(e^x + 1) - 4}{e^x - 1} - 4 \right) T_{\text{CMB}} y,
\]

\[
y = \frac{k_B}{m_e c^2} T_{\text{CMB}} \tau, \]

\[
x = \frac{h v}{k_B T}, \tag{16}
\]

where \(k_B\) is Boltzmann’s constant, \(m_e\) is the mass of an electron, \(h\) is Planck’s constant, and \(v\) is the frequency of the CMB map (94 GHz). We assume a uniform temperature for the electron gas in the clusters to be \(T_e = 4 \times 10^7\) K. Before we measure for a bulk velocity, we apply a Wiener filter to our templates and data. To do so, we use as the denominator of our filter the CMB power spectrum plus white noise and we take as numerator of our filter the power spectrum of a kSZ template with velocity [0, 0, 1200] km s\(^{-1}\) (Kashlinsky et al. 2008). Our Wiener filter is based on the theory power spectrum and is not derived from the data unlike the Wiener filter of Kashlinsky et al. (2009). For a study of different filters in this context, see Osborne et al. (2011).

Then we use the least-square minimization to fit the above templates to the data

\[
\chi^2 = (\mathbf{D} - \alpha \cdot \mathbf{T})^T \mathbf{C}^{-1} (\mathbf{D} - \alpha \cdot \mathbf{T}), \tag{17}
\]

where \(\mathbf{D}\) is the CMB map and \(\alpha \cdot \mathbf{T} = v_x T_x^{\text{kSZ}} + v_y T_y^{\text{kSZ}} + v_z T_z^{\text{kSZ}} + \alpha T^{\text{tSZ}}\) is the tSZ plus kSZ fit to the map. We take the covariance matrix to be diagonal and determined by the pixel noise in WMAP. This is a good approximation for the present data because the cluster sample is sparse and we are dominated by the pixel noise on small angular scales of interest. We use Monte Carlo simulations to test our method. The result of the fit is the four-vector \(\alpha\) that contains the \(x\)-, \(y\)-, and \(z\)-components of the bulk flow and the tSZ template amplitude. Results are presented in Section 4.

In order to assess the statistical significance of the results, we use Monte Carlo simulations of the CMB sky. Simulated maps have three components

\[
\Delta T(\hat{n}) = (\Delta T_{\text{CMB}}(\hat{n}) + \Delta T^{\text{tSZ}}(\hat{n})) \otimes B(\hat{n}) + N(\hat{n}), \tag{18}
\]

where \(\Delta T_{\text{CMB}}\) is a realization of the Gaussian CMB field, \(\Delta T^{\text{tSZ}}\) is the thermal component of the SZ signal simulated as described in Equation (16), \(N(\hat{n})\) is the pixel noise, and \(\otimes B(\hat{n})\) means convolved with the proper beam of the experiment.

We make 100 realizations of the CMB sky using synfast\(^6\) routine of HEALPix\(^7\) with the underlying theory power spectrum computed with CAMB\(^*\) using the concordance model. The maps are then convolved with WMAP beam for W band.

6 We use healpy, the Python version of HEALPix.
7 http://camb.info

with

\[
n_{e,0} = \frac{N_e}{4\pi r_s^2 (c - \arctan c)}, \tag{9}
\]

and we take \(\beta = 2/3\) to describe the X-ray surface brightness profile of observed clusters (Waizmann & Bartelmann 2009). \(r_s\) is defined within the virial radius of the cluster. We calculate \(N_e\), the total number of electrons in each cluster, according to

\[
N_e = \frac{1 + f_H}{2m_p} f_{\text{gas}} M_{\text{vir}}. \tag{10}
\]

Here, \(f_H = 0.76\) is the hydrogen fraction, \(f_{\text{gas}} = \Omega_b/\Omega_m = 0.0168\), and \(m_p\) is the proton mass. Taking the line-of-sight integrals, the optical depth of a cluster in the \(\beta\)-model is given by

\[
\tau(\theta) = 2\sigma_T \frac{r_n n_{e,0}}{\sqrt{1 + \frac{\theta^2}{\theta_s^2}}} \tan^{-1} \sqrt{\frac{c^2 - \rho^2}{c^2 + \rho^2}}. \tag{11}
\]

In order to check the effect of the assumed cluster profile on our results, we do our analysis using the Navarro et al. (1996, NFW) model as well. The electron density in this model is given by

\[
n_e(r) = \frac{n_{e,0}}{r_s} \left(1 + \frac{\rho}{\rho_s}\right)^{-\alpha}, \tag{12}
\]

with

\[
n_{e,0} = \frac{N_e}{4\pi r_s^2 \left(\ln(1 + c) - \frac{c}{1 + c}\right)}. \tag{13}
\]

The optical depth is given by

\[
\tau(\theta) = \begin{cases} 
\frac{2r_n n_{e,0}}{x^2 - 1} \left(1 - \frac{2}{1 - x^2} \tan^{-1} \sqrt{1 - \frac{1 - x}{1 + x}}\right) & x < 1 \\
\frac{2r_n n_{e,0}}{3} & x = 1 \\
\frac{2r_n n_{e,0}}{x^2 - 1} \left(1 - \frac{2}{1 - x^2} \tan^{-1} \sqrt{x - 1/1 + x}\right) & x > 1,
\end{cases}
\]

where \(x \equiv r/r_s\) (Wright & Brainerd 2000). The key difference between the two models is that the NFW profile places most electrons at the central region of the cluster whereas the \(\beta\)-model is more extended throughout the cluster and beyond. In both the cases we cutoff the model at \(r_{\text{vir}}\). In practice, we project the cluster profiles onto a pixelized sphere. To pixelize our models, we calculate

\[
\tau_{\text{total}} = D^2 \tau_n N_e, \tag{14}
\]

with \(\sigma_T\) being the Thomson scattering coefficient. Every cluster is built within its \(\theta_{\text{vir}}\). For each pixel in the cluster, \(\tau(\theta)\) is computed and assigned to that pixel. Pixel values are normalized in each cluster by \(\tau_{\text{total}}/\sum_i \tau_i \Omega_{\text{pix}}\), where the sum is taken over all the pixels within the given cluster, and \(\Omega_{\text{pix}}\), the pixel area of the map, is a constant for the entire map given by \(4\pi / n_{\text{pix}}\). Our normalization is such that

\[
\sum_i \tau_i \Omega_{\text{pix}} = \tau_{\text{total}}, \tag{15}
\]

where \(\tau_i\) is the normalized value of each pixel. The typical optical depths that we obtain using this algorithm are of the order of \(10^{-3}\).
Noise realizations are added to the beam convolved maps in the error bars. Results do not show a significant bulk flow and are consistent with zero within Figure 2. The Astrophysical Journal spectrum.

By comparing their average power spectra with the data power templates: templates based on the NFW model for the cluster profiles and templates using the X-ray catalog and SZ catalog. The results for the NFW profile are shown in Figure 2. Using a β-model does not significantly change the results. For the β-model described above, we obtain the bulk velocity of \([-78, 592, 650]\) ± \([2770, 2600, 1700]\) km/s for the X-ray catalog and \([-2940, -1120, 4840]\) ± \([3512, 3443, 2441]\) km/s for the SZ catalog. For the tSZ parameter \(α\), we get \(α = 1.4 ± 0.5\) and \(α = 1.9 ± 0.6\) for the NFW and the β-model using Planck ESZ sample and \(α = 1.0 ± 0.4\) and \(α = 1.2 ± 0.5\) for the X-ray sample. In our model, the clusters are assumed to have an average constant temperature given by \(α \times 4000\) K. Therefore, the best-fit average temperature of the clusters in our model is about \(5 \times 10^7\) K–\(7 \times 10^7\) K. In order to measure the bulk flow at different redshifts, we divided the X-ray catalog into three catalogs at redshifts \(z < 0.068, 0.068 < z < 0.13,\) and \(z > 0.13\). The redshift bins are chosen so that all bins have roughly the same number of clusters in them. We repeated our analysis for each of these samples. The bulk flow was consistent with zero in all three redshift bins.

5. SUMMARY AND CONCLUSION

We use cluster catalogs and the highest resolution maps of the WMAP data (W band) to measure the bulk flow using the kSZ effect. We do not detect a significant bulk flow. The best constraint we get on the bulk flow velocities is from the RASS X-ray catalog, assuming an NFW profile for the clusters. The result is shown in Figure 2. Using a β-model leads to similar results. This is due to the size of the WMAP beam which makes the details in the cluster profiles indistinguishable at this resolution. The results based on the Planck ESZ catalog have larger uncertainties due to the smaller number of clusters in the catalog. Our results are not sensitive to the kSZ signal of the free electrons in our own galaxy because we mask the galactic plane. We repeated our analysis using different masks. We report no significant effect on the results due to a more aggressive masking of the galactic plane or masking the point sources in the map. Our results agree with the results of Osborne et al. (2011) and Keisler (2009) and are consistent with the absent of a large bulk flow one the scales of 300–400 h\(^{-1}\) Mpc as predicted by the ΛCDM model. Our results do not agree with the findings of Kashlinsky et al. (2011) which report a significant detection of a bulk flow inconsistent with zero. It is important to have as many independent statistical methods as possible to measure and constraint the bulk flow velocities. Future cluster catalogs and CMB maps will help us tighten these constraints.

This analysis can be improved by using larger cluster catalogs such as the future X-ray-selected catalog of eRosita All-Sky Survey (Cappelluti et al. 2011), and the next releases of Planck SZ-selected clusters combined with the SZ-detected clusters of ACTPol (Niemack et al. 2010) and SPTpol (McMahon et al. 2009). However, using more clusters alone will not improve the analysis much; one needs to use a higher resolution CMB map as well to increase the signal-to-noise ratio in the measurement. The only full-sky maps of the CMB at higher resolution in the near future are going to be Planck maps. Using Planck data with future cluster catalogs will help us put tighter constraints on the bulk flow (Mak et al. 2011). As the data get better, it is important to improve the theoretical models used for making the templates. For example, second-order effects like the changes in the SZ cluster brightness, flux, and number counts induced by the motion of the solar system (Chluba et al. 2005) and the relativistic corrections to the kSZ signal (Nozawa et al. 2006) need to be taken into account. In order to be consistent, we have only used the Planck model for the Planck ESZ clusters. There are other variations of this model that could be used which affect the \(Y–M\) scaling relation. We also assume a universal value for the \(f_{\text{gas}}\), but there might be corrections to the universal \(f_{\text{gas}}\) value (Battaglia et al. 2012). Varying these models and assumptions can potentially affect the results by 10%–30%, but it will not drastically change our results.

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