Constraining the evolution of the CMB temperature with SZ measurements from Planck data

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Abstract. The CMB temperature-redshift relation, $T_{\text{CMB}}(z) = T_0(1 + z)$, is a key prediction of the standard cosmology but is violated in many non-standard models. Constraining possible deviations from this law is an effective way to test the ΛCDM paradigm and to search for hints of new physics. We have determined $T_{\text{CMB}}(z)$, with a precision up to 3%, for a subsample (103 clusters) of the Planck SZ cluster catalog, at redshifts in the range 0.01–0.94, using measurements of the spectrum of the Sunyaev-Zel’dovich (SZ) effect obtained from Planck temperature maps at frequencies from 70 to 353 GHz. The method adopted to provide individual determinations of $T_{\text{CMB}}(z)$ at cluster redshift relies on the use of SZ intensity change, $\Delta I_{\text{SZ}}(\nu)$ at different frequencies and on a Monte Carlo Markov chain approach. By applying this method to the sample of 103 clusters, we limit possible deviations of the form $T_{\text{CMB}}(z) = T_0(1 + z)^{1-\beta}$ to be $\beta = 0.012 \pm 0.016$, at 1σ uncertainty, consistent with the prediction of the standard model. Combining these measurements with previously published results, we get $\beta = 0.013 \pm 0.011$.

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1 Introduction

In the past two decades cosmology became a data-driven science, and we have learned more about the universe in this period than in all the rest of mankind’s history. The synthesis of this knowledge is provided by the so-called concordance cosmological model, which provides a very good fit to a plethora of data with only a fairly small number of free parameters and theoretical assumptions. Still, this comes with some cost: about 96% of the contents of the universe should be in two forms — dubbed dark matter and dark energy — that have never been detected in the laboratory, but have only been ‘statistically discovered’ in astrophysical and cosmological data, through their inferred gravitational properties.

As a matter of fact, the observational evidence for the recent acceleration of the universe demonstrates that the canonical theories of cosmology and particle physics must be at least incomplete — if not incorrect — and that there is new physics waiting to be discovered. The next generation of flagship astrophysical facilities must therefore be optimized for the role of searching for, identifying, and ultimately characterizing this new physics. A key component of this roadmap is a significant improvement in the precision of consistency tests of the standard paradigm. This paper provides a contribution along these lines.

If the expansion of the Universe is adiabatic and the cosmic microwave background (CMB) spectrum was originally a black-body, its shape will be preserved by the subsequent evolution, with its temperature behaving as

\[ T_{\text{CMB}}(z) = T_0(1 + z). \]
This is a robust prediction of standard cosmology, but it is violated in non-standard models, the most obvious scenarios being those involving photon mixing and/or violation of photon number conservation. There are many non-standard, but nevertheless theoretically well-motivated, physical processes in which photon number is not conserved. Examples include a non perfectly transparent Universe, decaying vacuum cosmologies (with photon injection mechanisms), models in which the fine-structure constant varies, physically motivated scenarios where photons mix with other particles (such as axions), many modified gravity scenarios, and so on. Therefore, direct observational constraints on this relation lead to constraints on a range of scenarios beyond the standard $\Lambda CDM$ paradigm. It’s also worth noting that additional indirect constraints stem from the distance duality relation (as discussed in [1, 2]) and from CMB spectral distortions [3].

The COBE-FIRAS experiment has revealed a very precise black-body spectrum, with a temperature of $T_0 = 2.725 \pm 0.002$ K [4], but this measurement per se tells us nothing about the behavior of the CMB at non-zero redshifts. Currently, there are two astrophysical techniques that can probe this behavior. At low redshifts (typically $z < 1$), the CMB temperature can be measured via the Sunyaev-Zel’dovich (SZ) effect towards galaxy clusters [5, 6]. The SZ effect — Compton scattering of the CMB by hot intracluster (IC) gas — is a small change in the CMB spectral intensity, $\Delta I_{SZ}$, which depends on the integrated IC gas pressure along the line of sight to the cluster. The steep frequency dependence of $\Delta I_{SZ}$ allows the CMB temperature to be estimated at the redshift of the cluster. We refer the reader to section 4 for a more complete treatment. This method was first applied to ground-based CMB observations of a small number of clusters [7, 8], which demonstrated its potential; more recently, it was further explored with the current generation of ground and space experiments [1, 9–12]. Here we build upon these earlier studies.

At higher redshifts (typically $z > 1$), the CMB temperature can be determined from quasar absorption line spectra which show atomic and/or ionic fine-structure levels excited by the photon absorption of the CMB radiation [13]. The CMB is an important source of excitation for species with transitions in the sub-millimeter range, such as C, CO, or CN. (Of these, CN is in principle the best thermometer, but so far it has not been detected in high-redshift systems.) Although the concept is more than four decades old, measurements (as opposed to upper bounds) were only obtained much more recently [14], with errors at the ten percent level [15] and for one case at a few percent level at $z = 0.89$ [16]. Significant improvements are expected from ALMA [17, 18] and especially from the E-ELT high resolution spectrograph [19, 20], particularly through CO measurements which are signal-to-noise limited.

We note that the two techniques complement each other, not only in terms of redshift coverage but also because they have entirely different potential systematics. Spectroscopic observations probe the matter era, and despite the shortage of suitable targets (which is in fact the limiting factor for this method) the large redshift lever arm can lead to significant constraints. On the other hand, SZ clusters probe the epoch of dark energy domination and its onset, and large catalogs of SZ clusters are now available, making it a powerful probe.

In the present study we focus on a subsample (containing a total of 107 clusters) of the Planck SZ cluster catalog, in the redshift range 0.01–0.94, to constrain possible deviations of the temperature-redshift relation. As is common in the existing literature, we will phenomenologically parametrize possible deviations by

$$T_{CMB}(z) = T_0(1 + z)^{1-\beta},$$

(1.2)
as proposed by [21]. We will therefore obtain constraints on the dimensionless parameter $\beta$, both from our cluster sample alone and in combination with other direct measurements, thereby improving currently existing bounds [1, 10–12, 15, 16].

The structure of the rest of the paper is as follows. In section 2 we describe the different datasets used to determine the final SZ fluxes and the cluster catalog. In section 3 we explain the procedure to obtain the SZ fluxes. In section 4 we describe in detail the procedure to infer the $T_{\text{CMB}}(z)$ temperature at the position of each cluster from SZ measurements. In section 5 we present our final results, in section 6 we discuss possible future work, and in section 7 we summarize the main conclusions of the current analysis.

## 2 Data

The core of the present analysis rests upon a subsample of the Planck SZ cluster catalog (PSZ) [22] and Planck temperature maps at frequencies from 70 to 857 GHz [23], on the use of X-ray data from BAX (X-ray Cluster Database) [24], and from the MetaCatalog of X-ray detected clusters of galaxies (MCXC) [25].

The Planck spectral coverage allows us to explore the positive and negative part of the SZ spectral distortion; it is optimally suited for cluster detection and, more importantly for this project, allows for breaking cluster parameter degeneracies when including priors over one or more of the parameters (e.g., the electron temperature). Here we focus on a study dedicated to a sample of known clusters for which X-ray and optical informations are available, i.e., a subsample of the Planck SZ cluster catalog. Taking advantage of the multi-frequency capability, the high quality of data ($S/N$ ratio $\geq 6$) and the precise absolute calibration (known to be better than 1%) we will show that it is possible to determine the CMB temperature at cluster redshift with a precision of up to 3%, comparable to the results based on the use of radio-mm molecular absorbers at $z = 0.89$ from [16].

### 2.1 Planck temperature maps

To derive the SZ fluxes we use Planck DR1 maps [23], which cover a wide frequency range delimited by nine independent channels, provided by the LFI (30, 44, and 70 GHz) and the HFI (100, 143, 217, 353, 545, and 857 GHz) instruments.¹ These maps are projected in HEALPix pixelization [26], using a pixel resolution of $N_{\text{side}} = 2048$ for the HFI channels and $N_{\text{side}} = 1024$ for the LFI channels. All the results presented in this paper were obtained at full resolution, $N_{\text{side}} = 2048$, for which we had to re-pixelize the LFI maps. Although we clean the foreground contributions from these maps at each cluster position, to avoid contamination from residuals we ignore the extreme frequencies and focus our analyses in the five frequency bands between 70 and 353 GHz. The first three channels lie in the negative part of the SZ spectrum, the 217 GHz channel is close to the null, whereas at 353 GHz the SZ effect is positive.

### 2.2 Ancillary maps

Ancillary data will be used to clean our maps of thermal dust emission and CMB fluctuations, following the methodology explained in subsection 3.1. As a template to correct for the dust emission around each cluster we use the 100 $\mu$m IRIS map [27]. This map is a reprocessing of

¹These maps, and all the rest of Planck-related public products that have been used in this paper, have been downloaded from the Planck Legacy Archive, http://pla.esac.esa.int/pla.
the original map from the *Infrared Astronomical Satellite* (*IRAS*), containing improvements on the calibration and determination of the zero level, and a better correction of the striping problems.

To remove the emission from the CMB we resort to LGMCA (local-generalized morphological component analysis), \(^2\) a CMB map produced by [28] using a combination of *Planck* DR1 and *WMAP* 9-year data. We initially attempted to use three of the CMB maps released in *Planck* DR1, resulting from different component-separation techniques [29]: SMICA, NILC, and SEVEM. However, as will be shown in subsection 3.1, these maps suffer from important SZ contamination, so we use LGMCA instead, which does not have this problem.

2.3 Selection of the PSZ subsample

We use the Planck all-sky SZ (PSZ) cluster catalog. PSZ has 1227 entries; among these, 861 are confirmed clusters, and 813 have known redshifts. Among these 813 clusters, we have selected a sample of 107 clusters organized into 4 subsamples. The first subsample of 75 clusters with \(z < 0.4\) have a signal-to-noise threshold of 7. In these clusters, \(R_{500}\), \(^3\) is taken from MCXC and the electron temperature, \(T_e\), is given by BAX. The second subsample is made of 11 clusters at intermediate redshifts \((0.3 < z < 0.6)\) with a signal-to-noise threshold of 7. Here \(R_{500}\) is taken from MCXC, and \(T_e\), under an assumption of isothermal gas, is estimated using the relation \(\bar{T} - M_{500}\) given in [30]:

\[
E(z)M_{500} = A_{500} \left(\frac{kT}{5\text{keV}}\right)^{\alpha_T},
\]

with \(\alpha_T = 1.49\), \(A_{500} = 4.10 \times 10^{14} h^{-1} M_{\odot}\), and \(M_{500}\) taken from MCXC. The third subsample is made up of 19 high-redshift clusters, with \(0.6 < z < 0.75\). For these clusters we use the \(R_{500}\) value as estimated by *Planck*, and \(T_e\) is estimated using the scaling relation according to eq. (2.1). In particular, to estimate \(R_{500}\), when no X-ray information is available, we marginalize over \(Y\) (the integrated Compton parameter within \(5R_{500}\)) the two-dimensional probability distribution in \(\theta_{500}\) (the estimated size), and \(Y\) given by the PWS detection algorithm\(^4\) [33], one of the three detection algorithms used by the Planck collaboration to produce the union Planck SZ catalog (see Planck release 2013). These 19 high-redshift clusters have considerably larger uncertainties on \(R_{500}\) with respect to other clusters in our sample. We have included them because of the higher lever arm on \(\beta\), due to the exploration of the distant universe, and also to show the power of a per cluster analysis with the *Planck* frequency coverage (with respect to the SPT results [11]) and to compare our results to those obtained by [10].\(^5\) The fourth subsample is made up of only two clusters, ACT-CLJ0102-4915 (El Gordo) and PSZ1 G266.56-27.31, at redshifts \(z = 0.87\) and \(z = 0.97\), for which \(R_{500}\) and \(T_e\) are available from [31] and [32] respectively.

\(^2\)Downloaded from http://www.cosmostat.org/research/cmb/planck_wpr1/.

\(^3\)The radius within which the mean overdensity of the cluster is 500 times the critical density at the cluster redshift.

\(^4\)A fast Bayesian multi-frequency detection algorithm designed to identify and characterize compact objects buried in a diffuse background.

\(^5\)They have applied a stacking of PSZ clusters in different redshift bins, with only one cluster in each of their highest redshift bins \(z = 0.8\) and \(z = 1\).
3 Estimation of the SZ fluxes at Planck frequencies

3.1 Map cleaning

In order to obtain reliable SZ fluxes we have to clean the Planck frequency maps of other contributions. In particular, synchrotron and free-free emissions, which mainly affect the low-frequency LFI data, the thermal dust emission, which is important at the HFI frequencies, the CMB, and extragalactic point sources. There are two further contaminants that affect the HFI maps: the zodiacal light, and CO emission, which affects the 100, 217, and 353 GHz channels. For the HFI channels, we use publicly available zodiacal-light corrected maps, which have been produced by analyzing data from different surveys which are subject to different levels of zodiacal light intensities as explained in [34]. The Planck collaboration has also released templates to correct for the CO emission [35], using three different methodologies. Two of these maps suffer from significant contamination from other foregrounds, including the SZ signal [35], while the other is noise-dominated at higher galactic latitudes. Therefore, we prefer not to correct for CO emission.

Contamination from extragalactic point sources is removed through the application of the SZ union mask used by the Planck collaboration when building the SZ catalogue [22]. All the pixels affected by this mask are ignored in our analysis, which results in the removal of not only point sources but of regions along the Galactic plane affected by strong diffuse foregrounds. However, care must still be taken with less strong contamination in regions not covered by the mask. Free-free and synchrotron emission may affect the lowest LFI frequencies. The Planck collaboration has provided maps of these emissions at 30 GHz, but at a low angular resolution of 30 arcmin. As the median angular size of the clusters in our catalog is $\theta_{500} \sim 6$ arcmin, the large-scale emission traced by these maps will be largely canceled through the subtraction of the background in our aperture photometry technique. Therefore, we do not perform any cleaning of the synchrotron or free-free emission, and instead decide to ignore in our analysis the first two LFI bands (30 and 44 GHz), which present the highest contamination from these foregrounds, and which also have the coarsest angular resolutions. We have estimated that the typical fluctuations on the synchrotron/free-free map extrapolated to 70 GHz are less than 5% of the measured SZ fluxes.

The thermal dust emission is the most important contaminant at HFI frequencies. The publicly-available Planck dust model [36] which, for each sky pixel, gives the three parameters that define the modified black-body (MBB) emission law (dust-grains temperature, emissivity index and optical depth), could be used to this purpose, as is done in [37]. However, we have figured out that this model has significant SZ residuals, which reach an average level of $\sim 100 \mu$K at 353 GHz. Therefore, we instead apply the well-known method, proposed by [38] in the context of SZ studies, consisting in finding the parameter $\alpha(\nu)$ that minimizes the variance of the subtraction

$$M_{dc}(\nu, x) = M(\nu, x) - \alpha(\nu)M_d(x), \quad (3.1)$$

where $M_d$ is a template tracing the dust emission, and $M$ is the map at frequency $\nu$ that we want to clean at a given position $x$. The value of this parameter that minimizes the variance is

$$\alpha(\nu) = \frac{\sum_i M(\nu, x_i)M_d(x_i)}{\sum_i M_d(x_i)^2}, \quad (3.2)$$

where the sum extends over all pixels in a given region of the sky. Instead of assuming the same $\alpha$ value for the whole sky, we build cleaned mini-maps around each cluster position,
and calculate the $\alpha$ parameter using all pixels enclosed by a ring between $\max[\theta_1]$ (note that $\theta_1$ is different for each frequency, so we take here the maximum value of $\theta_1$ among all frequencies) and $25 \times \theta_{500}$, $\theta_1$ being the radius defining the circle where we apply the aperture photometry (see next section). Note that, in order to avoid possible biases introduced by dust-TSZ correlations, in the calculation of $\alpha$ we ignore all pixels within an angular distance $\theta_1$ of the cluster. As the dust template, $M_d$, we first use the 100 $\mu$m IRIS [27] map.\footnote{Downloaded from \url{http://www.cesr.fr/~bernard/Ancillary/IRIS/}.} To further reduce possible residuals, we perform a second iteration using the Planck 857 GHz map.

The last step in our cleaning procedure consists of removing the CMB fluctuations. Whereas the 217 GHz map is commonly used as a template to remove the CMB in the context of SZ studies, in our case this approach would introduce important modifications in our analysis. Including the subtraction of the 217 GHz map in the fitting procedure would introduce a strong degeneracy between the optical depth and $T_{\text{CMB}}$, thus preventing a meaningful determination of the CMB evolution. In fact, in the fitting formula for only the thermal SZ component ($TSZ$) we have: $TSZ(\nu, T(z), \tau, T_e) - TSZ(217, T(z), \tau, T_e)$. If $\tau$ is not known a priori then the same effect can be mimicked by different values of $\tau$ or of $T_{\text{CMB}}(z)$. For this reason, we decide to resort to a CMB map extracted from a component-separation technique. None of the three Planck DR1 CMB maps (SMICA, NILC and SEVEM; see [29]) are suitable for this purpose owing to the presence of significant SZ residuals. These are evident in figure 1, where we show a stack of each of these maps in the positions of the 107 clusters of our catalog. A negative feature is seen toward the center of these maps, with a value of $\sim -60 \mu$K, that represents the average minimum SZ temperature decrement in these clusters. On the contrary, the same stack on the LGMCA CMB map [28] renders no visible thermal SZ residuals. Therefore, we will use the LGMCA map to subtract the CMB from each of the sky maps at the six frequencies that we use. When using LGMCA, the fitting formula for the TSZ is just: $TSZ(\nu, T(z), \tau, T_e)$, thus no degeneracy is introduced between the optical depth and $T_{\text{CMB}}$. The side effect is that the LGMCA method takes the standard thermal SZ spectrum explicitly into account during the component separation (without relativistic corrections and assuming the standard scaling of the CMB temperature). This could bias our analysis. Assuming, for example, that the CMB temperature is systematically lower with respect to the standard case means that the LGMCA maps should show an excess at cluster positions. By making the stacking (figure 1) we see that there is no such effect, or at least it is at noise level. Of course, this does not mean that we are no longer sensitive to the determination of $T_{\text{CMB}}(z)$ because, in order to extract it, we use multifrequency informations and not only the 217 GHz channel. It is anyway possible that, in case of non-negligible relativistic corrections to the thermal and kinematic SZ components, we mimic a kinematic SZ (KSZ) in our spectrum because of the subtraction at each frequency of the same amount of signal. As will be shown in subsection 4.1 we fit for a KSZ component in our analysis. The uncertainty in the determination of $T_{\text{CMB}}(z)$ takes this into account.

The final cleaned map is given by

$$M_c(\nu,x) = M(\nu,x) - \alpha_{\text{IRIS}}(\nu)M_{\text{IRIS}}(x) - \alpha_{857}(\nu)M_{857}(x) - M_{\text{LGMCA}}(x),$$

where $M$, $M_{\text{IRIS}}$, $M_{857}$, and $M_{\text{LGMCA}}$ are respectively the original Planck map, the IRIS 100 $\mu$m map, the Planck 857 GHz map, and the LGMCA CMB map. $\alpha_{\text{IRIS}}$ is obtained through equation (3.2), using as a dust template the IRIS map and as the data the initial Planck map. In the calculation of $\alpha_{857}$ we use the 857 GHz map as template and the map cleaned using IRIS as the data.
Figure 1. Stack of different CMB-reconstructed maps at the positions of the clusters of our catalogue. The maps are 4 degrees on a side. The units of the color scale are $\mu K_{\text{CMB}}$, and the maps have been divided by 10^7 in such a way that each pixel represents the average of the temperatures of the 10^7 maps around each cluster in that specific position. We consider three foreground-cleaned CMB maps delivered by the Planck collaboration [29] which are the result of independent component-separation methods (SMICA, NILC, and SEVEM) and also the LGMCA map produced by [28]. It is clear that the LGMCA map is the only one showing no clear SZ residuals; therefore, we use this map in our analysis.

When applying equation (3.3), we take all maps to a common angular resolution. This means that for $\nu \geq 217$ GHz we degrade $M_{\text{IRIS}}$, $M_{887}$ to 5 arcmin, the angular resolution of the LGMCA map. The beam full width half maxima (FWHM) for $\nu < 217$ GHz are larger than 5 arcmin; therefore, in those cases we degrade $M_{\text{IRIS}}$ and $M_{887}$ and $M_{\text{LGMCA}}$ to the angular resolution of $M(\nu)$.

In figure 2 we show the final cleaned maps at the position of the galaxy clusters PSZ1G044.24+48.66 (A2142) and PSZ1G046.09+27.16, where the SZ effect shows up at all frequencies except 217 GHz. PSZ1G044.24+48.66 is a nearby cluster at $z = 0.0894$ and with a relatively large angular size, $\theta_{500} = 13.8$ arcmin. Note, however, that our cleaning technique allows us to unveil the SZ signal at 143 and 353 GHz from the more distant cluster PSZ1G046.09+27.16, which has $z = 0.389$ and $\theta_{500} = 4.5$ arcmin.

3.2 Aperture photometry

In order to derive the SZ flux of each cluster, we use an aperture photometry technique, consisting in integrating all pixels in a circle of radius $\theta_1$, and subtracting a background level calculated as the median of all pixels enclosed in an external ring between radii $\theta_2$ and $\theta_3$. For the aperture we use $\theta_1 = \max[\theta_{500}, 0.75\theta_{\text{FWHM}}(\nu)]$, where $\theta_{500}$ is the angular radius at which the mean density has dropped to 500 times the critical density at the cluster redshift, and $\theta_{\text{FWHM}}(\nu)$ is the beam FWHM at a given frequency $\nu$. This ensures capturing most of the SZ flux for each cluster. The bulk (typically $> 60\%$, depending on the cluster profile) of the SZ flux is enclosed inside $\theta_{500}$. On the other hand, in order to avoid the possible loss of flux produced by the beam convolution, in those cases where $0.75\theta_{\text{FWHM}}(\nu) > \theta_{500}$ we use $0.75\theta_{\text{FWHM}}$ as the aperture radius. The external ring must not be too close to the cluster as this would result in an auto-subtraction of SZ flux; neither should it be too far as it would not be representative of the true background around the cluster. We initially consider three cases: $[\theta_2, \theta_3] = [1.5, 2.5] \theta_1$, $[2.0, 2.24] \theta_1$ (in this case the aperture and the ring have equal areas), and $[2.5, 3.5] \theta_1$. As shown in figure 3, we get fluxes consistent at the $1\sigma$ level for these three cases. In order to minimize the level of SZ flux that is removed when performing the
Figure 2. Planck LFI and HFI maps around the position of the clusters PSZ1G044.24+48.66 (A2142; first two lines) and PSZ1G046.09+27.16 (third and fourth lines). From left to right we show maps from 70 to 353 GHz, the five frequencies used. The first and third lines correspond to the original Planck frequency maps, while the second and fourth lines correspond to the maps after cleaning for the thermal dust and CMB using our methodology (see subsection 3.1). The solid circle depicts the aperture we use to integrate the SZ flux, and the two concentric dashed circles the ring used for background subtraction. The cleaned maps of PSZ1G044.24+48.66 (z = 0.089) clearly show the expected SZ decrements at frequencies below 217 GHz, no effect at 217 GHz, and a positive signal at 353 GHz. In the case of PSZ1G046.09+27.16, despite its high redshift (z = 0.389) and small angular size (θ500 = 4.5 arcmin), its SZ signal is still evident at 143 and 353 GHz, which demonstrates the efficiency of our cleaning methodology.
Figure 3. We show the SZ fluxes derived through aperture photometry in two nearby clusters (A2744 and A0085), using three different sets of parameters for the radius of the aperture ($\theta_1$) and for the internal ($\theta_2$) and external ($\theta_3$) radii of the ring used for background subtraction. We use $[\theta_1, \theta_2, \theta_3] = [1.0, 1.5, 2.5] \theta_{500}$ (black points), $[1.0, 2.0, 2.4] \theta_{500}$ (cyan), and $[1.2, 5.3, 5] \theta_{500}$ (blue).

background subtraction, we decided to use the farthest background ring, $[\theta_2, \theta_3] = [2.5, 3.5] \theta_1$. Using a universal profile [39], we have verified that the SZ flux that is subtracted in this case is $\lesssim 1\%$. Given this low value, and taking into account the possible errors on the modeling of the cluster profile, we decided not to apply this correction.

The final flux density is then given by

$$S_{\text{SZ}}(\nu) = \left[ \frac{\sum_{i=1}^{n_1} M(\nu)_{c,i}}{n_1} - \bar{M}(\nu)_{c,j} \right] n_1 \Omega_{\text{pix}},$$  \hspace{1cm} (3.4)

where the first term in the brackets represents the mean of the $n_1$ pixels in the aperture with temperature values in the final cleaned maps $M(\nu)_{c,i}$, and the second term is the median of the $n_2$ pixels with temperatures $M(\nu)_{c,j}$ enclosed by the external ring. $\Omega_{\text{pix}}$ is the solid angle subtended by each pixel.

The calculation of the error associated with the flux derived through equation (3.4) is crucial. It could be calculated analytically as

$$\sigma(S_{\text{SZ}}(\nu)) = \left[ \frac{\sum_{i=1}^{n_1} \sigma_{i}^2}{n_1^2} + \frac{\pi}{2} \frac{\sum_{j=1}^{n_2} \sigma_{j}^2}{n_2^2} \right]^{1/2} n_1 \Omega_{\text{pix}} = \sigma(M_{c,j}) \left[ \frac{1}{n_1} + \frac{\pi}{2} \frac{1}{n_2} \right]^{1/2} n_1 \Omega_{\text{pix}},$$ \hspace{1cm} (3.5)

where $\sigma_{i,j}$ represents the error associated with each individual pixel, which is estimated through the pixel-to-pixel dispersion in the background annulus, $\sigma(M_{c,j})$. This equation however assumes perfect white noise (no pixel-to-pixel correlations). This would be a reliable assumption in the case of maps dominated by instrumental noise, but not in the case of non-negligible foreground residuals. Furthermore, the convolution that is applied to some of the maps introduces correlations between the instrumental noise in different pixels. We then chose a more conservative way of estimating the noise, consisting in calculating the flux via aperture photometry (with the same values of $\theta_1$, $\theta_2$, and $\theta_3$ as in the central position) in ten evenly separated positions located along a circle of radius $3\theta_3$. The final error is given
by the standard deviation of the ten calculated fluxes. We have checked that this estimate is consistent with equation (3.5) for 70 GHz, where the foreground residuals are minimal. At higher frequencies the difference with respect to equation (3.5) increases progressively, reaching a factor $\sim 3.5$ at 353 GHz. This indicates that the contribution of the foreground residuals to the noise might be $\sim 3$ times larger than the instrumental noise at this frequency. The same ten apertures around each cluster are used to determine the covariance matrix between different frequency bands. The cleaned maps at different frequencies may not be completely independent owing to the possible presence of correlated foreground residuals and of common instrumental noise coming from the IRIS, 857 GHz, and LGMCA maps used at all frequencies. We found that the off-diagonal terms of the normalized covariance matrix are typically below 0.5, in agreement with [12] but significantly lower than [10]. The exact values depend strongly on the angular size of the cluster. We see higher correlation terms mainly for the two highest frequencies in our analysis (217 and 353 GHz) and only for clusters whose $\theta_{500}$ is greater than 8 arcmin.

4 Method for obtaining $T_{\text{CMB}}(z)$ measurements

The possibility of determining $T_{\text{CMB}}(z)$ from measurements of the Sunyaev-Zel’dovich effect was suggested long ago [5, 6]. Compton scattering of the CMB in a cluster causes an intensity change, $\Delta I_{\text{SZ}}$, that can be written as:

$$
\Delta I_{\text{SZ}} = \frac{2k^3T_0^3}{h^2c^2} x^4e^x \left[ \theta f(x) - \beta + R(x, \theta, \beta) \right],
$$

(4.1)

where $\tau = \sigma_T \int n_e dl$ is the optical depth, $T_0$ is the CMB temperature at redshift $z = 0$, $\theta = \frac{k_B T_e}{m_e c^2}$ with $T_e$ electron cluster temperature (we are assuming isothermality), $\beta = \frac{v_z}{c}$ with $v_z$ the radial component of the peculiar velocity of the cluster, $f(x) = [x \coth(x^2) - 4]$, and the $R(x, \theta, \frac{v_z}{c})$ function which includes relativistic corrections [40–42].

The spectral signature of the SZ, $\Delta I_{\text{SZ}}$, depends on the frequency $\nu$ through the non-dimensional frequency $x = \frac{h\nu(z)}{kT(z)} = \frac{h\nu}{kT_0}$; it is redshift-invariant only for the standard scaling of $T_{\text{CMB}}(z)$. In all other non-standard scenarios, the ‘almost’ universal dependence of SZ on frequency becomes $z$-dependent, resulting in a small dilation/contraction of the SZ spectrum on the frequency axis. In terms of thermodynamic temperature, $\Delta T_{\text{SZ}}$ of the CMB due to the SZ effect is given by

$$
\Delta T_{\text{SZ}}(x) = T_0 \tau \left[ \theta f(x) - \beta + R(x, \theta, \beta) \right].
$$

(4.2)

If we assume that $T_{\text{CMB}}$ scales with $z$ as $T_{\text{CMB}}(z) = T_0(1 + z)^{1-\beta}$, while the frequency scales as $(1 + z)$ as usual, then the non-dimensional frequency will be $x' = \frac{h\nu_0}{k_BT_{\text{CMB}}}$ and $T_{\text{CMB}}^* = T_{\text{CMB}}(z)/(1 + z) = T_0(1 + z)^{-\beta}$ will be slightly different from the local temperature $T_0$ as measured by COBE-FIRAS. In this way it is possible to measure the temperature of the CMB at the redshift of the cluster, thus directly constraining scenarios such as those discussed in the introduction. Actually, what we measure is the temperature change integrated over the solid angle corresponding to the chosen aperture radius $\theta_1$ (as defined in 3.2), so we have:

$$
\Delta \bar{T}_{\text{SZ}} = \int \Delta T_{\text{SZ}}(x) d\Omega = T_0 \left[ \theta f(x) - \beta + R(x, \theta, \beta) \right] \int \tau d\Omega.
$$

(4.3)
In the following we will use $\mathcal{T} = \int \tau d\Omega$. We use the SZ fluxes at Planck frequencies for each cluster in our sample. In order to estimate the $\Delta \mathcal{T}_{\text{SZ}}(\nu_0)$ we need to evaluate the band integration of the SZ signal

$$
\Delta \mathcal{T}_{\text{SZ}}(\nu_0) = \int \Delta \mathcal{T}_{\text{SZ}}(\nu) t'(\nu) d\nu,
$$

where $t'(\nu)$ is the spectral transmission. We use the band-averaged spectral transmission for each of the Planck frequency channels, as given in the RIMO (Reduced Instrument Model)\(^7\) and described in detail in [43]. Assuming that the SZ data are gaussianly distributed allows us to construct the single cluster likelihood function. The likelihood for the $i$-th cluster is:

$$
P(\Delta \mathcal{T}_{\text{obs}}|\Theta_i) \propto \exp \left\{ -\sum_{jk} \left[ \Delta \mathcal{T}_{\text{SZ}}(\nu_j, \Theta_i) - \Delta \mathcal{T}_{\text{obs}}(\nu_j) \right] \text{Cov}^{-1}(\nu_j, \nu_k) \left[ \Delta \mathcal{T}_{\text{SZ}}(\nu_k, \Theta_i) - \Delta \mathcal{T}_{\text{obs}}(\nu_k) \right] \right\},
$$

where $\Theta_i = [T_i, \theta_i, \beta_i, T_{\text{CMB}}(z_i), C]$, $\text{Cov}(\nu_j, \nu_k)$ is the covariance matrix between frequencies $\nu_j$ and $\nu_k$, and $C$ is an uncertain scale factor, accounting for the calibration uncertainty. The CMB temperature at the redshift of each cluster was extracted by performing statistical analysis on the observed thermodynamic temperature integrated over the solid angle related to the aperture radius $\theta_1$ in the $j$-th band. Here we apply one of the two direct methods developed in [8].

### 4.1 MCMC analysis

The analysis has been performed through a Monte Carlo Markov chain (MCMC) approach, which allows us to explore the full space of the cluster parameters (integrated optical depth $T$, peculiar velocity $v_{\text{pec}}$, electron temperature $T_e$), and the CMB brightness temperature at the redshift of the cluster. In the analysis we allowed for calibration uncertainty, an uncertain scale factor, $C$, modeled as a Gaussian with mean 1 and 1% standard deviation (calibration uncertainty is at a level of 0.5% for the lower frequencies and 1% at 353GHz [44]). The impact of absolute calibration accuracy will mainly influence the $T$ parameter estimation, since $\Delta \mathcal{T}$ depends linearly on $T$ in the first order. The MCMC generates random sequences of parameters, which simulate posterior distributions for all parameters [45]. The sampling approach we used is that proposed by Metropolis and Hastings [46, 47]. We run three chains for each cluster; convergence and mixing of the MCMC runs was tested through the Gelman-Rubin test [48]. We included gaussian prior over the cluster gas temperature, as provided by X-ray data when available, or as specified in subsection 2.3.

As noted in subsection 3.1 we clean our frequency maps of CMB. Kinematic SZ (KSZ) and the CMB primary anisotropy have the same spectral shape in the non-relativistic limit, thus in cleaning for CMB we have also removed the kinematic component of the SZ. In order to take into account possible CMB and KSZ residuals after the removal, we model them as a kinematic SZ component and adopt as a prior a Gaussian with a universal vanishing mean and with a 500 km/s standard deviation. This corresponds to a residual CMB signal of $\sim 50 \mu K$, which is compatible with the expected residual level of the LGMCA map [28]. As was already noted in [8] there is a degeneracy between $T_{\text{CMB}}(z)$ and $v_{\text{pec}}$. In order to reduce

\(^7\)http://wiki.cosmos.esa.int/planckpla/index.php/The_RIMO#Effective_band_transmission_profiles.
the impact of this degeneracy and then to reduce the uncertainty in the determination of $T_{\text{CMB}}(z)$, a better knowledge of the peculiar velocity is required or it is necessary to remove the kinematic component from the thermal component, together with the CMB primary anisotropy. Even if after the cleaning we are left with only a residual kinematic component, this prevented us from obtaining 1% sensitivity on $T_{\text{CMB}}(z)$ measurements, as forecast in [1].

For the integrated optical depth $\tau$ we use a very broad gaussian prior, which is centered on the $Planck$ value of the Compton parameter at $R_{500}$ from SZ-proxy $Y_z$ (after converting it in the cylindrical quantity), divided by the $T_e$ value from X-rays and with standard deviation equal to its central value.

As already specified in subsection 3.2, we have adopted the universal pressure profile of [39] in our analysis; nevertheless, we have also verified that assuming that the isothermal $\beta$ model [49] produces almost no difference with respect to the final $T_{\text{CMB}}(z)$ extraction, the only difference being in the $\tau$ determination.

For the $T_{\text{CMB}}(z)$ we allow for a broad gaussian prior centered on the standard value $T_0(1+z)$ and with standard deviation $0.5K(1+z)$. We will show that this has no impact on the final precision with which we extract $T_{\text{CMB}}(z)$ but prevents the chains from spending a lot of time exploring unphysical values for this parameter. The need for a good knowledge of $T_e$ is mainly dictated by the fact that we want to use the same cluster subsample (i.e., use the extracted $\tau$) to build the Hubble diagram and do distance duality tests. Having a narrow prior on $T_e$ has as first outcome that $\tau$ is better constrained; moreover, the MCMC converge more quickly with respect to the case in which the prior on $T_e$ is broad.

In our analysis we have included the relativistic expression $R(x, \theta, \beta)$; we used the formulation given in [41]. To provide a hint of the effect of relativistic corrections we report results for $T_{\text{CMB}}(z)$ for the two highest $z$ clusters in our sample. ACT-CLJ0102-4915 (El Gordo) is at $z = 0.87$, $T_X = 14.5 \pm 0.1 K$ [31]; with relativistic corrections we have $T_{\text{CMB}}(z) = (4.71 \pm 0.15) K$ (5.096 K standard value), and without relativistic corrections $T_{\text{CMB}}(z) = (4.83 \pm 0.15) K$. For PSZ1 G266.56-27.31, with $z = 0.97$, $T_X \sim 11 K$ [32]; with relativistic corrections we have $T_{\text{CMB}}(z) = (5.35 \pm 0.27) K$ (5.374 K standard value), and without relativistic corrections $T_{\text{CMB}}(z) = (5.47 \pm 0.24) K$. Both values are consistent within the error, still using relativistic corrections (when $T_e$ is relatively high) changes the $T_{\text{CMB}}(z)$ determination by $\sim 2\%$.

In figure 4 we show the SZ fluxes and best fit spectra for a selection of our cluster sample.

5 Results

5.1 Cosmological constraints

In figure 5 we plot the measurements of the CMB temperature as a function of redshift. We report expected values and standard deviation of each single $T_{\text{CMB}}(z)$ distribution. Our measurements reach a precision of up to 3\% (7\% on average) on 103 clusters. Of our initial sample of 107 clusters, Abell1430, Abell2219, and PSZ1G319.20-48.61 did not converge, and PSZ1G205.94-39.46 is an outlier; a more extended analysis of this cluster will be given in a follow-up publication. Since the distributions of $T_{\text{CMB}}(z)$ for individual clusters are in general slightly non-gaussian, and are in addition frequently skewed, performing a best fit as if they were gaussian can introduce a bias in the result. In order to limit possible deviations of the form $T_{\text{CMB}}(z) = T_0(1+z)^{1-\beta}$ we have taken the full posteriors of $T_{\text{CMB}}(z)$ at each redshift and we derive the joint pdf for the parameter $\beta$. The posterior for $\beta$ is shown in figure 6.
Figure 4. Measured SZ fluxes. Solid lines are the best-fit spectra, cyan dash-dotted lines are 1σ errors on the $T_{\text{CMB}}(z)$ parameter; these plots show the importance of including high frequency measurements for $T_{\text{CMB}}(z)$ extraction. From top to bottom: each row corresponds to the various cluster subsamples, selected with the criteria explained in 2.3. Clusters in each row have SNR on $T_{\text{CMB}}(z)$ corresponding to the average SNR in the specific subsample.

The best-fit result we get is: $\beta = 0.012 \pm 0.016$, at 1σ uncertainty, in agreement with the predictions of the standard model. Our result, obtained with individual determinations of $T_{\text{CMB}}(z)$ at each cluster redshift, on 103 Planck selected clusters, is compatible with, and at the same level of precision as, the result from [10], who found for 813 Planck stacked clusters $\beta = 0.009 \pm 0.017$. Our result is also compatible with, and at a higher level of precision than, the result of [11], who found for 158 SPT-selected clusters $\beta = 0.017^{+0.030}_{-0.028}$. Assuming the standard evolution of the CMB temperature with redshift, we can use our measurements of $T_{\text{CMB}}(z)$ to put constraints on the value of $T_{\text{CMB}}$ at redshift zero. We get: $T_{\text{CMB}}(0) = 2.719 \pm 0.014$ K, at 1σ uncertainty, a value consistent with the COBE-FIRAS measurement, $T_0 = 2.7260 \pm 0.0013$ K [50].
Measurements of the CMB temperature as a function of redshift for 103 Planck selected clusters. The solid line is the best fit to the scaling $T_{\text{CMB}}(z) = T_0 (1 + z)^{1-\beta}$. The dot-dashed line is the standard scaling, with $\beta = 0$.

Posterior of the $\beta$ parameter as derived from the joint pdf on our cluster sample. The black line is the posterior on the full cluster sample, and colored lines show the joint pdf for each cluster subsample selected as in 2.3.

5.2 Combined constraints with previous measurements
By combining our results with previous result from SZ measurements [11] (we have excluded from our sample four SPT clusters which are part of the sample analyzed by [11]) and from
spectroscopic studies of lines in absorption against quasars [14–16, 51–53], (see figure 7), we obtain a tighter constraint on $\beta$, finding $\beta = 0.013 \pm 0.011$. Our results are compatible with the constraints found by [11], $\beta = 0.005 \pm 0.012$, who combined their SPT results with those from spectroscopic measurements and from 813 Planck stacked clusters from [10]. We could not include the result from [10], $\beta = 0.009 \pm 0.017$, since it was obtained from 813 stacked textitPlanck clusters, and this sample includes also the 103 clusters we have used for our analysis. Although the analyses are completely different, there is a redundancy of measurements in some cluster: it is not possible for us to isolate from the constraints of [10] the contribution from our sample. We get comparable precision with respect to [10] even if using a smaller subsample of objects. The main reason for this is that we use a per cluster analysis, and so we can make a better use of all the available X-ray information and of the SZ spectral properties for each cluster. Also, we degrade the high frequency maps ($\nu \geq 217$ GHz) to 5 arcmin, and not to 10 arcmin as done in [10], thereby improving the S/N at high frequencies. We preserve the 70 GHz channel, which, even if with lower resolution, is still helpful, considering the number of parameters involved. There is a small contribution due to our CMB removal with respect to the method (stacking) used in [10], and this happens mainly for the high-redshift clusters since there are few clusters in the highest-redshift bins. We also note that, most probably because of the larger spectral coverage of Planck with respect to SPT data, with the method we adopted to provide individual determinations of $T_{CMB}(z)$ at each cluster redshift we can provide stronger constraints on a per cluster basis and on the overall $\beta$, even though the 158 SPT-selected clusters in [11] span a larger redshift range.

6 Future work

The selection of the present sample has been motivated by our aim of using the same cluster sample, through SZ and X-ray measurements, to study not only the CMB evolution but also the Hubble diagram and the distance duality relation, $\eta(z) = D_L(z)/(1+z)^2D_A(z) = 1$, where the last equality holds for the standard model, but not for others. Identical sky coverage and redshift distribution will considerably reduce the impact of astrophysical systematics (in particular for the distance duality test) and represents a unique opportunity to check the consistency of those models for which the cosmological distance duality relation and the CMB temperature scaling law are simultaneously modified [1]. In a follow-up publication we will investigate the distance duality relation, applying the methods proposed by [55, 56], in this case we will not include the 18 clusters of our subsample for which we do not have X-ray information on $R_{500}$.

7 Conclusions

We have obtained reliable SZ spectra in the frequency range 70–353 GHz for a subsample of the Planck SZ cluster catalog with known X-ray properties. Taking advantage of the multifrequency measurements of the SZ effect and of the high quality of the data, we have obtained individual determinations of $T_{CMB}(z)$ at cluster redshift for 103 clusters, with a precision of up to 3% (7% on average) for the full sample. We have shown that relativistic corrections have an impact on the determination of $T_{CMB}(z)$ for clusters with high electron temperature and when including high frequencies, the latest being much needed for this study. We have studied possible deviations of the form $T_{CMB}(z) = T_0(1+z)^{1-\beta}$ and get the
Figure 7. Measurements of the CMB temperature as a function of redshift. Black points are measurements from SZ spectra of individual clusters (103 Planck-selected clusters); blue points are absorption lines measurements [16] and references therein, and red points are the SPT SZ cluster constraints [11, 54]. The solid line is the best fit to the scaling $T_{\text{CMB}}(z) = T_0(1 + z)^{1-\beta}$ obtained by combining our result with [16] and with [11]. The dot-dashed line is the standard scaling. For visualization purposes we also plot in cyan previous SZ measurements toward galaxy clusters [8] and, in green, stacked Planck SZ selected clusters [10]. We have not used these two last datasets for our combined constraints on $\beta$ because of common clusters in our sample.

constraint $\beta = 0.012 \pm 0.016$. Our results are in agreement with the predictions of the standard model. They are compatible with, and at the same level of precision as, previously published results based on galaxy clusters [10, 11] and on spectroscopic studies of lines in absorption against quasars [16]. Our results are compatible with those obtained by [12], who used a similar foreground-cleaning methodology, and a larger sample of 481 X-ray selected clusters out to $z = 0.3$. We work to extend our analysis to a larger sample, namely the 813 Planck confirmed clusters with known redshift, thereby improving the level of homogeneity of the available X-ray information. In the longer term, a COrE-like experiment [57], with extended frequency coverage with respect to Planck, will bring significant further improvements.

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References

[1] A. Avgoustidis, G. Luzzi, C.J.A.P. Martins and A.M.R.V.L. Monteiro, Constraints on the CMB temperature redshift dependence from SZ and distance measurements, *JCAP* 02 (2012) 013 [arXiv:1112.1862] [SPIRE].

[2] A. Avgoustidis, C.J.A.P. Martins, A.M.R.V.L. Monteiro, P.E. Vielzeuf and G. Luzzi, Cosmological effects of scalar-photon couplings: dark energy and varying-α Models, *JCAP* 06 (2014) 062 [arXiv:1305.7031] [SPIRE].

[3] J. Chluba, Tests of the CMB temperature-redshift relation, CMB spectral distortions and why adiabatic photon production is hard, *Mon. Not. Roy. Astron. Soc.* 443 (2014) 1881 [arXiv:1405.1277] [SPIRE].

[4] J.C. Mather, D.J. Fixsen, R.A. Shafer, C. Mosier and D.T. Wilkinson, Calibrator design for the COBE far infrared absolute spectrophotometer (FIRAS), *Astrophys. J.* 512 (1999) 511 [astro-ph/9810373] [SPIRE].

[5] R. Fabbri, F. Melchiorri and V. Natale, The Sunyaev-Zel’dovich effect in the millimetric region, *Astrophys. Space Sci.* 59 (1978) 223.

[6] Y. Rephaeli, On the determination of the degree of cosmological Compton distortions and the temperature of the cosmic blackbody radiation, *Astrophys. J.* 241 (1980) 858.

[7] E.S. Battistelli et al., Cosmic microwave background temperature at galaxy clusters, *Astrophys. J.* 580 (2002) L101 [astro-ph/0208027] [SPIRE].

[8] G. Luzzi et al., Redshift Dependence of the CMB Temperature from S-Z Measurements, *Astrophys. J.* 705 (2009) 1122 [arXiv:0909.2815] [SPIRE].

[9] I. de Martino et al., Measuring the redshift dependence of the CMB monopole temperature with PLANCK data, *Astrophys. J.* 757 (2012) 144 [arXiv:1203.1825] [SPIRE].

[10] G. Hurier, N. Aghanim, M. Douspis and E. Pointecouteau, Measurement of the T_{CMB} evolution from the Sunyaev-Zel’dovich effect, *Astron. Astrophys.* 561 (2014) A143 [arXiv:1311.4694] [SPIRE].

[11] SPT collaboration, A. Saro et al., Constraints on the CMB temperature evolution using multiband measurements of the Sunyaev-Zel’dovich effect with the South Pole Telescope, *Mon. Not. Roy. Astron. Soc.* 440 (2014) 2610 [arXiv:1312.2462] [SPIRE].

[12] I. de Martino et al., Constraining the redshift evolution of the Cosmic Microwave Background black-body temperature with PLANCK data, arXiv:1502.06707 [SPIRE].

[13] J. Bahcall and R.A. Wolf, Fine-Structure Transitions, *Astrophys. J.* 152 (1968) 701.

[14] R. Srianand, P. Petitjean and C. Ledoux, The microwave background temperature at the redshift of 2.33771, *Nature* 408 (2000) 931 [astro-ph/0012222] [SPIRE].
P. Noterdaeme, P. Petitjean, R. Srianand, C. Ledoux and S. Lopez, The evolution of the Cosmic Microwave Background Temperature: Measurements of TCMB at high redshift from carbon monoxide excitation, Astron. Astrophys. 526 (2011) L7 [arXiv:1012.3164] [nSPIRE].

S. Muller et al., A precise and accurate determination of the cosmic microwave background temperature at z = 0.89, Astron. Astrophys. 551 (2013) A109 [arXiv:1212.5456] [nSPIRE].

V. Fish et al., High-Angular-Resolution and High-Sensitivity Science Enabled by Beamformed ALMA, arXiv:1309.3519 [nSPIRE].

R.P.J. Tilanus et al., Future mmVLBI Research with ALMA: A European vision, arXiv:1306.4650 [nSPIRE].

V. Fish et al., High-Angular-Resolution and High-Sensitivity Science Enabled by Beamformed ALMA, arXiv:1309.3519 [nSPIRE].

R. Sadat et al., Introducing BAX: A database for X-ray clusters and groups of galaxies, Astron. Astrophys. 424 (2004) 1097 [astro-ph/0405457] [nSPIRE].

M.-A. Miville-Deschênes and G. Lagache, IRIS: A New generation of IRAS maps, Astrophys. J. Suppl. 157 (2005) 302 [astro-ph/0412216] [nSPIRE].

J. Bobin, F. Sureau, J.L. Starck, A. Rassat and P. Paykari, Joint Planck and WMAP CMB Map Reconstruction, Astron. Astrophys. 563 (2014) A105 [arXiv:1401.6016] [nSPIRE].
33] P. Carvalho, G. Rocha, M.P. Hobson and A. Lasenby, *Powellsnakes II: a fast Bayesian approach to discrete object detection in multi-frequency astronomical data sets*, *Mon. Not. Roy. Astron. Soc.* **427** (2012) 1384 [arXiv:1112.4886] [inSPIRE].

34] PLANCK collaboration, P.A.R. Ade et al., *Planck 2013 results. VI. High Frequency Instrument data processing*, *Astron. Astrophys.* **571** (2014) A6 [arXiv:1303.5067] [inSPIRE].

35] PLANCK collaboration, P.A.R. Ade et al., *Planck 2013 results. XIII. Galactic CO emission*, *Astron. Astrophys.* **571** (2014) A13 [arXiv:1303.5073] [inSPIRE].

36] PLANCK collaboration, A. Abergel et al., *Planck 2013 results. XI. All-sky model of thermal dust emission*, *Astron. Astrophys.* **571** (2014) A11 [arXiv:1312.1300] [inSPIRE].

37] R. Génova-Santos, F. Atrio-Barandela, F.S. Kitaura and J.P. Mücket, *Constraining the baryon fraction in the Warm Hot Intergalactic Medium at low redshifts with PLANCK data*, *Astrophys. J.* **806** (2015) 113 [arXiv:1501.01445] [inSPIRE].

38] J.M. Diego, P. Vielva, E. Martínez-González, J. Silk and J.L. Sanz, *A Bayesian non-parametric method to detect clusters in Planck data*, *Mon. Not. Roy. Astron. Soc.* **336** (2002) 1351 [astro-ph/0110587] [inSPIRE].

39] M. Arnaud, G.W. Pratt, R. Piffaretti, H. Boehringer, J.H. Croston and E. Pointecouteau, *The universal galaxy cluster pressure profile from a representative sample of nearby systems (REXCESS) and the YSZ–M500 relation*, *Astron. Astrophys.* **517** (2010) A92 [arXiv:0910.1234] [inSPIRE].

40] Y. Rephaeli, *Cosmic microwave background comptonization by hot intracluster gas*, *Astrophys. J.* **445** (1995) 33.

41] N. Itoh, T. Sakamoto, S. Kusano, Y. Kawana and S. Nozawa, *Radiative processes in the intracluster plasma*, *Astron. Astrophys.* **382** (2002) 722.

42] M.S.Y. Rephaeli and Y. Rephaeli, *CMB comptonization by energetic nonthermal electrons in clusters of galaxies*, *Astrophys. J.* **575** (2002) 12 [astro-ph/0204355] [inSPIRE].

43] PLANCK collaboration, P.A.R. Ade et al., *Planck 2013 results. IX. HFI spectral response*, *Astron. Astrophys.* **571** (2014) A9 [arXiv:1303.5070] [inSPIRE].

44] PLANCK collaboration, P.A.R. Ade et al., *Planck 2013 results. VIII. HFI photometric calibration and mapmaking*, *Astron. Astrophys.* **571** (2014) A8 [arXiv:1303.5069] [inSPIRE].

45] A. Lewis and S. Bridle, *Cosmological parameters from CMB and other data: a Monte Carlo approach*, *Phys. Rev. D* **66** (2002) 103511 [astro-ph/0205436] [inSPIRE].

46] N. Metropolis, A.W. Rosenbluth, M.N. Rosenbluth, A.H. Teller and E. Teller, *Equation of state calculations by fast computing machines*, *J. Chem. Phys.* **21** (1953) 1087 [inSPIRE].

47] W.K. Hastings, *Monte Carlo sampling methods using Markov chains and their applications*, *Biometrika* **57** (1970) 97.

48] A. Gelman and D. Rubin, *Inference from Iterative Simulation Using Multiple Sequences*, *Statist. Sci.* **7** (1992) 457 [inSPIRE].

49] A. Cavaliere and R. Fusco-Femiano, *The distribution of hot gas in clusters of galaxies*, *Astron. Astrophys.* **70** (1978) 677.

50] D.J. Fixsen, *The Temperature of the Cosmic Microwave Background*, *Astrophys. J.* **707** (2009) 916 [arXiv:0911.1955] [inSPIRE].

51] J.-a. Ge, J. Bechtold and J.H. Black, *A New measurement of the cosmic microwave background radiation temperature at z = 1.97*, *Astrophys. J.* **474** (1997) 67 [astro-ph/9607145] [inSPIRE].

52] P. Molaro, S.A. Levshakov, M. Dessauges-Zavadsky and S. D’Odorico, *The cosmic microwave background radiation temperature at zabs = 3.025 toward QSO 0347-3819*, *Astron. Astrophys.* **381** (2002) L64 [astro-ph/0111589] [inSPIRE].
[53] J. Cui, J. Bechtold, J. Ge and D.M. Meyer, Molecular hydrogen in the damped Ly$_\alpha$ absorber of Q1331+170, Astrophys. J. 633 (2005) 649 [astro-ph/0506766] [inSPIRE].

[54] A. Saro, private communication.

[55] J.-P. Uzan, N. Aghanim and Y. Mellier, The Distance duality relation from x-ray and SZ observations of clusters, Phys. Rev. D 70 (2004) 083533 [astro-ph/0405620] [inSPIRE].

[56] R.F.L. Holanda, R.S. Goncalves and J.S. Alcaniz, A test for cosmic distance duality, JCAP 06 (2012) 022 [arXiv:1201.2378] [inSPIRE].

[57] PRISM collaboration, P. André et al., PRISM (Polarized Radiation Imaging and Spectroscopy Mission): An Extended White Paper, JCAP 02 (2014) 006 [arXiv:1310.1554] [inSPIRE].