Measuring the redshift dependence of the CMB monopole temperature with PLANCK data.

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The adiabatic evolution of the Universe and the photon number conservation imply that the CMB temperature evolves linearly with redshift. This assumption needs to be tested observationally. There are currently two methods to determine the CMB temperature, $T(z)$, at redshifts $z > 0$: (a) using the Quasar's absorption lines; (b) from the thermal Sunyaev-Zeldovich (SZ) anisotropies. Recently, $T(z)$ scaling relation was tested using the spectral measurements of the SZ effect and the results are in agreement with adiabatic evolution. We analyze how PLANCK data can be used to test the standard scaling relation of the CMB temperature with redshift.

I. INTRODUCTION

One of the most importatn prediction of the Big Bang theory is the adiabatic evolution of the Universe. Early thermal equilibrium among the different particle species, entropy and photon number conservation produce a Cosmic Microwave Background (CMB) with a blackbody spectrum. The CMB temperature was measured to be $T_0 = 2.725 \pm 0.002$K by Far Infrared Absolute Spectrometer (FIRAS) of the Cosmic Background Explorer (COBE) satellite [8]. However, there are models like decaying vacuum energy density and gravitational adiabatic photon creation that predict different scaling relations [6, 10] and evade the tight FIRAS constraints [8]. There are currently two methods to determine the CMB temperature, $T(z)$, at redshifts $z > 0$: (a) using the Quasar's absorption lines, due to the atomic or molecular transitions. They provide a measurement of the CMB temperature in high redshift Universe [9]; (b) from the thermal Sunyaev-Zeldovich (SZ) anisotropies [12, 13], due to the inverse Compton scattering of photons by the free electrons within the potential wells of clusters of galaxies. $T(z)$ scaling relation was tested using the spectral measurements of the SZ effect in the COMA ($z = 0.0231$) and A2163 ($z = 0.203$) clusters of galaxies [1]. They measured $\alpha = -0.16^{+0.34}_{-0.32}$. Recently, using multi-frequency measurements, it is determined the CMB temperature at cluster location in the redshift range $0.023 - 0.546$. Recently, $T(z)$ scaling relation was tested using the spectral measurements of the SZ effect and the results are in agreement with adiabatic evolution [1, 7]. We analyze how PLANCK data can be used to test the standard scaling relation of the CMB temperature with redshift. We use a two-fold approach: first, our pipeline is tested on simulated clusters drawn from a full hydrodynamical simulation; second, using a catalog of 630 clusters derived from ROSAT data and with well measured X-ray properties, we predict the accuracy that PLANCK measurements will reach using those clusters. In comparison with earlier analysis [2], we use a catalog of X-ray selected clusters and in our simulations, gas evolution is fully taken into account.

II. METHOD

Goal: determine the CMB temperature, $T(z)$, at redshifts $z > 0$ to test the scaling relation. The tSZ varies in frequency as $G(x) = x\coth\left(\frac{x}{2}\right) - 4$, where $x = \frac{h\nu(z)}{k_B T(z)}$. For an adiabatic evolution of the Universe, x is redshift independent. If $T(z) = T_0(1+z)^{1-\alpha}$, with $\alpha \neq 0$, then $G = G(\nu, \alpha)$ and measuring G at different frequencies and redshifts will constrain α.

Two methods can be used:

Ratio Method: taking the ratio of the tSZ anisotropy at different frequencies [11]., $R(\nu_1, \nu_2, \alpha) = \frac{G(\nu_1,\alpha)}{G(\nu_2,\alpha)}$.

Fit Method: the tSZ effect is null at $\nu \simeq 217$GHz for adiabatic evolution. Measuring the zero cross frequency of spectral dependence of the clusters at different redshifts will constrain α [4].

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Problem: in the range of the Planck's frequencies, the contribute of intrinsic CMB signal dominates over the tSZ signal except for the most massive clusters.

Solution (A): CMB subtraction in the Time Ordered Information (TOI) plus foreground removal using templates would produce maps with only instrumental noise, kSZ and tSZ with some unknown levels of primordial CMB and foreground residuals.

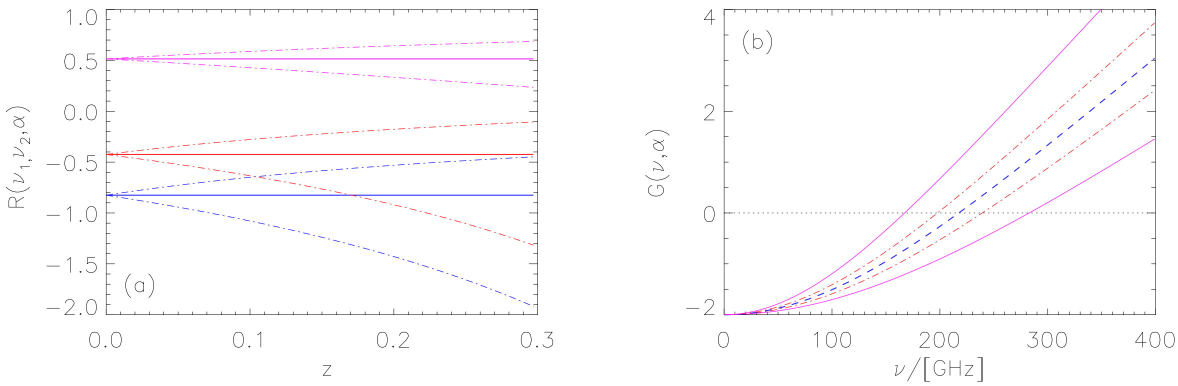

FIG. 1: In the panel (a) the variation of the ratio $\frac{G(\nu,\alpha)}{G(353GHz,\alpha)}$ as a function of redshift for 143GHz (magenta), 100GHz (red) and 44GHz (blue). The solid line represents $\alpha = 0$, it corresponds to the standard adiabatic evolution, and the dot-dashed lines represent $\alpha = 1, -1$. In the panel (b) the spectral dependence for $\alpha = -1, 1$ and two clusters located at z=0.3 (magenta) and z=0.1 (red). The blue line correspond to adiabatic evolution and is the same for a cluster located at any redshift. The zero amplitude of the tSZ effect is indicated by the dotted line.

Solution (B): the primordial CMB is removed using the foreground clean 217GHz map. We degrade the angular resolution of the 217GHz channel to that of the other 5 channels before subtracting it from the corresponding map. The intrinsic CMB and kSZ anisotropies are removed exactly. In Fig 2a, we represent the ratio of the CMB-kSZ removed maps at different frequencies.

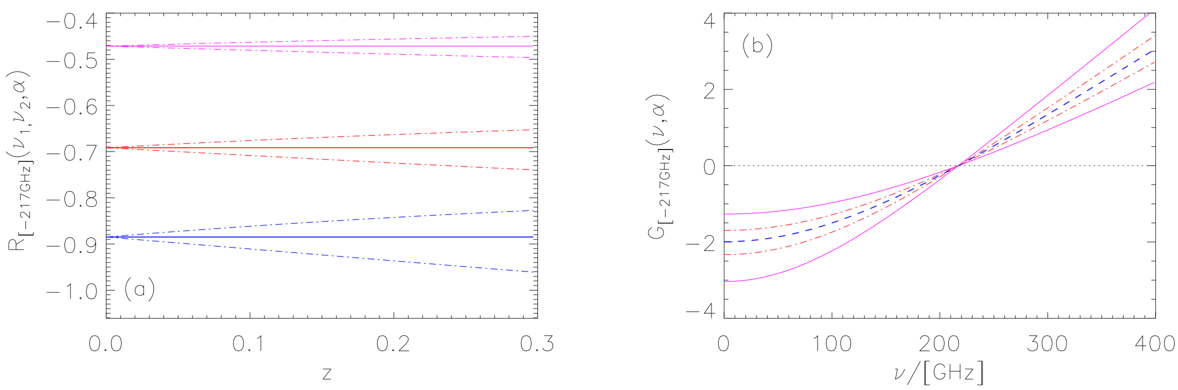

FIG. 2: Curves follow the same convention as in Fig. 1

Problem: substracting the 217GHz, the zero cross frequency is independent of α (Fig. 2b).

Solution: we have to fit the spectral dependence of the tSZ effect.

***Difficulties 1*:** this method requires an independent measurement of y_c.

***Difficulties 2*:** different frequencies have different resolutions. The cluster anisotropies are diluted by the antenna beam and the tSZ signal does no scale exactly as $G(\nu, 0)$, see Fig. 3.

Solution: the amplitude of the tSZ effect, convolved with the antenna beam, depends on the cluster profile and angular extent but does not depend on the scaling of the tSZ signal with redshift. This uncertainty is uncorrelated with the instrumental noise at the cluster location and can be included in the Likelihood analysis by adding it in quadrature to the instrumental noise.

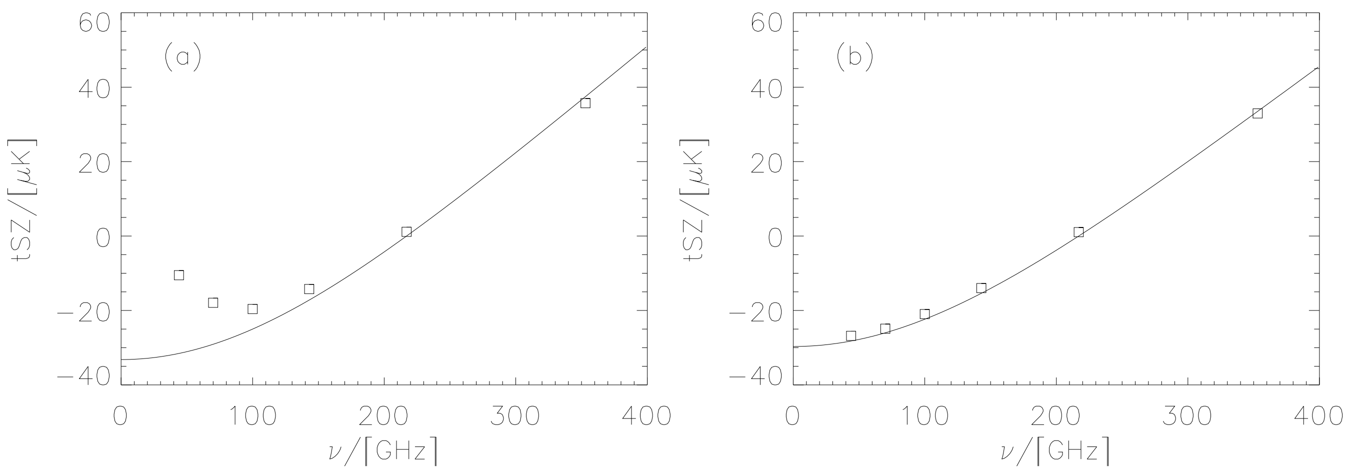

FIG. 3: Effect of the beam dilution on the spectral dependence of the tSZ effect: The solid line represent the tSZ scaling $G_{[-217GHz]}(\nu, 0)$ and the open squares tSZ signal of the cluster measured on simulated PLANCK maps. (a) we show a cluster with mass $\sim 5 \times 10^{14} M_{\odot}$ at $z = 0.22$; (b) we show a cluster with mass $\sim 10^{15} M_{\odot}$ at $z = 0.06$.

III. RESULTS

The ratio method performs differently if the CMB is removed in the TOI (method A) or in the final map (method B) but the differences are small for the fit method. Our analysis is based on two different maps

Y-map from X-ray selected clusters. Our cluster sample was created combining REFLEX, eBCS, and CIZA. All three surveys are X-ray selected and X-ray flux limited (for a detailed description of the creation of the catalog see [5]). The position, flux, X-ray luminosity and angular extent of the region containing the measured X-ray flux were determined directly from RASS. All clusters have spectroscopically measured redshifts. The X-ray temperature was derived from the $L_X - T_X$ relation. The β was fixed at the canonical value of 2/3. We construct Y-maps from the X-ray cluster catalog (a) using the universal pressure profile and (b) using the $\beta = 2/3$ model. The Comptonization parameter is computed integrating the electron pressure profile along the line of sight. Clusters are assumed to be spherically symmetric and extending up to R_{200}. To determine the effect of the cluster profile, the central value of y_c is assumed to be the same. Finally, the cluster templates are convolved with the corresponding antenna beams

Y-map from simulated clusters. We also use the low-redshift all-sky maps and the associated galaxy cluster catalogues of the hydrodynamic diffuse and kinetic SZ simulations included in the pre-launch Planck Sky Model [3]. The catalogues containing cluster positions, mass and radius (R_{200}) was created using seven concentric layers around the observer to achieve $z \simeq 0.25$. These simulations include explicit treatment for gas cooling, heating by UV, star formation and feedback processes. Then, they include clusters with different dynamical states (relaxed, mergers, etc), shapes and ellipticities and the projection effect due to low mass clusters and groups in the y-map is included.

For the ratio method we present the results obtained with the simulated cluster template and simulation type (A) (Fig 4). For the fit method, we present the results using the template constructed from X-ray selected clusters and simulation type (B) (Fig. 5). In Fig. 5c we represent the histograms of 10^3 simulations together with their linear fits for cluster templates constructed using the universal pressure profile (dot-dashed line) and the $\beta = 2/3$ (solid line). The mean and rms dispersion of the estimated values are $\bar{\alpha} = 0.013 \pm 0.016$ and $\bar{\alpha} = 0.003 \pm 0.008$ respectively. In Fig. 4c we rapresent 10^3 simulations using method A and the hydrodynamical template and we obtain $\bar{\alpha} = -0.003 \pm 0.011$.

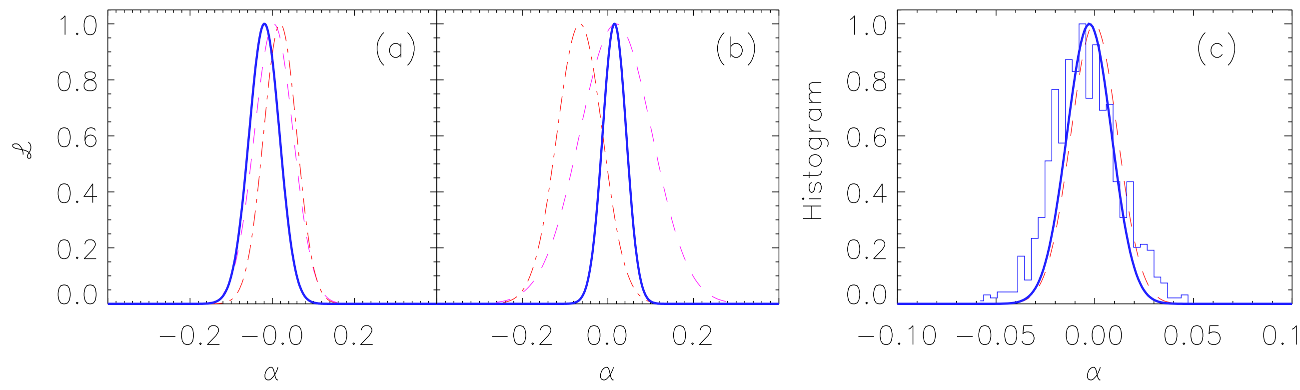

FIG. 4: **Ratio Method**.The following results obtained with the simulated cluster template and simulation type (A). Likelihood function for subsamples of 623 clusters distributed (a) in three redshift bins $z = ([\leq 0.11], [0.11-0.17], [> 0.17])$ of equal number of clusters and (b) in three mass bins $M_{500} = ([\leq 1.9], [0.19 - 0.37], [\geq 3.7]) \times 10^{14} h^{-1} M_{\odot}$. In both plots, magenta/red/blues lines correspond to low/intermediate/high redshift/mass bin. (c) Histograms of the value of α derived from 10^3 simulations, arbitrarily normalized to unity (blue lines). The mean and rms dispersion of the estimated values are $\bar{\alpha} = -0.003 \pm 0.011$

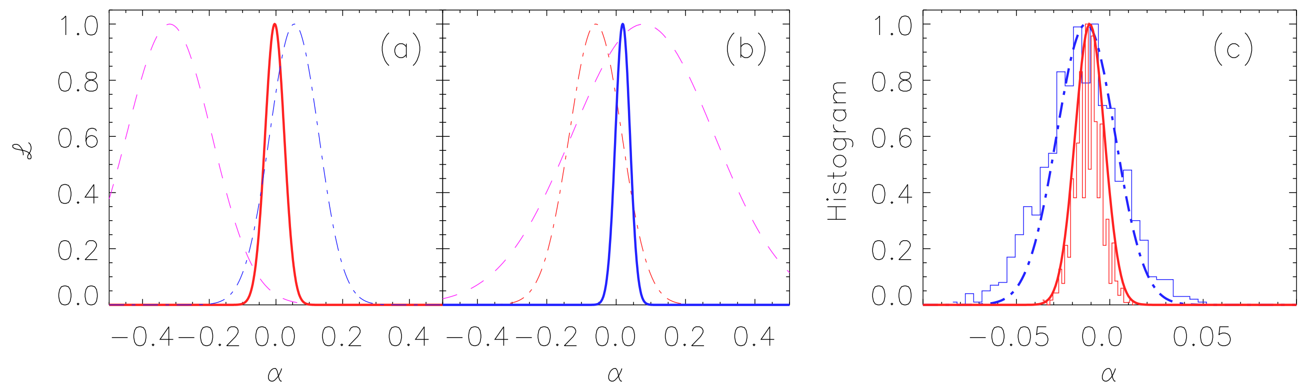

FIG. 5: **Fit method**. Results obtained using the template constructed from X-ray selected clusters and simulation type (B). The cluster template was constructed using the universal pressure profile. (a) Likelihoods for three different frequencies: 44GHz (magenta), 100 GHz (red) and 343GHz (blue) and (b) for three mass bins the curves follow the same convention as in Fig. 3b. (c) Histograms of the value of α derived from 10^3 simulations, arbitrarily normalized to unity. The dot-dashed and solid lines correspond to the gaussian fits to the histograms of Y-maps constructed with the universal (blue lines) and $\beta = 2/3$ profiles (red lines). The mean and rms dispersion of the estimated values are $\bar{\alpha} = 0.013 \pm 0.016$ and $\bar{\alpha} = 0.003 \pm 0.008$ respectively.

IV. CONCLUSION

Planck offers an excellent opportunity to constrain the evolution history of the CMB blackbody temperature with better precision than quasar excitation lines using currently availabe X-ray cluster catalogs. We can constraint α with an accuracy of $\sigma_\alpha = 0.011$ in the most optimal case with the ratio method and with $\sigma_\alpha = 0.016$ for a less optimal case and with the fit method. These results represent a factor 3-6 improvement over similar measurements carried out using a small sample of clusters or quasar spectral lines.

V. ACKNOWLEDGEMENTS

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