Constraining the CMB temperature evolution with SZ measurements from Planck data

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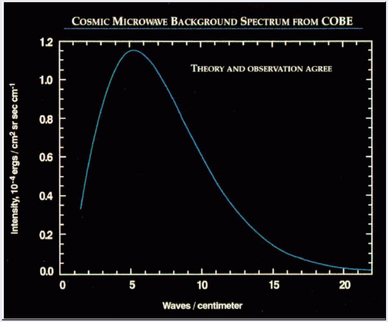
How to test fundamental assumptions of cosmology?



CMB: Black-body spectrum

The COBE-FIRAS experiment revealed a very precise black-body spectrum with temperature $T_0 = (2.725 \pm 0.002)$K Mather et al. 1999.

CMB temperature evolution

Strong prediction of the standard model $\Rightarrow$ $T_{CMB}(z)=T_0(1+z)$, but violated in many non standard models (Jaeckel et al. 2010).
Testing its validity is an important task both for cosmology and fundamental physics.

$T_{CMB}(z)$: Previous measurements

Two astrophysical techniques probe $T_{CMB}(z)$ at $z \neq 0$:

- $z < 1$ SZ effect towards clusters.

  Fabbri et al. Astrop. Space Sci. 59 (1978)
  Rephaeli ApJ.241 (1980)

  First measurement: Battistelli et al. ApJ 580, (2002)

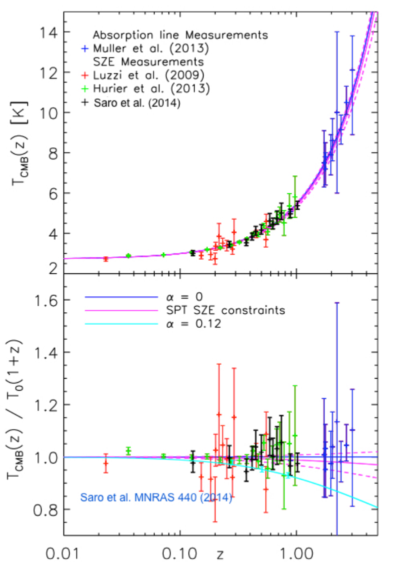
- $z > 1$ Quasar absoption line spectra

  Bahcall and Wolf, ApJ 152 (1968)

  First measurement: Srianand et al. Nature 408 (2000)

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

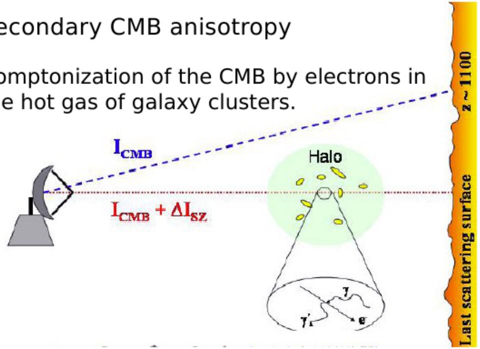
Lima et al. MNRAS 312 (2000)

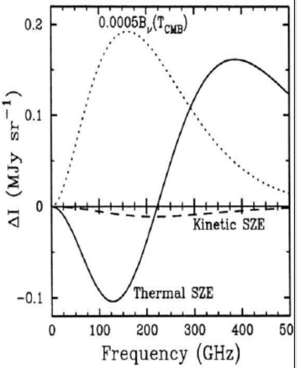


The Sunyaev Zel'dovich Effect

Secondary CMB anisotropy

Comptonization of the CMB by electrons in the hot gas of galaxy clusters.





(Carlstrom JE A&A , 40, 643,2002)

Spectral distorsion of the CMB due to the SZE

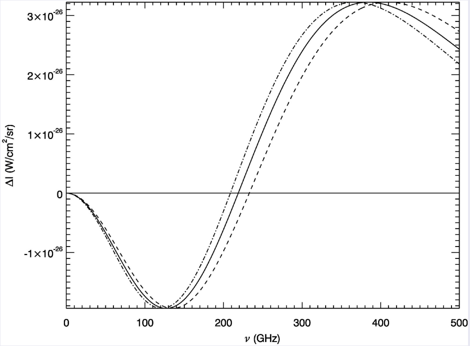
$$\Delta I_{SZ} = TSZ + KSZ + SZ_{CORREL}$$

Random motions of the scattering electrons

Systematic motions of the scattering electrons (Doppler effect)

How to measure $T_{CMB}(z)$ from SZ

Fabbri R., F. Melchiorri & V. Natale. Ap&SS 59, 223, 1978;
Rephaeli Y Ap.J. 241, 858, 1980



$\Delta I_{SZ} = \Delta I_{SZ}(x)$
$x = h\nu(z)/kT(z) = h\nu_0/kT_0$,
z-invariant only for standard scaling of T(z).
In all other scenarios:
small dilation-contraction of the SZ spectrum.

Accurate SZ spectra fundamental!

Data

- Planck temperature maps [a](30, 44, 70, 100, 143, 217, 353, 545, 857 GHz)
- Subsample of Planck SZ catalog [a]:
  103 clusters with z: 0.01-0.94
- SZ union mask [a] (to remove extragalactic point sources)
- Ancillary maps for thermal dust emission and CMB fluctuations cleaning (IRIS [b], 857 GHz, LGMCA [c])
- X-ray data from BAX [d] and MCXC [e]

[a] Planck Legacy Archive, http://pla.esac.esa.int/pla.
[b] M.-A. Miville-Deschênes Astrophys. J. Suppl. 157 (2005)
[c] J. Bobin et al. Astron. Astrophys. 563 (2014)
[d] R. Sadat et al., Astron. Astrophys. 424 (2004)
[e] R. Piffaretti et al. Astron. Astrophys. 534 (2011)

CMB and Dust cleaning

Cleaned mini-maps around each cluster positions.

Find $\alpha(\nu)$ that minimizes the variance of:

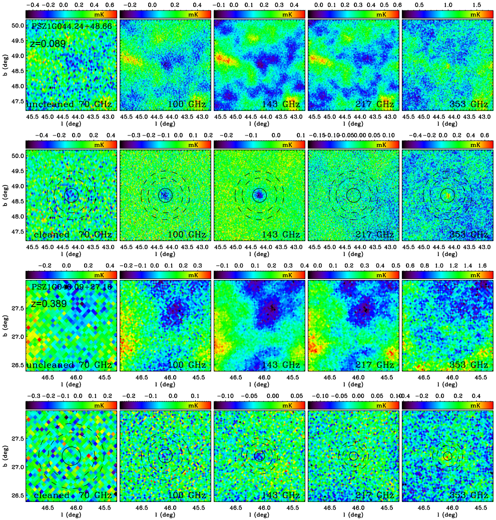
$$M_{\rm dc}(\nu, x) = M(\nu, x) - \alpha(\nu) M_{\rm d}(x)$$

$$\alpha(\nu) = \frac{\sum_i M(\nu,x_i) M_{\rm d}(x_i)}{\sum_i M_{\rm d}(x_i)^2}$$

Diego et al. MNRAS 336 (2002)

$$M_{\rm c}(\nu, x) = M_{\rm dc}(\nu, x) - M_{\rm CMB}(x)$$

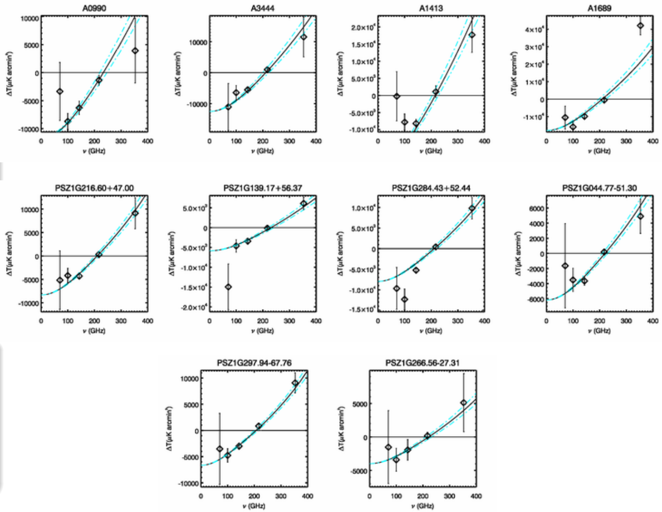
Also for z=0.389 and θ_{500}=4.5arcmin SZ signal evident at 143 and 345 GHz ⇒ efficiency of our cleaning metodologhy



Reliable SZ spectra

Measured SZ fluxes.
Solid lines:
best-fit spectra
Cyan lines:
1σ error on $T_{CMB}(z)$
$\Rightarrow$ Importance of including high frequency measurements for $T_{CMB}(z)$ extraction

Case of high z clusters with $T_e > 11\mathrm{keV}$: using relativistic corrections changes $T_{CMB}(z)$ by $\sim 2\%$

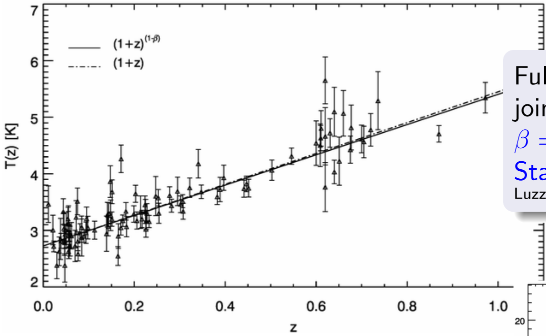


Individual measurements of $T_{CMB}(z)$

Method for the $T_{CMB}(z)$ extraction at cluster redshift:

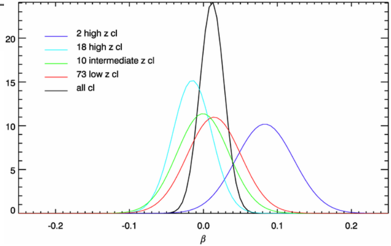
- Use of SZ intensity change, $\Delta I_{SZ}(\nu)$ at different ν
- Single likelihoods for each clusters, as in Luzzi et al ApJ 705 (2009)
- MCMC approach: cluster parameters $(\tau,\ v_p,\ T_e)$ + T_{CMB}+calibration uncertainty
- use of relativistic corrections
- individual determination of $T_{CMB}(z)$ with precision up to 3%, (7% on average on full sample)

Results

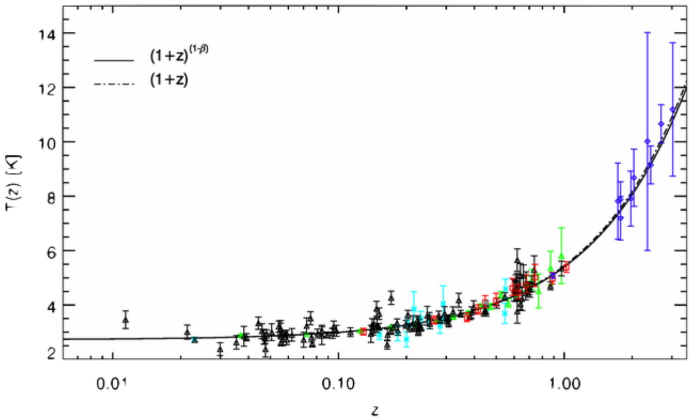


Full posteriors of $T_{CMB}(z) \Rightarrow$ joint pdf for β:
$\beta = 0.012 \pm 0.016$
Standard model consistent
Luzzi, Génova-Santos et al. JCAP (2015)

Assuming the standard evolution of CMB temperature $\Rightarrow$
$T_{CMB}(0) = 2.719 \pm 0.014\text{K}$,
COBE-FIRAS: $T_0 = 2.7260 \pm 0.0013\text{K}$
(Fixsen ApJ 2009)



T vs z all



Combined constraints (SZ + quasar absorption line spectra):
$\beta = 0.013 \pm 0.011$

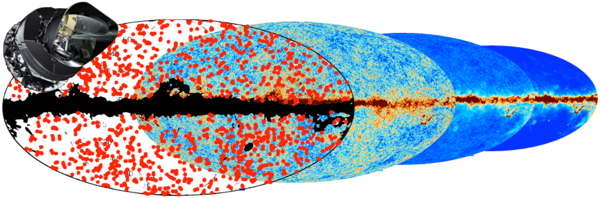
Comparison with latest SZ constraints

- $\beta = 0.017^{+0.030}_{0.028}$, 158 SPT cl, z: 0.05-1.35 [1] Saro et al. 2014
- $\beta = 0.009 \pm 0.017$, 813 stacked Planck cl, z: 0.01-0.94 [2] Hurier et al. 2014
- $\beta = -0.007 \pm 0.013$, 481 X-ray cl, $z \leq 0.3$ [3] De Martino et al. 2015
- $\beta = 0.012 \pm 0.016$, 103 Planck clusters, z: 0.01-0.94 [4] Luzzi et al. 2015

Future works

- Combine our constraint on β with indirect measurements from distance measurements to get the first sub-percent constraints on β (Avgoustidis et al. in preparation).
- Extend our analysis to a larger sample, improving the homogeneity of the available X-ray informations.

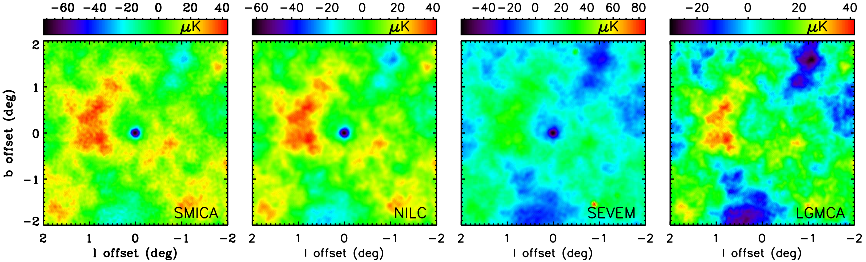
Conclusions



- Reliable SZ spectra in the range 70-353 GHz for a subsample of the Planck SZ cluster catalog with known X-ray properties.
- Individual determinations of $T_{CMB}(z)$ for 103 clusters with a precision of up to 3%.
- We studied possible deviations of the form $T_{CMB}(z) = T_0(1+z)^{1-\beta}$ and get constraint $\beta = 0.012 \pm 0.016$, standard model consistent.
- Our results are compatible with, and at the same level of precision as, previous results based on SZ and quasar absorption line spectra.
- A COrE-like experiment, with extended frequency coverage wrt Planck $\Rightarrow$ significant further improvements.

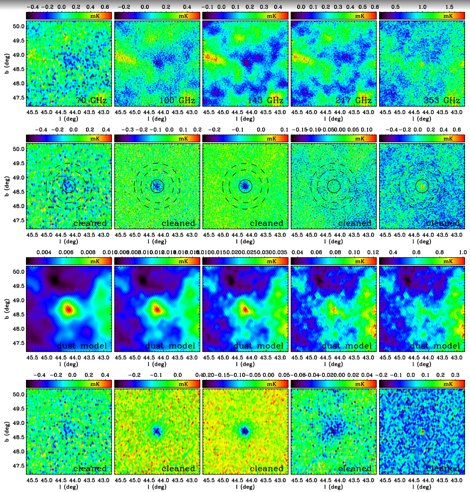
CMB cleaning

Removing CMB fluctuations: subtracting 217 GHz map or CMB map from component separation



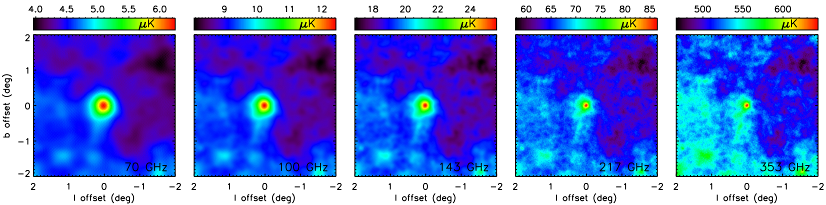
Subtraction of 217GHz introduce degeneracy between τ and T_{CMB}: not good for CMB evolution study.
⇒ CMB from component separation: LGMCA the only one showing no clear SZ residuals.

Dust cleaning II



Last line: maps cleaned using the Planck dust model. The negative feature at 217 GHz comes from the SZ residuals ⇒ unsuitability of these maps.

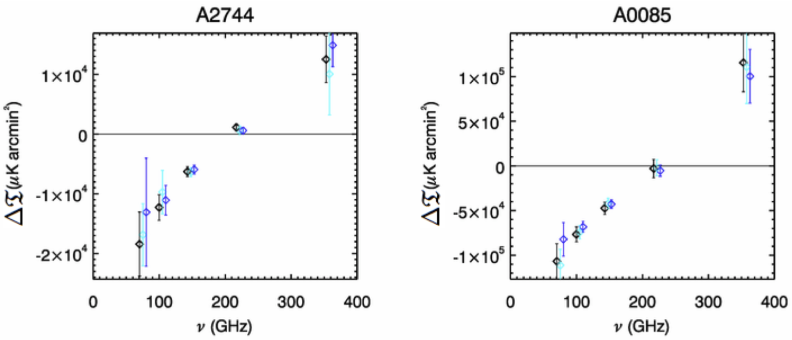
Dust cleaning III



Stacks of the Planck dust model, at frequencies between 70 and 353 GHz, at the positions of the 107 clusters of our catalogue.

Aperture photometry - ring selection

Integrating all pixels in a circle of radius Θ_1 and subtracting a background level in an external ring between radii θ_2 and θ_3 with: $\theta_1 = max[\theta_{500}, 0.75\theta_{FWHM}(\nu)]$ and $[\theta_2, \theta_3] = [2.5, 3.5]\theta_1$



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- wrt [1]: Larger spectral coverage of Planck wrt SPT data
- wrt [2]:
  - Per cluster analysis: better use of X-ray information and SZ spectral properties.
  - Maps @ $\nu \geq$ 217GHz degraded to 5 and not 10 arcmin, improving S/N at high frequencies.
  - Use of the 70 GHz channel
  - CMB removal
- wrt [3]: similar cleaning procedure, smaller sample but larger redshift lever arm.

Future works

Same cluster sample to study:

- The Hubble diagram: first local measurement of H_0 with Planck clusters!
- The distance duality relation, $\eta(z) = D_L(z)/[(1+z)^2 D_A(z)] = 1$, for the standard model.

- Combine our constraint on β with indirect measurements from distance measurements to get the first sub-percent constraints on β (Avgoustidis et al. in preparation).
- Extend our analysis to a larger sample, improving the homogeneity of the available X-ray informations.

The Comptonization parameter

$$\Delta I = I_0 h(x) \sigma_T \int n_e \, dl \left[\theta f(x) - \beta + R(x,\theta,\beta)\right]$$

$x = h\nu/kT$

$\theta = kT_e/mc^2$

$\beta = V/c$

R function= relativistic corrections

(Rephaeli 1995-Itoh et al. ApJ **502**, 7, 1998 – Shimon & Rephaeli ApJ **575**, 12, 2002)

$$\Delta I_{TSZ} = g(x) I_o y$$

$$\Delta I_{KSZ} = -\beta h(x) I_o \tau$$

$$y = \int \frac{kT_e}{m_e c^2} \sigma_T n_e \, d\ell = \frac{kT_e}{m_e c^2} \tau = y_0 f(\theta)$$

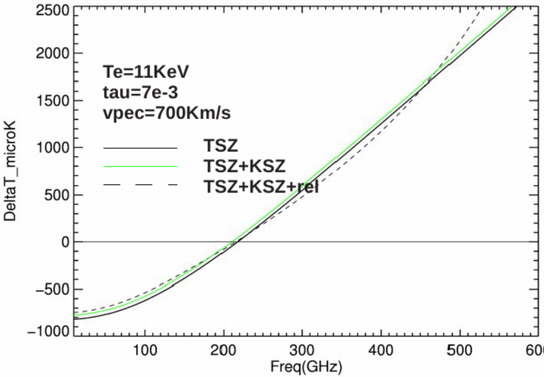
$$Y = \int y \, d\Omega$$

Ω = solid angle occupied by the source in the sky

$$\Delta T_{TSZ} = f(x) y T_{CMB}$$

$$\Delta T_{KSZ} = -\beta \tau T_{CMB}$$

The SZ in thermodynamic temperature



For massive clusters with Te∼10KeV the relativistic corrections to the SZE can be substantial near the null of the thermal effect (at high frequencies are order of few percent of the TSZ).

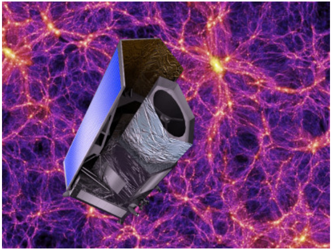
Relativistic corrections essential in determining H_0 (Battistelli et al 2003) ,v_{pec} (Rephaeli 1995) and $T_{CMB}(z)$ (Battistelli et al 2002).

Timeliness in perspective of Euclid and COrE

Euclid is an approved ESA mission to map the geometry and the evolution of the dark universe: dark matter, dark energy and modified gravity.

- Weak gravitational lensing.
- BAO.
- Deep survey: $\sim$ 3000 low-z SNIa.

BAO+SNIa $\Rightarrow$ improve constraints on T_{CMB}(z) and η(z).



COrE Cosmic Origins Explorer, ESA Cosmic Vision (2015-2025) project shortlisted but not selected. New proposal for COrE+ project: extended frequency coverage$\Rightarrow$ improving constraints on T_{CMB}(z), H_0 and η(z) with respect to Planck.