Cosmology with the SZ spectrum: measuring the Universe's temperature with galaxy clusters

Gemma Luzzi

ASI – Space Science Data Center

Observing the mm Universe with the NIKA2 camera

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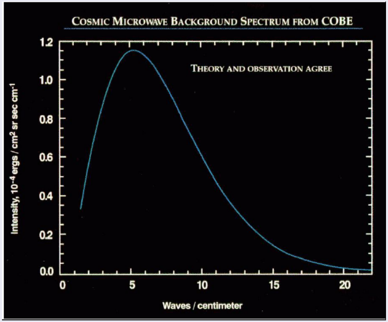
Outline

- Measurements of CMB temperature at cluster redshift ($T_{CMB}(z)$) for a sample extracted from the Second Catalog of galaxy clusters produced by Planck (PSZ2) and containing 75 clusters selected from the Heritage project of the ESA X-ray satellite XMM-Newton.
- Forecasts for future CMB experiments about the constraints on the monopole of the y-type spectral distortion of the CMB spectrum via the spectrum of the SZ.

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

If adiabatic expansion of the Universe + CMB BB ⇒ $T_{CMB}(z)=T_0(1+z)$.
Strong prediction of the standard model, but violated in many non standard models (Jaeckel et al. Ann. Rev. Nucl. Part. Sci. 60, 2010).
Testing its validity is important for cosmology and fundamental physics.

$T_{CMB}(z)$: Direct 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 absorption line spectra

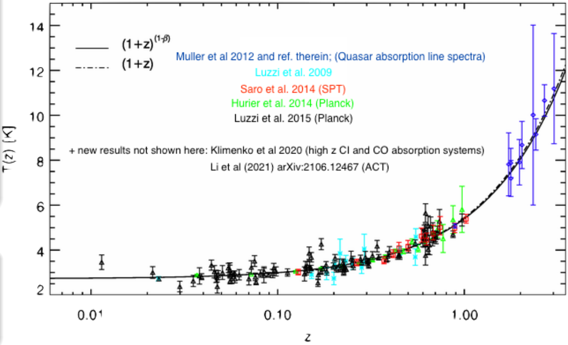
  Bahcall and Wolf, ApJ 152 (1968)

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

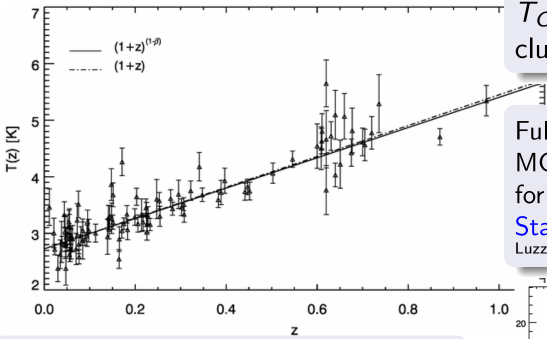
Phenomenological parametrization:
$T_{CMB}(z) = T_0(1+z)^{1-\beta}$

Lima et al. MNRAS 312 (2000)

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

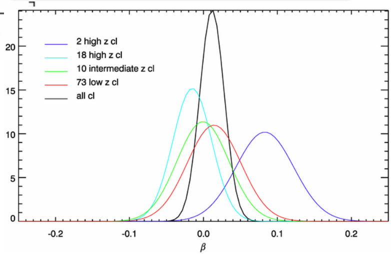


$T_{CMB}(z)$ and T_0 from Planck SZ clusters



$T_{CMB}(z_i)$ for 103 individual clusters: precision up to 3%

Full posteriors of T_{CMB}(z) by MCMC analysis $\Rightarrow$ 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 $\Rightarrow$
$T_{CMB}(0) = 2.719 \pm 0.014$K,
COBE-FIRAS: $T_0 = 2.7260 \pm 0.0013$K
(Fixsen ApJ 2009)

$T_{CMB}(z)$ for the Heritage sample

Constraining the evolution of the CMB temperature for the Heritage sample of Planck SZ clusters

E. D'Angelo,[a,b,1] G. Luzzi[b,1] H. Bourdin,[c] F. De Luca,[c] P. Mazzotta,[c] F. Oppizzi[c] and G. Polenta[b]

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Astronomy & Astrophysics

The Cluster HEritage project with *XMM-Newton*: Mass Assembly and Thermodynamics at the Endpoint of structure formation

I. Programme overview

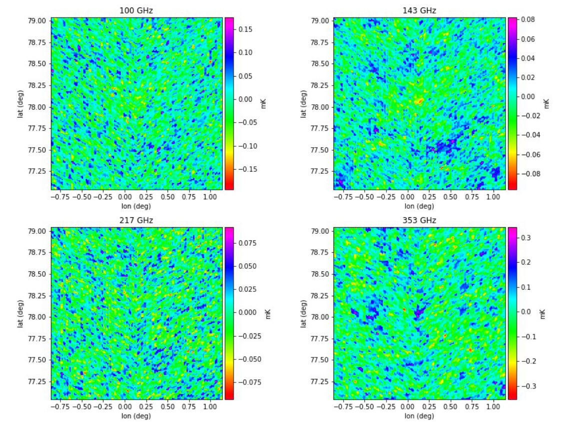
The CHEX-MATE Collaboration: M. Arnaud[1], S. Ettori[2,3], G. W. Pratt[1], M. Rossetti[4], D. Eckert[5], F. Gastaldello[4], R. Gavazzi[6], S.T. Kay[7], L. Lovisari[2,8], B.J. Maughan[9], E. Pointecouteau[10], M. Sereno[2,3], I. Bartalucci[1,4], A. Bonafede[11,12,13], H. Bourdin[14], R. Cassano[12], R.T. Duffy[9], A. Iqbal[1], S. Maurogordato[15], E. Rasia[16,17], J. Sayers[18], F. Andrade-Santos[8], H. Aussel[1], D.J. Barnes[19], R. Barrena[20,21], S. Borgani[22,16,17,23], S. Burkutean[12], N. Clerc[10], P.-S. Corasaniti[24,25], J.-C. Cuillandre[1], S. De Grandi[26], M. De Petris[27], K. Dolag[28,29], M. Donahue[30], A. Ferragamo[27], M. Gaspari[2,31], S. Ghizzardi[4], M. Gitti[11,12], C.P. Haines[45], M. Jauzac[32,33,34,35], M. Johnston-Hollitt[36,37], C. Jones[8], F. Kéruzoré[38], A.M.C. LeBrun[24,1], F. Mayet[38], P. Mazzotta[14], J.-B. Melin[39], S. Molendi[4], M. Nonino[16], N. Okabe[40], S. Paltani[5], L. Perotto[38], S. Pires[1], M. Radovich[47], J.-A. Rubino-Martin[20,21], L. Salvati[16,40], A. Saro[22,16,17,23], B. Sartoris[16,17], G. Schellenberger[8], A. Streblyanska[20,21], P. Tarrío[1,48], P. Tozzi[41], K. Umetsu[42], R.F.J. van der Burg[43,1], F. Vazza[11,12,13], T. Venturi[12], G. Yepes[44], and S. Zarattini[1,46]

SZ maps at Planck frequencies (1)

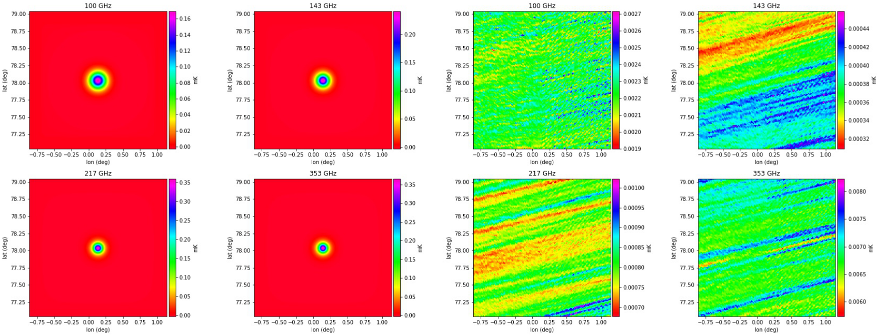
Planck DR2 maps (Planck 2015 results. I.,A & A594(2016))

Map filtering and cleaning

New cleaning for CMB and dust anisotropies: spectrally modelled using all HFI frequency maps outside each galaxy cluster ($7R500 \leq R \leq 12R500$), and spatially modelled using a linear combination of wavelet filtered frequency maps at 857 and 217 GHz (Bourdin et al ApJ843 2017)



SZ maps at Planck frequencies (2)

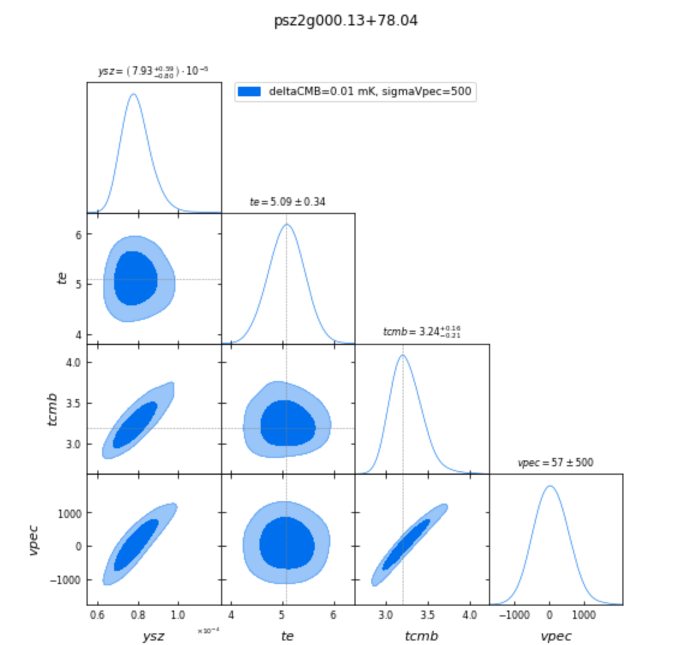


Modelling of SZ signal on cleaned maps

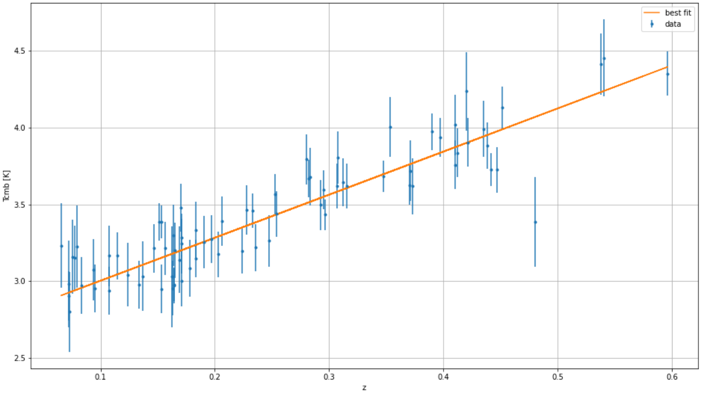
$$P(\mathrm{map_{obs}}|\Theta_n) \propto \exp\left\{-\sum_{\nu}\sum_{ij}\frac{[\Delta T_{\mathrm{SZ}}(\nu,\Theta_n)\times \mathrm{template}(\nu,i,j)-\mathrm{map_{obs}}(\nu,i,j)]^2}{\mathrm{varmap}(\nu,i,j)+\delta CMB^2}\right\}$$

R500 from analysis of the Heritage sample; prior on Te as obtained from analysis of Heritage sample; prior on the residual KSZ.

$T_{CMB}(z)$ with the MCMC sampler Cobaya (Torrado et al. JCAP 2021 057)



Results: CMB temperature measurements

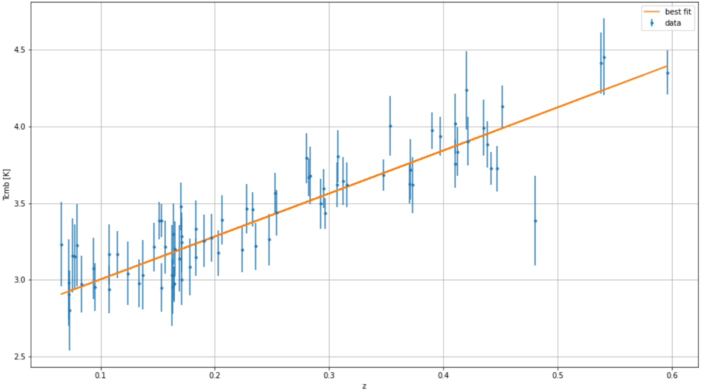


$T_{CMB}(z_i)$ for 77 individual clusters: precision up to 3%

Test on mock maps

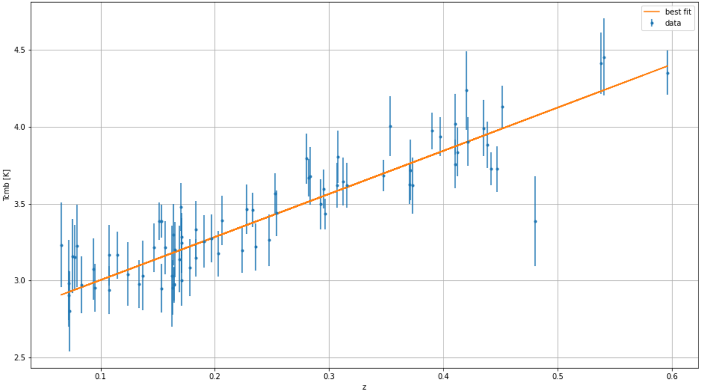
- SZ signal maps generated using data from X-ray measurements
- CMB maps and dust emission signals are added to the cluster maps
- The resulting maps are convolved with the Planck beam
- The cleaning procedure is applied on the maps, obtaining the final signal maps
- The MCMC sampler Cobaya is applied on the cleaned maps to extract $T_{CMB}(z)$

Results: Constraining the CMB temperature evolution



With the parametrization $T_{CMB}(z) = T_0(1+z)^{1-\beta}$ we get for 77 clusters $\beta = -0.019 \pm 0.022$. Standard model consistent
D'Angelo, Luzzi et al. in preparation

Results: Independent estimate of T_0



T_0 as a free parameter when fitting the data with the standard relation $T_{CMB}(z) = T_0(1+z)$: $T_{CMB}(0) = 2.736 \pm 0.014K$,
COBE-FIRAS: $T_0 = 2.7260 \pm 0.0013K$ (Fixsen ApJ 2009)

Why T_0?

- H_0 tension or T_0 tension? Mikhail M. Ivanov, Yacine Ali-Haïmoud, and Julien Lesgourgues Phys. Rev. D 102, 063515 - 2020
- Benjamin Bose and Lucas Lombriser Phys. Rev. D 103, L081304 – 2021
- The role of T_0 in CMB anisotropy measurements Yunfei Wen, Douglas Scott, Raelyn Sullivan, J. P. Zibin arXiv:2011.09616
- V.V. Klimenko, A.V. Ivanchik, P. Petitjean, P. Noterdaeme, R. Srianand - Astronomy Letters, Volume 46, Issue 11, p.715-725, 2020
- Carlos A.P. Bengaly, Javier E. Gonzalez, Jailson S. Alcaniz,Eur.Phys.J.C 80 (2020) 10, 936

Can we improve the limit on CMB y distortions via the SZ spectrum?

- Departures of the CMB frequency spectrum from a pure black body encode information about the thermal history of the early Universe.
- COBE/FIRAS measurements: the average CMB spectrum is extremely close to a perfect blackbody with possible distortions $< 10^{-5}$.
- If $T_{CMB}(z) = T_0(1+z)$:
  $T_{CMB}(z)$ from SZ clusters $\Rightarrow$ constraints on the degree of its cosmological Compton distortion y.

ON THE DETERMINATION OF THE DEGREE OF COSMOLOGICAL COMPTON DISTORTIONS AND THE TEMPERATURE OF THE COSMIC BLACKBODY RADIATION

YOEL REPHAELI

Center for Radiophysics and Space Research, Cornell University

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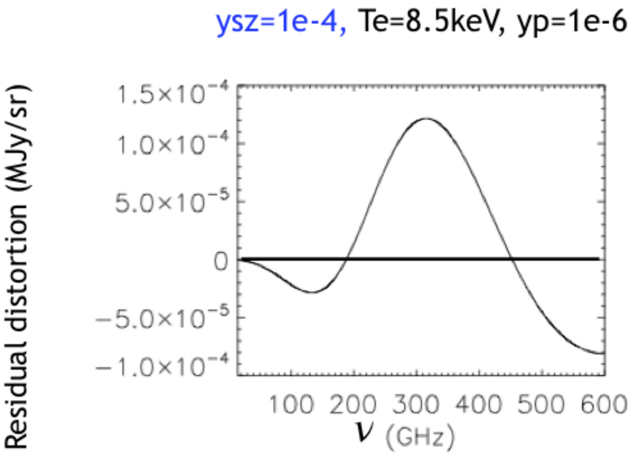
Cosmological y distortion: amplitude of the residual distortion on a SZ spectrum



The effect of primordial y_p distortion on the SZ spectrum has been included by following the formalism of Fabbri et al 1978.

The "Millimetron" Mission in one slide …

The first 10-m deployable and cooled space
sub-mm and FIR telescope.

The mission is approved and supported by Russian Space Agency

- FIR, sub-mm and mm range
- In orbit deployable and adjustable antenna
- Mechanically cooled (<10K) with post-cryo life
- Orbit around L2 Lagrange point
- Lifetime: 10 years; at cryo >3 years

Two operation modes:

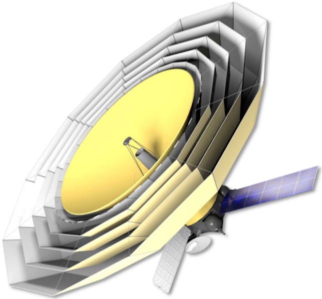
Space-VLBI at 0.3 – 7 mm

Single dish at 0.08 – 3 mm

- Step forward with respect to earlier missions
- Sensitivity: 10^{-22} W/m^2 for spectroscopy and 0.5 μJy
- for photometry (single dish)

- **Spacecraft bus in Phase-A**
- **Scientific payload in Phase-B**
- **Launch date : 2029**

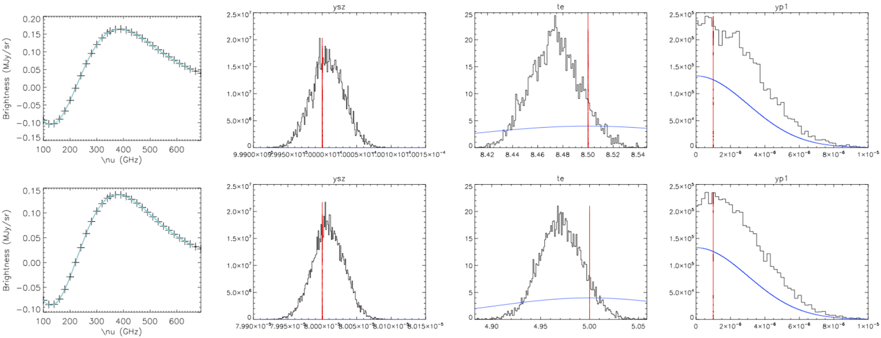
More information: http://millimetron.ru/



Slide from S. Likhachev, PI of the Millimetron project

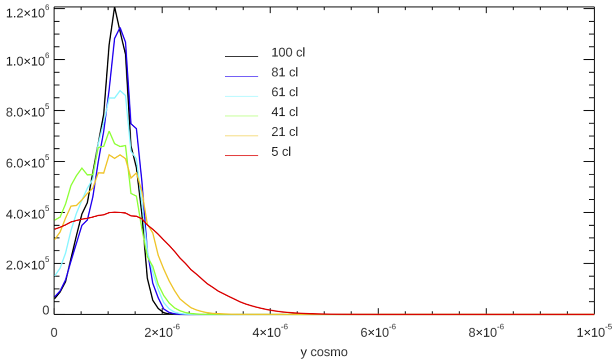
Cosmological y distortion from Millimetron simulated SZ spectra (1)

FTS sensitivity in 1 hour integration time (D. Novikov):
Band: 100-200; 200-350; 350-700 GHz
Sensitivity: 69.24; 148.6; 140.6 Jy/sr
Simulated spectra and posterios for y_{SZ}, T_e and y_p. Input of the simulation in red, prior in blue, posterior in black.



Cosmological y distortion from Millimetron simulated SZ spectra (2)

Joint pdf - extrapolated to 100 clusters



Differential approach complementary to absolute spectroscopic measurements of the CMB y distortions

- Cleaned SZ maps in the range 100-353 GHz for a subsample of the PSZ2 Planck catalog containing 75 clusters selected from the Heritage project of the X-ray satellite XMM-Newton
- Individual determinations of $T_{CMB}(z)$ for 75 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 $\beta = -0.019 \pm 0.022$, standard model consistent.
- We get an independent estimate of the CMB tempertaure at redshift zero: $T_0 = 2.729 \pm 0.014$ K, at 1σ uncertainty, a value consistent with the COBE-FIRAS measurement, $T_0 = 2.7260 \pm 0.0013$ K.
- Forecasts for Millimetron experiment: possible to improve the constraints on the cosmological y distortions with SZ spectrum measurements for less than 100 clusters.