LiteBIRD's view on the relativistic SZ effect: a parametric fitting method to obtain the electron gas temperature of galaxy clusters

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Abstract: We present a forecast of the capability of the upcoming Cosmic Microwave Background (CMB) experiment *LiteBIRD* to detect the relativistic Sunyaev-Zeldovich (rSZ) effect and measure the electron gas temperature (T_e) of selected galaxy clusters. Following the approach of Remazeilles & Chluba, (2020)[11], we implement a moment expansion of the rSZ signal for a set of pivot temperatures ($\bar{T}_e$) and use a Constrained Internal Linear Combination (CILC) component separation method to extract two moment maps: the Compton-y map and the temperature modulated Compton-y map, $y(T_e - \bar{T}_e)$. Subsequently, we employ a parametric fit using the statistical framework Cobaya to jointly extract the thermal SZ parameter, y, and the electron temperature, T_e. This fitting assumes predefined spatial profile templates for the cluster's compton-y parameter and electron gas temperature. This analysis uses simulations combining *LiteBIRD* and *Planck* frequency channels.

Introduction

- The Sunyaev-Zeldovich (SZ) effect is the spectral distortion of CMB caused by Compton scattering of CMB photons with electrons in ionised media (Galaxy clusters)[1].
- Electron gas temperature (T_e) of Galaxy Clusters can be 5 - 15 keV resulting in small relativistic correction to the SZ spectrum (rSZ)[2][3] important while using the SZ clusters as a cosmological probe.
- The rSZ effect provides a direct mm-wave probe of T_e that is complementary to X-rays.
- Previous studies[4–8] estimated average T_e of cluster samples via stacking.

LiteBIRD and Mapping the Hot Gas in the Universe:

- Lite (Light) spacecraft for the study of B-mode polarization and Inflation from cosmic background Radiation Detection[9].
- JAXA's L-class Mission, Frequency Bands: 34 to 448 GHz (15), Angular Resolution: 70.5' to 17.9', Sensitivity: 2.2 μK.arcmin[9].

SZ science with *LiteBIRD*:
- Producing the next-generation all-sky SZ signal map[10].
- Detecting the rSZ effect from individual clusters, Constrain the CMB y-type distortion, Synergy with X-ray surveys, Structure formation studies[10].
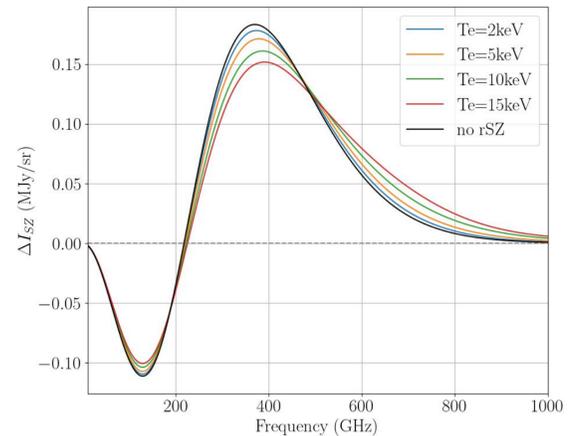
Thermal SZ spectrum along the line-of-sight of a galaxy cluster for different electron gas temperature values (T_e)

rSZ 0th and 1st Order Moment Maps

- Simulation[10]*: *LiteBIRD* and *Planck* frequency maps including astrophysical foregrounds and nominal noise. A simulated galaxy cluster catalog, based on real *Planck* PSZ2 clusters and random clusters generated using a halo model mass function, is used.

- Taylor expansion of the rSZ spectrum up to first order about a pivot temperature($\bar{T}_e$)[11]:

$$\Delta I_{SZ}(\nu) = y(\hat{n})f(\nu, \bar{T}_e) + y(\hat{n})(T_e(\hat{n}) - \bar{T}_e)\frac{\partial f(\nu, \bar{T}_e)}{\partial \bar{T}_e}$$

- A Constrained Internal Linear Combination (CILC) component separation method produces the following maps at angular resolution of 5'
  - Compton-y map (0th Moment)
  - Temperature modulated Compton-y map (1st Moment)

*Simulations created by Mathieu Remazeilles as part of the *LiteBIRD* SZ science activities
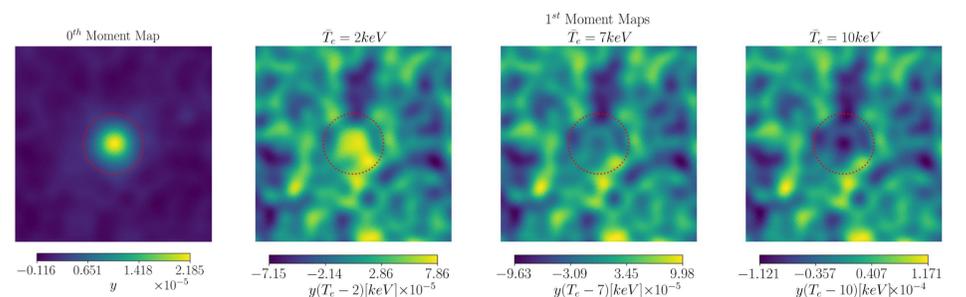
The 0th moment map and 1st moment maps of Coma cluster smoothed to 30' beam in a 5° × 5° patch generated using $\bar{T}_e$ = 2, 7, and 10 keV. At Cluster position (indicated by a red dotted circle) in the 1st Moment map, the signal appears positive, null or a negative depending on whether the cluster T_e is greater than, equal to or less than the $\bar{T}_e$, respectively. This provides a rough estimate of the cluster T_e by creating maps at different pivots.

Parametric fitting method to recover T_e

- Two-parameter MCMC fit (Cobaya[12]) using the below likelihood scheme. Covariance between 0th and 1st Moments is not considered yet.

$$M_{0^{th},(i,j)} = G_{FWHM} * [y_{cl} \cdot T_{Y(i,j)}]$$

$$M_{1^{st},(i,j)} = G_{FWHM} * [y_{cl} \cdot T_{Y(i,j)} \cdot (T_e \cdot T_{T_e(i,j)} - \bar{T}_e)]$$

$$\chi^2_{0^{th}} = \sum_{i,j}\frac{[M_{0^{th},(i,j)} - CILC_{0^{th}(i,j)}]^2}{\sigma^2_{0^{th}(i,j)}}, \quad \chi^2_{1^{st}} = \sum_{i,j}\frac{[M_{1^{st},(i,j)} - CILC_{1^{st}(i,j)}]^2}{\sigma^2_{1^{st}(i,j)}}$$

$$L(y_{cl}, T_e) \propto \exp\{-0.5(\chi^2_{0^{th}} + \chi^2_{1^{st}})\}$$

Spatial profile Templates
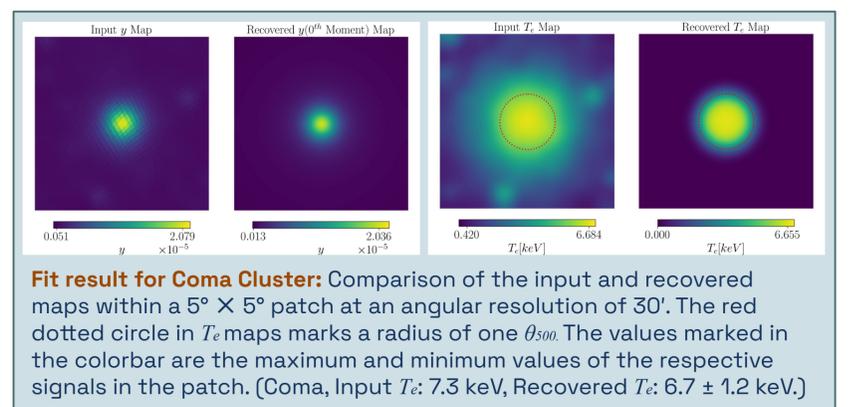
- $T_{Y(i,j)}$: Beta profile for Compton-y parameter

$$T_y(\theta) = y_0\left(1 + \frac{\theta^2}{\theta_c^2}\right)^{(1-3\beta)/2}$$

$$\beta = 1, \theta_c \sim 0.2\theta_{500}$$

- $T_{T_e(i,j)}$: Top-hat profile for T_e

$$T_{T_e}(\theta) = \begin{cases} 1, & \theta \leq \theta_{500} \\ 0, & \theta > \theta_{500} \end{cases}$$

θ_{500}: Cluster characteristic radius

Fit result for Coma Cluster: Comparison of the input and recovered maps within a 5° × 5° patch at an angular resolution of 30'. The red dotted circle in T_e maps marks a radius of one θ_{500}. The values marked in the colorbar are the maximum and minimum values of the respective signals in the patch. (Coma, Input T_e: 7.3 keV, Recovered T_e: 6.7 ± 1.2 keV.)
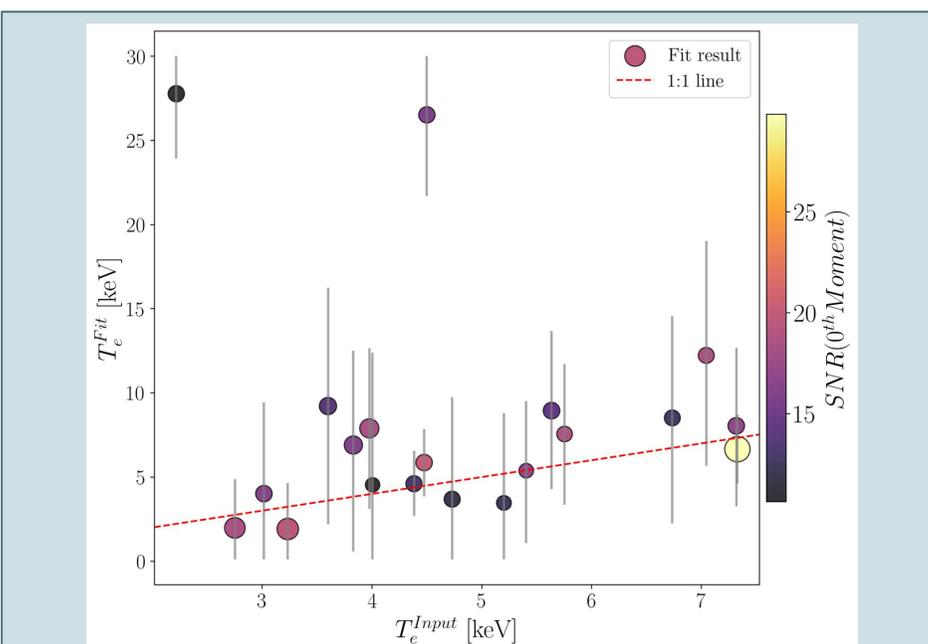
Fit Result Summary for all Clusters: Fit result of 20 clusters selected based on the SNR (0th Moment Map) larger than 10 and angular size θ_{500} larger than 15 arcminute. The x-axis shows the input T_e values of clusters, and the y-axis shows the fitted T_e values. The color bar represents the SNR of the clusters, and point size scales with their θ_{500}. Error bars show the 95% credible intervals. The red dashed line indicates where input T_e equal to fitted T_e. The two outlier clusters have map-level issues that need further investigation. The maps are smoothed to an effective beam of 30' before fitting as it provides better fit result mainly due to lower noise.

Conclusion:

- For *LiteBIRD* in combination with *Planck*, the parametric fitting method is able to extract the electron gas temperature of clusters selected with higher signal-to-noise ratio and larger angular size. The current sample of selected clusters constitutes ~ 50% of the clusters with angular size larger than 15'.
- Clusters with 95% credible interval for T_e less than 15 keV are excluded: these clusters have lower SNRs and smaller angular sizes making the fit difficult.
- The *LiteBIRD* instrument configuration used for this work is under rescope studies, and subsequent revisions may change the results.

Future steps:

- Include the cross-covariance between the 0th and 1st Moment in likelihood.
- Calculate the mean cluster temperature in different mass bins via stacking.
- Look for more realistic spatial profile templates, particularly for the electron gas temperature.

Bibliography:

1. Zeldovich Y. B., Sunyaev R. A., 1969, Ap&SS, 4, 301
2. Rephaeli Y., 1995, ApJ, 445, 33
3. Itoh N. et al., 1998, ApJ, 502, 7
4. Hurier, G. 2016, A&A, 596, A61
5. Erler, J. et al., 2018, MNRAS, 476, 3360
6. Perrott, Y. 2024, PASA, 41, e087
7. Coulton, W. R., Duivenvoorden, A. J., Atkins, Z., et al. 2024, arXiv:2410.19046
8. Remazeilles, M., & Chluba, J. 2025, MNRAS, 538, 1576
9. LiteBIRD Collaboration et al., 2023(4), PTEP, 042F01
10. Remazeilles, M. et al. 2024 JCAP, 12, 026
11. Remazeilles, M., & Chluba, J. 2020, MNRAS, 494, 5734
12. Torado, J., & Lewis, A., (Cobaya) https://arxiv.org/abs/2005.05290

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