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Planck and SPT cluster catalogs: A combined analysis

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Abstract. We show the results for the first combined analysis of clusters detected by the Planck satellite and the South Pole Telescope. The combination of these two experiments, with different resolution, mass and redshift range, allows to track the full cosmological evolution of galaxy clusters and the interplay between astrophysics and cosmology. In particular, we exploit the cosmological constraining power of SPT-SZ clusters to provide an independent calibration of Planck scaling relations, and therefore a new estimation of Planck cluster masses. Combining the two cluster catalogs we are thus able to test the hypotheses of self-similarity and hydrostatic equilibrium. We show therefore the huge potentiality of combining catalogs from different experiments, in improving the cosmological analysis and the treatment of different astrophysical and systematic uncertainties.

1 Introduction

Galaxy clusters are the most massive gravitationally bound structures in the Universe. They are a powerful cosmological probe, able to describe the matter distribution in the recent Universe and provide constraints on cosmological parameters such as the matter density Ω_m and the amplitude of the matter power spectrum σ_8. They provide a unique tool to explore extensions to the standard cosmological model, e.g. constraining the equation of state for dark energy and the impact of massive neutrinos on the recent evolution of structures.

Galaxy clusters provide observables at different wavelengths and in the last decade several experiments produced catalogs of hundreds of clusters used for the cosmological analysis, from observations in millimetre (mm), optical, near-IR and X-ray bands. While producing competitive cosmological constraints, all these analyses highlight the impact of the cluster mass calibration on the full cosmological analysis (see e.g. discussion in [1]). Indeed, extracting cosmological informations from galaxy clusters passes through the knowledge of their mass and redshift distribution. However, since clusters are composed mainly by dark matter, their total mass cannot be measured directly. Cluster mass estimation is therefore obtained from statistical scaling relations that link the different survey observables to the cluster mass. The modelling of the scaling relations is based on cluster physics and in particular on the behaviour of the baryonic components (i.e. galaxies and hot gas) in the dark matter potential well. A unique way to improve the modelling and calibrate these relations passes through the combination of different wavelength observations. Furthermore, in general the combination of different observations is a unique way to test the assumptions used in the full

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cosmological pipeline, such as the modelling of the cluster detection approach (and therefore the full selection function).

In this paper, we focus on the first combined analysis of cluster catalogs detected in the mm wavelengths through the thermal Sunyaev-Zeldovich effect [2] by the Planck satellite [3, 4] and South Pole Telescope (SPT) [5, 6]. The final goal of this analysis is to build a full coherent combined analysis from observations of the two different experiments. In this first work we focus on an independent calibration of Planck cluster masses, exploiting the cosmological constraining power of the SPT-SZ cluster sample. The main results reported here are based on [7]. We recall here that we define clusters as objects contained in a sphere of radius R_{500}, such that the over-density within the sphere corresponds to 500 time the critical density of the Universe.

2 Data

2.1 Planck and SPT cluster catalogs

The Planck cluster catalog [3] is based on full-sky observations from six channels, from 100 GHz to 857 GHz. The cosmological sample is composed by 439 clusters detected with signal-to-noise ratio $S/N > 6$, on the 65% of the sky remaining after masking high dust emission regions and point sources, in the redshift range $z = [0, 1]$ and mass range $M_{\rm SZ} = [2, 10] \cdot 10^{14} M_\odot$. The approach for the cluster mass calibration in the cosmological pipeline is introduced in the following section (Sect. 2.2).

The SPT-SZ cluster catalog [5] is obtained from observations of 2500 deg^2 of the sky in the 95 and 150 GHz bands. The cosmological sample is composed by 365 detections from redshift $z > 0.25$ and with a detection significance greater than 5. The cosmological analysis is fully described in [6]. We just recall here that results are obtained from a multi-observable likelihood, in which X-ray and weak lensing (WL) observations are included directly in the likelihood function to calibrate cluster masses. We refer to this approach of modelling and sampling the mass-observable relations as "internal calibration".

2.2 Planck scaling relations

We summarise the assumptions beneath the modelling of scaling relations for the cluster cosmological analysis performed by the Planck collaborations. All details can be found in [4]. From the assumptions of self-similarity, spherical symmetry and hydrostatic equilibrium (HE), the mean relation between the integrated Compton parameter Y_{500} and cluster mass M_{500} is defined as:

$$E^{-\beta_{\rm SZ}}(z)\left[\frac{D_A^2(z)\bar{Y}_{500}}{10^{-4}{\rm Mpc}^2}\right] = Y_{*,\rm SZ}\left[\frac{h}{0.7}\right]^{-2+\alpha_{\rm SZ}}\left[\frac{(1-b)_{\rm SZ}M_{500}}{6\cdot 10^{14}M_\odot}\right]^{\alpha_{\rm SZ}} \quad (1)$$

where $D_A(z)$ is the angular diameter distance and $E(z) = H(z)/H_0$. The parameters $\alpha_{\rm SZ}$, $Y_{*,\rm SZ}$ are calibrated using X-ray observations from XMM satellite of 71 clusters, obtaining $\alpha_{\rm SZ} = 1.79 \pm 0.08$ and $\log Y_{*,\rm SZ} = -0.19 \pm 0.02$, while $\beta_{\rm SZ} = 0.66$ following the self-similarity assumption. X-ray observations provide a mass estimation based on the HE assumption, $M_{\rm HE}$. The parameter $(1-b)$, usually referred to as "mass bias", is introduced to take into account departures from the HE condition (due e.g. to cluster physics) and is defined as $(1-b) = M_{\rm HE}/M_{500}$. From numerical simulations, the HE assumption is estimated to bias low the mass measurements by $\sim 20\%$. In cosmological analysis, an estimation of the mass bias is often obtained from WL mass estimations, assuming them to be unbiased. Planck baseline analysis assumes $(1-b)_{\rm SZ} = 0.780 \pm 0.092$, obtained for WL mass measurements of 20 clusters. We refer to this full approach for the modelling and calibration of the scaling relations as "external calibration".

We recall here that the value of the mass bias plays a crucial role in the tension found in the Planck 2015 analysis: CMB primary anisotropies results were pointing towards values of σ_8 larger than constraints found by the cluster analysis and a possible way to reconcile these results pointed towards having low values of the mass bias, $(1-b) \sim 0.6$. This low value of the mass bias is nevertheless not in agreement with most of the estimations from WL observations, simulations (see a collection of results in [8]) and other cluster probes (such as the gas fraction).

Several analyses in recent years focused on the role of the mass bias and the HE assumption. Indeed, while this parameter is introduced solely to take into account deviations from the HE assumption, it can encompass different sources of uncertainties entering the mass measurement modelling and calibration, or more general systematics related to the full analysis (e.g. observational or selection effects). In [8, 9] we showed that the $[\sigma_8, (1-b)]$ tension might not be related to the need for extensions to the standard cosmological model. We explored a possible mass and redshift evolution of the mass bias, finding that results are highly dependent on the considered cluster sample. We find therefore that systematics related to cluster catalog selection might impact cosmological results. As a consequence, using mass calibrations based on small sub-samples of the full cosmological sample might introduce errors on the cosmological constraints. In the ideal scenario, we would have access to multi-wavelength observations for clusters of the full cosmological sample. Otherwise, we can explore alternative ways of calibrating the scaling relations, exploiting the tight correlation with cosmology.

3 Method

We describe here the approach to combine Planck and SPT observations. We summarise the main steps and refer to [7] for the detailed discussion. We combine Planck and SPT observations avoiding covariance between the two samples. In particular, since SPT-SZ catalog starts at $z = 0.25$, we modify the Planck cluster catalog (and consequently the cosmological likelihood), splitting the analysis in two redshift ranges. For $z \leq 0.25$ we keep the full sub-sample of Planck clusters and the full sky area. For $z > 0.25$ we remove 27 Planck clusters in common with the SPT-SZ catalog. Furthermore, we identify patches of Planck sky that overlap with SPT-SZ observations. We recall here that Planck sky for cluster detections is divided into 417 patches of constant values of detection noise, see details in [3]. We identify and remove 16 patches that fully overlap with SPT-SZ observations. We also find 35 patches that partly overlap with SPT observations. In this case, we simply reduce the sky fraction in each patch, according to the area that is actually observed by both experiments. We further remove 2 clusters from the Planck cosmological catalog that fall in the removed patches. This new version of Planck likelihood is labelled "PvSPLIT".

With this analysis, we aim at testing the capability of the Planck+SPT combination to provide independent constraints on Planck scaling relation parameters. For this reason, we do not consider the full X-ray+WL calibration applied in [4]. In particular we focus on the mass bias $(1-b)_{\rm SZ}$ and mass slope parameter $\alpha_{\rm SZ}$ constraints. For these parameters we therefore do not use the original external calibration describe in Sec. 2.2. As baseline cosmological model, we assume a $\nu\Lambda$CDM scenario, with varying massive neutrinos.

As a further step in the analysis, we produce also new estimations of total Planck cluster masses, $M_{500}^{\rm new}$. Starting from the new constraints on the scaling relation parameters, following

Eq. 1 we can evaluate the cluster mass for each cluster detected in the cosmological sample, considering the relation between the mean detected S/N $\bar{q}$ and the mean Compton parameter

$$\bar{q} = \frac{\bar{Y}_{500}}{\sigma_f(\bar{\theta}_{500}, l, b)}\,, \tag{2}$$

where $\sigma_f(\bar{\theta}_{500}, l, b)$ is the detection noise in the given position in the sky (l, b) and for the mean cluster size $\bar{\theta}_{500}$.

These mass measurements allow us also to measure a mass bias for each cluster, using cluster masses released by the Planck collaboration, $M_{\rm SZ}$, evaluated following the HE assumption. We can therefore estimate possible systematics impacting the mass bias (and cluster mass) evaluation: for this reason we fit a possible evolution of the measured mass bias

$$(1-b)_M = \frac{M_{\rm SZ}}{M^{\rm new}_{500}} = A_{\rm bias}\left(\frac{M^{\rm new}_{500}}{M_*}\right)^{\gamma_m}\left(\frac{1+z}{1+z_*}\right)^{\gamma_z}\left(\frac{\sigma_f(\theta_{500}, l, b)}{\sigma_{f,*}(\theta_{500})}\right)^{\gamma_n}\,. \tag{3}$$

In Eq. 3 we analyse a mass and redshift evolution (as already studied in [9] and reference therein) to test if the general model of scaling relations (based on astrophysical assumptions) needs to be improved. Furthermore, we add an evolution with respect to the detection noise σ_f. Given the direct link between detection noise and sky position, this dependence might be related to the observational strategy, or to assumptions related to the detection approach, and therefore hints that the modelling of the whole pipeline might have an impact on the mass definition and on the cosmological results. The full details for the mass and mass bias analysis can be found in [7].

4 Results

We start discussing the results for the cosmological and scaling relation parameters, comparing results from the original SPT analysis (labelled SPTcl, which include the full internal calibration introduced in Sec. 2.1), the original Planck analysis (labelleb PvFULL) and the new combined Planck+SPT analysis (labelled SPTcl+PvSPLIT). Results are shown in figure 1 and in table 1. We see that SPT cluster data drive the constraining power for the SPTcl+PvSPLIT combination: the (Ω_m, σ_8) contours are shifted towards lower values of Ω_m and larger values of σ_8 with respect to the PvFULL results. From this cosmological constraining power, we are able to put constraints on the scaling relation parameters for which we are not considering external calibrations. We find $(1-b)_{\rm SZ} = 0.69^{+0.07}_{-0.14}$. This value is slightly lower than the original WL calibration, but given the larger error bars, results are both in agreement with expectations of $(1-b) \sim 0.8$ and results obtained when combining Planck cluster and Planck CMB $(1-b) \sim 0.6$. We will discuss further these results when focusing on the cluster mass and mass bias evaluations. For the mass slope, we find $\alpha_{\rm SZ} = 1.49^{+0.07}_{-0.1}$. This value is lower than the original one, pointing even further away from the assumption of self-similarity. We find that these new constraints are mainly driven by the shift in the Ω_m results. We stress therefore that we are able to provide tight constraints on scaling relations, that are independent on the assumptions of self-similarity and HE, and on external calibrations. These results show the tight correlation between cosmological and mass calibration parameters, and therefore the interplay between cosmology and astrophysics in cluster formation and evolution. In [7] we discuss further results, testing for different parameterisation and extensions of the scaling relation model.

From these results on the scaling relation parameters, we provide evaluation of masses $M^{\rm new}_{500}$ for all the clusters in the Planck cosmological sample. The full catalog can be find in

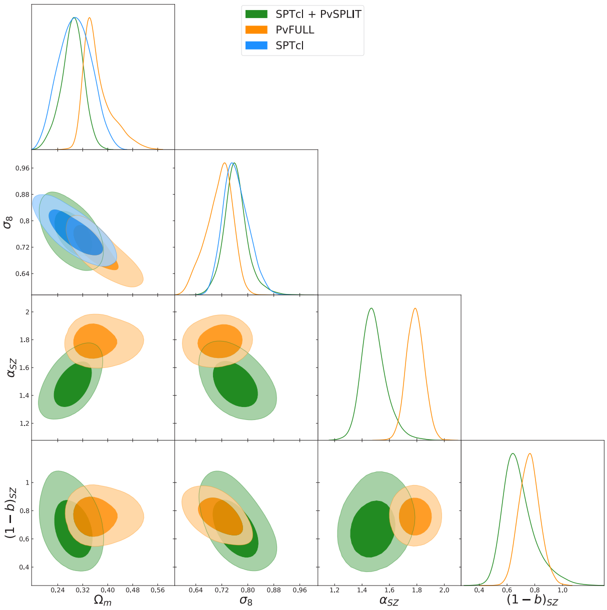

Figure 1. One-dimensional and two-dimensional probability distributions for the cosmological (Ω_m, σ_8) and Planck scaling relation ($\alpha_{\rm SZ}, (1-b)_{\rm SZ}$) parameters. We show results for: SPTcl + PvSPLIT in green (baseline results of this analysis), PvFULL in orange, and SPTcl in blue.

Table 1. 68% CL constraints on cosmological and scaling relation parameters for different dataset combinations.

	SPTcl+PvSPLIT	PvFULL	SPTcl
Ω_m	$0.29^{+0.04}_{-0.03}$	$0.37^{+0.02}_{-0.06}$	0.3 ± 0.03
σ_8	$0.76^{+0.03}_{-0.04}$	$0.71^{+0.05}_{-0.03}$	$0.76^{+0.03}_{-0.04}$
$\alpha_{\rm SZ}$	$1.49^{+0.07}_{-0.1}$	1.79 ± 0.06	-
$(1-b)_{\rm SZ}$	$0.69^{+0.07}_{-0.14}$	$0.076^{+0.07}_{-0.08}$	-

[7] and link therein. We discuss now the results when fitting the evolution of the measured mass bias. Constraints on the parameters are reported in tab. 2: in the first column we show the results when fitting the full mass, redshift and detection noise evolution. As a further test, we also fit only for the (M,z) evolution (second column) and only for the detection noise evolution (third column). When considering the full scenario, the amplitude $A_{\rm bias}$ is consistent with $(1-b)_{\rm SZ}$ results find for the SPTcl+PvSPLIT analysis. We also find a hint for mass and redshift evolution, while γ_n is consistent with 0. These results are consistent with the (M,z) only case. This evidence for a (M,z) dependence might point to the necessity of improving the theoretical model assumed for the cluster mass evaluation (and therefore possibly change the scaling relation formulation). Astrophysical uncertainties are therefore still the dominant source of systematics for the cosmological analysis of galaxy clusters. When analysing only the fit for the detection noise dependence, we find $\gamma_n = -0.37^{+0.14}_{-0.12}$, pointing to a decreasing trend of $(1-b)_M$ with respect to the noise. This implies that the $M_{\rm SZ}$ estimation for clusters detected in patches with higher detection noise is more biased, possibly due to a loss of tSZ signal. We find therefore that, even if sub-dominant, the pre-processing of data and

Table 2. 68% CL constraints on measured mass bias $(1 - b)_M$ parameters.

	(M, z, σ_f)	(M, z)	(σ_f)
A_{bias}	$0.69^{+0.04}_{-0.09}$	$0.69^{+0.05}_{-0.1}$	$0.60^{+0.06}_{-0.14}$
γ_M	$-0.41^{+0.04}_{0.06}$	$-0.40^{+0.04}_{-0.06}$	-
γ_z	0.81 ± 0.13	0.74 ± 0.13	-
γ_n	$0.05^{+0.06}_{-0.08}$	-	$-0.37^{+0.14}_{-0.12}$

the detection approach pipeline might induce further systematics in the mass estimation and therefore on the final cosmological constraints.

5 Conclusions

We present here the first combined analysis of galaxy clusters detected in the mm-wavelengths by the Planck satellite and the South Pole Telescope. We showed the capability of SPT cosmological constraining power to provide independent constraints on the mass-observable relation parameters for Planck clusters, leading to new mass measurements for clusters in the Planck cosmological sample. These results show the power of combining experiments observing the sky in the same wavelengths, that helps in disentangling different types of systematics (theoretical, astrophysical and instrumental).

In general, this analysis confirms the importance of an accurate mass calibration for cluster cosmology. We find that the simple model, based on the assumptions of self-similarity, spherical symmetry, and hydrostatic equilibrium, needs to be improved toward a more realistic description. Furthermore, we find that the adopted modelling should take into account the cluster sample selection, from the cluster mass–redshift distribution to the impact of the detection approach. This project is building the way toward a full joint analysis of SPT and Planck cluster catalogs, with a joint mass calibration, allowing for more stringent tests of cosmology beyond the standard model.

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