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Small-scale CMB cosmological information

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Abstract.
The small-scale CMB angular power spectrum contains many contaminants from secondary anisotropies created by large-scale structures. Although their contribution is taken into account in the analyses, their cosmological dependence is often ignored. We propose a new analysis of SPT data focusing on the cosmological contributions of the Sunyaev Zel'dovich effects (tSZ and kSZ). After modelling these two effects and building a power spectrum emulator, we show that using the cosmological information of the tSZ and kSZ in addition to that of the primordial CMB contained in the small-scale SPT data provides comparable constraints on the reionisation history to those of the large-scale data of Planck.

1 Introduction

Observations of the sky in the millimetre range contain the sum of many signals coming form the last scattering surface (primordial CMB) and from all gravitational and electromagnetic effects along the line of sight. Among these, the thermal SZ (tSZ) and kinetic SZ (kSZ) effects are tracers of the hot gas in the Universe and the epoch of reionisation, respectively [1]. For CMB analyses, these two contributions are contaminants, usually simplistically modelled and marginalised over. Most current analyses of CMB observations at small-scales are done following the same approach [see, e.g., 2–6].

Commonly, a theoretical CMB power spectrum is added to the templates of each non-CMB signal to model the observed power spectrum. The cosmological influence is exclusively reliant on the CMB spectrum, while the amplitudes of the templates are marginalised over. There are several drawbacks to this approach. First, it results in the loss of cosmological information contained within the secondary anisotropy spectra. Second, since the templates may originate from different models or simulations, the cosmological assumptions may lack coherence. Following [7], we propose to keep the cosmological information in the tSZ and kSZ power spectrum by modelling the two signals coherently with the primordial CMB one. After a first study on the consequence of such approach on tSZ signal only [8] we investigate here the constraints on the reionisation history with a new SPT data ([4]) analysis including both tSZ and kSZ with cosmology-dependent modelling thanks to emulators. While the complete modelling of the kSZ spectrum and its results are described in [9] and [10], the tSZ modelling is covered in [8]. Here, we focus on presenting only a few key characteristics of

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the semi-analytical kSZ model and its emulator in Section 2, as well as the main results in Section 3.

2 Reionisation and kSZ spectrum model

CMB power spectrum is one of the many indirect observations of reionisation. However, at large-scales, it is sensitive to the integrated value of the optical depth, thus weakly probing the redshift evolution of the IGM ionised fraction (and even less the morphology of reionisation). Nevertheless, current CMB constraints [6] on the reionisation epoch show that it happened quite late (low value of the reionisation optical depth leading to low value of the redshift of mid-reionisation). On the other hand, kSZ power spectrum (observed at small-scales) has been shown to contain information on both the history of reionisation and its morphology (e.g. [11]). Furthermore, the kSZ power spectrum varies with cosmological parameters. We thus try to retrieve all those pieces of informations from small-scales SPT observations by using our approach. For this, we need to model the kSZ spectrum for any cosmology and reionisation history (and morphology).

We use the semi-analytical model presented in [9] in our analysis and recall here only the main characteristics. The modelling takes into account both homogeneous and patchy contributions. The former takes into account the signal coming from post-reionisation time due to density and velocity inhomoegenities. The later is produced during reionisation in particular because of ionisation anisotropies. We model it thanks to an approximation of the power spectrum of the free electron fluctuation of the form:

$$P_{ee}(k,z) = \frac{\alpha_0 \; x_e(z)^{-1/5}}{1 + [k/\kappa]^3 x_e(z)} \tag{1}$$

where $x_e(z)$ is the IGM ionised fraction, α_0 and κ are free parameters, describing the plateau level and a typical size respectively (see Fig. 1 left). We have shown that α_0 can be related to the variance of the reionisation field and thus is strongly correlated to the amplitude of the

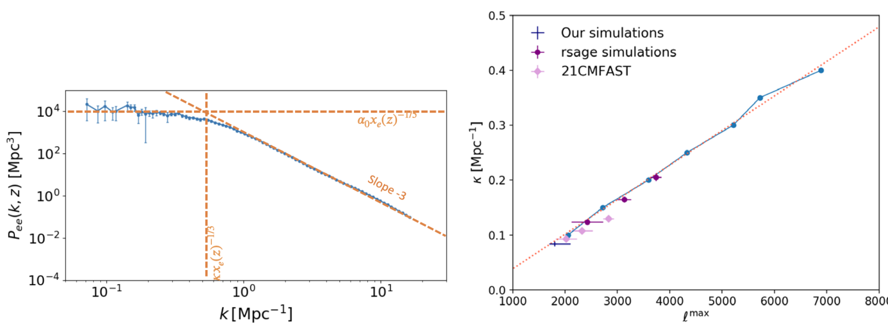

Figure 1. *Left:* Electron power spectrum for the EMMA simulation [12] at $z = 10.1$ ($x_e = 0.01$). Orange dashed lines represent the different elements of the power-law parameterisation in Eq. (1). *Right:* Evolution of the peaking angular scale of the patchy kSZ power spectrum for one given reionisation history but different values of the κ parameter. The red dotted line is the result of a linear regression. Inferences are compared to results for different simulations ('Our simulations' correspond to EMMA.). Figure from [9].

kSZ spectrum while κ encodes the size of the reionisation bubbles and is correlated to the multipole (ℓ_{max}) at which the kSZ spectrum is maximal (see Fig. 1 right).

Note that the parameterisation given in Eq. (1) matches the high-redshift ($x_e \lesssim 0.5$) behaviour of the electron power spectrum which slowly transitions into a biased matter power spectrum, enclosing an additional dependence on cosmology.

Any constraint on the shape of the power spectrum from observation, and thus determination of α_0 and κ, will give information on the history and morphology of the cosmic reionisation. For this, one should be able to compute the kSZ power spectrum for any values of the cosmological parameter, any IGM ionised fraction history and any α_0 and κ values. This computation should be fast enough to not slow down a cosmological analysis using, for example, an MCMC approach. Unfortunately, a brute force computation of our semi-analytical kSZ spectrum is too long compared to the primordial CMB computation (about one second per multipole). We therefore use the same approach as used in [8], building an emulator of the power spectrum based on random forest. The reconstruction of the kSZ power spectrum with the emulator and its comparison with the full computation is shown in Fig. 2. We achieve a mean absolute error of 3%.

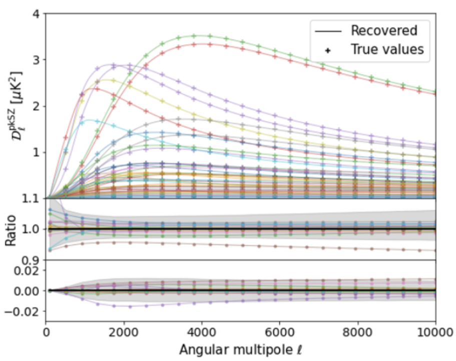

Figure 2. Patchy kSZ spectra recovered by our random forest regressors, compared to true values. The lower panels show the 95% confidence intervals on the ratio and absolute difference between the two. Figure from [10].

3 Reionisation constraints

We start by comparing the results obtained when analysing the SPT data [4], cosmology fixed, with and without the cosmology-dependent tSZ and kSZ spectra. Note that not using the random forest-emulated spectra (RF) is equivalent to reproducing the results of [4]. When including the cosmological information enclosed in the SZ spectra, we are able to break the degeneracy between their two amplitudes at $\ell = 3000$, leading to their clean and consistent measurement. As shown in Fig. 3, we obtain $\mathcal{D}_{\mathrm{kSZ}} = 3.4 \pm 0.6\ \mu\mathrm{K}^2$ (1σ), which corresponds to a $\sim 6\sigma$ measurement compared to the 3σ measurement of [4]. Note that we confirm their result of a negative tSZxCIB correlation, with a zero correlation being disfavoured above the 2σ level.

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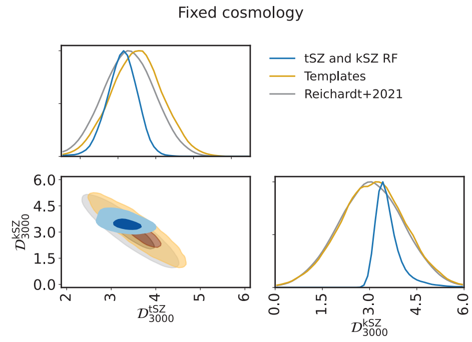

Figure 3. Constraints on the amplitude of the tSZ and kSZ power spectra at $\ell = 3000$, in μK^2, obtained with SPT high-ℓ data [4] using either templates (in yellow) or RF-inferred tSZ and kSZ power spectra (in blue), as well as a physical parameterisation of reionisation. Inferences are compared to the initial analysis, with templates and fixed reionisation (in grey). For all cases, the cosmology is fixed. Figure from [10].

forest-emulated spectra (RF) is not perfectly equivalent to reproducing the results of [4] (shown as grey solid lines in Fig. 3) because the parameterisation used to model reionisation has been changed from a redshift-symmetric (tanh) one to an asymmetric one [13].

However, we find that the constraints on reionisation parameters derived from this analysis strongly depend on the values chosen for the fixed cosmological parameters. Hence, we now free the cosmology, using Planck 2018 [14] priors on parameters that have a weak-to-non influence on reionisation ($\Omega_b h^2$, $\Omega_c h^2$, θ_{MC}, n_S) and flat priors on the remaining parameters (A_S, z_{re}, z_{end}, α_0, κ). We show results in Fig. 4. Freeing the cosmology barely impacts the constraining power of the cosmology-dependent SZ spectra as we report a more than 5σ measurement of the amplitude of the kSZ angular power spectrum, marginalised over cosmology $\mathcal{D}_{\mathrm{kSZ}} = 3.4 \pm 0.6\,\mu\mathrm{K}^2$ (68% C.L.). These values result in a well-constrained reionisation history, compatible with Planck one, with slight differences: the SPT data indeed seem to favour earlier reionisation scenarios, with $z_{\mathrm{re}} = 7.9^{+1.1}_{-1.3}$ (68% C.L.), corresponding to $\tau = 0.062^{+0.012}_{-0.015}$ (68% C.L.), in agreement with current constraints on the IGM ionisation level obtained from Lyman-α emitters and quasar spectra.

The parameterisation used to derive the kSZ spectra allows us to decompose the signal between its patchy and homogeneous component, measure both amplitudes and see the shape of both spectra. Hence, we provide the first direct upper limit on the amplitude of the kSZ power stemming from reionisation $\mathcal{D}_{3000}^{\mathrm{pkSZ}} < 1.6\,\mu\mathrm{K}^2$ (95% C.L.), about half of the previous upper limit [4]. Regarding the shape, our results favour a stronger small-scale power of the tSZ and kSZ effects than traditionally allowed by templates.

4 Conclusions

This work demonstrates the potential of small-scale CMB data to constrain reionisation and cosmology, even at the 2-point level and even with current data. Results should considerably improve with the new generations of both SPT and ACT, and, later, with CMB-Stage 4 experiments. We also show that leveraging the cosmological information in foregrounds leads to cleaner measurements of the tSZ and kSZ amplitude, and in particular allow a measurement of the purely reionisation-sourced kSZ power (patchy amplitude). With our random-forest-based framework, we obtain self-consistent constraints on reionisation, with a reionisation model consistent throughout the CMB multipoles analysed.

However, our results suffer from the poor modelling of other secondary anisotropies and foregrounds, and, in particular, the use of a template for the CIB angular power spectrum. A fully consistent analysis of large- (Planck) and small-scale (SPT) data, modelling foregrounds

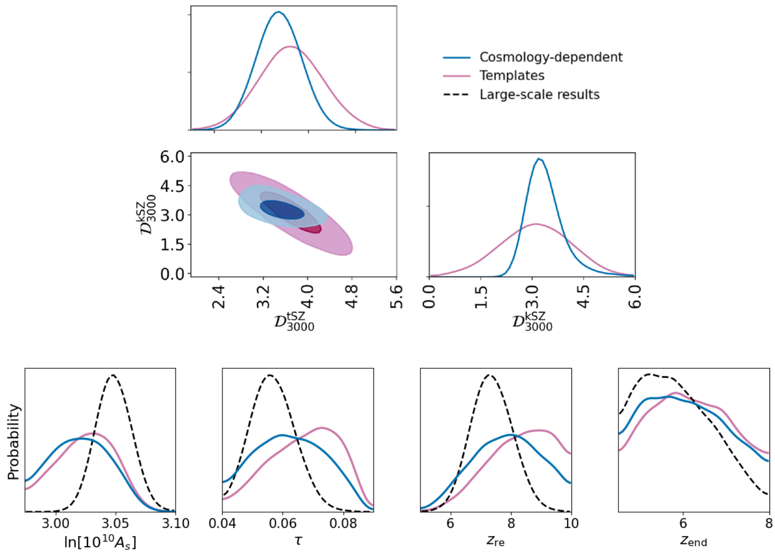

Figure 4. Constraints on the tSZ and kSZ amplitudes at $\ell = 3000$ (*top*) and on cosmological parameters (*bottom*) obtained with SPT data when freeing the cosmology. The Planck 2018 priors used are shown as dashed black lines. Figures from [10].

other than SZ consistently across scales, is required to improve our results, as we have only included the large-scale data as priors here.

Finally, the model of the electron power spectrum used to derive the kSZ spectrum, based on Eq. (1), could also be used to compute the corresponding 21 cm signal, enabling joint constraints on reionisation from CMB and 21 cm observations.

The tSZ & kSZ emulators are public and available at https://szdb.osups.universite-paris-saclay.fr.

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