Future CMB polarization observatory in the presence of foregrounds and gravitational lensing: the Simons Array

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We present a new forecasting method for future CMB instruments, as well as an overview of the design and status of the Simons Array experiment. CMB4CAST is a new code allowing the CMB community to estimate the scientific performance of a given instrumental design in the presence of astrophysical foregrounds and gravitational lensing. The Simons Array is a CMB polarimetry experiment which aims at characterizing the arcminute angular scale B-mode signal from weak gravitational lensing and search for the degree angular scale B-mode signal from inflationary gravitational waves. It is composed of three receivers observing at 95, 150, 220 and 280GHz, each of them having a 365 mm diameter focal plane cooled to 270 milli-Kelvin. The entire array has 22,764 polarization sensitive Transition Edge Sensor (TES) detectors, associated with lenslet-antenna coupled pixels that are sensitive to two frequency bands simultaneously. The first receiver, named POLARBEAR-2, will deploy in 2016 in the Atacama desert in Chile. The Simons Array will achieve first light in 2018 and will be able to constrain tensor-to-scalar ratio to $\sigma(r = 0.1) = 6 \times 10^{-3}$, and the sum of neutrino masses to $\sigma\left(\sum m_\nu\right) = 40$ meV when combined with spectroscopic galaxy surveys.

1 Introduction

Measurements of the Cosmic Microwave Background (CMB) temperature and polarization anisotropies open a unique window onto the physics of the early and late Universe, bringing powerful observational constraints on cosmological models. The observation of even parity polarization patterns, E-mode, of the CMB are in agreement with temperature anisotropy observations [15], and fit up to a high level of fidelity the standard cosmological model, ΛCDM. Recently, the first direct and cross-correlated measurements of the odd parity polarization pattern, B-mode, were also reported [12,13,10,11,17,9,18]. The B-mode polarization has two primary sources; First, primordial gravitational waves, if present, would polarize the CMB at degree angular scale [2]. Tighter upper limits or detection of this signal will constrain inflation model and energy level associated to the inflation potential. Second, weak gravitational lensing induced by large scale structures breaks E-mode patterns' symmetry and produces small amounts of B-mode polarization patterns [3]. The B-mode signal from weak gravitational lensing peaks around ten arcmin angular scales. Its characterization could constrain the cosmological parameters governing the formation of large scale structures such as the sum of neutrino masses and the evolution of dark energy equation of state.

In parallel to the contamination from gravitational lensing, detection of primordial B-modes is obscured by astrophysical signals coming from our galaxy. There is now growing evidence that there are no regions of the sky in which B-mode emission from galactic dust can be neglected when attempting to extract inflationary B-modes at frequencies above $\sim$ 100 GHz. Planck's results suggest that polarized foregrounds such as synchrotron radiation and dust emission need to be carefully subtracted for accurate CMB polarization measurements [16,14]. In this context, as detailed below, the Simons Array uses highly sensitive receivers with a broad frequency coverage which has been optimized for foreground mitigation.

2 Forecasting in the presence of foregrounds and gravitational lensing

Errard et al (2016) [19] presents a new framework to forecast the scientific performance of future CMB observatories in the presence of polarized astrophysical foregrounds (dust, synchrotron) and gravitational lensing – that can potentially be removed using the so-called delensing methods. The parametric maximum likelihood approach (PMLA) uses the following reasoning:

- For each sky pixel p, the observation at a frequency f is given as a linear combination of the sky components s_p, with the weights being encapsulated into a so-called mixing matrix $\mathbf{A}$,

$$d_{f,\,p} = \sum_c \mathbf{A}_{fc}\, {s_p}^c + n_p \tag{1}$$

  where the index c goes over sky components {CMB, dust, synchrotron} and n_p corresponds to the noise in each sky pixel.

- The parametric component separation assumes that the emission laws can be parametrized i.e. that the mixing matrix, $\mathbf{A}$, has a known functional form involving "spectral" parameters that have to be estimated. Given the data model in Eq. 1, the PMLA estimates the spectral parameters via the maximization of a so-called spectral likelihood [1,4,5]. Note that any imperfect estimation of the spectral parameters might lead to the presence of foregrounds residuals in the component-separated CMB map [6,7].

- Once the mixing matrix is estimated, we can "invert" Eq. 1 to disantangle the CMB signal from the other sky components:

$$\tilde{s}_p = \left(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{N}^{-1}d \tag{2}$$

  Note that the noise variance, after component separation, associated with the reconstructed CMB map is given by $\sigma_{\rm CMB} = \left[\left(\mathbf{A}^T\mathbf{N}^{-1}\mathbf{A}\right)^{-1/2}\right]_{\rm CMB\times CMB}$, which is higher than the simple quadratic combination of sensitivities from each observed frequency map.

CMB4cast uses the approximation described in Errard et al (2011,2012) [7,8] which evaluates the spectral likelihood at its peak and approximates the error bars on spectral parameters using the curvature of the spectral likelihood [a].
The code also evaluates the delensing performance: given a measurement of E-mode and the reconstruction of the lensing potential, it is possible to estimate and remove the contribution of lensing B-modes from the observed total B-mode signal. In addition, the estimation of the lensing potential can be performed using the observation of the CMB alone, or by exploiting the cross-correlation between CMB and large scale structures observations such as the cosmic infrared background [19].
Finally, CMB4cast estimates the error bars on cosmological parameters using a Fisher approach, which includes contributions from post-component separation noise, foregrounds residuals and delensing. The code has been applied to many planed ground-based and space-borne instruments, and the numerical efficiency of the implementation has allowed for an optimization of the instrumental designs with respect to the achievable constraints on inflation or on the dark sector. This led, in particular, to the Simons Array's current configuration.

[a] Errard et al (2011) [7] gives a semi-analytical expression for the curvature of the likelihood, which allows for quick numerical evaluation of it.

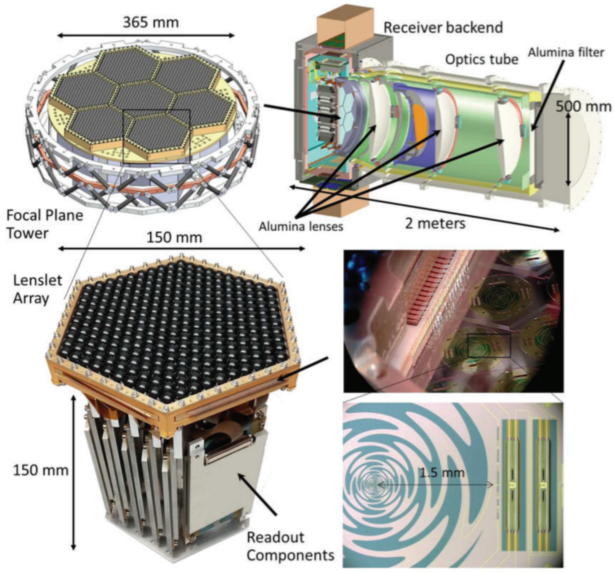

Figure 1 – (Color online) CAD drawing of the POLARBEAR-2 receiver (upper right), and CAD drawing of the focal plane tower (upper left). Three temperature stages (250 milli-Kelvin, 350 milli-Kelvin, 2 Kelvin) are separated by vespel support structures. Photograph of a detector module (bottom left), which consists of a detector wafer, lenslet wafer, Invar holder, and cryogenic readout electronics. Automated wirebonds have 100 μm pitch (bottom right). The Sinusoidal circular structure is a broadband antenna. Large rectangular structures are TES bolometers. The RF diplexer filter is visible between the antenna and the bolometers (bottom right). From Suzuki et al (2016) [20].

3 The Simons Array project

The POLARBEAR-2 receiver, first among three involved in the Simons Array, will observe from the James Ax observatory at 5,200 meter altitude in the Chilean Atacama Desert. The site has access to 80% of the sky, which allows for powerful cross-correlation with other experiments (LSST, Euclid, etc.). The POLARBEAR-2 receiver will be mounted on a telescope with the same design as the Huan Tran Telescope (HTT) that is currently observing with the POLARBEAR-I receiver. The HTT features an offset Gregorian design obeying the Mizuguchi-Dragone condition to minimize instrumental cross-polarization. The HTT has co-moving baffles to minimize sidelobes. The 3.5 meter primary mirror produces a 5.2/3.5/2.8/2.2-arcmin FWHM beam at 95/150/220/280 GHz. The POLARBEAR-2 receiver will deploy at 95 and 150 GHz frequencies in 2016. The second receiver will cover 95 and 150 GHz as well, and the third receiver will cover 220 and 280 GHz bands. The second and third receivers will deploy in 2017. Sensitivity of the Simons Array in its final configuration is $8.3\,\mu\mathrm{K_{CMB}}\sqrt{s}$ at both 95 and 150 GHz, $26.9\,\mu\mathrm{K_{CMB}}\sqrt{s}$ at 220 GHz and $57.7\,\mu\mathrm{K_{CMB}}\sqrt{s}$ at 280 GHz. The Simons Array will be able to constrain the tensor-to-scalar ratio r to $\sigma(r = 0.1) = 4 \times 10^{-3}$ when considering only CMB signal, and $\sigma(r = 0.1) = 6 \times 10^{-3}$ when foregrounds are cleaned in combination with Planck data sets [19]. The Simons Array will also be able to constrain the sum of neutrino masses to 19 meV at 1-σ when considering CMB signal alone — and 40 meV when foreground cleaning is considered — and when cross-correlations with spectroscopic galaxy surveys are used. A cross-sectional view of a typical POLARBEAR-2 receiver is shown in Figure 1.

4 Conclusion

We have presented the new forecasting framework for CMB instruments named CMB4CAST, with a world wide accessible interface at `http://portal.nersc.gov/project/mp107/index.html`. The Simons Array experiment will measure and characterize the polarization of the CMB with high sensitivity. Its first receiver, POLARBEAR-2, will deploy in 2016 and the Simons Array will be fully deployed in 2017.

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