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Constraints on the primordial universe through the cosmic microwave background polarisation

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If parity invariance is broken in the primordial universe, the cosmic microwave background TB and EB cross-correlations, usually vanishing, become non zero. Their detection would then constrain the level of parity violation, δ. I propose to present forecasts on the detection of this parameter by realistically estimating the uncertainties on the TB and EB spectra via the *pure* pseudo spectrum method, which efficiency has been shown in [1]. I will present the results of this forecast (Ref. [2]) in the case of two typical experimental setups: a small-scale experiment and a large scale survey. Our results show that no constraints can be put on δ in the former case. However a range of model would be accessible with a future CMB satellite-like mission: for instance, a parity violation of at least 50% with $r = 0.2$ could be detected.

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1. Introdution: the CMB polarisation

Before the release of the cosmic microwave background (CMB), the photons were coupled to the electrons via Thomson scattering. When the diffracting electron is surrounded by a quadropular intensity anisotropy, it scatters light with a prefered polarisation. Such quadrupolar anisotropies can be caused by density fluctuations and gravitational waves. As a consequence, the CMB anisotropies are linearly polarised, as imprints left by the scalar and tensor perturbations present in the primordial Universe.

The CMB polarisation is completly described by the Stokes parameters Q and U from which we define the spin-2 polarisation filed $P_{\pm 2}$:

$$P_{\pm 2}(\vec{n}) = Q(\vec{n}) \pm iU(\vec{n}), \tag{1.1}$$

with $\vec{n}$ the direction of the line of sight. Its decomposition on the spinned spherical harmonics gives:

$$P_{\pm 2}(\vec{n}) = \sum_{\ell m} {}_{\pm 2}a_{\ell m}\ {}_{\pm 2}Y_{\ell m}(\vec{n}). \tag{1.2}$$

This polarisation field can also be decomposed in two scalar fields, the so-called E and B modes. Their multipoles are defined as:

$$\begin{cases} a^E_{\ell m} &= -\frac{1}{2}[\ {}_2a_{\ell m} + {}_{-2}a_{\ell m}\ ], \\ a^B_{\ell m} &= \ \ \frac{i}{2}[\ {}_2a_{\ell m} - {}_{-2}a_{\ell m}]. \end{cases} \tag{1.3}$$

From the CMB temperature, E and B modes multipoles, we construct six angular power spectra as:

$$\left\langle a^X_{\ell m} a^{Y}_{\ell' m'}{}^* \right\rangle = C^{XY}_\ell \delta_{\ell\ell'} \delta_{mm'}, \tag{1.4}$$

where X, Y stand for the temperature T, E or B. However, the TB and EB correlations vanish in the standard model of cosmology, thanks to parity argument.

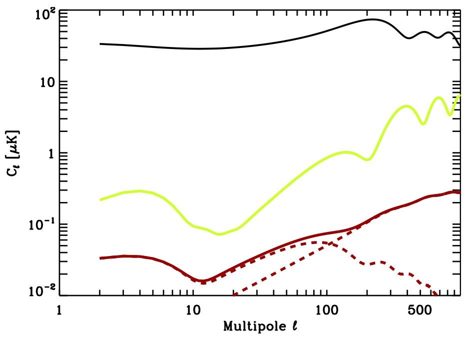

Figure 1: The temperature, EE and BB angular power spectra in black, green and red respectively with $r = 0.05$. The dashed red line dominating at large (small) angular scales is the primordial (respectively lensed) contribution to the BB power spectrum.

The temperature and EE power spectra are mainly produced by scalar perturbations (the density fluctuations). On the contrary, the BB power spectrum at large angular scales is only sourced by primordial gravitational waves. Its amplitude is therefore scaled by the tensor-to-scalar ratio r. On small angular scales, the BB power spectrum is dominated by the lensing of the E modes by the large scale structures. The figure 1 depicts the temperature, EE and BB power spectra, highlitghting the expected low amplitude of the BB power spectrum (for $r = 0.05$) compared to EE and TT power spectra (as B modes are caused by tensor perturbations).

The lensed BB power spectrum has been already detected by the SPTPOL [3] and POLARBEAR [4] experiments while its primordial part still remains unobserved despite the various experiments dedicated to their detection. The presence of gravitational waves is predicted by cosmic inflation, the detection of the BB power spectrum at large angular scales would therefore be a smoking gun for the existence of inflation.

The CMB polarisation is thus an open window to the physics of the early universe. In this talk, we present the results for realistic forecasts of constraints to be set firsly on the tensor-to-scalar ratio r and on a potential parity violation δ at the level of the gravitation. The approach we adopted in both analysis is to start from a parametrisation of a model and then use a realistic estimation of the CMB polarised power spectra and uncertainties to forecast constraints on the paramter by the use of the Fisher matrix.

Due to the finite amount of independant directions to average on, the CMB power spectra cannot be reconstructed with an infinite precision. The smallest variance that can be achieve on the reconstructed CMB power spectrea is the so-called *sampling variance* for which an analytic formula can be derived. For a given expriment, the sampling variance ΔC_ℓ^{BB} formula (refered to as the *mode counting* variance in the following) for BB power spectrum for instance is given by:

$$\Delta C_\ell^{BB} = \frac{2}{(2\ell+1)f_{sky}} \left(C_\ell^{BB} + \frac{N_\ell}{B_\ell^2} \right)^2 \tag{1.5}$$

with f_{sky} the observed sky fraction, B_ℓ the beam power spectrum and N_ℓ the noise power spectrum. However, this variance underestimates what is generally achieve and is therefore idealised. One major statistical issue arising when estimating the CMB polarised power spectra is the E-to-B leakage due to the observation of the CMB on a partial part of the celestial sphere. The so-called *pure* estimation of the CMB polarisation power spectra (see [5, 6]) has been proved to be very efficient to correct for this leakage and achieve small variance on the reconstructed CMB polarised power spectra (see [1]). We therefore propose to make use of this powerful method to derive the uncertainties on the CMB polarised power spectra entering the Fisher matrix. We will compare the forecasts obtained using the *ideal* sampling variance and the *realistic* variance derived from the pure method.

Furthermore, we investigate the constraints that could be set from two kinds of experiment. The two fiducial expiremental set ups used in the analysis are:

- a satellite-like experiment with an observed sky fraction of $f_{sky} = 71\%$, an 8 arcmin beam and a noise of $2.2\mu K-$arcmin (typical of forthcoming space based telescope dedicated to CMB observed). It will be refered to as a large scale experiment. The binary mask used in our analysis is shown on the right panel of Fig. 2;
- a fiducial ground-based or ballon-borne experiment with $f_{sky} = 1\%$, an 8 arcmin beam and a noise of $5.75\mu K-$arcmin. It will be refered to as a small scale experiment. The binary mask used in our analysis is shown on the left panel of Fig. 2.

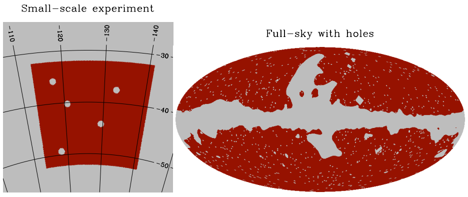

Figure 2: The binary masks of a fiducial small (large) scale experiement on the left (right) panel. The red (grey) part is the observed (unobserved respectively) pixels.

In the following, we will present the forecasts obtained firstly on the tensor-to-scalar ratio r and secondly on a potential parity violation δ.

2. Forecast on the detection of the tensor-to-scalar ratio

As mentioned before, the primordial *BB* power spectrum amplitude is scaled by the tensor-to-scalar ratio r[1]. The BB power spectrum can therefore be parametrised as:

$$C_\ell^{BB}(r) = r \times \mathscr{T}_\ell^{BB} + \mathscr{T}_\ell^{E\to B} \tag{2.1}$$

with $\mathscr{T}_\ell^{BB}$ and $\mathscr{T}_\ell^{E\to B}$ are fiducial power spectra which do not depend on r. The former (latter) is the primordial (resp. lensed) contribution of the *BB* power spectrum.

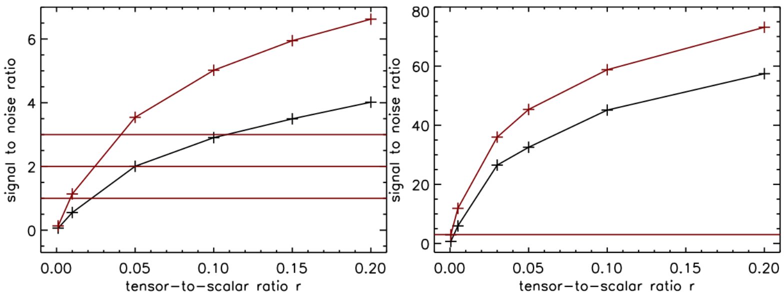

Figure 3: The signal-to-noise ratio on the tensor-to-scalar ratio r obtained using the mode counting (pure) approach is shown in red (resp. black) for the case of a small sky survey in the left panel and a large scale survey in the right panel.

We perform our analysis in the case of the two approaches for the both kind of experiments using the information that could be given from the detection of the *BB* power spectrum. The obtained forecasts are shown in Fig. 3, the left panel corresponding to a small scale experiment and the right one to a large scale survey. We vary the tensor-to-scalar ratio r from 0.001 (0.0005 for the large scale experiment) to 0.2. We observe that the signal-to-noise ratios on r is smaller in the case of the pure approach than in the mode counting estiamation. The latter is indeed an underestimation of the power spectrum variance as explained above. According to our results, we could realistically expect a detection of r above 3σ greater than 10^{-3} in the case of a forthcoming satellite survey.

[1]The pivot scale is 0.002 Mpc^{-1} in our analysis.

A typical current ground-based or balloon-borne experiment would give a detection above 3σ of r greater than 10^{-1}. A satellite-like survey would consequently help distinguishing between small and large field models of inflation while a small scale experiment would be sensitive only to large field. The complete study can be found in [7].

3. Forecast on the detection of parity violation

In this section, we focus on the detection of a parity violation in the primordial universe at the level of the gravity waves. Such a symetry breaking could indeed occur according to the re-formulation of general relativity in [8]. In this case, gravity would be chiral meaning that left- and right-handed gravitational waves would be generated in different amount. They can be described by two different power spectrum $P^{R(L)}(k)$ for the right-(left-) handed gravitational waves. Their difference would generate non-zero TB and EB power spectra (see [9]) that can be parametrised by a parameter r_- in the same way C_ℓ^{BB} is parametrised by r in the standard model. However, in the case of chiral gravity, the primordial part of the BB power spectrum is parametrised by r_+. We define the strength of the parity violation δ as:

$$\delta = \frac{r_-}{r_+}. \tag{3.1}$$

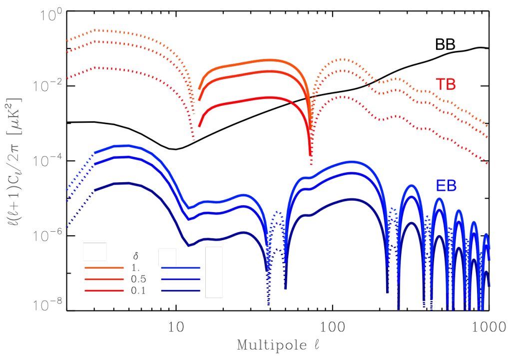

Figure 4: The BB, TB and EB correlations in black, red shaded and blue shaded curves respectively for $\delta = 100\%, 50\%$ and 10% and $r_+ = 0.05$. The dashed lines stand for negative values of the correlations.

In order to investigate the constraints that could be set on δ, we consider the information contained in BB, TB and EB power spectra. An exemple of these power spectra for different values of δ is represented in Fig.4. We derived the uncertainties on these corellations in the case of the mode counting and the pure approaches. The obtained error bars are depicted in Fig. 5 with the TB correlations as an example. The binned version of the error bars are shown in dashed lines and indicate that a part of the TB correlations can eventually be detected thus allowing to set constraints on δ.

The results of our analysis shows that a current ground-based or balloon-borne experiments would not be able to set constrain in δ, the variance being too high, particularly on large angular scales. However, a potential space-based telescope would be able to set constraints on a range of parity violation model. We indeed checked that the signal-to-noise ratio on δ for different values of

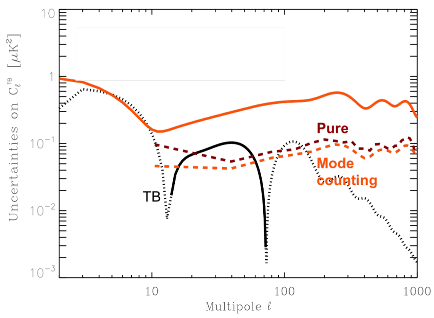

Figure 5: The TB correlation for $\delta = 1$ and $r_+ = 0.1$ is shown in black with its error bars computed multipole-by-multipole with the mode counting approach in orange. The dashed orange curve is the binned version of these error bars while the red dashed line stands for the pure estimation of the error bars.

δ and r_- using the mode counting estimation of the variance on CMB power spectra is above 3σ. We therefore investigate more precisely the signal-to-noise ratio that one could realistically expect. Our results reveal that a $\sim 5\sigma$ ($\sim 3.5\sigma$ resp.) detection of $\delta = 100\%$ for $r_+ = 0.2$ ($r_+ = 0.1$ resp.) would be possible. A potential satellite survey would thus be able to set constrain on a range of δ which can be translated in the relevant parameter of the considred theory predicting a parity violation. The detailed analysis can be found in [2].

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