Exercises for Experimental methods in Astroparticle Physics

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Sheet 10

1. CMB Anisotropies

Temperature fluctuations in the CMB can be described by making an expansion in spherical harmonics:

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{\ell=1}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_m^{\ell}(\theta,\phi) \tag{1}$$

The analysis of the CMB temperature anisotropies are based on the computation of the parameters C_ℓ:

$$C_\ell \equiv \left\langle |a_{\ell m}|^2 \right\rangle = \frac{1}{2\ell+1} \sum_m \left\langle |a_{\ell m}|^2 \right\rangle, \quad \text{where} \tag{2a}$$

$$a_{\ell m} = \int \mathrm{d}\Omega \, Y^*_{\ell m}(\theta,\phi) \frac{\delta T}{T}(\theta,\phi). \tag{2b}$$

Demonstrate that the area under the curve given by plotting $\frac{(2\ell+1)}{4\pi} C_\ell$ versus ℓ returns the squared deviation from the average CMB temperature.

2. CMB Polarization and Primordial Fluctuations

The next frontier of CMB research is dedicated to measuring the polarization of the CMB, in particular the B modes. In Figure 1, the total power spectrum as well as the contributions of the different modes are plotted. The B modes, however, are unique in that measuring them could allow us to infer something on the gravitational waves that appeared during cosmic inflation, called primordial B-modes. The amplitude of the primordial waves is usually parametrized by r, the tensor-to-scalar ratio. Mapping the CMB is most efficient with the use of photon-noise limited detectors - that is, detectors for which the dominant noise source arises from the incident photons and not from the detector or other sources. For this kind of detectors, we can define the observation time t required to achieve a polarization map depth M (a kind of measure for RMS noise) which allows reaching the sensitivity to detect small B-mode fluctuations in a sky area A_{sky}, given by

$$t = 2\left(\frac{NET_{\text{CMB}}}{M}\right)^2 \frac{A_{\text{sky}}}{\eta_0}, \tag{3}$$

where NET_{CMB} is the **n**oise **e**quivalent **t**emperature relative to the CMB, η_0 is the observation efficiency, i.e. the fraction of time the instrument can measure.

- Calculate the required time to reach a polarization depth of $M = 7\,\mu\text{K}\,\text{arcmin}$ necessary to achieve a sensitivity on primordial gravitational wave signals foreseen by a model

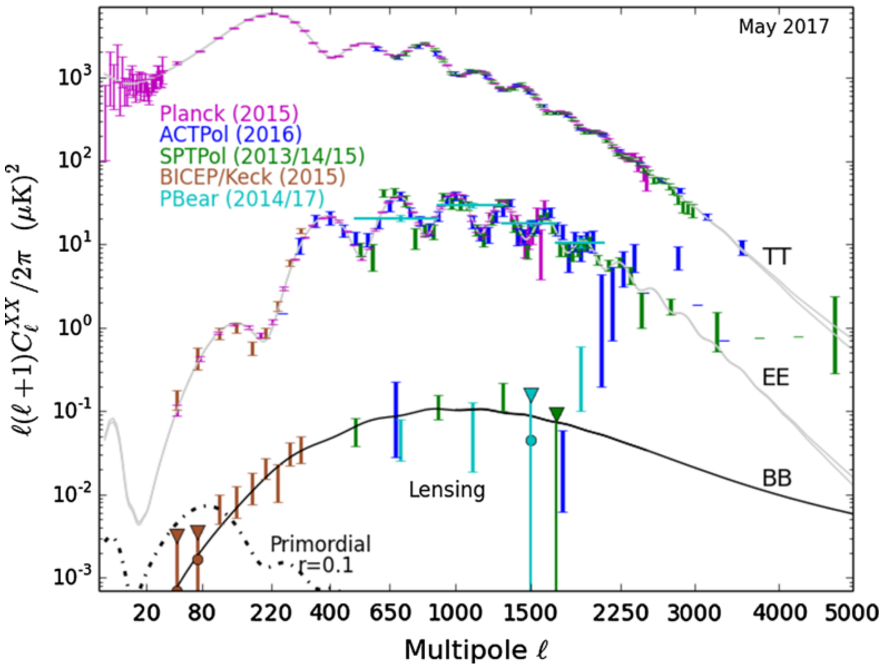

Figure 1: The CMB angular power spectrum with contributions from temperature anisotropy ("TT"), E-mode polarization ("EE"), and B-mode polarization ("BB"), containing lensing and primordial effects (at an tensor-to-scalar ratio $r = 0.1$,
from: arXiv:1807.01384

with $r = 0.07$ by observing $1\,\%$ of the sky, with an ideal observation efficiency of $\eta_0 = 1$ and with a noise equivalent temperature $NET_{\mathrm{CMB}} \simeq 10\,\mathrm{\mu K}\sqrt{\mathrm{s}}$.

- Calculate the required time for the realistic (and sobering) case, with $\eta_0 \simeq 0.2$ and a state-of-the-art sensitivity of $NET_{\mathrm{CMB}} \simeq 200\,\mathrm{\mu K}\sqrt{\mathrm{s}}$. Give reasons why η_0 is smaller than 1.

3. The High Frequency Instrument on the Planck Satellite

The Planck space mission was launched in May 2009 and ended operations in October 2013. One of the two focal instruments of the Planck mission is the High Frequency Instrument (HFI), which has been observing the whole sky in six bands in the $100\,\mathrm{GHz}$ to $857\,\mathrm{GHz}$ range. The HFI instrument is designed to measure the CMB anisotropy and polarization with angular resolution ranging from $5\,'$ to $9\,'$ with a sensitivity limited only by fundamental sources, namely the photon noise of the CMB itself and the residuals left after the removal of foregrounds. The HFI focal plane contains 52 silicon-nitride micro-mesh bolometers operating at $100\,\mathrm{\mu K}$. You can read the paper doi:10.1116/1.1642644 to get some more information on the development and fabrication of Planck HFI CMB detectors.

(a) Briefly describe the concept of CMB detection using low temperature bolometers.

(b) List the benefits of having a spiderweb design for CMB detection.

Table 1 summarizes the detector forming the HFI focal plane. Each polarized channel has dual-polarization cabalities, meaning there are two orthogonal directions within the same device.

(c) Why have these frequency bands been selected?

Band (GHz)	Polarized channels	Unpolarized channels	Modes	Bandwidth (GHz)
100	4	0	Single	83.5 - 116.5
143	4	4	Single	119.5 - 166.5
217	4	4	Single	181 - 253
353	4	4	Single	295 - 411
545	0	4	Few-moded	455 - 635
857	0	4	Multi-moded	716 - 999

Table 1: Focal plane composition

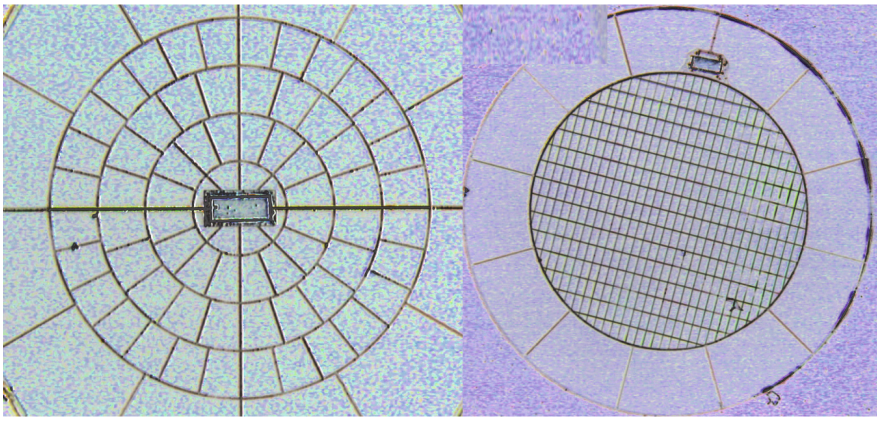

Figure 2: Picture of a 143 GHz *(left)* and of a 217 GHz spiderweb bolometer *(right)*, with a temperature sensor in the centre and at the upper edge respectively.

Figure 2 shows two spiderweb detectors for 143 GHz and 217 GHz respectively.

(d) Indicate which of the two spiderweb detectors is polarization sensitive, and why.

(e) Which suspended structures are metallized?

(f) *(Optional)* In the two pictures, the NTD-Ge detector can be clearly seen. Knowing that such a sensor is about 300 µm long, 50 µm wide, and 25 µm thick, extrapolate the size of the spiderwebs and interpret the dimension in relation to the wavelength to be detected.

(g) *(Optional)* The web legs are 4 µm wide and 1 µm thick. Estimate the filling factor for the detector in Figure 2 on the right.