HEMISPHERICAL POWER ASYMMETRY IN INTENSITY AND POLARIZATION FOR PLANCK PR4 DATA

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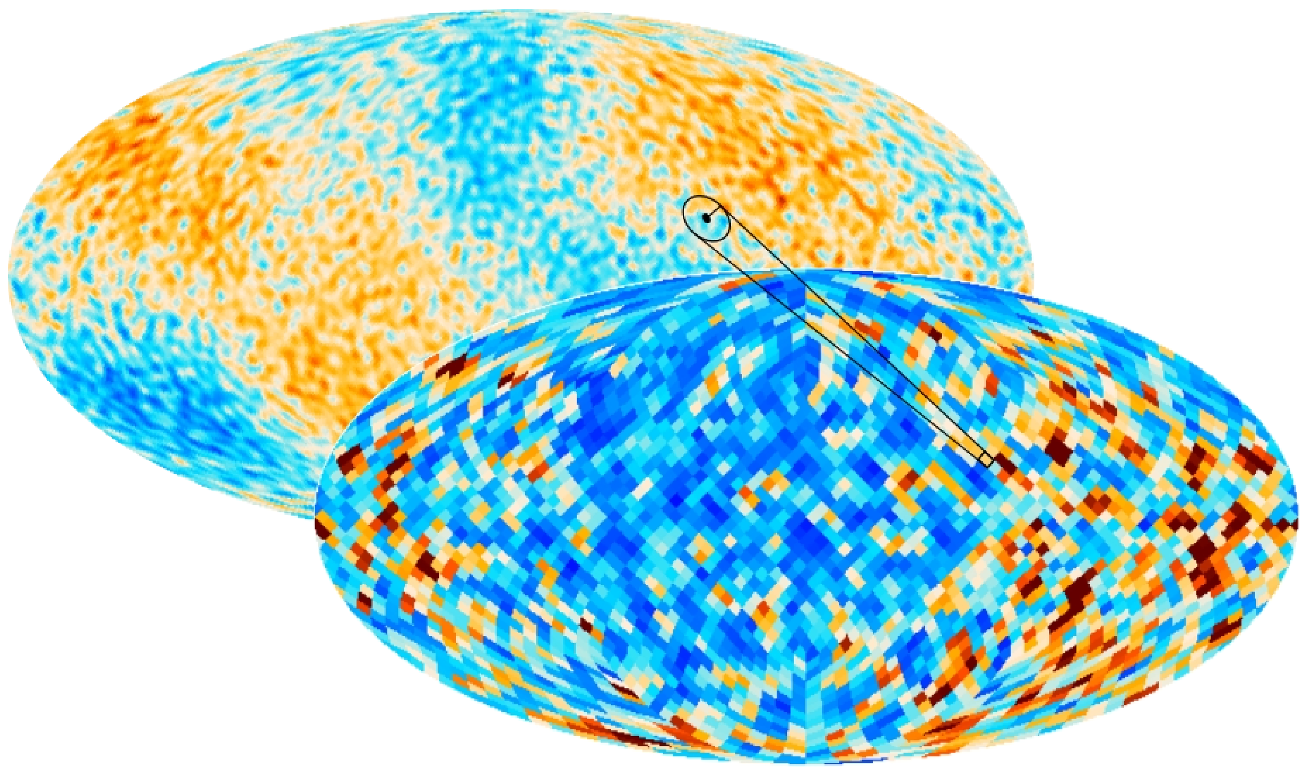
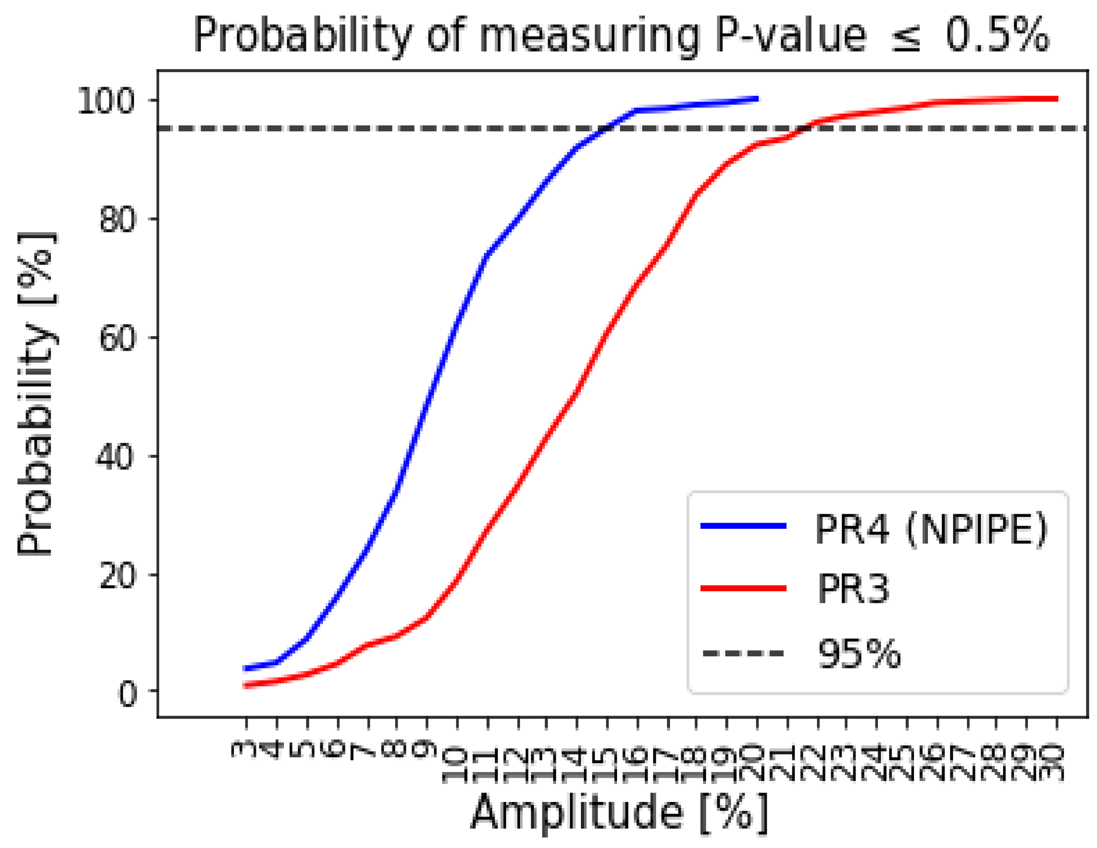
I. Introduction

One of the fundamentals of the standard model of cosmology is the statistical isotropy of the universe at large scales. However, WMAP and Planck temperature data show evidence of several anomalies hinting that the large-scale anisotropies are not fully compatible with the statistical isotropy assumption. In particular, one of them, known as "hemispherical power asymmetry" **[1]**, suggests a directional dependency of the anisotropies. This asymmetry has been found using different estimators with a significance close to **3σ** **[2, 3, 4]**. Modeling the asymmetry in terms of a dipolar modulation **[2]** allows us to determine the statistical significance, the direction, and the amplitude. In temperature the observed asymmetry is compatible with a modulation of ~7% **[2, 4]**. Applying the same analysis to the Planck third release (PR3) data, a dipolar modulation was found at modest significance **[4]** in the E-mode maps. However, anisotropic noise and large scale systematics plays an important role in this analysis. In this work we repeat the analysis using both, PR3 and the **new Planck fourth release (PR4)** data **[7]**, which provides an improved data set (especially in polarization) with reduced systematics and noise. In addition, we also work with a new **alternative inpainting** approach, which is necessary to reduce the E/B mixing. The **preliminary results** show that using a set of **300 simulations** the p-value increases up to **3.3%**, while we have not found differences in the intensity analysis.

II. Dipolar Modulation Analysis



Local-Variance map at N_{side} = 16



Following **[3]**, we study the asymmetry by computing the local-variance maps over disks of a certain size. A dipolar modulation, of the form

$$E_{mod}(\vec{n}) = E_{iso}(\vec{n}) \cdot (1 + A\vec{p} \cdot \vec{n})$$

in the fluctuation map would manifest itself as a dipole structure in the local-variance map, so we can fit it by a χ^2. The first figure shows how a local-variance map looks like starting from a modulated E-mode map.

Using simulations we can calibrate numerically the proportionality between the amplitude of the local-variance dipole and the amplitude of the modulation. We can also predict the ability of the method to detect modulations of a given amplitude (see figure on the left).

If we apply a mask, we only consider disks where at least 10% of the pixels are unmasked.

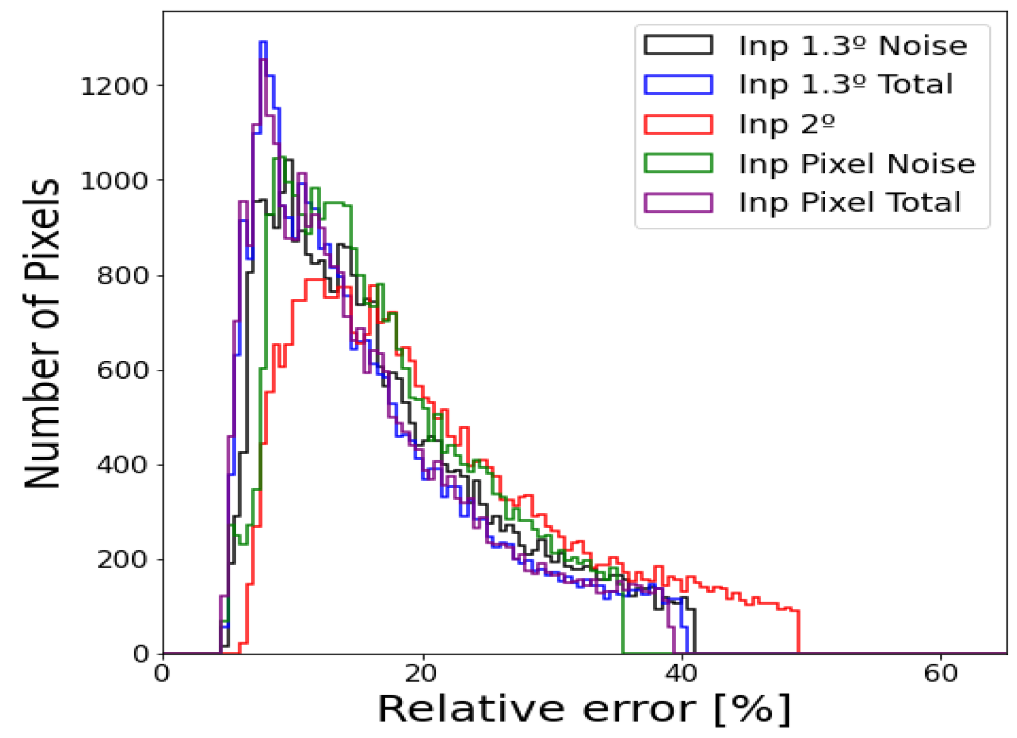
III. Inpainting

Working with masked QU maps produce an E/B mixing. In order to have a better E-mode reconstruction we need to fill masked pixels by using an inpainting technique.

For the first time in polarization we have implemented an inpainting technique known as **"Gaussian constrained realization"** **[6]**. We fill the masked pixels coherently with a cosmological model and taking into account the unmasked pixels. The pixel covariance matrix needed for this has 2 contributions: the CMB signal, and the noise and systematics. CMB can be computed from the angular power spectra **[5, 6]**, while noise must be estimated numerically. We have split the noise simulations and used the first half for estimating the covariance matrix and the second for the analysis. Unfortunately, the number of simulations is not enough for the matrix to reach convergence, and the inpainting is not as good as we predicted using only CMB. We have tried a variety of ways of estimating the matrix, and we have chosen the one that minimizes, for the same f_{sky}, the maximum relative error (see green line in the figure in the right side). Using simulations it is shown that the residuals are lower than just masking, and also that this method produces more stability in the p-values.

The mask used in the analysis has been obtained by expanding the PR3 polarization common mask and thresholding the error in the residuals to **38%** of the real signal (**35.5%** for PR4), which admits **64% of the sky**, similar to the f_{sky} in **[4]**.

Relative error outside the mask (NPIPE) for different approaches for estimating covariance matrix



IV. Results and discussion

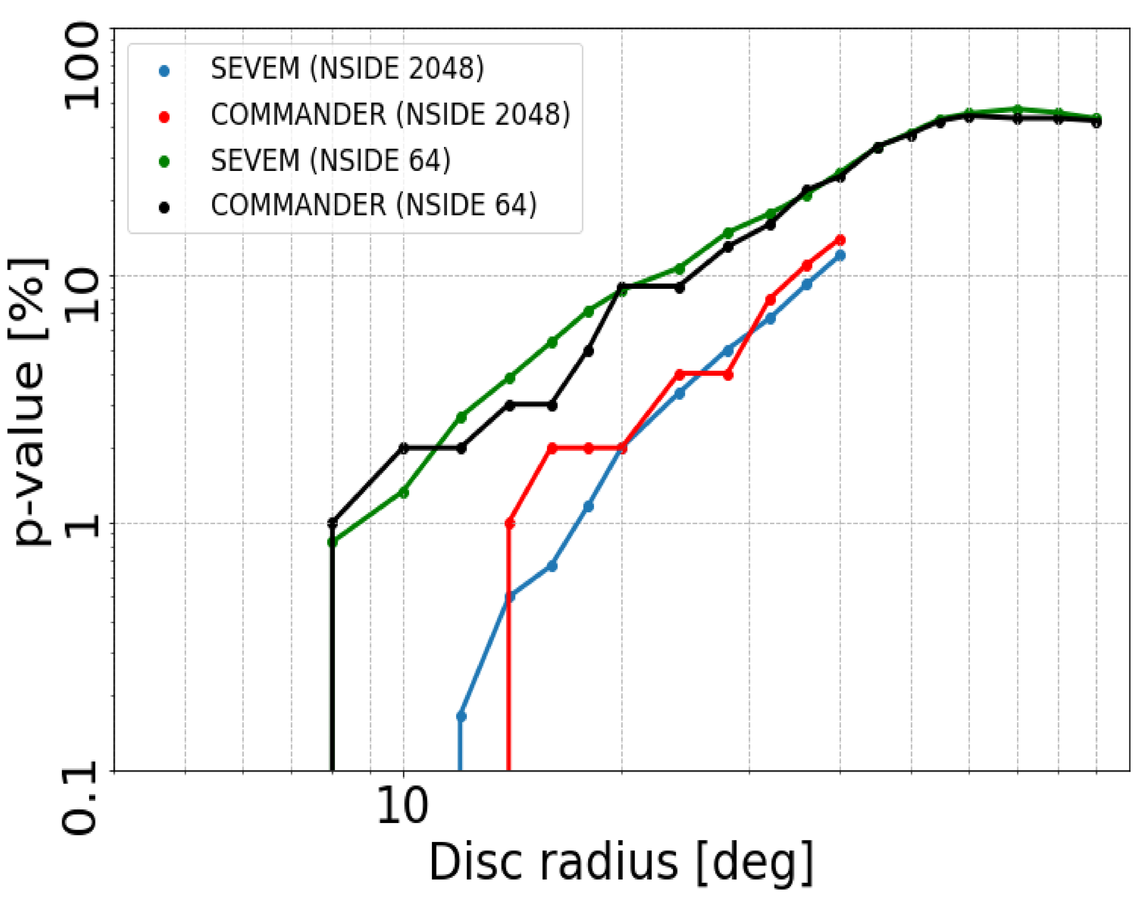
The analysis for the intensity maps is fully consistent with respect to PR3. As in **[4]**, we have computed the local-variance maps for Nside = 2048 and Nside = 64. In both cases **p-values for disks of 4 and 6 degrees are below the limit of sensitivity** (1/600 for SEVEM and 1/100 for COMMANDER). This means that if we focus on variances over this range of angular scales the **temperature sky is asymmetric**. Once the size of the disk increases, the significance falls rapidly, and we obtain curves for the p-value (see figure on the right) similar to **Fig. 31** in **[4]**.

These results are not surprising, and is what we expected, as the major difference between PR3 and PR4 pipelines is in polarization.

We have also obtained the direction of the modulation. They are very similar to those obtained for PR3 in **[4]**, with the small differences between the considered cases within the large uncertainty expected for this quantity (especially for small modulations) and the different number of simulations used in each case.

Table below summarises all the results for temperature.

P-values against disk radius for temperature



The analysis of the **PR3** polarization data applying our inpainting is in good agreement with the results from **[4]**, with **a probability to reject the null hypothesis below 1% and similar direction**.

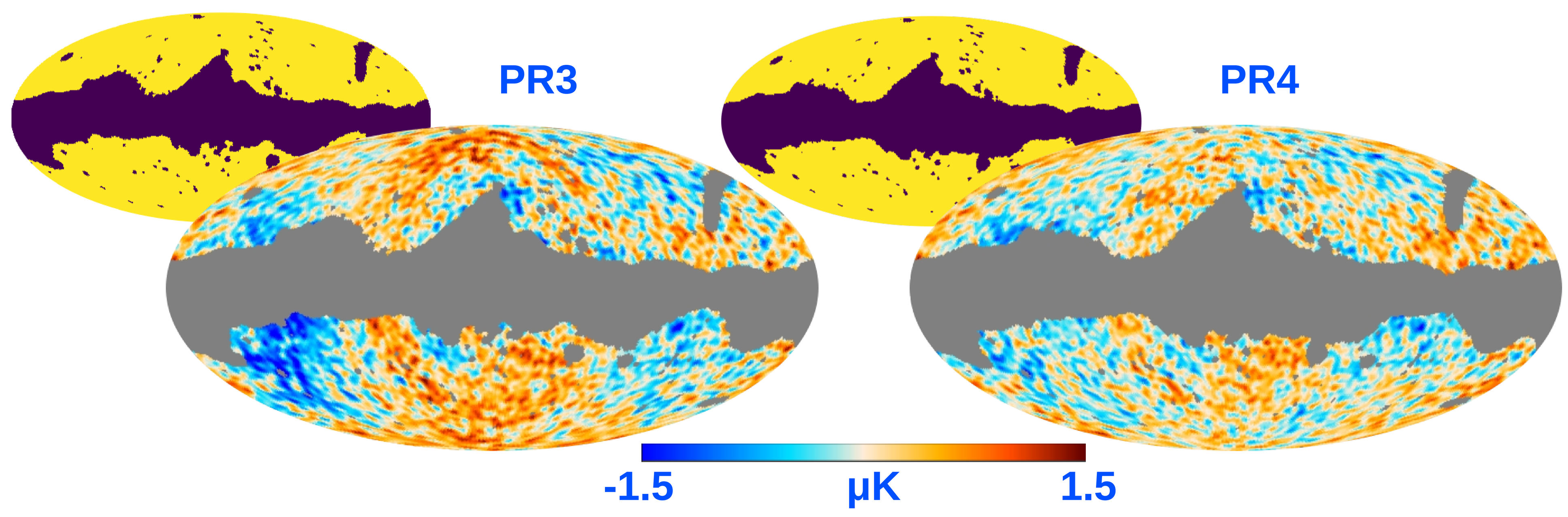
PR4 data points towards a large p-value of **3.3%**. This means that we have found 10 simulations with a local-variance dipole amplitude larger than the one inferred from the data. However, the direction has not changed much between the two pipelines.

Although more work is needed to establish a clear conclusion, since we know that PR4 has less systematics at large scales, this could be the origin of the modest detection in PR3. Moreover, we found that **lower amplitudes are more likely to be detected with PR4 data** and, therefore, this data set should be more sensitive to a dipolar modulation if present in the CMB signal.

All the results for the polarization analysis are summarised in the table below, together with the E-mode inpainted and masked maps.

	PR3 (SEVEM)	PR4 (SEVEM)
P-value [%]	<(1/450)	3.3 (10/300)
Direction [deg]	(240º, -6º)	(235º, -14º)

	P-values [%]			
	NSIDE 64		NSIDE 2048	
Disc radius [deg]	SEVEM	COMMANDER	SEVEM	COMMANDER
4	<(1/600)	<(1/100)	<(1/600)	<(1/100)
6	<(1/600)	<(1/100)	<(1/600)	<(1/100)
8	0.83	1.0	<(1/600)	<(1/100)
Direction [deg]	(208º, -15º)	(213º, -16º)	(205º, -20º)	(207º, -20º)



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