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Statistical Probes of secondary CMB anisotropies and non-Gaussianities

PhD thesis booklet by

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Introduction

The standard model of cosmology describes an expanding Universe governed by the laws of general relativity. The cosmic history began with the Big Bang which was followed by a rapid inflationary expansion. Inflation dramatically interspaced the almost perfectly homogeneous field of matter, and formed the seeds of the Universe we see today (Guth, 1981). In simple inflationary models, early quantum fluctuations are characterized by a statistically homogeneous, Gaussian random field, while statistical properties of primordial fluctuations are closely related to those of the anisotropies in the Cosmic Microwave Background (CMB). Any reliable detection of non-Gaussianity in the CMB, therefore, would constrain the physics of inflation (Bartolo et al., 2010). If CMB temperature fluctuations are characterized by a Gaussian random field, then the two point correlation function fully determines all the statistical properties of such a field. The study of non-Gaussian fields, however, demands to take higher order statistical moments of the field into account for a complete description.

Several interesting variants of non-Gaussian properties have been claimed in the context of the CMB. Low quadrupole (Efstathiou, 2004), parity asymmetry (Bernui, 2008), the Cold Spot (Cruz et al., 2005), and the Axis of Evil (Land and Magueijo, 2005) are well-studied anomalies related to CMB non-Gaussianities and anisortopies, especially on large scales. See Planck 2013 results. XXIII. (2013) for a complete review. Several “anomalies” and alignments were identified, and several tests have been performed to explore their origin (Rassat et al., 2013). These marginally significant anomalies were originally detected in Wilkinson Microwave Anisotropy Probe (WMAP) data, and recently confirmed by *Planck* (Planck 2013 results. I., 2013).

However, a great deal of information is written in the CMB about the dark matter and the gas clouds across the Universe, as they both introduce new patterns into the CMB fluctuations via electromagnetic or gravitational interactions (Aghanim et al., 2008). These effects are known as CMB secondary anisotropies, that are often called as ”foregrounds” as they are enclaved between the surface of the last scattering and the observer. Measurements and modeling of these secondary effects are essential for complete and reliable statistical studies of non-Gaussianities, as they possibly further complicate the picture. We pursued the detection of the Integrated Sachs-Wolfe effect (Sachs and Wolfe, 1967, ISW), i.e. the secondary effect on the CMB caused by decaying gravitational potentials, in order to uncover some properties of dark energy by its possible hot or cold imprints. We thus probed not only the inflationary epoch with the CMB, but also late time physics and properties of the cosmic web.

Accomplishments

We puzzled out several open questions with a widening range of modeling, data analysis, and astro-statistical techniques. We demonstrated how the physical conditions of different epochs in the history of the Universe can be tested with the statistical analysis of CMB data sets. The theses of my dissertation are the following:

1. We performed complex phase analyses using WMAP's 7-year data sets. In our exploratory paper, **Kovács** et al. (2013a), we detected 4.7σ deviation from randomness with random walk statistics. Further tests highlighted, however, that we detected residual foreground contamination at multipoles $200 < \ell < 300$, rather than real cosmological effects, although we constrained $f_{\mathrm{NL}} \approx 40 \pm 200$ as a measure of non-Gaussianity.

2. We generalized the definition of spherical harmonic phases, and built the corresponding statistical and modeling framework for testing the coherence of WMAP and *Planck* data. In the analytical paper, **Kovács** et al. (2013b), we identified excess decoherence compared to our noise model at multipoles $\ell < 300$ for WMAP's 9-year Q, V, and W maps.

3. In the modeling part of **Kovács** et al. (2013b), we used our calibrated decoherence model to forecast generalized phase angles of *Planck* and a hypothetical perfect CMB experiment without noise. Decoherence is predicted

at multipoles $\ell \approx 2900$, beyond which any non-Gaussian information should be dominated by noise.

4. As a further perspective in **Kovács** et al. (2013b), we find that $\tilde{C}_\ell^{\mathrm{WMAP}}$ powers in Q,V,W maps are on average 2.6% higher than $\tilde{C}_\ell^{Planck}$, in approximately the same range of ℓ's, where we found less coherence than predicted by our theory. We considered multipoles $10 < \ell < 300$ for each band.

Next we endeavored to combine CMB observations with large-scale structure galaxy data to detect correlations. The corresponding thesis statements are the following:

5. We created a galaxy map using infrared data collected by the Wide-field Infrared Survey Explorer (WISE), and clarified most of the potential systematic effects in analytical letter **Kovács** et al. (2013c). In particular, we created a full sky mask for the WISE galaxy sample based on Moon contamination flags provided by the WISE team.

6. we used the resulting all sky WISE galaxy catalog for cross-correlations with WMAP's 7-year sky maps, finding $S/N \approx 1$, i.e. no significant detection of the ISW effect (**Kovács** et al., 2013c). While some recent studies, especially Goto et al. (2012), raised the possibility that the ISW correlations may be higher than ΛCDM predictions, we concluded that the signal we found is consistent with ΛCDM and previous measurements (Rassat et al., 2007, Francis and Peacock, 2010). Our analysis highlighted that higher ISW amplitude measurements on certain parts of the sky are strongly affected cosmic variance.

7. As a logical continuation of the ISW analysis with WISE galaxies, we created an advanced all sky galaxy map WISE and 2MASS infrared surveys, based on machine learning techniques. The final masked WISE-2MASS catalogue covers 21,200 deg^2 and has an estimated $\sim 2\%$ stellar contamination among 2.4 million galaxies with $z_{med} \approx 0.14$, as described in the map making paper

Kovács and Szapudi (2014). We compared the new WISE-2MASS map to existing WISE and 2MASS galaxy maps, and concluded that the resulting catalog is deeper than 2MASS, and more uniform than WISE.

8. We used the WISE-2MASS map by **Kovács** and Szapudi (2014) to further investigate the possibility of a low redshift underdensity aligned with the CMB cold spot. We combined our data with Pan-STARRS1 (PS1) optical observations for photometric redshift estimation, created a tomographic map, and performed galaxy density statistics in the line of sight (Szapudi et al., 2014). We modeled our observations with a top hat void centred at $z = 0.22 \pm 0.01$ with radius $R_v = (192 \pm 15)h^{-1}$Mpc and depth of $\delta = -0.13 \pm 0.03$.

9. We then focused on the physical connection between the CMB temperature depression and the supervoid discovered in Szapudi et al. (2014). The corresponding paper, Finelli et al. (2014), is completely based on our WISE-2MASS galaxy map. We found that a spherically symmetric LTB supervoid model can simultaneously fit the underdensity in the WISE-2MASS catalogue and the cold spot in the CMB. Such an LTB supervoid gives an almost perfect explanation, via a Rees-Sciama effect, of the Cold Spot anomaly, and is strongly preferred over the null hypothesis of statistical fluctuation or a cosmic texture model. The parameters of the LTB supervoid are $z = 0.16 \pm 0.04$ with radius $r_0 = (195 \pm 35)h^{-1}$Mpc and depth of $\delta = -0.10 \pm 0.03$, thus we report excellent agreement with the result of the PS1 photo-z analysis.

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