

## HABILITATION SUMMARY

1. Name and surname: **Paweł Bielewicz**

2. Scientific degrees and titles:

- Master of Science (MSc) in theoretical physics, University of Warsaw, 2000  
Thesis title: "Influence of inhomogeneities in the Universe on determination of cosmological parameters"
- Doctor of Philosophy (PhD) in physical sciences, University of Warsaw, 2006  
Thesis title: "Studies of the large scale structure of the Universe through the statistical analysis of the temperature anisotropy and polarisation of the cosmic background radiation"

3. Employment in scientific institutes:

- Institut d'Astrophysique de Paris (France), post-doc, 2006-2008
- Institut d'Astrophysique de Paris (France), developer engineer, 2009
- Institut de Recherche en Astrophysique et Planétologie (France), post-doc, 2009-2012
- Scuola Internazionale Superiore di Studi Avanzati (Italy), post-doc, 2012-2015
- Centrum Astronomiczne im. Mikołaja Kopernika PAN (Poland), tenure-track, from 2016

4. Habilitation achievement:

- Title:  
**"Observational constraints on the topology of the Universe"**
- Publications:
  - [P1] Bielewicz, P., Riazuelo, A., 2009, "The study of topology of the universe using multipole vectors", MNRAS, **396**, 609
  - [P2] Bielewicz, P., Banday, A.J., 2011, "Constraints on the topology of the Universe derived from the 7-year *WMAP* data", MNRAS, **412**, 2104
  - [P3] Bielewicz, P., Banday, A.J., Górski, K.M., 2012, "Constraining the topology of the Universe using the polarised CMB maps", MNRAS, **421**, 1064
  - [P4] Planck collaboration et al. (including Bielewicz P.), 2014, "Planck 2013 results. XXVI. Background geometry and topology of the Universe", A&A, **571**, A26
  - [P5] Planck collaboration et al. (including Bielewicz P.), 2016, "Planck 2015 results. XVIII. Background geometry and topology of the Universe", A&A, **594**, A18

A&A = Astronomy and Astrophysics

MNRAS = Monthly Notices of the Royal Astronomical Society

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# Summary of the habilitation achievement

## 1 Introduction

The cosmic microwave background (CMB) is one of the most important source of information about structure and evolution of the Universe. It comes from very early epoch of the Universe evolution when radiation was tightly coupled with ionized baryonic matter. As the Universe expanded and cooled down, baryonic matter recombined and became neutral. After recombination, the Universe became transparent for CMB photons which travel since then unaltered. For this reason, observations of the CMB give unique opportunity to see the surface of the last scattering and to find out how the Universe looked like just after recombination, around 380 000 years after the Big Bang. Together with other cosmological probes, such as observations of supernova or galaxy surveys, measurements of the CMB undertaken to-date have enabled the establishment of the standard cosmological model. This model is based on the Big Bang theory extended by the inflationary paradigm.

The distance to the surface of the last scattering of the CMB photons is almost as big as the distance to the horizon of the observable Universe, therefore observations of the CMB also enable to test global features of the Universe. In particular, they allow us to test global geometry of the Universe, i.e. its topology. The simplest models of spacetime are globally isotropic and simply connected. Although both are supported by both local observations and CMB observations, without a fundamental theory of the birth of the Universe, observational constraints on departures from global isotropy due to multi-connected topology are necessary.

The Einstein field equations relate local properties of the curvature to the matter content in spacetime. By themselves they do not restrict the global properties of the space, allowing a universe with a given local geometry to have various global topologies (de Sitter, 1917). Friedmann–Robertson–Walker (FRW) models (Friedmann, 1922; Robertson, 1935) of the Universe observed to have the same average local properties everywhere still have freedom to describe quite different spaces at large scales. Perhaps the most remarkable possibility is that we can still be living in a universe of finite volume due to the global topological multi-connectivity of space, even if described by the flat or hyperbolic FRW solutions. This possibility is especially interesting since quantum fluctuations can produce compact spaces of constant curvature, both flat (e.g., Zeldovich & Starobinskii, 1984) and curved (e.g., Coule & Martin, 2000; Linde, 2004), within the inflationary scenario.

The main observational effect of topology is in setting boundary conditions on perturbation modes that can be excited and developed into the structure that we observe. The first searches for multi-connected topology on cosmic scales looked for repeated patterns or individual objects in the distribution of galaxies (Sokolov & Shvartsman, 1974; Fang & Sato, 1983; Fagundes & Wichoski, 1987; Lehoucq et al., 1996; Weatherley et al., 2003; Fujii & Yoshii, 2011). The last-scattering surface from which the CMB is released represents the most distant source of photons in the Universe, hence studying structure on the last-scattering surface is the best-known way to probe the global organisation of our Universe and the CMB provides the most detailed and best understood dataset for this purpose. This first became possible with the Differential Microwave Radiometer (DMR) instrument on the Cosmic Background Explorer (*COBE*) satellite (Bennett et al., 1996). Various searches found no evidence for multi-connected topologies (e.g., Starobinskij 1993; Sokolov 1993; Stevens et al. 1993; de Oliveira-Costa & Smoot 1995; Levin et al. 1998; Bond et al. 1998, 2000; Rocha et al. 2004; but see also Roukema 2000a,b), but sparked the creation of robust statistical tools, along with greater care in the enumeration of the possible topologies for a given geometry (Lachize-Rey & Luminet, 1995; Levin, 2002). With data from the Wilkinson Microwave Anisotropy Probe (*WMAP*) satellite (Bennett et al., 2003), these theoretical and observational tools were applied to a high-quality dataset for the first time. Luminet et al. (2003) and Caillerie et al. (2007) claimed the low value of the low multipoles, compared to standard  $\Lambda$ CDM cosmology, as evidence for missing large-scale power as predicted in a closed universe with a small fundamental domain (see also Aurich 1999; Aurich et al. 2004, 2005, 2006, 2008; Aurich & Lustig 2013; Lew & Roukema 2008; Roukema et al. 2008). However, searches in pixel space (Cornish et al., 2004; Key et al., 2007; Niarchou et al., 2004; Dineen et al., 2005) and in harmonic space (Kunz et al., 2006) determined that this was an unlikely explanation for the low power.

Nevertheless, apart from the low value of the low multipoles, more general tests of statistical properties of the *WMAP* CMB temperature map revealed also some deviations from statistical isotropy at large angular scales which could be a signature of the topology (Tegmark et al., 2003; Copi et al., 2006; Eriksen et al., 2007; Copi et al., 2009; Hansen et al., 2009; Hoftuft et al., 2009). During my Ph.D. studies I worked on analysis of



robustness of these anomalies with respect to systematic effects such as the Galactic emission and uncertainties related to the calibration of the maps (Bielewicz et al., 2004, 2005). Large part of my research after getting Ph.D. was devoted to studies of one of the most fascinating theoretical explanation of these anomalies, i.e. multi-connected topology of the Universe. In the following I will discuss my contribution to the studies on the topology of the Universe and, in particular, on research presented in the habilitation papers [P1-P5]. In the paper [P1] I considered the multi-connected universe as a possible explanation of one of the anomalies, i.e. the quadrupole-octopole alignment. In the remaining papers I focused on looking for signatures of the topology using the matched circles method. In the papers [P2] and [P4] the method was applied to the CMB temperature anisotropy maps derived from the *WMAP* and *Planck* data, respectively. Extension of the method to CMB polarisation maps was considered in the paper [P3], while in the paper [P5] results of the first application of CMB polarisation data for constraining topology are presented.

## 2 Testing topology of the universe using multipole vectors [P1]

Since the first-year *WMAP* data release (Bennett et al., 2003), considerable effort has been spent on analyzing the statistical properties of the CMB maps. Remarkably, this effort has resulted in several reports of both non-Gaussianity and a breaking of statistical isotropy, as established by many qualitatively different methods (Tegmark et al., 2003; Bielewicz et al., 2004, 2005; Copi et al., 2006; Eriksen et al., 2007; Copi et al., 2009). These results have been recently confirmed for the state-of-the-art CMB measurements performed by the *Planck* satellite (Planck Collaboration et al., 2014c, 2016c). One of the observed anomaly is alignment of the preferred directions of the quadrupole and octopole moments. It can be a consequence of shorter size of the fundamental domain of the multi-connected universe in the direction perpendicular to the plane determined by the quadrupole and octopole. In [P1] I, together with a collaborator, investigated this possibility for the topology of a 3-torus.

In the studies we used the multipole vector decomposition of the CMB maps (Copi et al., 2004). In contrast to the coordinate dependent coefficients of the spherical harmonic decomposition, the vectors associated with a given multipole point toward the same direction on the sky independently of the reference frame employed. Thus, they are useful tools for the study of statistical isotropy. Computations of the multipole vector statistics were performed using codes developed by me for testing the CMB anomalies during my Ph.D. studies (Bielewicz et al., 2005).

We showed that for universe with the topology of 3-torus, where at least one dimension of the fundamental domain is significantly shorter than the diameter of the observable Universe, distribution of the multipole vectors reflects symmetries of the fundamental cell and the quadrupole and octopole show preference for the alignment. Nevertheless, the integrated Sachs-Wolfe (ISW) effect significantly diminishes the signature of a multi-connected topology.

A more quantitative assessment indicates that the data do indeed slightly prefer the multi-connected topology. Nevertheless, the simply-connected universe hypothesis is not clearly ruled out ( $\sim 97\%$  confidence level). We also found that the multipole vector statistics are not very sensitive to the signatures of the 3-torus topology if the shorter dimension of the fundamental domain is comparable to the observable diameter of the Universe.

## 3 Constraints on topology of the Universe using the matched circles method [P2], [P3]

The primary observable effect of a multi-connected universe is the existence of directions in which light could go around the space in cosmological time more than once, i.e., the radial distance  $\chi_{\text{rec}}$  to the surface of last scattering exceeds the size of the Universe. In these cases, the surface of last scattering can intersect the notional edge of a fundamental domain. At this intersection, we can view the same spacetime event from multiple directions — conversely, it appears in different directions when observed from a single point.

Thus, temperature perturbations in one direction,  $\Delta T(\hat{n})$ , become correlated with those in another direction,  $\Delta T(\hat{m})$ . Because the intersection of the topological fundamental domain with the surface of last scattering is a circle, one can potentially observe CMB anisotropy that matches around pairs of correlated circles (see Fig. 1). However, the matches are not exact due to noise, foregrounds, the integrated Sachs-Wolfe (ISW) and Doppler effects along the different lines of sight.

The idea of using the matched circles to study topology is due to Cornish et al. (1998). In that work, a statistical tool was developed to detect correlated circles in all sky maps of the CMB anisotropy — the

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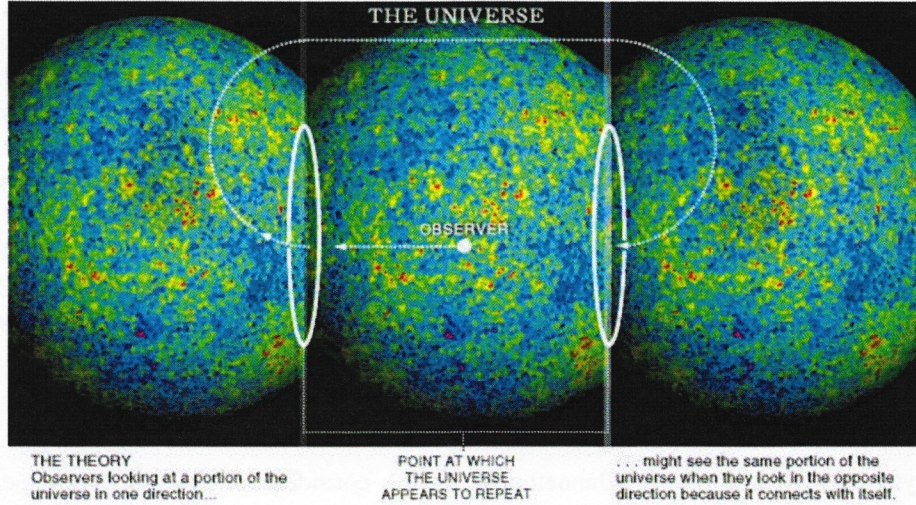


Figure 1: Correlation of the CMB fluctuations around pair of circles seen from two different directions in the multi-connected universe is a result of intersection of the last scattering surface with the edge of the topological fundamental domain. Image by Max Tegmark.

circle comparison statistic. There are two versions of the statistic: for pairs of circles with the points ordered in a clockwise direction (phased, denoted as  $S^+$ ) and for pairs of circles where along one of the circles the points are ordered in an anti-clockwise direction (anti-phased, denoted as  $S^-$ ). This allows the detection of both orientable and non-orientable topologies. For orientable topologies the matched circles have anti-phased correlations while for non-orientable topologies they have a mixture of anti-phased and phased correlations.

To draw any conclusions from an analysis based on the statistic it is very important to correctly estimate the threshold for a statistically significant match of the circle pairs. The chance of random matches is especially large for circles with smaller radii. For this reason, the statistic shall be calibrated for detections using Monte Carlo (MC) simulations of the CMB skies for the simply-connected universe.

In studies presented in [P2] and [P3] we constrained the topology of the Universe using version of the statistic optimised for small-scale anisotropies (Cornish et al., 2004) which helps to reduce negative impact of the ISW effect. In [P2] we analysed CMB temperature anisotropy maps while in [P3] we considered extension of the method to the CMB polarisation maps.

A code for computation of the matched circles statistic used in these studies was developed by me. In order to speed up the computations the algorithm uses the fast Fourier transform along the circles. To test the reliability of the code, I developed also a code for simulations of the CMB skies for a flat universe with the topology of a 3-torus. The simulation code computes directly the spherical harmonic coefficients what enables to generate CMB maps with higher angular resolution than an alternative method of simulations employing a covariance matrix (Riazuelo et al., 2004; Phillips & Kogut, 2006). It is worth noticing that the maps generated using my code are the highest resolution simulations of the CMB maps for the multi-connected universe as have been done so far. Sufficiently high resolution of the maps is especially important for testing the matched circles statistic which is sensitive to small and intermediate angular scales of the CMB anisotropy.

The spherical harmonic coefficient were computed by summing up all perturbation modes that are present given the boundary conditions imposed by the multi-connected topology. However, the topology does not affect local physics, so the equations governing the evolution of cosmological perturbations are left unchanged and can be computed using publicly available algorithms such as CAMB (Lewis et al., 2000). At the end, simulated maps were convolved with the beam profile corresponding to considered CMB map and to the maps was added, characteristic for the CMB map, noise. The codes for the analysis and simulations were also adapted for parallel computing on supercomputers.

In [P2] we paid special attention to aspects of the search for the matched circles that have been neglected in the majority of previous studies, i.e. the impact of Galactic foreground residuals on the constraints, the use of higher resolution data and estimation of the false detection level on the basis of detailed Monte Carlo



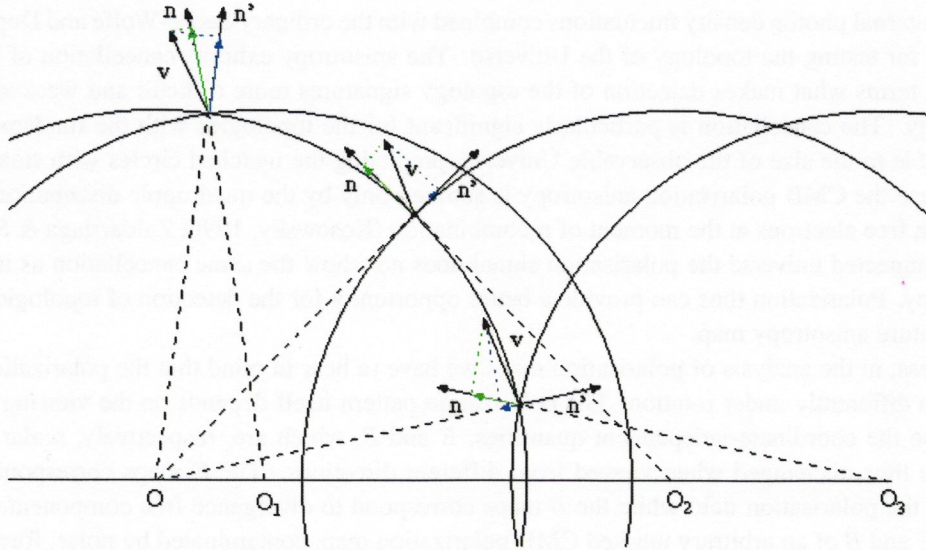


Figure 2: The baryon velocity  $v$  at the last scattering surface seen from two different directions  $n, n'$  in the multi-connected universe. For the radius of the matched circles larger than  $45^\circ$  the projections of the baryon velocity on the direction of observations (dashed lines) for the observers  $O$  and  $O_1$  are strongly correlated. For the radius equal to  $45^\circ$  (observers  $O$  and  $O_2$ ) the velocity projections are independent and for the radius smaller than  $45^\circ$  (observers  $O$  and  $O_3$ ) the projections are anti-correlated. The projections are denoted by blue and green arrows. Figure from [P3].

simulations of the sky maps. In particular, we analysed the 7-year *WMAP* Internal Linear Combination (ILC) and foreground corrected W-band ( $\sim 94$  GHz) temperature maps with masked the most contaminated parts of the sky. The use of higher resolution map, i.e. the W-band map, implies a lower level of false detection and therefore tighter constraints on the size of the fundamental domain. In order to estimate the false detection level correctly, we used 100 MC simulations of the ILC and W-band maps assuming the simply-connected universe.

Because general searches for matched circles are computationally very intensive, we restricted our analysis to a search for pairs of circles centered around antipodal points, so called back-to-back circles. Although restricted, the search constrains a wide class of topologies predicting pairs of such circles. The strongest constraints are imposed on topologies predicting back-to-back circles in all directions i.e., all the single action manifolds, among them tori of any shape and the three spherical cases. Weaker constraints are imposed on topologies with all back-to-back circles centred on a great circle of the celestial sphere such as half-turn, quarter-turn, third-turn and sixth-turn spaces, as well as Klein and chimney spaces. The statistic can also constrain the multi-connected spaces predicting one pair of antipodal matching circles such as Klein or chimney spaces with horizontal flip, vertical flip or half-turn and slab space translated without screw motion.

The analysis of the *WMAP* W-band map, after correction using templates of the Galactic foreground emission, did not reveal any significant correlations for pairs of back-to-back circles with a radius greater than  $\alpha_{\min} \simeq 10^\circ$ . Lower false detection level allowed to obtain substantially smaller the minimum radius of detectable matched circles compared to the previous one given by Key et al. (2007) of  $20^\circ$ . It implies that in a flat universe described by the best-fit 7-year *WMAP* cosmological parameters, a lower bound on the size of the fundamental domain is  $L \gtrsim 2\chi_{\text{rec}} \cos(\alpha_{\min}) = 1.97\chi_{\text{rec}} = 27.9\text{ Gpc}$ , where  $\chi_{\text{rec}}$  is comoving distance to the last-scattering surface.

In publication [P3] we considered extension of the matched circles method to CMB polarisation maps. Because noise level of the *WMAP* polarisation data is too high to enable detection of the matched circles, we investigated sensitivity of the matched circles statistic using simulations of the CMB polarisation maps with an angular resolution and noise level corresponding to, not yet released at that time, data from the *Planck* satellite as well as next generation CMB experiments such as the Cosmic Origin Explorer (CORe) mission (The CORe Collaboration et al., 2011). The simulated CMB maps corresponded to a flat universe with the topology of a 3-torus.

We have shown that using the temperature anisotropy, sourced by multiple terms at the last-scattering sur-



face (i.e., the internal photon density fluctuations combined with the ordinary Sachs-Wolfe and Doppler effects), is not optimal for testing the topology of the Universe. The anisotropy exhibits cancellation of contributions from different terms what makes detection of the topology signatures more difficult and weakens constraints on the topology. The cancellation is particularly significant for the topologies with the fundamental domain sizes comparable to the size of the observable Universe, predicting the matched circles with small radius (see Fig. 2). Because the CMB polarisation anisotropy is sourced only by the quadrupole distribution of radiation scattering from free electrons at the moment of recombination (Kosowsky, 1996; Zaldarriaga & Seljak, 1997), in the multi-connected universe the polarisation signal does not show the same cancellation as in the temperature anisotropy. Polarization thus can provide a better opportunity for the detection of topological signatures than a temperature anisotropy map.

Nevertheless, in the analysis of polarisation maps we have to bear in mind that the polarization is a tensor which behaves differently under rotation. The polarization pattern itself depends on the viewing angle hence, we need to use the coordinate-independent quantities,  $E$  and  $B$ , which are, respectively, scalar and pseudo-scalar, and are thus unchanged when viewed from different directions. The  $E$  maps correspond to curl free component of the polarisation field while the  $B$  maps correspond to divergence free component. The decomposition into  $E$  and  $B$  of an arbitrary masked CMB polarization map, contaminated by noise, foregrounds, and systematic errors, is itself a computationally demanding task, non-local on the sky. Assuming negligible initial  $B$  polarization, we used only the  $E$  maps produced from component-separated CMB polarization maps using the same approach as Kim (2011).

In the paper we analysed in detail all mentioned above issues related with use of the polarisation maps and tested the matched circles method using simulations of the maps for the multi-connected universe. We have shown that use of the polarisation maps allows to provide tighter constraints on the topology. The detection is robust with respect to the secondary CMB polarisation generated after reionisation. However, the application of polarisation data to studies of the topology of the universe depends to a large extent on noise and Galactic foreground residuals.

Using simulations of the *Planck* polarisation data we demonstrated that the level of the instrumental noise should be sufficiently low to enable the detection of the signatures of a multi-connected topology, though it would not be low enough to significantly improve constraints on the topology derived from the temperature maps. Nevertheless, we showed that significant improvement of the constraints would be possible for polarisation data from the COrE satellite (Fig. 3). Very brief discussion of the prospects of using the COrE data for constraining topology, based on the results from [P3], was also included to the COrE white paper (section 2.3 in The COrE Collaboration et al., 2011).

#### 4 Constraints on the topology of the Universe from *Planck* data [P4], [P5]

As a member of the *Planck* Core Team I had an opportunity to apply developed by me algorithms of the matched circles method to search for the signatures of the multi-connected topology in *Planck* CMB maps. Tests of the *Planck* anisotropy maps released in 2013 and 2015 are presented in the papers [P4] and [P5], respectively. In the former I focused on analysis of the temperature maps while in the latter – on analysis of the polarisation maps.

The *Planck* 2013 nominal mission data (i.e. the first 15.5 months of *Planck* observations) have enabled to estimate CMB anisotropy maps by the various component-separation pipelines described in Planck Collaboration et al. (2014a). The methods produce largely consistent maps of the sky, with detailed differences in pixel intensity, noise properties, and masks. In the paper [P4] we considered temperature maps produced by the Commander-Ruler, NILC, SEVEM and SMICA methods. This allows us to test sensitivity of the analysis to details of separation of the cosmological signal from astrophysical foreground contamination.

Similarly as in the papers [P2] and [P3], we estimated the threshold for a statistically significant match of circle pairs using MC simulations of the CMB maps for a simply-connected universe. The threshold was set such that fewer than 1 % of 300 simulations would yield a false event. The algorithm was also tested on, described in the previous section, simulation of the CMB map for the universe with the topology of a 3-torus.

We did not find any statistically significant correlation of circle pairs with a radius greater than  $20^\circ$  in any map. Thus, we can exclude at the confidence level of 99 % any topology that predicts matching pairs of back-to-back circles larger than this radius, assuming that relative orientation of the fundamental domain and mask allows its detection. This implies that in a flat universe described otherwise by the *Planck* fiducial  $\Lambda$ CDM



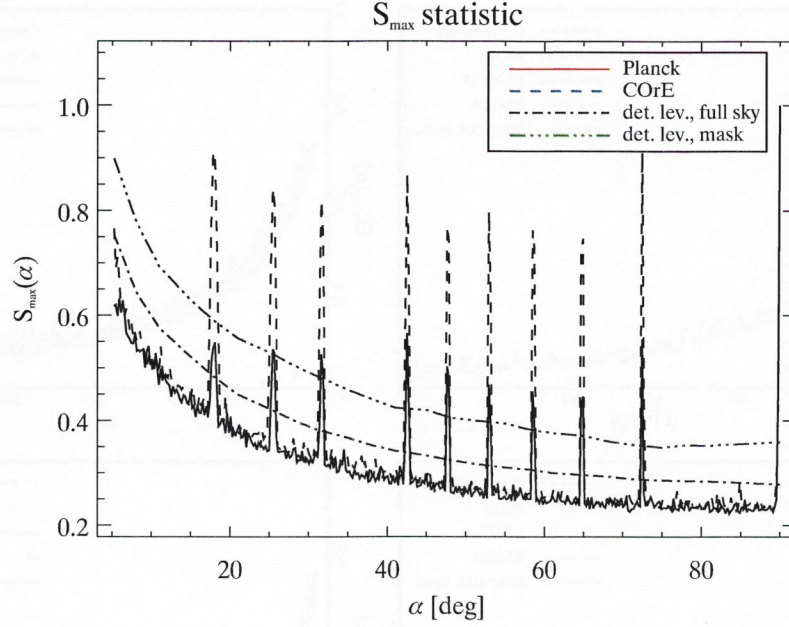


Figure 3: An example of the  $S_{\max}^-$  statistic (i.e. the maximum value of the corresponding  $S^-$  circle comparison statistic) as a function of circle radius  $\alpha$  for a simulated polarised CMB map of universe with the topology of a cubic 3-torus of dimension  $L = 2 c/H_0$ . The solid and dashed lines show the statistic for simulated polarisation maps with angular resolution and noise level corresponding to the *Planck* and CORe data, respectively. The dot-dashed and three dot-dashed lines show the false detection levels for the statistic estimated from 100 Monte Carlo simulations of the *Planck* coadded 100, 143 and 217 GHz frequency polarisation maps for the full sky and cut sky analysis, respectively. Figure from [P3].

model, a 99 % confidence-limit lower bound on the size of the fundamental domain is  $L \gtrsim 2\chi_{\text{rec}} \cos(\alpha_{\min}) = 1.88\chi_{\text{rec}} = 26.4\text{Gpc}$ . This is slightly weaker constraint than that obtained for the *WMAP* maps in [P2]. It is a result of using more conservative foreground mask than for the analysis of the *WMAP* data. The smaller fraction of the sky used in the search of the matched circles increases a false detection level. As a result we obtain weaker, but more conservative, constraints on the topology.

It is worth noticing that the limit on the size of the fundamental domain is comparable or even slightly better than the limits obtained using the likelihood approach also considered in the paper. However, the matched circles method provides constraints upon a much wider class of topologies than those explicitly considered in the likelihood approach. It concerns all topologies listed in Sect. 3, predicting matching pairs of back-to-back circles.

My contribution in the paper [P4] is presented in section 5.1, first part of section 5.3.1 (including figures 4 and 5), first paragraph of section 6.1 (including figure 11) and parts of sections 1, 2, 3.1 and 7 referring to the matched circles analysis.

Release of high sensitivity *Planck* CMB polarisation maps in 2015 has allowed us to employ for the first time polarisation data in studies of the topology of the Universe. In the paper [P5] we considered CMB polarisation maps produced by four component-separation methods, i.e. Commander, NILC, SEVEM and SMICA maps (Planck Collaboration et al., 2016a). Similarly as in the paper [P3] we used in the analysis the  $E$  map produced from the original Stokes parameter maps. For completeness we also analysed the updated CMB temperature maps derived from the full mission data.

We did not find any statistically significant correlation of circle pairs in any map (see Fig. 4). Results for the temperature maps are consistent with the [P4] results. The minimum radius at which the peaks expected for the matched circles statistic are larger than the false detection level for the polarization map is around  $\alpha_{\min} \simeq 15^\circ$ . This is slightly smaller radius than for the 2013 *Planck* temperature map analysis, i.e.  $20^\circ$ . As a result, we got somewhat stronger constraint on a lower bound on the size of the fundamental domain in a flat universe,

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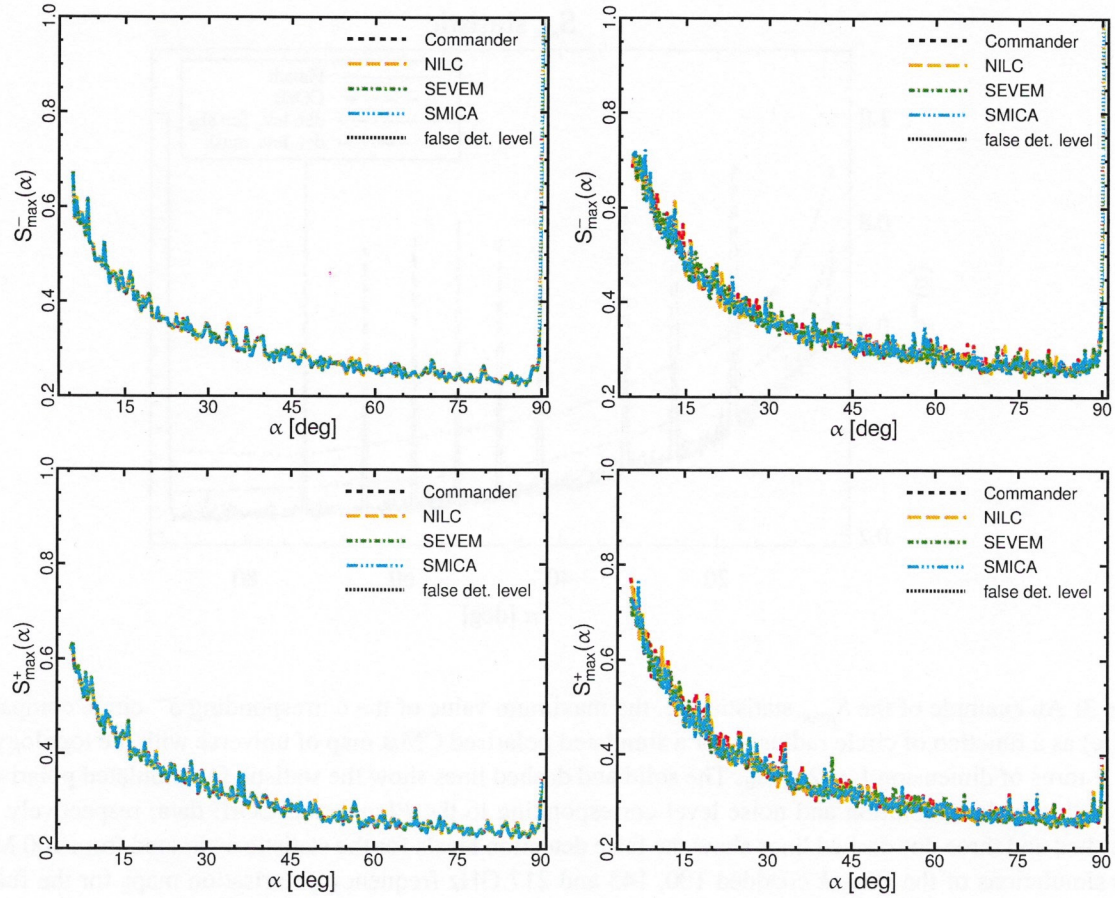


Figure 4:  $S_{\max}^-$  (upper panels) and  $S_{\max}^+$  (lower panels) statistics (the maximum value of the  $S^-$  and  $S^+$  circle comparison statistics, respectively) as a function of circle radius  $\alpha$  for the *Planck* Commander (short-dashed red line), NILC (long dashed orange line), SEVEM (dot-dashed green line), and SMICA (three dot-dashed blue line) 2015 temperature (left panels) and polarisation  $E$ -mode (right panels) maps. The dotted line shows the false detection level established such that fewer than 1 % of 300 Monte Carlo simulations of the SMICA CMB temperature or  $E$ -mode map, respectively, smoothed and masked in the same way as the data, would yield a false event. The peak at  $90^\circ$  corresponds to a match between two copies of the same circle of radius  $90^\circ$  centred around two antipodal points. Figure from [P5].

i.e.  $L \gtrsim 1.94 \chi_{\text{rec}}$ . It is worth mentioning that this result is independent confirmation of the constraints obtained for the *WMAP* and *Planck* temperature maps. Nevertheless, we have to bear in mind that due to significantly stronger Galactic foreground emission with respect to the cosmological signal, we used considerably smaller amount of sky in the polarization analysis than in the temperature analysis (40 % compared to 74 %).

My contribution in the paper [P5] is presented in second paragraph of section 4.1, section 4.2, first part of section 4.4.1 (including figure 6), section 5.1.1 (including figures 11 and 12) and parts of sections 1, 2 and 6 referring to the matched circles analysis.

## 5 Summary

In the series of five papers [P1], [P2], [P3], [P4] and [P5], a comprehensive studies of constraints on the topology of the Universe from CMB observations were presented. In the first paper the multi-connected topology was considered as a possible explanation of the observed quadrupole-octopole alignment. The analysis was performed using decomposition of the CMB maps on the multipole vectors as they are useful tool for study of statistical isotropy. We have shown that the data do indeed slightly prefer the multi-connected topology of 3-torus however, the simply-connected universe is not clearly rule out. In the remaining papers I focused on constraining the topology using the matched circles method. It uses the fact that the intersection of the

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topological fundamental domain with the surface of last scattering is a circle, potentially viewed from different directions in a multiply-connected universe. In the papers [P2] and [P4] I looked for the matched circles in the state-of-the-art CMB temperature maps at that time, i.e. the *WMAP* and 2013 *Planck* maps, respectively. I paid special attention to the impact of the Galactic foreground residuals and calibration of the statistic using realistic Monte Carlo simulations. We also used higher resolution maps than in the previous studies and produced the highest resolution simulations of the CMB map for the multi-connected universe as have been done so far. Although, we did not find signatures of the multi-connected topology, we were able to substantially improve previous constraints on the lower bound on the size of fundamental domain for a wide class of topologies.

Extension of the matched circles method to CMB polarisation was considered in the paper [P3]. There were discussed the advantages of using the CMB polarisation maps in studies of the topology over simply analysing the temperature data as have been done to-date. Using simulated CMB polarisation map I have shown that the noise level of *Planck* data is no longer prohibitive and should be low enough to enable the use of the polarisation maps for such studies. Furthermore, I have also shown that constraints on the topology obtained from polarisation maps of the next generation CMB experiments should be much tighter than for temperature maps. Theoretical predictions referring to the *Planck* data were confirmed in the paper [P5] where the analysis of the *Planck* polarisation data released in 2015 is presented. The analysis was the first search in CMB polarisation data for correlations induced by the multi-connected topology. Similarly, as in the case of CMB temperature maps, signatures of the multi-connected universe were not found and there was placed the lower bound on the size of fundamental domain similar as for the temperature data. As such, this result provides independent confirmation of the constraints derived from the CMB temperature maps. It also opens prospects of testing the topology of the Universe with better data from future CMB polarisation experiments.

## Other studies which are not part of the habilitation achievement

Besides studies on the topology of the Universe after my Ph.D. I worked also on testing statistical properties of CMB maps and gravitational lensing of the CMB. In particular, I tested CMB maps for statistical isotropy and Gaussianity in the context of CMB anomalies observed at large angular scales. These fundamental properties are expected in the standard cosmology paradigm thus, testing them is crucial for the validation of the paradigm, and has profound implications for our understanding of the physical nature of the Universe and the initial conditions of structure formation. Moreover, the confirmation of the isotropic and Gaussian nature of the CMB is essential for justifying the corresponding assumptions usually made when estimating the CMB power spectra and other quantities from the CMB data.

In the paper Bielewicz et al. (2013) we searched in the *WMAP* CMB maps for the concentric rings with unusual variance. One of the goals of these studies was verification of claims by Gurzadyan & Penrose (2010) concerning the unusual low variance profile of rings centred at two locations on the sky that had drawn special attention in the context of the conformal cyclic cosmology scenario proposed by Penrose (2009) (see also Penrose 2010). We extended this analysis to rings with larger radii and centred on other points in the sky. Using a fast convolution technique enabled us to perform this search with higher resolution and a wider range of radii than in previous studies. We showed that for one of the two special points rings with radii larger than  $10^\circ$  have systematically lower variance in comparison to the concordance  $\Lambda$ CDM model predictions. However, we showed that this deviation is caused by the multipoles up to order  $\ell = 7$ . Therefore, the deficit of power for concentric rings with larger radii is yet another manifestation of the well-known anomalous CMB distribution on large angular scales. Furthermore, low variance rings can be easily found centred on other points in the sky. In addition, we showed also the results of a search for extremely high variance rings.

Since joining the *Planck* collaboration in 2008 I actively took part in analysis of the *Planck* data. Within this activity, apart from the studies on the topology of the Universe, I was responsible for the implementation of the real-space  $N$ -point correlation function estimators used for tests of statistical isotropy and non-Gaussianity (sections 4.3 and 5.3 in Planck Collaboration et al. 2014c, sections 4.3, 5.2 and 7.2 in Planck Collaboration et al. 2016c, sections 7.2, E.3 in Planck Collaboration et al. 2016a and sections 4.7, H in Planck Collaboration et al. 2018a). This was a key science project within *Planck*. The analysis of the *Planck* temperature maps confirmed the hemispherical asymmetry reported previously for the *WMAP* data (Eriksen et al., 2004, 2005) showing that

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this anomaly is not caused by some systematic effects or processing of data as the *WMAP* and *Planck* experiments use different instrument technologies and algorithms.

I was also asked to join a special group of experts on non-Gaussianity in the *Planck* Core Team that did validation tests of the CMB estimates. On base of these tests four the most reliably component separation methods were chosen to be used for the official *Planck* products for the 2013, 2015 and 2018 data releases (Planck Collaboration et al., 2014a, 2016a, 2018a). I also regularly performed validation tests of the CMB estimates and associated products for internal releases of the *Planck* data.

In the *Planck* project I was also responsible for testing the alignment between the quadrupole and octopole (section 5.1 in Planck Collaboration et al. 2014c) which I analysed during my Ph.D. studies using the *WMAP* data (Bielewicz et al., 2004, 2005). The analysis confirmed the existence of the alignment at similar significance as for the *WMAP* maps and demonstrated that it is not caused by some effects related with systematics or processing of data.

Another area of my research interests is gravitational lensing of the CMB. In the paper Hanson et al. (2011) together with collaborators I studied the reconstruction of the lensing potential power spectrum from CMB temperature data. We worked with the optimal quadratic estimator of Okamoto & Hu (2003), which we characterized thoroughly in its application to the reconstruction of the lensing power spectrum. We found that at multipoles  $\ell < 250$  our current understanding of this estimator is biased at the 15 % level by beyond-gradient terms in the Taylor expansion of lensing effects. We presented the full  $\mathcal{O}(\phi^4)$ , where  $\phi$  is lensing potential, lensed trispectrum to explain this effect. We showed that in the case of *Planck* data the low- $\ell$  bias, as well as a previously known bias at high- $\ell$  (Kesden et al., 2003), is relevant to the determination of cosmology and must be corrected for in order to avoid significant parameter errors. My contribution to this paper was the description of a useful method of correction of the power spectrum estimator for the low- $\ell$  bias and an expression of the trispectrum in the flat-sky approximation (appendix B in Hanson et al. 2011). The method has recently been used in estimation of the lensing power spectrum for the *Planck* data (Planck Collaboration et al., 2014b, 2016b, 2018b).

Provided by the *Planck* team the reconstructed gravitational lensing potential (Planck Collaboration et al., 2014b, 2016b) enables to study formation of the large scale structure at high redshift ( $1 \lesssim z \lesssim 5$ ). The gravitational potential should exhibit significant cross-correlation with the observed density of galaxies and other tracers of the large scale structure providing additional information that can be used to constrain cosmology. In fact, a number of such cross-correlations have been detected in recent years. In the paper Bianchini et al. (2015) led by a PhD student Federico Bianchini, whom I co-supervised, we reported the first measurement of the correlation between the gravitational potential and high-redshift galaxies detected by the *Herschel* Astrophysical Terahertz Large Area Survey (H-ATLAS) survey. The highly significant detection was possible because of employing sample of galaxies with higher redshift ( $z \gtrsim 1.5$ ) than those of galaxy samples considered so far.

An improved and extended analysis of the cross-correlation was presented in the paper Bianchini et al. (2016). We compared there the results based on the 2013 and 2015 *Planck* datasets, and investigate the impact of different selection criteria of the H-ATLAS galaxy samples. Significant improvements over our previous analysis have been achieved thanks to the higher signal-to-noise ratio of the new CMB lensing map released by the *Planck* collaboration in 2015. Furthermore, the first tomographic analysis of the cross-correlation signal was implemented, by splitting the galaxy sample into two redshift intervals:  $1.5 \leq z < 2.1$  and  $z \geq 2.1$ , what allowed us to test models of evolution of the large-scale structure of the Universe.

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- , 2014b, A&A, 571, A17
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6. The most important publications:

- a) "Planck 2015 results. XVIII. Background geometry and topology of the Universe"  
Planck Collaboration, et al. (including **Bielewicz P.**), 2016, A&A, 594, A18
- b) "Planck 2015 results. XVI. Isotropy and statistics of the CMB"  
Planck Collaboration, et al. (including **Bielewicz P.**), 2016, A&A, 594, A16
- c) "Planck 2015 results. IX. Diffuse component separation: CMB maps"  
Planck Collaboration, et al. (including **Bielewicz P.**), 2016, A&A, 594, A9
- d) "Toward a Tomographic Analysis of the Cross-Correlation between Planck CMB Lensing and H-ATLAS Galaxies",  
Bianchini F., Lapi A., Calabrese M., **Bielewicz P.**, et al., 2016, ApJ, 825, 24
- e) "Cross-correlation between the CMB lensing potential measured by Planck and high-z sub-mm galaxies detected by the Herschel-ATLAS survey",  
Bianchini F., **Bielewicz P.**, et al., 2015, ApJ, 802, 64
- f) "Planck 2013 results. XXVI. Background geometry and topology of the Universe",  
Planck Collaboration et al. (including **Bielewicz P.**), 2014, A&A, 571, A26
- g) "Planck 2013 results. XXIII. Isotropy and Statistics of the CMB",  
Planck Collaboration et al. (including **Bielewicz P.**), 2014, A&A, 571, A23
- h) "Planck 2013 results. XII. Component separation",  
Planck Collaboration, et al. (including **Bielewicz P.**), 2014, A&A, 571, A12
- i) "A search for concentric rings with unusual variance in the 7-year WMAP temperature maps using a fast convolution approach",  
**Bielewicz P.**, Wandelt B.D., Banday A.J., 2013, MNRAS, 429, 1376
- j) "Constraining the topology of the Universe using the polarised CMB maps",  
**Bielewicz P.**, Banday A.J., Górski K.M., 2012, MNRAS, 421, 1064
- k) "Constraints on the topology of the Universe derived from the 7-year WMAP data",  
**Bielewicz P.**, Banday A.J., 2011, MNRAS, 412, 2104
- l) "CMB temperature lensing power reconstruction",  
Hanson D., Challinor A., Efstathiou G., **Bielewicz P.**, 2011, PhRvD, 83, 043005
- m) "The study of topology of the Universe using multipole vectors",  
**Bielewicz P.**, Riazuelo A., 2009, MNRAS, 396, 609
- n) "Multipole vector anomalies in the first-year WMAP data: a cut-sky analysis",  
**Bielewicz P.**, Eriksen H. K., Banday A. J., Górski K. M., Lilje P. B., 2005, ApJ, 635, 750
- o) "Low order multipole maps of CMB anisotropy derived from WMAP"  
**Bielewicz P.**, Górski K. M., Banday A. J., 2004, MNRAS, 355, 1283
- p) "Influence of the gravitational lensing effect on distance determination"  
**Bielewicz P.**, 2001, Acta Physica Polonica B, vol.32, No.10, 3115

7. Publication statistic (sources Web of Science and NASA ADS, 1st October 2018; values refer only to peer-reviewed articles):

- 112 peer-reviewed articles in scientific international journals (WoS, NASA ADS)
- Total refereed citations (excluding self-citations): 16890 (WoS), 22104 (NASA ADS)
- Average number of refereed citations (excluding self-citations) per article: 151 (WoS), 197 (NASA ADS)
- *h*-index: 53 (WoS), 64 (NASA ADS)
- Total impact factor according to Journal Citation Reports list: 543.960

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8. Scientific collaborations:

- 2002-2003: participating member of CMBNet, EU funded research training network
- from 2008: Planck Scientist and LFI and HFI Core Team member
- from 2015: Collaborator of the Euclid project

9. Awards for scientific activity:

- 2018: Gruber cosmology prize for the Planck Team

10. Refereeing experience:

- Referee for the Monthly Notices of the Royal Astronomical Society
- Referee for the Astronomy and Astrophysics

11. Organization of conferences:

- Member of the Local Organizing Committee of the Planck Joint Core Team meeting, May 2014, Trieste

12. Conferences:

- August 2017: Understanding cosmological observations, Benasque, Spain  
Talk: "Constraints on the topology of the Universe derived from the Planck CMB maps"
- June 2016: Nicolaus Copernicus Astronomical Center jubilee, Warsaw, Poland  
Talk: "Latest results from Planck"
- March 2016: 51st Rencontres de Moriond, La Thuile, Italy  
Talk: "Testing significance of the large angular scale CMB anomalies using Planck data"
- 2009-2015: several talks at Planck Core Team and Working Group meetings
- September 2015: International Conference on Particle Physics and Cosmology COSMO 2015, Warsaw, Poland  
Talk: "Cross-correlation between the CMB lensing potential measured by Planck and high-redshift Herschel-ATLAS galaxies"
- January 2015: Workshop on conformal Universe, Warsaw, Poland  
Talk (invited): "A search for concentric rings with unusual variance in CMB maps"
- September 2014: Experimental search for quantum gravity, Trieste, Italy  
Talk (invited): "Planck 2013 cosmological results"
- July 2014: String phenomenology, Trieste, Italy  
Talk: "Planck 2013 cosmological results"
- August 2013: Workshop on New Light in Cosmology from the CMB, Trieste, Italy  
Talk: "Testing statistical properties of the Planck CMB maps using the real-space N-point correlation functions"
- July 2013: G20th and 10th Amaldi international conferences, Warsaw, Poland  
Talk: "Constraints on the topology of the Universe derived from the Planck CMB maps"  
Poster: "A search for concentric rings with unusual variance in the CMB maps"
- March 2012: 47th Rencontres de Moriond, La Thuile, Italy  
Talk: "Constraints on the topology of the Universe derived from the 7-year WMAP CMB data and perspectives of constraining the topology using CMB polarisation maps"
- June 2011: Statistical Challenges in Modern Astronomy V, State College, USA  
Poster: "Estimation of moments on azimuthally symmetric patches on the sphere by means of fast convolution"
- June 2007: Planck consortium meeting, Toulouse, France  
Poster: "Study of topology of the universe using multipole vectors"



### 13. Seminars:

- January 2017: Institute of Experimental Physics, Warsaw, Poland  
Seminar: "Planck 2015 cosmological results"
- November 2016: National Centre for Nuclear Research, Warsaw, Poland  
Seminar: "Planck 2015 cosmological results"
- February 2016: Nicolaus Copernicus Astronomical Center, Warsaw, Poland  
Seminar: "Cosmic microwave background anomalies at large angular scales"
- October 2014: Center for Theoretical Physics, Warsaw, Poland  
Seminar: "Studies of the cosmic microwave background at large angular scales"
- June 2014: Imperial College, London, UK  
Seminar: "Constraining the topology of the Universe using temperature and polarisation CMB maps"
- December 2012: SISSA, Trieste, Italy  
Seminar: "Studies of the cosmic microwave background at large angular scales"
- December 2009: CERN, Toulouse, France  
Seminar: "Gravitational lensing of the CMB"
- May 2008: LAL, Orsay, France  
Seminar: "Estimation of the gravitational lensing potential for CMB maps with mask"
- September 2007: IAP, Paris, France  
Seminar: "Study of topology of the Universe using multipole vectors"
- February 2007: APC, Paris, France  
Seminar: "Removing gravitational lensing B-modes"

### 14. Teaching:

- from 2013 to 2016: co-supervisor of the Ph.D. student Federico Bianchini (supervision prof. Carlo Baccigalupi) working at SISSA in Italy on Ph.D. thesis "Cosmic Microwave Background and Large Scale Structure: Cross-Correlation as seen from Herschel and Planck satellites" (defended on 29.09.2016)
- July 2016: supervising student Katarzyna Kruszyńska during summer student programme at Nicolaus Copernicus Astronomical Center.
- February 2013, March 2014, February 2015: Lectures on CMB observations to Ph.D. students at SISSA
- 2000 - 2004: Exercises to lectures of mathematical analysis and numerical methods for undergraduate students at the Faculty of Physics at University of Warsaw (in total 360 hours).

### 15. Scientific outreach:

- October 2017: Nicolaus Copernicus Astronomical Center, Warsaw, Poland  
Popular science talk: "Mission of the Planck satellite"
- October 2017: article in popular science monthly "Delta"
- November 2012: lecture to visiting high school students at IRAP in Toulouse, France

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