Nicoletta Krachmalnicoff

Research activity report

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Overview of the candidate

I am an observational researcher in Cosmology. In the past 6 years my research activity has been focused on the study of the distant universe, with the goal of investigating its history and evolution by analyzing data coming from different telescopes and satellites.

I am part of several collaborations for CMB experiments, in particular Planck, Polarbear, Simons Array and LSPE. Within these teams my main tasks are related to the analysis of foreground contamination coming from the diffuse emissions of our Galaxy, and to the study and mitigation of instrumental systematic effects. These two topics have also been the principal aspects of my PhD activity.

From October 2015 to August 2016 I was also involved in the QUBIC collaboration, working on the testing and development of the simulation pipeline.

I have strong computational and numerical skills, which I apply everyday to my data analysis work and which I also expanded by attending specific courses related to Data Science.

Moreover, versatility, team working and communication represent important and fundamental aspects in the way I pursue my scientific goals.

1 Introduction

The Cosmic Microwave Background (CMB) is the first radiation emitted by our universe. It started to freely propagate ~ 13.8 billion years ago, about 380.000 years after the Big Bang when the temperature of the primordial universe dropped below 3000 K allowing the disentanglement between matter and radiation. Since the discovery of the CMB signal, by Penzias & Wilson (1965), several experiments, both ground based and from satellites, have been built with the specific goal of understanding its characteristics. The study of CMB radiation offers, indeed, the unique possibility to investigate directly the very young universe, shedding light on its evolution and its composition.

The CMB radiation has a black body frequency spectrum at the temperature of about 2.7 K (Fixsen 2009) and it is characterized by a high level of isotropy. Anisotropies at the order of $\Delta T/T \simeq 10^{-5}$ have been measured for the first time by the COBE (COsmic Background Explorer) satellite and represent the trace of density dishomogeneity in the primordial universe, seeds of the structure that we observe today in our universe (Smoot et al. 1992).

The shape of the CMB angular power spectrum critically depends on the values of cosmological parameters, therefore by fitting it with different models we can retrieve important information on the properties of the universe. The ESA Planck satellite measured the amplitude of the CMB temperature power spectrum up to multiple $\ell \simeq 2500$ corresponding to an angular resolution of about 5 arcminutes

(Planck Collaboration I 2016). Data are extremely well fitted by a standard ΛCDM model, characterized by a set of six main cosmological parameters whose values have been retrieved with a precision $\lesssim 1\%$ (Planck Collaboration XIII 2016).

CMB radiation is also partially linearly polarized (at the level of $\sim 10\%$) due to Thomson scattering events during the recombination era. The linear polarization field in the sky can be be studied by measuring the amplitude of the Stokes parameters, Q and U or by decomposing it into two different modes, the so-called E and B-modes (in analogy with the electromagnetic field), which have different geometrical pattern in the sky (Hu & White 1997).

The peculiarity of CMB polarization modes is that different physical perturbations in the primordial universe generates different polarization patterns. In particular scalar perturbations at the recombination (i.e. density fluctuations) generates only E-modes, while tensor perturbations (i.e. primordial gravitational waves) could cause both E and B-modes patterns. Therefore a detection of a B-mode signal would represent a first indirect measurements of primordial gravitational waves, and would open the study and investigation of the very first instant of the evolution of our universe, the so-called inflation era.

Primordial B-modes are subdominant with respect to the scalar E-modes, and their amplitude is defined by the tensor-to-scalar ratio r. The value of this parameter is directly linked to the unknown energy scale of inflation. The B-modes signal is extremely faint ($\lesssim 1\,\mu$K) and it is expected to reach its maximum amplitude at the degree angular scales. Sophisticated experiments with very high sensitivity are needed in order to observe such a faint signal. In the last years several experiments have been designed and built with this goal, and thanks to this effort the value of r has been constrained to be < 0.07 at 95% confidence level (BICEP2 Collaboration & Keck Array Collaboration 2016).

The detection of CMB primordial B-modes represents one of the major challenge of modern observational cosmology and is the context in which I have been developing my research activity.

2 PhD research activity

I conducted my PhD research activity at the University of Milano, in the group led by Prof. Marco Bersanelli, and under the supervision of Prof. Aniello Menella. The activity lasted for about 3.5 years and started in November 2011.

During my PhD I investigated two of the most influent challenges for experiments aimed at observing the CMB polarized signal: the control of instrumental systematic effects and the characterization of Galactic diffuse foregrounds l which strongly contaminates the cosmological observations.

I carried out the work related to the instrumental systematic effects in the context of the Planck experiments, by analyzing data coming from the Low Frequency Instrument (LFI) on board of the satellite, and as part of the collaboration designing the LSPE experiment (Large Scale Polarization Explorer) by developing a simulation pipeline for the STRIP instrument.

For what concerned the characterization of diffuse Galactic foregrounds in polarization I was deeply involved in the analysis of the Planck data in the BICEP2 field and I took part at the joint analysis of Planck and BICEP2 data.

The details of the analysis carried on in these two contexts are reported in the following sections.

2.1 Instrumental systematic effects

Activity:

- Developing of an end-to-end simulation pipeline for the LSPE-STRIP experiment.
- Involved in the characterization of systematic effects for the Planck-LFI data analysis.

Main publications:

- "A coherent polarimeter array for the Large Scale Polarization Explorer (LSPE) balloon experiment", LSPE-STRIP Collaboration 2012, Proceedings of the SPIE, Vol. 8446, 7

- "Planck intermediate results. XLVI. Reduction of large-scale systematic effects in HFI polarization maps and estimation of the reionization optical depth", Planck Collaboration 2016, A&A, Vol. 596, A107

As pointed out, the CMB B-mode signal is extremely fainted and therefore its observation demand instruments with very high level of sensitivity. Reaching performances of this kind represents a major challenge: it requires instruments with large number of detector and a great control of instrumental systematic effects, in order to limit their impact on the scientific results. The implementation of pipelines, able to perform end-to-end simulations of the instrument architecture and behavior, is a key step to identify the most important systematic effects that could affect observations and to study removal and control strategies. The pipeline I developed for the STRIP instrument has precisely this goal.

The LSPE (Large Scale Polarization Explorer) experiment, funded by the Italian Space Agency (ASI) is a future experiment aiming at observing the CMB polarized signal, at large angular scales ($\gtrsim 1^\circ$) with a sensitivity that would allow the detection of primordial B-modes with $r \simeq 0.05$ (LSPE Collaboration 2012). It will be equipped with two instruments (STRIP and SWIPE) observing the sky in four frequency bands between 40 and 240 GHZ, and it is expected to operate at the beginning of 2018. At the moment when I developed my work (between 2012 and 2015) the experiment was designed as a ballon-borne one, expected to perform a long duration flight (about 15 days) from the Svalbard Islands during the arctic night, observing about 30% of the sky.[1].

The STRIP instrument is composed by an array of coherent polarimeters coupled with corrugated feed horns, circular polarizer and Ortho-mode Transducer (OMT) and located in the focal plane of a telescope. Each module measures directly the Stokes Q and U parameters of the observed sky at a frequency of 43 GHz.

During the first part of my PhD I developed an end-to-end pipeline for this instruments. The pipeline takes as input realistic simulated maps of the sky, which include the polarized signal of the different astrophysical components (CMB and foreground radiations) and simulates the observation of these maps by the instrument, considering the pointing direction, the sky scanning strategy, the optical characteristics and the polarimeter architecture. Its outputs are the Time Ordered Data (TOD) of this simulated observations which include realistic representations of the noise and the presence of different possible systematic effects. The obtained TOD can then be projected on maps to get a representation of the sky as observed by the instrument and from them the related power spectra can be computed (an example of maps as obtained as output from the simulation pipeline is shown in Figure 1).

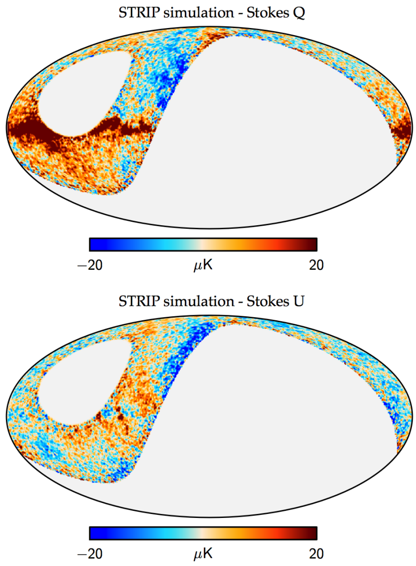

Figure 1: Simulated maps of STRIP sky observations as obtained though the developed end-to-end pipeline.

This pipeline has been intensively used with several goals, including: (i) optimization of the focal plane configuration; (ii) optimization of the sky scanning strategy; (iii) assessment of the realistic level of noise components; (iv) assessment of the contamination coming from instrumental systematic effects on the final scientific observations. For the latter point I took into account the presence of several non-idealities in the polarimeter behavior, computing first analytical calculation to understand their propagation through the polarimeter architecture up to the final signal detection, and then including them in the simulation process to derive their impact on the observed maps and power spectra.

[1]In 2016 ASI revised the design of the experiment, mainly for financial reasons. In the new configuration the STRIP instrument will do observations from the ground covering the same $\sim 30\%$ of the sky.

All the effects I took into account result in having a negligible impact on the measurement of sky radiation at 43 GHz, showing therefore that the STRIP polarimeter architecture is capable of minimizing the systematic effects.

Some of the results of this work are published in LSPE-STRIP Collaboration (2012), and a detailed description of the simulation pipeline is reported in chapter 4 of my PhD manuscript, also attached to this application.

During my PhD I also took part at the characterization of instrumental systematic effects for the LFI instrument on board of the Planck satellite. I have been involved in the analysis of Planck data since January 2013 as member of the Planck-LFI Core Team. My main activity within the Planck collaboration as been related to foreground analysis, as described in the next sections, but I also followed more technical aspects related to the LFI instrument, in collaboration with the group of the University of Milano. In particular, my effort has been dedicated to asses the impact of LFI instrumental systematic effect on the analysis of the low-multipoles side of the polarization E-modes power spectrum as measured by combining the data taken by the two Planck instruments (LFI and the High Frequency Instrument, HFI). The precise measurement of the low-ℓ E-mode spectrum is of particular interested since it allows to retrieve the value of the optical depth of Thomson scattering (τ) during the epoch of reionization. Results of this analysis are summarized in Planck Collaboration Int. XLVI (2016) and in particular the description of the work I carried out in this context is reported in Section 4 of the paper.

2.2 Foreground analysis of Planck data in the BICEP2 field

Activity:

- Analysis of Planck-HFI data in the context of BICEP2/Planck joint collaboration, to study the contamination coming from polarized thermal dust radiation to BICEP2 CMB measurements.

Publications:

- "Planck intermediate results. XXX. The angular power spectrum of polarized dust emission at intermediate and high Galactic latitudes", Planck Collaboration 2016, A&A, Vol. 586, A133
- "Joint Analysis of BICEP2/Keck Array and Planck Data", BICEP2/Keck and Planck Collaborations 2015, PRL, Vol. 114, 10

During my PhD I also started to be deeply involved in the analysis and characterization of the diffuse Galactic foreground radiation. The separation of the polarized CMB signal from the other kinds of polarized emission coming from our Galaxy represents, indeed, another huge challenge in the measurements of primordial B-modes signal.

Our Galaxy emits two kinds of highly polarized radiation: (i) synchrotron radiation, resulting from the acceleration of cosmic rays electrons in the Galactic magnetic field, and dominating at low frequency ($\lesssim$ 100 GHz); (ii) thermal emission from Galactic dust grain, partially aligned to the Galactic magnetic field, dominating the sky emission at high frequency ($\gtrsim$ 100 GHz). Both kinds of radiation can reach up to $\sim$ 20% of polarization fraction at intermediate and high Galactic latitudes, contaminating the CMB signal even far away from the Galactic plane (see fore example Gold et al. (2011) and Planck Collaboration X (2016)).

The problem of contamination to the CMB polarized signal coming from Galactic diffuse signals is a well known one and has been studied intensively in the recent years. Nevertheless the real extent of this issue has become more and more clear with the income of instruments with increasingly sensitivity. A relevant example of this point comes from the BICEP2 observations.

BICEP2 observed from the South Pole a small region of the sky, with an effective area of about 380 square degrees, at high Galactic latitude, at a frequency of $\sim$ 150 GHz, and reached a sensitivity of about 90 nK on Stokes Q and U maps (angular resolution of about 0.5°) during three seasons of observations, from 2010 to 2012 (BICEP2 collaboration II 2014). Results from these observation campaign have been published in March 2014, showing the first detection of a B-mode signal at such a high Galactic latitude. This detection has been originally interpreted as the first detection of primordial gravitational wave signal with a tensor-to-scalar ration $r \simeq 0.2$ (BICEP2 collaboration I 2014).

The Planck satellite, with its full sky coverage, also observed the BICEP2 field, with multi-frequency measurements, giving therefore the possibility to further investigate the results presented by the BICEP2 collaboration. I was directly involved in this project, in close collaboration with the Planck group at the IAS institute in Orsay (France).

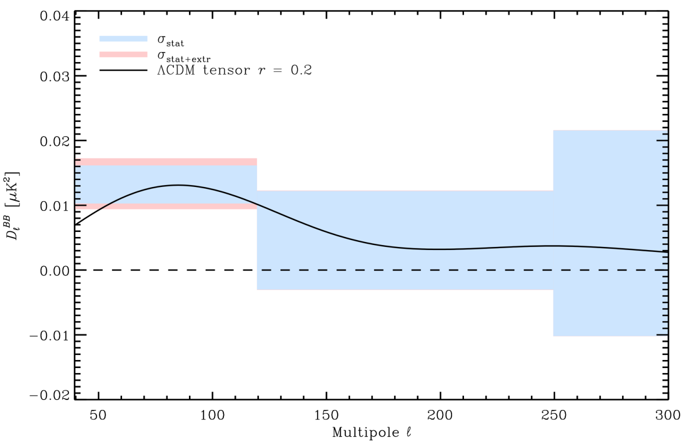

Figure 2: B-modes amplitude of thermal dust emission as measured from Planck at 353 GHz extrapolated to 150 GHz and compared to a CMB signal with $r = 0.2$. Figure from Planck Collaboration Int. XXX (2016).

The main goal of our analysis of Planck data, was to understand the level of contamination coming from polarized thermal dust radiation to the BICEP2 B-mode observations. We focused our efforts on the investigation of the Planck polarized observations at 353 GHz, the highest of the Planck polarized frequencies, where the thermal dust signal dominates the sky emission. By computing power spectra of the 353 GHz map in the BICEP2 field we were able to asses the amplitude of the thermal dust emission, which we found being compatible with the signal observed by the BICEP2 telescope as shown in Figure 2. In this context my main task was to analyze Planck data with independent tools, in order to be able to cross-check all the results we obtained, and to be sure that they were free of artefacts coming from issues in the data analysis.

Results of this work are reported in Planck Collaboration Int. XXX (2016) and in particular the bulk of my job is summarized in appendix D.

After the publication of the results of the Planck analysis in the BICEP2 field, we started a collaboration with the BICEP2 team in order to simultaneously analyze the data coming from the two complementary instruments (high sensitivity of BICEP2 and multi-frequency coverage of Planck). I was also directly involved in this analysis with the role of characterizing the impact of the BICEP2 filtering and map-making process on a thermal dust signal, through simulations. The results of this joint analysis are described in BICEP2/Keck Array and Planck Collaborations (2015). At the moment of the publication of this paper the upper limit on the value of r that we were able to put was the most stringent one available from direct B-modes measurements.

3 Postdoctoral research activity

My postdoctoral research carried out at the University of Milano (Italy), the APC institute in Paris (France) and the SISSA school of Trieste (Italy) is in line with the work conducted during my PhD. In particular I have been constantly working on the characterization of foreground polarized emissions, both continuing by work as part of the Planck collaboration and with my own and independent projects. Recently I have been in charge of the estimation of the diffuse foreground contribution to the Polarbear second season CMB observations. I have also been involved in the development and testing of the simulation pipeline for the QUBIC experiment.

3.1 Foreground characterization and modelization

Activity:

- Characterization of synchrotron and thermal dust radiation as contaminant for CMB B-modes experiments at the degree angular scales.
- In charge of the analysis of S-PASS data to study synchrotron radiation.
- Studying of foregrounds spectral energy distribution and correlation within the Planck collaboration.
- Modelization of foregrounds for future CMB experiments
- Estimation of foregrounds contribution to Polarbear measurements.

Publications:

- "Characterization of foreground emission on degree angular scales for CMB B-mode observations . Thermal dust and synchrotron signal from Planck and WMAP data", Krachmalnicoff N. et al. 2016, A&A, Vol. 588, A65
- "The B-mode angular power spectrum measured by Polarbear in two observing seasons", Polarbear Collarboration 2017, to be submitted
- "Planck 2016 results. Dust polarized foreground", Planck Collaboration 2017, in preparation

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The work and results about foreground contamination in the BICEP2 CMB observations made clear that a pricise characterization of the diffuse foreground emission at intermediate and high Galactic latitude is of primary importance for CMB experiments. Without a proper component separation and estimation of foreground residuals in CMB observations it will be impossible to detect any primordial B-modes signal in the future.

Starting from this consideration, I therefore continued my activity in the field, by quantifying the contamination from synchrotron and thermal dust emissions to the B-modes of the CMB anisotropies on the degree angular scale and on several regions at intermediate and high Galactic latitude, using data from the Planck and Wilkinson Microwave Anisotropy Probe (WMAP) satellites. In particular, I computed polarization angular power spectra of foreground emissions in 352 circular sky patches located at Galactic latitude $|b| > 20°$, each of which covers about 1.5% of the sky. Using spectral properties derived from Planck and WMAP data to extrapolate, in frequency, the amplitude of synchrotron and thermal dust B-mode spectra in the multipole bin centered at $\ell \simeq 80$, I estimated the amplitude and frequency of the foreground minimum for each analyzed region.

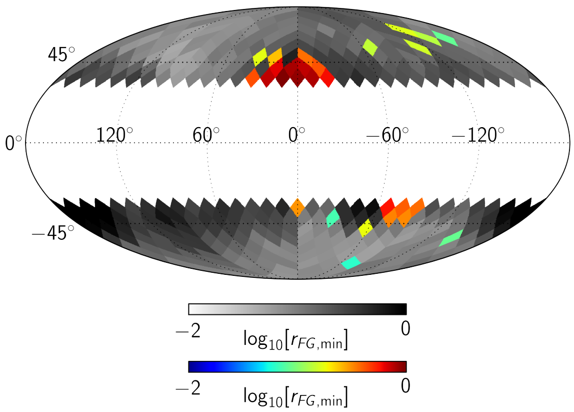

Figure 3: Estimated amplitude of the minimum of foreground emissions at $\ell \sim 80$ in different sky regions. Colored pixels refer to detection, grey pixels to upper limits. Figure from Krachmalnicoff et al. (2016).

Results shows detection of both dust and synchrotron signal on degree angular scales and at a 3σ confidence level in 28 out of 352 regions. In these regions the minimum of the foreground emission is found at frequencies between 60 and 100 GHz with an amplitude expressed in terms of the equivalent tensor-to-scalar ratio, $r_{FG,\min}$, between ~ 0.06 and ~ 1. Some of these regions are located at high Galactic latitudes in areas close to the ones that are being observed by suborbital experiments. In all the other sky patches where synchrotron or dust B modes are not detectable with the required confidence, I was able to put upper limits on the minimum foreground contamination and found values of $r_{FG,\min}$ between ~ 0.05 and ~ 1.5 in the frequency range 60-90 GHz. A map reporting the estimated amplitude of the minimum of foreground emission in the considered areas is shown in Figure 3.

These results are important mainly for two aspects: first they give a map of the level of contamination in the different regions of the sky, together with an estimation of the frequency of the foreground minimum, which could be important in defining the strategy of sky observations (i.e. region to observe and frequency coverage) for current and future CMB ground-based experiments. Second, they indicate that, with the current sensitivity in low frequency observations, it is not possible to exclude the presence of synchrotron contamination to CMB cosmological B modes at the level requested to measure a gravitational waves signal with $r \simeq 0.01$ at frequency $\lesssim 100$ GHz anywhere. This work as been published in January 2016 (Krachmalnicoff et al. 2016).

In September 2016 I moved to the SISSA school (International School for Advanced Studies) in Trieste, where I am currently employed, joining the group led by Prof. Carlo Baccigalupi. My work in SISSA is collocated in the context of the RadioForeground project[2] and my main activity is related to the analysis of different low frequency data sets in order to investigate as much as possible synchrotron properties.

I am currently in charge of the analysis of the S-PASS data (survey P.I. Dott. Ettore Carretti, Carretti (2010)). Whit an observing frequency of 2.3 GHz, a sky coverage of $\sim 50\%$ (Southern hemisphere), an angular resolution of about 10 arcminute, and a signal-to-noise ratio $\gtrsim 3$ everywhere, the S-PASS data give the unique possibility of studying the synchrotron radiation at the Galactic latitudes where the signal is too faint to be detected by Planck or WMAP. This analysis started at the end of 2016 and we expect to publish results in few months. These results, in particular, will include the first measurements of synchrotron angular power spectrum up to arcminutes scales together with an estimation of the amplitude of the signal in those regions where several CMB experiments are currently observing (like for example BICEP-2/Keck and Polarbear).

Precise studies of foreground emission are also important to be able to construct foregrounds model representative of the data. A realistic modelization of foregrounds, including all the complexity of these radiations, is essential to develop and test component separation algorithms to be used in the future CMB experiments, as, for example, Simons Observatory and CMB-StageIV (Abazajian et al. 2016). In this context I am involved in an ambitious and long term project, in collaboration with people at SISSA and with the group led by Francois Boulanger at IAS (Orsay). The goal of this work is doable: within the Planck collaboration we are analyzing the new Planck data, together with WMAP products, in order to get precise measurements of thermal dust and synchrotron spectral energy distribution, frequency decorrelation of the two, and spatial decorrelation between them. In parallel we are trying to model synchrotron and thermal dust in coordination, by using the same underlying magnetic field. The final products of this work will be a set of foregrounds simulation reproducing the observed data features to be used for component separation algorithm validation, as mentioned before.

In May 2016 I also joined the Polarbear collaboration (The Polarbear Collaboration 2014). So far, my role in the collaboration as been related to foregrounds and in particular I have been in charge of the estimation of the foreground contribution to the CMB polarized measurements in the first two seasons of observations. A paper reviewing the observation and results of Polarbear, together with the description of the foreground estimation is currently in preparation and will be submitted in the next weeks.

3.2 QUBIC

Activity:

- Developing and testing of the simulation pipeline for the QUBIC experiment.

[2]http://www.radioforegrounds.eu

From October 2015 to August 2016 I worked, first as visiting researcher supported by the University of Milano and then with support of the CNRS, at the Astroparticle and Cosmology Laboratory (APC) in Paris, as part of the QUBIC collaboration, in the group led by Dott. Jean-Christophe Hamilton.

QUBIC is a future experiment aimed at observing the CMB polarized signal with the goal of detect or constrain on the amplitude of the B-mode signal generated by the primordial gravitational waves.

QUIBIC is a peculiar experiment compared to other instruments aiming at observing the CMB: it implements a bolometric interferometry technology that allows a superior control of instrumental systematic effects (Aumont et al. 2016). The QUBIC experiment represents the main topic of my research project for this application and therefore more detail about its architecture and capabilities are described in the attached proposal.

In the period of my activity at APC I was involved in the developing and testing of the data analysis and simulation pipeline for the QUBIC experiment. This pipeline, originally developed by Dott. Pierre Chanial, has the primary goal of simulating the QUBIC data acquisition giving, as final output, the polarization maps of the sky as observed by the QUBIC instrument. The pipeline uses the object-oriented programming paradigm and is coded in Python and Fortran languages.

I intensively made use of this pipeline running realistic simulations, with the objective of getting realistic realizations of the instrumental noise, together with testing the performance of the map-making algorithm. It is important to say that my work gave the possibility to use several of the pipeline modules for the first time for scientific scopes, therefore the work itself needs also to be seen as a validation of the whole code. During this phase I applied several modifications to the pipeline in order to solve problems and bugs, or add features. As part of this work I also studied the impact of including the observations of the Planck satellite as a preconditioner in the numerical solution of map-making problem.

During this period I also supervised (together with Pierre Chanial and Jean-Christophe Hamilton) the internship project of a master student. This work consisted in including in the pipeline the frequency bandwidth effect, studying in particular its effect on the synthesized beam of the instrument (Incardona 2016).

4 Other activities

4.1 Radio interferometry

From August 2010 to November 2011 I worked as research student at the Max Planck Institute for Astrophysics (MPA) in Garching (Germany), under the supervision of Dott. Benedetta Ciardi, in the cosmology group led by Prof. Simon White.

My activity was related to the data analysis of the LOFAR (LOw Frequency Array) radio interferometer as a member of the Epoch of Reionization Key Science Project (van Haarlem et al. 2013). During this period I learnt the basic of radio interferometry and how to reduce data coming from these kind of instrument. In particular in my project I developed a pipeline to analyze the obtain images from the raw data of the telescope and analyze the frequency spectra of the detected point sources.

4.2 Student tutoring and outreach

During my research activity I followed as supervisor four bachelor and master students with long term projects ($\gtrsim$ 6 months) on different subjects: (i) calibration strategy for LSPE-STRIP instruments; (ii) foreground component separation techniques for the LSPE experiment: (iii) studying of the spatial correlation between polarized thermal dust and synchrotron radiations; (iv) impact of frequency bandwidth for QUBIC data analysis.

Another important aspect in my research activity is the dedication to scientific communication to the public. During this years I gave several public lessons about CMB and Cosmology in general both in schools and at public events. At SISSA I recently started to be involved in the science communication program.

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