Cosmology from LiteBIRD and synergy with large-scale surveys like *Euclid*

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Abstract

This PhD proposal will estimate the cross-correlation between galaxy surveys like the forthcoming *Euclid* space mission, and Cosmic Microwave Background (CMB) observations: the latter include available data from *Planck*, forecasts for missions from ground (as in the *Simons Observatory)* and from space (as in the *LiteBIRD* mission proposal).
The PhD project is co-supervised by Valeria Pettorino (CEA/DRF/IRFU/DAp/LCS) and Dr. Stéphane Ilic (IJLAB, Orsay), who has just been hired for a postdoc position on LiteBIRD. This is a timing opportunity to work together, CEA/DAp and Orsay, during the postdoc of S. Ilic: on one side V. Pettorino is leading the *Euclid* likelihood development, led the dark energy analysis for the *Planck* satellite, and has now joined the cross-correlation paper group in LiteBIRD; on the other side, S. Ilic implemented the first forecasts that combine *Planck priors with the Euclid* observables, and has therefore a software that can be adapted for this project and for the LiteBIRD analysis. This will give a concrete estimate of the cross-correlation, which is useful for *Euclid* (as CMB breaks degeneracies among early time and late time parameters) and for LiteBIRD, at a time in which it is necessary to understand the impact of this mission on cosmology.

Context

The Cosmic Microwave Background radiation has demonstrated to be a powerful probe for cosmology: its temperature anisotropies carry information on the early-time Universe, as well as on the structure encountered along the light path. The early time Universe includes a phase of accelerated expansion, referred to as 'inflation', which appears to be driven by (at least) a scalar field: its energy scale, dynamics and origin is tightly connected to primordial gravitational waves, whose impact is expected at large scales in the polarization of the Cosmic Microwave Background.

Temperature and polarization of the CMB have been observed via the *Planck* satellite, which allowed a full-sky survey with unprecedented resolution. Measurements from balloons and detectors from ground are contributing to detail this picture, with higher resolution at smaller angular scales (from ACTPol, SPTPol, as well as the coming generation of detectors such as the Simons Observatory (SO)).

In this context, a new space mission on CMB polarization has been proposed: LiteBIRD [1], a Large-Class mission, selected by JAXA for launch in the late 2020's, designed to search for primordial gravitational waves through the measurement of their imprint on large-scale polarization. The LiteBIRD instruments consist of three telescopes, namely the Low-, Medium and High-Frequency Telescope with over 15 frequency bands measured between 34 GHz and 448 GHz. The project is currently supported for phase-A by other partners, including notably France and CNES: it is therefore particularly important to be able to provide reliable expectations on the impact that this mission would have on science, in view of systematics and foregrounds, in order to best contribute to its design and development. Four thematic areas are currently under investigation: they concern systematics, foregrounds, payload and calibration. *Project study groups* have just been formed within the collaboration, and will concern reionization, early universe, as well as cross-correlation (V.Pettorino has recently joined the cross-correlation group in LiteBIRD). CMB adds information about early-time Universe, baryons, primordial fluctuation amplitude, which are complementary to the late-time ones of galaxy surveys.

Within galaxy surveys, ESA *Euclid* satellite[1], to be launched in 2023, will observe how galaxies formed to study the nature of dark energy and dark matter. *Euclid* will collect 170 million gigabytes of data, observe the shapes of 1.5 billion galaxies in different redshift epochs, thus providing the largest data set available to test dark energy. The *Euclid* likelihood is under development (within a taskforce led by the V. Pettorino) and its interface with the cross-CMB group is now being put in place. CMB lensing and polarization depend on structure formation, the same structures studied via galaxy surveys. The impact of their cross-correlation is particularly important to discriminate a cosmological constant from alternative theories which modify the evolution of structures.

This PhD proposal will develop the science and software needed to combine the information from CMB experiments (including available data from *Planck* and forecasts for LiteBIRD and SO) with the coming data from large-scale structure surveys as the *Euclid* satellite.

The PhD Thesis

We have identified three main goals for the PhD student, within a collaboration between CosmoStat Lab at CEA and IJLAB at Orsay:

1. Start from the code developed by S. Ilic to analyze the impact of CMB and galaxy survey cross-correlation. The student will estimate the synergy between CMB experiments and *Euclid,* extend the *Euclid* likelihood development led by V. Pettorino to CMB observables, and directly contribute to the *Euclid* scientific exploitation within the X-CMB group of the collaboration;
2. adapt the software to the LiteBIRD design, and estimate the scientific impact of LiteBIRD via forecasts, thanks to the experience developed in *Euclid* and *Planck* by the two supervisors;
3. investigate different methods to separate foreground components and improve the reconstruction of the CMB signal, thanks to the collaboration with CEA CosmoStat.

[1] https://www.euclid-ec.org/

Intermediate objectives will include:

- getting familiar with CMB theory and the current range of experiments (including available data and proposals for new missions such as LiteBIRD)
- start from the code developed for the *Euclid* CMB cross correlation (CMB-XC) science working group by Stéphane Ilic (who will act as co-supervisor), learn how to use it and apply it to LiteBIRD specifications;
- calculate the cross-correlation with large-scale surveys, profiting of the validated tools and reference Fisher forecasts made available within the *Euclid* taskforce led by V.Pettorino and in collaboration with Martin Kilbinger from CosmoStat, who is one of the developer of the validated forecast codes;
- present results to Carlo Baccigalupi and Nabila Aghanim, leads of the Euclid CMB-XC science working group. The student will contribute to merge the CMB likelihood into the CLOE likelihood developed in *Euclid*;
- familiarize with the different existing methods of component separation and methods to improve reconstruction of the signal, in collaboration with Jean-Luc Starck and Sam Farrens.

The student will join the *Euclid* and LiteBIRD collaboration and participate to the activity of the cross-correlation paper groups. A visit of the PhD student to SISSA during the second year can be arranged, in order to present first results and interact with the cosmology group there, which is very much involved in the next generation of CMB surveys.

The PhD Candidate

The candidate is expected to have a master in physics (preferably with some classes in cosmology, cosmological evolution and/or astrophysics), and would have preferably used already a Boltzmann code to derive cosmological evolution and CMB spectra in the standard model. The candidate would have experience with at least one programming language (python, C, fortran), in order to use and develop the cross-correlation code that will be made available publicly. The candidate would show interest in working at the interface between data, software development and theory. The PhD student will be able to concretely collaborate to the Euclid and LiteBIRD collaborations, and develop tools that will be useful also for large structure formation surveys and other CMB datasets, such as the Simons Observatory or future proposals recently encouraged within the CMB Decadal Recommendations.

The student will have the possibility to learn how to derive CMB spectra from a Boltzmann code, calculate cross-correlation terms with large-scale structure and infer forecasts on different cosmological parameters. In addition, the student will learn first tools to deal with systematics in CMB experiments, and will get familiar with methods for foreground component separation which have been developed in the community and within CosmoStat group.

The scientific environment

The thesis will take place at CosmoStat, within the Astrophysics Department (DAp) under the supervision of Valeria Pettorino; co-supervision with Stéphane Ilic, at IJCLab in Orsay from November 2021, is planned.

V. Pettorino has been a key contributor to *Planck* and *Euclid* space missions; she has given lectures on CMB theory, led the *Planck* Dark Energy analysis [4,5], and is now leading the inter-science taskforce responsible for the *Euclid* Likelihood development. Among her publications, she worked on CMB polarization, that she proposed to use as a tool to test early time modifications of gravity [2,3]. Pettorino has supervised 4 PhD students so far and was in charge of the forecast validation for the Euclid survey [7]. This effort provided a set of validated, reliable, tools that were used in several (>10) follow-up scientific papers by the collaboration. V.Pettorino has recently joined the LiteBIRD collaboration and the cross-correlation effort led by Marina Migliaccio. The CosmoStat group has a vast experience in component separation, delensing, and software development: both Jean-Luc Starck (head of CosmoStat) and Sam Farrens (staff computational scientist) have joined LiteBIRD in 2021. CosmoStat is also key contributor to the *Euclid* space mission: the project will benefit of the collaboration of Martin Kilbinger, and of his experience in large-scale weak lensing surveys.

The thesis will be in collaboration with Orsay: the Astroparticles, Astrophysics and Cosmology (A2C) pole at IJCLab has two major research axes: the study the dark components of the Universe through the observation of large structures; the primordial Universe, its inflation phase and its evolution, through the search for primordial gravitational waves via measurements of the cosmic microwave background at large and small scales (Planck, LiteBIRD, and Simons Observatory). Stéphane Ilic, joining Orsay to work on LiteBIRD, has in particular led the Euclid paper [6] that produced forecasts on cross-correlation between Planck CMB and Euclid. The validated software used in this analysis will be the starting point for the application to LiteBIRD and *Euclid*.

The student will be able to take part to monthly group training sessions organised within CosmoStat on a variety of topics (from cosmology, to astrophysics to software development to communication, available on the YouTube Channel of the group).

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