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Deliverable 7.1: Cosmological Interpretation Module

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Work Package WP7 - Physical Interpretation

Revision History

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1. Introduction

Under very reasonable assumptions, the primary CMB temperature and polarization anisotropies field is expected to be very nearly Gaussian and statistically isotropic. The average amplitude of CMB fluctuations at the various angular scales is related to the details of the underlying cosmological model through well understood physical processes, while tiny deviations from Gaussianity and isotropy provide additional information on the properties of the Universe.

Extraction of the cosmological information encoded in CMB maps proceeds then through the detailed characterization of their statistical properties. Several methods have been developed within the CMB community for such a task, each of them optimized for a specific dataset.

As BeyondPlanck is focused on a reanalysis of LFI data, we expect the major improvements to come from a better characterization of the large angle CMB polarization. The statistical properties of large angle CMB polarization are driven by two main physical processes: the formation of the first sources of light, defining the epoch of **Cosmological Reionization**, and the generation of primordial gravitational waves during **Inflation**. Given LFI (and overall Planck) sensitivity, we expect to provide an improved measurement of the optical depth to reionization, and improved upper limits on the amount of primordial gravitational waves.

Therefore, the BeyondPlanck Cosmological Interpretation Module builds on the tools we developed for the analysis of LFI large angle polarization measurements and described in detail in Planck Collaboration (2016) and Planck Collaboration (2019). Here we briefly summarize the main steps involved in going from maps to cosmological parameters:

- **Foreground Cleaning**: Polarized foreground emission at the target frequency (e.g. 44GHz or 70GHz) is removed by regressing out 30GHz and 353GHz maps, respectively as tracers of polarized synchrotron and dust.

- **Power Spectrum Estimation**: The power spectra of the foreground cleaned maps are computed via a Quadratic Maximum Likelihood Estimator, i.e. the full likelihood is approximated as a quadratic function of the power spectra, and the code computes the values that maximize that expression. While the actual parameter estimation is based directly on maps and does not involve the power spectra, the power spectra are a powerful diagnostic tool to assess the quality of the cleaned maps.

- **Likelihood evaluation**: the full likelihood of the cleaned map is a multivariate Gaussian, with a dense covariance matrix. Our implementation of this likelihood is based on the dimensionality reduction described in Planck Collaboration (2016), resulting in an algorithm which is ~ 1 order of magnitude faster than the classical implementation.

2. Software

The main Cosmological Interpretation Module consists of a library called `BFLike`, which implements all the functionalities described above, and a set of wrapper programs (`tempfit`, `qml`, `gridlike`) which call library routines to perform each of the individual steps of the pipeline.

This setup reflects the differences in the expected usage of the pipeline during data processing and validation, and the final science extraction. During data processing, estimation of power spectra and parameters for different choices of sky cuts, data selection, processing options,... allows to test for stability, consistency, and the presence of residual systematics which may not be readily apparent at the map level. We will need to repeatedly run the full pipeline until we have identified a sky region and frequency range which is science grade.

Once the specifics of the science grade data have been defined, the final cosmological parameter estimation requires only the evaluation of the likelihood. The de-facto standard tool for parameter estimation in the cosmological community is `CosmoMC` [3], which provides a framework to analyze data from a wide range of cosmological probes. We expect the majority of the likelihood end users to access BeyondPlanck results via such tool, rather than through the wrapper programs used in our internal validation.

2.1 New features

`BFLike` was originally developed for the analysis of Planck data. The most significant new features implemented for BeyondPlanck include:

- Redefinition of the basis used for the dimensionality reduction. The new basis is directly related to spherical harmonics and the corresponding functions for polarization, which can be efficiently computed by `HEALPix` routines. This eliminates the need to precompute and store the basis.
- Removal of hard coded restrictions, which required the code to run on maps including both temperature and polarization data.
- Core routines for QML estimation now take advantage of the same dimensionality reduction used for the main likelihood evaluation, reducing computational time from ~ hour to minutes.

The main benefit of these changes is faster turnaround during the data testing and validation phase of the analysis, where we want to compare results for different sky masks, data cuts, etc., each of which requires lengthy pre-computations. The changes will be mostly transparent for end users interested only in the final likelihood. In particular the core likelihood evaluation routines are mostly unchanged compared to the Planck pipeline version which is already included in `CosmoMC`.

2.2 Distribution and Compilation

The codes can be checked out from the GitLab repository at:

- https://gitlab.com/BeyondPlanck/repo/tree/master/like

Compiling the codes requires:

- A Fortran 2008 compiler. In addition, some of the prerequisite libraries require a C/C++ compiler. The pipeline has been successfully tested on Owl with Intel/19.0 compilers, and on a Mac OS X 13 environment with the GNU 8.2 compilers.
- CFITSIO, https://heasarc.gsfc.nasa.gov/fitsio/fitsio.html.
- HEALPix 3.40 or later versions, http://healpix.sourceforge.net/
- A Lapack implementation, e.g. MKL or Atlas.

The repository also includes sample Makefile for different configurations, including Owl/Intel, Mac OSX/GNU, and NERSC Edison/Intel. The Makefile requires the location of the cfitsio and healpix libraries and include files, passed through environment variables.

As an example, for compilation and execution on the Owl17-24 nodes, taking advantage of already installed CFITSIO and HEALPix libraries, we suggest the following steps:

- `module load Intel_parallel_studio/2019/2.057`
- `export CFITSIO_LIB_DIR=/mn/stornext/d14/bp/loris/Tools/CFITSIO/3450/build_intel19.0/lib`
- `export CFITSIO_INCLUDE_DIR=/mn/stornext/d14/bp/loris/Tools/CFITSIO/3450/build_intel19.0/include`
- `export HEALPIX_LIB_DIR=/mn/stornext/d14/bp/loris/Tools/Healpix/3.50/lib_intel19.0`
- `export HEALPIX_INCLUDE_DIR=/mn/stornext/d14/bp/loris/Tools/Healpix/3.50/include_intel19.0`
- `cd <your_path>/src/`
- `make -f Makefile.owl`

2.3 Usage

The standalone wrappers follow a similar invocation pattern:

- `<your_path>/bin/[tempfit|qml|gridlike] params.ini`

For better performance, we suggest linking to parallel implementation of Lapack. The number of threads can then be controlled through the environment variable `OMP_NUM_THREADS`.

As discussed above, we expect that the cosmology parameter estimation community will overall be better served by us releasing BP likelihood in a format compatible with `CosmoMC`, which already links to a collection of Plank likelihood codes, including `BFLike`. Therefore, in addition to the full pipeline, we will provide a new `BFLike` dataset, allowing `CosmoMC` users to access our likelihood data simply by pointing at this new file rather than the one currently distributed within the Planck release.

3. References

[1] Planck Collaboration (2016), *Planck 2015 results*. XI. CMB power spectra, likelihoods, and robustness of parameters. 2016, A&A 594, A11.

[2] Planck Collaboration (2019), *Planck 2018 results*. V. Legacy power spectra and likelihoods, to be submitted.

[3] https://cosmologist.info/cosmomc/