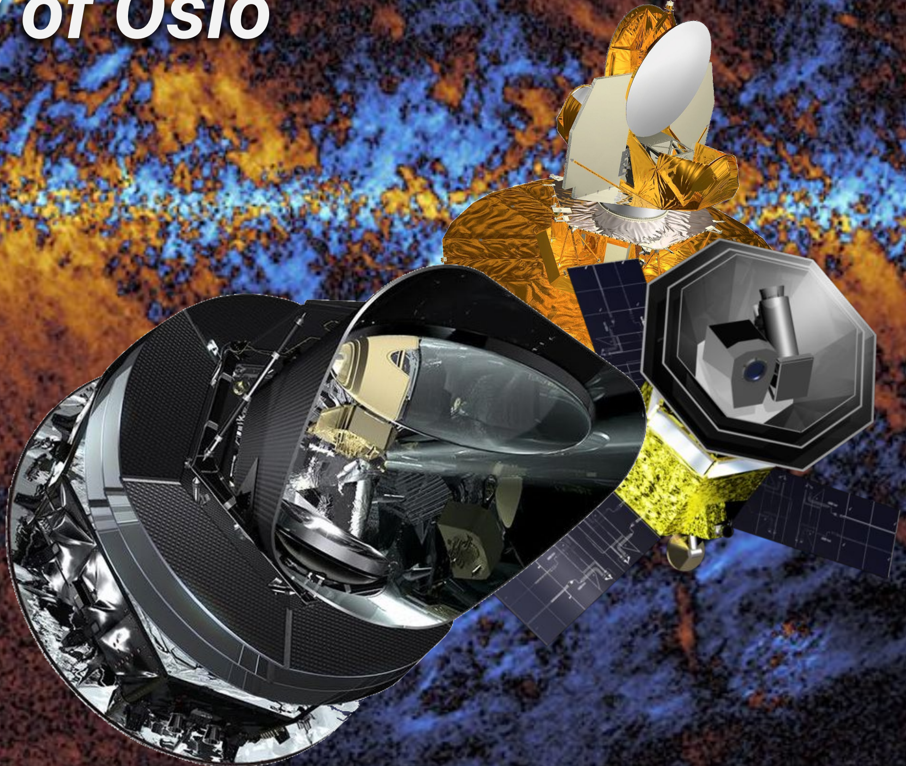
European Commission

Beyond PLANCK

WP1 Summary

Mathew Galloway
University of Oslo



BeyondPlanck final review, December 15, 2020

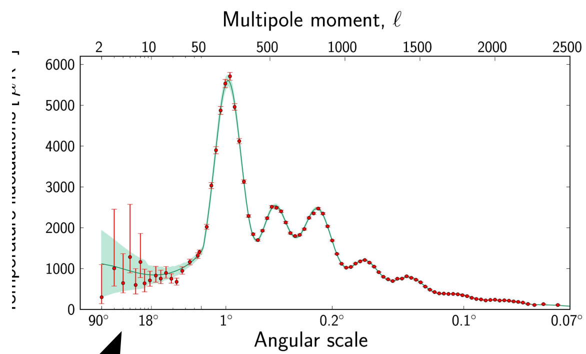
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776282

WP1 Commitments

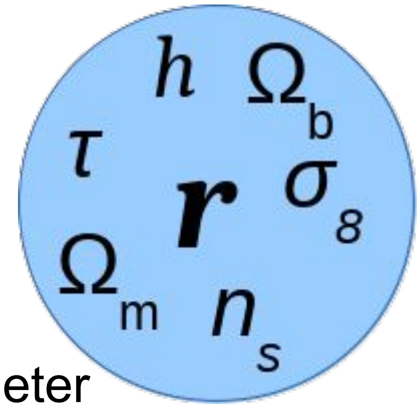
Objectives This WP serves as the framework that provides contact between the various sub-modules, feeding data and partial results from one operation to the other. For now, this task is performed by human interaction, limiting the number of iterations to a handful. The main objective of this WP is to automate and streamline this process, such that hundreds of iterations may be run completely without human intervention. After cross-module integration, this work package will also be responsible for delivering the final joint products.

Description of work The work will consist of two phases, namely infrastructure construction and module population. In the first phase, we will implement a placeholder pipeline that is able to input raw time-ordered data, pass them on to simplified sub-modules, and then output final maps and deliveries to disk. This process will be coordinated by HKE (with responsibility for the Gibbs sampling aspects of the work) and SG (with responsibility for the TOD access aspects), while most of the work will be done by PD1; we foresee this work to require continuous attention for the first 12 months of the project. In the second phase, each of the sub-modules will be replaced with fully functional modules; these include gain estimation and data flagging (SG), map making (EK, PD3), component separation (IKW, PD2) and cosmological interpretation (LC).

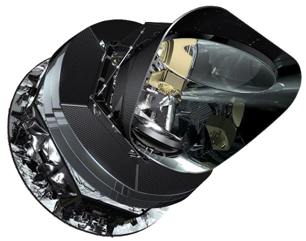
End-to-end iterative analysis

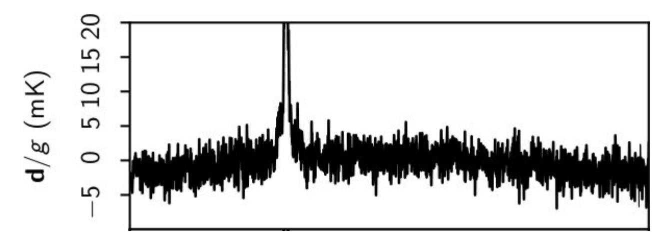


Power spectrum estimation

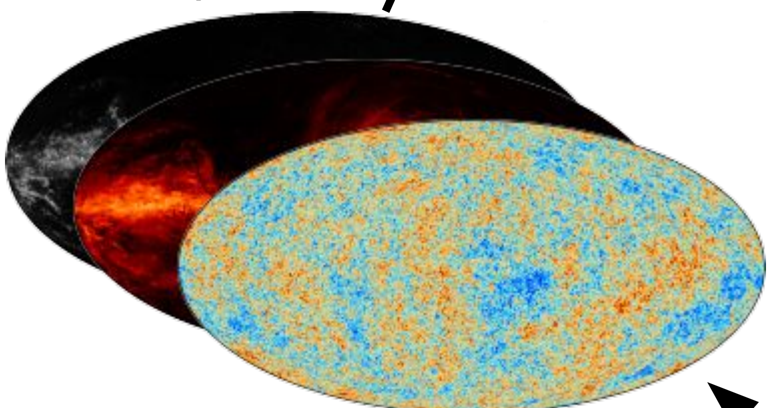


Parameter estimation

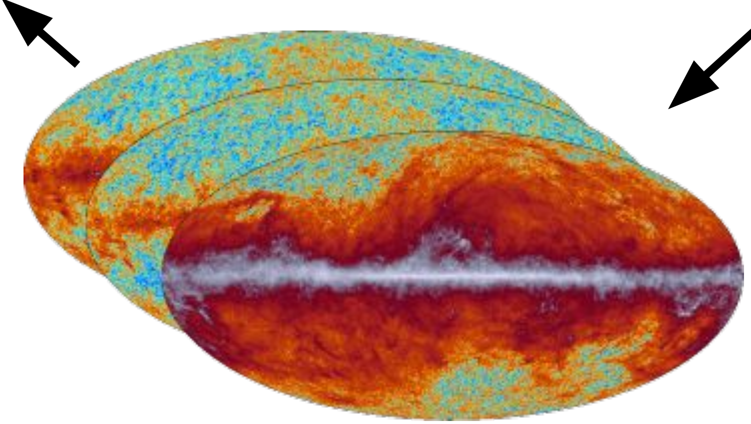




Calibration + mapmaking



Component separation



WP1 Deliverables

European Commission

Deliverables The deliverables from the WP are:

- A prototype pipeline, useful for allowing other partners to start their work; due in Month 3
- A fully functional pipeline, useful for full analysis; due in Month 12.
- Final scientific data products, due in month 21.

- Deliverable 1.1 - Prototype Pipeline
  - Approved 22 January, 2020
- Deliverable 1.2 - Analysis Pipeline
  - Approved 22 January, 2020
- Deliverable 1.3 - Final Scientific Data Products
  - Submitted 25 November, 2020
  - Available online at https://beyondplanck.science -> Products
  - Consists of 3 chains files:
    - Main analysis chain (1200 samples)
    - Resampled high-res CMB Temperature chain (~23000 samples)
    - Resampled low-res CMB T+QU chain (~23000 samples)

Beyond PLANCK

Data products

European Commission

Beyond PLANCK

Home Project Products Publications Documentation Dissemination Cosmoglobe Contact

BEYONDPLANCK PRODUCTS

Parameter Files

Filename	Content	Filesize	Format specification
BP_param_c0001.txt	Main Commander parameter file	69 kB	Commander parameter file documentation
BP_param_Tresamp_v1.txt	Commander parameter file for high-resolution CMB TT resampling	69 kB	Commander parameter file documentation
BP_param_resamp_c0001.txt	Commander parameter file for low-resolution CMB polarization resampling	x kB	Commander parameter file documentation

Chain Files

Filename	Content	Filesize	Format specification
BP_c000x_v1.h5 (1, 2, 3, 4, 5, 6)	Main chain files	329 GB each	File Formats
BP_c000x_Tresamp_v1.h5 (1, 2, 3, 4, 5, 6)	High-res CMB T resamp chain files	(2.3, 1.5, 1.7, 1.6, 1.5, 1.7) GB	File Formats
BP_c000x_Presamp_v1.h5 (1, 2, 3, 4, 5, 6)	Low-res CMB P resamp chain files	(437, 437, 437, 376, 397, 392) MB	File Formats

Frequency Maps

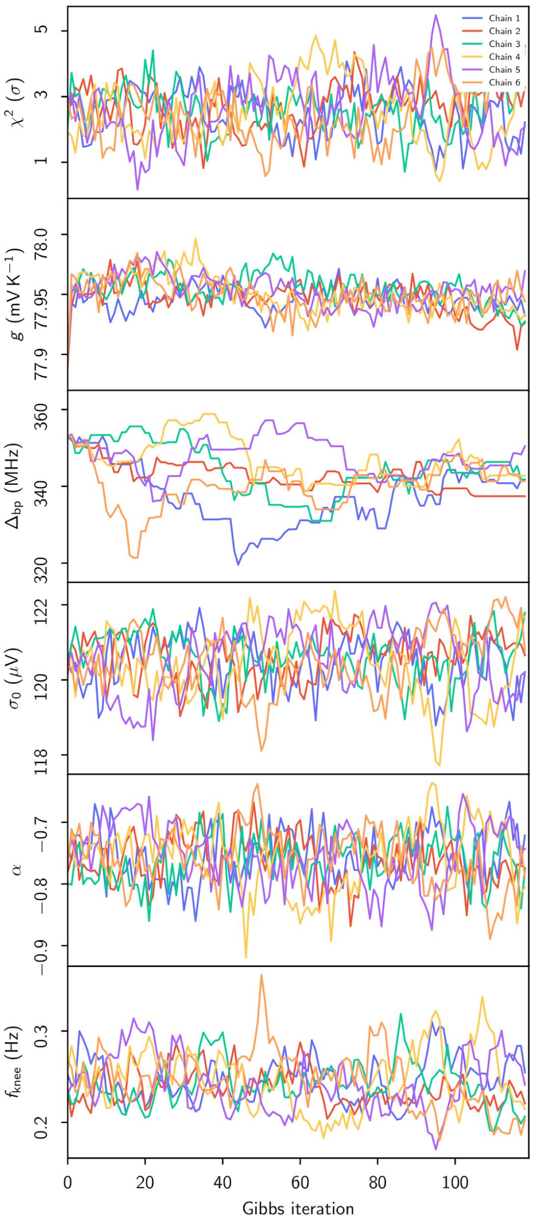
Filename	Content	Filesize	Format specification
BP_030_IQU_n0512_v1.fits	LFI 30 GHz frequency map	108 MB	
BP_044_IQU_n0512_v1.fits	LFI 44 GHz frequency map	108 MB	

Beyond PLANCK

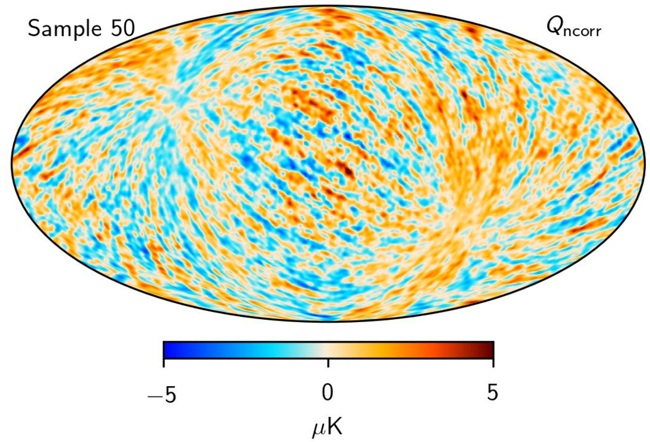
European Commission

Main product: Ensemble of full sample sets

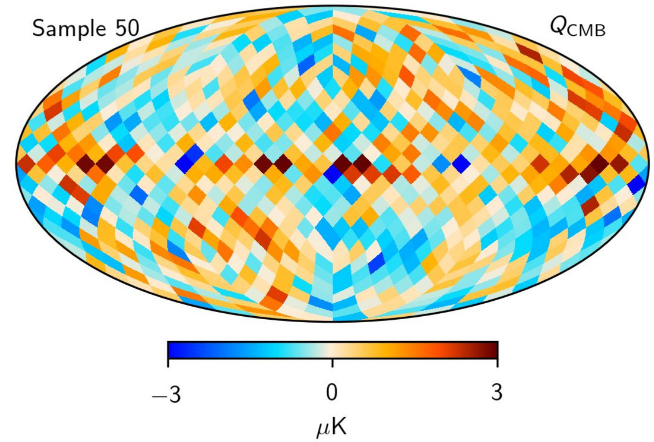
Instrument



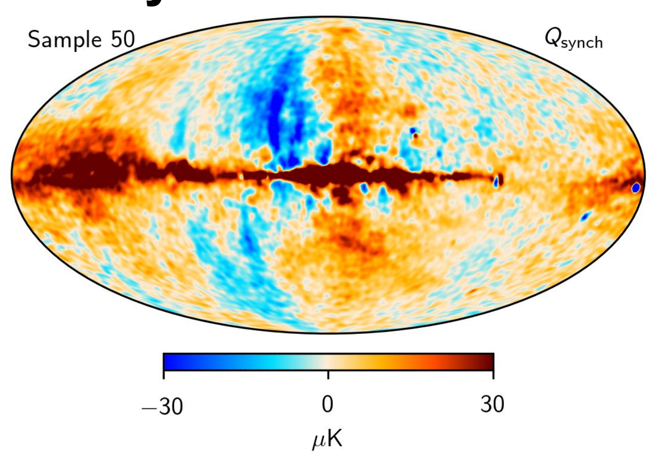
Correlated noise



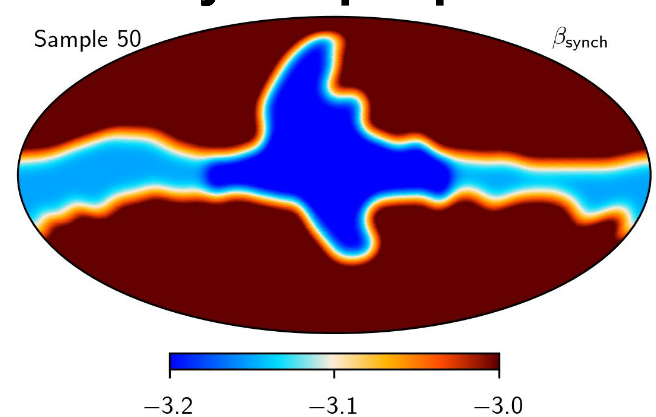
CMB Stokes Q



Synch Stokes Q



Synch pol β



...

Beyond PLANCK

Commander3

- The BeyondPlanck results were generated using the Commander3 codebase
- Based on the legacy Commander code that was used for component separation for Planck
- Written in object oriented Fortran90 (Approved by Grey-Beards everywhere!)
- Implements the iterative Gibbs-sampling of specific data models, for LFI this was:

$$d_{j,t} = g_{j,t} \mathsf{P}_{tp,j} \left[\mathsf{B}^{\mathrm{symm}}_{pp',j} \sum_{c} \mathsf{M}_{cj}(\beta_{p'}, \Delta^{j}_{\mathrm{bp}}) a^{c}_{p'} + \mathsf{B}^{\mathrm{asymm}}_{j,t} \left(\boldsymbol{s}^{\mathrm{orb}}_{j} + \boldsymbol{s}^{\mathrm{fsl}}_{t} \right) \right] + n^{\mathrm{corr}}_{j,t} + n^{\mathrm{w}}_{j,t}.$$

- ~45000 lines of code, ~6000 for TOD processing, ~14000 in component separation, ~25000 in auxiliary modules

Algorithm Overview

European Commission

Commander3 pseudo-code:

$$\begin{aligned}
\boldsymbol{g} &\leftarrow P(\boldsymbol{g} \mid \boldsymbol{d}, \xi_n, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta, C_\ell) \\
\boldsymbol{n}_{\mathrm{corr}} &\leftarrow P(\boldsymbol{n}_{\mathrm{corr}} \mid \boldsymbol{d}, \boldsymbol{g}, \xi_n, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta, C_\ell) \\
\xi_n &\leftarrow P(\xi_n \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta, C_\ell) \\
\Delta_{\mathrm{bp}} &\leftarrow P(\Delta_{\mathrm{bp}} \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \boldsymbol{a}, \beta, C_\ell) \\
\beta &\leftarrow P(\beta \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \Delta_{\mathrm{bp}}, C_\ell) \\
\boldsymbol{a} &\leftarrow P(\boldsymbol{a} \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \Delta_{\mathrm{bp}}, \beta, C_\ell) \\
C_\ell &\leftarrow P(C_\ell \mid \boldsymbol{d}, \boldsymbol{g}, \boldsymbol{n}_{\mathrm{corr}}, \xi_n, \Delta_{\mathrm{bp}}, \boldsymbol{a}, \beta),
\end{aligned}$$

i) Read parameter file
ii) Initialize data sets; store in global array called `data`
iii) Initialize model components; store in global linked list called `compList`
iv) Initialize stochastic parameters

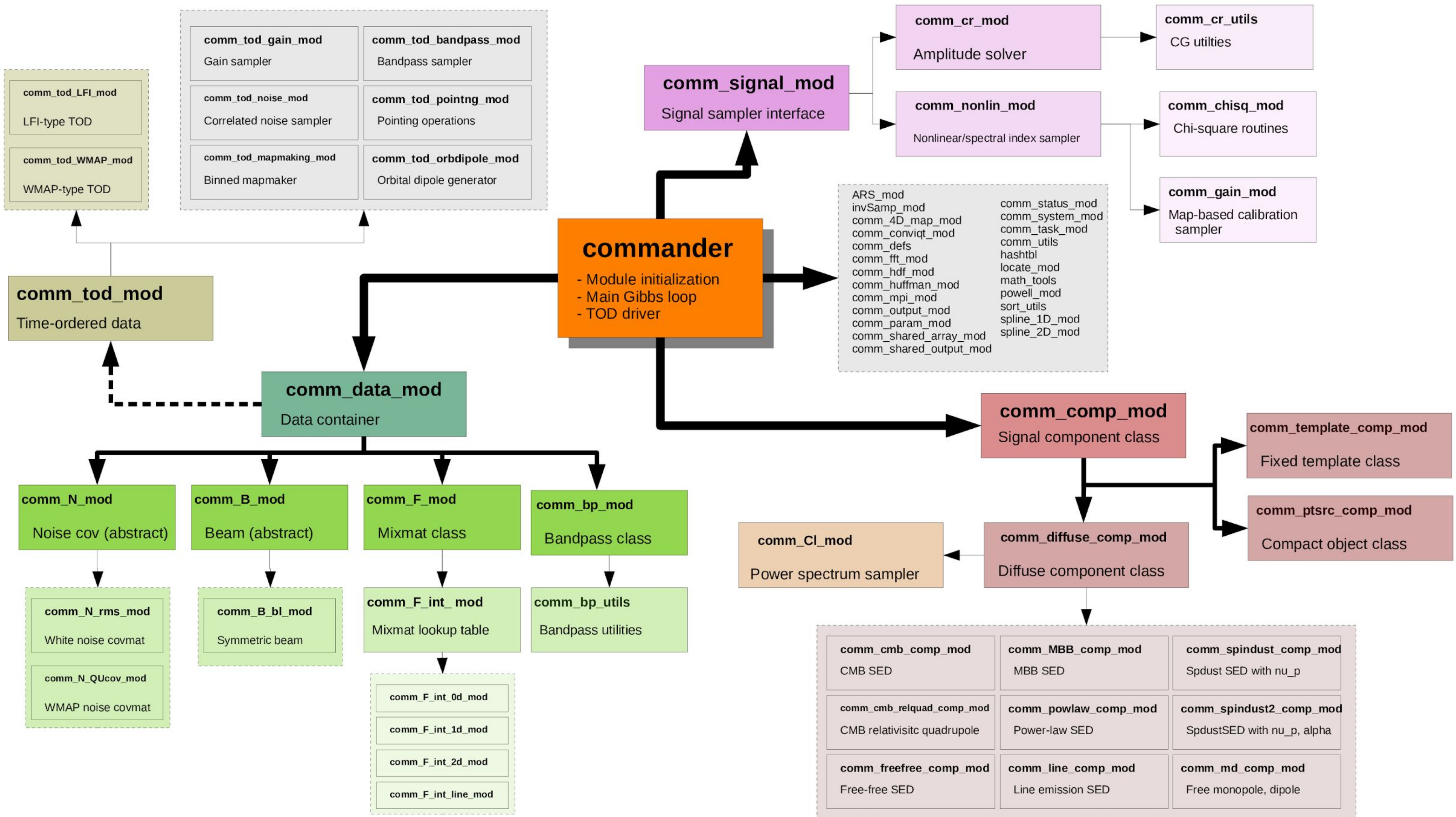
for $i = 1, N_{\mathrm{Gibbs}}$ do

1) Sample TOD parameters; make frequency maps
   a) Sample gain
   b) Sample correlated noise
   c) Clean and calibrate TOD
   d) Sample bandpass corrections
   e) Bin TOD into maps
2) Sample astrophysical amplitude parameters
3) Sample angular power spectra
4) Output current parameter state to disk
5) Sample astrophysical spectral parameters
6) Sample global instrument parameters for non-TOD data sets, e.g., calibration, bandpass corrections

- Gibbs Sampling: Iteratively sample each parameter while holding the others fixed
- Easily suggests Object Oriented programming solutions, each sampling step can be one or more classes

Beyond PLANCK

Block Diagram



Benchmarking

Item	30 GHz	44 GHz	70 GHz	Sum
Data volume				
Uncompressed data volume	761 GB	1 633 GB	5 522 GB	7 915 GB
Compressed data volume/RAM requirements	86 GB	178 GB	597 GB	**861 GB**
Processing time (cost per run)				
TOD initialization/IO time	176 sec	288 sec	753 sec	1217 sec
Other initialization				663 sec
Total initialization				**1880 sec**
Gibbs sampling steps (cost per sample)				
Data decompression	36 sec	105 sec	252 sec	393 sec
TOD projection (P operation)	33 sec	49 sec	248 sec	330 sec
Sidelobe evaluation ($\boldsymbol{s}_{\mathrm{sl}}$)	58 sec	85 sec	337 sec	480 sec
Orbital dipole ($\boldsymbol{s}_{\mathrm{orb}}$)	45 sec	61 sec	343 sec	449 sec
Gain sampling (g)	13 sec	10 sec	71 sec	94 sec
Correlated noise sampling ($\boldsymbol{n}_{\mathrm{corr}}$)	355 sec	390 sec	2393 sec	3138 sec
TOD binning (P^t operation)	22 sec	34 sec	442 sec	498 sec
Loss due to poor load-balancing	62 sec	305 sec	135 sec	502 sec
Sum of other TOD steps	32 sec	135 sec	139 sec	306 sec
TOD processing cost per sample	656 sec	1074 sec	4666 sec	**6396 sec**
Amplitude sampling, $P(\boldsymbol{a} \mid \boldsymbol{d}, \omega \setminus \boldsymbol{a})$				527 sec
Spectral index sampling, $P(\beta \mid \boldsymbol{d}, \omega \setminus \beta)$				1080 sec
Other steps				149 sec
Total cost per sample				**8168 sec**

Data Formats

- All data is stored in RAM during pipeline execution, so the data discussed here is just inputs and outputs
- TODs are stored in HDF5 files, using a custom compression scheme (coming up)
- HDF5 has faster IO than fits, and supports more data customization (almost like a directory structure)
- Skymaps are stored in standard .fits format
- All of the samples are stored in a chains.h5 file, which contains the complete history of all the parameter values throughout the entire sampling run
- We have written a tool for Commander3 Post Processing (c3pp) that reads and makes plots from the output chains files, available here:

  https://github.com/Cosmoglobe/c3pp

The BeyondPlanck Legacy

- The code will be improved to work with other experiments and collaborations
- Available under the GPL3 license here:
  https://github.com/Cosmoglobe/Commander
- Contains all the analysis code as well as data file generation scripts, examples of adding new data sets, etc.
- A data download tool is also available to make it easier to get started, the code installs with cmake
- Documentation and support can be found on our webpage:
  https://beyondplanck.science/
- The code is still under active development, and will be used in the future for datasets such as HFI, WMAP, LiteBIRD, Spider, DIRBE, FIRAS...
- Hands on code and data tutorial was held Nov 23 + 24, 2020. Was a big success with ~50 participants!

WP1 Timesheets

Institute	EU Funded Person Months	In-Kind Person Months
INAF	2	0.07
University of Oslo	28	0
Total	30	0.07
Budgeted	25	0
Deviation	5	0.07

Additional complexity caused by the integration of the Gibbs loop inside Commander means that WP1 expanded in scope slightly but this was mostly offset by the reduced complexity of other work packages.

The BeyondPlanck collaboration

EU-funded institutions

Kristian Joten Andersen
Ragnhild Aurlien
Ranajoy Banerji
Maksym Brilenkov
Hans Kristian Eriksen
Johannes Røsok Eskilt
Marie Kristine Foss
Unni Fuskeland
Eirik Gjerløw
Mathew Galloway
Daniel Herman
Ata Karakci
Håvard Tveit Ihle
Metin San
Trygve Leithe Svalheim
Harald Thommesen
Duncan Watts
Ingunn Kathrine Wehus

Marco Bersanelli
Loris Colombo
Cristian Franceschet
Davide Maino
Aniello Mennella
Simone Paradiso

Sara Bertocco
Samuele Galeotta
Gianmarco Maggio
Michele Maris
Daniele Tavagnacco
Andrea Zacchei

Elina Keihänen
Anna-Stiina Suur-Uski

Stelios Bollanos
Stratos Gerakakis
Maria Ieoronymaki
Ilias Ioannou

External collaborators

Brandon Hensley
Jeff Jewell
Reijo Keskitalo
Bruce Partridge
Martin Reinecke

Funding

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776282

- "*BeyondPlanck*"
  - COMPET-4 program
  - PI: Hans Kristian Eriksen
  - Grant no.: 776282
  - Period: Mar 2018 to Nov 2020

Collaborating projects:

- "*bits2cosmology*"
  - ERC Consolidator Grant
  - PI: Hans Kristian Eriksen
  - Grant no: 772 253
  - Period: April 2018 to March 2023
- "*Cosmoglobe*"
  - ERC Consolidator Grant
  - PI: Ingunn Wehus
  - Grant no: 819 478
  - Period: June 2019 to May 2024

Questions?

European Commission

Beyond PLANCK

Commander

UNIVERSITAS OSLOENSIS MDCCCXI

UNIVERSITAS STUDIORUM MEDIOLANENSIS

INAF ISTITUTO NAZIONALE DI ASTROFISICA — OSSERVATORIO ASTRONOMICO DI TRIESTE

HELSINGIN YLIOPISTO
HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

planetek hellas

JPL

BERKELEY LAB

HAVERFORD COLLEGE

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020

erc

Cosmoglobe

Beyond PLANCK