Cosmic Microwave Background activities at IN2P3

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I - Context

The Cosmic Microwave Background (CMB), relic radiation emitted 13 billion years ago when the universe was about three hundred thousand years old, carries a wealth of information about the cosmological scenario that depicts the properties and history of the universe we live in. As of today, three space missions have already scrutinized the sky to observe the CMB, among which the highly successful ESA Planck space mission (Section II), in which IN2P3 has played a major role.

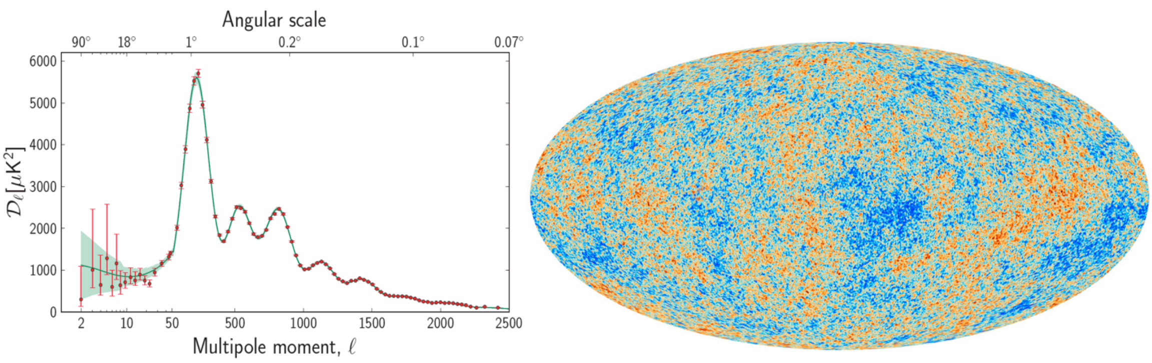

Figure 1. Left: Angular power spectrum of CMB temperature anisotropies observed by Planck; Right: Full-sky map of CMB temperature anisotropies as obtained from the Planck nominal mission data set using the SMICA method developed at IN2P3.

Much of the French participation in Planck has been through the laboratories of the IN2P3 with important contributions to all stages of the project, from instrumentation to data analysis to exploitation of the scientific results. The Planck satellite was launched in 2009, and so far two series of papers of cosmological results have been released: a first release in 2013 based on the temperature anisotropies alone (Fig. 1), and a second release in 2015 including the polarisation at all but the largest angular scales. Currently an intensive effort is underway to improve the analysis of the polarisation on the very largest angular scales, and it is expected that low-multipole polarisation results will be released around mid-2016 in what is likely to be the last official release. The Planck data holds considerable legacy value, and we may expect that in the years to come researchers in France and elsewhere will still undertake a wide range of projects to exploit the Planck microwave sky maps to address questions in many diverse areas of astrophysics and cosmology.

As explained in more detail below, the Planck project is coming to and end, and a key issue for the IN2P3 to reflect on is how best to manage the expertise that has been developed in CMB observation in the IN2P3 laboratories. To be sure, the skills and experience gained from Planck will be invaluable for other projects, for example wide-field astronomy or the ESA Euclid mission, to name just two examples. But the CMB continues to be an extremely active and visible area of research worldwide, and happily, France is at present the leader in space-based observations at microwave frequencies using cryogenically cooled bolometric detection, which is the most sensitive technique. We must consider how best to use this leadership position, that is the outcome of massive past European investments, by ESA, by CNES, and by the IN2P3.

The frontier of observational cosmology involving the CMB is the ultra-precise measurement of the CMB polarised signal, and in particular pseudo-scalar modes of polarisation (the so-called B-modes) with two principal goals: (1) to detect primordial gravitational wave generated by inflation, and (2) to map the gravitational lensing of the CMB and measure the B-mode power spectrum due to gravitational lensing, of great interest for achieving a number of scientific goals, including measuring absolute neutrino masses with a precision that is not possible from more conventional laboratory experiments such as KATRIN. The stakes are high, as was evidenced by the excitement surrounding the BICEP2 claimed discovery of primordial B-modes (Fig. 2), which generated a degree of excitement without precedent. How to achieve these scientific goals is currently being debated: there is at present no consensus on what can be done from the ground and what is better done from space. Most probably, full and robust achievement of such goals will require exploitation of different and complementary observational strategies and techniques.

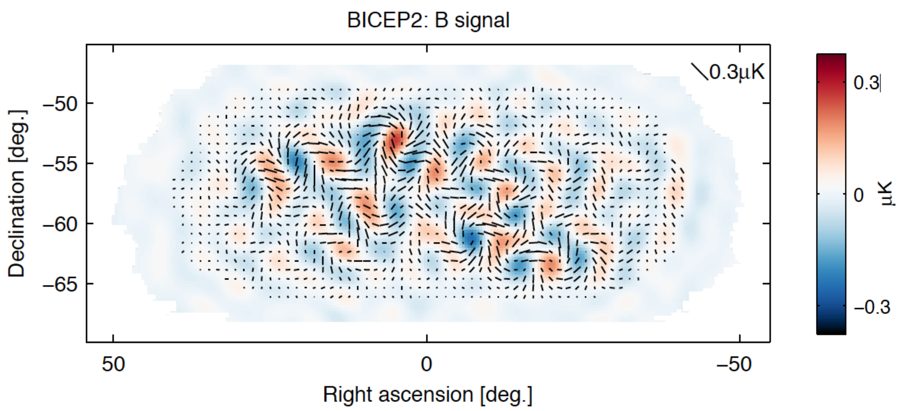

Figure 2. B-modes of polarised sky emission detected by the BICEP2 experiment.

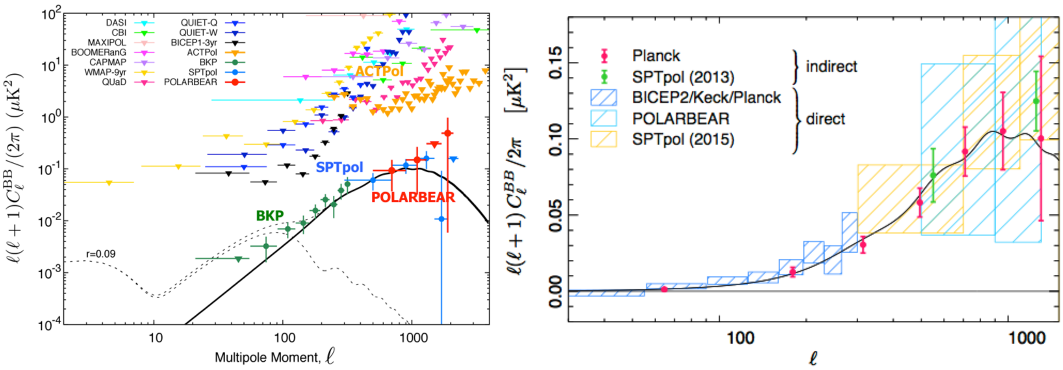

Figure 3. Left: Current status of B-mode polarisation detection and upper limits, including the joint Bicep/Keck and Planck analysis (BKP), the SPTpol lensing detection, and new data from ACTpol. The dotted curve represents primordial CMB B-modes for r=0.09, while the plain curve is the lensing-B-modes prediction for the current best-fit cosmological model. Right: Detection of lensing B-modes with both direct measurements of the B-modes C_l spectrum, and with indirect techniques involving correlation with tracers of structures.

Ground-based observatories offer the best opportunity to perform high-resolution, deep integration over the small sky areas, while space-borne instruments benefit from a broad, unhindered by the terrestrial atmosphere, frequency coverage and potential to access a nearly full sky. This complementarity has been amply demonstrated by the BICEP discovery, which originally claimed a detection of a tensor-to-scalar ratio of 0.2, much larger than anyone had expected. In the aftermath, Planck showed that the entire signal at 150 GHz could be attributed to polarised thermal dust emission, and later joint work between the Planck collaboration and the BICEP2 and Keck Array team studied cross-correlations, and thus managed to establish an upper bound that r < 0.12 at 95% confidence (See Fig. 3 for the present status of CMB B-mode power spectrum measurements).

In this document we review the various experiments in which the IN2P3 CMB community is involved or considering getting involved. The present targets for the tensor-to-scalar ratio, denoted r or T/S now being discussed both for ground based and space based experiments are in the ballpark of 10^{-3}. Stage 4 (S4) discussed in Section V is the most ambitious of the proposed ground-based initiatives, aiming to deploy $O(10^5)$ detectors, translating into unprecedented sensitivity. This is without a doubt going to be one of the most exciting undertakings in the field on the intermediate timescale, even if delivering all the stated science goals may prove to be challenging. For the French community, involvement in such a project can be on the one hand a natural evolution of the current suborbital projects envisaged on the short time scale and on the other hand a stepping stone towards long term efforts such as a CMB satellite mission.

A call for an ESA medium-sized satellite mission (which corresponds to an ESA contribution of ~500 M€) is expected in early 2016 (Section V), and the French community along with its European partners is gearing up to define what sort mission to propose taking into account feedback from previous similar bids (COrE+, PRISM, COrE, BPol, SAMPAN).

II - The Planck satellite experiment

Planck is a 3rd generation CMB space mission, following COBE and WMAP. The project was initiated in 1992, and was selected by ESA in 1996. Three IN2P3 institutes (APC, LAL and LPSC) joined Planck's high frequency instrument (HFI) consortium soon afterwards, in 1997.

Planck was successfully launched on May 14, 2009. Observations started on August 15, 2009 and were stopped on January 15, 2013 (for HFI, following the exhaustion of the 100 mK cryogenic fluid) and on August 4, 2014 (for the low frequency instrument, LFI). First cosmological results were presented in April 2013. A second batch of results, together with full mission temperature and polarisation sky maps, was released in December 2014 / January 2015. We expect the mainstream data processing work to continue for the next two years, in order to understand and correct the subtle systematics in the polarisation of the large-angular-scale anisotropies. CNES funded our work but this funding will be already significantly reduced next year, and probably will end after that.

Technical contributions: hardware and processing

- IN2P3 labs made several important contributions to the Planck hardware. LAL has built, delivered and monitored till the end of the mission the HFI on-board control system (DPU). LPSC was in charge of the control electronics for one of Planck's cryogenic stages (the 18 K sorption cooler) and for the dilution software. LAL, LPSC and APC took part in the ground-based calibration for HFI and Planck. APC and LPSC led a posteriori ground tests to interpret the impact of cosmic ray hits in the HFI bolometers.
- IN2P3 labs and scientists had key roles and responsibilities in various parts of the HFI pipeline, going from the raw data to maps and finally to power spectra. The timeline analysis pipeline (detector time response deconvolution, decorrelation and filtering, cosmic ray hits detection and removal) was primarily developed by LPSC with contributions from APC (lead of the Planck paper on cosmic ray glitch removal). APC and LAL played a key role in measuring (with data recorded after the end of HFI cryogenic life) and correcting ADC non-linearity, which has been a major systematic contaminant in the Planck HFI data. LAL was responsible for the photometric calibration and for producing sky maps for the various releases (and IN2P3 scientists led the two Planck papers on sky map construction and characterization for the 2013 and 2014-5 releases). The HFI map-making software was mainly developed by LAL with early contributions from APC.

Primary CMB anisotropies analysis & cosmology

IN2P3 scientists have a major involvement in the scientific exploitation of the Planck data.

- IN2P3 scientists from APC have played a leading role in the developing the Planck Sky Model (PSM) and component separation methods. Two of the four methods selected to produce the official foreground-cleaned temperature and polarisation maps for the consortium (out of ten international competitors) were developed at APC. In particular the SMICA pipeline lead by the APC team was selected as the front-runner to produce the CMB maps used for the public data release (see SMICA CMB map in Fig. 1).
- Power-spectra, likelihood and cosmological parameters:
    - LAL proposed a high-multipole power spectrum likelihood that was used for systematic and robustness test in the 2015 release, complementing the Cambridge and IAP likelihoods used in the parameters papers.
    - In collaboration with LPSC (and IAS), LAL also set up a low-multipole likelihood method for total intensity and polarisation (Lollipop), which will be used the forthcoming Planck low-multipole analysis papers. The reionisation paper will be led by an IN2P3 scientist.
    - A complete pipeline for extracting cosmological parameters was set up by the LAL group using frequentist techniques as an alternative to the Bayesian techniques. These results were presented in one of the Planck intermediate papers, and were also used for systematic checks in the 2013 and 2015 papers.

- APC scientists co-lead the two Planck papers constraining Inflation.
- APC scientists had a major role in the search for primordial non-Gaussian signatures in the CMB maps.

Secondary anisotropies

In addition to observing the primary CMB anisotropies that constitutes its main science objective, the Planck mission provided unprecedented data sets on secondary anisotropies and on astrophysical foreground emission. IN2P3 researchers have been involved in particular in the detection and scientific exploitation of the thermal and kinematic Sunyaev Zel'dovich (SZ) effects, which allow to trace the distribution of hot gas and to constrain the velocity flows of ionised structures, and of gravitational lensing of the primary CMB:

- Scientists from APC developed and applied one of the three SZ cluster detection routines (MMF3) used by Planck in the three released SZ catalogues. APC led the validation of the 2015 SZ cluster sample using the redMaPPer optical cluster catalogue and the LPSC was in charge of the a posteriori validation of the cluster sample.
- APC scientists have played a central role in obtaining cluster cosmology constraints from the 2013 Planck SZ catalogue and co-led the 2015 SZ cluster cosmology analysis.
- LPSC and APC played a major role in the construction, validation and analysis of the Planck all-sky thermal SZ maps and LPSC led the two Planck papers related to this subject in 2013 and 2015.
- LPSC, and earlier LAL, has a key role in the CMB lensing extraction and analysis both in temperature and polarisation. LPSC scientists are leading the Planck lensing B-mode paper describing the Planck lensing B-mode map to be released in 2016.

Foreground emission studies

- LPSC was in charge of the reconstruction of the CO emission maps with specific component separation techniques and led the corresponding paper.
- Zodiacal light (the thermal emission from particles of dust in our Solar System) reconstruction paper was led by APC.

III - Current ground-based CMB experiments at IN2P3

In parallel to a major involvement in Planck, IN2P3 institutes have been leading some of the French sub-orbital CMB observations, with leadership or strong implication in three main ground-based projects: QUBIC, NIKA / NIKA2, and POLARBEAR / Simons array.

QUBIC

QUBIC is the first bolometric interferometer project aiming at measuring the primordial B-modes of the Cosmic Microwave Background (CMB) to explore the inflationary phase of the early Universe through the estimation of the tensor to scalar amplitudes ratio ($r=T/S$). Background-limited sensitivity is achieved using Transition-Edge-Sensors cooled down to 300 mK. QUBIC is designed to control systematics effects thanks to the observation of interference fringe patterns. Foreground contamination is monitored through the observation of the sky at two frequencies: 150 GHz, where the CMB is dominant, and 220 GHz, where the polarised dust emission is larger, and which thus serves to trace the dust contamination. We anticipate a sensitivity of $r < 0.016$ at 95% C.L., taking into account realistic observation efficiency and dust removal from the QUBIC 220 GHz band and from the Planck 353 GHz data (Fig. 4).

The sky radiation entering the QUBIC cryostat is first modulated by a metal-mesh Half-Wave-Plate, allowing a direct modulation of the sky polarisation. A polarised grid then picks up one polarisation orientation. A set of 400 corrugated, back-to-back feed horns subsequently selects baselines (in the interferometric sense) that are then re-emitted inside the cryostat where a telescope optically combines them and images the superposition of each back-horn's radiation onto two focal planes separated by a dichroic plate. With this instrumental setup, one of the focal planes observes at 150 GHz while the other one observes at 220 GHz (Fig. 5). The detailed design of the instrument can be found in the QUBIC white paper [The QUBIC Collaboration, Astroparticle Physics 34 (2011) 705-716, arXiv:1010.0645].

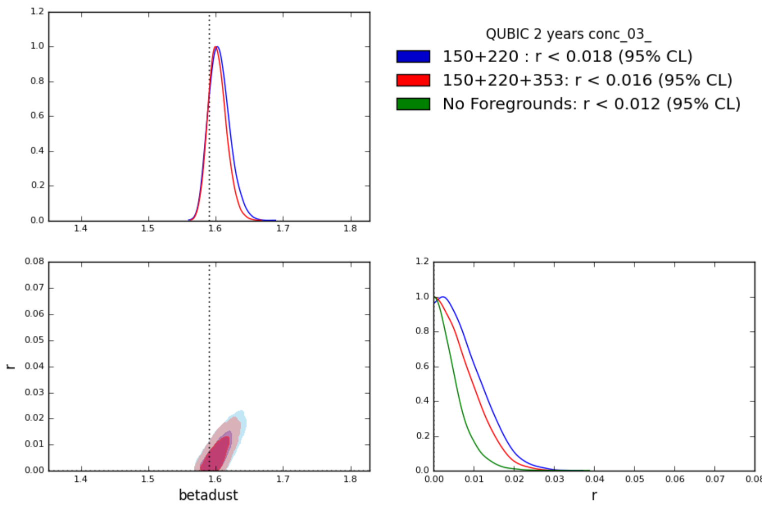

Figure 4. QUBIC forecasts on constraints on r, taking into account realistic dust foreground emission (assuming here two years of integration).

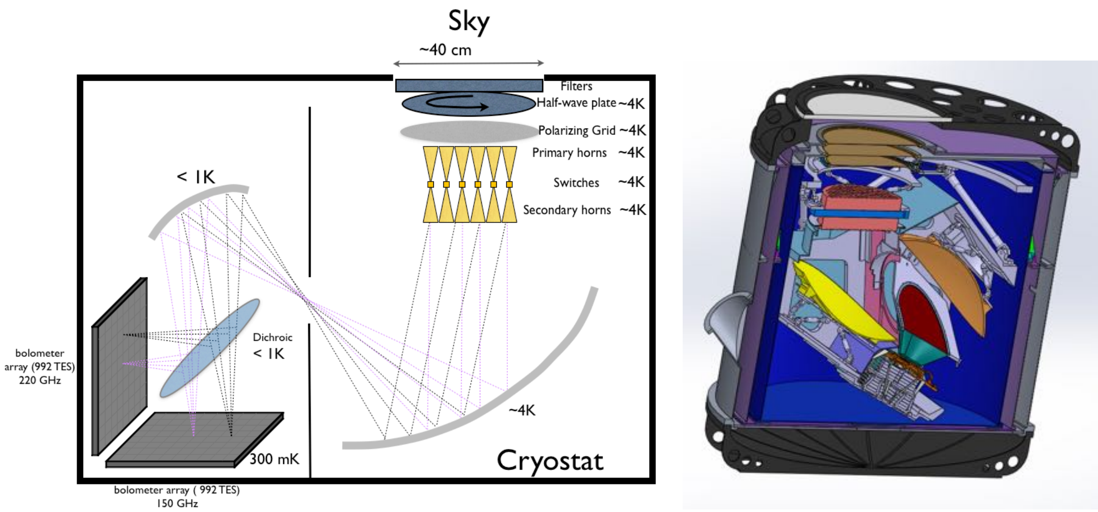

Figure 5. Left: Sketch of the QUBIC instrumental concept. Right: CAD view of the inner part of the instrument.

QUBIC is an international collaboration led by APC (Project Scientist: J.-Ch. Hamilton, Instrument Scientist M. Piat, Project Manager L. Grandsire) with the help of a Steering Committee. It comprises 78 collaborators from France (IN2P3 and INSU), Italy, United Kingdom, Ireland, USA and the Netherlands. The IN2P3 labs involved in QUBIC are

CSNSM and the APC, recently joined by LAL (conditional to the agreement of the LAL Scientific Council). Besides leading the collaboration, France is responsible for:

- *Providing the detection chain based on two arrays of 1024 Transition Edge Sensors (TES) read using cryogenic time domain multiplexing based on SiGe ASIC and SQUIDs*: The TES arrays (Fig. 6) are fabricated at CSNSM (S. Marnieros) and IEF (B. Belier) while the cryogenic readout is developed at APC (F. Voisin, D. Prêle, M. Piat). We have recently achieved a first testing of a quarter QUBIC focal plane (Fig. 6) achieving a multiplexing factor of 128:1 (first time in the world, with typical multiplexing factors of 32:1 from other teams).
- *Calibrating the instrument, developing the data analysis and the simulation pipeline for QUBIC*: A full end-to-end pipeline based on Monte-Carlo simulations has been developed. It confirms the sensitivity anticipated from analytical estimates. The LAL team will significantly reinforce this simulations aspect, and build the real-size pipeline for QUBIC.

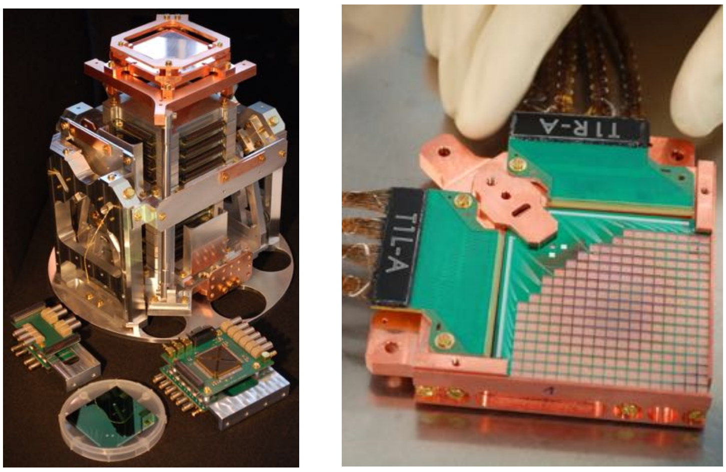

Figure 6. Left: Cryo-mechanical architecture for 1/4 focal plane of the QUBIC instrument tested in 2015. Right: detail of the 256 pixels TES array.

A review of the QUBIC project by IN2P3 / INSU / IPEV took place in June 2015. Since this review, a precise calendar is being set up, with a detailed commitment of all sub-systems responsible for the different tests and delivery of each component. In parallel, an extensive in-lab calibration plan of a reduced version of the instrument is being prepared to validate the interferometer and check that it matches its specifications. This process will allow to tune the model of the instrument used as an input in the simulations and to perform direct tests of some of the offline analysis.

The baseline site for QUBIC operations is the French-Italian base Concordia at Dome C, Antarctica. However, the complexity of the logistics and the long delays imposed by this remote site have triggered the search for an alternative. Fast progress has been made recently on the assessment of a high quality site on the Puna plateau in the North-East of Argentina, at an altitude of 4870 m. All the logistics would be shared with an existing project installed on the same site, the LLAMA radio-telescope. QUBIC could be installed on this site as early as mid-2017 (one to two years earlier than in Concordia). Both options are being examined.

The schedule for QUBIC is the following:

- December 2015: Technical Design Review including all partners (in France and abroad);
- Early 2016: Start of the integration of the instrument with the final cryostat and optics, with the number of detectors allowed by the current funding in France (256 pixels for

each frequency channel). This will be followed by calibration in the lab to demonstrate the bolometric interferometry technique and sensitivity of the instrument.

- Mid 2016: Review including IN2P3, INSU and IPEV after which we will request the funds to complete the focal planes with the missing detectors (need for 120 k€ for the procurement of superconducting cryogenic cables than can only be subcontracted).
- Mid 2016-mid 2017: procurement of the cryogenic cables, upgrade of the instrument to the final one and more extensive calibration measurements in the laboratory.
- Mid 2017: installation in Argentina if this option is selected. If not, we will interact with IPEV to accelerate our installation in Concordia. An ANR for the QUBIC scientific exploitation (laboratory and field calibration, data analysis and simulations personnel) requesting 800 k€ is being submitted this year.

NIKA and NIKA2

The NIKA2 (Monfardini et al, 2014, JLTP, 176, 787M) camera is a next-generation instrument for millimetre astronomy made of Kinetic Inductance Detectors (KIDs). It is operated at 100 mK and has been installed (Fig. 7) in October 2015 on the 30-m telescope of IRAM (Institut de RadioAstronomie Millimétrique). NIKA2 observes the sky at 150 and 260 GHz with a wide field of view (6.5 arcmin), high-angular resolution (nominally 18 and 12 arcseconds respectively), state-of-art sensitivity (requirement 20 and 30 mJy.s$^{1/2}$, respectively), and high mapping speed (using 5000 detectors in total). It also provides polarisation capabilities at 260 GHz (Ritacco et al, JLTP, 2015, arXiv150800747R).

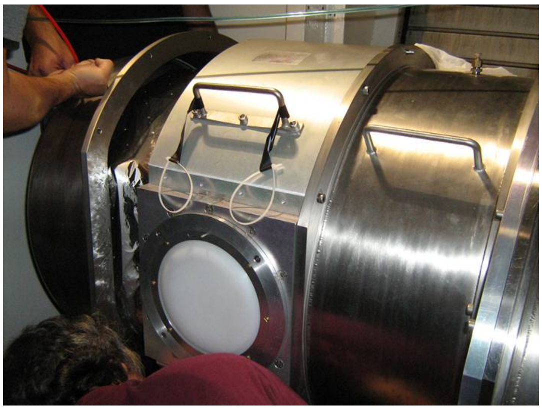

Figure 7. The NIKA2 camera installed at the IRAM 30 m telescope Nasmyth cabin.

The NIKA2 consortium is an international collaboration gathering 14 laboratories from France, the UK and Italy, that has successfully answered in 2011 a call for tender issued by the IRAM concerning the next generation large field continuum instrumentation at the 30 m telescope. The NIKA2 collaboration is led by Institut Néel, with the help of LPSC and IPAG. The construction of the NIKA2 camera has been partially funded by an ANR (1 M€) and by an ERC (300 k€) with smaller contributions from the labex FOCUS, the University of Grenoble and by IN2P3.

During the NIKA2 construction phase (2012-2015), a prototype camera, NIKA1 (Monfardini et al, 2011, ApJS, 194, 24M), dual-band with a total of about 300 KIDs, has also been built and installed at the IRAM 30 m telescope. NIKA1 has reached state-of-art scientific performance (Calvo, 2013, A&A, 551L, 12; Catalano et al, 2014, A&A, 569A, 9C), and as a consequence, was open to the external community for three campaigns, in addition to technical runs.

The second phase (2016-2020) of the NIKA2 project concerns the scientific exploitation. A large amount of 1300 hours have been allocated to the NIKA2 consortium for large scientific programs (this is the largest amount of guaranteed time ever given by IRAM to a single collaboration). Three large programs led by French institutes have been granted 300 hours of observation each (900 hours in total), and are supported by the NIKA2Sky ANR.

The LPSC is highly involved in two cosmology programs, dedicated to the study of the inner structure of galaxy clusters via Sunyaev-Zel'dovich (SZ) effect, and to the mapping of dusty star-forming galaxies up to redshift 6.

The NIKA SZ large program consists of follow-up observations of about 50 Planck and ACT SZ detected clusters of galaxies at high redshift (z=0.5-1.5). It aims at understanding the cluster morphology (merging events, departure from spherical symmetry, cooling processes) and the detailed characterization of their physical properties: temperature, entropy and mass radial profiles. This will help us to understand possible biases on scaling relations relating cluster observables to their mass, which currently limit cluster cosmology accuracy. In this context, the NIKA prototype (NIKA1) has been used as a pathfinder for NIKA2. During the three NIKA1 open campaigns, several clusters of galaxies, chosen to cover the various configurations and observation conditions expected for NIKA2, have been observed (Adam et al, 2014, A&A, 569A, 66A; Adam et al, 2015, A&A, 576A, 12A; see Fig. 8). These observations have been extremely successful and confirm the status of NIKA2 as a powerful SZ instrument.

LPSC is a privileged member of the NIKA2 consortium, being one of the three Grenoble laboratories in charge of the construction of the camera. LPSC is responsible for construction of the electronics and polarisation system, and participates on the day-to-day testing and characterisation of KIDs. Furthermore, LPSC is a major contributor to the data reduction and analysis pipeline. LPSC is also strongly involved in the management of the consortium (project manager and president of the editorial board), and lead the SZ large program.

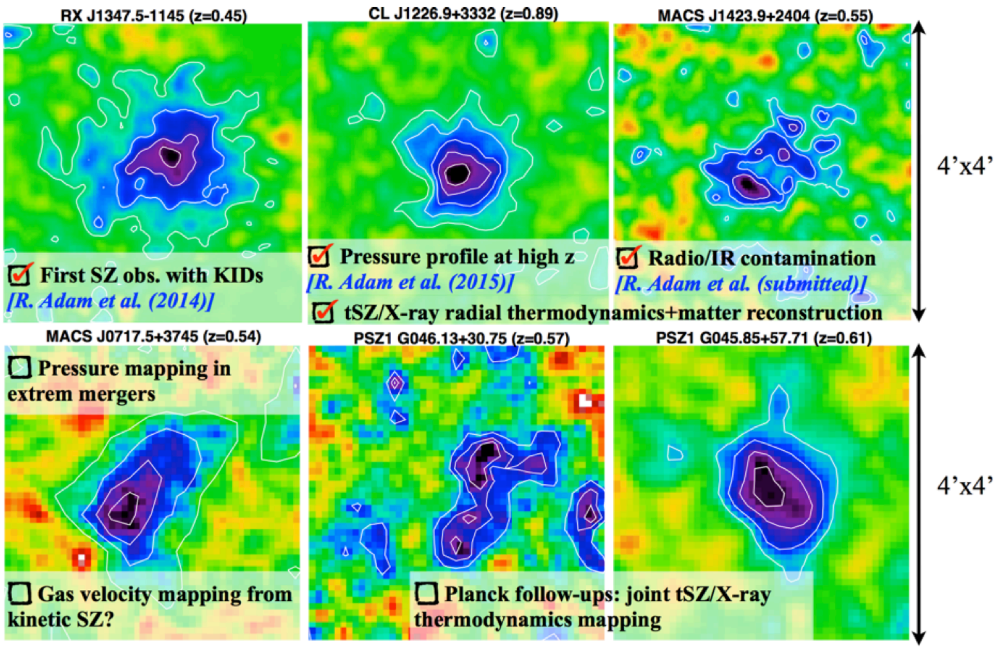

Figure 8. A sample of galaxy clusters observed with the NIKA camera at the IRAM 30m telescope via the SZ effect.

POLARBEAR and the Simons Array

POLARBEAR (PB) is an operating (2nd generation) CMB experiment targeting the polarisation signature of the CMB anisotropies (Fig. 9). The experiment is US-led, with important international contributions from Japan, Canada and France. The PB observatory is located in the Atacama Desert in Chile. It has conducted to-date three observational campaigns. The results of the first campaign were published in 2014 in the series of three high-profile papers, which reported some of the first, and in some cases very first, detections of the B-mode signal on small-angular scales (Fig. 3). Since then, the observatory has been constantly developed. It will be expanded with an additional telescope later this year and a third one soon after. These will feature multi-frequency detectors sensitive to incoming signals in at least three different frequency bands. This enhanced observatory, which will operate under the name of Simons Array (SA), is designed to be capable of detecting, or setting an upper limit on, the presence of the primordial gravity waves with relative amplitudes as low as corresponding to $r \sim 0.01$ (2σ), as well as of providing competitive constraints on the sum of neutrino masses.

To-date, the French involvement in the PB/SA effort has been through work of a group of students (one of whom is now a postdoc at LPNHE), led by a researcher at APC (R. Stompor) and supported by a software engineer (M. Le Jeune). The group has been active since 2009 and 3 PhD theses have been written and defended during that time. The group has made significant and recognisable contributions to the project, predominantly to data analysis, but also to the instrument design and optimisation, as well as to observational campaigns. The group is currently in charge of the analysis of the 2nd season of the observations, and spearheads the effort of optimising the Simons Array in the light of new information concerning astrophysical foregrounds.

The Simons Array, together with contemporary experiments of SPTpol-3G, Advanced ACT, BICEP3/Keck and CLASS, is considered a 3rd generation CMB experiment, and is therefore a pathfinder for the CMB-S4 project (Section V). The work of the PB/SA group at APC therefore paves the way for a possible IN2P3 contribution to CMB-S4.

To continue its successful involvement in the PB/SA experiment the group needs travel support on order of 10 k€ yearly for the next 5 years to permit participation in project bi-annual meetings and working visits to US and Japanese partners.

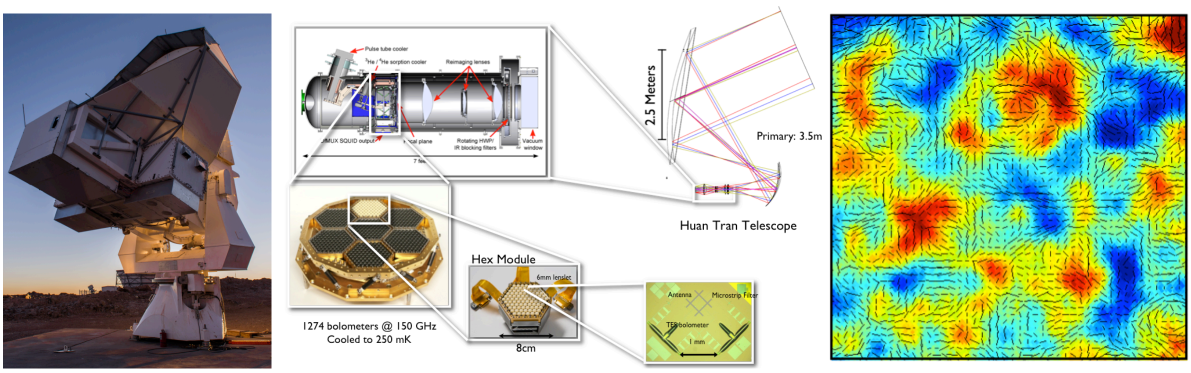

Figure 9: Left: The POLARBEAR telescope operating from the Atacama Desert in Chile. Middle: The main systems of the instrument, Right: map of the polarised sky estimated from the data of the first observational campaign by the APC group.

IV - R&D studies and simulations

Transition Edge Sensors (TESs)

Based on a previous collaboration (DCMB) that allowed us to place the tools and the competence to develop cryogenics detectors, the BSD (B-mode Superconducting Detectors) project started in 2007 with an ANR funding and is now supported by CNRS and CNES. The goal is to develop (i) TES arrays and associated multiplexed readout electronics (with APC, CSNSM, IAS, IEF and IRAP), (ii) RF superconducting components (antennas, filters, couplers, phase shifters, with APC and IEF) and (iii) contribute to KIDs development in Grenoble (with Institut Néel and LPSC).

The TESs are based on NbSi alloy developed at CSNSM, which allows to tune the critical temperature by changing the proportion of Nb. The bolometer design is classical, using an absorber grid coupled to the thermal sensor. The readout electronics has been developed at APC and is based on time domain multiplexing (TDM) using SQUIDs (Superconducting QUantum Interference Device) and a cryogenic SiGe ASIC (Application Specific Integrated Circuit). This technology allows putting inside the cryostat many functions currently performed at room temperature [Prêle et al, 2011, IEEE TAS; Prêle et al, 2009, AIoP, Voisin et al., 2008, JLTP]. The performance obtained with a first version of TESs at 300 mK was sufficient for a ground-based instrument [PhD Martino, 2012]. These TESs and associated readout electronics has therefore been chosen as the baseline for the first module of the QUBIC experiment. The TDM readout system developed for QUBIC allow reaching a 128:1 multiplexing rate, which is a first in the world.

In addition to the development of TDM, APC developed part of the readout chain (SQUID biasing and low noise amplifier) of frequency domain multiplexer (FDM) for the Athena ESA L class mission.

APC also started to work on warm digital readout electronics, to replace the traditional use of FPGAs by ASICs to generate tones (carriers) in frequency domain multiplexing (FDM). ASIC is an interesting technology to reduce the power consumption of this part of a FDM, both for TES or KID detectors. Specific ASICs could be developed for upcoming experiments as well for a space mission (CORE++) environment (using rad-hard technologies and design techniques).

The development of RF superconducting components has been triggered to allow the development of new detection architectures, directly sensitive to polarisation, as already used at lower frequencies (see for example the detection chain of the QUIET CMB experiment). We have successfully designed and tested a superconducting 90 GHz planar ortho-mode transducer (OMT) [Ghribi PhD 2009, Bordier PhD 2014] and a superconducting RF switch which can also be used as a phase shifter [Bordier, 2014, PhD thesis]. In the framework of the ANR COSMOS (COmposantS millimétriques Main gauche pour la détection des Ondes gravitationnelles primordiales, lead by F. Gadot, IEF), we are currently building a superconducting meta-material hybrid coupler working at 90 GHz. We also participate in the development of broadband planar antenna through the ESA ITT contract "Next Generation Sub-millimetre Wave Focal Plane Array Coupling Concepts".

Kinetic Inductance Detectors (KIDs)

In the last few years the French community, under the leadership of the Institut Néel in Grenoble, pioneered the utilization of arrays of KIDs at millimetre frequencies and developed a unique worldwide expertise (see Boudou et al, 2012, CRPhy, 13, 62B for a review). LPSC and CSNSM have been strongly involved in this work in terms of material development, film fabrication and array characterisation, as well as of warm readout electronics design and fabrication. For the next four years the plans for KID developments, already expressed in various forms (e.g. CNES working group on mm and sub-mm detectors and instrumentation; labex FOCUS roadmap) are to extend the range of action both in the frequency coverage (60-600 GHz, from the present 120-300 GHz) and in dynamic range (lower background, down to 0.5 pW per pixel compared to 5-10 pW at present) as well as susceptibility to cosmic rays. This will make LEKID array competitive for a future CMB space mission. For the sake of simplicity, the axes of development have been separated into six major points. For each of those, there is both a fundamental R&D on the detectors and an instrumental program based on a strong scientific case.

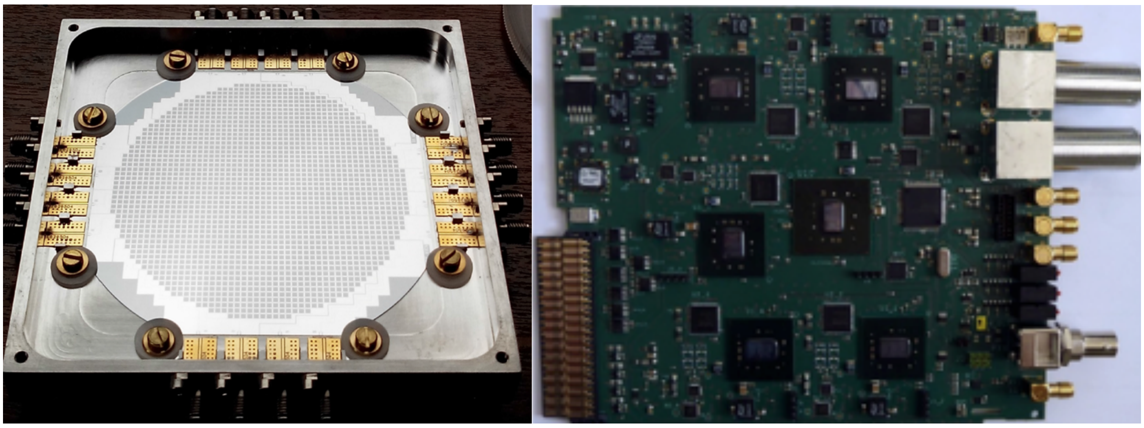

Figure 10. Right: Array of 1200 KIDs for NIKA2. Left: NIKEL RF electronic board.

Development studies are planned on the following main topics:

- **Low frequencies (60-120 GHz)**. Observing the CMB at frequencues lower than 120 GHz is interesting for monitoring better possible contamination by low-frequency astrophysical foreground emission, in particular synchrotron, which is strongly polarised. The very efficient pure Aluminium KID developed for NIKA and NIKA2 has a fundamental cut-off around 100-120 GHz due to the superconducting gap. To avoid this fundamental limitation we have investigated in the last couple of years a large range of new materials. We have found actually a viable solution for the 80-120 GHz band using superconducting multi-layers (Catalano et al., A&A, 580A, 15C). The plan is to investigate in more detail this solution when applied to large arrays of KID realized in multi-layer. This program is led by the LPSC and Néel institutes and developed between LPSC, Néel Institute and CSNSM.
- **CMB frequencies (120-300 GHz)**. This frequency range is where most of the sensitivity to the CMB can be obtained, both from space and from the ground in atmospheric windows at 150 and 220 GHz. We intend to maintain active the NIKA-like LEKID design (Fig. 10), production and testing process in order to ensure best performance and upgrades of the instrument. In addition, this continuous process of development and optimization will permit to explore at the same time lower background application in particular in view of a future CMB satellite like CORE+ (section V). This program naturally fits with the previous point.
- **High frequencies (300-600 GHz)**. Current CMB polarisation studies and in particular possible primordial B-modes detection at 100 and 150 GHz are limited by polarised galactic dust emission, which is the dominating astrophysical foreground. For monitoring dust, high frequency observations (300-800 GHz) are required. In this context, we have recently proposed the development of a new balloon-borne instrument to CNES called

PlanB, in collaboration with Institut Néel, IPAG, IAS-Orsay and IRAP-Toulouse. CNES has already approved the PlanB preliminary study, and we are currently working on the instrument definition and on preparing a suitable test-bench operating at these frequencies.

- **Susceptibility to cosmic rays.** The coupling between the detectors and cosmic rays has been proven by Planck satellite to be one of the most important sources of uncertainties, which could strongly affect science data. We intend to build an experimental setup able to mimic the in-flight conditions by exposing the LEKID arrays to accelerator beams (e.g. TANDEM accelerator at IPN-Orsay and/or Le Grand Accélérateur National d'Ions Lourds (GANIL) - CEA/CNRS). This program is led by the LPSC and Néel institutes, with contributions from APC.
- **Multi-frequency dual-polarisation KIDs arrays.** The perspective of observing the CMB in a large number of frequency channels (~20, in the case of the COrE+ M4 proposal to ESA) raises the necessity of separating orthogonal polarisations and/or frequency bands directly at the focal plane level. The effectiveness of NIKA-like pixels suggests in the first instance to study possible LEKID design modifications to allow dual-band operation (Néel study, in progress) and, on the other side, to allow polarimetric operation (APC-Néel-IEF joint study, A. Tartari et al., JLTP 176, 2014). MKIDs can be also coupled to antennas, which could open the way for multi-frequency operation (this possibility is exploited by POLARBEAR2 and other CMB experiments). This last option is certainly harder to implement, but due to its potential impact, it deserves a detailed study. Statements of interest going in this direction comes from APC, Néel and LPSC.
- **KID readout electronics.** Current KID readout electronics at IN2P3 (Fig. 10) have been designed specifically for ground-based experiments, optimizing mainly the overall cost (Bourrion et al, 2012, SPIE, 8452E; Bourrion et al, 2012, JInst, 7,7014; Bourrion et al, 2011, JInst, 6.6012B). It is not optimized for space missions and balloon experiments, which have different requirements. First, the power consumption (40 Watts for 400 detectors) has to be reduced significantly to be compatible with the total power available on a balloon or on a satellite. Second, high performance components (in particular immune to cosmic ray hits) will have to be used. Finally, the total bandwidth must be increased to improve the multiplexing factor (and hence increase the number of detectors per cable, to decrease the thermal conduction between the cold focal plane and the warm readout). The homogeneity across the bandwidth must be improved (the current electronic is composed of 5 distinct bands, producing noticeable differences between detectors). LPSC, in collaboration with Institut Néel in Grenoble is leading these developments. In parallel, the development of ASICs for frequency domain multiplexing, applicable to both TES and KIDs, has been proposed by APC for use in future balloon-borne experiments and for a space mission.

These lines of development aim at raising the TRL of KIDs to 5 or 6 so that they can be used on a future CMB satellite mission.

Superconducting planar antennas and devices

The study of the antennas can be largely decoupled from the choice of a particular detector. This is one of the subjects in which APC is active, through the CNES BSD program. Niobium-based planar polarisation diplexers at 90 GHz have already been built at APC as stand-alone devices, with the support of IEF-Minerve.

On a wider scope, APC is partner in an ESA ITT (Next Generation Sub-millimetre Wave Focal Plane Array coupling Concepts, lead by N.Trappe, NUI, Ireland) dedicated to the investigation of multichroic dual-polarisation systems for an efficient use of focal plane area.

This ITT is currently in an advanced stage, and a breadboard prototype operating around 10 GHz has already been defined.

If antenna-coupled MKIDs are proven to be a relevant option for future CMB experiments, a substantial R&D activity, regrouping APC, CSNSM, LPSC, Néel and IEF must be foreseen, going from design to micro-fabrication and test of large arrays.

Simulations, data analysis, and forecasting

Simulation and data analysis tools are a strength of the IN2P3 teams that should be capitalized upon. APC, LAL, and the LPSC have had major roles in all aspects of the data processing and analysis chain of Planck, and APC is in charge of the analysis of the 2nd season of the POLARBEAR observations and leads the effort of optimising the Simons Array to minimize the impact of astrophysical foregrounds.

A model of sky emission in particular is an invaluable resource for a wide variety of scientific investigations, ranging from validating data analysis pipelines to planning future observations. APC has been leading for many years the development of a model of the microwave band sky emission, the Planck Sky Model (PSM), which allows both

- To predict, as well as models based on existing observations permit, the multi-component polarised sky emission at any point of the sky, at any frequency from 3 to 3000 GHz;
- To generate plausible simulated skies, representative of the emission of the real sky and based on phenomenological or physical models of all known sources of emission.

The model is based on the analysis and interpretation of the data gathered from the ESA Planck mission as well as the WMAP, IRAS and DIRBE data sets, surveys of radio sources, of galaxies and of galaxy clusters, and available maps of molecular line emission originating from the galactic interstellar medium.

The PSM is a synthesis of observational data and theoretical understanding of sources of millimetre-wavelength astrophysical emissions. In the next few years, all CMB experiments will need such a modelling tool, and maintaining a PSM software and producing reference simulations is essential for a future space mission. It is also a way to contribute valuable in-kind inputs to a future large-scale ground-based project such as CMB-S4. Support (software engineers and computing resources) will be required to take advantage of this sky-modelling expertise.

V – Perspectives

In order to fully exploit the potential of the CMB to further constrain the cosmological model, it is necessary to still gain more than an order of magnitude in sensitivity over what has been achieved with Planck and what is currently being done or planned with existing and upcoming sub-orbital experiments observing the CMB with a few thousand detectors. Plans for the future are dominated by

- Proposals for a 4th generation CMB space mission with thousands of detectors in many frequency channels, for a sensitivity 10-30 times better than Planck, and increased control of systematic effects on large scales and of contamination by astrophysical foregrounds (COrE+ in Europe, LiteBIRD in Japan, PIXIE in the US);
- A very ambitious ground-based effort with hundreds of thousands of detectors on several telescopes, observing the sky from multiple sites to cover a large fraction of the sky, to be deployed in the 2020-2025 time frame (CMB-S4).

With the ramping down of the involvement of European CMB scientists on Planck, an involvement in the planning and design of these future CMB experiments is timely. A meeting to discuss the European coordination of the CMB programme has been organised by APPEC and ASTRONET in Florence, Italy, on August 31 and September 1, 2015, with participation from representatives of the CMB community worldwide. In France, a "CMB future" working group has been set-up by CNES and PNCG to discuss the CMB roadmap.

A proposal to support the preparation of a 4th generation CMB space mission in synergy with ground-based observations, called CMB-4G, led by APC and involving all the main CMB research institutes in France, is being submitted to the ANR, with a requested budget of 490 k€.

A future space mission

A large European consortium has proposed to ESA, in answer to the M4 call for a Medium-size mission in ESA's Science Programme for a launch in 2025, an ambitious next-generation CMB space mission, the Cosmic Origins Explorer + (COrE+) to be launched in the second half of the 2020s. The main science goal is to perform a near-ultimate measurement of all the CMB temperature and polarisation anisotropy signals on the entire sky, i.e., COrE+ is designed as a near-ultimate CMB mission, with essentially no compromise on the main CMB science. This mission concept has been optimised for best sensitivity to primordial B-modes of CMB polarisation expected from inflationary gravitational waves, and for the precise mapping of matter structures responsible for the lensing of the CMB temperature and polarisation patterns.

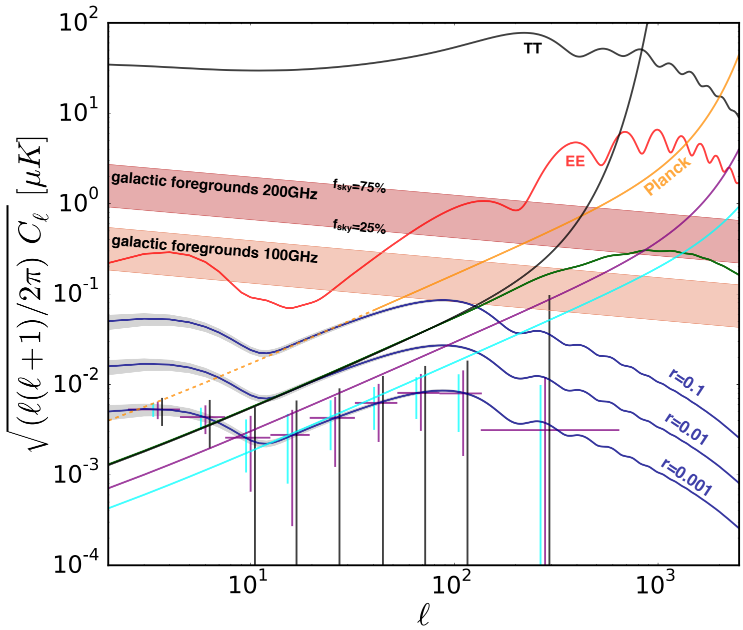

Figure 11. CMB Temperature and polarisation E and B-mode power spectra, compared to galactic foreground emission at 100 and 200 GHz. Noise power spectra and projected error bars on the measurement of the primordial inflationary B-mode spectrum for r=0.001 are shown for three levels of experimental performance. Black: 4.5 μK. arcmin noise level and 30' angular resolution; Purple: 2.5 μK. arcmin noise level and 6' angular resolution; Light blue: 1.5 μK. arcmin noise level and 4' angular resolution.

For this purpose, the proposed mission is capable of resolving all of the primary CMB signals with a S/N better than 2-3 (i.e. an angular resolution of order 4-6' and sensitivity between 1.5 and 2.5 μK.arcmin over the complete sky, see Fig. 11). A very good control of systematic effects is obtained thanks to the very stable environment of space (on an orbit around the Sun-Earth L2 Lagrange point) and thanks to a dedicated, highly redundant scan strategy for which each pixel is observed by all detectors with a wide range of different scan angles, and re-observed at many different timescales. Robustness against foreground contamination even for complex polarised emission from the Galactic interstellar medium is obtained thanks to about 20 close-packed (overlapping) frequency bands covering the 60-600 GHz frequency domain at least.

In addition to its primary CMB science goals, such a mission is capable of detecting and mapping the extragalactic hot gas in clusters and filaments (and in particular of detecting more than one hundred thousands galaxy clusters up to redshift z > 2), of detecting many extragalactic dusty galaxies up to very high redshift (z > 5), and of mapping with great precision the polarised dust emission that traces the structure of the Galactic magnetic field, enabling unprecedented studies of the role of the galactic magnetic field in structuring the ISM and in galactic star formation. Although this extra science is only a by-product of the mission, with its current CMB-centred design, a significant fraction of it cannot be obtained by any means short of a similar multi-frequency high angular resolution space mission observing the full sky in the same frequency domain.

While strongly supported by the international CMB community, and considered a priority by a number of national space agencies and institutions including CNES, the COrE+ proposed mission was considered by ESA as too challenging to be selected for a phase-A study in the context of M4, both in terms of technological readiness for a flight in 2025 (detector arrays, cooling system), and from a programmatic point of view (cost at completion, calendar, international partnership).

ESA preliminary plans for the next Medium-size mission (M5) have been announced in July 2015. With an extended budget (ESA cost of 550 M€ instead of 450 M€), later launch date (2029 instead of 2025), the M5 call is likely to be better suited for a mission such as the Cosmic Origins Explorer we propose. An updated version of COrE+ (COrE++) will be submitted to ESA in that context, with a strong involvement of France and in particular of IN2P3 labs. This is an outstanding opportunity to participate in a CMB space mission with a major role from IN2P3 while the involvement of IN2P3 scientists in Planck, in contrast, came too late to have representatives in the high-level management structures of the mission. This did not give IN2P3 the opportunity to fully achieve (outside of the Planck consortium) the international visibility it deserves for all its major contributions to the Planck mission.

The intended proposal in answer to the M5 call is led in France by APC, with formal responsibilities of Martin Bucher (member of the Steering committee and coordinator of the CMB science working group), Jacques Delabrouille (overall coordinator and spokesperson for the M5 proposal), and Michel Piat (coordinator of the instrument working group). It involves IN2P3 scientists and engineers from APC, CSNSM, LAL and LPSC. The European consortium also involves major contributions from leading institutions in Italy (Paolo de Bernardis in Rome being the spokesperson from previous incarnations of the proposal), from INSU in France (François Bouchet at IAP), as well as from partners in the UK, Germany, Spain, and many other European ESA member states. The proposal is prepared in collaboration with potential non-European partners, notably in the United States. A possible Japanese contribution is also being discussed.

Next-generation space missions have also been proposed in other contexts, all emphasising the quest for polarisation B-modes, essential for understanding the physics at work in the very early Universe. In Europe, the first incarnation of the COrE space mission was proposed to ESA in December 2010 in answer to the M3 Call for Proposal within Cosmic Vision 2015-2025. It followed the B-Pol concept, proposed earlier within the same programme, and a

French version, the SAMPAN satellite, proposed to CNES around 2006. The idea of a Japanese satellite to study CMB polarisation called LiteBIRD was proposed to JAXA in 2008 and is actively pursued in Japan. In the US, a mission concept study called EPIC / CMBpol was carried-out under a NASA contract in 2008-2009. A different concept, PIXIE, using a Fourier Transform Spectrometer to observe in 400 narrow frequency bands between 30 GHz and 6 THz with only four bolometric detectors, has been proposed to observe not only CMB B-modes, but also measure spectral distortions of the Cosmic Background.

Though both the EPIC and PIXIE US-proposals have been rejected at the time of first submission, PIXIE is expected to be re-submitted as a MIDEX proposal to NASA in 2017. Recently, LiteBIRD has been successfully down-selected for the phase A study in Japan for a target possible launch in 2025, as well as for a phase A study in the US as a NASA mission of opportunity. If selected, both LiteBIRD and PIXIE may provide interesting alternate options in the future, were the M5 / CORE++ proposal proven to be unsuccessful. However, at this time the baseline plan is to prepare a European-only option to propose to ESA, while pursuing in parallel discussions with the other teams.

In the context of the scientific preparation of a CMB space mission proposal with European partners and potential international partners in the US and in Japan, a minimum budget for networking activities is needed, at the level of 25 k€, which could be obtained partly from CNES and partly from IN2P3 (for the IN2P3 labs specifically).

The CMB S4 project

CMB-Stage 4, or S4 for short, is a plan for the future of US ground-based CMB measurements. It builds upon current CMB projects predominantly developed and conducted by the US CMB community. The plan is predicated on anticipated, increased interaction and participation from the US Department of Energy and of the high-energy physics community. It aims to be complementary to, and consistent with, CMB balloon and satellite programs, but not dependent upon them. If successfully implemented, CMB-S4 promises significant discovery potential in multiple science areas.

The project's scientific objectives are comprehensive, polarisation and high angular-resolution temperature measurements with the following main goals:

- Inflationary gravitational waves. A detection of CMB polarisation B-Modes or a limit of less than 0.001 on the tensor-to-scalar ratio, r.
- CMB lensing and synergies with other tracers of large-scale structure. S4 should reach $\sigma(\Sigma m_\nu) = 16$ meV (with DESI BAO) and $\sigma(N_{eff}) = 0.02$.
- Cosmology with SZ clusters. S4 should attain a Dark Energy Figure of Merit of 1250 (in conjunction with DESI and LSST) and detect ~100,000 galaxy clusters with the thermal Sunyaev-Zel'dovich Effect.

Reaching all of these goals will require of order 500,000 detectors, covering around 70% of the sky, with arcminute angular resolution, over frequencies from roughly 30 to 300 GHz. This is significantly larger than the sum of all experiments currently operating and therefore multiple telescopes, at multiple sites, are anticipated. This implies coordinated, coherent community-wide effort on a scale hitherto unheard of in the sub-orbital CMB experimentation, and will require change of operational mode for the CMB community as well as new funding and management needs.

While the details have not yet been worked out and funding has not yet been approved, S4 is likely to begin to dominate the CMB landscape in the years 2020-2025 and after, with the major DOE funding expected from 2018 onwards. Given this, we consider it very important that we both contribute to and follow on the project's developments, as part of an international partnership with the US-led S4 team, which has manifested its strong interest in those.

Some of the members of the IN2P3 CMB community are already involved in the S4 process, in part building on our past and current involvement in on-going US-led CMB experiments, e.g., POLARBEAR, and we also plan to keep following on developments of the S4 project to identify possible areas of involvement of IN2P3 in the project. We request funding for participating to the roughly bi-annual meetings and for miscellaneous other associated expenses.

VI - Priorities and roadmap

IN2P3 institutes are involved in several CMB experiments, existing or planned, and in technological developments relevant to these experiments. Rather than competing, these activities are complementary and fit together in a roadmap that extends until roughly 2030, and builds on the expertise developed in years of involvement on Planck, on sub-orbital experiments, and on R&D and software development activities that have been going-on for more than a decade in IN2P3 laboratories.

The scientific topics addressed by the IN2P3 CMB programme in the future concern both primary anisotropies, for constraining cosmological scenarios and parameters and for probing inflation through the detection of primordial B-modes, and on the cosmological exploitation of the secondary CMB signals that are CMB lensing and the Sunyaev-Zel'dovich effect. In addition, there is growing interest in the community for the study and observation of CMB spectral distortions, which is the foreseen milestone in CMB physics and one of the scientific objectives of the PIXIE proposal in the US.

On the short term (2015-2020), in addition to continuing the scientific exploitation of Planck, the priority of the IN2P3 CMB community is to continue developing a sub-orbital programme that will have a visible place among the vigorous international (US-led) effort. This is done through the pursued development of the QUBIC experiment, focussed on the detection of large-scale primordial inflationary B-modes; of high-resolution observations of galaxy clusters with the NIKA2 camera; and on the continuing involvement in POLARBEAR and the Simons Array to observe both lensing and primordial B-modes of CMB polarisation.

On the intermediate term (2020-2025), the priority is to join the planned CMB-S4 ground-based experiment with a significant contribution both on the hardware side, and on the development of simulation, data analysis and forecasting tools. Among those, we propose in particular to invest in the upgrading of the existing Planck Sky Model, to turn it into a robust sky-modelling tool that can be used for many upcoming CMB projects worldwide, and could be a useful contribution in specific future projects such as CMB-S4.

These sub-orbital experiments are also of prime importance as part of the roadmap to a future space mission. A strong contribution to the M5 CMB satellite mission proposal for a flight in 2028-2030 is our long-term priority.

The above objectives require specific R&D work on detectors and readouts. In particular, the space qualification of KID detector arrays (detectors, electronics and possible balloon flight) is major priority for IN2P3 in the 2016-2020 time frame.

VII – Summary of resources requested

The following table summarizes the resources requested to meet the objectives presented in this report.

Experiment	Action / Task	Resources requested	Time period
Planck	Meetings and conferences	15 k€ / year	2 years
NIKA2	Observational campaigns and meetings	20 k€ / year	4 years
QUBIC	Instrument construction	120 k€	2016
POLARBEAR	Observational campaigns and meetings	10 k€ / year	5 years
CMB-S4	Meetings	15 k€ / year	> 5 years
M5 (COrE++)	Proposal preparation (networking)	25 k€ from CNES and/or IN2P3	2016
R&D	KID space qualification	1-2 M€ overall budget shared by various institutions	
R&D	Development / distribution / maintenance of a sky-model software tool	Human resources and infrastructure	> 5 years