Cosmology

The APC Cosmology group works on a number of aspects of cosmology, from theory to instrumentation. There are two overarching themes to the group of roughly equal size: optical and infrared surveys, and the Cosmic Microwave Background. In addition, there are various smaller efforts. At the moment, the large optical and/or infrared projects on which we work are the Vera C. Rubin Observatory, and the Euclid Satellite. For the CMB, the large projects we work on are QUBIC, the Simons Array and Observatory, and *LiteBIRD*.

The Cosmology group is composed of 20 permanent researchers (5 IN2P3; 5 University; 2 CEA; 1 INP; 1 Observatory; 5 emeritus and 1 benevol), 12 doctoral students, and 6 postdocs. Another dozen or so APC members are affiliated with the Cosmology group (i.e. this is their "second affiliation" or they are engineers working with the Cosmology). We have a mailing list with approximately 50 recipients, which includes group members as well as others such as external affiliates, associates, and the like, and we have nominally weekly meetings, though we will skip meetings where there is nothing significant to report or a number of people are out of the office.

The group addresses these wavelength priorities using both ground-based and space-based platforms. Below we discuss both of these axes in turn.

Ground-based efforts

The APC has been involved in a number of ground-based experiments in the past. For example, QUAD and Polarbear in the CMB, and BOSS in the optical. Today, the group is part of the Rubin, Simons and QUBIC experiments, each of which is described in the following.

Vera C. Rubin Observatory

The Vera C. Rubin Observatory, previously referred to as the Large Synoptic Survey Telescope (LSST), is an astronomical observatory currently under construction in Chile. The Rubin Observatory hosts a wide-field telescope with an 8.4-meter primary mirror that will scan the entire sky every 3 nights. Its main task will be to conduct a 10-year deep survey of the southern hemisphere, called the Legacy Survey of Space and Time (LSST), which will enable breakthroughs in many astrophysical fields, cosmology in particular.

Figure 2: July, 2021 drone photo of the Rubin Observatory summit facility (provided by Dome Surveyor, Oscar Rivera) showing advancement to near 100% on the dome cladding completion as well as closure of the louvers, rear door, and shutters. Sublocation: Cerro Pachón, Chile. Credit: Rubin Obs/NSF/AURA

France, through IN2P3, has been involved for the last decade in the construction of the LSST Camera. At APC, the technical contribution of the camera has been focused on the software for the filter exchange system (FES), a part of the camera that takes care of swapping filters during the night and ensures the precise (re-)positioning of each filter.

As of October 2021, There are five permanent researchers and professors in the APC Rubin group, two permanent engineers, one postdoc, one non-permanent engineer, and two students. Our largest technical contributions to LSST are focused on the construction of its camera: the architecture and development of the camera control and command systems and development of the filter exchange subsystem. We also do scientific coordination for the French camera construction. Principal scientific themes are galaxy clusters, joint analyses and cross-correlations between different probes, and gravitational lensing.

Filter Exchange System The FES is a complex online system designed to complete a dozen of filter exchanges every night for 10 years, and conceived by five IN2P3 labs : APC, LPNHE (Paris), CPPM (Marseille), LPSC (Grenoble), and LPC (Clermont-Ferrand). It is composed of 3 sub-systems: the filter loader, the autochanger and the carousel (see figure 3). All three are controlled by a common software called the Filter Control System (FCS).

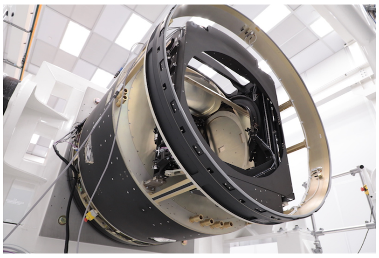


Figure 3: Picture of the assembled LSST camera under testing. One can catch a glimpse of the filter exchange system with the dummy filters inside – IR2 clean room – SLAC, California – December 2019. Credit: Gaëlle Shifrin, CNRS/IN2P3

APC has been deeply involved in the construction since the beginning of the project around 2010, and has taken the lead on the development of the FCS software, written in Java. We have also been contributing to the larger Camera Control System (CCS), the distributed system that controls most of the operations and communications related to the hardware of the LSST camera and which is mainly developed at SLAC, California.

During summer 2019, the French team tested and validated a standalone production-ready version of the FES that concluded successfully (see photo on figure 4). The subsystems were then sent to SLAC, California for an integration into the full camera body, which happened between November 2019 and February 2020.

After a long pandemic break that prevented live-support from French people, travel resumed in September-October 2021, allowing the whole FES team to tune the system and starting validating both the hardware and the software directly on the camera body and with the true filters. This resulted in a huge improvement of the timing of a full filter exchange, reaching a value well below the specification of 90 seconds from the project.

Figure 4: Snapshot of happy engineers after the completion and success of the filter exchange tests with the production-ready FES, before shipment to California – LPNHE clean room, September 2019

Key figures

The Filter Exchange System engineering team was awarded the *Cristal collectif du CNRS 2021.* At APC, Françoise Virieux is listed among the recipients of this award. [See `https://www.cnrs.fr/fr/personne/changeur-de-filtres-lsst`]

Weak lensing science The cosmological probe on which we focus in these surveys is weak gravitational lensing. Gravitational lensing corresponds to the deflection of light from distant sources (background galaxies) due to the bending of space-time by matter along the line of sight, resulting in distortions and displacements of their image. The statistical study of weak gravitational lensing distortions at large scales provides a "mapping" of the matter (dark or visible) between the observer and source (more accurately, the effect of coherent deformation described here is called cosmic shear).

This type of measurement gives a window on the properties and the evolution of cosmic structures as well as the geometry of the Universe. Its study can therefore bring higher constraints on the origin of the current accelerated expansion of the Universe that led to the notion of dark energy. In the absence of systematic errors, weak lensing is even recognised as the single most constraining probe of dark energy. As such, it is one of the main science drivers for a survey like the LSST and Euclid.

Weak lensing correlations are statistically inferred by associating the measured shapes of numerous galaxies, meaning that weak lensing estimates of the matter distribution generally improve with the number of well-measured galaxy shapes, as long as the uncertainties can be controlled. To address one of the challenges set by the shape measurements on the images of the coming surveys, our group has started to develop an approach based on Bayesian neural networks. The development of this type of analyses has lead us to build new collaborations leading to the defense of an ANR project *AstroDeep*. The BNNs offer a formalism to quantify and propagate uncertainties associated with deep neural networks models and also with the data themselves, which are both key for cosmological analyses. As such their study and the construction of a full shear analysis relying on them is one of the goals of our team.

We have demonstrated the feasibility of their use, first in a simple context for Euclid,[4] and then in a configuration with several simulated galaxies per image in a recent publication for LSST and Euclid.[5] This work is still part of an ongoing effort in the LSST Dark Energy Science Collaboration (DESC [6]). A first PhD thesis has taken place in the group (B. Arcelin, defense in Sep 2021) bringing forth these progresses with two main contributions based on Bayesian deep learning methods while tackling the effect of blending of galaxies, which is an effect we have to address in large and deep ground surveys like the LSST. The first avenue to address this problem is a deblending algorithm which uses a deep generative network called variational autoencoder. This neural network allows to learn a prior for the generation of isolated galaxy images. The latter is used in a second network to perform the deblending of the centred galaxy on images of simulated galaxies. Using this analysis, we have been able to show that the pixel joint analysis of LSST and Euclid data decreases the median error on galaxy shape reconstruction from 8 to 47%. An iterative process is then designed in order to separate all the galaxies in an image going through detection, classification and deblending of sources and this work is currently pursued.

Tested on images extracted from the DC2 simulation, generated within the DESC to prepare for the analysis of futures images taken by LSST, this

[4] Alexandre Boucaud et al. "Photometry of high-redshift blended galaxies using deep learning". In: *MNRAS* 491.2 (Jan. 2020), pp. 2481–2495. arXiv: 1905.01324 [astro-ph.GA].

[5] Bastien Arcelin et al. "Deblending galaxies with variational autoencoders: A joint multi-band, multi-instrument approach". In: *MNRAS* 500.1 (2020), pp. 531–547. arXiv: 2005.12039 [astro-ph.IM].

[6] https://lsstdesc.org

method shows an improvement of 70 to 120 % on the median ellipticity error compared to the generic method used in the current LSST pipeline.

Additional work by B. Arcelin proposed a neural network allowing for the direct estimation of galaxy shape and redshift parameters from DC2 images, without going through the deblending. This neural network allows for a precise measurement of these parameters, even when sources are blended, and can be compared to the ones obtained with deblending. This other axis will also be developed further in our group in the next few months.

Supporting grants

2019–2024 ANR **AstroDeep** – PI: E. Aubourg – https://astrodeep.net

2021–2024 PhD grant B.Biswas - Marie Skłodowska-Curie Actions (MSCA) - COFUND Horizon 2020

Team

B. Arcelin (PhD 2018-2021, CDD engineer), **E. Aubourg** (DR CEA), B. Biswas (PhD 2021-2024), **A. Boucaud** (IR CNRS), **C. Doux** (PhD 2014-2017, associate researcher), **J. Errard** (CR CNRS), **K. Ganga** (DR CNRS), A. Guinot (postdoc 2020-2022), **S. Mei** (professor UParis), **C. Roucelle** (associate professor UParis), T. Sainrat (long-term intern 2020-2021), **F. Virieux** (IR CNRS), J. Zeghal (PhD 2021-2024).

Simons Observatory

The Simons Observatory (SO) is a new Cosmic Microwave Background (CMB) experiment and one of the leading Stage-III experiments worldwide. It grew from a merger of two major Stage-II experiments: the POLARBEAR/Simons Array and Atacama Cosmology Telescope collaborations. SO is under construction at the same site as POLARBEAR/Simons Array, the Cerro Toco in Chile. It is due to achieve first light in 2022 and start scientific observations in the early 2023.

Figure 5: Overview of the SO site (Credits: D Kellner)

The team at APC has had central role in the data analysis and scientific exploitation of the previous generation, POLARBEAR observations. We took part in the design, deployment, calibration, map-making and cosmological interpretation of POLARBEAR data sets. Historically, POLARBEAR was the first experiment which delivered direct evidence in favor of the presence of the B-mode at small angular scales. In the period covered by this report our main achievements include

- the first iterative delensing using polarized data sets [The POLARBEAR collaboration (2020)].
- the demonstration of the rotating half wave plate, which is a crucial

element for future experiments such as CMB-S4 and LiteBIRD.

- the publication of independent upper limits on the inflationary tensor-to-scalar ratio [The POLARBEAR collaboration (2019, 2021 in prep)].

The Simons Array is an evolution of the POLARBEAR project, which features three POLARBEAR telescopes, furnished with $\sim 21,000$ TES detectors sensitive to polarization in four frequency bands: 90, 150, 220 and 280GHz. The project, based on a high sensitivity and a strong control of instrumental systematics, aims at constraining the tensor-to-scalar ratio with a statistical sensitivity $\sigma(r=0) \sim 0.006$, about half of the current sensitivity [The Bicep/Keck collaborations (2021)]. Its angular resolution allows the measurement and characterization of gravitational lensing, and in particular the setting of constraints on late Universe cosmological parameters such as the total mass of neutrinos. As of 2021, the three SA telescopes are operating, and the instrument is under commissioning.

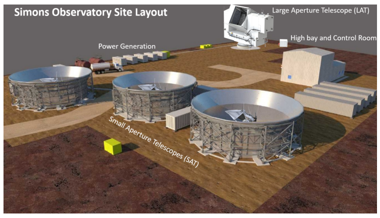


Figure 6: An artist's impression of the SO layout

The POLARBEAR/Simons Array experiments will pave the way to the third generation experiment, SO, at the same site. Its initial configuration will have three small-aperture 0.5-m telescopes (SATs) and one large-aperture 6-m telescope (LAT), with a total of 60,000 cryogenic bolometers. The SATs will target the largest angular scales observable from Chile, mapping around 10% of the sky to a white noise level of 2 μK-arcmin in combined 93 and 145 GHz bands, to measure the primordial tensor-to-scalar ratio, r, at a target level of σ(r)=0.003. The LAT will map around 40% of the sky at arcminute angular resolution to an expected white noise level of 6 μK-arcmin in combined 93 and 145 GHz bands, overlapping with the majority of the sky area of the Large Synoptic Survey Telescope (LSST) on the Vera C. Rubin Observatory sky region. It will also partially overlap with the Dark Energy Spectroscopic Instrument (DESI) field of view.

SO key science goals include the characterization of primordial perturbations, the measurement the number of relativistic species and the mass of neutrinos, the test for deviations from a cosmological constant, the improvement of our understanding of galaxy evolution, and the constraint of the duration of reionization. With up to ten times the sensitivity and five times the angular resolution of the Planck satellite, and roughly an order of magnitude increase in mapping speed over currently operating ("Stage 3", like SA) experiments, SO will measure the CMB temperature and polarization fluctuations to exquisite precision in six frequency bands from 27 to 280 GHz. The high-resolution sky maps will constrain cosmological parameters derived from the damping tail, gravitational lensing of the CMB, the primordial bispectrum, and the thermal and kinematic Sunyaev-Zel'dovich effects, and will aid in delensing the large-angle polarization signal to measure the tensor-to-scalar ratio. The survey will also provide a legacy catalog of 16,000 galaxy clusters in the nominal SO mission, and more than 20,000 extragalactic sources.

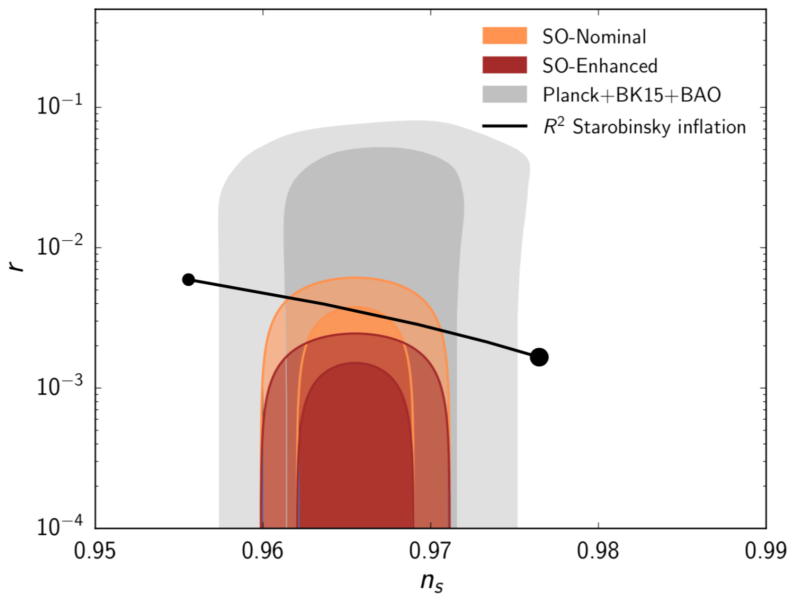


Figure 7: Projection of SO performances in constraining inflationary parameters. From `https://simonsobservatory.org/primordial/`.

Design optimization and forecast The team played an important role in the definition of the science goals of the project and design of its instruments. This work has been summarized in the article [The Simons Observatory (2018)]. In particular we have co-led the work on the impact of the forergounds on the science performance of the experiment.

Data analysis, from raw data to science The team has had an important role in the development, testing and validation of map-making techniques suitable for the Stage-III (and beyond) class experiments. In particular, we have developed a publicly-available, massively parallel software package MAPPRAISER [El Bouhargani et al (2021)]. Such codes are the backbones of any CMB data analysis pipelines and our code, developed under the auspices of the SO Pipeline Working Group, is one of the two codes currently under the development by the SO project and arguable the most advanced one. This effort was supported in part by a multi-discplinary ANR project, B3DCMB.

Since the inception of the project in 2016 we have continuously co-led the SO Working Group focused first on the optimization of the SATs design and operation in the presence of galactic foregrounds, instrumental systematics and gravitational lensing. Most recently, this group, still under our co-leadership, has been developing data analysis tools aiming at extracting of the B-mode signal from the SAT data. In addition to central contribution to the foreground cleaning and characterization of inflationary science, APC is involved in the study and exploitation of SZ clusters as well as the cross correlation of its data sets with other projects such as Rubin, Euclid and DESI.

Calibration and other activities The team is involved in delivering a high frequency (280GHz) calibration source which will be flown on a drone above the SATs, with the goal of calibrating the pointing, optical response, polarization angles of the detectors and bandpasses. This has been funded by a Émergences grant from the Université de Paris Idex.

The team has been deeply involved in the governance of the SO project and had several organizational positions. These include a membership of the Theory and Analysis Committee (TAC), the collaboration and membership committees, talk panel, analysis working group co-leads, etc.

More information about SO can be found at.[7]

[7] https://simonsobservatory.org/.

Supporting grants

2018-22 ANR B3DCMB - PI : R. Stompor – http://b3dcmb.in2p3.fr

2018-22 ANR BxB - PI: F. Boulanger (ENS) – https://anr.fr/Project-ANR-17-CE31-0022

Team

J. Bartlett, D. Beck (PhD 2016-2019), H. El Bouhargani (PhD 2018-2021), **C. Doux** (Associate researcher), **J. Errard**, **K. Ganga**, B. Jost (PhD 2019-2022), **J.-B. Melin** (Associate researcher), M. Morshed (PhD 2021-2024), **R. Stompor**, **M. Tristram** (Associate researcher), C. Vergès (PhD 2017-2020).

QUBIC

The Q & U Bolometric Interferometer for Cosmology (QUBIC)[8] is a novel kind of polarimeter optimized for the measurement of the B-mode polarization of the CMB, which is one of the major challenges of observational cosmology. The signal is expected to be of the order of a few tens of nK, prone to instrumental systematic effects and polluted by various astrophysical foregrounds which can only be controlled through multichroic observations.

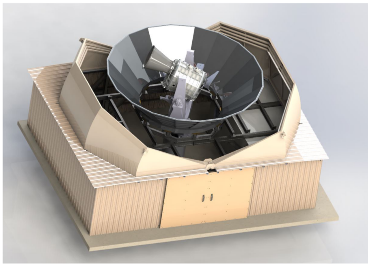


Figure 8: Artist view of QUBIC on the alt-azimuth mount in the shelter, as will be installed in early 2022 at the observing site at 5000m a.s.l. near San Antonio de los Cobres, Salta Province, Argentina

[8] J. -Ch. Hamilton et al. "QUBIC I: Overview and ScienceProgram". In: *JCAP* (Nov. 2020). arXiv: 2011.02213 [astro-ph.IM].

QUBIC is designed to address these observational issues with a novel approach that combines the advantages of interferometry in terms of control of instrumental systematic effects with those of bolometric detectors in terms of wide-band, background-limited sensitivity. The QUBIC synthesized beam has a frequency-dependent shape that results in the ability to produce maps of the CMB polarization in multiple sub-bands within the two physical bands of the instrument (150 and 220 GHz). These features

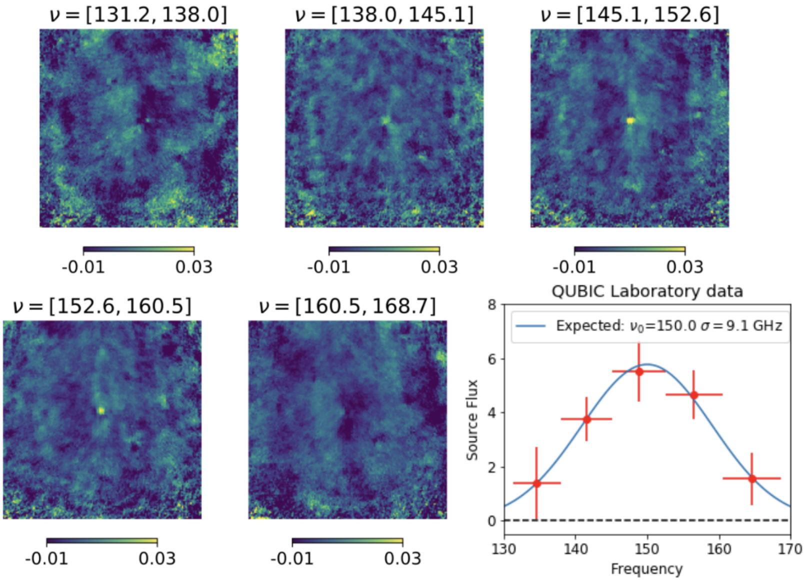


Figure 9: Reconstructed images of our artificial calibration source using spectral imaging in 5 sub-bands. The source was set to 150 GHz. The measured intensity of the source is shown on the right as a function of frequency (red points) while the expected spectral resolution (8 GHz) is superimposed in blue (no fitting).

make QUBIC complementary to other instruments and makes it particularly well suited to characterize and remove Galactic foreground contamination.

In QUBIC, pairs of back-to-back horns act like pupils of a Fizeau interferometer forming fringes on the focal plane equipped with bolometers. This is the optical equivalent of a correlator in classical interferometry. BI performs this over a wide-band, at low cost, with a sensitivity comparable to that of a classical imager,[9] with the possibility of self-calibration as in a classical interferometer.[10] Thanks to the frequency dependence of its synthesized beam, QUBIC can perform spectral imaging with $\Delta\nu/\nu$ 0.05.[11] This has been demonstrated with real data in the laboratory[12] as shown in Fig. 9 from.[13] This is a key feature for foreground contamination control, unique to Bolometric Interferometry.

End-to-end simulations with three years of integration, assuming perfect foreground removal as well as stable atmospheric conditions showed that we can achieve polarization maps depth of 2.7 and 3.7 μK.arcmin at 150 and 220 GHz respectively. This results in a statistical sensitivity to the effective tensor-to-scalar ratio (including primordial and foreground B-modes) $\sigma(r) = 0.015$[14]).

After a phase of R&D on subsystems, the QUBIC collaboration began building the Technological Demonstrator (TD) in 2016. It is the same as the Full Instrument (FI) but with fewer detectors (256 at 150 GHz instead of 2048 at 150 and 220 GHz), and with fewer horns (64 instead of 400). The TD was then integrated at APC laboratory starting in 2018 and went through a detailed calibration and testing phase throughout 2019 and 2020. A review, organized in 2020 by CNRS/IN2P3, with INFN, highlighted the innovation

[9] J. -Ch. Hamilton et al. "Sensitivity of a bolometric interferometer to the cosmic microwave backgroud power spectrum". In: *A&A* 491.3 (Dec. 2008), pp. 923–927. arXiv: 0807.0438 [astro-ph].

[10] M. -A. Bigot-Sazy et al. "Self-calibration: an efficient method to control systematic effects in bolometric interferometry". In: *A&A* 550 (Feb. 2013), A59. arXiv: 1209.4905 [astro-ph.IM].

[11] L. Mousset et al. "QUBIC II: Spectro-Polarimetry with Bolometric Interferometry". In: *JCAP* (Oct. 2020). arXiv: 2010.15119 [astro-ph.IM].

[12] S. A. Torchinsky et al. "QUBIC III: Laboratory Characterization". Aug. 2020.

[13] Torchinsky et al., "QUBIC III: Laboratory Characterization".

[14] Hamilton et al., "QUBIC I: Overview and ScienceProgram".

from this first ever Bolometric Interferometer, assessed the concept's capabilities as "excellent" and found the spectro-imaging feature "of utmost utility for foreground control". QUBIC was shipped to Argentina in mid-2021 and is now operational, cooled-down and undergoing tests and training of the Argentinean teams in our integration laboratory in Salta, Argentina. The next step is the installation of the TD on its 5000m a.s.l. site in Argentina (3h drive from Salta). A control building in San Antonio de los Cobres (45 min drive) is already operational, while the works on the site are underway. The installation on-site is scheduled for early 2022 and will be shortly followed by commissioning and data taking with the QUBIC-TD. The upgrade to the QUBIC-FI is anticipated in 2023 after one year of operations with the TD.

Team

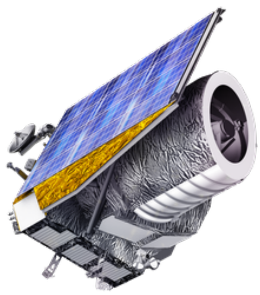
C. Chapron (IR CNRS), **S. Dheilly** (AI CNRS), **K. Ganga** (DR CNRS), M. Gonzalez (Postdoc), **L. Grandsire** (IR CNRS), **J.-Ch. Hamilton** (DR CNRS), **J. Kaplan** (Emeritus), **M. Karacak** (AI CNRS), **S. Loucatos** (DR CEA), L. Mousset (PhD 2018-2021), **M. Piat** (Professor Université de Paris), **D. Prêle** (IR CNRS), M. Régnier (Internship), G. Stankowiak (PhD 2018-2021), **J.-P. Thermeau** (IR CNRS), **S. Torchinsky** (IR Obs. de Paris), **F. Voisin** (IR CNRS)

Space-based efforts

In space-based work, *Planck* was a flagship project at the APC, and the group has also been involved in balloon measurements such as those by Archeops. Today, *Euclid* and *LiteBIRD* are the main satellite missions on which the group works (though there are also smaller contributions to balloon-based efforts as well). The APC laboratory also played a leading role in the study of a European post-Planck CMB space mission, for polarization observations (CORE space mission), and for CMB polarized spectroscopy (in the context of the ESA Voyage-2050 process).

Euclid

APC scientists have responsibilities in the coordination of the Euclid SWG Clusters, and working package Distance Measurements. We lead several papers within the Pre-Launch Key Projects in the SWG Clusters, Galaxy Evolution and Local Universe. The APC scientist and engineer team has the responsability for the CODEEN platform, and for the scientific coordination of the French Science Data Centre at CCIN2P3. The CODEEN platform allows more than 1500 developers in 14 countries to work collaboratively, and it is an important contribution to the mission. We develop software for the Euclid Ground Segment for the simulation and integration of LSST images, and for the estimation of cluster galaxy luminosity and mass function.



In June 2010, the APC Cosmology group joined the consortium that proposed the Euclid mission to ESA. The Agency selected Euclid as its M2 mission in 2012, and the launch is planned in 2023.

Euclid's goal is to constrain the nature of dark energy, using two primary probes - gravitational lensing and galaxy clustering - plus additional probes based on galaxy clusters and cross-correlations of large-scale structure with the CMB. The instrument consists of an optical imager with a single broad band (VIS) and a near infrared imager with three photometric bands and a grism spectrograph (NISP) optimized to detect the hydrogen H-alpha line in emission from galaxies at redshifts around unity. Euclid will survey the extragalactic sky, measuring the shapes of over one billion galaxies, for gravitational lensing studies, and spectroscopic redshifts of 50 million galaxies for precise galaxy clustering measurements. Euclid's high quality imaging and infrared photometry from space, and its redshift survey complement the deep, six-band optical imaging survey by the ground-based Rubin Observatory's Legacy Survey of Space and Time (LSST). The combination of Euclid and LSST surveys will enable science beyond the scope of either alone.

The cosmology group has positioned itself on the interface of the two surveys to take full advantage this complementarity. Just as the group has done in the CMB, using a combination of the space-based Planck and ground-based QUBIC and Polarbear, we anticipate that the combination of the Euclid and LSST observations will allow us to better achieve our scientific goals. Building on its recognized expertise with galaxy clusters and CMB observations, the APC team is focusing on galaxy clusters and cross-correlations with the CMB as cosmological probes that are complementary to gravitational lensing and galaxy clustering.

The Euclid team at APC contributes to both the scientific development and the project infrastructure, employing the laboratory's technical services. We have contributed to and hold scientific responsibilities in the Galaxy Cluster, Galaxy Evolution and Local Universe Science Working Groups (SWGs), and we lead the Cluster SWG Key Project on evaluating the cluster survey selection function. Working with colleagues at CEA/Irfu, we have proposed a novel cluster mass measurement technique and used it in a pipeline for the cluster cosmology likelihood analysis. This work led to two Ph.D.theses completed in 2020 (C. Murray, APC, and E. Artis, CEA) and associated papers. R. Kou joined the team as doctoral student in 2020 and is working cross-correlations of Euclid large-scale structure measurements and the CMB.

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We study the first epochs of cluster assembly using current observations of clusters and proto-clusters at $z > 1.5$ in preparation of Euclid surveys. In the SWG Local Universe, we develop a pipeline to measure galaxy distances up to ~100 Mpc. We develop Deep Neural Network for cluster detection and cosmology. In this context, we obtain funding from Université de Paris for the project AIR (Artificial Intelligence for Research; 2020-2022, PI: Bartlett) and a Chair for S. Mei's arrival at APC (2021-2022), and a PSL project that started when Simona Mei was working at the Observatory of Paris (2019-2021, PI: Mei). We hired one postdoctoral fellow and an intern, who developed Deep Convolutional Network for cluster detection. Our results show that our networks are more efficient then conventional methods to detect galaxy clusters and estimate their properties for cosmology. With the arrival of a new Ph.D. student, Kirill Grishin, we are extending this work to Bayesian Neural Networks, in collaboration with the AstroDeep team.

The APC's involvement in the preparation of the Euclid project is in the:

- Co-coordination of the SWG Clusters (James Bartlett), and leadership on the Pre-Launch Key Project Cluster selection function and other Pre-Launch Key Project papers in SWG Clusters and SWG Galaxy Evolution on clusters and proto-clusters at $z > 1.5$ and the role of environment in galaxy evolution;
- Coordination of the working package Distance Measurements in the SWG Local Universe (Simona Mei). This includes the developement of the pipeline for the measurements of Surface Brightness Fluctuations in local galaxies (< 100Mpc);
- Simulation and integration of LSST images in the Euclid Ground Segment. This is aimed to the estimation for Euclid's photometric redshift estimation of the over one billion galaxies which will be detected by Euclid, and it is key for the Euclid weak analysis and galaxy cluster analysis;
- Responsibility for the CODEEN collaborative platform, with FACe engineers providing work without which CODEEN could not be done;
- Responsibility for the scientific coordination of the French Science Data Centre at CCIN2P3;
- Responsability for developing algorithms to measure cluster galaxy luminosity and mass function in the context of the Euclid Ground Segment,

and the leadership for the paper that describe the algorithms and their validation within the Pre-Launch Key Projects;

- Studies of the impact of cosmic rays on the infrared detector behaviour, using our experience on the Planck mission.

Eight APC CNRS or faculty researchers work and/or have responsabilities in Euclid, three post-docs and one student are working on the scientific preparation, and twelve technicians and engineers (among them three CDD engineers funded by CNES) develop and maintain software for the Euclid Ground Segment.

Euclid Ground Segment The APC team is in charge of the SIM-EXT (production of pixel image simulations of ground-based astronomy surveys) and the EXT-LSST (calibration and euclidization of external data) software development activities in the framework of the Euclid Ground Segment. Ground-based multi-band surveys, such as the Rubin Observatory's Legacy Survey of Space and Time, are needed to enable accurate estimation of photometric redshifts in the Euclid wide and Deep survey areas. The Rubin field will cover two-thirds of the Euclid survey area providing critical data in the southern parts of the sky. While an agreement on the exchange of data between the two experiments is in progress, the APC team has already developed several software tools for the enabling the rendering and processing of raw LSST-like pixel images of Euclid targets within the Euclid ground segment environment.

CODEEN The APC Euclid team is in charge of providing the software development platform COllaborative DEvelopment ENvironment (CODEEN) for the Euclid mission in France. CODEEN is a central web based infra, relying on Jenkins engine, allowing the continuous integration and deployment of Euclid software coming from the code delivered through Gitlab by the Euclid Developers' community. CODEEN complies with EDEN too. It covers: source code extraction, binaries generation, bindings generation, Data Model and software documentation generation, quality check and dashboards, unit, smoke and pre-integration tests and dashboards, software packaging, software distribution repository update.

A first version of the platform has been installed end of 2012 at the former FACe and since 2018 all the plateform is hosted on the OpenStack cloud at CC-IN2P3, the French Science Data Center (SDC).

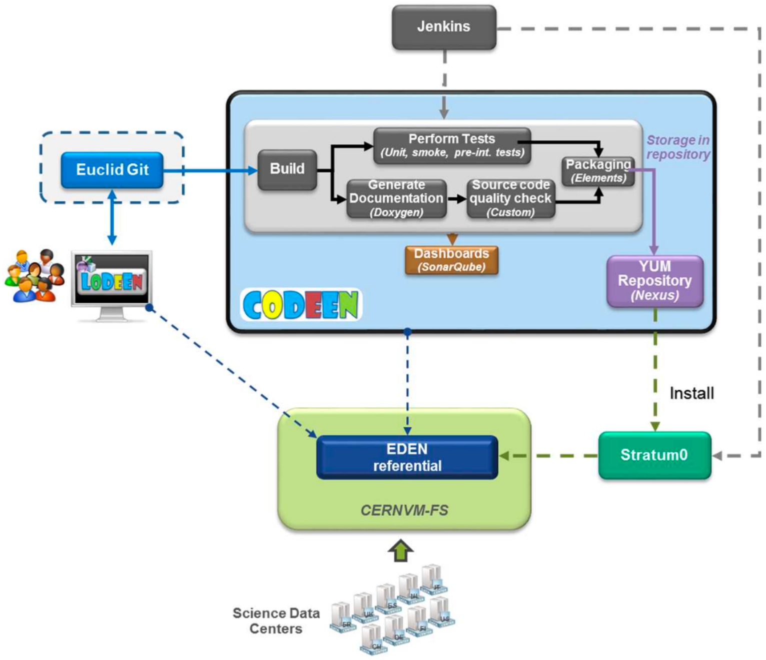

Figure 11: CODEEN is at the core of the Euclid Development Environment

Supporting grants

2021-2022	Chaire Université de Paris – Simona Mei
2020-2022	Project AIR - Université de Paris (PI: Bartlett)
2012-2022	CNES Research grants for galaxy clusters (PI: Bartlett) and proto-clusters studies (PI: Mei)
2010-2022	CNES grants for the Euclid Ground Segment development and maintenance, CODEEN (Project manager: Cécile Cavet)

Team

Anton Afanasiev (2019-2022), **Eric Aubourg, James Bartlett**, Antoine Boizard, **Alexandre Boucaud**, Hubert Bretonnière (2019-2022), **Cécile Cavet**, Rémi Fahed, **Ken Ganga**, Stéphane Ilic (2019-2021), Raphaël Kou (2020-2023), **Maude Le Jeune, Simona Mei**, Jennifer Pollack, **Cyrille Rosset, Martin Souchal, Sébastien Zappino**.

LiteBIRD

Lite (Light) satellite for the studies of B-mode polarization and Inflation from cosmic background Radiation Detection (LiteBIRD) is a Japan-led space mission aiming at constraining primordial cosmology and funda-

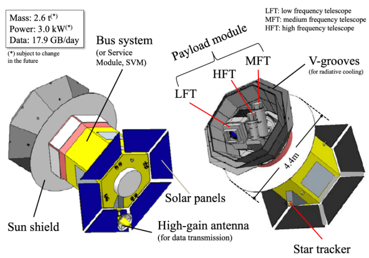

Figure 12: Conceptual design of the LiteBIRD spacecraft. The payload module (PLM) houses the low-frequency telescope (LFT), the medium-frequency telescope (MFT), and the high-frequency telescope (HFT). From Hazumi et al. 2021

mental physics via high precision measurement of the Cosmic Microwave Background (CMB) polarization. LiteBIRD is a strategic large-class mission in Japan and is strongly supported in Europe by French (CNES) and Italian (ASI) space agencies. The launch is expected in the late 2020s using JAXA's H3 rocket and the mission will survey the full sky from its vantage point at L2. LiteBIRD will map the CMB polarization over the full sky with unprecedented precision. Its main scientific objective is to carry out a definitive search for the signal from cosmic inflation, either making a discovery or ruling out well-motivated inflationary models. The measurements of LiteBIRD will also provide us with an insight into the quantum nature of gravity and other new physics beyond the standard models of particle physics and cosmology. To reach these goals LiteBIRD will carry out observations over three years, scanning the full sky in 15 frequency bands between 34 and 448 GHz with three telescopes, to achieve a total sensitivity of 2.16 μK-arcmin with a typical angular resolution of 0.5° at 100 GHz. Beyond the use of more than 4,000 TES detectors, LiteBIRD design is also based on a high control of instrumental systematic effects, in particular via the use of three continuously rotating half-wave plates.

APC has central hardware and data analysis contributions to the project:

- thermal architecture – thermal architecture responsibility has been transferred from LESIA to APC in 2021;
- instrumental and astrophysical systematic effects, modeling and correction – APC plays a central role in the modeling, simulations and derivation of calibration requirements. The team is also expert in the modeling, characterization and removal of galactic foregrounds, which are the main limitation to the detection of primordial gravitational waves;
- data analysis and cosmological interpretation – APC is also performing the cosmological analysis on the systematic-corrected and foreground-cleaned CMB maps;
- theory – although not official LiteBIRD members, several APC researchers are studying the performance of LiteBIRD in constraining inflationary or other exotic early Universe scenarios.

Several APC members are also active members of the Interim Governance Board, co-leading the international systematic Joint Study Group as well as the performance team.

More information about LiteBIRD can be found at.[15]

[15] http://litebird.jp/eng/.

Supporting grants

2018 - 2022 ANR B3DCMB - PI : R. Stompor – http://b3dcmb.in2p3.fr/

2018 - 2022 ANR BxB - PI: F. Boulanger (ENS) – https://anr.fr/Project-ANR-17-CE31-0022

Team

M. Bucher, **J. Errard**, **K. Ganga**, **L. Grandsire**, **J.-Ch. Hamilton**, **M. Le Jeune**, C. Leloup (2019-2022), **G. Patanchon**, **M. Piat**, **D. Prêle**, A. Rizierri (2021-2024), **R. Stompor**, **J.-P. Thermeau**, **M. Tristram** (Associate researcher), **F. Voisin**, W. Wang (2021-2024).

Other activities

Millimetric wavelength laboratory

The millimeter laboratory is contributing to the development of detection chains and instrumentation required for precise polarisation measurement for astrophysical observations in the millimeter and sub-millimeter wavelength range.

The current projects are three-fold:

1. The QUBIC experiment: the millimeter lab is a major contributor to the QUBIC experiment. The design of the instrument and especially of the detection chain has been made in the millimeter lab. The detectors and readout electronics are tested in the dilution fridge, before intergration in the instrument.

2. The *B-mode Superconducting Detectors* project is developing Kinetic Inductance Detectors (KIDs) for astrophysical observations in two wavelength ranges:

   - In relation with the SPIAKID project at the Observatoire de Paris, the team tests visible and near infrared KIDs produced at GEPI. SPIAKIDs is an ERC-funded instrument aimed to detect ultra-faint galaxy in the near-infrared and optical bands (400 nm-1600 nm) using MKIDs. SPIAKIDs is planning to be deployed at NTT in 2025. The MKIDs will consist of 4 times 20000-pixel arrays. The detector characterization for the project is carried out in the test bench based on an adiabatic demagnetization cryostat (ADR) at APC. The instrument will also be integrated and tested at APC. This part of the project is supported by the LabEx UnivEarthS.
   - In the millimeter wavelength range, the optimization of an instrument's optical performance would be greatly simplified if the physical

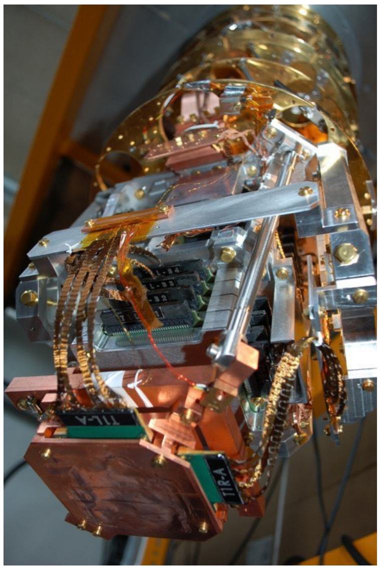

Figure 13: The dilution fridge in the millimetric wavelength laboratory

dimensions of the focal plane could be reduced without decreasing the number of detectors. An elegant way to reach such architecture would be to realize multi-frequency cryogenic detectors, i.e. integrating new functionalities approaching spectroscopy. In practice, such a detection architecture is based on the use of a broadband antenna connected to a planar circuit and then to detectors (bolometers or KIDs), all at cryogenic temperatures (T<0.3K). Several options are considered for the planar circuit, the simplest being a set of filters feeding several detectors. This is the main subject of a PhD that started in October 2021 (Pham Viet Dung). CNES is supporting these developments through a R&D funding.

3. APC is leading a R&T program started early 2020, the *Next Generation Cryogenics system* project (NGCryo) funded by IN2P3 through a R&D project. NGCryo is dedicated to the development of new cryogenic technologies for detectors operating in the subKelvin temperature range. Three others IN2P3 laboratories (IJCLab, GANIL, LPNHE) are involved in this program which is composed of four work packages: continuous refrigeration, cryogenic micro-electronics, thermometers calibration and thermal properties measurements. The APC team is mainly involved in the following developments:

   - The first concerns the design of an ASIC able to measure 16 thermometers in a time domain multiplexing scheme and operating at cryogenic temperatures. A first ASIC version was designed in 2020, manufactured during the first half of 2021 and is planned for testing for the end of 2021.
   - The second APC contribution concerns the design of a thermometer calibration facility which will use the ASIC circuit and adsorption refrigerators. The facility will allow the calibration of 10 thermometers in the temperature range from 4K to 0.3K. These developments are done in collaboration with IJCLab. The cryostat for the calibration facility is currently in manufacturing and the assembly of its main components is planned for the end of 2021.
   - The last contribution is the development of subKelvin continuous refrigeration using the adsorption process. A single shot adsorption refrigerator operating at 1K was designed and is being manufactured, while a 0.3K version is being studied. To compensate for the need for regeneration, it is possible to combine two sets of adsorption refrigerators with alternating operating and regeneration cycles, which makes it possible to obtain quasi-continuous cooling of the detectors. The NGCryo project proposes to go further by combining the use of a dilution refrigerator system with adsorption pumps, replacing the usual 4He and 3He circulation pumps. This will be the main subject

of a PhD thesis that will start in 2022 in the framework of a research collaboration with the MyCryoFirm company.

These projects are carried out with the low temperature modeling and characterization means available at APC (cryostats with 3He/4He adsorption refrigerators, dilution cryostat, cryostat with adiabatic demagnetization system, 70-250GHz millimeter wave network analyzer, low noise characterization equipment).

The millimeter laboratory has collaborations with the the University of Manchester, INFN teams (Roma, Milano, Pisa), IJCLab (Orsay), C2N (Palaiseau), GANIL (Caen), LPNHE (Paris), Paris Observatory, the Néel Institute and LPSC (Grenoble) as well as the Centro Atómico in Bariloche and the CNEA in Buenos Aires (Argentina).

Team

M. Piat, J.P. Thermeau, S. Torchinsky, F. Voisin, D. Cammilleri, J. Hu, D. Pham Viet, J. Lesrel, G. Monier, C. Chapron, M. Karakac, S. Dheilly

HIRAX, Spider, SKA... Members of the group are also involved in other projects that do not belong to the lab's priorities. In addition to CMB experiments such as Spider there is interest in 21 cm cosmology – Three researchers (Martin BUCHER, Ken GANGA, and Zheng ZHANG) in the group are involved in the Hydrogen Intensity Real-time Analysis eXperiment (HIRAX) intensity mapping experiment, which is presently under construction. Although it was primarily designed for intensity mapping of the 21 cm line from galaxies in the redshift range between z=0.8 and 2.5, HIRAX will also discover a host of FRBs and new pulsars when it comes online.

Figure 14: The beginnings of the HIRAX array.

HIRAX is a radio interferometer of closely packed 6 m dishes observing between 400 and 800 MHz. The array is currently funded for up to 256 dishes with a possible future expansion to 1024 dishes. The array will be co-located with the Square Kilometer Array at the MeerKAT radio telescope site, which is operated by the South African Radio Astronomy Observatory in the Karoo, South Africa. The experiment will conduct ground-breaking science in a number of areas, including the cutting-edge fields of Dark Energy and Fast Radio Bursts. The collaboration is led out of the University of KwaZulu-Natal with seven additional South African consortium members and 17 international partners. The project is currently funded by the South African Department for Science and Innovation and National Research Foundation, the HIRAX South African Consortium, McGill University in Canada, and a partnership of Swiss universities with funding from the SNF.

The thesis of Zheng ZHANG will study the impact of polarized emission from the galaxy on the extraction of the cosmological signal in intensity mapping studies. This work is being carried in collaboration with François BOULANGER from ENS, who is a co-supervisor together with

Martin Bucher.

Team

M. Bucher, K. Ganga, Z. Zhang

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