CMB-S4 experiment: the science case, the project, and a proposed IN2P3 contribution.

on behalf of the CMB-S4@IN2P3 Team:

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1 Summary

CMB-S4 is the next generation, ”Stage IV”, ground-based, cosmic microwave background (CMB) experiment designed to exploit the scientific potential contained in CMB anisotropies observations as we currently understand it. The experiment will be an ultimate cosmological laboratory of fundamental physics, as it will make crucial progress towards a detection of primordial gravitational waves as predicted from inflation, will search for signatures of relic particles, including neutrinos, provide insights into dark energy and potential non-gravitational interactions of dark matter particles with baryons, and test theories of gravity. It will also have significant impact on a range of other science areas from astrophysics, to solar system physics. The experiment will participate in time-aware multi-messenger campaigns and produce legacy maps, opening opportunities for unique joint analyses with other data sets.

CMB-S4 is designed to be a crowning achievement of the ground-based experimentation in the CMB domain and will outperform by a significant margin any other on-going and planned efforts, including South Pole Observatory and Simons Observatory, two main precursor experiments, which will pave the way to, and inform the work on, CMB-S4. CMB-S4 will be complementary to LiteBIRD, a contemporary to CMB-S4, JAXA-led, CMB satellite mission, and the two co-analyzed together will provide an opportunity for unique and very powerful cross-checks and robustness demonstration, ensuring more precise and accurate results.

CMB-S4 is a DOE/NSF-supported, US-led effort, with the Lawrence Berkeley National Laboratory and University of Chicago playing the lead roles for the DOE and NSF, respectively, parts of the projects. The early implementation stage of the project is on-going, the instrument construction is expected to start in 2026 upon a succesful passing of Critical Decision 2 review at DOE, and the first light is project for 2031. The operations will then take between 7 and 10 years and will be followed by intense data analysis and scientific exploitation of the collected data sets.

In this document we describe plans for engaging the CMB@IN2P3 group in this international project. The proposed involvement is two-pronged including important contributions to warm readout electronics – one of the key elements of proposed instruments, and to the Data Management, both its low-level processing stages (as coordinated by the CMB-S4 Project Office) as well as high-level, scientific exploitation (under auspices of the CMB-S4 Scientific Collaboration).

2 Context and science case

2.1 CMB-S4 science

Some of the most profound and exciting questions of modern physics can be most readily answered with help of cosmological observations. These include questions concerning the origin of the Universe, the nature of dark matter and dark energy, the existence and properties of relativistic particles, but also about physical laws at extremely high energies. Observations of the cosmic microwave background (CMB) anisotropies have proven over the years to be one of the most reliable and fruitful sources of knowledge about the Universe and particle physics alike. Owing to striking progress in technology over the last decade, the new generation of the CMB experiments aims at providing tantalizing clues concerning many of these questions in a comprehensive and robust way.

CMB-S4 experiment is the most advanced and ambitious of the currently planned, ground-based efforts (1), (2), (3), (4), (5). It will build on the experience of the precursor efforts, South Pole Observatory and Simons Observatory (6), to field multiple telescopes and instruments, which will allow to exploit the scientific potential of the CMB anisotropies to the limit currently thought possible from the ground. CMB-S4 will be complementary to the planned satellite mission, LiteBIRD (7). Synergies between them will allow to further enhance impact of each of them separately and combined together, while providing invaluable opportunity for mutual cross-checks.

The CMB-S4 science case is, however, broader than cosmology and particle physics. Indeed, in addition to these fundamental questions, CMB-S4 will be a goldmine for studies ranging from astrophysics of transient objects, to Solar system science. The targeted science topics fall in four major scientific themes,

1. primordial gravitational waves and inflation;
2. the dark Universe;
3. mapping matter in the cosmos;
4. the time-variable millimeter-wave sky.

In addition, CMB-S4 will provide high quality legacy maps of the sky in multiple frequency bands spanning the microwave range and covering over 60% of the sky providing opportunity for innovative joint analyses with other data sets, such Vera Rubin Observatory (VRO) Legacy Survey of Space and Time or conducted by the Nancy Grace Roman Space Telescope, Euclid, and others yet to be proposed.

CMB-S4 will reach and cross necessary, critical thresholds ensuring significant breakthroughs in many of these areas and it will have transformational impact on our current understanding of cosmology and fundamental physics. The highlights include (1),

- The search of primordial gravitational waves as predicted by inflation, a currently leading class of models of the origin of the Universe as we know it, will not only provide evidence in its favor but allow to single out the successful candidate models. It will also furnish the very first evidence for quantization of gravity as well as insights into physics on energy scales of grand unified theories and the presence of symmetries.
- The detection of tale-telling features in the CMB power spectra will allow to detect light relic particles as the decouple from the other components and thermalize, exploring times going down all the way to 5 nano-seconds after the Big Bang, thus improving on Planck by a factor of nearly 10,000. Specifically, CMB-S4 will be sensitive to constrain Weyl fermion and vector particles, which froze out at the energies a few hundred times higher than that of the QCD transition.
- CMB-S4 will map with unprecedented precision the dark matter distribution via gravitational lensings. This will allow to set tight constraints on the absolute mass scale of neutrinos, dark energy, and test modified gravity models. CMB-S4 will also map the baryonic matter in the Universe via Sunyaev-Zel'dovich effects, what will allow to study possible non-gravitational interactions between dark matter particles and baryons with unprecedented hitherto precision.
- CMB-S4 will add the microwave-window to multi-messenger observations providing a long-baseline with high-cadence sampling in both intensity and linear polarization. This will provide new, complementary information on time-variable sources including those with gravitational wave counterparts.

2.2 CMB at IN2P3

The IN2P3 community has vested long term interests in all these science areas, which address scientific questions relevant to the IN2P3 mission and which complement numerous efforts and investigations undertaken by the IN2P3 scientists. They also naturally follow from past and current efforts with significant IN2P3 involvement.

The CMB research within IN2P3 has over two decades of tradition, which was solidified via its strong involvement in the Planck mission. Since then, IN2P3 researchers were involved in a number of ground-based projects, including France-led NIKA, NIKA-II, QUBIC, as well as international, US-led projects, such as POLARBEAR or ACT. These have allowed the CMB group at IN2P3 to develop world-level expertise in this area, establishing the CMB research at IN2P3 nationally and internationally. At IN2P3 there are three key laboratories which have historically played a major role in the effort, APC, IJCLab, LPSC, which were joined more recently by a Berkeley-based international research laboratory, CPB.

There is currently strong involvement of the IN2P3 researchers (APC, IJCLab, CPB) in Simons Observatory, which is expected to make important progress in some of the CMB-S4 science areas but also to serve as a major precursor experiment for it. In addition, IN2P3 CMB group (APC, CPB, IJCLab, LPSC) is heavily involved in preparation of the JAXA-led satellite mission, LiteBIRD. CMB-S4 involvement fits naturally in this landscape, permitting to continue the on-going work on Simons Observatory and to complement the LiteBIRD effort. CMB-S4 is the major large-scale, ground-based project in this area for the forthcoming decades, and the one, which, given its broad science case, is attractive to a large community at IN2P3 and therefore capable of uniting large part of the CMB at IN2P3 community around a single project. Involvement in CMB-S4 will provide access to unprecedented, unique data set, in the proprietary period, but also will ensure that important expertise on how to use these data sets beyond it is available at IN2P3. This will facilitate collaborative efforts across IN2P3 on joint analyses, e.g., with the LSST and Euclid teams or VIRGO.

CMB-S4 will be a hugely impactful project through its direct contributions as well as legacy data products, which will ensure that its impact on the field will continue to reverberate for many years after its conclusion. It is of paramount importance for the CMB group at IN2P3, and IN2P3, to be part of this undertaking. Moreover, the size and complexity of the experiments makes it not only capable of accommodating a coordinated, large involvement, but also ensuring visibility and important roles for the IN2P3 researchers.

Such an involvement will allow to capitalize on the investments made over the last decade during the Planck mission executions and will valorize the experience and expertise gained during the on-going work on Simons Observatory. These will further ensure pivotal role for the IN2P3 CMB community in CMB-S4. Combined involvement in CMB-S4 and LiteBIRD will position us to play a unique role not only within each of these projects but also as leaders of any synergistic activities between them, while allowing us to mutualize the investments and resources. We discuss these multi-prong strategy in more detail in Section 5.

3 Project

3.1 Technical design

In order to meet its science goals CMB-S4 will deploy a number of telescopes of two different aperture sizes, operating from two different geographical sites, from the South Pole and the Atacama Desert in Chilean Andes. These are the two best sites for microwave observations with long history of conducting successfully such measurements. Indeed, the two major forthcoming CMB observatories: South Pole Observatory and Simons Observatory, are based at South Pole and Atacama, respectively. The total number of polarization-sensitive detectors observing the sky deployed by CMB-S4 will be nearly $500,000$ ensuring unprecedented leap in sensitivity over the present and forthcoming efforts.

The specific design of the instruments is driven by two main science goals (8),

- reaching the sufficient on-the-sky sensitivity to set a limit on the amplitude of the primordial gravitational waves of $r < 0.001$ (95σ) or conversely detect $r > 0.003$ with more than 5σ significance; (r denotes a so-called tensor-to-scalar ration and defines the amplitude of the primordial gravitational waves relative to that of scalar (density) perturbations as produced by inflation.)
- constraining the effective number of relativistic species of light particles ($n_{\rm eff}$) in the early Universe down to $\Delta N_{\rm eff} < 0.06$ (95σ).

These are illustrated in Fig. 1.

The current plans (so-called post-AoA[1], see next section) assume a deployment of two large, 6m, aperture telescopes (CHLATs) in Chile, each having a 85 tube cryostat and operating in low (LF: 25, 40GHz), medium (MF: 90, 150 GHz), and high (HF: 220, 280 GHz) frequency bands as defined by atmospheric windows. On the South Pole, the project will deploy one large, 5m, aperture telescope (SPLAT) with a 85 tube cryostat and detectors operating in ultra low frequency (ULF: 20GHz), in addition to low, medium and high frequency bands as defined above. This will be complemented by three mounts for small aperture telescopes (SATs), each with three, 0.6m, optical tubes and

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[1] J. Strait, CMB-S4 collaboration meeting, April 2023

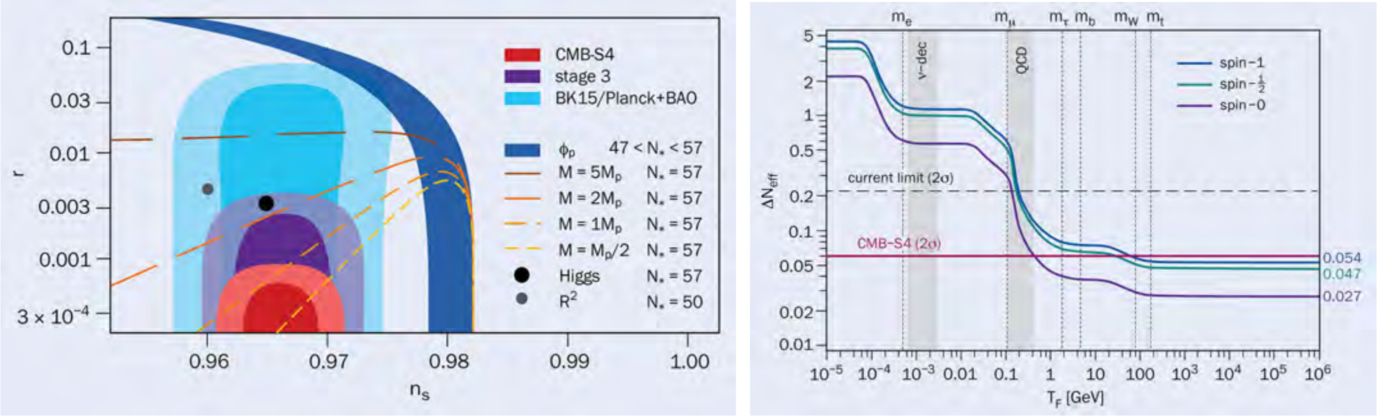

Figure 1: The science reach of CMB-S4 showing the projected improvement in the constraint on amplitude of the primordial gravitational waves (expressed as a tensor-to-scalar ratio, r), left, and the effective number of light particles, $\Delta N_{\rm eff}$, right. These are two main science drivers behind the CMB-S4 design. The stage 3 experiment referred to in the left panel roughly corresponds to the anticipated performance of the forthcoming, precursor experiments, Simons or South Pole Observatory. These plots are taken from (4) and still assume the pre-AoA configuration for CMB-S4.

detectors operating at 4 medium frequency bands (85, 145 and 90, 150 GHz), in addition to low and high ones. The experimental set-up is visualized in Fig. 2. The projected length of the observational campaigns is 10 years for SATs and SPLAT is 10years, while for CHLATs 7years as driven by the respective science goals.

The South Pole site is dedicated to the search for primordial gravitational waves. These will be achieved via constraining the amplitude of the primordial CMB B-mode (curl like) polarization signal. This requires an ultra-deep observation of a small patch of the sky (initially 3% but may be increased once the detection is reached) and will be performed with SATs capitalizing on the fact that the same sky area can be seen constantly from the South Pole. The SPLAT will re-observe the same patch with much higher resolution permitting a removal of the B-mode signal contamination due to the so called gravitational lensing effect.

The Chilean LATs will perform a deep and wide survey of nearly 60% of the sky mapping it in both total intensity and linear polarization. This will allow reaching the requirements on the limit on the number of relativistic particles as well as delivering on all other science goals, including production of major legacy data sets. The Chilean site is particularly well-suited for this purpose owing to access to the large part of the sky, which could not be seen from the South Pole.

The cost of the experiment is estimated to be $770M and it is expected to be largely covered by DOE and NSF.

3.2 Organization

CMB-S4 started off a scientific collaboration but it is now also a DOE/NSF project. (See Section 4 for some history.) Both of these work together for the final success of the experiment, however they play different roles. The overall organization of CMB-S4 reflects this duality.

The CMB-S4 Project is led for DOE by Berkeley Lab and its NSF counterpart is led by University of Chicago. The Project is responsible for ensuring timely delivery of all the instruments and required infrastructure, as well as the development of the Data Management segment which is charged in delivering pre-processed, validated data products to the scientific collaboration. This is reflected in the Work Breakdown Structure shown schematically in Fig. 3 and described in some detail in Table 1.

The same Project Office coordinates both DOE and NSF funded work and is referred to as Integrated Project Office (IPO). There are roughly 150 researchers, engineers, and technicians involved in its activities, with at least a half coming from the scientific collaboration itself. The IPO is also responsible for forming partnerships with other stakeholders, including foreign institutions, which in addition to participating in the work of the CMB-S4 Scientific Collaboration are also willing to contribute to the CMB-S4 Project.

The scientific collaboration is coordinated by the Executive Team and Spokespeople, and overseen and legislated by the Governance Board, see Fig. 4. Both of these are elected by the collaboration members. There are nearly 500 members (junior and senior) registered at this time. The collaboration aims at the preparation of the scientific exploitation of the data products provided by the CMB-S4 Project Office. These are defined as fully characterized, in terms of their statistical uncertainties, but also systematic effects, maps at each of the frequency bands. The collaboration is then charged in turning those into constraints on cosmological and physical models. The collaboration work is divided between 6 analysis working groups (AWGs), with each group focused on different aspect of the

WBS	WBS Title	WBS Description
1.01	Project Office	Labor, travel, and materials necessary to plan, track, organize, manage, maintain communications, conduct reviews, and perform necessary safety, risk, and QA tasks during all phases of the project. Overall project Systems Engineering is a subsection of this WBS element. However, subsystem-related management and support activities for planning, estimating, tracking, and reporting as well as their specific EH&S and QA tasks are included in each of the subsystems.
1.03	Detectors	Labor, materials, and equipment associated with the design, fabrication and testing of the detector wafers. R&D activities to support development of a Conceptual Design pre CD-1 for DOE.
1.04	Readout	Labor, materials, and equipment associated with the design, fabrication and testing of the detector readout system. R&D activities to support development of a Conceptual Design pre CD-1 for DOE.
1.05	Module Assembly and Testing	Labor, materials, and equipment associated with the design, parts fabrication, assembly and testing of the detector modules. R&D activities to support development of a Conceptual Design pre CD-1 for DOE.
1.06	Large Aperture Telescopes	Labor, materials, and equipment associated with the design, prototyping, materials selection, construction and certification for the Large Aperture Telescope System. Integration and commissioning in North America.
1.07	Small Aperture Telescopes	Labor, materials, and equipment associated with the design, prototyping, materials selection, construction and certification for the Small Aperture Telescope System. R&D activities to support development of a Conceptual Design pre CD-1 for DOE. Integration and commissioning in North America.
1.08	Data Acquisition and Control	Labor, materials, and equipment associated with the design, construction, certification, and delivery of the control systems for the observatories and data acquisition. R&D activities to support development of a Conceptual Design pre CD-1 for DOE.
1.09	Data Management	Labor, materials, and equipment associated with the design, construction, certification, and delivery of the data management system. R&D activities to support development of a Conceptual Design pre CD-1 for DOE.
1.10	Chile Infrastructure, Integration and Commissioning	Labor, travel, and materials necessary to plan, track, manage, maintain communications, conduct reviews, and perform necessary safety monitoring on site including oversight of all shipping of CMB-S4 components to Chile and oversight of construction activities on site. On-site Integration and Commissioning of the CMB-S4 telescopes and infrastructure in Chile.
1.11	South Pole Infrastructure, Integration and Commissioning	Labor, travel, and materials necessary to plan, track, manage, maintain communications, conduct reviews, and perform necessary safety monitoring on site including oversight of all shipping of CMB-S4 components to the South Pole and oversight of construction activities on site. On-site Integration and Commissioning of the CMB-S4 telescopes and infrastructure at the South Pole.

Table 1: Definition of the main Level 2 tasks of the CMB-S4 Work Breakdown Structure. From (1).

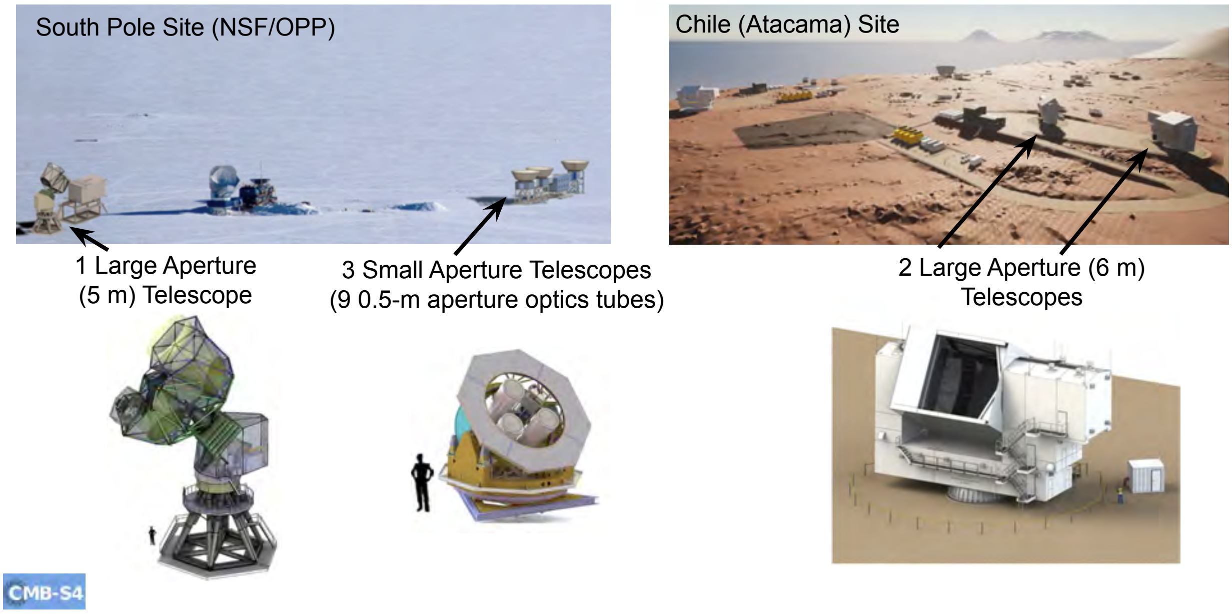

Figure 2: Graphical summary of the planned CMB-S4 experiment post-AoA exercise. (Credit: J. Strait, CMB-S4 collaboration meeting, April 2023.)

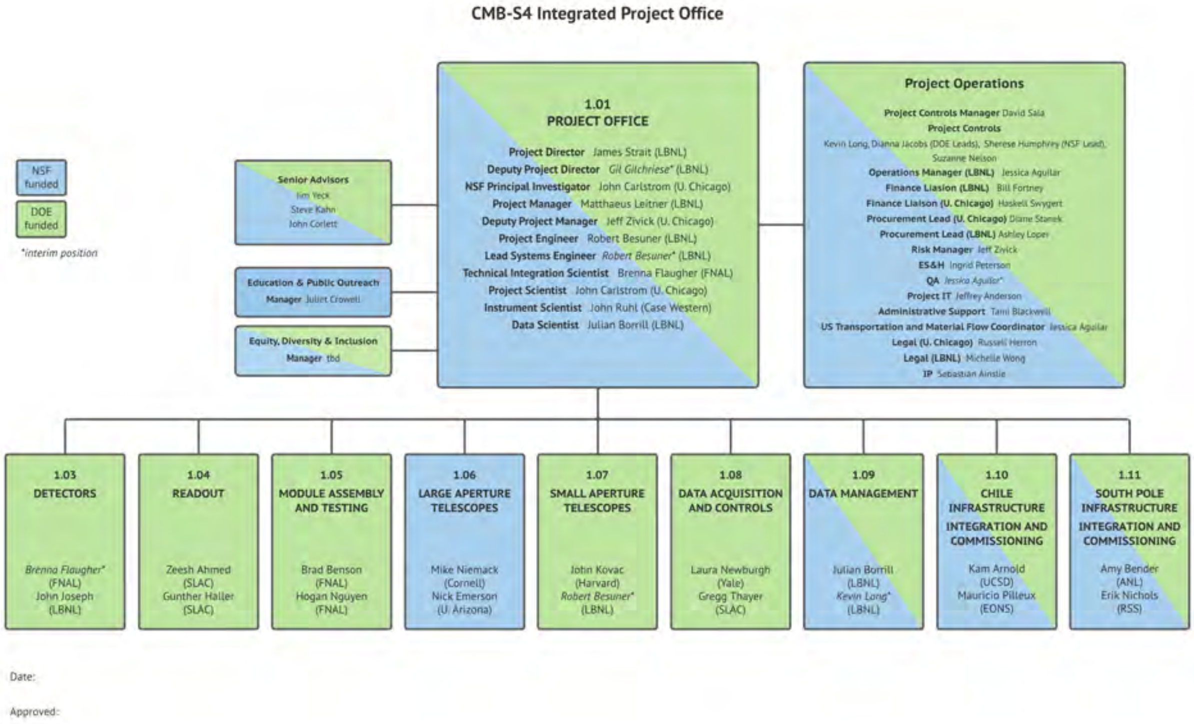

Figure 3: The structure of the Integrated Project Office, showing the two main levels of the project Work Breakdown Structure. The proposed IN2P3 contribution pertain to two Level2 tasks shown here: Readout (1.04) and Data Management (1.09). (Credit: CMB-S4 Project Office.)

exploitation. The AWGs develop scientific models, data analysis tools, as well as software which is necessary for this. The AWGs also provide feedback to the Project Office, which informs the instruments' design and their specifications.

The AWGs work is performed on 'the best of effort' basis. While the collaboration is widely open to international, non-US based contributors, their work is only acknowledged through authorship of the papers published in the preparatory period and, later on, potentially on the selected papers to which they have made specific, key contributions over the years. However, in general, involvement in the collaboration work, however deep, does not ensure any data rights within the proprietary period and authorship on major scientific papers issued as the result of the experiment. The situation here is very different for researchers from US institutions, for whom a collaboration membership automatically ensures such rights. This is due to the fact that the major funding for the projects comes from the US federal sources.

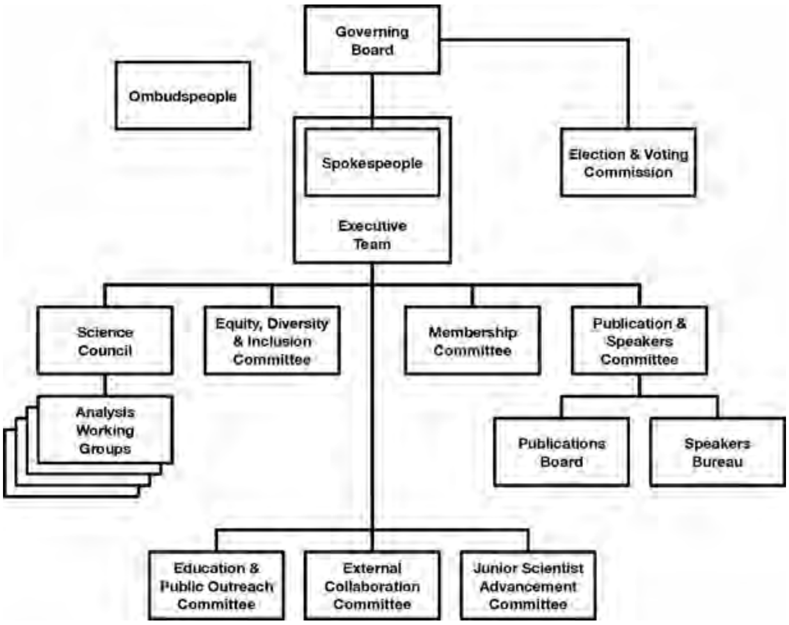

Figure 4: The organizational structure of the CMB-S4 scientific collaboration. (Credit: CMB-S4 Collaboration)

In contrast, an involvement in the work overseen by the Project Office is based on more formal commitment towards deliverables, deadlines, etc, all clearly defined and agreed on prior to performed work. This adds an extra burden in terms of the organization and agreements, however leads to the work being counted as a formal, 'in-kind' contribution to the project and therefore facilitates obtaining data rights access at the end of the process. The 'in-kind' contributions are computed as a project cost offset, what is very advantageous for us, as the workforce costs are evaluated according to the US rates and include overheads. While such in-kind contributions and agreements could happen on an individual level, the eventually gained data rights in such cases would have been limited to the contributing individual. It is therefore more effective to have such an agreement on institutional level covering a group of researchers. In such cases, the data rights will extend to some number (depending on the final contribution) of researchers and will include new comers as well as future students and postdocs. This is indeed a path which seems the most appropriate for the CMB group at IN2P3, as we describe it in more detail in the following. While the precise level of an 'in-kind' contribution required to cover data rights for a single researcher is not formally defined yet. It is expected, following similar arrangements in other contemporary experiments, to be on order of ~ 1 FTE integrated over the time.

4 Project history and timeline

4.1 Globally.

CMB-S4 started off as a scientific collaboration around 2015, following on a white paper submitted to the Snowmass process in 2013, which led to the 2014 Particle Physics Project Prioritization Panel (P5)[2] and the 2015 National Academies[3] reports, both of which strongly recommended this science area, recognizing its transformational potential, and emphasized need for a large scale project required to explore it. The initial goal of the collaboration was to build the science case and proposed a hardware design for an 'ultimate', ground-based CMB experiment. This was followed up by the CMB-S4 Science Book published in 2016 (5) and CMB-S4 Technology Book in 2017 (9). This work formed the foundation for the Concept Definition Task Force set up by DOE and NSF in the fall of 2017. The task force report complemented by the community inputs collected, reviewed, and approved over the series of annual collaboration meetings eventually resulted in a foundational document "Science Case, Reference Document, and Project Plan", which was made public in the summer of 2019 (8). This became a basis for the white paper submitted to the 2020 Decadal Review[4], which in turn returned unequivocal, very strong recommendation of the project. Concurrently, the project passed the DOE Critical Decision 0 review in 2019 becoming a DOE project and, soon after that, an NSF project upon an award of a project development funding by NSF. In 2020 Berkeley Lab was appointed as a DOE lead laboratory, while the University of Chicago serves as an NSF lead institution. This lead to the establishment

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[2] https://www.usparticlephysics.org/resources/

[3] https://www.nationalacademies.org/our-work/a-strategy-to-optimize-the-us-optical-and-infrared-system-in-the-era-of-the-large-synoptic-survey-telescope-lsst

[4] https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

of the Integrated Project Office coordinating the overall project and responsible for the delivery of the instruments. According to the schedule adapted at that time, the project implementation phase was supposed to take from 2022 till 2028, with the instrument deployment and the first light in 2028/29, followed up by 7 years of operations. However, in late 2021, it was recognized that infrastructural constraints at the South Pole, in particular, those on power production, were not consistent with the CMB-S4 design. This kicked off an Analysis of Alternative process, during which a number of alternatives have been considered, which could replace the original design without compromising the science case and conforming with all the constraints. This work was concluded in early 2022, and following a combined DOE/NSF review a new design was accepted as a new baseline. The required trade-offs readjusted the number of instruments operating from the South Pole, at the expense of the length of their operations, and involved novel ecological solutions to power generation. As a result, the overall schedule of the project was pushed back by three years, with the start of the formal implementation stage expected in 2024, deployment/first light in 2031, and operations taking as long as till 2041.

4.2 At IN2P3.

The involvement of the individual IN2P3 researchers in the global CMB-S4 collaboration goes back to its very beginning in 2015, with 4-5 researchers regularly participating in the collaboration meetings, building the science case for the projects, and its design and strategy. The number of involved researchers from IN2P3 kept growing with time with 6 IN2P3 researchers co-authoring the foundational CMB-S4 Science Case, Reference Design, Project Plan (8) document in 2019, and 11, including PhD students and postdocs, appearing on the Snowmass White Paper (1) in 2021. With the project becoming more concrete and its organizational structure becoming better defined, a more formal discussion also started within the IN2P3 CMB community. In the fall 2020 this led to regular (initially weekly) telecons dedicated to defining the interests of the CMB group at IN2P3 with regard to the CMB-S4 experiment and later towards a definition of potential contributions to the project. These discussions in somewhat different form continue till this day. They are consistently attended by over 20 researchers from three key CMB laboratories at IN2P3. As of today, CMB-S4 is one of the IN2P3 Master Projects and is coordinated by R. Stompor (CPB) and D. Prêle (APC) as a referent scientist and an instrument scientist, respectively, as well as local leads in all implicated laboratories, J. Errard (APC), T. Louis (IJCLab), and L. Perotto (LPSC).

Concurrently, a direct contact has been established with the CMB-S4 Project Office and a bilateral discussion has been initiated, aided by the presence of the International Research Laboratory, Centre Pierre Binétruy, IRL2007, set up by CNRS on the UC Berkeley Campus since fall 2021. These helped to define broad areas of common interests, where the contributions from the IN2P3 researchers could be particularly welcome and impactful. In the summer of 2021 this led to a letter of interest sent to the CMB-S4 Interim Project Director, John Corlett, by the IN2P3 direction on behalf of the IN2P3 CMB group, expressing our desire to continue the discussion in view of converging towards a MOU between both sides at some later date. Since then two specific areas have emerged as particularly promising as described elsewhere in this document. The work towards an MOU is on-going and it is expected that it could be signed as early as this summer. As of this time we are an international group the most advanced in discussions with the CMB-S4 Project Office, and therefore have significant freedom in selecting prospective contributions. The MOU will cover the preliminary period of the next three years (till Critical Decision 2 (CD2) expected in 2026). This will allow the IN2P3 researchers to contribute to the project, without yet the full burden of DOE-imposed reviews and deadline, while already providing trackable in-kind contributions toward future data rights. It is expected that this early period will allow us to define detailed plan for the next period covering the stage from the CD2 to the deployment, with well-identified, concrete contributions and responsibilities of the IN2P3 group. This is expected to be the object of the follow-up agreements.

5 Current status of the field

Following the successful crop of Stage-II ground-based CMB experiments, in particular, ACT/ACTPOL, e.g., (10), BICEP/KEK, e.g., (11) POLARBEAR, e.g., (12), SPT/SPTPOL, e.g., (13), the CMB field started undergoing a transformation, with geographically close CMB projects coalescing into bigger and more powerful experiments capable of delivering more demanding and ambitious science goals (6). This led to an emergence of essentially two major Stage-III observatories that are in the processes of being deployed or about to be deployed. These are South Pole Observatory (SPO), combining BICEP/KEK and South Pole Telescope at the South Pole, and Simons Observatory (SO) (and its evolution Advanced Simons Observatory (ASO)), which originally came about as a fusion of POLARBEAR and ACT experiments, both operating at the Atacama Desert.

These two experiments, SPO and SO/ASO, are the main predecessors of CMB-S4. They will become operational within the next few years and will cease their operations before the deployment of CMB-S4, setting therefore the stage for it. On one hand they will provide invaluable knowledge about their instruments, based on technologies largely shared with CMB-S4, as well as their operations, both of which will inform the CMB-S4 development, capitalizing on the fact that vast majority of members of both these teams are also members of CMB-S4. On the other hand, these experiments are both expected to deliver exciting science and bring significant progress towards the science goals aimed also by CMB-S4, e.g., (14). Nevertheless, due to its unique design and sheer size, CMB-S4 is bound to improve on most of the key science goals in a very significant manner (15), (1).

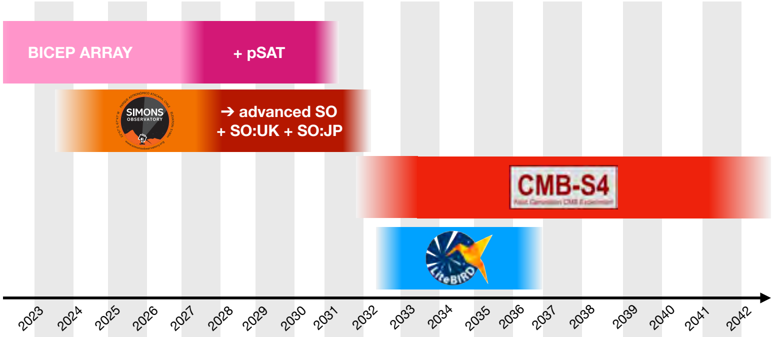

Figure 5: The time line of the main current and forthcoming CMB experiments. (Credit: Josquin Errard)

For the search of primordial gravitational waves, CMB-S4 will benefit from superior conditions on the South Pole (over SO/ASO) both in terms of the atmospheric loading as well as flexibility in scanning the sky offered by the site, and from substantially increased sensitivity (over SPO/BICEP) due significantly larger number of detectors (SATs). Moreover, CMB-S4 will be unique in having a dedicated, large aperture telescope (SPLAT) matched to allow for efficient removal of the so-called lensing noise. Consequently, the improvement on the limit on r, the tensor-to-scalar ratio, reflecting the amplitude of the primordial gravitation waves, is expected to be on order of a factor of $2.5-3$, thus allowing, for the first time, to reach the levels of the theoretical predictions of some of the popular, and the best-motivated inflationary models. However, even, if the value of r, happens to be large enough to be detectable by SPO or SO/ASO or both, it will be left to CMB-S4 to unequivocally, and with a higher signal-to-noise ratio, confirm the detection and start the process of tightening the constraints in order to single out specific class of inflationary models consistent with such a detection. The will be as transformational as getting the first hint of the primordial gravitational waves. We note that given that most likely any detection on such levels will be limited by systematic effects, due to either astrophysical or environmental signals or instruments themselves, rather then merely statistical uncertainties, such a high-sensitivity follow-up will be truly indispensable.

Similarly, the two Atacama-based large aperture telescopes (CHLATs) will double the mapping speed over that of SO/ASO, allowing to reach the sensitivity twice, on the power spectrum, and root of two on the signal amplitude, better in the same period of time as SO/ASO. This will ensure a gain of at least 1.5 up to 2 in the constraints on the effective number of relativistic species, $N_{\rm eff}$, what in turn will have significant impact in terms of range of probed energy scales, Fig 1 and therefore science output.

The CMB-S4 will also improve the constraint on the non-Gaussianity of the primordial perturbations, expressed in terms of the parameter, $f_{\rm NL}$, by almost a factor of 2 as compared to that expected from the SO/ASO data.

The gains over SO/ASO and SPO will be arguably smaller for some other parameters, albeit often still important, where the best cosmological constraints rely on combination of different probes. Indeed, projected constraints on the total neutrino mass of SO/ASO combined with some, new generation, Baryonic Acoustic Oscillation data sets (e.g., DESI), will be essentially the same as the one expected from combining CMB-S4 data with the same auxiliary data sets and assuming the same range of probed angular scales. If the latter, however, can be extended owing to CMB-S4 data better overall sensitivity, this can lead rapidly to a significant improvement. Moreover, the increased sensitivity of CMB-S4 will lead to improved CMB-only constraints over any prior CMB experiment providing a better consistency check between results derived from different probes adding invaluable justification to their combinations.

In addition, CMB-S4 will produce a unique catalog of clusters, exceeding by a factor of 2 ($\sim$70,000 objects vs $\sim$30,000) those expected from SO/ASO, as well as catalogs of many other astrophysical objects, leaving a unique, superior, legacy data set as compared to any other available at that time.

In space, there is a newly proposed, JAXA-led satellite mission, LiteBIRD, which also aims, as its main science goal, on detecting the primordial gravitational waves. LiteBIRD is an exciting experiment, which will capitalize on all the benefits of space, access to the full sky, access to the broad range of frequencies, no atmospheric noise, and very stable environment. It will be also a subject to constraints limiting its resolution or length of operations. As such the science reach of LiteBIRD (7), as far as primordial gravitational waves are concerned, is expected to be similar to that of CMB-S4. Both experiments are expected to to start their observations at a similar time, but CMB-S4 will need to operate for longer to reach the required sensitivity. This notwithstanding both experiments will be highly complementary, deriving their constraints on r from different ranges of angular scales and a subject to different environmental and instrumental effects. Any hint of a signal delivered by any of them will need to be confirmed by the other if any significance is to be attached to it. Moreover, there are exciting opportunities present in mutually enhancing each other science, which can improve on whatever limit each of them can set independently. It is also worth keeping in mind that CMB-S4's science case, ”beyond r”, is very broad and distinct from that of LiteBIRD, and

Laboratory	Name		Current	Projected involvement (person-years)					
	Last	First	Position	2023	2024	2025	2026	2027	2028
Laboratoire AstroParticule et Cosmologie (APC)	Arnaldi	Horacio	postdoc	0.5	1	0.5			
	Bartlett	Jim	full professor (PR)	0.05	0.05	0.05	0.05	0.05	0.05
	Errard	Josquin	researcher (CR)	0.05	0.1	0.1	0.1	0.15	0.15
	Ganga	Ken	senior researcher (DR)	0.05	0.05	0.05	0.05	0.1	0.1
	Gonzalez	Manuel	postdoc	0.2	0.3	0.3			
	Hamilton	Jean-Christophe	senior researcher (DR)	0.05	0.05	0.05	0.05	0.05	0.05
	Loucatos	Sotiris	senior researcher (CEA)	0.2	0.2	0.2			
	Piat	Michel	full professor (PR)	0.05	0.05	0.05			
	Prêle	Damien	research engineer (IR)	0.2	0.3	0.3			
	Si	Chen	research engineer (IGR)	0.1	0.2	0.3			
	Thermeau	Jean-Pierre	research engineer (IR)	0.1	0.1	0.1			
Lab total:				1.55	2.4	2	0.25	0.35	0.35
Centre Pierre Binétruy (CPB)	Delabrouille	Jacques	senior researcher (DR)	0.5	0.5	0.5	0.5	0.5	0.6
	de la Hoz	Elena	postdoc	0.6	0.6	0.6			
	Stompor	Radek	senior researcher (DR)	0.4	0.4	0.4	0.5	0.6	0.6
Lab total:				1.5	1.5	1.5	1	1.1	1.2
Laboratoire de Physique de 2 Infinis - I. Joliot-Curie (IJCLab)	Garrido	Xavier	associate professor (MdC)	0.05	0.05	0.05	0.05	0.05	0.05
	Henrot-Versillé	Sophie	senior researcher (DR)	0.05	0.05	0.05	0.05	0.05	0.05
	Louis	Thibaut	researcher (CR)	0.05	0.05	0.05	0.05	0.05	0.05
	Peloton	Julien	research engineer (IR)		0.05	0.05	0.1	0.1	0.2
	Tristram	Matthieu	senior researcher (DR)			0.05	0.1	0.1	0.1
Lab total:				0.15	0.2	0.25	0.35	0.35	0.45
Laboratoire de Physique Subatomique et Cosmologie (LPSC)	Catalano	Andrea	researcher (CR)	0.05	0.05	0.05	0.05	0.05	0.05
	Combet	Céline	senior researcher (DR)				0.15	0.15	0.15
	Doux	Cyrille	researcher (CR)			0.15	0.15	0.3	0.3
	Fernandez-Torreiro	Mateo	postdoc		0.25	0.25			
	Fulachier	Jérôme	research engineer (IR)		0.05	0.05	0.05	0.05	0.05
	Lambert	Fabian	research engineer (IR)	0.05	0.05	0.05	0.05	0.05	0.05
	Macias Pérez	Juan	senior researcher (DR)	0.05	0.05	0.15	0.15	0.2	0.2
	Mayet	Frédéric	full professor (PR)	0.05	0.05	0.15	0.2	0.3	0.3
	Odier	Jérôme	research engineer (DR)	0.05	0.05	0.05	0.05	0.05	0.05
	Perotto	Laurence	researcher (CR)	0.05	0.05	0.15	0.2	0.3	0.3
	Rarbi	Fatah	research engineer (IR)	0.2	0.2	0.2			
	Vescovi	Christophe	research engineer (IR)	0.05	0.05	0.05			
	Waquet	Jonathan	technician	0.2	0.2	0.2			
Lab total:				0.75	1.05	1.5	1.05	1.45	1.45
Totals over all labs:				3.95	5.15	5.25	2.65	3.25	3.45
- Readout (WBS 1.04):				1.6	2.4	2			
- Data Management (Project + Collaboration):				2.35	3.75	3.25	2.65	3.25	3.45

Table 2: Projected FTEs dedicated to the CMB-S4 work for the members of the CMB-S4@IN2P3. The table does not include PhD students. The contribution of people highlighted in gray is mostly instrumental (WBS 1.04). It is now defined only for the next 3 years, with a follow-up to be decided later on.

arguably as exciting as the primordial gravitational waves.

Whatever therefore happens, the position of CMB-S4 is well-assured and the experiment is bound to make a profound mark on our understanding of cosmology and fundamental physics. Moreover, the success of the entire endeavor will hinge on these efforts being implemented in unison rather than competitively. Indeed, pushing the sensitivity as far as possible by SPO and SO/ASO will allow us to better design and optimize CMB-S4 and LiteBIRD instruments and operations. CMB-S4 will deliver the high resolution data which LiteBIRD will lack, while LiteBIRD broad frequency coverage may be a key to successful removal of Galactic data from the CMB-S4 data. SO/ASO will ensure access to some of the most advanced data sets already a couple of years from now. This will inform development of new data analysis tools and techniques appropriate for CMB-S4 and LiteBIRD. This will also be a source of invaluable, hands-on experience for junior researchers, who will lead the actual analysis and scientific exploitation of these future data sets a decade from now.

This logic of complementarity and commonality is what has been driving the strategy of our CMB group at IN2P3 as it is heavily involved in SO/ASO, CMB-S4, and LiteBIRD. This is not only cost-efficient but this will also allow us to share know-how and experience, and to use resources more effectively. It will give us invaluable, first hand knowledge of these very different data sets, positioning us in a unique way to play a major role in obtaining the ultimate, most robust and reliable constraints, capitalizing on their complementarity and redundancies.

6 Resources, level of involvement

6.1 Current status.

There are currently 6 IN2P3 researchers, plus 4 students and a postdoc who are formal members of the CMB-S4 collaboration. Out of these, 4 are already participating in the work coordinated by the Project Office, and 2 are actively involved in governing bodies of the collaboration. Joining the collaboration is still rather straightforward at this time, it however requires a definition of potential contributions (either to the project or the collaboration) and areas of interest. We have therefore deferred signing up more people at this time yet in order to maintain consistency with the forthcoming MOU. We expect that all other interested researchers will join formally the collaboration in the fall this year.

On the collaboration side, we are particularly visible in the Low-ll B-mode (5 researchers from IN2P3), transients and point source (co-leadership, J. Bartlett (APC)), and systematics working (4) groups. On the project side we contribute to the L2 WBS tasks: Data Management and Read-out Electronics. These contributions are described in detail in the next section.

There are nearly 30 researchers and research engineers from four IN2P3 laboratories, APC, IJCLab, LPSC and CPB, who have been involved in the CMB-S4 activities in France, and who have envisaged gradually developing a substantial involvement in the project. These are listed at the beginning of this document. Table 2 shows also their projected level of involvement integrated over the period of the initial three years (2023-2026, the period covered by the forthcoming MOU), as well as in the remainder of the pre-deployment stage (2026-2028).

In addition, there is a number of PhD students (not listed) already involved (on a part-time basis) in the CMB-S4 collaboration work and funded from diverse sources. On the hand, the technical forces, engineers and technicians, involved in the project are still very limited but will be a key in the Project-level involvement.

Our plan is to predominantly rely on the existing resources in order to build progressively significant involvement in the CMB-S4 effort. This is reflected in the projected FTEs, Table 2, where the FTEs per person (excluding non-permanent people and hardware work) increase significantly with time as the project progresses. The collaboration work will greatly benefit from sharing resources with SO/ASO and LiteBIRD projects. This work is better suited for short-term researchers, PhD students and postdocs, and we will need resources to support them.

The simultaneous involvement in both, the project and collaboration effort, is a keystone of the proposed plan. This will ensure, on the one hand, data access to interested current, but also future CMB researchers at IN2P3, and, at the same time, in order to develop expertise in the low-level data processing (project) and, on the other hand, to ensure our place in the high-level stages of the CMB-S4 data processing and scientific exploitation of its data sets.

These plans, as outlined in detail in the next section, can be only fully successful if sufficient support from IN2P3, both in terms of funds and human resources is provided as commented on below.

6.2 Expectations for the future.

This project is merely a beginning of a long-term effort extending for more than 20 years from now, it is therefore of particular importance that new permanent researchers are regularly recruited to work in the CMB area. This issue obviously transcends the CMB-S4 project as it is of key relevance for all the other CMB projects the CMB group at IN2P3 is involved in. Indeed, we anticipate that the newly recruited researchers would support work on multiple efforts capitalizing on their common objectives, and complementarity as explained earlier. Conversely, we believe that such opportunities will permit attracting some of the best junior researchers in the field.

Of particular concern in this respect is the fact that a dominant fraction of the current CMB group are researchers of the age of ~ 50 or more and the last permanent junior researcher in this science area was recruited by IN2P3 over 5 years ago and there were only two recruitments in this area in the last 10 years. Consequently, there is a significant generational imbalance and growing gap, which soon will start hindering the group's contributions. This is going to be particularly disadvantageous for long-term projects like CMB-S4 and LiteBIRD, as for these we need to nurture in a timely manner future leaders of these efforts on the international scale. Only then we, as a community, can hope to continue playing recognizable part in this very fruitful and profoundly impactful science area in the future. We estimate that having a new recruitment with the cadence of 3-4 years is needed in order to alleviate these problems.

Concerning non-permanent posts, in the immediate term, till 2026, i.e., the period all the way to CD2 as covered by the anticipated MOU, we estimate that we will need ideally 3-4 postdoctoral researchers (each for 2 years), 2-3 on data analysis and scientific exploitation and 1 for the warm readout electronics. We also need funding to support 3 PhD students. These would correspond to roughly having one data analysis postdoc and one PhD student every year for the forthcoming 3 years, plus an additional postdoc working on the instrumentation. We will also need an effective 1 FTE of software engineer, who could lead the contributions to the Data Movement/Software infrastructure WBS task as discussed in the next Section. We note that there are already two postdoctoral positions funded for CMB-S4 work, one on data analysis at CPB (Elena de la Hoz) and another on warm readout electronics (Horacio Arnaldi) at APC.

7 Technical contributions

We plan on strong involvement in instrumental and data management aspects of the projects throughout the pre-deployment period (till 2031) and later during and post operations (2031-2041+). Below we describe in some details our plans concerning the initial 3 year period. Its main objective is to define and organize our involvement for the post-CD2 period by developing concrete collaborations with the CMB-S4 project in a number of most promising areas. These will then set the ground for the future work.

7.1 Hardware

7.1.1 Context

CMB-S4 is a large-scale project in an advanced stage of design and planning. Consequently, many of the technological choices have already been made, particularly with regard to the detectors (transition edge sensors, TES) and the readout chain (time-domain multiplexing, TDM). The goal of CMB-S4 is to have about 500,000 detectors, which are read out in a 2D grid of 80 rows and 6000 columns. In TDM (see fig 6), the 80 detectors of each column are sequentially read out. Two stages of superconducting quantum interference devices (SQUIDs) are used at cryogenic temperatures for multiplexing and amplifying the signals respectively. In this way, 5 analog signals are needed for the readout of one column of 80 detectors.

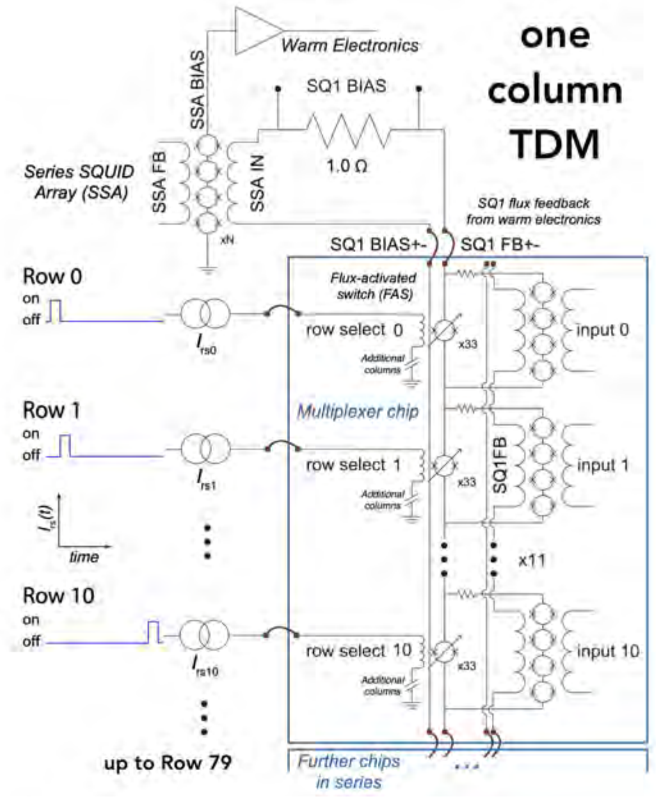

Figure 6: Schematic illustration of a single column of the TDM. Each TES is coupled inductively to a first SQUID stage - SQ1. All SQ1s in a column are wired in series to the input of a series SQUID array (SSA). The SSA is readout at room temperature by an LNA in the readout board. One row of SQ1s is biased at a time by a flux-activated switch. The various row-select lines are biased in sequence with low-duty-cycle square waves from row address board (9).

From the electronics point of view, one readout module manages the readout of 8 columns. In addition, for multiplexing, the first SQUID stage is controlled using 18 (10+8) two-level addressing signals. A single row addressing electronic module provides the 18 addressing signals that are shared by 16 columns. This means that there is one row address board every two readout boards.

- 500,000 superconducting bolometers (TES);
- 6,000 SQUID time-division multiplexers (mux factor 80);
- 1,000 warm readout boards;
- 500 row address boards.

The technologies chosen here are the most mature in the field with long history of successful applications by the US-based CMB groups. Incidentally, this is also the technology used by the IN2P3 QUBIC instrument and the ATHENA X-IFU instrument, with WFEE supplied by IN2P3/APC. This is currently state-of-the-art technology for CMB observatories.

Nevertheless, a number of challenges still exits, in particular due to the high multiplexing factor (80) targeted by the project. This, in turn, implies a strong constraint on noise levels that has to be met. In fact, the first prototype of warm readout system developed in 2020 at SLAC has been shown to have only half of its expected sensitivity, with several not fully operational functions. This is where the experience of the IN2P3 teams in terms of TES detection chain and ultra low noise electronics design comes into play and sets the context for the IN2P3 involvement in this part of the CMB-S4 WBS.

We propose to work in close contact with our American colleagues to redefine and produce the analog front-end for the warm readout boards.

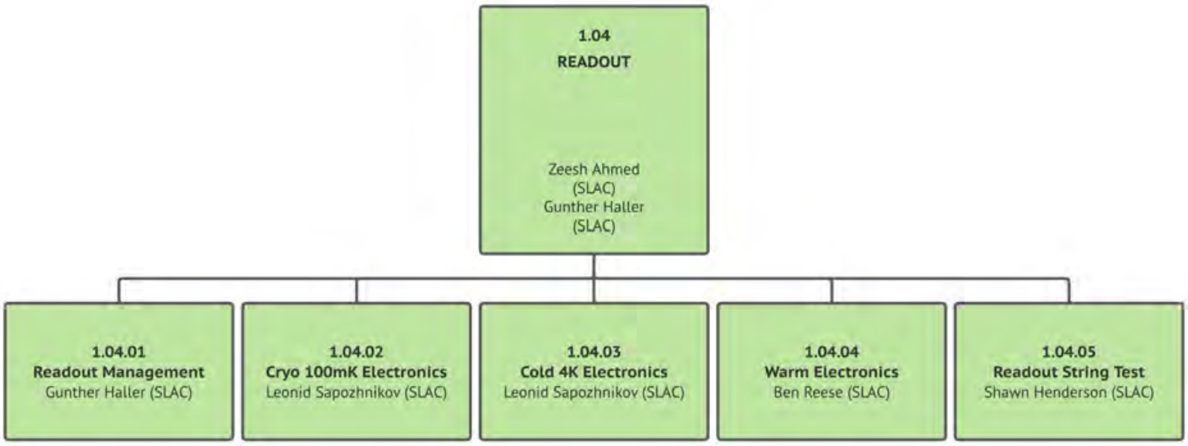

Figure 7: The Work Breakdown Structure of the Level 2 Readout task (1.04). The proposed contribution would be part of Warm Readout package, 1.04.04. (Credit: CMB-S4 Project Office.)

7.1.2 Proposed contribution

The proposed contribution is divided into two stages. The first stage consist of the development and test of a demonstrator model of the analog front-end electronics. It will be based on the existing integrated circuit AwaXe_v3, developed for the ATHENA X-IFU instrument. It will need to be adapted to the needs and current architecture of the CMB-S4 readout electronics. The goal of this first stage is to be able to validate the performances of our design and to evaluate the potential improvements in terms of noise levels reduction and simplification of the readout chain that an ASIC driven design can offer. The ASIC and the new design based on differential architecture will be essential contributions from IN2P3 to the CMB-S4 detection chain. This first stage will be tested at SLAC and it is not intended to be fully representative of the full CMB-S4 architecture in terms of number of channels, required board size, etc.

The identified key steps for this first stage are:

1. Identification of the ”analog front-end” perimeter and interfaces definition in agreement with SLAC.
2. Design and production of an analog front-end daughterboard for one or two channels readout based on the ASIC AwaXe_v3. Spare ATHENA ASICs are available for this purpose.
3. Testing in France, delivery and testing at SLAC. Tests include noise and thermal drift performance tests.
4. Analysis of the performances and discussion about possible improvements like moving to a fully differential architecture.

Based on the results of the first stage, a second stage of the contribution consist of the development of the representative analog front-end part of the CMB-S4 readout. Some obstacles have been identified regarding the use of the current ASIC for the second stage. Namely, the package size being too big and some desired features missing in its design. This is why, in parallel with this activities listed before, some tasks have been identified to prepare the ground for the next steps. This include the design and integration of a new package for the current ASIC and the modification of the ASIC design to include some important features like offset compensation at the input of the low-noise amplifiers. This last point is complementary to similar developments being done for ATHENA X-IFU.

At longer term, the key steps for the second stage are:

1. Production of a first daughter board with compact ASIC packaging, and interfaces in line with SLAC motherboards. Requires effective exchange with SLAC teams in charge of WP ”warm readout”.
2. Preparation for the production stage of the project: design of boards at the expected scale and development of dedicated ASICs with study and supply, associated management plan.

On organizational level, the system responsibility will be taken by Manuel Gonzalez (APC) as an Instrument/Readout Scientist, who will monitor the work and consistency of interfaces between IN2P3 developments and those of SLAC. LPSC (Fatah Rarbi) will take responsibility for daughterboard design and ASIC integration (with ultra-compact packaging). We have already achieved a fluid and efficient collaboration with the American colleges in the readout working group. This activity receives some funds from IN2P3, in particular, a dedicated postdoc, Horacio Arnaldi, is funded by IN2P3 to work on this project starting this fall.

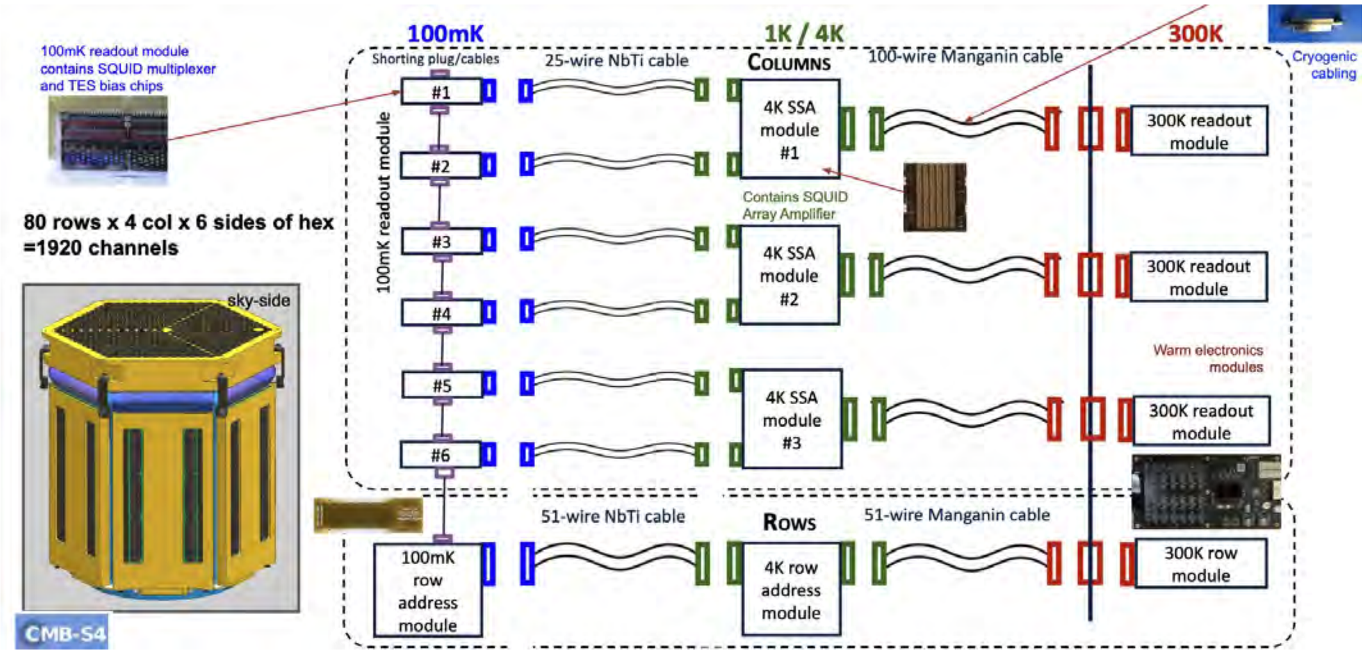

Figure 8: Elements of the readout stages as planned form CMB-S4. On the right, the warm (room temperature) readout and row-address boards.

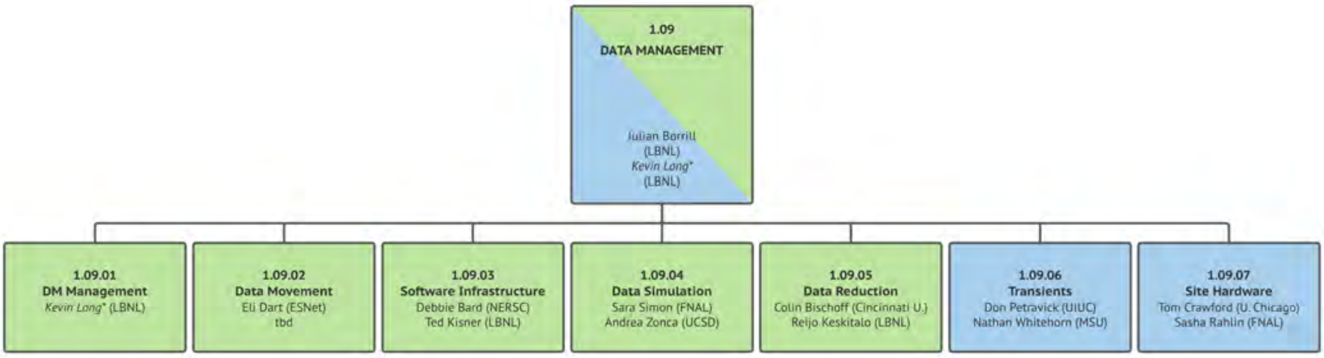

Figure 9: The Work Breakdown Structure of the Level 2 Data Management task (1.09). The proposed contributions would be part of 1.09.02, 1.09.03, 1.09.04, 1.09.05 Level 3 tasks with potential Level4 responsibilities for IN2P3 (WBS 1.09.02) and some specific Level 4 and 5 responsibilities to be defined. (Credit: CMB-S4 Project Office.)

We will also work alongside CEA on the development of superconducting flexible cables for S4 detectors (ANR requested in 2022). This activity is under the responsibility of Sotiris Loucatos (APC/CEA) and Jean Pierre Thermeau (APC).

7.2 Data management

Due to its volume and complexity, data sets produced by CMB-S4 will be very challenging to manage and analyze. While the actual scientific exploitation of the CMB-S4 data sets lies with the collaboration, this is the Project Office which shoulders the responsibility of delivering the data from the observatories, storing and archiving them, and reduce them from their enormous raw data volumes to more manageable data objects. The break point between the collaboration and the project work has been defined to be well-characterized, single frequency maps produced from subsets of the full data sets in a rendition manageable for the processing by the collaboration.

Given the heritage of our group at IN2P3, combining experiences from Planck with those from stage-II and stage-III CMB experiments, we are very well positioned to contribute to the project-level Data Management work. In addition to contributing to the future data rights, this also will allow us to gain unique understanding of the data products issued by the Project, what we could bring to the further, collaboration-level processing.

In this spirit, there are three level-3 task of the WBS which have been identified as of particular interest for the

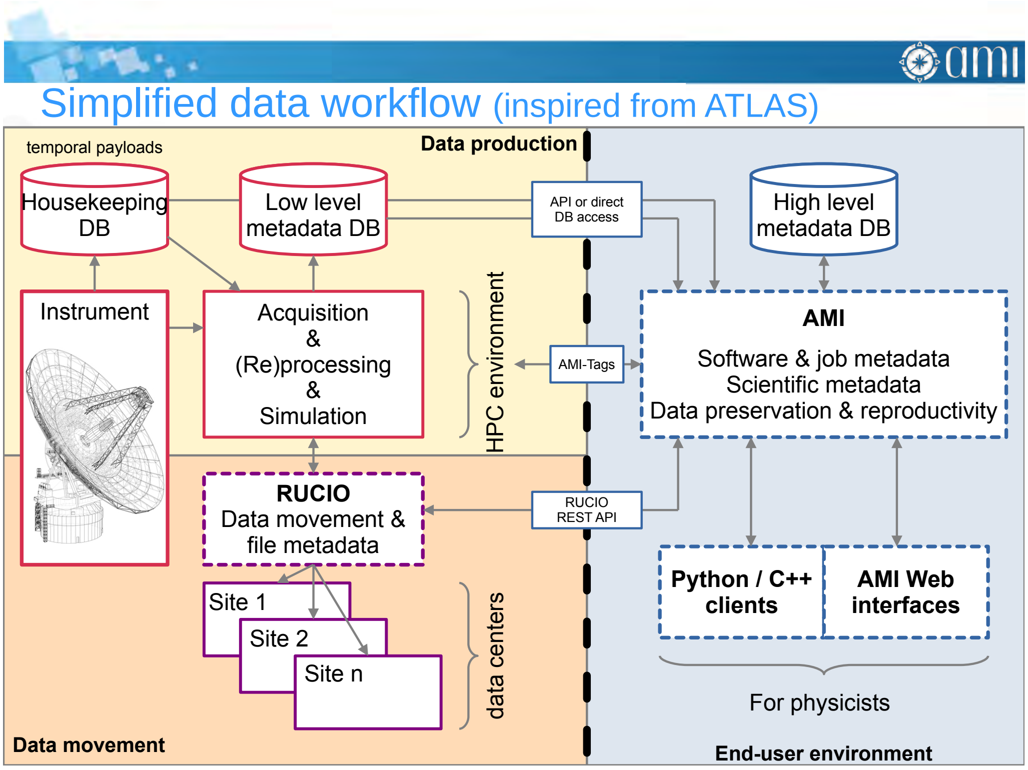

Figure 10: An example of a Data Movement/Management workflow studied for an application to CMB-S4 and based on AMI and RUCIO software packages. (Credit: AMI team@LPSC.)

CMB group at IN2P3
These are:

Data movement (1.09.02) and **Software infrastructure** (1.09.03) – these tasks cover all data storage and (local) data movement infrastructure for the project work and the collaboration. The work is led by Ted Kisner (LBL) and Debbie Bard (NERSC) at the Project Office level. Our potential contributions could revolve around using the Atlas Metadata Interface (AMI)[5] for tracking and managing the CMB-S4 database on the metadata level, capitalizing on the expertise at LPSC, who are main developers of this software, or on porting and adapting RUCIO[6] as an actual data movement tool developed for ATLAS, but broadly employed by many current and forthcoming astroparticule experiments, CTAO, SKAO, K3MNET, etc, which have significant IN2P3 involvement and thus relevant, hands-on experience. We have had a number of bilateral discussions with the respective CMB-S4 project coordinators and there is significant interest in us taking specific responsibilities in these areas. An example of a possible workflow is shown in Fig 10.

Specific, level 4 and 5 tasks covering these contributions are:

- Registration for Data Movement, 1.09.02.01;
- Data and Metadata Indexing, 1.09.03.01.3;
- Tracking of Workflows and Data Products, 1.09.03.04.2.

Data Simulations (1.09.04) – development and implementation of progressively more realistic, in terms of data volumes and complexity of numerical tools, and production of data sets with increasing level of realism to validate design choices, set requirements, and demonstrate data analysis tools.This effort is led at the Project Office by Andrea Zonca (UCSD) and Sara Simon (Fermilab). The specific areas we plan on contributing to are:

- development, implementation and validation of new sky, realistic sky models;
- development, implementation and validation of numerical modules simulating instrumental effects.

These correspond to WBS Level 4 tasks: 01.09.04.02-04.

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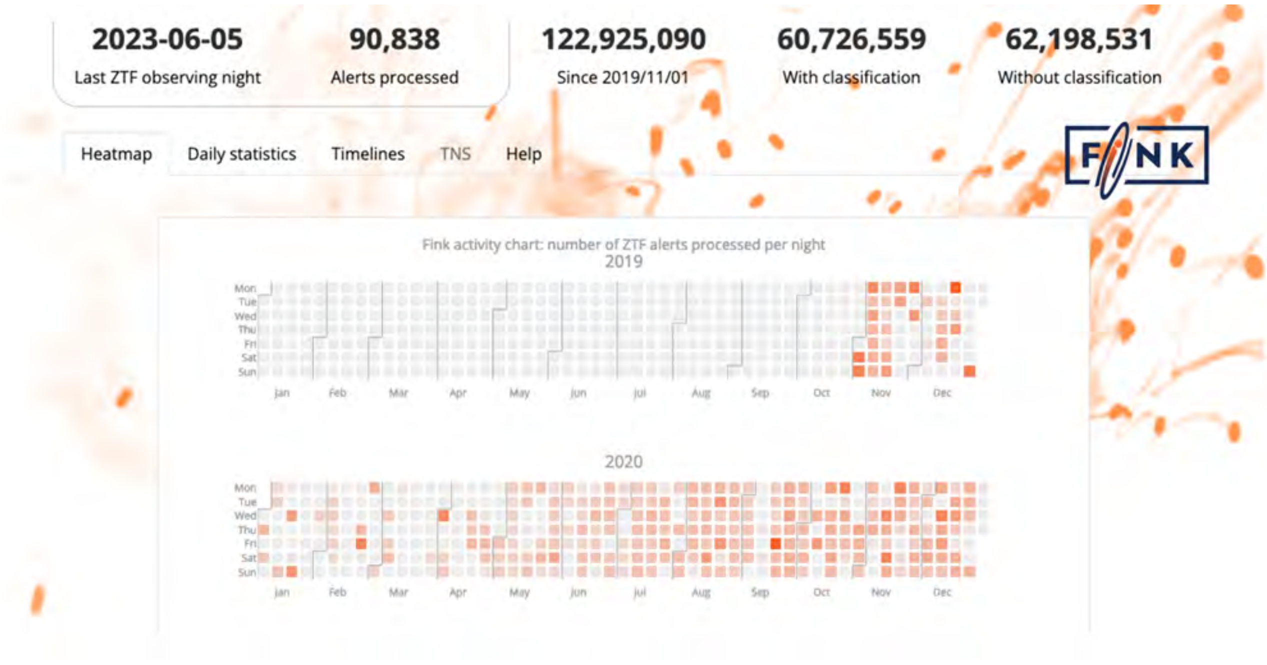
[5] https://ami.in2p3.fr/?subapp=document

[6] https://rucio.cern.ch/



2023-06-05
Last ZTF observing night

90,838
Alerts processed

122,925,090
Since 2019/11/01

60,726,559
With classification

62,198,531
Without classification

Figure 11: A screenshot showing recent statistics of nearly real-time transients event candidates captured by FINK in Zwicky Transient Factory (ZTF) data. (Credit: J. Peloton (IJCLab) and the FINK team.)

Data Reduction (1.09.04) – development and implementation of progressively more capable, precise, and efficient numerical tools for characterization of the raw CMB-S4 data and of reducing them to more manageable, pixel-domain objects, together with their sufficient statistical characterization, including residual systematic effects. The leads of this effort are Reijo Keskitalo (LBNL) and Colin Bischoff (Cincinnati). The specific contributions we envisage here include:

- development, implementation, and validation of new generalized map-making techniques and codes, including methods for statistical characterization of all the derived pixel domain products;
- Development, implementation, and validation of new techniques for systematic effects mitigation;
- application of the developed tools to the project-wide Data Challenges as those become available, starting with DC0 which will become available this summer.

These contributions correspond to the level 4 tasks 1.09.05.03 and 1.09.05.04 in the WBS. We expect to play eventually coordinating role on some of these tasks.

In addition we are exploring potential involvement in the multi-messenger program undertaken within CMB-S4 as part of Level-2 Transients task of WBS (1.09.06). There is significant experience within IN2P3 in this area centered around the real-time event detection software, FINK[7], (J.Peloton, IJCLab). FINK is one of the leading so-called brokers, selected for use by Rubin Observatory and is currently validated on data of Zwicky Transient Factory, Fig. 11. The proposed work would include extending the software to allow for an efficient, candidate event determination in microwave band and porting and maintaining it in the CMB-S4 software infrastructure.

All these contributions match very well the expertise and experience the group has, and will in turn benefit the work performed for Simons Observatory, as well as forthcoming satellite mission, LiteBIRD. Our projected time involvement in these areas is shown in Table 2. While it is clearly significant, the full implementation of these plans will require an active support from the Institute. In particular, some of the anticipated tasks are rather technical and will require involvement of software engineers, which are still to be identified. PhD students and postdocs will also be necessary. The work here is expected to start here already in the fall of this year, upon the approval of the Memorandum of Understanding by both sides, and will be initially conducted in a highly collaborative manner with the relevant members of the Project Office and without a specific task assignment to the IN2P3 group. This is expected to evolve in the course of the three years, with the IN2P3 researchers progressively taking upon themselves specific (Level-4 and Level-5) responsibilities, which will then be formalized as part of the follow-up MOU expected in 2026 (just prior DOE's Critical Review 2). This will set the stage for the follow-up, formal contribution to the CMB-S4 project.

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[7] https://fink-portal.org/

Nevertheless, already in the initial three-year period, actual contributions in terms of FTEs, will be accrued on the yearly basis and counted toward the integrated in-kind contribution of the IN2P3 team and towards the data rights in the future.

7.3 Collaboration work

We also plan on active participation in the Analysis Working Groups. These operate on the best-effort basis and aim at the objectives on longer, post-deployment timescales. Our focus in the first phase of the proposed involvement will be therefore on the project office work however we will progressively build a substantial, visible contribution on the level of AWGs, which will dominate the proposed effort once the CMB-S4 operations get under way.
The specific AWGs of particular interest for us are,

Low-ell BB: working toward developing tools and techniques appropriate for the B-mode detection, using predominantly data from Small Aperture Telescopes envisaged to operate from the South Pole. The work of this AWG will be a key for constraining the physics of inflation and therefore fundamental physics laws at the extremely high energies.

Maps to power spectra: working on techniques and software for CMB power spectrum estimation and targeting Large Aperture Telescopes (high resolution/large sky coverage). This AWG will play a key role in constraining the properties of relativistic particles present in the Universe, including neutrinos, and those from beyond the standard model of particle physics.

Maps to other statistics: working on higher order statistics, which will allow to improve on the constraints on inflation (via e.g., delensing and constraints on primordial non-Gaussianity) and provide clues about the nature of dark energy via characterization of the kinematic and thermal Sunyaev-Zel'dovich effects.

Clusters: studying the properties of clusters and therefore contributing to the constraints on cosmology from clusters. Jim Bartlett of APC is currently one of the two coordinators of this Working Group.

We also plan on contributing to special task forces such as the Joint Litebird-CMB-S4 study group which will position us at the forefront of the future, joint analysis of the LiteBIRD and CMB-S4 data (coordinated jointly by Andrea Zonca (UCSD) and Toshiya Namikawa (IPMU)) and continue our participation in the transverse Systematic Effects Working Group (coordinated by John Ruhl (CWU)).

The collaboration work is where we see significant potential for capitalizing on work performed in the context of different experiments, where sharing tools, expertise and resources, could be particularly fruitful and cost-effective.

8 SWOT

strengths: the proposed involvement builds on demonstrated, recognized strengths of the CMB group at IN2P3. These are well-appreciated by the CMB-S4 Project Office. The lead group at IN2P3 demonstrated strong commitment to contributing to the project. The proposed contribution is very cost effective given the overall size and cost of the CMB-S4 project. There is significant potential for the IN2P3 researchers to play significant roles in the Project and Collaboration structures.
While there is significant interest from other international groups (Italy, Japan, Canada, ...), the discussion with IN2P3 are by far the most advanced, what gives us significant freedom in selecting the contributions according to our interests and strengths.

weaknesses: at this time the potential CMB-S4 contributions are not defined on sufficiently detailed level in particular for the Data Management segment and no specific responsibilities are defined for the team. This is in part due to the recent delay in the project implementation in the US (post-AoA) but also uncertainties in France related to resources. For the hardware part the follow-up after the 3-year R&D study phase is not clear. While the overall FTE estimates are rather significant, a substantial fraction of per-person contributions is often quite low (5% of FTE). This seems to be unavoidable given that the work is only starting and the actual execution of the project still quite distant. We expect that this will progressively go away and a strong core of the group with significant time commitment will emerge in due time.

opportunities: There are numerous opportunities to develop further the involvement of the IN2P3 group in the CMB-S4 project, which have not been covered yet. These include complementary hardware and data management contributions, such as a CC-IN2P3 based European Data center. We will explore these options in due time.

threats: an unclear situations with resources, human (software engineers, PhD students, postdocs) and otherwise, is a potential threat in the situation when a strong, well-defined, prior commitment is required. Why the CMB-S4 needs are significant, we are in competition with both US-based and international research groups, which often bring with them concrete funds and human resources. This threat will come to the fore at the end of the 3-year period. While we believe we will have by then clear leadership position on some specific topics, this may not be enough to ensure our continuing leadership, if we can not commit upfront sufficient resources.

9 Conclusion

CMB-S4 is a major planned CMB experiment, which will be deployed on the timescale of a decade from now, and which will deliver outstanding science in a broad range of science areas, from cosmology and fundamental physics, through astrophysics and transients, to Solar system studies, promising revolutionary impact in many of them. The participation of the IN2P3 CMB group in the project is critical if the group is supposed to continue playing a major role in this science area on the international scene. The proposed involvement builds on, continues, or complements work on other main projects on the roadmap of the CMB group: Simons Observatory (SO/ASO) and LiteBIRD. This combination will ensure a very cost-effective, mutually beneficial and scientifically sound presence of the group in the three most anticipated experimental efforts in the field, and therefore significant lasting impact on it on the international level.

In this document we describe plans to build progressively such an involvement first focusing on the next three years, where the definitive design of the instrument and plans for Data Management are supposed to be prepared in the view of Critical Decision 2 scheduled to be conducted in 2026 by DOE. The ultimate objective of this initial phase is to define important involvement for the actual project implementation phase (2026-2031), with well-specified and recognized areas of responsibilities and leadership for IN2P3 researchers, while already contributing to the project in an important and visible manner.

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