Observations of polarized cosmic microwave background anisotropies from the ground: Simons Observatory and CMB-S4 experiments

(Report for the Scientific Council of IN2P3, October 2020)

Contents

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[0] Image credits: B. Benson (left); J.Groh (right)

1 Introduction

Studies of Cosmic Microwave Background (CMB) anisotropies have played a prominent role in establishing modern cosmology as a high precision science area, where questions fundamental to our understanding of the Universe but also basic laws of physics can be efficiently investigated and reliably answered. This progress has been driven by experimental efforts carried out from space-borne platforms, COBE, WMAP, and Planck, from stratospheric balloons, e.g., BOOMERANG, MAXIMA, Archeops, and from ground-based observatories, e.g., DASI, QUIET, POLARBEAR, ACT, SPT, BICEP, and combined with data delivered by supernovae, galaxy clustering, and baryonic acoustic oscillation surveys.

These past efforts led to a standard model of cosmology, based on the hot Big Bang paradigm, where the Universe, initially very hot, dense, and ionized, expands and cools down adiabatically while the gravitational instability of initially minute fluctuations has led to the variety of structures we observe today. Major tenets of the model have been extensively confirmed and refined by diverse set of cosmological probes and, as of today, the model is capable of accounting for essentially all existing observational data. This has been a crowning achievement of many years of efforts including the unprecedented spurt seen by the last two decades driven by developments in relevant technologies, observations, and data analysis.

The Universe is today understood to be spatially flat, dominated by dark matter, which played a key role in turning the initial, scale-invariant fluctuations into observed structures, and with an accelerating expansion which is thought to be a signature of dark energy. In spite of apparent complexity of the currently observable Universe there are merely 6 parameters necessary to fully characterize the model all of which, but one – the optical depth, τ, are constrained with the percent-level precision [1].

2 Science

The standard cosmological model provides an efficient framework within which to interpret existing observations and plan on new ones. It leaves however many questions still unanswered. Those concern the nature of dark matter and dark energy, the mechanism responsible for the generation of the primordial fluctuations, the mass-scale of the neutrinos and their mass hierarchy, the number of species of light, relic particles, as well as many others. Those constitute major scientific conundrums with impact extending beyond cosmology itself and often will need diverse evidence, from cosmological observations and laboratory measurements, to be unequivocally resolved.

Cosmology, in general, and CMB observations in particular are posed to continue playing a key role in this process. The new frontier in the CMB field are high-fidelity measurements of the polarization signature of the CMB anisotropies. To date the major CMB observable was that of fluctuations of total intensity of the CMB photons arriving from different directions. Thanks to Planck on the one hand, and high resolution ground-based efforts the cosmological content of this observable is to large extent already explored. These are the measurements of the total intensity which established the main aspects of the current standard model.

The potential of the polarization measurements is still however to be fully exploited. CMB polarization comes in two flavors, gradient-like, curl-free, E-mode polarization and divergence-free, with non-zero curl, B-mode polarization. As the CMB polarization originates from Thomson scattering of the CMB photons off the free electrons it is only weakly polarized and the amplitudes of the E and B-mode polarization anisotropies are expected to be an order of magnitude and, respectively, at least two orders of magnitude lower than those of the total intensity signal. To date the E-mode polarization has been detected with high significance by many experiments, including Planck and many sub-orbital efforts. There is still however room for significant improvements in particular on large and small angular scales. E-mode polarization is generated by the same density perturbations which have given rise to the currently observed large-scale structures of the Universe. Measuring them provides then an additional consistency test of the overall model of gravitational instability and allows to improve on precision of the constraints on the cosmological parameters. Of particular interest is the optical depth parameter, τ, which is coupled with other cosmological parameters, such as neutrino masses, affecting the precision with which those can be determined. Its precise determination will need a satellite mission as it relies on information contained on the largest angular scales. Other parameters of interest include, for instance, the number of species of light relic particles. High-precision measurements of the E-mode polarization could shed also some of the most conspicuous tensions in the current standard model such as apparent discrepancy between the CMB total intensity determination of the Hubble parameter and those derived from other probes based on the cosmic distance ladder, or the large scale anomalies present in the spectrum of the total intensity fluctuations of the CMB. The potential resolution to these problems may provide hints of new physics.

In contrast, B-mode polarization can not be generated at least to the linear order from the density fluctuations and requires more exotic mechanisms. One of the most exciting ones is primordial gravitational waves, which if present at the time when the CMB photons were scattered off the free electrons for the last time would generate a B-mode signal in particular on large angular scales. Such gravitational waves are indeed generically expected in a broad class of models of the very early Universe invoking inflation, a short period of exponential expansion driven but yet unknown quantum field (or fields). Inflationary models have been spectacularly successful in explaining many of the features of current Universe, ranging from its flatness to the scale-dependence of the amplitude of the putative initial fluctuations. Detecting the B-mode polarization of a primordial origin would provide a strong indication that the primordial gravitational waves indeed existed providing probably the most compelling piece of evidence in favor the inflationary models and could further serve as a source of information about the energy scale of inflation. This would in turn be the most direct insight available to us into the physics at energies as high as billion times those currently accessible by the human made experiments. As of now probably the biggest enemy of inflation is its own success which led to (over)abundance of specific realizations and models. Constraining the B-mode signal on large-angular scales will at last start restricting the space of plausible models to the extent not possible today.

There is more to the B-modes than just inflation. The B-mode signal on small angular scales is thought to be dominated by the E-mode signal converted to the B-mode one by the gravitational lensing effect. As the lens in this case serves the large-scale structure of matter and therefore the lensing B-modes are the source of information about the statistical properties of matter integrated over the path of the CMB photons. This information can be effectively converted into constraints on neutrino masses or properties of dark energy at the onset of the acceleration but also about non-standard neutrino models and dark matter (self)interactions. The lensing B-mode signal dominates on small scales over the primordial one and first detections of its non-zero amplitude have become available over the last 5 years. So far the emerging picture is consistent with the general expectations derived from the standard model. Significant improvement in the precision is needed to allow for more quantitative conclusions.

Other CMB observables also promise exciting science and have not been fully exploited, such observations of the Sunyaev-Zel'dovich effect, both thermal and kinematic, which could provide new insights in two the properties of dark energy and dark matter.

Yet another, quickly growing area aims at exploiting joint-analyses of different data sets, such for instance as cross-correlations of CMB lensing with optical/NIR surveys from Rubin Observatory, DESI, and Euclid. This not only improve the statistical uncertainties on a determination of many cosmological parameters but also allow to control systematic errors to the extent not possible with data from any of the probes separately.

More details of the science case for CMB can be found in the IN2P3 prospective (2020) contributions coordinated by J. Errard[1], T. Louis[2], and G.Moultaka[3].

3 Challenges

The next step in the CMB experimentation aims at improving further the precision of the existing constraints and investigating signals of progressively lower amplitudes, with special focus on the B-modes. This calls for unprecedented sensitivity of the future experiments, control of instrumental effects, and redundancy which will allow to minimize and mitigate effects due to the environment, be it our Galaxy, the Solar system, Earth's atmosphere or the ground. This unavoidably lead to increased complexity of future instruments and drives the need for extended time of observations. The forthcoming efforts will typically resort to multiple signal modulators, field multiple kilo-pixel arrays of multichroic detectors operated at cryogenic temperatures and read out by complex electronic systems. While necessary these will unavoidably pose numerous challenges on

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[1] https://indico.in2p3.fr/event/20036/contributions/76710/attachments/55887/73876/Cosmic_Inflation_Observation_from_the_Ground-Based_CMB_Polarization_Experiments.pdf

[2] https://indico.in2p3.fr/event/20036/contributions/76710/attachments/55887/73877/Fundamental_physics_from_high_resolution_CMB_experiments_v2.pdf

[3] https://indico.in2p3.fr/event/20036/contributions/76620/attachments/55857/74624/SUSY_Cosmic_Inflation.pdf

their own related to characterization and control of instrumental effects and their impact on the final science goals.

The main astrophysical challenge common to all the experimental efforts is related to the presence of polarized emissions in the microwave band due to our own Galaxy but also extragalactic sources. Two main diffuse Galactic emissions originate from the dust particles (anti-)aligned with the Galactic magnetic field and synchrotron radiation emitted by charged particles spiralling in the magnetic field. However, the picture is likely to be more complex with the polarized (extragalactic) point source contribution likely important on small-angular scales and other potential polarized emissions such as anomalous microwave emissions (AME). Any measurement undertaken in the CMB band is bound to combine all these contributions together. While this is also the case for the total intensity measurements, the situation is particularly stark for polarization where the relative strength of the Galactic emissions with respect to that of the CMB is greatly increased. This is particularly important for the B-mode polarization where the Galactic emissions alone are thought to dominate the cosmological signal within the entire frequency range and over all range of angular scales. The only robust answer to this problem is therefore in observing the sky in multiple frequency bands followed by involved analysis techniques, so called component separation methods. The success of this approach depends on the number of experimental frequency bands, the frequency range they cover, and the sensitivity of each of them, as well as, hitherto not fully known, the complexity of the actual signals. The success here is however necessary if the science objectives are to be reached.

Another challenge for the primordial B-mode detection is related to the presence of the lensing B-mode signal. This signal originates from the E-mode signal converted to B-modes due to gravitational lensing and is a valuable source of unique cosmological information. While dominant at small scales it extends all the way to large angular scales adding additional uncertainty to any direct detection of the B-mode amplitude at those scales. If the primordial B-mode signal is low, this can prevent us from detecting it. However, given the measured E-mode signal and some estimate of the projected matter distribution in the Universe the lensing signal can be in principle estimated and subtracted from the large scale B-mode signal effectively removing the related uncertainty. The procedure called delensing has been demonstrated on the real data but needs to be further refined and demonstrated in particular in the presence of instrumental effects. Any such procedure requires high resolution observations of the CMB polarization, which are needed even if our scientific objectives may lay on large-angular scales.

Last but not least, those future efforts will produce overwhelmingly large and complex data sets which will pose their own challenges to data analysis and scientific exploitation, and will require novel data analysis methods but also numerical algorithms and their implementations.

4 CMB observations from the ground

Ground-based observatories have played a significant role in delivering the science from CMB, alongside the balloon-borne and satellite missions. Their sensitivity has been

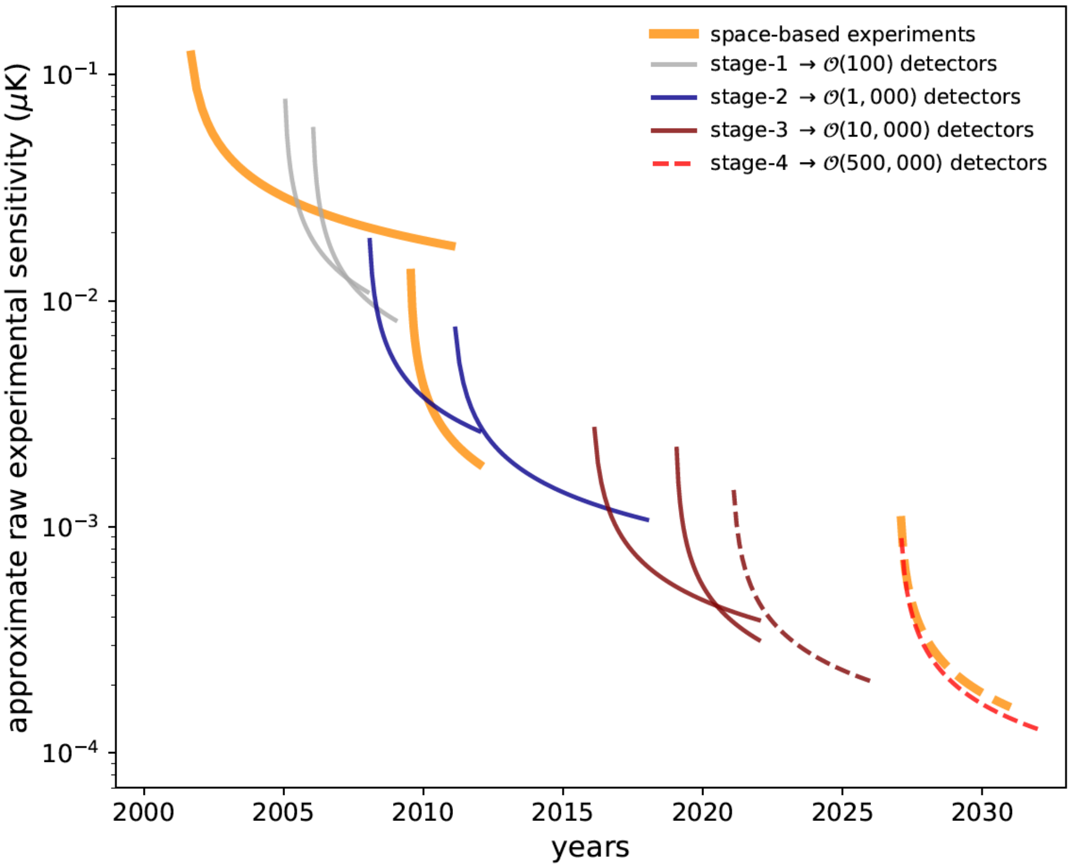


Figure 1. The evolution of the sensitivity of ground-based experiments over time showing different stages. A beginning of each stage marks a tenfold increase in the number of detectors per experiment enabled by new detector technology. Satellite missions are also shown. The space environment and their higher observation efficiency allow them to reach sensitivity comparable to that of the ground efforts with many fewer detectors. The two right most curves roughly correspond to the CMB-S4 experiment, $\mathcal{O}(10^6)$ detectors, dashed red line, and the satellite mission LiteBIRD, $\mathcal{O}(10^4)$. The nominal deployment of Simons Observatory is a stage-III experiment and roughly corresponds to the deep purple dashed line. In contrast, SO-enhanced will cross the threshold to be considered a Stage-IV effort. (Adapted by J. Errard from the original figure by the CMB-S4 collaboration.)

constantly improving over the years owing to technological progress allowing to deploy progressively bigger and more sensitivity arrays of detectors. They are conventionally divided into stages with every new stage bringing a tenfold increase in the number of deployed detectors, see Fig. 1. The current, cutting-edge ground experiments are that of Stage III featuring tens of thousands of detectors. The next generation, Stage IV, will increase this number to an excess of 100,000. Over the past few years the ground-based efforts, Stage-II, have led the effort of zooming on CMB B-mode signal be it that of primordial or secondary origin. The best current limit on the tensor-to-scalar ratio, r, has been derived from the analysis of the data set collected by the BICEP/Keck experiment and combined with the Planck data [2]. Concurrently, a number of past ground efforts have set constraints on the B-mode power on small-angular scales either directly [3–5] or via cross-correlations with some traces of matter distribution in the Universe [6, 7]. These results demonstrated the ability of the ground observations to play important roles in the next stages of the exploitation of the CMB potential.

Observing from the ground comes however with multiple downsides. The presence of the atmosphere leads to extra loading on the detectors making them significantly noisier (a rule of thumb: 1 detector in space $\sim 10^2$ detectors on the ground) and restricts the number of available frequency windows, and in particular introducing a high-frequency cut-off (at around $\sim$ 300GHz – in practice, those have been demonstrated up to $\sim$ 280GHz.) beyond which observations from the ground are essentially impossible. Atmospheric instabilities generate strong correlations in the measured data between measurements of the same detector but also between measurements of different detectors, further impacting the sensitivity of large-arrays of detectors. Ground emissions lead to ground pick-up typically synchronous with a position of a telescopes with respect to the ground and therefore difficult to differentiate from the actual sky signal. The weather and environmental changes lead to variable observational conditions. To mitigate those factors the ground based observatories operate from selected sites on the Earth, South Pole, the Atacama Desert, Tenerife, which are particularly dry an stable, observe in a limited number of appropriately chosen frequency bands, and use specifically adapted scanning strategies.

All of these factors are clearly absent in the case of satellite missions. However, ground based experiments have also numerous advantages. A deployment cycle of ground based efforts is typically much shorter than that for space missions allowing for a quicker turn around and a deployment of the latest, most effective technologies. They are also amenable to corrections and improvements while operating. The ground observatories can easily involve multiple telescopes, furnished with very large-arrays of detectors, and feature a range of apertures. The largest telescopes of $\sim 6-10$m and therefore reaching arcminute resolutions at frequencies $\sim$ 150GHz can realistically be deployed only from the ground at this time. High-resolution observations of the sky are therefore the domain of the ground efforts, as are intermediate resolutions observations but at the low ($\lesssim$ 60GHz) frequency end. The ground can deliver deep observations focused on selected small sky areas but can also observe large sky areas, up to $\sim$ 70% of the sky, (though losing the information on the largest angular scales).

These features make the ground observatories highly complementary to satellite missions, which can observe the full sky in a very stable environment, and thus have access to the largest angular scales, in a broad range of frequencies but with a limited resolution.

Delivering the science goals posed currently for the field will require access to small and large angular scales, a broad frequency coverage and redundancy to demonstrate control of instrumental effects in order to meet the challenges listed above. This will

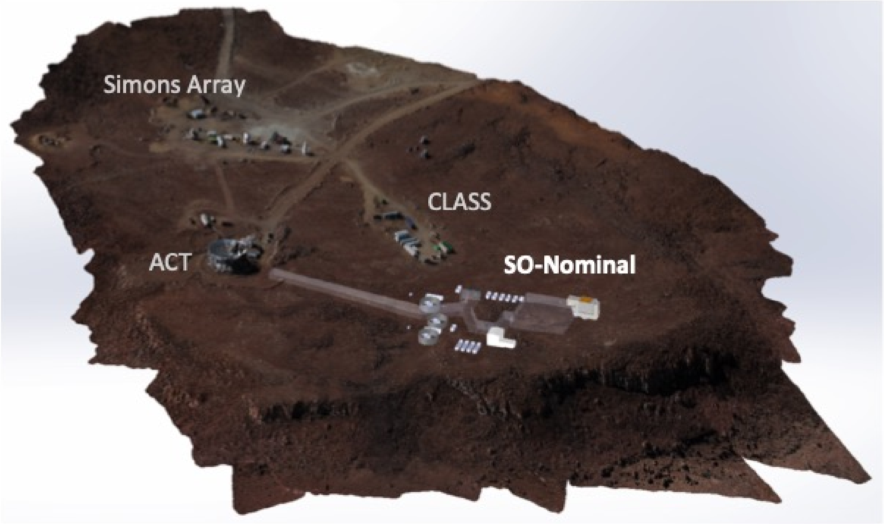


Figure 2. The Atacama CMB observatories, shown are currently operating Simons Array and ACT experiments, which merged together to deploy Simons Observatory and an independent experiment, CLASS. Credit: SO Collaboration.

unavoidably require a combination of ground-based and satellite-borne efforts.

5 Simons Observatory

Simons Observatory [8] is a novel Stage-III CMB experiment and a technological pathfinder for the 4th generation, Stage-IV, efforts. Its deployment is scheduled to be implemented in two phases: SO-nominal (fully funded) followed by SO-enhanced (funds not secured yet), which with over 100,000 detectors will reach the threshold of a Stage-IV experiment. SO will operate from the Atacama Desert in Chile and deploy multiple telescopes with different apertures, Fig. 2. Simons Observatory is a large international project including ~ 300 scientists in 10 countries from more than 40 institutes. It is funded by private funds and managed by the Planning Committee, composed of PIs from 5 main US institutions.

5.1 Instruments and operations

SO-nominal will have 3 small aperture telescopes (SATs) with refracting optics systems and aperture diameters of 48cm and one 6m large aperture, Cross-Dragone telescope (LAT). The SATs will operate in a coordinated manner observing the same sky area. Each pixel of the focal planes will be sensitive to two frequency bands: 30/40GHz, 90/150GHz, or 220/270 giving an effective coverage in 6 frequency bands. The SATs will have continuously rotating, broad-band half wave plate as the first optics element of their optics chain. It will modulate the polarization signal thus guarding against many

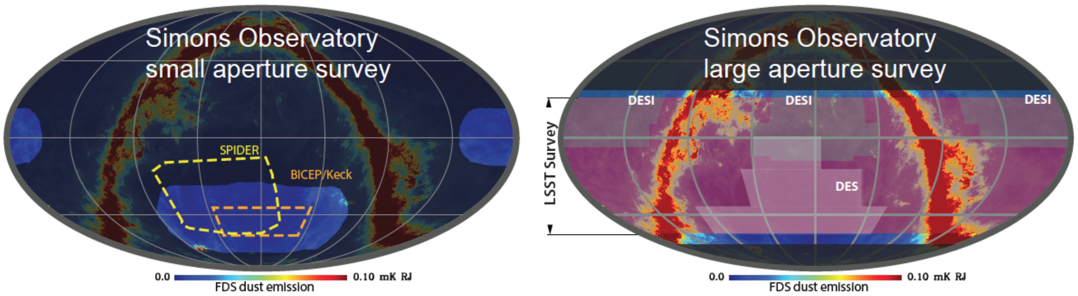


Figure 3. The sky coverage of the small aperture telescopes, optimized for the primordial B-mode searches, left, and the large aperture telescope, right. In the right panel selected sky coverages of complementary surveys are shown. From [8].

of systematic effects. Signal in each dichroic pixel will be registered by two transition-edge sensor (TES) detectors measuring two orthogonal polarization states. The total number of detectors will be $\simeq$ 30k. The SATs design and operations are optimized for the primordial B-mode science and they will scan a small sky area producing deeply integrated maps of $\sim$ 10% of the sky, left panel of Fig 3. The scanning strategy will consist of constant elevation scans with a throw of $\sim$ 10 degrees and the elevation gradually modified to compensate for the sky rotation. SO-enhanced will add another 3 SATs and $\simeq$ 30k detectors to produce even deeper maps. The overall noise level expected in the B-mode power spectrum after component separation is expected to be lower than the lensing floor.

The LAT will be coupled to 13 optical tubes, out of which only 7 will be filled during the nominal phase of the operationst. Each tube will have an independent focal plane composed of dichroic pixels operating at 30/40GHz (1 tube), 90/150GHz (4 tubes), 220/270GHz (2 tubes). Each focal plane pixel will have two detectors measuring two orthogonal polarization states. The total number of detectors operating during the nominal stage will be $\simeq$ 40k.The telescope will scan at constant elevation and the ground-pick up will be mitigated by a stationary, ground shield. SO-extended will in addition fill in the 6 remaining tubes, increasing the number of LAT detectors to $\simeq$ 70k. LAT will cover between $\sim$ 40% (the baseline) and $\sim$ 70% (an option) of the sky and will be optimized for lensing, cross-correlation science and sources, right panel of Fig 3. The LAT will cover the sky patch observed by the SATs enabling the delensing of the B-mode observations.

At the time of its deployment SO will be one of the two largest CMB observatories world-wide, with the other being the South Pole-based South Pole Observatory. Both these efforts demonstrate the convergence of the CMB communities around progressively bigger common projects in preparation to, and anticipation of, the ultimate CMB-Stage IV effort.

	Parameter	SO-Baseline^a (no syst)	**SO-Baseline^b**	SO-Goal^c	Current^d	Method	Sec.
Primordial	r	0.0024	**0.003**	0.002	0.03	BB + ext delens	3.4
perturbations	$e^{-2\tau}\mathcal{P}(k=0.2/\mathrm{Mpc})$	0.4%	**0.5%**	0.4%	3%	$TT/TE/EE$	4.2
	$f_{\mathrm{NL}}^{\mathrm{local}}$	1.8	**3**	1	5	$\kappa\kappa \times$ LSST-LSS + 3-pt	5.3
		1	**2**	1		kSZ + LSST-LSS	7.5
Relativistic species	N_{eff}	0.055	**0.07**	0.05	0.2	$TT/TE/EE + \kappa\kappa$	4.1
Neutrino mass	Σm_ν	0.033	**0.04**	0.03	0.1	$\kappa\kappa$ + DESI-BAO	5.2
		0.035	**0.04**	0.03		tSZ-N × LSST-WL	7.1
		0.036	**0.05**	0.04		tSZ-Y + DESI-BAO	7.2
Deviations from Λ	$\sigma_8(z=1-2)$	1.2%	**2%**	1%	7%	$\kappa\kappa$ + LSST-LSS	5.3
		1.2%	**2%**	1%		tSZ-N × LSST-WL	7.1
	H_0 (ΛCDM)	0.3	**0.4**	0.3	0.5	$TT/TE/EE + \kappa\kappa$	4.3
Galaxy evolution	η_{feedback}	2%	**3%**	2%	50-100%	kSZ + tSZ + DESI	7.3
	p_{nt}	6%	**8%**	5%	50-100%	kSZ + tSZ + DESI	7.3
Reionization	Δz	0.4	**0.6**	0.3	1.4	TT (kSZ)	7.6

Figure 4. The key science goals of the nominal phase of Simons Observatory, expressed as improvements on constraints on some of the key cosmological parameters. The right column lists auxiliary data sets which will be used in the analysis. From [8]

5.2 Science

SO will address a broad range of astrophysical and cosmological science questions capitalizing on its access to the broad range of angular scales (from a few degrees (SATs) down to a couple of arminutes (LAT)) and appropriately designed surveys [8]. These include some of the major cosmological and fundamental questions as discussed earlier,

- Origin of the universe (including primordial gravitational waves, shape of primordial spectrum, non-Gaussianity, etc)
- Dark matter (including dark matter properties, neutrino masses, number of light relic particles, etc).

It will also shed light on a number of diverse astrophysical problems, such as,

- Baryonic feedback and Interstellar Galactic Medium;
- Variable radio sky;
- Search for Planet 9;
- Galactic Science (including legacy arcmin-resolution mm-wave sky maps, and constraints on large-scale magnetic fields, etc).

A sample of projected improvements on some of the key cosmological and physical parameters expected for the SO-nominal are shown in Fig. 4, (Simons Observatory Collaboration, 2019) and Fig. 5 shows projected constraints on CMB polarization power

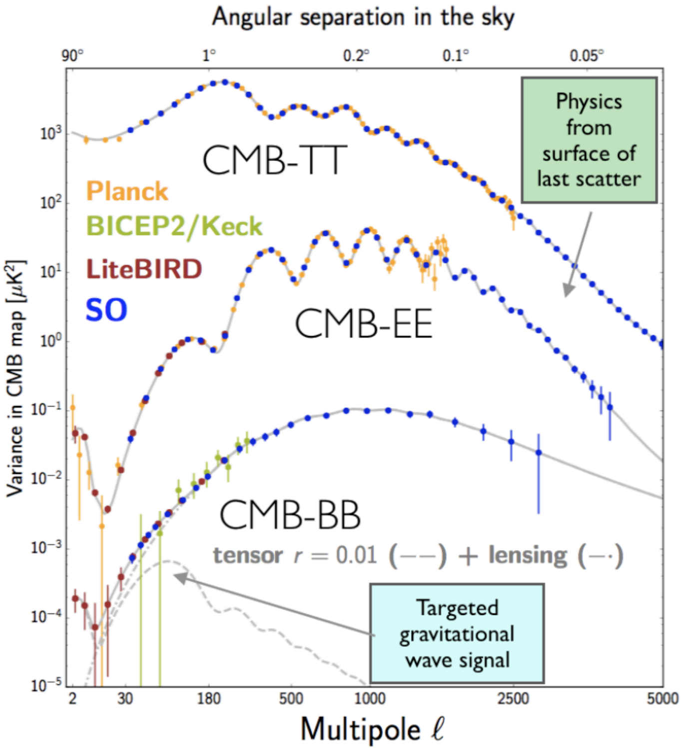


Figure 5. Projected SO constraints on CMB power spectra superimposed on those of other selected experiments, including the planned satellite mission LiteBIRD. Credit: SO collaboration.

spectra. Specifically, SO will allow constraining the tensor-to-scalar ratio with a precision $\sigma(r) \sim 0.002$ (SO-nominal) and ~ 0.001 (SO-enhanced), thus approaching the threshold values of this parameters as motivated by the current inflationary models and current limits on the spectral index of the initial power spectrum of the density fluctuations. Figure 6 shows the constraints SO will set on some of the popular inflationary models.

The LAT survey of SO will also enable very rich cross-correlation science overlapping with surveys performed by DESI, Rubin Observatory, and Euclid. A combination of the SO-nominal data, Sunyaev-Zel'dovich cluster surveys, with the DESI Baryon Acoustic Oscillations and the Rubin Observatory Weak lensing will allow to constrain the total neutrino mass down to $\sigma(\Sigma m_\nu) \sim 30$meV which could be further improved if a cosmic-variance limited constraint on total optical depth, τ, from a space mission, such as LiteBIRD [9], is available, down to 20meV, both of which could permit determining the neutrino mass hierarchy if their total mass happens to be sufficiently low, Fig. 6.

5.3 Timeline

The overall timeline of SO is shown in Fig. 7. As shown it does not include delays due to the on-going pandemic, which is expected to shift the schedule by approximately 1 year. The deployment of the first SAT should happen in 2021, followed by remaining

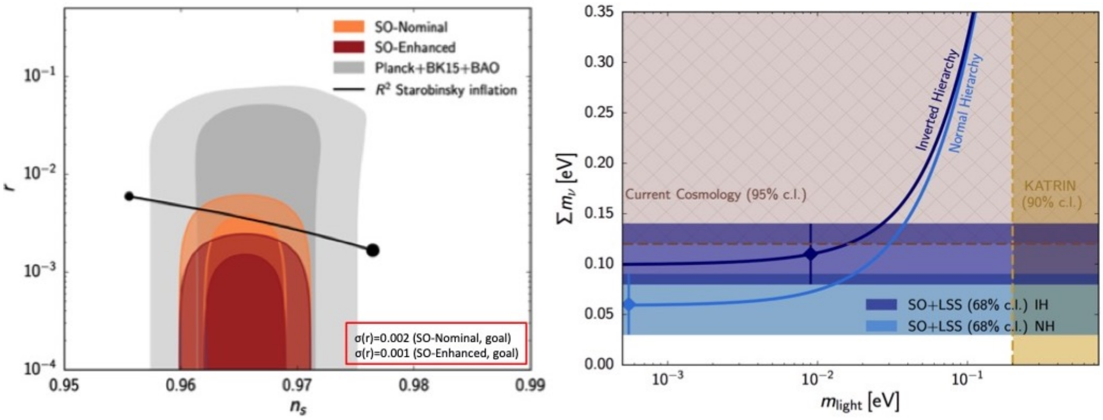


Figure 6. Left panel: Projected SO constraints on some inflationary models in the plane showing the tilt of the primordial density power spectrum, n_s, and the tensor-to-ratio parameter, r, shown together with theoretical predictions of the Starobinsky inflationary models. Right panel: Projected SO constraint on neutrino masses shown as a function of the lightest neutrino species. From [8].

two SATs and the LAT in 2023. The operations should start in 2024 and last for 3 years with the fourth year contingent on securing additional funds. The construction of SO-enhanced should start in 2025/26 and the full project should start operations in 2027/28. These should last for additional 5 years. The funds for the SO enhancement are not secured at this time.

SO is very well timed as far as other large-scale projects are concerned. It overlaps with the operations of DESI, Rubin Observatory, and Euclid. Discussions are already in place concerning different forms of collaborations and common projects.

5.4 French involvement and prospects

At this time there are two French (and IN2P3) laboratories which are involved in the project: AstroParticle and Cosmologie Laboratory (APC) and Irene Joliot-Curie Laboratory (IJCLab), with 4 permanent researchers (Bartlett, Errard, Ganga, Stompor) and 3 PhD students (El Bouhargani, Jost, Vergès) working on the project at APC and two permanent researchers (Garrido, Louis) and a PhD student (LaPorta) at IJCLab. The current involvement of France-based scientists in SO is limited to data analysis, performance forecasting, and scientific optimization of the SO instruments. Nevertheless, French researchers play important and coordinating roles on the global project scale. J. Errard (APC) is a member of SO Theory and Analysis Committee, 6-person body coordinating preparations of the overall analysis effort as well as scientific exploitation of the SO data sets. J. Errard (APC) is also a co-leader of the working group focused on development of tools and techniques for analysis of the SAT data sets and targeting the primordial gravitational wave detections. R. Stompor (APC) is a member of the Membership Committee and a senior advisor of the SAT data analysis working group and a former member of the SO Theory and Analysis Committee. T. Louis (IJCLab) is

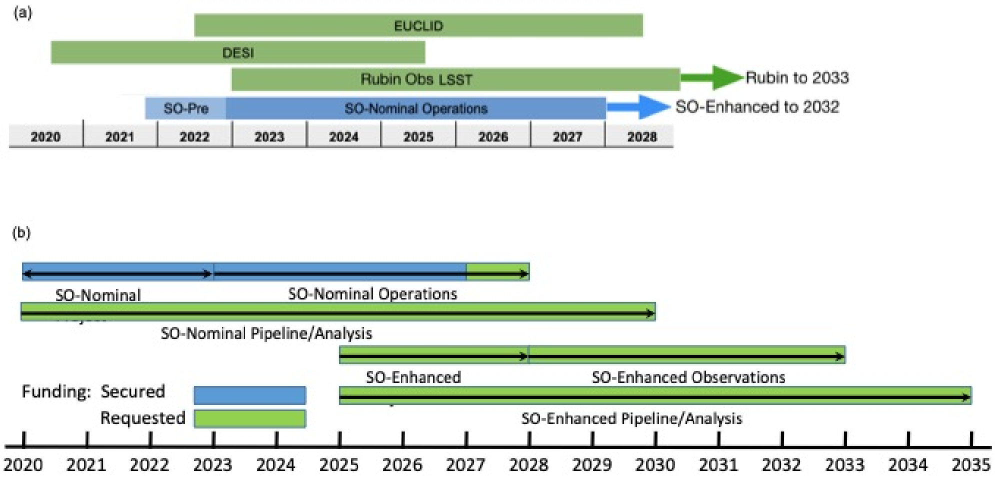


Figure 7. The current schedule of Simons Observatory (bottom) and superposed with selected major projects (top). Adapted from the SO Decadel Review White Paper.

a co-lead of the likelihood working group focused on development of tools and techniques for LAT data sets.

Membership of the SO collaboration is based on in-kind (typically hardware or monetary) contributions which the research groups are supposed to provide. The current French members of the collaboration have been absolved from those so far given their past contributions to the previous generation of projects, which led to SO. Those are POLARBEAR/Simons Array for the APC group and ACT for the IJCLab. Extending the French involvement will however require defining some in-kind/hardware contribution to the project. Some discussions have been already undertaken but need to continue to converge. In addition to its exciting scientific impact it is expected that the SO collaboration will become a partner in the follow-up and much bigger and more ambitious project, CMB-S4. Participating in SO at this time could therefore pave the way for the CMB IN2P3 community to that latter project. (Other options are also plausible and studied at this time.)

6 CMB-S4

CMB-S4 [10] is an ultimate, ground-based, Stage-IV experiment designed to exploit all scientific potential of the CMB polarization anisotropies as anticipated today. In addition to being multi-telescope it will also be a multi-site experiment with telescopes deployed from the South Pole and the Atacama Desert, capitalizing on different and complementary advantageous of these sites.

6.1 Instruments and operations

The reference design of CMB-S4 anticipates a deployment of 14 small aperture (~ 55cm) refractors observing at frequencies lower than 155 GHz and complemented by 4, 44cm small aperature telescopes operating at 220/270GHz. All these SATs will feature focal planes made of dichroic, horn-coupled, superconducting TES detectors observing in total of 8 frequency bands between 30 and 270GHz. Those will be deployed at the South Pole and will make ultra-deep observations of small, ~ 3%, patch of the sky with an aim of constraining the amplitude of primordial gravitational waves. The South Pole SATs will be complemented by a 6m large aperture telescope observing the sky in 7 frequency bands from 20 to 270GHz with main aim of providing the data necessary for delensing the small patch, deep observations.

The total number of SATs detectors operating from the South Pole will exceed 150k while the LAT will have nearly 120k of them. The operations are planned for 7 years.

There will be further two LATs deployed at the Atacama Desert from where they will conduct deep and wide survey of nearly ~ 70% of the entire sky. Each will be equipped with ~ 120k detectors and will cover 7 frequency bands between 30GHz and 270GHz.

The total number of detectors deployed by CMB-S4 will be $511,184$ and it will require 432 science grade wafers, making it a unique undertaking in terms of the scale, sensitivity, and science reach.

6.2 Science

The rich and diverse set of CMB-S4 scientific goals is organized into four major themes [10],

- primordial gravitational waves and inflation;
- the dark Universe;
- mapping matter in the cosmos;
- the time-variable millimeter-wave sky,

covering essential all the science goals of Simons Observatory, with however significantly increased sensitivity, Fig. 8. CMB-S4 is the only currently proposed experiment which would cross a number of important sensitivity thresholds making it in this sense an ultimate ground based effort.

For the detection of primordial gravitational waves the goal is to reach $\sigma(r) \simeq 0.001$ a factor of 2 to 3 better than the projected reach of Simons Observatory and comparable to the goal of the satellite mission, LiteBIRD. While there is no theoretical lower limit on the amplitude of the primordial gravitational waves there is a broad family of well-motivated, observationally-viable inflationary models which predicts $r \gtrsim 0.001$. Reaching the sensitivity on order of 10^{-3} in r would allow a robust detection (or rejection) of many such models. We note that in the case of the ground-based experiment this constraint will be mostly determined by the degree (a couple of degrees) scale anisotropies, the so-called recombination bump), while in the case of the space observations, such as LiteBIRD, the constraint comes to big extent from the largest angular scales (~ 30deg, the so-called reionization bump), and are therefore potentially complementary.

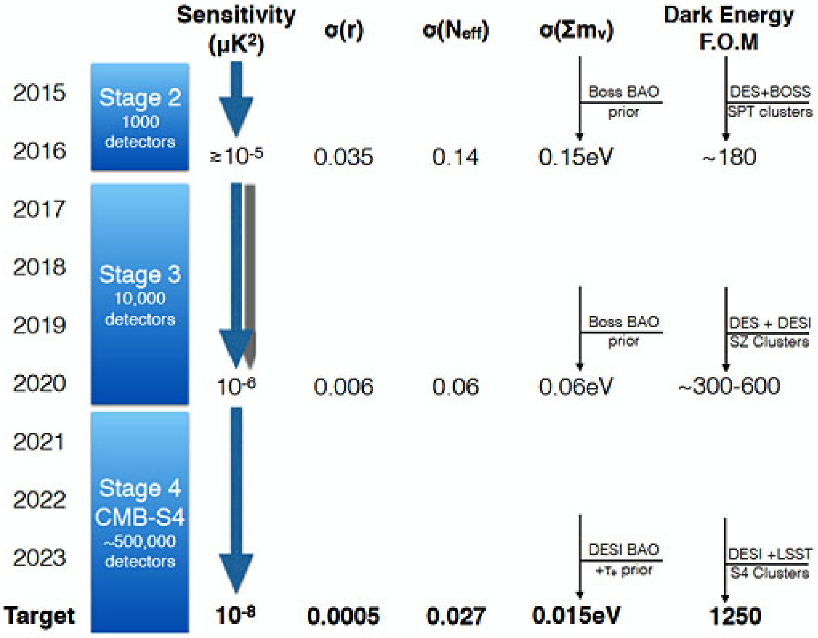


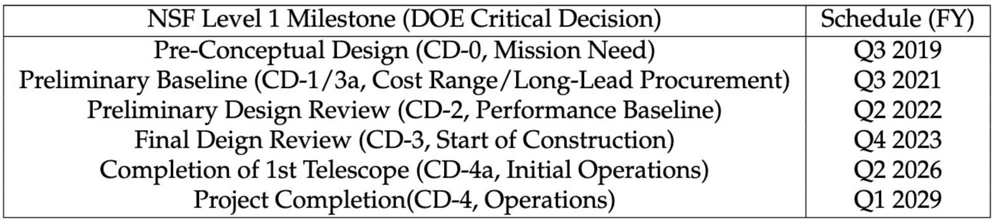
Figure 8. Precision on selected key cosmological parameters expected (or achieved) by various generations of CMB experiments as defined in Fig. 1. (Credit: CMB-S4 collaboration)

In the context of detecting light relic particles, the enhanced sensitivity will allow CMB-S4 to be the first experiment to detect particles which froze prior to the QCD particles such as hypothetical Weyl fermions and vector particles.

The high significance detection of the impact of the gravitation lensing on the CMB signal will allow CMB-S4 to set tight constraints on the neutrino masses, dark energy properties, and theories of modified gravity. Combining the reconstructed projected mass density maps with other observations would allow weighing the galaxies and clusters, providing redshift-dependent information on the matter distribution in the Universe and providing new means to constrain cosmological and fundamental physics parameters. This will permit setting constraints on many non-standard models of neutrinos and interactions of dark matter particles.

CMB-S4 will produce unique catalogs of galaxy clusters thanks to the Sunyaev-Zel'dovich effect reaching redshift as high as $z \sim 2$ at the time when the galaxies were particularly active accreting hot gas and forming most of its stars and therefore providing key clues about these poorly understood processes.

CMB-S4 legacy data will allow for diverse science on their own and in conjunction with other data sets anticipated on similar timescales: DESI, Rubin Observatory, WFIRST, and many others.



NSF Level 1 Milestone (DOE Critical Decision)	Schedule (FY)
Pre-Conceptual Design (CD-0, Mission Need)	Q3 2019
Preliminary Baseline (CD-1/3a, Cost Range/Long-Lead Procurement)	Q3 2021
Preliminary Design Review (CD-2, Performance Baseline)	Q2 2022
Final Deign Review (CD-3, Start of Construction)	Q4 2023
Completion of 1st Telescope (CD-4a, Initial Operations)	Q2 2026
Project Completion(CD-4, Operations)	Q1 2029

Figure 9. The proposed schedule of the CMB-S4 project. The project ’completion’ in the first quarter of 2029 refers to the end of the construction and the beginning of the science operations. Taken from [11]

6.3 Timeline and organization

The expected timeline of the implementation of the project is shown in Fig 9. The construction is expected to start in the fall of 2023, and the operations at the beginning of 2029. The operations are planned to last 7 years till 2026. CMB-S4 is a scientific collaboration but since this year also a US Department of Energy and National Science Foundation project. As a scientific collaboration CMB-S4 is governed by the elected Governance Board and is composed of roughly 200 researchers from 11 countries and 76 institution. A DOE/NSF project office will lead the implementation of the project and is based at Lawrence Berkeley National Laboratory in Berkeley. In particular, the project office will be responsible for forming partnership, via Memoranda of Understanding, with other projects such as Simons Observatory but also foreign partners.

6.4 French involvement and prospects

The current involvement of France-based scientists is on a personal, best-of-the-effort basis. There are 7 senior researchers from France and 5 of those from the IN2P3 Labs (Bartlett, Delabrouille, Ganga, Stompor (APC), Tristram (IJCLab) who are formally members of the CMB-S4 collaboration. The involvement is focused on data analysis and scientific optimization, and building the science case for the project. The future prospects and plans are discussed by the CMB community in France and at IN2P3. The discussions involve essentially all the members of the CMB community at IN2P3, including, in addition to the aforementioned current members of CMB-S4, Catalano, Macias-Perez (LPSC), Henrot-Versillé, Louis (IJCLab), Hamilton, Piat, and Torchinsky (APC). Considered options aim at capitalizing on the expertise developed by the IN2P3 groups from their involvement in the past experiments, notably on experiences stemming from the construction and deployment of the French-led NIKA, NIKA2, Kiss and Concerto and QUBIC experiments and the participation in Planck, as well as on technological developments undertaken at IN2P3 and France, such as arrays of KIDS detectors, time domain multiplexing read-out electronics, or bolometric interferometry. Discussions are also held on the European level as well as directly with our American partners. The output of these discussions may depend on the validation of the proposal made to CNES by the CMB IN2P3 community for a technical participation to the LiteBIRD satellite and in particular the evolution of this involvement beyond phase A2.

7 Ground and space complementarity

The scientific potential of the CMB remains to be truly extraordinary and is, and will continue to be, unique in many of its aspects. Exploiting it needs addressing successfully and comprehensively the challenges mentioned above, and doing so in a demonstrably reliable way. No CMB experiment is however self-contained and therefore the full success can be only achieved by a combination of multiple concurrent experimental efforts operating in diverse conditions, employing different observational strategies, different instrumental solutions, and operating from different vantage points of view. Only consistent results from majority of them can, and would, be accepted as robust and reliable. Ground-based observatories and space-borne missions are particularly powerful combinations due to their very different limitations, different technical solutions they use, and very different environments they operate in.

7.1 Angular scales and sky coverage

Satellite missions have unique access to the entire sky and are able to scan between even the most distant sky areas on relatively short times. This combined with the exquisite thermal stability provided by space enables satellites to constrain anisotropies on the largest angular scales. Ground-based experiments can also observe large fractions of the sky: up to ~ 70%, of the sky can be seen from a single location at the Atacama Desert in Chile. However, the unstable environment, ground and atmospheric emissions, combined with scanning strategies often resulting in an incremental increase of the observed sky area throughout the observation make the largest angular scales difficult to constraint reliably and with sufficient precision.

In contrast, the size of the aperture which can be realistically deployed in space is limited by both cost and weight considerations. These limitations are less of an issue for the ground-based experiments and consequently these are the ground-based observatories which provide information concerning small-angular scales.

Therefore only a combination of space missions and ground efforts can provide us a full picture of the CMB anisotropies extending from the largest to the smallest angular scales where non-cosmological effects starts on being dominant. This complementarity has been capitalized on in the past as far as total intensity and E-mode polarization is concerned, see for example, Fig. 10.

For the B-mode measurements the complementarity goes even further as the high resolution observations of the E-modes are necessary in order to clean the large angular scale, i.e., presumably primordial, B-modes of the lensing contribution. The importance of such a delensing operation will depend on the amplitude of the primordial B-mode signal and the intrinsic noise of the observations, however, in any case if properly implemented is expected to at least enhance the significance of the primordial signal detection if not enable the detection at all. The suitable E-mode data not only need to have high

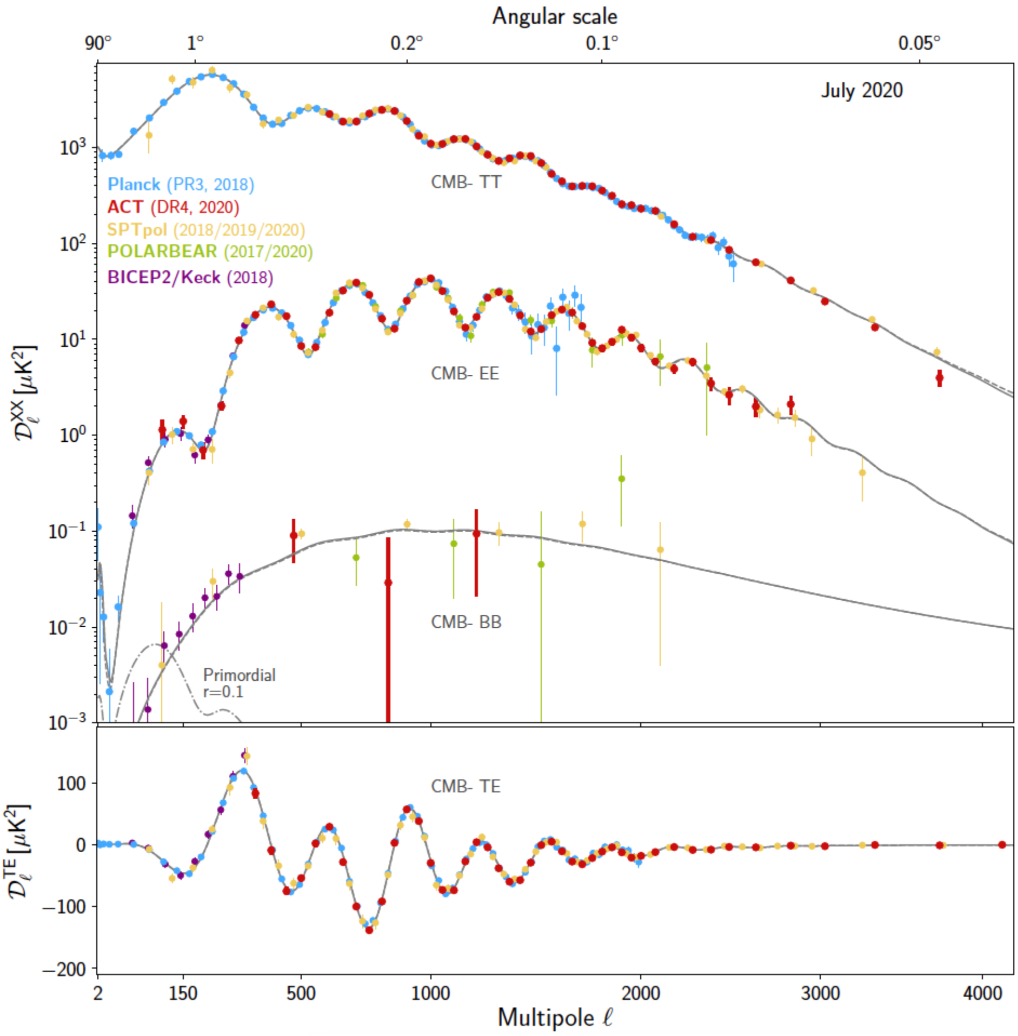


Figure 10. Summary of the current constraints on the CMB power spectra, showing constrainted from the satellite mission, Planck, overplotted over those from ground based efforts, ACT, POLARBEAR, SPT, and BICEP. From [5].

resolution but have to cover the same sky as the experiment providing constraints on the large angular scales signal. They do not have to however extend to largest angular scales as most of the relevant information comes from the smaller ones. The combo of low(er) resolution satellite and high resolution ground based data is therefore particularly effective here.

The large angular scales, the domain of the satellites, are also needed to improve constraints on the optical depth parameter, τ. This can be only achieved if the so-called reionization peak in the E-mode (as well as B-mode) power spectrum corresponding to scales $\gtrsim 30°$ is fully characterized. The uncertainty on τ is a key source of error of the total neutrino mass constraints derived from the CMB measurements and which in turn requires small-scale angular data accessible only from the ground. Exploiting the full information contained in the CMB anisotropies and concerning the absolute mass scale of neutrinos (and potentially deciding on their mass hierarchy) will require both satellite and ground based data.

Sky coverage/scanning. Capitalizing on their vantage point of view CMB satellites scan typically the entire sky producing full sky albeit limited in resolution maps of the sky. These are also typically quite noisy on the smaller scales due to the need of scanning the full sky and the fact that they are optimized merely to ensure that the noise uncertainty does not exceed that expected due to inherent statistical uncertainty of the CMB signals (cosmic/sample variance). Ground based efforts are more flexible in this respect and instead have a choice of deep observations focused on a small patch of the sky or broader sky surveys, shallower and with information likely compromised on largest angular scales. The first choice is typical of small aperture experiments and the latter of large aperture experiments. Maps of the deeply-integrated, small sky patches obtained by the ground-based efforts provide therefore complementary information to that obtained from the satellites. For CMB and cosmological parameters it encodes, both those data sets can effectively set up limits on relevant parameters, owing to the fact that the CMB signal is assumed to be statistically stationary and homogeneous over the sky. However, only observations with large sky coverage can effectively test these assumptions, as could a combination of small (ground) and large (space) sky coverage date. Both these data sets can be used to set constraints on the same physical parameters, as mentioned above in the case of the amplitude of the primordial gravitational waves. However, due the limited sky coverage the source of the constraints can be different providing additional cross-check for the constraints. For non-stationary sky signals, like Galactic emissions, both types of observation will highlight their different aspects, large angular scales properties vs high precision constraints on local amplitudes. Both these pieces of information constitute necessary and complementary inputs for modeling of the astrophysical emissions in order to successfully subtract them from the measured data.

7.2 Frequency coverage

The atmosphere is effectively opaque in many microwave bands due to the presence of water vapor and O_2 molecules. This limits the number of potential frequencies at which a ground-based instrument can efficiently operate. In particular, there is an almost hard upper limit on maximal frequency potentially accessible from the ground around ~ 350GHz. In practice, only frequencies up to ~ 280GHz have been successfully demonstrated from the ground. The impact of the atmosphere on CMB measurements are multiple, it does not only increase the overall noise level but also introduces strong correlations both temporal in data of any single detector but also spatial correlating the atmospheric noise in different detectors of a focal plane, limiting the sensitivity gains due to large, densely-packed arrays of detectors. While the atmospheric emissions are thought not to be polarized, there small ice crystals present in the upper layers of the atmosphere may induce polarized signals leading also to systematic in addition to statistical effects.

None of these effects affects satellite missions, which can observe in a very broad frequency bands and at frequencies most suitable for a given purposes.

Multiple frequency bands and a broad frequency coverage are a key to a successful component separation procedure which is a major step down the analysis pipeline of any CMB polarization experiment. Its successful resolution is necessary for the success of the entire effort. In this respect the satellite observations will furnish additional information necessary to validate, or even to enable the analysis of the ground-based data.

The relevant information will be in form of actual full sky maps in frequency bands not accessible from the ground and covering the sky areas observed from the ground. It will also be in form of general knowledge (priors) of the foreground properties. The complementarity is relevant for all small- and large- aperture ground based efforts with the actual maps directly relevant in the former case thanks to the matching resolution of both data sets and the latter relevant to both these cases.

In contrast in the frequency bands common to both types of experiments the high-resolution maps derived from ground observations will provide the small-scale information about the foregrounds which will be readily useful to demonstrate and validate assumptions behind the component separation techniques employed in the analysis of the satellite data. This can be particularly relevant for low frequencies ($\lesssim 40$GHz) where the resolution of the satellite maps can be particularly poor as compared to the one of the satellite maps at higher frequencies, say, $\sim 90 - 150$GHz where the bulk of the CMB information resides.

7.3 LiteBIRD vs SO and CMB-S4

With its sub-degree resolution in the CMB frequency range and post-component separation noise just under the lensing floor, LiteBIRD provides a particularly good match to the forthcoming ground-based efforts [9]. Its resolution is such that there is a angular scale overlap between LiteBIRD and the ground efforts, such as SO or CMB-S4, see, e.g., left panel of Fig. 4. This will allow for cross-checks and intercalibration of all these surveys and full exploitation of their synergistic potentials. Combined together these data sets will provide a detailed picture of the CMB anisotropies from the largest angular scales down to a few arcminutes. This will define the reference in the field for years to come and which could be only, and potentially, superseded in the future by a single, high-resolution, dedicated CMB satellite.

LiteBIRD will moreover directly benefit from the delensing capitalizing on the high signal-to-noise, high resolution maps of the E-mode polarization issued by large aperture telescopes. While both LiteBIRD and CMB-S4 aim at a limit on the tensor-to-scalar ratio on order of 10^{-3} the delensing of the LiteBIRD data can improve on that by a factor as much as two.

In turn, LiteBIRD will provide an ultimate (cosmic variance limited) constraint on optical depth parameter, τ, paving the way to improved neutrino constraints, by as much as a factor of 2 in the case of neutrino masses, which can be then derived with help of the high resolution data from the ground.

LiteBIRD constraints on foreground properties, derived at large angular scales but within a very broad range of frequencies will provide complementary information to that available from the ground making their analysis process more robust. Combined together they will produce constraints on Galactic magnetic field structure over a broad range of angular scales.

8 Synergies between CMB and other surveys and projects

The success of modern cosmology has been driven by diverse, complementary data sets. This is going to come even more to the fore in the near future thanks to high quality large-scale structure probes and CMB data sets. As highlighted in Fig. 4 the most stringent and robust constraints on some of the key cosmological parameters can be only obtained via cross-correlation and co-analysis of diverse data sets. There is a strong expertise and interest within the CMB community at IN2P3 to pursue those options in the future. A visible participation in ground and satellite CMB projects, and therefore firsthand access to and knowledge of their data sets, will be a key element of such a program.

A more detailed discussion of specific synergies between future CMB surveys and large scale surves from Euclid and Rubin Observatories is given in the report "EUCLID-RUBIN SYNERGIES: A SUMMARY FOR THE OCTOBER, 2020 IN2P3 SCIENTIFIC COUNCIL" prepared by K. Ganga and collaborators.

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