EUROPEAN WORK ON FUTURE GROUND-BASED CMB EXPERIMENTS

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We describe work to define potential contributions from the European community towards the next generation of ground-based Cosmic Microwave Background experiments.

The long-term objective defined by the volunteer ”European CMB Coordinator” group is to promote major contributions to ground-based CMB studies by the end of the next decade, when CMB-S4 comes online. To achieve this long-term ambition, we have identified a mid-term roadmap consisting of three axes. One axis is to build and deploy a large-aperture (5 m) reflecting telescope at the South Pole, facilitating high-resolution CMB science over relatively large survey areas. We envisage that this telescope would operate as an integral part of a South Pole CMB observatory composed of the SPT and BICEP Collaborations. A second axis is to build and deploy a series of small-aperture (0.5 m) refracting telescopes in the Atacama Desert in Chile. Operating as an integral part of the Simons Observatory, these small-aperture telescopes will perform a very deep, low-resolution, survey over the cleanest parts of the sky, focused on the search for observational signatures of primordial gravitational waves. The third axis of the European mid-term program is to build and deploy a number of low-frequency telescopes, potentially including both northern-hemisphere and southern-hemisphere components, aimed at characterizing the sky emission in the frequency range 5–120 GHz. The primary science goal of the low-frequency axis is to facilitate a precise and accurate separation of “foreground” signals, primarily those arising from our own Galaxy, from the CMB signal.

While independent proposals at the moment, the ambition is that these be funded and integrated.

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1 Introduction

Since its discovery [26], measurements of the cosmic microwave background (CMB) have been a driving force in establishing the standard model of cosmology. European scientists have played an important role in general in this work, and recently with experiments such as the European Space Agency's *Planck* mission [28] in particular. Advances so far have been enormously important, but the CMB's greatest contribution to fundamental physics could well be yet to come. The field is now turning to the search for primordial gravitational waves, which, if present, would imprint a very specific pattern (termed "B-modes") on the polarisation of the CMB [21, 32]. This signal is predicted to be present in many theories of Inflation, a period of rapid expansion thought to have occurred at the very beginning of our Universe [14] (see [3] for a review). Observing primordial B-modes would thus provide a probe of physics at very early times – or equivalently at very high energies, far beyond the energies accessible to particle physics experiments such as colliders. A detection of the primordial B-mode signal would represent a phenomenal achievement and would open a unique observational window on fundamental physics. In addition to early-Universe physics, future CMB experiments will also provide unique insights into neutrino physics, cosmic acceleration and dark energy, the nature of dark matter, and the end of the dark ages through high-resolution CMB observations, including measurements of both CMB lensing and of galaxy clusters through the Sunyaev-Zeldovich effect.

Given such a wide range of potentially rich scientific rewards, and along with its heritage and expertise in the field, the European CMB community is keen to continue to play a major role in this science area. To this end, over the course of the last five years, a panel of senior European CMB scientists (the European CMB coordinators group, or "E-CMB" panel) has discussed the emerging CMB landscape, its likely direction in the coming decades, and Europe's role therein. As part of these discussions, we have consulted widely with the European CMB community, both through a series of annual international conferences (the "Florence meetings", held annually since 2015 [8, 9, 10, 11]), and via direct consultations and "Town Hall" meetings at the national level. We have also coordinated and consulted with key stakeholders in the CMB science area outside of Europe, including with the leaders of the CMB-S4 project.

In the last year, the E-CMB panel has converged on a recommended future roadmap for Europe in this field. Our long-term objective is to make major contributions to ground-based CMB studies by the end of the next decade, when CMB-S4 comes online. To achieve this long-term ambition, we have identified a mid-term roadmap consisting of three axes. One axis is to build and deploy a large-aperture (5 m) reflecting telescope at the South Pole, facilitating high-resolution CMB science over relatively large survey areas. We envisage that this telescope would operate as an integral part of a South Pole CMB observatory composed of the SPT and BICEP Collaborations. A second axis is to build and deploy a series of small-aperture (0.5 m) refracting telescopes in the Atacama Desert in Chile. Operating as an integral part of the Simons Observatory, these small-aperture telescopes will perform a very deep, low-resolution, survey over the cleanest parts of the sky, focused on the search for observational signatures of primordial gravitational waves. The third axis of the European mid-term program is to build and deploy a number of low-frequency telescopes, potentially including both northern-hemisphere and southern-hemisphere components, aimed at characterizing the sky emission in the frequency range 5–40 GHz. The primary science goal of the low-frequency axis is to facilitate a precise and accurate separation of “foreground” signals, primarily those arising from our own Galaxy, from the CMB signal. The ability to separate the signals in this way is a critical requirement of most future CMB science experiments.

The European CMB roadmap is summarized in Fig. 1. In terms of the wider scientific context in Europe, we note that the European Astroparticle Physics Strategy (2017–2026) report by the Astroparticle Physics European Consortium (APPEC) includes a recommendation that Europe should work towards “a next-generation ground-based CMB experiment complementary to initiatives in the US” [2]. The E-CMB roadmap presented here is aimed at delivering this high-level recommendation from APPEC. In more detail, efforts are now underway to direct ongoing European CMB efforts towards cohesive contributions to the longer-term goals. These are represented by the three axes discussed above and shown in the top part of Fig. 1. Ultimately, we anticipate and will be working towards the integration of these three axes with each other, and with the larger community, as imagined in the bottom part of Fig. 1. In the remainder of this document, we summarise the three axes of the mid-term program.

2 A Large-Aperture Telescope at the South Pole

One focus of our efforts is the contribution of a large-aperture telescope to the observatory at the South Pole. This new telescope would operate in coordination with the existing 10 m South Pole Telescope [4] and is targeted for operation starting in 2024. On that timescale, this new telescope would be available to fill the gap between the end of the ongoing SPT-3G program and the beginning of the CMB-S4 program, currently scheduled for 2027.

We envision a wide-field 5 m telescope [25] designed to provide optimal performance for polarization studies (Fig. 2). The three-mirror anastigmat design (similar to JWST, E-ELT, LSST) includes monolithic mirrors to minimize scattering, a comoving baffle to reduce pickup from the ground, and the ability to rotate around the boresight to enable polarization modulation. The combination of features is unique, and would allow the telescope to make polarization measurements on larger angular scales than is possible with existing or planned large CMB telescopes. The new telescope would deliver 1.6 arcmin resolution at 150 GHz over a 100 deg^2 field of view, with a 3.5 m diameter focal plane that could host 424k, 136k, and 63k Fλ pixels at $\lambda =$1, 2, and 3 mm, respectively. The estimated cost is $16M, and we are currently pursuing funding in Germany, the US, and at the European Union level.

The current focal plane design has an array of seven separate cameras, each with up to 19 receiver tubes that could focus solely on primary CMB frequencies or could provide coverage to both lower and higher frequencies to support foreground removal and additional mm-wave survey science. It is expected that the receiver components will be provided through a partnership between the existing SPT collaboration and the new European partners. Depending on the complement of instruments, the fast, new survey telescope could be used to push deeper than the 2–3 μK-arcmin depths at 90, 150, and 220 GHz that will have been reached by SPT-3G over 1500 deg^2 by 2023, could be used

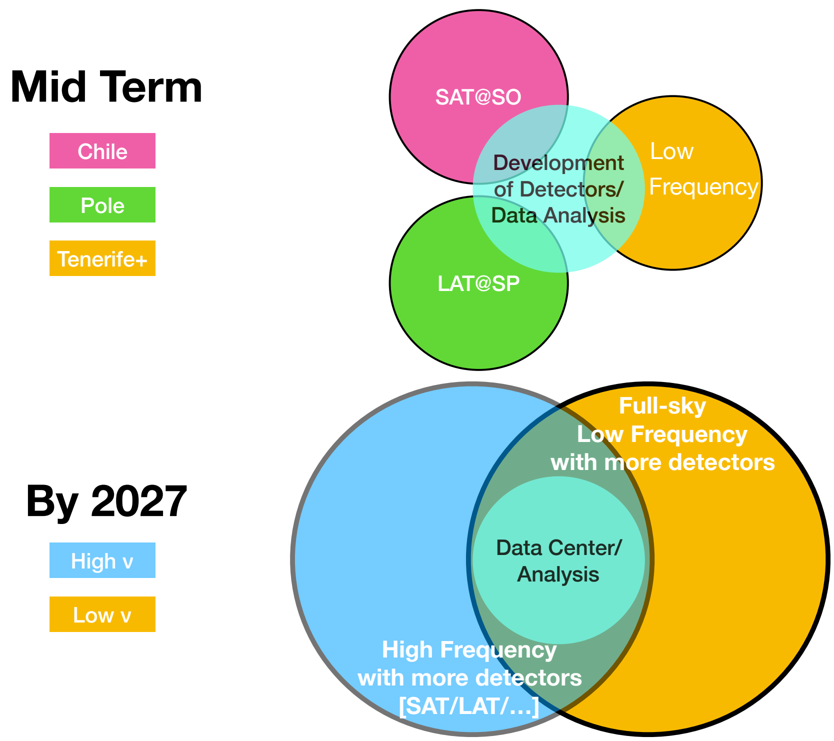

Figure 1: A roadmap for future European contributions to the ground-based CMB program, as recommended by the E-CMB panel. The mid-term component of our roadmap covers the period 2020–2025 and consists of three main strands: a large-aperture telescope (LAT) at the South Pole, small-aperture telescopes (SATs) in Chile, and a European low-frequency survey facility. We envisage that these projects would be linked through a coherent European development program in both instrumentation and data analysis techniques. Our envisaged long-term (CMB-S4 era) role is less well-defined at present but would retain both high-frequency and low-frequency components, and we would aspire to have a single coherent European data processing and analysis framework in place by that time.

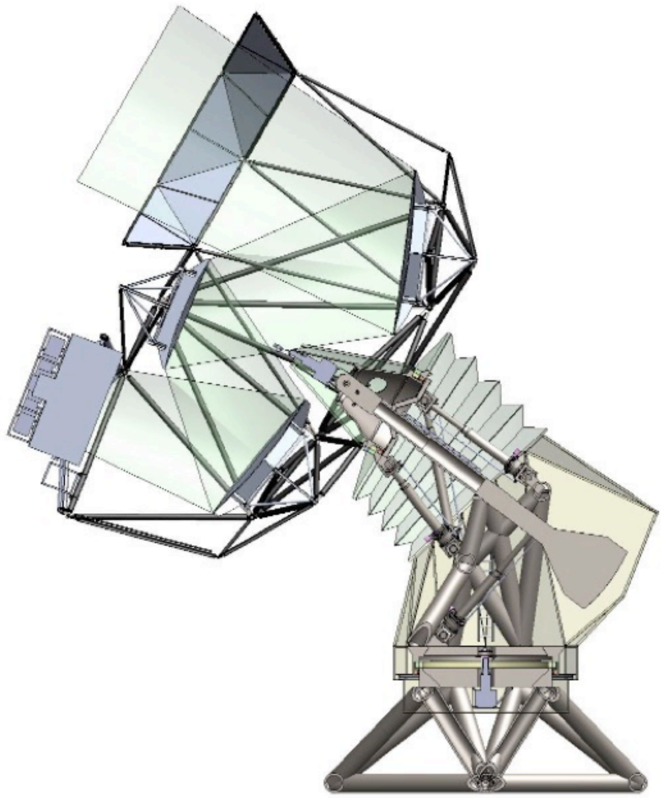

Figure 2: A wide-field, 5 m telescope for polarization studies [25]. The three-mirror design includes monolithic mirrors to minimize scattered light, a co-moving baffle to reduce ground pickup, and the ability to modulate polarized signals by rotating the optics. It will deliver 1.6 arc-minute resolution at 150 GHz over a 100 $\deg^2$ field of view.

to complement these unique depths at primary CMB frequencies with imaging at higher or lower frequencies, or could be used to carry out a larger area survey of the clean, extra-Galactic sky visible from the South Pole (around 5000 $\deg^2$). An optimization of the survey plans will be carried out by the collaboration as part of the design process.

We view this element of our plan as an important stepping stone toward European participation in the CMB-S4 program. If the telescope design meets the CMB-S4 requirements, then it could be considered an in-kind contribution to this longer-term project as well, perhaps being upgraded with the latest generation of receivers available for the CMB-S4 program.

3 A Small-Aperture Telescope Array in Chile

The second strand of the E-CMB mid-term programme involves building an array of three small-aperture telescopes (SATs; Fig 3). These instruments will be deployed to Chile where they will operate as an integral part of the Simons Observatory (SO). This aspect of the E-CMB program has been developed over the last three years, primarily by members of the SO collaboration at UK institutes. In particular, a collaboration of UK CMB scientists has recently submitted a proposal (hereafter referred to as "SO:UK") to the UK's Science and Technology Facilities Council (STFC) to fund a major UK role in the SO. The scope of the envisaged UK-based work includes instrument development, deployment and operations, data analysis, and theoretical support. The approximate cost of the SO:UK project

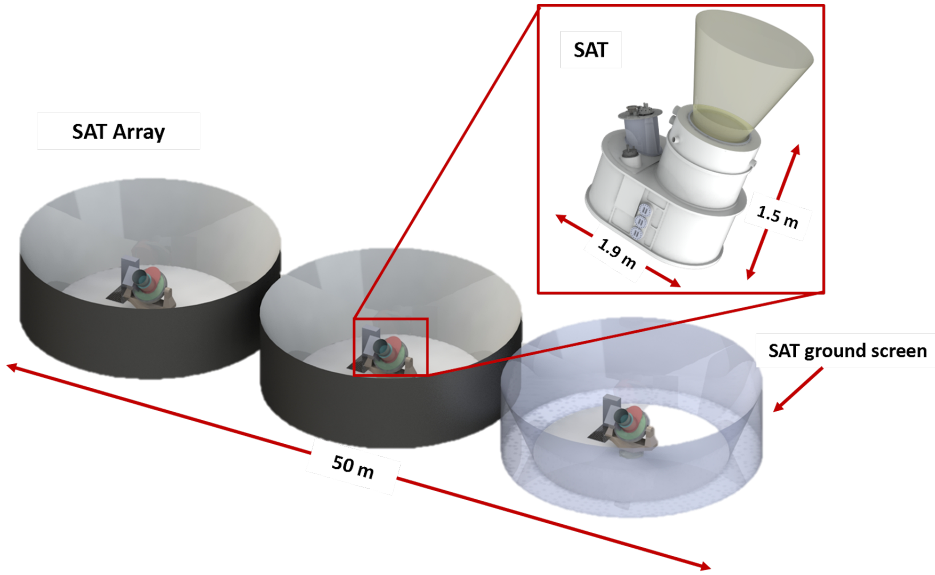

Figure 3: The three half-meter aperture telescopes currently under construction as part of the Simons Observatory project [13]. The SO:UK project aims to add a further three half-meter telescopes housing of order 30,000 KIDs detectors, a technology being rapidly developed in Europe.

is around $20M.

The proposed instrumental component will form a major component of the wider SO. The US-funded SO will comprise a single 6-m large-aperture telescope (LAT) and three 0.5-m small-aperture telescopes (SATs). The SATs will provide the sensitivity to primordial B-modes while the LAT will provide high-resolution observations that will facilitate a wide range of science goals, including the partial removal of the lensing B-mode signal. Current SO plans envisage a total of 30k detectors on the LAT and another 30k detectors across all of the SATs. The frequency coverage will range from 27 GHz to 270 GHz, and will facilitate the accurate removal of "foreground" signals, such as the Galactic dust signal, which we now know must be removed, even on the cleanest parts of the sky. The SO:UK project will add an additional three SATs (around 30k detectors) and hence will double the sensitivity available on small apertures. Simulations indicate that this enhancement will lead to a 1σ uncertainty in SO's measurement of the tensor-to-scalar ratio of $\sigma(r) = 1.5 \times 10^{-3}$ (assuming a 5-year survey), which will improve on the current best limits by a factor of around 20.

It is worth noting that the additional sensitivity provided by SO:UK could prove very significant: there are entire classes of inflationary models, broadly grouped under the umbrella of "R^2" models (e.g., [33]), which predict values of the tensor-to-scalar ratio r in the range $0.003 < r < 0.005$. The additional sensitivity provided by SO:UK could therefore transform a non-detection into tantalizing 2σ evidence for these models, or even comprehensively disprove them if a signal with $r \gtrsim 0.01$ is detected.

However, the SO:UK project represents much more than a simple scaling up of detector numbers. It will employ several state-of-the-art technological innovations that make it complementary to existing instruments (including to the other telescopes of the SO). In particular, the SO:UK project will be the first B-mode facility to employ Kinetic Inductance Detectors (KIDs; [31]; see also Fig. 4), a relatively new technology that holds great promise.

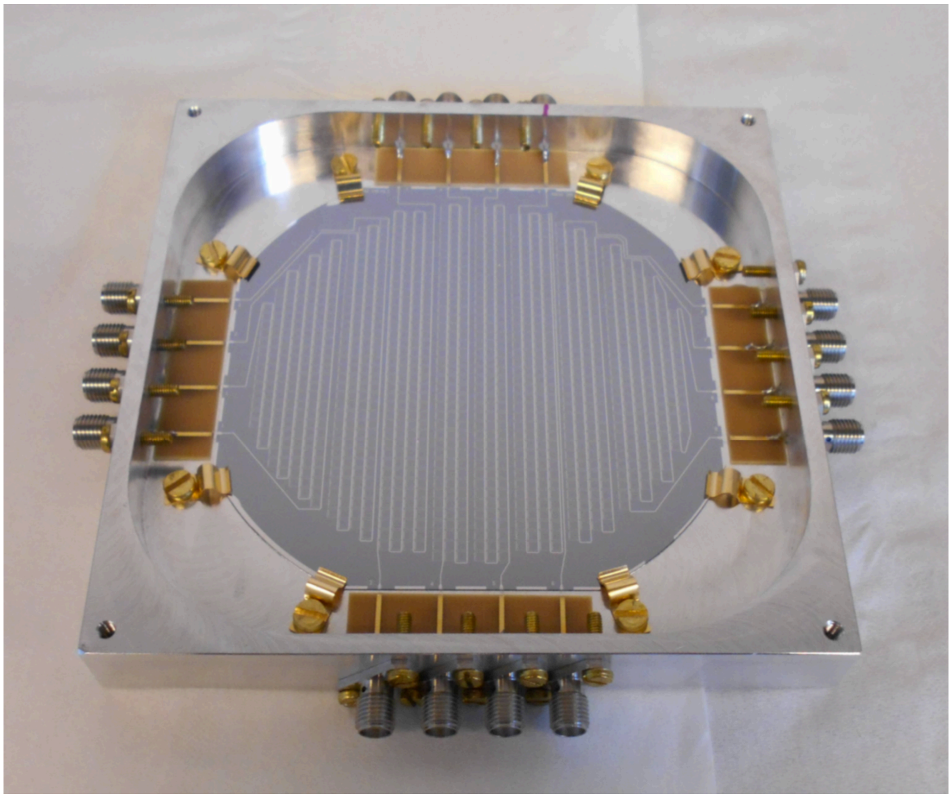

Figure 4: The front of a 260 GHz NIKA2 Lumped Element Kinetic Inductance (LEKID) array designed for 1,140 pixels [1]. In addition to the NIKA2 instrument, housed at the IRAM 30 m telescope, KIDs have already seen sky in the European balloon Olimpo [23], and the A-MKID experiment on APEX in Chile [17].

Generally speaking, KIDs are much easier to fabricate than the Transition Edge Sensors (TESs) used in almost all other CMB experiments (they are the baseline for CMB Stage-4, and are being used, with some variation, in the upcoming European LSPE/SWIPE [6] and QUBIC [24] experiments). However, the KID performance is critically dependent on the quality of the superconducting films and oxides used. European groups possess particular expertise in this area, and hence are ideally placed to fabricate the high-quality devices needed for the SO:UK receivers. KIDs are also much easier to multiplex than TES detectors, and in particular do not require the complex (cold) SQUID technology needed to read out TES arrays. We note that the other two strands of the E-CMB roadmap also plan to leverage Europe's significant leadership role in this area, and we anticipate that this technology could become a key enabling technology for precision studies of the CMB in the CMB-S4 era towards the end of the next decade.

4 The European Low-Frequency Survey (ELFS)

4.1 Key science goals and objectives

The European Low-Frequency Survey (ELFS) is a European effort aimed at producing the most advanced, full-sky surveys in the frequency range 5–120 GHz. In this context, the European CMB community plans to deploy and operate two large-aperture telescopes by the end of the next decade, one of which will be located in the Northern hemisphere and one of which will be in the South, to obtain full-sky coverage.

The primary ELFS goal is to complement the other two major existing CMB programs currently being planned on the same timescales – i.e., the LiteBIRD space mission and the CMB-S4 ground-based program – by providing state-of-the-art low-frequency measurements. Moreover, by including a W-band channel, the ELFS will also be capable of probing the region of the spectrum where Galactic foregrounds to the CMB are at a minimum, allowing an independent detection of primordial B-modes, and cover the highest northern latitudes and thereby complement CMB-S4 observations, which are not planned to cover the most northerly parts of the sky. The low-frequency end of ELFS's observations (5–45 GHz) will contribute deep observations of the low-frequency foregrounds that will be crucial to disentangle cosmological B-modes from polarization measurements. It will allow us, in particular, to perform a full parametric reconstruction of the polarized synchrotron emission, achieving a full characterization of its frequency spectrum, spectral index and curvature, over the entire sky. Moreover, it will accurately characterize the poorly-known properties of anomalous microwave emission (AME) in polarization, detecting or constraining its relevance with respect to the CMB and synchrotron. As is well known from the latest results [22, 16, 27, 29], these observations, complementing foreground monitoring at higher frequencies, will be of crucial importance in the era of CMB-S4 and LiteBIRD for extending the capabilities of these probes to deal with the contamination from diffuse foregrounds.

In addition to this unique and critical contribution, the ELFS will also impact non-CMB science significantly. Its unprecedented multi-frequency, full-sky mapping of synchrotron and AME will allow us to gain unique insight into the physics of cosmic rays and the Galactic magnetic field, as well as to study star-forming regions in our own Galaxy.

4.2 Technical Overview

The main technical specifications of the ELFS are as follows. The system will consist of two 6 m-class telescopes, based on a crossed-Dragone design. The optical system will be similar to the CCAT-p and SO LATs, but with relaxed surface and pointing specifications, thus greatly reducing the cost. The design includes highly-shielded optics to eliminate groundspill. Tenerife (Fig. 5) and the Atacama provide high-quality observing sites in the two hemispheres with excellent properties for the ELFS spectral range and well-developed infrastructure. Other sites may be considered as well, compatible with the constraint of achieving full-sky coverage.

The target sensitivity at each low-frequency band corresponds to 1 μK-arcmin when scaled to 100 GHz, assuming a synchrotron spectral index of $\beta = -3.0$. The survey will have sufficient angular resolution to resolve multipoles of at least $\ell \simeq 300$ at its lowest frequency (5 GHz), corresponding to a beam of about 40 arcmin, reaching 10 arcmin scales in the 20-45 GHz range; this will fulfill the requirement of mapping polarized synchrotron emission to scales useful for removal from LiteBIRD and CMB-S4 data.

Two independent focal-plane arrays will be developed. One will be in the 5–45 GHz range and will use HEMT-based radiometers with about 100 elements. Broad-band, corrugated feed horns will be adopted to accommodate several frequency bands in the same element. Digital back-end technology, developed for the Square Kilometer Array, will en-

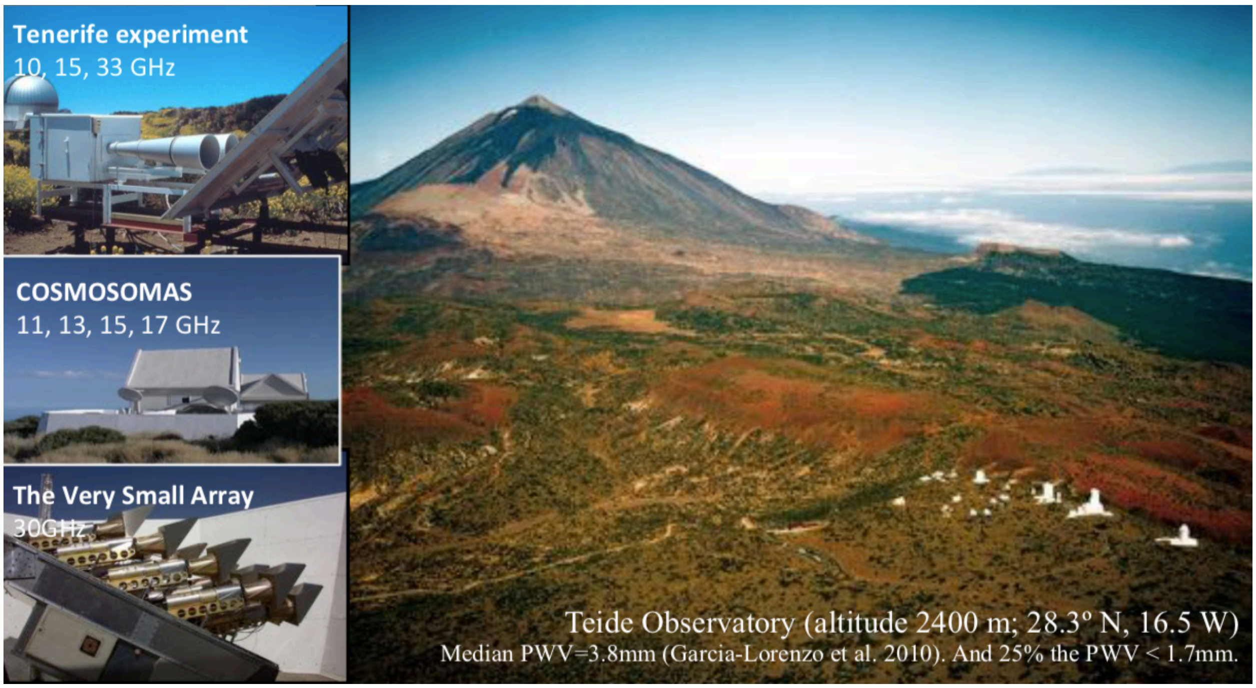

Figure 5: The Teide Observatory in the Canary Islands. This site has housed a number of European CMB experiments, including the Tenerife experiment [15], COSMOSOMAS [18], the Very Small Array [7], and now the QUIJOTE [30], Groundbird [5], LSPE/STRIP [12] and KISS experiments. It is unique among currently operating CMB sites, as it is in the northern hemisphere.

sure nearly-continuous and flexible band coverage with simultaneous Stokes I, Q, and U measurements for each pixel. In this respect, the ELFS will inherit technology and know-how developed in past and on-going experiments dedicated to observations in the 5–45 GHz range (QUIJOTE [30], CBASS [20], LSPE/STRIP [12] and NextBASS [19]). The other array will be in the 90–120 GHz range and will be based on KIDs technology. A possible operational scheme is to have the HEMT and KID focal planes installed on the separate telescopes in different hemispheres, and then to switch them between locations to achieve full-sky coverage over the extended frequency range. All the key detector technology is ready and available in Europe, including low-noise cryogenic HEMT amplifiers (noise temperatures of 0.25 K GHz^{-1} are achieved by commercially-available units), and KIDs arrays (e.g., those recently employed for OLIMPO, KISS, NIKA2). Concerning polarimeter back-ends, FPGA/digitizers were developed for SKA, including firmware, software, commercially-available hardware. World-leading expertise is available for cryogenic and optical systems (including telescopes, feeds, OMTs). Finally, experience in system testing, integration, and operations is widespread in the collaboration and it has been coordinated between countries on common programs (especially France, Italy, Spain and the UK).

4.3 Cost Estimates and Support

An approximate cost breakdown and evaluation is as follows: (i) two telescopes at 5 M€ each, totalling 10 M€; (ii) site infrastructure over two sites at 1 M€ each, totalling 2 M€; (iii) five years of operations at 0.5 M€ per annum per site, totalling 5 M€; (iv) polarimeter array – 5 M€; (v) polarimeter backend – 5 M€; (vi) KIDS array receiver – 10 M€; (vii) construction, operations, and analysis – 10 M€; and (viii) computing – 3 M€. The approximate total cost to completion is 50 M€.

Ongoing ground-based programs such as QUIJOTE, C-BASS and LSPE-STRIP represent the basis of the development for the necessary expertise for ELFS. Specific funding for its realization will be pursued through the European Union and from National Agencies. In the short term, the ELFS collaboration plans to submit an ERC proposal for a Synergy Grant (in 2019 or 2020). The latter should allow the development of polarimeter focal planes and at least one telescope. The group will also prepare an ESFRI proposal (Fall 2019) focused on the ELFS programs as a framework for seeking support from agencies of partner countries for implementing the program.

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