CMB-S4 Decadal Survey APC White Paper

Draft date: July 2, 2019

List of collaboration and project members to go here
(all included, unless opted out)

CMB-S4 Overview and Context

The CMB-S4 concept was originally formulated during the 2013 Snowmass physics planning activity as the path forward to realizing the enormous potential of CMB measurements for crossing critical thresholds in our understanding the origin and evolution of the Universe, from the highest energies at the dawn of time through the growth of structure to the present day. The CMB-S4 science case is spectacular, including the search for primordial gravitational waves as predicted from inflation, constraints on relic particles including neutrinos, unique insights into dark energy and tests of gravity on large scales, elucidating the role of baryonic feedback on galaxy formation and evolution, opening up a window on the transient universe at millimeter wavelengths, and even the exploration of the outer solar system. The CMB-S4 sensitivity to primordial gravitational waves will probe physics at the highest energy scales and cross a major theoretically motivated threshold in constraints on inflation. The CMB-S4 constraint on light relic particles will shed light on the early universe 10,000 times farther back than current experiments can reach. Finally, the CMB-S4 Legacy Survey covering 70% of the sky with unprecedented sensitivity through the millimeter wave band will open a new window on the thermal Universe. Through regular public data releases and an accessible archive, CMB-S4 will have profound and lasting impact on Astronomy and Astrophysics and provide a powerful complement to surveys at other wavelengths, such as LSST and WFIRST, and others yet to be imagined. We emphasize that these critical thresholds cannot be reached without the level of community and agency investment and commitment required by CMB-S4. In particular, the CMB-S4 science goals are out of the reach of any projected precursor experiment by a significant margin.

CMB-S4 is planned to be a joint NSF and DOE project, with the construction phase to be funded as an NSF MREFC project and a DOE HEP MIE project. An interim project office has been constituted and tasked with developing the CMB-S4 project through the NSF MREFC Preliminary Design Phase and through DOE CD-1. Support for the office is being provided in part by DOE, and a funding proposal to the NSF MSRI-R1 program is pending. DOE CD-0 is expected imminently and will be a major milestone for the project.

CMB-S4 was recommended by the 2014 Particle Physics Project Prioritization Panel (P5) report *Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context* and by the 2015 NRC report *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research*. The community further developed the science case in the 2016 *CMB-S4 Science Book* and surveyed the status of the technology in the 2017 *CMB-S4 Technology Book*. This work formed the foundation for the joint NSF-DOE Concept Definition Task Force (CDT), a subpanel of the Astronomy and Astrophysics Advisory Committee (AAAC), a FACA committee advising DOE, NASA, and NSF. The CDT report was enthusiastically accepted by the AAAC in October 2017.

Building on the CDT report, the CMB-S4 Collaboration and the pre-Project Development Group composed of experienced project professionals drawn primarily from the national laboratories have produced the comprehensive document, *The CMB-S4 Science Case, Reference Design, and Project Plan*, which we refer to here at the Decadal Survey Report (DSR).

The material presented in this white paper has been extracted from the DSR, and we encourage the reader to see the DSR for more detail. It and numerous other reports, collaboration bylaws, workshop and working group wiki pages, email lists, and much more may be found at the website `http://CMB-S4.org`.

To achieve its transformational, threshold-crossing science goals, CMB-S4 requires an enormous increase in sensitivity over all current CMB experiments combined, and roughly an order of magnitude over any projected precursor experiment. A significant and unique feature of CMB-S4 from its earliest beginnings is the use of the two best currently developed sites on Earth for millimeter-wave observing: the high Atacama Plateau in Chile and the geographical South Pole. In particular, the design of CMB-S4 explicitly exploits key features of the two sites, namely the ability to drill deep on small patches of the sky through an exceptional stable atmosphere from the South Pole, and the ability to image 70% of the sky from the exceptionally high and dry Atacama Chilean site. The experimental efforts from these two sites are already being consolidated into two major observatories, the Simons Observatory (SO) and the South Pole Observatory (SPO), which will make significant advances in key CMB science goals but will fall well short of the critical science thresholds targeted by CMB-S4. For example, to match the CMB-S4 sensitivity to primordial gravitational waves, the SPO would have to integrate for nearly 50 years; it would take SO a similar amount of time to carry out the CMB-S4 Legacy Survey.

In short, CMB-S4 will enable transformational science, the CMB-S4 concept has clear community and agency support, and the CMB-S4 collaboration and project are established and moving forward. CMB-S4 thus represents a unique and timely scientific opportunity.

Key Science Goals and Objectives

The papers should summarize the most important scientific goals and objectives, justifying the timeliness of the scientific opportunities, and placing them in as broad a context as possible. We encourage the authors, where relevant, to reference Science White Papers submitted to the Survey (these are posted on the Astro2020 website, and may be referenced by author and title). Submitters may also make reference to web sites and other outside materials, but should strive to make this section as self-contained as possible.

We have organized the rich and diverse set of CMB-S4 scientific goals into four themes:

1. *Primordial gravitational waves and inflation*
2. *The Dark Universe*
3. *Mapping matter in the cosmos*
4. *The time-variable millimeter-wave sky*

The first two science themes relate to fundamental physics. The other two themes relate to the broader scientific opportunities made possible by a millimeter-wave survey of unprecendented depth and breadth; together we refer to them as our Legacy Survey themes. Here we briefly review the key high-level goals and refer the reader to the science case detailed in the DSR, and in the decadal survey science white papers referenced.

Primordial Gravitational Waves and Inflation. We have a historic opportunity to open up a window to the primordial Universe [1]. If the predictions of some of the leading models for the origin of the hot big bang are borne out, CMB-S4 will detect primordial gravitational waves. This detection would provide the first evidence for the quantization of gravity, reveal new physics at the energy scale of Grand Unified Theories, and yield insight into the symmetries of nature and possibly into the deep properties of quantum gravity. Conversely, a null result would force a dramatic shift in our understanding of basic early universe cosmology. These advances can only be achieved by an experiment the scale of CMB-S4.

The leading scenario for the origin of structure in our Universe is an epoch of cosmic inflation, a period of accelerated expansion prior to the hot big bang. During this epoch, quantum fluctuations were imprinted on all spatial scales in the Universe. These fluctuations seeded the density perturbations that developed into all the structure in the Universe today. While we cannot yet claim with high confidence that the Universe underwent cosmic inflation, the simplest models of inflation are exceptionally successful in comparison with data.

Tantalizingly, the observed scale dependence of the amplitude of density perturbations has quantitative implications for the amplitude of primordial gravitational waves, commonly parameterized by r, the ratio of fluctuation power in gravitational waves to that in density perturbations. All inflation models that naturally explain the observed deviation from scale invariance and that also have a characteristic mass scale M equal to or larger than the gravitational mass scale (the Planck mass) predict $r \gtrsim 0.001$. A well-motivated sub-class within this set of models, a sub-class that includes Starobinsky inflation, Higgs inflation, Fiber inflation [2], and α attractors [3], is detectable by CMB-S4 at 5σ. The observed departure from scale invariance is a potentially important clue that strongly motivates exploring down to $r = 10^{-3}$. With an order of magnitude more detectors than precursor observations, and exquisite control of systematic errors, CMB-S4 will improve upon limits from pre-CMB-S4 observations by a factor of five to reach this target, allowing us to either detect primordial gravitational waves or force a paradigm shift in our understanding of the early Universe.

The Dark Universe. In the standard cosmological model, about 95% of the mass–energy density of the Universe is in dark matter and dark energy. With CMB-S4 we can address numerous questions about these dark ingredients, such as: How is matter distributed on large scales? Does the dark matter have non-gravitational interactions with baryons? Are there additional unseen components beyond dark matter and dark energy?

Light relic particles are one very well-motivated possibility for additional mass-energy, as additional light particles appear frequently and numerously in extensions to the standard model of particle physics [4]. For large regions of the unexplored parameter space in these models, the light particles are thermalized in the early Universe. CMB observations with the Planck satellite can probe the creation of light particles back to the first $\simeq 50$ microseconds of the Universe. With CMB-S4 we can push back this frontier by over a factor of 10,000, to the first fractions of a nanosecond.

The contribution of light relics to the energy density, often parameterized as the "effective number of neutrino species," $N_{\rm eff}$, leads to observable consequences in the CMB temperature and polarization anisotropy. Current data are only sensitive enough to detect additional relics that froze out after the quark-hadron transition, and Stage-3 CMB experiments can only push somewhat into that epoch, so CMB-S4's ability to probe times well before the transition is a major advance. Specifically CMB-S4 will constrain $\Delta N_{\rm eff} < 0.06$ at 95% C.L., achieving sensitivity to Weyl fermion and vector particles that froze out at temperatures *a few hundred times higher* than the temperature of the QCD phase transition.

CMB-S4 will also enable a broader exploration of the dark universe in combination with other probes, often significantly enhancing them by breaking their intrinsic degeneracies. It will improve or detect various possibilities for the dark matter properties beyond the simplest cold dark matter models, as described in the DSR [5]. It will add to dark energy constraints through precision measurements of the primordial power spectrum (where dark energy effects enter as projection effects), through precision measurements of the lensing convergence power spectrum, through the CMB-lensing-derived mass calibration of galaxy clusters, and through CMB lensing tomography [6].

Mapping matter in the cosmos. Matter in the Universe can be sorted into two categories, "normal" or "baryonic" matter that undergoes all the Standard Model interactions and "dark" matter that only interacts gravitationally. According to observations, there is much more dark matter than baryonic matter, and most of the baryonic matter in the form of hot ionized gas rather than stars. CMB-S4 will be able to map out the location of both types of matter by measuring the total mass density (using gravitational lensing) and the ionized gas density (using Compton scattering).

Observations of gravitational lensing of the CMB are key to many CMB-S4 science goals. CMB-S4 lensing data will lead to a precise two-dimensional map of the total matter distribution, with redshift sensitivity peaking at $z \simeq 2$, with important applications to dark energy [6], modified gravity [6], and studies of neutrino masses [7]. In concert with catalogs of objects, we can use CMB-lensing maps to weigh samples (of e.g. galaxies and galaxy clusters) to as high a redshift as such sources can be found. The technique of CMB lensing tomography, enabled by CMB-S4 and galaxy catalogs from, for example, LSST, will allow for the creation of mass maps in broad redshift slices out to redshifts as high as $z \sim 5$, making possible new precision tests of cosmology. Such results explore the connection between visible baryons and the underlying dark matter scaffolding. In conjunction with cosmic shear surveys that measure the low-redshift mass distribution, a map of the high-redshift mass distribution can be constructed, shedding new light on the first galaxies. By calibrating cluster masses at high redshift, the abundance of galaxy clusters can be used as an additional probe of dark energy and neutrino masses.

Most of the baryons in the late universe are believed to be in a diffuse ionized plasma that is difficult to observe [8, 9, 10]. This ionized plasma can leave imprints in the CMB through Compton scattering, the so-called Sunyaev-Zeldovich effects. The two leading effects are either a spectral distortion from hot electrons interacting with the relatively cold CMB (thermal SZ or tSZ), or a general redshift or blueshift of the scattered photons due to coherent bulk flows along the line of sight (kinematic SZ or kSZ).

The nature of the scattering makes the tSZ independent of redshift, providing a means to detect galaxy clusters out to $z \sim 2$, a time when galaxy clusters were vigorously accreting new hot gas while at the same time converting cold gas into stars at a high rate [11]. The CMB-S4 catalog of more than 50,000 clusters will be more than an order of magnitude larger than current catalogs based on tSZ or X-ray measurements, and more than a factor of two larger than what can be discovered with Stage 3 CMB experiments [12, 13]. With the wide-area survey covering a large amount of volume and the ultra-deep survey imaging lower-mass clusters, CMB-S4 will be an effective probe of the crucial regime of $z \gtrsim 2$, when today's galaxy clusters are thought to have formed the bulk of their stars. CMB-S4 will also measure the diffuse tSZ signal everywhere on the sky and make a temperature-weighted map of ionized gas which can be used to measure the average thermal pressure profiles around galaxies and groups of galaxies.

Maps of the kSZ effect, in conjunction with information from other large scale structure surveys, also allow us to make maps of ionized gas around a particular sample of objects, this time with no temperature weighting. Applications of these maps are widely varied: the measured ionized gas as a function of distance directly constrains the impact of feedback from active galactic nuclei and supernovae on the intergalactic medium [14]; the bulk flow amplitude as a function of separation constrains theories of modified gravity; the large scale bulk flows uniquely measures the large scale clustering on scales that are difficult to reliably constrain using galaxy surveys. Even without overlapping galaxy catalogs, the kSZ signal can be used to probe the epoch of reionization. These measurements are completely complementary to the measurements of the neutral gas that can be obtained with redshifted Ly-α or redshifted 21-cm studies [15, 16, 17, 18].

In addition, CMB-S4 will detect the emission from galaxies in the mm-wave band, including AGN and dusty star forming galaxies [19, 20], and map the matter in our own Galaxy in intensity and polarization over a large fraction of the sky, resulting in high-fidelity maps of synchrotron and dust emission on scales from arcminutes to several degrees.

The time-variable millimeter-wave sky. There have been relatively few studies of the variable sky at millimeter wavelengths, with only one systematic survey done to date (by a CMB experiment [21]). A deep, wide, millimeter-wave survey with time-domain capability would provide key insights into transient or burst events, moving sources such as solar-system objects, and variable sources such as AGN.

Targeted follow-up observations of gamma-ray bursts, core-collapse supernovae, tidal disruption events, classical novae, x-ray binaries, and stellar flares have found that there are many transient events with measured fluxes that would make them detectable by CMB-S4. A systematic survey of the mm-wave sky with a cadence of a day or two over a large fraction of the sky with an ultra-deep daily survey of a few percent of the sky would be an excellent complement to other transient surveys, filling a gap between radio and optical searches [22].

Thermal emission from planets, dwarf planets, and asteroids have been measured at these wavelengths, and as these sources move across the sky they should be easily differentiated from the relatively stationary extrasolar sky. Using the thermal emission rather than reflected light has several complementary aspects: the fall-off with distance is less severe, providing unique information on possible large objects in the distant reaches of the solar system; the physical information available is also very different, measuring long-wavelength emissivity rather than optical reflectivity; and with long time baselines for observation it will be possible to build up rotation curves for a large number of objects, for detailed comparison with the optical and infrared versions.

CMB-S4 will play an active role in multi-messenger astronomy. Accreting black holes are known to be highly variable. A CMB survey can provide a long baseline with high time sampling in both intensity and linear polarization. This will provide an archive for multi-messenger astronomy, in particular for future blazars that are discovered to be sources of high-energy neutrinos, such as the blazar TXS 0506+056, thought to be associated with the IceCube event IC170922A. With a large catalog of time-variable blazars, it will be possible to derive detailed variability statistics over several years with nearly daily monitoring for both the detected objects and the sources that are observed to not be neutrino sources. The natural wide-area nature of the survey will make it straightforward to search for gravitational wave sources that happen to be poorly localized. Although the first binary neutron star merger, GW170817, was not detected at millimeter wavelengths, this was likely due to the low density of the merger environment [23]. There is reason to expect, based on observations of short gamma-ray bursts, that at least some mergers can occur in denser environments, which will enhance their mm emission [24].

Technical Overview

The team should provide a description of the technical aspects of the pursuit, including a description of the essential performance parameters for achieving the project's science goals.

For ground-based activities/projects, papers should describe the telescope or observatory architecture, key performance requirements, technical requirements, anticipated site and infrastructure requirements, as well as any public/private partnerships.

In the DSR we present the technical details of the Reference Design for CMB-S4 that meets the measurement requirements and therefore can deliver the CMB-S4 science goals. The Reference Design is supported by the extensive use of simulations based on our current understanding of the expected level and complexity of the foreground emission, as summarize in the DSR appendices. Noise levels in the simulations are based on assumptions for the instrumental performance that are directly scaled from existing CMB instruments. This work expands on that done for the CDT report in that it includes realistic scanning strategies and carries through the specific characteristic of the technology choices, such as dichroic pixels and feedhorn coupling. This has led to an increase in the number of small aperture telescopes (SATs) required from 14 to 18, and an increase in the number of detectors on the large aperture telescopes (LATs).

The major components of the Reference Design are as follows:

- An r survey covering 3% of the sky, more if a signal is detected, to be conducted over seven years using: (1) fourteen 0.55-m refractor SATs (at 155 GHz and below) and four 0.44-m SATs (at 220/280 GHz), with dichroic, horn-coupled superconducting transition-edge-sensor (TES) detectors in each SAT measuring two of the eight targeted frequency bands between 30 and 270 GHz; and (2) a 6-m class cross-Dragone design LAT, equipped with detectors distributed over seven bands from 20 to 270 GHz. Measurements at degree angular scales and larger made using refractor telescopes with roughly 0.5-m apertures have been demonstrated to deliver high-fidelity, low-contamination polarization measurements at these scales. The combination of the SATs with the 6-m LAT therefore provides low-resolution B-mode measurements with excellent control of systematic contamination, as well as the high-resolution measurements required for delensing. The r survey SATs and 6-m LAT are to be located at the South Pole to allow targeted observations of the single deep narrow field, with provisions to relocate a fraction of the SATs in Chile if, for example, a high level of r is detected or unforeseen systematic issues are encountered.

  The total detector count for the eighteen SATs is 153,232 with the bulk of the detectors allocated to the 95 to 150 GHz bands. There are four pixel designs. The total number of science-grade 150-mm detector wafers required for eighteen SATs is 204.

  The delensing LAT will have a total TES detector count of 114,432, with the bulk of the detectors allocated to the 95 to 150 GHz bands. There are four pixel designs. The total number of science grade 150-mm diameter detector wafers required is 76.

- The Legacy Survey and N_{eff} survey covering approximately 70% of the sky to be conducted over seven years using two 6-m cross-Dragone design LATs located in Chile, each equipped with 121,760 TES detectors distributed over eight frequency bands spanning 30 to 270 GHz. The total number of science grade 150-mm diameter detector wafers required is 152.

The total detector count for CMB-S4 is 511,184 and it requires 432 science grade wafers. This is an enormous increase over the detector count of all Stage-3 experiments combined. Such drastic scaling up is required to meet the CMB-S4 science goals.

Technical Drivers

If the pursuit requires new technologies, the paper should identify and describe them, along with an outline of technology maturation plans and timescales.

The CMB-S4 reference design uses proven existing technology that has been developed and demonstrated by the CMB experimental groups over the last decade, scaled up to unprecedented levels. The design and implementation plan addresses the considerable technical challenges presented by the required scaling up of the instrumentation and by the scope and complexity of the data analysis and interpretation. Features of the design and plan include: scaled-up superconducting detector arrays with well-understood and robust material properties and processing techniques; high-throughput mm-wave telescopes and optics with unprecedented precision and rejection of systematic contamination; full internal characterization of astronomical foreground emission; large cosmological simulations and improved theoretical modeling; and computational methods for extracting minute correlations in massive, multi-frequency data sets, which include noise and a host of known and unknown signals.

A CMB-S4 Risk and Opportunity Management Plan describes the continuous risk and opportunity management process implemented by the project, consistent with DOE O413.3B, "Project Management for the Acquisition of Capital Assets," and the NSF 17-066, "NSF Large Facilities Manual." The plan establishes the methods of assessing CMB-S4 project risk and opportunities for all subsystems as well as the system as a whole.

The CMB-S4 risk registry has 213 risks identified. There are three risks that are currently assessed at Critical and 26 risks at High. The project is working on mitigations to ensure that these risks are lowered to reasonable levels on a time scale consistent with our overall project timeline.

For example, a current identified critical risk is meeting the scaled up production and testing timeline of the transition-edge-sensor detector arrays. This is a major focus of the R&D program supported by the DOE. The Interim Project Office formed a Detector and Readout (D&R) Task Force in early 2019 to evaluate existing fabrication and testing capabilities and to provide recommendations on production plans A formal review of the resulting detector fabrication plan will be completed in mid-2019.

Organization, Partnerships, and Current Status

All pursuits should describe the participating organizations, any planned partnerships, and their current status.

CMB-S4 is both a scientific collaboration and a nascent DOE/NSF project. While these are certainly tightly coupled, they do have different roles and responsibilities; the overall organization of CMB-S4 therefore decouples into the organization of the collaboration and the project.

The formal CMB-S4 Science Collaboration was established in 2018. The collaboration bylaws were refined at the Spring 2018 CMB-S4 community workshop, and overwhelmingly ratified on March 19th 2018, and the first elections for the various officers of the collaboration were completed by the end of April 2018. As of summer 2019 the collaboration has 198 members, 71 of whom hold positions within the organizational structure. These members represent 11 countries on 4 continents, and 76 institutions comprising 16 national laboratories and 60 universities.

The CMB-S4 Collaboration and a pre-Project Development Group of experienced project professionals drawn largely from the national labs, jointly contributed to the development of the project Work Breakdown Structure (WBS), Organization, Cost Book, Resource Loaded Schedule, and Risk Registry. The top level WBS Structure and Cost is summarized in Table 1. The schedule has 1110 activities, 1928 relationships, 5 Level 1, 20 Level 2 and 299 Level 3 Milestones for the CMB-S4 project.

Table 1: CMB-S4 WBS Structure and Cost

WBS Level 2 Element	Total Cost ($M)
Total Estimated Cost (TEC)	
1.01 – Project Management	19.6
1.03 – Detectors	39.5
1.04 – Readout	59.9
1.05 – Module Assembly & Testing	31.8
1.06 – Large Aperture Telescopes	86.5
1.07 – Small Aperture Telescopes	52.3
1.08 – Observation Control & Data Acquisition	13.9
1.09 – Data Management	26.9
1.10 – Chile Infrastructure	38.1
1.11 – South Pole Infrastructure	37.0
1.12 – Integration & Commissioning	7.7
Direct TEC	413.2
TEC Contingency (35%)	144.6
Total TEC	557.9
Other Project Cost (OPC)	
1.01 – Project Management	7.0
1.02 – Research & Development	24.2
Direct OPC	31.2
OPC Contingency (35%) - excludes R&D	2.5
Total OPC	33.7
Total Project Cost (TPC)	
TEC + OPC with contingency	591.6

The reference design and project baseline summarized here and detailed in the DSR is the basis for subsequent design and project development work to be completed by the Interim Project Office (see Fig. 1) and the Collaboration during 2019-2020. A permanent Integrated Project Office will be established in 2020 to manage the construction phase which is anticipated to start in 2021.

As shown in the org chart shown in Fig. 1, a key feature of the organization is the role of collaboration members in the project office, in particular as leaders of the Level 2 systems. The Level 2 managers are supported by engineering and project management professionals. The NSF/DOE scope distribution will promote the engagement and participation of universities and national laboratories. Graduate students, postdocs, professional technicians and engineers are expected to be involved in all aspects of the project.

The project office is responsible for forming partnerships with key stakeholder institutions including DOE National Laboratories, universities, and potential collaborating observatories/projects such as the Simons Observatory, South Pole Observatory, and the CCAT-prime project. Partnerships are also expected to include foreign institutions participating in the CMB-S4 Science Collaboration and contributing to the CMB-S4 Project.

The CMB-S4 project is expected to include significant contributions from collaborating

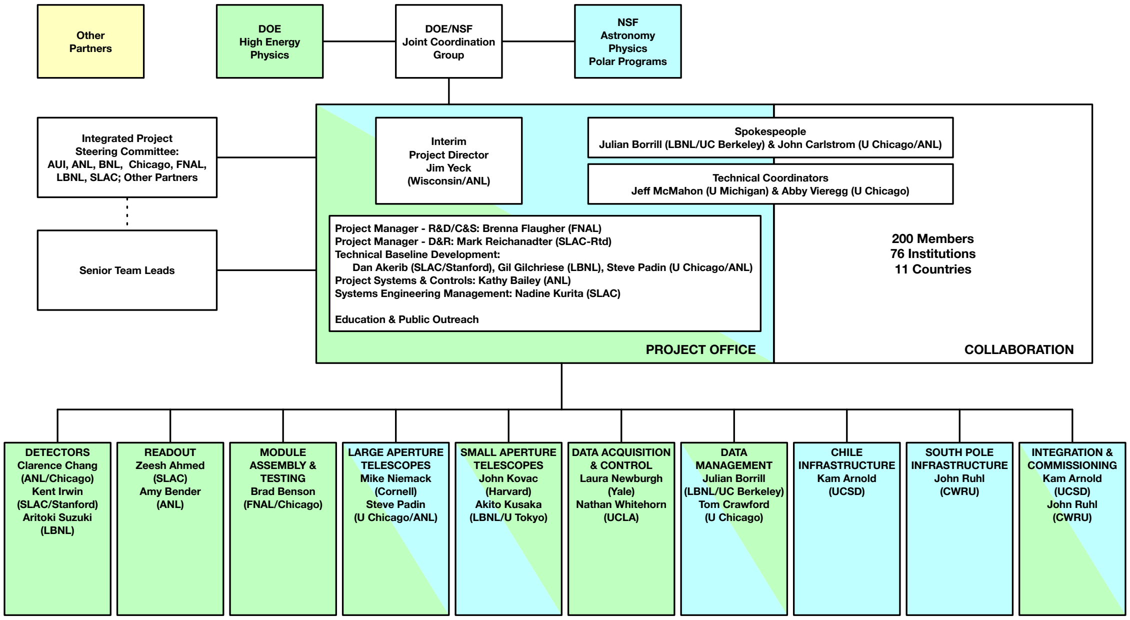

Figure 1: Organizational Chart of the Interim Project Office. The figure includes a notional distribution of project scope by funding agency (NSF = blue, DOE = green, Other = yellow). We are actively pursuing partners who could make significant scope contributions in areas aligned with their expertise.

institutions supported by funding agencies other than NSF and DOE. These "in-kind" contributions will be defined as deliverables to the project. The collaborating institutions agree to deliver items, e.g., instrumentation and effort, required for the success of the CMB-S4 project. The actual cost of each item is the responsibility of the collaborating institution providing the In-kind deliverable. The current best estimate of the value of in-kind contributions is 20-25% of the total project cost. This includes both existing infrastructure, telescopes currently under construction, and telescopes and instrumentation proposed by international collaborators.

Schedule

The team should outline the development and operations schedule. The schedule should also indicate the operational lifetime of the pursuit.

Table 2 shows proposed timeline via the NSF Level 1 Milestones along with the corresponding DOE Critical Decision Milestones. The schedule development strategy is to define a schedule that is consistent with the funding potentially available during FY2019-FY2021, and subsequently technically driven. The project is working towards an early completion milestone that contains limited schedule float. A year of schedule float following this early project complete milestone is included in the overall project complete milestone CD-4. The Interim Project Office will continue to optimize the schedule and include explicit float for activities that are not on the critical path. The best opportunity to improve on the schedule is to reduce the time required to deliver the full quantity of the Detectors and Readout (D&R) components.

Seven years of operations are needed to achieve the CMB-S4 science goals.

Table 2: Timeline and Funding Agency Milestones

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

Cost Estimates

The team should provide any cost estimates that have been developed for the current version of the pursuit. This should include the date the cost estimate was performed, should reference the base fiscal year, the organization that performed the estimate, and the top level results of the estimate, broken out by the major development and operational phases. Operating costs should be divided into direct funding to the science community (if planned) and costs required to keep facilities, missions, or other necessary infrastructure running. Any unusual end-of-life (e.g. decomissioning) costs should be noted.

Also, if applicable, a breakdown of the assumed funding from federal, other public, international, or private sources should be provided. Specific sources of funding need not be identified.

The CMB-S4 project total estimated cost is currently $591.6M (fully loaded and escalated to the year of expenditure) including a 35% contingency budget. The breakdown of the costs by major components of the construction phase is shown in Table 1. The cost estimate is the full cost, i.e., does not take credit for use of any legacy infrastructure or for contributions from collaborating institutions supported by private and international partners, e.g., Large Aperture Telescopes currently under construction in Chile as part of the Simons Observatory, and Large and Small Aperture Telescopes proposed by international collaborators. In-kind contributions delivered by Private and International partners are expected and would reduce the total cost to NSF and DOE. It is estimated that the value of in-kind contributions could reduce the total cost of the CMB-S4 project by 20-25%.

The total estimated cost is built on detailed cost estimates made for each task in the project schedule. The estimates are documented with a Basis of Estimate (BOE) developed by the subsystems leads The task resources and their quantities are assigned from a standardized list of resources. The list includes multiple resource classes in each of the categories: labor, materials/non-labor, or travel. A task estimate consists of the number of hours of each labor resource class, the base-year dollar cost of each materials/non-labor resource class, the number of trips for each travel resource class, and the basis for each estimate.

The cost contingency estimate was constructed using input from subject matter experts with previous experience in previous CMB experiments and similar NSF MREFC projects and DOE MIE projects. As the design, cost estimates, and schedules mature the contingency as a percentage of the base cost estimate is expected to decrease to 30% or less. The target range for the start of the CMB-S4 construction project is 25-30%.

A notional distribution of project scope by funding agency is shown in org chart shown Fig. 1, where blue indicates NSF and green DOE. The level of the NSF and DOE costs are expected to be comparable.

The basic operations model for CMB-S4 will be observations with multiple telescopes and cameras distributed across two sites, with observing priorities and specifications optimized for the CMB-S4 science goals, and data from all instruments shared throughout the entire CMB-S4 collaboration. The operations cost is based on a preliminary bottom-up estimate that includes management, site staff, utilities, instrument maintenance, data transmission, data products, pipeline upgrades, collaboration management, and science analysis. The annual operations cost is $32M in 2019 dollars, excluding 20 FTE/year of scientist effort supported by DOE research funds.

Normal end-of-life decommissioning costs for South Pole and Chile infrastructure are anticipated.

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