Project Overview of the Stage-4 Cosmic Microwave Background Experiment (CMB-S4)

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ABSTRACT

The ground-based Stage-4 Cosmic Microwave Background Experiment (CMB-S4) is a forefront scientific endeavor aimed at mapping the cosmic microwave background (CMB) with unprecedented sensitivity. The cosmic microwave background is the afterglow of the Big Bang and provides crucial insights into the origin and evolution of the universe. CMB-S4 will enhance our understanding of the universe's history, from the highest energy density at the moment of the Big Bang to the formation and evolution of cosmic structures up to the present day.

CMB-S4 is a collaborative effort proposed to be jointly pursued by the U.S. Department of Energy, the National Science Foundation, and international partners. CMB-S4 will deploy the largest arrays of superconducting microwave detectors ever built. The receiver cryostats will be integrated into three different types of highly optimized survey telescopes.

The paper briefly describes the main elements of the proposed CMB-S4 construction project and the key technologies required to build the survey telescopes. The CMB-S4 project management organization is designed as a unified single project integrating the complex organization and support from the two funding agencies. A possible project schedule is introduced, which maps out mass-producing large quantities of superconducting detector wafers, superconducting readout electronics, and testing of final focus module assemblies.

Keywords: CMB Telescopes, Cosmic Microwave Background, Millimeter Wave Telescopes, Cosmology, Inflation, Gravitational Waves

1. INTRODUCTION

The Cosmic Microwave Background (CMB) radiation, released roughly 380,000 years after the Big Bang, is the farthest and oldest light we can observe left over from the primordial phase of the Universe. Precision CMB experiments have been instrumental in establishing the ΛCDM Standard Cosmological Model of the Universe by measuring anisotropies in CMB temperature and polarization maps.

A new proposed astronomical survey experiment, the Cosmic Microwave Background Experiment - Stage 4 (CMB-S4) [1], plans to incorporate on the order of 10 times more detectors than any current CMB experiment and is designed cross critical thresholds in confining cosmological models. CMB-S4 aims to directly measure the imprint of quantum gravitational waves generated during the primordial inflationary phase of the universe. If successful, CMB-S4

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Ground-based and Airborne Telescopes X, edited by Heather K. Marshall,
Jason Spyromilio, Tomonori Usuda, Proc. of SPIE Vol. 13094, 130941N

· 0277-786X · doi: 10.1117/12.3018095

could be either the first experiment to confirm evidence of gravitational quantum fluctuations or would significantly constrain models of inflation and its energy scale. Post-inflation, the universe transitioned into a hot radiation phase, and CMB-S4 is also designed to investigate the existence of light relic species produced in this early universe as motivated by extensions to the Standard Model of particle physics. In addition, CMB-S4 will measure the sum of neutrino masses and probe the physics of dark matter and dark energy, in addition to a rich and exciting astrophysics program. A full description of the broad science case can be found in the CMB-S4 Science Book [2].

CMB-S4 is strongly endorsed by the community. Independent U.S. scientific advisory panels have consistently rated the experiment as a top priority for new scientific construction projects [3, 4, 5]. This paper describes proposed CMB-S4 experiment configurations motivated by the science case and its measurement requirements. The last part of the paper describes the project plan and the schedule for finalizing the design and construction of CMB-S4.

2. DESIGN CONSIDERATIONS

CMB-S4 has broad and compelling science goals (see Table 1), probing fundamental cosmological and particle physics questions while delivering a deep and wide millimeter-wave sky survey map of the Universe complementing other large sky surveys. These goals directly impact experiment design and telescope siting decisions. Details of the CMB-S4 science case and corresponding experiment design optimizations have been thoroughly documented in three reports (CMB-S4 Science Book [2], CMB-S4 Technology Book [6], CMB-S4 Design Report [7]).

Table 1. CMB-S4 pursues broad and compelling science goals.

1	**Primordial Gravitational Waves and Inflation**	Test models of inflation by measuring or putting upper limits on r, the ratio of tensor fluctuations to scalar fluctuations.
2	**The Dark Universe**	Determine the role of light relic particles in fundamental physics beyond the Standard Model, and in the structure and evolution of the Universe.
3	**Mapping Matter in the Cosmos**	Measure the emergence of galaxy clusters as we know them today. Quantify the formation and evolution of the clusters and the intracluster medium during the crucial early period of galaxy formation.
4	**The Time-Variable Millimeter-Wave Sky**	Explore the millimeter-wave transient sky. Measure the rate of mm-transients. Use the rate of mm-wave Gamma-Ray Bursts (GRB) to constrain GRB mechanisms. Provide mm-wave variability and polarization measurements for stars and active galactic nuclei.

2.1 The search for primordial gravitational waves and cosmic inflation

The cosmic microwave background radiation has a blackbody temperature of 2.725 K, which peaks in the microwave frequency range and is uniform across the sky to roughly one part in 100,000. The observed temperature anisotropies, which can be plotted in a power spectrum (see Figure 1), are the result of primordial density (scalar) fluctuations and vary depending on angular scales on the sky. These temperature fluctuations are a snapshot of the distribution of matter in the early Universe, which would later develop into large-scale structures we see today.

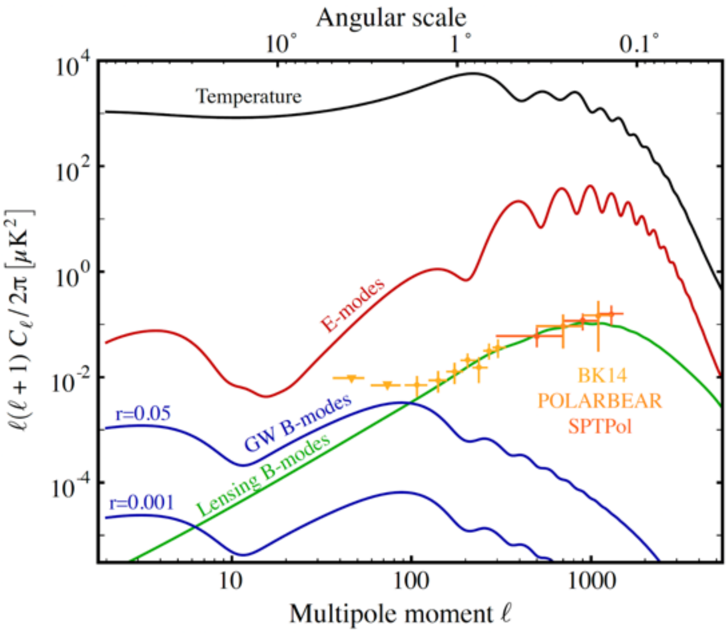

Figure 1. Theoretical predictions for the temperature (black), E-mode (red), and tensor B-mode (blue) power spectra. Primordial B-mode spectra are shown for two representative values of the tensor-to-scalar ratio: r = 0.001 and r = 0.05. Also shown are expected values for the contribution to B modes from gravitationally lensed E modes (green). Current measurements of the B-mode spectrum are shown for BICEP2/Keck Array (light orange), POLARBEAR (orange), and SPTPol (dark orange). The lensing contribution to the B-mode spectrum can be partially removed by measuring the E and exploiting the non-Gaussian statistics of the lensing. (Graphic adapted from [2].)

Primordial fluctuations also imprint angular scale variations in the polarization of a small fraction of CMB radiation. CMB polarization can be decomposed into curl-free "E-modes" and curl-like "B-modes" (see Figure 2). The E-mode polarization anisotropy is driven by density (scalar) perturbations and has been measured with high precision over a wide range of angular scales, supplementing temperature anisotropy data. Of greater interest to CMB-S4 is the B-mode component of the polarization, which cannot be generated by primordial density fluctuations. B-modes are expected to be an order of magnitude weaker than E-modes and arise due to either (1) gravitational lensing of E-modes into B-modes or (2) primordial gravitational waves as predicted by cosmic inflation.

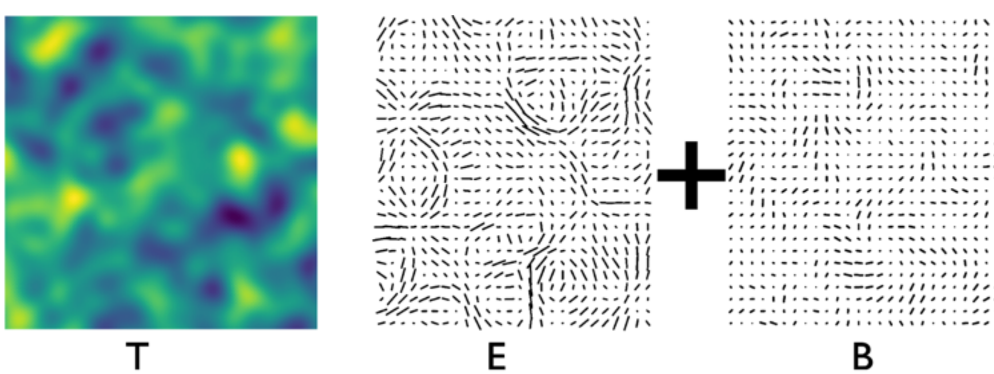

Figure 2. CMB sky maps include information about temperature and polarization anisotropies. Primordial fluctuations imprint angular scale variations in the polarization of a small fraction of CMB radiation, which can be decomposed into curl-free E-modes and curl-like B-modes. B-modes can only arise due to either (1) gravitational lensing of E-modes into B-modes or (2) primordial gravitational waves as predicted by cosmic inflation. (Graphic adapted from [8].)

CMB-S4 is designed to search for the faint B-mode polarization signal imprinted by quantum fluctuations in the gravitational field during inflation. Models of inflation predict that gravitational waves will source B-modes at angular scales of a degree or larger. Detection would provide the first experimental insight into the quantum nature of gravity. In addition, the strength of the B-mode polarization signal, as indicated by the tensor-to-scalar ratio *r*, would directly measure the Universe's expansion rate during inflation. Even non-detection of the signal within the forecasted experimental sensitivity of CMB-S4 would significantly advance our understanding of inflation since it would rule out the most popular and widely studied classes of theoretical models.

2.2 Experiment design

The degree-scale B-mode polarization signal expected from primordial gravitational waves is significantly smaller than two sources of astrophysical contamination: (1) gravitational lensing and (2) foregrounds from within our Galaxy.

As observers today, we see a distorted version of the primordial map of the CMB radiation due to the gravitational lensing of CMB photons by large-scale structure. This deflection occurs as CMB photons travel near massive objects, such as galaxies and galaxy clusters, which act as lenses. Gravitational lensing is cosmologically interesting in its own right and can be used to measure the projected mass distribution and constrain cosmological parameters such as the sum of neutrino masses. The deflection of CMB photons by gravitational lensing creates a distinct non-Gaussian signature on the CMB. This includes converting E-mode polarization into a mixture of E- and B-modes, forming a non-primordial foreground with the same spectrum as the original CMB.

It is possible to determine the gravitational lensing potential by measuring the conversion of E-modes to B-modes at smaller angular scales. The E-mode polarization anisotropy of the Cosmic Microwave Background (CMB) can be precisely measured, and in the arc-minute angular range, the B-mode polarization signal is more pronounced. This allows to establish the lensing potential which can then be extrapolated to larger angular scales (degree-angular scale) where gravitational effects are weaker, but still correlated to the stronger arc-minute scale signal (see Figure 1).

Since CMB-S4's primary goal is to measure B-mode polarization as the signature of inflation, this leads to several general aspects of the instrument design and the survey strategy. The measurement goals require sensitivity on angular scales ranging from arcminutes to tens of degrees. This drives the optimization to two types of telescopes with different angular resolutions: Lower resolution (degree-angular scale) is needed for detecting inflationary B-modes (see Figure 1). Moderately higher resolution (arcminute-angular scale) is needed to measure B-modes caused by gravitational lensing. The latter information is used to remove lensing contamination from the inflationary B-mode signals on the degree-angular scale.

Due to their compact size, lower resolution, and small aperture (~0.6 m diameter), refracting telescopes have set the best limits to date on degree scale B-modes and have the best-demonstrated understanding of systematic effects at those angular scales [7]. Therefore, CMB-S4 will utilize an array of easily-baffled small aperture cryogenic refracting telescopes for the degree angular-scale measurements. A higher resolution, large aperture (~5 m to 6 m diameter) reflecting telescope [7] is needed for the arcminute delensing measurements on the same patch of sky the small telescopes target.

As mentioned in section 2.2, foreground radiation emanation from within our Galaxy cannot be avoided and must also be subtracted with high accuracy. Therefore, both telescope types will utilize detector modules operating at nominal low-, mid-, and high-frequency bands. Foreground contribution through dust dominates at high frequencies, while synchrotron radiation dominates at lower frequencies. Two separate high-frequency and two low-frequency detector bands (see Figure 3) allow for measurements of the dust and synchrotron contamination amplitude and spectral index. That information is used to clean the CMB channels in the mid-frequency range. In addition, the small telescopes feature split mid-frequency bands for added spectral resolution near the frequencies where the CMB is measured to allow subtraction of more complex foreground contamination.

The frequency bands span the four atmospheric transmission windows available for ground-based CMB experiments. Figure 4 shows the calculated atmospheric brightness temperature spectra for the South Pole at 0.5 mm precipitable water vapor (PWV) and Atacama at 1.0 mm PWV and the detector frequency bands implemented for observation [10]. CMB observations need to reject considerable atmospheric noise contributions. Although atmospheric fluctuations are not expected to be polarized, the significantly stronger unpolarized temperature signal leaks into the measured polarization signal on the detector level. CMB-S4 mitigates these issues by including additional modulations into the telescope design, such as boresight rotation or modulation of the entire optics with a polarization modulation scheme in front of the telescope.

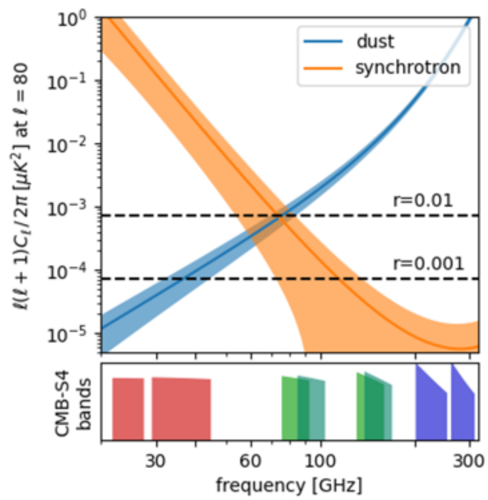

Figure 3. Foreground radiation emanation from within our Galaxy cannot be avoided and must be subtracted with high accuracy. Foreground contribution through dust dominates at high frequencies, while synchrotron radiation dominates at lower frequencies. Two separate high-frequency and two low-frequency detector bands are utilized to allow for measurements of the dust and synchrotron contamination amplitude and spectral index. That information is used to clean the channels in the mid-frequency range where the CMB is measured. Uncertainty bands are based on BICEP results. (Graphic by Colin Bischoff, University of Cincinnati)

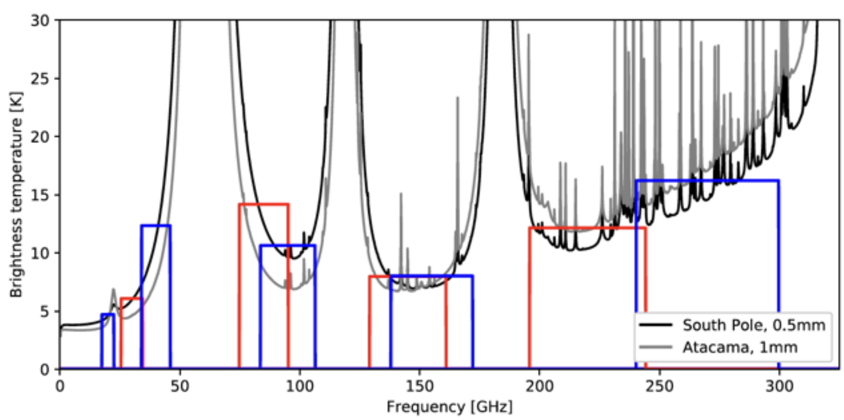

Figure 4. Calculated atmospheric brightness temperature spectra (at zenith) for the South Pole at 0.5 mm precipitable water vapor (PWV) and Atacama at 1.0 mm PWV (both are near the median values). Atmospheric spectra are generated using the *am* Atmospheric Model [9]. Blue: LAT frequency bands, Red: SAT frequency bands. (Graphic adapted from [10].)

2.3 CMB-S4 survey configuration and telescope siting options

State-of-the-art CMB observations require Earth's highest and driest sites to achieve increased atmospheric transmittance and low atmospheric emission within the required spectral bands. The two best sites developed for CMB observations are the South Pole (2,800 m elevation) in Antarctica and Cerro Toco (5,200 m elevation) in the Chilean Andes. Both sites have been in use for several decades, have hosted many CMB telescopes, and are the only mature CMB sites that can meet the stringent CMB-S4 science objectives.

In principle, it would be possible to meet all CMB-S4 science requirements with a single wide-area, ultra-deep, high-resolution, multi-frequency survey. However, achieving the necessary depth across a wide sky area would be prohibitively slow and expensive. Therefore, CMB-S4 implements two independent sky surveys utilizing sets of dedicated telescopes optimized for the different science cases. Due to the exceptionally small signal and the statistics required in detecting inflationary B-modes an ultra-deep "*r*"-survey focuses survey weight on a single, small, and (ideally) continually measured sky area. This ultra-deep survey is designed to detect primordial gravitational wave B-modes (science goal 1, see Table 1). It will also deliver results for science goals 3 and 4 (deep cluster and transient measurements). A second, independent, wide-area survey is performed for science goals that require large sky coverage, e.g. related to light relic particles, galaxy clusters, and transients (science goals 2, 3, 4). Each survey will enhance the other's science results with respect to statistics and systematics. A brief summary of the two survey types can be found in Table 2. Figure 5 illustrates the nominal sky coverage for both surveys. The ultra-deep field in Figure 5 reflects the optimized South Pole field. Two ultra-deep fields optimized for observation from Chile are located in the southern and northern hemispheres.

Table 2. CMB-S4 implements two independent sky surveys utilizing sets of dedicated telescopes optimized for the different science cases (see Figure 5 for sky coverage). The number of telescopes depends on the siting alternatives, see Table 3.

Survey Type	**Science Goals**	**Sky Coverage**	**Telescope Types**	**Nominal Frequency Bands**
ultra-deep "*r*" survey	1, 3, 4	small patch (~3%)	array of small aperture (⌀0.6 m) refractor telescopes one or two large aperture (⌀5 m) reflecting telescopes for delensing	SAT: 25, 40, 85, 145, 95, 155, 230, 280 GHz SPLAT: 20, 25, 40, 90, 150, 230, 280 GHz
deep-wide N_{eff} and Legacy survey	2, 3, 4	large patch (60%)	two large aperture (⌀6 m) reflecting telescopes	LAT: 25, 40, 90, 150, 230, 280 GHz

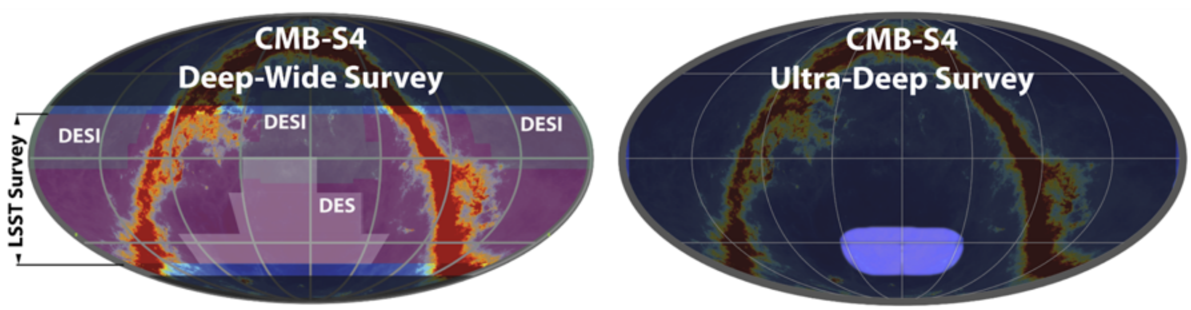

Figure 5. The sky coverage in blue of the CMB-S4 Ultra-Deep Survey from South Pole, covering 3% of the sky, and the Deep-Wide Survey from Chile, covering 60% of the sky, with other complementary sky surveys overlaid. (Graphic adapted from [2].)

At mid-latitude, the Chilean Atacama site has access to more than 80% of the sky, enabling observation of the 60% of sky required by many of the science goals discussed above. The South Pole site, on the other hand, is better suited to deep integration on a small portion (~3%) of the sky. This makes the South Pole site particularly well-suited for observations on the ultra-deep field since the stationary sky patch is available most of the year. CMB-S4 is also pursuing an experiment configuration where the ultra-deep survey can be performed from Chile. Such a configuration requires many more (at least a factor of 3) detectors since a Chile-optimized deep sky patch is not available all the time due to the Earth's rotation, sun avoidance needs, and weather conditions. Therefore, a Chile-based ultra-deep survey experiment requires more aggressive optics with much higher detector pixel density to stay cost-competitive with a South Pole ultra-deep survey experiment.

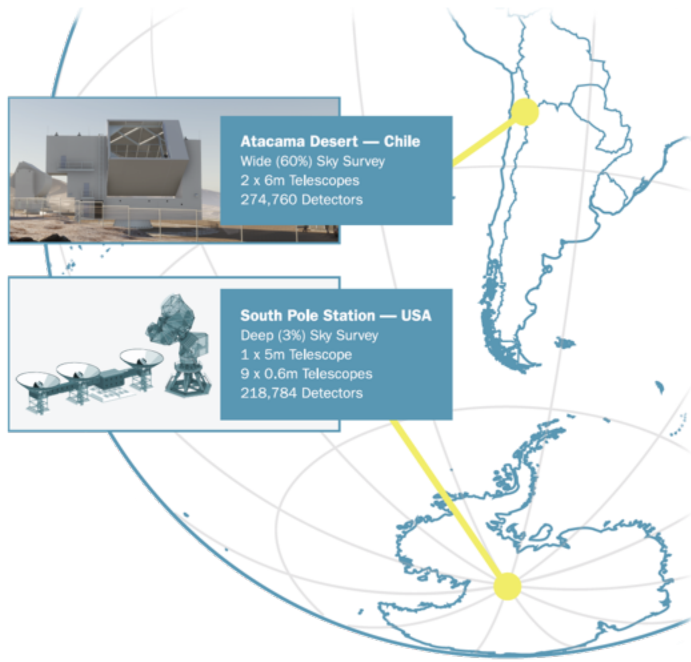

Figure 6. CMB-S4 has developed a preferred experiment configuration utilizing the South Pole and Chilean Atacama sites. CMB-S4 is also pursuing an experiment configuration with all telescopes sited in Chile, which would reduce dependence on South Pole logistics constraints. Table 3 lists telescope counts for both siting options. (Graphic by Samantha Trieu, LBNL)

Table 3. Two siting alternatives for CMB-S4 with required telescope counts. Option 2 in Chile is currently under development, and details may change as the configuration is optimized.

Experiment Configuration	Sites	Small Aperture Telescope Count	Large Aperture Telescope Count	Detector Count
Option 1	South Pole + Chile	9 at the South Pole	1 at the South Pole for delensing 2 in Chile for the large sky survey	~500,000
Option 2	Chile only	27 in Chile	2 in Chile for delensing plus 2 in Chile for the large sky surveys	~760,000

CMB-S4 has developed a preferred experiment configuration utilizing the South Pole and Chilean Atacama sites, see Figure 6. Unfortunately, the South Pole site will not be accessible for new projects for at least the next ten years due to critical South Pole base infrastructure maintenance needs caused by deferred maintenance. Therefore, CMB-S4 is currently developing an experiment alternative with all telescopes sited in Chile and with both surveys (ultra-deep and deep-wide) performed from the same site. Due to the reduced availability of a deep sky patch from Chile, the Chile-only experiment configuration needs three times more small aperture telescopes and at least one additional delensing telescope. Higher-density detectors on the focal plane are required to develop a cost-competitive alternative and to keep the survey duration within acceptable (~10 years) limits. Table 3 summarizes the two siting options and the required telescope counts.

3. CONCEPTUAL DESIGN

To achieve the ambitious science goals set out in the CMB-S4 Science Book [2], CMB-S4 requires ~500,000 effectively background-limited detectors. Since this exceeds the number of detectors that could fit in any current single telescope design, CMB-S4 will consist of an array of multiple telescopes. Technology tradeoffs have been documented in the CMB-S4 Technology Book [6]. The current conceptual design is detailed in the CMB-S4 Design Report [7], which will be continually updated as the design matures. Most of CMB-S4's subsystem design choices are based on existing and proven technologies, reflecting a conservative design approach. That approach has been adopted since measuring the inflationary B-mode polarization signature is exceptionally challenging. CMB-S4 has to measure a nano-K level imprint on the 2.725 K radiation background with the telescopes embedded in a 300 K environment, requiring experimental systematics to be reduced to a minimum and well understood. A fundamental challenge for CMB-S4 will be the large-scale production of the superconducting detector modules. Therefore, the project has developed a robust, multi-year production plan that utilizes several expert fabrication sites across the US; see chapter 4.

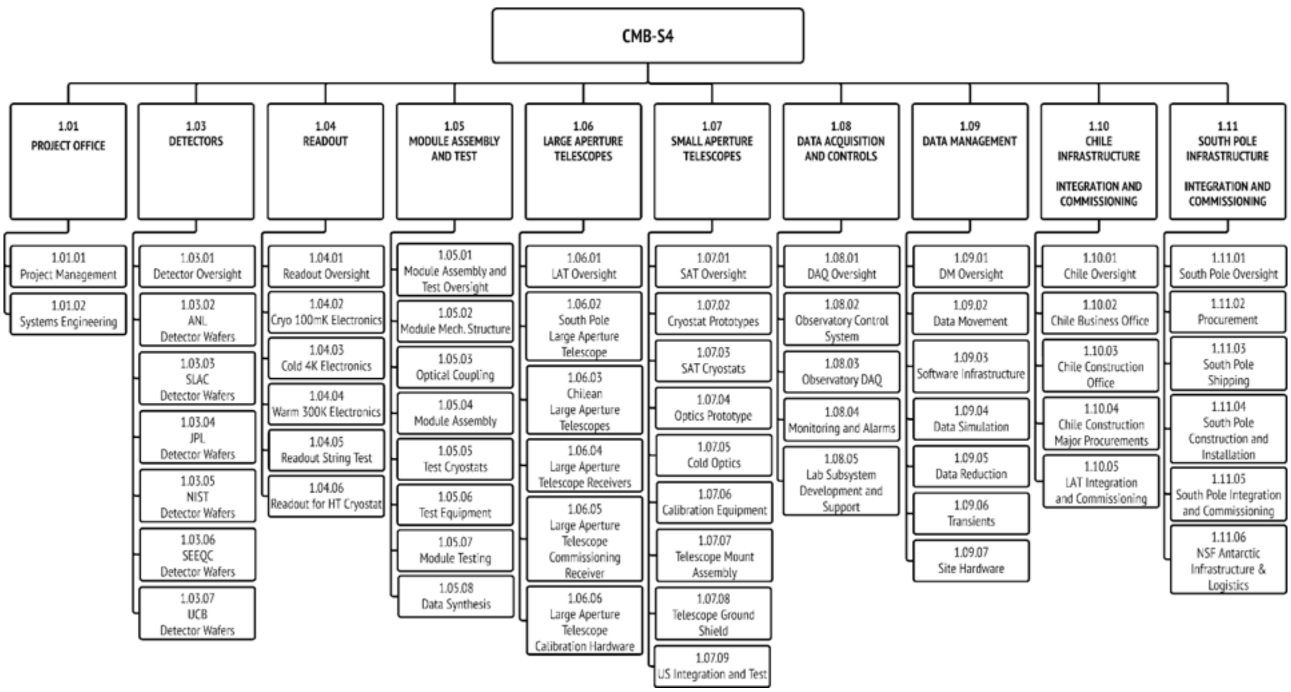

Figure 7. CMB-S4 project work breakdown structure, which captures all elements of the CMB-S4 experiment.

The project work breakdown structure (see Figure 7) captures each element of the CMB-S4 experiment. According to that breakdown, the following subsections briefly describe the main experiment components.

3.1 Detector Module Package and Readout Chain

A fundamental building block of CMB-S4 is the mechanically integrated detector module package [11] mounted on the receiver's final focus and operated at 100 mK; see Figure 8. The CMB-S4 detector and readout system utilizes arrays of Transition Edge Sensor (TES) bolometers coupled to the sky via feedhorns and read out and amplified using time-division multiplexing (TDM) of Superconducting Quantum Interference Devices (SQUIDs). Microwave power from the sky is focused through the receiver optics system and coupled to each of the detector wafer pixels through a gold-plated aluminum feedhorn. The feedhorn, detector wafer, and three gold-plated silicon interface wafers represent the radio-frequency (RF) detector package, which couples the microwave signal to the micro-fabricated superconducting RF structures on the detector wafer while minimizing RF leakage between detector pixels. Feedhorns coupled to a single detector pixel with planar ortho-mode transducers (OMTs) have been demonstrated to provide excellent beam quality and polarization efficiency. Recent advances in free-form machining and electromagnetic optimization simulations enable high-quality horns to be manufactured economically at scale (see Figure 8 for a cross-section of a machined horn).

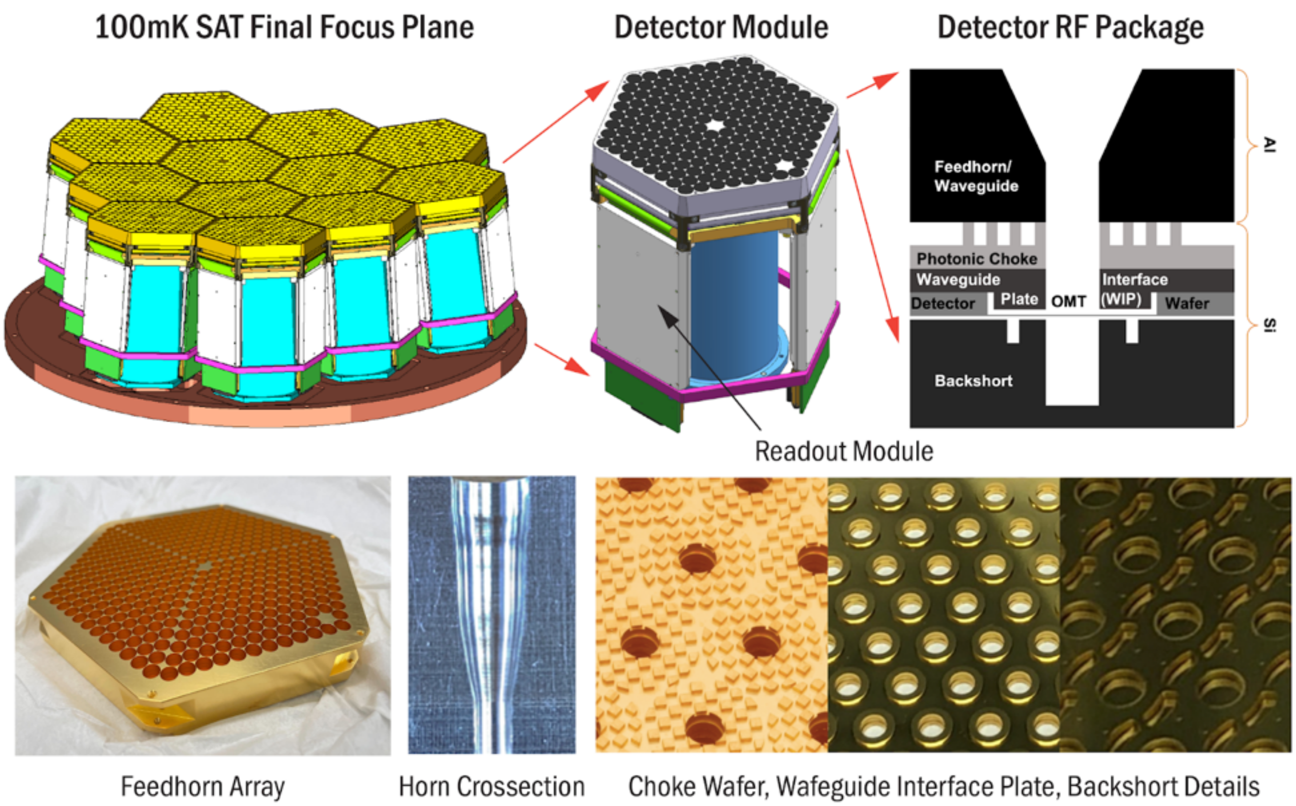

Figure 8. A fundamental building block of CMB-S4 is the mechanically integrated detector module package mounted on the receiver's final focus and operated at 100 mK. As an example, 12 modules are assembled on the SAT (curved) focal plane. The module consists of the detector package on the top and several 100 mK readout modules - the number of readout modules depends on the wafer frequency. As described in the main text, the feedhorn, detector wafer, and three gold-plated silicon interface wafers represent the radio-frequency (RF) detector package, which couples the microwave signal to the micro-fabricated superconducting RF structures on the detector wafer while minimizing RF leakage between detector pixels. (Images are adapted from [11].)

As shown in Figure 9, a readout amplification chain [11] with two superconducting stages at 100 mK and 4 K plus one room-temperature stage carries the signals outside the receiver cryostat for subsequent integration into the data acquisition system. The first-stage SQUID amplifiers, multiplexing, TES biasing, and signal filtering components are contained in 100 mK readout modules co-located with the detector wafers in the integrated detector module package (see Figure 8). The readout modules are electrically connected to the wafer via a short flexible circuit with superconducting traces to limit parasitic impedances between the TES detector and the first-stage amplifier. The first-stage SQUID amplifiers and flux-activated row-select switches are fabricated onto a multiplexer chip (MUX) serving ~10 TES channels each. The shunt resistors for TES voltage-biasing and the series inductors that define the TES signal and noise bandwidth are fabricated onto a "Nyquist" filter chip (NYQ), also called a TES biasing chip. The MUX and NYQ chips for a readout column are seated on and bonded to a larger silicon wiring chip. This chip contains superconducting traces that connect to the Nyquist chips on one edge and present bond pads for connection to the TES detectors on a perpendicular edge. Sets of chips for four columns are assembled into a readout module. Figure 10 shows a smaller, 2-column 100 mK readout board used to prototype the electronics design configuration.

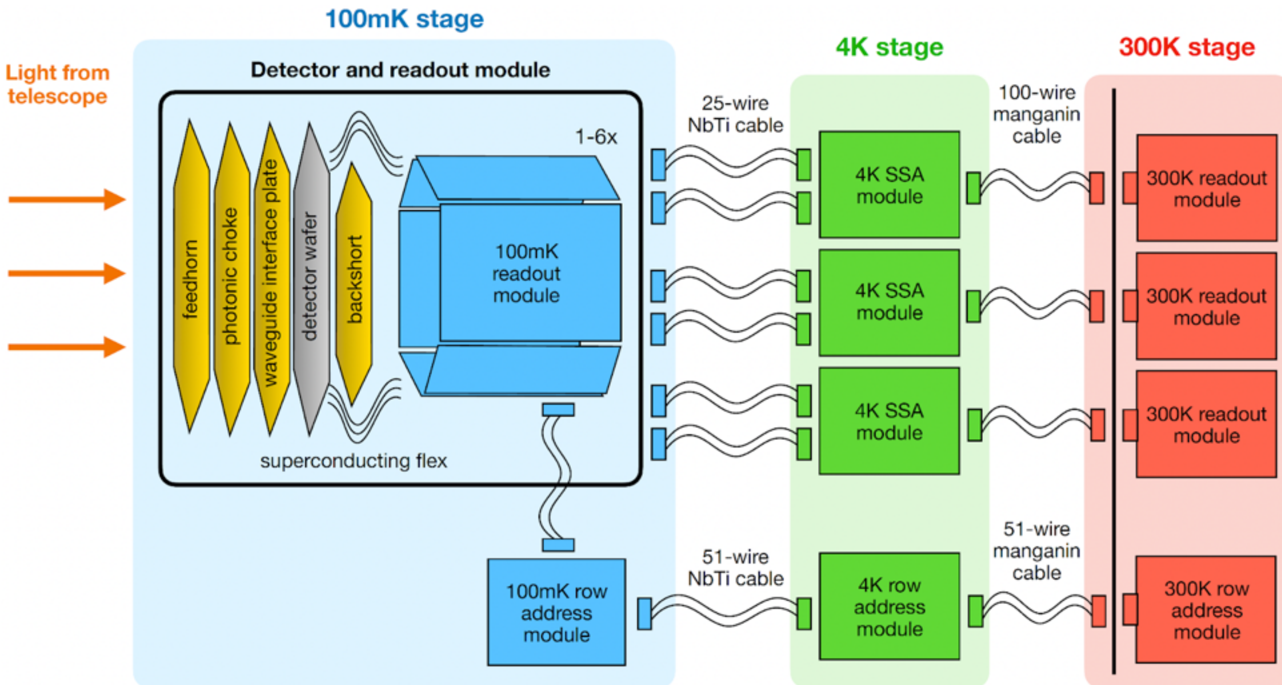

Figure 9. The readout amplification chain with two superconducting stages at 100 mK and 4 K plus one room-temperature stage carries the detector signals outside the receiver cryostat for subsequent integration into the data acquisition system. (Graphic adapted from [11].)

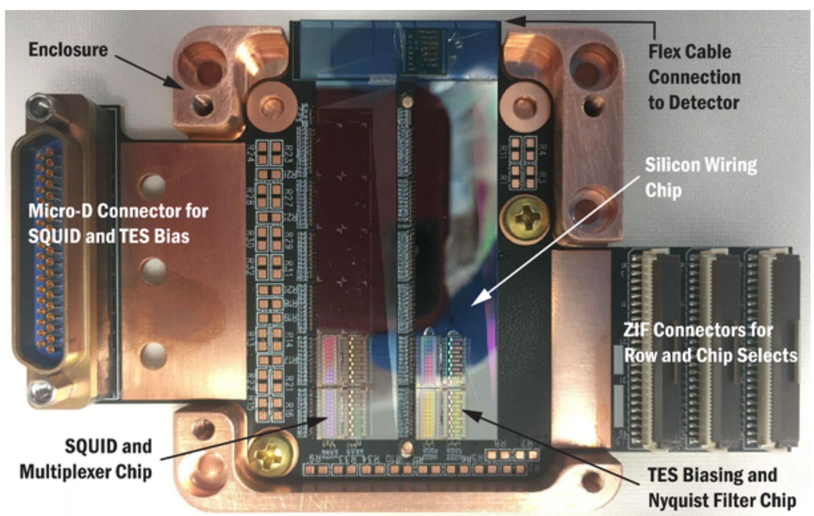

Figure 10. A 2-column 100 mK readout board that houses the first stage SQUID amplifier and multiplexer (MUX) chips and the TES biasing (NYQ) chips was used to prototype the electronics design configuration. (Image adapted from [11].)

Each CMB-S4 feedhorn will deliver power to a single detector pixel. Depending on the wafer type, each wafer contains from ~50 to more than ~1,800 detectors, see Table 4. Each detector pixel couples to the optical signal through a planar Ortho-Mode Transducer (OMT) comprised of four niobium probes suspended in the waveguide. The OMT separates the two linear polarizations and launches each of these signals onto one of the optical chains, where the signal is transmitted along superconducting transmission lines. A wide-band stepped impedance transformer transitions the transmission line from the high-impedance OMT to the low-impedance micro-strip. The signal is then fed into an in-line diplexer that channels the signal into the two optical bands. This dichroic architecture allows for high sensor density (2 optical bands, each with 2 polarization directions) while maintaining high end-to-end optical efficiency in all observing bands.

Table 4. Summary of detector and readout counts for the eight wafer types of CMB-S4. Counts are for experiment configuration 1 (see Table 3). All wafers are dichroic (except the ULF wafer). Each pixel incorporates four detectors (two frequencies with two polarization directions each): ULF…ultra-low-frequency: SPLAT only: 20 GHz; LF…low-frequency: LAT and SAT: 25 and 40 GHz; MF…mid-frequency: LAT: 90 and 150 GHz, SAT: 85 + 145 GHz and 95 + 155 GHz; HF…high-frequency: LAT and SAT: 230 and 280 GHz

Wafer Type	**3 Large Aperture Telescopes (LAT)**				**9 Small Aperture Telescopes (SAT)**			
	ULF	**LF**	**MF**	**HF**	**LF**	**MF1**	**MF2**	**HF**
Number of Wafers	4	25	162	64	12	36	36	24
Pixels per Wafer	27	48	430	467	12	145	167	467
Detectors per Wafer	54	192	1,720	1,868	48	580	668	1,868
Total Active (Unvignetted) Detectors	216	4,800	278,640	119,552	504	18,288	21,312	40,032
Readout Modules per Wafer	1	1	6	6	1	3	3	6
Readout Columns per wafer	4	4	24	24	4	12	12	24
Readout Rows	80 with 2-level addressing				80 with 2-level addressing			

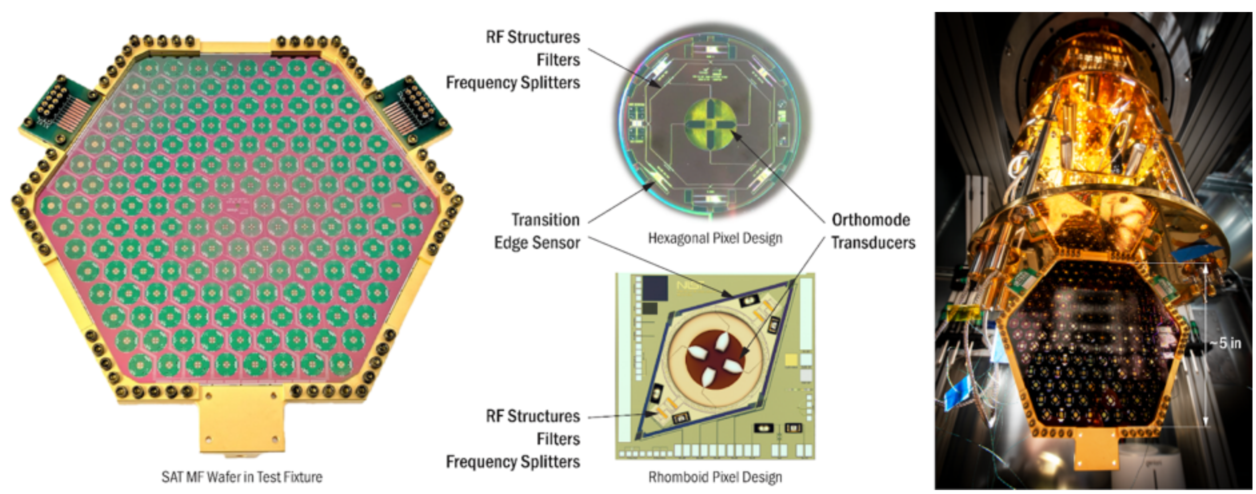

Figure 11. A CMB-S4 SAT mid-frequency detector wafer mounted in a testing frame. Depending on the specific wafer design optimization, CMB-S4 uses hexagonal or rhomboid pixel arrangements. The middle two images show enlarged images of the detector pixels with the RF structures visible (top image by Aritoki Suzuki, LBNL; bottom image by Shannon Duff, NIST). A test arrangement of a single wafer in a dilution refrigerator is shown in the right image (the wafer is approx. 120 mm across flats).

The geometry of the superconducting optical components is tuned to match the specifications for each CMB-S4 observing band. The transmission lines are eventually terminated with lossy material, dissipating the signal power onto one of four Transition Edge Sensor (TES) bolometers. These TES bolometers are thermal detectors consisting of a heat capacity that is suspended from the silicon wafer so that it is weakly heat sunk. Changes in absorbed power (e.g. from changes in the optical signal) produce changes in temperature that are sensed by one of two TESs. One of the TESs is a

"Calibration TES" that is optimized for observing terrestrial signals under high optical loading (room temperature). The other TES is the "Science TES", which is optimized for the CMB survey and has low optical loading. Both TESs operate under the same principle where their steep superconducting-to-normal transition works together with a resistively-shunted voltage bias to establish a strong negative electro-thermal feedback. The temperature at which the TES transitions from superconducting to normal is called the transition temperature or Tc.

Figure 11 shows, as an example, a CMB-S4 SAT mid-frequency wafer mounted in a testing frame. The microwave frequency range determines the wafer's pixel density (see Table 4). Depending on the specific wafer design optimization, CMB-S4 uses hexagonal or rhomboid pixel arrangements. Figure 11 shows enlarged images of the detector pixels with the previously described RF structures clearly visible. A test arrangement of a single wafer in a dilution refrigerator is shown for size comparison.

The detectors are fabricated in cleanrooms on 150-mm ("6-in") diameter wafers using several cycles of material deposition, patterning, and etching to build up a complete device. Superconducting materials (niobium, aluminum, and manganese-doped aluminum) and normal metals (gold and palladium) are grown via physical vapor deposition (PVD), typically sputter or e-beam evaporation. Dielectric films are deposited by either PVD or chemical vapor deposition (CVD). Features are defined using a combination of stepped and direct-write lithography. Lift-off, chemical wet etch, plasma etching, and ion milling can be used to define lithographed features. A deep reactive silicon etch is used to release membranes for the OMT and the TES bolometer thermal isolation. It takes several weeks to complete a batch (4 to 6 units) of wafers.

3.2 Telescope Designs

As previously mentioned, the CMB-S4 science case requires refracting Small Aperture Telescopes (SAT) for degree angular scale measurements to detect B-modes plus reflecting Large Aperture Telescopes (LAT) for arcminute scale measurements for delensing and the Legacy Survey. The CMB-S4 scan strategies determine the telescope design requirements, which are described in detail in the CMB-S4 Design Report [7]. The different science goals, surveys, and environments of the LATs have led to the development of different designs for the South Pole LAT (SPLAT) and the Chilean LAT (CHLAT). In particular, the deep and wide survey covering approximately 60% of the sky requires modestly higher angular resolution, and a telescope design was selected based on the mature CCAT-prime Observatory and Simons Observatory (SO) 6-meter aperture telescopes currently under construction. The ultra-deep survey covering only 3% of the sky does not require as high angular resolution, and the inflation science goal motivates the pursuit of additional features to improve image quality and mitigate systematics using both gapless mirrors and boresight rotation. However, the focal ratios of the two telescope designs have been optimized such that nearly identical LAT receivers can be developed and deployed on both telescope designs.

Figure 12 shows the two large aperture telescope designs for Chile and the South Pole. Both telescopes incorporate the same receiver cryostat design. The LAT receiver houses the refractive optics used to couple light onto the detector modules. Each detector wafer is illuminated by its own optics tube. The large (2.5 m diameter) LAT receivers are mounted at the focal point of each telescope. The Chile LAT incorporates a mechanism that allows the receiver to rotate on its optical axis. The South Pole telescope has full boresight rotating capabilities, as described in [7].

3.3 Chilean Large Aperture Telescope (CHLAT)

The Chilean Large Aperture Telescopes (CHLAT) utilize a 6-m Crossed-Dragone (CD) design [7, 12] on a conventional elevation over azimuth mount, with the instrument boresight aligned with the elevation axis. This alignment facilitates instrument rotation and enables partial telescope boresight rotation because the elevation axis can rotate a full 180° from horizon to horizon, enabling two distinct telescope orientations at every azimuth position. Each mirror is approximately 6 m in diameter and will be segmented into many panels. The 6 m diameter primary aperture gives an angular resolution of 1.4 arc-min at $\lambda = 2$ mm (150 GHz). The design copies the CCAT Observatory and SO LAT designs. The CD layout offers several advantages compared to other telescope designs. For CMB-S4, the most important advantages are the large diffraction-limited field of view (FOV) combined with the compactness of the two-mirror configuration. While modestly larger diffraction-limited FOVs have been achieved with other telescope configurations, including three mirror anastigmat designs, the alternative designs were not nearly as compact, and the use of a third mirror with panel gaps would degrade the sensitivity of the detectors due to the extra emission from the gaps. The polarization properties of the

CD configuration have been shown to be superior to Gregorian and Cassegrain designs, partly due to the smaller angles of incidence on the reflecting surfaces. Systematics associated with the telescope mirrors are much smaller than systematics caused by the lenses, filters, and feedhorns inside the receivers. The reference design provides a 7.8° FOV. A FOV this large can make coupling to arrays of detectors challenging. A natural approach to take advantage of such a large FOV is to split the receiver optics into multiple independent optical paths or optics tubes [7]. These optics tubes are designed to be modular and easily replaceable, which facilitates the deployment of different frequencies in each optics tube as described above (see also Figure 12).

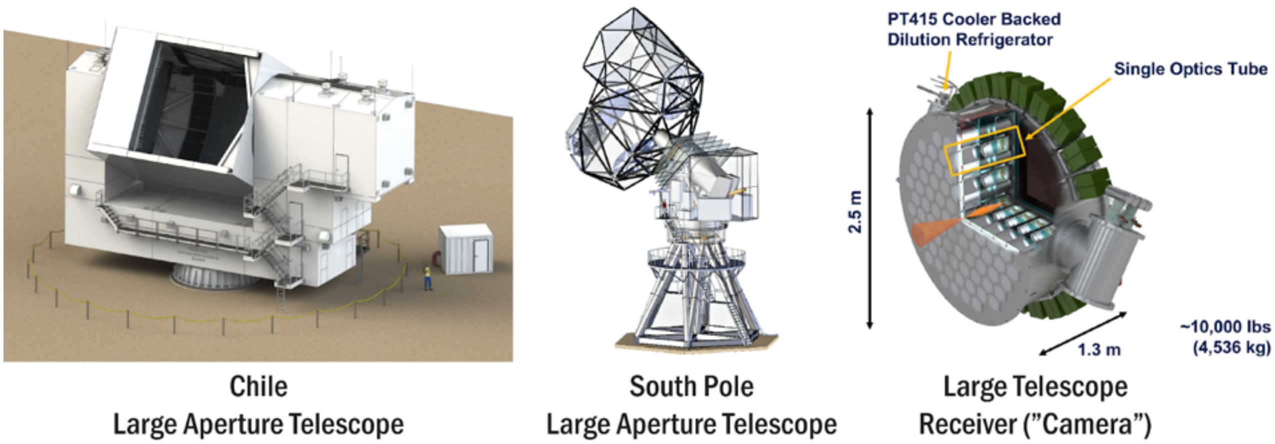

Figure 12. CAD models of the two large aperture telescope designs for Chile and the South Pole. While the Chilean LAT design is based on existing telescopes currently under construction, the SPLAT is a new development. Both telescopes incorporate the same receiver cryostat design, which houses 85 individual optics tubes. (Graphics adapted from [7, 12, 13].)

3.4 South Pole Large Aperture Telescope (SPLAT)

The South Pole Large Aperture Telescope (SPLAT) is an off-axis Three-Mirror Anastigmat (TMA) on an elevation over azimuth mount with an additional boresight rotation axis [7, 13]. The design incorporates a unique combination of features not seen before in a telescope of this size that are key to achieving the science goals. Full bore-sight rotation allows for the measurement and characterization of polarization errors. The 5 m diameter primary aperture gives an angular resolution of 1.7 arc-min at $\lambda = 2$ mm (150 GHz). Monolithic mirrors avoid segment gaps for low scattering. The TMA layout enables high throughput with a 9.4° Field of View. A co-moving shield surrounding the full telescope optics controls ground pickup. The elevation axis is about 16 m above the foundation raft, and the elevation structure has a maximum vertical sweep radius of about 16m. The total mass of the structure above the raft is about 414 tons.

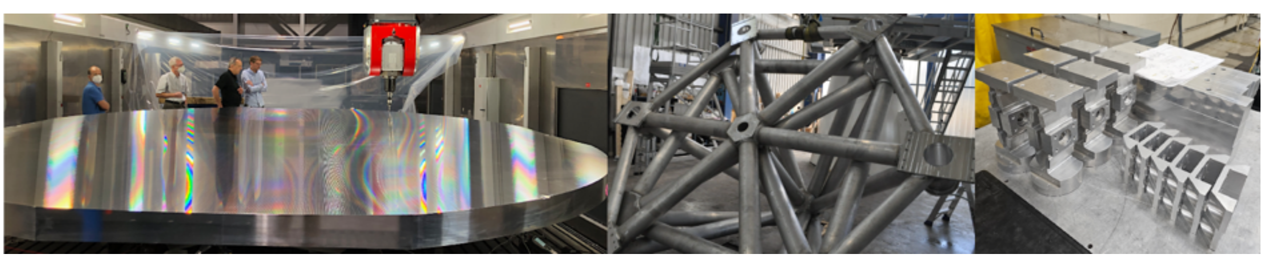

Figure 13. Fabrication of a prototype monolithic 5 m aluminum reflector for the South Pole LAT primary mirror. The left image shows CMM profile measurements after fabrication has been completed. The two right images show the mirror support structure and mounts. (Left image adapted from [14].)

While the Chilean LAT design is based on existing telescopes currently under construction, the SPLAT is a new development. Monolithic 5 m diameter aluminum mirrors have not previously been built at the surface accuracy required for CMB-S4. To mitigate the risk associated with this uncertainty, a prototype mirror was fabricated in 2022 to validate manufacturing processes and surface verification methods [14]. The front of this mirror after final machining is shown in Figure 13. Other prototype components, e.g., the mirror mounts and mirror support structure, are currently being assembled.

3.5 Small Aperture Telescope (SAT)

The ultra-deep survey, which targets the signature of primordial gravitational waves, drives the key design requirements for the Small Aperture Telescopes (SATs). Due to their compact size, lower resolution, and small aperture (~0.6 m diameter), refracting telescopes have set the best limits to date on degree scale B-modes and have the best-demonstrated understanding of systematic effects at those angular scales. For instance, small aperture telescopes from the BICEP/Keck series at the South Pole have produced all the leading r constraints to date from ground-based B-mode measurements through Stages 1, 2, and 3.

The baseline SAT design [7] calls for three telescope mounts at the South Pole (see Figure 7), each with a single three-tube cryostat, for a total of nine telescope tubes. Figure 14 shows the SAT cryostat design, where three telescope tubes are connected to a common refrigeration system. A single SAT mount houses three telescope tubes. The tubes house detectors of four different frequency types. Each tube's focal surface contains 12 identical detector modules designed for the specified frequency bands. The CMB-S4 SATs maintain the BICEP/Keck two-lens refractive optics design. However, the optical prescriptions of the SATs are optimized to give consistent throughput and aperture illumination over a larger physical diameter on the focal plane. The physical constraints on two-lens optical systems and the limited diameter of the optical elements have led to the decision to use a slightly concave focal surface, which is implemented by mounting the flat detector modules at shallow angles to approximate a curved surface (see Figure 8). The baseline lens material for all bands is HDPE plastic, though silicon is being retained as a possible option in the highest-frequency bands owing to its especially low bulk attenuation.

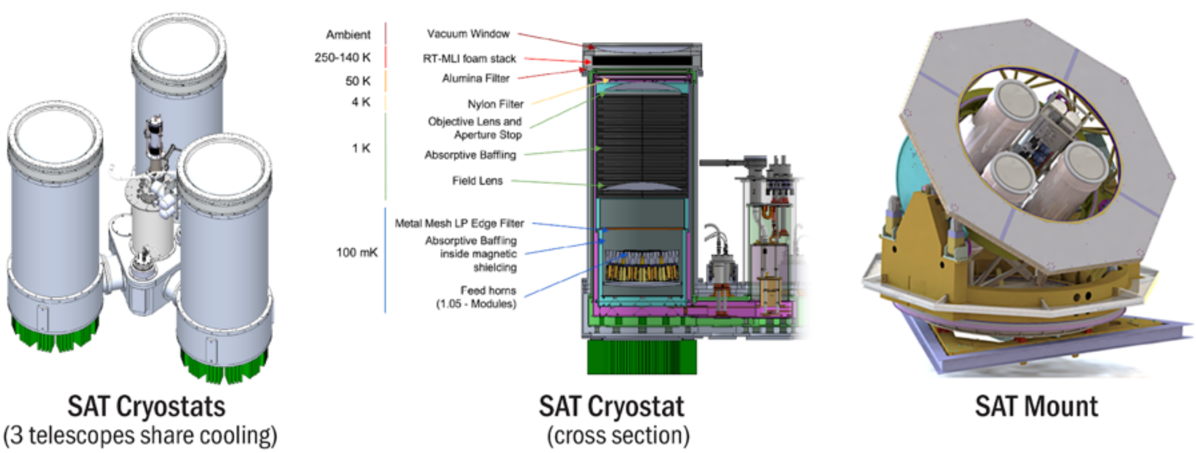

Figure 14. The left image shows the current SAT cryostat design, where three telescope tubes are connected to a common refrigeration system. The CMB-S4 SATs maintain the BICEP/Keck two-lens refractive optics design but are enhanced by implementing a slightly curved focal plane. A single SAT mount, shown on the right, houses three telescope tubes. (Graphics adapted from [7].)

The use of dichroic detectors with substantial frequency separation requires similarly broadband cryogenic anti-reflection coatings on the optical elements to prevent reflections at percent or better levels. Part of the critical engineering effort to finalize the SAT designs includes the design and prototyping of anti-reflection coating layers, special (Dyneema-laminate) vacuum windows, and thermal filters.

Coupling to emission from the warm ground or the Galaxy/Sun/Moon during CMB scans needs to be limited. A key advantage of the small-aperture telescope approach is that the telescope field of view can be completely surrounded by multiple levels of ground shielding, significantly reducing the effect of sidelobes. The first level of baffling is a co-moving absorptive cylinder that extends around each SAT receiver tube window aperture. CMB-S4 will also use an additional fixed, reflective ground shield that surrounds the entire telescope mount. While no rays from the aperture couple directly to the ground shield, those that diffract over the lip of the co-moving forebaffle tubes do. The ground shield ensures that rays must diffract twice before terminating on the warm ground. The forebaffles plus the fixed ground shields are visible in the site image in Figure 17.

3.6 Data acquisition and experiment control system

The reference design for the data acquisition and experiment control subsystem is closely based on existing Stage-3 CMB experiments, with a clear technical path to handling the higher data rates from CMB-S4. The DAQ subsystem encompasses (a) the acquisition of high-rate data (∼400 Hz, ∼32 bits per detector) from the detector arrays and the acquisition of low-rate data from "housekeeping" sources on each telescope (e.g. cryogenic thermometry, telescope position encoders, and motion metrics, pressure gauges, calibrators, networking statistics) and from the site if requested (eg. networking, disk space, power, and water cooling data); (b) control of these subsystems including an observation sequencer for each telescope; (c) real-time monitoring of housekeeping and data quality statistics; (d) non-critical alarms for out-of-range data; and (e) the provision of timing and frequency reference signals. The scope of DAQ and the experiment control system is shown schematically in Figure 15.

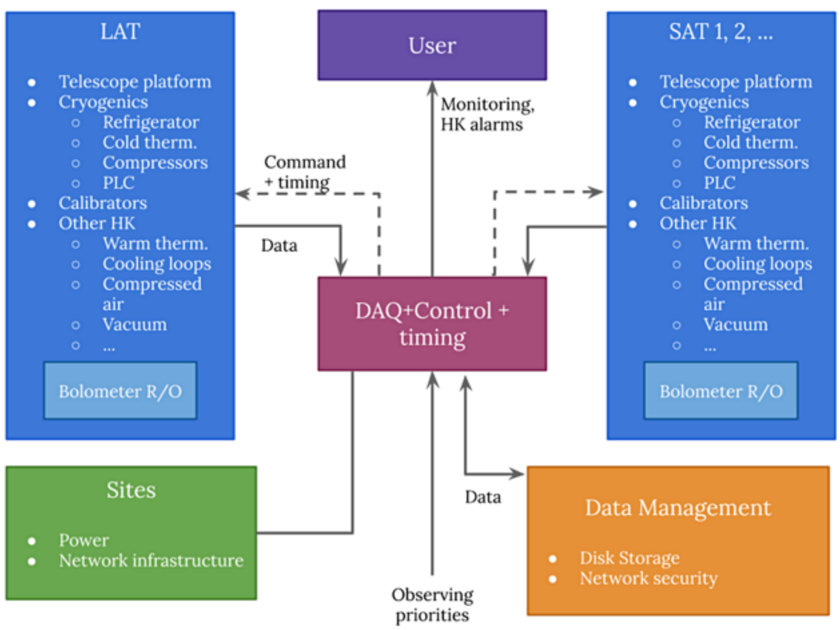

Figure 15. Data acquisition and experiment control system scope. (Graphic by Laura Newburgh, Yale University.)

3.7 Data management

The Data Management (DM) subsystem receives the raw instrument data from the Data Acquisition subsystem at each observing site and delivers a range of intermediate data products to the scientific collaboration, and all intermediate and final data products, together with the software used to generate them, to the scientific community. A high-level flow chart of the data management pipeline is shown in Figure 16.

Data Management is a major and critical part of the project and subsequent CMB-S4 operation since it prepares and makes scientific survey results available in a timely cadence. In addition, during the construction project, the DM platform is regularly exercised to validate and verify the overall experiment's design, including the DM subsystem itself and the various science analysis pipelines.

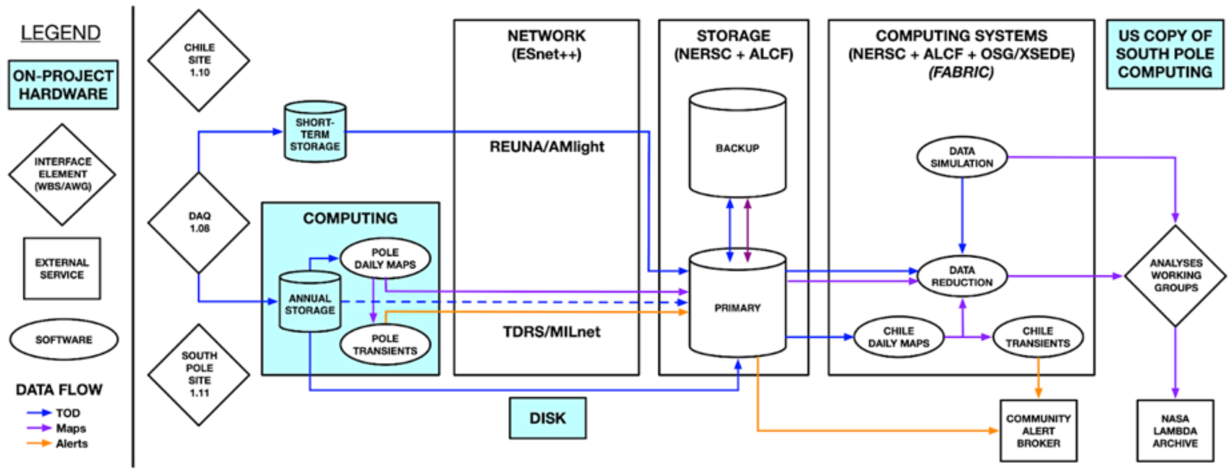

Figure 16. The Data Management subsystem receives the raw instrument data from the Data Acquisition subsystem at each observing site and delivers a range of intermediate data products to the scientific collaboration, and all intermediate and final data products to the scientific community. (Graphics adapted from [7].)

3.8 Observation Sites

The planned Chilean Atacama site is the Cerro Toco Site within the Parque Astronomico Atacama (PAA) that was home to the ACT experiment, is currently home to the CMB experiments CLASS and POLARBEAR, and where the Simons Observatory is currently under construction. A rendering of the conceptual site design is shown in Figure 17, with Simons Observatory, CLASS, ACT, and POLARBEAR in the background. The proposed layout uses the area that has been studied by existing CMB instruments and satisfies CMB-S4's requirements for operation. The site's elevation is 5,200 m, and the maximum horizon blockage seen within this area (presented by Cerro Toco) is 15°. Rock in this area is generally appropriate for the construction of the necessary foundations, and the instruments will mostly not present significant new horizon blockage to existing instruments.

At the South Pole (2,800 m elevation), telescopes could be sited in the Dark Sector, a designated radio-quiet zone in the Antarctic Treaty. Fig. 17 shows a partial view of the dark sector with existing installations (SPT-3G and BICEP-Array) and the proposed location of the CMB-S4 telescopes. The cold temperatures at the South Pole would necessitate buildings along with the telescopes to support the assembly of the receivers and general maintenance throughout operations. The three SAT telescopes would be adjacent to the Martin A. Pomerantz (MAPO) building at the location of the current BICEP Array. The SPLAT would be supported with a dedicated high bay. The placement of the buildings within the dark sector would have three general requirements. First, the view around the SATs is required to be clear 2° above the lip of the ground shields. Second, the prevailing wind direction and snow drift should be accounted for in the relative placement of the buildings and telescopes. The locations should not conflict with the existing scientific installations (i.e, IceCube Neutrino Observatory, South Pole Telescope) and other zones where construction is not allowed. Finally, the existing South Pole Telescope requires no obstructions higher than 5° above the bottom of its mirror. Outdoor construction can only be performed in the austral summer (November-February), while interior work can be done in the austral winter (February-November). Unfortunately, based on National Science Foundation guidance, the South Pole site will not be accessible for new projects for at least the next ten years due to critical South Pole base infrastructure maintenance needs caused by deferred maintenance. Therefore, CMB-S4 is currently developing an experiment configuration with all telescopes sited in Chile.

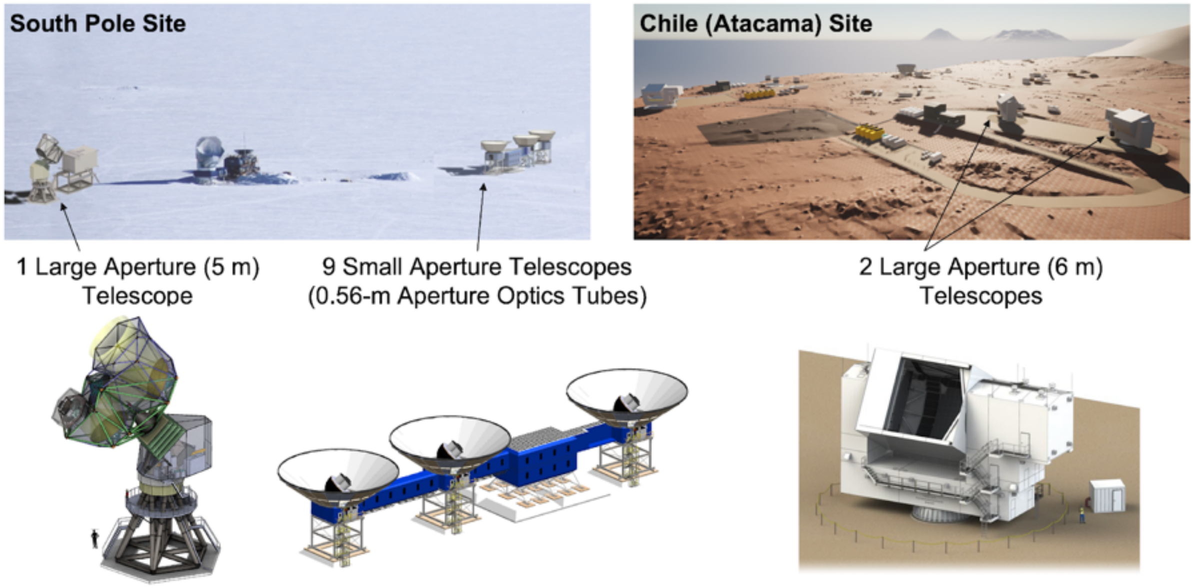

Figure 17. Proposed CMB-S4 observing sites. CMB-S4 has developed a preferred experiment configuration utilizing the South Pole and Chilean Atacama sites. CMB-S4 is also pursuing an experiment configuration with all telescopes sited in Chile, which would avoid dependence on South Pole logistics constraints. (Graphics adapted from [7].)

4. PROJECT PLAN

Development of the CMB-S4 design is supported by two independent US funding agencies, but the project organization is designed to be a unified, single entity that integrates the complex organization, policies, procedures, and support from the two separate federal agencies – the Department of Energy/Office of Science (DOE) and the National Science Foundation (NSF). In August 2020, the DOE selected Lawrence Berkeley National Laboratory (LBNL) to carry out the DOE roles and responsibilities in developing and executing the project. DOE has awarded CD-0, Approval of Mission Need, and is currently funding conceptual design studies, equipment prototyping efforts, and standing up the project management structure for CMB-S4. NSF has awarded the University of Chicago a Continuing Design Award to develop the design of the NSF project scope in preparation for becoming a candidate for a Major Research Equipment and Facilities Construction (MREFC) award. NSF has previously funded early design efforts through an MSRI-1 grant in addition to a Mid-Scale Innovations Program (MSIP) award for the preliminary design of a South Pole Large Aperture Telescope (SPLAT).

4.1 Project organization and governance

Over the last few years, the project has developed a thorough understanding and definition of the project scope based on a single Work Breakdown Structure (WBS), a corresponding multi-institutional organization, and a risk registry for the entire project. The structure to capture cost and schedule information has been established and is being utilized with the goal of developing a realistic cost estimate.

The CMB-S4 Work Breakdown Structure (WBS), see Figure 7, includes ten major subsystems, including the project office, and captures all project deliverables required to meet the scientific and technical requirements. The previous section briefly described the details of each technical subsystem. As part of the full project plan, each subsystem scope includes all work required for conceptual, preliminary, and final engineering design, all fabrication and construction activities, quality assurance, installation and component verification, and commissioning.

Figure 18 shows the top-level organizational structure of the CMB-S4 project. The project office funds all key management roles, such as the Project Director, NSF Principal Investigator, and the Project Managers. It also manages the scientific and engineering integration to ensure the experiment can ultimately deliver its scientific goals. The project engineer oversees the overall design integration and progression and leads the project systems engineering group responsible for capturing requirements and interfaces for each subsystem [15]. The Technical Integration Scientist also fulfills a critical integration role. Given that each subsystem is overseen by individual experts, this role is responsible for ensuring seamless integration and coordination across all subsystems throughout the project's lifecycle. The Project Scientist, Instrument Scientist, and Data Scientist each oversee specific areas of the project's scientific aspects, ranging from the scientific measurement requirements and the instrument model to the development and implementation of the survey strategies and data products.

The CMB-S4 project is staffed by a team of national and international experts in their fields, assembled to address the challenges in the design, development, construction, installation, commissioning, and eventual operation of CMB-S4. The currently proposed scope division between the two funding agencies is indicated with blue and green colors in Figure 18. DOE supports the development of the detector, readout, module assembly, SAT, and data acquisition systems. NSF funds the development of the LAT and its receivers, plus the majority of the site planning. Integration and commissioning, which is captured within the site scope, is shared between the two agencies. In addition, DOE funds data management, with NSF supporting two areas (transients and site hardware). Agency scope is well segregated in the accounting systems, and effort can be tracked separately and audited accordingly.

Critical additional project functions are captured in the project support area, e.g., project controls, which maintains the project baseline and records cost and schedule; project operations support and financial reporting; procurement; risk management; project IT support; and various other supporting roles. A quality assurance manager implements and oversees the quality program for CMB-S4, and similarly, an EH&S manager ensures a safe work environment and compliance with safety requirements.

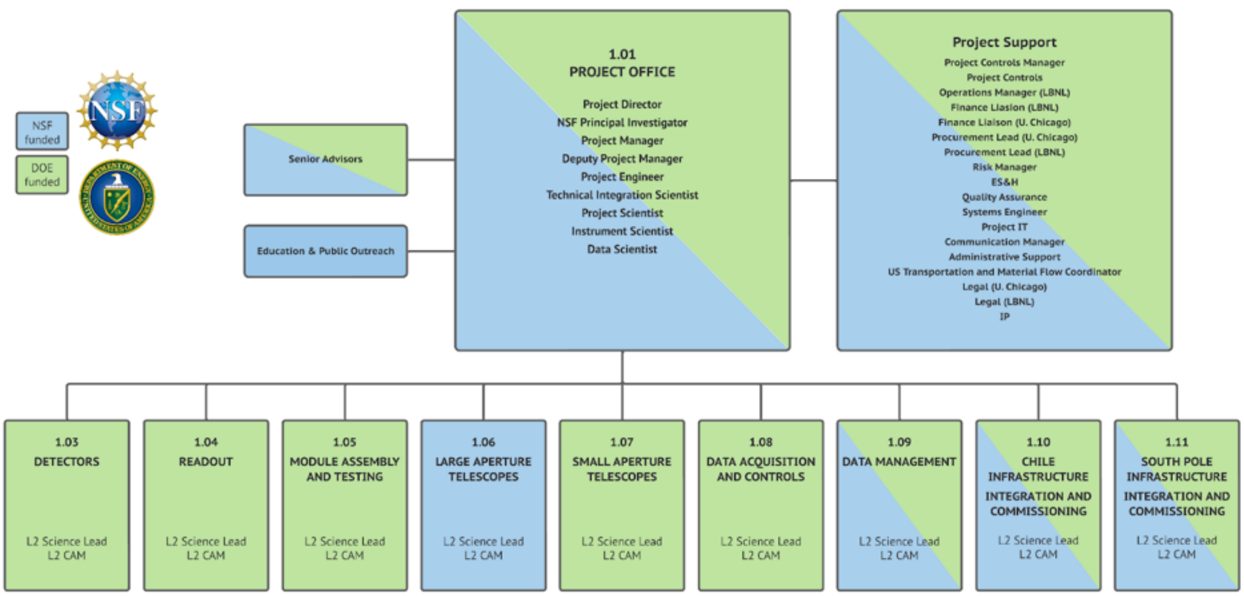

Figure 18. The top-level organizational structure of the CMB-S4 project. The currently proposed scope division between the two funding agencies is indicated with blue and green colors. (L2 ... level 2 manager, CAM … control account manager)

The CMB-S4 project is a collaborative project with scientific collaboration members serving in technical leadership roles. This is similar to many successful projects, including IceCube, ATLAS, and CMS. However, the project organization shown in Figure 18 is ultimately accountable for the successful delivery of the project. The project office which is situated in Berkeley is responsible for forming partnerships with key stakeholder institutions, including DOE National Laboratories, other US government laboratories, universities, and potential collaborating observatories/projects. Partnerships also include foreign institutions participating in the CMB-S4 Science Collaboration and contributing to the CMB-S4 Project. The collaborating institutions agree to provide resources and/or deliver items, e.g., instrumentation and effort, required for the success of the CMB-S4 project.

Figure 19 highlights the institutional reporting chains for the project. The two funding agencies are listed at the top. A Joint Oversight Group (JOG), established by both agencies, coordinates the combined effort. The project reports to the JOG on progress or issues. Accountability flows to the project team through Lawrence Berkeley National Laboratory (for DOE scope) and the University of Chicago (for NSF scope) and their respective organizational hierarchies. The Director's Council advises the project, which includes Laboratory Directors and University representatives of the biggest institutions involved in CMB-S4. The CMB-S4 Science Collaboration conducts the science program centered on CMB-S4. Collaboration activities include advocating for and advancing the design of CMB-S4.

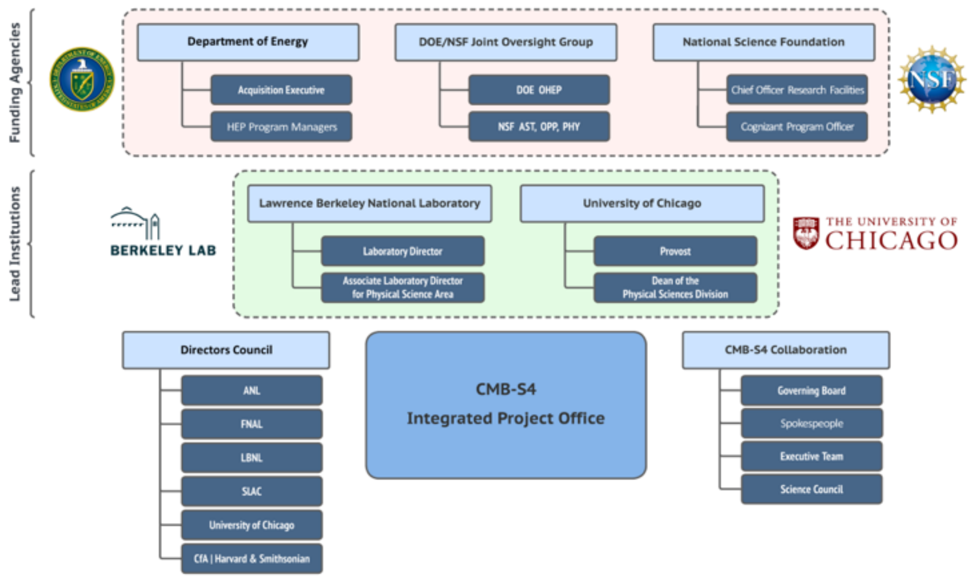

Figure 19. Development of the CMB-S4 design is supported by two independent US funding agencies, but the project organization is designed to be a unified, single entity that integrates the complex organization, policies, procedures, and support from the two separate federal agencies – the Department of Energy/Office of Science (DOE) and the National Science Foundation (NSF). The graphic shows the institutional reporting chain, which reflects the dual-agency nature of the project.

4.2 Cost and Schedule Development

The CMB-S4 project cost and schedule estimate has been established bottom-up by developing detailed design and construction activities for the entire scope as defined in the project work breakdown structure. It takes approx. 10 years to complete CMB-S4 construction, assuming a technically limited schedule, and will cost around $1 billion, roughly split 60% DOE and 40% NSF. However, eventual construction duration and cost are strongly dependent on the available funding and the start of construction. For instance, every year of funding or start-of-construction delay adds approx. $40M to $60M cost due to escalation.

The project scope is described in a WBS dictionary and responsibilities are defined for each subsystem. The project schedule is broken down into activities of sufficiently short duration to permit accurate allocation of labor and non-labor resources. The data is captured in a formal Project Management Control System (PMCS), which encompasses the costs, schedules, work scope definitions, and other activity attributes (e.g. responsible institutions) that determine how the project will be executed. Figure 20 highlights the database systems that capture the project baseline plans.

For task-based estimating, formal procedures are used to define tasks and assign them to the lowest-level elements of the WBS. The collection of tasks represents all the required resources, activities, and components of the total project. Each of the tasks is included in the Integrated Master Schedule (IMS) and estimated by expert teams using accepted cost and schedule estimating techniques. The estimates are documented by a Basis of Estimate (BOE) and captured in the project cost aggregating tool Dash360. Figure 21 shows an example of a Dash360 database entry, highlighting the type of information captured in addition to the cost and labor data.

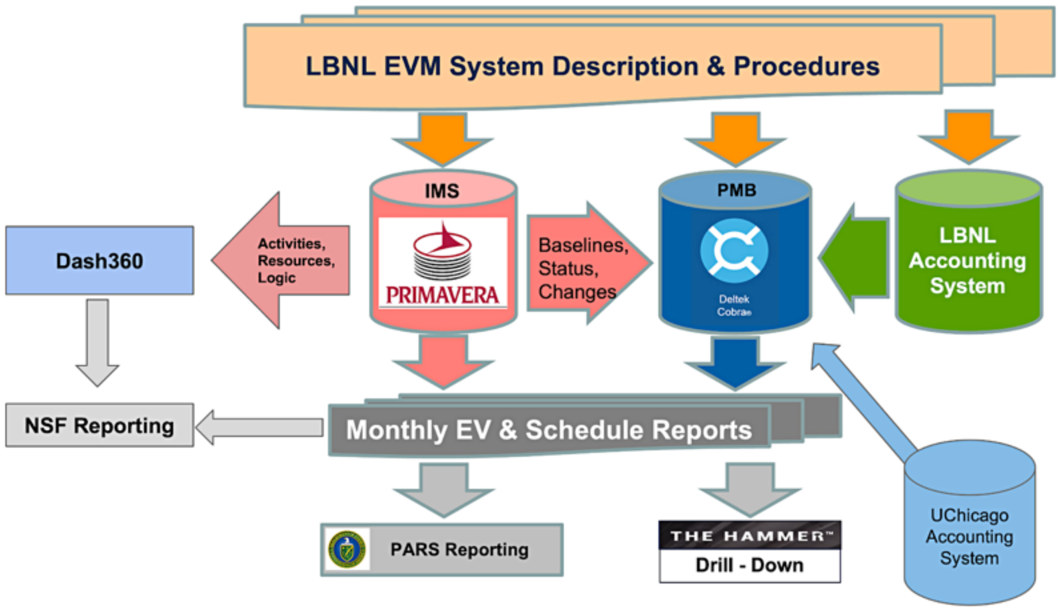

Figure 20. CMB-S4 has implemented a robust Project Management Control System (PMCS) for cost and schedule development and maintenance. The Integrated Master Schedule (IMS) is maintained in Primavera P6™. The cost database Deltek Cobra™ collects schedule and cost data in a central location to enable cost control and performance measurement. Data from the institutional accounting systems of the two CMB-S4 lead institutions are also fed into Deltek Cobra™. The project utilizes additional databases (Dash360™ and The Hammer Drill Down™) for collecting basis of estimate information and for enabling earned value management. Atlassian Jira™ databases are used for project tracking and the risk registry.

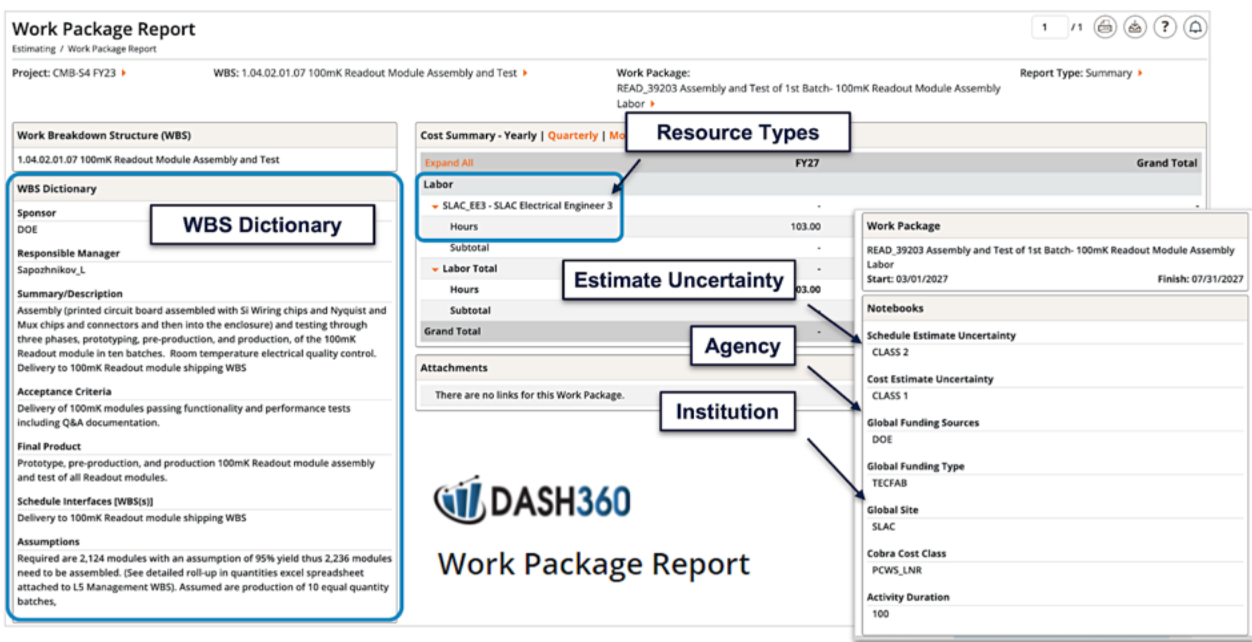

Figure 21. Each activity in the Integrated Master Schedule (IMS) is fully resource-loaded. Expert teams estimate labor and non-labor items using accepted cost and schedule estimating techniques. The estimates are documented by a Basis of Estimate (BOE) and captured in the project cost aggregating tool Dash360™. The image shows an example of a Dash360™ database entry, highlighting the type of information captured in addition to the cost and labor data.

Similarly, the CMB-S4 project schedule is developed from the work scope defined in the WBS by decomposing effort into work packages and detailed activities, estimating the duration of each activity, sequencing the activities in time, and establishing necessary logical links (predecessors and successors). At the current conceptual design stage, the CMB-S4 project schedule includes in excess of 12,000 activities with more than 17,000 logical links. The project schedule includes key production details. For instance, fabrication and testing activities for every single detector wafer to be produced are tracked (by frequency and telescope type) from the wafer foundry all the way to receiver assembly and telescope installation. This detailed logic allows for predicting telescope-specific schedule delays caused by holdups in the detector module fabrication. Figure 22 shows the detailed workflow sequence for CMB-S4 construction, tracking each single wafer by frequency and telescope type, each readout component, and subsequent assembly and testing steps.

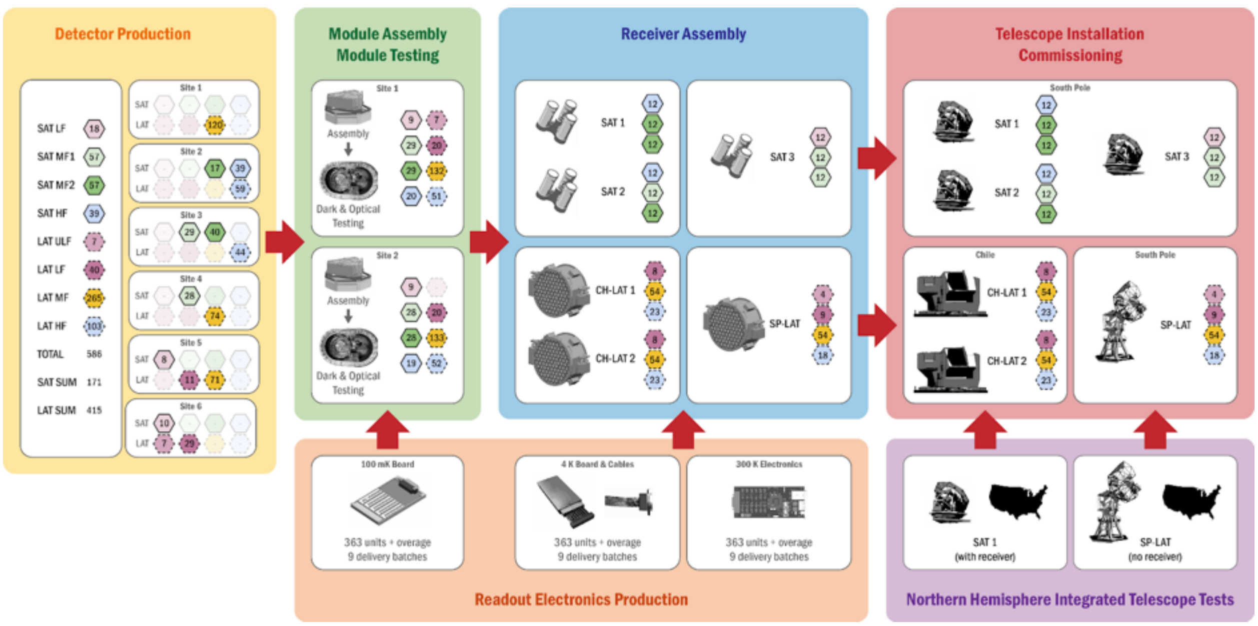

Figure 22. The graphic illustrates the detailed workflow sequence for CMB-S4 construction, tracking each single wafer by frequency and telescope type, each readout component, and subsequent assembly and testing steps. This detailed information plus schedule logic is implemented in the project's Integrated Master Schedule and allows for predicting telescope-specific schedule delays caused by holdups in the detector module fabrication.

Based on such a workflow, Figure 23 shows a nominal schedule developed for the Chile + South Pole experiment configuration (see Table 3). The schedule is developed as a "technically limited" schedule, which is optimistic. First, it does not reflect the actual funding profiles provided by the agencies. Once these are known, the schedule can be optimized (usually stretched) until the overall cash flow is within the available budget authority. Second, it does not include "schedule contingency", which is required to account for unforeseen events or risk occurrences. Depending on the chosen experiment configuration schedule contingency of up to three years will be required. Figure 24 shows an example result of a Monte Carlo simulation, which considers the stochastic occurrence of approximately 300 active project risks tracked in the project risk registry. These risks are logically linked as part of the overall project schedule and allow analyzing exposure to schedule risk. The Monte Carlo simulation also considers possible schedule delays caused by low design maturity levels. (A similar analysis has been performed for project cost contingency needs.) Unique to the South Pole configuration of CMB-S4, possible schedule variants jump in yearly steps, which reflects the special situation at the South Pole. If the South Pole austral summer window (Nov - Feb) available for construction activities is missed, the project automatically gets delayed by a year, see Figure 24.

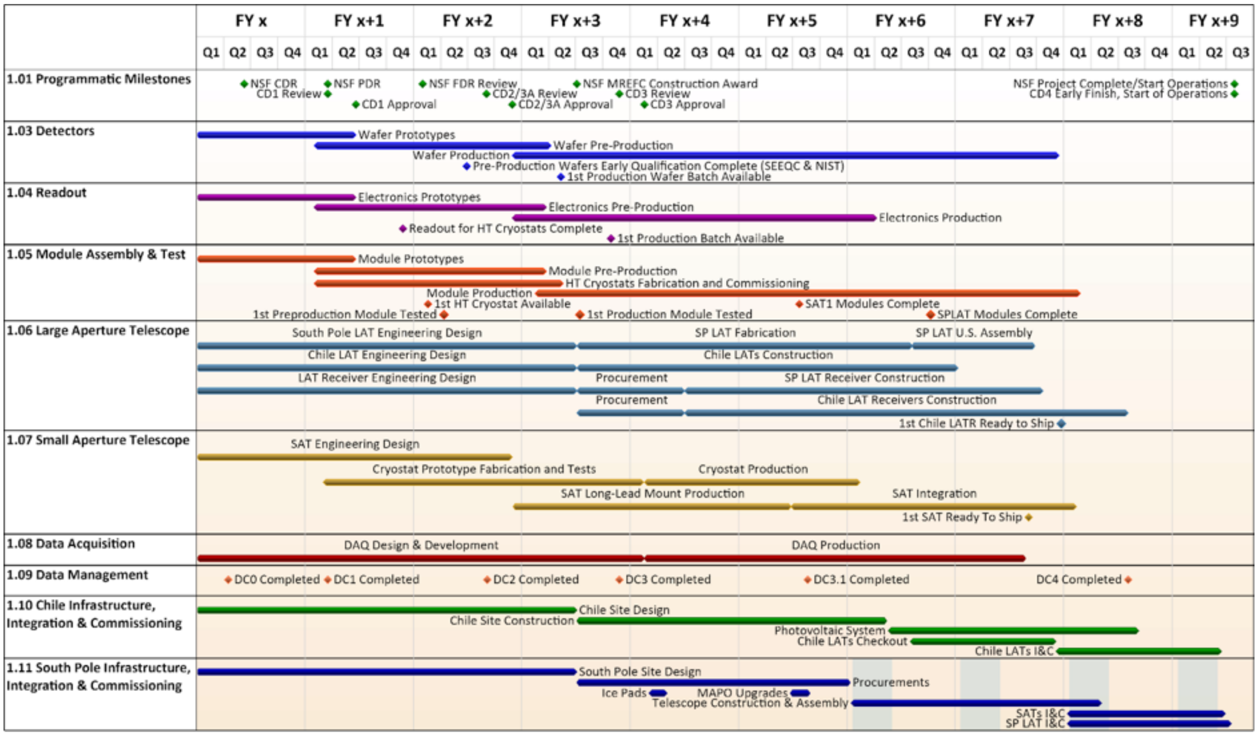

Figure 23. A nominal project schedule was developed for the Chile + South Pole experiment configuration. The telescope and receiver schedules follow a standard engineering process consisting of engineering design, prototyping, fabrication, installation, and commissioning. The biggest challenge for the CMB-S4 schedule is the fabrication of the detector, readout, and module assembly components due to the large number of detector modules required. The project implements early prototyping, preproduction, and production phases to methodically build up the required production rates. Nominally, all detector wafers for the Chile + South Pole configuration are planned to be built within a five-year production timeline.

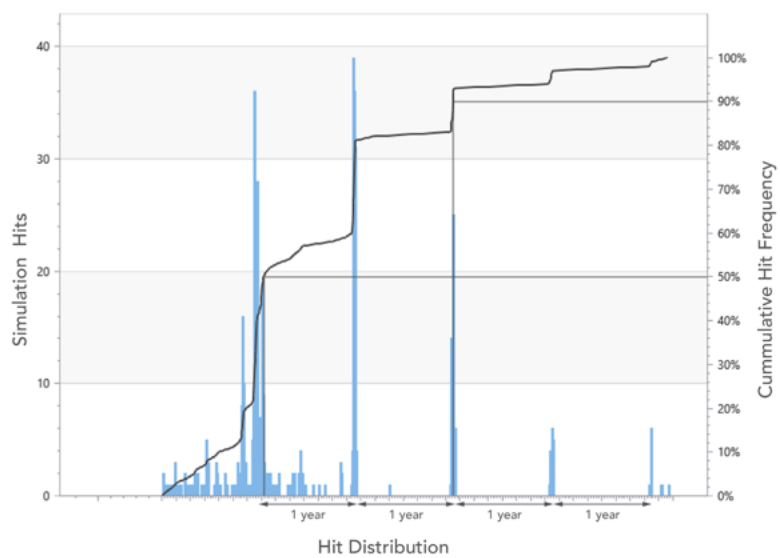

Figure 24. Example result of a Monte Carlo simulation, which considers the stochastic occurrence of approximately 300 active project risks tracked in the project risk registry. Unique to the South Pole configuration of CMB-S4, possible schedule variants jump in yearly steps, which reflects the special situation at the South Pole. If the South Pole austral summer window (Nov - Feb) available for construction activities is missed, the project automatically gets delayed by a year. (Graphic by Jeff Zivick, U. Chicago.)

As shown in Figure 23, the telescope and receiver schedules follow a standard engineering process consisting of engineering design, prototyping, fabrication, installation, and commissioning. The biggest challenge for the CMB-S4 schedule is the fabrication of the detector, readout, and module assembly components due to the large number of detector modules required. The project implements early prototyping, preproduction, and production phases to methodically build up the required production rates. Nominally, all detector wafers for the Chile + South Pole configuration are planned to be built within a five-year production timeline (see Figure 23). The project assumes the availability of six independent production facilities for that effort.

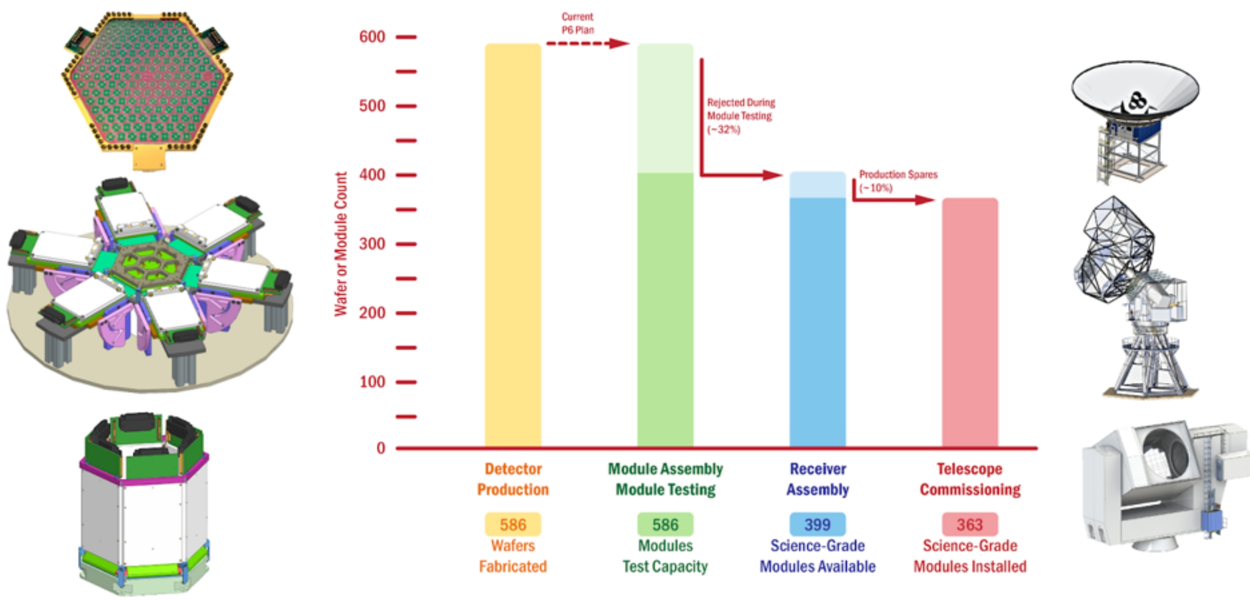

Figure 25. The graphic illustrates the yield assumptions embedded in the current project schedule. As shown, the project starts with fabricating 586 wafers to end with 363 science-grade wafers installed on the telescopes.

The detector module production plan considers nominal yield, module rework, and production spare needs to predict production output. Figure 25 illustrates the yield and rework assumptions embedded in the current project schedule. As shown, the project starts with fabricating 586 wafers to end with 363 science-grade wafers installed on the telescopes. The schedule also includes added module testing cycles required by rework. These assumptions are based on existing experiences, albeit for much lower production quantities. Therefore, reaching and maintaining the detector module production rate is one of the highest project risks. Since detector wafers can only be fully qualified in an assembled detector module during optical cryogenic tests, significant time delays occur between detector fabrication and accepting a detector wafer. The project will implement added quality assurance steps during wafer production to counter that risk. However, this approach is not clear-cut since measuring wafer properties does not necessarily predict optical performance in a fully assembled detector module.

4.3 Quality assurance

Quality assurance is a critical concern for any project the size of CMB-S4. If detected late, permitting non-conforming components into the production pipeline can have serious cost and schedule consequences. Since most research staff are usually not exposed to such needs or consequences, the project must develop a culture of quality awareness. For instance, project controls requires the implementation of specific handoff milestones in the schedule if a component is shipped to a subsequent assembly step, see Figure 26. The subsystem shipping the component needs to complete and record quality assurance steps before shipping. On the other hand, the receiving subsystem is required to inspect the quality assurance documentation before accepting the received component. Each of these handoff activities is resource-loaded, which encourages the responsible system manager to consider manufacturing and quality assurance labor needs.

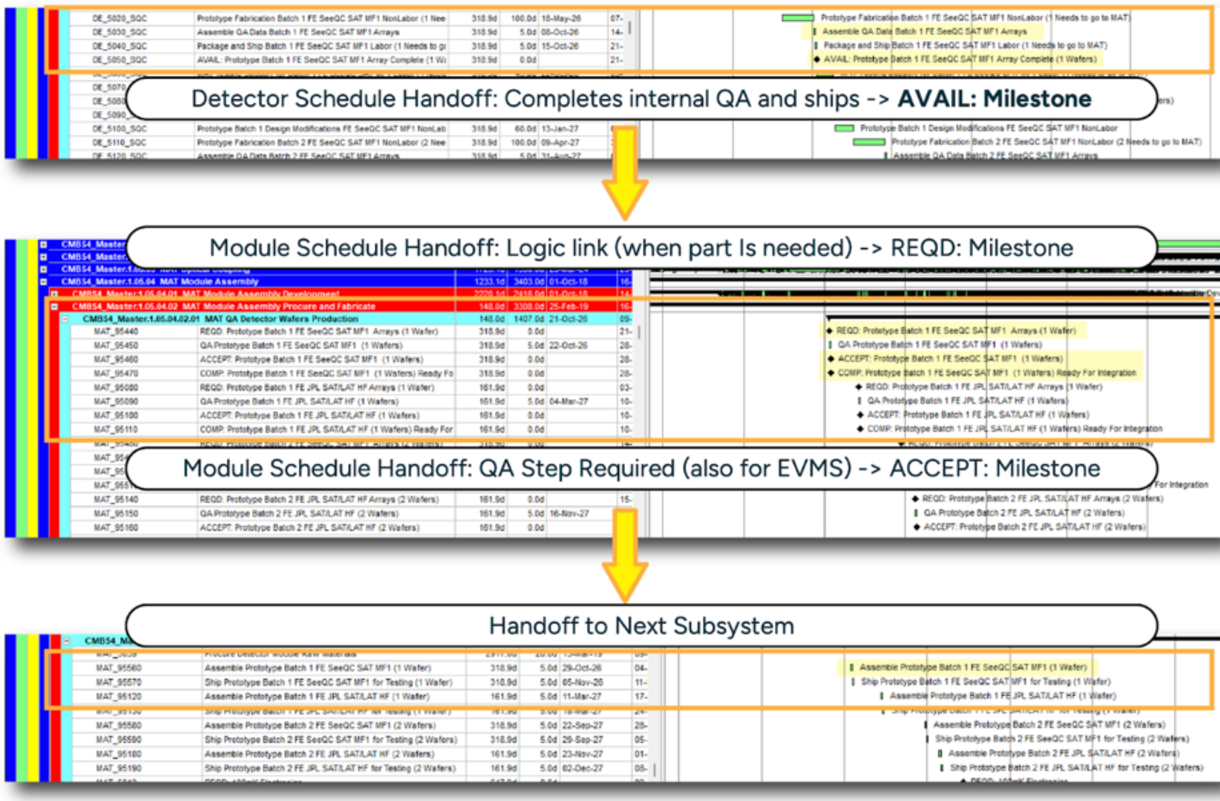

Figure 26. The project schedule includes handoff milestones and activities if subcomponents are handed off or shipped to a subsequent assembly step. These activities are implemented in a standardized manner to encourage the responsible system manager to consider and estimate manufacturing and quality assurance labor needs.

The CMB-S4 project office includes a quality assurance manager who is also involved in developing a strong quality assurance culture. Figure 27 shows the flow of quality assurance responsibilities. The project allows each fabrication site significant flexibility in using its own quality assurance processes as long as they fulfill the project-defined minimum standards. The project develops a top-level database that collects the quality assurance documentation from each site trackable by component serial number all the way to the full assemblies. As shown in Figure 27, the project quality assurance manager works closely with the fabrication sites to implement quality assurance functions as well as a sufficient count of manufacturing support personnel who develop work instructions, non-conformance reports, change requests, etc. That process has helped significantly in supporting the CMB-S4 system managers in adequately estimating labor needs for manufacturing and quality assurance.

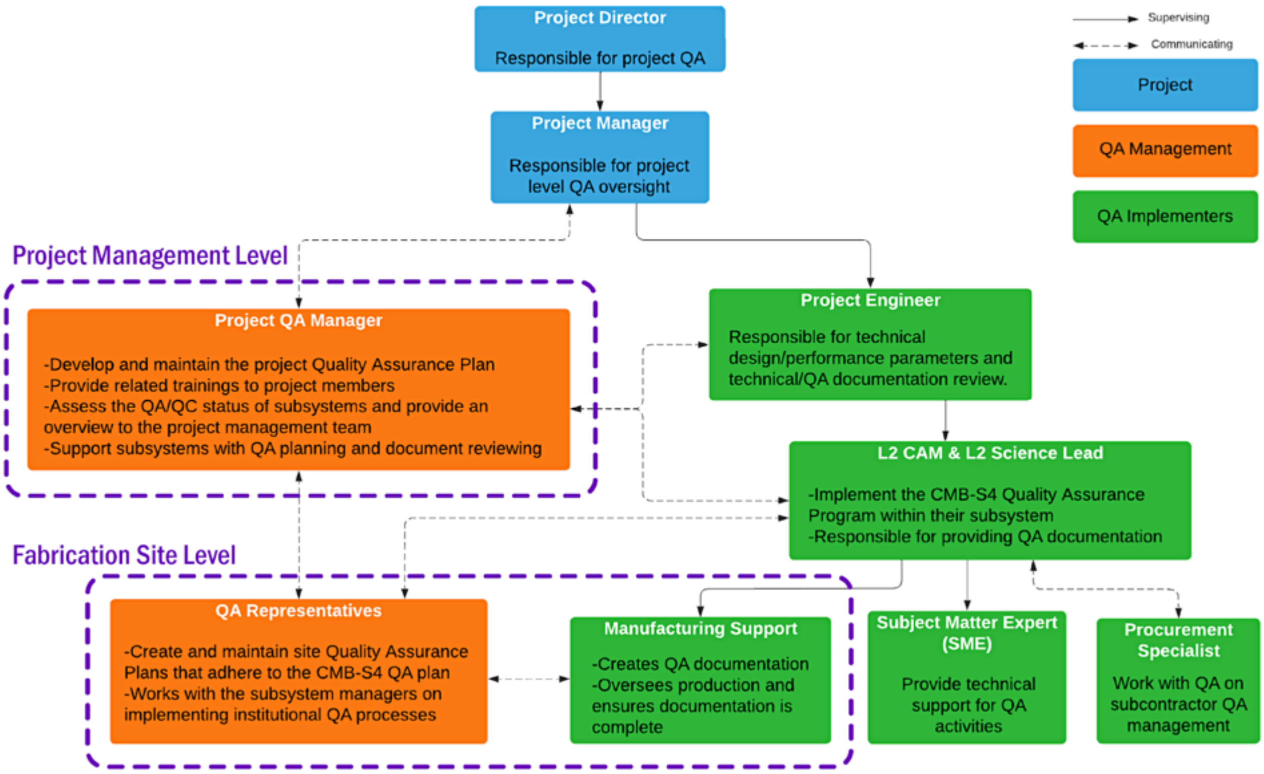

Figure 27. Quality assurance is a critical concern for any project the size of CMB-S4. Permitting non-conforming components into the production pipeline can have serious cost and schedule consequences if detected late. The graphic shows the flow of quality assurance responsibilities. The project allows each fabrication site significant flexibility in using its own quality assurance processes as long as they fulfill the project-defined minimum standards. (Graphic by Jessica Aguilar, LBNL.)

5. SUMMARY

CMB-S4, with its compelling scientific objectives and strong community support, has consistently been ranked as a top priority by independent scientific advisory panels. This paper briefly outlined the key scientific goals that shape the experiment design. A conservative approach to the experiment design has been adopted due to the considerable challenge of measuring the CMB polarization signature of inflationary gravitational waves. Each subsystem of CMB-S4 was briefly introduced and described. As a dual-agency major construction project, CMB-S4 requires a robust project management organization. Key aspects of cost and schedule development were also briefly discussed.

The CMB-S4 project initially planned to use telescopes at both the South Pole and Cerro Toco in Chile, two prime locations for observing the Cosmic Microwave Background (CMB). However, the National Science Foundation's recent decision to pause new projects at the South Pole for a decade due to necessary infrastructure improvements has forced the project to redesign the experiment. The CMB-S4 collaboration is now working on a new configuration that will use telescopes in Chile only, a process estimated to take about a year.

6. ACKNOWLEDGEMENTS

CMB-S4 is supported by the Director, Office of Science, Office of High Energy Physics of the U.S. Department of Energy under Contract No.DE–AC02–05CH11231; by the National Energy Research Scientific Computing Center, a DOE Office of Science User Facility under the same contract; and by the Divisions of Physics and Astronomical

Sciences and the Office of Polar Programs of the U.S. National Science Foundation under Mid-Scale Research Infrastructure award OPP-1935892.

Considerable support is provided by the many CMB-S4 team members and their institutions.

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