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# Design, Planning, and Performance of the CMB-S4 Experiment

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## ABSTRACT

The Cosmic Microwave Background Stage Four Experiment (CMB-S4) is a planned DOE/NSF ground-based experiment, endorsed as a high priority mission in the Astro2020 report, with scientific impacts reaching from transformative measurements of the cosmic microwave background (CMB) to a deep legacy millimeter-wavelength dataset covering a large fraction of the sky. To meet its ambitious goals, CMB-S4 plans to have multiple small-aperture (0.55-meter) and large-aperture (6-meter) telescopes located both in the Chilean Atacama desert (to access a large fraction of the sky) and at the South Pole (for targeted deep-field observations). Over 500,000 superconducting detectors will be distributed across these telescopes, enabling a necessary leap in sensitivity. We present an overview of the project organization, technical design, construction plans, and predicted performance of CMB-S4. We highlight some driving programmatic and technical considerations of the current experimental design.

**Keywords:** Cosmology, Inflation, Light Relics, Gravitational Waves, Galaxy Clusters, Gamma Ray Bursts, Millimeter-Wave, Transition Edge Sensor

## 1. INTRODUCTION

The Cosmic Microwave Background Stage-4 Experiment (CMB-S4) will produce millimeter-wave sky surveys of unprecedented quality, giving us a snapshot of the early Universe via the Cosmic Microwave Background (CMB). It will also measure contributions from a myriad of phenomena over the whole history of the cosmos.

CMB-S4 was conceived from the 2013 Snowmass Cosmic Frontier planning process, when experimental groups in the cosmic microwave background (CMB) and broader cosmology communities together produced planning papers outlining the science case and instrumental concept[1,2]. The community proposed CMB-S4 to the 2014 Particle Physics Project Prioritization Process (P5), which recommended supporting CMB-S4 under all budget scenarios[3]. In 2016, the CMB-S4 community completed a CMB-S4 Science Book[4] that laid out the science goals and a CMB-S4 Technology Book[5] describing the then-current state of CMB instrumentation technology and identifying necessary development areas. These led to the US Department of Energy (DOE) and the National Science Foundation (NSF) requesting that the Astronomy and Astrophysics Advisory Committee (AAAC) establish a CMB-S4 Concept Definition Taskforce (CDT) to develop a concept report for a CMB-S4 experiment. The CDT report[6] was accepted by the AAAC in late 2017, and in 2018 the CMB-S4 Collaboration was officially formed.

In 2019, an Interim Integrated Project Office was formed, DOE CD-0 (Mission Need) was approved, and the University of Chicago was designated the NSF host institution for CMB-S4. Lawrence Berkeley National Laboratory (LBNL) was appointed as the DOE Lead Laboratory for the project. The National Academies Astro2020 report, released in 2021, strongly recommended that NSF and DOE should pursue the CMB-S4 project[7].

As described in detail in the CMB-S4 Science Book, CMB-S4 has four main science goals, each related to a science theme: primordial gravitational waves and inflation; the dark Universe; mapping matter in the cosmos; and the time-variable millimeter-wave sky. These science goals can be achieved within a reasonable survey duration only by a cohesive millimeter-wave experiment of unprecedented scale[8].

CMB-S4 is a single unified DOE/NSF project designed to achieve all four of these science goals. The CMB-S4 Conceptual Design, which is described in this paper, is projected to meet all four goals over a seven-year operations phase, conducting sky surveys that employ telescopes and instruments deployed in the Chilean Atacama Desert and at the South Pole. Though funded by both DOE and NSF, the project has a single management structure and employs integrated management and technical approaches and tools, with the management team distributed at institutions across the project. Note that the

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CMB-S4 Science Collaboration is a separate body from the CMB-S4 Project, though there are many individuals and institutions who are members of both. The project is responsible for building and commissioning the experiment, while the collaboration is charged with setting the scientific goals, validating and verifying the experimental design, and performing the numerous scientific analyses of the maps and transient alerts the experiment produces during its operations phase. As of summer 2022, the CMB-S4 Collaboration and Project include 402 individual members from 114 institutional affiliations in 26 U.S. states and 19 countries.

## 2. CONCEPTUAL DESIGN

CMB-S4 is currently in the conceptual design phase. The design described here is the current design, which continues to be developed, iterated, and refined.

The CMB-S4 scientific requirements necessitate a site with access to wide area sky coverage and a site that allows for the small area ultra-deep survey. Chile and the South Pole are the only mature CMB sites that can meet these two needs. The science requirements flow through the instrument design into requirements on the site infrastructure required to support the instruments themselves, the instruments required to commission and calibrate them, and the logistics to support the entire project through commissioning and into operations.

State-of-the-art CMB observations require the highest and driest sites on Earth to achieve high atmospheric transmittance and low atmospheric emission within the spectral bands required. The two best sites developed for CMB observations are South Pole in Antarctica and Cerro Toco in the Chilean Andes. The atmospheric transmittance at the relevant frequencies has been studied extensively[9,10]. Both of these sites have been in use for several decades and have hosted many CMB telescopes[11,12,13,14,15]. Known information about the atmospheric conditions at these sites was used in the sensitivity forecasts used to predict CMB-S4 performance on-sky.

The Chilean Atacama site, at a latitude of 23° South, has access to more than 80% of the sky, enabling observations of the 70% of the 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 of the sky because all fields visible from the South Pole are always above the horizon and are at constant elevation. This characteristic, along with stable atmospheric conditions that enable large angular scale observations, makes the South Pole site particularly well-suited to making observations on the ultra-deep field.

CMB-S4 will consist of large and small aperture telescopes (LATs and SATs, shown in Figure 1) located at the Chilean Atacama and South Pole sites. The requirement to measure a wide range of angular scales with good control of systematic uncertainties drives us toward two sizes of telescope. The SATs measure large angular scales (degree-scale) while controlling systematic uncertainties at the level required to constrain primordial gravitational waves (tensor perturbations) in terms of the tensor-to-scalar ratio r, while the LATs measure smaller angular scales (on the order of arc minutes) with unprecedented precision. The requirements also drive us to use two different observing sites with different observing strategies.

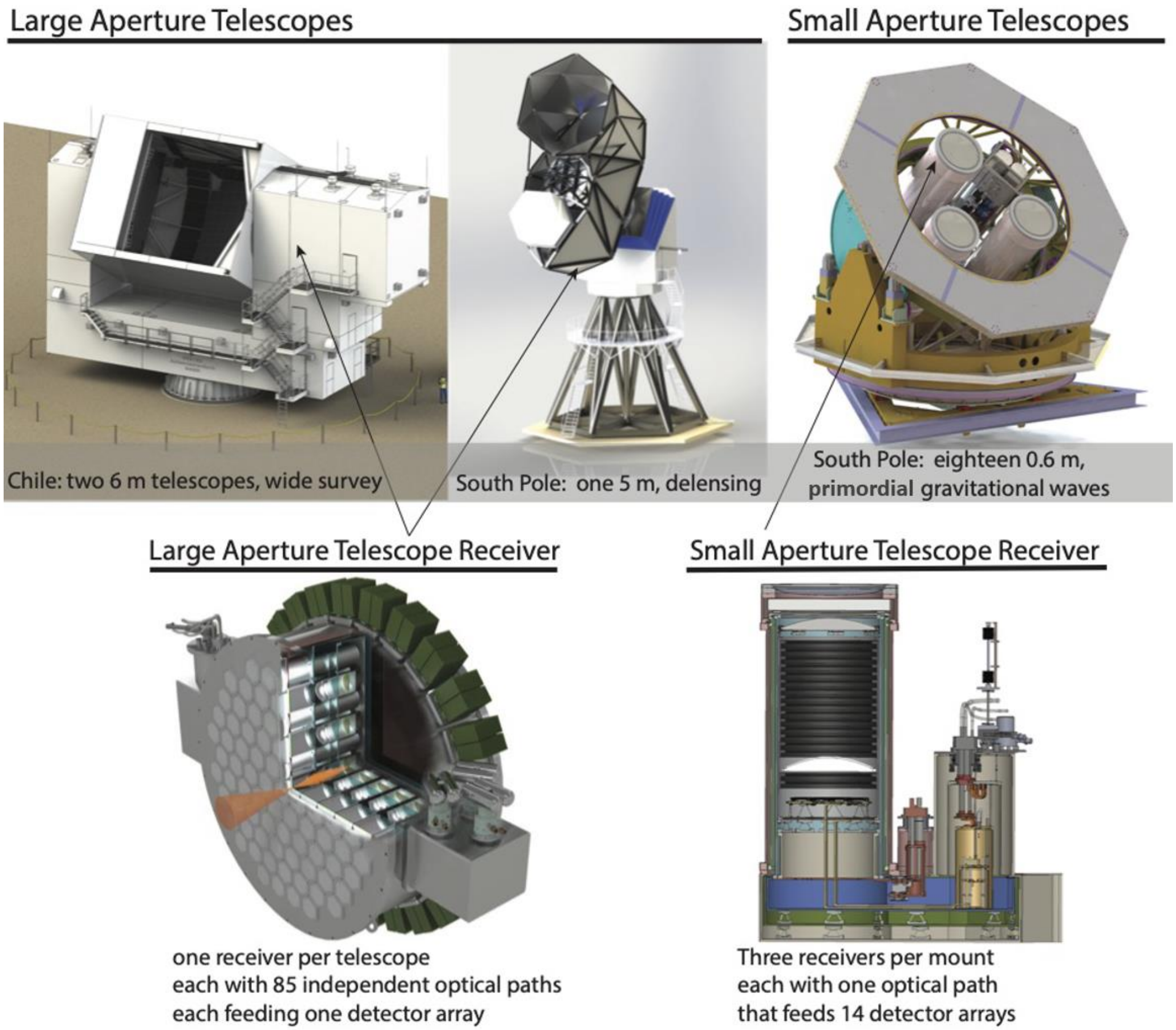


*Figure 1: The CMB-S4 telescope and receiver conceptual designs. Shown are the LAT designs for the South Pole and Chile, and the SAT design for the South Pole.*

The Chile LAT design (CHLAT) is a 6-meter crossed Dragone design[16], based directly on the design of the CCAT-prime / Fred Young Submillimeter Telescope and the Simons Observatory (SO) Large Aperture Telescope[17,18]. To meet the measurement requirements, 275,000 detectors are required for the wide field survey. These detectors will be housed in two CHLATs, each outfitted with a camera containing 85 individual optics tubes. Each optics tube is comprised of a set of filters and three reimaging lenses which feed a single detector array. Each tube operates over a pair of neighboring frequency bands with the full instrument covering the observing bands from 25 to 280 GHz.

The South Pole LAT (SPLAT) design is an off-axis Three-Mirror Anastigmat (TMA) on a three-axis mount (elevation, azimuth, and boresight rotation), with a 5-meter primary aperture. The SPLAT design is optimized to maximize throughput. Boresight rotation allows for control and measurement of polarization systematics. The SPLAT has monolithic mirrors, which eliminates segment gaps and reduces scattering at large angles. There is a co-moving shield that surrounds all optical elements to control pickup. The SPLAT receiver is identical to that on the CHLAT except for slightly different lenses to correct for different optical aberrations inherent to the different telescope designs, and the addition of optics tubes for the 20 GHz band which will improve constraints on synchrotron foregrounds.

The SAT design is a cryogenic refractor system coupled directly to a camera, and draws significant heritage from the SO SATs and the BICEP series of experiments. Sets of three SAT optics tubes and receivers are housed in a single cryostat system. There are a total of 18 optics tubes and receivers, corresponding to six cryostats and mounts. The SATs are on a three-axis mount with full boresight rotation that enables tight control of polarization systematics. Each telescope has two lenses, and the detectors sit on a curved focal plane surface, enabling high optical performance across a wide focal plane. Each of the SAT telescopes houses dichroic horn-coupled transition-edge sensor (TES) detectors. Together, the SATs cover the frequency range from 25 GHz to 280 GHz. The lenses are made of plastic or alumina in low-frequency tubes and silicon at high frequencies.

The detectors used in all of the telescopes are horn-coupled TES bolometers fabricated on hexagonal silicon wafers by six different collaborating fabrication facilities. Each of the detector wafers, with the exception of the lowest frequency SPLAT detectors, is dichroic, sensitive to two nearby bands. Each dichroic pixel includes four detectors: two orthogonal polarity modes, with two frequencies each. Each detector can operate at two transition temperatures, one around 170 mK for science measurements and a higher temperature transition for calibrations. A key technical feature of CMB-S4 is the low operating temperature of the detectors, enabled by use of dilution refrigerators for cooling, resulting in very low noise levels per detector. The left panel of Figure 2 is a photograph of an early prototype CMB-S4 detector wafer. The right panel of Figure 2 shows some key features of a pixel. A more detailed description of CMB-S4 detectors, readout, and modules is presented in Ahmed, et al, these proceedings[19].

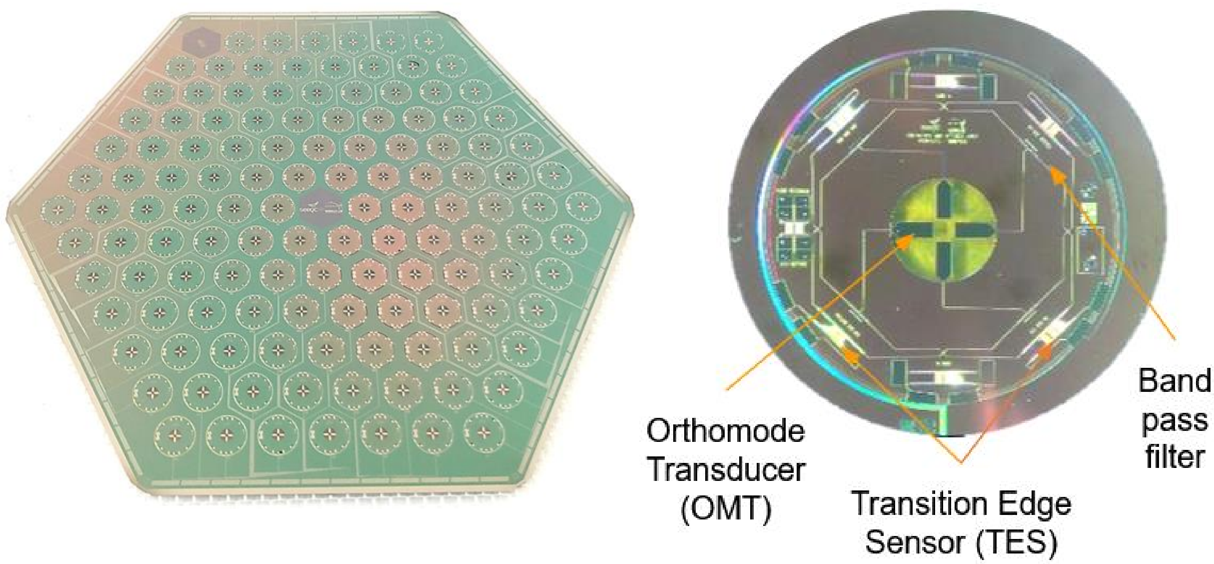


*Figure 2: Left - Photograph of an early CMB-S4 prototype detector array fabricated on a 150-mm diameter silicon wafer using a Hexagonal layout. Right - Close-up photograph of a single pixel similar to those planned for CMB-S4.*

The Readout subsystem will provide a stable and precise voltage bias to the TES bolometers at 0.1 K, measure the current signals from them, amplify and transport the signals back to the room-temperature exterior of the receiver cryostats and then digitize and package the signals to send to the Data Acquisition system. The current is amplified by very low-noise, low-impedance amplifiers called Superconducting QUantum Interference Devices (SQUIDs). Because of the extremely large number of individual signals to measure cryogenically and report out to room temperature, the signals require cryogenic multiplexing for management of thermal loads and for ease of system integration. We accomplish this using a time-division multiplexing (TDM) architecture, used extensively by previous CMB experiments. Figure 3 is a schematic representation of the Readout system at various temperature stages, along with its interfaces with detector modules.

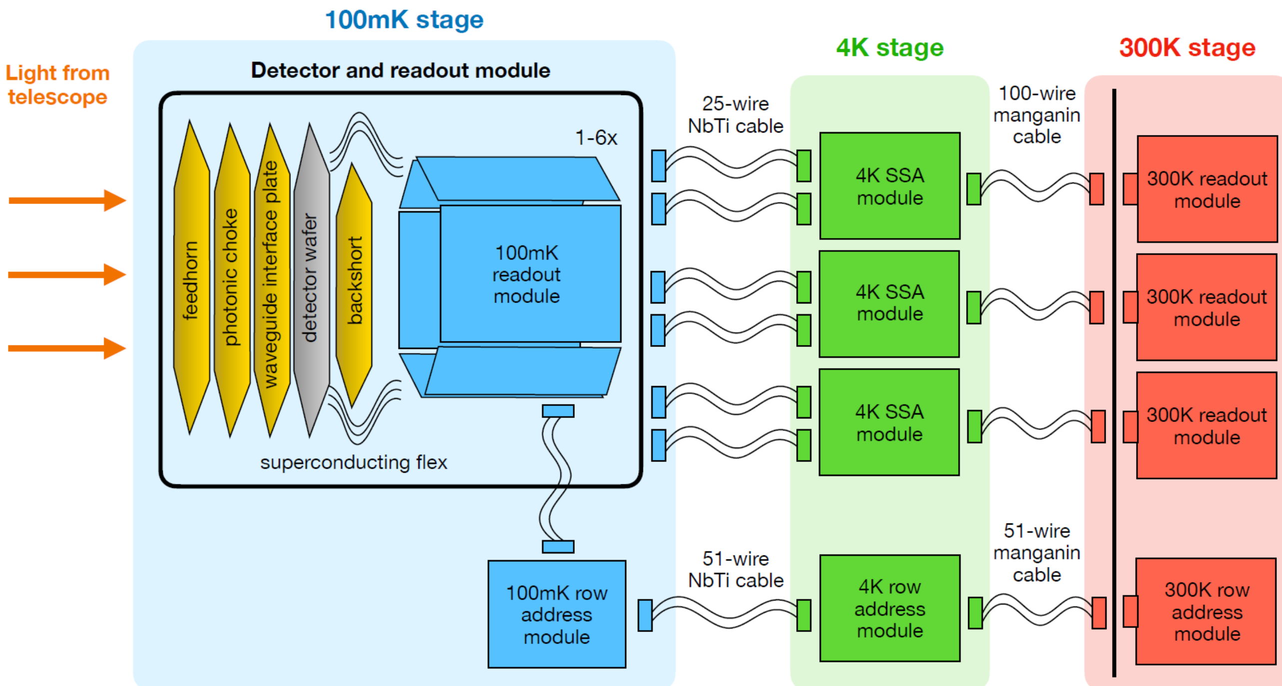


*Figure 3: System-level schematic of modular readout scheme showing components at each temperature stage and inter-connects. Light from the telescope optics is incident on the optical coupling components and detectors, which are coupled to readout modules at 100mK, and comprise the integrated detector and readout module. Cabling connects the 100 mK readout to boards at 4 K containing SQUID series arrays (SSA), which are connected to room-temperature readout electronics outside the cryostat. Row addressing signals are carried by another series of cables and modules that pass from the room-temperature electronics to the 100 mK readout modules.*

The Module Assembly and Testing (MAT) subsystem is responsible for the assembly and testing of the CMB-S4 detector modules. The detector modules (see Figure 4) are an integrated assembly consisting of feedhorns that couple microwave power to a detector array, which are readout by multiplexed readout electronics. This sub-system is responsible for the design of the module interface components, microwave coupling hardware, and the assembly of these components into an integrated package with the Detector and Readout sub-systems that can be installed and operated at 100 mK in the SAT and LAT cryostats. The MAT sub-system is also responsible for characterizing the performance of these integrated detector modules to verify that they meet CMB-S4 requirements.

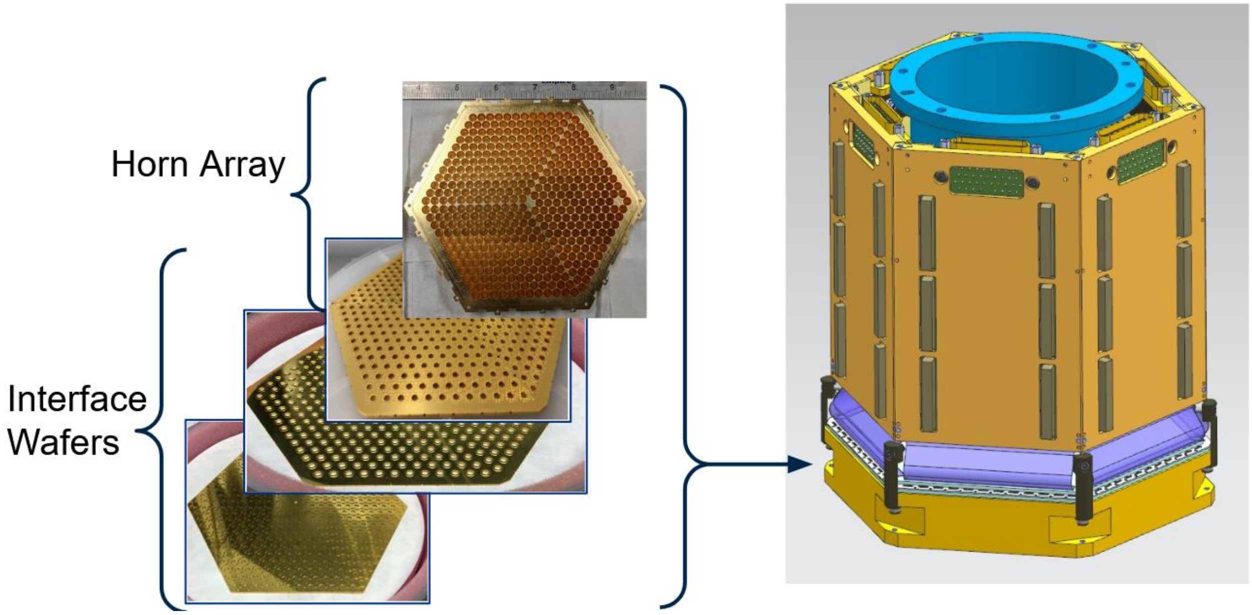


*Figure 4: Left - Photographs of elements in the stackup of a CMB-S4 detector module (from bottom) a backshort array, a waveguide interface plate, a photonic choke wafer, and a feedhorn array. The detector is sandwiched between the backshort and the waveguide interface plate. Right - Conceptual design for the 100mK base-temperature detector module. In this view, the horn array and detector wafer are at the bottom, with the readout boards at the top. The readout boards are connected to the detector wafer via a flexible superconducting flexible circuit, represented in purple. The blue flange is the mechanical interfacing feature to the focal plate.*

The Data Acquisition and Control (DAQ) Subsystem is closely based on that used in Simons Observatory, with a clear technical path to handling the higher data rates from CMB-S4. This 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 at the site if requested (e.g. networking, disk space, power and water cooling data); (b) control of these subsystems including an observation sequencer to command the subsystems in series 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 purview of the Observatory Control System (OCS) including control, data aggregation, and monitoring connections to the telescopes and data management is shown in Figure 5.

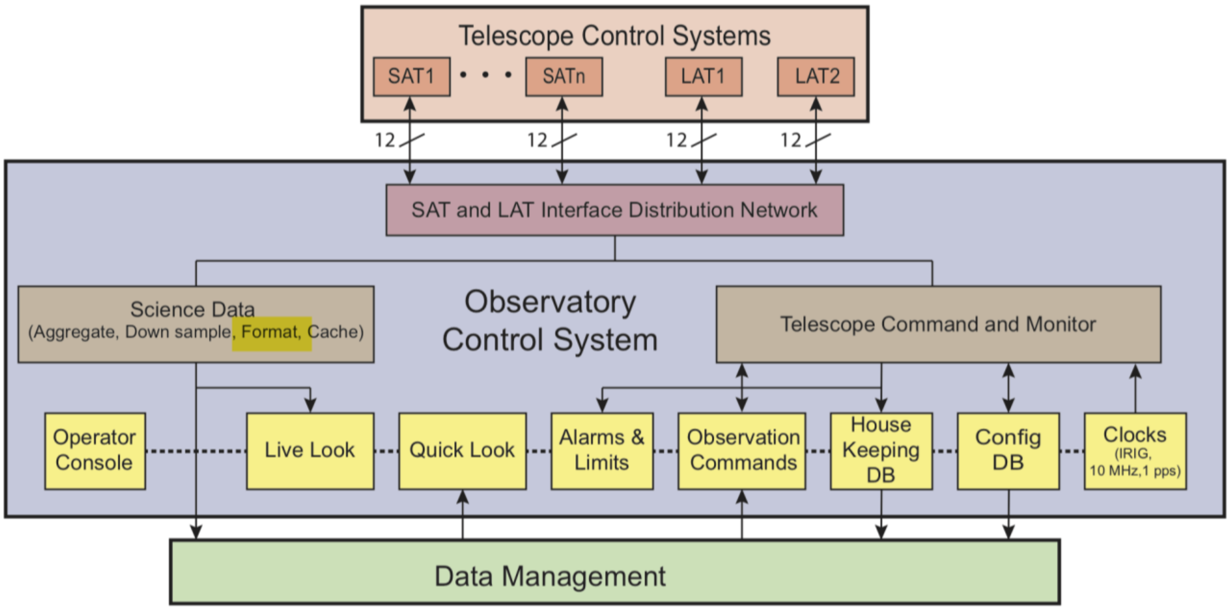


*Figure 5: An overview of the observatory control system, including the alarms, data acquisition control, and monitoring, including the interface to all telescope platforms. Note that interfaces to the site facilities are not shown*

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. On a daily basis, maps are generated, data quality assessed, transient events identified, and alerts issued relative to those transients. On an annual basis, maps are re-processed to science-grade maps with metadata, and these maps are distributed to the collaboration. On a periodic basis releases are made to the community of well-documented data products and software.

Figure 6 shows a schematic view of the Preliminary Baseline Design of the DM subsystem, including on-site resources, data-transport systems, archival storage, computing systems, the overall software stack, and data distribution within and outside of the project. This design is based on the assumption that there will be sufficient bandwidth to transfer the Chilean data to the US in real time, but that this will not be the case for South Pole data. Should the bandwidth from the South Pole become sufficient, the design will be adjusted accordingly.

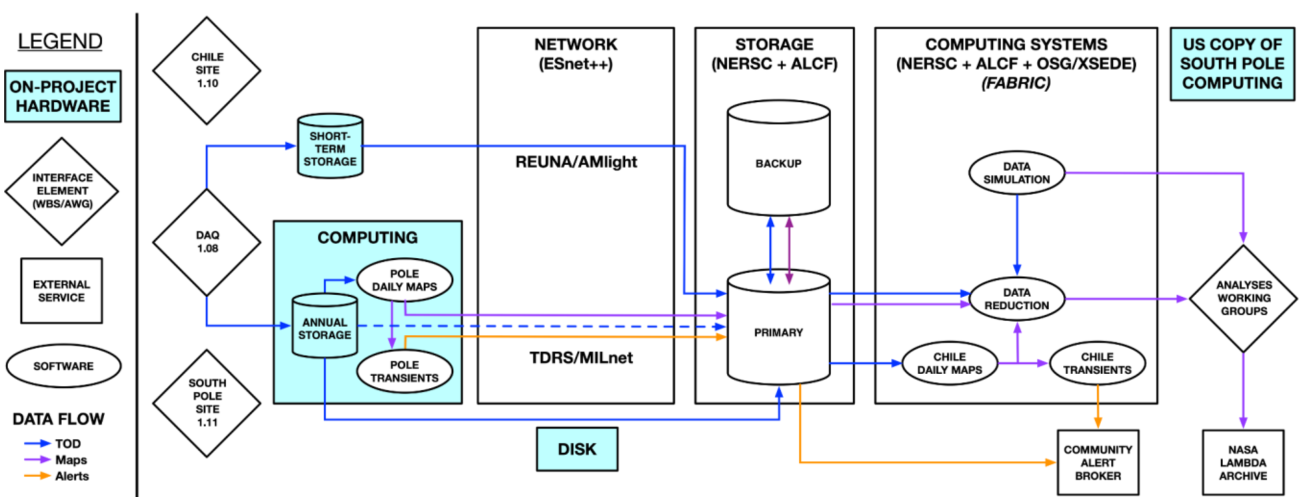


*Figure 6: Schematic view of the DM infrastructure, spanning the range from Data Acquisition to Science Analyses, with on-project hardware highlighted in cyan. Note that the named allocated networking, storage and compute resources are indicative and anticipated, not yet confirmed.*

## 3. FLOWDOWN FROM SCIENCE GOALS TO TECHNICAL REQUIREMENTS

The performance of the entire CMB-S4 experiment is established by requirements that define minimum, quantitative performance metrics at every level, from the four main Science Goals down to individual assemblies and assemblies. The project employs a systems engineering approach, with requirements flowing down from the highest levels to progressively smaller elements of the system. The performance defined at any level will be achieved if all of the requirements are met at the level below. The four main Science Goals are achieved by meeting the quantitative Science Requirements, which in turn are met by fulfilling the experiment's Measurement Requirements, which define the reach of the CMB-S4 survey.

An iterative process of developing and analyzing the performance of various alternative technical implementations, including siting, is being used to specify the survey design and overall technical design and define a set of high-level technical requirements that are achievable and can achieve the Measurement Requirements. These Level 1 technical requirements then flow down to subsystems requirements which are further parsed into requirements on finer elements of the system, such that the elements of the experiment work together to meet all the higher-level requirements and goals. The hierarchical structure of the requirements flowdown is shown in Figure 7.

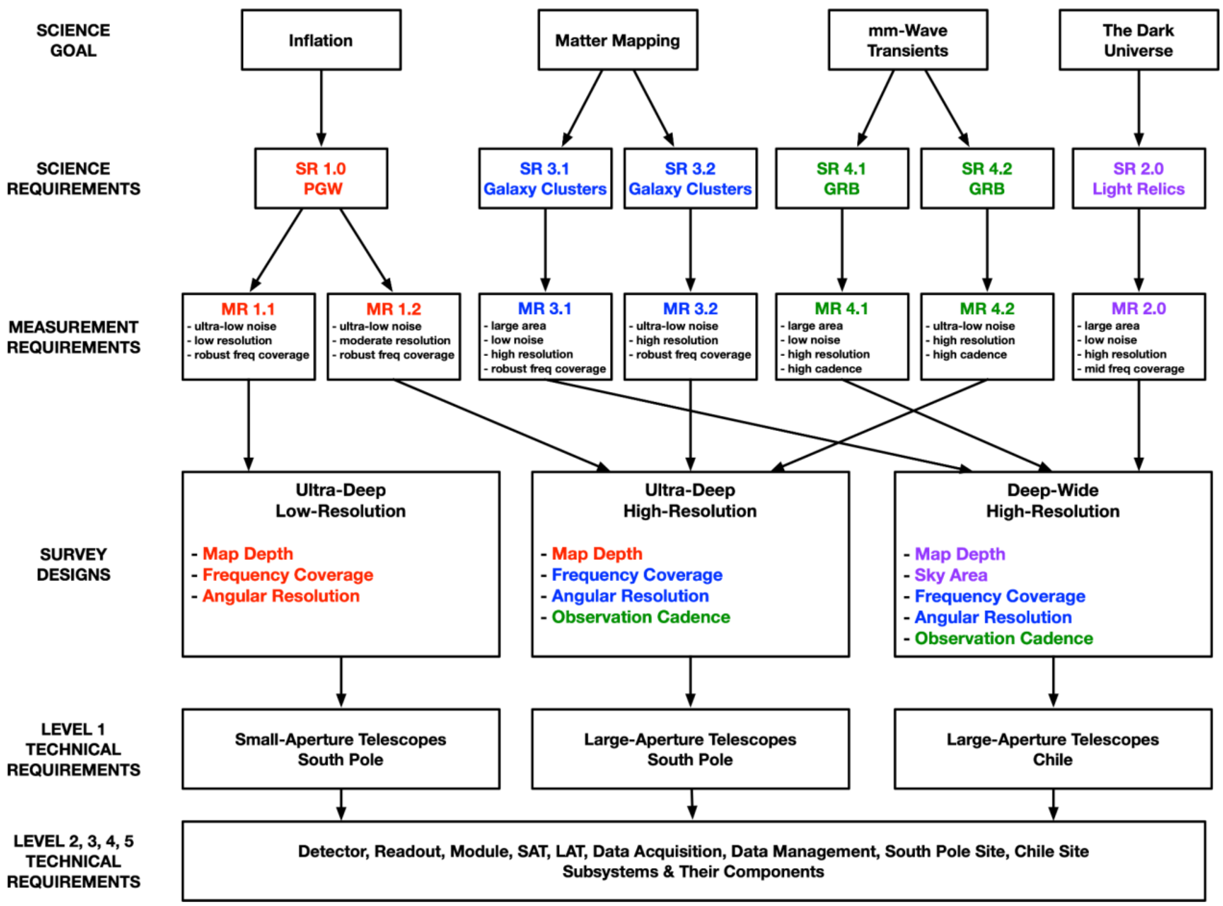


*Figure 7: Each CMB-S4 Science Goal has an associated Science Requirement, which then sets the corresponding Measurement Requirements; these are illustrated in the top half of the figure, including the qualitative measurement properties spanned by each measurement requirement. We can then define a set of three surveys, which collectively meet all of the measurement requirements and identify the instruments and sites that can make these in the most cost-effective way, capturing their minimum performance as Level 1 Technical Requirements. These high-level requirements are further broken down into more detailed requirements on the subsystems and components. The color-coding in the survey properties identifies the driving science requirement.*

This process is not exclusively a matter of flowing requirements down from higher levels to lower ones. The iterative nature of this approach allows for "flow-up" from lower levels, based on assessments of feasibility, design maturity, cost, and technical risk. A key element of this iterative process is the use of performance modeling tools that predict overall performance given varying implementations of designs under consideration, resulting in a cohesive system design that efficiently meets the highest level requirements and goals, and that is achievable within fiscal and technical constraints.

Technical requirements are managed as part of the systems engineering framework that governs the technical execution of the CMB-S4 project. Requirements, along with their verification plans, are maintained and tracked using the Jama Connect web-based requirements management database. The left panel of Figure 8 shows the overall structure of the CMB-S4 requirements, with the levels of requirements aligning with the work breakdown structure level at which they apply. The right panel of Figure 8 is the project's "N-squared" interface matrix that identifies where there are interfaces between CMB-S4 subsystems, the types of interfaces, and the document numbers where the interface details are published.

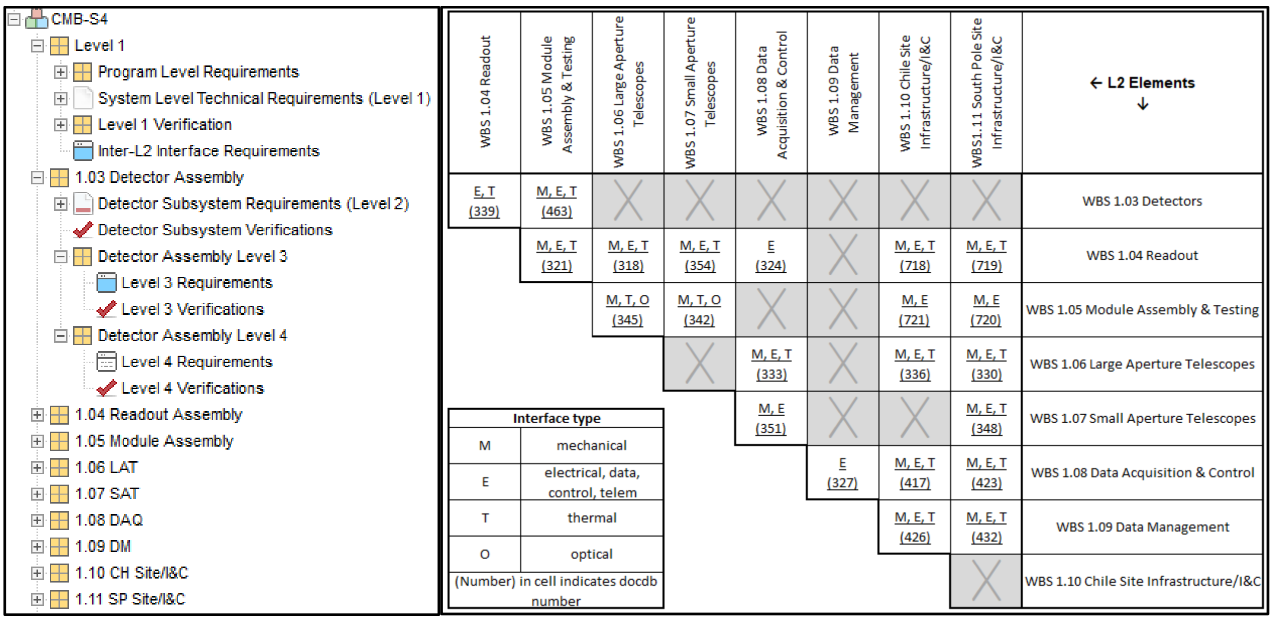


*Figure 8: Left - CMB-S4 requirements hierarchical organization in the Jama. Connect tool. Right - CMB-S4 N-squared subsystem interface matrix.*

## 4. PERFORMANCE PROJECTIONS AND MARGIN APPROACH

CMB-S4 aims to deliver unprecedented CMB science reach, with an order of magnitude greater sensitivity than Stage-3 CMB experiments. The CMB-S4 project's purpose and commitment is to deploy an experiment that can meet the Measurement Requirements in no more than the planned survey duration, currently seven years. In much the same way as the project will have budget and schedule contingency above the baseline, it also needs to have performance margin to account for risks and uncertainties.

The CMB-S4 project and collaboration employ several modeling and simulation tools to estimate the experiment's performance[20,21]. These are largely based on the performance of previous and current CMB experiments, with adjustments and extrapolations to reflect planned improvements for CMB-S4's implementation, such as lower transition temperatures for the detectors, larger numbers of deployed detectors, and updated survey strategies. Current projections show the conceptual design has positive performance margin to complete the Measurement Requirements within seven years of operations.

As the iterative design/analysis process continues, we seek to identify additional opportunities to improve performance and build margin. Our general approach is to first characterize and break down the performance of previous and current experiments to quantify what factors contribute to and degrade performance. We then assess which factors offer opportunities to improve and perform analyses to assess and quantify possible benefits. Low-risk improvements that can be credibly achieved are folded into the conceptual design and captured in the requirements, and the overall experiment performance and margin are re-calculated. Current areas of focus are on increasing the fraction of deployed detectors that are effective for survey mapping and improving observing efficiency, meaning the fraction of calendar time that effective survey mapping is to be conducted. Improvements in the former are expected due to CMB-S4's large production of detector and readout elements, along with high detector acceptance thresholds afforded by expected levels of project funding. The latter is being studied in detail to optimize survey strategies and to understand the causes of downtime for previous experiments, implementing technical and procedural changes to minimize projected down time for CMB-S4.

## 5. PROJECT ORGANIZATION

The CMB-S4 project organization chart from Work Breakdown Structure (WBS) Level 1 to WBS Level 3 is shown in Figure 9. The WBS includes all the scope required to construct and commission an experiment that can meet the science goals. The roles in this chart are filled with team members broadly distributed across the participating national laboratories, universities, and industrial partners. The Project Office manages the entire project, reporting to both funding agencies, and the Project Operations functions are provided for the benefit of the project as a whole.

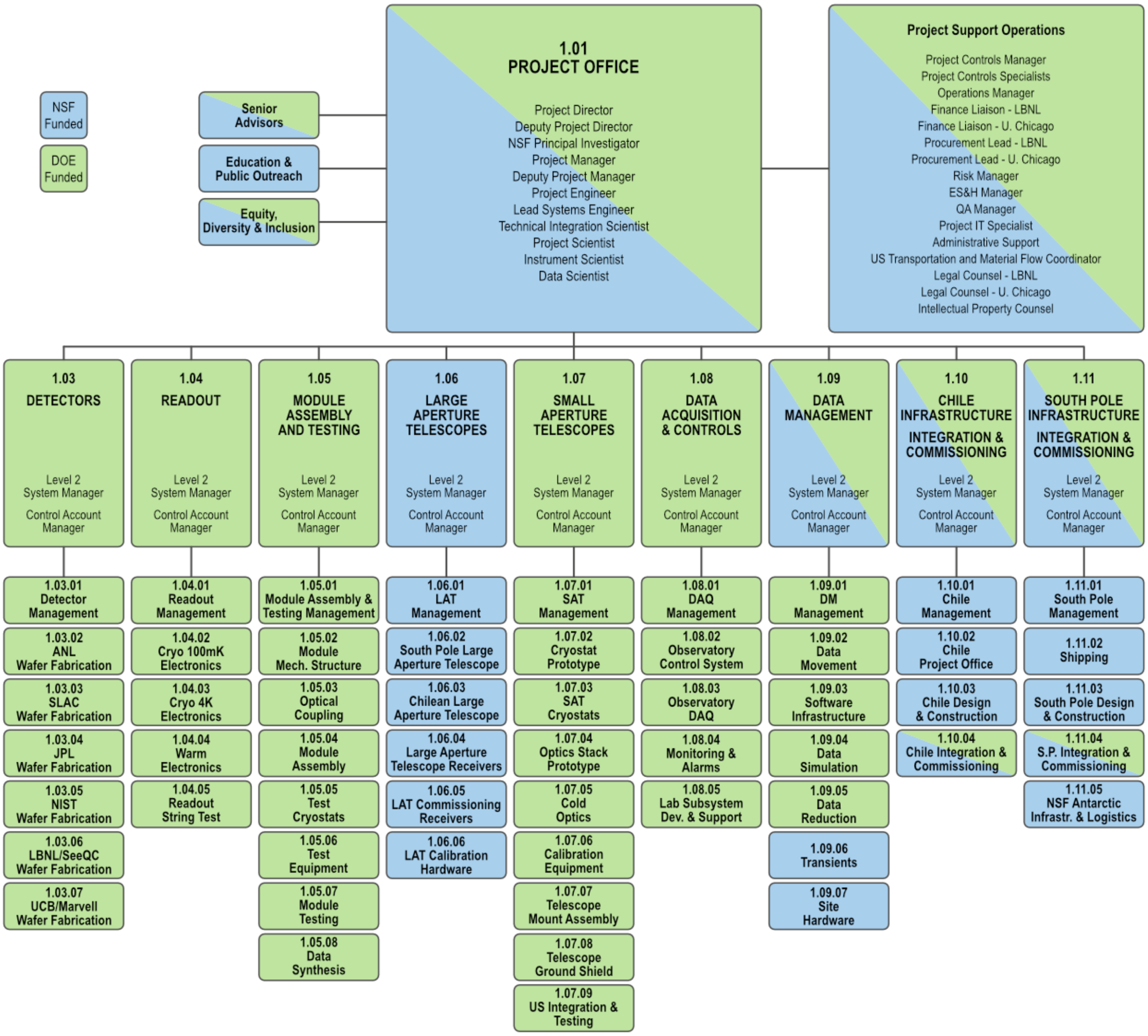


*Figure 9: CMB-S4 is a single, unified project. This diagram illustrates the project organization to Level 3 of the work breakdown structure. Not shown for clarity is the further breakdown to Levels 4 and 5, which is fully-developed in the project plan. The color-coding illustrates the notional division of funding by agency, with expected NSF-funded scope in blue and DOE-funded scope in green.*

The project's nine subsystems, designated 1.03 through 1.11, are managed at Work Breakdown Structure (WBS) Level 2, each with a Level 2 System Manager, generally the lead scientist of the subsystem, who provides overall subsystem leadership, and a Control Account Manager (CAM) who is responsible for managing the subsystem's fiscal performance and reporting. These two Level 2 leads work closely together in managing the work in their subsystems. That subsystem work is divided into WBS Level 3 elements, which generally describe a major deliverable within their subsystems, and each of which has a Level 3 manager. The Project's WBS hierarchy tree is developed down to Level 5, with smaller elements of each subsystem at each lower WBS level.

## 6. CONCLUSION / NEXT STEPS

CMB-S4's science goals are a high priority for the science community, with construction of the CMB-S4 experiment strongly endorsed both by P5 and in the Astro2020 report. The CMB-S4 conceptual design is tailored to meet those science goals, leveraging experience from previous CMB and other scientific experiments. The CMB-S4 is a single, unified project with a distributed team that has deep and broad CMB experience. Effective project organization, systems engineering, and infrastructure are in place and are being actively exercised. Key research and development efforts are ongoing, advancing technical readiness and retiring risks. Iterative technical design and performance modeling processes are being effectively used to refine and improve the conceptual design and to adapt to any external constraints. CMB-S4's scientific reach will enable transformational science, crossing critical thresholds in physics, cosmology, and astrophysics at the frontier of our knowledge. We are on track to construct an exciting, groundbreaking experiment.

## ACKNOWLEDGEMENTS

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