CMB-S4

The birth, life and death of a major science project

Jim Strait, ex-Project Director

25 September 2025

What was CMB-S4?

CMB-S4 was envisioned to be

- a comprehensive ground-based CMB experiment to make transformative discoveries and new insights in fundamental physics, cosmology, astrophysics, and astronomy.
- a vehicle to unite the entire CMB community to enable a ground-based experiment with capabilities beyond that of any of the smaller individual experiments
- a way to realize the enormous potential of CMB measurements for understanding the origin and evolution of the Universe, from the highest energies at the dawn of time through the growth of structure to the present day.

CMB-S4

- Was launched with great promise and enthusiasm at the 2013 Snowmass Summer Study,
- Grew into a large collaboration and built a capable project organization,
- Developed advanced technical designs and scientific strategies,
- Was endorsed by multiple high-level advisory committees

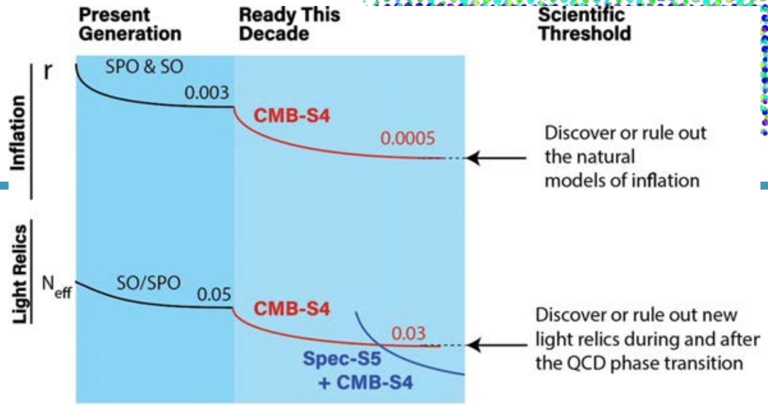
But ultimately it was cancelled by the funding agencies in 2025.

Outline of the talk

- CMB-S4 Science Goals
- The CMB-S4 Collaboration and Project
- CMB-S4 Technical Development and Accomplishments
- CMB-S4 Science Impacts
- CMB-S4 History
- Why Didn’t CMB-S4 Move Forward
- Summary and Outlook for the Future

CMB-S4 Science Goals

CMB-S4 Primary Science Goals



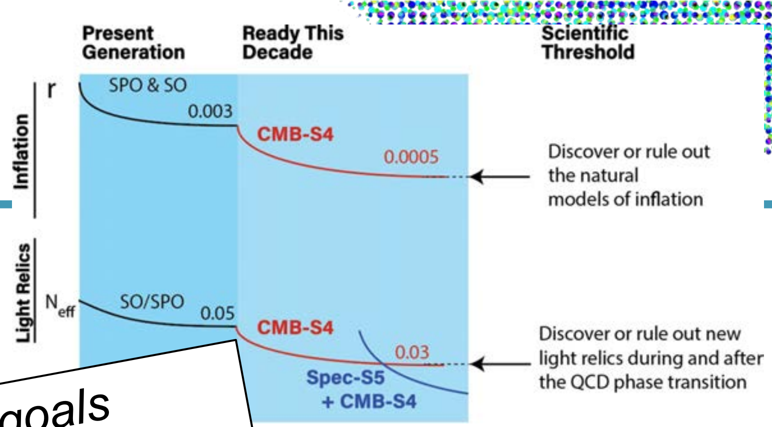
Inflation: CMB-S4 will cross a critical threshold **(σ_r < 0.0005)** to discover or rule out the natural models of inflation.

Relic Particles: CMB-S4 will cross a critical threshold to discover or rule out light relic particles that freeze out during and after the QCD phase transition extending our knowledge of relic particles by orders of magnitude in the freeze out temperature.

Matter Mapping: CMB-S4 will provide legacy maps that probe cosmology and astrophysics and that enable diverse new science including dark energy and dark matter studies and neutrino mass scale, complementing LSST DESC and DESI and the proposed Spec-S5.

Time Domain: CMB-S4 will provide ~hourly maps which detect millimeter wave transients relevant for wide range of astrophysics, e.g., solar system objects, stars, TDEs, SN, AGN, and multi-tracer studies with LSST, IceCUBE, and LIGO.

CMB-S4 Primary Science Goals



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Relic Particles: CMB-S4 will cross a critical thre[illegible] discover or rule out light relic parti[illegible] the QCD phase transition extending [illegible]itude in the freeze out temperature.

A design that achieves these driving goals enables broad and rich program of cosmology, astrophysics and physics research.

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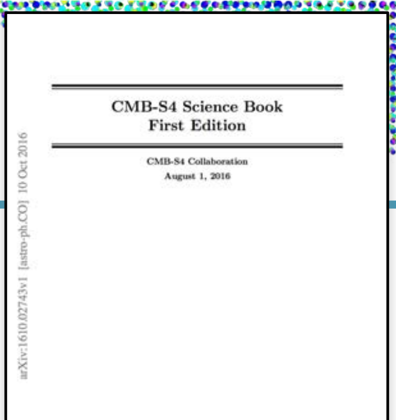
Extremely Broad Science Program

Primary CMB Anisotropy: Inflationary gravitational waves • Inflation energy scale • Quantum Gravity • Light relics • BSM particles • Primordial power spectrum • Cosmic census (baryons-dark matter-dark energy) …

Secondary Anisotropy and using the CMB as a backlight: Neutrino mass • Dark Energy • Cosmic birefringence • Axion dark matter • Dark matter-baryon scattering • Sunyaev-Zeldovich scattering effects • Galaxy clusters • Galaxy evolution and feedback • Gravitational lensing • Cross-correlations with gas/mass/galaxies • Cosmological momentum field • Reionization/1st stars…

Time-domain, Deep, Wide-area, Millimeter-wave Surveys: Gamma ray bursts • Tidal disruption events • Fast blue optical transients • Supernovae • Time-variable active galactic nuclei • Multi-messenger correlations with time-domain observatories • Dusty star-forming galaxies • Stellar flares • Galactic black hole flares • Fast radio bursts • Interstellar medium • Galactic magnetic field • Exo-Oort Clouds • Planet 9 • Asteroids…

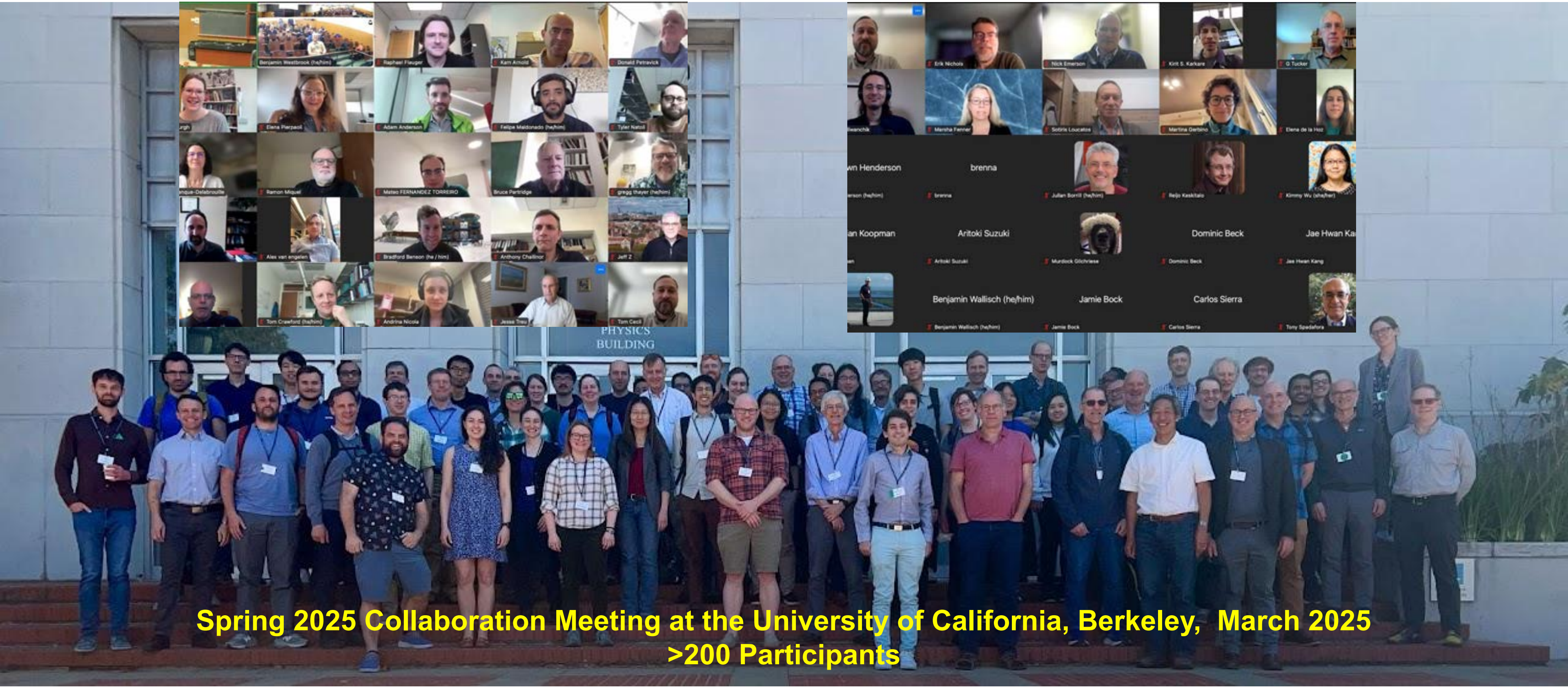

CMB-S4 Science Book
First Edition
CMB-S4 Collaboration
August 1, 2016
arXiv:1610.02743v1 [astro-ph.CO] 10 Oct 2016

CMB-S4 Science Book (2016)

200 pages, >1400 citations
arXiv:1610.02743

The CMB-S4 Collaboration and Project

A Strong and Enthusiastic CMB-S4 Science Collaboration

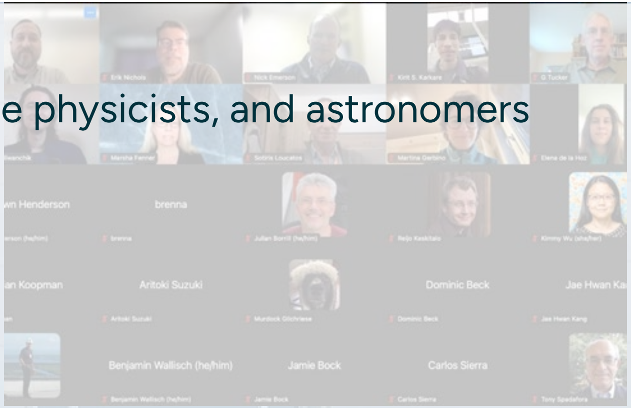


Spring 2025 Collaboration Meeting at the University of California, Berkeley, March 2025
>200 Participants

A Strong and Enthusiastic CMB-S4 Science Collaboration

- CMB-S4 Science Collaboration
  - >500 members: primarily cosmologists, particle physicists, and astronomers (~⅓ international)
  - >115 institutions (>50 non-US)
  - >21 countries
  - >20 U.S. States
  - 2 major collaboration meetings/year
  - 1st collaboration meeting in 2015
  - Established a formal collaboration in 2018

- Laid the foundation for the Project:
  - Produced *CMB-S4 Science Book* (arXiv:1610.02743) and *CMB-S4 Technology Book* (arXiv:1706.02464).
  - Produced *CMB-S4 Science Case, Reference Design, and Project Plan*, for input to Astro2020 (arXiv:1907.04473)



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CMB-S4 Site Selection

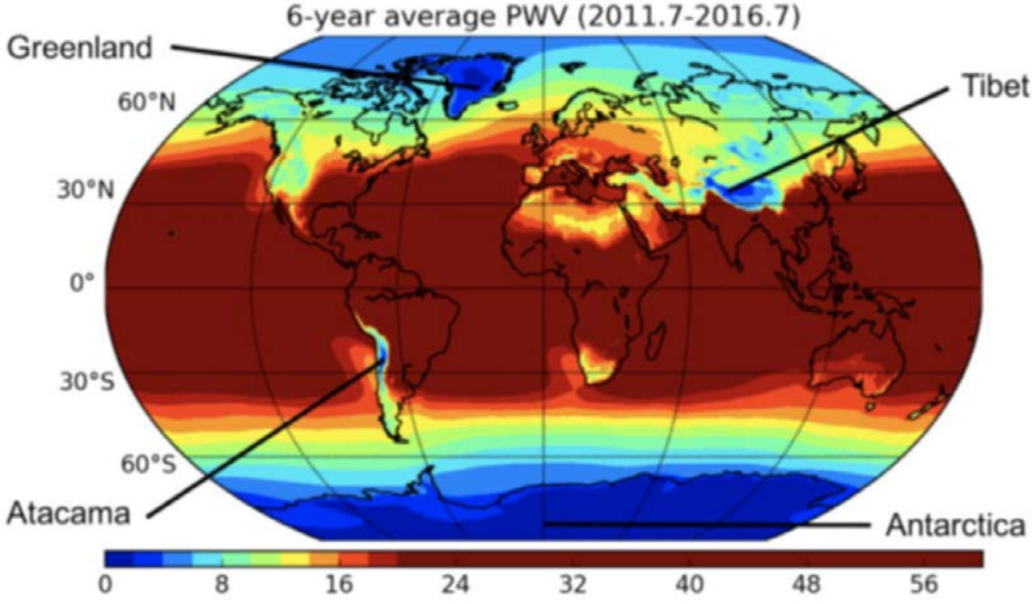


Figure 1. Mean precipitable water vapor (PWV) in mm across the globe. Candidate sites (dark blue) are the South Pole, Chilean and Argentinian Atacama Desert, Tibetan Plateau and Greenland. Ref: H. Li et al., arXiv:1710.03047

- There are four regions on the globe with minimal mean precipitable water vapor (PWV).
- The best atmospheric conditions are at the South Pole.
- The most straightforward access is to the high Atacama site in Chile and Argentina.

=> Most ground-based CMB experiments have used these two sites, and CMB-S4 was no exception.

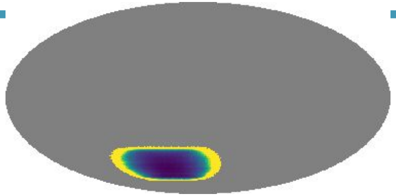
CMB-S4 Project Analysis of Alternatives, CMB-S4-doc-1005, 11 Nov 2023

CMB-S4 Site Selection

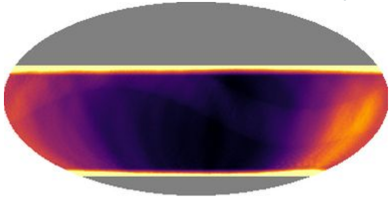
CMB-S4 Required Two Complementary Surveys:

- **An ultra-deep survey** over a small fraction of the sky, mainly to test models of inflation.
- **A wide-deep survey** covering the largest possible fraction of the sky, mainly to address other goals - light relic particles, formation and evolution of galaxy clusters, and transients.
- CMB-S4 conducted a rigorous Analysis of Alternatives (AoA) to select a preferred configuration of telescopes and sites, most recently documented [CMBS4-doc-1004 and -1005] for an LBNL Director's Review in 2023.
  - **CMB-S4 selected a two-site configuration with telescopes at the South Pole to conduct the ultra-deep survey and in the high Atacama desert in Chile to conduct the wide-deep survey.**
  - *The AoA also concluded that a configuration with all telescopes in Chile "could offer a way to make the measurements, if CMB-S4 is unable to access the Pole."*

Ultra-deep survey



Wide-deep survey



CMB-S4 Configuration 2023

CMB-S4 Design Report 2023, CMBS4-doc-716-v6, November 2023

- CMB-S4 focused on a two-site configuration from its inception, with details of the numbers and types of telescopes evolving as the project developed and boundary conditions changed.
- The configuration [CMBS4-doc-716-v6] presented to a Director's Review in November 2023 comprised:
  - At the South Pole:
    - Nine 0.56-m Small-Aperture Telescopes (SAT)
    - One 5-m Three Mirror Anastigmat (TMA) Large Aperture Telescope (LAT)
  - In Chile:
    - Two 6-m Crossed Dragone (CD) LATs

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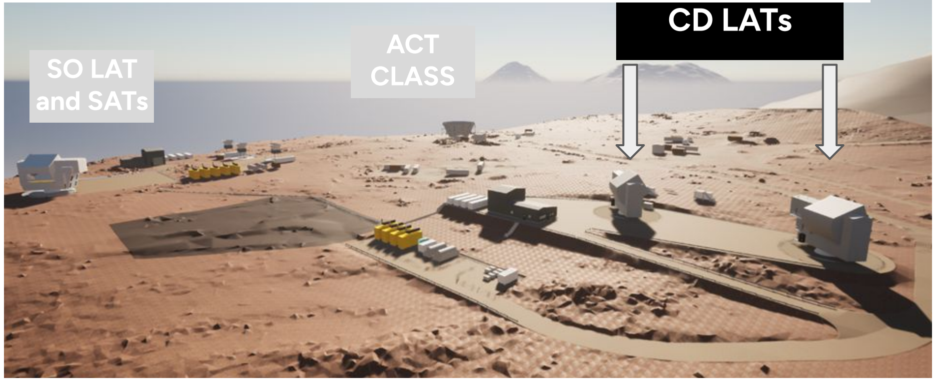
  - In Chile:
    - Two 6-m Crossed Dragone (CD) LATs
- This configuration was shown to be able to achieve all of the science goals of CMB-S4 in a 7-10 year survey duration without reference to or dependence on any other experiment.



NSF Decision Regarding CMB-S4 at the South Pole

On May 7, 2024, at a meeting of the NAS Board on Physics and Astronomy, Chris Smith, Director of NSF Astronomy; and then on May 9, 2024, at a meeting of the High-Energy Physics Advisory Panel, Jean Cottam Allen, Director of the NSF Office of Polar Programs made the following announcement:

> After extensive analysis, **NSF has made the decision not to move the CMB-S4 project in its current form into the NSF Major Facility Design Stage at this time.** The agency must prioritize the recapitalization of critical infrastructure at the South Pole so that the groundbreaking research it enables can continue to thrive.
>
> NSF is committed to cosmic microwave background science and will continue to support current CMB activities at the South Pole and in Chile. We are in active discussions with DOE and the CMB-S4 Project about the path forward. NSF will work with the community to explore possible options for future CMB science.

Following the NSF decision to exclude CMB-S4 from accessing the Pole, CMB-S4 developed an all-Chile option, in which the ultra-deep survey is also conducted in Chile.

CMB-S4 Revised Configuration Report

CMBS4-doc-1095, June 2025

CMBS4-doc-1095-v1

Revised CMB-S4 Project Plan

CMB-S4 Project
and Collaboration

June 4, 2025

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On June 4, 2025, CMB-S4 delivered a report to the funding agencies proposing a revised project plan with new instrumentation only in Chile. An initial configuration of CMB-S4 would comprise:

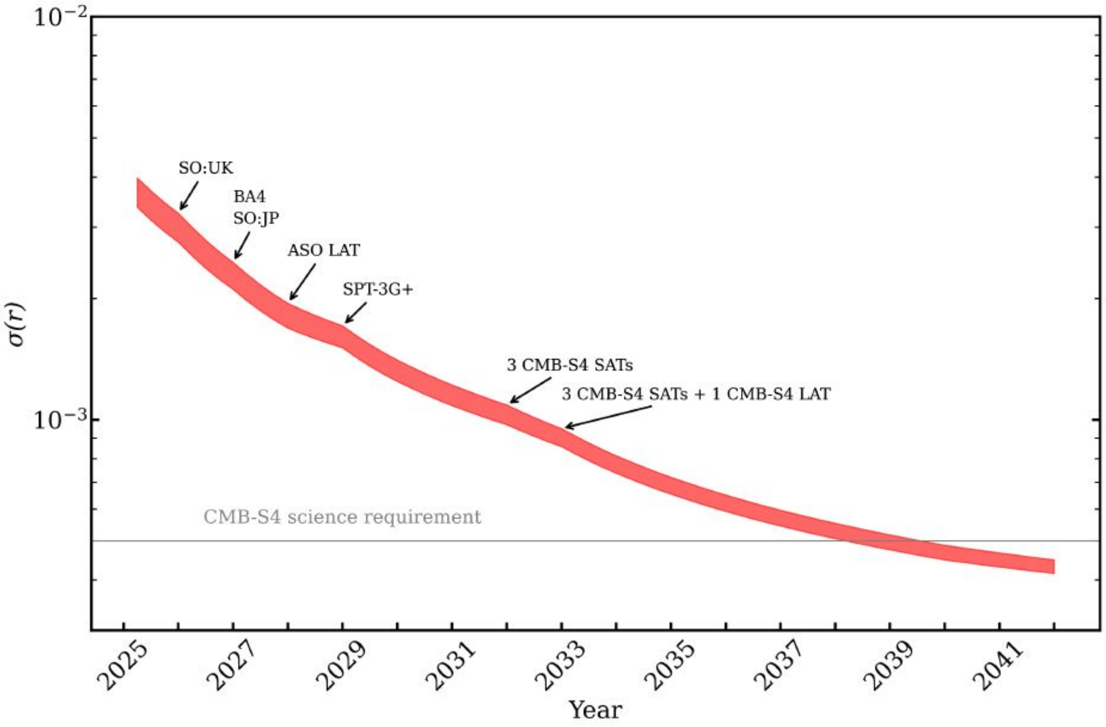
- 6 CMB-S4 SATs (three each on a common mount)
- 1 CMB-S4 LAT

It proposed a substantially new strategy that would build on, rather than replace the instrumentation in place or planned by the existing Stage 3 experiments: BICEP, Simons Observatory (SO) and the South Pole Telescope (SPT).

- SO, BICEP and CMB-S4 SATs would follow a coordinated survey strategy focused on a common, small deep field, and would share data from 2028 to allow a combined map-based analysis.
- Delensing for all SATs would be provided by SPT-3G+ and by the CMB-S4 LAT.
- The SO LAT and a fraction of the CMB-S4 LAT time that would not be devoted to delensing would share responsibility for executing the wide-deep Legacy Survey.

The 3-experiment combination would be able to achieve essentially all CMB-S4 science goals within 10 years of the start of CMB-S4 observations.

Inflation Science: σ(r) as a function of time



LB Figure 4.1: Forecast for $\sigma(r) = f(t)$ for combined observations by SPO, SO, and CMB-S4 with six SATs and one LAT. The years when additional instrumentation are assumed to be brought online are indicated.

ΔN_{eff} versus time

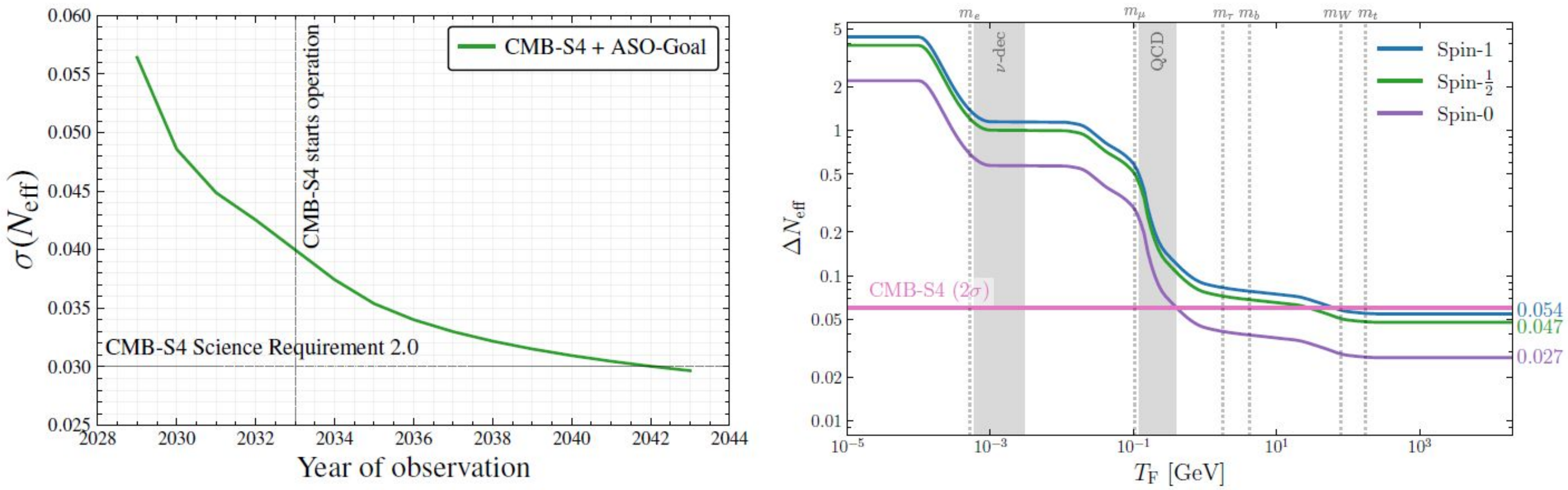


Figure 4.2: *Left:* Forecast for $\sigma(N_{\rm eff})$ (68 % C.L.). The ASO observations begin in 2028, and assume goal noise levels and $f_{\rm sky} = 0.62$. After 2033, the constraint comes from combining three sets of observations: the CMB-S4 Hybrid Wide LAT Survey, the CMB-S4 Ultra-deep LAT Survey, and the wide ASO survey (total $f_{\rm sky} = 0.62$), hitting the science requirement by 2042. *Right:* $\Delta N_{\rm eff}$ as a function of relic particle freeze-out temperature, T_F. The increase in sensitivity to $\Delta N_{\rm eff}$ allowed by CMB-S4 improves constraints on the freeze-out temperature to times before the QCD phase transition for particles of any spin, which sets the science requirement. For particles with spin 1/2 or 1, the freeze-out temperature is a strong function of $N_{\rm eff}$ and the constraint improves by more than an order of magnitude.

High Redshift Galaxy Clusters

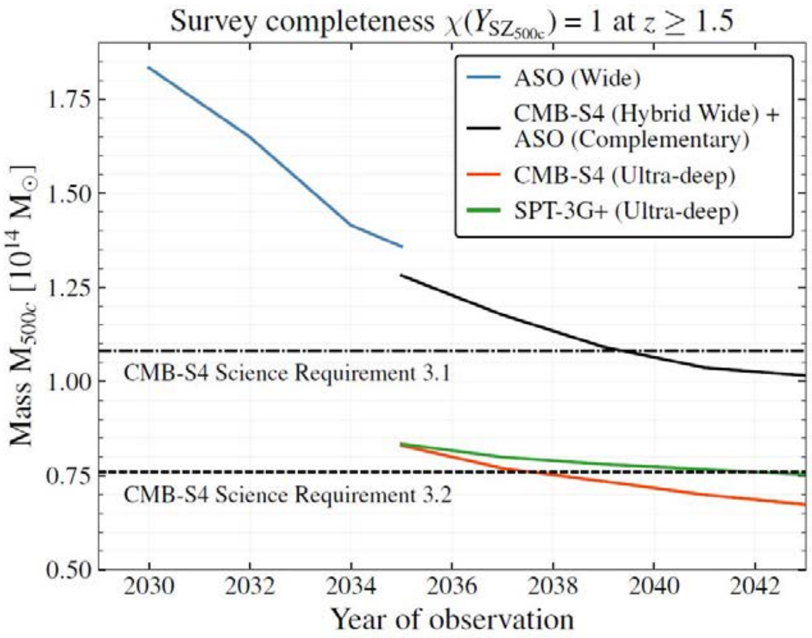


Figure 4.3: Minimum detectable cluster mass with 100% completeness at $z \geq 1.5$ for different survey configurations. Blue shows ASO assuming goal noise levels following the Wide Survey. Black shows the combination of the CMB-S4 LAT executing the Hybrid Wide Survey combined with ASO, which meets the CMB-S4 requirement SR3.1. The CMB-S4 LAT executing the Ultra-deep Survey, shown in red, surpasses the SR3.2 threshold in just 3 years. SPT-3G+, also following the Ultra-deep Survey, meets requirement SR3.2 after 7 years of survey.

CMB-S4 Technical Development

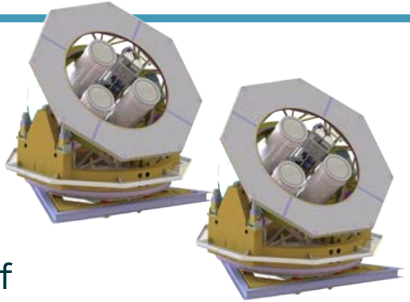
CMB-S4 Instrumentation Development

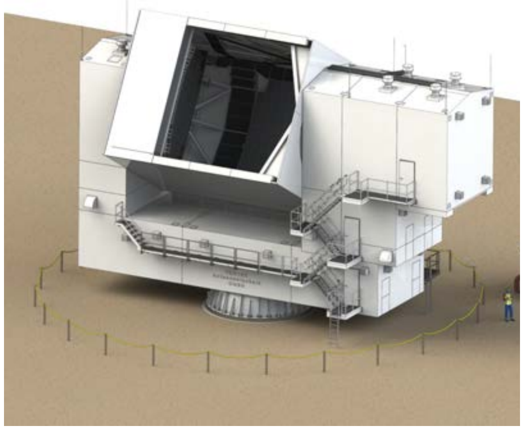
R&D to support the development of CMB-S4 has substantially advance the capabilities of instrumentation needed for CMB research.

- Development of designs of TES detector arrays covering the required frequency bands from 20 GHz to 270 GHz and development of multiple fabrication sites that would be needed to produce the large number of detector arrays.
- A complete TDM readout system from 100 mK to room temperature.
- A module design combining the detectors, optical coupling wafers, and 100 mK electronics.
- Designs of the SATs, with versions optimized for operation at the South Pole and in Chile.
- Design of a 5-m TMA LAT, including full-scale prototype monolithic 5-m mirror.
- Adaptation the 6-m CD LAT design developed by CCAT and SO.
- Design a high-density receiver for use on all the LATs.
- Development of requirements for the Chile site and preliminary work towards establishing the legal basis for CMB-S4 to operate there.
- Conceptual designs for CMB-S4 facilities at the South Pole.

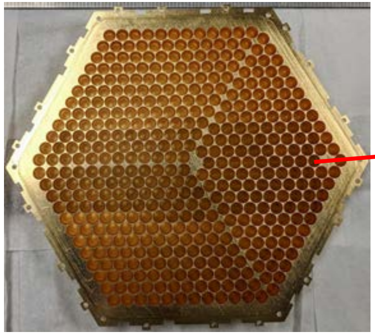
CMB-S4 Instruments

- The **ultra-deep survey** is conducted by:
  - Multiple small-aperture (~0.5m) telescopes (SAT) measuring degree-scale structures in the CMB
  - One or more large-aperture (~6m) telescopes (LAT) for de-lensing, i.e., using CMB lensing reconstruction to remove the contribution of B-mode polarization caused by gravitational lensing of the CMB E-mode polarization by large scale structure
- The **wide-deep survey** is conducted by:
  - One or more additional LATs measuring small-scale structures over as large as possible an area of the sky
- The design of the LATs for delensing and for the wide-deep survey may be the same and the two surveys may be shared among the LATs to optimize efficiency.

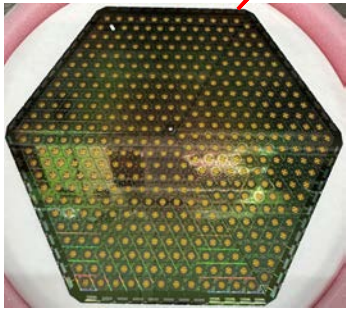




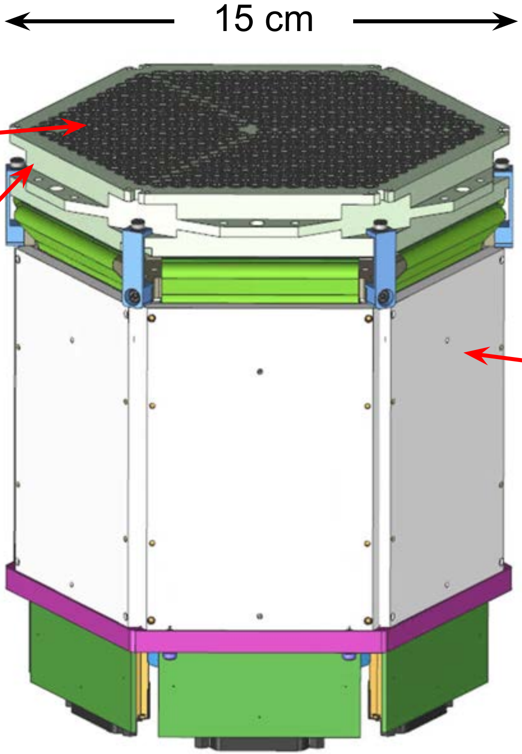
Readout Modules

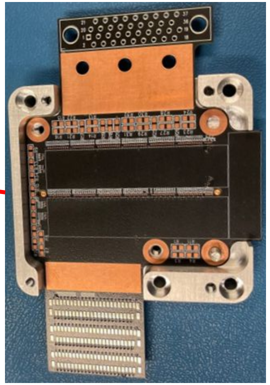


Horn Array and coupling wafers



Detector Array

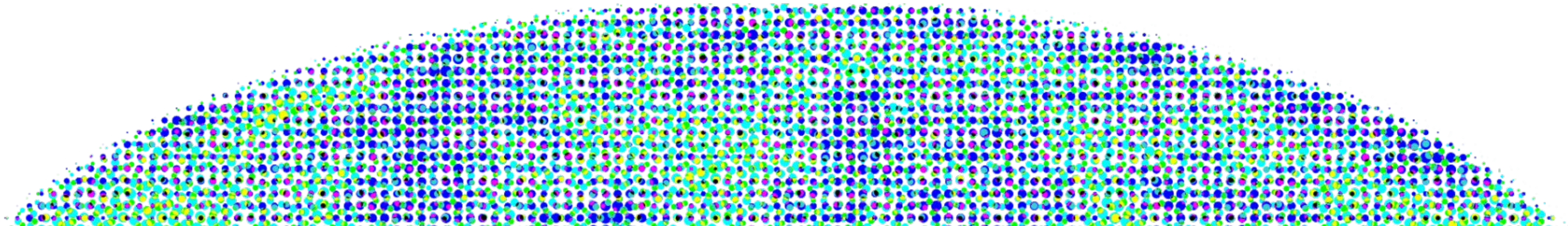




100 mK Superconducting Readout

CMB-S4 Detectors

LBNL, ANL, Caltech/JPL, NIST, SLAC, UCB

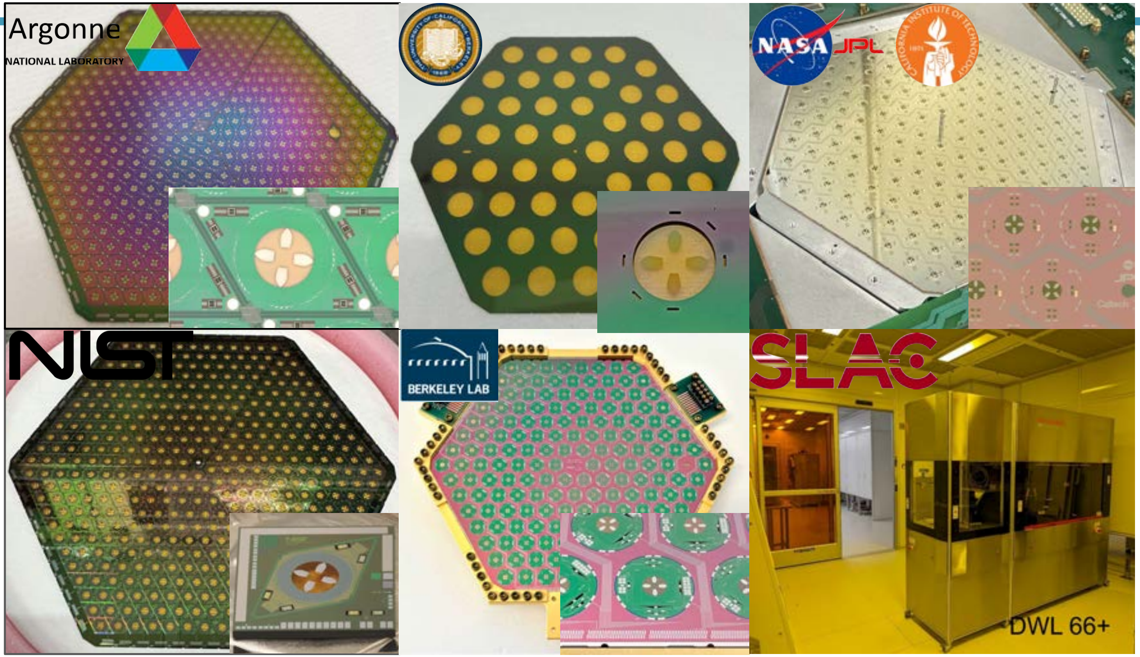


Detector Team - 6 Fabrication Sites

Experienced detector team came together to deliver detectors for CMB-S4

- Fabrication team delivered detectors to: ACTPol, AdvACT, Four generations of BICEP, EBEX, Herschel, MUSTANG-2, Planck, POLARBEAR, Simons Array, Simons Observatory, SPIDER, SPT-3G, SPT-POL, SPT-POL

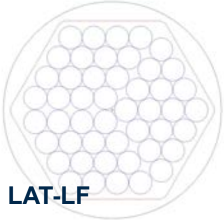
Detector fabrication development

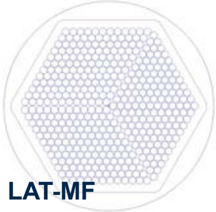


Fabrication team made significant progress for future CMB experiments

- Prototype detector array fabrication for LAT-MF, SAT-MF and LAT-LF
- Openly shared mistakes and findings for all sites to make rapid progress
- Wafers were delivered for the module team to be characterized

CMB-S4 Project: Baseline Detector Wafer Count


LAT-LF


LAT-MF

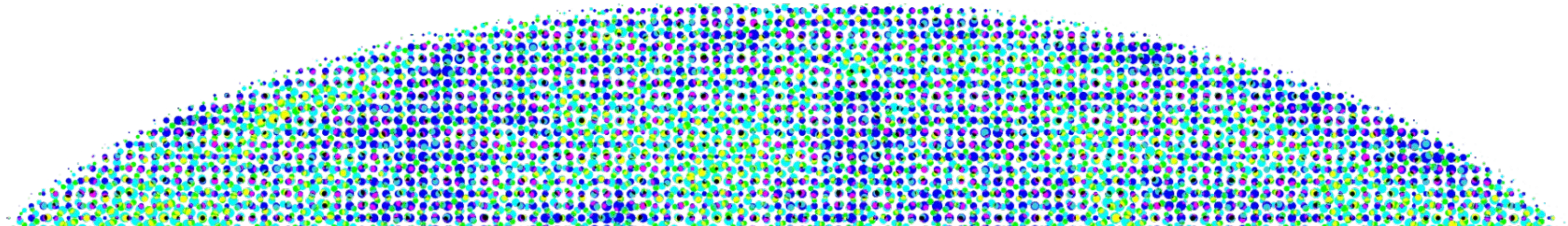

LAT-HF

Telescope	Type	Frequency	Fabricate (586 wafers)	Deployment (363 wafers)
Large Aperture	ULF	20 GHz	7	4
Large Aperture	LF	30 GHz, 40 GHz	40	25
Large Aperture	MF	90 GHz, 150 GHz	265	162
Large Aperture	HF	220 GHz, 270 GHz	103	64
Small Aperture	LF	30 GHz, 40 GHz	18	12
Small Aperture	MF1	85 GHz, 145 GHz	57	36
Small Aperture	MF2	95 GHz, 155 GHz	57	36
Small Aperture	HF	220 GHz, 270 GHz	39	24

CMB-S4 required >5 times more wafers than any previous experiment.

CMB-S4 Readout

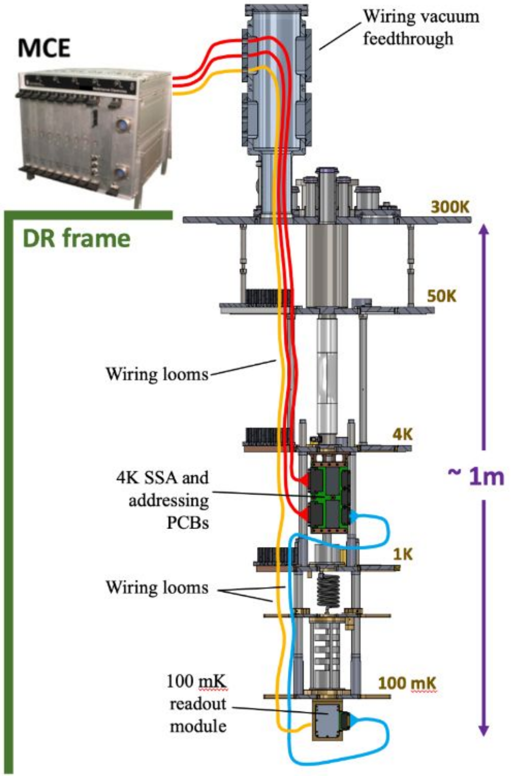
SLAC, UIUC, UNM, APC Paris, CEA Paris,
NIST Boulder, FNAL, LBNL, ANL.



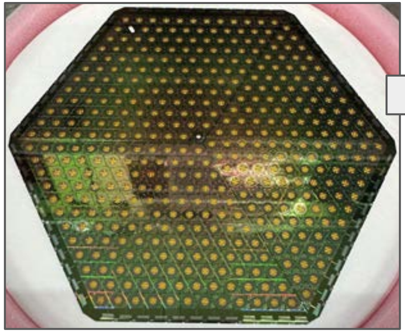
Readout System Accomplishments

- Developed a complete and novel control and superconducting sensor readout chain for the focal planes of next-generation CMB Time-Division Multiplexing (TDM) experiments, from 100mK superconducting electronics to 300K warm electronics including hardware, firmware, and software.
- CMB-S4 readout system was assembled with a 90-150 GHz TES detector wafer fabricated at NIST and tested in the SLAC test stand, showing functionality and performance from on-detector Transition Edge Sensors.
- Test stands were also commissioned at UIUC and UNM for end-to-end testing the full cryogenic readout system and to support prototype detector module testing.
- The R&D was close to complete. 6-8 months of R&D required to produce a production model system to be installed into an experiment.

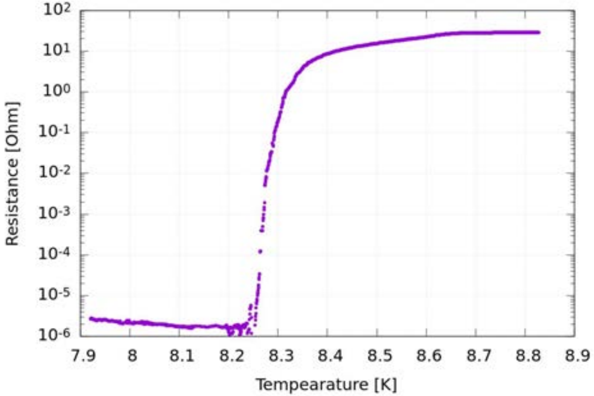
Cryo Electronics Test Stand



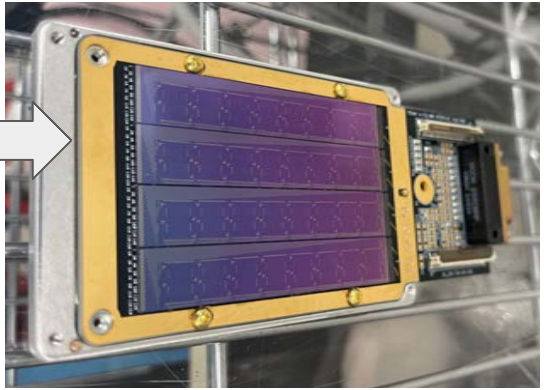
100 mK Readout Electronics Chain



Detector Wafer



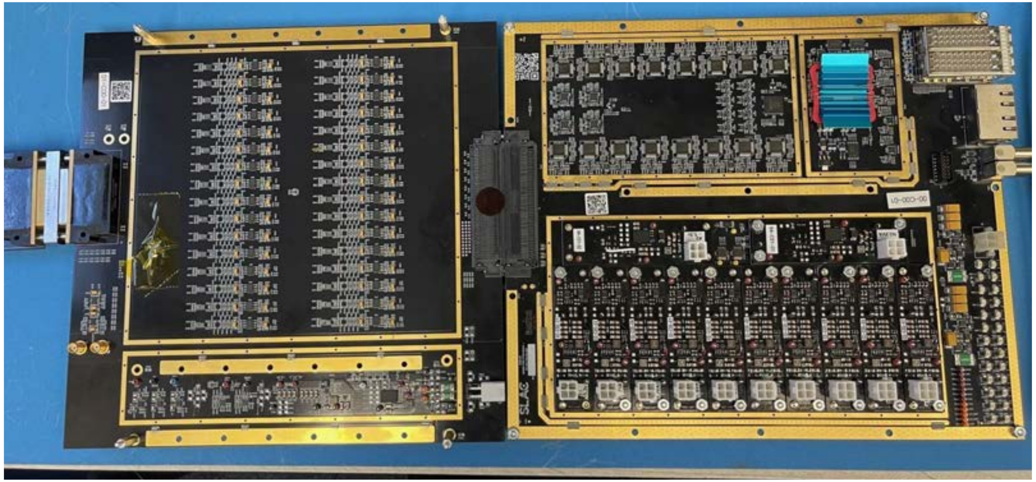
Superconducting flex cable.



100mK readout modules with
4 columns for tower module assembly.

4 K and 300 K Electronics

4K amplifier module with
SQUID amplifiers.



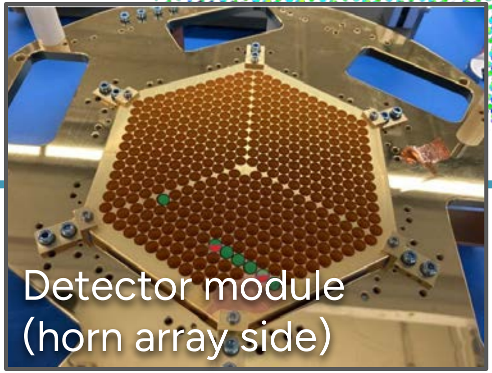
Warm Electronics row address module
with FPGA board and row address front-end module

CMB-S4 Module Assembly and Test

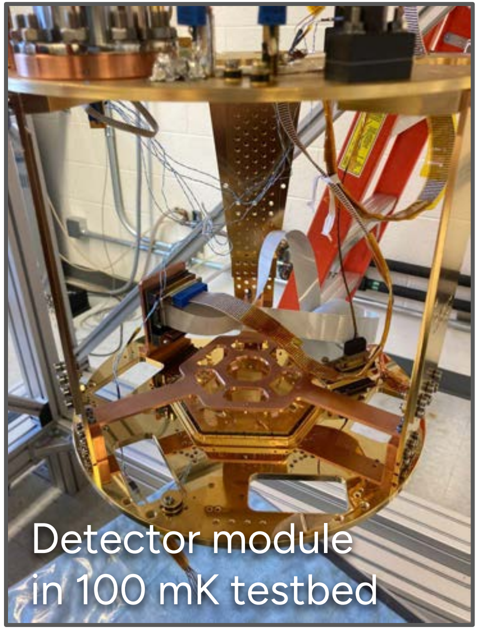
Fermilab, UIUC, CWU

Modules, Assembly, and Testing (MAT) Overview

- Developed and tested prototype detector modules for CMB-S4, which included all the key detector, readout, and module components.
- Designed and tested the module RF coupling components:
  - “Optical” silicon coupling wafers
  - Gold-plated aluminum horn arrays
- Developed and tested the assembly of two prototype module designs:
  - “Flat” detector module for initial prototyping testing
  - “Tower” detector module designed for production arrays
- Commissioned three 100 mK detector module testbeds



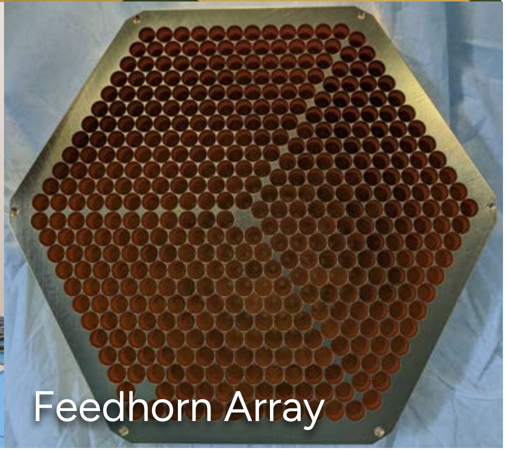
Detector module (horn array side)



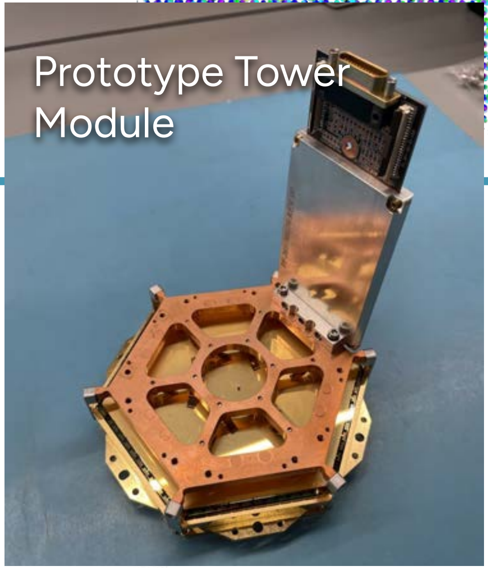
Detector module in 100 mK testbed

Optical Coupling

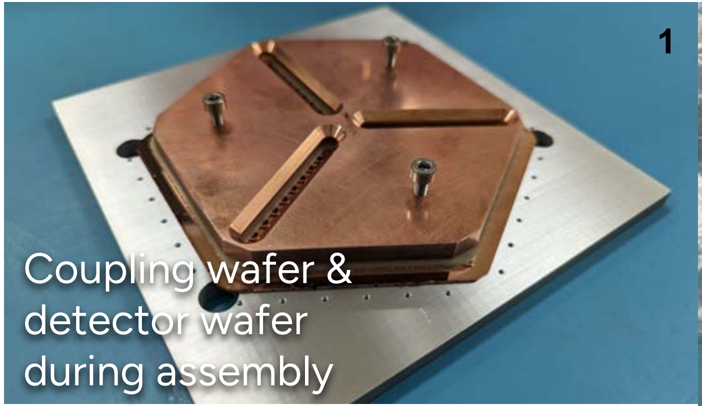
- Developed designs for different frequency bands and optics→ demonstrated flexibility of the optical coupling technology design
- Developed new commercial vendors for optical coupling wafers and feedhorns and demonstrated their fabrication
- Completed tolerance studies on feedhorns and optical coupling wafers to better understand manufacturing constraints
- Developed QA/QC procedures and beam mapping test setup

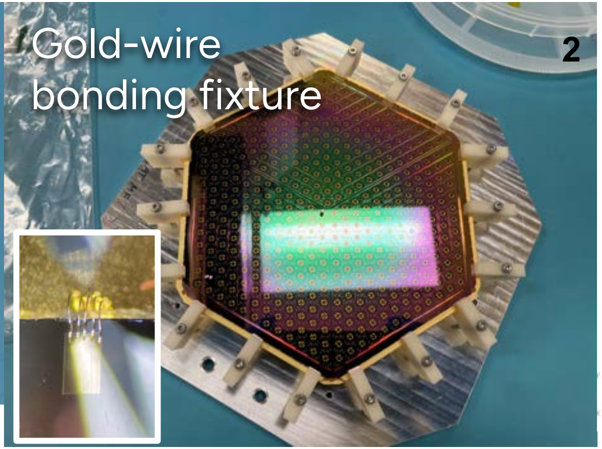


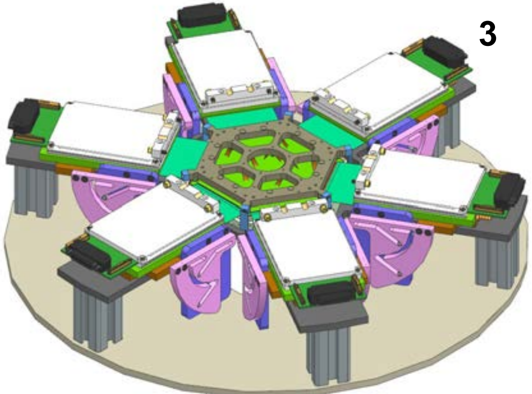
Module Mechanical Design



- Developed module design
- Developed assembly procedures for each step of the module assembly including:
  - Assembly of the coupling wafers and the detector wafer (1)
  - Integration with the horn array including Au bonding (2)
  - Integration with readout modules including bonding (3)





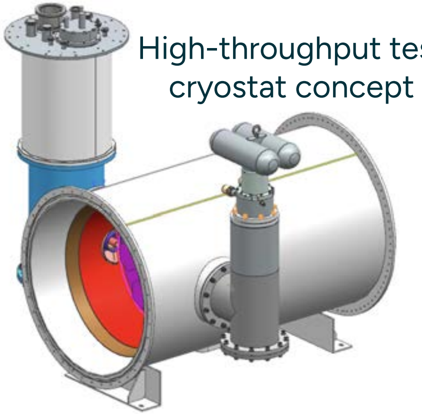


WIre-bonding readout modules during assembly

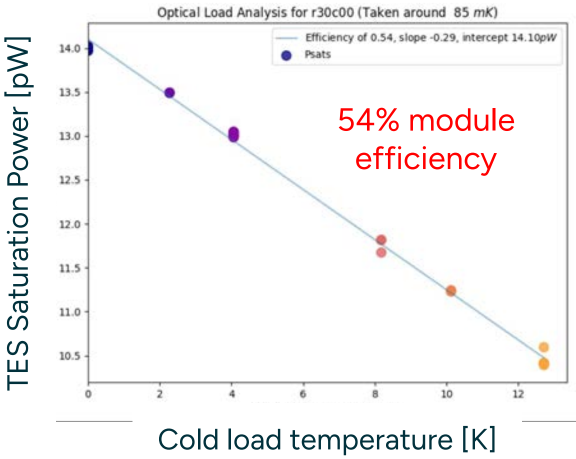
Testing

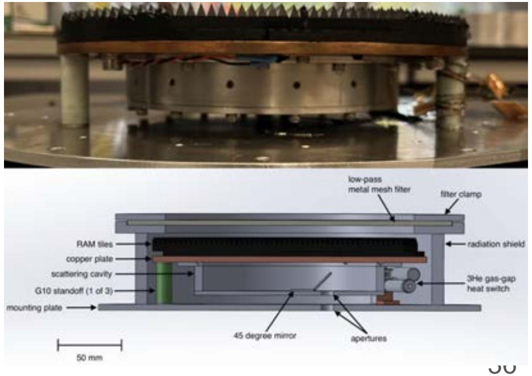
- ***Test sites*** - Commissioned three test sites for prototyping of integrated tests of detectors, optical coupling, and readout electronics at Fermilab, SLAC, and UIUC, using common test hardware (e.g. cold load, windows, and module mechanical assemblies).
- ***Prototype measurements*** - Full string test was performed with SO and S4 prototype detectors and S4 prototype electronics at UIUC and SLAC, measuring optical efficiency.
- ***High-throughput testing*** - Plan was developed, though not implemented, to perform rapid testing of >500 detector modules during a multi-year production, with a suite of 8x large test cryostats

100 mK module test facility (UIUC)



High-throughput test cryostat concept





CMB-S4 cold load (C. King, et al. 2406.17695)

CMB S4

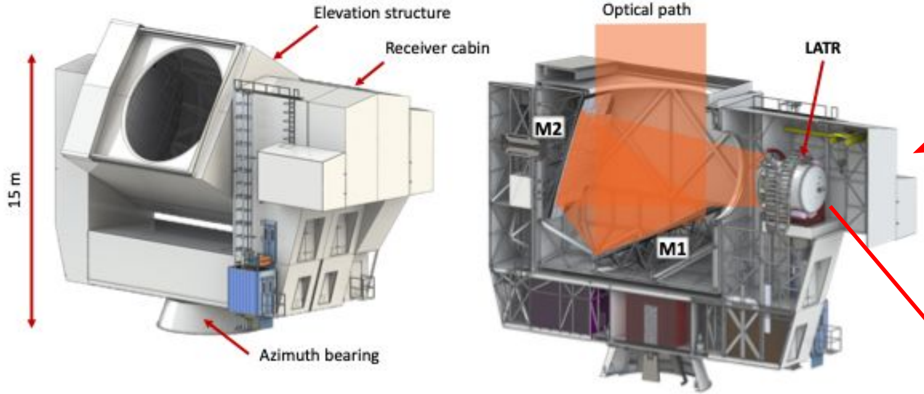
CMB-S4 Large Aperture Telescopes

Cornell, Arizona, Chicago, CWU, Pontificia,
Fermilab, Argonne

LAT Design Development

- CMB-S4 focused on designing and optimizing the highest throughput 5-6 meter aperture CMB telescopes and instruments yet.
  - A three mirror anastigmat (TMA) telescope design was optimized for construction at the South Pole
  - A two mirror Crossed Dragone (CD) telescope design that was developed by the CCAT Observatory and Simons Observatory was adopted for CMB-S4
  - Optimized LAT receivers (LATR) for both the TMA and CD telescopes that achieve approximately x2 greater optical throughput than the Advanced Simons Observatory LATR (which in turn has about x2 the optical throughput of the initial SO LATR)

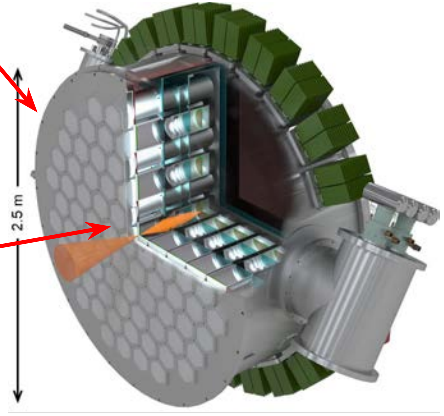
CMB-S4 Large-Aperture Telescope (LAT) Design



6m Crossed Dragone (CD) Reflecting Telescope

Common Telescope Design with CCAT and SO

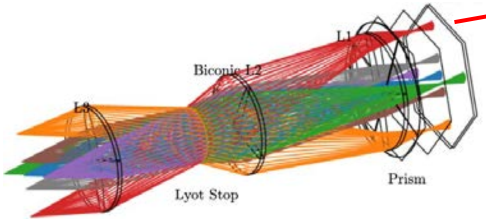
Simons Observatory (SO) LAT in Chile



LAT Receiver
85 Optics Tubes, each with 1 detector array.

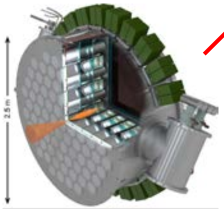
130,000 detectors

Optics design of one of the 85 individual optics tubes in each LATR

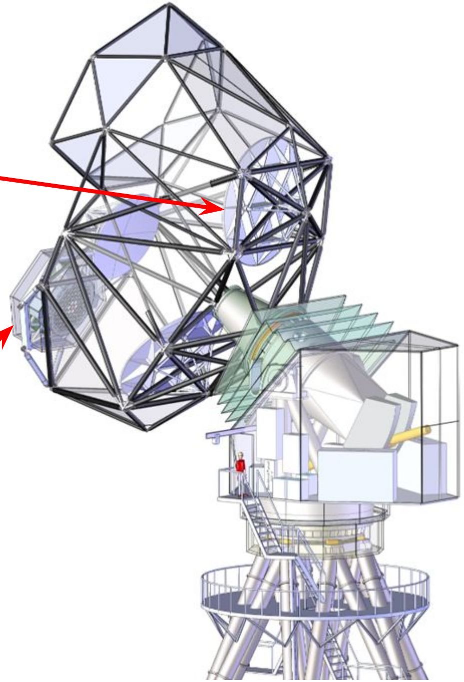


Alternate Large-Aperture Telescope Design

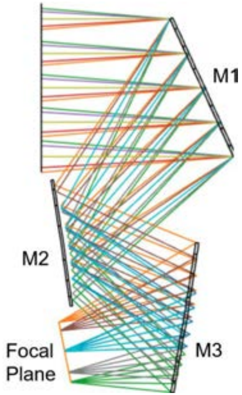
TMA Primary mirror prototype successfully fabricated and characterized



Same receiver design as for CD telescope



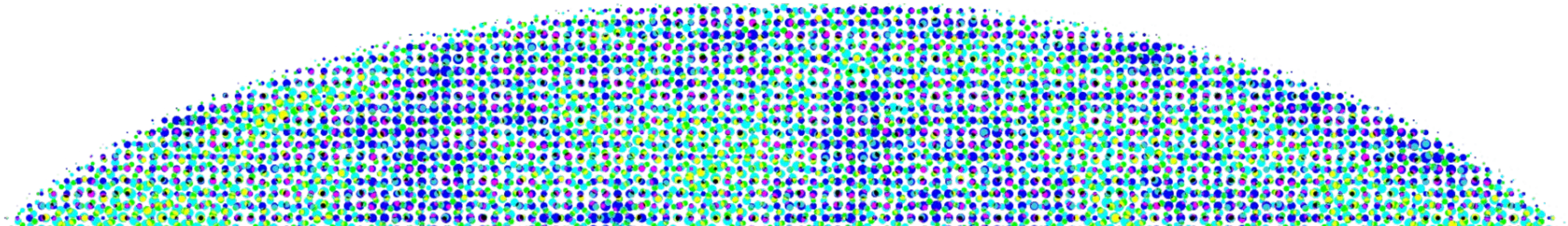
5 m Three Mirror Anastigmat (TMA)



- 5-meter aperture allows monolithic (gapless) mirrors.
- 3-mirror design provides more uniform optics across the 2-m diameter focal plane.
- Superior optics may offer advantages for delensing survey.
- Originally designed for use at the South Pole where it could contribute to the low-ℓ measurements of B-modes.

CMB-S4 Small Aperture Telescopes

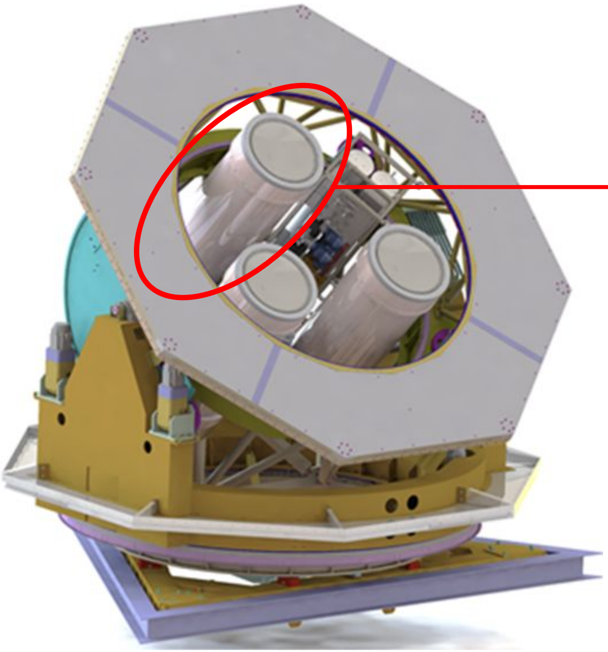
Harvard, SAO, LBNL, Chicago, SLAC,
BU, Penn, CWU, UMN, Tokyo



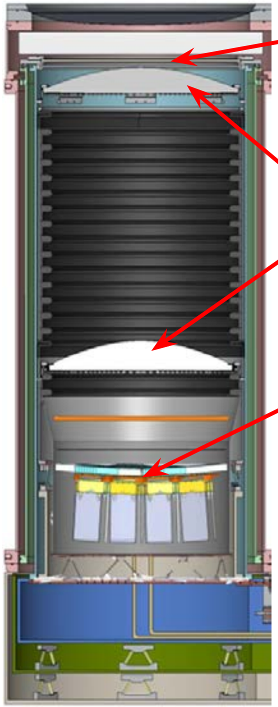
SAT Design Development

- CMB-S4 Small Aperture Telescope (SAT) efforts have been directed toward developing the instruments capable of meeting the extreme measurement requirements of the ultra-deep survey.
    - The science goal of measuring *r* to a precision ($\sigma(r) = 5 \times 10^{-4}$) demands measuring primordial B-mode polarization pattern with uncertainties of < 10nK at angular scales of a few degrees.
- The CMB-S4 SAT design built on and cross-fertilized with the BICEP and SO SAT design. Some key design developments include:
    - Improved cryostat and cryogenics system efficiency to minimize power consumption.
    - Advancing the optical design and characterization of materials to improve optical and thermal efficiency and maintain diffraction-limited resolution across all frequencies.
    - R&D towards larger half-wave plate polarization modulators.
    - Optimization of the system of co-moving baffles and fixed ground shields for the specific conditions at both the SP and Chile site.
    - Development of an comprehensive calibration system plan.

CMB-S4 Small-Aperture Telescope (SAT) Design



3 Optics tubes on a common mount in a common cryostat



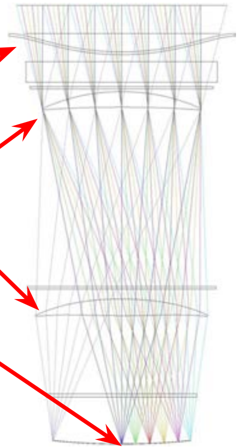
Rotating Half-Wave Plate Polarization Modulator

Thin vacuum window

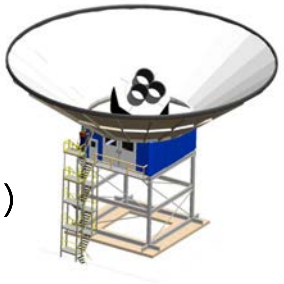
Simple 2-lens refracting optics - 56 cm aperture

100 mK curved focal plane with 12 detector arrays based on 6″ silicon wafers.

Up to 22,000 detectors, depending on the frequency band.

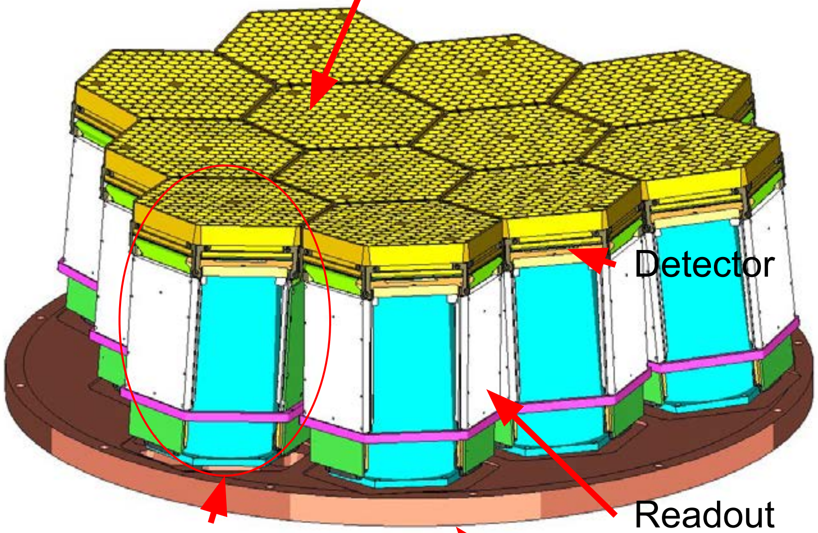


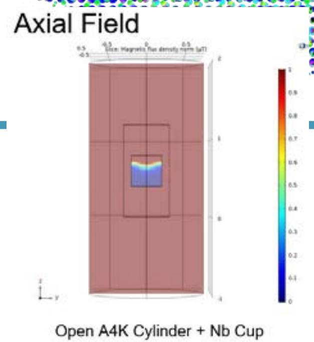
Telescope mount and ground shield (South Pole version)

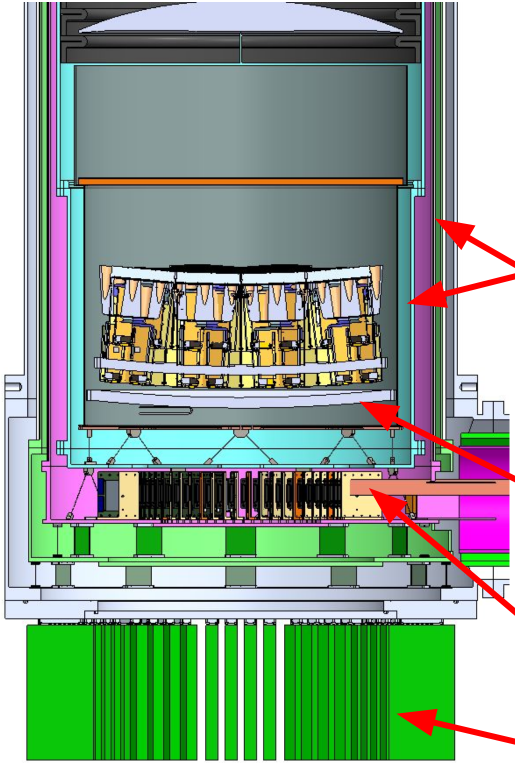


100mK Curved Focal Plane Assembly

12 Detector modules are assembled to a common baseplate in quasi-spherical layout for better optical performance



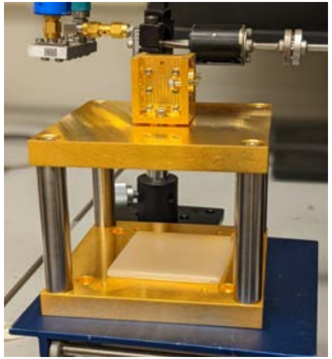


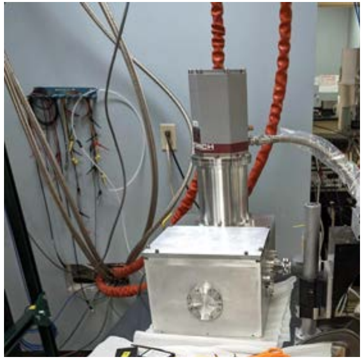


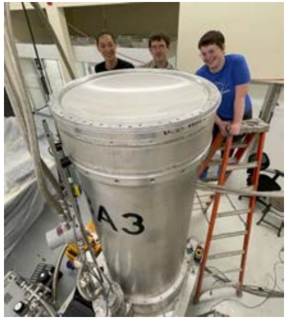
SAT Optics Assessment Plan and Progress

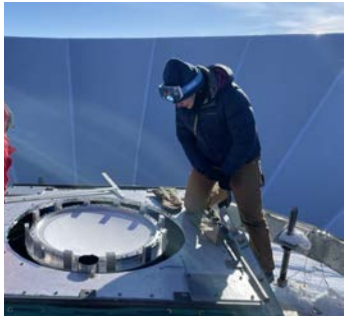
Plan for comparative validation testing at different levels, e.g.

- **Materials test:** capability expanded with quasi-optical test cavity and dedicated test cryostat.
  - Precise loss & scattering (-50dB), index at low temperature for design assessment, also QC in production (see Elwood et al. SPIE, arXiv:2411.01058)
- **Component test**: Ultra-thin windows now baselined
  - ~1mm polyethylene, reduces loading
  - Deployed in past 2 years on BICEP 95, 150, and 220 GHz receivers, providing field data and risk retirement (see Eiben, et al. SPIE 12190:121902L and arXiv:2411.10428)
- **Full Optics Stack test:** preSAT (preliminary SAT receiver) project initiated:
  - 100mK optics tube in 4th BICEP Array cryostat
  - enables validation of cold optics design









CMB S4

CMB-S4 Data Management

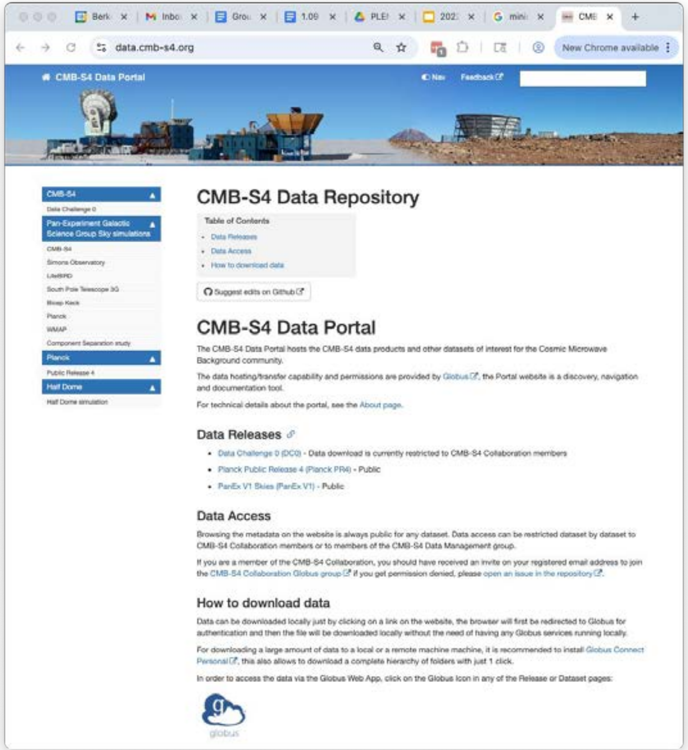
LBNL, ESNet, NERSC, FNAL, UCSD, Cincinnati, UIUC, MSU
Chicago

CMB-S4 Data Management Highlights

- Developed & deployed:
  - A parametric model for computational requirements as a function of experiment design
    - Bandwidth, cycles, memory, spinning & archival storage
    - On-site (South Pole, Chile) and at data centers (NERSC etc)
  - A globus-based, access-controlled, data portal at NERSC for distributing CMB datasets within CMB-S4 and to the wider community.
  - A parameterized experiment (instrument + observation) model.
  - A robust, massively-parallel, well-optimized, software stack at NERSC.
  - Full time-domain full simulation & reduction workflows, used to generate Data Challenge 0.
  - A validated & verified approximate simulation/reduction workflow, enabling fast turn-around for exploring the experiment design space as the project boundary conditions evolved.
  - A toy transient injection/detection pipeline for assessing whether particular survey strategies would meet the science requirements.
  - A complete plan for computing hardware at the South Pole, adapted as the boundary conditions evolved.
- Acted as a key use-case for NERSC system procurement, ESnet networking projections, FABRIC deployment, etc.

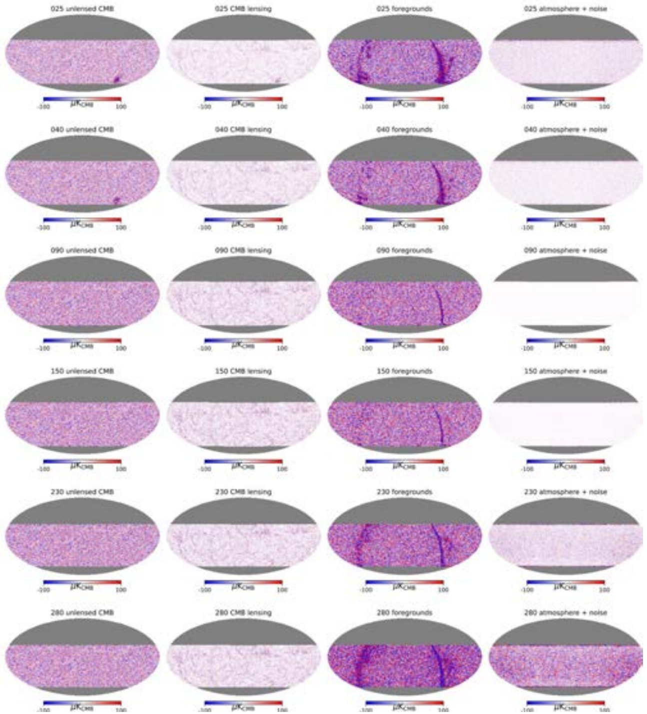
Data Portal

https://data.cmb-s4.org/



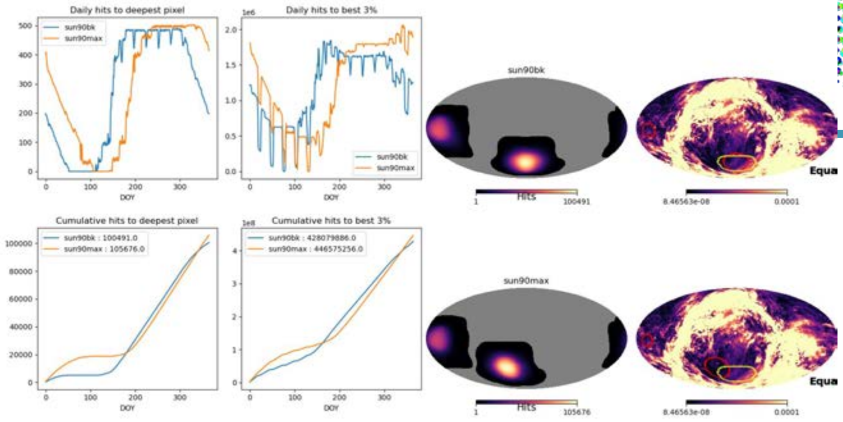
Data Challenge 0

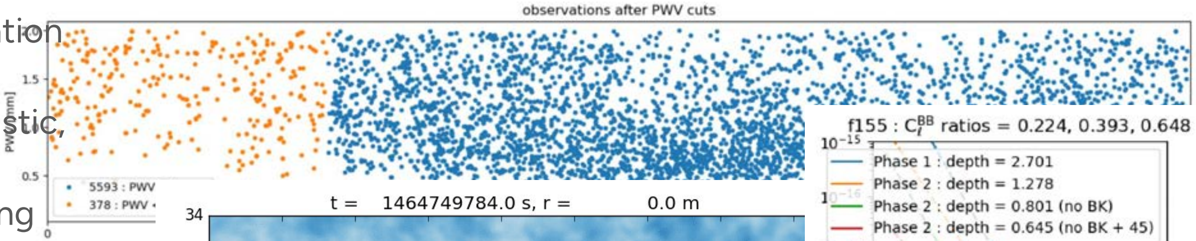
Single-season maps of each of 4 sky components at each frequency for the Chilean LATs

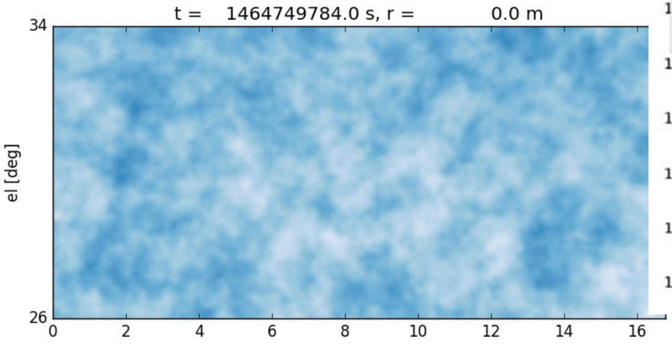


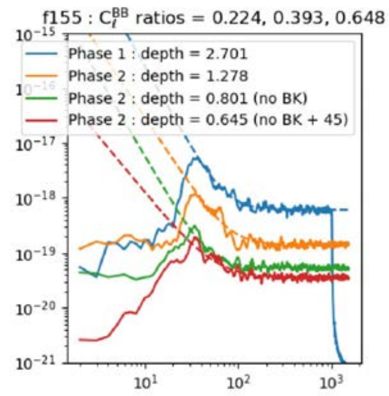
Accurate and Fast-Turnaround Forecasting

- Detector noise model that accounts for observing elevation and PWV
- Accounting of total observing efficiency subject to weather, detector yield, calibration campaigns, field availability and Sun/Moon avoidance
- Suite of noise and systematics simulation modules to generate mock data
- Versatile scheduler code to build realistic, full season observing schedules
- Rapid time-domain pipeline for deriving depth map forecasts from the instrument model and observing strategy
- Map-domain pipeline to derive noise and signal simulations from depth maps (with low-ell-BB working group)





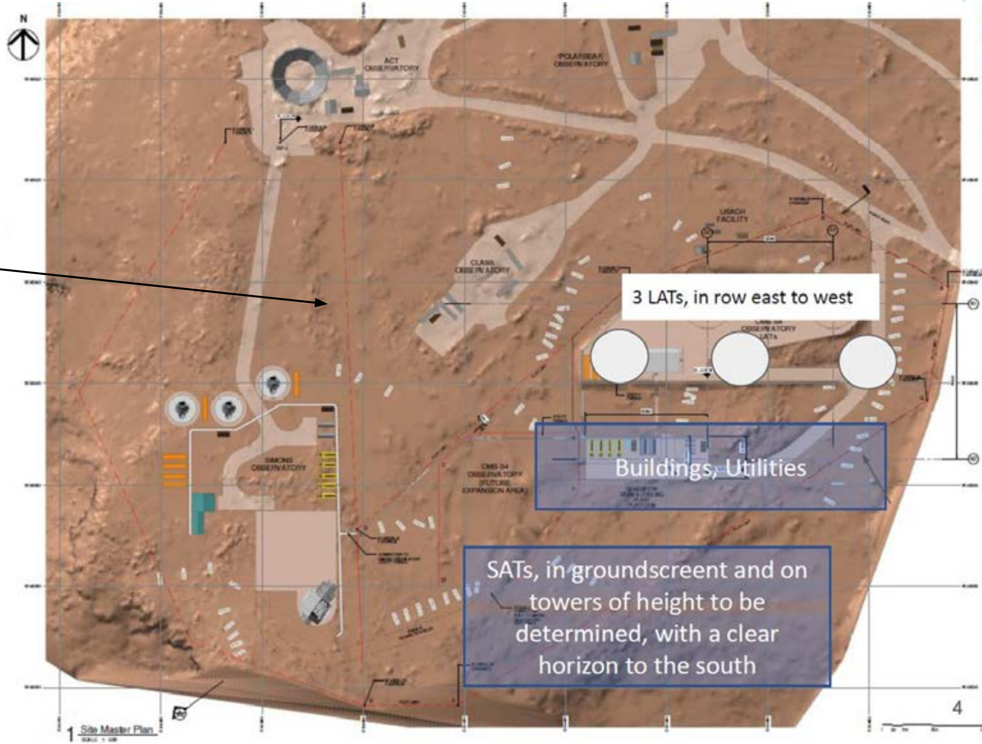




CMB-S4 Chile Infrastructure

UCSD, EONS, Chicago, LBNL

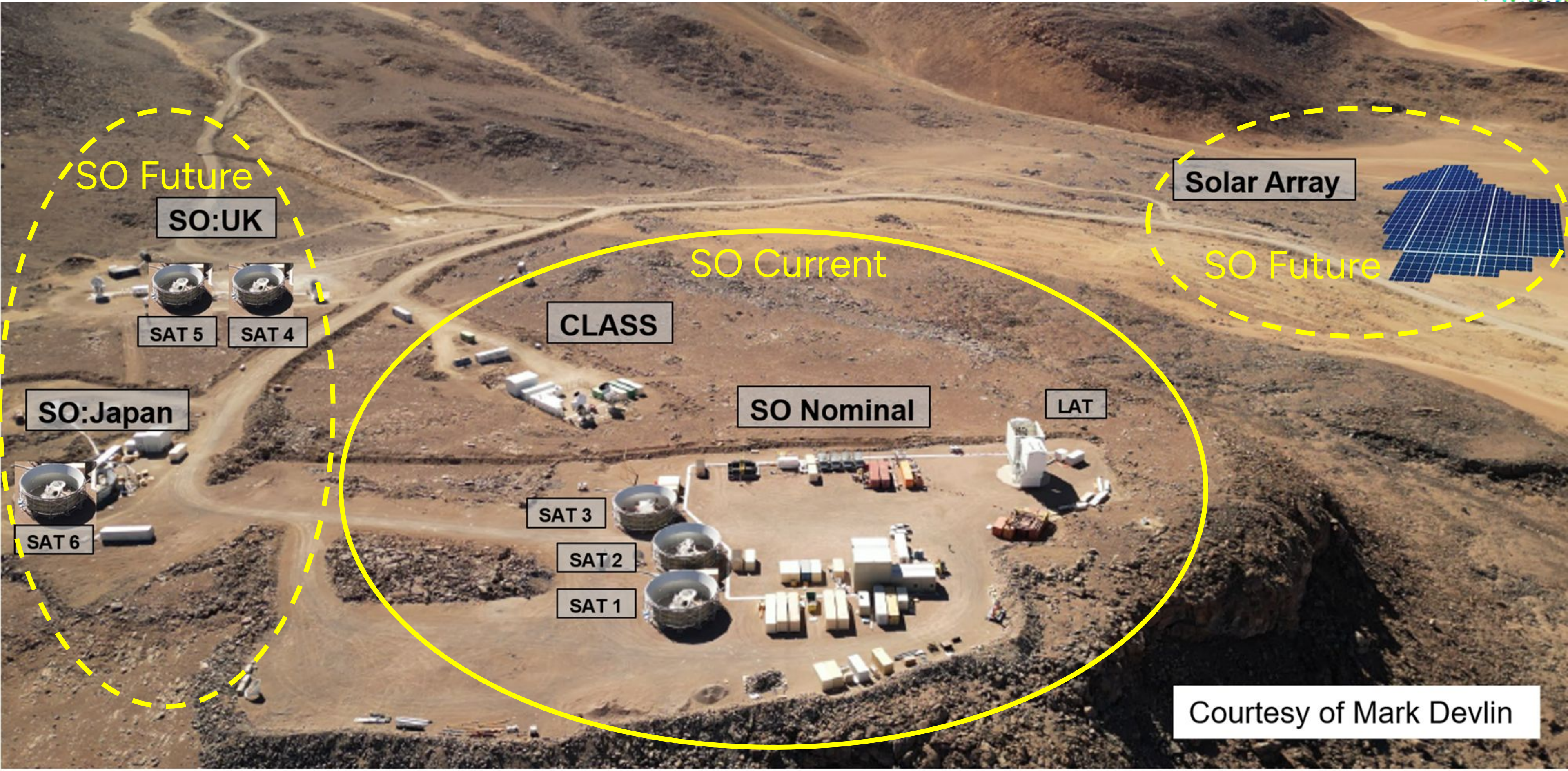
Chile Site



CMB-S4

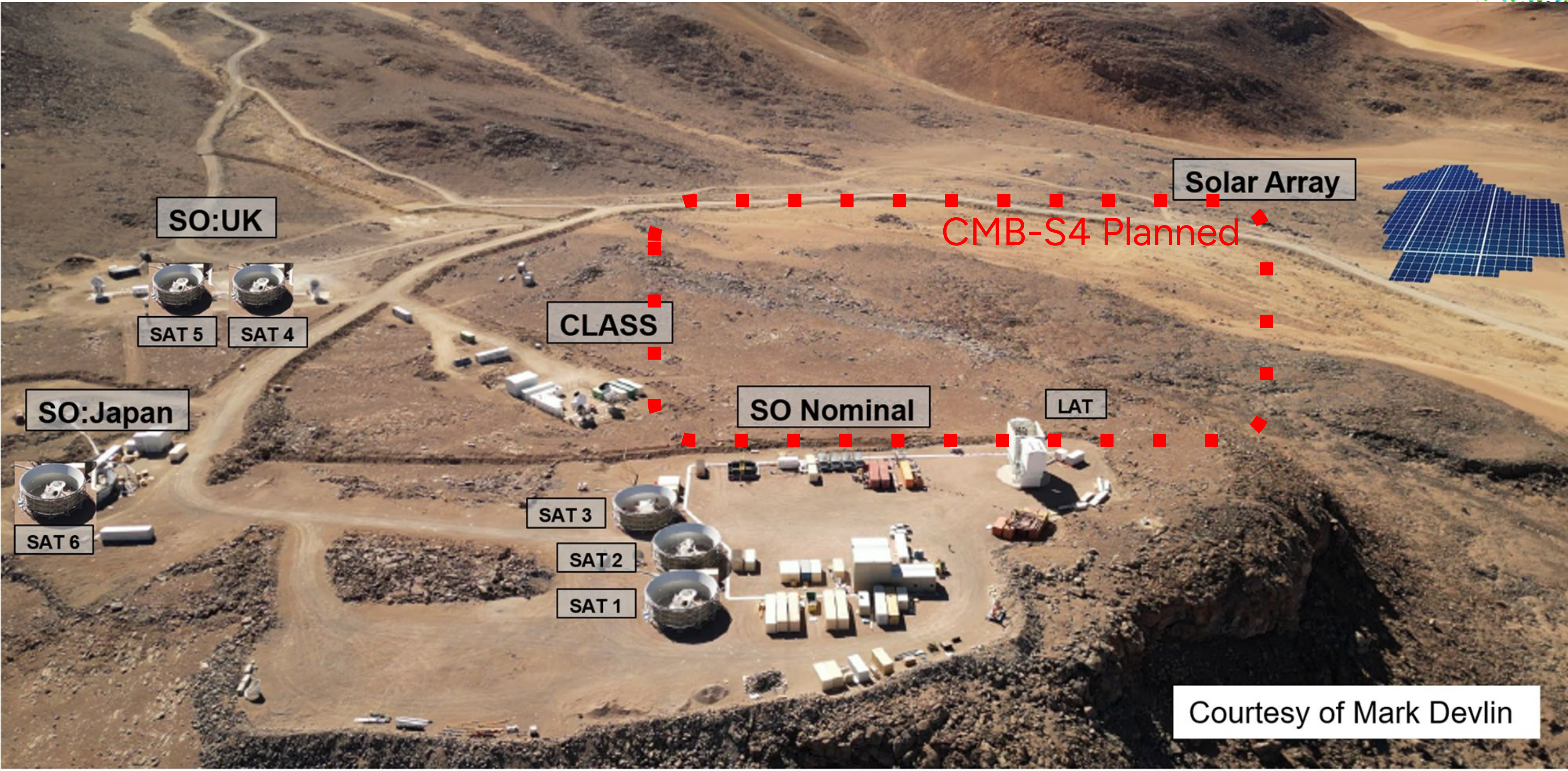
- Developed requirements place on the site by the project and on the project by the site.
- Developed design concept for the site and infrastructure to meet the requirements.
- Layed the legal groundwork for CMB-S4 to perform the experiment in Chile.

Chile Site



SO Future
SO:UK
SAT 5
SAT 4
SO:Japan
SAT 6
SO Current
CLASS
SO Nominal
LAT
SAT 3
SAT 2
SAT 1
Solar Array
SO Future
Courtesy of Mark Devlin

Chile Site

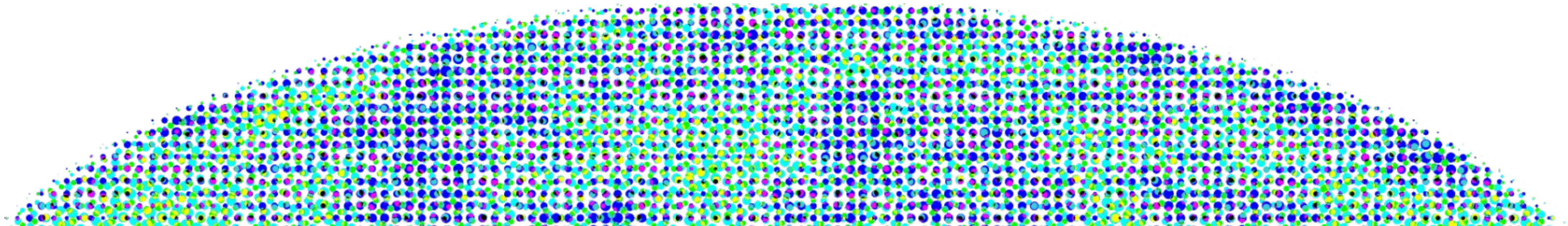


SO:UK
SAT 5
SAT 4
CLASS
Solar Array
CMB-S4 Planned
SO:Japan
SAT 6
SO Nominal
LAT
SAT 3
SAT 2
SAT 1
Courtesy of Mark Devlin

CMB S4

CMB-S4 South Pole Infrastructure

Argonne, RSS, Harvard, Chicago



South Pole Site Now

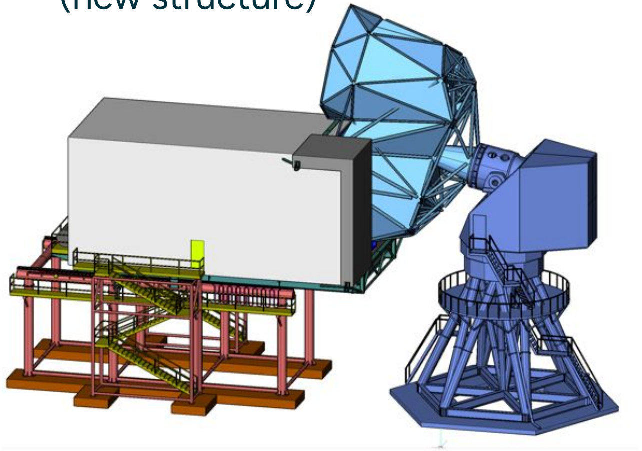
Figure 69: Photograph of existing scientific facilities in the dark sector at the South Pole.

South Pole Site – Would have been

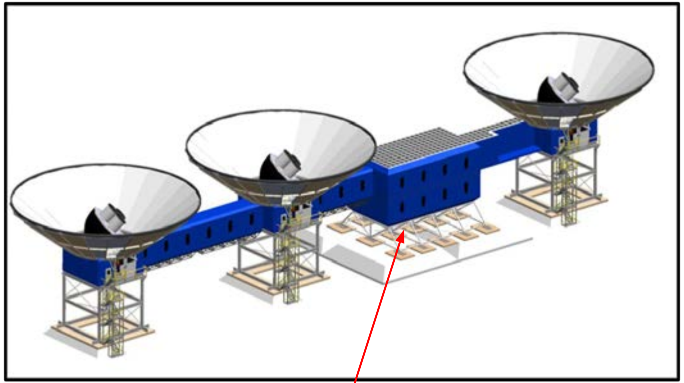
Figure 70: A conceptual rendering of the future CMB-S4 SPLAT and SATs in their baseline locations at the South Pole site.

South Pole Site - CMB-S4 Conceptual Designs

High-bay to service the LATR (new structure)



SAT mounts, ground shield, and support facilities



MAPO (existing)
(other structures new)

CMB-S4 Science Impacts

Science Impact of CMB-S4

CMB-S4 never took data, but its impact on maturing the the field of CMB research is considerable.

- CMB-S4 produced a comprehensive case for the broad range of cosmology, astrophysics and physics that can be studied with the CMB and documented it in many reports, including:
  - CMB-S4 Science Book [arXiv:1610.02743],
  - CMB-S4 Science Case, Reference Design, and Project Plan [arXiv:1907.04473],
  - CMB-S4 Preliminary Baseline Design Report [CMBS4-doc-716-v4] and CMB-S4 Design Report 2023 [Design Report CMBS4-doc-716-v4]
  - Revised CMB-S4 Project Plan [CMBS4-doc-1095]

  This will help guide the field as it moves forward.

Science Impact of CMB-S4

- CMB-S4 developed systematic methods of experiment design that are necessary to carry the field to the next level.
  - Defined clear thresholds and corresponding science requirements for the driving science goals.
  - Developed a systematic flow-down from science *goals* → science *requirements* → *survey* requirements → *instrument* requirements → instrument *specifications*
- CMB-S4 developed several analysis pipelines to quantify or "forecast" the capabilities of different experiment configurations.
  - Multiple pipelines with different approaches have allowed cross-checking results and gaining understanding of systematics induced by the analysis methods (as well as those induced by the instruments and the complex nature of the observables).

Science Impact of CMB-S4

- CMB-S4 developed a bottom-up accounting of observing, instrumental and analysis (in)efficiencies.
  - This is an invaluable guide to understanding where greater efficiency can be gained.
  - Largely resolves the long-standing discrepancy between between *ab initio* forecasts and forecasts scaled from achieved performance.
- CMB-S4 developed highly efficient scan strategies from both the South Pole and Chile that focus on various science topics, and developed methods for interleaving the different scan program to optimize the use of all of the instruments to execute the full science program.
- CMB-S4 demonstrated the power of making combined and coherent observing plans and data analysis between Chile and the SP, i.e. between SO and BICEP+SPT (a.k.a. SPO, the South Pole Observatory), in which the whole is greater than the sum of the parts.

Science Impact of CMB-S4

- The CMB-S4 Collaboration developed a modern and mature structure that
  - Is inclusive, welcoming and integrates collaborators from the whole field, independent of previous or other current affiliations.
  - Allows evolution of the collaboration leadership.
  - Provides opportunities for career advancement for young and mid-career scientists.
- The CMB-S4 Collaboration and Project have been at least partially successful in achieving the decade-old vision of uniting the entire CMB community to enable a ground-based experiment with capabilities beyond that of any of the smaller individual experiments.
  - This, beyond combined survey plans and analysis, can make the whole greater than the sum of the parts.
  - I hope that this move toward a unified community can continue to grow without CMB-S4.

The impact of CMB-S4 will be felt for years (or decades) to come.

CMB-S4 History

The History of CMB-S4

2013

Snowmass Community Summer Study [https://inspirehep.net/literature/1479234]

- The origins of CMB-S4 are 12 years ago. The concept of a single comprehensive ground-based "Stage 4" experiment with capabilities far beyond existing experiments was born during the 2013 "Snowmass" process in the U.S.
    - Envisioned a "generation IV CMB polarization experiment" to improve sensitivity to *r*, the tensor-to-scalar ratio of CMB polarization, by 2 orders of magnitude, from ~10^{-1} to ~10^{-3}.
    - "This would require a change from the way things have been done in the past. Groups would merge into one coordinated effort, tapping national lab facility design, integration, computing, and management capabilities."

The History of CMB-S4

2014

P5 - Strategic Plan for U.S. Particle Physics in the Global Context
[https://usparticlephysics.org/wp-content/uploads/2018/03/FINAL_P5_Report_053014.pdf]

- CMB-S4 got a major push from the 2014 P5 report
  - "Current CMB probes will lead to a Stage 4 Cosmic Microwave Background (CMB-S4) experiment, with the potential for important insights into the ultrahigh energy physics that drove inflation."
  - Recommendation 18: "Support CMB experiments as part of the core particle physics program. The multidisciplinary nature of the science warrants continued multiagency support."
  - Recommended as a "Medium" project ($50M - $200M).

The History of CMB-S4

2015

Formation of the CMB-S4 Collaboration

- The first meetings of what became the CMB-S4 Science Collaboration were in 2015 and the Collaboration was officially formed in 2018 with the adoption of by-laws and election of spokespeople and other officers.
- The collaboration produced a Science Book (2016) and Technology Book (2017).

2017

Setting the overall scope of CMB-S4

- The fundamental scope of CMB-S4 was established in 2017 by a Concept Definition Task Force[1], which was established under the auspices of the Astronomy and Astrophysics Advisory Committee at the request of the U.S. Funding Agencies, DOE (Office of High Energy Physics) and NSF (Divisions of Physics, Polar Programs, and Astronomical Sciences).

[1] https://www.nsf.gov/mps/ast/aaac/cmb_s4/report/CMBS4_final_report_NL.pdf

The History of CMB-S4

2019

Establishing the DOE CMB-S4 Project

- The DOE CMB-S4 Project came into existence in 2019 when DOE approved CD-0 (Mission Need), finding that there is a "need for the U.S. to continue to lead research in particle physics, dark matter, dark energy, and inflation by mounting a stage 4 CMB discovery-focused project."
- *But the analogous step by NSF, placing the project in the Major Facilities Design Stage, was never taken.*

2020

Selection of the DOE Lead Lab

- DOE selected LBNL as the Lead Lab, which is "accountable to HEP for executing the CMB-S4 project for DOE, in the context of [a] partnership" between HEP and the relevant NSF divisions.
- NSF has supported CMB-S4 in the Development (R&D) Stage through a series of Awards to the University of Chicago but *NSF has never formally identified a CMB-S4 Lead Institution.*

The History of CMB-S4

2021

The first complete CMB-S4 Project Plan

- CMB-S4 presented a complete project plan[1] with instruments at the South Pole and in Chile at a Director's Review in November 2021, in preparation for a February 2022 DOE Review.
- Technical Scope:
    - One 5-m Three-Mirror Anastigmat (TMA) Large-Aperture Telescope (LAT) at the South Pole
    - Eighteen 0.56-m refracting Small-Aperture Telescopes (SAT) at the South Pole
    - Two 6-m aperture Crossed Dragone (CD) LATs in Chile
- Complete Project Plan, including full project organization, draft project documents, resource-loaded schedule, etc.

[1] Preliminary Baseline Design Report, CMBS4-doc-716-v3, January 2022

The History of CMB-S4

2022

Major Detour - required descoping at the South Pole

- In January 2022, the NSF Office of Polar Programs (OPP) stated that they could not accommodate the full scope of CMB-S4 a the South Pole, and the DOE review was "postponed"
    - CMB-S4 undertook an Analysis of Alternatives to identify a new configuration that would be consistent with the constraints at the South Pole, *which were never presented by NSF.*
- In April 2022 NSF issued a "Dear Colleague"[1] letter stating that "South Pole Station is saturated with already-funded projects, and required critical infrastructure and maintenance activities that can no longer be deferred, until late in the decade. … proposers seeking support for new projects at South Pole Station should consult the cognizant program officer to discuss alternative pathways to accomplish science goals."

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[1] https://www.nsf.gov/pubs/2022/nsf22078/nsf22078.jsp?WT.mc_ev=click&WT.mc_id=USNSF_32&utm_medium=email&utm_source=govdelivery

The History of CMB-S4

2022

Revised scope at the South Pole

- In December 2022, CMB-S4 presented[1] results from an extensive Analysis of Alternatives (AoA) that concluded
  - The preferred alternative reduced the number of SATs at the SP from 18 to 9, reducing the logistics and infrastructure requirements to a level comparable to the existing CMB experiments there.
  - An alternative with all telescopes in Chile “could offer a way to make the measurements, if we are unable to access the Pole.”
- *No formal response from the Funding Agencies was provided.*

[1] https://indico.cmb-s4.org/event/44/

The History of CMB-S4

2023

A complete revised CMB-S4 Project Plan

- CMB-S4 presented a complete revised project plan at a Director's Review in November 2023 (2-year delay!)
- The review committee concluded that CMB-S4 was nearing readiness for DOE CD-1 and NSF CDR.
- Technical Scope:
  - One 5-m Three-Mirror Anastigmat (TMA) Large-Aperture Telescope (LAT) at the South Pole
  - Nine 0.56-m refracting Small-Aperture Telescopes (SAT) at the South Pole
  - Two 6-m aperture Crossed Dragone (CD) LATs in Chile

The History of CMB-S4

2024

An even more major detour - CMB-S4 is ejected from the South Pole

- In May 2024, NSF announced, “After extensive analysis, the NSF has made the decision not to move the CMB-S4 project in its current form into the NSF Major Facility Design Stage at this time. The agency must prioritize the recapitalization of critical infrastructure at the South Pole so that the groundbreaking research it enables can continue to thrive.”
- In September 2024, the funding agencies charged CMB-S4 to
    - “develop a revised plan for the CMB-S4 project that does not include significant new instrumentation or facilities at the South Pole.”
    - To ”include data and information from existing and planned experiments, including those that are continuing at South Pole with support from both NSF and DOE, to benefit from and incorporate their scientific data, results and lessons learned.”

The History of CMB-S4

2025

A completely revised CMB-S4 Project Plan

- On June 4, 2025, CMB-S4 presented a completely revised project plan to the funding agencies (another 2-year delay!)
- The revised plan took a new approach that proposed a close partnership among CMB-S4, the Simons Observatory (SO), BICEP and SPT that would be able to achieve essentially all the CMB-S4 Science Goals within 10 years after the first observations by CMB-S4 at less than half the cost of the stand-alone configuration presented in 2023.
- CMB-S4 was proposed to comprise:
    - Six 0.56-m SATs
    - One 6-m CD LAT

  Operating in Chile adjacent to SO.

The History of CMB-S4

2025

The end of CMB-S4

- On July 10, 2025, the funding agencies issued the following statement:

DOE and NSF Statement on the CMB-S4 Project

Scientific research using data from the Cosmic Microwave Background (CMB) continues to be a priority for the DOE, Office of Science, Office of High Energy Physics, and the U.S. National Science Foundation, providing crucial information on the fundamental nature of matter and energy in the universe.

As recommended by P5 and Astro2020, DOE and NSF have been partnering on funding the design and development of a proposed next generation project, CMB-S4, with precision instrumentation at two sites, the South Pole and the Atacama Desert in Chile, dedicated to detecting primordial gravitational waves that would confirm the model of the Universe with a Big Bang followed by a period of rapid Inflation.

DOE and NSF have jointly decided that they can no longer support the CMB-S4 Project. DOE and NSF will continue to partner with the CMB science community to explore the potential science that can be achieved with limited upgrades to existing experiments to further this important U.S.-led research.

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This is the way CMB-S4 ends.
Not with a bang but a whimper. – T.S. Eliot

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What went wrong?
Why didn't CMB-S4 move forward?

(My personal view)

Why was CMB-S4 ultimately cancelled?

Disclaimers

- Clearly there is no one reason that CMB-S4 did not come to fruition.
- My analysis is based on only partial understanding from my somewhat over 3-year involvement, but also from discussions with a number of people who lived the whole experience and from consulting some relevant documents … and some knowledge and experience about how the world works.
- Others may disagree with some aspects, but I think the following captures much of the essence of what happened.
- While I consulted with others, the analysis is mine and any limitations or errors are mine, and not those of the people I have gotten information and insights from.
- My intent is ***NOT*** to point fingers or lay blame, but rather to understand what happened and why, so that we can do better the next time.

The immediate cause of the cancellation

The proximate reason that CMB-S4 was canceled is that time and the progress of science was passing it by. What was an exciting program 12 years ago, is no longer so compelling.

- When CMB-S4 was conceived, it was to advance sensitivity to *r* by two orders of magnitude. Our final report to the funding agencies showed that, if the current Stage 3 experiments continue on their planned paths and can figure out how to coordinate their observations and analyses, they can reach with a factor of about 2 of the original CMB-S4 goals.
    - Bryan Field at the DPF Community Meeting (July 31-August 1, 2025), stated [1] that the cancellation of CMB-S4 was a “Programmatic decision based on cost vs. benefits to our scientific mission/program.”
- Clearly a factor of 2 in *r*, and similar factors for the other science goals, was not deemed to be worth the ~$400M that the final configuration of CMB-S4 would have cost.

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[1] https://indico.global/event/14967/contributions/130488/attachments/61689/118807/25.08.01%20DPF%20-%20Cosmic%20Frontier%20COMBINED%20TALK%20(Turner,%20Field,%20Bautista).pdf

Why was the progress so slow?

If CMB-S4 was cancelled because time had passed it by, why did it progress so slowly so that this was the outcome?

- CD-0 (DOE determination that there is a “mission need”) wasn’t approved until > five (5!) years after CMB-S4 was recommended by the 2014 P5 report. NSF never got to making the equivalent determination.
- DOE did not select a lead lab until >6 years after the P5 recommendation.
- The experiment design underwent multiple significant iterations:
  - 2 sites but distribution of telescopes not set in 2017 Concept Definition Task Force;
  - Large SP footprint at 2021 Director’s Review
  - Reduced SP footprint at 2023 Director’s Review
  - No SP footprint in 2025 “final report.”
- Limitations in NSF’s ability to support science at the South Pole became apparent.

Underlying causes

CMB-S4 faced heavy headwinds from the beginning:

- It was launched explicitly as a multi-agency project by the 2014 P5.
    - CMB-S4 depended on two different funding agencies, and within NSF three different Divisions in two different Directorates.
    - Neither funding agency clearly took the lead nor took ownership of CMB-S4.
- It was never the top priority in either funding agency or any Division within them.
- From the beginning, it was in direct competition with high-priority mega projects with powerful backers.
- The initial scope and cost estimate in the 2014 P5 report were unrealistically small, which became apparent as the scale required became clearer.

CMB-S4 was tacking into a gale.

Contributing causes

- To overcome the structural challenges facing CMB-S4, the CMB community would have needed to be 100% united and 100% focused on pushing CMB-S4 forward, despite the headwinds.
- Within the CMB-S4 Collaboration and Project, there was a solid collegial approach that did, to a real measure, bring together people from all of the predecessor Stage 3 experiments.
- But the proponents and leaders of the Stage 3 experiments continued to push them forward.
  - Intense rivalry between the Pole and Chile continued.
  - It appeared to me that at least the leaders of the Stage 3 experiments placed them at higher priority than CMB-S4.
- Without all hands on deck, working as a tight team, CMB-S4 could not overcome the headwinds.
- *But even if we had all worked seamlessly together with 100% dedication to CMB-S4 as the top – or only – priority, we might not have been able to succeed.*
- *And without the "lifeboats" of the Stage 3 experiments, the cancellation of CMB-S4 would have been devastating to the field.*

Summary
Outlook for the Future

Summary of the role CMB-S4 has played

Although CMB-S4 will not go forward, the considerable effort that went into it was not wasted.

- Technical development in detectors, readout, modules, telescope designs, etc. will be of lasting value. New facilities that were motivated by CMB-S4 will be valuable to future projects.
- The science analyses and tools developed to do them by CMB-S4 will be used by future projects.
- CMB-S4 was to bring the entire CMB research community together. Although it did an imperfect and incomplete job, I hope this broader collaborative approach will continue to grow.
- The CMB-S4 Project and Collaboration organizations helped to mature the field, in both scientific and engineering approaches, as will be necessary for any future effort to push this challenging and exciting science forward.
- The final CMB-S4 report demonstrated how powerful the combination of observations from the SP and Chile can be if done in a coherent way – the whole is greater than the sum of the parts.
- Future experiments can and will build on what we have accomplished.

Outlook for the Future

- The promise of measurements of the CMB to elucidate some of the most profound questions about how the universe works remains strong.
- What has been the CMB-S4 Collaboration and Project is filled with skilled, experienced, dedicated and enthusiastic scientists and engineers, who have all the knowledge and strength to drive the field forward.
- The funding agencies have pledged their continued support of CMB research, albeit at a lower level than we had hoped. (But watch out for the pitfalls of multi-agency projects!)
- CMB-S4 has essentially provided a road map of how the CMB field could evolve to achieve our science goals in an efficient and robust way.
- The future of CMB science remains bright, but it is up to us to make it so!