An Introduction To CMB-S4

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CMB-S4

Outline

- CMB-S4 is the first non-satellite CMB experiment designed to reach specific science goals, rather than just to do as much as possible within a particular funding opportunity cost-cap.
- Consequently CMB-S4 is managed more like a satellite mission.
- This determines both
  1. How we design the experiment
  2. How we get it funded

Design

Design Process

- CMB observations (primary anisotropies, secondary anisotropies, mm-wave foregrounds) support a huge range of science in fundamental physics, cosmology, astrophysics & astronomy.
- Formally, for each science case we
  a. identify a critical scientific threshold,
  b. identify the measurement(s) required to reach that threshold,
  c. identify the instrument(s) and observation(s) required to make those measurements.
- Design the optimal (cheapest, fastest, lowest-risk) experiment satisfying the complete set of instrument and observation requirements.

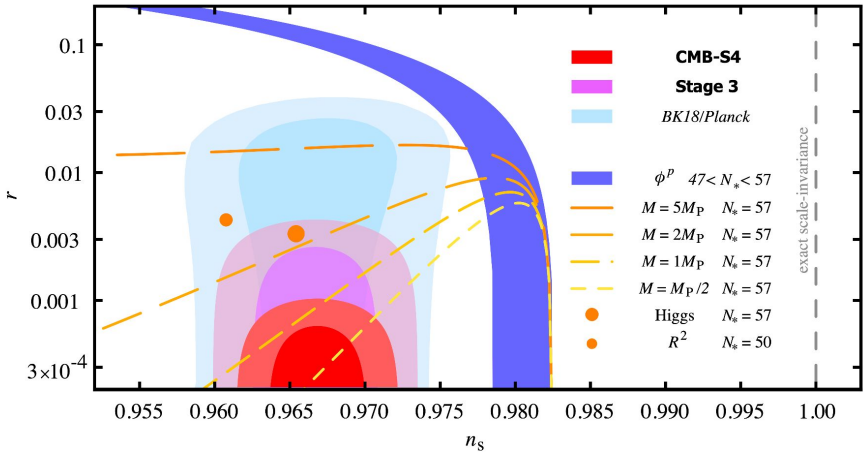
Experimental Degrees Of Freedom

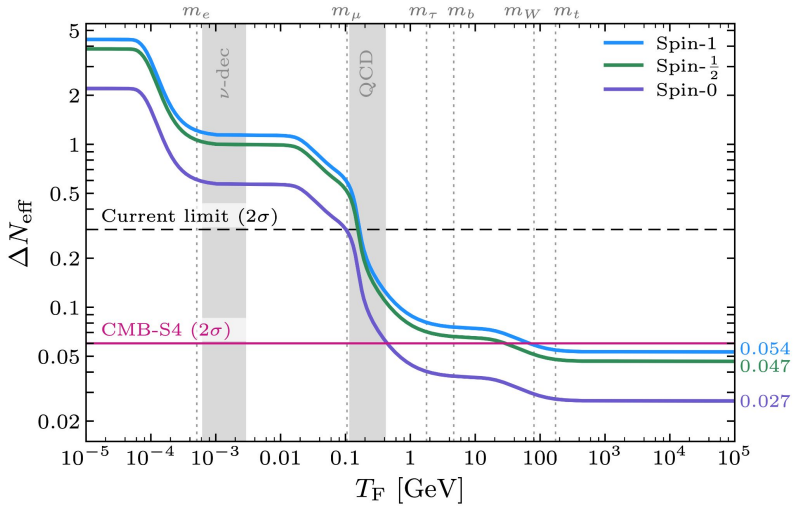
- For any instrument we can choose
  - The frequency coverage
  - The sensitivity at each frequency
  - The angular resolution
- For any observation we can choose
  - The sky area
  - The observation duration
  - The observation cadence

Science Drivers

- CMB-S4 has 4 science drivers, understanding that any experiment that meets their requirements will make measurements sufficient for the wealth of other science cases.
    1. Test models of inflation
    2. Count light relic particles
    3. Study the formation of galaxy clusters
    4. Explore the mm-wave transient sky

Science Requirements 1 & 2





SR 1.0: CMB-S4 shall test models of inflation by putting an upper limit on r of r ≤ 0.001 at 95% confidence if r = 0, or by measuring r at a 5σ level if r > 0.003.

SR 2.0: CMB-S4 shall determine Neff with an uncertainty ≤ 0.06 at the 95% confidence level.

Science Requirements 3 & 4

Galaxy Cluster Catalog:

SR3.1: CMB-S4 shall detect at ≥ 5σ all galaxy clusters at $z \geq 1.5$ with an integrated Compton $Y_{SZ,500} \geq 2.4 \times 10^{-5}$ arcmin^2 over at least 50% of the sky.

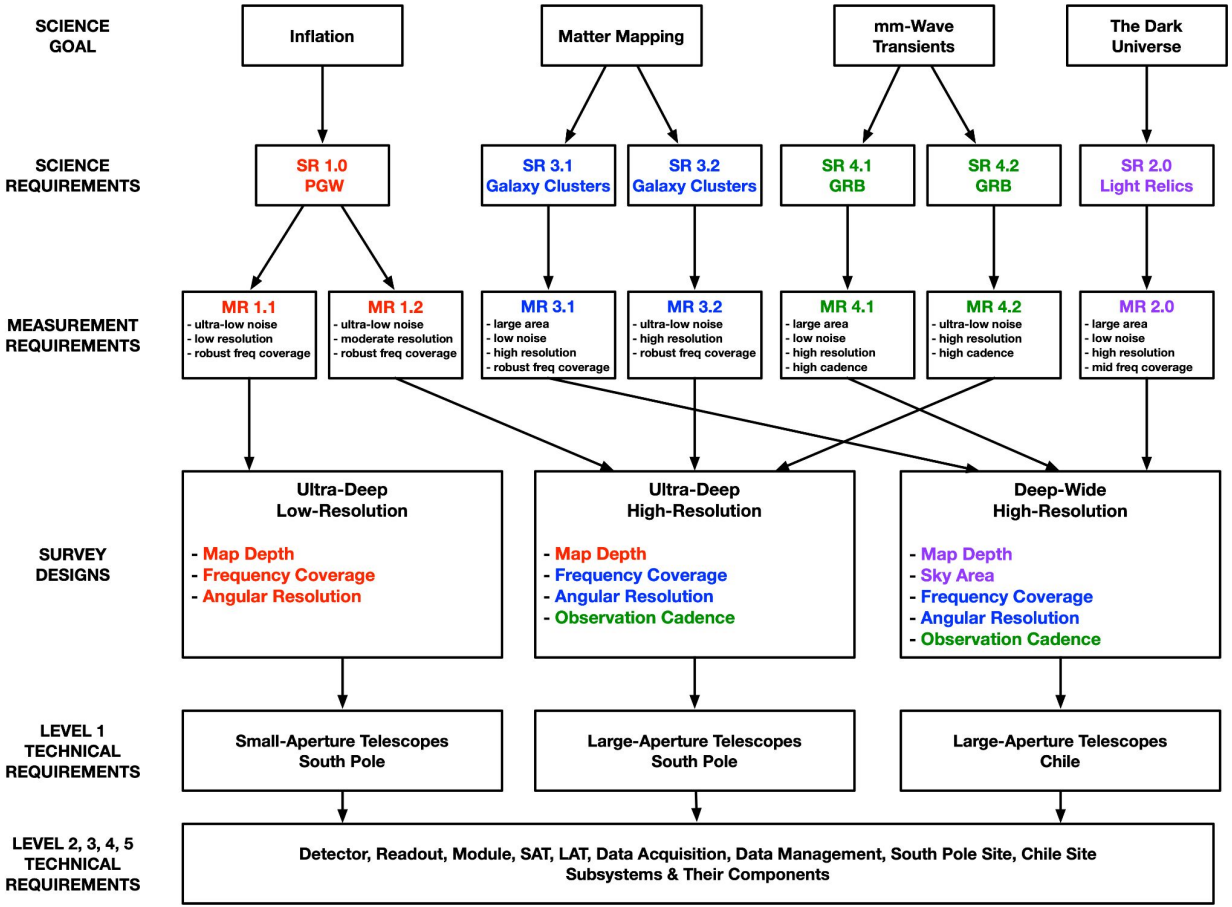
SR 3.2: CMB-S4 shall detect at ≥ 5σ all galaxy clusters at $z \geq 1.5$ with an integrated Compton $Y_{SZ,500} \geq 1.2 \times 10^{-5}$ arcmin^2 over at least 3% of the sky.

Gamma Ray Burst Catalog:

SR 4.1: CMB-S4 shall detect GRB afterglows brighter than 30 mJy at 90 and 150GHz over at least 50% of the sky and enable follow-up by issuing timely alerts to the community.

SR 4.2: CMB-S4 shall detect GRB afterglows brighter than 9 mJy at 90 and 150 GHz over at least 3% of the sky and enable follow-up by issuing timely alerts to the community.

Flowdown


SCIENCE GOAL
Inflation
Matter Mapping
mm-Wave Transients
The Dark Universe
SCIENCE REQUIREMENTS
SR 1.0 PGW
SR 3.1 Galaxy Clusters
SR 3.2 Galaxy Clusters
SR 4.1 GRB
SR 4.2 GRB
SR 2.0 Light Relics
MEASUREMENT REQUIREMENTS
MR 1.1
- ultra-low noise
- low resolution
- robust freq coverage
MR 1.2
- ultra-low noise
- moderate resolution
- robust freq coverage
MR 3.1
- large area
- low noise
- high resolution
- robust freq coverage
MR 3.2
- ultra-low noise
- high resolution
- robust freq coverage
MR 4.1
- large area
- low noise
- high resolution
- high cadence
MR 4.2
- ultra-low noise
- high resolution
- high cadence
MR 2.0
- large area
- low noise
- high resolution
- mid freq coverage
SURVEY DESIGNS
Ultra-Deep Low-Resolution
- Map Depth
- Frequency Coverage
- Angular Resolution
Ultra-Deep High-Resolution
- Map Depth
- Frequency Coverage
- Angular Resolution
- Observation Cadence
Deep-Wide High-Resolution
- Map Depth
- Sky Area
- Frequency Coverage
- Angular Resolution
- Observation Cadence
LEVEL 1 TECHNICAL REQUIREMENTS
Small-Aperture Telescopes South Pole
Large-Aperture Telescopes South Pole
Large-Aperture Telescopes Chile
LEVEL 2, 3, 4, 5 TECHNICAL REQUIREMENTS
Detector, Readout, Module, SAT, LAT, Data Acquisition, Data Management, South Pole Site, Chile Site Subsystems & Their Components

Forecasting

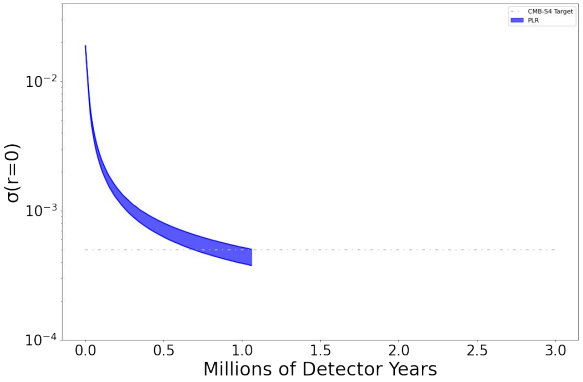
- Quantifying the design requires forecasts of the science return with effort.
- The required effort (in detector-years) can then be factorized into the number of detectors and duration of the survey.
    - Transient science is the exception, where the dependency is just on the number of detectors
- Each science goal has a working group to generate such forecasts.
- We have assembled all of these into a web app

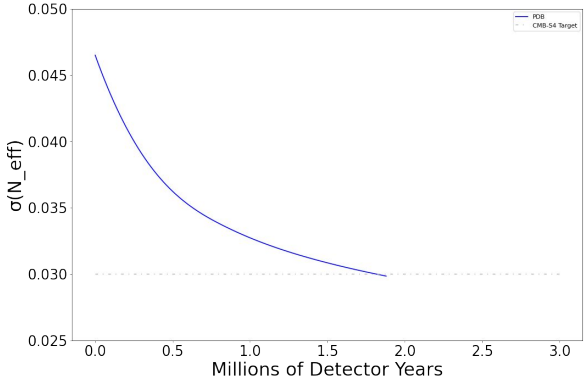
  https://webapp.cmb-s4.org/Science-With-Effort/

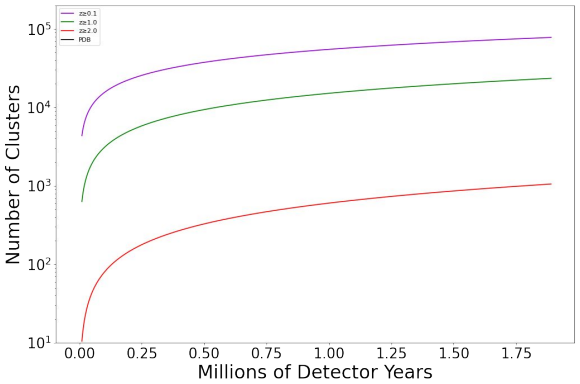
- We can also use this to give quick, qualitative, estimates of the science return from other configurations (eg. including other data and/or telescopes) by scaling with effort and assuming a relative per-detector efficiency.

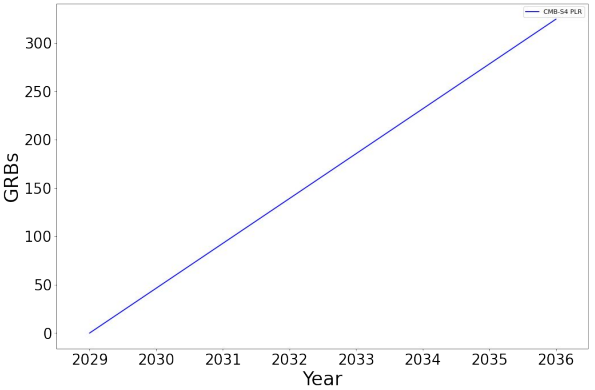
Science With Effort

Based on forecasts like these we have settled on a 7 year survey with 550,000 detectors.









Funding

Experiments vs Projects

EXPERIMENT	PROJECT
Grant-funded ● Scope driven by the cost cap ● Selection by annual/biannual peer review committees ● Oversight through annual reports ● Management by the PI ● “Best effort”	Project-funded (MIE, MREFC, …) ● Scope driven by science goals ● Recommendation by community(s) through decadal survey report(s) + agency(s) gates ● Oversight through multiple reviews ● Professional project management ● “Can’t fail”

Decadal surveys necessary for CMB-S4:

- Particle Physics Project Prioritization Panel (DOE High Energy Physics + NSF Physics)
- NAS Antarctic & Southern Ocean Research (NSF Polar Programs)
- Decadal Survey of Astronomy & Astrophysics (NSF Astrophysics)

2014: P5

“Recommendation 18: Support CMB experiments as part of the core particle physics program. The multidisciplinary nature of the science warrants continued multiagency support.”

DOE HEP ✅✅

NSF Physics ✅

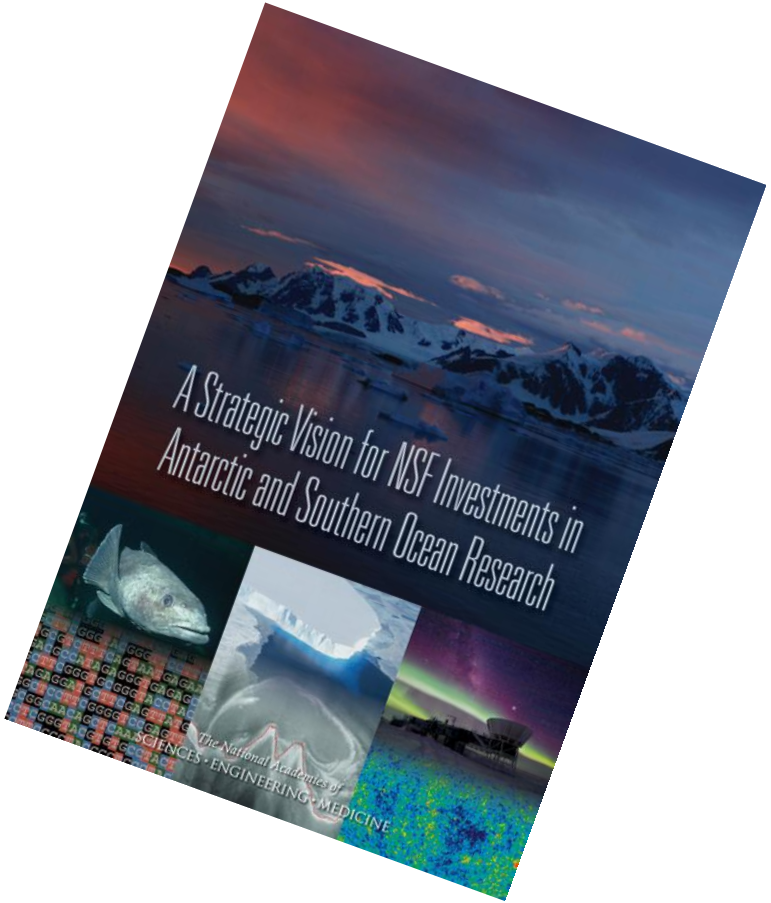
2015: NAS Antarctic & Southern Ocean

“Recommendation: NSF should pursue the following [three] strategic priorities in Antarctic and Southern Ocean research for the coming decade:

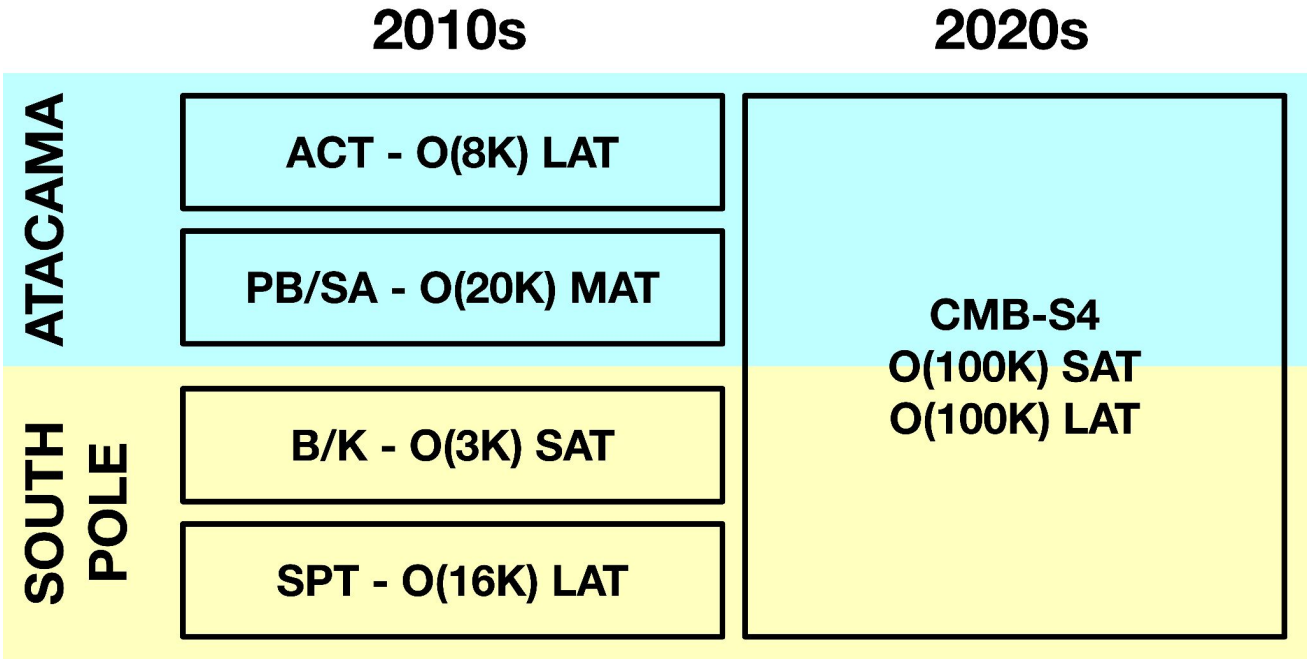
...

III. How did the universe begin and what are the underlying physical laws that govern its evolution and ultimate fate? A next-generation cosmic microwave background program.”

NSF OPP ✅



2015 Landscape



Reality Check

1. NSF needed an Astro2020 recommendation to proceed & DOE needed an NSF commitment to proceed
    - CMB-S4 operations would not start till the late 2020s
    - The “Founding Four” Stage 3 experiments needed to fill the gap
2. The level of r we needed to target *required* precise foreground cleaning and delensing
    - Future experiments needed to be multi-frequency and multi-scale

- The funding agencies (AAAC) convened a Taskforce to develop a Concept Definition for the CMB-S4 project (CDT Report)
- The Atacama experiments (ACT, PB/SA) joined forces and obtained private funding for the all-new Simons Observatory
- The South Pole experiments (BK, SPT) joined forces and coupled their existing/planned resources as the South Pole Observatory

South Pole Observatory

1 LAT (SPT-3G)

+

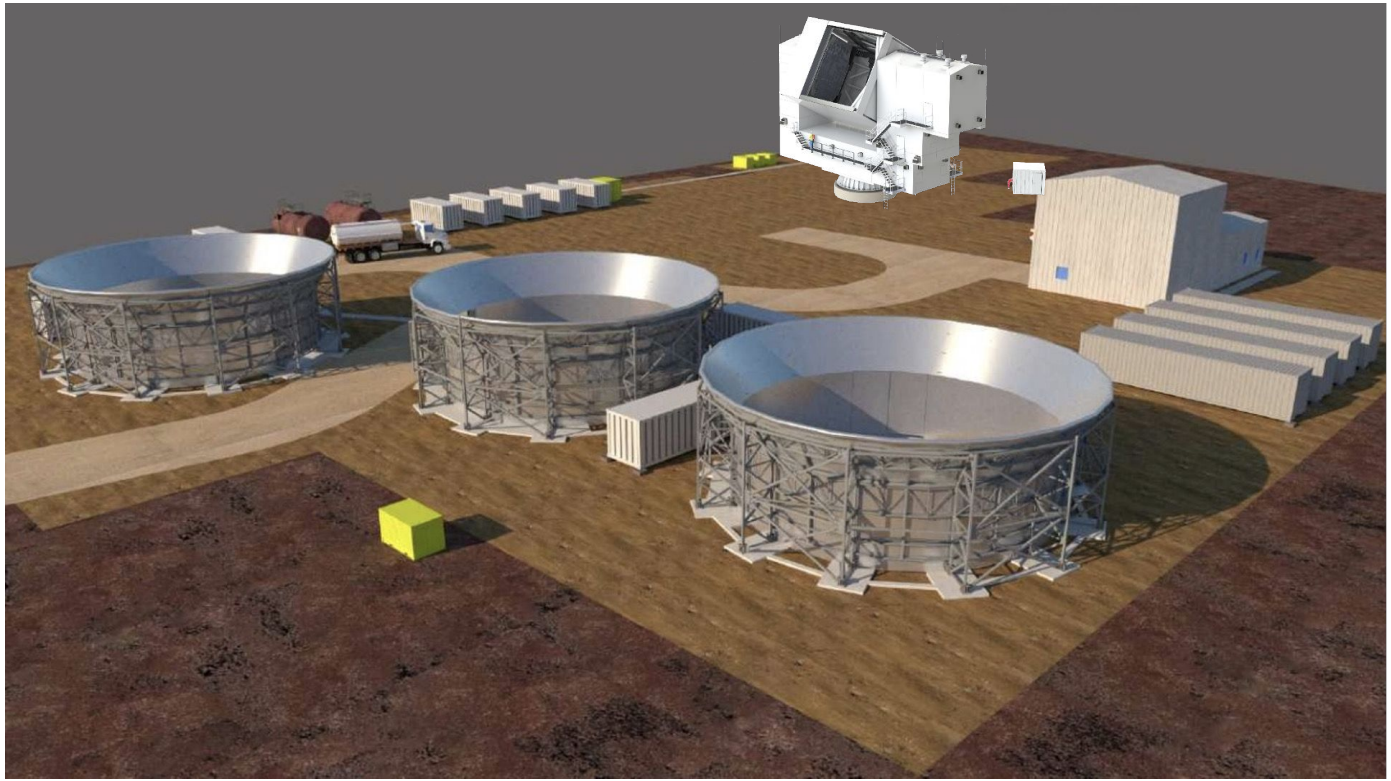
4 SATs (BA)

Simons Observatory

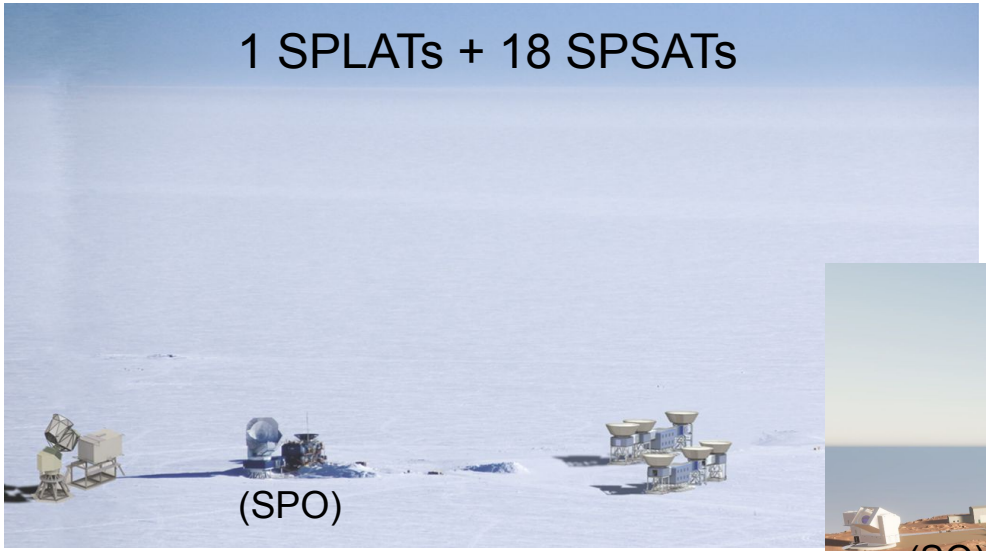
½ LAT

+

3-4 SATs



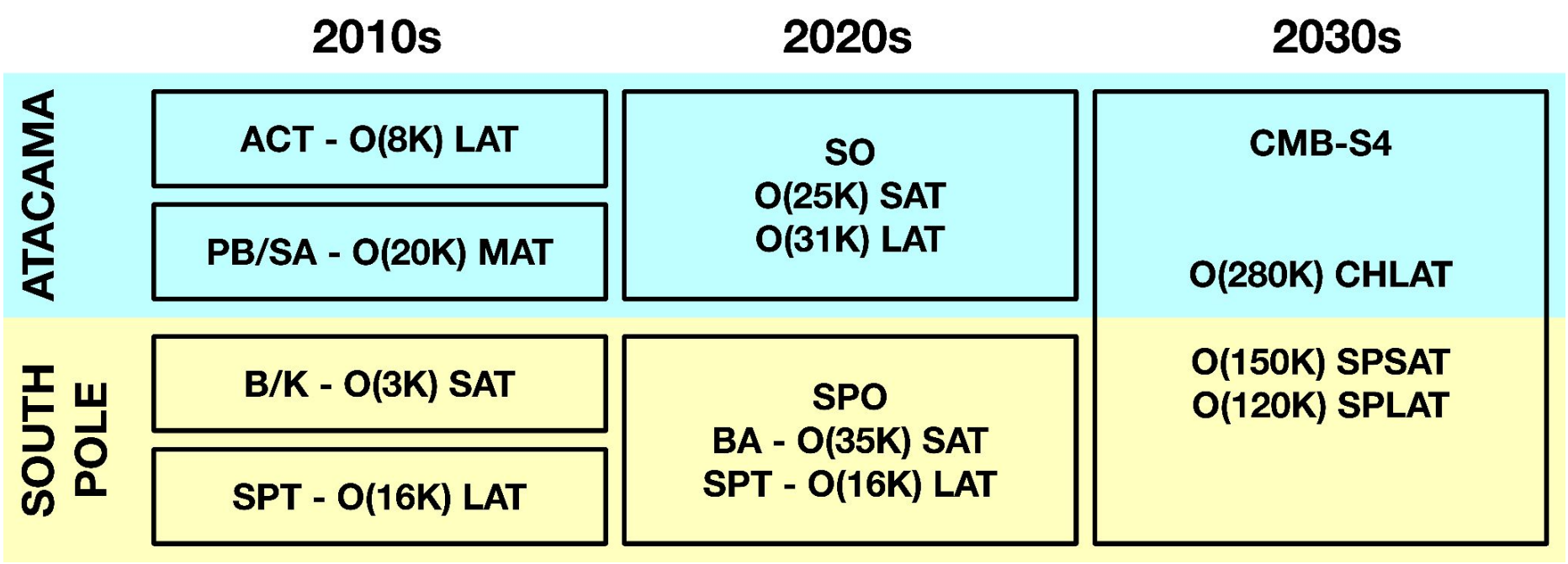
Preliminary Baseline Design



By design CMB-S4 uses the best technologies and techniques of all of its predecessors, unconstrained by site, scale, etc.

We plan a 7-year observation using both large and small aperture telescopes from both the South Pole and the Chilean Atacama Desert.

2020 Landscape

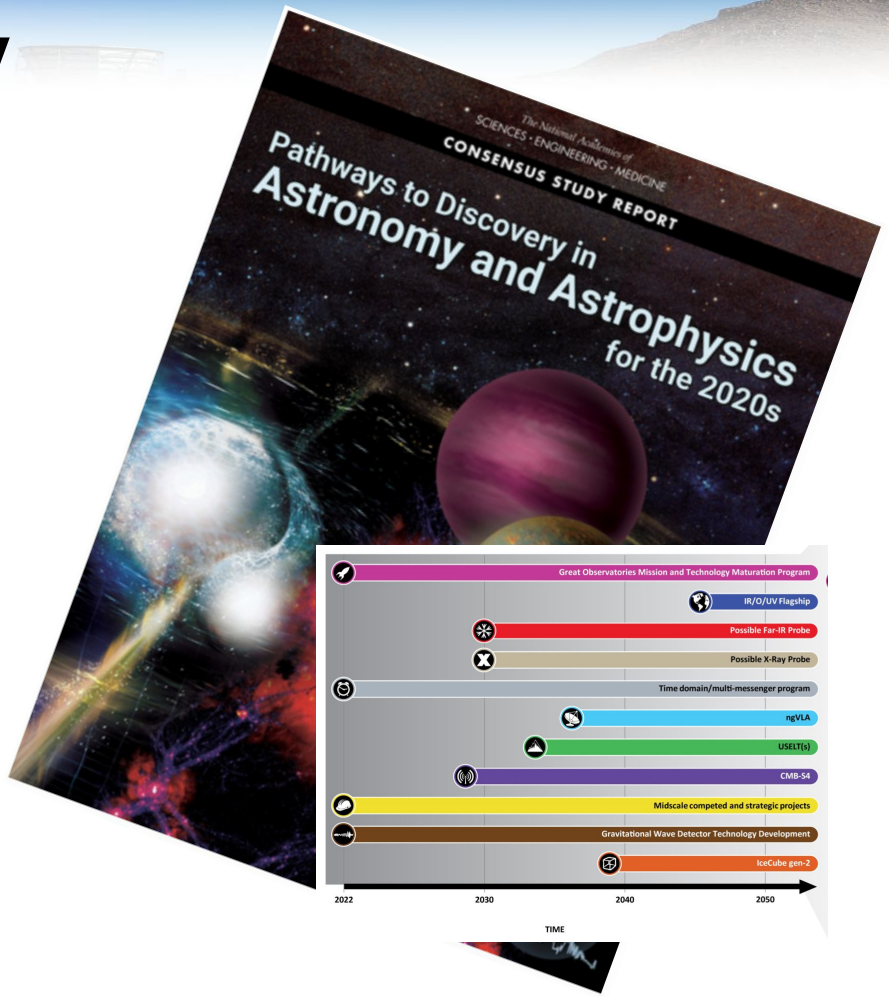


2021: Decadal Survey

“Recommendation: The National Science Foundation and the Department of Energy should jointly pursue the design and implementation of the next generation ground-based cosmic microwave background experiment (CMB-S4).”

“The panel suggests that third-generation CMB experiments aligned with CMB-S4 - specifically, the SPO and the nominal version of the SO - be high priorities for federal support.”

NSF Astrophysics ✅✅

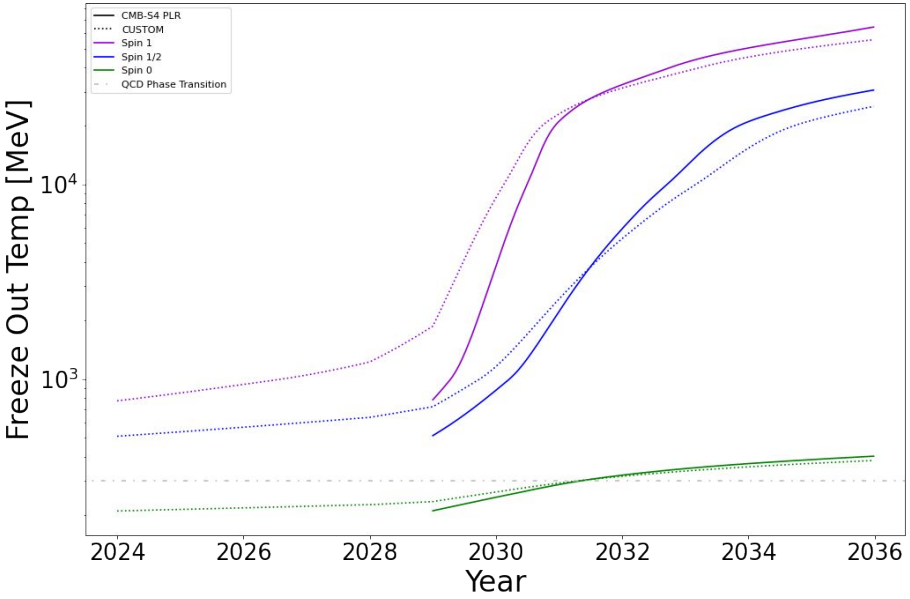


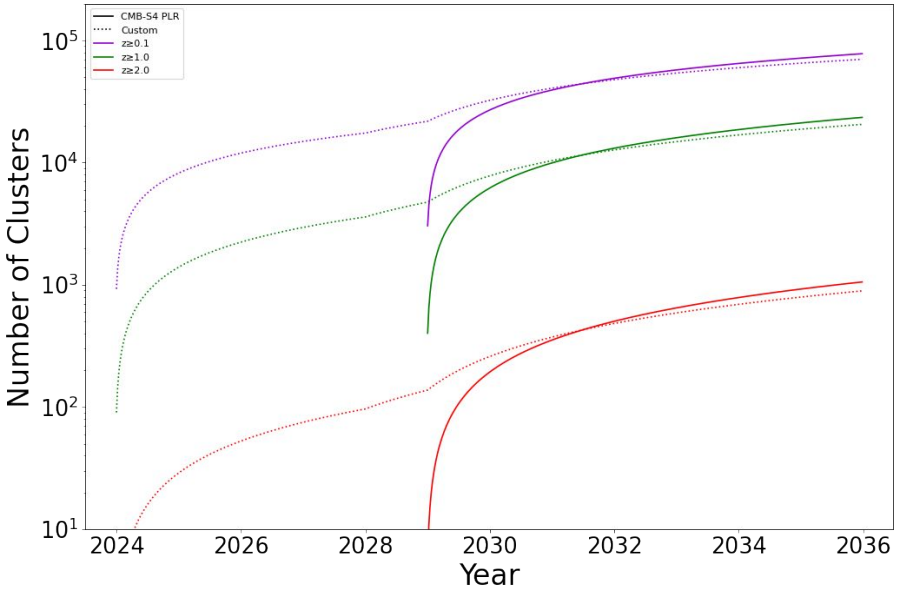
2022: The Good …

- The Simons Observatory proposal (endorsed by CMB-S4) to
  - fill out the LAT focal plane
  - deploy a solar power array
  - enable rapid delivery of astrophysical maps

  is under consideration at NSF.
- Even though the fully-filled SO LAT would still be smaller than a CMB-S4 CHLAT, when the previous observations are included it would be sufficient to replace a CMB-S4 CHLAT.
- The SO and CMB-S4 teams are having positive discussions about the ways their programs can productively be aligned.

Using the SO LAT





Light relic freeze-out temperatures and galaxy cluster counts:

Solid lines: 2 x CMB-S4 CHLATs

Dashed lines: 1 x CMB-S4 CBLT + SO/ASO LAT

2022: … The Bad …

- 10 years have passed us by, and the P5 decadal process is starting up again!
- Given the lack of progress on the construction project, it is important that CMB-S4 gets another strong endorsement.

- The CMB community needs to be active in the Snowmass process that will feed into P5.
- Many dedicated and joint white papers have already been submitted.
- Please consider attending the Community Summer Study Workshop

http://seattlesnowmass2021.net/

2022: … And The Ugly

"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. South Pole Station will continue to host its current suite of large-scale science projects, such as the IceCube Neutrino Observatory; *however, proposers seeking support for new projects at South Pole Station should consult the cognizant program officer to discuss alternative pathways to accomplish science goals.*"

NSF 22-078

Dear Colleague Letter: Update on Science Support and Infrastructure in Antarctica

April 29, 2022

Dear Colleagues:

This letter provides an update on the status and future of science support and infrastructure recapitalization in Antarctica as affected by the COVID-19 pandemic.

To date, protocols intended to prevent COVID-19 transmission to the stations and continent, such as extended periods of quarantine, careful monitoring of COVID-19 exposure, and reductions in personnel, have successfully prevented COVID-19 outbreaks at United States Antarctic Program's (USAP) capacity to support funded science projects, and halted some construction and limited medical facilities on station, have constrained the U.S. Antarctic Program's (USAP) capacity to support funded science projects, and halted some construction and maintenance activities, creating a substantial backlog in both.

Despite these challenges, the USAP successfully supported science projects in the 2021-22 season at approximately 30-40% of 'normal' levels, in accordance with a tiered system of prioritization. The highest priority science projects included fieldwork involving international collaborations, projects with critical time-series data, and projects involving instrument maintenance to prevent irreversible damage to, or loss of, science infrastructure.

Assuming pandemic restrictions ease in the coming season, the USAP will prioritize efforts to support already-funded science projects, to the greatest extent possible. Working through the extensive backlog may take several years to complete, and will require continued vigilance, thoughtful execution, and patience.

While OPP will continue to accept proposals involving fieldwork, the USAP's ability to support new field deployments will be limited in certain sectors, as described below. OPP also continues to encourage the submission of proposals that promote discovery and innovation but do not require Antarctic deployment. Examples include projects that emphasize model development and validation, advance technology and cyberinfrastructure, or include analysis of already-collected data and/or samples. Under limited circumstances, proof-of-concept projects, e.g., testing instrumentation, may include fieldwork at non-polar sites that offer comparable data and/or samples. Under limited circumstances, proof-of-concept projects, e.g., testing instrumentation, may include fieldwork at non-polar sites that offer comparable conditions.

Before the pandemic, the USAP had developed plans (see Blue Ribbon Panel report) to maintain or replace critical infrastructure at all stations through the Antarctic Infrastructure Modernization for Science (AIMS) program, and its successor, the Antarctic Infrastructure Recapitalization (AIR) program. These plans also were disrupted by the COVID-19 pandemic. In the upcoming season, work is expected to continue on these activities, including replacement of a lodging facility and the development of a new Vehicle Equipment and Operations Center at McMurdo Station.

The imperative to address the backlog of funded projects and to improve critical infrastructure at McMurdo will make it difficult to accommodate new initiatives with a large field footprint in some sectors. Specific information concerning the availability of field assets is below:

McMurdo Station will be unable to accommodate new, large field teams until the second half of the decade. However, new smaller efforts involving helicopter support from McMurdo Station, starting in the 2023-2024 field season, are potentially supportable. Likewise, new near-field initiatives based out of McMurdo and requiring small fixed-wing support can be implemented starting in the 2024-2025 field season. LC-130 airlift support and both science traverse platforms are highly constrained through the 2026-27 season, due to support of already-funded deep field and South Pole Station activities.

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. South Pole Station will continue to host its current suite of large-scale science projects, such as the IceCube Neutrino Observatory; however, proposers seeking support for new projects at South Pole Station should consult the cognizant program officer to discuss alternative pathways to accomplish science goals.

Palmer Station is fully allocated from January to mid-February through 2024, but is able to support smaller projects in the early and late season in 2022-2023, 2023-2024 and 2024-2025, and larger projects overwinters for all seasons.

The **R/V Nathaniel B. Palmer** is fully allocated during the peak summer (November - February) through 2023-2024, but availability exists during the shoulder seasons (i.e., April/May and September/October), and thereafter, for new science proposals. There are opportunities for the **R/V Laurence M. Gould** to support additional science on planned cruises around the Antarctic Peninsula in 2022-2023 and 2023-2024.

As we navigate the COVID-19 pandemic's impacts, OPP will provide regular updates about resource capabilities. OPP encourages prospective investigators to consult program officers concerning projects requiring field support. In addition, we will soon launch, with input from the scientific community, a South Pole Station Master Planning effort, similar to the master planning effort that established infrastructure renewal priorities for McMurdo and Palmer Stations. More information will be available at USAP.gov, through the OPP quarterly newsletter, Antarctic Community Office Hours, and the OPP Advisory Committee.

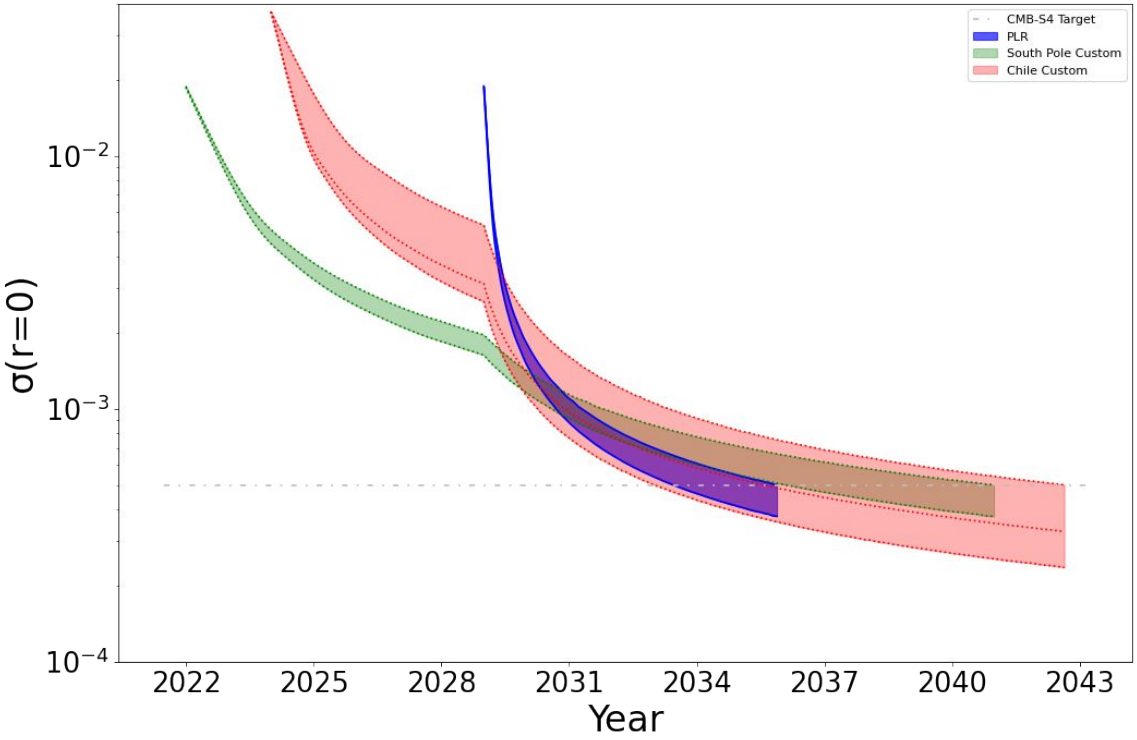
Sincerely,

Alexandra R. Isern
Assistant Director for Geosciences

Analysis of Alternatives

- Given the unexpected restriction on deployments at the South Pole, we must *rapidly* assess possible alternative configurations.
- These will necessarily involve some combination of higher risk, higher cost, and reduced science.
- Examples:
  - using a SPLAT for both primordial and lensing B-modes
  - using a more aggressive SAT design (like SO's)
  - using CHSATs
  - using delensing CHLATs for SPSATs
  - extending operations beyond 7 years
  - dropping the two-tier cluster & transient surveys

Examples:



Ranges include foreground complexity and (for Chile) performance uncertainty:

- Blue: CMB-S4 at SP
- Green: SPO + ½ x CMB-S4 at SP
- Red: SO + 2 x CMB-S4 in Chile

Summary

- CMB-S4 is the first ground-based CMB *project*, designed from the outset to reach key scientific thresholds.
- The gap from the end of the “Founding Four” Stage 3 experiments to the start of CMB-S4 operations has been filled by SPO and SO.
- These are important standalone experiments in their own right *and* valuable pre-Stage 4 activities:
  - Maintaining community continuity and scientific advancement
  - Informing the design of the CMB-S4 instrument and operations
  - Potentially providing data/software/hardware to augment CMB-S4
- Despite bumps in the road, we still have a route to CMB-S4 operations through the 2030s.

International support - from endorsement to participation - is extremely valuable