Fundamental Physics with CMB-S4

2014 P5: "Support CMB experiments as part of the core particle physics program."

CMB-S4 recommended under all budget scenarios (currently has CD-0, mission need)

P5 Townhall Feb 23, 2023

Jeff McMahon

(U. Chicago & FNAL, Co-Spokesperson)

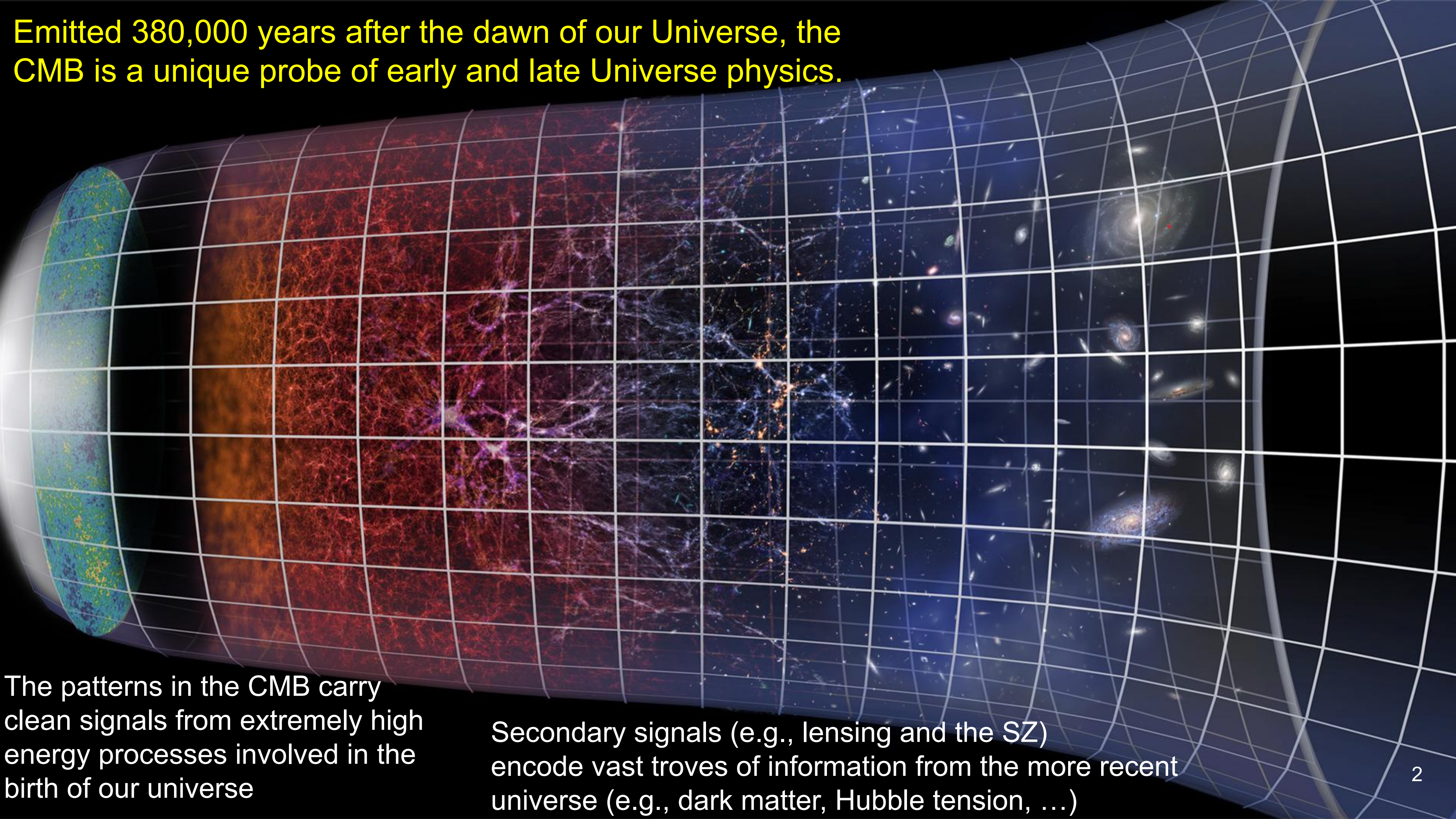
and

Jim Strait

(LBNL, Project Director)

On behalf of the CMB-S4 Collaboration and Project

Emitted 380,000 years after the dawn of our Universe, the CMB is a unique probe of early and late Universe physics.



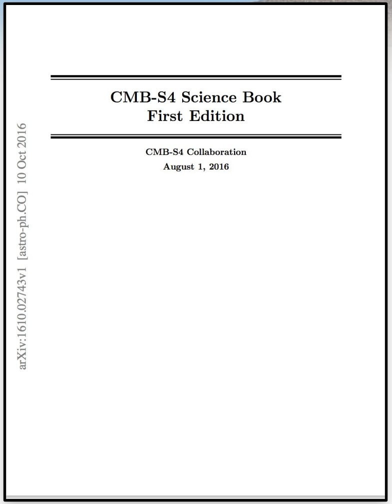
The patterns in the CMB carry clean signals from extremely high energy processes involved in the birth of our universe

Secondary signals (e.g., lensing and the SZ) encode vast troves of information from the more recent universe (e.g., dark matter, Hubble tension, …)

Extremely Broad Science Reach

Primary CMB Anisotropy: Inflationary gravitational waves • Inflation energy scale • Quantum Gravity • Light relics • BSM particles • Inflationary non-gaussianity • 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…



CMB-S4 Science Book
First Edition

CMB-S4 Collaboration
August 1, 2016

arXiv:1610.02743v1 [astro-ph.CO] 10 Oct 2016

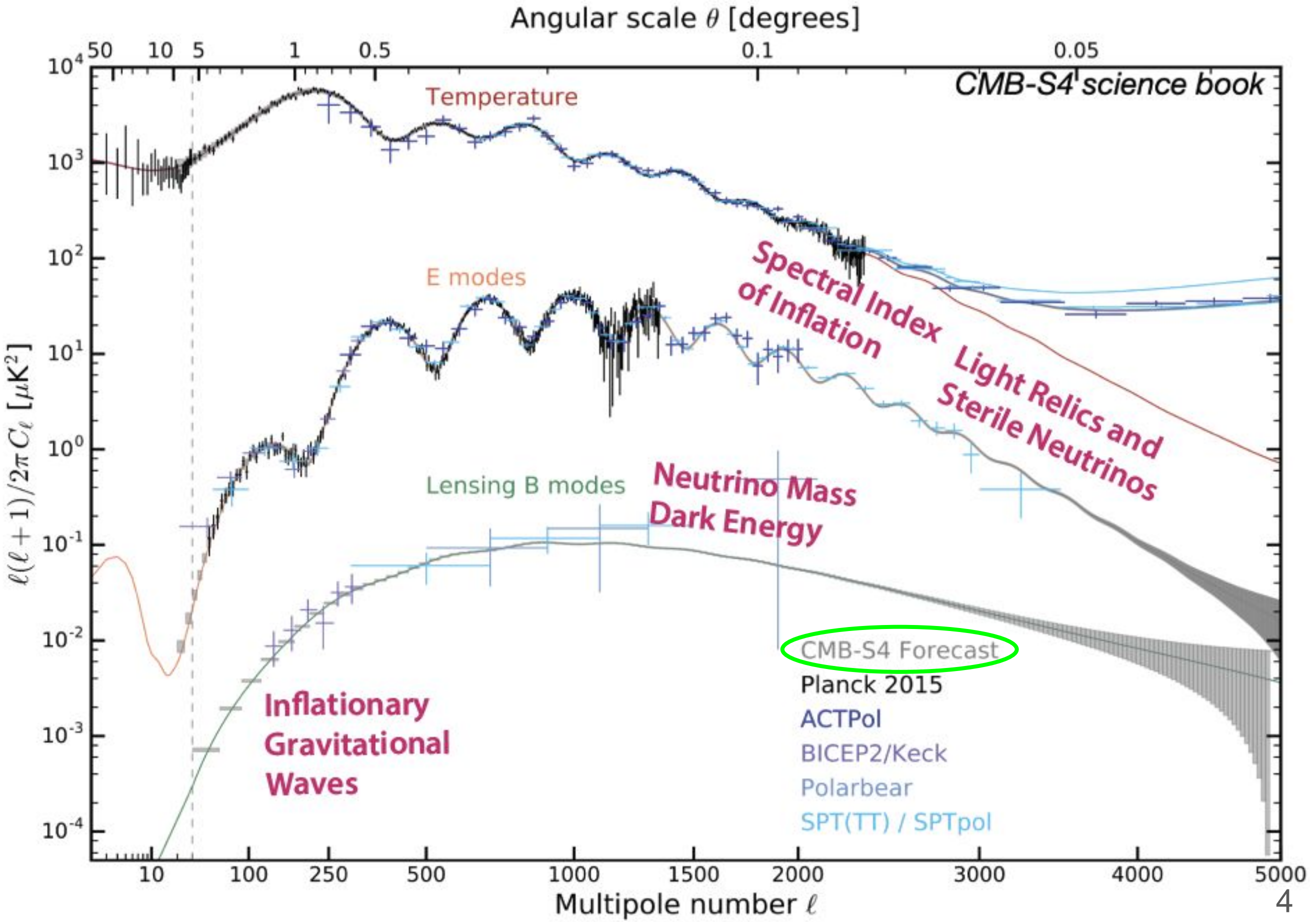
CMB-S4 Science Book
First Edition (2016)
200 pages, >1250 citations
available at http://cmb-s4.org
arXiv:1610.02743

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: A Precision CMB Powerhouse

CMB-S4 is designed to make transformative measurements of the CMB temperature and polarization in order to cross critical thresholds in key cosmological parameters.

This is not just sensitivity, it requires control of foregrounds and systematics!

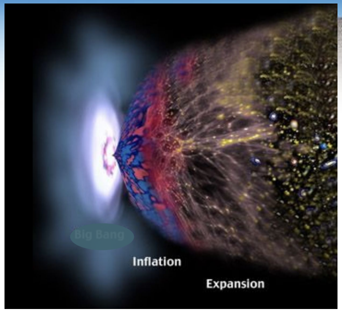


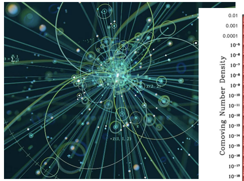
Primary Science Goals

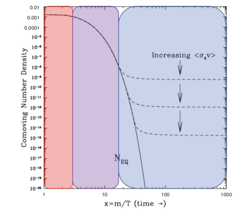
Topics highlighted in this talk

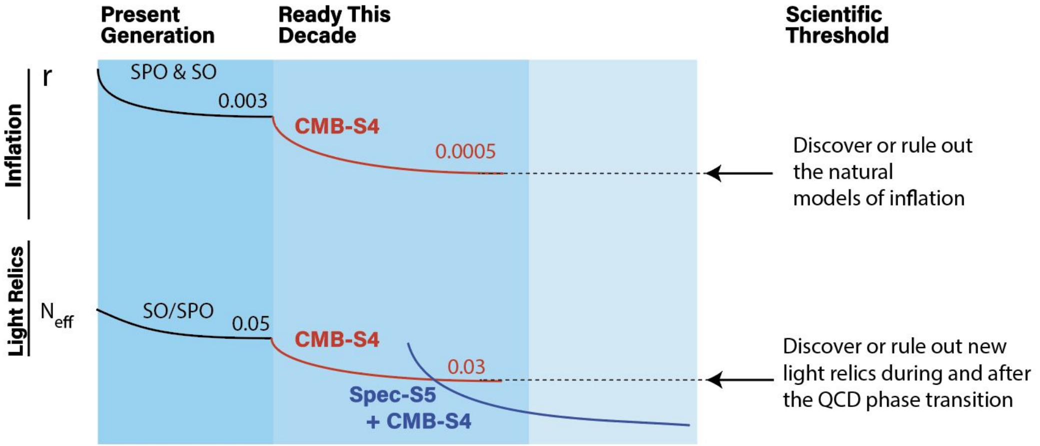
Inflation CMB-S4 will cross a critical threshold ($\sigma_r < 0.0005$) to discover or rule out the natural models of inflation.

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.



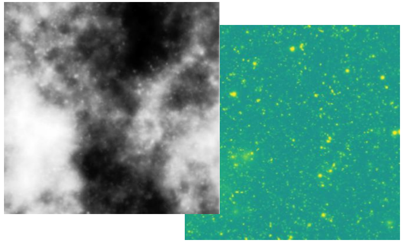




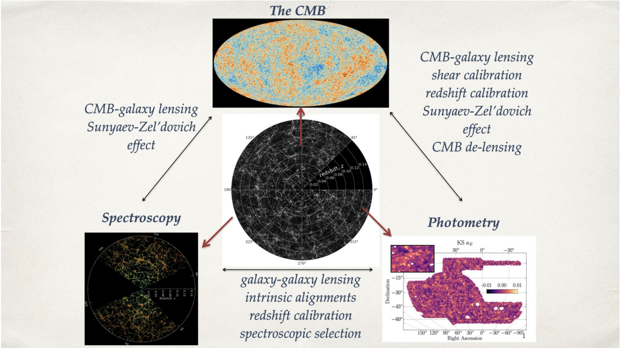


Primary Science Goals

Matter Mapping CMB-S4 will provide legacy lensing, baryon pressure, and multifrequency maps which probe cosmology, star formation, galaxy clusters and enable diverse new science including dark energy and dark matter studies complementing LSST DESC and DESI.



Time Domain CMB-S4 will provide ~hourly maps which detect millimeter wave transients relevant for solar system objects (e.g. planet 9), stars, TDEs, and enable multi-tracer studies with LSST, ICECUBE, and LIGO.



Slide from Joe DeRose

Primordial Gravitational Waves and Inflation

Inflationary B-modes are a Big Deal!

- A key test of inflation and our origins.

$$\text{time} = 10^{-36} \left(\frac{r}{0.01}\right)^{-\frac{1}{2}} \text{seconds}$$

- A relic from 10^{36} times earlier than the light elements created at t = 1 second.

$$\text{energy} = 10^{16} \left(\frac{r}{0.01}\right)^{\frac{1}{4}} \text{GeV}$$

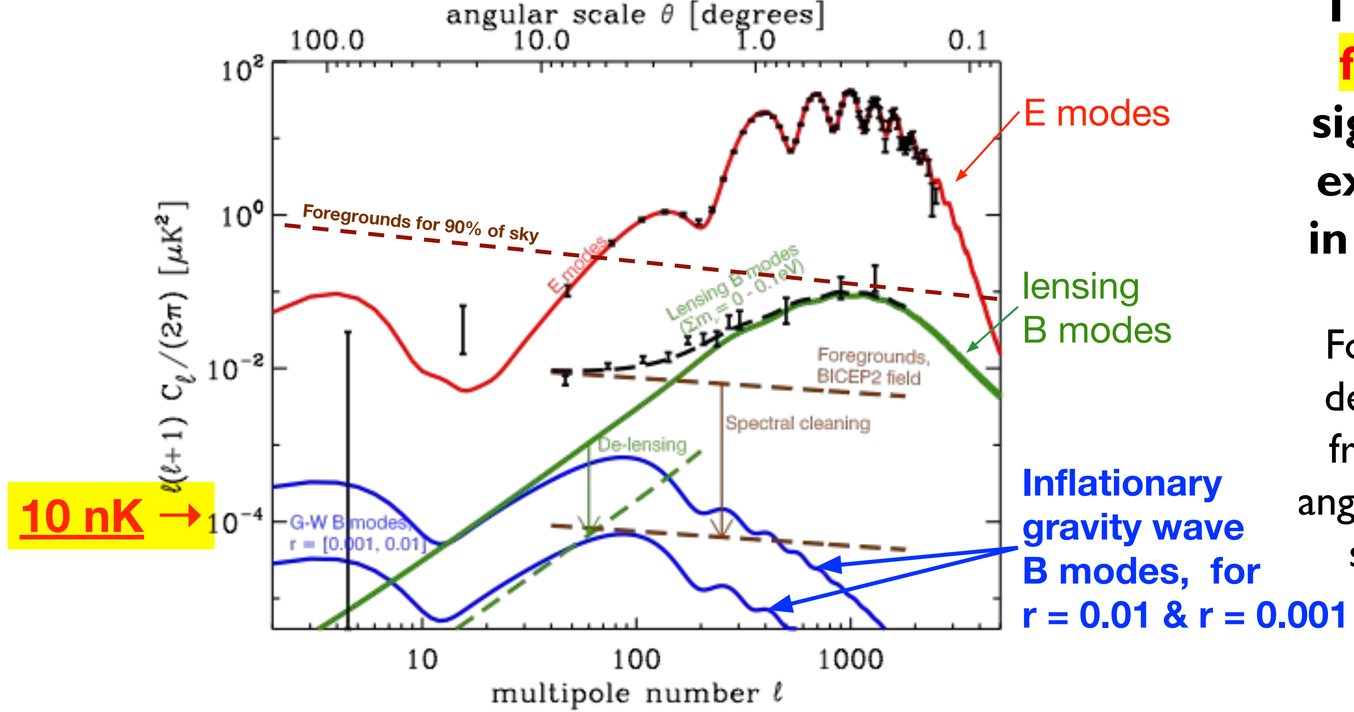
- Probing physics at the scale of superstring theory, a trillion times beyond the reach of the LHC.
- Insights into quantum gravity.

From 2014 P5 Report:
"(CMB) experiments now have the capability to access the ultra-high energy physics of inflation and important neutrino properties. These measurements are of central significance to particle physics."

From 2020 A&A Decadal Survey:
"One of the most exciting opportunities in the coming decade is that CMB measurements may reveal remnant gravitational waves from this early epoch."

r = ratio of the primordial tensor to scalar fluctuations

Making a definitive measurement of the Inflationary signal



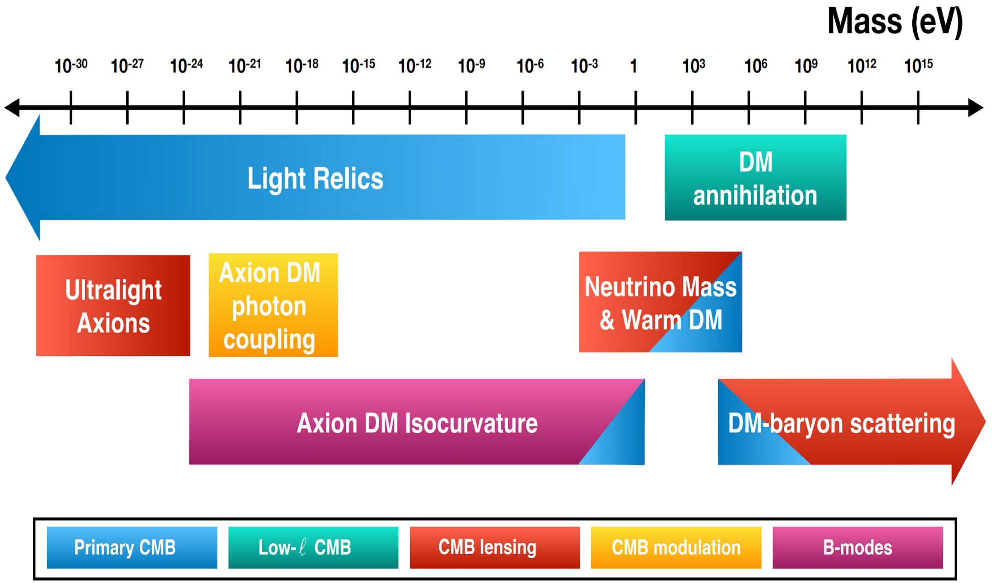
The signature is 10nK fluctuations on a 3K signal, measured by an experiment operating in a 300K environment

Foregrounds mitigation and de-lensing requires multiple frequency bands and broad angular range with exceptional sensitivity and control of systematics

CMB-S4 must dig two orders of magnitude deeper than current experiments, and through the foreground-dominated regime

Light Thermal Relics and the Dark Universe

CMB Insights Into The Dark Universe Across The Mass Spectrum



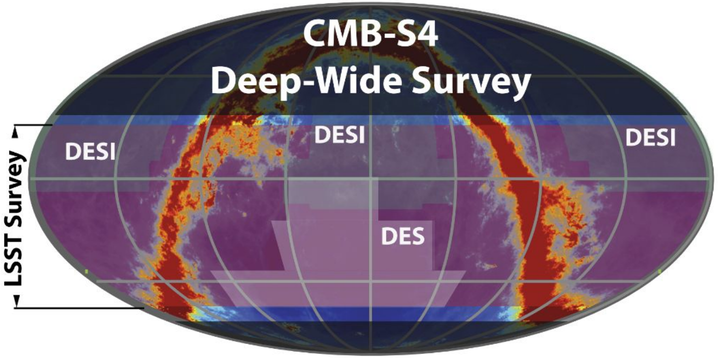
CMB-S4 will probe dark sector physics across an enormous range in mass

CMB-S4 will **detect all light relics that decoupled after the start of the QCD transition (from Quark Soup to Matter-as-we-know-it), providing orders of magnitude improvement on the freeze-out temperature of any thermal relic.**

Additional **light particles that appear in extensions to the standard model will be constrained by CMB-S4, e.g., sterile neutrinos, axions, dark radiation, gravitinos, etc.**

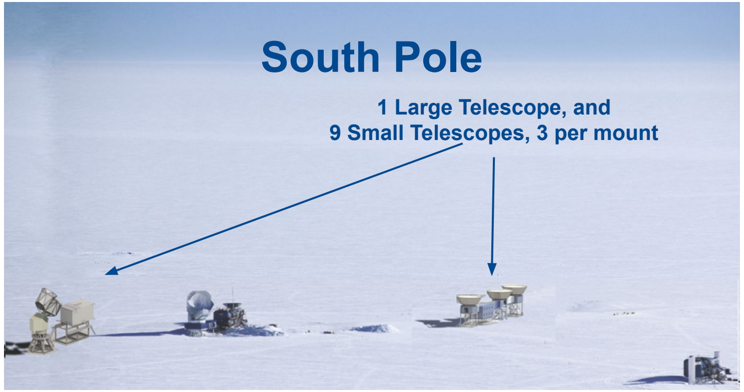
CMB-S4 will provide many constraints of cosmology and particle physics over a enormous range of mass scales.

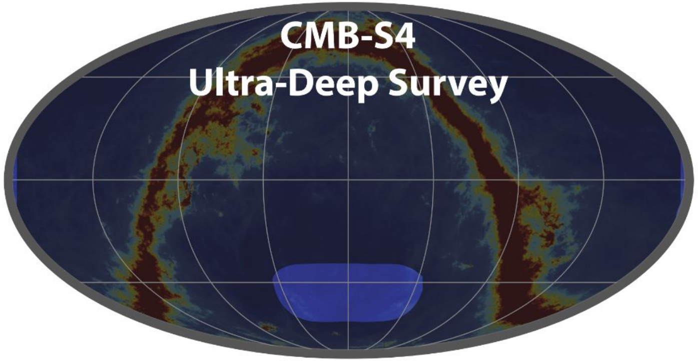
Four science goals, two superb sites, one collaboration



Observed from Chile

Large area survey motivated by N_{eff}, matter mapping, and time domain science and enabled by the mid-latitude site





Observed from South Pole

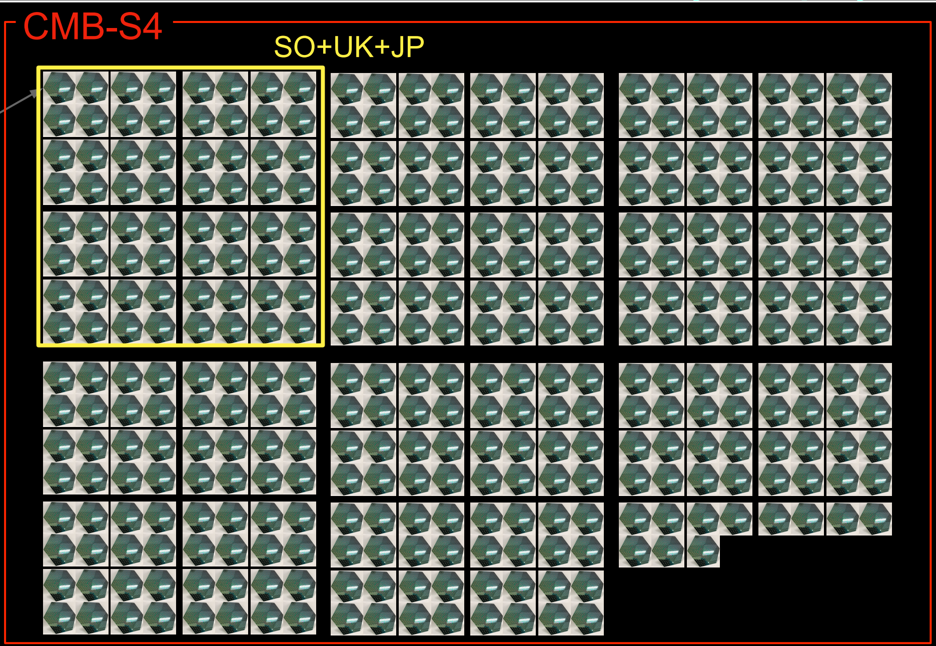
Small area survey primarily targeting inflationary gravitational waves, enabled by the sky coverage, low horizon blockage, and ultra stable atmosphere of the polar site.

Sensitivity CMB detectors are background limited. The only way to meet our science targets is to deploy more detectors.

State-of-the-art: SPT-3G

- 16k superconducting TES detectors
- 10 detector wafers (0.17 sq. meters)
- The largest deployed focal plane

CMB-S4: more than 10x all CMB detectors yet deployed!



- 496k superconducting TES detectors
- **363 detector wafers (6.4 sq. meters)**
- A major scale-up requiring the expertise of DOE labs

CMB-S4 and other CMB experiments

CMB-S4 is based on a strong heritage of previous and current ground-based CMB experiments, including the BICEP, SPT and Simons Observatory (SO).

- The CMB-S4 detectors are an evolutionary extension of those used by the prior experiments.
- The survey strategies, analysis techniques, understanding and control of systematic errors being developed and employed by BICEP, SPT, ACT, Polarbear, and SO all feed directly into the far-more capable CMB-S4.
- The U.S. has the world-leading ground-based CMB science program.

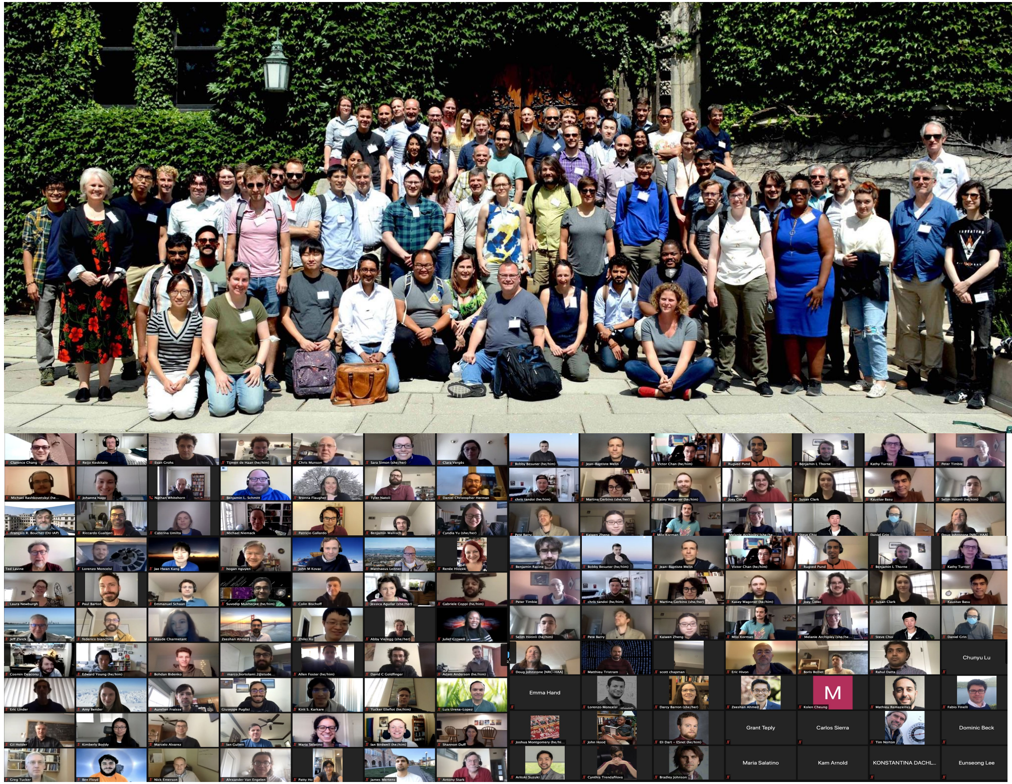
The planned Japanese-European satellite LiteBIRD will operate on the same timescale and targets the inflation goal with similar reach as CMB-S4.

- The strategies for measuring r are quite different as are the expected systematic uncertainties. The two experiments are strongly complementary and science will benefit from the operations of both.
- A joint MOU has recently been signed between CMB-S4 and LiteBIRD to formalize the working relationship between the collaborations to maximize the complementarity and therefore our ability to understand nature.

Community Organization

building the partnership

- CMB-S4 held our **1st collaboration meeting in 2015**
- CMB-S4 ***established a formal collaboration in 2018***
- The CMB-S4 Science Collaboration is highly active and engaged
  - 427 members: primarily cosmologists, particle physicists, and astronomers
  - 116 institutions
  - 18 countries
  - 26 U.S. States
  - 2 major collaboration meetings/year
- Produced *CMB-S4 Science Book* (2016, arXiv:1610.02743) and *CMB-S4 Technology Book* (2017, arXiv:1706.02464)
- Produced *CMB-S4 Science Case, Reference Design, and Project Plan,* for input to Astro2020 (arXiv:1907.04473)
- *CMB-S4 Preliminary Baseline Design Report* (under revision)



15th Collaboration meeting, August 2022

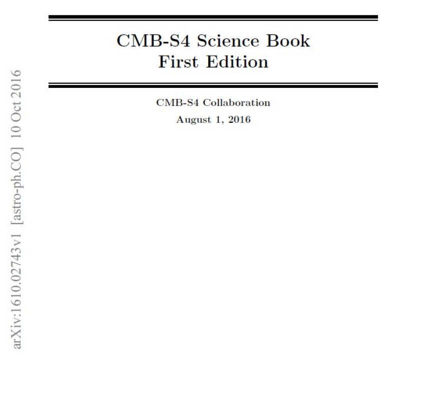
Strong heritage of community endorsements

- 2014: P5 recommended CMB-S4 under all budget scenarios
- 2015: NAS report recommended CMB-S4 science case as 1 of 3 strategic investments for Antarctic Research
- 2017: AAAC unanimously approved CMB-S4 Concept Definition Task Force charged by DOE & NSF
- 2021: Astro2020: "***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).***" Calls out broad science case.
- 2022: Snowmass Cosmic Frontier report: "***The HEP community has identified potentially transformative opportunities to address fundamental physics questions. We aspire to … Complete the CMB-S4 cosmic microwave background experiment.***"

CMB-S4 Project Development

The CMB-S4 Project that will enable the CMB-S4 science program has been developed over many years through a systematic and rigorous process involving:

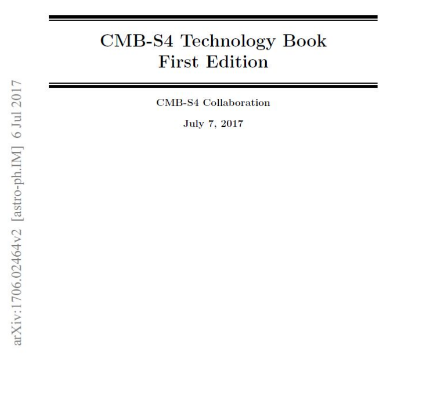
- Development of Science Goals that drive the design
- Flowdown of the Science Goals to Science Requirements to Engineering Requirements to detailed specifications
- R&D, engineering development and project planning


arXiv:1610.02743v1 [astro-ph.CO] 10 Oct 2016

CMB-S4 Science Book
First Edition

CMB-S4 Collaboration
August 1, 2016

200 pages 2016
arXiv:1610.02743


arXiv:1706.02464v2 [astro-ph.IM] 6 Jul 2017

CMB-S4 Technology Book
First Edition

CMB-S4 Collaboration
July 7, 2017

191 pages 2017
arXiv:1706.02464

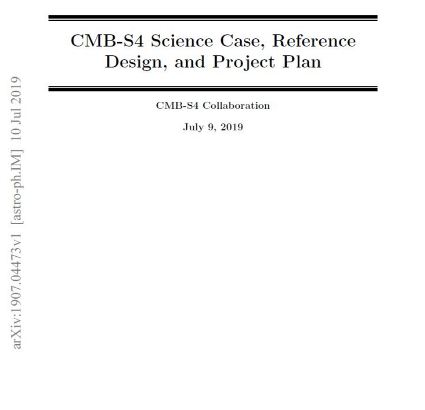

https://www.nsf.gov/mps/ast/aaac/cmb_s4/report/CMBS4_final_report_NL.pdf

Cosmic Microwave Background
Stage 4
Concept Definition Task Force

REPORT
TO THE AAAC

23 October 2017

57 pages 2017
NSF Link


arXiv:1907.04473v1 [astro-ph.IM] 10 Jul 2019

CMB-S4 Science Case, Reference Design, and Project Plan

CMB-S4 Collaboration
July 9, 2019

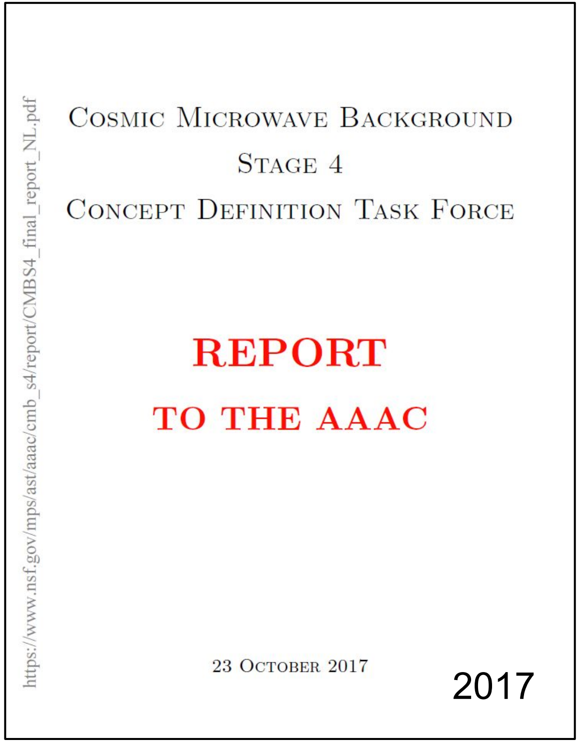
287 pages 2019
arXiv:1907.04473

CMB-S4 Project Development

The fundamental scope and organizational structure of CMB-S4 was established in 2017 by the Concept Definition Task Force, which was established under the auspices of the AAAC at the request of DOE and NSF.

It put forward:

- The key science goals that drive the design
- The basic configuration of the experiment
  - Two sites: South Pole and Atacama
  - An ultra-deep survey conducted by an array of small-aperture telescopes and a large-aperture telescope
  - A wide-deep survey conducted by 2 large-aperture telescopes
- The basic management structure
  - A unified Project structure combining both sites and supported by funding from both DOE and NSF
  - A science collaboration with its own structure, interacting closely with the Project


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

COSMIC MICROWAVE BACKGROUND

STAGE 4

CONCEPT DEFINITION TASK FORCE

REPORT

TO THE AAAC

23 OCTOBER 2017

2017

CMB-S4 Project Development

The project design was further developed and documented in a Preliminary Baseline Design Report.

CMB-S4 Science Case, Reference Design, and Project Plan

CMB-S4 Collaboration

July 9, 2019

arXiv:1907.04473v1 [astro-ph.IM] 10 Jul 2019

2019

Draft CMB-S4 Preliminary Baseline Design Report

CMB-S4 Collaboration

Version: CMBS4-doc-716-v4
February 11, 2022

2021

Over the past year, the configuration has been further refined based on a better understanding of the logistical and infrastructure constraints at the South Pole.

CMB-S4
Analysis of Alternatives

Briefing to NSF and DOE
December 7, 2022

2022

Preliminary Baseline Design

The Preliminary Baseline Design now comprises the following configuration:

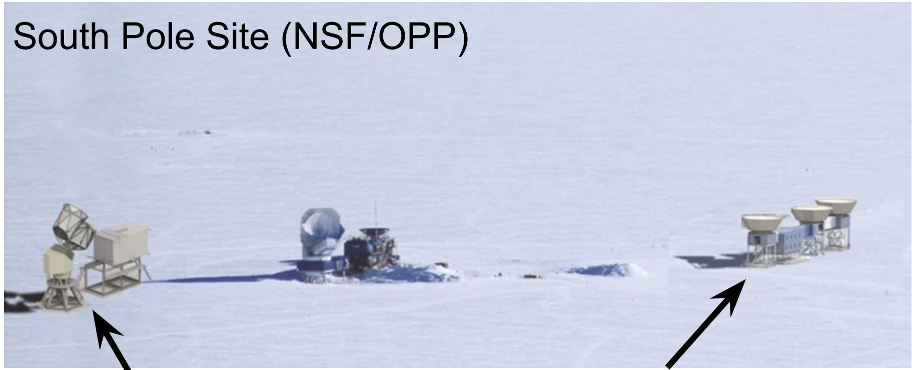
- 3 Small-Aperture Telescopes (9 Optics Tubes) + 1 Large-Aperture Telescope at the South Pole
- 2 Large Aperture Telescopes in the high Atacama desert in Chile

This is the optimal configuration (within constraints) because:

- The South Pole offers the best observing conditions for the ultra-deep survey that focuses on the inflation science.
- The combination of small- and large-aperture telescopes observing the same patch of the sky provides unique checks on systematic errors.
- The Atacama site in Chile provides excellent conditions for the deep, wide-field survey with 2 large-aperture telescopes that addresses N_{eff} and many other science goals.

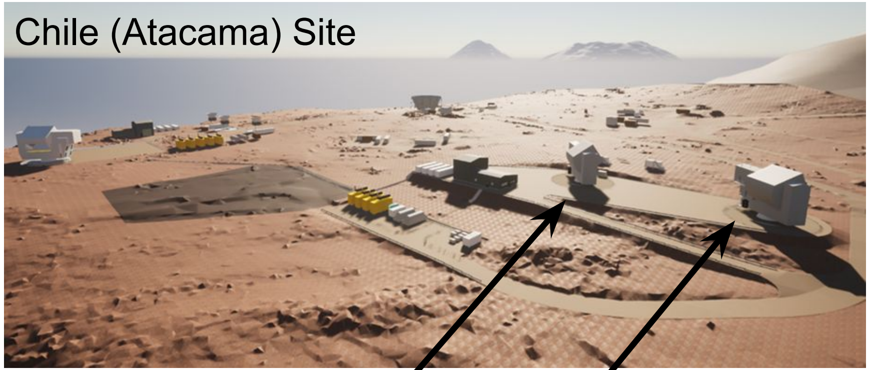
This configuration is being developed for NSF CDR and DOE CD-1.

Preliminary Baseline Design

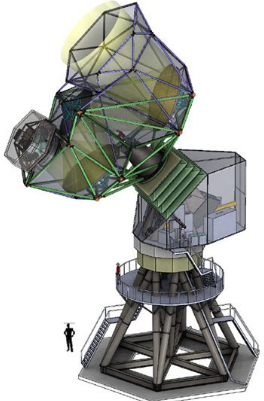


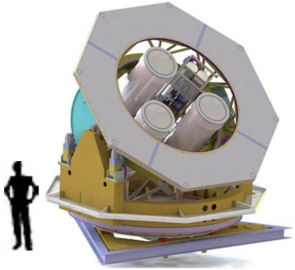
1 Large Aperture (5 m) Telescope

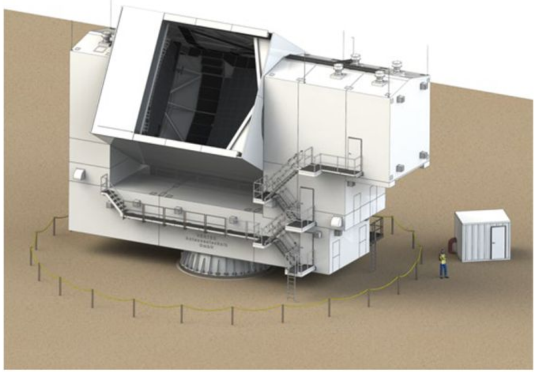
3 Small Aperture Telescopes
(9 0.5-m aperture optics tubes)



2 Large Aperture (6 m) Telescopes







South Pole Infrastructure Considerations

The recently completed Analysis of Alternatives has resulted in a configuration that aligns better with the existing logistics and infrastructure constraints at the South Pole, including power, fuel, cargo and people.

The power required at South Pole for this configuration (~170 kW) modestly exceeds that of the existing experiments (~140 kW).

We are pursuing options for ensuring the ability to power the full configuration within the constraints at the South Pole:

- Seek further power efficiency opportunities.
- Use renewable energy and energy storage.

As part of the engineering development of the CMB-S4 Conceptual Design for NSF CDR and DOE CD-1, we are engaging with the NSF Office of Polar Programs to more precisely understand the constraints and incorporate them into our project design.

Renewable Energy at the South Pole

A feasibility study done by Argonne in collaboration with NREL indicates that a combination of solar, wind and energy storage could be a viable way to ensure the ability to power all of the telescopes at the South Pole, while also reducing the carbon footprint and saving on operating and life-cycle costs.

CMB-S4 is investigating including this as part of the project plan.

Specific implementation for CMB-S4 to be coordinated with NSF/OPP.

RENEWABLE ENERGY IS VIABLE AT THE SOUTH POLE

- A **significant reduction in carbon footprint and savings of 10s of $M in cost of operations** is possible using mature renewable energy technology.
  - Payback time on capital investment is ~ 2 years
- **Technical risks and developments are identified**
  - Primary risk is durability in extreme environment
  - Risks can be mitigated with engineering development and eventual demonstration
- Implementation can be extremely flexible and staged
  - Even a minimal system can reap economic benefits while retiring technical risks
- We welcome engagement from NSF-OPP!

U.S. DEPARTMENT OF ENERGY — Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC. 11 Argonne NATIONAL LABORATORY

Argonne NATIONAL LABORATORY

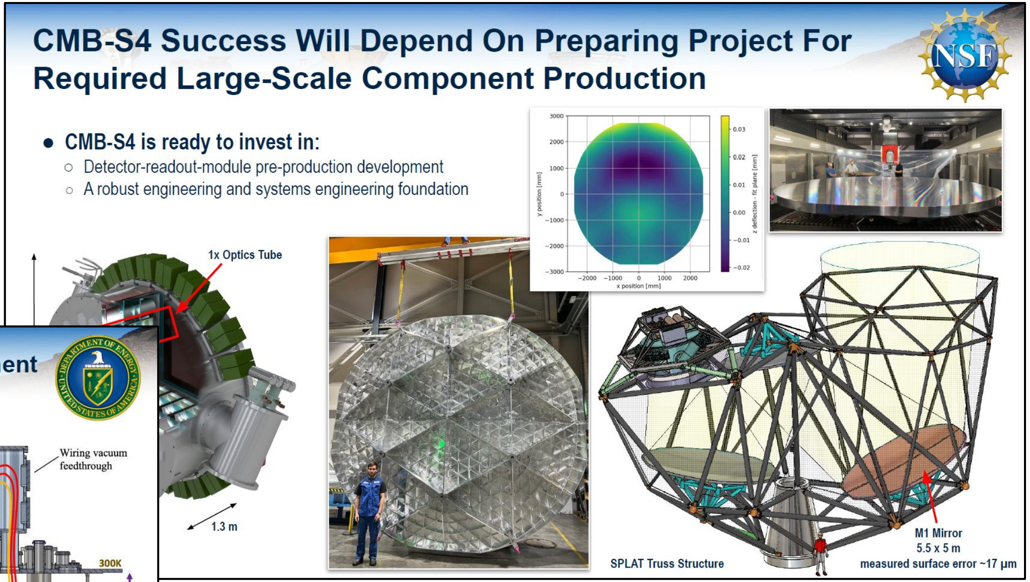
Susan Babinec (energy storage)
Amy Bender (CMB experiments, S. Pole)
Ralph Muehleisen (solar modeling & system design)
Rik Yoshida (HEP experiments)

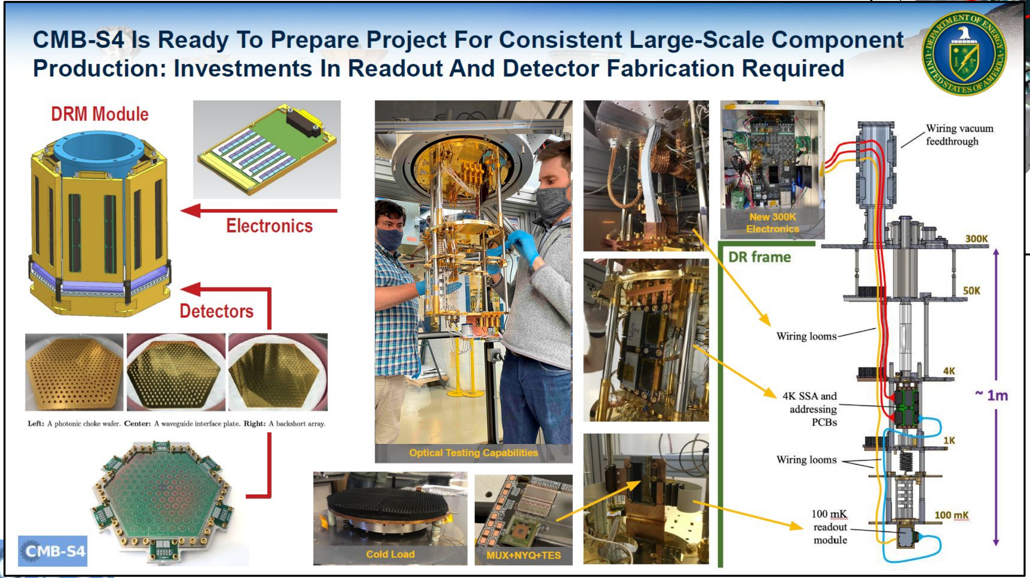
NREL *Transforming ENERGY*

Ian Baring-Gould (wind modeling)
Nate Blair (economics)
Xiangkun Li (system optimization)
Dan Olis (system optimization)
Silvana Ovaitt (solar modeling)

Technical Development

Substantial progress on designs and prototypes, working with and building on the experience of BICEP, SPT, SO, and other CMB experiments.





The experiment technology is well in hand. The focus is now on scaling up by an order of magnitude with respect to previous CMB experiments.

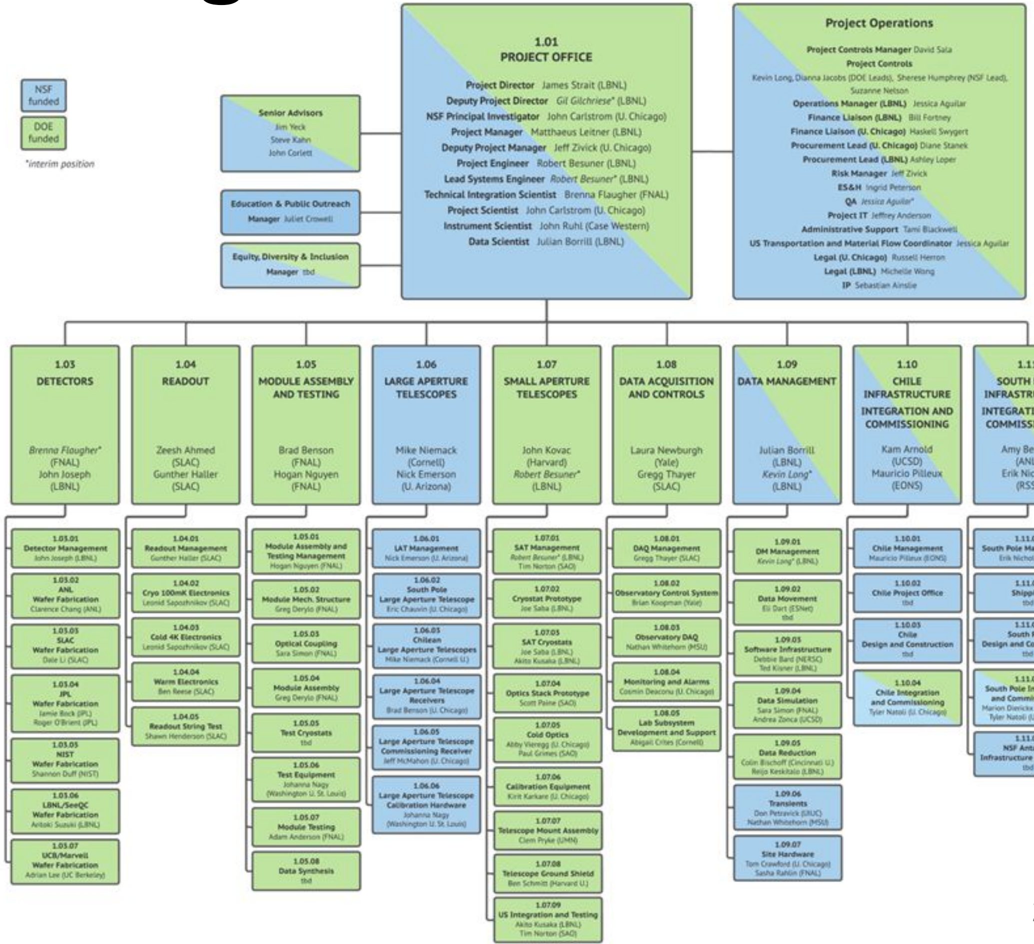
CMB-S4 Project Management

DOE CD-0 (Mission Need) was approved in 2019.

DOE selected LBNL as the lead lab in 2020, with the University of Chicago as the NSF lead institution.

A unified Project Office has been established and a full organizational structure is in place.

This is a U.S.-led project. There are discussion with several countries regarding potential contributions.

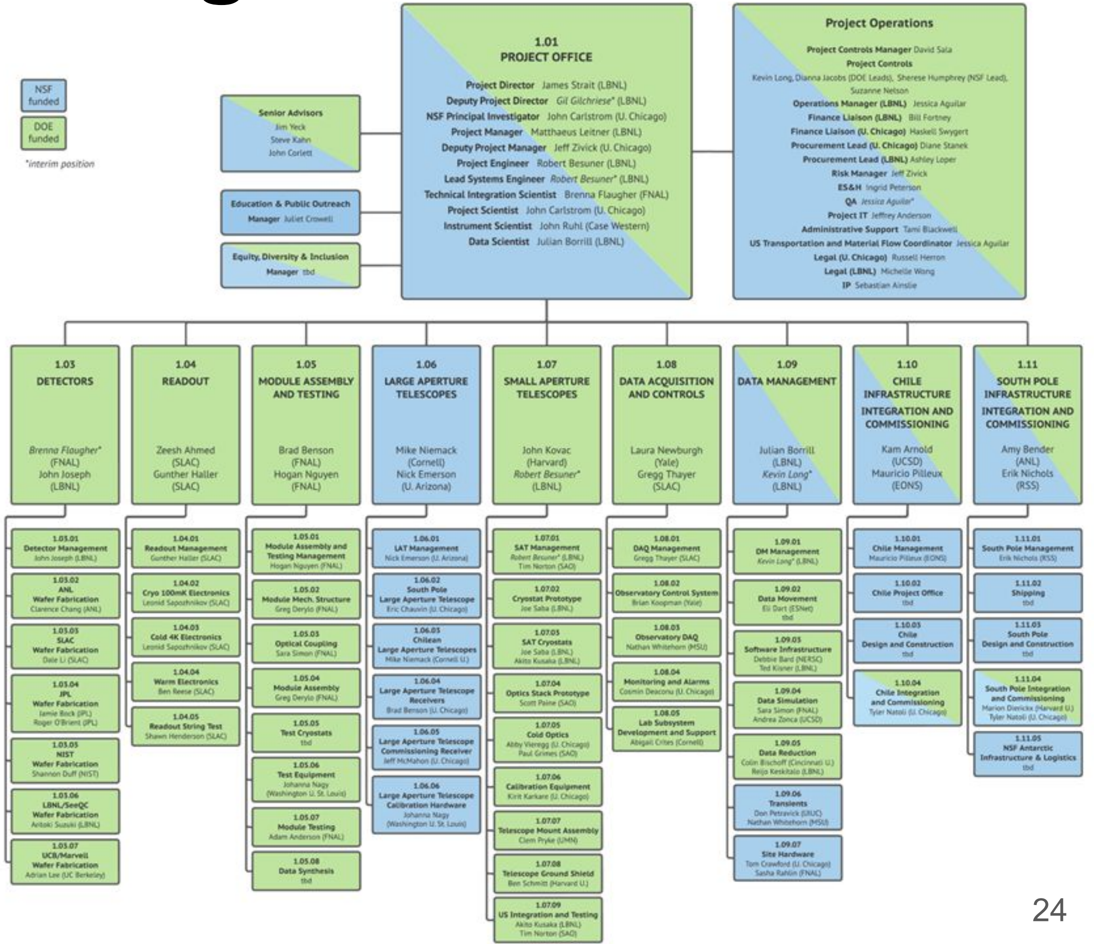


CMB-S4 Project Management

Accomplished management and CMB instrument scientists fill key positions.

The Project Organization personnel are drawn mostly from members of the CMB-S4 Science Collaboration.

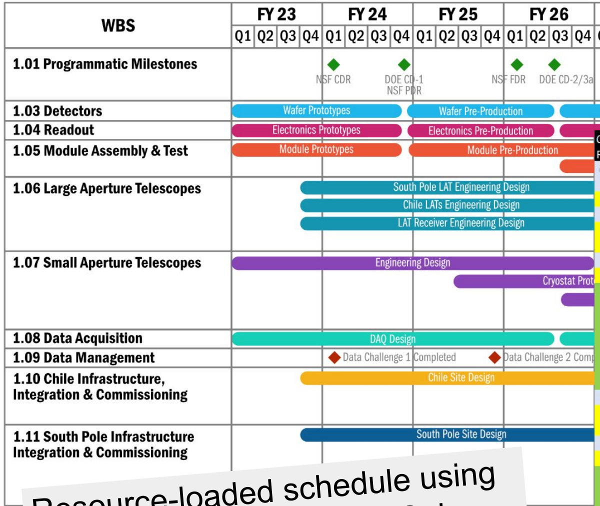
The Collaboration and the Project are working extremely well together.



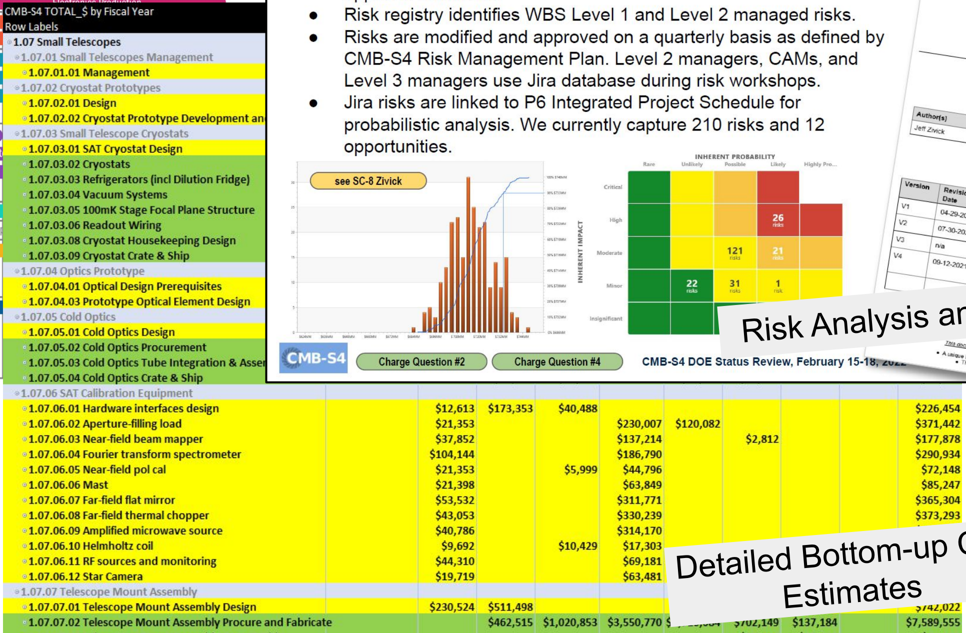
Berkeley Lab · The University of Chicago · Case Western Reserve University · UC San Diego · Argonne National Laboratory · Jet Propulsion Laboratory, California Institute of Technology · Cornell University · SLAC · The University of Arizona · Michigan State University · Fermilab · Washington University in St. Louis · Berkeley, University of California · University of Minnesota · Harvard University · Yale University · Caltech · NIST, National Institute of Standards and Technology · University of Illinois Urbana-Champaign · Center for Astrophysics, Harvard & Smithsonian

Mature Project Planning

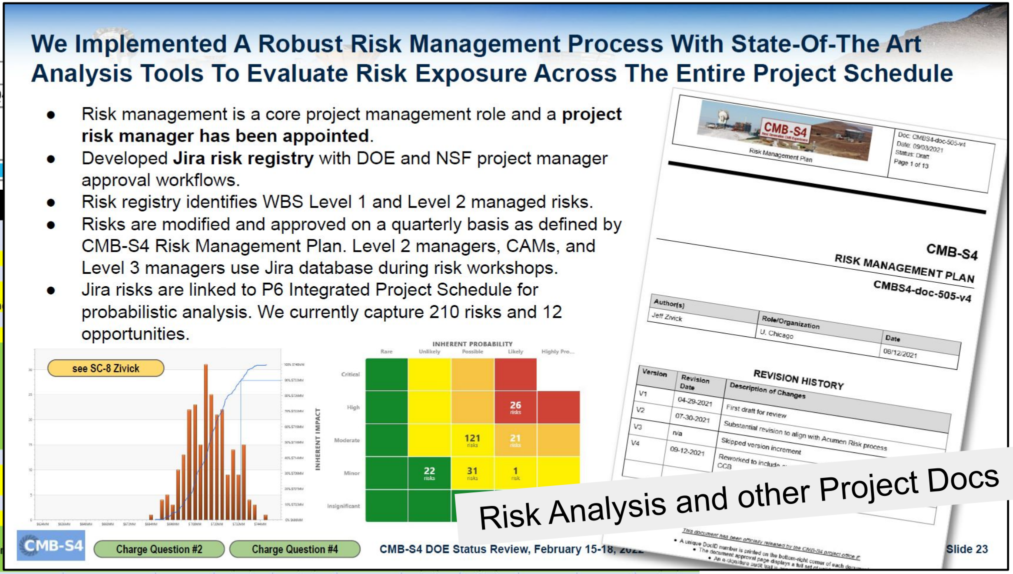
Project planning and documentation are well-advanced and are approaching a CDR / CD-1 level of readiness.



Resource-loaded schedule using Primavera P6 and Deltek Cobra

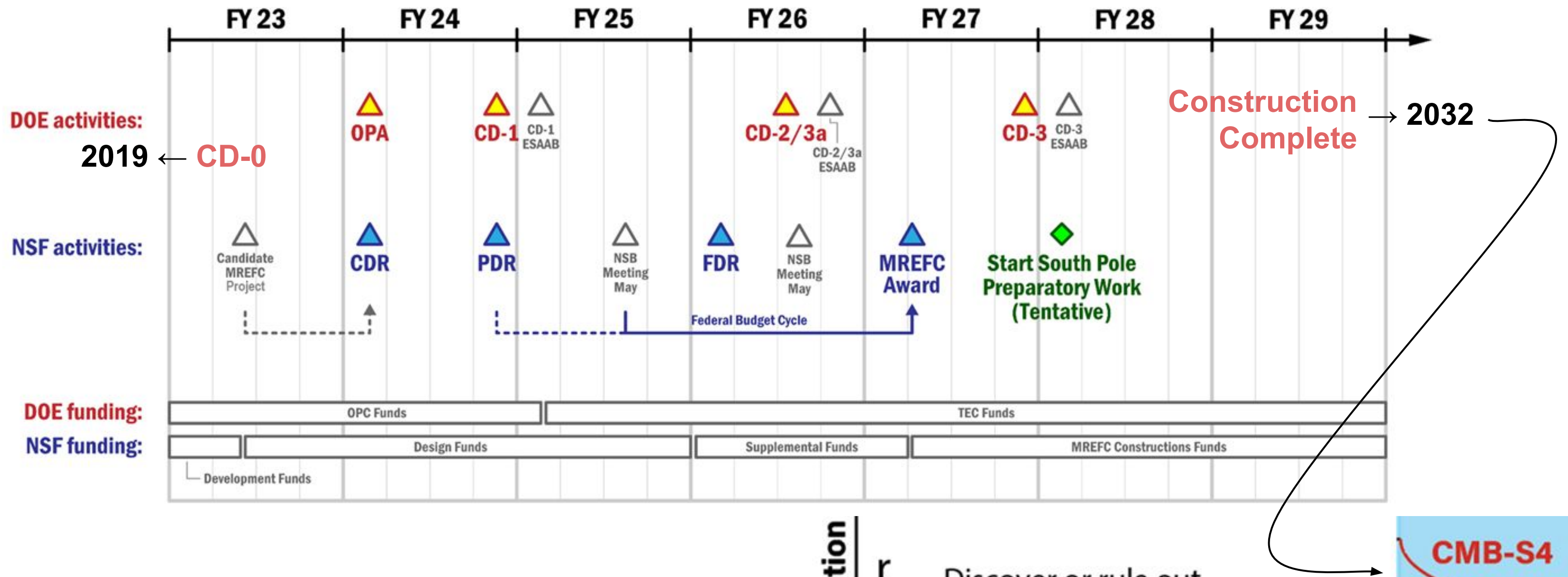


Detailed Bottom-up Cost Estimates

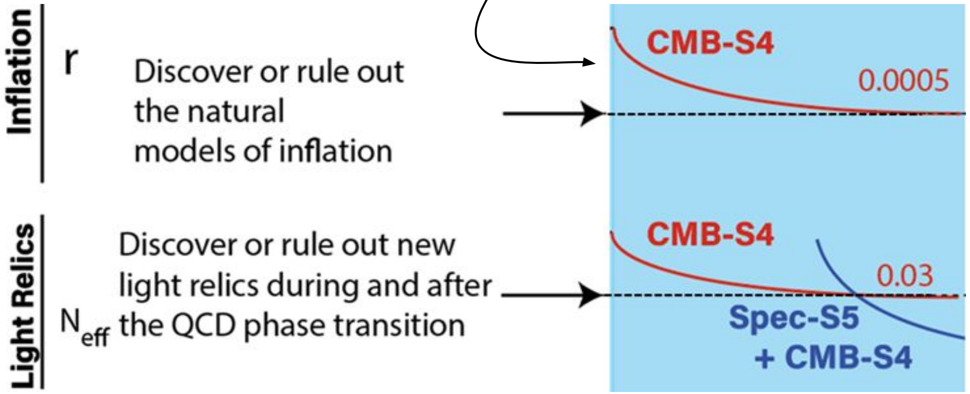


Risk Analysis and other Project Docs

CMB-S4 Project Timeline



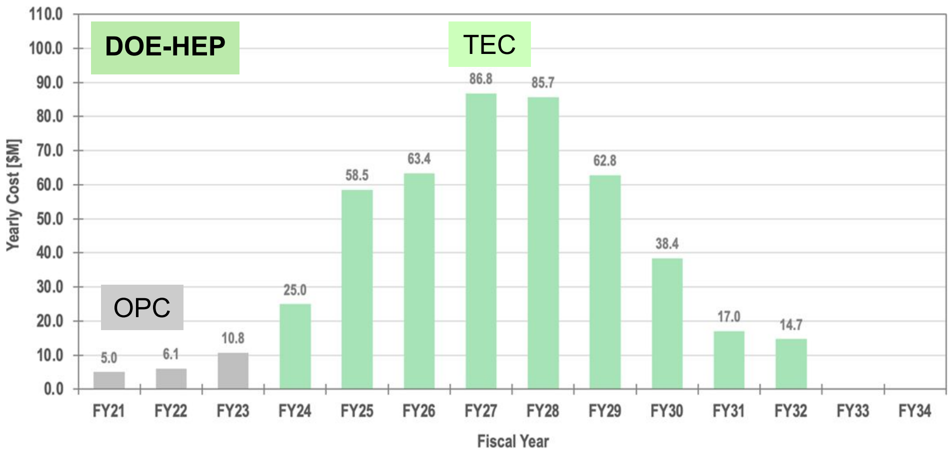
- Forecast 7-9 years observing time to reach inflation goal with CMB-S4 alone. Could be shortened by ~1.5 years by combining with BICEP data.
- All other science goals are reached in 7 years.

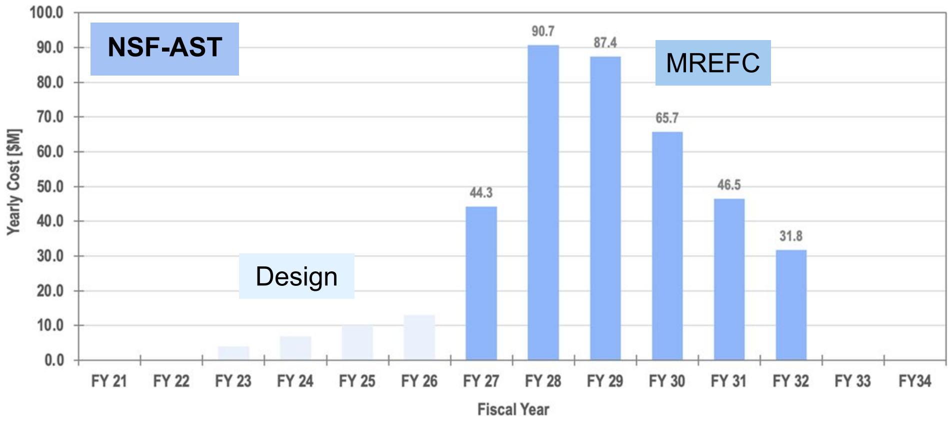


CMB-S4 Cost Estimates and Profiles

Bottom-up cost estimate including direct and indirect costs, escalation and contingency

	DOE-HEP (TPC)	NSF-AST (MREFC)
1.01 Project Management & Systems Engineering	$ 68.4M	$ 16.6M
1.03 Detectors	$ 58.6M	
1.04 Readout	$ 62.8M	
1.05 Module Assembly and Test	$ 36.5M	
1.06 Large Aperture Telescope (LAT) and Receivers		$ 97.7M
1.07 Small Telescopes	$ 54.9M	
1.08 Observatory Control and Data Acquisition System	$ 17.2M	
1.09 Data Management	$ 33.5M	$ 6.4M
1.10 Chile Site	$ 6.6M	$ 47.9M
1.11 South Pole Site	$ 2.7M	$ 93.2M
SUBTOTAL	**$ 341.2M**	**$ 261.8M**
~40% contingency (developed bottom-up)	$ 133.1M	$ 104.7M
TOTAL DOE OPC+TEC and NSF MREFC Costs	**$ 474.2M**	**$ 366.5M**





Conclusions (I)

- CMB-S4 offers a spectacular opportunity to make transformative discoveries in fundamental physics, cosmology, astrophysics, and astronomy.
- CMB-S4 will build on and dramatically extend the reach of the science done by the Stage 3 experiments: BICEP, SPT, and SO.
- The experiment is designed to fit within the constraints at the South Pole (power, fuel, cargo, people).
- The ground-based CMB-S4 and the Japanese/European satellite LiteBIRD will be strongly complementary, addressing the inflation science with very different techniques and systematic uncertainties.
- CMB-S4 will ensure continued U.S. leadership in ground-based CMB research.

Conclusions (II)

- The design of CMB-S4 is technically advanced and the Project organization and planning are mature. We are ready to go.
- We request that P5:
  - Reaffirm the recommendation of the 2014 P5 report to "Support CMB experiments as part of the core particle physics program."

    and the recommendation of Astro2020 that NSF and DOE "should jointly pursue the design and implementation of … CMB-S4."
  - Endorse the importance of the broad and unique contributions to particle physics to be made by CMB-S4 and support its timely construction and operation.