History & status of CMB-S4

John Carlstrom
(he, him)

CMB-S4 Collaboration Meeting
May 9-13, 2022

Outline

- Context pre-Snowmass 2013
- Snowmass 2013
- Particle Physics Project Prioritization Panel (P5) input and output
- Building the partnership
- Getting the word out; making the case
- Established Collaboration
- Building the Integrated Project Office, CD-0
- DOE lead Lab and NSF lead institution
- Snowmass2021

Context pre-Snowmass 2013

- Previous and ongoing CMB experiments had made enormous progress, both scientific:
  - Establishing the ΛCDM model:
    - TT and EE angular power spectrum with 9+ peaks through the damping tail
    - Lensing B-mode detected at expected level
    - SZ cluster cosmology
    - CMB-lensing from large scale structure
  - Beginning to constrain extensions to the ΛCDM model:
    - Limits on neutrino mass
    - Limits on other light relic particles
  - Closing in on Inflation
    - $n_s < 1$; saturated TT limit on “r”; polarization limits would soon take over

  And technical progress:
  - Proven observing techniques and sites
    - Coalesced on South Pole and Atacama, Chile (SPT, BICEP/Keck, Polarbear, ACT)
  - Detectors
    - Background limited, scalable, superconducting transition-edge-sensor (TES) detectors

Context pre-Snowmass 2013

Ready to take the next bold step

CMB summary talk from pre-Snowmass planning meeting at SLAC (3/8/13)

Inflation-era High Energy Physics and neutrino constraints via CMB measurements

Gearing up for a Stage IV CMB polarization experiment

WARNING

Read before opening

1) This is a quickly assembled talk. Many of the future projections are gross estimates of work in progress, or from someone in the audience during one the sessions, or rumors from experiments.
2) The momentum and excitement of the field is very real and highly addictive.

Context pre-Snowmass 2013

Ready to take the next bold step

CMB summary talk from pre-Snowmass planning meeting at SLAC (3/8/13)

What stages?

- **Stage II: (>1K detector elements)**
  - e.g: EBEX, SPTpol, BICEP2/Keck, Polarbear, ACTpol...
  - already observing (or about to)
- **Stage III: (>10K detector elements)**
  - 10x mapping speed over Stage II (a few in the works, 2015+)
- **Stage IV: (>100K detector elements)**
  - 100x mapping speed over Stage II
  - Baseline: deploy ~2020, observe ~ 5 years

VERY CHALLENGING! – Requires 100k to 500k detectors;
Incredible attention to systematics.
Commensurate increases or more in HPC.

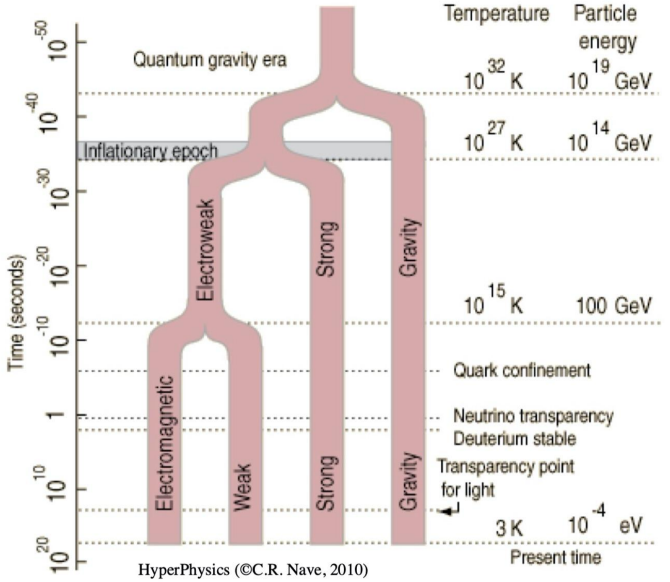
It is a HEP multilab scale project using the highest energy accelerator in the universe!

Context pre-Snowmass 2013

Ready to take the next bold step

CMB summary talk from pre-Snowmass planning meeting at SLAC (3/8/13)

Early universe as an HEP lab



Context pre-Snowmass 2013

Ready to take the next bold step

CMB summary talk from pre-Snowmass planning meeting at SLAC (3/8/13)

Summary

CMB measurements are at the heart of cosmology and fundamental physics.

Stage IV CMB experiment is needed.

It will be extremely challenging, but achievable, with 100x or more increase in detectors from current Stage II, incredible attention to systematics, and commensurate increase in computing.

It is a HEP multilab-scale project!

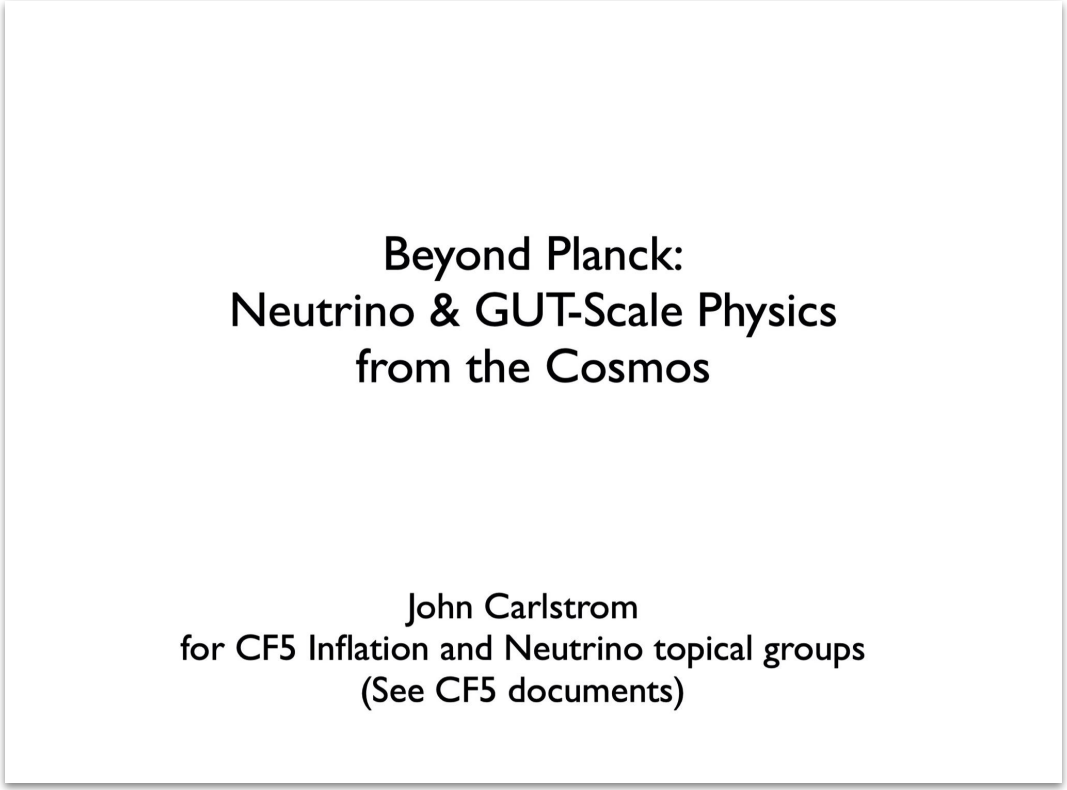
Snowmass meeting Aug 2013, Minnesota

Many meetings on the Cosmicc Frontier science case

Communicated the excitement of the CMB science case for HEP and the momentum of CMB measurements.

Developed CMB-S4 concept

Featured CMB colloquium from Snowmass Minnesota meeting (8/1/13)



Snowmass meeting Aug 2013, Minnesota

Many meetings on the Cosmicc Frontier science case

Communicated the excitement of the CMB science case for HEP and the momentum of CMB measurements.

Developed CMB-S4 concept

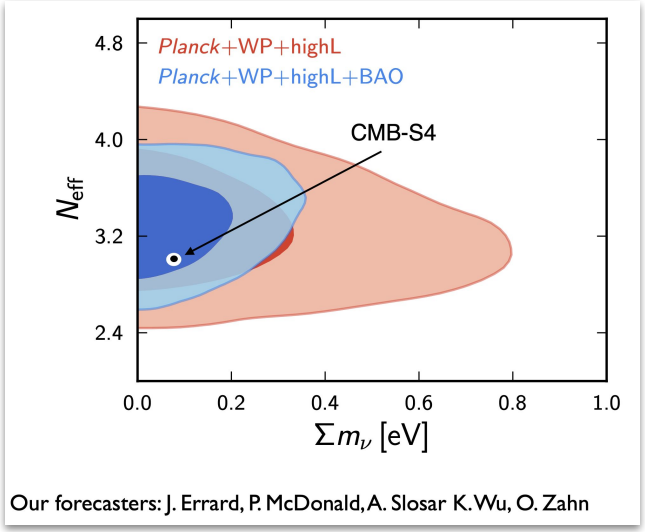
Featured CMB colloquium from Snowmass Minnesota meeting (8/1/13)

National lab and HEP community involvement in CMB-S4

- **CMB-S4 requirements exceed capabilities of University-based experiments**
  - –Focal-plane Arrays and Readout
    - Improved Production Reliability
    - Increased Production Volume and Throughput
      - –500,000 detectors ~ 300 silicon arrays
    - Multiplexed TES Readout
    - Large Cryogenic Optics
  - –Computing Infrastructure and Analysis tools
    - ~10,000 x *Planck* data size (~ 3 TB/day)
  - –Project Organization/Management

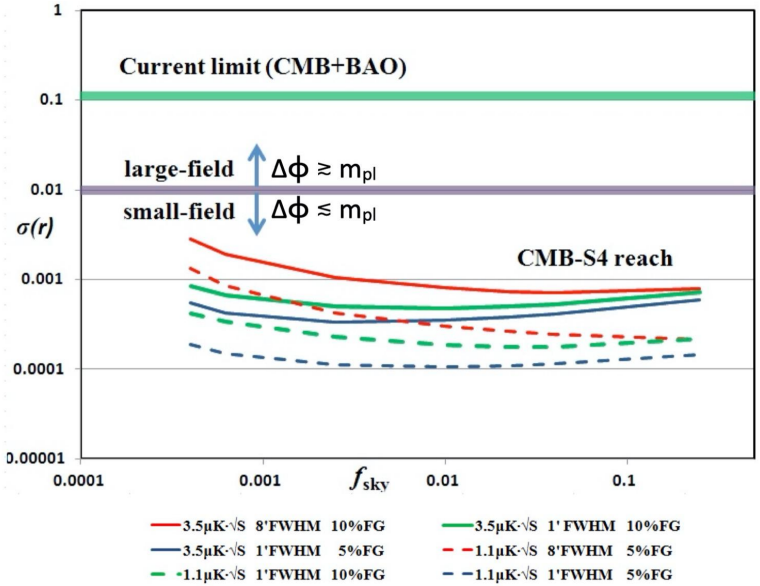
Snowmass meeting Aug 2013, Minnesota

CF CMB colloquium from Snowmass Minnesota meeting (8/1/13)



Our forecasters: J. Errard, P. McDonald, A. Slosar K. Wu, O. Zahn

Inflation projection for CMB-S4



Snowmass meeting Aug 2013, Minnesota

Many meetings on the Cosmicc Frontier science case

Communicated the excitement of the CMB science case for HEP and the momentum of CMB measurements.

Developed CMB-S4 concept

Featured CMB colloquium from Snowmass Minnesota meeting (8/1/13)

Summary

CMB measurements are at the heart of cosmology and fundamental physics.

Stage IV CMB experiment is needed.

It will be challenging, but achievable, with 100x or more increase in detectors from current Stage II, incredible attention to systematics, and commensurate increase in computing.

It is a HEP multilab-scale project!

Influential Snowmass CMB / CMB-S4 papers

Community CMB Snowmass HEP Science papers

Including appendix with CMB-S4 concept

Inflation Physics from the Cosmic Microwave Background and Large Scale Structure

Topical Conveners: J.E. Carlstrom, A.T. Lee

Executive Summary

arXiv:submit/0872081 [astro-ph.CO] 19 Dec 2013

Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure

Topical Conveners: K.N. Abazajian, J.E. Carlstrom, A.T. Lee

arXiv:1309.5383v3 [astro-ph.CO] 30 May 2014

20

Appendix: A Stage-IV CMB experiment, CMB-S4

CMB-S4 is a Stage-IV CMB experiment with two goals: to search for inflationary B-modes and to measure the sum of neutrino masses to an accuracy of 10-15 meV at 68% confidence. It occupies a unique position in the HEP science portfolio as the measurement of CMB polarization is the only method known to probe high-scale physics. As discussed in this document, measurement of CMB polarization provides a powerful and complementary approach to understanding the neutrino masses. The Stage IV CMB-S4 experiment is the logical next step for the U.S. world-leading ground-based CMB program. It will provide the order of magnitude increase in sensitivity required to reach the goal of $\sigma(\Sigma m_\nu) = 16$meV (when combined with data from DESI) and an uncertainty in the tensor to scalar ratio of $\sigma(r) = 0.001$.

To achieve these goals, CMB-S4 will observe 50% of the sky to the unprecedented noise level of $\leq 1\mu$K per arcminute pixel with an angular resolution of ≤ 3 arcminutes. At higher angular resolutions the sensitivity of CMB-S4 to secondary CMB anisotropy would greatly expand its science reach, e.g., through probing Dark Energy and Σm_ν through Sunyaev-Zel'dovich (SZ) cluster cosmology. Reaching noise levels of $\leq 1\mu$K-arcminute is an ambitious undertaking requiring of order 500,000 background limited detectors on the sky with broad spectral coverage over 40 - 240 GHz, and integrating for several years. The detectors would be distributed across multiple platforms at two or more sites to provide large sky coverage and optimized optical throughput. Thus, realizing CMB-S4 requires reshaping the HEP CMB program from its current state of fragmented small efforts into a coherent well-supported experimental program.

Detector Technology for CMB-S4

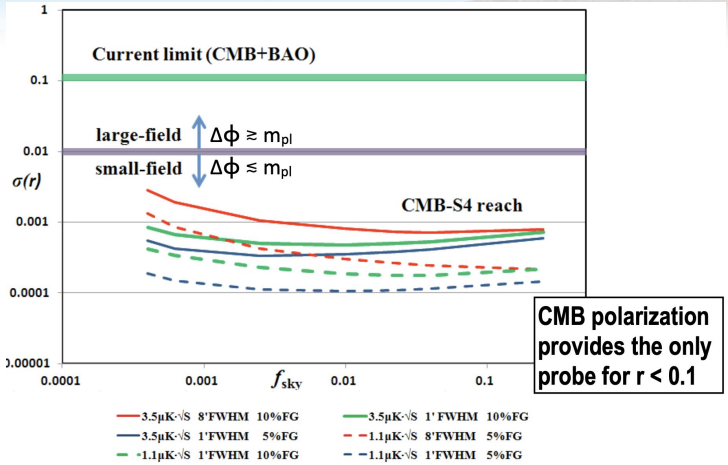
The technical requirements for CMB-S4 are dictated by the fundamental limitations of CMB measurements. Specifically, all competitive CMB detectors are sensitivity-limited where the dominant noise in an individual detector element comes from shot noise arising from the arrival time of the photons. Thus, achieving the required CMB-S4 sensitivity requires increasing the number of detected modes, which is straightforward to achieve by increasing the number of detectors (see Fig. 6). CMB-S4 will have 500 times more detectors than the current state-of-the-art Stage II experiments, 30 times more than planned Stage III experiments, making scaling the primary technical challenge of CMB-S4.

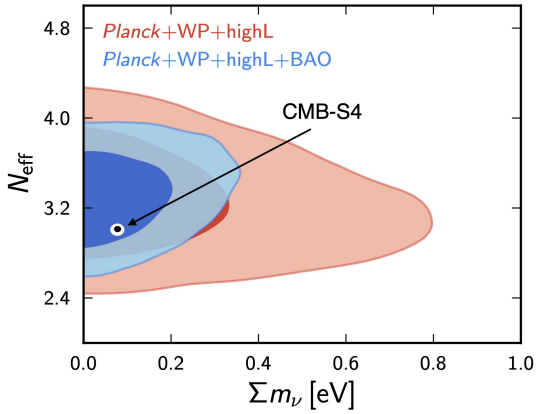
Towards this end, CMB-S4 will utilize Transition Edge Sensor (TES) bolometers as its baseline detector technology[7]. A TES is an ultra-sensitive thermometer consisting of a thin superconducting film weakly heat-sunk to a bath temperature much lower than the superconductor T_c (see Fig. 7, left). The principles of operation are simple to understand. By supplying electrical power to the TES, we can raise the temperature of the sensor so that the film is in the middle of its superconducting-to-normal transition (see Fig. 7, right). If the electrical power is supplied via a voltage bias, a negative feedback loop is established [95]. Small changes to the TES temperature, arising from thermal fluctuations (noise) or changes in the absorbed power from a source (signal), lead to large changes in the TES resistance. The change in resistance creates a canceling effect because increases (or decreases) in temperature produce decreases (or increases) in Joule heating power. This negative electro-thermal feedback is very strong because the transition is very sharp. It linearizes the detector response and expands the detector bandwidth.

P5 - input

December 2013 CMB-S4 Invited to present to P5

- Presentation attended by representatives from the 4 founding CMB experiments
- We stressed the unique and fundamental “must do” HEP science case, supported by the Snowmass papers
- We stressed the readiness of technology, and challenge to scale up
- We stressed the coherent plan of the community
- We stressed CMB-S4 would require the partnership of University and National Laboratories

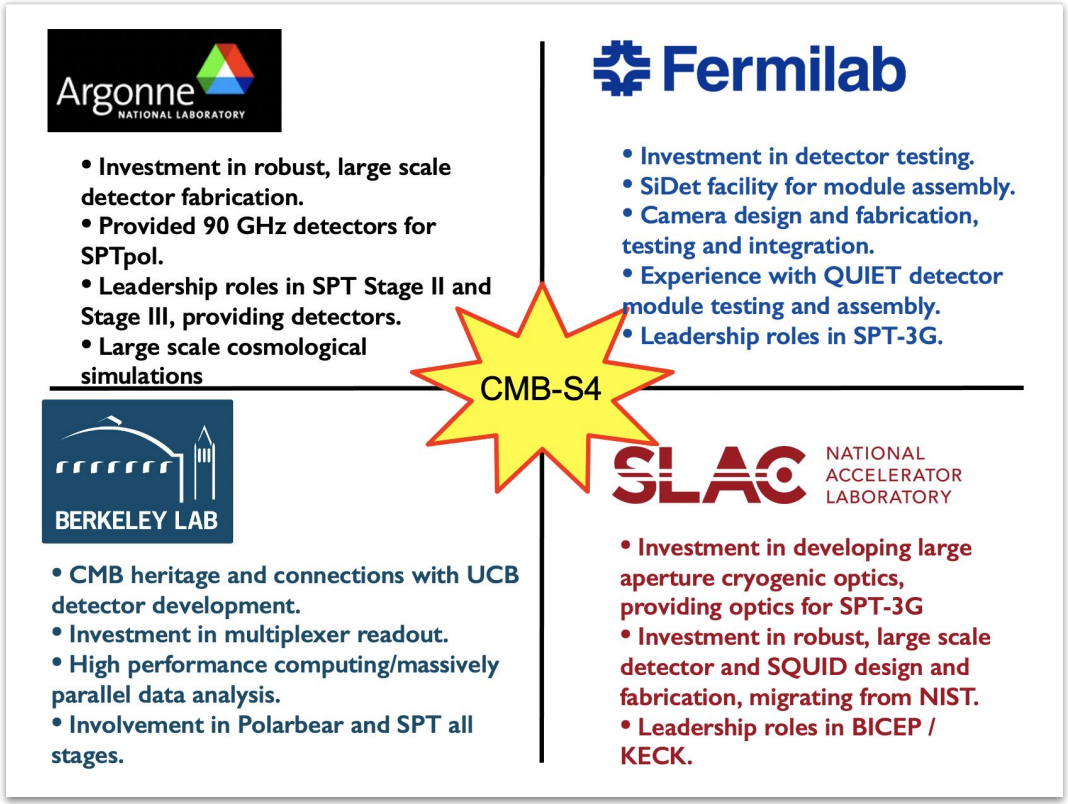




 Our forecasters: J. Errard, P. McDonald, A. Slosar K.Wu, O. Zahn

P5 - input

With DOE Lab involvement from the start



P5 output

2014 P5 recommends CMB-S4

"Increase particle physics funding of CMB research and projects in the context of continued multiagency partnerships."

R18: "Support CMB experiments as part of the core particle physics program. The multidisciplinary nature of the science warrants continued multiagency support."

CMB-S4 recommended under all funding scenarios

Table 1
Summary of Scenarios

Project/Activity	Scenario A	Scenario B	Scenario C	Higgs	Neutrinos	Dark Matter	Cosm. Accel.	The Unknown	Technique (Frontier)
Large Projects									
Muon program: Mu2e, Muon g-2	Y, Mu2e small reprofile needed	Y	Y					✓	I
HL-LHC	Y	Y	Y	✓		✓		✓	E
LBNF + PIP-II	Y, LBNF components delayed relative to Scenario B	Y	Y, enhanced		✓			✓	I,C
ILC	R&D only	R&D, possibly small hardware contributions. See text.	Y	✓		✓		✓	E
NuSTORM	N	N	N		✓				I
RADAR	N	N	N		✓				I
Medium Projects									
LSST	Y	Y	Y		✓		✓		C
DM G2	Y	Y	Y			✓			C
Small Projects Portfolio	Y	Y	Y		✓	✓	✓	✓	All
Accelerator R&D and Test Facilities	Y, reduced	Y, some reductions with redirection to PIP-II development	Y, enhanced	✓	✓	✓		✓	E,I
CMB-S4	Y	Y	Y		✓		✓		C
DM G3	Y, reduced	Y	Y			✓			C
PINGU	Further development of concept encouraged				✓	✓			C
ORKA	N	N	N					✓	I
MAP	N	N	N	✓	✓	✓		✓	E,I
CHIPS	N	N	N		✓				I
LAr1	N	N	N		✓				I
Additional Small Projects (beyond the Small Projects Portfolio above)									
DESI	N	Y	Y		✓		✓		C
Short Baseline Neutrino Portfolio	Y	Y	Y		✓				I

Post P5: we really got busy…

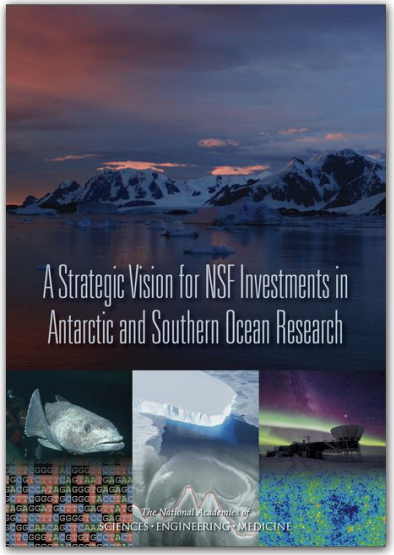
Building the Partnership

- Began twice yearly CMB-S4 Collaboration mtgs
- DOE HEP Cosmic Frontier CMB Cosmic Vision group (1st one); regular meetings with OHEP, many reports and OHEP briefings
- Began DOE / NSF Joint Oversight Group meetings

U. Minnesota Jan 16, 2015

Building support and national recommendations

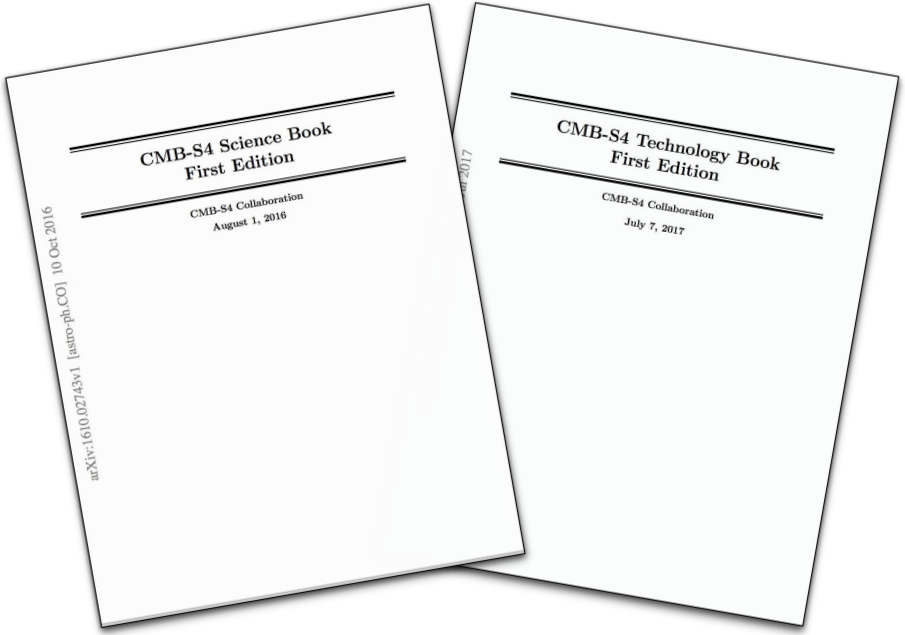
- Astronomy and Astrophysics Advisory Committee briefings and rec's; e.g., 2016 AAAC report: "We encourage DOE, NSF, and the university community to continue working toward a plan for a future (Stage 4) ground based CMB experiment"
- 2015 NAS/NRC report,: *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research* recommended CMB as one of three strategic priorities, specifically calling out CMB-S4



Post P5: we really got busy…

Getting the work out; making our case

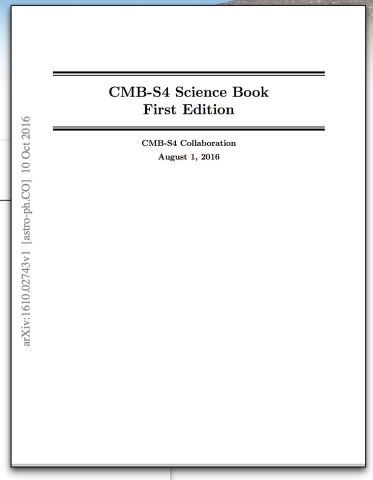
- CMB-S4 Science Book, First edition (220 pages, >1100 citations):
  - Inflation
  - Neutrinos
  - Light Relics
  - Dark Matter
  - Dark Energy
  - CMB lensing
  - Data Analysis, Simulations & Forecasting
- CMB-S4 Technology Book, First edition (184 pages):
  - Telescope Design
  - Receiver Optics
  - Focal Plane Optical Coupling
  - Focal Plane Sensors and Readout



Science Goals

Threshold crossing science goals.

Goals have remained consistent; their definition has been refined and flowed down to measurement requirements



1.4 The Road from Stage 3 to Stage 4

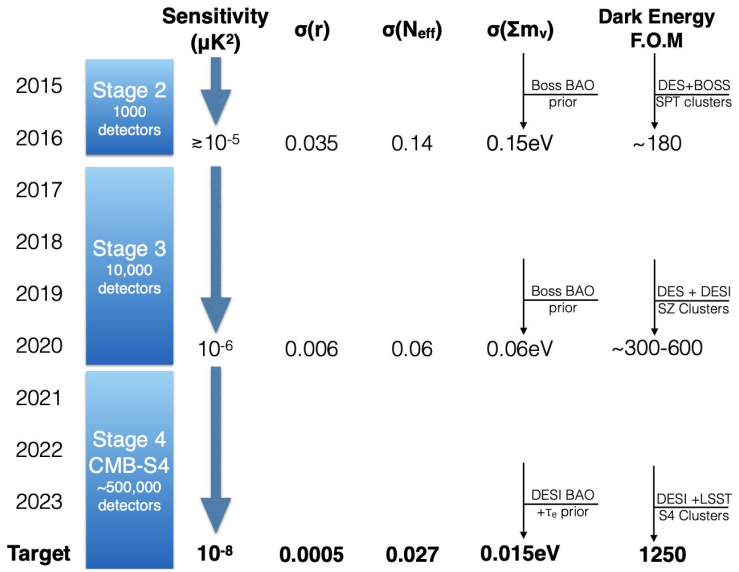
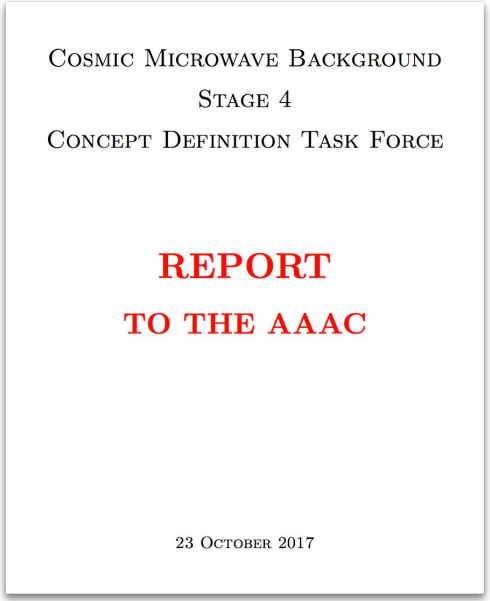


Figure 3. *Schematic timeline showing the expected increase in sensitivity (μK^2) and the corresponding improvement for a few of the key cosmological parameters for Stage-3, along with the threshold-crossing aspirational goals targeted for CMB-S4.*

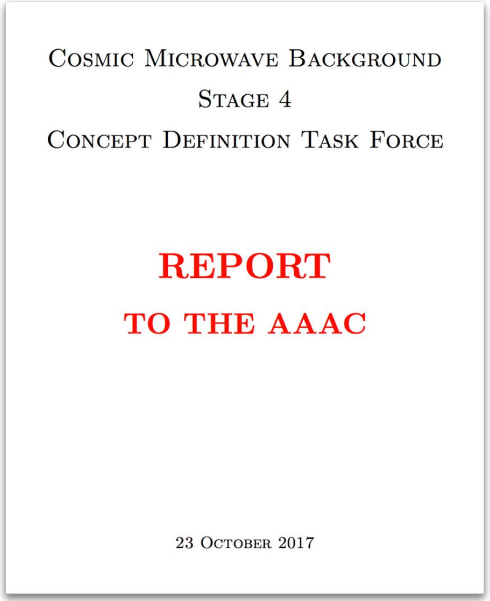
Concept Definition Task Force

- Fall 2016: DOE OHEP and NSF AST, PHY & OPP requested that the AAAC establish a Cosmic Microwave Background Stage 4 Concept Definition Task force (CMB-S4 CDT) as a subcommittee in order to develop a concept for a CMB-S4 experiment.
- One year later the resulting CDT report was delivered and was unanimously and enthusiastically accepted by the AAAC in Oct 2017



Concept Definition Task Force

- Three Science Priorities
  - Inflation: $r < 0.001$ (95% conf.) or detection for $r > 0.003$
  - Light relics: constrain $\Delta N_{eff} < 0.06$ (95% conf.)
  - Legacy Cosmology and Astrophysics Survey
- Measurement Challenges
  - Many frequencies to characterize foregrounds
  - Control of polarization systematics
- Strawperson Concept
  - Multiple sites, telescopes, cameras, apertures.
  - One collaboration, one project, one dataset.
- South Pole: exceptional atmosphere, ultra-deep field
- Atacama: wide area sky coverage



Post CDT report: got even busier...

Set up preProject Development Group (directed by Jim Yeck) to:

- Facilitate communications with both DOE and NSF.
- Facilitate securing CD-0 (mission need) by DOE.
- Supports collaboration efforts to prepare plans and documents for the Decadal Survey, e.g., the reference design report.
- Assist with the formation of a structured R&D program based on identified priorities for risk mitigation, performance improvement, and cost savings, and work with the agencies to secure the needed funding support.
- Propose options for project implementation strategies and explore the implications for required funding profiles, agency coordination, external agreements and institutional support.
- Begin annual Project Reviews; soon to ramp up to many reviews…

Post CDT report: got even busier..

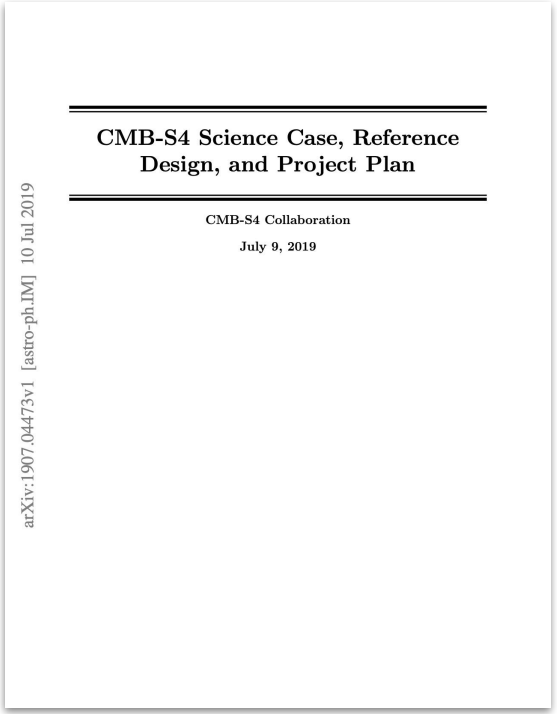
Established the formal Collaboration

- Interim Collaboration Coordination Committee elected by the community to guide the establishment of collaboration
- Bylaws drafted and ratified in March 2018, establishing official collaboration
- Election of Collaboration officers and Governing Board completed by July 1, 2018, including co-Spokepersons

Post CDT report: got even busier..

Astro2020 preparations (2019):

- Decadal Survey Report finished and posted *CMB-S4 Science Case, Reference Design, and Project Plan* (287 pages, 516 references, 340 citations)
  Included transients in expanded science case for NSF Astronomy
- CMB-S4 Decadal Input White Paper submitted and posted
- Response to the Astro2020 RFI, and the many follow-up questions and presentation to Astro2020 in Feb 2020



Input to Astro2020

Why CMB-S4?
To make transformational advances

- CMB-S4 will provide unique astrophysical information in areas ranging from the reionization of the Universe, to the role of baryonic feedback in structure and galaxy formation. It will provide a unique and unprecedented legacy catalog of high-redshift clusters and galaxies, and open up the mm-wave transient universe for Multi-Messenger Astrophysics.
- CMB-S4 will cross critical thresholds in key cosmological parameters in the search for primordial gravitational waves and relic particles.
- These goals drive the experimental design and cannot be met with any precursor experiments.
- CMB-S4 instrument and survey strategy are designed to be an extremely powerful complement to other cosmological surveys— breaking degeneracies and increasing sensitivity —to investigate neutrino properties, dark energy, and dark matter through measuring the growth of structure in the universe.

CMB-S4 *Irvine, February 4th 2020* 4

Input to Astro2020

What would it take?

- Tenfold increase in sensitivity over Stage 3 experiments, to cross critical science thresholds.
- O(500,000) detectors spanning 20 - 270 GHz using multiple telescopes, large and small, at Chile and South Pole to map most of the sky, as well as deep targeted fields.
- Broad participation of the CMB community, including those in the existing CMB experiments (e.g., ACT, BICEP/Keck, CLASS, POLARBEAR/Simons Array, Simons Observatory & SPT), the National Labs and the High Energy Physics community.

Scale of CMB-S4 exceeds capabilities of the University CMB groups.

→ Partnership of CMB community and National labs will do it.

CMB-S4 *Irvine, February 4th 2020* 5

Post CDT report: got even busier...

- 2019: Achieved DOE Critical Decision-0, for a Major Item of Equipment (MIE) project
- 2019: Awarded NSF MSRI-RI Design and Development grant to help us work toward a Major Research Equipment & Facilities Construction (MREFC) project; UChicago lead.
- 2020: DOE OHEP selects LBNL as lead lab for CMB-S4 Integrated Project
- 2020: DOE Agency Status Review
- 2021: NSF MSRI-1 Design Development mid-term review
- 2021: Astro2020 recommendation
- 2021: Directors Review
- 2022: Complete draft of the Preliminary Baseline Design Report (PBDR) (282 pages, 88 figures, 361 references)

Astro2020

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)."

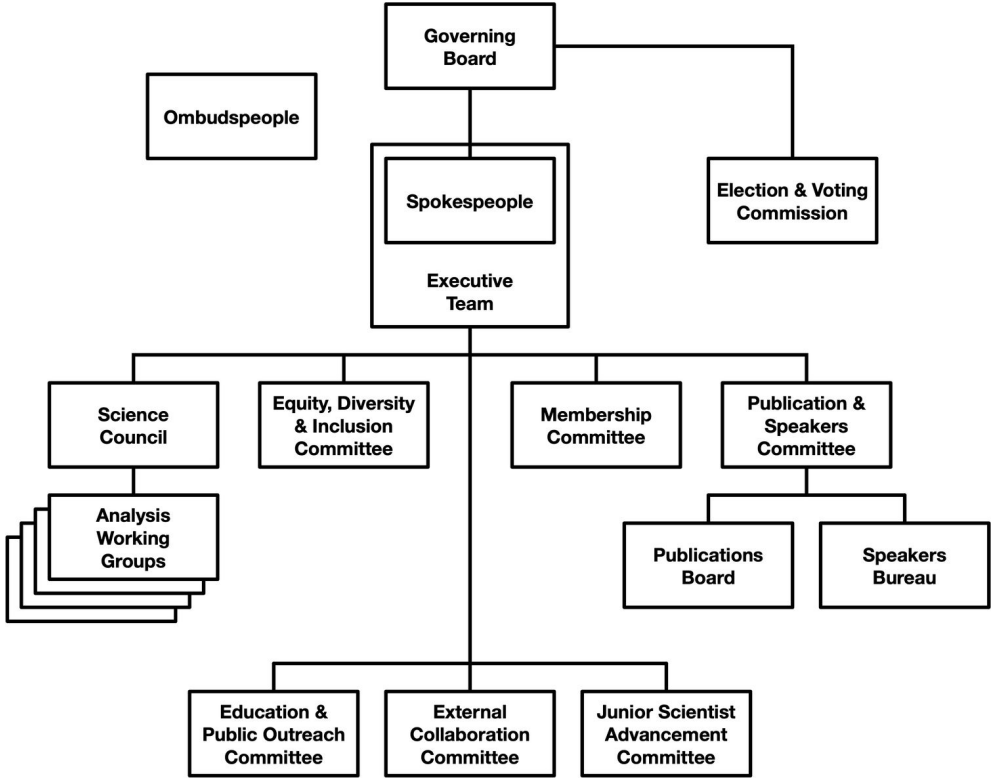
Astro2020 is the final key recommendation, following those in the 2014 P5 report *Building for Discovery* and the 2015 NAS report *A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research* and its recent mid-term assessment.

Collaboration Status

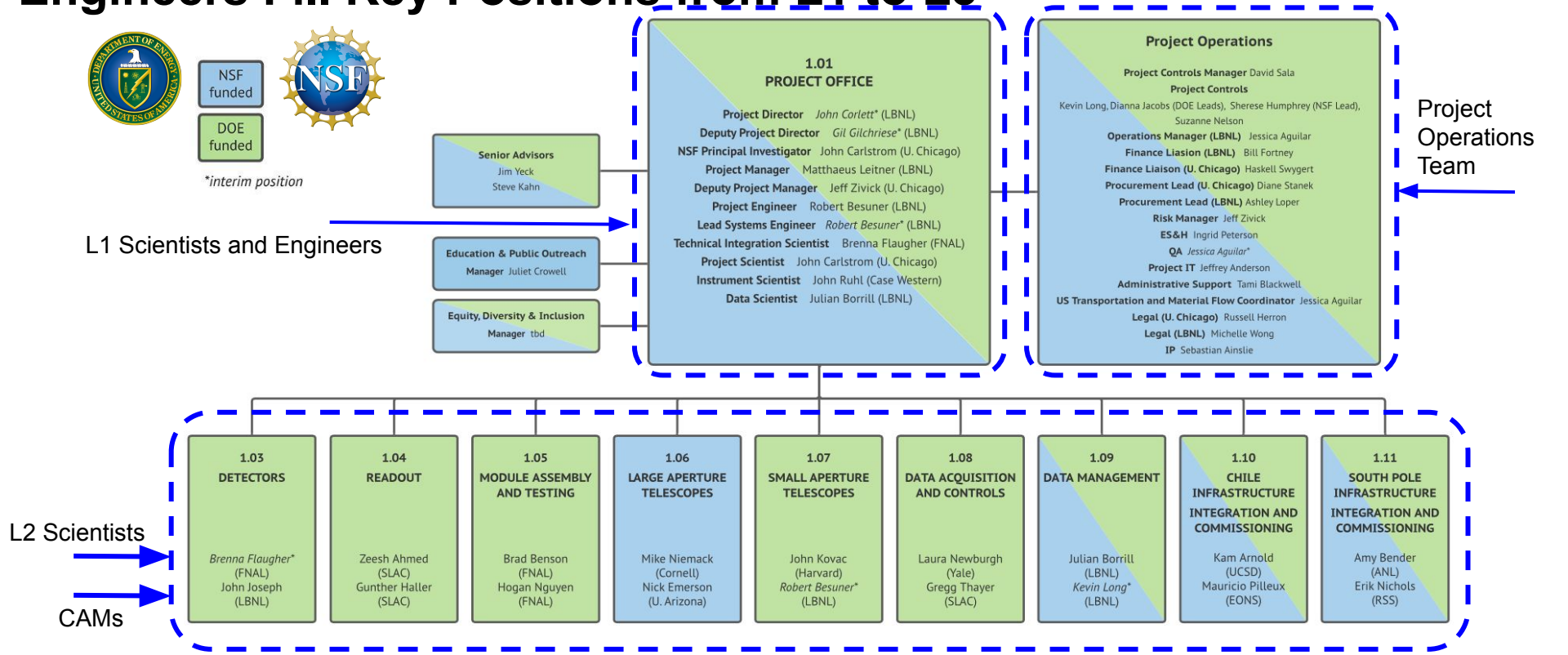
There are 394 Members
- 330 Collaboration
- 121 Project

spanning
- 19 countries
- 26 US States
- 114 Institutions

132 collaboration roles are held by 83 individuals (see governance wiki page)



Accomplished Management, CMB, and Telescope Scientists and Engineers Fill Key Positions from L1 to L3

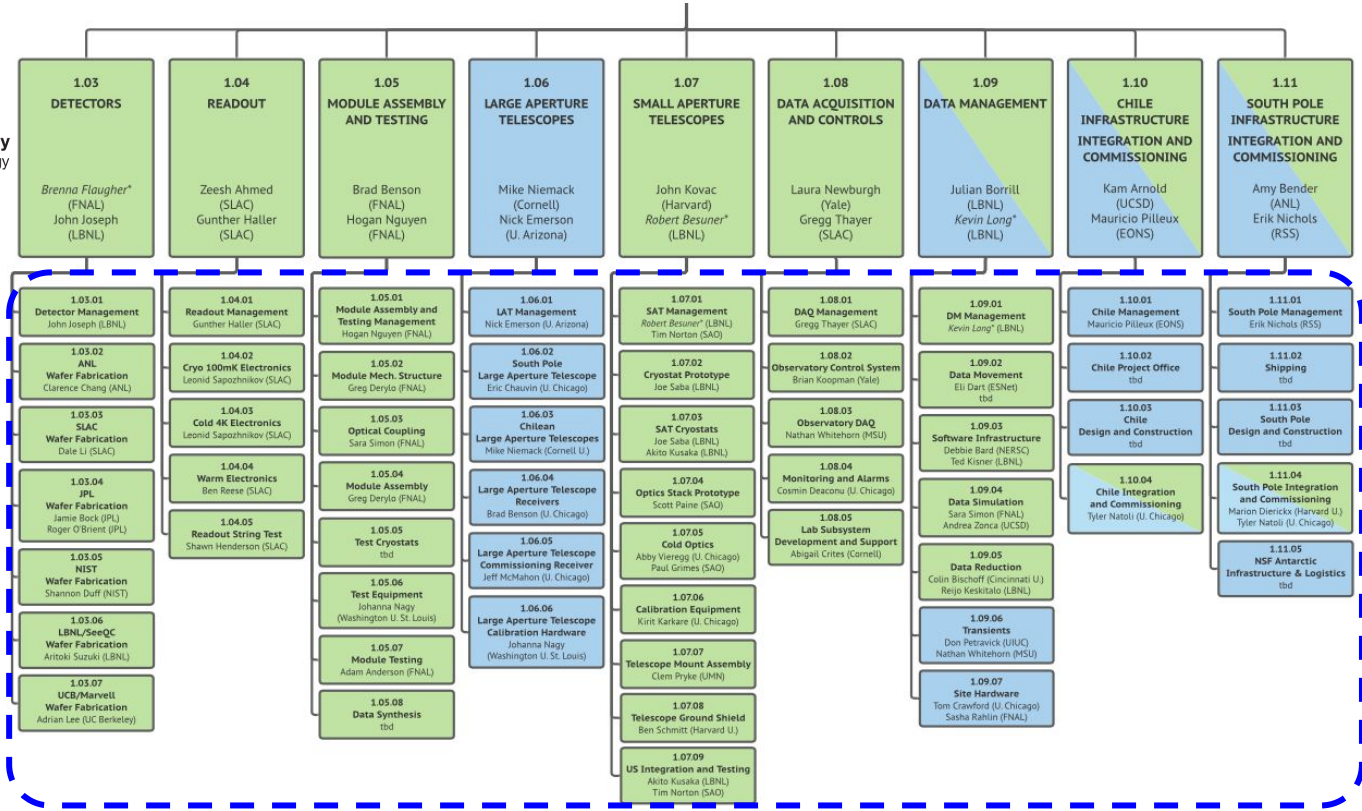


L2s are responsible for preparing designs and plans, and managing the cost and schedule of their subsystems

CMB-S4 Organization Is Developed To The Lowest Technical Levels

Project Organization Is Distributed Across National Laboratories and Universities

BERKELEY LAB
THE UNIVERSITY OF CHICAGO
Argonne NATIONAL LABORATORY
Jet Propulsion Laboratory, California Institute of Technology
THE UNIVERSITY OF ARIZONA
MICHIGAN STATE UNIVERSITY
Berkeley UNIVERSITY OF CALIFORNIA
UNIVERSITY OF MINNESOTA
Caltech
NIST National Institute of Standards and Technology
CASE WESTERN RESERVE UNIVERSITY EST. 1826
UC San Diego
Cornell University
SLAC
Fermilab
Washington University in St. Louis
HARVARD UNIVERSITY
Yale University
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN



L3 Technical Leads

Snowmass2021

We need to ensure that CMB-S4 is part of the core Cosmic Frontier Program!
It's science case is even stronger now than it was in 2013

Submitted white papers:

- *Snowmass 2021 CMB-S4 White Paper*, arXiv:2203.08024
- *Dark Matter Physics from the CMB-S4 Experiment*, Dvorkin et al., arXiv:2203.07064

- *Inflation: Theory and Observations, arXiv:2203.08128*
- *Cosmic Frontier Cosmic Microwave Background Measurements White Paper,* Chang et al., arXiv:2203.07638
- *Data-Driven Cosmology,* Cyr-Racine et al., arXiv:2203.07946
- *Synergy between Cosmological and Laboratory Searches in Neutrino Physics*, Gerbino et al., arXiv:2203.07377
- *The Physics of Light Relics,* Dvorkin et al., arXiv:2203.07943
- *Enabling Flagship Dark Energy Experiments to Reach their Full Potential*, Newman et al., arXiv:2204.01992

Summary

- CMB-S4 is a great experiment; the science case is even stronger now than in 2013
  - Unique / must do science: accelerated expansion & inflation, light relics and thermal history of the Universe
  - Complementary science: large scale structure cosmological constraints, transients
- CMB-S4 has a strong history with HEP
- CMB-S4 has evolved through several HEP planning processes, leading to CD-0 and a path to CD-1
- CMB-S4 has developed a rich and broad science program, which resulted in extremely strong Astro2020 Decadal Survey recommendation
- CMB-S4 has a strong established Collaboration and Integrated Project Office

CMB-S4 is ready to go. It will have enormous scientific impact and provide a solid foundation for cosmological physics for decades to come