CMB-S4

Presentation to the Astro2020 Radio, Millimeter, and Submillimeter Ground Concepts Panel

Julian Borrill - Collaboration Co-Spokesperson [remote]

John Carlstrom - Collaboration Co-Spokesperson

Jim Yeck - Project Director

CMB-S4

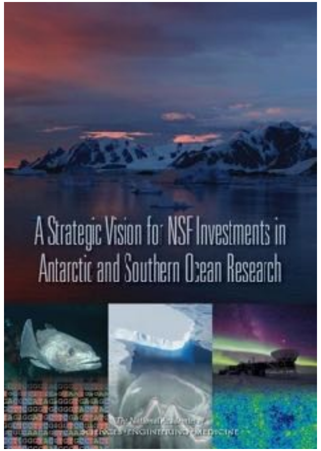
Irvine, February 4th 2020

Outline

- Genesis and Overview of CMB-S4
- Breadth of Astronomy and Astrophysics
  - From the Origin of the Universe to the exploration of the Solar System
- Overview of Instrument
- CMB-S4 Project
  - Organization
  - Project Baseline
  - Annual Review Results
- Summary/Conclusion
- Detailed Responses to Panel Questions

Genesis of CMB-S4

- 2013: during the Snowmass Physics Planning exercise, building on the success of the field, the US CMB community conceived CMB-S4 as the definitive ground-based experiment with sufficient sensitivity to achieve transformative science goals using field-proven technology.
- 2014: recommended by Particle Physics Project Prioritization Panel (P5) under all budget scenarios.
- 2015: one of three strategic priorities for Antarctic Science in the NAS/NRC report “A Strategic Vision for NSF Investments in Antarctic and Southern Ocean Research”
- 2015: start of twice yearly CMB-S4 workshops.



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 <u>cannot be met with any precursor experiments</u>.
- 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.

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.

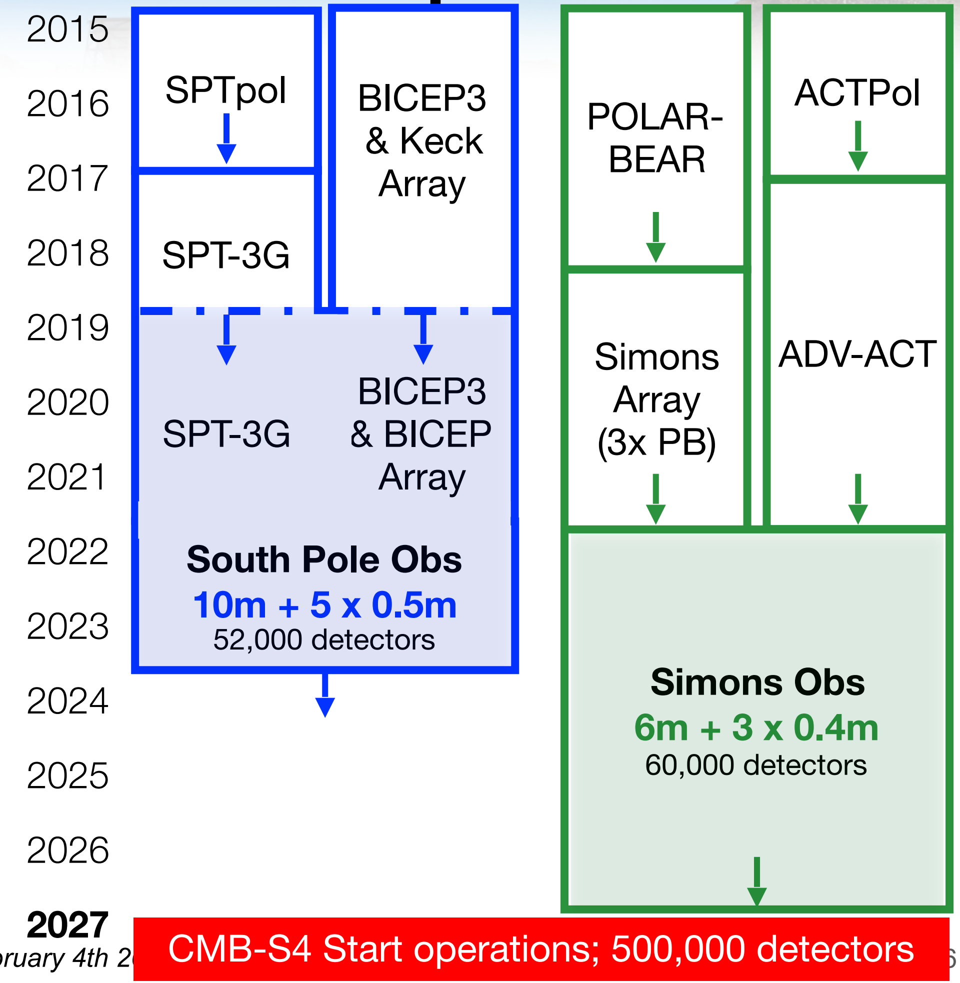
Scale of CMB-S4 exceeds capabilities of the University CMB groups.

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

Evolution of Ground-Based CMB Experiments

Science-driven expansion of capabilities + cost-driven consolidation of teams

- Late 2010s:
  - single-site, single resolution
  - O(10K) detectors
  - ACT, BICEP/Keck, POLARBEAR, SPT, etc
- Early 2020s:
  - single-site, dual-resolution
  - O(50K) detectors
  - Simons Observatory (SO), South Pole Observatory (SPO)
- Late 2020s:
  - dual-site, dual-resolution
  - O(500K) detectors
  - CMB-S4

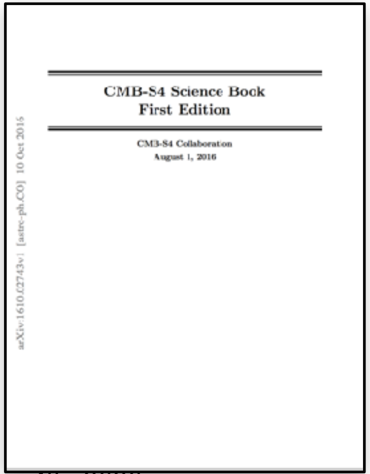


Community Organization

building the partnership

- CMB community brought together twice a year since 2015 for major workshops, alternating venues between universities and DOE labs
- CMB-S4 working groups advance Science and Technology areas, refining CMB-S4 concept
- Produced CMB-S4 Science Book (2016, arXiv:1610.02743)
- Produced CMB-S4 Technology Book (2017, arXiv:1706.02464)

10th CMB-S4 Workshop, UCSD October 2019



CMB-S4 Science Book
First Edition

CMB-S4 Collaboration
August 1, 2016

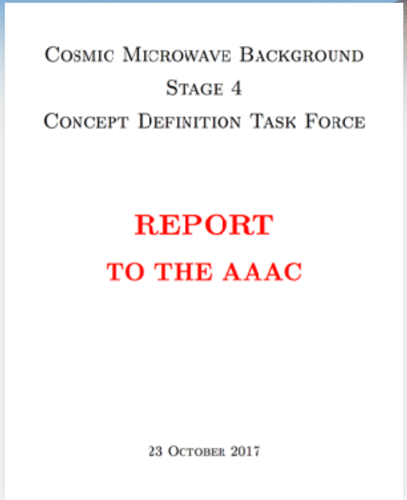
arXiv:1610.02743v1 [astro-ph.CO] 10 Oct 2016

CMB-S4 Science Book

86 authors, 200 pages
630 citations
available at http://cmb-s4.org

2017 NSF & DOE sponsored Concept Definition Task Force

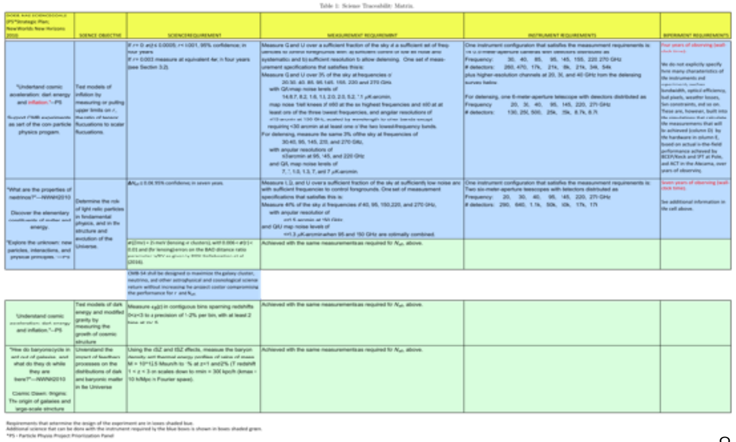
- 21 member task force work for 1 yr to produce CDT report
  - Concept Definition including risks, schedule, and costing
  - Unanimously and enthusiastically accepted by the AAAC
- Three Science Priorities
  - Inflation: $r < 0.001$ (95% conf.) or 5σ detection for $r > 0.003$
  - Light relics: constrain $\Delta N_{eff} < 0.06$ (95% conf.)
  - Legacy Cosmology and Astrophysics Survey
- Measurement Challenges
  - Many frequencies to characterize foregrounds
  - Control of polarization systematics
- Principles
  - One collaboration, one project, one dataset.
  - Two sites:
    - South Pole: ultra-deep field
    - Atacama, Chile: wide area sky coverage


Cosmic Microwave Background
Stage 4
Concept Definition Task Force

REPORT
TO THE AAAC

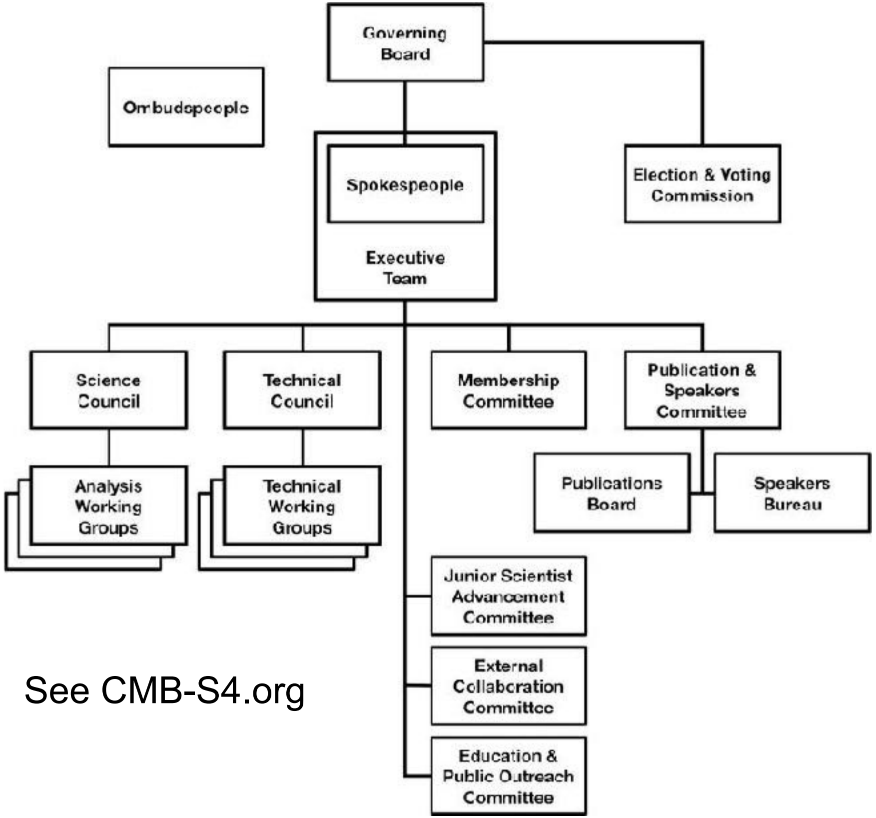
23 October 2017

Science Traceability Matrix



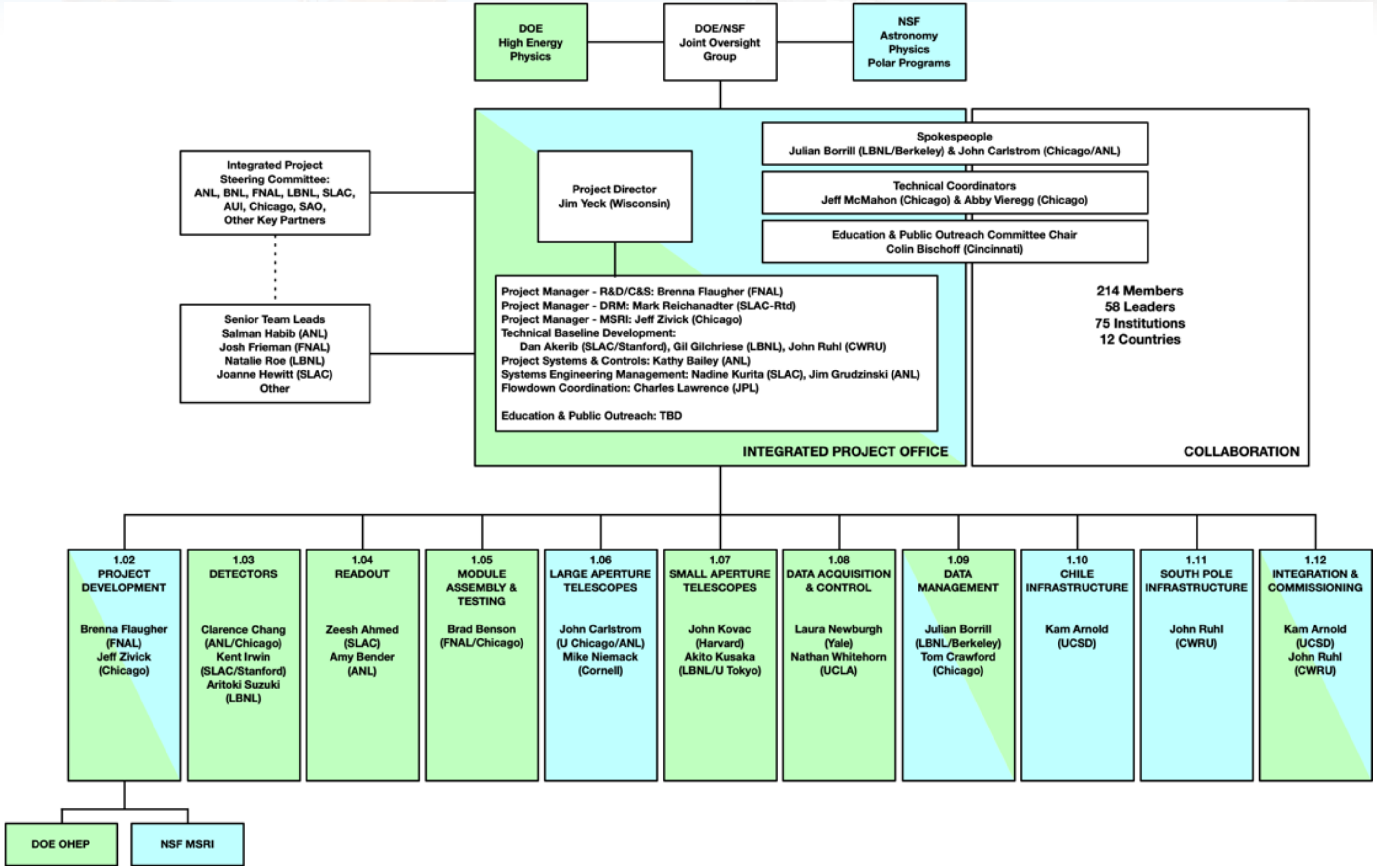
2018 Established CMB-S4 Collaboration

- Interim Collaboration Coordination Committee elected by the community to guide the establishment of collaboration (15 members, co-chairs Carlstrom & Staggs).
- Open working groups drafted bylaws; reviewed by community and ratified.
- Elections held, all posts term-limited.
    - Ensured elected membership to the GB include key stakeholders (including founding 4 experiments), underrepresented groups, and a postdoctoral fellow.



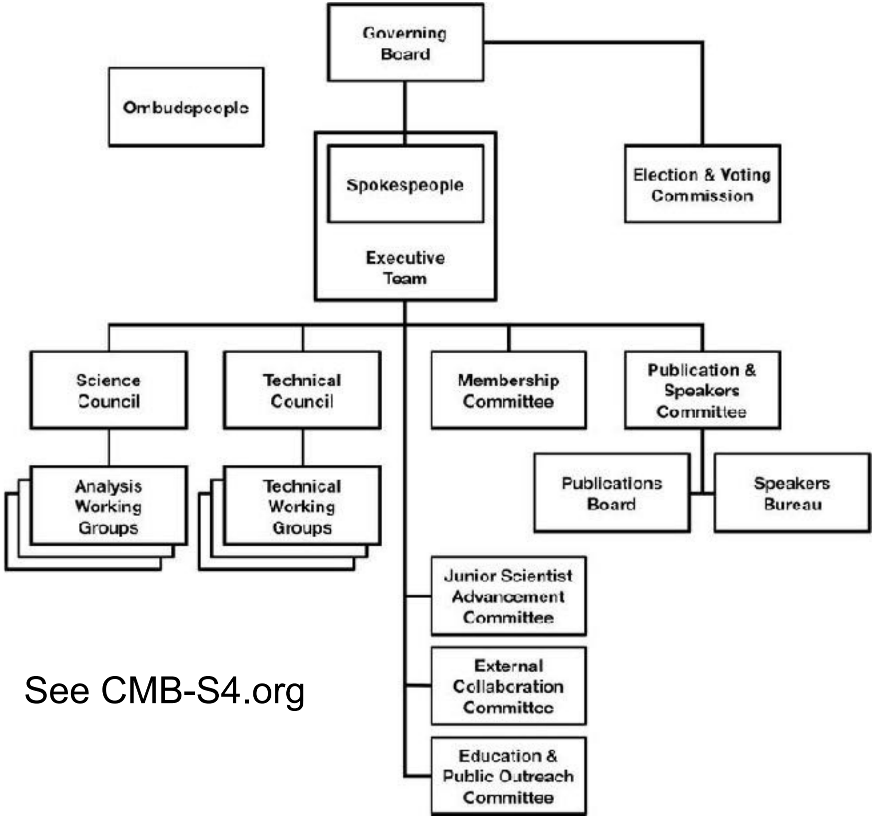
See CMB-S4.org

2018 Established Integrated Project Office



CMB-S4 Collaboration status

- Collaboration overview
  - 217 Members: ~60% SO, ~40% SPO
  - 75 Institutions & 12 Countries
  - 58 members have leadership roles
- Integrated with the Project Office
- Produced *CMB-S4 Science Case, Reference Design, and Project Plan* (DSR, 282 pp. arXiv:1907.04473)
- Provided input to Decadal Survey



See CMB-S4.org

Recent advances and anticipated schedule

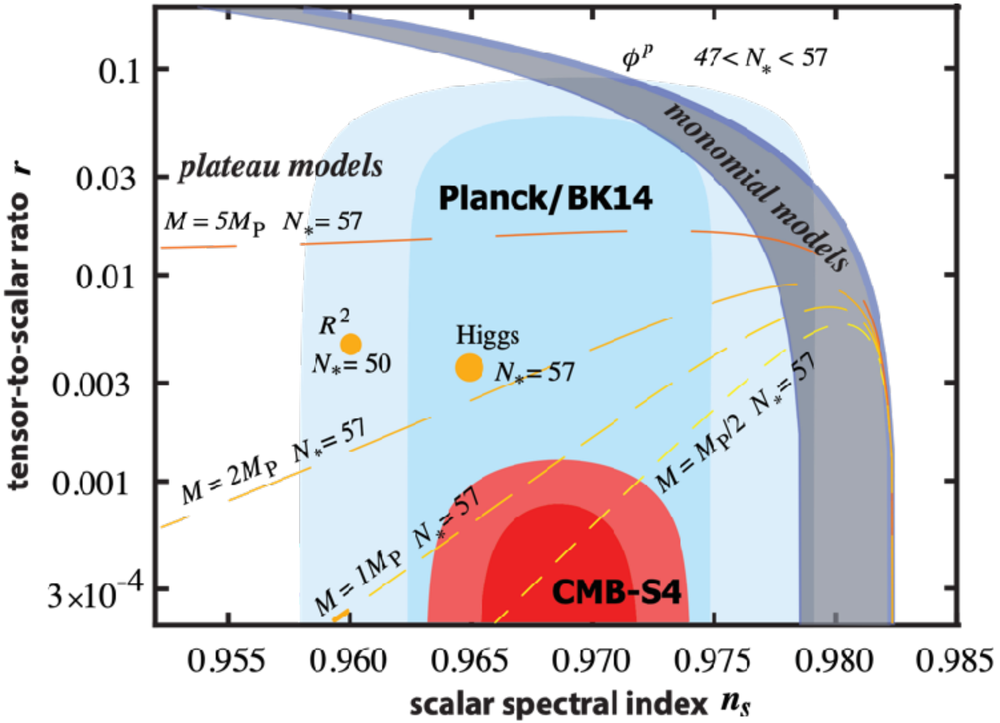
- Recent Major Milestones:
  - July 2019: Achieved DOE Critical Decision CD-0 for a Major Item of Equipment (MIE)
  - Oct 2019: Awarded NSF MSRI-RI Design and Development award to prepare NSF Preliminary Design
- Anticipated schedule:
  - 2020 - DOE lead lab selection (March)
  - 2020 - NSF CDR for MREFC
  - 2021 - Decadal Survey recommendation; DOE CD-1/3a, NSF PDR
  - 2022 - DOE CD-2, NSF FDR
  - 2023 - DOE CD-3
  - 2024 - NSF MREFC
  - 2028 - DOE CD-4

Breadth of CMB-S4 Astronomy and Astrophysics

(a few examples; for full scope see Science Book, DSR, and the many publications citing them)

Primordial gravitational waves and inflation

Historic opportunity to open up a window to the primordial Universe



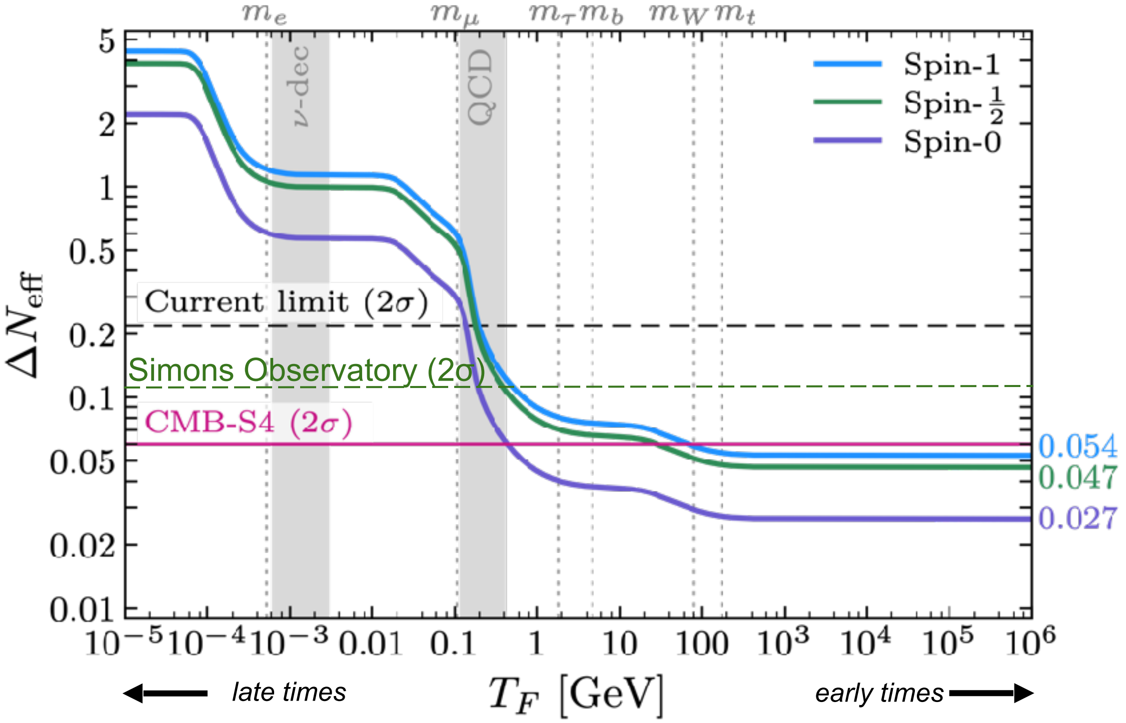
Detection of ***r*** would give the energy scale of inflation, provide evidence for the quantization of gravity, and fundamental insights into physics and cosmology.

All inflation models that naturally explain the observed deviation from scale invariance and that also have a characteristic scale equal to or larger than the gravitational mass scale predict $r > 10^{-3}$. A well-motivated sub-class within this set of models is detectable by CMB-S4 at 5σ.

CMB-S4 sensitivity of $\sigma(r) < 0.0005$ and ensures that a non-detection of r will rule out the leading inflationary models, and motivate alternate models for the origin of the universe.

CMB-S4 upper limit goal $r < 10^{-3}$ at 95% C.L. (SPO and SO goals ~10^{-2})

Light Thermal Relics



freeze-out temperature

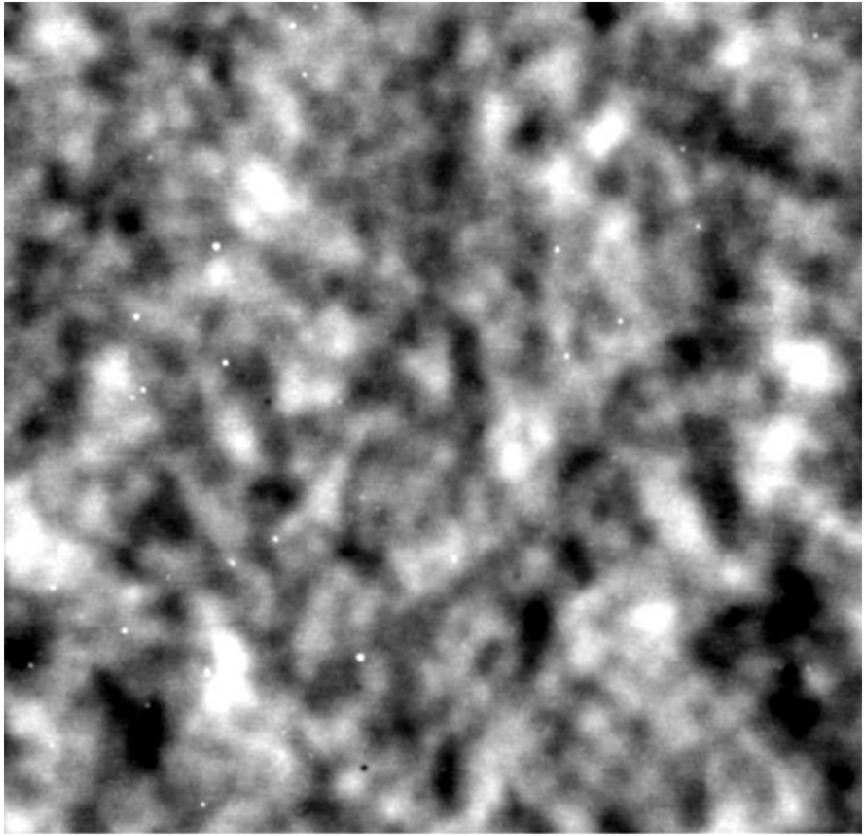
Additional light particles that appear frequently in extensions to the standard model of particle physics will be constrained by CMB-S4.

CMB-S4 requirement to achieve ΔNeff < 0.06 at 95%C.L. will detect all light relics that decoupled after the start of the QCD transition, providing orders of magnitude improvement on the freeze-out temperature of any thermal relic.

ΔNeff goal sets the CMB-S4 sky area and sensitivity requirement.

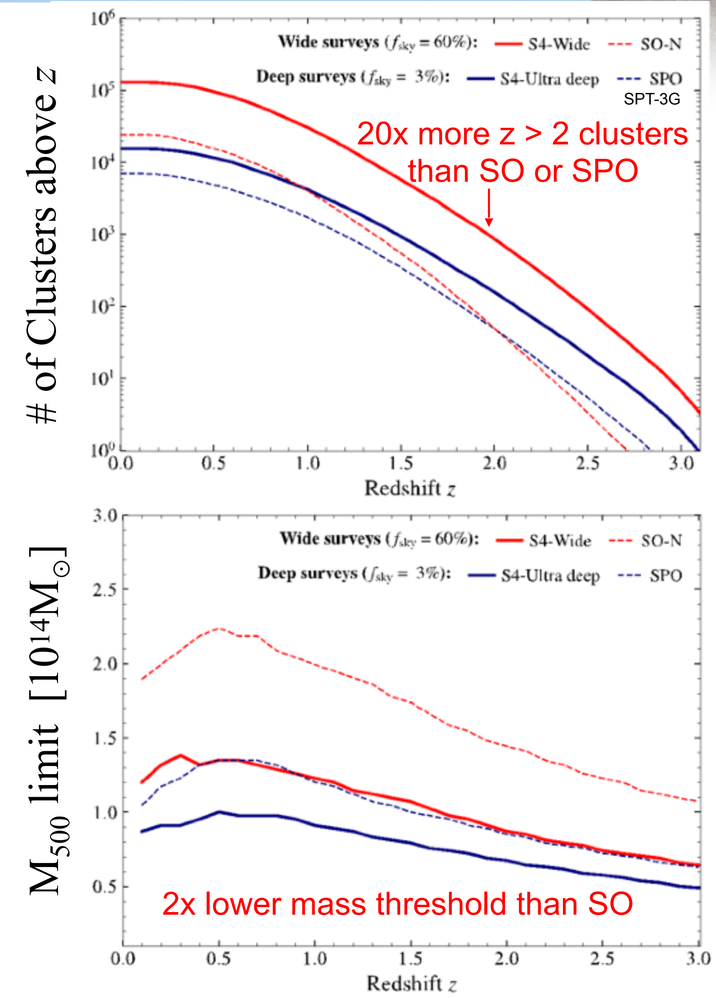
Mapping the millimeter sky - it's not just CMB

- Our CMB science goals require maps of the mm-wave sky at high sensitivity and resolution.
- These necessarily include a wide range of additional science, from CMB lensing, sources appearing either backlit by the CMB or as mm-wave foregrounds.
- Extragalactic: large scale structure, galaxies, galaxy clusters, GRBs, ...
- Galactic: dust & synchrotron emission, ...
- Solar system: planet 9, ...



A Millimeter-wave VRO/LSST

- **Legacy Catalog** of massive galaxy clusters out to the highest redshifts at which they exist.
  - Including hundreds of clusters at z ≳ 2, at the peak of cosmic star formation.
- **Legacy Catalog** of high-redshift galaxies out to the highest redshifts at which they exist.
  - Including **protoclusters** at z > 4 (such as SPT 2349, arXiv:1804.09231)
- **Open a new observational window: The Millimeter-wave Transient Universe**
  - See next slides



The Millimeter-wave Transient Universe


NSF'S 10 BIG IDEAS

Windows on the Universe

Using powerful new syntheses of observational approaches to provide unique insights into the nature and behavior of matter and energy and help to answer some of the most profound questions before humankind.

For years, we have been making observations across the known electromagnetic spectrum -- from radio waves to gamma rays -- and many great discoveries have been made as a result. Now, for the first time, we are able to observe the world around us in fundamentally different ways than we previously thought possible. Using a powerful and synthetic collection of approaches, we have expanded the known spectrum of understanding and observing reality.

CMB-S4 is **designed from the ground up** to participate in Multi-Messenger Astronomy.

- ~arcminute resolution at 2mm
- Groundbreaking depth and sky coverage
  - ~mJy noise on 70% of the sky in one observing day (plus polarization info)
- **High-cadence observing** (not in baseline observing plan for any other mm-wave survey of >50% of the sky)

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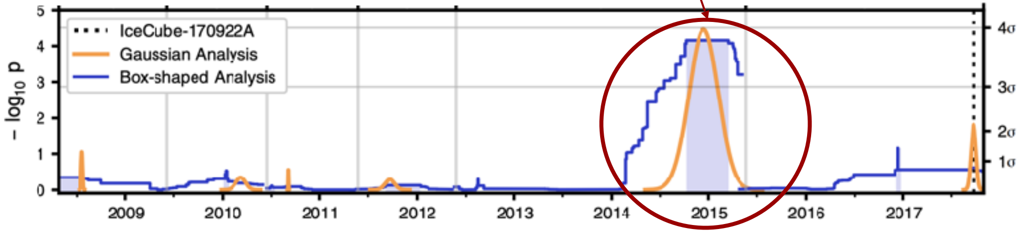
No Fermi Obs gamma-ray flare here, but what about mm?

Neutrino events associated with TXS 0506+056



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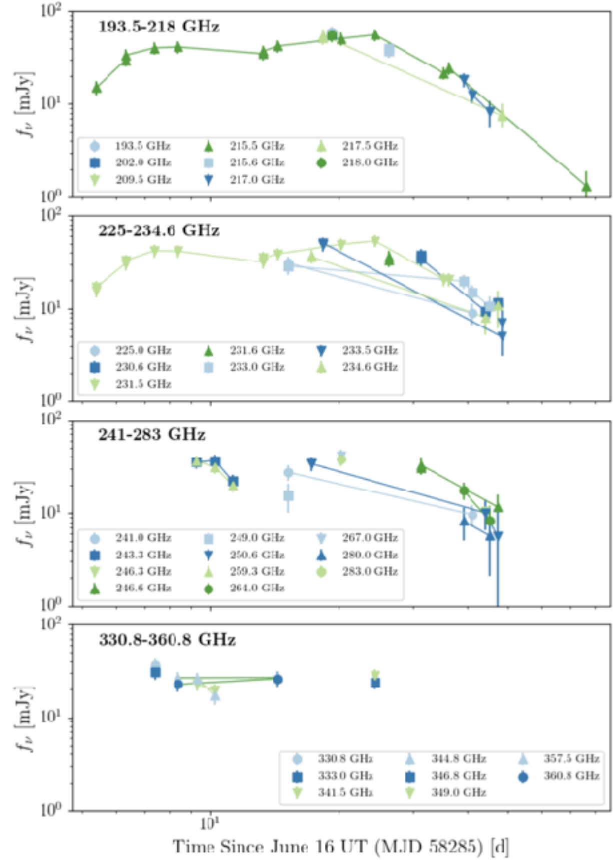
One of the few examples of MMA event would have benefited from mm-wave monitoring.

The Millimeter-wave Transient Universe: Beyond MMA

- **GRB afterglows**
  - With and without actual GRBs! (mm-wave signal much less beamed → "orphan afterglows")
  - Estimated >1000 detections (see answer to Panel Question #3 for more details)
- **Solar System objects**
  - Easier to see in direct emission than reflected light for d > ~1000 AU and T > 30K.
- **Unexpected Discoveries**
  - Brand new window → huge discovery space
  - One example: **AT2018cow** would have been detected at S/N > 10 *every day* for weeks.

AT2018cow



arXiv:1810:10880

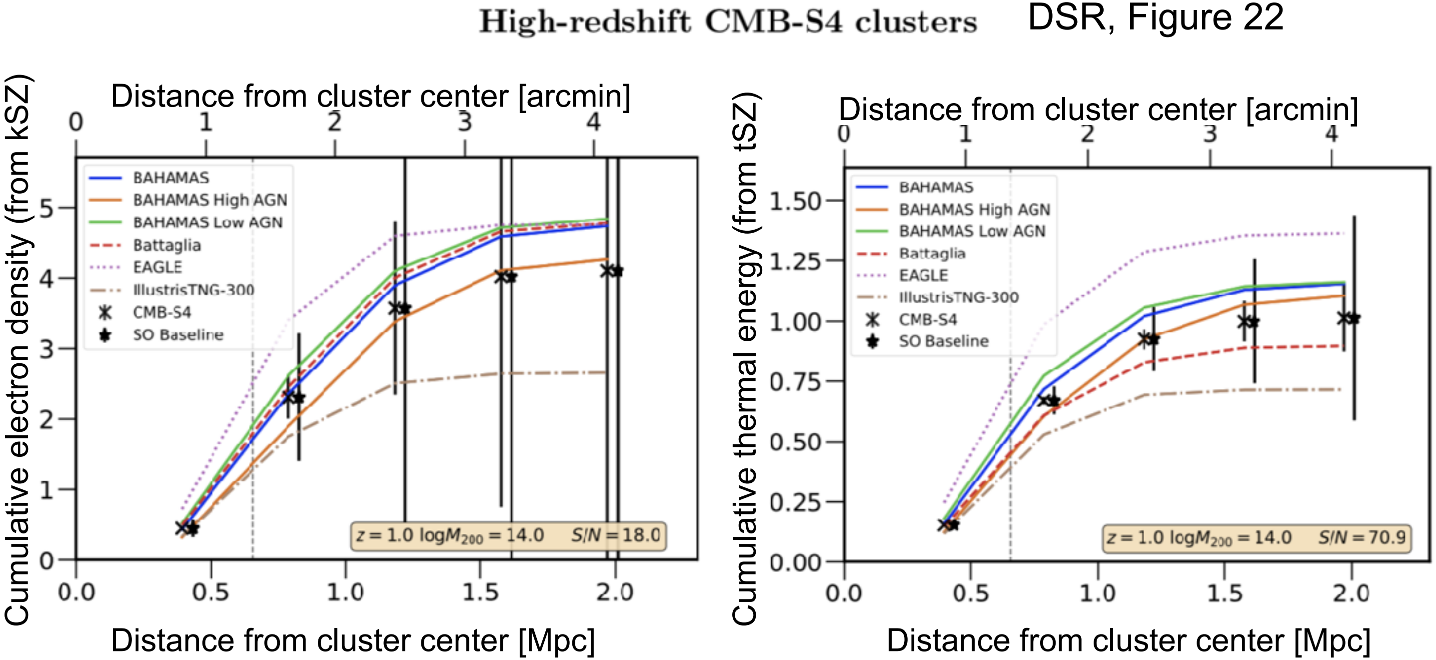
Mapping matter in the cosmos: Feedback in the outskirts of galaxies and clusters

Constrain galaxy and cluster feedback models.

Use thermal SZ and kinematic SZ to simultaneously measure electron density and pressure / thermal energy out to large radii.

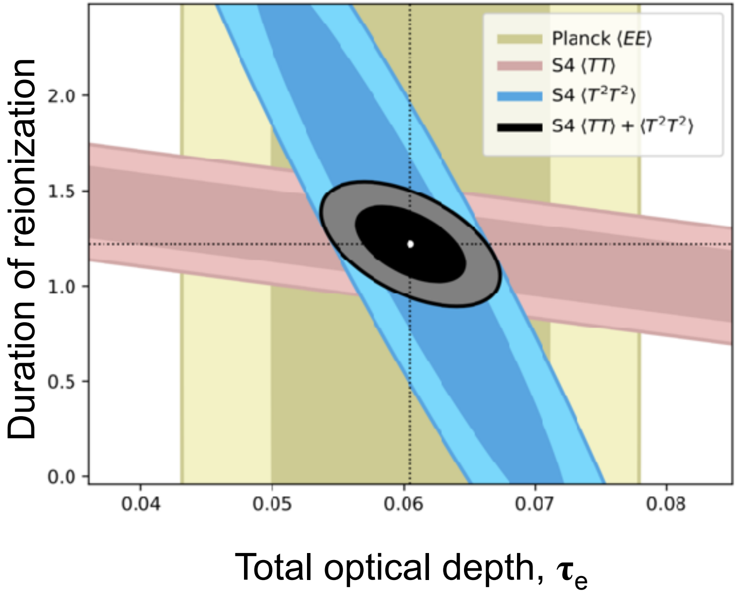
Lower noise + more SZ-selected clusters = much stronger constraints on density and pressure profiles.

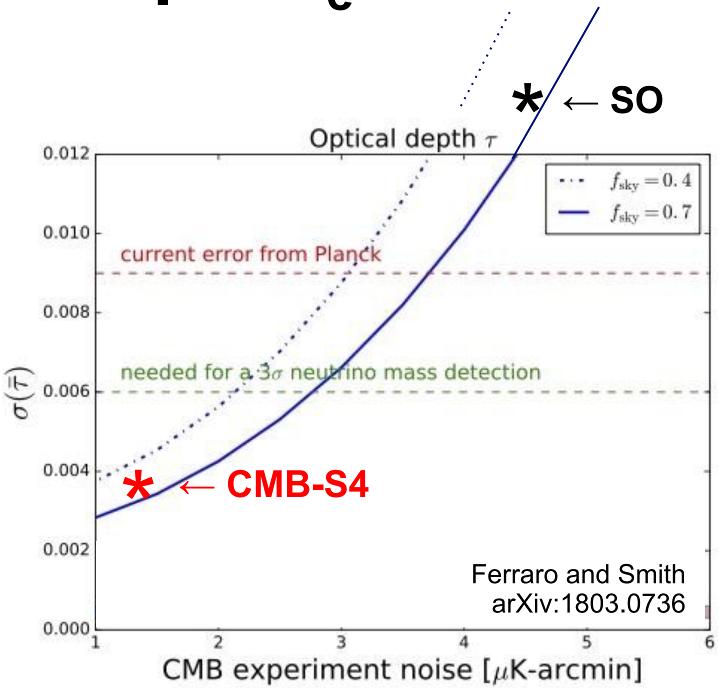
DSR, Figure 22



Mapping matter in the cosmos: Reionization and total optical depth τ_e from kSZ

DSR, Figure 24

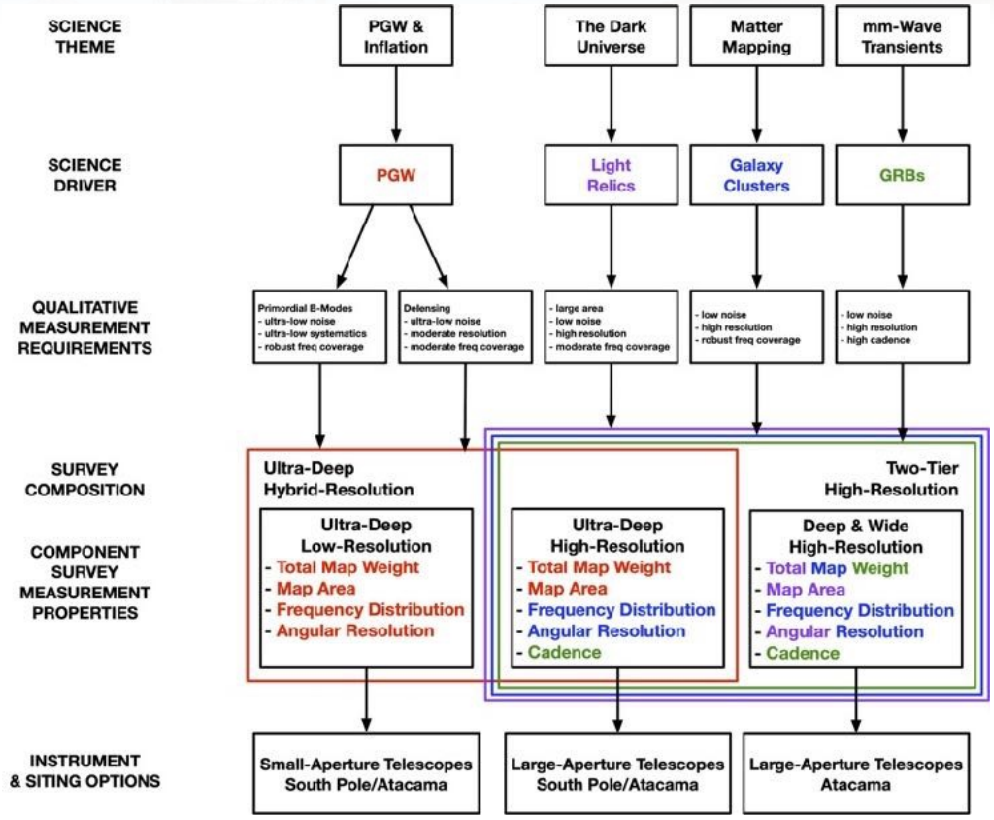




This is a **four-point function** of the kSZ map, so low noise is extremely important, especially at high multipoles.

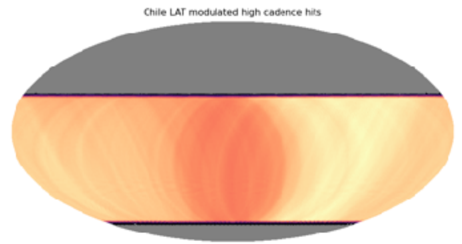
Science goals to experiment design

- Four science themes spanning the full range of ground-based CMB and mm-wave capabilities.
- Four key science goals, crossing critical thresholds in each area.
- Flowdown to detailed measurement and technical requirements.
- Scale existing proven technologies to meet these requirements.

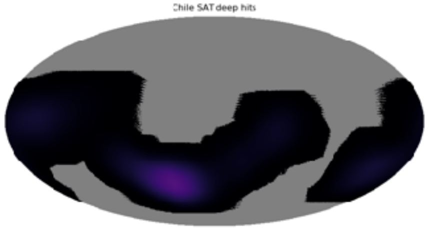


Experiment Design - Site-Specific Opportunities

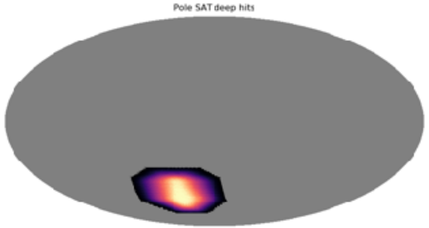
- CMB-S4 is unique in having two exceptional observing sites available; the experiment design takes advantage of the best each site has to offer.
- The biggest difference between the sites is in the sky surveys they can support.
  - Wide-area surveys can only be performed from the Atacama.
  - Compact ultra-deep surveys can only be performed from the South Pole.
- Atmosphere differences also motivate using half-wave plates on Atacama SATs.



Atacama wide survey hitmap



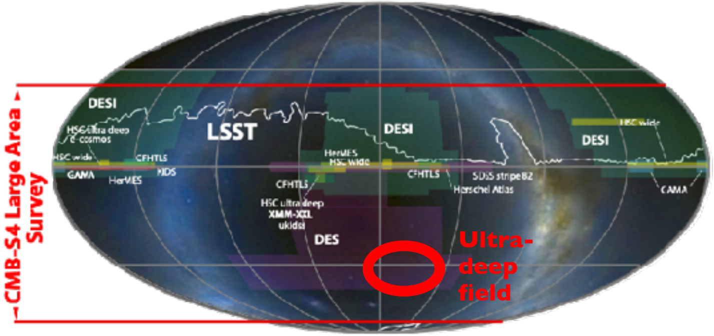
Atacama deep survey hitmap

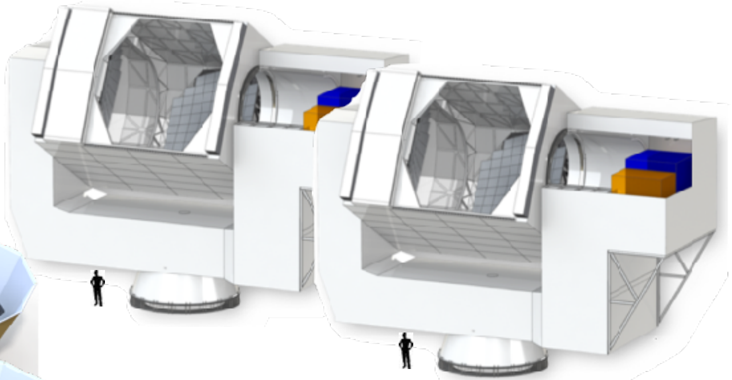


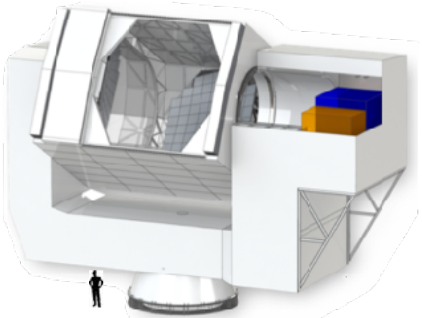
South Pole ultra-deep survey hitmap

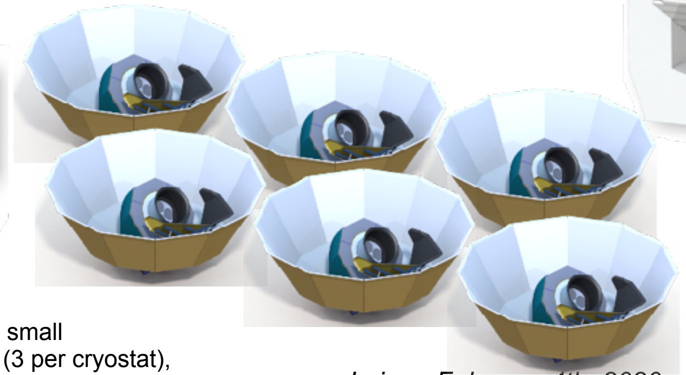
CMB-S4 Reference Design in a nutshell
Nested deep-wide and ultra-deep-narrow surveys

- Deep wide N_{eff} and Legacy Survey with 2 x 6m telescopes targeting ~60% of sky with 240,000 detectors over 6 bands. From Chile over 7 yrs.
- Ultra-deep "r" survey with 18 x 0.55m small refractor telescopes targeting ≥ 3% of sky with 150,000 detectors over 8 bands and a dedicated de-lensing 6m telescope with 120,000 detectors. Nominally from South Pole over 7 yrs, with option to move up to 9 SATs to Chile





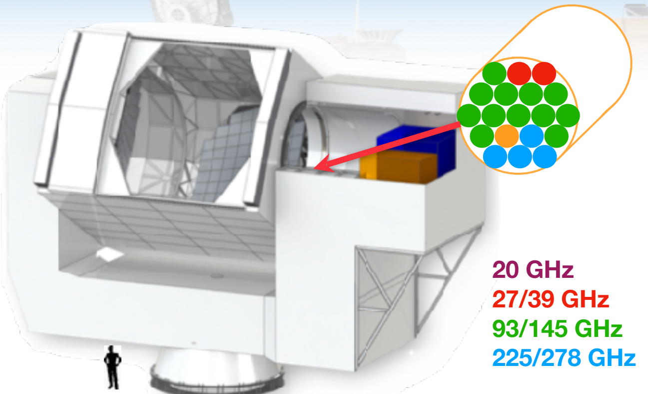




6m large telescopes,
e.g., like Simons Obs.

18 x 0.55m small telescopes (3 per cryostat), e.g., like BICEP Array

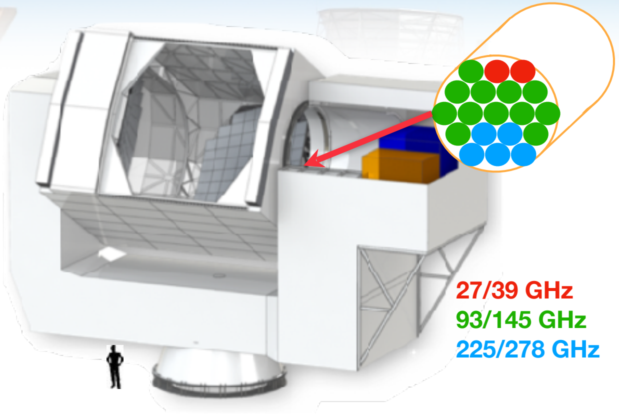
Ultra-Deep *r* Surveys

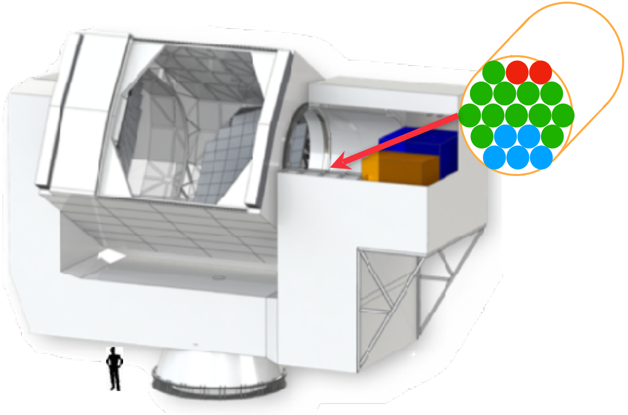


Large Aperture Telescope (LAT)

Small Aperture Telescopes (SATs)

Deep Wide Survey





- Uses field proven technology, including multiplexed TES detectors
- CMB-S4 requires 500 science-grade 150 mm detector wafers
- CMB-S4 has 57 LAT optics tubes and 18 SAT tubes, **500,000** detectors
- SPO has 1 LAT and 5 SAT tubes, 52,000 detectors (CMB-S4 compatible LAT proposed)
- SO nominal has 7 LAT optics tubes plus 3 SAT tubes, 60,000 detectors (CMB-S4 compatible LAT)

CMB-S4 Project Overview (Jim Yeck)

CMB-S4 Project Planning Context and Priorities

- Preparing a baseline design and project execution plan building on the "Decadal Survey Report" reference design and preliminary project plans
- Investing in R&D, design, and project development to reduce project cost, schedule, and performance risks
- Completing design work and plans to enable the start of long lead activities, both DOE and NSF, prior to potential NSF MREFC and DOE CD-3 funding
- Transitioning from predominantly contributed institutional and individual support to direct DOE OHEP and NSF financial support (DOE Lead Lab)
- Preparing for a successful DOE/NSF status review in summer 2020 confirming plans for DOE CD-1 and NSF Preliminary Design reviews in 2021
- Committed to a CMB-S4 total project cost goal of \$600M (currently assuming a DOE MIE project = \$350M and NSF MREFC project = \$250M

Approach to managing collaboration (Q11)

- Key elements of the project delivery approach
  - Established collaboration governance structure
  - Well-defined and embraced project organization, the CMB-S4 Integrated Project Office, with clear lines of accountability for project development and delivery
  - Central core team of experienced project management and technical personnel
  - Collaborators, supported by experienced engineers, appointed to project delivery roles aligned with the Work Breakdown Structure (project organization aligned with the WBS)
  - Technical Baseline Development (TBD) group, chaired by John Ruhl, includes the Technical Committee co-chairs, Abby Vieregg and Jeff McMahon, and experienced project and technical experts, Gil Gilchriese and Dan Akerib, provide a strong bridge to the collaboration
  - Explicit institutional accountability for the lead NSF and DOE institutions and other key stakeholders through the Integrated Project Steering Committee
  - Collaboration meetings structured to provide an opportunity for the entire collaboration to engage in project planning
- The approach is similar to successful large particle physics experiments

Project leadership experience – Ingredients to success

- ✔ Facility is a priority of the science community!
- ✔ Strong funding agency commitments and host role
- ✔ Project leaders viewed as enabling success of others
- ✔ Establish realistic goals – “Experience over hope”
- ✔ Credibility through openness and transparency
- ✔ Collective ownership of problems and solutions
- ✔ Populate organization with critical experience
- ✔ Success requires energy and enthusiasm!

Project leaders who prioritize on schedule performance and exhibit behaviour that is consistent with a “project culture” are likely to be successful!

CMB-S4 Organization Structure

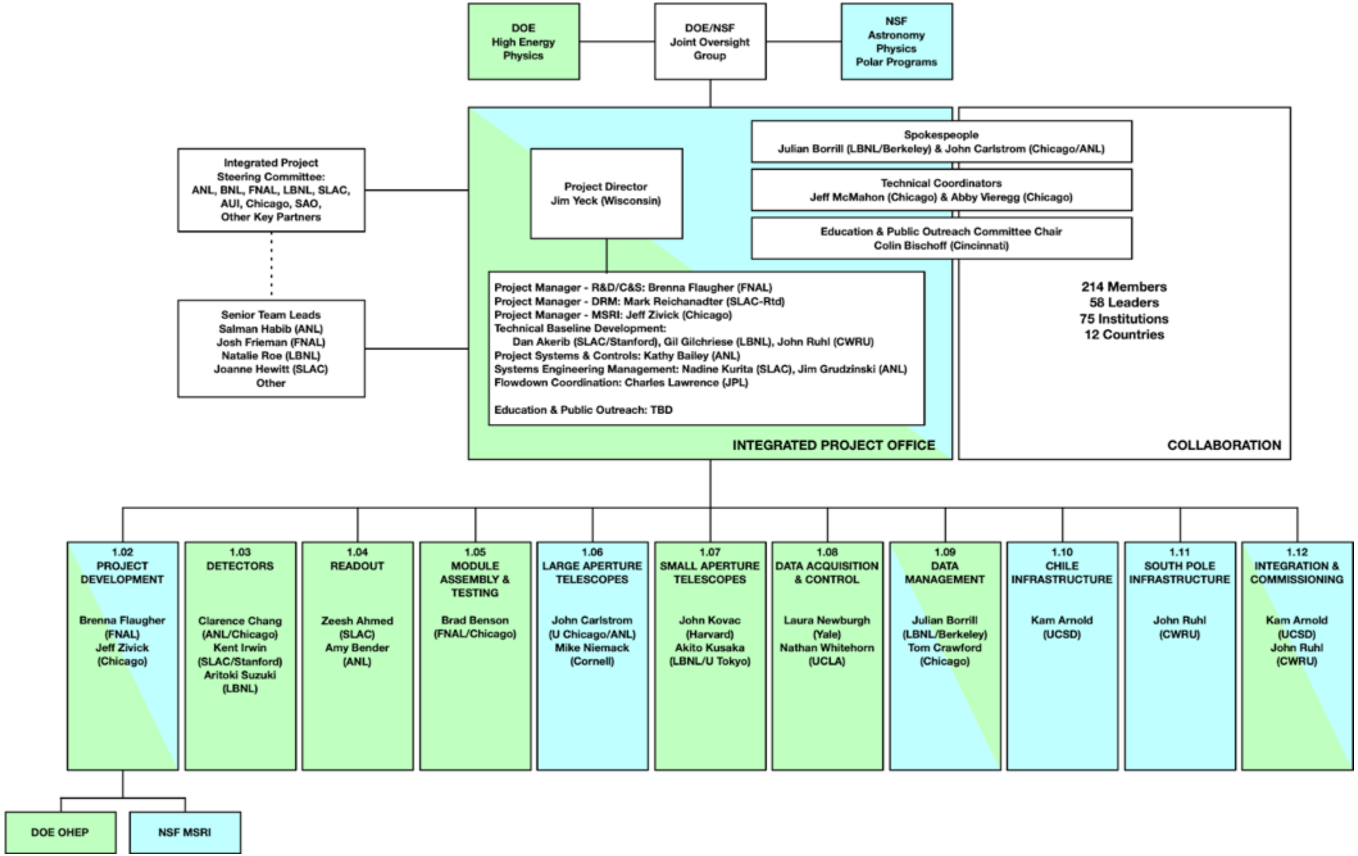
NSF/DOE Joint Oversight Group (JOG) – Agency Coordination and Oversight
- Joint Coordination Group transitioned to JOG with NSF MSRI-1 award
- Lead US agency to be decided based on level of project investment and other factors

Integrated Project Steering Committee (IPSC) – Accountability and Oversight
- DOE Lab directors, U. Chicago, AUI, SAO, …evolving
- Quarterly teleconference meetings – next meeting after DOE lead lab decision

Level 1 Integrated Project Office (IPO) – Responsible for Integrated Project Delivery
- Integration and coordination: cost & schedule, R&D, risk, systems engineering and requirements flow down, baseline development, E&O, etc.
- Includes institutional representatives (Senior Team Leads) and L2 Leads
- Agency coordination and development of in-kind partners

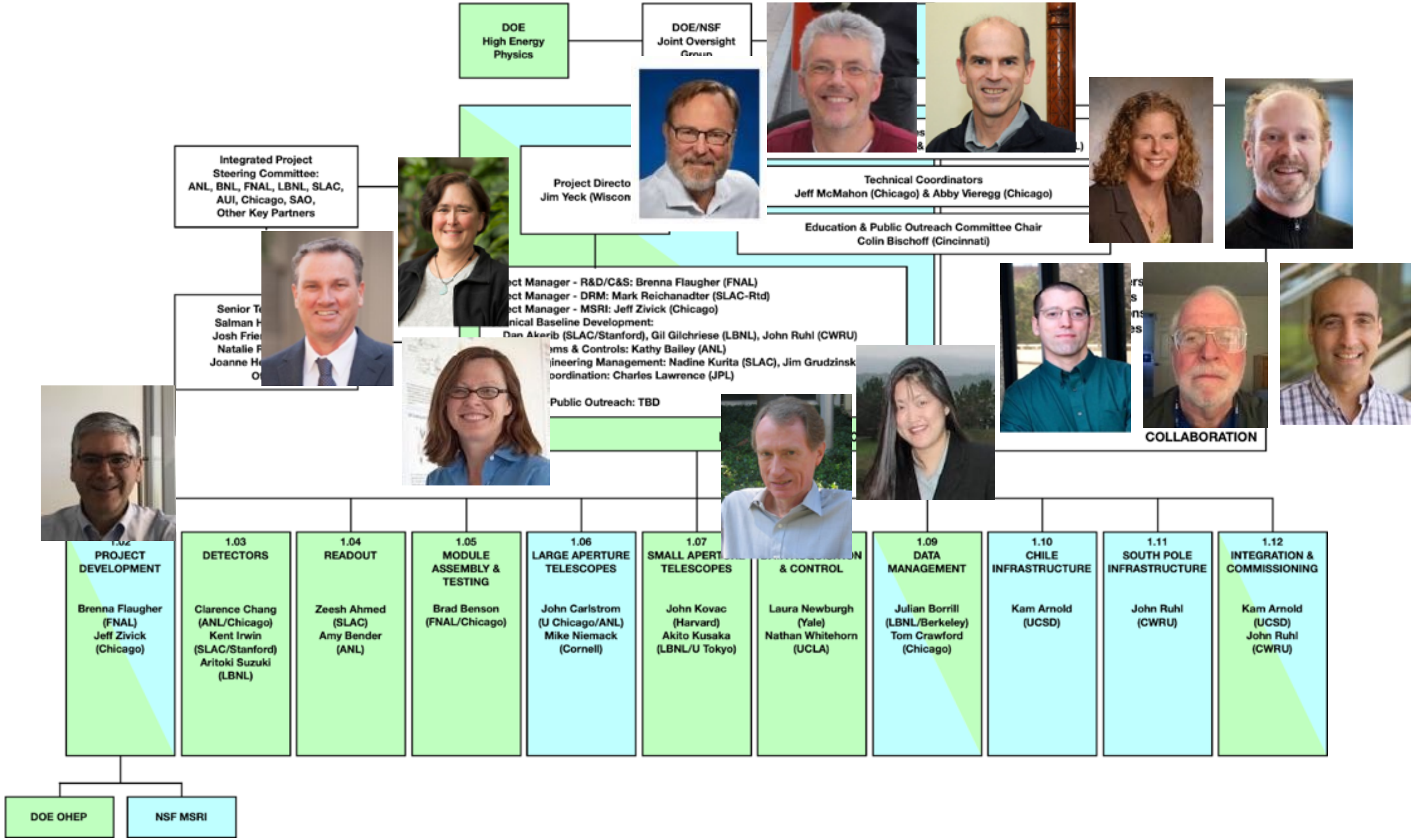
Level 2 IPO – Responsible for Subsystem Delivery
- Level 2 Leads responsible for their subsystems, engaging collaboration resources and building subsystem delivery teams
- Jointly responsible for the overall CMB-S4 project delivery and supporting an integrated approach using common tools and management systems

CMB-S4 Integrated Project Office (IPO)



CMB-S4

CMB-S4 Integrated Project Office



Irvine, February 4th 2020

CMB-S4 Level 2 Leadership

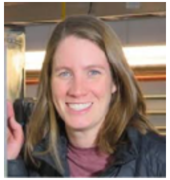
Detectors


Clarence Chang


Toki Suzuki


Kent Irwin

Readout


Amy Bender


Zeesh Ahmed

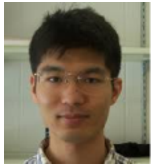
LATs


Mike Niemack


John Carlstrom

SATs


John Kovac


Akito Kusaka

Data Acquisition


Laura Newburgh


Nathan Whitehorn

Data Management


Tom Crawford


Julian Borrill

S. Pole Site + I&C


John Ruhl

Chile Site + I&C


Kam Arnold

Modules & Testing


Brad Benson

NSF/DOE Project Decision Timeline

	NSF	DOE	Comments
FY2018-19	Interim Project Office Established		Coordinated pre-project development
Q3 FY2019	Initial Input to Decadal Survey White Paper Decadal Survey Report		Reference Design (NSF Conceptual Design) and Initial Project Plans
Q4 FY2019	Critical Decision 0 July 2019		Based on Decadal Survey Report/ IPO Plans
FY2020	NSF Lead Institution Q1 - October 1, 2019	DOE Lead Laboratory Q2 – March 1, 2020	Permanent Integrated Project Organization
Q2 FY2021	Decadal Survey Report Forecast – February 2021		NSF scientific merit review
Q3 FY2021	PD Stage Concluded Provisional Report	CD1/3a Review / Approval	Coordinated agency review plans
FY2022	Final Design Proposal Submitted 09/21	CD2/3b Approved Q2 FY2022	Potential MREFC budget request approval 08/21
Q4 FY2023	FD Complete	CD3 Approved	NSB Approval
Q1 FY2029	MREFC Project Complete	CD4 Approved	Schedule includes 1 year of float (Q1 FY28 Early Finish)

Comparing DOE and NSF Requirements Checklists

DOE Critical Decision-1

- Preliminary Project Execution Plan – identifies project governance and tailored CD-3a process
- Acquisition Strategy (w/Life Cycle Cost Analysis) – identifies lead labs
- Preliminary Cost and Schedule Baseline (to support cost range)
- Conceptual Design Report (w/external review) ~30% design maturity
- Preliminary Hazard Analysis Report
- Integrated Safety Mgmt Plan
- Quality Assurance Program
- Safeguards and Security
- National Environmental Policy Act Strategy
- Project Data Sheet (in draft form)
- Risk Management Plans
- Project Risk Registry

NSF Preliminary Design

- Project governance and management team in place to support FD and MREFC.
- Credible "risk-adjusted" TPC and resource-loaded performance baseline.
- Management systems, systems integration, document configuration.
- All components defined although some not in final design state.
- Site-specific preliminary design and environmental assessment/impacts.
- Develop enabling technologies.
- Drill downs into Cost Book to test defined scope, BOE, and associated risk.
- Evaluate contingency, including scope and schedule contingency.
- Maturity of operational cost projections

CMB-S4 Project Priorities - 2020

Detector Fabrication Collaboration and Wafer Production

- Address recommendations from the Detectors & Readout Task Force (summer 2019), DOE Detector Fabrication Review (8/19), Annual Reviews (12/18 and 11/19)
- Resolve barriers to collaboration - CMB-S4 Detector Fabrication Group (CDFG), MoUs
- Ramp-up support of DOE sites (ANL, LBNL/SeeQC, SLAC) and engage other non-DOE sites

Adhere to Established Technical Decision Timeline

- Technical Baseline Development group assists the IPO and the L2 Leaders in efforts to address a relatively small number but high schedule impact technical decisions
- Timely decisions essential to the NSF Preliminary Design and DOE CD-1/3a schedule
    - Readout, Optical Coupling, SAT and LAT designs, etc.

Transition to Permanent Integrated Project Organization

- U. Chicago Host for NSF MSRI-1 project and MREFC preparation
- DOE “Host/Lead Lab” proposals submitted in January and decision planned for March 2020

Prepare In-kind Agreements

- Finalized by lead DOE and NSF institutions

CMB-S4 Project Funding

Current

- DOE OHEP CMB-S4 support in FY2019 ~$3M
- NSF MSRI-1 CMB-S4 support in FY2020, FY2021 is $2M/year

Future Possibilities

- *DOE OHEP request for FY2020 is $10.9M* ($2M so far) *and FY2021 is $20.0M*
- *Additional NSF requests planned including a potential MREFC project in FY2024*

Notional DOE and NSF Funding Scenario	FY2020	FY2021	FY2022	FY2023
DOE OHEP Updated Request	*$10.9M*	*$20M*	*TBD*	*TBD*
NSF Mid-Scale Research Infrastructure - 1 (MSRI-1)	*$2M*	*$2M*		
NSF MSRI-2 - Potential CMB-S4 Site Infrastructure			*$50M*	
NSF Final Design Support (included in a 2nd MSRI-1 or -2?)			*$4M*	*$4M*

Preparing for DOE CD-1 & NSF MREFC Decisions

Mid-Scale Research Infrastructure (MSRI) Project Start	October 1
Collaboration Meeting/Workshop @ UC San Diego	October 17-19
CMB-S4 Annual Project Review @ U Chicago	November 4-5
Response to ASTRO2020 RFI	November 10
Revised Funding Request submitted to DOE OHEP	November 19
Discussions on In-kind with SO, SPO, CCAT', SAO, International	Mid November
CMB-S4 Readout Assessment	December 10-11
NSF/DOE Joint Oversight Group Meeting w/ CMB-S4	February 2020
Optical Coupling Assessment @ Fermilab	February 27-28, 2020
DOE Lead Lab Decision (Proposals from ANL, LBNL, and SLAC)	March 1, 2020
Collaboration Meeting/Workshop @ LBNL	March 30-April 1
Detectors & Readout and Module A&T Advisory Committee Meeting	March/April 2020
DOE/NSF Status Review (NSF CD & MSRI-1 Status, DOE Status)	Summer 2020

Potential In-kind Contributions to CMB-S4 (Q8)

- Existing/Planned LATs
  - SPO (NSF MSIP proposal; possible contributions from Germany, France)
  - SO
  - CCAT-prime
  - ELFS-S (EU Synergy proposal from Italy/Spain/UK/US for low frequency LAT)
- Existing/Planned SATs
  - BICEP Array
  - SO, SO-UK (UK STFC proposal)
- New In-Kind
  - Smithsonian Astrophysical Observatory partnering in delivering SATs
- Site Infrastructure
  - Atacama infrastructure coordination with SO (common site L2 lead), AUI (site partner)
  - South Pole infrastructure coordination with SPO (BICEP Array Tower, etc.), IceCube
- Data Management
  - Common software development & deployment with SO/SPO (e.g., SO NSF MSIP)

WBS and Dictionary

Control Account
1.01 - Project Management
1.02 - Pre-CD1/PDR
1.03 - Detectors
1.04 - Readout Electronics
1.05 - Module Assembly and Test
1.06 - Large Telescope
1.07 - Small Telescope
1.08 - Observation Control and Data Acquisition Systems
1.09 - Data Management
1.10 - Chile Infrastructure
1.11 - South Pole Infrastructure
1.12 - Integration and Commissioning

1.01 Project Management - includes management, systems engineering, safety, risk, QA and EPO for overall project

P6 schedule development started in Aug. 2018, reviewed in Dec. 2018 and updated in July 2019 for the DSR submission.

Schedule includes 1100 activities, 1928 relationships, 6 Level 1, 20 Level 2 and 299 Level 3 Milestones

Project organization aligned w/ WBS

CMB-S4 Total Project Cost

- Bottoms up estimate using Primavera P6, COBRA
- Estimates based on similar projects (SO, CCAT', SPT, BICEP/KECK): experience, quotes and actual costs when available
- Escalation and contingency at 35% included, consistent with similar projects at this stage
- Prepared in 2018, external review in December 2018, scrubbed and updated in July 2019*
- NSF/DOE scope split is roughly $250M/$350M
- Work in progress includes
  - NSF MSRI-R1 project activities
  - DOE R&D activities
  - Cost review in spring
  - Joint Agency review in summer

* Parametric estimate prepared for CDT in 2017.

WBS Level 2 # - Title	Total $ M
Total Estimated Cost (TEC)	
1.01 - Project Management	19.6
1.03 - Detectors	39.5
1.04 - Readout Electronics	59.9
1.05 - Module Assembly and Test	31.8
1.06 - Large Telescopes	86.5
1.07 - Small Telescopes	52.3
1.08 - Observation Control and Data Acquisition Systems	13.9
1.09 - Data Management	26.9
1.10 - Chile Infrastructure	38.1
1.11 - South Pole Infrastructure	37.0
1.12 - Integration and Commissioning	7.7
Direct TEC	413.2
TEC Contingency (35%)	144.6
Total TEC	557.8
Other Project Costs (OPC)	
1.01 - Project Management (DOE)	7.0
1.02 - R&D (DOE)	24.2
Direct OPC	31.2
OPC Contingency (35%) - excludes R&D	2.5
Total OPC	33.7
TPC	591.5

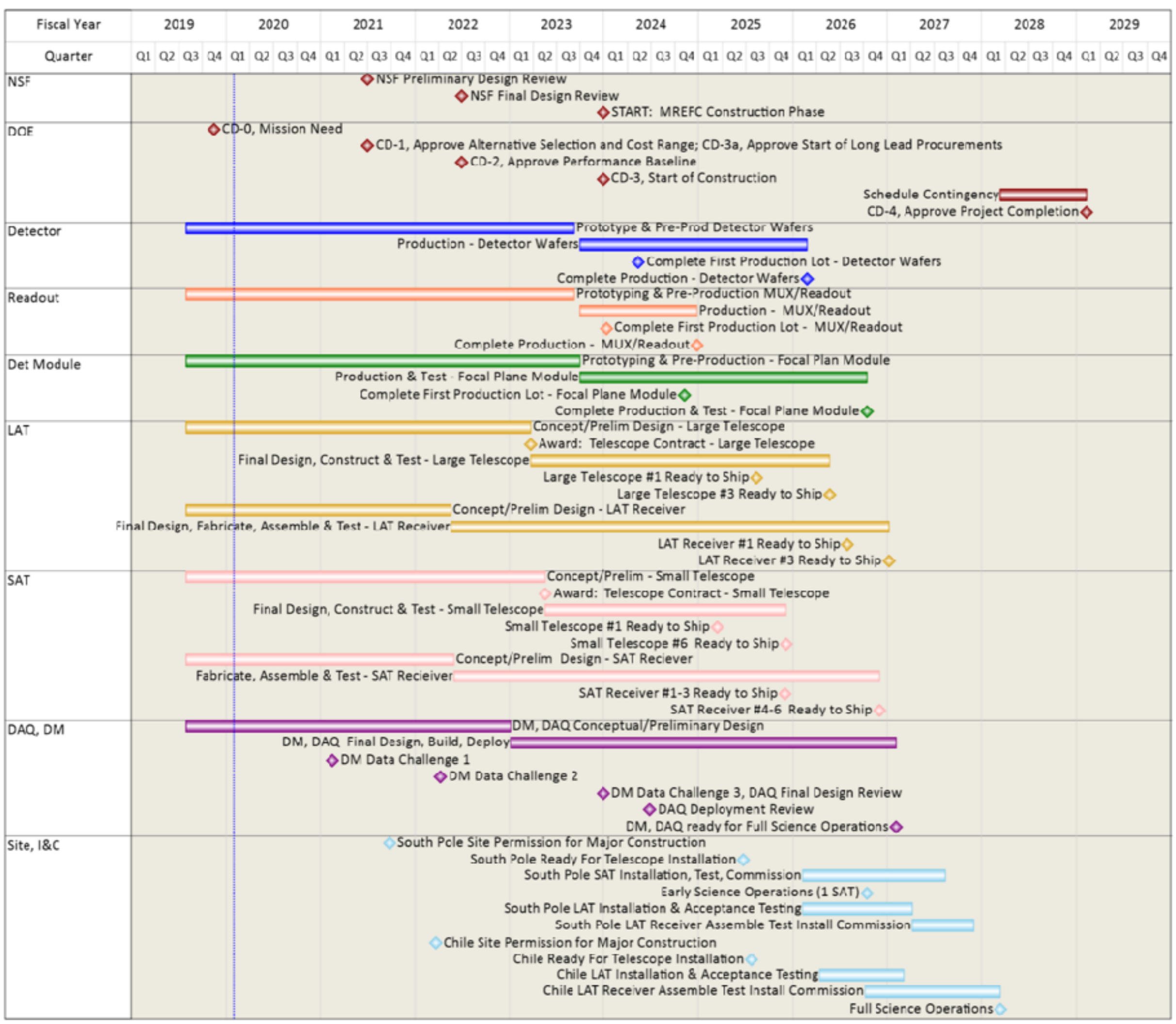
CMB-S4
Project Schedule

~10 year schedule: DOE CD-0 and NSF MSRI-1 award in 2019, DOE CD-4 in 2029.

NSF and DOE large project gateway milestones aligned

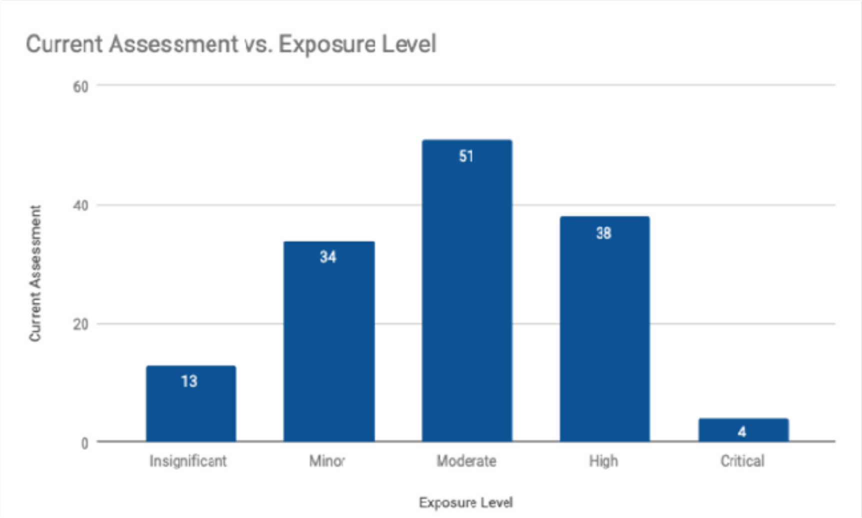
Near term goal is passing agency reviews in 2021 (informed by the Decadal Survey). Lead institutions will jointly organize review preparations.

Critical path is detector fabrication. R&D support for prototype wafers.



CMB-S4 Risk Registry

- Risk register development followed approach used for the LSST camera (N. Kurita)
- >3 meetings with each L2 subsystem: Identify risks and mitigation strategy, review
- Risk Review Board Meeting to normalize risks across the project
- Risk registry identified 140 risks, 4 Critical, 38 High
- Critical risks are related to detector production and performance
- R&D is focused on reducing/mitigating the highest risks



CMB-S4 Annual Review
Gleacher Center, Chicago, IL
November 4-5, 2019

Closeout Presentation

Irvine, February 4th 2020

2019 Annual Review General Charge

- Assess the preliminary project execution plans including the effectiveness of the organization and project management structure for this stage of the project.
- Is the DOE/NSF preliminary scope of work reasonable for this stage of the project?
- Assess the plan for preparing a DOE Conceptual Design Report (CDR) in support of CD−1 and an NSF Preliminary Design. [Note: Baseline Design Document is intended to meet the needs of the CMB-S4 Project and both funding agencies.]
- Assess the status of the project planning documentation required for DOE CD-1 and NSF Preliminary Design Reviews.
- Evaluate the case for potential DOE Critical Decision 3a items in FY2021 and a potential SPO NSF Mid-Scale Innovation Program proposal in FY2020 and Mid-Scale Research Infrastructure proposal in FY2021.

CMB-S4 Annual Reviews in 2018, 2019

December 2018

CMB-S4 DSR Review Committee	
Mark Reichanadter, CMB-S4 Co-Chair	SLAC
Steve Ritz, CMB-S4 Co-Chair	UC-Santa Cruz
SC1 – Sites & Infrastructure AND Integration & Commissioning	
Erik Nichols*	RSS LLC
Herman Cease	ANL
SC2 – LAT plus Cryostats AND SAT plus Cryostats	
Jamie Bock*	Caltech
Bill Holzapfel	UC-Berkeley
SC3 – Detectors & Readout AND Data Acquisition & Control	
Ed Wollack*	GSFC
Klaus Honscheid	OSU
Dan McCammon	Wisconsin
SC4 – Project Management, Systems Engineering & Risk	
Victor Krabbendam*	LSST
Jolie Macier	FNAL-LBNF/DUNE
Vincent Riot	SLAC-LSST
SC5 – Science AND Data Management	
Marcia Rieke*	Arizona
Scott Dodelson	CMU
Wil O'Mullane	LSST
Risa Wechsler	KIPAC

November 2019

Jamie Bock, JPL – D&R, Module Assembly & Testing
Diane Hatton, BNL – Project Management**
Klaus Honscheid, OSU – DAQ and DM
Robbie Leftwich-Vann, LBNL – LATs, SATs, and Cyrostats
Victor Krabbendam, AURA – Sites and Integration (S&I) and Integration & Commissioning (I&C)**
Petra Merkel, FNAL – D&R, Module Assembly & Testing*
Paolo Natoli, University of Ferrara – DAQ and DM*
Erik Nichols, Remote Science Services LLC – S&I and I&C*
William O'Mullane, AURA/LSST – DAQ and DM
Vincent Riot, LLNL – LATs, SATs, and Cyrostats*
Anders Ryd, Cornell – Project Management*
Ed Wollack, Goddard – D&R, Module Assembly & Testing

*Subcommittee Chair, **Review Co-Chair

Agency program managers participate as observers

Annual Review November 2019 Closeout

- Thanks to the Project team for a well-organized review
- The team was open and our discussions seemed meaningful
- Our intention is to be helpful and we are available to discuss comments and recommendations
- Collaboration has made great progress to develop the “Project” this past year
  - Technical definition, Management approach, Cost and Schedule definition
- Dedication to a single centrally managed Project is clear
  - This is the road to success for complex CMB-S4 endeavor
  - Efforts with Agencies appear good and we continue to be impressed with engagement

Annual Review November 2019 Closeout

- Preparation for CD-1 / PD is a significant level of effort
  - This will be a challenge at all levels of the Project
  - Agencies have clear expectations so basic path is defined
  - Agency cooperation seems high but details still matter
  - One Project but specific agency expectations must be recognized, fulfilled and/or negotiated well ahead of review
- Science Requirements Flow Down, Systems Engineering and Documentation to support designs and plans is critical for success in next phase
  - CD-1 / CD-3a / PD / Early development work
    - Sometimes just documenting what you know
    - Sometimes defining how you'll proceed
    - But, in most cases, it is not optional

Annual Review November 2019 Closeout

- Road to CD-1 / PD / CD-3a is aggressive
  - Technically limited schedule is appreciated
  - Agency support (DOE Funding / Lead Lab) is vital to support schedule
  - Reconsider CD-1 / CD-3a joint review - This is a significant hurdle
- CD-1 / PD preparation plans
  - Consider several targeted preparation reviews
    - OPA-led preparation review
    - Cost review

CMB-S4 Project Summary

- Single comprehensive CMB-S4 experiment with project investments enabling research undertaken by a single scientific collaboration
- Multiple telescopes/cameras distributed across two sites, Chile and South Pole
- Joint NSF and DOE program management & oversight (Joint Oversight Group)
- NSF and DOE identified institutions accountable for project delivery
- Integrated Project Office engaging expertise across the collaboration and drawing on large project experience within the community
- NSF/DOE Total Project Cost of $600M (AY $); Operations in 2028 at ~$32M/year (2019 $) for 7 years

Response to Questions from the Panel

Science Summary

- CMB-S4 is driven by a range of transformational mm-wave science goals, from fundamental physics and cosmology to multi-messenger astronomy.
- Meeting these goals requires
  - A 10x scaling of existing, field-proven, technologies tracks long-term history of the field.
  - Appropriate project management, systems engineering, etc - for the first time combining full DOE capabilities with the long-standing NSF program.
  - Both wide (Atacama) and compact (South Pole) survey capabilities - uniquely making all of CMB science available to the entire community.

Project Summary

- CMB-S4 has been in development by the entire US community for the last 7 years, with endorsements by P5, NAS/NRC, and AAAC.
    - This Decadal Survey is the last remaining piece.
- CMB-S4 has effective collaboration and project structures, with strong coordination between them and with the key stakeholders.
- CMB-S4 has the strong joint support of the federal agencies, with DOE HEP and NSF AST, PHY & OPP meeting regularly in a Joint Oversight Group.

Question 1:

Section 5.6 of the DSR refers to “a quasi-realtime alert system linked to the transient alert mechanisms in the wider community... [that will] require on-site computing and analysis software that runs autonomously.”

What data products (alerts, difference maps, etc.) would be provided by this system to the community, with what astrometric accuracy, and on what timescales relative to observations?

Answer 1:

Our baseline plan for transients follows the current SPT-3G model and includes:

- Daily maps, differenced to identify transients, which are then issued to the community as alerts within 24 hours of the observation and with sub-arcminute accuracy.
- Annual data releases which may include single-epoch thumbnail maps and time-series photometry, with shorter latency possible for particular objects in extraordinary circumstances.

This plan is being refined in consultation with the wider community, with the goal of maximizing CMB-S4's utility for Multi-Messenger Astronomy.

- E.g., it was the topic of April 2019 workshop at KICP, Chicago

Question 2:

Section 1.3.1 of the RFI response identifies “failure to meet our LAT angular resolution requirements” as a threat to Science Goal 3 (only); would such a failure also be a threat to Science Goal 2, as suggested by the use of color in Figure 1?

Answer 2:

Yes, the LAT resolution is required for both the light relic and mass-mapping Science Goals.

- Mass-mapping sets a more stringent angular resolution requirement; meeting that automatically meets our light relic requirement. See DSR Figure 75.

Question 3:

Science Goal 4 refers to measurement of “many gamma-ray burst afterglow light curves”; does “many” here refer to the number of afterglows detected (estimated to be ~1700 in Section 1.5.1 of the DSR), or the number that can be effectively identified as afterglows?

Answer 3:

- Based on existing mm-wave follow-up of selected known ("on-axis") GRBs, we expect to measure 100-200 afterglows with clear counterparts across the electromagnetic spectrum
- "Off-axis" events are largely unexplored, and high-redshift events are strongly underrepresented in current samples; some theoretical estimates suggest that including these events in our sample could lead to 1700 measured events over the course of the survey
    - Identification as an "GRB afterglow" may be possible from information learned by the catalog of 100-200 afterglows with clear counterparts, but may require counterparts at other wavelengths to ensure that these are members of the same class. There will be clear synergies with contemporaneous wide-field surveys (e.g., SKA, LSST, WFIRST).

Question 4:

What are the possible decision pathways for (re)deploying a subset of the SATs to Chile?

Answer 4: Overview & Reference Design

- Current forecasts show that the tightest bounds on r are achieved by siting all of the SATs at the South Pole, taking advantage of that site's unique ability to support continuous observations of a single, small, patch of the sky.
- A feature of CMB-S4 is that we don't need to finalize our full SAT deployment until 2024.
- We can use the intervening years to improve our forecasting inputs (informed by the experiences of SO and SPO) and methodology (better addressing multi-site configurations, foreground removal, and delensing).
- We also have the option to re-deploy SATs from South Pole to Atacama during operations, should that be motivated by early CMB-S4 results.
- In the Reference Design (i) SATs can be equipped with the half-wave plates needed in the Atacama, and (ii) Site Infrastructure and Schedule support South Pole/Atacama SAT distributions ranging from 18-0 to 9-9.

Answer 4: Deployment Schedule

SAT-Siting Deadline	Project Milestones	Year	Information timeline
	CD-0	2019	sigma(r) = 0.020 (BK15)
		2020	
	CD-1	2021	SPO 1-year SAT data taken
	CD-2	2022	SO 1-year SAT data taken
SATs 1-3	CD-3	2023	
SATs 4-6	Ship SAT 1-3 mounts	2024	
	Ship SAT4-6 mounts & SATs 1-3	2025	
	Ship SATs 4-6	2026	SPO end of observing
	Commissioning / Start Observing	2027	SO end of observing
	CD-4	2028	

Answer 4: Decision Drivers

Drivers on the decision pathway include:

- Improved CMB-S4 forecasts, incorporating
  - Site-specific atmospheric noise measurements from SO/SPO.
  - Instrument optical/electronic performance results from SO/SPO.
    - Atacama HWP performance from SO is a particular point of interest.
  - Foreground cleaning and delensing approaches from SO/SPO/CMB-S4.
  - Systematics mitigation approaches from SO/SPO/CMB-S4.
- Any hint of a detection of r, either before deployment or during operations
  - The ability to make a high-significance observation on the same sky patch.
  - The ability to make a confirmatory detection on a second sky patch.

Question 5:

The ultra-deep low-resolution survey is described as targeting “the 3% if the sky with the lowest foreground contamination” (p14 of RFI response); is this area already known, and if not, how would it be selected? Can the project team comment on what new steps would be needed to characterize foregrounds “at much higher precision” (p47 of RFI response) than has been done by existing experiments?

Answer 5:

"is this area already known, and if not, how would it be selected?"

- The goal is to minimize contamination from polarized galactic foregrounds (primarily synchrotron and dust).
- The BICEP/Keck patch was chosen based on the data available at that time; by the time CMB-S4 commences operations we will know more about polarized foregrounds from SPO, SO, CCAT-prime, ELFS-S, etc.

"what new steps would be needed to characterize foregrounds "at much higher precision" (p47 of RFI response) than has been done by existing experiments?"

- Observe at many more frequencies in order to enable robust foreground removal; eg. the Reference design includes
    - Split bands at 90GHz and 150GHz for greater redundancy
    - A 20GHz channel on the delensing LAT for synchrotron control
- Optimize foreground removal methods for such data to the required precision.

Question 6:

How does CMB-S4 view itself in relation to the Simons Observatory, LiteBIRD, PICO, and any other concepts for CMB projects on the ground and missions in space? Does the CMB-S4 team see these projects/missions as essential for CMB-S4, helpful for CMB-S4, and/or competitive with CMB-S4 in their scientific and/or technical aspects?

Answer 6: Ground-Based Experiments

- CMB-S4 has always been a broad, open, collaboration, spanning the entire US ground-based CMB community and beyond.
  - CMB-S4 was conceived in 2013 by a convergence of (primarily) the ACT, BICEP/Keck, POLARBEAR, and SPT experiments.
  - Collaboration and project leadership is drawn from the entire community; seats are reserved on the Governing Board for representatives of each of the “founding four” experiments as key stakeholders.
- The pairs of experiments at each site subsequently merged into SO (2016) and SPO (2018); from its origins, CMB-S4 automatically encompasses both of these.
  - 216 Members: ~60% SO, ~40% SPO
  - 2 Spokespeople: 1 SO, 1 SPO
  - 2 Technical Council chairs: 1 SO, 1 SPO
  - 8 Executive Team members: 3 SO, 5 SPO
  - 19 Governing Board members: 8 SO, 7 SPO
  - 18 Project L2 leads: 9 SO, 8 SPO

7 of the 11 members of the SO Planning Committee have leadership roles in CMB-S4.

Answer 6: Ground-Based Experiments

- SO/SPO are undoubtedly helpful to CMB-S4 ...
  - Valuable experience building & deploying similar hardware.
  - Valuable experience scaling data management from ~1% to ~10% of CMB-S4 data volume.
  - Valuable scientific input to the CMB-S4 observing strategy
    - survey footprints, SAT deployment, SAT/LAT survey coordination.
  - Valuable coordination between teams at each site.
  - Possible contribution of hardware and site infrastructure at the end of their missions.
  - Letters of commitment from both to share technical, scientific, and cost/schedule information.
- … as CMB-S4 is helpful to them …
  - Leveraging “pathfinder” status with agencies.
  - Letters of support from CMB-S4 for proposals.
  - Joint-funded positions & common research programs.
- … but neither SO or SPO is essential to CMB-S4
  - From its conception, well before either, CMB-S4 has represented an unprecedented scaling of already well-established technologies and methodologies.

Answer 6: Ground-Based Experiments

- SO/SPO are neither scientific nor technical competition:
  - CMB-S4 is a next-generation experiment compared to SPO/SO, starting observations after they have completed their nominal operations.
    - CMB-S4 is to SO/SPO as SO/SPO are to ACT/BK/PB/SPT.
  - CMB-S4 has an order of magnitude more detectors than either, and
  - CMB-S4 uniquely combines the scientific advantages of both sites.
    - See backup slides for the comparative science reach of SPO/SO/CMB-S4
  - CMB-S4 is uniquely supported by large-scale project management, systems engineering, and fabrication engineering, adding the resources of the DOE laboratories to the long-standing NSF program.
    - Eg. CMB-S4 reference construction plan involves 3 major new detector fabrication lines (ANL++, LBL/SeeQC, SLAC) and new module assembly & testing infrastructure (FNAL), alongside existing facilities.

Answer 6: Satellite Missions

- Space- and ground-based CMB experiments are inherently complementary
  - Space can cover the whole sky and support a wider range of observing frequencies.
  - Ground can target specific low-foreground sky patches and support higher angular resolution.
- LiteBIRD is highly complementary to CMB-S4
  - Same observing epoch.
  - Primary PGW targets are reionization ($l < 10$) and recombination ($l \sim 80$) bumps respectively
    - Possibility of independent confirmation of any detection
  - Neither requires the other, but both could enhance the other
    - LiteBIRD tau constraint improves CMB-S4 neutrino mass measurement.
    - CMB-S4 lensing signal improves LiteBIRD delensing.
    - Complementary microwave sky surveys (frequency/resolution).
    - Possibility of joint cosmological analysis.
  - Preliminary discussions about an MOU have been very positive; initial work on joint simulations.
  - Many people are members of both collaborations

Answer 6: Satellite Missions

- PICO is at a much earlier stage of development
  - The PICO decadal submission is one of ~10 demonstrating the broad range of science that could be supported were a Probe class of missions to be reinstated.
  - The PICO path to execution seems to be
    - Astro2020 recommends reinstating the Probe class of NASA missions.
    - Probe class is funded.
    - PICO wins the subsequent competition.
    - International partners make successful Mission of Opportunity proposals (ESA, JAXA, CSA, …)
    - PICO meets all of its mission development and deployment milestones.
  - Even if all of these steps are successful, it seems inevitable that PICO would occur after CMB-S4 (and LiteBIRD) have completed their missions.
- CMB-S4 members have been involved in developing the PICO concept; PICO members are active in CMB-S4.

Question 7:

What is the Basis of Estimate for the “$10M investment in a hybrid photovoltaic / battery / diesel power plant” (p34 of RFI response) as a backup to a site-wide power solution in Chile?

Answer 7: Basis of Estimate

- Our Basis of Estimate is a preliminary feasibility study done by Kraftwerk, a company that has photovoltaic installations in the area. It uses local weather data as input and creates a system with enough batteries and panels to reduce the need for diesel generation to about 50 days/yr.
    - Kraftwerk considers the study to be confidential. We may be able to provide further information under an appropriate confidentiality agreement.
    - An existing, much smaller, photovoltaic installation at the Toco site supporting a Universidad de Santiago experiment has been working well for the past 4 years.

Answer 7: Alternative Approach

- AUI has started a study of electrical power supply options for the Parque Astronomico Atacama (PAA) in Chile, with potential long-term goals including bringing the grid to the Chajnantor plateau and the PAA area.
  - The preliminary study is completed, identifying a handful of good options for further consideration.
  - Once the final report is available, AUI will hold a videoconference to present the major findings and plans for moving forward (~early February).
  - Implementation of a communal power system for the PAA appears technically feasible and will provide benefits for the existing and planned projects.
  - Funding, necessary approvals, and timescales are not yet defined.
  - AUI is working closely with ANID (successor to CONICYT) on this project.
  - Recent civil unrest has slowed progress on this.
- The CMB-S4 reference design does not depend on the AUI plan, but future designs could easily incorporate it to our advantage; AUI is our partner in Chilean site development.

Question 8:

Can the project team provide more information about the "in-kind contributions with a value of 10-15% of the project scope" that are "under discussion and expected" (per p4 of the RFI response)?

Answer 8: (repeat from Project slides)

- Existing/Planned LATs
  - SPO (NSF MSIP proposal; possible contributions from Germany, France)
  - SO
  - CCAT-prime
  - ELFS-S (EU Synergy proposal from Italy/Spain/UK/US for low frequency LAT)
- Existing/Planned SATs
  - BICEP Array
  - SO, SO-UK (UK STFC proposal)
- New In-Kind
  - Smithsonian Astrophysical Observatory partnering in delivering SATs
- Site Infrastructure
  - Atacama infrastructure coordination with SO (common site L2 lead), AUI (site partner)
  - South Pole infrastructure coordination with SPO (BICEP Array Tower, etc.), IceCube
- Data Management
  - Common software development & deployment with SO/SPO (e.g., SO NSF MSIP)

Question 9:

Does the project team's experience building and operating facilities at the South Pole suggest that sufficient logistical support of CMB-S4 activities (including transport) could become a limiting factor for the project?

Answer 9:

- Antarctic and South Pole logistics and infrastructure support limitations are important planning considerations and a project risk. These risks are mitigated by early identification of requirements and engagement with the NSF Office of Polar Programs (OPP) Antarctic Infrastructure and Logistics (AIL) Section and their contractor, ASC.
  - CMB-S4 submitted documentation on our requirements to OPP in 2018.
  - The CMB-S4 Mid-Scale Infrastructure (MSRI) award includes detailed planning for OPP support requirements assuming a future CMB-S4 MREFC project.
  - OPP scheduled a review of CMB and IceCube future field work plans on March 18, 2020
- OPP successfully supported construction of the South Pole Station Modernization (SPSM) MREFC project, the IceCube MREFC project, and the construction of the South Pole Telescope from 2000-2010. OPP worked closely with the projects to develop an integrated and optimized support plan.
- The South Pole Station and the McMurdo - South Pole traverse provide additional support capability and an over land transport option.

Question 10:

Has agreement been reached on sharing of intellectual property across the detector and readout fabrication centers?

Answer 10:

- Sharing information and expertise across the various detector & readout design, development, and fabrication centers is essential.
- All parties agree on the principles:
  - All parties should be able to communicate freely and openly
  - All parties should be able to re-use all of this collective work after CMB-S4
- A large amount of information is already in the public domain, so IP does not apply; “tricks of the trade” can be more guarded.
- Following a DOE review of CMB-S4 detector fabrication plans, we have established the CMB-S4 Detector Fabrication Group with representatives from all the potential fabrication sites (ANL, LBNL/SeeQC, SLAC, GSFC, NIST, JPL, UCB), which will work with the Project Office to:
  - Develop a single, coherent, detector fabrication plan by June 2020.
  - Produce prototype detectors which meet established acceptance criteria at multiple sites by November 2020.

Question 11:

What is the project team's approach to managing a large and diverse collaboration so that its size and complexity do not become a source of risk?

Answer 11: (repeat from Project slides)

- Key elements of the project delivery approach
  - Established collaboration governance structure
  - Well-defined and embraced project organization, the CMB-S4 Integrated Project Office, with clear lines of accountability for project development and delivery
  - Central core team of experienced project management and tecnical personnel
  - Collaborators, supported by experienced engineers, appointed to project delivery roles aligned with the Work Breakdown Structure (project organization aligned with the WBS)
  - Technical Baseline Development (TBD) group, chaired by John Ruhl, includes the Technical Committee co-chairs, Abby Vieregg and Jeff McMahon, and experienced project and technical experts, Gil Gilchriese and Dan Akerib, provide a strong bridge to the collaboration
  - Explicit institutional accountability for the lead NSF and DOE institutions and other key stakeholders through the Integrated Project Steering Committee
  - Collaboration meetings structured to provide an opportunity for the entire collaboration to engage in project planning
- The approach is similar to successful large particle physics experiments

Question 12:

Are the hardware and software capabilities necessary for generating transient science data products included at full scope within the project budget? Could bandwidth constraints on data transfer from the South Pole limit the effective use of that site's data stream for transient science?

Answer 12:

1. Are the hardware and software capabilities necessary for generating transient science data products included at full scope within the project budget?
    - All of the hardware and software for the baseline plan is included in the project scope; validation of the software and the data products is in the purview of collaboration scientists.
    - As noted above, this baseline may be expanded in consultation with the wider community; any such expansion would have to be costed, although it would undoubtedly be small compared to the overall project data management scope and cost.

2. Could bandwidth constraints on data transfer from the South Pole limit the effective use of that site’s data stream for transient science?
    - No. The project plan includes sufficient on-site computing at the South Pole to generate and analyze the daily maps, and the resulting maps and any identified events will place no strain on even the current bandwidth. This is currently being done with SPT-3G.

Question 13:

How, if at all, would the limited rate of data transfer from and limited access to the South Pole affect the rapidity with which a redeployment of SATs to Chile could take place?

Answer 13: Redeployment Schedule

Up to 16 months for SAT redeployment from South Pole to Chile; up to 8 months observing time lost.
Could redeploy up to three 3-shooter SATs in single season (full complement).

	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J
Decide to redeploy			■															
Arrange logistics; finalize Chile prep				■	■	■	■	■	■	■								
Remove from Pole											■	■	■					
Ship from Pole to Chile													■	■	■			
Install in Chile															■	■	■	■

Answer 13: Data Transfer Dependency

- With no improvement to current satellite data transfer capabilities, we can return daily maps and other diagnostics to monitor instrument performance.
- Full timestream data would be returned at the start of the austral summer (November).
- The r analysis is not quick-turnaround, and is typically done on data sets with significantly improved statistical power, e.g., year-by-year.
- It seems unlikely that a robust detection could “sneak up” on us between March and October.

Backup Comparative Science Slides

Comparative Science Reach

- Comparing forecasts from different experiments can be challenging, particularly when different assumptions are made
  - Instrument configuration & performance
  - Observing conditions & efficiencies
  - Systematics residuals, including foregrounds & lensing.
  - Degrees of optimism (e.g., baseline & goal forecasts, foreground complexity, …)
- The comparisons here are constructed to be as like-with-like as possible:
  - Use single-site configurations to factor out most variables:
    - Atacama wide LAT; South Pole deep LAT; extremal SAT distributions (18-0, 0-18)
  - Where possible, use the same methodology and assumptions to define the survey strategy and forecast the resulting parameters across all the experiments at a site.
- Sensitivity ratios (integrated detector-years, instantaneous detectors)
  - Wide-area LAT SO-N:SO-E:CMB-S4 - 1:3:11 integrated, 1:2:8 instantaneous
  - Ultra-deep LAT SPO:CMB-S4 - 1:10 integrated, 1:7 instantaneous
  - SAT SPO:SO-N:SO-E:CMB-S4 - 1:2:7:13 integrated

Primordial Gravitational Waves

sigma(r=0) x 10^3	End of Operations	Lensing Residual			Methodology
		10%	25%	50%	
SPO	2023	-	2.50	-	Buza/SPO
SO-Nominal	2027	-	1.73	2.08	Errard/SO
SO-Enhanced	2032	-	0.87	1.14	Errard/SO
CMB-S4: Atacama SATs	2034	-	0.56	0.96	Errard/SO
CMB-S4: Atacama SATs		-	0.57	-	Buza/SPO
CMB-S4: Pole SATs		0.40	-	-	Buza/SPO

Best case forecasts for σ(r=0), fixing all variables except each experiment's sensitivity and each site's survey area (no site-dependent efficiency, atmosphere, etc).

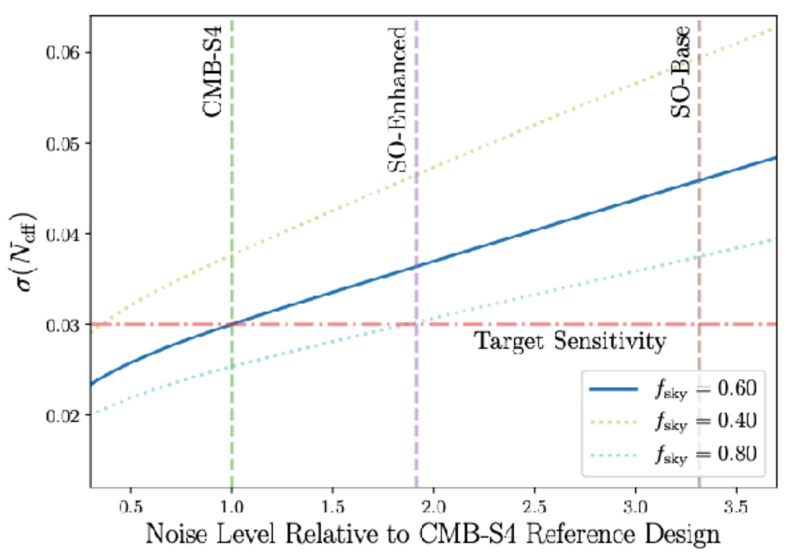
Only CMB-S4 can:

a) achieve a 5σ detection of the Starobinsky and Higgs inflation models with r=0.003, and

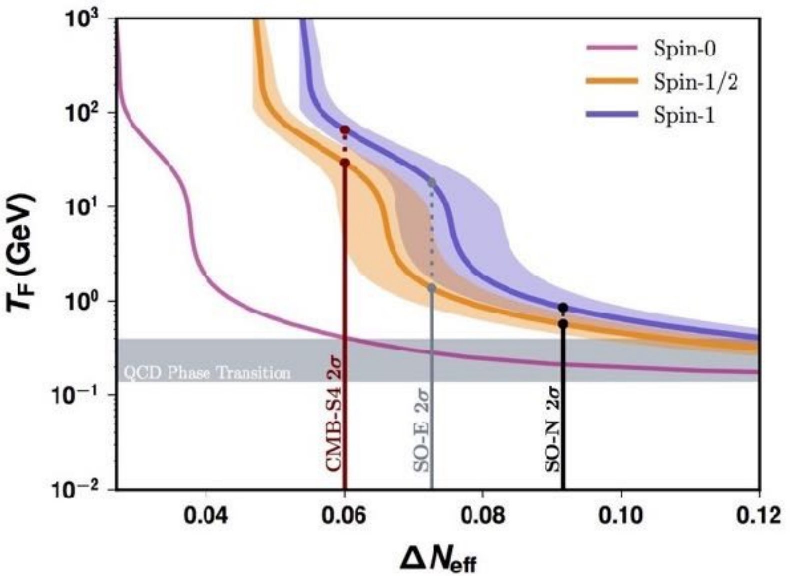
b) exclude at 95% confidence all models that

- naturally explain the tilt of the spectral index
- have a characteristic field scale ≥ the Planck mass.

Light Relics



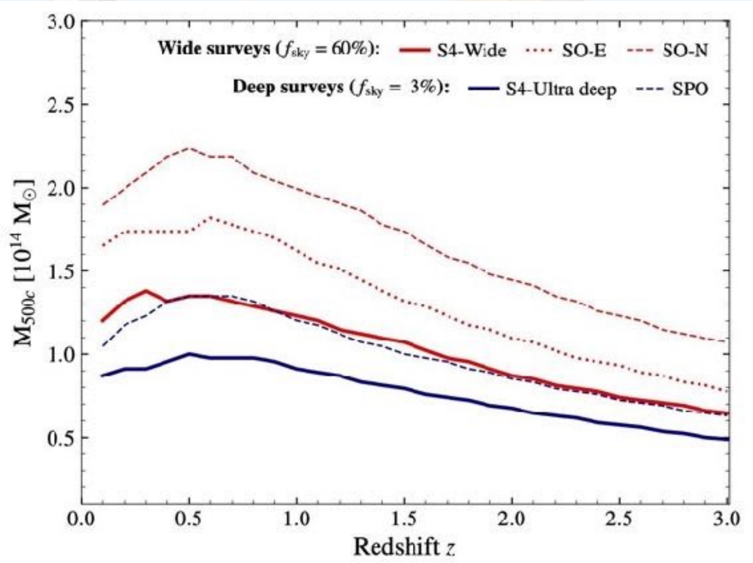
SO and CMB-S4 sensitivity to N_{eff} for various sky coverages.



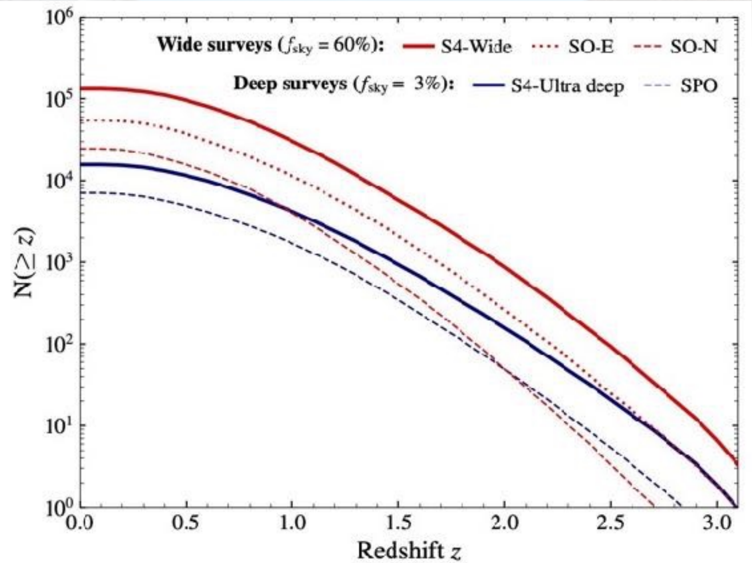
SO and CMB-S4 sensitivity to light relics of different spins for f_{sky}=60%

Sensitivity to a higher freeze-out temperature means sensitivity to particles with weaker couplings.

High Redshift Galaxy Clusters



Mass threshold with redshift for the wide and ultra-deep CMB-S4 LAT surveys, compared with SO and SPO respectively.



Number count with redshift for the wide and ultra-deep CMB-S4 LAT surveys, compared with SO and SPO respectively.

Redshift 2-3 is discovery space for virialized clusters.

GRB Afterglows

- Event rate scales as $S^{-1.5}$ (Euclidean)
- Event resolution (#light curve bins) scales as $(S/N)^2$

For the wide survey

- CMB-S4 event rate is 5x SO-N, 3x SO-E, event total is 7x SO-N, 4x SO-E
- CMB-S4 event resolution is 8x SO-N, 4x SO-E

Note:

- This is Poisson-statistic discovery science - information increases linearly with events.
- CMB-S4 should be 5-10x better than SKA simply due to observing frequency.

CMB-S4 Follows Historical Scaling