Evaluation of P5 Report Execution Status
CMB-S4

Co-Spokespeople: John Carlstrom & Julian Borrill
Project Director: Jim Yeck
on behalf of the CMB-S4 Collaboration
Outline

- CMB-S4 Science Goals, Why CMB-S4?
- Vision, Genesis, and Trajectory, How did we get here?
- Instrument Design, What is CMB-S4?
- Science Collaboration and Integrated Project Office, Who are we?
- Status and Project Plan
Why CMB-S4? To make transformational advances

- CMB-S4 is designed to 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 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, and by opening up the mm-wave transient universe for **Multi-Messenger Astrophysics**.
Why CMB-S4? To make transformational advances

Gravitational waves generated by Inflation will induce unique B mode CMB polarization

Energy scale of inflation; quantum gravity

CMB released at 380,000 years

CMB provides backlight to probe all matter in the universe and the growth of structure.

CMB provides measure of all contributions to the energy density of the Universe, independent of particle interaction cross sections.
Why CMB-S4? To make transformational advances

<table>
<thead>
<tr>
<th>Inflation: $\sigma_r$</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>CMB-S4 Goal</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>0.1</td>
<td>0.003</td>
<td>0.0005</td>
<td>Detect or rule out the simplest and most compelling classes of inflationary models.</td>
</tr>
<tr>
<td><strong>Light Relativistic Species: $\Delta N_{\text{eff}}$ (95% upper limit)</strong></td>
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<td>Detect or rule out all light relic particles that decoupled after the start of the QCD phase transition</td>
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<td>0.28</td>
<td>0.1</td>
<td>0.06</td>
<td>3σ detection of the neutrino mass sum</td>
</tr>
<tr>
<td>Neutrino Masses: $\sigma_{\Sigma m}$</td>
<td>0.20eV</td>
<td>0.04eV</td>
<td>0.020eV</td>
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<td><strong>lower limit $\Sigma m$</strong></td>
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<tr>
<th>Survey Weight [$\mu$K$^{-2}$]</th>
<th>Stage 2</th>
<th>Stage 3</th>
<th>Stage 4</th>
<th>Requirement for S4</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>$10^5$</td>
<td>$10^6$</td>
<td>$10^8$</td>
<td>500,000 detectors on multiple platforms with sensitivity from $10^4$ to 1’ scales</td>
</tr>
<tr>
<td>Detector Count</td>
<td>~1,000</td>
<td>~10,000</td>
<td>~500,000</td>
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</table>
Genesis with the 2013 Snowmass Physics planning exercise

The CMB community advocated CMB-S4 -- a single, multiagency, ground-based experiment to obtain sufficient sensitivity to achieve unique and fundamental science goals.

The technology had matured sufficiently to design the definitive, ground based CMB experiment. The challenge is in scaling up to unprecedented levels.
CMB-S4 Design in a nutshell
Nested deep-wide and ultra-deep-narrow surveys

- **Deep wide $N_{\text{eff}}$ and Legacy Survey** with 2 x 6m telescopes targeting ~60% of sky with 240,000 detectors over 6 bands. Conducted 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.

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

6m large telescopes, e.g., like Simons Obs.
Atacama CMB (Stage 3)

6m Atacama Cosmology Telescope

Simons Array
(POLARBEAR 2.5m x 3)

CLASS
(1.5m x 2)

Keck Array
(0.55m x 4)

BICEP3
(0.55m)

South Pole CMB (Stage 3)

10m South Pole Telescope

Simons Observatory is coming.

Photo: Cynthia Chiang

Photo: Debra Kellner
A lot of detectors, a lot of data, large cryogenics, unprecedented precision required…

LAT cryostat
19 optics tubes
(each tube is dichroic, except 20GHz)

SAT cryostat
3 optics tubes
(each tube is dichroic)
Ultra-deep $r$ survey

Deep Wide Survey

Large Aperture Telescope (LAT)

Small Aperture Telescopes (SATs)

20 GHz
27/39 GHz
93/145 GHz
225/278 GHz

30/40 GHz
85/145 GHz
95/155 GHz
220/270 GHz

27/39 GHz
93/145 GHz
225/278 GHz
CMB-S4 requires 500 science grade detector wafers

Detector wafers and modules


Input/Output (IO) wafer. Routes Input/Output lines.

Detector Interface (DI) wafer (Nyquist inductors, shunt resistors) w. mux chip

Backshort wave plate w/ A4K shield.
Backshort wave guide.

Detector wafer.

Feedhorn array. Includes mechanical mounting flange/feet.

150 mm detector wafer
CMB-S4 power spectra

Angular scale $\theta$ [degrees]

$10^{4.5} - 10^{5}$

Temperature

$10^{3}$

E modes

damping tail: $N_{\text{eff}}, n_s$

Cosmological parameters

$10^{2}$

Lensing B modes

CMB lensing: $\Sigma m_\nu$

primordial

gravitational waves

Multipole number $\ell$
CMB-S4: Light Relics, $N_{\text{eff}}$

$N_{\text{eff}}$ constraint leads to orders of magnitude improvement of constraint on the freeze-out temperature of any thermal relic.

The diagram shows the freeze-out temperature $T_F$ in GeV on the x-axis, with $N_{\text{eff}}$ on the y-axis. The graph includes different lines for spin-1, spin-$\frac{1}{2}$, and spin-0 particles, with shaded regions indicating current limits and CMB-S4 limits. The QCD phase transition is marked, and the freeze-out temperature is divided into early and late times.
CMB-S4 will detect or exclude models that naturally explain the observed value of $n_s$.

Detection of $r$ would give the energy scale of inflation, provide evidence for the quantization of gravity, and fundamental insights into physics and cosmology.
CMB-S4: Trajectory

• 2014: Recommended by Particle Physics Project Prioritization Panel (P5); CMB-S4 project phasing in as LSST phases out.

• 2015: NAS/NRC report calls out CMB-S4 as a strategic priority for Antarctic Science

• 2017 DOE & NSF sponsored CMB-S4 Concept Definition Task Force (CDT report) enthusiastically accepted by AAAC

• 2018 *Official* Collaboration established and elections held

• 2018 Integrated Project Office (IPO) started

* AAAC: Astronomy and Astrophysics Advisory Committee, FACA cmt advises NSF, DOE and NASA
Recent progress and next goal

- **CMB-S4 Science Case, Reference Design, and Project Plan** (aka Decadal Survey Report, 282 pages) posted July 9, 2019
- **CMB-S4 Decadal Input White Paper** submitted July 10, 2019 and detailed RFI response submitted Nov 8th, 2019
- **CMB-S4 project established:**
  - Achieved DOE Critical Decision CD-0 for a Major Item of Equipment (MIE) project on July 26, 2019
  - Awarded NSF MSRI-RI Design and Development grant to help get on the Major Research Equipment & Facilities Construction (MREFC) track, started Oct 1, 2019
- **Next goal:**
  - Advance from Reference Design to Baseline Design for DOE CD-1 and NSF PD, targeting April 2021
  - Transition to Permanent Integrated Project Organization
    - U. Chicago is Host for NSF MREFC preparation
    - DOE “Host/Lead Lab” is required, planned for March 2020
CMB–S4 Collaboration

- CMB-S4 twice a year major workshops since 2015
- CMB-S4 working groups have advanced the Science case and Technology areas; see wiki on cmb-s4.org
- Technical groups integrated with the Integrated Project Office (IPO)
- Dedicated community; a lot of contributed effort.
CMB-S4 Collaboration

- Twice yearly CMB-S4 workshops
- Communications through many telecons, CMB-S4 wiki, etc.
- Formally established in Spring 2018
  - 217 Members
  - 76 Institutions & 12 Countries
  - 65 members have leadership roles
- Integrated with the IPO
- Produced the
  - CMB-S4 Science Book
  - CMB-S4 Technology Book
  - Decadal Survey Report (287 pages, 82 figures):
    CMB-S4 Science Case, Reference Design, and Project Plan
  - Decadal Survey Project White Paper (10 pages)
  - Submitted RFI-I response to Decadal Survey
IPO – Primarily Contributed Support

Other Partners

DOE
High Energy Physics

DOE/NSF

Julian Borrelli (BNL/Berkeley) & John Carlstrom (Chicago)

Technical Coordination
Jeff McMahon (Chicago) & Abbey Viehage (Chicago)

Education & Public Outreach Committee Chair
Colin Bischoff (Cincinnati)

Integrated Project Steering Committee:
ANL, BNL, FNAL, LBNL, SLAC, AUI, Chicago, Smithsonian.
@EFL/Alliance

Savannah,
Mary,
Andrew,
Joanne Heibel (SLAC)

Project Manager - R&D/C&I: Brenna Flaugher (FNAL)
Project Manager - DRM: Mark Reichenbacher (SLAC-Rtk)
Project Manager - NSF: Jeff Zwick (Chicago)

Critical Baseline Development:
EN Monte (SLAC/Stanford), Gil Gilchrisse (LBNL), John Ruhl (Systems & Controls; Kathy Bailey, ANL)
Joint Engineering Management: Nadine Kurita (SLAC), Jim G.
Town Coordination: Charles Law

Education & Public Outreach: TBD

COLLABORATION

PROJECT DEVELOPMENT
1.02
Brannon Beigher (FNAL), Jeff Zwick (Chicago)

READOUT
1.04
Clayton Chang (ANL/Chicago)
Kent Irwin (SLAC/Stanford)
Arnold Suzuki (BNL)

MODULE ASSEMBLY & TESTING
1.05
Brad Benson (FNAL/Chicago)

LARGE APERTURE TELESCOPES
1.06
John Carlstrom (UChicago/ANL)
Miko Narain (Cornell)

SMALL APERTURE TELESCOPES
1.07
John Kovac (Harvard)
Akito Kusaka (LBNL/Paris)

DATA ACQUISITION & CONTROL
1.08
Laura Nowak (Yale)
Nathan Whitehorn (UCLA)

DATA MANAGEMENT
1.09
Julian Borrelli (BNL/Berkeley)
Kom Arnold (UCSD)

CHILE INFRASTRUCTURE
1.10
Kom Arnold (CWRU)

SOUTH POLE INFRASTRUCTURE
1.11
John Ruhl (CWRU)

INTEGRATION & COMMISSIONING
1.12
John Ruhl (CWRU)
**L2 Leads – Currently 100% Contributed Support**

<table>
<thead>
<tr>
<th>Detectors</th>
<th>Readout</th>
<th>LATs</th>
<th>SATs</th>
<th>Data Acquisition</th>
<th>Data Management</th>
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<tbody>
<tr>
<td>Clarence Chang</td>
<td>Amy Bender</td>
<td>Mike Niemack</td>
<td>John Kovac</td>
<td>Laura Newburgh</td>
<td>Tom Crawford</td>
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<tr>
<td>Toki Suzuki</td>
<td>Zeesh Ahmed</td>
<td>John Carlstrom</td>
<td>Akito Kusaka</td>
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<td>Julian Borrill</td>
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<td>Kent Irwin</td>
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**S. Pole Site + I&C**

- John Ruhl

**Chile Site + I&C**

- Kam Arnold

**Modules & Testing**

- Brad Benson

*NSF MSRI will cover summer salary for some L2 managers.*

Includes:
- 1100 activities, 1928 relationships
- 6 Level 1, 20 Level 2, and 299 Level 3 Milestones

<table>
<thead>
<tr>
<th>Control Account</th>
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<tbody>
<tr>
<td>1.01 - Project Management</td>
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<tr>
<td>1.02 - Pre-CD1/PDR</td>
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<td>1.03 - Detectors</td>
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<td>1.04 - Readout Electronics</td>
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<tr>
<td>1.05 - Module Assembly and Test</td>
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<td>1.06 - Large Telescope</td>
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<td>1.07 - Small Telescope</td>
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<td>1.08 - Observation Control and Data Acquisition Systems</td>
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<td>1.09 - Data Management</td>
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<td>1.10 - Chile Infrastructure</td>
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<td>1.11 - South Pole Infrastructure</td>
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<td>1.12 - Integration and Commissioning</td>
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CMB-S4 Project Schedule Overview

FY2029 end date includes 1 year of schedule contingency

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
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<td>LAT</td>
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<td>SAT</td>
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<td>Site, ISc</td>
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Critical path is fabrication and testing of detectors.
The TPC escalated to year of expenditure and including 35% contingency is $600M.

In-kind contributions with a value of 10-15% of the project scope are under discussion, and expected. They would lower cost to agencies.

Project is funding limited up to CD-1/PD (June 2021)

Technically limited from 2022, except high level milestones limit start of activities (i.e. Start of Construction 2023)
**NSF/DOE Project Development/Decision Timeline**

<table>
<thead>
<tr>
<th>Year</th>
<th>NSF</th>
<th>DOE</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY2018-19</td>
<td>Interim Project Office Established</td>
<td></td>
<td>Coordinated pre-project development</td>
</tr>
<tr>
<td>Q3 FY2019</td>
<td>Initial Input to Decadal Survey White Paper</td>
<td>Critical Decision 0 July 2019</td>
<td>Reference Design (NSF Conceptual Design) and Initial Project Plans</td>
</tr>
<tr>
<td>Q4 FY2019</td>
<td>NSF MSRI award to start Preliminary Design.</td>
<td>DOE Lead Laboratory Q2 – March 1, 2020</td>
<td>Permanent Integrated Project Organization</td>
</tr>
<tr>
<td>FY2020</td>
<td>NSF Lead Institution Q1 - October 1, 2019</td>
<td>Decadal Survey Report Forecast – February 2021</td>
<td>NSF scientific merit review</td>
</tr>
<tr>
<td>Q2 CY2021</td>
<td>Decadal Survey Report Forecast – February 2021</td>
<td></td>
<td></td>
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<tr>
<td>Q3 FY2021</td>
<td>PD Stage Concluded Provisional Report – 4/1</td>
<td>CD1/3a Approval Review – 4/1</td>
<td>Coordinated agency review plans</td>
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<tr>
<td>FY2022</td>
<td>Final Design Proposal Q1 FY2022</td>
<td>CD2/3b Approved Q2 FY2022</td>
<td>Potential MREFC budget request approval 08/21</td>
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<tr>
<td>Q4 FY2023</td>
<td>FD Complete</td>
<td>CD3 Approved</td>
<td>NSB Approval</td>
</tr>
<tr>
<td>Q1 FY2029</td>
<td>MREFC Project Complete</td>
<td>CD4 Approved</td>
<td>Schedule includes 1 year of float (Q1 FY28 Early Finish)</td>
</tr>
</tbody>
</table>
CMB-S4 is launched and continues to gain momentum

- It will deliver the transformational science goals first envisioned in Snowmass / P5.
- We are on the path to baseline design for CD-1/PD in April 2021.
- Project plan is in place and the team is in executing.
- Need funding to ramp up. Collaborators are ready to bet their careers, we need to enable their success with development support.
Extra slides
CMB-S4: Neutrino mass scale

Cosmology (current)
(95% C.L.)

Inverted Hierarchy

Cosmology (forecast)

Normal Hierarchy

Cosmology (forecast)

LAB (forecast)
(90% C.L.)

Dvorkin, et al. 1903.03689

CMB + BAO + cosmic variance-limited measurement of $\tau$
The path forward is through extremely challenging multi-frequency polarization measurements.
Multiple frequency channels to remove foregrounds

Planck polarized all sky maps at seven frequencies

CMB S-4 Detector Fabrication Review, August 22-23, 2019

Planck I 2018
CMB detector requirements and specifications:

**Figure 67.** Calculated atmospheric brightness spectra (at zenith) for the South Pole at 0.5mm PWV and Atacama at 1.0mm PWV (both are near median values). Atmospheric spectra are generated using Ref. [563]. The tophat bands are plotted on top of these spectra, with the height of each rectangle equal to the band-averaged brightness temperature using the South Pole spectrum.