CMB-S4

Concept Definition Task

Force Update

AAAC, NSF

2017 June 22

Charge To the CDT

Excerpt from the letter to Buell from three NSF Divisions and DOE HEP requesting the AAAC to 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".

The CMB-S4 CDT is asked to develop a concept for implementing a ground-based CMB-S4 experiment. The CDT will take as input the community CMB-S4 Science Book and any further community information as appropriate, and will consider the global landscape of CMB experiments (including ground, balloons, and space).

Specifically, the CDT is asked to deliver:

- The Science Requirements and their rationale
- Measurement and Technical Requirements derived from the Science Requirements
- Project Strawman Concept
- Options and Alternatives (prioritized to the extent possible) for:
  - Concept design (e.g. sites, telescopes, detectors)
  - Concept staging and schedule
  - Collaboration and Data models and interfaces
- R&D development needed, with priorities, to demonstrate technical readiness
- Cost ranges for the strawman concept, including explanations for how they were developed.

The CDT should provide a report on the Science and Measurement Requirements to the AAAC by June 2017 and a final report to AAAC by October 2017 for consideration. In accordance with Federal Advisory Committee Act (FACA) rules, the reports will be discussed and approved by the AAAC before formal transmittal to the agencies.

CDT Members

CDT

Julian Borrill	LBNL
John Carlstrom	Chicago
Tom Crawford	Chicago
Mark Devlin	Penn
Jo Dunkley	Princeton
Raphael Flauger	UCSD
Brenna Flaugher	FNAL
Shaul Hanany	U Minnesota
Kent Irwin	Stanford/SLAC
Bill Jones	Princeton
Brian Keating	UCSD
John Kovac	Harvard
Akito Kusaka	LBNL
Charles Lawrence (Chair)	JPL
Adrian Lee	Berkeley/LBNL
Jeff McMahon	Michigan
Mike Niemack	Cornell
Steve Padin	Chicago
Clem Pryke	Minnesota
Suzanne Staggs	Princeton
Ed Wollack	GSFC

Contacts:

Kathy Turner	DOE
Rich Barvainis	NSF
Brian Keating	AAAC

Advisory Board:

Lloyd Knox	UCD
Sarah Church	Stanford
Amber Miller	USC
Lyman Page	Princeton
John Ruhl	CWR
Martin White	Berkeley

Introduction

- The CDT has had weekly telecons and four face-to-face meetings since December. A final pre-report face-to-face meeting is scheduled for the end of August.

- The Technology Book has been completed by the CMB-S4 collaboration. It and the Science Book are both available on-line.

  https://arxiv.org/abs/1706.02464 http://arxiv.org/abs/1610.02743

- Initial version of science and measurement requirements completed

  - Supported by new and more realistic simulations

- Synergies with other measurements/experiments have been considered in science requirements

- Costing model well underway

- Starting to consider strawman concept options, R&D development needed

Science — I

- Since the first detection of the CMB over 50 years ago, CMB measurements have continuously transformed our understanding of the early universe.
- Measurements of the CMB by ground-based, balloon, and satellite experiments have determined the age and composition of our universe, and provide strong evidence that the seeds of structure are quantum-mechanical.
- Observations have nearly exhausted the information accessible in primary temperature anisotropies, but with "Stage 3" experiments, precision measurements of polarization, lensing, and secondary effects have just begun.
- The "Stage 4" experiment CMB-S4 is the natural next step for ground-based CMB measurements, and will transform our understanding of the early universe and of particle physics yet again.

Science — II: Gravitational Waves

- CMB-S4 will be exquisitely sensitive to gravitational waves at recombination.
- If observed, these gravitational waves are a pristine relic of the primordial universe.
- In the foreseeable future, their imprint on the polarization of the CMB is our only way to detect them.
- These gravitational waves are independent from density perturbations, and a detection would provide a new window onto the early universe.

Science — III: Inflation 1

- Many models of inflation predict a gravitational wave signal large enough to be detected with CMB-S4.
- According to inflation, primordial gravitational waves arose as quantum fluctuations in the metric of spacetime.
- As a consequence, a detection of gravitational waves with CMB-S4 would provide insight into quantum gravity.
- In addition, a detection would measure the expansion rate and energy density during inflation.

Science — III: Inflation 2

- In the absence of a detection, constraints from CMB-S4 would rule out widely-studied classes of inflationary models.
- CMB-S4 will measure the polarization of the CMB on small scales with unprecedented precision.
- This will reduce uncertainties on many other primordial observables (e.g., primordial power spectrum, non-Gaussianity, isocurvature modes) by a factor of 2–3.

Science — IV: Light Relics

- CMB-S4 will explore and constrain a wide range of extensions of the standard model currently explored in the particle physics community.
- Many well-motivated extensions of the standard model to higher energies predict light, long-lived particles.
- CMB-S4 will be sensitive to light relics even if they interact too weakly to be detected in lab-based experiments.
- CMB-S4 will provide the most robust and precise cosmological constraints on light relics.

Science — V: Neutrinos

- Neutrinos are the least explored corner of the Standard Model of particle physics.
- A major effort is underway to study their properties in short- and long-baseline as well as neutrino-less double beta decay experiments.
- CMB-S4 will probe the properties of neutrinos in a way that is important and complementary to lab-based experiments.
- CMB-S4 will provide a measurement of the sum of neutrino masses through weak gravitational lensing of the CMB even for the minimum mass in the normal mass hierarchy.
- CMB-S4 will independently measure the sum of neutrino masses through cluster counts, with comparable sensitivity.

Science — VI: Evolution of Cosmic Structure

- CMB-S4 will determine the impact of feedback processes on the distributions of dark and baryonic matter in the Universe, by measuring the thermodynamic profiles of the ionized gas in galaxies, groups, and clusters.

- CMB-S4 will measure the growth of cosmic structure with galaxy clusters, enabling tests of modified gravity and dark energy in a complementary way to LSST.

- CMB-S4 will provide a legacy-class high-z ($z > 2$) cluster sample that will be the definitive target list for astrophysics studies with other experiments (e.g., JWST, LSST, Euclid, WFIRST, Athena).

- CMB-S4 will determine the duration of reionization using the kSZ effect.

Science Goals: Design Drivers & "Free" Science

- Design drivers:
  - Primordial gravitational waves and inflation
  - Light relics
- "Free science":
  - Neutrino mass measurements
  - Measurement of the evolution of cosmic structure
  - ...

Simulations

Science $\overset{}{\underset{\text{sims}}{\longleftrightarrow}}$ Measurements $\overset{}{\underset{\text{sims}}{\longleftrightarrow}}$ Hardware

- The fidelity of the inferences depends on the fidelity of the simulations.
- We've worked hard on improving the fidelity of the simulations, in particular trying to capture the real-world complexities of foregrounds and systematic errors
  - Cannot simulate either foregrounds or systematics exactly. The goal is to be representative.
  - Sims for inflation science are map-based, to be able to represent the serious non-Gaussianity of foregrounds and systematics.
- Now implementing improved dust and systematic residuals
  - Realistic low-frequency foregrounds still being developed
- So far, no major surprises or cliffs have been seen in more realistic sims.

Costing — I

- Approach
  - Parametric model supports various experiment configurations

    various telescope sizes and types

    number of cameras per telescope

    number of detectors at each wavelength in each camera
  - Cost estimates based on

    scaling from Stage-2 and 3 experiments

    quotes for current projects

    expert opinion
  - Cost uncertainty based on

    scatter between several estimates for each major component

    DOE practice for contingency vs. maturity of design
- Status
  - Cost models for telescopes, cryostats, and detectors are well developed. Models for pre-fabrication development, data management, the analysis pipeline, and assembly, integration, test, and commissioning are preliminary.
  - Missing: pre-project R&D

Costing — II: WBS

1. Management (project manager, EVMS project controls, L2 and L3 managers, annual NSF/DOE reviews, directors reviews, etc.).
   Estimated as a percentage of WBS items 2–10.
2. Systems engineering
3. Chile site preparation
4. South Pole site preparation
5. Telescopes
   - Large
   - Small
6. Cryostats
   - For large telescopes
   - For small telescopes
7. Detectors and readout
8. Data acquisition
9. Data and pipeline management
10. Integration
11. Commissioning

Costs from Stage 3 projects provide the basis of estimate for WBS items 3–8.

Costing — III: Reviews

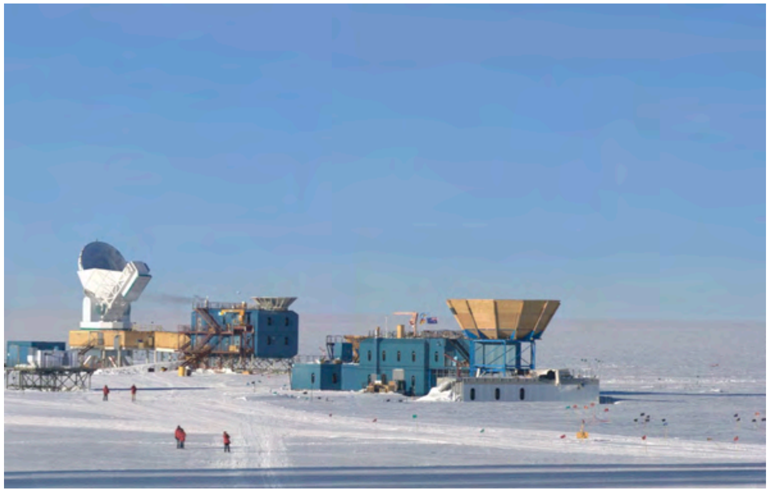
- Ongoing internal review by CDT
- Reviews by DOE experts who are not on CDT
- September "red team" review

Report

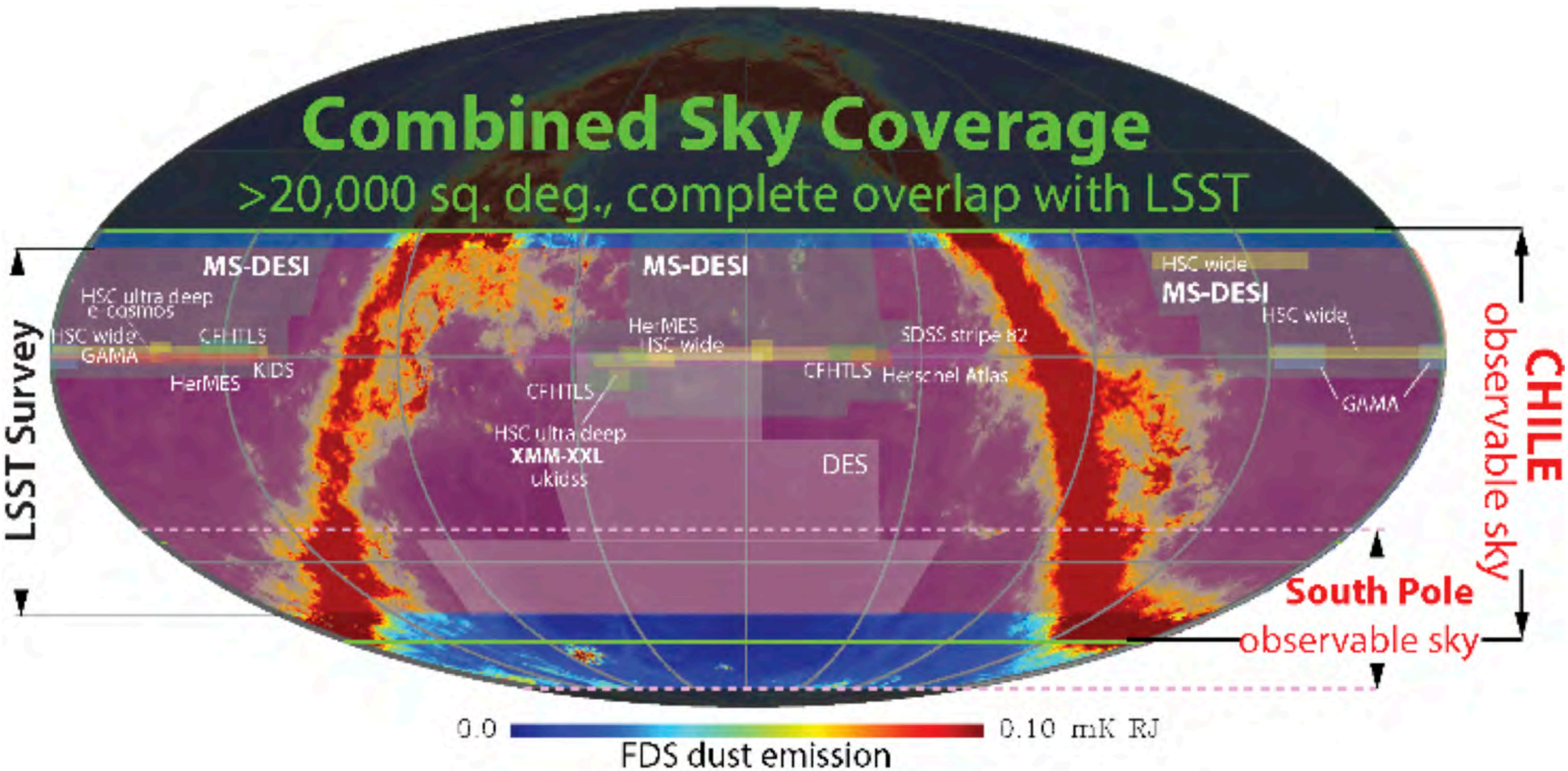
Major Design Features

- CMB-S4 will be a single experiment and collaboration

- Two sites: South Pole and Atacama
  - South Pole has the best atmospheric conditions of any developed site
  - Atacama is also an excellent site and is needed to get to $f_{\text{sky}} = 0.4$



Sky Coverage



– Low foreground regions - inflation and lensing

– Overlap with optical surveys —- combine with LSS measurements for neutrinos, dark energy, dark matter, and astrophysics.

The End

- We have a settled structure for the science and measurement requirements
  - Numbers are still tentative
  - Simulations are iterating to higher levels of realism
- We will have the final report in October, as promised!