CMB-S4 CDT Report

Overview

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Introduction

- Observations of the CMB have taught us an enormous amount about the early Universe
- CMB-S4 is the natural next step in CMB experiments
- At the request of the NSF and DOE, the Concept Definition Task Force (CDT) was set up to represent the CMB community and recommend a concept design for CMB-S4.

Excerpt from the letter 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":

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.

- We identified three science goals

Science I

- Two goals become design-driving science requirements, crossing clear critical science thresholds that cannot be reached with the upgrades planned for current (Stage 3) experiments
  - To test many of the simplest models of inflation, including those based on symmetry principles, that occur at high energy and large inflaton field range, CMB-S4 will detect or constrain the imprint of gravitational waves on the CMB polarization anisotropy, quantified by the tensor-to-scalar ratio r.

If $r = 0: \ \sigma(r) \leq 0.0005; \quad r < 0.001, 95\%$ confidence in four years

If $r = 0.003:$ measure at equivalent 4σ in four years

  - To probe the thermal history of our universe and detect or constrain the imprint of a wide range of possible low mass relic particles on the small scale CMB temperature and polarization anisotropy.

$\Delta N_{\mathrm{eff}} \leq 0.06, \ 95\%$ confidence in seven years

Science II

- A third science goal is achievable with the hardware implemented for the first two

  – Provide a legacy survey of nearly half the sky at centimeter to millimeter wavelengths.

    Gravitational interactions with all matter and EM interactions with baryonic matter leave signatures in the CMB as it traverses the Universe.

    Neutrino masses: In combination with large-scale-structure surveys.
    Independently through cluster counts.

    Evolution of cosmic structure: Trace the distribution of normal, baryonic matter in its ionized phase through the thermal SZ effect. Feedback.
    Map the total mass distribution through lensing of the CMB. Cross-correlations with other astrophysical tracers.

    Evolution of massive galaxy clusters from $z \approx 3$ to the present.

    Map the momentum field of LSS through kinetic SZ measurements.

    Catalogs of clusters and high-z galaxies.

  – Will have broad benefit to both the cosmological and astronomical communities

Simulations

- Simulations are the basis for the flowdown from science requirements to measurement requirements to instrument and experiment requirements
  - Worked hard on improving realism of foreground and instrumental systematic effects
  - Drew on a variety of sources to incorporate multiple effects
  - Projections are based on achieved, end-to-end performance over years of observing at two sites

Strawperson Concept I

The design of CMB-S4 is conservative, using an evolutionary approach grounded in things we know how to build

- A four-year r survey covering 3% (up to 8%) of the sky using
  - Fourteen 0.5-m-aperture cameras, each one measuring two of eight frequency bands from 30 to 270 GHz, and
  - A 6-m-class telescope covering seven frequency bands from 20 to 270 GHz
  - Broad frequency coverage is needed to deal with foregrounds
  - Low resolution for primordial B modes; high resolution needed for delensing
  - Total detector count is about 170,000 for the 0.5-m cameras, and 70,000 for the 6-m telescope.
- A seven-year $N_{\rm eff}$ survey covering 40% of the sky using
  - Two 6-m-class telescopes covering seven frequency bands from 20 to 270 GHz
  - Total detector count is about 140,000

Strawperson Concept II

- Two sites: South Pole and Atacama
  - South Pole has superior atmospheric stability, and offers continuous observations of a small, low-foreground patch of the sky. But it more restricted in the available sky coverage.
  - Atacama is also exceptional for mm-wave observations, and provides access to the 40% sky coverage needed for N_{eff} and the legacy survey.
- The optimum distribution of the 6-m and small-aperture cameras between the two sites has not been determined, and has little effect on cost.
- No new inventions are required. All technologies are based on existing capabilities
  - Pre-Project development investments would reduce risk and possibly cost

Cost

- We developed a comprehensive cost model to capture all aspects of the experiment
  - Pre-Project development; the construction Project; and post-Project operations
  - Incorporated all of the experience of the Stage-2 and Stage-3 experiments, plus help from project-costing experts at four DOE labs (Argonne, Fermi, Lawrence Berkeley, SLAC), plus a review of cost methodology with senior DOE/NSF project managers.
  - Much greater fidelity than simply "scaling up"

Estimate	Cost including contingency [$M in 2017]	Contingency [%]
Pre-Project development	9	
Construction Project	412	45
Annual operations		
Sites	18	100
Science analysis	14	150

Collaboration

- CMB-S4 will be a single experiment and collaboration

- The CDT report is built on a foundation of work by the CMB-S4 Collaboration, which was fully engaged and contributed throughout the process.

- The Collaboration is in the process of setting up a more formal and operational structure. It is eager, willing, and definitely will be ready for its role in building, operating, and extracting secrets of the Universe from CMB-S4!

Backup

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.