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The Simons Array CMB Polarization Experiment

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ABSTRACT

The Simons Array is a next generation cosmic microwave background (CMB) polarization experiment whose science target is a precision measurement of the B-mode polarization pattern produced both by inflation and by gravitational lensing. As a continuation and extension of the successful POLARBEAR experimental program, the Simons Array will consist of three cryogenic receivers each featuring multichroic bolometer arrays mounted onto separate 3.5m telescopes. The first of these, also called POLARBEAR-2A, will be the first to deploy in late 2016 and has a large diameter focal plane consisting of dual-polarization dichroic pixels sensitive at 95 GHz and 150 GHz. The POLARBEAR-2A focal plane will utilize 7,588 antenna-coupled superconducting transition edge sensor (TES) bolometers read out with SQUID amplifiers using frequency domain multiplexing techniques. The next two receivers that will make up the Simons Array will be nearly identical in overall design but will feature extended frequency capability. The combination of high sensitivity, multichroic frequency coverage and large sky area available from our mid-latitude Chilean observatory will allow Simons Array to produce high quality polarization sky maps over a wide range of angular scales and to separate out the CMB B-modes from other astrophysical sources with high fidelity. After accounting for galactic foreground separation, the Simons Array will detect the primordial gravitational wave B-mode signal to $r > 0.01$ with a significance of $> 5\sigma$ and will constrain the sum of neutrino masses to 40 meV (1σ) when cross-correlated with galaxy surveys. We present the current status of this funded experiment, its future, and discuss its projected science return.

Keywords: cosmic microwave background radiation, polarization, polarimeters, inflation, neutrinos, dark matter, dark energy, gravitational lensing

1. INTRODUCTION

Precision measurements of the temperature anisotropy in the cosmic microwave background (CMB) have revolutionized our understanding of the observable universe and are considered a pillar of the ΛCDM Standard

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Cosmological Model. While many parameters that describe our universe have been measured with high precision, there remain striking gaps in our understanding of many of the underlying physical processes that took place in the very early universe. Polarization of the CMB is an observational probe that promises to open a window onto a dark age in the early history of the universe and to provide the first glimpses of the physics in this ultra-high energy epoch.

Modern ideas about the evolution of the universe generally include a brief epoch of exponential spatial expansion driven by a non-zero scalar field potential. While the evocation of a hypothetical inflationary era in the early universe solves a number of observational problems that cannot be explained using the standard model alone, the quantum mechanical nature of the physics underlying inflation remains shrouded in mystery. One of the most striking predictions of inflation is the generation of a stochastic background of gravitational waves with an amplitude proportional to the energy scale at which inflation occurred. These primordial gravitational waves would have created a tensor contribution to the CMB polarization pattern that should still be detectable today in the form of 'B-mode' polarization.[1] The so-called tensor to scalar ratio, r, in the B-mode polarization is thus a direct measure of the energy scale of inflation; a scale that is thought to be near the grand unified theory (GUT) scale - many orders of magnitude beyond the reach of the most powerful current or future terrestrial collider. A detection of this inflationary B-mode polarization signal in the CMB would represent a major scientific breakthrough and has thus generated intense interest.

Beyond the revolutionary nature of the detection of primordial gravitational waves and a look at the physics at the GUT scale, CMB polarization probes the evolution of large scale structure through the mechanism of gravitational lensing. The reprocessing of CMB photons through the gravitational potential wells created by clusters of galaxies can generate B-mode polarization on small angular scales. This 'lensed' B-mode signal can be used to construct maps of the gravitational potential at high redshift,[2] thus providing information on the formation of large-scale structure that is complementary to that provided by baryon accoustic oscillation (BAO) measurements obtained from sky surveys such as the Dark Energy Survey (DES), Dark Energy Spectroscopic Instrument (DESI), Hyper-Supreme CAM (HSC), the Large Synoptic Survey Telescope (LSST) and Herschel. While the neutrino mass hierarchy is still not known, neutrinos are expected to play an important role in the formation of large-scale structure. The Simons Array will have the ability to either place new upper limits on the neutrino masses or illuminate non-standard neutrino models.

2. EXPERIMENTAL OVERVIEW

The Simons Array will consist of three cryogenic receivers featuring kilo-pixel focal plane bolometer arrays observing on independent telescopes at an altitude of 5,200m in the Atacama Desert in Northern Chile. The receivers will be deployed in stages; the first to observe will be POLARBEAR-2A which will deploy in late 2016 for science observations in 2017 and will feature 7,588 TES bolometers operating at 95 GHz and 150 GHz.[3] POLARBEAR-2B will be an identical receiver to POLARBEAR-2A and will deploy on a different telescope later in 2017. Finally, POLARBEAR-2C will utilize a 220 GHz and 280 GHz array on a third telescope in mid-2018. The three telescopes will operate independently over a nominal observation campaign of three years. The Simons Array will heavily leverage the experience gained from the successful deployment and multi-season observation campaign of the POLARBEAR-1 experiment.[4–7]

2.1 Multichroic focal plane arrays

The key technology of the Simons Array is a scaling of the TES bolometer technology into large-scale multichroic arrays.[8–10] Each focal plane of 7,588 detectors is assembled from 7 close packed hexagonal sub-array modules containing 1,084 bolometers each. Individual pixels are optically coupled via an anti-reflection coated hemispherical silicon lenslet mounted onto a lenslet sub-array wafer.[11] These lenslets arrays feed lithographed planar sinuous antennas that are patterned onto a detector sub-array wafer. Each pixel features four superconducting TES bolometers; two orthogonal linear polarizations for each of the two frequencies, each fed by superconducting microstrip transmission lines that incorporate band defining stripline filters that form an approximately 30% bandwidth. The individual TES bolometers are designed to be photon-noise limited and consist of a resistive metal termination and an AlMn sensor patterned onto a suspended silicon-nitride membrane. The

TES bolometer arrays in the Simons Array are read out using cryogenic SQUID amplifiers connected to the array modules using custom niobium-titanium stripline cables designed to have both low parasitic inductance and low thermal conductance. A 40× frequency domain multiplexing system will read out the detector array.[12,13] POLARBEAR-2A and 2B will both consist of multi-chroic detector arrays operating at 95 GHz and 150 GHz. POLARBEAR-2C will operate at 220 GHz and 280 GHz. The combined three focal plane array of 22,764 photon-limited detectors will have an instantaneous sensitivity of 2.5 $\mu K_{cmb}\sqrt{s}$.

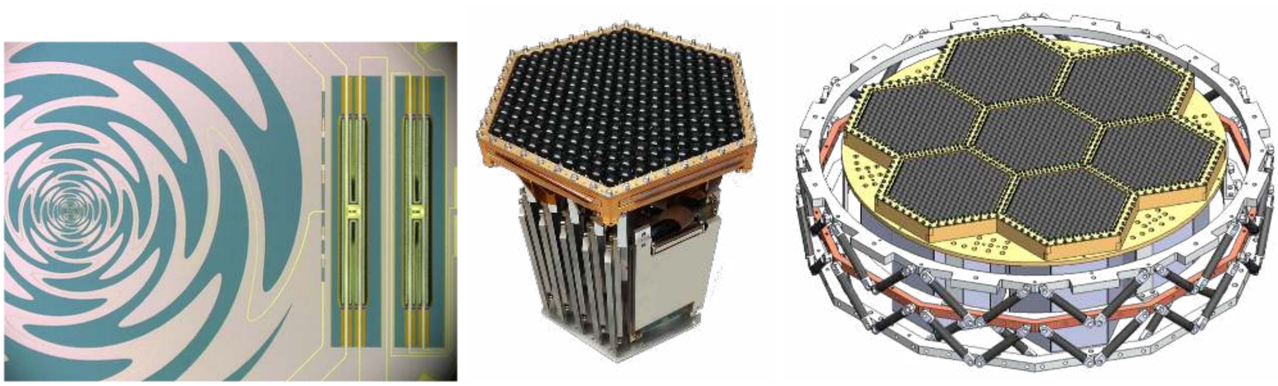

Figure 1. Left: A magnified image of a detector array pixel. A broadband planar sinuous antenna feeds four different TES bolometers (only two are shown here); both orthogonal linear polarizations for each frequency band. Center: A single detector module assembly consisting of a lenslet array, a detector array and LC modules required for the fMUX readout. Each hexagonal module is roughly 150 mm in diameter. Right: A CAD image showing the tiling of the individual detector modules to form the focal plane array.

2.2 Cryogenic receivers

The cryogenic receivers designed for the Simons Array consist of two parts; a 'backend' enclosure that houses the focal plane, readout and mK fridge, and an optics tube that contains all of the re-imaging optics. To achieve the desired instantaneous sensitivity, the focal plane detector arrays will be operated at 250 mK using a multi-stage He-3/He-4 sorption refrigerator. The cryogenic receivers will feature two commercial pulse tube refrigerators, one to cool down the receiver backend and the other to cool down the large optics tube. The optics tube contains three high-purity alumina reimaging lenses that are each anti-reflection coated to achieve high optical efficiency across the entire focal plane.[14]

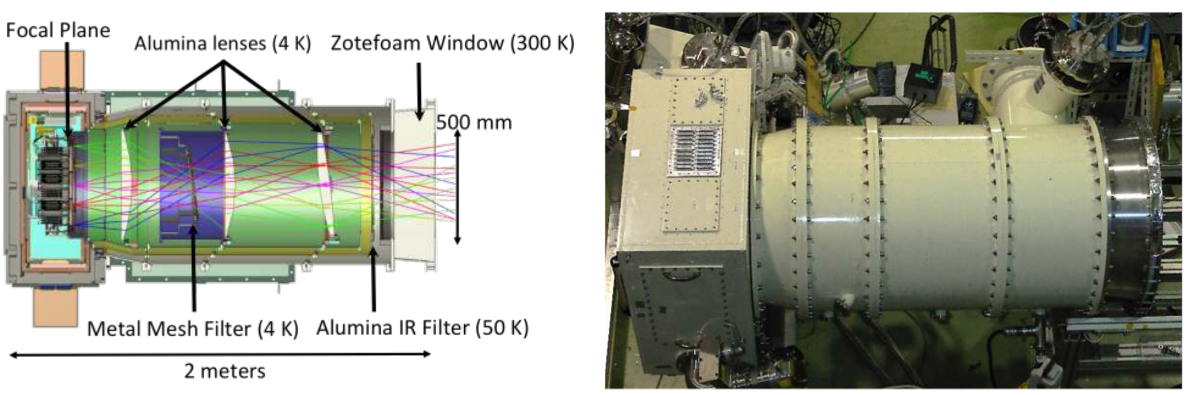

Figure 2. Left: Cross-sectional CAD image of the POLARBEAR-2A and -2B receiver cryostats. Right: Photo of the POLARBEAR-2A receiver being tested in the KEK lab.

2.3 Telescopes

The three telescopes that comprise the Simons Array are identical off-axis Gregorian Dragone designs that utilize a 3.5 m primary mirror. The telescope optics are designed to provide a flat, telecentric focal plane over a wide diffraction-limited field of view with an angular resolution of $3.5'$ at 150 GHz. Each telescope has a co-moving shield to prevent sidelobe pickup from ground emission and an optical baffle around prime focus to block straylight from reaching the window and scattering into the receiver. Each Simons Array receiver will employ a rapidly rotating half wave plate to modulate the incoming polarization signal well above any $1/f$ knee produced by atmospheric or gain drifts. The first telescope comprising the Simons Array - the Huan Tran Telescope (HTT) - was installed in Chile in 2011 and has been operating continuously with the POLARBEAR-1 experiment since.[4] The second and third telescopes were installed in early 2016.

Figure 3. The Simons Observatory site at 5,200m in Northern Chile. The foreground shows the three telescopes comprising the Simons Array. The background is the Atacama Cosmology Telescope (ACT) experimental site.

2.4 Observational campaign

The Simons Array will operate from the Simons Observatory; a 5,200m high-altitude site near Cerro Toco in the Atacama Desert of Northern Chile. The site has excellent mm-wave visibility and low precipital water vapor content and is accessible by roads throughout the year. The POLARBEAR-1 experiment was deployed at this site in 2011 and Simons Array will heavily leverage the existing infrastructure and experience gained from the five years already invested there. This mid-latitude site allows access to 80% of the sky at elevation angles above 30 degrees, including a number of key celestial sources useful for pointing reconstruction and calibration. Observational patches are tracked across the sky as they rise and set and observed using azimuth scans at stepped elevations. This strategy has the benefit of providing a natural sky rotation of the sky patches (and hence, the sky polarization), which provides an important systematic check on our data. Access to large sky area also allows Simons Array to cross-correlate with other planned surveys with overlapping fields, allowing the Simons Array to constrain the sum of the neutrino masses. The Simons Array is scheduled to deploy in stages beginning in late 2016 and will observe for three years.

3. SCIENCE CAPABILITIES

After three years of observations, the Simons Array will have the sensitivity to make several important contributions to the study of the early universe. Figure 4 shows a theoretical ΛCDM CMB polarization amplitude power spectrum with Simons Array projected sensitivity error bars overplotted. Simons Array will have the ability to measure primordial gravitational waves down to a tensor-to-scalar ratio of $r > 0.01$ with 5σ significance when accounting for foreground separation residuals.[15] The high-resolution capability of the Simons Array will also allow it to determine the spectral index (n_s) of the inflation potential to 0.0015 at 1σ by characterizing the E-mode polarization power spectrum with high fidelity. Taken together, these high-precision measurements of both r and n_s will allow Simons Array to make powerful statements about the nature of inflation, even allowing rejection of many classes of slow-roll models.

By measuring the signal produced by gravitational lensing, Simons Array will have the ability to constrain the sum of the neutrino masses to 40 meV (at 1σ, including foreground removal) when combined with the future DESI experiment.[16]

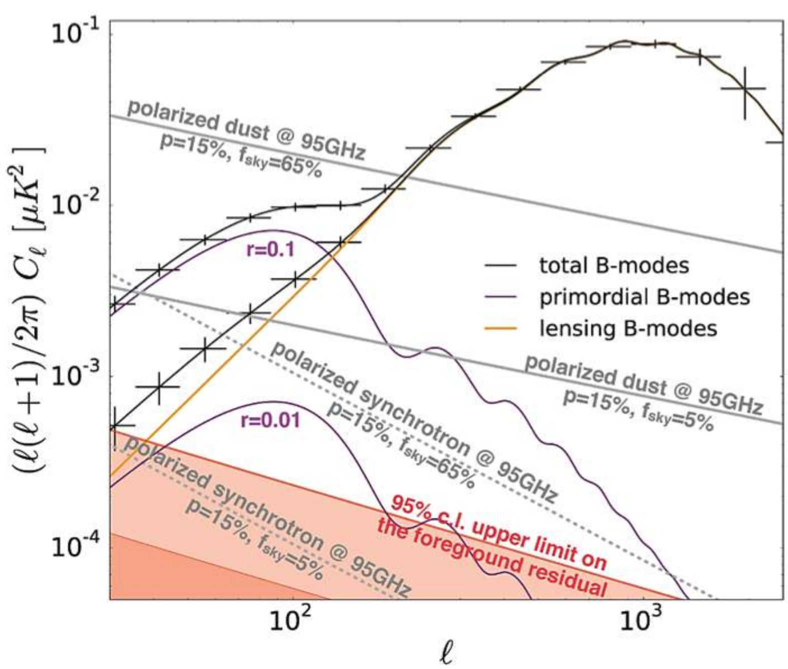

Figure 4. Theoretical power spectra for B-mode CMB polarization from a ΛCDM universe showing inflationary B-modes at $r = 0.1$ and $r = 0.01$ (purple curves) and B-modes generated via gravitational lensing of E-modes (orange curve). Binned error bars from three years of Simons Array data observing a sky fraction of 65% are overplotted.

4. CONCLUSION

The Simons Array is designed to achieve the combination of high sensitivity, excellent control of polarization systematics and astrophysical foreground subtraction necessary to make a high signal-to-noise detection of B-mode polarization over a wide range of angular scales. The multi-chroic sensitivity in three bands will allow galactic foregrounds to be discriminated from the cosmic signals of interest. The high angular resolution afforded by the Simons Array telescopes allows the experiment to measure the B-mode power spectrum produced by gravitational lensing with excellent fidelity and will be used to reconstruct a map of the projected gravitational structure between the surface of last scattering and now. This map will allow Simons Array to probe the sum of the neutrino masses and the early equation of state for dark energy. It will also allow us to de-lens the CMB,[17] effectively separating the polarization signal generated from gravitational lensing from the primordial B-modes that probe inflation. The combination of large sky coverage available from Northern Chile along with enhanced control of instrumental systematic effects allows the Simons Array to achieve excellent sensitivity on the large angular scales where the primordial B-mode signal is expected to peak.

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