Snowmass Letter of Intent

Complementarity of ground- and space-based observations of the cosmic microwave background

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CMB measurements provide a unique probe of fundamental physics and the origin and evolution of structure in the Universe. Observations of CMB temperature fluctuations have played a pivotal role in establishing the standard cosmological model and provide insights into the origin of structure, the density of baryons, dark matter, and dark energy, the number of neutrino species, and the global properties of spacetime. Many remaining questions about the Universe can best be answered through precise measurements of CMB polarization anisotropy. Observations of CMB polarization caused by density perturbations are already beginning to refine constraints on the standard cosmological model.

More significantly, a detection of CMB polarization generated by primordial gravitational waves would open an unexplored frontier of physics and shed light on processes that occurred even before the Universe became filled with a hot plasma of standard model particles. A detection of these gravitational waves would provide a window to the primordial Universe, which leaves in its wake primordial density perturbations in radiation and matter that are the seeds for all the structure we see today. The leading paradigm for the generation of these primordial density perturbations is inflation, a period of nearly exponential expansion of the Universe. This expansion not only generates density perturbations, but in addition creates gravitational waves. These gravitational waves persist and become imprinted in the CMB temperature and polarization anisotropies. Characterization of this signal would provide access to fundamental physics at energies far beyond the reach of CERN's Large Hadron Collider, revolutionizing our understanding of physics and the early Universe.

This Letter of Intent describes the complementarity of ground- and space-based experiments for achieving the full set of rich science outcomes possible with cosmic microwave background data. Future work in this area – that can start within the Snowmass process – is to better quantify the physics constraints from the combination of ground- and space-based experiments which could uncover changes to the experimental designs, scan strategies, or calibration strategies that give more powerful constraints.

Historically, ground- and space-based cosmic microwave background experiments have strong complementarity. COBE, WMAP, and Planck have complemented a suite of ground-based experiments, largely sited at the South Pole or the Atacama desert in Chile. Ground-based experiments can have a higher angular resolution than space-based experiments since cost scales rapidly with the size of a space-based telescope. Space-based experiments have measured the entire sky, since that is best achieved from an orbital scan pattern and therefore signals at the largest angular scales have been measured from space. Ground-based experiments often focus on small region of sky and measure to a low noise level, since that is convenient given typical terrestrial scan patterns. Space-based experiments can observe over a very broad range of frequencies, whereas on the ground some frequencies are impeded by water and oxygen absorption bands.

Future space-based experiments include LiteBIRD which was selected by JAXA in 2019. LiteBIRD will survey the full sky in 15 frequency bands from 40 to 402 GHz, with combined polarization sensitivity of 2 μK-arcmin and angular resolution of 31 arcmin (at 140 GHz). The 4,736 100 mK detectors are distributed between three 5-K cooled telescopes, called the Low-, Medium-, and High-frequency telescopes (LFT, MFT, and HFT). The first optical element in each telescope is a continuously rotating Half-Wave Plate (HWP) which rotates the polarization of the incident CMB photons. LiteBIRD will map 20 times deeper than *Planck*, with a total error of $\delta r < 0.001$, conservatively assuming equal contributions of statistical error, systematic error, and margin. The statistical error alone, including the effect of foreground subtraction, is $\sigma_r \sim 0.0006$.

Future ground-based experiments include Simons Observatory, South Pole Observatory, and CMB-S4. CMB-S4 will perform a combination degree-scale and arc-min resolution observation on a single 3% sky fraction region of the sky and an arc-minute resolution observation on up to 70% of the sky. CMB-S4 will observe in 7-9 frequency bands (varying with camera type) with bands centers from 20 to 280 GHz. The baseline design includes 18 0.5-meter diameter small-aperture telescopes, 2 6-meter aperture large-aperture telescope, and a single 5-meter telescope dedicated to the deep 3% sky region which will perform delensing measurements. There are 511,184 100mK detectors in CMB-S4. The map depth on the 3% region per band is in the range of 0.78 to 1.3 μK-arcmin for the 4 bands from 85 to 155 GHz, and the map depth of wide survey is 2.9 and 2.8 μK-arcmin for the 90 and 150 GHz bands. For the primordial B-mode search CMB-S4's constraint has a statistical error including the effect of foreground subtraction of $\sigma_r \sim 0.0006$.

The complementarity between CMB-S4 and LiteBIRD gives stronger constraints on many observables than can be achieved with either experiment alone. LiteBIRD measures both the reionization peak ($\ell \sim 5$) and the recombination peak ($\ell \sim 100$), and CMB-S4 can provide delensing data in the recombination peak angular range that improves the LiteBIRD constraint on r by a factor of 2. CMB-S4's measurement of large-scale structure gives measurement of the sum of masses for neutrinos, and LiteBIRD's measurement of the optical depth to reionization τ improves the CMB-S4 measurement from 3 to 5 σ for the normal-hierarchy minimal-mass case. LiteBIRD can also improve CMB-S4's foreground subtraction since LiteBIRD measures to 402 GHz compared to 280 GHz for CMB-S4, a significant increase since the dust spectrum is steep. Also, LiteBIRD will characterize foregrounds over the entire sky allowing a detailed model of foreground emission to be built which has the potential to improve CMB-S4's measurement of inflationary B-modes. CMB-S4's high resolution survey of 70% of the sky (including the galactic plane) is a powerful complement to the lower-resolution, higher-frequency, LiteBIRD foreground survey. Finally, the combination of the LiteBIRD and CMB-S4 data sets will give an improved constraint on primordial B-modes with an improvement in σ_r of up to a factor of 2.