Snowmass2021 - Letter of Interest

CMB-HD: An Ultra-Deep, High-Resolution Millimeter-Wave Survey Over Half the Sky

Thematic Areas:

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF9) Theory Frontier/Astro-Particle Physics & Cosmology
■ (NF2) Neutrino Frontier/Sterile Neutrinos

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Abstract: CMB-HD is a proposed ultra-deep (0.5 μK-arcmin), high-resolution (15 arcseconds) millimeter-wave survey over half the sky that would answer many outstanding questions about the fundamental physics of the Universe. It will allow 1.) the use of gravitational lensing of the primordial microwave background to map the distribution of matter on small scales ($k \sim 10$ hMpc^{-1}), which probes dark matter particle properties. It will also allow 2.) measurements of the thermal and kinetic Sunyaev-Zel'dovich effects on small scales to map the gas density and velocity, another probe of cosmic structure. In addition, CMB-HD would allow us to cross critical thresholds: 3.) ruling out or detecting any new, light (< 0.1 eV) particles that were in thermal equilibrium with known particles in the early Universe, 4.) testing a wide class of multi-field models that could explain an epoch of inflation in the early Universe, and 5.) ruling out a purely primordial origin of galactic magnetic fields. CMB-HD would also 6.) constrain or discover axion-like particles. The CMB-HD survey would be delivered in 7.5 years of observing 20,000 square degrees, using two new 30-meter-class off-axis crossed Dragone telescopes to be located at Cerro Toco in the Atacama Desert. Each telescope would field 800,000 detectors (200,000 pixels), for a total of 1.6 million detectors.

CMB-HD is an ambitious leap beyond previous and upcoming ground-based millimeter-wave experiments. It will allow us to cross critical measurement thresholds and definitively answer pressing questions in both astrophysics and the fundamental physics of the Universe. The combination of CMB-HD with contemporary ground and space-based experiments will also provide countless powerful synergies.

Two critical advances uniquely enabled by CMB-HD are mapping over half the sky: i) the distribution of all matter on small scales ($k \sim 10\ h\mathrm{Mpc}^{-1}$) using the gravitational lensing of the cosmic microwave background (CMB), and ii) the distribution of gas density and velocity on small scales using the thermal and kinetic Sunyaev-Zel'dovich effects (tSZ and kSZ). The combination of high-resolution and seven frequency bands in the range of 30 to 350 GHz allows for separation of foregrounds from the CMB. That plus the unprecedented depth of the survey over half the sky allows one to answer the fundamental physics questions listed below. A summary of the key science goals motivating the CMB-HD survey are given in this letter of interest and discussed in more detail in the Astro2020 Science White Paper[1], Astro2020 CMB-HD APC[2], and Astro2020 CMB-HD RFI[3]. In addition, details can be found at https://cmb-hd.org.

- What is the distribution of matter on small scales?
- What are the particle properties of dark matter?
- Do new light particles exist that were in equilibrium with known particles in the early Universe?
- Do axion-like particles exist?
- If inflation happened, did it arise from multiple or a single new field?
- Do primordial gravitational waves exist from an epoch of inflation?
- Was the early Universe magnetized?

1 CMB-HD Key Science Objectives

1.1 Fundamental Physics of the Universe

To answer the science questions listed above, CMB-HD has the following science objectives:

1. *Measure the small-scale matter power spectrum from weak gravitational lensing using the CMB as a backlight; with this CMB-HD aims to distinguish between a matter power spectrum predicted by models that can explain observational puzzles of small-scale structure, and that predicted by vanilla cold dark matter (CDM), with a significance of at least 8σ.* This measurement would be a clean measurement of the matter power spectrum on these scales, free of the use of baryonic tracers. It would greatly limit the allowed models of dark matter and baryonic physics, shedding light on dark-matter particle properties and galaxy evolution[4–6]. Specifically, this measurement would constrain ultra-light axions, warm dark matter, self-interacting dark matter, and any other dark matter model that alters the matter power spectrum on scales of $k \sim 10\ \mathrm{Mpc}^{-1}$.[4–8]

2. *Measure the number of light particle species that were in thermal equilibrium with the known standard -model particles at any time in the early Universe, i.e. N_{eff}, with a 1σ uncertainty of $\sigma(N_{\mathrm{eff}}) = 0.014$.* This would cross the critical threshold of 0.027, which is the amount that any new particle species changes N_{eff} away from its Standard Model value of 3.04. Such a measurement would rule out or find evidence for new light thermal particles with at least 95% confidence level. This is particularly important because many dark matter models predict new light thermal particles[9,10], and recent short-baseline neutrino experiments have found puzzling results possibly suggesting new neutrino species[11,12].

3. *Constrain or discover axion-like particles by observing the resonant conversion of CMB photons into axions in the magnetic fields of galaxy clusters.* Nearly massless pseudoscalar bosons, often generically called axions, appear in many extensions of the standard model[13–18]. A detection would have major implications both for particle physics and for cosmology, not least because axions are also a well-motivated dark matter candidate. CMB-HD has the opportunity to provide a world-leading probe of the electromagnetic interaction between axions and photons using the resonant conversion of CMB photons and axions[19,20] in the magnetic field of galaxy clusters[21], independently of whether axions constitute the dark matter. CMB-HD would explore the mass range of 10^{-14} GeV $< m_a \lesssim 2 \times 10^{-12}$ GeV and improve the constraint on the axion coupling constant by over two orders of magnitude over current particle physics constraints to $g_{a\gamma} < 0.1 \times 10^{-12}$ GeV. These ranges are unexplored to date and complementary with other cosmological searches for the imprints of axion-like particles on the cosmic density field.

4. *Measure the primordial non-Gaussian fluctuations in the CMB, characterized by the parameter $f_{\rm NL}$, with an uncertainty of $\sigma(f_{\rm NL}) = 0.26$, by combining the kSZ signal from CMB-HD with an over -lapping galaxy survey such as LSST.* Reaching a target of $\sigma(f_{\rm NL}) < 1$ would rule out a wide class of multi-field inflation models, shedding light on how inflation happened[22–27]. This cross-correlation could also resolve the physical nature of several statistical anomalies in the primary CMB[28] that may suggest new physics during inflation (see Ref.[29] for a review), and provide constraints on the state of the Universe before inflation[30].

5. *Remove 90% of the CMB B-mode fluctuations from gravitational lensing over half the sky, leaving only 10% remaining, i.e. achieve $A_{\rm lens} = 0.1$.* This would enable other CMB experiments with small-aperture telescopes, such as CMB-S4, to achieve their target measurement of the amplitude of primordial gravitational waves[31], given by the parameter r, with an uncertainty of $\sigma(r) < 5 \times 10^{-4}$; CMB-HD would serve as the large-aperture telescope required for B-mode "de-lensing".

6. *Probe the existence of primordial magnetic fields (PMFs) to find evidence for magnetogenesis in the early Universe and reveal the seeds of observed galactic magnetic fields.* CMB-HD will have the high resolution and sensitivity needed to probe the magnetic vortical vector mode[32–35] - the high-ℓ feature of PMFs that survives Silk damping. CMB-HD's data on magnetic signatures in non-Gaussianity[36–38], improved measurement of B-modes and Faraday rotation[39], and measurement of the small-scale matter power spectrum[40] would improve magnetic field limits by an order of magnitude. CMB-HD could tighten this bound well below the 1 nG threshold, which would rule out a purely primordial origin of galactic magnetic fields[39].

1.2 Astrophysics

CMB-HD would also address many questions in astrophysics, such as 1.) the evolution of gas and galaxies in the Universe. Such a survey would also 2.) monitor the transient sky by mapping the full observing region every few days, which opens a new window on gamma-ray bursts, novae, fast radio bursts, and variable active galactic nuclei. Moreover, CMB-HD would 3.) provide a census of planets, dwarf planets, and asteroids in the outer Solar System, and 4.) enable the detection of exo-Oort clouds around other solar systems, shedding light on planet formation. Finally, 5.) CMB-HD will provide a catalog of high-redshift dusty star forming galaxies and active galactic nuclei over half the sky down to a flux limit of 0.5 mJy at 150 GHz. The CMB-HD survey will be made publicly available, with usability and accessibility a priority.

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