Snowmass2021 - Letter of Interest

Future of CMB

Thematic Areas: (check all that apply □/■) □ (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
□ (Other) *[Please specify frontier/topical group]*

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Abstract: As the US CMB community is actively planning our next-generation ground-based CMB experiment, CMB-S4, which passed CD-0 and is on-track towards CD-1 in 2021, we outline here key science goals that CMB-S4 will achieve and discovery space for a post CMB-S4 survey. We intend to broadly outline areas of possibilities and potentials.

When CMB-S4 completes its observations, it will provide the deepest measurements at millimeter wavelengths of more than half of the sky[1]. This dataset will be critical for answering questions not only in cosmology, but in fields like particle physics as well. Three important science goals of CMB-S4 are

1. The measurement of the tensor-to-scalar ratio, r,
2. The measurement of the neutrino mass and other light relics,
3. Dark matter properties/clustering.

After CMB-S4, the path forward on r will depend on whether a detection is made. If a highly significant detection is made, then the likely path towards ever greater significance is increasing the sky coverage and measuring more CMB modes, including the reionization bump. If there is no detection, then the path is dependent on what is limiting the measurement. If foregrounds are not sufficiently modeled by simple power laws, constraining more complex models will likely require high sensitivity maps across more electromagnetic frequencies. If foregrounds are effectively removed and the limit is raw sensitivity, then deploying more telescopes and/or observing longer is the only approach. If we are limited by delensing, then more high resolution telescopes will be required.

Assuming no extensions to ΛCDM, CMB-S4 will measure the sum of the neutrino masses, M_ν, to 2-3 σ. Moreover, if the sum of the neutrino mass is less than 0.1 eV, CMB-S4 can rule out the inverted hierarchy. The constraint on M_ν will be limited by our knowledge on the optical depth to reionization, τ. Therefore, the effort beyond CMB-S4 in constraining M_ν from cosmological measurements will focus on more sensitive probes on τ. These measurements include measuring the CMB at large angular scales as well as using the sensitivity of kSZ to the reionization history to constrain τ. In addition to measuring the neutrino mass, the CMB is a sensitive probe of axion mass via polarization oscillations of the CMB signal[5]. These oscillations are across the entire sky and continue in perpetuity, thus there is no cosmic variance limit. In other words, there is no fundamental limit to the measurement, and it will always be improved with more CMB modes and more time.

Another potential avenue of discovery is the particle nature of dark matter. Observations of the CMB continue to enable useful cross-checks on limits on dark-matter self interaction and dark-matter/baryon interaction cross-sections. By measuring more modes in both sky area and in the range of the angular sizes of the modes, we can enable discovery or stringent upper limits on dark matter interaction models. Pushing to even smaller angular scales will further constrain these models.

There are four obvious ways to extend observations beyond CMB-S4.

1. Extending to smaller scale measurements (e.g. 15 arcsec resolution at 150GHz, like CMB-HD[8])
2. Covering larger angular scales ($\ell < 30$)
3. Expand coverage to the Northern sky
4. More frequency bands

The breakdown between scientific goal and required data is shown in Table 1. The experimental approaches can be easily broken down into ground based and space based instruments. Ground based experiments will have clear advantages for small scales, where a large reflector can be deployed. Space telescopes will have an advantage at large angular scales and frequency coverage due to the lack of an atmosphere. Ground based experiments can also cover large angular scales[4]. The Northern sky can be accessed via space[2] or ground[7]. There is ongoing technological development to make both ground and space platforms more powerful in the future.

	Small Scales	Large Scales	Northern Sky	More Freq Bins
r detection		x	x	
r non-detection due to insufficient sensitivity		x		
r non-detection due to foregrounds			x	x
τ	x	x		
DM clustering	x			

Table 1: The experimental approach post-CMB-S4 depends on the scientific goal and outcome of CMB-S4. Many of these goals can be achieved from both ground and satellite missions. We break the future experiments into small and large angular scales as they require different experimental setups.

There will continue to be important unanswered questions after CMB-S4 which can be resolved with further observations of the millimeter sky. A detection of r would be a landmark discovery that would demand further verification. We already know the constraints on neutrino mass will be limited by our knowledge of τ, so further work is already warranted. And the mysteries of dark matter will continue to demand more measurements. The future experimental approach will depend on the results of CMB-S4 and other contemporary experiments[3;6]. However we can be certain that further developing theoretical, computational, and experimental techniques will be a worthwhile investment well into the post CMB-S4 world.

References

[1] Kevork N. Abazajian et al. CMB-S4 Science Book, First Edition. 10 2016.

[2] Y. Akrami et al. Planck 2018 results. I. Overview and the cosmological legacy of Planck. 7 2018.

[3] Michelle J. Dolinski, Alan W.P. Poon, and Werner Rodejohann. Neutrinoless Double-Beta Decay: Status and Prospects. *Ann. Rev. Nucl. Part. Sci.*, 69:219–251, 2019.

[4] Thomas Essinger-Hileman et al. CLASS: the cosmology large angular scale surveyor. 9153:91531I, July 2014.

[5] Michael A. Fedderke, Peter W. Graham, and Surjeet Rajendran. Axion dark matter detection with cmb polarization. *Phys. Rev. D*, 100:015040, Jul 2019.

[6] F. Fraenkle. The neutrino mass experiment katrin. *Ukrainian Journal of Physics*, 64(7):573, Sep. 2019.

[7] Hong Li et al. Probing Primordial Gravitational Waves: Ali CMB Polarization Telescope. *Natl. Sci. Rev.*, 6(1):145–154, 2019.

[8] Neelima Sehgal et al. Science from an Ultra-Deep, High-Resolution Millimeter-Wave Survey. 3 2019.

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