Snowmass2021 - Letter of Interest

CMB-S4: Mapping matter in the Cosmos

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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This Letter is adapted from the CMB-S4 Science Case, Reference Design, and Project Plan[1]
arxiv:1907.04473v1

Abstract:

We encourage the Snowmass process to consider the role that measures of the cosmological distribution of material can play in constraining fundamental physics. In particaular, joint probes and cross-correlations between cosmic surveys will control systematics and open new opportunities for discoveries.

The CMB-S4 project's survey will provide a unique census of 70% of the sky. In particular, for this region we will measure the gravitational potential (as it coherently shears the image of the CMB fluctuations) and the baryonic gas (as its electrons scatter CMB photons and distort the Blackbody spectral energy distribution). Many astronomical objects also emit their own radiation in our frequency windows. The CMB-S4 survey will complement and enhance the Rubin-LSST optical survey of the same region[3], the DESI spectroscopic survey[2], the *eROSITA* all-sky X-ray survey[4], and other planned and yet-to-be-imagined surveys from both ground- and space-based facilities. CMB-S4, by going dramatically deeper than previous CMB surveys and covering a large fraction of the sky, enables physics constraints beyond what individual projects can deliver, and this type of joint work is worthy of support.

A Detailed Cosmic Census

Matter in the Universe can be sorted into two categories, normal (baryonic) matter that is described by the Standard Model of particle physics and dark matter that has only been observed to interact gravitationally. Observations indicate there is more than five times more dark matter than baryonic matter, and most of the baryonic matter is in the form of hot ionized gas rather than cold gas or stars. CMB-S4 will be able to map out normal and dark matter separately by measuring the fluctuations in the total mass density (using gravitational lensing) and the ionized gas density (using Compton scattering).

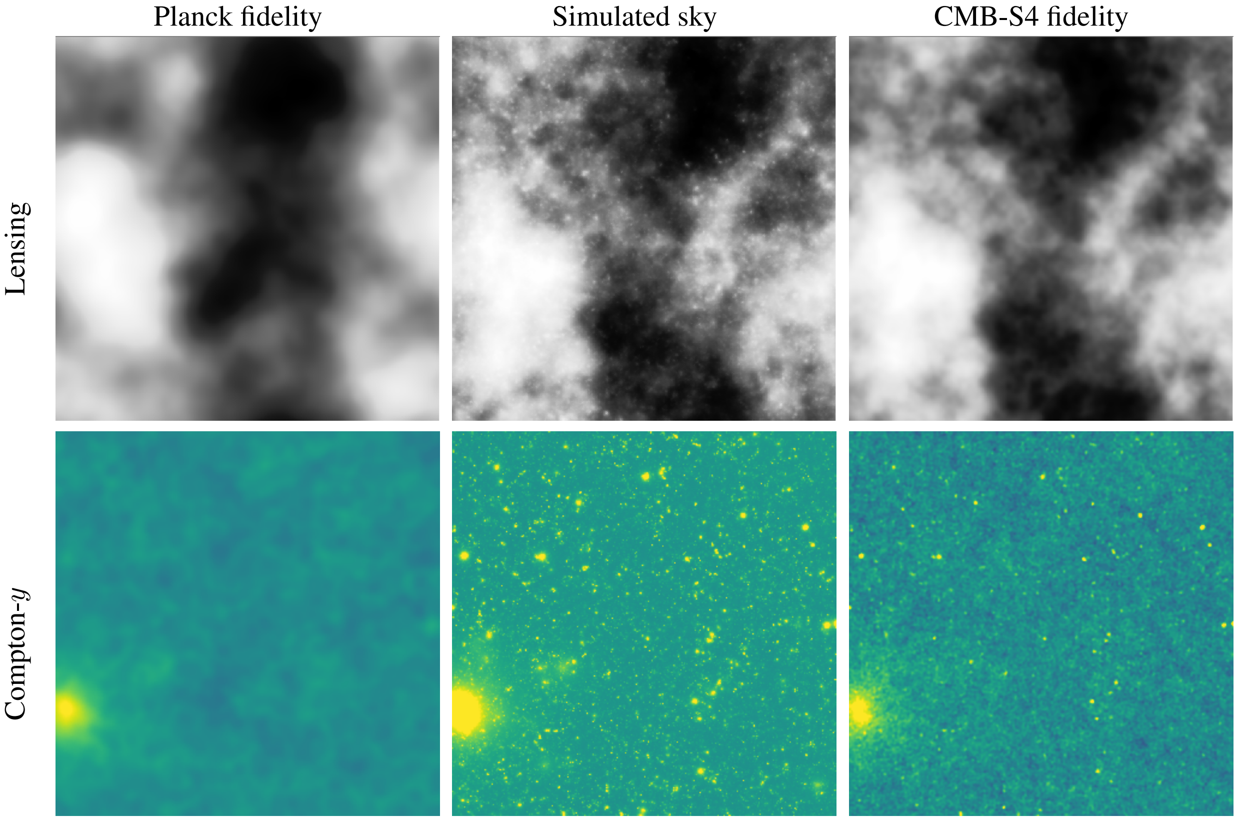

Figure 1: Example lensing-reconstructed density (top) and thermal SZ (Compton y, bottom) maps reconstructed with *Planck* (left) and CMB-S4 data (right). The center panels show a 25 deg^2 patch of the all-sky lensing-deflection field in the WebSky simulations (top) and Compton y (bottom). The left panels show Wiener-filtered maps of the signal after adding (Gaussian) noise and residual foregrounds with levels corresponding to the *Planck* 2018 lensing-deflection map (top) and the *Planck* 2015 “Needlet Internal Linear Combination” tSZ map (bottom). The right panel shows analogous Wiener-filtered maps with noise expected for CMB-S4 (top) and residual foregrounds determined by the CMB-S4 + *Planck* tSZ noise power spectrum. The significantly higher fidelity of the CMB-S4 reconstruction is evident.

Gravitational lensing of background sources by intervening gravitational potentials leads to detectable distortions that can be used to reconstruct fluctuations in the mass density. Virtually all of the the density fluctuations within the observable Universe leave an imprint when the CMB is the background source. The map resulting from CMB lensing reconstruction will be wide-area, highly sensitive, and extremely well-calibrated.

On its own, we can use this map to precisely measure the amplitude of large-scale structure at intermediate redshifts, with important applications to dark energy, modified gravity, and studies of neutrino masses. In concert with catalogs of objects, we can use this map to weigh samples (of e.g., galaxies and galaxy clusters) to as high a redshift as such sources can be found. The technique of CMB lensing tomography, enabled by CMB-S4 and galaxy catalogs from—for example—the Vera Rubin Observatory Legacy Survey of Space and Time (LSST), will allow for the creation of mass maps in broad redshift slices out to redshifts as high as 5, making possible new precision tests of cosmology. Such results explore the connection between visible baryons and the underlying dark-matter scaffolding. In conjunction with cosmic-shear surveys (e.g., Rubin-LSST) that measure the low-redshift mass distribution, a map of the high-redshift mass distribution can be constructed, gaining new insight into the first galaxies. By calibrating cluster masses at high redshift, the abundance of galaxy clusters can be used as an additional probe of dark energy and neutrino masses.

Low-redshift structure acts to lens both the CMB and the images of intermediate-z galaxies. Detailed comparisons provides a valuable cross-check on galaxy shear measurement calibration and enables geometric tests using the longest possible lever arm.

Most of the baryons in the late Universe are believed to be in a diffuse ionized plasma that is difficult to observe. This ionized plasma can leave imprints in the CMB through Compton scattering, the so-called Sunyaev-Zeldovich effects. The two leading variants are either a spectral distortion from hot electrons interacting with the relatively cold CMB (thermal SZ or tSZ), or a general redshift or blueshift of the scattered photons due to coherent bulk flows along the line of sight (kinematic SZ or kSZ).

The nature of the scattering makes the tSZ independent of redshift. With the deep and wide field covering a large amount of volume and the ultra-deep field imaging lower-mass clusters, CMB-S4 will be an effective probe of the crucial regime of $z \gtrsim 2$, when galaxy clusters were vigorously accreting new hot gas while at the same time forming the bulk of their stars. The CMB-S4 catalog will be more than an order of magnitude larger than current catalogs based on tSZ or X-ray measurements, and will contain an order of magnitude more clusters at $z > 2$ than will be discovered with Stage 3 CMB experiments. CMB-S4 will also measure the diffuse tSZ signal everywhere on the sky and make a temperature-weighted map of ionized gas which can be used to measure the average thermal pressure profiles around galaxies and groups of galaxies.

CMB-S4 will measure the kSZ effect, which will be combined with data from other surveys to make maps of the projected electron density around samples of objects. Applications of these maps include measuring ionized gas as a function of radius, directly constraining the impact of feedback from active galactic nuclei and supernovae on the intergalactic medium and constraining theories of modified gravity with the bulk flow amplitude as a function of separation.

Even without overlapping galaxy catalogs, the kSZ signal adds extra small-scale power that is significantly non-Gaussian. Some of this excess power and non-Gaussianity will be coming from the relatively local Universe where the galaxy catalogs overlap, but there should also be a substantial signal coming from the epoch of reionization. By directly probing the ionized gas distribution, these measurements are completely complementary to the measurements of the neutral gas that can be obtained with redshifted Ly-α or redshifted 21-cm studies.

In the course of its survey, CMB-S4 will catalog the emission from galaxies in the mm-wave band, including AGN and dusty star-forming galaxies. The matter in our own Galaxy will also be mapped in intensity and linear polarization over a large fraction of the sky, with extracted images of synchrotron and dust emission with high fidelity on scales ranging from arcminutes to several degrees.

References

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