Snowmass2021 - Letter of Interest

CMB-S4: Primordial Graviational Waves and Inflation

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]*

Contact Information:
CMB-S4 Collaboration Science Council [sc@cmb-s4.org]

Authors:

The CMB-S4 Collaboration

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

Abstract:

Detecting gravitational waves and constraining early-universe models are keys goals of CMB-S4. This LOI provides an overview of what CMB-S4 is projected to achieve, and through this Snowmass process we emphasize the benefits of coordinated development of cosmological simulations and analyses, including sky simulations that can be used jointly with large-scale structure probes. We also highlight the need for simulations of polarized foreground emission from the Milky Way.

Cosmologists widely regard inflation as the most compelling paradigm for the very early Universe. Many of the predictions of the simplest models of inflation have been verified, such as the departure from scale invariance. This departure implies that gravitational wave constraints from CMB-S4 will confirm or rule out many inflation models. In addition, CMB-S4 will provide unprecedented constraints on the primordial "isocurvature" fluctuations and non-Gaussianties that are predicted by inflationary models beyond the simplest forms. Discovery of such non-Gaussianities would present a breakthrough on par with a detection of primordial gravitational waves. To enable cross-checks and complementarity in the constraints on these signals, joint simulations of large-scale structures and robust simulations of Galactic foregrounds are crucial.

We have a historic opportunity to open up a window to the primordial Universe. If the predictions of some of the leading models for the origin of the hot big bang are borne out, CMB-S4 will detect primordial gravitational waves. This detection would provide the first evidence for the quantization of gravity, reveal new physics at the energy scale of grand unified theories, and yield insight into the symmetries of nature and possibly into the properties of quantum gravity. Conversely, a null result would rule out large classes of models and put significant strain on the leading paradigm for early-Universe cosmology, the theory of cosmic inflation.

Cosmic inflation refers to a period of accelerated expansion prior to the hot big bang. During this epoch, quantum fluctuations were imprinted on all spatial scales in the cosmos. These fluctuations seeded the density perturbations that developed into all the structure in the Universe today. While we cannot yet claim with high confidence that the Universe underwent cosmic inflation, the simplest models of inflation are exceptionally successful at matching the data. Specifically, these predictions include small mean spatial curvature and initial density perturbations drawn from a nearly Gaussian distribution with a variance that is slightly larger on large scales than on small scales. Each of these predictions has been verified to high precision.

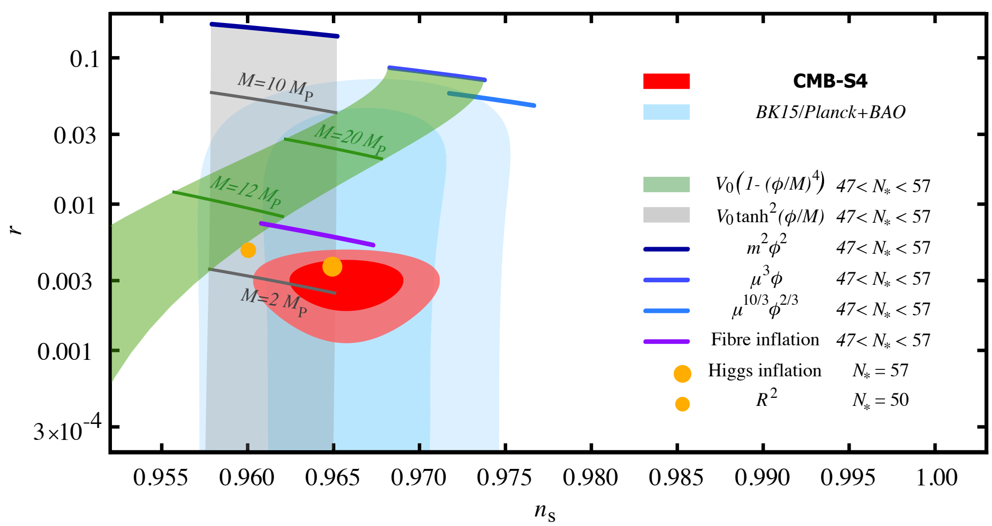

Figure 1: Forecast of CMB-S4 constraints in the n_s–r plane for a fiducial model with $r = 0.003$. Also shown are the current best constraints from a combination of the BICEP2/*Keck Array* experiments and *Planck* [2]. Models that naturally explain the observed departure from scale invariance separate into two viable classes: monomial and plateau. The monomial models ($V(\phi) = \mu^{4-p}\phi^p$) are shown for three values of p as blue lines for $47 < N_* < 57$ (with the spread in N_* reflecting uncertainties in reheating, and smaller N_* predicting lower values of n_s). This class is not completely ruled out by the data, but is disfavored. The plateau models divide into those with plateaus near the scalar field origin, for which we include the quartic hilltop (green band) as an example, and those with plateaus away from the origin, for which we include the $tanh$ form (gray band) as an example, as this form arises in a sub-class of α-attractor models [5]. Some particular realizations of physical models in the plateau class are also shown: the Starobinsky model [6] and Higgs inflation [3] (small and large orange filled circles, respectively) and fibre inflation [4] (purple line). The differing choices of N_* for Higgs and Starobinsky reflect differing expectations for reheating efficiency.

The observed (weak) scale-dependence of the amplitude of density perturbations has quantitative implications for the detection of primordial gravitational waves. In the simplest class of models, the amplitude of primordial gravitational waves is comparable to the deviation from scale invariance, quantified by $n_s - 1$. **However, *all* inflation models that naturally explain the observed $n_s - 1$ value, and that also have a characteristic scale larger than the Planck mass, generate primordial gravitational waves above the 95% confidence upper limit that CMB-S4 can set (see Fig. 1 for example models). A well-motivated**

sub-class within this set of models is detectable by CMB-S4 at 5σ.

Because the Universe has expanded by a tremendous amount since the time when primordial perturbations were imprinted, CMB observations can probe physics at extraordinarily small length scales, up to 10^{10} times smaller than those probed in terrestrial particle colliders. The CMB provides a unique window to test new phenomena at these length scales. **The observation and analysis requirements are also clear: we must measure the polarization to high precision on angular scales from several arcminutes to degrees, with exquisite control of astrophysical and instrumental systematics.**

The CMB-S4 reference design has sufficient sensitivity to detect or tightly constrain the degree-scale B modes generated by gravitational waves in many models, and to measure the amount of gravitational waves (tensor perturbations), detecting or setting an upper limit on the tensor-to-scalar ratio r. With an order of magnitude more detectors than precursor observations, and exquisite control of systematic errors, we will improve upon limits from previous observations by a factor of 5, allowing us to either detect primordial gravitational waves or rule out a broad class of models with a super-Planckian characteristic scale.

Complementary to the search for gravitational waves, CMB-S4 will provide exquisite measurements of primordial *density* fluctuations via E modes. The polarization sensitivity will surpass current measurements of E-mode polarization, which are far from being sample-variance-limited. Because polarization has lower Galactic foregrounds than temperature, we will improve measurements across the angular scales already observed in temperature, and push to yet smaller angular scales. These polarization measurements will significantly extend and enhance searches for non-power-law features in the primordial power spectrum, small variations in the equation of state, and small departures from Gaussianity. All of these enables the broader understanding and modelling of the mechanisms through which inflation (or similar models) happened.

The CMB is the most robust observable for non-Gaussianities to date and CMB-S4 will provide the tightest constraints on the most compelling signatures, improving the constraints from the *Planck* satellite by a factor of 2 for the local and orthogonal shapes. Additionally, non-Gaussianities can arise in models with undetectably small gravitational wave production, and provide an independent handle on the early Universe. To further tighten the constraints on non-Gaussianities, we can include information from galaxy surveys for cross-correlation. **When combined with Rubin-LSST, CMB-S4 is projected to constrain the local type of non-Gaussianity $f_{\rm NL}^{\rm local}$ to $\sigma(f_{\rm NL}^{\rm local}) < 1$, a measurement that has the potential to rule out a large class of inflationary models.**

In any of these analyses, simulations play central roles in the modeling of the measurement uncertainties, providing physically motivated bounds for potential biases from scales below the experiments' sensitivities, and the testing of pipelines. For constraining r, we need to remove two sources of astrophysical contaminants to the primordial B-mode measurement with high confidence. They are (1) polarized dust emission and synchrotron radiation from the Milky Way galaxy and (2) gravitational lensing generated B-modes. Having high fidelity simulations of the Galactic interstellar medium and magnetic field aids in predicting the polarized dust emission and synchrotron radiation across the mm-wave bands, which enables confidence-building in both constraining Galactic foregrounds and its impacts on estimating the lensing B-modes. For the joint analysis with optical surveys, simulations with the same underlying density fluctuations will be required to capture the covariance between each probe.

References

[1] Kevork Abazajian, Graeme Addison, Peter Adshead, Zeeshan Ahmed, Steven W. Allen, David Alonso, Marcelo Alvarez, Adam Anderson, Kam S. Arnold, Carlo Baccigalupi, Kathy Bailey, Denis Barkats, Darcy Barron, Peter S. Barry, James G. Bartlett, Ritoban Basu Thakur, Nicholas Battaglia, Eric Baxter, Rachel Bean, Chris Bebek, Amy N. Bender, Bradford A. Benson, Edo Berger, Sanah Bhimani, Colin A. Bischoff, Lindsey Bleem, Sebastian Bocquet, Kimberly Boddy, Matteo Bonato, J. Richard Bond, Julian Borrill, François R. Bouchet, Michael L. Brown, Sean Bryan, Blakesley Burkhart, Victor Buza, Karen Byrum, Erminia Calabrese, Victoria Calafut, Robert Caldwell, John E. Carlstrom, Julien Carron, Thomas Cecil, Anthony Challinor, Clarence L. Chang, Yuji Chinone, Hsiao-Mei Sherry Cho, Asantha Cooray, Thomas M. Crawford, Abigail Crites, Ari Cukierman, Francis-Yan Cyr-Racine, Tijmen de Haan, Gianfranco de Zotti, Jacques Delabrouille, Marcel Demarteau, Mark Devlin, Eleonora Di Valentino, Matt Dobbs, Shannon Duff, Adriaan Duivenvoorden, Cora Dvorkin, William Edwards, Joseph Eimer, Josquin Errard, Thomas Essinger-Hileman, Giulio Fabbian, Chang Feng, Simone Ferraro, Jeffrey P. Filippini, Raphael Flauger, Brenna Flaugher, Aurelien A. Fraisse, Andrei Frolov, Nicholas Galitzki, Silvia Galli, Ken Ganga, Martina Gerbino, Murdock Gilchriese, Vera Gluscevic, Daniel Green, Daniel Grin, Evan Grohs, Riccardo Gualtieri, Victor Guarino, Jon E. Gudmundsson, Salman Habib, Gunther Haller, Mark Halpern, Nils W. Halverson, Shaul Hanany, Kathleen Harrington, Masaya Hasegawa, Matthew Hasselfield, Masashi Hazumi, Katrin Heitmann, Shawn Henderson, Jason W. Henning, J. Colin Hill, Renée Hlozek, Gil Holder, William Holzapfel, Johannes Hubmayr, Kevin M. Huffenberger, Michael Huffer, Howard Hui, Kent Irwin, Bradley R. Johnson, Doug Johnstone, William C. Jones, Kirit Karkare, Nobuhiko Katayama, James Kerby, Sarah Kernovsky, Reijo Keskitalo, Theodore Kisner, Lloyd Knox, Arthur Kosowsky, John Kovac, Ely D. Kovetz, Steve Kuhlmann, Chao-lin Kuo, Nadine Kurita, Akito Kusaka, Anne Lahteenmaki, Charles R. Lawrence, Adrian T. Lee, Antony Lewis, Dale Li, Eric Linder, Marilena Loverde, Amy Lowitz, Mathew S. Madhavacheril, Adam Mantz, Frederick Matsuda, Philip Mauskopf, Jeff McMahon, Matthew McQuinn, P. Daniel Meerburg, Jean-Baptiste Melin, Joel Meyers, Marius Millea, Joseph Mohr, Lorenzo Moncelsi, Tony Mroczkowski, Suvodip Mukherjee, Moritz Münchmeyer, Daisuke Nagai, Johanna Nagy, Toshiya Namikawa, Federico Nati, Tyler Natoli, Mattia Negrello, Laura Newburgh, Michael D. Niemack, Haruki Nishino, Martin Nordby, Valentine Novosad, Paul O'Connor, Georges Obied, Stephen Padin, Shivam Pandey, Bruce Partridge, Elena Pierpaoli, Levon Pogosian, Clement Pryke, Giuseppe Puglisi, Benjamin Racine, Srinivasan Raghunathan, Alexandra Rahlin, Srini Rajagopalan, Marco Raveri, Mark Reichanadter, Christian L. Reichardt, Mathieu Remazeilles, Graca Rocha, Natalie A. Roe, Anirban Roy, John Ruhl, Maria Salatino, Benjamin Saliwanchik, Emmanuel Schaan, Alessandro Schillaci, Marcel M. Schmittfull, Douglas Scott, Neelima Sehgal, Sarah Shandera, Christopher Sheehy, Blake D. Sherwin, Erik Shirokoff, Sara M. Simon, Anze Slosar, Rachel Somerville, David Spergel, Suzanne T. Staggs, Antony Stark, Radek Stompor, Kyle T. Story, Chris Stoughton, Aritoki Suzuki, Osamu Tajima, Grant P. Teply, Keith Thompson, Peter Timbie, Maurizio Tomasi, Jesse I. Treu, Matthieu Tristram, Gregory Tucker, Caterina Umiltà, Alexand er van Engelen, Joaquin D. Vieira, Abigail G. Vieregg, Mark Vogelsberger, Gensheng Wang, Scott Watson, Martin White, Nathan Whitehorn, Edward J. Wollack, W. L. Kimmy Wu, Zhilei Xu, Siavash Yasini, James Yeck, Ki Won Yoon, Edward Young, and Andrea Zonca. CMB-S4 Science Case, Reference Design, and Project Plan. *arXiv e-prints*, page arXiv:1907.04473, July 2019.

[2] P. A. R. Ade et al. Improved Constraints on Cosmology and Foregrounds from BICEP2 and Keck Array Cosmic Microwave Background Data with Inclusion of 95 GHz Band. *Phys. Rev. Lett.*, 116:031302, 2016.

[3] Fedor L. Bezrukov and Mikhail Shaposhnikov. The Standard Model Higgs boson as the inflaton. *Phys. Lett.*, B659:703–706, 2008.

[4] M. Cicoli, C. P. Burgess, and F. Quevedo. Fibre Inflation: Observable Gravity Waves from IIB String Compactifications. *JCAP*, 0903:013, 2009.

[5] Renata Kallosh and Andrei Linde. Universality Class in Conformal Inflation. *JCAP*, 1307:002, 2013.

[6] Alexei A. Starobinsky. A New Type of Isotropic Cosmological Models Without Singularity. *Phys.Lett.*, B91:99–102, 1980.