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Inflation physics from the cosmic microwave background and large scale structure

K.N. Abazajian, K. Arnold, J. Austermann, B.A. Benson, C. Bischoff, J. Bock, J.R. Bond, J. Borrill, I. Buder, D.L. Burke, E. Calabrese, J.E. Carlstrom, C.S. Carvalho, C.L. Chang, H.C. Chiang, S. Church, A. Cooray, T.M. Crawford *, B.P. Crill, K.S. Dawson, S. Das, M.J. Devlin, M. Dobbs, S. Dodelson, O. Doré, J. Dunkley, J.L. Feng, A. Fraisse, J. Gallicchio, S.B. Giddings, D. Green, N.W. Halverson, S. Hanany, D. Hanson, S.R. Hildebrandt, A. Hincks, R. Hlozek, G. Holder, W.L. Holzapfel, K. Honscheid, G. Horowitz, W. Hu, J. Hubmayr, K. Irwin, M. Jackson, W.C. Jones, R. Kallosh, M. Kamionkowski, B. Keating, R. Keisler, W. Kinney, L. Knox, E. Komatsu, J. Kovac, C.-L. Kuo, A. Kusaka, C. Lawrence, A.T. Lee, E. Leitch, A. Linde, E. Linder, P. Lubin, J. Maldacena, E. Martinec, J. McMahon, A. Miller, V. Mukhanov, L. Newburgh, M.D. Niemack, H. Nguyen, H.T. Nguyen, L. Page, C. Pryke, C.L. Reichardt, J.E. Ruhl, N. Sehgal, U. Seljak, L. Senatore, J. Sievers, E. Silverstein, A. Slosar, K.M. Smith, D. Spergel, S.T. Staggs, A. Stark, R. Stompor, A.G. Vieregg, G. Wang, S. Watson, E.J. Wollack, W.L.K. Wu, K.W. Yoon, O. Zahn, M. Zaldarriaga
Topical Conveners: J.E. Carlstrom, A.T. Lee

University of Chicago, Astronomy & Astrophysics, Kavli Institute for Cosmological Physics, 933 East 56th Street, Chicago, IL 60637, United States

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ABSTRACT

Fluctuations in the intensity and polarization of the cosmic microwave background (CMB) and the large-scale distribution of matter in the universe each contain clues about the nature of the earliest moments of time. The next generation of CMB and large-scale structure (LSS) experiments are poised to test the leading paradigm for these earliest moments—the theory of cosmic inflation—and to detect the imprints of the inflationary epoch, thereby dramatically increasing our understanding of fundamental physics and the early universe. A future CMB experiment with sufficient angular resolution and frequency coverage that surveys at least 1% of the sky to a depth of 1 uK-arcmin can deliver a constraint on the tensor-to-scalar ratio that will either result in a 5σ measurement of the energy scale of inflation or rule out all large-field inflation models, even in the presence of foregrounds and the gravitational lensing *B*-mode signal. LSS experiments, particularly spectroscopic surveys such as the Dark Energy Spectroscopic Instrument, will complement the CMB effort by improving current constraints on running of the spectral index by up to a factor of four, improving constraints on curvature by a factor of ten, and providing non-Gaussianity constraints that are competitive with the current CMB bounds.

1. Introduction

Precision cosmological measurements push the boundaries of our understanding of the fundamental physics that governs our universe. In the coming years, cosmologists will be in a position to make major breakthroughs in our understanding of the physics of the very early universe and be able to probe particle physics and gravity at the highest energy scales yet accessed. A major leap forward in the sensitivity of cosmological experiments is within our technological reach, leveraging past and current experience to tackle some of the most interesting fundamental physics questions.

Cosmic inflation, the theory that the universe underwent a violent, exponential expansion during the first moments of time, is the leading theoretical paradigm for the earliest history of the universe and for the origin of the structure in the universe. Current measurements of the cosmic microwave background (CMB) and observations of the large scale distributions of dark matter and

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* Corresponding author. Tel.: +1 773 702 6452; fax: +1 773 834 1891.
E-mail address: tcrawfor@kicp.uchicago.edu (T.M. Crawford).

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galaxies in the universe are in stunning agreement with the concept of inflation. The next generations of experiments in observational cosmology are poised to decide central questions about the mechanism behind inflation. In this short document, we highlight the importance of experimentally determining the nature of inflation in the early universe and the unique opportunity these experiments provide to explore the physics of space, time, and matter at the highest energies possible: those found at the birth of the universe.

Although the landscape of possible models for inflation is potentially large—and sensitive to quantum gravity corrections to the low-energy quantum field theory—the phenomenology is sufficiently well understood to make concrete distinctions between fundamentally different classes of models that we can test observationally.

One key and generic prediction is the existence of a background of gravitational waves [1] from inflation that produces a distinct signature in the polarization of the CMB, referred to as "*B*-mode" polarization. The amplitude of primordial gravitational waves, or tensor modes, which can be detected or constrained by observations of the *B*-mode polarization in the CMB, is fundamentally interesting for several basic reasons. It is proportional to the energy scale of inflation and tied to the range of the inflaton field. In particular, observations promise to reach the level of sensitivity that will enable them to determine whether the field range is larger than the Planck scale in the simplest versions of inflation [2] . This provides a striking ultraviolet-sensitive probe of quantum field theory and quantum gravity, and an observational test of string theoretic large-field inflation. Additionally, in one theoretically developed (though currently speculative) alternative to inflation, the ekpyrotic scenario, the authors of [3,4] find no mechanism for generation of the tensor perturbations; hence, if these calculations are correct, detection of *B*-modes would present a convincing refutation of that model. Last but not least, a detection of tensor modes would constitute a stunning measurement of the quantum mechanical fluctuations of the gravitational field.

This motivates a next-generation CMB experiment with the sensitivity and systematics control to detect such a polarized signal at $\geqslant 5\sigma$ significance, thus ensuring either a detection of inflationary gravitational waves or the ability to rule out large classes of inflationary models. A program to meet these goals by developing a Stage IV CMB experiment, CMB-S4, with $O(500{,}000)$ detectors by 2020 is described in the companion cosmic frontier planning document (*Neutrino Physics from the Cosmic Microwave Background and Large Scale Structure* [5]). Such an experiment would also contribute to inflationary science by strongly constraining the spectrum of primordial density fluctuations, allowing us to distinguish different families of inflationary models.

Possibilities for self-interactions of the inflaton and for additional fields are tested by different limits of the correlation functions of the perturbations. Despite important recent progress, we require substantial improvements before observational constraints on these quantities limit the interactions to be small corrections to slow-roll, or to detect non-Gaussianity if it is present. A concerted theoretical effort combined with observations of large scale structure promises to fill this gap. A detection of primordial non-Gaussianity of the so-called local shape would effectively rule out all models of inflation that involve a single scalar field [6–8]). The CMB bound on local-model non-Gaussianity is now limited by having only one sky to observe; further improvements will come from measurements of the large scale structure of the universe. The next generation of large scale structure measurements will produce non-Gaussianity constraints that are an important cross-check of the CMB bound and will pave the way for more stringent bounds from future large scale structure measurements.

2. Inflation science: theoretical motivations

Cosmic inflation, the idea that the universe underwent a period of exponential expansion in the first 10^{-34} seconds of its existence, was proposed in the early 1980s to explain the apparent smoothness and flatness of the universe and the absence of relics such as magnetic monopoles [9]. Quantum fluctuations generated during inflation evolve into the distributions of dark matter and galaxies we observe today [10]. Inflation drives the spatial curvature to nearly zero, and introduces density perturbations that are adiabatic with a nearly scale invariant spectrum that depends on the details of the inflationary potential.

The frontier of inflation research currently lies in measurement of the polarization of the CMB and in searching for non-Gaussianity in the distribution of dark matter and galaxies in the late universe. The CMB offers a unique window between the late-time universe dominated by dark matter and dark energy, and the early universe when the energy density was dominated by the potential that drove cosmic inflation. The amplitude of tensor *B*-mode polarization in the CMB is proportional to the energy of inflation and tied to the range of the inflaton field. The rich phenomenology of non-Gaussianity in the distribution of dark matter and galaxies in the late universe offers opportunities to directly study the dynamics of inflation.

In the context of inflationary paradigm, we can be precise about the significance and interpretation of these measurements. Here we briefly summarize some highlights.

The predictions of most inflationary models can be characterized in terms of the statistical properties of perturbations to the metric away from a homogeneous background solution $a(t) \approx e^{Ht}$. We can parameterize the metric as

$$ds^2 = -N^2 dt^2 + h_{ij}(dx^i + N^i dt)(dx^j + N^j dt), \tag{1}$$

where

$$h_{ij} = a(t)^2 \left[e^{2\zeta} \delta_{ij} + \gamma_{ij} \right] \tag{2}$$

and N, N^i represent the lapse and shift, non-dynamical modes of the metric that enforce constraints. Here ζ contains the scalar perturbation (in a gauge where the inflaton perturbation has been gauged away via time reparameterization), and γ the tensor perturbation. The CMB and LSS are sufficiently linear in the regimes of interest that these primordial metric perturbations can by inferred directly from observations. The greater challenge is to make inferences about the physics of inflation from knowledge of ζ and γ_{ij}.

2.1. Tensor modes

Determining the tensor to scalar ratio

$$r = \frac{\langle \gamma\gamma \rangle}{\langle \zeta\zeta \rangle} \tag{3}$$

via a measurement of the primordial *B*-mode polarization [11–14] is important for three simple reasons.[1]

(1) A detection would constitute a measurement—for the first time—of the quantum mechanical fluctuations of the metric: in the absence of classical inhomogeneities ($\langle \gamma_{ij} \rangle = 0$) inflation generates a nonzero variance

$$\langle \gamma_{s,\mathbf{k}} \gamma_{s',\mathbf{k}'} \rangle' = \frac{1}{2k^3}\, 2\,\frac{H^2}{M_P^2}\, \delta_{ss'} \delta^{(3)}(\mathbf{k} + \mathbf{k}'), \tag{4}$$

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[1] Exceptions to these going beyond single field slow-roll inflation, for example postulating rapid variation of the slow-roll parameter $\dot{H}/H^2$ [15,16], or including gravitational waves from sources produced during inflation [17], bring in their own motivations on par with that derived from the relation (5) in the simplest cases. Although these more exotic possibilities are interesting, with space constraints we will not lay out the various caveats.