Snowmass2021 – Letter of Interest

Probing Physics at the Highest Energy Scales with Primordial Features

Thematic Areas:
■ (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
■ (TF09) Astro-Particle Physics & Cosmology

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Abstract:
Inflation provides unique insight into the physical laws, potentially at energy scales that cannot be replicated in any terrestrial experiment. Features in the primordial power spectrum are generically predicted in a wide class of inflationary models, and its alternatives, and are observationally one of the most overlooked channels for finding evidence for non-minimal inflationary models. Future cosmic surveys can make tremendous improvements in sensitivity and offer the potential for a dramatic discovery about the nature of cosmic acceleration in the very early universe. Features may also be produced at later times as a consequence of the evolution of the primordial plasma which could reveal unique information about the particles and forces at play in the universe.

Cosmic inflation may potentially provide access to the highest energy scales of nature. Generic models of inflation predict Gaussian fluctuations with a nearly scale-invariant power spectrum, but more complex models can imprint features in the primordial spectra (see [1–3] for reviews). Finding these imprints in future cosmic microwave background (CMB) and large-scale structure (LSS) experiments would be a groundbreaking discovery that would open an entirely new window into the primordial universe. This would shed light on the mechanism underlying inflation, which may be sensitive to ultraviolet (UV) physics and give theoretical hints about physics at the Planck scale.

The space of inflationary models (and their alternatives) is vast and includes a number of scenarios where the dynamics that give rise to the primordial density fluctuations are more complicated than in single-field inflation. The early universe would have involved many degrees of freedom with complicated interactions, leading to a variety of non-adiabatic or even classical production mechanisms. These dynamics can also give rise to an excited state for the degrees of freedom and significantly alter the description of this era in cosmic history. Any of these effects may leave a residual sharp feature in the initial conditions of the hot big bang.

Broadly speaking, features in the primordial spectra are rooted in one of the most fundamental challenges in inflationary model building: creating a flat potential or, more generally, making the slow-roll parameters small. While one can arrive at such a model by introducing a new symmetry, these very symmetries are known to be broken in a theory of quantum gravity. While such effects are known to be irrelevant for earthly phenomena, inflation is famously sensitive to them (see e.g. [4, 5]). Models which avoid the most drastic effects of quantum gravity can still have relics of this basic tension in various sub-leading violations of scale invariance in the form of features. Detecting such features would provide a unique insight into the physics of the primordial universe. In addition, it could provide evidence for particular models of inflation or one of its alternatives, or identify the existence of new particles and forces in the early universe.

For many purposes, primordial features can be characterized by density perturbations that contain some small components that significantly depart from scale invariance. These signatures arise in broad classes of models, including both inflation and its alternatives. There are several general types of feature models which we classify according to their underlying generation mechanisms and illustrate in the left panel of Fig. 1: (i) resonant features (oscillations in $\log k$), (ii) sharp features (oscillations in k) and (iii) primordial standard clocks. In the first class of models, the background evolution oscillates around the attractor solution with a frequency that is larger than the horizon scale, with the axion monodromy model being a well-known example [6–8]. Sharp features arise in models that deviate from the attractor solution at some point during their evolution due to a variety of physical origins [9–20]. Finally, massive fields in the primordial universe may oscillate either classically or quantum mechanically, imprinting primordial clock signals in the density perturbations [21–24]. All these types of features in the power spectrum have correlated signals in non-Gaussianities, i.e. higher-point statistics, which can be used as further supportive evidence [6, 25–32]. More generally, the physics responsible for these scenarios is often deeply tied to the fundamental origin of the respective model and may allow observations to reach to a scale higher than the inflationary Hubble scale [33]. At the same time, broader lessons for low-energy effective field theory and data analysis can also be extracted.

Alternatively, oscillatory features may also be imprinted in the cosmological observables as a result of the dynamics of the primordial plasma after the hot big bang. For instance, an interaction between all or a fraction of the dark matter and dark radiation (neutrinos or relativistic particles beyond the Standard Model) would result in so-called dark acoustic oscillations [35–45]. Features may also be the result of non-standard components affecting the expansion history at early times [46, 47]. A detection of these and similar signals may therefore provide a unique probe of the particles and their interactions present in the universe.

In the most general case, features represent any component that modulates a smooth "background" given by a near power-law primordial power spectrum. Some of these models are localized in Fourier space, e.g. those generated by kinks or other local features in the inflationary potential, others oscillate with a

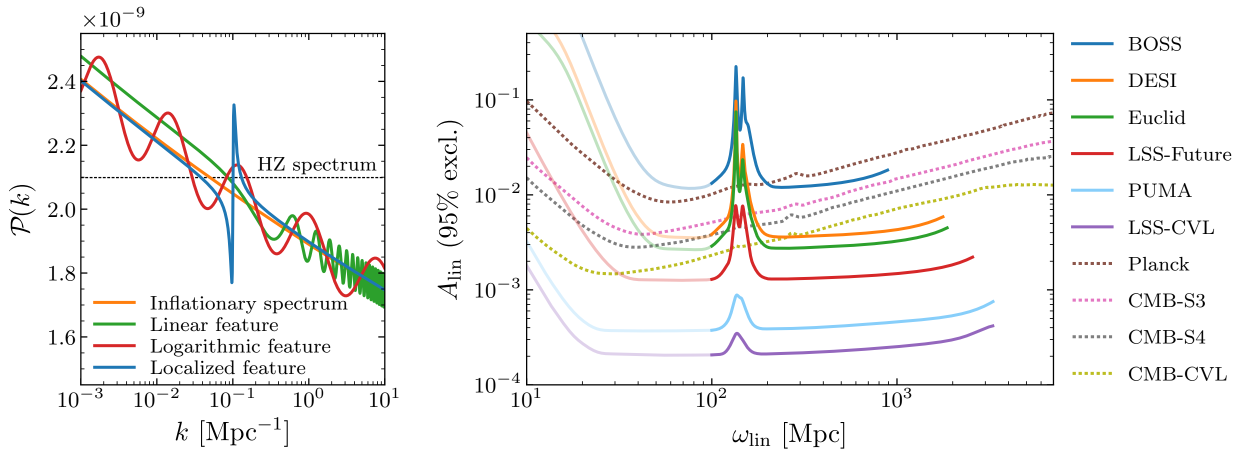

Figure 1: *Left:* Schematic illustration of the dimensionless power spectrum of primordial curvature fluctuations, $\mathcal{P}(k)$, including different types of features. *Right:* Forecasted sensitivity for the "feature spectrometer". The potential reach of various CMB (dotted) and LSS (solid) surveys to constrain the relative amplitude of linear features, $A_{\rm lin}$, is presented as a function of their frequency $\omega_{\rm lin}$. (Adapted from [3, 34] which include a detailed description.)

sufficiently high frequency to be distinguishable from the smooth component. The details and specific predictions vary significantly within the vast landscape of primordial, early universe and particle physics models.

Any features in the (primordial) power spectrum will result in signals in all observables that are sensitive to fluctuations in the universe. Employing different observables is useful since they probe complementary scales and have different advantages. Extensive searches have been performed in particular in CMB data, but no significant detection has been reported to date, constraining the feature amplitudes to the percent level relative to the primordial scalar amplitude $A_{\rm s}$ [48–60]. The current frontier in the quest for these oscillatory imprints are optical galaxy surveys, with present data leading to constraints competitive with those from the CMB over the currently accessible range of scales [34] and significant improvements being potentially achievable over the next decade (cf. Fig. 1) [34, 61–72]. Future 21 cm surveys, such as the Stage II experiment PUMA [73–77] or surveys targeting the era prior to reionization, hold the promise to improve the constraints by another few orders of magnitude [34, 73, 78, 79]. Finally, spectral distortions of the CMB black body spectrum provide an entirely complementary window on the primordial power spectrum and small-scale features [2, 80]. While the observational prospects for a detection of features in cosmological observables are bright, we still require additional theoretical advances (e.g. along the lines of [34, 56, 58, 81–100]) to fully exploit the large amount of data that will be collected by planned and proposed surveys over the next decade.

Primordial features are a generic prediction of many models of the primordial universe beyond the simplest incarnations of single-field slow-role inflation. In fact, departures from the minimal power-law power spectrum of initial fluctuations are ubiquitous in theoretical attempts to connect the inflationary modeling to fundamental physics. In addition, similar signals may be imprinted in observables during the cosmic evolution after the hot big bang. Future planned and proposed CMB and LSS surveys, especially 21 cm experiments, will be able to constrain a significant part of the parameter space. However, given our lack of understanding of fundamental physics at this point, cosmological searches have to consider a huge parameter space. Additional theoretical insights into particle physics models, and connections between UV- and Planck-scale physics would therefore tremendously help in the quest to uncover the particle content in the early universe, the nature of inflation and the physics at the highest energy scales testable in the universe.

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