Snowmass2021 Letter of Interest:
Primordial Non-Gaussianity

Thematic Areas:

■ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
■ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
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Abstract: All the information we will ever obtain about the primordial universe is contained in the detailed statistics and characterization of its initial conditions. Currently, experimental data can be explained with nearly scale-invariant Gaussian initial conditions. A minimal deviation from Gaussianity is perhaps the most robust theoretical prediction of "Beyond the Standard Model" cosmology; it is necessarily present even in the simplest scenarios that explain the observed Universe. A detection and characterization of non-Gaussianity would be a fantastic triumph of experimental and theoretical cosmology, probing the dynamics of the early Universe, and providing clues about physics at energy scales much higher than those of colliders. In this LOI we review the current understanding of primordial non-Gaussianity—from its detailed calculation to the various predicted shapes—as well as its imprints in cosmic microwave background and large scale structure observables. These theoretical advances will allow us to characterize, constrain, and potentially detect primordial non-Gaussianity this decade.

Introduction: The initial conditions of our Universe, sourced by a Gaussian random field with almost scale invariant power, are part of our Standard Model of cosmology. The assumption of Gaussianity has so far been confirmed by data [1–3]. However, all theories that explain the sourcing of initial conditions predict that there are deviations from Gaussianity. A measurement and characterization of non-Gaussianity is a window to "Beyond the Standard Model" physics. As inflation—the leading scenario for sourcing the fluctuations—likely occurred at energies way beyond the reach of particle colliders, non-Gaussianity provides a window and testbed to connect fundamental theory to experiment. This LOI explains the state of the art in understanding primordial non-Gaussianity, highlighting the theoretical effort devoted to precision calculations, as well as its imprints in cosmological observables.

Shapes of non-Gaussianity: The simplest probe of non-Gaussian statistics is the three-point correlation function, or bispectrum, of primordial scalar fluctuations. The bispectrum depends on the separations between the three points in the sky and its detailed *shape*—the amount of power as a function of the shape of the triangle—is controlled by the physical process that sourced the non-Gaussianity. A simple way of characterizing the bispectrum is to consider the coupling between a long wavelength mode and two short modes. In order of increasing strength, the shapes can be classified as follows:

- **Self-interactions (equilateral, orthogonal)** Non-Gaussianity can arise from non-linear self-interactions of the inflaton [4–15]. The fluctuations are all sourced at the same time, so there is weak coupling between long and short modes. A detection of such a signal would test the quantum origin of structure [16].
- **Interactions with heavy fields** Particles with mass of the order of the Hubble scale during inflation can be excited but are diluted quickly after horizon crossing. However, if they decay into inflatons, they generate non-Gaussianity [17–34]. The fluctuations can be sourced at mildly different times, as the heavy field can mediate a moderate range interaction.
- **Interactions with light fields (local)** Light degrees of freedom are excited with an amplitude set by the Hubble scale. They interact with the inflaton and are converted into curvature perturbations, during inflation or reheating, generating non-Gaussianity. There is strong correlation between long and short modes, as the light fields can mediate long range forces [7,35–37]. This non-Gaussianity has been studied extensively within inflation [38–68] and ekpyrosis [69–71].

Additionally, there are shapes that are theoretically well-motivated, but do not fall in the classification above. They typically involve features related to bursts of particle production, and the characteristics of the feature (together with possible cross-correlations with other observables) giving access to the specific mechanism behind its generation [72–96].

Another new direction of research is in the role of higher n-point functions of scalar fluctuations. Certain scenarios have signal to noise that peaks at higher-point functions, [97], probing scales higher than the inflationary Hubble scale. There has also been work in characterizing the contribution that tails of the distribution might make to phenomenology [98–102].

Inflation also predicts primordial gravitational waves. Their detection from B-mode polarization is an important experimental target. Therefore, recent effort has been put in characterizing bispectra of tensor fluctuations. Like in the scalar case, the bispectra can be sourced from self-interactions of gravitons and scalars. Moreover, exchange of certain types of massive particles with spin generate a nontrivial angular dependence in the squeezed limit [31]. Interesting signals also arise if the kinetic terms of the spinning fields strongly break the de Sitter symmetry [27, 103–105], if position-dependent background fields break the spatial isometries [106–110] or, more generally, if the tensors are sourced by additional fields [111–115]. Non-Gaussianities also arise from particles within [28,116–120] and beyond [121–127] the Standard Model.

Finally, there have been recent advances in calculational methods, leveraging techniques from scattering amplitudes, conformal field theory, etc. thus allowing for precise calculations of many new shapes of non-

Gaussianity [32, 122, 124, 128–138] as well as more formal developments in the theory of cosmological correlators [139–160] and their soft limits [161–163].

Imprints in cosmological observables: *Planck* has provided constraints [2, 3] on the simplest shapes of non-Gaussianity, significantly improving bounds from *WMAP* [1]. Leading up to *Planck*, the development of new methods [164–167] have opened up the space of constrained shapes, from a few to almost thirty thousand [2]. New methods were developed to constrain bispectra with features [83, 168–170], which have allowed the *Planck* collaboration to explore a significant part of this parameter space [2, 3]. In addition, since features in the power spectrum and the bispectrum generally contain correlated parameters [79, 81, 88, 92, 170, 171], statistical methods have been developed to use constraints from both the power spectrum and the bispectrum to further constrain model space [172–174] and joint analysis of the power spectrum and bispectrum were presented in [173, 175].

Various ongoing and planned cosmic microwave background (CMB) experiments will improve polarization sensitivity and measurements down to smaller scales further constraining non-Gaussianities [176–180]. Improved sensitivity requires a careful treatment of secondary effects that are imprinted in the CMB from both extra-galactic [181–186] and galactic origin [187–189], which could obscure the primordial signal. The latter would benefit from using multi-frequency data [190]. Non-Gaussian contributions to the covariance can also become important [181, 191]. Alternatively, the CMB can constrain local non-Gaussianities using spectral distortions [192–201].

Beyond the CMB, developments in large-scale structure (LSS) theory demonstrate that LSS can provide even stronger constraints than those from the CMB [36, 202–205]. Local non-Gaussianity leaves imprints on the power spectrum [206, 207] and bispectrum of tracers of LSS [208–215]; see also [216–219]. The effect of local non-Gaussianity on LSS is robust with respect to theoretical modeling, as gravitational interactions cannot generate this signal. While measuring power spectra is an advanced technique in LSS analysis, from a systematic point of view, clean measurements of very large scales are difficult due to imprints of our own galaxy, solar system neighbourhood and survey strategy [220–222]. Equilateral-like shapes suffer from the opposite problem; observations are likely to be cleaner, but theoretical modelling will suffer from our lack of understanding of non-linear gravitational evolution on smaller scales. Improved perturbative understanding of biased tracers at small scales [223, 224] give us access to more modes and improve constraints on correlation functions [36]. In addition to perturbative studies, numerical simulations are important tools to characterize the effects of primordial non-Gaussianity on LSS observables [210, 225, 226].

Different LSS tracers have different advantages. Galaxies from spectroscopic and photometric surveys are the most advanced tracers and will reach exquisite signal-to-noise ratios in the coming decade. Weak gravitational lensing probes dark matter directly and is theoretically easier to model. Furthermore, galaxy shapes are uniquely sensitive to anisotropy in primordial non-Gaussianity [227–230]. Neutral hydrogen traced by 21-cm allows one to go higher redshift, where the volume available is large and the universe is more linear and thus easier to model. This could significantly benefit the search for non-Gaussianities [231–234], especially when combined with low redshift probes of the LSS [215, 235, 236]. Besides neutral hydrogen, intensity mapping with other emission lines could further improve constraints on primordial non-Gaussianity [237, 238].

Finally, recent theoretical work has shown that impressive improvements can be made when combining multiple tracers, resulting in cosmic variance cancellation [239]. Forecasts show [240, 241] local non-Gaussianity could be measured to levels below the theoretically motivated threshold when combining Vera Rubin Telescope (LSST) data [242] with future CMB data [177].

Conclusion: Detecting and characterizing the initial conditions of the Universe remains one of the most important goals of cosmology. A detection of non-Gaussianity will give unprecedented access to the highest energy phenomena in the Universe, connecting fundamental theory to observations.

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