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Primordial Non-Gaussianity

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Abstract: Our current understanding of the Universe is established through the pristine measurements of structure in the cosmic microwave background (CMB) and the distribution and shapes of galaxies tracing the large scale structure (LSS) of the Universe. One key ingredient that underlies cosmological observables is that the field that sources the observed structure is assumed to be initially Gaussian with high precision. Nevertheless, a minimal deviation from Gaussianity is perhaps the most robust theoretical prediction of models that explain the observed Universe; it is necessarily present even in the simplest scenarios. In addition, most inflationary models produce far higher levels of non-Gaussianity. Since non-Gaussianity directly probes the dynamics in the early Universe, a detection would present a monumental discovery in cosmology, providing clues about physics at energy scales as high as the GUT scale.

This white paper aims to motivate a continued search to obtain evidence for deviations from Gaussianity in the primordial Universe. Since the previous decadal, important advances have been made, both theoretically and observationally, which have further established the importance of deviations from Gaussianity in cosmology. Foremost, *primordial* non-Gaussianities are now very tightly constrained by the CMB. Second, models motivated by stringy physics suggest detectable signatures of primordial non-Gaussianities with a unique shape which has not been considered in previous searches. Third, improving constraints using LSS requires a better understanding how to disentangle non-Gaussianities sourced at late times from those sourced by the physics in the early Universe. The development of the Effective Field Theory of Large Scale Structure and a number of proposed methods to ‘reconstruct’ the initial conditions have contributed significantly to that effort. Lastly, a new technique that utilizes multiple tracers to cancel sample variance in the biased power spectrum, promises constraints on local non-Gaussianities beyond those achievable with higher n -point functions in both the CMB and LSS within the coming decade.

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Introduction: Increasingly precise measurements of the Cosmic Microwave Background (CMB) and the large-scale structure (LSS) have shown that initial conditions for our Universe can be described by only a handful of parameters. Since the last decadal [1], the *Planck* satellite [2] has confirmed that the initial seeds of structure must have been close to Gaussian. Truly Gaussian seeds are characterized only by the power spectrum, which is currently well described by just two parameters: the overall power and scale dependence of primordial fluctuations. Yet gravity puts a lower bound on non-Gaussianity, which typically lies a few orders of magnitude below current constraints [3, 4]. A plethora of proposed models and mechanisms populate this unexplored window of non-Gaussian signals. Distinguishing among these possibilities provides a strong motivation to look for signatures beyond the current two-parameter description. Besides evident theoretical motivation, which we will elaborate on below, significant advancements in observational cosmology will allow us to obtain tighter bounds on cosmological parameters.

The scale of inflation is a most uncertain parameter and can range across a dozen orders of magnitude without contradicting current observations. If inflation takes place at the highest energies, significant efforts in trying to detect primordial gravitational waves will triumphantly determine this scale. But if inflation takes place at lower energies, *Primordial non-Gaussianities* will be our unique source of information as, unlike gravitational waves, their amplitude does not diminish with energy. Hence, by complementing gravitational wave searches, the study of non-Gaussianity will provide profound *new information about the early Universe* by directly probing inflationary dynamics and field content at energy scales far beyond those accessible through laboratory experiments. This is precisely why early Universe cosmology is considered one of the pillars of modern physics, connecting the disciplines of fundamental theory with empirical observations. We will summarize recent theoretical developments that have derived fundamentally new predictions for primordial non-Gaussianity, highlight physics that leads to interactions between the scalar and tensor sectors and identify the general mechanisms that produce detectable levels of non-Gaussianity. Although current bounds on non-Gaussianity are impressive, we will stress that there is ample opportunity for discovery, and such a discovery would instantly present one of the most important contributions to our understanding of the early Universe. We will end by identifying new avenues in observational cosmology that are most promising in improving bounds on non-Gaussianity in the next decade.

Exploring the early Universe through non-Gaussian statistics: Deviations from Gaussianity directly translate into signatures of the dynamics and the field content driving inflation [3, 5, 6]. Although non-Gaussian correlations are small in the simplest models of single-field slow-roll (SFSR) inflation, a much larger fraction of inflationary models is expected to produce non-Gaussianities that could be detectable. Currently, *WMAP* [7] and *Planck* [2] provide the most stringent limits on a wide range of non-Gaussian shapes that could be produced during inflation; however, today's measurements are not sufficiently sensitive to suggest a particular mechanism is favored by the data. At the same time, our understanding of inflation is continually refined, and there is an associated need to improve our understanding of the underlying dynamics directly through constraints on higher-order correlations [1, 8, 9].

Deviations from Gaussianity in the initial fluctuations are most easily measured through their effect on the bispectrum, the Fourier transform of the three-point correlation function (similar to skewness in 1D). By homogeneity and isotropy, the bispectrum is a function of the norm of three momenta (here $k_a = |\vec{k}_a|$, for $a = 1, 2, 3$), which combine to form a triangle; its *shape* describes

triangular configurations where the bispectrum is largest. Together with the *amplitude* f_{NL} this defines a unique bispectrum^a. Different physical scenarios generate distinguishable shapes and we can identify associated thresholds for the amplitude that allow us to classify the physics of inflation (and alternatives).

Generally, bispectra are most easily visualized according to the contributions in three distinct shapes; local, equilateral and folded triangles. Physically they correspond to a shape where $k_1 \ll k_2 \sim k_3$ (squeezed or local), with amplitude $f_{\text{NL}}^{\text{local}}$, $k_1 \sim k_2 \sim k_3$ (equilateral) with amplitude $f_{\text{NL}}^{\text{equil}}$ and $k_1 + k_2 \sim k_3$ (folded) with amplitude $f_{\text{NL}}^{\text{folded}}$. Detectable amounts of non-Gaussianity could be produced in the following scenarios:

- **Inflaton self-interactions** Non-gaussianity can arise from non-linear dynamics during single-field inflation. In the most well-studied case, these interactions also cause the fluctuations to propagate with a speed slower than the speed of light. Both a detection or an exclusion of such a signature provides a unique window into the mechanism behind inflation.
- **Additional light fields** Light degrees of freedom are excited from the vacuum with an amplitude set by the Hubble scale. When this degree of freedom is not the inflaton, these fluctuations freeze-out and describe isocurvature (entropy) fluctuations. These isocurvature modes may eventually convert into isocurvature perturbations, during inflation or reheating. These conversion processes induce correlations between modes that are necessarily non-Gaussian.
- **Additional heavy fields** Heavy degrees of freedom (e.g. particles with mass on the order of the Hubble scale during inflation, or larger) are excited during inflation but are diluted quickly after horizon crossing. However, when the inflaton couples to these additional degrees of freedom, their fluctuations can still correlate the adiabatic modes producing non-Gaussianity.

All bispectra that come from fluctuations of the field that drives inflation (“single-clock” scenarios) most strongly couple momenta of similar wavelengths. The “squeezed limit” of these bispectra is very restricted for adiabatic modes, which are necessarily the only fluctuations in attractor single-clock models. A large fraction of the parameter space for scenarios involving interactions during inflation that respect the underlying shift symmetry (i.e. are approximately scale-invariant) is captured by equilateral [12] and orthogonal shapes [13], where the latter is orthogonal to equilateral. Examples include scenarios in which inflaton fluctuations have non-trivial self-interactions [13–18] or couplings between the inflaton and other (potentially massive) degrees of freedom [19–26]. Vanilla SFSR inflation necessarily produces $f_{\text{NL}}^{\text{equil}} < 1$ [27] and therefore *any detection of $f_{\text{NL}}^{\text{equil}} \geq 1$ would rule out a large class of models* and would imply that inflation is a strongly coupled phenomenon and/or involved more than one field [28–30].

In single-field inflation, f_{NL} typically is related to a new energy scale, M , such that $f_{\text{NL}}^{\text{equil}} \propto (H/M)^2$ [18, 31], with H the hubble scale during inflation. At this energy scale self-interactions become strongly coupled and current limits on the bispectrum [2] translate into $M > \mathcal{O}(10)H$. In the presence of additional fields besides the inflaton, $f_{\text{NL}}^{\text{equil}}$ scales with the strength of the coupling between the inflaton and these additional fields, usually suppressed by an energy scale Λ . Current limits give $\Lambda > \mathcal{O}(10-10^5)H$ [32, 33]. Fixing the amplitude of scalar perturbations to its observed value, the tensor-to-scalar ratio $r \propto H^2$, and for $r > 0.01$ these constraints require some of the interactions to be *weaker than gravitational*.

^aSimilar to the power spectrum, the bispectrum could in principle inherit scale dependence which would introduce more degrees of freedom [10, 11].

When light degrees of freedom other than the inflaton contribute to the observed scalar fluctuations (i.e. multi-field inflation), coupling between modes of very different wavelengths is allowed. Historically, the most well-studied bispectrum is the local bispectrum, which couples short wavelength modes $k_2 \sim k_3$ to long wavelength modes k_1 . *A detection of this shape with an amplitude of $f_{\text{NL}}^{\text{local}} \sim \mathcal{O}(1)$ would rule out all attractor models of single-clock inflation* [34]. Non-attractor models exist that generate observable $f_{\text{NL}}^{\text{local}}$ [35–40] and are under continued investigation [41–45].

Multi-field inflationary models can produce observably large local non-Gaussianity and provide a well-motivated framework for interpreting upcoming observations. It has long been known that substantial levels of non-Gaussianity can be generated after the end of inflation [46–50], and $f_{\text{NL}}^{\text{local}} \sim \mathcal{O}(1)$ is a natural outcome when the primordial perturbations are generated by a so-called ‘spectator’ field [51–55]. Generating observational levels of local non-Gaussianity *during* multi-field inflation is more challenging, as can be understood from simple toy models [56], general arguments [57–61], and explicit solutions of inflationary models with many interacting fields [62–64]. Consequently, substantial multi-field contributions to the primordial curvature perturbations do not guarantee large non-Gaussianities, and *a detection of $f_{\text{NL}}^{\text{local}} \sim \mathcal{O}(1)$ would provide decisive insights into the origin of the primordial density perturbations*. Non-inflationary cosmologies can also produce large primordial non-Gaussianities of the local shape [65], and would be heavily constrained by improved limits on $f_{\text{NL}}^{\text{local}}$. Finally, we note that a detection of $f_{\text{NL}}^{\text{local}}$ would open the door to significant cosmic variance on all scales from coupling of fluctuations within our observed volume to any super-Hubble modes [66–69]. Indeed, there would be room for a significant shift between the observed amplitude of scalar fluctuations (and so the observed tensor-to-scalar ratio r) and the mean value of fluctuations on much larger scales [70].

Additional theoretically well-motivated shapes are not captured by local, equilateral, folded and orthogonal triangles. For example, in models in which the inflaton is an axion with monodromy [71–74], bursts of particle or string production naturally lead to *periodic features* in the bispectrum where the frequency of the feature can be linked to the axion decay constant [75–77]. Often these contributions will lead to counterparts in the power spectrum and are expected to be detected there first [78], but this need not be the case [79]. Various other mechanisms could also introduce non-trivial features in the primordial bispectrum [80–90], providing a rich phenomenology in bispectrum space.

The Hubble scale during inflation might have been as high as 10^{14} GeV, providing access to physics far beyond the reach of conventional particle colliders. At these energies, new massive particles, if they exist, are created by the rapid expansion of the inflationary space-time. When these particles decay, they can produce nontrivial correlations in the inflationary perturbations [20, 24, 26, 33, 91–103]. The characteristic signature of these new particles is a non-analytic scaling in the squeezed limit of the bispectrum or the collapsed limit of the trispectrum (the Fourier transform of the 4-point function). For masses above the inflationary Hubble scale, the signal will oscillate and frequencies of these oscillations encode the *masses of the new particles*.

Thus far, both theoretically and observationally, correlators involve only scalar degrees of freedom. However, in light of upcoming B-mode polarization experiments, in principle bispectra involving multiple tensors (e.g. the scalar-scalar-tensor bispectrum (SST)) can be constrained for the first time. Massive particles with spin generate a nontrivial angular dependence in the squeezed limit. Certain types of spinning particles—so-called partially massless (PM) particles—can lead to an enhanced signal in the SST bispectrum [100]. This would be a characteristic signature of the inflationary de Sitter spacetime, since PM particles have no analog in flat space. Alternatively, a

non-trivial signal in the SST bispectrum can arise if the kinetic terms of the spinning fields strongly break the de Sitter symmetry [96, 104–106], if position-dependent background fields break the spatial isometries [107–111] or, more generally, if the tensors are sourced by additional field, e.g. in gauge-flation [25, 112–115]). Non-Gaussian signals may also arise from particles within the Standard Model [116–118]. For instance, if the Higgs field has a coupling to curvature, it can acquire a mass of order the Hubble scale during inflation, and naturally couple to the inflaton in pairs, contributing to non-Gaussianity. Similarly, scalar partners in supersymmetric theories would produce non-Gaussianity if they exist anywhere up to the inflationary Hubble scale [24].

Finally, a more general question is the role of higher n -point functions of scalar fluctuations. For example, if the inflaton couples directly to other fields, additional particles may be produced at a mass scale up to of order the square root of the kinetic energy of the inflaton field. Axion fields in string theory introduce periodic events of this kind. The signal to noise for the resulting non-Gaussianity *peaks at a value of n which can be greater than 3* [119]. This implies a reach of observations to a higher scale than the inflationary Hubble scale. It is of interest to characterize the contribution that tails of the distribution might make to phenomenology. Early work covering aspects of this appeared in [120], and several groups are investigating the problem more generally [121, 122]. The amplitude of the tails exhibits exponential sensitivity to model parameters, whose characterization requires a careful theoretical analysis. This direction, as well as additional shapes of low-point correlation functions, *promise to increase the physics that can be learned from the analysis of primordial non-Gaussianity*.

Prospects for the measurement of non-Gaussianities in the next decade: *Planck* has provided constraints [2] on the most theoretically compelling shapes discussed in the previous section, improving bounds from *WMAP* by almost an order of magnitude [7]. The original method to constrain the primordial bispectrum in the CMB and in LSS relied on the primordial shape being of simple factorizable form, forcing the analysis to use specifically designed templates. Leading up to *Planck*, new methods [123–126] have been developed that have opened up the space of constrained shapes dramatically. Now, almost thirty thousand different shapes have been put to the test [2]. Despite these improvements, bispectra that contain features have proven hard to constrain, since the frequency and phase of the features have broad theoretical priors. New methods developed better equipped to look for such bispectra [85, 127–129] have allowed the *Planck* collaboration to explore a significant part of this parameter space, thus far without finding significant evidence for deviations from non-Gaussianity [2]. In addition, since features in the power spectrum and the bispectrum generally contain correlated parameters [23, 75, 83, 88, 90, 129], statistical methods have been developed to use constraints from both the power spectrum and the bispectrum to further constrain model space [130–132] and joint analysis of the power spectrum and bispectrum were presented in [131, 133].

Because of its computational complexity, the search for non-Gaussianity differs from the measurement of the primordial power spectrum. Unlike the power spectrum, the bispectrum and higher order n -point functions are pre-calculated spectra and the cosmology is held fixed; only the shape is varied and the amplitude f_{NL} is determined from the data. This implies that if we have yet to determine the correct shape of the primordial bispectrum, we could very well miss the signal entirely. On the other hand, the same richness of possible inflationary models increases the possibility of false detections due to the look-elsewhere effect.

Various ongoing and planned CMB experiments will significantly improve polarization sensi-

tivity and measurements down to smaller scales further constraining non-Gaussianities [134–136]. It must be noted that improved sensitivity requires a careful treatment of secondary effects that are imprinted in the CMB from both extra-galactic [137–141] and galactic origin [142, 143], which could obscure the primordial signal. The latter would benefit from using multi-frequency data [144]. Non-Gaussian contributions to the covariance can also become important [137, 145]. Alternatively, the CMB can constrain local non-Gaussianities using spectral distortions [146–155].

Beyond the CMB, developments in large-scale structure theory and analysis demonstrate that LSS could provide us with even better constraints than those obtained with the CMB [29, 156, 157]. Local non-Gaussianity uniquely produces effects on *both* power spectrum [158, 159] and bispectrum of tracers of large-scale structure. The effect of local non-Gaussianity on LSS is relatively robust with respect to theoretical modeling because gravitational interactions cannot generate this signal. While measuring power spectra is a remarkably advanced technique in LSS analysis, from a systematic point of view, clean measurements of very large scales are particularly difficult due to imprints of our own galaxy, solar system neighbourhood and survey strategy on the observed modes. Equilateral and orthogonal shape suffer from the opposite problem; observations are likely to be cleaner, but theoretical modelling will suffer from our understanding of non-linear gravitational evolution on smaller scales. Improved perturbative understanding [160–163] of small scales will allow us to utilize more modes and improve projected constraints on the primordial correlation functions [29]. 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 [164, 165]. 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 [166], initially at relatively low redshifts [167] and eventually throughout the entire observable universe [168], opening up the full potential of the cosmological collider experiment [169] when combined with low redshift probes of the LSS [170–172]. Besides neutral hydrogen, intensity mapping with other emission lines could further improve constraints on primordial non-Gaussianity [173, 174].

Finally, recent theoretical work has shown that impressive improvements can be made when combining multiple tracers, resulting in so-called cosmic variance cancellation [175]. Forecasts show [176, 177] local non-Gaussianity could be measured to levels below the theoretically motivated threshold when combining Large Synoptic Survey Telescope data [178] with future CMB data [135]. Similar cancellation could be achieved when combining multiple measurements of the shape of galaxies in a search for anisotropic non-Gaussianity [165].

Conclusion: Though non-Gaussianity has been significantly constrained, by necessity the bounds apply only to a tiny fraction of possible non-Gaussian directions in theoretical parameter space. There is a rich interplay between the analysis of non-Gaussianity and theoretical developments which continue to uncover novel dynamical mechanisms for inflation and its perturbations. Once data is collected, it can bear new fruit with each additional theoretical structure that motivates novel tests. Even null results can be very informative, illuminating the empirical boundaries in the space of well-defined theoretical parameters. This motivates a continued effort in constraining correlation functions beyond the two-point function, which ultimately hold the only key to access physics at energy scales close to the boundary of our knowledge.

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