Astro2020 Science White Paper

Primordial Non-Gaussianity

Thematic Areas: Cosmology and Fundamental Physics

Principal Author:
Name: P. Daniel Meerburg
Institution: University of Cambridge
Email: pdm46@cam.ca.uk
Phone:

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 provide 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.

Authors/Endorsers[a]:
Daniel Green[1], Muntazir Abidi[2], Mustafa A. Amin[3], Peter Adshead[4], Zeeshan Ahmed[5], David Alonso[6], Behzad Ansarinejad[7], Robert Armstrong[8], Santiago Avila[9], Carlo Baccigalupi[10,11,12], Tobias Baldauf[2], Mario Ballardini[13], Kevin Bandura [14,15], Nicola Bartolo[16], Nicholas Battaglia[17], **Daniel Baumann**[18], Chetan Bavdhankar[19], José Luis Bernal[20,21], Florian Beutler[22], Matteo Biagetti[18], Colin Bischoff[23], Jonathan Blazek[24,25], J. Richard Bond[26], Julian Borrill[27], François R. Bouchet[28], Philip Bull[29], Cliff Burgess[30], Christian Byrnes[31], Erminia Calabrese[32], John E. Carlstrom[33,34,35], Emanuele Castorina[36], Anthony Challinor[37,2,38], Tzu-Ching Chang[39], Jonás Chaves-Montero[35], Xingang Chen[40], Christophe Yèche[41], Asantha Cooray[42], William Coulton[38,37], Thomas Crawford[33,34], **Elisa Chisari**[43], Francis-Yan Cyr-Racine[44,45], Guido D'Amico [46], Paolo de Bernardis [47,48], Axel de la Macorra[49], Olivier Doré[39], Adri Duivenvoorden[50], Joanna Dunkley[51], **Cora Dvorkin**[44], Alexander Eggemeier [7], Stephanie Escoffier[52], Tom Essinger-Hileman[53], Matteo Fasiello[22], Simone Ferraro[27], **Raphael Flauger**[1], Andreu Font-Ribera[54], **Simon Foreman**[55], Oliver Friedrich[38], Juan García-Bellido[9], Martina Gerbino[56], Vera Gluscevic[57], **Garrett Goon**[2], Krzysztof M. Górski[39], Jon E. Gudmundsson[50], Nikhel Gupta [58], Shaul Hanany[59], Will Handley,[38,60], Adam J. Hawken[61], J. Colin Hill[62,63], Christopher M. Hirata[25], Renée Hložek[64,65], Gilbert Holder[4], Dragan Huterer[56], Marc Kamionkowski[66], Kirit S. Karkare[33,34], Ryan E. Keeley[67], William Kinney[68], Theodore Kisner[27], Jean-Paul Kneib[24], Lloyd Knox[69], Savvas M. Koushiappas[70], Ely D. Kovetz[71], Kazuya Koyama[22], Benjamin L'Huillier[67], Ofer Lahav[54], Massimiliano Lattanzi[72], Hayden Lee[44], Michele Liguori[16], **Marilena Loverde**[73], Mathew Madhavacheril[51], Juan Maldacena[62], **M.C. David Marsh**[74], Kiyoshi Masui[75], Sabino Matarrese[76], Liam McAllister[17], Jeff McMahon[56], Matthew McQuinn[77], Joel Meyers[78], Mehrdad Mirbabayi[79], **Azadeh Moradinezhad Dizgah**[44,80], Pavel Motloch[26], Suvodip Mukherjee[28], Julian B. Muñoz[44], Adam D. Myers[81], Johanna Nagy[64], Pavel Naselsky[82], Federico Nati[83], Newburgh[84], Alberto Nicolis[85], Michael D. Niemack[17] Gustavo Niz[86], Andrei Nomerotski[87], Lyman Page[51], **Enrico Pajer**[2], Hamsa Padmanabhan[26,88], Gonzalo A. Palma[89], Hiranya V. Peiris[54,50], Will J. Percival [90,91,30], Francesco Piacentni[47,48], **Guilherme L. Pimentel**[18], Levon Pogosian[92], Chanda Prescod-Weinstein[93], Clement Pryke[59], Giuseppe Puglisi[46,94], Benjamin Racine[40], Radek Stompor[95], Marco Raveri[34,33], Mathieu Remazeilles[96], Graça Rocha[39], Ashley J. Ross[97], Graziano Rossi[98], John Ruhl[99], Misao Sasaki[100], Emmanuel Schaan[27,101], Alessandro Schillaci[102], Marcel Schmittfull[62], Neelima Sehgal[103], Leonardo Senatore[94], Hee-Jong Seo[104], Huanyuan Shan[105], Sarah Shandera[106], Blake D. Sherwin[2,38], **Eva Silverstein**[46], Sara Simon[56], **Anže Slosar**[87], Suzanne Staggs[51], Glenn Starkman[99], Albert Stebbins[107], Aritoki Suzuki[27], Eric R. Switzer[53], Peter Timbie[108], Andrew J. Tolley[109], Maurizio Tomasi[110], Matthieu Tristram[111], Mark Trodden[83], Yu-Dai Tsai[107], Cora Uhlemann[2], Caterina Umiltà[23], Alexander van Engelen[26], M. Vargas-Magaña[49], Abigail Vieregg[33], **Benjamin Wallisch**[62,1], David Wands[22], **Benjamin Wandelt**[28,112], Yi Wang[113], Scott Watson[114], Mark Wise[102], W. L. K. Wu[34], Zhong-Zhi Xianyu[44], Weishuang Xu[44], Siavash Yasini[115], Sam Young[116], Duan Yutong[117], Matias Zaldarriaga[62], Michael Zemcov[118], Gong-Bo Zhao[119,22], Yi Zheng[120], Ningfeng Zhu[83]

[a]Names in bold indicate significant contribution.

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 $k_a = |\vec{k}_1|$, 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* $f_{\rm NL}$ 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 $f_{\rm NL}^{\rm local}$, $k_1 \sim k_2 \sim k_3$ (equilateral) with amplitude $f_{\rm NL}^{\rm equil}$ and $k_1 + k_2 \sim k_3$ (folded) with amplitude $f_{\rm NL}^{\rm folded}$. Detectable amounts of non-Gaussianity could be produced in the following scenarios:

- **Inflaton self-interactions** Non-gaussanity 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 $f_{\rm NL}^{\rm equil} < 1$ [27] and therefore *any detection of* $f_{\rm NL}^{\rm equil} \geq 1$ *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, $f_{\rm NL}$ typically is related to a new energy scale, M, such that $f_{\rm NL}^{\rm equil} \propto (H/M)^2$ [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, $f_{\rm NL}^{\rm equil}$ 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.*

[a] Similar 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* $f_{\rm NL}^{\rm local} \sim \mathcal{O}(1)$ *would rule out all attractor models of single-clock inflation* [34]. Non-attractor models exist that generate observable $f_{\rm NL}^{\rm local}$ [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 $f_{\rm NL}^{\rm local} \sim \mathcal{O}(1)$ 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* $f_{\rm NL}^{\rm local} \sim \mathcal{O}(1)$ *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 $f_{\rm NL}^{\rm local}$. Finally, we note that a detection of $f_{\rm NL}^{\rm local}$ 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 $f_{\rm NL}$ 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 sensitivity 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.

Institutions

[1]University of California San Diego, La Jolla, CA 92093
[2]DAMTP, Centre for Mathematical Sciences, Wilberforce Road, Cambridge, UK, CB3 0WA
[3]Department of Physics & Astronomy, Rice University, Houston, Texas 77005, USA
[4]Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA
[5]SLAC National Accelerator Laboratory, Menlo Park, CA 94025**??**
[6]The University of Oxford, Oxford OX1 3RH, UK
[7]Department of Physics, Lower Mountjoy, South Rd, Durham DH1 3LE, United Kingdom
[8]Lawrence Livermore National Laboratory, Livermore, CA, 94550
[9]Universidad Autónoma de Madrid, 28049, Madrid, Spain
[10]SISSA - International School for Advanced Studies, Via Bonomea 265, 34136 Trieste, Italy
[11]IFPU - Institute for Fundamental Physics of the Universe, Via Beirut 2, 34014 Trieste, Italy
[12]INFN – National Institute for Nuclear Physics, Via Valerio 2, I-34127 Trieste, Italy
[13]Department of Physics & Astronomy, University of the Western Cape, Cape Town 7535, South Africa
[14]CSEE, West Virginia University, Morgantown, WV 26505, USA
[15]Center for Gravitational Waves and Cosmology, West Virginia University, Morgantown, WV 26505, USA
[16]Dipartimento di Fisica e Astronomia "G. Galilei",Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy
[17]Cornell University, Ithaca, NY 14853
[18]Department of Physics, Science Park, University of Amsterdam - the Netherlands
[19]National Center for Nuclear Research, Ul.Pasteura 7,Warsaw, Poland
[20]ICC, University of Barcelona, IEEC-UB, Martí i Franquès, 1, E08028 Barcelona, Spain
[21]Dept. de Física Quàntica i Astrofísica, Universitat de Barcelona, Martí i Franquès 1, E08028 Barcelona, Spain
[22]Institute of Cosmology & Gravitation, University of Portsmouth, Dennis Sciama Building, Burnaby Road, Portsmouth PO1 3FX, UK
[23]University of Cincinnati, Cincinnati, OH 45221
[24]Institute of Physics, Laboratory of Astrophysics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland
[25]The Ohio State University, Columbus, OH 43212
[26]Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada
[27]Lawrence Berkeley National Laboratory, Berkeley, CA 94720
[28]Institut d'Astrophysique de Paris (IAP), CNRS & Sorbonne University, Paris, France
[29]Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom
[30]Perimeter Institute, Waterloo, Ontario N2L 2Y5, Canada
[31]Department of Physics Astronomy, University of Sussex, Brighton BN1 9QH, United Kingdom
[32]School of Physics and Astronomy, Cardiff University, The Parade, Cardiff, CF24 3AA, UK
[33]University of Chicago, Chicago, IL 60637
[34]Kavli Institute for Cosmological Physics, Chicago, IL 60637
[35]HEP Division, Argonne National Laboratory, Lemont, IL 60439, USA
[36]Department of Physics, University of California Berkeley, Berkeley, CA 94720, USA
[37]Institute of Astronomy, University of Cambridge,Cambridge CB3 0HA, UK
[38]Kavli Institute for Cosmology, Cambridge, UK, CB3 0HA
[39]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA
[40]Harvard-Smithsonian Center for Astrophysics, MA 02138
[41]IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France
[42]University of California, Irvine, CA 92697
[43]The University of Oxford, Oxford OX1 3RH, UK
[44]Department of Physics, Harvard University, Cambridge, MA 02138, USA
[45]University of New Mexico, Albuquerque, NM 87131
[46]Stanford University, Stanford, CA 94305
[47]Dipartimento di Fisica, Università La Sapienza, P. le A. Moro 2, Roma, Italy
[48]Istituto Nazionale di Fisica Nucleare, Sezione di Roma, 00185 Roma, Italy
[49]IFUNAM - Instituto de Física, Universidad Nacional Autónoma de Método, 04510 CDMX, México

[50]Oskar Klein Centre for Cosmoparticle Physics, Stockholm University, AlbaNova, Stockholm SE-106 91, Sweden
[51]Princeton University, Princeton, NJ 08544
[52]Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[53]Goddard Space Flight Center, Greenbelt, MD 20771 USA
[54]University College London, WC1E 6BT London, United Kingdom
[55]Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, ON M5S 3H8, Canada
[56]University of Michigan, Ann Arbor, MI 48109
[57]University of Florida, Gainesville, FL 32611
[58]School of Physics, The University of Melbourne, Parkville, VIC 3010, Australia
[59]University of Minnesota, Minneapolis, MN 55455
[60]Astrophysics Group, Cavendish Laboratory, J.J.Thomson Avenue, Cambridge, CB3 0HE, UK
[61]Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[62]Institute for Advanced Study, Princeton, NJ 08540
[63]Center for Computational Astrophysics, 162 5th Ave, 10010, New York, NY, USA
[64]Dunlap Institute for Astronomy and Astrophysics, University of Toronto, ON, M5S3H4
[65]Department of Astronomy and Astrophysics, University of Toronto, ON, M5S3H4
[66]Johns Hopkins University, Baltimore, MD 21218
[67]Korea Astronomy and Space Science Institute, Daejeon 34055, Korea
[68]Department of Physics, University at Buffalo, SUNY Buffalo, NY 14260 USA
[69]University of California at Davis, Davis, CA 95616
[70]Brown University, Providence, RI 02912
[71]Department of Physics, Ben-Gurion University, Be'er Sheva 84105, Israel
[72]Istituto Nazionale di Fisica Nucleare, Sezione di Ferrara, 40122, Italy
[73]C.N. Yang Institute for Theoretical Physics State University of New York Stony Brook, NY 11794
[74]The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, SE-106 91 Stockholm, Sweden
[75]Massachusetts Institute of Technology, Cambridge, MA 02139
[76]Dipartimento di Fisica e Astronomia "G. Galilei",Università degli Studi di Padova, via Marzolo 8, I-35131, Padova, Italy
[77]University of Washington, Seattle 98195
[78]Southern Methodist University, Dallas, TX 75275
[79]International Centre for Theoretical Physics, Strada Costiera, 11, I-34151 Trieste, Italy
[80]Department of Theoretical Physics and Center for Astroparticle Physics, University of Geneva, 24 quai E. Ansermet, CH-1211 Geneva 4, Switzerland
[81]Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071, USA
[82]The Niels Bohr Institute Discovery Center, Blegdamsvej 17, DK-2100 Copenhagen, Denmark
[83]Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
[84]Department of Physics, Yale University, New Haven, CT 06520
[85]Columbia University, New York, NY 10027
[86]División de Ciencias e Ingenierías, Universidad de Guanajuato, León 37150, México
[87]Brookhaven National Laboratory, Upton, NY 11973
[88]ETH Zurich, Institute for Particle Physics, 8093 Zurich, Switzerland
[89]Departamento de Física, FCFM, Universidad de Chile, Blanco Encalada 2008, Santiago, Chile
[90]Centre for Astrophysics, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada
[91]Department of Physics and Astronomy, University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1, Canada
[92]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6
[93]University of New Hampshire, Durham, NH 03824
[94]Kavli Institute for Particle Astrophysics and Cosmology, Stanford 94305
[95]Laboratoire Astroparticule et Cosmologie (APC), CNRS/IN2P3, Université Paris Diderot, 10, rue Alice Domon et Léonie Duquet, 75205 Paris Cedex 13, France
[96]Jodrell Bank Center for Astrophysics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester, M13 9PL, UK
[97]The Ohio State University, Columbus, OH 43212

[98]Department of Physics and Astronomy, Sejong University, Seoul, 143-747
[99]Case Western Reserve University, Cleveland, OH 44106
[100]Kavli Insitute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, 277-8583 Kashiwa , Japan
[101]Department of Physics, University of California Berkeley, Berkeley, CA 94720, USA
[102]California Institute of Technology, Pasadena, CA 91125
[103]Stony Brook University, Stony Brook, NY 11794
[104]Department of Physics and Astronomy, Ohio University, Clippinger Labs, Athens, OH 45701, USA
[105]Shanghai Astronomical Observatory (SHAO), Nandan Road 80, Shanghai 200030, China
[106]The Pennsylvania State University, University Park, PA 16802
[107]Fermi National Accelerator Laboratory, Batavia, IL 60510
[108]Department of Physics, University of Wisconsin - Madison, Madison, WI 53706
[109]Theoretical Physics, Blackett Laboratory, Imperial College, London, SW7 2AZ, U.K.
[110]Dipartimento di Fisica "Aldo Pontremoli", Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy
[111]Université Paris-Sud, LAL, UMR 8607, F-91898 Orsay Cedex, France & CNRS/IN2P3, F-91405 Orsay, France
[112]Institut Lagrange de Paris, Sorbonne Universit es, 98 bis Boulevard Arago, 75014 Paris, France
[113]The Hong Kong University of Science and Technology, Hong Kong SAR, China
[114]Syracuse University, Syracuse, NY 13244
[115]University of Southern California, CA 90089
[116]Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85741 Garching, Germany
[117]Boston University, Boston, MA 02215
[118]Rochester Institute of Technology
[119]National Astronomical Observatories, Chinese Academy of Sciences, PR China
[120]School of Physics, Korea Institute for Advanced Study, 85 Hoegiro, Dongdaemun-gu, Seoul 130-722, Korea

References

[1] E. Komatsu et al. Non-Gaussianity as a Probe of the Physics of the Primordial Universe and the Astrophysics of the Low Redshift Universe. 2009.

[2] Planck Collaboration. Planck 2015 results. XVII. Constraints on primordial non-Gaussianity. 2015.

[3] Juan Maldacena. Non-Gaussian Features of Primordial Fluctuations in Single-Field Inflationary Models. *JHEP*, 05:013, 2003.

[4] Giovanni Cabass, Enrico Pajer, and Fabian Schmidt. How Gaussian can our Universe be? *JCAP*, 1701(01):003, 2017.

[5] N. Bartolo, S. Matarrese, and A. Riotto. Nongaussianity from inflation. *Phys. Rev.*, D65:103505, 2002.

[6] Viviana Acquaviva, Nicola Bartolo, Sabino Matarrese, and Antonio Riotto. Second order cosmological perturbations from inflation. *Nucl. Phys.*, B667:119–148, 2003.

[7] G. Hinshaw et al. Nine-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Cosmological Parameter Results. *Astrophys. J. Suppl.*, 208:19, 2013.

[8] N. Bartolo, E. Komatsu, Sabino Matarrese, and A. Riotto. Non-Gaussianity from inflation: Theory and observations. *Phys. Rept.*, 402:103–266, 2004.

[9] Xingang Chen. Primordial Non-Gaussianities from Inflation Models. *Adv. Astron.*, 2010:638979, 2010.

[10] Christian T. Byrnes, Mischa Gerstenlauer, Sami Nurmi, Gianmassimo Tasinato, and David Wands. Scale-dependent non-Gaussianity probes inflationary physics. *JCAP*, 1010:004, 2010.

[11] Adam Becker and Dragan Huterer. First constraints on the running of non-Gaussianity. *Phys. Rev. Lett.*, 109:121302, 2012.

[12] Daniel Babich, Paolo Creminelli, and Matias Zaldarriaga. The Shape of Non-Gaussianities. *JCAP*, 0408:009, 2004.

[13] Leonardo Senatore, Kendrick M. Smith, and Matias Zaldarriaga. Non-Gaussianities in Single Field Inflation and their Optimal Limits from the WMAP 5-year Data. *JCAP*, 1001:028, 2010.

[14] Eva Silverstein and David Tong. Scalar speed limits and cosmology: Acceleration from D-cceleration. *Phys. Rev.*, D70:103505, 2004.

[15] Nima Arkani-Hamed, Paolo Creminelli, Shinji Mukohyama, and Matias Zaldarriaga. Ghost inflation. *JCAP*, 0404:001, 2004.

[16] Mohsen Alishahiha, Eva Silverstein, and David Tong. DBI in the sky. *Phys. Rev.*, D70:123505, 2004.

[17] Xingang Chen, Min-xin Huang, Shamit Kachru, and Gary Shiu. Observational signatures and non-Gaussianities of general single field inflation. *JCAP*, 0701:002, 2007.

[18] Clifford Cheung, Paolo Creminelli, A. Liam Fitzpatrick, Jared Kaplan, and Leonardo Senatore. The Effective Field Theory of Inflation. *JHEP*, 03:014, 2008.

[19] Xingang Chen and Yi Wang. Large non-Gaussianities with Intermediate Shapes from Quasi-Single Field Inflation. *Phys. Rev.*, D81:063511, 2010.

[20] Xingang Chen and Yi Wang. Quasi-Single Field Inflation and Non-Gaussianities. *JCAP*, 1004:027, 2010.

[21] Andrew J. Tolley and Mark Wyman. The Gelaton Scenario: Equilateral non-Gaussianity from multi-field dynamics. *Phys. Rev.*, D81:043502, 2010.

[22] Sera Cremonini, Zygmunt Lalak, and Krzysztof Turzynski. Strongly Coupled Perturbations in Two-Field Inflationary Models. *JCAP*, 1103:016, 2011.

[23] Ana Achucarro, Jinn-Ouk Gong, Sjoerd Hardeman, Gonzalo A. Palma, and Subodh P. Patil. Features of heavy physics in the CMB power spectrum. *JCAP*, 1101:030, 2011.

[24] Daniel Baumann and Daniel Green. Signatures of Supersymmetry from the Early Universe. *Phys. Rev.*, D85:103520, 2012.

[25] Neil Barnaby and Sarah Shandera. Feeding your Inflaton: Non-Gaussian Signatures of Interaction Structure. *JCAP*, 1201:034, 2012.

[26] Nima Arkani-Hamed and Juan Maldacena. Cosmological Collider Physics. 2015.

[27] Paolo Creminelli. On non-Gaussianities in single-field inflation. *JCAP*, 0310:003, 2003.

[28] Daniel Baumann, Daniel Green, and Rafael A. Porto. B-modes and the Nature of Inflation. *JCAP*, 1501(01):016, 2015.

[29] Marcelo Alvarez et al. Testing Inflation with Large Scale Structure: Connecting Hopes with Reality. 2014.

[30] Daniel Baumann, Daniel Green, Hayden Lee, and Rafael A. Porto. Signs of Analyticity in Single-Field Inflation. *Phys. Rev.*, D93(2):023523, 2016.

[31] Daniel Baumann and Daniel Green. Equilateral Non-Gaussianity and New Physics on the Horizon. *JCAP*, 1109:014, 2011.

[32] Daniel Green, Matthew Lewandowski, Leonardo Senatore, Eva Silverstein, and Matias Zaldarriaga. Anomalous Dimensions and Non-Gaussianity. *JHEP*, 10:171, 2013.

[33] Valentin Assassi, Daniel Baumann, Daniel Green, and Liam McAllister. Planck-Suppressed Operators. *JCAP*, 1401:033, 2014.

[34] Paolo Creminelli and Matias Zaldarriaga. Single-Field Consistency Relation for the 3-Point Function. *JCAP*, 0410:006, 2004.

[35] William H. Kinney. Horizon crossing and inflation with large eta. *Phys. Rev.*, D72:023515, 2005.

[36] Mohammad Hossein Namjoo, Hassan Firouzjahi, and Misao Sasaki. Violation of non-Gaussianity consistency relation in a single field inflationary model. *EPL*, 101(3):39001, 2013.

[37] Jerome Martin, Hayato Motohashi, and Teruaki Suyama. Ultra Slow-Roll Inflation and the non-Gaussianity Consistency Relation. *Phys. Rev.*, D87(2):023514, 2013.

[38] Xingang Chen, Hassan Firouzjahi, Mohammad Hossein Namjoo, and Misao Sasaki. A Single Field Inflation Model with Large Local Non-Gaussianity. *EPL*, 102(5):59001, 2013.

[39] Qing-Guo Huang and Yi Wang. Large Local Non-Gaussianity from General Single-field Inflation. *JCAP*, 1306:035, 2013.

[40] Sander Mooij and Gonzalo A. Palma. Consistently violating the non-Gaussian consistency relation. *JCAP*, 1511(11):025, 2015.

[41] Rafael Bravo, Sander Mooij, Gonzalo A. Palma, and Bastián Pradenas. Vanishing of local non-Gaussianity in canonical single field inflation. *JCAP*, 1805(05):025, 2018.

[42] Rafael Bravo, Sander Mooij, Gonzalo A. Palma, and Bastián Pradenas. A generalized non-Gaussian consistency relation for single field inflation. *JCAP*, 1805(05):024, 2018.

[43] Bernardo Finelli, Garrett Goon, Enrico Pajer, and Luca Santoni. Soft Theorems For Shift-Symmetric Cosmologies. *Phys. Rev.*, D97(6):063531, 2018.

[44] Yi-Fu Cai, Xingang Chen, Mohammad Hossein Namjoo, Misao Sasaki, Dong-Gang Wang, and Ziwei Wang. Revisiting non-Gaussianity from non-attractor inflation models. *JCAP*, 1805(05):012, 2018.

[45] Samuel Passaglia, Wayne Hu, and Hayato Motohashi. Primordial black holes and local non-Gaussianity in canonical inflation. *Phys. Rev.*, D99(4):043536, 2019.

[46] David H. Lyth, Carlo Ungarelli, and David Wands. The Primordial density perturbation in the curvaton scenario. *Phys. Rev.*, D67:023503, 2003.

[47] Kari Enqvist, Asko Jokinen, Anupam Mazumdar, Tuomas Multamaki, and Antti Vaihkonen. Non-Gaussianity from preheating. *Phys. Rev. Lett.*, 94:161301, 2005.

[48] N. Bartolo, S. Matarrese, and A. Riotto. On nonGaussianity in the curvaton scenario. *Phys. Rev.*, D69:043503, 2004.

[49] Matias Zaldarriaga. Non-Gaussianities in models with a varying inflaton decay rate. *Phys. Rev.*, D69:043508, 2004.

[50] David H. Lyth. Generating the curvature perturbation at the end of inflation. *JCAP*, 0511:006, 2005.

[51] Andrei Linde, Sander Mooij, and Enrico Pajer. Gauge field production in supergravity inflation: Local non-Gaussianity and primordial black holes. *Phys. Rev.*, D87(10):103506, 2013.

[52] Joel Meyers and Ewan R. M. Tarrant. Perturbative Reheating After Multiple-Field Inflation: The Impact on Primordial Observables. *Phys. Rev.*, D89(6):063535, 2014.

[53] Joseph Elliston, Stefano Orani, and David J. Mulryne. General analytic predictions of two-field inflation and perturbative reheating. *Phys. Rev.*, D89(10):103532, 2014.

[54] Roland de Putter, Jérôme Gleyzes, and Olivier Doré. Next non-Gaussianity frontier: What can a measurement with (fNL)1 tell us about multifield inflation? *Phys. Rev.*, D95(12):123507, 2017.

[55] Jesus Torrado, Christian T. Byrnes, Robert J. Hardwick, Vincent Vennin, and David Wands. Measuring the duration of inflation with the curvaton. *Phys. Rev.*, D98(6):063525, 2018.

[56] Thorsten Battefeld and Richard Easther. Non-Gaussianities in Multi-field Inflation. *JCAP*, 0703:020, 2007.

[57] Christian T. Byrnes, Ki-Young Choi, and Lisa M. H. Hall. Conditions for large non-Gaussianity in two-field slow-roll inflation. *JCAP*, 0810:008, 2008.

[58] Christian T. Byrnes, Ki-Young Choi, and Lisa M. H. Hall. Large non-Gaussianity from two-component hybrid inflation. *JCAP*, 0902:017, 2009.

[59] Christian T. Byrnes and Ki-Young Choi. Review of local non-Gaussianity from multi-field inflation. *Adv. Astron.*, 2010:724525, 2010.

[60] Courtney M. Peterson and Max Tegmark. Non-Gaussianity in Two-Field Inflation. *Phys. Rev.*, D84:023520, 2011.

[61] Courtney M. Peterson and Max Tegmark. Testing multifield inflation: A geometric approach. *Phys. Rev.*, D87(10):103507, 2013.

[62] Jonathan Frazer and Andrew R. Liddle. Multi-field inflation with random potentials: field dimension, feature scale and non-Gaussianity. *JCAP*, 1202:039, 2012.

[63] Liam McAllister, Sebastien Renaux-Petel, and Gang Xu. A Statistical Approach to Multifield Inflation: Many-field Perturbations Beyond Slow Roll. *JCAP*, 1210:046, 2012.

[64] Theodor Bjorkmo and M. C. David Marsh. Manyfield Inflation in Random Potentials. *JCAP*, 1802(02):037, 2018.

[65] Jean-Luc Lehners and Sebastien Renaux-Petel. Multifield Cosmological Perturbations at Third Order and the Ekpyrotic Trispectrum. *Phys. Rev.*, D80:063503, 2009.

[66] Elliot Nelson and Sarah Shandera. Statistical Naturalness and non-Gaussianity in a Finite Universe. *Phys. Rev. Lett.*, 110(13):131301, 2013.

[67] Marilena LoVerde, Elliot Nelson, and Sarah Shandera. Non-Gaussian Mode Coupling and the Statistical Cosmological Principle. *JCAP*, 1306:024, 2013.

[68] Sami Nurmi, Christian T. Byrnes, and Gianmassimo Tasinato. A non-Gaussian landscape. *JCAP*, 1306:004, 2013.

[69] Marilena LoVerde. Super cosmic variance from mode-coupling: A worked example. *Phys. Rev.*, D89(2):023505, 2014.

[70] Béatrice Bonga, Suddhasattwa Brahma, Anne-Sylvie Deutsch, and Sarah Shandera. Cosmic variance in inflation with two light scalars. *JCAP*, 1605(05):018, 2016.

[71] Eva Silverstein and Alexander Westphal. Monodromy in the CMB: Gravity Waves and String Inflation. *Phys.Rev.*, D78:106003, 2008.

[72] Liam McAllister, Eva Silverstein, and Alexander Westphal. Gravity Waves and Linear Inflation from Axion Monodromy. *Phys.Rev.*, D82:046003, 2010.

[73] Raphael Flauger, Liam McAllister, Enrico Pajer, Alexander Westphal, and Gang Xu. Oscillations in the CMB from Axion Monodromy Inflation. *JCAP*, 1006:009, 2010.

[74] Marcus Berg, Enrico Pajer, and Stefan Sjors. Dante's Inferno. *Phys. Rev.*, D81:103535, 2010.

[75] Raphael Flauger and Enrico Pajer. Resonant Non-Gaussianity. *JCAP*, 1101:017, 2011.

[76] Louis Leblond and Enrico Pajer. Resonant Trispectrum and a Dozen More Primordial N-point functions. *JCAP*, 1101:035, 2011.

[77] Raphael Flauger, Liam McAllister, Eva Silverstein, and Alexander Westphal. Drifting Oscillations in Axion Monodromy. 2014.

[78] Siavosh R. Behbahani, Anatoly Dymarsky, Mehrdad Mirbabayi, and Leonardo Senatore. (Small) Resonant non-Gaussianities: Signatures of a Discrete Shift Symmetry in the Effective Field Theory of Inflation. *JCAP*, 1212:036, 2012.

[79] Siavosh R. Behbahani and Daniel Green. Collective Symmetry Breaking and Resonant Non-Gaussianity. *JCAP*, 1211:056, 2012.

[80] Xingang Chen, Richard Easther, and Eugene A. Lim. Large Non-Gaussianities in Single Field Inflation. *JCAP*, 0706:023, 2007.

[81] Xingang Chen, Richard Easther, and Eugene A. Lim. Generation and Characterization of Large Non-Gaussianities in Single Field Inflation. *JCAP*, 0804:010, 2008.

[82] R. Holman and Andrew Tolley. Enhanced Non-Gaussianity from Excited Initial States. *JCAP*, 0805:001, 2008.

[83] Pieter Daniel Meerburg, Jan Pieter van der Schaar, and Pier Stefano Corasaniti. Signatures of Initial State Modifications on Bispectrum Statistics. *JCAP*, 0905:018, 2009.

[84] P. Daniel Meerburg, Jan Pieter van der Schaar, and Mark G. Jackson. Bispectrum signatures of a modified vacuum in single field inflation with a small speed of sound. *JCAP*, 1002:001, 2010.

[85] Peter Adshead, Cora Dvorkin, Wayne Hu, and Eugene A. Lim. Non-Gaussianity from Step Features in the Inflationary Potential. *Phys. Rev.*, D85:023531, 2012.

[86] Neil Barnaby, Enrico Pajer, and Marco Peloso. Gauge Field Production in Axion Inflation: Consequences for Monodromy, non-Gaussianity in the CMB, and Gravitational Waves at Interferometers. *Phys. Rev.*, D85:023525, 2012.

[87] P. Daniel Meerburg and Enrico Pajer. Observational Constraints on Gauge Field Production in Axion Inflation. *JCAP*, 1302:017, 2013.

[88] Ana Achúcarro, Jinn-Ouk Gong, Gonzalo A. Palma, and Subodh P. Patil. Correlating features in the primordial spectra. *Phys. Rev.*, D87(12):121301, 2013.

[89] Guido D'Amico, Roberto Gobbetti, Matthew Kleban, and Marjorie Schillo. Unwinding Inflation. *JCAP*, 1303:004, 2013.

[90] Gonzalo A. Palma. Untangling features in the primordial spectra. *JCAP*, 1504(04):035, 2015.

[91] Valentin Assassi, Daniel Baumann, and Daniel Green. On Soft Limits of Inflationary Correlation Functions. *JCAP*, 1211:047, 2012.

[92] Xingang Chen and Yi Wang. Quasi-Single-Field Inflation with Large Mass. *JCAP*, 1209:021, 2012.

[93] Toshifumi Noumi, Masahide Yamaguchi, and Daisuke Yokoyama. EFT Approach to Quasi-Single-Field Inflation and Effects of Heavy Fields. *JHEP*, 06:051, 2013.

[94] Daniel Baumann, Simone Ferraro, Daniel Green, and Kendrick Smith. Stochastic Bias from Non-Gaussian Initial Conditions. *JCAP*, 1305:001, 2013.

[95] Hayden Lee, Daniel Baumann, and Guilherme L. Pimentel. Non-Gaussianity as a Particle Detector. *JHEP*, 12:040, 2016.

[96] Alex Kehagias and Antonio Riotto. On the Inflationary Perturbations of Massive Higher-Spin Fields. *JCAP*, 1707(07):046, 2017.

[97] Soubhik Kumar and Raman Sundrum. Heavy-Lifting of Gauge Theories By Cosmic Inflation. *JHEP*, 05:011, 2018.

[98] Haipeng An, Michael McAneny, Alexander Ridgway, and Mark Wise. Quasi-Single-Field Inflation in the Nonperturbative Regime. *JHEP*, 06:105, 2018.

[99] Haipeng An, Michael McAneny, Alexander Ridgway, and Mark Wise. Non-Gaussian Enhancements of Galactic Halo Correlations in Quasi-Single-Field Inflation. *Phys. Rev.*, D97(12):123528, 2018.

[100] Daniel Baumann, Garrett Goon, Hayden Lee, and Guilherme L. Pimentel. Partially Massless Fields During Inflation. *JHEP*, 04:140, 2018.

[101] Nima Arkani-Hamed, Daniel Baumann, Hayden Lee, and Guilherme L. Pimentel. The Cosmological Bootstrap: Inflationary Correlators from Symmetries and Singularities. 2018.

[102] Emanuela Dimastrogiovanni, Matteo Fasiello, Donghui Jeong, and Marc Kamionkowski. Inflationary tensor fossils in large-scale structure. *JCAP*, 1412:050, 2014.

[103] Emanuela Dimastrogiovanni, Matteo Fasiello, and Marc Kamionkowski. Imprints of Massive Primordial Fields on Large-Scale Structure. *JCAP*, 1602:017, 2016.

[104] Lorenzo Bordin, Paolo Creminelli, Andrei Khmelnitsky, and Leonardo Senatore. Light Particles with Spin in Inflation. *JCAP*, 1810(10):013, 2018.

[105] Emanuela Dimastrogiovanni, Matteo Fasiello, Gianmassimo Tasinato, and David Wands. Tensor non-Gaussianities from Non-minimal Coupling to the Inflaton. *JCAP*, 1902:008, 2019.

[106] Ogan Ozsoy, Maria Mylova, Susha Parameswaran, Cari Powell, Gianmassimo Tasinato, and Ivonne Zavala. Squeezed tensor non-Gaussianity in non-attractor inflation. 2019.

[107] Solomon Endlich, Alberto Nicolis, and Junpu Wang. Solid Inflation. *JCAP*, 1310:011, 2013.

[108] Dario Cannone, Gianmassimo Tasinato, and David Wands. Generalised tensor fluctuations and inflation. *JCAP*, 1501(01):029, 2015.

[109] Dario Cannone, Jinn-Ouk Gong, and Gianmassimo Tasinato. Breaking discrete symmetries in the effective field theory of inflation. *JCAP*, 1508(08):003, 2015.

[110] Angelo Ricciardone and Gianmassimo Tasinato. Primordial gravitational waves in supersolid inflation. *Phys. Rev.*, D96(2):023508, 2017.

[111] Federico Piazza, David Pirtskhalava, Riccardo Rattazzi, and Olivier Simon. Gaugid inflation. *JCAP*, 1711(11):041, 2017.

[112] Neil Barnaby and Marco Peloso. Large Nongaussianity in Axion Inflation. *Phys. Rev. Lett.*, 106:181301, 2011.

[113] Neil Barnaby, Jordan Moxon, Ryo Namba, Marco Peloso, Gary Shiu, and Peng Zhou. Gravity waves and non-Gaussian features from particle production in a sector gravitationally coupled to the inflaton. *Phys. Rev.*, D86:103508, 2012.

[114] A. Maleknejad and M. M. Sheikh-Jabbari. Gauge-flation: Inflation From Non-Abelian Gauge Fields. *Phys. Lett.*, B723:224–228, 2013.

[115] Peter Adshead, Diego Blas, C. P. Burgess, Peter Hayman, and Subodh P Patil. Magnon Inflation: Slow Roll with Steep Potentials. 2016.

[116] Xingang Chen, Yi Wang, and Zhong-Zhi Xianyu. Standard Model Mass Spectrum in Inflationary Universe. *JHEP*, 04:058, 2017.

[117] Xingang Chen, Yi Wang, and Zhong-Zhi Xianyu. Standard Model Background of the Cosmological Collider. *Phys. Rev. Lett.*, 118(26):261302, 2017.

[118] Xingang Chen, Yi Wang, and Zhong-Zhi Xianyu. Loop Corrections to Standard Model Fields in Inflation. *JHEP*, 08:051, 2016.

[119] Raphael Flauger, Mehrdad Mirbabayi, Leonardo Senatore, and Eva Silverstein. Productive Interactions: heavy particles and non-Gaussianity. *JCAP*, 1710(10):058, 2017.

[120] J. Richard Bond, Andrei V. Frolov, Zhiqi Huang, and Lev Kofman. Non-Gaussian Spikes from Chaotic Billiards in Inflation Preheating. *Phys. Rev. Lett.*, 103:071301, 2009.

[121] Xingang Chen, Gonzalo A. Palma, Walter Riquelme, Bruno Scheihing Hitschfeld, and Spyros Sypsas. Landscape tomography through primordial non-Gaussianity. *Phys. Rev.*, D98(8):083528, 2018.

[122] Xingang Chen, Gonzalo A. Palma, Bruno Scheihing Hitschfeld, and Spyros Sypsas. Reconstructing the Inflationary Landscape with Cosmological Data. *Phys. Rev. Lett.*, 121(16):161302, 2018.

[123] J. R. Fergusson and E. P. S. Shellard. The shape of primordial non-Gaussianity and the CMB bispectrum. *Phys. Rev.*, D80:043510, 2009.

[124] J. R. Fergusson and Edward P. S. Shellard. Primordial non-Gaussianity and the CMB bispectrum. *Phys. Rev.*, D76:083523, 2007.

[125] J. R. Fergusson, D. M. Regan, and E. P. S. Shellard. Optimal Trispectrum Estimators and WMAP Constraints. 2010.

[126] Martin Bucher, Benjamin Racine, and Bartjan van Tent. The binned bispectrum estimator: template-based and non-parametric CMB non-Gaussianity searches. *JCAP*, 1605(05):055, 2016.

[127] Peter Adshead, Wayne Hu, Cora Dvorkin, and Hiranya V. Peiris. Fast Computation of Bispectrum Features with Generalized Slow Roll. *Phys. Rev.*, D84:043519, 2011.

[128] Moritz Münchmeyer, P. Daniel Meerburg, and Benjamin D. Wandelt. Optimal estimator for resonance bispectra in the CMB. *Phys. Rev.*, D91(4):043534, 2015.

[129] P. Daniel Meerburg and Moritz Münchmeyer. Optimal CMB estimators for bispectra from excited states. *Phys. Rev.*, D92(6):063527, 2015.

[130] J. R. Fergusson, H. F. Gruetjen, E. P. S. Shellard, and M. Liguori. Combining power spectrum and bispectrum measurements to detect oscillatory features. *Phys. Rev.*, D91(2):023502, 2015.

[131] J. R. Fergusson, H. F. Gruetjen, E. P. S. Shellard, and B. Wallisch. Polyspectra searches for sharp oscillatory features in cosmic microwave sky data. *Phys. Rev.*, D91(12):123506, 2015.

[132] P. Daniel Meerburg, Moritz Münchmeyer, and Benjamin Wandelt. Joint resonant CMB power spectrum and bispectrum estimation. *Phys. Rev.*, D93(4):043536, 2016.

[133] Y. Akrami et al. Planck 2018 results. X. Constraints on inflation. 2018.

[134] Kevork N. Abazajian et al. CMB-S4 Science Book, First Edition. 2016.

[135] James Aguirre et al. The Simons Observatory: Science goals and forecasts. 2018.

[136] PICO collaboration. https://sites.google.com/umn.edu/picomission/home, 2019.

[137] Antony Lewis, Anthony Challinor, and Duncan Hanson. The shape of the CMB lensing bispectrum. *JCAP*, 1103:018, 2011.

[138] Jaiseung Kim, Aditya Rotti, and Eiichiro Komatsu. Removing the ISW-lensing bias from the local-form primordial non-Gaussianity estimation. *JCAP*, 1304:021, 2013.

[139] A. Curto, M. Tucci, M. Kunz, and E. Martinez-Gonzalez. The CIB-lensing bispectrum: impact on primordial non-Gaussianity and detectability for the Planck mission. *Mon. Not. Roy. Astron. Soc.*, 450(4):3778–3801, 2015.

[140] William R. Coulton et al. Non-Gaussianity of secondary anisotropies from ACTPol and Planck. *JCAP*, 1809(09):022, 2018.

[141] J. Colin Hill. Foreground Biases on Primordial Non-Gaussianity Measurements from the CMB Temperature Bispectrum: Implications for Planck and Beyond. 2018.

[142] Gabriel Jung, Benjamin Racine, and Bartjan van Tent. The bispectra of galactic CMB foregrounds and their impact on primordial non-Gaussianity estimation. 2018.

[143] Sebastian von Hausegger, Aske Gammelgaard Ravnebjerg, and Hao Liu. Statistical properties of polarized CMB foreground maps. 2018.

[144] G. J. Stacey et al. CCAT-prime: Science with an Ultra-widefield Submillimeter Observatory at Cerro Chajnantor. 2018.

[145] Daniel Babich and Matias Zaldarriaga. Primordial bispectrum information from CMB polarization. *Phys. Rev.*, D70:083005, 2004.

[146] Enrico Pajer and Matias Zaldarriaga. A New Window on Primordial non-Gaussianity. *Phys. Rev. Lett.*, 109:021302, 2012.

[147] Jonathan Ganc and Eiichiro Komatsu. Scale-dependent bias of galaxies and mu-type distortion of the cosmic microwave background spectrum from single-field inflation with a modified initial state. *Phys. Rev.*, D86:023518, 2012.

[148] Enrico Pajer and Matias Zaldarriaga. A hydrodynamical approach to CMB μ-distortion from primordial perturbations. *JCAP*, 1302:036, 2013.

[149] Razieh Emami, Emanuela Dimastrogiovanni, Jens Chluba, and Marc Kamionkowski. Probing the scale dependence of non-Gaussianity with spectral distortions of the cosmic microwave background. *Phys. Rev.*, D91(12):123531, 2015.

[150] Rishi Khatri and Rashid Sunyaev. Constraints on -distortion fluctuations and primordial non-Gaussianity from Planck data. *JCAP*, 1509(09):026, 2015.

[151] Nicola Bartolo, Michele Liguori, and Maresuke Shiraishi. Primordial trispectra and CMB spectral distortions. *JCAP*, 1603(03):029, 2016.

[152] Atsuhisa Ota. Cosmological constraints from μE cross-correlations. *Phys. Rev.*, D94(10):103520, 2016.

[153] Andrea Ravenni, Michele Liguori, Nicola Bartolo, and Maresuke Shiraishi. Primordial non-Gaussianity with -type and y-type spectral distortions: exploiting Cosmic Microwave Background polarization and dealing with secondary sources. *JCAP*, 1709(09):042, 2017.

[154] M. Remazeilles and J. Chluba. Extracting foreground-obscured μ-distortion anisotropies to constrain primordial non-Gaussianity. *Mon. Not. Roy. Astron. Soc.*, 478(1):807–824, 2018.

[155] Giovanni Cabass, Enrico Pajer, and Drian van der Woude. Spectral distortion anisotropies from single-field inflation. *JCAP*, 1808(08):050, 2018.

[156] Olivier Doré et al. Cosmology with the SPHEREX All-Sky Spectral Survey. 2014.

[157] Scott Dodelson, Katrin Heitmann, Chris Hirata, Klaus Honscheid, Aaron Roodman, Uroš Seljak, Anže Slosar, and Mark Trodden. Cosmic Visions Dark Energy: Science. 2016.

[158] Neal Dalal, Olivier Dore, Dragan Huterer, and Alexander Shirokov. The imprints of primordial non-gaussianities on large-scale structure: scale dependent bias and abundance of virialized objects. *Phys. Rev.*, D77:123514, 2008.

[159] Sabino Matarrese and Licia Verde. The effect of primordial non-Gaussianity on halo bias. *Astrophys. J.*, 677:L77–L80, 2008.

[160] Raul E. Angulo, Simon Foreman, Marcel Schmittfull, and Leonardo Senatore. The One-Loop Matter Bispectrum in the Effective Field Theory of Large Scale Structures. *JCAP*, 1510(10):039, 2015.

[161] Tobias Baldauf, Lorenzo Mercolli, Mehrdad Mirbabayi, and Enrico Pajer. The Bispectrum in the Effective Field Theory of Large Scale Structure. *JCAP*, 1505(05):007, 2015.

[162] Valentin Assassi, Daniel Baumann, Enrico Pajer, Yvette Welling, and Drian van der Woude. Effective theory of large-scale structure with primordial non-Gaussianity. *JCAP*, 1511:024, 2015.

[163] Raul Angulo, Matteo Fasiello, Leonardo Senatore, and Zvonimir Vlah. On the Statistics of Biased Tracers in the Effective Field Theory of Large Scale Structures. *JCAP*, 1509(09):029, 2015.

[164] Fabian Schmidt, Nora Elisa Chisari, and Cora Dvorkin. Imprint of inflation on galaxy shape correlations. *JCAP*, 1510(10):032, 2015.

[165] Nora Elisa Chisari, Cora Dvorkin, Fabian Schmidt, and David Spergel. Multitracing Anisotropic Non-Gaussianity with Galaxy Shapes. *Phys. Rev.*, D94(12):123507, 2016.

[166] Dionysios Karagiannis, Andrei Lazanu, Michele Liguori, Alvise Raccanelli, Nicola Bartolo, and Licia Verde. Constraining primordial non-Gaussianity with bispectrum and power spectrum from upcoming optical and radio surveys. *Mon. Not. Roy. Astron. Soc.*, 478(1):1341–1376, 2018.

[167] Réza Ansari et al. Inflation and Early Dark Energy with a Stage II Hydrogen Intensity Mapping experiment. 2018.

[168] Julian B. Muñoz, Yacine Ali-Haïmoud, and Marc Kamionkowski. Primordial non-gaussianity from the bispectrum of 21-cm fluctuations in the dark ages. *Phys. Rev.*, D92(8):083508, 2015.

[169] P. Daniel Meerburg, Moritz Münchmeyer, Julian B. Muñoz, and Xingang Chen. Prospects for Cosmological Collider Physics. *JCAP*, 1703(03):050, 2017.

[170] Azadeh Moradinezhad Dizgah and Cora Dvorkin. Scale-Dependent Galaxy Bias from Massive Particles with Spin during Inflation. *JCAP*, 1801(01):010, 2018.

[171] Azadeh Moradinezhad Dizgah, Hayden Lee, Julian B. Muñoz, and Cora Dvorkin. Galaxy Bispectrum from Massive Spinning Particles. *JCAP*, 1805(05):013, 2018.

[172] Azadeh Moradinezhad Dizgah, Gabriele Franciolini, Alex Kehagias, and Antonio Riotto. Constraints on long-lived, higher-spin particles from galaxy bispectrum. *Phys. Rev.*, D98(6):063520, 2018.

[173] Azadeh Moradinezhad Dizgah, Garrett K. Keating, and Anastasia Fialkov. Probing Cosmic Origins with CO and [CII] Emission Lines. *Astrophys. J.*, 870(1):L4, 2019.

[174] Azadeh Moradinezhad Dizgah and Garrett K. Keating. Line intensity mapping with [CII] and CO(1-0) as probes of primordial non-Gaussianity. 2018.

[175] Uros Seljak. Extracting primordial non-gaussianity without cosmic variance. *Phys. Rev. Lett.*, 102:021302, 2009.

[176] Marcel Schmittfull and Uros Seljak. Parameter constraints from cross-correlation of CMB lensing with galaxy clustering. *Phys. Rev.*, D97(12):123540, 2018.

[177] Moritz Münchmeyer, Mathew S. Madhavacheril, Simone Ferraro, Matthew C. Johnson, and Kendrick M. Smith. Constraining local non-Gaussianities with kSZ tomography. 2018.

[178] LSST Science Collaboration. LSST Science Book, Version 2.0. *arXiv e-prints*, page arXiv:0912.0201, December 2009.