CMB EXCURSION SETS & PRIMORDIAL NON-GAUSSIANITY

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Non-Gaussianity as a new frontier in Cosmology

NG DATA $\rightarrow$ A phenomenological analysis from WMAP5

NG THEORY $\rightarrow$ Simulation approach

Large-scale structure implications and future prospect

MAIN REFERENCES


Non-Gaussianity as a Probe of the Physics of the Primordial Universe and the Astrophysics of the Low Redshift Universe

E. Komatsu,1,2 N. Afshordi,3 N. Bartolo,4 D. Baumann,5,6 J.R. Bond,7 E.I. Buchbinder,3 C.T. Byrnes,8 X. Chen,9 D.J.H. Chung,10 A. Cooray,11 P. Creminelli,12 N. Dalal,7 O. Doré,7 R. Easther,13 A.V. Frolov,14 K.M. Górski,15 M.G. Jackson,16 J. Khoury,17 W.H. Kinney,18 L. Kofman,7 K. Koyama,19 L. Leblond,20 J.-L. Lehners,21 J.E. Lidsey,22 ...

In the coming decade, non-Gaussianity will become an important probe of both the early and the late Universe. Specifically, it will play a leading role in furthering our understanding of two fundamental aspects of cosmology and astrophysics → NEW PHYSICS RELATED TO COSMOLOGY

- The physics of the very early universe that created the primordial seeds for large-scale structures
- The subsequent growth of structures via gravitational instability and gas physics at later times
Why is Non-Gaussianity Important?

**Canonical Slow-Roll Inflation**
- \( \varphi \) free scalar field in ground state of Bunch-Davis vacuum
- \( R = -[H(\phi)/\dot{\phi}_0] \varphi \) primordial curvature pert. (linear order)
- If \( p(\varphi) \rightarrow \text{Gaussian} \) then \( p(R) \rightarrow \text{Gaussian} \)

**Slow-Roll Inflation – Breaking Gaussianity**
- NG \( \rightarrow \) Allow interactions between scalar fields
- NG \( \rightarrow \) Non-linear corrections to the relation \( R \rightarrow \phi \)

**Beyond Canonical Models**
- Non-standard inflationary models (example \( \rightarrow \) Sasaki 2008)
- Alternative early-universe models (example \( \rightarrow \) Brandenberger 2009)
Gaussianity or non-Gaussianity?

Profound implications if non-Gaussianity detected

Non-Gaussianity → Evidence?
Detection?

- One-point statistics (Jeong & Smoot 2007)
- Bispectrum estimator (Yadav & Wandelt 2008)

Literature still controversial!

Anomalies of any kind → talks by E. Bunn, A. Lewis

- “The mystery of the WMAP cold spot” (Naselsky et al. 2008)
- “The CMB cold spot: texture, cluster or void?” (Cruz et al. 2008)
- “CMB cold spot: a gate to extra dimensions?” (Cembranos et al. 2008)
- Asymmetries, alignments (i.e. Räth et al. 2009; Kim & Naselsky 2010)
NON-GAUSSIANITY

OBSERVATIONAL SIDE
Clustering Statistics Analysis

Main Technique
Statistics of hot and cold pixels above threshold (excursion sets)

Theoretical Model

\[ D = T - \langle T \rangle \equiv \delta T = s + n \]

*Signal*: homogeneous, may have spatial correlations

*Noise*: independent of signal, inhomogeneous, spatial correlations

Basic Steps and Achievements
- Theory extension → clustering statistics with inhomogeneous noise
- Computation of correlation functions above threshold from WMAP5
- Main experimental artifacts considered (beams, masks, etc.)
**Inhomogeneous Noise Properties**

- Pixel covariance matrix is diagonal
- $\sigma(p) = \sigma_0 / \sqrt{N_{\text{obs}}(p)}$
- Noise is inhomogeneous

Distribution of the rms noise-per pixel at high resolution ($N_{\text{side}} = 512$) for the WMAP5 W1 coadded channel

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Rossi, Sheth et al. (2009)
**Temperature Distribution**

Rossi, Sheth et al. (2009)

**One-Point Statistics**
- **Dotted line** → Gaussian with the same rms as data
- **Solid line** → convolution of the expected Gaussian signal with the noise of rms $\sigma_n$, weighted by the $\sigma_n$ distribution
- **Skewness** → -1.2162E-002 mK

**Enough for NG?**
Two-Point Statistics from Data

Rossi, Sheth et al. (2009)

\[ \xi(\theta) \] vs. \( \theta / \text{arcmin} \)

- Homogeneous
- Inhomogeneous

W1 coad DA, \( N_{\text{side}} = 512 \)

\( \nu = 1.5 \)

HOT PIXELS
COLD PIXELS
NON-GAUSSIANITY
THEORETICAL SIDE
**Simple-minded NG model**

Many primordial inflationary models of NG can be represented in configuration space by the simple formula (Salopek & Bond 1990; Gangui et al. 1994; Verde et al. 1999; Komatsu & Spergel 2001)

\[ \Phi = \phi_L + f_{NL} \cdot (\phi_L^2 - \langle \phi_L^2 \rangle) + g_{NL} \cdot \phi_L^3 + \ldots \]

- Why \( f_{NL} \)?
- Why truncation in the expansion?
- What if scale-dependent bias?

Burt Ovrut complaining about \( f_{NL} \) ...
The $f_{NL}$ Business

Start from 3-point function in Fourier space ...

$$\langle \Phi(k_1)\Phi(k_2)\Phi(k_3) \rangle = (2\pi)^3 \delta^3(k_1 + k_2 + k_3) F(k_1, k_2, k_3)$$

- **Multi-Field Models** → Break Single-Field
  - Source of density perturbation → second light scalar field $\sigma$
  - Amplitude of bispectrum of "squeezed" triangles
  - Curvaton scenario, variable decay width model, ...

- **Single-Field Models** → Break Slow-Roll
  - Amplitude of bispectrum of "equilateral" configurations
  - Preheating, field-dependent variable, ...

- **Alternative Models**
  - Ekpyrotic scenario
  - String gas
  - Cosmic strings

Multi-Field Models $\rightarrow$ Break Single-Field

$$F(k_1, k_2, k_3) = f_{NL}^{\text{local}} 2\Delta^2 \left( \frac{1}{k_1^3 k_2^3} + \frac{1}{k_2^3 k_3^3} + \frac{1}{k_1^3 k_3^3} \right)$$

Single-Field Models $\rightarrow$ Break Slow-Roll

$$F(k_1, k_2, k_3) = f_{NL}^{\text{equil}} 6\Delta^2 \left( \frac{1}{k_1 k_2^2 k_3^2} + \ldots \right)$$
Non-Gaussian Simulations: $f_{NL}$ Mock Maps

- $\sim 10^\circ \times 10^\circ$
- $f_{NL} = 0$ ↑
- $f_{NL} = 500$ ↓
- $\nu = 0.50$
- FWHM=30’
**Pixel Number Density and NG**

No smoothing

$\nu = \delta T/\sigma$

$x =$ Hot Pixels

$\bullet =$ Cold Pixels

Solid lines → Theory predictions using the Edgeworth expansion

Note (1) regions where NG is maximized (2) non-optimal $\nu$ (3) $f_{\text{NL}}$ and ND

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Derived quantity which amplifies the $f_{NL}$ contribution
NON-GAUSSIANITY → THEORETICAL SIDE

PIXEL CLUSTERING AND NG

$|\nu| = 2.00, f_{NL} = 500 \rightarrow$ cold pixel clustering enhanced around $\theta \approx 75'$
Is Gaussianity well-constrained? Sensitive test?
NON-GAUSSIANITY
LSS IMPLICATIONS
NG AND LSS → IMPLICATIONS

**Primordial NG and LSS**

- **Statistics of voids** (i.e. Grossi et al. 2008; Song & Lee 2008)
- **Lyman-\(\alpha\) forest QSO spectra IGM** (i.e. Viel et al. 2009)
- **LS distribution of neutral H** (i.e. Pillepich et al. 2007)
- **Reionization history** (i.e. Crociani et al. 2009)
- **Abundance, clustering, biasing of DM halos** (i.e. Dalal et al. 2008; Slosar et al. 2008; Desjacques et al. 2009)
- **LSS topology** (Park et al. 2005; Gott et al. 2008)
- **LSS galaxy skewness** (Chodorowski & Bouchet 1996)
NG induced by secondary (second-order) anisotropies
(Pitrou et al. 2008; Bartolo & Riotto 2009; Senatore et al. 2009)

Cross-correlation of lensing/ISW or lensing/RS
(Hanson et al. 2009; Mangilli & Verde 2009)

N-body simulations with NG initial data
(Grossi et al. 2007; Hikage et al. 2008)

Searching for NG with rare events
(LoVerde et al. 2007; Grossi et al. 2009; Maggiore & Riotto 2009)

DM mass function vs $f_{\text{NL}}$
(LoVerde et al. 2008; Desjacques et al. 2009; Valageas 2009)

Halo bias in NG models
(Matarrese & Verde 2008; Desjacques & Seljak 2010)
## Summary

### Non-Gaussianity: New Frontier
- Reliable theoretical prediction of NG from models
- Extract information on non-Gaussianity from data
- Characterization of non-Gaussian confusion effects

### Achievements: Observational Side
- New model for the effects of inhomogeneous noise
- Anomalies detected and plausible explanations

### Achievements: Theoretical Side
- Excursion set statistics extended to $f_{\text{NL}}$ models
- Theoretical insights: optimal thresholds, Edgeworth approximation
- New statistical tests, in order to minimize cosmic variance

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