Title: CMB Anomalies and Non-Gaussianity

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Abstract: When the primordial fluctuations are non-Gaussian and inflation lasts longer than the minimum number of e-folds, the likelihood that we observe mild deviations from isotropy increases. I will present a single framework that encompasses many of the most promising scenarios for generating a hemispherical power asymmetry. This framework allows a comparison of the observational evidence for various models, including some with a natural connection between large scale power suppression and power asymmetry.

Large Scale CMB anomalies as a signature of non-Gaussianity

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with
Saroj Adhikari
Adrienne Erickcek
(1508.xxxxx)

Non-Gaussianity and Statistical Isotropy

We only need

$$C(\hat{n}, \hat{n}') \equiv \langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle$$

and it is given by

$$C(\hat{n}, \hat{n}') = C(\theta) \ , \qquad \theta = \arccos(\hat{n} \cdot \hat{n}')$$

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In harmonic space:

$$\Delta T(\hat{n}) = \sum_{l,m} a_{lm} Y_{lm}(\hat{n})$$

$$\langle a_{lm} a^*_{l'm'} \rangle = \underline{C_l \delta_{ll'} \delta_{mm'}}$$

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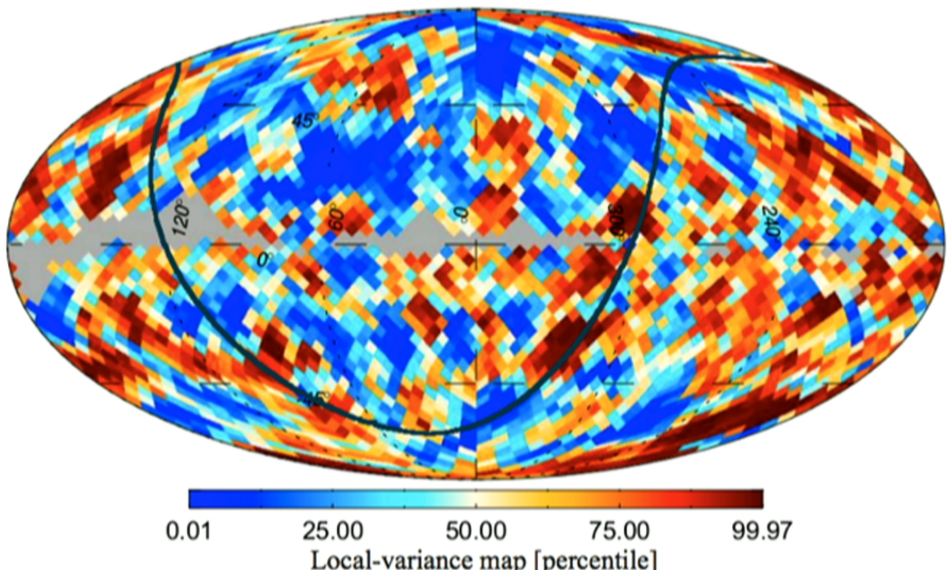
The hemispherical power asymmetry

- The amplitude of fluctuations is different on two halves of the sky



Planck 2015 (1506.07135)

, 10 Aug 2015, PI

An equation for that?

$$\frac{\Delta T}{T}|_{\rm mod}(\hat{n}) = (1 + A\,\hat{n}\cdot\hat{p})\frac{\Delta T}{T}|_{\rm iso}(\hat{n})$$

On large scales: $A \sim 0.07$

$$\text{significance} \sim 3\sigma$$

Akrami et al (1402.0870)
Planck 2013 (1303.5083)
Planck 2015 (1506.07135)

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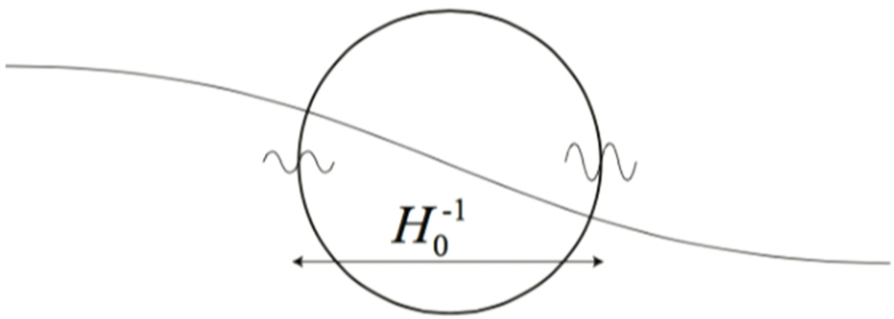
So what?

A) just a fluke
B) evidence of some departure from usual inflation lurking just outside the horizon
C) …..

(A,B = Two reasons not to work on this???)

The EKC idea

- Curvaton (or inflaton/curvaton) scenario
- Large amplitude super horizon fluctuation
- Non-Gaussianity: gradient ➜ power asymm.



Erickcek, Kamionkowski, Carroll (0806.0377) Figure 1
(many iterations since)

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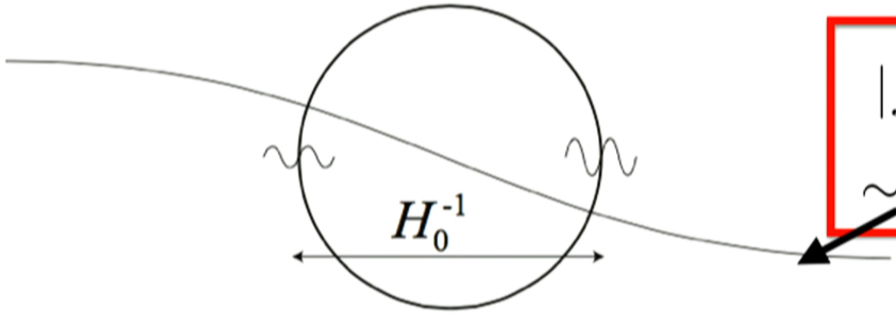

$|f_{\rm NL}| \lesssim 100$

$\sim 10\sigma$ fluct.

Erickcek, Kamionkowski, Carroll (0806.0377) Figure 1
(many iterations since)

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What we're doing

- Analytic expressions predicting probability of modulations from any isotropic, non-Gaussian model: *computing cosmic variance*
- Claim: With non-Gaussianty, don't need lurking super-Hubble specialness
- Connection means: can use power modulations to constrain non-Gaussianity
- Given analytic pdfs, can do Bayesian model comparison to compare evidence for Gaussian vs NG models

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Formalizing EKC

- Local non-Gaussianity:

$$\Phi(x) = \phi(x) + f_{\rm NL}(\phi^2 - \langle\phi^2\rangle)$$

- long wavelength modes affect short wavelength modes:

(easily generalizes beyond the local ansatz)

(Adhikari, Erickcek, Shandera, 1508.xxxxx)

Formalizing EKC

Consistency-relation violating fNL
(Mirbabayi, Zaldarriaga 1409.4777)

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$$P_\Phi(k,\mathbf{x}) = P_\phi(k)\left[1 + 4f_{\rm NL}\int \frac{d^3\mathbf{k}_\ell}{(2\pi)^3}\phi(\mathbf{k}_\ell)e^{i\mathbf{k}_\ell\cdot\mathbf{x}}\right]$$

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Formalizing EKC, cont'd

Expand the exponential:

$$e^{i\mathbf{k}_\ell\cdot\mathbf{x}} = 4\pi \sum_{LM} i^L j_L(k_\ell x) Y^*_{LM}(\hat{k}_\ell) Y_{LM}(\hat{n})$$

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Formalizing EKC, cont'd

Expand the exponential:

Then

$$P_\Phi(k,\hat{n}) = P_\phi(k)\left[1 + f_{\rm NL}\sum_{LM} g_{\rm LM} Y_{LM}(\hat{n})\right]$$

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The monopole

Monopole shift: L=0

$$P_\Phi(k) = P_\phi(k)\left[1 + A_0\right] = P_\phi(k)\left[1 + f_{\rm NL}\frac{g_{00}}{2\sqrt{\pi}}\right]$$

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Monopole shift: L=0

$$P_\Phi(k) = P_\phi(k)\,[1 + A_0] = P_\phi(k)\left[1 + f_{\rm NL}\frac{g_{00}}{2\sqrt{\pi}}\right]$$

IR sensitive

$$\langle g_{00}^2 \rangle = 64\pi \int \frac{dk_\ell}{k_\ell}\left[\frac{\sin(k_\ell x)}{k_\ell x}\right]^2 \mathcal{P}_\phi(k_\ell)$$

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The dipole modulation

(L=1)

$$P_\Phi(k,\hat{n}) = P_\phi(k)\left[1 + f_{\rm NL}\sum_{M=-1,0,1} g_{1M} Y_{1M}(\hat{n})\right]$$

Monopole shift is absorbed
These are the observed quantities

Variance not IR sensitive:

$$\langle g_{1M} g_{1M}^* \rangle = 64\pi \int \frac{dk_\ell}{k_\ell}\left[\frac{\sin(k_\ell x)}{(k_\ell x)^2} - \frac{\cos(k_\ell x)}{k_\ell x}\right]^2 \mathcal{P}_\phi(k_\ell)$$

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How big is the predicted dipole?

For a direction $\hat{d}_i$:

$$P_\Phi(k) = P_\phi(k)\left[1 + 2A_i \cos\theta\right]$$
$$\cos\theta = \hat{d}_i \cdot \hat{n}$$

$$A_i = \frac{1}{4}\sqrt{\frac{3}{\pi}} f_{\rm NL} g_{10}$$

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The direction is arbitrary:

decompose the line of maximum asymmetry into three orthogonal components and report

$$A = \left(A_1^2 + A_2^2 + A_3^2\right)^{\frac{1}{2}}$$

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Probability of dipole modulation

$$p_\chi(A,\sigma) = \sqrt{\frac{2}{\pi}}\frac{A^2}{\sigma^3}\mathrm{Exp}\left[\frac{-A^2}{2\sigma^2}\right]$$

$$\sigma = \sqrt{\sigma^2_{f_{\rm NL}} + \sigma^2_0}$$

Calculated, extrapolating our observed power spectrum to larger scales

measured from Gaussian maps

(Adhikari, Erickcek, Shandera, 1508.xxxxx)

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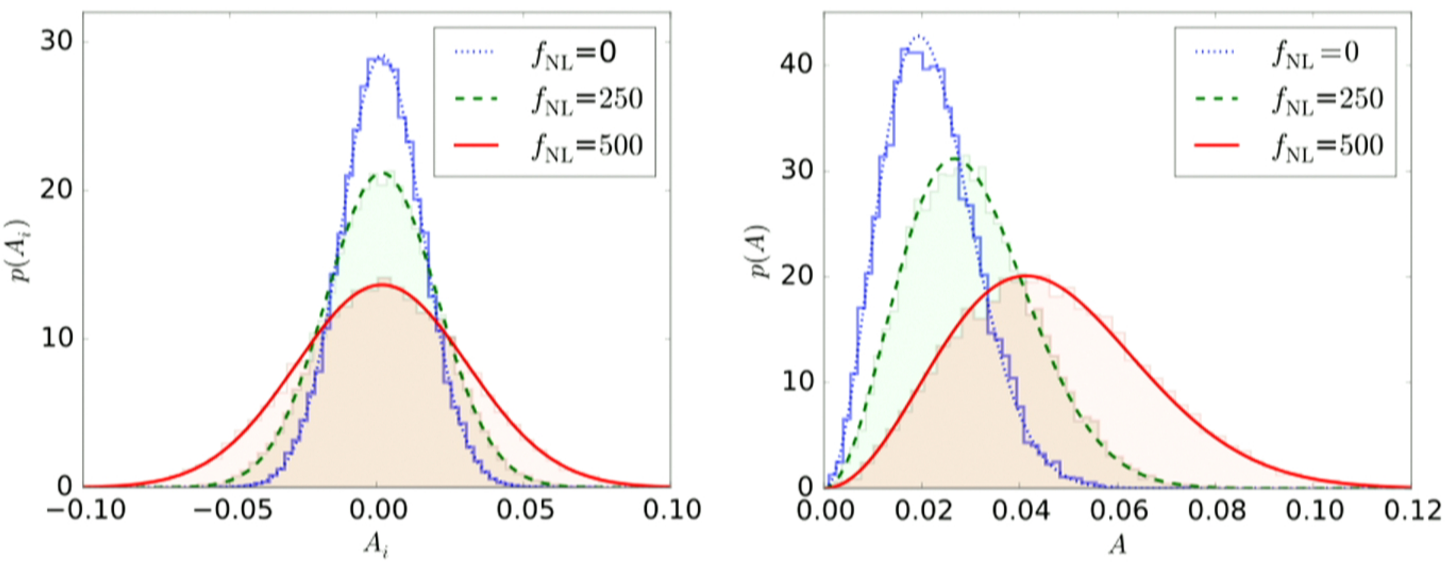
Check: Probability of dipole modulation



10,000 simulated CMB maps (Sachs-Wolfe approx)

(Curves are analytic)

(Adhikari, Erickcek, Shandera, 1508.xxxxx)

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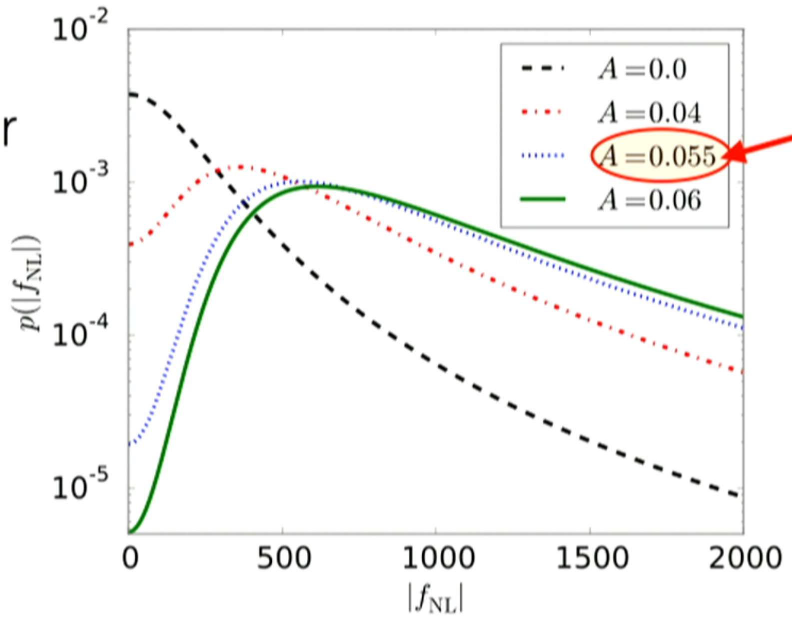
Using the asymmetry to constrain f_{NL}

Posterior



~ observed level (p-value)

(Adhikari, Erickcek, Shandera, 1508.xxxxx)

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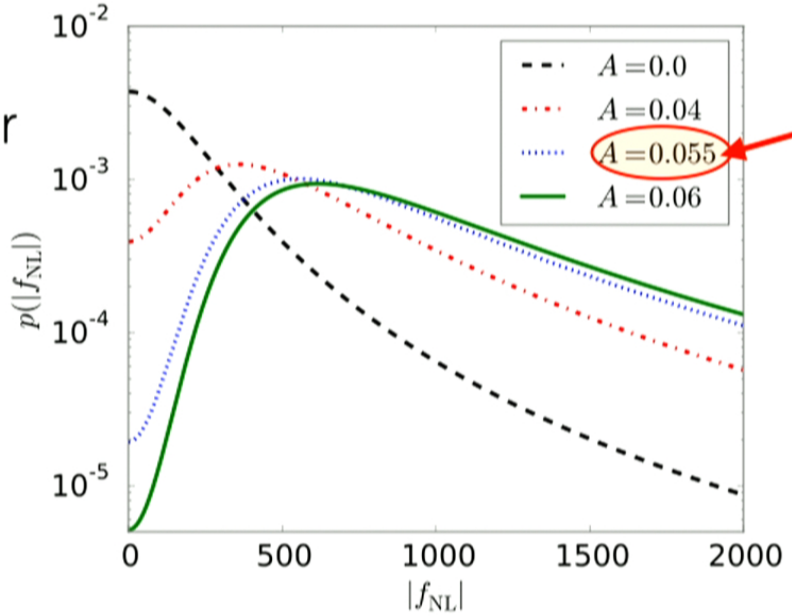
Using the asymmetry to constrain $f_{\rm NL}$

Posterior



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(Adhikari, Erickcek, Shandera, 1508.xxxxx)

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Include large scale bispectrum constraints

(Adhikari, Erickcek, Shandera, 1508.xxxxx)

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Include large scale bispectrum constraints

$$l \lesssim 100\,, \quad f_{\rm NL} = -100 \pm 100$$

(Smith, Senatore, Zaldarriaga, 0901.2572)

(Adhikari, Erickcek, Shandera, 1508.xxxxx)

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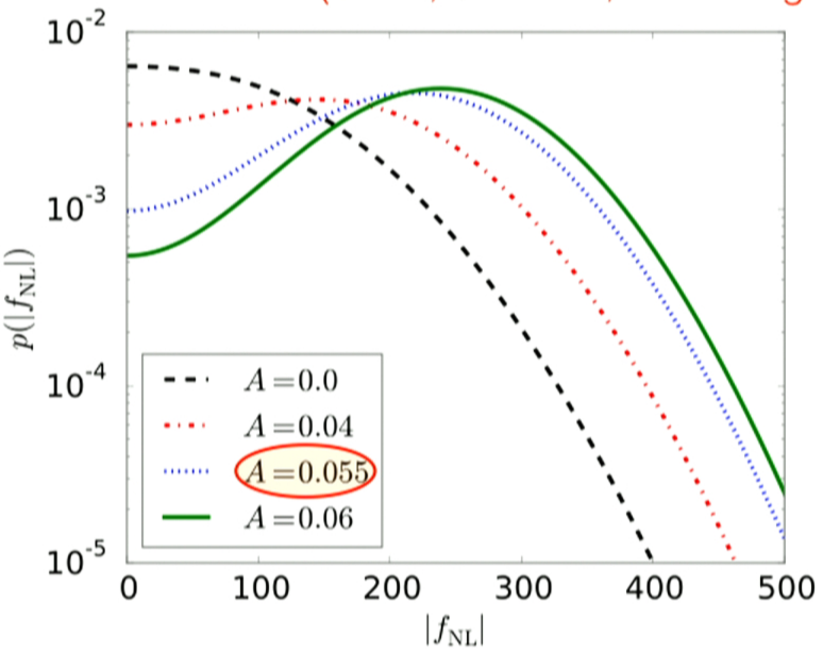

(Adhikari, Erickcek, Shandera, 1508.xxxxx)

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Two-source model

$$P_\Phi(k) = P_{\Phi,\sigma}(k) + P_{\Phi,\varphi}(k)$$

$$\xi = P_{\Phi,\sigma}/P_\Phi$$

$$f_{\rm NL} \to f_{\rm NL}/\sqrt{\xi}$$

(ie, smaller observed NG gives same asymmetry)

$$\xi > A$$

ξ constrained by tensor-to-scalar ratio, LSS stochasticity

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Evidence for the NG vs Gaussian model?

A_{obs}	p-value	Bayes factor	$\ln B_{01}$
0.02	0.5511	1.1362	0.128
0.04	0.0381	0.6174	-0.482
0.05	0.0043	0.3211	-1.136
0.055	0.001	0.2012	-1.603
0.06	0.0003	0.1123	-2.186

$|\ln B_{01}| = 5.0, 2.5$

={strong, moderate} evidence

Only weak evidence for the Non-Gaussian explanation

(Adhikari, Erickcek, Shandera, 1508.xxxxx)

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The scale-dependent power asymmetry

Any deviation from local ansatz gives scale-dependence

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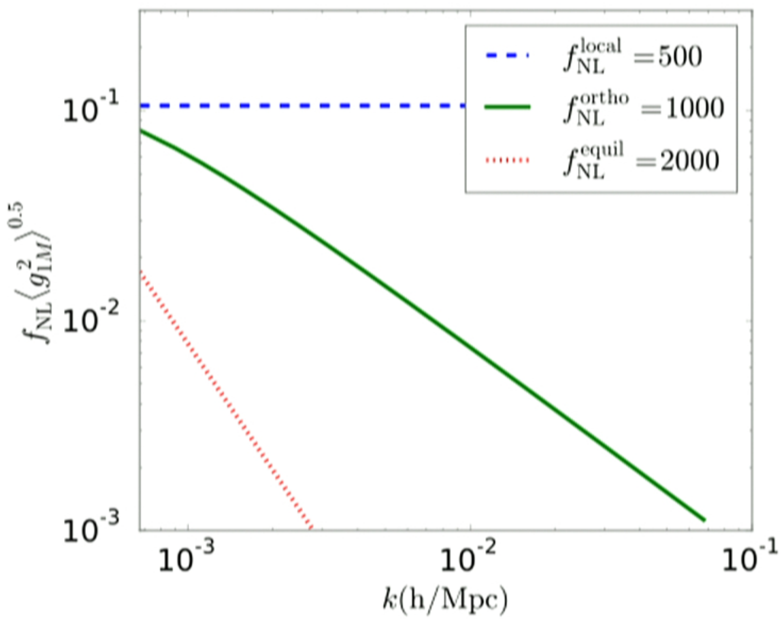

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Scale-dependent modulations

$$P_\Phi(k,\mathbf{x}) = P_\phi(k)\left[1 + 4 f_{\rm NL}(k_0)\left(\frac{k}{k_0}\right)^{n_f}\int \frac{d^3\mathbf{k}_\ell}{(2\pi)^3}\left(\frac{k_\ell}{k_0}\right)^{\alpha}\phi(\mathbf{k}_\ell)e^{i\mathbf{k}_\ell\cdot\mathbf{x}}\right]$$

$\alpha \lesssim -1$ Dipole modulation is IR divergent

$n_f < 0$ Dipole modulation decreases on small scales

Natural scale-dependence: $\xi = P_{\Phi,\sigma}/P_\Phi$

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A simple model

$$f_{\rm NL}(k) = f_{\rm NL}^{0} \left(\frac{k}{k_0}\right)^{n_{f_{\rm NL}}}$$

$$n_{f_{\rm NL}} = 0.3^{+1.9}_{-1.2} \quad (95\% C.L.)$$

Becker, Huterer
1207.5788

Now the monopole shift is also interesting

(Large scale power suppression)

$$P_{\Phi}(k) = P_{\phi}(k)\,[1 + A_0] = P_{\phi}(k)\left[1 + f_{\rm NL}\frac{g_{00}}{2\sqrt{\pi}}\right]$$

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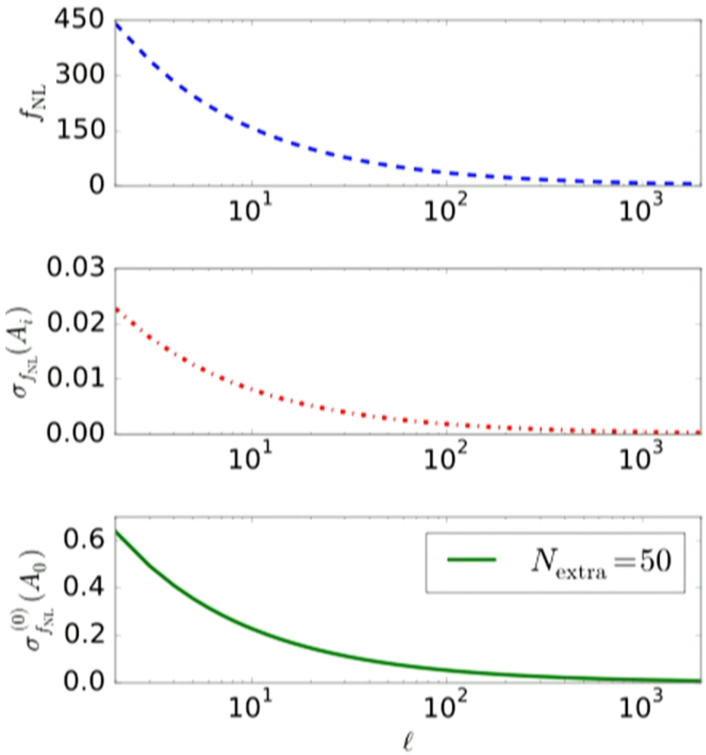
An example model

$$f_{\rm NL}(\ell) = 50(\ell/60)^{-0.64}$$

dipole

monopole



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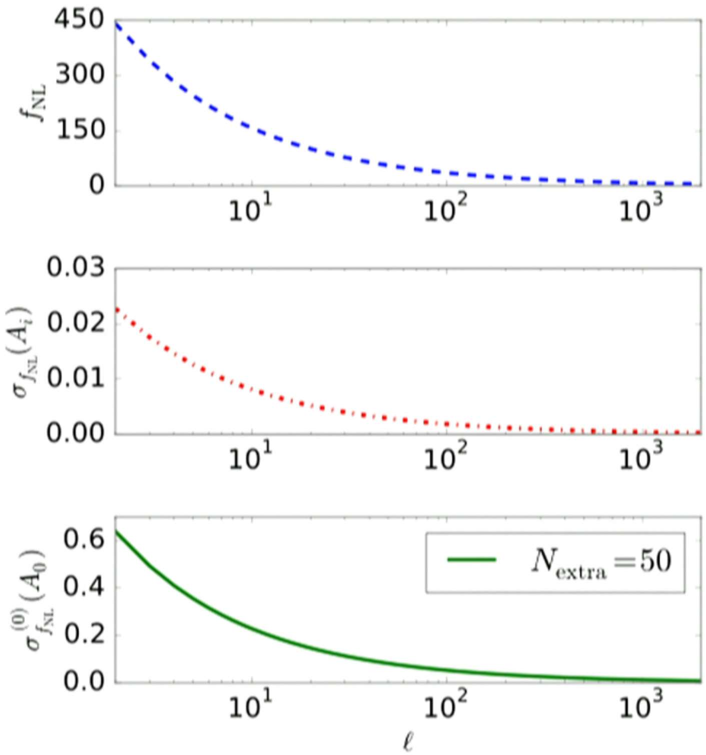

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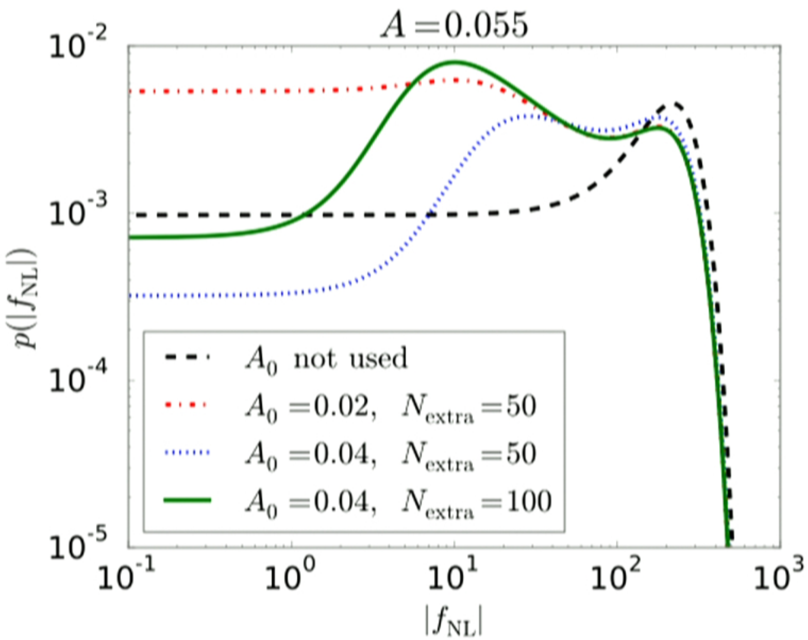
Constraining non-Gaussianity using power modulations



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Evidence?

Fixed dipole: $A = 0.055$

$A_{0,\mathrm{obs}}$	N_{extra}	Bayes factor	$\ln B_{01}$
-	-	0.2012	-1.603
0.02	50	1.107	0.102
0.04	50	0.0664	-2.712
0.04	100	0.1475	-1.914

$|\ln B_{01}| = 5.0, 2.5$

={strong, moderate} evidence

Still only moderate evidence

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Could there be evidence for this model?

- Polarization data (+kSZ) can increase significance of the observed modulations

- Fits to bispectrum can constrain all shape parameters (future data $\ell > 100$)

- alignment of the GZ (super horizon mode) contribution to CMB quadropole, octopole and asymmetry direction

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Conclusions

- Evidence for Non-Gaussianity: isotropic bispectrum and power modulations should be considered together.
- Scale-dependent non-Gaussianity: an appealing fit
  - bispectrum + hemispherical power asymmetry + large scale power suppression
  - scale-dependence of modulation from NG is generic
  - A mixed curvaton/inflaton scenario: natural scale-dependence and small NG
- No special physics lurking just beyond the Hubble scale required

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