Primordial non-Gaussianity (f_{NL}) in WMAP data

Amit Yadav
and
Benjamin Wandelt

University of Illinois at Urbana-Champaign

Collaborators:
Eiichiro Komatsu (Austin)
Michele Liguori (Cambridge)
Sabino Matarrese (INFN)
Frode Hansen (Oslo)

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Outline

- Motivation for inflation

  Standard model & standard model problems

- Primordial Non-Gaussianity from inflation

  Motivation for measuring NG

  Method for measuring NG

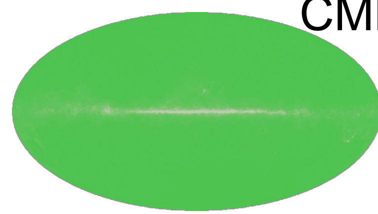
  Current constraints on NG, OUR RESULTS

- Future prospects for measuring NG

What standard model doesn't answer:

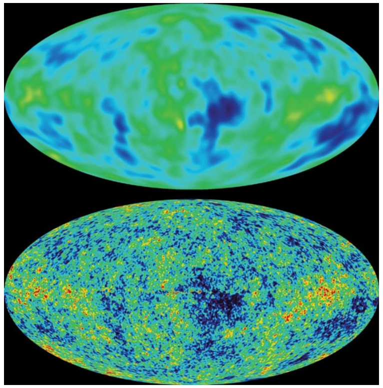
- Homogeneity and Isotropy

CMB



- Flatness
- Seed perturbations

COBE

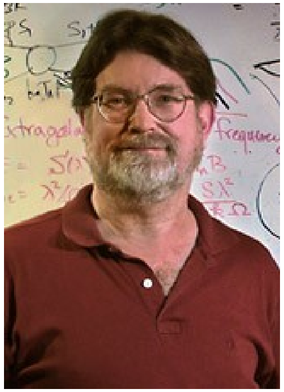


WMAP

1978 Nobel Prize in Physics

Robert Wilson and Arno Penzias

2006 Nobel Prize in Physics



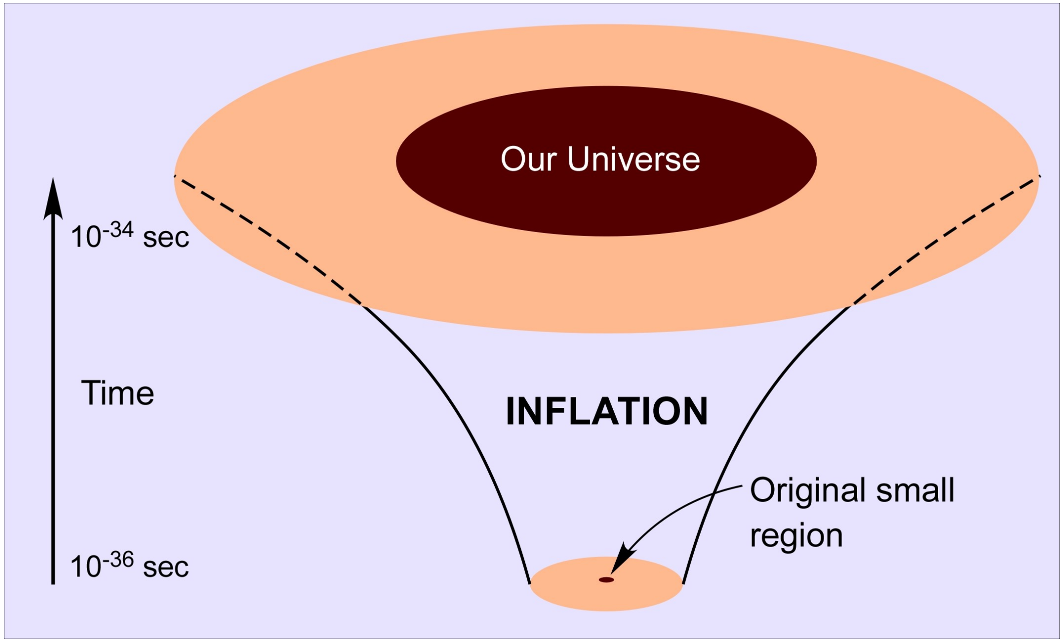
George Smoot

John C. Mather

Let's start at the very beginning- a very good place to start

Inflation is one of the most promising theories of the early universe. By exponentially expanding a small region of the universe, Inflation solves several standard model problems

- it solves the problems with standard model (flatness, homogeneity and isotropy)
- it also gives seed perturbations for the structure formation and
- other testable predictions (n_s, n_t , f_{NL})



BEWARE!

Inflation is not the only theory we have

Cyclic/Ekpyrotic model

Inflationary Universe

- The expansion of the universe decelerates when matter or radiation dominates
  - Matter (w=0) $\rho(a) \propto a^{-3}$
  - Radiation (w=1/3) $\rho(a) \propto a^{-4}$

- Universe accelerates (i.e inflation happens) when w<-1/3
  - density decreases slower than a^{-2}
  - For the cosmological constant (w= -1), the energy density is constant.
  - What is causing w<-1/3 (Inflaton field)

$$For \quad p = w\rho \qquad a(t) \propto t^{\frac{2}{3(1+w)}} \qquad \rho(a) \propto a^{-3(1+w)}$$

Inflationary Universe

A. Starobinsky (1979)

Universe can accelerate
- Quantum effects
- Left side of Einstein's Eq

Universe can accelerate
- First order phase transition

K. Sato (1981)

Alan Guth (1981)

Implications for cosmology.
Accelerating universe can solve some of the problems of the standard cosmology flatness, homogeneity, monopole...

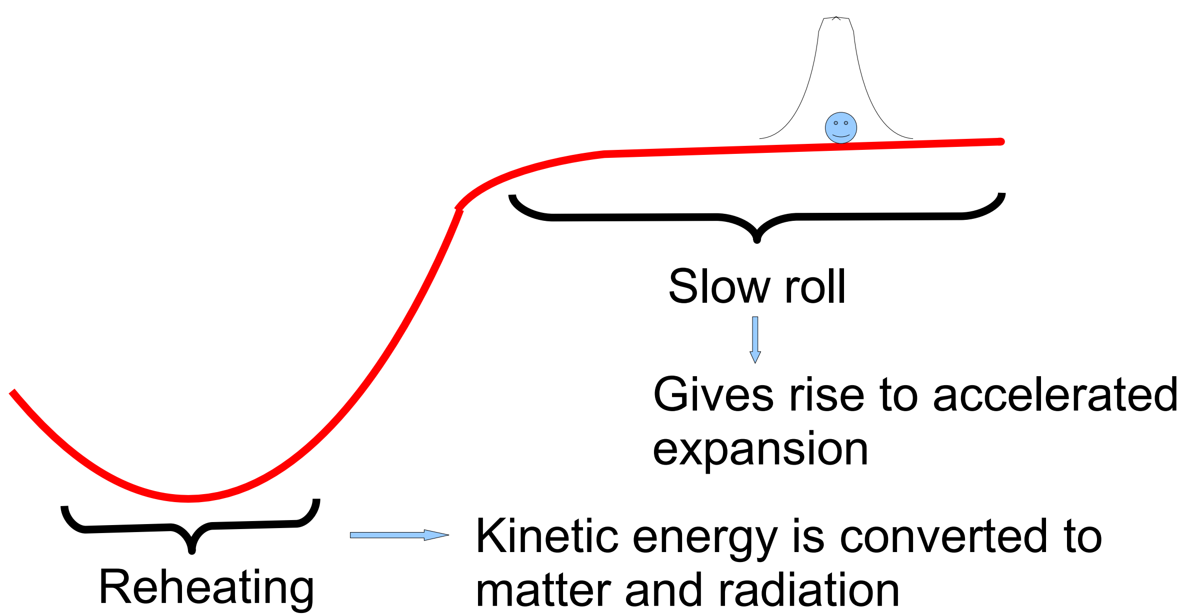
- Inflationary Zoo

- Canonical Inflation (single field with slow roll approximation)

$$H^2 = \frac{8\pi}{3m_{pl}^2}\left[V(\phi) + \cancel{\frac{1}{2}\dot{\phi}^2}\right]$$

Slow roll

$$\cancel{\ddot{\phi}} + 3H\dot{\phi} = -V'(\phi)$$



Inflation generates fluctuations in space time

Testing Inflationary Paradigm

- Probes of inflation:
  - Inflation generates primordial fluctuations in space-time
    - Fluctuations in radiation
      - CMB T
      - CMB E-polarization
    - Fluctuations in matter
      - Dark matter distribution (Gravitational lensing etc.)
      - Galaxy and gas distribution (Redshift surveys, Lyman-alpha clouds, cosmological 21-cm radiation, etc)
    - Fluctuations in space time itself
      - Primordial Gravitational Waves (eg. Primordial B-modes of CMB)

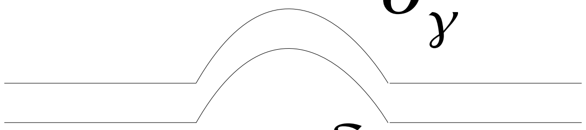
Testing Inflationary Paradigm

(i) Flat, homogeneous and isotropic ✓ Eg: WMAP 06

(ii) Seed perturbations: *canonical models predict*

- Nearly adiabatic:

$$\frac{\delta\rho_i}{\dot{\rho}_i} = \frac{\delta\rho}{\dot{\rho}}$$



- Close to Gaussian

$$\langle \Phi(\vec{k})\Phi(\vec{k}\,')\rangle = P_\Phi(k)\,\delta^3(\vec{k}-\vec{k}\,')$$?

- Nearly Scale Invariant

$$k^3 P_\Phi(k) = A\,k^{n_s - 1}$$

✓ Eg: WMAP 06

:

Do we expect primordial perturbations really Gaussian ?

- NO!
- Different inflationary model predict different amount of NG so detection of NG helps distinguishing them.
- Even the 2nd order GR perturbations produce some NG ($f_{NL} \sim 1$)

Amplitude of non-Gaussianity. fNL=0 for Gaussian perturbations and larger the value larger the non-Gaussianity

Are primordial perturbations really Gaussian ?

Non-Gaussianity from the Early Universe

f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives)

(Maldacena 2003, Acquaviva etal 2003)

f_{NL} ~ 0.1--100 higher order derivatives

DBI inflation (Alishahiha et. al 2004)

UV cutoff (Creminelli 2003)

f_{NL} >10 curvaton models (Lyth et. al 2003)

f_{NL} ~100 ghost inflation (Arkani-Hamed et al., 2004)

f_{NL} ~20-100 New Ekpyrotic models (Creminelli and Senatore 2007, Buchbinder et. al 2007, Koyama et. al 2007)

Sensitivity goal: Δf_{NL} ~ 1

2nd order GR produces f_{NL} ~ 1 so that sets the lower limit on NG one may hope to detect.

Shape of non-Gaussianities

Primordial non-Gaussianity can be described in terms of the n-point correlation function of curvature perturbations.

$$\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle = (2\pi)^3 \delta^3(\vec{k}_1+\vec{k}_2+\vec{k}_3) F(k_1, k_2, k_3)$$

Depending on the shape of 3-point function, non-Gaussianity can be broadly classified into two classes (Babich et. al 2004)

- The local (squeezed) non-Gaussianity

$$F(k_1, k_2, k_3) \;\; \textit{is large for the configuration for which} \;\; k_1 \ll k_2, k_3$$

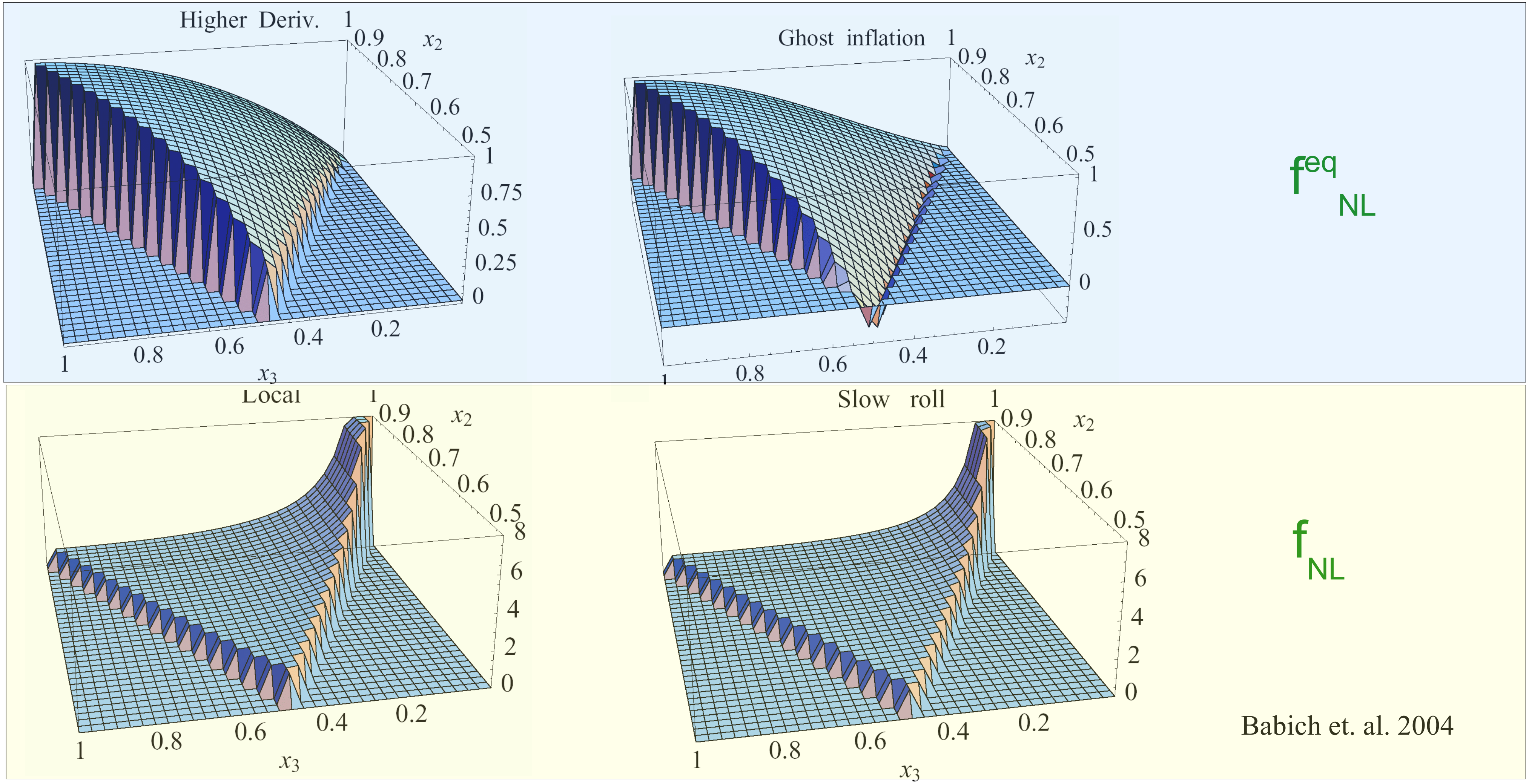
e.g. Curvaton models, New Ekpyrotic models, ..

- The equilateral non-Gaussianity

$$F(k_1, k_2, k_3) \;\; \textit{is large for the configuration for which} \;\; k_1 \approx k_2 \approx k_3$$

e.g. Ghost inflation, DBI, ...

Shape of non-Gaussianities



For different models the NG shape is different i.e shape of NG can be used to rule out inflationary models BUT
current data is not sensitive to the shape of NG but only sensitive to an overall amplitude f_{NL}

Outline

- How to search for primordial non-Gaussianity
- How to search for f_{NL}
- What we find
- How to interpret our result
- Future prospects

Two approaches for testing non-Gaussianity

[1] Null test approach (most widely used)

- use your favorite statistical tool and test for NG in the data
- Pros: model independent
- Cons: hard to interpret

  hard to compare different methods

Examples (Land and Magueijo 2005, Larson and Wandelt 2004, Eriksen et. al 2004, etc):

- North-south asymmetry
- Quadrupole-octopole alignment
- Hot and cold spots in CMB
- Axis of Evil
- Large-scale modulation

Two approaches for testing non-Gaussianity

[2] Model testing approach (much recent approach)

- Constrain non-Gaussianity parameter(s) eg f_{NL}
- Pros: easy to interpret
  easy to compare different models
- Cons: model dependent

Examples:

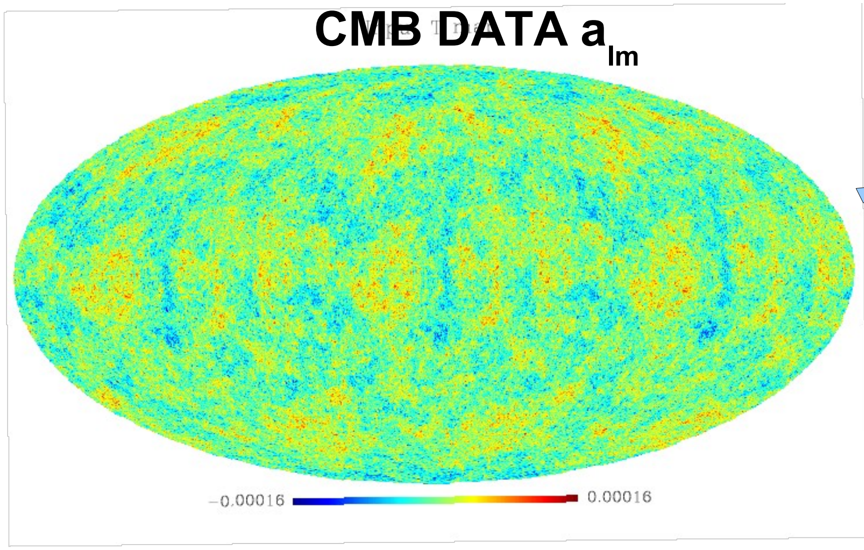
constrain NG parameter f_{NL} using

- Bispectrum
- Trispectrum
- Minkowski functionals

How to search for (weak) primordial non-Gaussianity in 3 easy steps

- Reconstruct curvature perturbation from data
- Test for non-Gaussian features
- Compute error bars using Gaussian Monte Carlo realizations of the data

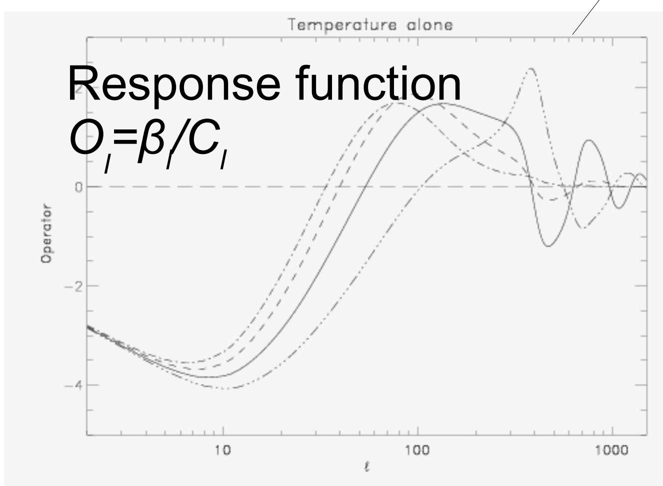
Reconstructed Primordial Perturbations

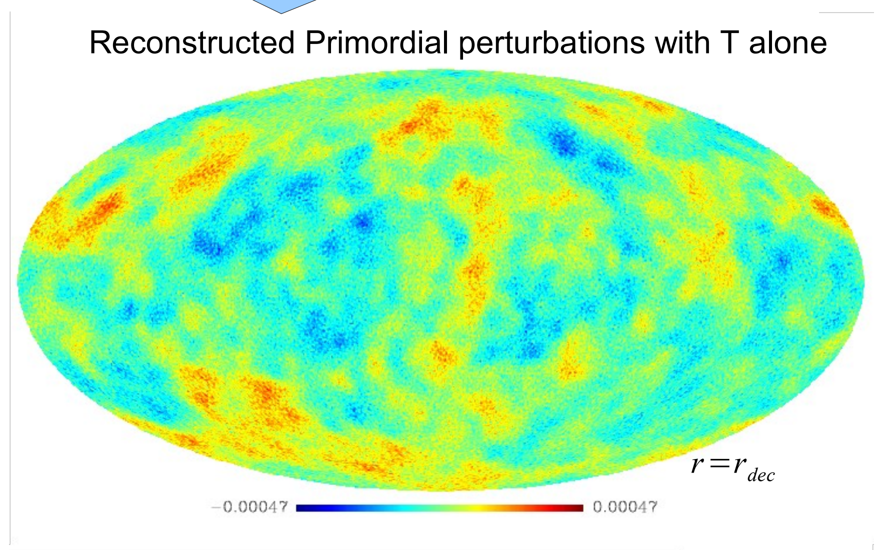


$\Phi_{lm} = O_l a_{lm}$

SW limit

$$\frac{\delta\phi}{\phi} = \frac{-1}{3}\frac{\delta T}{T}$$





$$\beta_\ell^i(r) = \frac{2b_\ell^i}{\pi}\int k^2 dk P_\phi(k) g_\ell^i(k)\, j_\ell(kr),$$

How to search for f_{NL} – a specific parameterization

$$\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$$

Salopek & Bond 1990
Komatsu & Spergel 2001

Characterizes the amplitude of non-Gaussianity

Non-Gaussianity from the Early Universe

f_{NL} ~ 0.05 canonical inflation (single field, couple of derivatives)

(Maldacena 2003, Acquaviva et al 2003)

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DBI inflation (Alishahiha, Silverstein and Tong 2004)

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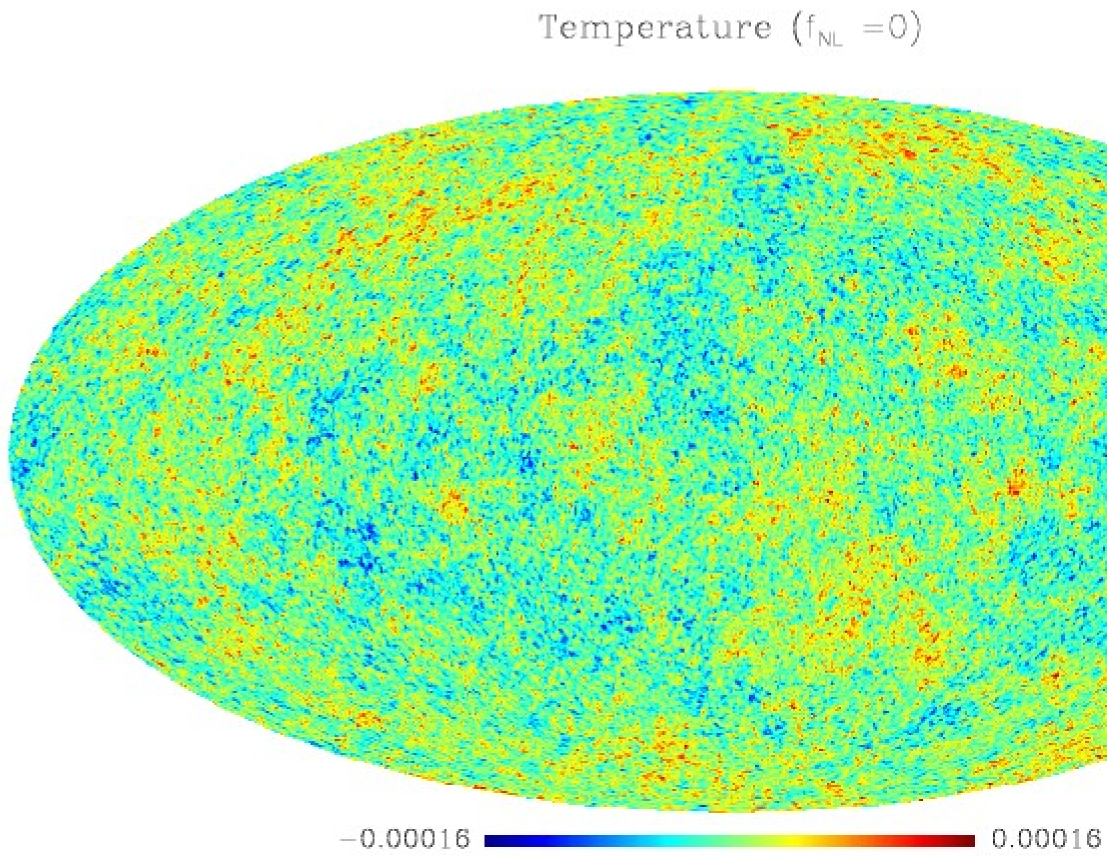
$f_{NL} > 10$ curvaton models (Lyth, Ungarelli and Wands, 2003)

f_{NL} ~100 ghost inflation (Arkani-Hamed et al. 2004)

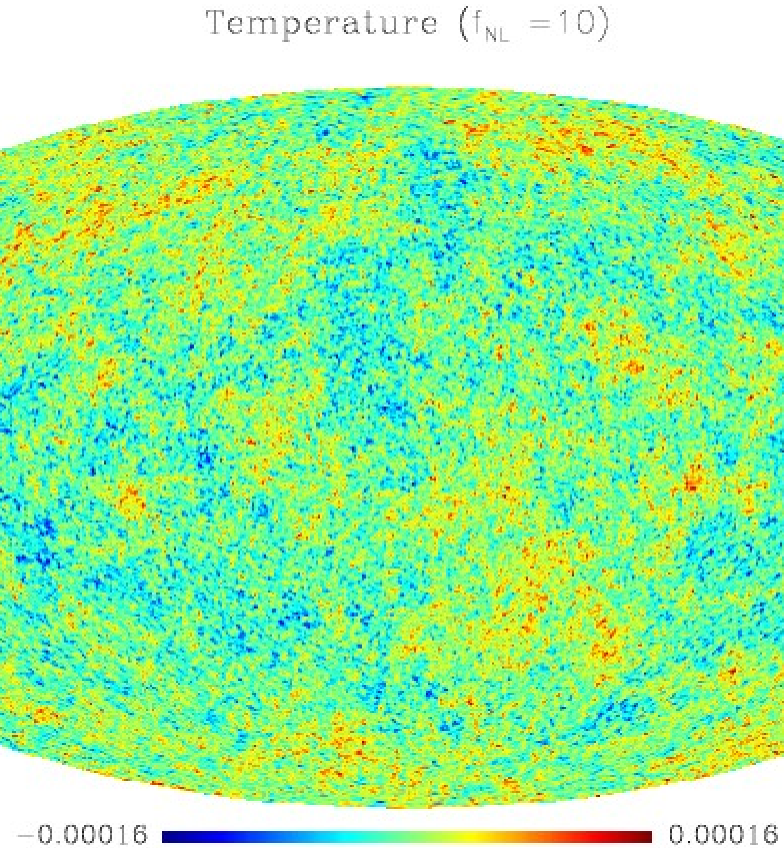
f_{NL} ~20-100 New Ekpyrotic models (Creminelli and Senatore 2007, Buchbinder et. al 2007, Koyama et. al 2007)

$$f_{NL} = 0$$



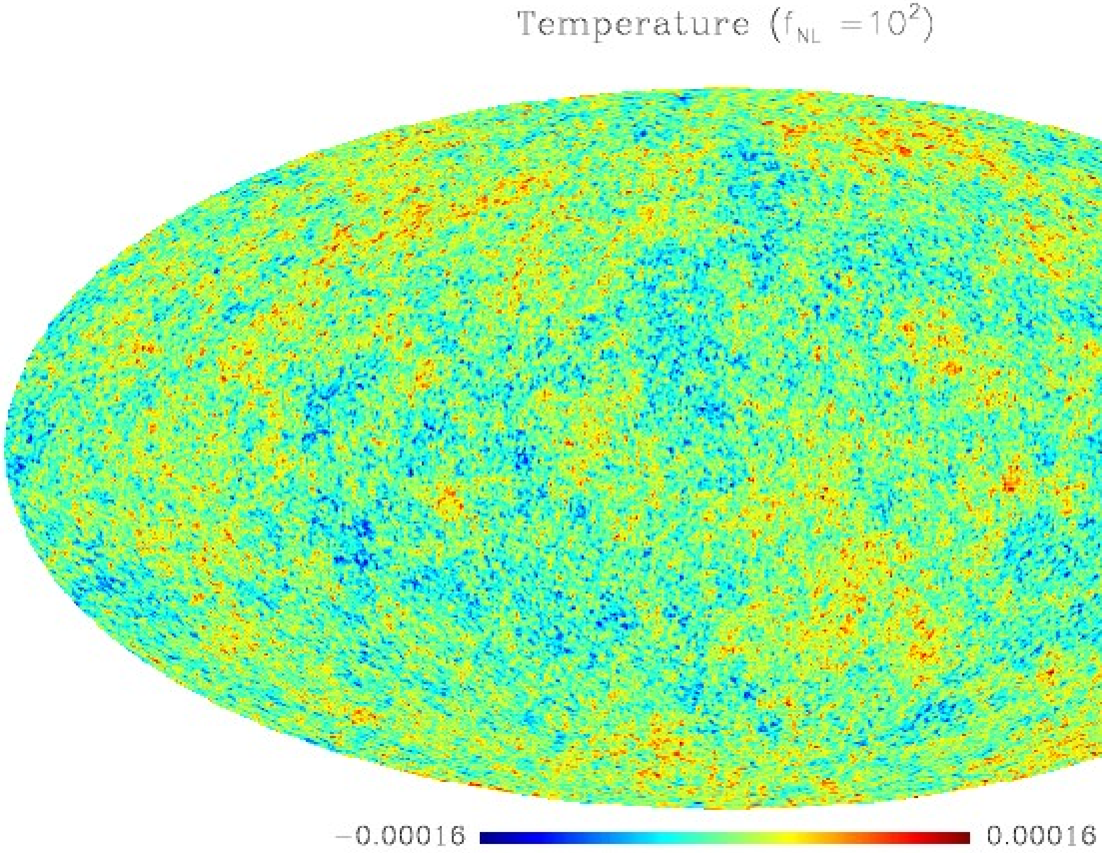
Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt, PRD (2007)

$$f_{NL} = 10^1$$



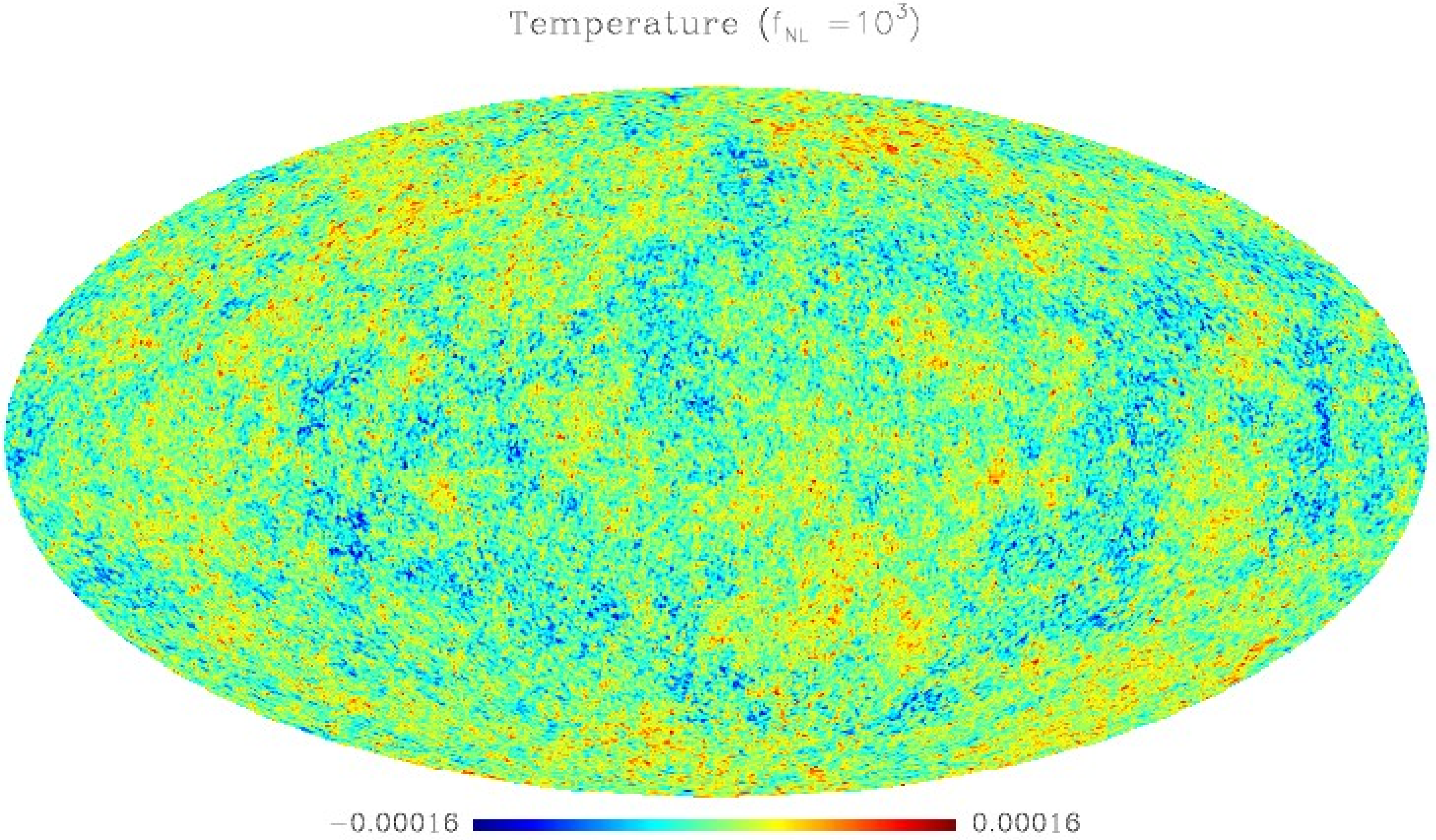
Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt, PRD (2007)

$$f_{NL} = 10^2$$



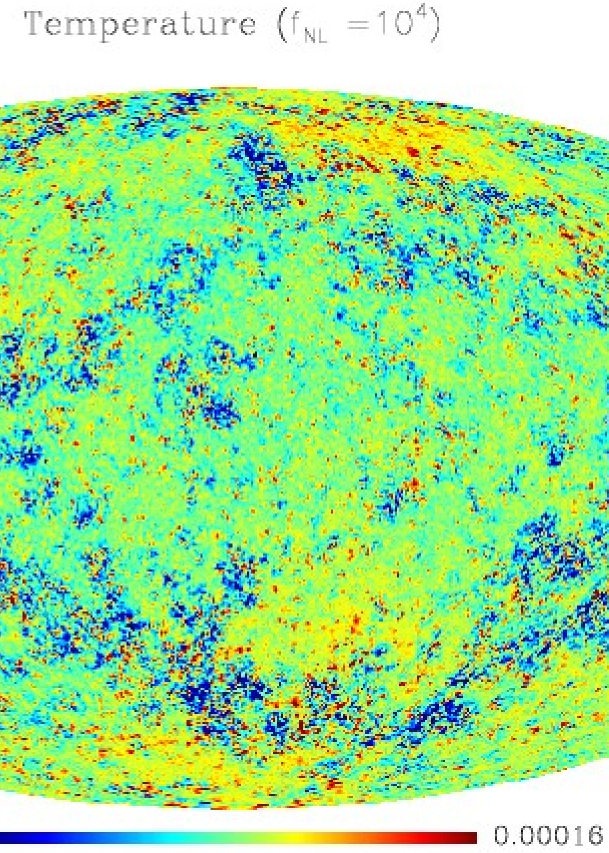
Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt, PRD (2007)

$f_{NL} = 10^3$



Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt, PRD (2007)

$$f_{NL} = 10^4$$



Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt, PRD (2007)

Why use the bispectrum?

$$C_{l\,\text{non-Gaussian}} = C_{l\,\text{Gaussian}} + f_{NL}^{2}\,\delta C_{l}$$

$$B_{\text{non-Gaussian}} = 0 + f_{NL} b^{2}$$

$$T_{\text{non-Gaussian}} = T_{\text{Gaussian}} + f_{NL}^{2}\,\delta T$$

For weak non-Gaussianity any even moment has a much larger contribution from Gaussian perturbations. This makes measuring the non-Gaussian component difficult.

Babich (2005) demonstrated that the **bispectrum contains nearly all the information about f_{NL}.**

Unfortunately **evaluating all $B_{l\,l'\,l''}$ is too expensive**.

f_{NL} phenomenology from the bispectrum using CMB Temperature data

- Komatsu & Spergel 2001 – CMB bispectrum from f_{NL}
- Komatsu Spergel & Wandelt 2003 – fast f_{NL} estimator for T
- Komatsu et al (WMAP team) 2003 – WMAP1 analysis using KSW
- Creminelli, Nicolis, Senatore, Tegmark, Zaldarriaga 2006 – introduce linear term to improve KSW estimator
- Spergel et al (WMAP team) 2006 – WMAP3 analysis using KSW
- Creminelli, Senatore, Tegmark, Zaldarriaga 2006 – apply cubic + linear term to WMAP3 data

Fast, bispectrum based estimator of local f_{NL}

Cubic Statistic:

$$\hat{S}_{prim} = \frac{1}{f_{sky}} \int r^2 dr \int d^2\hat{n} B(\hat{n}, r) B(\hat{n}, r) A(\hat{n}, r)$$

Komatsu, Spergel and Wandelt 2005

$$B(\hat{n}, r) \equiv \sum_{ip} \sum_{lm} (C^{-1})^{ip} a^i_{\ell m} \beta^p_\ell(r) Y_{\ell m}(\hat{n})$$

B(r) is a map of reconstructed primordial perturbations

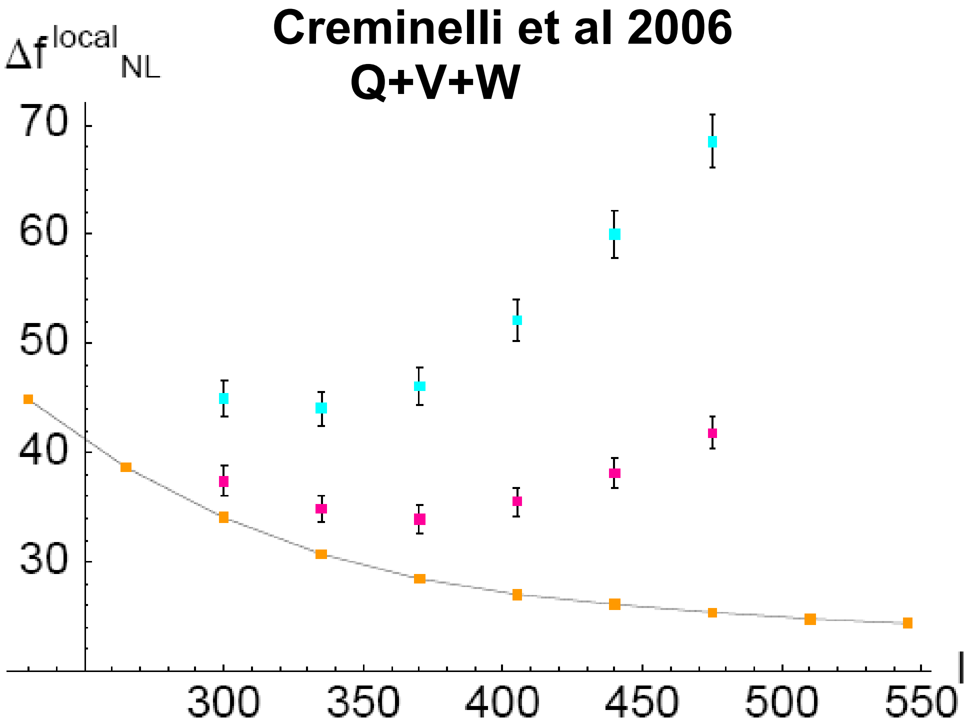
$$A(\hat{n}, r) \equiv \sum_{ip} \sum_{lm} (C^{-1})^{ip} a^i_{\ell m} \alpha^p_\ell(r) Y_{\ell m}(\hat{n}).$$

A(r) picks out relevant configurations of the bispectrum

Above statistics combine combine all configurations of bispectrum such that it most sensitive to "local" primordial non-Gaussianity i.e f_{NL}`

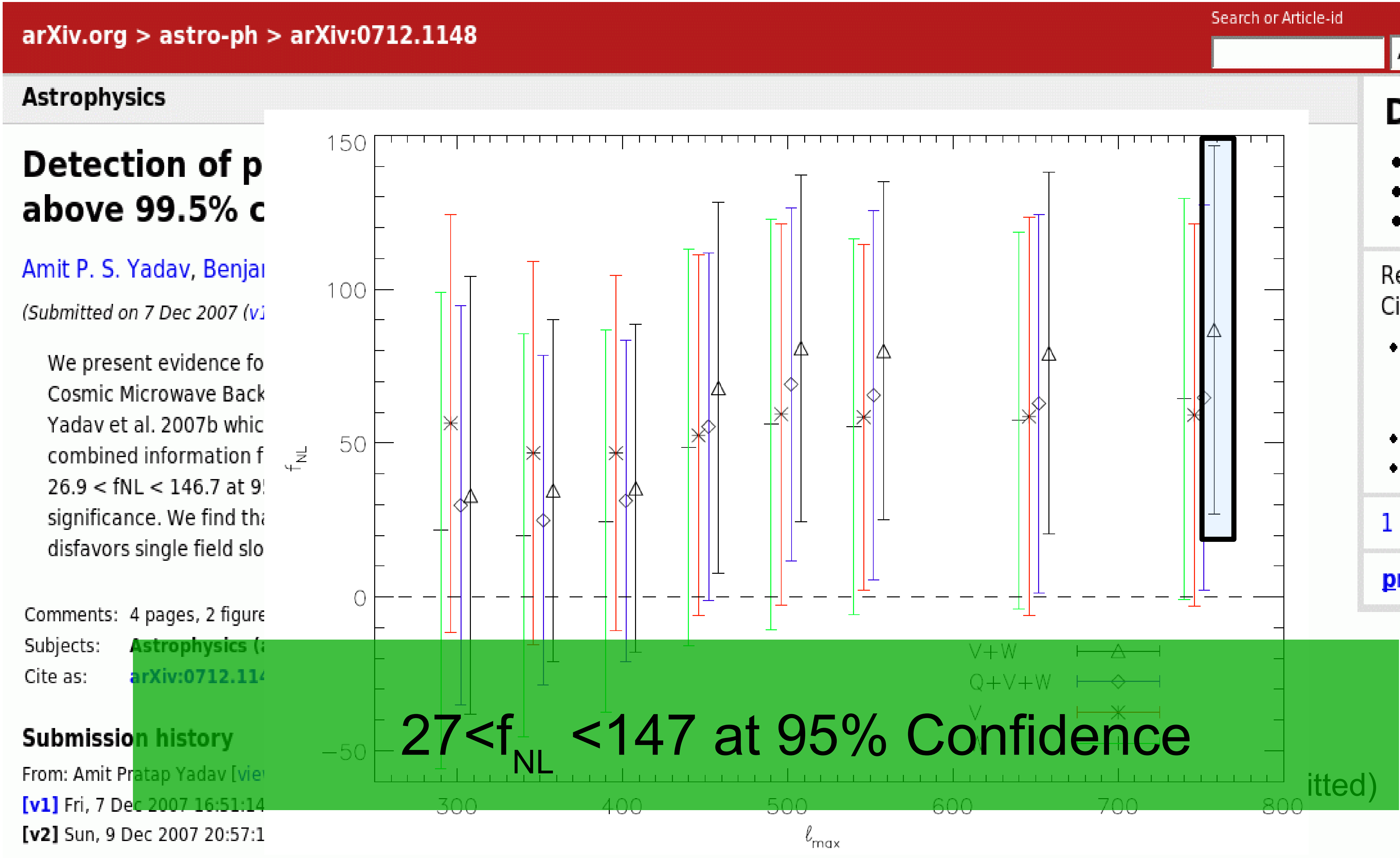
Status up to last month

$-58 < f_{NL} < 137$ (95%)	**WMAP 1yr using KSW**
$-54 < f_{NL} < 114$ (95%)	**WMAP 3yr using KSW**
$-27 < f_{NL} < 121$ (95%)	**Creminelli et. al. 2006,WMAP1**
$-36 < f_{NL} < 100$ (95%)	**Creminelli et. al. 2006,WMAP3**



- 10% improvement WMAP --> Creminelli et. al
- No evidence of primordial non-Gaussianity
- Unique minimum in the variance curve
- Only partial WMAP data has been analyzed
- We are far from $\Delta f_{NL} \sim 1$ but can already start putting constraints on some models like DBI inflation, ghost inflation etc.

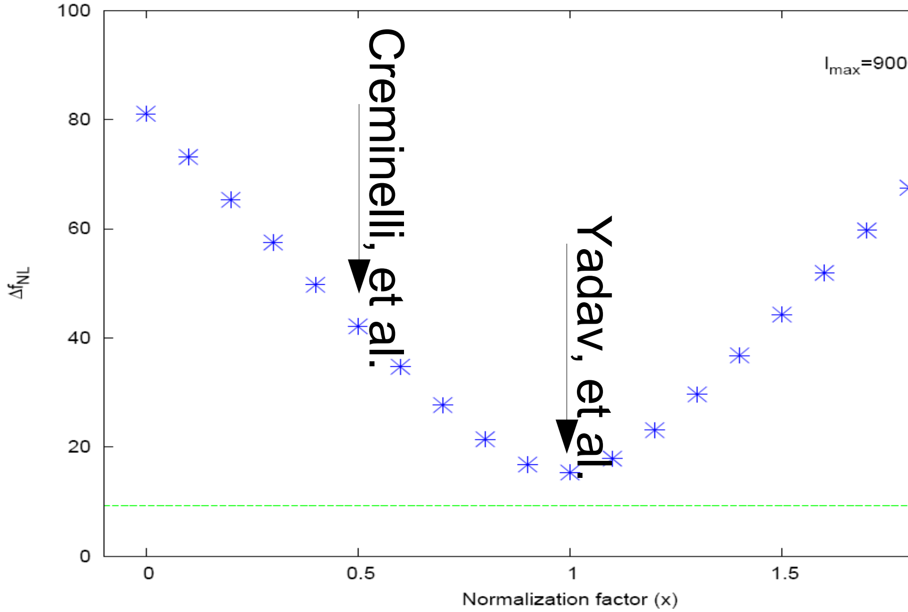
Our Result

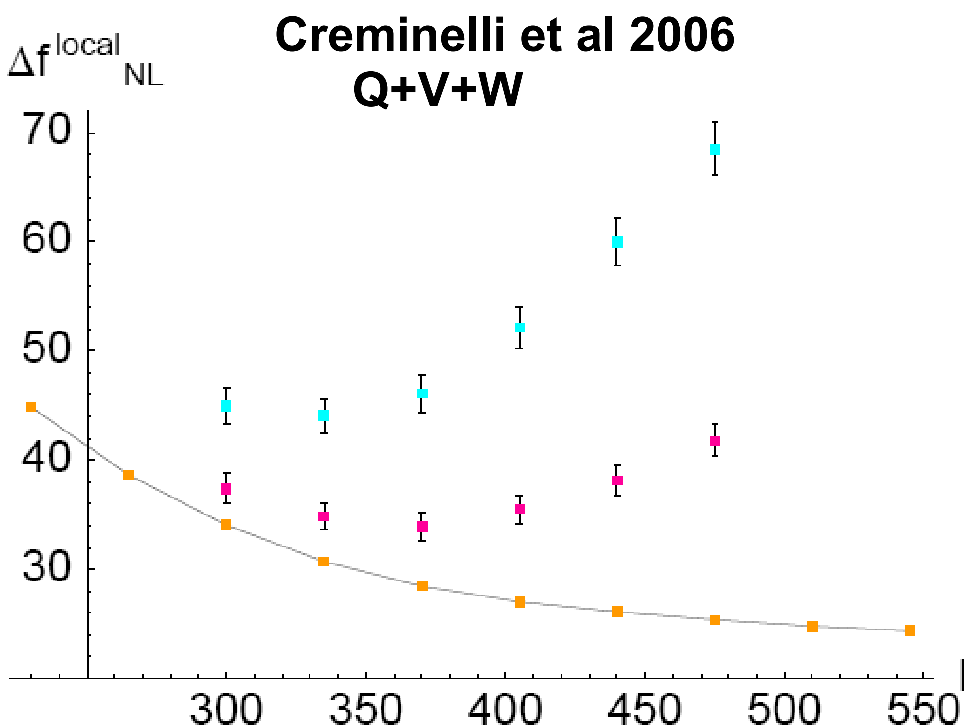


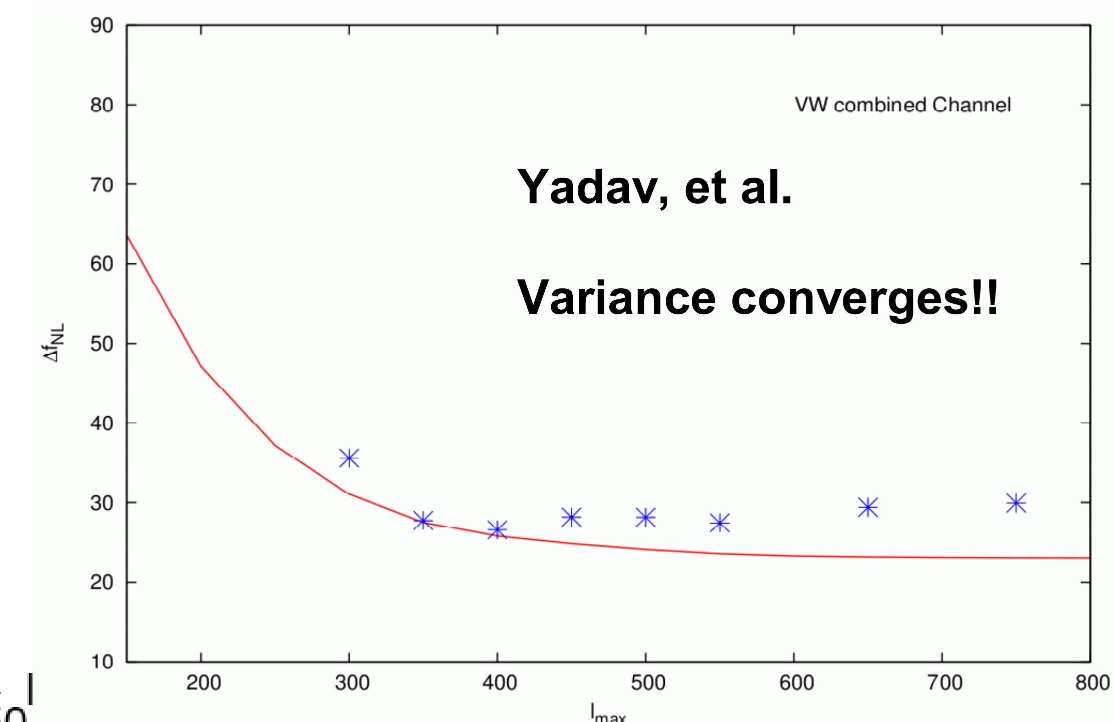
$27 < f_{NL} < 147$ at 95% Confidence

Status now!

$-58 < f_{NL} < 137$ (95%)	**WMAP 1yr using KSW**
$-54 < f_{NL} < 114$ (95%)	**WMAP 3yr using KSW**
$-27 < f_{NL} < 121$ (95%)	**Creminelli et. al. 2006,WMAP1**
$-36 < f_{NL} < 100$ (95%)	**Creminelli et. al. 2006,WMAP3**
$27 < f_{NL} < 147$ (95%)	**Yadav and Wandelt, WMAP3**







- $27 < f_{NL} < 147$ at 95% Confidence, for all of WMAP 3 using YKWLHM07
- First bispectrum-based analysis of the full WMAP3 data
- First significant departure of f_{NL} from 0.
- Estimators tested against Gaussian and non-Gaussian simulations with and without inhomogeneous noise

If our result holds up under scrutiny and the statistical weight of future data [...] the data disfavors all single field slow-roll inflation models.

Questions you might ask

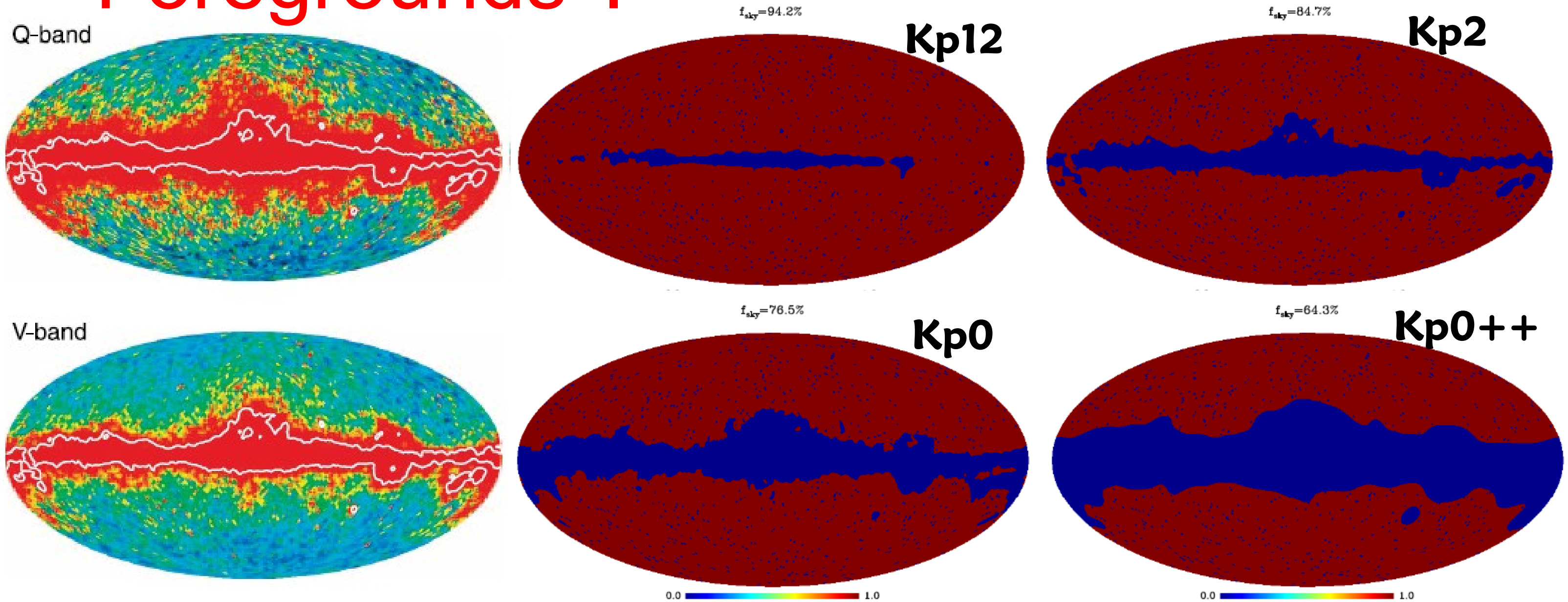
Might his result be due to...

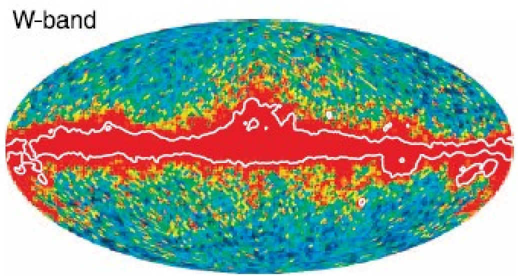
- Instrument systematics?
- Foregrounds?
- Just rediscovery of other non-Gaussian signals?
- Noise fluctuation?

Instrument systematics?

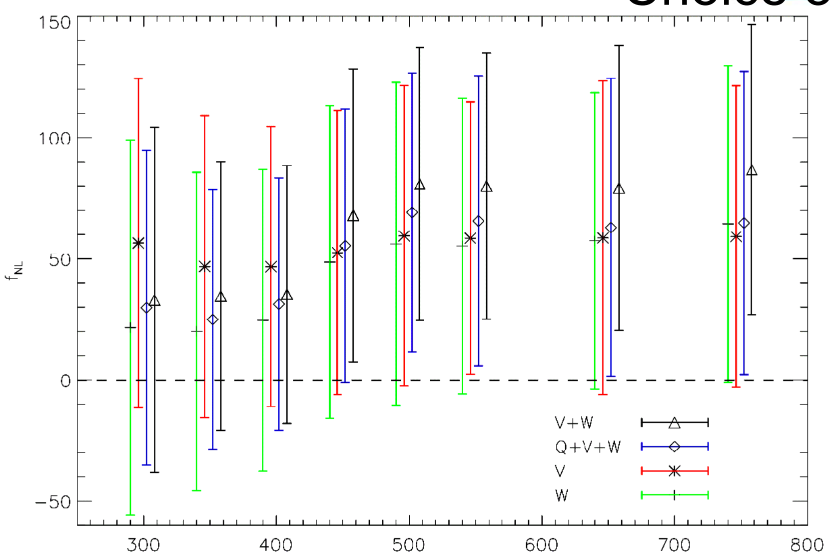
- Beam asymmetries?
  - If the CMB is Gaussian, no asymmetry of the main beam can produce non-vanishing bispectrum.
  - If there are large side-lobes that spread foreground around the sky they will produce large scale features
  - unlikely to affect the high l regime. Also, on large scales positively skewed foregrounds give *negative* contribution to f_{NL}.
- Noise correlations (striping)
  - As long as noise is Gaussian, no noise correlations will produce a bispectrum.
- So to explain this effect with an instrumental systematic it has to be non-Gaussian and also mimic the bispectrum signature of f_{NL}.

Foregrounds ?





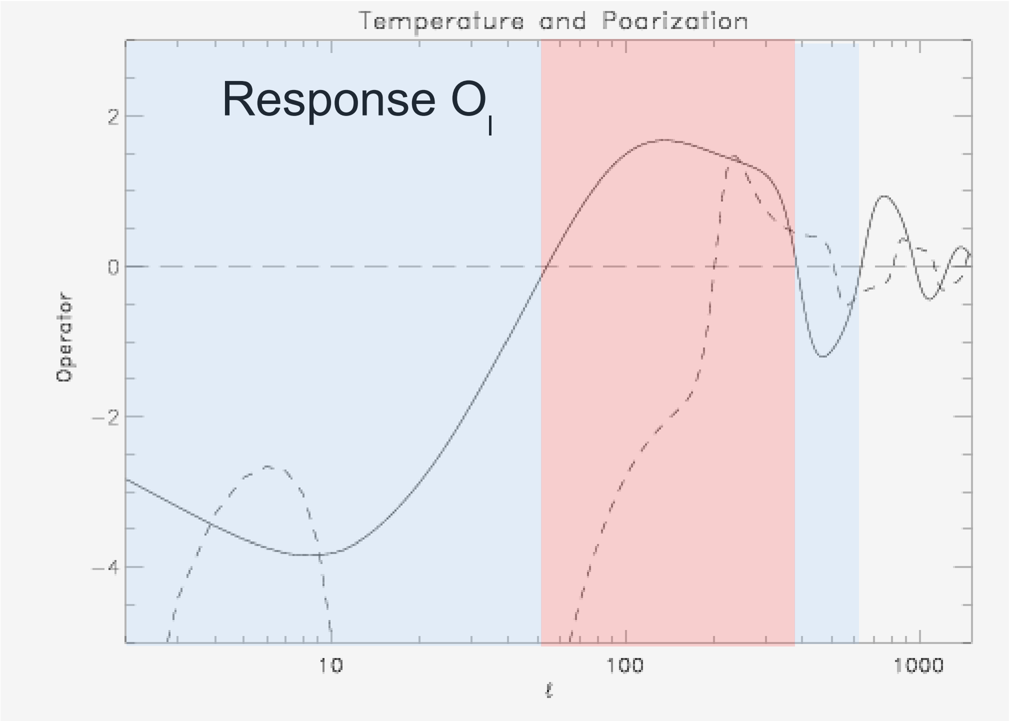
- We test the impact of foregrounds as a function of frequency and as a function of mask.
- V and W channels are the least foreground contaminated. Choice of V+W is driven by foreground considerations.



ℓ_{max}	f_{NL}			
	$f_{sky} = 94.2\%$ Kp12	$f_{sky} = 84.7\%$ Kp2	$f_{sky} = 76.8\%$ Kp0	$f_{sky} = 64.3\%$
350	-3145.22	-26.68	34.62	19.24
450	-1425.06	-15.63	67.94	64.69
550	-1509.92	-13.09	79.99	83.53
650	-1559.91	-22.43	79.18	81.29
750	-1575.11	-22.81	86.81	86.52

Foregrounds II

- Remember – large scale skewness in the Temperature map corresponds to *negative* f_{NL} .



- The added l modes at 400<l<550 correspond to modes where positive skewness also gives *negative* contributions.

- At intermediate scales positive skewness gives *positive* f_{NL}.

Re-discovery of another non-Gaussian signal?

- Larson/Wandelt (hot and cold spots not hot or cold enough):
  - at smaller angular scales **X**
  - symmetric-> no odd correlation.
- The Cold Spot (Vielva et al. 2004) is localized in the map and covers a particular range in scale. Very unlikely to give large contribution to f_{NL} and was also discovered as *kurtosis*. But should be checked. **X**
- Axis of Evil? Can check by redoing analysis removing large scale signal. Preliminary result:

  Removing l<21, f_{NL}=135.21 +/-48

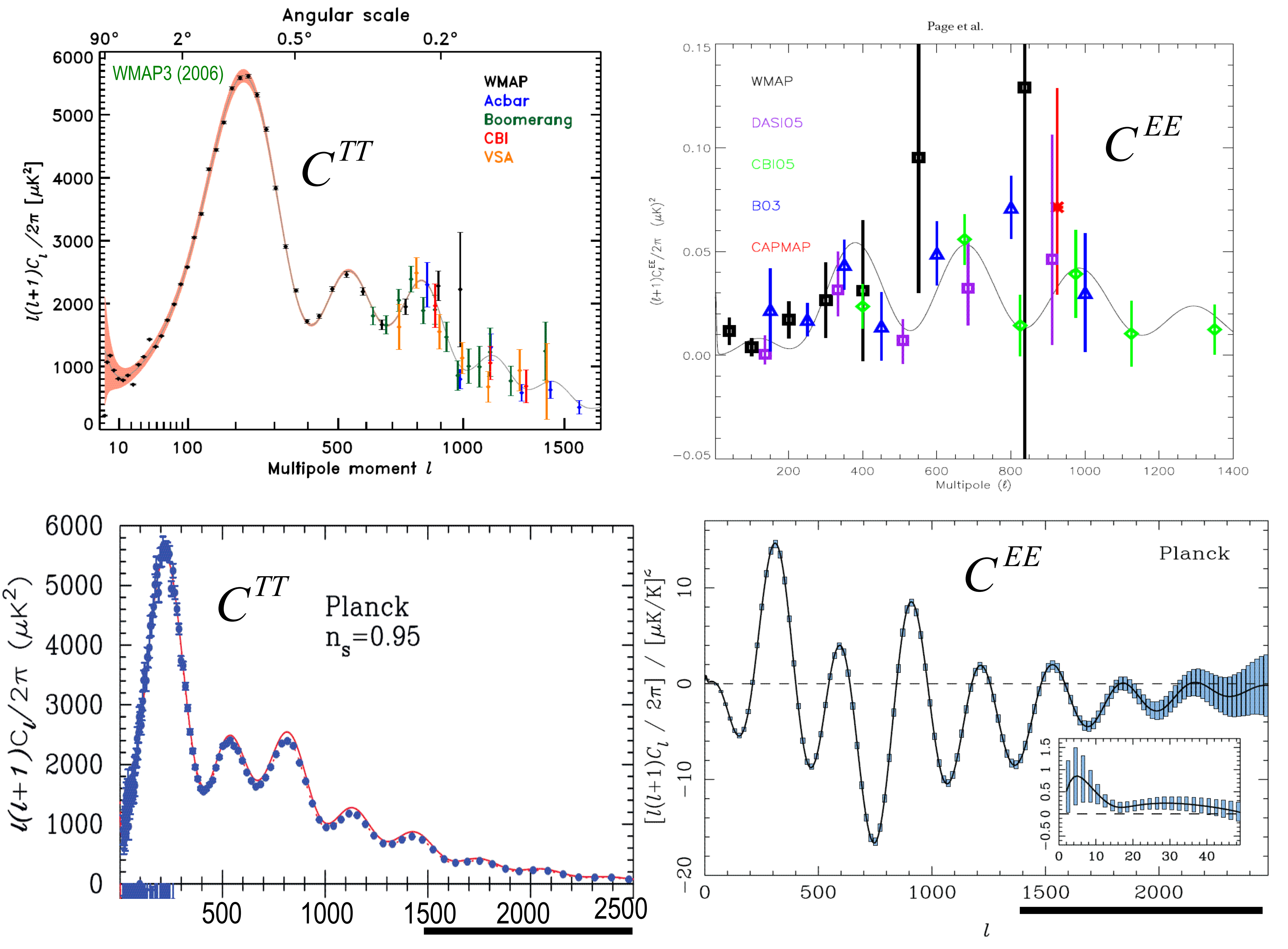
Noise fluctuation?

- Possible.
- It's a 2.5-3 sigma result. P~1/100

We conclude that the WMAP 3-year data contains evidence for primordial non-Gaussianity. If our result holds up under scrutiny and the statistical weight of future data [...] the data disfavors all single field slow-roll inflation models.

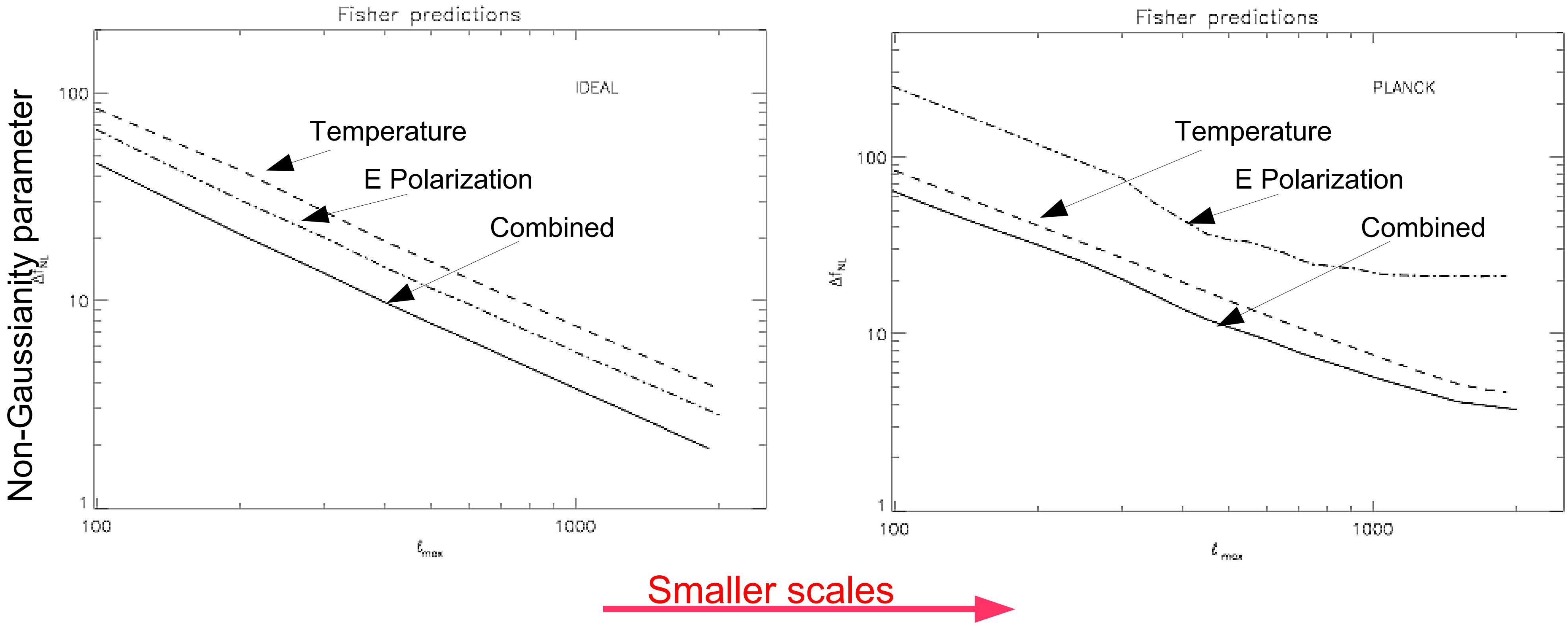
Non-Gaussianity post WMAP

- Probes of inflation:
  - Inflation generates primordial fluctuations in space-time
    - Fluctuations in radiation
      - CMB T
      - CMB E-polarization
      - Neutrino background
    - Fluctuations in matter
      - Dark matter distribution (Gravitational lensing, cosmological 21-cm radiation)
      - Galaxy and gas distribution (Redshift surveys, Lyman-alpha clouds)
    - Fluctuations in space time itself
      - Primordial Gravitational Waves (eg. Primordial B-modes of CMB)



Angular scale
90°
2°
0.5°
0.2°
WMAP3 (2006)
WMAP
Acbar
Boomerang
CBI
VSA
C^{TT}
$l(l+1)C_l/2\pi$ [μK^2]
6000
5000
4000
3000
2000
1000
0
10
100
500
1000
1500
Multipole moment l
Page et al.
WMAP
DASI05
CBI05
B03
CAPMAP
C^{EE}
$(\ell+1)C_\ell^{EE}/2\pi$ (μK)^2
0.15
0.10
0.05
0.00
−0.05
200
400
600
800
1000
1200
1400
Multipole (ℓ)
C^{TT}
Planck
n_s=0.95
$l(l+1)C_l/2\pi$ (μK^2)
6000
5000
4000
3000
2000
1000
0
500
1000
1500
2000
2500
C^{EE}
Planck
$[l(l+1)C_l / 2\pi]$ / $[\mu$K/K$]^2$
10
0
−10
−20
0
500
1000
1500
2000
l
1.5
1
0.5
0
−0.5
0
10
20
30
40

Non-Gaussianity post WMAP

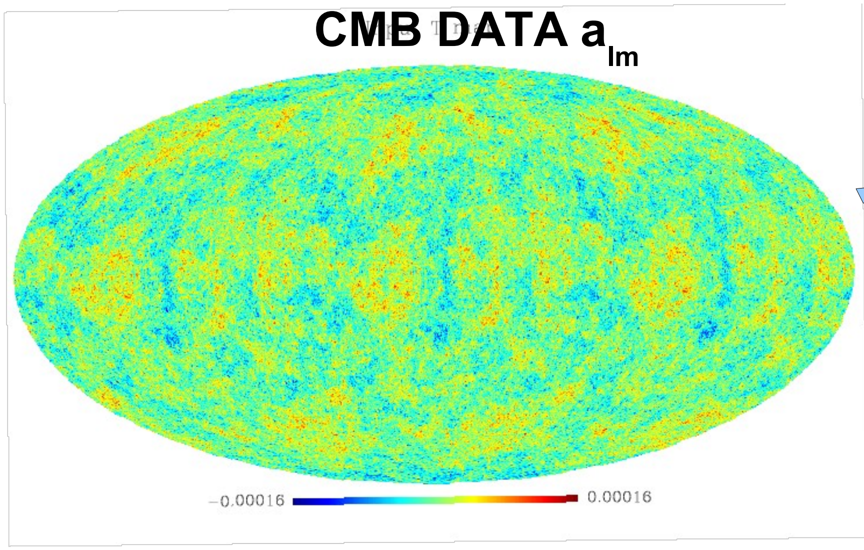


For and Ideal CMB experiment and using both temperature and polarization we can get down to $\Delta f_{NL} \sim 1$

For Planck the Cramer-Rao limit is $\Delta f_{NL} \sim 3$.

Yadav, Komatsu and Wandelt, ApJ (2007)

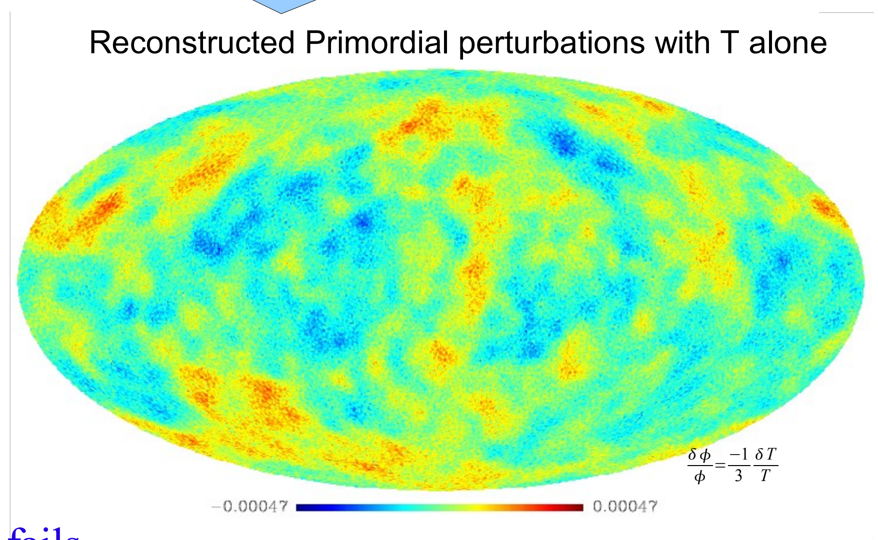
Reconstructed Primordial Perturbations

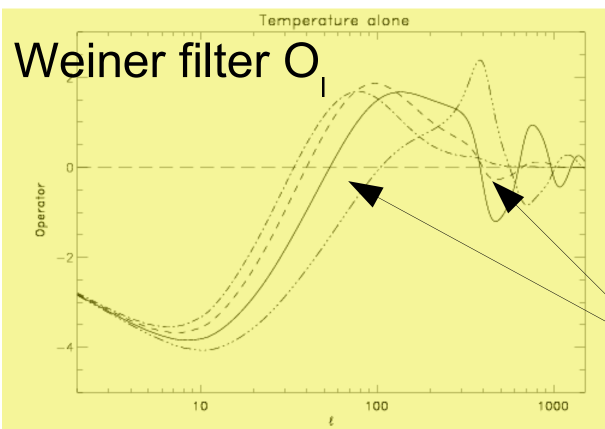


$\Phi_{lm} = O_l \, a_{lm}$

On large scales

$$\frac{\delta \phi}{\phi} = \frac{-1}{3} \frac{\delta T}{T}$$





Operator goes to zero
=> reconstruction fails

$$S_{prim} = \int B^2(r) \, A(r) \, r^2 \, dr$$

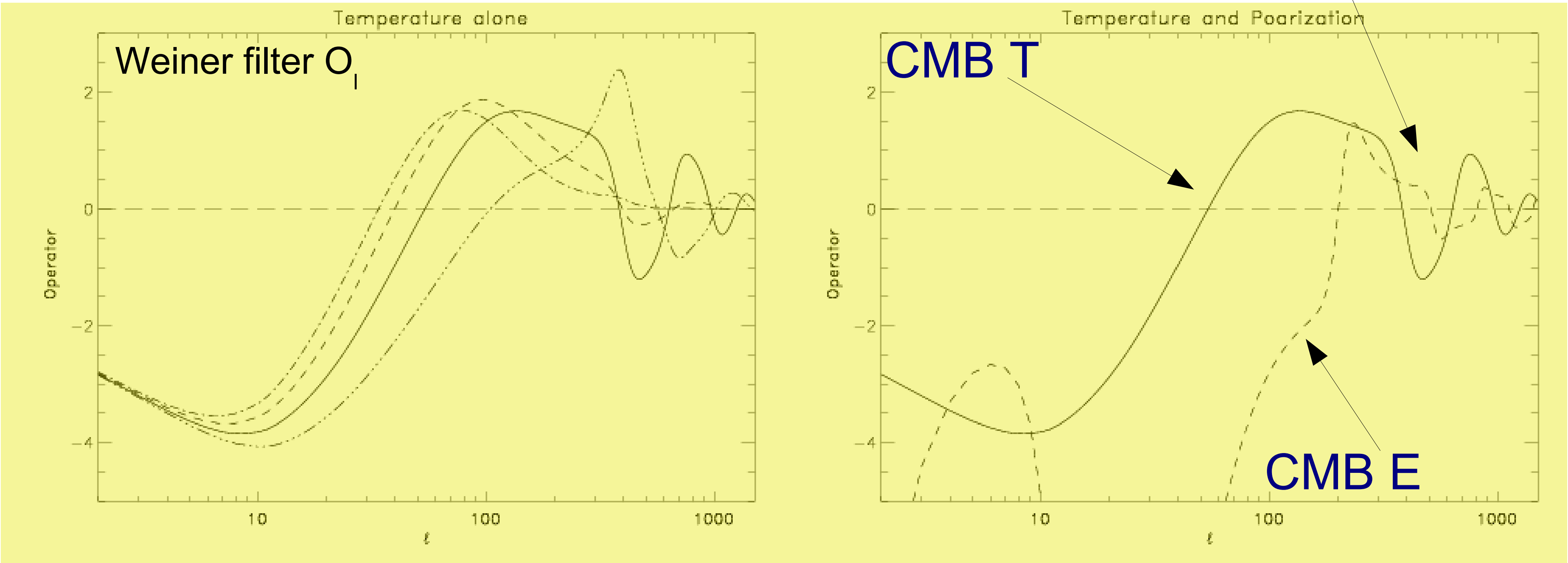
B(r) is a *reconstructed primordial perturbations*

Temperature and polarization are complementary

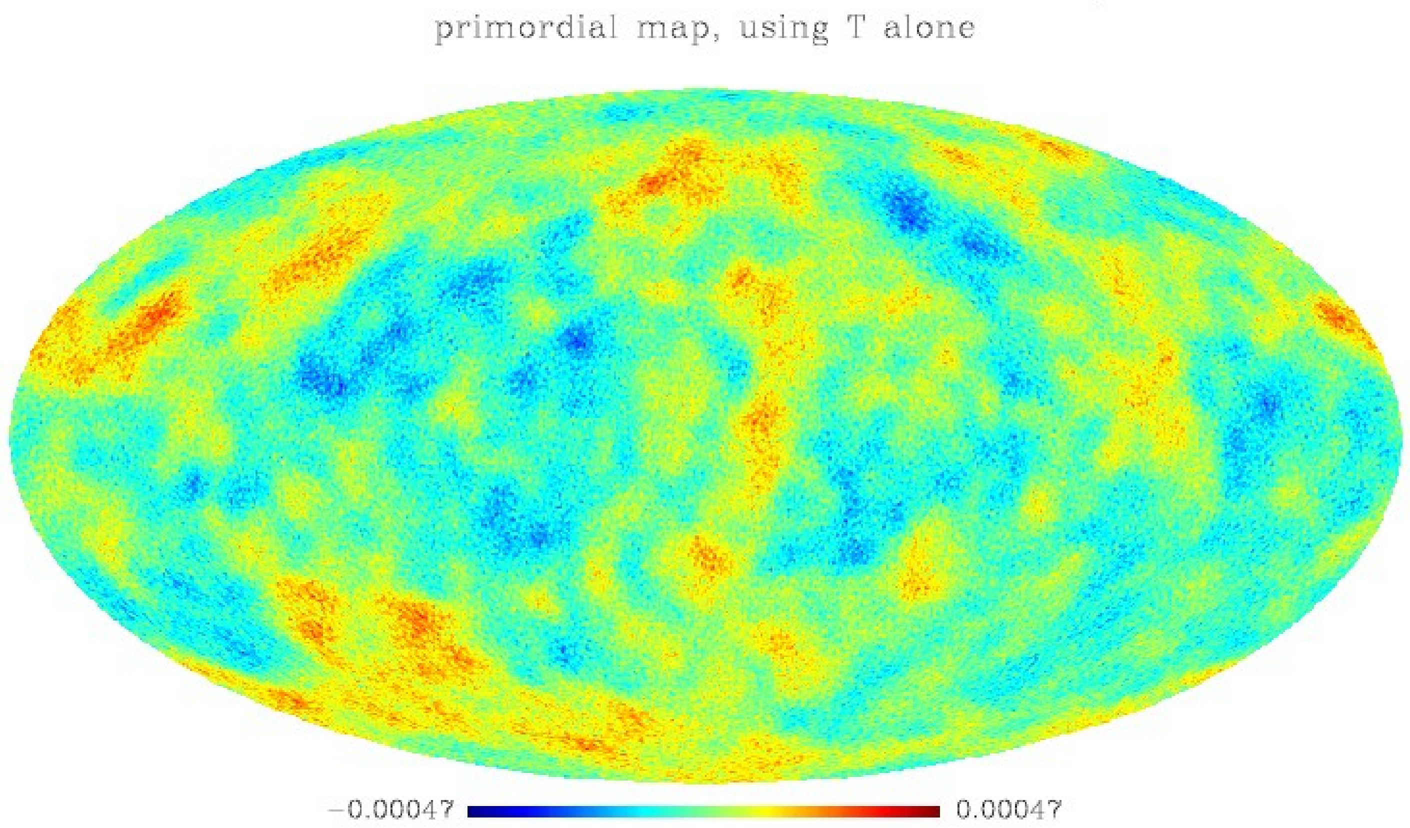
$$S_{prim} = \int B^2(r) A(r) r^2 dr$$

B(r) is a *reconstructed primordial perturbations*

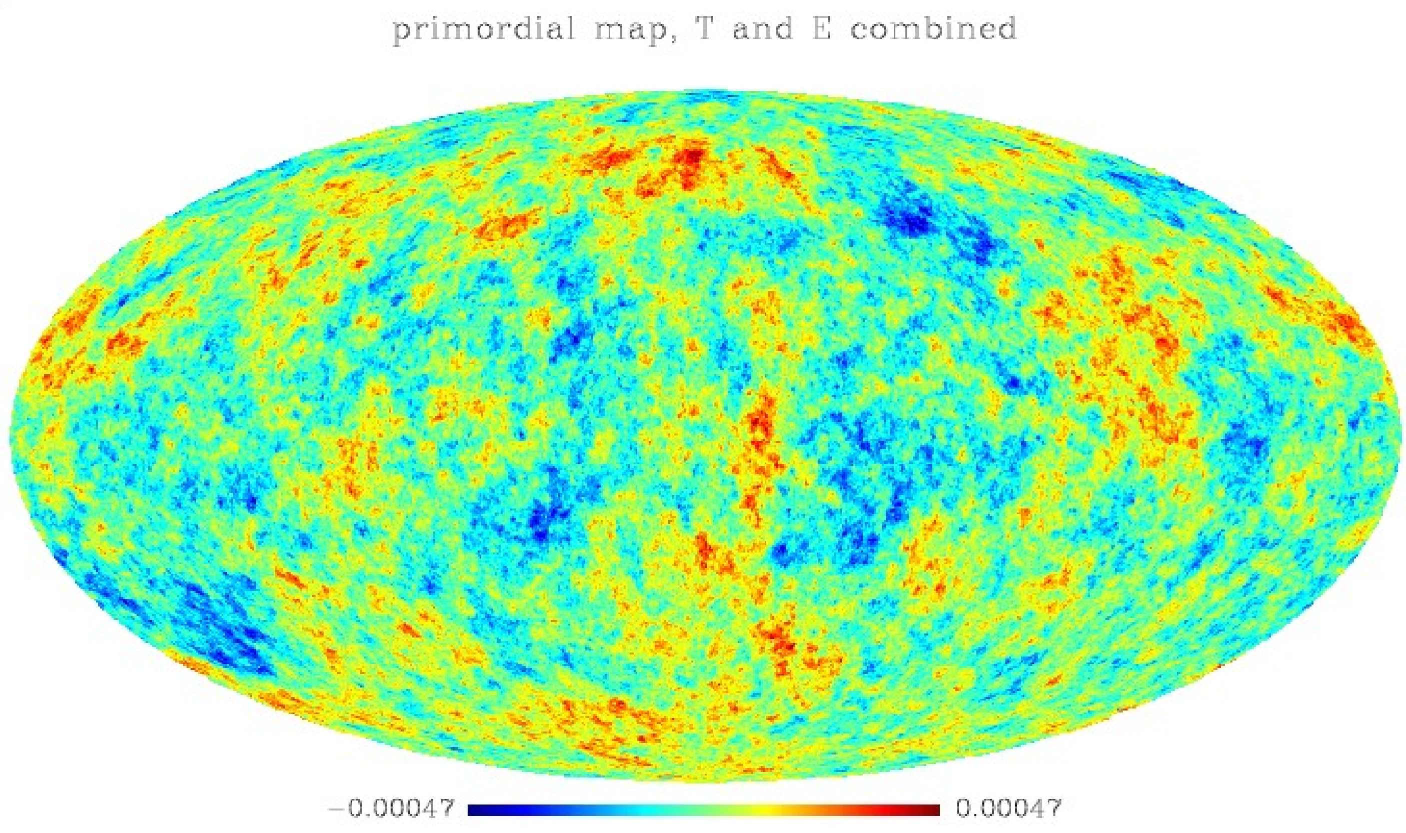
Out of phase



Yadav, and Wandelt, PRD (2005)

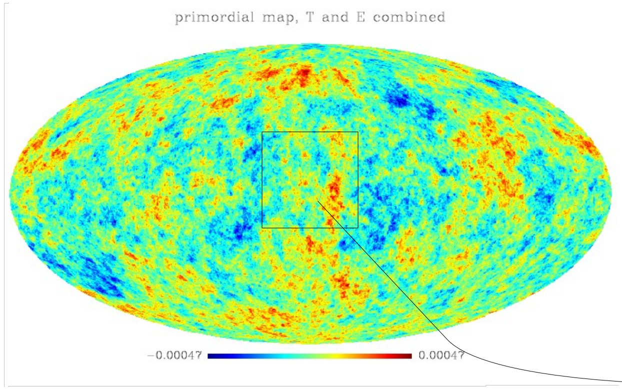


Yadav, and Wandelt, PRD (2005)

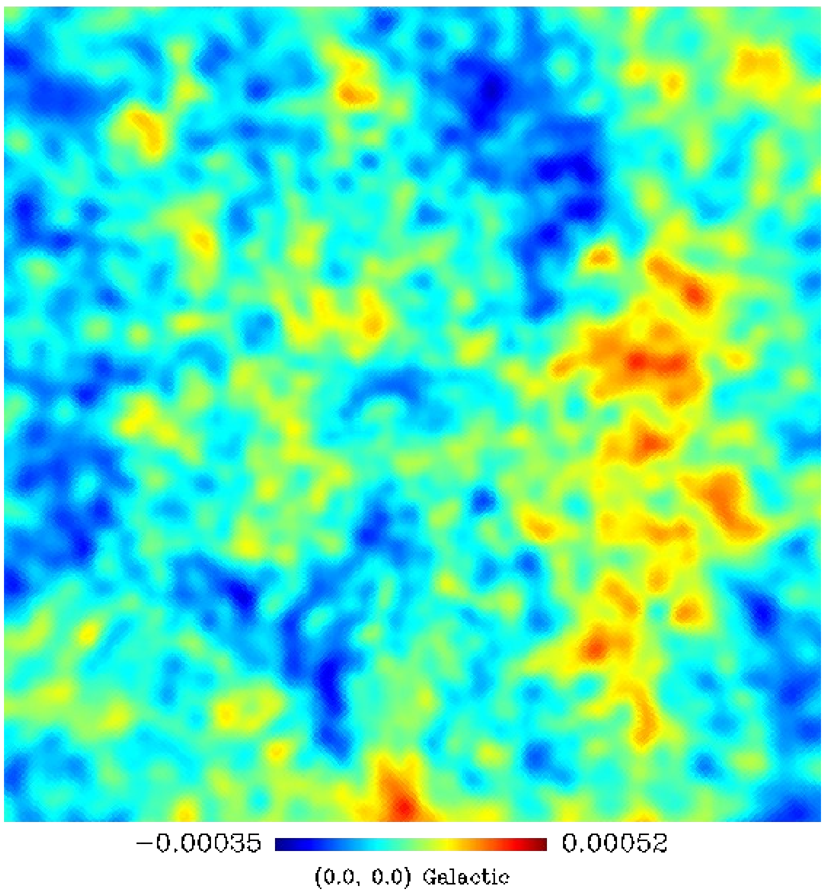


Yadav, and Wandelt, PRD (2005)

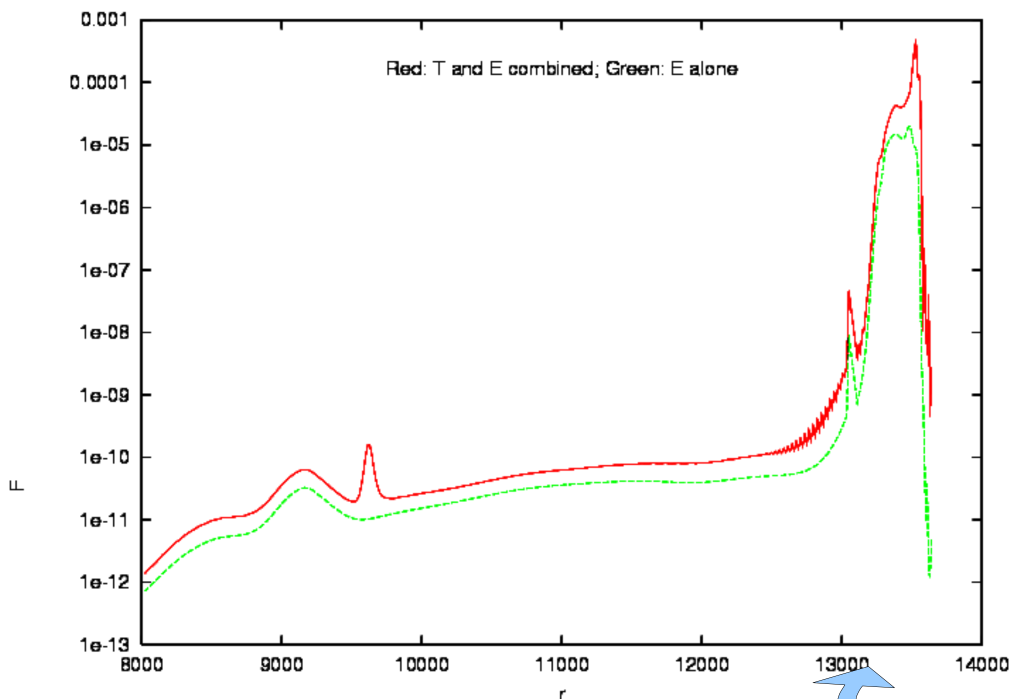
Reconstructed perturbations at different radii



Curvature fluctuations



Movie

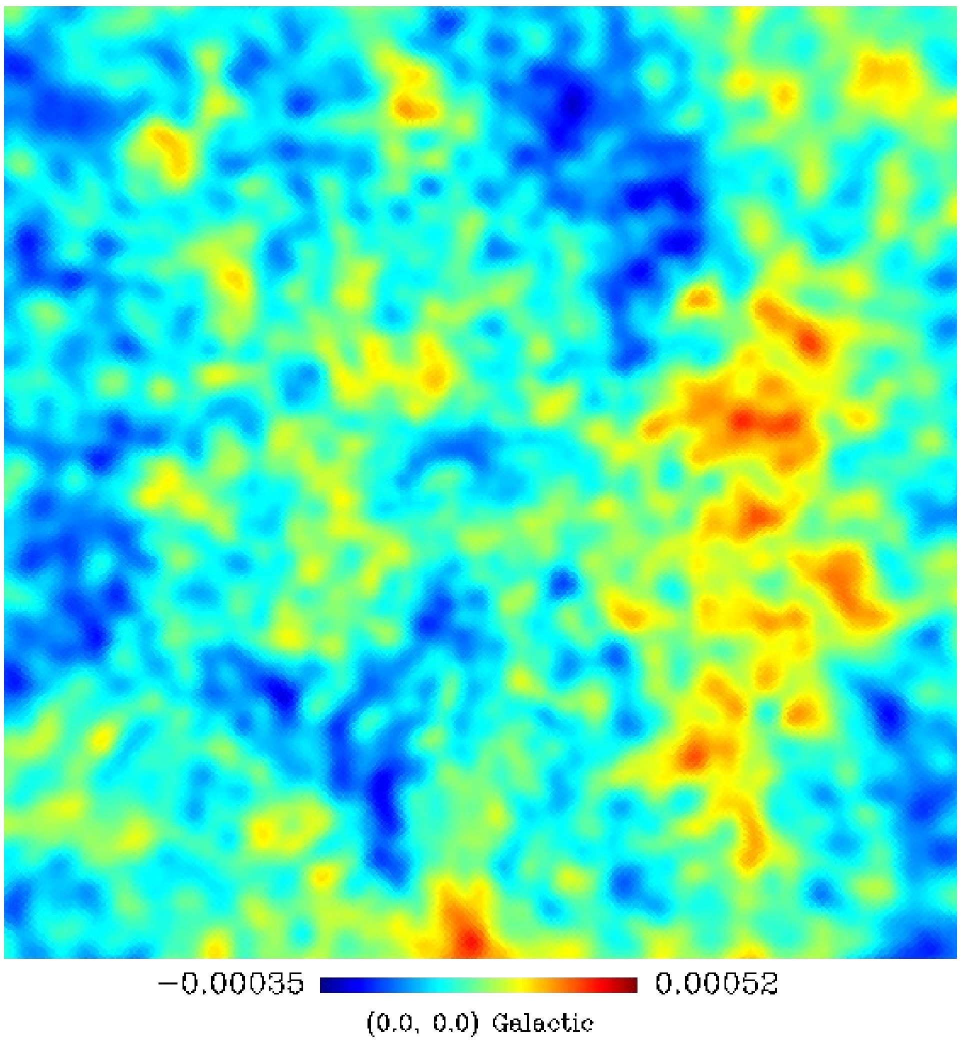


Yadav, and Wandelt, PRD (2005)

Decoupling

Tomographic reconstruction of inflationary scalar curvature perturbations from CMB temperature and polarization.

Curvature fluctuations



Movie

We construct filters that invert linear radiative transport.

Generates a single scalar that contains all the information from T&E.

Anyone intending to test primordial non-Gaussianity and anisotropy in T&E data should do so using curvature perturbations obtained with our filters.

Yadav and Wandelt 2005

f_{NL} phenomenology from the bispectrum using CMB combined T & E-Polarization

- Babich & Zaldarriaga 2004 – CMB T+E bispectrum from fnl
- Yadav & Wandelt 2005 – reconstruction of curvature perturbation
- Yadav, Komatsu & Wandelt 2007 – KSW generalized to T+P
- Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007 – calibrate YKW estimator against non-Gaussian simulations
- Yadav, Komatsu, Wandelt, Liguori, Hansen, Matarrese 2007 – Creminelli et al. corrected and generalized to T+P
- Yadav & Wandelt 2007 – application of YKWLHM07 to WMAP3

Non-Gaussianity using Bispectrum

- Physical non-Gaussianity is generated in real space so our statistic should be sensitive to real space NG
- The Central Limit Theorem makes a_{lm} coefficients more Gaussian.

Cubic Statistics:

CMB T+E Yadav, Komatsu, and Wandelt 2007

$$S_{prim} = \int B^2(r) A(r) r^2 dr \propto f_{NL}$$

B(r) is a reconstructed primordial perturbations

A(r) picks out relevant configurations of the bispectrum

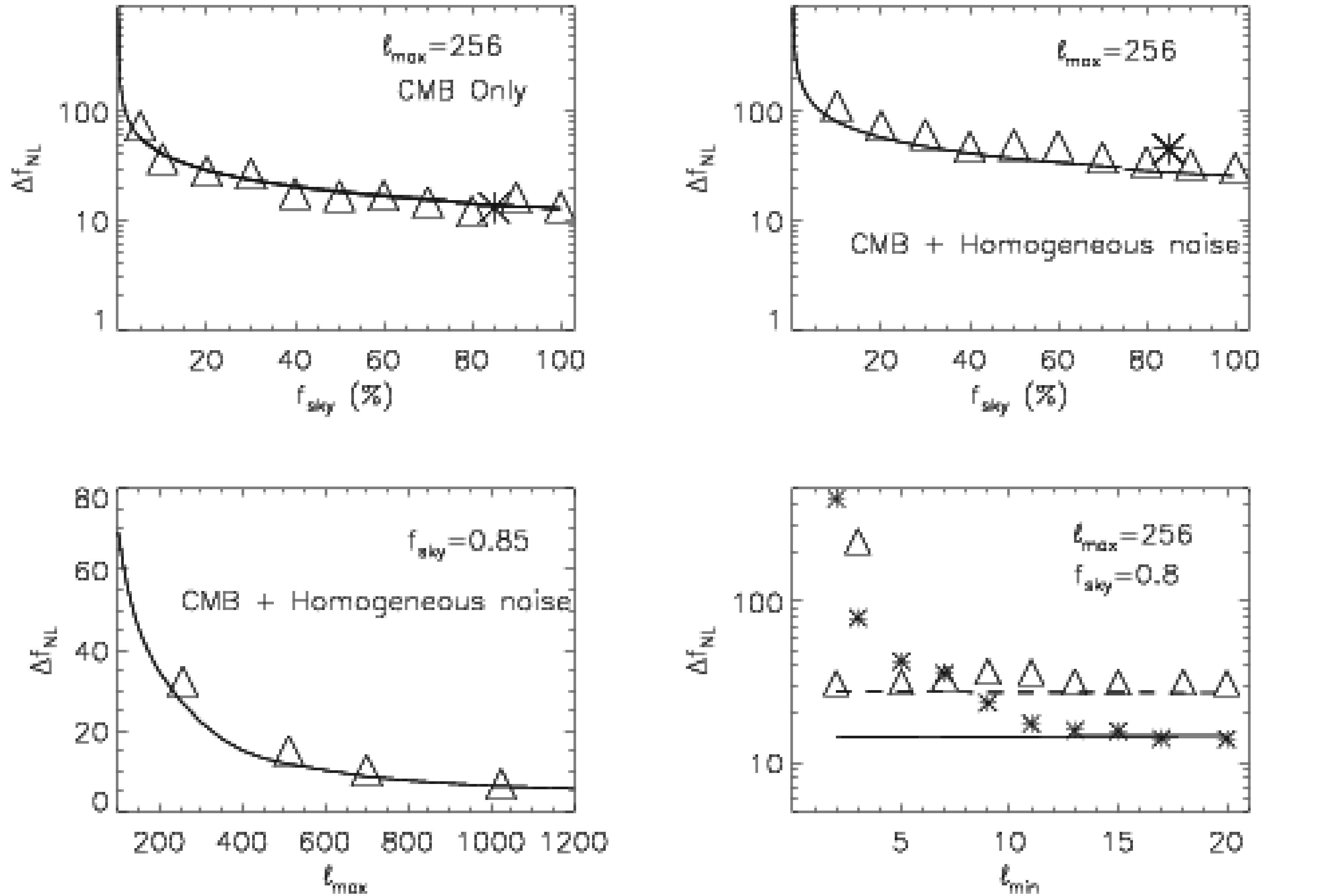
Above statistics combine combine all configurations of bispectrum such that it most sensitive to the primordial non-Gaussianity i.e f_{NL}

Fast estimator of f_{NL} using combined T and E polarization data

- Our estimator scales as $N^{3/2}$ as compared to $N^{5/2}$ scaling of the brute force bispectrum evaluation.
- For Planck this translates to speed-up by factors of millions
  - Allows us to study the properties of estimator
  - Estimator is optimal for homogeneous noise

Yadav, Komatsu, and Wandelt, ApJ (2007)

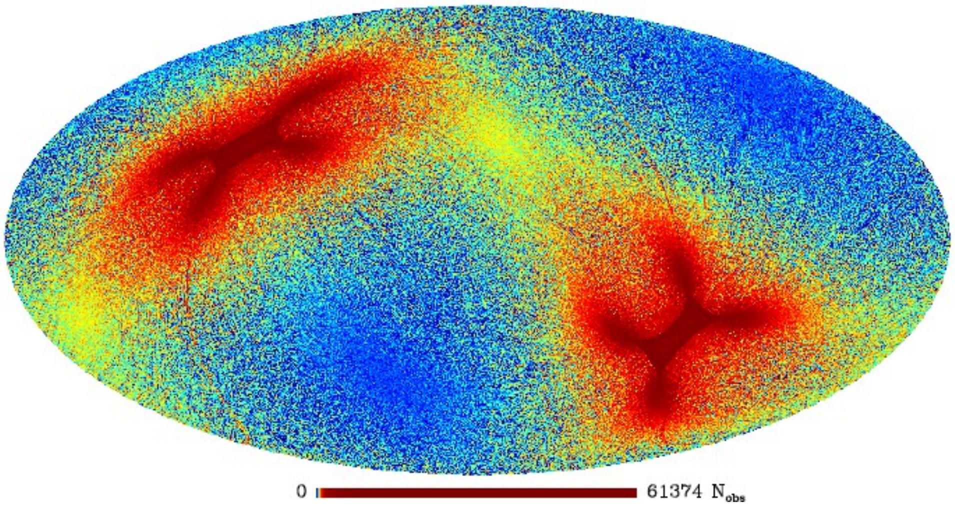
Estimator using combined CMB T+E



Yadav, Komatsu, and Wandelt, ApJ (2007)

Anisotropic sky coverage

- The estimators we wrote down are optimal only for uniform sky coverage and noise distribution. Anisotropic noise distribution couples different l and produces excess variance.
- For non-uniform noise the addition of a linear term reduces the variance of the estimator (Creminelli et al. 2005)
- We (Yadav, Komatsu, Wandelt, et al. arxiv:0711.4933) generalized this estimator to include polarization; and discovered and corrected an error in the linear term.



$$A(\hat{n}, r) \equiv \sum_{ip} \sum_{lm} (C^{-1})^{ip} a^{i}_{\ell m} \alpha^{p}_{\ell}(r) Y_{\ell m}(\hat{n})$$

$$B(\hat{n}, r) \equiv \sum_{ip} \sum_{lm} (C^{-1})^{ip} a^{i}_{\ell m} \beta^{p}_{\ell}(r) Y_{\ell m}(\hat{n})$$

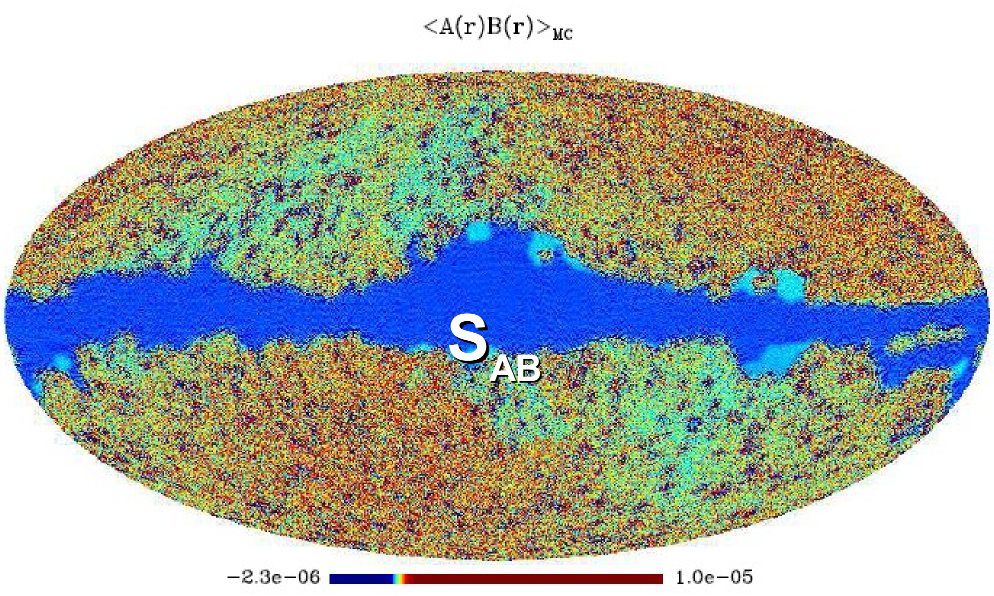
$$\hat{S}^{linear}_{prim} = \frac{-6}{f_{sky}} \int r^2 dr \int d^2\hat{n} \left\{ B(\hat{n}, r) S_{AB}(\hat{n}, r) + S_{BB}(\hat{n}, r) A(\hat{n}, r) \right\}$$

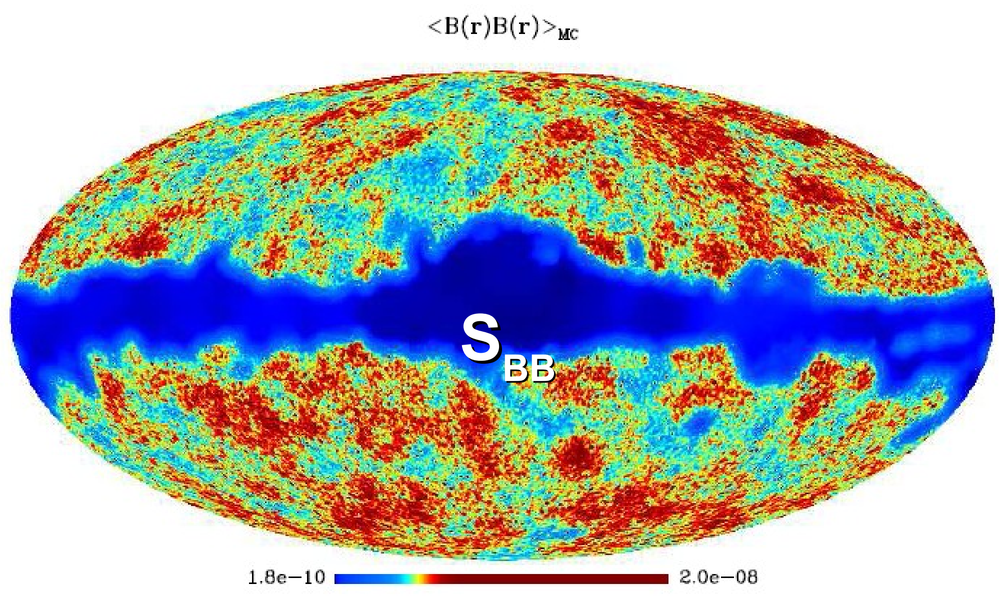
Anisotropic noise

- Linear weight maps make linear term maximally anticorrelated with the cubic term to reduce its variance due to anisotropic noise

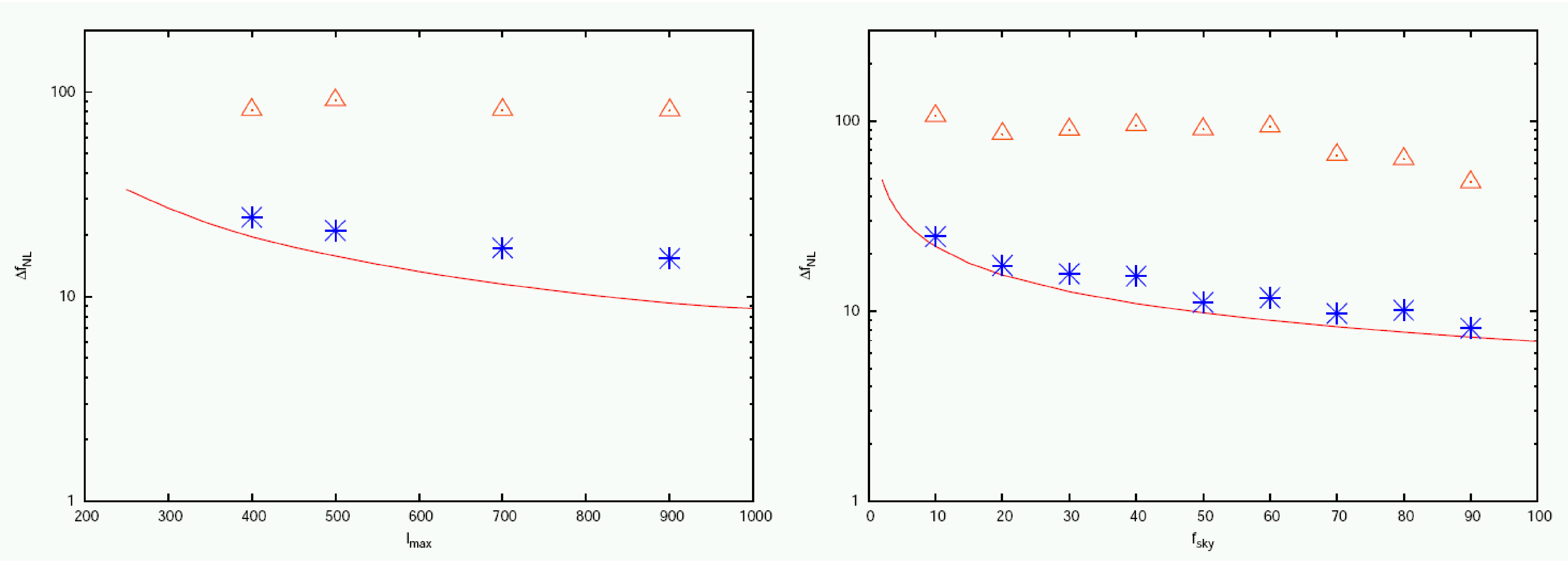
$$S_{AB}(\hat{n},r) \equiv \sum_{ipqr} \sum_{\ell_1 m_1 \ell_2 m_2} \beta^i_{\ell_1}(r)(C^{-1})^{ip})_{\ell_1} Y_{\ell_1 m_1}(\hat{n}) \alpha^j_{\ell_2}(r)(C^{-1})^{jq}_{\ell_2} Y_{\ell_2 m_2}(\hat{n}) \langle a^p_{\ell_1 m_1} a^q_{\ell_2 m_2} \rangle$$

$$S_{BB}(\hat{n},r) \equiv \sum_{ipqr} \sum_{\ell_1 m_1 \ell_2 m_2} \beta^i_{\ell_1}(r)(C^{-1})^{ip})_{\ell_1} Y_{\ell_1 m_1}(\hat{n}) \beta^j_{\ell_2}(r)(C^{-1})^{jq}_{\ell_2} Y_{\ell_2 m_2}(\hat{n}) \langle a^p_{\ell_1 m_1} a^q_{\ell_2 m_2} \rangle$$





Estimator using combined CMB T+E



CMB+ Inhomogeneous noise +
Kp0 Temp mask + Po6 polarization mask

CMB+ Homogeneous noise + Flat sky cut

Yadav, Komatsu, Wandelt, Liguori, Hansen, Matarrese Apj (submitted)

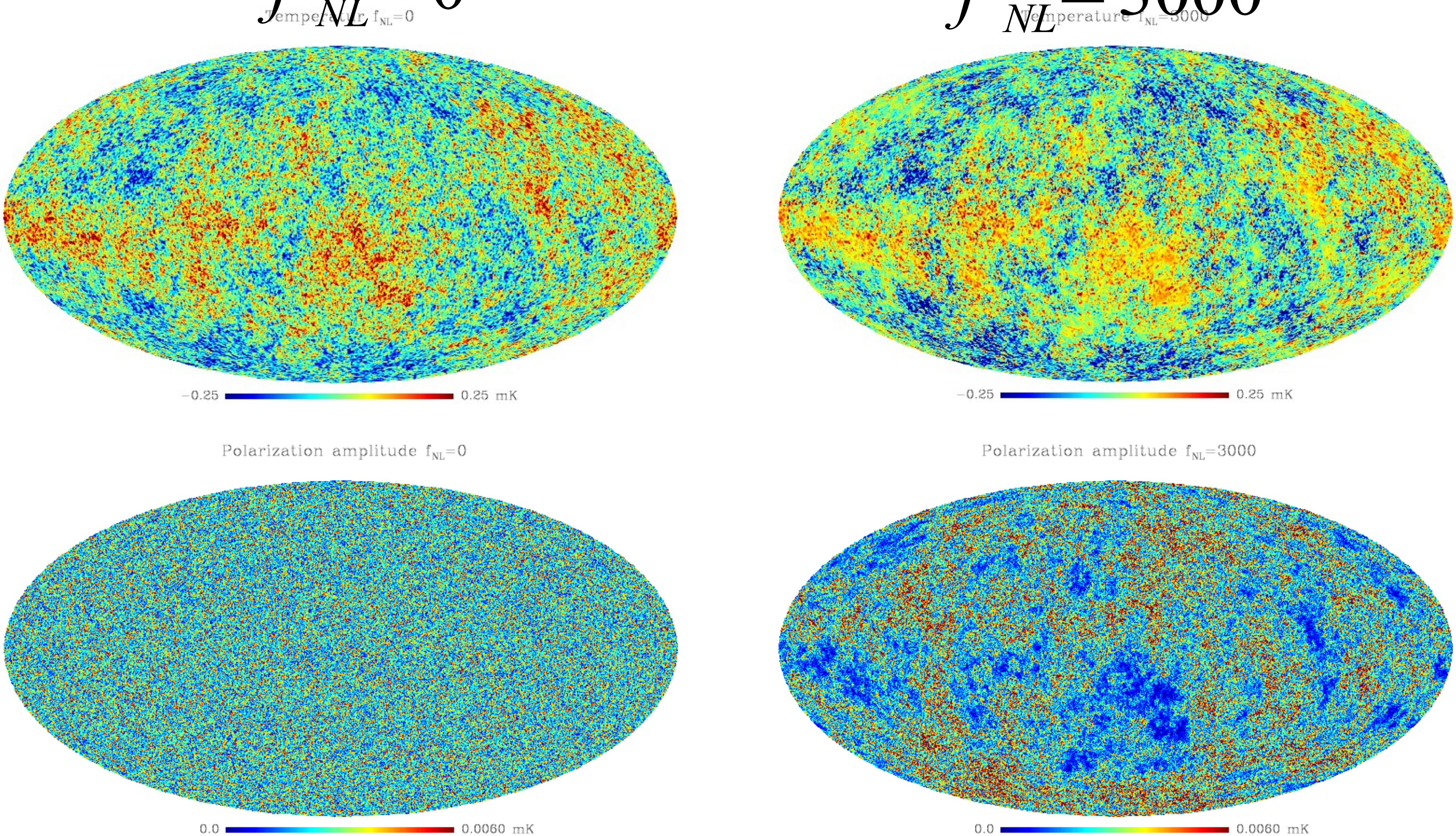
Non-Gaussian CMB T and E-Polarization Map Making

- Non-Gaussian maps are crucial for characterizing the estimator
  - Testing for unbiasedness
  - Testing for systematics
- We have developed an efficient tool for generating non-Gaussian CMB T and E-polarization maps

Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt, PRD (2007)

Non-Gaussian CMB T & E Maps

$f_{NL} = 0$ $\quad$ $f_{NL} = 3000$



Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt, PRD (2007)

Unbiasedness of the Estimator

Noise	Sky-cut	$\langle \mathrm{f_{NL}} \rangle$	$\mathrm{f_{NL}^{input}}$	σ_{sim}
No	flat cut, $f_{sky} = 0.8$	103.2	100	10.1
Inhomogeneous	WMAP Kp0 and P06 masks	108.7	100	21.04

Table 1: Unbiasedness of the generalized estimator. Non-Gaussian CMB maps with $\mathrm{f_{NL}^{input}} = 100$ are used for $\ell_{max} = 500$. The standard deviation of f_{NL}, σ_{sim}, was obtained using Gaussian simulations.

Yadav, Komatsu, Wandelt, Liguori, Hansen, Matarrese Apj (submitted)

f_{NL} dependent Variance

- Using non-Gaussian simulations we find a f_{NL} dependent correction to the variance!
- In agreement with predictions by Creminelli, Senatore and Zaldarriaga 2007

$$\frac{\sigma^2}{\sigma_0^2} - 1 = \frac{2n^2}{\pi \ln^2(N_{pix})}$$

Using non-Gaussian simulations

Using Gaussian simulations

$$f_{NL} = n\,\sigma_0$$

- We are now ready to use **both the temperature and polarization data** from to constrain f_{NL}.
- Planck ready

Conclusions and Outlook

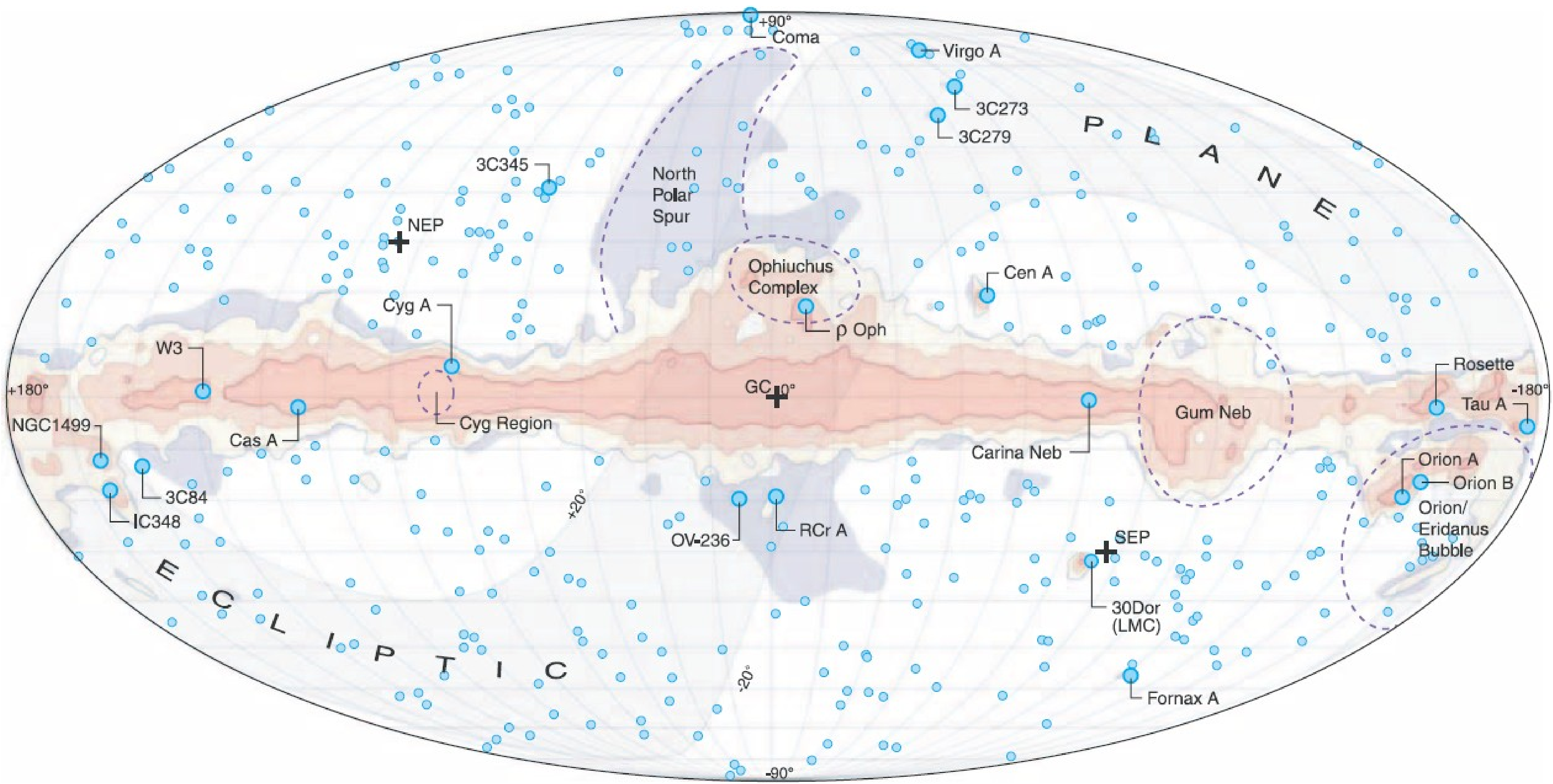
- "If our result holds up to scrutiny and the statistical weight of future data [...] we conclude that single field slow roll inflation is disfavored by the WMAP data."
- *Komatsu for WMAP team: "Independent analysis showed a similar level of f_{NL} local...."*
- Further tests should and will be done. This requires detailed look at dust and synchrotron foreground models.
  - *We are doing these tests and so far everything we have done confirms our results*
- Other bispectrum combinations can also be tested to test for non-specific vs specific non-Gaussianity.

Outlook

- New data to come soon! Forecasts:
  - WMAP 5 year: Δf_{NL} ~25
  - WMAP 8 year: Δf_{NL} ~21
- Δf_{NL} ~5 from Planck T and E polarization (in ~5 yrs!)

EXECUTIVE SUMMARY

- Detection of non-Gaussianity will give huge information about the early universe (class of inflationary models)
- Sensitivity goal $\Delta f_{NL} \sim 1$
- Current status: $\Delta f_{NL} \sim 30$ (using CMB T, Yadav, et. al. estimator)
  - Hints of primordial non-Gaussianity!!
- T and E polarization are complimentary
- With CMB T and E polarization: $\Delta f_{NL} \sim 5$ (within 5-10 yrs)
  - Fast estimator exists!
  - Estimator Tested against non-Gaussian simulations



+90°
Coma
Virgo A
3C273
3C279
P L A N E
3C345
North
Polar
Spur
NEP
Ophiuchus
Complex
Cen A
Cyg A
ρ Oph
W3
Rosette
+180°
GC 0°
-180°
Tau A
Cyg Region
Gum Neb
NGC1499
Cas A
Carina Neb
Orion A
Orion B
Orion/
Eridanus
Bubble
3C84
IC348
+20°
OV-236
RCr A
SEP
E C L I P T I C
30Dor
(LMC)
-20°
Fornax A
-90°

Q+V+W Channels

ℓ_{max}	f_{NL}			
	$f_{sky} = 94.2\%$ Kp12	$f_{sky} = 84.7\%$ Kp2	$f_{sky} = 76.8\%$ Kp0	$f_{sky} = 64.3\%$ **giant mask**
350	-2383.67	-75.16	24.91	8.32
450	-2791.83	-79.79	55.36	65.31
550	-3135.82	-93.49	65.57	79.93
650	-3307.15	-93.7	62.91	77.02
750	-3368.26	-108.23	64.75	78.35

V+W channels

ℓ_{max}	f_{NL}			
	$f_{sky} = 94.2\%$ Kp12	$f_{sky} = 84.7\%$ Kp2	$f_{sky} = 76.8\%$ Kp0	$f_{sky} = 64.3\%$ **giant mask**
350	-3145.22	-26.68	34.62	19.24
450	-1425.06	-15.63	67.94	64.69
550	-1509.92	-13.09	79.99	83.53
650	-1559.91	-22.43	79.18	81.29
750	-1575.11	-22.81	86.81	86.52