# Primordial Non-Gaussianity

August 28, 2008

Benjamin D. Wandelt
University of Illinois at Urbana-Champaign

# We now have a Standard Model of Cosmology!

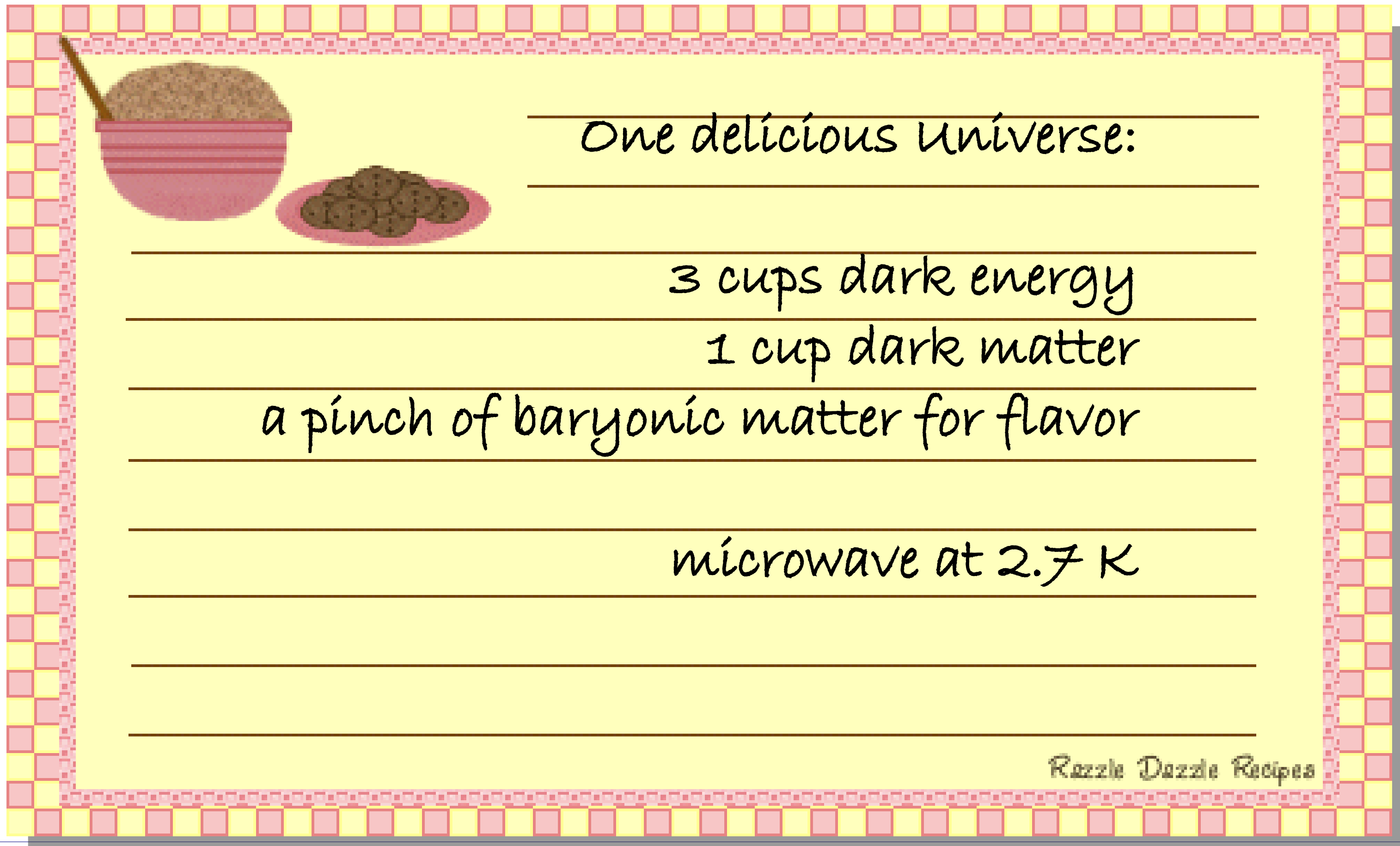
- Bad news for theorists:

  We now know the basic global properties of the Universe. The model correctly predicts (almost) all observed phenomena.

- Good news for theorists:

  We don't understand most of the constituents of the Universe.
  We don't know how it began

# How to make a Universe: the observer's recipe



# How to make a Universe: the theorist's view

One awesome inflationary Universe:

Use recipe below to make 4-D effective field theory.

Start with smooth patch + GR.

Let the field with the largest potential energy inflate patch while cooling. Reheat.

One 4-D effective theory:

Strings? 10 to 11 space-time dimensions.

Compactify to 4or 5 “large” dimensions, to taste.

How many branes in the Calabi-Yau? Where?

What causes inflation? Find effective 4-D description…

OR: set up parallel colliding branes. OR…

# How to make a Universe: the theorist's view

Dark matter recipes:

One awesome inflationary Universe:

Use recipe below to make 4-D effective field theory.

Start with smooth patch + GR.

Let the field with the largest potential energy inflate patch while cooling. Reheat.

One 4-D effective theory:

Strings? 10 to 11 space-time dimensions.

Compactify to 4 or 5 “large” dimensions, to taste.

How many branes in the Calabi-Yau? Where?

What causes inflation? Find effective 4-D description…

OR: set up parallel colliding branes. OR…

# How to make a Universe: the theorist's view

Dark energy recipes:

Dark matter recipes:

One awesome inflationary Universe:

Use recipe below to make 4-D effective field theory.

Start with smooth patch + GR.

Let the field with the largest potential energy inflate patch while cooling. Reheat.

One 4-D effective theory:

Strings? 10 to 11 space-time dimensions.

Compactify to 4 or 5 "large" dimensions, to taste.

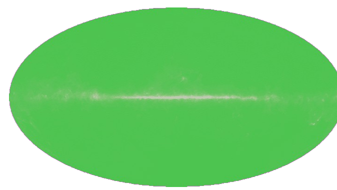
How many branes in the Calabi-Yau? Where?

What causes inflation? Find effective 4-D description...

OR: set up parallel colliding branes. OR...

# The Physics of the Beginning

- Why Homogeneity and Isotropy?

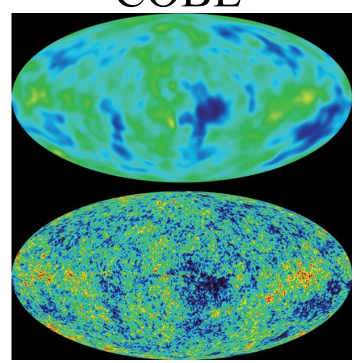


CMB

- Why Flatness?

- Whence
  seed perturbations?

COBE

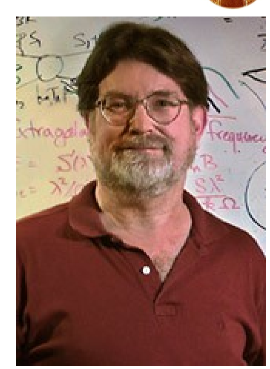


WMAP

1978 Nobel Prize
in Physics

Robert Wilson and Arno Penzias

**2006 Nobel Prize
in Physics**



**George Smoot**

**John C. Mather**

# Predictions of Standard Inflation

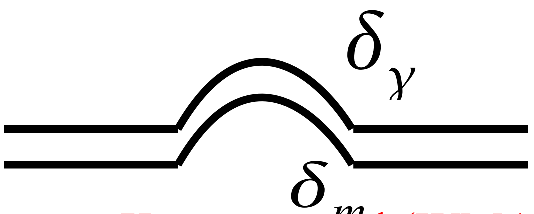
(i) Flat, homogeneous and isotropic

Komatsu et al (WMAP5) + e.g. HST: **~2%**

(ii) Seed perturbations:

*canonical models predict*

- Nearly adiabatic: $\frac{\delta \rho_i}{\dot{\rho}_i} = \frac{\delta \rho}{\dot{\rho}}$




Komatsu et al (WMAP5): **~10%**

- Close to Gaussian $\langle \Phi(\vec{k}) \Phi(\vec{k}') \rangle = P_\Phi(k) \delta^3(\vec{k} - \vec{k}')$

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

Komatsu et al (WMAP5): **a few percent.**

# CMB tests of inflation: Current Status

| Test | Std. Inflation | Ekpyrosis | Obs |
|---|---|---|---|
| • Is observable universe flat? | • Yes. | • Built in. | • Yes, to ~2% |
| • Do the fluctuations have the predicted correlations (nearly scale independent)? | • Yes. | • Yes. | • Yes, to few % |
| • Are fluctuation adiabatic? | • Yes. | • ? | • Yes, to ~10% |
| • primordial gravitational waves | • Maybe | • No | • ? |
| • **Are fluctuations nearly Gaussian?** | • **Yes: predicted to be true at 0.001%!** | • **Much higher deviations from Gaussianity** | • **Hints of deviation from Gaussianity from WMAP data!** |

**Yadav & Wandelt 2007**
**Komatsu et al. (WMAP5) 2008**

# Primordial perturbations and Gaussianity

- Slow-roll-> shallow potential-> nearly free field; has Gaussian quantum perturbations (field modes in S.H.O. potential). Theorem for single field.
- If multi-field, can have isocurvature perturbations that convert into non-Gaussian curvature perturbations outside horizon.
- Non-standard kinetic term: can inflate in spite of steep potential -> non-Gaussianity
- Standard choice of vacuum – can get flattened triangle contributions if not Bunch-Davies.

# Non-Gaussianity – a new frontier

- In addition to the information to be gained from 2-point correlations, non-Gaussianity opens a new window on the Physics of the Beginning.
- What is the program?
  - Reliable theoretical prediction of non-Gaussianity from models of the early Universe
  - Characterization of non-Gaussian confusion effects
  - Development of efficient and practical statistical methods to draw inferences about non-Gaussianity from the data.

# Our push at the frontier

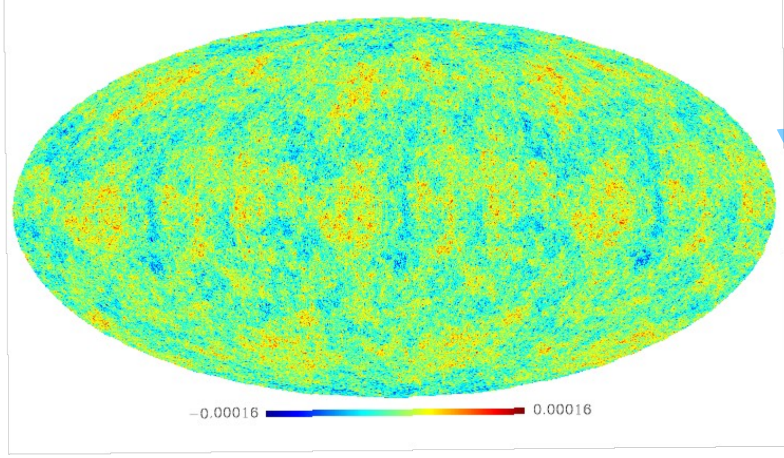
- How to search for primordial non-Gaussianity
- How to search for $f_{NL}$
- What we find
- How to interpret our result
- Future prospects

# 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

**CMB DATA $a_{lm}$**



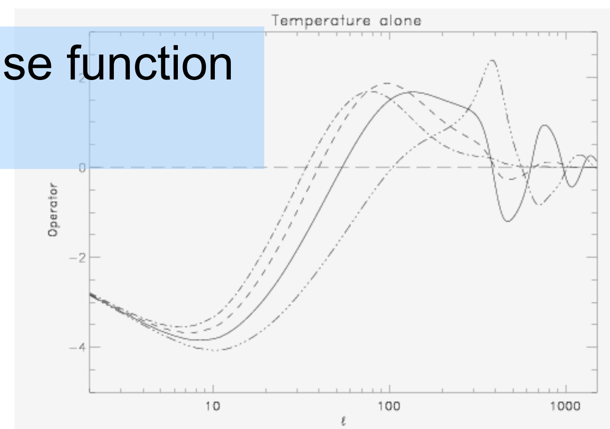

$\Phi_{lm} = O_l a_{lm}$

SW limit

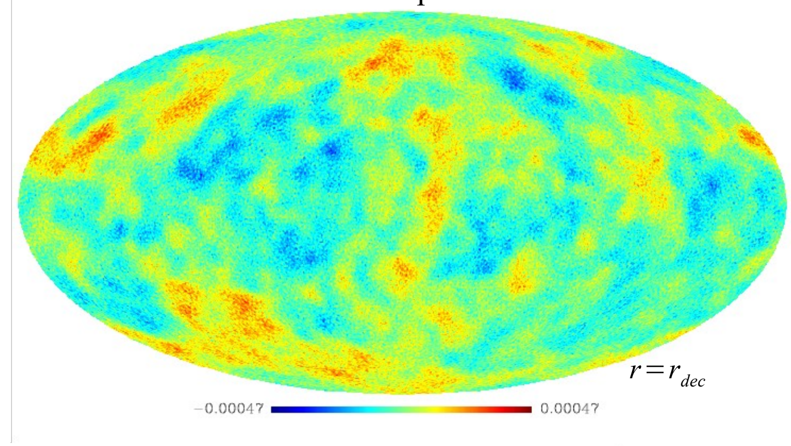
$$\frac{\delta\phi}{\phi} = -3\frac{\delta T}{T}$$

Response function

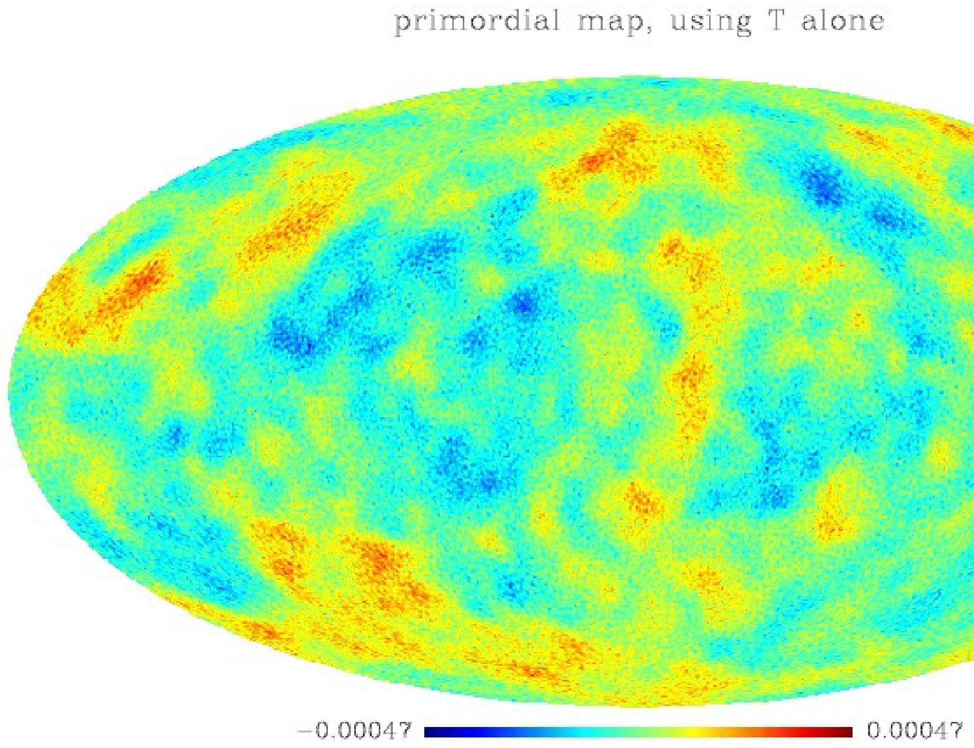
$O_l = \beta_l / C_l$



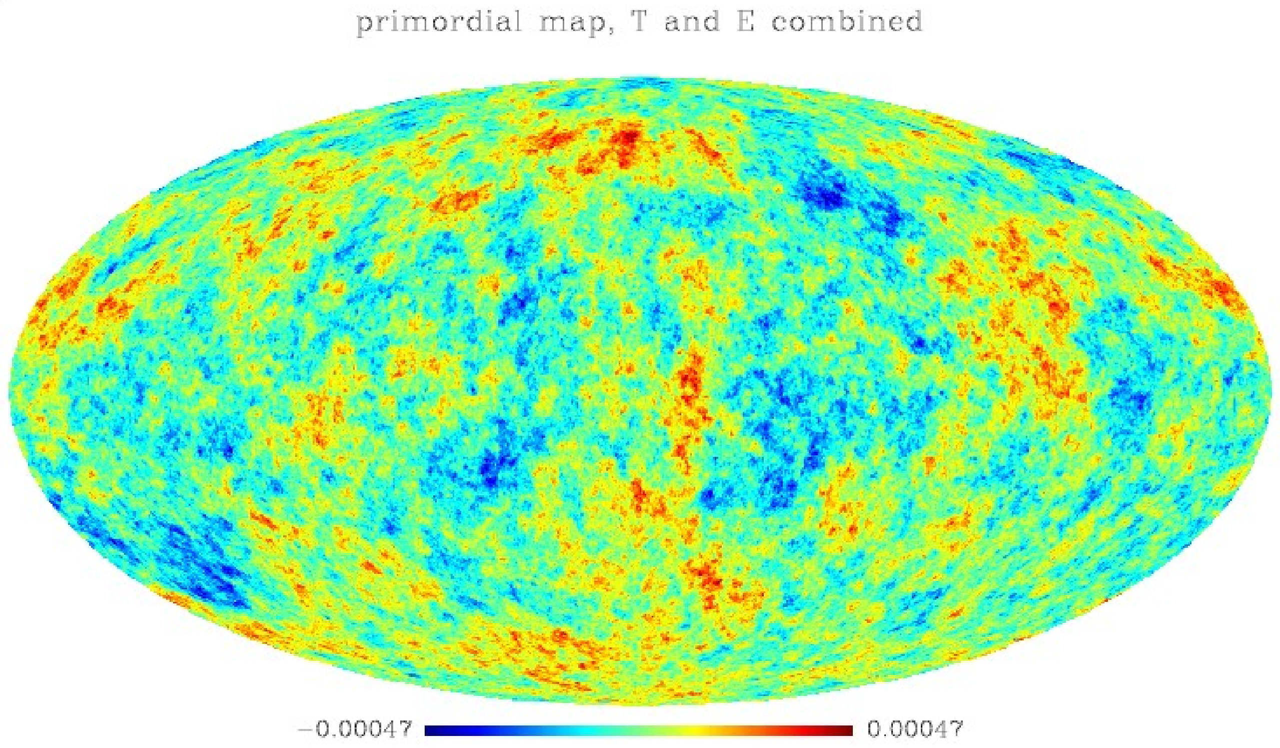

Reconstructed Primordial perturbations with T alone




$$\beta^i_\ell(r) = \frac{2b^i_\ell}{\pi}\int k^2 dk P_\phi(k) g^i_\ell(k)\, j_\ell(kr),$$

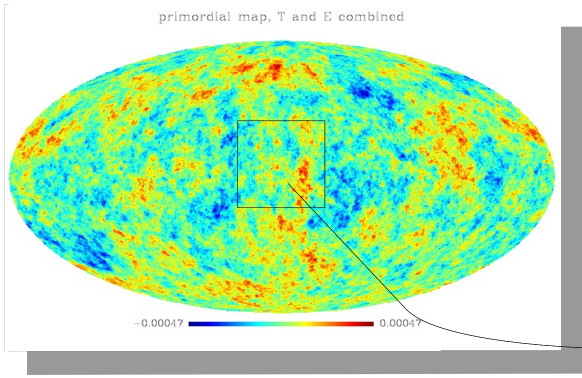



*Yadav, and Wandelt, PRD (2005)*

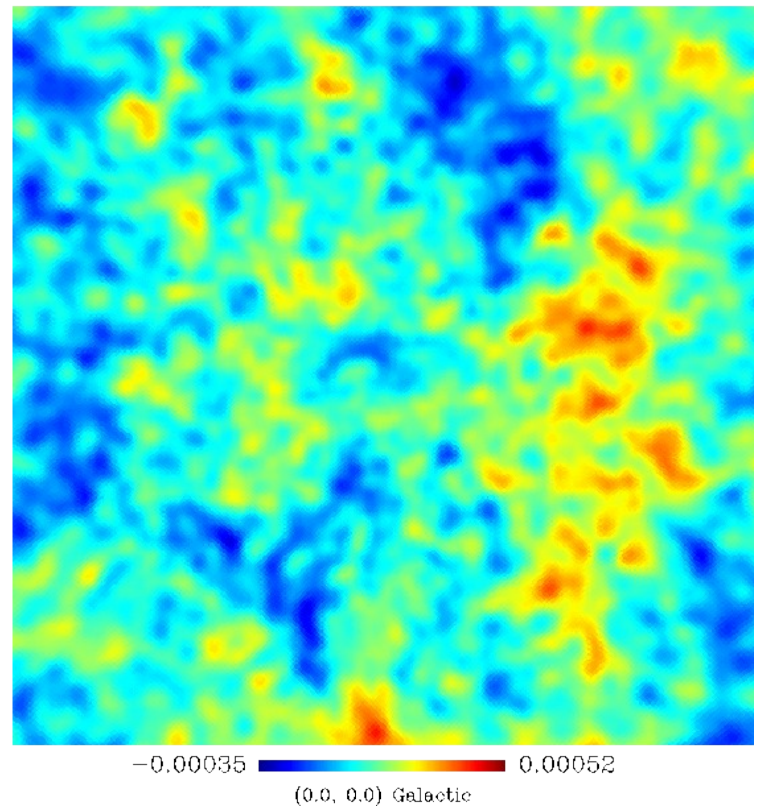


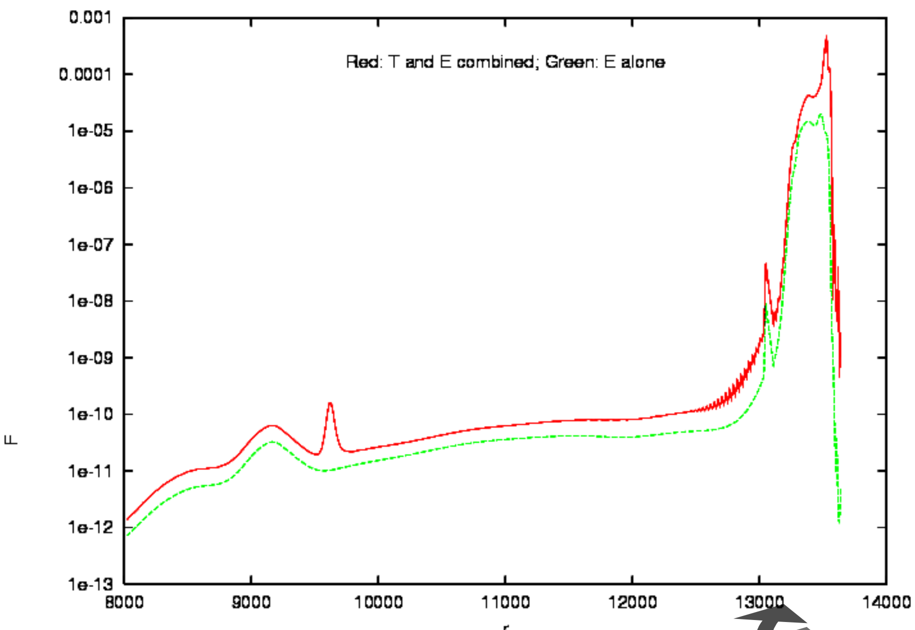

*Yadav, and Wandelt, PRD (2005)*

# Reconstructed perturbations at different radii




Curvature fluctuations



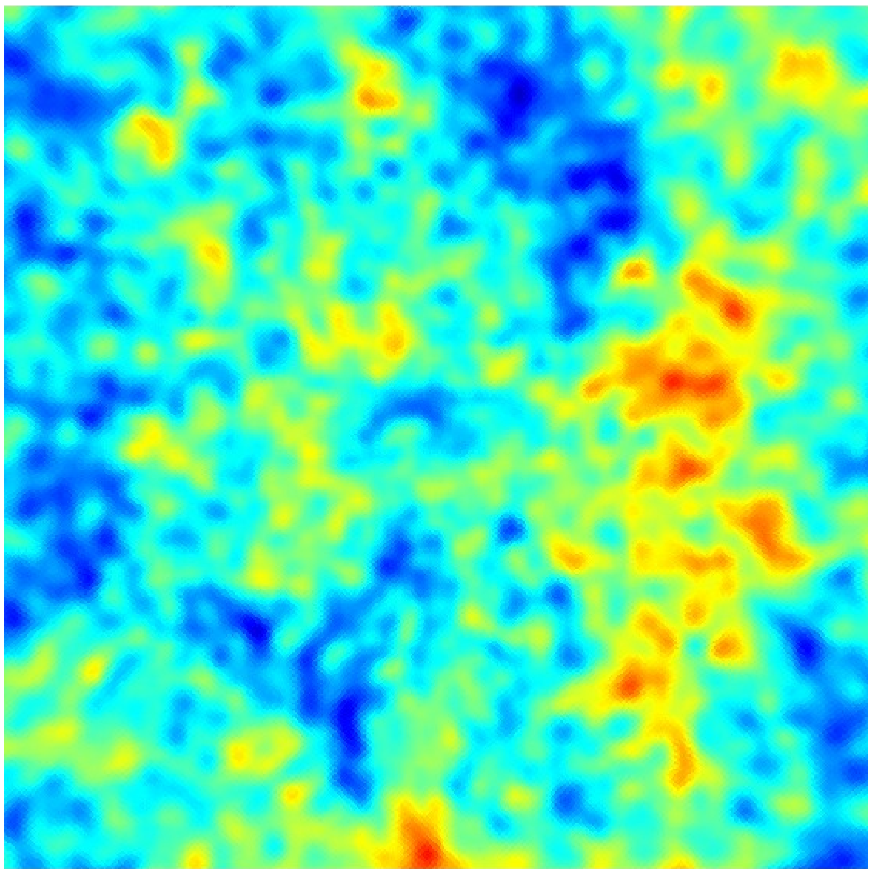




*Yadav, and Wandelt, PRD (2005)*

**Decoupling**

# Tomographic reconstruction of inflationary scalar curvature

Curvature fluctuations




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 and/or E data should do so using curvature perturbations obtained with our filters.

*Yadav and Wandelt 2006*

# $f_{NL}$ – a specific parameterization of non-Gaussianity

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

Salopek & Bond 1990
Komatsu & Spergel 2001

Characterizes the amplitude of non-Gaussianity

- This non-Gaussianity creates a bispectrum signature (as well as higher order moments)

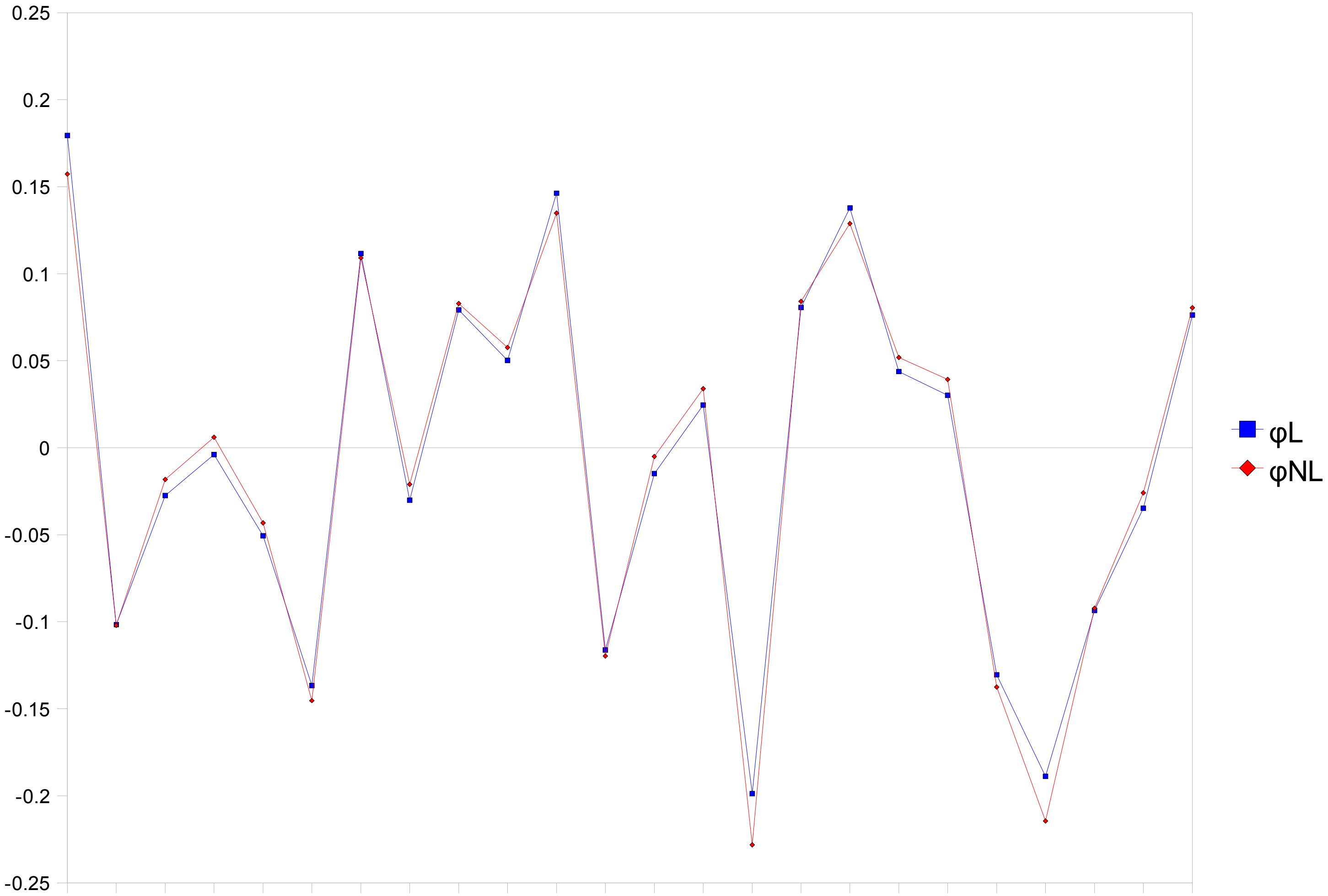
  $<\Phi(k_1)\Phi(k_2)\Phi(k_3)> = 2(2\pi)^3 f_{NL}\delta(k_1+k_2+k_3)P(k_1)P(k_2),$

  where $(2\pi)^3\delta(k_1+k_2)P(k_1) = <\Phi(k_1)\Phi(k_2)>$

- This translates into a bispectrum signature in the CMB through

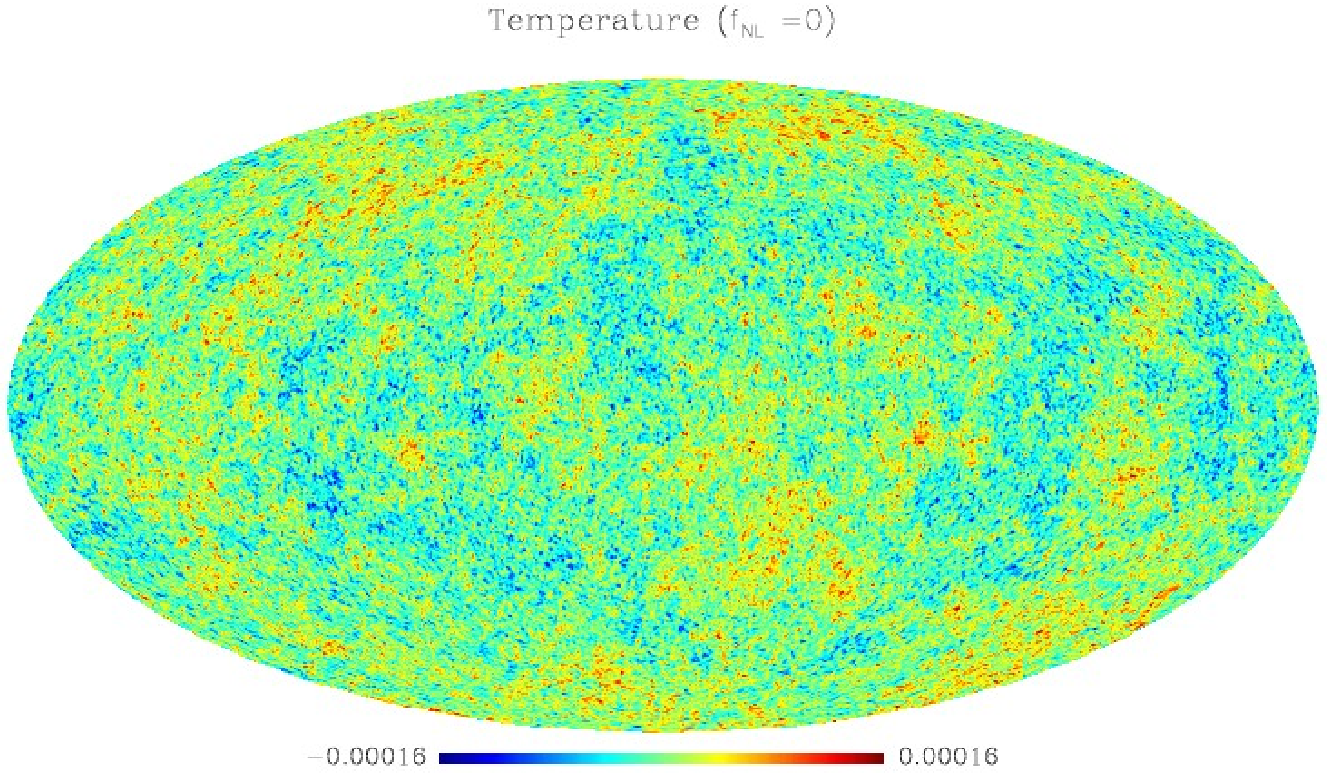
$$a_{lm} = 4\pi(-i)^l \int \frac{d^3\mathbf{k}}{(2\pi)^3}\Phi(\mathbf{k})g_{Tl}(k)Y^*_{lm}(\hat{\mathbf{k}})$$

# Statistics of local non-Gaussianity in the CMB



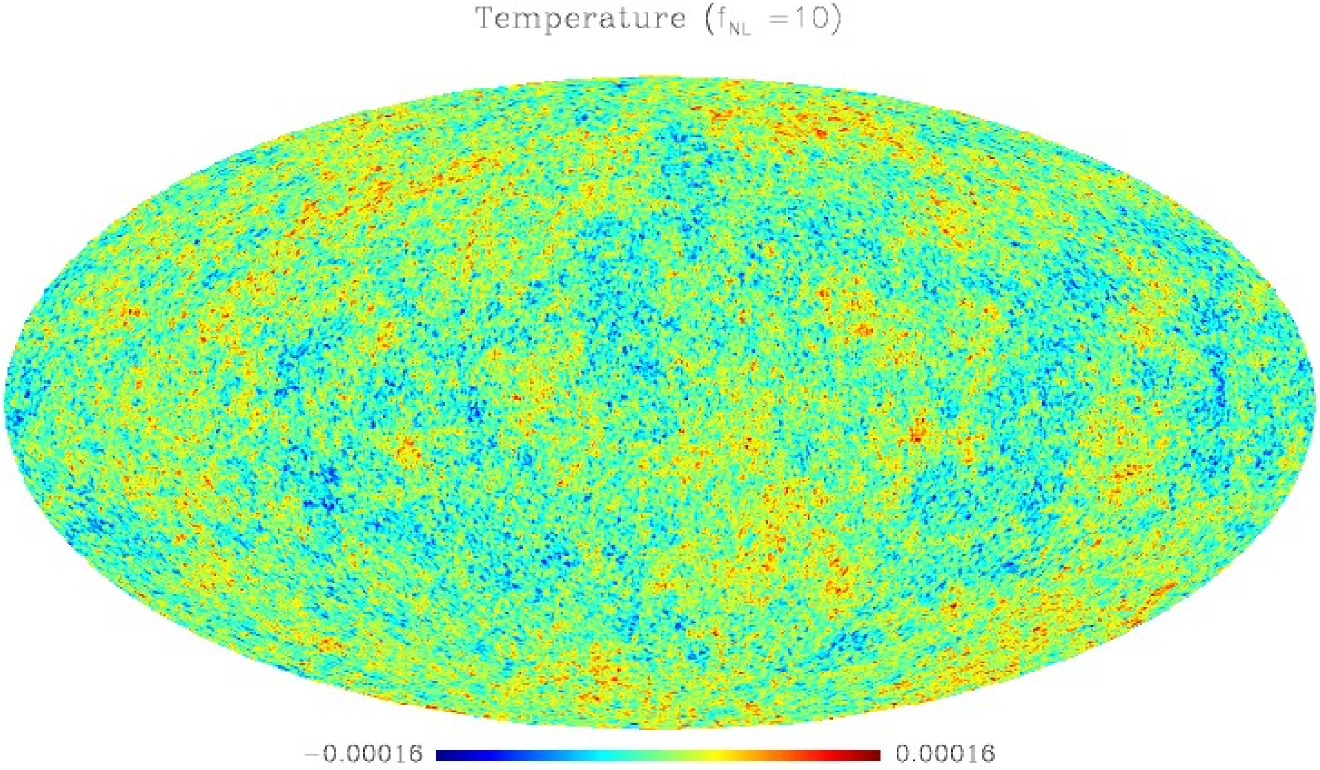

- Local non-Gaussianity smoothes hot spots and creates more structure in cold spots.

# $f_{NL} = 0$



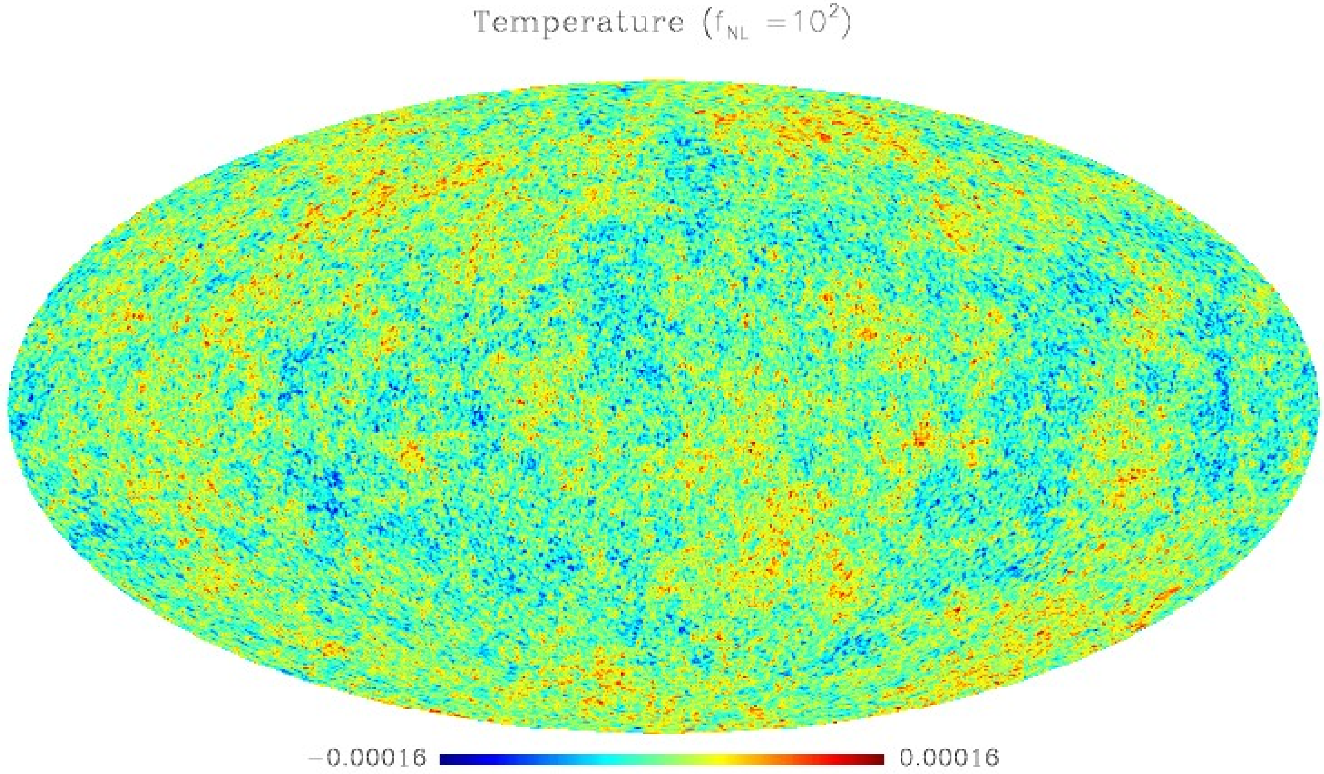

Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

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



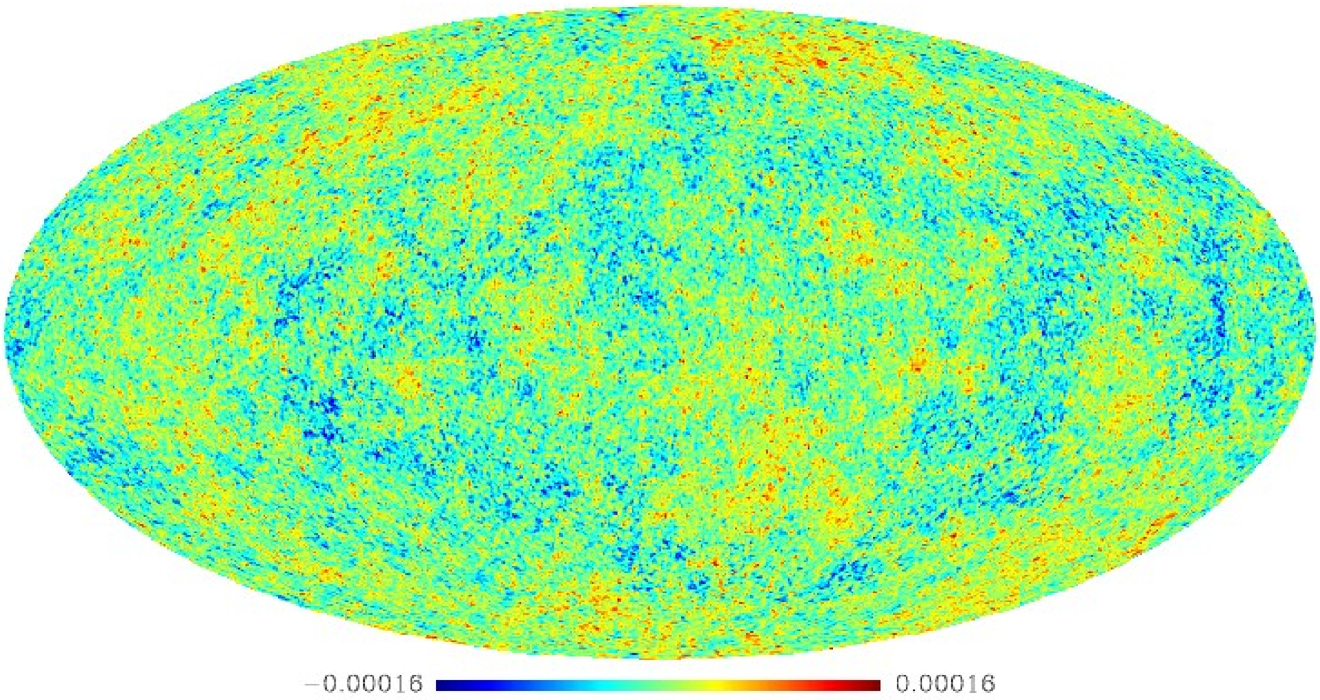

Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

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



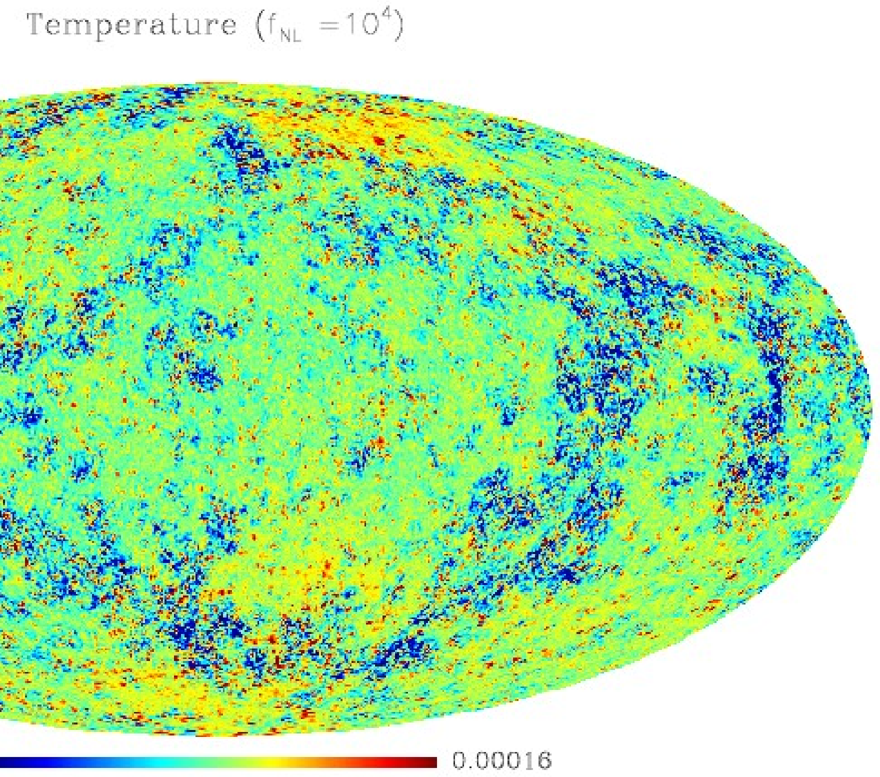

Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

$$f_{NL} = 10^3$$




Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

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




Liguori, Yadav, Hansen, Komatsu, Matarrese, Wandelt 2007

# Why use the bispectrum?

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

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

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): bispectrum contains nearly all the information about $f_{NL}$. Kogo&Komatsu: Trispectrum contains complementary information

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

# 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

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

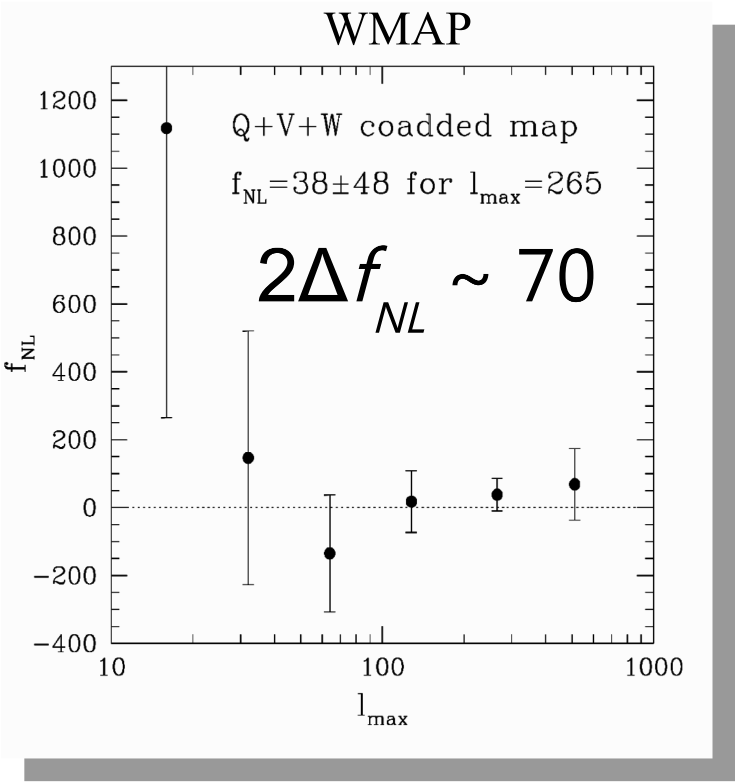
**B(r) is a map of reconstructed primordial perturbations**

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

**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 before December 2007




$-58 < f_{NL} < 137$ (95%) **WMAP 1yr**

$-54 < f_{NL} < 114$ (95%) **WMAP 3yr**

$-36 < f_{NL} < 100$ (95%) **Creminelli et. al. 2006 using WMAP3 data**

We are far from $\Delta f_{NL} \sim 1$ but can already start putting constraints on some models like DBI inflation, ghost inflation etc.

<u>Non-Gaussianity from Inflation</u>

$f_{NL} \sim 0.05$ canonical inflation (single field, couple of derivatives) (Maldacena 2003, Acquaviva etal 2003)

$f_{NL} \sim 0.1$--100 higher order derivatives

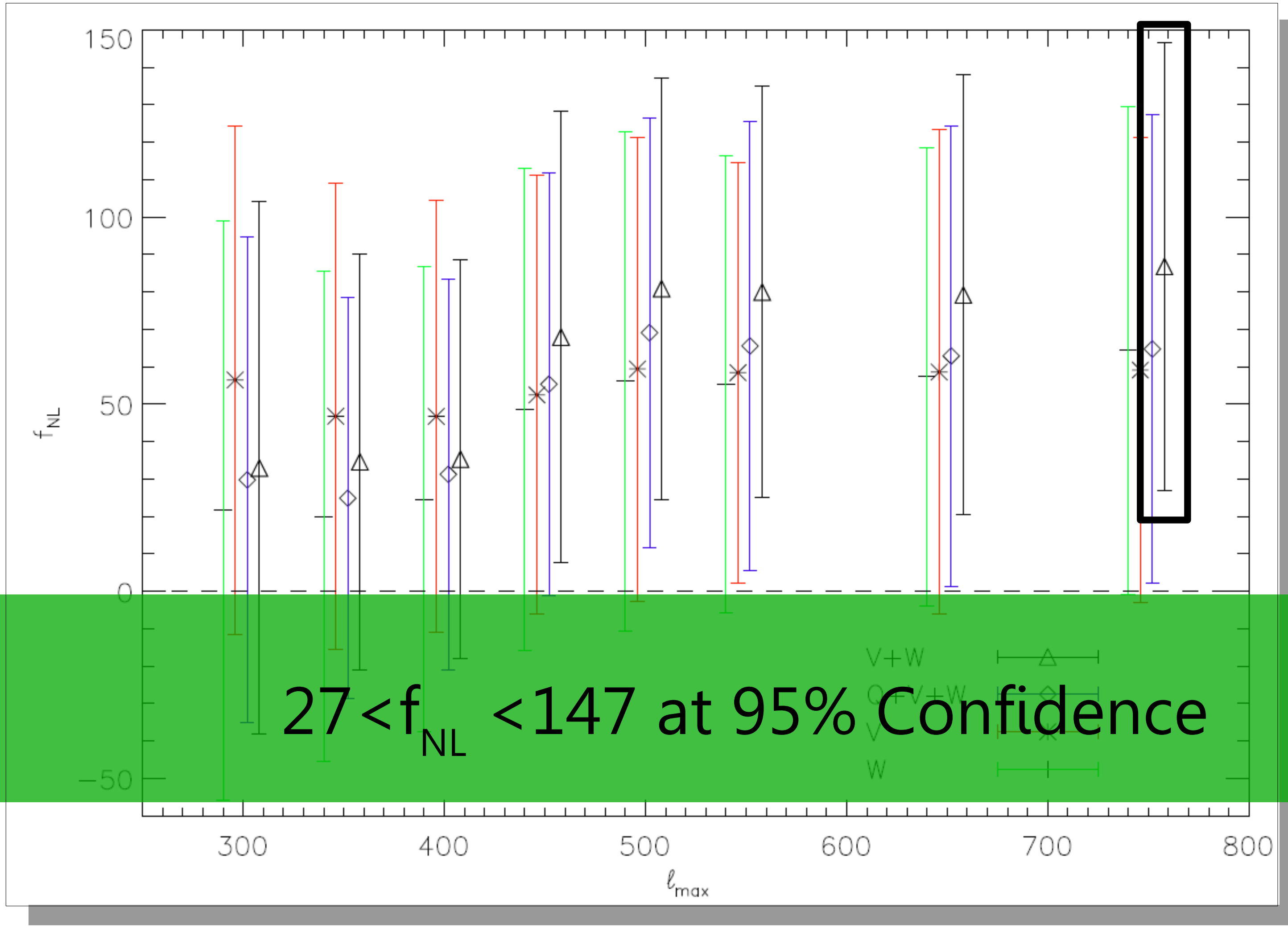
DBI inflation (Alishahiha, Silverstein and Tong 2004)

UV cutoff (Craminelli and Cosmol, 2003)

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

$f_{NL} \sim 100$ ghost inflation (Arkani-Hamed et al., Cosmol, 2004)

# Our result:




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

# Questions you might ask (and we did)

Might this result be due to…

- Known instrument systematic? **NO**
- Known Foregrounds? **NO**
- Secondary anisotropies? **($f_{NL}$~5)**
- Just rediscovery of other non-Gaussian signals? **NO**
- Noise fluctuation? Could be, P~0.01.

**Detailed analysis shows that standard inflation ($f_{NL}$~0) is disfavored by the data.**

# Noise fluctuation?

- Possible. Noise couples to any bispectrum form.
- It's a 2.5-2.8 sigma result. $P \leq 0.01$

  2.5 sigma when after conservative increase of error bar to model uncertainty in residual systematics

  [The most aggressive interpretation of the WMAP3 data would be a 3.3 sigma effect (correcting for negative foreground bias and using best fit WMAP parameters and $l_{max}$=750)]

# Summary of Yadav & Wandelt 2008

- ΔfNL ~ 30 for all of WMAP 3 using YKWLHM07 and WMAP best fit parameters (statistical)
- First bispectrum-based analysis of the full WMAP3 data
- First significant departure of fNL from 0 at >99% C.L.
- Estimators tested against Gaussian and non-Gaussian simulations with and without inhomogeneous noise
- If any bias, it is likely to be negative.
- 2.5-2.8 sigma, depending on choices and assumptions

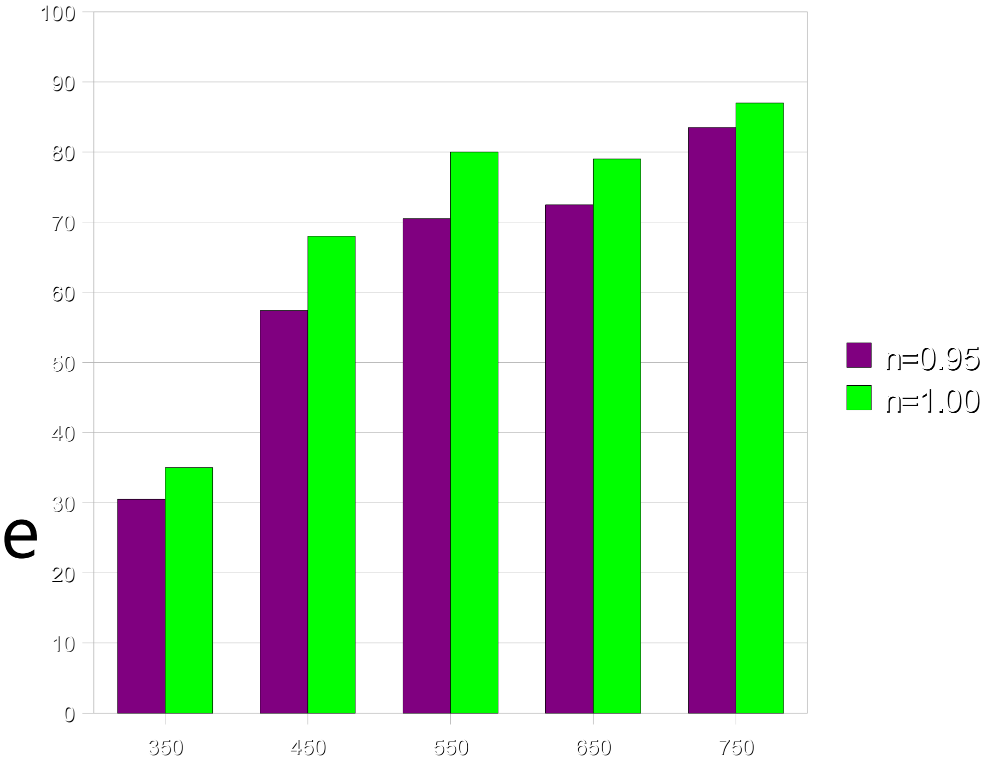
# WMAP 5-year analysis

- Komatsu et al. 2008
- Differences to our analysis:
  - mask shape that enhances the statistical error compared to the 3-yr mask;
  - stop at $l_{max}$=500
  - Different background cosmology
  - subtract generous estimate of point source bias.

- Quoted result: $f_{NL}^{local}$ = 51+/- 60 (95%)
- Significance: 1.7 sigma
- 2.3 sigma for most similar case to our analysis

# Sensitivity to assumed cosmology

- The filters depend weakly on assumed cosmology. We used n=1.
- Choosing n=0.95 reduces the error bars by 10%, and reduces the central values between 5% and 15%.
- At $l_{max}$=750, significance *increases* to just over 3 sigma; at lower $l_{max}$ significance *decreases a little.*



# WMAP 5 year constraint on $f^{equil}$

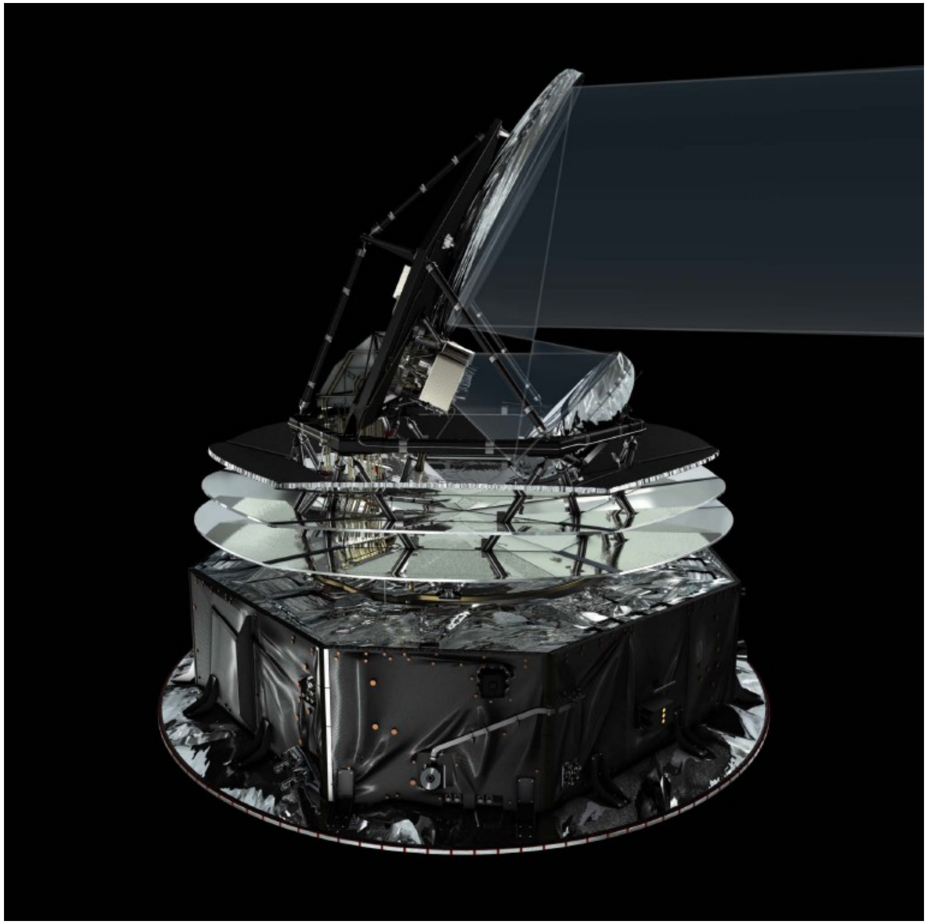
$$-151 < f_{NL}^{equil} < 253; \quad \Delta f_{NL}^{equil} = 201$$

- Of interest for DBI inflation, ghost condensation

(for reference: Planck should get $\Delta f_{NL}^{equil} \sim 35$)

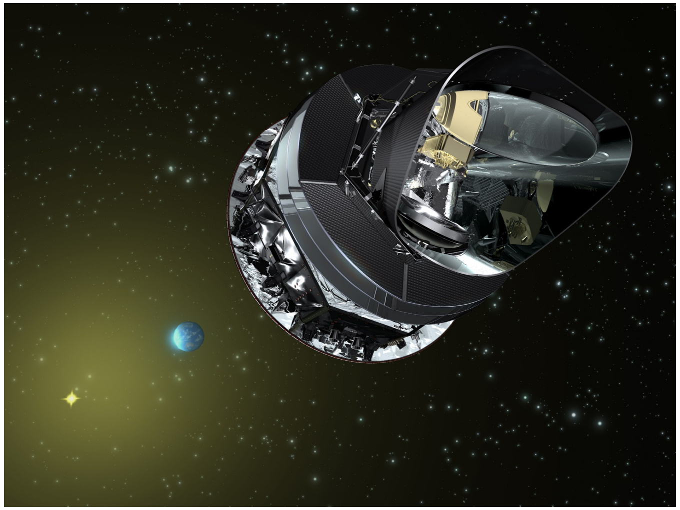
# The future

- Planck is a major joint ESA/NASA mission to L2.
- Principal scientific goal:
  - to make definitive all-sky maps of CMB temperature anisotropy down to 5' resolution.
- Two instruments:
  - Low Frequency Instrument (PI: Reno Mandolesi)
  - High Frequency Instrument (PI: Jean-Loup Puget)
- Temperature measurement at 9 frequencies
  - 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz
- Polarization measurement at 7 frequencies
  - 30, 44, 70, 100, 143, 217, 353 GHz
- **Detailed Planck Science Case in the "Blue Book." Google it.**



# Launch

- Planck will launch in months, not years!
  - Current launch date January – February 2009.
- Dual launch with Herschel on an Ariane 5 rocket
- Then cruise to L2

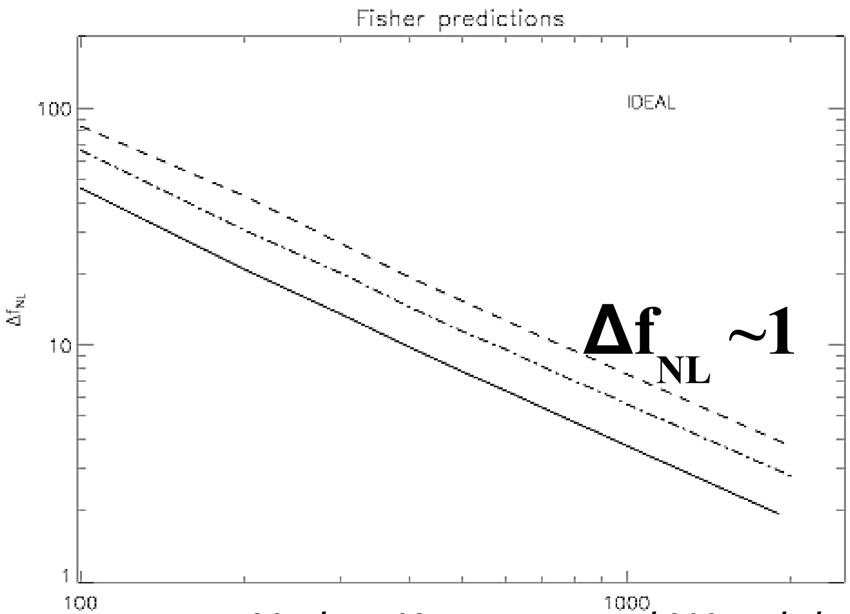


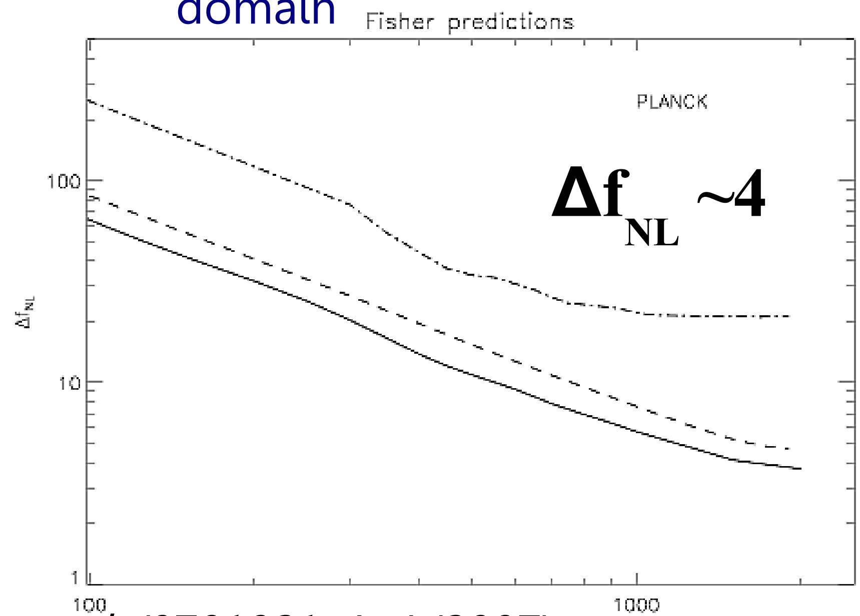
# Schedule

- Launch
  - ~February 2009?
- Cruise and checkout
  - ~3 months
- Two sky surveys
  - +12 months = L + 15
- Release of Early Release Compact Source Catalog
  - Based on first sky survey
  - L + 19 ( = September 2010?)
- Two more sky surveys (assuming mission extension approved by ESA)
  - + 12 months = L + 27 ( = May 2011?)
- Public release of 1-year data, first set of papers
  - L + 3 months + 3 years ( = May 2012?)
- Public release of 2-year data, etc, TBD.

# Planck's promise for Non-Gaussianity

- Many modes
  - large sky coverage
  - high resolution
- Frequency coverage
  - foreground removal
- Polarization
  - complementary to T
  - adds a great deal of information
- Multiple sky coverages
  - control of systematics in time-domain

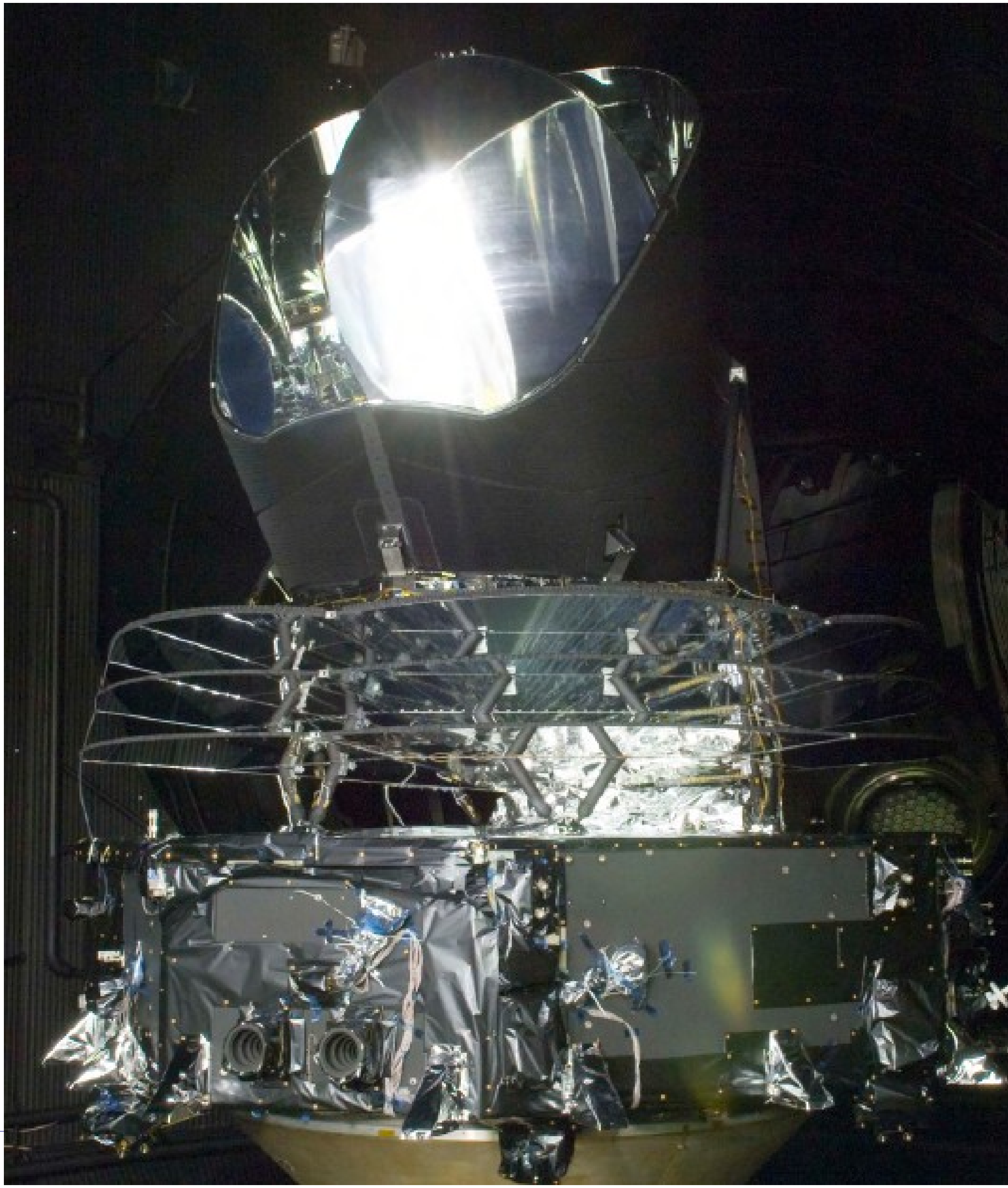



*Yadav, Komatsu and Wandelt, astro-ph/0701921, ApJ (2007)*

# The hope of doing NG with Planck

- One of the main outcomes of Yadav and Wandelt 2008:
  - Search for primordial NG using bispectrum templates is *much more robust* than was previously realized.
- Temperature and Polarization are complementary and can give independent and combined constraints.
- The radiation transfer functions give the bispectrum of primordial non-Gaussianity a very different signature from late time secondary effects, foregrounds, or non-Gaussian systematics.
- Expect that this robustness will make studying non-Gaussianity with Planck *possible* but not *easy.*



# Non-Gaussianity and Planck

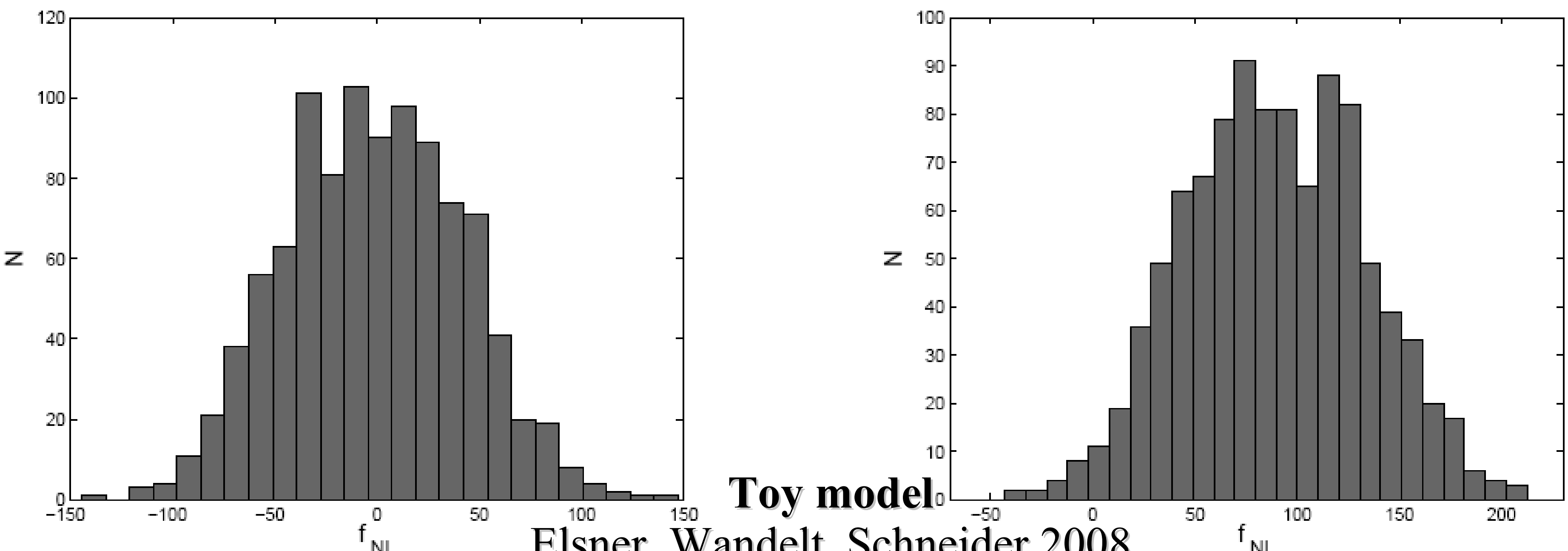
- Non-Gaussianity with Planck will be a new window on the early Universe, complementary to the wealth of information in the two-point function.
- Different early Universe models have distinct predictions for the type and amount of non-Gaussianity expected.
- Ekpyrotic/Cyclic models generically predict non-Gaussianity at detectable levels for Planck (Leners&Steinhardt 2008)
- The search for non-Gaussianity is complementary to the search for primordial gravitational waves
  - Primordial B-modes are the "smoking gun" of inflation
  - Finding primordial non-Gaussianity would rule out all single-field models of slow-roll inflation
- Planck will improve WMAP non-Gaussianity error bars by nearly on order of magnitude

# The challenge(s) of constraining NG with Planck

- Higher signal-to-noise requires understanding systematics at a much better level than WMAP
- Secondary anisotropies at Planck signal/noise
  - ISW-lensing bispectrum
  - SZ-lensing bispectrum
  - point sources
  - all triplets of second order effects...
- Foregrounds
  - Diffuse Galactic foregrounds
  - Unresolved Galactic and extra-Galactic point sources
- Instrument systematics
- Optimality of estimators
  - Fast estimators are better for smooth masks (have demonstrated near-optimality)
  - Planck's observing strategy

# Next generation $f_{NL}$ statistics: Fully Bayesian non-Gaussianity analysis

- Instead of going via the bispectrum, build full statistical model of the data, including non-Gaussianity, and a detailed model of the observations and systematics
- Returns the full $P(f_{NL}|data)$

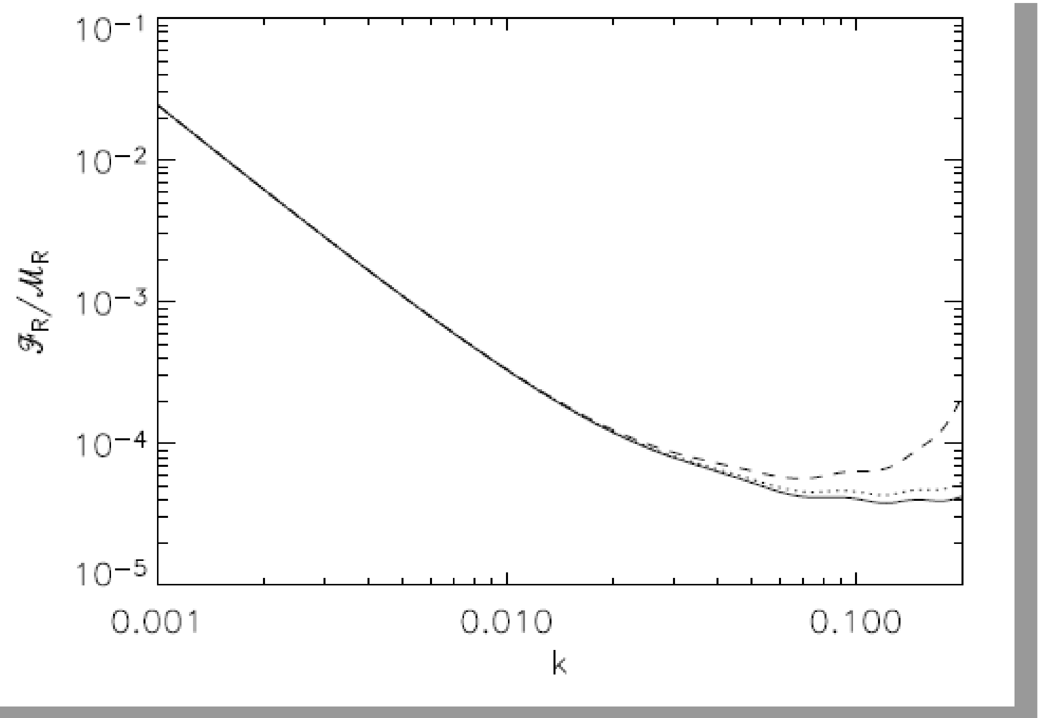



**Toy model**

Elsner, Wandelt, Schneider 2008

# $f_{NL}$ from large scale structure

- Halo mass function: Verde, Matarrese, Jimenez (2000); LoVerde, Miller, Shandera & Verde (2007)
- Halo correlations: Dalal et al. (2007) and Verde & Mattarrese(2008) find a universal, scale dependent bias on *large* scales.
- Afshordi (2008): *$f_{NL}$=240 +/- 120 from CMB/LSS X-correlations* Ho et al 2008
- Sloszar et al 2008: -29(-85)<f_nl<+70(+90) at 95% (99.7%)
- Ultimately, $\Delta f_{NL}$~5 ?



# NG status summary

- Yadav&Wandelt (2008) and Komatsu et al (2008) see 2.5-2.8 sigma and 1.7-2.3 sigma hints of local NG in the WMAP 3-year and 5-year data, respectively.
- Tightest LSS constraints consistent with CMB constraints (Sloszar et al 2008)
- Further analysis of the WMAP 5 year data continues

# Conclusions

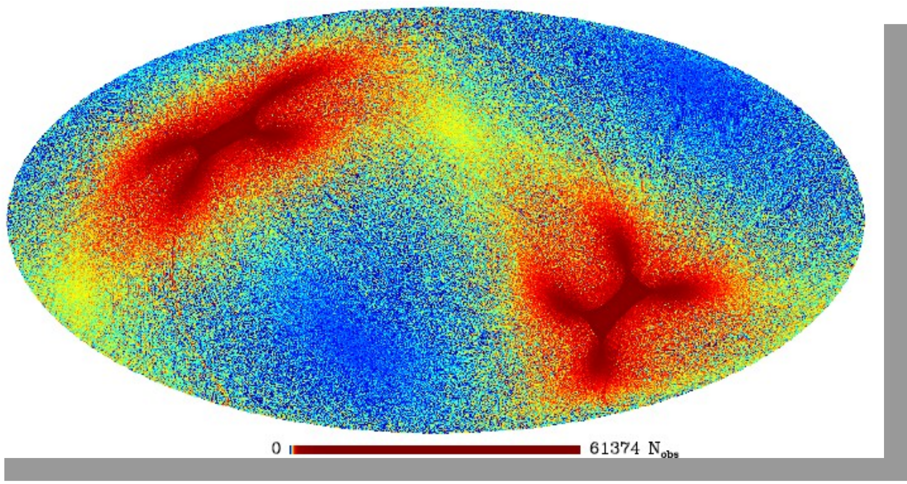
- Non-Gaussianity is a powerful probe of the physics of the beginning
- In combination with power spectrum very powerful test of inflation and its alternatives
- Currently the *highest precision* test of inflation
  - Non-Gaussianity is a ~0.1% test
  - flatness in second place ~1.5%
- A way to distinguish between classes of models that give similar predictions for the two-point correlations
- Already starting to rule out significant portions of parameter space, for inflation as well as cyclic/ekpyrotic/new ekpyrotic models.
- WMAP 8 and Planck are on the way.
- A new, exciting and fast-moving frontier

# $f_{NL}$ phenomenology from the bispectrum

- Komatsu & Spergel 2001 – CMB bispectrum from $f_{NL}$
- Komatsu, Wandelt, Spergel, Banday, Gorski 2001 – $f_{NL}$ from COBE
- Komatsu Spergel & Wandelt 2003 – fast $f_{NL}$ estimator
- Komatsu et al (WMAP team) 2003 – WMAP1 analysis using KSW
- Babich and Zaldarriaga 2004 – temperature + polarization
- 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
- Yadav & Wandelt 2005 – tomography of the curvature perturbations
- 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
- Komatsu et al 2008 – application of YKWLHM07 to WMAP5

# Anisotropic sky coverage

- The KSW and YKWLHM estimators 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 estima (Creminelli et al. 2005)

$$\hat{S}^{linear}_{prim} = \frac{-3}{f_{sky}} \int r^2 dr \int d^2\hat{n} \left\{ B(\hat{n},r) S_{AB}(\hat{n},r) + S_{BB}(\hat{n},r) A(\hat{n},r) \right\}$$

- 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.

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

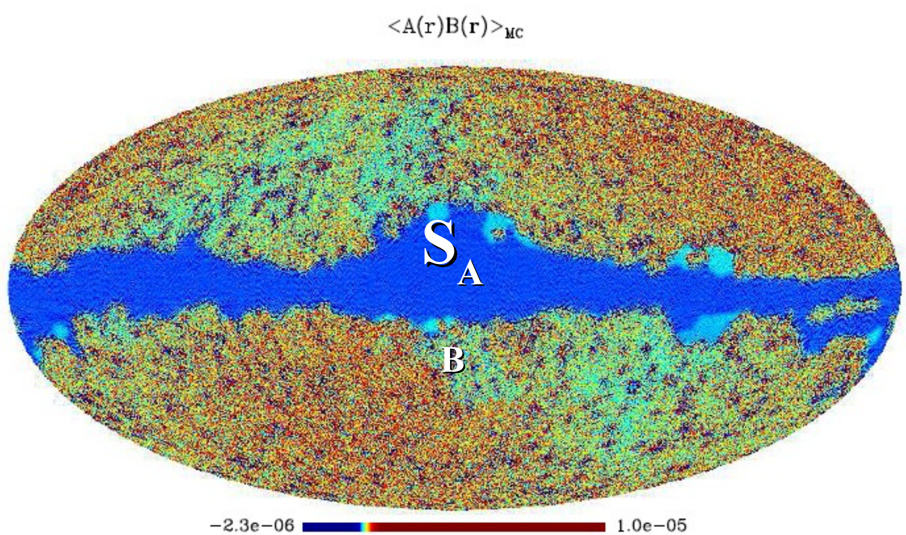
$$B(\hat{n},r) \equiv \sum_{ip} \sum_{lm} (C^{-1})^{ip} a^i_{\ell m} \beta^p_\ell(r) Y_{\ell m}(\hat{n})$$

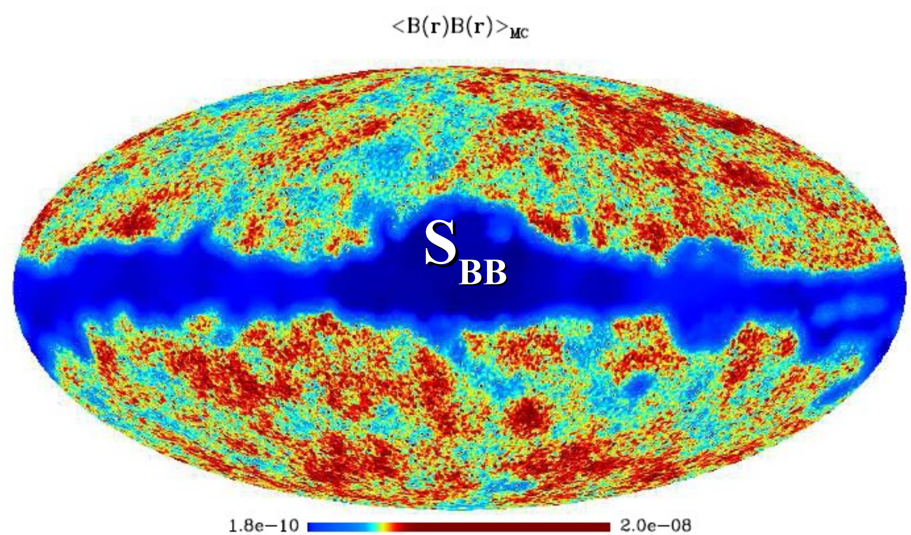
# Anisotropic noise

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

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

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



# Instrument systematics?
# I) Beam asymmetries

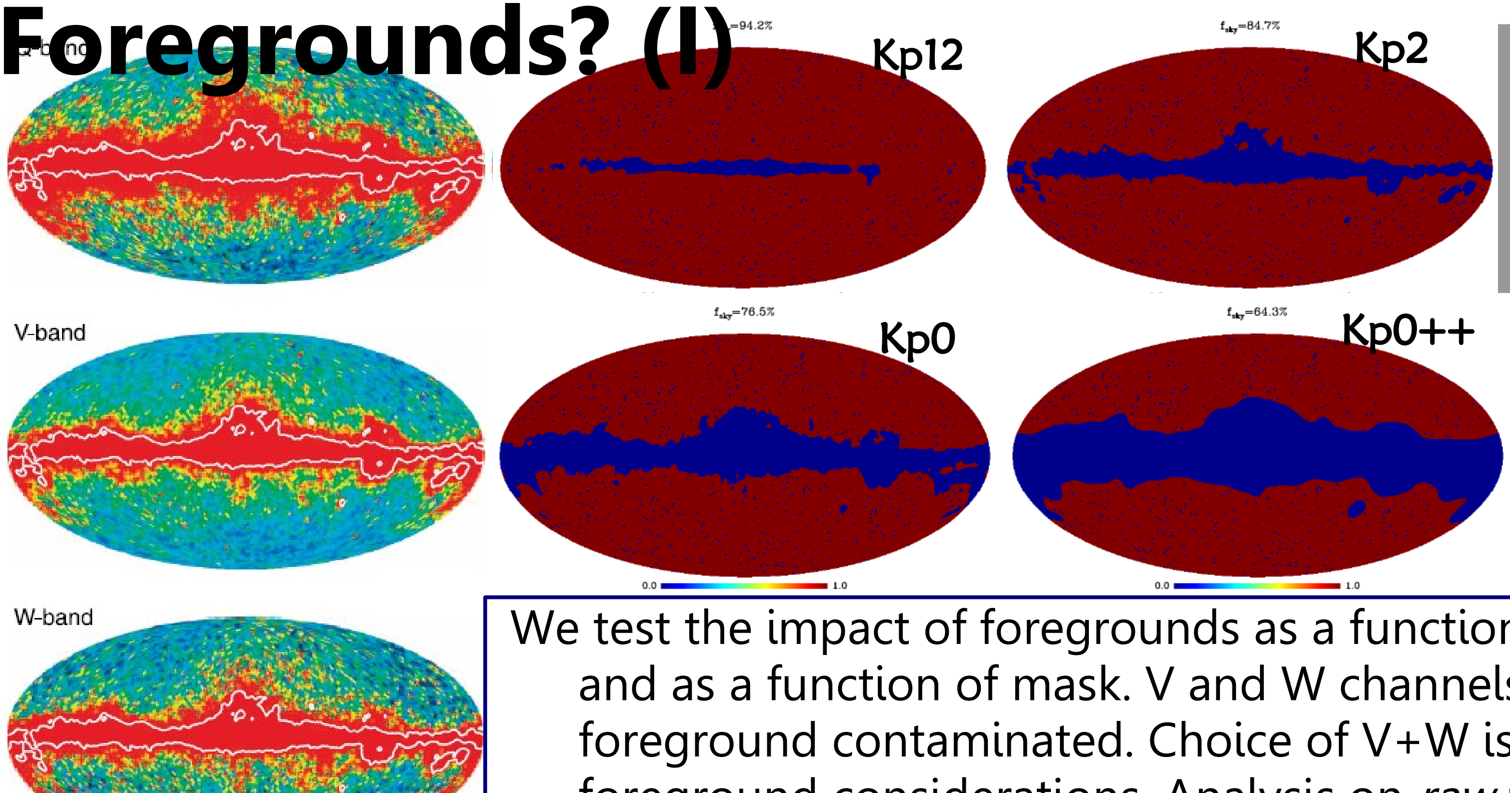
- If the CMB is Gaussian, no asymmetry of the main beam can produce non-vanishing bispectrum.

- 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. Further, we do not see evidence for frequency dependence.

# Instrument systematics? II: WMAP Noise

- Noise correlations (striping)
  - As long as noise is Gaussian, **no** noise correlations will produce a bispectrum.
- Non-Gaussian noise?
  Analyzed differences of WMAP yearly maps
  - year1-year2 $f_{NL}$=1.1 (+/- ~60 at 95% C.L.)
  - year2-year3 fNL=1.8
  - year1-year3 fNL=-3.4
- So to explain our results an instrumental systematic has to be 1) non-Gaussian, 2) the same in individual years and 3) mimic the specific bispectrum signature of $f_{NL}$.

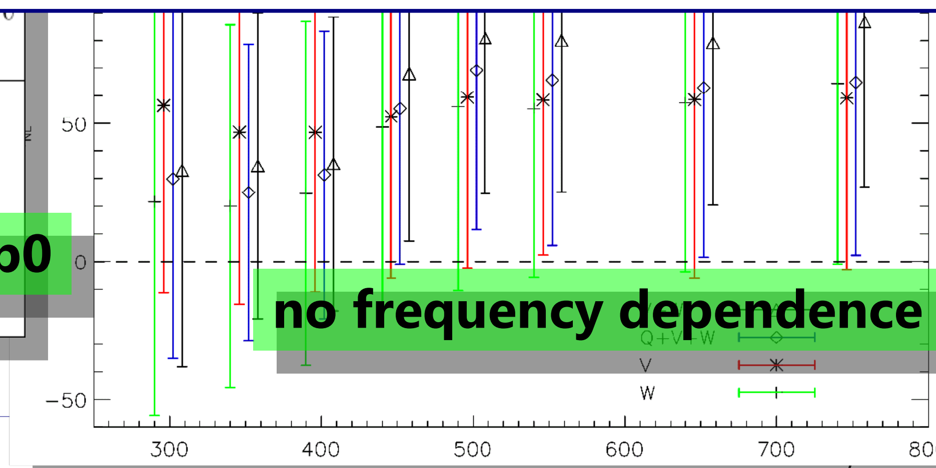
# Foregrounds? (I)




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. Analysis on *raw* maps to avoid FG oversubtraction.

| $\ell_{max}$ | $f_{sky} = 94.2\%$ Kp12 | $f_{sky} = 84.7\%$ Kp2 | Kp0 | |
|---|---|---|---|---|
| 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 | [illegible] | [illegible] |
| 750 | -1575.11 | -22.81 | 86.81 | 86.52 |

**stable beyond kp0**




**no frequency dependence**

# Foregrounds? (II)

- WMAP raw maps vs WMAP cleaned maps
  - Foreground subtracted maps do not show negative $f_{NL}$ behavior
  - Same level of $f_{NL}$, uniformly higher for FG subtracted maps
  - We quote the result from raw maps to be conservative and because the cleaned maps could contain *oversubtracted* foregrounds giving a positive bias.

# Foregrounds (III)

- Simulations ofGaussian CMB + Foregrounds + WMAP Noise
  - negative for smaller masks
  - goes to zero by the time you reach Kp0 mask
  - is consistent with zero for masks greater than kp0

| $\ell_{max}$ | VW | | | | Q | QVW | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Kp12 | Kp2 | Kp0 | Kp0+ | Kp0 | Kp12 | Kp2 | Kp0 | Kp0+ |
| 350 | -1290 | -27 | 35 | 19 | 1 | -2384 | -75 | 25 | 8 |
| 450 | -1425 | -16 | 68 | 65 | -6 | -2792 | -80 | 55 | 65 |
| 550 | -1510 | -13 | 80 | 84 | -11 | -3136 | -94 | 66 | 80 |
| 650 | -1560 | -22 | 79 | 81 | -14 | -3307 | -94 | 63 | 77 |
| 750 | -1575 | -23 | 87 | 87 | -20 | -3368 | -108 | 65 | 78 |
| $750^{\star}$ | $-1105\pm^{19}_{19}$ | $-42\pm^{5}_{5}$ | $-6\pm^{4}_{4}$ | $-0.3\pm^{4}_{4}$ | | | | $-13\pm^{5}_{5}$ | $1\pm^{6}_{6}$ |

# Secondary Anisotropies?

- Point sources, including SZ
  - Orthogonal overlap with primordial bispectrum. Bias of
    $|f_{NL}|<1|$. SZ and point sources have opposite signs. X
- Serra and Cooray (arxiv:0801.3276)
  - dominant secondary confusion level to WMAP bispectrum arises from
    - ISW-lensing bispectrum (positive bias)
    - SZ-lensing bispectrum (negative bias)
  - **If $f_{NL}$=20** effective bias around 10%. **Negligible** for $f_{NL}$>20, because effects add in quadrature. X

# Re-discovery of another non-Gaussian signal?

- Larson/Wandelt (hot and cold spots not hot or cold enough):
  - at smaller angular scales
  - symmetric-> no odd correlation. Probably noise model. X
- The Cold Spot (Vielva et al. 2004) is localized in the map and covers a particular range in scale. Preliminary result: $\mathbf{f_{NL}=94\ +/\text{-}60\ (95\%\ C.L.)}$ X
- Large Scale anomaly? Can check by removing large scale signal. Preliminary result: X

  **Removing l<21, $\mathbf{f_{NL}=135\ +/\text{-}96\ (95\%\ C.L.)}$**

# WMAP 5 year continued…

- A ***very preliminary*** result by K. Smith et al., obtained at the Perimeter Workshop in March:

$$f_{NL}^{local} = 21 +/- 44 \ (95\%)$$

- Note that this uses the exact same data as the WMAP 5, so the difference is entirely due to different weighting in the estimator.
  - Smaller error bar due to optimal weighting
  - This remains to be checked and the differences remain to be understood – no news since then.