Expectations for Planck and beyond

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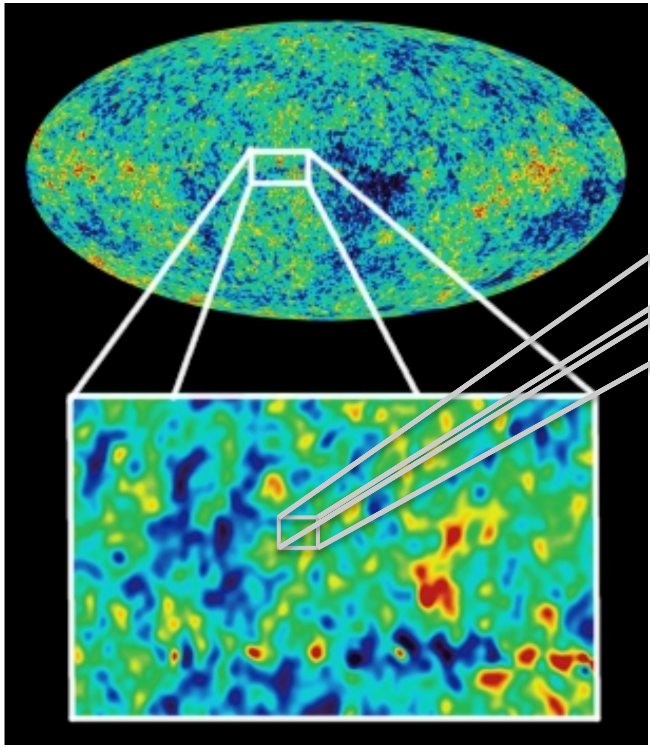
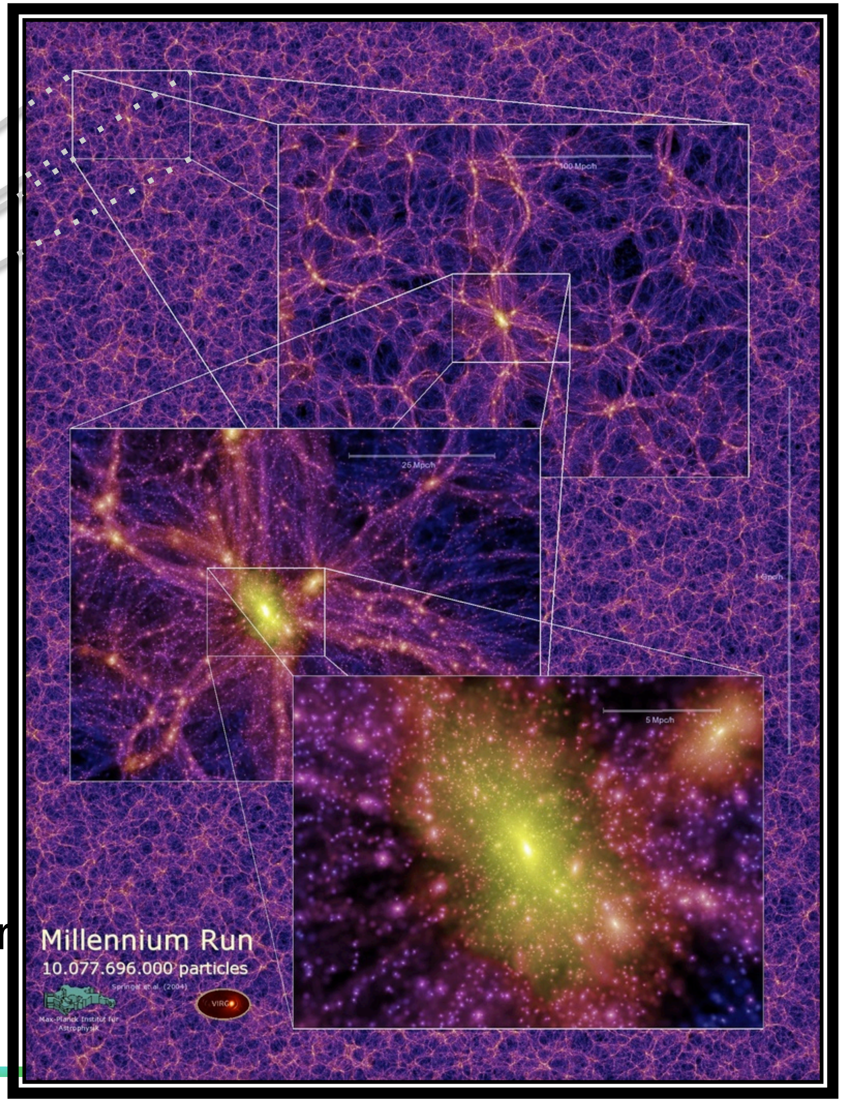
Outline

- The Planck mission

Inference from Large Scale Structure: the Big Picture



Primordial perturbations as seen in the Cosmic Microwave Background anisotropies (WMAP)



Dark matter distribution today (simulated)

Why Non-Gaussianity?

- Primordial non-Gaussianity is a separate window on the very early Universe

- In combination with power spectrum a powerful limit on inflationary model space.

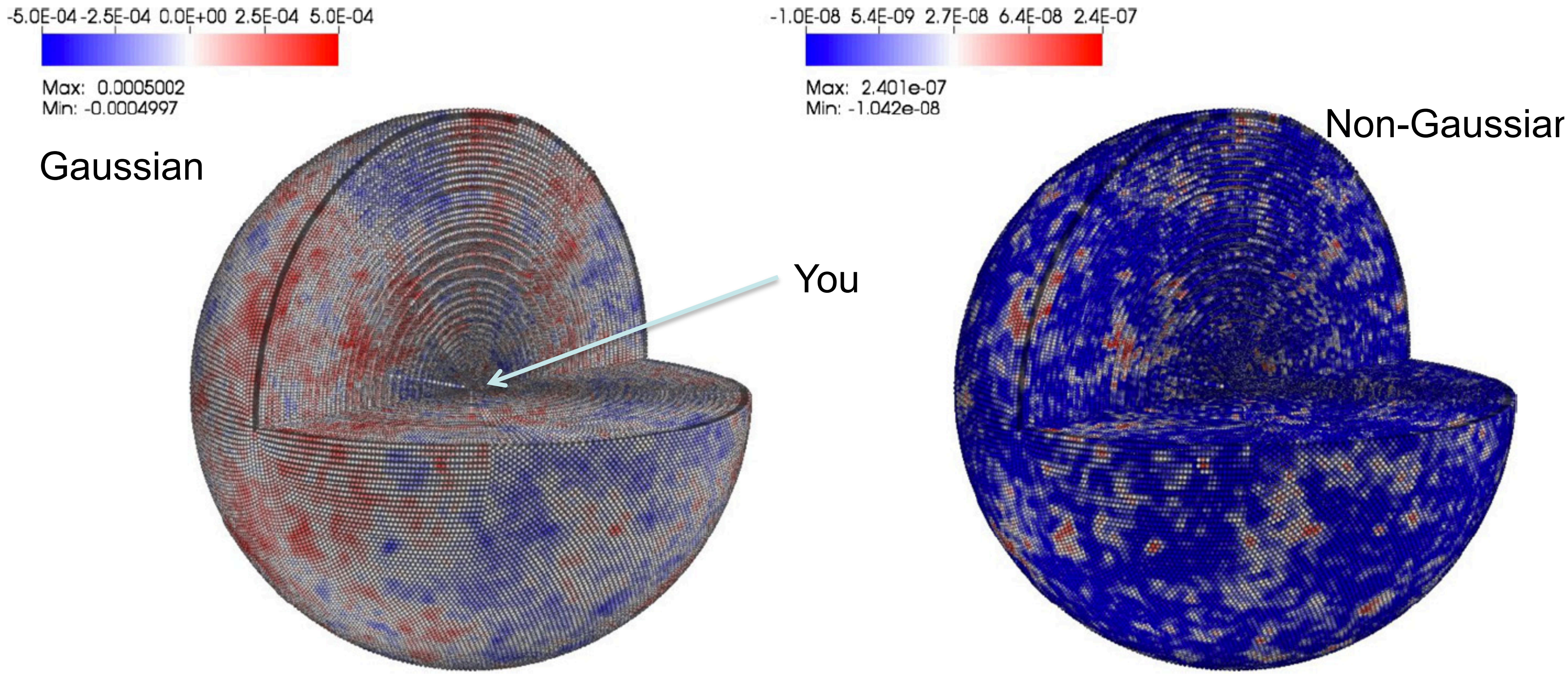
- Different models of the early Universe have distinct predictions regarding the type and the amount of non-Gaussianity expected.

- 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 (under mild assumptions)*

Why non-Gaussianity?

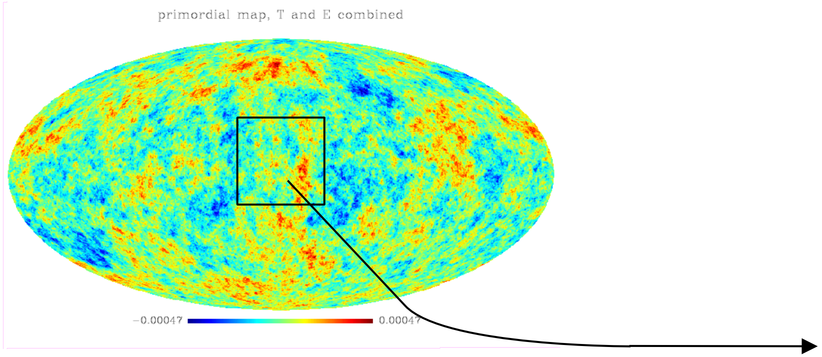
- NG is already the highest precision test of inflation!
  - *non-Gaussianity is now a <≈0.1% test (WMAP7, SDSS)*
  - *with Planck → ≈0.01%*
  - *flatness in second place ~1.5%*
- Already starting to rule out portions of inflationary parameter space, constrain "alternatives."
- Second order anisotropies produce known bispectrum signals which must be there (ISW-lensing, GR effects at last scattering, reionization etc).
- These are expected to be either small – or can act as calibrators and provide a separate cosmological information.

From curvature to CMB sky



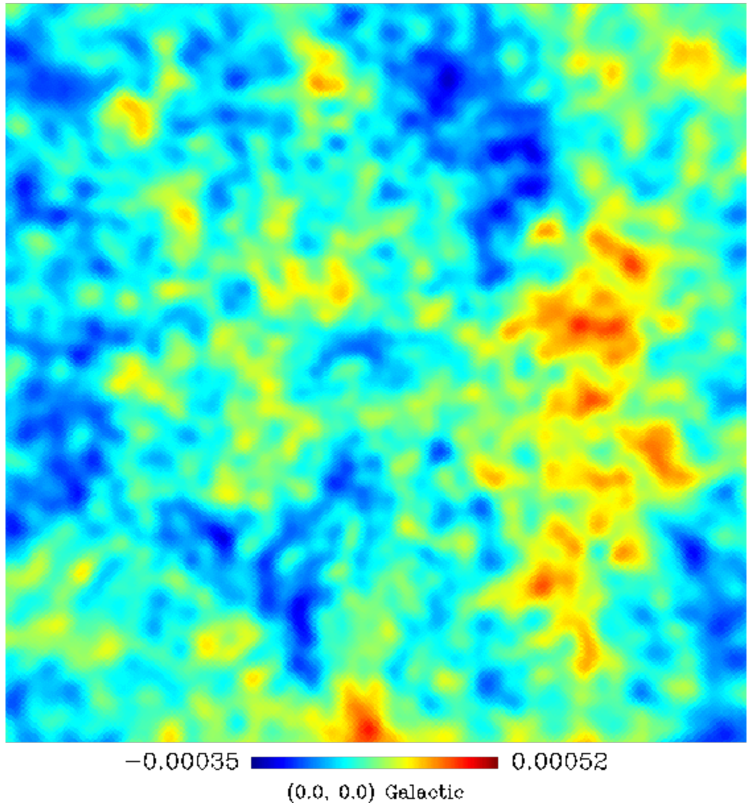
Elsner, Wandelt (2009)

Probing initial conditions with the CMB



- The CMB T&E provides a view of the primordial curvature perturbation.
- Can “reverse” processing by linear physics and test model predictions beyond the power spectrum.

Primordial curvature fluctuations



Komatsu, Spergel, Wandelt (2005)
Yadav, and Wandelt, PRD (2005)

An example: local f_{NL}

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

Characterizes the amplitude of non-Gaussianity

Salopek & Bond 1990
Gangui et al 1994
Verde et al 2000
Komatsu & Spergel 2001

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

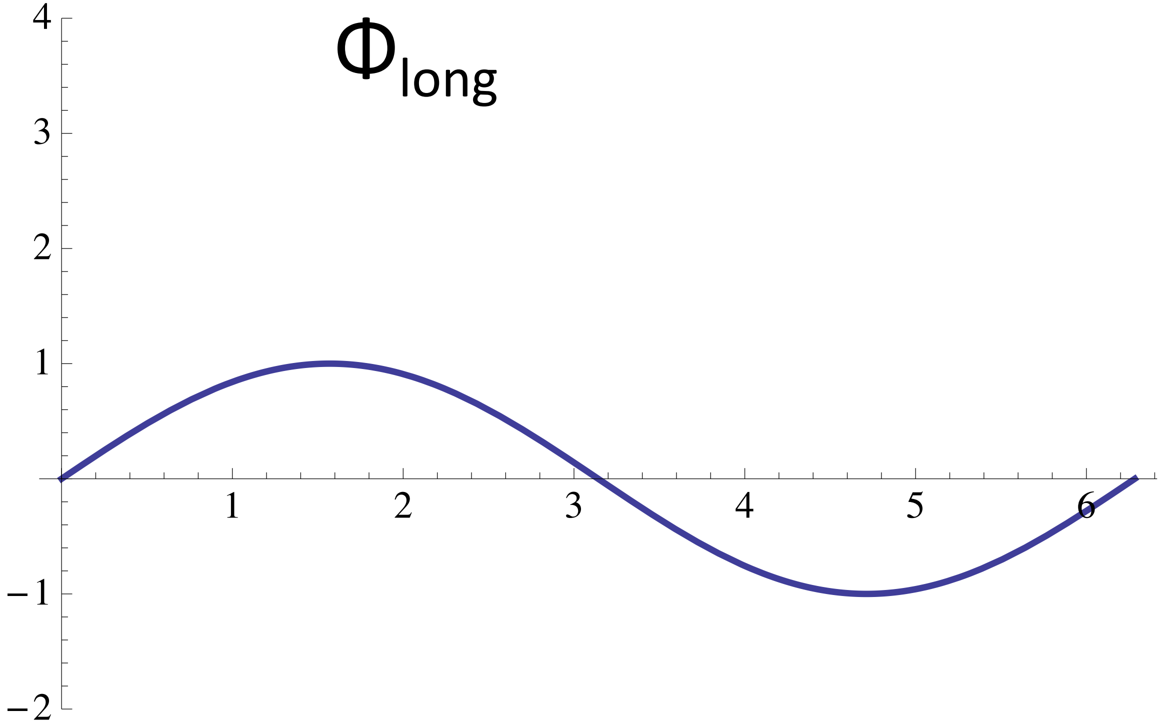
$$<\Phi(k_1)\Phi(k_2)\Phi(k_3)>=2(2\pi)^3 f_{NL}\delta(k_1+k_2+k_3)P(k_1)P(k_2),$$

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

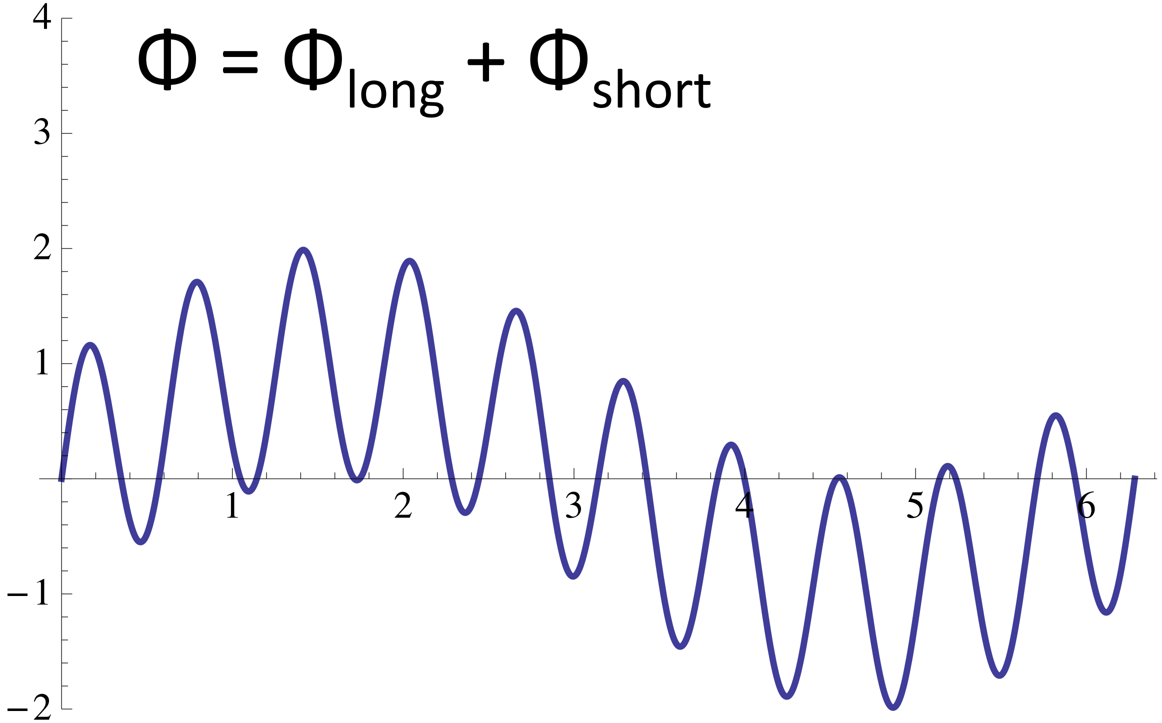
- **This translates into a bispectrum signature in the CMB through**

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

Local non-Gaussianity illustrated

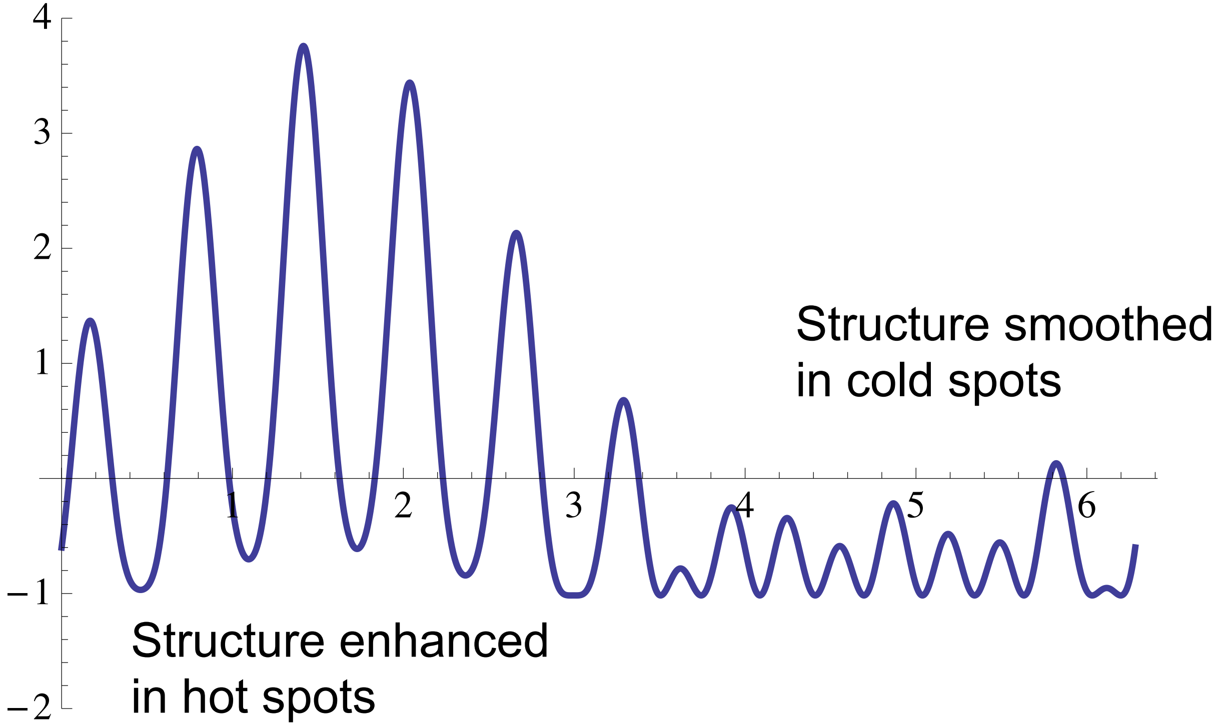


Local non-Gaussianity illustrated



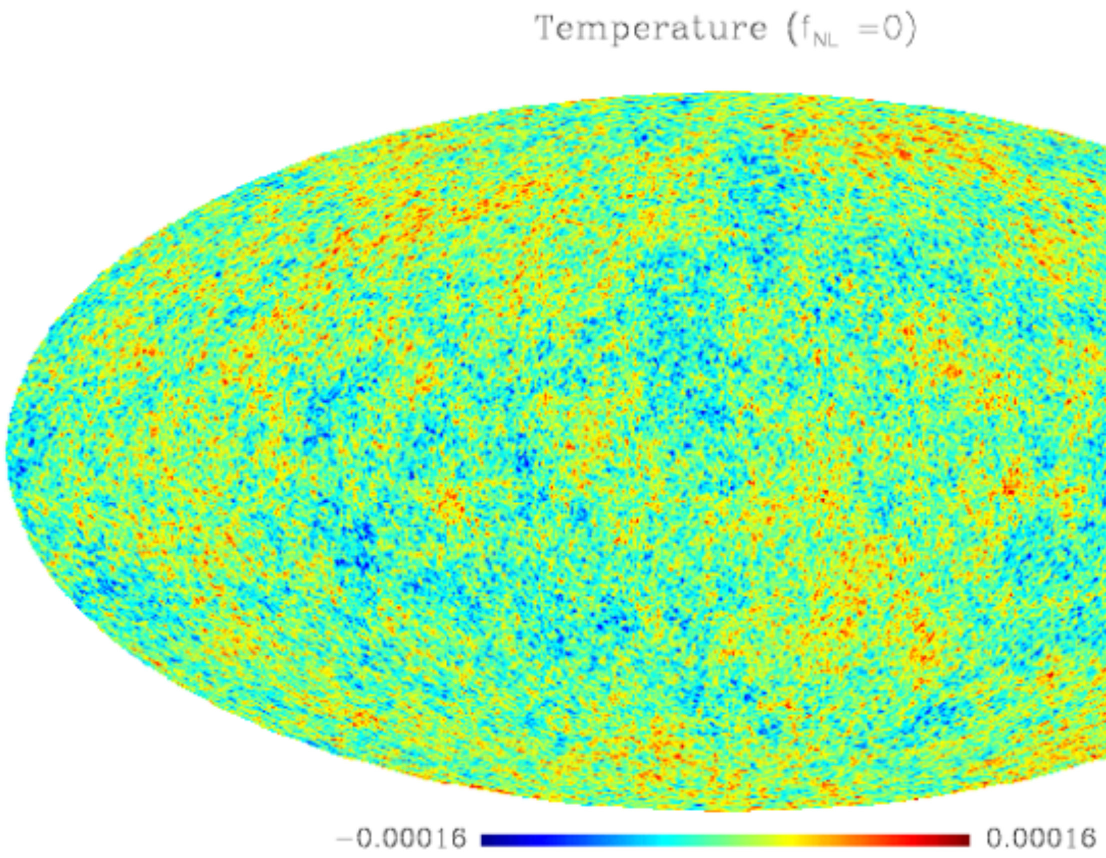
Local non-Gaussianity illustrated

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

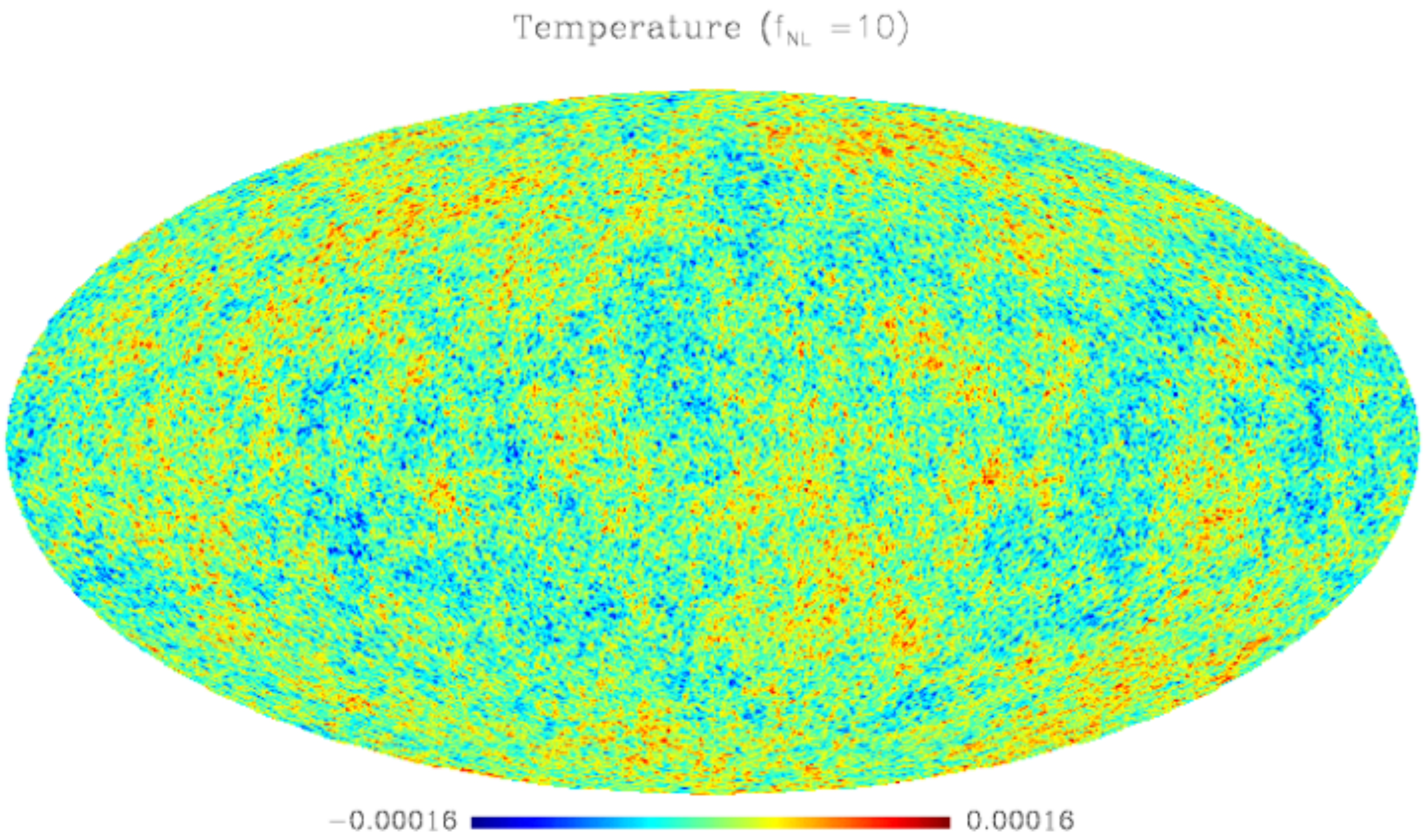


Note that this gives rise to both bispectrum and trispectrum signatures: f_{NL} an

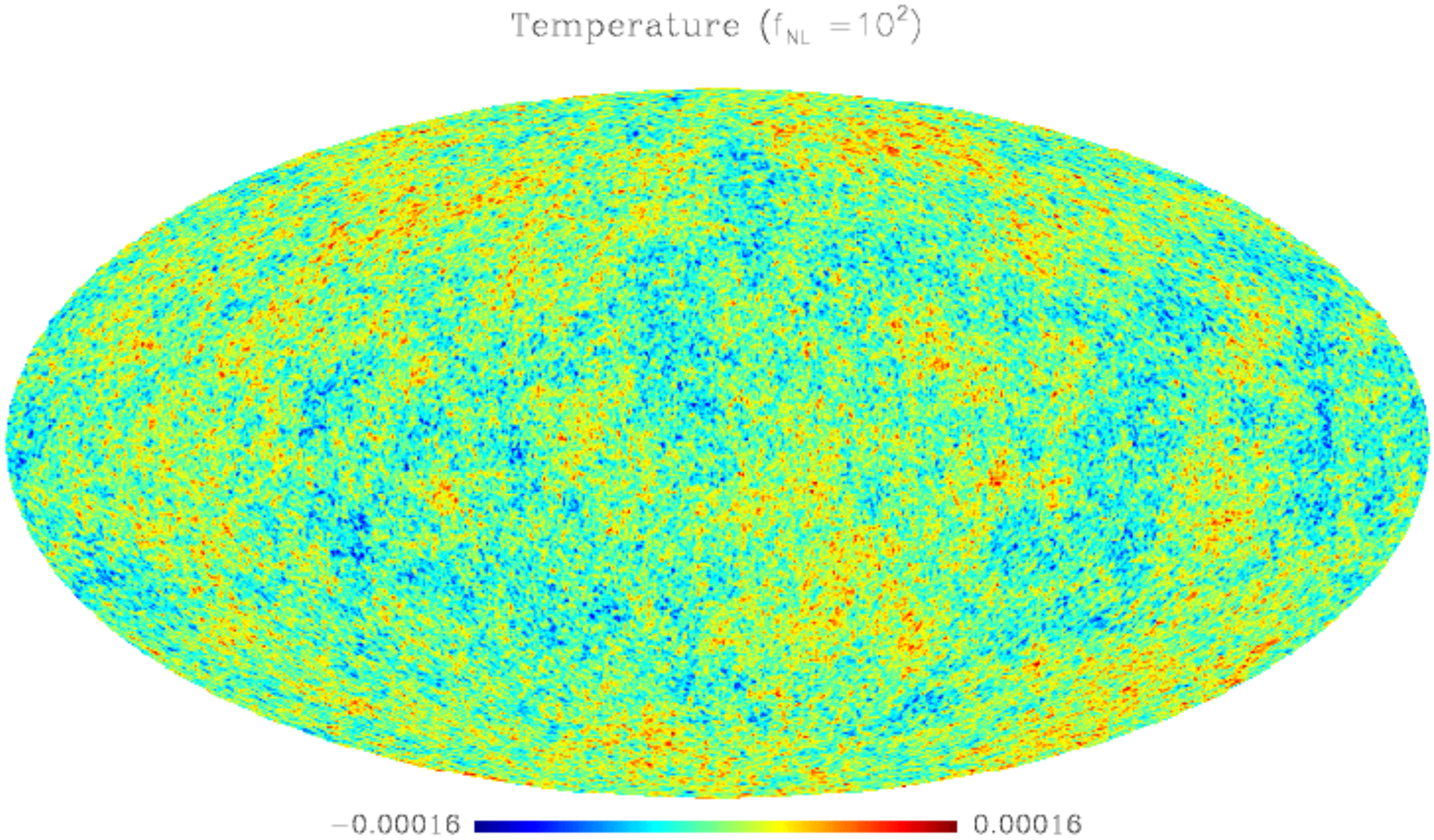
$f_{NL}=0$



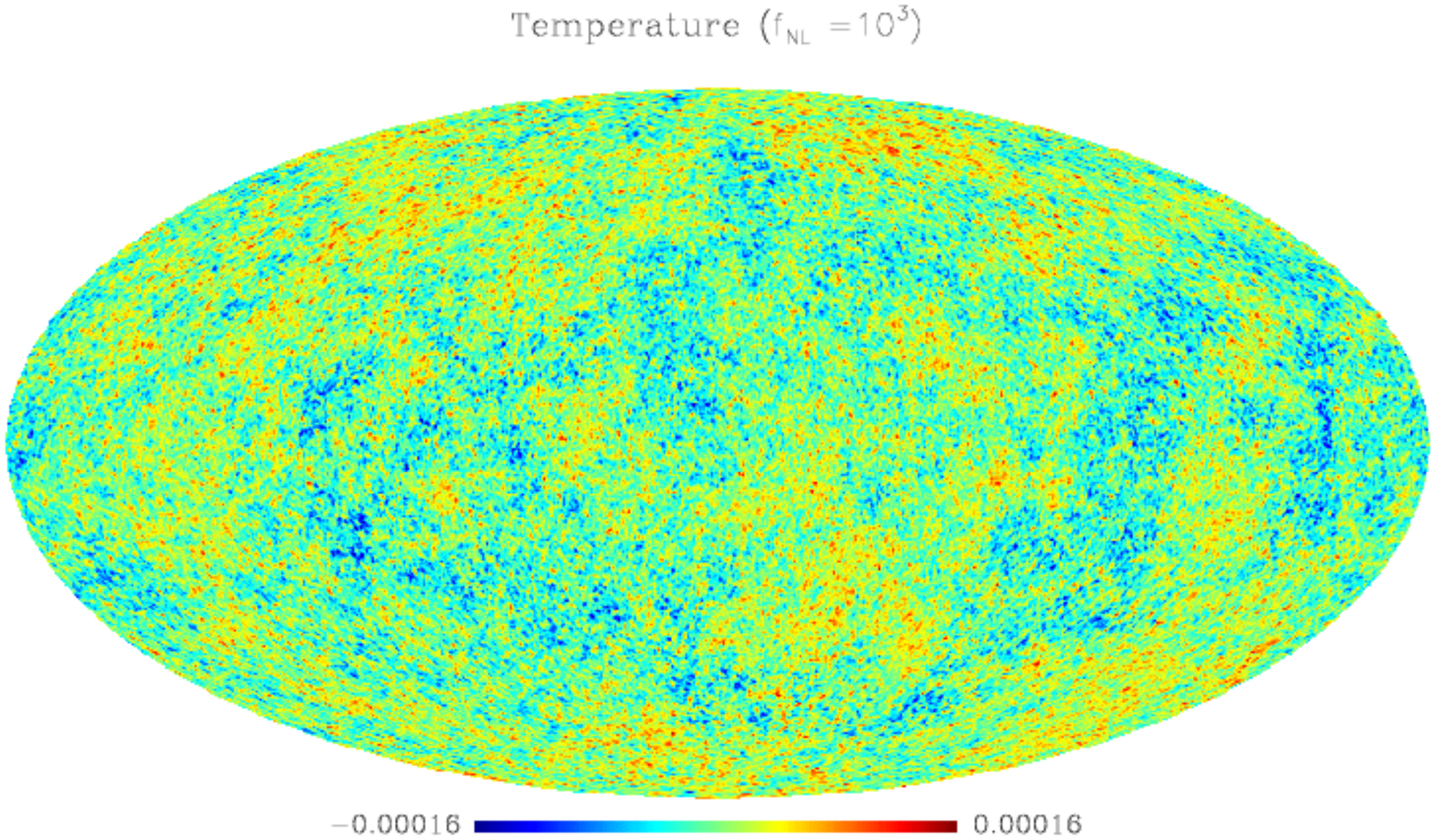
f_{NL}=10



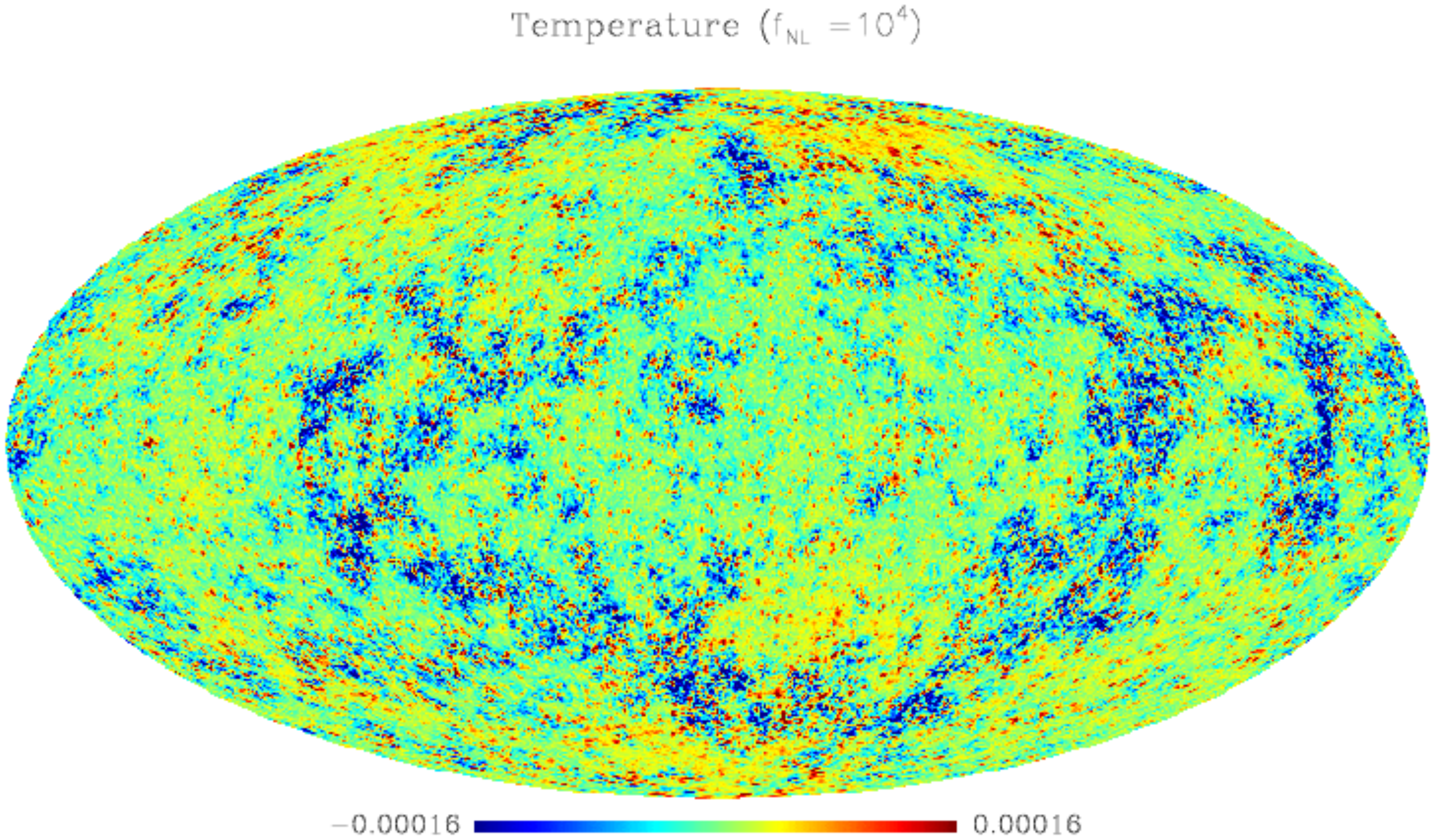
f_{NL}=



$f_{NL}=10^3$



$f_{NL}=10^4$



Why **CMB** non-Gaussianity?

- Already know that any primordial non-Gaussianity is small, but the bispectrum of primordial non-Gaussianity is significantly different from late time secondary effects, foregrounds, or generic non-Gaussian instrument systematics
- Search for primordial NG using bispectrum templates in the CMB is more *robust* to systematic error than was previously realized
- Non-Gaussianity is small because fluctuations are small. Can use linear perturbation theory – a big simplification.
- Polarization signal is orthogonal to T → Cross-checks!
- This robustness enables the study of primordial non-Gaussianity with current and future CMB probes.

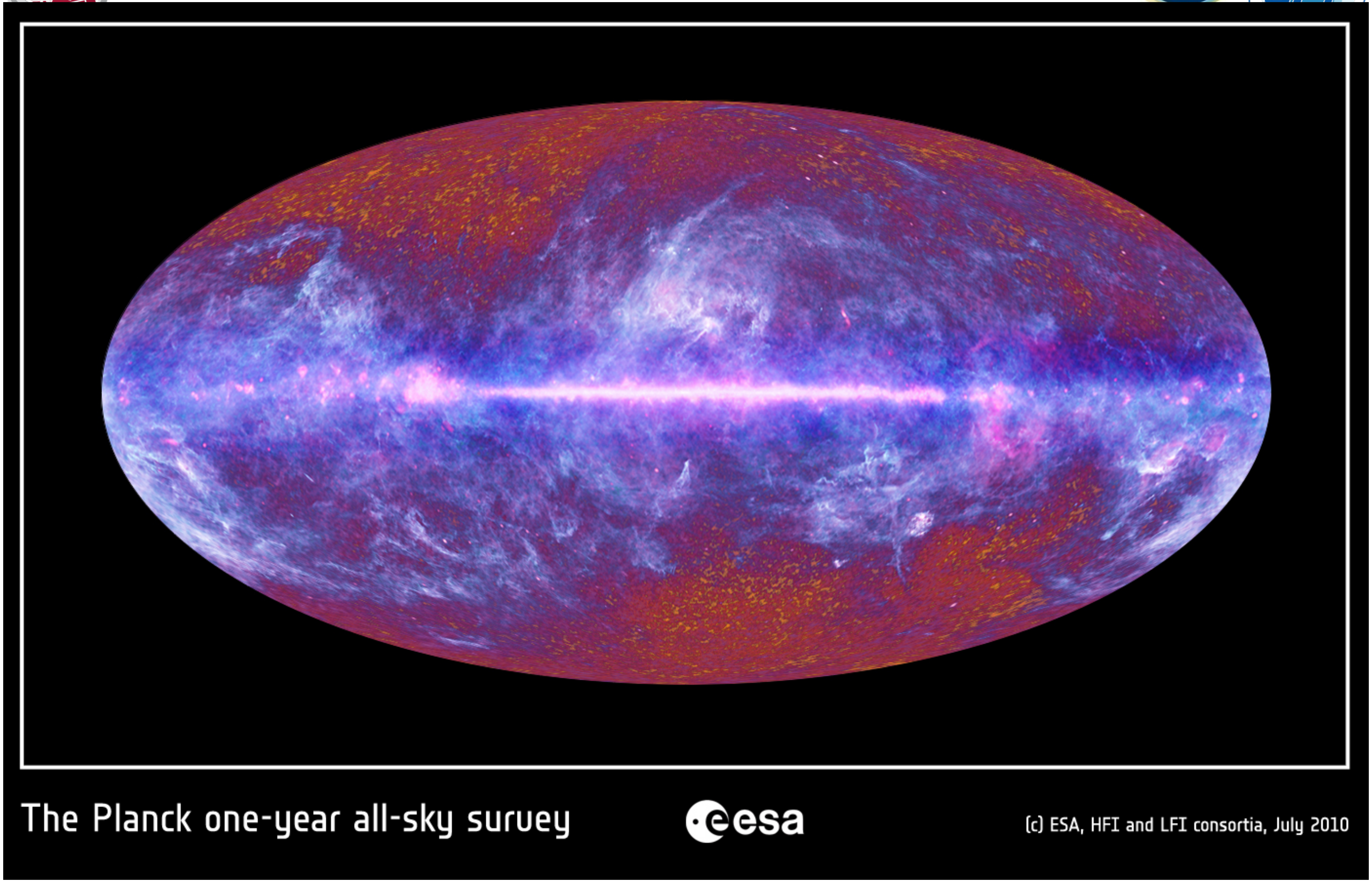
Current status: the "2-sigma hint" of non-Gaussianity

TABLE I: Hint of local non-Gaussianity at 2σ level

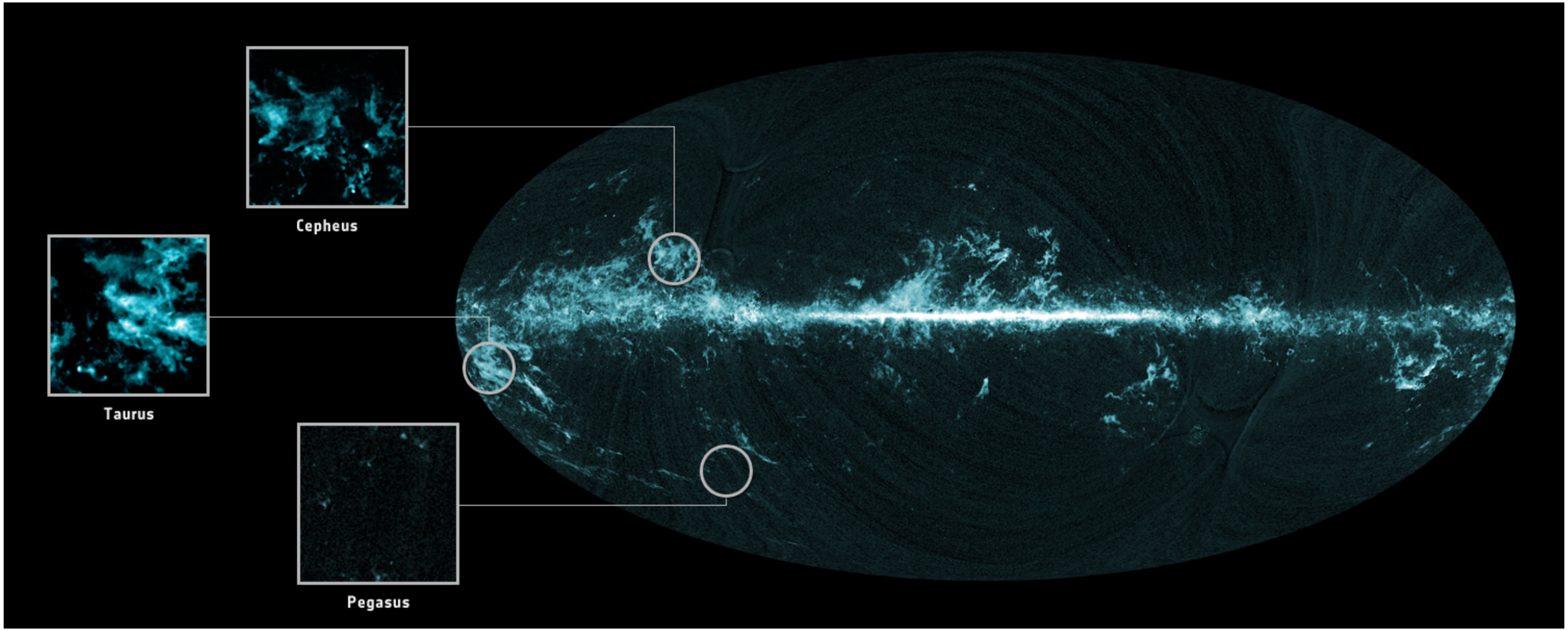
data (mask, estimator)	$f_{\rm NL}^{local} \pm 1\sigma$ error	deviation from Gaussianity	
WMAP 3-year (Kp0, near-optimal)	87 ± 31	2.8σ	Yadav and Wandelt [28]
WMAP 3-year (KQ75, optimal)	58 ± 23	2.5σ	Smith et al. [127]
WMAP 3-year (Kp0, near-optimal)	69 ± 30	2.3σ	Smith et al. [127]
WMAP 5-year (KQ75, near-optimal)	51 ± 30	1.7σ	Komatsu et al. [51]
WMAP 5-year (KQ75, optimal)	38 ± 21	1.8σ	Smith et al. [127]
WMAP 7-year (KQ75, optimal)	$f_{NL}^{\rm local} = 32 \pm 21$	1.5 σ	Komatsu et al. 2011

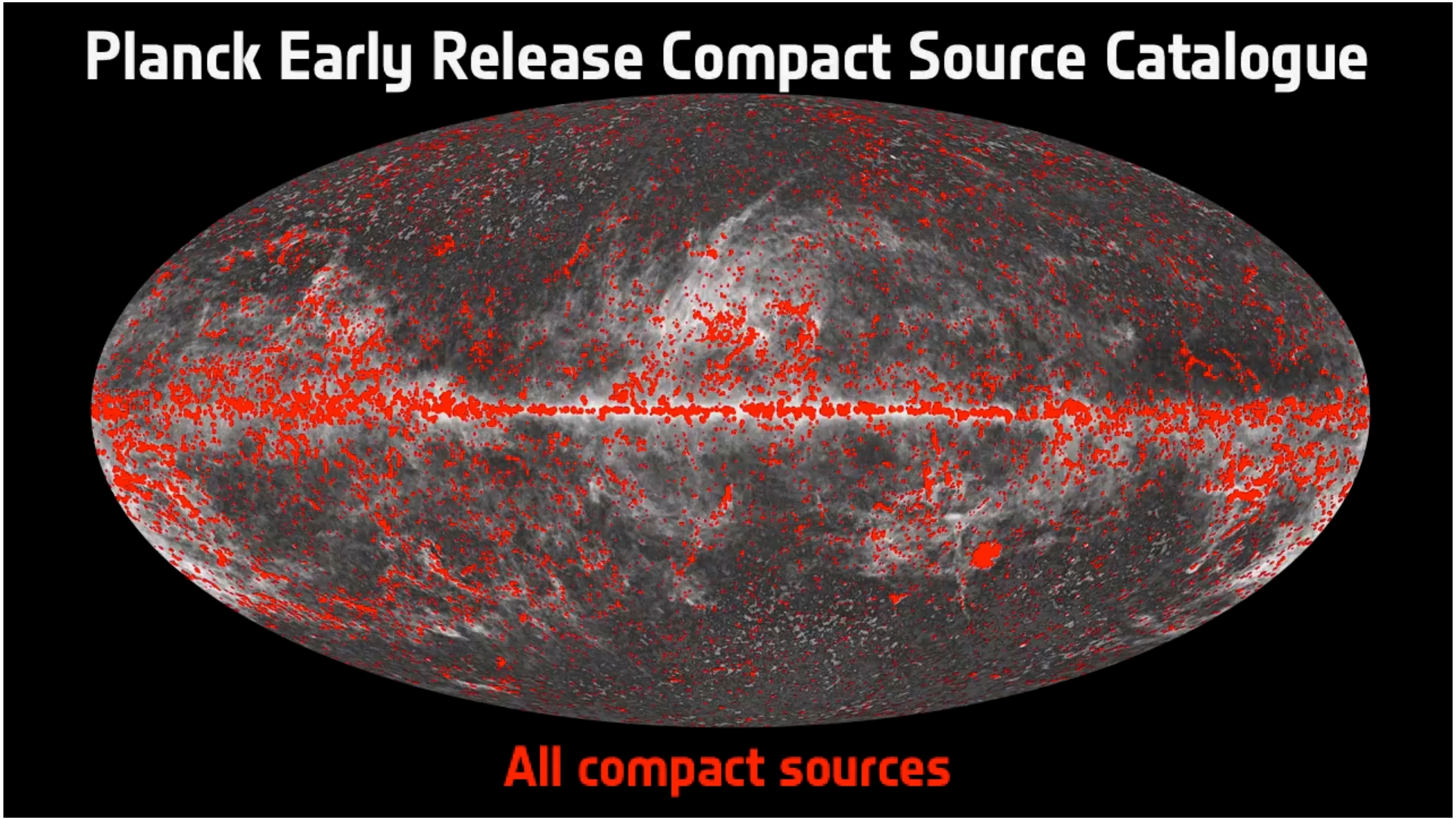
Broadly consistent with independent estimates from clustering in galaxy redshift surveys

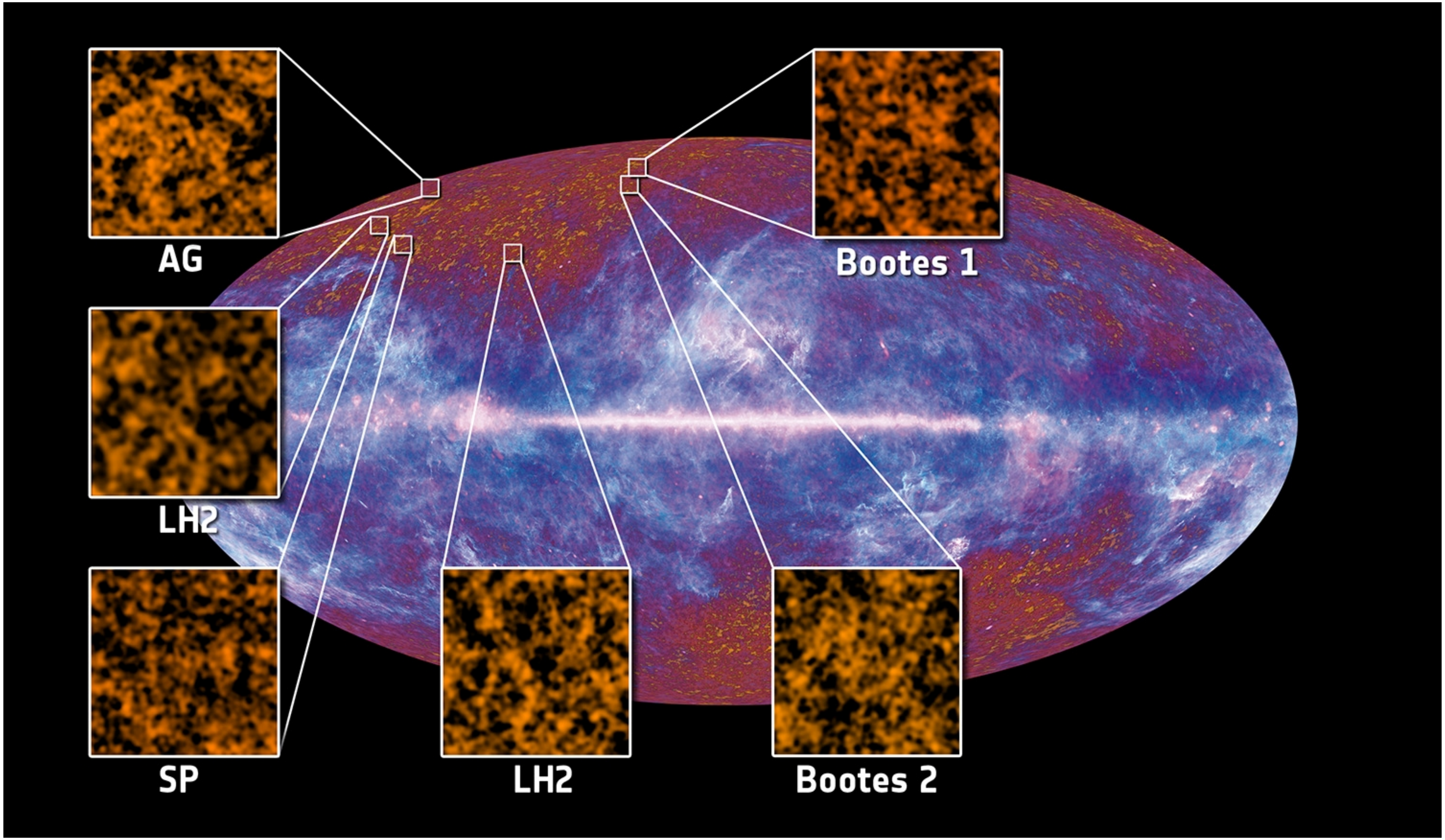
Planck


The Planck one-year all-sky survey
esa
(c) ESA, HFI and LFI consortia, July 2010

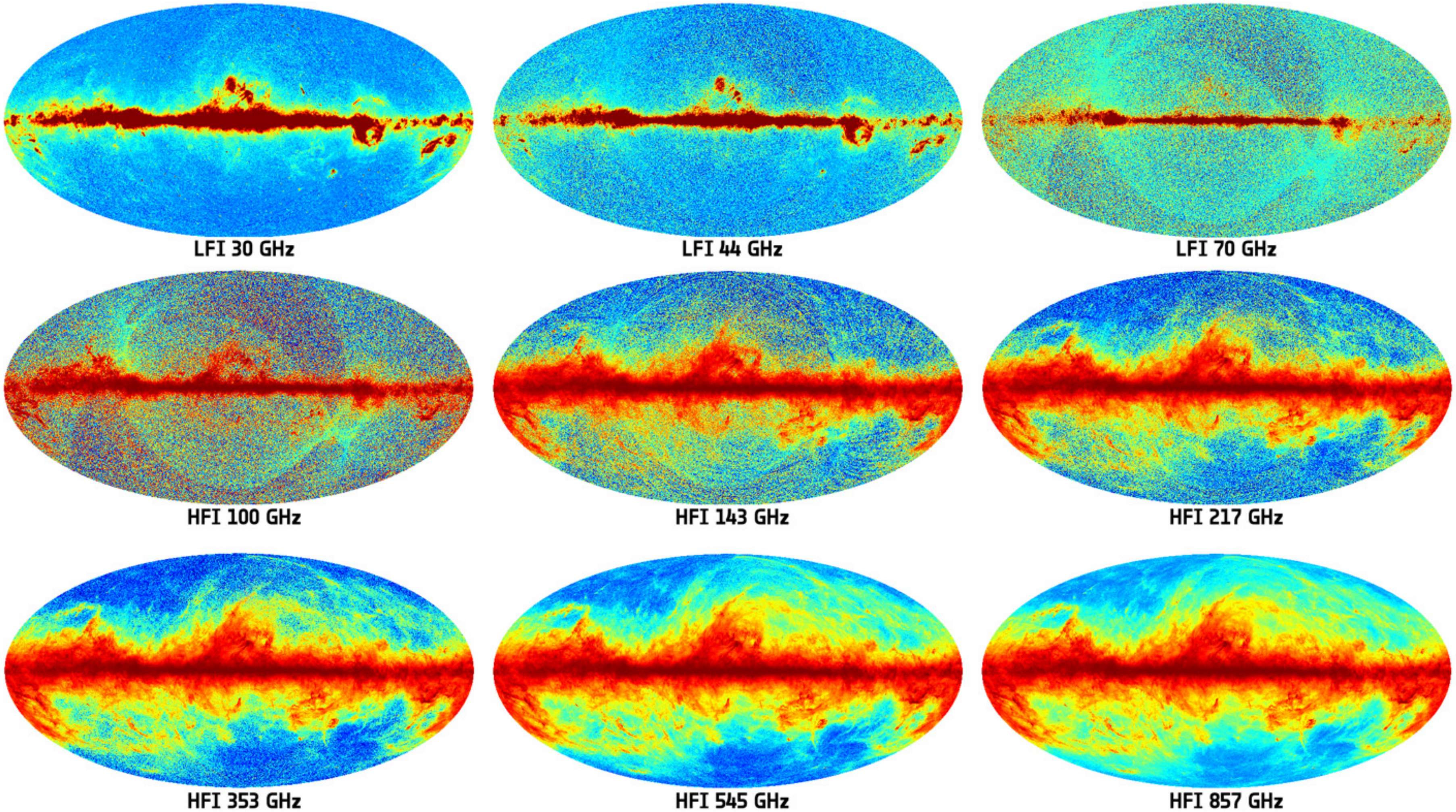
CO from Planck




Planck Early Release Compact Source Catalogue
All compact sources


AG
Bootes 1
LH2
SP
LH2
Bootes 2

Planck all-sky foreground maps



Estimators

Optimal cubic estimator

Minimize

$$\chi^2 = \sum_{ijkpqr} \sum_{\ell_1\ell_2\ell_3} \left(B^{ijk,obs}_{\ell_1\ell_2\ell_3} - f_{NL} B^{ijk,prim}_{\ell_1\ell_2\ell_3} \right) (\mathbf{Cov}^{-1})^{ijk}_{pqr} \left(B^{pqr,obs}_{\ell_1\ell_2\ell_3} - f_{NL} B^{pqr,prim}_{\ell_1\ell_2\ell_3} \right)$$

to get

$$\hat{f}_{NL} = \frac{\sum_{ijkpqr} \sum_{\ell_1\ell_2\ell_3} B^{ijk,obs}_{\ell_1\ell_2\ell_3} (\mathbf{Cov}-1)_{ijk,pqr} B^{pqr,prim}_{\ell_1\ell_2\ell_3}}{\sum_{ijkpqr} \sum_{\ell_1\ell_2\ell_3} B^{ijk,prim}_{\ell_1\ell_2\ell_3} (\mathbf{Cov}^{-1})_{ijk,pqr} B^{pqr,prim}_{\ell_1\ell_2\ell_3}}$$

For local f_{NL}:

$$B^{pqr,prim}_{\ell_1\ell_2\ell_3} = I_{\ell_1\ell_2\ell_3} \int r^2 dr [\beta^p_{\ell_1}(r)\beta^q_{\ell_2}(r)\alpha^r_{\ell_3}(r) + \beta^r_{\ell_3}(r)\beta^p_{\ell_1}(r)\alpha^q_{\ell_2}(r) + \beta^q_{\ell_2}(r)\beta^r_{\ell_3}(r)\alpha^p_{\ell_1}(r)]$$

Komatsu, Spergel 2001; Babich & Zaldarriaga 2005

Fast cubic statistics

$$\hat{f}_{NL} = \frac{\hat{S}_{prim}}{\left\{\sum_{ijkpqr}\sum_{\ell_1\le\ell_2\le\ell_3} B^{pqr,prim}_{\ell_1\ell_2\ell_3}(C^{-1})^{ip}_{\ell_1}(C^{-1})^{jq}_{\ell_2}(C^{-1})^{kr}_{\ell_3} B^{ijk,prim}_{\ell_1\ell_2\ell_3}\right\}}$$

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

Much faster: O(L^3) scaling!

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

B is the *Wiener Filtered* reconstruction of primordial perturbations

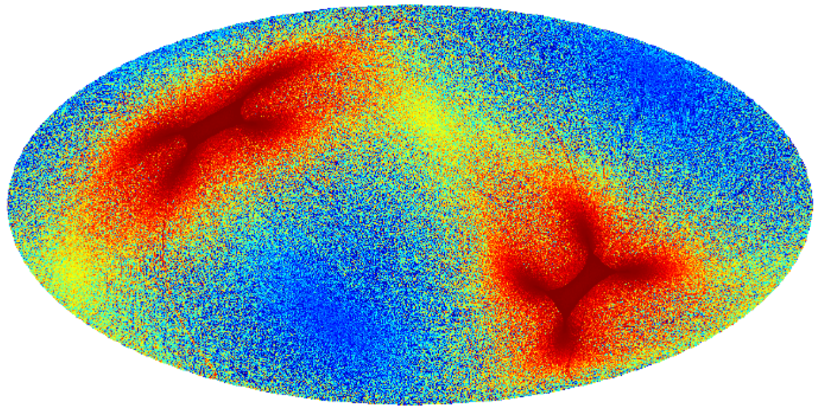
$$A(\hat{n},r) \equiv \sum_{ip}\sum_{lm}(C^{-1})^{ip}a^i_{\ell m}\alpha^p_\ell(r)Y_{\ell m}(\hat{n})$$

A picks out relevant configurations of the bispectrum

Komatsu, Spergel and Wandelt 2005; YKW 2007

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 estimator (Creminelli et al. 2005)



$$S_{improved} = S_{cubic} + S_{linear}$$

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

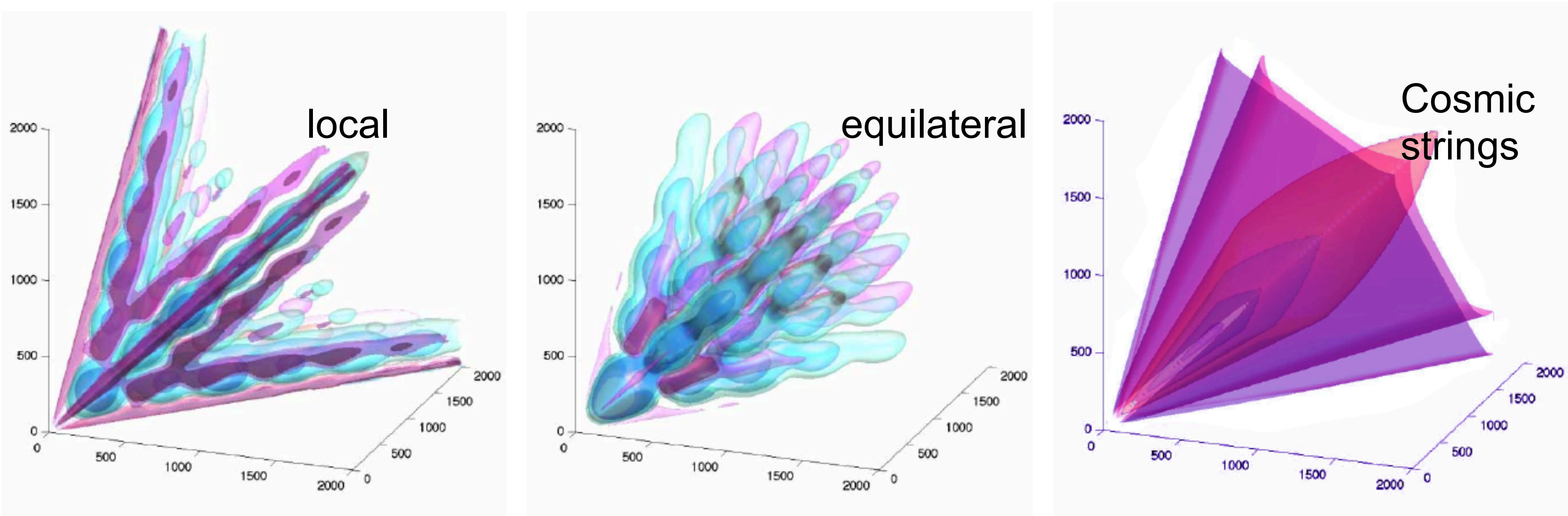
Non-Gaussian model testing

- The goal is to constrain the primordial Lagrangian
  - Path 1: Effective Field Theory of Inflation (e.g. Cheung, Creminelli, Fitzpatrick, Kaplan 2008)
    - A unifying frame work for inflationary models
    - Obtain slow-roll, multi-field, k-, DBI, ghost inflation as limits
    - Constrain model space using bispectrum signatures
    - Example for single field models: $c_s > 0.011$ Senatore, Smith, Zaldarriaga, 2010

Non-Gaussian model testing

- The goal is to constrain the primordial Lagrangian

Beyond local f_{NL}: More general bispectrum tests with CMB fingerprinting



Fergusson, Liguori, Shellard 2009; Fergusson and Shellard 2009

In the space of local, equilateral and orthogonal bispectrum modes Planck will reduce the constraint volume by 70 compared to WMAP **with a further factor of 20 possible for a next gen mission.**

Modal expansion (Fergusson, Liguori, Shellard) or binned bispectrum (van Tent, Bucher) allow further, model independent exploration.

Alternative implementations

- Wavelets (Curto et al.)
- Binned bispectrum (Bucher, van Tent)
- Skew-C_l (Heavens, Munshi)

- Minkowski functionals (suboptimal)

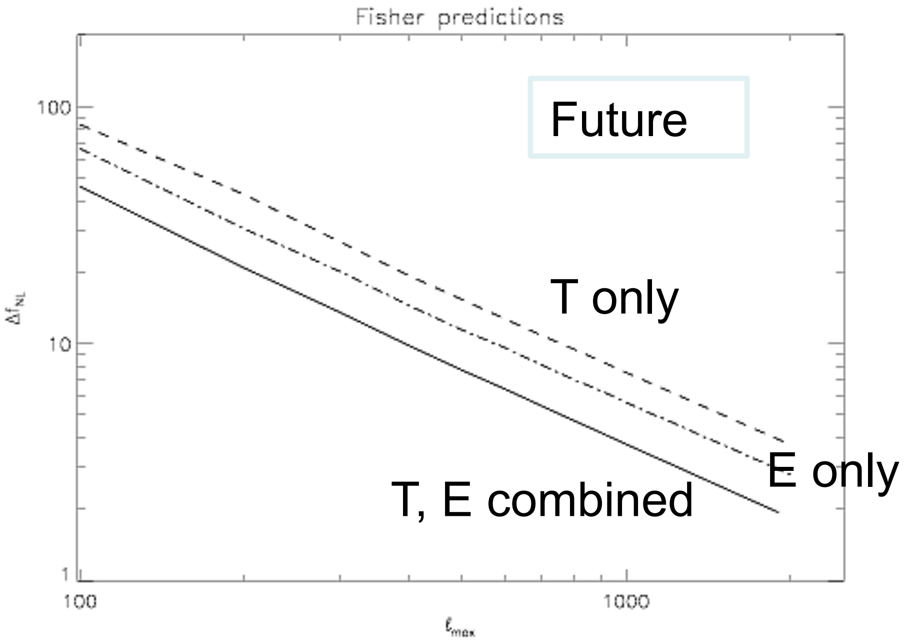
Non-Gaussianity from space

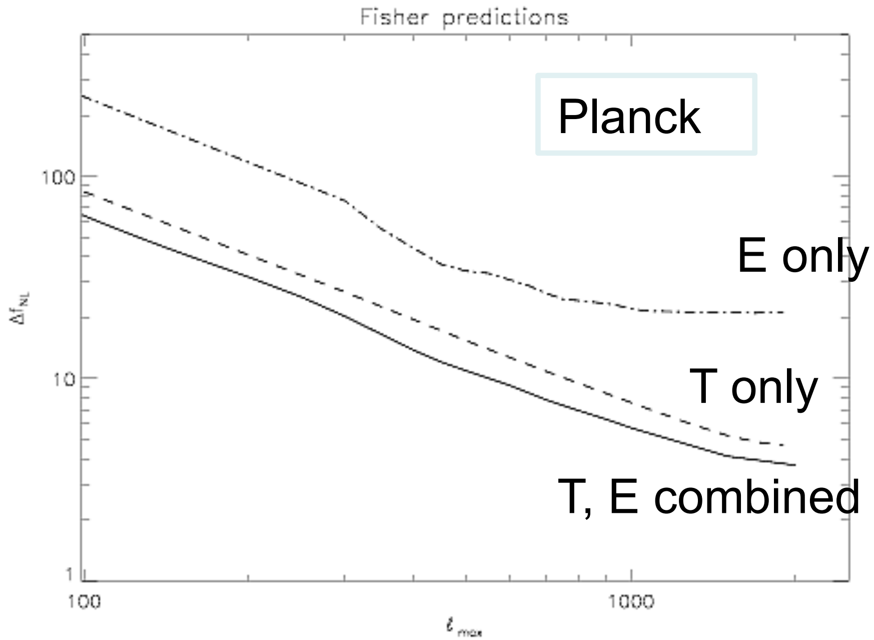
- Many modes
  - *large sky coverage*
  - *high resolution*
- Frequency coverage
  - *foreground removal*

- Polarization

  complementary to T

  adds a great deal of information





Yadav, Komatsu, Wandelt 2007

Assumptions

- This assumes systematics are under control
  - *Extragalactic Foregrounds*
  - *Diffuse galactic foregrounds*
  - *Instrument systematics*
  - *Analysis artifacts*

- At this point:
  - *The data appear to be useable as expected.*
  - *No show-stoppers so far.*

Perspectives beyond the bispectrum

- Some model signatures have no, subdominant or non-specific bispectrum signature
- In that case, need higher order moments
  - *Lensing*
  - τ_{NL}, *trispectrum signal of local NG; a modulation signal*
  - *Cubic non-Gaussianity,* g_{NL}
  - *trispectrum signatures from new physics during inflation, e.g. Jackson and Schalm 2012*
  - *Power modulation in the sky (e.g., Ma, Efstathiou, Challinor 2012)*
- Quadratic estimators are well-developed, but will ultimately limit detection (Hirata & Seljak 2004)

Conclusions

- Non-Gaussianity is an exciting new window on the Physics of the Beginning
- CMB robustly probes for primordial non-Gaussian signatures
- Cosmology results from Planck are due in spring of 2013.
- No show-stoppers so far.

Appendix

Details: linear term

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

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