Non-Gaussianity in Planck data

Benjamin Racine

On behalf of the Planck collaboration

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Rencontres du Vietnam

UiO : Institute of Theoretical Astrophysics
The Faculty of Mathematics and Natural Sciences

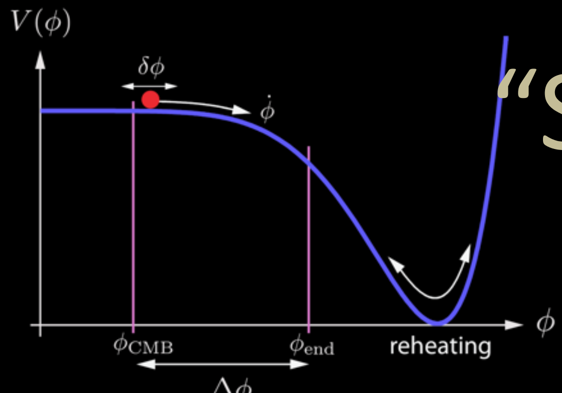
Outline

1) Introduction
    a) Inflation and CMB
    b) Non Gaussianity and bispectrum

2) Planck 2015
    a) Systematics, validations, etc.
    b) Results

1.a. Inflation and CMB

"Simplest" Inflation



from D.Bauman: 0907.5424

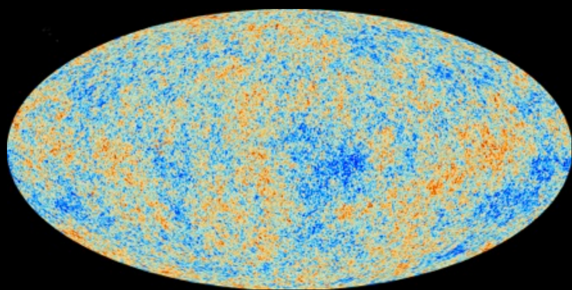
$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}R + \frac{1}{2}g^{\mu\nu}\delta_\mu\phi\delta_\nu\phi - V(\phi)\right]$$

- Single scalar field
- Slow roll
- Bunch Davies Vacuum
- Canonical Kinetic Term

Source of nearly Gaussian perturbations δΦ (x) => All statistical information is in power spectrum

<δΦ(k) δΦ(k)>

Inflation and CMB



$$T(\Omega) = \sum_{\ell=2}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\Omega)$$

Transfer functions (Baryon oscillations)

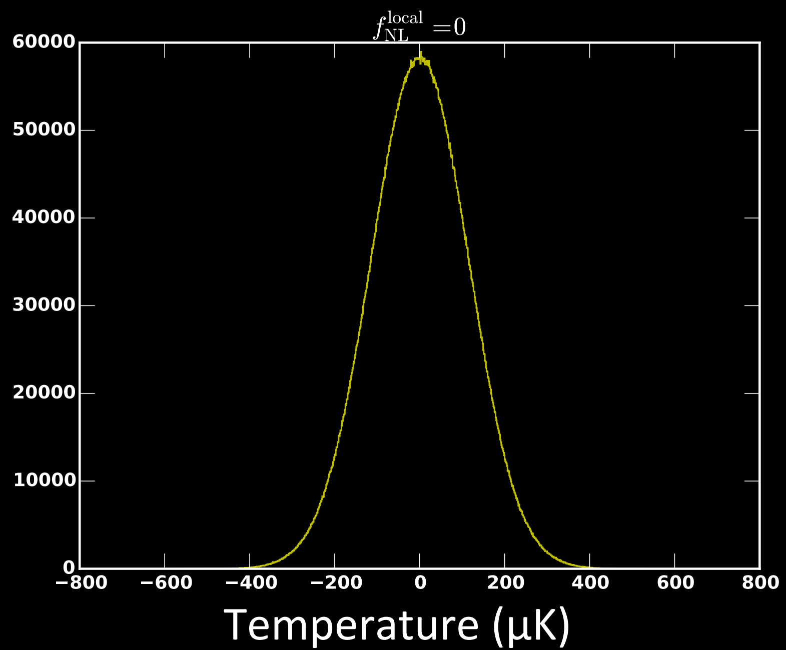
Primordial gravitational potential

$$a_{\ell m} \propto (-i)^{\ell} \int \frac{d^3k}{(2\pi)^3} \Delta_{\ell}(k) \Phi(k) Y_{\ell m}(\Omega)$$

Geometrical part: from k space to ℓ space

1.b. Non Gaussianity and Bispectum

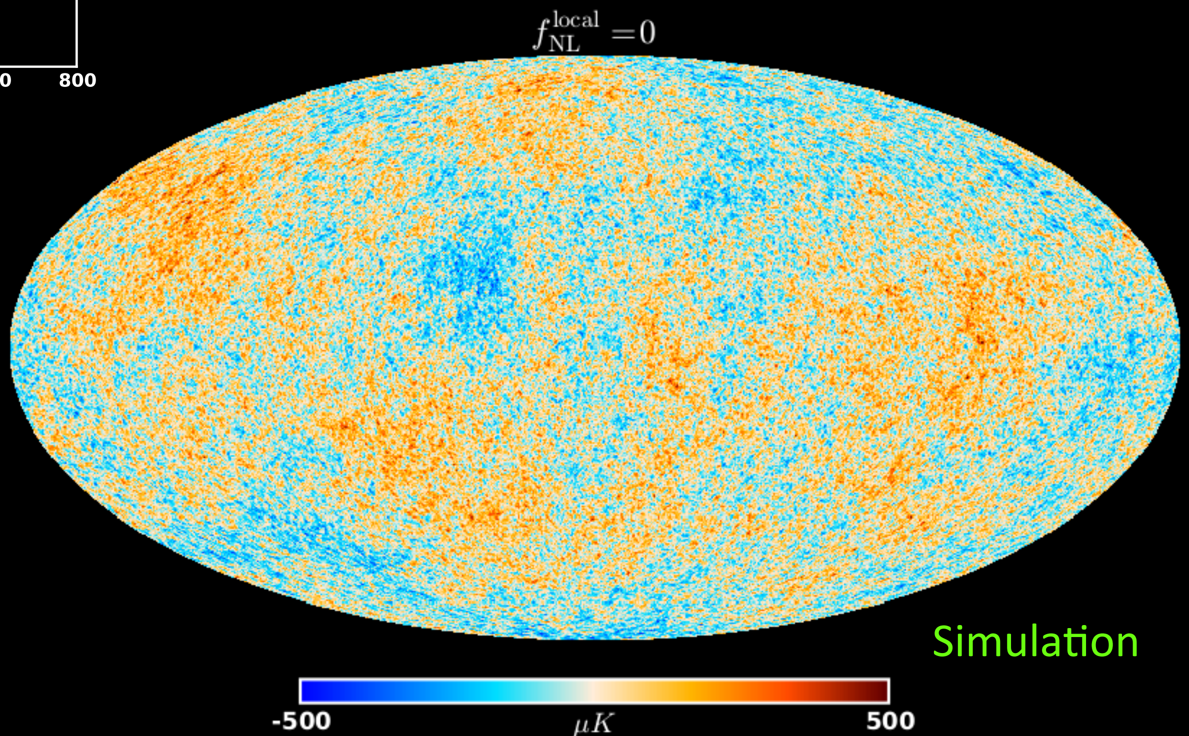
Gaussianity



Standard inflation

$\Downarrow$

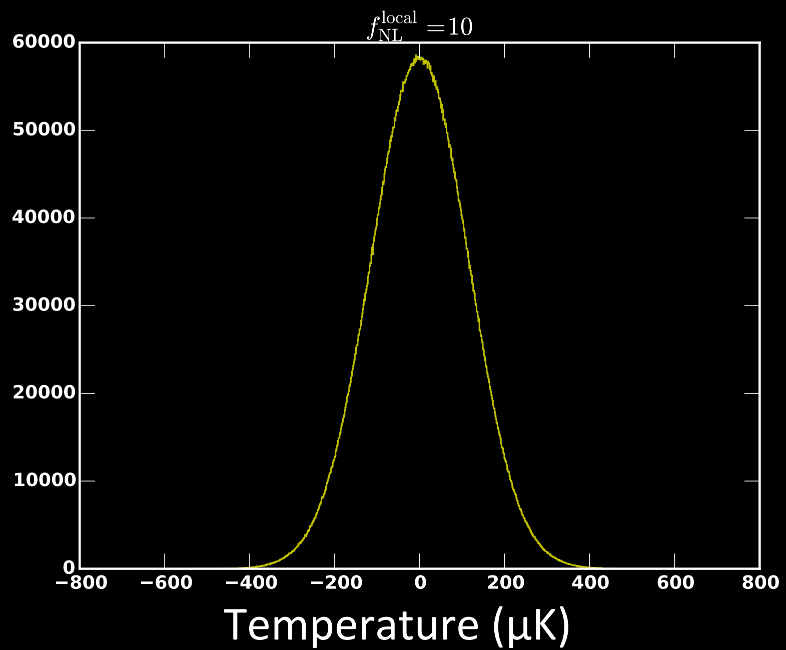
Gaussian perturbations $\Phi(x)$



Simulation

Standard inflation :
- 1 field
- Slow roll
- Initial conditions : flat space
- Canonical kinetic term

Non-gaussianity

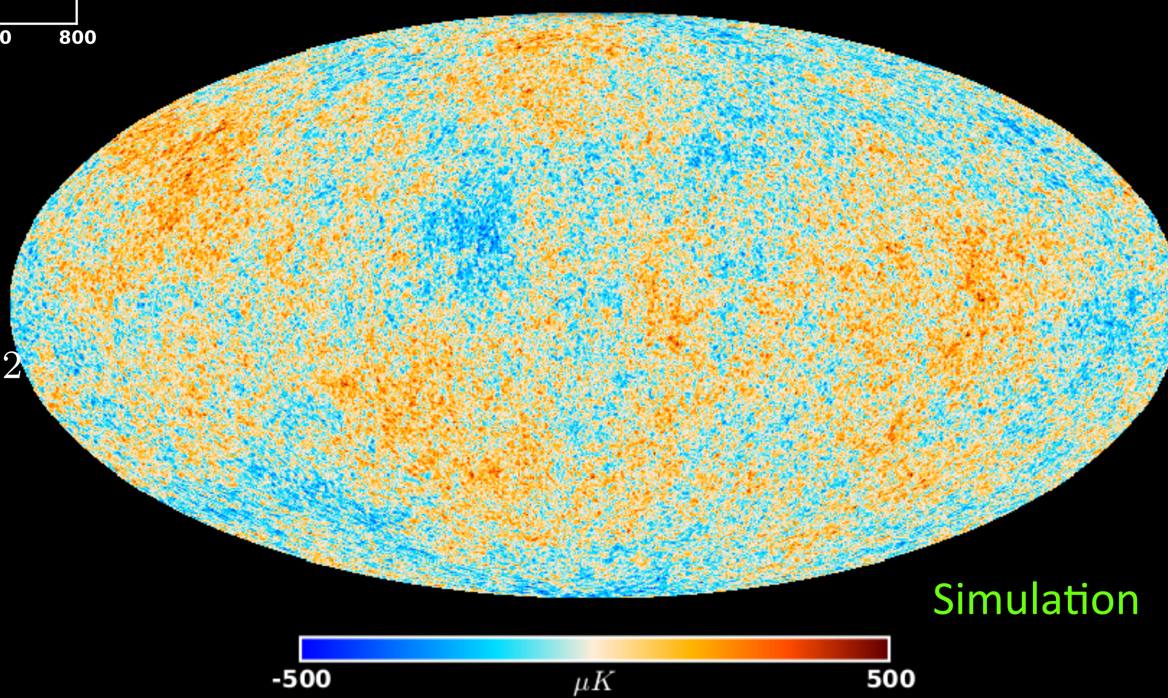


non-standard Inflation

$\Downarrow$

Non-Gaussian perturbations

$f_{NL} = 10$



Simulation

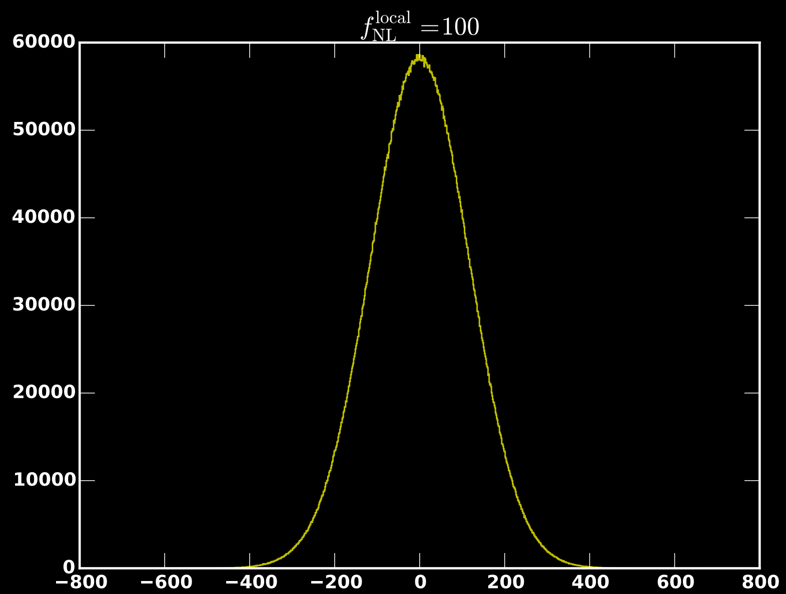
Non linearity parameter

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

ⓘ Typical models: f_{NL}= 0(10-100)

Standard inflation : $f_{NL} \approx 10^{-2}$

Non-gaussianity

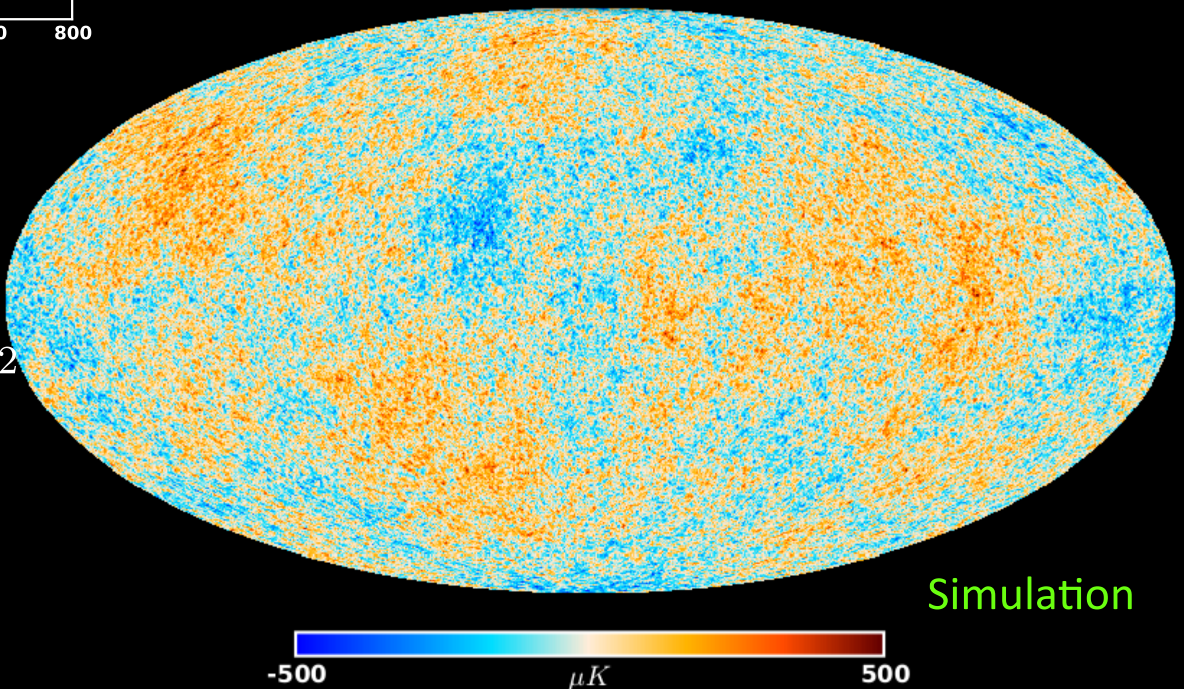


non-standard Inflation

⇓

Non-Gaussian perturbations

f_{NL} = 100



Simulation

Non linearity parameter

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

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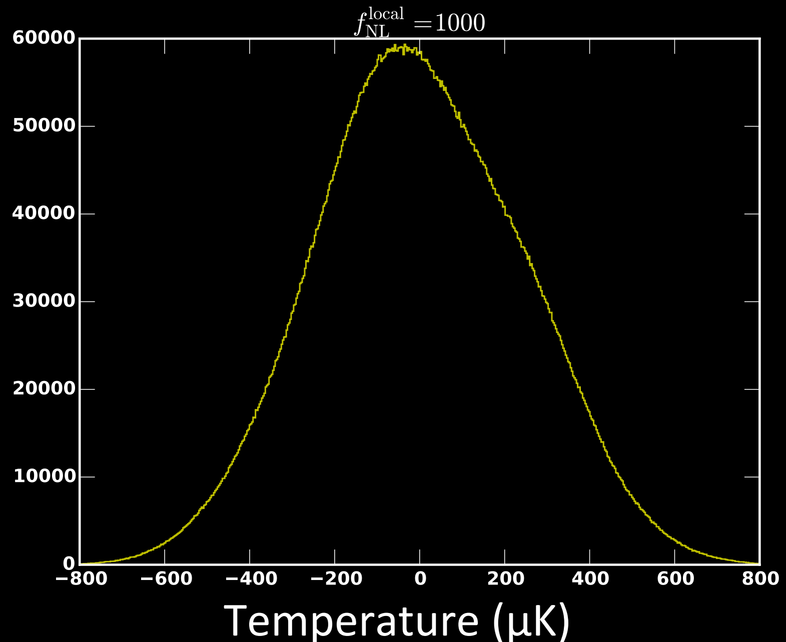
Non-gaussianity

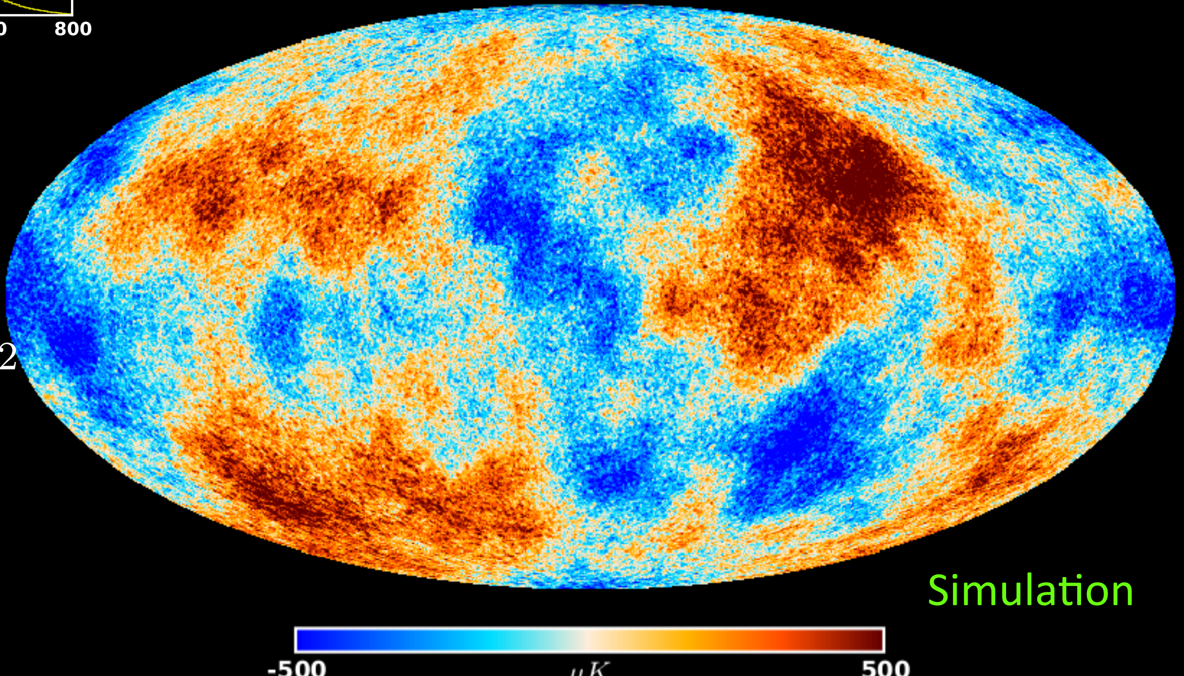


non-standard Inflation

⇓

Non-Gaussian perturbations

$f_{NL} = 1000$



Non linearity parameter

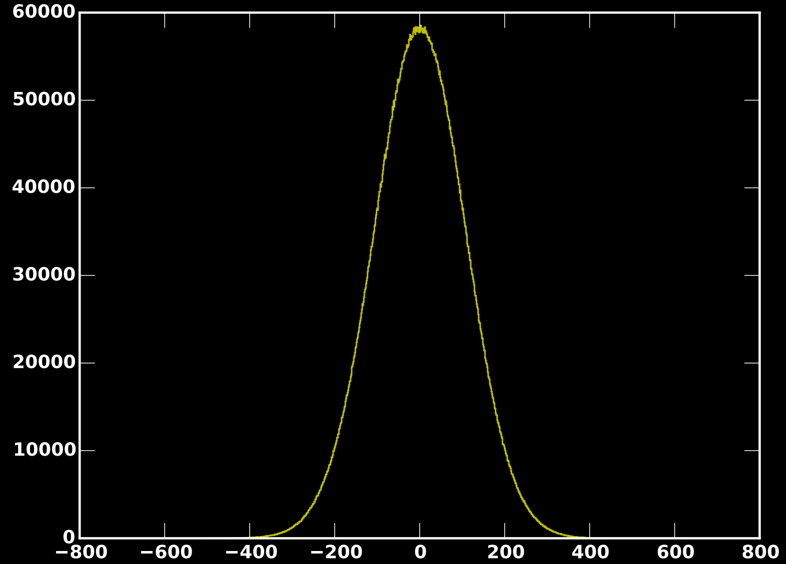
$$\Phi(\mathbf{x}) = \Phi_G(\mathbf{x}) + f_{NL}^{local}(\Phi_G(\mathbf{x}))^2$$

ⓘ Typical models: f_{NL}= 0(10-100)

Standard inflation : $f_{NL} \approx 10^{-2}$

Non-gaussianity

Planck Data



Temperature (μK)

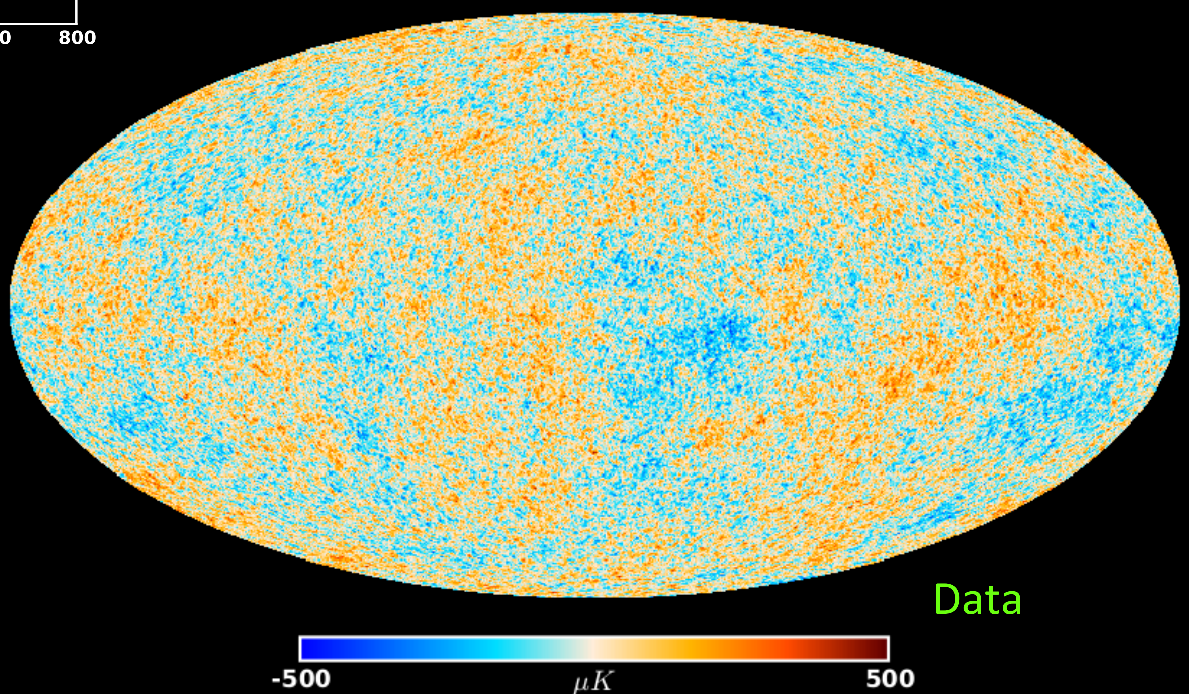
Really weak effect

⇓

More sophisticated statistical tool:

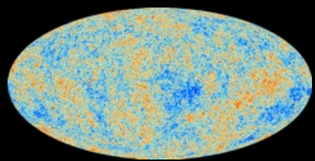
bispectrum

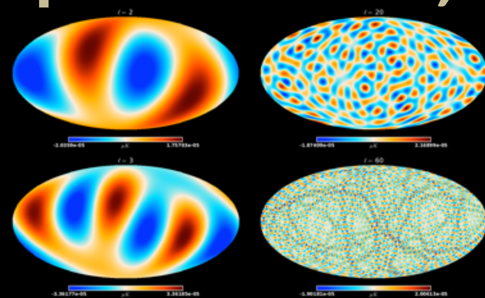
Planck Data



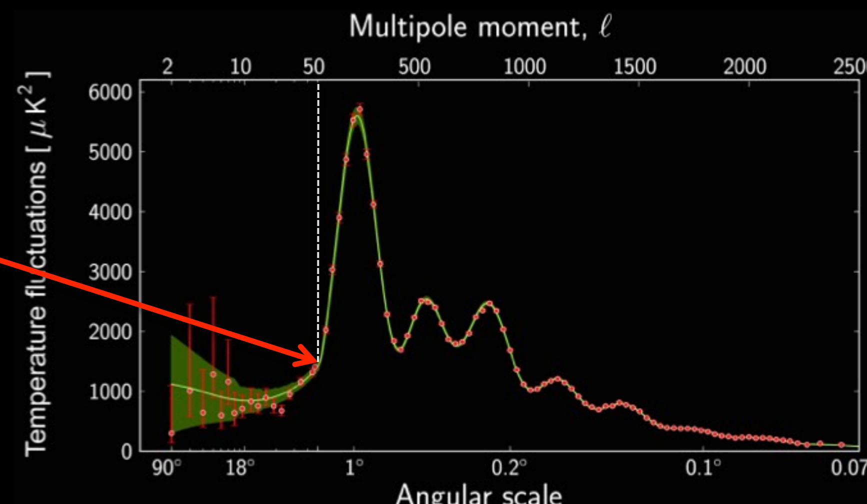
Here we show temperature, but same idea for E polarization

Spectrum, bispectrum

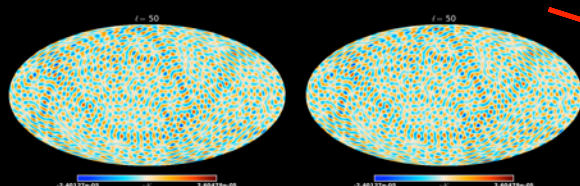




, etc… (2500 multipoles ℓ with Planck)

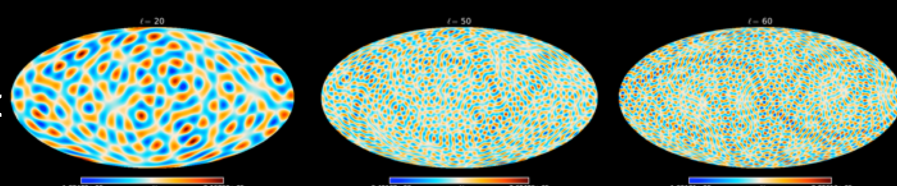


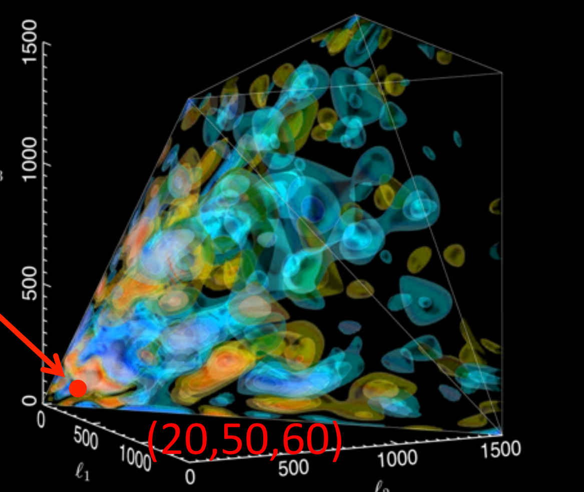
ℓ=50 ℓ=50

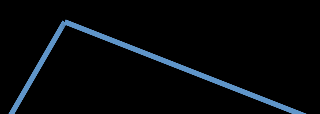
Spectrum : <  >

ℓ = ℓ'

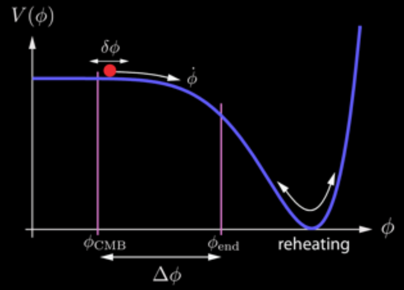
ℓ=20 ℓ=50 ℓ=60

Bispectrum : <  >





$$B_\Phi(k_1, k_2, k_3) = \sum_{i \in \text{shape}} f_{NL}^{(i)} F^{(i)}(k_1, k_2, k_3)$$

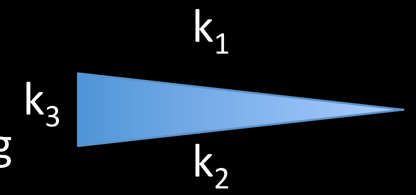


"~~Simplest~~" Inflation

⚠ Slow Roll inflation : $f_{NL} \approx 10^{-2}$

- ~~Single Field~~ **Local NG**

} Squeezed / local:
Multifields, curvaton,
inhomogeneous reheating
Late-time: ISW x lensing
f_{NL} = O(1-100)

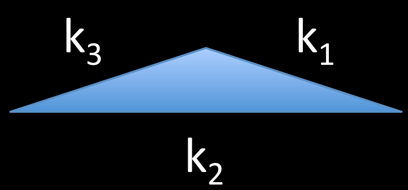


- ~~Slow roll~~ **Oscillatory NG**

} Oscillations : axion monodromy, features in potential.

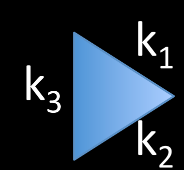
- ~~Bunch Davies Vacuum~~ **Flattened NG**

} Flattened: non BD vacuum



- ~~Canonical Kinetic Term~~ **Equilateral NG**

} Equilateral:
DBI, k-inflation
f_{NL} = O(10-100)



+ Isocurvature modes

Cf talks by Silverstein, Tolley, Vernizzi

Temperature bispectrum

$$B_{\ell_1\ell_2\ell_3} = f^{m_1 m_2 m_3}_{\ell_1\ell_2\ell_3} \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle$$

Primordial bispectrum

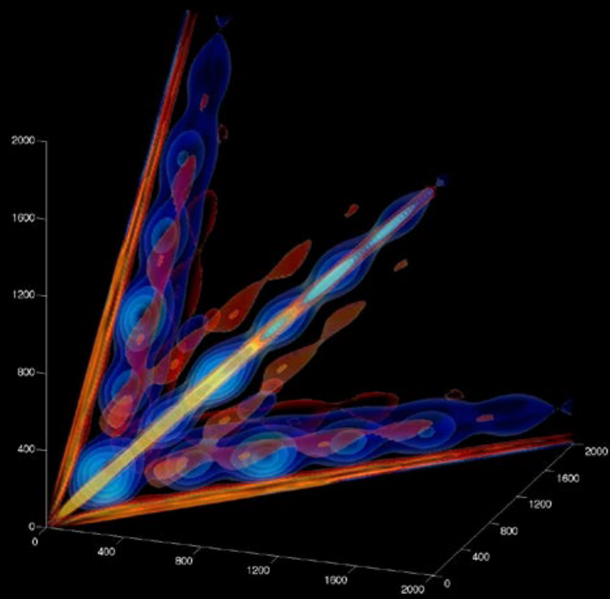
Transfer functions (Baryon oscillations)

$$B^{\rm th}_{\ell_1\ell_2\ell_3} = \left(\frac{2}{\pi}\right)^3 \int_0^\infty r^2 dr \int dk_1 dk_2 dk_3 (k_1 k_2 k_3)^2 B_\Phi(k_1, k_2, k_3) \Delta_{\ell_1}(k_1)\Delta_{\ell_2}(k_2)\Delta_{\ell_3}(k_3)$$
$$\times j_{\ell_1}(k_1 r) j_{\ell_2}(k_2 r) j_{\ell_3}(k_3 r) \int d\Omega Y_{l_1 m_1}(\Omega) Y_{l_2 m_2}(\Omega) Y_{l_3 m_3}(\Omega)$$

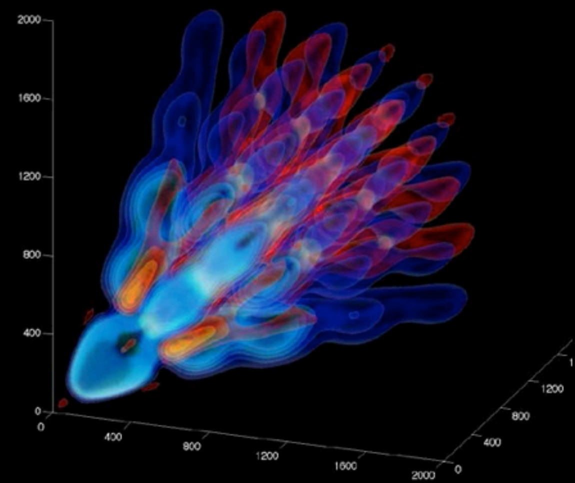
Temperature bispectrum

Geometrical part: from k space to ℓ space

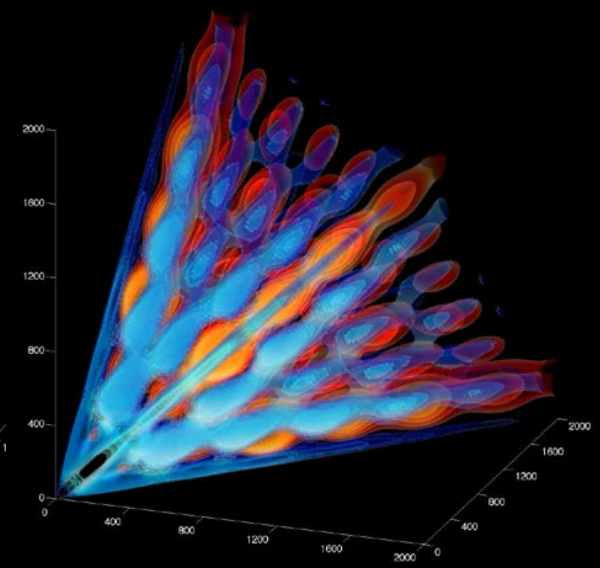
Reduced bispectra from: Liguori, Sefusatti, Fergusson, Shellard : 1001.4707



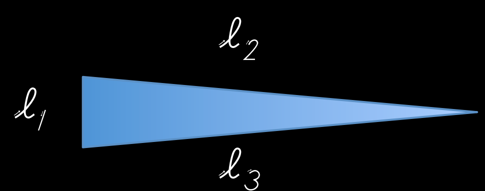
Local

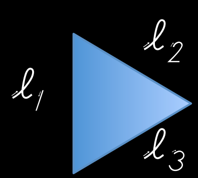


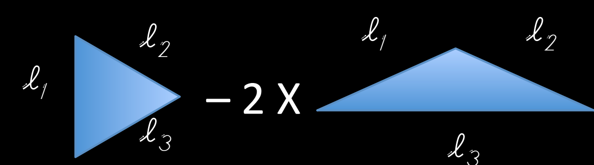
Equilateral



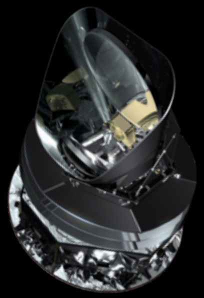
Orthogonal







Ortho. = Equil. – 2 X Flat.

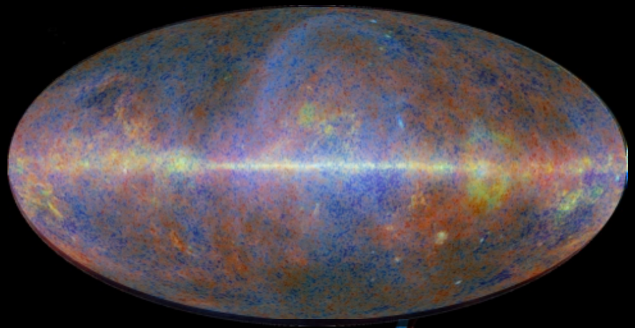


2. Planck 2015

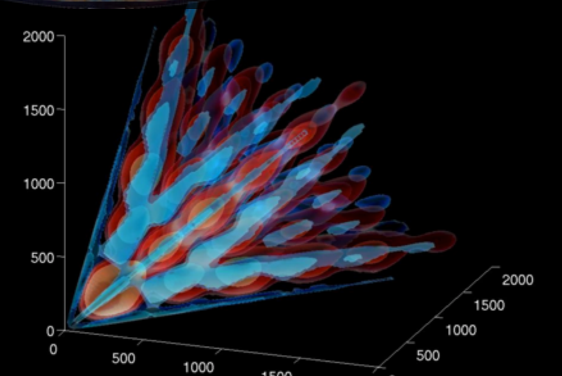
2.a. Systematics, validation, etc.

Late time – non primordial

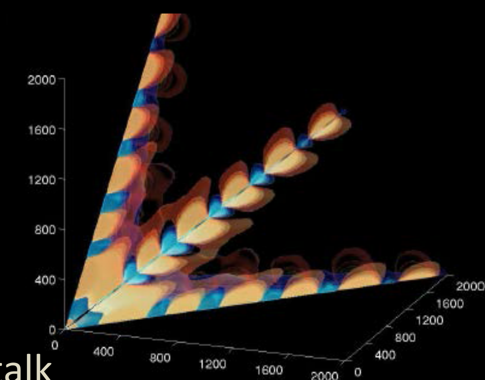
"Astrophysical" systematics



- Galaxy
  (Component separation + mask seems to clean most of it)
- Diffuse point sources
  (Flat bispectrum, detected, no impact on PNG)
- ISW-lensing cf. L. Perotto's talk
  (Biases the measurement, we correct for it using model by Lewis et al 2011)
- new Infrared Background
  (Prescription by Lacasa et al 2014, not detected, no impact on PNG)
- new Cosmic Rays
  (Based on simulations, effect is negligible)
- ✗ (not yet) 2^{nd} order effects at recombination
  (TBD, but expected below Planck sensitivity) cf. F. Vernizzi's talk
- …



Figures from Liguori et al. : 1001.4707



Other checks

- Agreement between different estimators ✔

- Validation on simple simulations with input NG ✔
- Validation on realistic Planck Simulations ✔

- Independence on the component separation method ✔
- Independence on the sky coverage ✔

- Stability in harmonic domain (varying ℓ_{max}) ✔

2.a. Results

f_{NL}

Temperature only

$$f_{\rm NL}^{\rm local} = 2.5 \pm 5.7$$

$$f_{\rm NL}^{\rm equil} = -16 \pm 70$$

$$f_{\rm NL}^{\rm ortho} = -34 \pm 33$$

Results obtained using the KSW method

Temperature & E polarization

(preliminary, no low-ell (<40) polarisation)

$$f_{\rm NL}^{\rm local} = 0.8 \pm 5.0$$

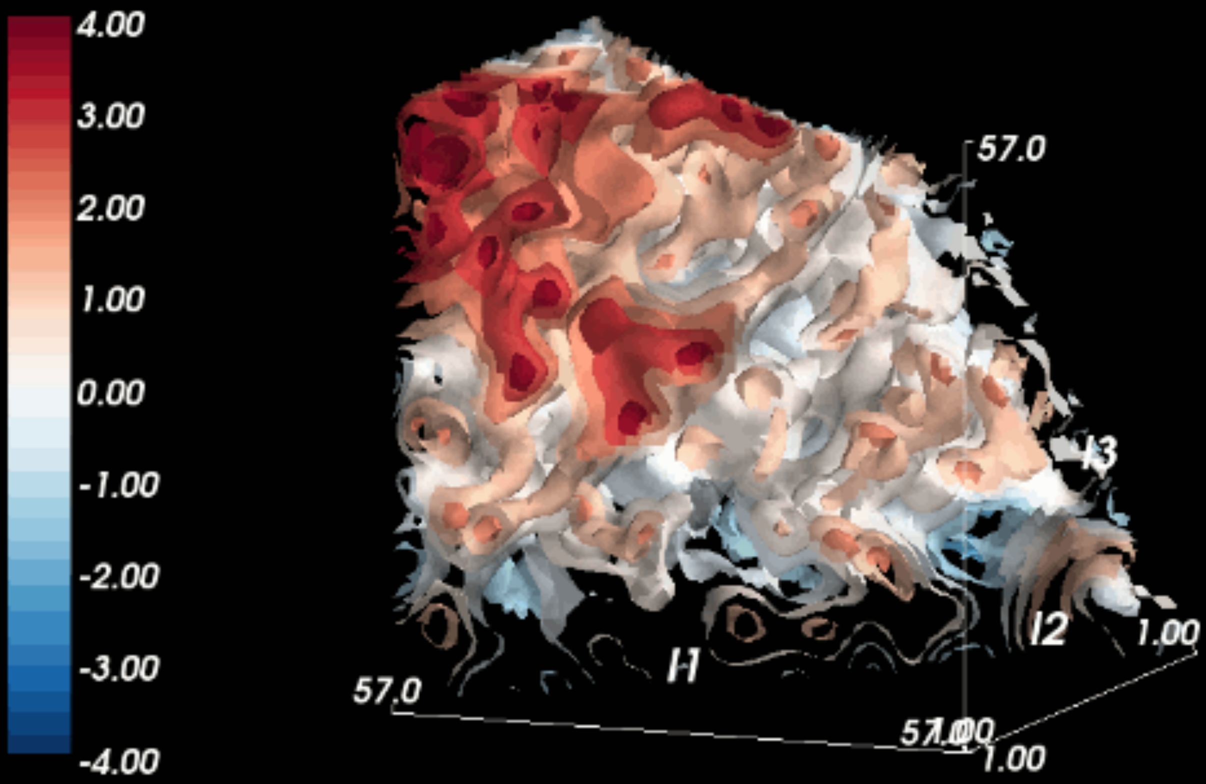
$$f_{\rm NL}^{\rm equil} = -4 \pm 43$$

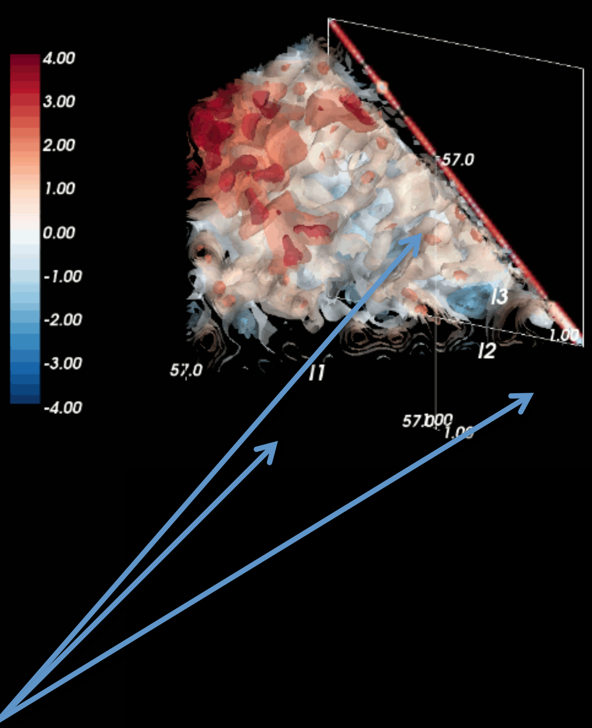
$$f_{\rm NL}^{\rm ortho} = -26 \pm 21$$

+ many other shapes
+ isocurvature
+ oscillatory bispectra (hint of signal)

f_{NL} analysis is vaslty compatible with a nearly Gaussian universe, i.e. simplest models of inflation.

Planck Smoothed Bispectrum

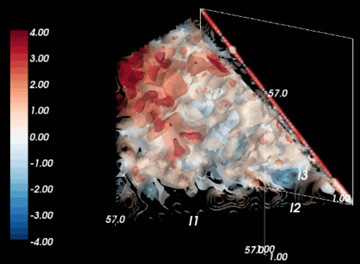




Bin
number

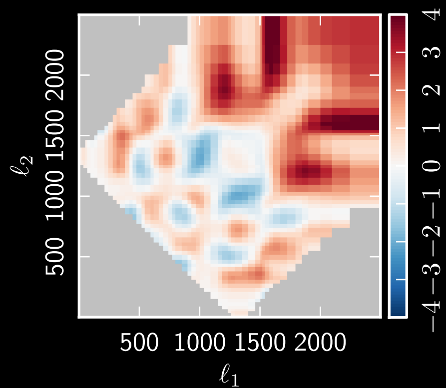
Here: 57 bins $\ell \in [2, 2500]$

Results obtained using
the binned bispectrum

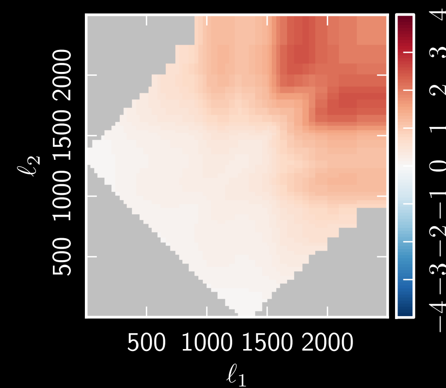


Smoothed Bispectrum

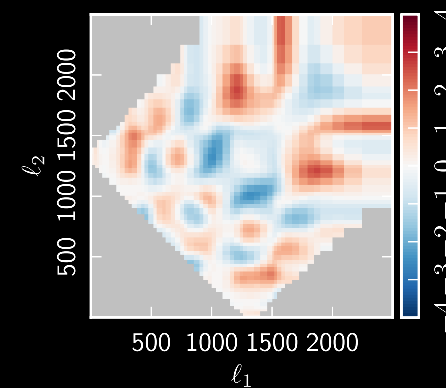
Total bispectrum



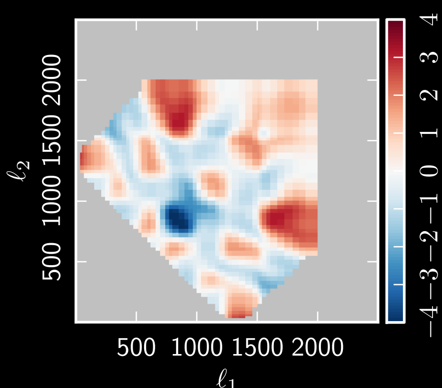
point source bispectrum



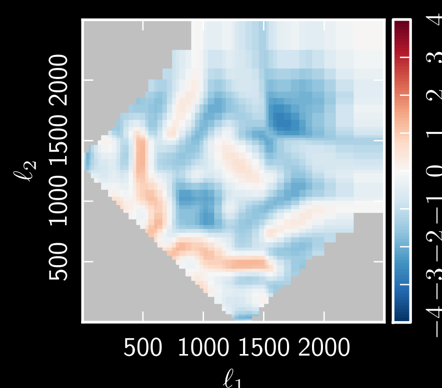
point source bispectrum removed



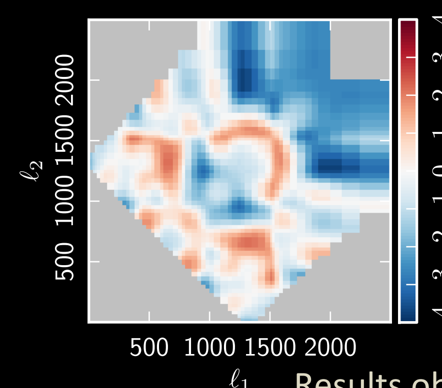
EEE



'TEE'



'TTE'



Results obtained using the binned bispectrum

Conclusion

- Inflation is needed as an early universe *add-on* to Big-Bang theory.
- Many models produce non-Gaussian signatures in the CMB.

- Planck 2015 results are more robust, and include part of the E polarization signal: $f_{\rm NL}^{\rm local} = 0.8 \pm 5.0$, $f_{\rm NL}^{\rm equil} = -4 \pm 43$, $f_{\rm NL}^{\rm ortho} = -26 \pm 21$
- Many more shapes, hints to be investigated (oscillations).
- Data are compatible with the simplest models of inflation.

- Future:
  - Planck full polarization.
  - Large-Scale Structures (SKA, Euclid, SPHEREx, ...).
  - CMB distortions ?

Cf O. Doré talk

Cảm ơn !

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.