Non-Gaussianity with Planck :

f_{NL} and the smoothed bispectrum using the binned bispectrum estimator

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On behalf of the Planck collaboration

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New Light in Cosmology from the CMB, Trieste

Outline

1) Inflation

2) Non Gaussianity & Bispectrum

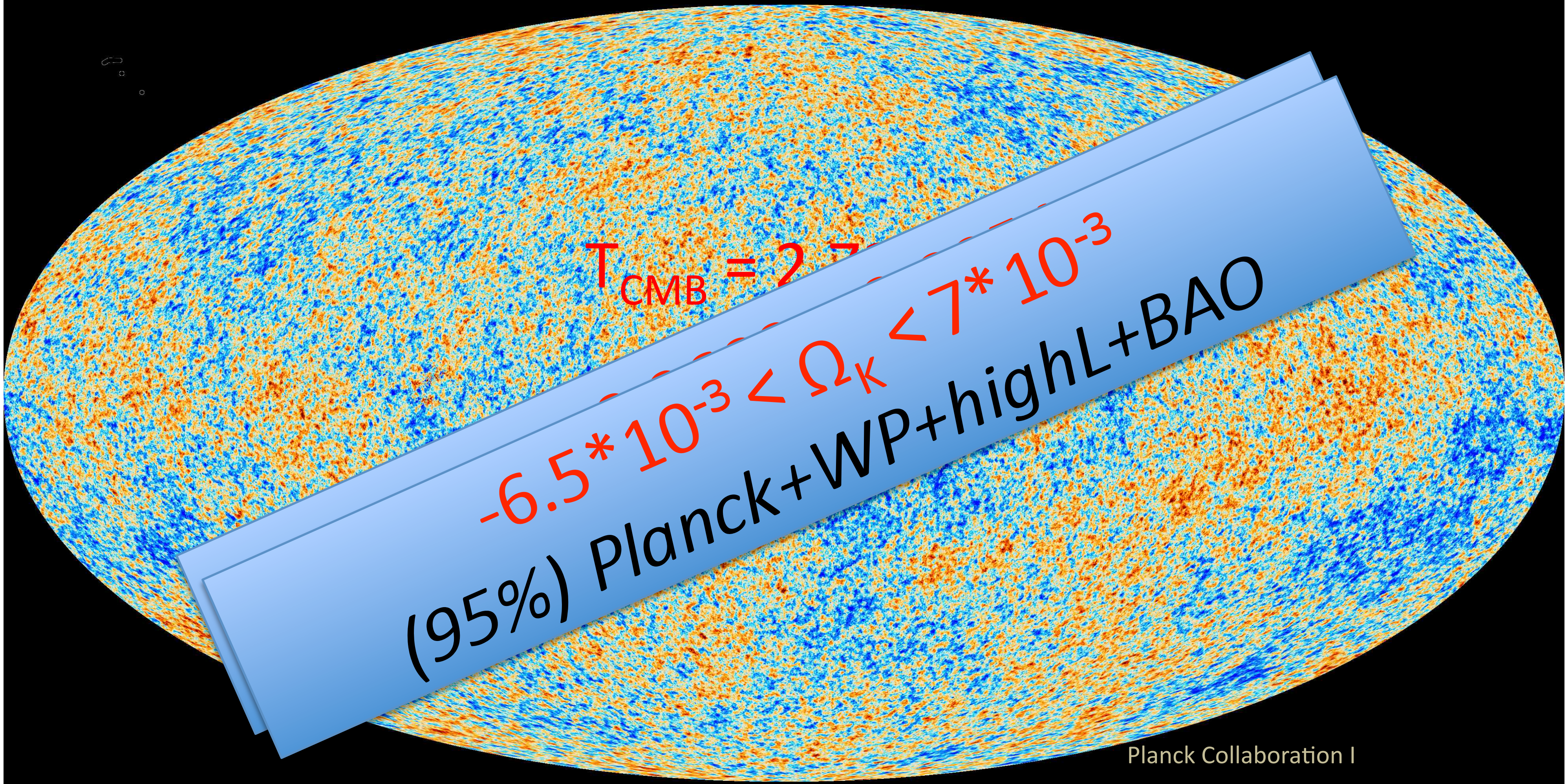
3) The binned bispectrum f_{NL} estimator

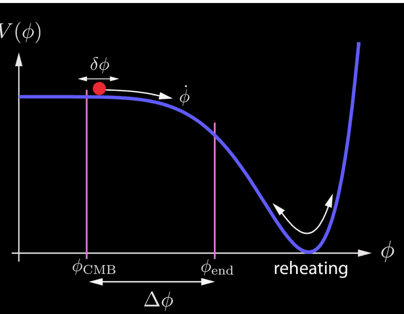
4) Results

1. Inflation

Results so far

- Almost homogeneous:





Cf. D.Bauman: 0907.5424

"Simplest" Inflation

- ~~Single Field~~ **Local NG**
- Slow roll
- ~~Bunch Davies Vacuum~~ **Flattened NG**
- ~~Canonical Kinetic Term~~ **Equilateral NG**

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

2. Non Gaussianity & Bispectrum

Observed bispectrum

3pt correlation function ←Fourier→ Bispectrum

$$B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3} = < a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} >$$

Angular Bispectrum

$$B_{\ell_1 \ell_2 \ell_3} = \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell_3+1)}{4\pi}} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ 0 & 0 & 0 \end{pmatrix} \sum_{m_1 m_2 m_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3}$$

rotationally-invariant reduced Bispectrum

Observed bispectrum estimator

3pt correlation function ←Fourier→ Bispectrum

$$\hat{B}_{\ell_1\ell_2\ell_3} = \int d\Omega\, T^{obs}_{\ell_1}(\Omega) T^{obs}_{\ell_2}(\Omega) T^{obs}_{\ell_3}(\Omega)$$

where

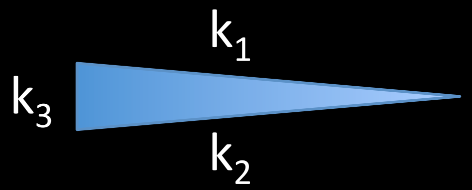
$$T^{\rm obs}_{\ell}(\Omega) = \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\Omega)$$

Primordial bispectrum

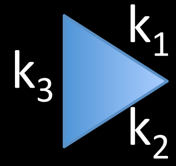
$$< \phi(\mathbf{k_1})\phi(\mathbf{k_2})\phi(\mathbf{k_3}) >= (2\pi)^3\delta^3(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})B_\phi(k_1,k_2,k_3)$$

Primordial gravitational potential

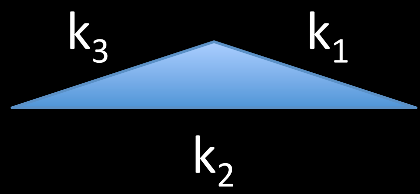
$$B_\phi(k_1,k_2,k_3) = \sum_{i\in\text{shape}} f_{NL}^{(i)}F^{(i)}(k_1,k_2,k_3)$$



Squeezed / local: Multifields, curvaton, inhomogeneous reheating.
Late-time: ISW x lensing



Equilateral: non-standard kinetic terms



flattened: non Bunch-Davies vacuum

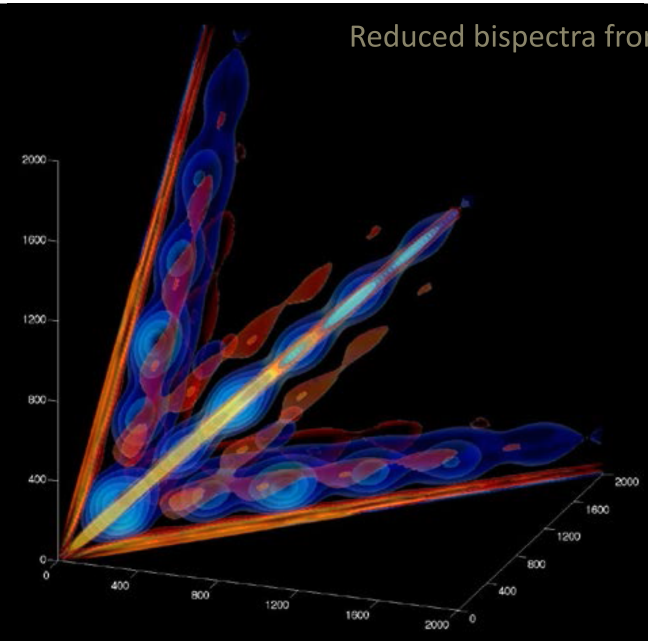
Primordial bispectrum

Transfer functions

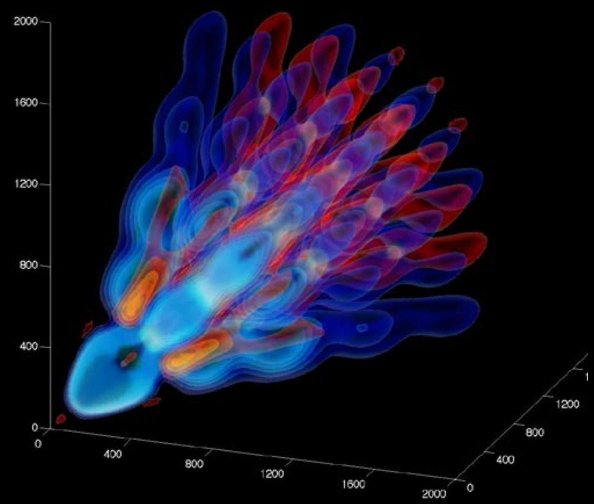
$$B_{\ell_1\ell_2\ell_3} = \left(\frac{2}{\pi}\right)^3 \int_0^\infty x^2 dx \int dk_1 dk_2 dk_3 (k_1k_2k_3)^2 B_\phi(k_1, k_2, k_1)\Delta_{\ell_1}(k_1)\Delta_{\ell_2}(k_2)\Delta_{\ell_3}(k_3)$$
$$\times j_{\ell_1}(k_1x) j_{\ell_2}(k_2x) j_{\ell_3}(k_3x) \int d\Omega \, Y_{\ell_1 m_1}(\Omega) Y_{\ell_2 m_2}(\Omega) Y_{\ell_3 m_3}(\Omega)$$

Temperature bispectrum

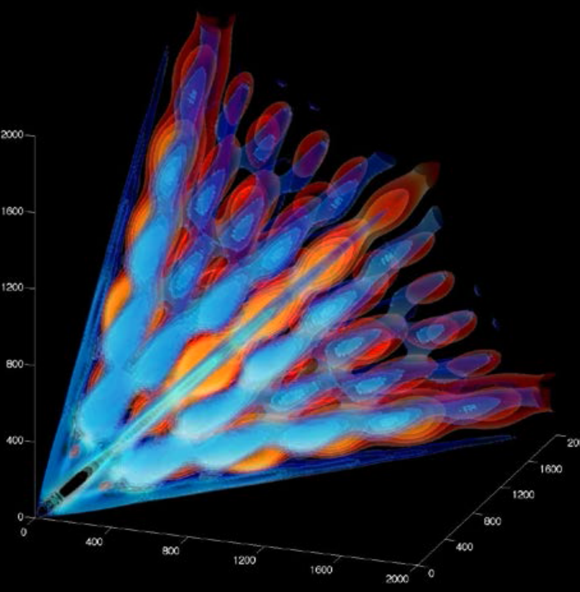
Reduced bispectra from: Liguori, Sefusatti, Fergusson, Shellard : arXiv:1001.4707



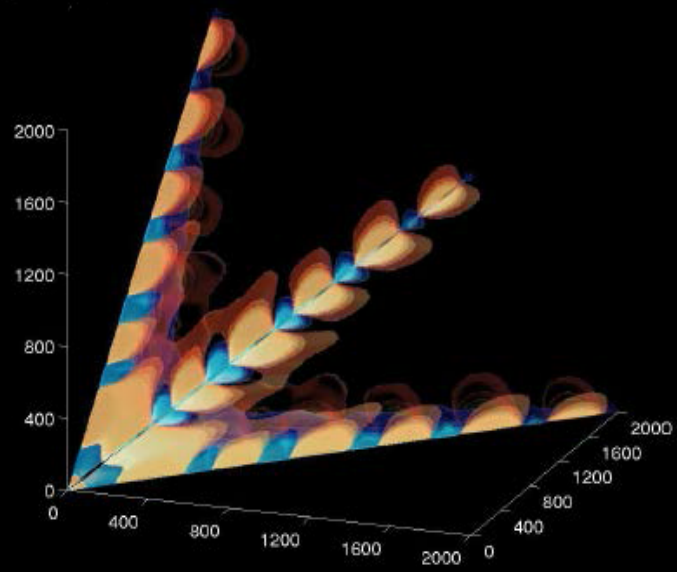
Local



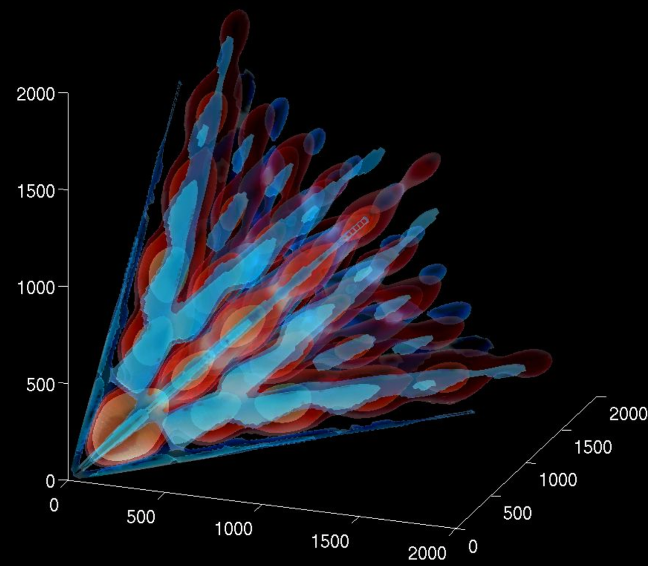
Equilateral



Orthogonal



Lensing x ISW



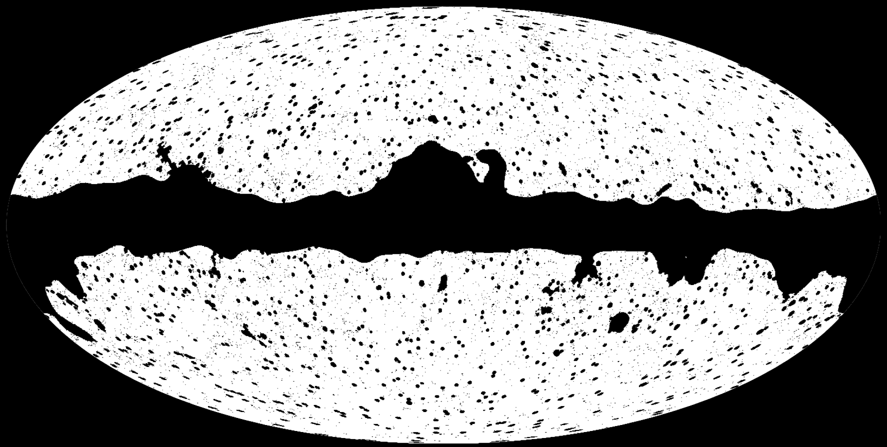
Unresolved point sources

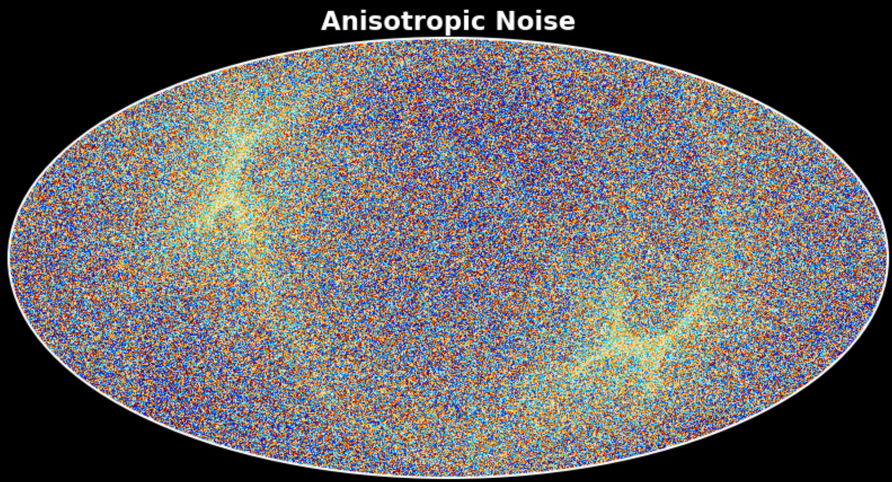
f_{NL}

$$\widehat{f}_{NL} = \frac{1}{N} \sum_{\ell_1\ell_2\ell_3=\ell_{min}}^{\ell_{max}} \frac{B^{obs}_{\ell_1\ell_2\ell_3} B^{th\ (f_{NL}=1)}_{\ell_1\ell_2\ell_3}}{\mathrm{Var}_{\ell_1\ell_2\ell_3}}$$

$$\mathrm{Var}_{\ell_1\ell_2\ell_3} \simeq (b^2_{\ell_1} C_{\ell_1} + N_{\ell_1})(b^2_{\ell_2} C_{\ell_2} + N_{\ell_2})(b^2_{\ell_3} C_{\ell_3} + N_{\ell_3})$$

Anisotropic noise and mask





Linear correction

$$B^{\mathrm{lin}}_{\ell_1\ell_2\ell_3} = \sum_p \left[T^{\mathrm{obs}}_{\ell_1} < T^{\mathrm{G}}_{\ell_2} T^{\mathrm{G}}_{\ell_3} > + T^{\mathrm{obs}}_{\ell_2} < T^{\mathrm{G}}_{\ell_1} T^{\mathrm{G}}_{\ell_3} > + T^{\mathrm{obs}}_{\ell_3} < T^{\mathrm{G}}_{\ell_1} T^{\mathrm{G}}_{\ell_2} >\right]$$

Averaged on gaussian maps with noise, beam and mask as in observed maps (typically O(100))

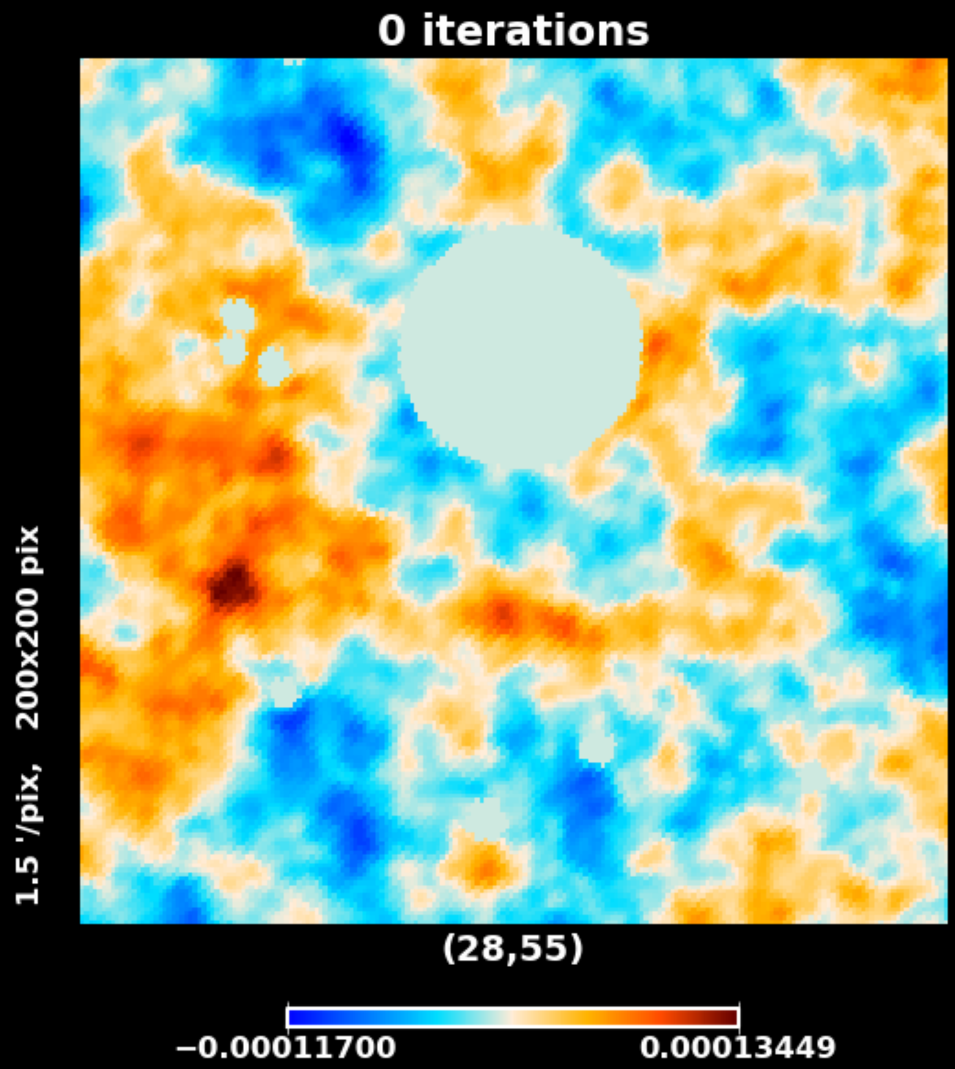
$$B^{\mathrm{obs}}_{\ell_1\ell_2\ell_3} \rightarrow B^{\mathrm{obs}}_{\ell_1\ell_2\ell_3} - B^{\mathrm{lin}}_{\ell_1\ell_2\ell_3}$$

Babich, D: 2005, Phys. Rev. D, 72, 043003, astro-ph/0503375

Creminelli, P., Nicolis, A., Senatore, L., Tegmark, M., & Zaldarriaga, M: 2006, JCAP, 5, 4, astro-ph/0509029

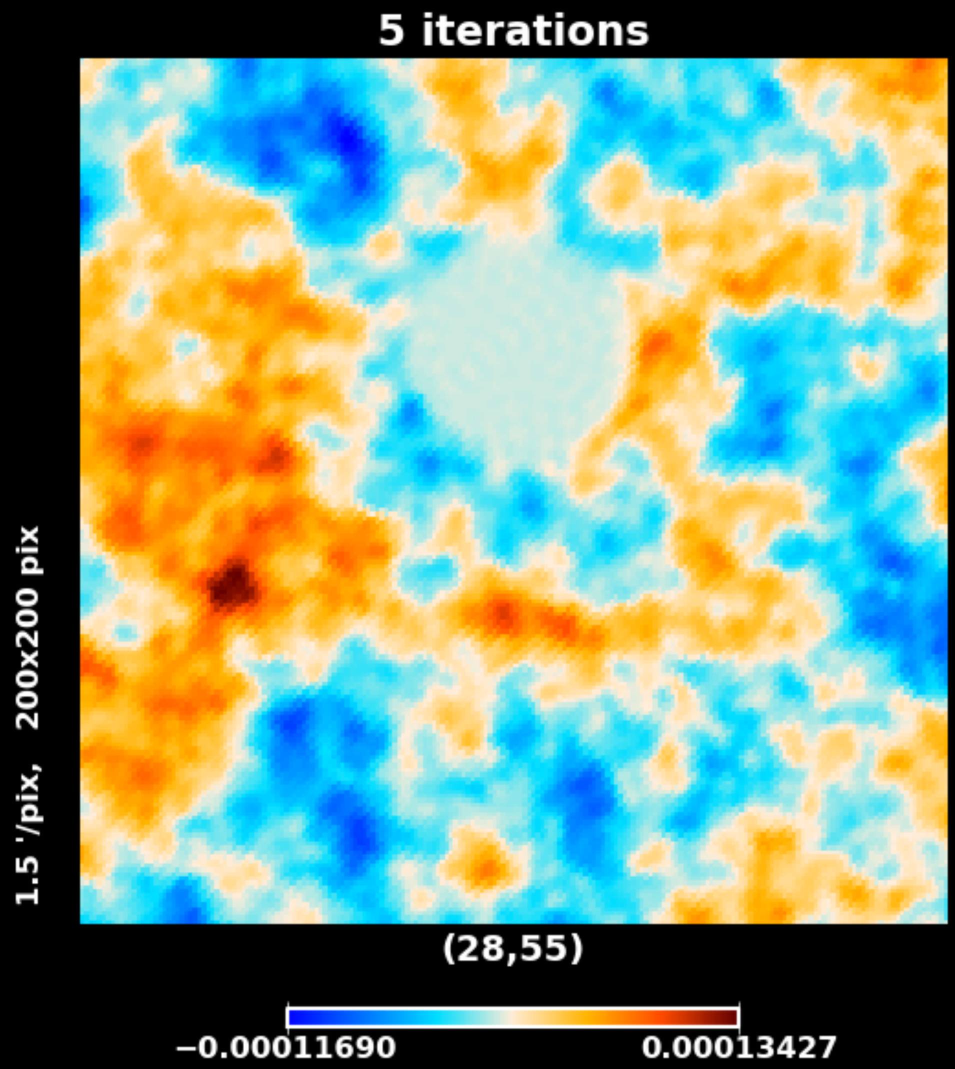
Inpainting

Diffusive inpainting: iterative, average over 8 neighboring pixels



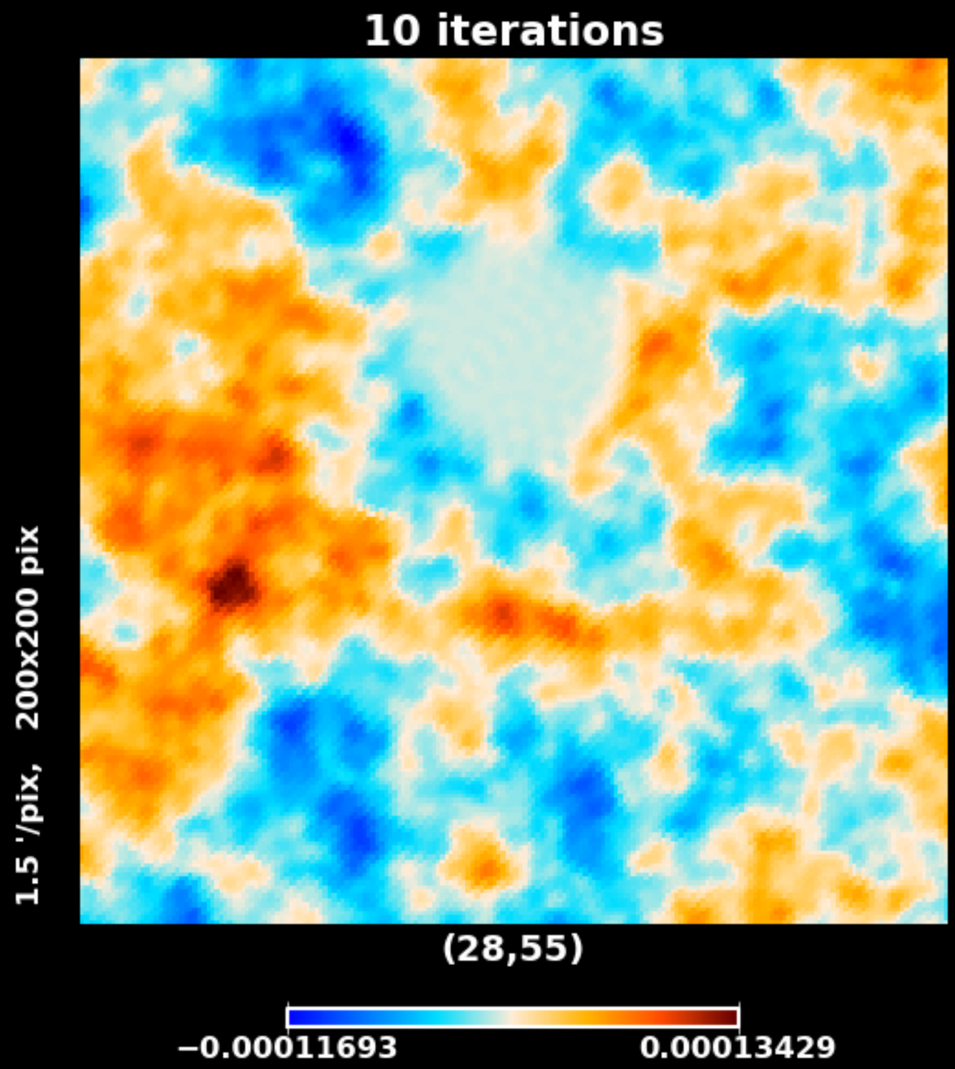
Inpainting

Diffusive inpainting: iterative, average over 8 neighboring pixels



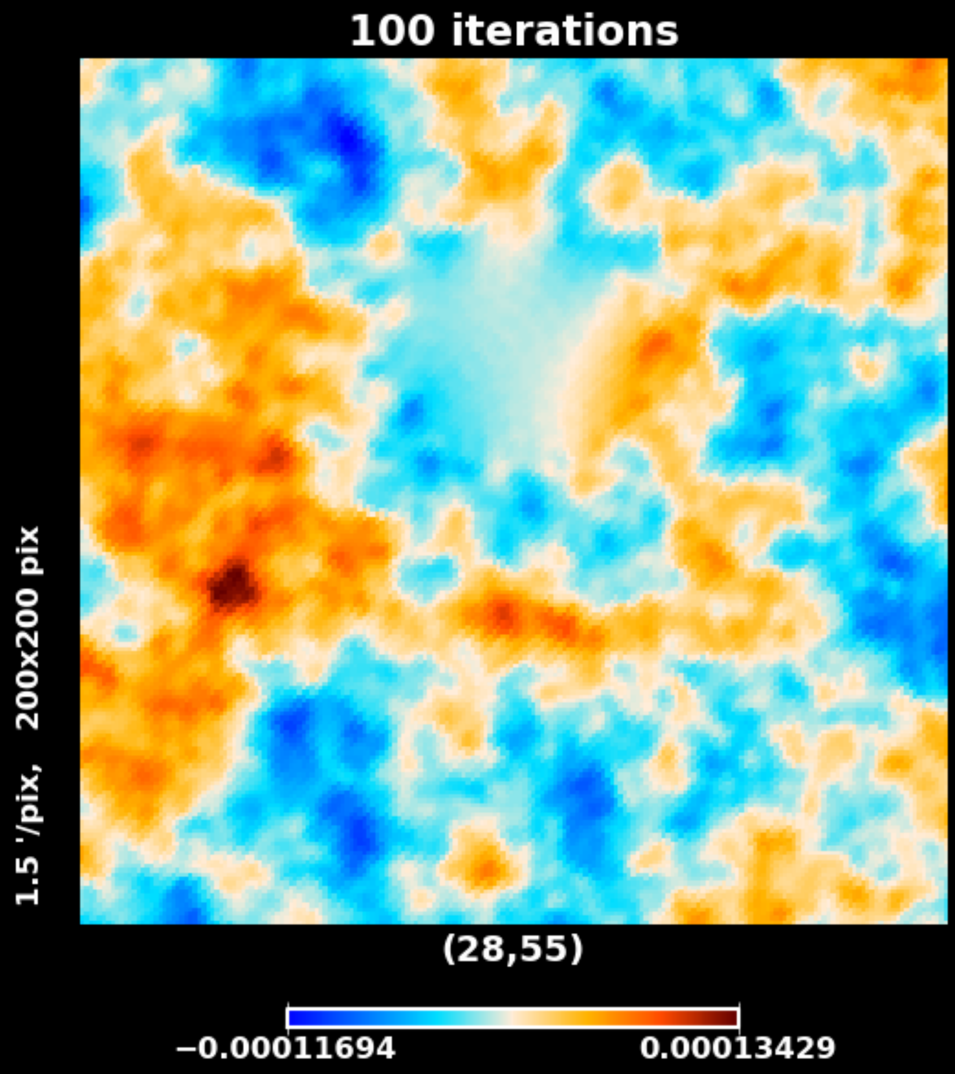
Inpainting

Diffusive inpainting: iterative, average over 8 neighboring pixels



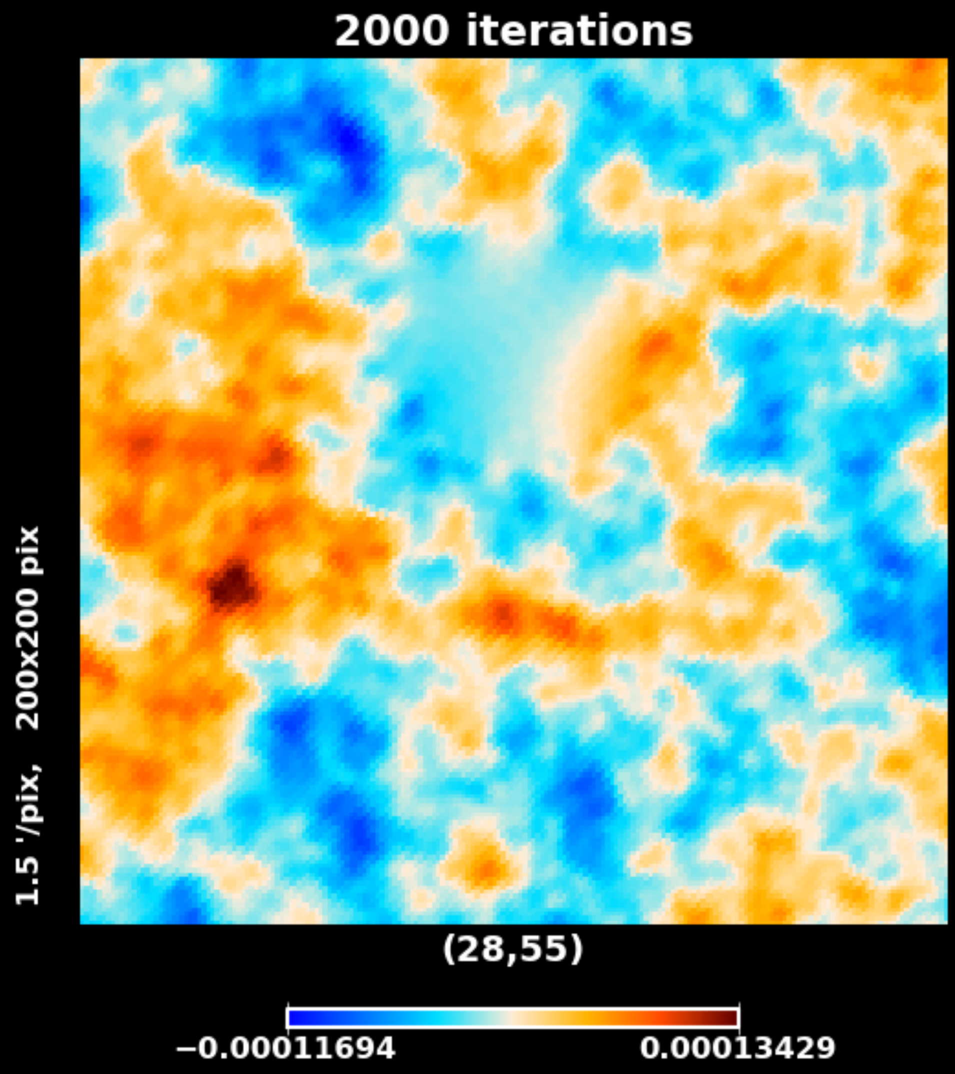
Inpainting

Diffusive inpainting: iterative, average over 8 neighboring pixels



Inpainting

Diffusive inpainting: iterative, average over 8 neighboring pixels



f_{NL}

Computationally impossible with current CPUs
(2500*200 Gb= 500 Tb)

$$\widehat{f}_{NL} = \frac{1}{N} \sum_{\ell_1\ell_2\ell_3=\ell_{min}}^{\ell_{max}} \frac{(B^{\rm obs}_{\ell_1\ell_2\ell_3} - B^{\rm lin}_{\ell_1\ell_2\ell_3})B^{th(f_{NL}=1)}_{\ell_1\ell_2\ell_3}}{{\rm Var}_{\ell_1\ell_2\ell_3}}$$

$$Var_{\ell_1\ell_2\ell_3} = (b^2_{\ell_1}C_{\ell_1} + N_{\ell_1})(b^2_{\ell_2}C_{\ell_2} + N_{\ell_2})(b^2_{\ell_3}C_{\ell_3} + N_{\ell_3})$$

3. Binned Bispectrum

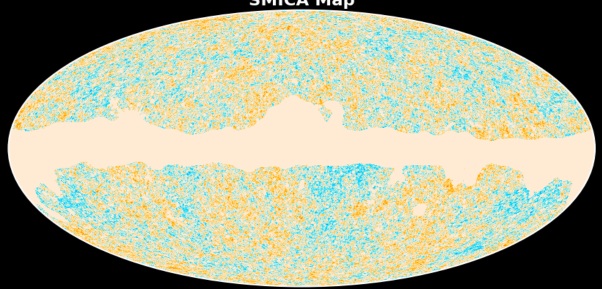
See: M.Bucher, B.Van Tent and C.S.Carvalho : 2010, MNRAS, 407, 2193, arXiv:0911.1642

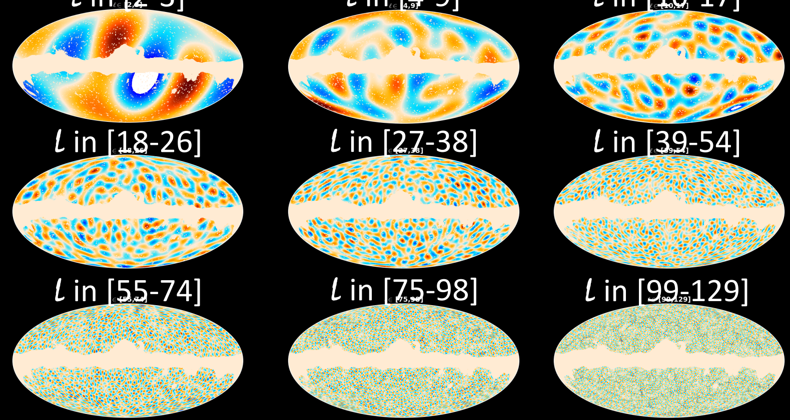
Other methods : - Komatsu, Spergel, Wandelt : 2005, APJ, 634, 14, astro-ph: 0305189

- Modal: Fergusson, Liguori, Shellard : 2010, PRD, 82, 2, arXiv:0912.5516

Binned Bispectrum

$$T_\ell^{\rm obs}(\Omega) \longrightarrow T_i^{\rm obs}(\Omega) = \sum_{\ell \in \text{bin i}} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\Omega)$$





$T^{\rm obs}(p)$ $\qquad$ $T_i^{\rm obs}(p) \times N_{bin}$

$$B^{\rm obs}_{i_1 i_2 i_3} \propto \sum_p T^{\rm obs}_{i_1}(p) T^{\rm obs}_{i_2}(p) T^{\rm obs}_{i_3}(p)$$

Linear correction

$$B^{\rm lin}_{i_1 i_2 i_3} = \sum_p \left[T^{\rm obs}_{i_1} < T^{\rm G}_{i_2} T^{\rm G}_{i_3} > + T^{\rm obs}_{i_2} < T^{\rm G}_{i_1} T^{\rm G}_{i_3} > + T^{\rm obs}_{i_3} < T^{\rm G}_{i_1} T^{\rm G}_{i_2} > \right]$$

Averaged on gaussian maps with noise, beam and mask as in observed maps (~200)

$$B^{\rm obs}_{i_1 i_2 i_3} \rightarrow B^{\rm obs}_{i_1 i_2 i_3} - B^{\rm lin}_{i_1 i_2 i_3}$$

Babich, D: 2005, Phys. Rev. D, 72, 043003, astro-ph/0503375
Creminelli, P., Nicolis, A., Senatore, L., Tegmark, M., & Zaldarriaga, M: 2006, JCAP, 5, 4, astro-ph/0509029

Binned Bispectrum

$$B^{th}_{i_1 i_2 i_3} = \sum_{\ell_1 \in \text{bin } \mathrm{i}_1} \sum_{\ell_2 \in \text{bin } \mathrm{i}_2} \sum_{\ell_3 \in \text{bin } \mathrm{i}_3} B^{th}_{\ell_1 \ell_2 \ell_3}$$

$$\widehat{f}_{NL} = \frac{1}{N} \sum_{i_1 i_2 i_3 = i_{min}}^{i_{max}} \frac{(B^{\text{obs}}_{i_1 i_2 i_3} - B^{\text{lin}}_{i_1 i_2 i_3}) B^{th(f_{NL}=1)}_{i_1 i_2 i_3}}{\text{Var}_{i_1 i_2 i_3}}$$

In the f_{NL} analysis we used 51 bins, that were optimized to get the weakest variance increase compared to non-binned case.

Smoothed Binned Bispectrum

- We want to look for significant features in the bispectrum of the data without theoretical prior on the expected NG signal.

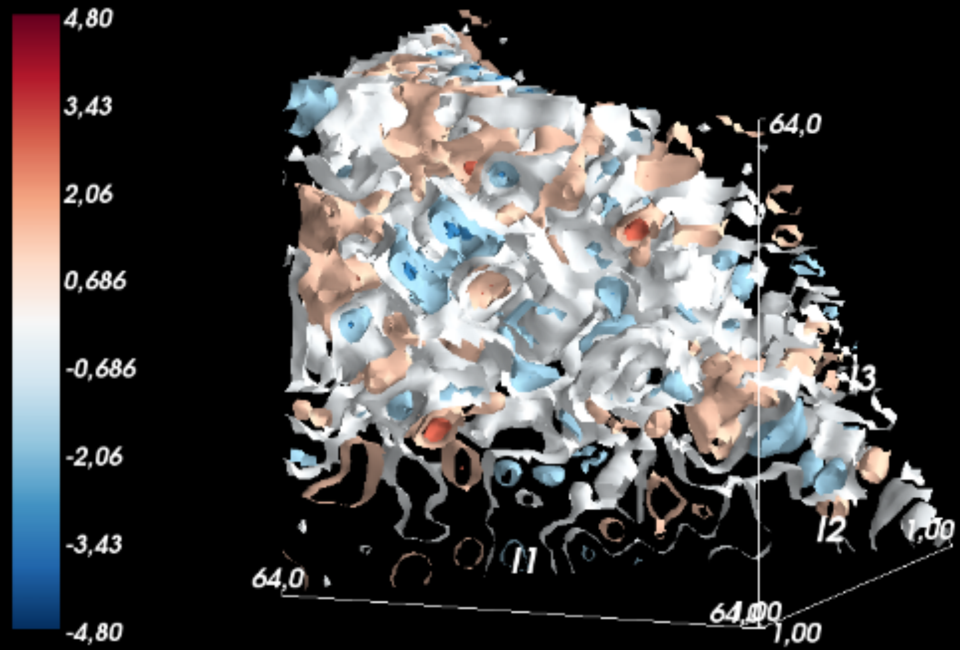
- We look at the SNR in the binned bispectrum :

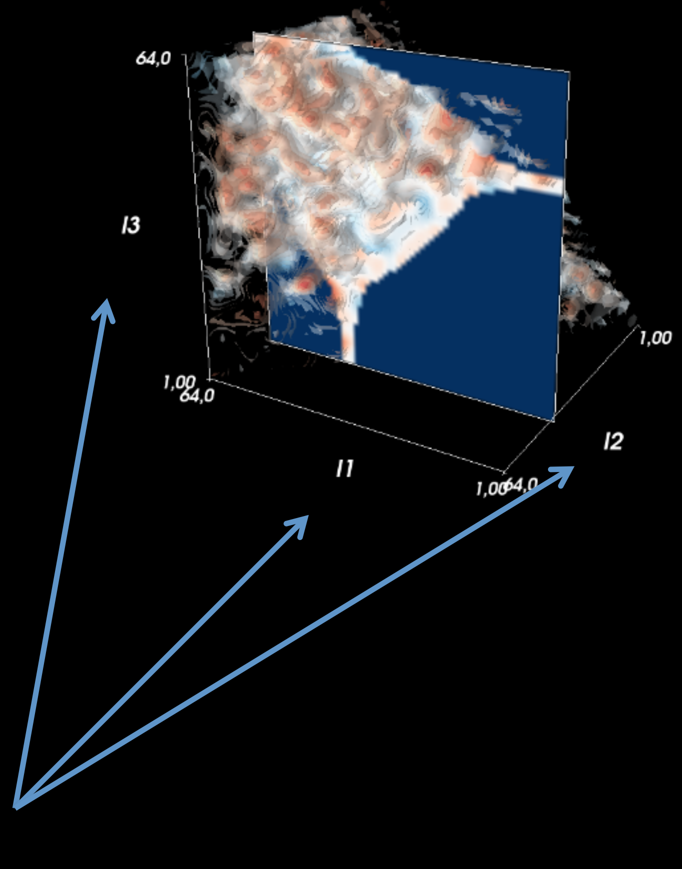
$$\frac{(B^{\mathrm{obs}}_{i_1 i_2 i_3} - B^{\mathrm{lin}}_{i_1 i_2 i_3})}{\sqrt{\mathrm{Var}_{i_1 i_2 i_3}}}$$

- We smooth the bispectrum in bin space with a gaussian kernel to make visible a signal that is coherent between bins.

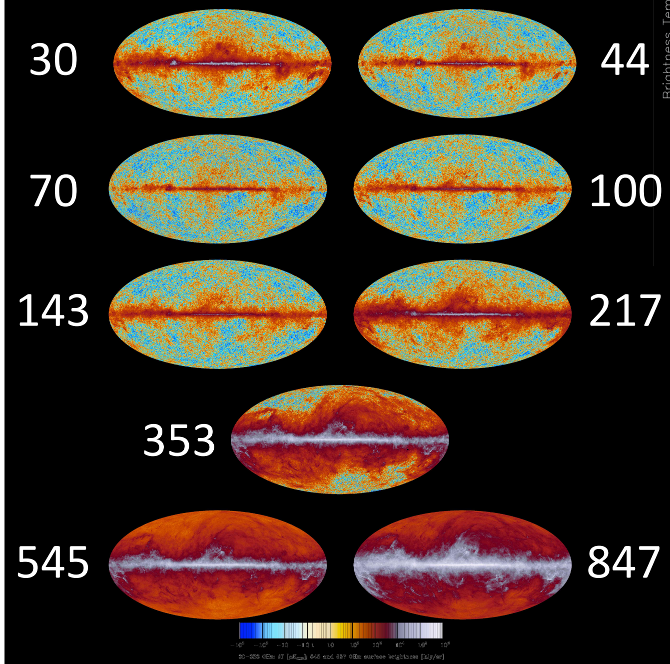
64 bins $\ell \in [2, 2000]$

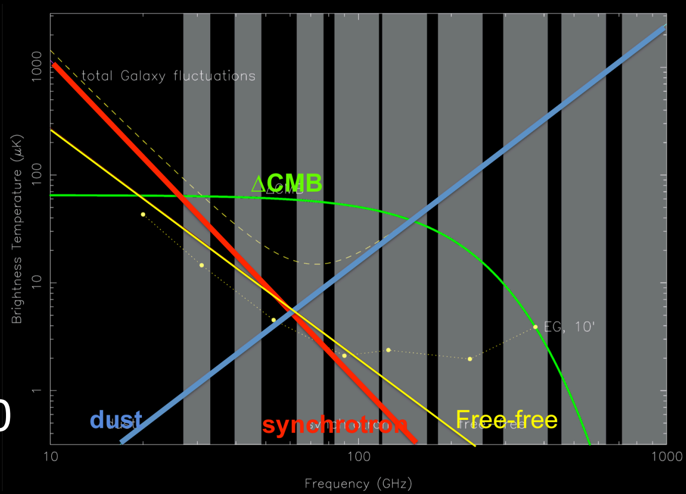
We have a 3D bispectrum, but slices are easier to study

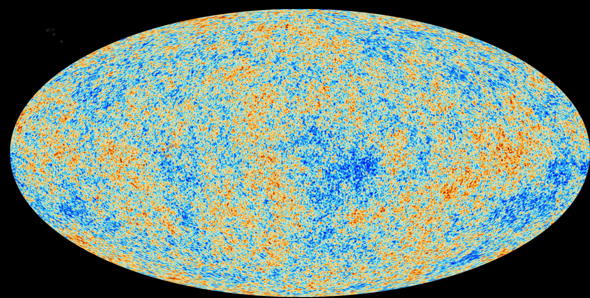




Component separation (snapshot)







SMICA

Spectral Matching ICA:
works in harmonic domain,
Resolution = 5’ (l_{max}=4000)

Using the Planck’s frequency coverage, we can separate foregrounds from the CMB

5. Results

Binned Bispectrum f_{NL}

	Independent				ISW-lensing subtracted		
	KSW	Binned	Modal		KSW	Binned	Modal
SMICA							
Local	9.8 ± 5.8	9.2 ± 5.9	8.3 ± 5.9	. . . . .	**2.7 ± 5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	−37 ± 75	−20 ± 73	−20 ± 77	. . . . .	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	−46 ± 39	−39 ± 41	−36 ± 41	. . . . .	**−25 ± 39**	−17 ± 41	−14 ± 42

	KSW	Binned
Diff point sources ($\times 10^{29}$) :	7.7 ± 1.5	7.7 ± 1.6
Lensing x ISW :	0.81±0.31	0.91 ± 0.37

« detection »

Cf Planck Collaboration XXIV

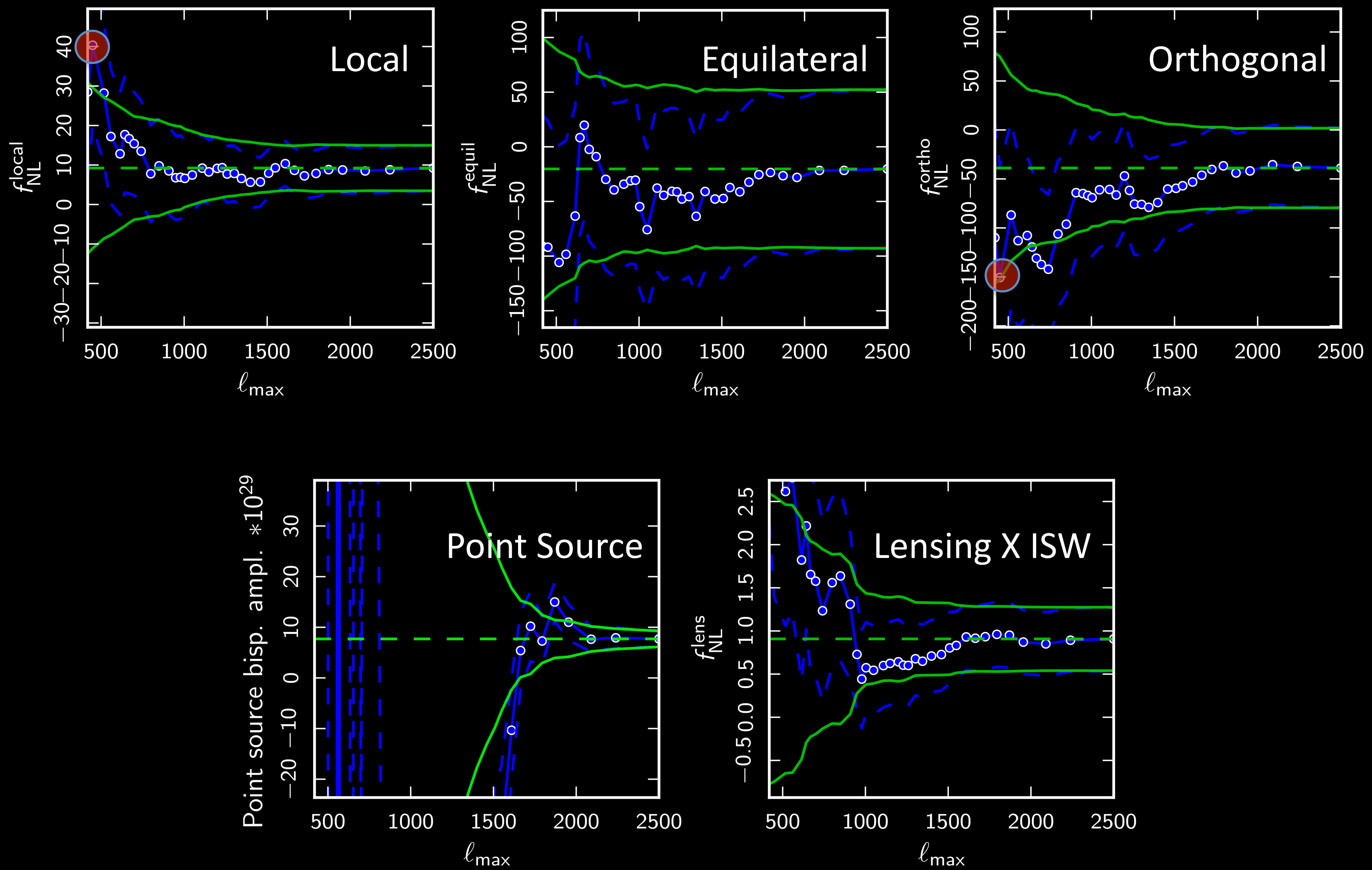
ℓ_{max} dependence

WMAP9

37.2±19.9

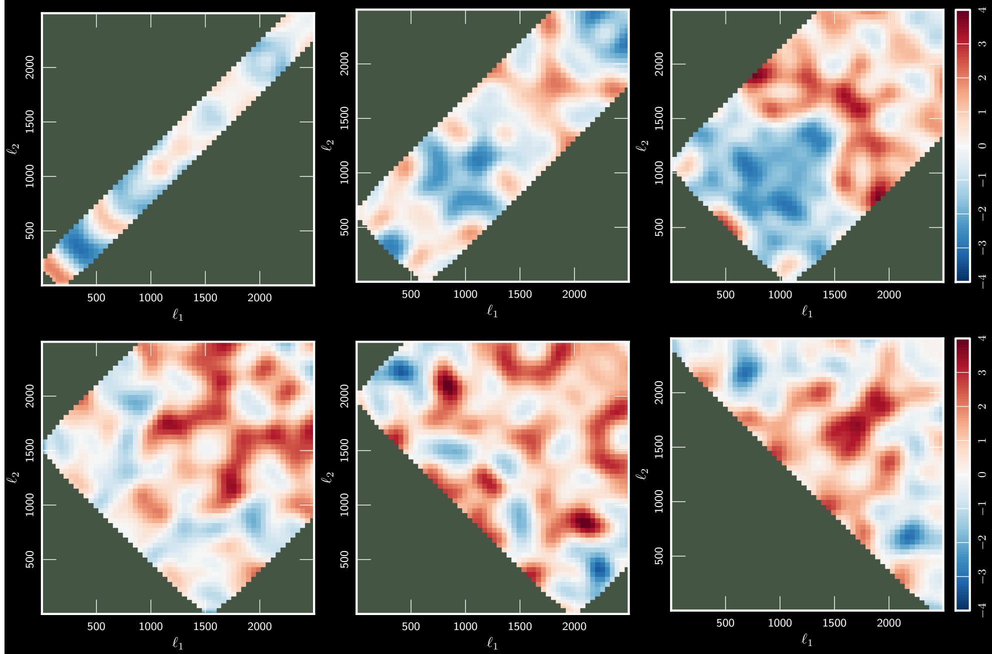
51 ± 136

−245 ± 100

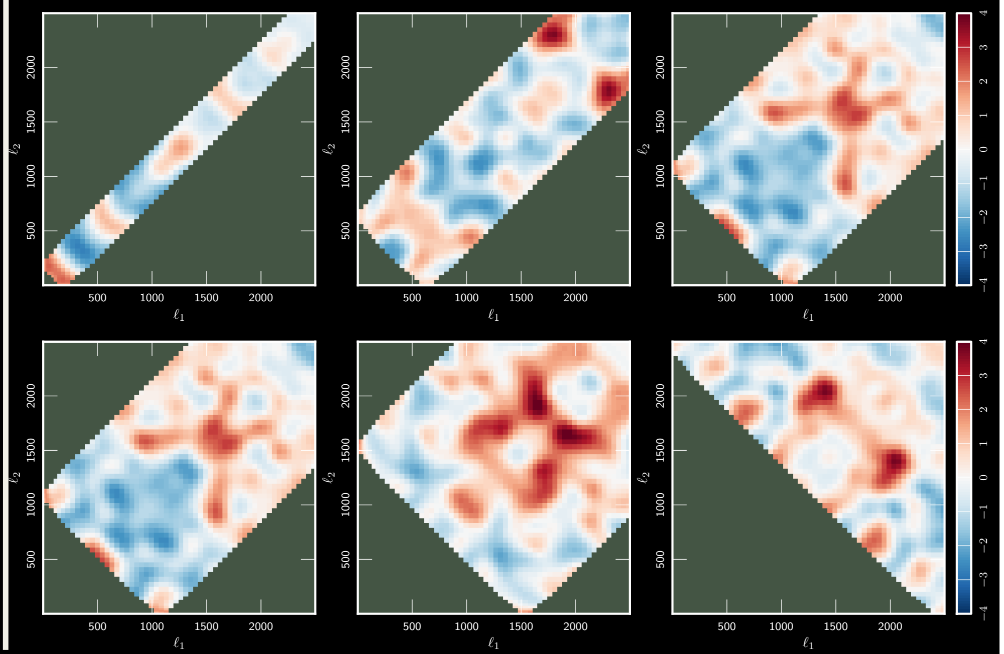


Smoothed Binned Bispectrum

SMICA smoothed bispectrum

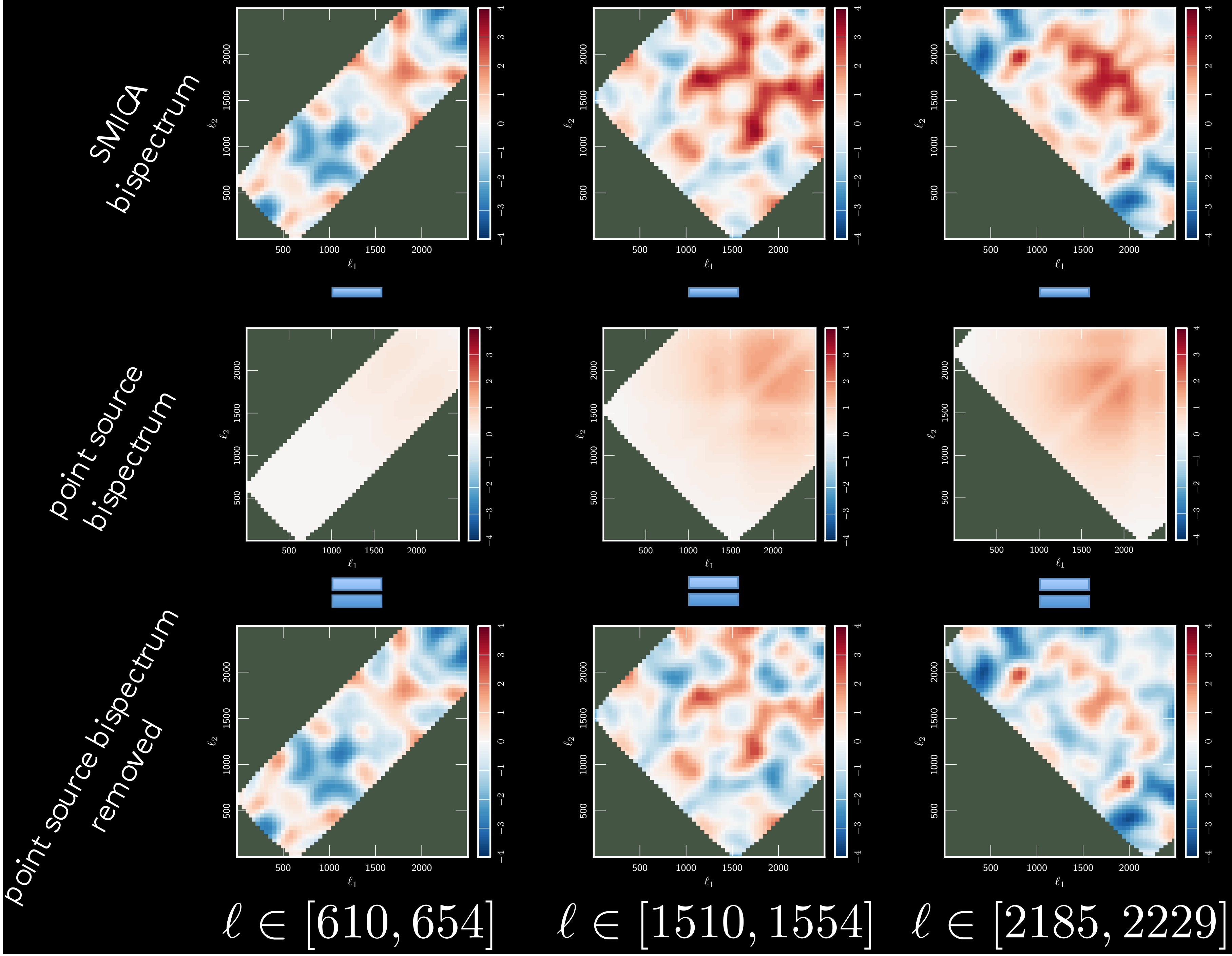


Raw 143Ghz smoothed bispectrum



Red: positive bispectrum → S/N < +4

Blue: Negative bispectrum → S/N > -4


SMICA bispectrum
point source bispectrum
point source bispectrum removed
$\ell \in [610, 654]$
$\ell \in [1510, 1554]$
$\ell \in [2185, 2229]$

Conclusion

- Binned Bispectrum allows a parametric (f_{NL}) and blind analysis of NG.

- No detection of local, equilateral and orthogonal NG, in agreement with other methods.
- Diffuse point source and lensing x ISW NG detected.

- We see the point sources NG at high l.

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.