Probing scale-dependent non-Gaussianities in the WMAP data using surrogates

Primordial non-Gaussianity: Theory Confronts Observations,
Ann Arbor, May 2011

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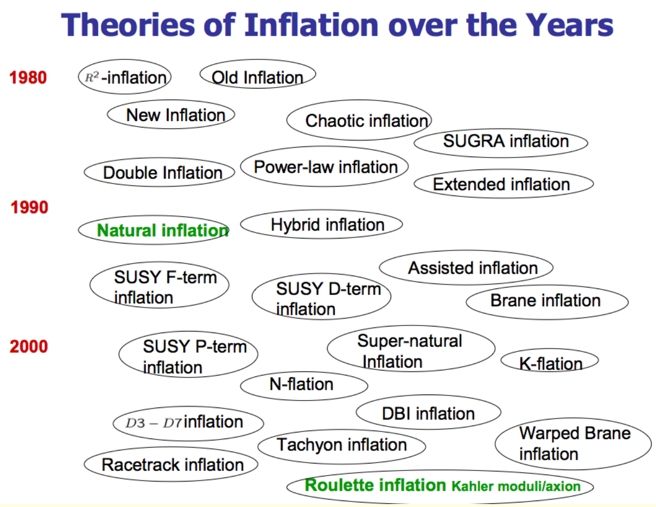
References:
C. Räth et al., PRL, 102, 131301, 2009; arXiv:0810.3805
C. Räth et al., MNRAS in press; arXiv:1012.2985

Motivations

„More shapes of non-Gaussianities (from inflation) than...stars in the sky."
(S. Matarrese, this meeting)



„I don't see a convergence of the theories."
(M. Rees, 2008)

„It doesn't matter how beautiful your theory is, it doesn't matter how smart you are.
If it doesn't agree with experiment, it's wrong."
(R. Feynman)

„The model is the data."
(C. Grebogi)
⇒ Method of surrogates (Theiler et al. 1992)

Model-independent („agnostic") test => „explorative data analysis", which is sensitive to *any* NG signatures (not „just" f_{nl} – models) and *any* other anomalies

Scaling indices for spherical data

Transformation of the data to a 3D point distribution:

Each „sky element" is characterised by two angles θ and φ (on the unit sphere) and its temperature.
Thus, one possible 3D representation of the WMAP data is given by:

$$x = (R + dR)\cos\varphi\sin\vartheta$$
$$y = (R + dR)\sin\varphi\sin\vartheta$$
$$z = (R + dR)\cos\vartheta$$

where:

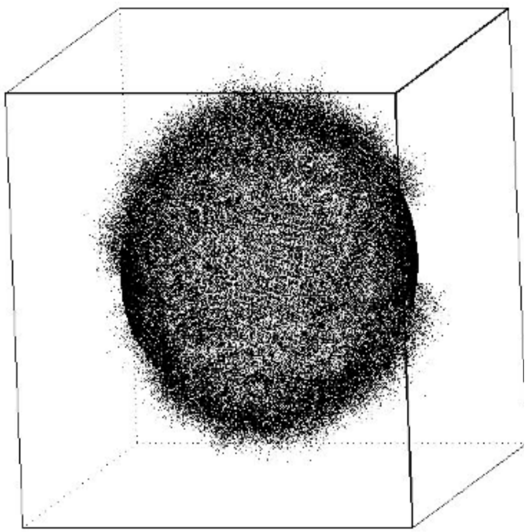
$$dR = a(r)\cdot(T - \langle T \rangle)/\sigma_T$$

=>Temperature fluctuations are transformed to variations in R-direction

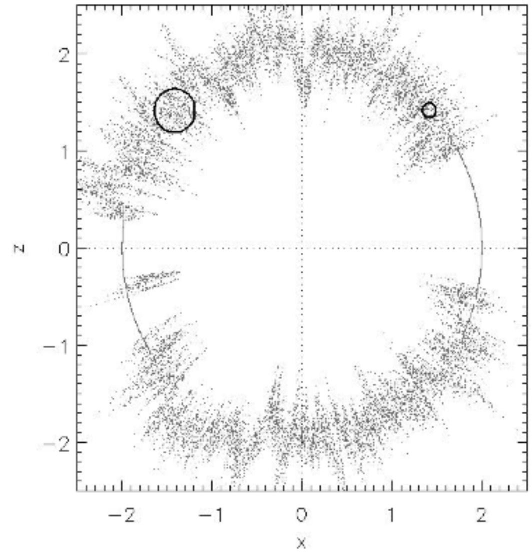
R, r and a are the free (scale) parameters.

SIM for spherical data

Transformation of the WMAP-data to a 3D point distribution:



3D representation
of WMAP data



x-z-projection for
all points with |y|<0.1

Consider a point distribution P:

$$P = \{\vec{p}_i\}, i = 1, \ldots, N_{points},$$
$$\vec{p}_i = \{x_i, y_i, z_i\}$$

Local cumulative weighted density:

$$\rho(\vec{p}_i) = \sum_{j=1}^{N} e^{-\left(\frac{d_{ij}}{r}\right)^n}, d_{ij} = \left\|\vec{p}_i - \vec{p}_j\right\|$$

Scaling Index:

$$\alpha(\vec{p}_i) \equiv \frac{\partial \log(\rho(\vec{p}_i))}{\partial \log(r)}$$

$$\Rightarrow \alpha(\vec{p}_i) = \frac{\sum_{j=1}^{N} n \cdot \left(\frac{d_{ij}}{r}\right)^n \cdot e^{-\left(\frac{d_{ij}}{r}\right)^n}}{\sum_{j=1}^{N} e^{-\left(\frac{d_{ij}}{r}\right)^n}}$$

See e.g.: CR, P. Schuecker, A. Banday, MNRAS, 2007
G. Rossmanith, CR, A. Banday, G. Morfill, MNRAS, 2009

Generating Surrogates (I.)

Fourier Transform of the temperature map:

$$T(n) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(n) \qquad \text{with} \qquad a_{lm} = \int T(n) Y_{lm}^{*} d\Omega_n$$

One can write:

$$a_{lm} = |a_{lm}| e^{i\phi_{lm}} \qquad \text{with} \qquad \phi_{lm} = \arctan\left(\frac{\mathrm{Im}(a_{lm})}{\mathrm{Re}(a_{lm})}\right)$$

Non-Gaussian Field :

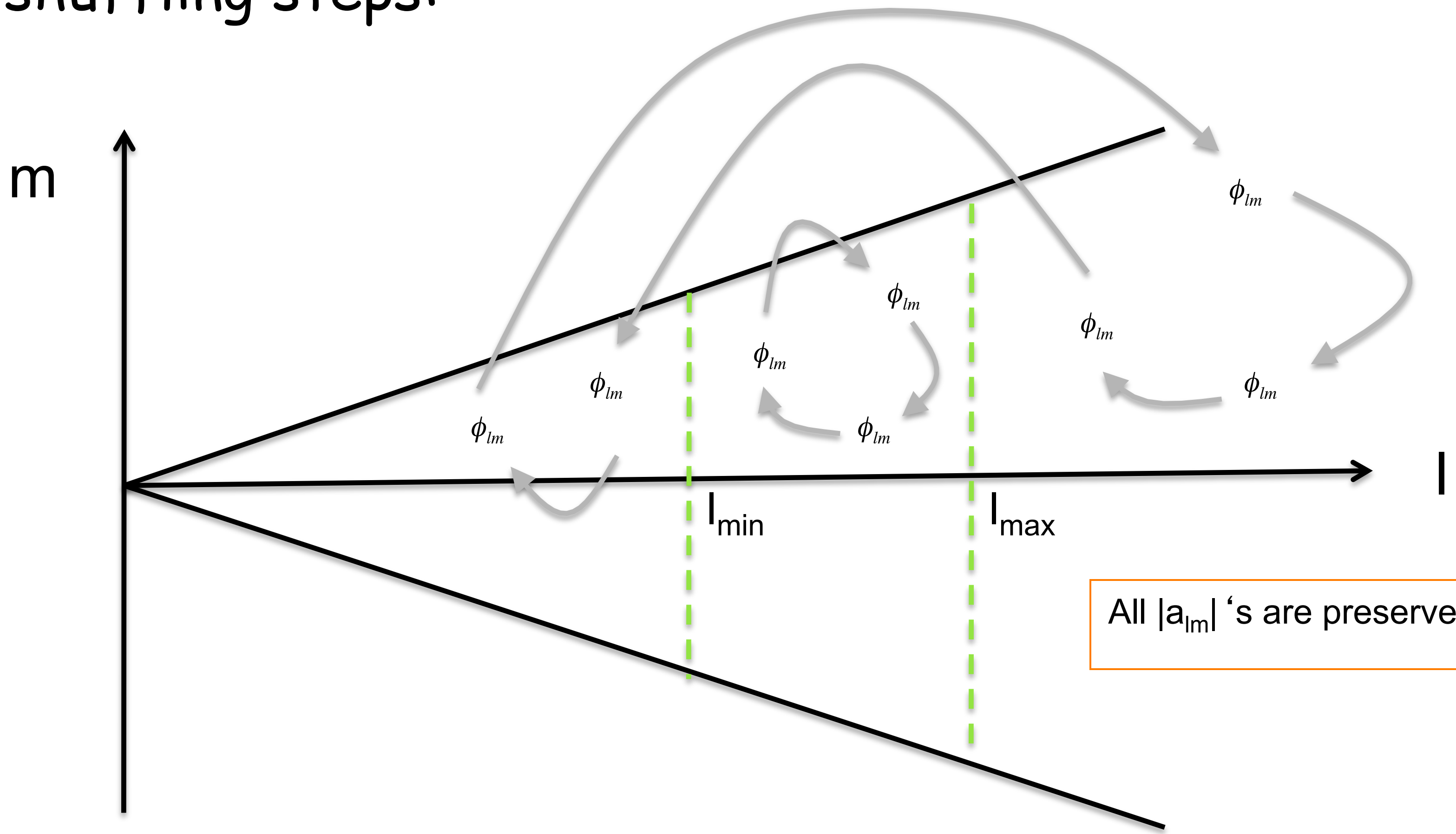
Fourier Phases are correlated and/or *not* uniformly distributed

How to test for possible phase correlations?

Destroy (only) them (by scale-dependent shuffling) and look what happens...

Generating Surrogates (II.)

Two shuffling steps:

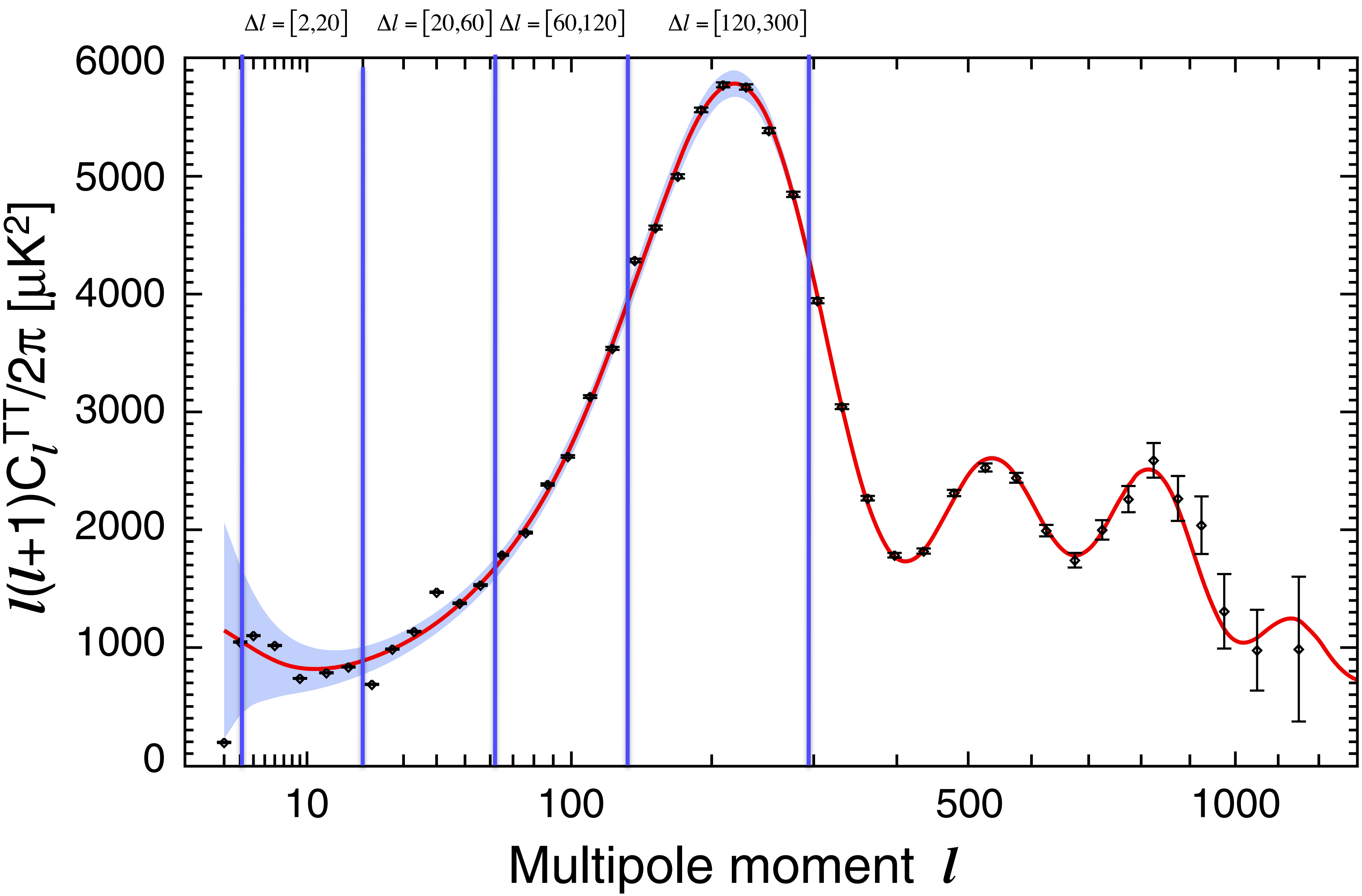


All $|a_{lm}|$ ‘s are preserved.

First order Surrogate: Shuffle outside (l_{min}, l_{max})

Second order Surrogates: Shuffle inside (l_{min}, l_{max})

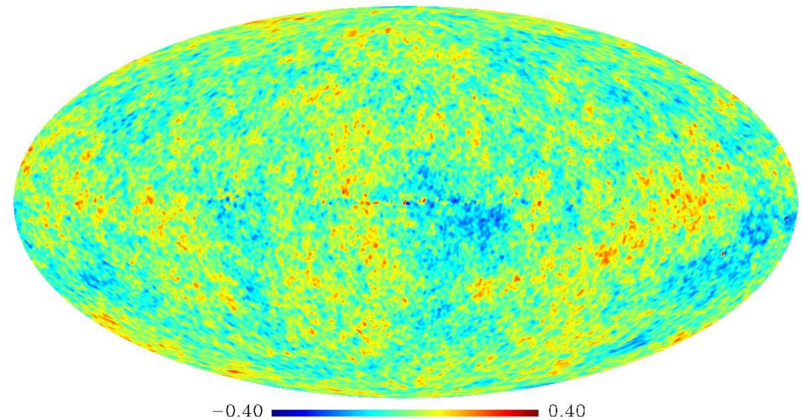
Generating Surrogates (III): Δl-intervals



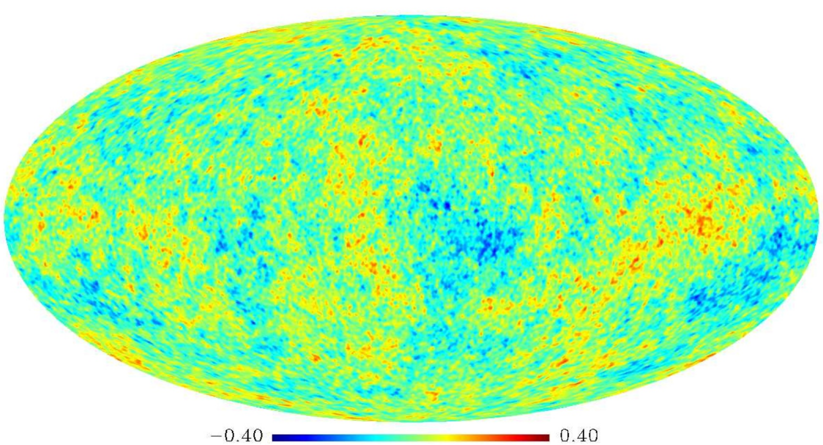
Generating Surrogates (IV.)

Two preprocessing steps:
Rank-ordered remapping of the Amplitudes (in real space) and Phases (in Fourier space).

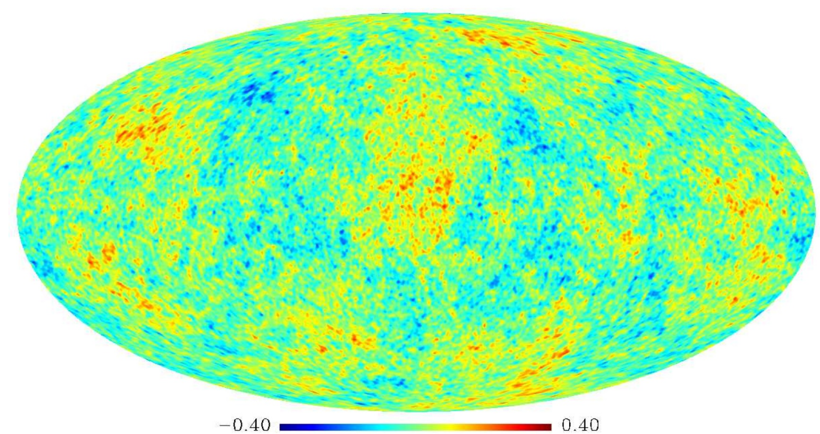
original



surro1 $\Delta l = [2,20]$

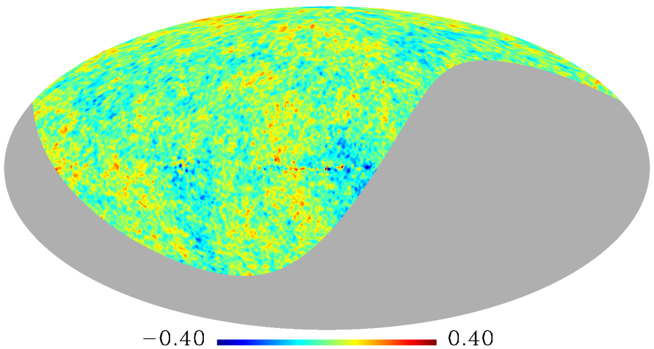


surro2 $\Delta l = [2,20]$



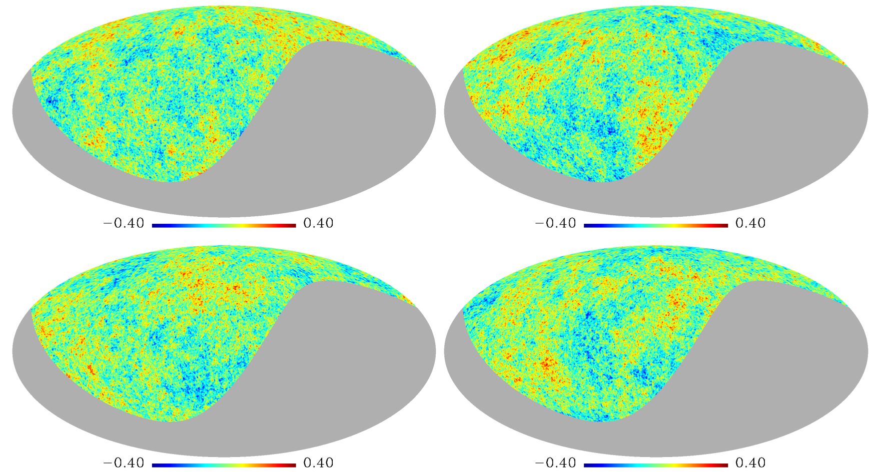
Deviation in rotated Hemispheres

WMAP data / 1st order surrogate



compare with

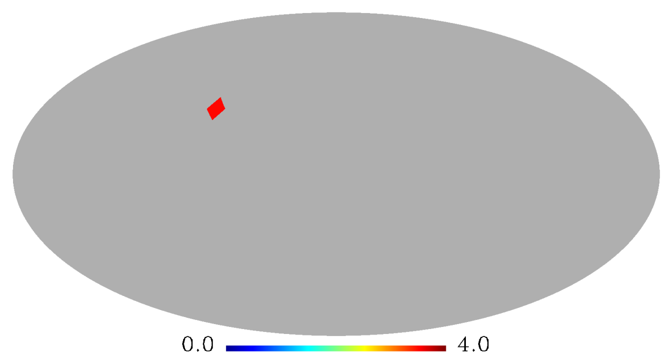
Simulations / 1st or 2nd order Surrogates



σ-normalised deviation:

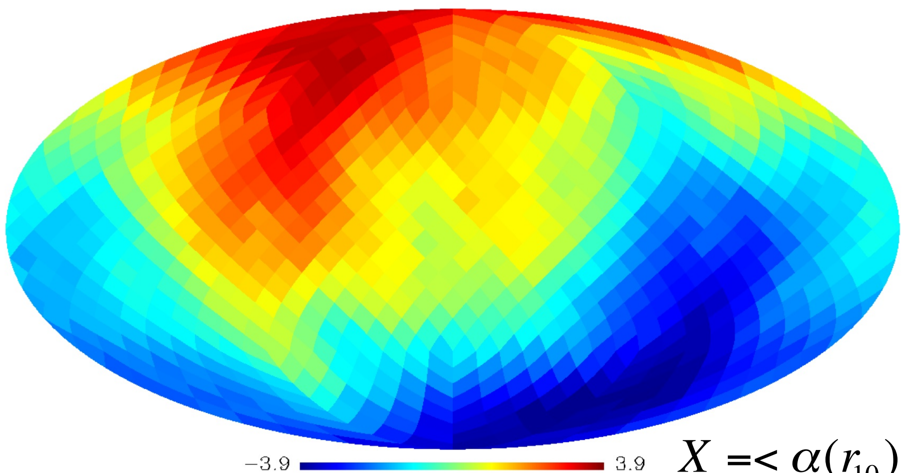
$$S(\vartheta,\phi) = \frac{X - \langle X \rangle}{\sigma_X},$$

$$X = <\alpha(r)>, \sigma_T, \chi^2(M_i), i = 1,\ldots 3$$

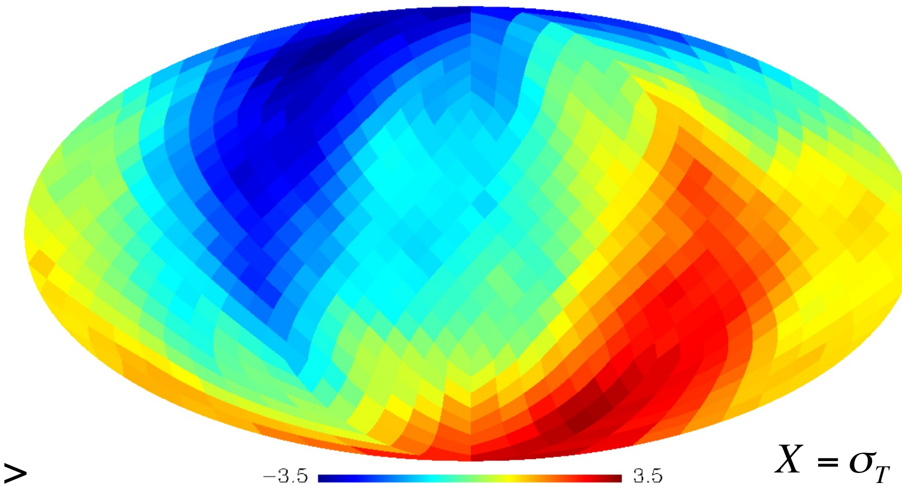


Results

S(X) in N rotated hemispheres (Δl=[2,20]):

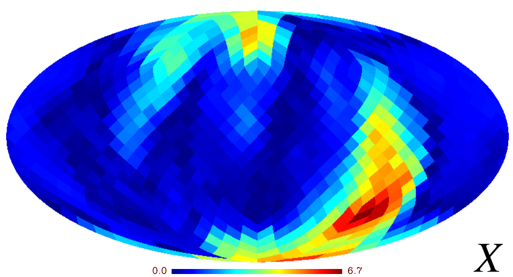


$X = < \alpha(r_{10}) >$

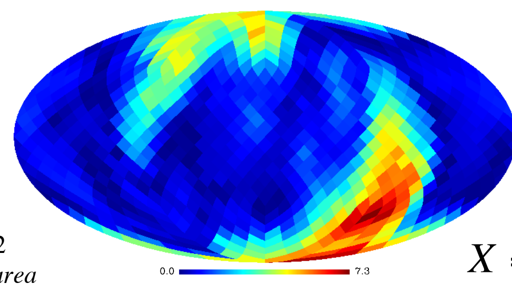


$X = \sigma_T$

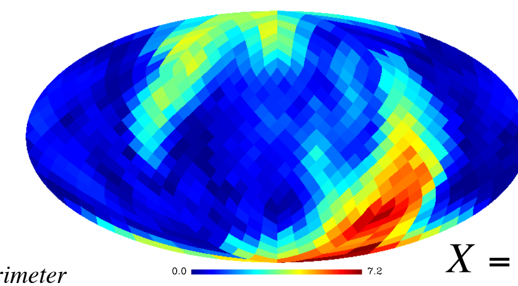
And remember also Heike ‘s results:



$X = \chi^2_{area}$



$X = \chi^2_{perimeter}$



$X = \chi^2_{euler}$

=> Highly significant signatures of non-Gaussianity and asymmetries. „Consistent picture of inconsistencies“

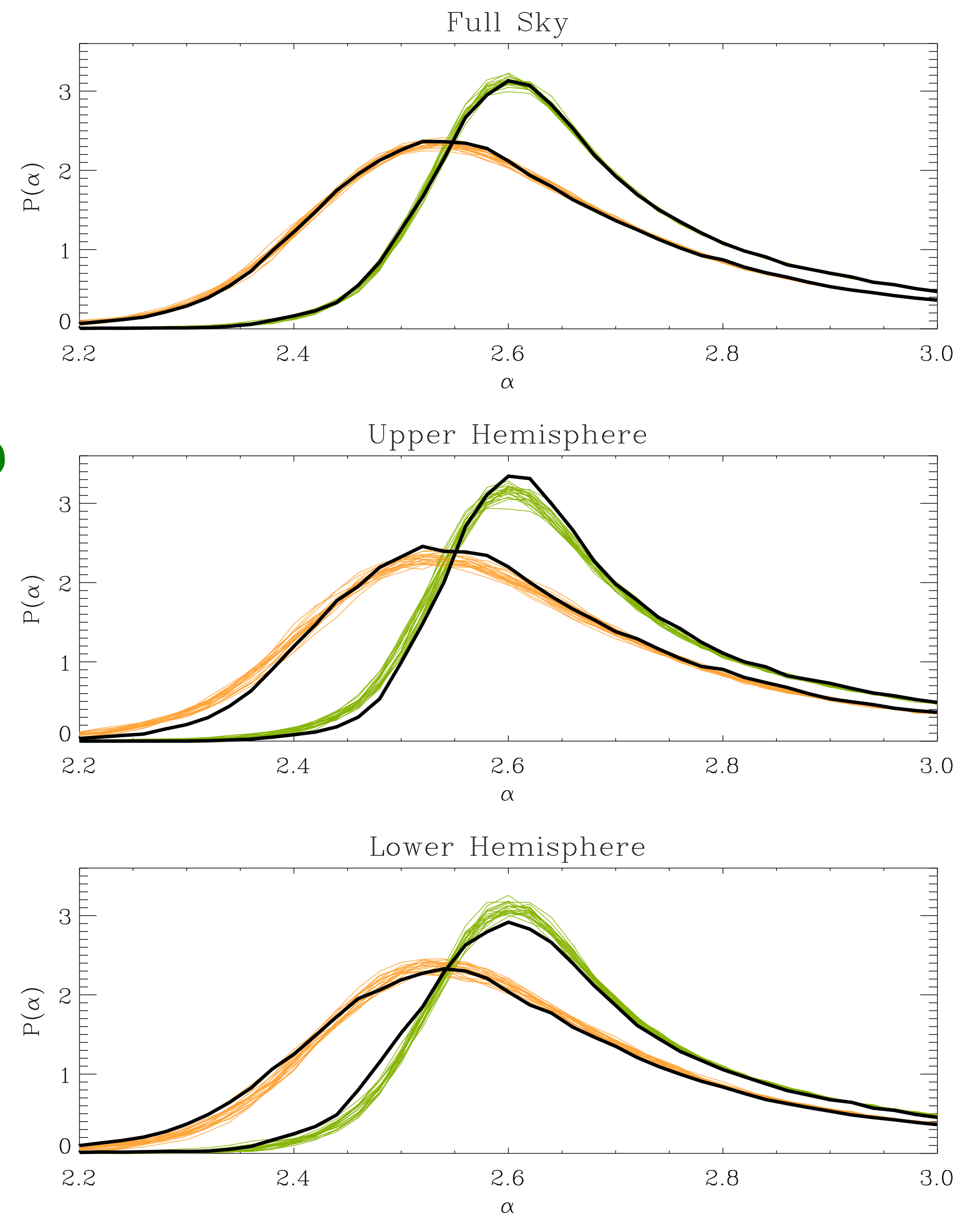
Results

Probability densities for the two different foreground-cleaned maps:

WMAP ILC 7 year map

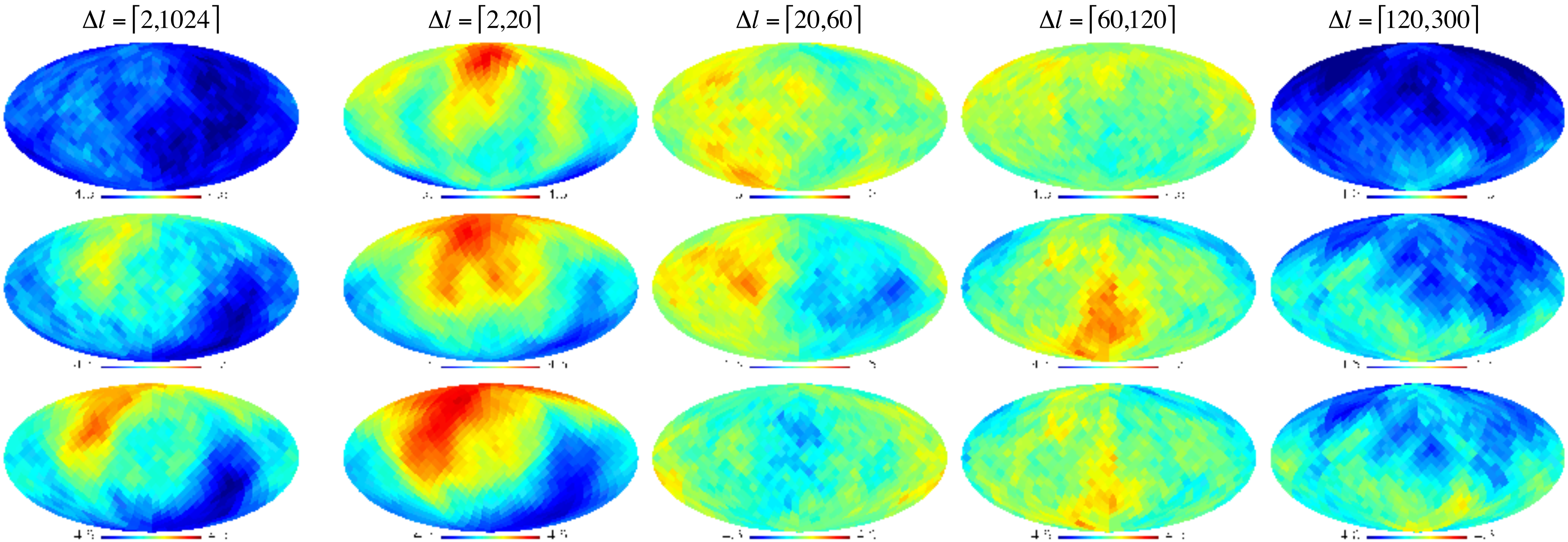
Needlet-based ILC 5 year map

Signature remains the same for the two maps



Results

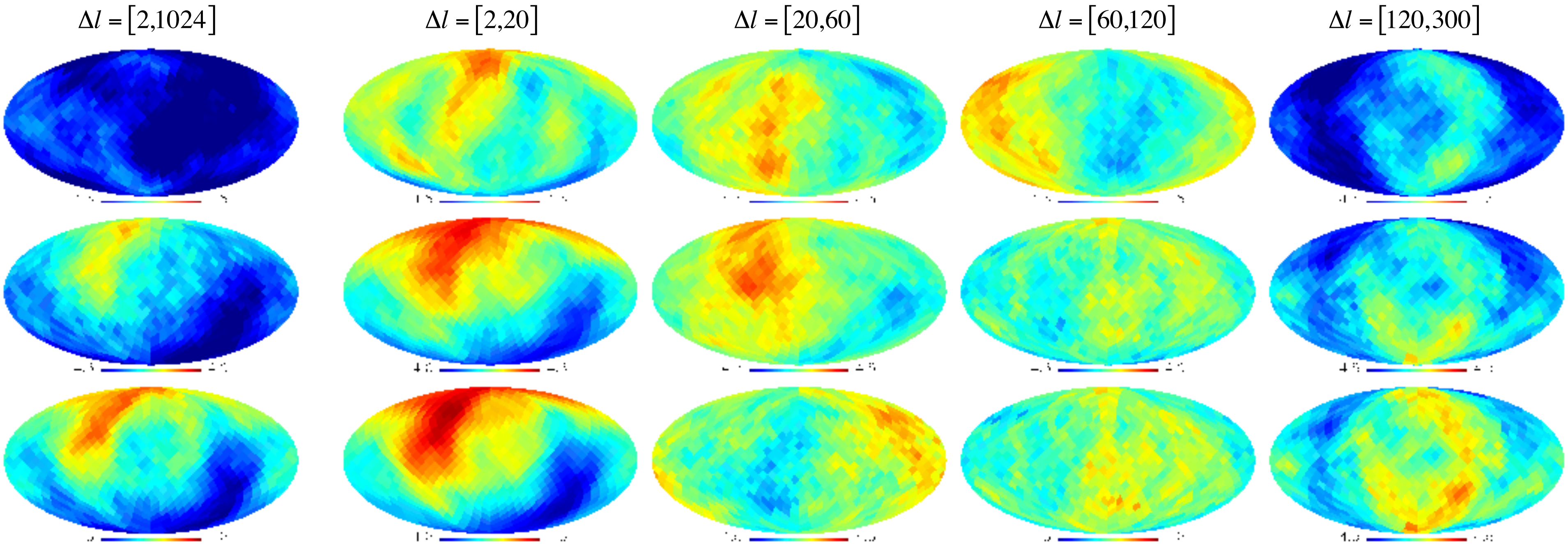
S(X) in rotated hemispheres for varying Δl and r:



ILC 7yr map, X = $\langle \alpha_{r2} \rangle$, $\langle \alpha_{r6} \rangle$, $\langle \alpha_{r10} \rangle$ (from top to bottom)

Results

S(X) in rotated hemispheres for varying Δl and r:

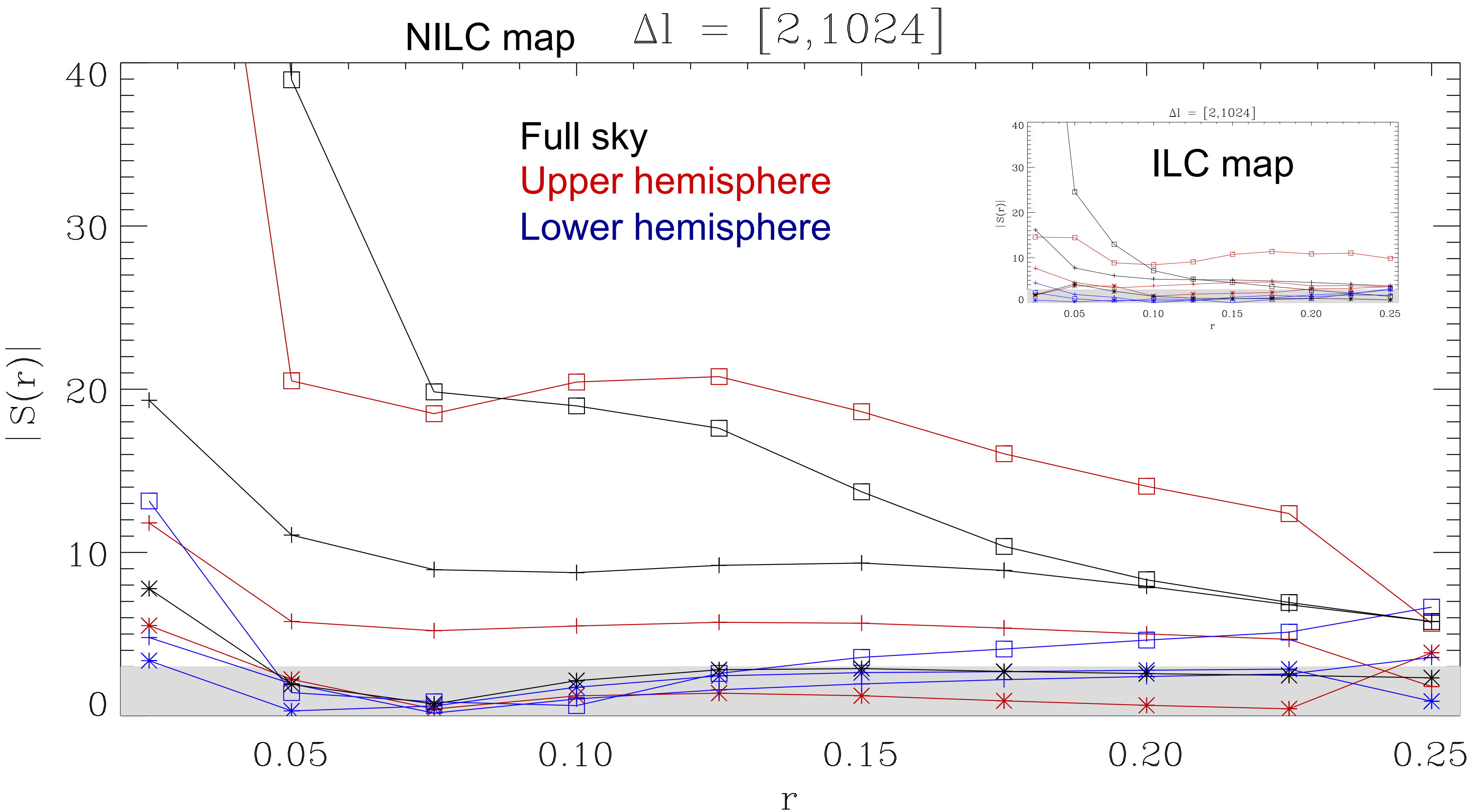


NILC 5yr map, X = $\langle\alpha_{r2}\rangle$, $\langle\alpha_{r6}\rangle$, $\langle\alpha_{r10}\rangle$ (from top to bottom)

- *Most significant deviations for Δ l = [2,20] and Δ l = [120,300]*
- *Signal in Δ l = [2,1024] to be interpreted as superposition of the signals in Δ l = [2,20] and Δ l = [120,300]*

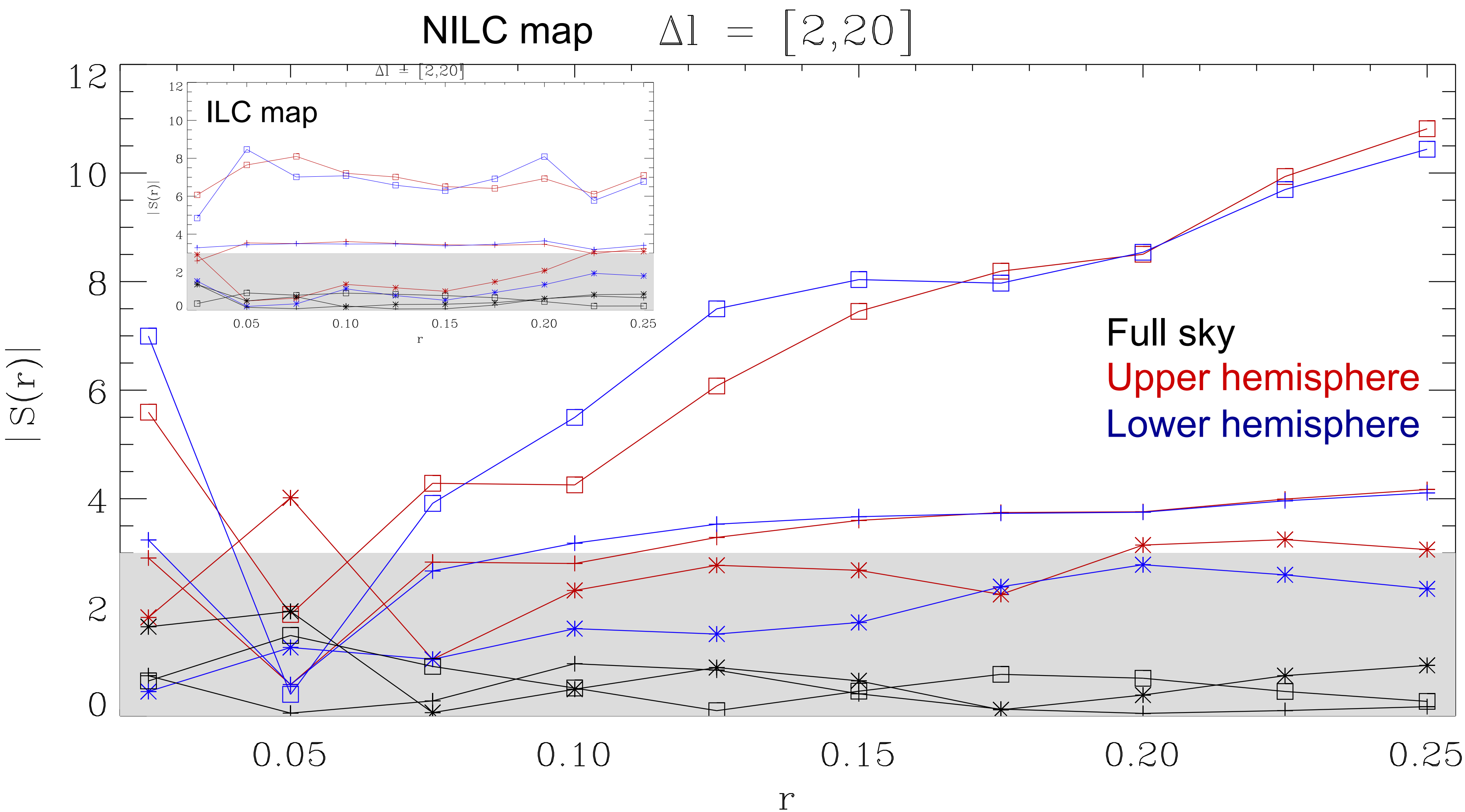
Results

Scale-independent NGs:



Results

Scale-dependent NGs on large scales:



Results

Some numbers (scale-independent χ^2-measures) :

ILC 7 yr map

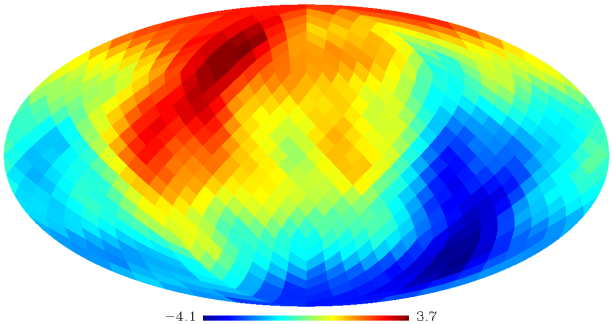
Δl	Full Sky	Upper Hemisphere	Lower Hemisphere
$\chi^2_{\langle\alpha\rangle}$:	$(S/\%)$	$(S/\%)$	$(S/\%)$
[2, 1024]	5.73 / >99.8	9.35 / >99.8	0.33 / 55.2
[2, 20]	0.97 / 95.0	4.57 / 99.6	4.01 / 99.2
[20, 60]	1.81 / 94.2	2.57 / 97.4	2.42 / 97.0
[60, 120]	1.41 / 99.0	1.53 / 99.6	0.91 / 83.8
[120, 300]	3.17 / 92.8	10.53 / >99.8	1.19 / 87.8
$\chi^2_{\sigma_\alpha}$:			
[2, 1024]	5.50 / >99.8	11.50 / >99.8	0.66 / 79.6
[2, 20]	0.32 / 52.8	4.03 / 98.6	4.04 / 99.6
[20, 60]	2.15 / 95.8	4.00 / 99.8	2.18 / 96.4
[60, 120]	1.40 /98.2	3.26 / 99.4	2.01 / 95.6
[120, 300]	3.10 / 99.0	8.90 / >99.8	1.90 / 95.8
$\chi^2_{\langle\alpha\rangle,\sigma_\alpha}$:			
[2, 1024]	1.89 / 94.2	8.38 / >99.8	3.03 / 98.8
[2, 20]	0.73 / 77.4	5.64 / >99.8	6.01 / 99.8
[20, 60]	1.60 / 92.8	3.42 / 99.2	1.49 / 91.0
[60, 120]	0.26 / 52.4	2.15 / 96.6	0.53 / 75.6
[120, 300]	1.68 / 92.8	5.34 / 99.8	0.22 / 63.2

NILC 5 yr map

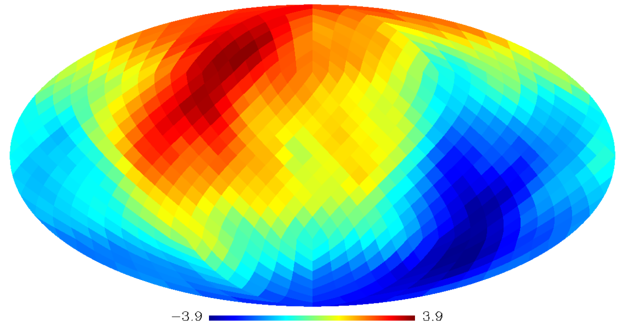
Δl	Full Sky	Upper Hemisphere	Lower Hemisphere
$\chi^2_{\langle\alpha\rangle}$:	$(S/\%)$	$(S/\%)$	$(S/\%)$
[2, 1024]	27.93 / >99.8	27.23 / >99.8	4.47 / 99.4
[2, 20]	0.39 /55.8	8.18 / >99.8	9.27 / >99.8
[20, 60]	0.61 / 69.6	2.02 / 96.0	0.74 / 83.0
[60, 120]	0.88 / 83.0	4.11 / 99.4	1.01 / 85.4
[120, 300]	1.57 / 93.6	5.16 / 99.8	0.06 / 55.2
$\chi^2_{\sigma_\alpha}$:			
[2, 1024]	20.09 / >99.8	20.37 / >99.8	3.61 / >99.8
[2, 20]	0.45 / 59.8	9.76 / >99.8	9.17 / >99.8
[20, 60]	0.69 / 73.4	1.54 / 92.2	0.41 / 71.6
[60, 120]	0.88 / 82.2	4.04 / 99.4	1.73 / 94.0
[120, 300]	1.19 / 88.8	5.29 / 99.8	0.15 / 61.6
$\chi^2_{\langle\alpha\rangle,\sigma_\alpha}$:			
[2, 1024]	9.73 / >99.8	10.04 / >99.8	4.03 / 99.8
[2, 20]	0.90 / 88.0	7.17 / >99.8	6.85 / >99.8
[20, 60]	1.21 / 94.6	0.70 / 77.4	0.64 / 70.6
[60, 120]	0.30 /55.2	2.73 / 98.4	0.08 / 51.6
[120, 300]	0.86 / 83.6	6.48 / >99.8	3.44 / 99.8

Results:

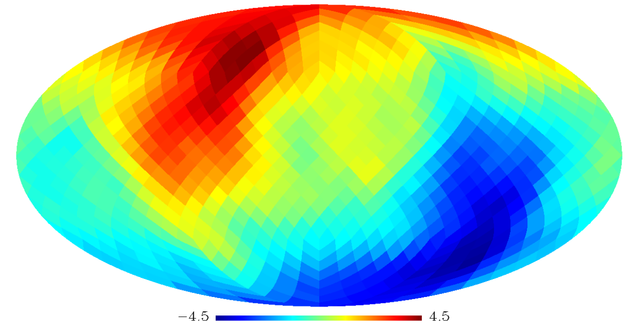
Robustness of results (Δl=[2,20]) :



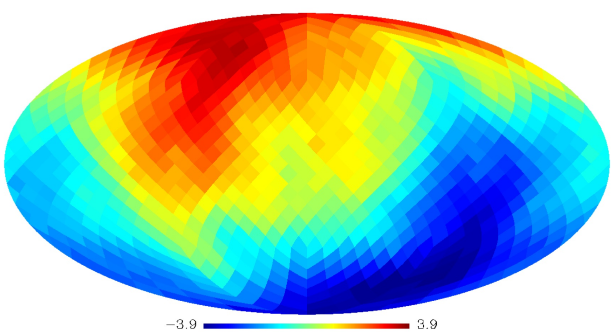
Three year Tegmark map



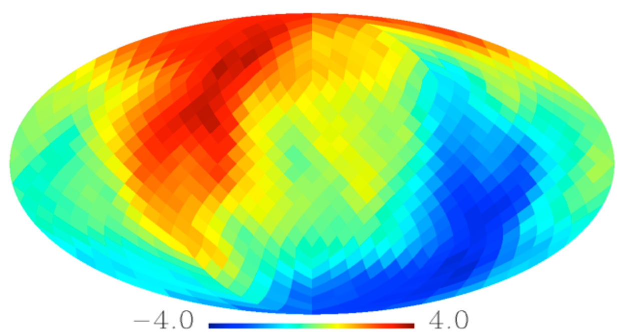
Three year Tegmark map (Wiener filtered)



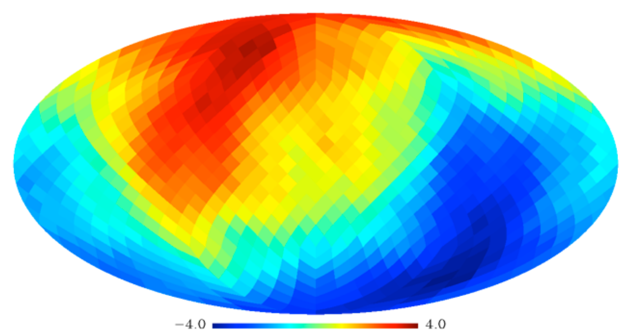
Five year needlet based ILC - map



Five year ILC - map



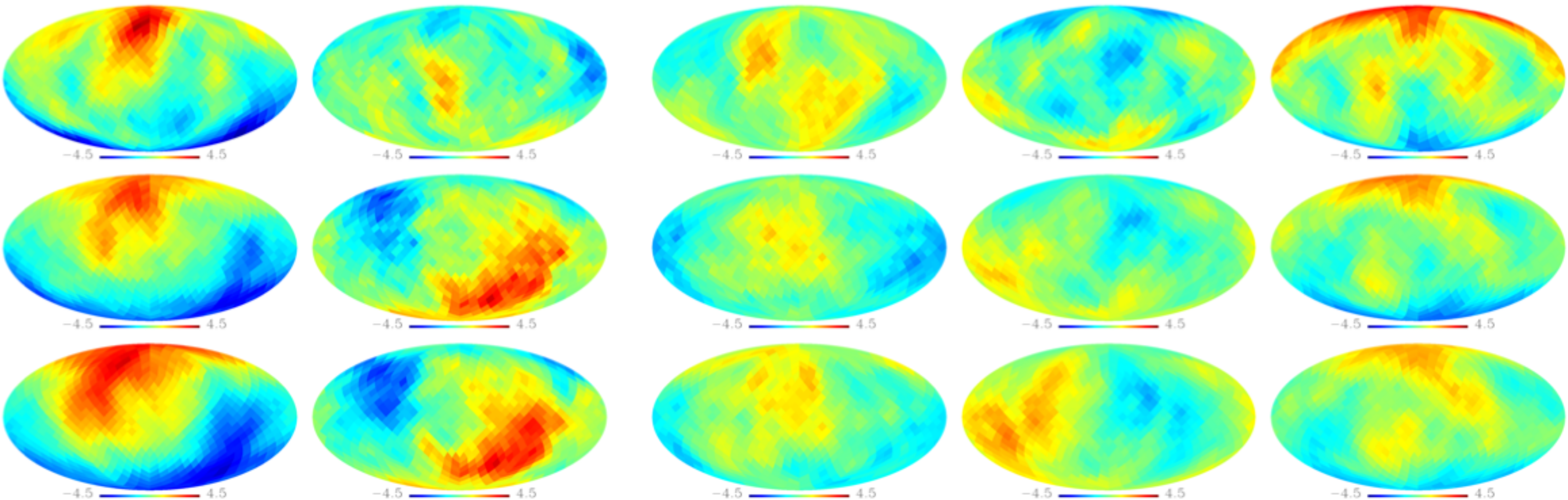
Five year ILC – map without the cold spot



Seven year ILC - map

Results:

Checks on systematics ($\Delta l = [2, 20]$):



Uncorrected ILC map

Difference ILC map (year 7 – year6)

Asymmetric Beam map

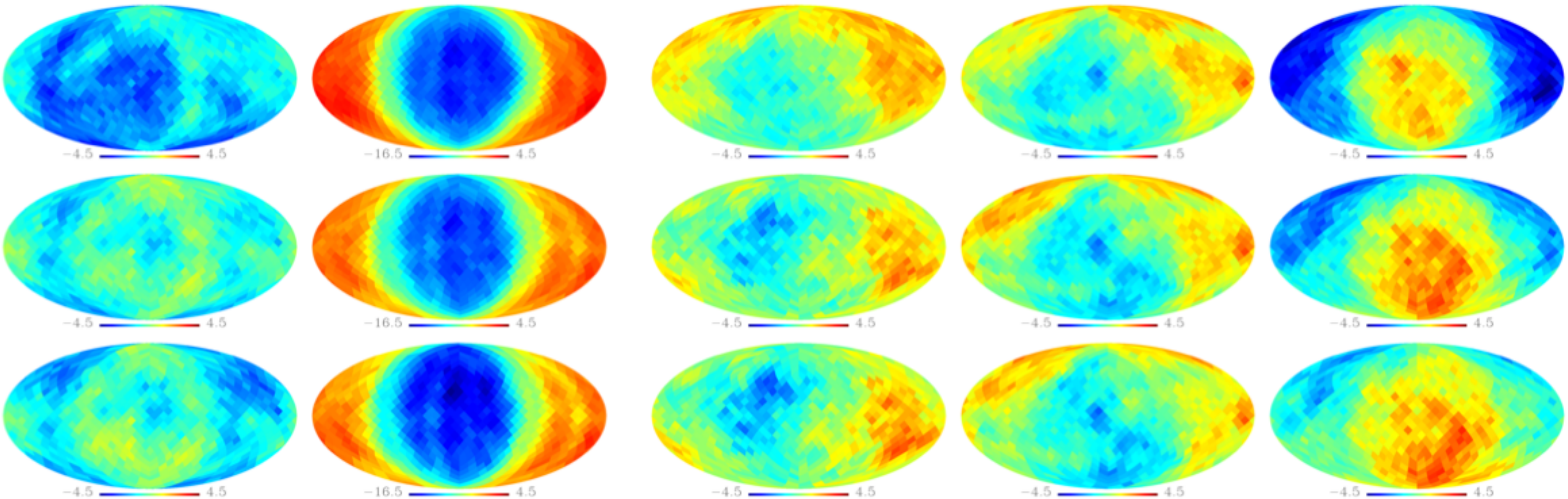
Simulated Coadded VW-band map

Simulated ILC-like map

=> No test can so far explain the low-l anomalies!

Results:

Checks on systematics ($\Delta l=[120,300]$):



Uncorrected ILC map	Difference ILC map (year 7 – year6)	Asymmetric Beam map	Simulated Coadded VW-band map	Simulated ILC-like map

=> A number of ‚residuals‘ found for the high-l case

Summary

•Using surrogates and scaling indices we performed a comprehensive study of scale-dependent non-Gaussianities in full sky CMB data and find a

5.0+x σ detection of non-Gaussianities

especially at the largest scales and

hemispherical asymmetries, i.e. violation of statistical isotropy

•The signal is stable and found using different test statistics (σ_T, scaling indices and Minkowski-functionals (see Heike 's Talk))

•All checks on systematics we performed so far revealed that no clear candidate can be found to explain the low-l signal.

$\Rightarrow$ The signatures at low l must so far be taken to be cosmological at high significance.

That would mean:

•*Single field slow roll inflation seriously questioned,*

•*Anisotropic model of NGs with running f_{nl} required*

Concluding Remarks

<u>A surprising statement...:</u>

„A detection of non-Gaussianity and/or phase correlations in the WMAP a_{lm} data would be of great interest. While a detection of non-Gaussianity could be indicative of an experimental systematic effect or of residual foregrounds, it could also point to new cosmological physics.“

(Bennett et al., 2011)

My immediate thoughts...:

Chiang et al. 03, Chiang et al. 06, Coles et al. 04, Naselsky et al. 05, etc.

and also CR et al. 09, CR et al. 11.

With this presentation I hope I could convince you that

it is no longer the question whether there *are* phase correlations (i.e. signatures of NGs) in the WMAP a_{lm} data.

It ‘s rather of interest what their origin is.

thank you
for
your
attention !

attention
your you
for !
thank

Results

Some numbers (small (r_2) and large (r_{10}) scaling ranges):

ILC 7 yr map

Δl	Full Sky	Upper Hemisphere	Lower Hemisphere
$\langle\alpha(r_2)\rangle$:	$(S/\%)$	$(S/\%)$	$(S/\%)$
[2, 1024]	7.73 / > 99.8	4.53 / >99.8	1.87 / 96.0
[2, 20]	0.14 / 56.6	3.54 / >99.8	3.44 / >99.8
[20, 60]	0.88 / 80.6	1.84 / 96.4	1.08 / 85.2
[60, 120]	0.26 / 60.4	0.32 / 64.8	0.64 / 71.6
[120, 300]	6.97 / >99.8	5.36 / >99.8	0.92 / 83.0
$\sigma_{\alpha(r_2)}$:			
[2, 1024]	4.16 / >99.8	3.77 / >99.8	0.25 / 61.8
[2, 20]	0.48 / 69.2	0.48 / 69.8	0.19 / 58.0
[20, 60]	1.70 / 95.2	3.18 / >99.8	1.02 / 84.8
[60, 120]	0.88 / 80.0	2.35 / 98.8	1.25 / 88.2
[120, 300]	3.54 / >99.8	1.03 / 83.4	3.69 / >99.8
$\chi^2_{\langle\alpha(r_2)\rangle,\sigma_{\alpha(r_2)}}$:			
[2, 1024]	24.55/>99.8	14.44 / >99.8	0.94 / 84.4
[2, 20]	0.90 / 85.2	7.67 / >99.8	8.47 / 99.8
[20, 60]	0.82 / 83.4	4.03 / 99.2	0.31 / 50.4
[60, 120]	0.51 / 61.4	3.63 / 98.6	1.00 / 85.2
[120, 300]	19.62 / >99.8	17.17 / >99.8	4.15 / 99.2

Δl	Full Sky	Upper Hemisphere	Lower Hemisphere
$\langle\alpha(r_{10})\rangle$:	$(S/\%)$	$(S/\%)$	$(S/\%)$
[2, 1024]	3.75 / >99.8	3.53 / >99.8	1.72 / 95.4
[2, 20]	0.64 / 74.2	3.24 / >99.8	3.41 / >99.8
[20, 60]	0.67/ 74.2	1.41 / 91.6	2.04 / 98.0
[60, 120]	0.01 / 50.5	2.28 / 99.0	2.19 / 98.6
[120, 300]	2.45 / 99.4	3.58 / >99.8	1.38 / 92.2
$\sigma_{\alpha(r_{10})}$:			
[2, 1024]	0.66 / 74.4	3.60 / >99.8	2.90 / >99.8
[2, 20]	0.84 / 80.0	3.09 / >99.8	1.79 / 96.4
[20, 60]	2.27 / 98.6	2.94 / 99.8	0.13 / 55.0
[60, 120]	0.77 / 79.0	1.63 / 94.6	0.47 / 67.6
[120, 300]	0.60 / 73.6	1.61 / 95.8	0.81 / 79.6
$\chi^2_{\langle\alpha(r_{10})\rangle,\sigma_{\alpha(r_{10})}}$:			
[2, 1024]	1.46 / 90.4	9.83 / >99.8	3.15 / 98.0
[2, 20]	0.21 / 54.8	7.10 / >99.8	6.77 / 99.8
[20, 60]	2.74 / 97.2	5.27 / 99.6	0.29 / 73.6
[60, 120]	0.38 / 50.2	2.09 / 94.2	0.43 / 75.8
[120, 300]	0.26 / 57.2	2.23 / 96.2	0.19 / 60.4

Probing non-Gaussianity

(CMB) data

Constrained Randomisation

Surrogate CMB maps with the same power spectrum (and partially randomised phases)

Calculation of statistical measures M sensitiv to higher order correlations

Statistical comparison in terms of e.g. significances, Confidence levels, etc.

M derived from e.g.:

- Bispectrum
- N-point corr. Funct.
- Minkowski-functionals
- Wavelets
- Needlets
- Scaling indices
- Etc.