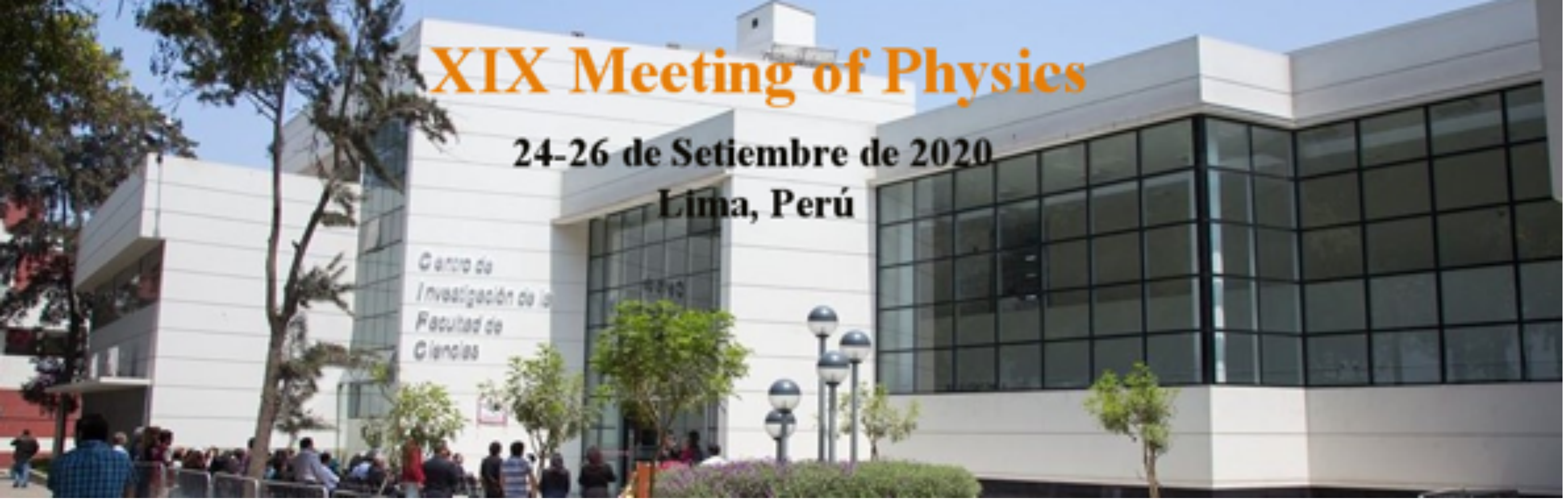


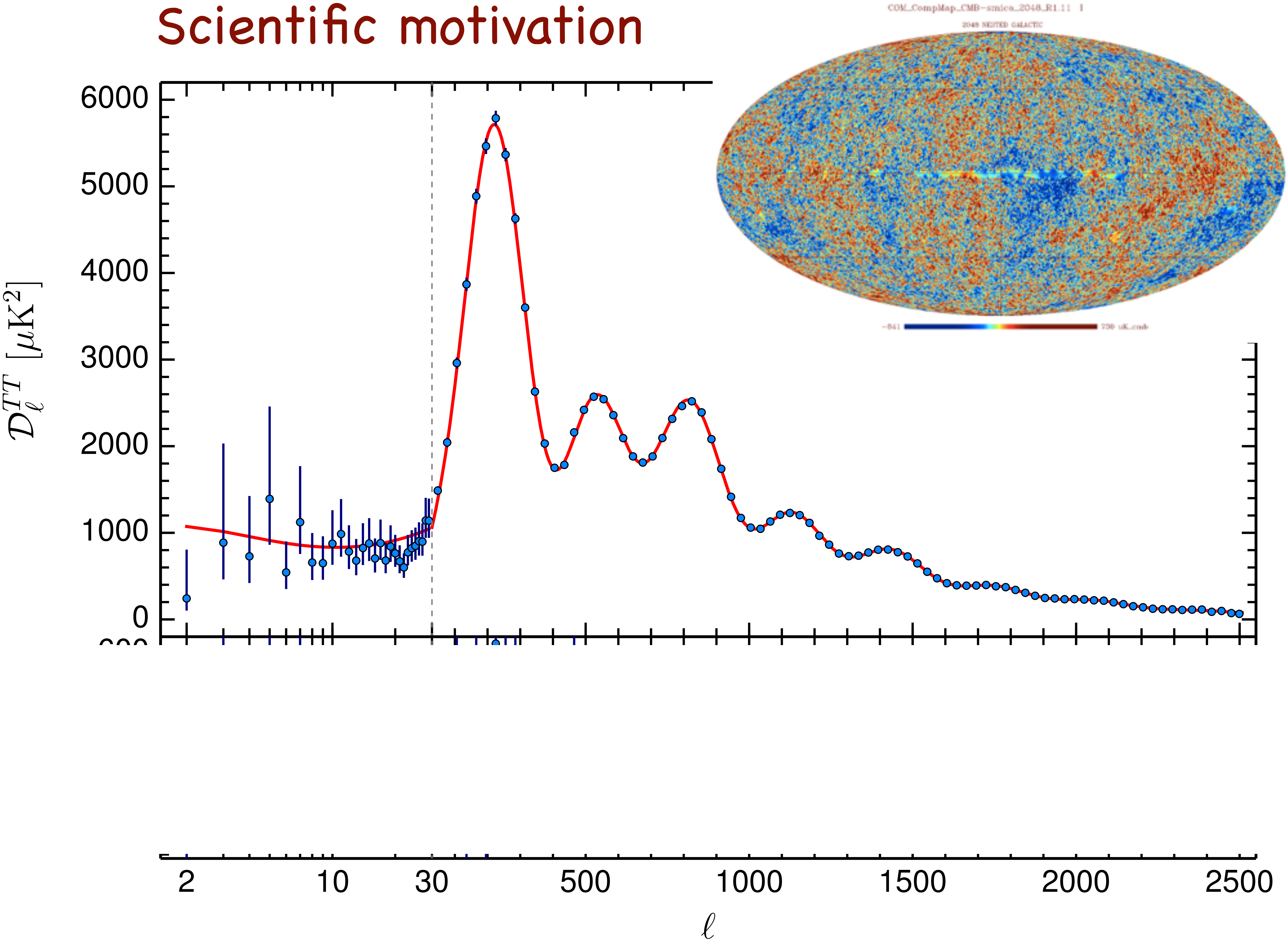
Observatório Nacional

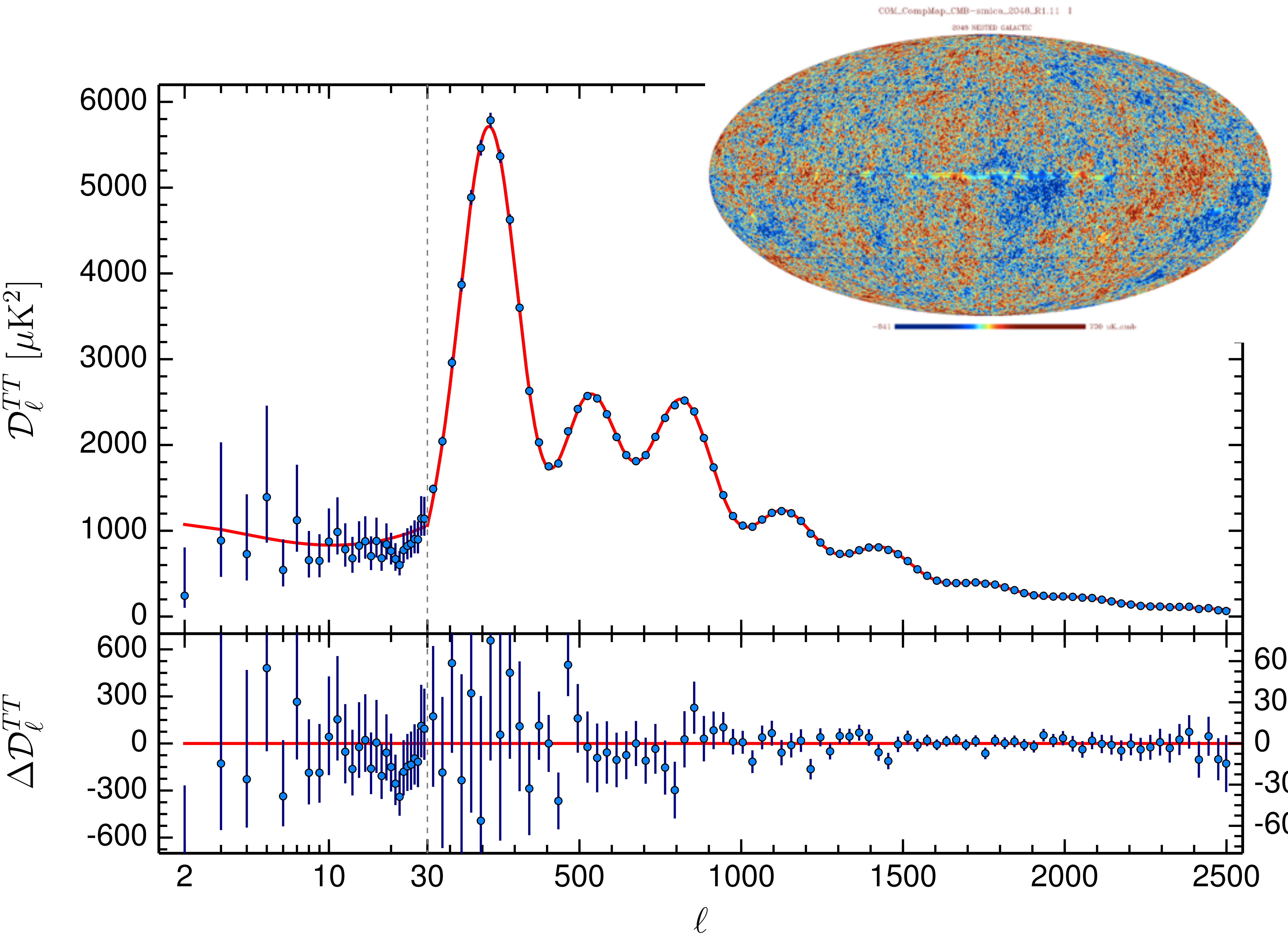
Primordial Non-Gaussianities ⋆ of inflationary step-like models

Armando Bernui

⋆ work in collaboration with Camila Novaes and Micol Benetti

Scientific motivation





COM_CompMap_CMB-smica_2048_R1.11 I
2048 NESTED GALACTIC
730 uK_cmb
6000
5000
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$\mathcal{D}_\ell^{TT}$ [μK^2]
600
300
0
-300
-600
$\Delta\mathcal{D}_\ell^{TT}$
2
10
30
500
1000
1500
2000
2500
ℓ

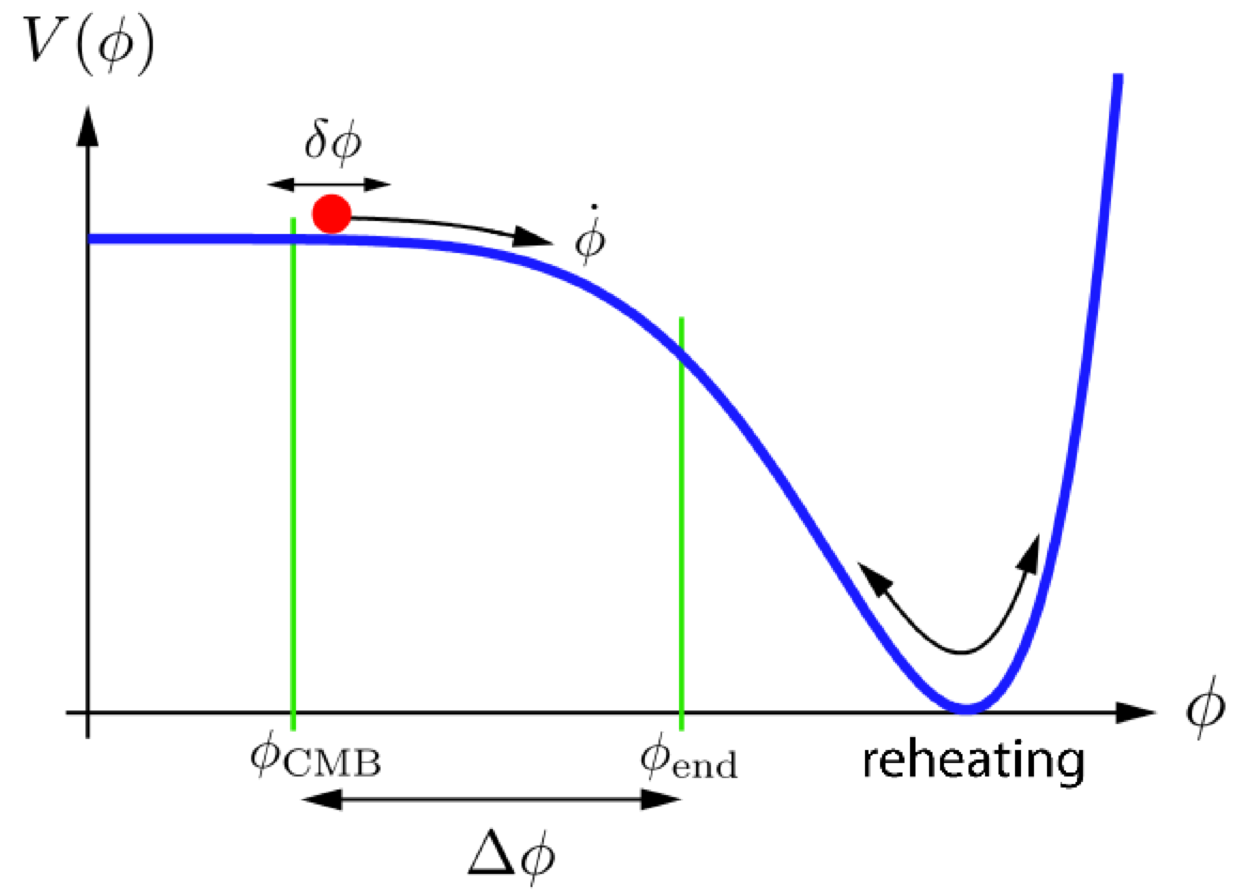
Outline

- Inflationary paradigm (and non-Gaussianity)
- Inflationary step-like models
- Challenge in detecting NG on CMB data
- Analysis method
  - The step-like models
  - Data description
  - The Minkowski Functionals
- Results
- Concluding remarks

Inflationary paradigm vs. Planck data

The simplest inflationary scenario

$\rightsquigarrow$



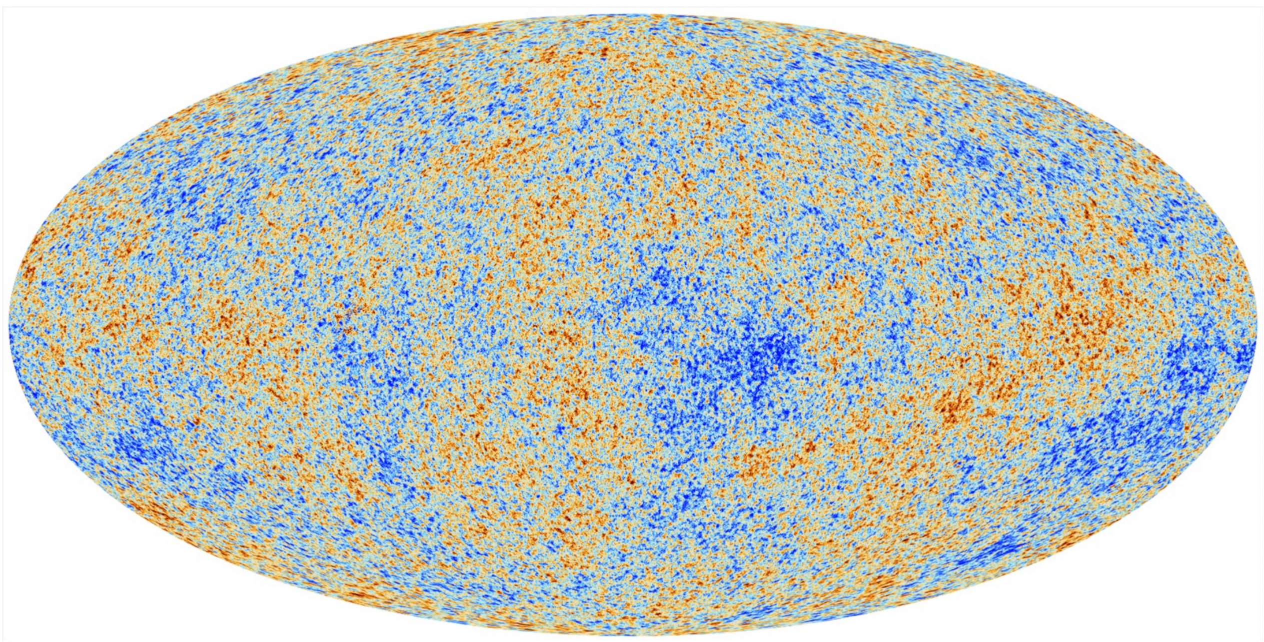
Supports the Standard Cosmological model.

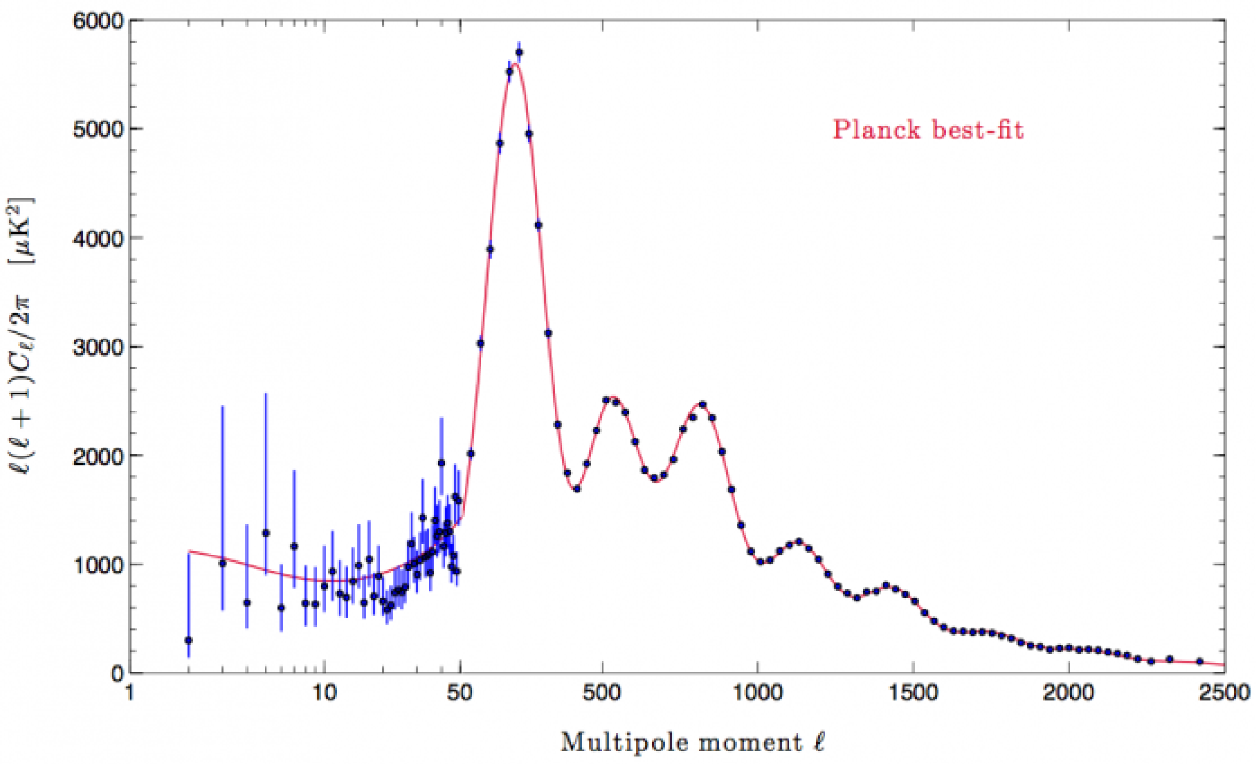
It produces primordial perturbations nearly:

- adiabatic,
- scale-invariant, $n_s \sim 1$,
- Gaussian.

$\hookrightarrow$ excellent agreement with the recent CMB data from the Planck satellite.

Gaussianity





Probability density function (PDF):

(Planck Collaboration, 2013)

$$P(f) = \frac{1}{(2\pi)^{N_{pix}/2}|\xi|^{1/2}} \exp\left[-\frac{1}{2} \sum_{ij} f_i (\xi^{-1})_{ij} f_j \right],$$

$f_i \equiv f(\widehat{n}) = \frac{\Delta T}{T_{RCF}}(\widehat{n})$ e $\xi_{ij} \equiv \langle f_i f_j \rangle \Longrightarrow$ two-point correlation function.

Non-Gaussianity

For non-Gaussian fluctuations:

- n-points correlation function.

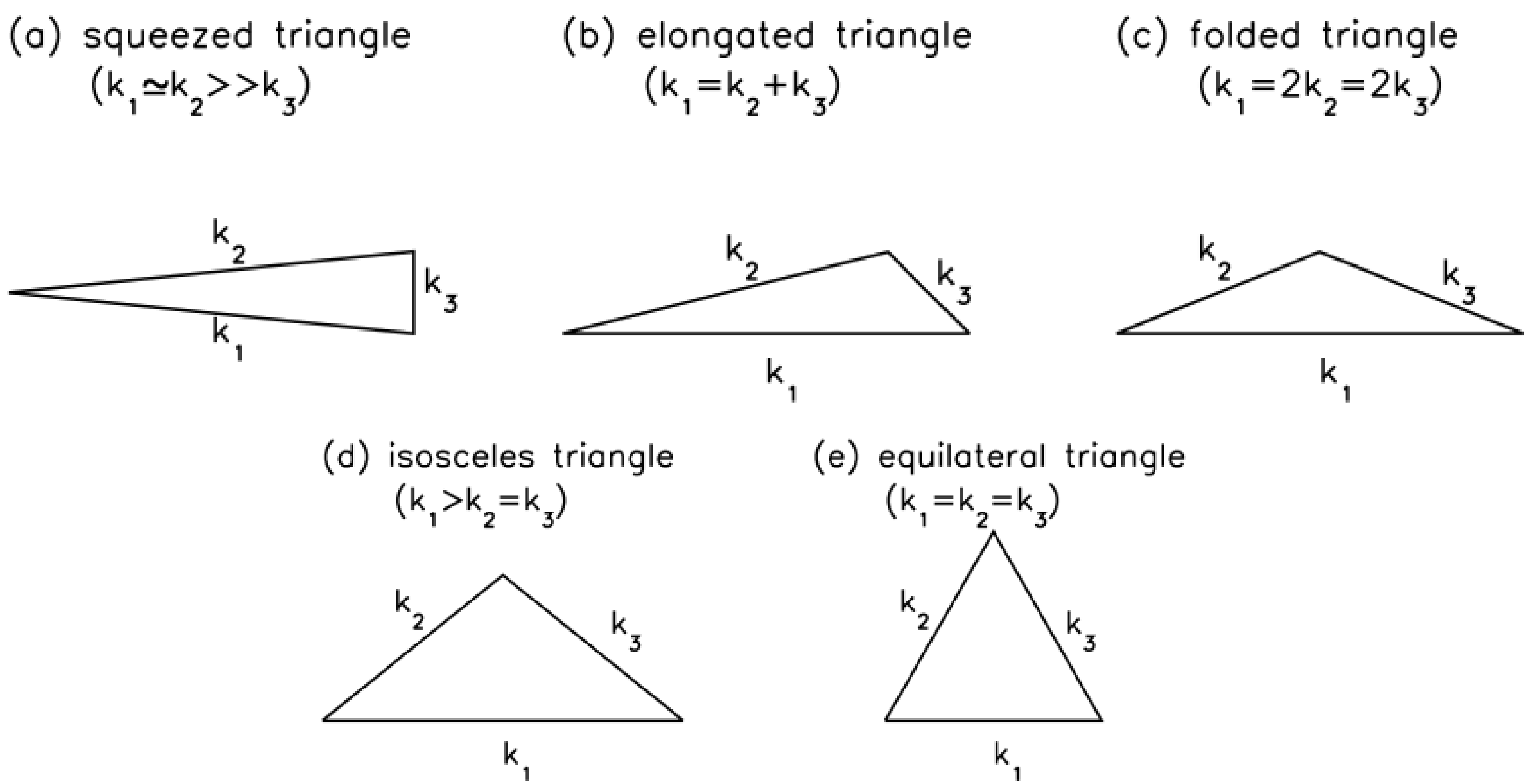
$$\langle f(\widehat{n}_1) f(\widehat{n}_2) ... f(\widehat{n}_n)\rangle.$$

- Bispectrum estimator $\langle a_{l_1m_1} a_{l_2m_2} a_{l_3m_3}\rangle \Longleftrightarrow a^{obs}_{l_1m_1} a^{obs}_{l_2m_2} a^{obs}_{l_3m_3}$.

Some NG types

$$B_\Phi(k_1, k_2, k_3) \equiv f_{NL} F(k_1, k_2, k_3)$$

- For example: Local, equilateral, orthogonal, ...



(Komatsu, 2010)

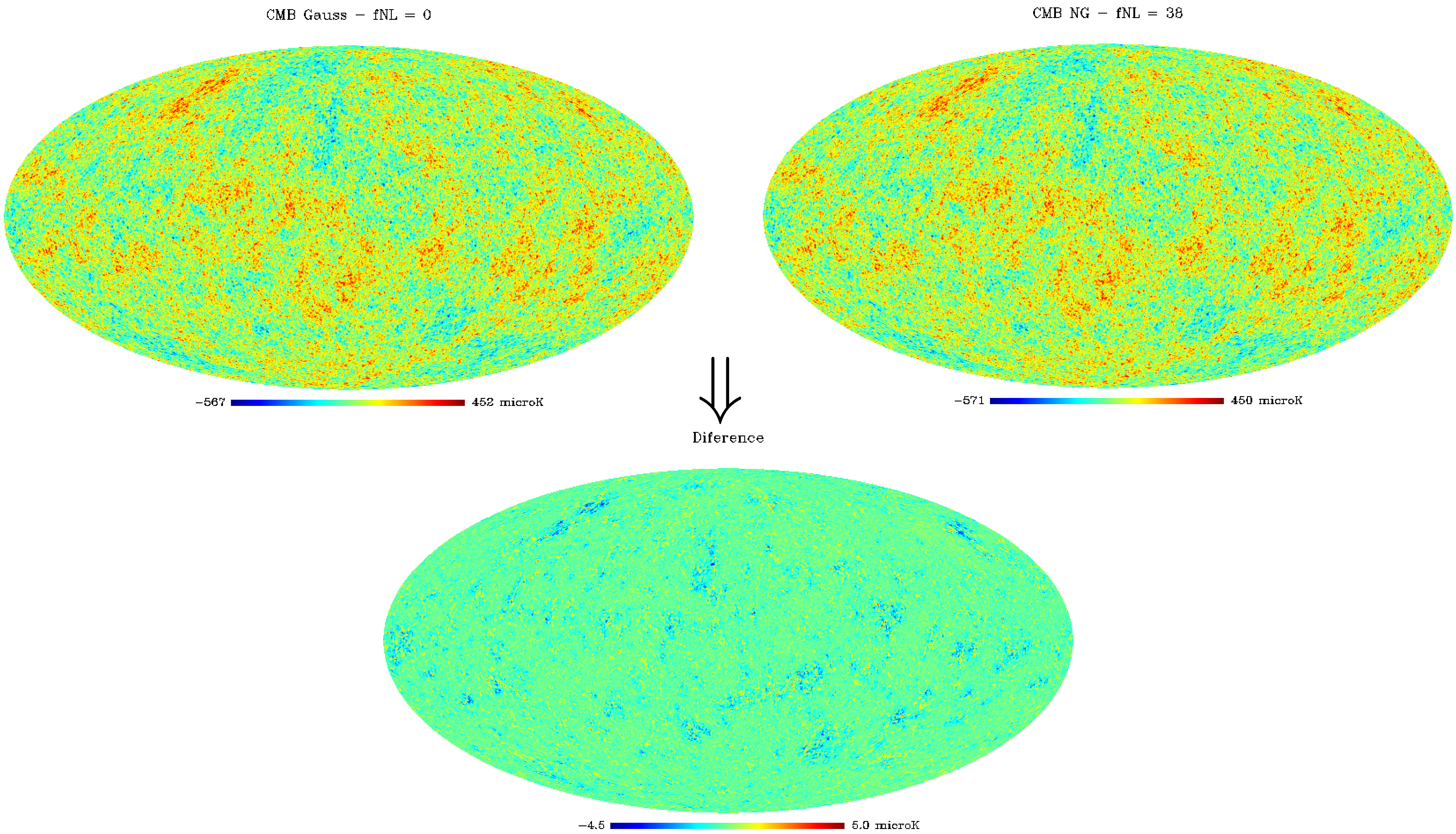
Some NG types

For the local type NG:

$$\Phi(\mathbf{x}) = \Phi_L(\mathbf{x}) + f_{NL}[\Phi_L^2(\mathbf{x}) - \langle\Phi_L^2(\mathbf{x})\rangle]$$

- Inflationary single-field models $\longrightarrow f_{NL} \sim \mathcal{O}(10^{-1})$.
- *However* ... Some non-minimally coupled inflationary models can produce various amounts of other types of NG.

Challenge detection: low amplitude



$\Rightarrow f_{\rm NL} = 38 \pm 18$, for $N_{\rm side} = 512$ (68% CL; Planck Collaboration, 2014)

Inflationary step-like models

$\rightarrow$ Slow-roll approximation: $(1/2)\dot{\phi}^2 \ll V(\phi)^2$ $\leftarrow$

$\rightsquigarrow$ A violation of this condition can be modelled by adding a local feature to an otherwise inflation potential: e.g. a step.
Our choice for this work:

$$V(\phi) = \frac{m^2\phi^2}{2} \quad \rightarrow \quad V(\phi) = \frac{m^2\phi^2}{2}\left[1 + c\,\mathrm{tanh}\left(\frac{\phi - b}{d}\right)\right]$$

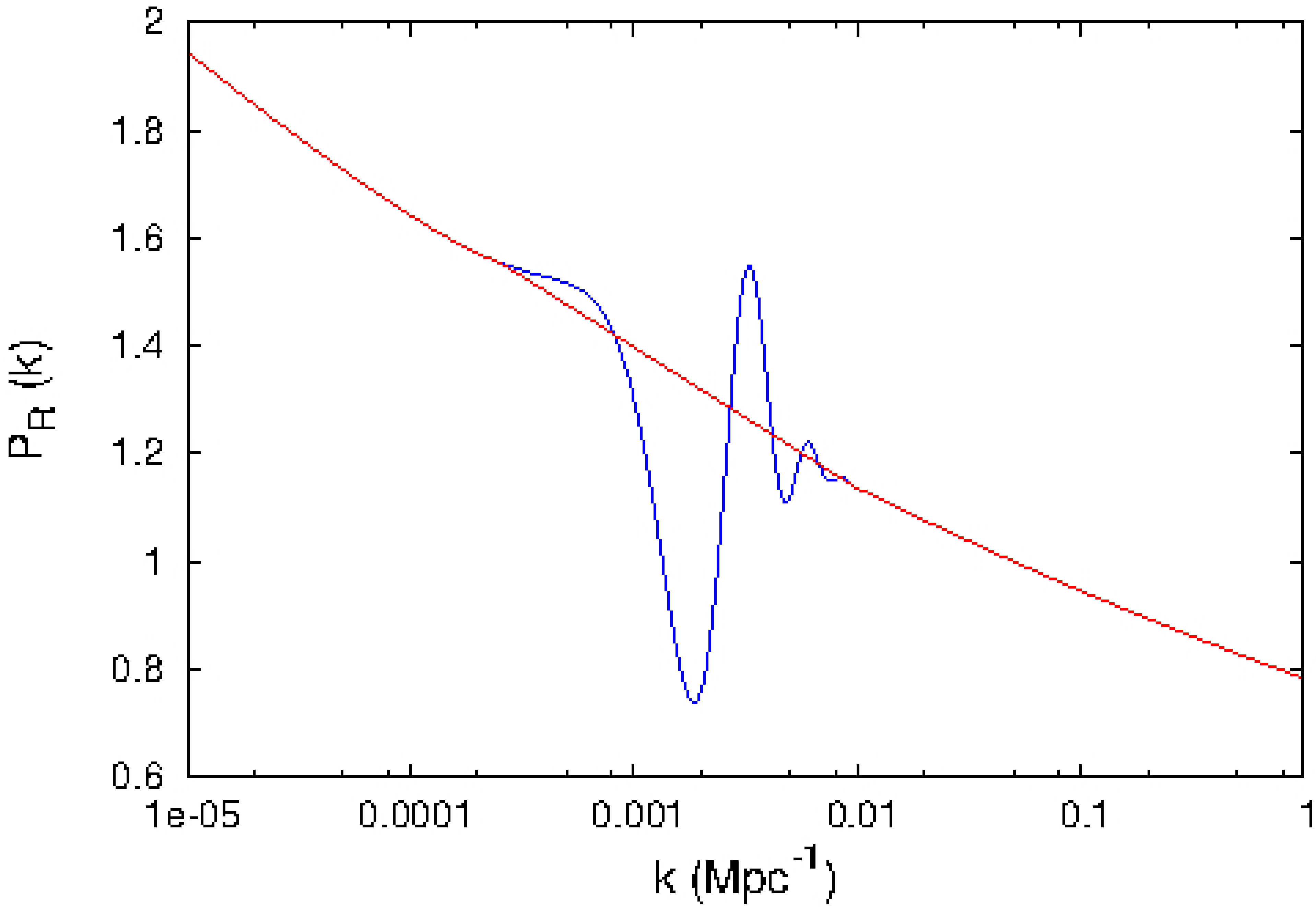
b $=$ field where the step is located,

c $=$ height of the step,

d $=$ slop.

Inflationary step-like models

The power spectrum of primordial perturbation is found to be a power-law with superimposed oscillations :



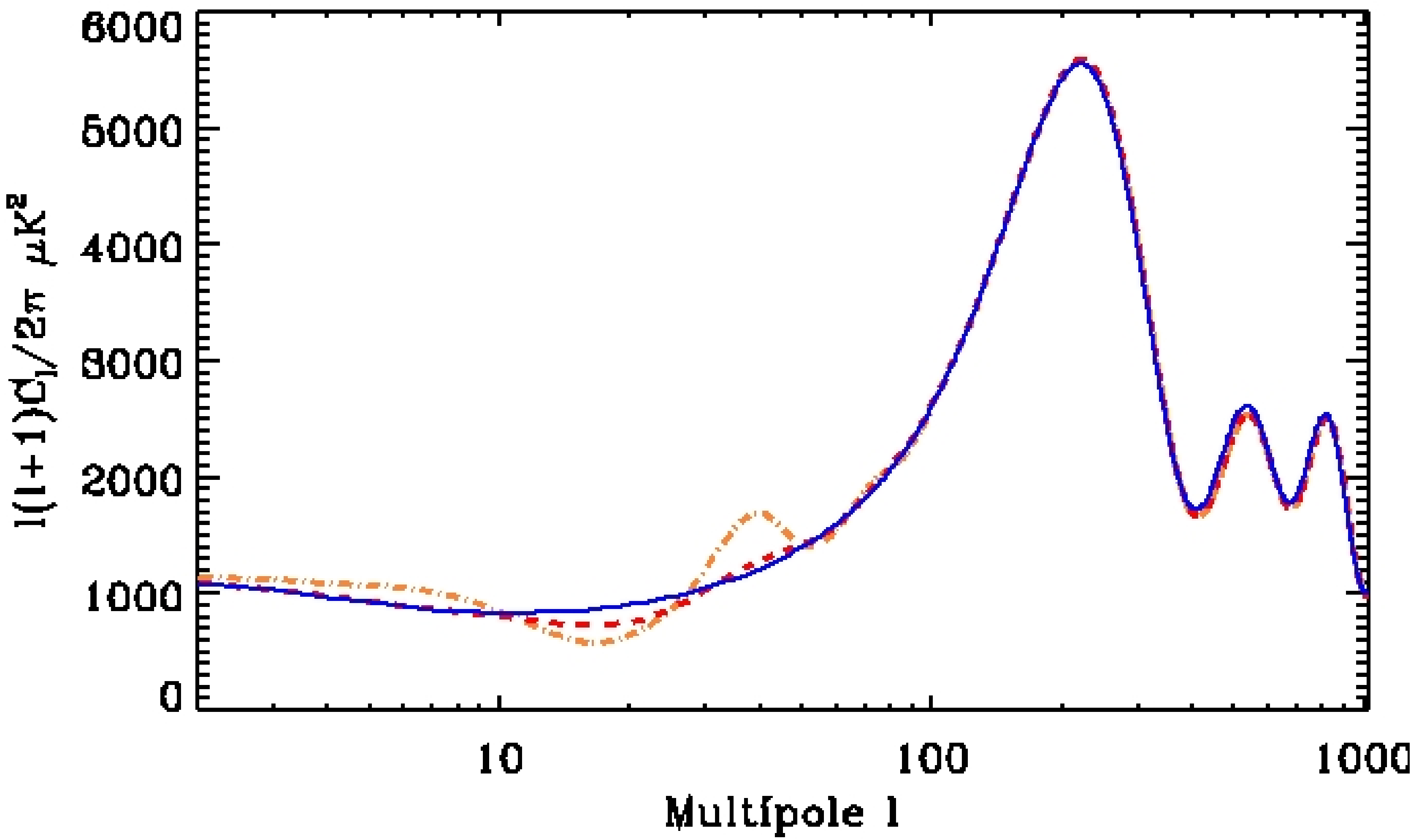
Analysis method

The step-like models:

- Cosmological parameters: $\Omega_b h^2 = 2.22$, $\Omega_c h^2 = 0.1212$, $\tau = 0.089$, $100\theta = 1.0411$, $n_s = 0.959$, and $10^9 A_s = 2.20$.
- Step parameters:
  - Model A: $b = 14.66$, log $c = -2.85$ log $d = -1.44$
  - Model B: Same as Model A but with log c 4 times higher.

Analysis method

The models A and B.



Analysis method

Data description

We analysed 5 sets of Monte Carlo CMB maps, constructed using:

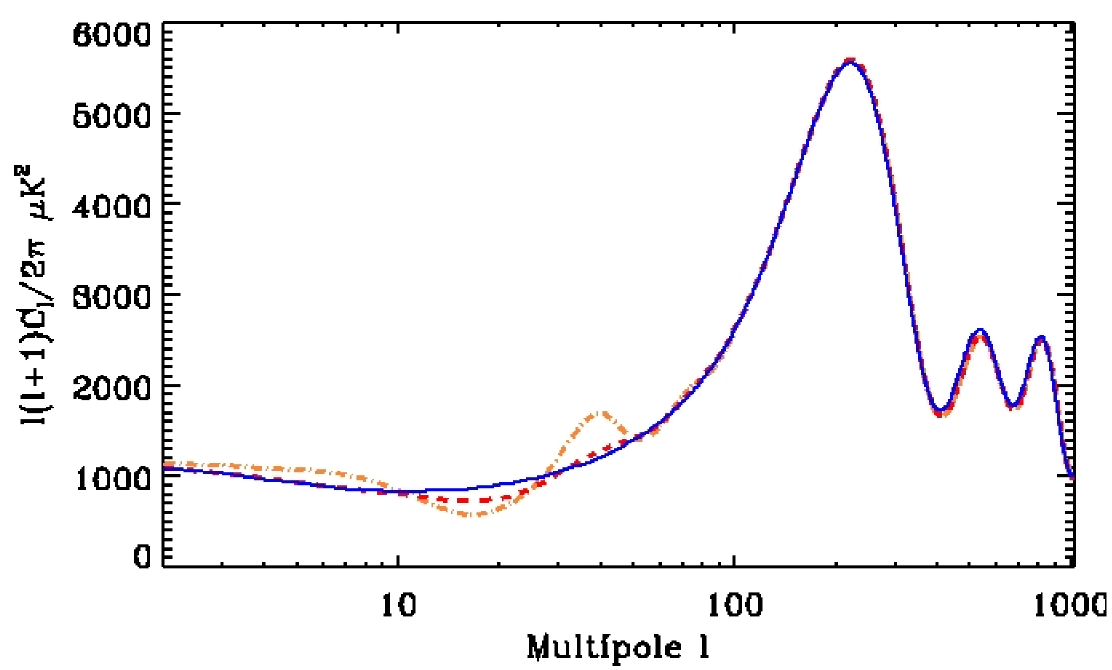
(i) ΛCDM power spectrum (Planck results);
(ii) Model A (best-fit to the angular power spectrum data);
(iii) Model B;
(iv) ΛCDM power spectrum + local-NG given by $f_{NL} = 38$;
(v) ΛCDM power spectrum + local-NG given by $f_{NL} = 100$.

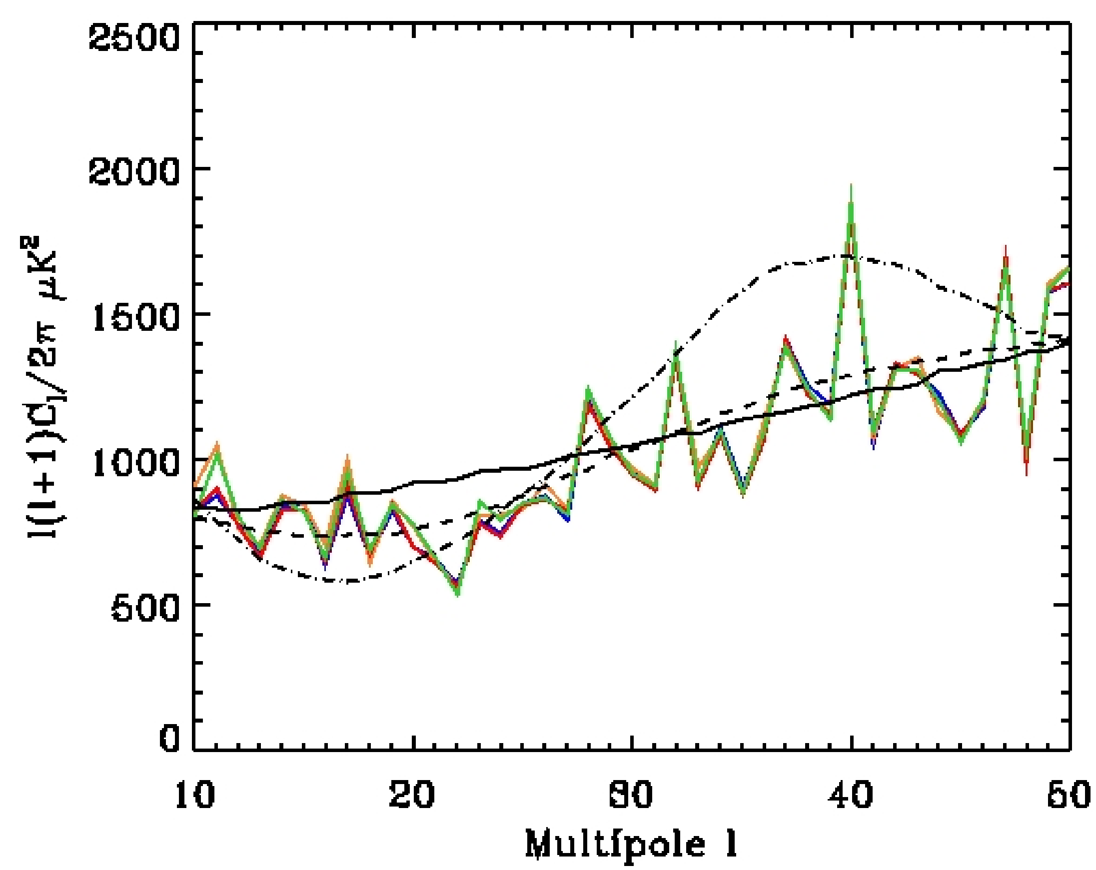
Analysis method

Data description

Each dataset is composed by 1000 CMB maps, constructed also considering:

- $N_{side} = 512$
- Multipole range: $10 \leq \ell \leq 50$





Analysis method

The Minkowski Functionals

- Widely used to study the statistical CMB properties.
- *Hadwiger theorem:* all the morphological properties of a d-dimensional space can be described using $d+1$ MFs.
- Given a connected region, such that, $\nu(\theta,\phi) = \Delta T/\sigma_0 > \nu_t$:
  - Area $\Rightarrow V_0 = A(\nu) = \sum a_i$,
  - Perimeter $\Rightarrow V_1 = P(\nu) = \sum l_i$,
  - Genus $\Rightarrow V_2 = G(\nu) = \sum g_i = N_{hot} - N_{cold}$,

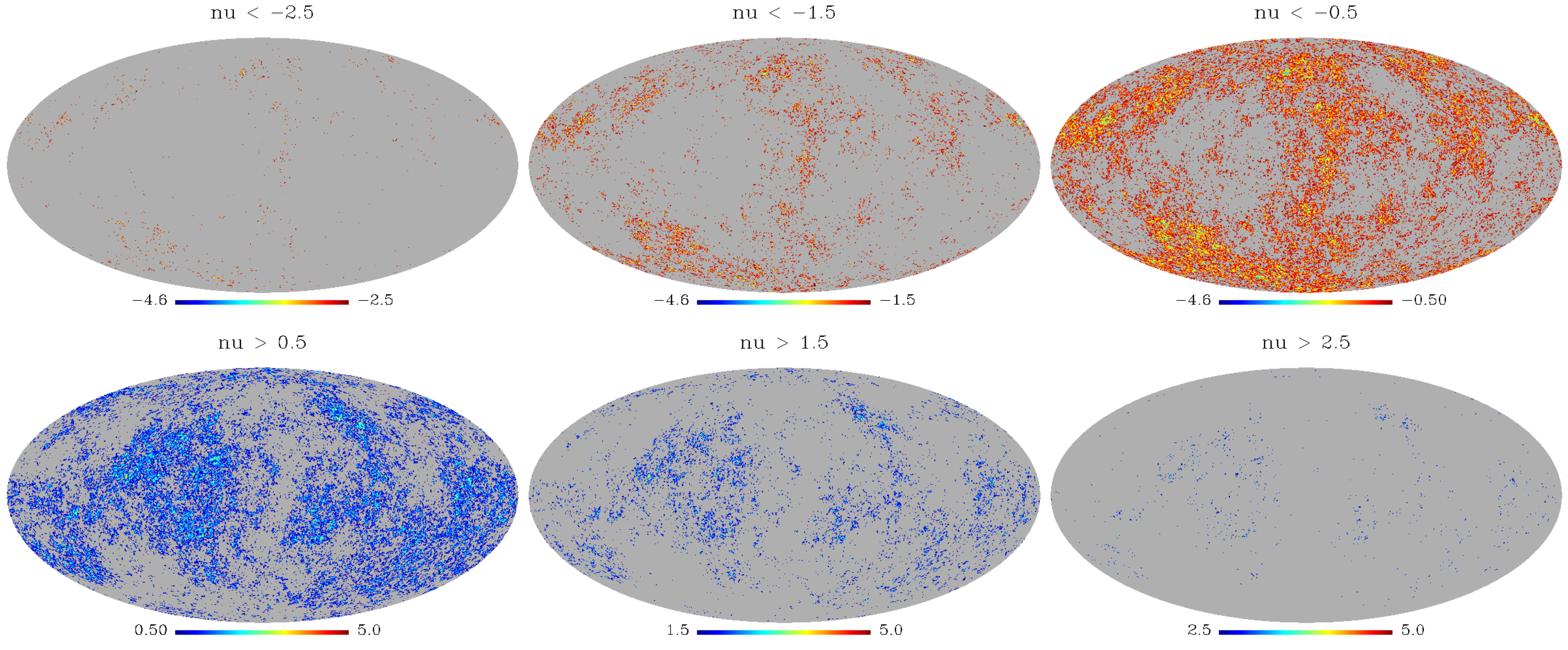
  $+$

  - $V_3 = N_{clusters}(\nu)$: number of connected regions.

Analysis method

The Minkowski Functionals

CMB maps for different ν thresholds



Analysis method

The Minkowski Functionals

MFs: Area ($k = 0$), Perimeter ($k = 1$), Genus ($k = 2$), $N_{clusters}$ ($k = 3$).

$$\{V_k\} \equiv (V_0, V_1, V_2, V_3)$$

$$[-\nu_{max} \text{ a } \nu_{max}] \Rightarrow \nu = \nu_{_1}, \nu_{_2}, \ldots \nu_n$$

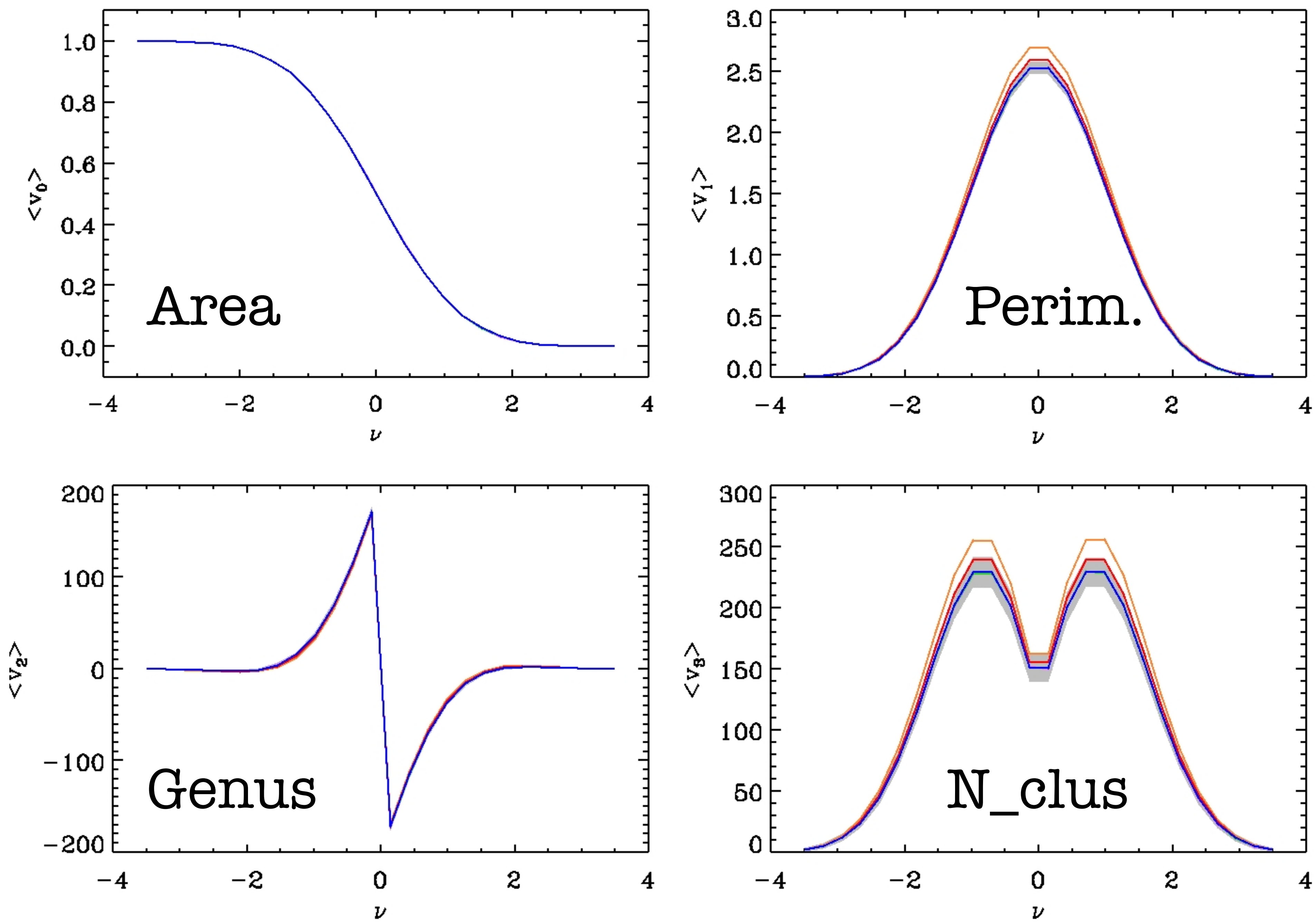
$$\{\nu_{max}, n\} = \{3.5, 26\}$$

For the i-th temperature map and for the k-th MF we have the vector:

$$v_k^i \equiv (V_k(\nu_{_1}), V_k(\nu_{_2}), \ldots V_k(\nu_n))\big|_{\text{for the } i\text{-th map}}. \tag{1}$$

MFs as non-Gaussian estimators

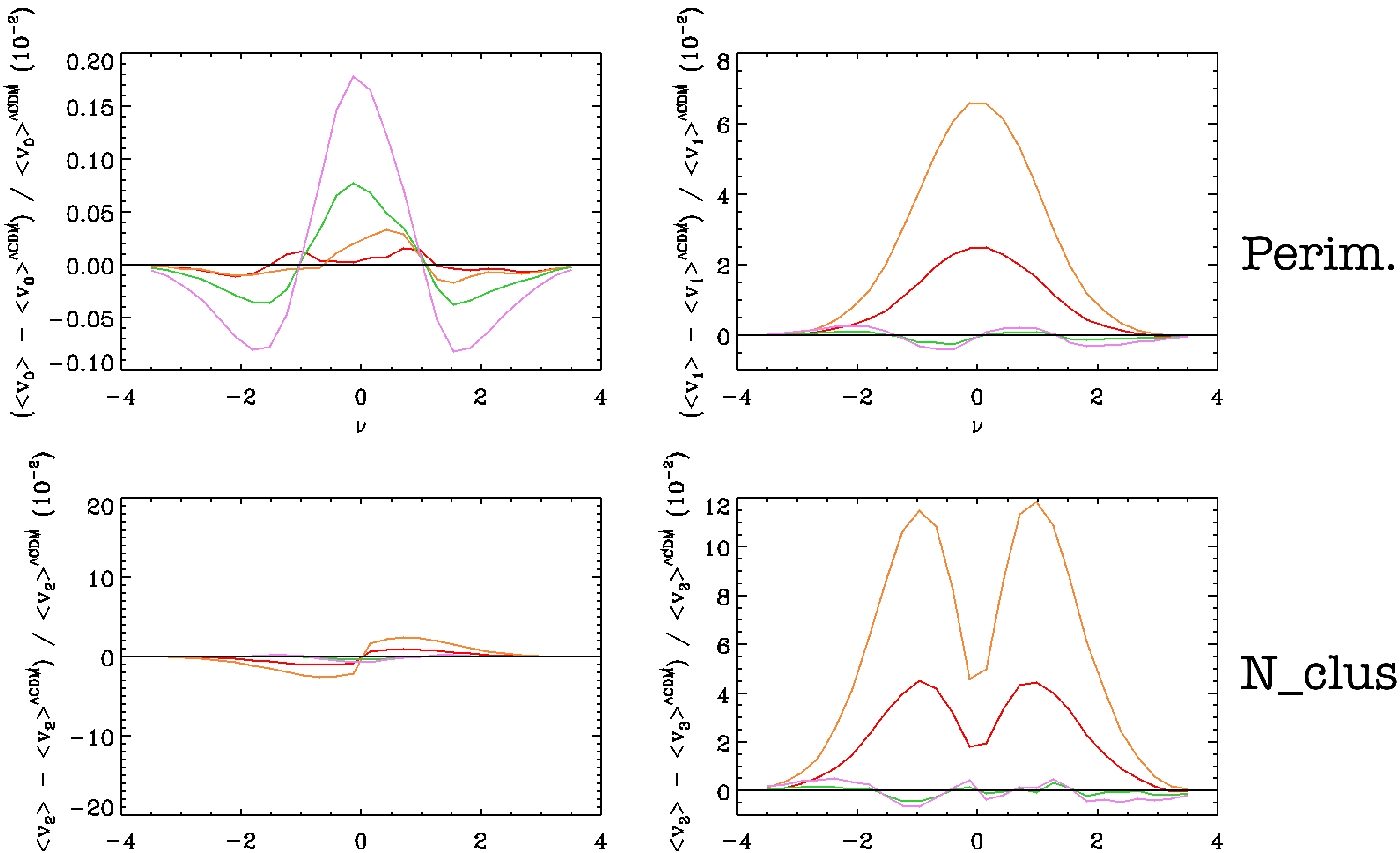
Average MFs curves: (i): ΛCDM, (ii): *Mod-A*, (iii): *Mod-B*, (iv): NG-$f_{NL} = 38$ and (v): NG-$f_{NL} = 100$



Conclusion: no clear signature left by different NGs.

MFs as non-Gaussian estimators

Relative difference with respect to ΛCDM: (ii) *Mod-A*, (iii): *Mod-B*, (iv): NG-$f_{NL} = 38$ and (v): NG-$f_{NL} = 100$



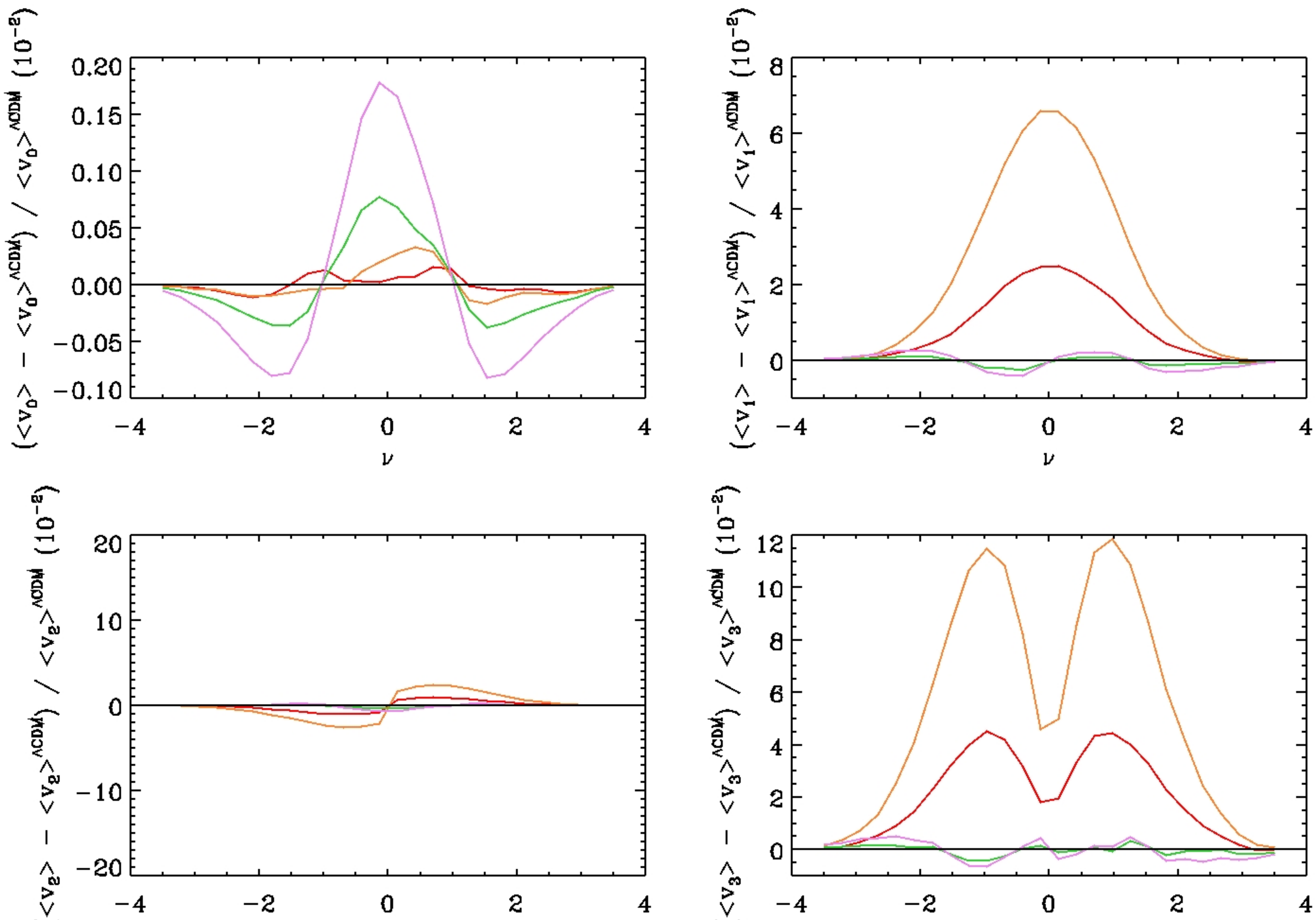
NG in MC CMB maps from Models A and B

Question: Are there distinguishable non-Gaussian features left in simulated CMB maps generated by *Models A* and *B*?

Coming back to the previous plots ...

NG in MC CMB maps from Models A and B

Relative difference with respect to ΛCDM: (ii) *Mod-A*, (iii): *Mod-B*, (iv): NG-$f_{NL} = 38$ and (v): NG-$f_{NL} = 100$



Perim.

N_clus

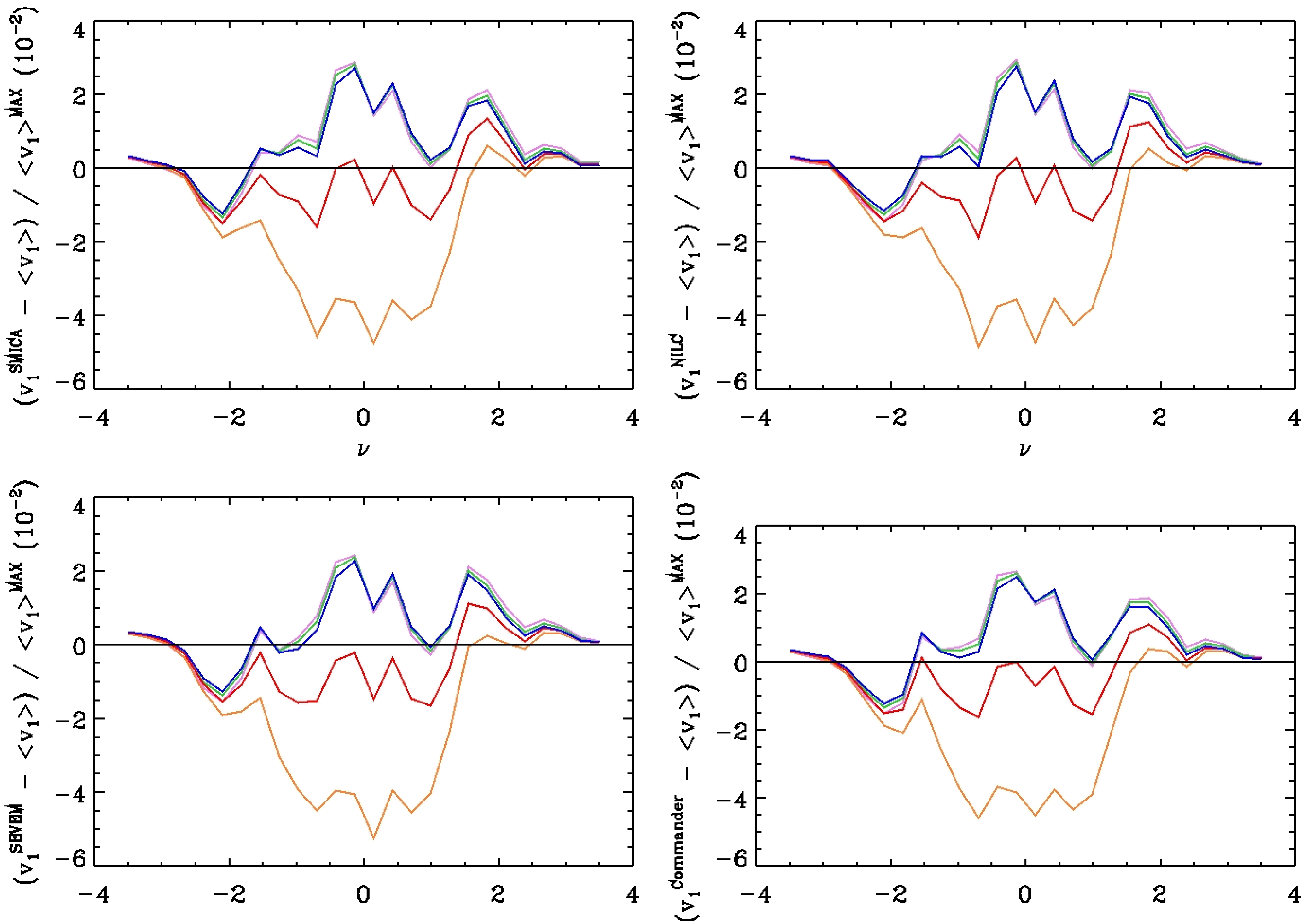
NG in MC CMB maps from Models A and B

- Inflationary Models A and B produce a **noticeable Gaussian deviation**;
- These deviations are best revealed by the Perimeter and $N_{clusters}$ MFs;
- The non-Gaussian signatures appearing in the sets of MC CMB maps emerging from *Models A* and *B* are **not of the type, neither intensity**, expected in maps contaminated with primordial *local*-NG.

NG from Models A and B are contributions with a definite signature **originated in the inflationary phase** $\Longrightarrow$ **probe** to the primordial universe.

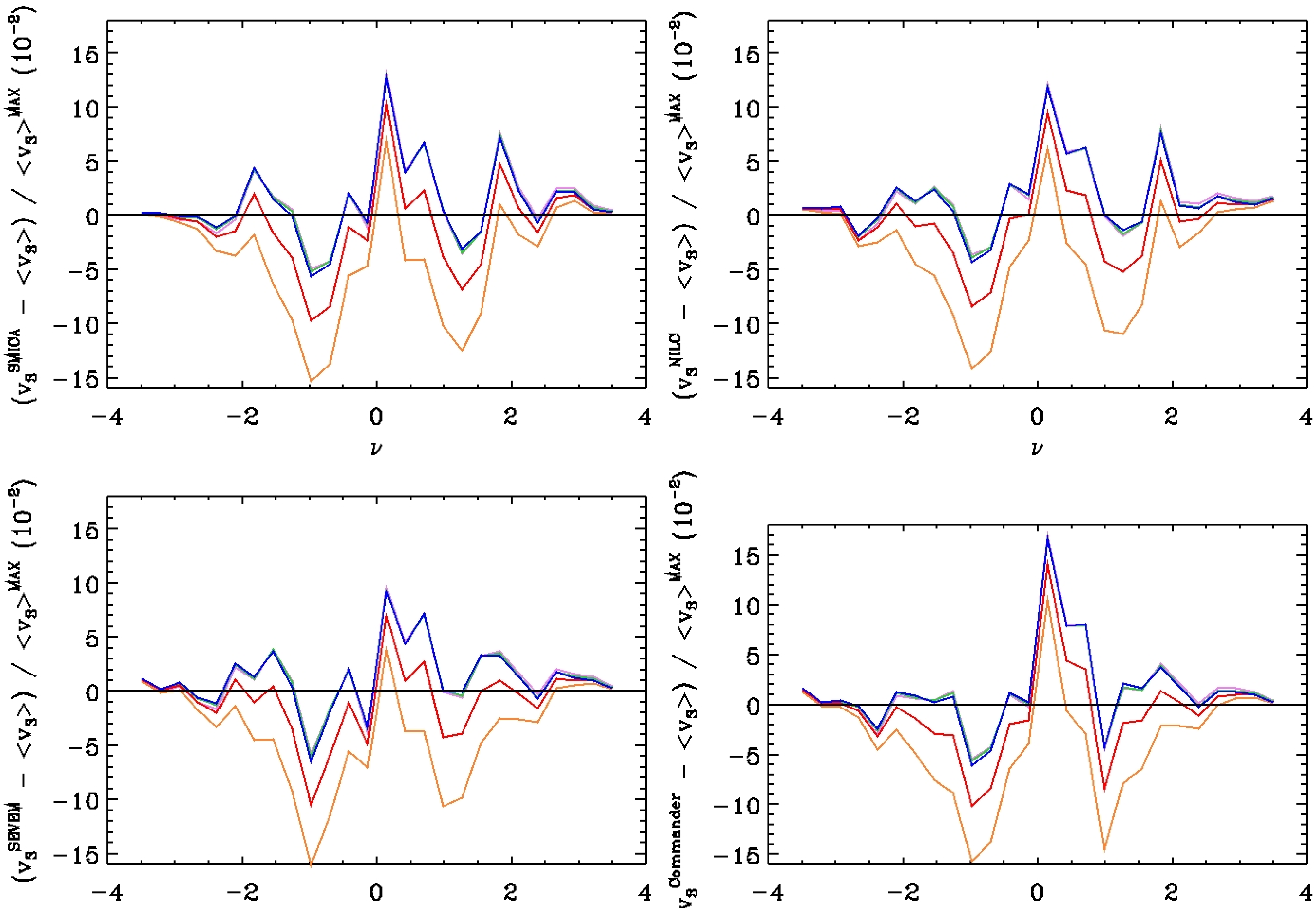
Mapping NG in Planck CMB maps

Perimeter: (i): ΛCDM, (ii): *Mod-A*, (iii): *Mod-B*, (iv): NG-$f_{NL} = 38$ and (v): NG-$f_{NL} = 100$



Mapping NG in Planck CMB maps

$N_{clusters}$: (i): ΛCDM, (ii): *Mod-A*, (iii): *Mod-B*, (iv): NG-$f_{NL} = 38$ and (v): NG-$f_{NL} = 100$



(i) ΛCDM power spectrum (Planck results);
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(v) ΛCDM power spectrum + local-NG given by $f_{NL} = 100$.

χ^2 values calculated from the MFs curves obtained for each Planck map and the average MFs over 1000 realisations of the sets (i) to (v). [UT78, 25 dof.]

MF	Planck map	Data set (i)	(ii)	(iii)	(iv)	(v)
Area (v_0)	SMICA	34.0	35.9	39.8	36.7	42.1
	NILC	34.3	36.3	40.3	37.3	43.0
	SEVEM	33.8	35.6	39.6	36.0	41.0
	Commander	33.0	34.9	38.8	35.5	40.9
Perimeter (v_1)	SMICA	26.2	21.0	78.4	29.5	34.1
	NILC	27.1	22.9	82.3	30.5	35.3
	SEVEM	24.8	24.9	92.3	27.7	32.2
	Commander	27.2	23.4	83.5	30.5	35.1
Genus (v_2)	SMICA	44.6	43.8	47.3	48.4	51.3
	NILC	47.7	47.8	50.3	54.5	58.2
	SEVEM	40.4	39.2	43.0	43.5	45.8
	Commander	44.7	43.5	46.7	48.0	50.4
$N_{clusters}$ (v_3)	SMICA	22.0	23.5	57.9	23.7	26.3
	NILC	27.1	26.1	55.3	29.8	32.5
	SEVEM	18.6	18.4	50.3	18.7	20.1
	Commander	30.0	30.9	63.9	30.1	31.7

Concluding remarks

[arXiv:1507.01657]

From the MFs:

- The MFs are able to discriminate the different types and amplitudes of NGs.
- Order in sensitivity: Perimeter $> N_{clusters} >$ Genus $\gg$ Area.

Detection of NGs - Models A and B:

- The non-Gaussian contribution found in these sets of MC CMB maps are of primordial origin.
- The Gaussian deviations are not accounted by primordial *local*-NG, neither intensity nor in signature.
- The non-Gaussian signatures in Planck CMB data are better described by MC maps seeded by *Model's A* CMB spectrum.

MFs as non-Gaussian estimators

- A **single statistical estimator** is not sensible enough to detect **any non-Gaussian contribution** (or combination of them) present in CMB maps;
- The Gaussian deviations shown in the plots make clear that: The MFs are able to **discriminate distinct NGs** imprinted in CMB maps!