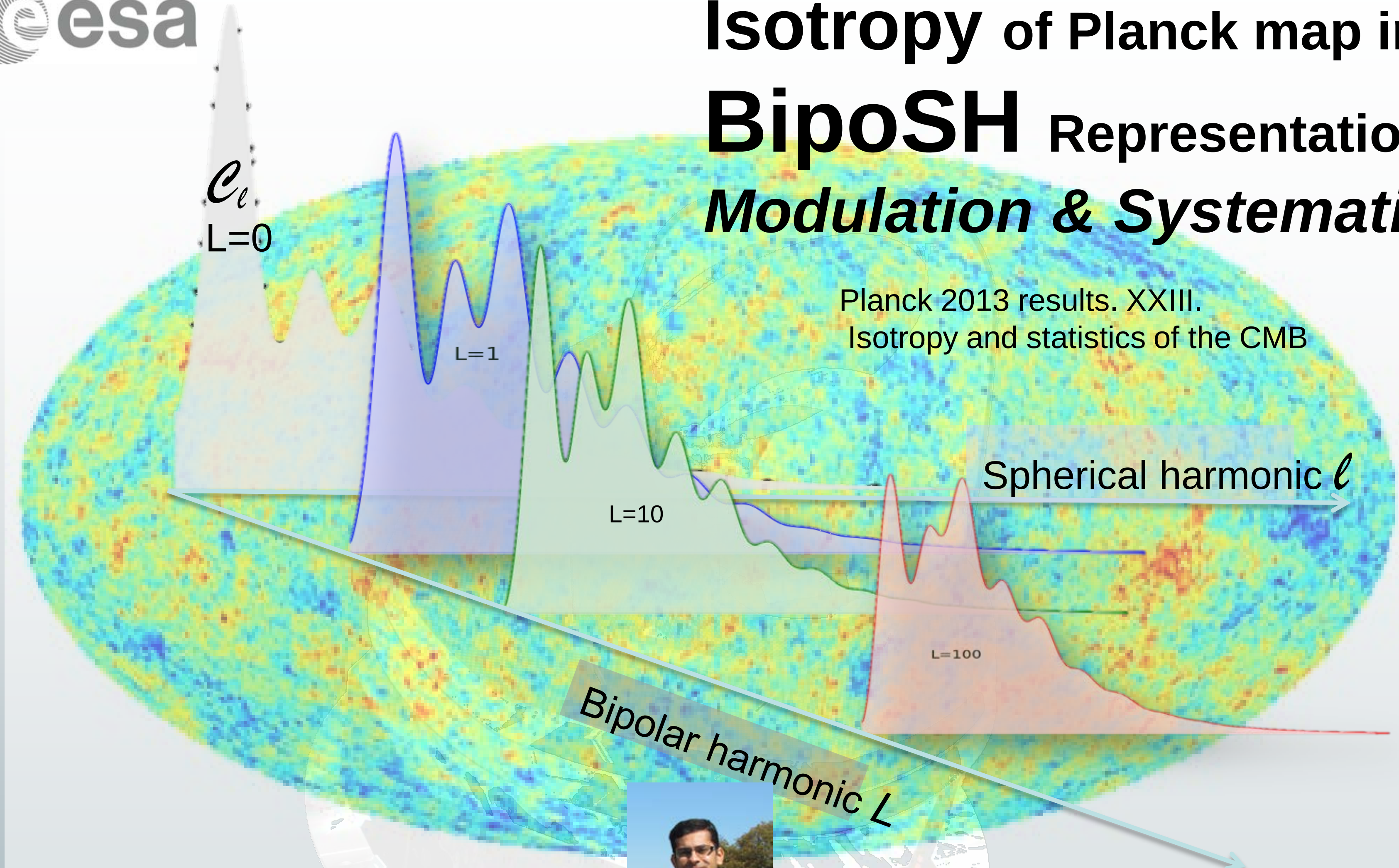
Isotropy of Planck map in **BipoSH** Representation: *Modulation & Systematics*



Planck 2013 results. XXIII.
Isotropy and statistics of the CMB

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On behalf of the Planck collaboration

Planck unveils the Cosmic Microwave Background
ESTEC, Netherlands
Apr 2-5, 2013

BipoSH : Natural generalization of C_ℓ

Bipolar Spherical Harmonic representation

Amir Hajian & Souradeep 2003

$$C(n_1 \bullet n_2) = \sum \frac{2l+1}{4\pi} C_l P_l(n_1 \bullet n_2)$$

$$C_\ell = \langle a_{\ell m} a^*_{\ell m} \rangle$$

$$C(\hat{n}_1, \hat{n}_2) = \sum_{l_1 l_2 LM} A^{LM}_{l_1 l_2} \{Y_{l_1}(\hat{n}_1) \otimes Y_{l_2}(\hat{n}_2)\}_{LM}$$

Bipolar spherical harmonics.

BipoSH Coefficients

$$A^{LM}_{l_1 l_2} = \sum_m \left\langle a^*_{l_1 m} a_{l_2 m+M} \right\rangle C^{LM}_{l_1 m_1 l_2 m_{+M}}$$

Linear combination of off-diagonal elements

BipoSH provide complete representation of SH space correlation matrix

BipoSH : *Natural* generalization of C_ℓ

Bipolar Spherical Harmonic representation

Amir Hajian & Souradeep 2003

A *complete* representation of two-point correlation

- Modulation of CMB sky *(rest of the talk)*
- non-uniform variance (e.g., inhomo. noise, anomaly in XXIII)

$$\langle \Delta T(\hat{n})^2 \rangle = \mathcal{R}(\hat{n}) = \sum_{LM} \mathcal{R}_{LM} Y_{LM}(\hat{n})$$

$$\mathcal{R}_{LM} = \sum_{l_1 l_2} A^{LM}_{l_1 l_2} \frac{\Pi_{l_1}\Pi_{l_2}}{\sqrt{4\pi}\Pi_L} \mathcal{C}^{L0}_{l_1 0 l_2 0}$$

- Weak lensing
  - *Scalar & Tensor lens*

    Books, Kamionkowski, TS 2012

$$A^{(+)LM}_{\ell\ell\prime} = \phi_{LM} \left[C_\ell G^L_{\ell\ell'} + (\ell \leftrightarrow \ell\prime)\right]$$

$$A^{(-)LM}_{\ell\ell\prime} = \Omega_{LM} \left[C_\ell G^L_{\ell\ell'} - (\ell \leftrightarrow \ell\prime)\right]$$

  - *Weak lensing of non-SI map affects C_ℓ*
- Beam non-circularity

  Joshi, Das, Rotti, Mitra, TS 2012

$$A^{L0}_{l_1 l_2} = \sum_{l'} C_{l'} \sum_{L_1 L_2} B^{L_1 0}_{l_1 l'} B^{L_2 0}_{l_2 l'} (-1)^{l_1+L_1} \sqrt{(2L_1+1)(2L_2+1)} C^{L0}_{L_1 0 L_2 0} \begin{pmatrix} l' & l_2 & L_2 \\ L & L_1 & l_1 \end{pmatrix}$$

- Cosmic topology, Magnetic fields , Lorentz violation…

Modulation model of SI violation

$$\Delta T(\hat{n}) = [1 + M(\hat{n})]\Delta T^{\mathrm{SI}}(\hat{n})$$

M(n) : modulation field searched $M(\hat{n}) = \sum_{LM} m_{LM} Y_{LM}(\hat{n})$

m_{LM} couples CMB multipoles a_{lm} and $a_{l'm'}$

$$A^{LM}_{ll'} = m_{LM} G^{L}_{ll'}$$

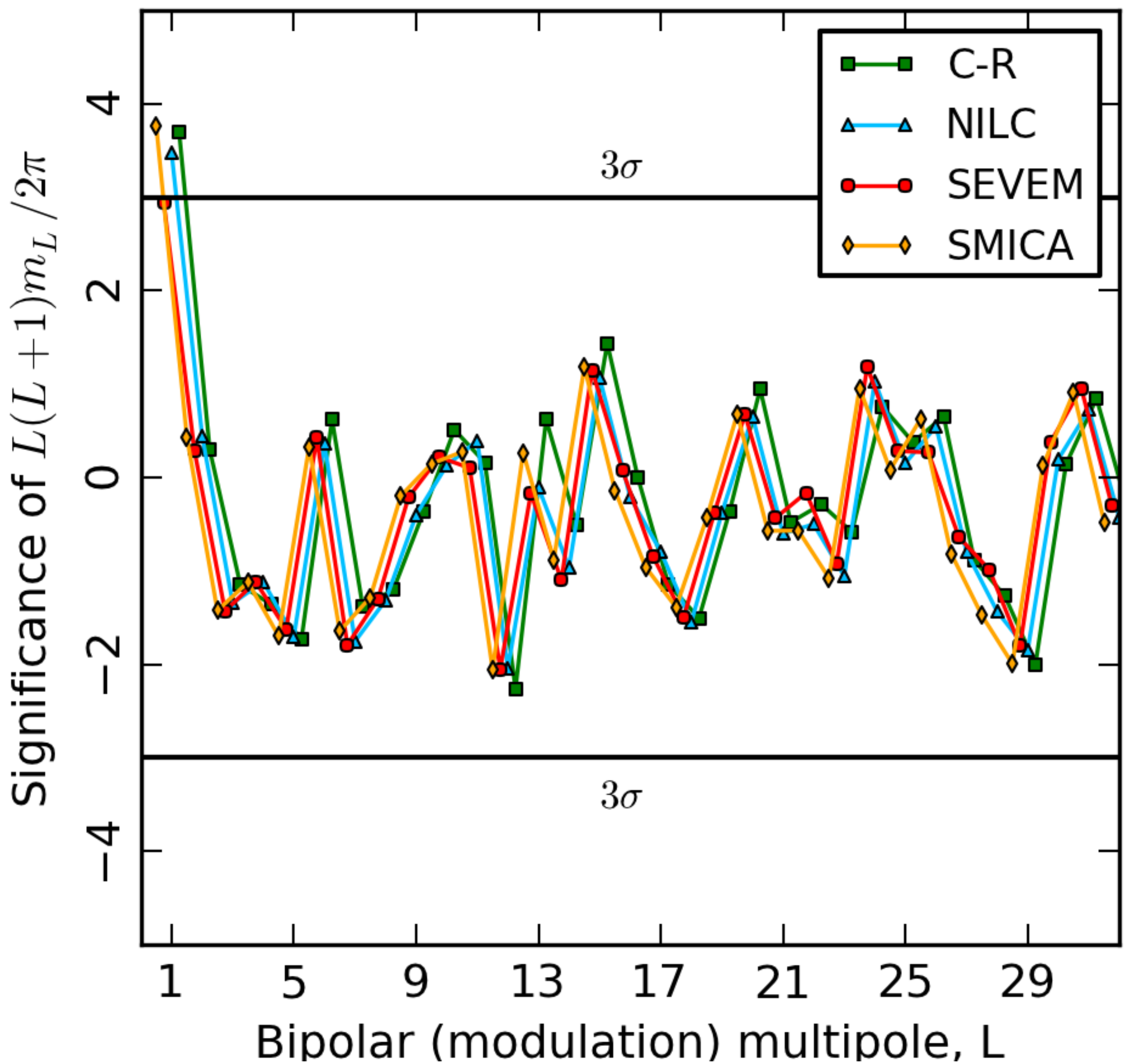
$$G^{L}_{ll'} = [C_l + C_{l'}]\mathcal{C}^{L0}_{l0,l'0}[..]$$

Constructed appropriate minimum variance estimator for m_{LM}

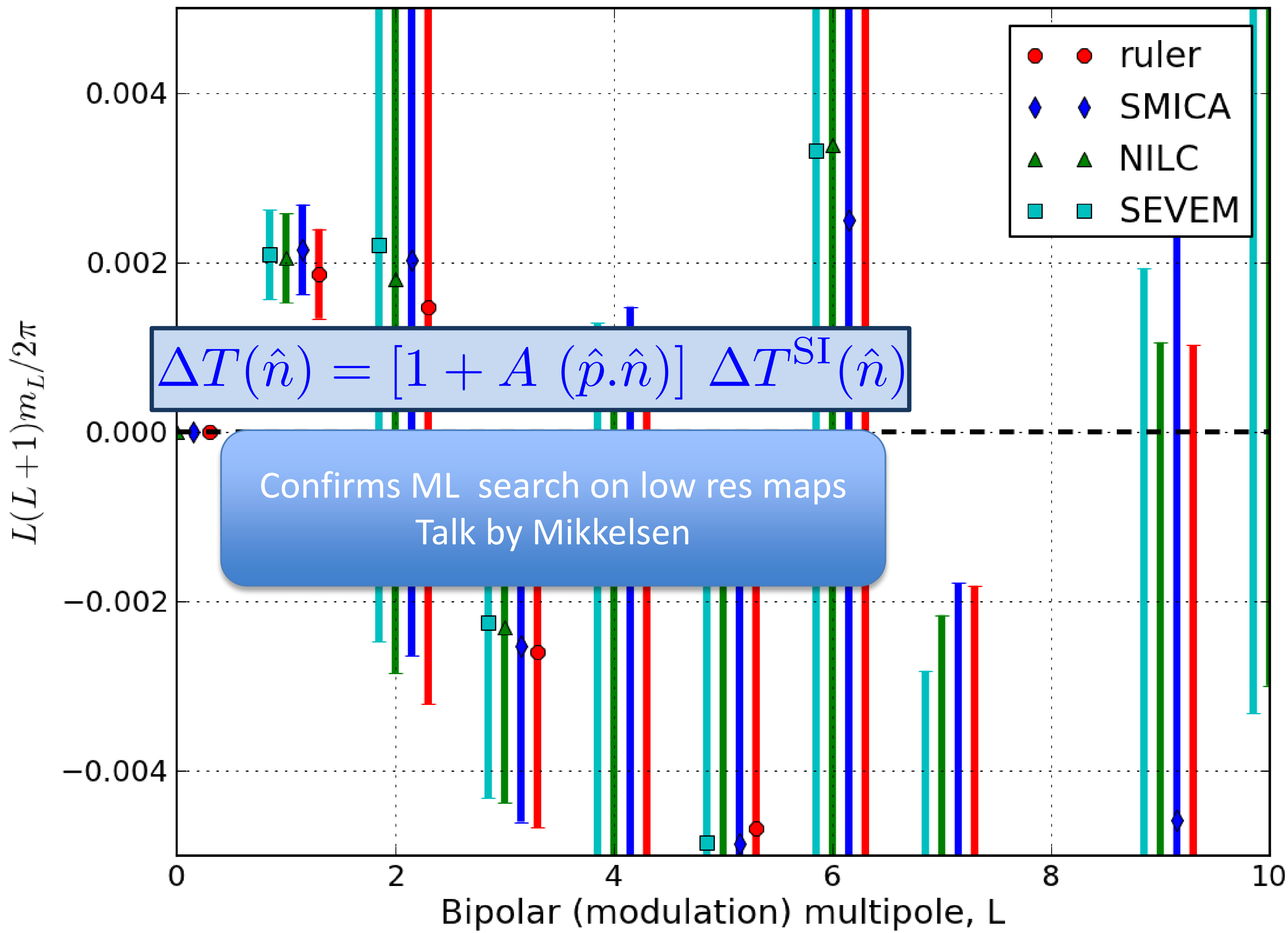
Non-SI effects of (common) mask, inhomogeneous Planck noise subtracted out using 1000 Planck simulations

Significance of Modulation Power.

Planck 2013 results. XXIII. Isotropy and statistics of the CMB



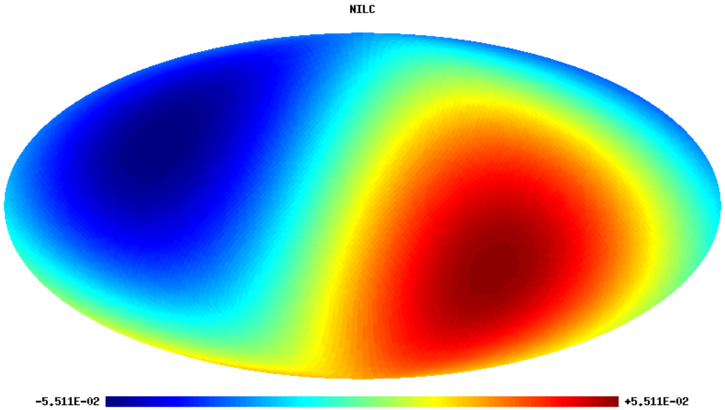
BipoSH Power spectrum of reconstructed modulation maps.



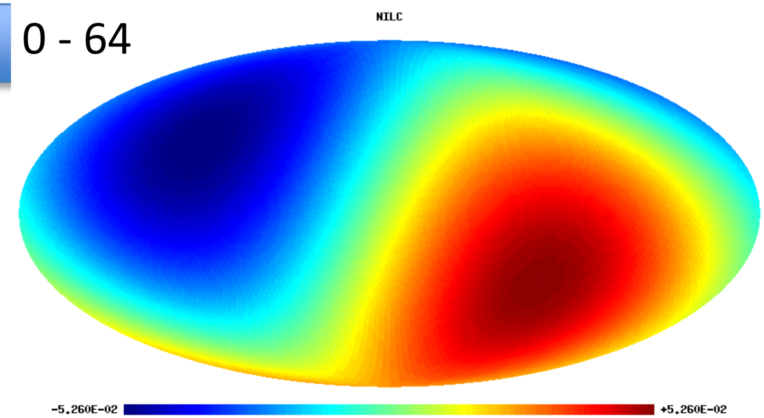
DIPOLE recovered from COMMANDER low resolution map

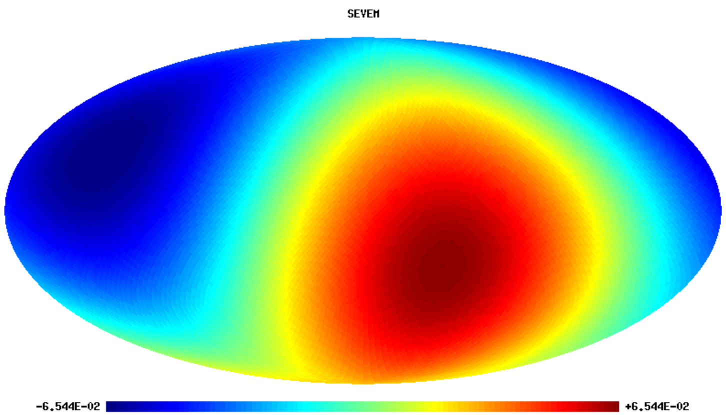
DIPOLE recovered from FULL RESOLUTION COMP SEP MAPS.

ℓ : 0 - 64

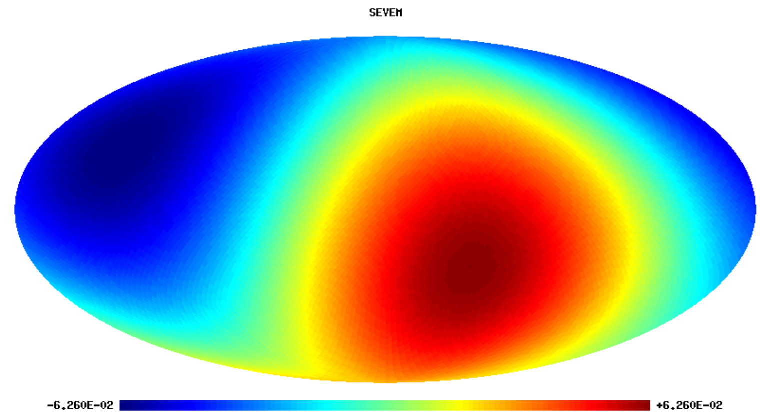


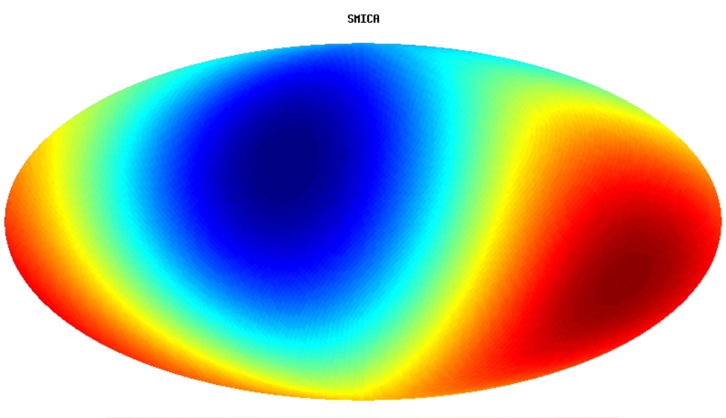
NILC



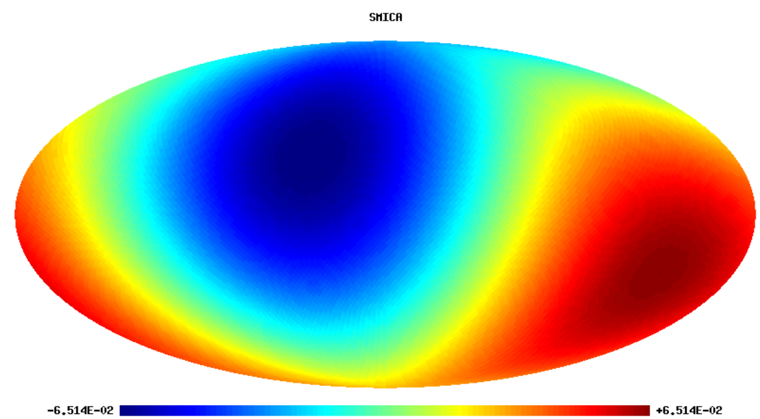


SEVEM



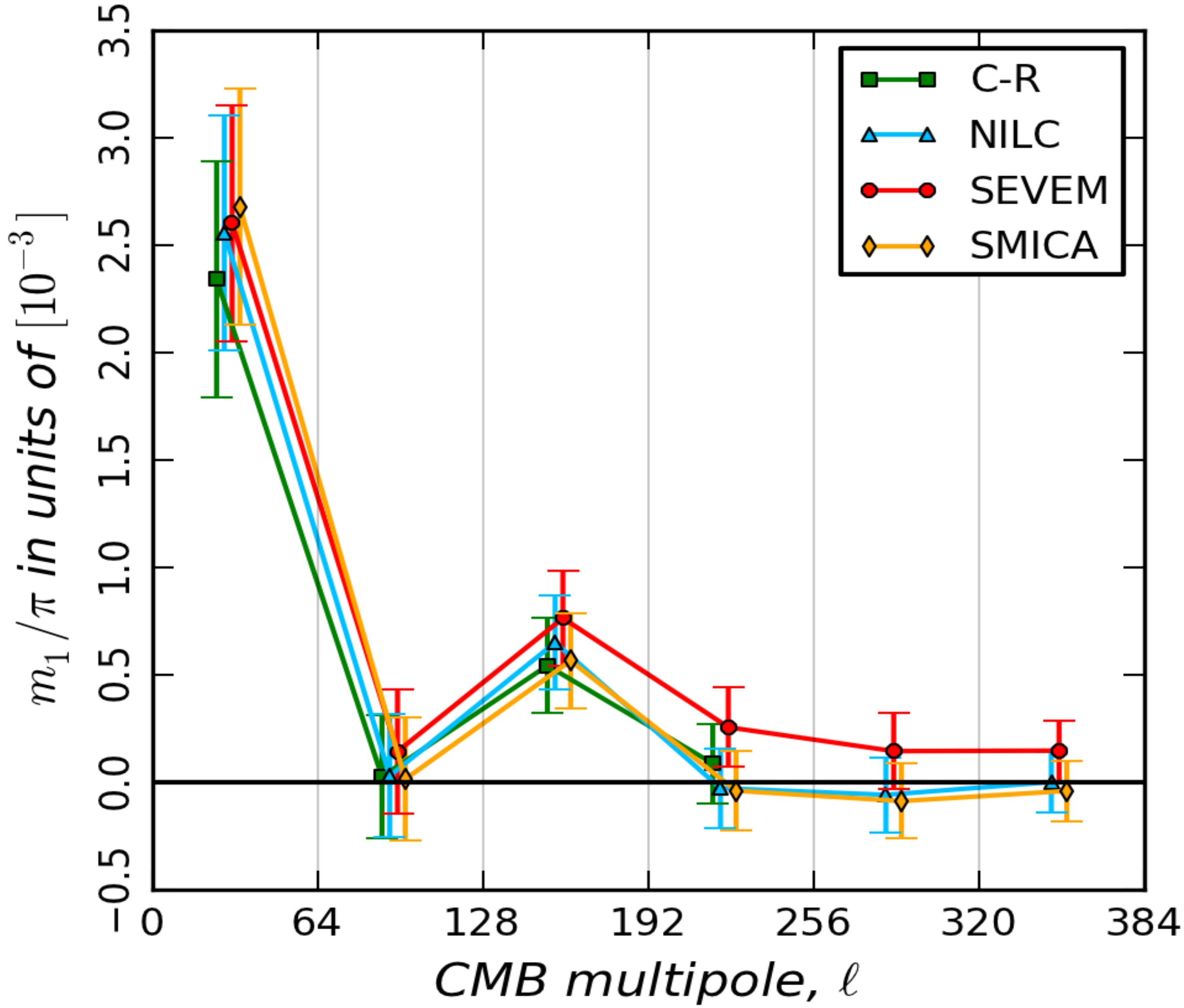


SMICA

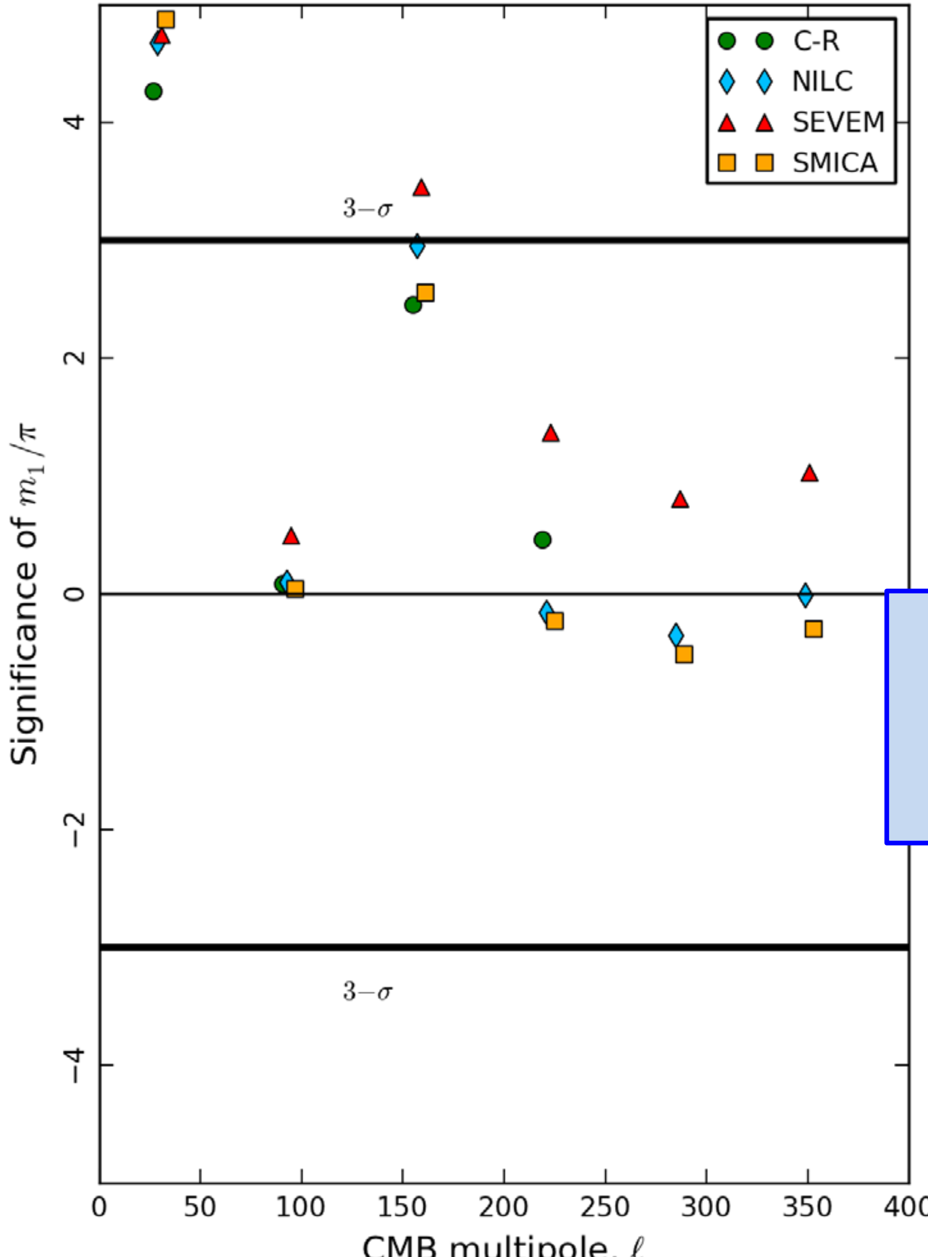


Scale dependent dipole modulation.

Planck 2013 results. XXIII. Isotropy and statistics of the CMB



Scale dependent dipole modulation.

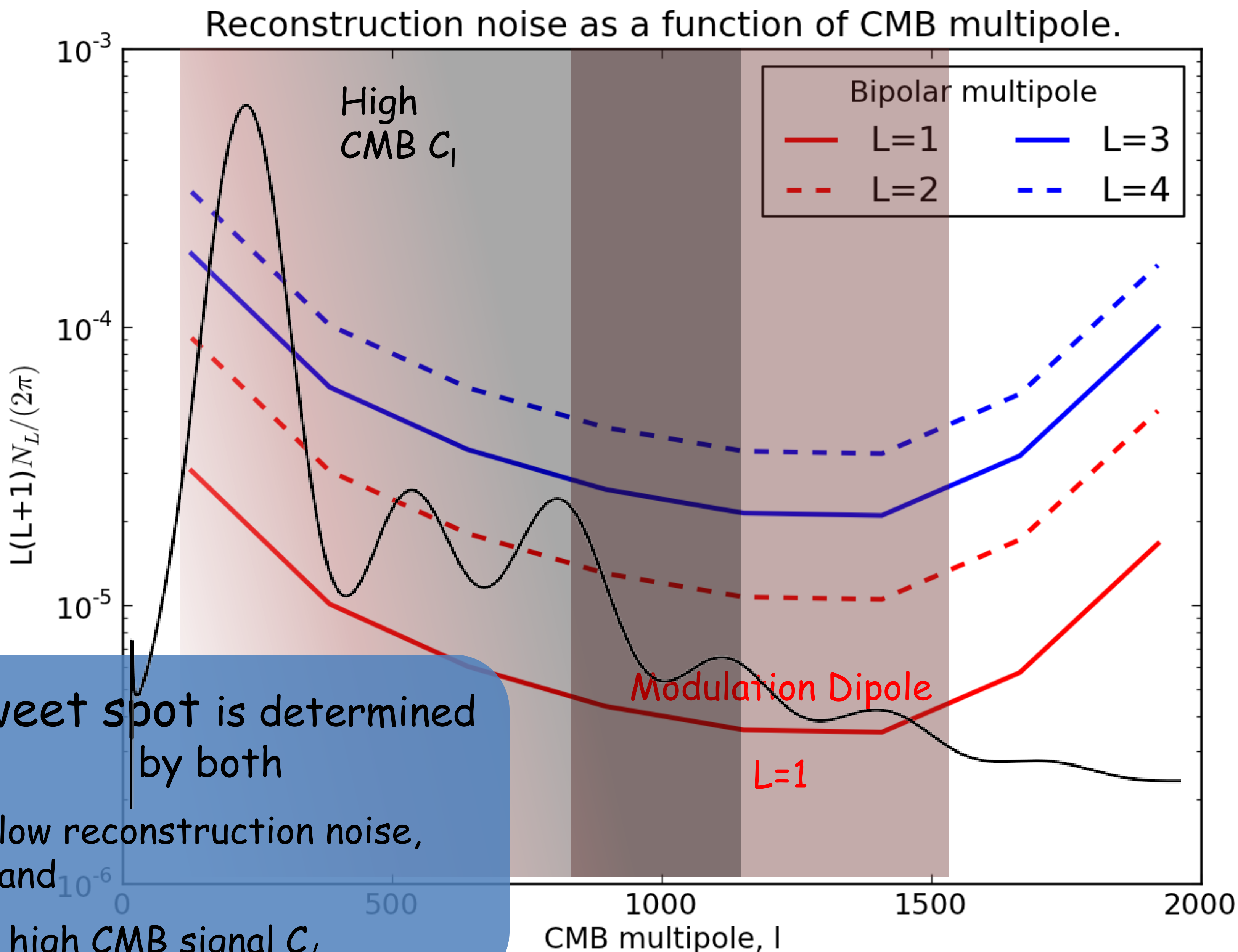


$$A \to A(\ell)$$

Perhaps Physically more reasonable?

k-dependent modulation mechanism

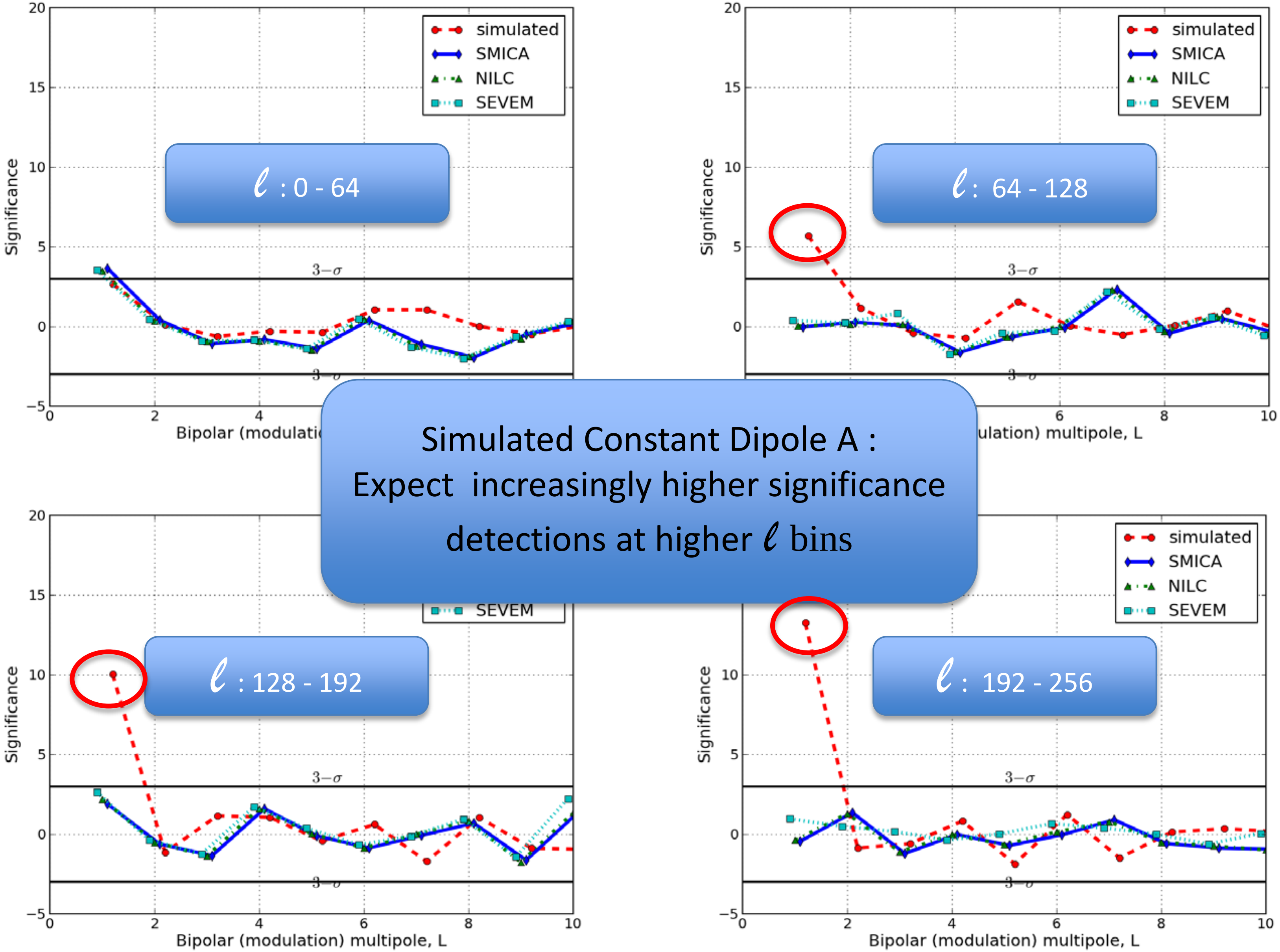
Higher detection significance at higher ℓ



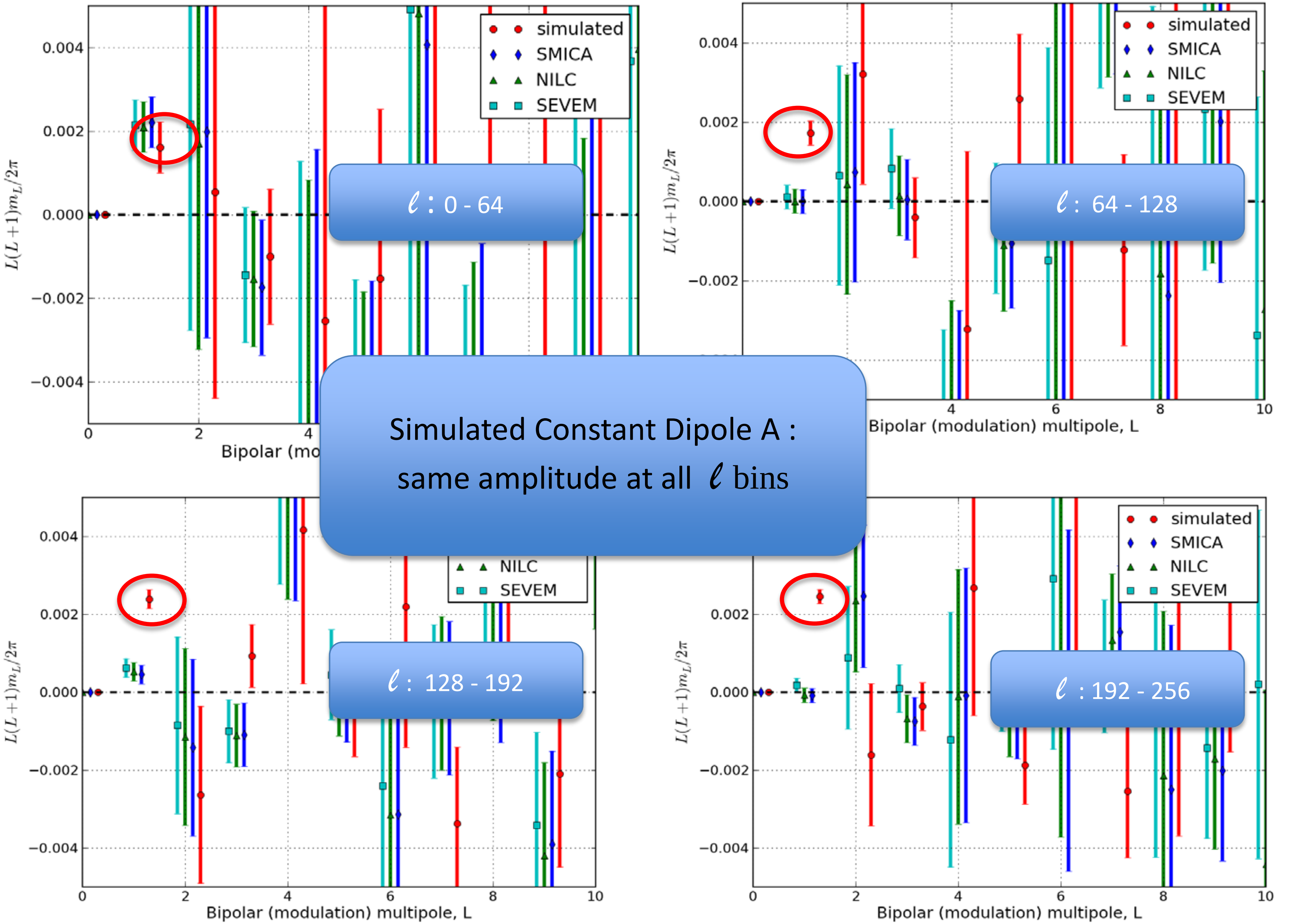
Sweet spot is determined by both

- low reconstruction noise, and
- high CMB signal C_l

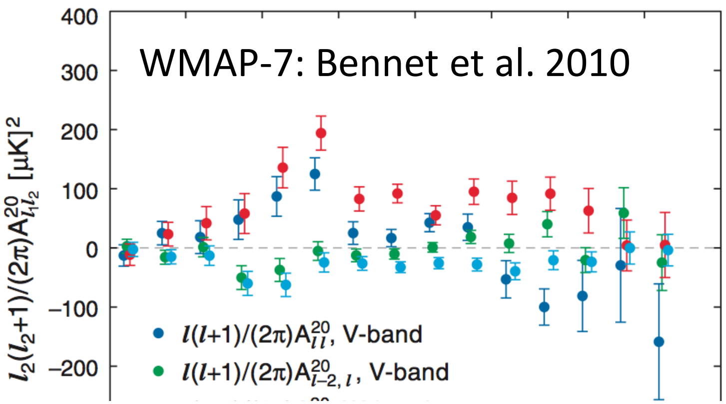
Significance of Dipole power vs. CMB multipole ℓ

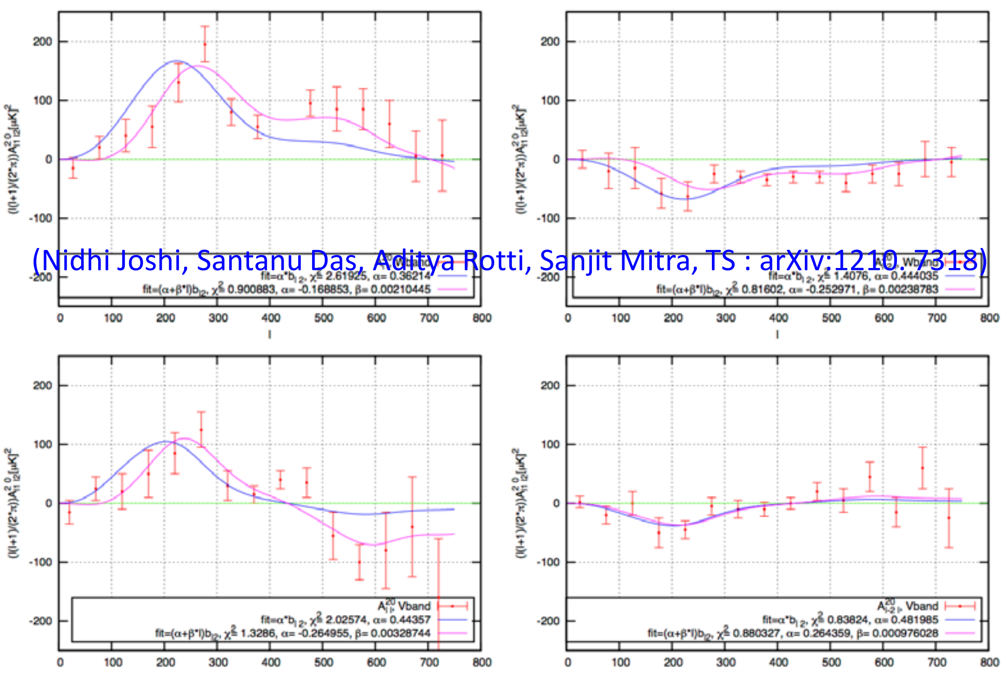


Modulation Power spectra: in ℓ bins

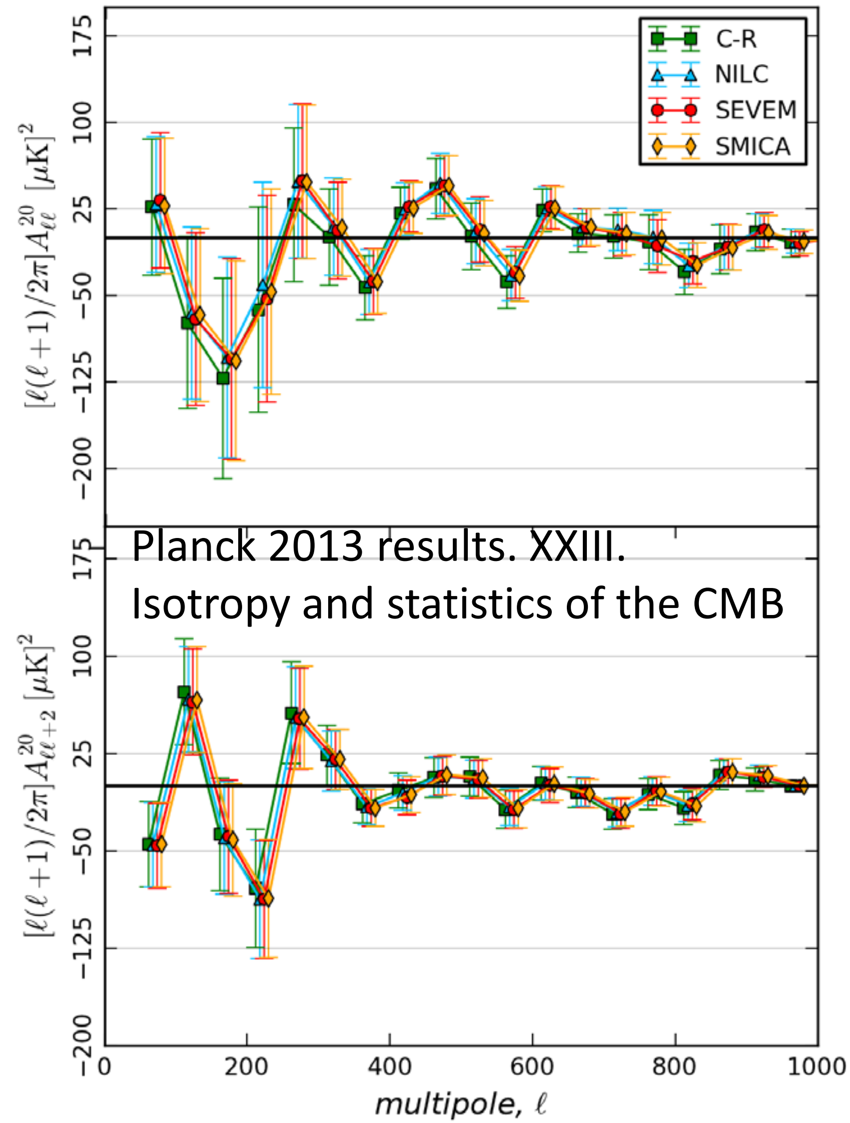


Quadrupolar BipoSH anomaly in WMAP-7



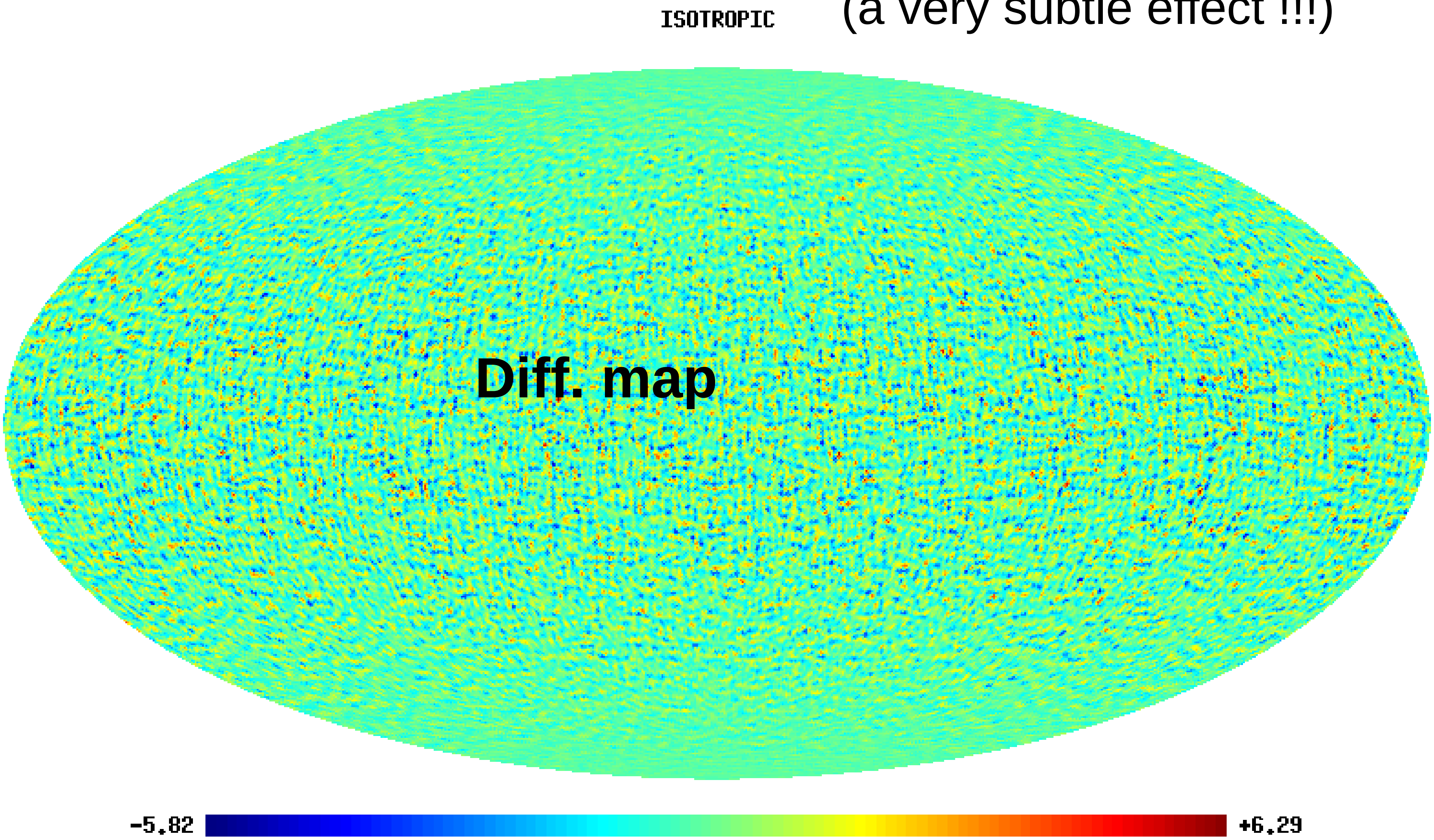


(Nidhi Joshi, Santanu Das, Aditya Rotti, Sanjit Mitra, TS : arXiv:1210.7318)



Non-SI by eye

(a very subtle effect !!!)



Non-SI map generation for given BipoSH: Suvodip Mukherjee

Summary

- Clear detection of dipolar modulation in Planck maps at well above 3σ with BipoSH analysis (consistent results from SMICA,RULER,NILC, SEVEM)
- Modulation harmonics and CMB harmonics are distinct in BipoSH representation allowing for identification of CMB multipole range (angular scales) that provide most significant signal.
- Dependence of the dipole modulation signal on the CMB multipole reveled by BipoSH is beyond modulation model.
  Intriguing at the least! Difficult to explain *(eg., see arXiv:1303:6949)*
- Verified that the WMAP-7 quadrupolar anomaly is absent in PLANCK maps. Establishing the fact that the anomaly was specific to WMAP systematics.
- Lots of possibilities to employ BipoSH representation to Planck temperature and **Polarization**

Thank you !!!

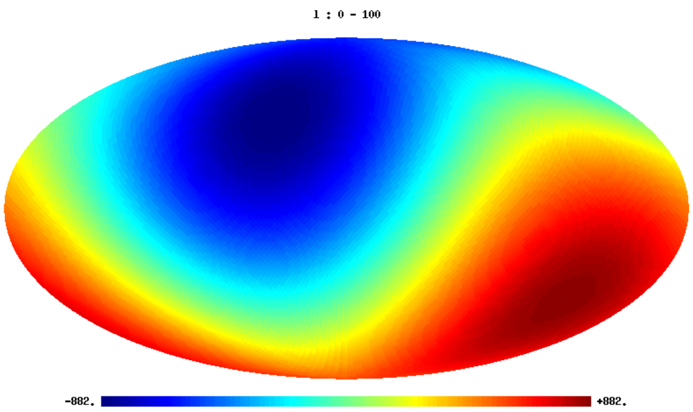
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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.

SUPPLEMENTARY SLIDES.

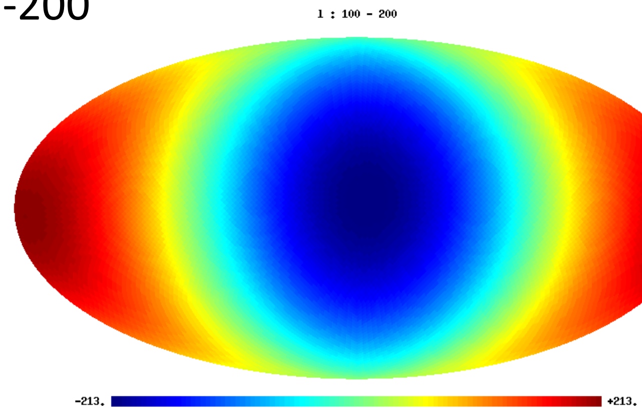
Alignment of the dipole directions in the rms power maps.

l : 0 -100

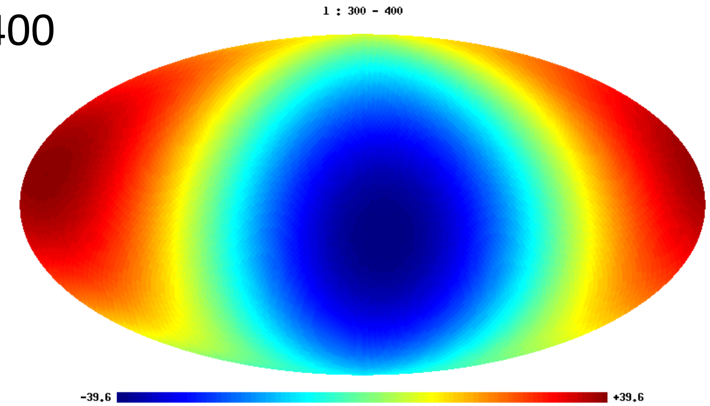


- Note that the direction of the dipoles of the rms maps derived for various CMB multipole bins appear aligned.
- The direction of the dipole recovered from the first bin l:{0-100} coincides with the direction of the dipole derived from modulation studies.
- The dipole direction in all other CMB multipole bins appear to allign together. However we suspect that the direction are biased due to the mask. Maps recovered from other multipolar bins on next slide.

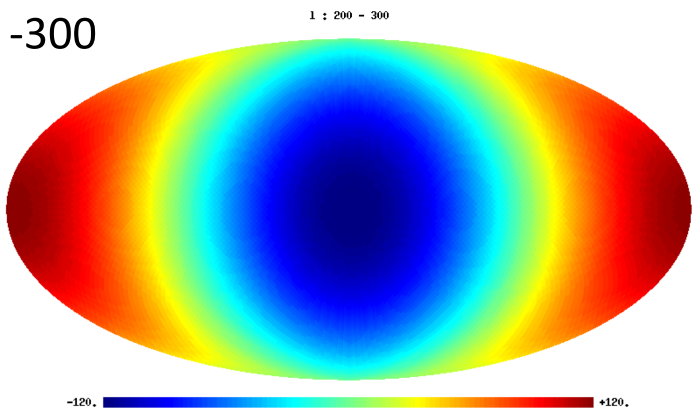
l : 100 -200



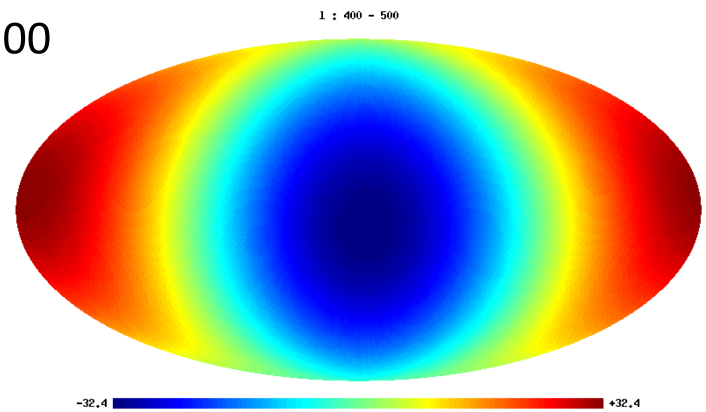
l : 300 -400



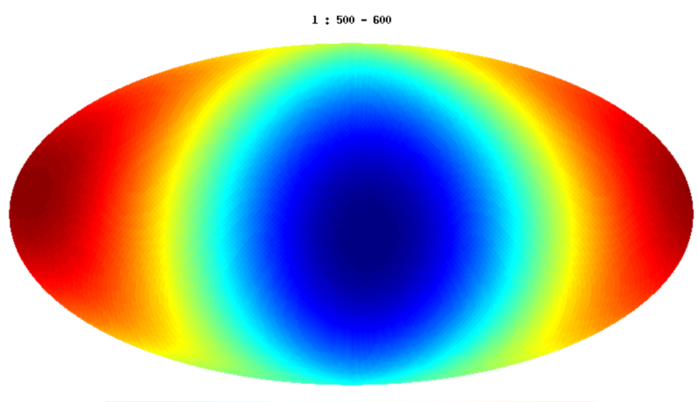
l : 200 -300



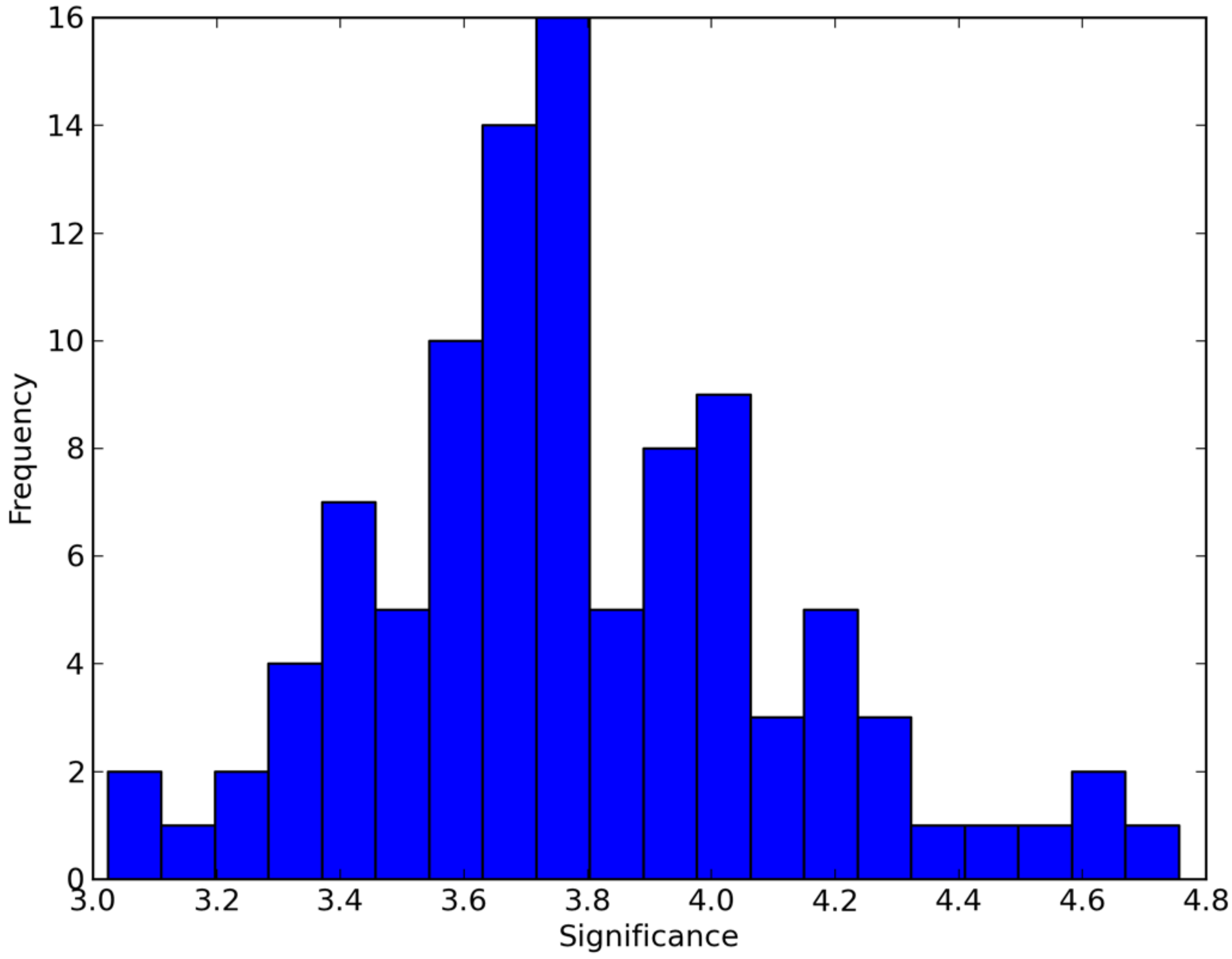
l : 400 -500

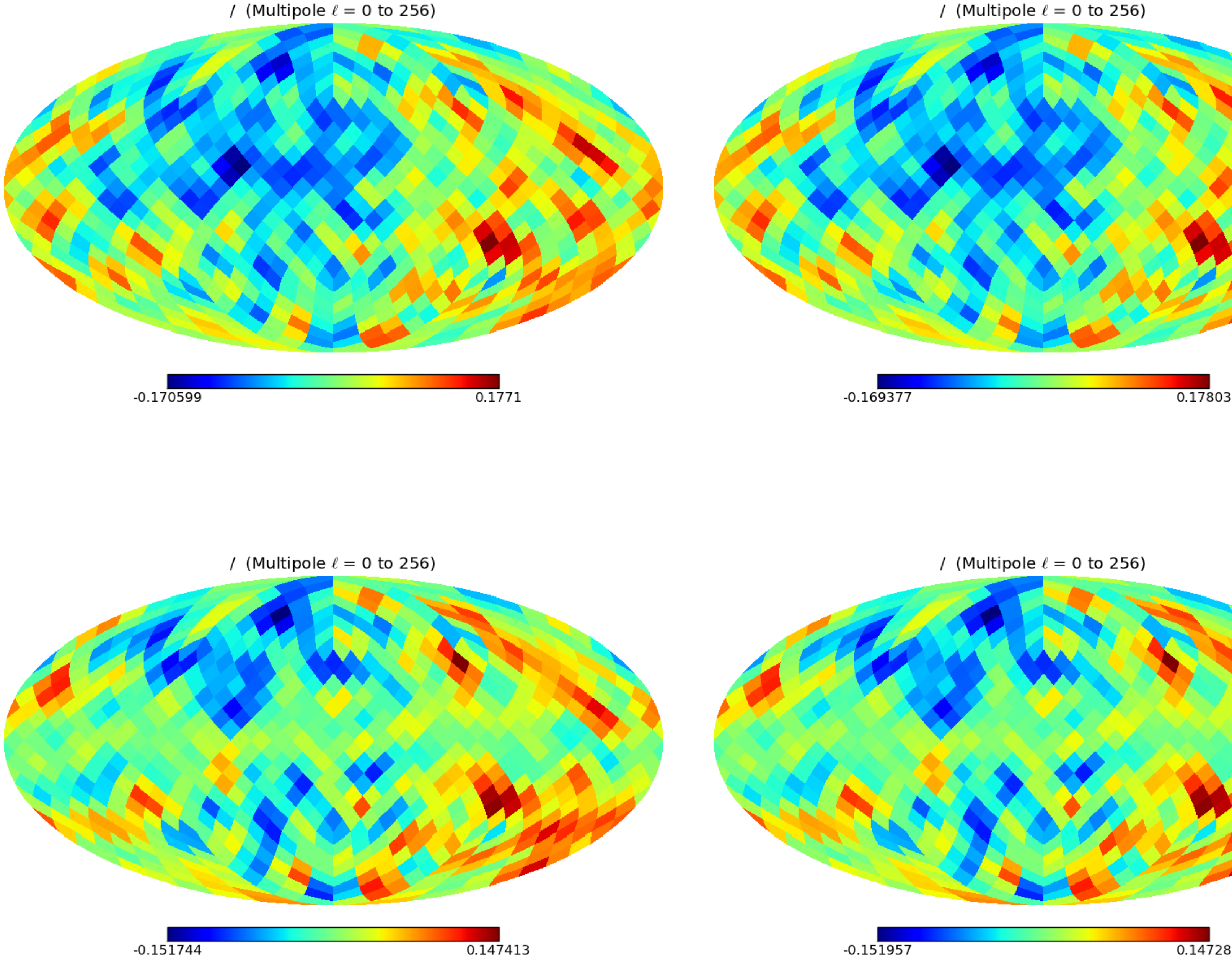


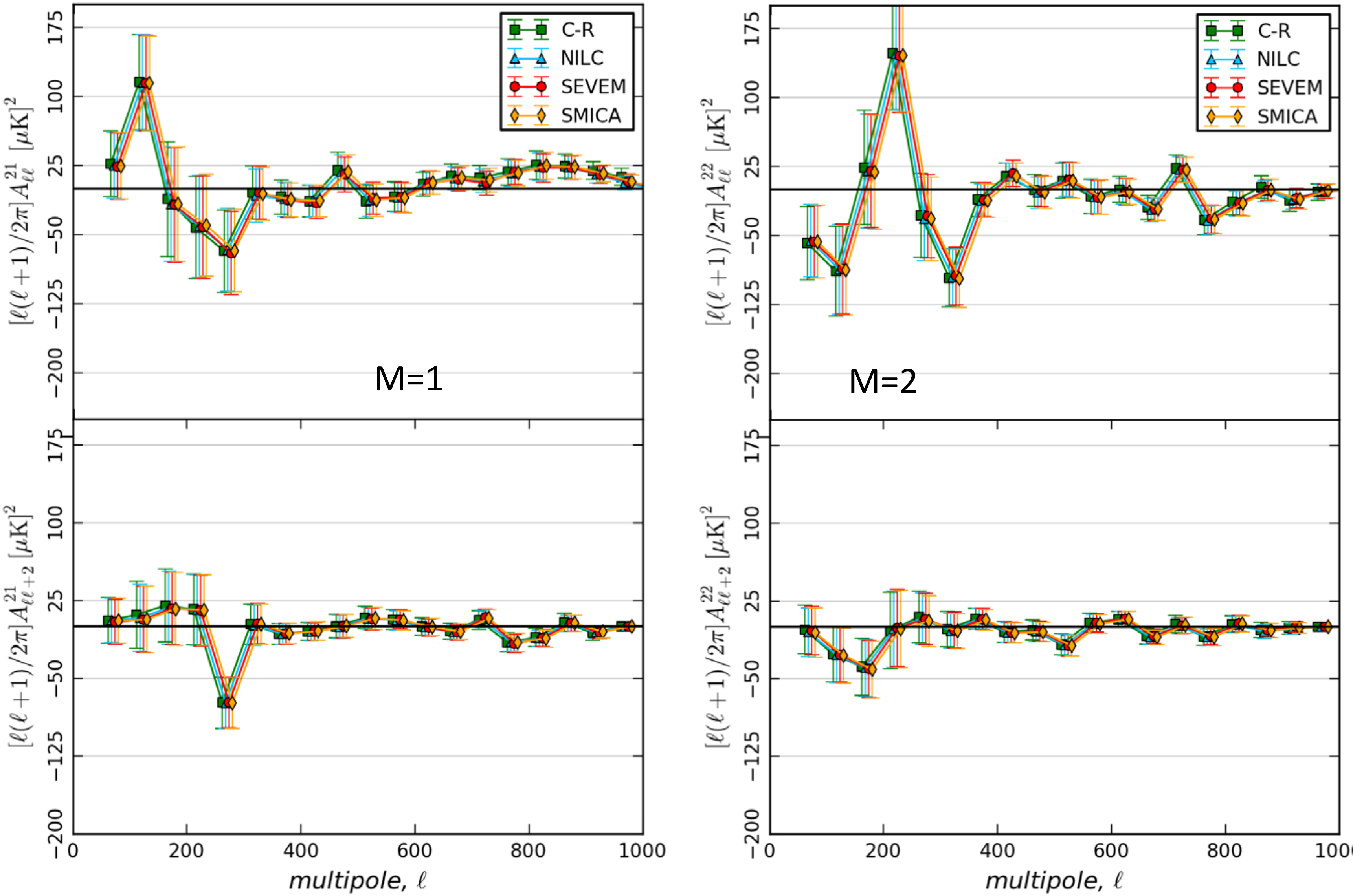
l : 500 -600



Variance in measurement due to inpainting

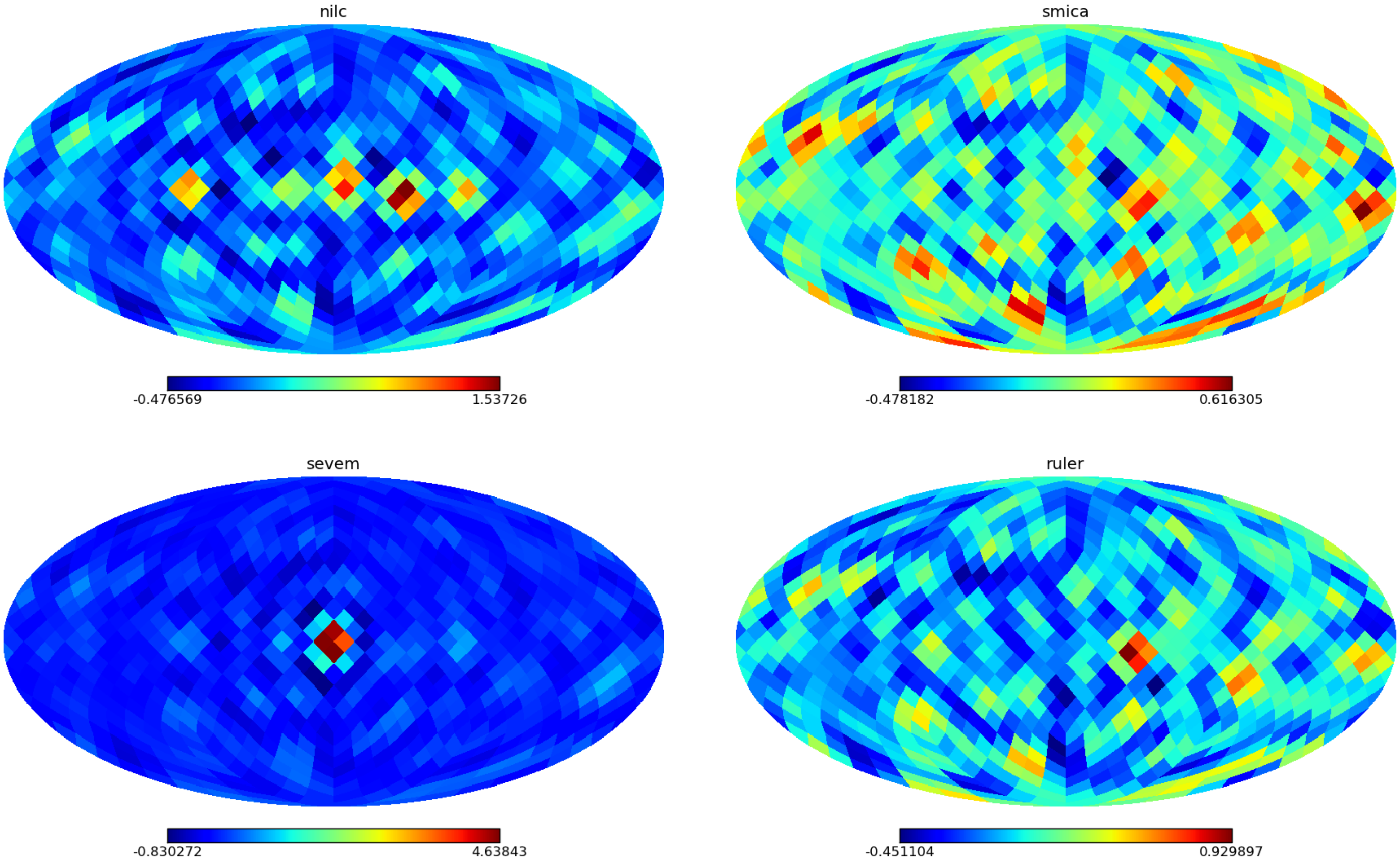



/ (Multipole ℓ = 0 to 256)
-0.170599
0.1771
/ (Multipole ℓ = 0 to 256)
-0.169377
0.178038
/ (Multipole ℓ = 0 to 256)
-0.151744
0.147413
/ (Multipole ℓ = 0 to 256)
-0.151957
0.147284



C-R
NILC
SEVEM
SMICA
M=1
M=2
$[\ell(\ell+1)/2\pi]A^{21}_{\ell\ell}$ $[\mu K]^2$
$[\ell(\ell+1)/2\pi]A^{22}_{\ell\ell}$ $[\mu K]^2$
$[\ell(\ell+1)/2\pi]A^{21}_{\ell\ell+2}$ $[\mu K]^2$
$[\ell(\ell+1)/2\pi]A^{22}_{\ell\ell+2}$ $[\mu K]^2$
175
100
25
−50
−125
−200
0
200
400
600
800
1000
multipole, ℓ

Reconstructed modulation maps.

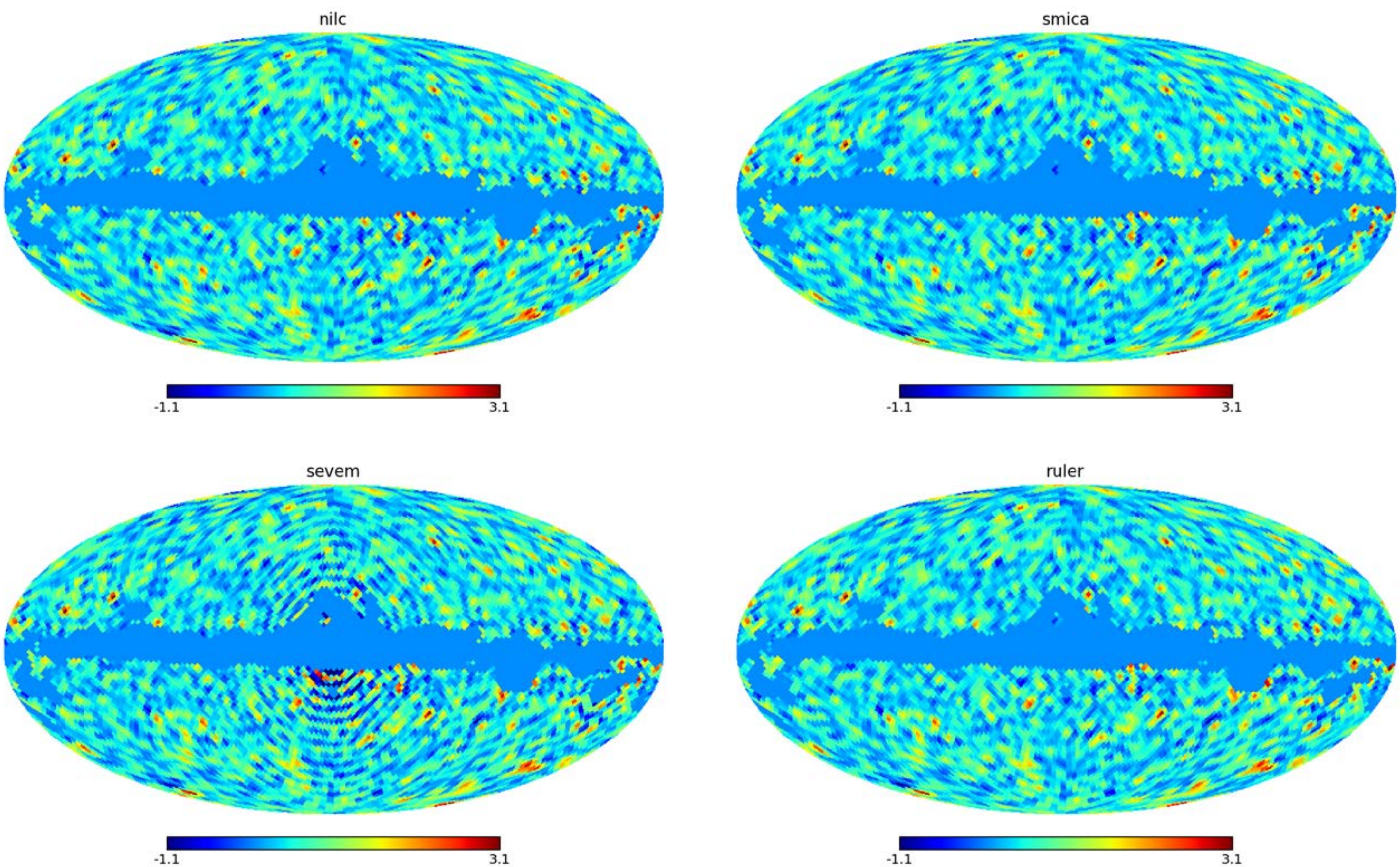


SEVEM & NILC

SMICA & RULER

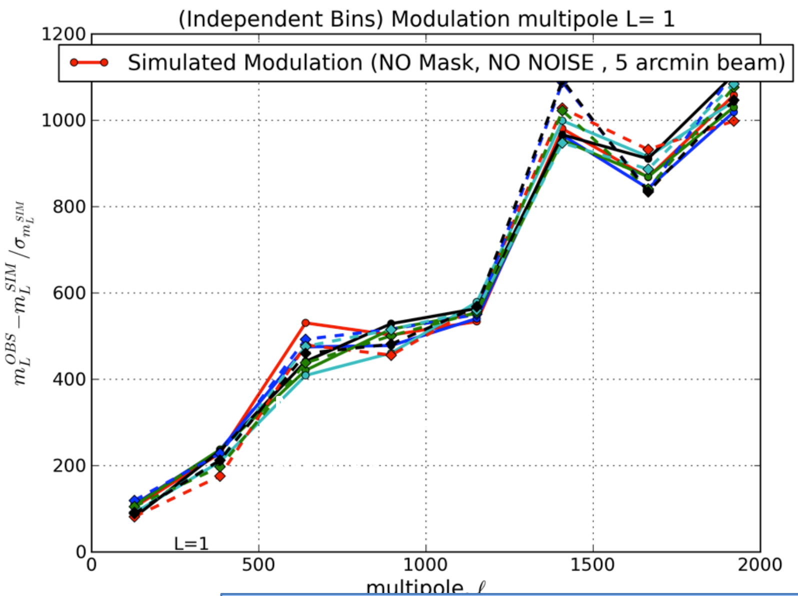
Strong anisotropic features in the original CMB map are picked up by the modulation estimator. These can then be subtracted by masking out the region where the contamination is expected.

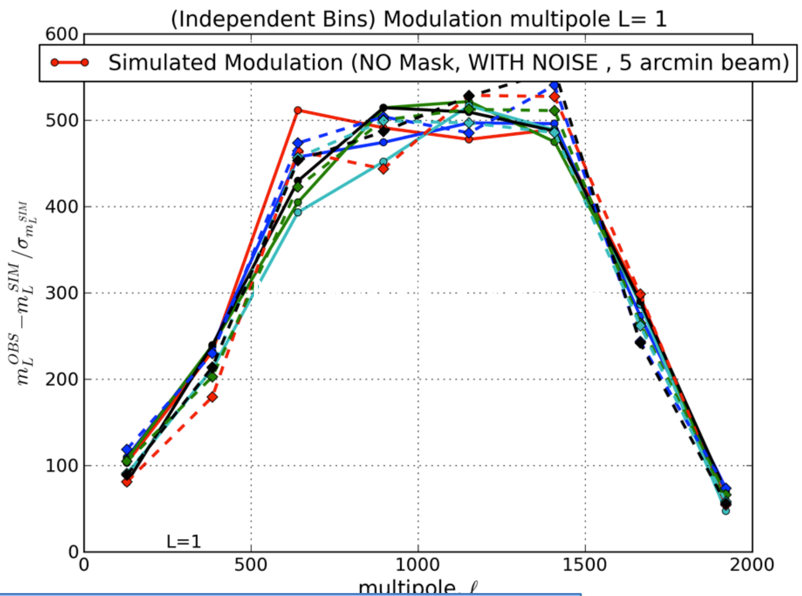
After masking the modulation maps, they look almost identical.



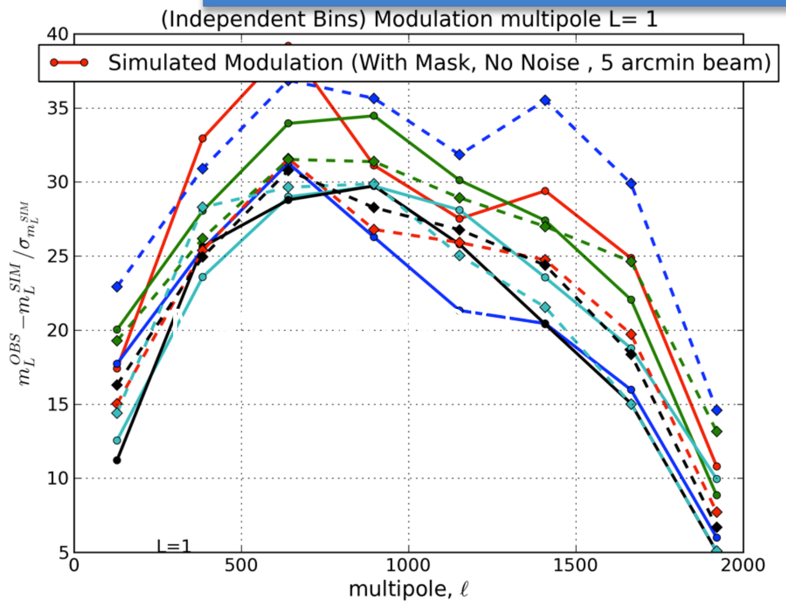
SEVEM & NILC

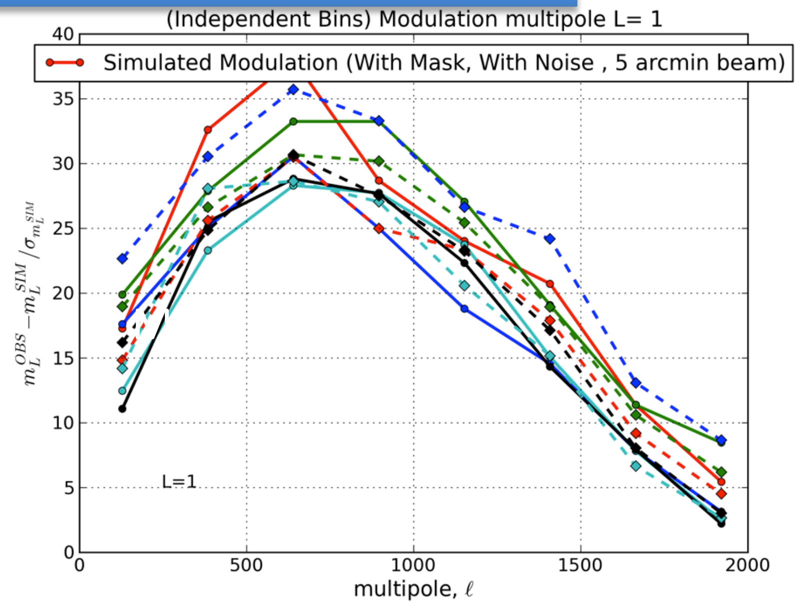
SMICA & RULER





VARIANCE OBTAINED FROM UN-MODULATED SIMULATIONS





Dipole Modulation dissected in ℓ- space

(BipoSH can also tell which angular scales are most relevant)