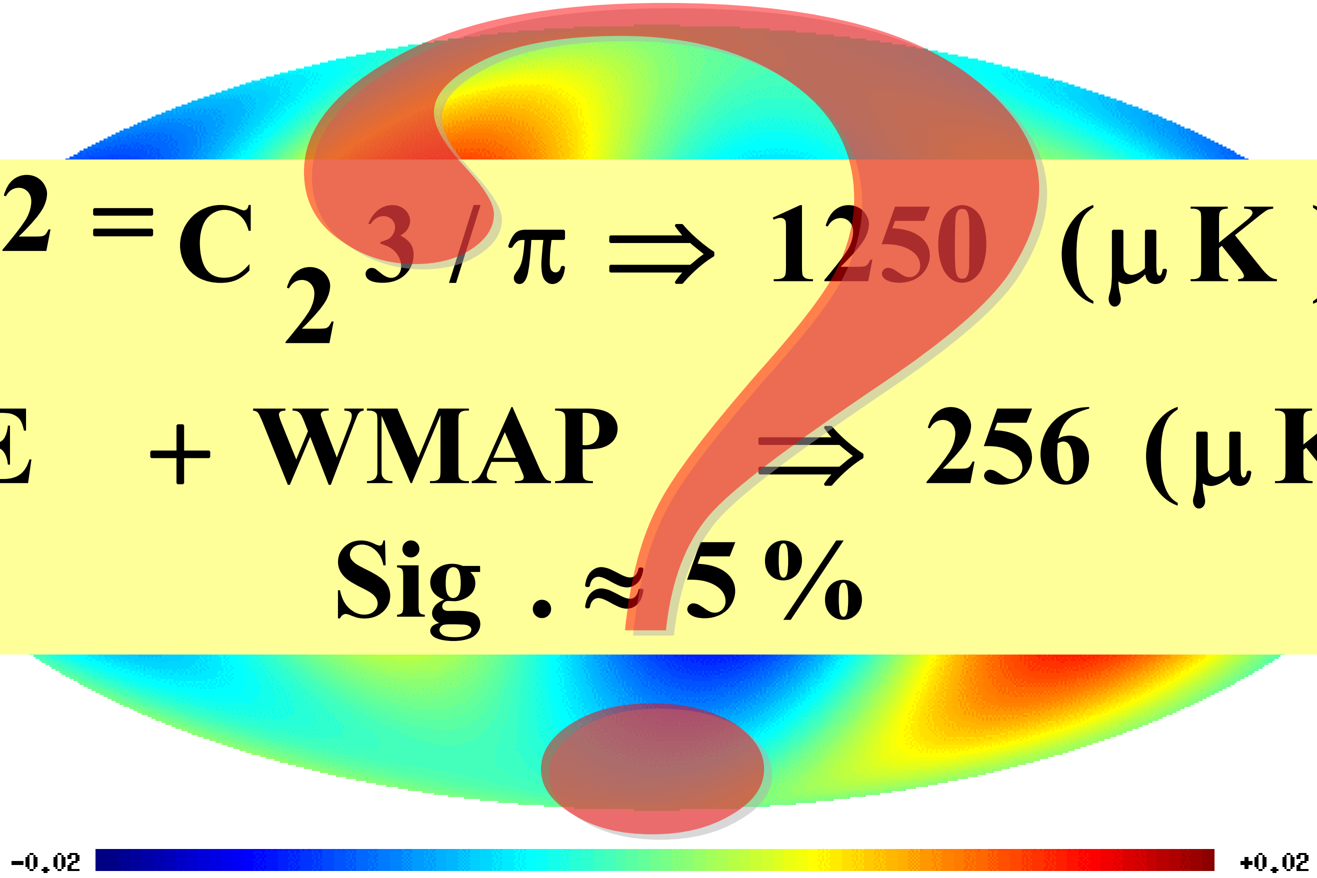
Why is the WMAP quadrupole power small ?



$$\Delta T^2 = C_2\, 3/\pi \Rightarrow 1250\ (\mu K)^2$$

$$\text{COBE} + \text{WMAP} \Rightarrow 256\ (\mu K)^2$$

$$\text{Sig.} \approx 5\%$$

Pavel Naselsky

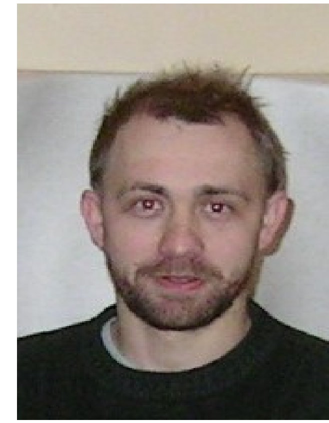
Niels Bohr Institute , Denmark

Collaborators within DK-*Planck* community

Igor D. Novikov (NBI)

Andrei Doroshkevich

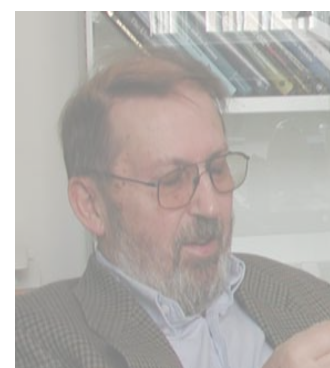
(ASC FIRAN)



Oleg V. Verhodanov

(SAO RAN)

Lung-Yih Chiang (NBI)



Per Rex Christensen (NBI)

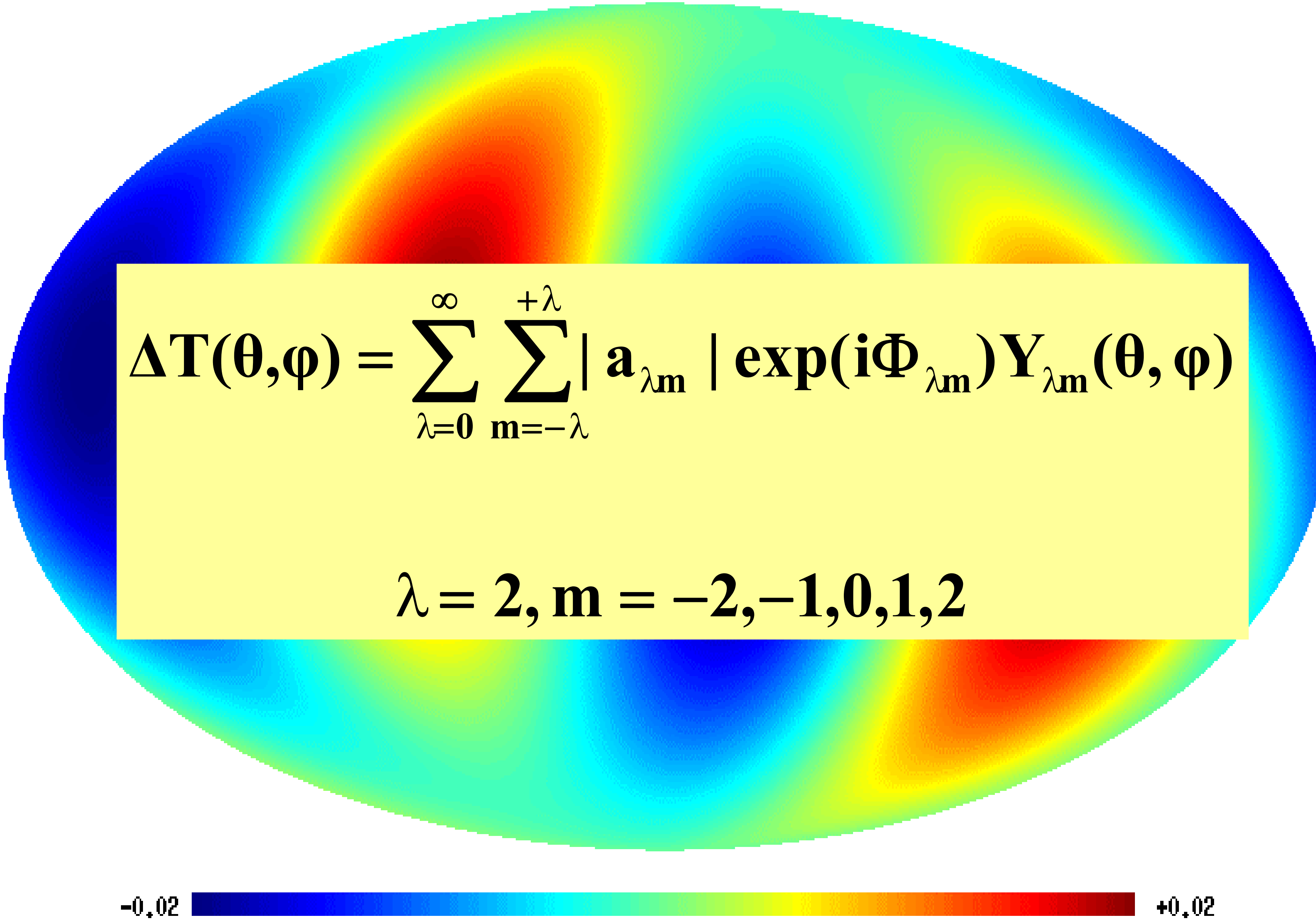
AND with thanks to

"What really interests me is whether God had any choice when he created the World"

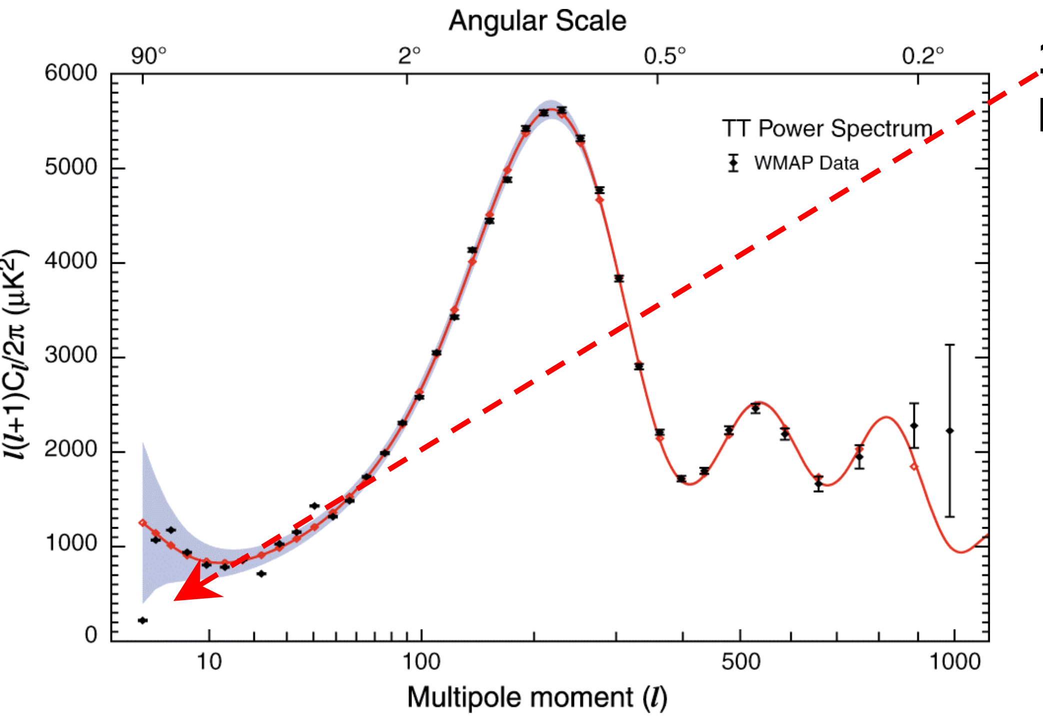
A. Einstein

$$\Delta T(\theta,\varphi) = \sum_{\lambda=0}^{\infty} \sum_{m=-\lambda}^{+\lambda} | a_{\lambda m} | \exp(i\Phi_{\lambda m}) Y_{\lambda m}(\theta, \varphi)$$

$$\lambda = 2, m = -2,-1,0,1,2$$

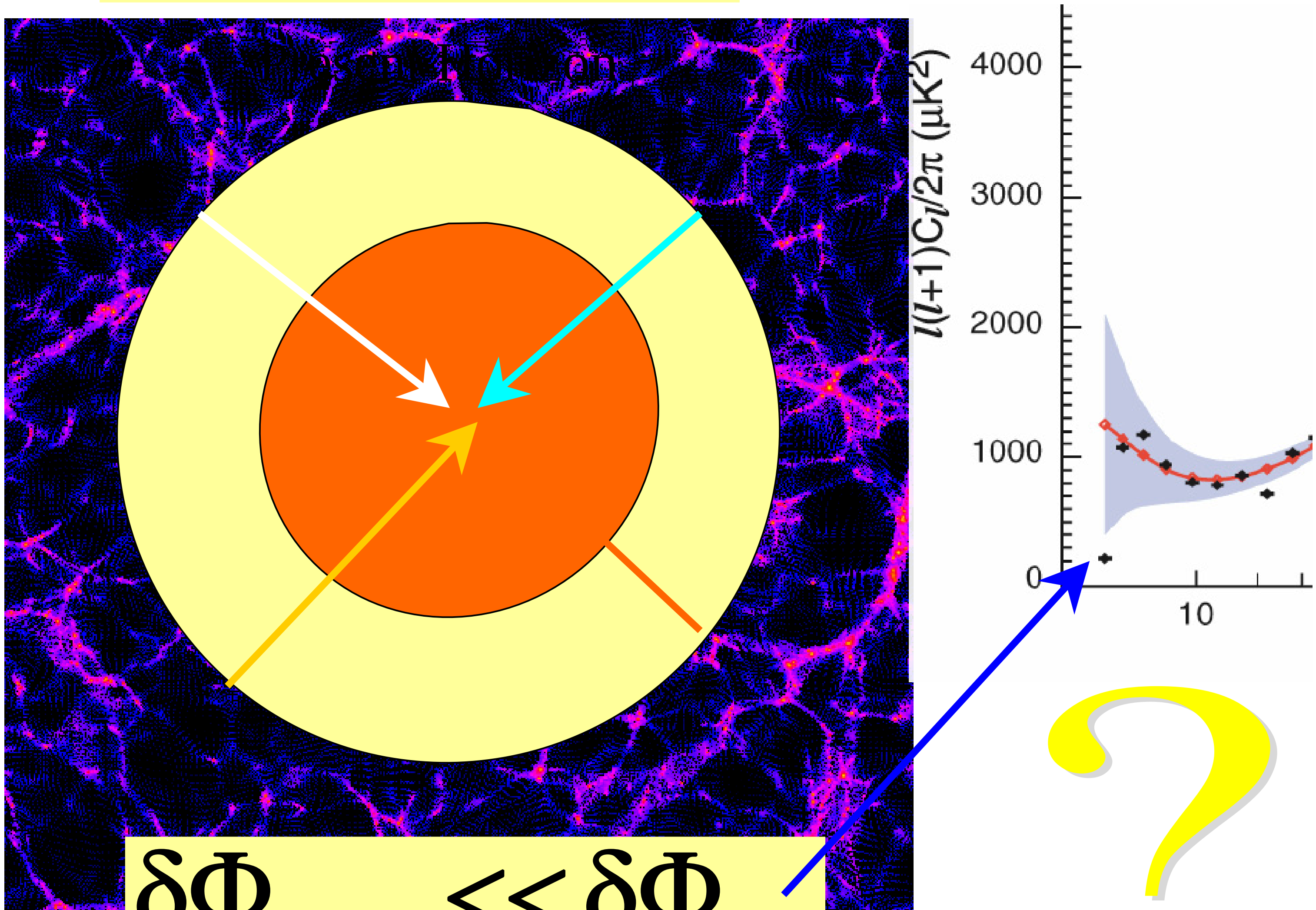


WHY Quadrupole ?



1. Direct test on dark energy and Its interaction with dark matter

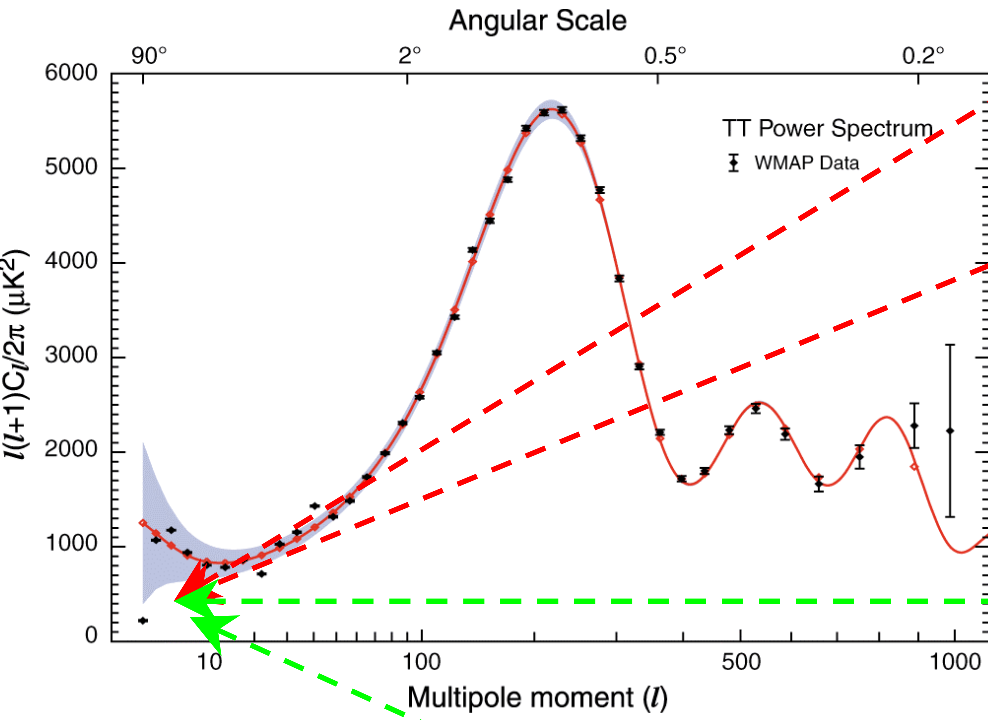
$$\delta\Phi_{out} > \delta\Phi_{in}$$



$$\delta\Phi_{out} << \delta\Phi_{in}$$

?

WHY Quadrupole ?



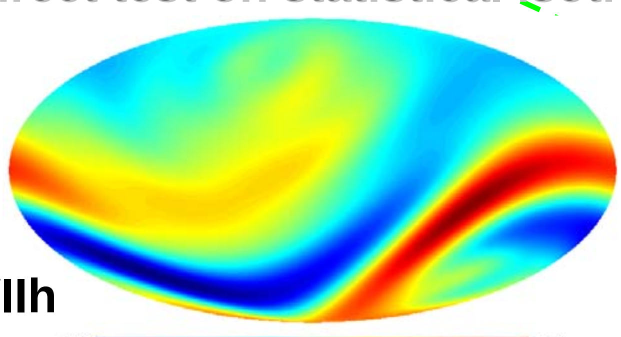
1. Direct test on dark energy and Its interaction with dark matter

2. Direct test on the expansion low between recombination and reionization

3. Test on the early stage of inflation

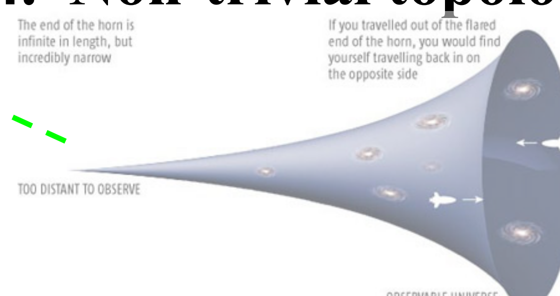
BSI (peculiarities of V)

5. Direct test on statistical isotropy



Bianchi VIIh

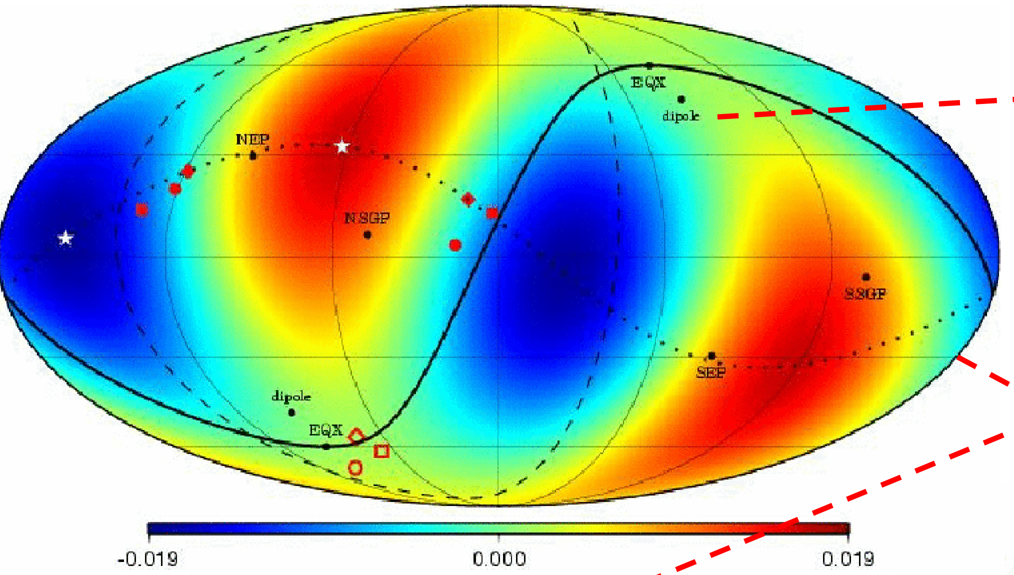
4. Non-trivial topology



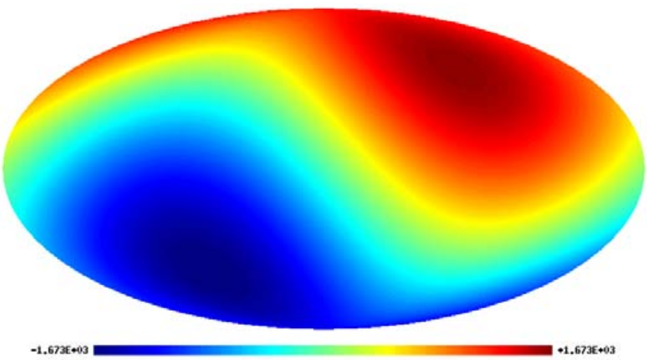
WHY Quadrupole ?

Correlations with Galactic structures

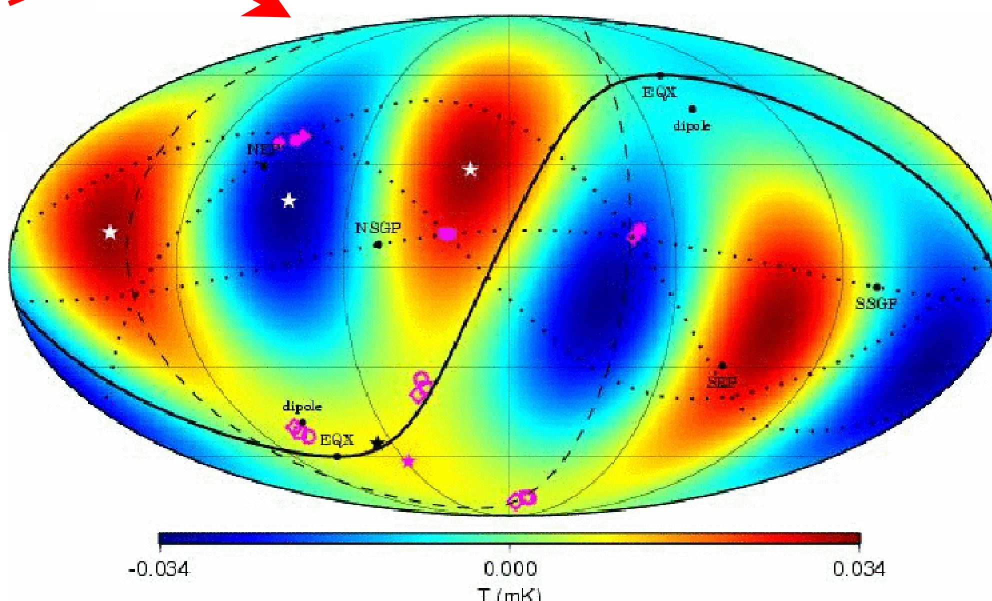
(multipole vector analysis, Copi et al,2004,2006)

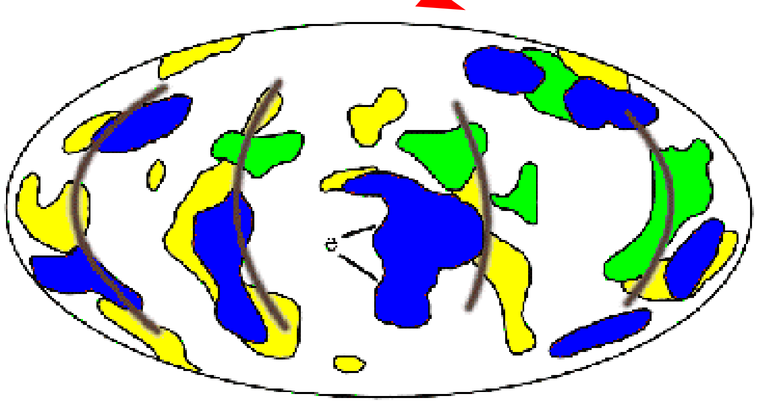


dipole

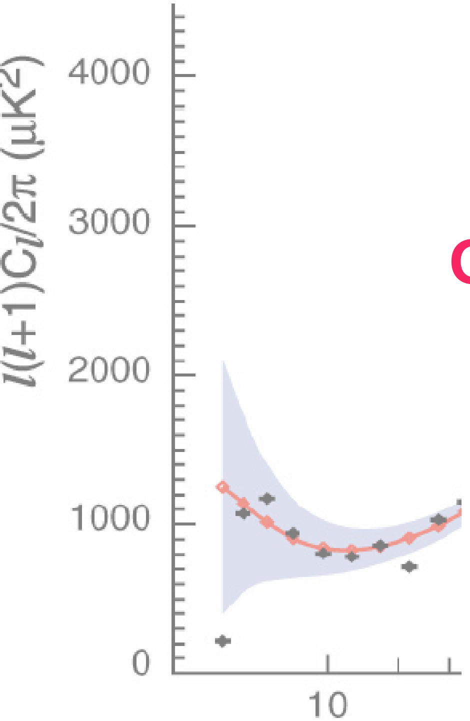


Q-Oct correlation





Non-Gaussianity and (or) statistical anisotropy ?



OK ! The power of the quadrupole is small.

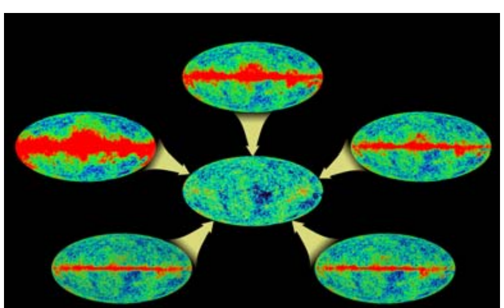
1. **Is the quadrupole some peculiar realization of the Gaussian random process ?** **YES !**

a) Quantum (Gaussian) fluctuations are still OK!

b) Standard model of inflation is OK !

c) Methods of the CMB-Foreground separation are OK !

Minimal Variance Method

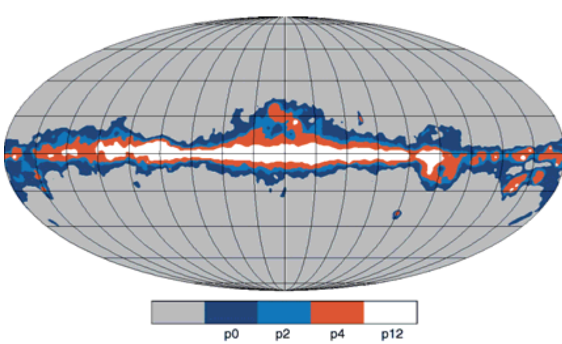


$$\Delta T(\theta_p,\varphi_p) = \sum_{j=1}^{N} \omega_j T_j(\theta_p,\varphi_p)$$

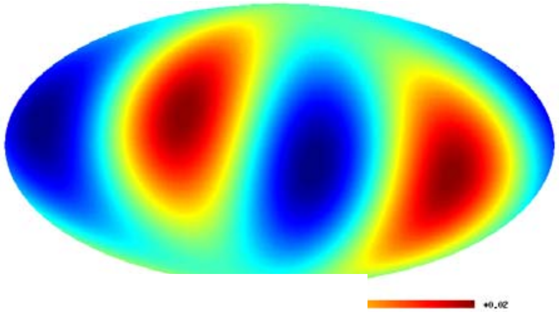
$$Var(\Delta T(\theta_p,\varphi_p)) \Rightarrow \min(\omega_j)$$

$$\sum_{j=1}^{N} \omega_j = 1$$

MASK

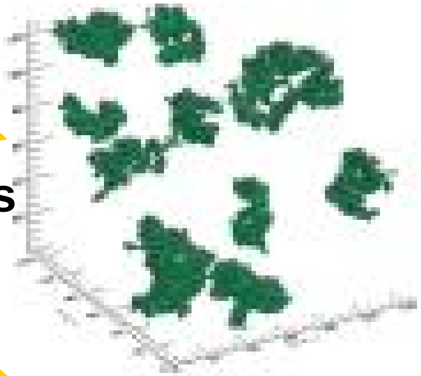


OK ! The power of the quadrupole is small.



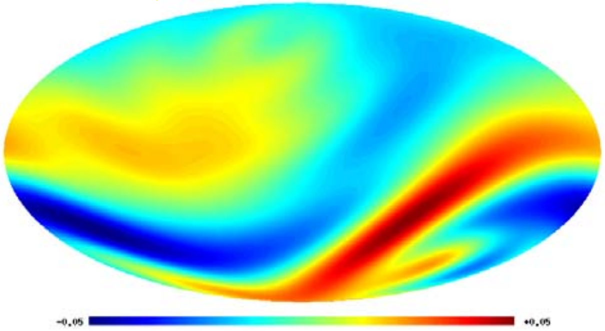
Is the WMAP quadrupole non-Gaussian ? Yes !

Link with new physics



Order of quantum fluctuations at Super Large Scales and chaos at small scales ?

Bianchi VIIh type statistical anisotropy ?



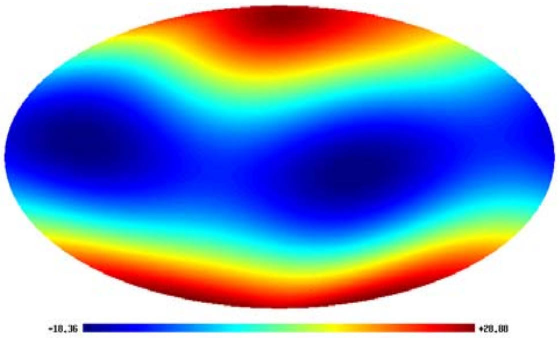
MVM is no longer available

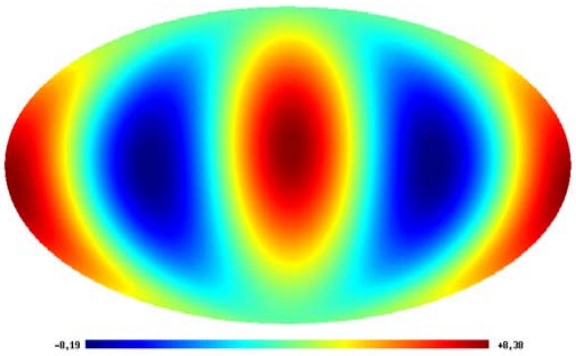
Galactic masks are not available

HOW we may test statistical properties of quadrupole ?

Problems

- Statistically not well established (the only 5 numbers !)
- The only one realization on the radio sky
- Very high level of uncertainties of the power spectrum ("cosmic variance")





Quadrupole components

$$a(2,m) = \left\{ \begin{array}{l} a(2,0) \\ a(2,1) \\ a(2,-1) \\ a(2,2) \\ a(2,-2) \end{array} \right\}$$

For Gaussian random field P[a(2,m)] uniformly distributed over m !

Amplitudes and Phases

$$a_{lm} = |a_{l,m}| \exp(i\Phi_{l,m})$$

$$C_\lambda = \frac{1}{2\lambda+1}\sum_m |a_{\lambda m}|^2$$

$$C_2 = \frac{1}{5}|a_{20}|^2 + \frac{2}{5}|a_{21}|^2 + \frac{2}{5}|a_{22}|^2$$

“Naive” expectations

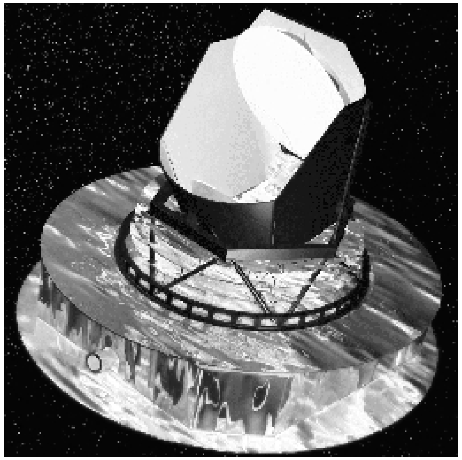
$$\frac{1}{5}|a_{20}|^2 \sim \frac{2}{5}|a_{21}|^2 \sim \frac{2}{5}|a_{22}|^2$$

The WMAP reality

$$|a_{20}| = 0.0115\text{mK};$$

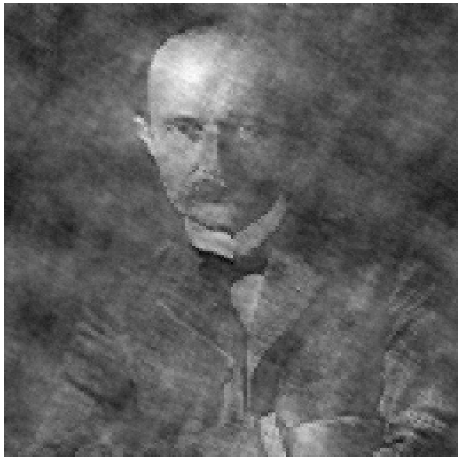
$$|a_{21}| = 0.00486\text{mK} \sim 0.2\,|a_{22}|$$

$$|a_{22}| = 0.0236\text{mK} \sim 2\,|a_{20}|$$



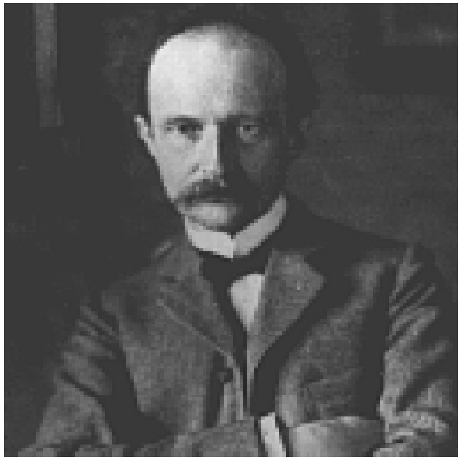
Planck satellite

$|\delta_k| \exp(i\Phi_k)$



transformed Planck

$FT^{-1}[\, |\delta_k| \exp(i\Phi_k) \,]$



Max Planck

$|\delta_k| \exp(i\Phi_k)$

Planck satellite and transformed Planck have the same power spectrum (same $|\delta_k|$), they have different "faces" due to different phases:

It is phase Φ_k that keep Max's face, not amplitude $|\delta_k|$!!

1. **If CMB is Gaussian, the phases should be non-correlated and uniformly distributed at [0,2π] for any cosmological models (Ω_{tot}, Ω_b,Ω_Λ,...)**

2. **If the topology of the Universe is non-trivial, the phases of spherical harmonics decomposition should have some auto-correlations.**

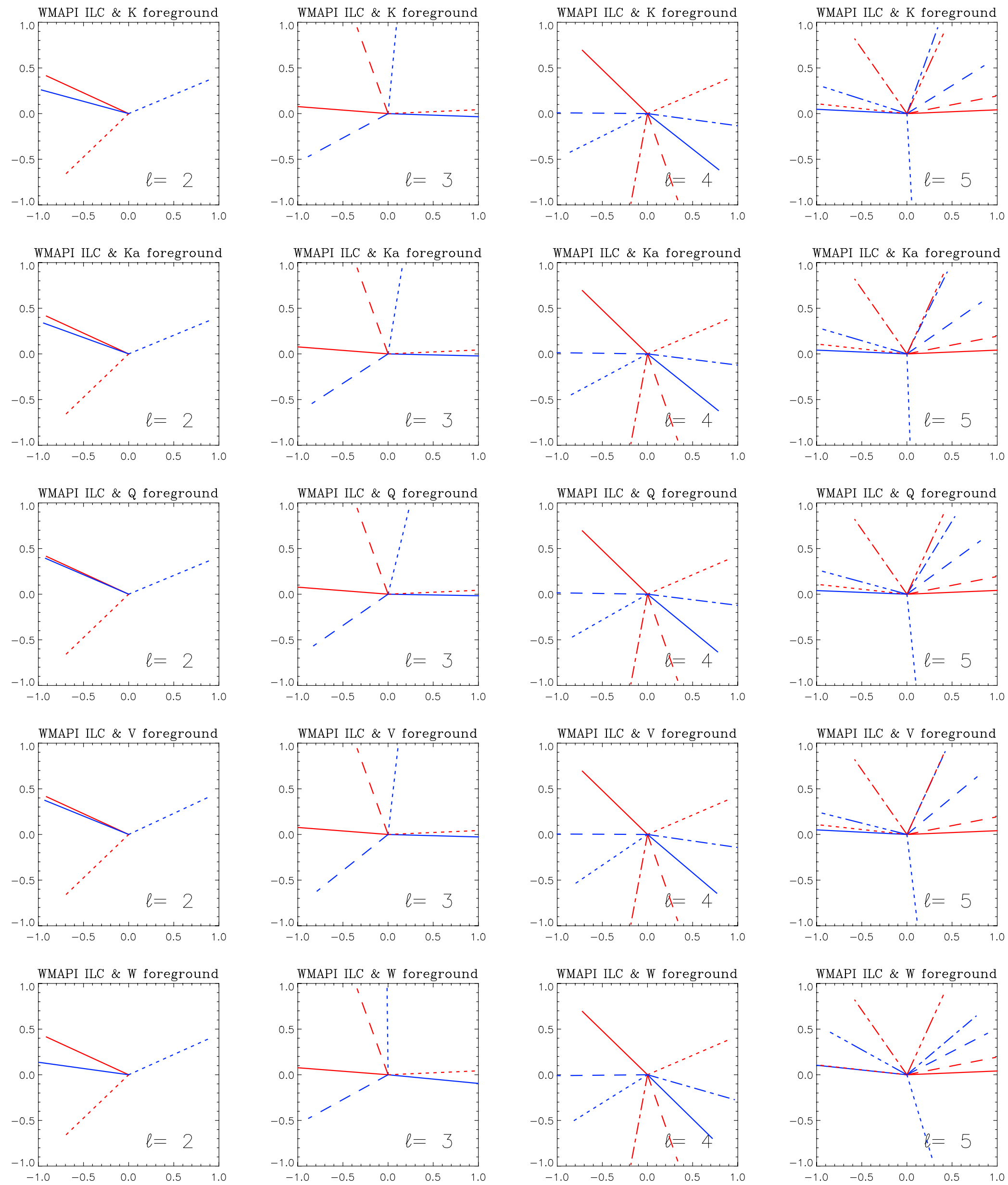
3. **If foregrounds and CMB are separated correctly, their phases should cross-correlate as minimal as possible.**

Analysis of CMB-Foreground coupling through phases

ILC (I)

For m=1

$$\xi_{L1} - \Phi_{L1} \Rightarrow (0, \pi)$$



Analysis of CMB-Foreground coupling through phases

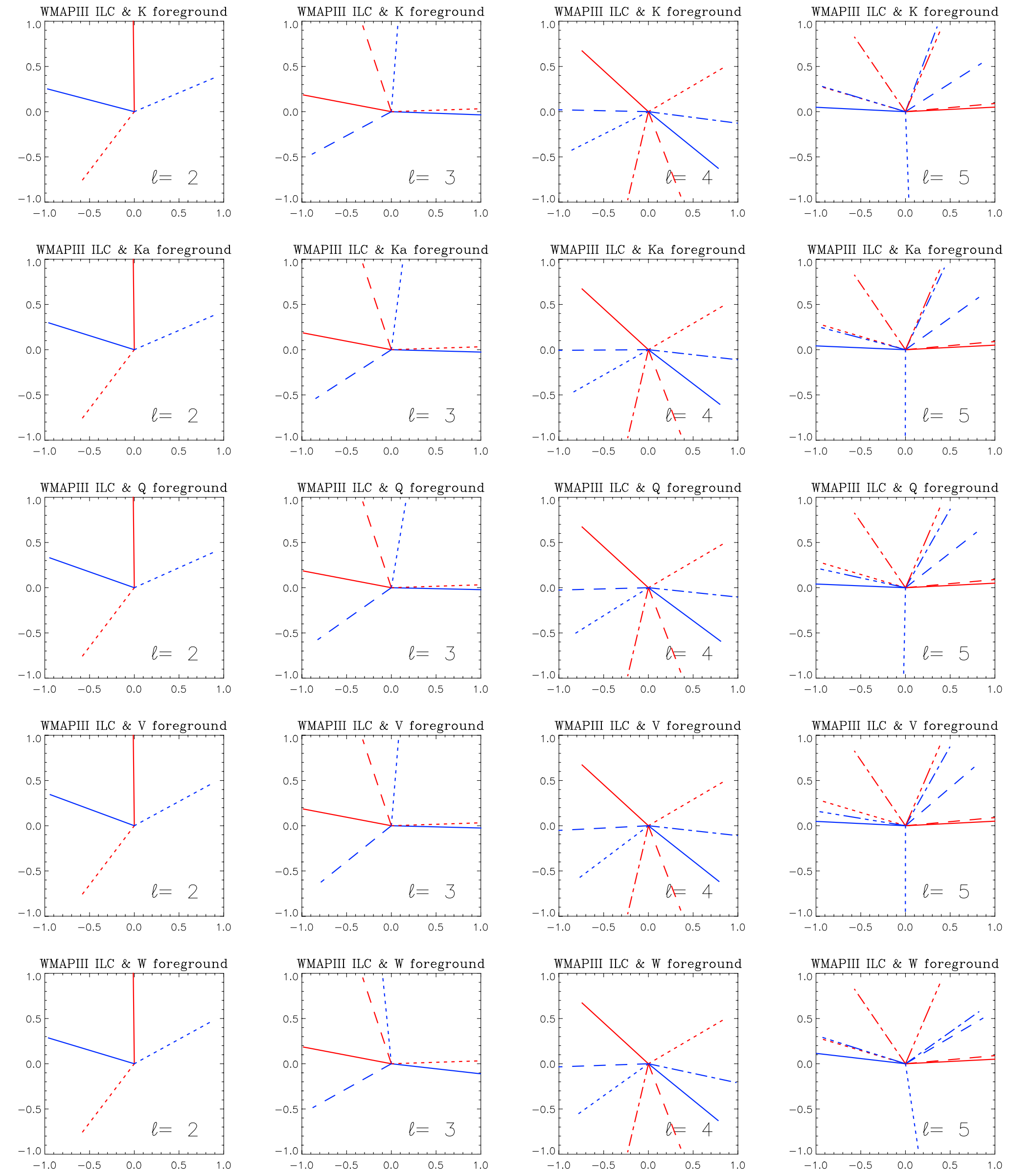
ILC (III)

For l+m=even

$$\xi_{lm} - \Phi_{lm} \Rightarrow (0, \pi)$$

For l+m=odd

$$\xi_{lm} - \Phi_{lm} \Rightarrow (\pi/2, 3\pi/2)$$



Link to the MVM. Statistical independency

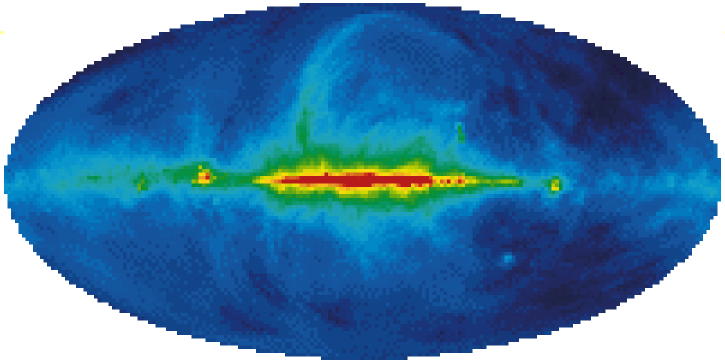
$$C_\lambda = \frac{1}{2\lambda+1}\sum_{m=-l}^{l} |c_{l,m}||F_{l,m}|\cos(\xi_{l,m} - \Phi_{l,m}) \Rightarrow (l = 2)$$

$$\frac{1}{5}|c_{20}||F_{20}|\cos(\xi_{20} - \Phi_{20}) + \frac{2}{5}|c_{21}||F_{21}|\cos(\xi_{21} - \Phi_{21}) +$$

$$+\frac{2}{5}|c_{22}||F_{22}|\cos(\xi_{22} - \Phi_{22}) = 0$$

$0, \pi$

$$|F_{20}| \geq |F_{22}| >> |F_{21}|$$



$$\cos(\xi_{22} - \Phi_{22}) \sim \frac{|c_{20}||F_{20}|}{|c_{22}||F_{22}|}(\pm 1) \Rightarrow$$

$$|c_{20}| \sim \frac{|F_{22}||c_{22}|}{|F_{20}|} < |c_{22}|$$

$$\xi_{22} - \Phi_{22} = (0, \pi) + \beta,$$

$$\beta << \pi / 2$$

$$\cos(\xi_{21} - \Phi_{21}) \sim \frac{1}{2}\beta^2 \frac{|F_{22}||c_{22}|}{|F_{21}||c_{21}|} \Rightarrow$$

$$\xi_{21} - \Phi_{21} \sim \pi / 2 + \frac{1}{2}\beta^2 \frac{|F_{22}||c_{22}|}{|F_{21}||c_{21}|}$$

Statistical independency (predictions)

$$|c_{21}| \ll |c_{22}|, |c_{20}| \qquad \xi_{22} - \Phi_{22} \Rightarrow (0, \pi) \qquad \xi_{21} - \Phi_{21} \sim \pi/2$$

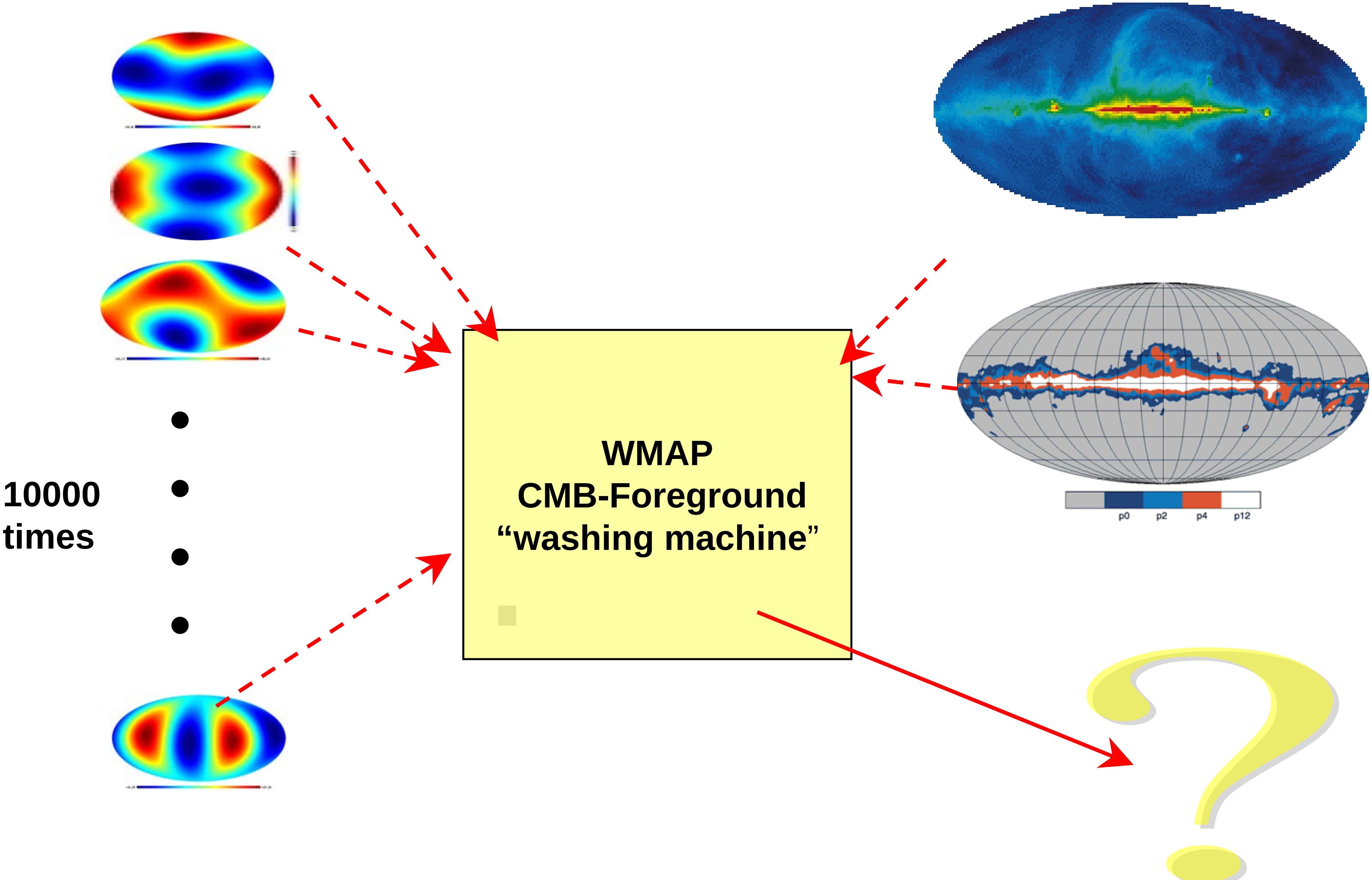
WMAP results

$$|c_{20}| = 0.0115\text{mK};$$

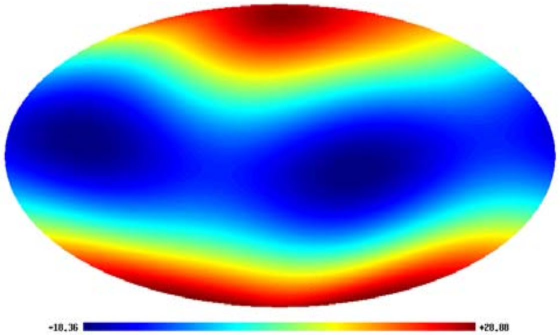
$$|c_{21}| = 0.00486\text{mK} \sim 0.2\,|a_{22}|$$

$$|c_{22}| = 0.0236\text{mK} \sim 2\,|a_{20}|$$

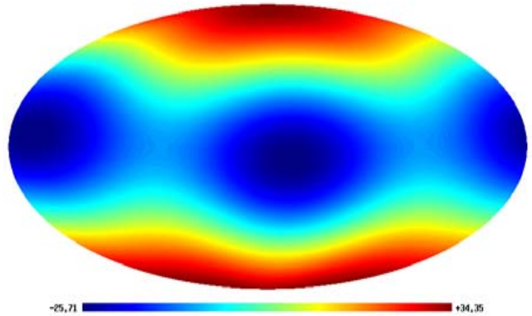
WMAP simulations



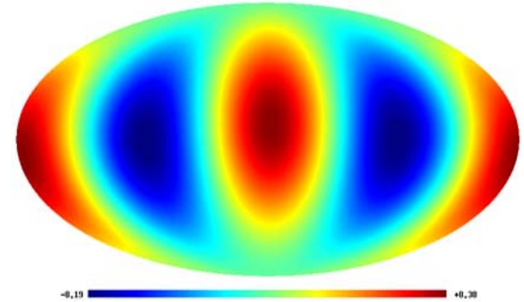
10000 realizations of the CMB



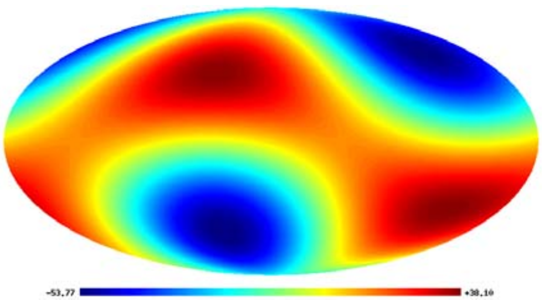
N1 input map



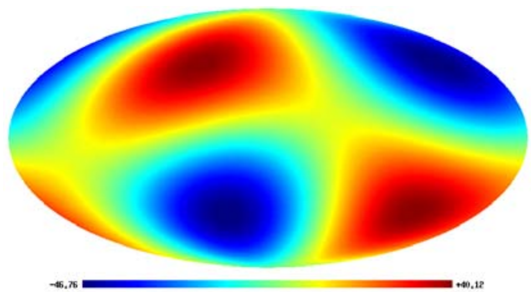
N1 output map



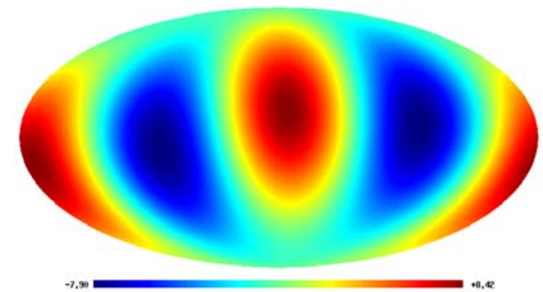
N1 in-output map



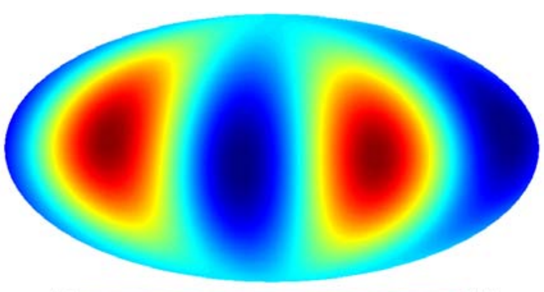
N4 input map



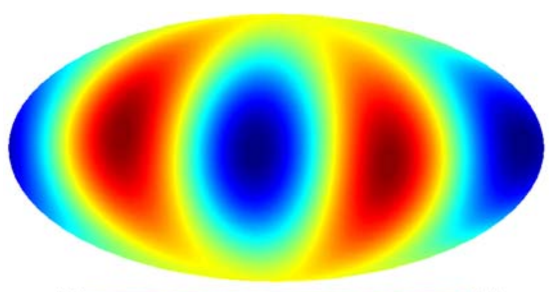
N4 output map



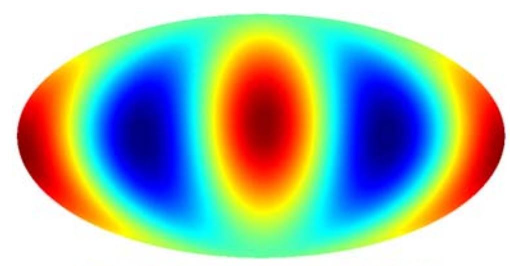
N4 in-output map



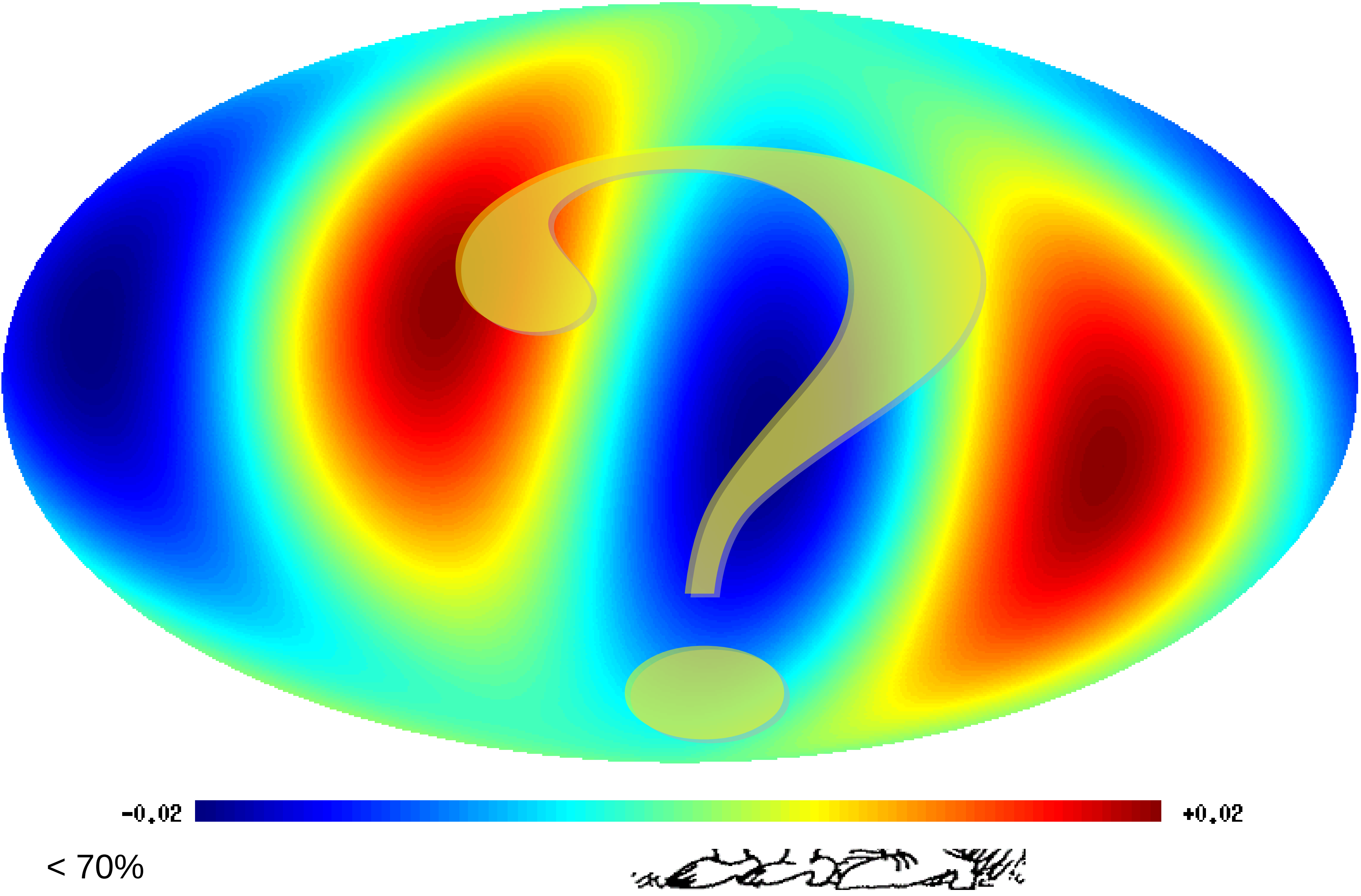
N8 input map



N8 output map

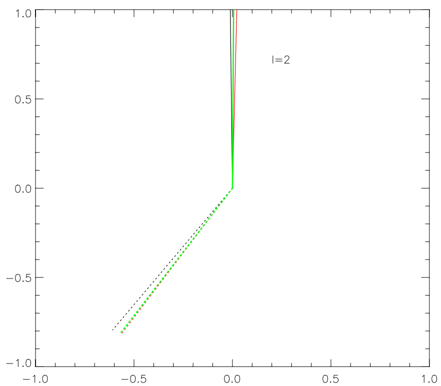


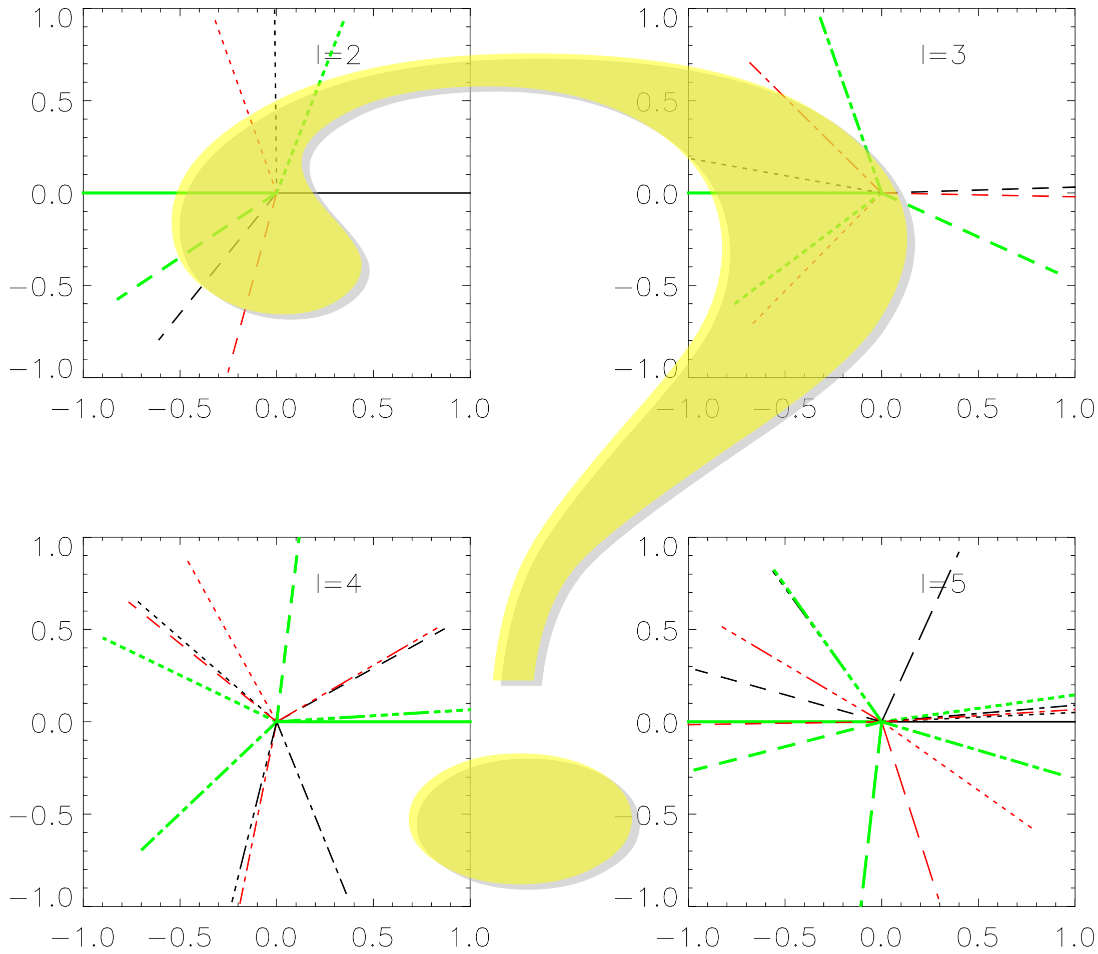
N8 in-output map



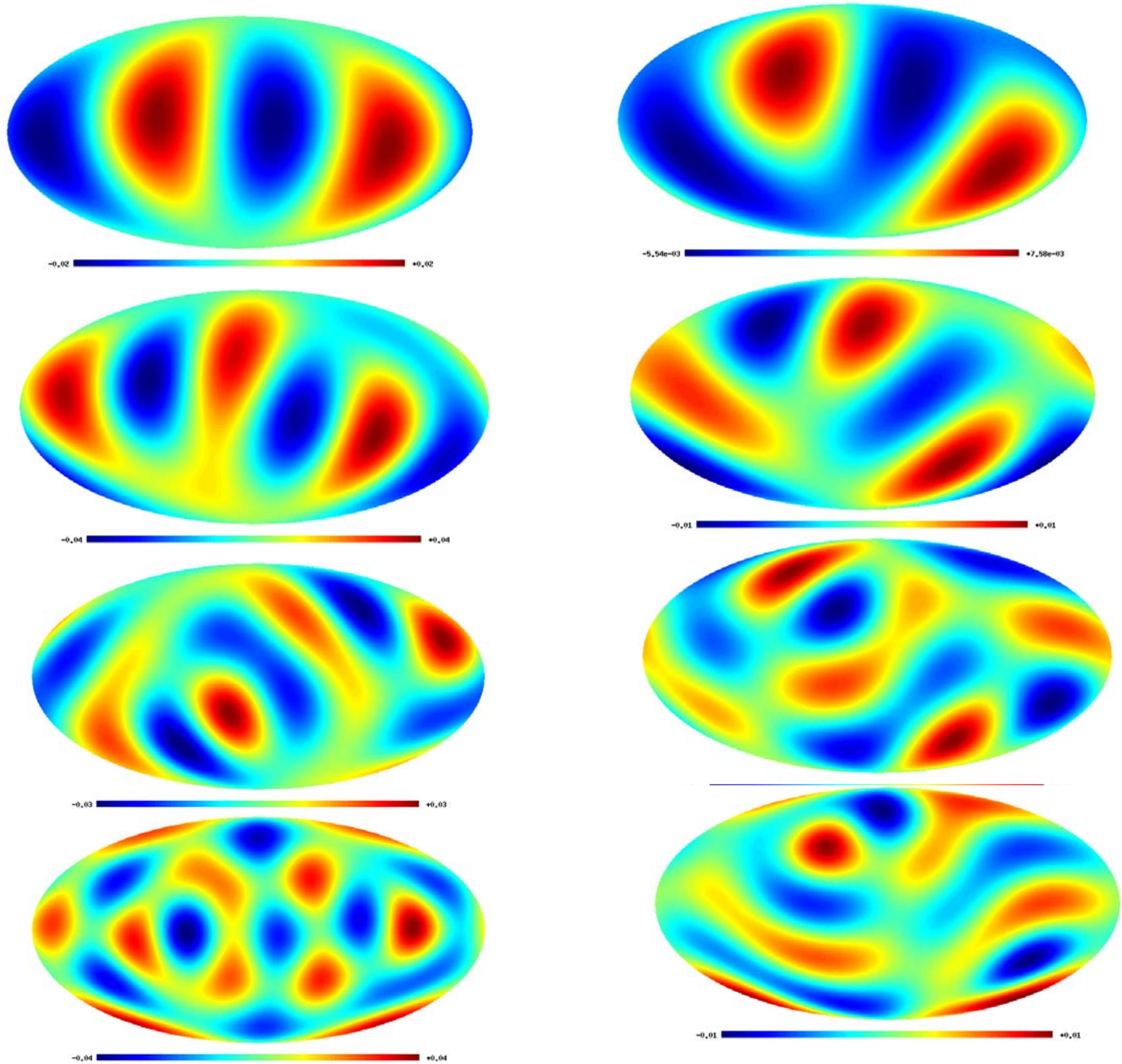
< 70%

Bianchi VIIh ?





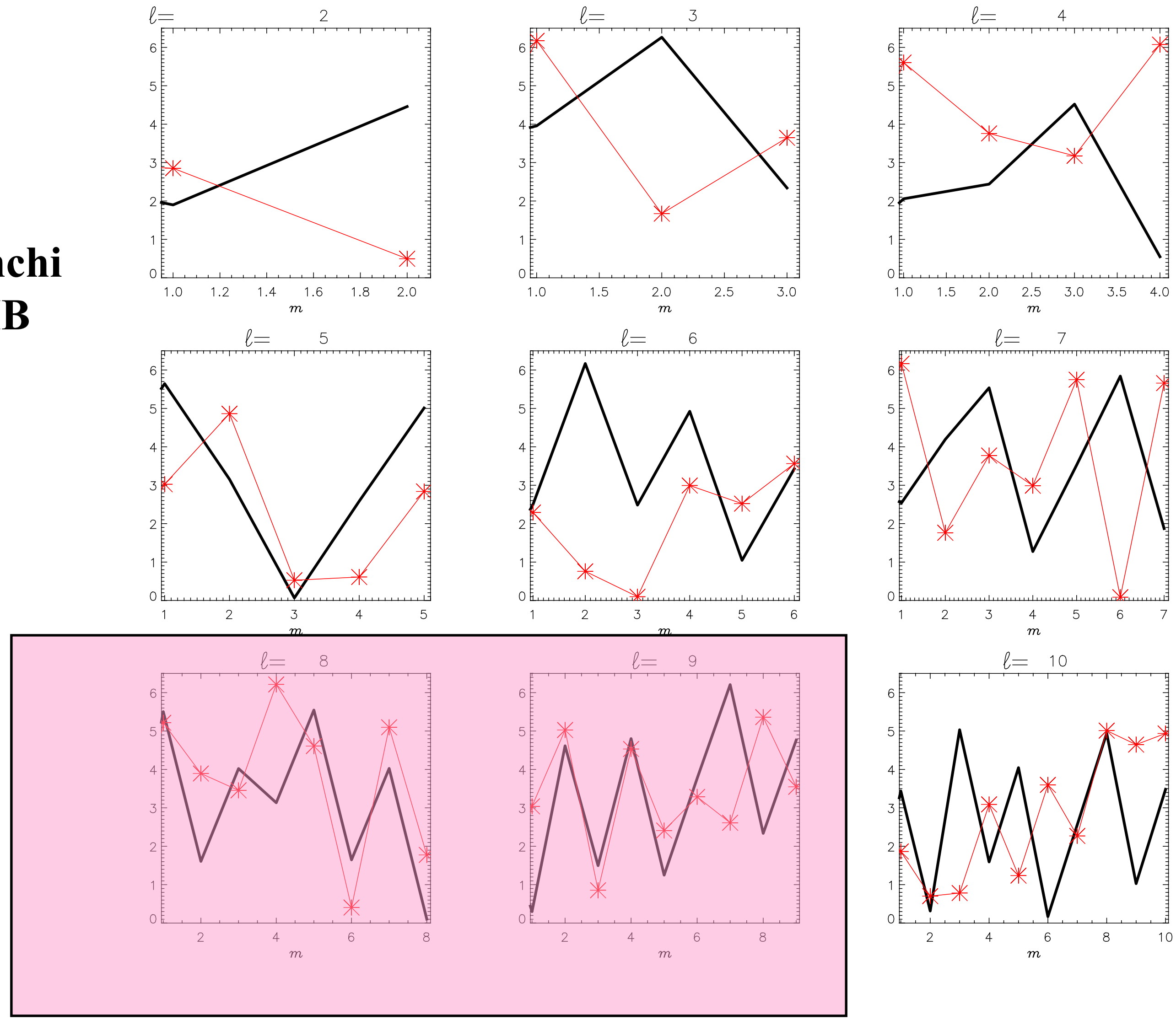
ILC



Why the Bianchi VIIh was useful for correction of the ILC ?

1.

Phases of the Bianchi VIIh-induced CMB versus the Wfgd



Properties of the Bianchi VIIh phases

$$\Psi_{l,m} = \tan^{-1}\left[\frac{a-b}{a+b}\tan(\phi_{l,m=1}-\gamma)\right] - \alpha m$$

$$a = d^{l}_{m,1}(\beta),$$

$$b = (-1)^{m} d^{l}_{m,-1}(\beta)$$

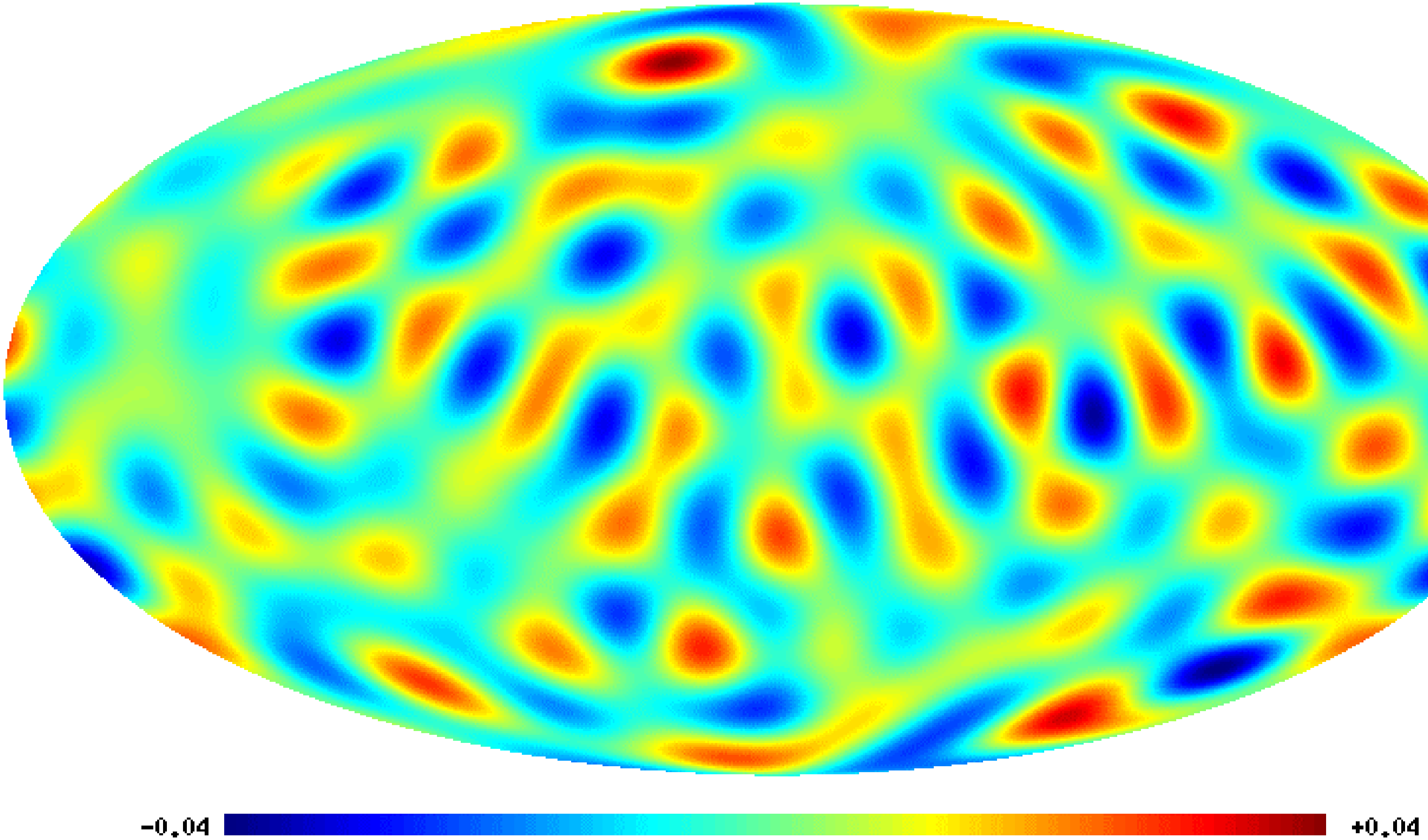
$$D^{l}_{m,m'}(\alpha,\beta,\gamma) = \exp(-im\alpha - im'\gamma)\, d^{l}_{m,m'}(\beta)$$

Linear term

Non-liner modulation

Non –Bianchi VIIh "toy model"

$$\Psi_{l,m} = \pi / 2 + m\pi,$$



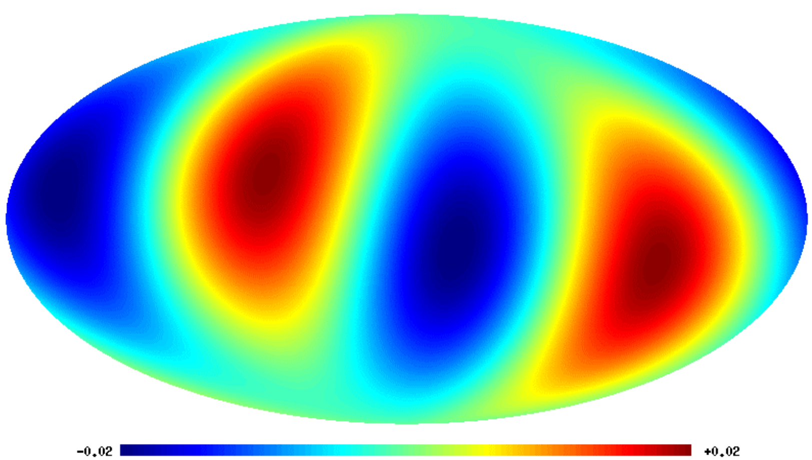
Conclusion

1. Phases of low multipoles reveal strong correlations with the phases of for

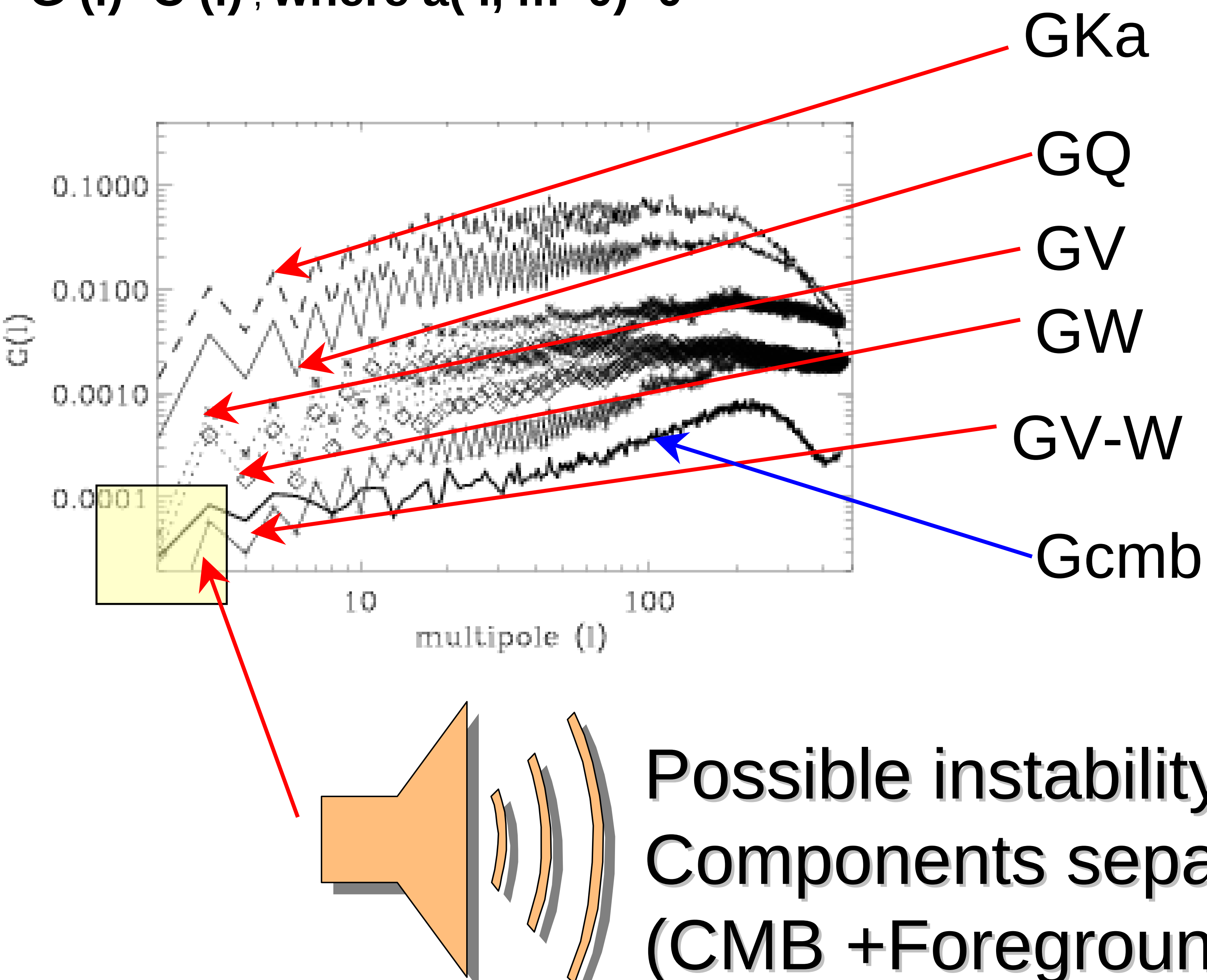
2. To reject a

3. Effects of systematic ?

MMM….. Nobel Prize after George?



G (l)=C (l) , where a(l, m=0)=0



Possible instability for Components separation (CMB +Foregrounds)