Is the large-scale microwave background cosmic?

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Outline

- Introduction and motivation
- Multipole vectors
- Evidence for non-isotropy/gaussianity
- Low-ℓ ecliptic correlations in WMAP
- Cosmological/instrumental proposals to create alignments
- Conclusions and future work

Bibliography

- Multipole vectors

  (Copi, Huterer & Starkman, PRD, 70, 043515, 2004)

- Ecliptic alignments WMAP temperature at large-scales

  (Schwarz, Starkman, Huterer & Copi, PRL, 93, 221301, 2004)

- More on MV, alignments, and relation to other work

  (Copi, Huterer, Schwarz & Starkman, MNRAS in press; astro-ph/0508047)

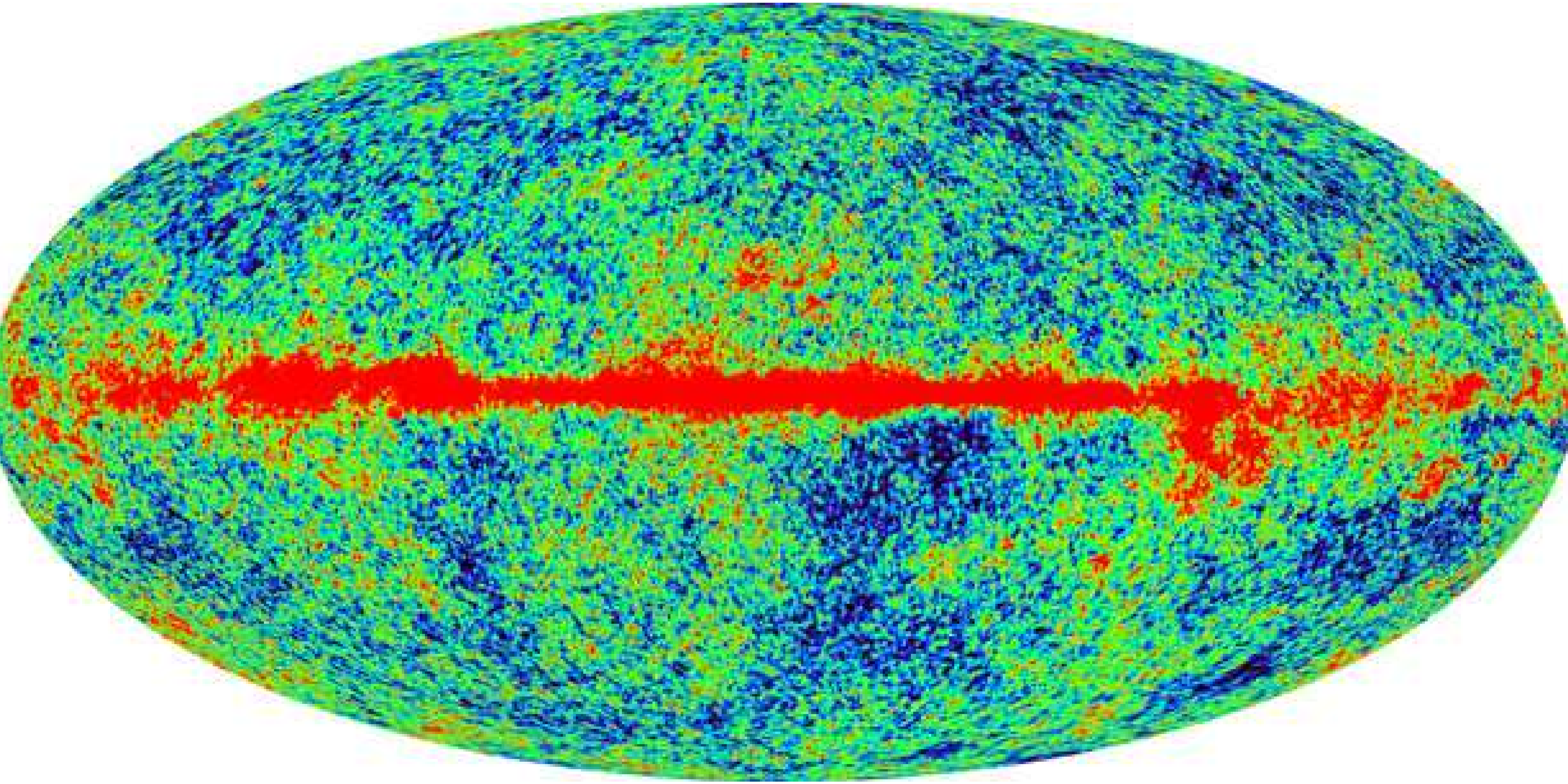
- Cosmological explanations and additive vs. multiplicative

  (Gordon, Hu, Huterer & Crawford, PRD in press, astro-ph/0509301)

- Popular-level overview

  (Starkman and Schwarz, "Is the Universe out of Tune?", Scientific American, Aug 2005)

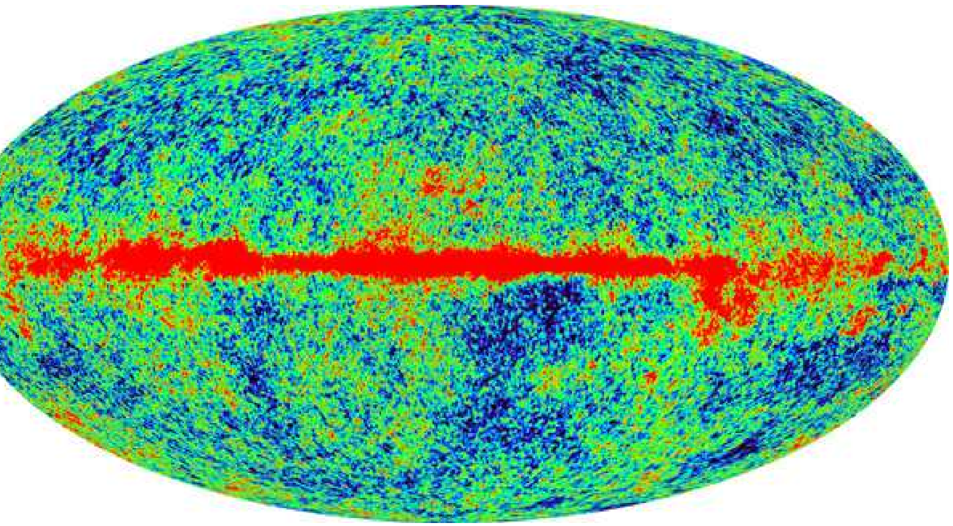
CMB Anisotropies

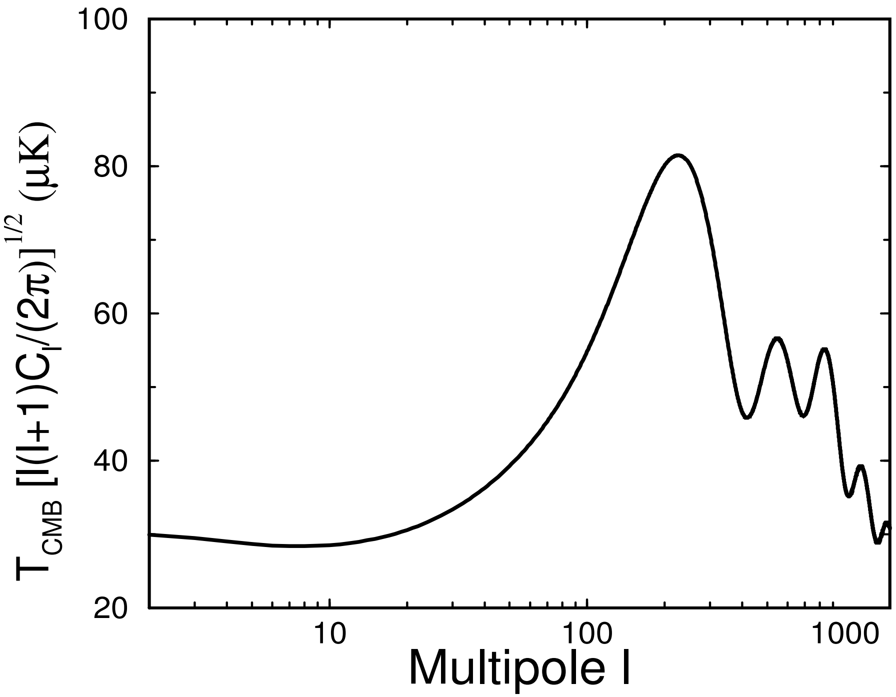


Bennett et al. 2003

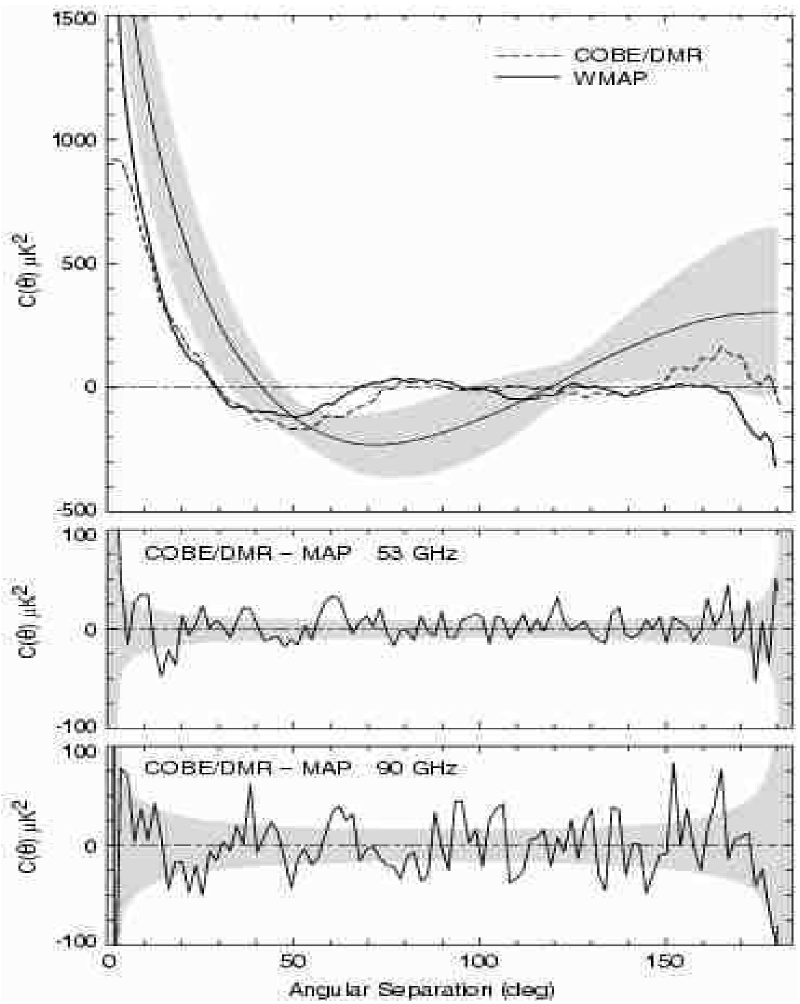
CMB Anisotropies

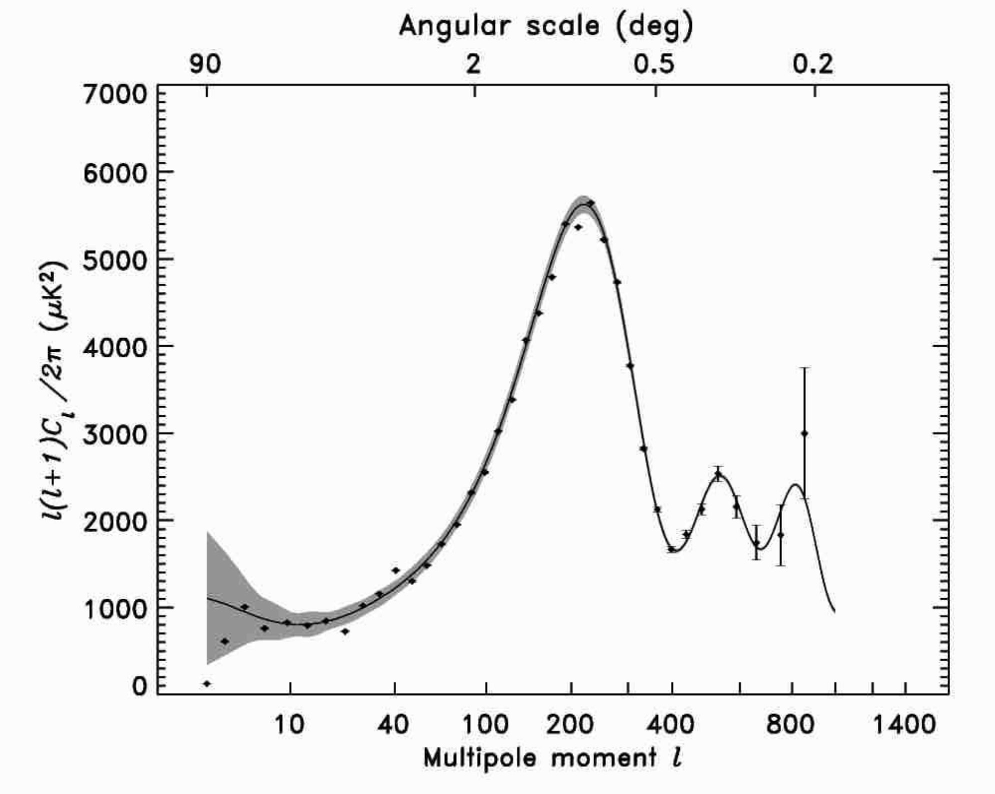
$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\phi), \qquad C_\ell \equiv \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$





“...answered old questions and raised new...”





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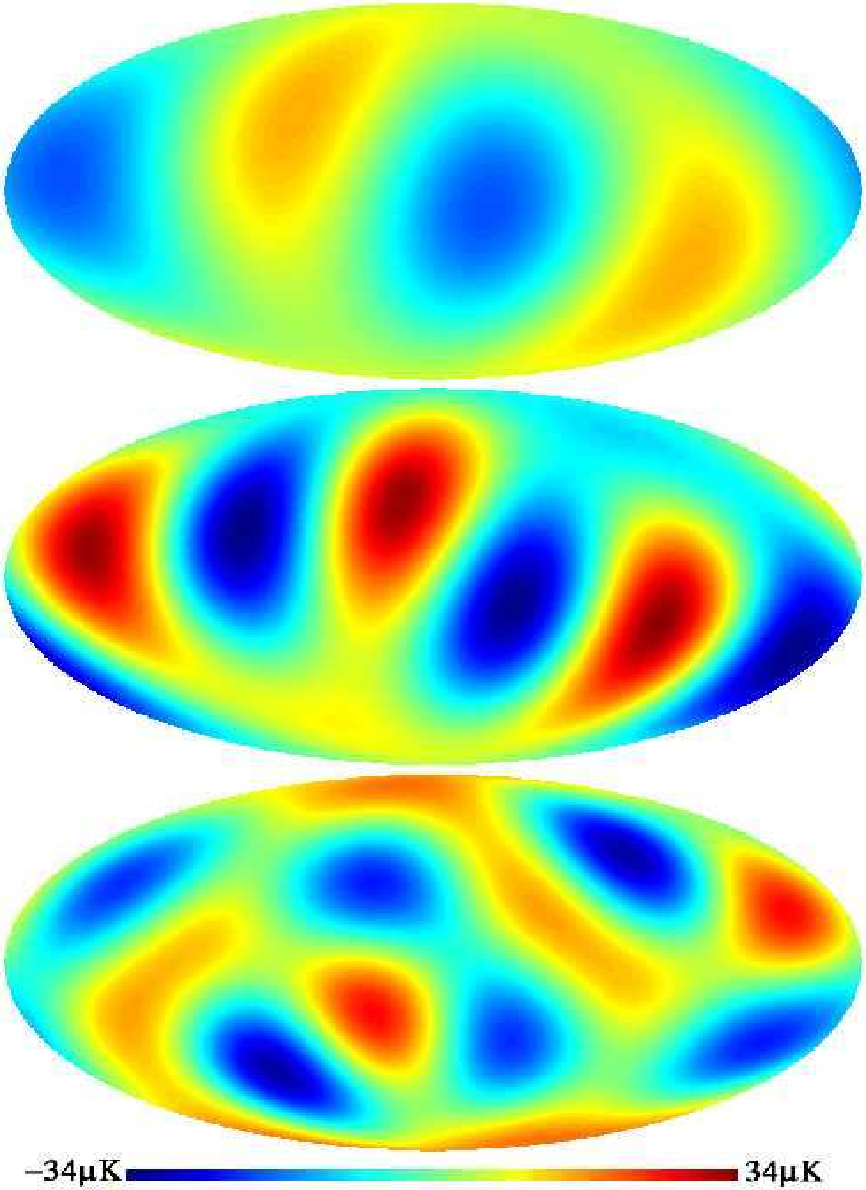
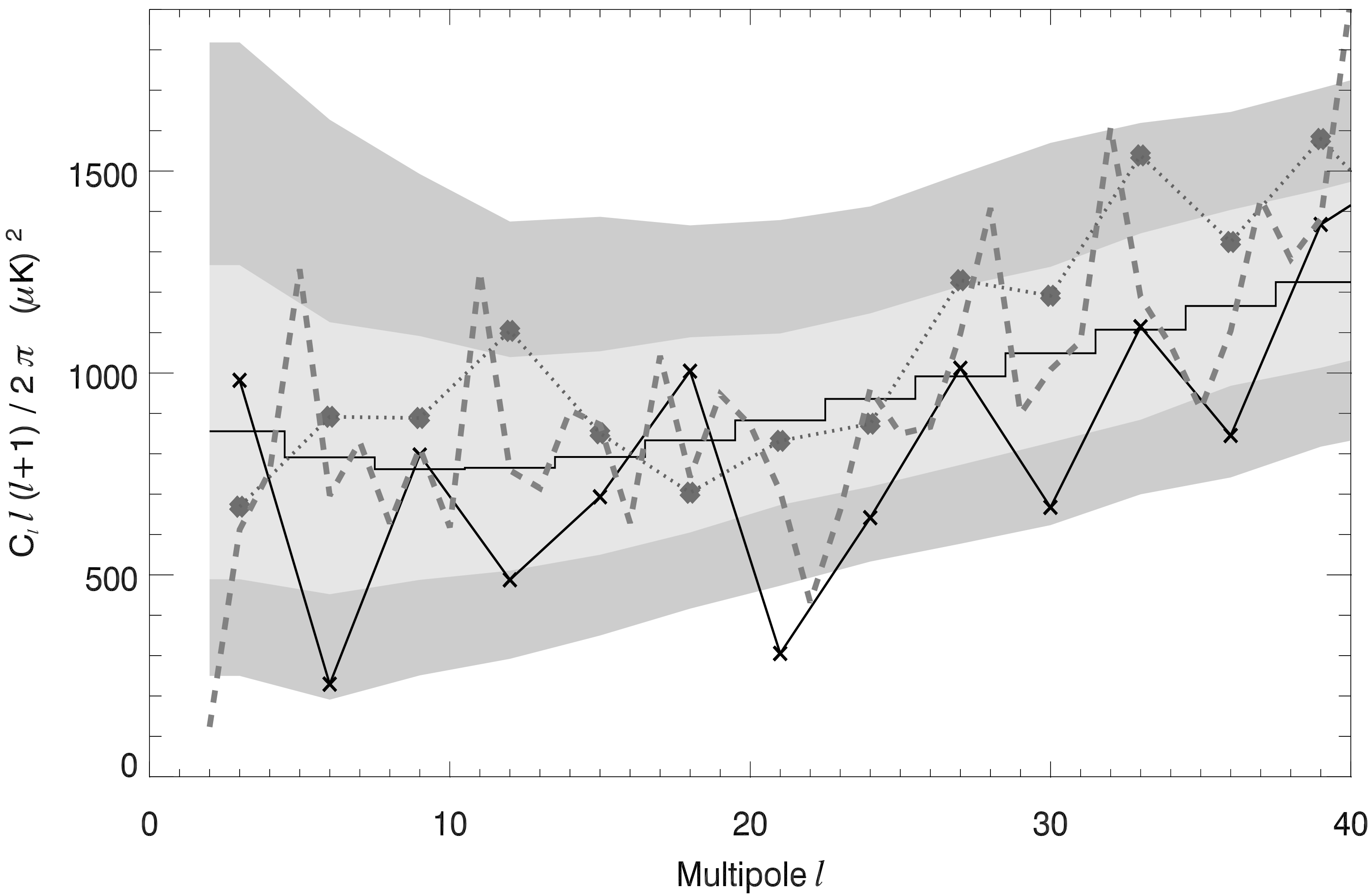
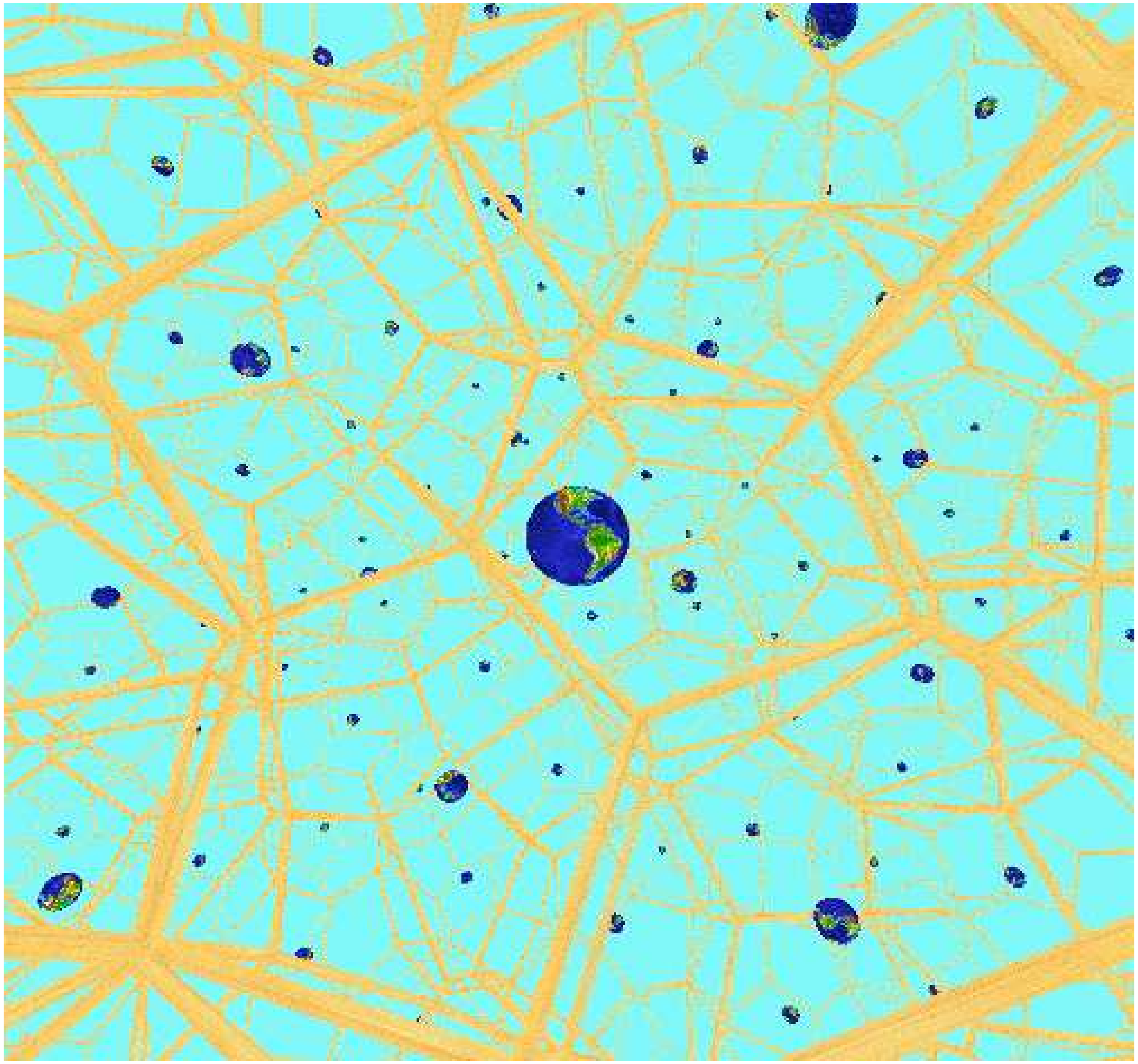


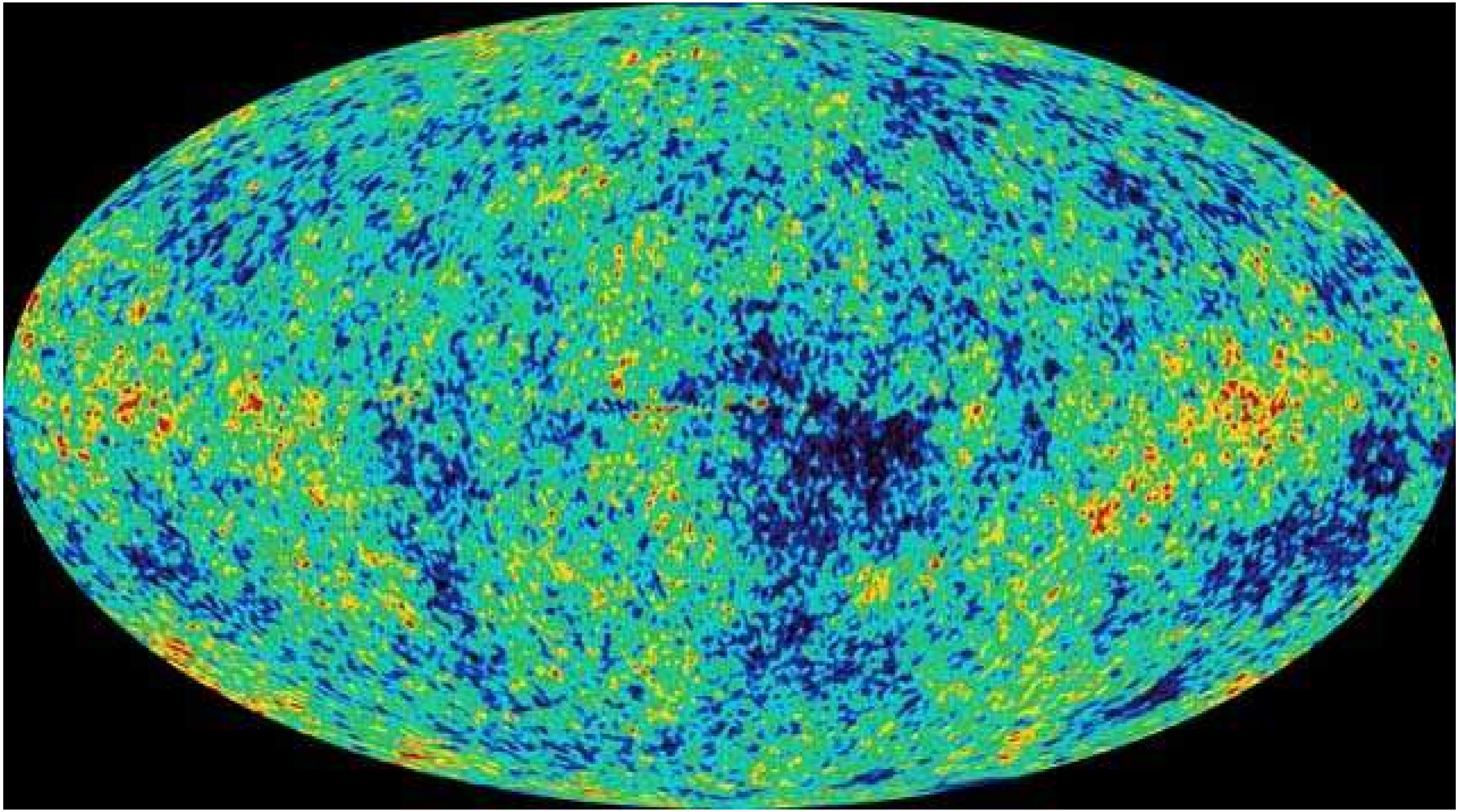
Tegmark et al. 2003



Eriksen et al. 2003



WMAP ILC map



Bennett et al. 2003

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Copi, Huterer & Starkman, 2004

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$$\sum_{m=-\ell}^{\ell} a_{lm} Y_{lm}(\theta,\phi) \quad = \quad A^{(\ell)}\left(\mathbf{v}_1^{(\ell)}\cdot\mathbf{e}\right)\cdots\left(\mathbf{v}_\ell^{(\ell)}\cdot\mathbf{e}\right)$$

$$\text{``}a^{(\ell)}_{i_1\ldots i_l} \quad \leftrightarrow \quad A^{(l)}\left[\mathbf{v}_1^{(\ell)}\otimes\mathbf{v}_2^{(\ell)}\otimes\ldots\mathbf{v}_\ell^{(\ell)}\right]''$$

Copi, Huterer & Starkman, 2004

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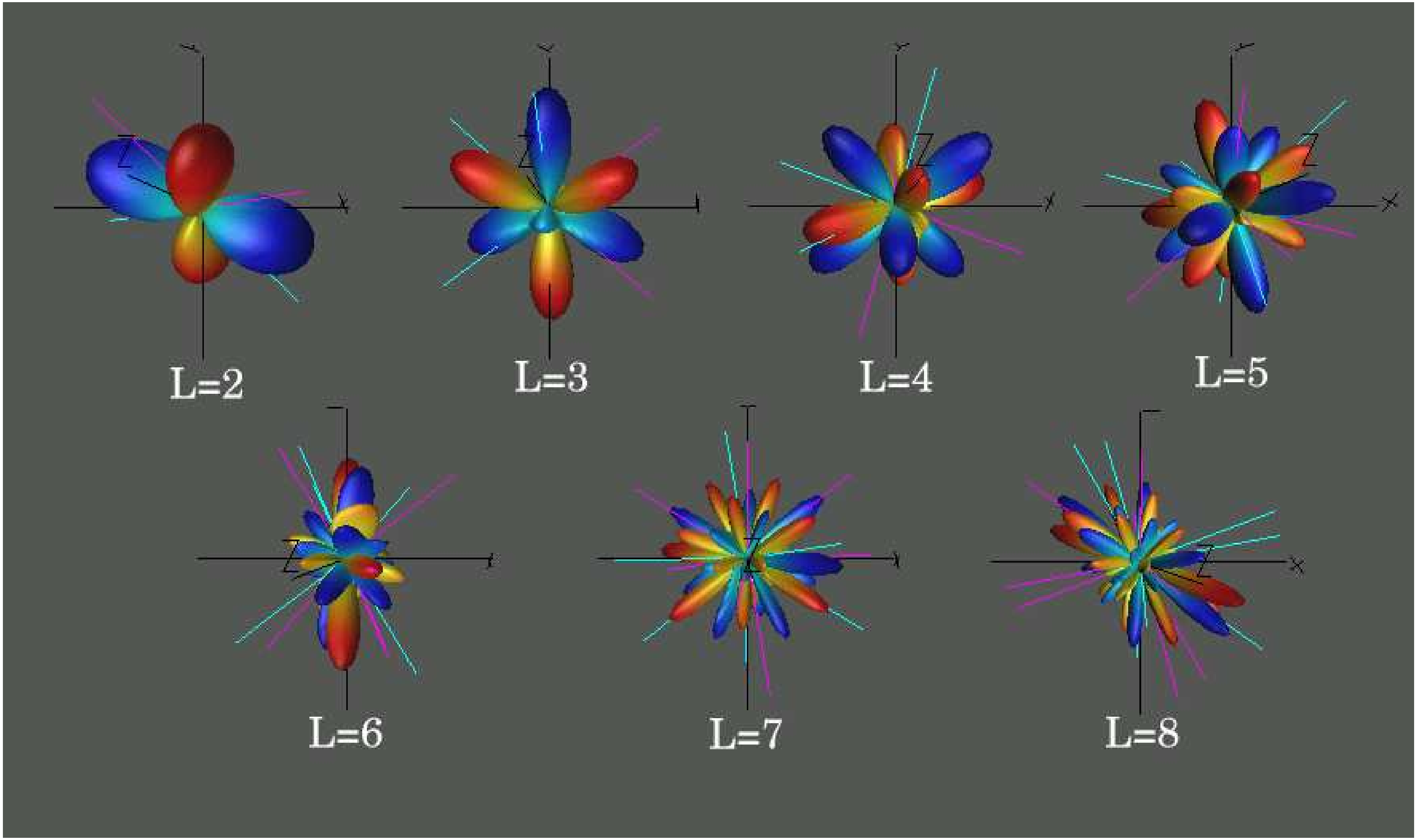
ℓ^{th} order equations?

Fortunately, can peel off one vector at a time

$\longrightarrow$ coupled quadratic equations.

Copi, Huterer & Starkman, 2004

WMAP's Multipole Vectors



Another view

Theorem: Every homogeneous polynomial P of degree ℓ in x, y and z may be written as

$$\begin{aligned} P(x,y,z) &= \lambda \cdot (a_1 x + b_1 y + c_1 z) \cdot (a_2 x + b_2 y + c_2 z) \ldots \cdot (a_\ell x + b_\ell y + c_\ell z) \\ &+ (x^2 + y^2 + z^2) \cdot R \end{aligned}$$

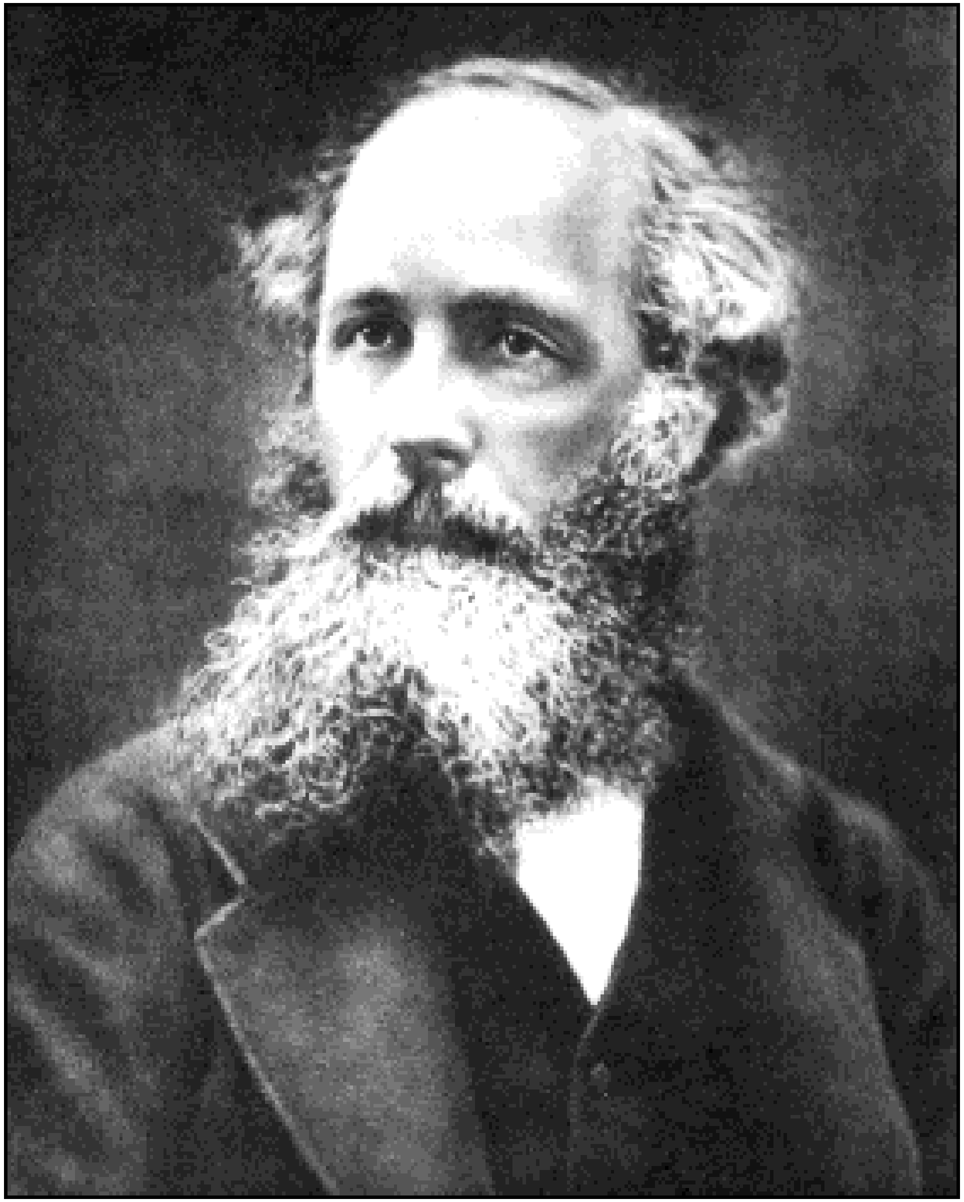
where R is a homogeneous polynomial of degree $\ell - 2$. The decomposition is unique up to reordering and rescaling the linear factors.

Example (Y_{20}):

$$\begin{aligned} P(x,y) &= x^2 + y^2 - 2z^2 \\ &= -3(z)(z) + (x^2 + y^2 + z^2)(1) \end{aligned}$$

Katz & Weeks, astro-ph/0405631

Scooped... 130 years ago!



James Clerk Maxwell

A Treatise on Electricity and Magnetism, 1873

Maxwell's multipole vectors

Potential of:

- dipole: $\nabla_{\mathbf{v_1}} \frac{1}{r}$ $\left[= -\frac{\mathbf{v_1} \cdot \mathbf{r}}{r^3}\right]$
- quadrupole:

$$\nabla_{\mathbf{v_2}} \nabla_{\mathbf{v_1}} \frac{1}{r} \qquad \left[= \frac{3(\mathbf{v_1} \cdot \mathbf{r})(\mathbf{v_2} \cdot \mathbf{r}) - r^2(\mathbf{v_1} \cdot \mathbf{v_2})}{r^5}\right]$$

.....

- ℓ-th multipole: $\nabla_{\mathbf{v}_\ell} \ldots \nabla_{\mathbf{v_2}} \nabla_{\mathbf{v_1}} \frac{1}{r}$

On a sphere, this expression can be written as

$$\lambda\,(\mathbf{v_1} \cdot \mathbf{r}) \cdot \ldots \cdot (\mathbf{v}_\ell \cdot \mathbf{r}) + r^2\,R$$

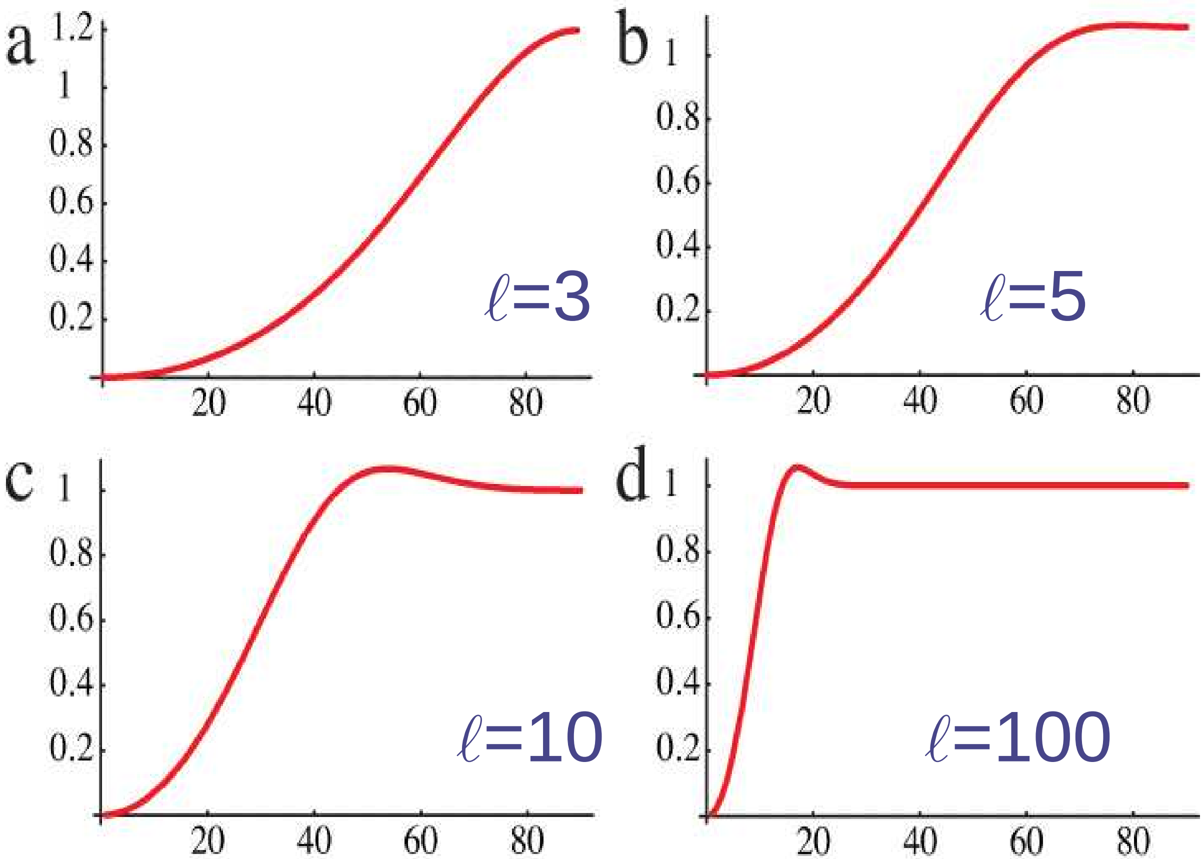
Maxwell (1873), Weeks, astro-ph/0412231

Correlations of vectors

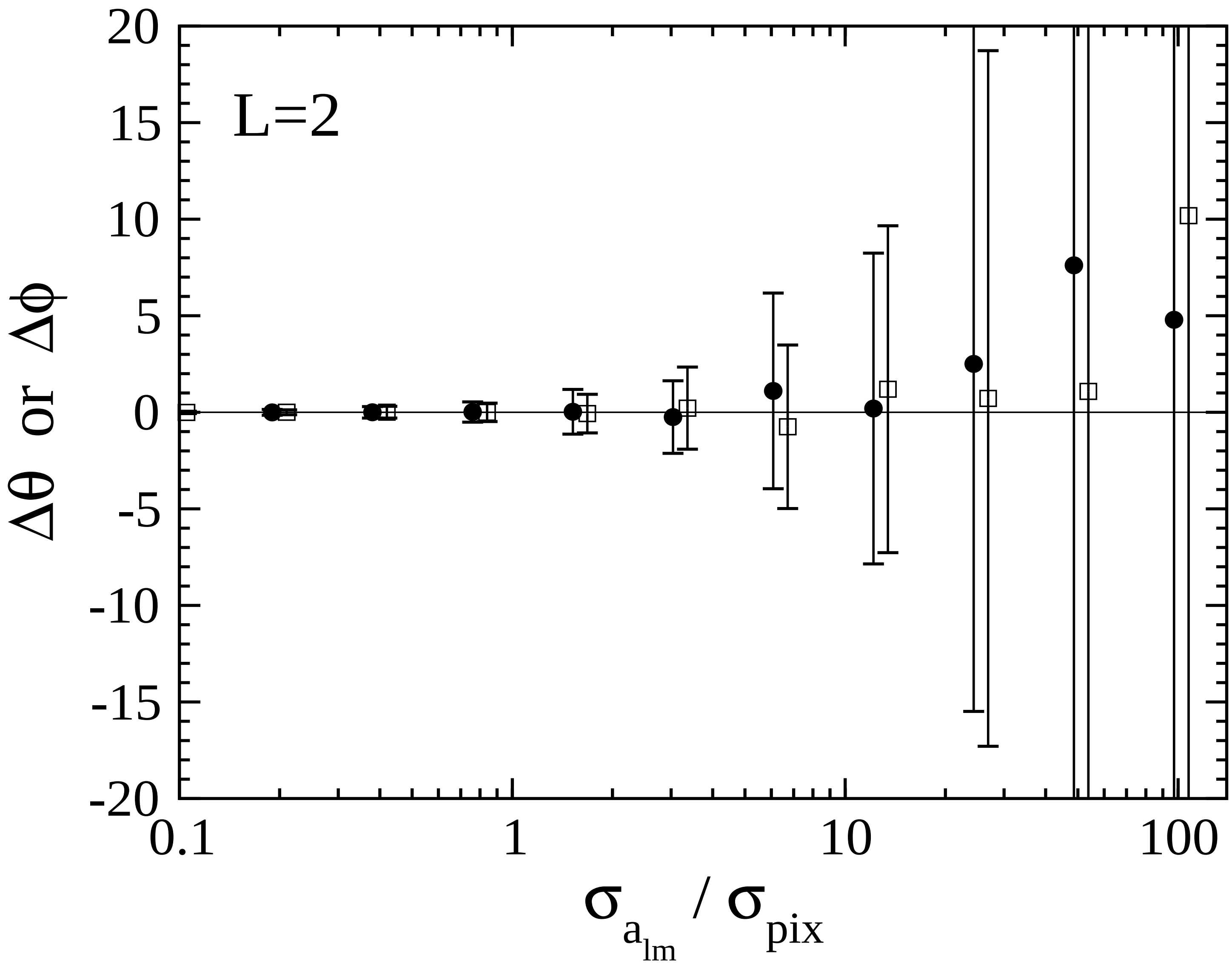
N-point correlation function derived (!) by Dennis (math-ph/0410004)

E.g. for $\ell = 2$

$$\rho_2(\theta) \propto \frac{1 - \cos^2\theta}{(3 + \cos^2\theta)^{5/2}}$$



Accuracy in determining MVs



Tests of Isotropy and Gaussianity with MV

Hypothesis:

$$\langle a_{\ell m} a^*_{\ell' m'} \rangle = C_\ell \, \delta_{\ell\ell'} \, \delta_{mm'}$$

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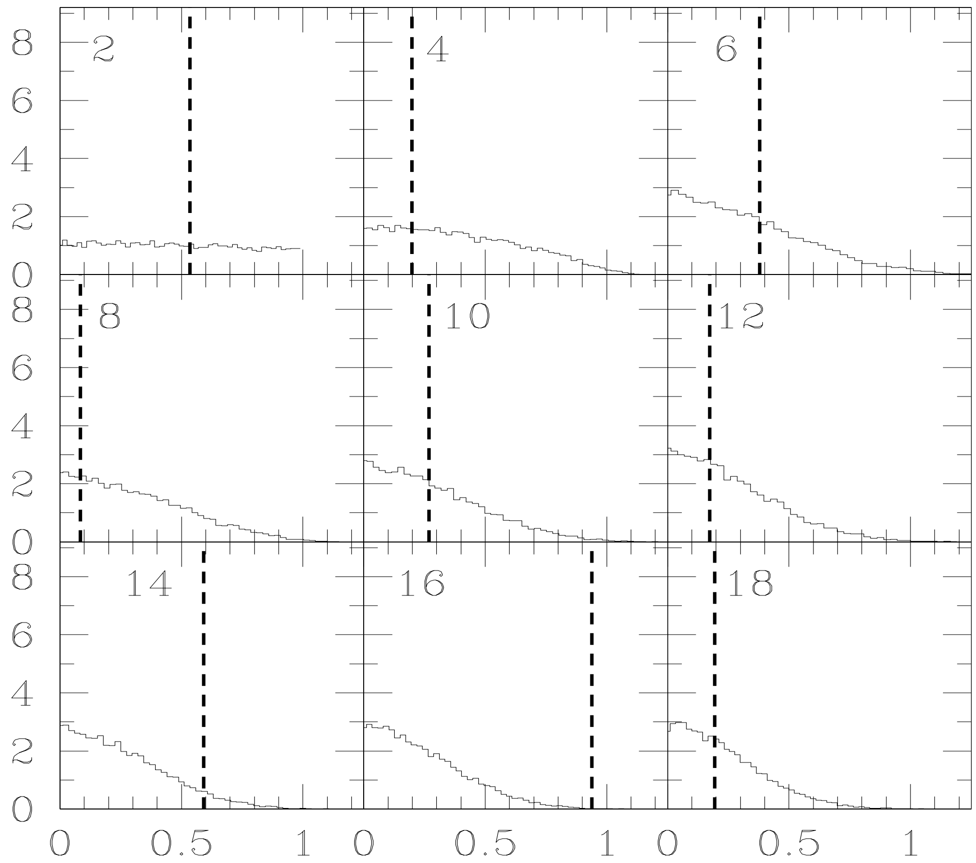

Ferreira, Magueijo & Gorski 1998

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Tests:

- $\left|\mathbf{v}_i^{(\ell_1)} \cdot \mathbf{v}_j^{(\ell_2)}\right|$

Copi, Huterer & Starkman, 2004

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- $\left|\mathbf{v}_i^{(\ell_1)} \cdot \mathbf{v}_j^{(\ell_2)}\right|$
- $\left|\mathbf{v}_i^{(\ell_1)} \cdot \left(\mathbf{v}_j^{(\ell_2)} \times \mathbf{v}_k^{(\ell_2)}\right)\right|$

Copi, Huterer & Starkman, 2004

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- $\left|\left(\mathbf{v}_i^{(\ell_1)} \times \mathbf{v}_j^{(\ell_1)}\right) \cdot \left(\mathbf{v}_k^{(\ell_2)} \times \mathbf{v}_m^{(\ell_2)}\right)\right|$

Copi, Huterer & Starkman, 2004

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- $\left|\left(\mathbf{v}_i^{(\ell_1)} \times \mathbf{v}_j^{(\ell_1)}\right) \cdot \left(\mathbf{v}_k^{(\ell_2)} \times \mathbf{v}_m^{(\ell_2)}\right)\right|$

Found: Planes defined by $2 \leq (\ell_1, \ell_2) \leq 8$ vectors are unusual at the level of 107 parts in a 10,000 (62 in a 10,000 for ILC map).

Copi, Huterer & Starkman, 2004

Normals to multipole vectors

$$\mathbf{w}_{ij}^{(\ell)} \equiv \pm \left(\mathbf{v}_i^{(\ell)} \times \mathbf{v}_j^{(\ell)} \right)$$

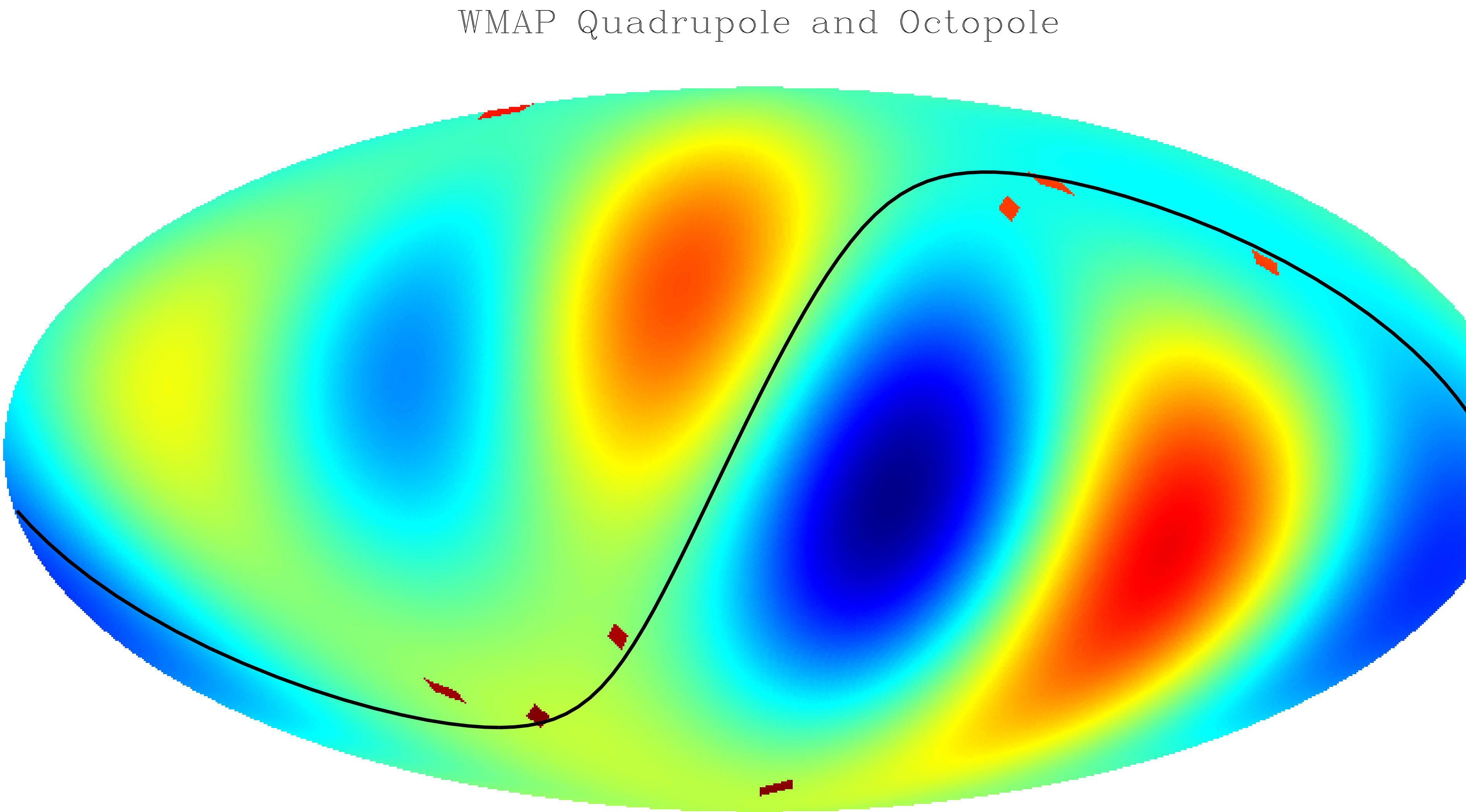
$\mathbf{w}_{12}^{(\ell=2)}$

$\mathbf{w}_{12}^{(\ell=3)}$

$\mathbf{w}_{23}^{(\ell=3)}$

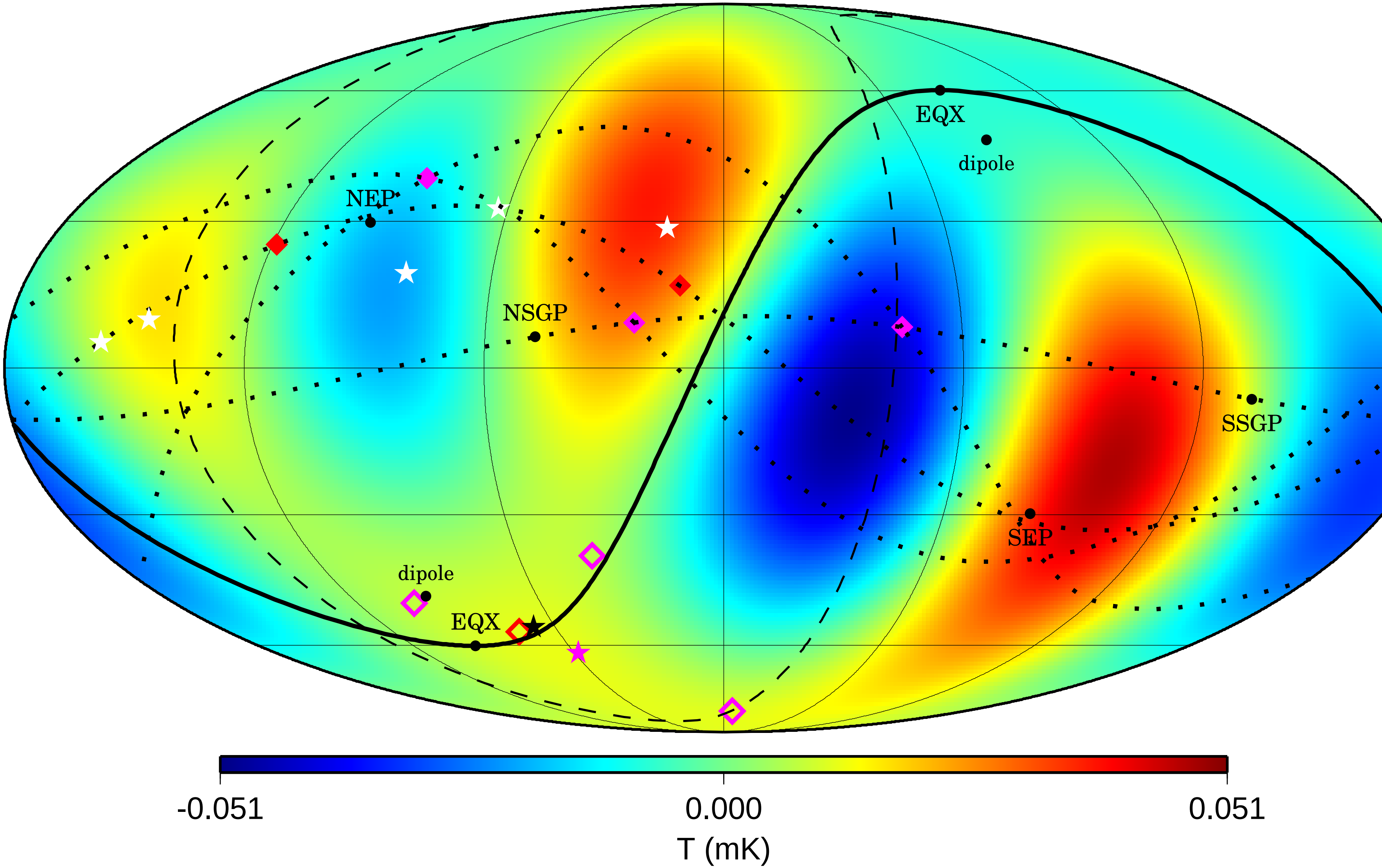
$\mathbf{w}_{31}^{(\ell=3)}$

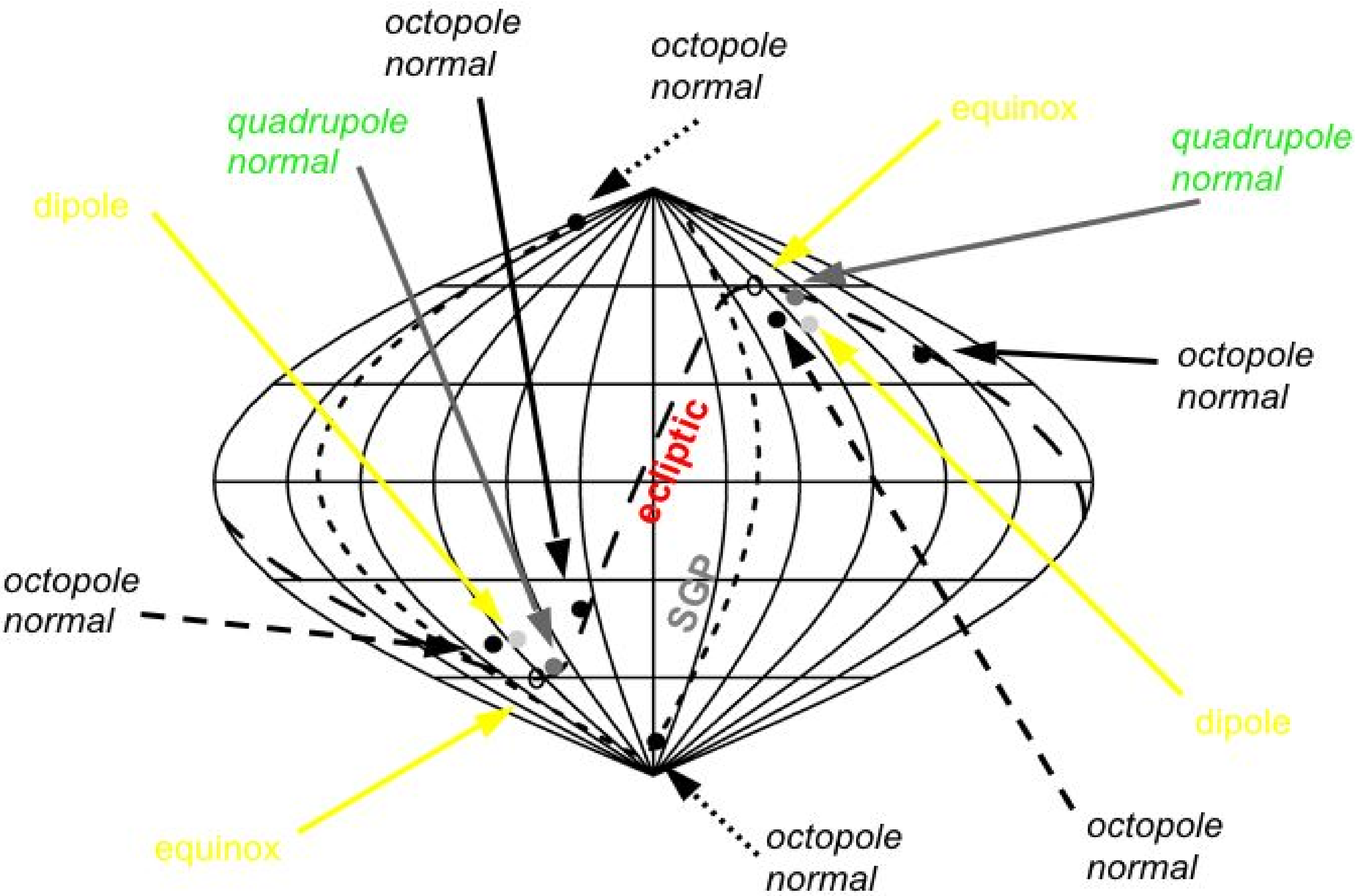
(Quad + Oct) map and the ecliptic plane



Schwarz, Starkman, Huterer and Copi 2005

(Quad + Oct) map and the ecliptic plane





octopole
normal
octopole
normal
equinox
quadrupole
normal
quadrupole
normal
dipole
octopole
normal
ecliptic
SGP
octopole
normal
dipole
equinox
octopole
normal
octopole
normal

Found: peculiar alignments

- The four oriented area normals $\mathbf{w}_{ij}^{(\ell)} \equiv \pm \left(\mathbf{v}_i^{(\ell)} \times \mathbf{v}_j^{(\ell)} \right)$ for $\ell = 2, 3$ are unusually close
- $\mathbf{w}_{ij}^{(\ell)}$ lie close to the ecliptic plane (unusual at the 99.8% CL)
- $\mathbf{w}_{ij}^{(\ell)}$ are aligned to the dipole and to the equinoxes at the 99.9% CL

Schwarz, Starkman, Huterer and Copi 2005

Significance of alignments

Statistic:

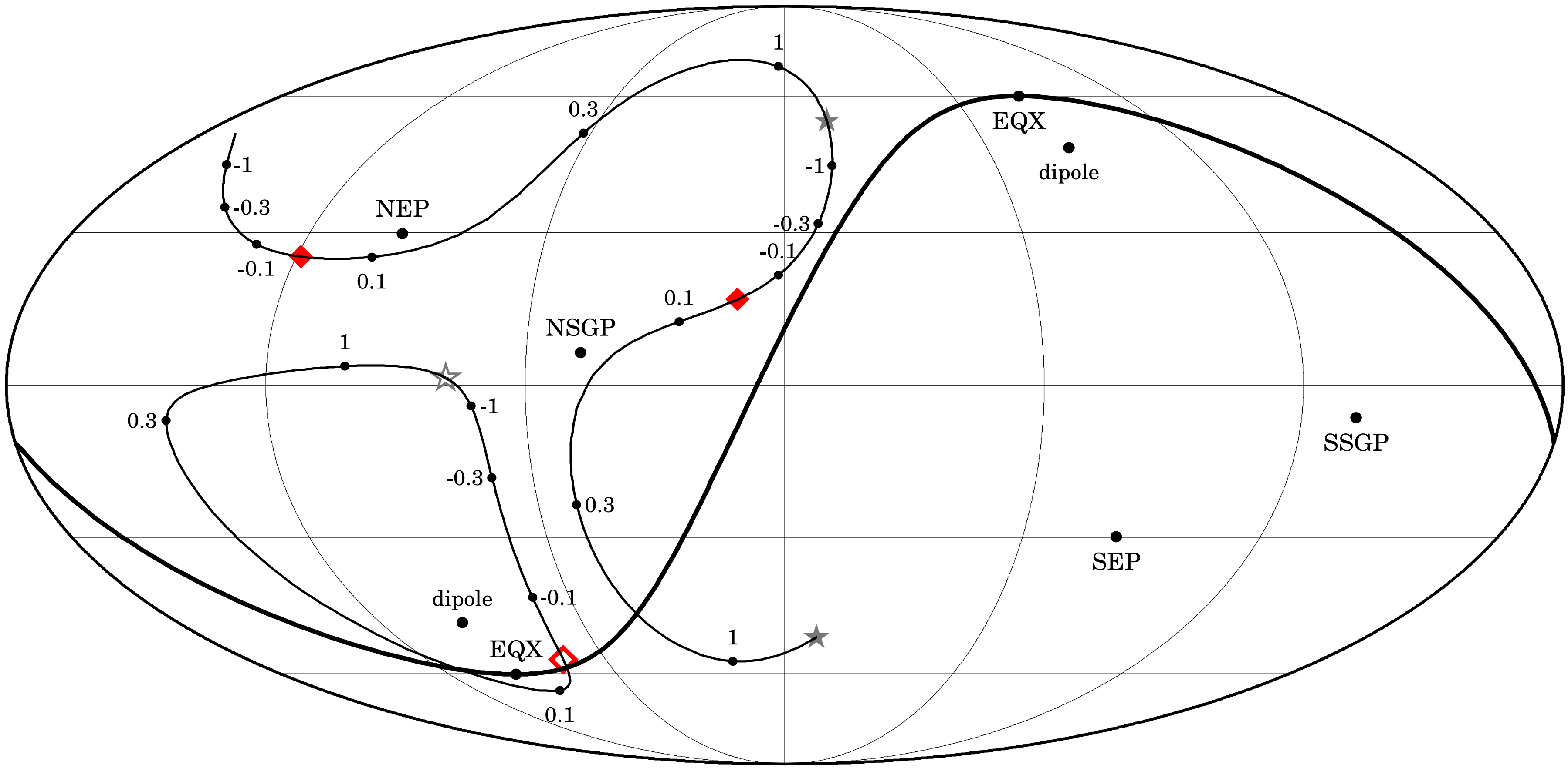
$$S \equiv \sum |\mathbf{w}_{ij}^{(\ell)} \cdot \mathbf{d}|$$

Test	TOH (%)	LILC (%)	ILC (%)
$\mathbf{w}_{ij}^{(\ell)}$ mutual	0.117	0.602	0.289
$\mathbf{n}_{ij}^{(\ell)}$ mutual	1.246	1.309	2.240
$\mathbf{w}_{ij}^{(\ell)} \cdot$ NEP	0.966	0.955	1.328
$\mathbf{w}_{ij}^{(\ell)} \cdot$ Dipole	0.394	0.605	0.669
$\mathbf{w}_{ij}^{(\ell)} \cdot$ Equinox	0.339	0.556	0.510

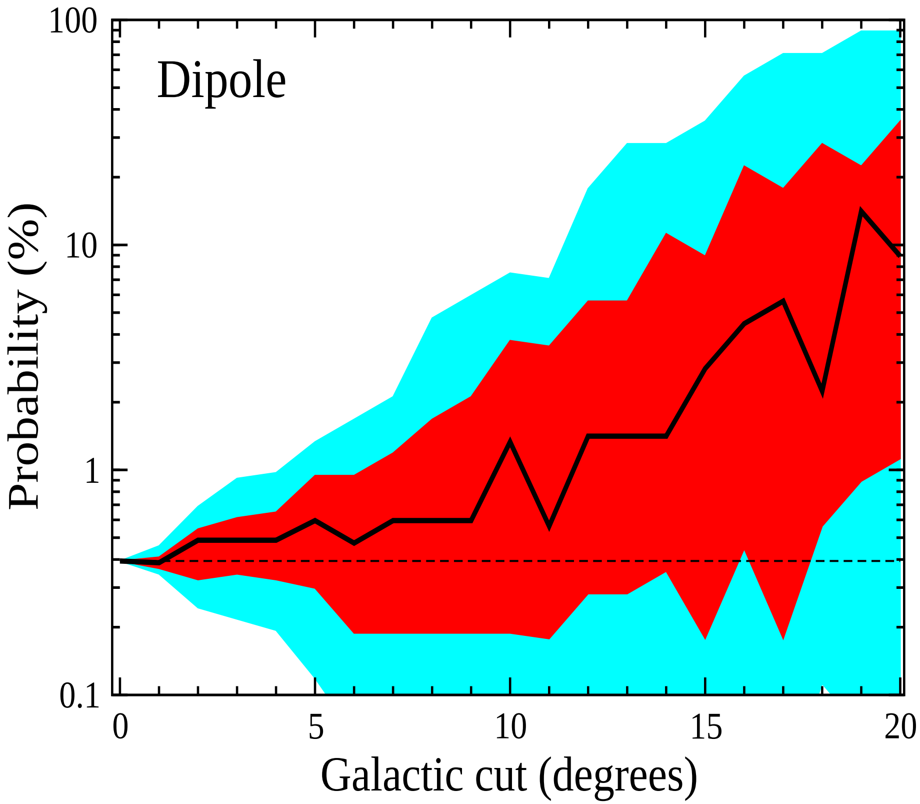
$(0.3\% \iff \text{“}3\sigma\text{”})$

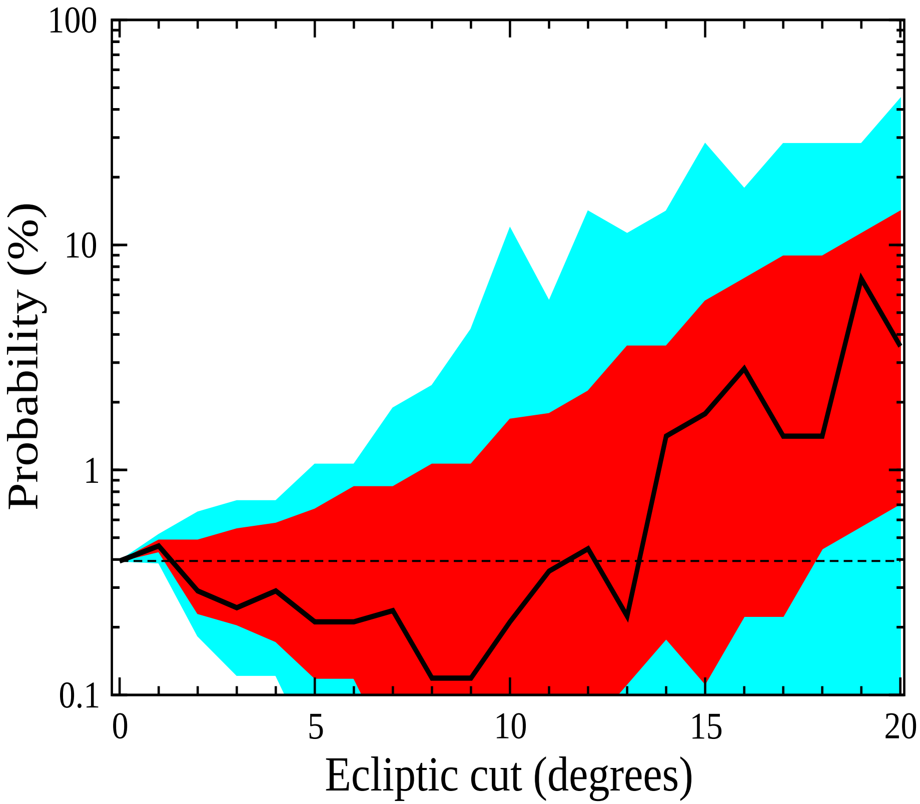
Systematic checks: foreground missubtractio

$$T_{\rm tot}(\theta) = T_{\rm CMB}(\theta) + c\,T_{\rm for}(\theta)\,\frac{{\rm Var}(T_{\rm CMB})}{{\rm Var}(T_{\rm for})}$$

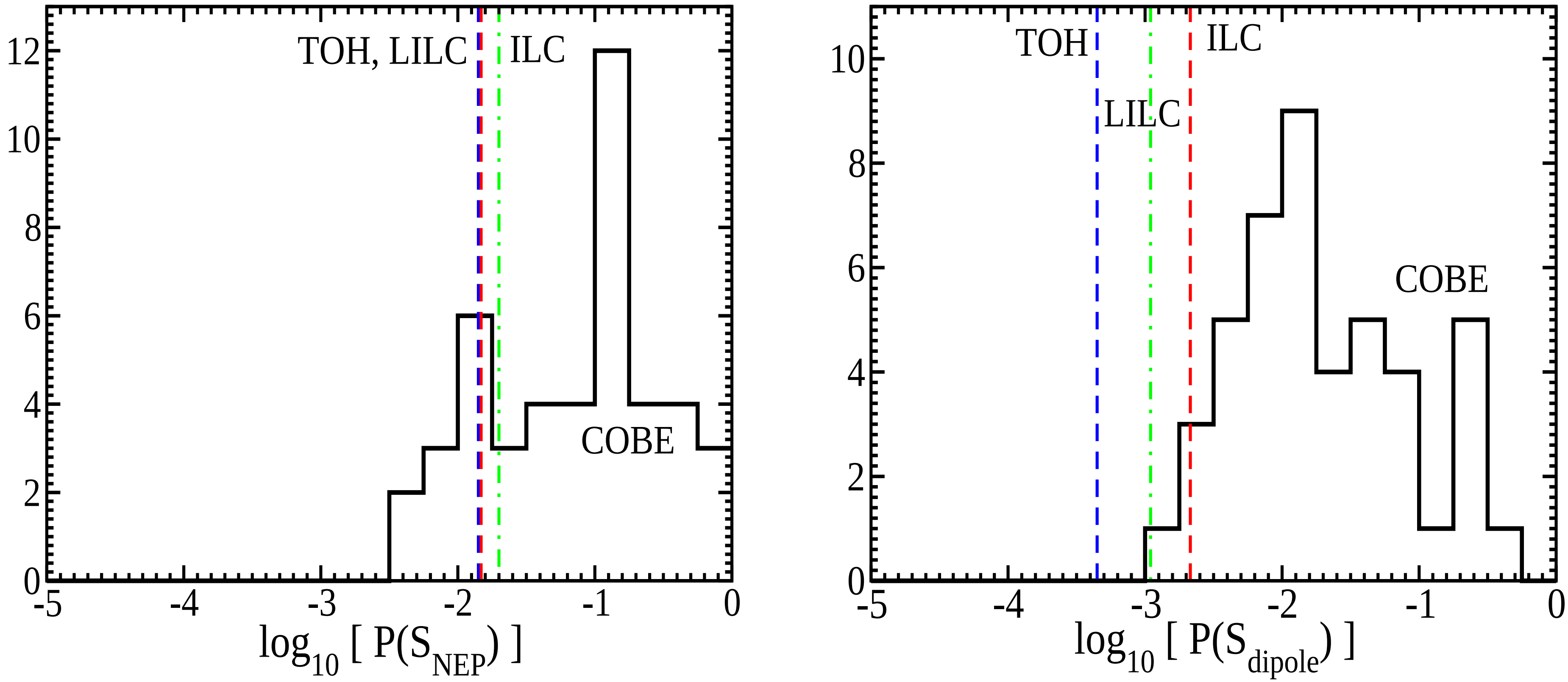


Systematic checks: sky cut





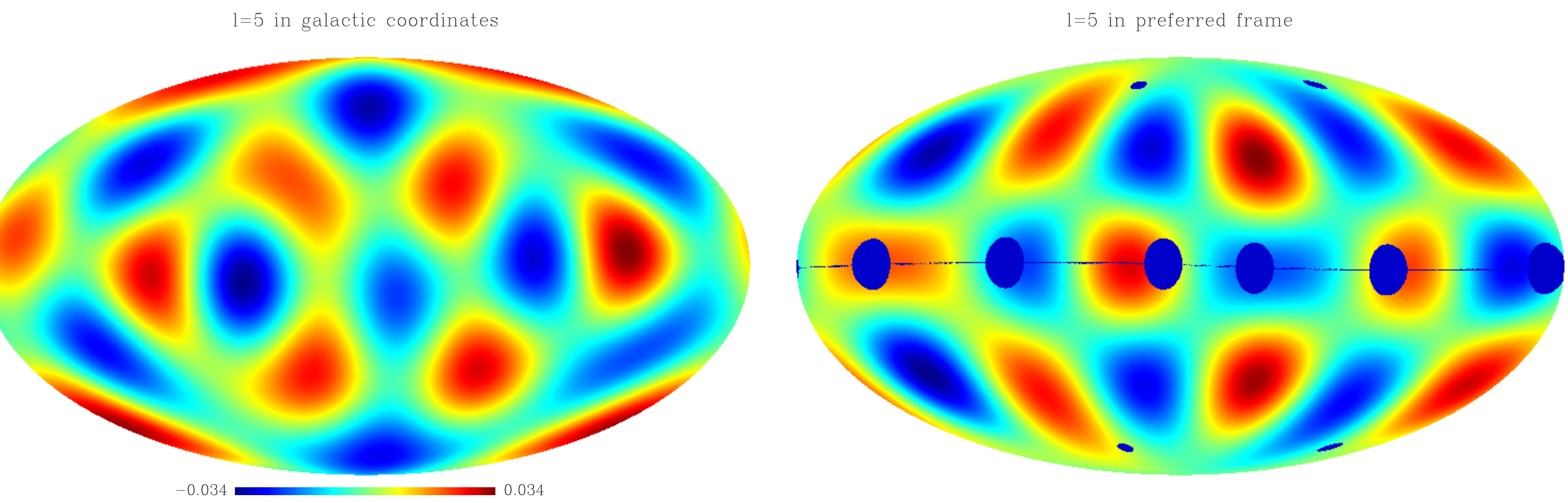
What about COBE?



Using the COBE MCMC maps from Wandelt et al. (2003)

The axis of evil: $(b, l) \approx (60, -100)$

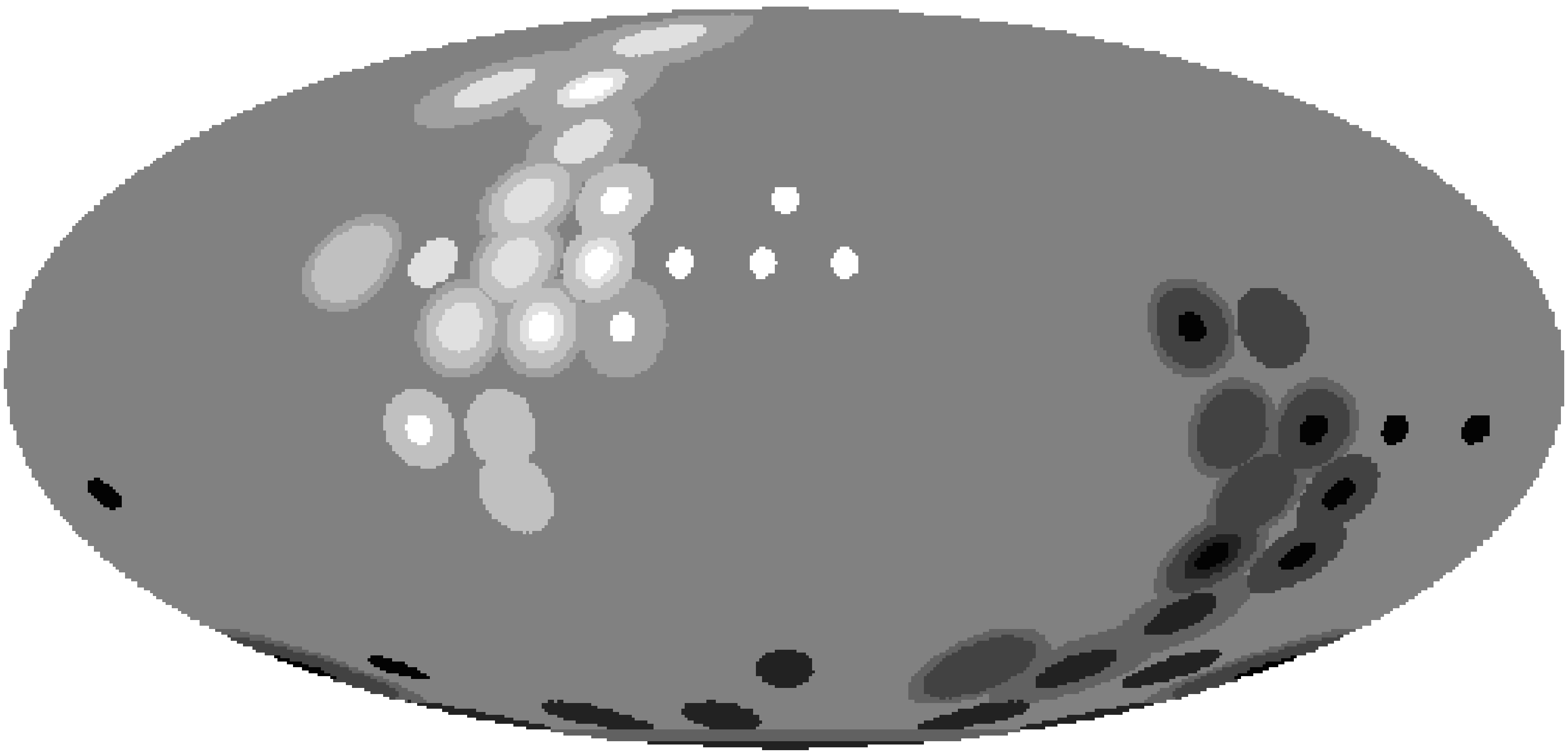
Average value of angles between preferred-axis vectors at $2 \leq \ell \leq 5$ is low at the 99.9% CL



Land & Magueijo, astro-ph/0502237

Asymmetry in the north-south power spectra

North has too little power, south too much.



Hansen, Banday & Gorski, astro-ph/0404206

4 classes of explanations:

- Astrophysical (e.g. an object or other source of radiation in the Solar System)
  - BUT: we think we know the Solar System. It would need to be a large source *and* undetected in data cross-checks.
- Instrumental (e.g. there is something wrong with WMAP instrument measuring CMB at large scales)
  - BUT: the instruments have been extremely well calibrated and checked. Plus, why would they pick out the Ecliptic plane?
- Cosmological (e.g. some property of the universe – inflation or dark energy for example – that we do not understand)
  - This is the most exciting possibility. BUT: why would the new/unknown physics pick out the Ecliptic plane?
- These alignments are a pure fluke!
  - BUT: they are <0.1% likely!

What could be going on?

- Dipole subtraction?
- Scanning strategy?
- Solar system signal?

or perhaps...

- Anisotropic universe?
(e.g. a slab space with a preferred axis)

Any of the above would have implications for cosmological parameter determination.

Additive and multiplicative errors

$$T(\hat{\mathbf{n}}) = \sum_{\ell m} t_{\ell m} Y_{\ell m}(\hat{\mathbf{n}}),\ A(\hat{\mathbf{n}}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\hat{\mathbf{n}}),\ B(\hat{\mathbf{n}}) = \sum_{\ell m} b_{\ell m} Y_{\ell m}$$

$$T(\hat{\mathbf{n}}) \equiv A(\hat{\mathbf{n}}) + f[1 + w(\hat{\mathbf{n}})]B(\hat{\mathbf{n}})$$

$$t_{\ell m} = a_{\ell m} + f b_{\ell m} + f \sum_{\ell_1 \ell_2} R_{\ell m}^{\ell_1 \ell_2} b_{\ell_2 m}$$

- $B = 1 \Rightarrow \langle t^*_{\ell m} t_{\ell' m} \rangle = \delta_{\ell \ell'} C_\ell^{aa} + f^2 w_\ell w_{\ell'} \delta_{m0}$ (additive)
- $w(\hat{\mathbf{n}})$, $B(\hat{\mathbf{n}})$ depend on $\hat{\mathbf{n}}$
  $\Rightarrow$ coupling between ℓ, ℓ' (multiplicative)

Gordon, Hu, Huterer & Crawford, astro-ph/0509301

Additive example 1: non-linear instrument

Suppose that the WMAP detectors are slightly (1%) nonlinear

$$T_{\rm obs}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}}) + \alpha_2 T(\hat{\mathbf{n}})^2 + \alpha_3 T(\hat{\mathbf{n}})^3 + \ldots$$

The biggest signal on the sky is the dipole

$$T(\hat{\mathbf{n}}) = 3.3mK\cos(\theta)$$

So with $\alpha_2 \sim \alpha_3 \sim 10^{-2}$, dipole anisotropy is modulated into a 10^{-5} quadrupole and octopole with $m = 0$ in the dipole frame.

Sadly: doesn't work since would have been seen when observing $\sim 1K$ sources (in lab, Jupiter, etc).

Additive example 2: DE perturbations

Say DE scalar field has a long-wavelength gradient

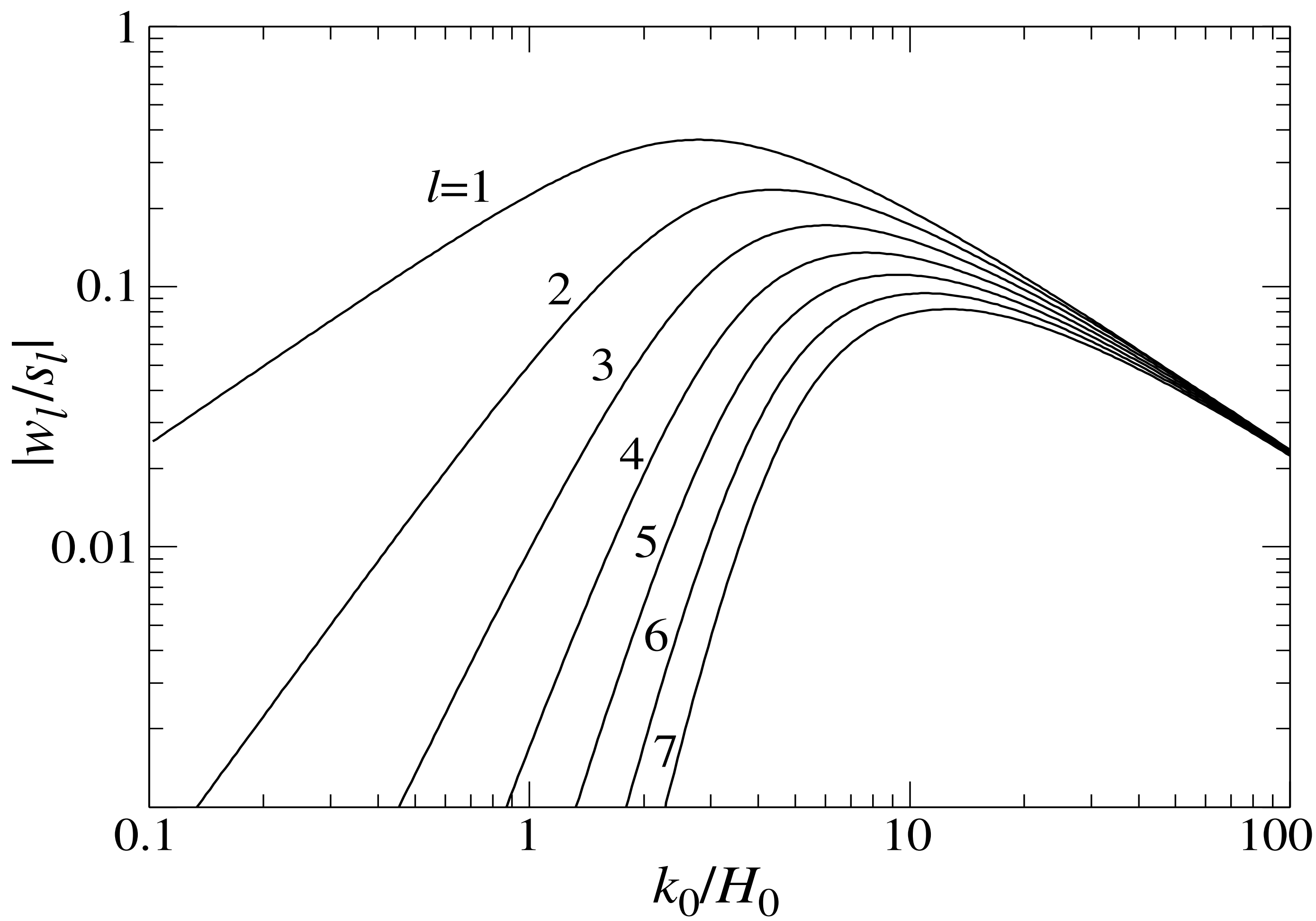
$$Q = Az + B$$

This gets mapped to sub-horizon modulation via the potential non-linear in Q:

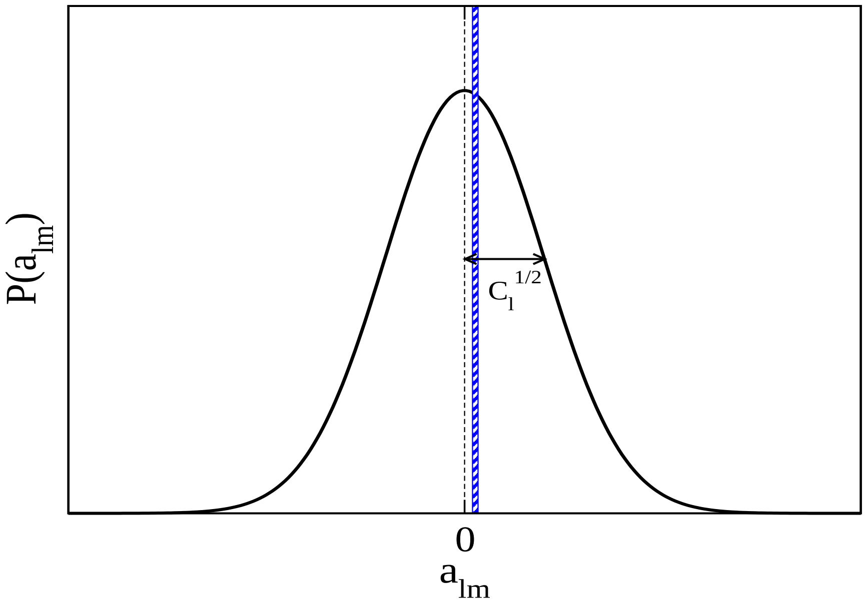
$$V(Q) = V_0 \left[1 + \cos\left(\frac{Q}{M}\right)\right] = V_0 \left[1 + \cos\left(k_0 z + \delta\right)\right]$$

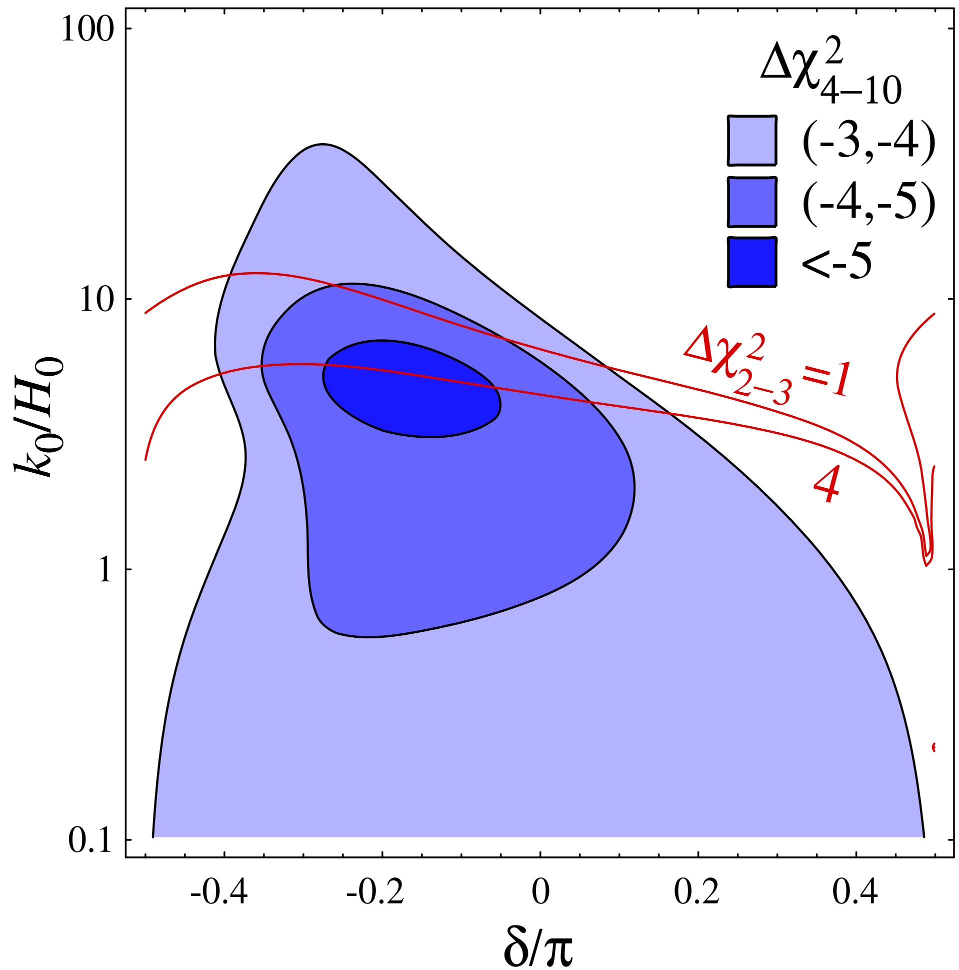
Also assume the field is light (i.e. frozen). Then the superhorizon fluctuations maps onto sub-horizon via $V(Q)$, and then we observe it projected on the sky.

Propagation to smaller scales



Additives “don’t work”

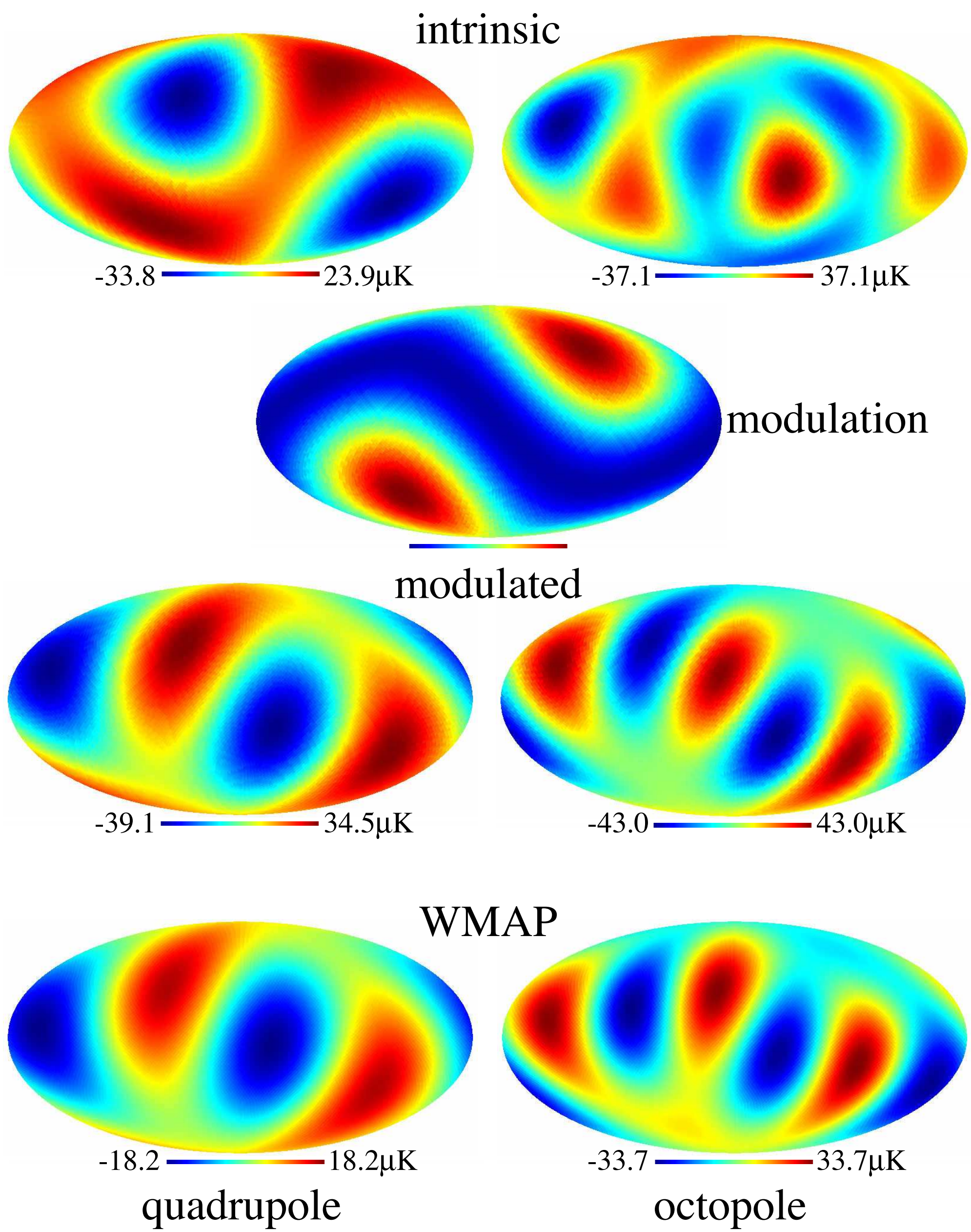




Same true for all additive schemes: Bianchi templates, Solar System contaminatio

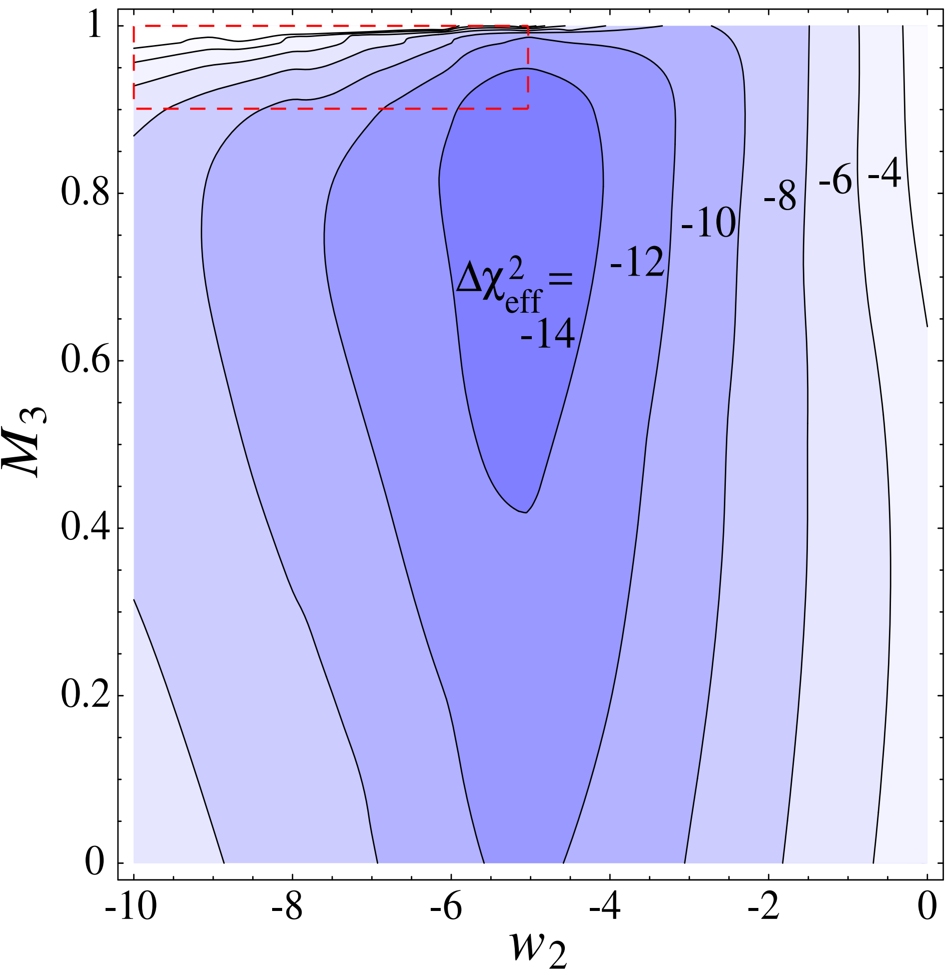
Gordon, Hu, Huterer & Crawford, astro-ph/0509301

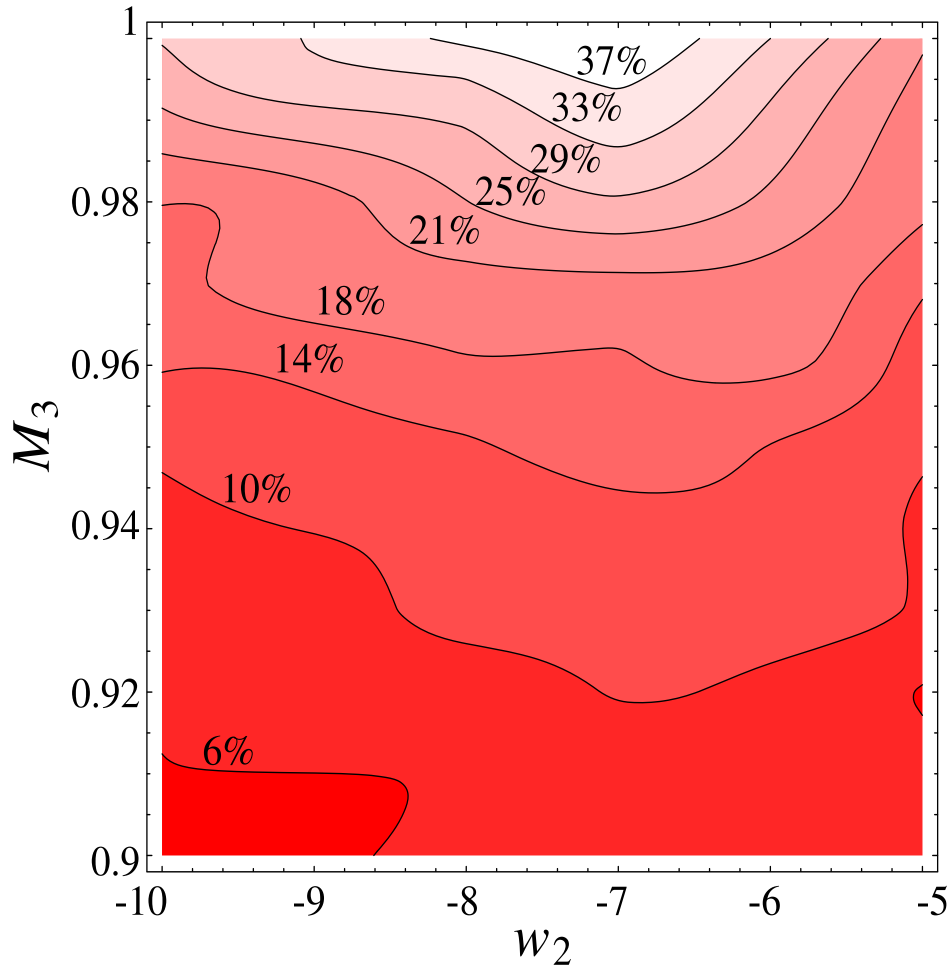
Multiplicative modulation: what it does



Multiplicative modulation: an example

$$T(\hat{\mathbf{n}}) = f[1 + w_2 Y_{20}(\hat{\mathbf{n}})]B(\hat{\mathbf{n}})$$



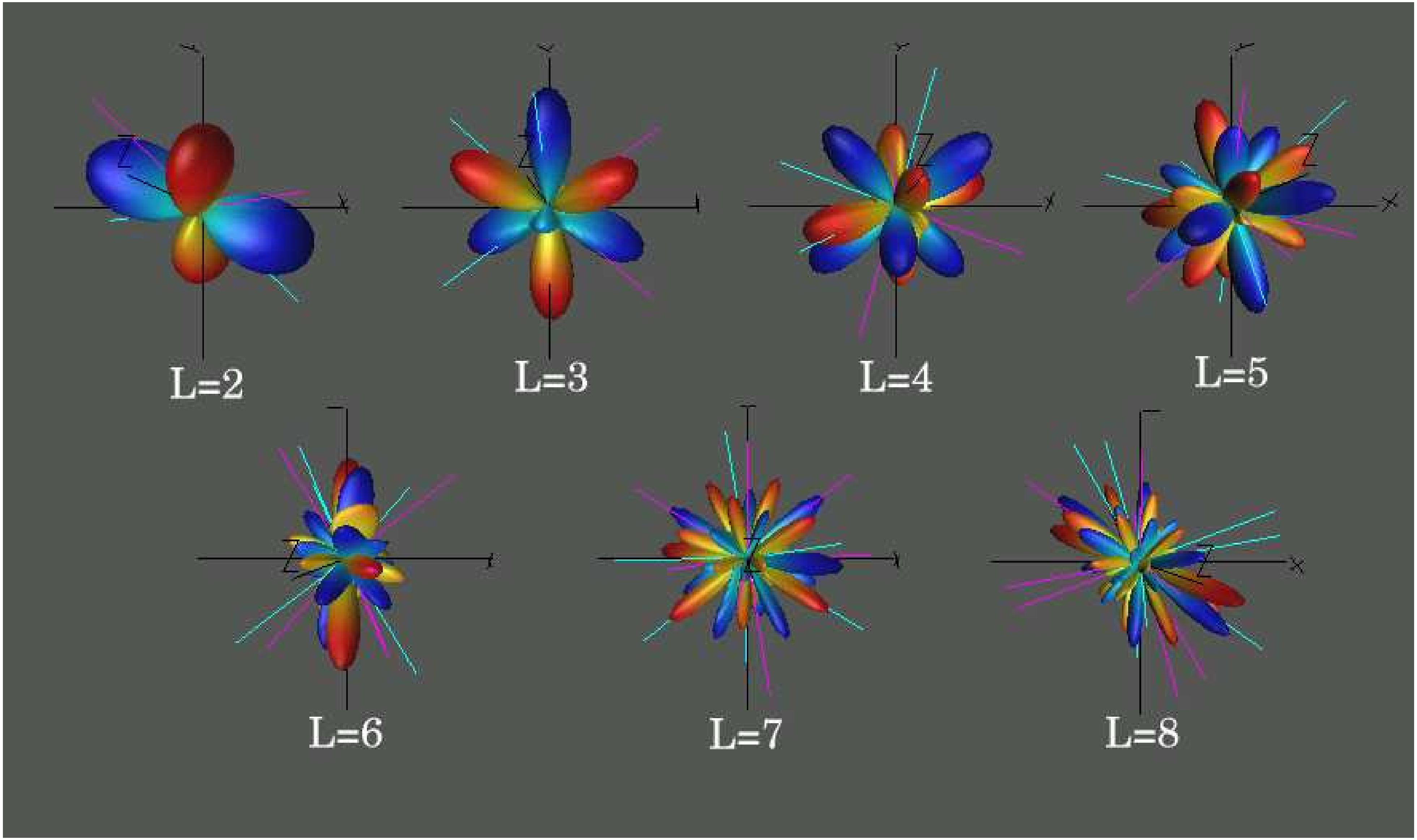


ame kind of improvement seen in $< 1\%$ of gaussian random skie

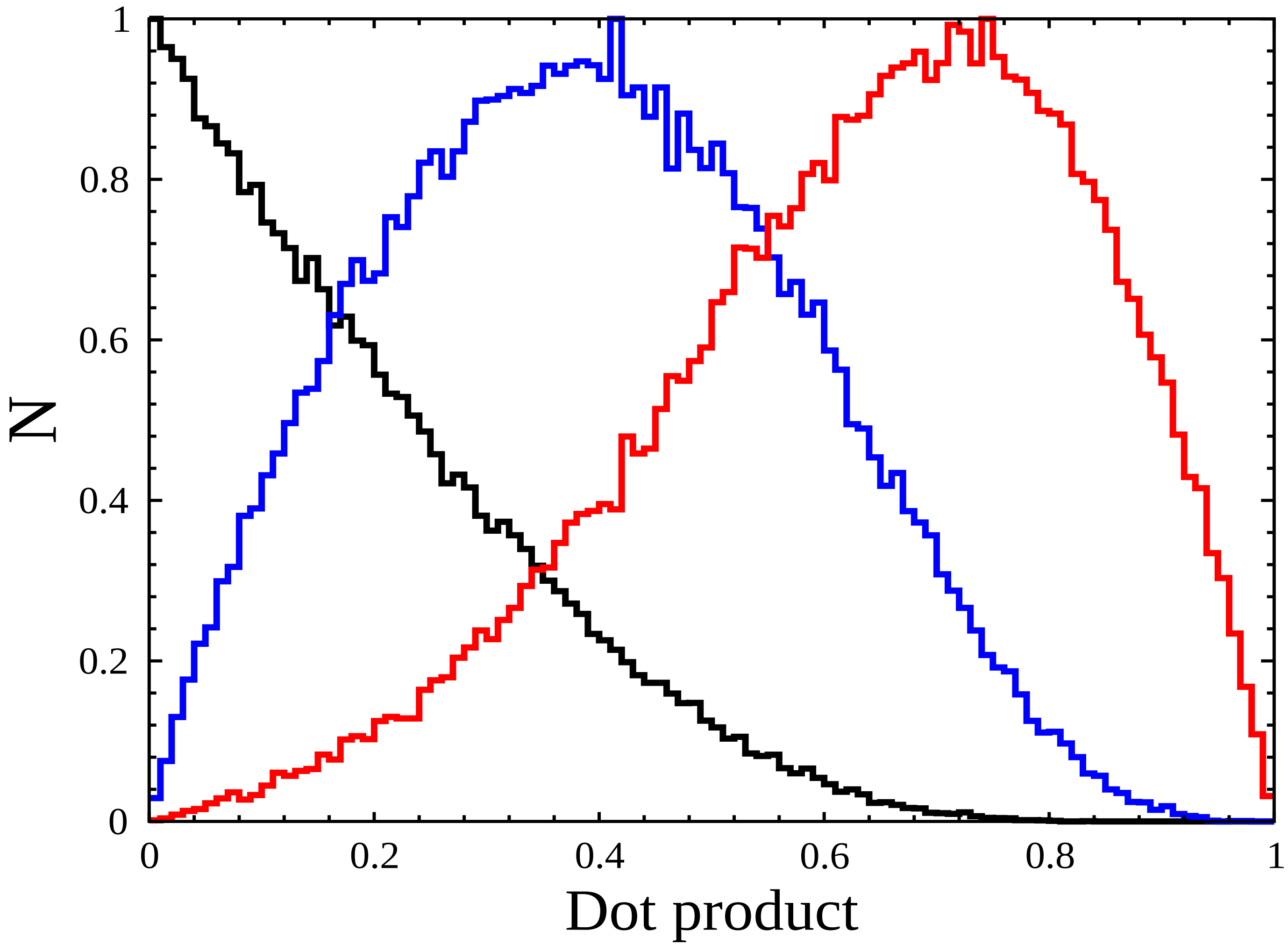
Conclusions

- Multipole vectors: a well defined, alternative basis to represent CMB anisotropy; very useful for doing isotropy/alignment tests.
- We (and others) observe a number of anomalies at large scales in WMAP, including correlations with the Ecliptic.
- Is dark energy or inflation doing something weird? Are there unaccounted-for local contaminants or foregrounds?
- No proposed mechanism works. Among the cosmological explanations, multiplicative mechanisms are promising.
- Future work: more data (esp. Planck). Polarization maps are expected to be systematics-dominated, and WMAP 2nd year etc temperature maps expected to be unchanged.

http://www.phys.cwru.edu/projects/mpvectors/



Comparison to Monte-Carlo realizations



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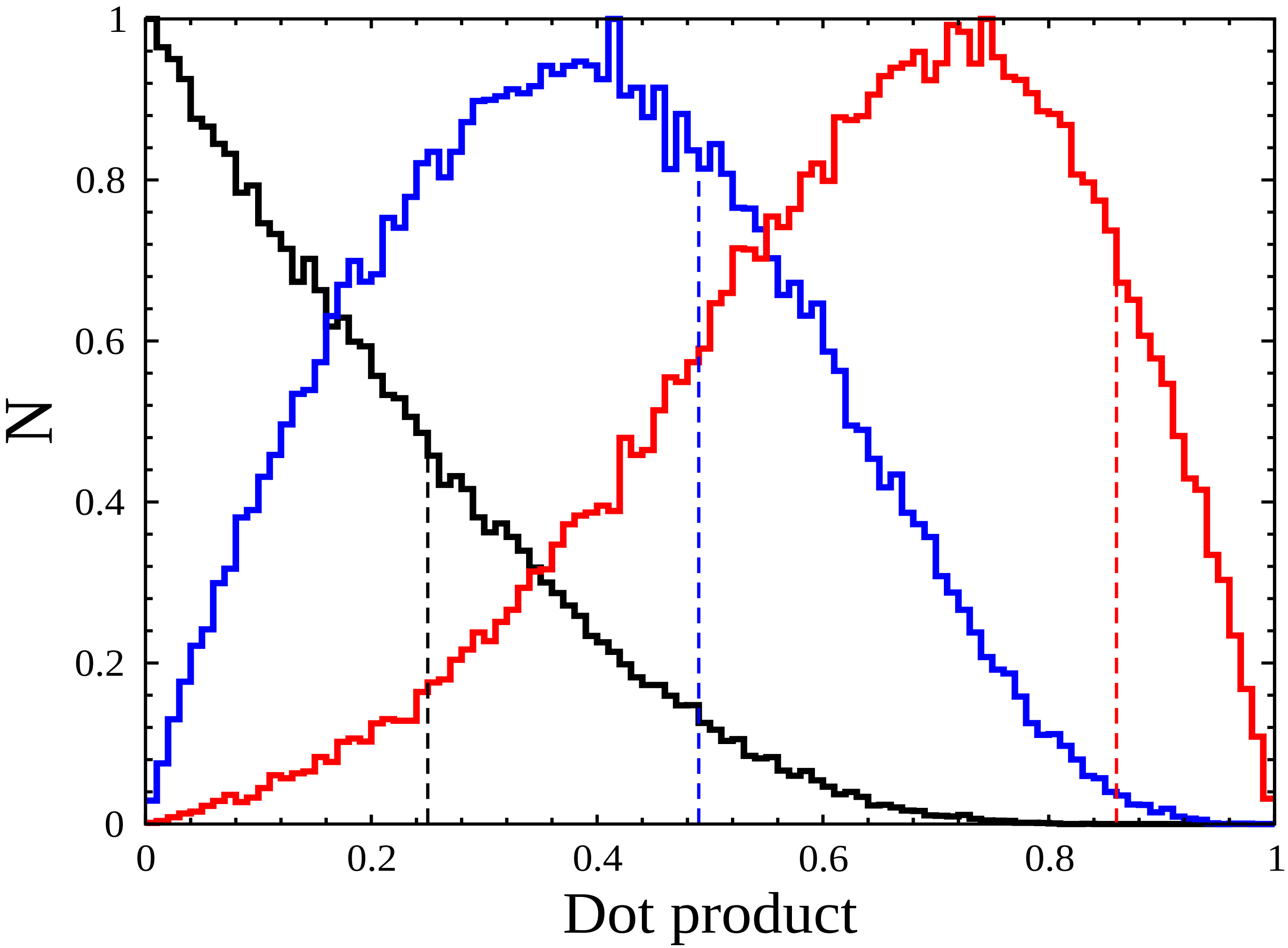

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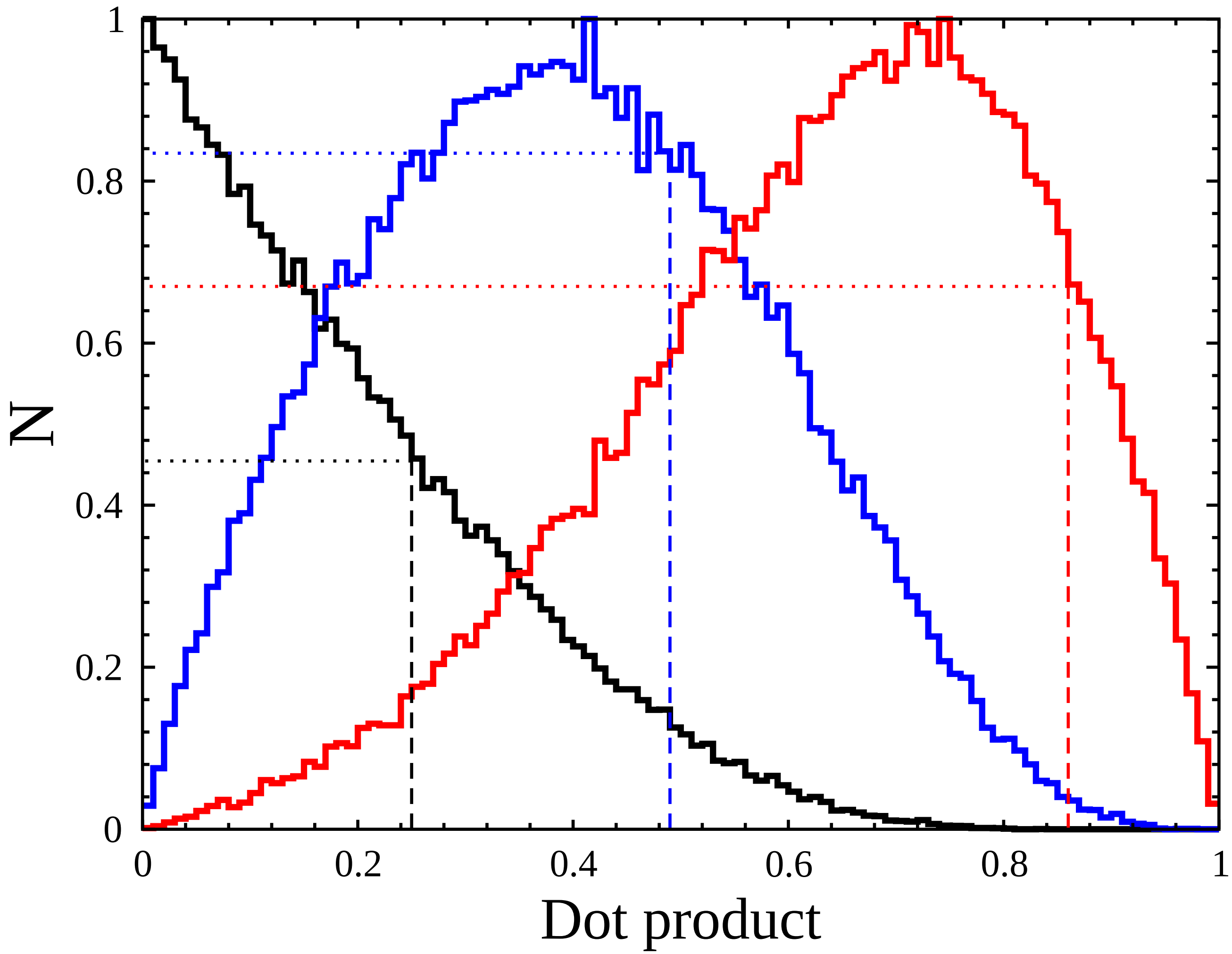
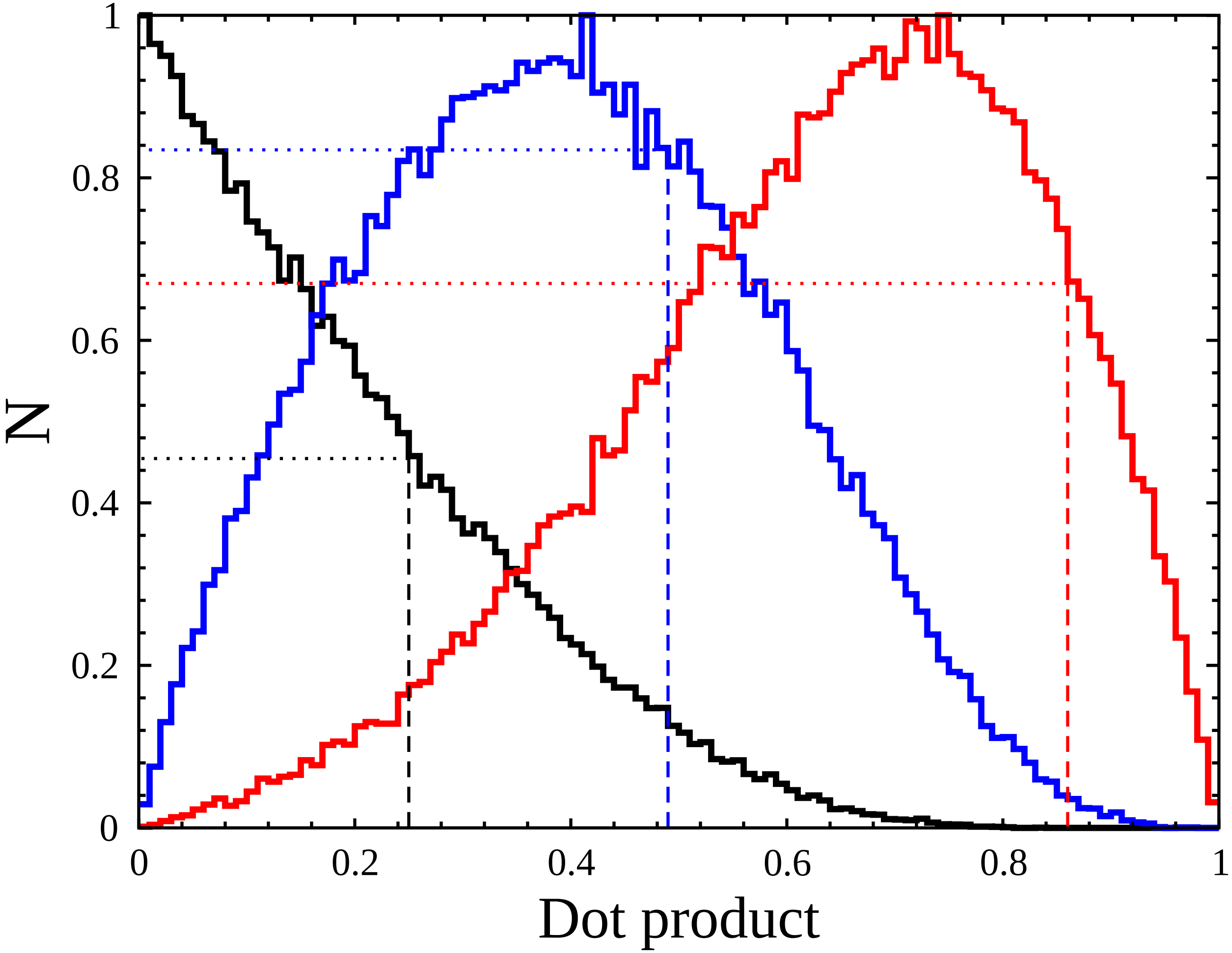


$$\mathcal{L}_{\mathrm{WMAP}} = \prod_{j=1}^{M} \frac{N_{j,\mathrm{WMAP}}}{N_{j,\max}}$$

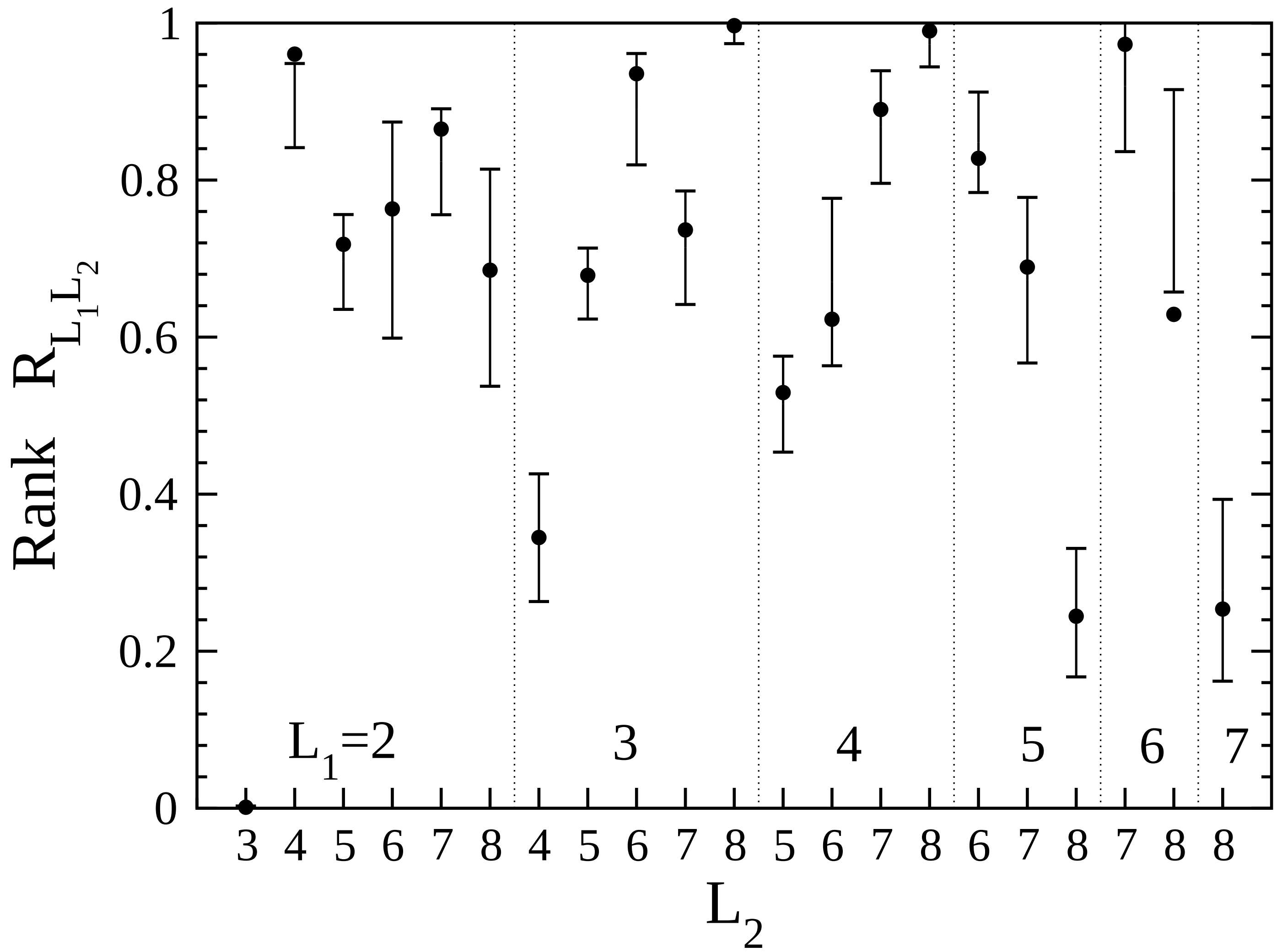
Comparison to Monte-Carlo realizations



$$\mathcal{L}_{\mathrm{WMAP}} = \prod_{j=1}^{M} \frac{N_{j,\mathrm{WMAP}}}{N_{j,\mathrm{max}}}$$

$$\mathcal{L}_{\mathrm{MC}} = \prod_{j=1}^{M} \frac{N_{j,\mathrm{MC}}}{N_{j,\mathrm{max}}}$$

WMAP Ranks relative to MC maps



How high are the ranks?

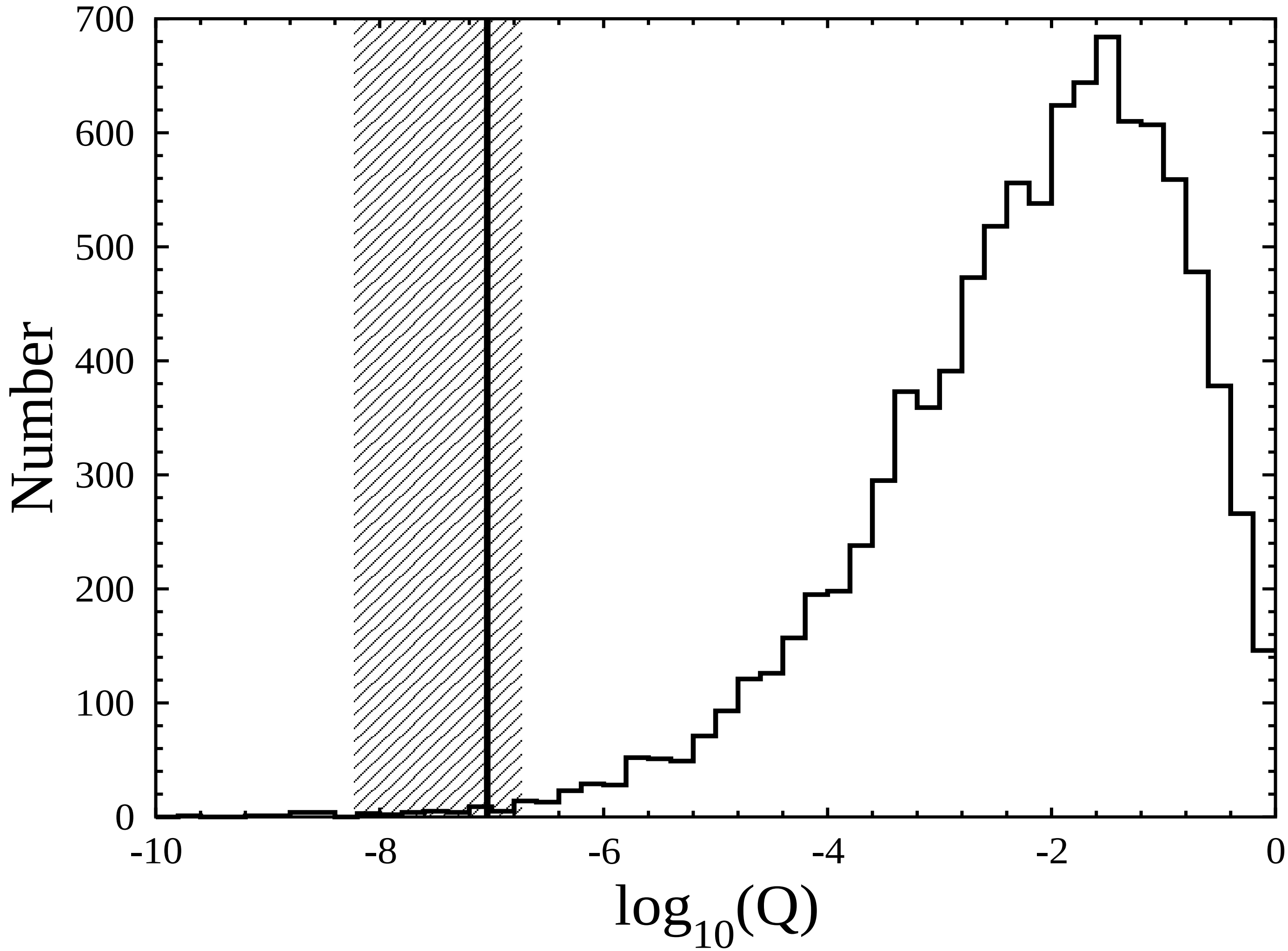
We use the following statistic:

$$Q(x_1, \ldots, x_N) = N! \int_{x_1}^{1} dy_1 \int_{x_2}^{y_1} dy_2 \ldots \int_{x_N}^{y_{N-1}} dy_N$$

For uniform random y's, this is equal to

$$\text{Probability}\left[(y_1 > x_1) \text{ AND } (y_2 > x_2) \text{ AND } \ldots \text{ AND } (y_N > x_N)\right]$$

Final Probability



Results

- Planes defined by $2 \leq (\ell_1, \ell_2) \leq 8$ vectors are unusual at the level of 107 parts in a 10,000 (62 in a 10,000 for ILC map)

Varying the Multipole Coverage		
$\ell_{\rm min}$	$Q_{\rm WMAP}$	$f(Q_{\rm MC} < Q_{\rm WMAP})$
2	7.61×10^{-7}	$107/10000$
3	3.13×10^{-6}	$105/10000$
4	3.12×10^{-4}	$565/10000$
$\ell_{\rm max}$	$Q_{\rm WMAP}$	$f(Q_{\rm MC} < Q_{\rm WMAP})$
8	7.61×10^{-7}	$107/10000$
7	3.72×10^{-5}	$394/10000$
6	3.62×10^{-3}	$2079/10000$