Mysteries of the large-angle microwave sky

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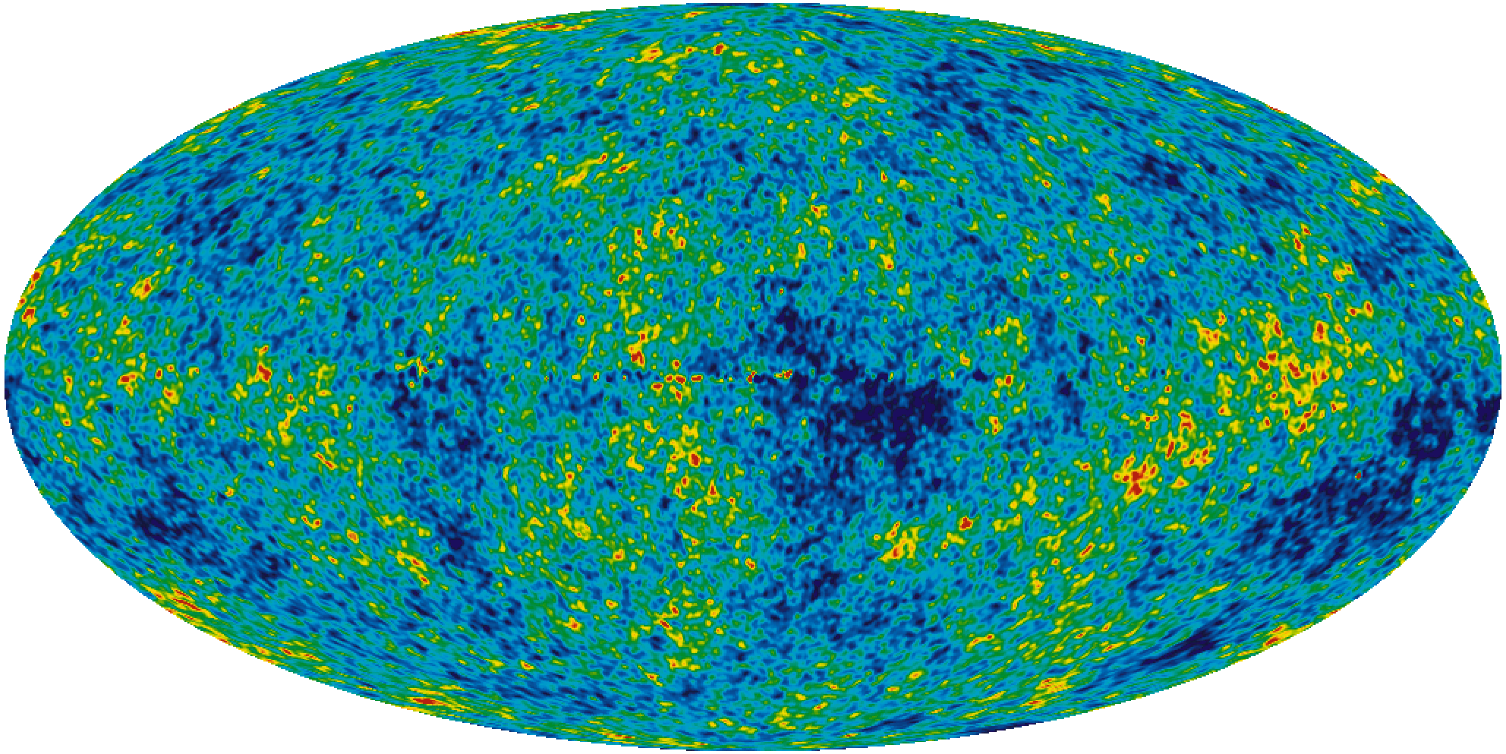
How does the universe look at largest observable scales?



ILC map, WMAP collaboration

Outline

Motivation and overview of concurrent findings

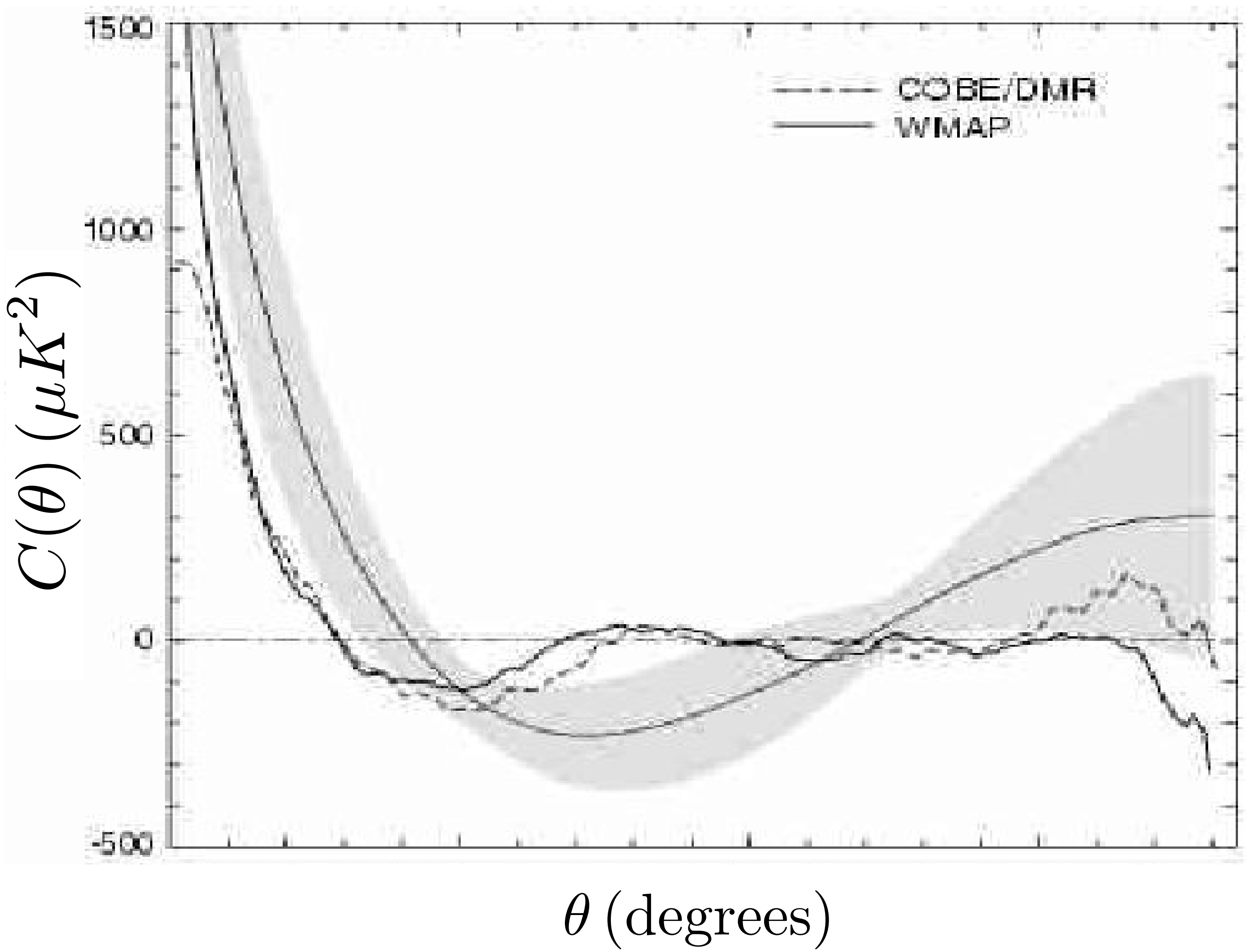
Multipole Vectors

Large-scale alignments

Various explanations

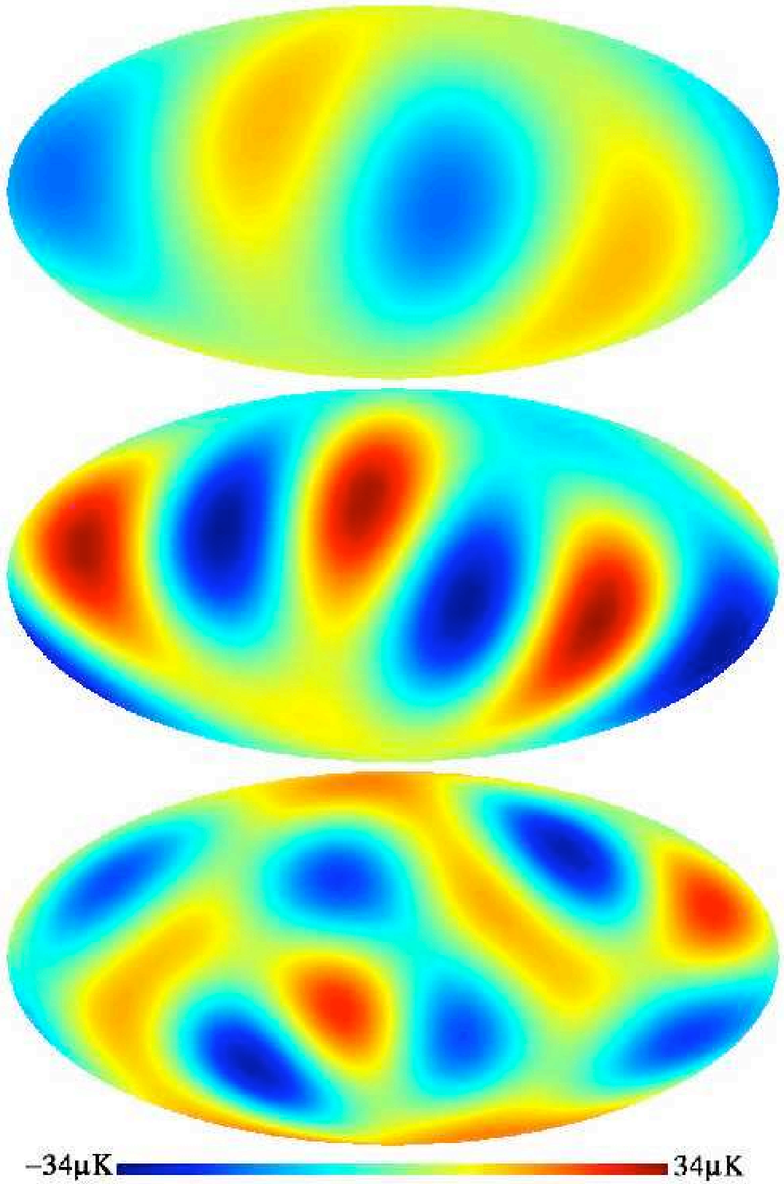
Future prospects and conclusions

Low power on large scales



Spergel et al 2003: 0.2% of sims have less power at angles >60 deg

l=2, 3 are aligned and planar



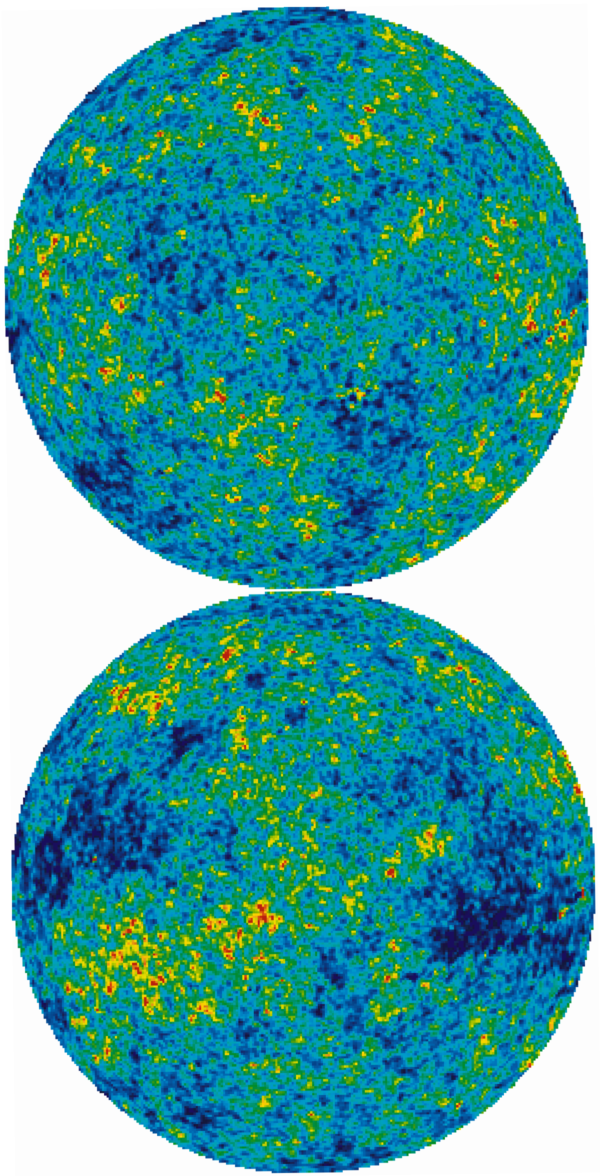
$$\hat{L}_\ell^2 \equiv \frac{\sum_{m=-\ell}^{\ell} m^2 \left|a_{\ell m}\right|^2}{\ell^2 \sum_{m=-\ell}^{\ell} \left|a_{\ell m}\right|^2}$$

l=3 is planar: P~1/20

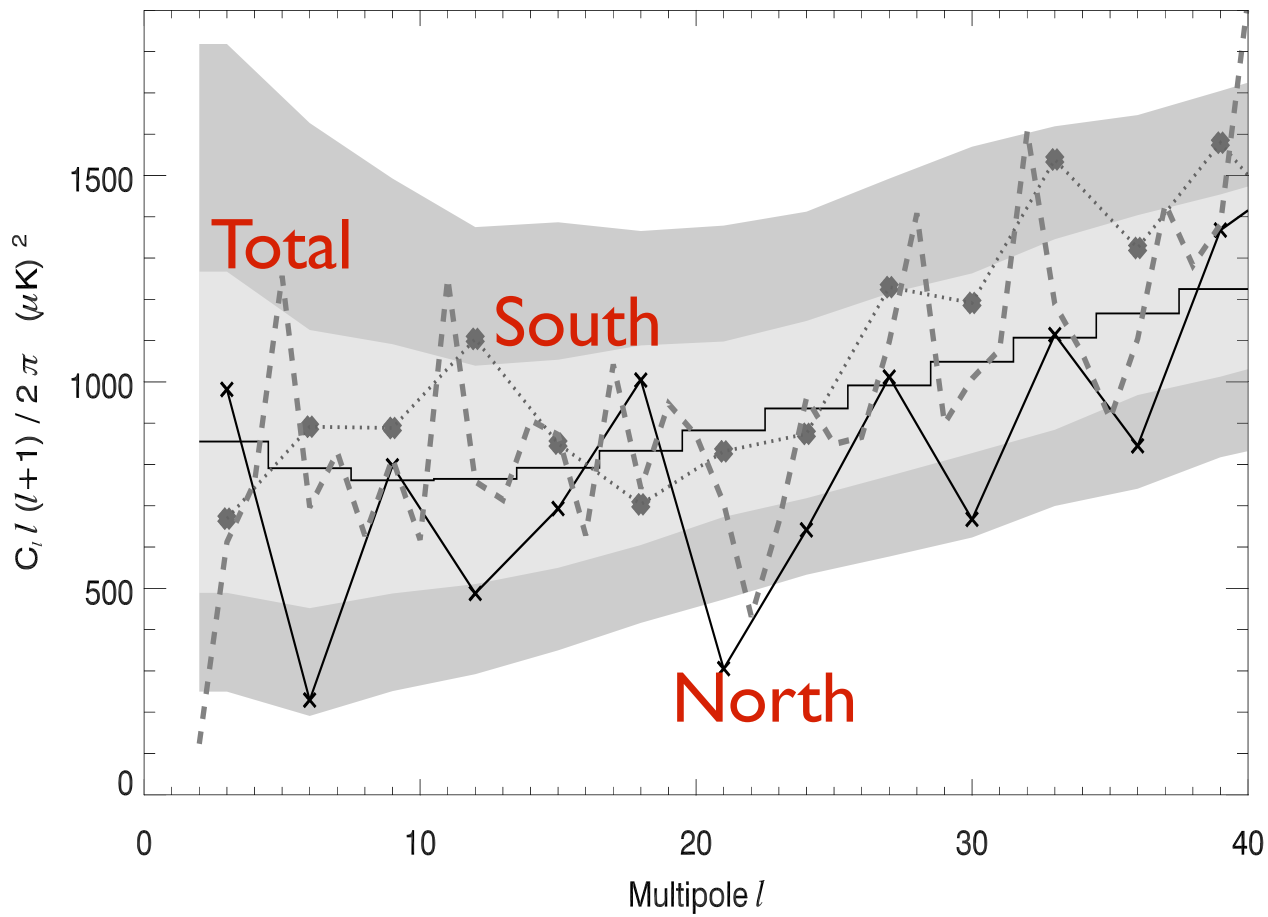
l=2,3 is are aligned: P~1/60

de Oliveira-Costa, Tegmark, Zaldarriaga & Hamilton 2004

N/S power asymmetry



South (ecliptic) has more power than north



Eriksen et al 2004;
Hansen, Banday and Gorski 2004

Multipole vectors!

Spherical Harmonics:

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

Multipole Vectors:

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

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

Lth multipole <=> L (headless) vectors, plus a constant

Copi, Huterer & Starkman 2003; http://www.phys.cwru.edu/projects/mpvectors/

Another view

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

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

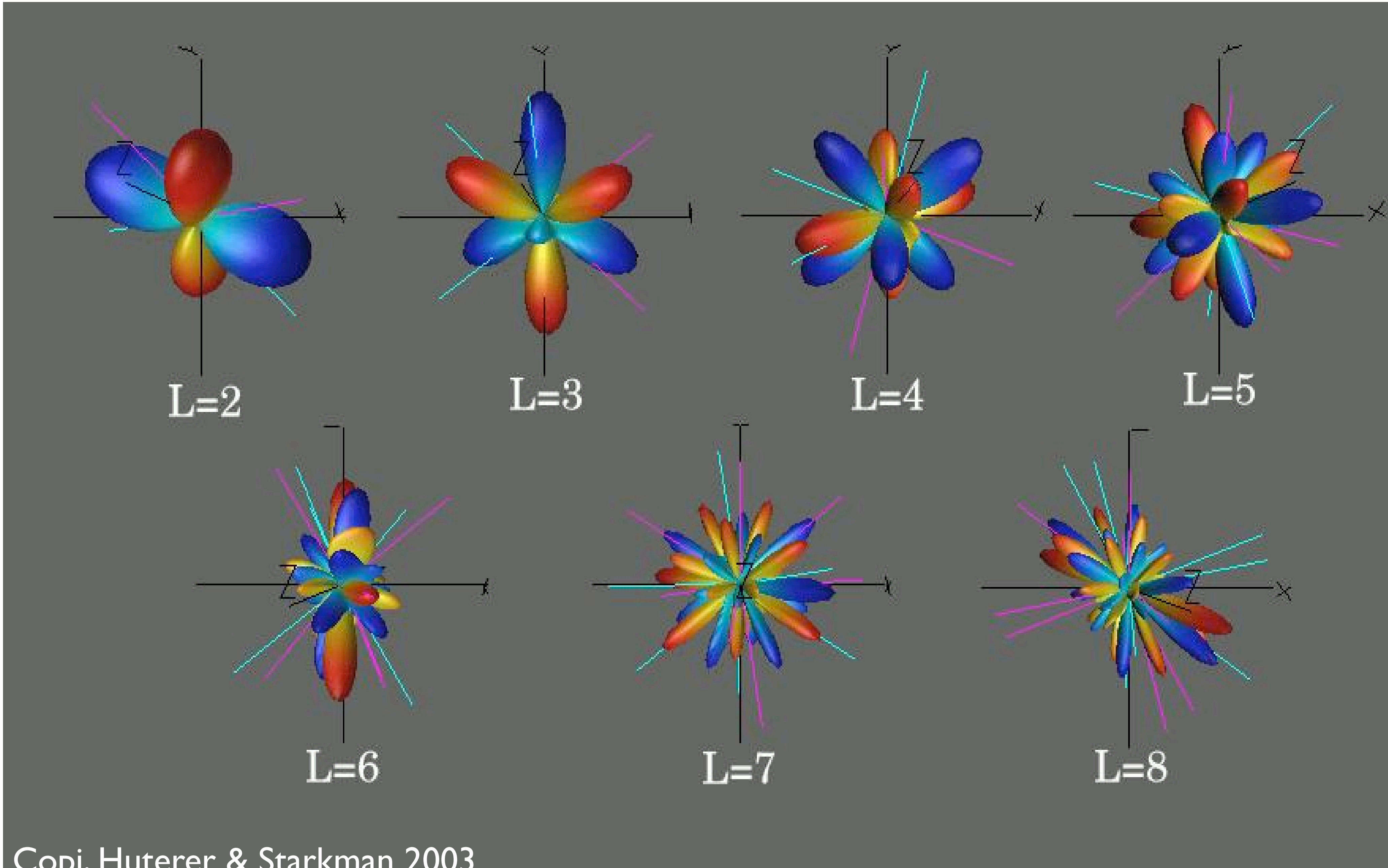
where R is a homogeneous polynomial of degree $\ell - 2$. The decomposition is unique up to reordering and rescaling the linear factors.

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

Multipole vectors of our sky



Maxwell's multipole vectors

Potential of:

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

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

....

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

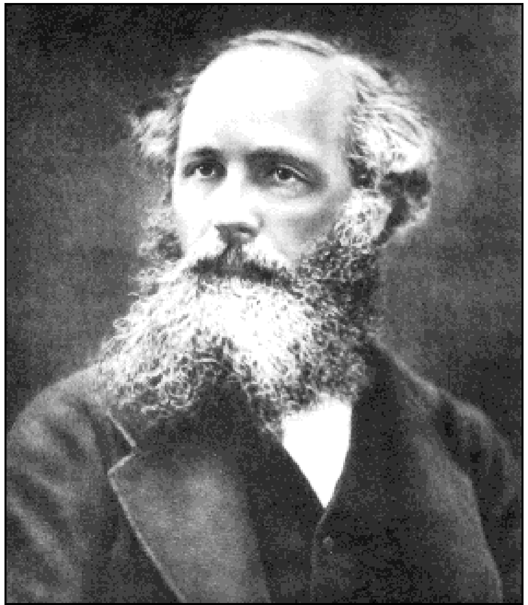
$\mathbf{v_1} \ldots \mathbf{v}_\ell$ are the multipole vectors

Maxwell 1892; Weeks 2004

Why multipole vectors?

- A different representation of the CMB sky than the spherical harmonics, related highly non-linearly
- Ideally suited for looking for planarity/directionality
- Many interesting properties, theorems (Katz & Weeks 2004, Weeks 2005, Lachieze-Rey 2004, Dennis 2005...)
- (Reviewed in Copi, Huterer, Schwarz & Starkman astro-ph/0508047)

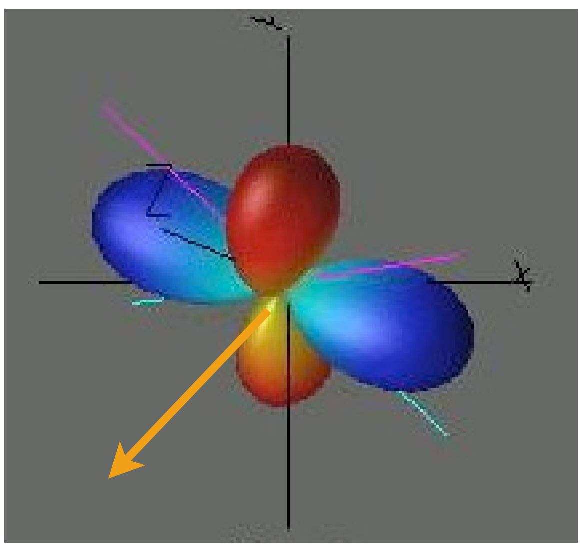
Also:
discussed by J.C. Maxwell in his "Treatise on Electricity and Magnetism" in 1892!!



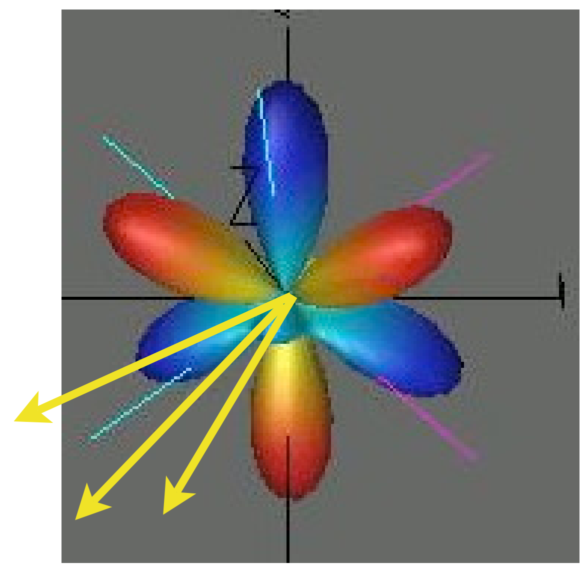
Normals to multipole vectors

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

"oriented areas"

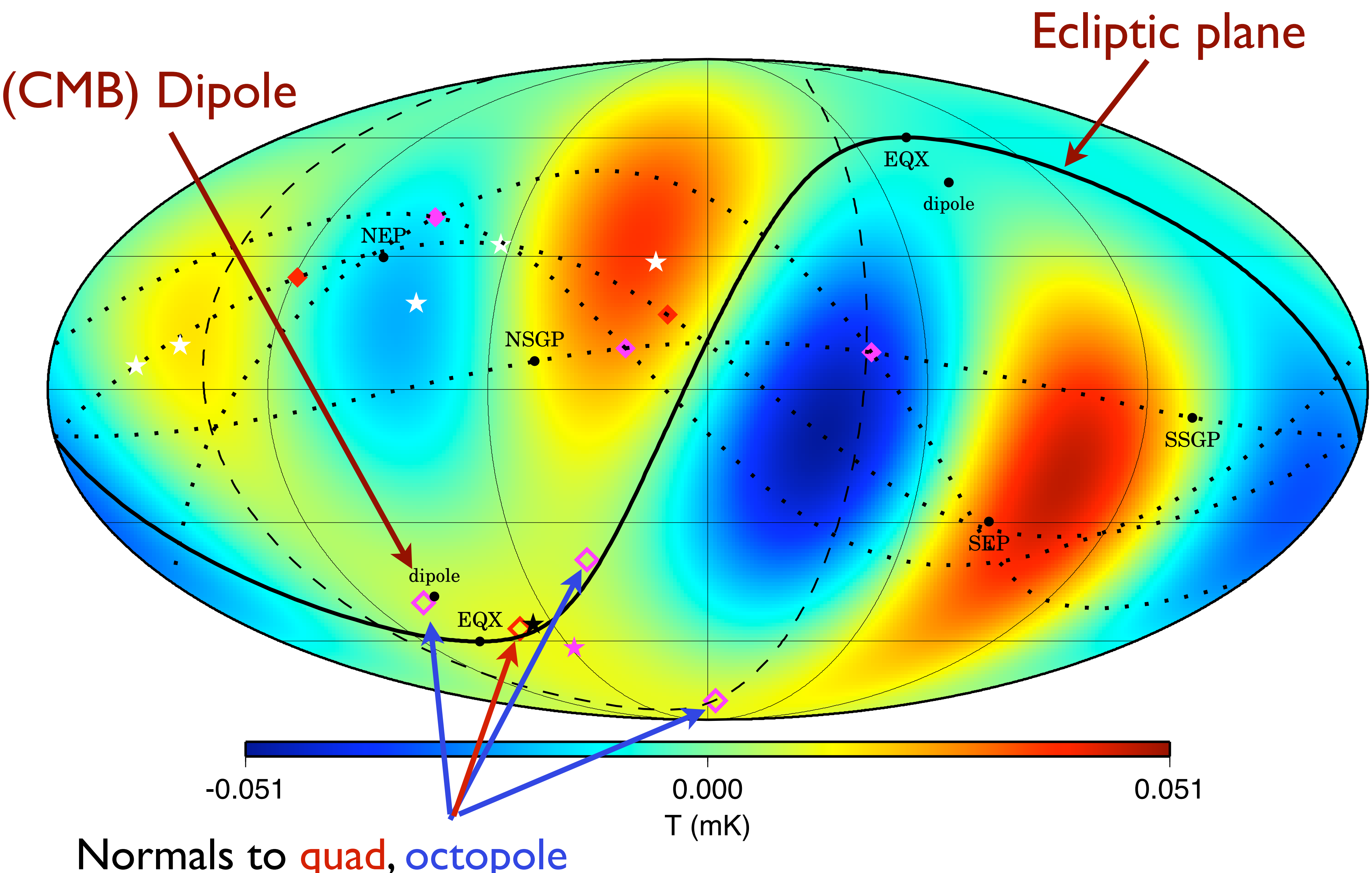


L=2



L=3

L=2+3 alignments

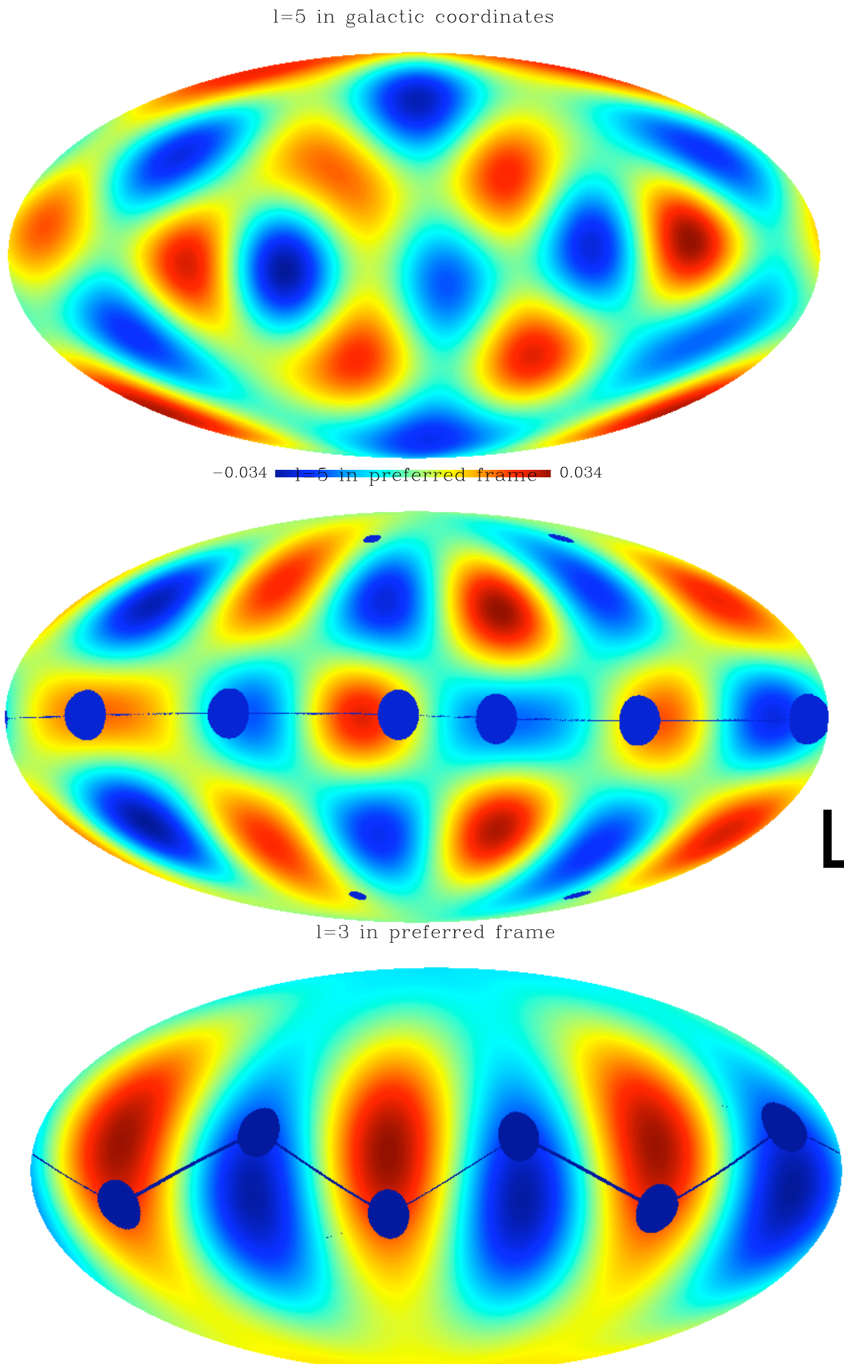


Schwarz, Starkman, Huterer & Copi 2004

Alignments found at L=2, 3

- The four area vectors are mutually close (99.0-99.9% CL)
- They lie close to ecliptic plane (98%-99% CL)
- They lie close to equinoxes and dipole (99.8% CL)
- Ecliptic plane carefully separates weak from strong extrema (93%-99.6% CL)

Axis of evil: (b, l)=(60, -100)



L=5, gal frame

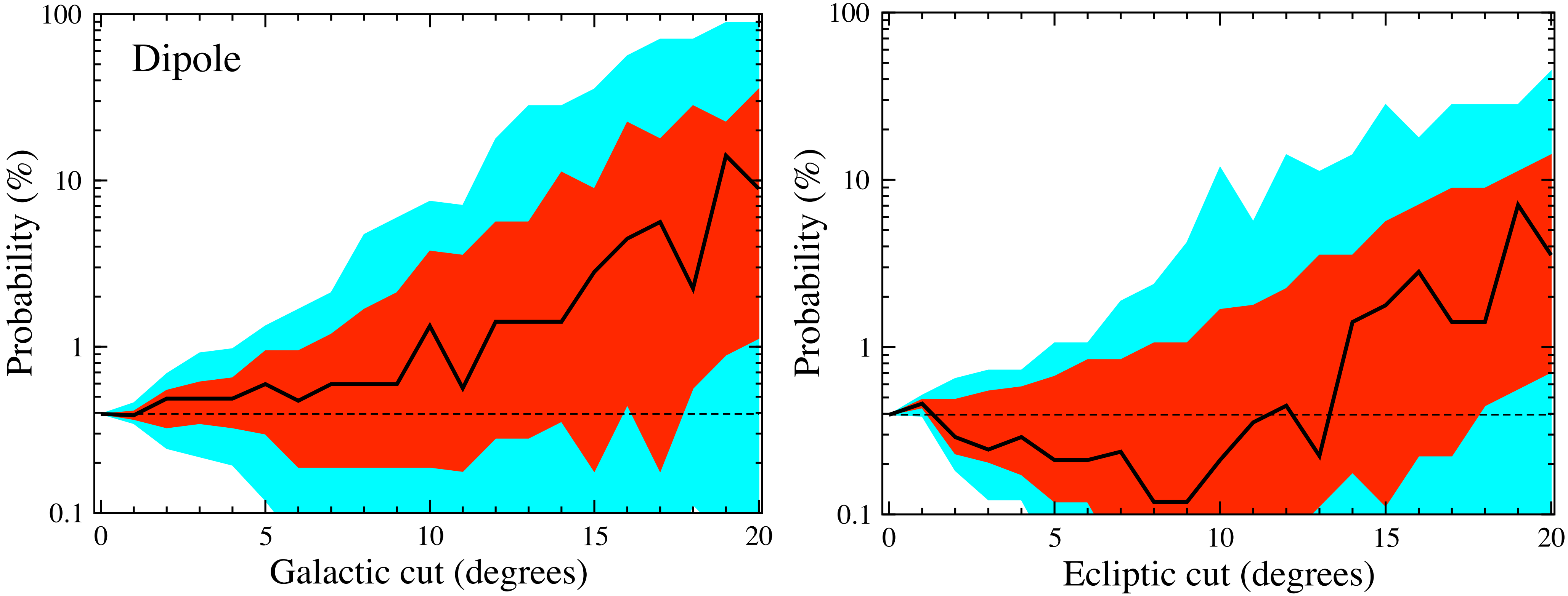
Preferred-axis vectors at 2<=L<=5 are unusually close (99.9% CL)

L=5, AOE frame

L=3, AOE frame

Land & Magueijo 2005

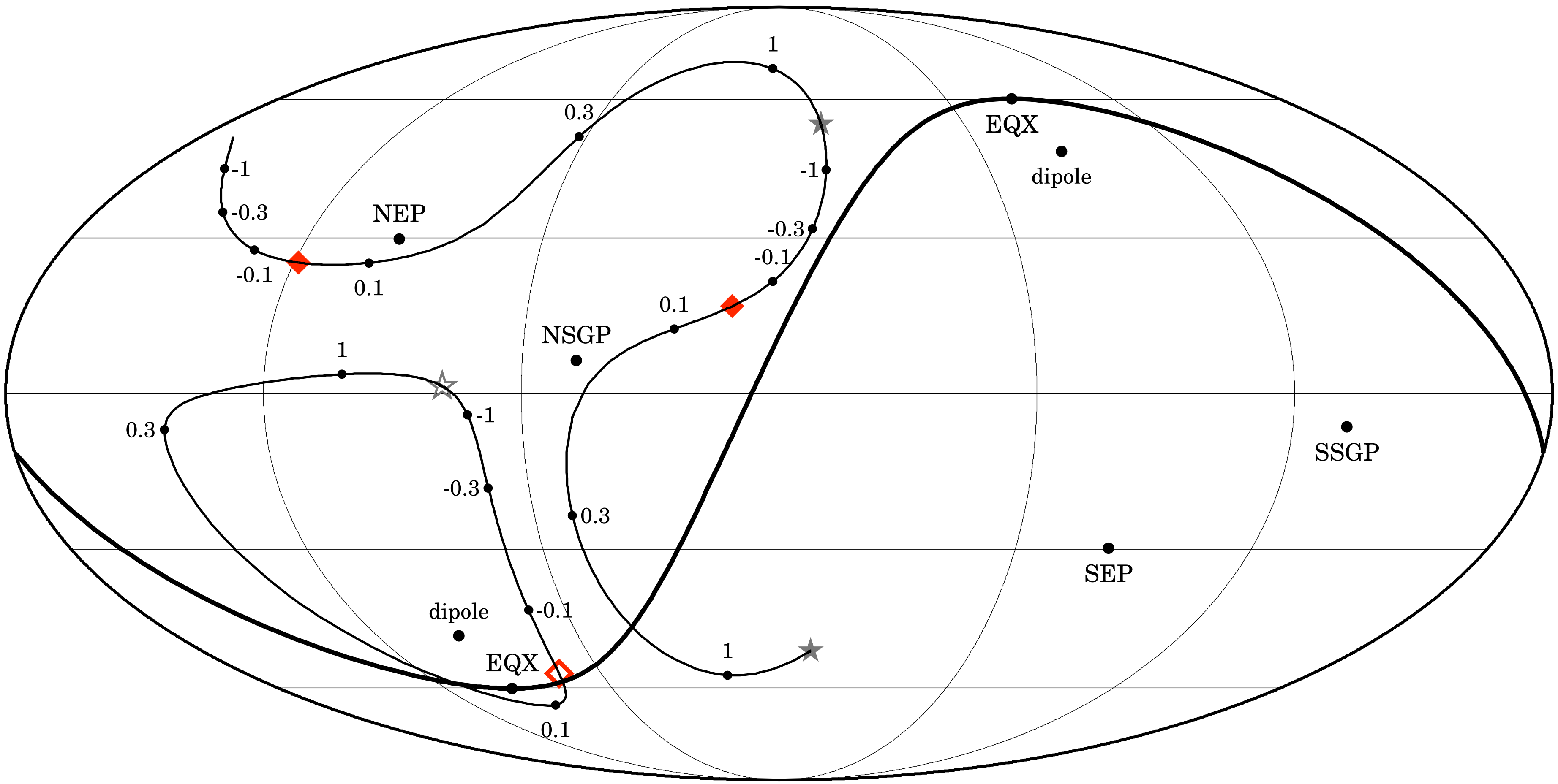
Systematic checks: sky cut



Errors increase sharply, but results consistent with full-sky result

Copi, Huterer, Schwarz & Starkman 2006

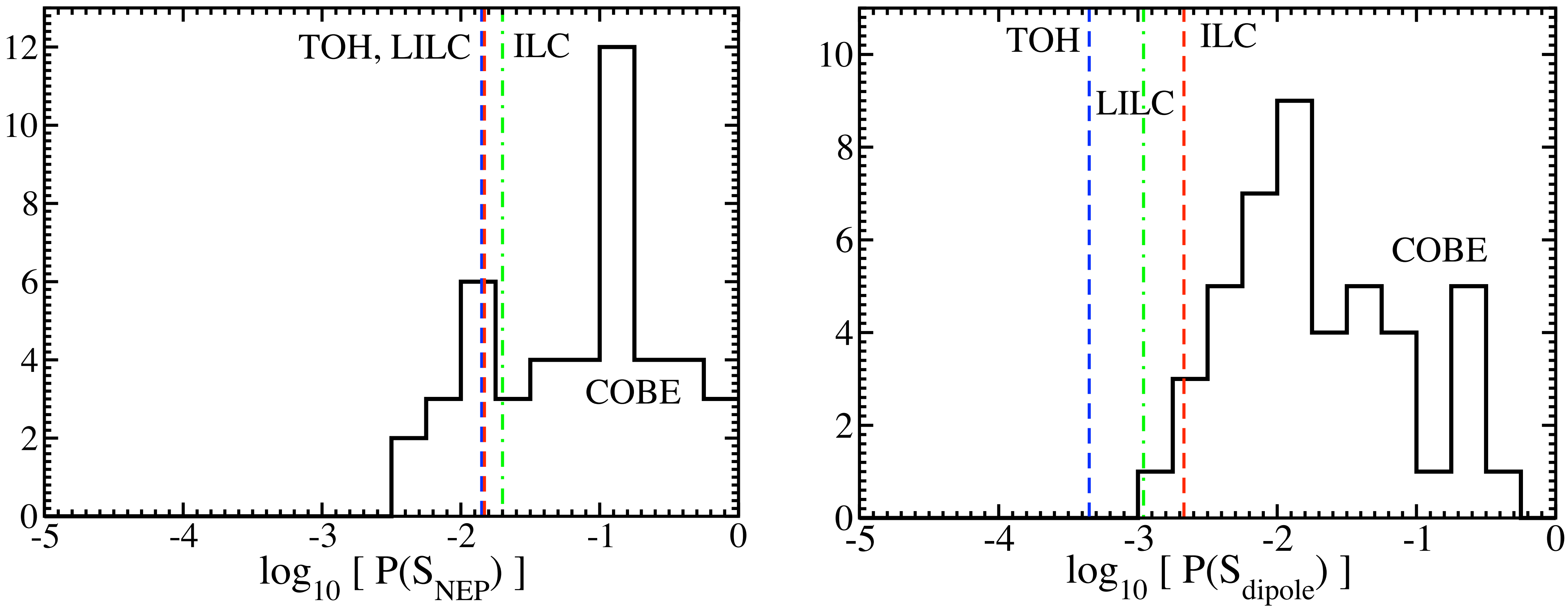
Systematic checks: foreground missubtraction



Adding (known) foregrounds leads to galactic, and not ecliptic, alignments

What about COBE?

Using COBE MCMC maps from Wandelt, Larson & Lakshminarayanan 2003



Copi, Huterer, Schwarz & Starkman 2006

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!

Example: non-linear detector

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).

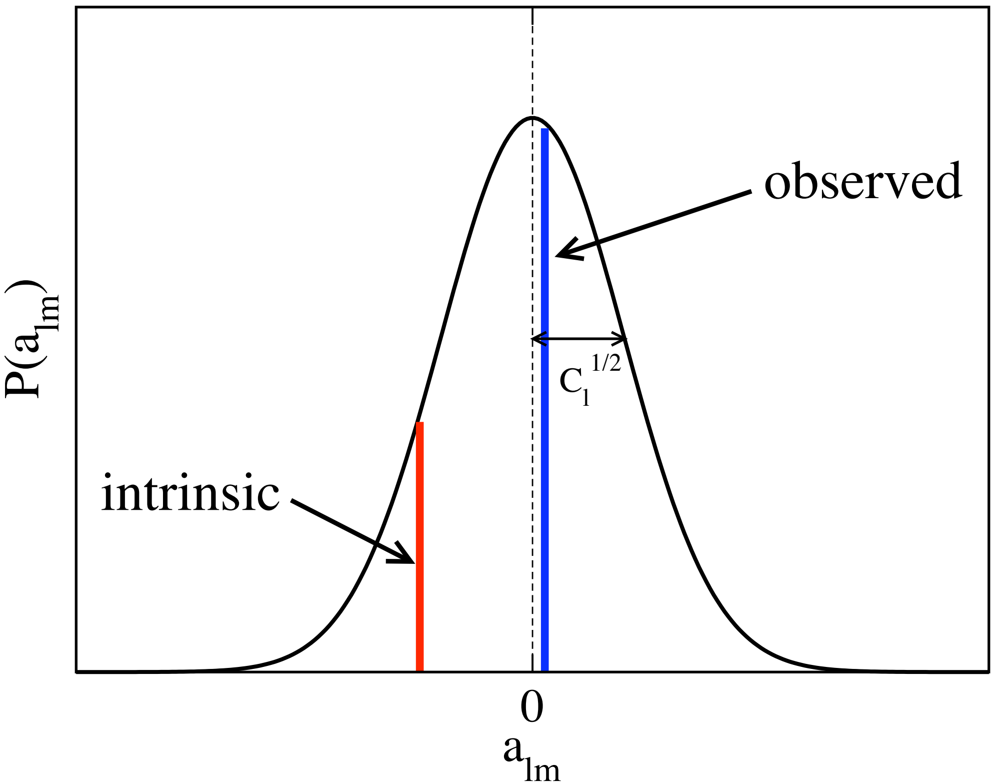
Gordon, Hu, Huterer & Crawford 2006

Additive schemes "don't work"

$$\hat{T}(\hat{\mathbf{n}}) = T_{\rm intr}(\hat{\mathbf{n}}) + T_{\rm extra}(\hat{\mathbf{n}})$$

Double (likelihood) penalty:

- Intrinsic sky is less likely than observed
- Requires a chance cancellation



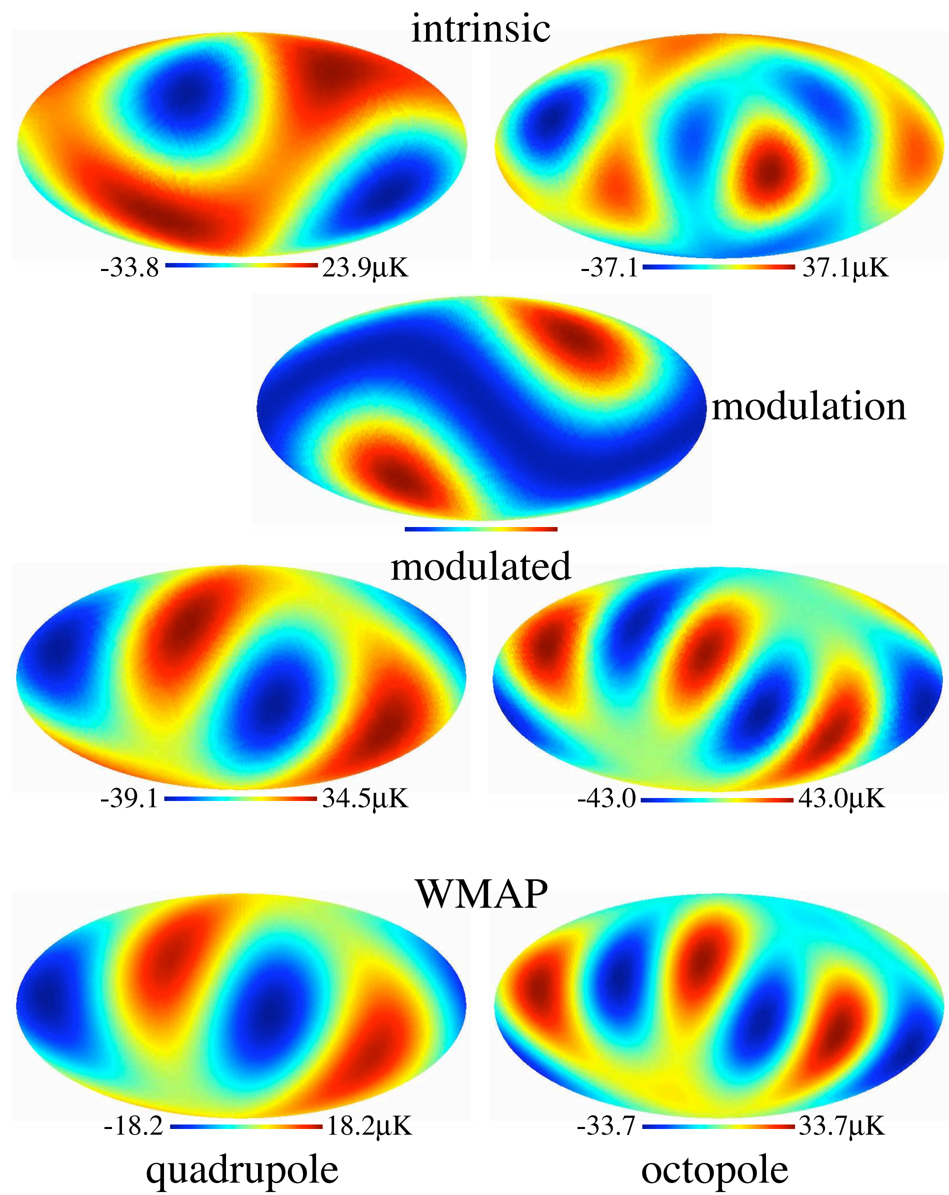
True for all additive schemes:
Solar System contamination,
Bianchi models,
etc

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

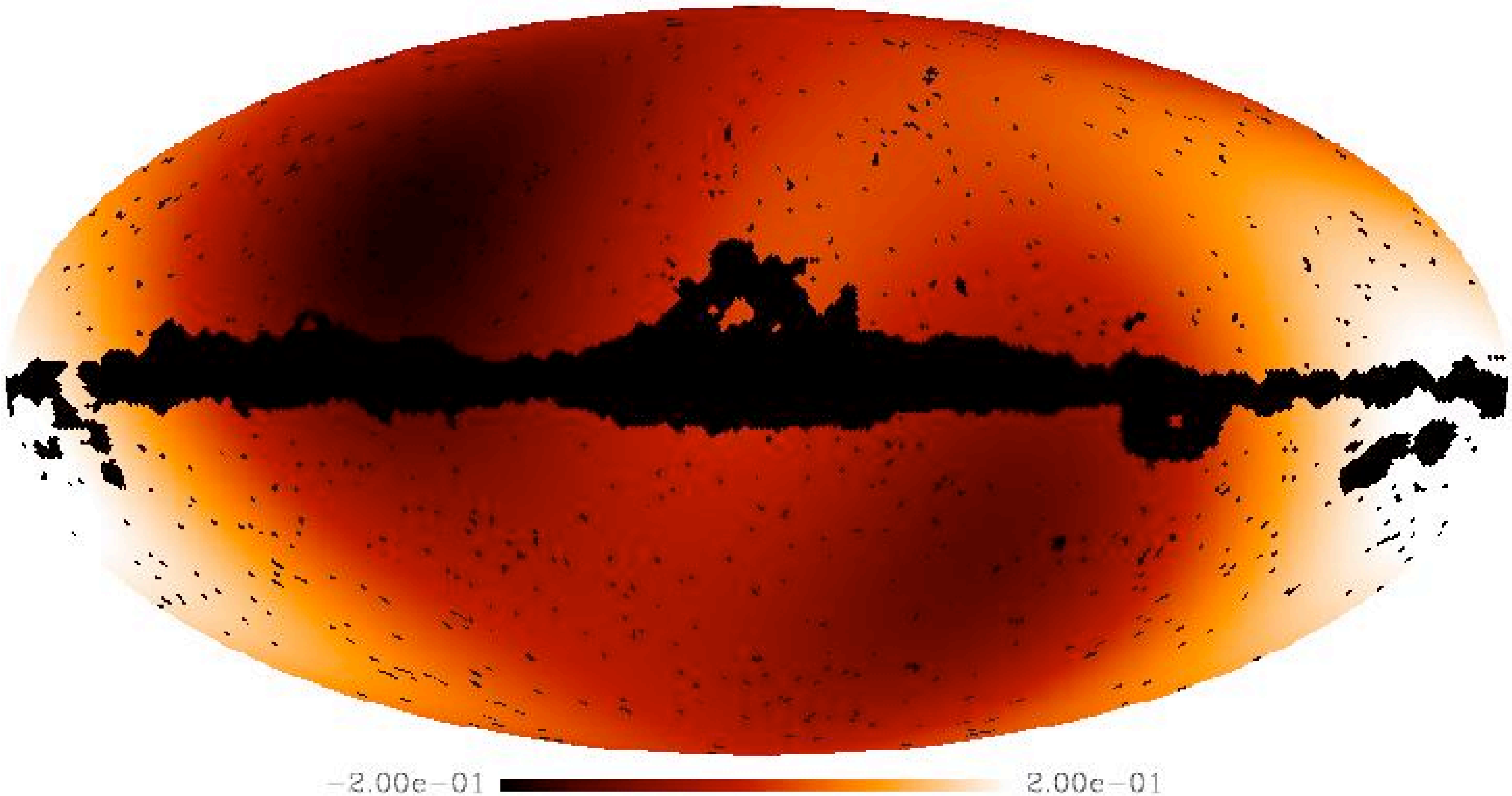
Multiplicative modulation can work

$$\hat{T}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}})\,[1 + w(\hat{\mathbf{n}})]$$

$w(\hat{\mathbf{n}}) \propto Y_{20}(\hat{\mathbf{n}})$ example

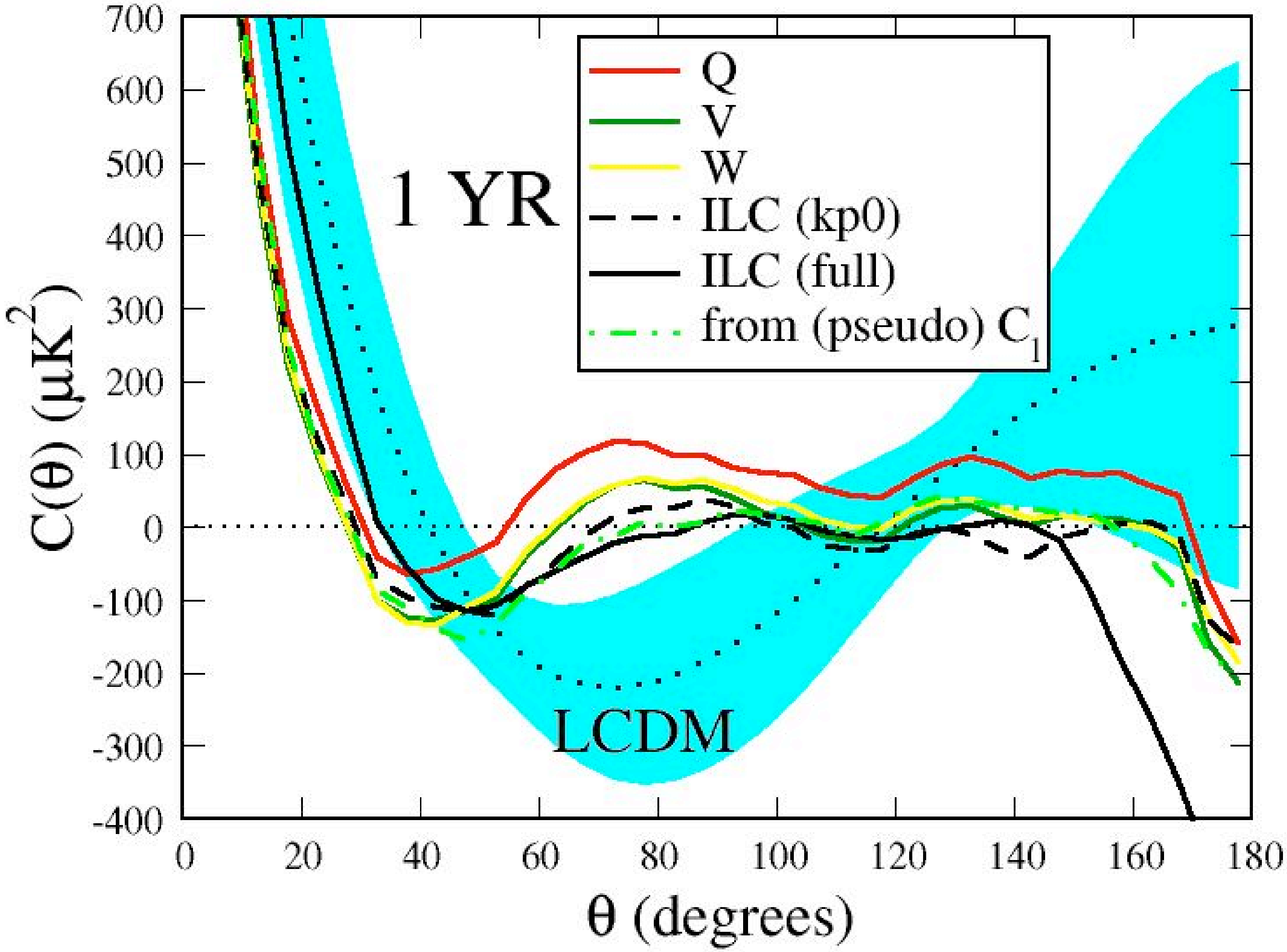


Best-fit L=1,2 multiplicative modulation from WMAP 123



Spergel et al, 2006

Low power on large scales



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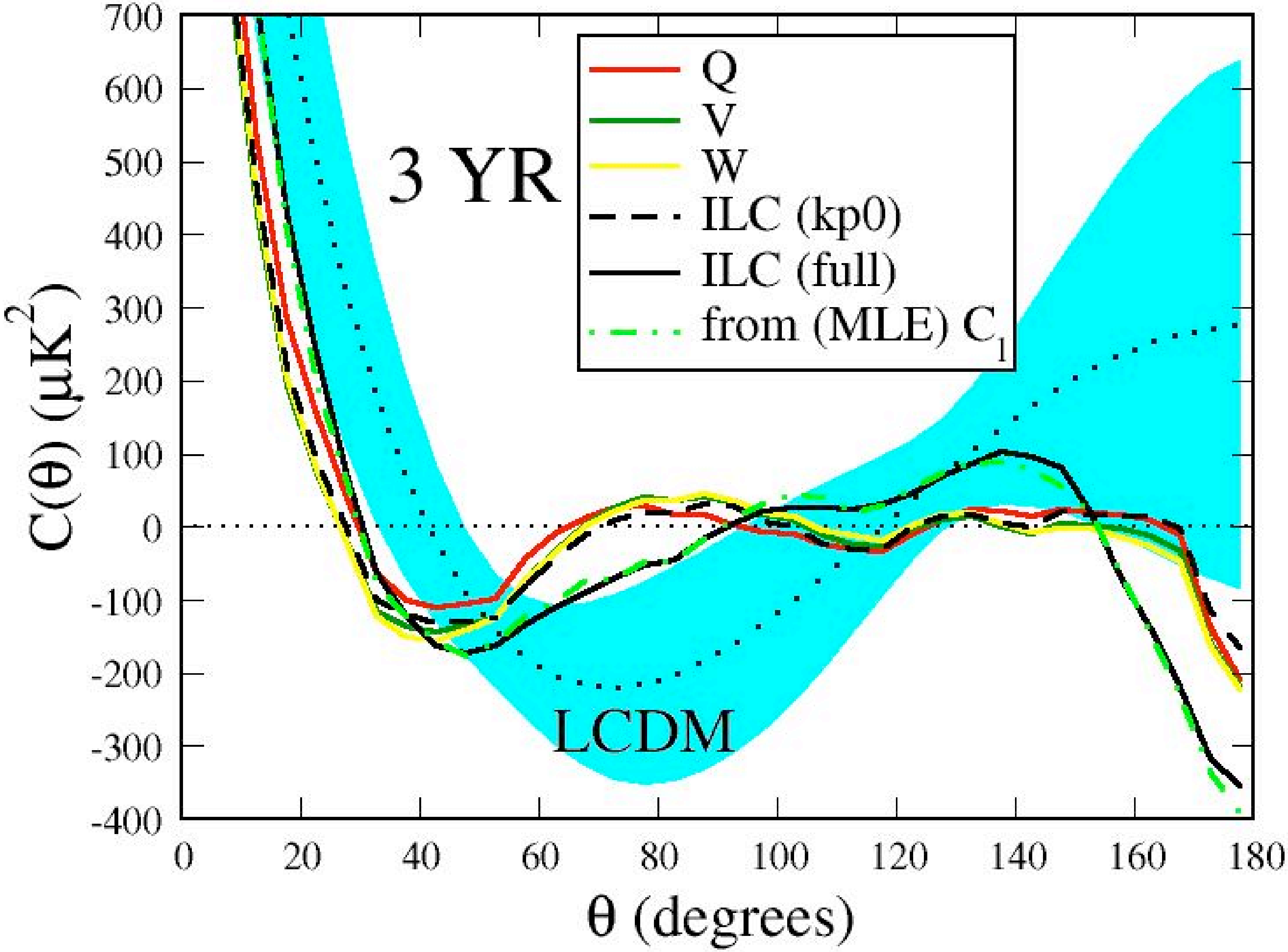
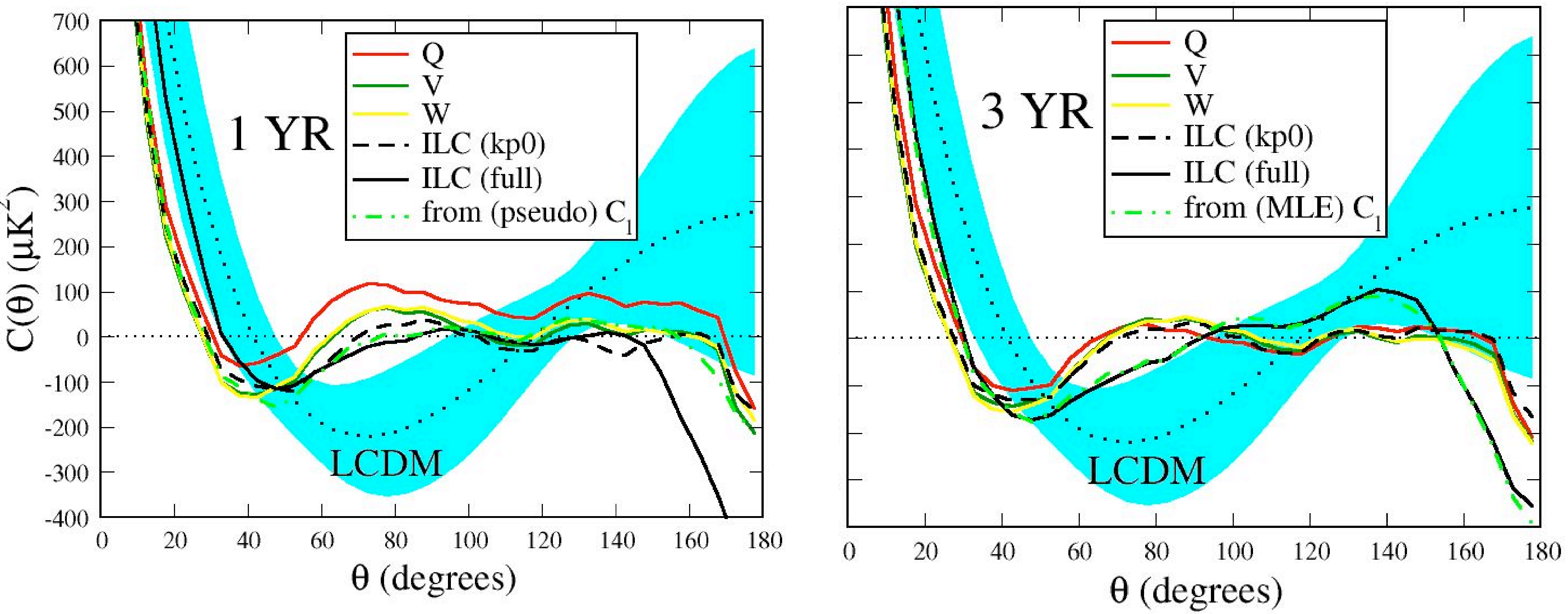
Copi, Huterer, Schwarz & Starkman astro-ph/0605135



Copi, Huterer, Schwarz & Starkman astro-ph/0605135



1 YR
3 YR
Q
V
W
ILC (kp0)
ILC (full)
from (pseudo) C_l
from (MLE) C_l
LCDM
C(θ) (μK^2)
θ (degrees)
700
600
500
400
300
200
100
0
-100
-200
-300
-400
0
20
40
60
80
100
120
140
160
180

Future data and prospects

- WMAP is probably as good as it will get on large scales (as seen in year 1 vs year 123)
- Nevertheless, understanding of fine details is improving and is crucial.
- Planck will provide a great check of these measurements (very different experiment)
- Polarization maps with relatively high S/N, when eventually available, will provide even more leverage.
- The level of expected polarization "alignments" is model dependent
- In principle, can map out largest-scale fluctuations from wide-field, large-volume large-scale structure surveys (e.g. LSST; Zhan, Knox et al 2005)

Conclusions

- Alignments with the ecliptic plane and/or dipole are sufficiently significant to be very interesting despite the a posteriori nature of these observations
- No convincing explanations so far
- Other observed anomalies (N/S asymmetry, L=4-6 etc) very intriguing and possibly related
- Multipole vectors are a great tool to study alignments and directionalities in the CMB
- Pixel-space C(theta) low at 99.97% CL - even more than in year 1

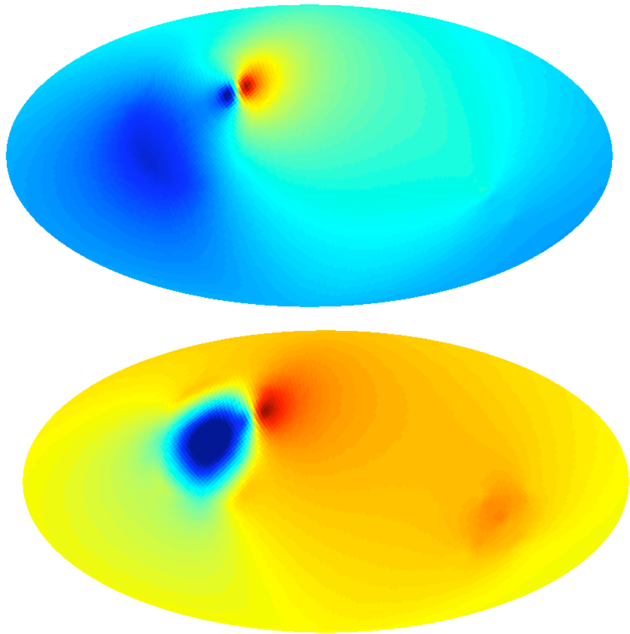
Example: lensing of the dipole

Small scale anisotropy is induced by the "moving cluster effect" (or, nonlinear ISW effect)

Picks up the dipole direction "for free"; itself has a dipolar pattern around the center of mass

Sadly, it's way too small:

$$\frac{\Delta T}{T} = 0.5\ \mu\mathrm{K}\ \left(\frac{v_\perp}{300\ \mathrm{km\ sec}^{-1}}\right)\left(\frac{M}{10^{16}\ M_{\mathrm{sun}}}\right)\left(\frac{R}{10\ \mathrm{Mpc}}\right)^{-1}$$



Vale astro-ph/0509039; Cooray & Seto astro-ph/0510137