Mysteries of the large-angle microwave sky

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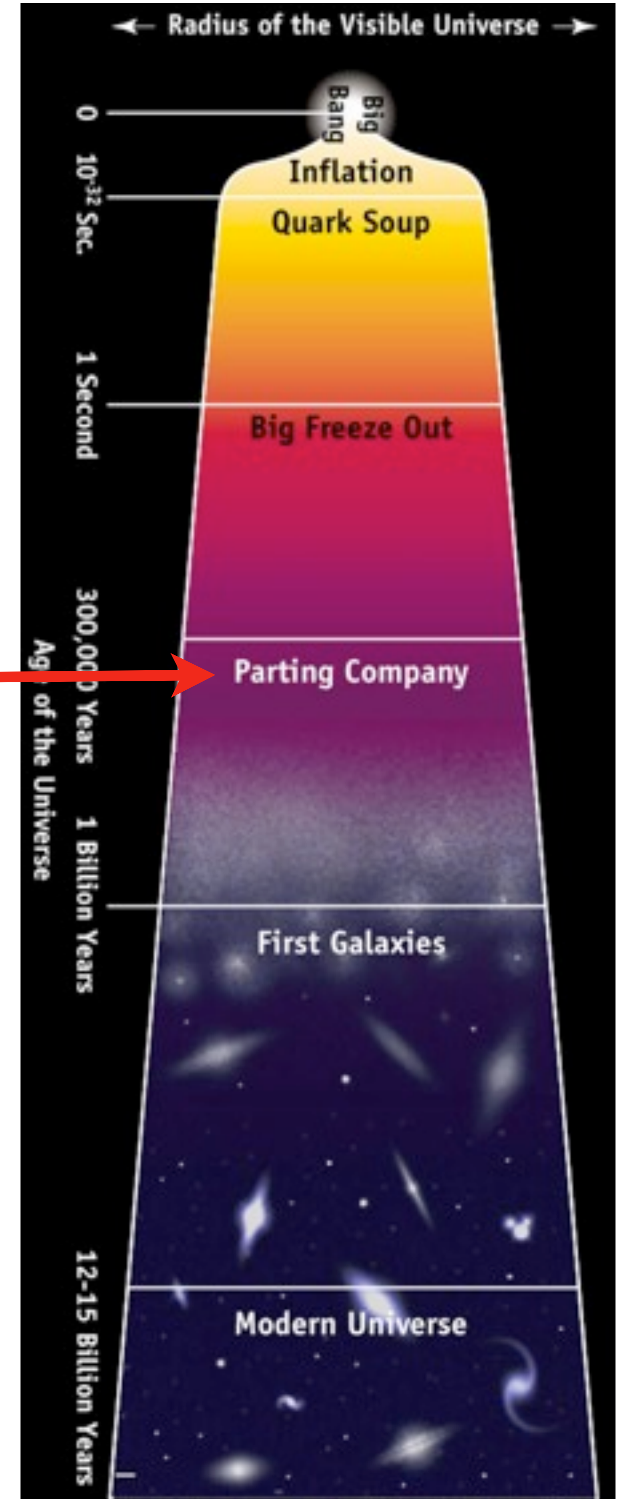
Universe becomes transparent (t=380,000 yrs)

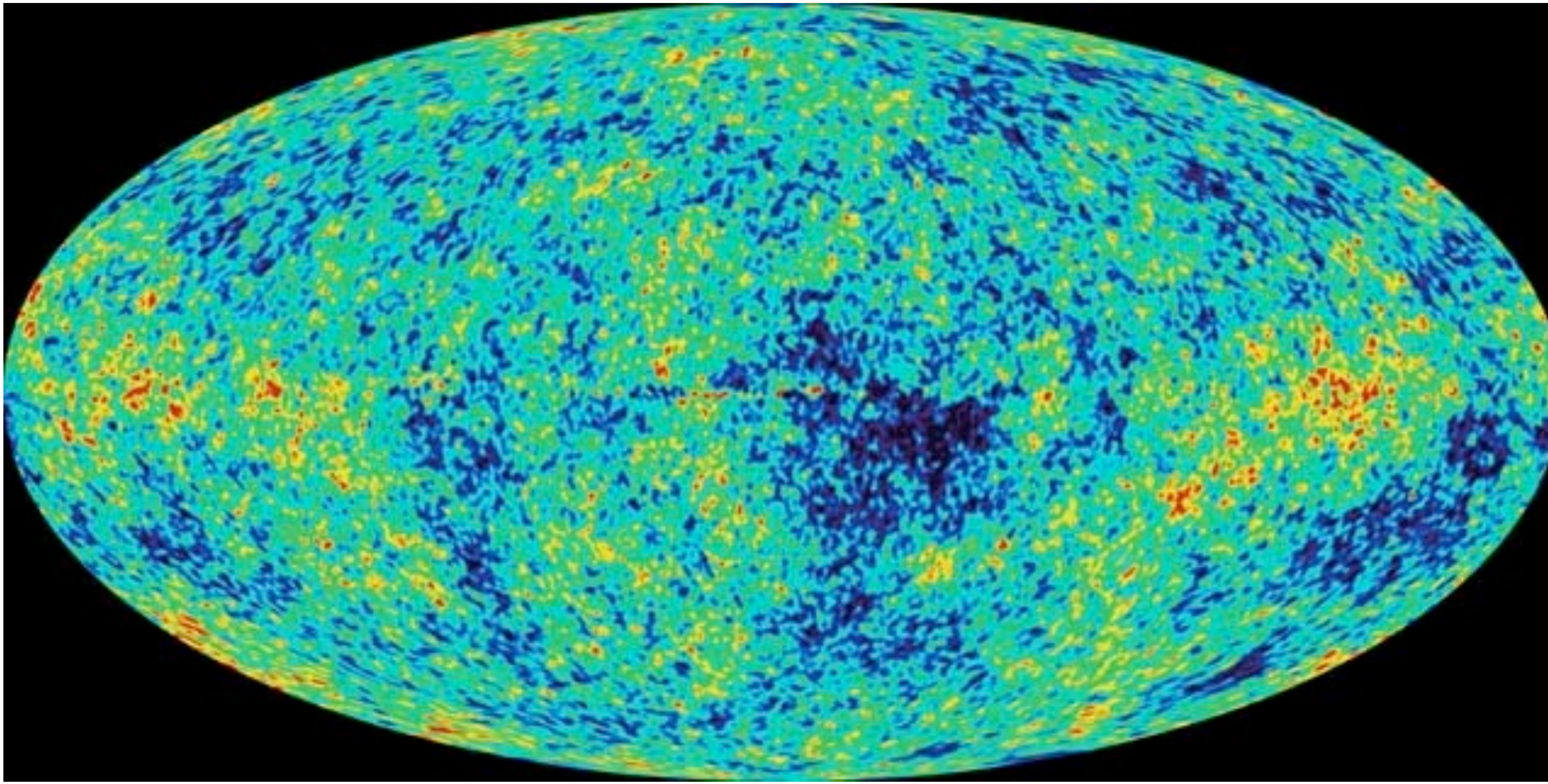
- Radiation finally free to propagate - universe has become cool enough for atoms to form
- The Cosmic Microwave Background radiation we observe has been released at this time
- Temp = 3000 Kelvin (2.725 Kelvin today)
- Uniform to one part in 100,000



T=2.725 Kelvin

As seen by Penzias & Wilson (1963)

Fluctuations 1 part in 100,000 (of 2.725 Kelvin)



As seen by Wilkinson Microwave Anisotropy Probe (2003-present)

The CMB: The Surface of Last Scattering

- We are at the center of 'last scattering surface'
- We see the cold/hot spot pattern on the (microwave) sky

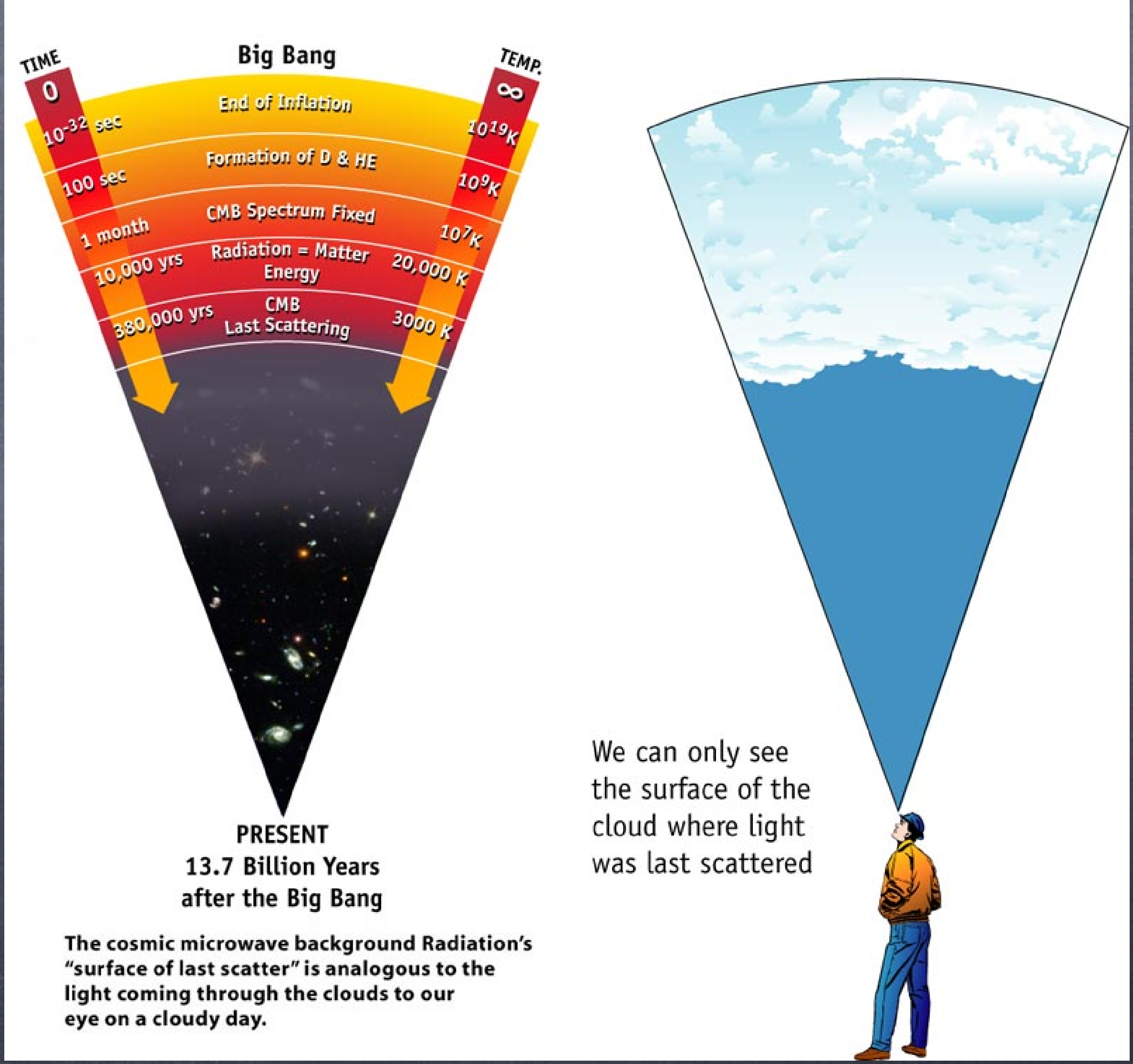
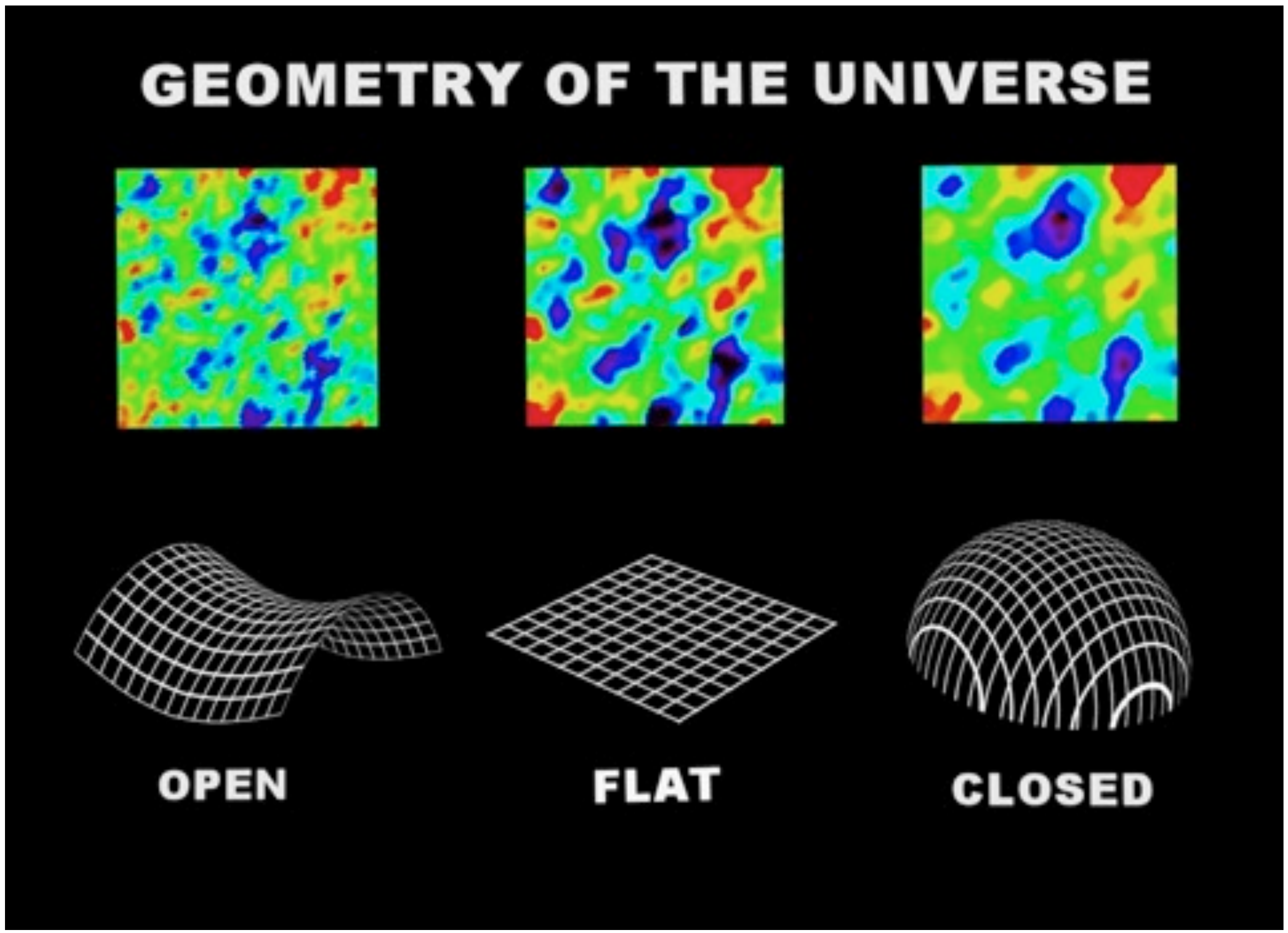
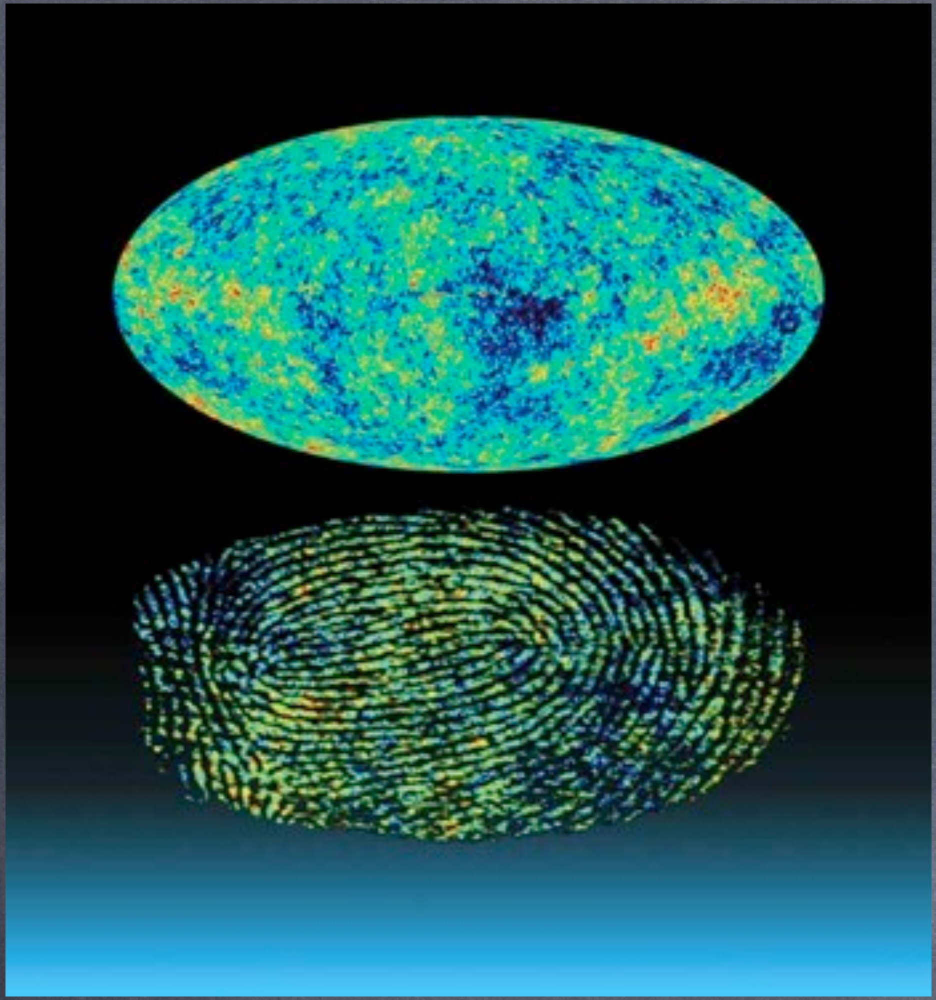


Image From http://map.gsfc.nasa.gov

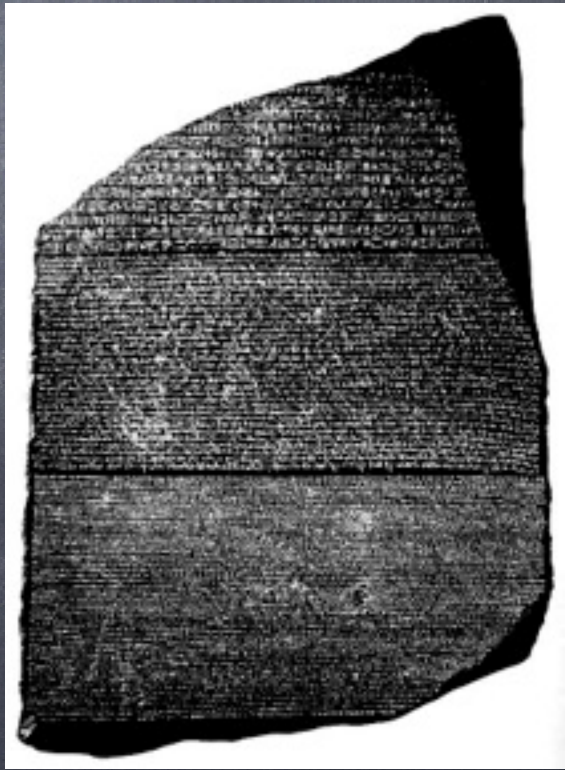
The CMB Spot Sizes Are A "Standard Ruler"





CMB Map provides a fingerprint of the cosmological model

A "Cosmological Rosetta Stone"



The cosmic Rosetta Stone

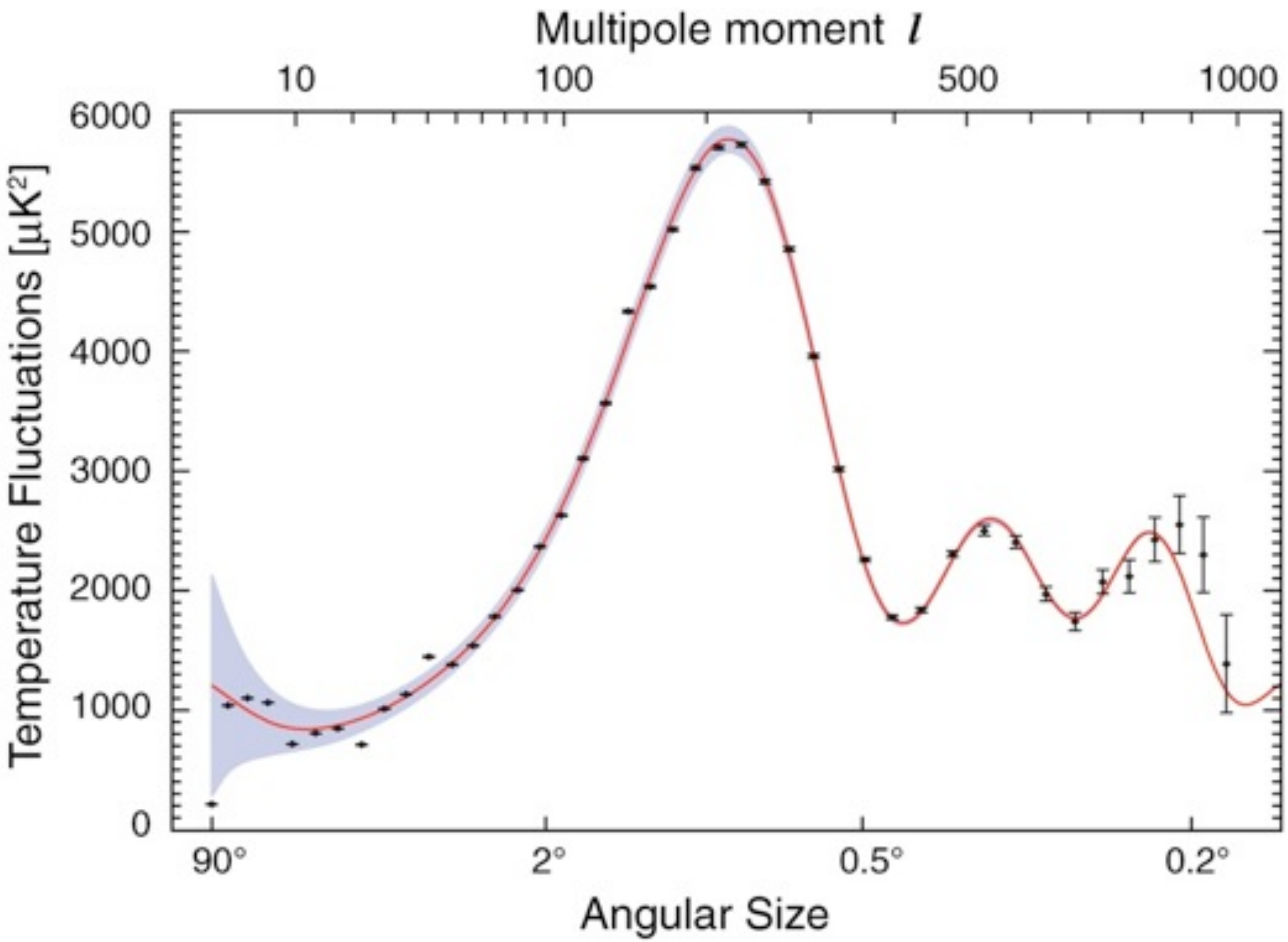


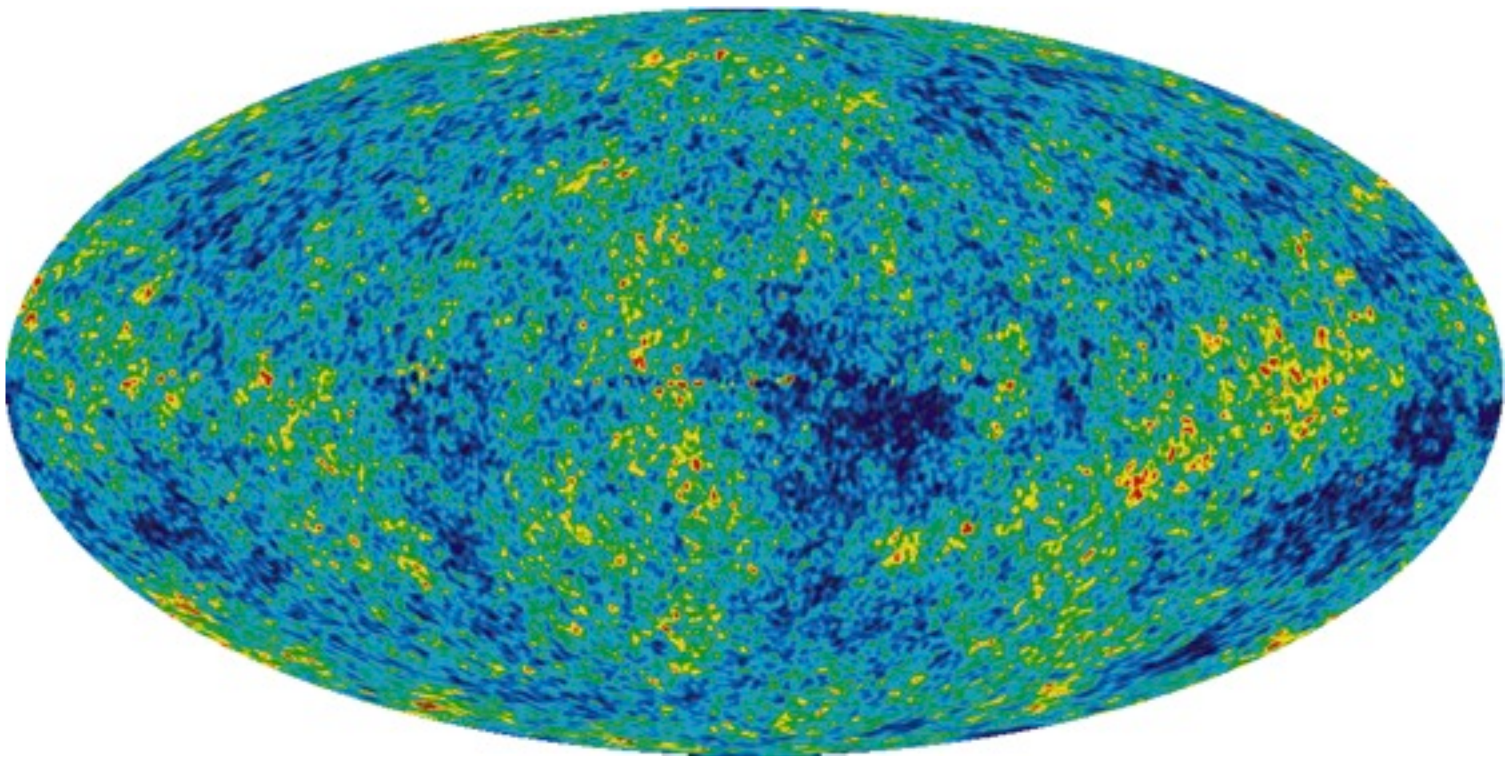
Image From http://map.gsfc.nasa.gov

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

Class	Parameter	*WMAP* 5-year ML[a]	*WMAP*+BAO+SN ML	*WMAP* 5-year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.263	2.273 ± 0.062	2.265 ± 0.059
	$\Omega_c h^2$	0.1081	0.1136	0.1099 ± 0.0062	0.1143 ± 0.0034
	Ω_Λ	0.751	0.724	0.742 ± 0.030	0.721 ± 0.015
	n_s	0.961	0.961	$0.963^{+0.014}_{-0.015}$	$0.960^{+0.014}_{-0.013}$
	τ	0.089	0.080	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	2.41×10^{-9}	2.42×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.457^{+0.092}_{-0.093}) \times 10^{-9}$
Derived	σ_8	0.787	0.811	0.796 ± 0.036	0.817 ± 0.026
	H_0	72.4 km/s/Mpc	70.3 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.1 ± 1.3 km/s/Mpc
	Ω_b	0.0432	0.0458	0.0441 ± 0.0030	0.0462 ± 0.0015
	Ω_c	0.206	0.230	0.214 ± 0.027	0.233 ± 0.013
	$\Omega_m h^2$	0.1308	0.1363	0.1326 ± 0.0063	0.1369 ± 0.0037
	$z_{\rm reion}{}^f$	11.2	10.5	11.0 ± 1.4	10.8 ± 1.4
	$t_0{}^g$	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.73 ± 0.12 Gyr

Section	Name	Type	*WMAP* 5-year	*WMAP*+BAO+SN
§ 3.2	Gravitational Wave[a]	No Running Ind.	$r < 0.43^b$	$r < 0.20$
§ 3.1.3	Running Index	No Grav. Wave	$-0.090 < dn_s/d\ln k < 0.019^c$	$-0.0728 < dn_s/d\ln k < 0.0087$
§ 3.4	Curvature[d]		$-0.063 < \Omega_k < 0.017^e$	$-0.0175 < \Omega_k < 0.0085^f$
	Curvature Radius[g]	Positive Curv.	$R_{\rm curv} > 12\ h^{-1}$Gpc	$R_{\rm curv} > 23\ h^{-1}$Gpc
		Negative Curv.	$R_{\rm curv} > 23\ h^{-1}$Gpc	$R_{\rm curv} > 33\ h^{-1}$Gpc
§ 3.5	Gaussianity	Local	$-9 < f_{NL}^{\rm local} < 111^h$	N/A
		Equilateral	$-151 < f_{NL}^{\rm equil} < 253^i$	N/A
§ 3.6	Adiabaticity	Axion	$\alpha_0 < 0.16^j$	$\alpha_0 < 0.067^k$
		Curvaton	$\alpha_{-1} < 0.011^l$	$\alpha_{-1} < 0.0037^m$
§ 4	Parity Violation	Chern-Simons[n]	$-5.9^\circ < \Delta\alpha < 2.4^\circ$	N/A
§ 5	Dark Energy	Constant w^o	$-1.37 < 1 + w < 0.32^p$	$-0.11 < 1 + w < 0.14$
		Evolving $w(z)^q$	N/A	$-0.38 < 1 + w_0 < 0.14^r$
§ 6.1	Neutrino Mass[s]		$\sum m_\nu < 1.3$ eV[t]	$\sum m_\nu < 0.61$ eV[u]
§ 6.2	Neutrino Species		$N_{\rm eff} > 2.3^v$	$N_{\rm eff} = 4.4 \pm 1.5^w$ (68%)

How does the universe look at largest observable scales?



ILC map, WMAP collaboration

Outline

Motivation and overview of concurrent findings

Multipole Vectors

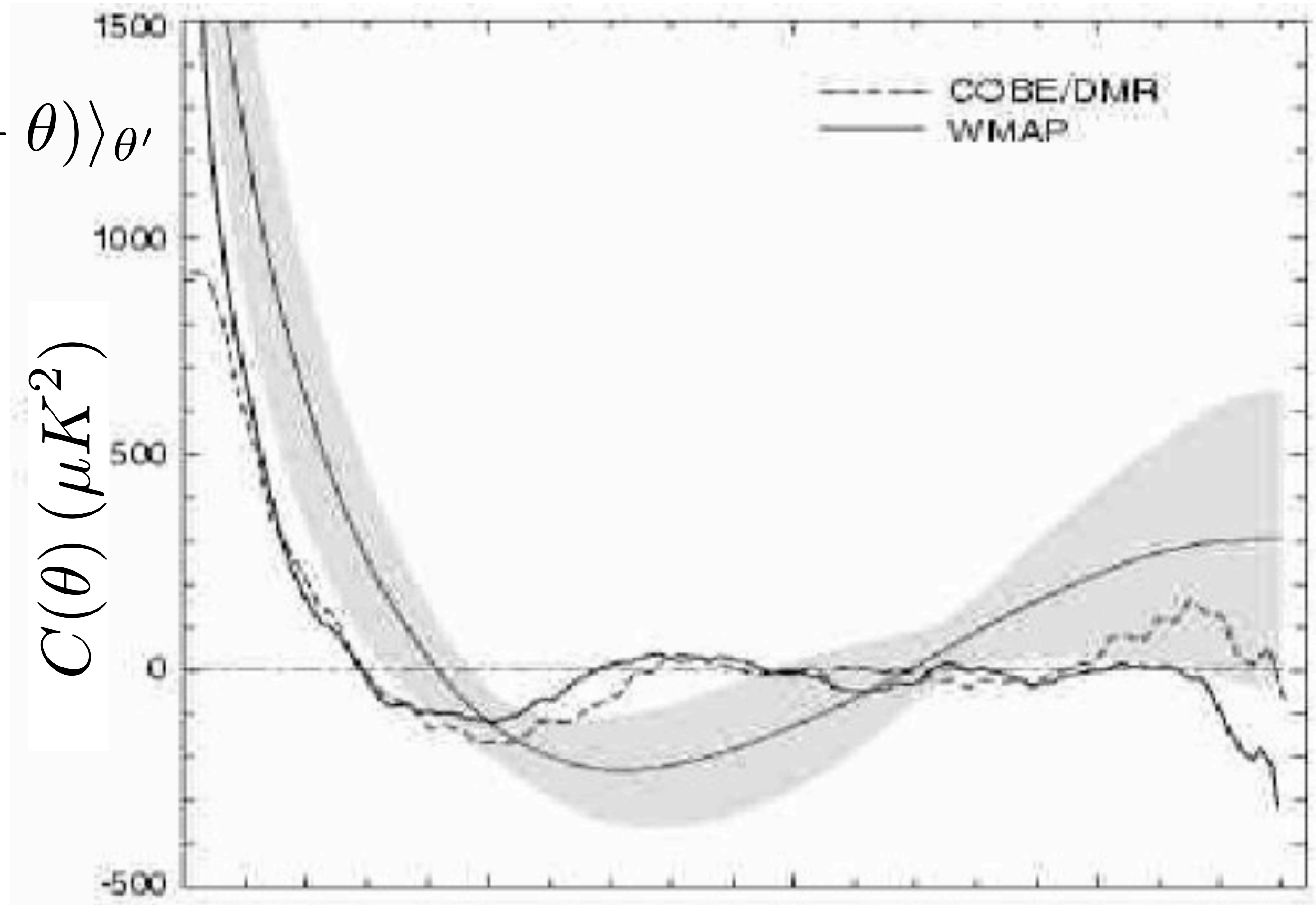
Large-scale alignments

Various explanations

Future prospects and conclusions

Low power on large scales

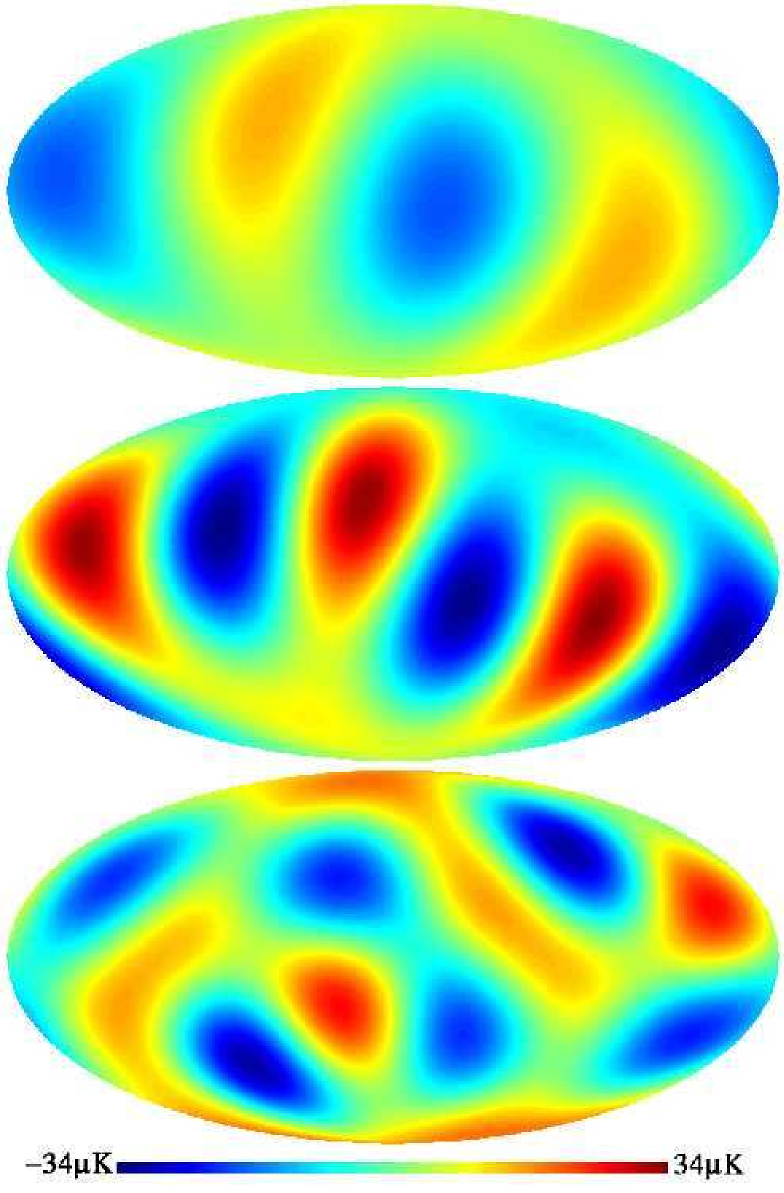
$$C(\theta) = \langle T(\theta')T(\theta' + \theta)\rangle_{\theta'}$$



θ (degrees)

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

l=2, 3 are aligned and planar



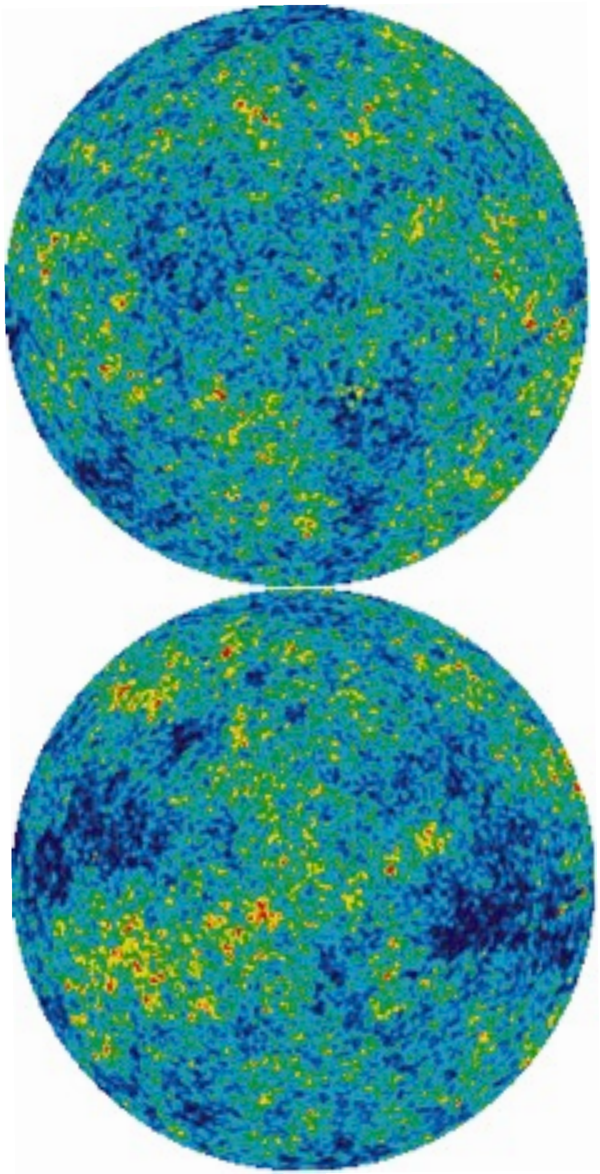
$$\hat{L}_\ell^2 \equiv \frac{\displaystyle\sum_{m=-\ell}^{\ell} m^2 \left|a_{\ell m}\right|^2}{\displaystyle\ell^2 \sum_{m=-\ell}^{\ell} \left|a_{\ell m}\right|^2}$$

l=3 is planar: P~1/20

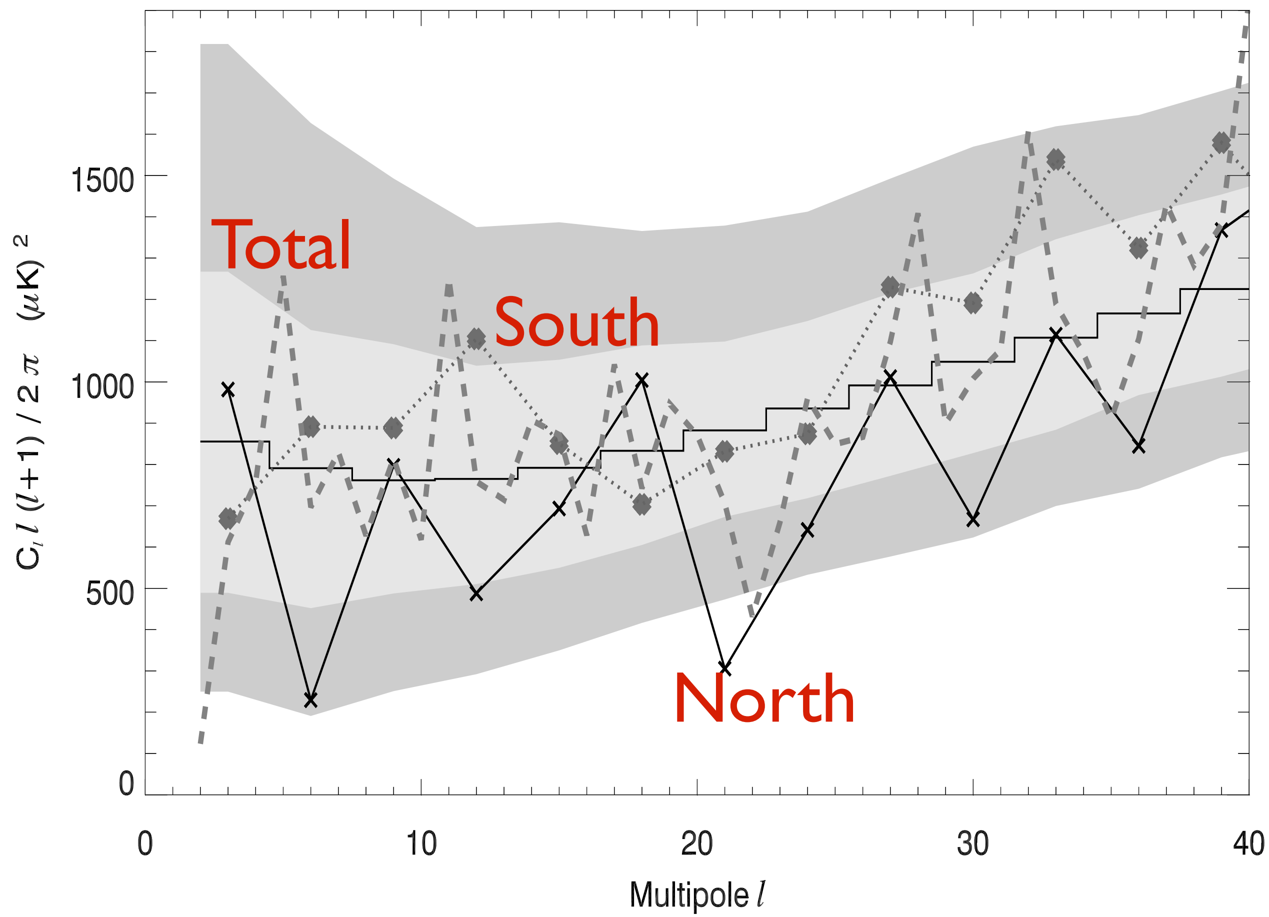
l=2,3 is are aligned: P~1/60

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:

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

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

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

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

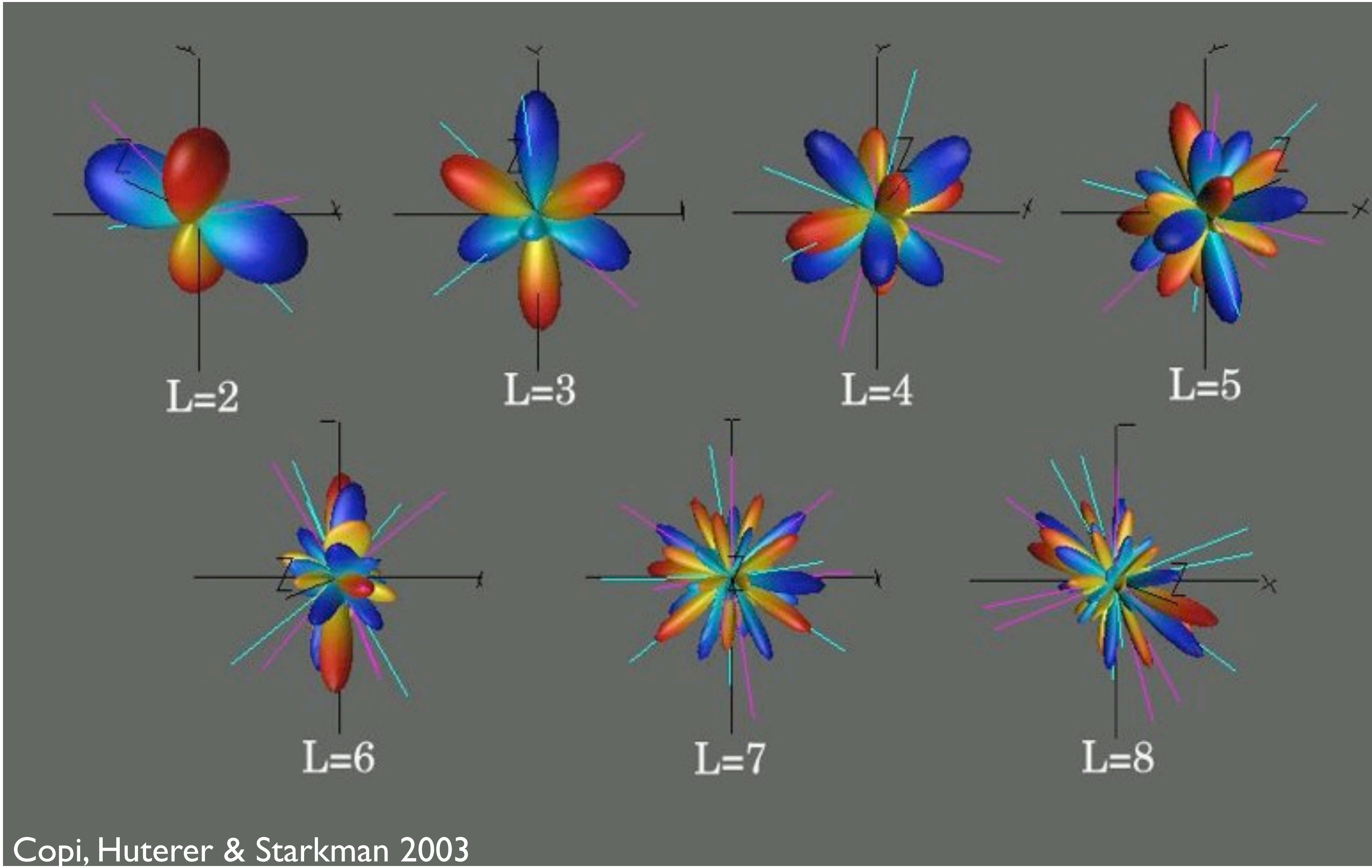
where R is a homogeneous polynomial of degree $\ell - 2$. The decomposition is unique up to reordering and rescaling the linear factors.

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: $\nabla \mathbf{v}_\ell \ldots \nabla_{\mathbf{v_2}} \nabla_{\mathbf{v_1}} \frac{1}{r}$

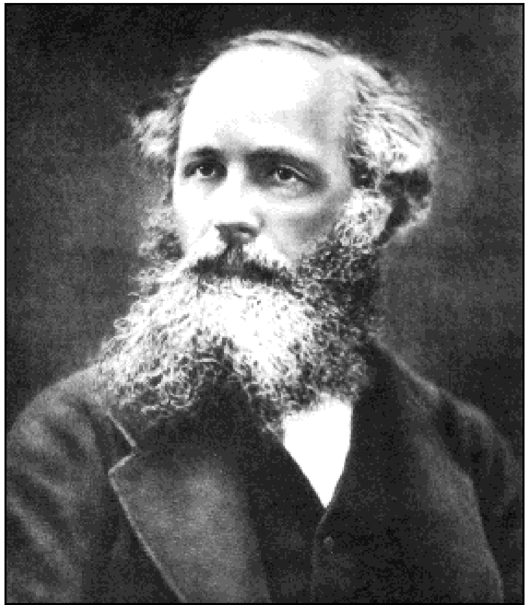
$\mathbf{v_1} \ldots \mathbf{v}_\ell$ are the multipole vectors

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)

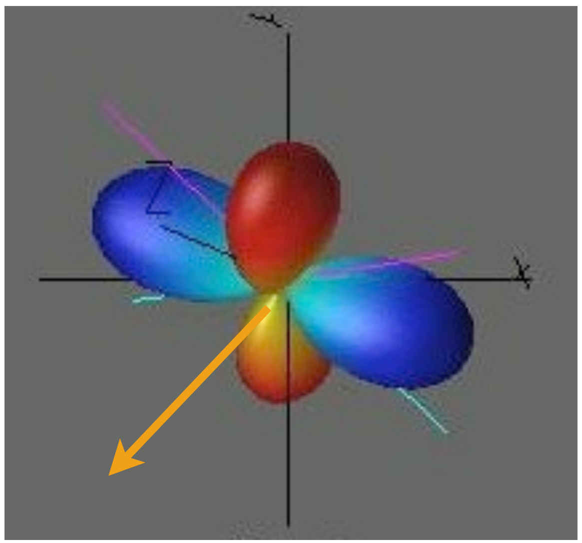
Also:
discussed by J.C. Maxwell in his "Treatise on Electricity and Magnetism" in 1892!!



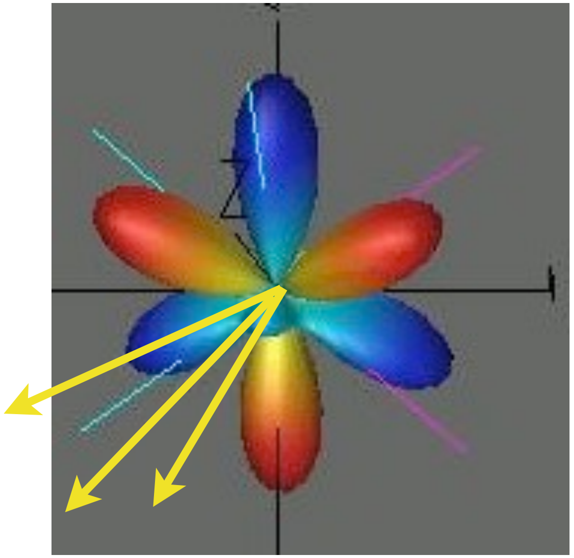
Normals to multipole vectors

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

"oriented areas"

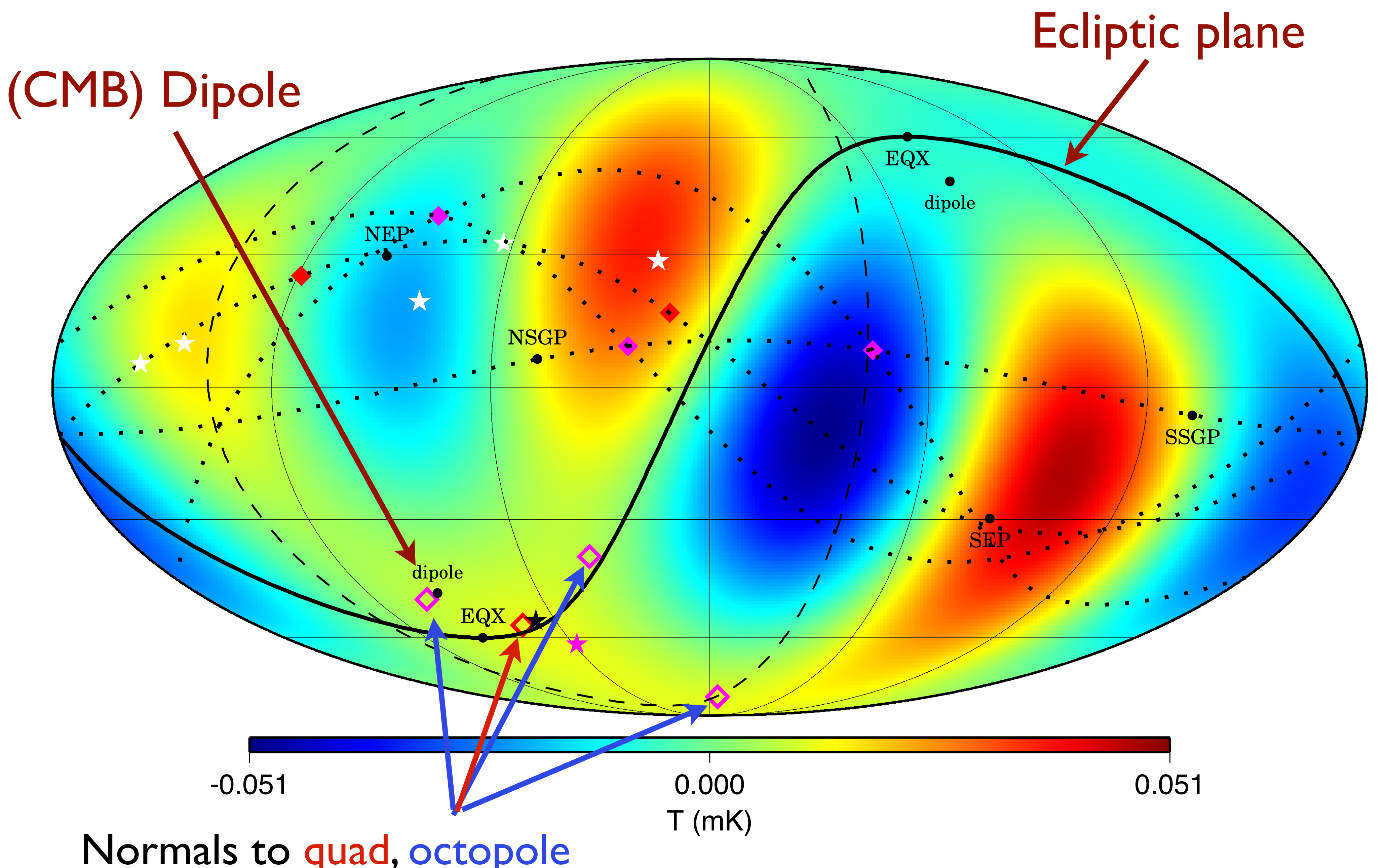


L=2



L=3

L=2+3 alignments



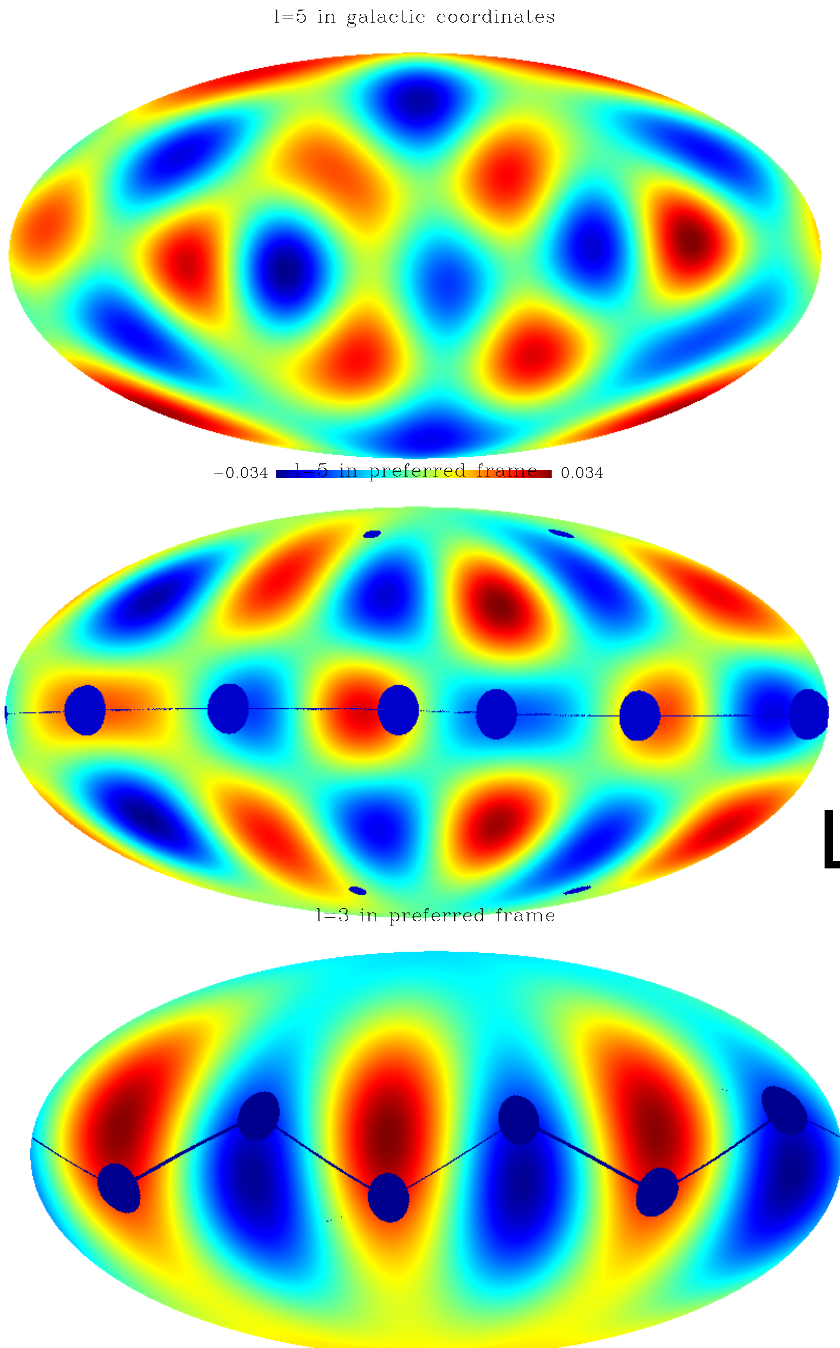
Schwarz, Starkman, Huterer & Copi 2004

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)

Land & Magueijo 2005



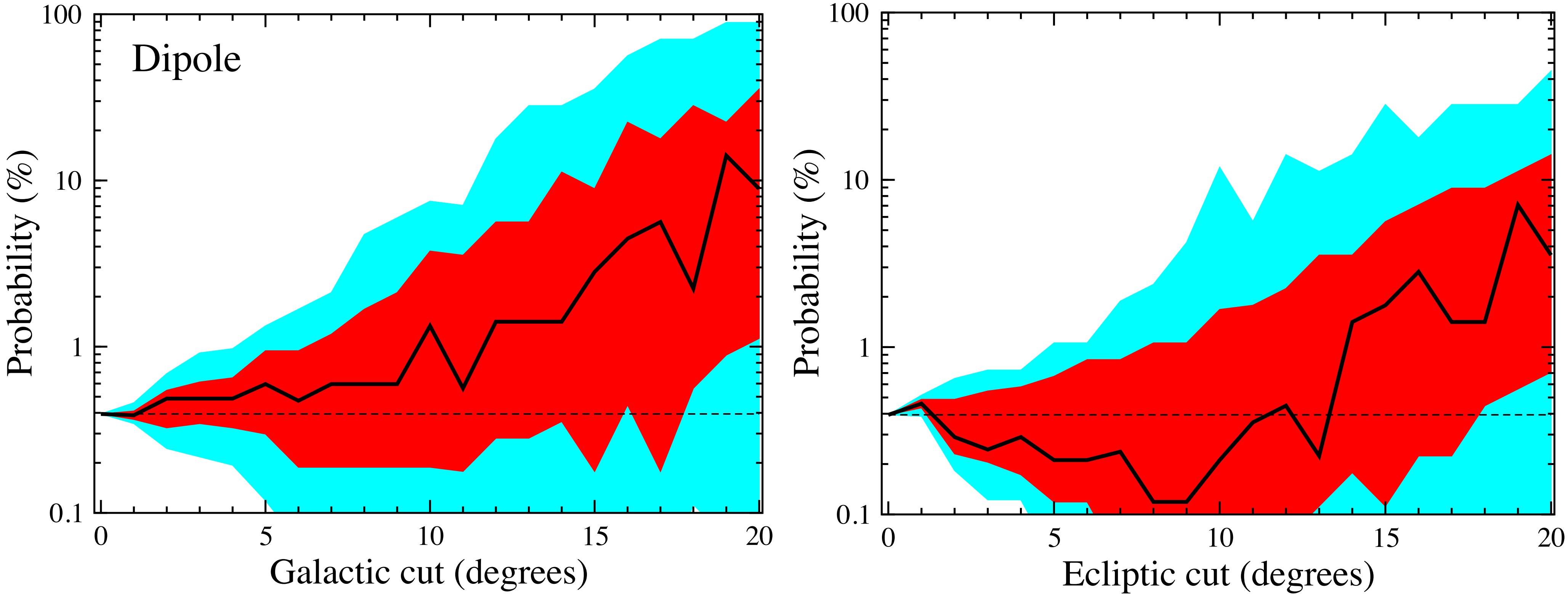
L=5, gal frame

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

L=5, AOE frame

L=3, AOE frame

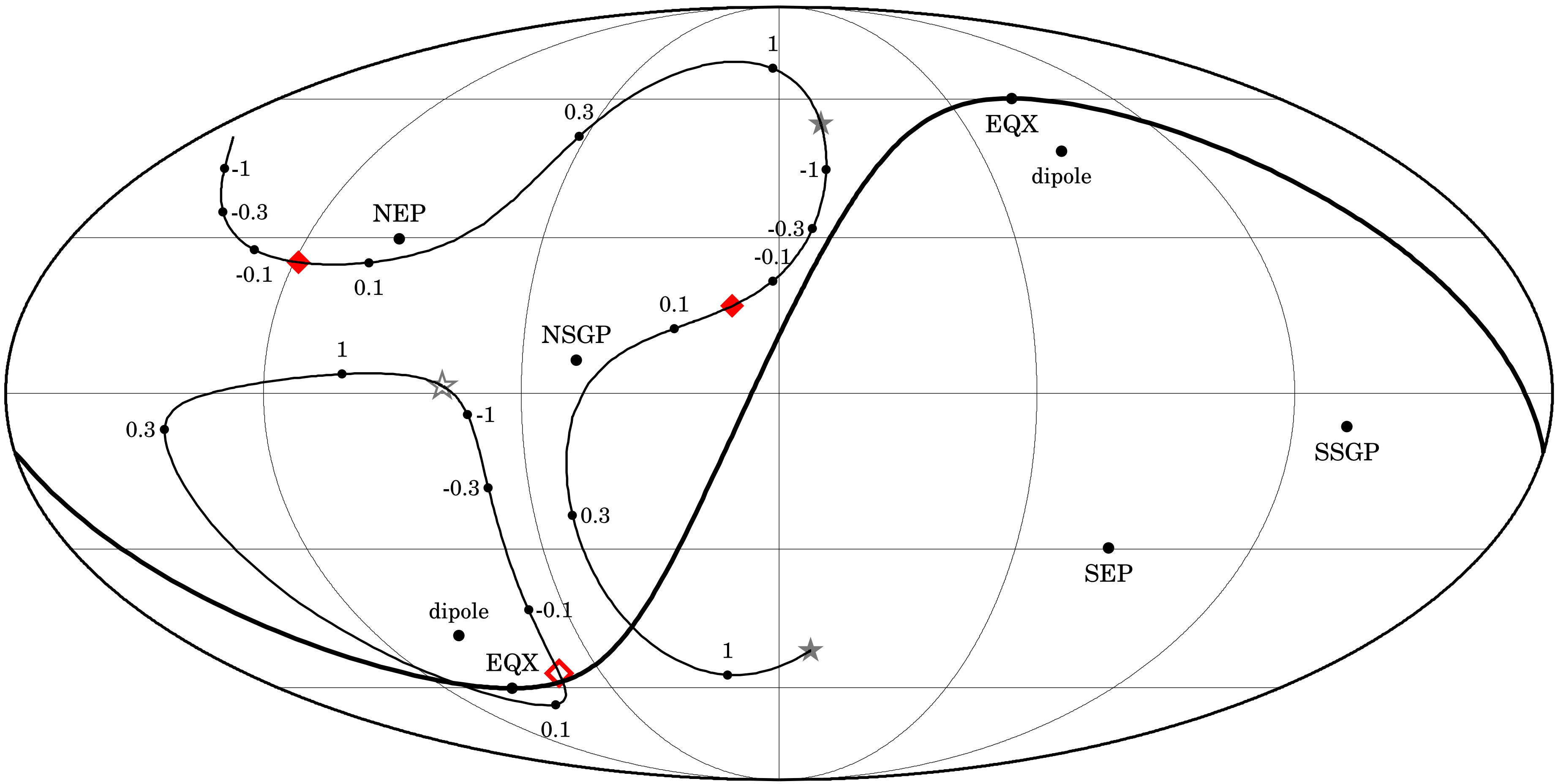
Systematic checks: sky cut



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

Copi, Huterer, Schwarz & Starkman 2006

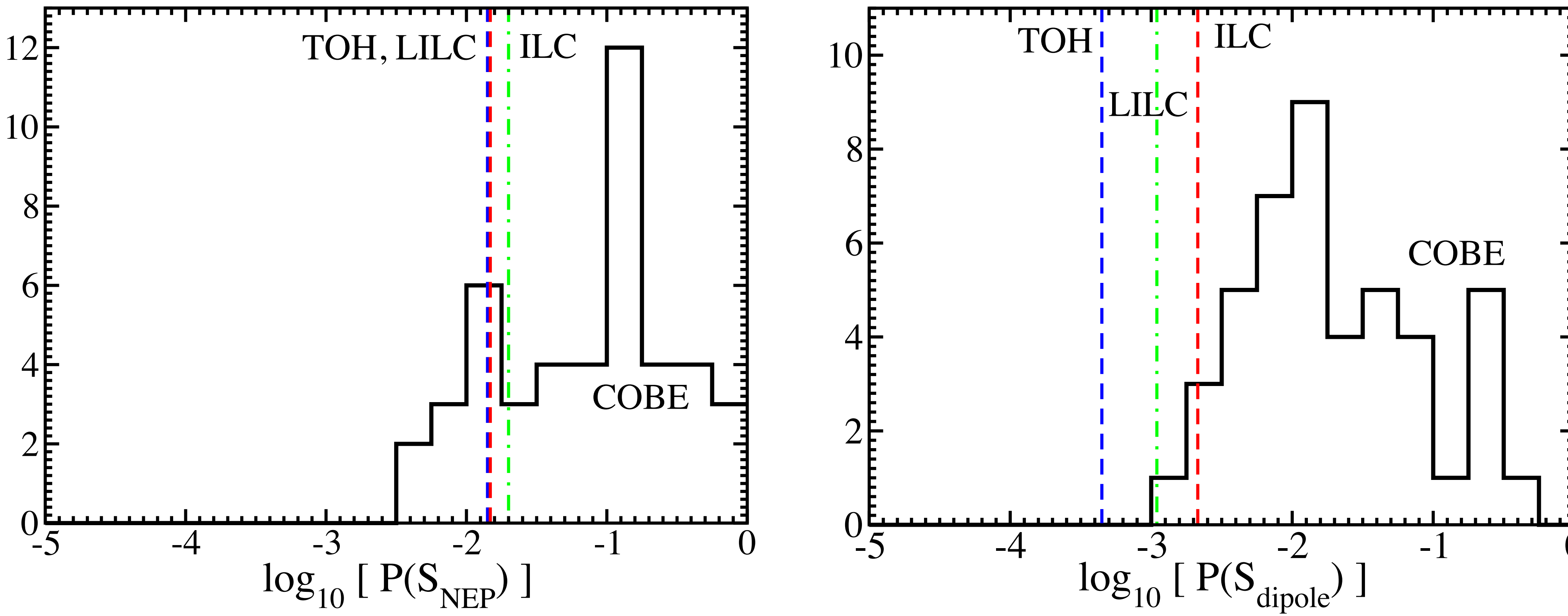
Systematic checks: foreground missubtraction



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

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

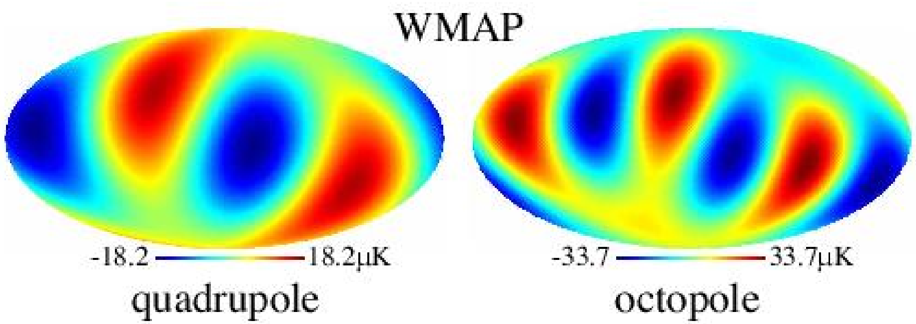
So with $\alpha_2 \sim \alpha_3 \sim 10^{-2}$, dipole anisotropy is modulated into a 10^{-5} quadrupole and octopole with $m = 0$ in the dipole frame.

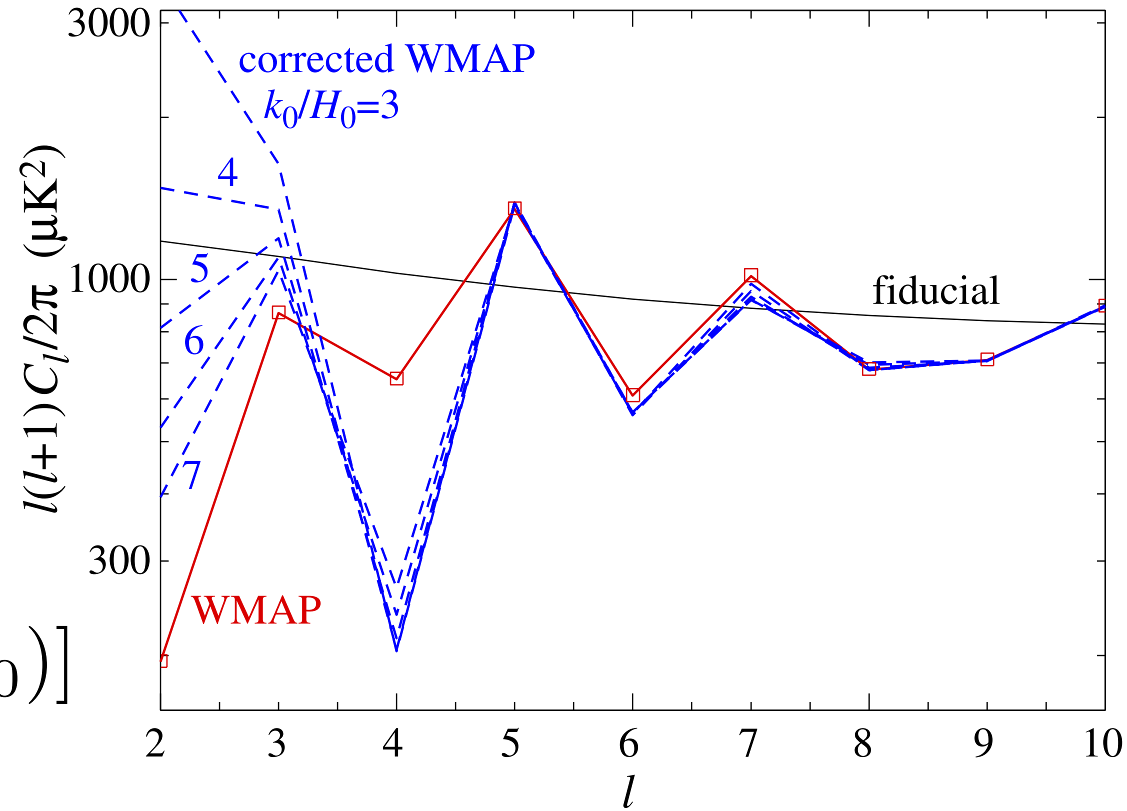
Sadly: doesn't work since would have been seen when observing $\sim 1K$ sources (in lab, Jupiter, etc).

Gordon, Hu, Huterer & Crawford 2006

Example: Spontaneous Isotropy Breaking

- To explain/model the apparent lack of isotropy on largest scales seen by WMAP





$$V(\phi) = V_0[1 + f\cos(\phi/M_0)]$$

$$\phi(z) = A + Bz$$

Modulates the CMB anisotropy through the ISW effect

Nonlinear modulation ⇨ a range of multipoles affected

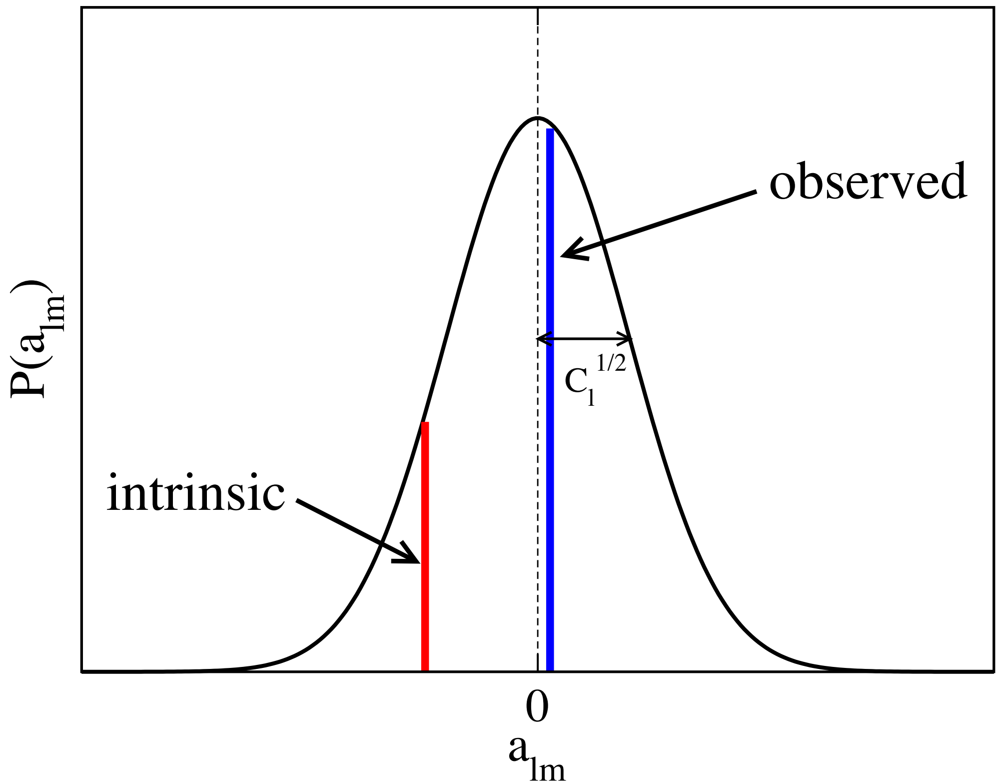
Gordon, Hu, Huterer & Crawford 2006

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

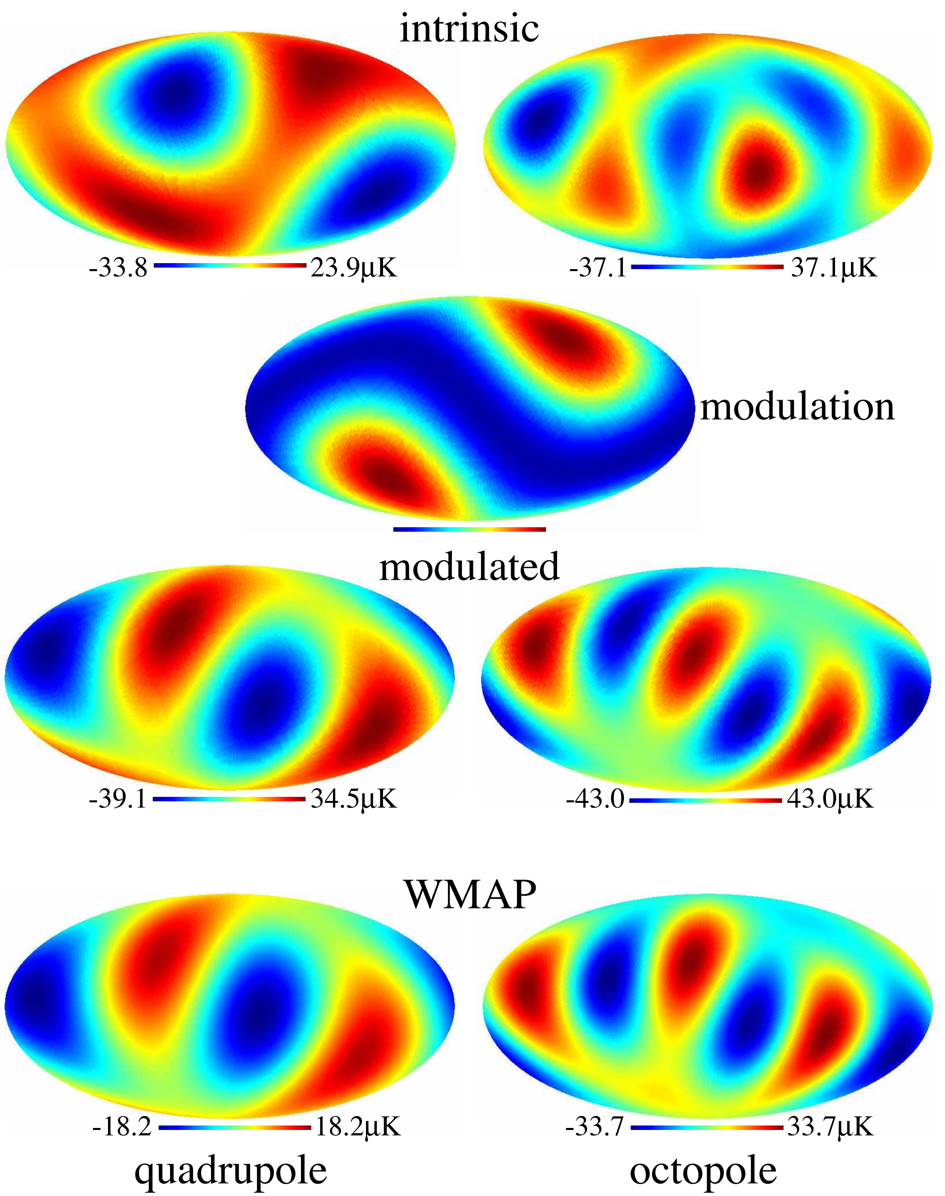


True for all additive schemes:
Solar System contamination,
Bianchi models,
etc

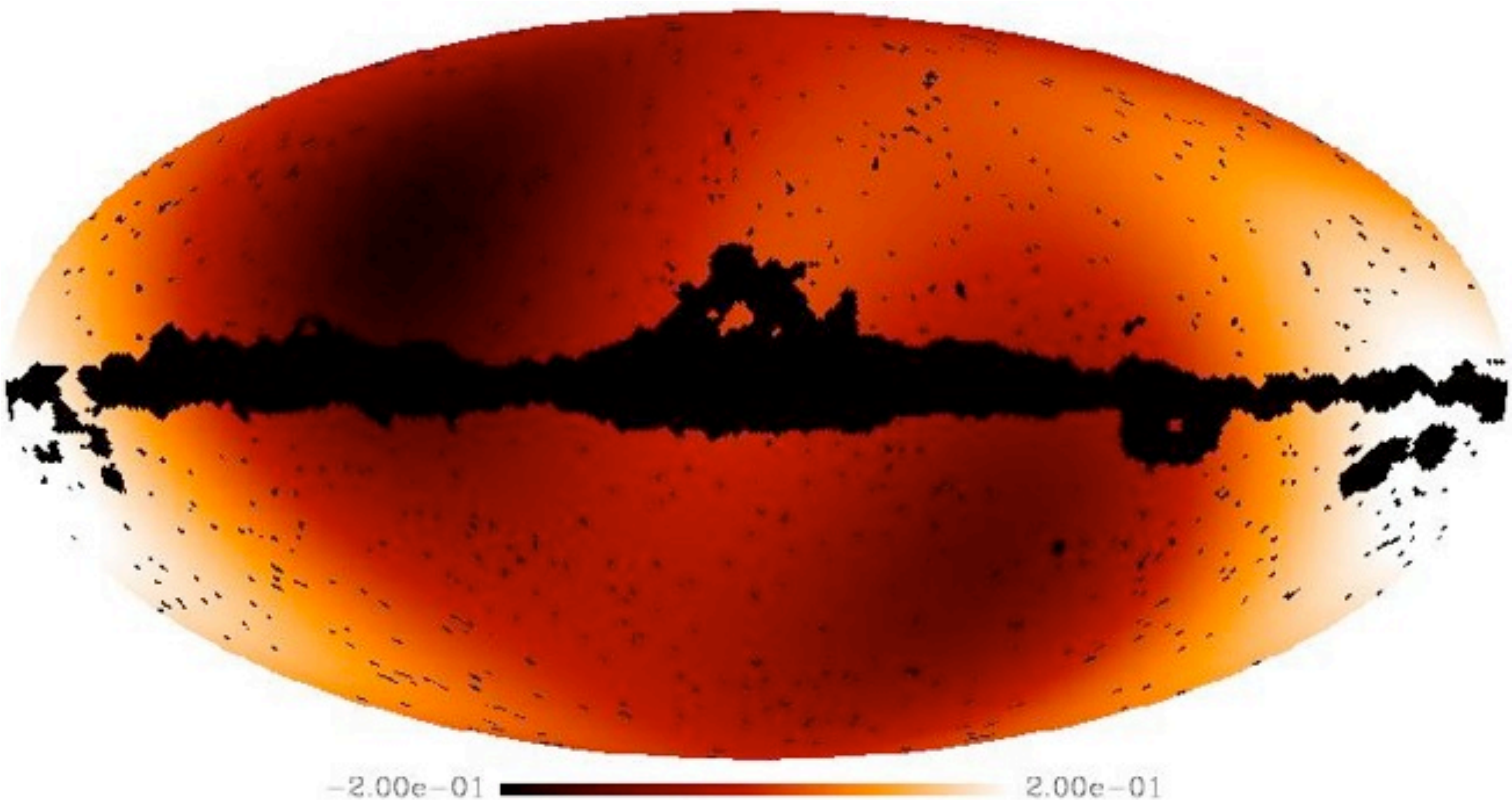
Multiplicative modulation can work

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

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

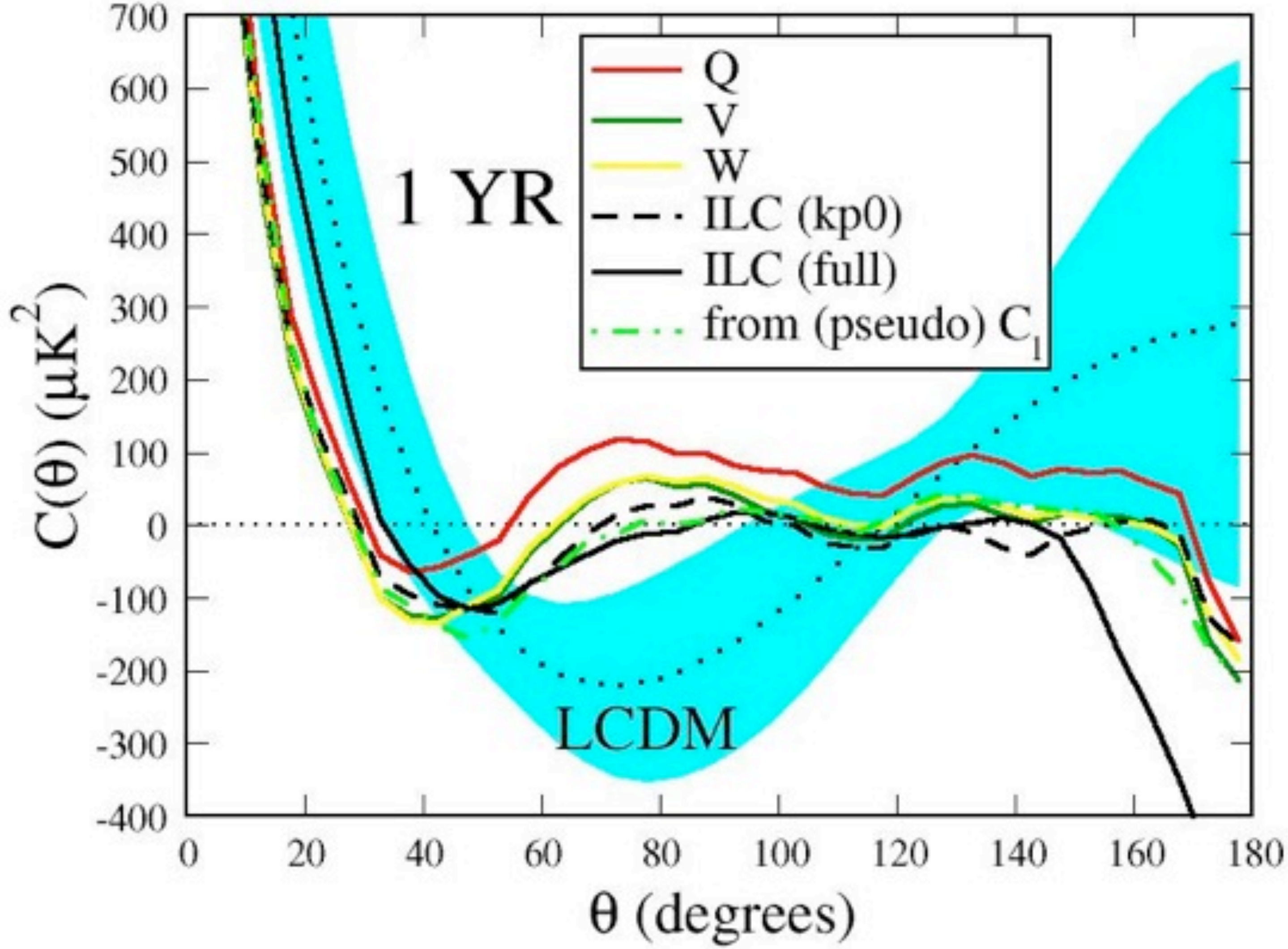


Best-fit L=1,2 multiplicative modulation from WMAP 123



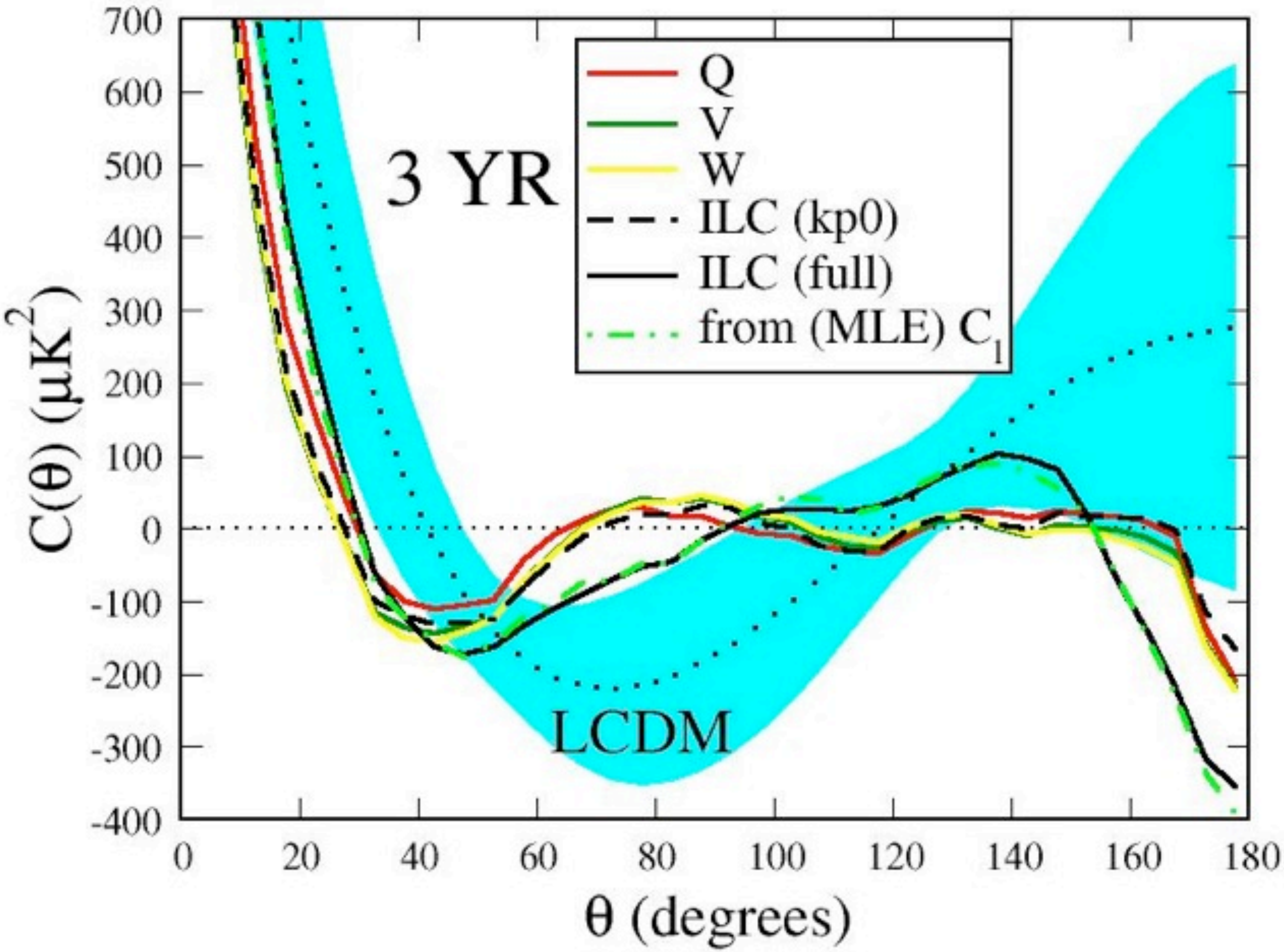
Spergel et al, 2006

Low power on large scales

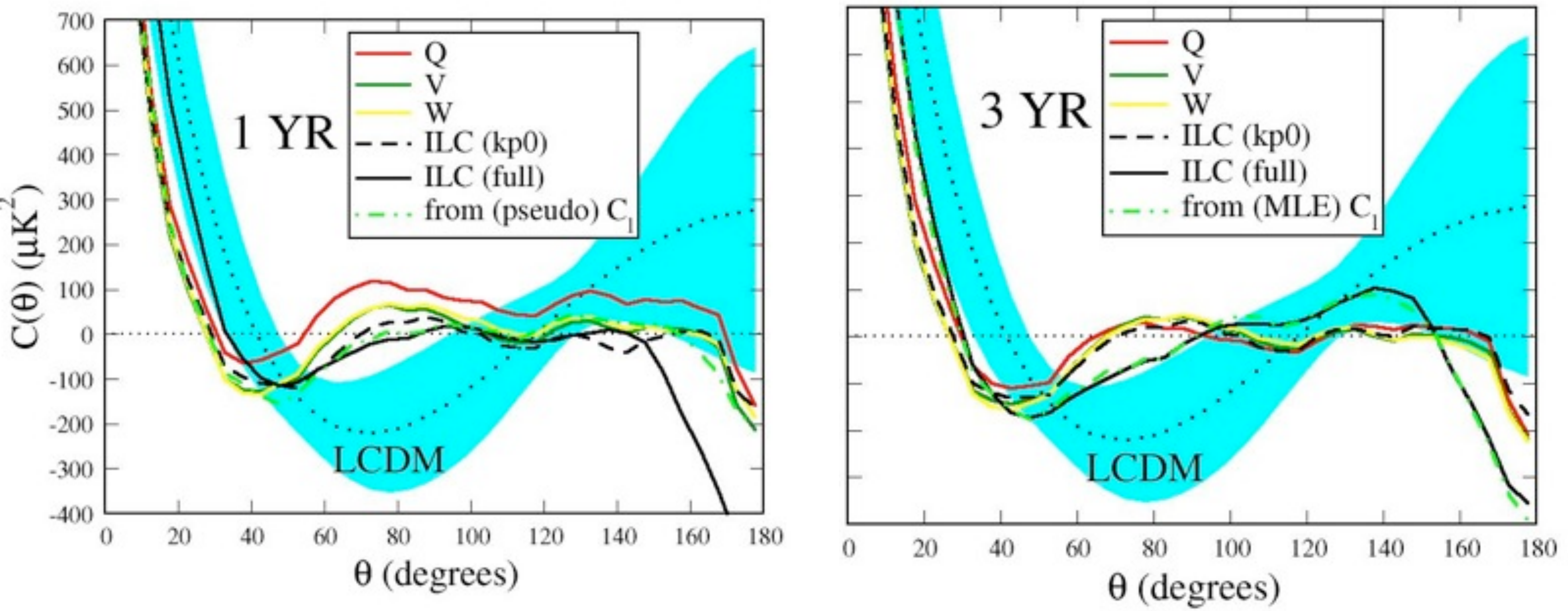


Spergel et al 2003: 0.2% of sims have less power at angles >60 deg

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



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



1 YR
Q
V
W
ILC (kp0)
ILC (full)
from (pseudo) C
LCDM
C(θ) (μK²)
θ (degrees)
0
20
40
60
80
100
120
140
160
180
700
600
500
400
300
200
100
0
-100
-200
-300
-400
3 YR
Q
V
W
ILC (kp0)
ILC (full)
from (MLE) C
LCDM
θ (degrees)

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

Reading/review references

CMB alignments (short) review:
Huterer, New Astronomy Reviews 50, 868 (2006),
www.arxiv.org/abs/astro-ph/0608318

CMB alignments (long) review and tests:
Copi, Huterer, Schwarz & Starkman MNRAS, 367, 79 (2006),
www.arxiv.org/abs/astro-ph/0508047

Popular articles:

G. Starkman and D. Schwarz, *Scientific American*, August 2005

D. Huterer, *Astronomy*, Dec. 2007 (also off my web site)