Large-angle anomalies of the microwave sky

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Are the low-ℓ modes cosmic?

Schwarz, Starkman, Huterer & Copi, PRL November 26, 2004

Copi, Huterer, Schwarz & Starkman, astro-ph/0508047

Starkman & Schwarz, Scientific American, August 2005

Vienna Central European Seminar 2005

Anisotropy of cosmic microwave background (CMB)

CMB probes the largest (angular) scales back to $t \sim 370,000$ years

temperature fluctuations

$$\delta T(\mathbf{e}) = \sum_{\ell} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{e})$$

with $a^*_{\ell m} = (-1)^m a_{\ell -m}$ (reality condition)
$\Rightarrow 2\ell + 1$ degrees of freedom for ℓth moment

Predictions from inflationary cosmology

statistical isotropy:

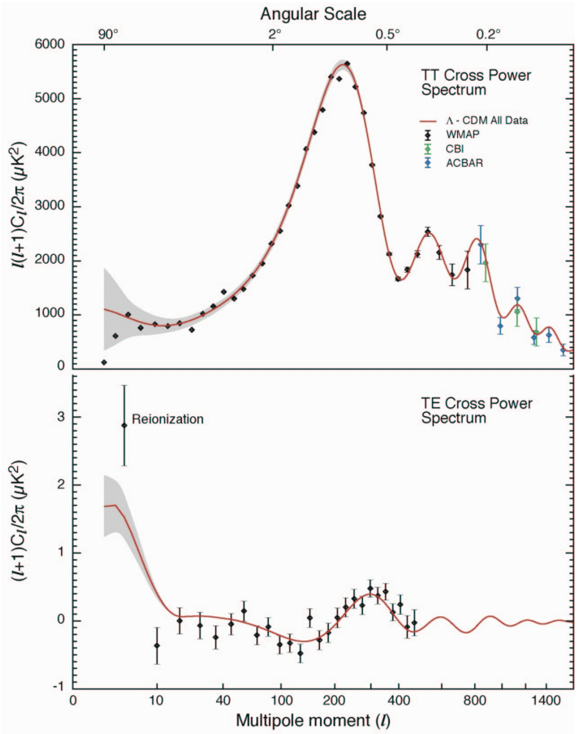
$\langle \delta T(\mathsf{R}\mathbf{e}_1)\dots\delta T(\mathsf{R}\mathbf{e}_n)\rangle = \langle \delta T(\mathbf{e}_1)\dots\delta T(\mathbf{e}_n)\rangle, \quad \forall \mathsf{R} \in \mathsf{SO(3)},\ \forall n > 0$

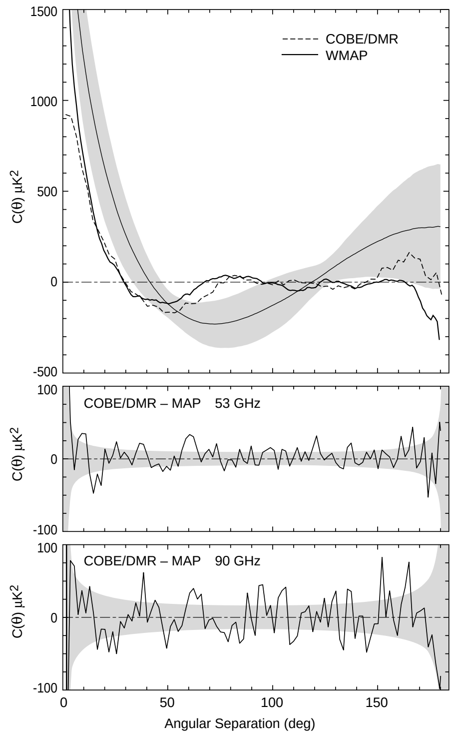
- $\langle \delta T(\mathbf{e})\rangle = 0$ and $\langle a_{\ell m}\rangle = 0$
- $\langle \delta T(\mathbf{e}_1)\delta T(\mathbf{e}_2)\rangle = f(\mathbf{e}_1 \cdot \mathbf{e}_2) = \frac{1}{4\pi}\sum_\ell (2\ell+1)C_\ell P_\ell(\cos\theta), \quad \cos\theta \equiv \mathbf{e}_1 \cdot \mathbf{e}_2$ with $\langle a_{\ell m} a^*_{\ell' m'}\rangle = C_\ell \delta_{\ell\ell'}\delta_{mm'}$, C_ℓ angular power spectrum

gaussianity: no extra information in higher correlation functions

(best) estimator: $\widehat{C}_\ell = 1/(2\ell+1)\sum_m |a_{\ell m}|^2$ (assumes statistical isotropy)
cosmic variance: $\mathrm{Var}(\widehat{C}_\ell) = 2C_\ell^2/(2\ell+1)$ (assumes gaussianity)

WMAP: 2-point correlations (cut sky)





Hinshaw et al. 2003, Kogut et al. 2003

Bennett et al. 2003

First indications of large-angle anomalies

angular correlation vanishes at > 60 deg

COBE-DMR and WMAP

small quadrupole (and octopole)

COBE-DMR and WMAP

planar octopole, aligned with quadrupole

de Oliveira-Costa et al., 2003

deficit of power in North (ecliptic) hemisphere

Eriksen et al., 2003

Multipole vectors

alternative representation of multipoles

Maxwell 1891, Copi, Huterer & Starkman 2003

one (real) amplitude A_ℓ and ℓ headless (unit) vectors:
$2\ell + 1$ degrees of freedom

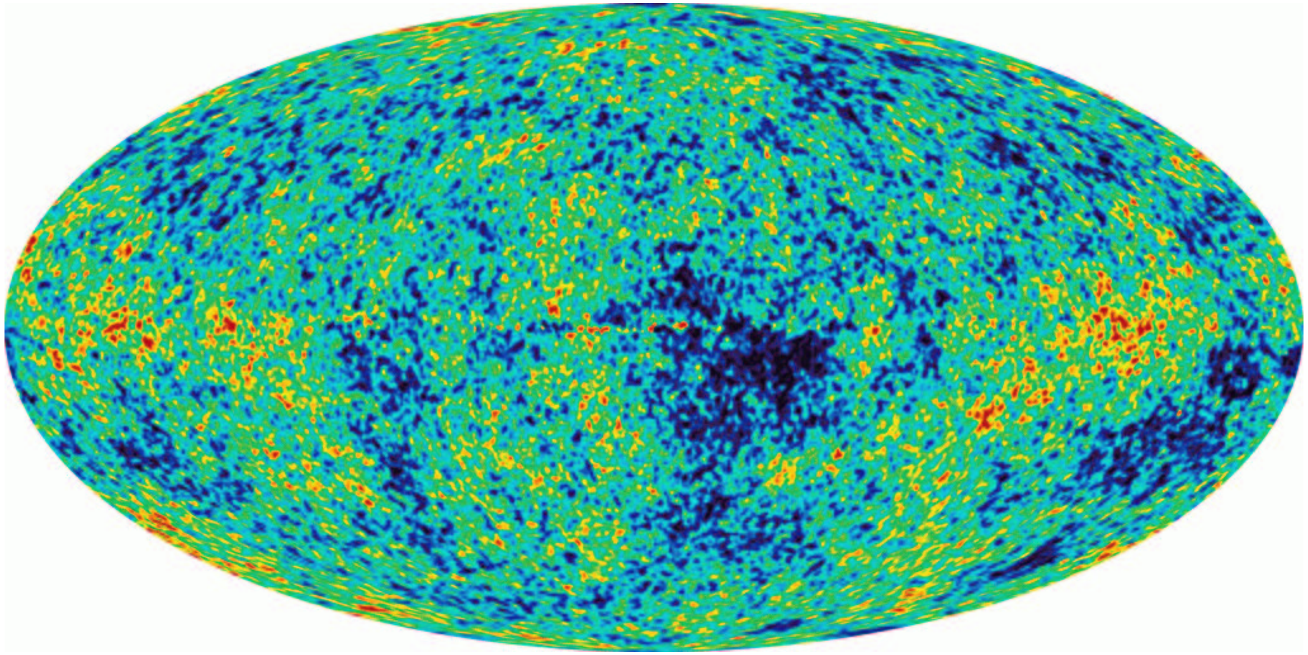
$$T_\ell(\mathbf{e}) = \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{e}) = A_\ell [\mathbf{v}^{(\ell,1)} \cdots \mathbf{v}^{(\ell,\ell)}]_{i_1 \ldots i_\ell} [\mathbf{e} \cdots \mathbf{e}]^{i_1 \ldots i_\ell}$$

$[\ldots]$ . . . symmetric, traceless tensor product

e.g. quadrupole: $T_2(\mathbf{e}) = A_2[(\mathbf{v}^{(2,1)} \cdot \mathbf{e})(\mathbf{v}^{(2,2)} \cdot \mathbf{e}) - \frac{1}{3}\mathbf{v}^{(2,1)} \cdot \mathbf{v}^{(2,2)}]$

Full sky cleaned maps

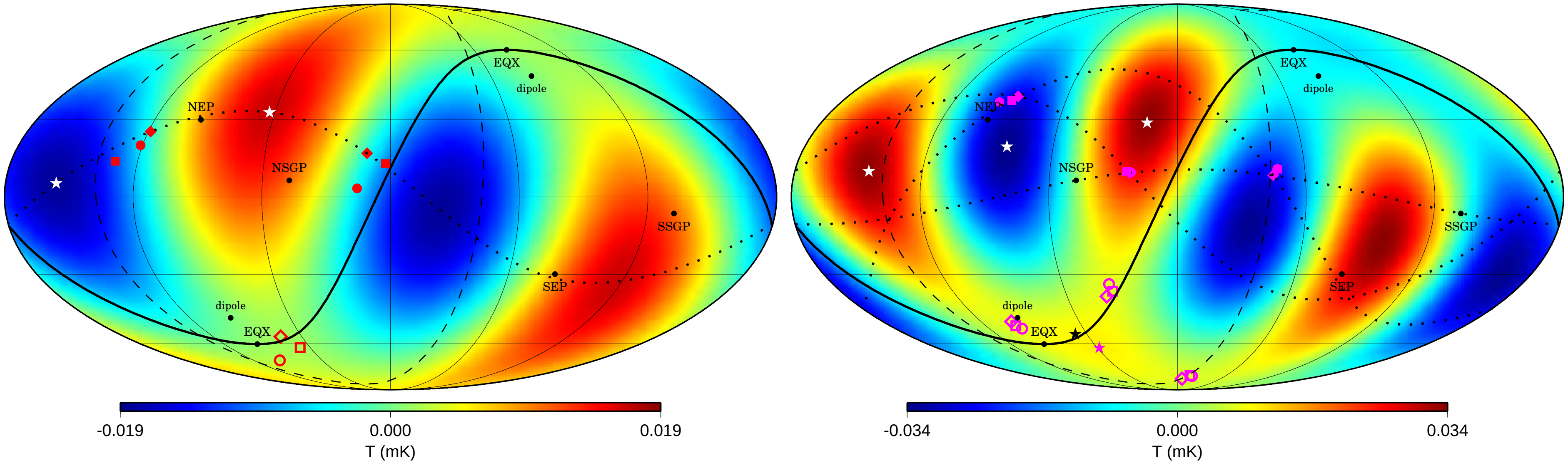
linear combination of 5 WMAP frequency bands with minimal variance



WMAP ILC: Bennett et al. 2003

also cleaned TOH map: Tegmark et al. 2003 and LILC: Eriksen et al. 2004

Quadrupole and octopole

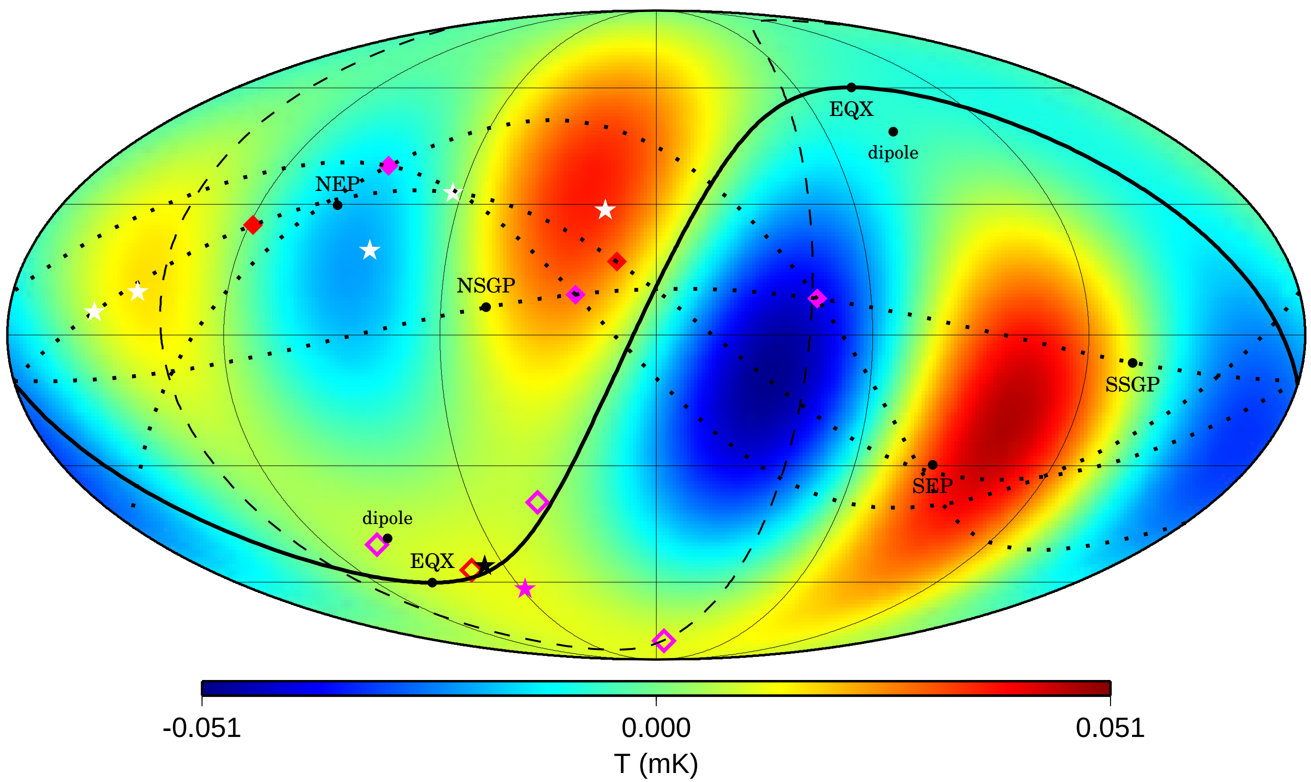


3 great circles defined by multipole vectors are nearly normal to ecliptic

1 great circle nearly normal to supergalactic plane

Schwarz et al. 2004, Copi et al. 2005

Quadrupole plus octopole



ecliptic is close to nodal line — Schwarz et al. 2004, Copi et al. 2005

significant power asymmetry for [2,3] and [6,7] — Freeman et al. 2005

Statistic

oriented areas $\mathbf{w}^{(\ell;i,j)} \equiv \mathbf{v}^{(\ell,i)} \times \mathbf{v}^{(\ell,j)}$

quadrupole-octopole alignement

$$S = \frac{1}{3} \sum_{i<j} |\mathbf{w}^{(2;1,2)} \cdot \mathbf{w}^{(3;i,j)}|$$

correlation with known planes and directions

especially galaxy, ecliptic, dipole

$$S = \frac{1}{4} \sum_{\ell,i<j} |\mathbf{w}^{(\ell;i,j)} \cdot \mathbf{d}|$$

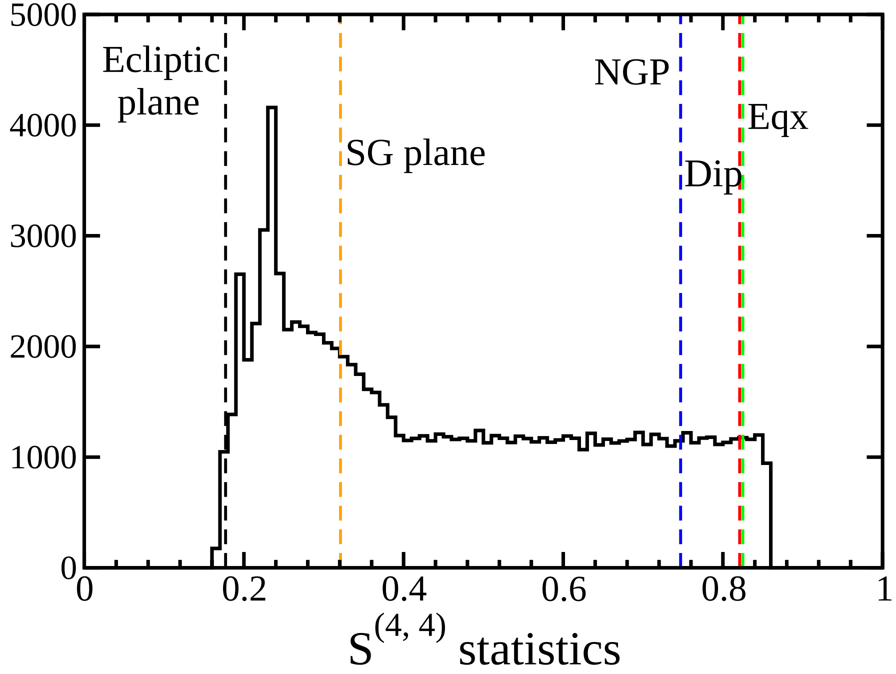
100,000 isotropic and gaussian Monte Carlo maps with WMAP pixel noise

Quadrupole and octopole are not cosmic

Test	TOH kqs	LILC kqs	ILC kqs	TOH	LILC	ILC
qo alignement	0.117	0.602	0.289	0.582	2.622	0.713
ecliptic plane	1.425	1.480	2.006	1.228	1.735	2.724
galactic pole	0.734	0.940	0.508	0.909	1.265	0.497
SG plane	14.4	13.4	8.9	11.6	10.2	6.5
dipole	0.045	0.214	0.110	0.093	0.431	0.207
equinox	0.031	0.167	0.055	0.064	0.315	0.080

Probabilities in % for six tests using the cleaned TOH (Tegmark et al.), LILC (Eriksen et al.) and ILC (Spergel et al.) maps, with and without substracting the kinematic quadrupole.

Evidence for a Solar System correlation



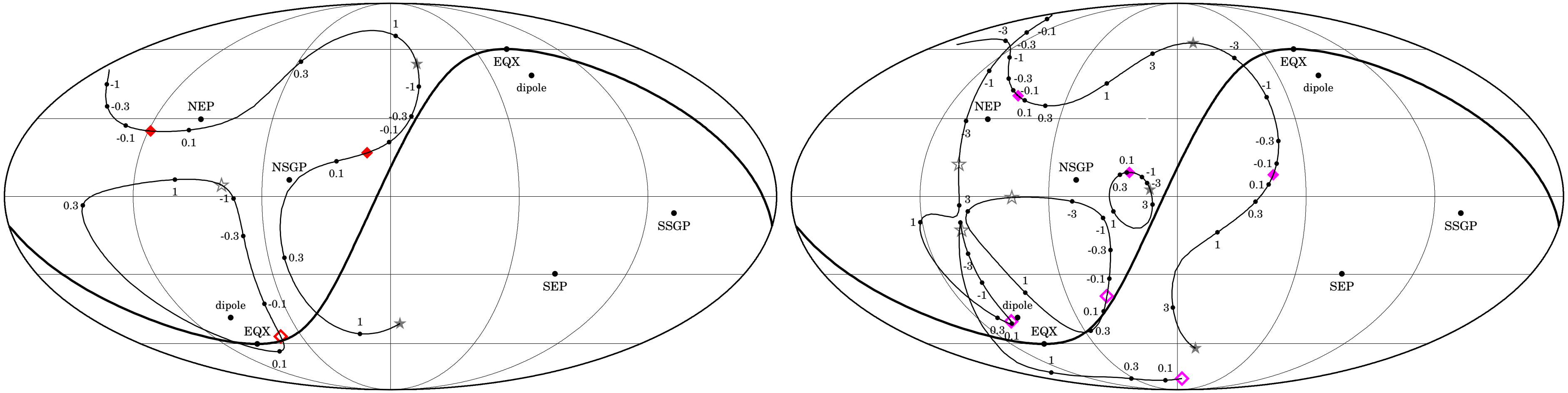
fixed quadrupole plus octopole pattern

ecliptic correlation $> 99.9\%$C.L.

Copi et al. 2005

Foreground effect?

known galactic foregrounds do not lead to observed correlations



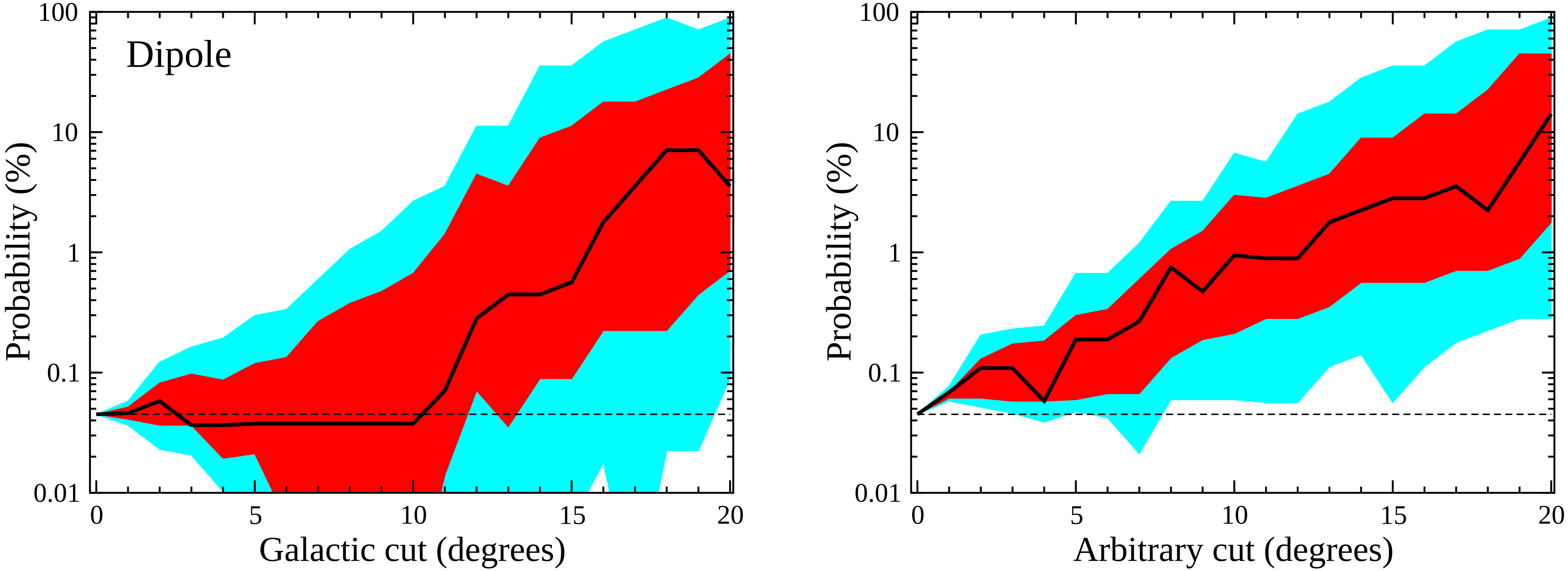
galactic foreground dominated by Y_{20} and Re(Y_{31})

add in scaled WMAP foreground map

Copi et al. 2005

Cut sky

error in multipole vector reconstruction from incomplete sky

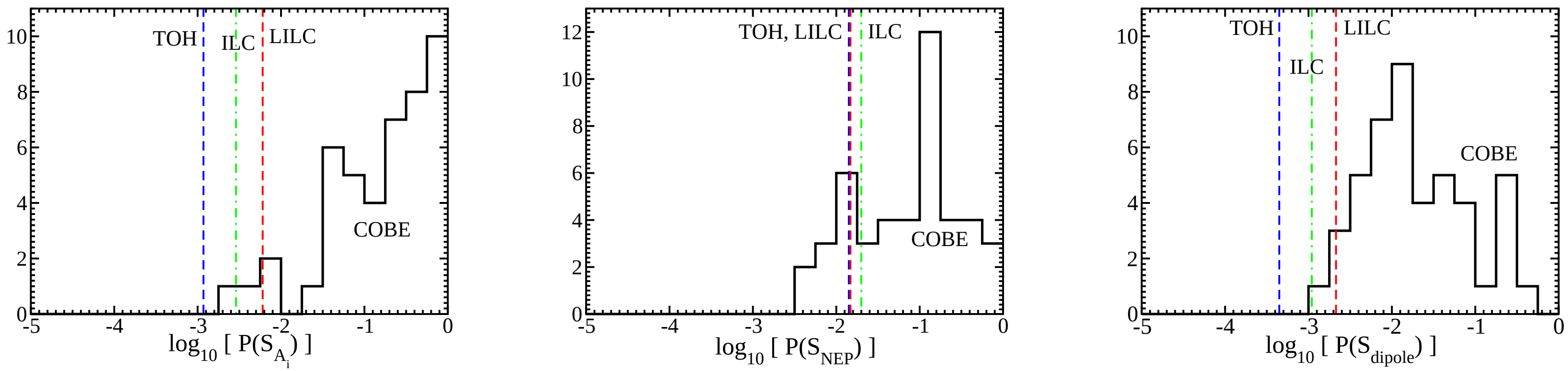


cut TOH cleaned map

Copi et al. 2005

Back to COBE

COBE-DMR observations are consistent with our findings



45 MCMC COBE maps from Wandelt et al. 2004

Copi et al. 2005

No convincing explanation

statistical issue:
Katz & Weeks 2004, Weeks 2004, Land & Magueijo 2004, Copi et al. 2005

systematic error:
full vs. cut sky Slosar & Seljak 2004, Bielewicz et al. 2005, Copi et al. 2005,
map-making algorithm Freeman et al. 2005,
calibration on modulation of dipole, beam asymmetries

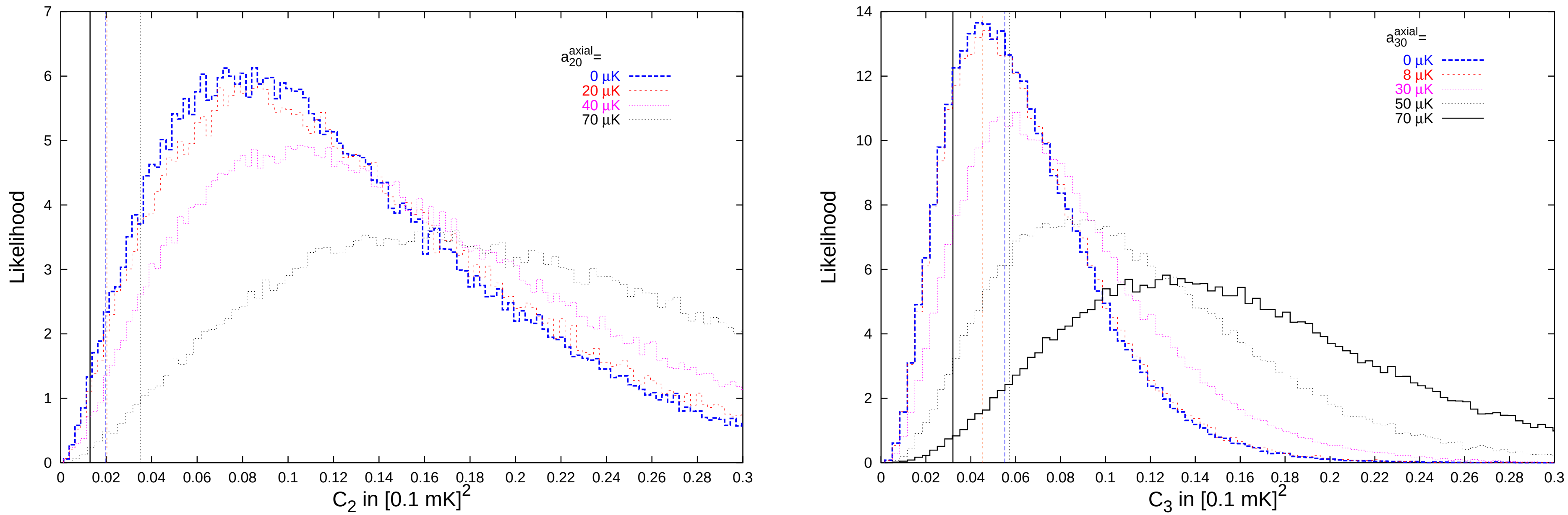
solar system foreground: Frisch 2005

galactic foreground: Slosar & Seljak 2004, Copi et al. 2005

extragalactic structure:
SZ Abramo & Sodre Jr 2003, Hansen et al. 2005,
weak lensing Vale 2005, Cooray 2005

cosmology: Jaffe et al. 2005, Gordon et al. 2005

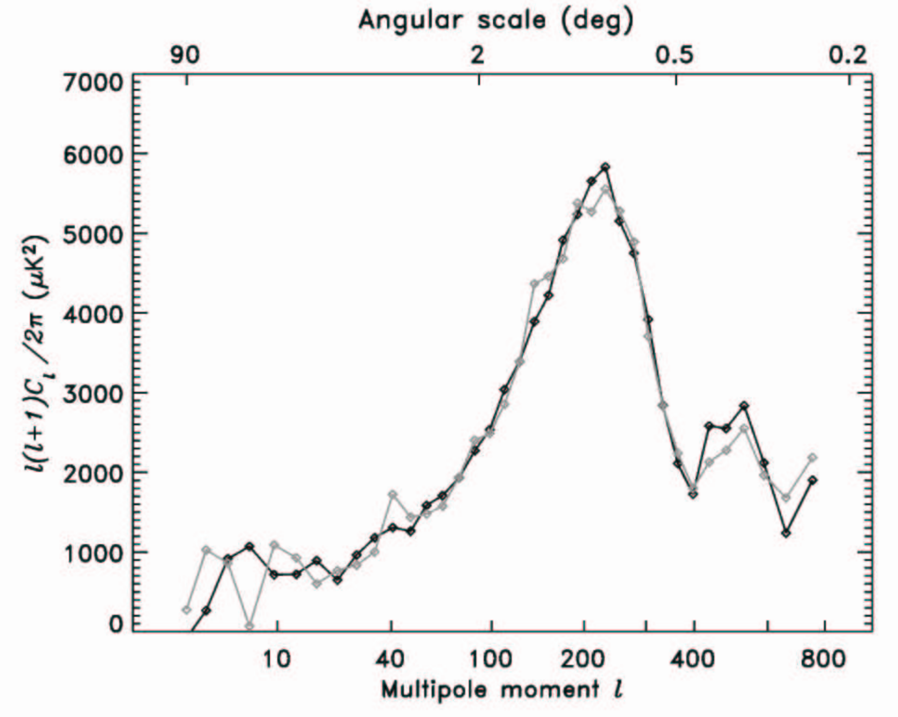
Extra foreground conflicts with low power



observed values: WMAP cut sky, WILC, TOH, LILC

Rakić, Räsänen & Schwarz, in preparation

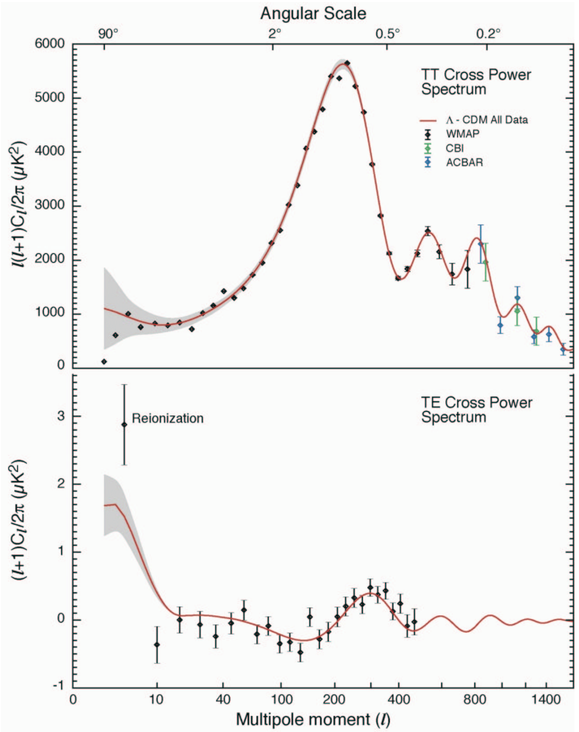
Higher multipoles



WMAP angular power spectrum analysis:
ecliptic plane (black) and poles (grey)

Hinshaw et al. 2003

The first stars?



Hinshaw et al. 2003, Kogut et al. 2003

WMAP analysis:
TE-correlation at $\ell < 7$ ($\tau \geq 0.1$)

WMAP interpretation:
very early star formation
(200 Myr)

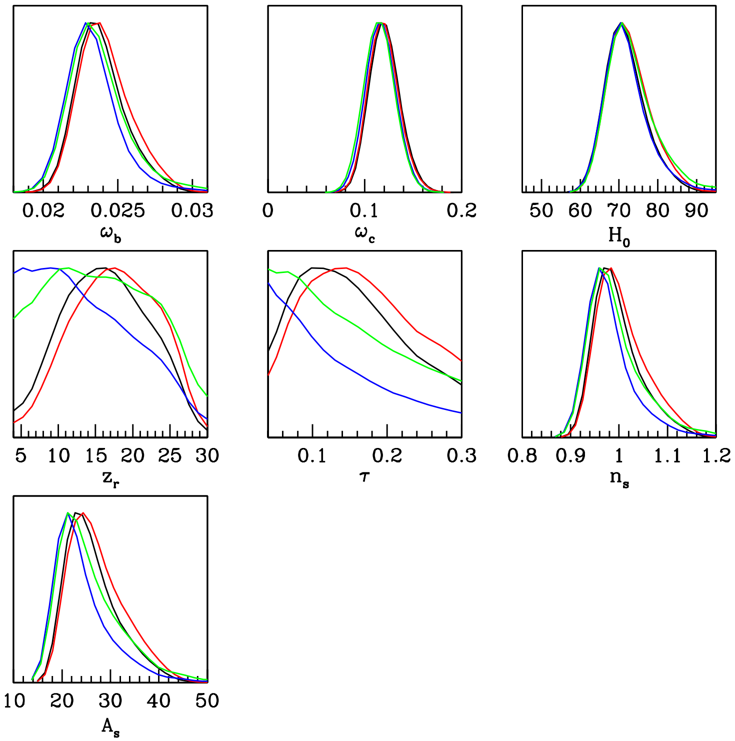
before WMAP (quasar spectra):
star formation starts before 1 Gyr

NEW:
TT-correlations with orientation and motion of solar system in $\ell = 2, 3$

$\Rightarrow$ TE-correlations for small ℓ suspect

Schwarz et al. 2004

The optical depth and z_r



WMAP TT & TE data with $\Omega = 1$

$\ell \geq 2$, flat prior on τ

$\ell \geq 6$, flat prior on τ

$\ell \geq 2$, flat prior on z_r

$\ell \geq 6$, flat prior on z_r

Leach & Trotta 2004, unpublished

Don't trust cosmological conclusions from low ℓ modes!

dropping low ℓ in TT and TE would

give stronger upper limit on τ,

provide a red spectrum ($n < 1$),

stronger limit on running,

allow for more tensor modes

Summary

results for cleaned WMAP full sky maps:

quadrupole and octopole

are aligned at $> 99\%$CL

are correlated with Ecliptic at $> 99.9\%$CL

are correlated with Dipole at $> 99.7\%$CL

first hints for odd behaviour of higher ℓ multipoles

known foregrounds cannot explain effect

cut skies reduce statistical significance