Preferred Axis in Cosmology

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REFERENCES:

Naselsky, **WZ**, Kim & Chen, ApJ (2012);

WZ, Wu & Zhang, Int.J.Mod.Phys.D (2013);

WZ, Phys.Rev.D (2014);

Cheng, **WZ**, Huang & Santos, Phys.Lett.B (2016);

WZ & Santos, the Universe (2016).

Standard Cosmological Model

- Based on various cosmological observations, including CMB, SNIa, LSS, BAO, lensing, et al., people have built the so-called ”standard model”: inflation+LCDM. This model depends on the following assumptions:

1. In large scale, the Universe is isotropic and homogeneous

2. General relativity is the correct theory that describes gravity on all macroscopic scales

3. The main components in Universe is: baryon + CDM + DE

4. Primordial fluctuations were created as quantum fluctuations, which gave rise to structure formation

Large-scale Anomalies

- At the same time, a number of large-scale "anomalies" have also been reported. It was noticed that, some of them are directional dependent:

Alignment of CMB low multipoles

Large-scale velocity flows

Alignment of polarization of QSOs

Directional dependence of CMB parity violation

Anisotropy of cosmic acceleration

Anisotropy of the fine structure constant

(see W.Zhao & L.Santos, arXiv:1604.05484 as a review)

OUTLINE

- **CMB parity violation**
- **Directional dependence of CMB parity violation**
- **Comparing with other preferred axes**
- **Possible explanations**

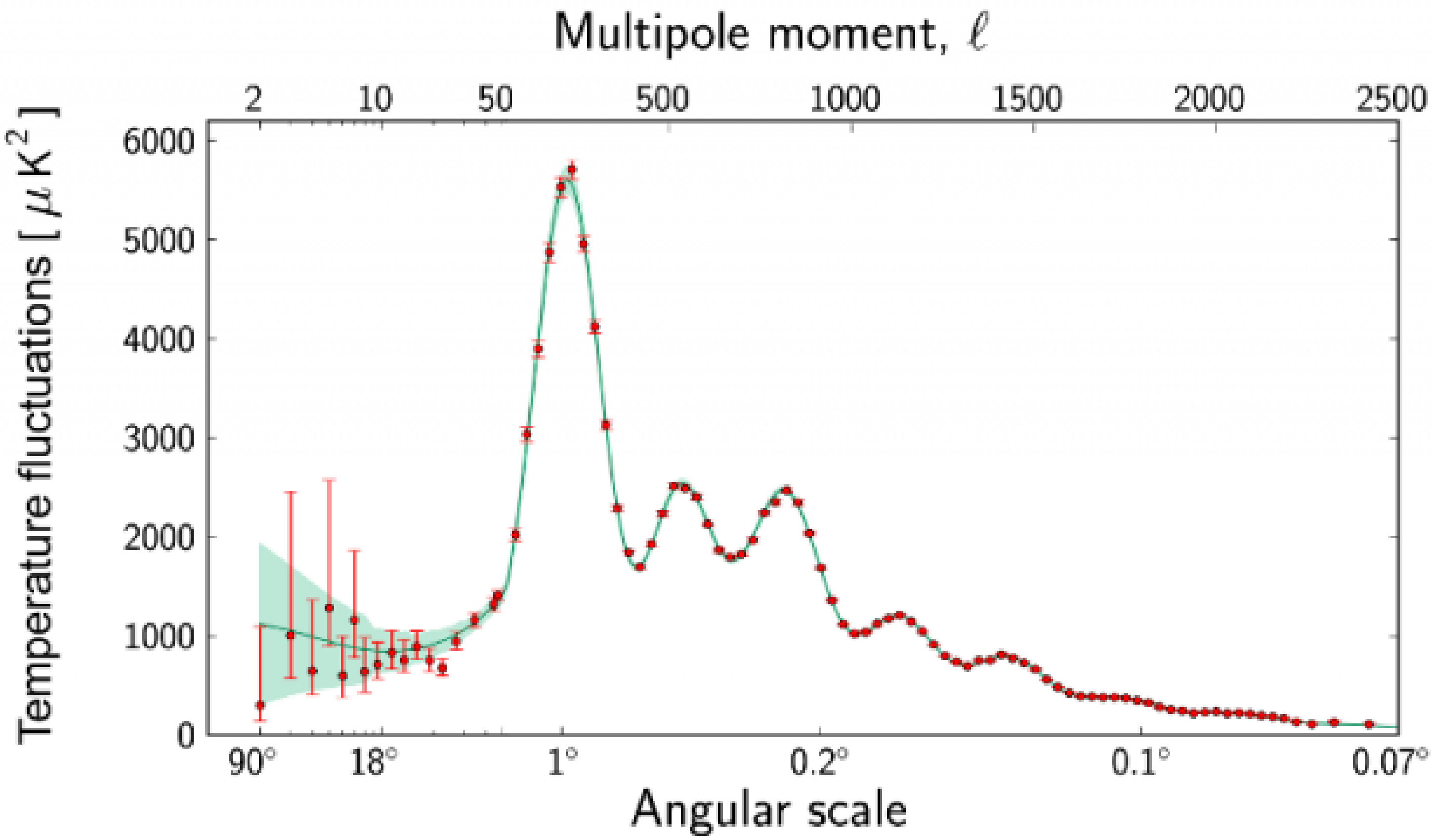
OUTLINE

- **CMB parity violation**
- **Directional dependence of CMB parity violation**
- **Comparing with other preferred directions**
- **Possible explanations**

SCIENTIFIC METHOD / SCIENCE & EXPLORATION

First Planck results: the Universe is still weird and interesting

We get a new view of the cosmic microwave background, courtesy of the ESA.



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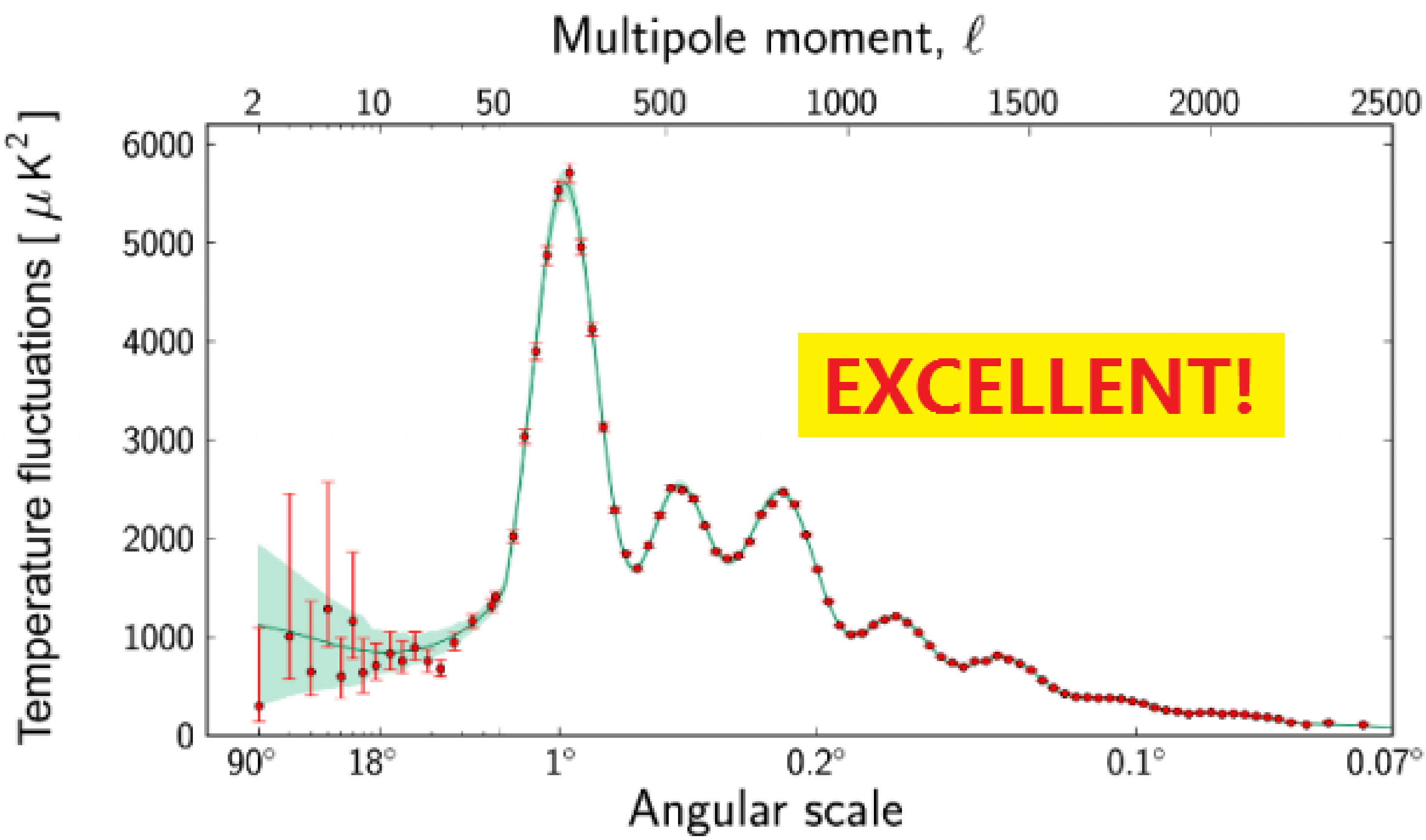

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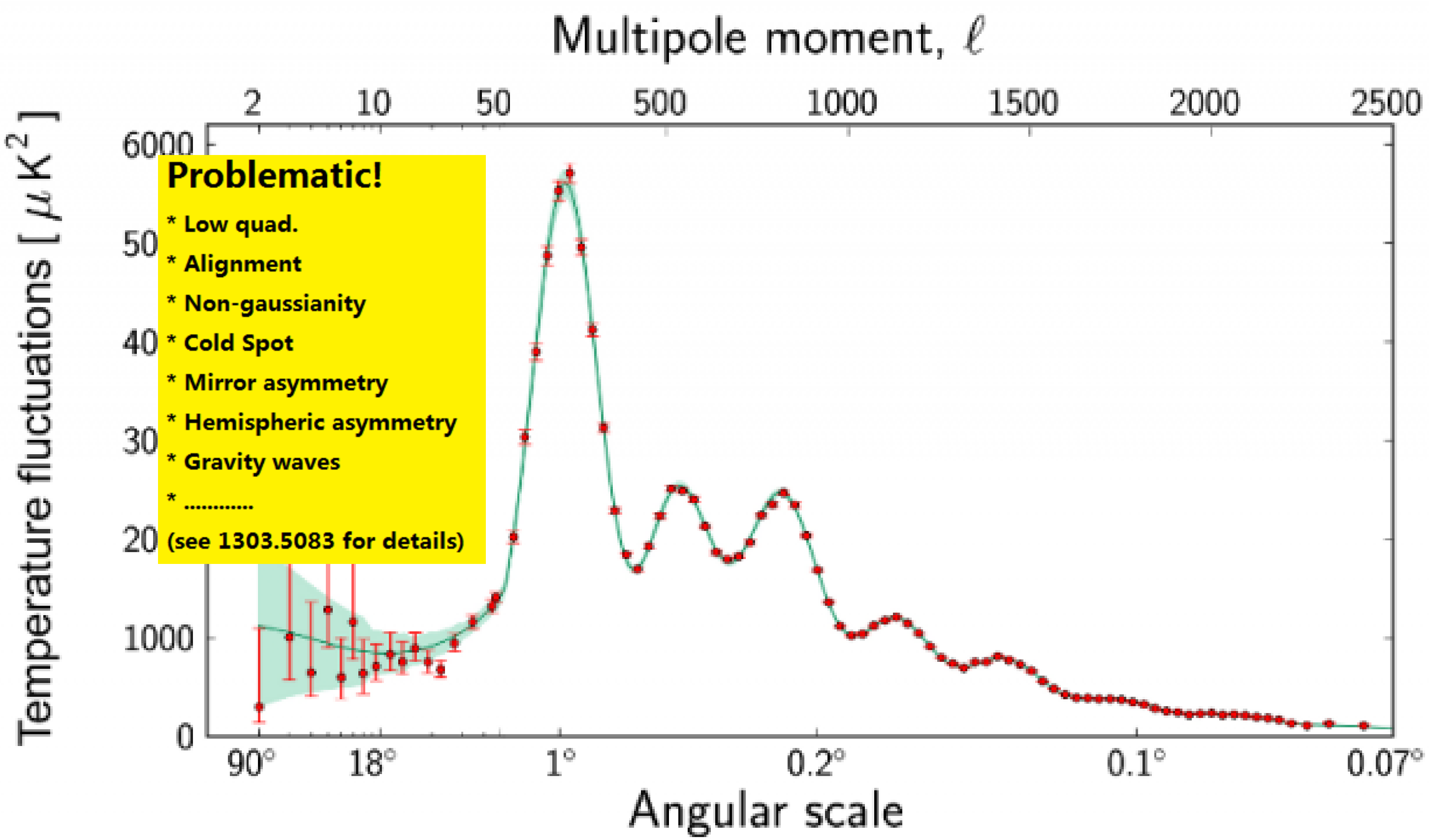
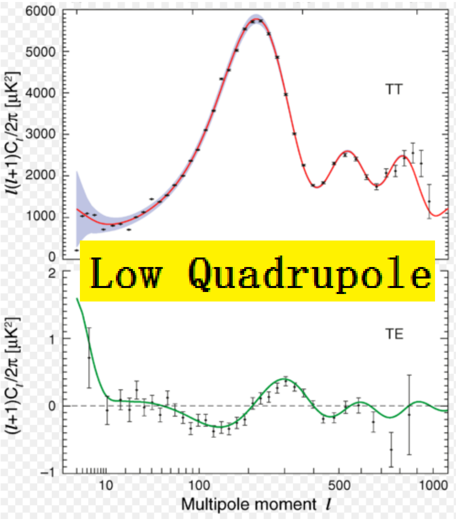
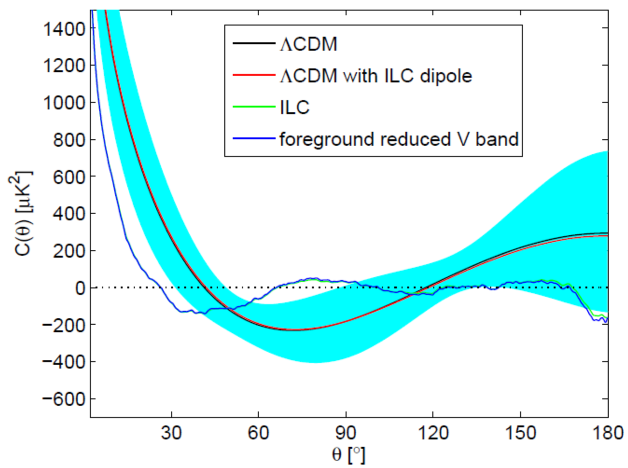


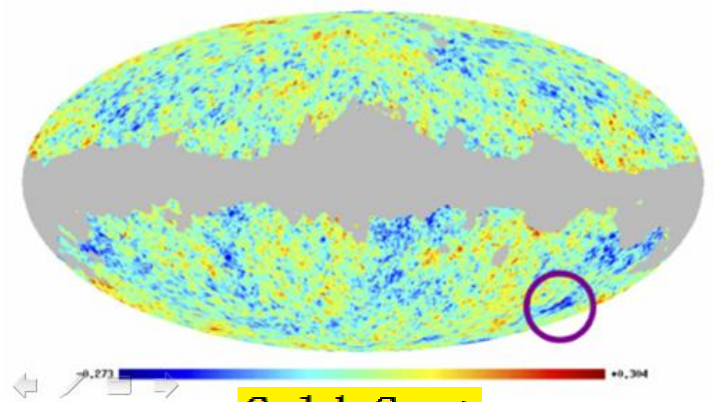
Large-scale CMB Anomalies

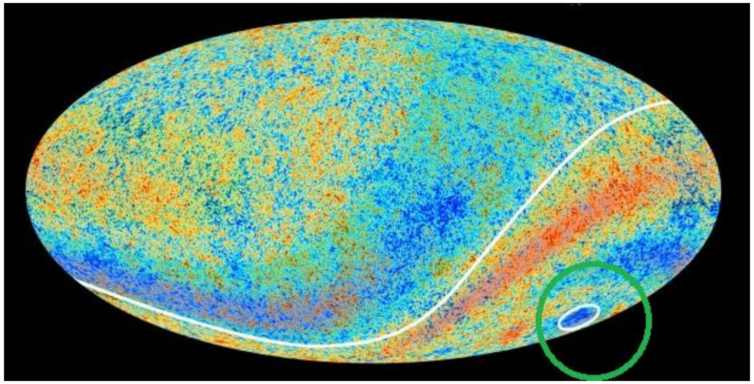


Low Quadrupole



Lack of large-scale correlation


Cold Spot


CMB Power Asymmetry

- Parity Asymmetry
- Mirror Asymmetry
- South-North hemisphere asymmetry
- Third peak of TT power spectrum asymmetry
- Large-scale quadrant asymmetry
- Alignment of the low multipoles
- ………

See arXiv:1001.4613 (WMAP), 1303.5083 (1-yr Planck), 1506.07135 (3-yr Planck) as reviews

CMB power spectra and the Gaussian distribution

The temperature fluctuation of CMB anisotropies can be decomposed as follows:

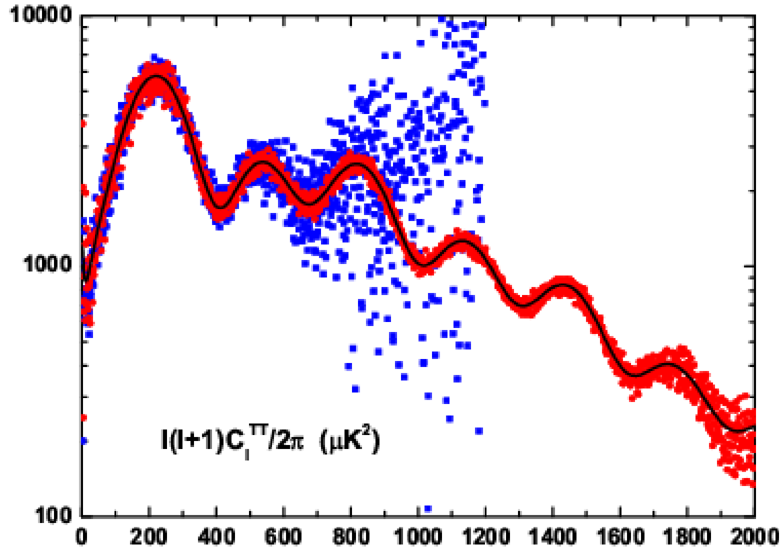
$$\Delta T(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi),$$

where a_{lm} are the coefficients, which satisfy the Gaussian distribution in the standard inflationary scenario. The power spectrum is defined as $C_l = \langle a_{lm} a^*_{lm} \rangle$, where the bracket denote the ensemble average.

In order to estimate the power spectrum, one can define the unbiased estimator as

$$\hat{C}_l = \frac{1}{2l+1} \sum_{m=-l}^{l} a_{lm} a^*_{lm},$$

which satisfies the χ^2-distribution with the expectation value $\langle \hat{C}_l \rangle = C_l$.



CMB parity asymmetry

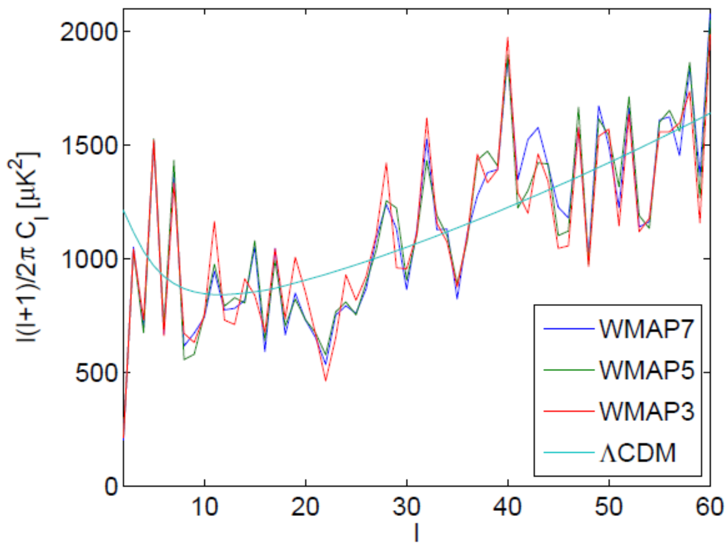


FIG. 1: CMB power spectrum: WMAP 7 year data (blue), WMAP 5 year data (green) and WMAP 3 year data (red), ΛCDM model (cyan)

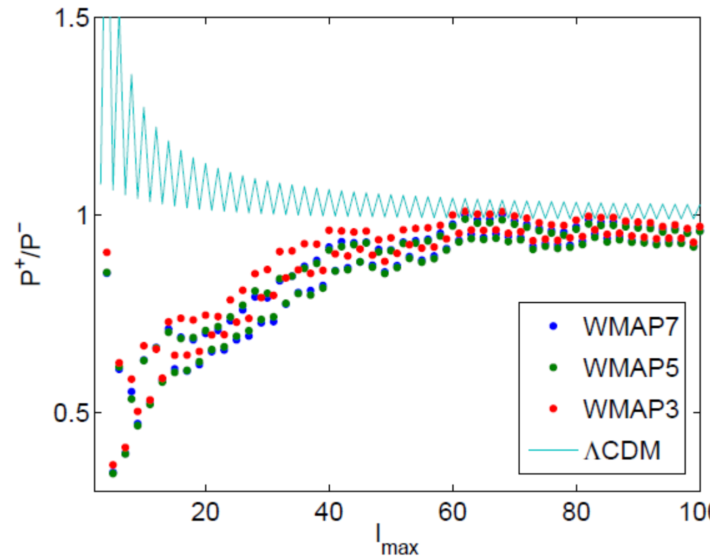


FIG. 3: P^+/P^- of WMAP data and ΛCDM

Even number multipoles lower than the odd

$$P^+ = \sum_{l=2}^{l_{\max}} \cos^2\left(\frac{l\pi}{2}\right) \frac{l(l+1)}{2\pi} C_l,$$

$$P^- = \sum_{l=2}^{l_{\max}} \sin^2\left(\frac{l\pi}{2}\right) \frac{l(l+1)}{2\pi} C_l,$$

where P^+ and P^- are the sum of $l(l+1)/2\pi\ C_l$ for even and odd multipoles respectively.

Symmetry and anti-symmetry of the CMB anisotropy pattern

Jaiseung Kim,* Pavel Naselsky, and Martin Hansen

Quantify parity asymmetry

$g(\ell)$ parameter and p-value(ℓ). The parity asymmetry at $\ell = 22$ is most anomalous, with a corresponding p-value in the range 0.002–0.004. Finally, the statistical significance of the parity asymmetry (i.e., low p-value) increases when we increase ℓ_{max} up to 22–25. Therefore, the odd parity preference cannot simply be attributed to the low quadrupole power. It is plausible the low quadrupole power is not an isolated anomaly, but that it shares an origin with the odd parity preference (see for details Kim & Naselsky 2010a; Naselsky et al. 2012; Kim & Naselsky 2010b).

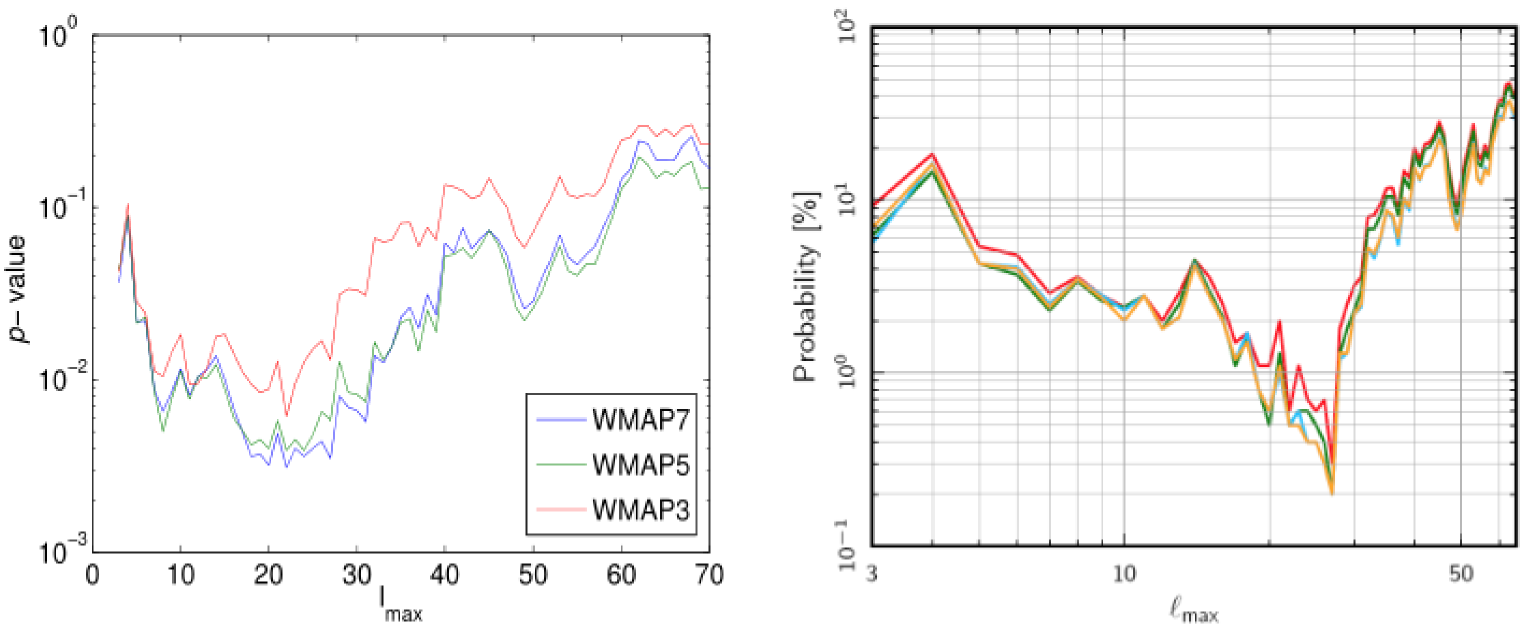
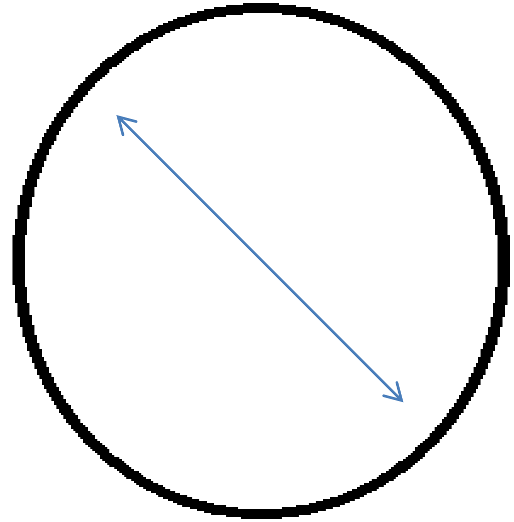


FIG. 2: Left panel: Probability of getting P^+/P^- as low as WMAP data for multipole range $2 \leq \ell \leq \ell_{max}$ [36]. Right panel: Probability of getting P^+/P^- as low as Planck Commander (red), NILC (orange), SEVEM (green), SMICA (blue) data for multipole range $2 \leq \ell \leq \ell_{max}$ [16].

Correlation (or anti-correlation) of the CMB temperatures in the two opposite directions!



The temperature fluctuations of CMB anisotropy can be conveniently decomposed as follows:

$$\Delta T(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi), \qquad (1)$$

The power spectrum is

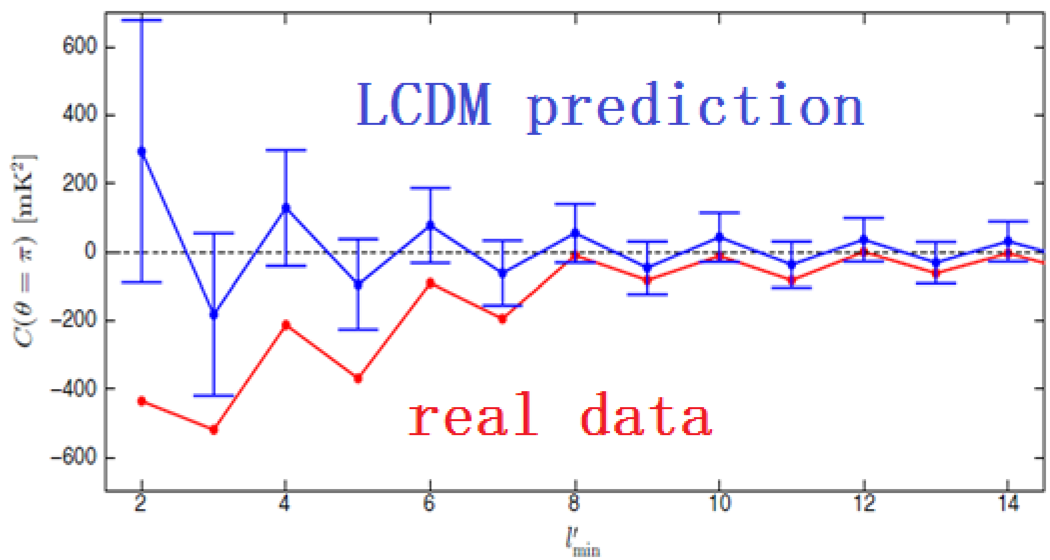
$$C(l) = \frac{1}{2l+1} \sum_{m=-l}^{l} a_{lm} a^*_{lm}$$

$$C_{\rm th}(l) = \langle C(l) \rangle = \frac{1}{2l+1} \sum_{m=-l}^{l} \langle a_{lm} a^*_{lm} \rangle$$

$$C_{\rm th}(\Theta) \equiv \langle \Delta T(\hat{\mathbf{n}}) \Delta T(\hat{\mathbf{n}}') \rangle = \sum_{l=l_{\rm min}}^{\infty} \frac{2l+1}{4\pi} C_{\rm th}(l) P_l(\cos\Theta), \qquad (3)$$

$$C_{th}(\Theta = \pi) = \sum_{l=l_{\rm min}}^{\infty} \frac{2l+1}{4\pi} C_{th}(l)(\Gamma^+(l) - \Gamma^-(l)), \qquad (4)$$

$$\Gamma^+(l) \equiv \cos^2(\pi l/2), \; \Gamma^-(l) \equiv \sin^2(\pi l/2),$$



OUTLINE

- CMB parity violation
- **Directional dependence of CMB parity violation**
- Comparing with other preferred directions
- Possible explanations

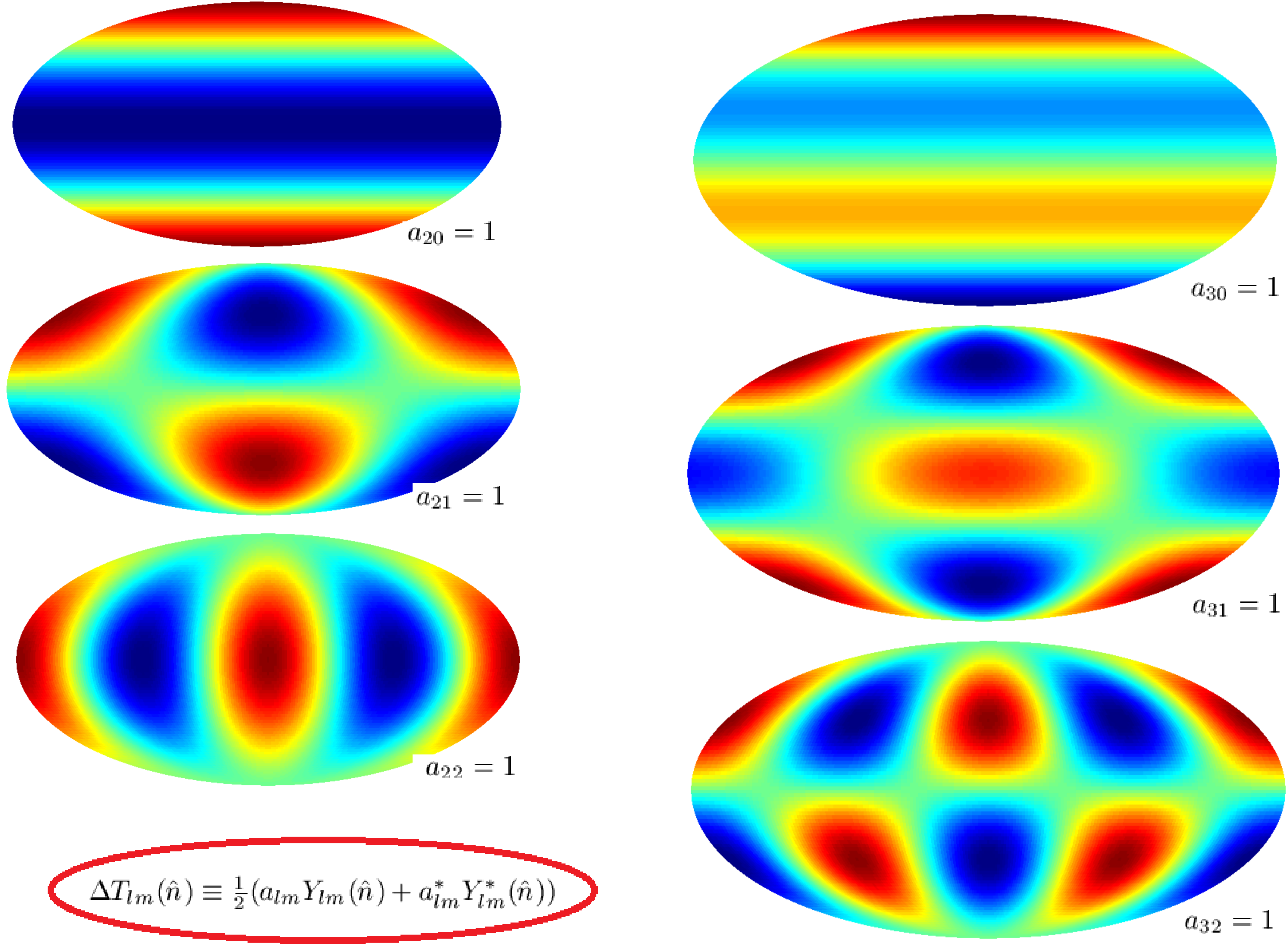
Problem!

- CMB parity statistics are all based on the "standard power spectrum", which is direction-independent by definition. Any statistics defined by them are rotational invariance!

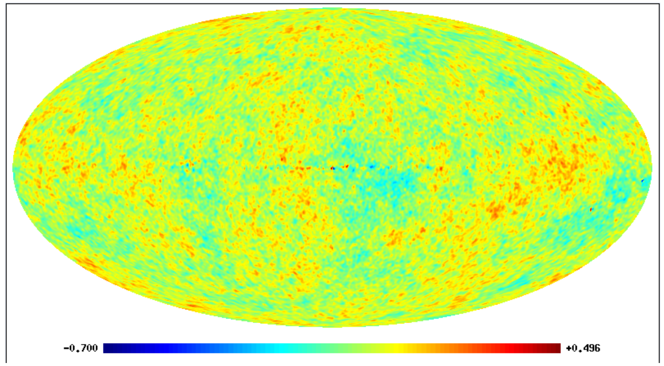
$$\Delta T(\theta,\phi)=\sum_{l=0}^{\infty}\sum_{m=-l}^{l}a_{lm}Y_{lm}(\theta,\phi), \qquad C(l)=\frac{1}{2l+1}\sum_{m=-l}^{l}a_{lm}a_{lm}^{*}$$

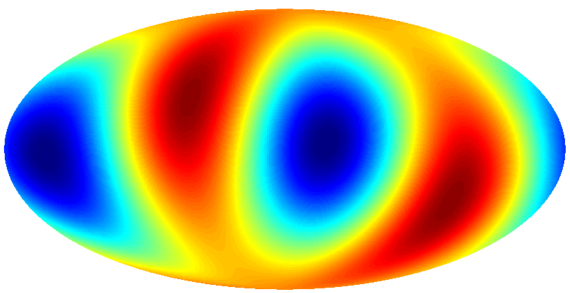
- However, in order to study the directional-dependent of the CMB data, we must define the direction-dependent spectrum.

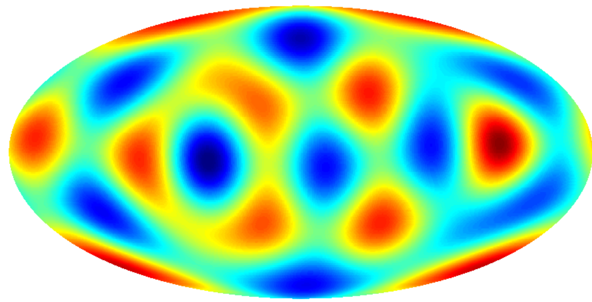
- Problem: how to define them?

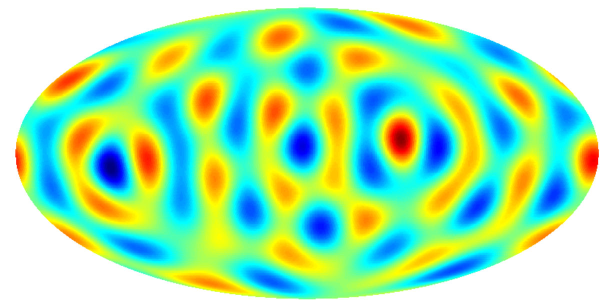


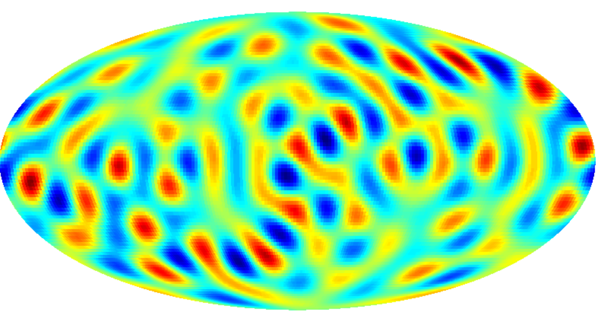
$$\Delta T_{lm}(\hat{n}) \equiv \frac{1}{2}(a_{lm} Y_{lm}(\hat{n}) + a^*_{lm} Y^*_{lm}(\hat{n}))$$

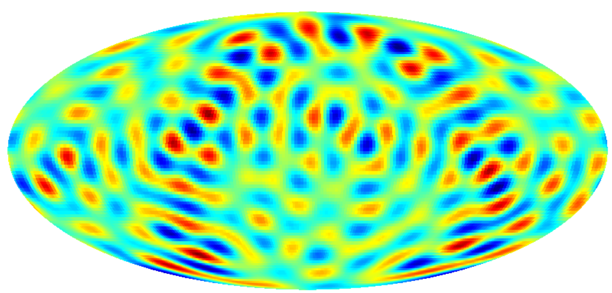

-0.700
+0.496

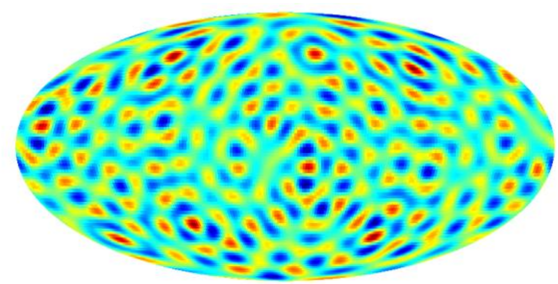












Directional statistic of the parity asymmetry

rotationally variant power spectrum $D(l)$, defined as

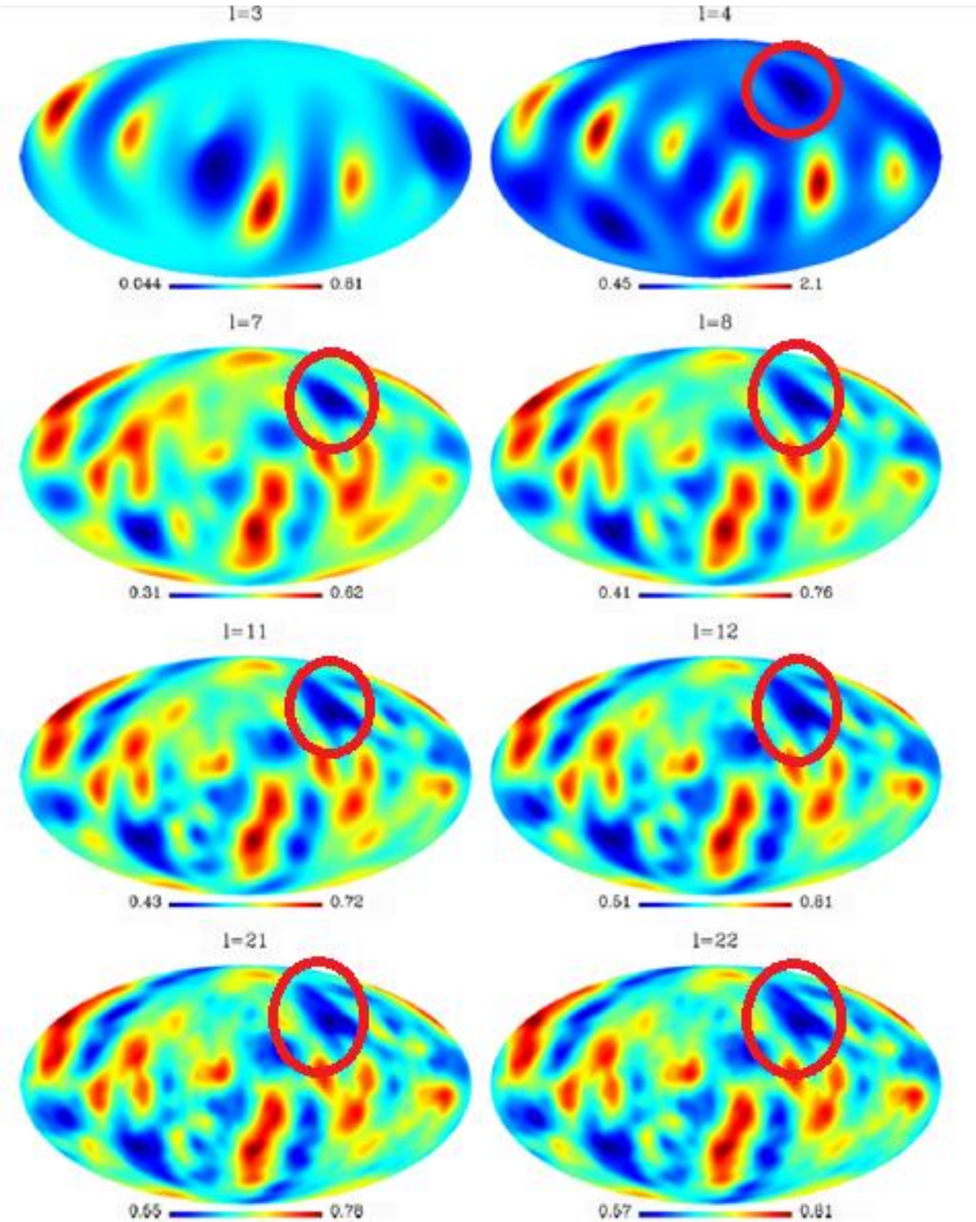
$$D(l) \equiv \frac{1}{2l+1} \sum_{m=-l}^{l} |a_{lm}|^2 (1 - \delta_{m0}), \qquad (7)$$

Now, we can study the power spectrum $D(l)$ in any coordinate system. Imagining the Galactic coordinate system is rotated by the Euler angle (ψ, θ, ϕ), the coefficients $a_{lm}(\psi, \theta, \phi)$ in this

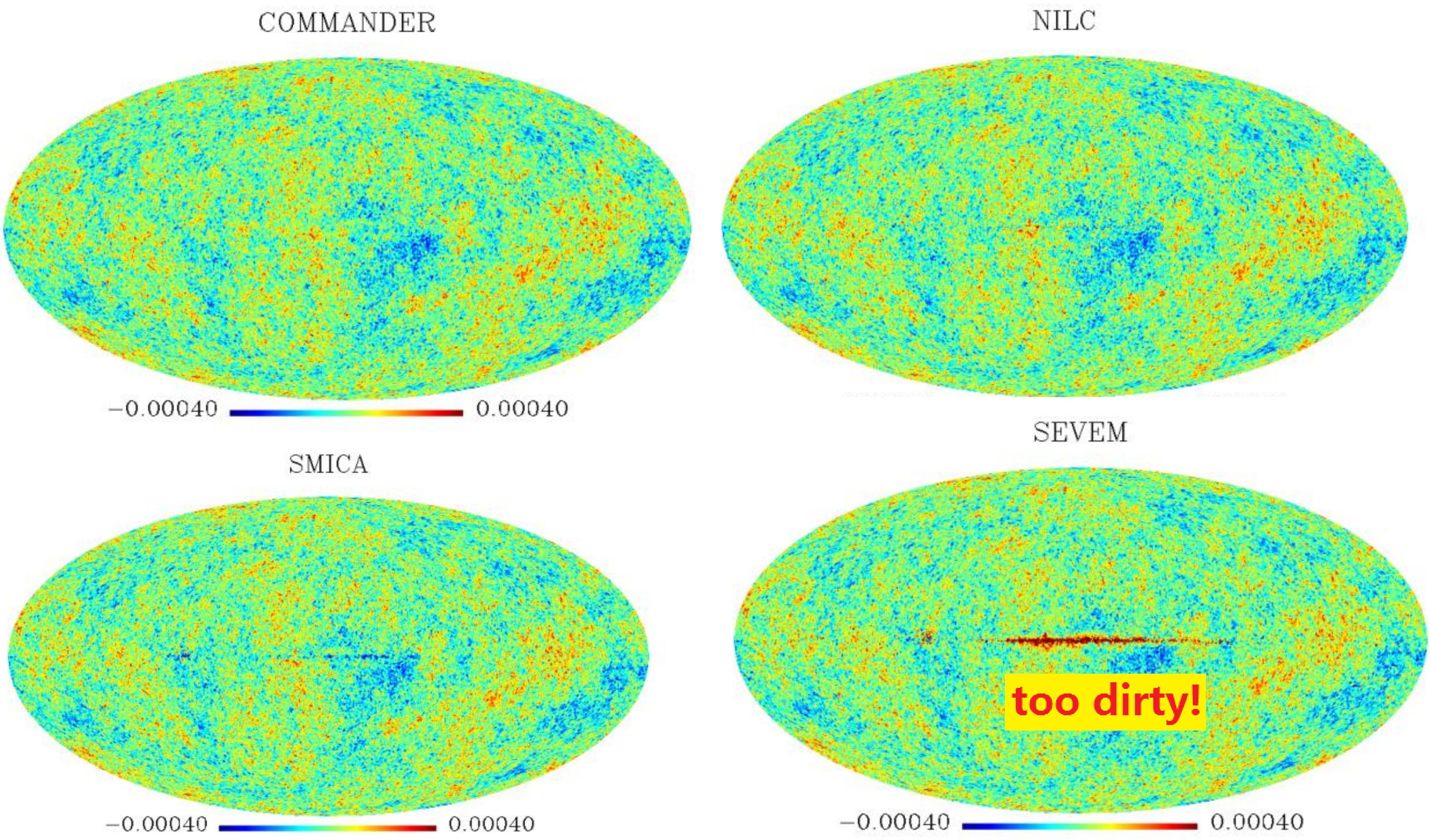
Now, we can define the rotationally variable parity parameter $G(l; \mathbf{q})$ by replacing $C(l)$ in Equation (5) with $D(l; \mathbf{q})$, and estimate the maxima and minima of $G(l; \mathbf{q})$ for different Euler angles $\mathbf{q}$. By the definition, the parity parameter $G(l; \mathbf{q})$ depends

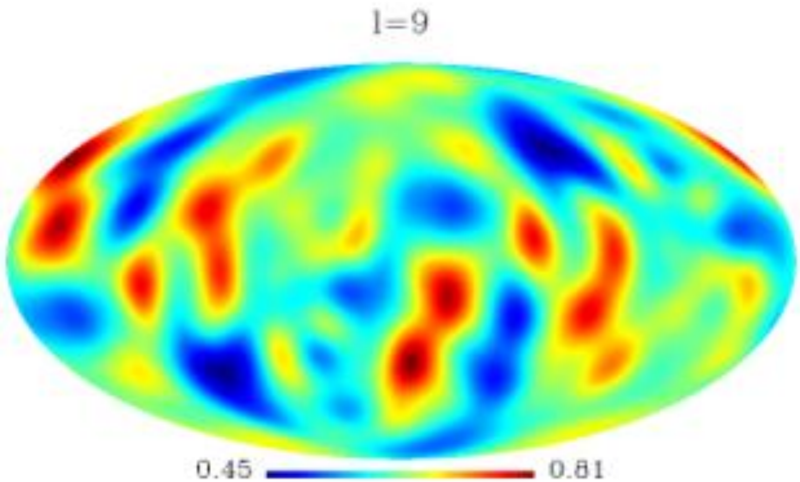
Defining the statistic:

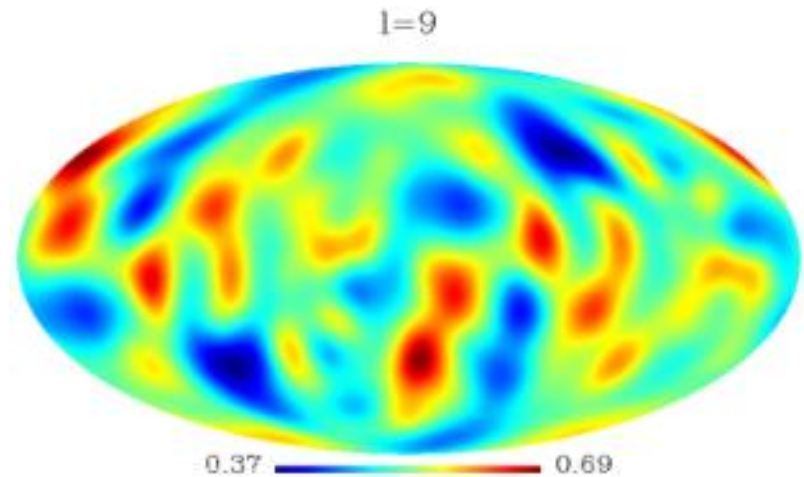
$$G(l; \hat{\mathbf{q}}) \equiv \frac{\sum_{l'=2}^{l_{\max}} \frac{2l'+1}{4\pi} D(l'; \hat{q}) \Gamma^{+}(l')}{\sum_{l'=2}^{l_{\max}} \frac{2l'+1}{4\pi} D(l'; \hat{q}) \Gamma^{-}(l')}$$

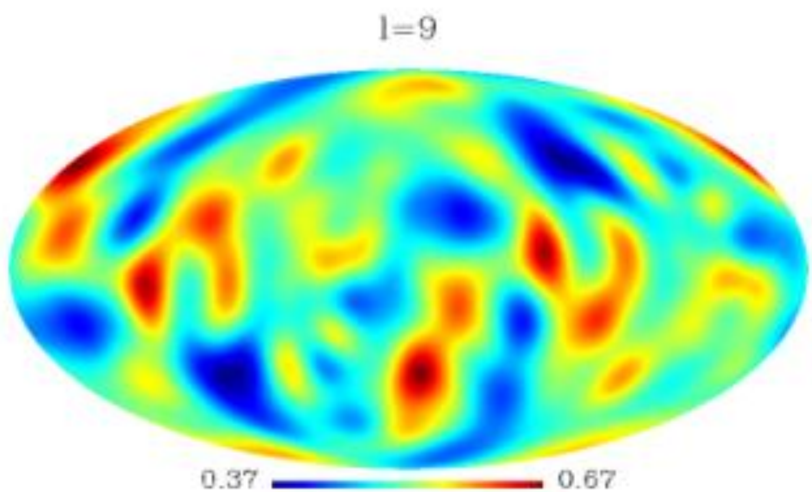


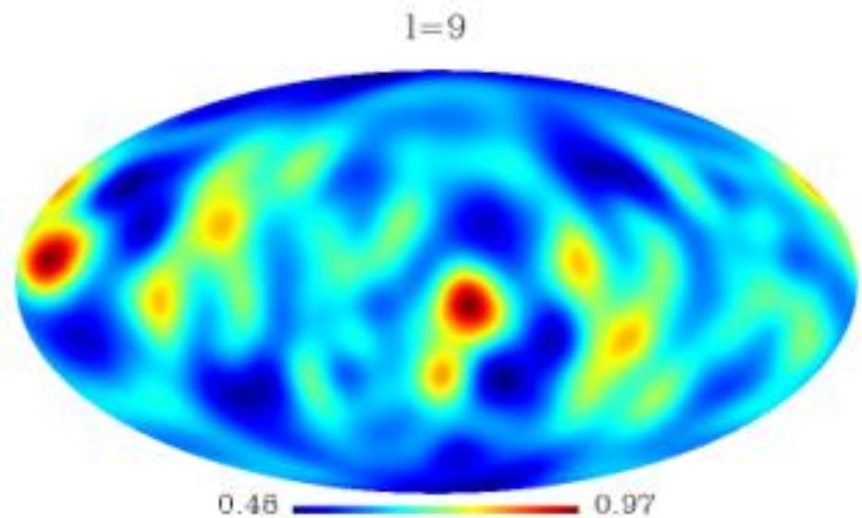
Independent of CMB maps




l=9
0.45
0.81


l=9
0.37
0.69


l=9
0.37
0.67


l=9
0.46
0.97

Independent of the definition of statistic

$$g_1(l,\hat{\mathbf{q}}) = \frac{\sum_{l'=2}^{l} l'(l'+1)D_{l'}(\hat{\mathbf{q}})\Gamma_{l'}^{+}}{\sum_{l'=2}^{l} l'(l'+1)D_{l'}(\hat{\mathbf{q}})\Gamma_{l'}^{-}},$$

$$g_2(l,\hat{\mathbf{q}}) = \frac{\sum_{l'=2}^{l}(2l'+1)D_{l'}(\hat{\mathbf{q}})\Gamma_{l'}^{+}}{\sum_{l'=2}^{l}(2l'+1)D_{l'}(\hat{\mathbf{q}})\Gamma_{l'}^{-}},$$

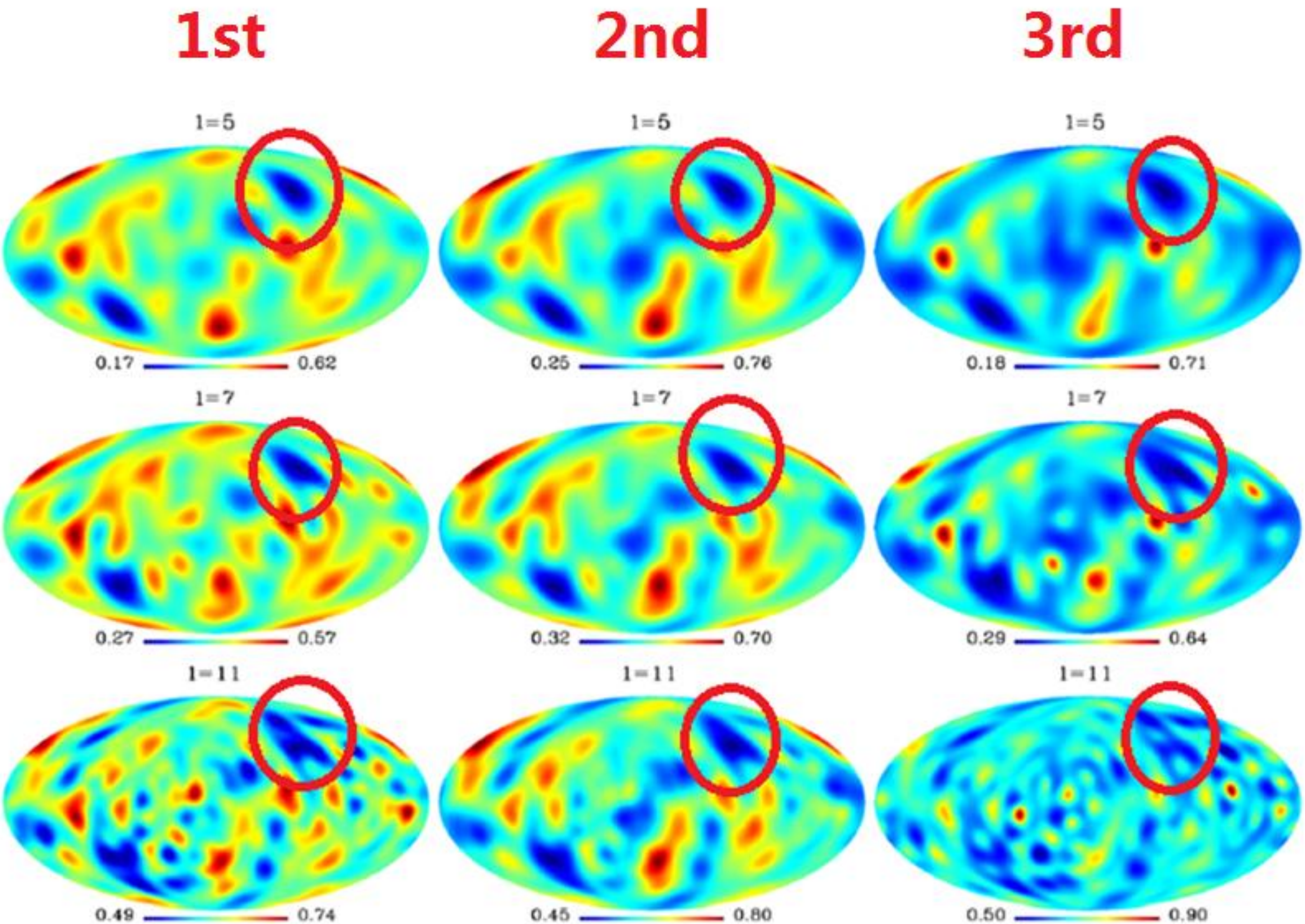
$$g_3(l,\hat{\mathbf{q}}) = \frac{2}{l-1}\sum_{l'=3}^{l}\frac{(l'-1)l'D_{l'-1}(\hat{\mathbf{q}})}{l'(l'+1)D_{l'}(\hat{\mathbf{q}})},$$

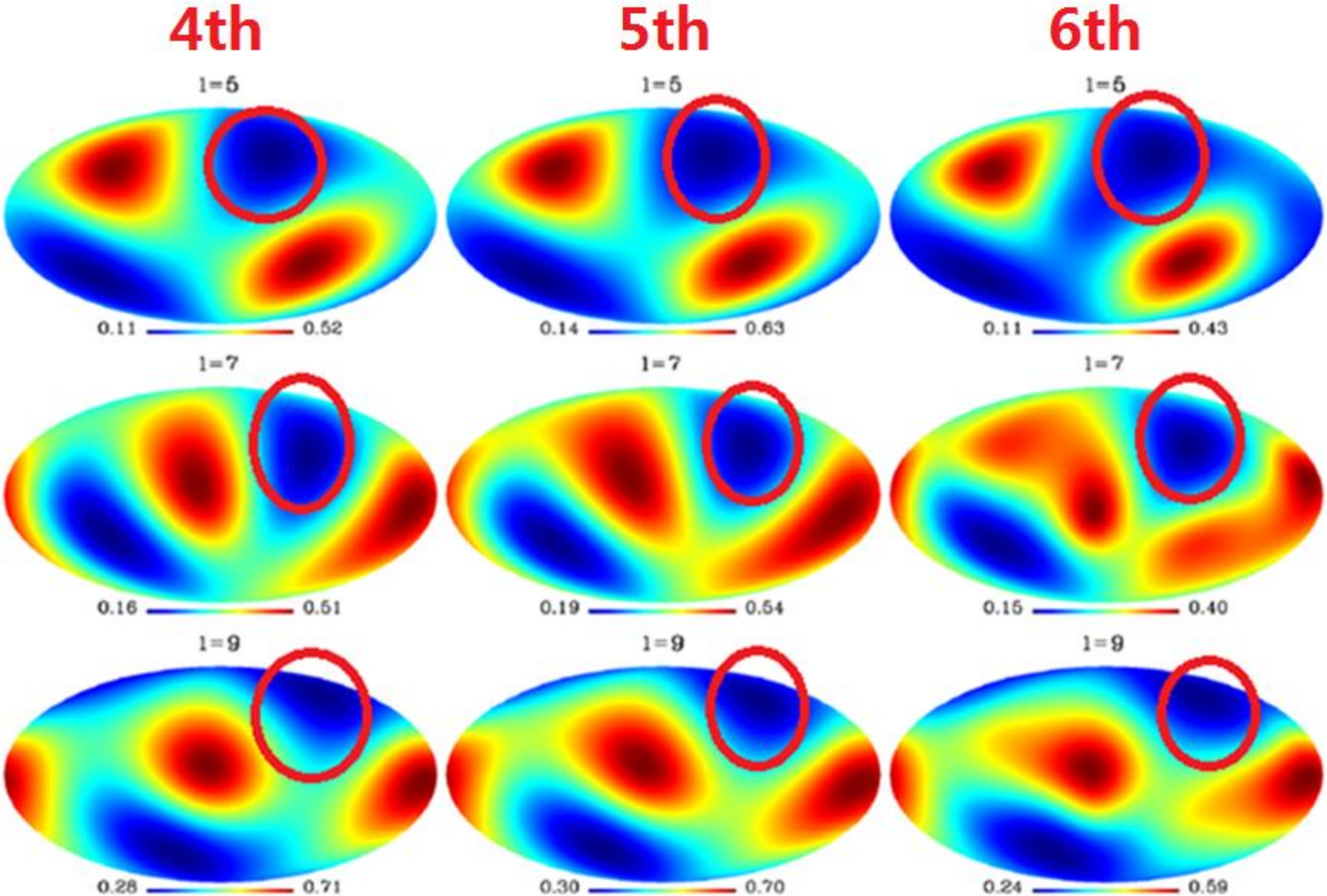
$$D_l(\hat{\mathbf{q}}) \equiv \frac{1}{2l}\sum_{m=-l}^{l}|a_{lm}(\hat{\mathbf{q}})|^2(1-\delta_{m0}).$$

$$\tilde{D}_l \equiv \frac{1}{2l+1}\sum_{m=-l}^{l} m^2|a_{lm}|^2.$$

The definitions of six directional statistics

Number of statistic	Definition
1st	$g_1(l,\hat{\mathbf{q}})$ with $D_l(\hat{\mathbf{q}})$
2nd	$g_2(l,\hat{\mathbf{q}})$ with $D_l(\hat{\mathbf{q}})$
3rd	$g_3(l,\hat{\mathbf{q}})$ with $D_l(\hat{\mathbf{q}})$
4th	$g_1(l,\hat{\mathbf{q}})$ with $\tilde{D}_l(\hat{\mathbf{q}})$
5th	$g_2(l,\hat{\mathbf{q}})$ with $\tilde{D}_l(\hat{\mathbf{q}})$
6th	$g_3(l,\hat{\mathbf{q}})$ with $\tilde{D}_l(\hat{\mathbf{q}})$

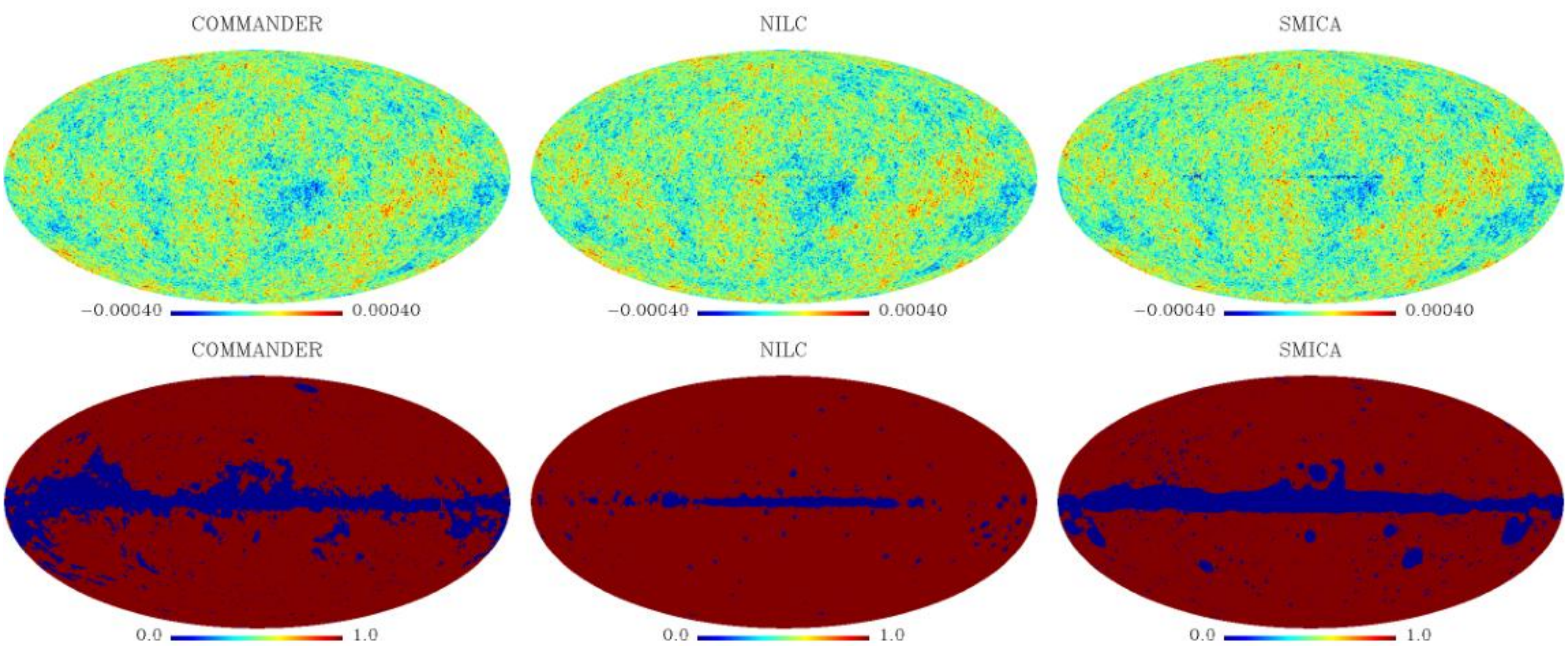

1st
2nd
3rd
l=5
0.17
0.62
l=5
0.25
0.76
l=5
0.18
0.71
l=7
0.27
0.57
l=7
0.32
0.70
l=7
0.29
0.64
l=11
0.49
0.74
l=11
0.45
0.80
l=11
0.50
0.90

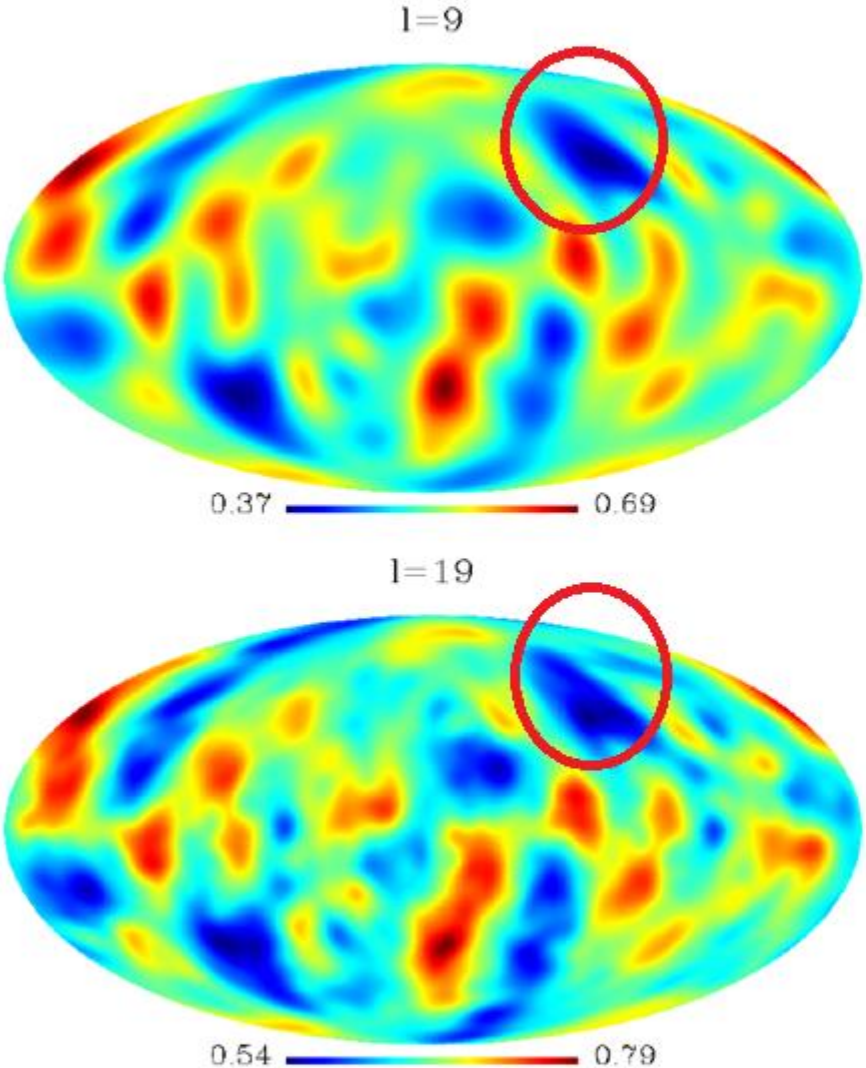

4th
5th
6th
l=5
0.11
0.52
l=5
0.14
0.63
l=5
0.11
0.43
l=7
0.16
0.51
l=7
0.19
0.54
l=7
0.15
0.40
l=9
0.28
0.71
l=9
0.30
0.70
l=9
0.24
0.59

Independent of used masks

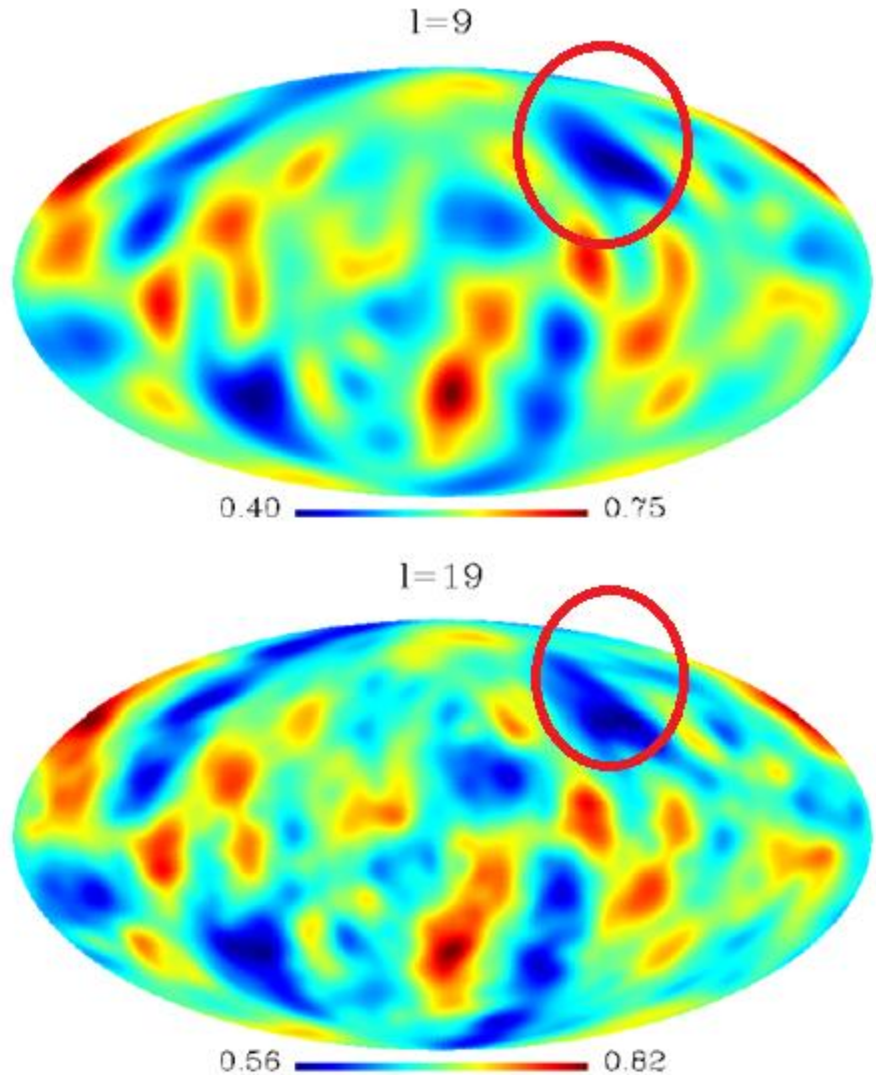
- In realistic observations, the foreground residuals are inevitable. So, is it possible that the preferred axis is caused by the foreground radiations?

- In order to avoid the contaminations, we should exclude the dirty regions by applying the proper mask, and do the similar analysis based on the masked CMB maps.





NILC no mask

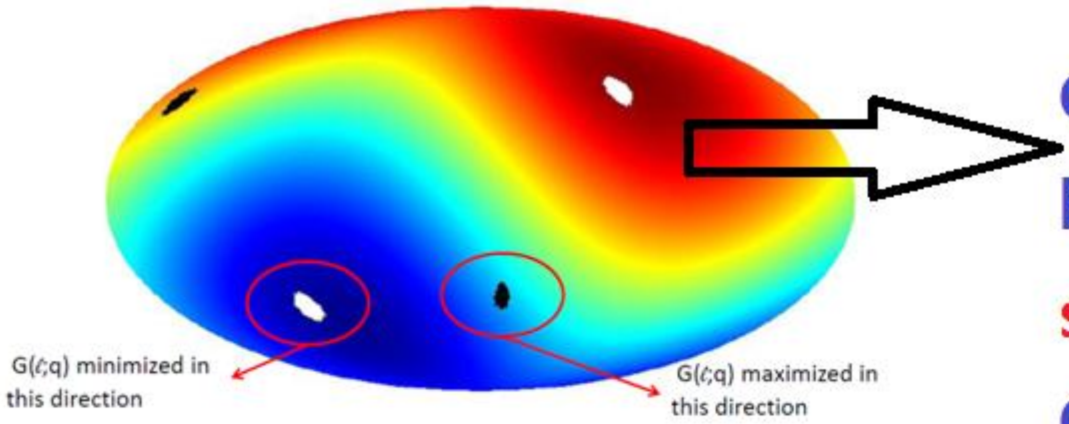


NILC with mask

OUTLINE

- CMB parity violation
- Directional dependence of CMB parity violation
- **Comparing with other preferred axes**
- Possible explanations

Strongly aligns with “CMB kinematic dipole”!



The direction of dipole according to WMAP 7 years data

CMB dipole is caused by the motion of solar system in the CMB rest frame

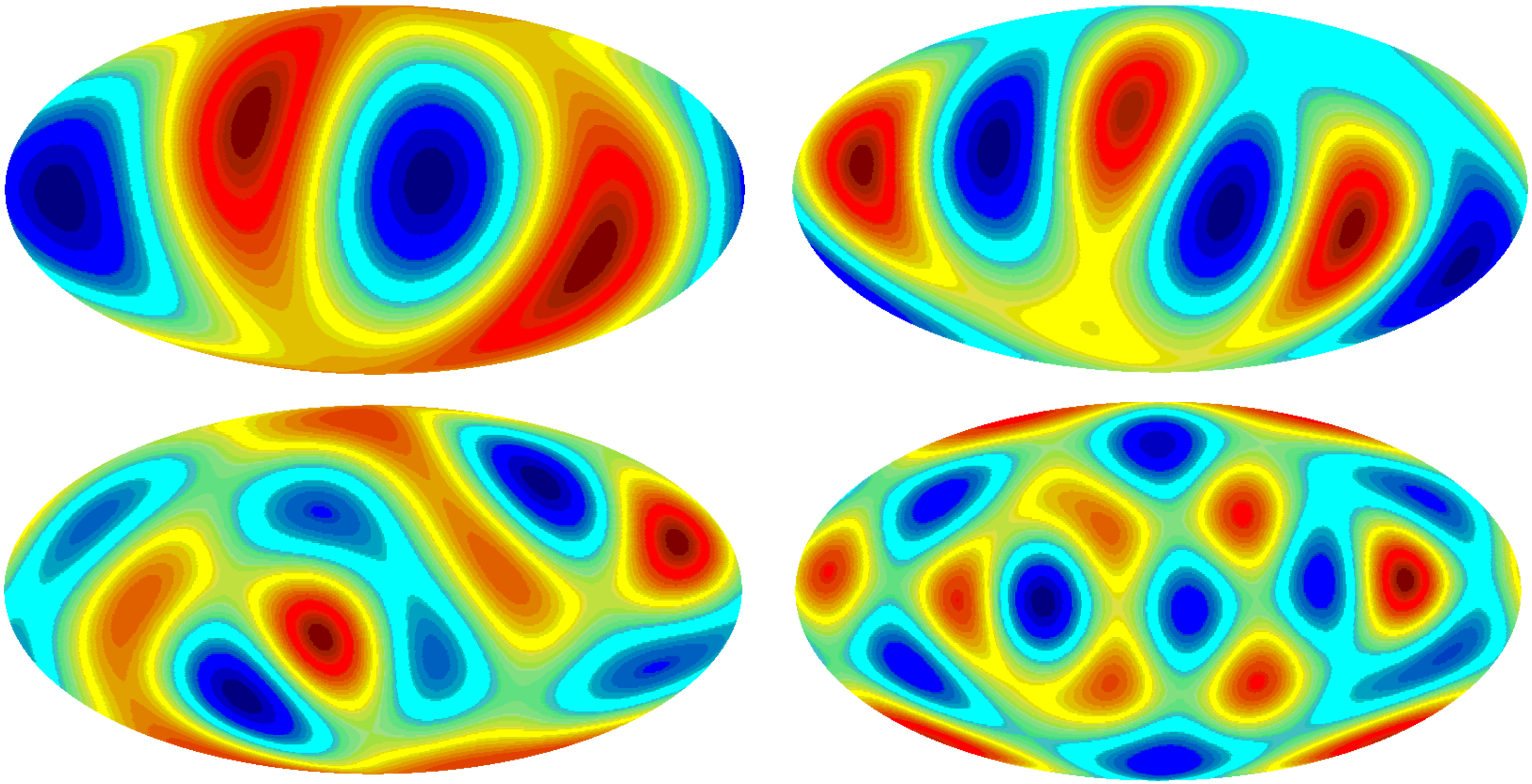
Table 1
The WMAP7 Kinematic Dipole Direction Compared with the Preferred Direction $\hat{\mathbf{q}} = (\theta, \phi)$, Where the Parity Parameter $G(l; \hat{\mathbf{q}})$ (Based on the Estimator in Equation (7)) is Minimized

	θ (°)	ϕ (°)	$\cos\alpha$[a]
KD	41.74	263.99	...
$l = 3$	85.22	204.61	0.400
$l = 4$	46.59	280.89	0.975
$l = 7$	48.19	279.14	0.976
$l = 8$	48.99	277.03	0.979
$l = 11$	49.77	277.73	0.976
$l = 12$	49.77	277.73	0.976
$l = 21$	51.32	283.36	0.957
$l = 22$	50.50	284.06	0.957

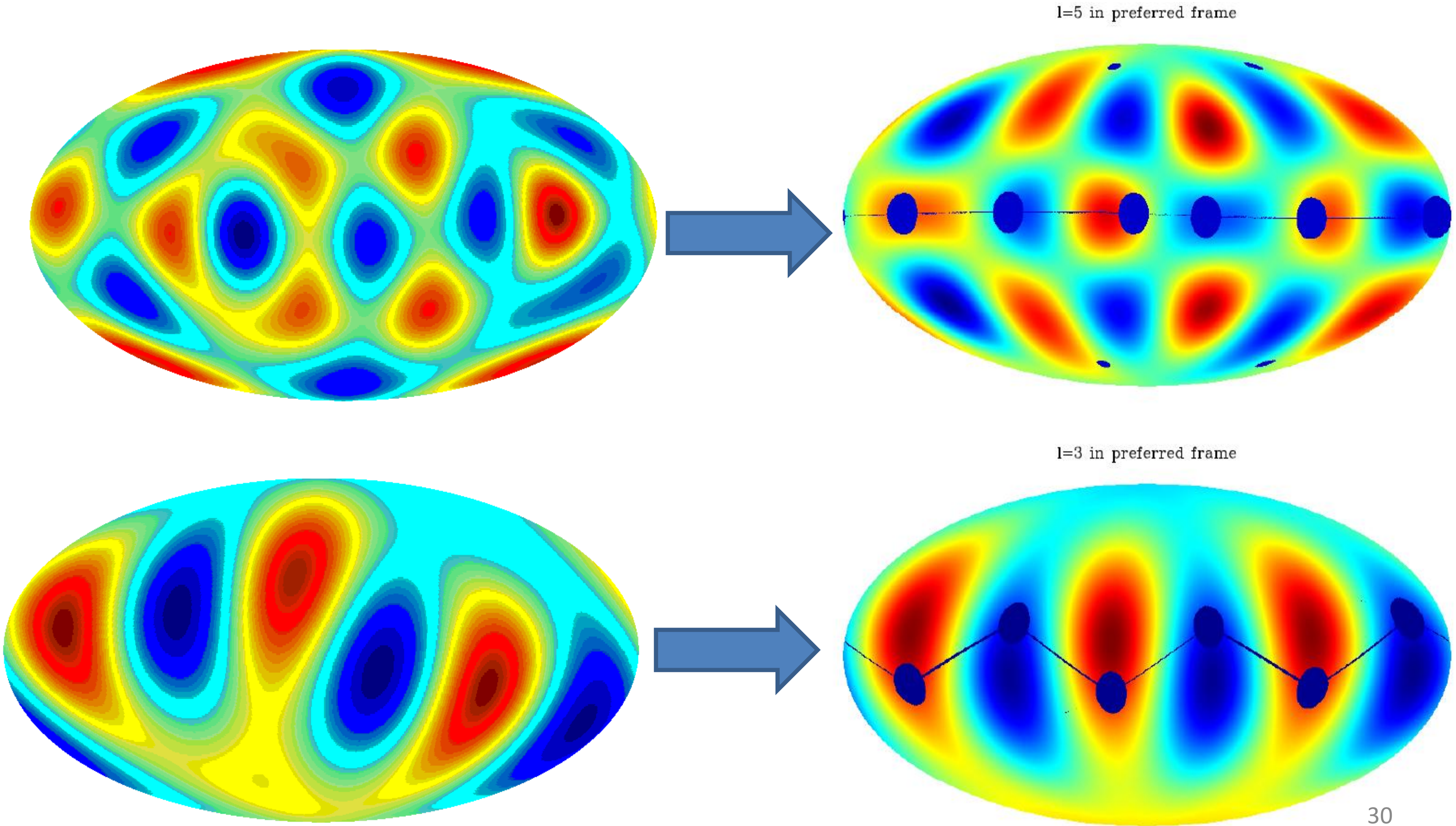
Aligning with other preferred axes

- CMB low multipoles (quadrupole, octopole, et al.)
- Large-scale velocity flows
- Polarization of QSOs
- Dipole in the handedness of spiral galaxies
- Dipole of cosmic dark energy
- Dipole of fine structure constant α

CMB Low Multipoles
------alignment of multipoles: l=2-5



Rotate the coordinate to the preferred frame



Examination of Evidence for a Preferred Axis in the Cosmic Radiation Anisotropy

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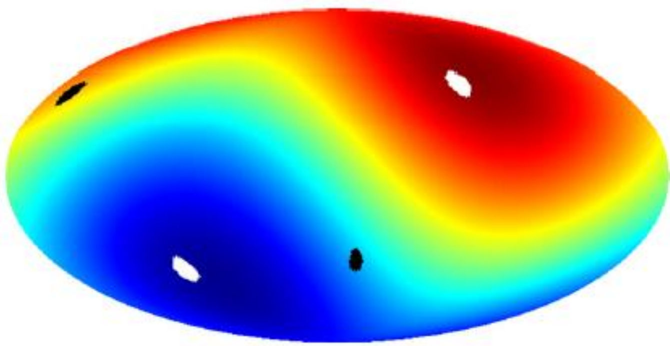
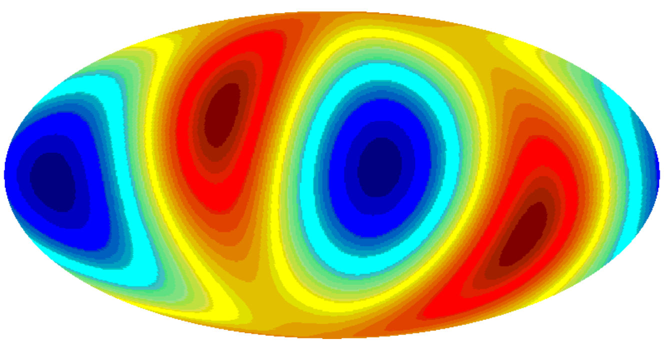
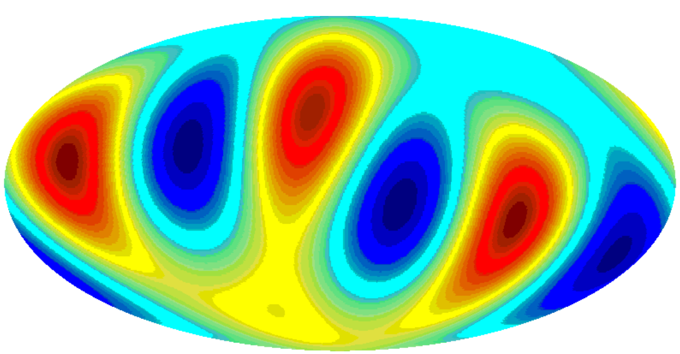
(Received 22 February 2005; published 11 August 2005)

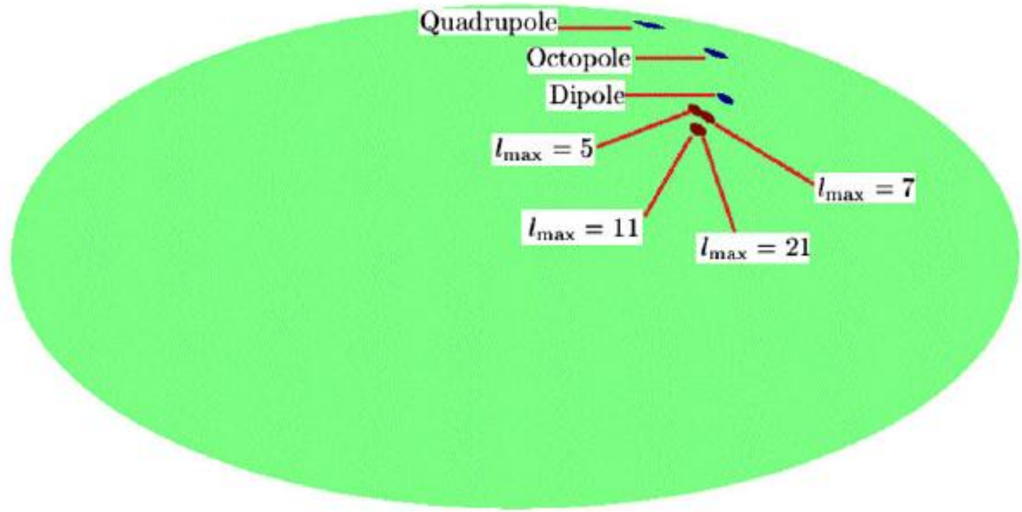
We examine previous claims for a preferred axis at $(b, l) \approx (60, -100)$ in the cosmic radiation anisotropy, by generalizing the concept of multipole planarity to any shape preference. Contrary to earlier claims, we find that the amount of power concentrated in planar modes for $l = 2, 3$ is not inconsistent with isotropy and Gaussianity. The multipoles' alignment, however, is indeed anomalous, and extends up to $l = 5$ rejecting statistical isotropy with a probability in excess of 99.9%. There is also an uncanny correlation of azimuthal phases between $l = 3$ and $l = 5$. We are unable to blame these effects on foreground contamination or large-scale systematic errors. This reappraisal may be crucial in identifying the theoretical model behind the anomaly.

Comparing with preferred directions in CMB parity asymmetry



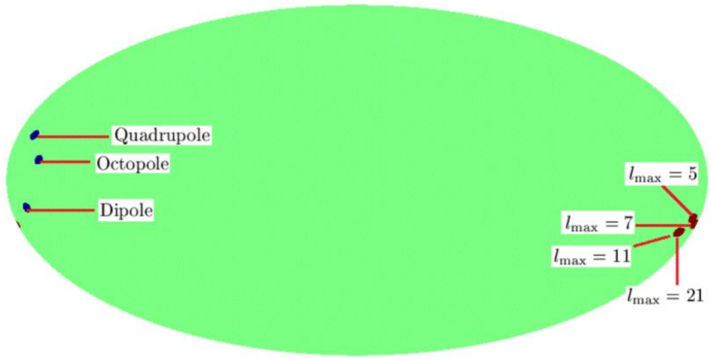






	$\theta[^\circ]$	$\phi[^\circ]$	$\lvert\cos\alpha\rvert$	$\langle\lvert\cos\theta_{ij}\rvert\rangle$	Δ_c/σ_c
$l_{\max} = 3$	90.00	23.20	0.3265	0.6066	0.90
	90.00	23.20	0.3265	0.6066	0.90
	90.00	23.20	0.3265	0.6066	0.90
$l_{\max} = 5$	45.80	281.07	0.9767	0.9015	3.40
	45.80	281.07	0.9767	0.9015	3.40
	45.80	281.07	0.9767	0.9015	3.40
$l_{\max} = 7$	48.19	277.73	0.9799	0.8979	3.37
	47.39	279.29	0.9782	0.8987	3.38
	52.83	267.89	0.9710	0.8915	3.32
$l_{\max} = 11$	52.08	284.06	0.9525	0.8744	3.17
	49.77	280.54	0.9697	0.8886	3.29
	53.58	226.41	0.8679	0.8793	3.21
$l_{\max} = 21$	52.08	285.47	0.9479	0.8721	3.15
	50.55	284.06	0.9575	0.8804	3.22
	21.32	131.90	0.5292	0.8295	2.79

The weird side of the Universe:
<u>Seeing in Ecliptic Coordinate System</u>



In plane of the ecliptic

Ecliptic alignment of CMB anisotropy

The Cosmic Microwave Background (CMB) radiation signature presents a direct large-scale view of the universe that can be used to identify whether our position or movement has any particular significance. There has been much publicity about analysis of results from the Wilkinson Microwave Anisotropy Probe (WMAP) and Planck mission that show both expected and unexpected anisotropies in the CMB.[1] The results appear to run counter to expectations from the Copernican Principle. The motion of the solar system, and the orientation of the plane of the ecliptic are aligned with features of the microwave sky, which on conventional thinking are caused by structure at the edge of the observable universe.[2][3]

Lawrence Krauss is quoted as follows in the referenced Edge.org article:[4]

> "But when you look at CMB map, you also see that the structure that is observed, is in fact, in a weird way, correlated with the plane of the earth around the sun. Is this Copernicus coming back to haunt us? That's crazy. We're looking out at the whole universe. There's no way there should be a correlation of structure with our motion of the earth around the sun — the plane of the earth around the sun — the ecliptic. That would say we are truly the center of the universe."

Some anomalies in the background radiation have been reported which are aligned with the plane of the Solar System, which contradicts the Copernican principle by suggesting that the Solar System's alignment is special.[5] Land and Magueijo dubbed this alignment the "axis of evil" owing to the implications for current models of the cosmos,[6] although several later studies have shown systematic errors in the collection of that data and the way it is processed.[7][8][9] Various studies of the CMB anisotropy data either confirm the Copernican principle,[10] model the alignments in a non-homogeneous universe still consistent with the principle,[11] or attempt to explain them as local phenomena.[12] Some of these alternate explanations were discussed by Copi, *et al.*, who claimed that data from the Planck satellite could shed significant light on whether the preferred direction and alignments were spurious.[13][14] Coincidence is a possible explanation. Chief scientist from WMAP, Charles L. Bennett suggested coincidence and human psychology were involved, *"I do think there is a bit of a psychological effect, people want to find unusual things."* [15]

Large-scale Velocity Flows

Large Scale Velocity Flows: ΛCDM predicts significantly smaller amplitude and scale of flows than what observations indicate. It has been found that the dipole moment (bulk flow) of a combined peculiar velocity sample extends on scales up to $100h^{-1}Mpc$ ($z \leq 0.03$) with amplitude larger than $400km/sec$ (Watkins, Feldman & Hudson 2009). The direction of the flow has been found consistently to be approximately in the direction $l \simeq 282°$, $b \simeq 6°$. Other independent studies have also found large bulk velocity flows on similar directions on scales of about $100h^{-1}Mpc$ (Lavaux *et. al.*, 2010) or larger (Kashlinsky *et. al.*, 2009). The expected rms bulk flow in the context of ΛCDM normalized with WMAP5 $(\Omega_{0m}, \sigma_8) = (0.258, 0.796)$ on scales larger than $50h^{-1}Mpc$ is approximately $110km/sec$. The probability that a flow of magnitude larger than $400km/sec$ is realized in the context of the above ΛCDM normalization (on scales larger than $50h^{-1}Mpc$) is less than 1%. A possible connection of such large scale velocity flows and cosmic acceleration is discussed by Tsagas (2010).

Polarization of QSOs

Large scale alignment in the QSO optical polarization data: Quasar polarization vectors are not randomly oriented over the sky with a probability often in excess of 99.9%. The alignment effect seems to be prominent along a particular axis in the direction $(l, b) = (267°, 69°)$ (Hutsemekers *et. al.*, 2005).

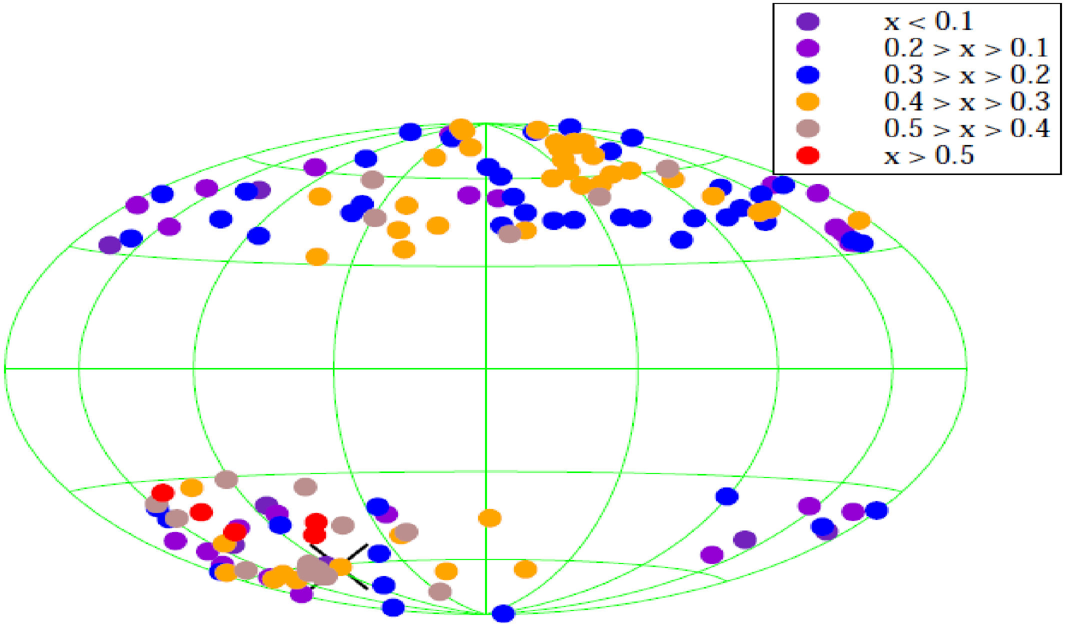


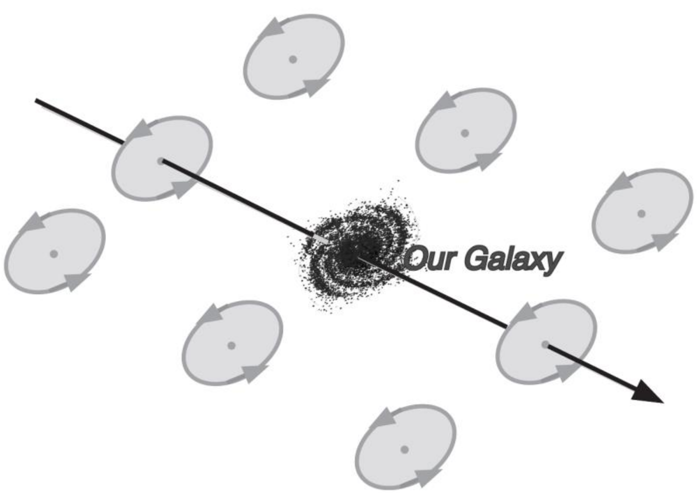
Figure 4: Optical polarization alignment observed by Hutsemékers [4] in (a) equatorial and (b) galactic coordinates. Here x refers to the correlation statistic, defined in text, with the number of nearest neighbours chosen to be 28. The data within the galactic plane was deleted [4] in order to minimize the effect of galactic extinction. Effects of population are taken into account in the construction of the prefered axis, shown as a black cross at $l = 85.94^o$, $b = -60.94^o$. Axial clustering is readily visible to the eye.

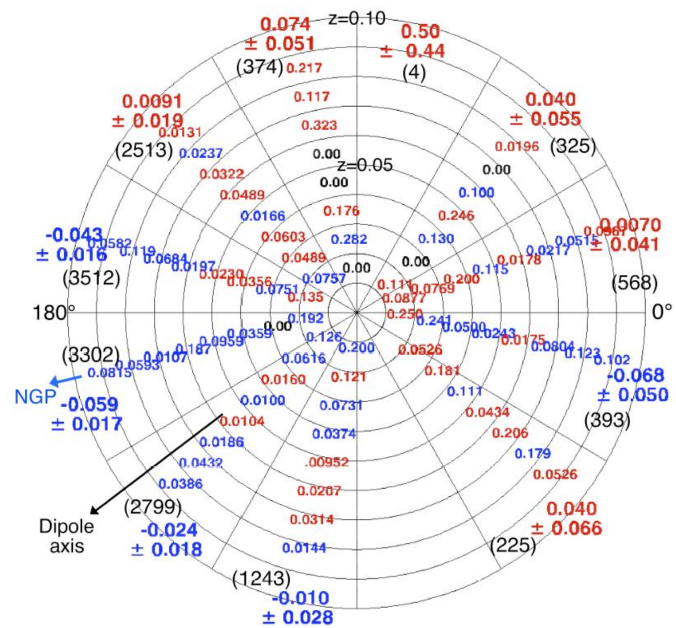
Dipole in the handedness of spiral galaxies

M.J.Longo, 2007a, 2007b, 2011

Abstract

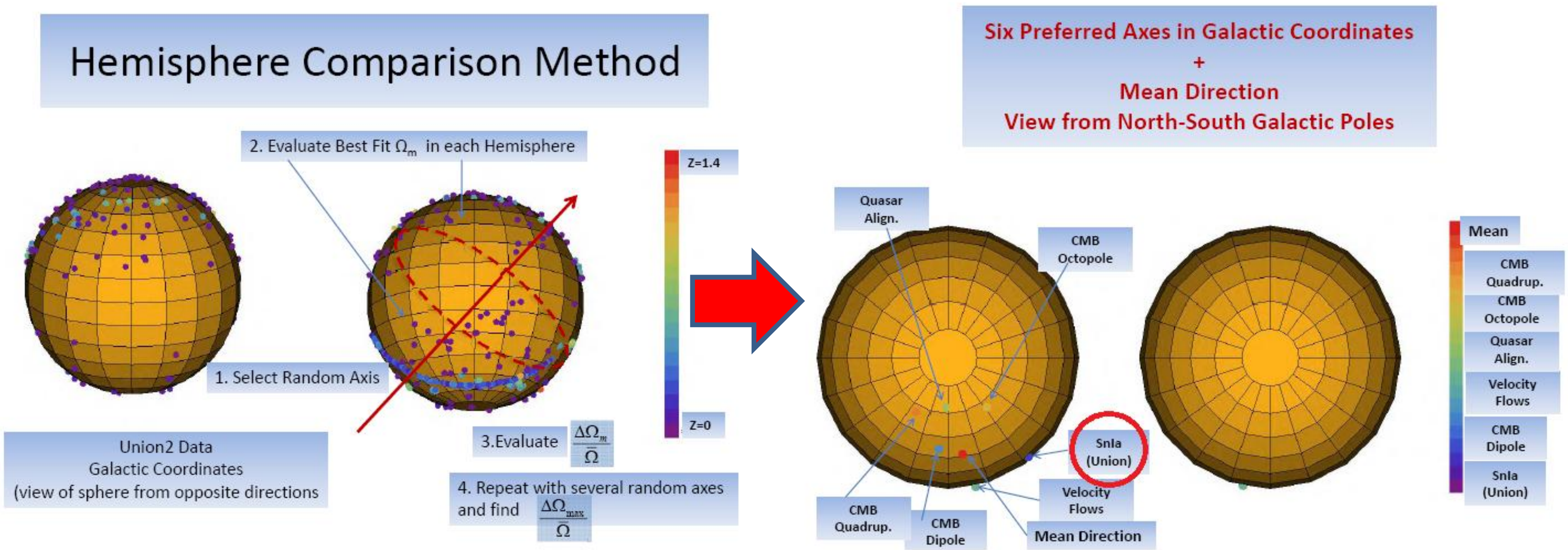
A preference for spiral galaxies in one sector of the sky to be left-handed or right-handed spirals would indicate a parity violating asymmetry in the overall universe and a preferred axis. This study uses 15158 spiral galaxies with redshifts <0.085 from the Sloan Digital Sky Survey. An unbinned analysis for a dipole component that made no prior assumptions for the dipole axis gives a dipole asymmetry of –0.0408±0.011 with a probability of occurring by chance of 7.9 x 10^{-4}. A similar asymmetry is seen in the Southern Galaxy spin catalog of Iye and Sugai. The axis of the dipole asymmetry lies at approx. (l, b) =(52°, 68.5°), roughly along that of our Galaxy and close to alignments observed in the WMAP cosmic microwave background distributions. The observed spin correlation extends out to separations ~210 Mpc/h, while spirals with separations < 20 Mpc/h have smaller spin correlations.





Dipole of cosmic dark energy

- Some people claimed the anisotropies of the dark energy, and the preferred axis also aligns with the CMB dipole. (see for instance, Antoniou & Perivolaropoulos, 2010, 2012; Javanmardi et al. 2015)



see however, Cai & Tuo, 2012, 2013; WZ, Wu & Zhang, 2013; Kalus et al. 2013; Yang et al. 2013; Chang et al. 2014, 2015; Lin et al. 2015

PROBING THE ISOTROPY OF COSMIC ACCELERATION TRACED BY TYPE IA SUPERNOVAE

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Draft version July 29, 2015

ABSTRACT

We present a method to test the isotropy of the magnitude-redshift relation of Type Ia Supernovae (SNe Ia) and single out the most discrepant direction (in terms of the signal-to-noise ratio) with respect to the all-sky data. Our technique accounts for possible directional variations of the corrections for SNe Ia and yields all-sky maps of the best-fit cosmological parameters with arbitrary angular resolution. To show its potential, we apply our method to the recent Union2.1 compilation, building maps with three different angular resolutions. We use a Monte Carlo method to estimate the statistical significance with which we could reject the null hypothesis that the magnitude-redshift relation is isotropic based on the properties of the observed most discrepant directions. We find that, based on pure signal-to-noise arguments, the null hypothesis cannot be rejected at any meaningful confidence level. However, if we also consider that the strongest deviations in the Union2.1 sample closely align with the dipole temperature anisotropy of the cosmic microwave background, we find that the null hypothesis should be rejected at the $95-99$ per cent confidence level, slightly depending on the angular resolution of the study. If this result is not due to a statistical fluke, it might either indicate that the SN data have not been cleaned from all possible systematics or even point towards new physics. We finally discuss future perspectives in the field for achieving larger and more uniform data sets that will vastly improve the quality of the results and optimally exploit our method.

Keywords: cosmology:dark energy, supernovae:general, methods:data analysis.

Dipole of fine structure constant

Some people claimed the anisotropies of the fine structure constant and its evolution with the redshift. They found the preferred axis also aligns with the CMB dipole. (see for instance, Webb et al. 2011; King et al. 2012; Antoniou & Perivolaropoulos, 2012; Perivolaropoulos 2014)

PRL **107,** 191101 (2011) PHYSICAL REVIEW LETTERS week ending 4 NOVEMBER 2011

Indications of a Spatial Variation of the Fine Structure Constant

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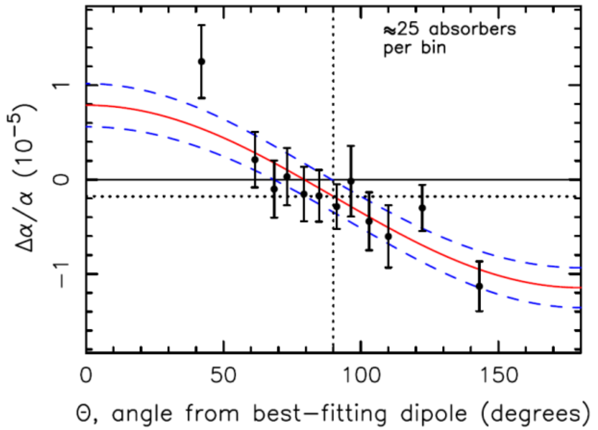
(Received 23 August 2010; published 31 October 2011)

We previously reported Keck telescope observations suggesting a smaller value of the fine structure constant α at high redshift. New Very Large Telescope (VLT) data, probing a different direction in the Universe, shows an inverse evolution; α increases at high redshift. Although the pattern could be due to as yet undetected systematic effects, with the systematics as presently understood the combined data set fits a spatial dipole, significant at the 4.2σ level, in the direction right ascension 17.5 ± 0.9 h, declination -58 ± 9 deg. The independent VLT and Keck samples give consistent dipole directions and amplitudes, as do high and low redshift samples. A search for systematics, using observations duplicated at both telescopes, reveals none so far which emulate this result.



see however, Cameron et al. 2012; Levshakov et al. 2012

List of Preferred Axes in Cosmology

TABLE VIII: Preferred directions in various large-scale observations

observations	θ [degree]	ϕ [degree]
CMB kinematic dipole	42	264
CMB quadrupole	13.4	238.5
CMB octopole	25.7	239.0
CMB parity asymmetry	45.82	279.73
Polarization of QSOs	69	267
Large-scale velocity flows	84	282
Handedness of spiral galaxies	158.5	232
Anisotropy of cosmic acceleration	23.4	247.5
Distribution of fine-structure constant	104	331

OUTLINE

- CMB parity violation
- Directional dependence of CMB parity violation
- Comparing with other preferred axes
- **Possible explanations**

A: Non-trivial topology of the universe

- The standard cosmological model is based on two assumptions: One is that Einstein's general relativity correctly describes gravity, the other assumes the universe as homogeneous and isotropic on large scales.

- If we believe that the anomalies have a cosmological origin, at least one of these two assumptions will be broken.

- One possibility relies on the Bianchi models. The Bianchi classification provides a complete characterization of all the known homogeneous but anisotropic exact solution to general relativity. So, in general, Bianchi models can provide preferred directions in the universe (see for instance Planck Collaboration, 2014).

B: Alternative gravitational theories

- In order to explain the bulk flow, some authors considered that the universe is influenced by large-scale "wind", and the cosmic matter is drifted by this "wind", which is described by the Finsler geometry (see for instance Chang et al. 2012).

- Another theoretical explanation of the observed preferred direction is motivated by the fact that the cosmological constant Λ is nonzero. So, the metric of the local inertial reference system in the standard model of cosmology is the Beltrami metric instead of the Minkowski one, and the basic spacetime symmetry has to be from de Sitter's group. In this model, the Minkowski point does exist in the universe, where the Beltrami metric returns to the Minkowski one, and the physics at this point returns to the Einstein's special relativity. (see for instance Yan et al. 2015).

C: Particular fluctuation modes or dark energy models

- The explanation for the directional anomalies with a minimum cost is to consider the possible anisotropic matter component and/or superhorizon fluctuation modes in the universe.

- For instance, we suggested to use the quantum Yang-Mills condensate to describe the dark energy and promote the cosmic acceleration. For the vector fields, the spatial distribution is always anisotropic, which could easily lead to a preferred axis in the large scales (see for instance WZ & Zhang, 2006).

- For the large-scale CMB anomalies, the mechanism of Grishchuk-Zeldovich effect is a possible explanation. It is the contribution to the CMB temperature anisotropy from an extremely large-scale adiabatic density perturbation mode.

D: Unsolved systematical errors or contaminations

- On the contrary, some other people believe that these anomalies are caused by some non-cosmological reasons: Unsolved systematical errors, calibration errors or foreground contaminations.

- One possible one is related to the contaminations generated by the collective emission of Kuiper Belt objects (see for instance Hansen et al. 2012).

- Another explanation may relate to a deviation measured in the CMB kinematic dipole (see for instance Liu et al. 2011).

- It is also possible that the preferred direction is caused by the tidal field originated from the anisotropy of our local halo (see for instance Zhang et al. 2015).

Conclusions

- As one kind of CMB anomalies in large scales, CMB parity asymmetry is directional dependent.
- The preferred axis in CMB parity asymmetry is discovered, which is independent of the CMB maps, CMB masks or the definition of statistic.
- The preferred axis stored in CMB parity asymmetry strongly aligns with those in CMB dipole, quadrupole, octopole, as well as those in other cosmological observations. These coincidences suggest their common origin.
- The alignment with CMB kinematic dipole hints their non-cosmological origin.

Thank you!