CMBR Alignment Anomaly and Foregrounds

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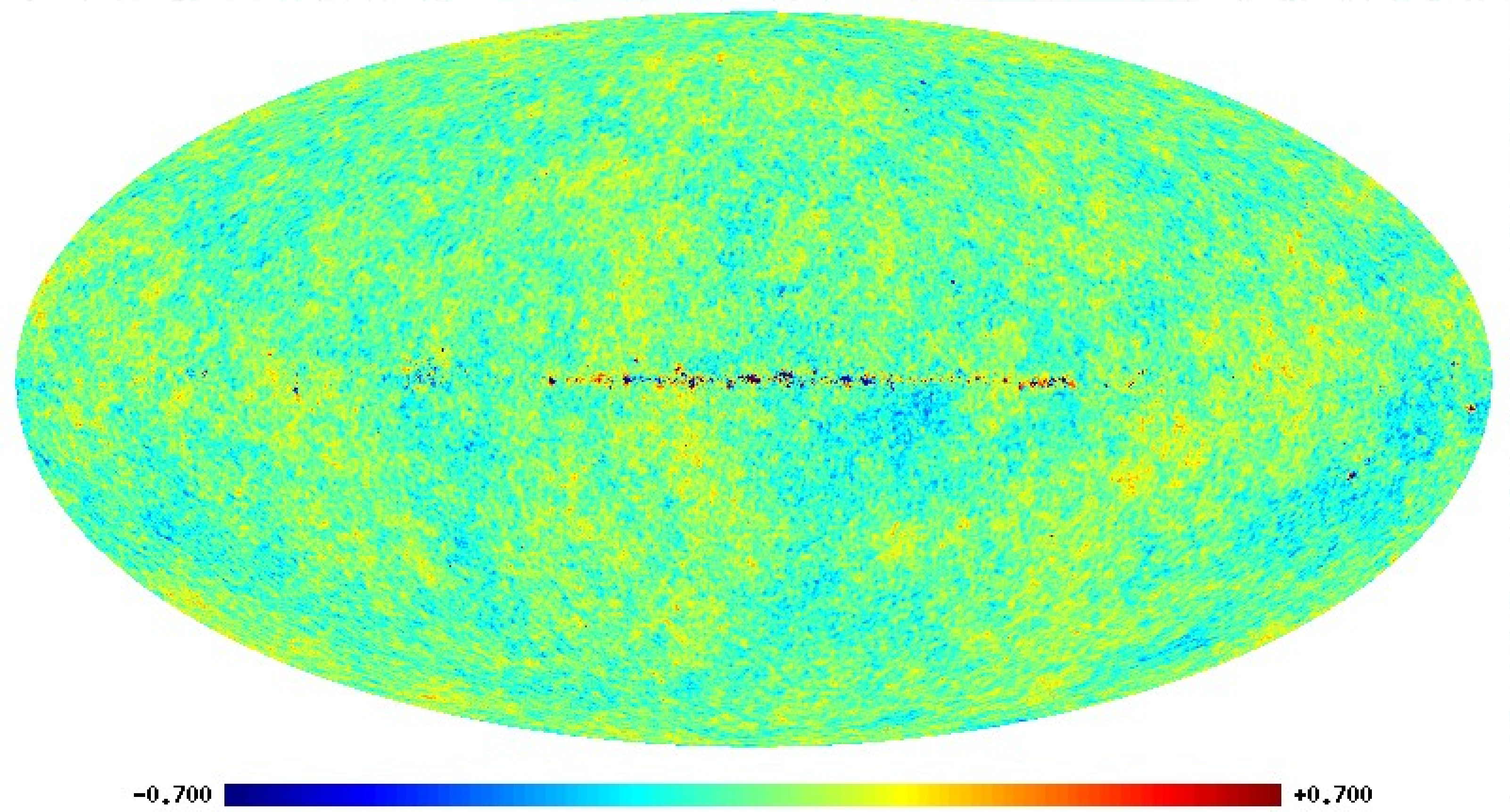
Dec. 17th, 2010 @ Harish Chandra Research Institute, Allahabad

The standard model of Cosmology, which rests on the **Cosmological Principle**, fits the data very well we acquired so far. But some anomalies were reported to exist which does not follow from this standard model.

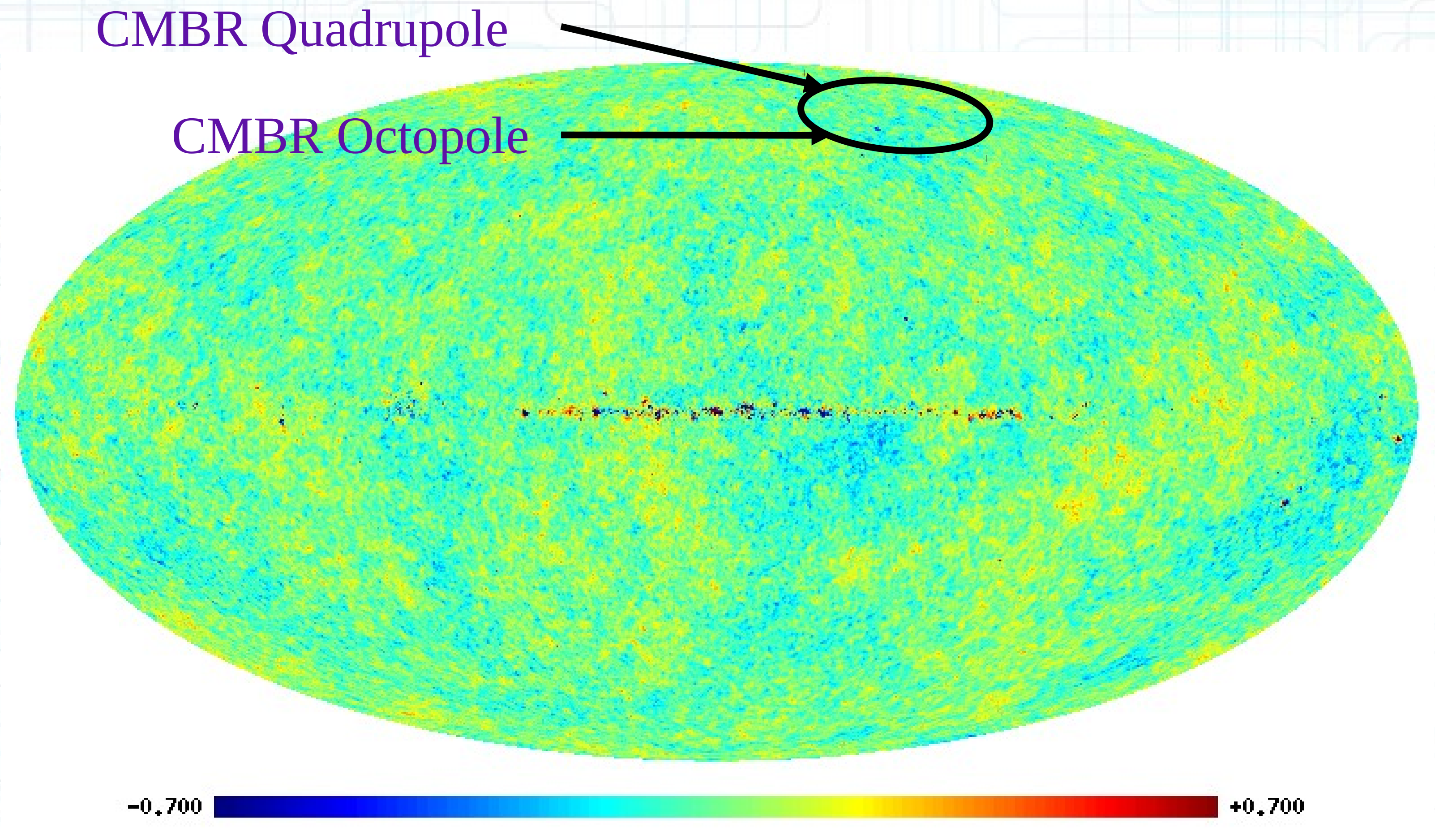
Particularly interesting studies have been on the ANOMOLOUS PREFERRED DIRECTIONs , found to be emerging from diverse data sets.

Cosmic Microwave Background Radiation

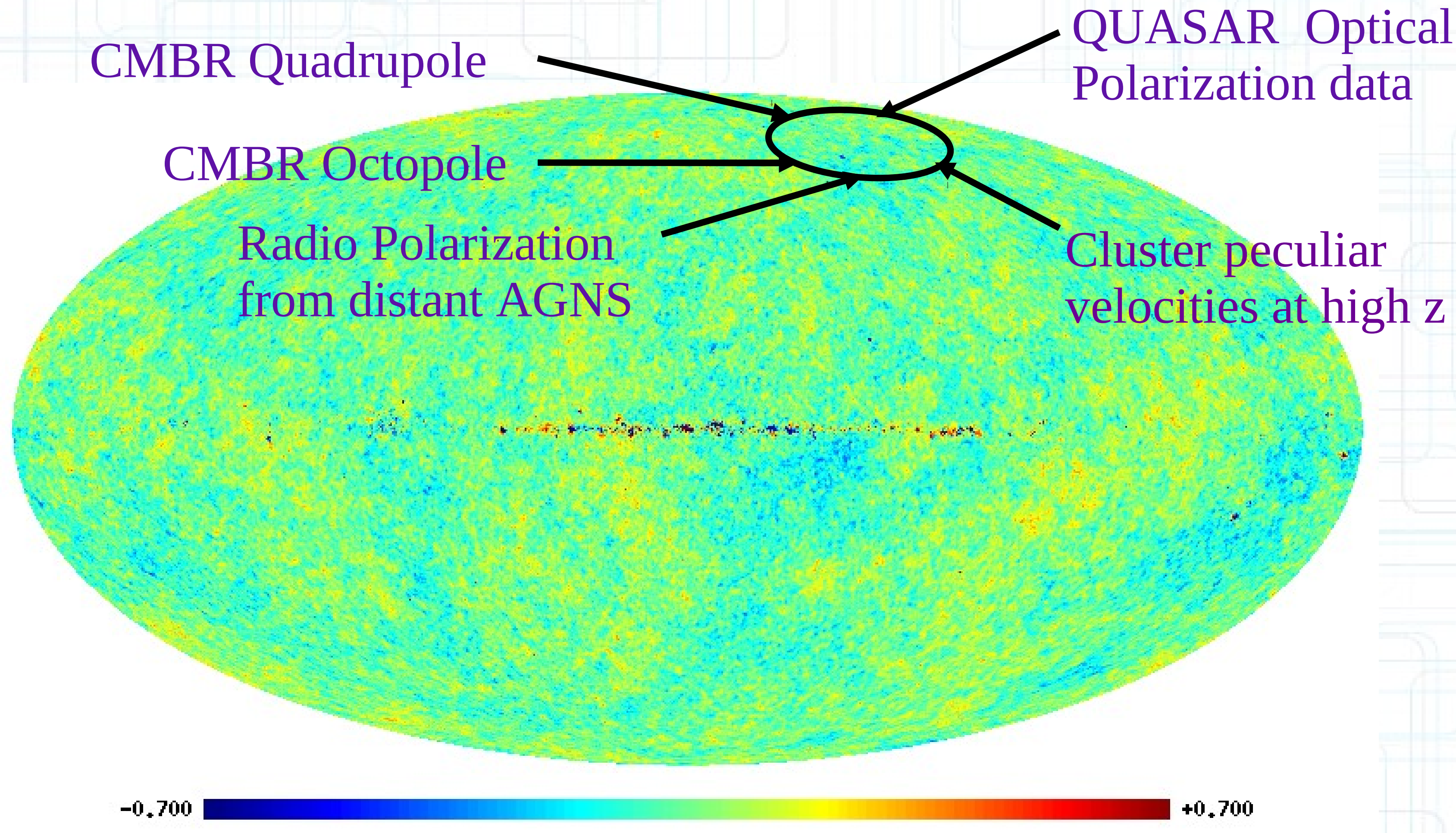


Cleaned map from WMAP 7yr data using IPSE procedure.
(Temperature scale is in mK)

Cosmic Microwave Background Radiation



Preferred Directions in various Cosmological data sets



All these axes are pointing towards VIRGO cluster, indicating a preferred axis.

This is called Virgo Alignment Puzzle*

*Ralston and Jain, 2004, Int. J. Mod. Phys., D13, 1857

Some of the ANOMOLOUS DIRECTIONs reported to have been found in various data sets :

- Low – *l* alignment anomalies in CMBR data from WMAP

de Oliveira-Costa et al., 2004, PR D69, 063516
Ralston and Jain, 2004, Int. J. of Mod. Phys., D 13, 1857
Schwarz et al., 2004, PRL, 93, 221301
Bernui et al., 2006, A&A, 454, 409
Copi et al., 2006, MNRAS, 367, 79
Magueijo and Sorkin, 2007, MNRAS, 377, L39
Samal et al., 2008, MNRAS, 385,1718
Samal et al., 2009, MNRAS, 396, 511
Frommert and Ensslin, 2010, MNRAS, 403, 1739

- Optical polarizations of EM waves from distant QUASARS

Hutsemekers, 1998, A&A, 332, 410
Jain et al., 2004, MNRAS, 347, 394
Hutsemekers et al., arXiv:0809.3088

Some of the ANOMOLOUS DIRECTIONs reported to have been found in various data sets :

- Polarization of Radio waves from Radio Galaxies

  Birch , 1982, Nature, 298, 451
  Jain and Ralston, 1999, Mod. Phy. Lett. A, 14, 417
  Jain and Sarala, 2006, J. Astrophys. Astron., 27, 443

- Cluster peculiar velocities

  Kashlinsky et al., 2008, ApJ, 686, L49
  Kashlinsky et al., 2009, ApJ, 691, 1479
  Watkins et al., 2009, MNRAS, 392, 743
  Lavaux et al., 2010, ApJ, 709, 483

- Large scale galaxy distribution

  Itoh et al., 2010, Phys. Rev., D 82, 043530

- Supernova data

  Antoniou and Perivolaropoulos, 2010, arXiv:1007.4347v3

A variety of proposals have been put forward to account for these PREFERED AXES :

- Anisotropic space-times

Berera et al., 2004, JCAP, 10, 16
Kahniashvili et al., 2008, PR D78, 063012

- Foreground contamination

Slosar and Seljak, 2004, PR D70, 083002
Abramo et al., 2006, PR D74, 083515
Rakic et al., 2006, MNRAS, 369, L27

- Noise bias or Systematics

Gruppuso et al., 2007, MNRAS, 376, 907
Naselsky et al., 2008, Astrophys. Bull., 63, 216

- Spontaneous breaking of isotropy

Gordon et al., 2005, PR D72, 103002
Land and Magueijo, 2006, MNRAS, 367, 1714
Erickcek et al., 2009, PR D80, 083507

- Inhomogeneous universe

Moffat, 2005, JCAP, 10, 12
Land and Magueijo, 2006, MNRAS, 367, 1714

- Violation of rotational invariance during inflation/ Inhomogeneous inflation

Ackerman et al. 2007, PR D75, 083502
Carroll et al., 2010, PR D81, 083501

Other **significant anomalies** were found to exist in CMBR data from WMAP :

- Low power at large angular scales (Spergel et al., 2003, ApJS,148, 175; Bennett et al., 2010, arXiv:1001.4758)
- No large angle corrections in CMBR (Copi et al., 2009, MNRAS,, 399, 295)
- North-south power asymmetry (Hansen et al., 2009, ApJ, 704, 1448)
- Dipole power modulation (Eriksen et al., 2004, ApJ, 605, 14; Eriksen et al., 2007,ApJ, 660, L81; Hoftuft et al., 2009, ApJ, 699, 985)
- Anomalously cold spot (Cruz et al., 2005, MNRAS, 356, 29)
- An anomalous signal in the ecliptic plane (Diego et al., 2010, MNRAS, 402, 1213)
- Parity asymmetry in CMB power at low multipoles (Kim and Naselsky, 2010, PR D82, 063002)

Can the observed alignment found between the quadrupole and octopole be caused by FOREGROUND RESIDUALS?

This has been the motivation for our recent work* which I will be presenting here.

***Effect of Foregrounds on the CMBR Multipole Alignment**

Pavan K. Aluri, Pramoda K. Samal, Pankaj Jain, John. P. Ralston

arXiv:1007.1827 (under review with MNRAS)

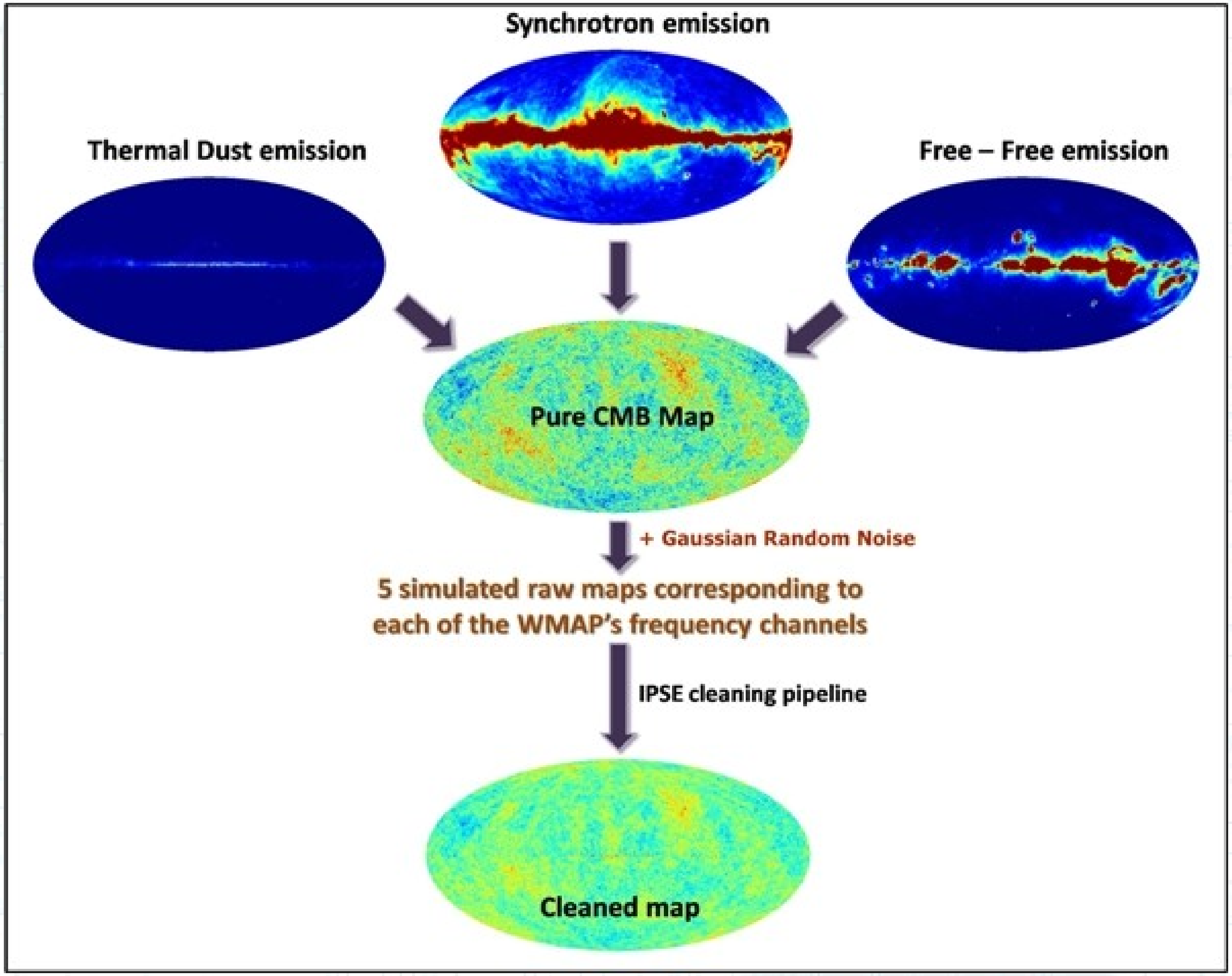
STUDY STRATEGY

- All the works we are aware of so far have estimated the significance of observed anomalies with <u>pure</u> CMBR realizations from best fit LCDM parameters.
- Here we worked with simulated full sky <u>cleaned maps</u>.
- We used a <u>symmetry based statistic</u> constructed using angular momentum operators to analyze any deviations from statistical isotropy.

STUDY STRATEGY (contd ..)

- We used PLANCK SKY MODEL(PSM) for foregrounds.
- By linearly combining the full sky maps in multipole space with appropriate weights(IPSE method), the foregrounds are subtracted from the raw data.
- From the spectral co-efficients of temperature anisotropies, we construct what is called a POWER TENSOR(our statistic) whose eigenvalues and eigenvectors contain the information about deviations from isotropy.

STUDY STRATEGY (contd ..)



IPSE Method

$$\Delta T(\hat{n}) = \sum_{l=0}^{\infty} a_{lm} Y_{lm}(\hat{n})$$

CMB multipole power is given by,

$$C_l = \frac{1}{2l+1} \sum_{l=0}^{\infty} a_{lm} a^{*}_{lm}$$

Linear combination of raw maps in multipole space

$$a_{lm}^{clean} = \sum_{k=1}^{n_c} \hat{w}^k \frac{a_{lm}^k}{B_l^k}$$

$$\mathbf{\hat{W}_l} = \frac{\mathbf{e_0^T \hat{C}_l^{-1}}}{\mathbf{e_0^T \hat{C}_l^{-1} e_0}} \;, \quad \hat{C}_l^{clean} = \frac{1}{\mathbf{e_0^T \hat{C}_l^{-1} e_0}} \;\&\; \mathbf{e_0} = \begin{pmatrix} 1 \\ \vdots \\ 1 \end{pmatrix}$$

POWER TENSOR

$$A_{ij} = \frac{1}{l(l+1)} Tr\{J_i|a(l)\rangle\langle a(l)|J_j\}$$

$$= \sum_{\alpha=1}^{3} \hat{e}_i^{\alpha} (\Lambda^{\alpha})^2 \hat{e}_j^{\alpha *}$$

$\hat{e}_i^{\alpha}$ defines an orthonormal frame for each multipole in real space and $(\Lambda^{\alpha})^2$ are the power associated with each of these orthonormal axes.

We associate an axis with each of the multipoles of CMB anisotropies as that of the direction of the eigenvector of the Power Tensor which carries the largest fraction of CMB power in each mode.

This axis is called Principle Eigen Vector (PEV).

A PEV represents only an axis and not a specified direction in space.

Description and results from implementation of IPSE method for cleaning raw satellite data in multipole space and POWER TENSOR for anisotropy analysis are given in the following earlier works :

CMB Power spectrum (T,E,B) estimation

- Saha et al., 2008, PR D78, 023003
- Samal et al., 2010, ApJ, 714, 840

Testing "Statistical Isotropy" in WMAP data

- Samal et al., 2008, MNRAS, 385, 1718
- Samal et al., 2009, MNRAS, 396, 511

Results from WMAP data

- In our current study we used 3 different foreground reduced maps – WMAP ILC map, IPSE cleaned WMAP data and TOH map.
- We did the analysis with both the 5yr and 7yr data sets from WMAP.
- We examined the quadrupole and octopole alignment.
- We find that the alignment has only become better with each data release.

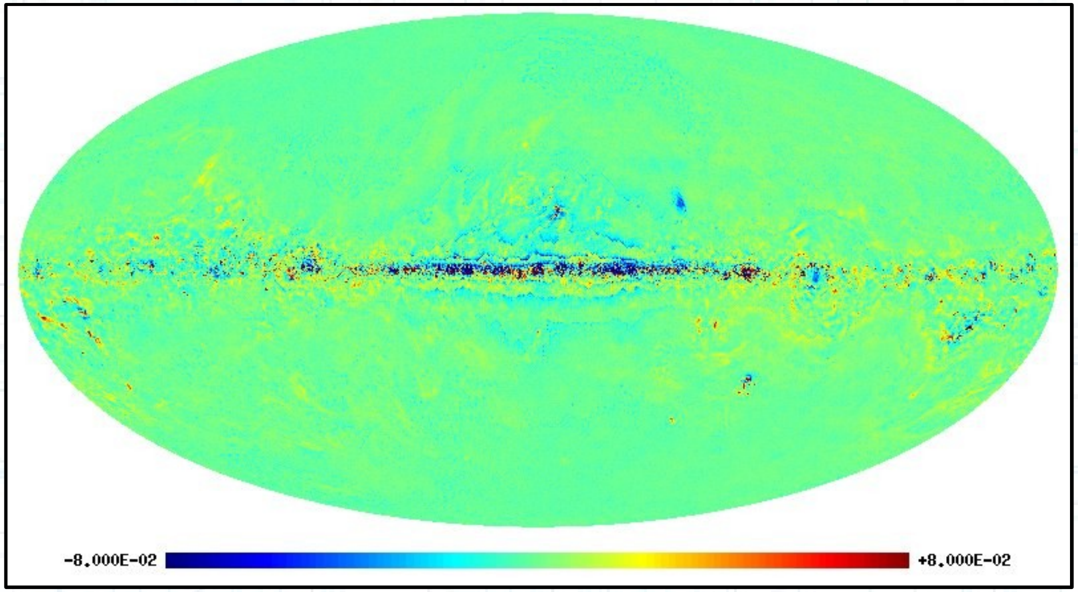
The l=2 and l=3 alignment results :

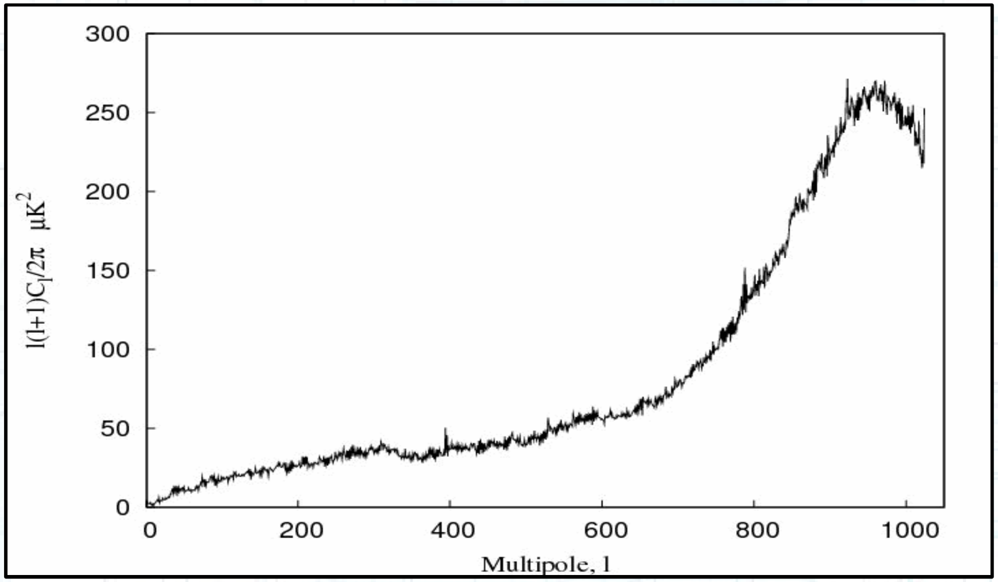
	$\delta\Theta$	$1-\cos(\delta\Theta)$
WMAP ILC map (5 yr)	1.95^o	0.00058
WMAP ILC map (7 yr)	0.6^o	5.5×10^{-5}
IPSE cleaned map (5 yr)	12.27^o	0.023
Bias corrected IPSE map (5 yr)	5.44^o	0.0045
IPSE cleaned map (7 yr)	11.28^o	0.019
Bias corrected IPSE map (7 yr)	4.25^o	0.0027

2nd column lists the observed quadrupole – octopole alignment angles and 3rd column lists the corresponding analytic estimate of the probability of the observed alignment to be a random chance occurrence.

*In WMAP 3yr ILC map, quadrupole-octopole alignment was ~ 5.8 deg.

Bias correction map, and it's power spectrum, generated from the simulations with PSM for foregrounds.





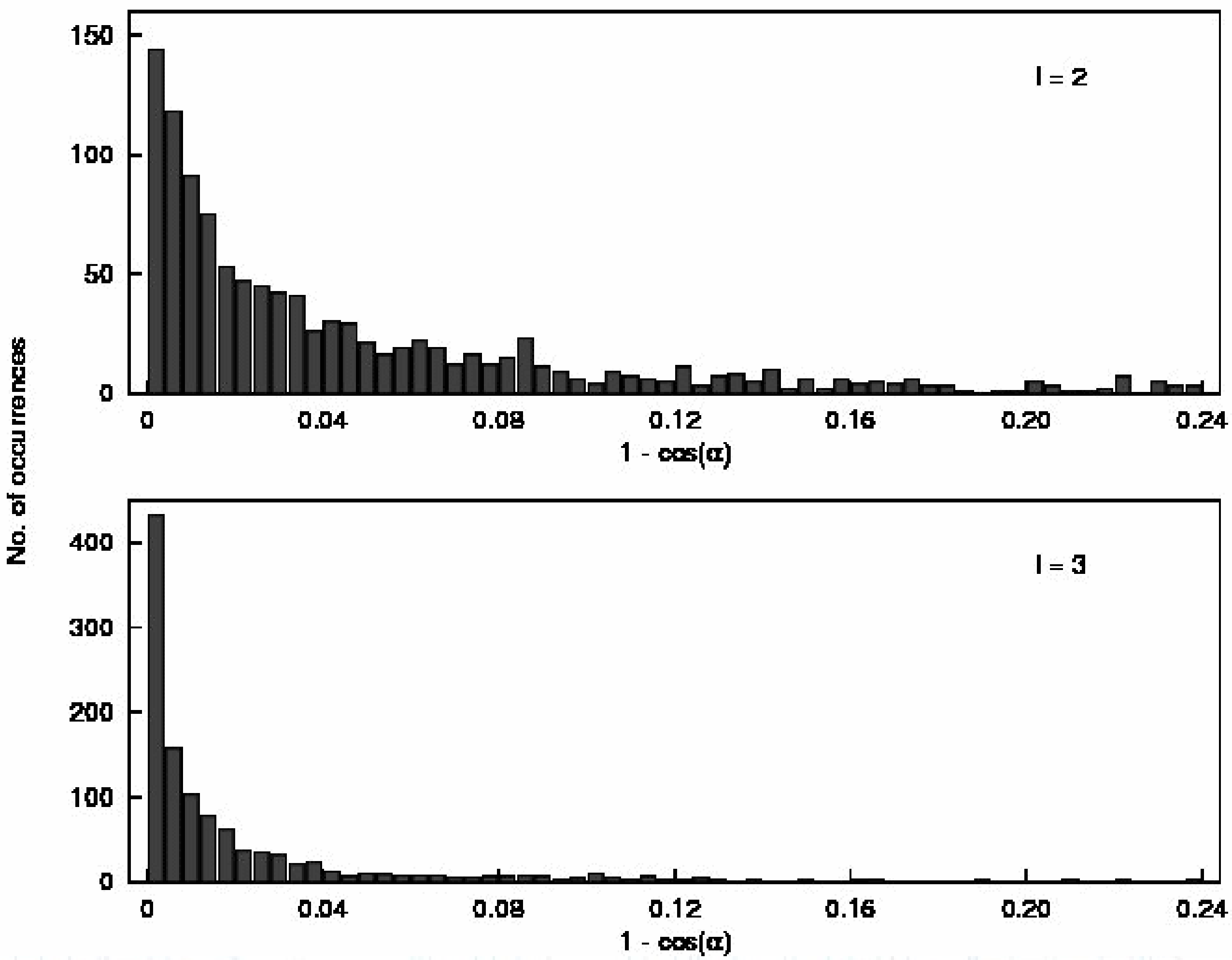
Simulation results

- We generated an ensemble of 1000 random realizations of CMB sky(PURE MAPS) according to the best fit cosmological parameters.
- The raw sky maps generated by adding the foregrounds from PSM and random Gaussian noise are cleaned using the IPSE procedure.
- Then a bias correction map is derived from these CLEANED MAPS and subtract this out from all the maps. We extract the eigen values and PEVs from the Power Tensor for each of these maps.

Aluri et al., 2010 (arXiv : 1007.1827) used PLANCK SKY MODEL for foregrounds.

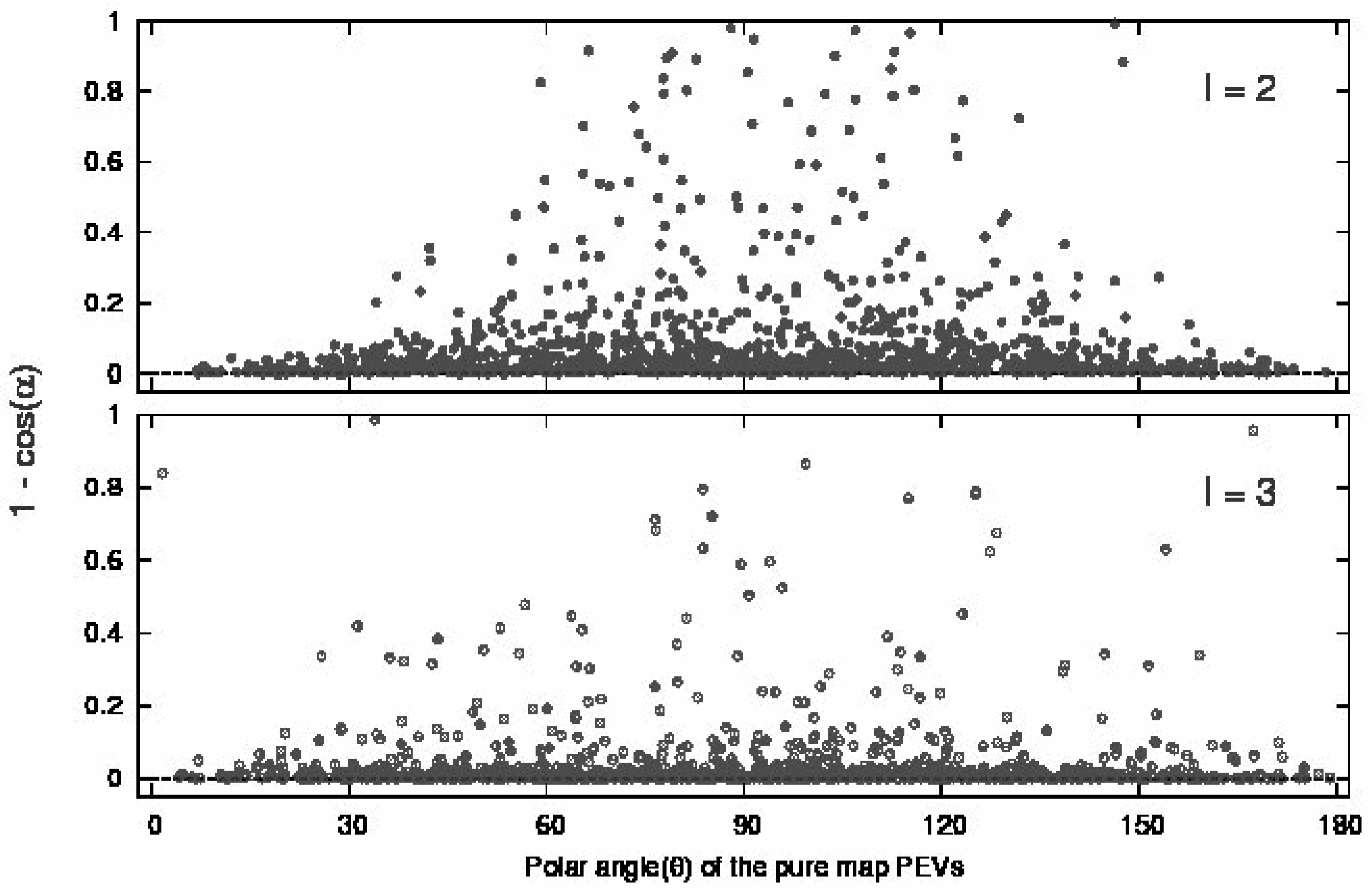
Here I present our studies with MEM7 foreground maps (Maximum Entropy Method(MEM) characterized 7yr galactic synchrotron, free-free and thermal dust emission maps from WMAP team).

Change or "ROTATION" of pure map PEVs in the presence of residual foregrounds in the Clean maps



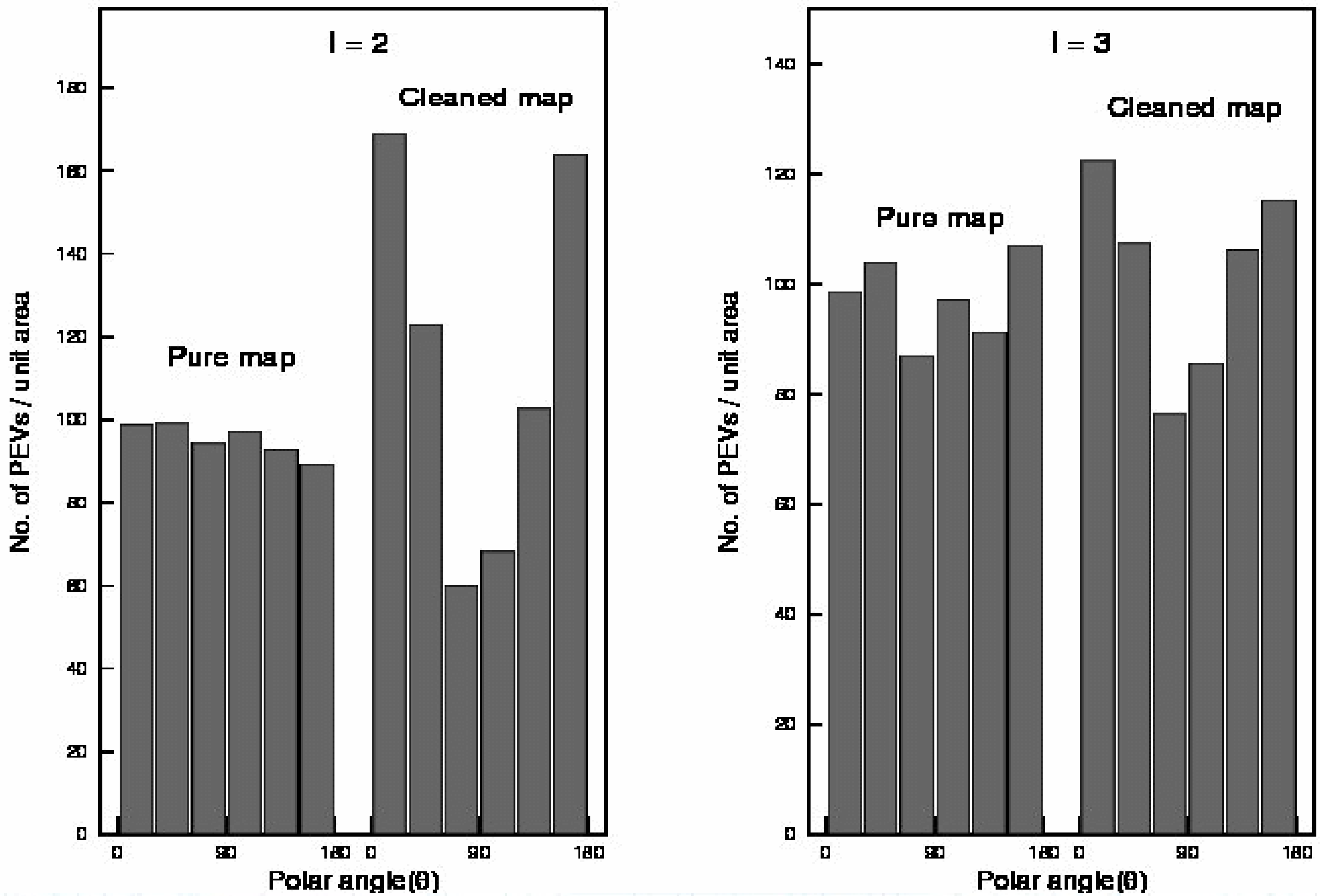
The shift in the position of PEVs is in general low.

Profile of this “ROTATION” of pure map PEVs in different sky regions



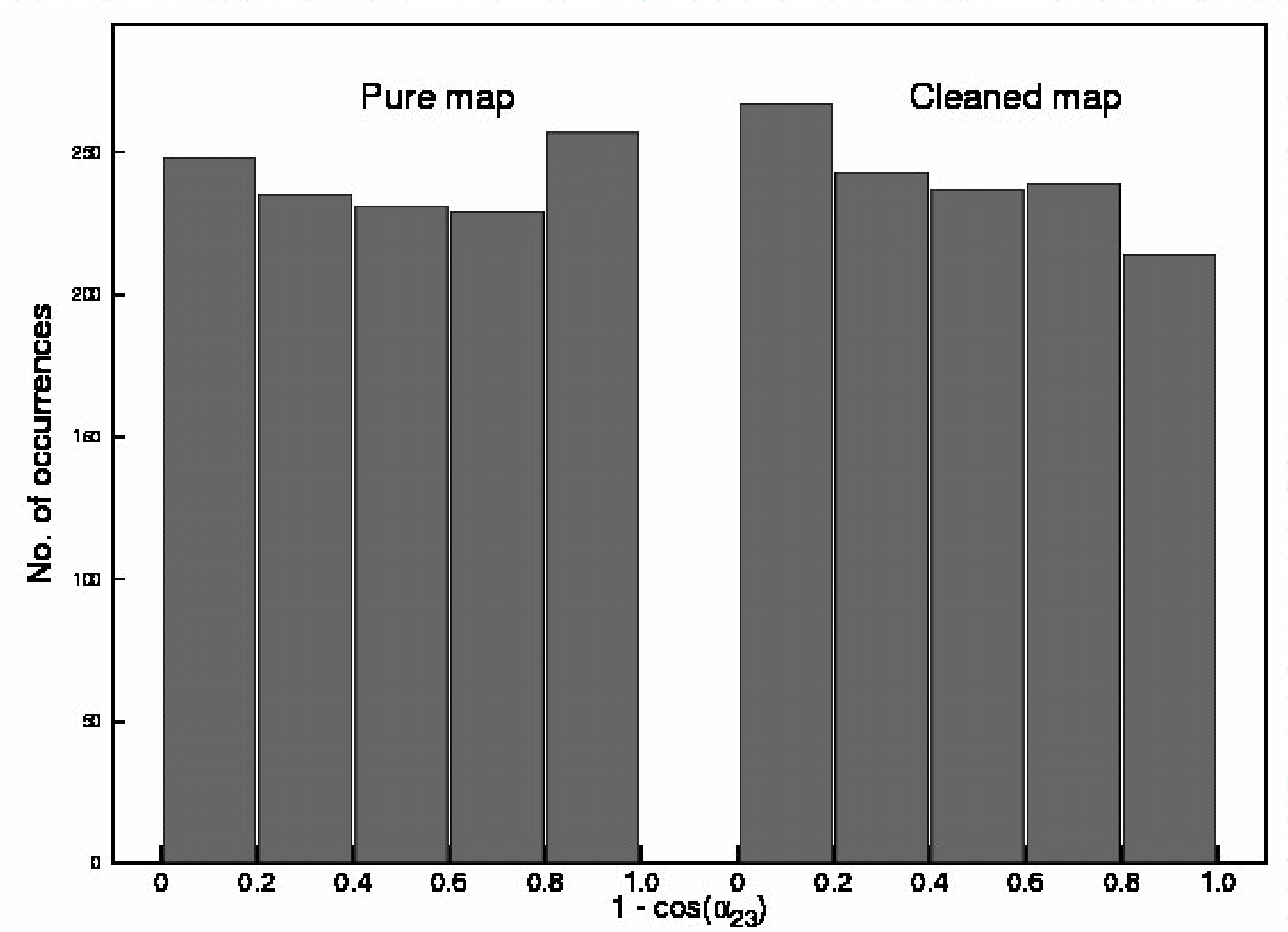
The rotation of PEVs is very pronounced in those which were lying initially close to the galactic place

Distribution of PEVs in different sky regions



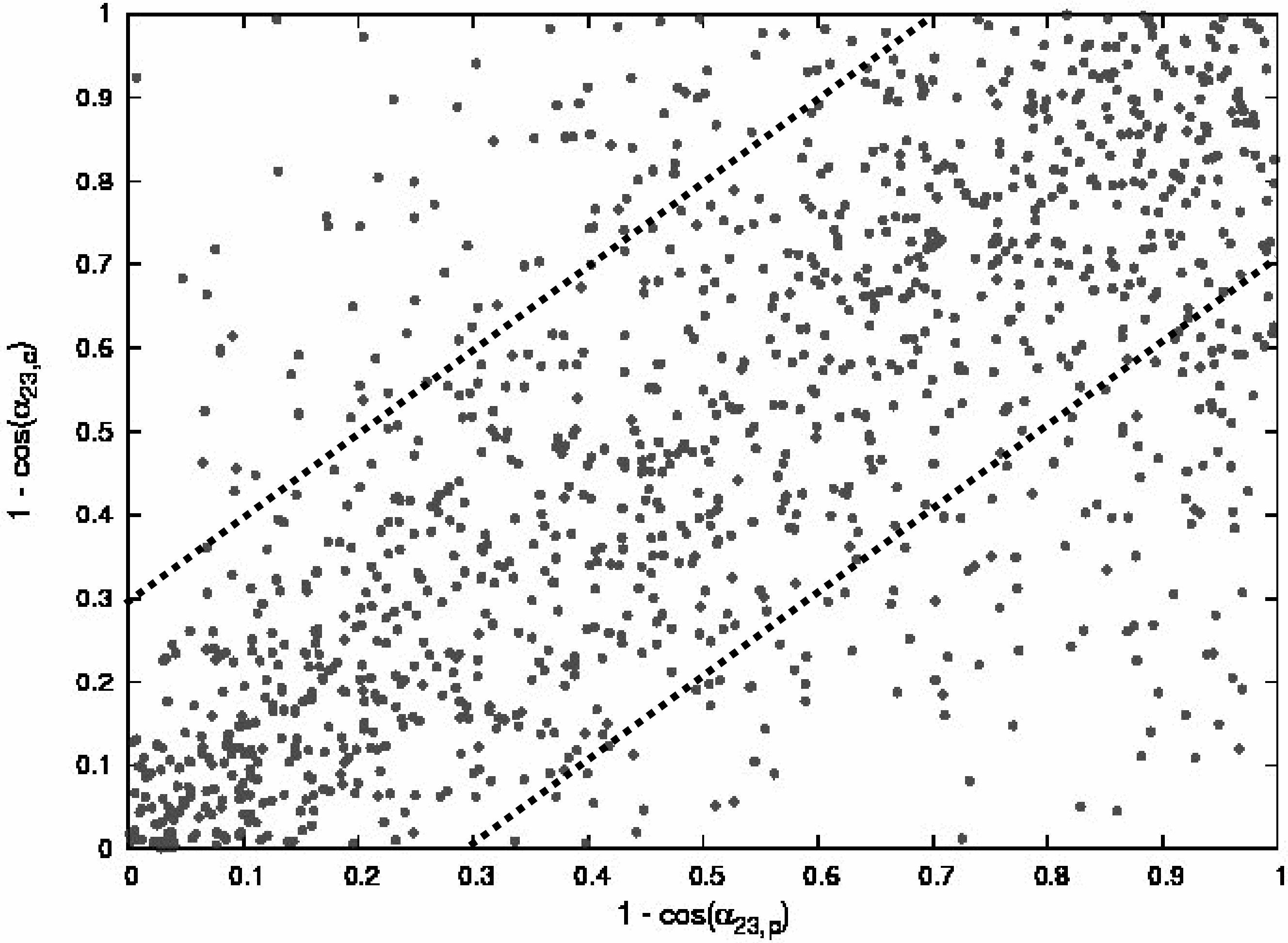
PEVs show a tendency to rotate away from the galactic plane in the cleaned maps

Distribution of alignments between quadrupole and octopole PEVs in the simulated maps

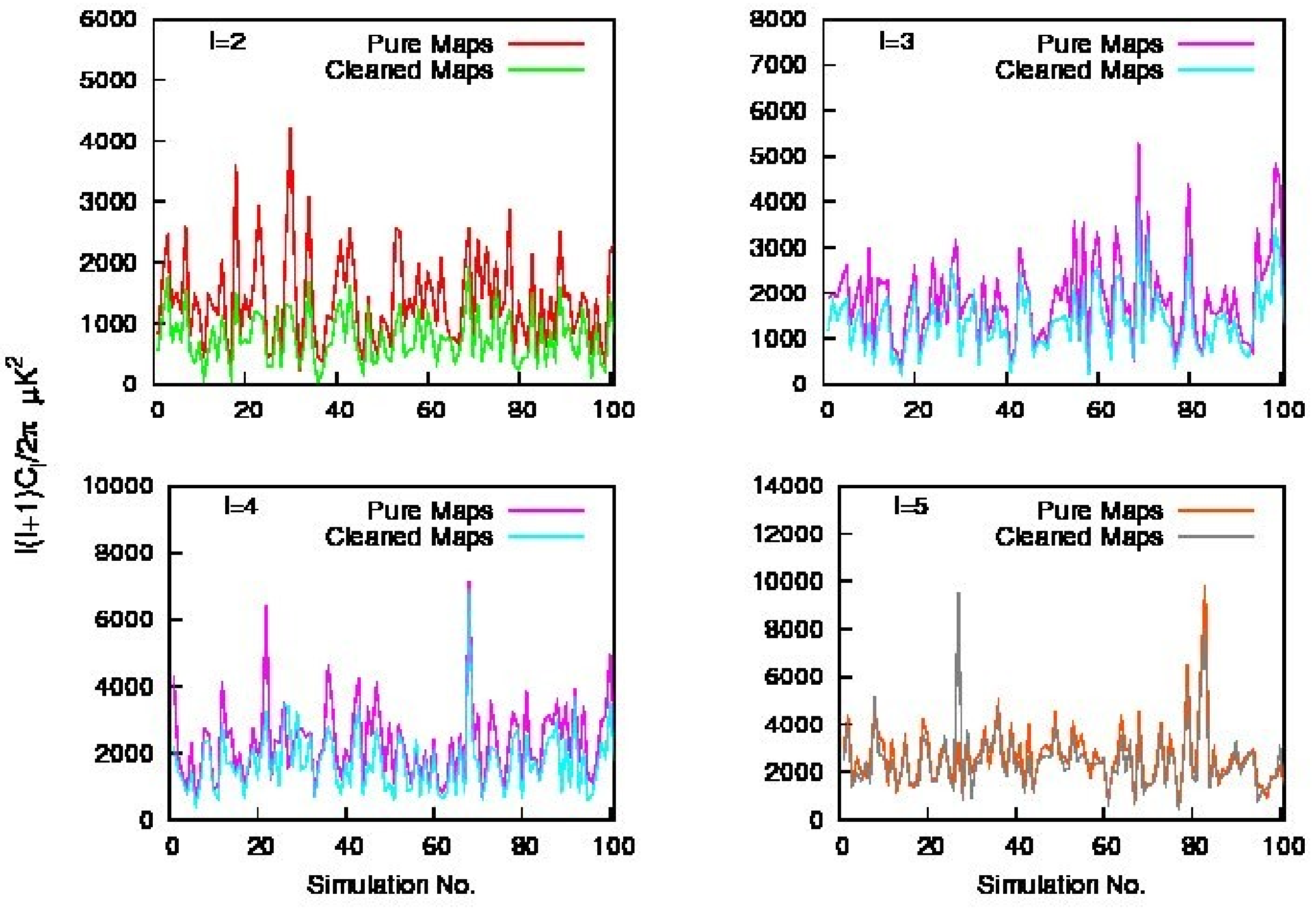


The alignments between l=2,3 in the simulated ensemble are randomly distributed

Alignments of l=2 and 3 in the Pure maps Vs Clean maps

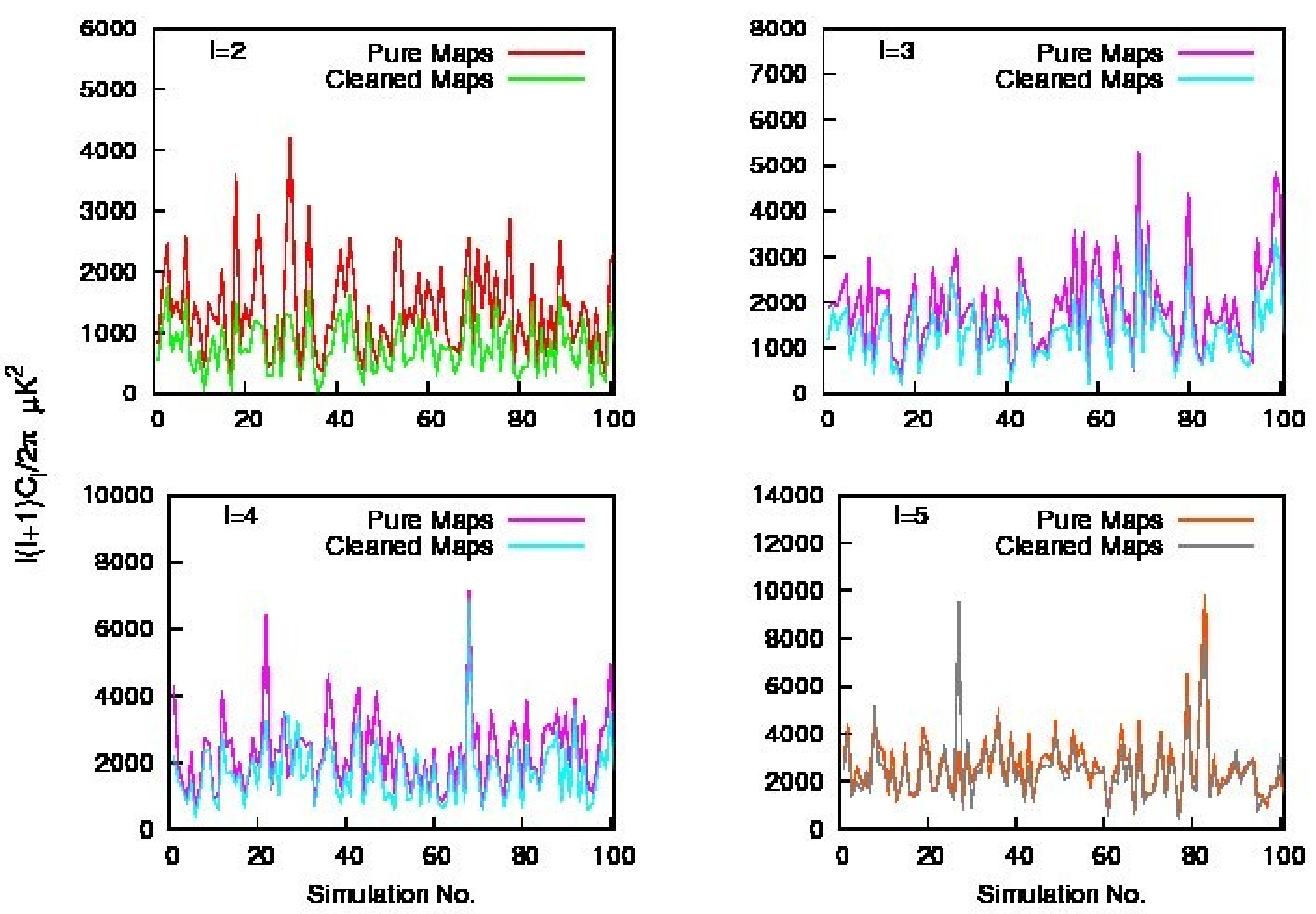


CMB power of the multipoles l=2,3,4,5 in all the maps of our simulation ensemble



Notice the systematic reduction in multipole power in the cleaned maps compared to the Pure maps.

CMB power of the multipoles l=2,3,4,5 in all the maps of our simulation ensemble



Quadrupole power reduction ~ 40%

Octopole power reduction ~ 20%

SUMMARY

- There is no signal of foreground induced alignment between l = 2,3. The significances estimated from PURE maps and CLEAN maps are very close and agree well with the analytic probability estimates.

- In the cleaned maps, we find that the foreground power is systematically reduced compared to the PURE maps, which we attribute it to chance correlation of CMB signal with foregrounds.

- Despite the presence of a systematic lowering in power in the cleaned maps we find no evidence for any systematic effect in alignment due to residual foregrounds.

- Hence, we also conclude that the alignment of the low multipoles and observed low power at these low-*l* are mutually exclusive.

So far, the results presented here include only dominant foregrounds as provided by PLANCK SKY MODEL viz., Synchrotron, Free-Free and Thermal dust galactic emissions.

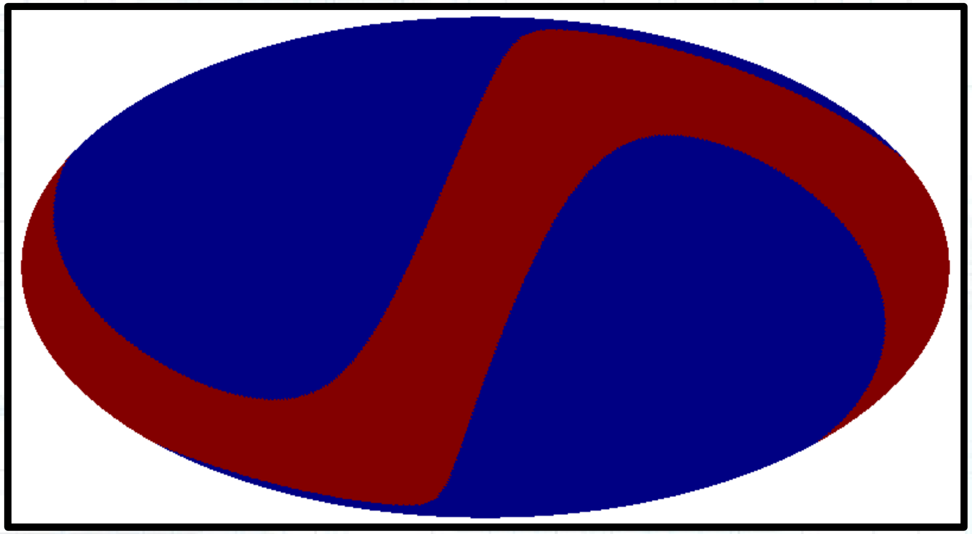
But some of the studies reported in the literature claimed to have detected anomalous sub-dominant foreground emissions in CMBR data.

The WMAP papers also mention the presence of an anomalous foreground component with a soft Synchrotron spectral index/Spinning dust component in their foreground analysis.

Some of the studies reported are anomalous ecliptic signal/ haze component/ sub-dominant synchrotron like foreground emission at higher latitudes.

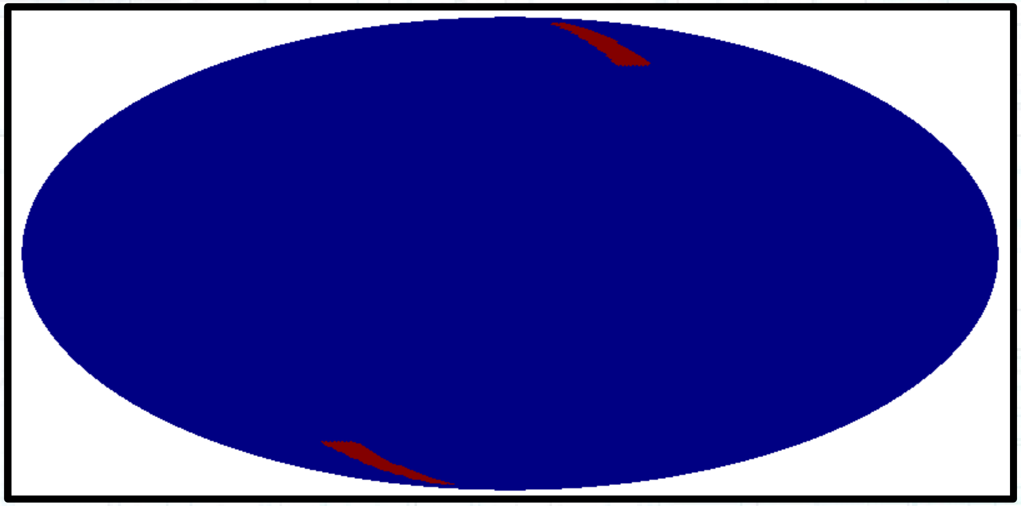
So, it is clear to study the effect these sub-dominant emissions on the CMB anomalies. Even before that we should be able to characterize them well.

Sub-dominant foreground components



Mock anomalous ecliptic foreground scaled with a soft synchrotron spectral index with 10% of synchrotron power at 23Ghz.

A 20 deg X 20 deg artificial foreground patches along the Virgo axis were created at 20% the intensity of synchrotron map with a soft spectral index scaling from Ka-band of WMAP.



Astrophysical foreground components may in general be modeled as scaling a reference template, created at a reference frequency where it is dominant, to other frequencies.

$$F_{\nu}(\hat{n}) = A_{\nu_0}(\hat{n}) \left(\frac{\nu_0}{\nu}\right)^{\beta(\hat{n})}$$

The foreground maps we created were scaled from Ka-band to W-band following a rigid frequency hypothesis, where the spectral index is assumed to be constant over the full sky.

Bouchet F. R. and Gispert R., 1999, New Astronomy, 4, 443
Leach et al., 2008, A&A, 491, 597

We repeated our analysis with these anomalous foreground maps we created.

But, we found <u>no signal of foreground induced alignment or preferred direction</u> in our simulated clean maps.

The quadrupole – octopole alignments or their axes are isortopically distributed over the whole sky.

CONCLUSIONS

- No signal of foreground induced alignment is found at low multipoles.
- The alignment of the low multipole PEVs and their axes are isotropically distributed.
- The quadrupole axis is sensitive to presence of residual contaminations where as octopole axis is relatively stable.
- We see a systematic reduction in CMB power in the cleaned maps in these multipoles, which is attributed to correlation between CMB and residual foregrounds.
- The absence of such a systematic effect in the case of alignment prompts us to say that they may be mutually exclusive phenomena.
- The presence of sub-dominant anomalous foreground emissions does not induce any preferred alignment.

Acknowledgements

- We used WMAP satellite data from Legacy archive site (http://lambda.gsfc.nasa.gov/)
- HEALPix software is used as a base package for our analysis (http://healpix.jpl.nasa.gov/)
- PLANCK SKY MODEL was used for foreground model (http://www.planck.fr/heading79.html)

THANK YOU

for your attention