Direction dependence of cosmological parameters due to Cosmic Hemispherical Asymmetry

Pavan Kumar Aluri
Dept. of Mathematics and Applied Mathematics,
University of Cape Town

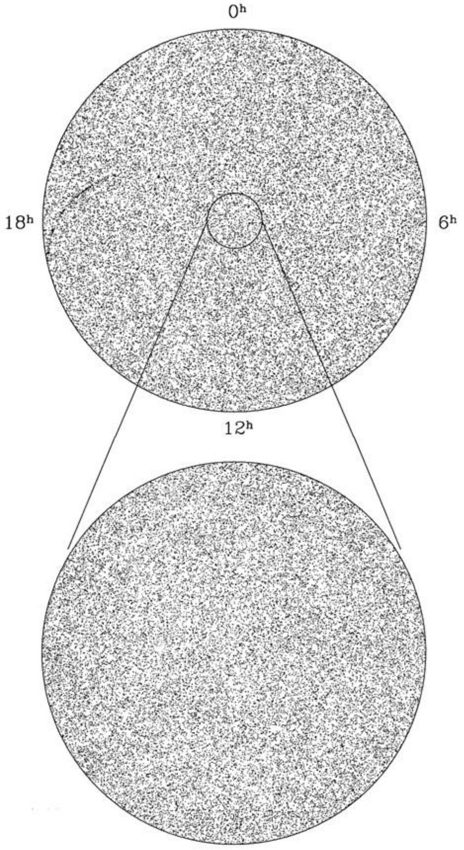
Nov. 22nd, 2016

Cosmology with Large Surveys - The first South Africa-China bilateral workshop

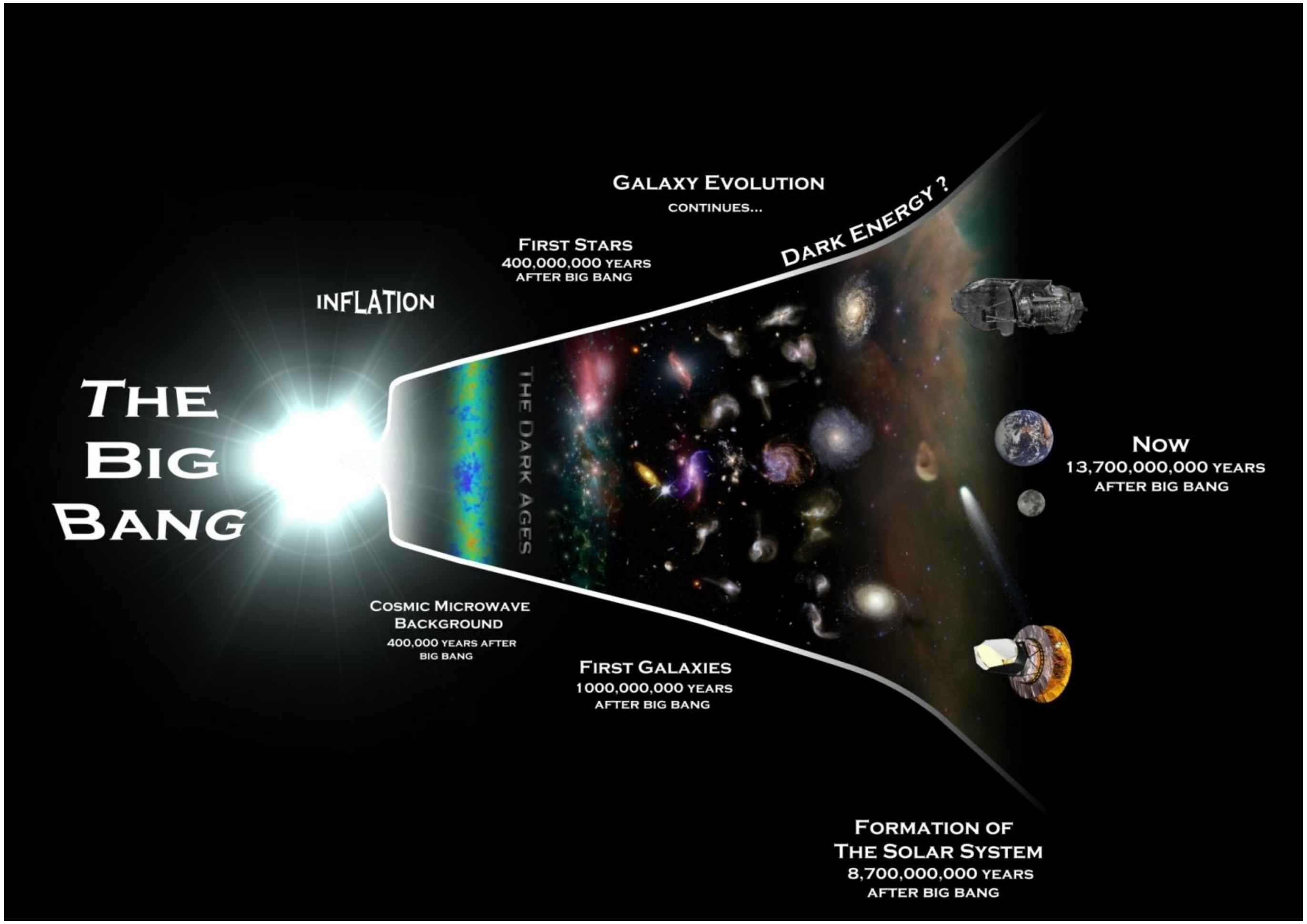
19th – 26th November, 2016, Durban, South Africa

Cosmological Principle :

Universe is homogeneous and isotropic on very large scales.



Cosmic Microwave Background (CMB) radiation



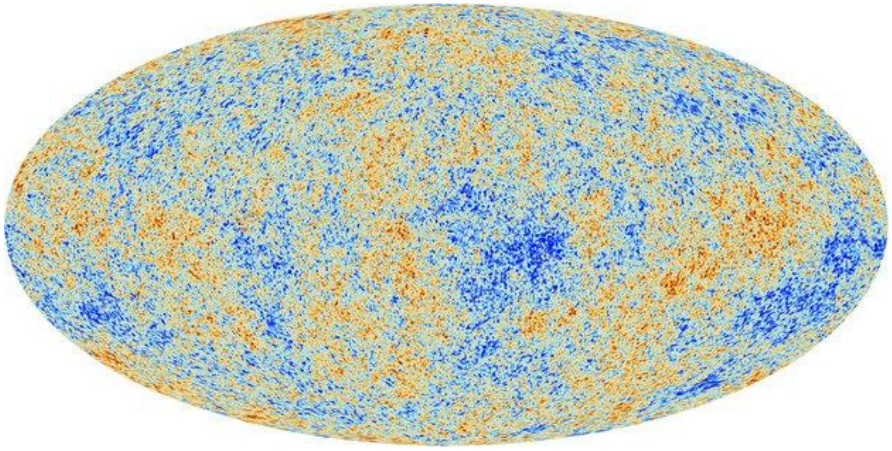
Cosmic time line of standard model cosmology

Spherical harmonics

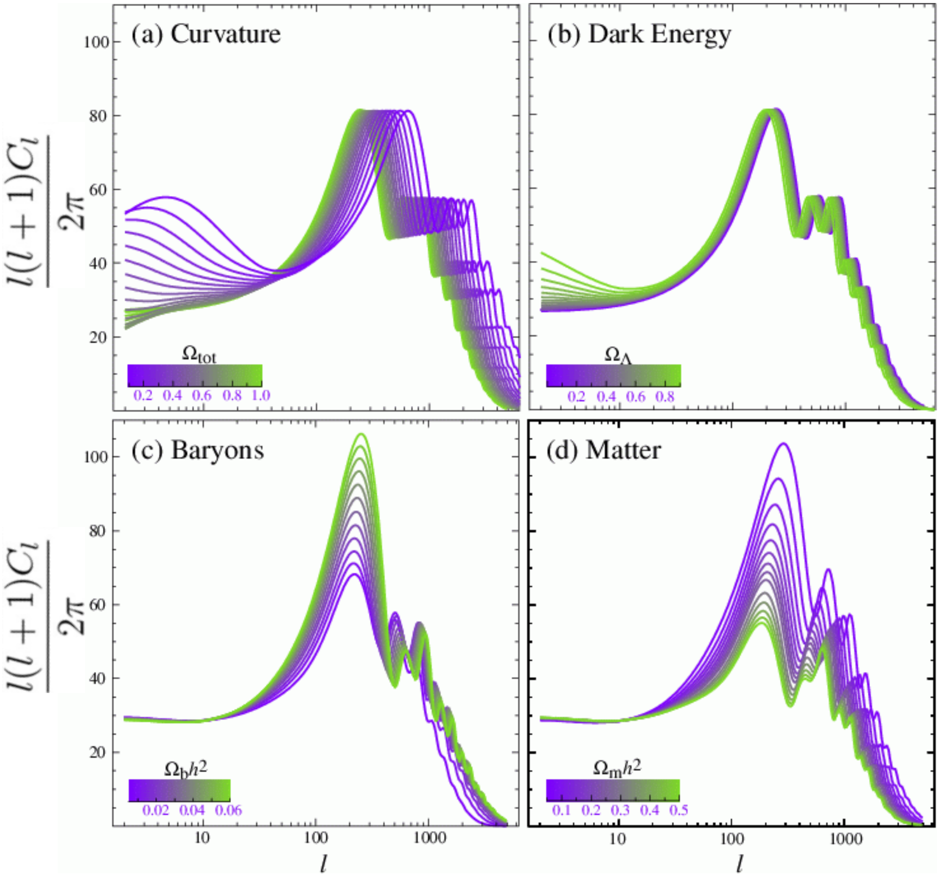
$$\Delta T(\hat{n}) = T(\hat{n}) - T_0 = \sum_{l=1}^{\infty} \sum_{-m}^{m} a_{lm} Y_{lm}(\hat{n})$$

Angular power spectrum

$$C_l = \frac{1}{2l+1} \sum_{-m}^{m} a_{lm} a_{lm}^*$$



CMB anisotropies map from PLANCK



Hu & Dodelson (2002)

Two-point function

$$C(\hat{n}_1, \hat{n}_2) = \langle \Delta T(\hat{n}_1) \Delta T(\hat{n}_2) \rangle$$

Isotropy :

$$C(\hat{n}_1, \hat{n}_2) = C(\theta)$$ **where** $\hat{n}_1 \cdot \hat{n}_2 = cos\theta$

$$= \frac{1}{4\pi} \sum_{l=1}^{\infty} (2l+1) C_l P_l(cos\theta)$$

and $$\langle a_{lm} a^*_{lm} \rangle = C_l \delta_{ll'} \delta_{mm'}$$

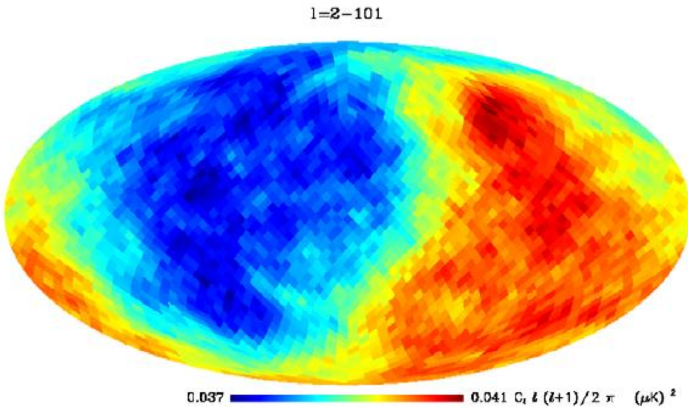
Hemispherical Power Asymmetry

Hemispherical power asymmetry

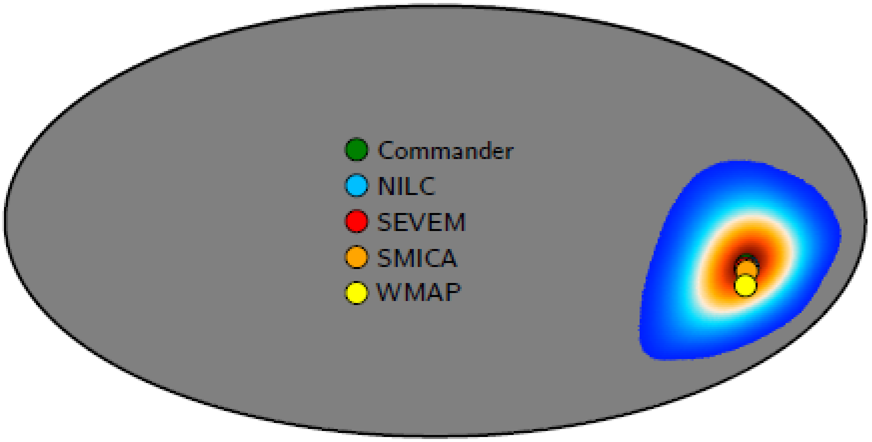
C_l is rotationally invariant quantity if SI holds.

Test of isotropy? – measure C_l in different directions/hemispheres of the sky

Hansen et.al., 2009



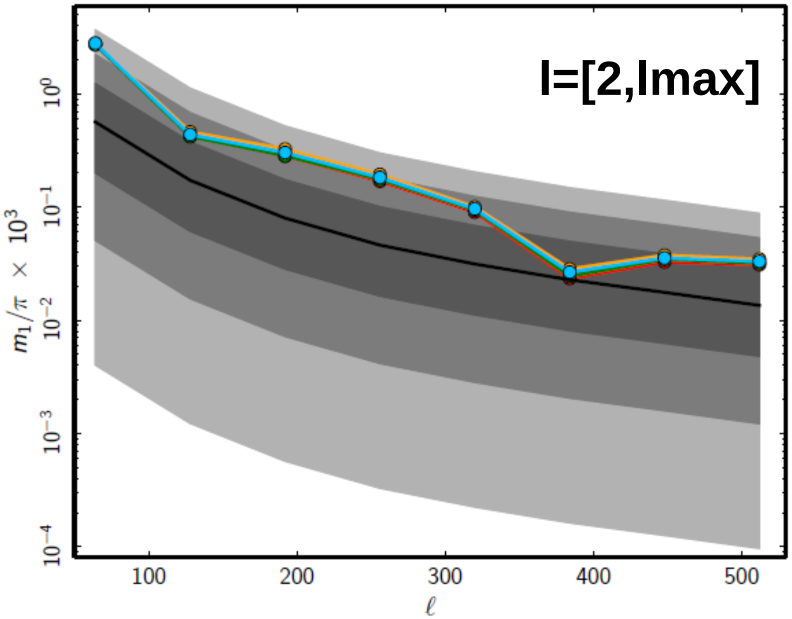
Direction of hemispherical power asymmetry from PLANCK 2013 data



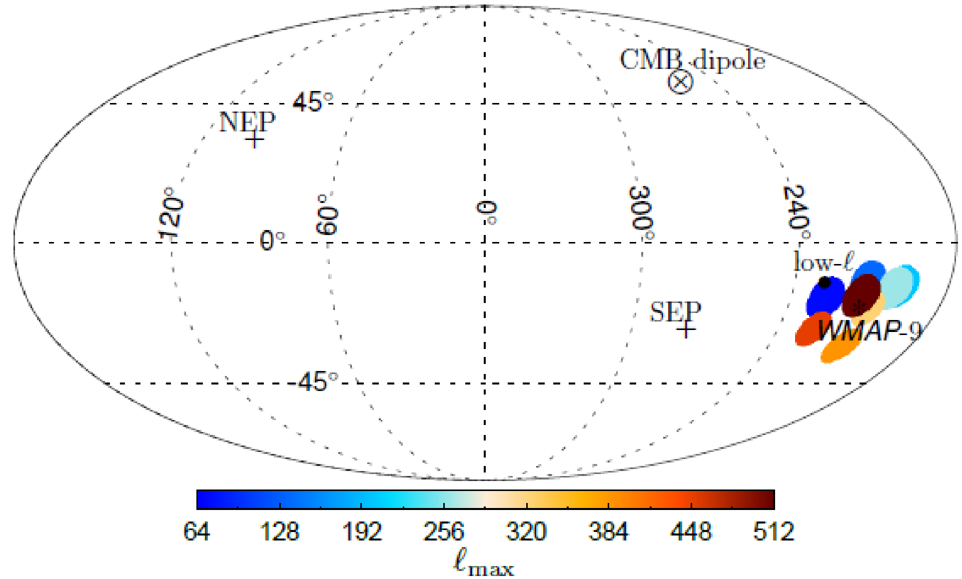
A significant dipole only modulation component at low-l is present ==>

$$T(\hat{n}) = \Theta(\hat{n})[1 + \mathcal{M}(\hat{n})]$$

$$T(\hat{n}) = \Theta(\hat{n})[1 + A\,\hat{\lambda}\cdot\hat{n}]$$



Amplitude of dipole modulation



Direction of dipole modulation

Hemispherical power asymmetry, modeled as Dipole modulation of CMB anisotropies, as measured from PLANCK 2015 data

Table 24. Amplitude (A) and direction of the dipole modulation in Galactic coordinates as estimated for the multipole range $\ell \in [2, 64]$ using a BipoSH analysis. The measured values of the dipole amplitude and direction are consistent for all maps.

Method	A	Direction (l, b) [°]
Commander . .	0.067 ± 0.023	$(230, -18) \pm 31$
NILC	0.069 ± 0.022	$(228, -17) \pm 30$
SEVEM	0.067 ± 0.023	$(230, -17) \pm 31$
SMICA	0.069 ± 0.022	$(228, -18) \pm 30$
SEVEM-100 . .	0.070 ± 0.023	$(231, -19) \pm 30$
SEVEM-143 . .	0.068 ± 0.023	$(230, -17) \pm 31$
SEVEM-217 . .	0.069 ± 0.023	$(229, -20) \pm 31$

Planck 2015 Results : XVI – Isotropy and Statistics

IUCAA/India team : T. Souradeep, S. Mitra, *Pavan K. Aluri*, Nidhi Pant, Aditya Rotti

Direction dependence in Cosmological parameters

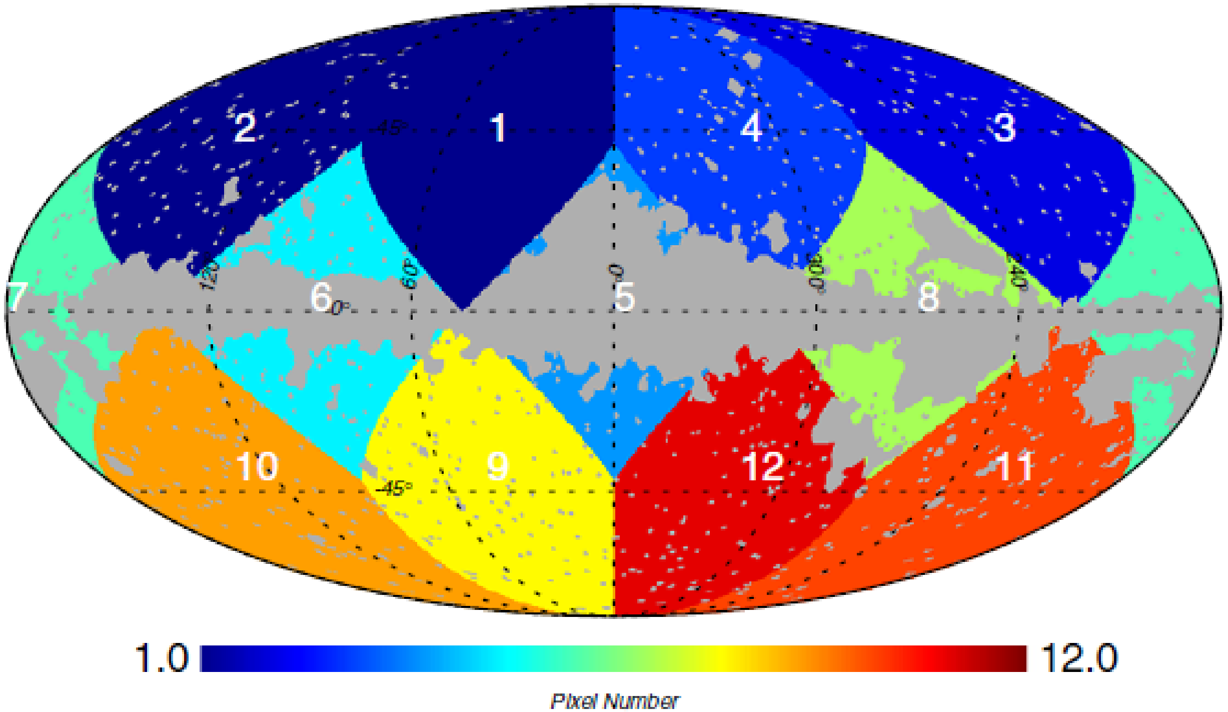


Figure 1. Twelve sky patches used in this Letter: the regions are delineated by the intersection of the 12 HEALPix base pixels with the *WMAP*9 KQ85 mask.

Axelsson et al., ApJ, 2013, 773, L3

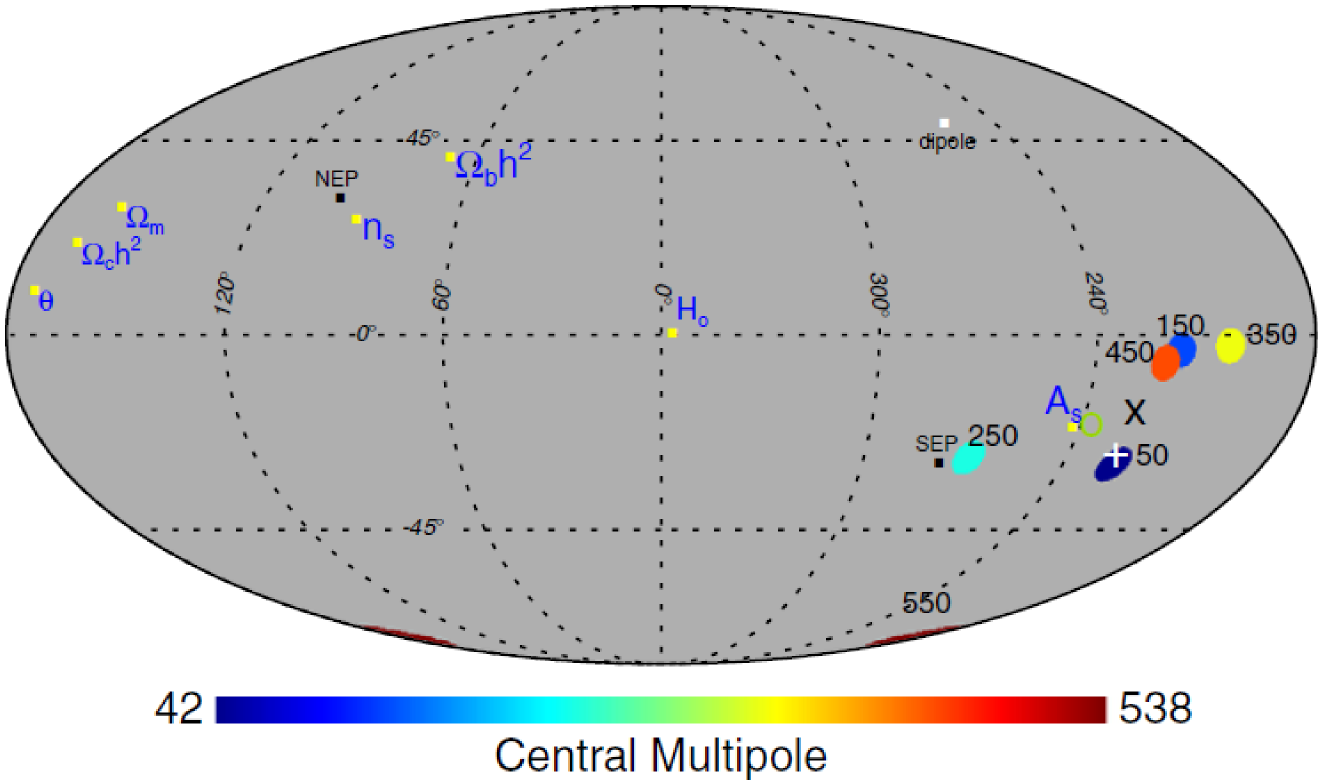
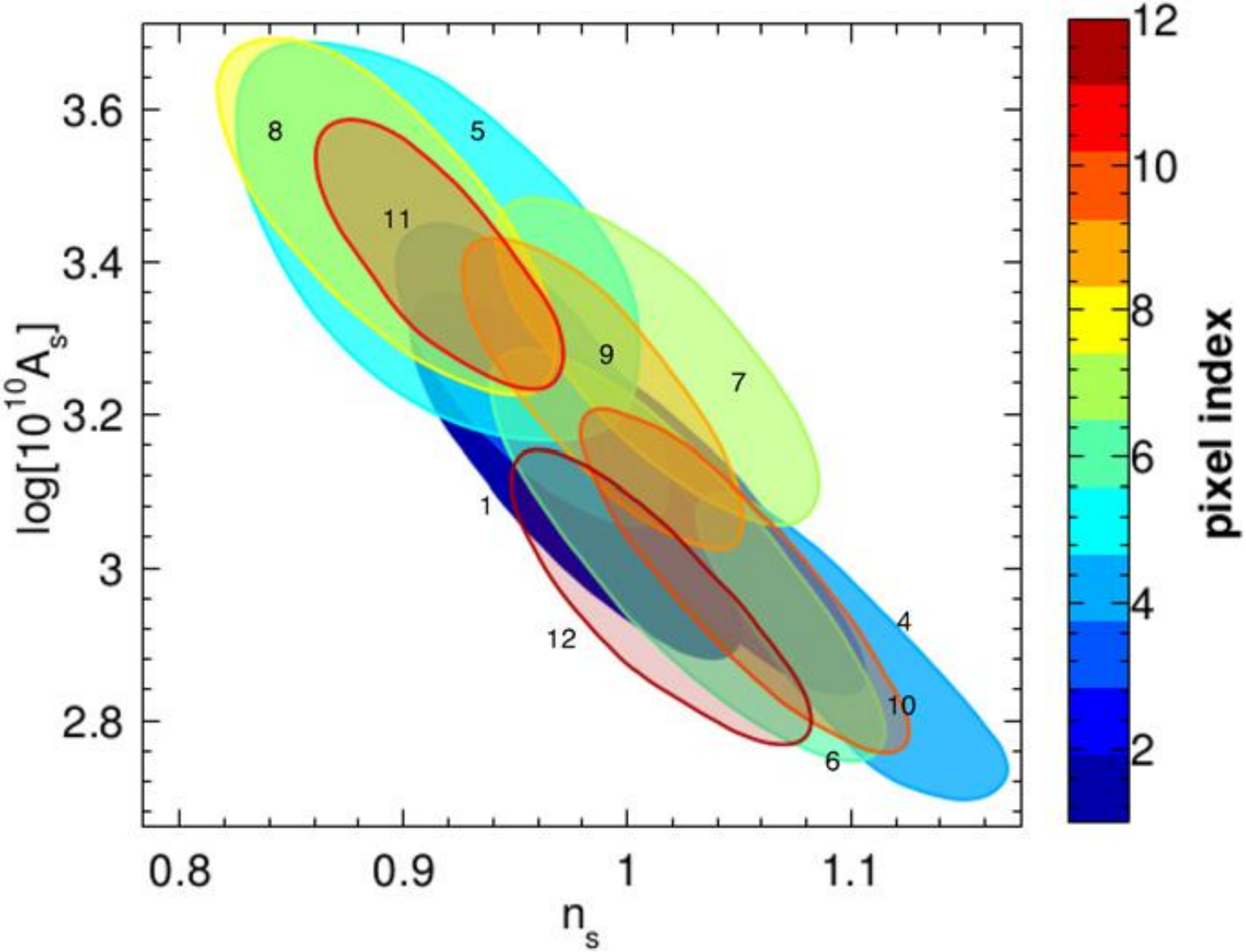


Figure 2. Dipole directions for maps of the local power spectrum computed for the 12 regions in Figure 1 from the *WMAP*9 combined *V*- and *W*-band data and separated into six 100-multipole bins. We also show the direction for the full $\ell = 2$–600 range (white cross), for the $\ell = 2$–40 interval determined from *WMAP*1 (green circle), and the $\ell = 2$–600 range from *WMAP*5 (black cross). NEP and SEP denote the north and south ecliptic poles, respectively. The dipole directions for the local parameter estimate maps are also shown.

Axelsson et al., ApJ, 2013, 773, L3



Summary of the n_s–log(10^{10} As) posterior in terms of 1σ contours for the 12 partitions of the sky.

Axelsson et al., ApJ, 2013, 773, L3

Quantifying isotropy violation

Two-point function

$$C(\hat{n}_1, \hat{n}_2) = \langle \Delta T(\hat{n}_1) \Delta T(\hat{n}_2) \rangle$$

Isotropy :

$$C(\hat{n}_1, \hat{n}_2) \equiv C(\theta) \quad \textbf{where} \quad \hat{n}_1 \cdot \hat{n}_2 = cos\theta$$

$$= \frac{1}{4\pi} \sum_{l=1}^{\infty} (2l+1) C_l P_l(cos\theta)$$

Anisotropy : ??

Bipolar spherical harmonics (BipoSH)

$$C(\hat{n}_1, \hat{n}_2) = \sum_{L,M,l_1,l_2} A^{LM}_{l_1 l_2} \left\{ Y_{l_1}(\hat{n}_1) \otimes Y_{l_2}(\hat{n}_2) \right\}_{LM}$$

Bipolar spherical harmonics (BipoSH)

Anisotropy :

$$\langle a_{lm} a_{l'm'} \rangle \neq C_l \delta_{ll'} \delta_{mm'}$$

$$C(\hat{n}_1, \hat{n}_2) = \sum_{L,M,l_1,l_2} A^{LM}_{l_1 l_2} \{Y_{l_1}(\hat{n}_1) \otimes Y_{l_2}(\hat{n}_2)\}_{LM}$$

$$A^{LM}_{l_1 l_2} = \sum_{m_1,m_2} C^{LM}_{l_1 m_1 l_2 m_2} a_{l_1 m_1} a_{l_2 m_2}$$

$$|l_1 - l_2| \leq L \leq l_1 + l_2, \quad |M| \leq L$$

Isotropy ➔

$$\begin{aligned} A^{00}_{ll'} &\propto C_l \delta_{ll'} \\ A^{LM}_{l_1 l_2} &= 0, \quad L > 0 \end{aligned}$$

What are the implications of this anisotropic low-l dipole modulation to CMB mutlipoles?

$$\tilde{T}(\hat{n}) = T(\hat{n})(1 + \alpha\,\hat{p}\cdot\hat{n}) \quad (\alpha \equiv \alpha_l\,)$$

$$A^{1N}_{ll+1|TT} = \mathcal{M}^{1N}[C^{TT}_l + C^{TT}_{l+1}]\frac{\Pi_{ll+1}}{\sqrt{4\pi}\Pi_1}C^{10}_{l\,0l+1\,0}$$

$$\mathcal{M}^{1N} \leftarrow \mathcal{M}(\hat{n}) = \alpha\,\hat{p}\cdot\hat{n}$$

True implications of Hemispherical Power Asymmetry

Low-l dipole modulation

$\xrightarrow{?}$ **Direction dependence in cosmological parameters**

Yes :

→ **Potential source of tension between different small sky missions!!**

No :

→ **Direction dependence arising due foregrounds/systematics**

Low-l dipole modulation

$\xrightarrow{?}$ Direction dependence in cosmological parameters

Yes :

→ Potential source of tension between different small sky missions!!

No :

→ Direction dependence arising due foregrounds/systematics

Study ideal (no beam smoothing/ foregrounds/ noise) dipole modulated CMB sky !!

Direction dependence of cosmological parameters due to cosmic hemispherical asymmetry

Suvodip Mukherjee, Pavan K. Aluri, Santanu Das, Shabbir Shaikh and Tarun Souradeep

Inter University Centre for Astronomy and Astrophysics,
Post Bag 4, Ganeshkhind, Pune-411007, India

E-mail: suvodip@iucaa.in, aluri@iucaa.in, santanud@iucaa.ernet.in,
shabbir@iucaa.in, tarun@iucaa.in

JCAP, 2016, 06, 042

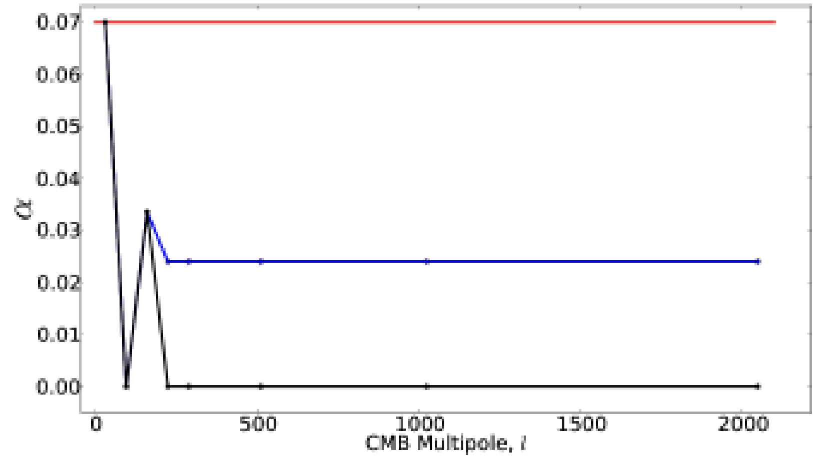


Figure 1. The profiles of amplitude of modulation for the three different cases studied in the present work — (*i*) SD-1: a scale dependent modulation profile with some residual anisotropy at small scales, (*ii*) SD-2: scale dependent profile as seen in PLANCK data, and (*iii*) SID: a scale independent modulation, are shown here in blue, black and red respectively.

Simulated CMB maps with three different amplitude profiles using CoNIGS (Code for Non-Isotropic Gaussian Sky) (Mukherjee S. & Souradeep T., 2014)

Using these ideal simulations, assess directional dependence of cosmological parameters :

Recover angular power spectrum (C_l) from 12 different non-overlapping sky partitions :

MASTER algorithm (Hivon et al, 2002)

Parameter likelihood estimation using small patch C_l :

SCoPE (Slick Cosmological Parameter Estimator)
(Das S. & Souradeep T., 2014)

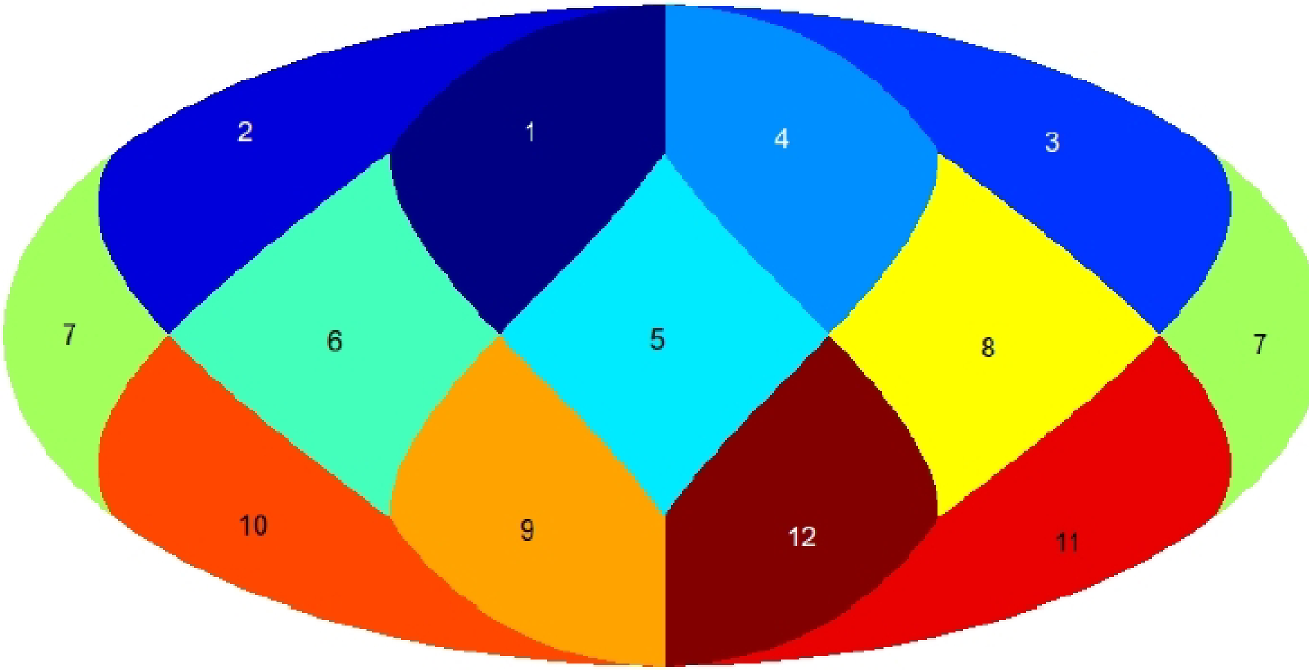
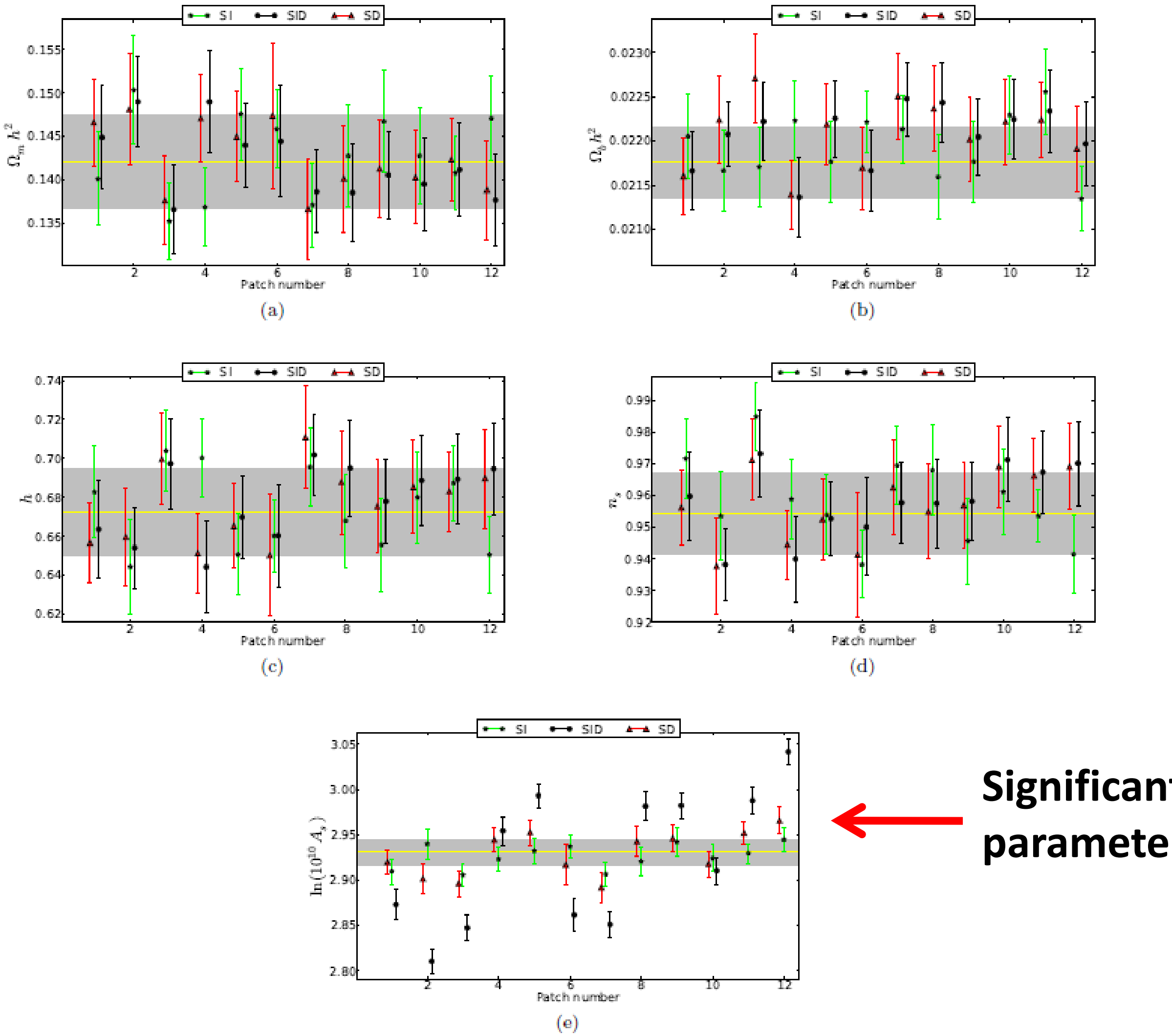


FIG. 2.— Full sky realizations of CMB are partitioned into 12 different regions as depicted in this diagram. Cosmological parameters are estimated from these 12 different patches from SI and nSI simulations. The anisotropic simulations are produced with cosmic hemispherical asymmetry injected in the direction of pixel center of patch 12.

Results



Significantly affected parameter, A_s

FIG. 4.— The mean and standard deviation of the best-fit five cosmological parameters $\{\Omega_m h^2, \Omega_b h^2, h, n_s, A_s\}$ obtained from the 12 sky patches (shown in Fig. 2) for (*i*) Statistically Isotropic (SI) (green) (*ii*) scale independent (SID) statistically non-isotropic (black) and (*iii*) scale dependent (SD) statistically non-isotropic (red). In grey, we show the 1σ region from the full sky SI simulation with the mean depicted in yellow. None of the parameters except the amplitude A_s show significant variation with sky patch in comparison to that arising due to cosmic variance in statistically isotropic model.

Summary :

1. Hemispherical power asymmetry seen in CMB Temperature data
   → Dipolar in nature

2. Modulation profile as seen in Temperature data cannot induce direction dependence in cosmological parameters

3. Origin → Primordial, Foreground residuals, unknown systematic?
   CMB Polarization?
   Model building?

4. Future polarization data will shed light on this very important issue

THANK YOU

FOR YOUR ATTENTION