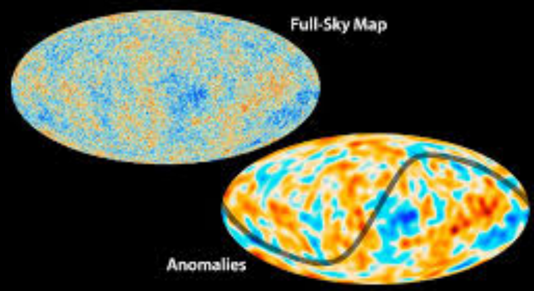
Imprints of Isotropy Violated Gravitational Wave Background in CMB

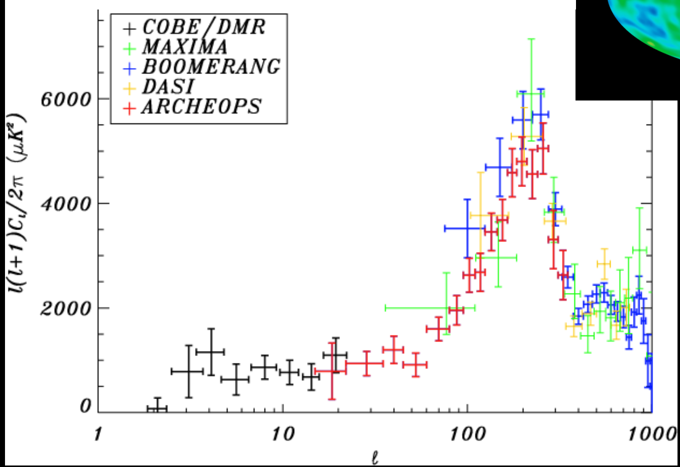


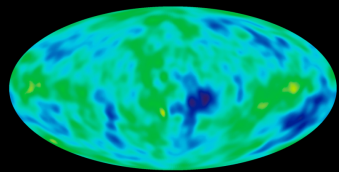
Suvodip Mukherjee

Supervisor
Prof. Tarun Souradeep

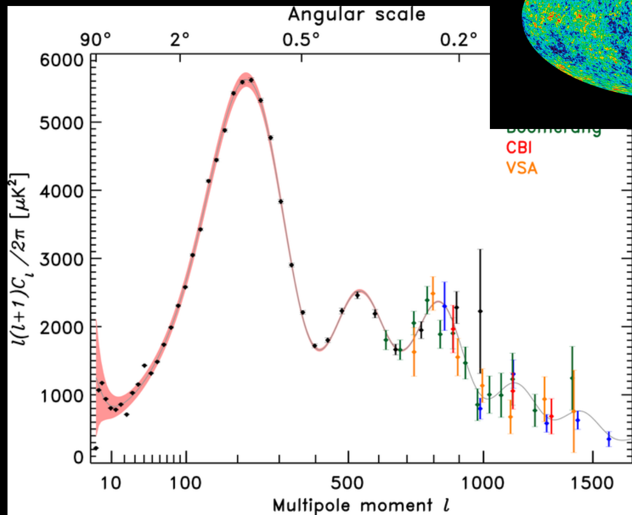
Journey so far

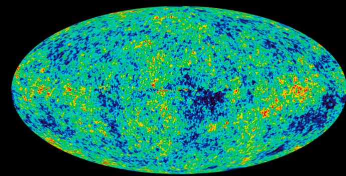
By COBE in 1992



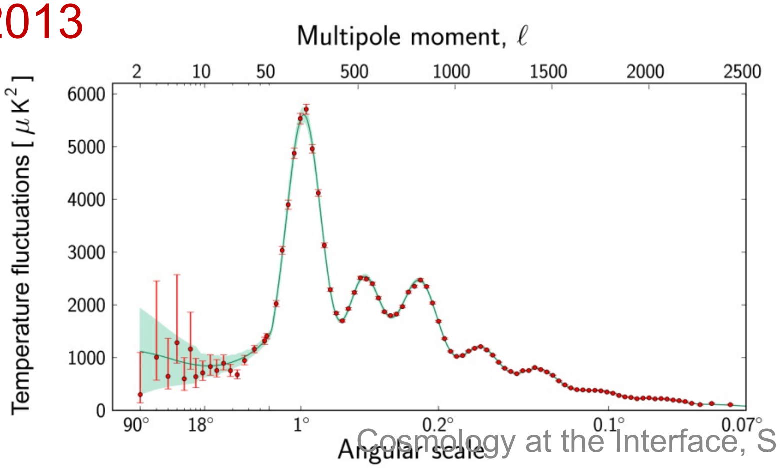


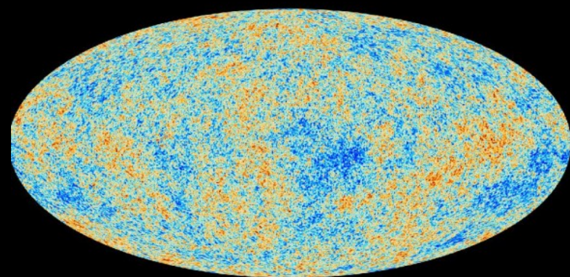
By WMAP in 2003





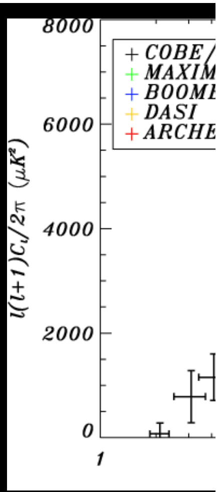
By Planck in 2013



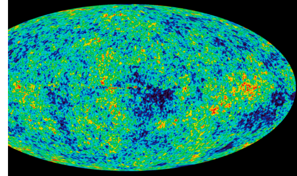


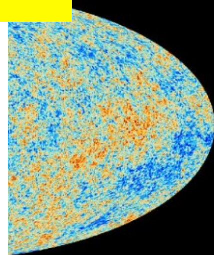
Journey so far

COBE in



By Planck





Planck Collaboration: Cosmological parameters

arXiv: 1303.5076

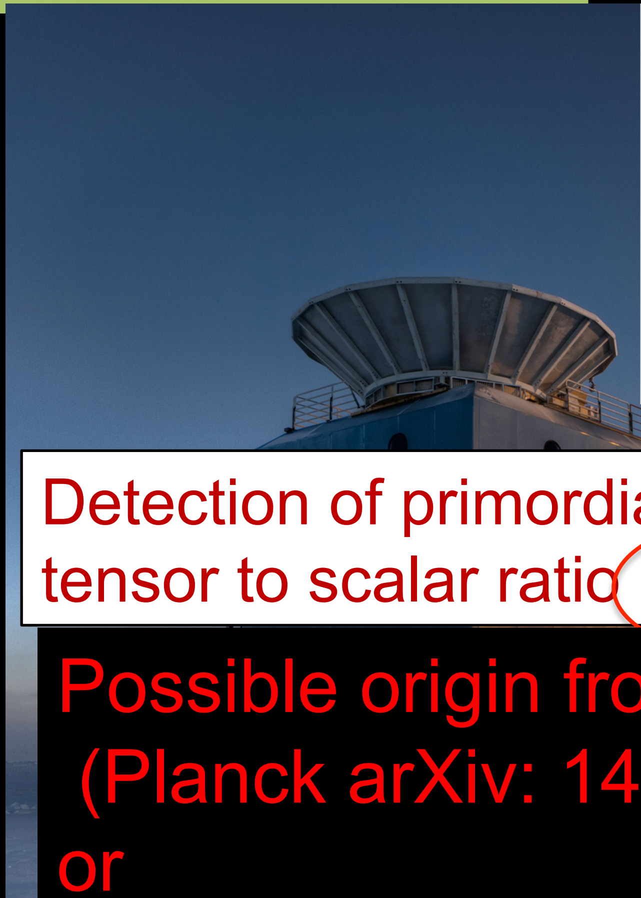
Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limits	*Planck*+lensing+WP+highL Best fit	*Planck*+lensing+WP+highL 68% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
A^{PS}_{100}	152	171 ± 60	209	212 ± 50	204	213 ± 50	204	212 ± 50
A^{PS}_{143}	63.3	54 ± 10	72.6	73 ± 8	72.2	72 ± 8	71.8	72.4 ± 8.0
A^{PS}_{217}	117.0	107^{+20}_{-10}	59.5	59 ± 10	60.2	58 ± 10	59.4	59 ± 10
A^{CIB}_{143}	0.0	< 10.7	3.57	3.24 ± 0.83	3.25	3.24 ± 0.83	3.30	3.25 ± 0.83
A^{CIB}_{217}	27.2	29^{+6}_{-9}	53.9	49.6 ± 5.0	52.3	50.0 ± 4.9	53.0	49.7 ± 5.0
A^{tSZ}_{143}	6.80	...	5.17	$2.54^{+1.1}_{-1.9}$	4.64	$2.51^{+1.2}_{-1.8}$	4.86	$2.54^{+1.2}_{-1.8}$
$r^{PS}_{143\times217}$	0.916	> 0.850	0.825	$0.823^{+0.069}_{-0.077}$	0.814	0.825 ± 0.071	0.824	0.823 ± 0.070
$r^{CIB}_{143\times217}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.928	1.0000	> 0.930

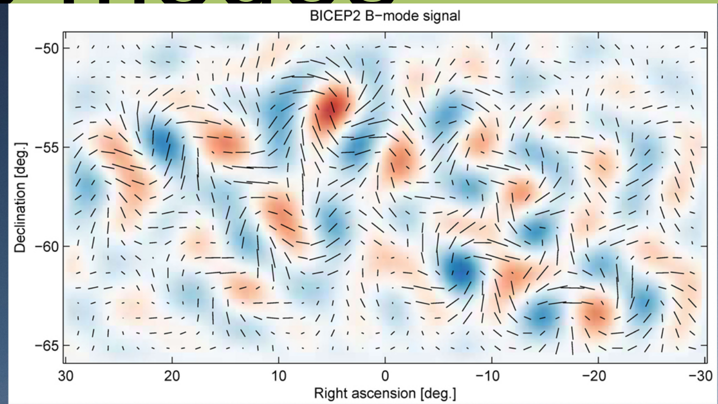
LCDM Model is the Best fit Cosmological Model

Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limits	*Planck*+lensing+WP+highL Best fit	*Planck*+lensing+WP+highL 68% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68% limits
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

Table 5. Best-fit values and 68% confidence limits for the base ΛCDM model. Beam and calibration parameters, and additional nuisance parameters for "highL" data sets are not listed for brevity but may be found in the Explanatory Supplement (Planck Collaboration ES 2013).

Recent Measurement of B modes





Detection of primordial gravitati [redacted] ave with tensor to scalar ratio (r) of 0.2

??

Possible origin from dust
(Planck arXiv: 1409.5738, (2014))
or
Something else ??(This talk)

.037
00056
.45

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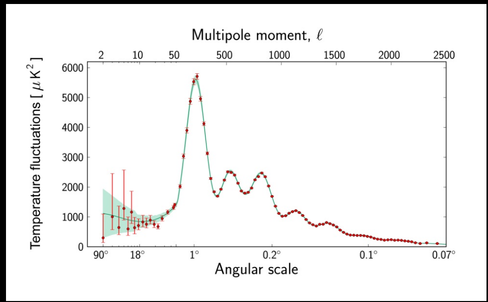

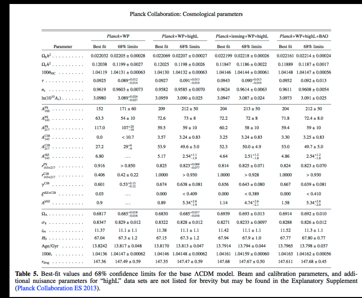

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	Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
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$r^{CIB}_{143\times217}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.928	1.0000	> 0.930
γ^{CIB}	0.601	$0.53^{+0.13}_{-0.12}$	0.674	0.638 ± 0.081	0.656	0.643 ± 0.080	0.667	0.639 ± 0.081
$\xi^{tSZ\times CIB}$	0.03	...	0.000	< 0.409	0.000	< 0.389	0.000	< 0.410
A^{kSZ}	0.9	...	0.89	$5.34^{+2.8}_{-1.9}$	1.14	$4.74^{+2.6}_{-2.1}$	1.58	$5.34^{+2.8}_{-2.0}$
Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
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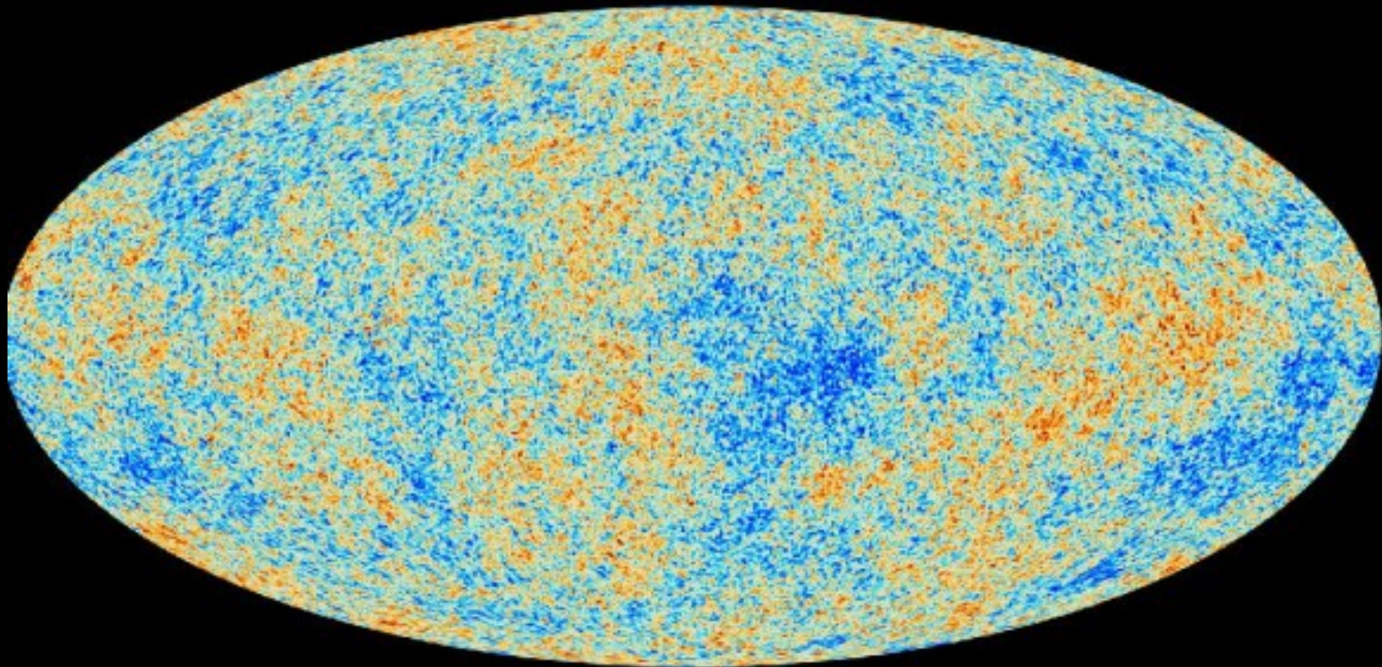
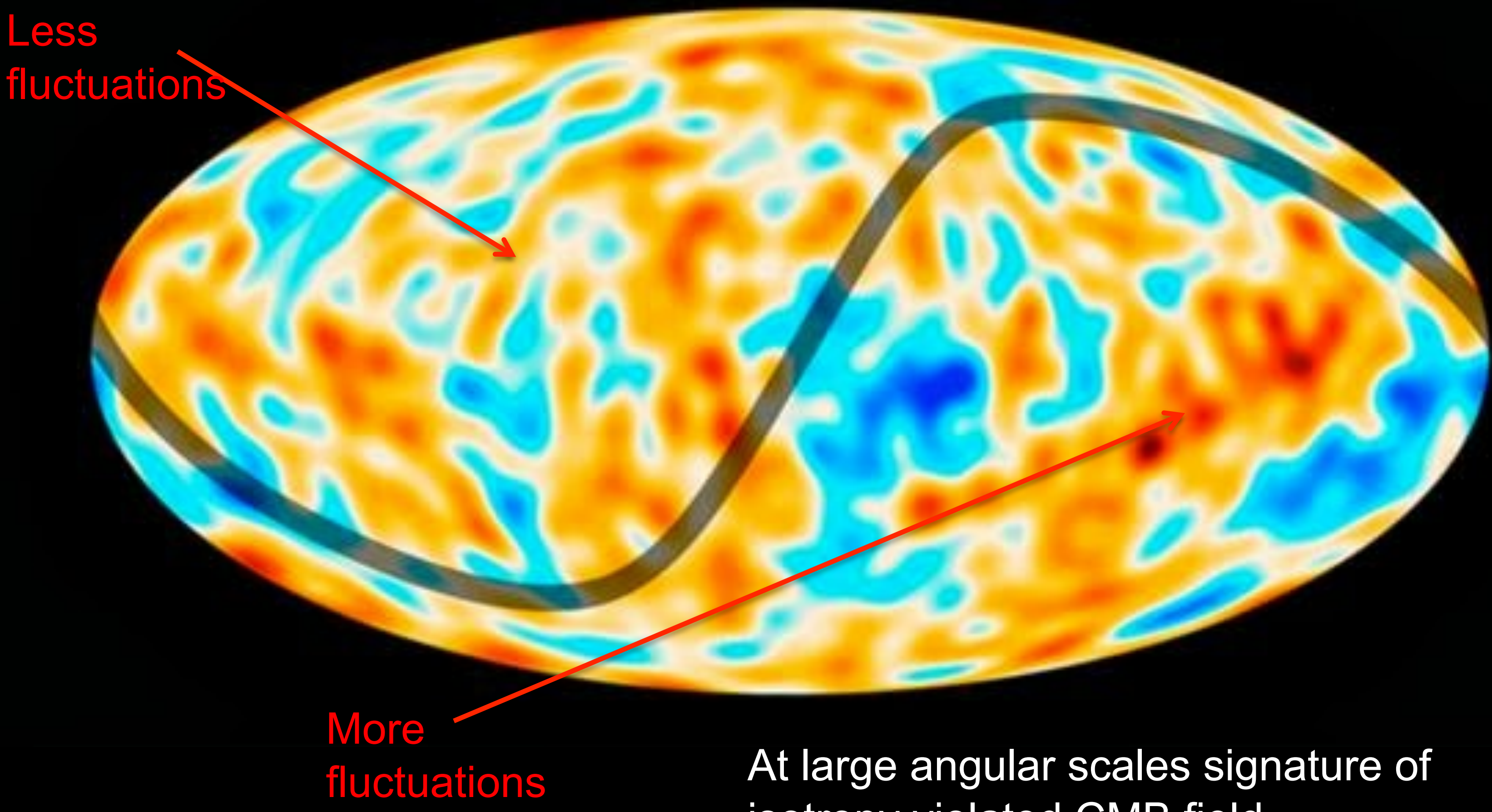
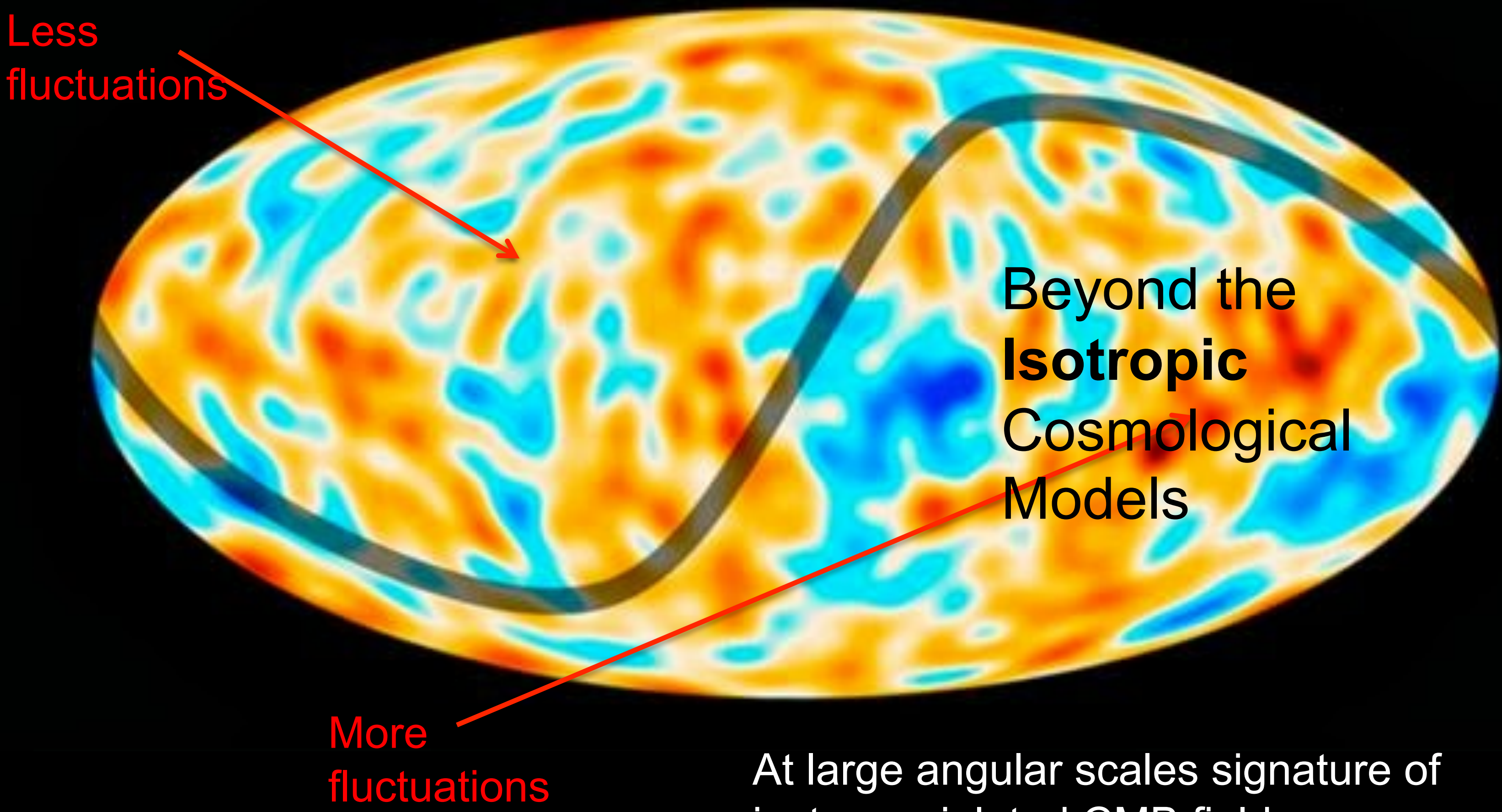




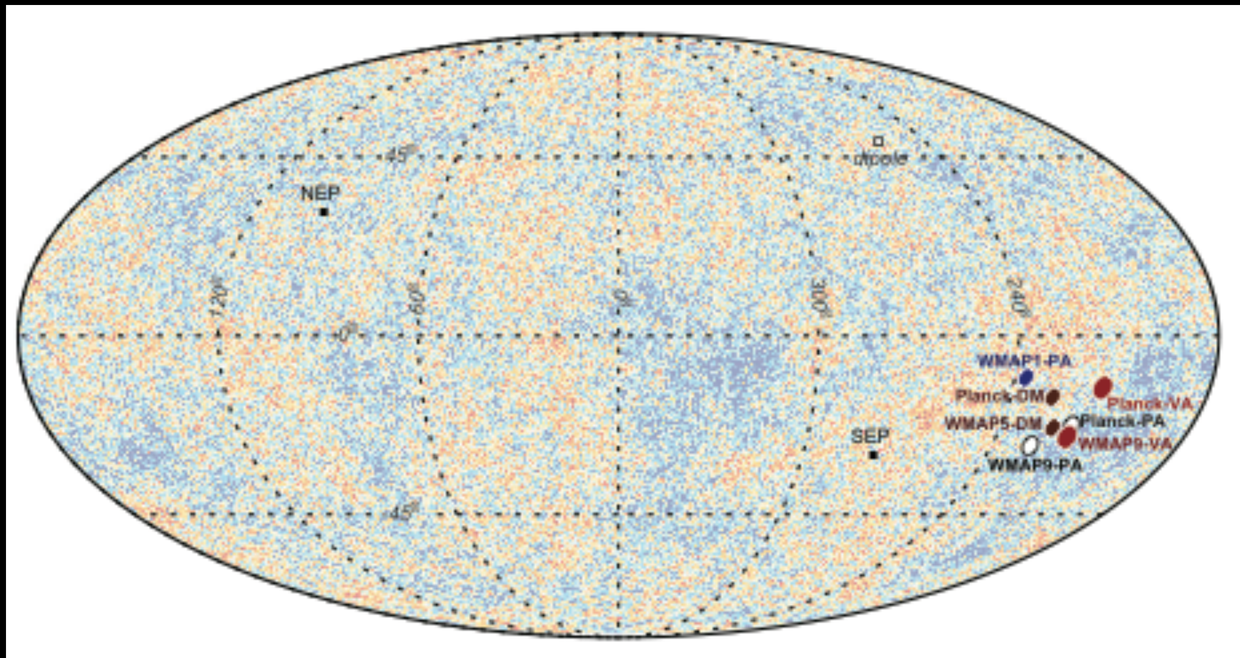
At large angular scales signature of isotropy violated CMB field



Beyond the **Isotropic** Cosmological Models

At large angular scales signature of isotropy violated CMB field

Signature observed in WMAP and Planck



F. K. Hansen, A. J. Banday and K. M. Gorski, M. N. R. A. S. 354, 641, (2004).
H. K. Eriksen et al., Astrophys. J., 605,14, (2004).
Y. Akrami et al., Astrophys. J., 784, L42, (2014)

Language to quantify isotropy violation : **BipoSH coefficients**

Hajian and Souradeep
Astrophys. J. 597, L5, (2003).

$$\delta T(\hat{n}) = \sum_{lm} a_{lm} Y_{lm}(\hat{n}).$$

$$Q(\hat{n}) \pm iU(\hat{n}) = \sum_{l=2}^{\infty} \sum_{m=-l}^{+l} (E_{lm} \pm iB_{lm})_{\pm 2}Y_{lm}(\hat{n})$$

$$C^{XX'}(\hat{n}_1, \hat{n}_2) = \sum_{JNl_1l_2} A^{JN}_{l_1l_2|XX'} \{Y_{l_1}(\hat{n}_1) \otimes Y_{l_2}(\hat{n}_2)\}_{JN}$$

Bipolar Spherical Harmonics (BipoSH) coefficients

Isotropic Universe BipoSH coefficents are zero

Under the assumption of Statistical Isotropy

$$\left\langle a^*_{lm} a_{l'm'} \right\rangle = C_l^{TT} \delta_{ll'} \delta_{mm'},$$

$$\left\langle E^*_{lm} E_{l'm'} \right\rangle = C_l^{EE} \delta_{ll'} \delta_{mm'},$$

$$\left\langle B^*_{lm} B_{l'm'} \right\rangle = C_l^{BB} \delta_{ll'} \delta_{mm'},$$

$$\left\langle E^*_{l'm'} a_{lm} \right\rangle = C_l^{TE} \delta_{ll'} \delta_{mm'}.$$

Isotropy violated Universe, BipoSH coefficents are non-zero

~~Under the assumption of Statistical Isotropy~~

$$\left\langle a^*_{lm} a_{l'm'} \right\rangle = C_l^{TT} \delta_{ll'} \delta_{mm'},$$

$$\left\langle E^*_{lm} E_{l'm'} \right\rangle = C_l^{EE} \delta_{ll'} \delta_{mm'},$$

$$\left\langle B^*_{lm} B_{l'm'} \right\rangle = C_l^{BB} \delta_{ll'} \delta_{mm'},$$

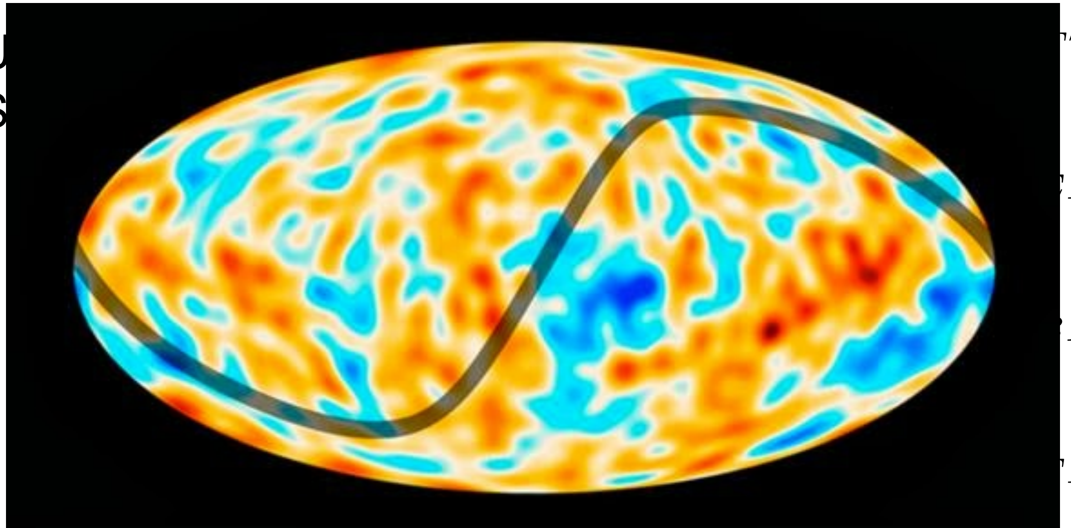
$$\left\langle E^*_{l'm'} a_{lm} \right\rangle = C_l^{TE} \delta_{ll'} \delta_{mm'}.$$

$$\left\langle X_{l_1 m_1} X'^{*}_{l_2 m_2} \right\rangle = \sum_{LM} A^{LM}_{l_1 l_2|XX'} (-1)^{m_2} C^{LM}_{l_1 m_1 l_2 -m_2}, \;\; X = E, B, T$$

Bipolar Spherical Harmonics (BipoSH) coefficients

Isotropy violated Universe, BipoSH coefficents are non-zero

U
S



$^{T}\delta_{ll'}\delta_{mm'},$

$^{E}\delta_{ll'}\delta_{mm'},$

$^{B}\delta_{ll'}\delta_{mm'},$

$^{E}\delta_{ll'}\delta_{mm'}.$

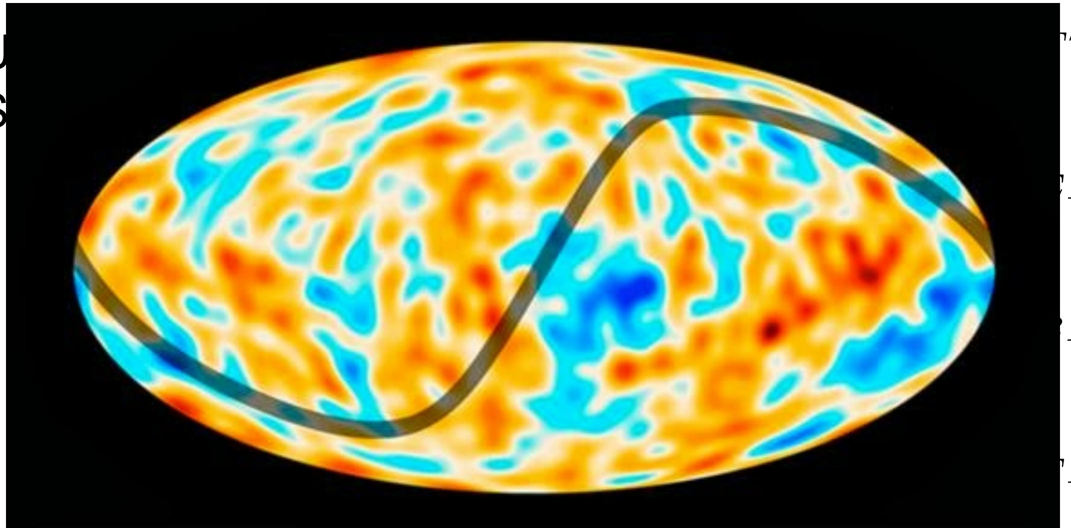
$$\langle X_{lm_1} X'^{*}_{l+1 m_2} \rangle = \sum_N A^{1N}_{ll+1|XX'} (-1)^{-m_2} C^{1N}_{lm_1 l+1 -m_2}$$

Dipolar Asymmetry

Isotropy violated Universe, BipoSH coefficents are non-zero

U

S



$^{TT}\delta_{ll'}\delta_{mm'}$,

$^{E}\delta_{ll'}\delta_{mm'}$,

$^{B}\delta_{ll'}\delta_{mm'}$,

$^{E}\delta_{ll'}\delta_{mm'}$.

$$\langle X_{lm_1} X'^{*}_{l+1 m_2}\rangle = \sum_N A^{1N}_{ll+1|XX'}(-1)^{-m_2} C^{1N}_{lm_1 l+1 -m_2}$$

Signal in Planck ??

Dipolar Asymmetry

Results from Planck-2013

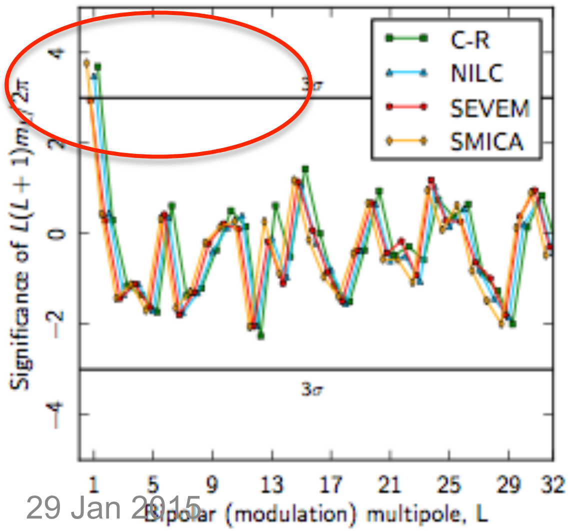
$$\tilde{T}(\hat{n}) = [1 + M(\hat{n})]T(\hat{n})$$

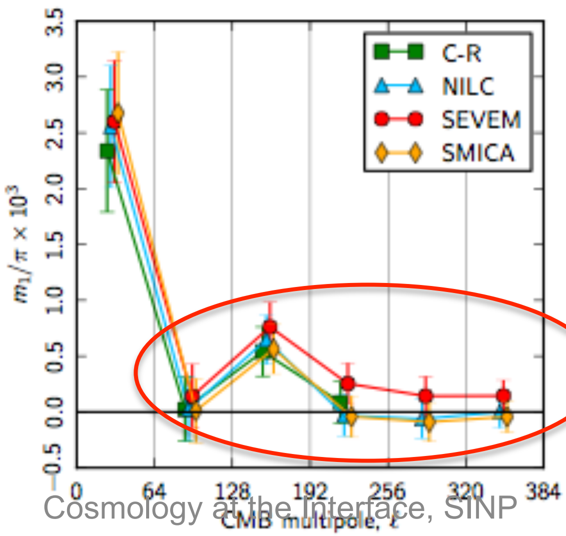
Souradeep et al.
Planck XXIII
A&A 571, A23, 2014

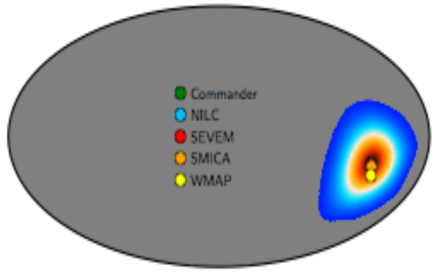
$$\tilde{T}(\hat{n}) = [1 + \sum_{LM} m_{LM} Y_{LM}(\hat{n})]T(\hat{n})$$

Only Dipolar (L=1)

$$(l = 217.5^\circ, b = -20.2^\circ)$$







No signal at **small scale**

Salient Features of isotropy violation

- Dipolar in nature. All higher L terms are consistent with zero.

- Scale dependent feature. Signal decays beyond (l>60)

No Known model yet to explain these two features

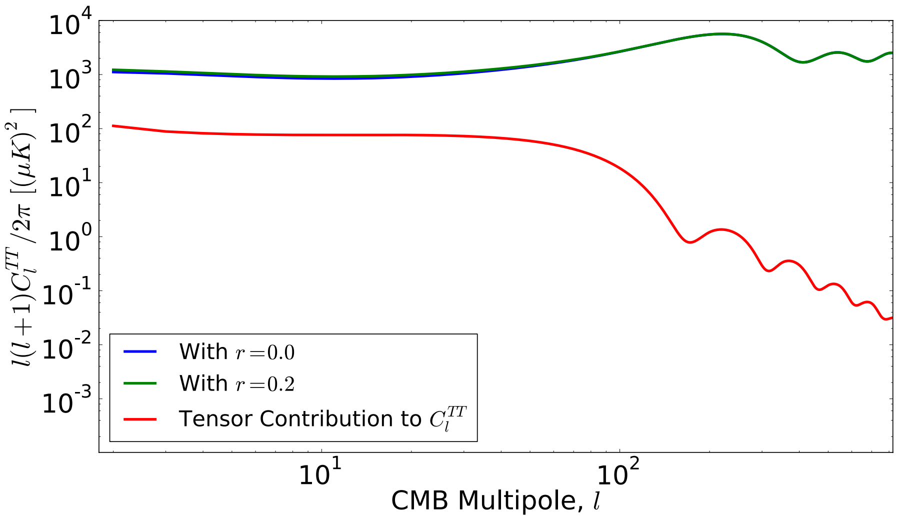
Salient Features of isotropy violation

- Dipolar in nature. All higher L terms are consistent with zero.

- Scale dependent feature. Signal decays beyond (l>60)

Physical Mechanisms which decays at large angular scale.

Mixed Modulation Model



Mukherjee,
arXiv:1412.2491

Need to determine

$$\tilde{X}(\hat{n}) = [1 + (1-\alpha)M_s(\hat{n})]X^s(\hat{n}) + [1 + \alpha M_t(\hat{n})]X^t(\hat{n})$$

Unequal contribution from scalar and tensor

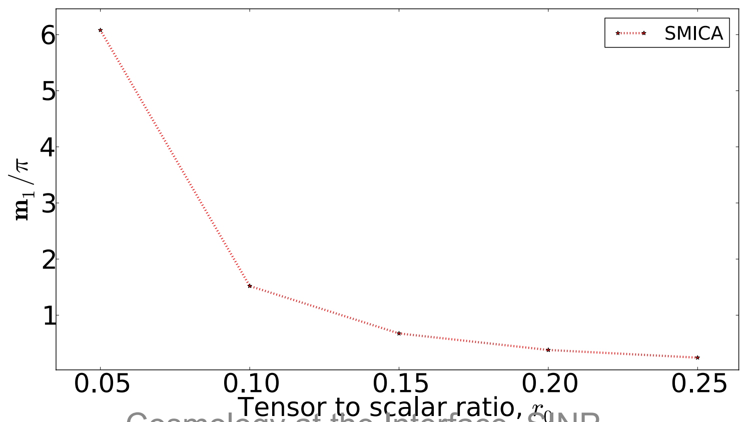
Solves the scale dependent problem.

Determining the value of M_t (A)

Mukherjee,
arXiv:1412.2491

$$ {}^{t}A^{1N}_{ll+1|TT} = M^{1N}_{t} \frac{\Pi_{ll+1}}{\Pi_1} \frac{\left[{}^{t}C^{TT}_{l} + {}^{t}C^{TT}_{l+1} \right]}{\sqrt{4\pi}} \mathcal{C}^{10}_{l0l+1\,0} $$

$$ \Pi_{l_1 l_2 .. l_n} = \sqrt{(2l_1+1)(2l_2+1)..(2l_n+1)} $$



Mixed Modulation Model

Mukherjee,
arXiv:1412.2491

$$\tilde{X}(\hat{n}) = [1 + (1-\alpha)M_s(\hat{n})]X^s(\hat{n}) + [1 + \alpha M_t(\hat{n})]X^t(\hat{n})$$

Implication:
Direction dependent tensor to scalar ratio

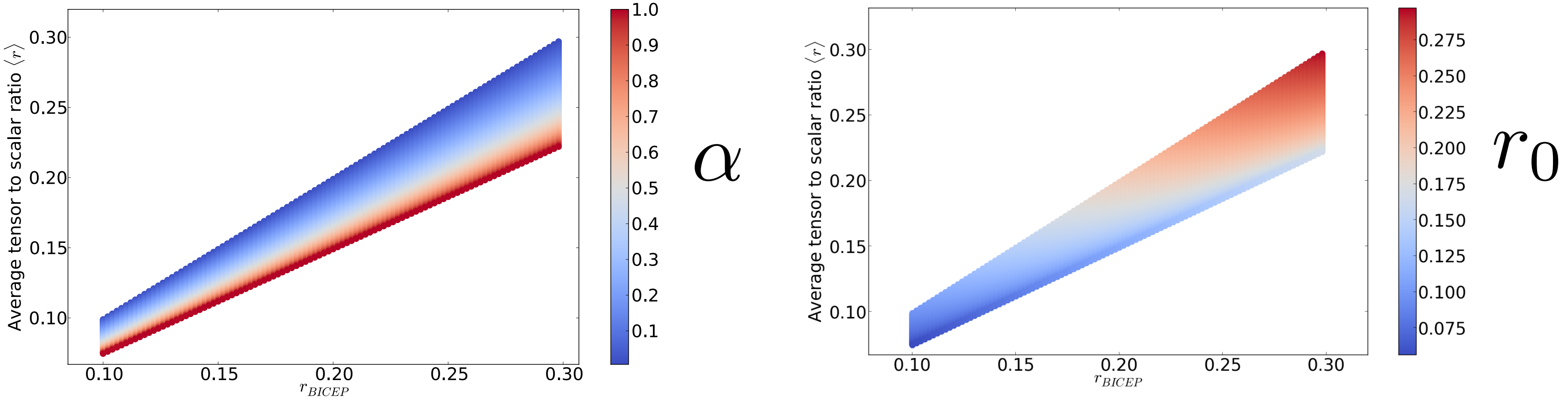
$$r(\hat{n}) = r_o\,[1 + \alpha A\,\hat{p}.\hat{n}]^2$$

$$\langle r(\hat{n})\rangle = r_o(1 + (\alpha A)^2/3)$$

$$A = 1.5\sqrt{\frac{m_1}{\pi}}$$

Determining the value of α and r_0

Mukherjee,
arXiv:1412.2491



Different values of tensor to scalar ratio from Planck and BICEP

Prediction of Mixed Modulation model: Measurable SI violated B modes

Mukherjee,
arXiv:1412.2491

$$ {}^{t}A^{1N}_{ll+1|BB} = \alpha M^{1N}_{t} \frac{\Pi_{ll+1}}{\Pi_{1}} \frac{\left[{}^{t}C^{BB}_{l} + {}^{t}C^{BB}_{l+1} \right]}{\sqrt{4\pi}} \mathcal{C}^{10}_{l\,2\,l+1\,-2} $$

Prediction of Mixed Modulation model:

Measurable SI violated B modes

Mukherjee,
arXiv:1412.2491

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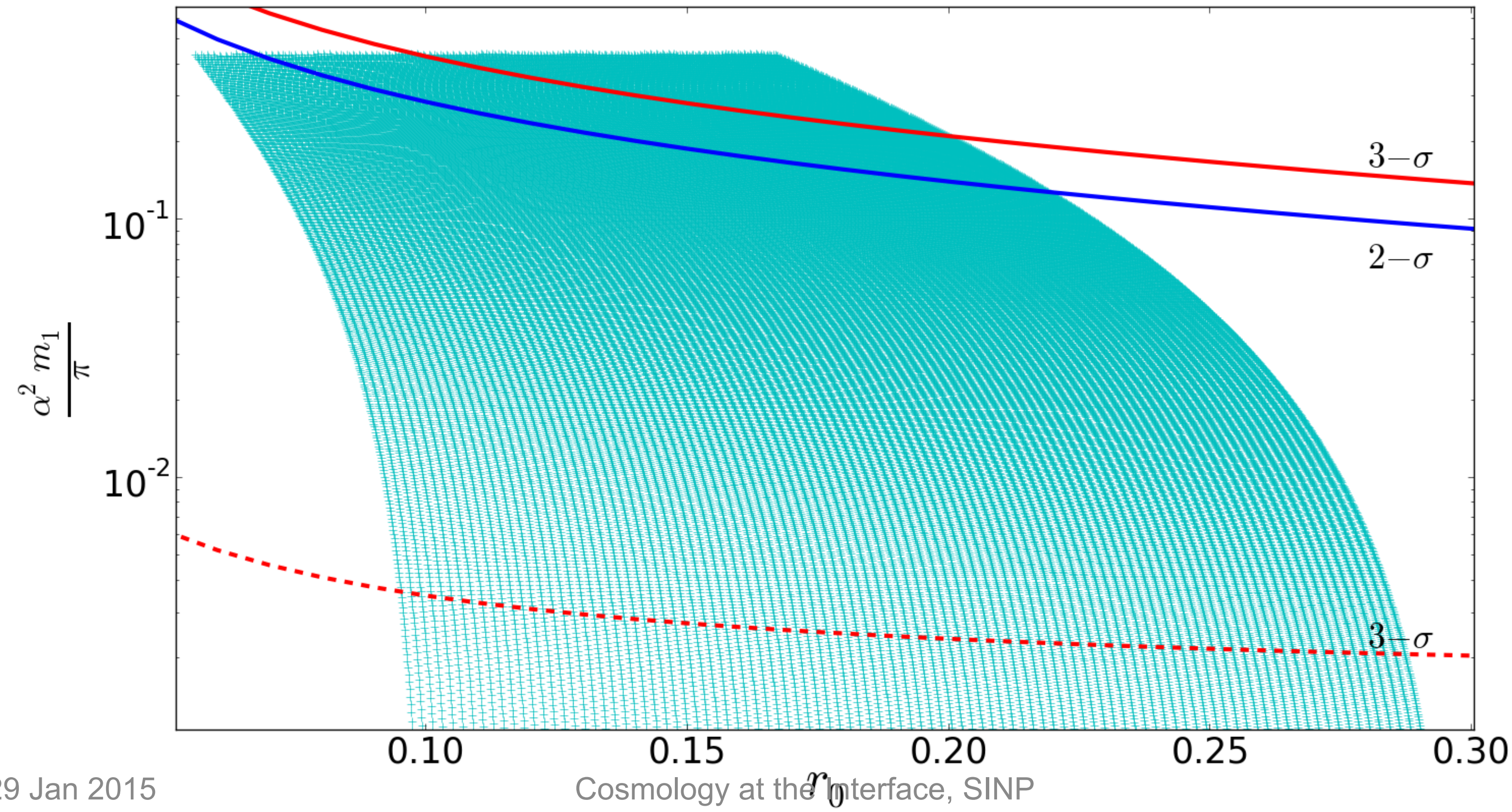

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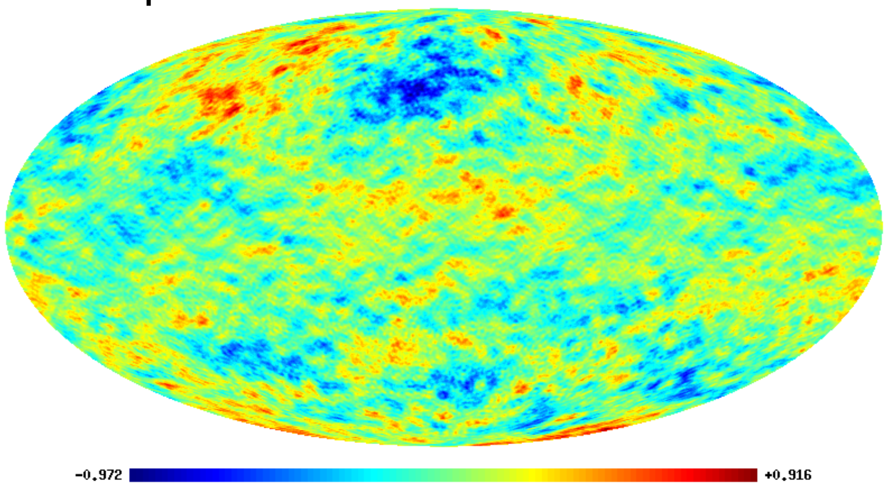
Comparison of Mixed modulation maps and scale dependent temperature modulation map

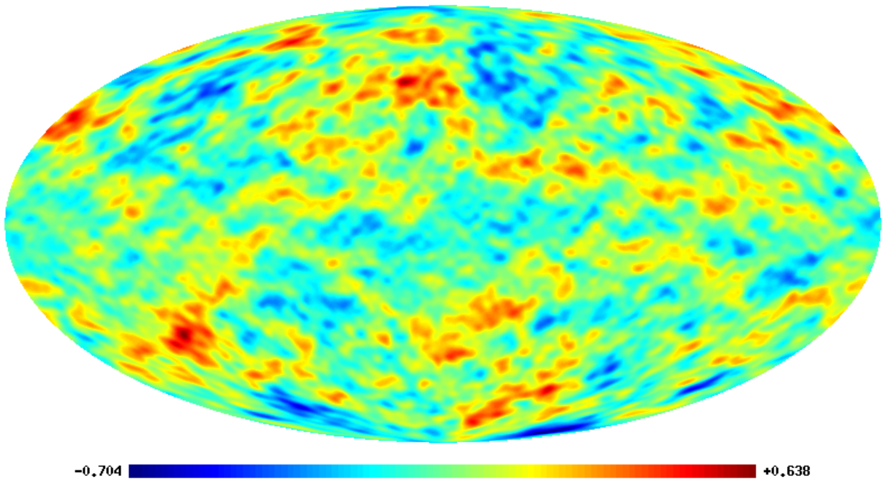
- We developed a numerical algorithm CoNIGs (Code for Non Isotropic Gaussian sky) to produce SI violated Gaussian realization of CMB

Mukherjee and Souradeep Phys. Rev. D 89 063013 (2014)

Scale dependent temperature modulation



Mixed Modulation model



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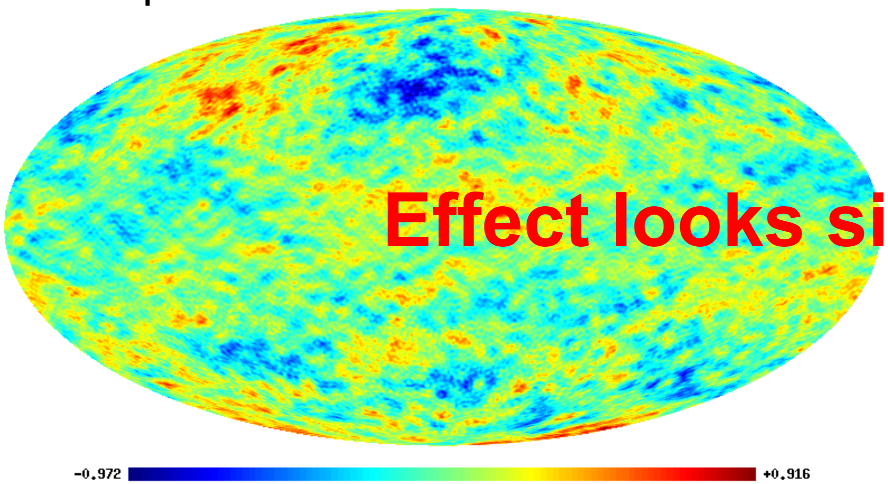

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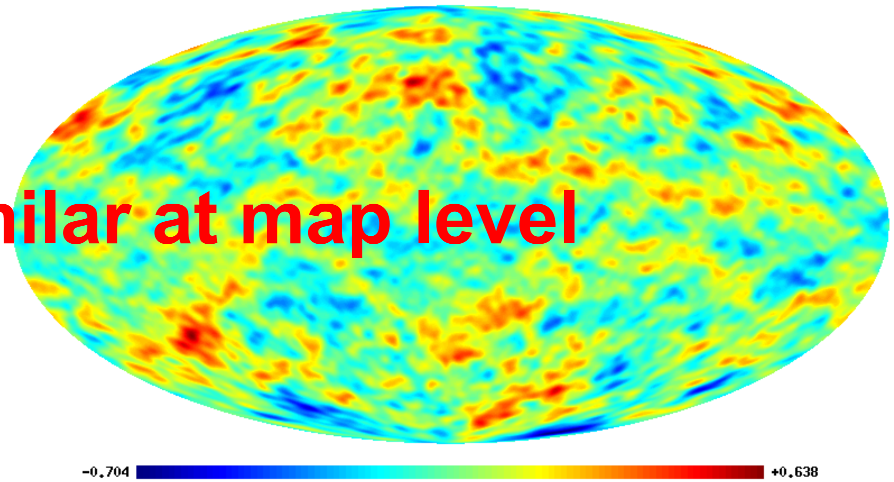

Effect looks similar at map level

- Dipolar in nature. All higher L terms are consistent with zero.
- Scale dependent feature. Signal decays beyond (l>60)
- Physical Mechanisms which decays at large angular scale: Stochastic Gravitational Wave Background

Possible Origin from inflation

Mukherjee and Souradeep [in preparation]

$$X = \frac{H_a}{H} << 1$$

$$Y = \frac{\dot{H}_a}{\dot{H}} << 1$$

A. A. Abolhasani, et al. Phys. Rev. D 89, 063511, (2014).

L. Dai, et al. Phys. Rev. D, 87, 123005, (2013).

$$\tilde{P}_s(k) = P_s(k)[1 + (4X - Y)\hat{p}.\hat{x}]$$

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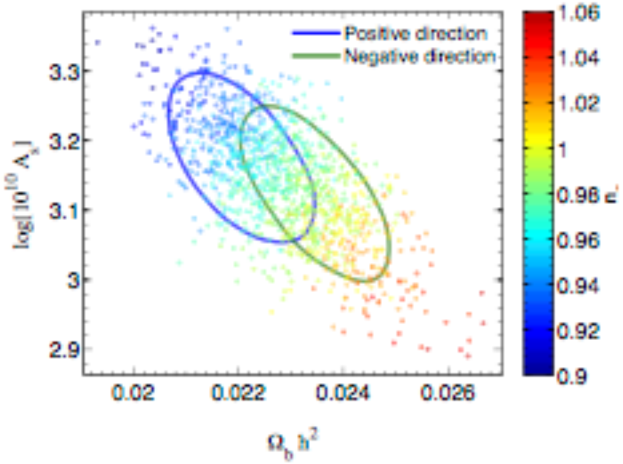
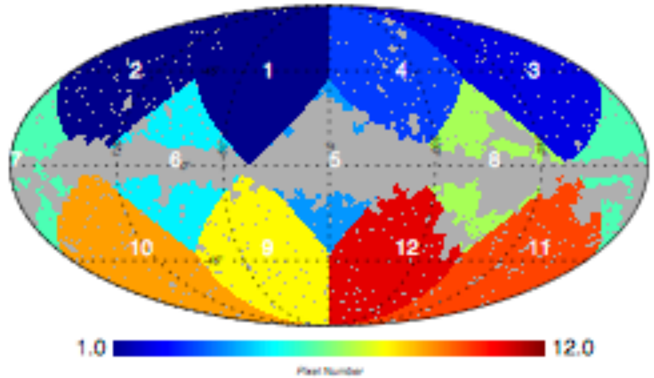
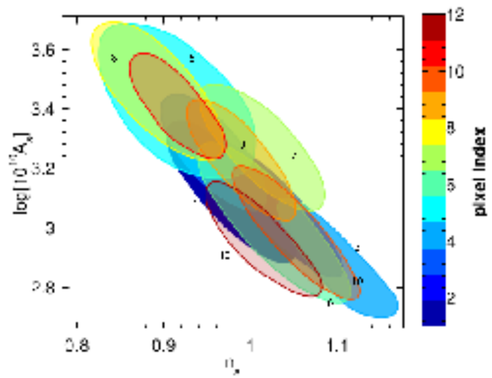
Signature of direction dependent cosmological parameters in Planck

M. Axelsson et al.
ApJ, 773, L3, (2013)







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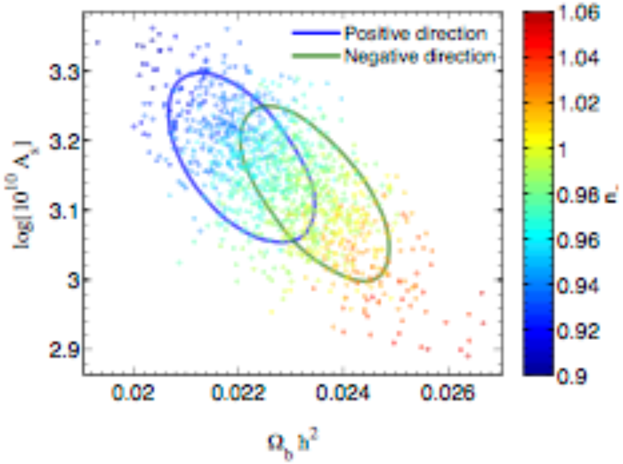

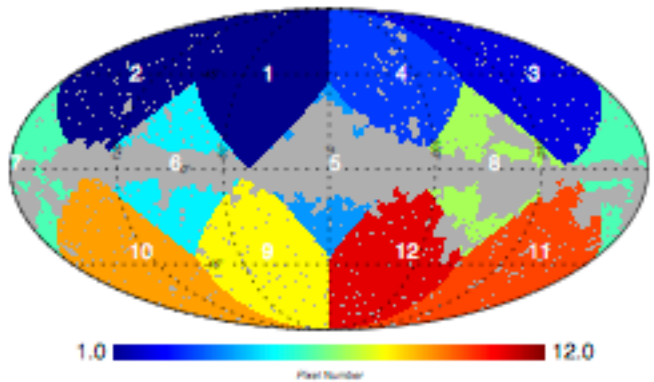

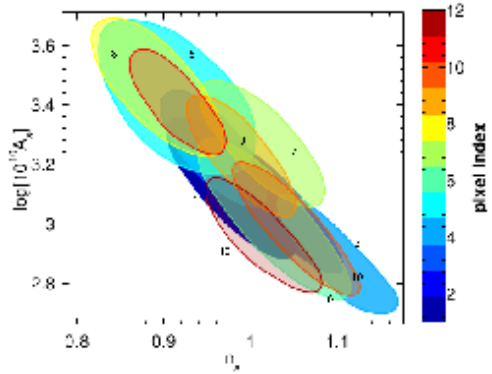

Mukherjee and Souradeep [in preparation]

$$4X \geq Y > 2X$$

Conclusions

- A signature of isotropy violated CMB temperature field is observed in both WMAP and Planck.
- Signature is present only at large angular scales (l<60).
- This can be model by isotropy violated Stochastic Gravitational Wave Background.
- Implies direction dependent tensor to scalar ratio and is measurable from Planck and BICEP-2.
- Observable dipolar BipoSH spectra for B mode polarization are measurable from Planck and PRISM. As a result MM model can be falsified.
- These signatures can be related to the anisotropic Hubble parameter and its derivative.

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Thank you