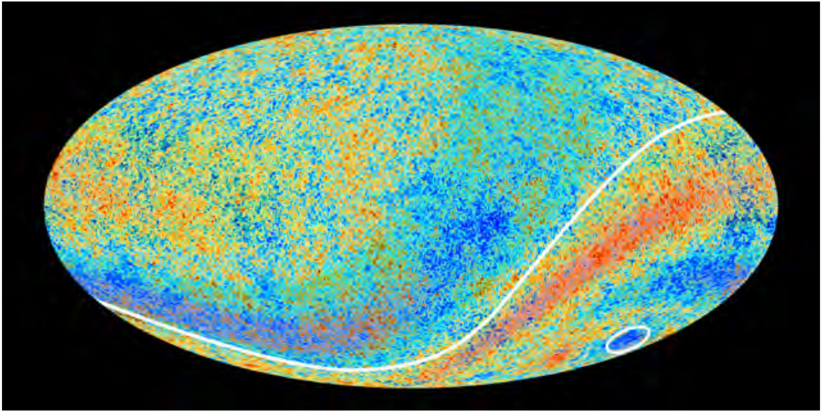
The hemispherical power asymmetry after Planck

2019 CCNU-USTC Junior Cosmology Symposium

Shamik Ghosh

Department of Astronomy
University of Science and Technology of China

The hemispherical power asymmetry



ESA and the Planck Collaboration 2013

The Dipole Modulation of CMB

$$\Delta T(\hat{n}) = \Delta T_{\text{iso}}(\hat{n}) \left[1 + A\hat{\lambda} \cdot \hat{n}\right]$$

gives:

$$a_{T,\ell m} = \tilde{a}_{T,\ell m} + A \sum_{\ell' m'} \tilde{a}_{T,\ell' m'} \sqrt{(2\ell+1)(2\ell'+1)}$$

$$\times \left[\frac{\sqrt{(\ell-m)(\ell+m)}}{(2\ell+1)(2\ell-1)} \delta_{\ell' \ell-1} \delta_{m' m} + \frac{\sqrt{(\ell-m+1)(\ell+m+1)}}{(2\ell+1)(2\ell+3)} \delta_{\ell' \ell+1} \delta_{m' m} \right]$$

$$= \tilde{a}_{T,\ell m} + A\xi_-(\ell, m)\tilde{a}_{T,\ell-1 m} + A\xi_+(\ell, m)\tilde{a}_{T,\ell+1 m}$$

So:

$$\langle a_{T,\ell m} a^*_{T,\ell' m'} \rangle = \tilde{C}^{TT}_\ell \delta_{\ell' \ell} \delta_{m' m} + [\tilde{C}^{TT}_{\ell'} + \tilde{C}^{TT}_\ell]$$
$$\times \{A\xi_-(\ell, m)\delta_{\ell' \ell-1}\delta_{m' m} + A\xi_+(\ell, m)\delta_{\ell' \ell+1}\delta_{m' m}\}$$

The S_H^{TT} estimator

Define:

$$S_H^{TT} = \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} \frac{\ell(\ell+1)}{2\ell+1} \sum_m a_{T,\ell m} a^*_{T,\ell+1 m}$$

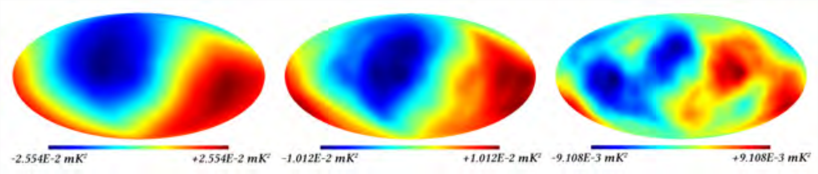
Map	S_H^{TT} in 10^{-2} mK^2	A	(l, b)	P-value
Comm	2.55 ± 0.68	0.082 ± 0.018	$(232° \pm 18°, -14° \pm 18°)$	0.20%
SMICA(i)	2.39 ± 0.70	0.069 ± 0.013	$(236° \pm 27°, -11° \pm 20°)$	0.70%
SMICA(f)	2.44 ± 0.71	0.078 ± 0.019	$(242° \pm 16°, -17° \pm 20°)$	0.50%

with $\ell_{\rm min} = 2$ and $\ell_{\rm max} = 64$.

Scale Dependence

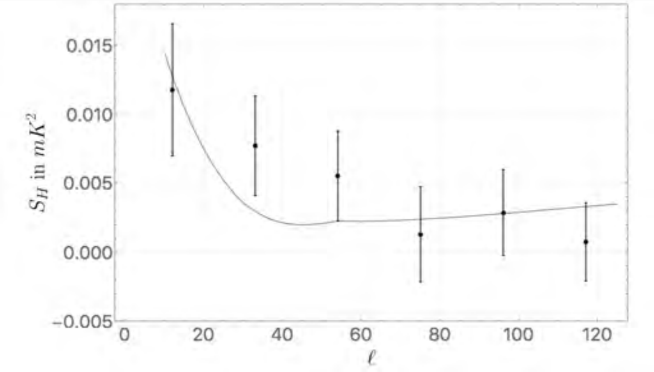
$$r_{TT} = \frac{S_H^{TT}}{\sum_{\ell=\ell_{\min}}^{\ell_{\max}} \ell(\ell+1)C_\ell^{TT}}$$

l Range	S_H^{TT} in 10^{-2} mK^2	A	(l, b)	P-value	r_{TT}
2-64	2.55 ± 0.68	0.082 ± 0.018	$(232°, -14°)$	0.20%	0.065
30-64	1.00 ± 0.43	0.052 ± 0.019	$(194°, -4°)$	66.6%	0.040
30-100	0.91 ± 0.72	0.018 ± 0.011	$(277°, 4°)$	83.0%	0.013



Ghosh, S. et al. 2016

Scale Dependence



CMB Polarization

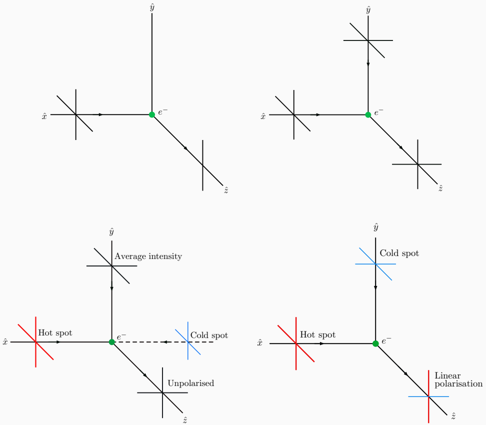
Thompson scattering $\rightarrow$ Polarization

Quadrupole anisotropy needed.

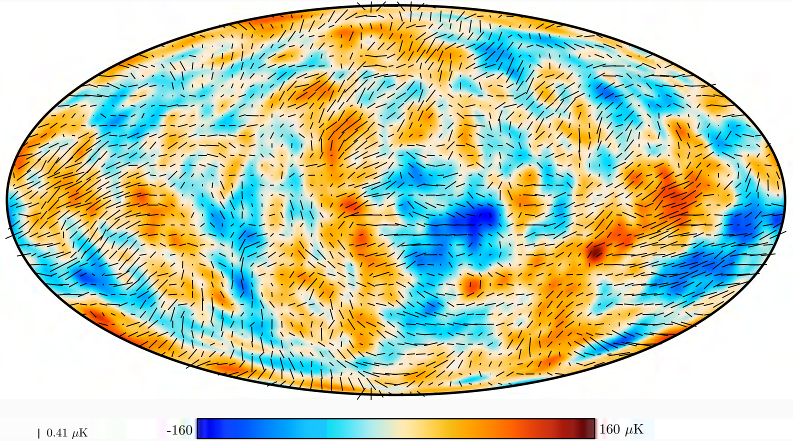
Stokes Parameters:

$$Q = \frac{\langle E_1^2 \rangle - \langle E_2^2 \rangle}{\langle E_1^2 \rangle + \langle E_2^2 \rangle}$$

$$U = \frac{\langle E_{1'}^2 \rangle - \langle E_{2'}^2 \rangle}{\langle E_1^2 \rangle + \langle E_2^2 \rangle}$$



The polarized CMB sky



The Ps, Es and Bs

Define:

$$P(\hat{n}) = Q(\hat{n}) + iU(\hat{n})$$
$$P^*(\hat{n}) = Q(\hat{n}) - iU(\hat{n})$$

On rotation: $(Q \pm iU)'(\hat{n}) = (Q \pm iU)(\hat{n})e^{\mp i2\psi}$

$$P(\hat{n}) = \sum_{\ell,m} a_{2,\ell m\,2}Y_{\ell m}(\hat{n}) = -\sum_{\ell,m}(a_{E,\ell m} + ia_{B,\ell m})\,{}_2Y_{\ell m}(\hat{n})$$
$$P^*(\hat{n}) = \sum_{\ell,m} a_{-2,\ell m\,-2}Y_{\ell m}(\hat{n}) = -\sum_{\ell,m}(a_{E,\ell m} - ia_{B,\ell m})\,{}_{-2}Y_{\ell m}(\hat{n})$$
$$= -\sum_{\ell,m}(a^*_{E,\ell m} - ia^*_{B,\ell m})\,{}_2Y^*_{\ell m}(\hat{n}),$$

Modulation of CMB Polarization

$$(Q \pm iU)(\hat{n}) \propto \int dr \frac{d\tau}{dr} e^{-\tau(r)} \sum_m a_{T,2m}(r\hat{n})\, {}_{\pm 2}Y_{2m}(\hat{n})$$

Hu, W. 2000; Contreras, D. 2017

Since $a_{T,2m}(r_{\rm ls}\hat{n}) = \tilde{a}_{T,2m}(r_{\rm ls}\hat{n}) \left[1 + A\hat{\lambda} \cdot \hat{n}\right]$:

$$P(\hat{n}) = \tilde{P}(\hat{n}) \left(1 + A\hat{\lambda} \cdot \hat{n}\right).$$

So:

$$a_{\pm 2,\ell m} = \tilde{a}_{\pm 2,\ell m} + A\sqrt{\frac{4\pi}{3}} \sum_{\ell' m'} \tilde{a}_{\pm 2,\ell' m'} \int {}_{\pm 2}Y_{\ell' m'}(\hat{n}) Y_{10}(\hat{n})\, {}_{\pm 2}Y^{*}_{\ell m}(\hat{n}) d\Omega.$$

The E/B-mode modulation

$$a_{E,\ell m} = \tilde{a}_{E,\ell m} + A\alpha_- \tilde{a}_{E,\ell-1 m} + iA\alpha_0 \tilde{a}_{B,\ell m} + A\alpha_+ \tilde{a}_{E,\ell+1 m}$$
$$a_{B,\ell m} = \tilde{a}_{B,\ell m} + A\alpha_- \tilde{a}_{B,\ell-1 m} - iA\alpha_0 \tilde{a}_{E,\ell m} + A\alpha_+ \tilde{a}_{B,\ell+1 m},$$

where,

$$\alpha_- = \frac{1}{\ell}\sqrt{\frac{(\ell-2)(\ell+2)(\ell-m)(\ell+m)}{(2\ell-1)(2\ell+1)}}$$
$$\alpha_0 = \frac{2m}{\ell(\ell+1)}$$
$$\alpha_+ = \frac{1}{\ell+1}\sqrt{\frac{(\ell-1)(\ell+3)(\ell-m+1)(\ell+m+1)}{(2\ell+1)(2\ell+3)}}.$$

The Correlations

The different auto correlations, written up to first order in A, are:

$$
\begin{aligned}
\langle a_{E,\ell m} a^*_{E,\ell' m'} \rangle &= \tilde{C}^{EE}_{\ell} \delta_{\ell' \ell} \delta_{m' m} + [\tilde{C}^{EE}_{\ell'} + \tilde{C}^{EE}_{\ell}] \\
&\quad \times \{A\alpha_-(\ell, m) \delta_{\ell' \ell-1} \delta_{m' m} + A\alpha_+(\ell, m) \delta_{\ell' \ell+1} \delta_{m' m}\} \\
\langle a_{B,\ell m} a^*_{B,\ell' m'} \rangle &= \tilde{C}^{BB}_{\ell} \delta_{\ell' \ell} \delta_{m' m} + [\tilde{C}^{BB}_{\ell'} + \tilde{C}^{BB}_{\ell}] \\
&\quad \times \{A\alpha_-(\ell, m) \delta_{\ell' \ell-1} \delta_{m' m} + A\alpha_+(\ell, m) \delta_{\ell' \ell+1} \delta_{m' m}\} \, .
\end{aligned}
$$

The P^2 map

With noise $N_P(\hat{n})$ and mask $W(\hat{n})$:

$$P_{\text{obs}} = \tilde{P}_s(\hat{n})W(\hat{n})\left(1 + A\hat{\lambda}\cdot\hat{n}\right) + N_P(\hat{n})W(\hat{n})$$

So:

$$\begin{aligned}|P_{\text{obs}}(\hat{n})|^2 =& |\tilde{P}_s(\hat{n})|^2 W^2(\hat{n})\left(1 + 2A\hat{\lambda}\cdot\hat{n}\right) + \tilde{P}_s(\hat{n})N_P^*(\hat{n})W^2(\hat{n})\left(1 + A\hat{\lambda}\cdot\hat{n}\right)\\ &+ \tilde{P}_s^*(\hat{n})N_P(\hat{n})W^2(\hat{n})\left(1 + 2A\hat{\lambda}\cdot\hat{n}\right) + |N_P(\hat{n})|^2 W^2(\hat{n})\end{aligned}$$

Ensemble average:

$$\begin{aligned}\langle|P_{\text{obs}}(\hat{n}_i)|^2\rangle = W^2(\hat{n}_i)\sum_\ell \left(\frac{2\ell+1}{4\pi}\right)\Big\{&\left[\bar{C}_\ell^{EE} + \bar{C}_\ell^{BB}\right]\left[1 + 2A\hat{\lambda}\cdot\hat{n}_i\right]\\ &+ \left[\bar{N}_\ell^{EE} + \bar{N}_\ell^{BB}\right]\Big\}\end{aligned}$$

The Harmonic Space Estimator

The S_H^{EE} statistic:

$$S_H^{EE} = \sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} \frac{\ell(\ell+1)}{2\ell+1} \sum_m a_{E,\ell m} a^*_{E,\ell+1m}$$

The r_{EE} measure:

$$r_{EE} = \frac{S_H^{EE}}{\sum_{\ell=\ell_{\rm min}}^{\ell_{\rm max}} \ell(\ell+1) C_\ell^{EE}}$$

Weighted Pixel-space Direction Estimators

The weight factor:

$$\omega_j = |\cos\theta_j|$$

Weighted average:

$$\langle |P_{\rm obs}(\hat{n})|^2 \rangle_w = \frac{\sum_j \omega_j |P_{\rm obs}(\hat{n}_j)|^2}{\sum_{j'} W(\hat{n}_{j'})\omega_{j'}}$$

The direction estimators:

$$R_i^w = \frac{\langle |P_{\rm obs}(\hat{n})|^2 \rangle_{U_i,w}}{\langle |P_{\rm obs}(\hat{n})|^2 \rangle_{L_i,w}}$$

$$D_i^w = \frac{\langle |P_{\rm obs}(\hat{n})|^2 \rangle_{U_i,w} - \langle |P_{\rm obs}(\hat{n})|^2 \rangle_{L_i,w}}{\langle |P_{\rm obs}(\hat{n})|^2 \rangle_{U_i,w} + \langle |P_{\rm obs}(\hat{n})|^2 \rangle_{L_i,w}}$$

The pixel space amplitude estimator

$$\hat{A} = \frac{\left[\langle |P_{\rm obs}(\hat{n})|^2\rangle_U - \langle |P_{\rm obs}(\hat{n})|^2\rangle_L\right]_{\rm max}}{K\sum_\ell \left(\frac{2\ell+1}{2\pi}\right)\left(\bar{C}_\ell^{EE} + \bar{C}_\ell^{BB}\right)}$$

$$K = \left\{\int_U W^2(\hat{n})d\Omega\right\}^{-1}\int_U W^2(\hat{n})\cos\theta d\Omega - \left\{\int_L W^2(\hat{n})d\Omega\right\}^{-1}\int_L W^2(\hat{n})\cos\theta d\Omega.$$

Planck Polarization Data

Planck polarization data has significant contamination from systematics on large angular scales.

Source of contamination are the LFI calibration uncertainties, affecting frequency channels: 30GHz, 44GHz and 70GHz.

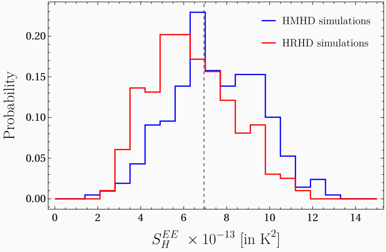
Affects large angular scales. $\ell \leq 30$, with 44GHz being the major problem.

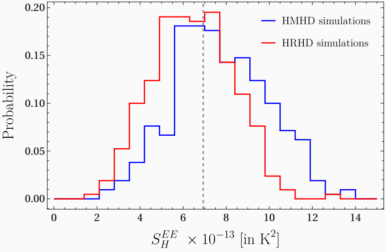
Planck 2015 data: Large angular scale data, i.e. $\ell \leq 20$ removed. Data from $20 < \ell \leq 40$ high pass filtered. Data did not agree well with FFP8 simulations.

Planck 2018 data: Data from all angular scales present. Systematics issues acknowledged and modelled in FFP10 simulations.

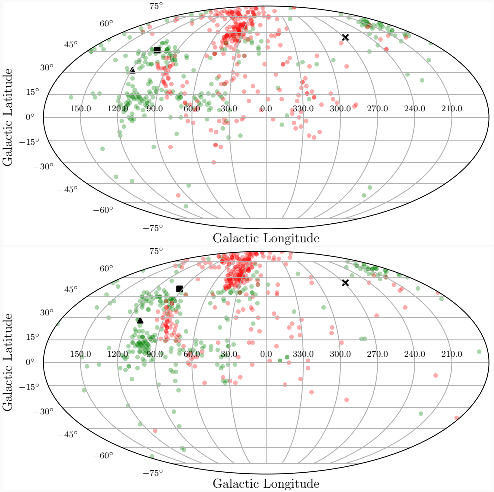
Planck 2015 Results

ℓ_{min}	ℓ_{max}	$S_H^{EE} \times 10^{-13}$ [in K^2]	r_{EE}	$\hat{\lambda}$	p-value
40	100	6.94	0.031	$(l = 268°, b = 56°)$	0.37
40	125	6.92	0.029	$(l = 268°, b = 56°)$	0.57
50	100	6.36	0.036	$(l = 260°, b = 57°)$	—
50	125	6.36	0.036	$(l = 260°, b = 57°)$	—



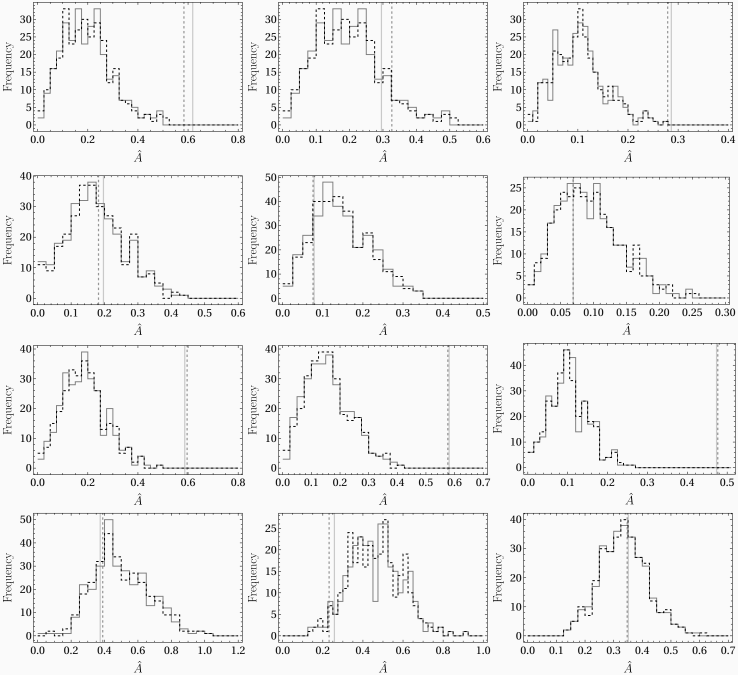


Planck 2015 Results



Planck 2018 Results

Map	ℓ_{min}	R estimator			D estimator		
		A	$\hat{\lambda}$	p-value	A	$\hat{\lambda}$	p-value
Comm.	10	0.618	$(l = 352^\circ b = -13^\circ)$	$< 1/300$	0.584	$(l = 350^\circ b = -14^\circ)$	$< 1/300$
	20	0.295	$(l = 346^\circ b = -18^\circ)$	0.15	0.326	$(l = 347^\circ b = -20^\circ)$	0.09
	40	0.286	$(l = 352^\circ b = -13^\circ)$	$< 1/300$	0.279	$(l = 352^\circ b = -13^\circ)$	$< 1/300$
SMICA	10	0.197	$(l = 228^\circ b = -1^\circ)$	0.37	0.182	$(l = 226^\circ b = -2^\circ)$	0.44
	20	0.078	$(l = 232^\circ b = -30^\circ)$	0.83	0.076	$(l = 233^\circ b = -31^\circ)$	0.84
	40	0.069	$(l = 53^\circ b = 75^\circ)$	0.65	0.069	$(l = 58^\circ b = 75^\circ)$	0.65
SEVEM	10	0.587	$(l = 352^\circ b = -21^\circ)$	$< 1/300$	0.596	$(l = 350^\circ b = -22^\circ)$	$< 1/300$
	20	0.581	$(l = 346^\circ b = -4^\circ)$	$< 1/300$	0.576	$(l = 344^\circ b = -5^\circ)$	$< 1/300$
	40	0.473	$(l = 345^\circ b = 0^\circ)$	$< 1/300$	0.476	$(l = 344^\circ b = -1^\circ)$	$< 1/300$
NILC	10	0.374	$(l = 332^\circ b = -16^\circ)$	0.77	0.389	$(l = 333^\circ b = -17^\circ)$	0.75
	20	0.258	$(l = 329^\circ b = -29^\circ)$	0.94	0.231	$(l = 332^\circ b = -29^\circ)$	0.97
	40	0.351	$(l = 2^\circ b = -1^\circ)$	0.41	0.347	$(l = 3^\circ b = -2^\circ)$	0.44


Frequency
Â

Summary

- Planck temperature data has confirmed the presence of the dipole modulation of the CMB temperature signal with an amplitude of 0.07 along $(232°, -14°)$ at about 3σ.
- The dipole modulation is scale dependent and is only present upto $\ell \sim 60$.
- The exact form of the scale dependence is unknown.
- Due to the large residual systematics in the Planck polarization data, there hasn't been any detection of power asymmetry in Planck polarization data.
- Future of the hemispherical asymmetry study would be to use CMB polarization with CMB temperature to improve understanding of the effect.

Thank you!