

The hemispherical power asymmetry after Planck

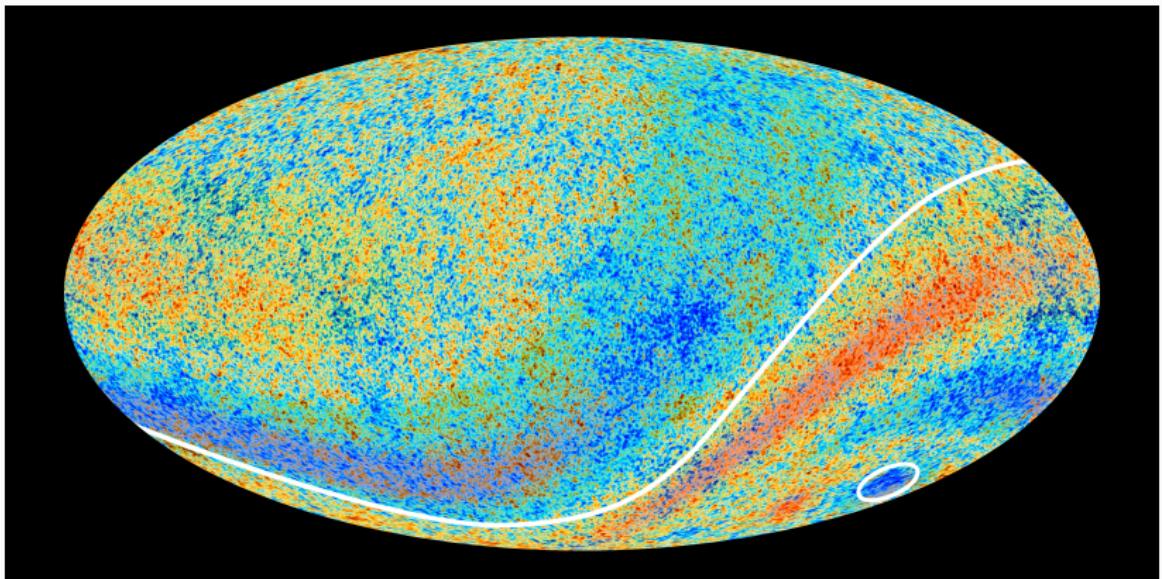
The 2nd Symposium on Cosmology and the AliCPT

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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:

$$\begin{aligned} a_{T,\ell m} &= \tilde{a}_{T,\ell m} + A \sum_{\ell' m'} \tilde{a}_{T,\ell' m'} \sqrt{(2\ell+1)(2\ell'+1)} \\ &\quad \times \left[\frac{\sqrt{(\ell-m)(\ell+m)}}{(2\ell+1)(2\ell-1)} \delta_{\ell'\ell-1} \delta_{m'm} + \frac{\sqrt{(\ell-m+1)(\ell+m+1)}}{(2\ell+1)(2\ell+3)} \delta_{\ell'\ell+1} \delta_{m'm} \right] \\ &= \tilde{a}_{T,\ell m} + A \xi_-(\ell, m) \tilde{a}_{T,\ell-1 m} + A \xi_+(\ell, m) \tilde{a}_{T,\ell+1 m} \end{aligned}$$

So:

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

The S_H^{TT} estimator

Define:

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

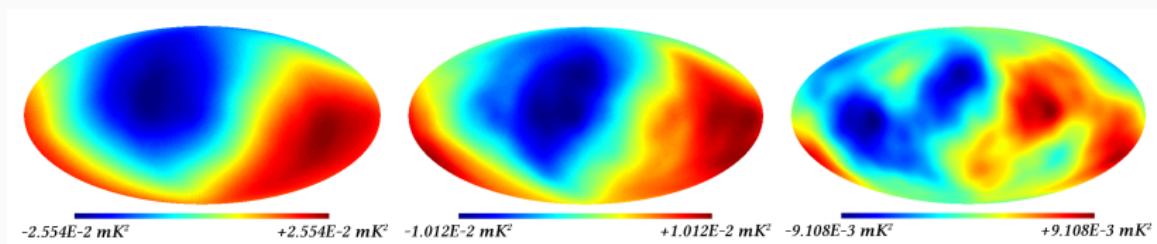
Map	S_H^{TT} in 10^{-2} mK 2	A	(l, b)	P-value
Comm	2.55 ± 0.68	0.082 ± 0.018	$(232^\circ \pm 18^\circ, -14^\circ \pm 18^\circ)$	0.20%
SMICA(i)	2.39 ± 0.70	0.069 ± 0.013	$(236^\circ \pm 27^\circ, -11^\circ \pm 20^\circ)$	0.70%
SMICA(f)	2.44 ± 0.71	0.078 ± 0.019	$(242^\circ \pm 16^\circ, -17^\circ \pm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

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

Scale Dependence

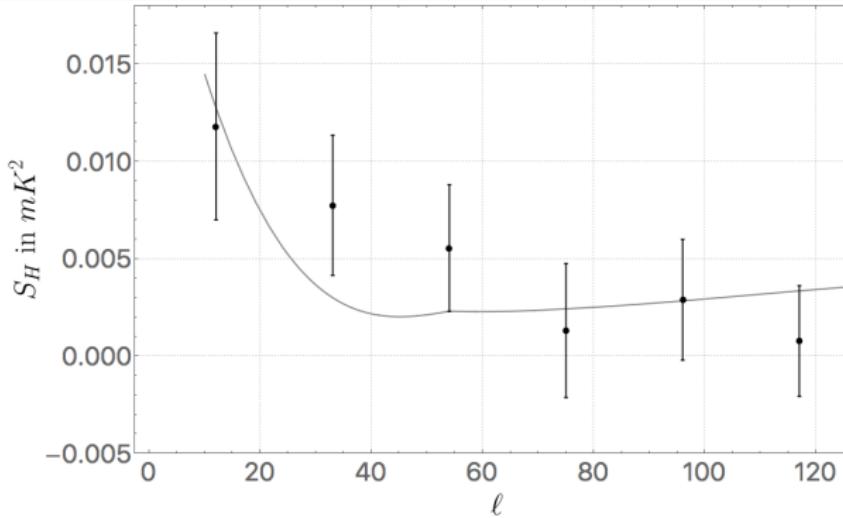
$$r_{\pi\pi} = \frac{S_H^{\pi\pi}}{\sum_{\ell=\ell_{\min}}^{\ell_{\max}} \ell(\ell+1) C_{\ell}^{\pi\pi}}$$

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



Ghosh, S. et al. 2016

Scale Dependence



The Polarised CMB Sky

Define:

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

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

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

$$P(\hat{n}) = \sum_{\ell,m} a_{2,\ell m} Y_{\ell m}(\hat{n}) = - \sum_{\ell,m} (a_{E,\ell m} + ia_{B,\ell m})_2 Y_{\ell m}(\hat{n})$$

$$\begin{aligned} P^*(\hat{n}) &= \sum_{\ell,m} a_{-2,\ell m} Y_{\ell m}(\hat{n}) = - \sum_{\ell,m} (a_{E,\ell m} - ia_{B,\ell m})_{-2} Y_{\ell m}(\hat{n}) \\ &= - \sum_{\ell,m} (a_{E,\ell m}^* - ia_{B,\ell m}^*)_2 Y_{\ell m}^*(\hat{n}), \end{aligned}$$

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

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

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

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

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:

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

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:

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

Ensemble average:

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

The Harmonic Space Estimator

The S_H^{EE} statistic:

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

The r_{EE} measure:

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

Weighted Pixel-space Direction Estimators

The weight factor:

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

Weighted average:

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

The direction estimators:

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

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

The pixel space amplitude estimator

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

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

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.

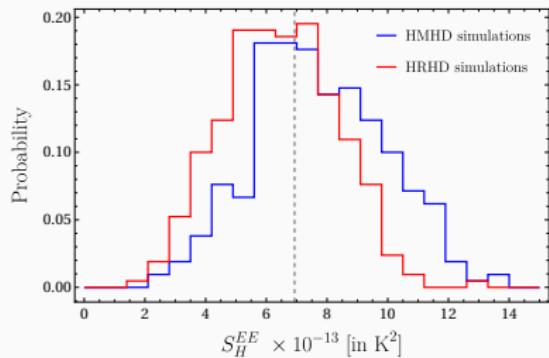
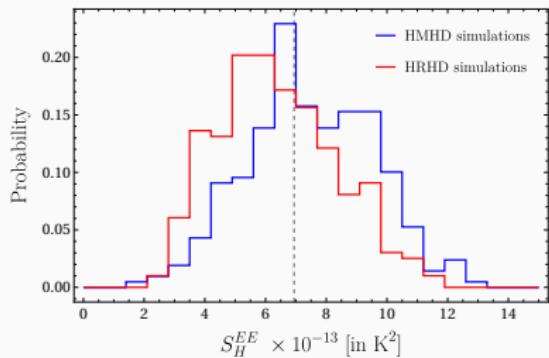
Affects large angular scales. $\ell \leq 30$, with 44GHz being the major problem.

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.

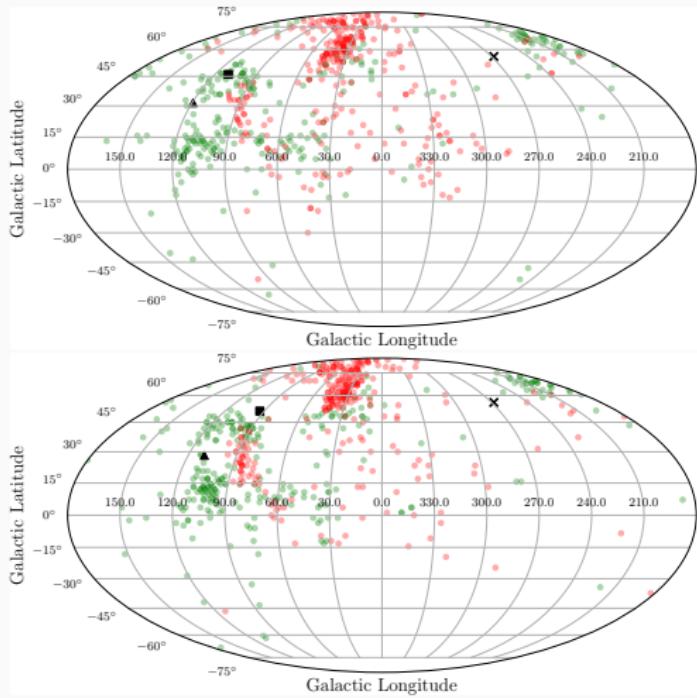
Planck 2018 data: Data from all angular scales present. Systematics issues acknowledged and modelled in FFP10 simulations.

Planck 2015 Results

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

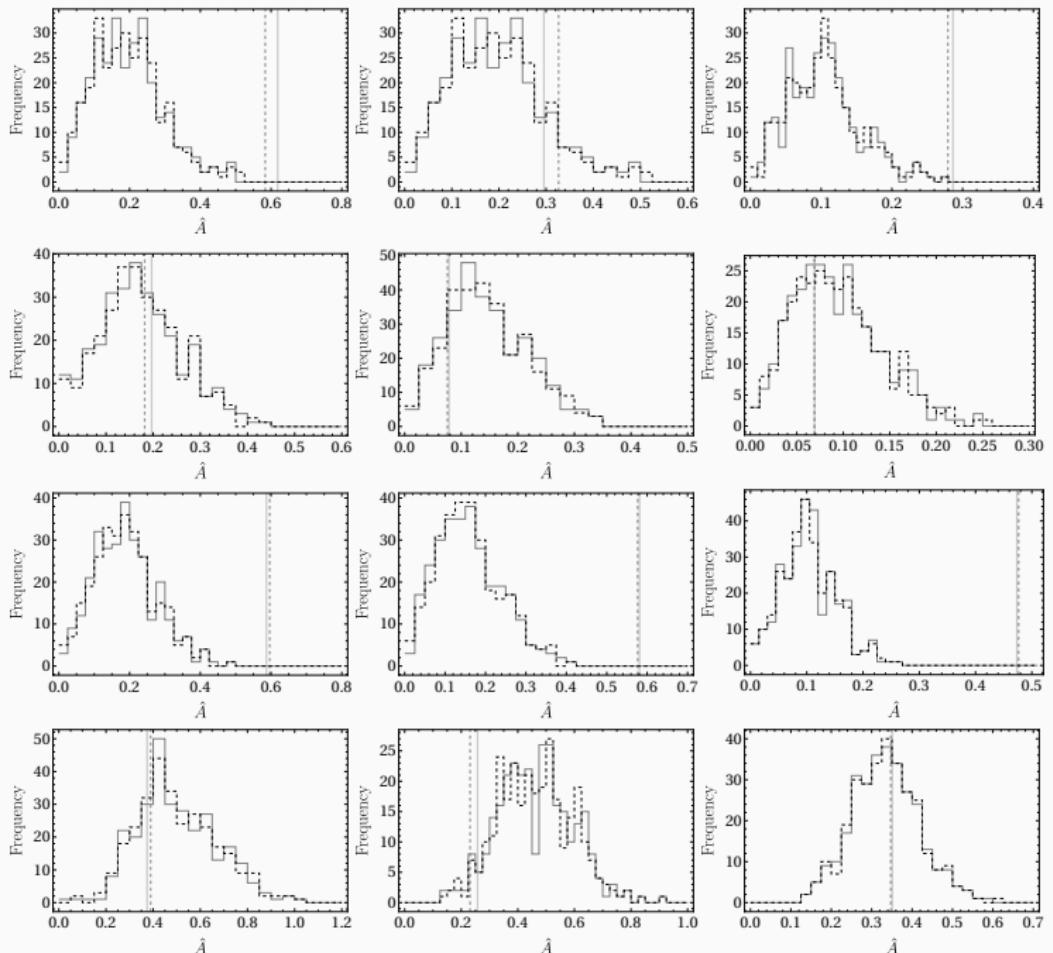


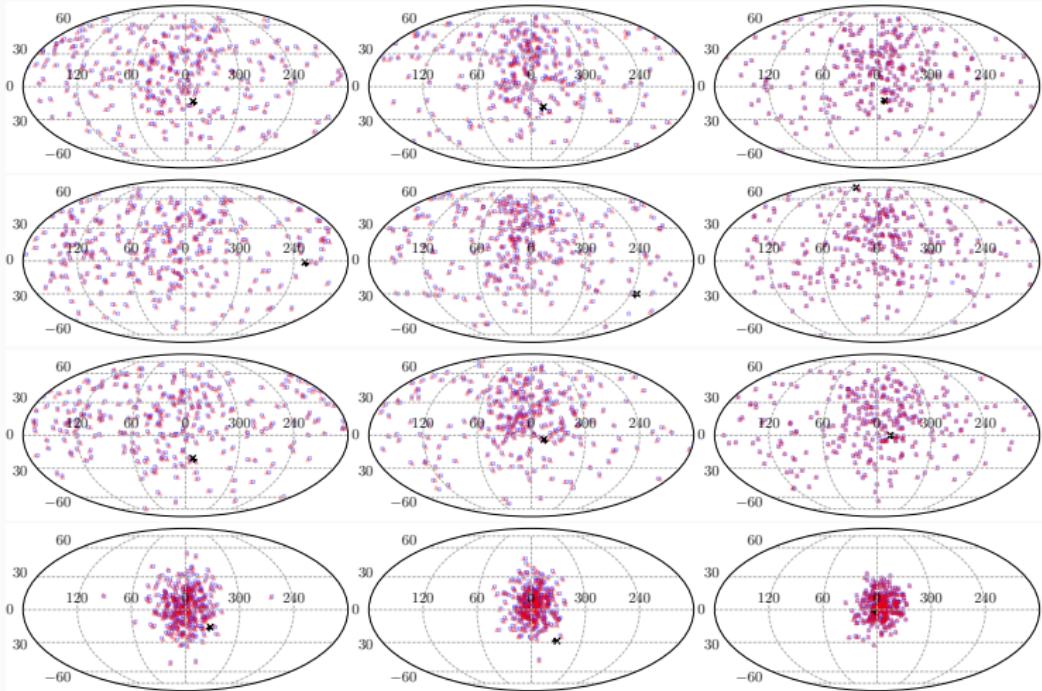
Planck 2015 Results



Planck 2018 Results

Map	ℓ_{\min}	R estimator			D estimator		
		A	λ	p-value	A	λ	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





Can we detect the power asymmetry in CMB polarisation from ground based experiments?

Ongoing preliminary study setup:

- Assume scale independent dipole modulation of the CMB polarisation.
- Consider two polar caps with $f_{\text{sky}} \sim 10\%$ each.
- Modulation direction along z axis.
- Consider different types of noise complexity.
- Setup estimator with proper mixing matrix corrections.
- Compare the estimation for isotropic and modulated cases.

Summary

- Confirmation of dipole modulation in the CMB temperature with amplitude of 0.07.
- The direction of modulation is ($l = 232^\circ, b = -14^\circ$).
- The amplitude of the effect is scale dependent and becomes negligible after $\ell \sim 60$.
- The exact form of this scale dependence is not known.
- No significant detection of power asymmetry in CMB polarisation yet.