Modelling Polarized Dust Emission

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PICO Collaboration Science Meeting

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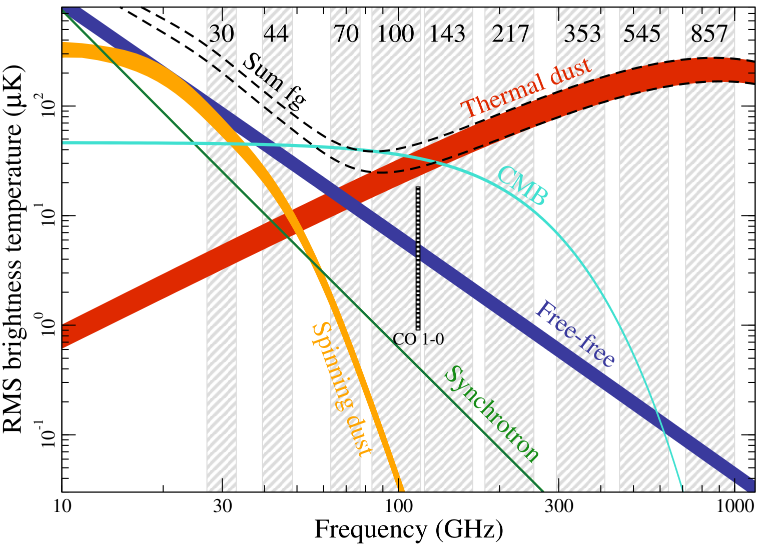
CMB vs. Astrophysical Foregrounds

◦ Intensity ◦ Polarization ◦ Atmospheric Transmission ◦



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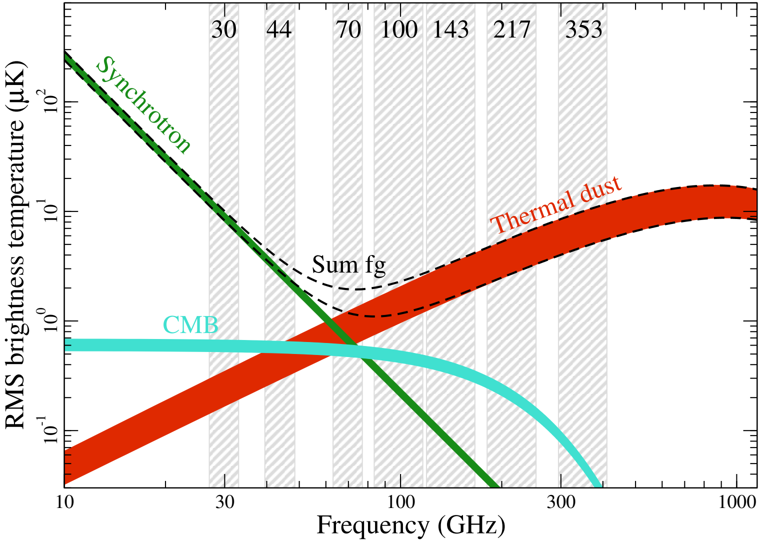
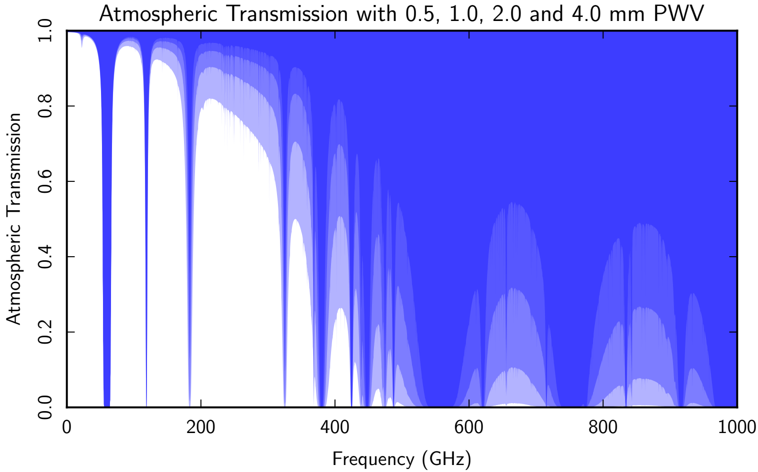
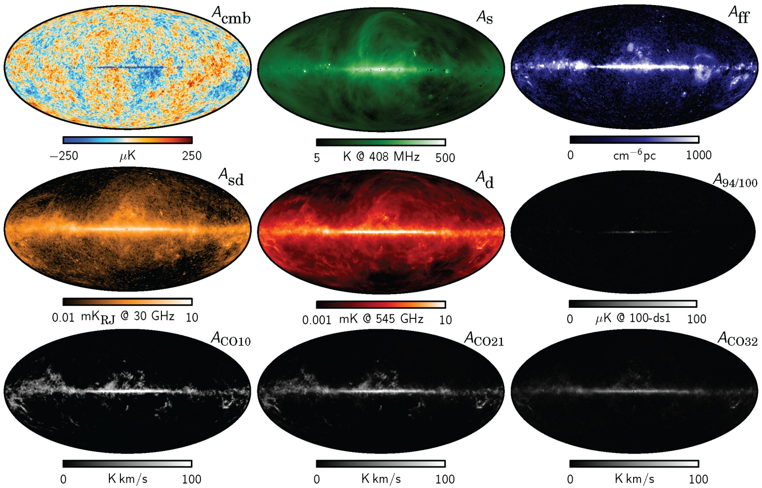


CMB vs. Astrophysical Foregrounds



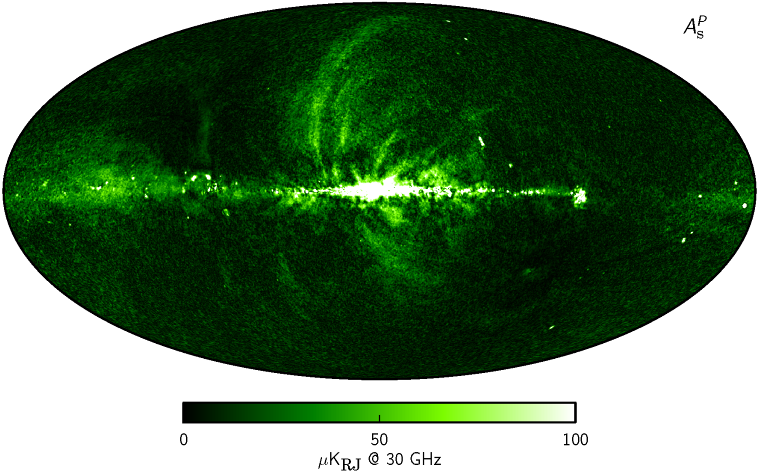
Temperature Component Maps



Polarization Component Maps

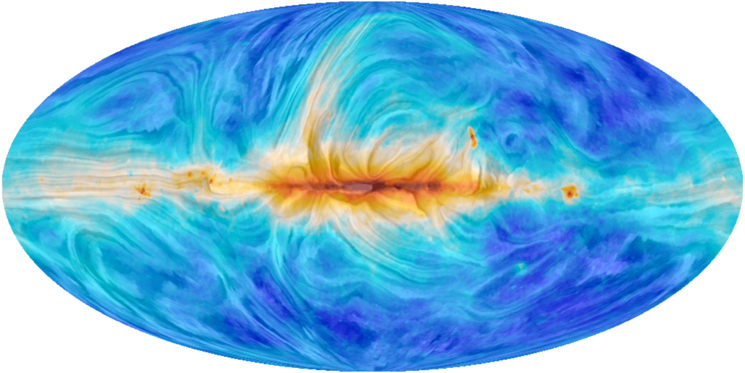
- Two main foregrounds, synchrotron emission and thermal dust
- Amplitude of CMB polarization is less than foregrounds
- Dust emission is highly polarized (polarization fraction is up to 20%)

Synchrotron Polarization Amplitude



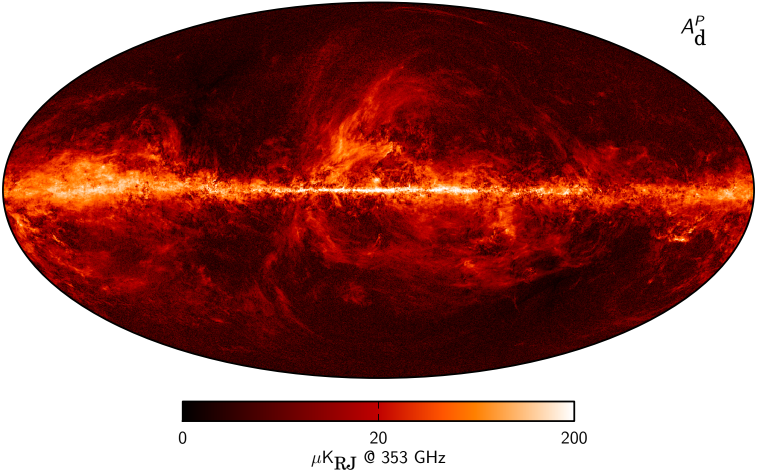
$P = \sqrt{Q^2 + U^2}$, at 30 GHz, smoothed to $40'$

Magnetic Field and Total Intensity



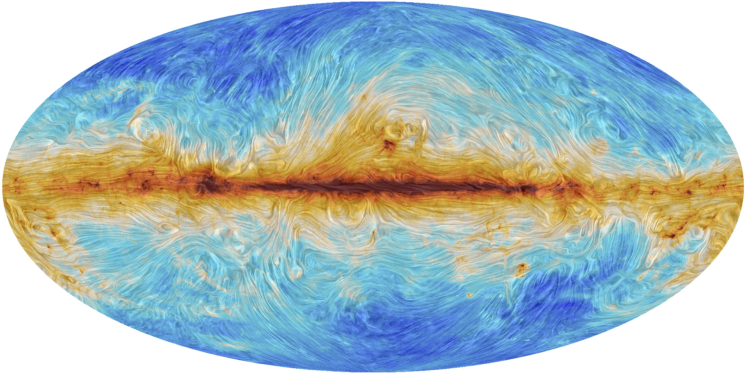
The colours represent intensity. The “drapery” pattern indicates the orientation of magnetic field projected on the plane of the sky, orthogonal to the observed polarization.

Dust Polarization Amplitude



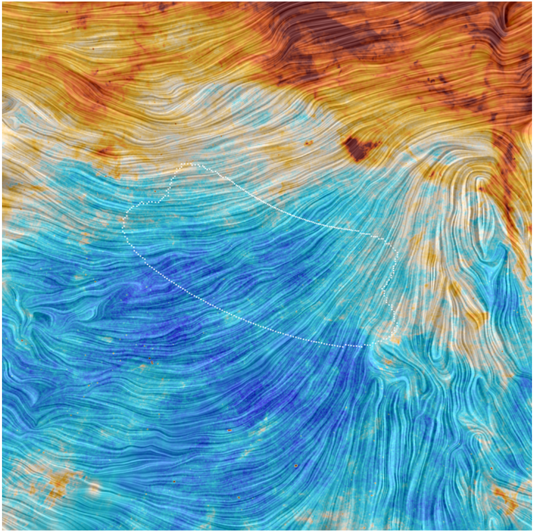
$P = \sqrt{Q^2 + U^2}$, at 353 GHz, smoothed to $10'$

Magnetic Field and Total Intensity



The colours represent intensity. The “drapery” pattern indicates the orientation of magnetic field projected on the plane of the sky, orthogonal to the observed polarization.

Planck View of BICEP2 Field



Modelling Polarized Dust Emission

Polarized Dust Emission

Polarization is caused by magnetic field alignment:

$$I = \int S_\nu e^{-\tau_\nu} d\tau_\nu \left[1 - p_0\left(\cos^2\gamma - \frac{2}{3}\right)\right]$$

$$\left\{ \begin{array}{c} Q \\ U \end{array} \right\} = \int S_\nu e^{-\tau_\nu} d\tau_\nu \left\{ \begin{array}{c} \cos 2\phi \\ \sin 2\phi \end{array} \right\} p_0 \cos^2\gamma$$

(p_0 is intrinsic polarization fraction ~ 0.21)

For a single layer, P/I determines magnetic field orientation:

$$\frac{I-P}{I+P} = 1 - \frac{6p_0}{2p_0+3}\cos^2\gamma$$

Polarization Fraction Tensor

Transform polarization tensor into polarization fraction tensor:

$$\begin{bmatrix} i+q & u \\ u & i-q \end{bmatrix} = \ln \begin{bmatrix} I+Q & U \\ U & I-Q \end{bmatrix}$$

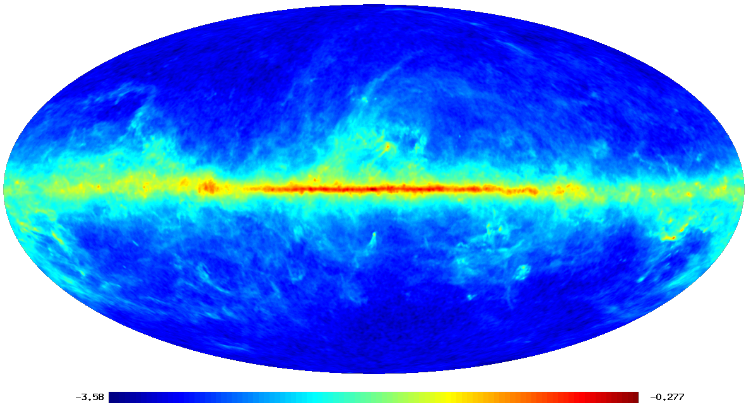
This is an invertible transformation on IQU maps:

$$i = \frac{1}{2}\ln\left(I^2 - P^2\right), \quad q = \frac{1}{2}\frac{Q}{P}\ln\frac{I+P}{I-P}, \quad u = \frac{1}{2}\frac{U}{P}\ln\frac{I+P}{I-P}$$

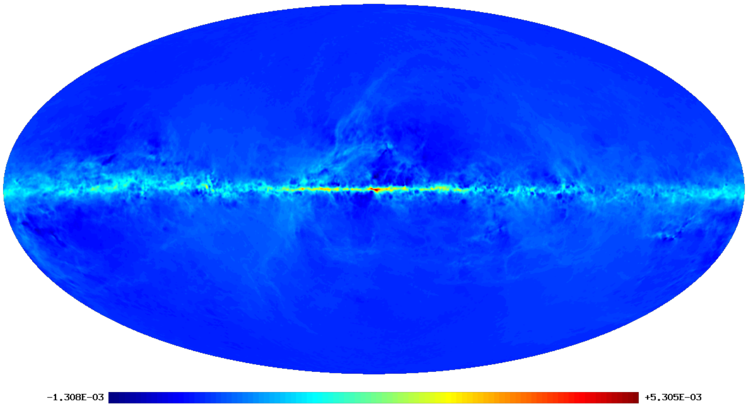
$$I = e^i \cosh p, \qquad Q = \frac{q}{p} e^i \sinh p, \qquad U = \frac{u}{p} e^i \sinh p$$

Polarization Fraction Tensor

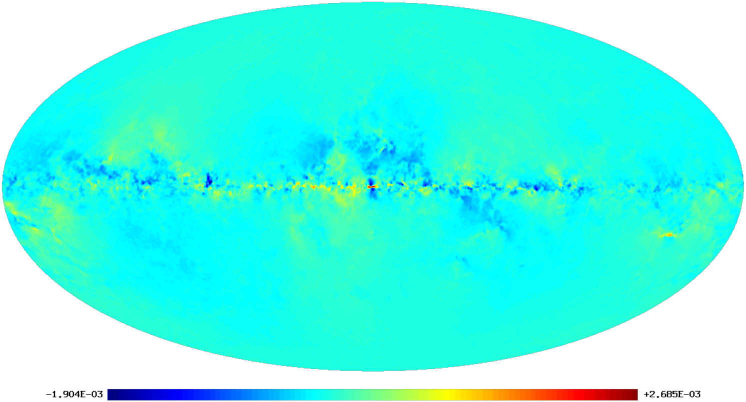
○ ln I ○ E ○ B ○ i ○ e ○ b ○



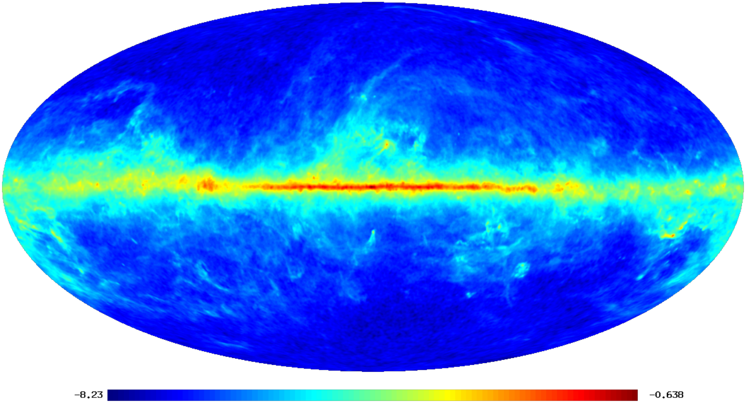
Polarization Fraction Tensor



Polarization Fraction Tensor

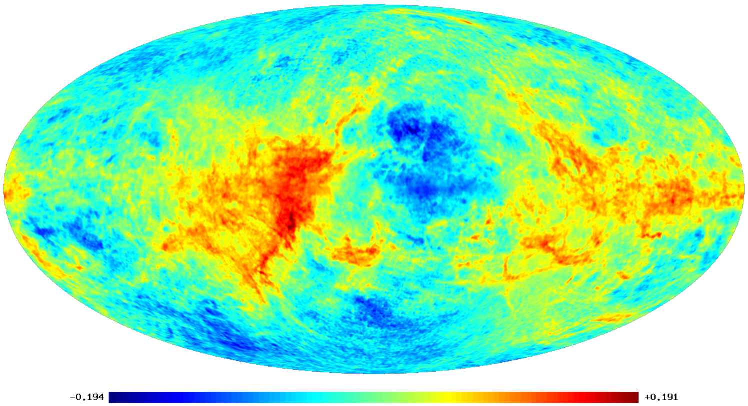


Polarization Fraction Tensor

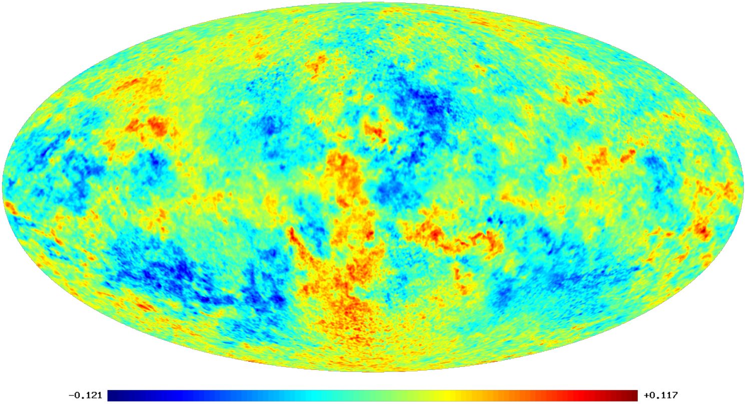


Polarization Fraction Tensor

○ In I ○ E ○ B ○ i ○ e ○ b ○

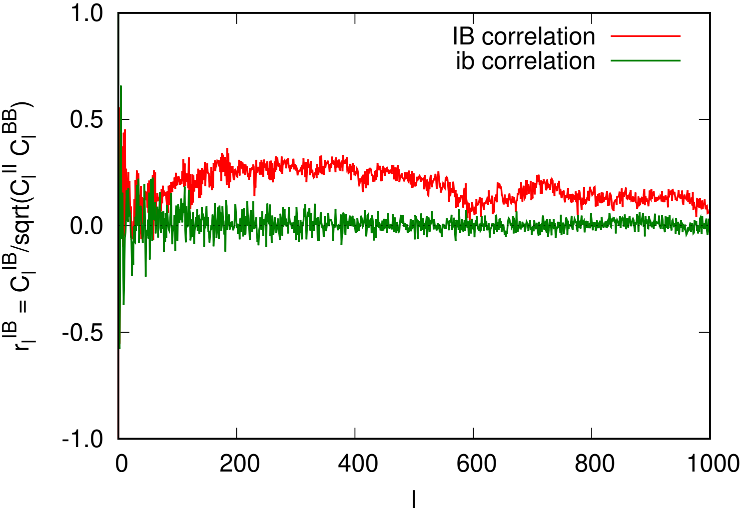


Polarization Fraction Tensor



Parity-Violating Correlations Disappear!

○ I x B ○ E x B ○ I x E ○



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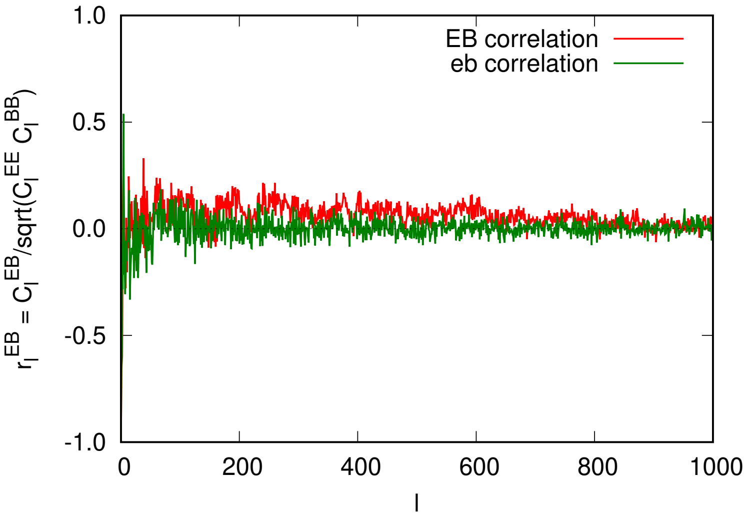
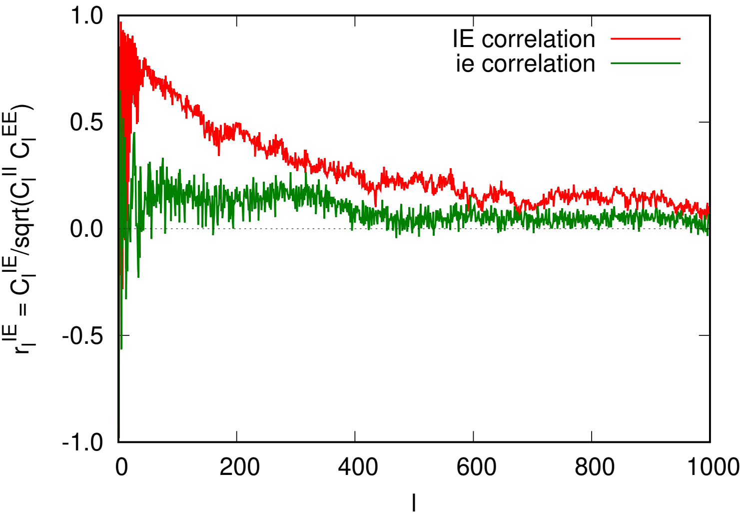


Parity-Violating Correlations Disappear!

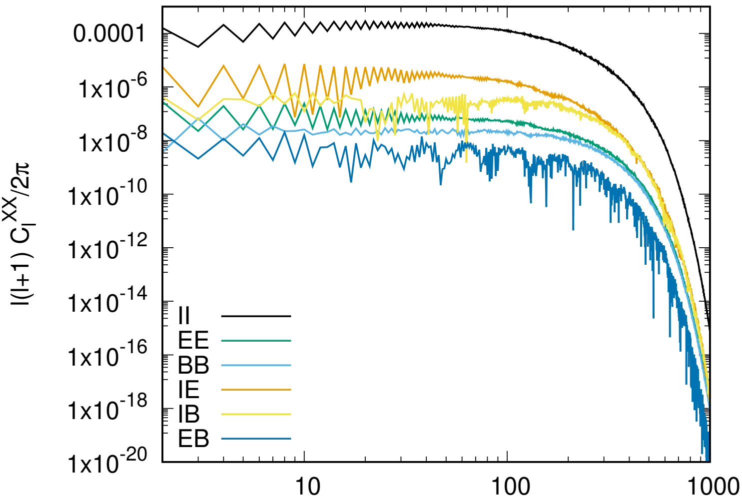
◦ I x B ◦ E x B ◦ I x E ◦



Randomize b to Make It Uncorrelated GRF

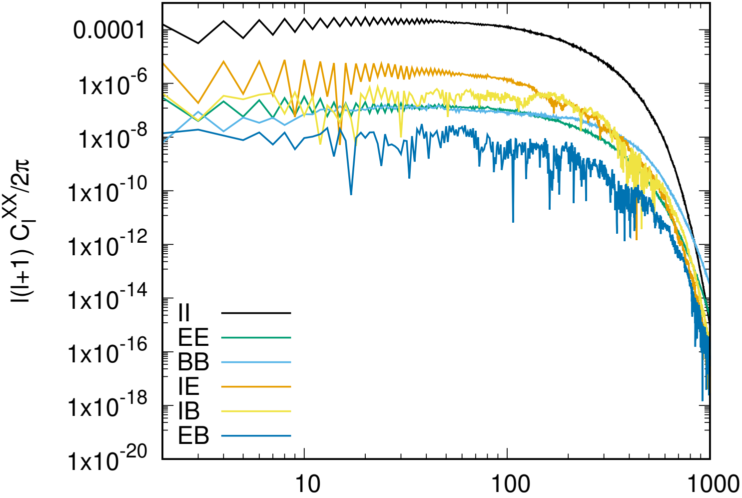
$$a_{\ell m}^{(b)} \mapsto \exp\left[2\pi i \phi_{\ell m}\right] \cdot a_{\ell m}^{(b)}$$

Parity-Violating Correlations Re-appear!



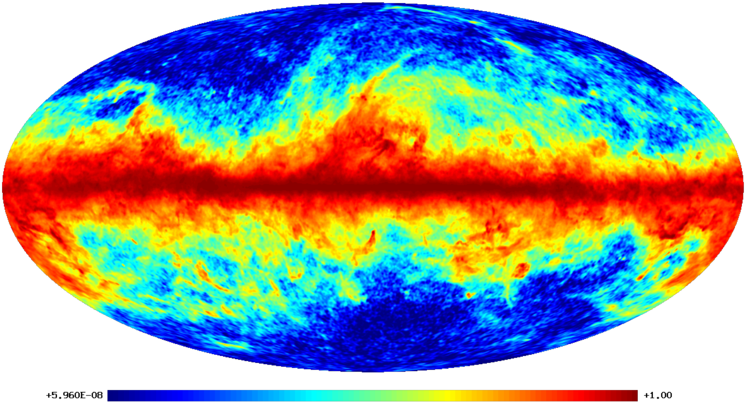
Parity-Violating Correlations Re-appear!

○ original ○ randomized b ○



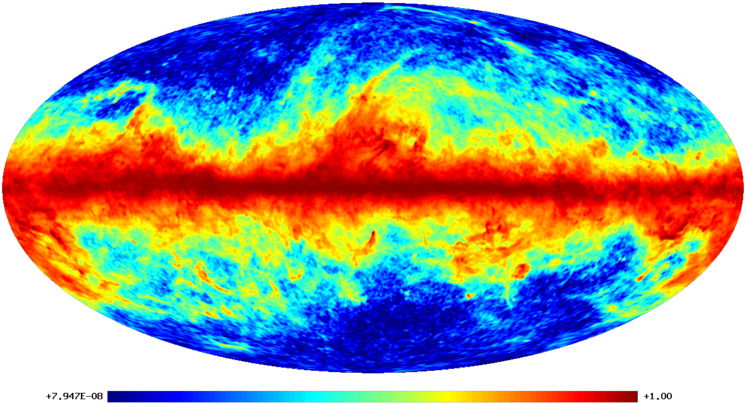
Randomized Polarization Fraction Tensor

○ original I ○ random I ○ original Q ○ random Q ○ original U ○ random U ○



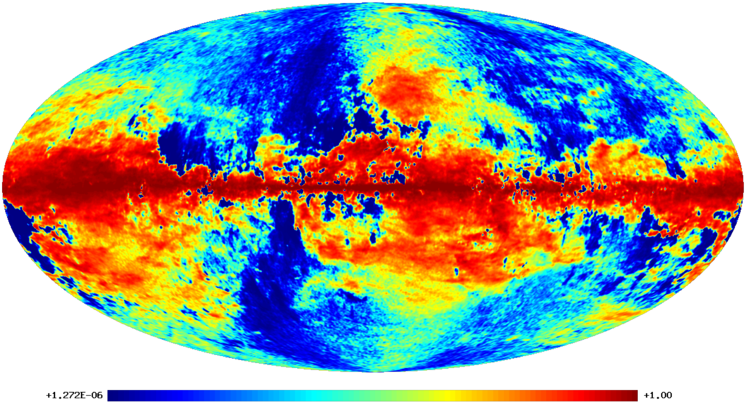
Randomized Polarization Fraction Tensor

◦ original I ◦ random I ◦ original Q ◦ random Q ◦ original U ◦ random U ◦

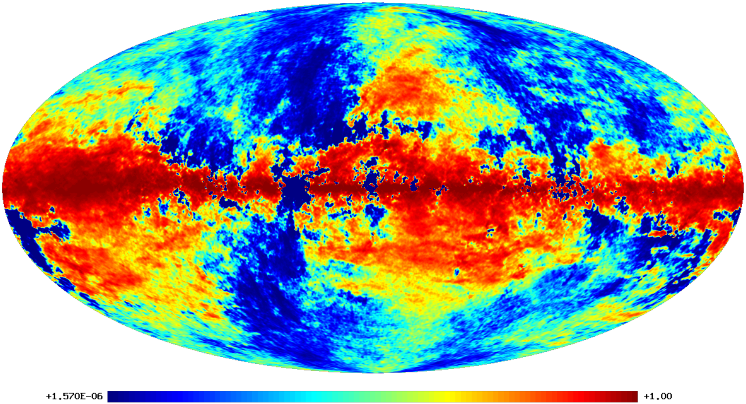


Randomized Polarization Fraction Tensor

○ original I ○ random I ○ original Q ○ random Q ○ original U ○ random U ○

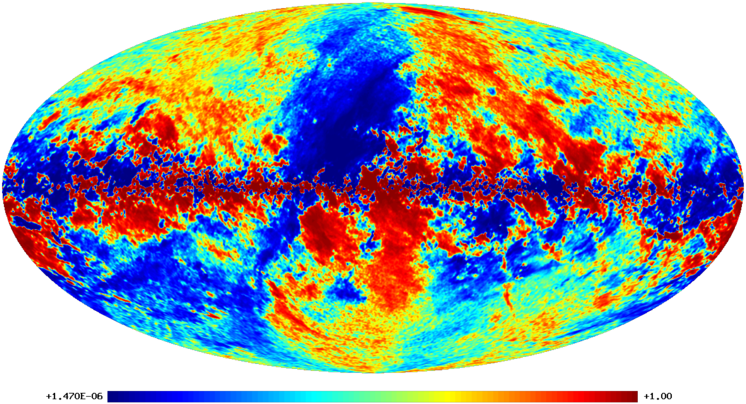


Randomized Polarization Fraction Tensor



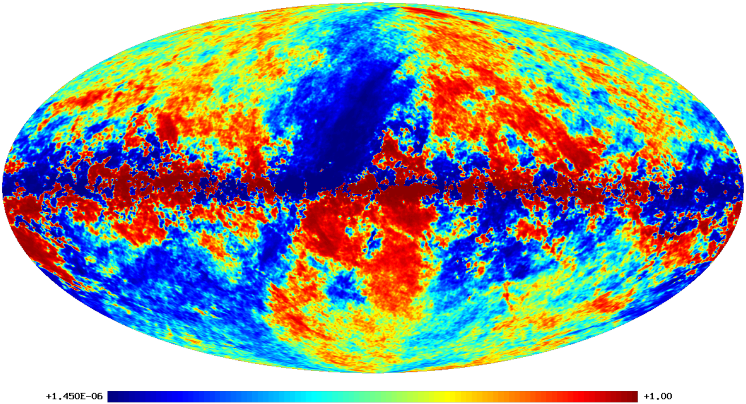
Randomized Polarization Fraction Tensor

○ original I ○ random I ○ original Q ○ random Q ○ original U ○ random U ○

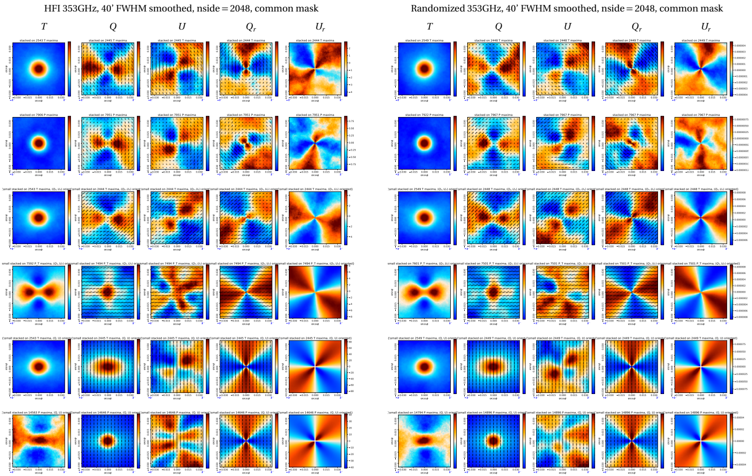


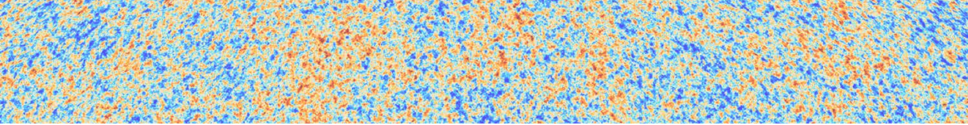
Randomized Polarization Fraction Tensor

◦ original I ◦ random I ◦ original Q ◦ random Q ◦ original U ◦ random U ◦



Realizations Reproduce Sky Statistics!





Non-Gaussian Map Characterization with Oriented Stacking

The Stacking Family

Three key elements:

A What to stack? (cosmic field u)

B Where to stack? (selection of patches, e.g., peaks)

C How to stack? (patch orientations)

"where" and "how" give constrained parameter(s) q;

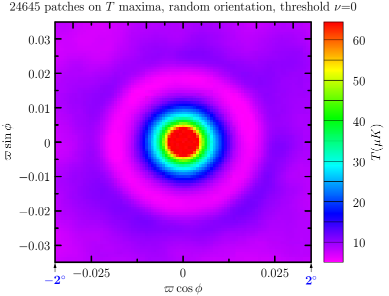
	WMAP & Planck 2013	Planck 2015
What	T, Q, U, Q_r, U_r	T, Q, U, Q_r, U_r, E, B, Q_T, U_T, $\zeta_{\rm dv}$, …
Where	T peaks	T, E, B, Q^2+U^2, $Q_T^2+U_T^2$, $\zeta_{\rm dv}$… peaks
How	unoriented	oriented and unoriented

For Gaussian fields,

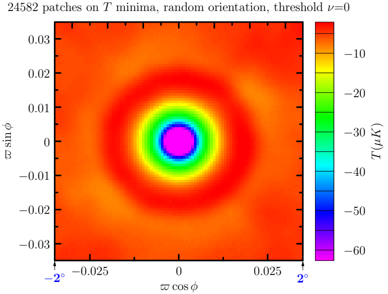
$$\langle u|q;\text{peak},\text{orientation}\rangle = \langle u q^\dagger\rangle\langle q q^\dagger\rangle^{-1}\langle q|\text{peak},\text{orientation}\rangle.$$

Planck 2015: Stacking Temperature

T on hot spots



T on cold spots

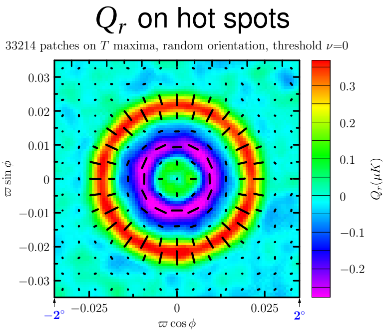


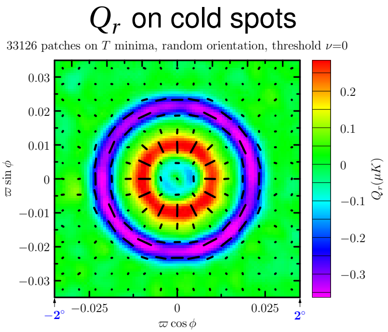
resolution: FWHM 15 arcmin

Peaks are selected above a threshold $|T_{\rm peak}| > \nu\sqrt{\langle T^2\rangle}$ ($\nu = 0$ here).

Full statistics in Isotropy and Statistics paper!

Planck 2015: Stacking Polarization





resolution: FWHM 15 arcmin

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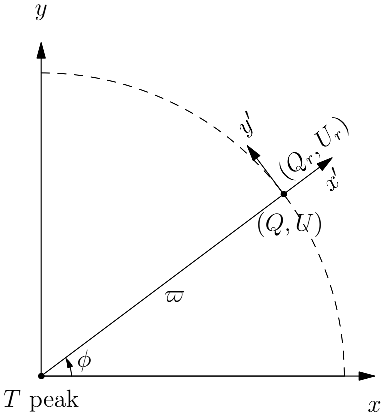
Full statistics in Isotropy and Statistics paper!

How to Rotate the Polarization Field



flat-sky polar coor. (ϖ, ϕ):

$$\varpi = 2\sin\frac{\theta}{2}$$

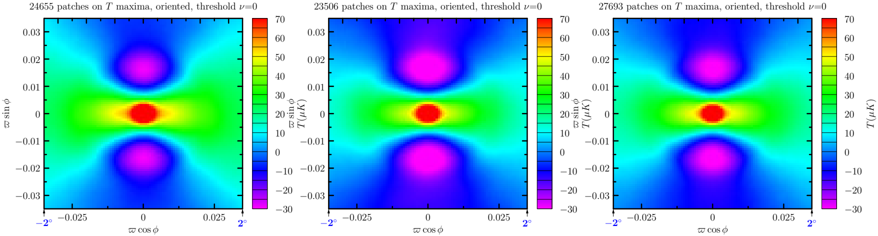
$$Q_r = -Q\cos 2\phi - U\sin 2\phi$$

$$U_r = -U\cos 2\phi + Q\sin 2\phi$$

Oriented Stacking: T on T peaks

peak threshold $\nu = 0$, resolution FWHM 15 arcmin:

Planck 2015 | FFP8 | noise-free sims



Angular dependence ($\cos m\phi$, m = 0, 2)

Noise has no noticable impact.

How to Orient a Patch around a Peak

First derivative vanishes on the peak. Need to use the 2nd derivatives.

Intuitively (flat-sky limit):
$Q_T \equiv \nabla^{-2}(\partial_y^2 - \partial_x^2)T$, $U_T \equiv -2\nabla^{-2}(\partial_x\partial_y)T$

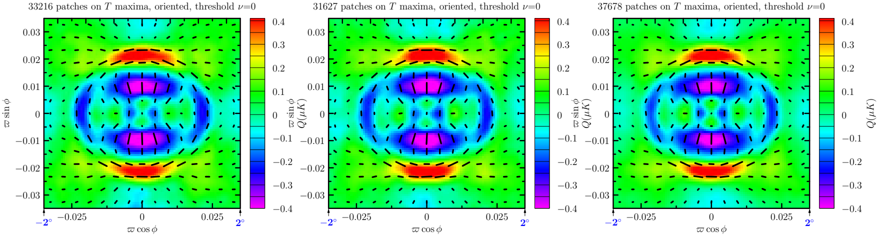
Slightly non-intuitive (on the sphere):
$Q_T(\mathbf{n}) \pm iU_T(\mathbf{n}) \equiv \sum_{l,m}\left[\int T(\mathbf{n}')\, Y_{lm}^*(\mathbf{n}')\, d^2\mathbf{n}'\right]{}_{\pm 2}Y_{lm}(\mathbf{n})$

Orient the patch such that U_T **vanishes in the centre.**
$\langle u|q;\mathrm{peak},\mathrm{orientation}\rangle(\varpi,\phi)$ decomposes to $\cos m\phi$, $m = 0, 2, 4$.

Oriented Stacking: Q on T peaks

peak threshold $\nu = 0$, resolution FWHM 15 arcmin:

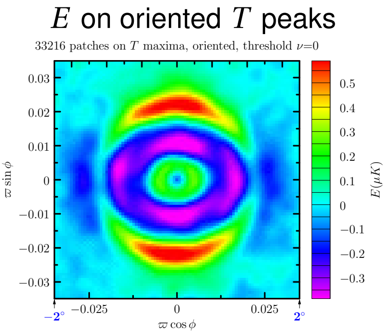
Planck 2015 FFP8 noise-free sims

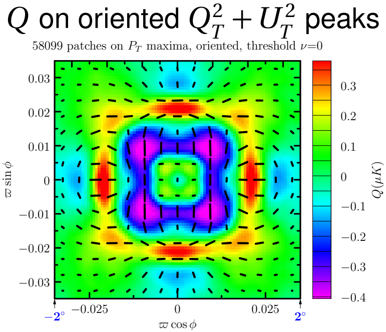


Angular dependence ($\cos m\phi$, m = 0, 2, 4)

Again noise has no noticable impact.

Oriented Stacking of Polarization

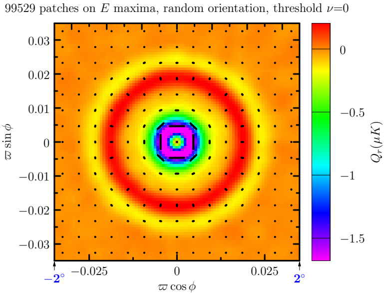




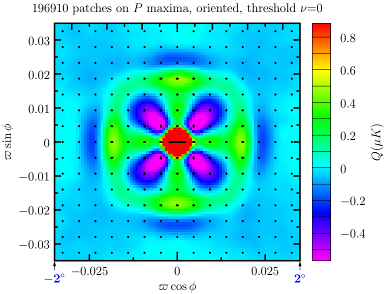
Planck 2015 (peak threshold $\nu = 0$; resolution FWHM 15 arcmin)

Stacking on Polarization Peaks

Q_r on unoriented E peaks



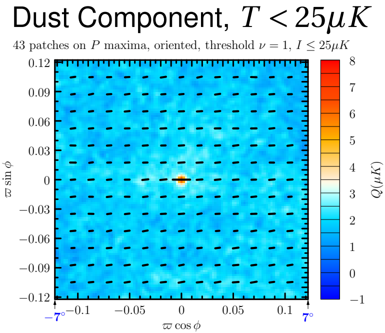
Q on oriented $Q^2 + U^2$ peaks

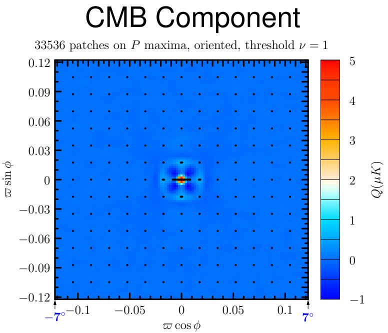


Planck 2015 (peak threshold $\nu = 0$; resolution FWHM 15 arcmin)

Stacking Polarized Dust

Planck 2015 Component Separated Commander Dust Map





Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

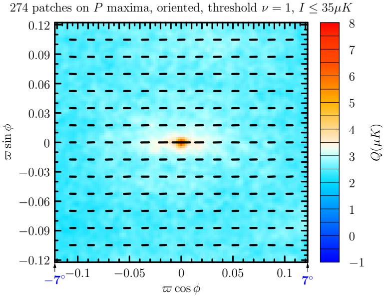
Patch size: $\varpi <= 7°$; threshold $\nu = 1$

T map FWHM 2°; Q, U maps FWHM 15 arcmin.

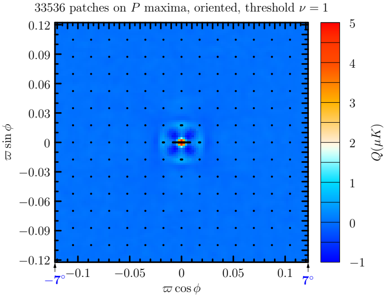
Stacking Polarized Dust

Planck 2015 Component Separated Commander Dust Map

Dust Component, $T < 35\mu K$



CMB Component



Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

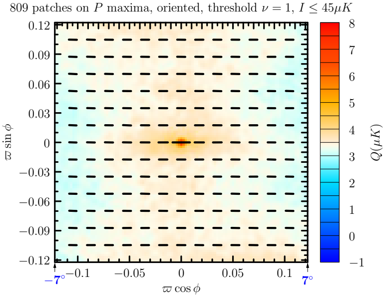
Patch size: $\varpi <= 7°$; threshold $\nu = 1$

T map FWHM 2°; Q, U maps FWHM 15 arcmin.

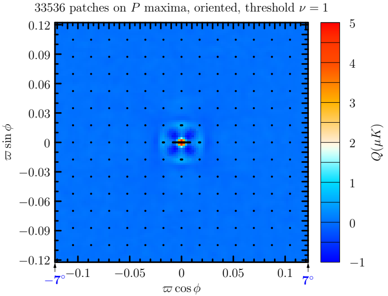
Stacking Polarized Dust

Planck 2015 Component Separated Commander Dust Map

Dust Component, $T < 45\mu K$



CMB Component



Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

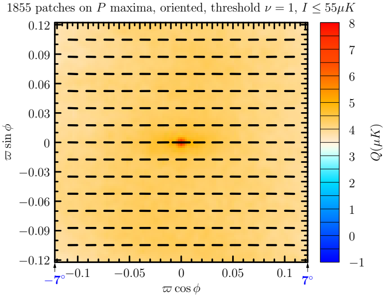
Patch size: $\varpi <= 7^\circ$; threshold $\nu = 1$

T map FWHM 2°; Q, U maps FWHM 15 arcmin.

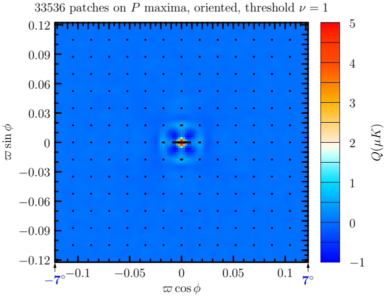
Stacking Polarized Dust

Planck 2015 Component Separated Commander Dust Map

Dust Component, $T < 55\mu K$



CMB Component



Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

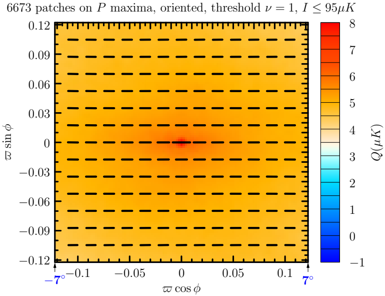
Patch size: $\varpi <= 7°$; threshold $\nu = 1$

T map FWHM 2°; Q, U maps FWHM 15 arcmin.

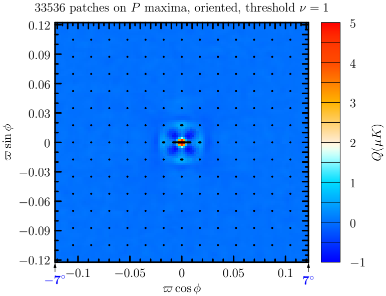
Stacking Polarized Dust

Planck 2015 Component Separated Commander Dust Map

Dust Component, $T < 95\mu K$



CMB Component



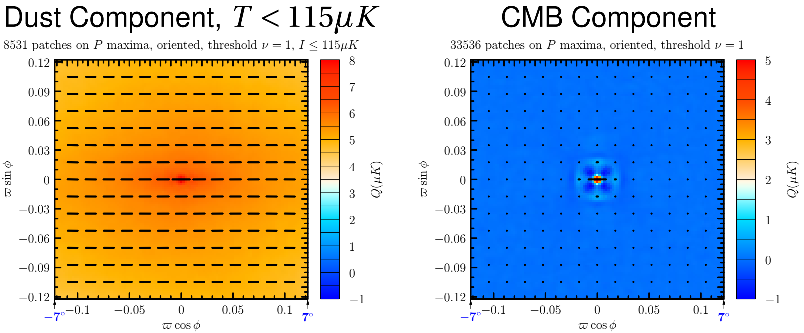
Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

Patch size: $\varpi <= 7°$; threshold $\nu = 1$

T map FWHM 2°; Q, U maps FWHM 15 arcmin.

Stacking Polarized Dust

Planck 2015 Component Separated Commander Dust Map



Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

Patch size: $\varpi <= 7°$; threshold $\nu = 1$

T map FWHM 2°; Q, U maps FWHM 15 arcmin.