
PLANCK 2014
THE MICROWAVE SKY IN
TEMPERATURE AND POLARIZATION

Stacking of Planck 2014 temperature, polarization and primordial curvature maps

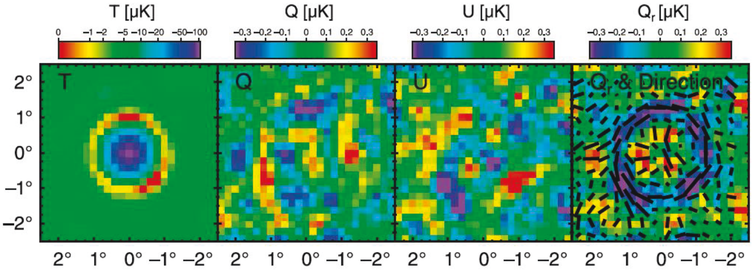
Zhiqi Huang on behalf of Planck Collaboration

3 December 2014

Outline

Back to WMAP Era

WMAP7 Stacking *(source: Komatsu et al. 2011)*

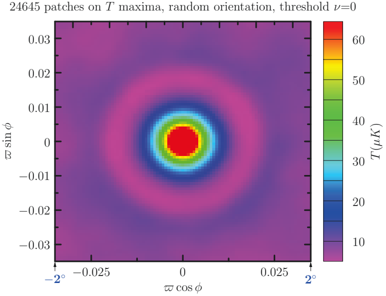


resolution: FWHM 30 arcmin

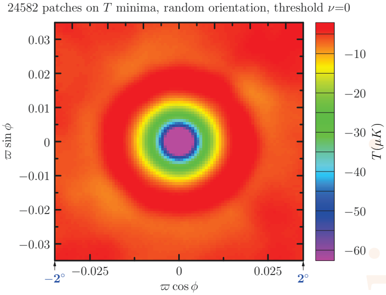
c.f. Enrique's talk for basic stacking results.

Planck 2014: T, Q_r

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).

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Planck 2014: T, Q_r

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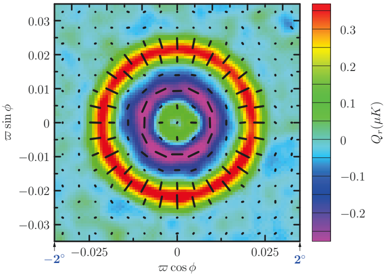
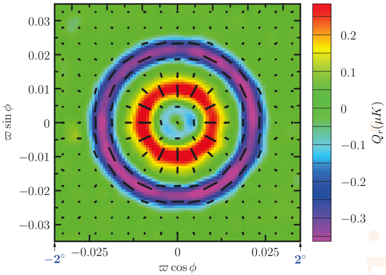
Q_r on hot spots



Q_r 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).

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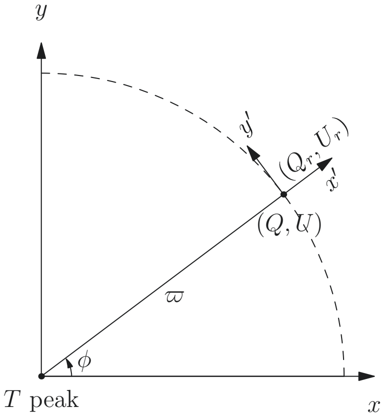
How to Rotate the Polarization Field



flat-sky polar coor. (ϖ, ϕ):

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

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

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

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 2014
What	T, Q, U, Q_r, U_r	$T, Q, U, Q_r, U_r, E, B, Q_T, U_T, \zeta_{\rm dv}, \ldots$
Where	T peaks	$T, E, B, Q^2+U^2, Q_T^2+U_T^2, \zeta_{\rm dv}\ldots$ peaks
How	unoriented	oriented and unoriented

For Gaussian fields,

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

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):

$$Q_T(\mathbf{n}) \pm i U_T(\mathbf{n}) \equiv \sum_{l,m} \left[\int T(\mathbf{n}') Y_{lm}^*(\mathbf{n}')\, d^2\mathbf{n}' \right] {}_{\pm 2}Y_{lm}(\mathbf{n})$$

Orient the patch such that U_T **vanishes in the centre.**

$\langle u|q;\mathrm{peak,orientation}\rangle(\varpi,\phi)$ decomposes to $\cos m\phi$, $m = 0, 2, 4$.

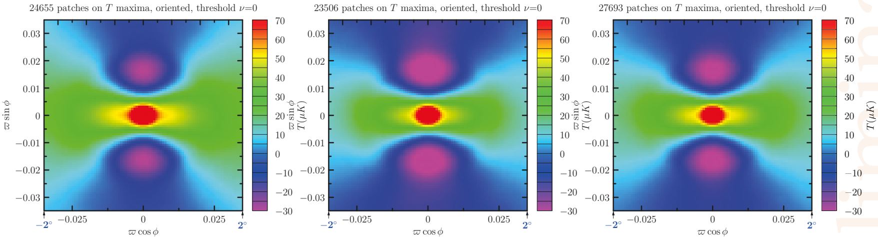
Maps

- Planck 2014: component separated full-mission maps. (only SMICA shown in this talk, others are quantitatively similar.)
- FFP8: component separated maps from simulated Planck full-mission maps, assuming a fiducial cosmology (Planck 2013 best-fit).
- Noise-free: Random-Gaussian maps from the same fiducial cosmology, assuming perfect observation.
- Derived maps: E, B, and $\zeta_{\rm dv}$ maps. $\zeta_{\rm dv}$ is visibility-weighted line-of-sight integral of the primordial curvature fluctuations ζ.
- All polarization maps are high-pass filtered maps.

Oriented Stacking: T on T peaks

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

Planck 2014 | FFP8 | noise-free sims



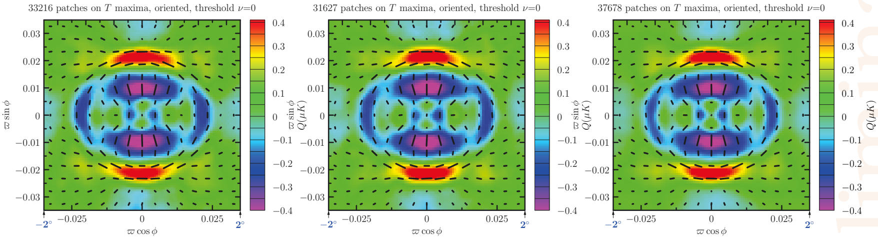
Angular dependence ($\cos m\phi$, m = 0, 2)

Noise has no noticable impact.

Oriented Stacking: Q on T peaks

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

Planck 2014 | FFP8 | noise-free sims



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

Again noise has no noticable impact.

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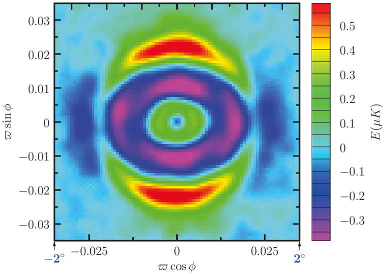
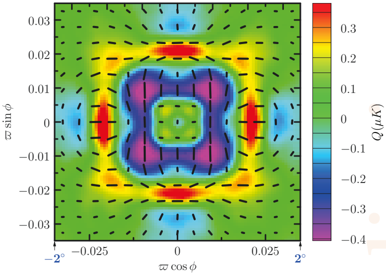
Oriented Stacking: More Polarization

E on oriented T peaks



Q on oriented $Q_T^2 + U_T^2$ peaks



Planck 2014 (peak threshold $\nu = 0$; resolution FWHM 15 arcmin)

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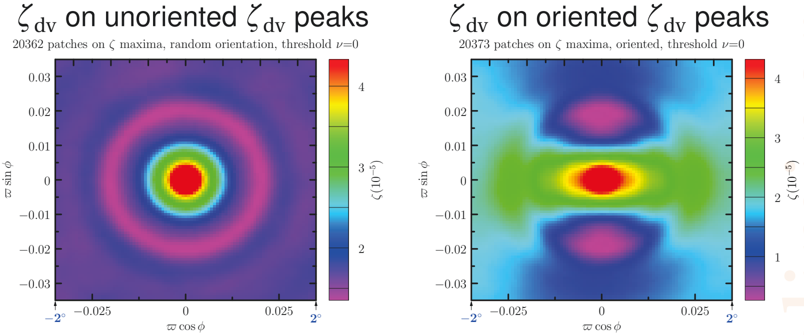
Stacking Primordial Curvature



Planck 2014 (peak threshold $\nu = 0$; resolution FWHM 15 arcmin)

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Stacking on Polarization Peaks

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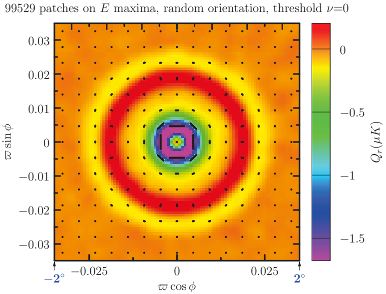
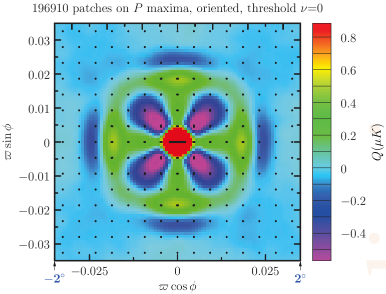
Q_r on unoriented E peaks



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



Planck 2014 (peak threshold $\nu = 0$; resolution FWHM 15 arcmin)

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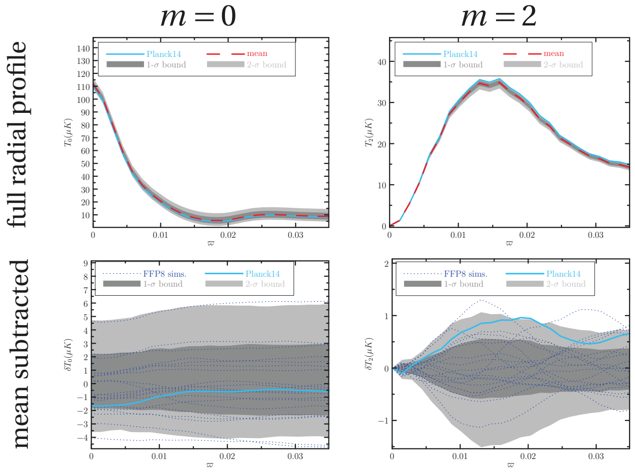
Statistics: T on oriented T peaks

- Cosmological contribution to $\delta T_m(\varpi)$ are mostly from low ℓ where cosmic variance is large.
- Statistical isotropy $\Rightarrow$:
  $\delta T_m(\varpi) = \varpi^m(c_0 + c_1\varpi^2 + c_2\varpi^4 + \dots)$
- Truncate at order n and compute the mean and cov. of $(c_0, c_1, c_2, \dots, c_n)$.
- Compare χ^2 for Planck map and sims:
  p-value := $\chi^2_{\text{sim.}} > \chi^2_{\text{data}}$ rate.

Statistics: T on oriented T peaks



24 uniform bins in $0 < \varpi < 2$ degrees (pixel size 5 arcmin)

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Statistics: Comparison of Maps

1000 FFP8 sims.: use subset#1 to compute cov. , and use subset#2 compute p-value

Example: **Truncation** $n = 4$ (5 d.o.f. c_0, c_1, c_2, c_3, c_4)

map	subset#1	subset#2	δT_0 p-value	δT_2 p-value
SMICA	1-500	501-1000	0.33	0.22
SMICA	501-1000	1-500	0.27	0.23
SMICA	1-1000	250-750	0.29	0.25
SMICA	1-1000	1-1000	0.30	0.22
COMMANDER	1-1000	1-1000	0.21	0.24
NILC	1-1000	1-1000	0.54	0.33
SEVEM	1-1000	1-1000	0.38	0.39

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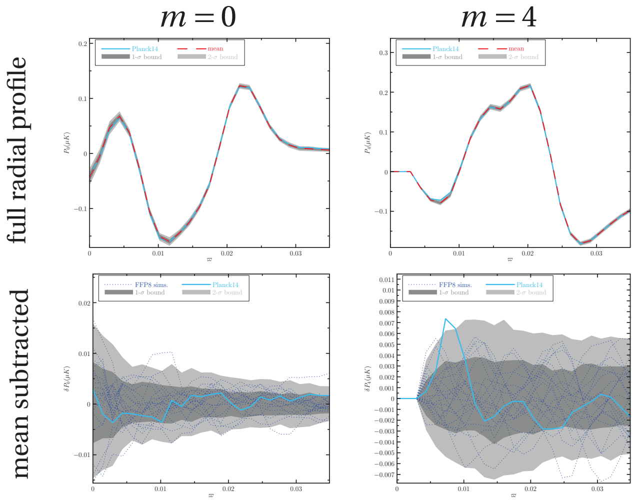
Statistics: Q, U on $Q_T^2 + U_T^2$ peaks



(p-value 0.89 for truncation $n = 4$)

(p-value 0.20 for truncation $n = 4$)

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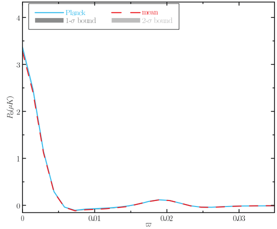
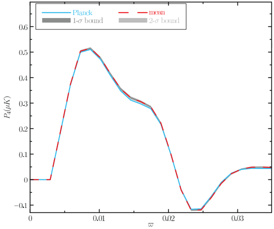
Statistics: Q, U on Q^2+U^2 peaks

full radial profile

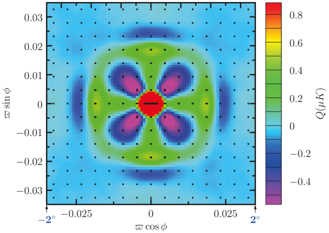
$m=0$



$m=4$



196910 patches on P maxima, oriented, threshold ν=0



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Small discrepancy around $\varpi = 0$ is due to noise mismatch on small scales in FFP8 simulations.

Noise bias does not spoil the main feature.

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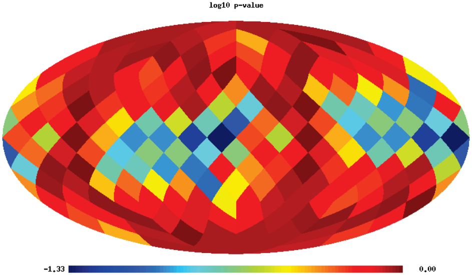
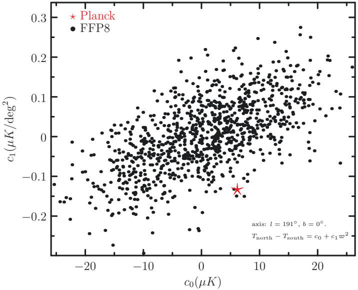
Hemisphere Power Asymmetry

Planck 2014 (Smica map; Common Mask)





Most asymmetric direction $l = 191°$, $b = 0$, p-value 0.041

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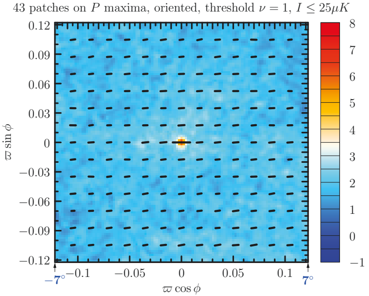
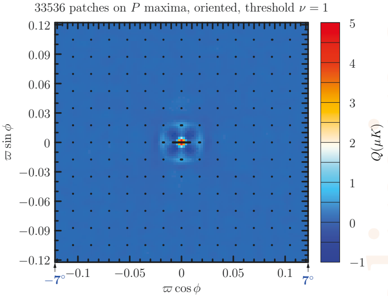
Stacking Polarized Dust

Planck 2014 Component Separated Commander Dust Map

Dust Component, $T < 25\mu K$



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.

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Stacking Polarized Dust

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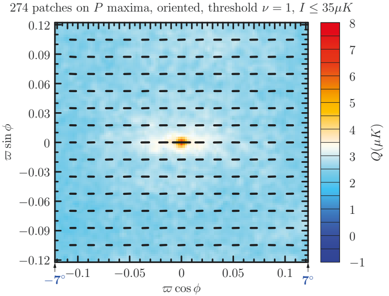
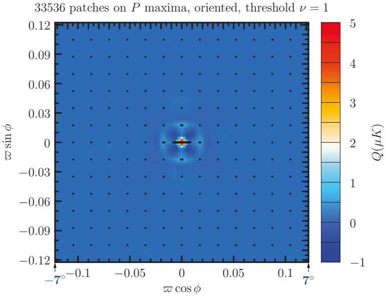
Planck 2014 Component Separated Commander Dust Map

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.

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Stacking Polarized Dust

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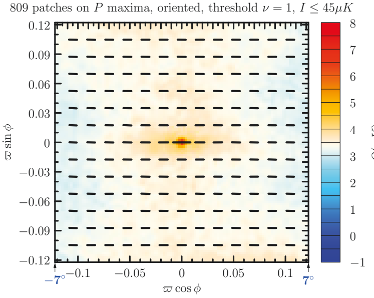
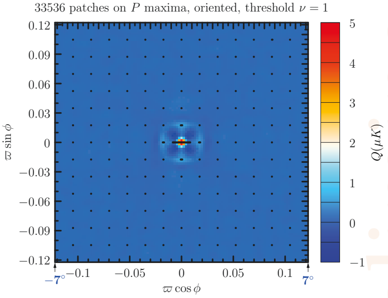
Planck 2014 Component Separated Commander Dust Map

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).

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

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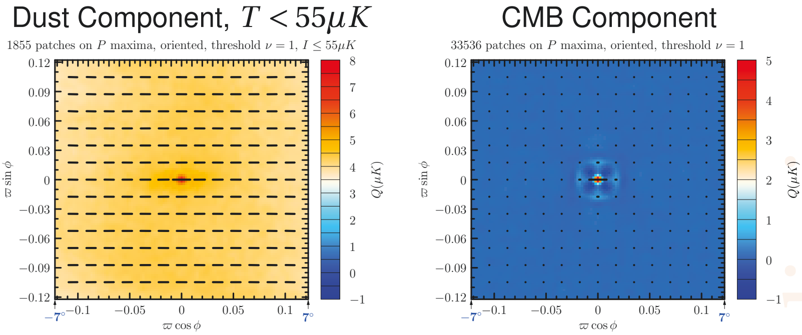
Stacking Polarized Dust

Planck 2014 Component Separated Commander Dust Map



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Stacking Polarized Dust

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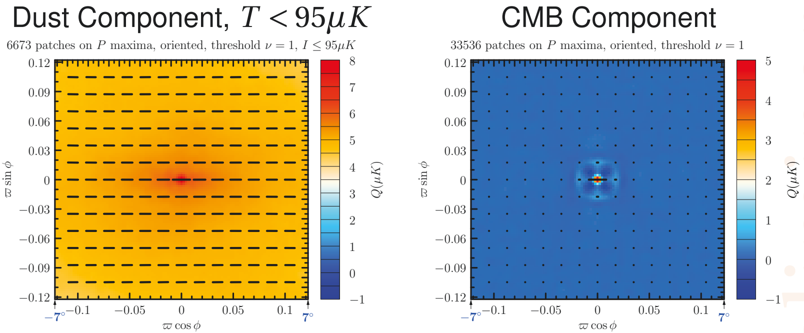

Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

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

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

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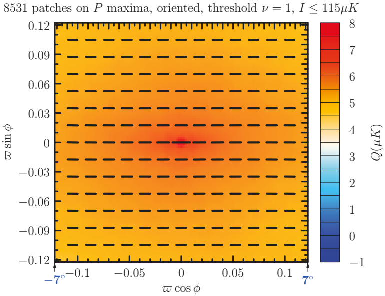
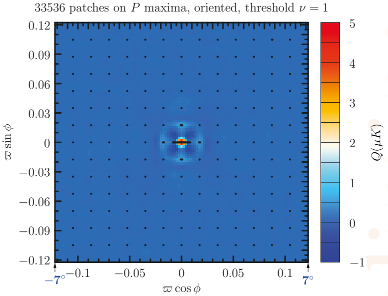
Stacking Polarized Dust

Planck 2014 Component Separated Commander Dust Map

Dust Component, $T < 115\mu K$



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.

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Conclusions

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- Planck 2014 I&S explores a large family of novel stacking methods.
- Unoriented stacks of T and Q_r probe $m=0$ TT, TE, EE correlation functions.
- Oriented stacks probe either $m=0,2$ or $m=0,2,4$ TT, TE, EE correlation functions, many spatially localized probes of Random Fields, Gaussian or not.
- Statistics of stacked Planck 2014 data is compatible with the FFP8 ensemble - no “smoking gun” anomalies.
- Stacking gives a complimentary approach for probing hemispherical asymmetry.
- Stacked oriented dust maps are more directional than CMB stacks. A future test for contamination?

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The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada.

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.


Thank you
X, Ferrara, Dec 2014

How to derive a $\zeta_{\rm dv}$ map

$\zeta_{\rm dv}(\mathbf{n}) \equiv \int_0^{\eta_0} \zeta_{\rm prim}\big(\mathbf{n}(\eta_0 - \eta)\big)\, \dot{\tau} e^{-\tau}\, d\eta$, where $\tau(\eta)$ is the optical depth and η conformal time. $\zeta_{\rm prim}(\mathbf{x})$ is the primordial curvature fluctuations.

In Harmonic space (given measured T_{lm}):

$\zeta_{lm} = \zeta_{lm}|_{\rm constrained} + \zeta_{lm}|_{\rm unconstrained}$

$\zeta_{lm}|_{\rm constrained} = \frac{C_l^{T\zeta}}{C_l^{TT} + N_l} T_{lm}$

$\zeta_{lm}|_{\rm unconstrained}$ is a random Gaussian field with power $Z_l = C_l^{\zeta\zeta} - \frac{(C_l^{T\zeta})^2}{C_l^{TT} + N_l}$.

C_l^{TT} and $C_l^{T\zeta}$ are computed from best-fit ΛCDM. Noise spectrum N_l is computed from FFP8 #0 (for the scales we are considering $N_l \ll C_l^{TT}$ so doesn't matter which model to use).