Stacking of Planck 2014 temperature, polarization and primordial curvature maps

Zhiqi Huang on behalf of Planck Collaboration

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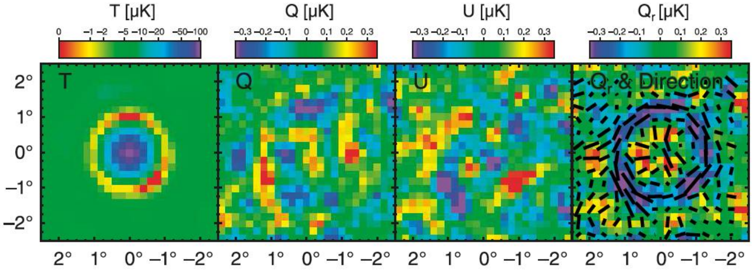
Outline

Back to WMAP Era

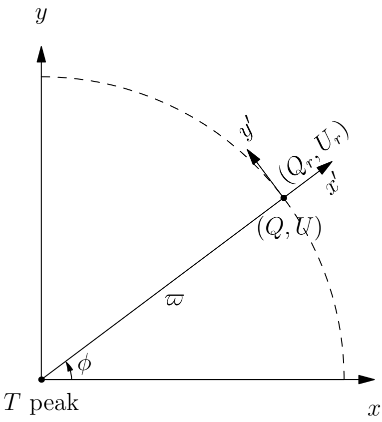
WMAP7 Stacking (source: Komatsu et al. 2011)



resolution: FWHM 30 arcmin

see Enriquez's talk for basic stacking results.

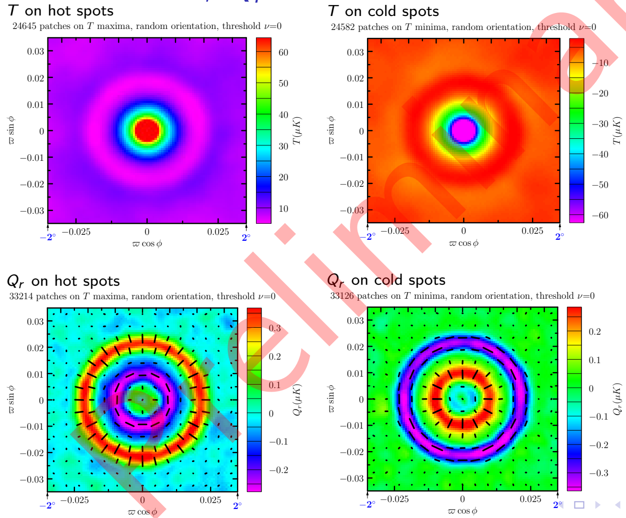
How to Symmetrize the Polarization Field



flat-sky polar coor. (ϖ, ϕ):
$\varpi = 2\sin\frac{\theta}{2}$

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

Planck 2014: T, Q_r



resolution: FWHM 15 arcmin;

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

see Enriquez's talk for basic stacking results.

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, $\zeta_{\rm dv}$, ...
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, $\langle u|q;\mathrm{peak},\mathrm{orientation}\rangle = \langle uq^\dagger\rangle\langle qq^\dagger\rangle^{-1}\langle q|\mathrm{peak},\mathrm{orientation}\rangle$.

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

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

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.

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

$\zeta_{\rm dv}(\mathbf{n}) \equiv \int_0^{\eta_0} \zeta_{\rm prim}\left(\mathbf{n}(\eta_0 - \eta)\right) \dot{\tau} e^{-\tau} d\eta$, 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}):

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

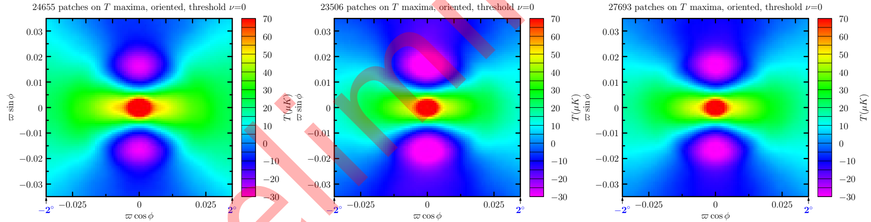
$\zeta_{lm}|_{\rm constrained} = \frac{C_l^{T\zeta}}{C_l^{TT}+N_l} T_{lm}$

$\zeta_{lm}|_{\rm unconstrained}$ 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).

Oriented Stacking: T on Oriented T peaks

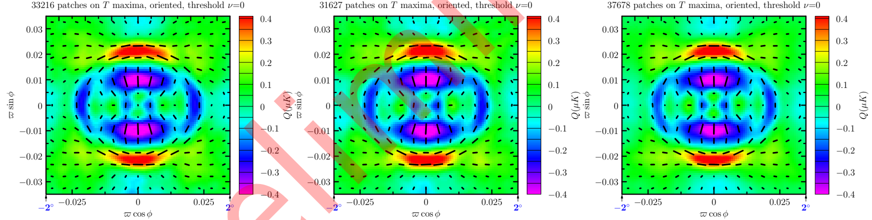
Planck 2014 vs. FFP8 vs. noise-free (peak threshold $\nu = 0$, resolution FWHM 15 arcmin.)



Angular dependence ($\cos m\phi$, m = 0, 2)
Noise has no noticable impact.

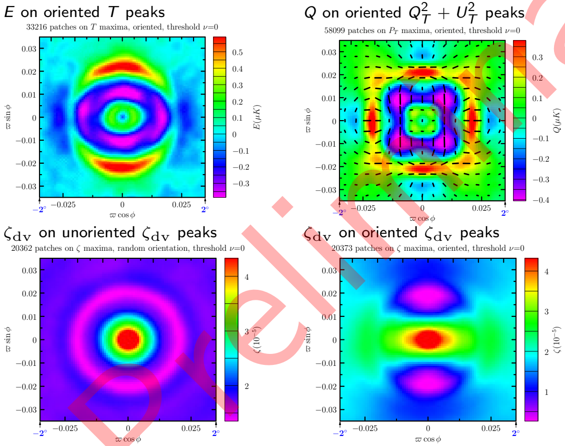
Oriented Stacking: Q on oriented T peaks

Planck 2014 vs. FFP8 vs. noise-free sim. (peak threshold $\nu = 0$; resolution FWHM 15 arcmin.)



Angular dependence ($\cos m\phi$, m = 0, 2, 4)
Again noise has no noticable impact.

Oriented Stacking: Other T-related examples



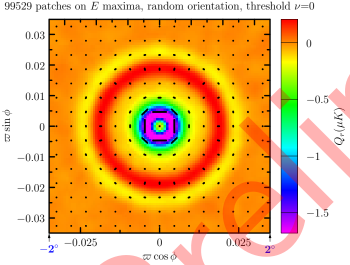
Planck 2014

peak threshold ν = 0; resolution FWHM 15 arcmin.

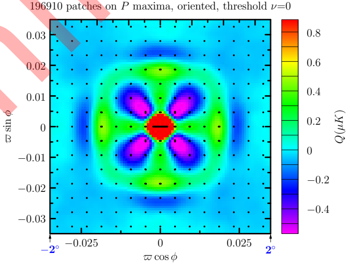
Stacking on Polarization Peaks

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

Qr on unoriented E peaks



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

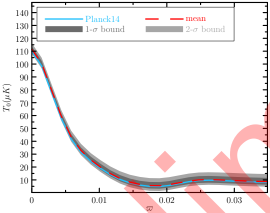


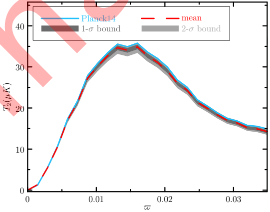
Statistics: T on oriented T peaks

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

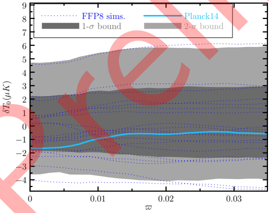
$m = 0$ $\qquad\qquad$ $m = 2$

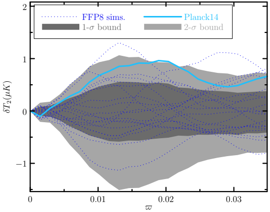
full radial profile





mean subtracted





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 $:=$ $\chi^2_{\rm sim.} > \chi^2_{\rm data}$ rate.

Statistics: Convergence Test and 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)

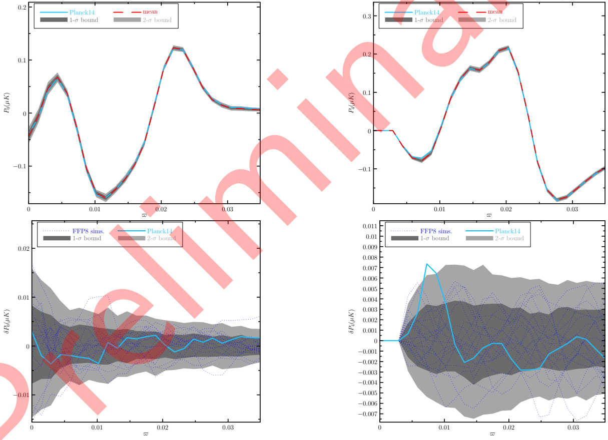
map	subset#1	subset#2	δT_0 p-value	δT_2 p-value
SMICA	1-500	501-1000	0.33	0.22
SMICA	501-1000	1-500	0.27	0.23
SMICA	1-1000	250-750	0.29	0.25
SMICA	1-1000	1-1000	0.30	0.22
COMMANDER	1-1000	1-1000	0.21	0.24
NILC	1-1000	1-1000	0.54	0.33
SEVEM	1-1000	1-1000	0.38	0.39

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

$m = 0$ $m = 4$

full radial profile

mean subtracted

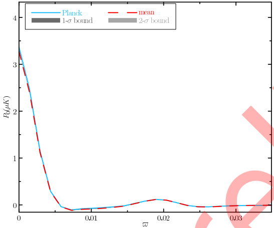


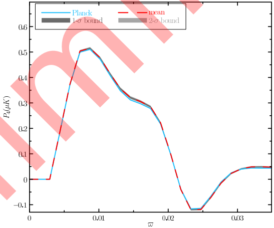
(p-value 0.89 for truncation $n = 4$) (p-value 0.20 for truncation $n = 4$)

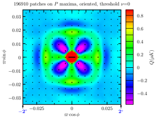
Q, U on $Q^2 + U^2$ peaks

Noise bias does not spoil the main feature.

$m = 0$ $m = 4$



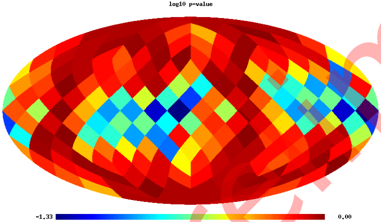


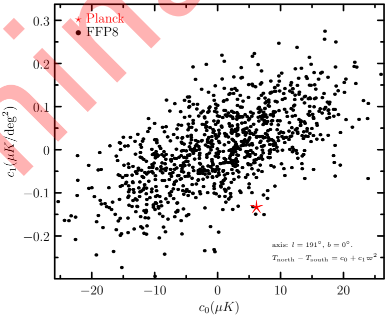


Small discrepancy around $\varpi = 0$ is due to noise mismatch on small scales in FFP8 simulations.

Hemisphere Power Asymmetry

Smica map; Common Mask; Most asymmetric direction $l = 191^\circ$, $b = 0$, p-value 0.041

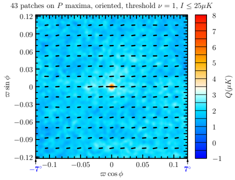




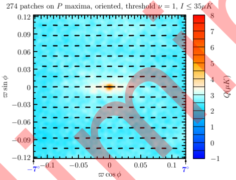
Component Separated Commander Dust Map

Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre). Patch size: $\varpi <= 7^\circ$; treshold $\nu = 1$; T map FWHM 2°; Q, U maps FWHM 15 arcmin.

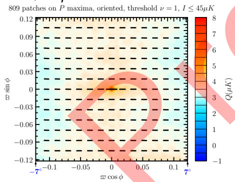
$T < 25\mu K$



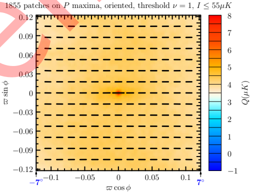
$T < 35\mu K$



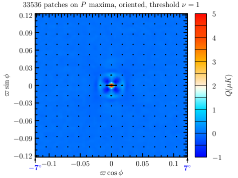
$T < 45\mu K$



$T < 55\mu K$



This is how a CMB map looks like:



Conclusions

- We have proposed a large family of novel stacking methods.
- Compared to unoriented stacking of T and Q_r, these extended stacking methods explore many different templates covering a wider range of scales.
- Planck 2014 is fully consistent with FFP8.
- Many other applications: hemisphere asymmetry; properties of non-CMB maps . . .