Testing Isotropy and Statistics of the CMB with Planck

Andrei Frolov on behalf of Planck Collaboration

Rencontres du Vietnam:
Cosmology - 50 years after CMB discovery

International Centre for Interdisciplinary Science Education
Quy Nhon, Vietnam, 21 August 2015

Outline

1 Instrument and Mission Overview

2 Variance Asymmetry

3 Peak Statistics & Cold Spot

4 Stacking & Polarization

5 Conclusions

Planck 2015: What's New?

- **More data:** 48/29 months of LFI/HFI observations, enabling further checks
- **Improved data processing:** systematics removal, calibration, beam reconstruction
- **Improved foreground model:** larger sky-fraction used for analysis
- **More robust to systematics:** based on half-mission cross power spectra
- **The 2015 analysis includes polarization**

Planck 2015: What's New?

planck

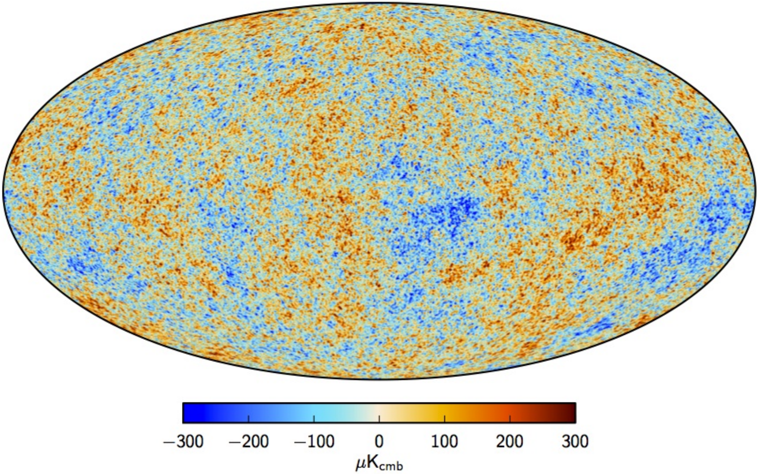
- **More data:** 48/29 months of LFI/HFI observations, enabling further checks
- **Improved data processing:** systematics removal, calibration, beam reconstruction
- **Improved foreground model:** larger sky-fraction used for analysis
- **More robust to systematics:** based on half-mission cross power spectra
- **The 2015 analysis includes polarization**

esa

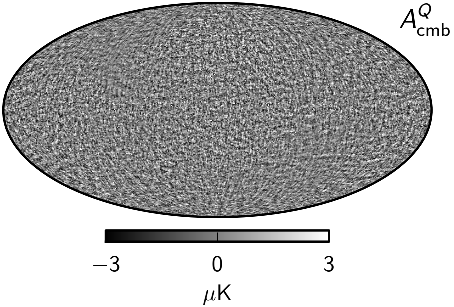
PLANCK LFI

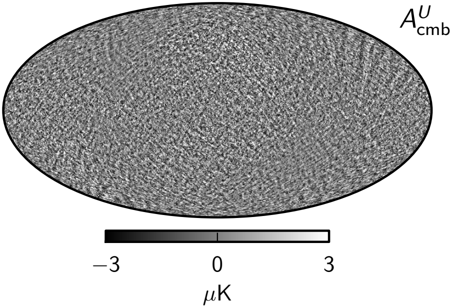
HFI PLANCK

CMB Intensity Map



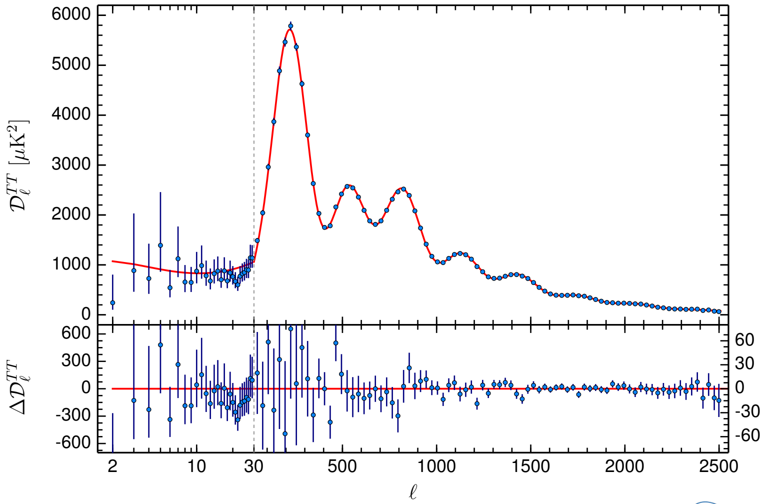
CMB Polarization Maps



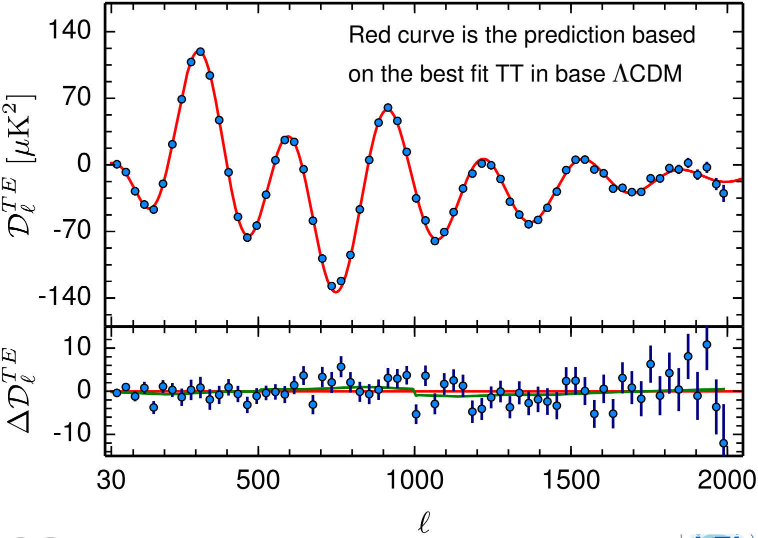


- Smoothed to 1 degree resolution
- High-pass filtered with l=20-40 cosine filter
- Galactic plane replaced with constrained Gaussian realization

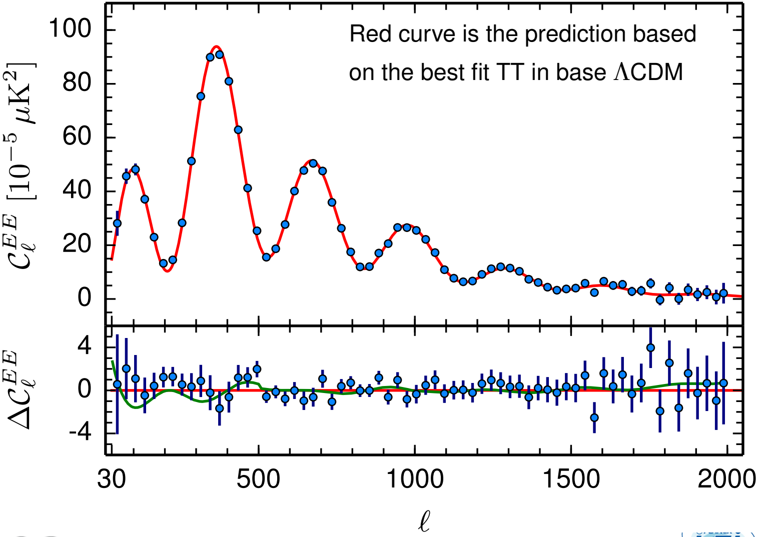
Planck 2015 TT Power Spectrum



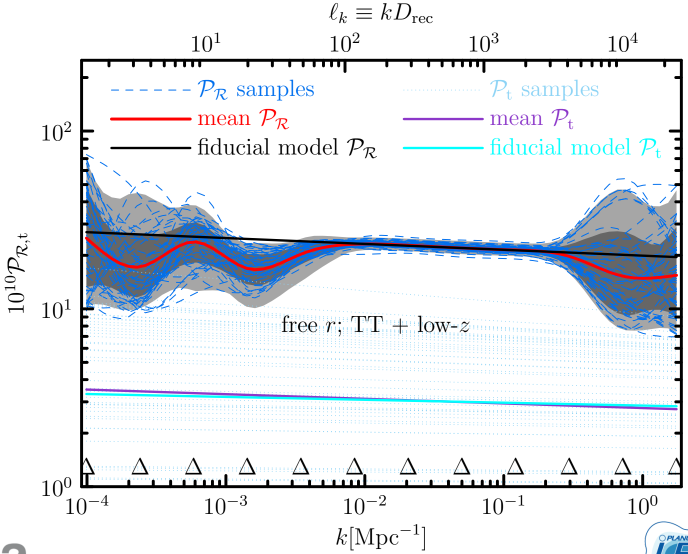
Planck 2015 TE Power Spectrum



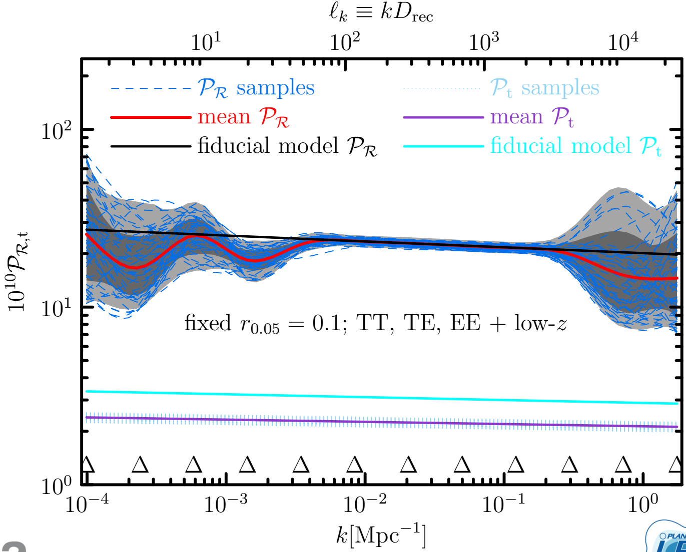
Planck 2015 EE Power Spectrum



Primordial Spectrum Reconstruction

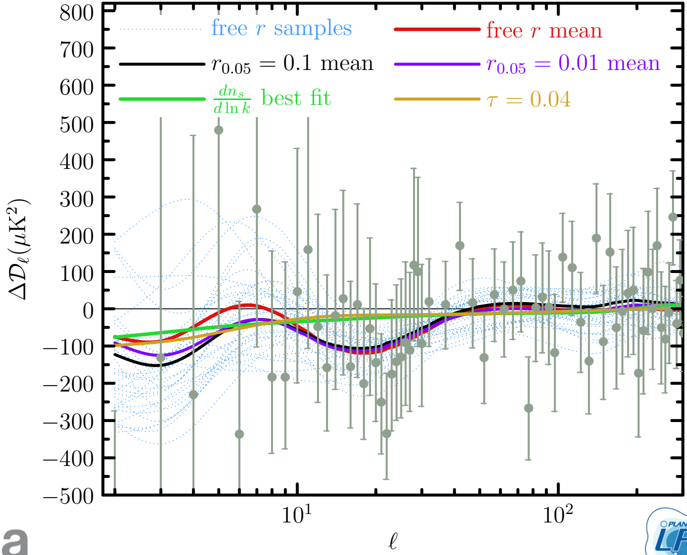


Primordial Spectrum Reconstruction



Running Spectral Index is Not a Good Fit!

planck

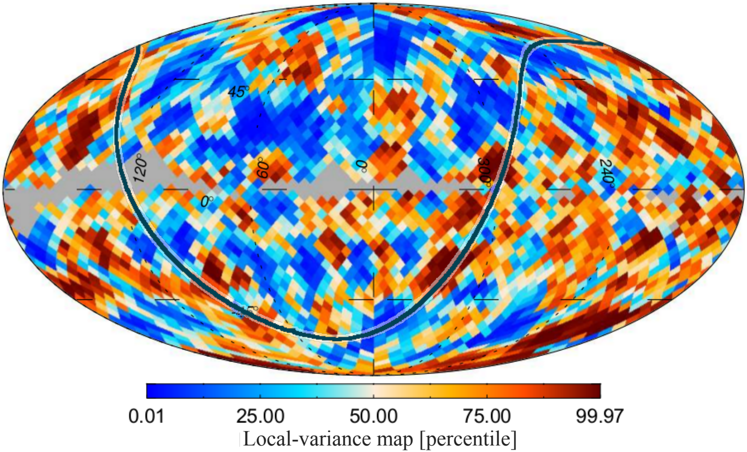


esa

PLANCK LFI

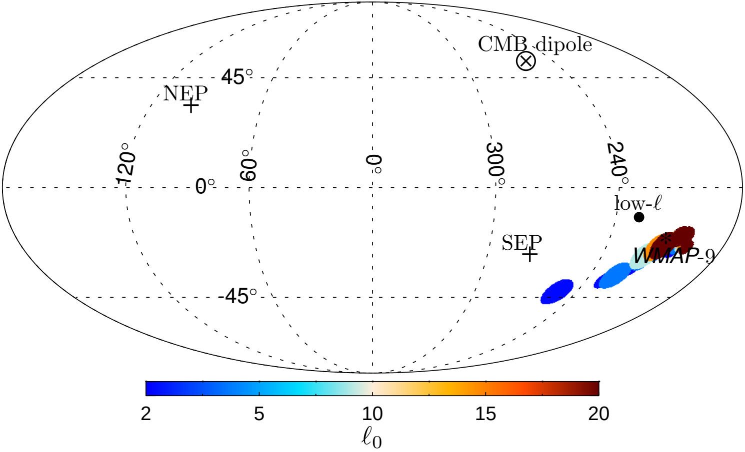
HFI PLANCK

Local Variance Map of CMB



mean-subtracted and inverse-variance-weighted local-variance map for 8° discs in Commander component-separated CMB map

Local Variance Dipole Modulation



variance dipole amplitude 0.052 ± 0.016, direction $(l, b) = (210°, -26°)$
(no high-pass filter applied)

Going after localized anomalies…

Let’s look at peaks!

Optimal (Wiener) Deconvolution

planck

Estimating observable from a noisy data:

$$\underbrace{o(\vec{x})}_{\text{observable}} = \underbrace{h(\vec{x})}_{\text{transfer}} * \underbrace{s(\vec{x})}_{\text{signal}} + \underbrace{\epsilon(\vec{x})}_{\text{noise}} \implies \underbrace{\hat{s}(\vec{x})}_{\text{estimate}} = \underbrace{g(\vec{x})}_{\text{filter}} * \underbrace{o(\vec{x})}_{\text{observable}}$$

In Fourier domain, optimal Wiener filter is:

$$G = \frac{\bar{H} \cdot S}{|H|^2 \cdot S + N} \simeq \frac{\bar{H}}{N} \cdot S$$

Take a shortcut - whiten data using isotropic CMB+noise model!

$$G \sim C_\ell^{-\frac{1}{2}} \cdot S$$

Whiten and filter, search for peaks!

esa

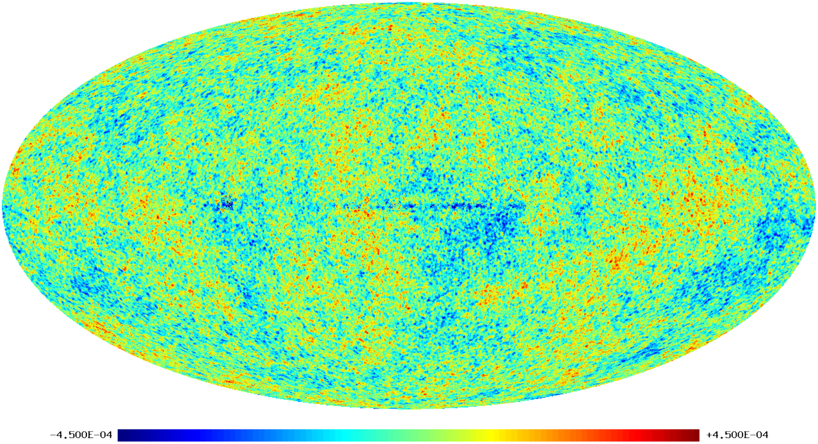
PLANCK LFI

HFI PLANCK

CMB Data Analysis Pipeline

○ SMICA ○ Whiten ○ Mask ○ Filter ○ Find Peaks ○

planck



Planck 2014 release [SSG84 filter at 240′$_{\text{FWHM}}$]

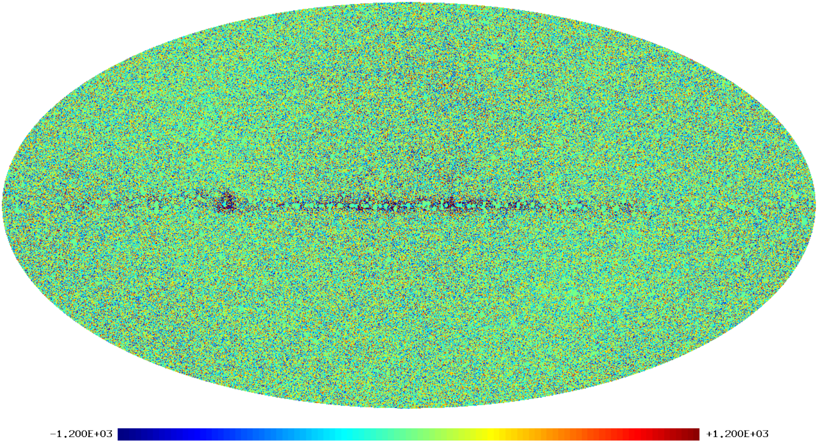
esa

PLANCK LFI

HFI PLANCK

CMB Data Analysis Pipeline

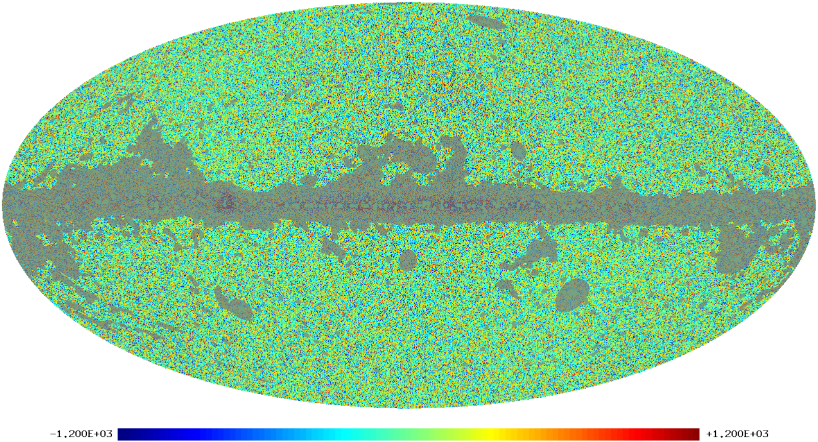
○ SMICA ○ Whiten ○ Mask ○ Filter ○ Find Peaks ○



Planck 2014 release [SSG84 filter at $240'_{\mathrm{FWHM}}$]

CMB Data Analysis Pipeline

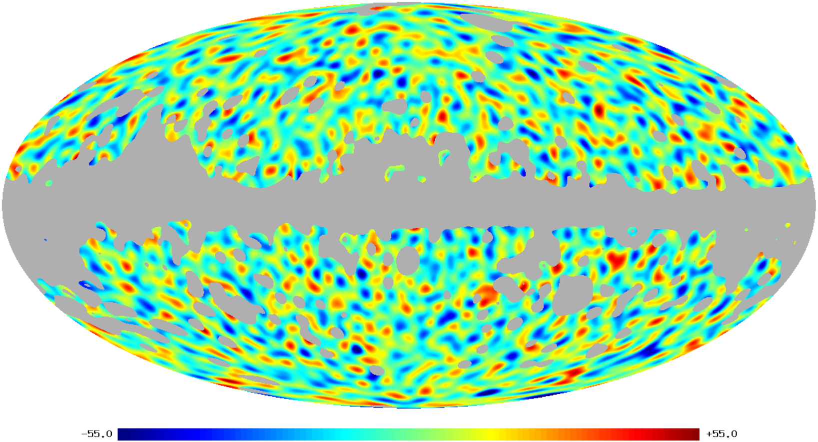
○ SMICA ○ Whiten ○ Mask ○ Filter ○ Find Peaks ○



Planck 2014 release [SSG84 filter at 240′ FWHM]

CMB Data Analysis Pipeline

○ SMICA ○ Whiten ○ Mask ○ Filter ○ Find Peaks ○

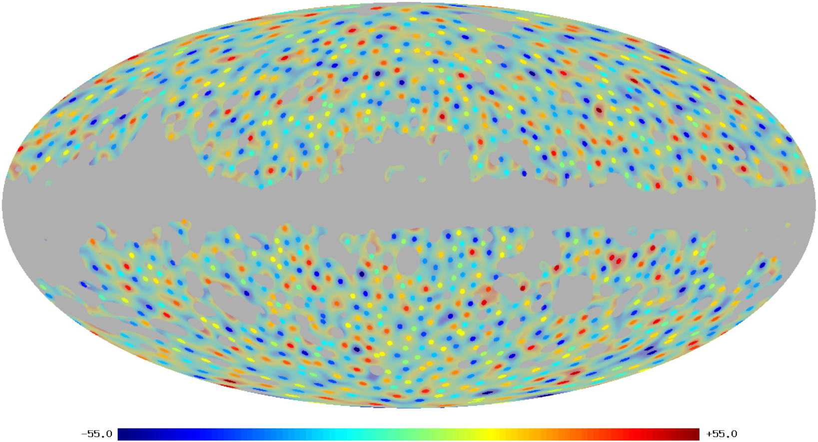


Planck 2014 release [SSG84 filter at 240′$_{\text{FWHM}}$]

CMB Data Analysis Pipeline

○ SMICA ○ Whiten ○ Mask ○ Filter ○ Find Peaks ○

planck

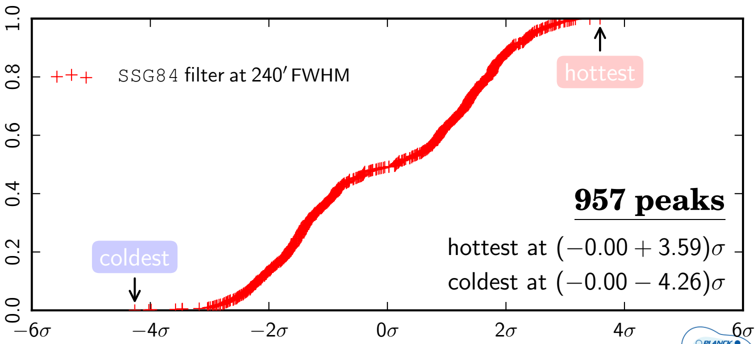


Planck 2014 release [SSG84 filter at 240′$_{\text{FWHM}}$]

esa

PLANCK LFI

HFI PLANCK

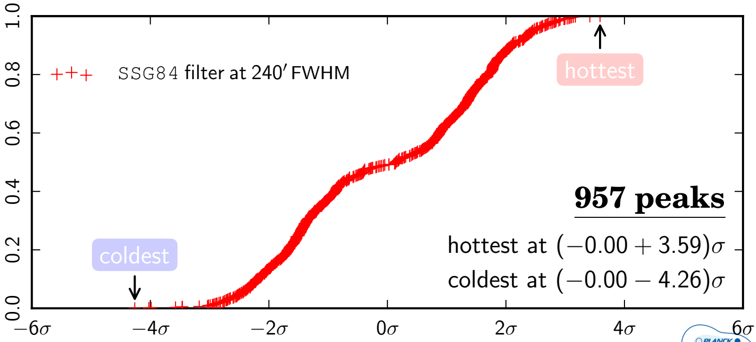


1.0
0.8
0.6
0.4
0.2
0.0
+++ SSG84 filter at 240′ FWHM
hottest
coldest
957 peaks
hottest at $(-0.00 + 3.59)\sigma$
coldest at $(-0.00 - 4.26)\sigma$
-6σ
-4σ
-2σ
0σ
2σ
4σ
6σ

Testing CMB Peak Statistics

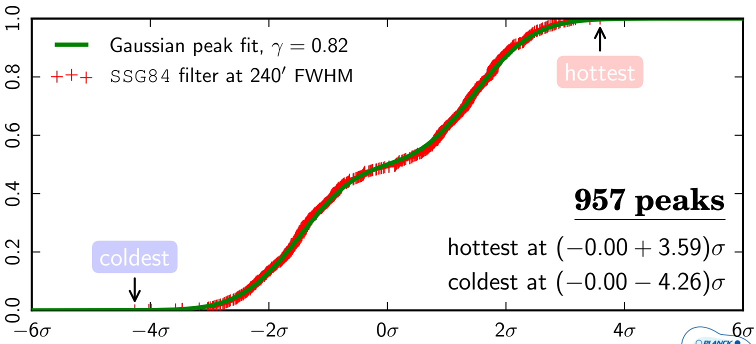
Bond and Efstathiou (1987)

$$\frac{n_{\mathrm{max}}+n_{\mathrm{min}}}{n_{\mathrm{pk}}}\left(\frac{x}{\sigma}>\nu\right)=\sqrt{\frac{3}{2\pi}}\gamma^2\,\nu\exp\left(-\frac{\nu^2}{2}\right)+\frac{1}{2}\operatorname{erfc}\left[\frac{\nu}{\sqrt{2-\frac{4}{3}\gamma^2}}\right]$$

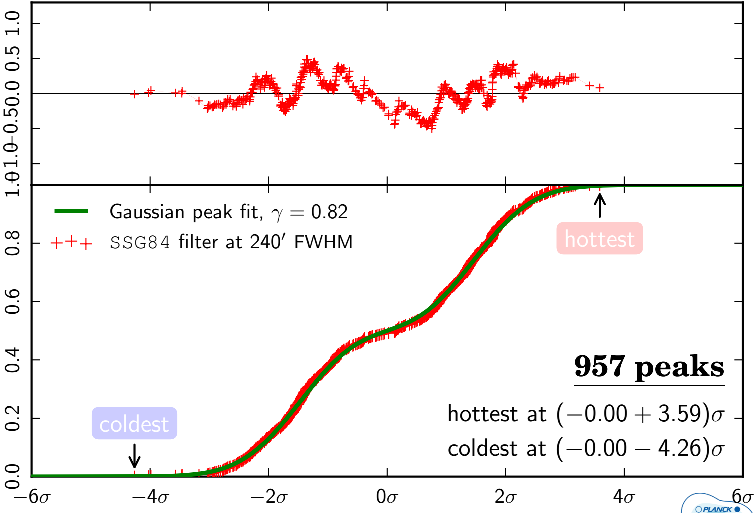


Bond and Efstathiou (1987)

$$\frac{n_{\mathrm{max}} + n_{\mathrm{min}}}{n_{\mathrm{pk}}}\left(\frac{x}{\sigma} > \nu\right) = \sqrt{\frac{3}{2\pi}\gamma^2}\,\nu \exp\left(-\frac{\nu^2}{2}\right) + \frac{1}{2}\,\mathrm{erfc}\left[\frac{\nu}{\sqrt{2 - \frac{4}{3}\gamma^2}}\right]$$



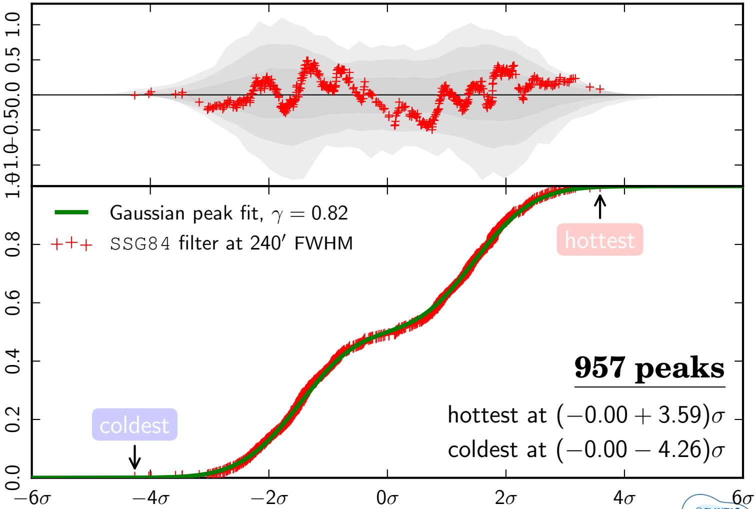
Kolmogorov deviation from FFP8 peak CDF



Testing CMB Peak Statistics

planck

Kolmogorov deviation from FFP8 peak CDF

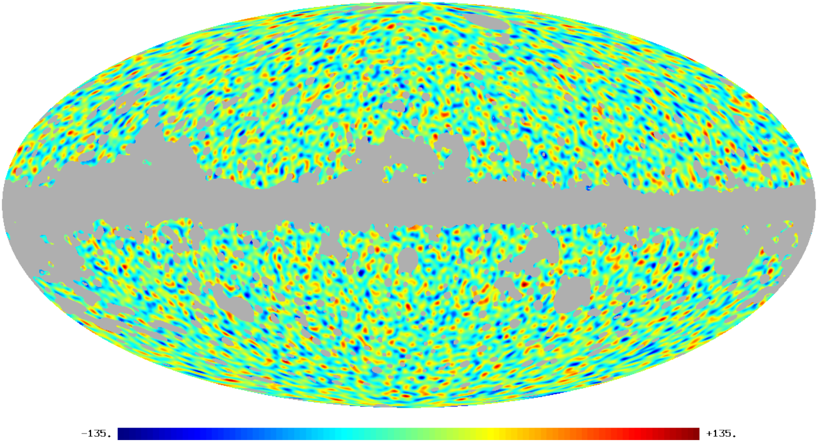


esa

PLANCK LFI

HFI PLANCK

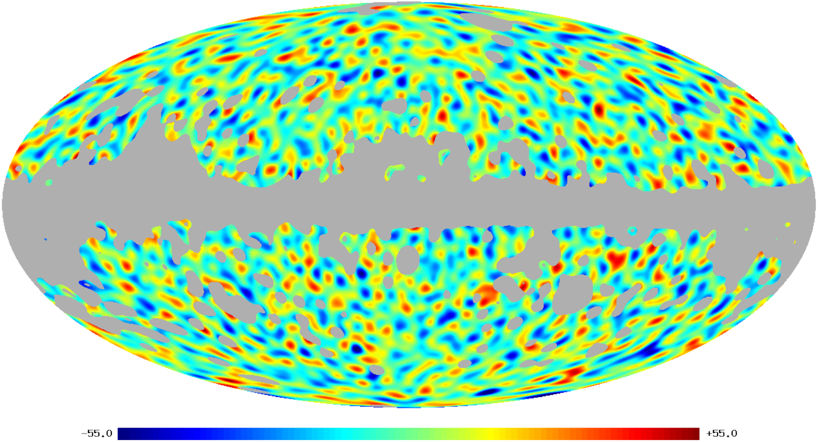
SSG84 Filter Sweep



Planck 2014 release [SSG84 filter at $120'_{\mathrm{FWHM}}$]

SSG84 Filter Sweep

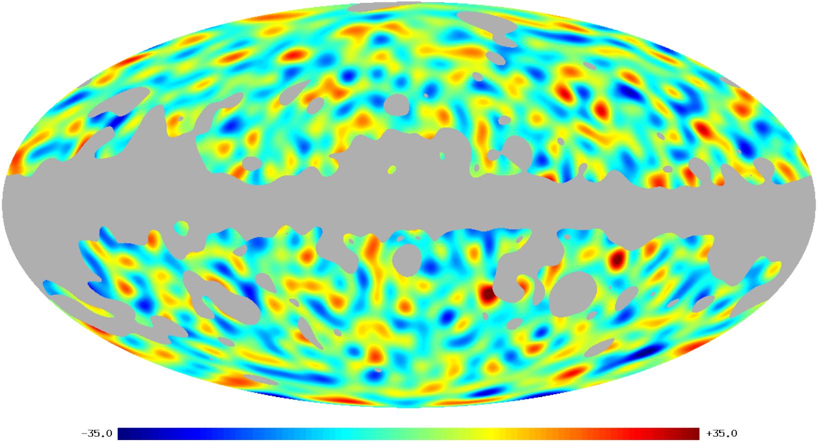
planck



Planck 2014 release [SSG84 filter at 240′$_{\mathrm{FWHM}}$]

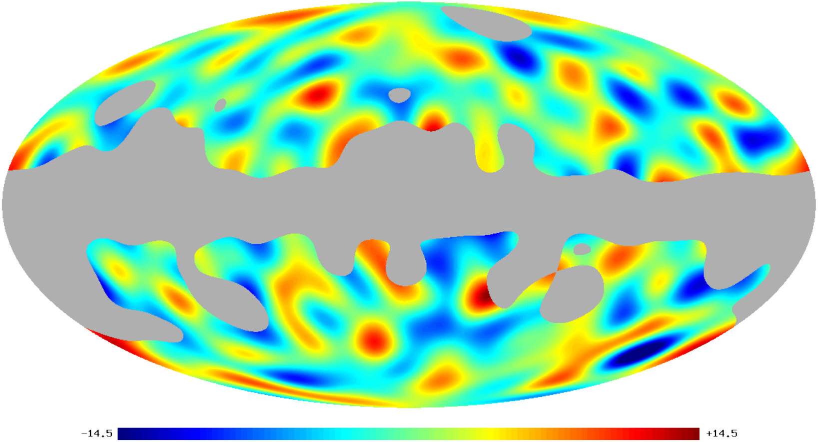
esa

SSG84 Filter Sweep



Planck 2014 release [SSG84 filter at 400′$_{\text{FWHM}}$]

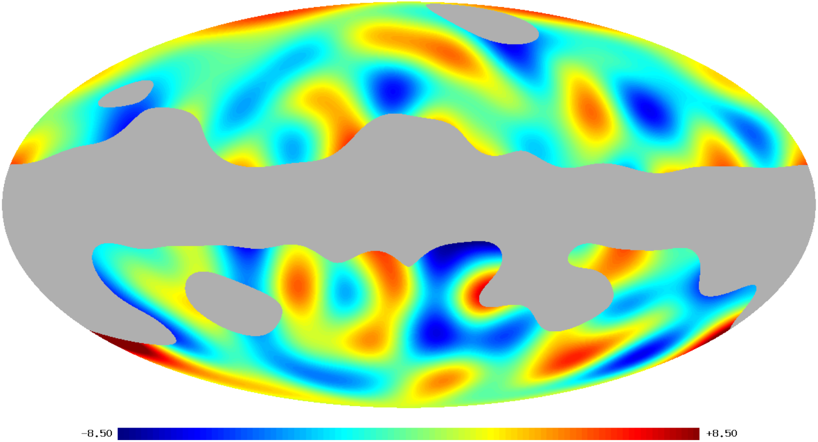
SSG84 Filter Sweep



Planck 2014 release [SSG84 filter at 800′ FWHM]

SSG84 Filter Sweep

planck



Planck 2014 release [SSG84 filter at 1200′ FWHM]

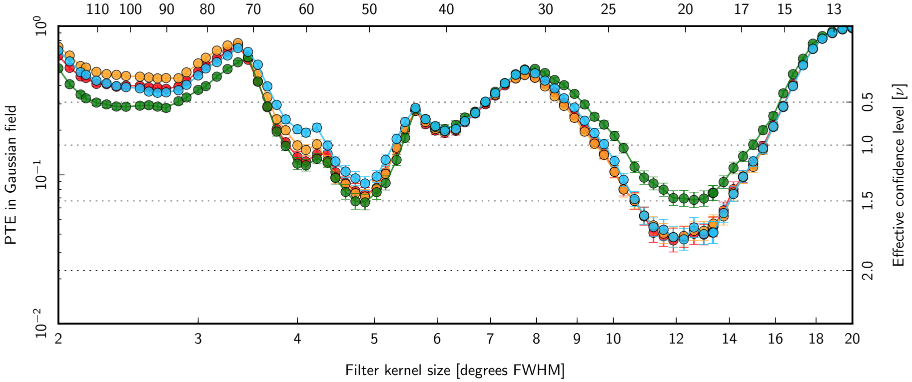
esa

PLANCK LFI

HFI PLANCK

Significance of Cold Spot

○ Whitened Savitzky-Golay ○ Mexican Hat Wavelet ○

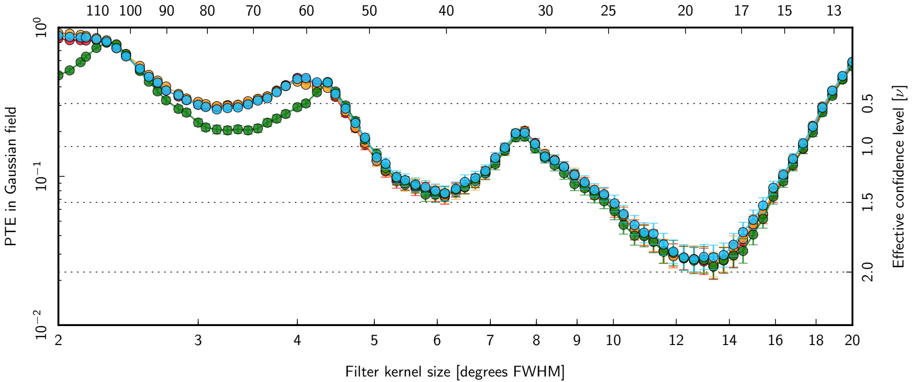


Significance evaluated by counting simulations which exceed observed value –

For full details see Isotropy and Statistics paper.

Significance of Cold Spot

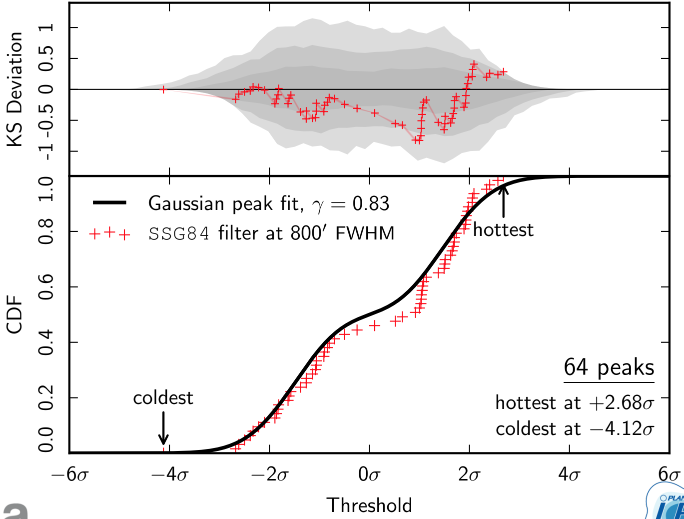
○ Whitened Savitzky-Golay ○ Mexican Hat Wavelet ○



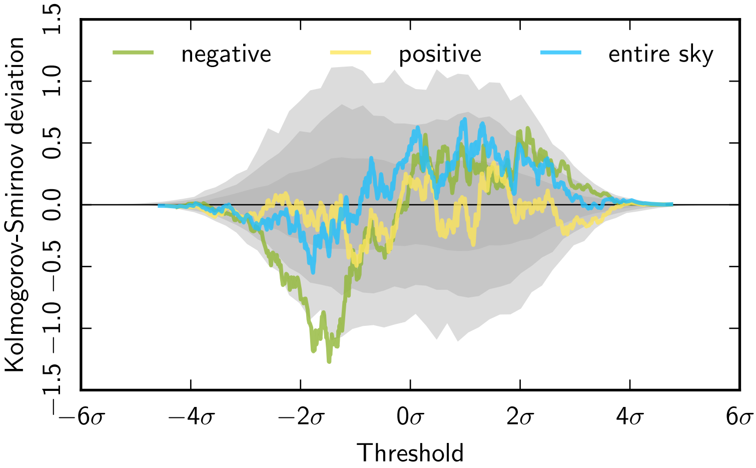
Significance evaluated by counting simulations which exceed observed value –

For full details see Isotropy and Statistics paper.

Cold Spot is Fairly Cold!



Asymmetry in Peak Distributions



peak distributions are also different in two hemispheres!

(pre-whitened GAUSS filter at 40′ full-width half-max)

How does a neighbourhood of a peak look like?

Let’s do some stacking!

The Stacking Family

planck

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)

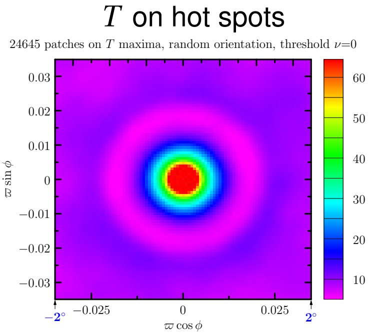
"where" and "how" give constrained parameter(s) q;

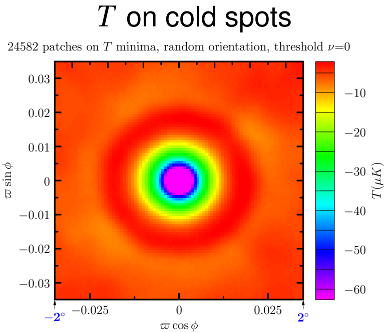
	WMAP & Planck 2013	Planck 2014
What	T, Q, U, Q_r, U_r	$T, Q, U, Q_r, U_r, E, B, Q_T, U_T, \zeta_{\rm dv}, \ldots$
Where	T peaks	$T, E, B, Q^2+U^2, Q_T^2+U_T^2, \zeta_{\rm dv}\ldots$ peaks
How	unoriented	oriented and unoriented

For Gaussian fields,

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

Planck 2014: Stacking Temperature





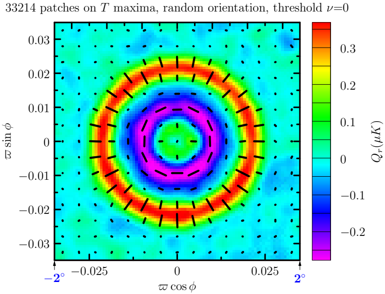
resolution: FWHM 15 arcmin

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

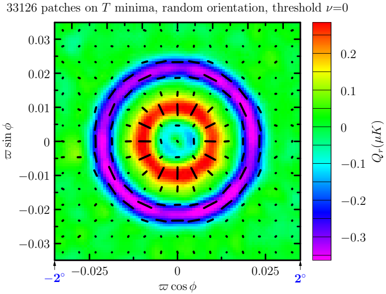
Full statistics in Isotropy and Statistics paper!

Planck 2014: Stacking Polarization

Q_r on hot spots



Q_r on cold spots

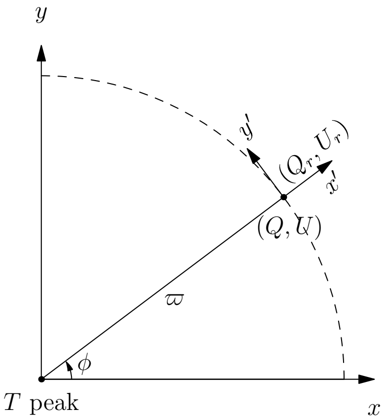


resolution: FWHM 15 arcmin

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

Full statistics in Isotropy and Statistics paper!

How to Rotate the Polarization Field



flat-sky polar coor. (ϖ, ϕ):

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

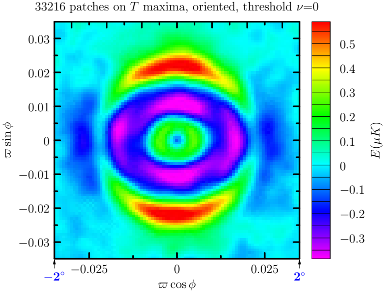
$$Q_r = -Q\cos 2\phi - U\sin 2\phi$$

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

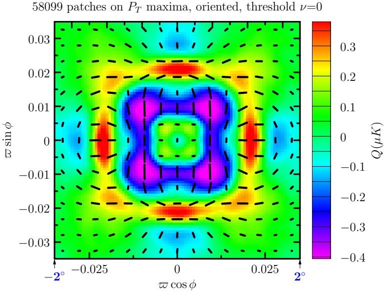
Oriented Stacking of Polarization

planck

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)

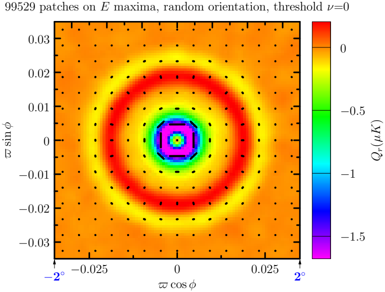
esa

PLANCK LFI

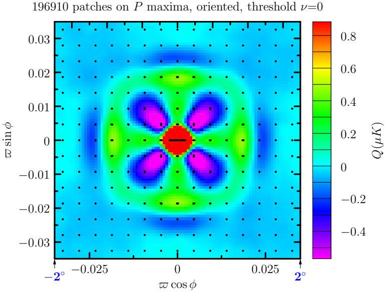
HFI PLANCK

Stacking on Polarization Peaks

Q_r on unoriented E peaks



Q on oriented Q^2+U^2 peaks



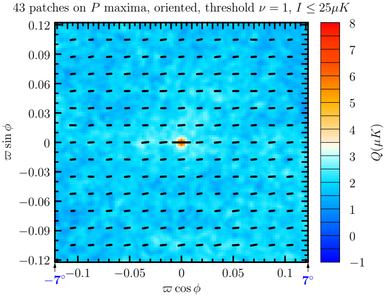
Planck 2014 (peak threshold $\nu = 0$; resolution FWHM 15 arcmin)

Stacking Polarized Dust

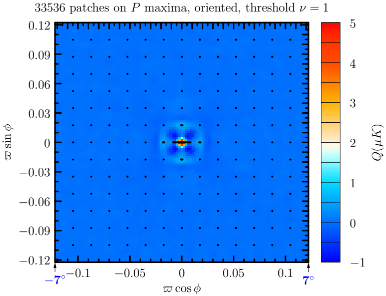
planck

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.

esa

PLANCK LFI

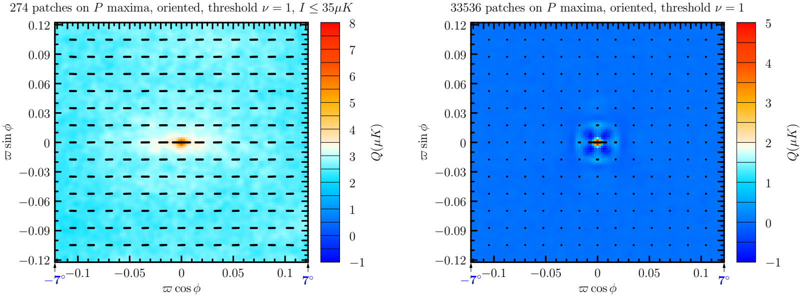
HFI PLANCK

Stacking Polarized Dust

planck

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.

esa

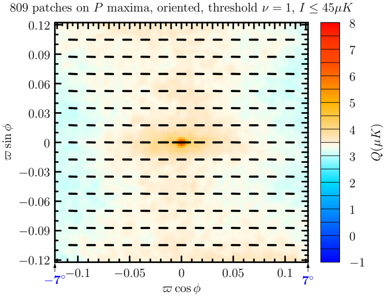
PLANCK LFI

HFI PLANCK

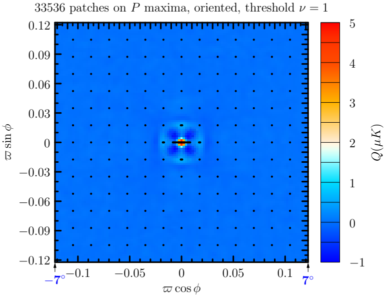
Stacking Polarized Dust

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).

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

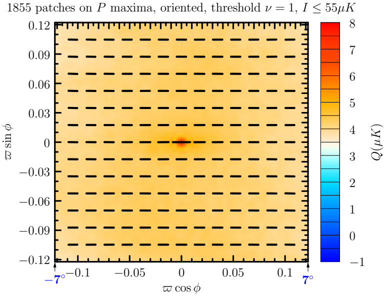
T map FWHM 2°; Q, U maps FWHM 15 arcmin.

esa

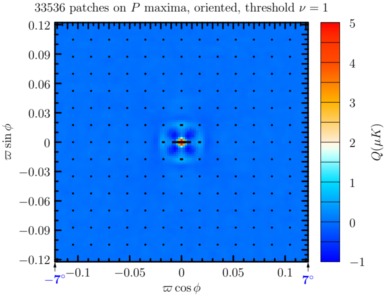
Stacking Polarized Dust

Planck 2014 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).

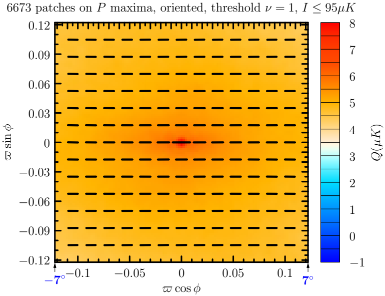
Patch size: $\varpi <= 7°$; threshold $\nu = 1$

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

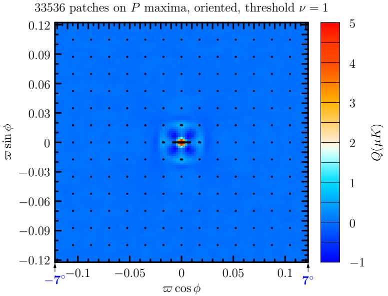
Stacking Polarized Dust

Planck 2014 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).

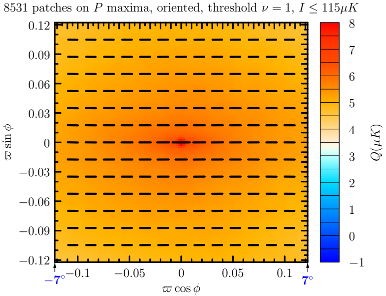
Patch size: $\varpi <= 7°$; threshold $\nu = 1$

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

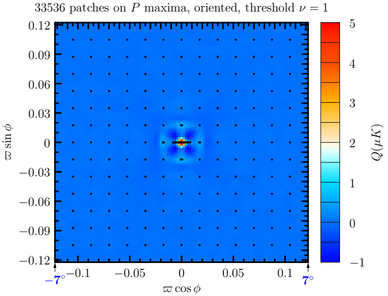
Stacking Polarized Dust

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

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

Conclusions

- A lot more and better processed and analyzed data.
- As in 2013, base ΛCDM continues to be a good fit to the Planck data, including polarization.
- Polarization has a degeneracy lifting capability often comparable to BAO.
- No convincing evidence for any simple extensions. Scalar fluctuations consistent with pure adiabatic modes with a featureless tilted spectrum.
- 2015 statistics: mostly Gaussian, but with similar anomalies than 2013. Many new methods explored, including of novel oriented stacking and peak statistics methods.
- Stacking and peak statistics give a complimentary approach for probing hemispherical asymmetry and component separation tests.

Conclusions

2015 papers and data are released!

+ more to come...

The End.

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.

Generalized Savitzky-Golay Filters

Generalized Savitzky-Golay filter kernel:

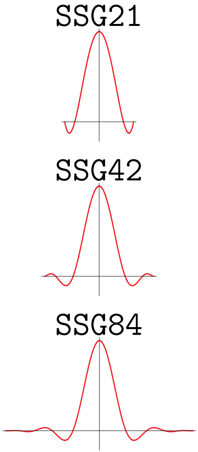
$$F_{n,k}(x) = \left(\sum_{i=0}^{n/2} a_i x^{2i} \right) (1 - x^2)^k$$

Orthogonal to polynomials up to order n:

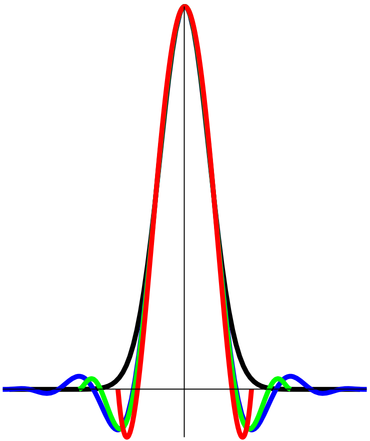
$$\int_0^1 x F_{n,k}(x)\, dx = 1, \qquad \int_0^1 x^{i+1} F_{n,k}(x)\, dx = 0$$

Savitzky and Golay (1964)

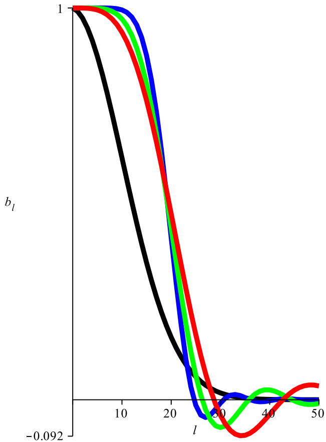
locate peaks in noisy spectra – topcite in Analytical Chemistry!



Filter Kernels in Harmonic Space



real space [compact support]



harmonic space [low-pass filter]

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 $\cos m\phi$, $m = 0, 2, 4$.