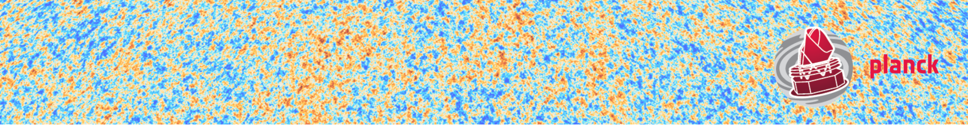

Testing Isotropy and Statistics of the CMB with Planck

Andrei Frolov on behalf of Planck Collaboration

11th International Workshop
Dark Side of the Universe 2015

Yukawa Institute for Theoretical Physics
Kyoto, Japan, 14 December 2015

It's Nice to be Here...

Outline

- 1 Instrument and Mission Overview
- 2 Foregrounds and Component Separation
- 3 CMB Maps and Spectra
- 4 Variance Asymmetry
- 5 Peak Statistics & Cold Spot
- 6 Stacking & Polarization
- 7 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**

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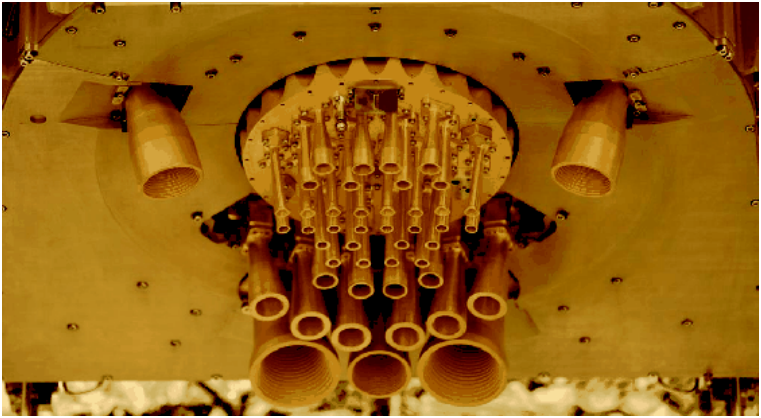
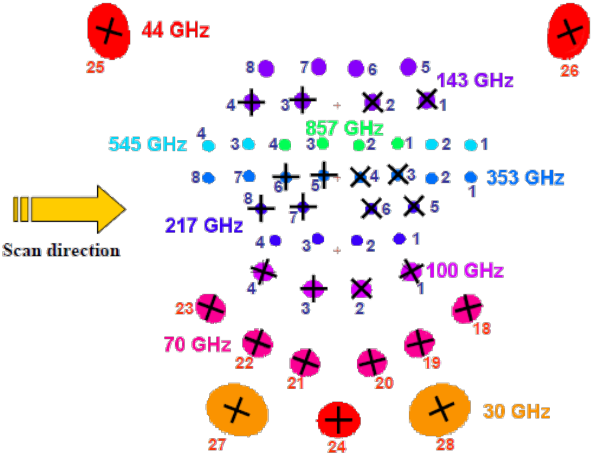
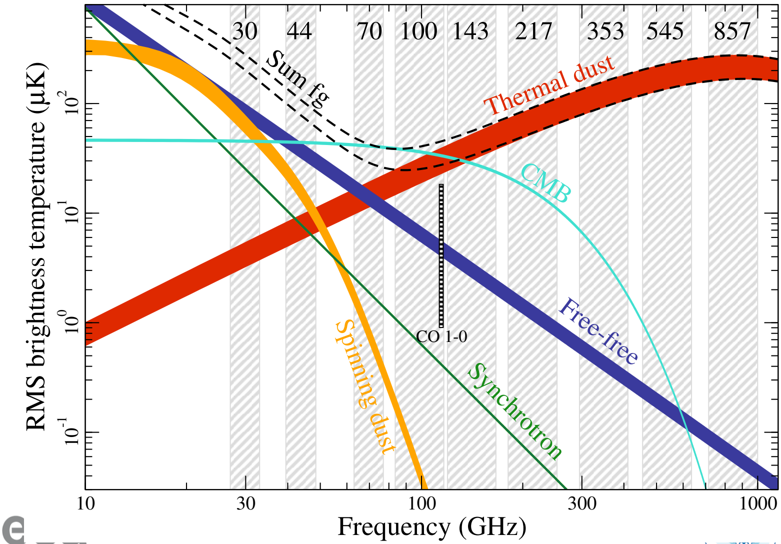
Planck Focal Plane



Planck Focal Plane Schematics

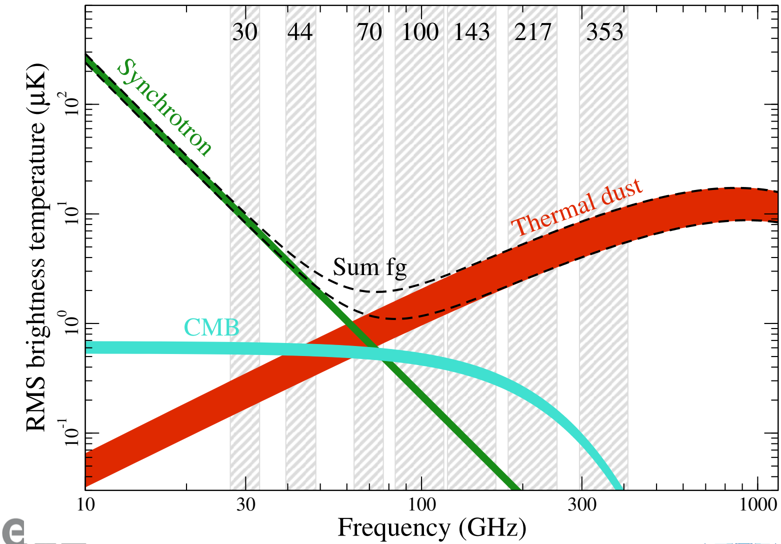


CMB vs. Astrophysical Foregrounds



CMB vs. Astrophysical Foregrounds

○ Intensity ○ Polarization ○ Atmospheric Transmission ○



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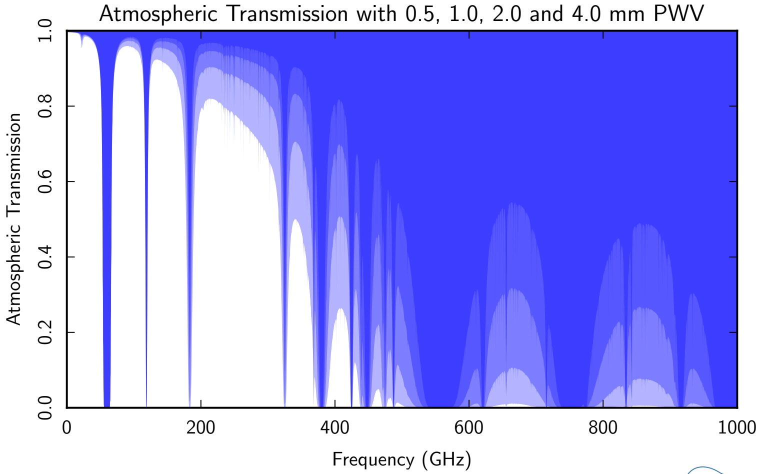
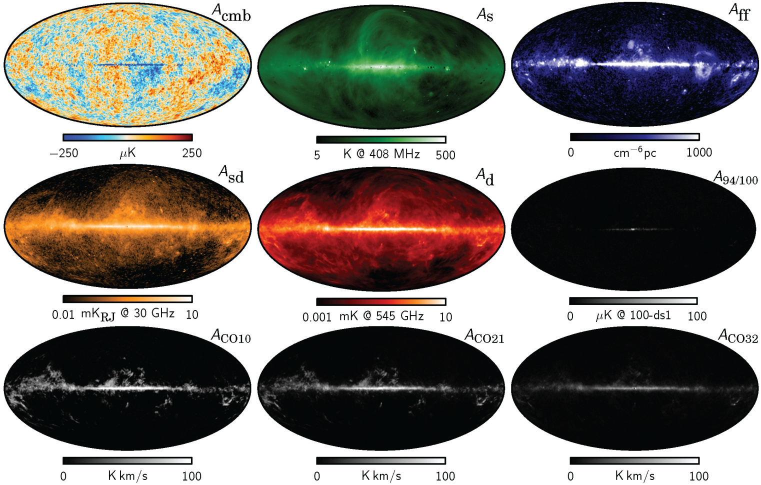


Component Separation Methods

Like in 2013, three CMB cleaning methods (SMICA, SEVEM, NILC) & 1 explicit Component Separation method (Commander).

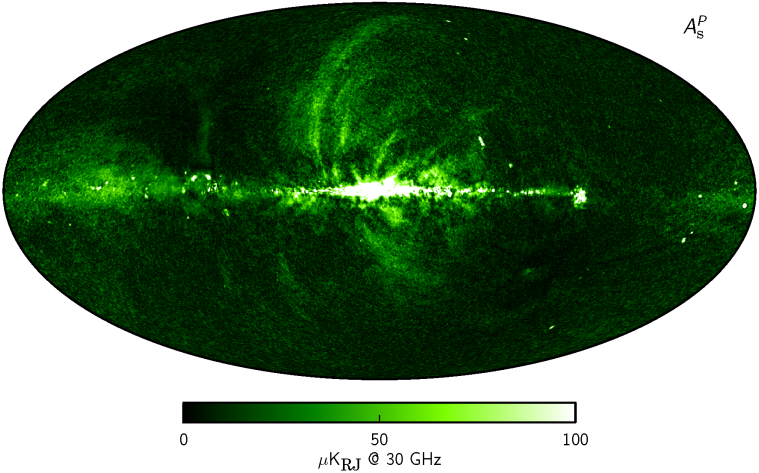
Temperature Component Maps



Polarization Component Maps

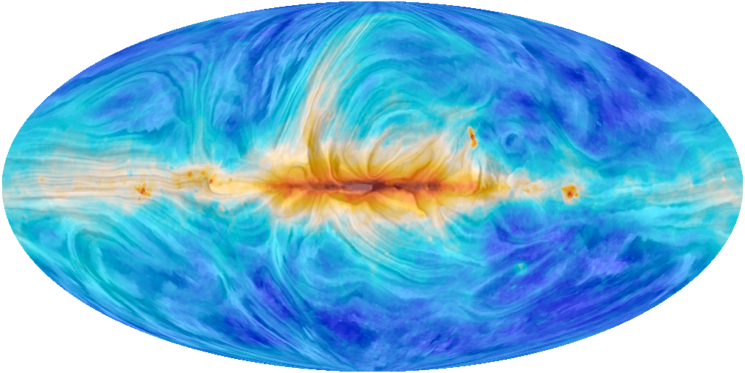
- Two main foregrounds, synchrotron emission and thermal dust
- Amplitude of CMB polarization is less than foregrounds
- Dust emission is highly polarized (polarization fraction is up to 20%)

Synchrotron Polarization Amplitude



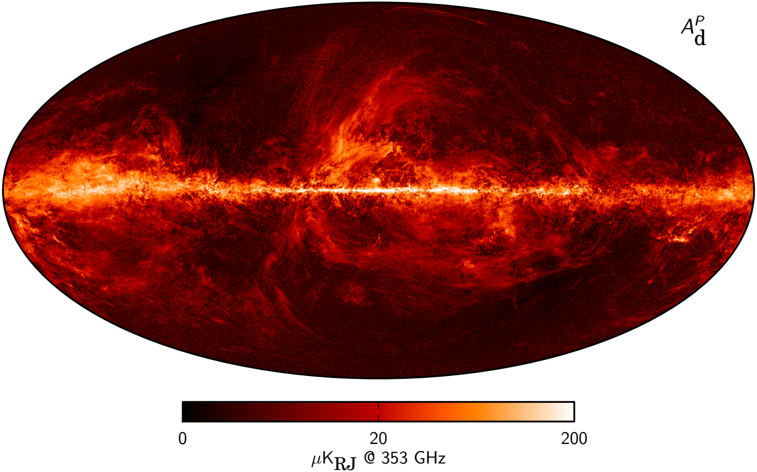
$P = \sqrt{Q^2 + U^2}$, at 30 GHz, smoothed to $40'$

Magnetic Field and Total Intensity



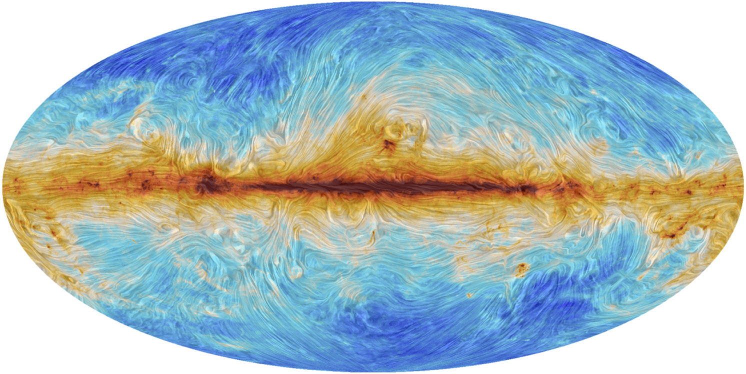
The colours represent intensity. The “drapery” pattern indicates the orientation of magnetic field projected on the plane of the sky, orthogonal to the observed polarization.

Dust Polarization Amplitude



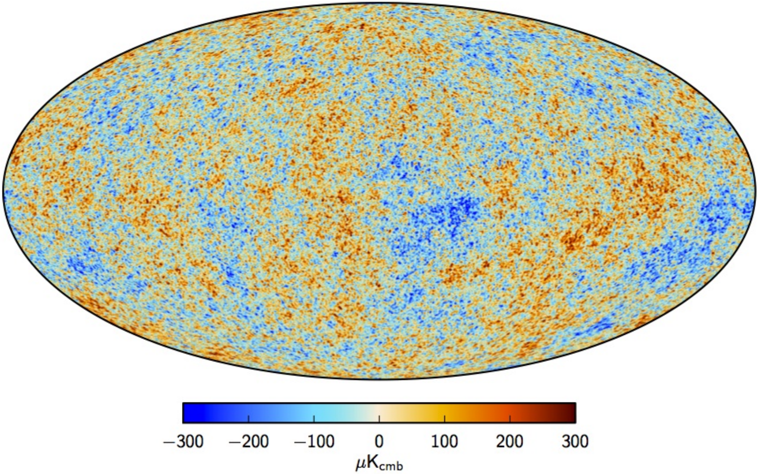
$P = \sqrt{Q^2 + U^2}$, at 353 GHz, smoothed to $10'$

Magnetic Field and Total Intensity

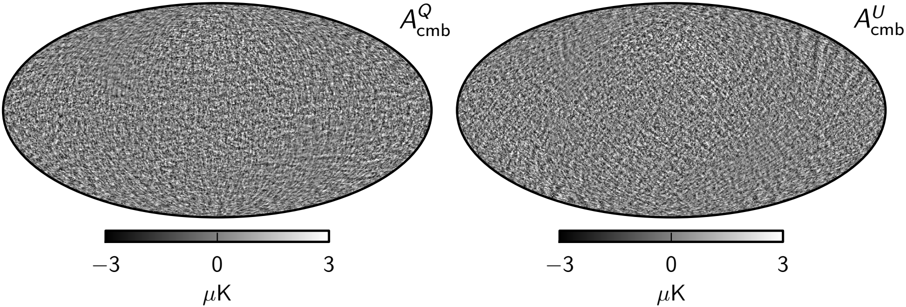


The colours represent intensity. The “drapery” pattern indicates the orientation of magnetic field projected on the plane of the sky, orthogonal to the observed polarization.

CMB Intensity Map

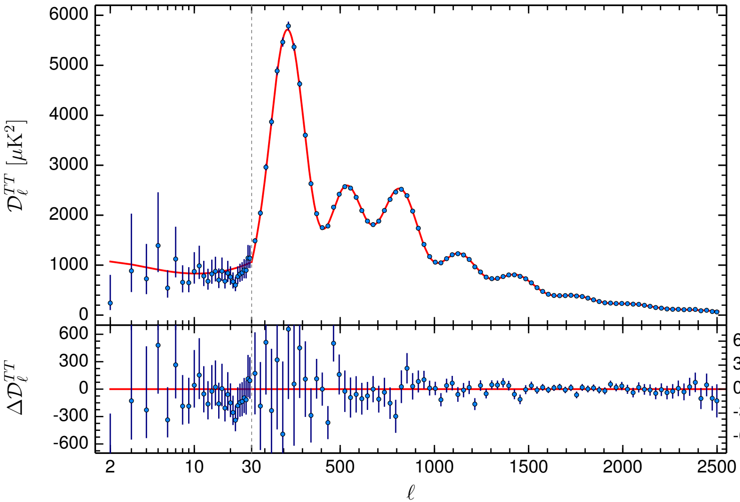


CMB Polarization Maps

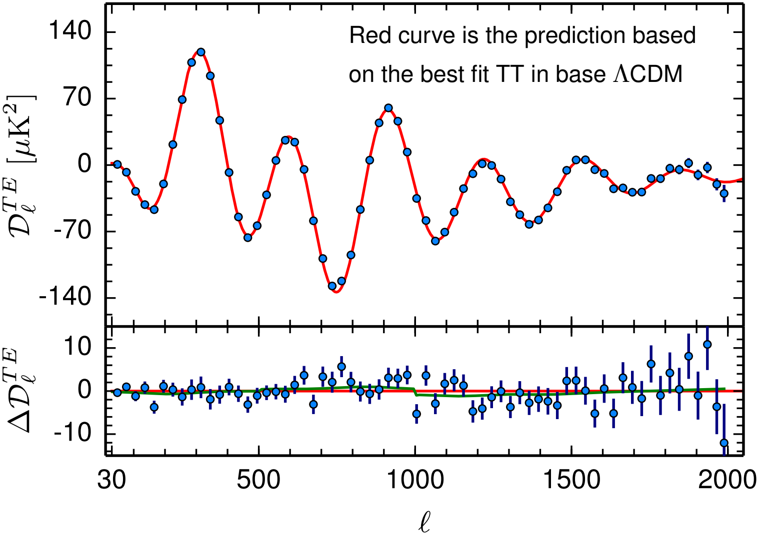


- Smoothed to 1 degree resolution
- High-pass filtered with l=20-40 cosine filter
- Galactic plane replaced with constrained Gaussian realization

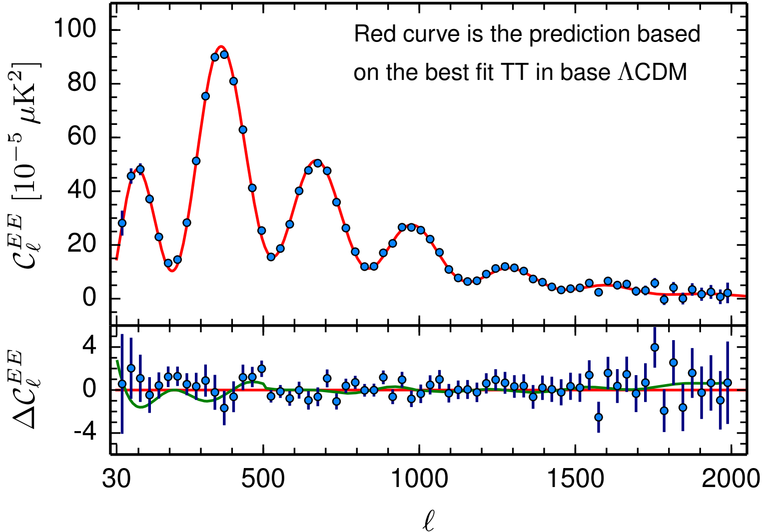
Planck 2015 TT Power Spectrum



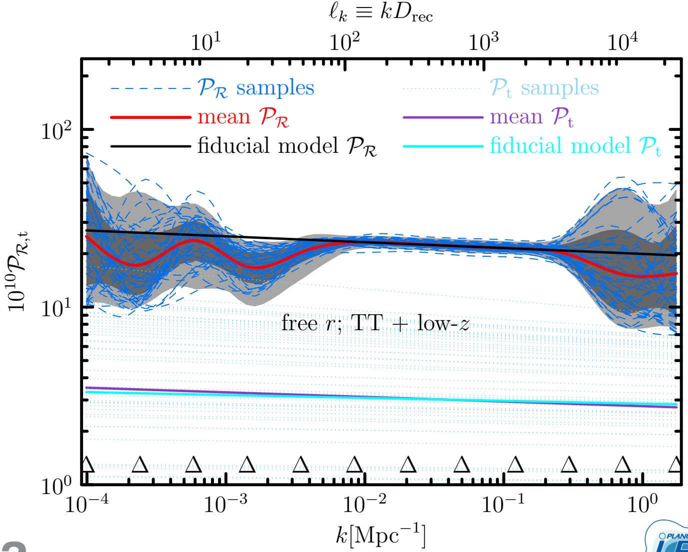
Planck 2015 TE Power Spectrum


Red curve is the prediction based on the best fit TT in base ΛCDM

Planck 2015 EE Power Spectrum



Primordial Spectrum Reconstruction



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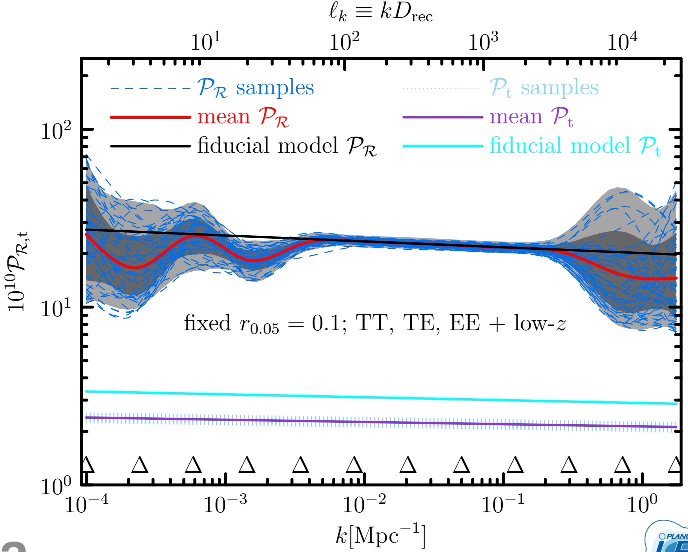
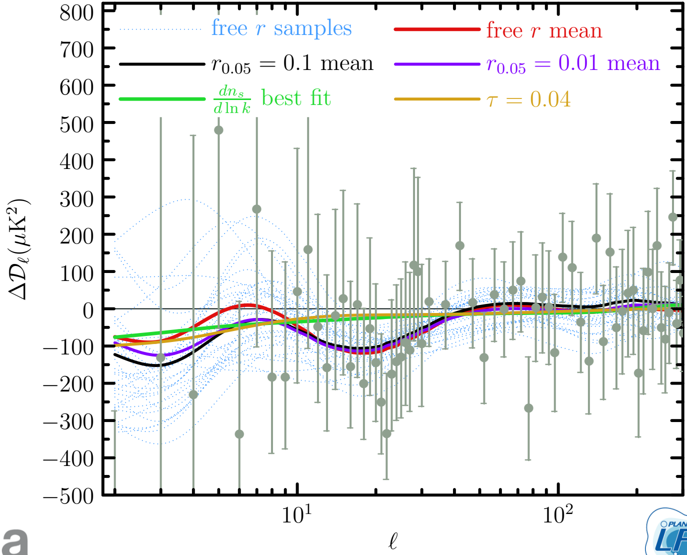
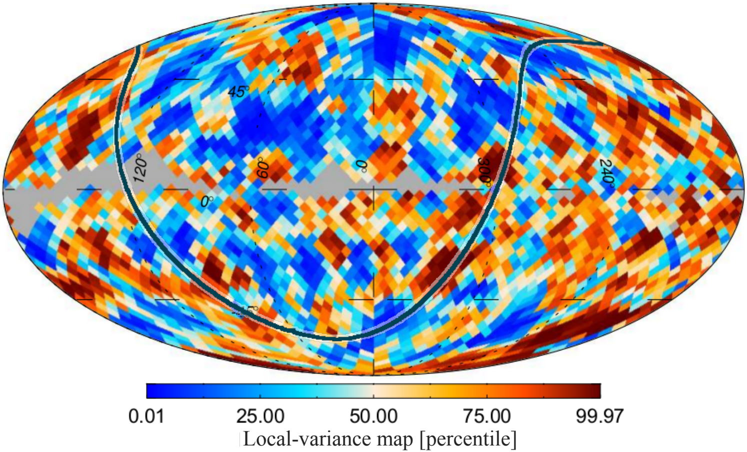


Running Spectral Index is Not a Good Fit!

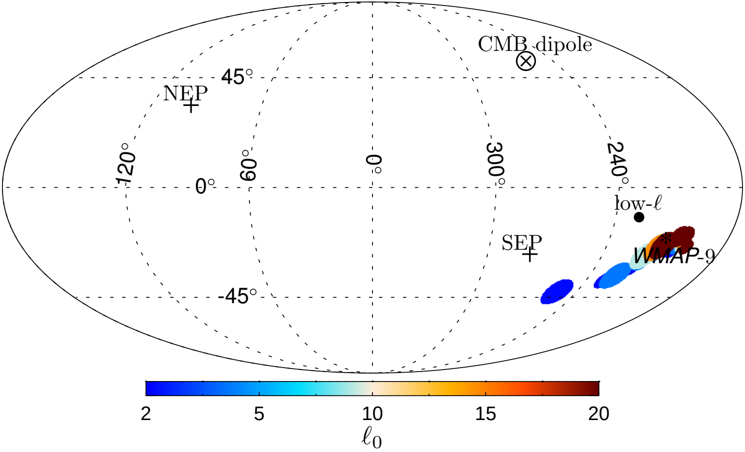


Local Variance Map of CMB



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

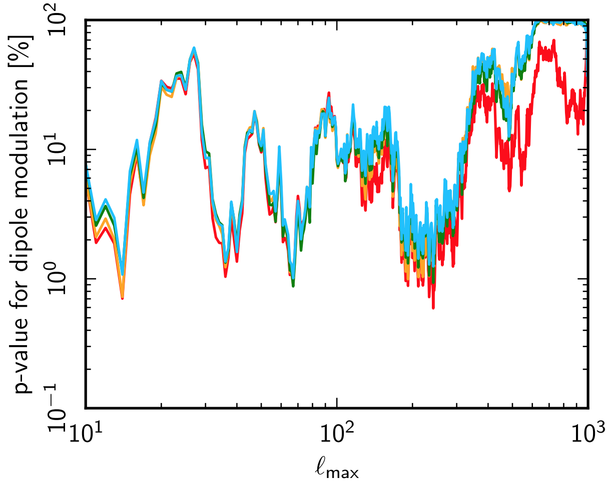
Local Variance Dipole Modulation



variance dipole amplitude 0.052 ± 0.016, direction $(l, b) = (210°, -26°)$

(no high-pass filter applied)

QML Estimator of Dipole Modulation



Go after $\delta C_{\ell\ell+1}$ in $2 < \ell < \ell_{\mathrm{max}}$ range, compare to sims

(remove $\ell < 100$ modes)

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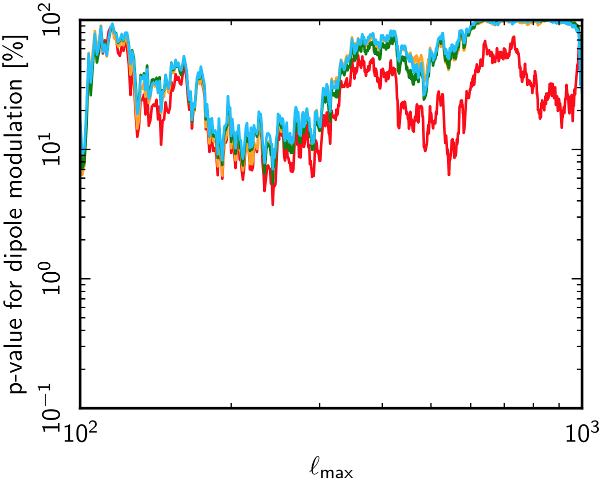

Go after $\delta C_{\ell\ell+1}$ in $2 < \ell < \ell_{\max}$ range, compare to sims
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Going after localized anomalies…

Let’s look at peaks!

Optimal (Wiener) Deconvolution

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:

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

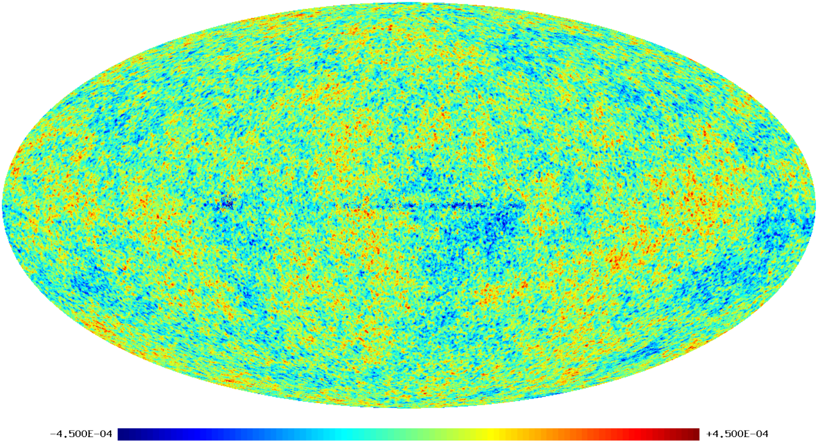
Take a shortcut - whiten data using isotropic CMB+noise model!

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

Whiten and filter, search for peaks!

CMB Data Analysis Pipeline

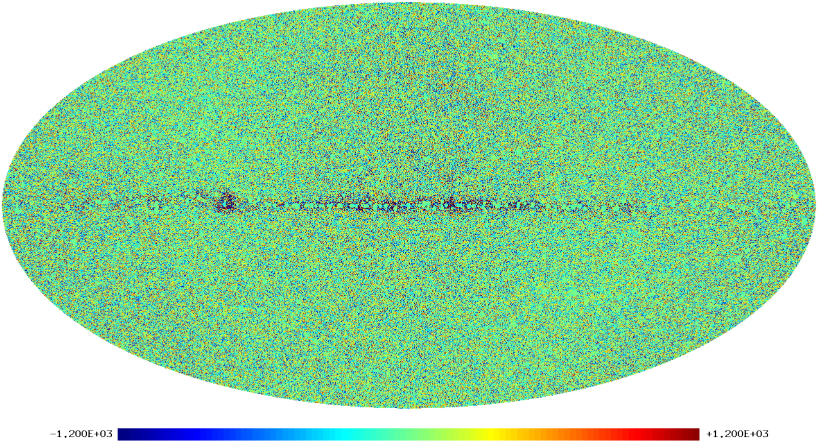
○ SMICA ○ Whiten ○ Mask ○ Filter ○ Find Peaks ○



Planck 2015 release [SSG84 filter at 240′$_{\mathrm{FWHM}}$]

CMB Data Analysis Pipeline

∘ SMICA ∘ Whiten ∘ Mask ∘ Filter ∘ Find Peaks ∘



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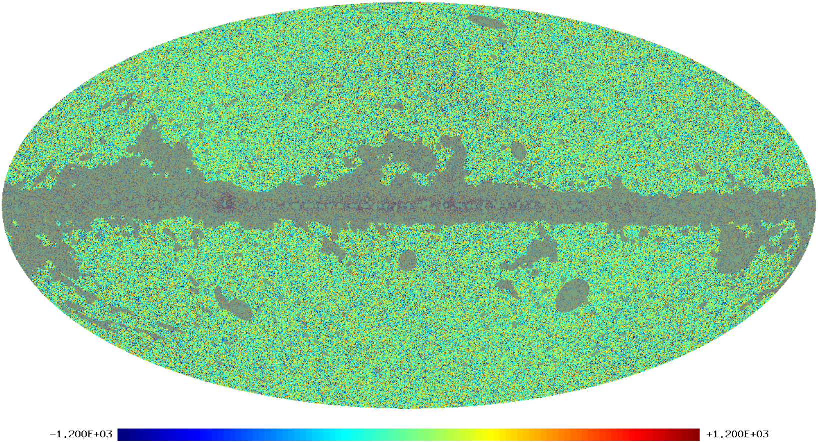

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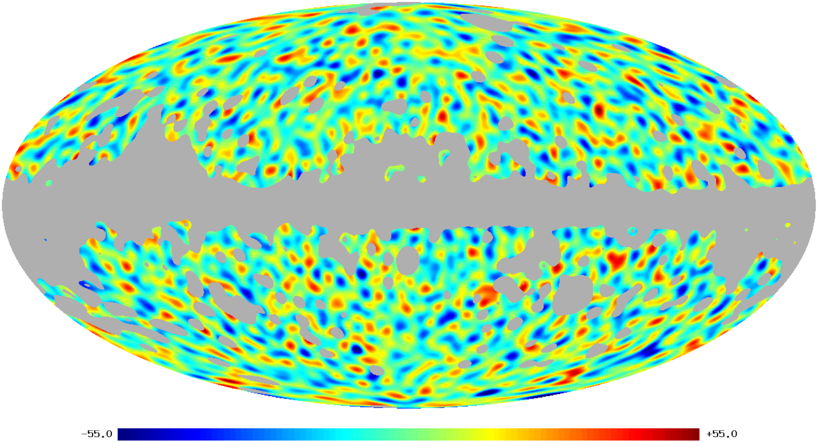

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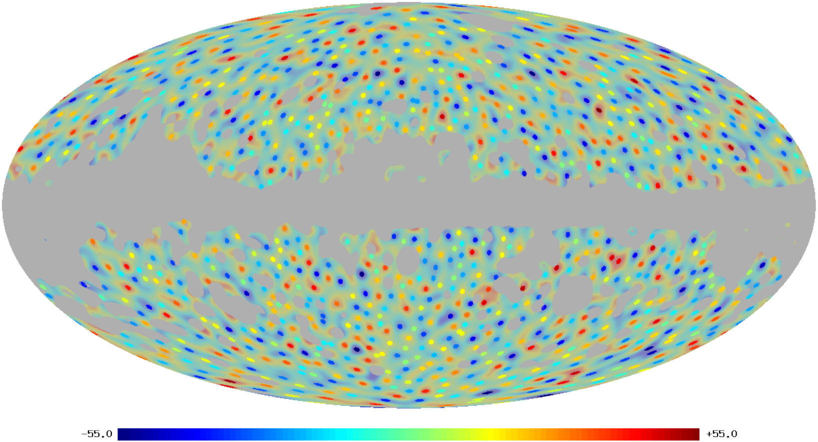
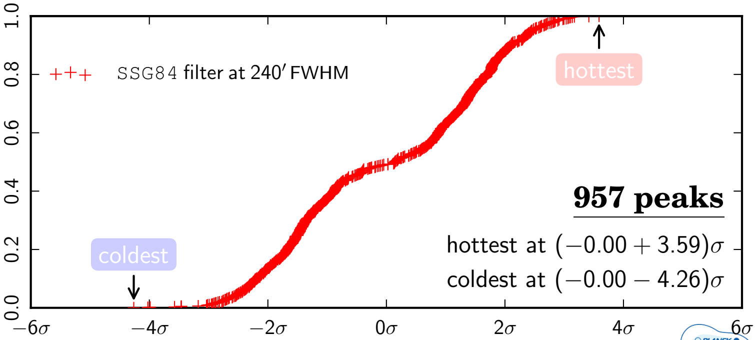


Planck 2015 release [SSG84 filter at 240′$_{\mathrm{FWHM}}$]

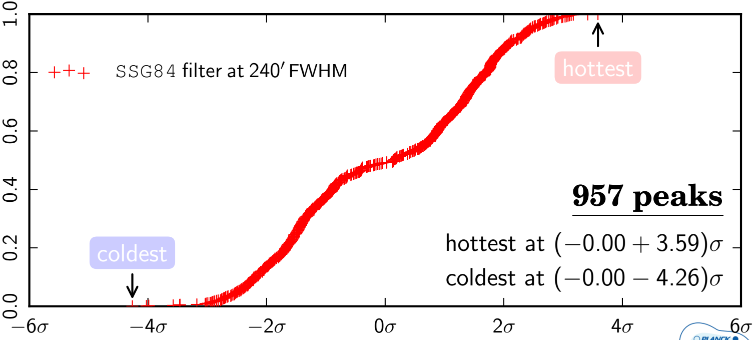
Testing CMB Peak Statistics



Testing CMB Peak Statistics

Bond and Efstathiou (1987)

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



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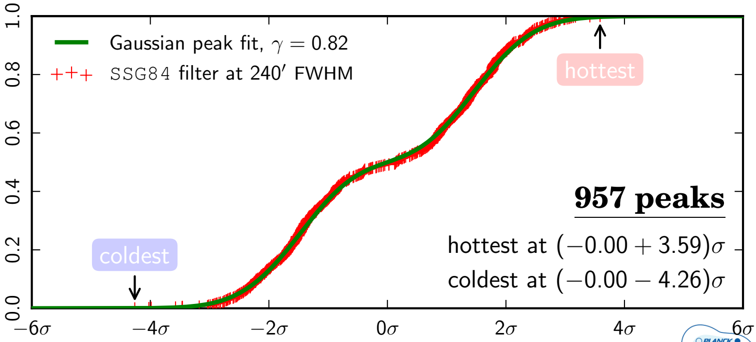
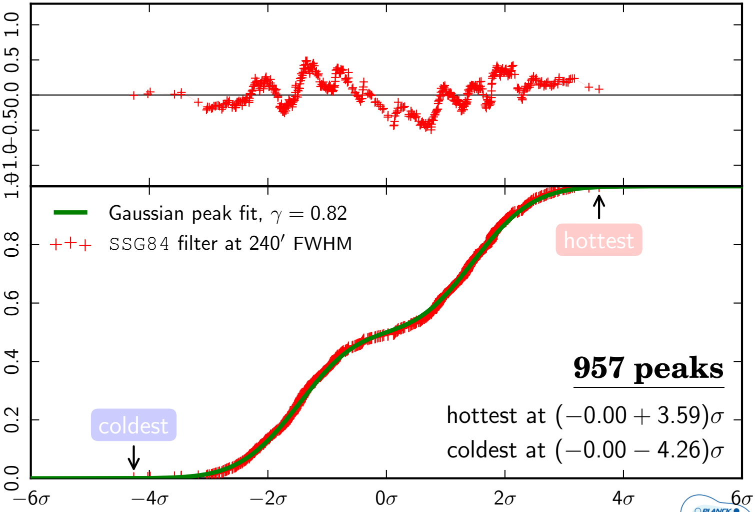
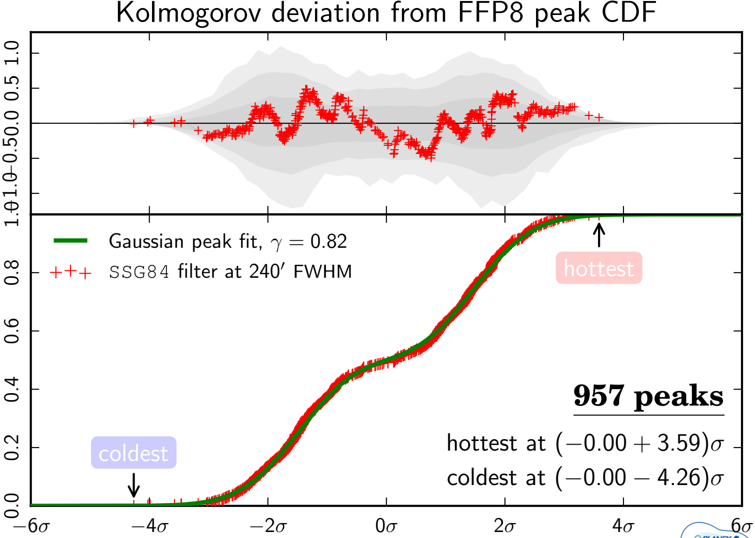


Testing CMB Peak Statistics

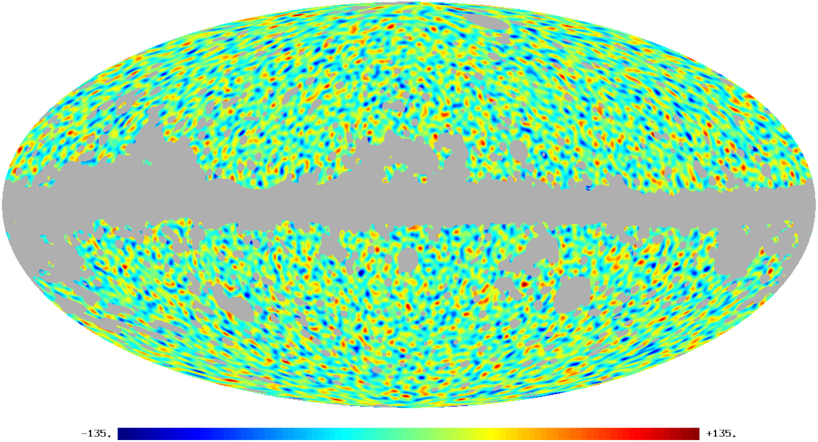
Kolmogorov deviation from FFP8 peak CDF



Testing CMB Peak Statistics

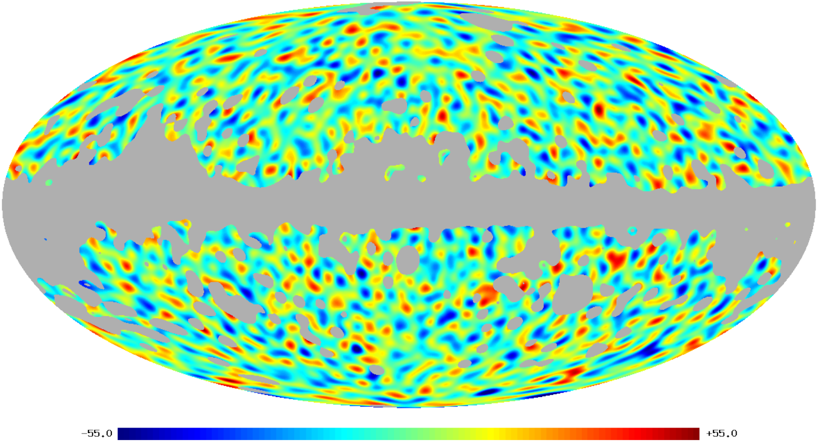

Kolmogorov deviation from FFP8 peak CDF

SSG84 Filter Sweep



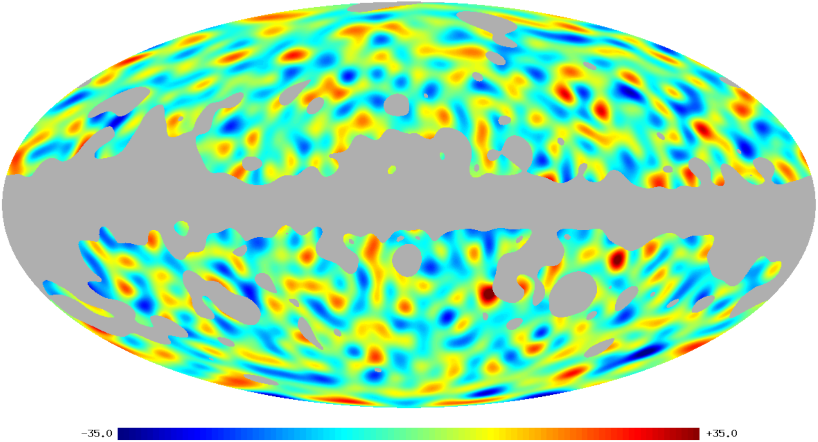
Planck 2015 release [SSG84 filter at 120′$_{\mathrm{FWHM}}$]

SSG84 Filter Sweep



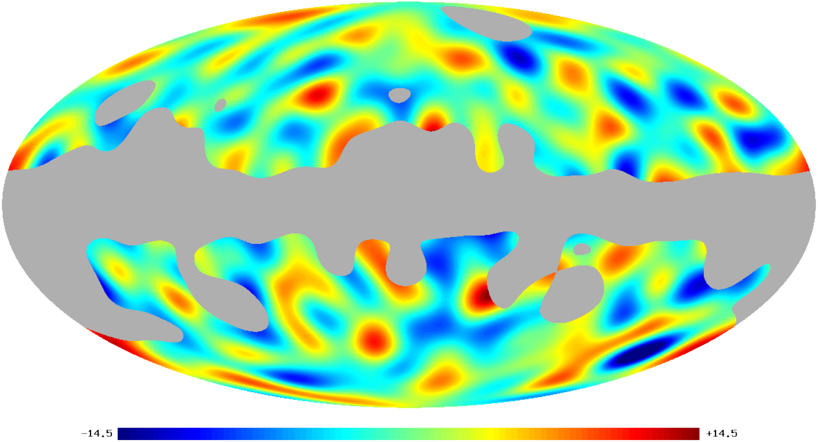
Planck 2015 release [SSG84 filter at 240′$_{\text{FWHM}}$]

SSG84 Filter Sweep



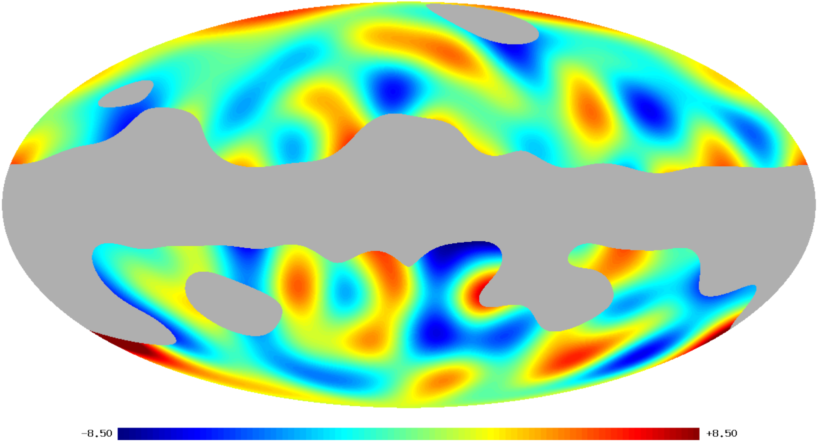
Planck 2015 release [SSG84 filter at 400′$_{\mathrm{FWHM}}$]

SSG84 Filter Sweep



Planck 2015 release [SSG84 filter at 800′$_{\mathrm{FWHM}}$]

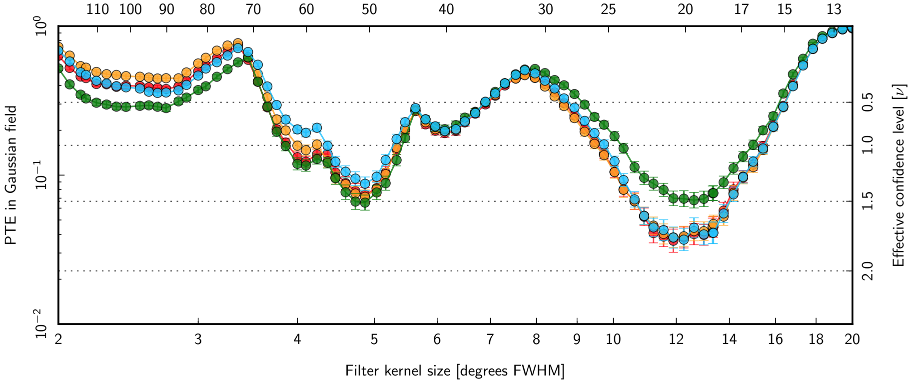
SSG84 Filter Sweep



Planck 2015 release [SSG84 filter at 1200′$_{\text{FWHM}}$]

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.

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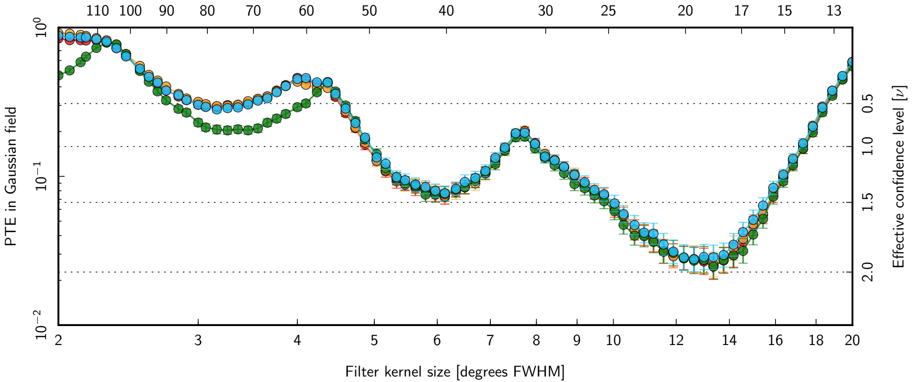
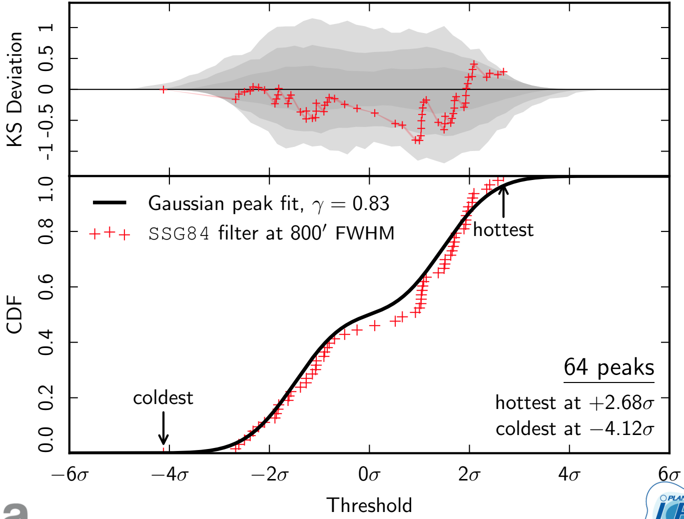


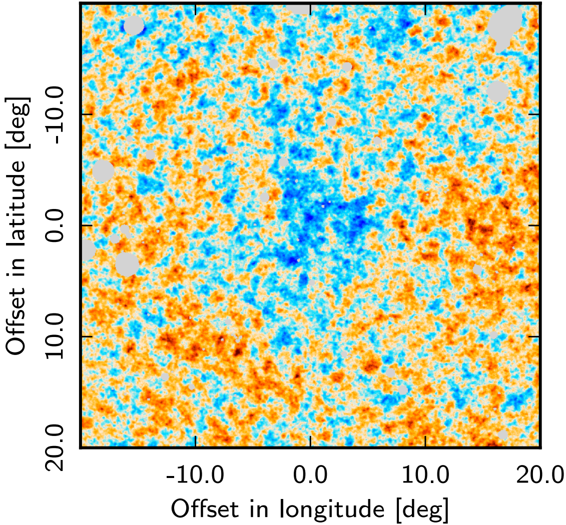
Significance evaluated by counting simulations which exceed observed value –

For full details see Isotropy and Statistics paper.

Cold Spot is Fairly Cold!



A Closer View at the Cold Spot



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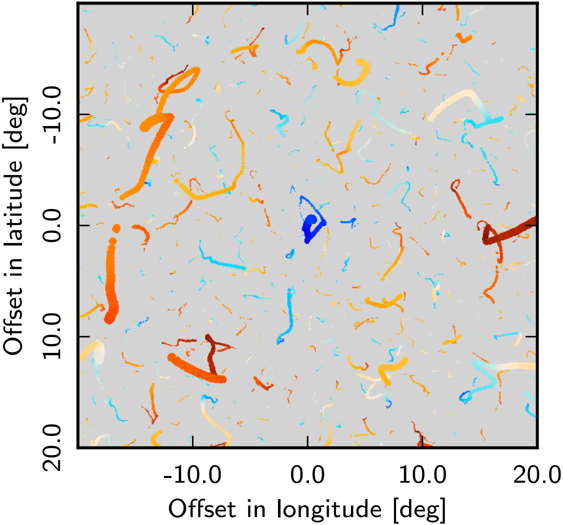
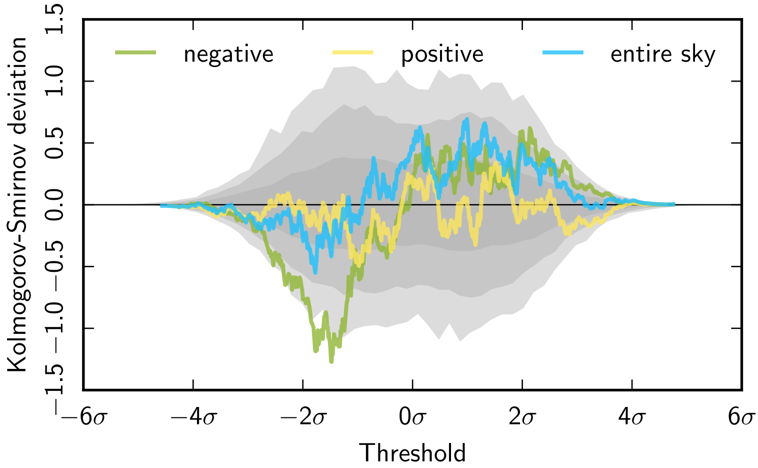


Asymmetry in Peak Distributions



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

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;

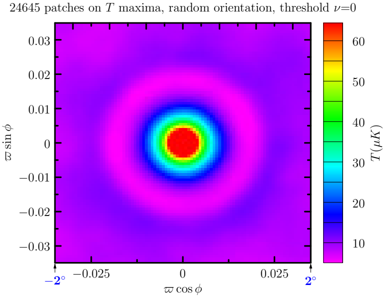
	WMAP & Planck 2013	Planck 2015
What	T, Q, U, Q_r, U_r	$T, Q, U, Q_r, U_r, E, B, Q_T, U_T, \zeta_{\rm dv}, \dots$
Where	T peaks	$T, E, B, Q^2+U^2, Q_T^2+U_T^2, \zeta_{\rm dv}\dots$ peaks
How	unoriented	oriented and unoriented

For Gaussian fields,

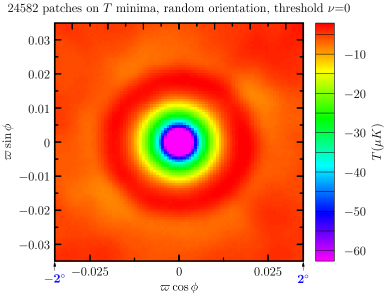
$$\langle u|q;\text{peak, orientation}\rangle = \langle u q^\dagger\rangle\langle q q^\dagger\rangle^{-1}\langle q|\text{peak, orientation}\rangle.$$

Planck 2015: Stacking Temperature

T on hot spots



T on cold spots

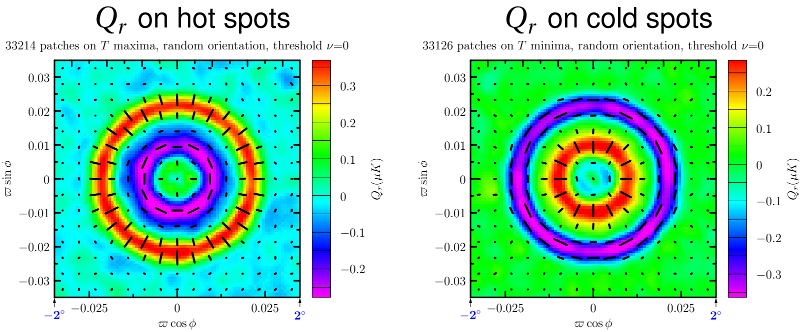


resolution: FWHM 15 arcmin

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

Full statistics in Isotropy and Statistics paper!

Planck 2015: Stacking Polarization

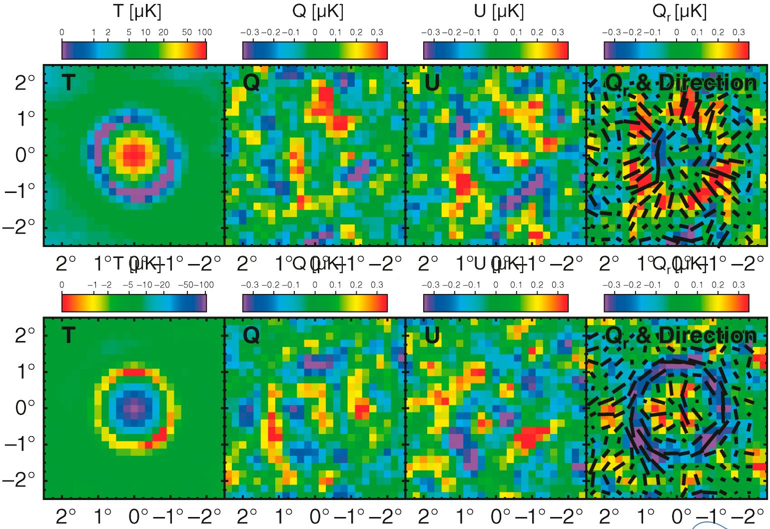


resolution: FWHM 15 arcmin

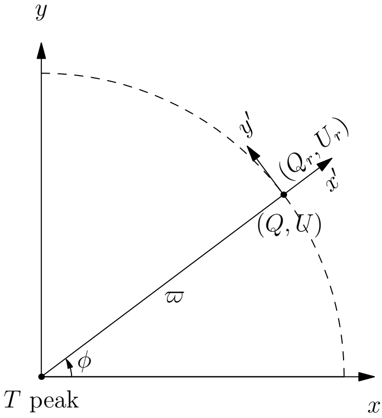
Peaks are selected above a threshold $|T_{\rm peak}| > \nu\sqrt{\langle T^2\rangle}$ ($\nu = 0$ here).

Full statistics in Isotropy and Statistics paper!

WMAP-7: Stacking T & Q_r



How to Rotate the Polarization Field



flat-sky polar coor. (ϖ, ϕ):

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

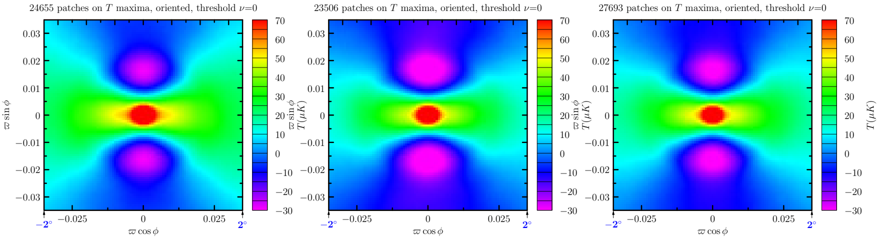
$$Q_r = -Q\cos 2\phi - U\sin 2\phi$$

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

Oriented Stacking: T on T peaks

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

Planck 2015 FFP8 noise-free sims

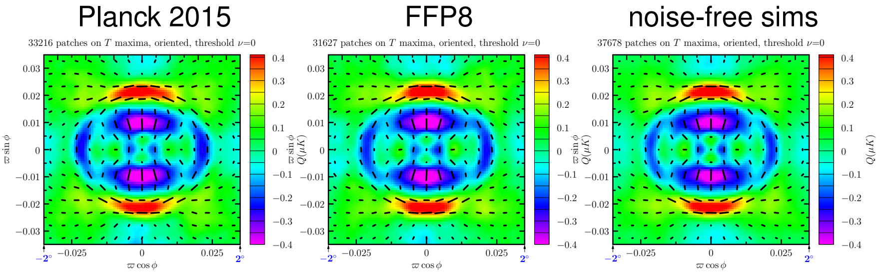


Angular dependence ($\cos m\phi$, m = 0, 2)

Noise has no noticable impact.

Oriented Stacking: Q on T peaks

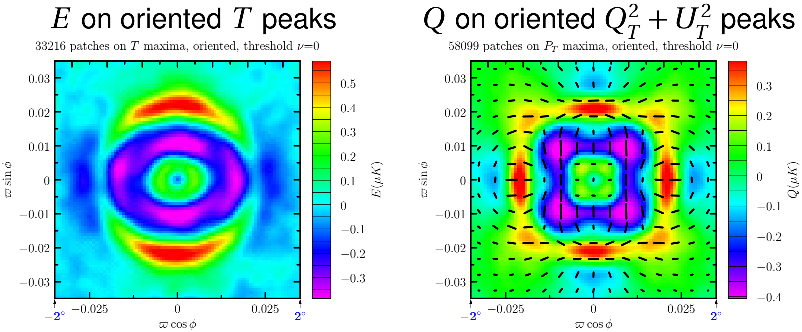
peak threshold $\nu = 0$, resolution FWHM 15 arcmin:



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

Again noise has no noticable impact.

Oriented Stacking of Polarization

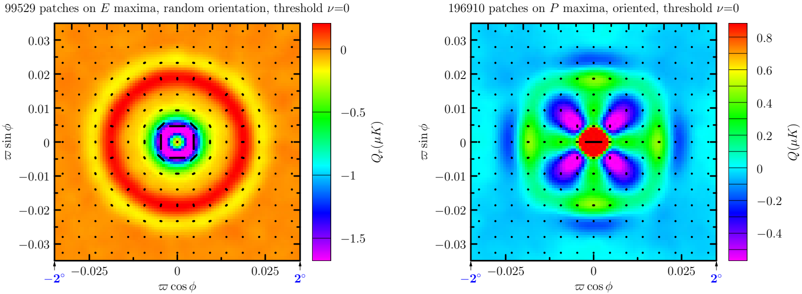


Planck 2015 (peak threshold $\nu = 0$; resolution FWHM 15 arcmin)

Stacking on Polarization Peaks

Q_r on unoriented E peaks

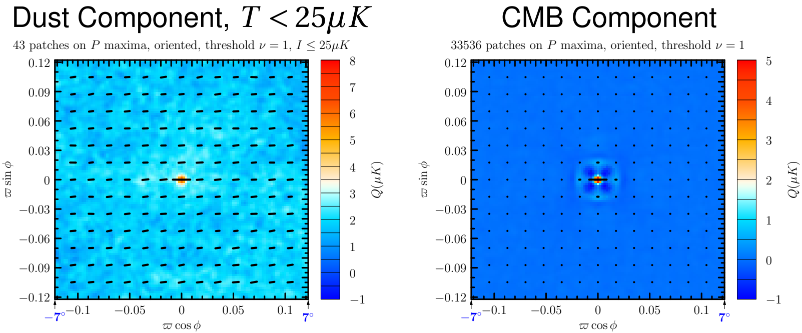
Q on oriented Q^2+U^2 peaks



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

Stacking Polarized Dust

Planck 2015 Component Separated Commander Dust Map



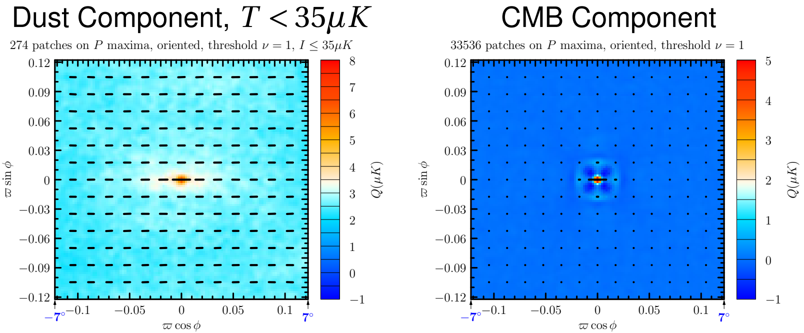
Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

Patch size: $\varpi <= 7^\circ$; 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, $T < 35\mu K$

CMB Component

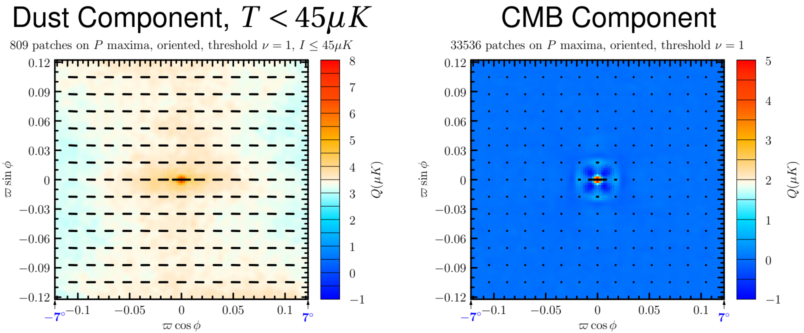
Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

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

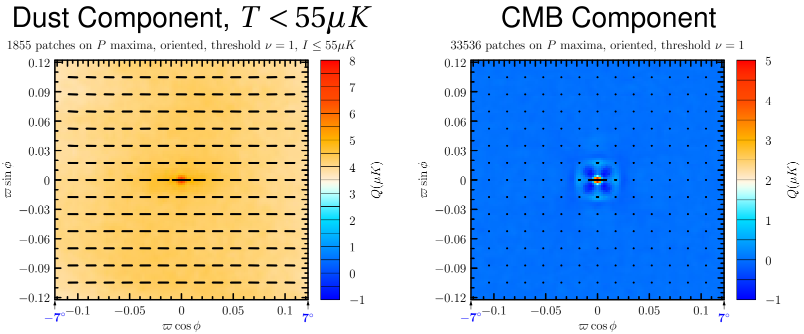
Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

Patch size: $\varpi <= 7°$; 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

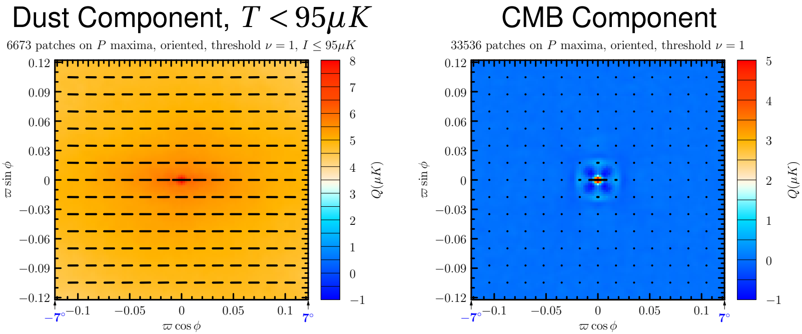
Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

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



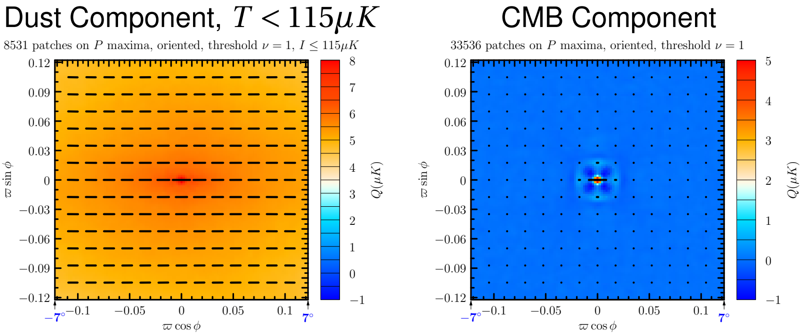
Q stacked on $Q^2 + U^2$ oriented peaks (oriented s.t. U vanishes in the centre).

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.

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 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.

16th Canadian Conference on General Relativity and Relativistic Astrophysics

6-8 July 2016, SFU Segal Building, Vancouver

http://www.sfu.ca/physics/cosmology/CCGRRA-16/

Appendix: Technical Details

Generalized Savitzky-Golay Filters

Generalized Savitzky-Golay filter kernel:

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

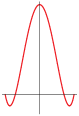
Orthogonal to polynomials up to order n:

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

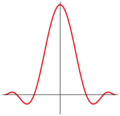
Savitzky and Golay (1964)

locate peaks in noisy spectra – topcite in Analytical Chemistry!

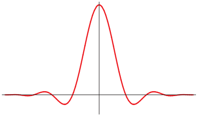
SSG21



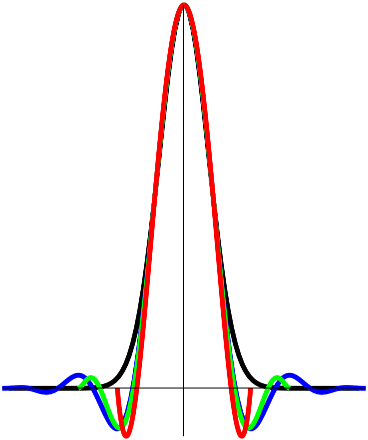
SSG42

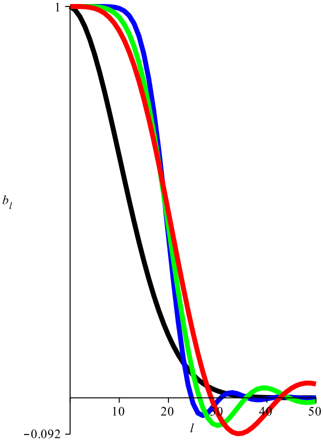


SSG84



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.**

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