Primordial and Doppler modulations with Planck

Planck 2013 results. XXIV.

Planck 2013 results. XXVII

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On behalf of the Planck collaboration

http://cosmologist.info/

Outline

- Primordial modulations and power asymmetry
- τ_{NL} trispectrum
- Kinematic Doppler dipoles

Note: statistical anisotropy $\equiv$ trispectrum

The closet non-Gaussianity of anisotropic Gaussian fluctuations

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In this paper we explore the connection between anisotropic Gaussian fluctuations and isotropic non-Gaussian fluctuations. We first set up a large angle framework for characterizing non-Gaussian fluctuations: large angle non-Gaussian spectra. We then consider anisotropic Gaussian fluctuations in two different situations. Firstly we look at anisotropic space-times and propose a prescription for superimposed Gaussian fluctuations; we argue against accidental symmetry in the fluctuations and that therefore the fluctuations should be anisotropic. We show how these fluctuations display previously known non-Gaussian effects both in the angular power spectrum and in non-Gaussian spectra. Secondly we consider the anisotropic Grischuk-Zel'dovich effect. We construct a flat space time with anisotropic, non-trivial topology and show how Gaussian fluctuations in such a space-time look non-Gaussian. In particular we show how non-Gaussian spectra may probe superhorizon anisotropy.

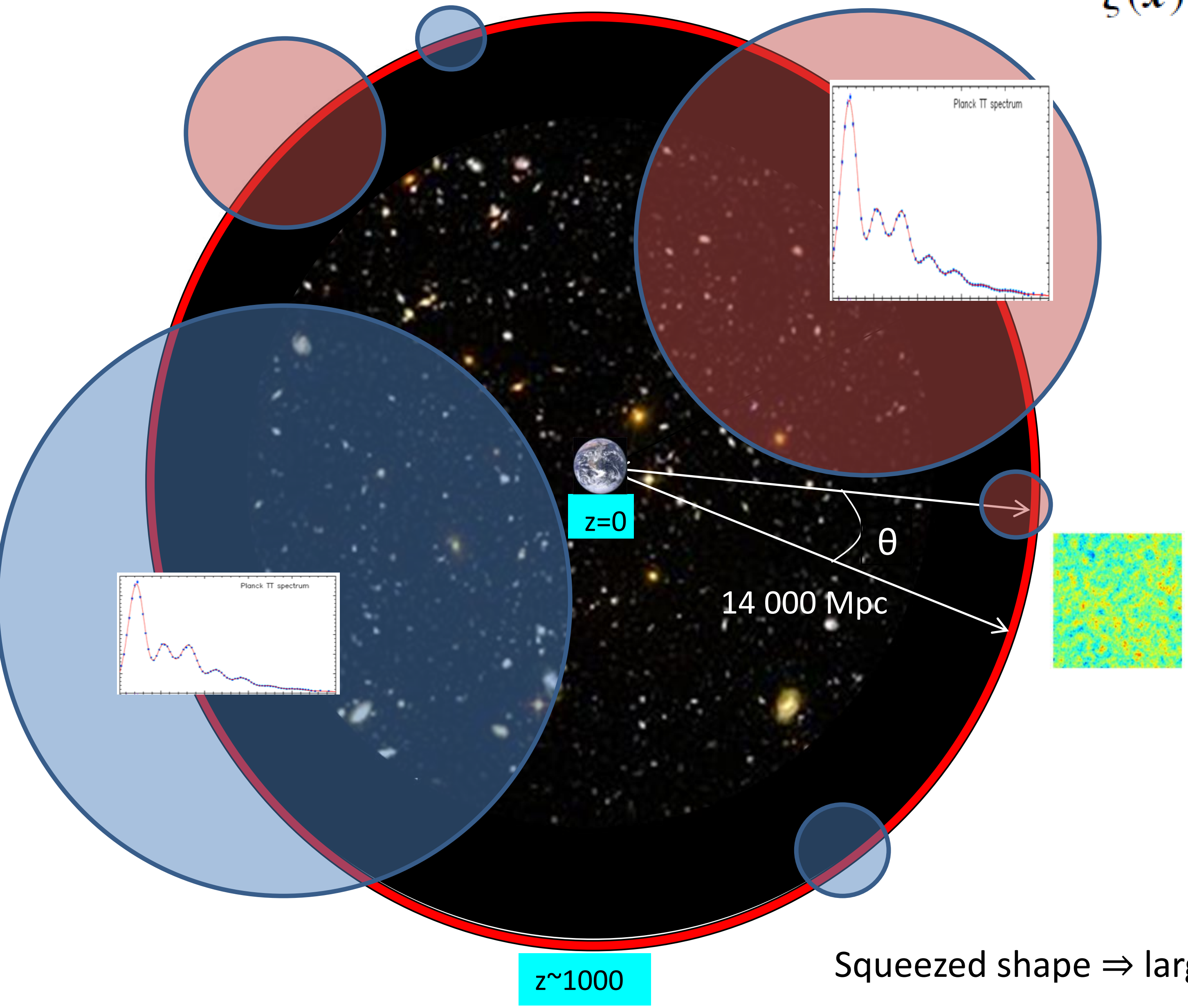
arXiv:astro-ph/9704052v1 5 Apr 1997

$T \sim P(T|\Omega)$ is statistically anisotropic in direction Ω

$\Rightarrow \; T \sim \int P(T,\Omega) d\Omega$ is statistically isotropic and non-Gaussian

Primordial curvature modulation:

$$\zeta(\boldsymbol{x}) = \zeta_0(\boldsymbol{x})[1 + \phi(\boldsymbol{x})]$$



Squeezed shape ⇒ large-scale modulations

$$T(\hat{\boldsymbol{n}}) \approx T_{\rm g}(\hat{\boldsymbol{n}})[1 + \phi(\hat{\boldsymbol{n}}, r_*)] \equiv T_{\rm g}(\hat{\boldsymbol{n}})[1 + f(\hat{\boldsymbol{n}})]$$

e.g. local NG $\zeta(\mathbf{x}) = \zeta_0(\mathbf{x}) + \frac{3}{5} f_{\rm NL}(\zeta_0(\mathbf{x})^2 - \langle\zeta_0^2\rangle)$

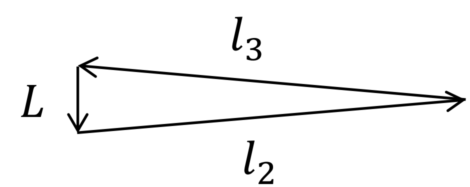
Long + short modes: $\zeta_0 = \zeta_s + \zeta_l$

$$\begin{aligned}\zeta &= \zeta_s(1 + \frac{3}{5} f_{\rm NL}[2\zeta_l + \zeta_s]) + \zeta_l(1 + \frac{3}{5} f_{\rm NL}\zeta_l) - \frac{3}{5} f_{\rm NL}\langle\zeta_0^2\rangle \\ &\approx \zeta_l + \zeta_s\left(1 + \frac{6 f_{\rm NL}}{5}\zeta_l\right).\end{aligned}$$

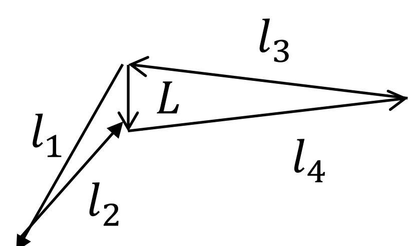
i.e. modulated $\zeta \sim \zeta_s\,(1+\phi)$ with $\phi = \frac{6 f_{NL}}{5}\zeta_l$

Large-scale modulations ⇒

CMB bispectrum $\sim \frac{6}{5} f_{NL} C_L^{T\zeta_*}(C_{l_2} + C_{l_3})$



CMB trispectrum $\sim \left(\frac{6}{5} f_{NL}\right)^2 C_L^{\zeta_*\zeta_*}(C_{l_1} + C_{l_2})\,(C_{l_3} + C_{l_4})$



Define τ_{NL} trispectrum by $\tau_{\rm NL}(L) \equiv \frac{C_L^f}{C_L^{\zeta_\star}}$ (almost all S/N at $L < 10$, half in dipole)

Note $f \sim O(10^{-3}) \Rightarrow \tau_{NL} \sim 500$

$$f = \frac{6f_{NL}}{5}\zeta_l \quad \Rightarrow \quad \tau_{\rm NL}(L) = (6f_{\rm NL}/5)^2$$

$$f = \frac{6f_{NL}}{5}\zeta_l + \chi \quad \Rightarrow \quad \tau_{\rm NL}(L) \geq (6f_{\rm NL}/5)^2$$

Combined estimator for nearly scale-invariant modulation

$$\Rightarrow \quad \hat{\tau}_{\rm NL} \approx N^{-1} \sum_{L=L_{\rm min}}^{L_{\rm max}} \frac{2L+1}{L^2(L+1)^2} \frac{\hat{C}_L^f}{C_L^{\zeta_\star}}$$

(optimal to percent level)

Just need to reconstruct $f(\hat{\mathbf{n}})$ to find its power spectrum

QML estimator for f:

$$\tilde{h}^f_{lm} = \int d\Omega Y^*_{lm} \left[\sum_{l_1 m_1}^{l_{\max}} \bar{\Theta}_{l_1 m_1} Y_{l_1 m_1} \right] \left[\sum_{l_2 m_2}^{l_{\max}} C_{l_2} \bar{\Theta}_{l_2 m_2} Y_{l_2 m_2} \right]$$

Optimally filtered temperature

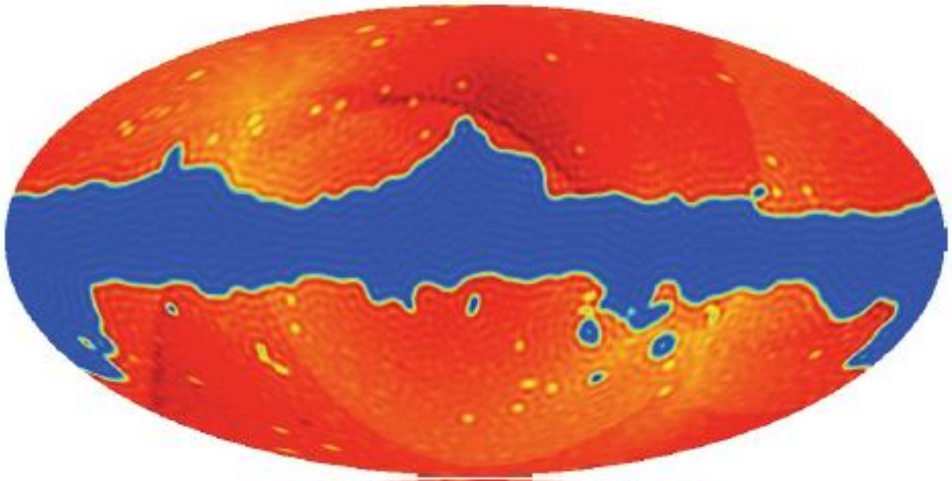
Pipeline almost identical to CMB lensing, but with different weight functions. General anisotropy estimator is

$$\hat{x}_{LM}[\bar{T}] = \frac{1}{2} N_L^{x\beta_v} \sum_{\ell_1=\ell_{\min}}^{\ell_{\max}} \sum_{\ell_2=\ell_{\min}}^{\ell_{\max}} \sum_{m_1,m_2} (-1)^M \begin{pmatrix} \ell_1 & \ell_2 & L \\ m_1 & m_2 & -M \end{pmatrix} W^{\hat{x}}_{\ell_1 \ell_2 L} \times \left(\bar{T}_{\ell_1 m_1} \bar{T}_{\ell_2 m_2} - \langle \bar{T}_{\ell_1 m_1} \bar{T}_{\ell_2 m_2} \rangle \right)$$

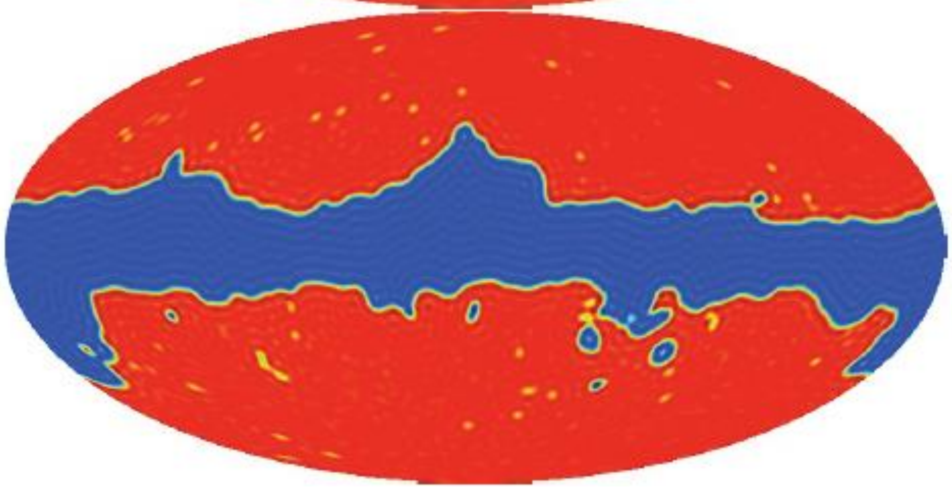
Mean field
(estimate from sims)

Hanson & Lewis 2009

Modulation mean field: mainly noise + mask



143x143



143x217

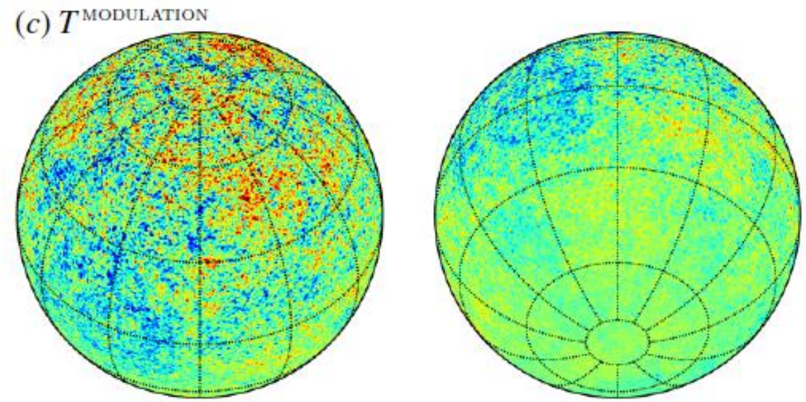
Avoids uncertainty in noise modelling (mask is well known)

Kinematic dipole signal

Modulation

$$\Delta\Theta(\hat{n}) \;\rightarrow\; \left[1 + \hat{n}\cdot\boldsymbol{v} + T\frac{\mathrm{d}^2 I_\nu/\mathrm{d}T^2}{\mathrm{d}I_\nu/\mathrm{d}T}\hat{n}\cdot\boldsymbol{v}\right]\Delta\Theta(\hat{n})$$
$$= \;(1 + [x\coth(x/2) - 1]\,\hat{n}\cdot\boldsymbol{v})\,\Delta\Theta(\hat{n}),$$

$$x \equiv h\nu/k_b T$$

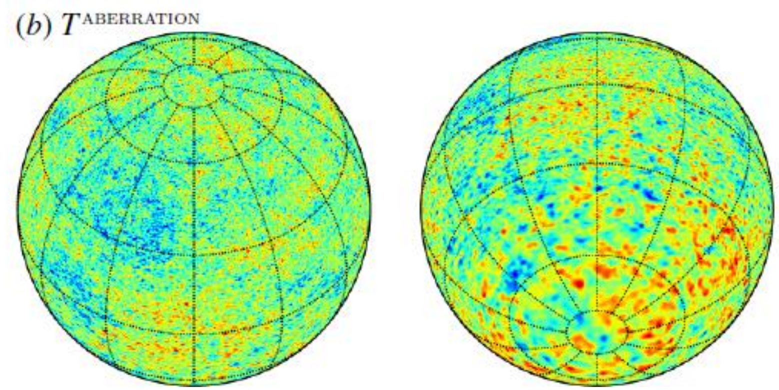


Illustrated for $\frac{v}{c} = 0.85$

Aberration

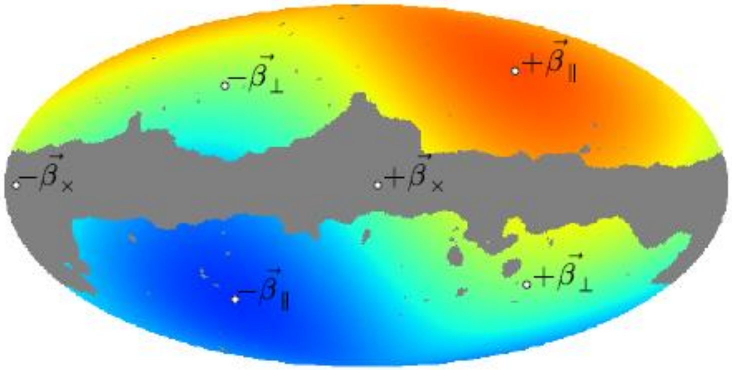
$$\hat{\boldsymbol{n}} \rightarrow \hat{\boldsymbol{n}} \quad + \nabla(\hat{\boldsymbol{n}}\cdot\boldsymbol{v})$$

- just like a dipole lensing convergence



Challinor & van Leeuwen 2002

known dipole amplitude and direction



$$\frac{v}{c} \approx 1.23 \times 10^{-3}$$

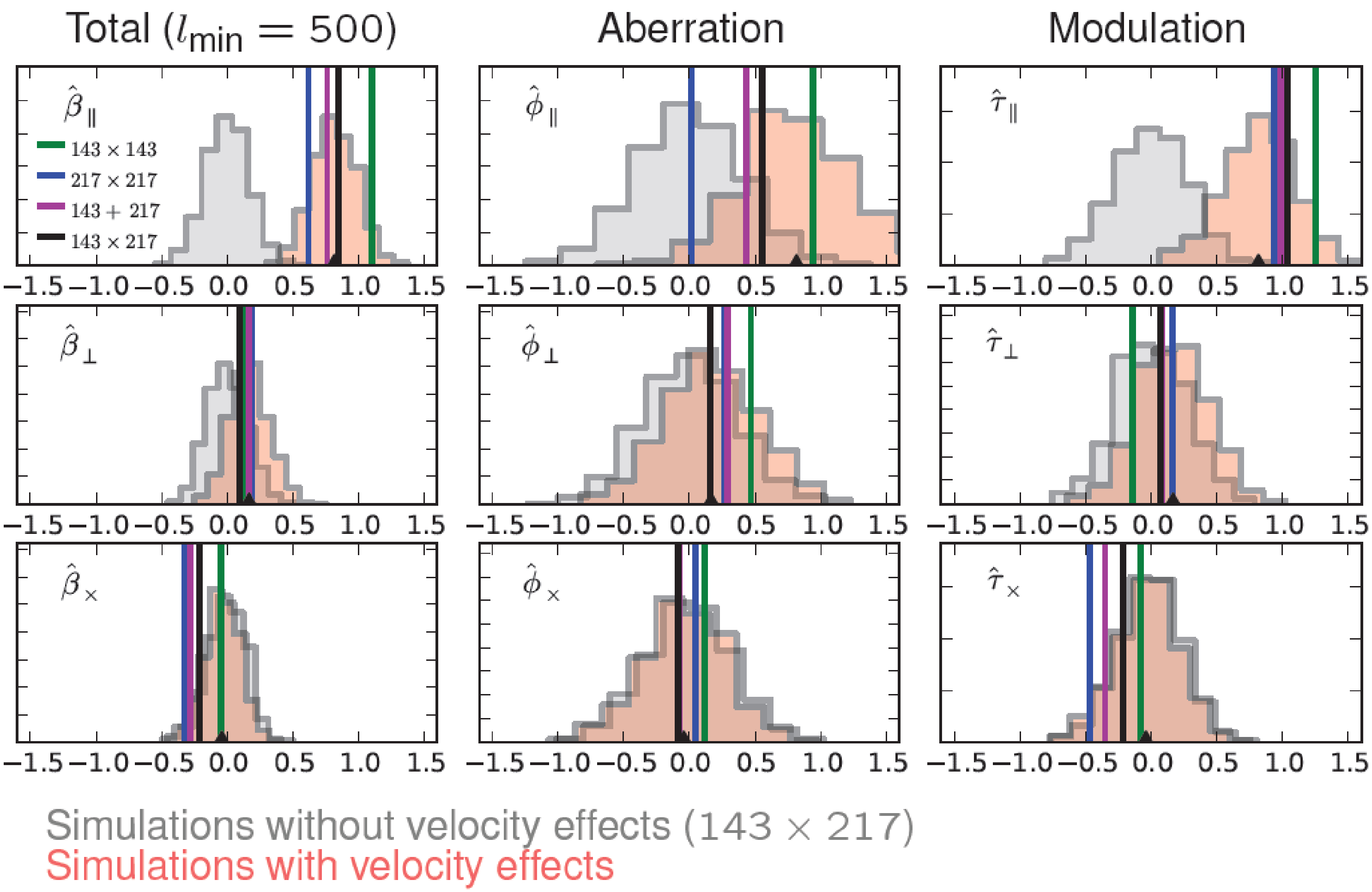
Modulation $f = \left(x \coth\frac{\left(\frac{x}{2}\right)}{2} - 1\right) \hat{\boldsymbol{n}} \cdot \boldsymbol{v} \equiv b_\nu \, \hat{\boldsymbol{n}} \cdot \boldsymbol{v}$

		Approx boost factor $b_\nu = x \coth\left(\frac{x}{2}\right)/2 - 1$	Map modulation amplitude
Planck maps:	100 GHz	1.5	0.18%
	143 GHz	2	0.24%
	217 GHz	3	0.37%
	353 GHz	5	0.64%
	545 GHz	9	1.1%
	857 GHz	14	1.7%

Use 143, 217 only (with dust subtraction from 857)

Note: SMICA maps are a complicated mixture; modulation effect not currently included in FFP6 sims

Dipole kinematic effect using appropriate quadratic estimators

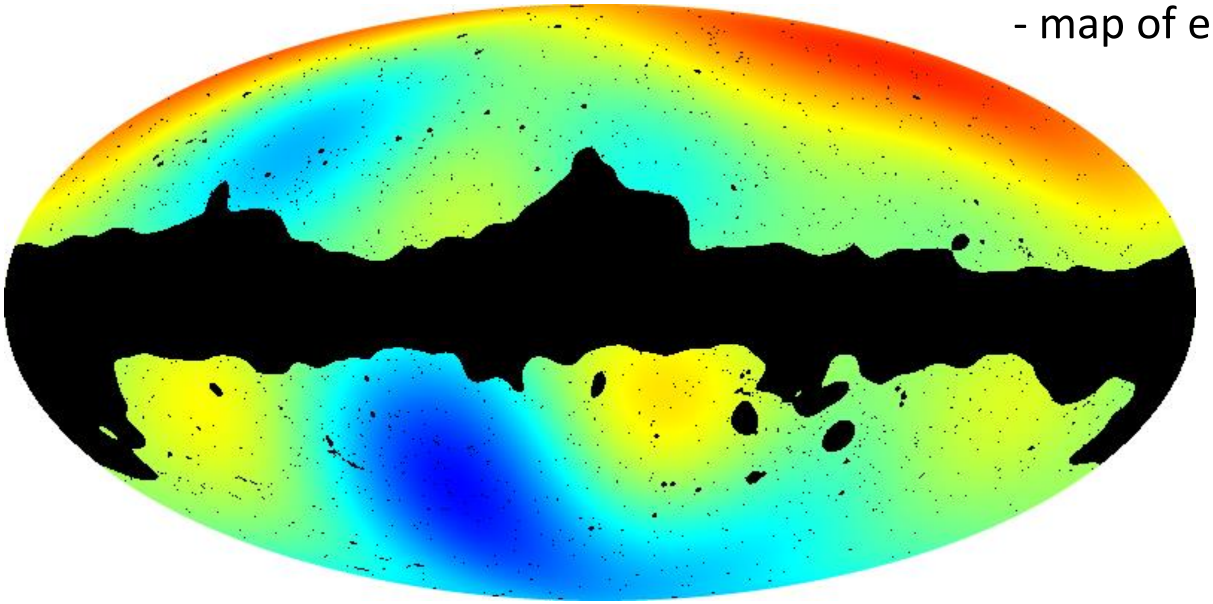


- 5σ detection in 143×217: $v_\parallel = (384 \pm 78)\,\mathrm{km\,s^{-1}}$
- Foreground issue at 217×217 in $\hat\beta_\times$ (driven by $\hat\tau_\times$)?

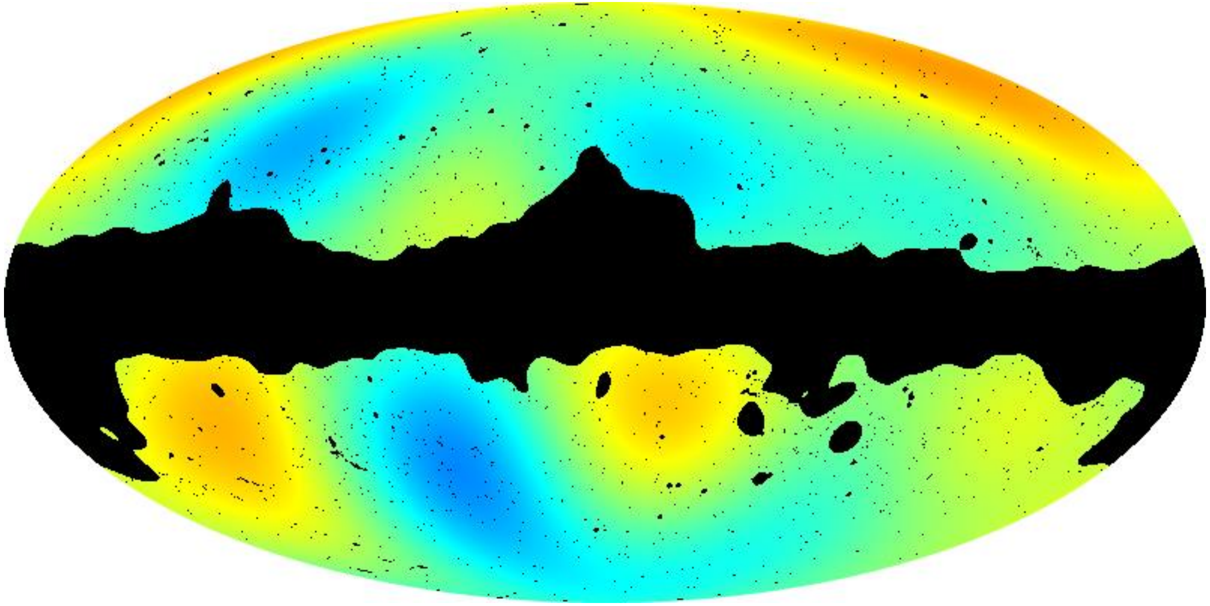
Note: not included in parameter analysis $\theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724° \pm 0.00038°$

- bias due to aberration average over mask $\sim 0.25\sigma$

143x217 modulation reconstruction ($L \leq 5$)
- map of estimated modulation field f



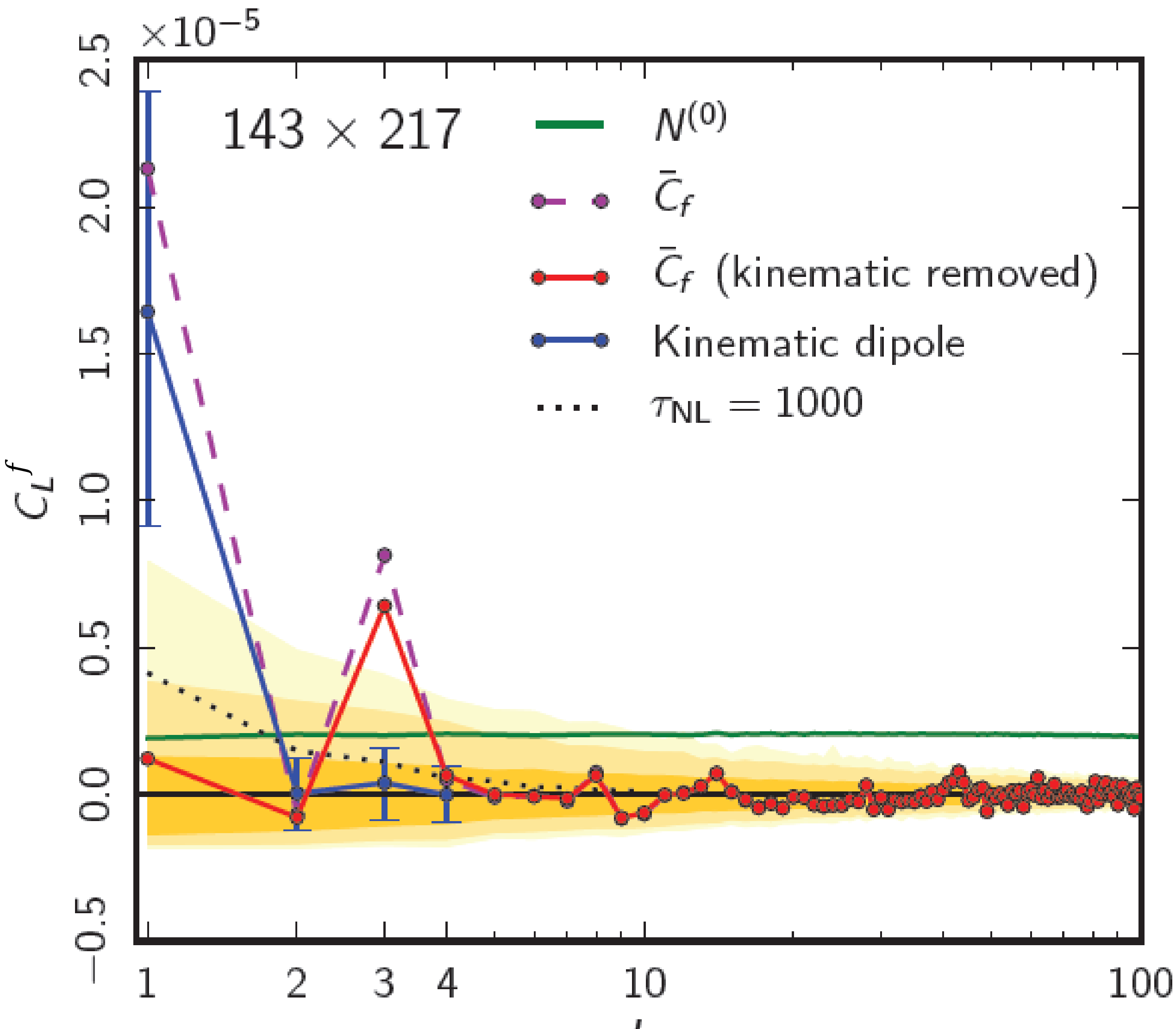
Kinematics not subtracted



Kinematics subtracted
in mean field from sims

Modulation pseudo-power spectrum

$$\tau_{\rm NL}(L) \equiv \frac{C_L^f}{C_L^{\zeta_\star}}$$



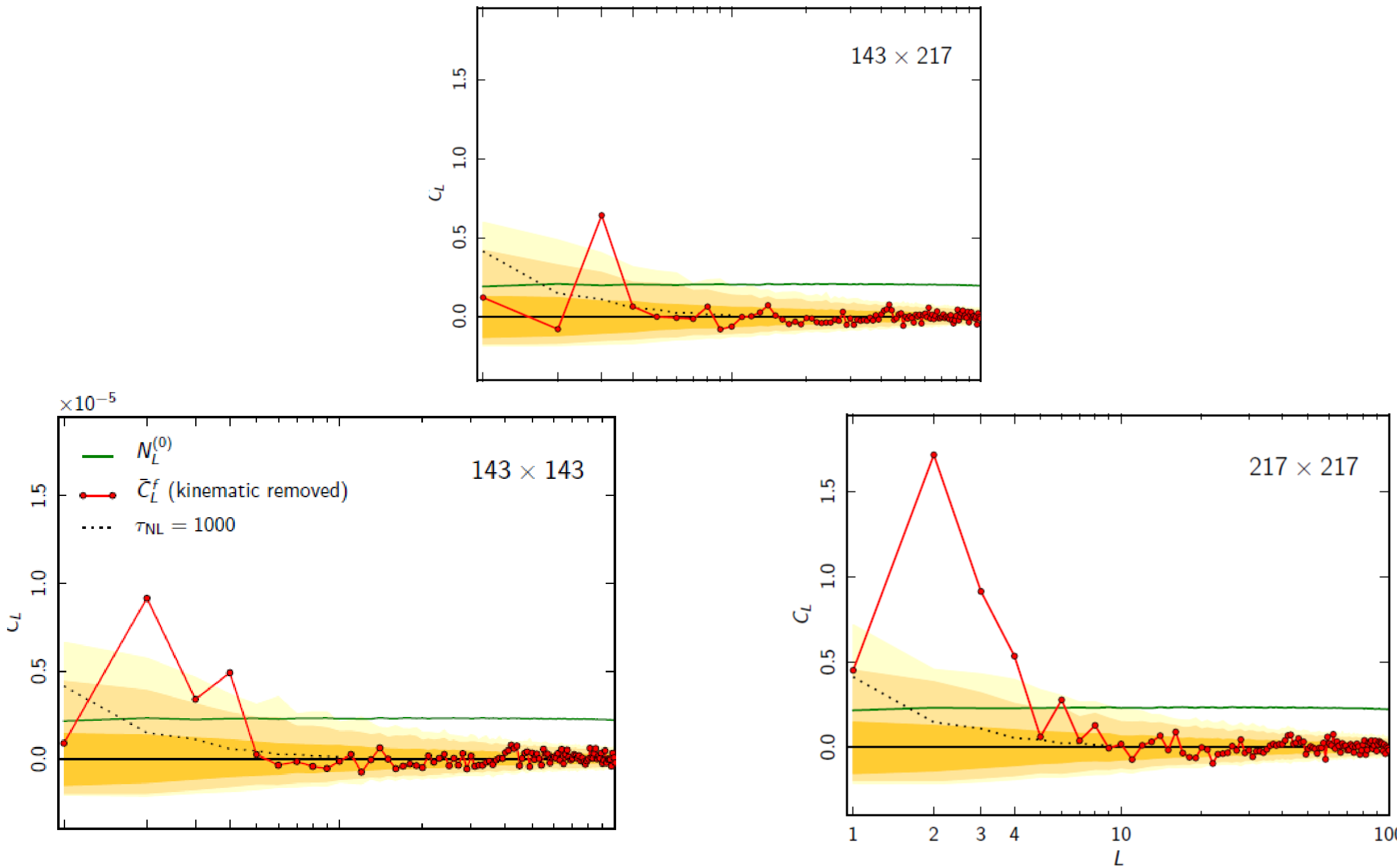
Consistent with zero except for anomalous octopole

Anomalous signal seems to be mostly due to 217

- may be related to $\beta_{\times}$ (frequency dependence from dust?)

Octopole signal varies between frequencies:

(large auto-quadrupole expected from noise bias)



Planck τ_{NL} trispectrum constraint

Estimator result $\hat{\tau}_{\rm NL} = 442$

Gaussian simulations:

$$-452 < \hat{\tau}_{\rm NL} < 835 \text{ at } 95\% \text{ CL } (\sigma_{\tau_{\rm NL}} \approx 335)$$

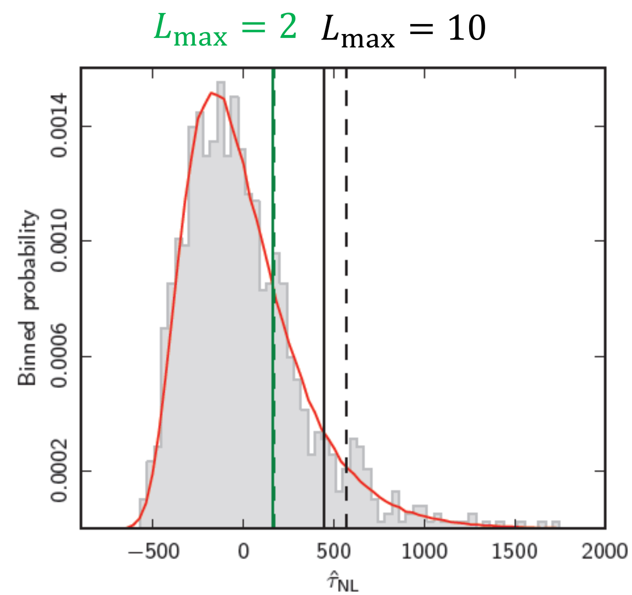
Consistent with Gaussian null hypothesis (octopole has small weight)

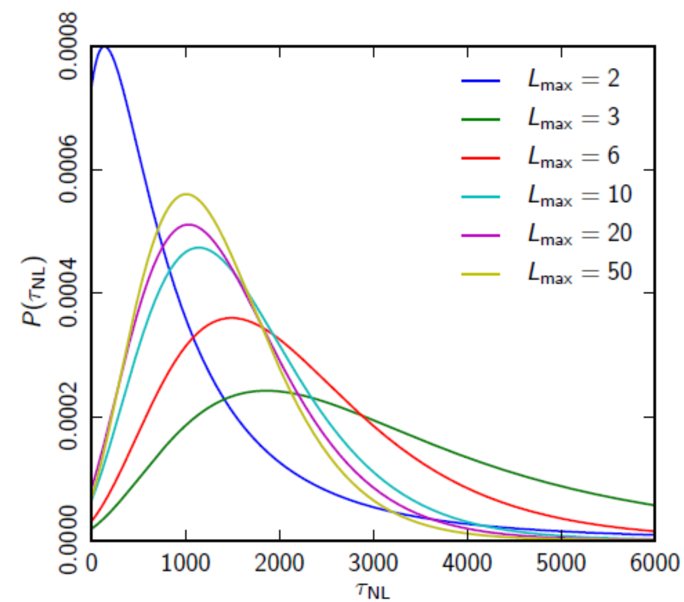
Note: signal most L<5 - small number of modes

- Skewed distribution
- Upper limits weaker than you might expect

Conservative upper limit, allowing octopole to be physical using Bayesian posterior

$$\tau_{\rm NL} < 2800 \text{ at } 95\% \text{ CL}$$





Scale-dependent dipole modulation and power asymmetries

Full analysis suggests no non-kinematic dipole power asymmetry

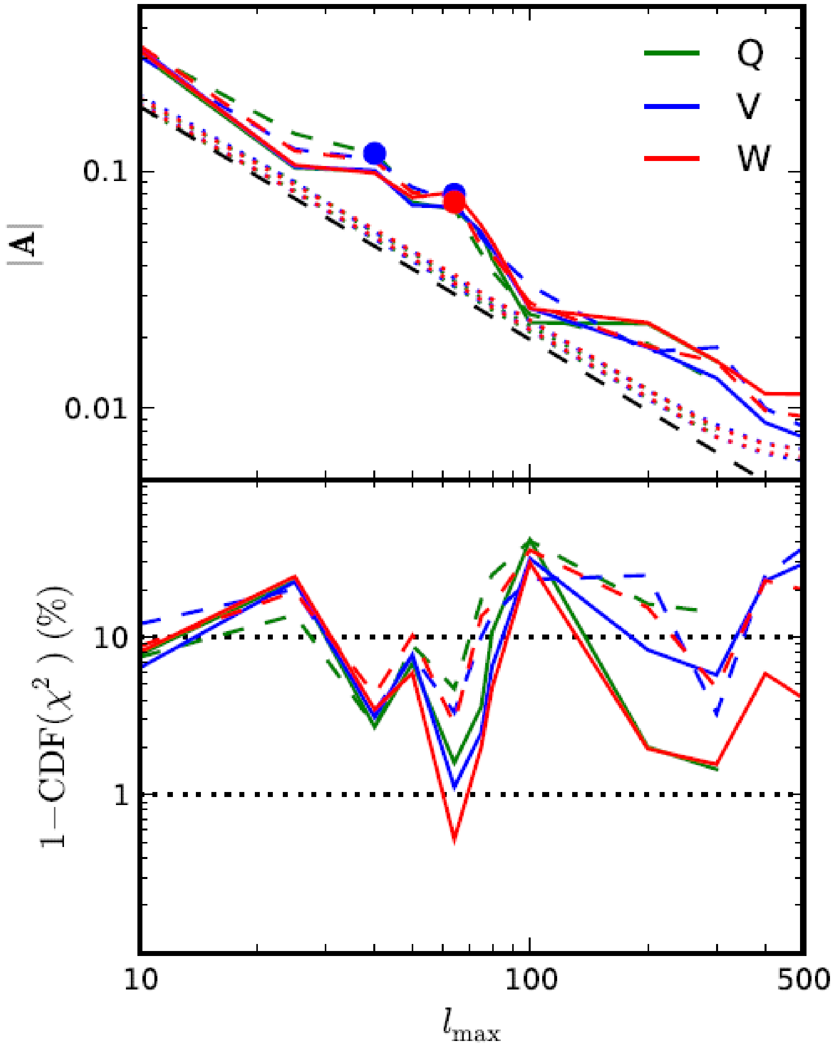
Can also look for scale-dependent effect: filter range of scales used in quadratic estimator

$$\tilde{h}^f_{lm} = \int d\Omega Y^*_{lm} \left[\sum_{l_1 m_1}^{l_{\rm max}} \bar{\Theta}_{l_1 m_1} Y_{l_1 m_1} \right] \left[\sum_{l_2 m_2}^{l_{\rm max}} C_{l_2} \bar{\Theta}_{l_2 m_2} Y_{l_2 m_2} \right]$$

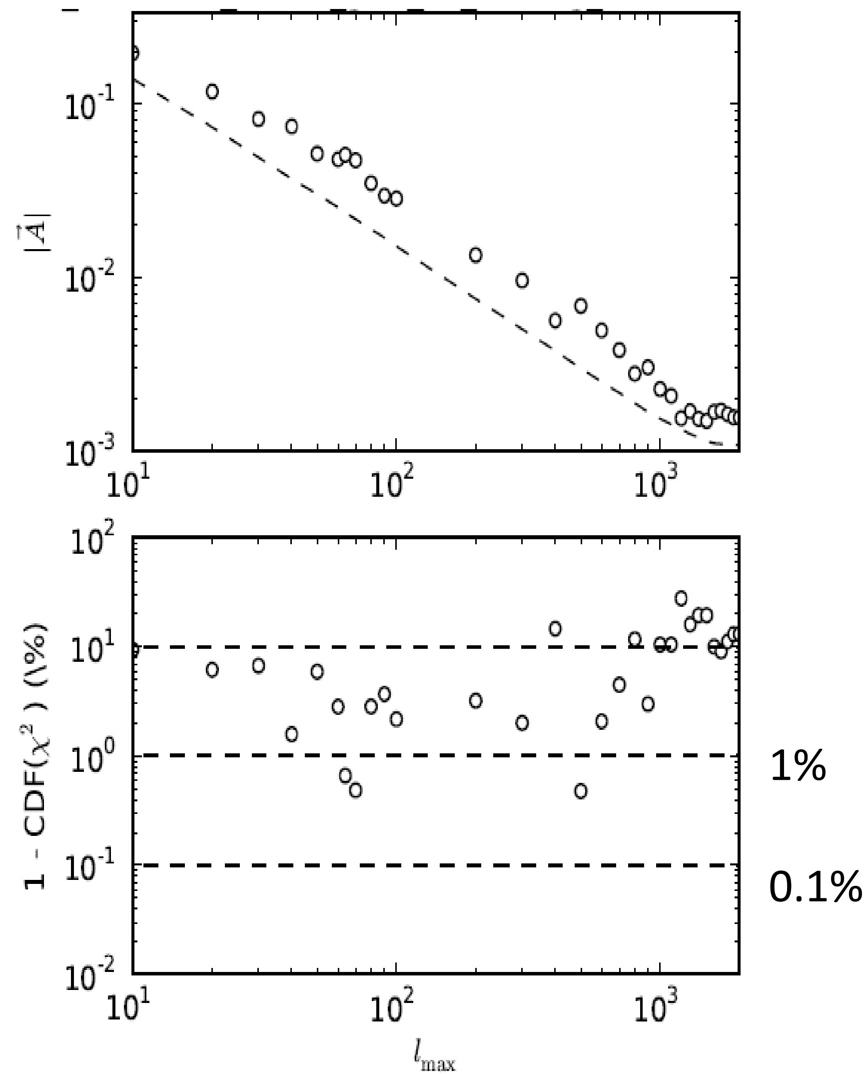
(new results, thanks Duncan)

Power modulation dipole amplitude for $l \leq l_{\max}$

WMAP 5 (Hanson & Lewis 2009)



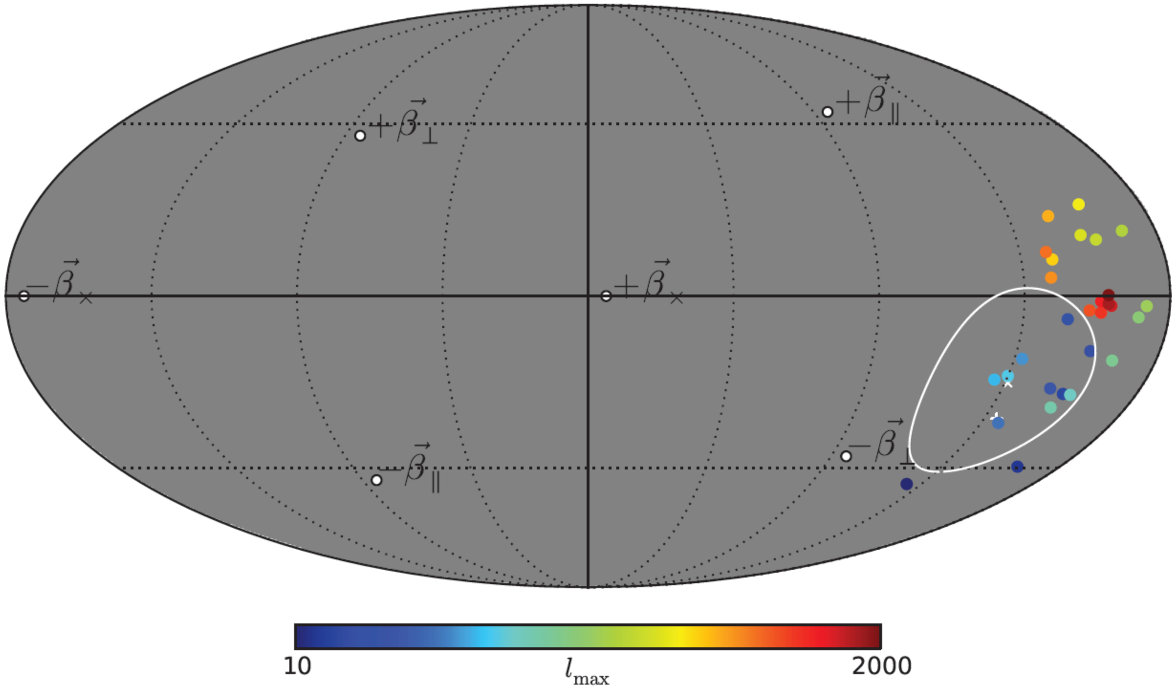
Planck 217x143 (kinematic subtracted)



Modulation < 1% for $l \leq l_{\max} = 500$

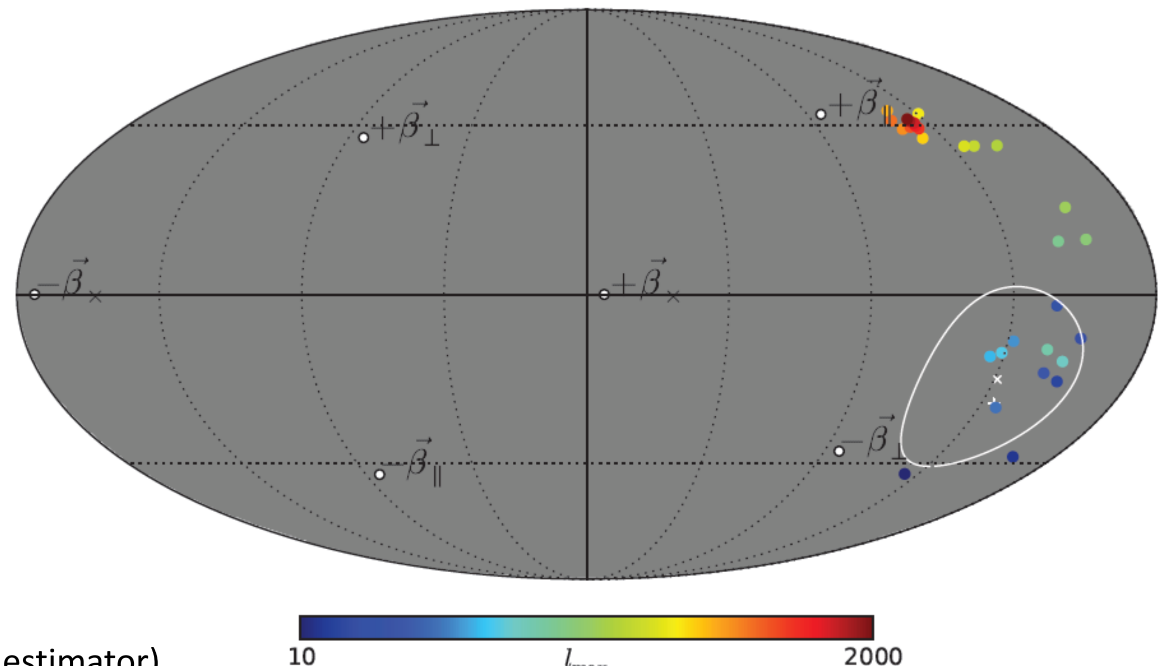
Modulation < 0.2% for $l_{\max} = 1500 - 2000$

Power dipole directions ($l \le l_{\max}$)



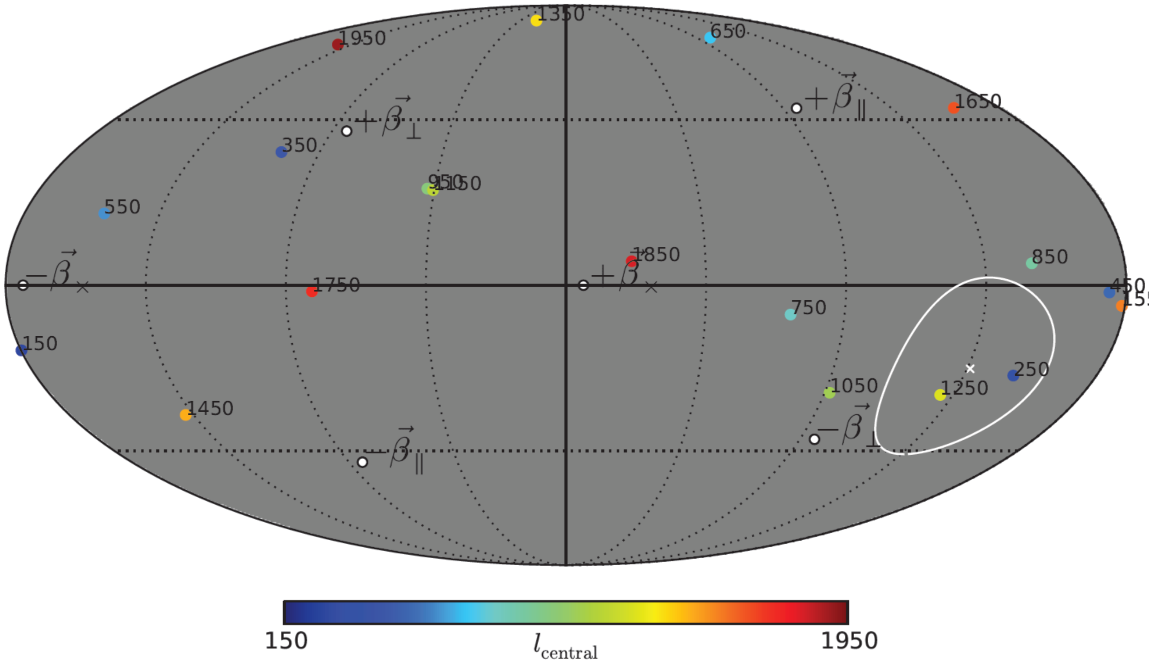
Kinematic subtracted

Kinematics not subtracted

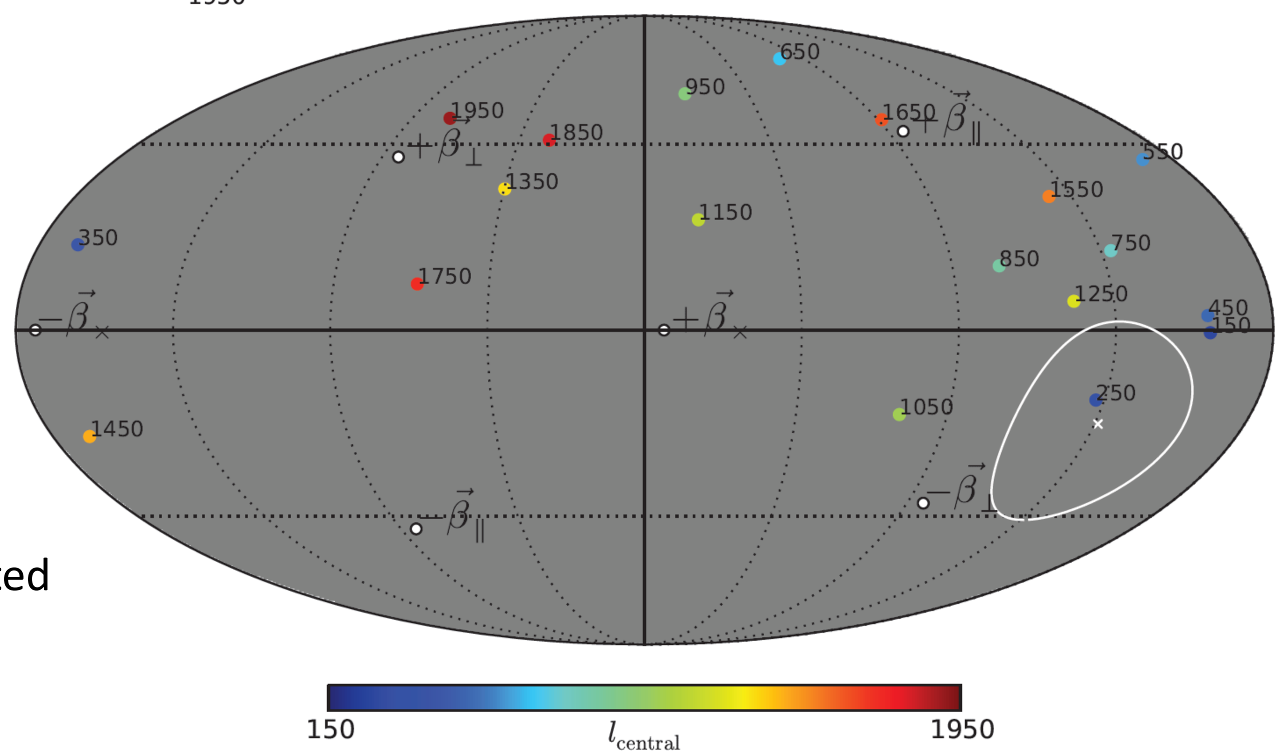


(as in Doppler paper but here pure modulation estimator)

Power dipoles in $\Delta l = 100$ bands



Kinematic subtracted



Kinematics not subtracted

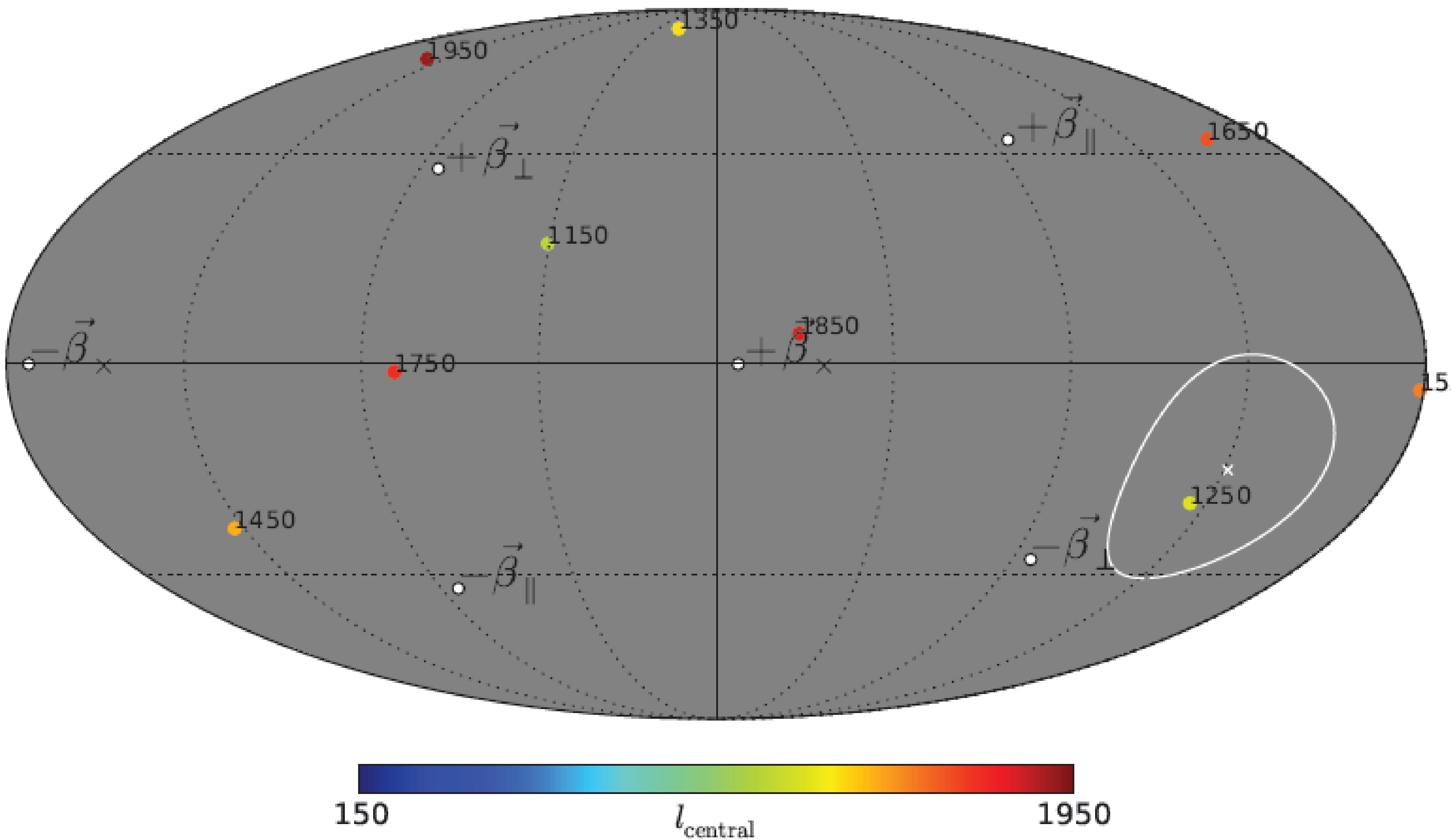
Conclusions

- 5σ detection of kinematic dipole effects in *Planck* maps
- Large-scale modulation power "nearly" consistent with zero after kinematic subtraction (foreground octopole?)
- Conservative limit $\tau_{NL} < 2800$ (95% CL)
- Power at $l \leq 400$ consistent with WMAP and previous analyses
  (must be – maps looks the same)
- Dipole power modulations at low L do not persist to high L after kinematic subtraction: |f| < 0.2% at $l_{\max} = 2000$.
  (but possible foreground issues, ongoing work..)
- Kinematic effects currently not included in *Planck* isotropy paper results, e.g. hemisphere and patch anisotropy constraints.
  Different model, mask, maps, filtering… so not directly comparable; ongoing work…

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

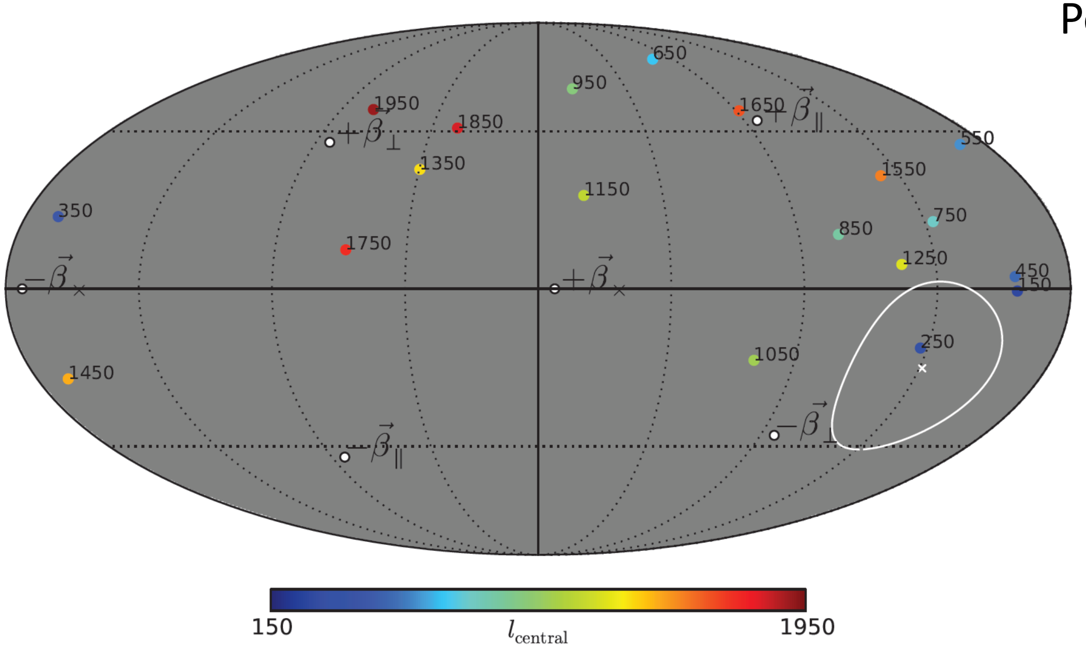
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

$l \geq 1100$ only



SMICA (sims subtract aberration but not modulation)

Power in $\Delta l = 100$ bands



Cumulative