Anomalies ?

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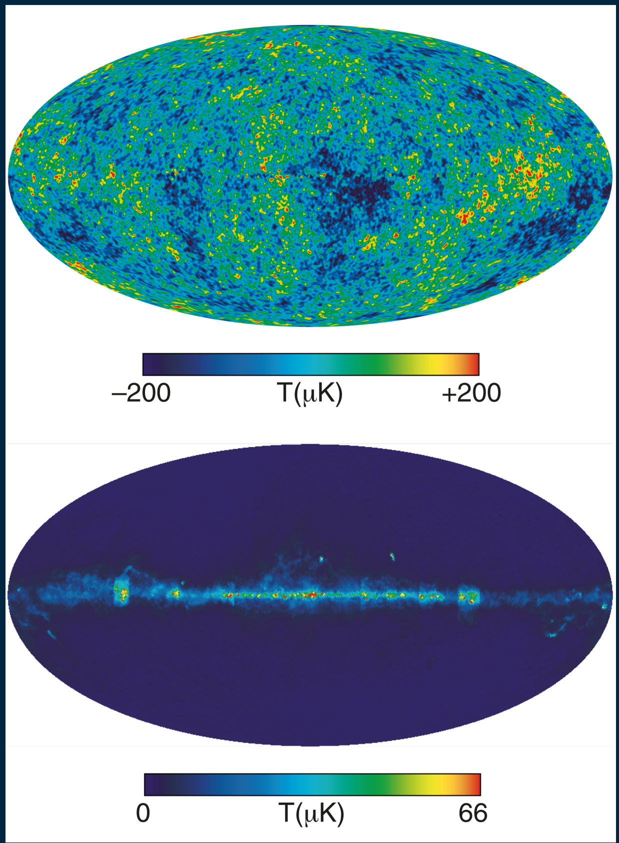
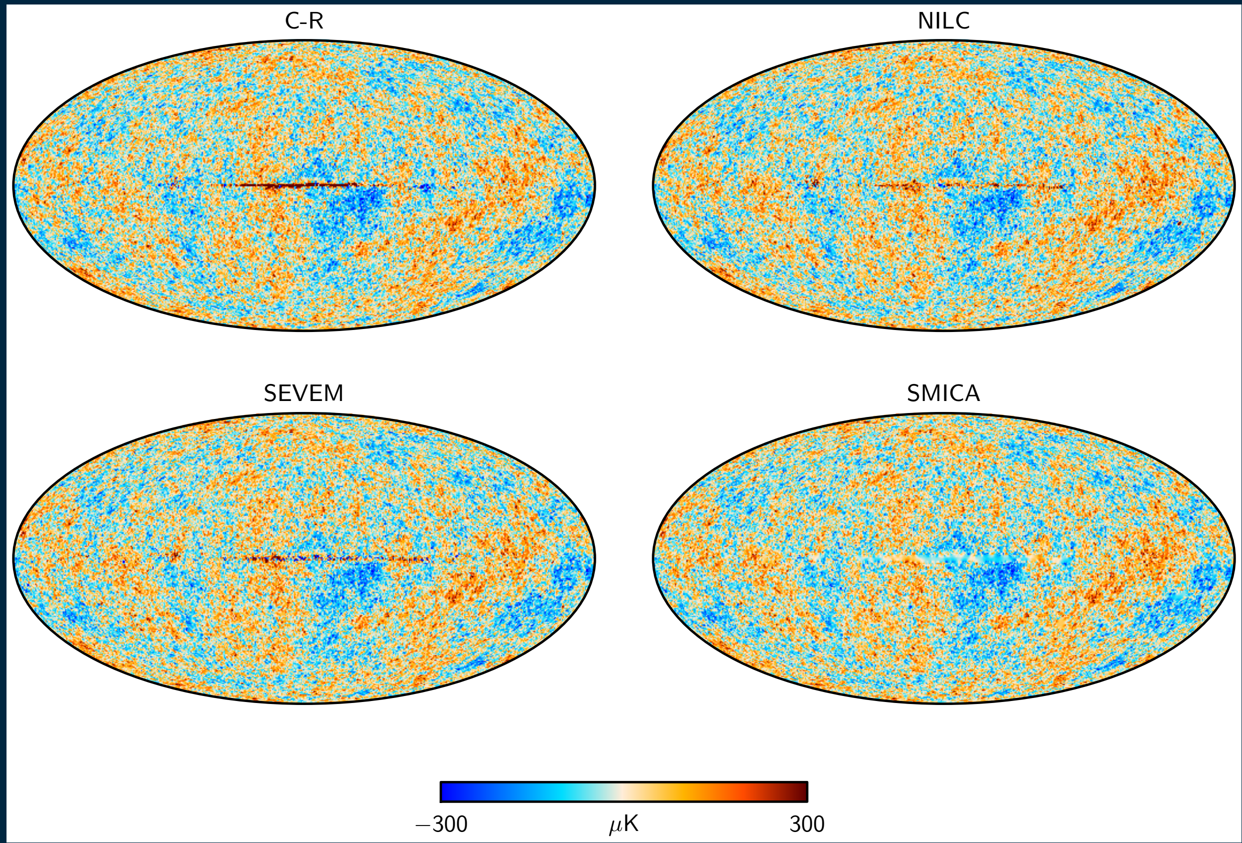
a|nom|a|ly
noun (pl. -lies)
1. something that deviates from what is standard, normal, or expected.
2. ASTRONOMY the angular distance of a planet or satellite from its last perihelion or perigee.
ORIGIN late 16th cent.: via Latin from Greek.

based on work with
Craig Copi, Dragan Huterer, Glenn Starkman

Durham, 2013

WMAP 9yr and Planck 1.3yr full sky CMB maps





Bennett et al. 2013

Planck collaboration 2013

The status of large angle CMB anomalies

Planck confirms several anomalies seen by WMAP

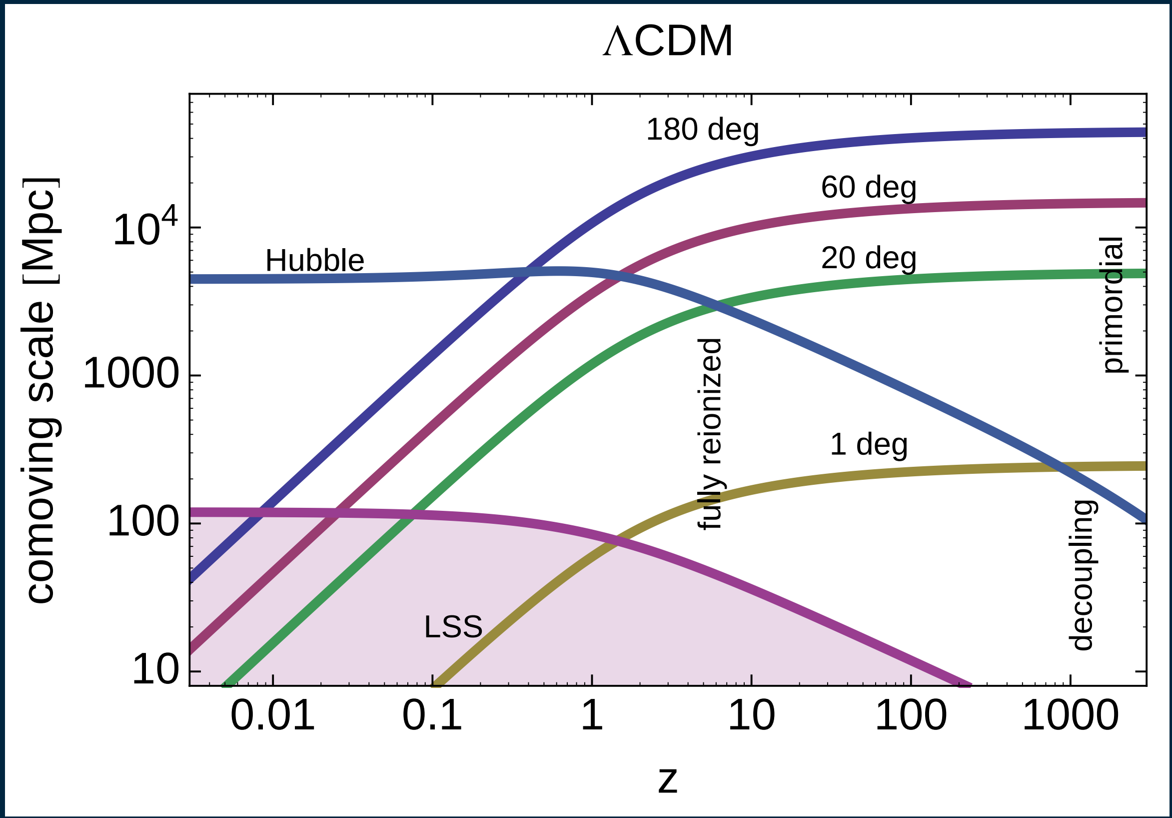
effects at $\sim 3\sigma$ from Planck analysis: Planck collaboration. XXIII. 2013

- lack of power (low variance) already seen by COBE & WMAP
- mode alignment now below 3σ WMAP: de Olivera-Costa et al. 2004
- hemispherical asymmetry WMAP: Eriksen et al. 2004
- parity asymmetry WMAP: Kim & Naselsky 2010
- cold spot(s) WMAP: Vielva et al. 2004

our (preliminary) analysis adds at $\sim 3\sigma$:

- lack of correlation on large angular scales COBE & WMAP
- after Doppler correction: mode alignment more significant
- aligned dipole, quadrupole and octopole WMAP: Schwarz et al. 2004

Why are large angular scales interesting?



$$s(z) = \theta \, d_{\mathrm{C}}(z)$$

Why are large angular scales interesting?

360° dominant monopole: isotropy; $T_0 = 2.7255 \pm 0.0006$ K; free parameter of cosmological model; T_0 fixes epoch of observer

180° dipole $T_1 = 3.355 \pm 0.008$ mK; motion of solar system; fixes observer frame

$> 60^\circ$ modes cross Hubble horizon at $z < 1$
inflation; ISW/RS (nonlinear at $z < 0.02$)

$> 20^\circ$ fully reionized when modes cross inside Hubble horizon
inflation; ISW/RS (nonlinear at $z < 0.1$); reionization

Cosmological inflation — Generic CMB predictions

temperature fluctuations:

$\delta T(\mathbf{e}) = \sum_{\ell m} a_{\ell m} Y_{\ell m}(\mathbf{e})$; $2\ell + 1$ degrees of freedom for each ℓ

statistical isotropy:

$\langle \delta T(\mathsf{R}\mathbf{e}_1) \ldots \delta T(\mathsf{R}\mathbf{e}_n) \rangle = \langle \delta T(\mathbf{e}_1) \ldots \delta T(\mathbf{e}_n) \rangle, \quad \forall \mathsf{R} \in \mathsf{SO}(3), \forall n > 0$

- $\langle \delta T(\mathbf{e}) \rangle = 0$ and $\langle a_{\ell m} \rangle = 0$
- $\langle \delta T(\mathbf{e}_1) \delta T(\mathbf{e}_2) \rangle = f(\mathbf{e}_1 \cdot \mathbf{e}_2) = \frac{1}{4\pi} \sum_\ell (2\ell + 1) C_\ell P_\ell(\cos\theta), \quad \cos\theta \equiv \mathbf{e}_1 \cdot \mathbf{e}_2$ with $\langle a_{\ell m} a^*_{\ell' m'} \rangle = C_\ell \delta_{\ell\ell'} \delta_{mm'}$, C_ℓ angular power spectrum

gaussianity: no extra information in higher correlation functions

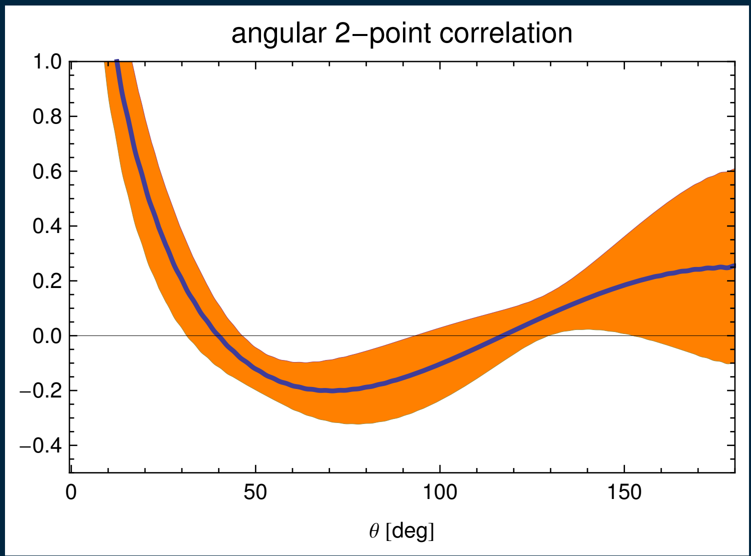
(best) estimator: $\hat{C}_\ell = 1/(2\ell + 1) \sum_m |a_{\ell m}|^2$ (assumes statistical isotropy)

cosmic variance: $\mathsf{Var}(\hat{C}_\ell) = 2C_\ell^2/(2\ell + 1)$ (assumes gaussianity)

Cosmological Inflation — Generic CMB predictions

almost scale invariance, $n \approx 1$:

$C_\ell \approx 2\pi A/[\ell(\ell+1)]$, at the largest scales $\qquad A \approx 1000\mu K^2$ (obs.)



$C(\theta)$ without $\ell = 0, 1$ (arbitrary units)

What do we expect?

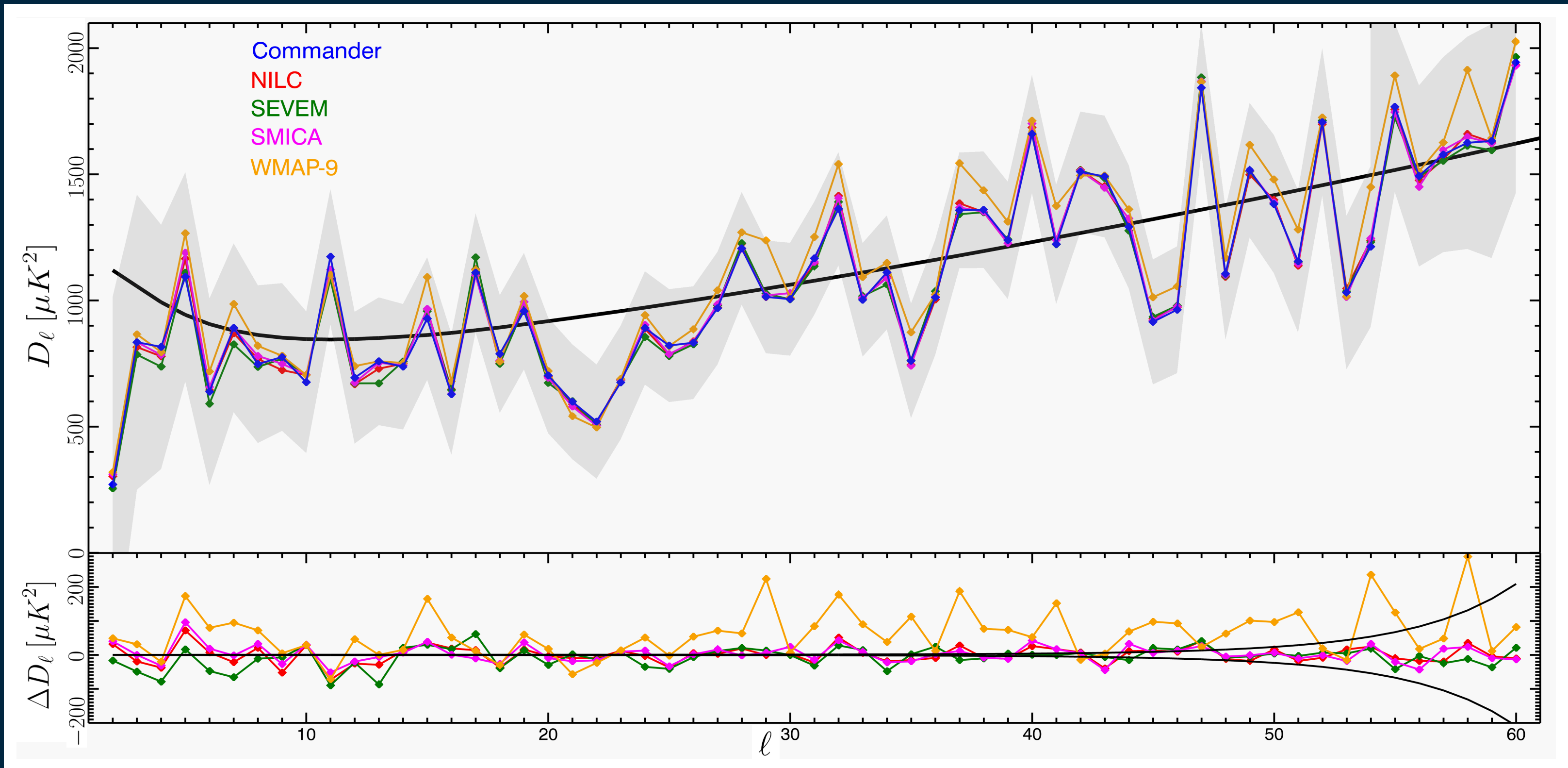
statistically isotropic, gaussian, nearly scale invariant fluctuations

potential issues:
instrument, algorithms, solar system, galaxy, local structure at $z < 0.1$

one or two anomalies at $\sim 3\sigma$ could be chance
several anomalies at $\sim 3\sigma$ cannot, but could be caused by
a systematic or local physics ($V_{\mathrm{local}} = 10^{-3} V_{\mathrm{H}}$)

otherwise, several statistically independent anomalies at $\sim 3\sigma$ would rule out standard model

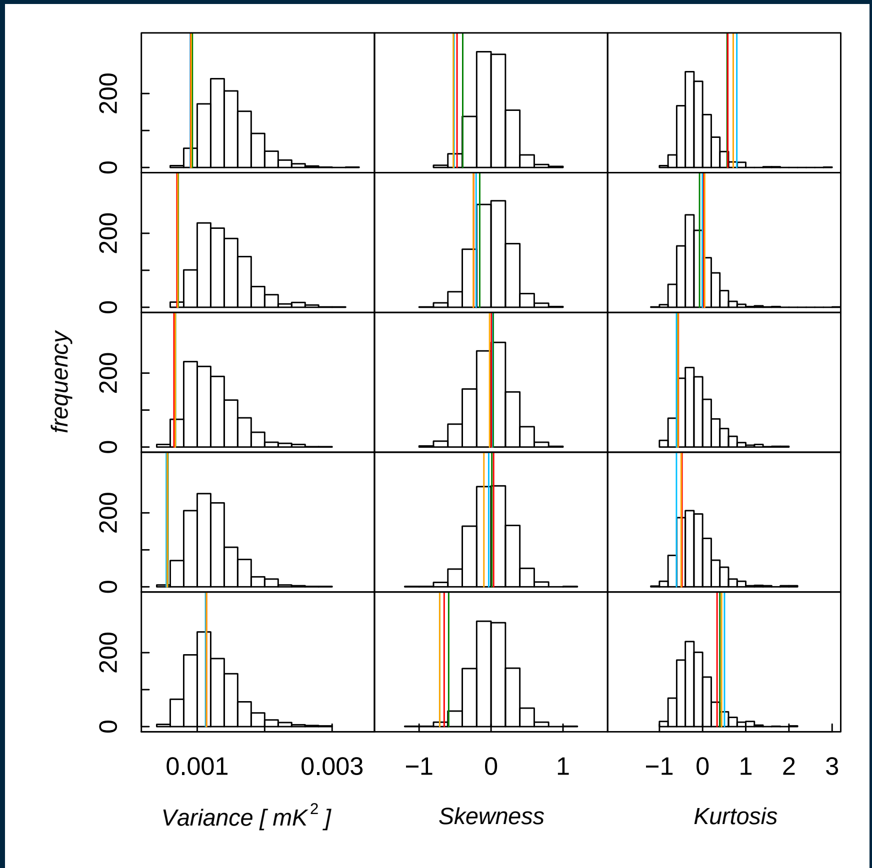
Low-ℓ angular power spectrum



Fisher matrix errors include cosmic variance

Planck collaboration. XV. 2013

Lack of power and hemispherical asymmetry



one point function

$N_{\text{side}} = 16$

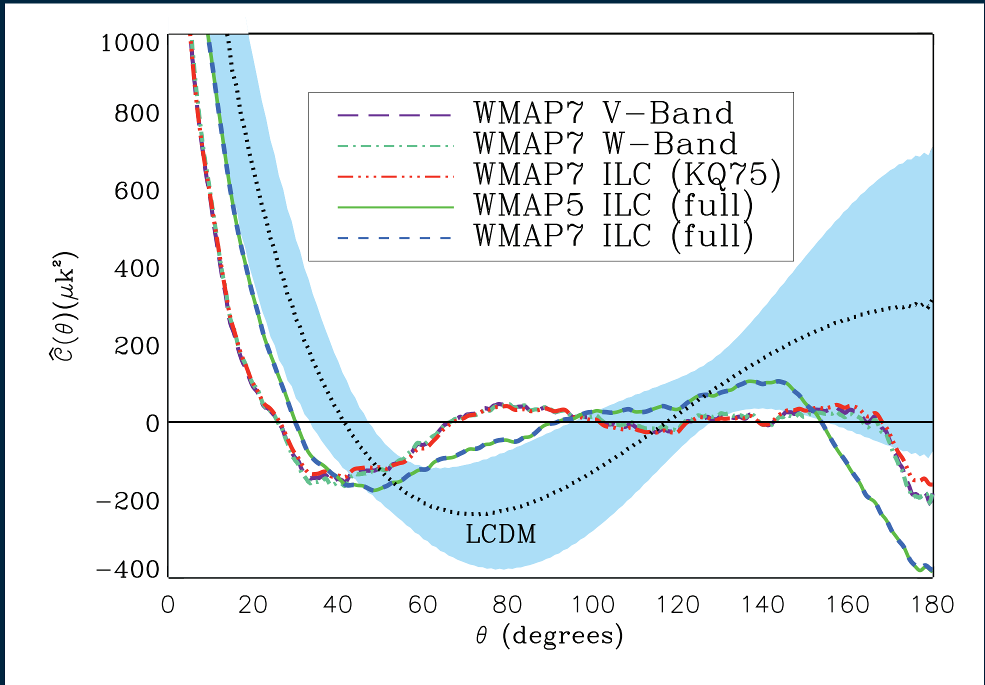
rows:

U73, CL58, CL37, ecliptic N/S

70 GHz, 100 GHz, 143 GHz, 217 GHz

Planck collaboration. XXIII. 2013

WMAP 5yr & 7yr angular correlation function



Sakar et al. 2010

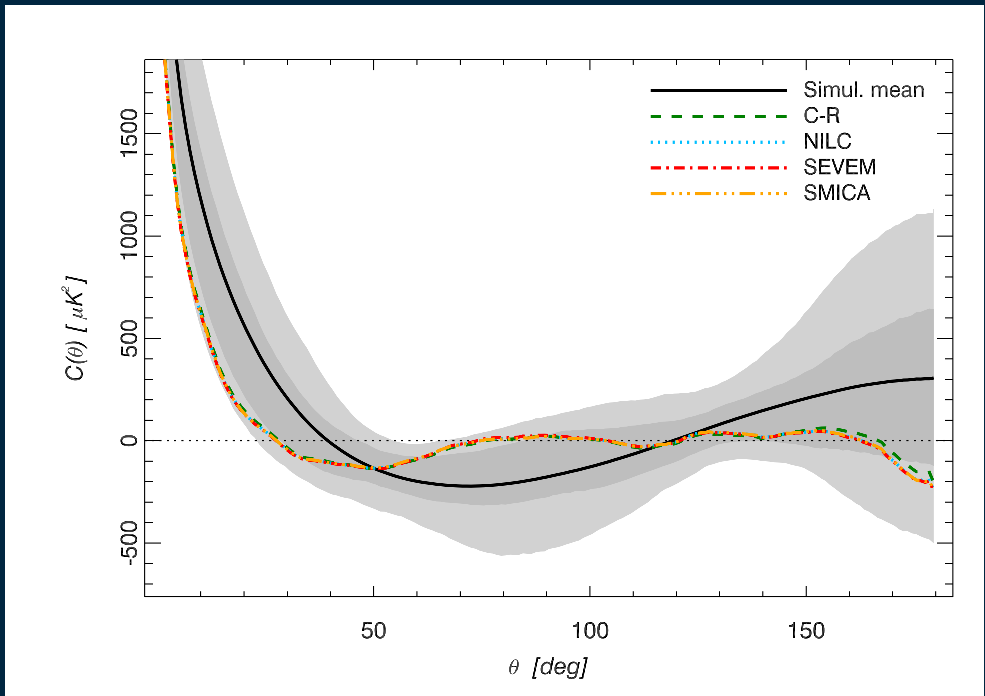
lack of correlation Spergel et al. 2003

compare to 10^5 MC cut sky maps

$$S_\alpha = \int_{-1}^{\alpha} \mathrm{d}\mu \, C^2(\mu)$$

$$P(S_{1/2}^{\mathrm{cut\,sky}}) < 0.1\%$$

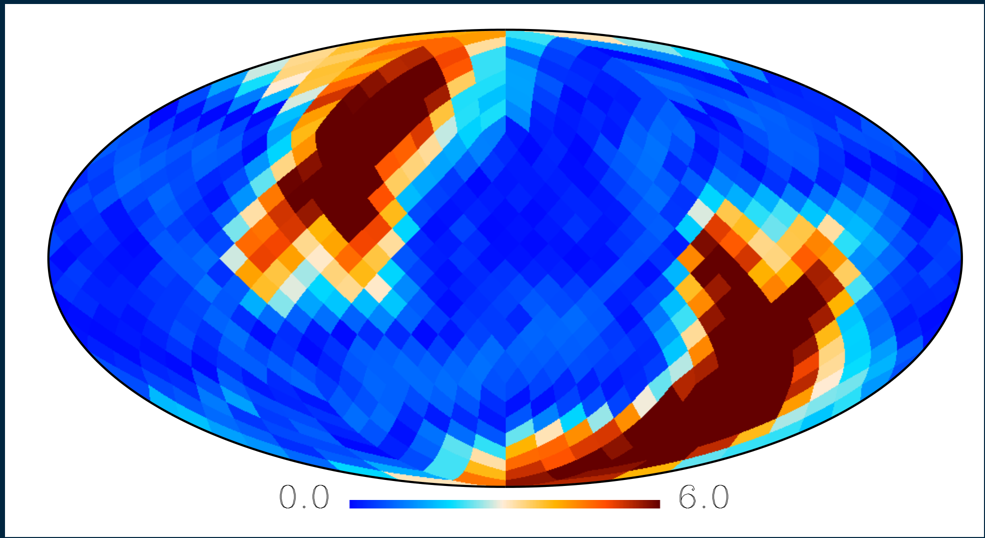
Planck angular correlation function



Planck collaboration. XXIII. 2013

Planck (smica, nilc, sevem, 70 GHz, 100 GHz; U74, KQ75y9):
robust at $P(S_{1/2}^{\text{cut sky}}) < 0.3\%$ Copi et al. (preliminary)

Phases correlations



surrogates (shuffle data): unexpected scaling indices, up to 6σ

WMAP: Räth et al. 2009; Planck collaboration. XXIII. 2013

A test of statistical isotropy — Multipole vectors

alternative representation of multipoles

Maxwell 1891, Copi, Huterer & Starkman 2003

one (real) amplitude A_ℓ and ℓ headless (unit) vectors:

$2\ell + 1$ degrees of freedom

$$T_\ell(\mathbf{e}) = \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\mathbf{e}) = A_\ell [\mathbf{v}^{(\ell,1)} \ldots \mathbf{v}^{(\ell,\ell)}]_{i_1 \ldots i_\ell} [\mathbf{e} \cdots \mathbf{e}]^{i_1 \ldots i_\ell}$$

$[\ldots]$ . . . symmetric, traceless tensor product

e.g. quadrupole: $T_2(\mathbf{e}) = A_2[(\mathbf{v}^{(2,1)} \cdot \mathbf{e})(\mathbf{v}^{(2,2)} \cdot \mathbf{e}) - \frac{1}{3}\mathbf{v}^{(2,1)} \cdot \mathbf{v}^{(2,2)}]$

Our pipeline to analyse WMAP 9yr and Planck 1.3yr data

- harmonic inpainting for full sky analysis — Kim et al. 2012

- remove monopole and dipole from map

- correct for kinetic quadrupole — Schwarz et al. 2004

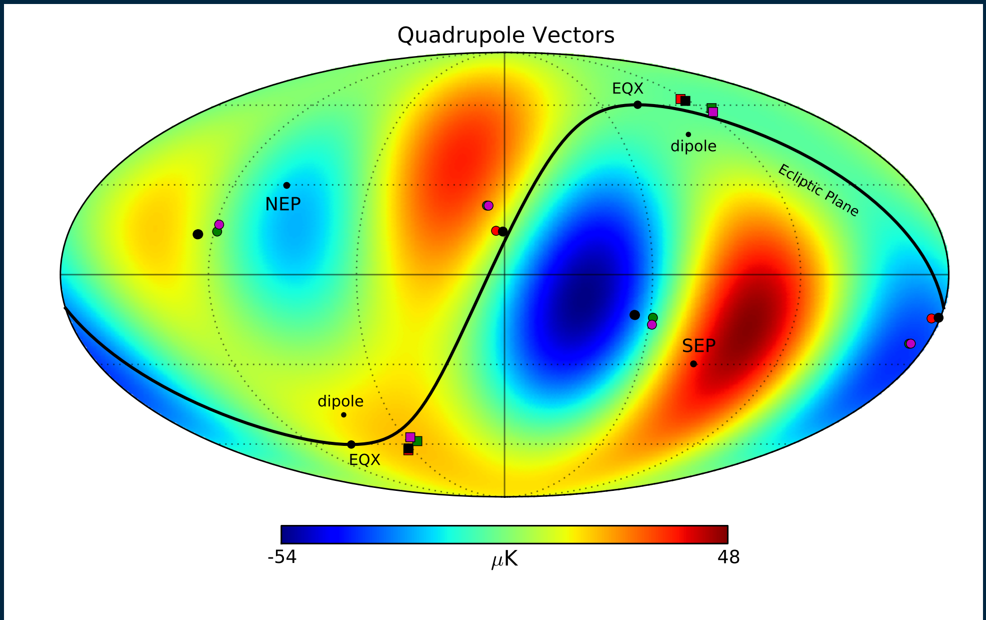
- study full sky cleaned maps and frequency band maps

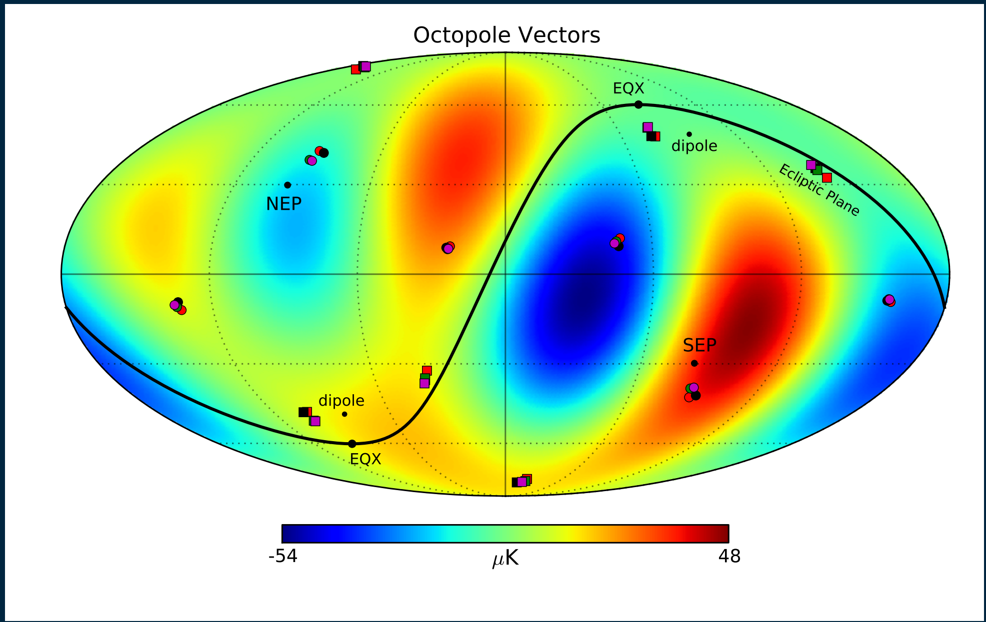
(V & W for WMAP; 70 GHz LFI, 100 GHz & 143 GHZ, HFI)

- consider several masks

typically KQ75y9 or U74 [our version of Planck U73 (not online)]

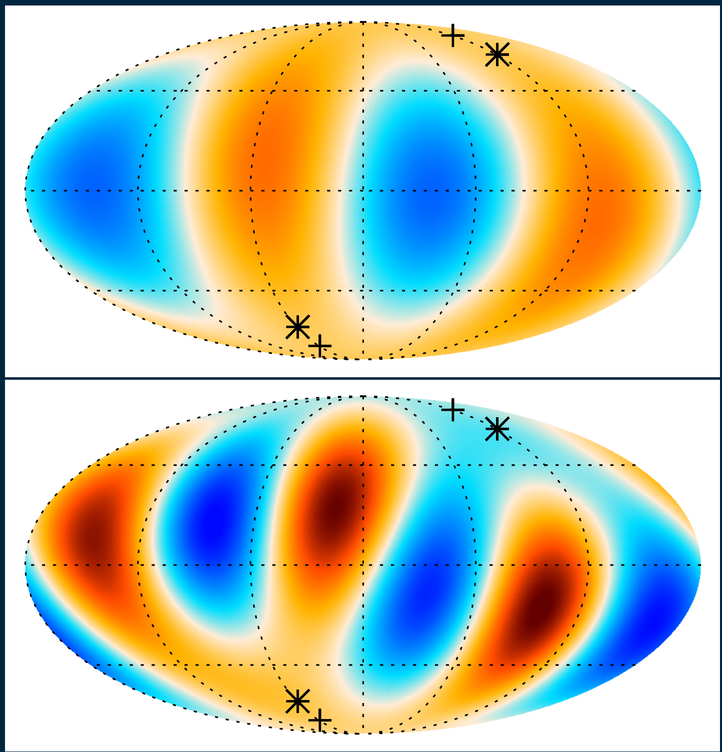
WMAP and Planck quadrupole-octopole alignment

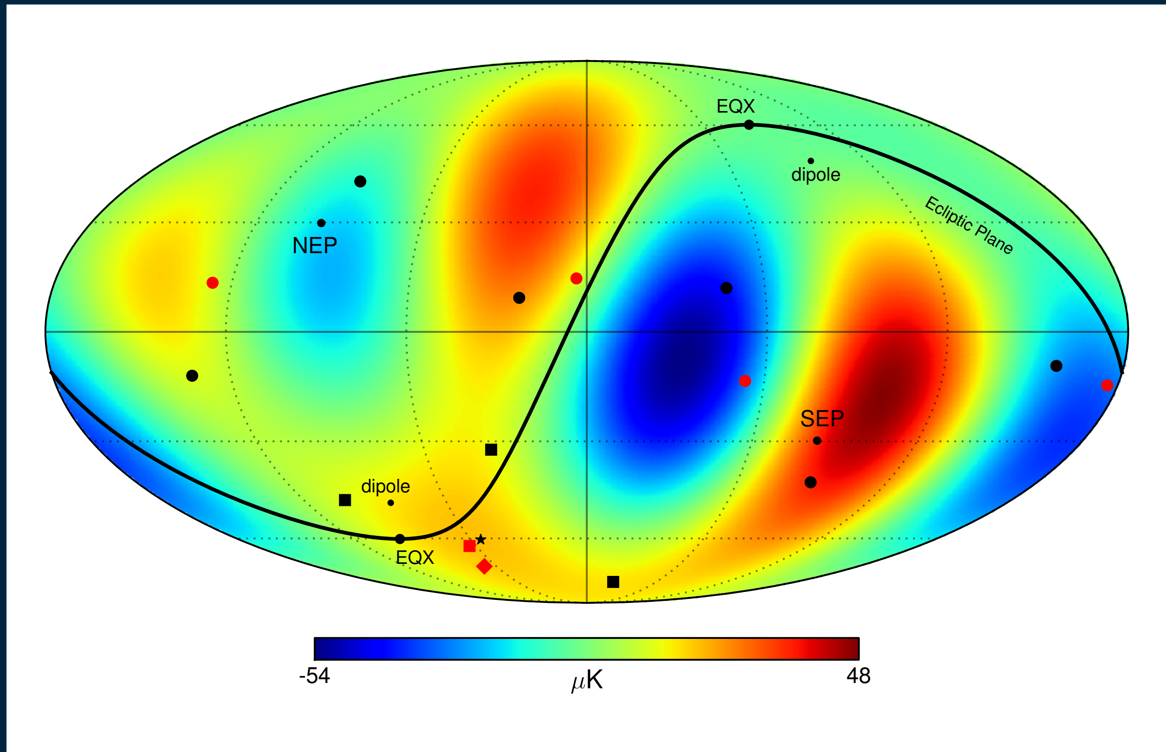




smica, nilc, wmap7, wmap9 are consistent with each other   Copi et al. (prel.)

Planck-SMICA quadrupole-octopole alignment

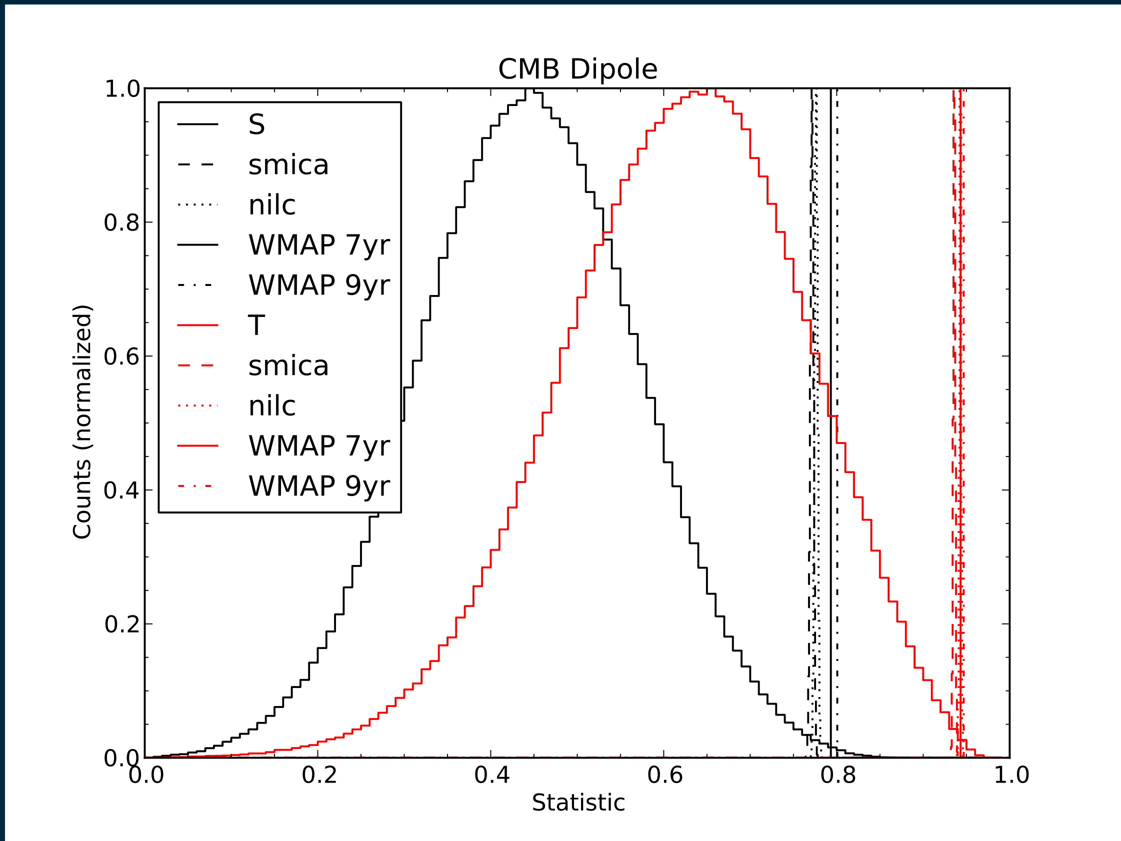




Planck collaboration 2013

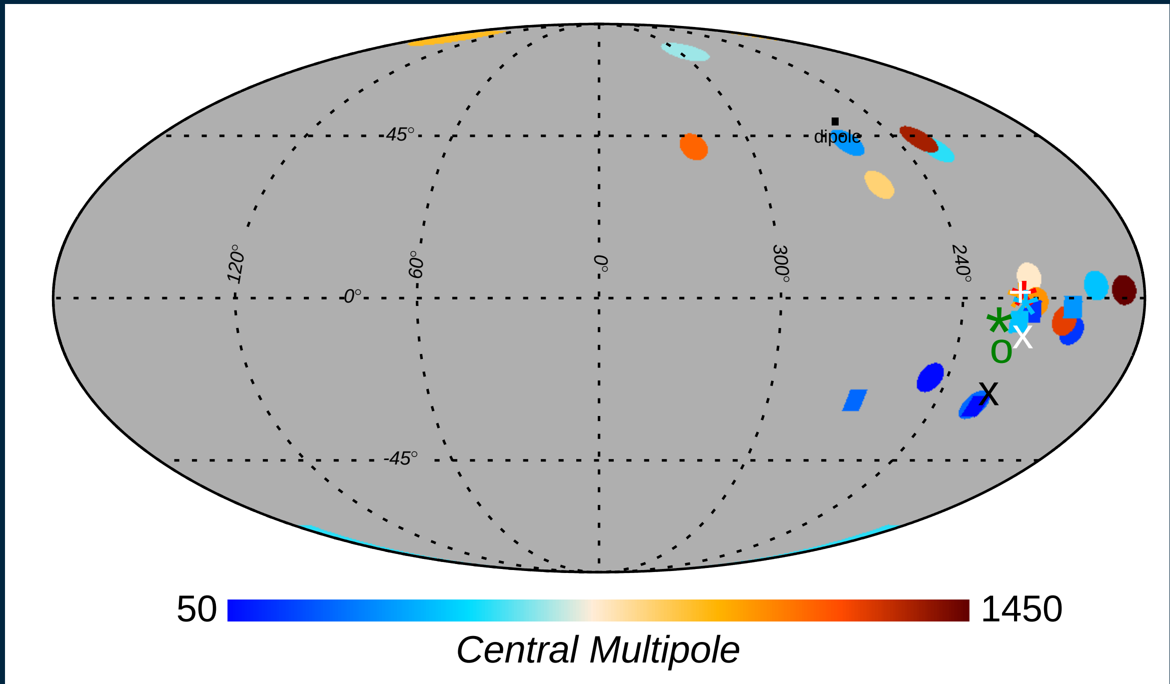
Doppler corrected quadrupole   Copi et al. (prel.)

Dipole-quadrupole-octopole alignment



most robust and significant alignment $>$ 99.6% C.L. Copi et al. (preliminary)

Power asymmetry at higher ℓ and dipolar power modulation?



Planck collaboration. XXIII. 2013

at high ℓ affected by motion, mask & mode mixing   Flender & Hotchkiss 2013

Status of CMB large angle anomalies

observed microwave radiation at > 60 deg disagrees with prediction

2-point correlation too low at 99.7%CL (Planck) (99.9%CL WMAP 9yr)

quadrupole and octopole
aligned with each other at 98%CL (Planck) (99.7%CL WMAP 9yr)
correlated with dipole at 99.6%CL (Planck) (99.8%CL WMAP 9yr)
correlated with ecliptic at 95%CL (Planck) (97%CL WMAP 9yr)

unlikely explanations after Planck: instrument, algorithm, foreground

possible: (statistical fluke), local large scale structure, cosmology, . . .

Origin of large angle CMB anomalies?

- statistical fluke ($P \sim 10^{-6}$)

lack of power and alignment uncorrelated in standard model? Sakar et al. 2010

- alignment from ISW of local structure ($z \sim 0.1$)

why should local structure cancel primordial fluctuations? WISE, radio, ...?

- suppression of power from break in power spectrum, e.g. short inflation

would be regenerated by ISW and needs fine tuning

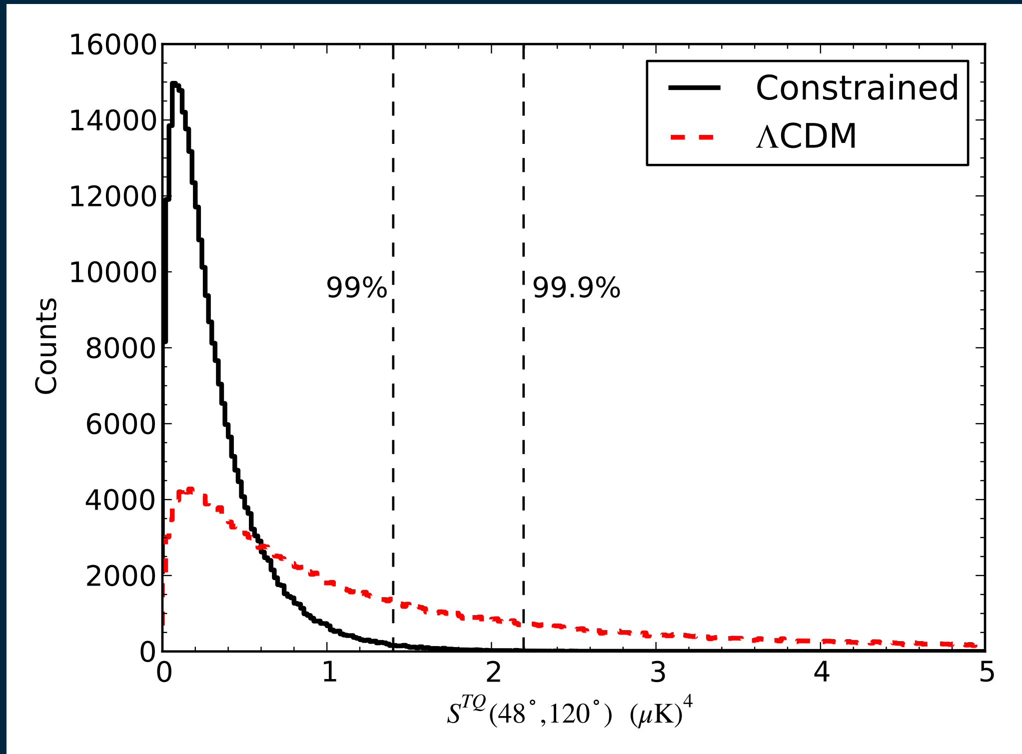
- suppression of power from topology

would need fine tuning of duration of inflation, constrained by data

- Hubble horizon sized perturbation

may explain asymmetries, but not lack of correlation and alignment

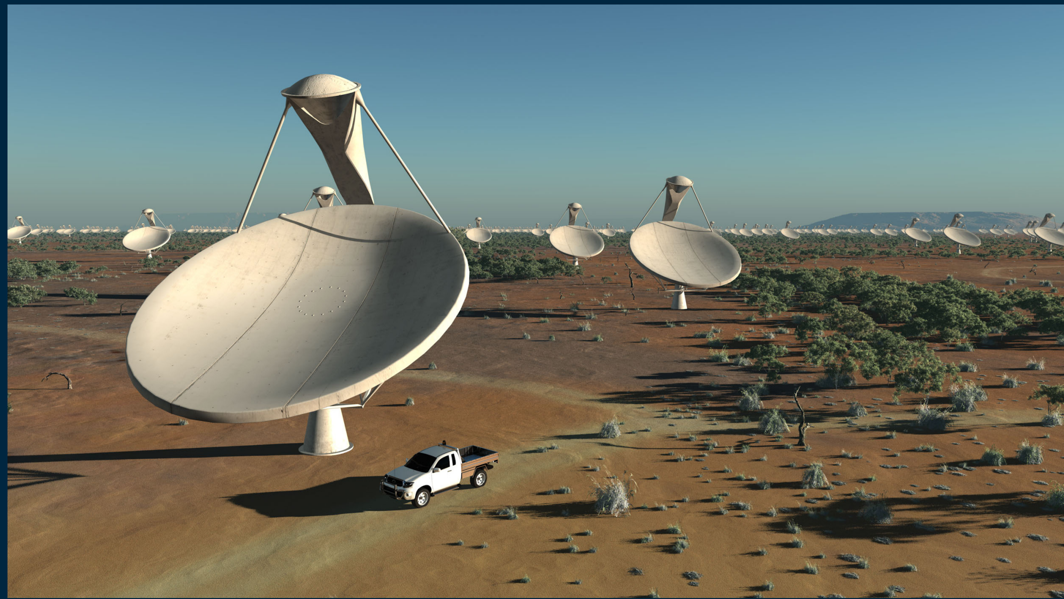
CMB polarization as an independent probe



large S^{TQ} would exclude a statistical fluke

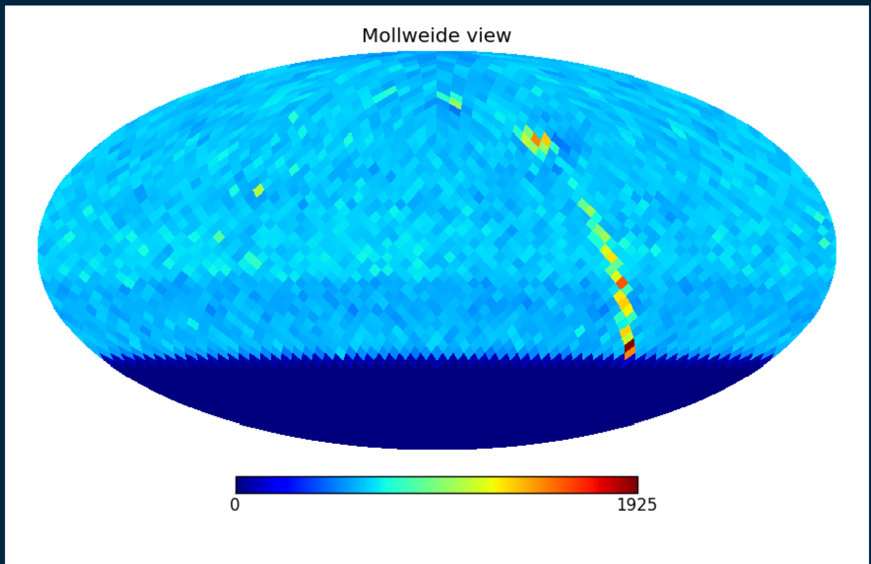
Copi et al. 2013

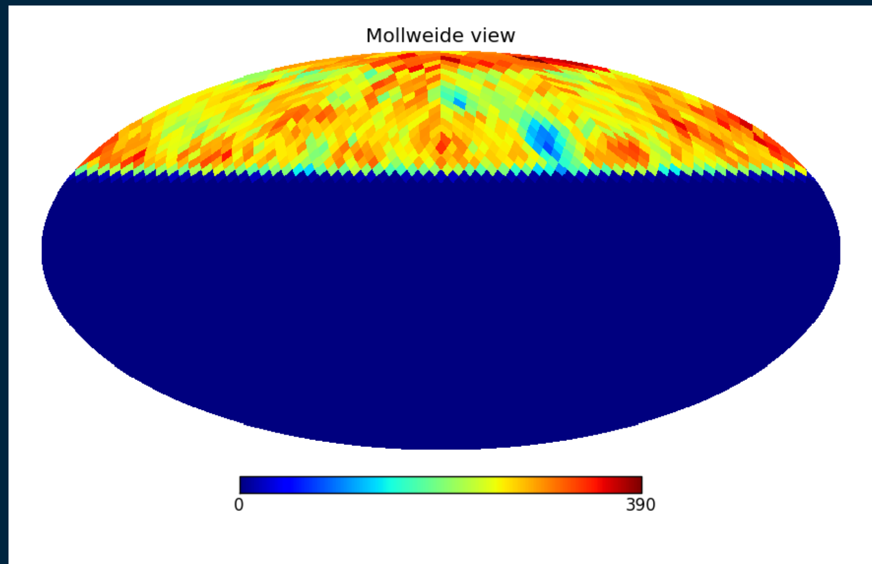
Radio (multifrequency) surveys can probe large angles/scales



LOFAR, ASKAP, MeerKat, Apertif, . . . , SKA

Radio dipole analysis NVSS (1.4 GHz) and WENSS (325 MHz)

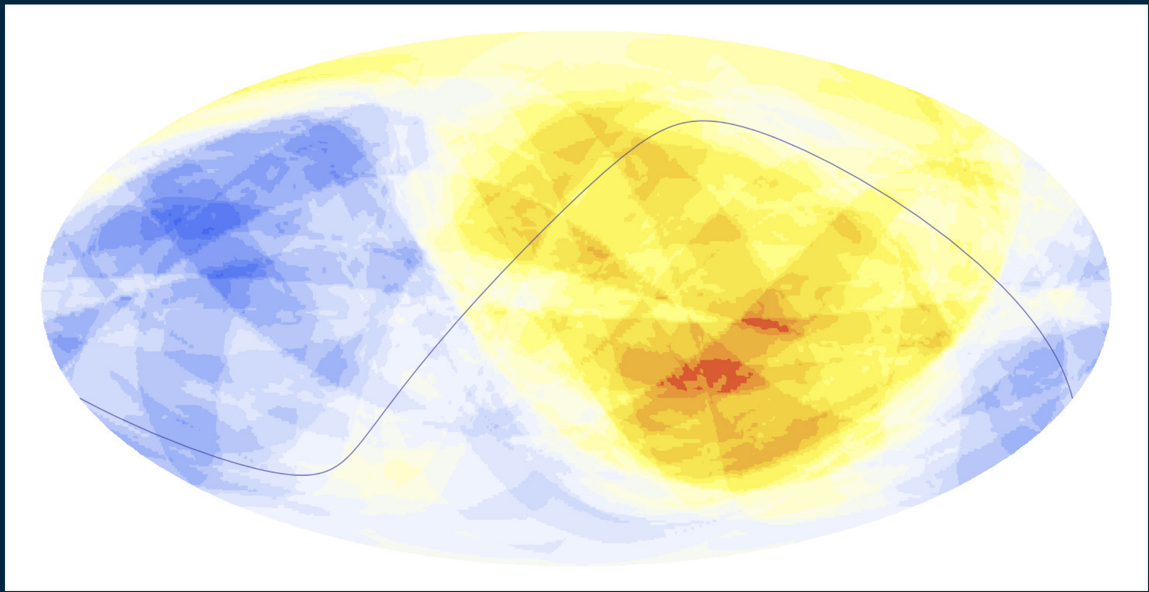




direction of cosmic radio dipole agrees with CMB dipole direction, but

amplitude too large by factor of 4!? Singal 2012; Rubart & Schwarz 2013

Other probes of anisotropies: Hubble expansion rate



hemispherical asymmetry $\delta_H < 0.04$ at 95% CL from $z < 0.2$ SN 1a (here SALT2)

Kalus et al. 2013

Conclusions

◇ Planck confirms WMAP but statistically slightly less significant
different full sky reconstructions vary significantly, but all show the same anomalies

◇ lack of power and correlation at > 60 degrees

◇ alignment of dipole-quadrupole-octopole

◇ proposed explanations fail on one or several aspects
need to explain how they come along, typically go away for arbitrary modifications

◇ ways forward: CMB polarisation, large sky radio surveys, . . .

Anomalies !

Harmonic inpainting

Copi et al. (preliminary)