Probing the Dark Flow signal in WMAP 9yr and PLANCK CMB Maps.

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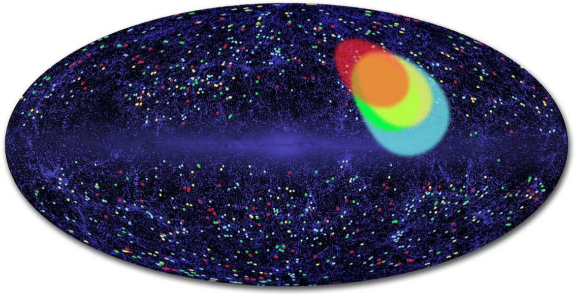
Summary.

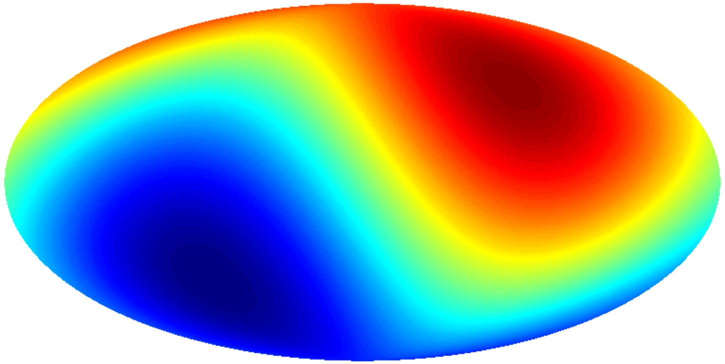


Introduction: The CMB dipole.
Measuring Peculiar Velocities.
Results with WMAP.
Results with PLANCK (Planck Collaboration).
Results with PLANCK (Our Analysis).
Cosmological Implications and Conclusions.

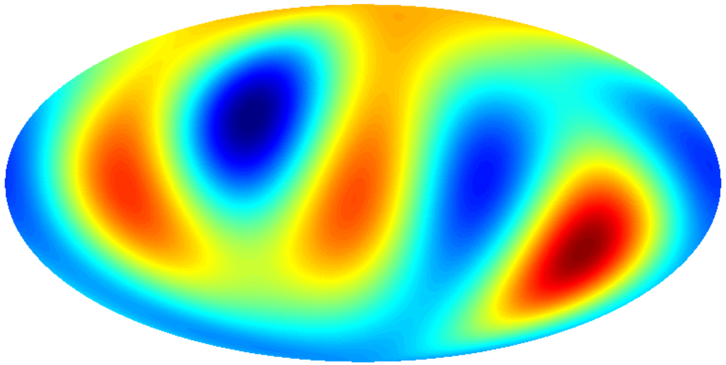
Introduction: The CMB dipole.

The Cosmic Microwave Background.

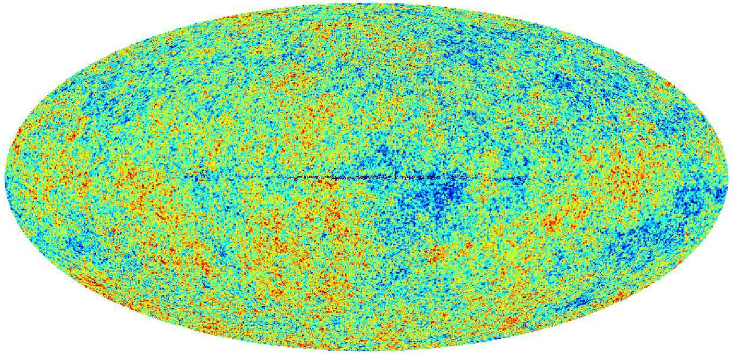
Monopole T=2.73K



Dipole T=3mK



Octupole O=33μK



Planck Nominal Map at 353GHz

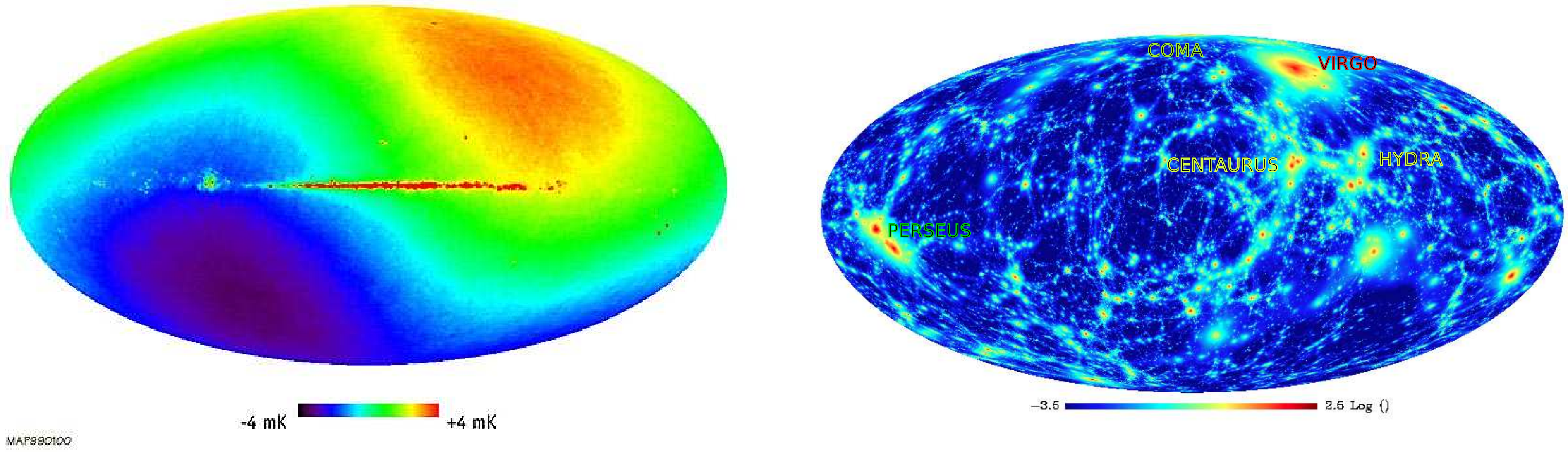
The CMB dipole.

• If density perturbations are adiabatic, generated during inflation, then the low order multipoles verify:

$$\ell(\ell+1)C_\ell = const \quad \Rightarrow \quad 2C_1 = 12C_3 = 12 * 1000(\mu K)^2 \quad \Rightarrow \quad D \sim 70\mu \ll 1mK$$

Then, the dipole CAN NOT BE PRIMORDIAL. It is a Doppler effect due to the local motion of the Local Group with velocity ~ 600km/s in the direction of $l = 270^0$, $b = 30^0$.

The convergence of the CMB dipole.



(Left) CMB dipole measured by COBE. (Right) Large Scale Structure and gas distribution in the Local Universe.

What are the scales that contribute to the $\sim 600km/s$ peculiar velocity of the LG?

Bulk Flows.

The zero order moment of the velocity field is the mean peculiar velocity of a sphere of radius R or bulk flow

$$\langle V^2(R)\rangle = \frac{1}{2\pi^2}\int P(k)W^2(kR)dk \qquad\qquad P(k) = |\delta(k)|^2.$$

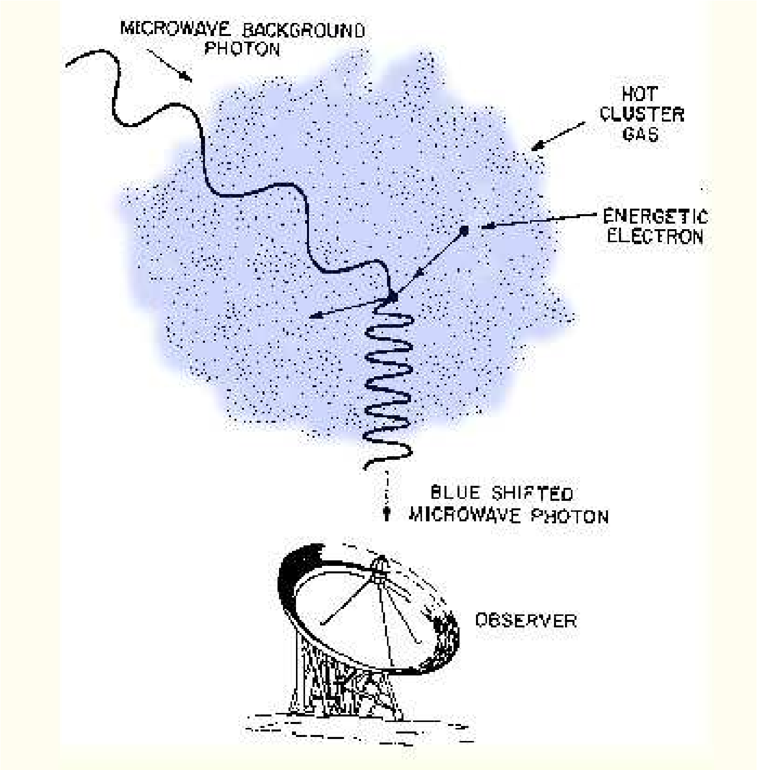
For all scales larger than Matter-Radiation equality [$\sim 100Mpc/h$], bulk flows probe the primordial matter power spectrum generated during inflation.

$$P(k) \propto k \qquad \Rightarrow \qquad V_{rms}(R) \simeq \left(\frac{R}{100Mpc/h}\right)^{-1} 100km/s \qquad \Rightarrow$$

Test of the Inflation Paradigm!!!

Measuring Peculiar Velocities.

The Thermal and Kinematic SZ Effects.



- **Thermal:**

$$\frac{\Delta T}{T}(\hat{n}) = G(\nu)\tau\frac{K_e T_X}{m_e c^2}$$

with $\tau = \sigma_{Th}\int n_e dl$ **and** $G(\nu) \simeq -2$ **in the RJ part of the spectrum and** $G(217GHz) = 0$.

- **Kinematic:**

$$\frac{\Delta T}{T}(\hat{n}) = -\tau\frac{\hat{n}\cdot\vec{v}_{cl}}{c}$$

Measuring Velocities of Individual Clusters.

♠ **In the line of sight of a cluster:**

$$T(\vec{n}) - T_0 = \Delta T_{CMB}(\hat{n}) + T_0\tau\left[G(\nu)\frac{T_X}{mc^2} + \frac{\vec{v}\cdot\hat{n}}{c}\right] + N(\hat{n})$$

Orders of magnitude:

$$T_X = 7KeV,\ \tau = 4\times 10^{-3},\ v = 300km/s \Rightarrow \begin{cases} \Delta T_{tSZ} = -300\mu K\ (RJ) \\ \Delta T_{kSZ} = 10\mu K. \end{cases}$$

♠ **If $\Delta T_{CMB} = 100\mu$K, $Noise = 40\mu$K the error is $\sim 3000km/s$.**

Bulk Flows with the KSZ effect.

Adding the velocities of cluster sample gives their CM motion $\Rightarrow$ BULK FLOW.

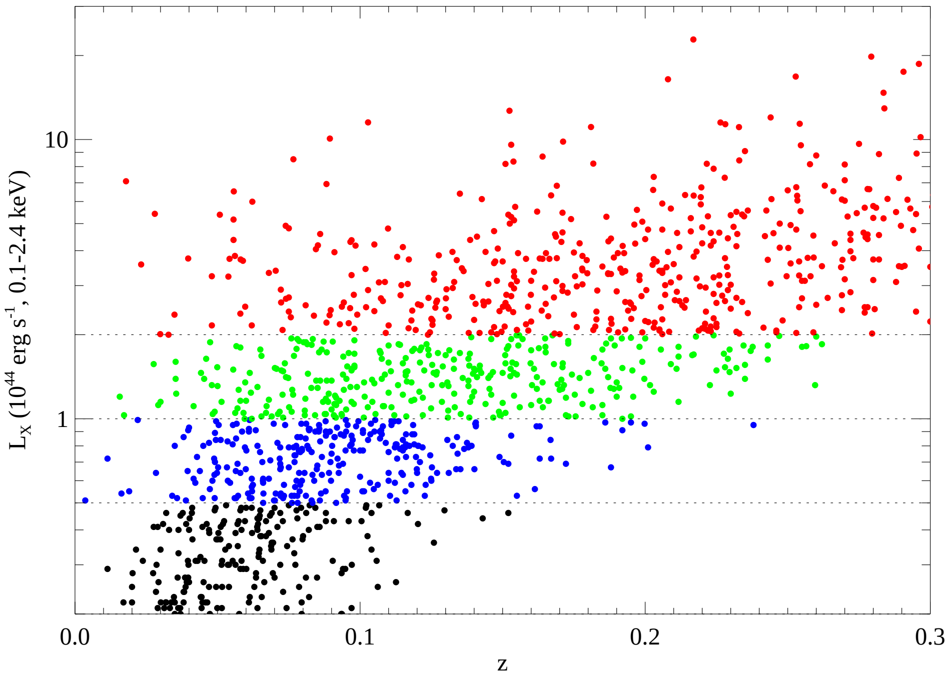
$$a_{1m} = 1\mu K \frac{v}{300km/s} \pm 3\mu K \left[\frac{N_{cl}}{1000}\right]^{1/2} \pm 0.6\mu K \left[\frac{N_{pixels}}{10000}\right]^{1/2} \pm 0.2\mu K \left[\frac{N_{cl}}{1000}\right]^{1/2}$$

signal **Intrinsic CMB** **Noise** **tSZ Dipole**

The dominant source of error is the cosmological CMB signal.

How can we measure the kSZ dipole?

The SCOUT Cluster Sample.



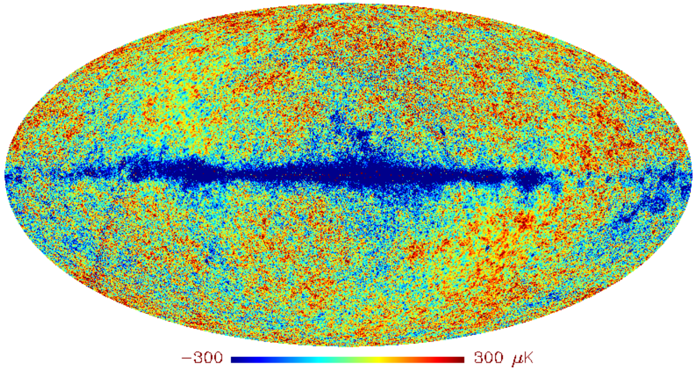
1400 Clusters with $L_X \geq 2 \times 10^{43}$ergs/s

Clusters outside the Galaxy (on 70% of the sky): 1144

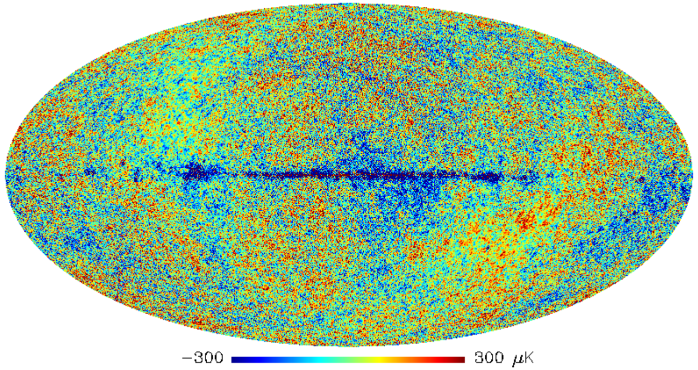
z_{mean}	L_X **bin** 10^{44} **erg/s**	N_{cl}
0.096	**0.5-1**	**225**
0.133	**1-2**	**267**
0.243	> 2	**515**
	TOTAL:	**1007**

Foreground Clean Planck Nominal Maps (30-100GHz).

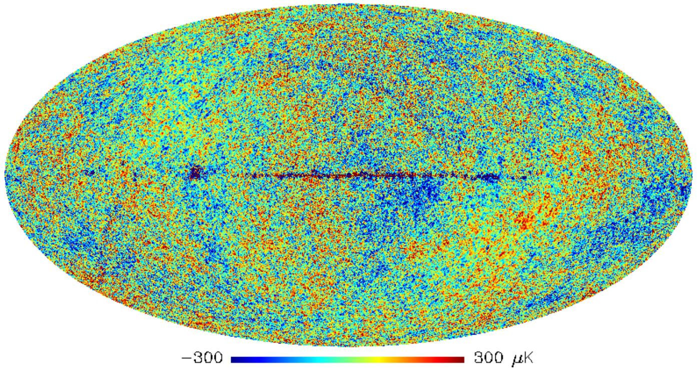
Planck Nominal Map At 30GHz



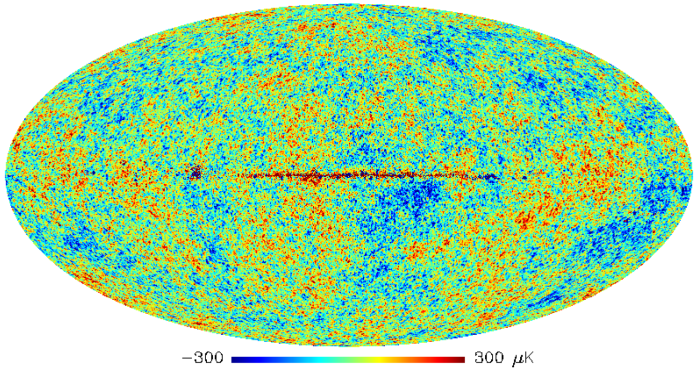
Planck Nominal Map At 44GHz



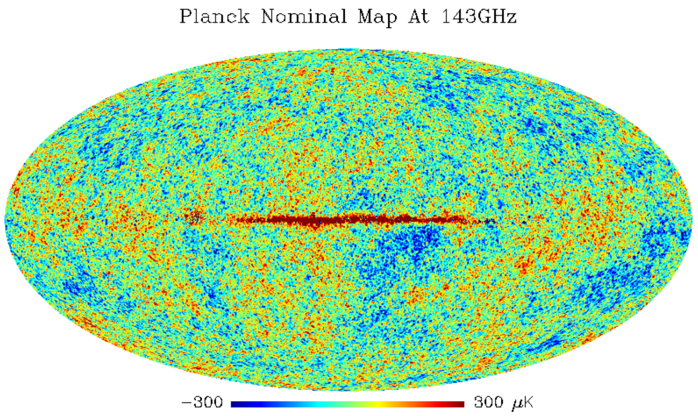
Planck Nominal Map At 70GHz

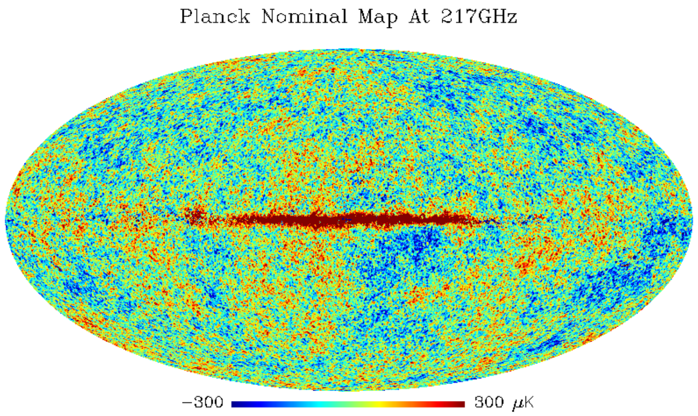


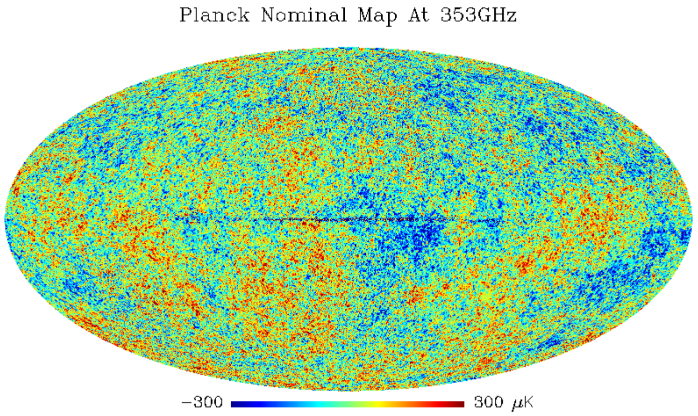
Planck Nominal Map At 100GHz

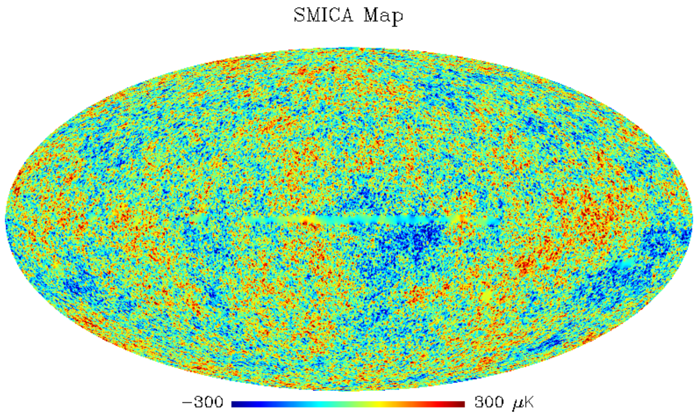


Foreground Clean Planck Nominal Maps (143-353GHz).

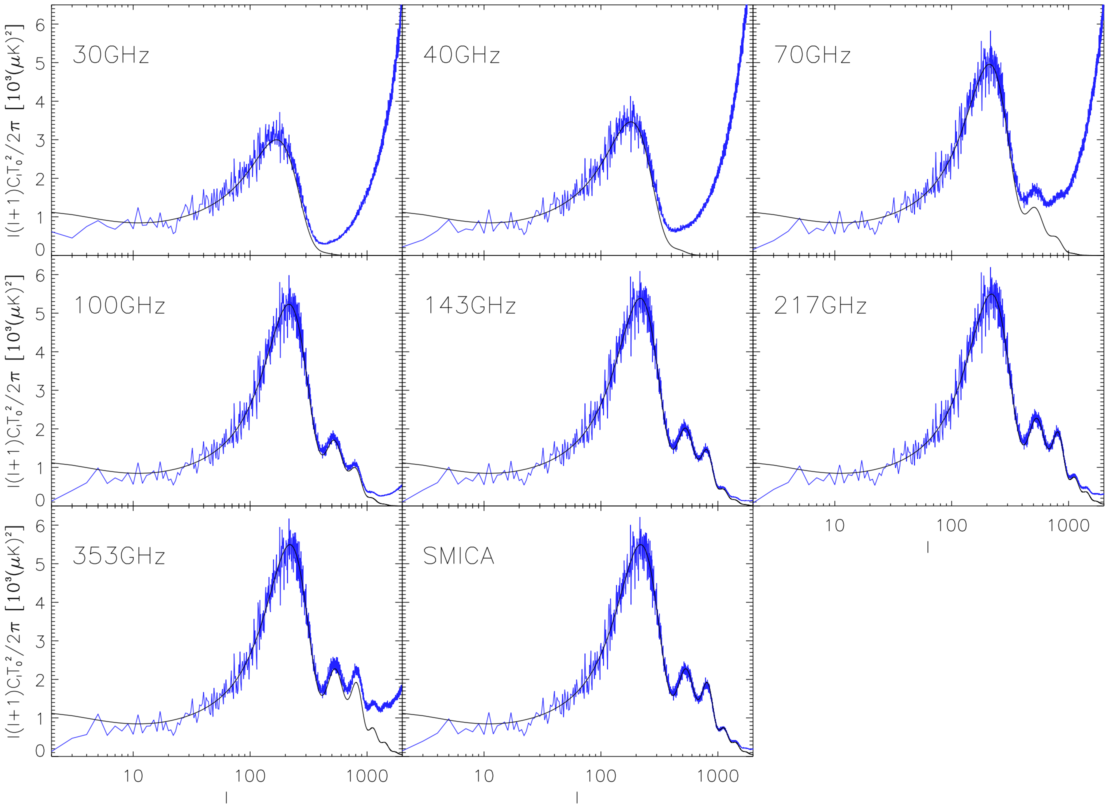








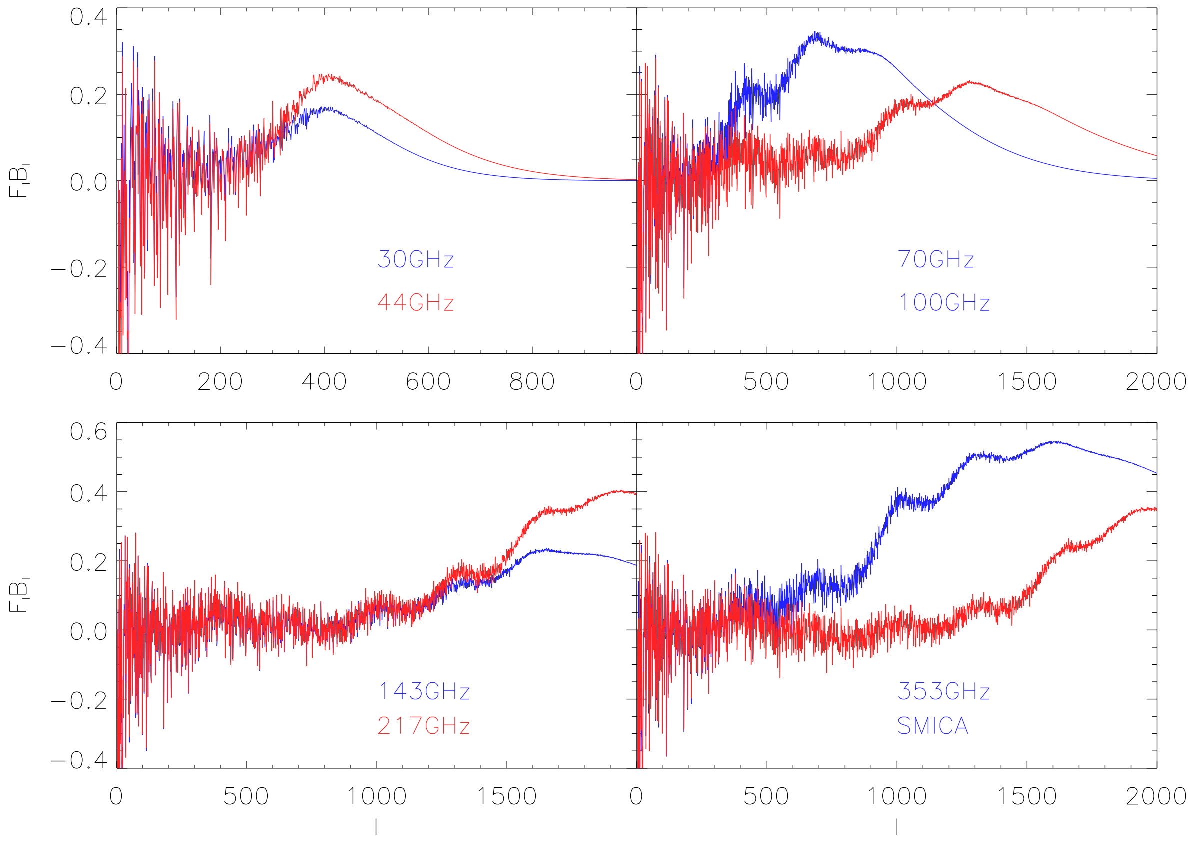
Theoretical and Measured Power Spectra.



Solid line: Theoretical LCDM model with Planck measured parameters $C_\ell^{th} B_\ell^2$.

Broken blue line: measured power spectra $\sum_m |d_{\ell,m}|^2$.

Step III: Removing CMB cosmological signal.

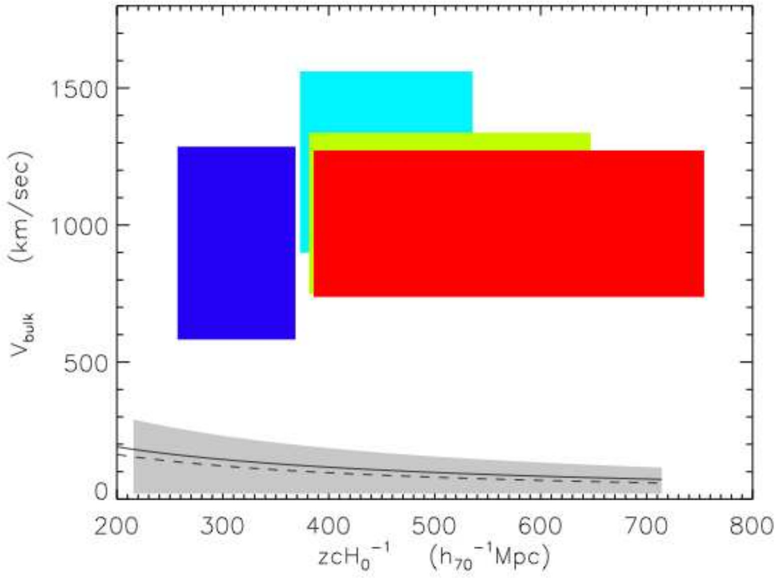


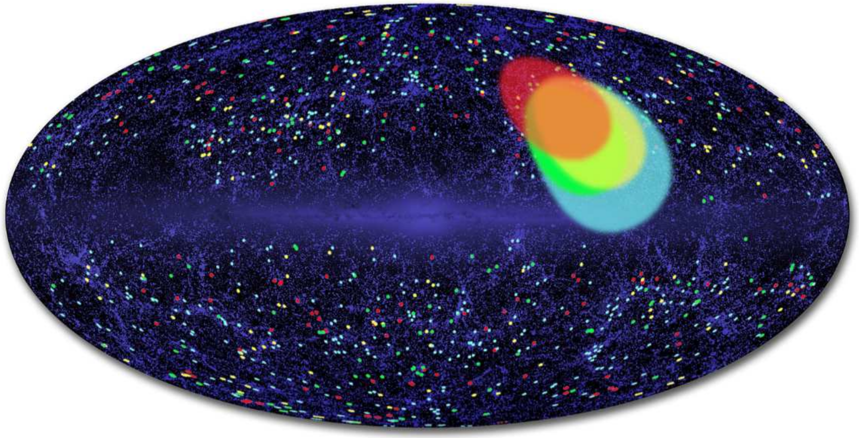
$$F_l = \frac{\sum_m |d_{\ell,m}|^2 - C_\ell^{th} * B_\ell^2}{\sum_m |d_{\ell,m}|^2}$$

♠ **There are 2 contributions: residual CMB and** $noise$**.**

Results with WMAP.

Bulk Flows in WMAP 7yr Data.



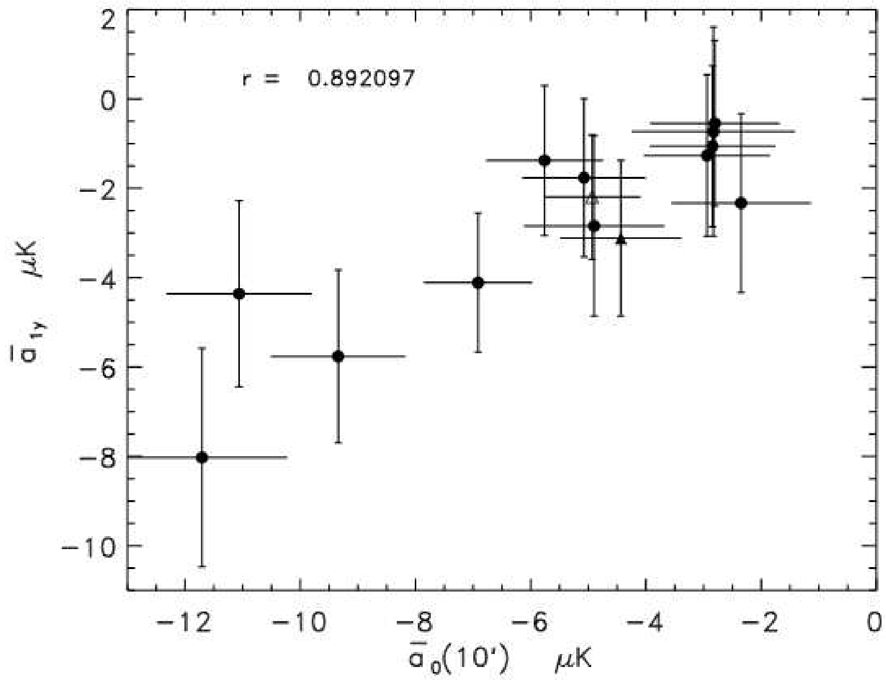


Dipole amplitude measured in μK. The conversion factor to km/s and the scale of the flow are our major uncertainties.

Amplitude and direction of the flow.

Distance/$h_{70}^{-1}Mpc$	N_{cl}	Amplitude/[km/s]	Direction
250-370	**516**	934 ± 352	$(282 \pm 34, 22 \pm 20)^o$
370-540	**547**	1230 ± 331	$(292 \pm 21, 27 \pm 15)^o$
380-650	**694**	1042 ± 295	$(284 \pm 24, 30 \pm 15)^o$
385-755	**838**	1005 ± 292	$(296 \pm 28, 39 \pm 14)^o$
LG-CMB		627 ± 22	$(276^o \pm 3^o; 30^o \pm 3^o)$
SUN-CMB		369.5 ± 22	$(264^o.4 \pm 0^o.3; 48^o.4 \pm 0^o.5)$

L_X-Dipole Correlation.



A Statistical Fluke?

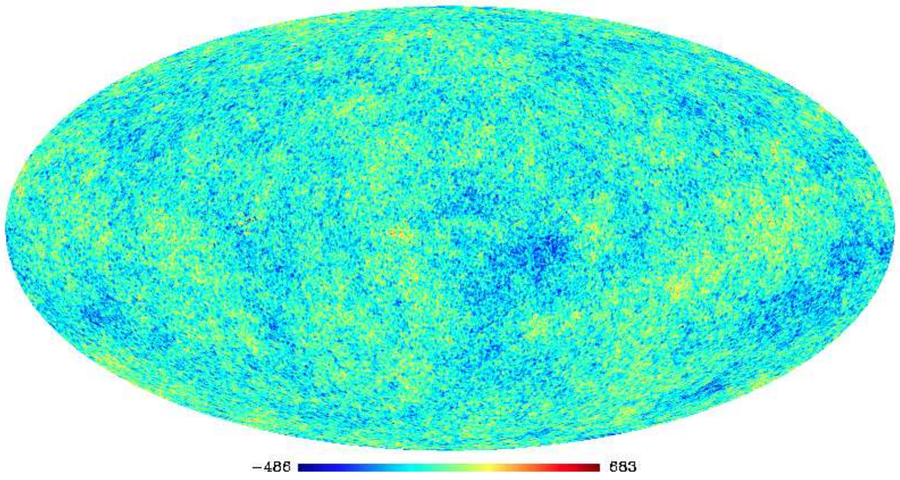
$$v \sim \Delta T/\tau \quad \tau = \sigma_{Th} \int dl n_e.$$

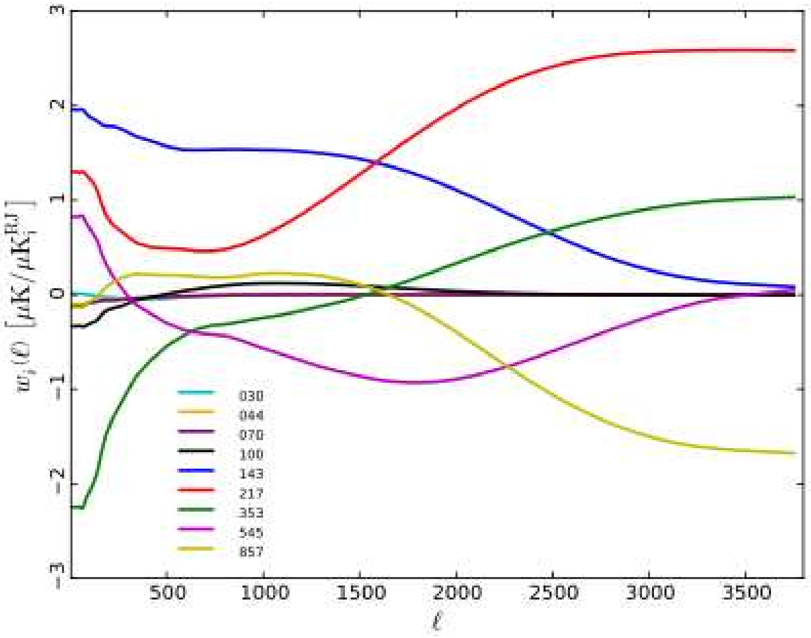
For the signal to be real, IT MUST correlate with X-ray Luminosity (TSZ amplitude). More luminous clusters MUST have larger kSZ signal AS SHOWN.

Could it be TSZ??

Results with PLANCK (Planck Collaboration).

The ILC map.

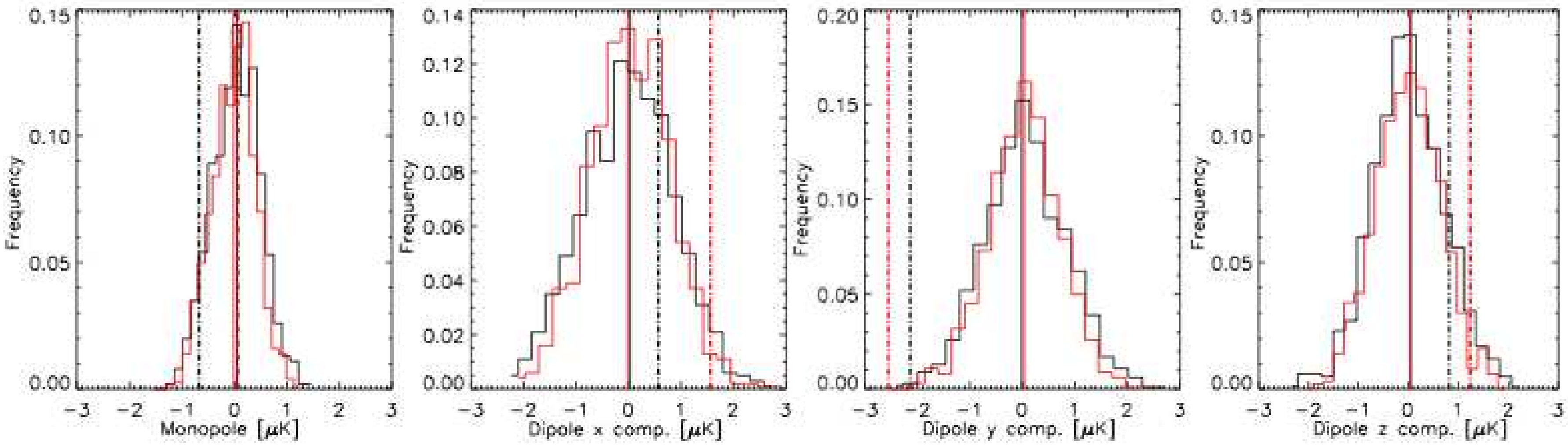




(Right) The Internal Linear Combination used by the Planck Collaboration had the TSZ anisotropy removed.

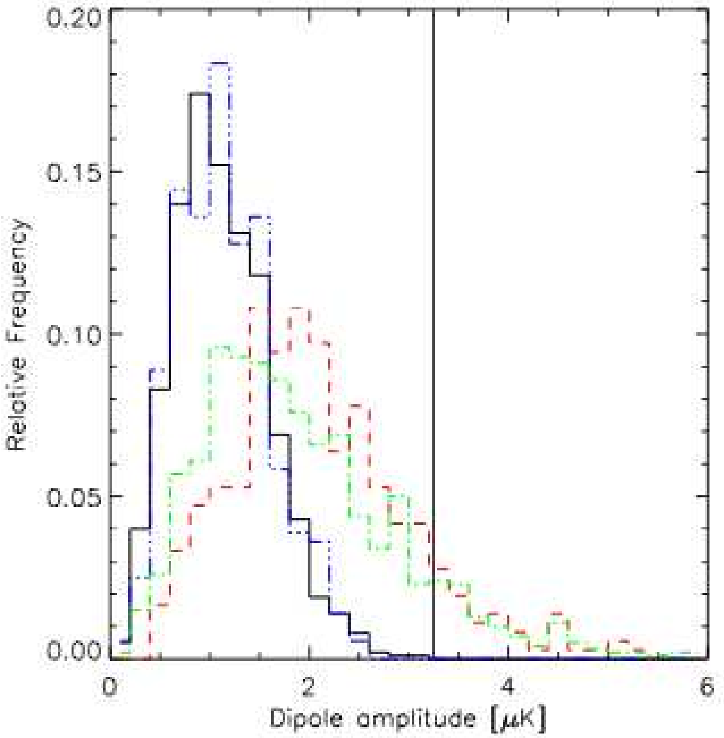
(Left) Weights of the SMICA foreground clean map.

Monopole and Dipole at cluster locations.



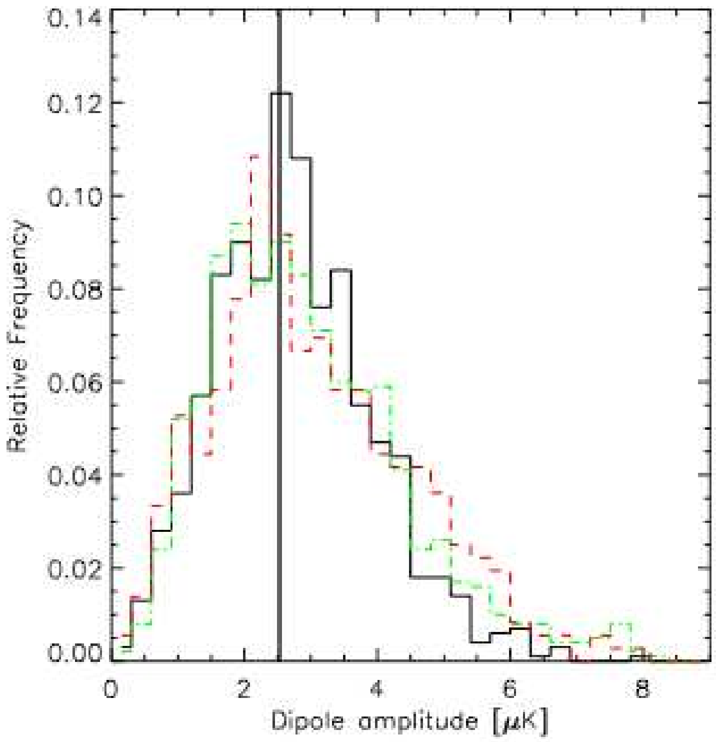
WMAP W-band (black dot-dashed lines) and ILC map results (red dot-dashed) lines and histograms of 1000 realizations of the cluster template outside the cluster positions.

Dipole amplitude.



Histograms of dipole from random clusters on the filtered map (solid black line), rotation of a simulated cluster template (triple dots), rotation of the actual cluster template (red, dashed), random templates on a simulated sky (green).

X-ray Dependence.

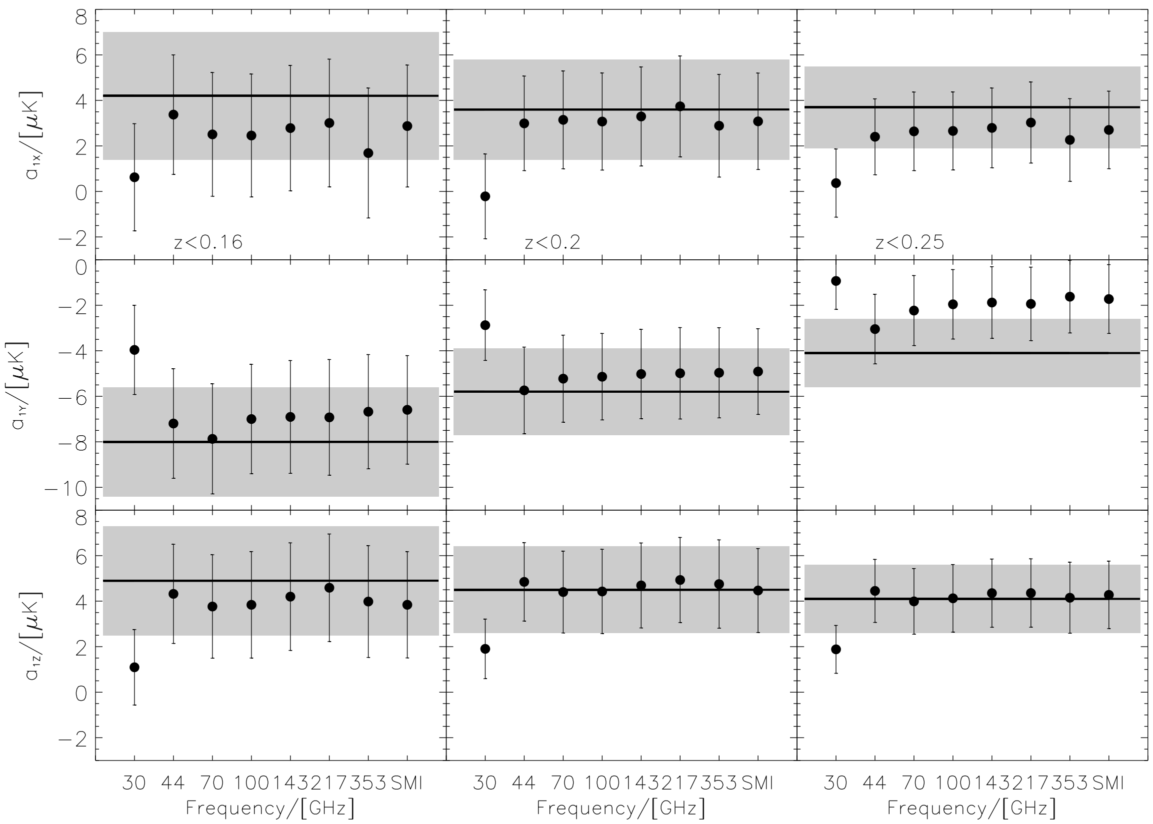


Dipole of the 200 most massive clusters with histograms of the 4 methods.

No X-ray dependence!!

Results with PLANCK (Our Analysis).

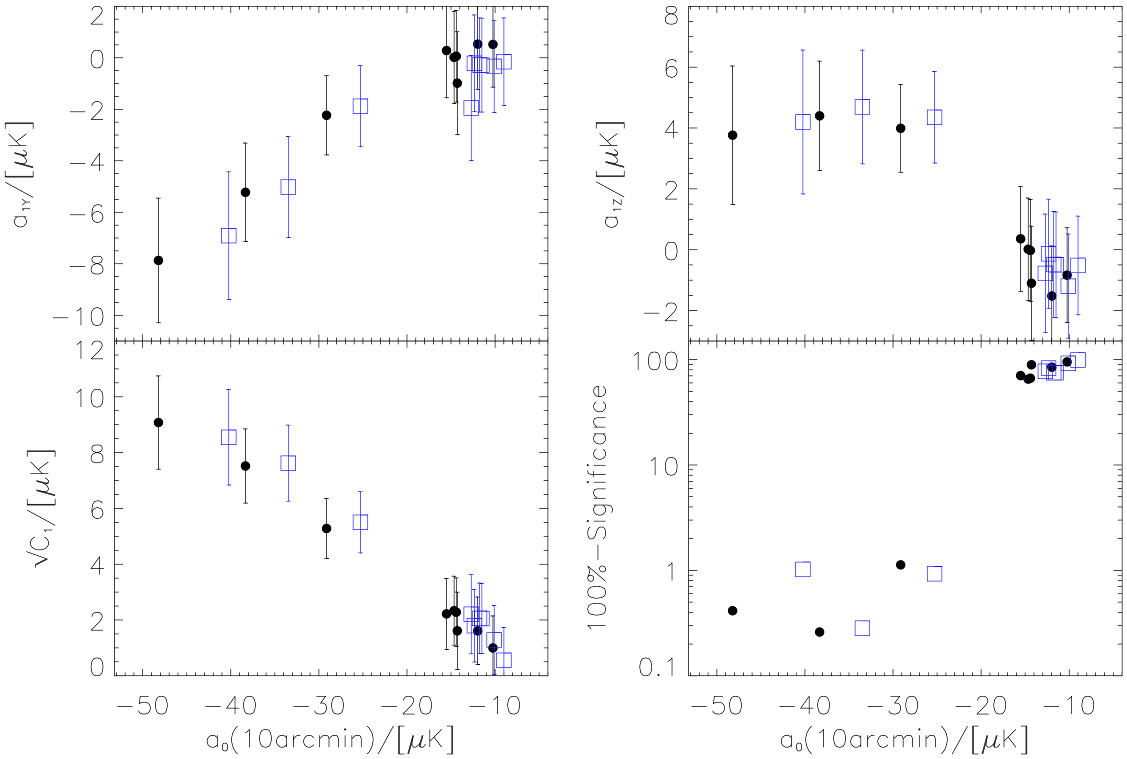
The Dipole is independent of frequency.



Three dipole components for clusters with $L_X > 2 \times 10^{44}$erg/s.

Shaded area: results from WMAP 5yr data.

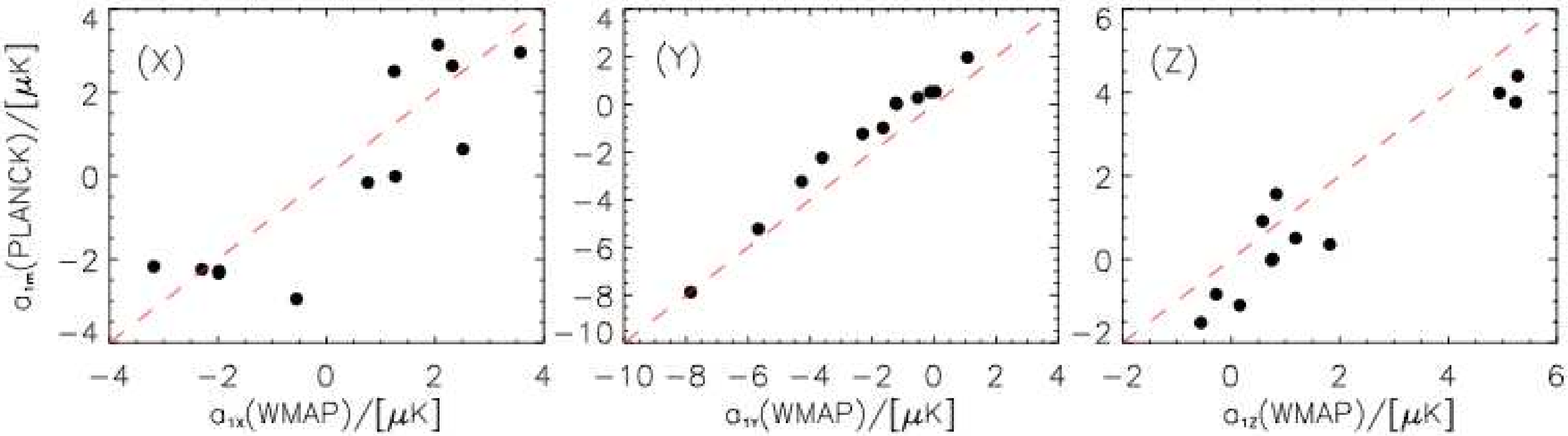
Correlation with X-ray luminosity.



The dipole amplitude correlates with the TSZ signal $\Longrightarrow$

The X-ray dependence persists!

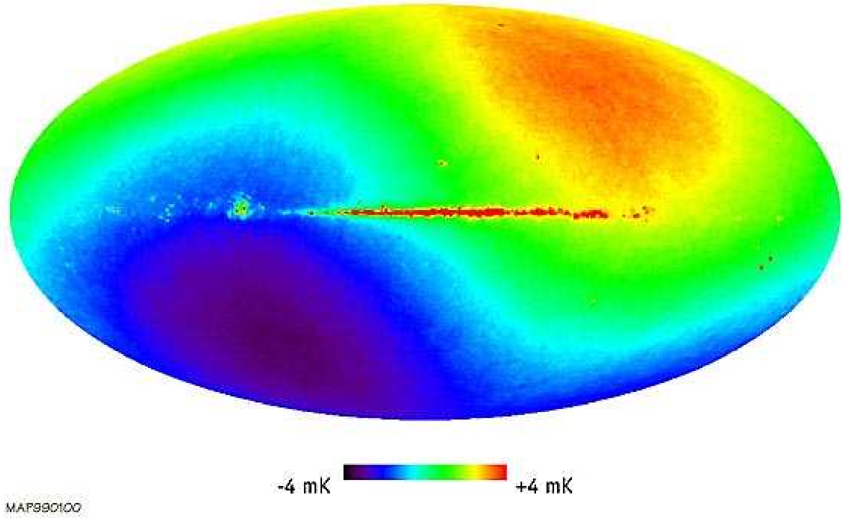
Comparison with WMAP 9yr data.



Comparison of the measured dipoles with Planck and WMAP 9yr data.

Cosmological Implications and Conclusions.

Two interpretations of the dipole.



MRF: Matter rest frame.
ICF: Isotropic CMB frame.

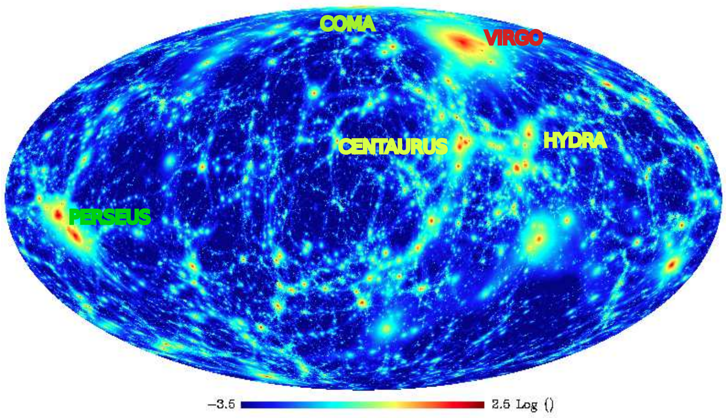
1.- MRF and ICF coincide: The LG moves with peculiar velocity $v_{LG} = 600$km/s.

2.- MRF and ICF DO NOT coincide: The CMB dipole is intrinsic to the last scattering surface.

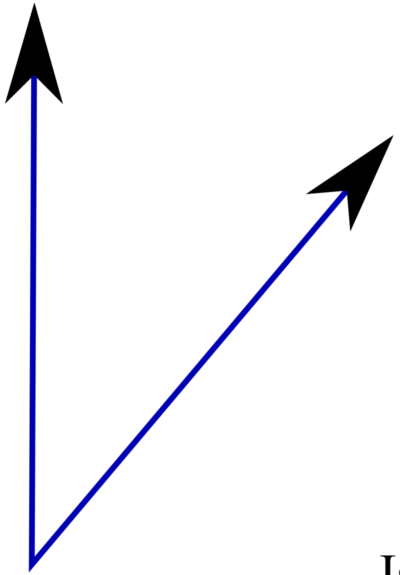
$\Downarrow$

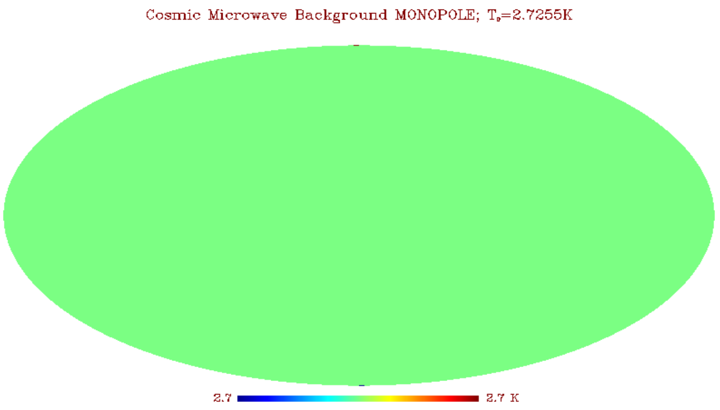
BUT IT CAN NOT BE GENERATED DURING INFLATION.

Is the Universe “tilted”?.



Matter Rest Frame





Isotropic CMB Frame, CMB rest frame

In a tilted Universe, the 4-velocity of observers at rest with the mean matter distribution and observers at rest in the CMB frame does not coincide.

Superhorizon Isocurvature Perturbations.

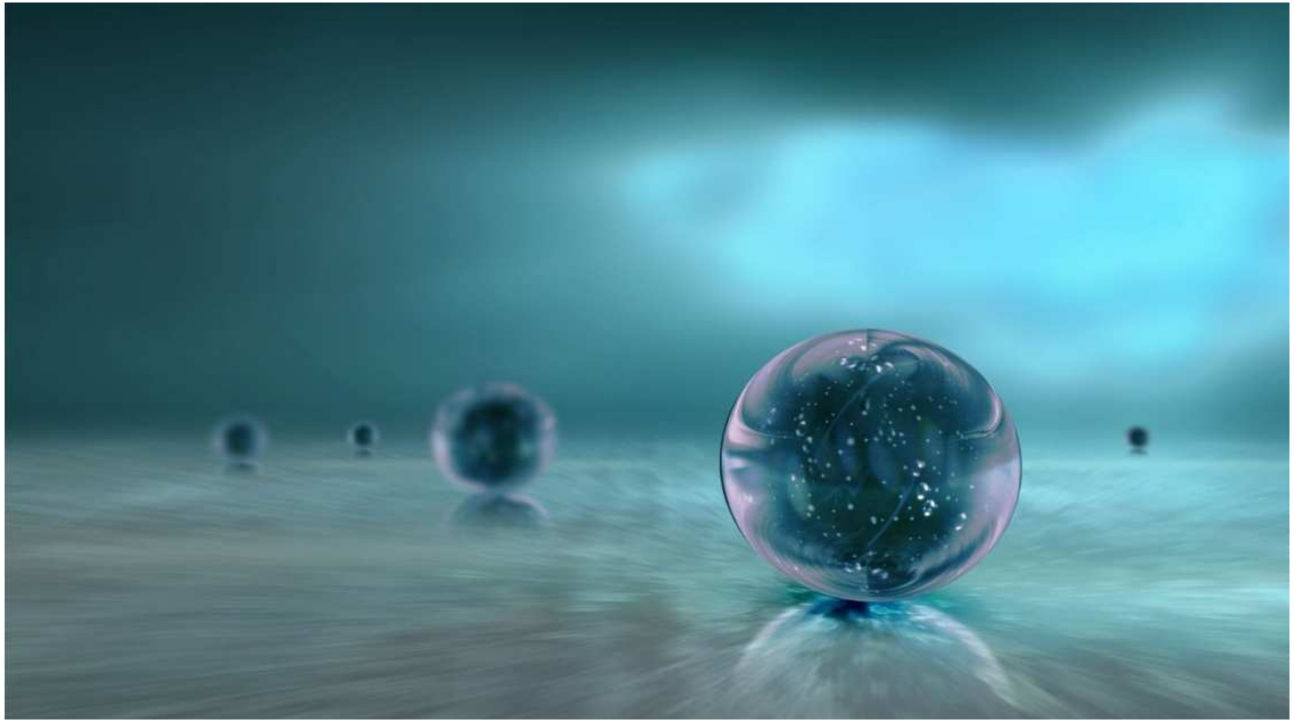
♠ **A Superhorizon Isocurvature perturbations of wavelength L and amplitude δ can produced anisotropies:**

$$\frac{v}{c} \sim \left(\frac{d_H}{L}\right) \delta_L \sim 2 \times 10^{-3} \qquad Q \sim \left(\frac{v}{c}\right) \left(\frac{d_H}{L}\right) \delta_L \sim 4 \times 10^{-6}$$

A pre-inflationary remnant of $\delta_L \sim 1$ and $L \sim 500 d_H$ could generate a 'tilt'.

Is the origin of our local motion dominated by a preinflationary structure of L$\sim 10^3 d_H$?

Pocket Universes.



The Dark Flow could be the observational evidence of the interaction between pocket Universes in a Multiverse Scenario.
From http://www.ozytive.com/2013/09/09/parallel-universe/

Conclusions: Is the flow real?.

- **Two data sets with different systemantics (Planck and WMAP) show consistent results:**

- There is a dipole at the cluster location.

- The signal is persistent from ~ 150 up to ~ 900 clusters.

- The dipole shows a strong correlation with X-ray luminosity.

- It has a statistical significance above 99% for the subset of 320 clusters with $L_X[0.1 - 2.4KeV] > 2 \times 10^{44}$erg/s

- **It does not show a significant profile.**

- **Independent confirmation from peculiar velocities of galaxies, SN, etc, is needed.**

Literary Summary.

The "dark flow" dipole is a statistically significant dipole found at the position of galaxy clusters in filtered maps of CMB temperature anisotropies measured by $WMAP$, roughly aligned with the all-sky CMB dipole and correlated with cluster X-ray luminosity. The signal is dominated by the most massive clusters, with a statistical significance better than 99%.

The dipoles measured in $Planck$ maps agree with the findings in WMAP and, being independent of frequency, rule out the Thermal Sunyaev-Zeldovich as the source of the effect. Since both data sets differ in foreground contributions, instrumental noise and other systematics, the agreement between $WMAP$ and $Planck$ dipoles argues against them being due to systematic effects in either of the experiments.

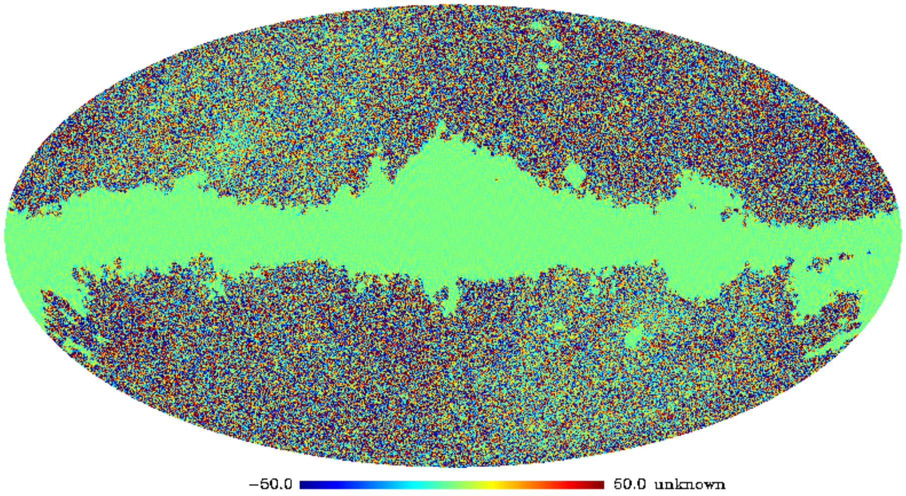
If confirmed, the result implies the Universe is tilted.

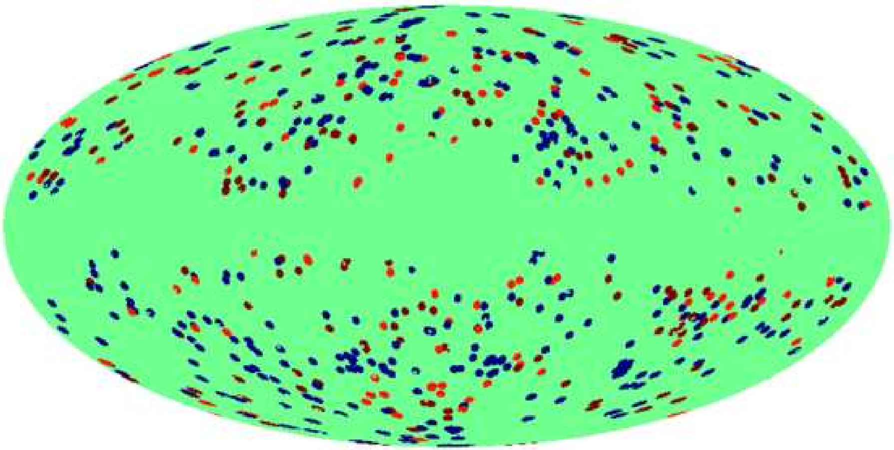
References.

- Kashlinsky & Atrio-Barandela (2000) ApJL, 536, L67
- Atrio-Barandela et al (2004) ApJL, 601, L111
- Atrio-Barandela et al (2008) ApJL 675, L57
- Kashlinsky et al (2008) ApJL 686, L49
- Kashlinsky et al (2009) ApJ 691, 1479
- Kashlinsky et al (2010) ApJL, 712, L81
- Atrio-Barandela et al (2010) ApJ (2010) 719, 77
- Kashlinsky, Atrio-Barandela & Ebeling (2011) ApJ,732, 1
- Atrio-Barandela (2013) A&A, 557, 116
- Atrio-Barandela et al (2014) A&A, submitted. ArXiv:1411.4180

Errors.

Estimating Error Bars.



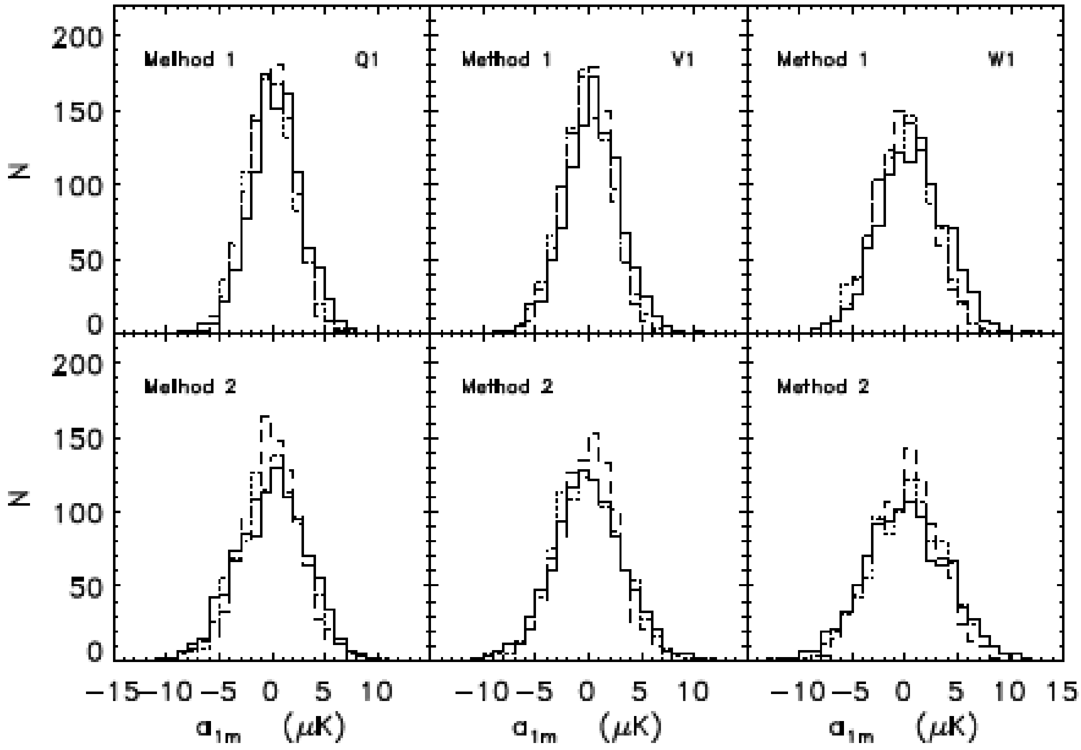


Method 1:

Clusters are placed at random on filtered data.

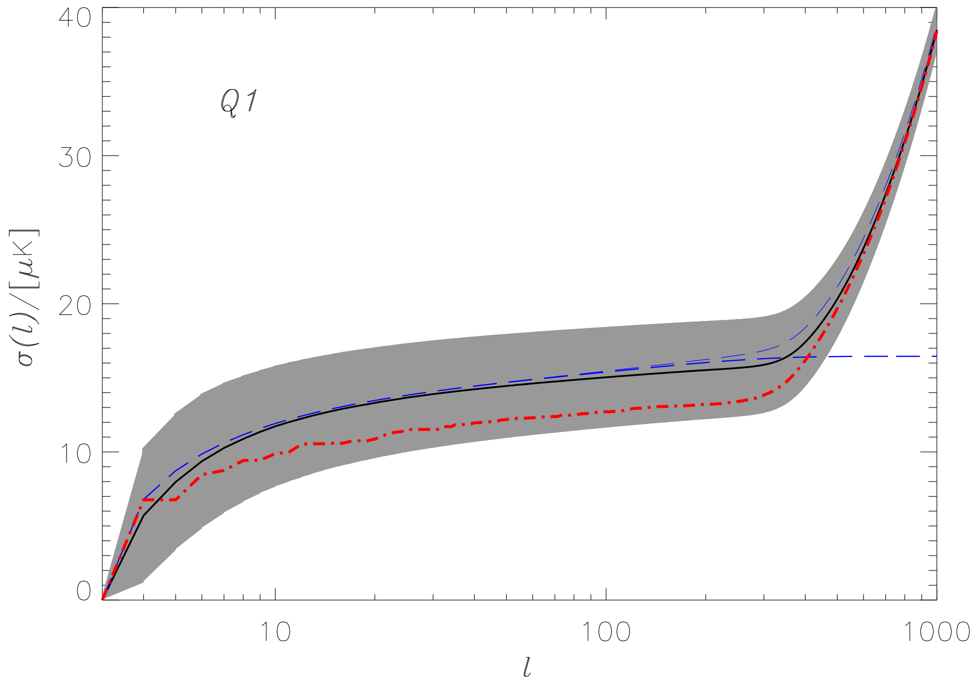
Method 2:

The dipole is estimated over simulated maps with fixed cluster template.



Error bars: a_{1x} (solid), a_{1y} (dotted) and a_{1z} (dashed) for Q1, V1, W1 channels. Upper panels: Method 1; Lower panels: Method 2 (10-15% larger).

The Expected Uncertainty.

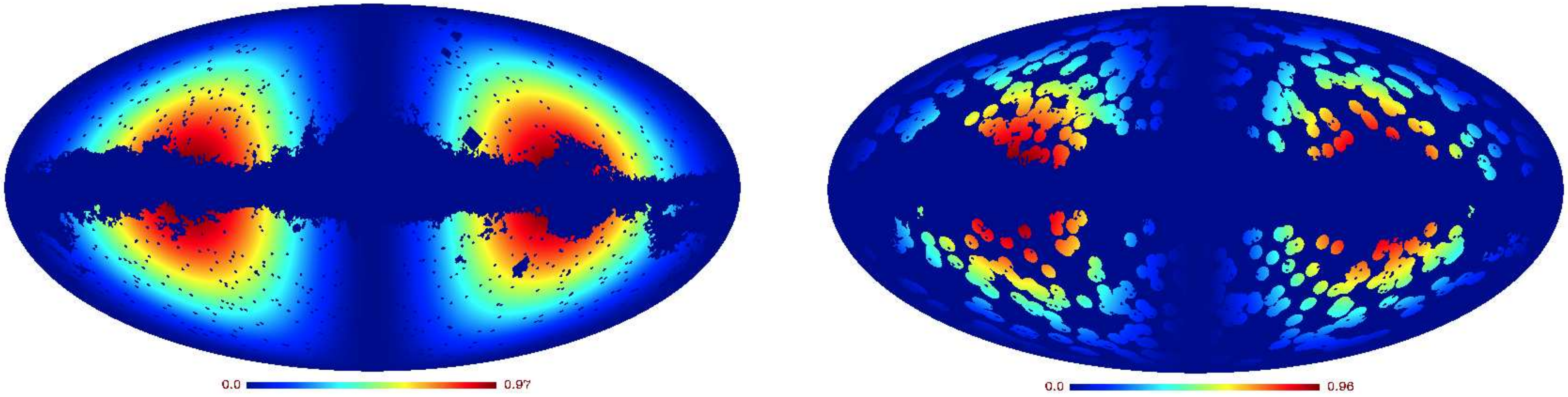


♠ **There are 2 contributions: residual CMB at $l \leq 200$ and $noise$ at $l \geq 200$:**

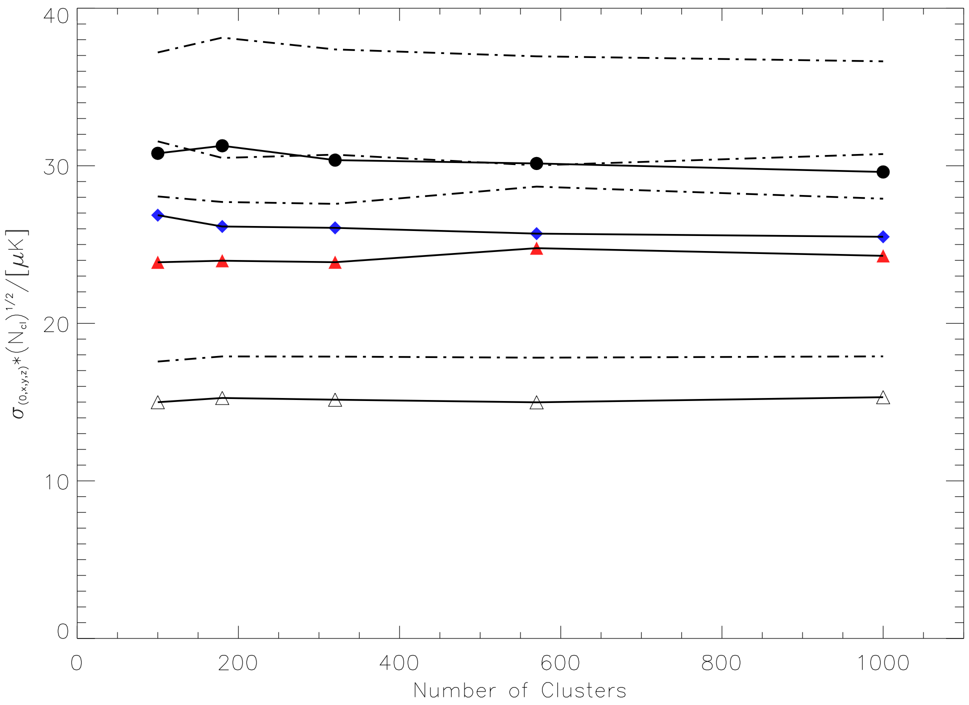
$$\sigma^2 = \frac{\sigma^2_{resCMB}}{3N_{cl}} + \frac{\sigma^2_{noise}}{3N_{DA}N_{pix}}$$

Already in WMAP 5yr, the residual CMB contribution dominates.

The Anisotropy of the Cluster Catalog.



Due to the Mask, the three dipole (X,Y,Z) can not be measured with the same accuracy.

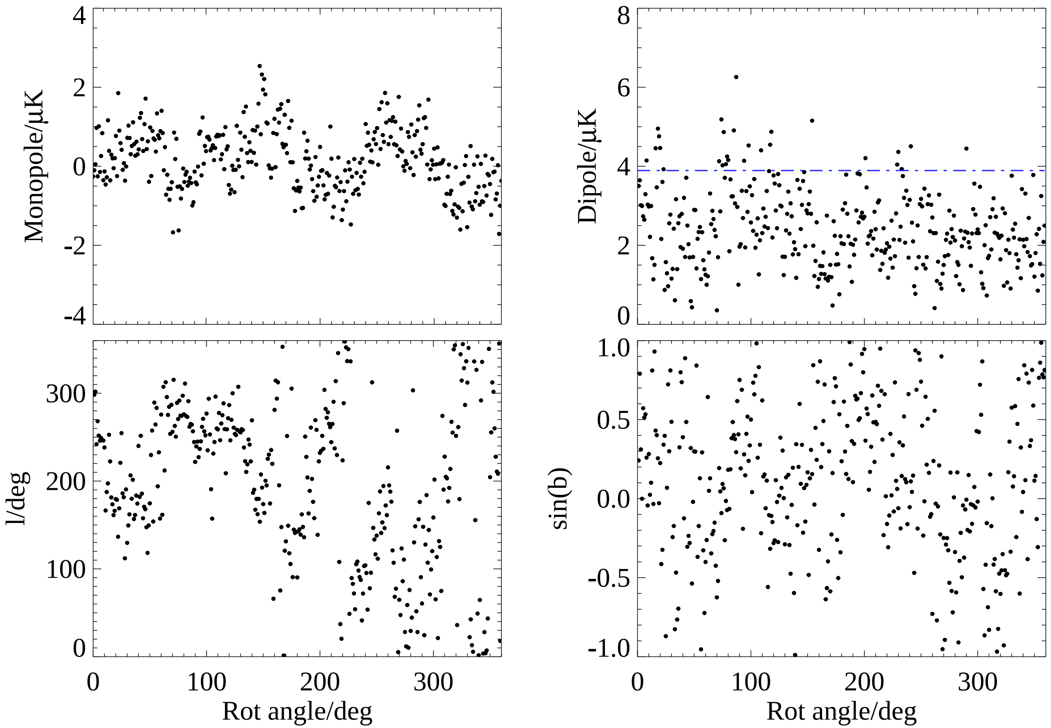


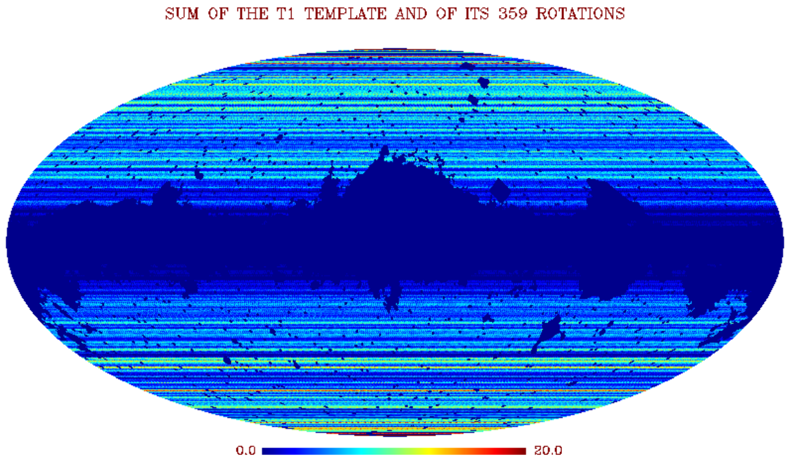
Errors on the X,Y and Z dipole components:

$$\sigma_{[0,x,y,z]} = \frac{[15, 30, 26, 25]}{\sqrt{N_{cl}}}$$

The error budget on the Planck Collaboration Results.

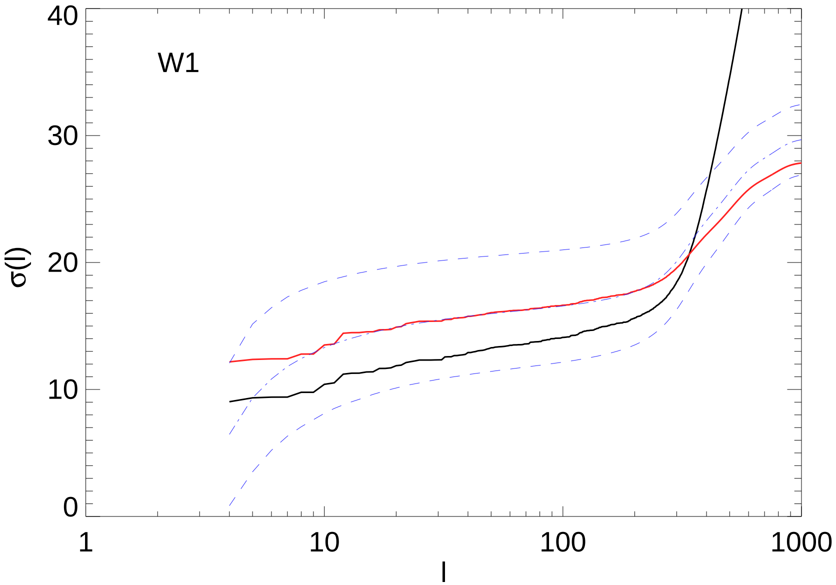
Error bars using rotations.

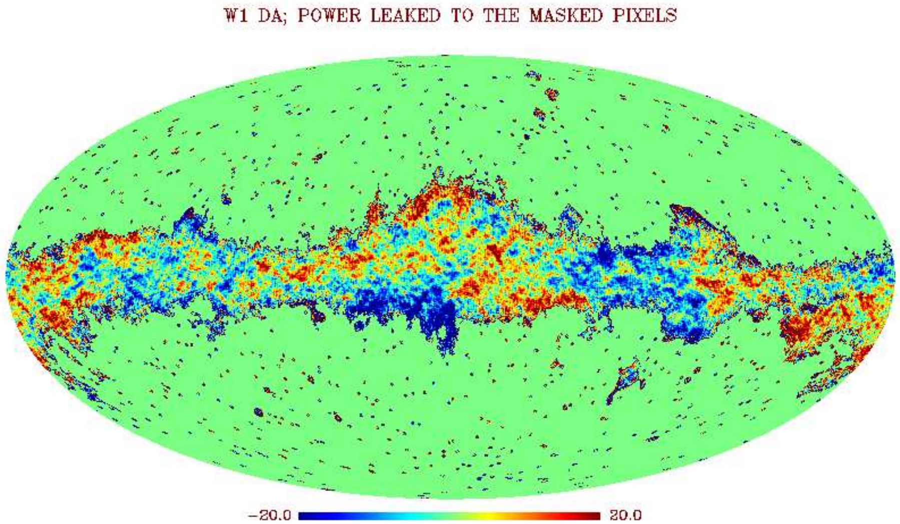




Rotations do not sample the parameter space homogeneously. Increase the error bars by 15%

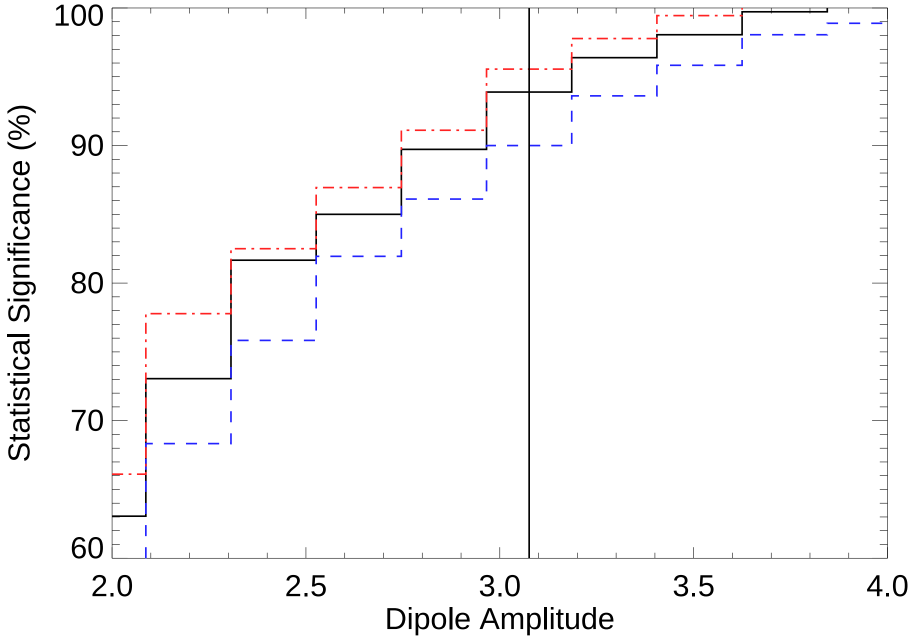
Error bars using simulations.





The average CMB residual of 1000 simulations is larger than that of the actual sky. Power leakage to the mask also reduces the CMB residuals on the real map. Increases the error bars by 15%.

The statistical Significance.



Overestimating the error bars by a factor 15% reduces the statistical significance from 97% to below 90%.