Large Scale Flows with WMAP & PLANCK

Fernando Atrio-Barandela.
Física Teória. Facultad de Ciencias.
Universidad de Salamanca.
eml: atrio@usal.es

In Collaboration with:

A. Kashlinsky, Goddard SFC, Maryland.
D. Kocevski, UC at Davis.
H. Ebeling, University of Hawaii.
A. Edge, University of Durham.

Summary.

1.- Large Scale Flows.
2.- Large Scale Flows with WMAP.
3.- Error Bars.
4.- Cosmological Implications.
5.- Large Scale Flows with PLANCK.

References:

- 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) arXiv:1001.1261.

1.- Large Scale Flows.

♠ **For a given matter power spectrum, the variance of the velocity field on a scale R is:**

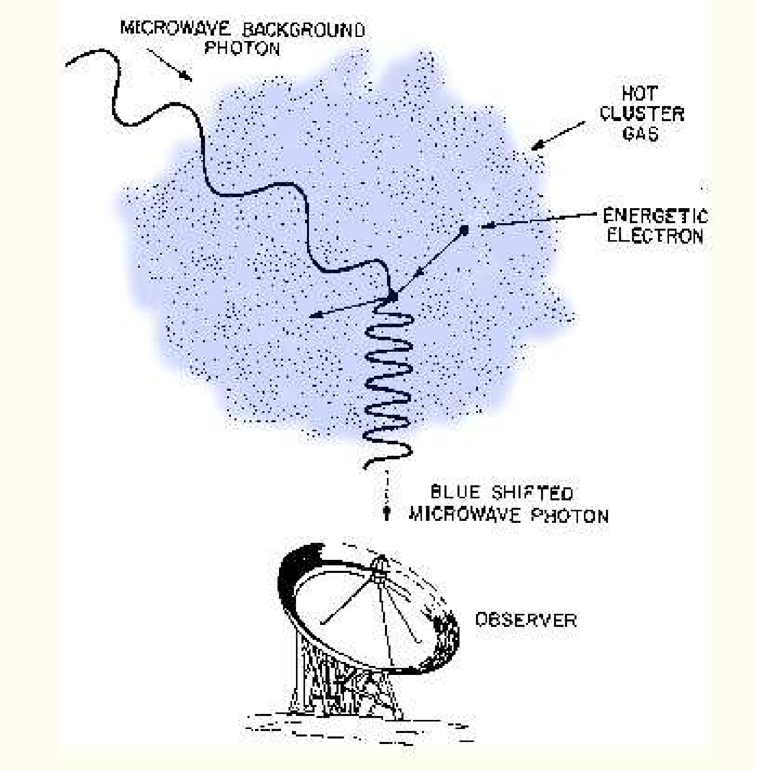
$$\langle V^2(R) \rangle = \frac{1}{2\pi^2} \int P(k) W^2(kR) dk$$

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

$$P(k) \propto k \qquad \Rightarrow \qquad V_{rms} \simeq \left(\frac{r}{100 Mpc/h} \right)^{-1} 300 km/s \qquad \Rightarrow$$

Test of the Inflation Paradigm!!!

The Sunyaev-Zeldovich Effect.



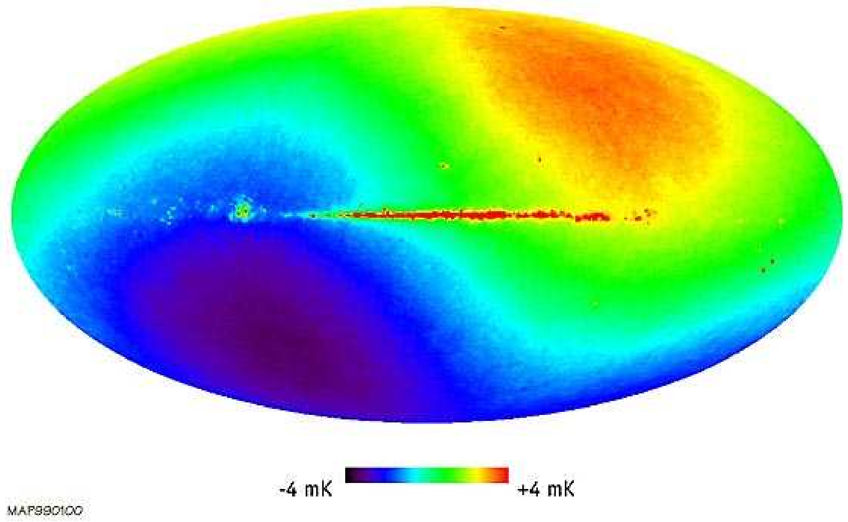
- **Thermal:**

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

- **Kinematic:** Measures the motion of the WHOLE CLUSTER with respect to the isotropic CMB frame.

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

Matter Rest Frame vs Isotropic CMB Frame.



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

1.- MRF and ICF coincide: Clusters move with peculiar velocity v_{cl}.

2.- MRF and ICF DO NOT coincide:
The KSZ effect is generated because in the Cluster rest frame the CMB is not isotropic.

Moments of the Velocity Field at Cluster Locations.

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?

2.- Large Scale Flows with WMAP.

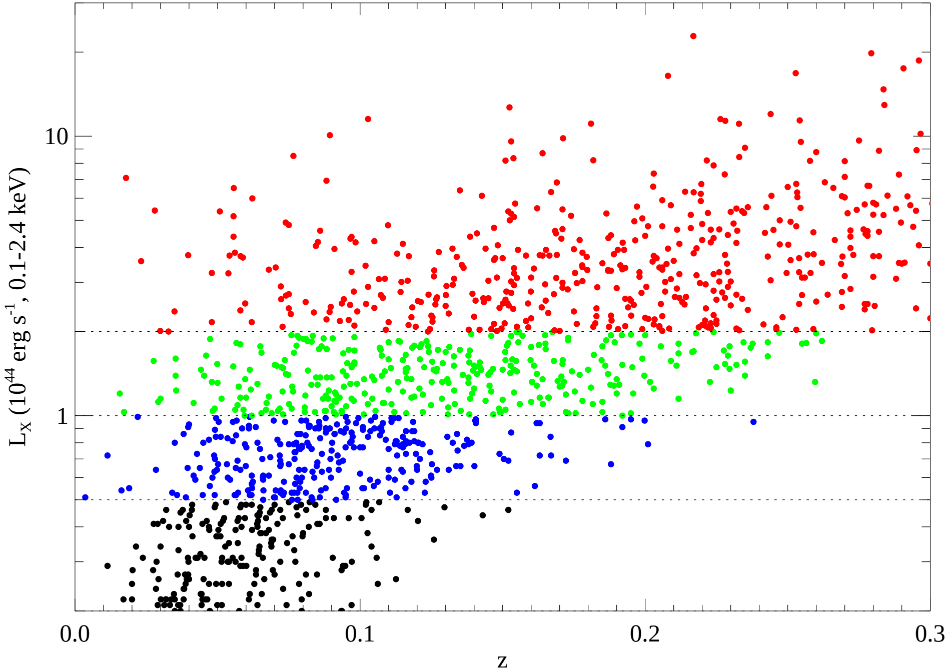
♠ **Ingredients:**

1.- Cluster Sample derived from Rossat All Sky Survey:
a- 660 clusters were used in the analysis of WMAP 3yr
b- 1485 clusters and groups. 838 clusters were used in the analysis of WMAP 5yr.

Is the largest homogeneous X-ray cluster sample ever compiled.

2.- CMB all-sky map.

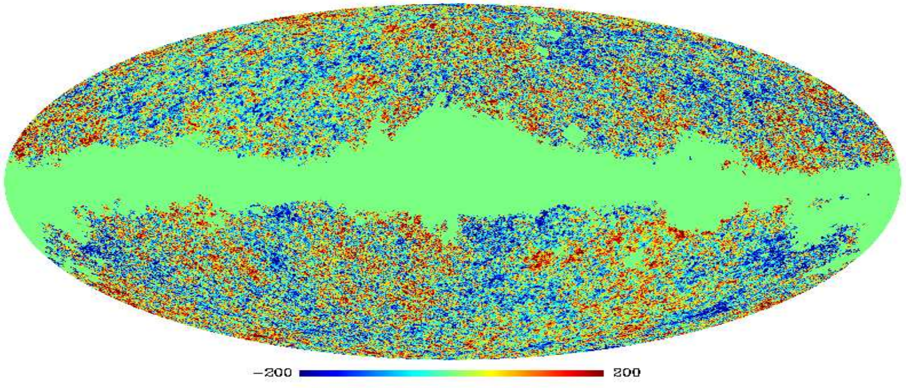
3.- Filter that effectively removes the intrinsic CMB.

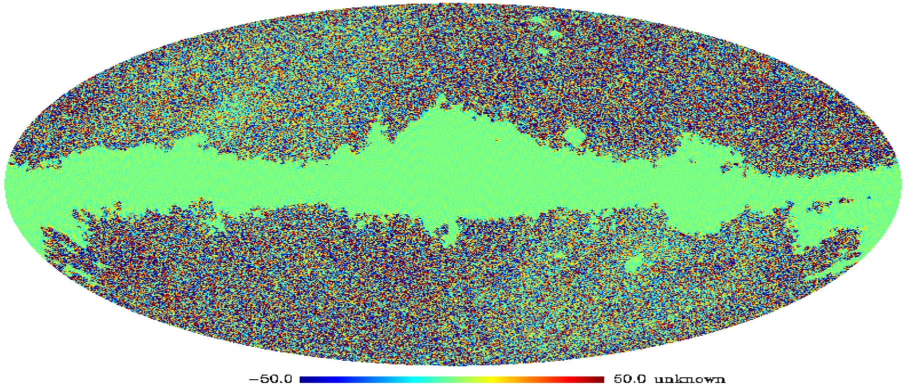


z_{mean}/z_{median}	L_X **bin** 10^{44} **erg/s**	N_{cl}
0.094/0.090	**0.5-1**	**240**
0.133/0.133	**1-2**	**276**
0.169/0.176	> 2	**322**

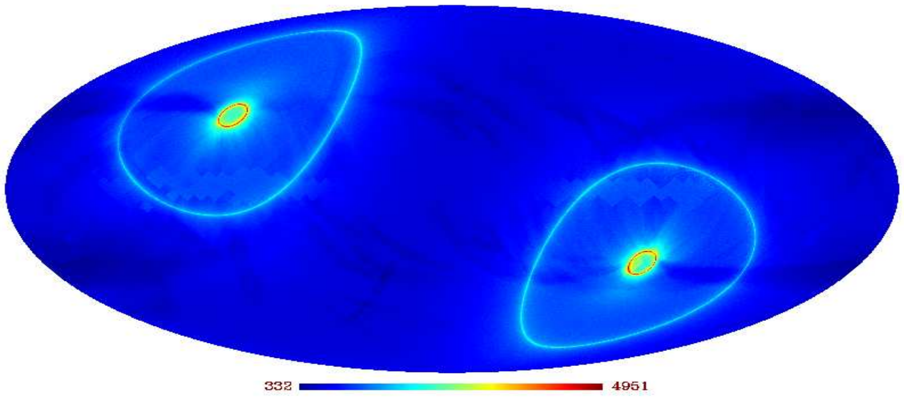
838 clusters with $L_X \leq 0.5 \times 10^{44}$**erg/s.**

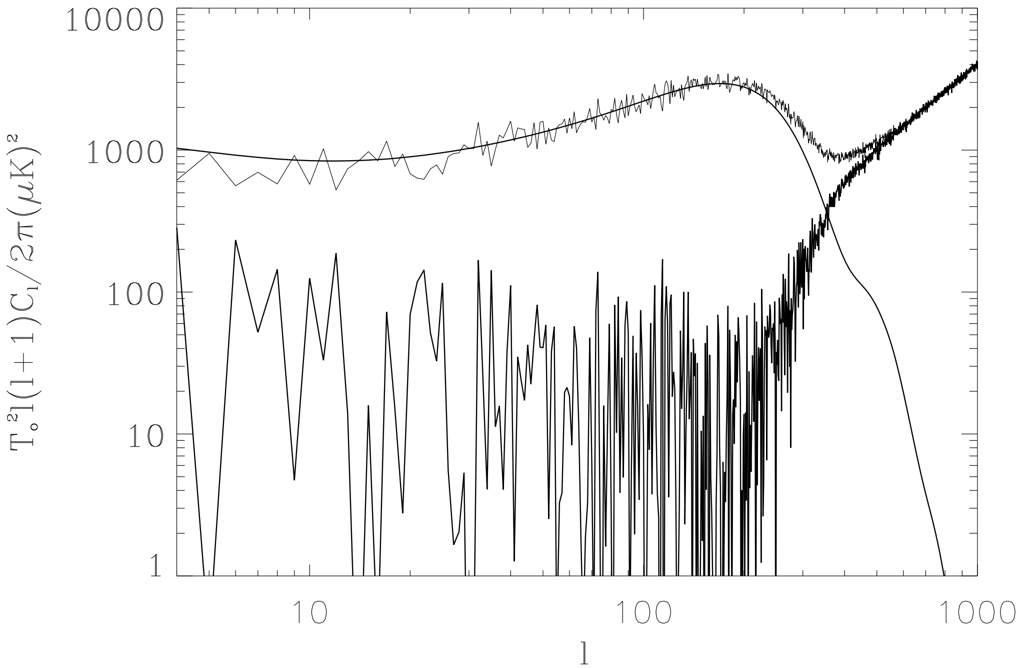
CMB data and Filtered data.





Upper Left: Unfiltered CMB data.
Upper Right: Filtered Q1 Map.
Right: Number of observations.

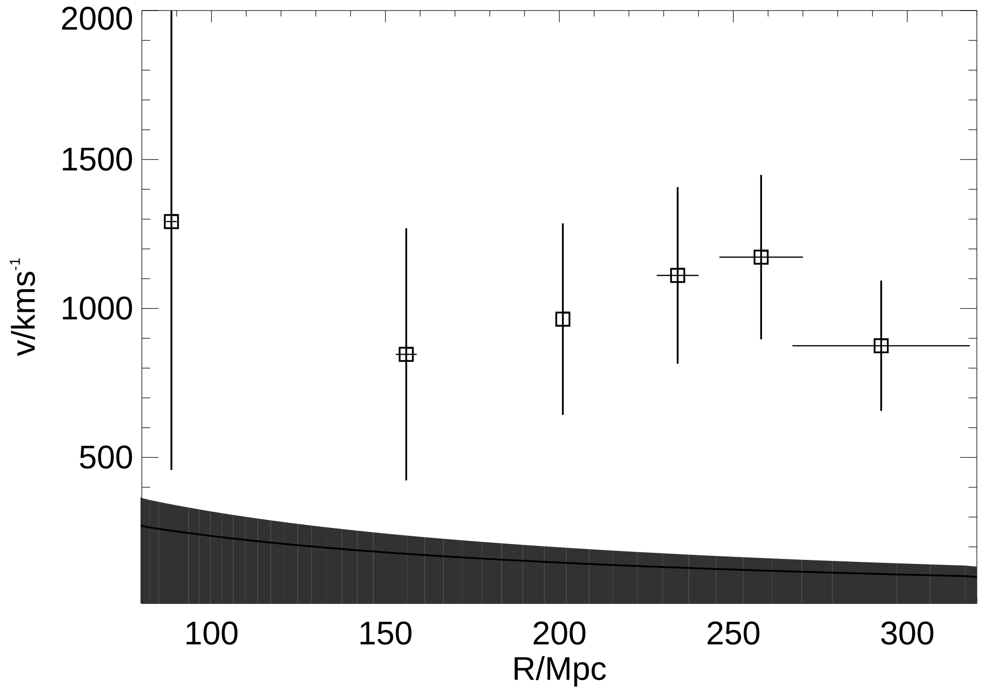




Power spectrum of the original map and filtered maps; ΛCDM best fit model.

Contributions: the residual CMB dominates at $l \leq 200$ and the *noise* at $l \geq 200$.

DARK FLOW in WMAP 3yr Data.



dipole	(l,b)
CMB	$(276^o \pm 3^o; 30^o \pm 3^o)$
Clusters	$(283^o; 11^o) \pm 13^o$

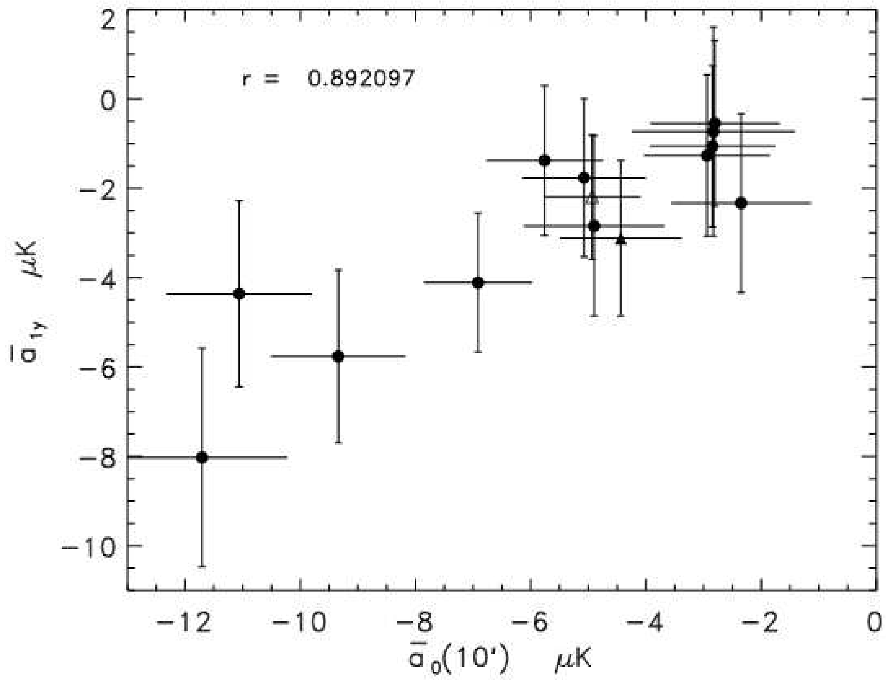
Amplitude and direction, WMAP 3yr.

DARK FLOW in WMAP 5yr Data.

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	$(264^o.4 \pm 0^o.3; 48^o.4 \pm 0^o.5)$

Amplitude and direction, WMAP 5yr.

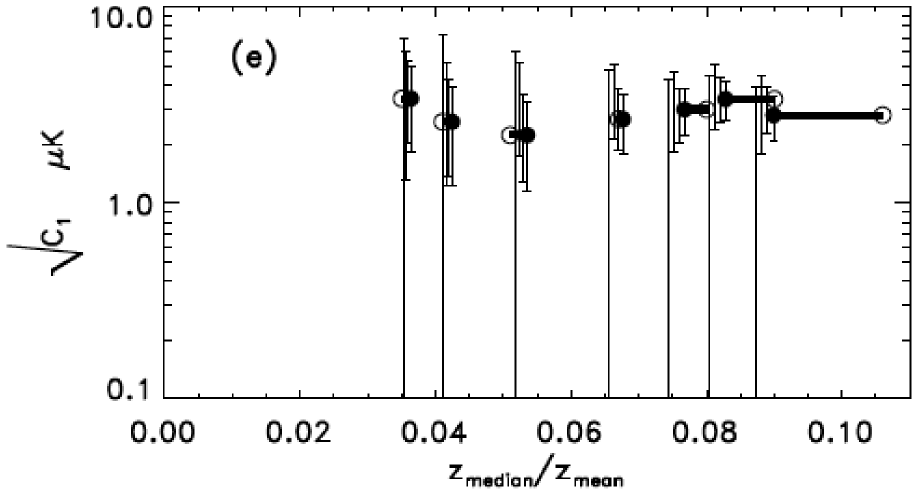
L_X-Dipole Correlation.



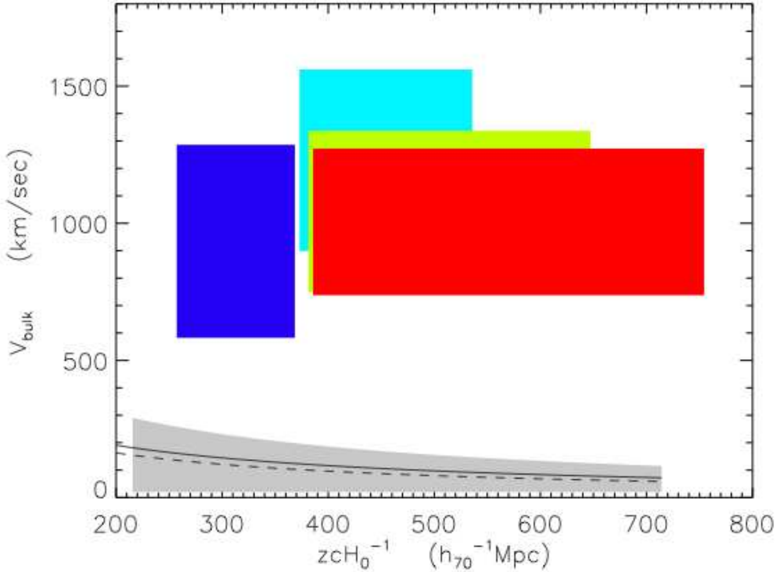
$$v \sim \Delta T/\tau \quad \tau = \sigma_{Th} \int dl n_e.$$

The signal MUST correlate with X-ray Luminosity (TSZ amplitude). More luminous clusters MUST have larger kSZ signal.

Scale and Coherence of the Flow.

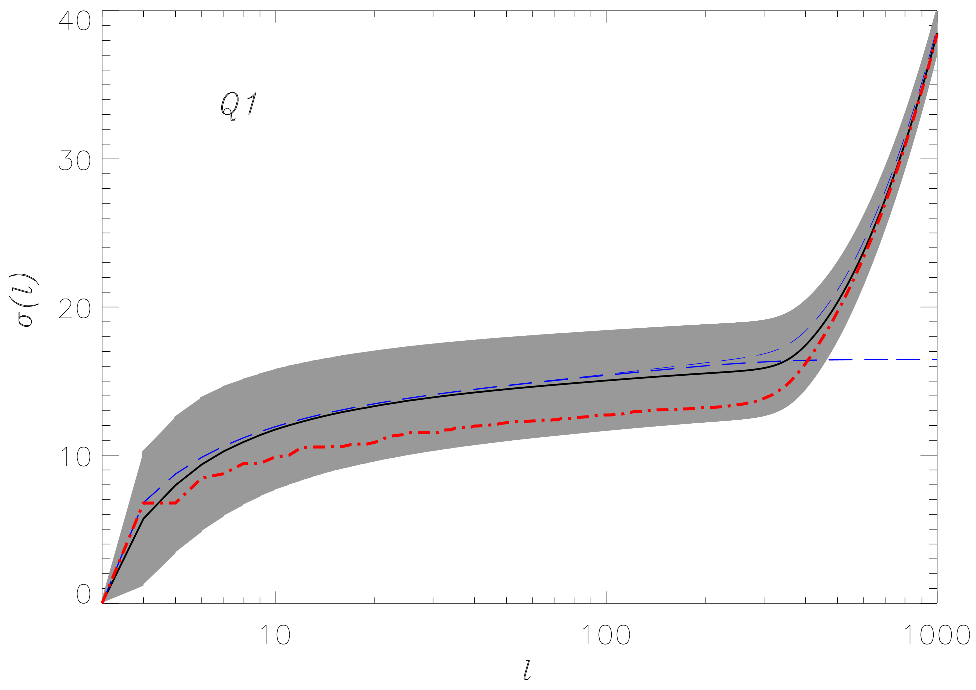


$\longrightarrow$



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

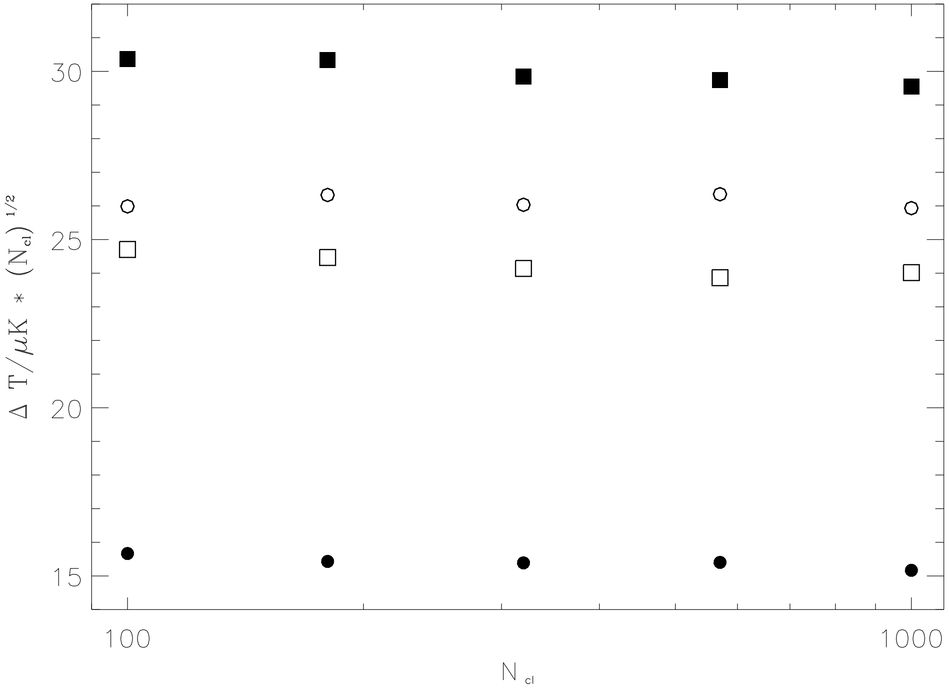
3. Error Bars.



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

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

In WMAP 5yr, the residual CMB contribution dominates.



Due to the anisotropies in the cluster template, the X,Y and Z components are measured with different accuracy:

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

Evidence & Significance.

Our Evidence:

-The signal is present at cluster locations.
-The signal is persistent for subsamples from ~ 150 up to ~ 900 clusters.
-Clusters are not isothermal but follow a NFW profile $\Longrightarrow$ the KSZ component can be measured when the TSZ goes to zero.
-New: The TSZ signal correlates with the cluster dipole.

Statistical Significance:

- $WMAP$ 3yr results: 90%
- $WMAP$ 5yr results: 94%

4. Cosmological Implications.

- Subhorizon
  - 1Gpc void [Garcia-Bellido & Haugboelle ArXiv0810.4939]
  - Dark Energy and Dark Matter reference frames move with respect to each other [Beltran-Jimenez & Maroto ArXiv0812.2206]
- Superhorizon
  - Tilted Universe [Turner 1991].
  - Quantum coherence of vacua in the string landscape [Mersini-Houghton & Holman ArXiv0810.5388].
  - Breaking translational invariance during inflation [Carroll, Tseng & Wise ArXiv0811.1086].

A Tilted Universe?

Can a flow across the horizon exist? [Turner (1991)]

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

$$\frac{v}{c} \sim \left(\frac{cH_o^{-1}}{L}\right)\delta_L \sim 2\times 10^{-3} \qquad Q \sim \left(\frac{v}{c}\right)\left(\frac{cH_o^{-1}}{L}\right)\delta_L \sim 4\times 10^{-6}$$

A pre-inflationary remnant of $\delta_L \sim 1$ requires $L \sim 500cH_o^{-1}$.

5. Large Scale Flows with PLANCK.

	LFI			HFI					
ν/GHz	30	44	70	100	143	217	353	545	857
FWHM/arcmin	33	24	14	9.5	7.1	5.0	5.0	5.0	5.0
δT [μK/sqr-deg]	3.0	3.0	3.0	1.1	1.4	2.2	6.8		
TSZ amplitude	-1.95	-1.90	-1.75	-1.51	-1.04	0.0	2.23	5.9	11

PLANCK vs. WMAP: Higher resolution and frequency coverage. Lower noise levels.

- Eliminate 'undiagnosed' systematics.
- Cluster extent and profile will be derived from CMB data $\Rightarrow$ correct callibration.
- Homogeneously selected cluster sample $\Rightarrow$ scale and coherence of the flow.

Conclusions.

- **We have developped a new method to measure peculiar velocities.**
- **KSZ has very different systematics than peculiar velocity surveys**
- **We have determined a coherent bulk flow on the direction of the CMB dipole on a scale of ~ 750Mpc.**
- **The amplitude of the flow is ~ 1000km/s.**
- **This large scale flow could be generated by density perturbations on superhorizon scales.**