Bulk Flows from Clusters of Galaxies.

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Summary.

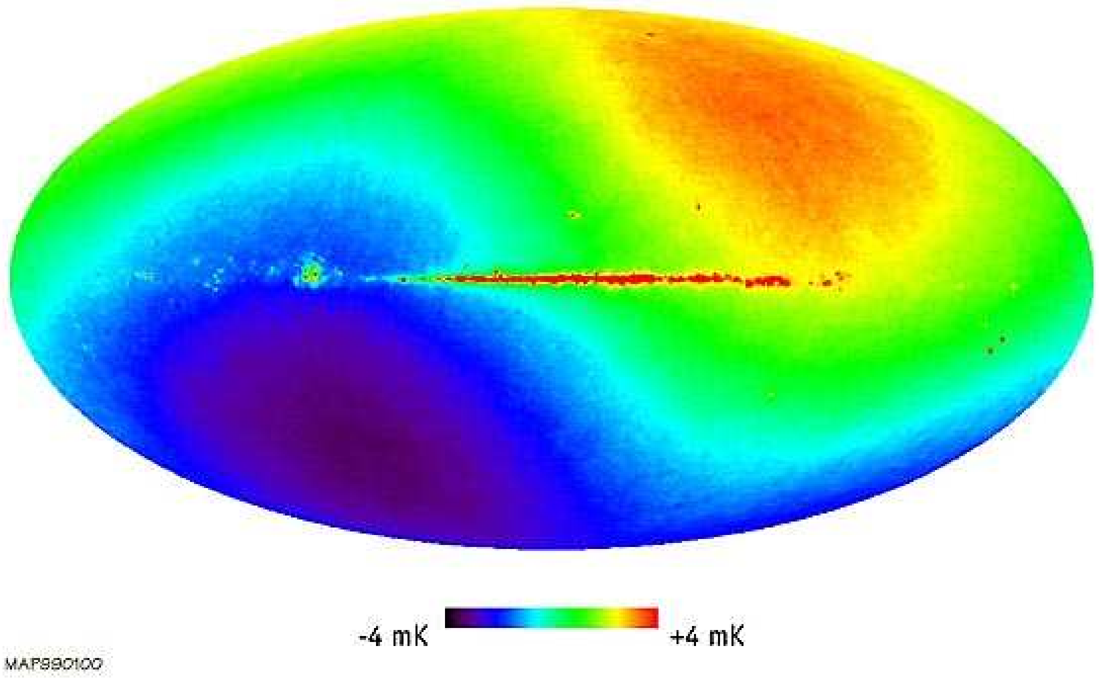
1.- The Problem.
2.- Results with WMAP 5 year data.
3.- Cosmological Implications.

References:

- Atrio-Barandela et al (2008) ApJ 675, L57.
- Kashlinsky et al (2008) ApJ 686, L49.
- Kashlinsky et al (2009) ApJ 691, 1479.
- Kashlinsky et al (2010) ApJ 712, L81.
- Atrio-Barandela et al (2010) 719, 77.

1.- The Problem.

1.1 The CMB dipole.



Is the CMB dipole a Doppler shift generated by the inhomogeneities of the matter distribution near the Local group?

1.2 Peculiar Velocities.

- **Peculiar velocities are local departures of the Hubble expansion:**

$$cz = H_o r + \hat{r}(\vec{v} - \vec{v}(0))$$

Description	Velocity [km/s]	l [deg]	b [deg]	Source
Sun-CMB	369.5 ± 3.0	264.4 ± 0.3	48.4 ± 0.5	Kogut et al (1993)
Sun-LG	308 ± 23	105 ± 5	-7 ± 4	Yahil et al (1977)
LG-CMB	627 ± 22	273 ± 3	30 ± 3	

Distances are required, then peculiar velocities are very hard to measure.

1.3 First Moment of the velocity field: Bulk Flow.

♠ **Motion of the Center of Mass of a region of a given size. Related to the irregularities in the matter distribution $P(k)$.**

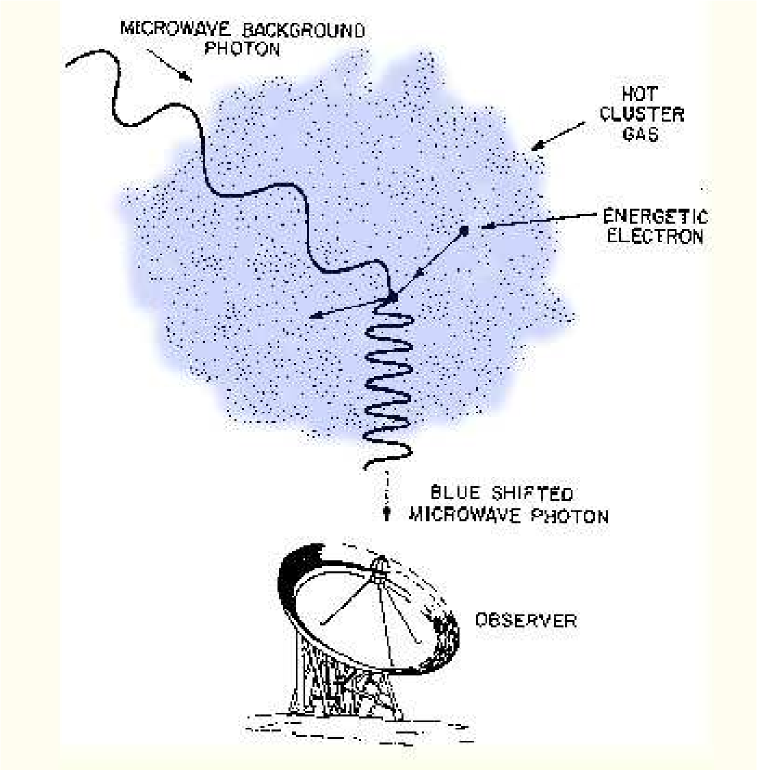
$$\langle V^2(R)\rangle = \frac{1}{2\pi^2}\int P(k)W^2(kR)dk$$

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

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

Test of the Inflation Paradigm!!!

1.4 The Sunyaev-Zeldovich effect.



• **Thermal:**

$$\frac{\Delta T}{T}(\hat{n}) = G(\nu)\sigma_{Th}\int \frac{n_e T_X}{m_e c^2}\hat{n}\cdot d\vec{l} \simeq G(\nu)\tau\frac{n_e T_X}{m_e c^2}$$

• **Kinematic:**

$$\frac{\Delta T}{T}(\hat{n}) = \frac{\hat{n}\cdot\vec{v}_{cl}}{c}\sigma_{Th}\int n_e dl = \tau\frac{\hat{n}\cdot\vec{v}_{cl}}{c}$$

1.5 Moments of the velocity field at cluster locations.

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

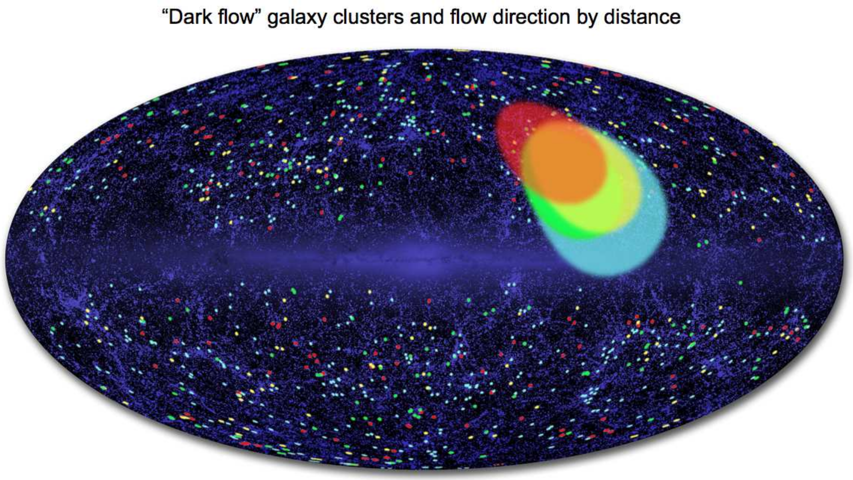
$$a_{1m} = 1\mu K \frac{v}{300km/s} \pm 3\mu K \left[\frac{N_{cl}}{1000}\right]^{1/2} \pm 0.6\mu K \left[\frac{N_{pixels}}{10000}\right]^{1/2} \pm 0.2\mu K \left[\frac{N_{cl}}{1000}\right]^{1/2}$$

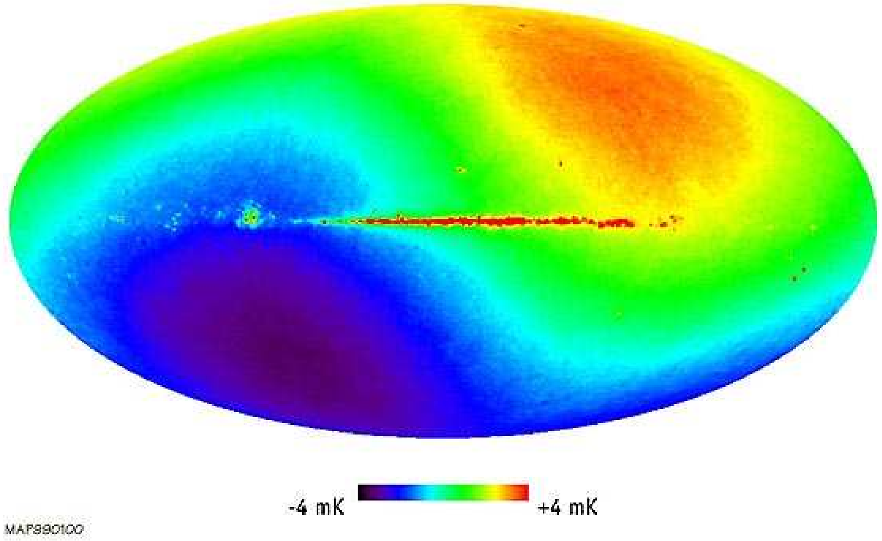
signal **Intrinsic CMB** **Noise** **tSZ Dipole**

The dominant source of error is the cosmological CMB signal.

2.- Results with WMAP 5yr data.

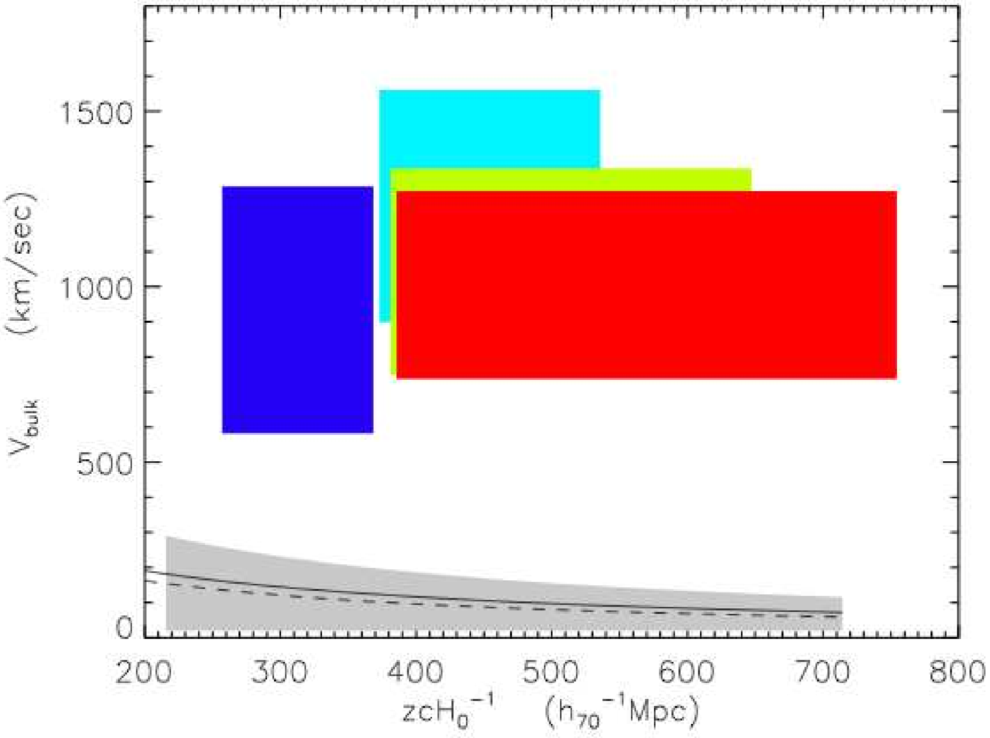
2.1 Cluster DARK FLOW: Direction.





Direction of the cluster bulk flow for subsamples with $max(z) = 0.12, 0.16, 0.2, 0.25$ **and direction of the CMB dipole.**

2.2 Cluster DARK FLOW: Amplitude.



Amplitude of the flow for different subsamples.

color	max(z)	N_{cl}
Blue	0.12	516
Cyan	0.16	547
Yellow	0.20	694
Red	0.25	838

2.3 Is the Signal a Statistical Fluke?.

Our Evidence:

-The signal is present at cluster locations.

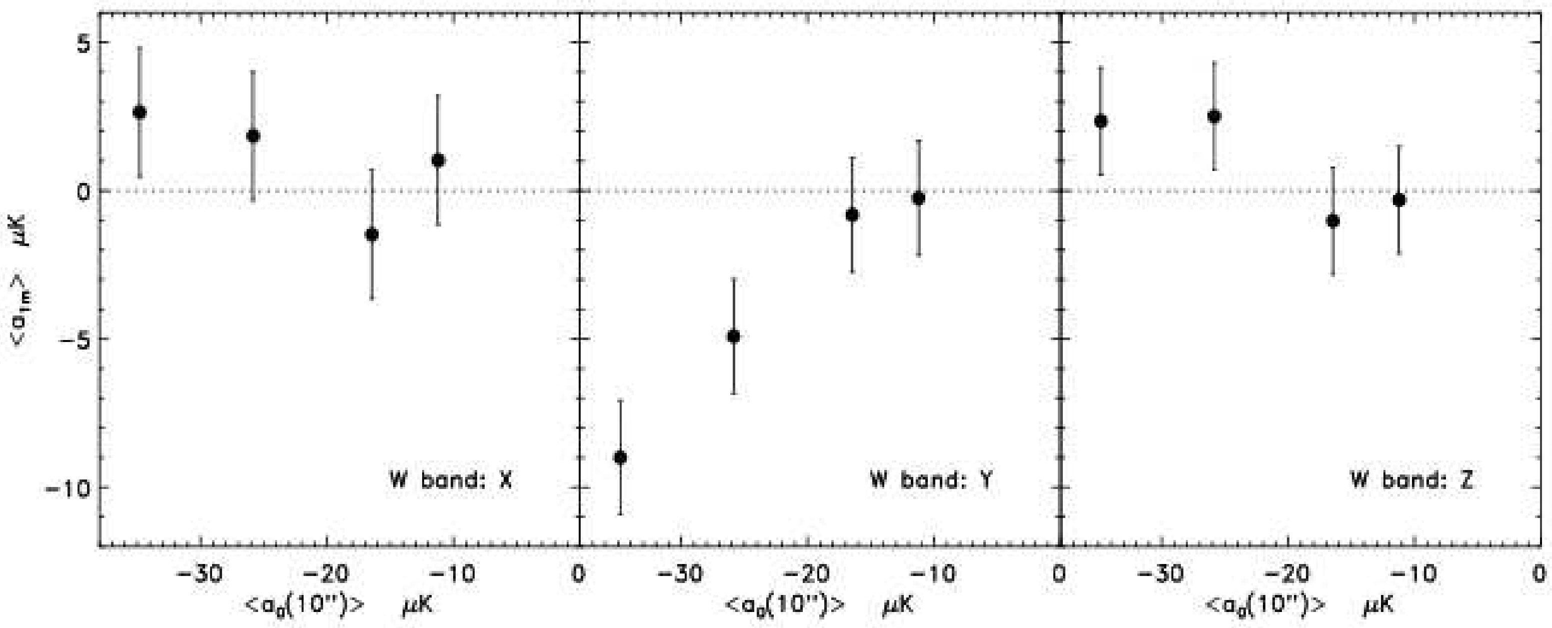
-The signal is persistent for subsamples from 100 to 1000 clusters.

One Further Test:

If all Clusters move with the same velocity, then:

$$\Delta T = v\tau \propto \tau \qquad \qquad \tau = \sigma_{Th} \int dl n_e .$$

Then the kSZ signal **MUST** correlate with tSZ effect. Brighter clusters **MUST** have larger dipole.



The Y-component of the dipole at cluster locations correlate with the tSZ amplitude.

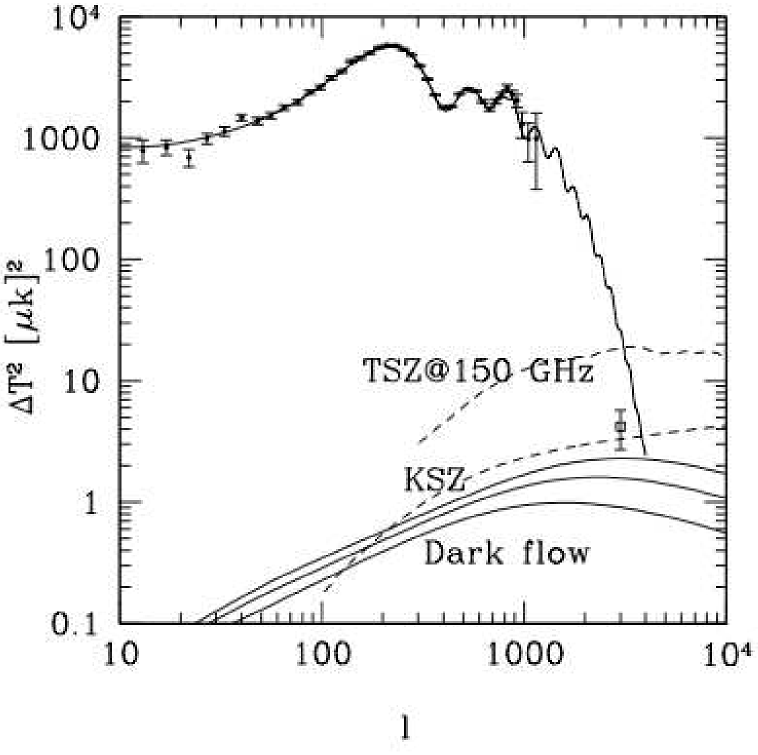
2.4 A word of caution.

- **We measure a dipole in μK and it needs to be translated into km/s. The conversion depends on the "unknown" cluster profiles.**

- **We have not estimated the shear of the flow. We can not distinguish between a local (~ 1 Gpc) from a cosmological origin (~ 30 Gpc).**

- **The signal is dominated by the most luminous clusters.**

2.5 Independent confirmation.



P. Zhang (2010)

The Dark Flow will produce an extra kSZ component, measurable by Planck.

3.- Cosmological Implications.

3.1 Matter and CMB frames.

- MRF: Rest frame where the average matter distribution is at rest.

- CMBF: Reference frame where the Cosmic Microwave Background is isotropic.

If the measured CMB dipole is of cosmological origin, then MRF and CMBF DO NOT coincide.

PROBLEM: how can generate an intrinsic CMB dipole?

3.2 A Tilted Universe?

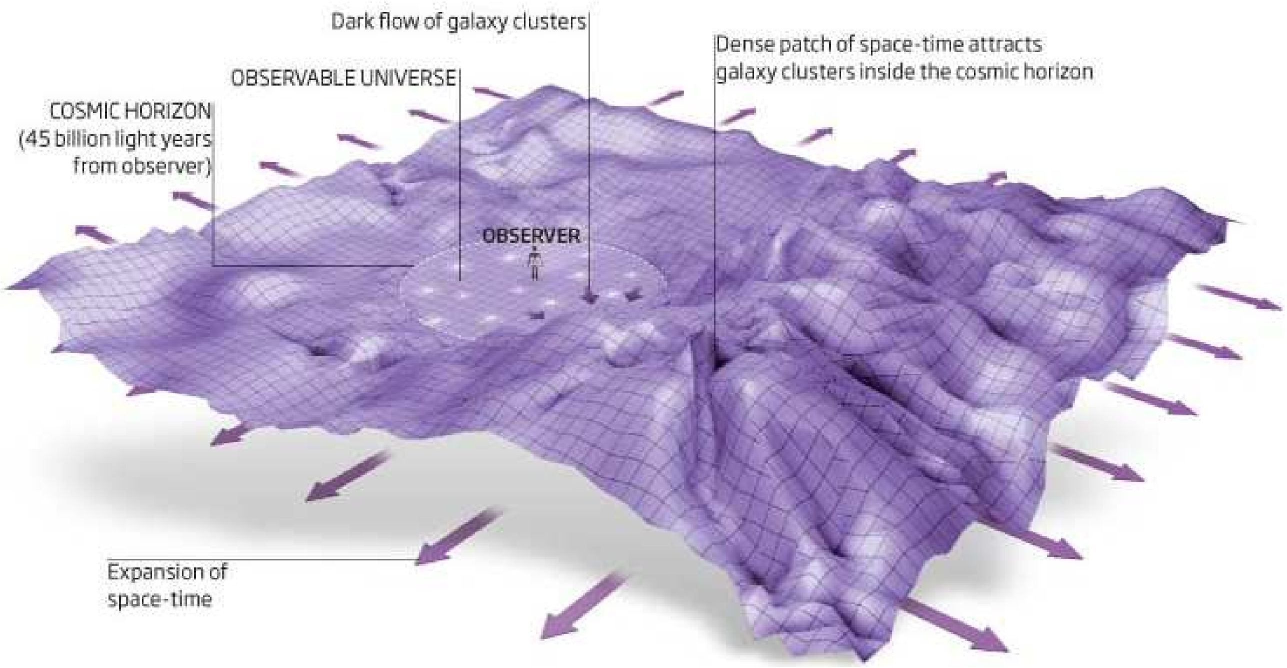
• **The flow can not be generated during inflation:**

$P(k) \sim k \quad \Rightarrow \quad C_l = A/l(l+1) \quad \Rightarrow \quad D = \sqrt{3}Q \sim 10^{-5} \neq 10^{-3}$

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

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

A pre-inflationary remnant of $\delta_L \sim 1$ requires $L \sim 500cH_o^{-1}$
[Turner (1991), Kashlinsky et al (1992)]



New Scientist, Jan 2009.

If the CMBR anisotropy is intrinsic, then viewed from the rest frame of the CMBR the Universe appears to be tilted (!), with galaxies moving from one side of our Hubble volume to the other with speeds of the order of 600 km s^{-1}.

-M. Turner, 1st **Prize on General Relativity Essays, 1993.**

3.3 Conclusions.

- **We have developped a new method to measure peculiar velocities.**

- **kSZ measurements have very different systematic that peculiar velocity surveys.**

- **We have determined a coherent bulk flow on the direction of the CMB dipole on a scale of ~ 1Gpc**

- **The amplitude of the flow is $600 - 1000$km/s, can not be generate during inflation.**

- **This large scale flow could be generated by Isocurvature density perturbations on Superhorizon scales.**