Large-scale peculiar flows of clusters of galaxies

A. Sasha Kashlinsky (GSFC)

with
F. Atrio-Barandela (Salamanca, Spain),
D. Kocevski (UCDavis),
H. Ebeling (U Hawaii)

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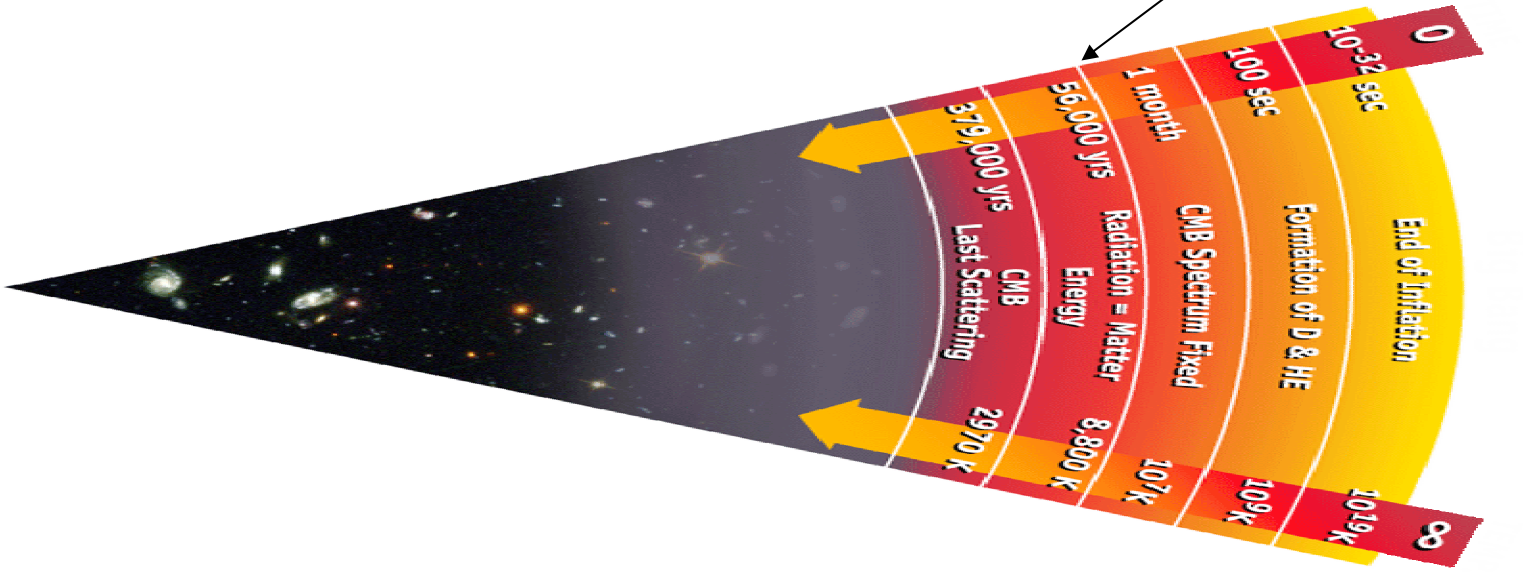
OUTLINE

- Standard precision cosmology and inflation
- Gravitational instability and peculiar flows
- SZ effect: K(inematic)SZ and T(hermal)SZ in clusters
- KA-B method for measuring velocities from KSZ
- Measurement of bulk flow from WMAP and X-ray clusters
- Error estimation, systematics and results
- Cosmological interpretation

Cosmology on 1 slide:

- $v_H = H_0 r$ with H_0=100 h km/sec/Mpc and h=0.7
- $\rho_m = \Omega_m \, 3H_0^2/8\pi G$ – mean matter density
- “Dark energy” dominates: $\Omega_\Lambda \approx 0.7$
- Universe is flat: $\Omega_{tot} = \Omega_m + \Omega_\Lambda = 1$
- Age of the Universe: $t_0 \approx 14$ Gyr
- Structure forms via ΛCDM
- $T_{CMB} = 2.73$K



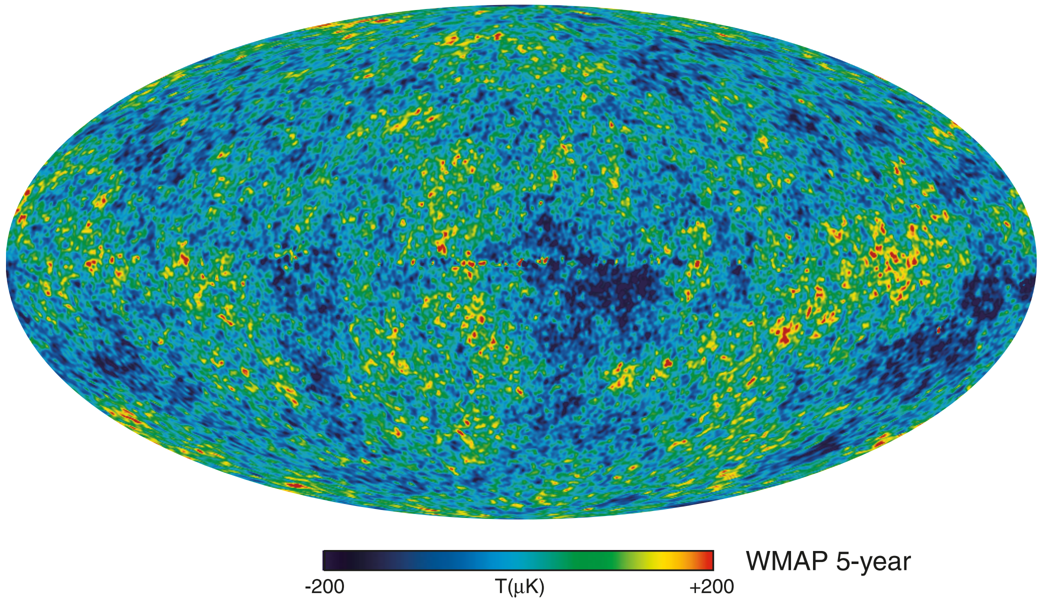
$R_{hor} \propto (\Omega h)^{-1}$

Inflation solves horizon problem and produces density perturbations:

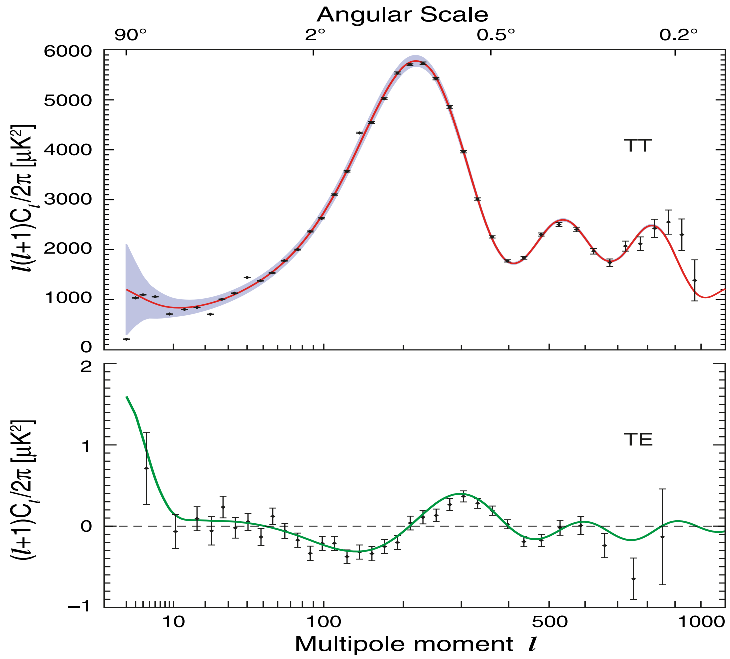
- Inflation generates $P = -\rho$ and then expands *initially homogeneous* region (destined to become our U.) by $N \sim 60\text{-}80$ e-foldings producing quantum fluctuations w/n it
- Harrison-Zeldovich spectrum: $P(k) \sim k$
- Or $\delta\rho \sim r^{-2}$, so that $\delta g \sim G\, \delta\rho\, r^2 \sim$ const
- Inflation requires to produce $\delta \sim 10^{-5}$ at $t \sim 10^{-32}$ sec
- After inflation the spectrum of density field is modified: sub-horizon fluctuations do not grow during radiation-dominated era, whereas super-horizon scales grow self-similarly (Horizon scale ~ time)

CMB sky:

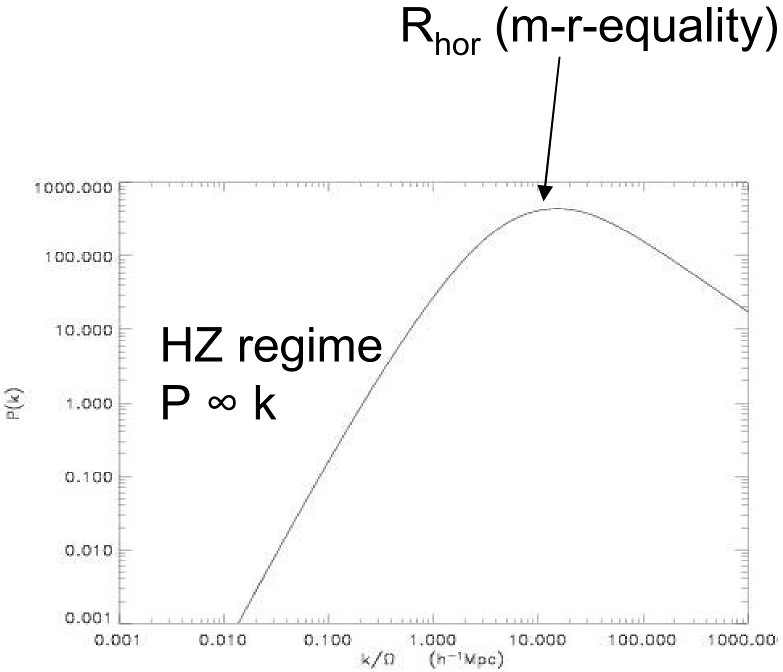
$$\delta T = \Sigma a_{lm} Y_{lm}(\theta;\phi) \quad \& \quad C_l = \Sigma \, | \, a_{lm} \, |^2$$



WMAP 5-year



CMB



R_{hor} (m-r-equality)

HZ regime
P ∞ k

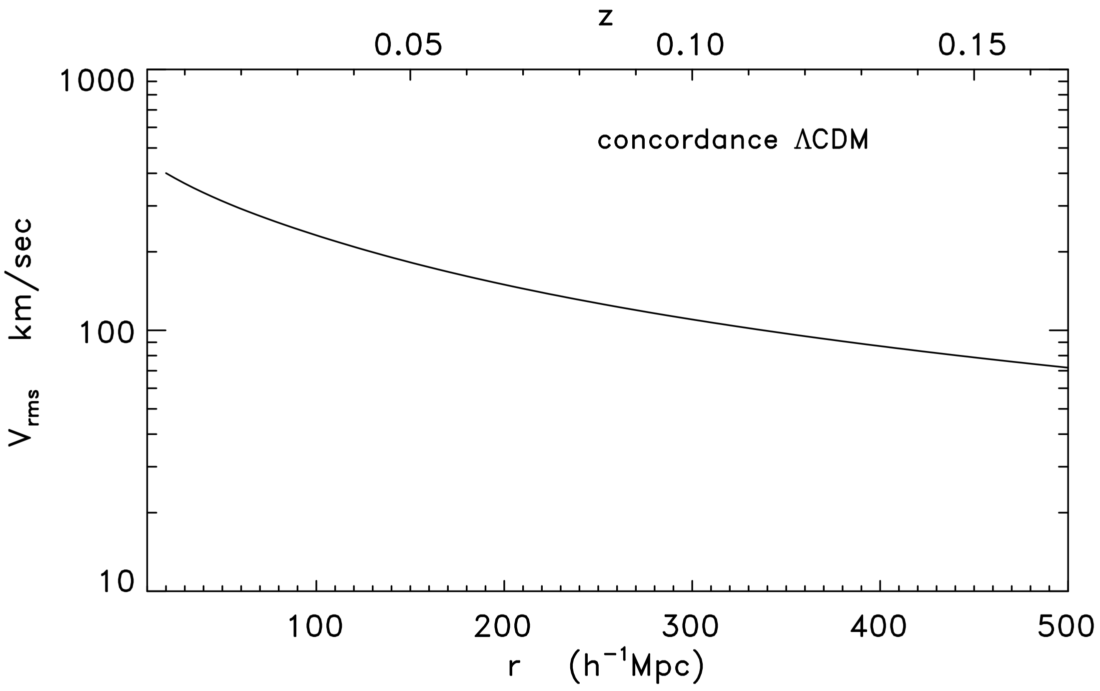
Matter P(k)

Peculiar velocities: *gravitational instability*

$$V_p \sim g_p t_0 \sim \frac{4\pi}{3} G\rho_m r\delta t_0 \sim \frac{\Omega_m}{2} H_0 r\delta H_0 t_0 \sim \frac{1}{3}\delta V_H \Omega^{0.6} (\propto r^{-1}$$ in HZ regime)

$$\dot{\rho} + \nabla(\rho\mathbf{V}) = 0 \Rightarrow \nabla\mathbf{V} = -\dot{\delta} \;\&\; \nabla\times\mathbf{V} = 0 \Rightarrow \mathbf{V}_k \uparrow\uparrow \mathbf{k} \Rightarrow V_k \propto \delta_k / k$$

$$V_{rms}(r) = \frac{\Omega^{1.2} H_0^2}{2\pi^2} \int P(k)W(kr)dk \approx 250(r/100h^{-1}Mpc)^{-1}\, km/\mathrm{sec}$$



Galaxy surveys: distance indicators

- Measure apparent *l(uminosity)*, know absolute L from other info. Then determine distance, compare to $H_0^{-1}zc$
- Ellipticals: fundamental plane (L,σ, etc)
- Spirals: Tully-Fisher relation (L, V_{rot})
- SNIa: (L is known)

Important methods, but

subject to biases, systematics, large uncertainties

(empirical) distance indicators are not well understood

results from different surveys disagree

do not measure with respect to CMB directly

cannot probe velocities at > $100h^{-1}$Mpc

Sunyaev-Zeldovich effect

- Clusters of galaxies: 10^{14}-$10^{15} M_{sun}$; $\sigma \sim 10^3$ km/sec, X-ray gas $T \sim 10^7$-10^8K
- Compton scattering of CMB photons: $e+\gamma \rightarrow e'+\gamma'$ – physics well known
- SZ creates *z-independent* spectral distortion of CMB with two components

thermal $\delta T_{CMB} = G(v)\ \boldsymbol{\tau}\ (T_e/511\text{ Kev})\ T_{CMB}$
kinematic $\delta T_{CMB} = \boldsymbol{\tau}\ V/c\ T_{CMB}$

where $\boldsymbol{\tau} = \sigma_T \int n_e\, dx$ – optical depth ($\sim 10^{-3}$ typically)

KSZ, in principle, gives a way to measure V. But the magnitude of KSZ for individual clusters is tiny:

$$\delta T_{CMB} \sim 10\ (\boldsymbol{\tau}/10^{-3})\ (V/1000\text{ km/sec})\ \mu K$$

KA-B method (*Kashlinsky & Atrio-Barandela 2000, ApJLett, 536, L67*)

Take all-sky CMB map: at pixels associated with an X-ray cluster:

$$\delta T(\boldsymbol{x})=\delta T_{TSZ}(\boldsymbol{x})G(\nu)+\delta T_{KSZ}(\boldsymbol{x})\ H(\nu)+\delta_{CMB}+n$$

Note: G < 0 over the the WMAP frequencies

Identify N clusters. Evaluate the dipole of the CMB at cluster positions, i.e $<\delta \cos\theta>$. Then:

$$a_{1m}^{KSZ} = <\tau>\ \mathbf{v}_{\mathbf{bulk}}/\mathbf{c}$$

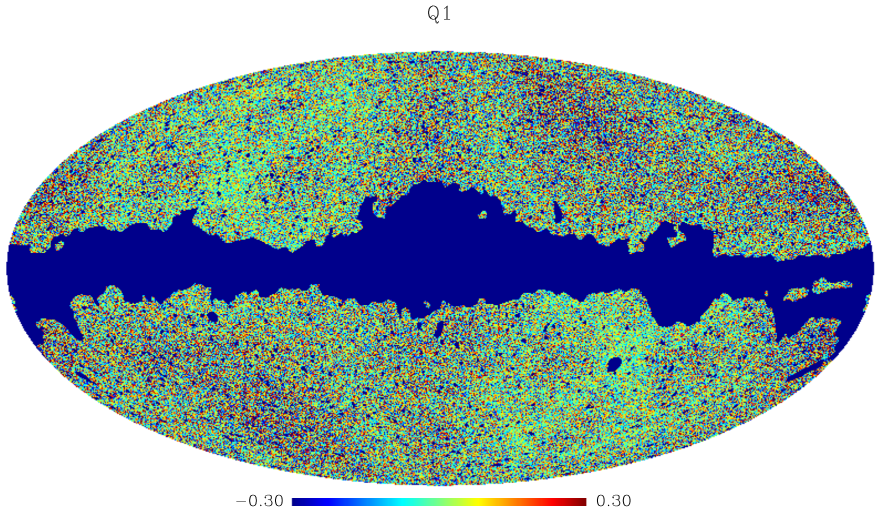
$$a_{1m}=a_{1m}^{KSZ} + a_{1m}^{TSZ} + a_{1m}^{CMB} + \sigma_{noise}/\sqrt{N}$$

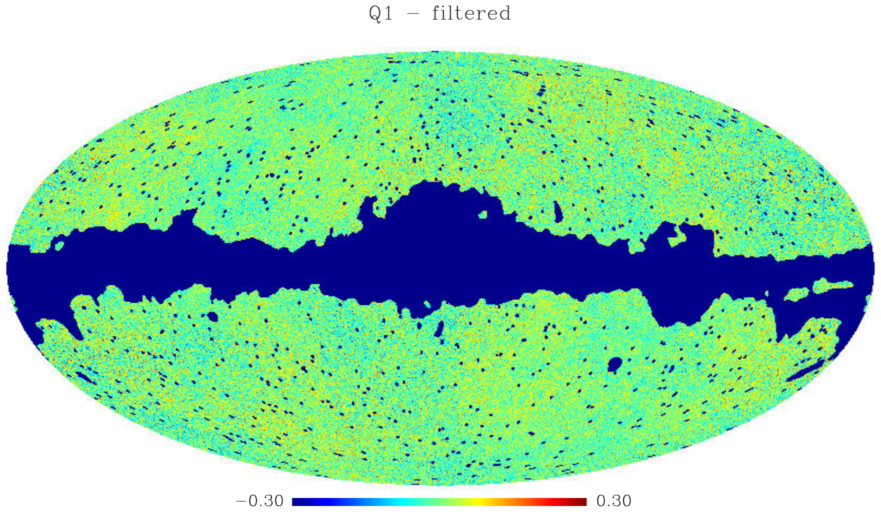
Hence, if N>>1 clusters move coherently, one can isolate the KSZ term through the cumulative dipole measurement.

1. *CMB data*

- 3-yr WMAP all-sky *dipole-subtracted* CMB data at Q1,Q2, V1,V2, W1…W4 (40,60,90 Ghz)
- Apply mask (KP0) to mask out the Galaxy contribution
- CMB contribution to dipole at cluster positions does *not* integrate down as 1/√N because CMB fluctuations are strongly correlated.
- But the power spectrum, C_ℓ, of the CMB-ΛCDM is well known.
- Hence we can use Wiener-type filtering to filter out this component. Specifically to minimize $<(\delta\text{-noise})^2>$, when the power spectrum of the dominant component is well known, one can use a low-pass filter

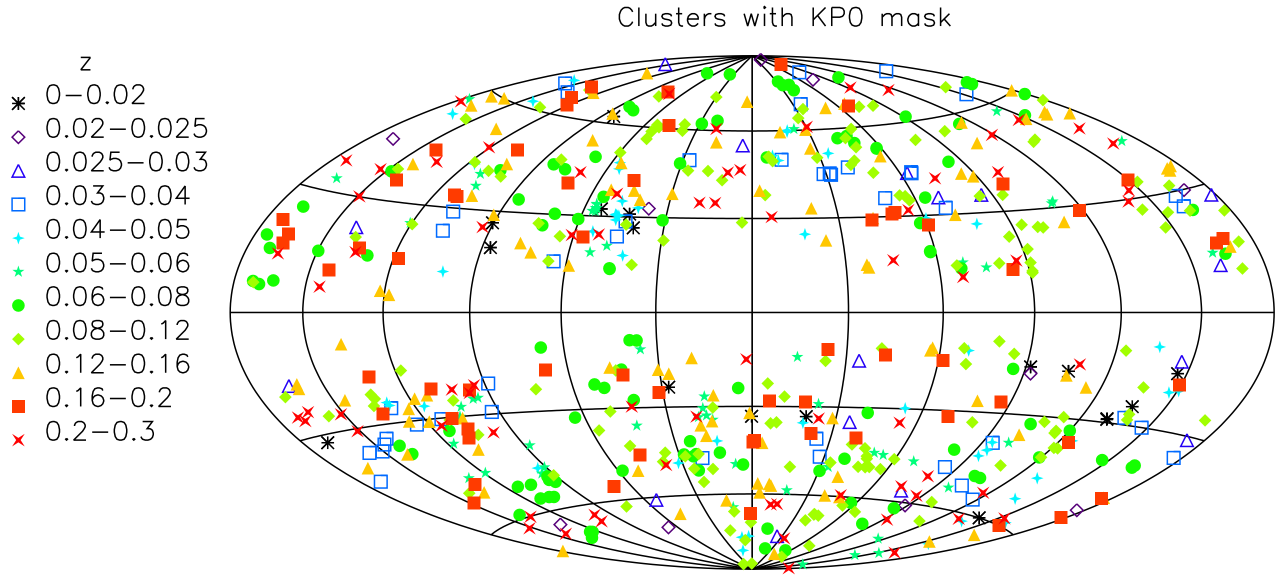
$$F_\ell = \frac{C_\ell(sky) - C_\ell^{\Lambda CDM} B_\ell^2}{C_\ell(sky)}$$





2. *X-ray cluster data*

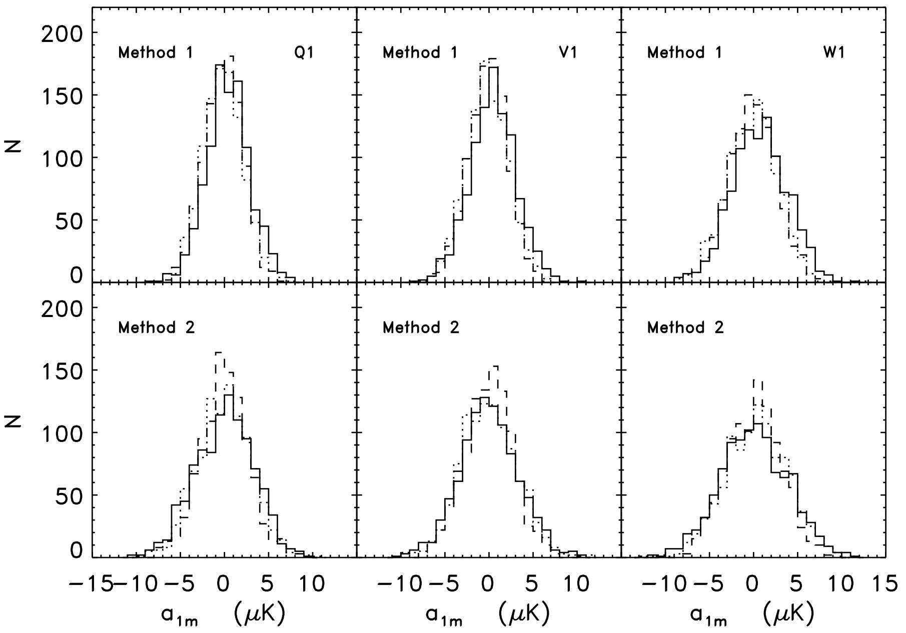
- Assembled the largest all-sky cluster catalog of 782 clusters to z=0.3.
- Of them, 674 survive the KP0 CMB mask
- 603 are at $z<0.2$; 541 at $z<0.16$; 444 at $z<0.12$; 292 at $z<0.08$
- Catalog contains (RA, DEC), z, θ_X (ultimately unnecessary)
- Computed for each cluster *using iso-T β-model:* n_e, T_X, r_{core}



3. *Dipole and error computation*

- Dipole computed over pixels associated with clusters in each of 8 channels
- *z*-bins selected for clusters w. *z*<0.04, 0.05, 0.06, 0.08, 0.12, 0.16, 0.2, 0.3
- Then averaged over all channels weighted with errors
- Errors computed in two (independent) ways:

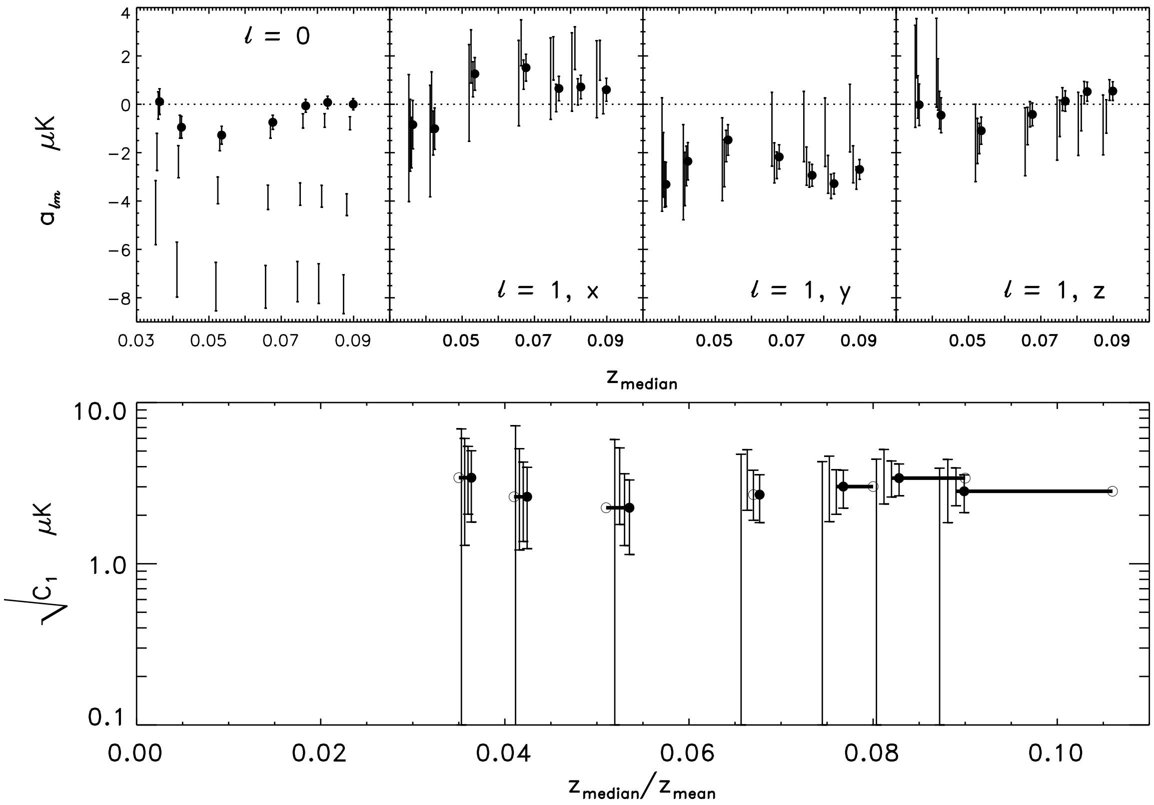
1. Random pixels selected outside the mask and catalog cluster pixels (*preserves the CMB mask imprint*).
2. The entire catalog is rotated over random angles (*preserves the cluster catalog geometry)*



Both methods give similar errors w/n <10%.

4. Isolating KSZ component to the dipole

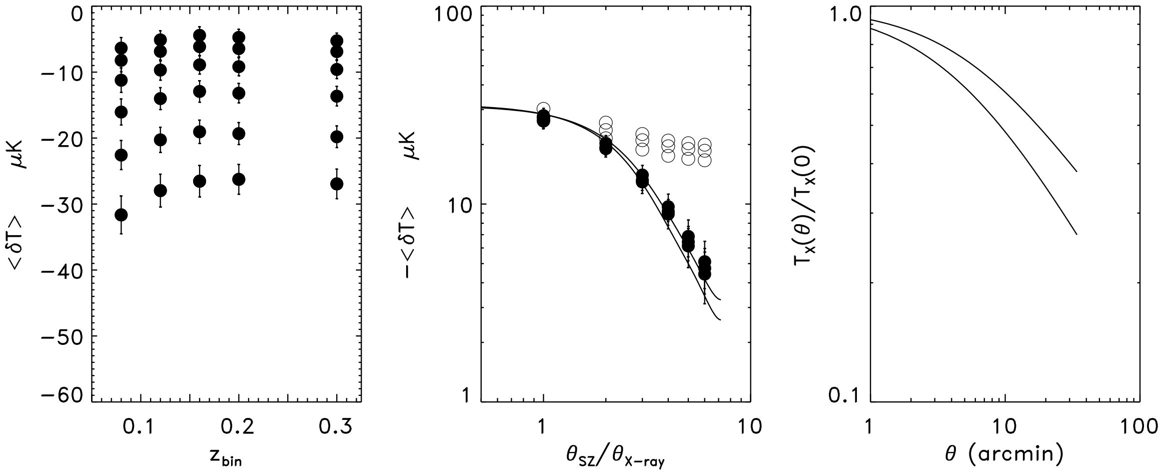
- SZ effect goes as n_e while L_X goes as n_e^2. Hence SZ extent > X-ray extent.
- When measuring dipole, we increase aperture to min[1,2,4,6θ_X,30’].
- At the final aperture, *all* clusters are aprox 30’ in radius.
- We detect X-ray emitting gas out to largest aperture.
- TSZ residual contribution is measured via monopole.
- The remaining dipole arises at *zero monopole* – must come from KSZ.



- ***The dipole appears only at cluster positions.***
- ***Must originate from CMB photons which interacted w cluster gas.***
- ***The final dipole is independent of distance/redshift.***

5. More on (negligible) TSZ contribution to dipole

- TSZ goes as τT_X, whereas KSZ goes as τ
- When T_X decreases w *r* TSZ monopole vanishes as KSZ dipole remains



Open: β-model Lines – NFW profiles

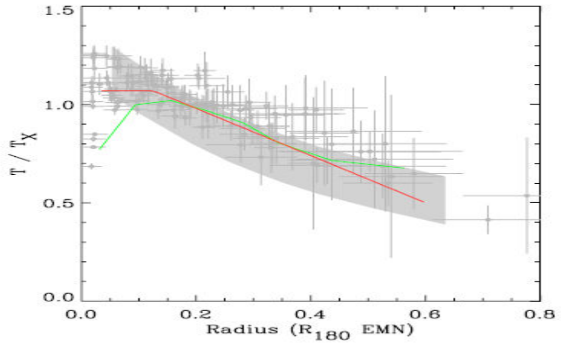


Fig. 5. Scaled projected temperature profiles compared with the average profiles from *ASCA* (Markevitch et al. 1998, grey band), *BeppoSAX* observations of cooling core clusters (De Grandi & Molendi 2002, green line), and *Chandra* observations of cooling core systems (Vikhlinin et al. 2005, red line). The observed profiles have been scaled using R_{180} derived from the simulations of Evrard et al. (1996). (This figure is available in colour in the online version of the journal.)

Table 4. TSZ component in filtered maps: observed and modelled.

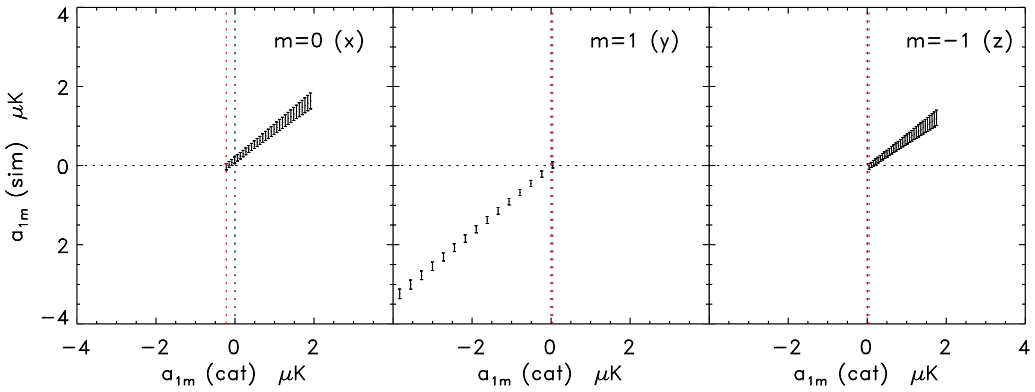
(1)	(2)	(3)							
	CMB maps	TSZ estimate using catalogs: (a) | (b)							
$z \le$	$\langle\Delta T\rangle$	$\langle\Delta T\rangle$	$\frac{a_{1,x}}{\langle\Delta T\rangle}$	$\frac{a_{1,y}}{\langle\Delta T\rangle}$	$\frac{a_{1,z}}{\langle\Delta T\rangle}$	$\langle\Delta T\rangle$	$\frac{a_{1,x}}{\langle\Delta T\rangle}$	$\frac{a_{1,y}}{\langle\Delta T\rangle}$	$\frac{a_{1,z}}{\langle\Delta T\rangle}$
	μK	μK				μK			
0.05	−4.5 ± 1.3	−5.3	0.3	−0.2	−0.2	−5.6	0.2	−0.2	−0.2
0.06	−6.8 ± 1.1	−5.7	0.3	−0.3	−0.2	−6.1	0.3	−0.2	−0.2
0.08	−7.5 ± 1.0	−6.2	0.2	−0.0	−0.1	−6.7	0.2	−0.1	−0.1
0.12	−7.6 ± 0.9	−7.5	0.1	0.0	−0.2	−7.8	0.1	0.1	−0.2
0.16	−7.3 ± 0.8	−7.9	0.2	−0.1	−0.1	−8.6	0.2	−0.0	−0.1
0.20	−7.4 ± 0.8	−8.8	0.1	−0.0	−0.1	−9.75	0.1	−0.0	−0.1
0.30	−7.9 ± 0.8	−11.	0.2	−0.0	−0.0	−11.9	0.2	−0.1	−0.0

At $\theta_{SZ}=\theta_X$ where β-model and NFW coincide:

1. TSZ component w fits the measured values well, but
2. Residual TSZ dipole

is negligible.

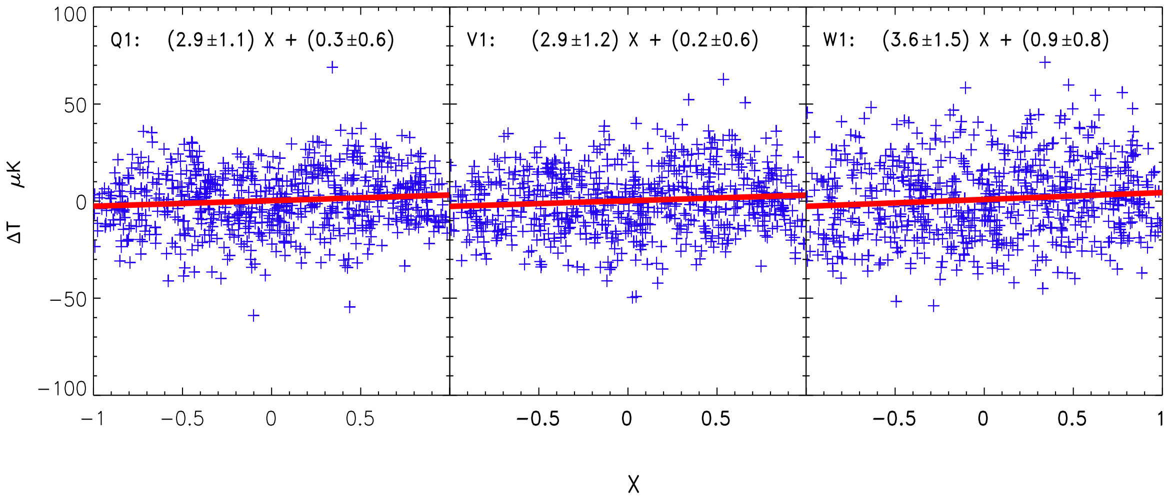
Cluster catalog cross-talk (small)



Random vs real clusters:
Each cluster is given TSZ and KSZ components and 1,000 realizations with random cluster positions at given V_{bulk} from 0 to 3,000 km/sec

Cluster ΔT vs X=cos(∠ to apex)

Dipole exists at each channel at ~2.5 σ.



KSZ dipole etc

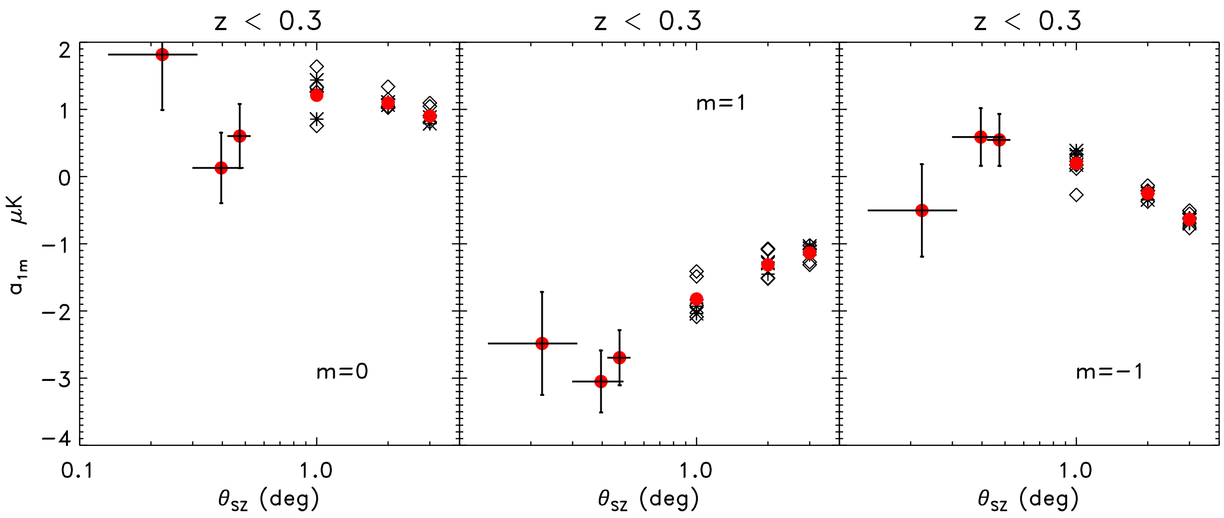
Table 3. TSZ monopole vs KSZ dipole contributions from rings.

Ring	$N_{\rm pixels}$	Monopole	Dipole components (filtered)		
		(unfiltered)	$a_{1,x}$	$a_{1,y}$	$a_{1,z}$
		μK	μK	μK	μK
$0' - 5'$	1,183	-24.5 ± 9.2	3.5 ± 4.4	-0.9 ± 3.7	-6.2 ± 3.5
$5' - 10'$	3,283	-18.0 ± 5.5	1.2 ± 2.6	-4.4 ± 2.2	-5.2 ± 2.1
$10' - 15'$	5,546	-12.6 ± 4.3	2.2 ± 2.0	-5.2 ± 1.7	2.9 ± 1.6
$15' - 20'$	7,673	-6.8 ± 3.6	0.6 ± 1.7	-4.8 ± 1.5	2.0 ± 1.4
$20' - 25'$	9,744	-6.0 ± 3.2	-0.3 ± 1.5	-2.8 ± 1.3	0.5 ± 1.2
$25' - 30'$	11,845	-5.8 ± 2.9	0.9 ± 1.4	-1.0 ± 1.2	-0.3 ± 1.1
$30' - 45'$	47,064	-4.6 ± 1.5	2.7 ± 0.7	-2.0 ± 0.6	1.4 ± 0.6
$45' - 60'$	63,987	-4.3 ± 1.3	0.5 ± 0.6	-0.7 ± 0.5	-0.9 ± 0.5

Differential measurements for z<0.3

Hot gas is detected via monopole TSZ out to >30’.

Over that range KSZ is likewise detected in rings



Dipole decrease at larger apertures.

At larger apertures KSZ dipole decreases until eventually overtaken by noise.

Calibration: converting μK into km/sec

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(1)	(2)	(3)							
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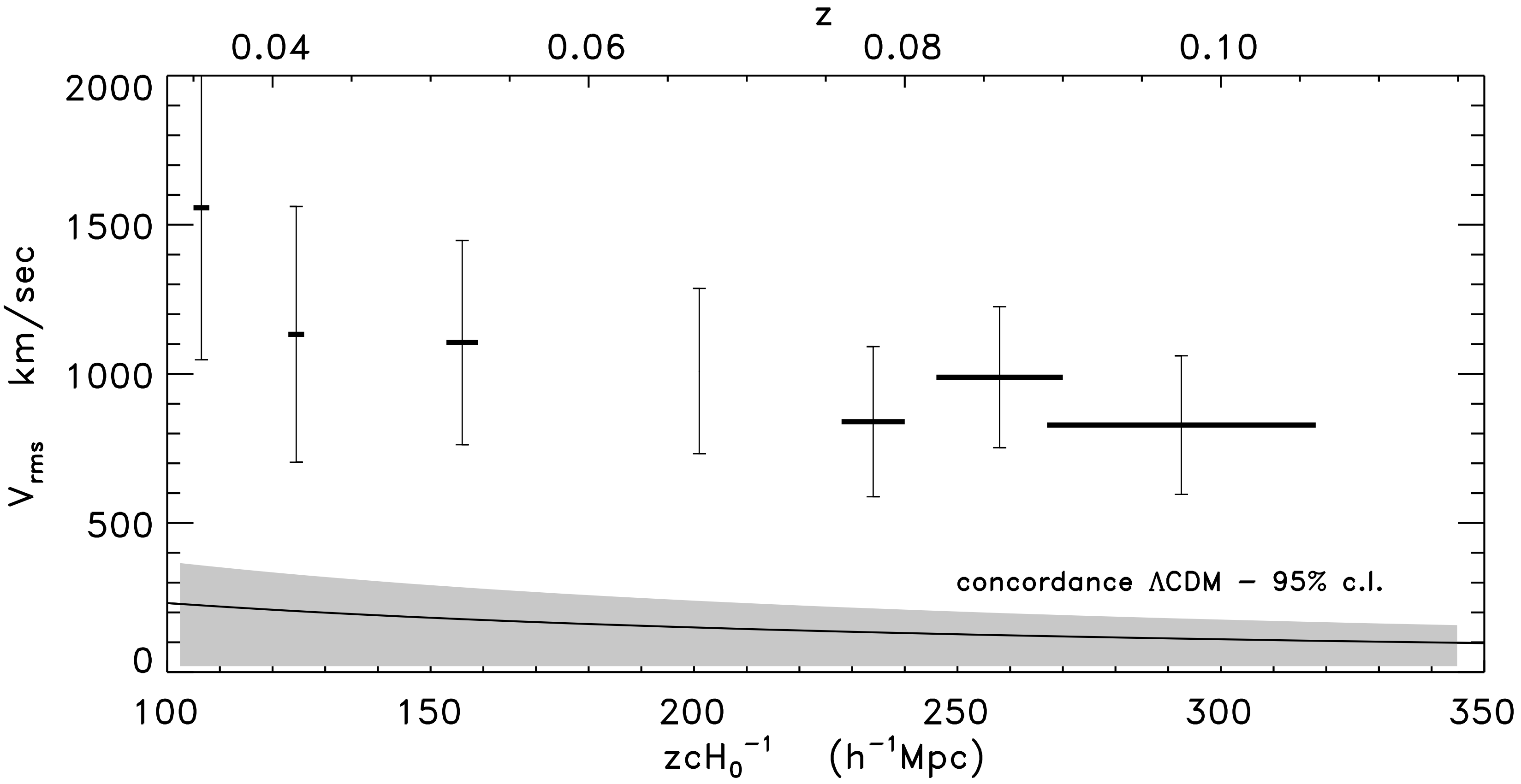
	μK	μK				μK			
0.05	-4.5 ± 1.3	-5.3	0.3	-0.2	-0.2	-5.6	0.2	-0.2	-0.2
0.06	-6.8 ± 1.1	-5.7	0.3	-0.3	-0.2	-6.1	0.3	-0.2	-0.2
0.08	-7.5 ± 1.0	-6.2	0.2	-0.0	-0.1	-6.7	0.2	-0.1	-0.1
0.12	-7.6 ± 0.9	-7.5	0.1	0.0	-0.2	-7.8	0.1	0.1	-0.2
0.16	-7.3 ± 0.8	-7.9	0.2	-0.1	-0.1	-8.6	0.2	-0.0	-0.1
0.20	-7.4 ± 0.8	-8.8	0.1	-0.0	-0.1	-9.75	0.1	-0.0	-0.1
0.30	-7.9 ± 0.8	$-11.$	0.2	-0.0	-0.0	-11.9	0.2	-0.1	-0.0

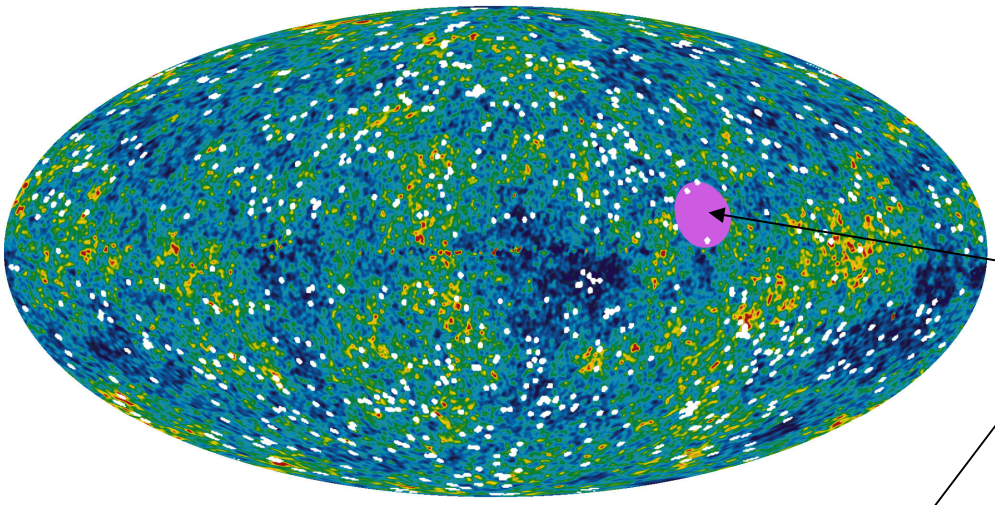
- Good agreement between catalog TSZ and measurements for $\theta_{SZ} \sim \theta_X$ w β-model
- Hence, we calibrate dipole: assign V=100km/sec in the direction of motion
- And compute dipole amplitude $C_{1,100}$ in μK^2 for our catalog and this motion
- Find robust values of $\sqrt{C_{1,100}} = 0.3$ μK in filtered maps from which dipole computed
- Filtering reduces $\sqrt{C_{1,100}}$ by a factor of ~3 (from ~0.8μK)
- Note: we may have systematic bias because β-model fails
- Correct modeling must use NFW cluster fits, which we do not yet have in pipeline
- NFW profile would lead to smaller $C_{1,100}$ in unfiltered maps
- But filtering would remove less power
- So NFW clusters may lead to (at most) $\sqrt{C_{1,100}}$ larger by ~20-30%

Cosmological implications: ΛCDM

Concordance ΛCDM model cannot explain the amplitude AND coherence of the flow



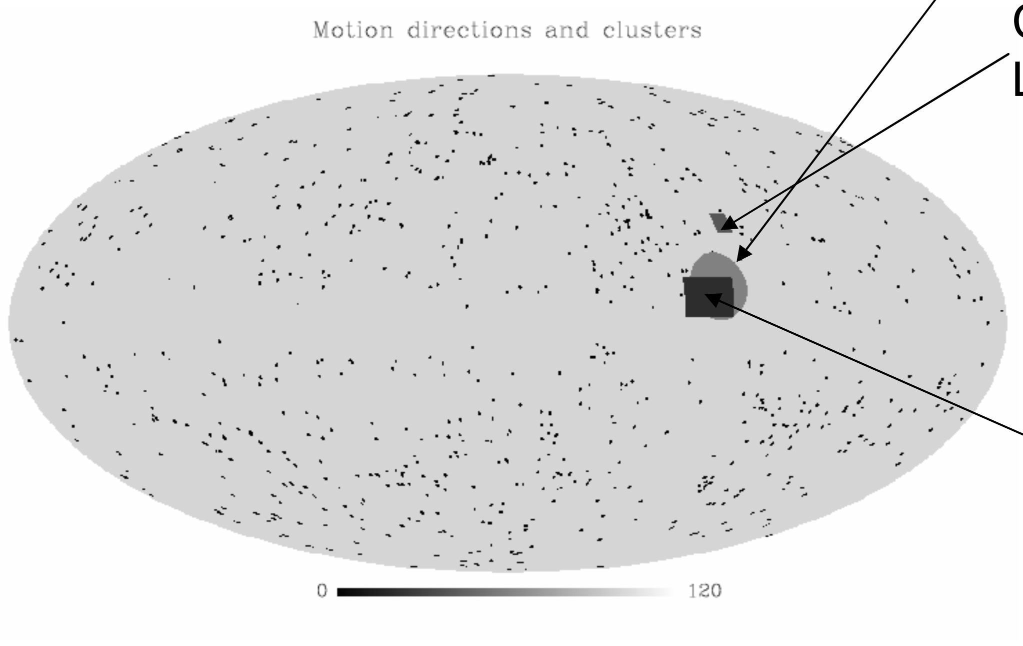
Direction of motion



100 to > ~300 h^{-1} Mpc
coherent flow:

(l,b) = (283, 11) ± 10 deg

V ~ 600-800 km/sec



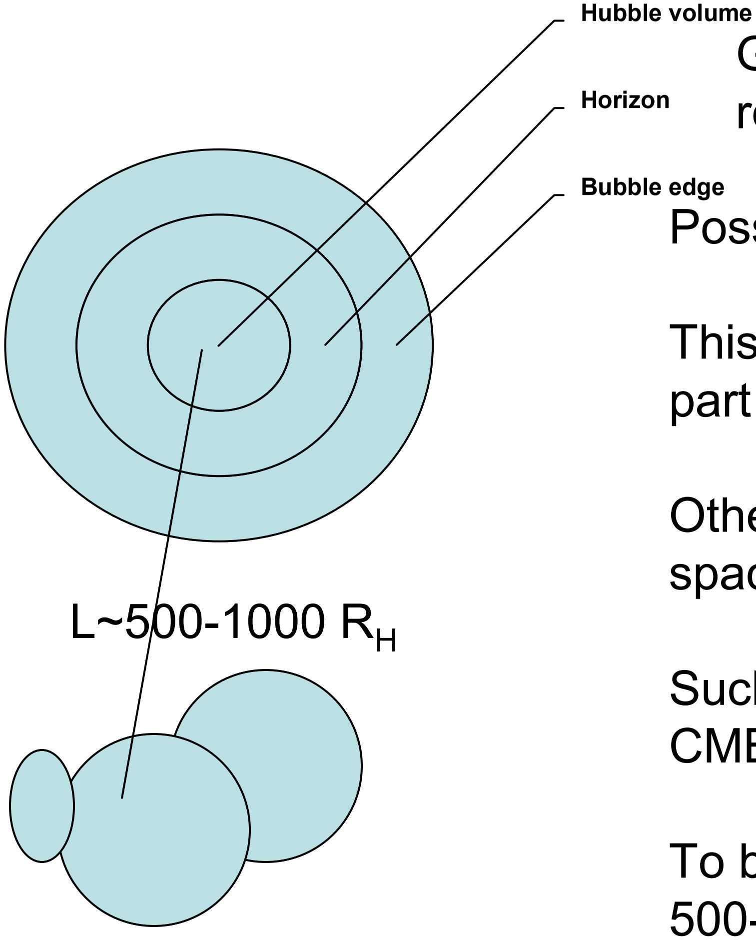
CMB ***local*** dipole correction for
LG motion: (l,b) = (276±3, 30 ± 3)

V=627±22 km/sec

Watkins et al (2008) motion
w/n ~ 50-100 h^{-1} Mpc:
(l,b) = (287±9, 8±6) deg

V=407±81 km/sec

Cosmological implications: “dark flow”?



Grav. instability cannot account for the flow and it remains coherent to >300-400 h^{-1} Mpc

Possibly the flow extends across the entire horizon.

This can be explained w/n inflationary picture if our part of space-t is just a homogeneous inflated blob.

Other remnants would be parts of (inhomogeneous) space-t inflated at different times/rates.

Such remnants would induce Grischuk-Zeldovich CMB quadrupole of $Q \sim h\,(R_H/L)^2$

To be consistent with Q<2-3x10-5, L must be > 500-1000 R_H (Turner 1991, Kashlinsky, Tkachev & Frieman 1994)

Such tilted Universe would have flow induced across R_H due to density gradient
$V \sim c\,h(R_H/L) \sim Q\,(L/R_H)$ (Turner 1991)

Specific model – an example (Turner 1991)

- Assume flat space: $ds^2=c^2dt^2-R^2\,[dx^2 + x^2\,d\omega]$
- Long wavelength wave with *h>>1*: $\delta = h\,\exp(-i\boldsymbol{kx}) = h(1 - i\boldsymbol{kx} + O[(kx)^2])$
- Would induce CMB anisotropy in curvature perturbations via Sachs-Wolfe effect:

$$\frac{\delta T}{T} = \frac{1}{2}[\,R^{1/2}(\mathbf{x}\bullet\nabla)(h\,\exp(-i\,\mathbf{kx})) + h\,\exp(-i\,\mathbf{kx})\,]_{E}^{O}$$

- The dipole term (***kx***) ***cancels exactly***
- Hence even in the presence of superhorizon curvature perturbation the rest-frames of expansion and CMB coincide.
- (Isocurvature perturbation would have *intrinsic* dipole)

More generally: a link to Multiverse?

- The flow is caused by a tilt from preinflationary remnants now pushed far away by cosmological inflation reflecting the initial configuration of the inflaton field(s) (Turner et al 1991, KA-BKE1,2).

- The flow is caused by a tilt due to quantum entanglement of different bubbles/universes pertaining to the string landscape of the Multiverse. Here the amplitude of the flow is fixed by the scale of inflation via the entanglement, and the amplitude of the flow must be ~700 km/s, reasonably close to the measured value (Mersini-Houghton & Hollman 2009).

- If the flow does not extend to the horizon, then, in certain higher dimensional models such as the DGP scenario of a 3-D brane with an extra dimension, gravity is modified on scales large enough to explain the present accelerated expansion without dark energy; these models also predict stronger gravitational coupling of matter on scales of 10 to few 100 Mpc, which could explain a coherent flow such as the one observed (Afshordi et al 2009; Khoury & Wyman 2009).

Future prospects: *SCOUT* experiment

- *SCOUT* = ***S***unyaev-Zeldovich ***C***luster ***O***bservations as probes of the ***U***niverse’s ***T***ilt (Kashlinsky, Atrio-Barandela, Ebeling, Kocevski)

- Will construct a deeper all-sky catalog with upward of ~ 1,500 X-ray clusters with spectroscopic redshifts extending to z=0.7.

- Will measure the cluster bulk flow (amplitude and direction) out to z ~ 0.5 – 0.7 (distances > $1h^{-1}$Gpc) with greatly increased statistical accuracy

- Improve further understanding of possible systematics (so far negligible)

- Determine the flow's shear and coherence length

- PLANCK is particularly useful here with its low noise and frequency coverage (on both sides of 217 GHZ) + better angular resolution

- STAY TUNED!

Conclusions

- Our measurements indicate CMB dipole at cluster pixels out to $>300h^{-1}$Mpc
- Cross-talk etc effects are small and cannot mimic the dipole
- The dipole arises at cluster pixels – cannot come from noise/foreground
- We prove that it arises from hot SZ producing gas: $\langle \Delta T \rangle < 0$
- The gas is distributed via the NFW profile with decreasing T_X from center
- As cluster aperture increases to encompass the gas the CMB monopole goes to zero because of decreasing T_X, while the dipole remains
- Outside these regions the dipole begins to decrease
- This suggests that the dipole originates from the KSZ effect
- The bulk flow implied by this dipole is high: $V_{bulk} \sim 600\text{-}1000$ km/sec
- There may be systematic overestimate of V_{bulk} (but likely < 20% or so)
- The coherence length is high – and perhaps $\sim R_H$
- Gravitational instability cannot account for this motion
- Perhaps it is indicative of structures well beyond the present-day horizon left over from pre-inflationary epochs
- More generally, do we see part of the pre-inflationary landscape?