Large-scale peculiar flows of clusters of galaxies

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2008, ApJ(Letters),686, L49
2009, ApJ, 691, 1479
2010, ApJ(Letters), 712, L81
2010, ApJ, 719, 77
2011, ApJ, 732, 1

- Physics Report DRAFT on “dark flow” is now available for comments – arxiv:1202.0717

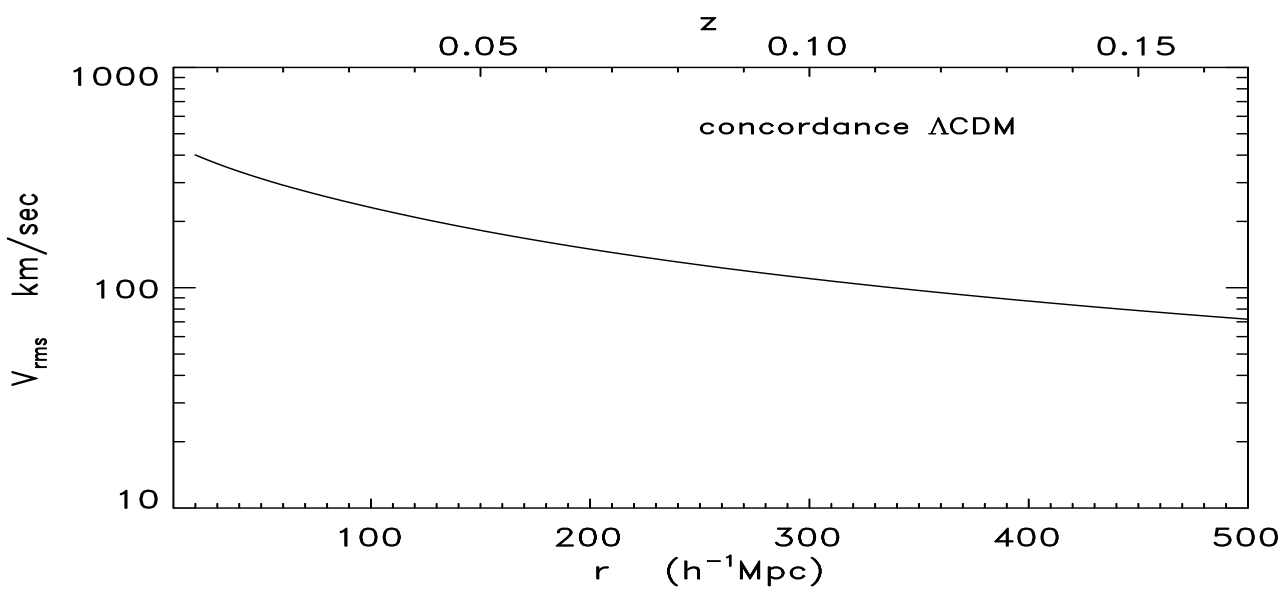
- The data needed to verify Dark Flow results has been posted at http://www.kashlinsky.info/bulkflows/data_public

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)

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

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



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

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 $\langle\delta \cos\theta\rangle$. Then:

$$a_{1m}^{KSZ} = \langle\tau\rangle\ \mathbf{V}_{\mathbf{bulk}}/\mathbf{c}$$

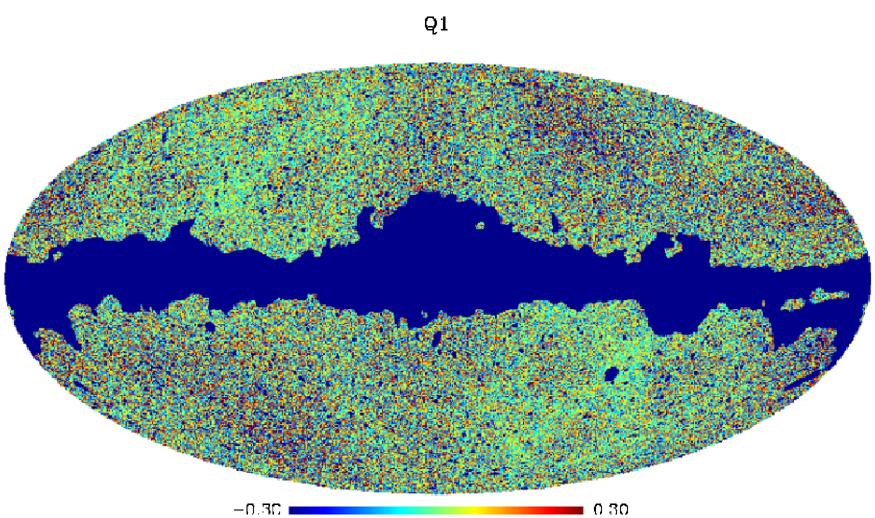
$$a_{1m}=a_{1m}^{KSZ} + a_{1m}^{TSZ} + a_{1m}^{CMB} + \sigma_{noise}/\sqrt{N}$$

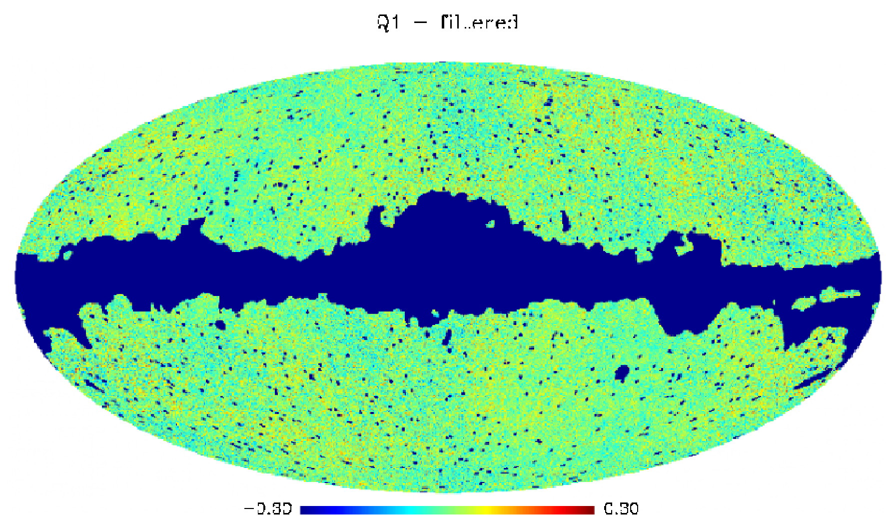
Hence, if N>>1 clusters move coherently, one can isolate the KSZ term through the cumulative dipole measurement.

1. *CMB data*

- 3/5-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 <(δ-noise)^2>, when the power spectrum of the dominant component is well known, one can use a low-pass filter

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





***Theorem*:** in the absence of instrument noise the error on each dipole component for isotropic cluster sample is $\sigma \sim 15\sqrt{3/N_{cl}}$ μK

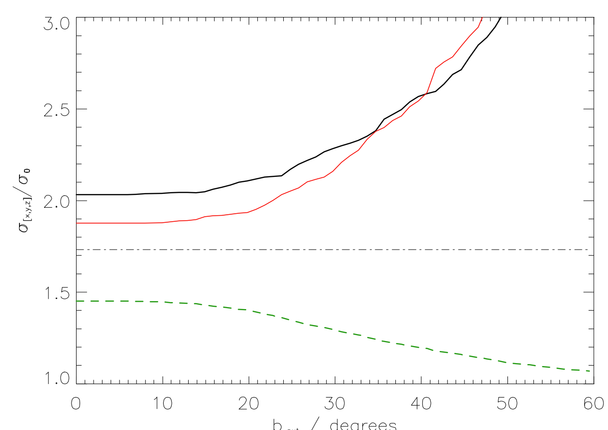
PROOF:

1. Maps are filtered with $\boldsymbol{F_l=(C_l-C_l^{theor})/C_l}$
2. Dispersion in filtered maps is then $\boldsymbol{4\pi\sigma_{fil}^2=\Sigma\,(2l+1)F_l^2C_l=\Sigma(2l+1)(C_l-C_l^{theor})^2/C_l}$
3. *C_l differs from C_l^{theor} by i) cosmic variance (cv) and ii) instrument noise*
4. CV: $\boldsymbol{\Delta_{CV}(l)=(2l+1)\,C_l^{theor}/f_{sky}}$ *and is common to all channels*
5. Propagating cv into 2 leads to:

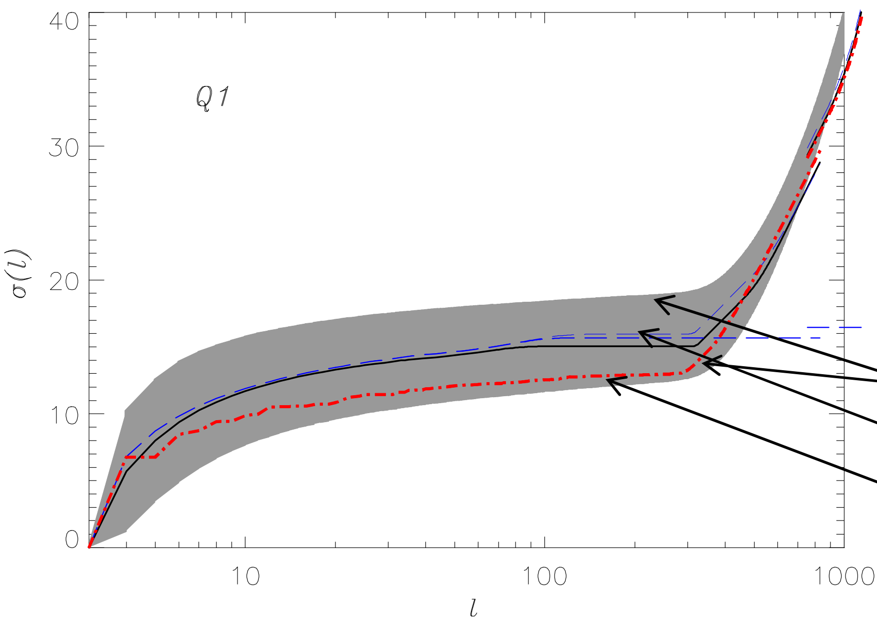
$$\sigma_{fil}^2=\frac{1}{4\pi}\Sigma(2l+1)\left[\frac{\Delta_l^2}{C_l^{theor}+\Delta_l+N_l}+\frac{N_l^2}{C_l^{theor}+\Delta_l+N_l}\right]=\sigma_{CV,fil}^2+\sigma_{N,fil}^2(t_{obs})$$

6. Contribution to dipole from1st term $\boldsymbol{\sim 15\sqrt{3/N_{cl}}}$ ***μK***; 2nd is small for post-5yr WMAP

7. For errors estimated via MII: be careful when dealing with incomplete coverage: e.g. *n* – unit vector. Then ***a_0=<ΔT> and a_{1m} =<n_mΔT>.*** If your catalog misses clusters at |b|<30-35 deg or has N/S asymmetries, you will not estimate errors correctly. (Our catalog has not such problems)



Error budget theorem: numerical proof



Map variance in μK: $\sigma^2(l) \equiv \Sigma_{q=4}^{l}\sigma^2(q)$

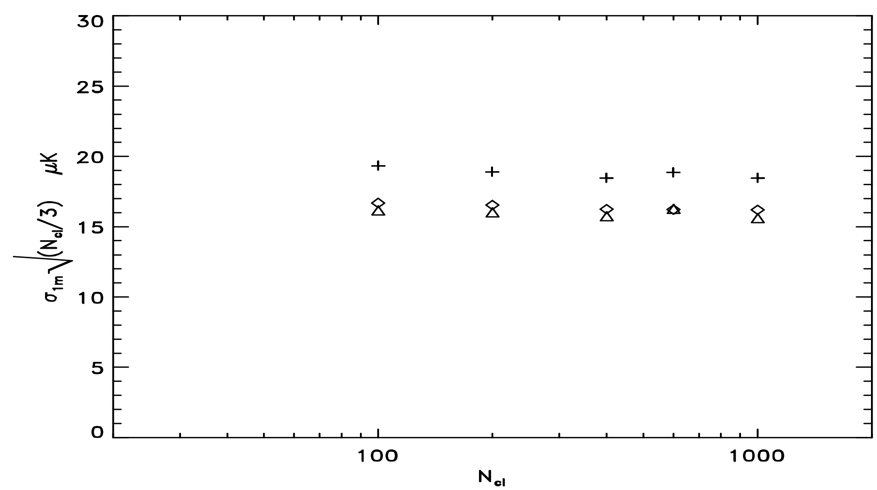
$$\sigma^2_{fil} = \frac{1}{4\pi}\Sigma(2l+1)\left[\frac{\Delta_l^2}{C_l^{theor} + \Delta_l + N_l}\right] \equiv \Sigma_q \sigma^2(q)$$

4000 random ΛCDM universes (1σ range)

mean

Our Universe:
the *only relevant* realisation

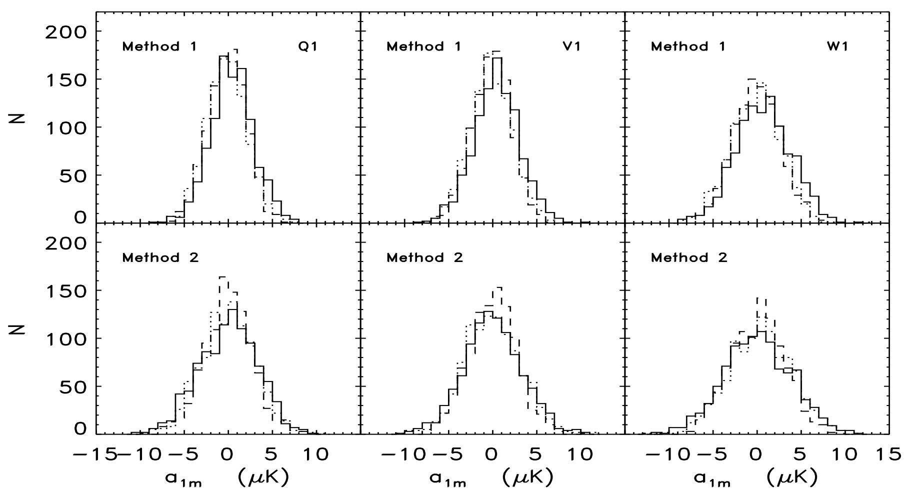
Results of 4,000 runs of random cluster realisations:
X (+), Y (◊), Z(▲)



3. *Dipole and error computation*

- Dipole computed over pixels associated with clusters in each of 8 channels
- *z*-bins selected for clusters w. *z*< 0.12, 0.16, 0.2, 0.25 (also L_X-bins at each z-bin)
- Compute mean dipole over 8 DA's (errors of 8 DAs are correlated because of CV)
- Errors computed in three (independent) ways:

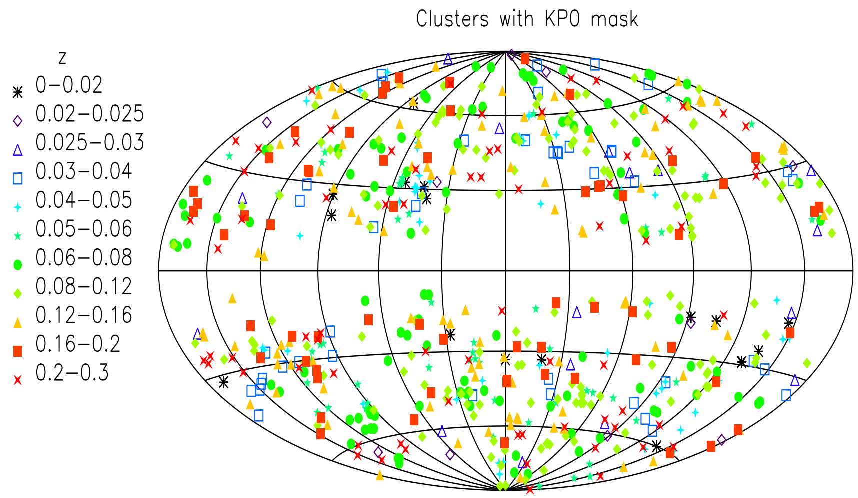
1. Random pixels selected outside the mask and catalog cluster pixels (*preserves the CMB mask imprint*).
2. The entire catalog is fixed and CMB sky is a) rotated over random angles in simulated maps (*preserves the cluster catalog geometry) OR* b) realized 4,000 times
3. Subgroups of clusters are randomly selected at various N_{cl}



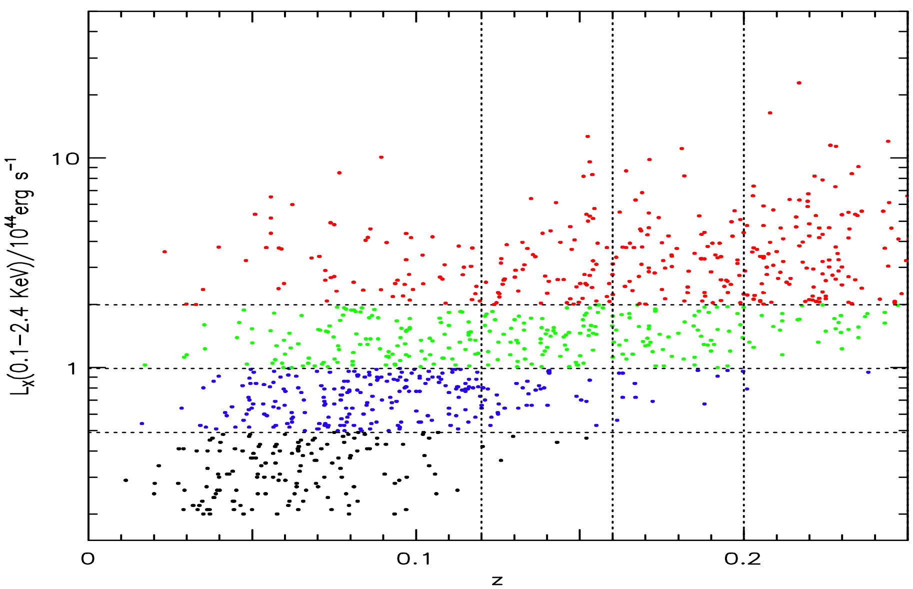
All methods give similar errors w/n <10%.

2. *X-ray cluster data*

- Assembled the largest all-sky cluster catalog of now >1,400 clusters to z=0.7.
- At present ~1,000 clusters are isotropic to z~0.3 (& reasonably resolved by WMAP)
- New version enables to bin by L_X as well as z
- Catalog contains (RA, DEC), z, θ_X (ultimately unnecessary)
- Computed for each cluster *using iso-T β-model:* n_e, T_X, r_{core}



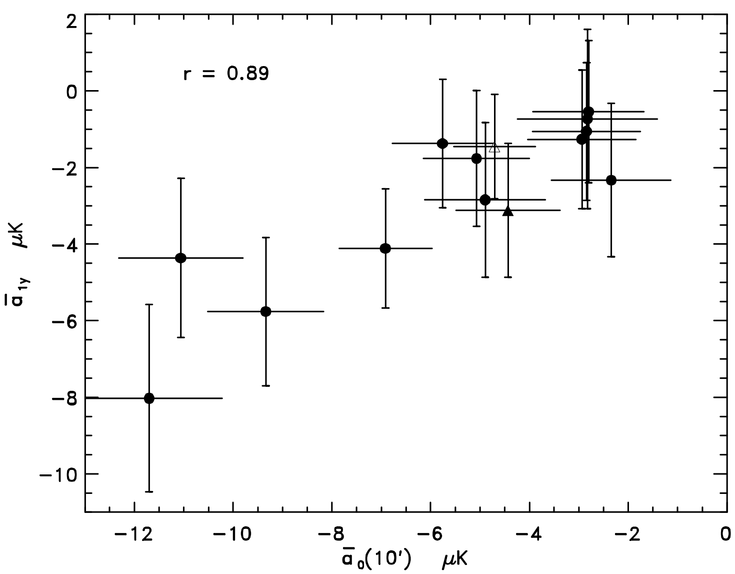
2008 – KABKE1,2 (674 clusters)
flux-lumited



2010 – KAEEK (985 clusters)
L_X-limited

From KAEEK (2010): dipole at zero monopole (30')

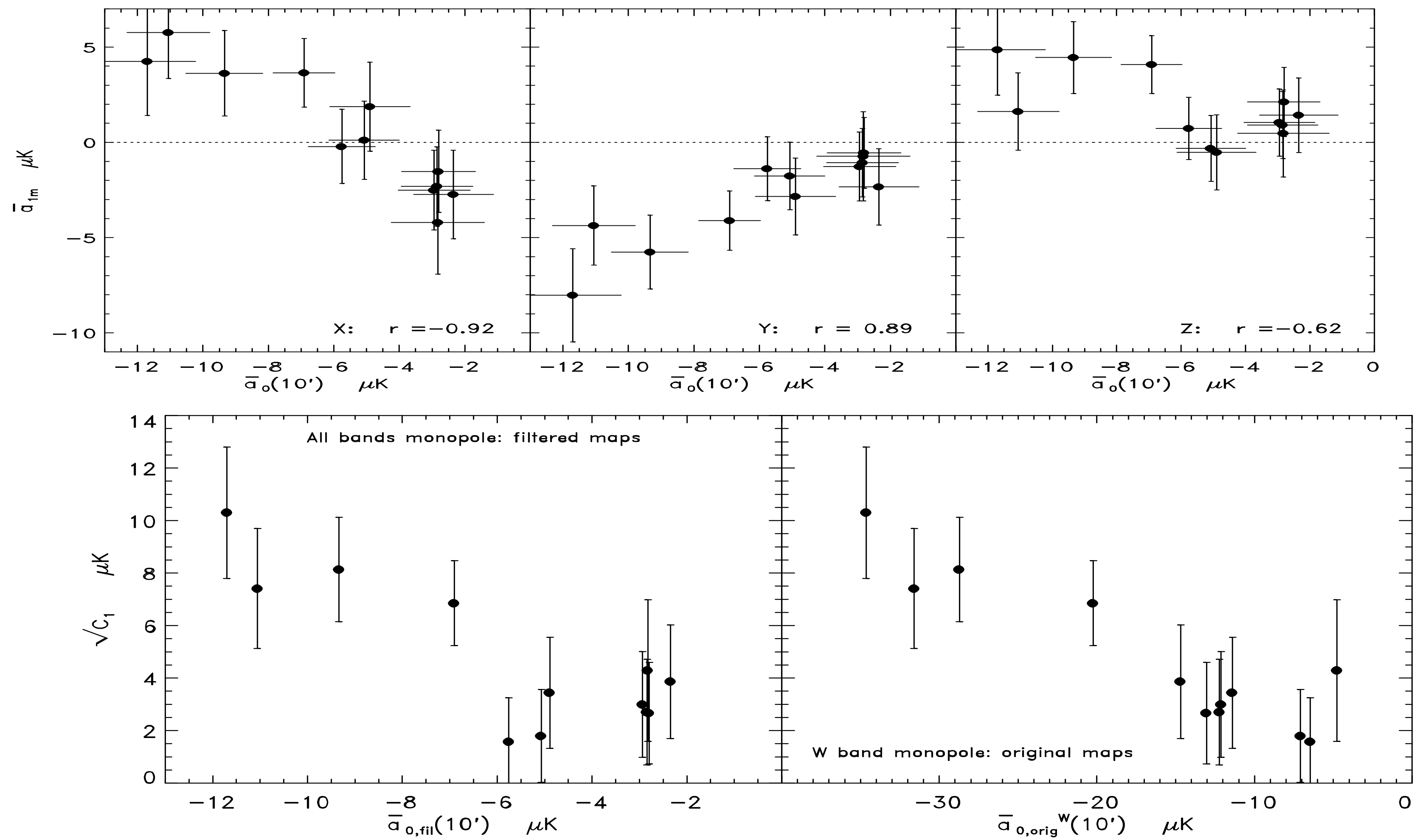
Z<	L_X	N_{cl}	a_{1x}	a_{1y}	a_{1z}	$\sqrt{C_1}$
0.12	0.2-0.5	142	-4.2±2.7	-0.7±2.3	0.5±2.3	4.3±2.7
---	0.5-1	194	-2.7±2.3	-2.3±2.0	1.4±2.0	3.9±2.2
---	>1	180	4.9±2.4	-4.5±2.1	1.5±2.0	6.8±2.2
0.16	>2	130	-4.2±2.8	-8.0±2.4	4.9±2.4	10.3±2.5
0.2	>2	208	3.6±2.2	-5.8±1.9	4.5±1.9	8.1±2.0
0.25	>2	322	-3.7±1.8	-4.1±1.5	4.1±1.5	6.9±1.6



Higher L_X-clusters exhibit higher CMB dipole as they should if the cause is coherent flow. *This rules out systematics and primary CMB causing this measurement.*

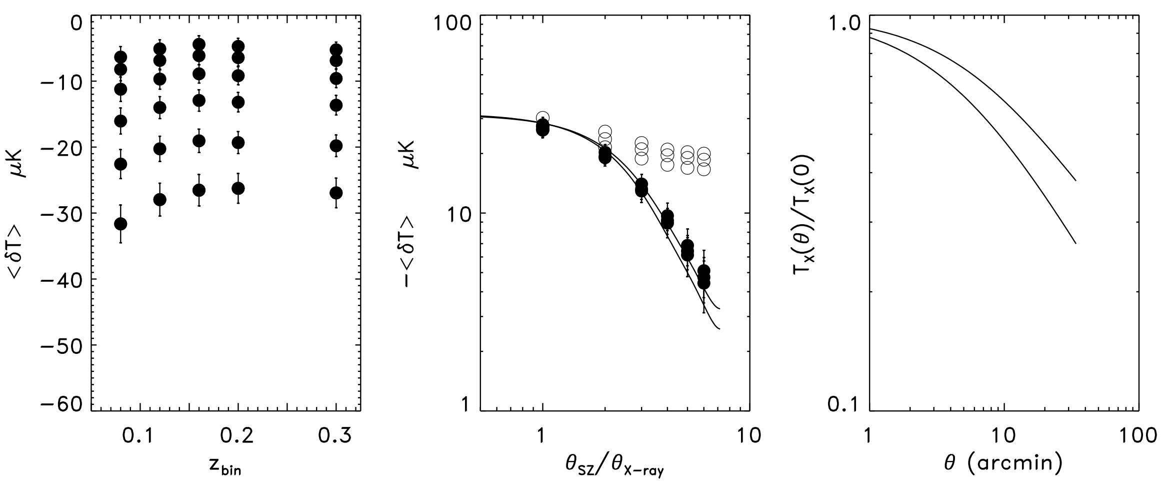
`Important: Dipole is evaluated at aperture containing ZERO monopole. This eliminates TSZ contribution.`

More on dipole – L_X correlation



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

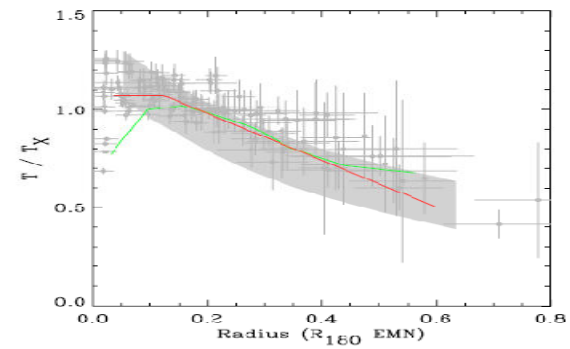


Fig. 5. Scaled projected temperature profiles compared with the average profiles from *ASCA* (Markevitch et al. 1998, grey band), *BeppoSAX* observations of cooling core clusters (De Grandi & Molendi 2002, green line), and *Chandra* observations of cooling core systems (Vikhlinin et al. 2005, red line). 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.)

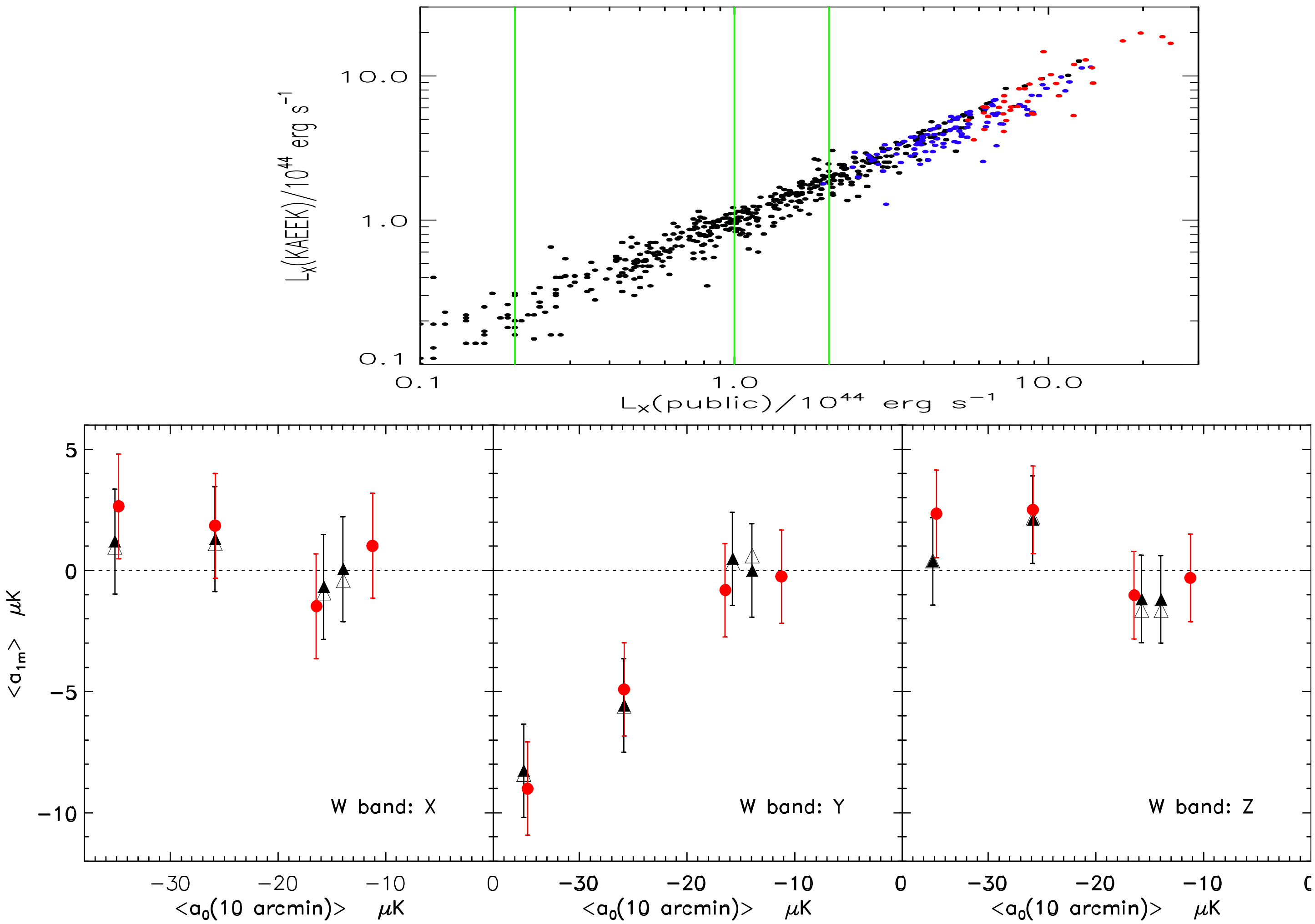
Table 4. TSZ component in filtered maps: observed and modelled.

(1)	(2)	(3)							
	CMB maps	TSZ estimate using catalogs: (a) | (b)							
$z \leq$	$\langle \Delta T \rangle$	$\langle \Delta T \rangle$	$\frac{a_{1,x}}{\langle \Delta T \rangle}$	$\frac{a_{1,y}}{\langle \Delta T \rangle}$	$\frac{a_{1,z}}{\langle \Delta T \rangle}$	$\langle \Delta T \rangle$	$\frac{a_{1,x}}{\langle \Delta T \rangle}$	$\frac{a_{1,y}}{\langle \Delta T \rangle}$	$\frac{a_{1,z}}{\langle \Delta T \rangle}$
	μK	μK				μK			
0.05	$-4.5 \perp 1.3$	−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:

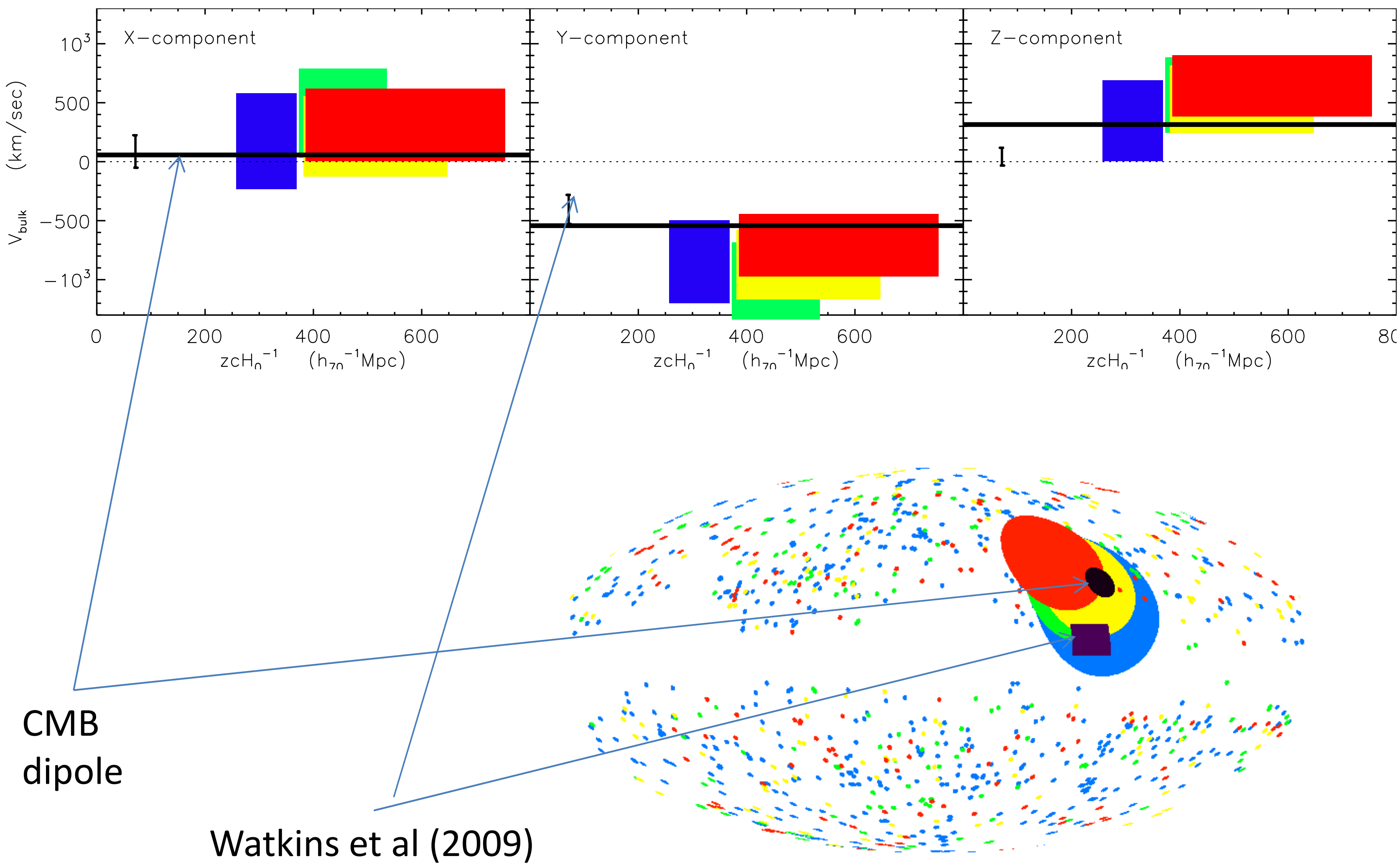
1. TSZ component w fits the measured values well, but
2. Residual TSZ dipole is negligible.

KSZ dipole using public X-ray data (2011, ApJ, 732, 1)



A. Kashlinsky *GSFC/Paris* *2011*

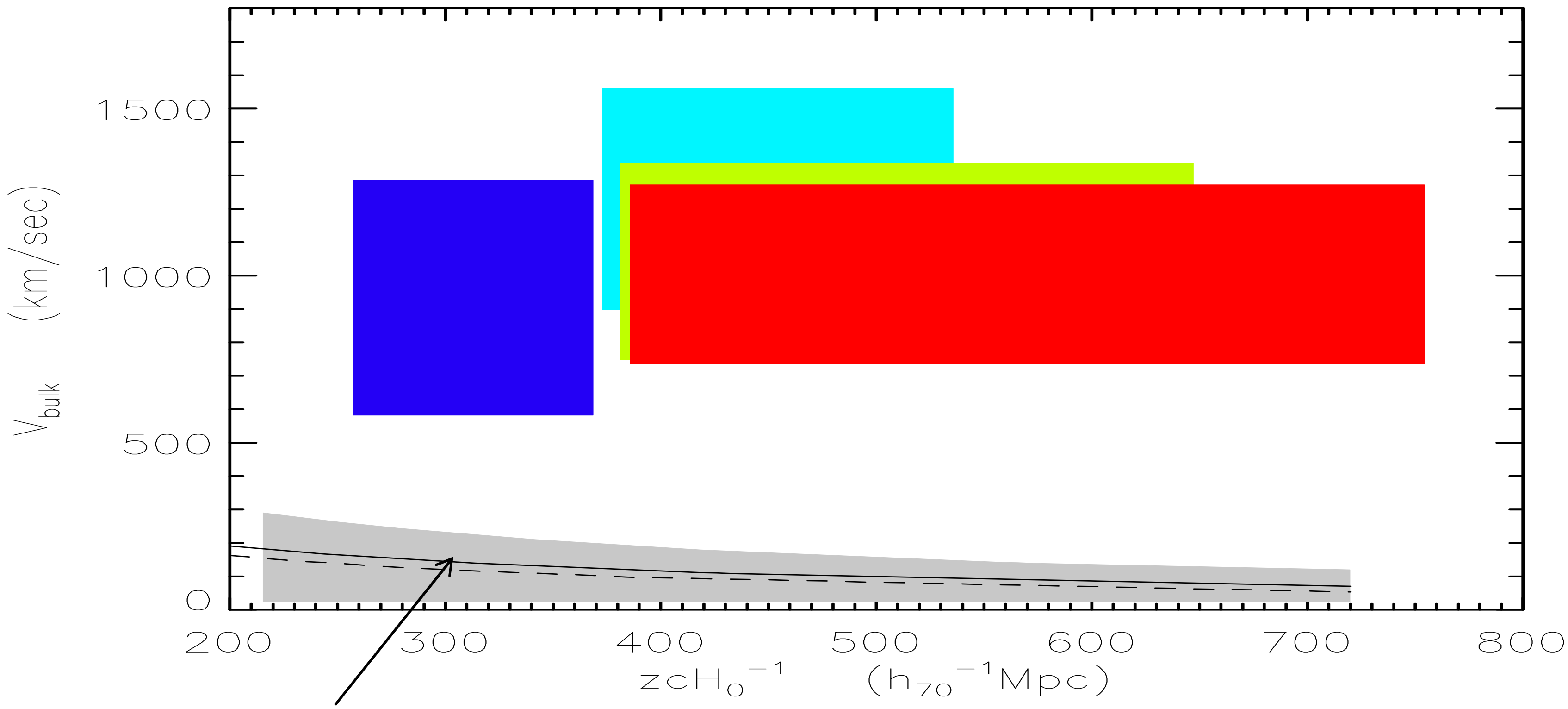
Results & comparison



Cosmological implications: ΛCDM

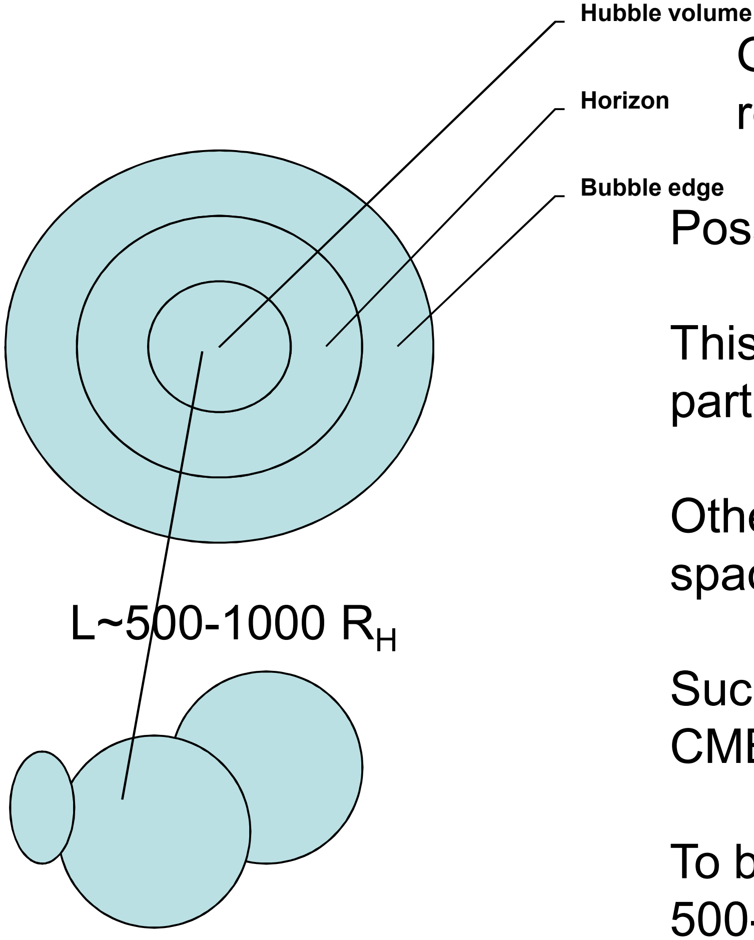
At each z-bin we divided clusters into 3 independent L_X bins and model the dipole:

$\boldsymbol{a^n_{1m}=\alpha^n V_m}$ with n denoting L_X bins. Regression gives $\boldsymbol{V_m}$



Gravitational instability with concordance ΛCDM model cannot explain the amplitude AND coherence of the flow

Cosmological implications: “dark flow”?



Grav. instability cannot account for the flow and it remains coherent to >100-800 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 $Q<2\text{-}3\times10^{-5}$, 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)

Alternative tests

- DF induces observable CMB component correlated with LSS (Zhang 2010)
- Lorentz boost aberration and galaxy counts: downstream vs upstream (Itoh et al 2010)
- Lorentz boost and CMB power spectrum directional dependence (Kosowsky & Kahniashvili 2010)
- Far-IR CIB dipole and its direction – can be measurable soon (Fixsen & Kashlinsky 2011)
- SNIa velocity measurements – already began with mixed results: Ma et al (2011) claim a tilt (DF) velocity using 103 SN, but Dai et al (2011) and Turnbull et al (2011) claim none or very little
- Isotropy/uniformity of universal expansion. Wiltshire et al (2012, arxiv:1201.5371) claim the Hubble flow is uniform for a sample of >4,500 galaxies if measured in the Local Group frame, but is not in the CMB dipole frame – consistent with DF (primordial CMB dipole)

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, Edge)
- 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 $z \sim 0.5$ – 0.7 (distances > 1-2h^{-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!

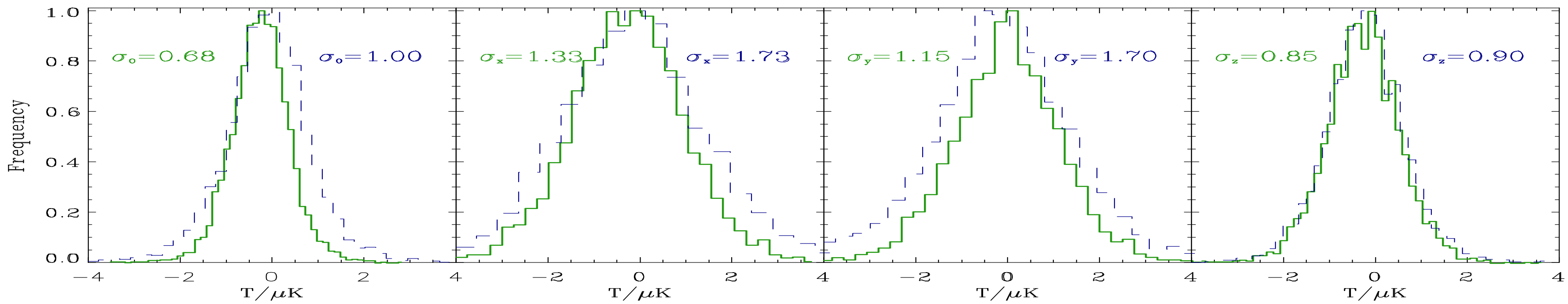
Conclusions

- Our measurements indicate CMB dipole at cluster pixels out to ~ 800 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
- The dipole correlates with L_X-cut of the sample – *this rules out primary CMB*
- This suggests that the dipole originates from the KSZ effect
- The bulk flow implied by this dipole is high: V_{bulk} ~ 600-1000 km/sec
- There may be systematic overestimate of V_{bulk} (but likely < 20% or so)
- The coherence length is high – and perhaps ~ 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?

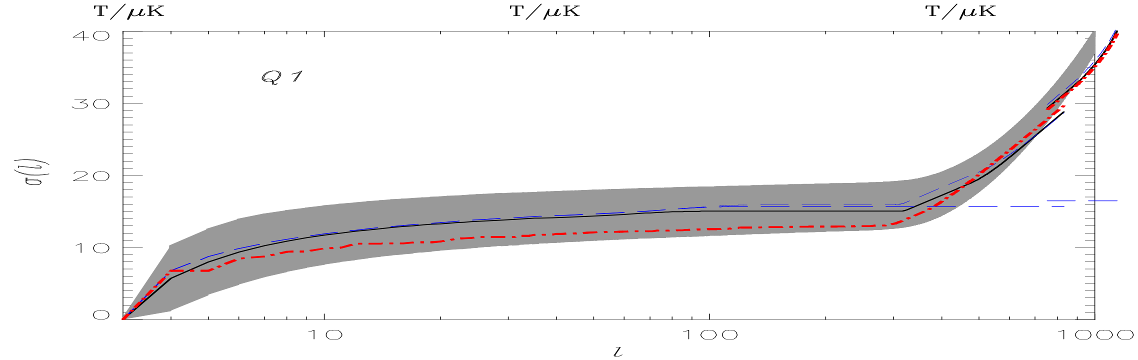
Keisler's claim: reconstructed the catalog of ~ 700+ clusters from public data

- Keisler claims: $(a_{1x}, a_{1y}, a_{1z}) = (1.2+/-1.7, -2.4+/-1.7, 0.2+/-1.1)$ μK
- KABKE1,2 get: $(a_{1x}, a_{1y}, a_{1z}) = (0.7+/-1.2, -3.3+/-1.1, 0.5+/-1.)$ μK at z<0.3 and
  $(0.6+/-1.2, -2.7+/-1.1, 0.6+/-1.)$ μK at z<0.2

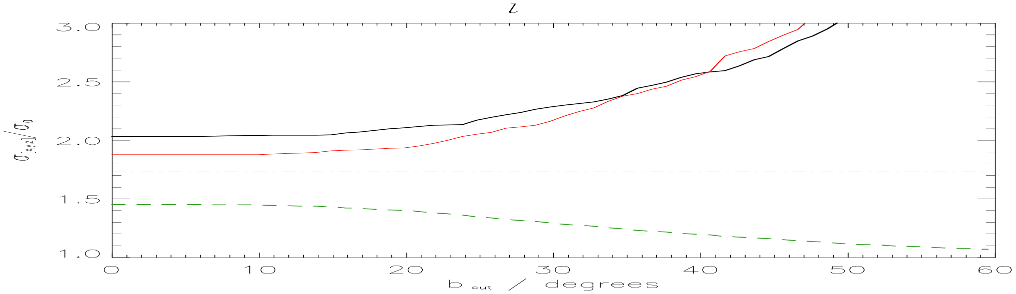
The only way to get such errors and the y/z ratio is when the dipole outside the mask has not been subtracted in simulated maps (Keisler confirmed this dipole-subtraction mistake). ***This is 50% increase in*** $\boldsymbol{a_{1y}}$. AKEKE show:



Furthermore, Keisler simulates ΛCDM universes and pumps up cosmic variance – **another ~15%.** Our Universe is the only relevant realisation for error analysis. (99% of CMB pixels are left for this.)



Lastly Keisler's assembled catalog has deficit of low-b clusters – pumps up y/z by **further ~10-15%**



Osborne et al (OMCP - arxiv1011.2781 - unpublsihed)

• OMCP introduce different filters – cannot be compared directly as filtering is non-unitary, ***BUT***

•***The numbers in the tables there violate - at face - value the precise mathematical theorem proven in AKEKE. Still:***

•***Their figure 13 proves that their filters actually REDUCE S/N of KSZ measurement:***

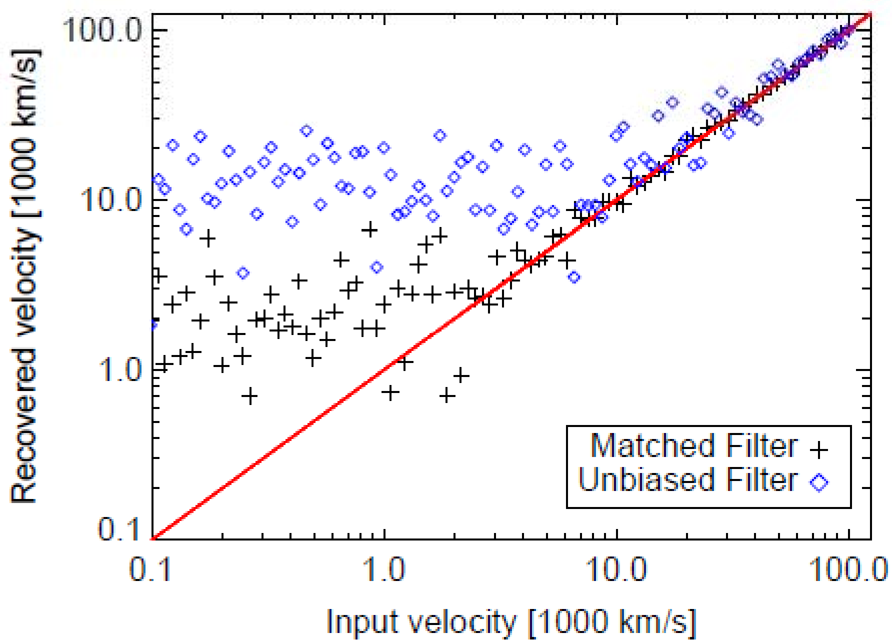


Fig. 13 of OMCP arxiv posting

Their clusters have $<\tau>\sim 7\times10^{-3}$ – hence:
Where their filters recover *V,* their average clusters should have $dT_{KSZ}\sim$ 500-1,000 μK or greater. Thus they should be recoverable from ***unfiltered maps*** – the fact that they are not recovered in filtered maps means S/N is reduced with filtering.