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 on “dark flow” is in preparation – call for relevant references

- The data needed to verify Dark Flow results has been posted at

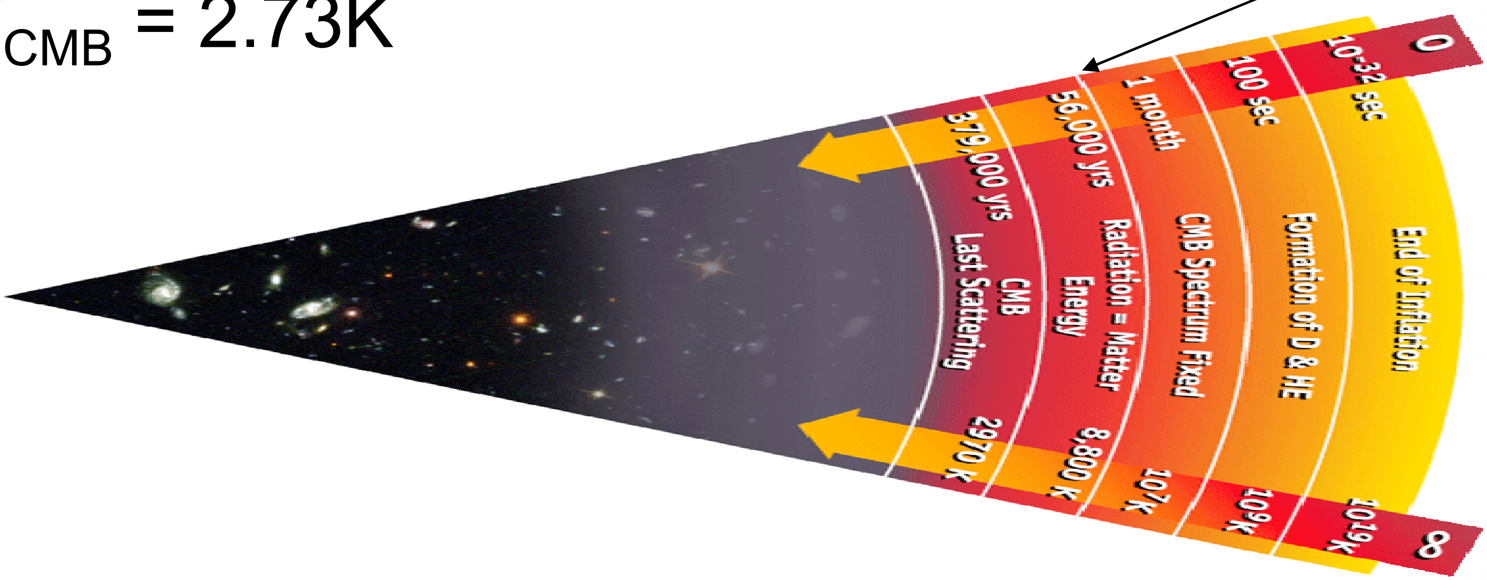
http://www.kashlinsky.info/bulkflows/data_public

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} = 2.73K



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~60-80 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)

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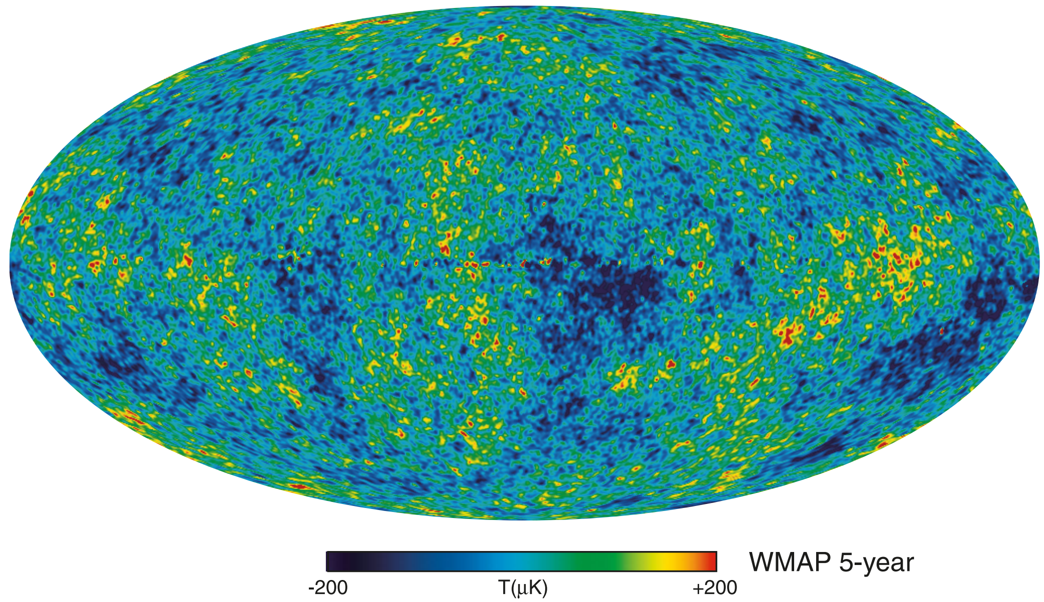
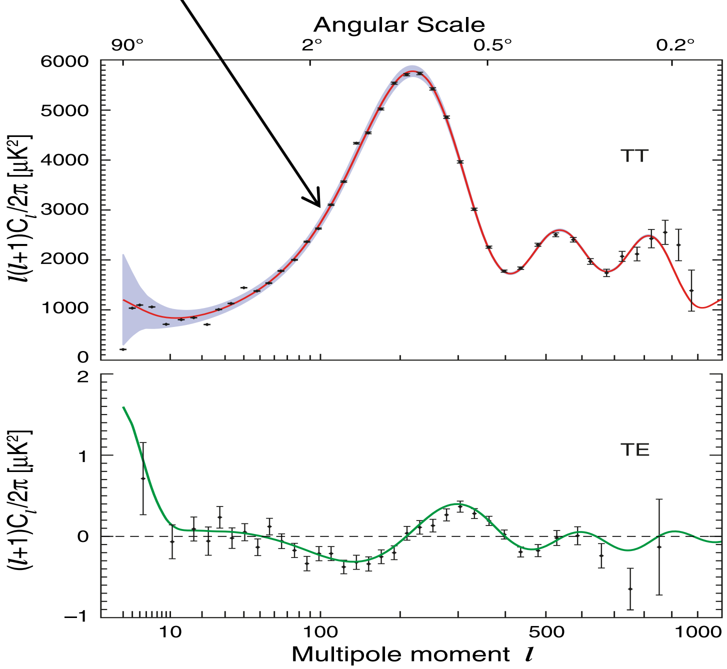
CMB sky:

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



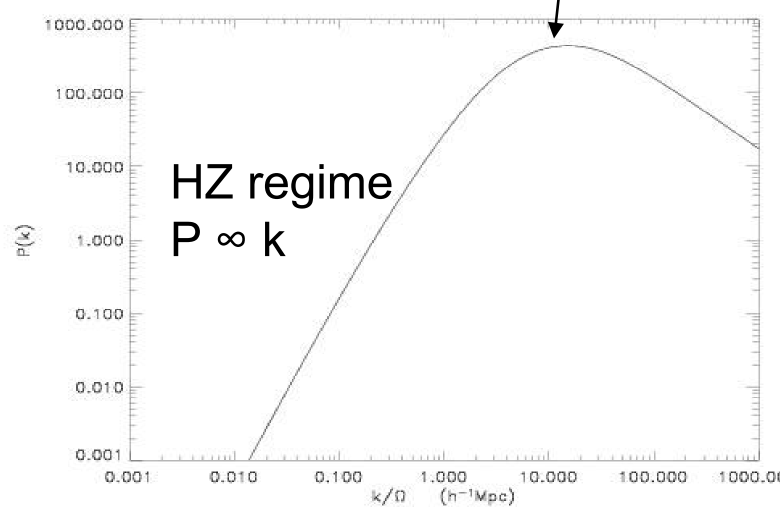
Establishes concordance model (ΛCDM)



CMB

R_{hor} (m-r-equality)

Matter P(k)



HZ regime

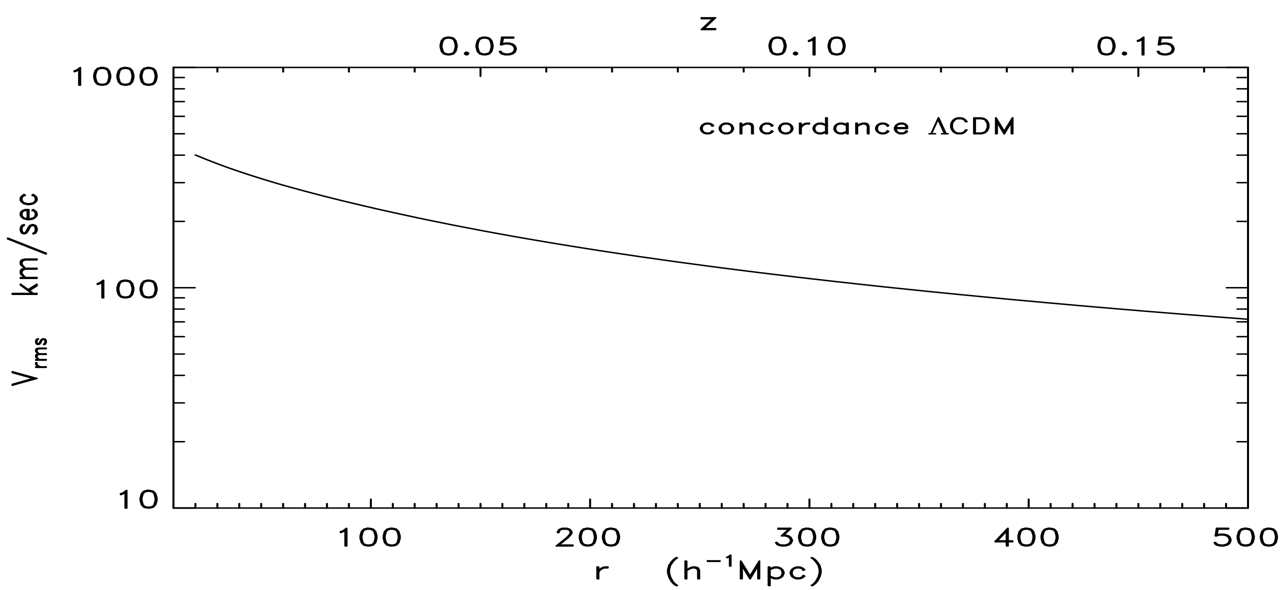
P ∝ k

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)

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

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



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

Sunyaev-Zeldovich effect

- Clusters of galaxies: 10^{14}-$10^{15}M_{sun}$; $\sigma\sim10^3$km/sec, X-ray gas $T\sim10^7$-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 ($\sim10^{-3}$ 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:

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

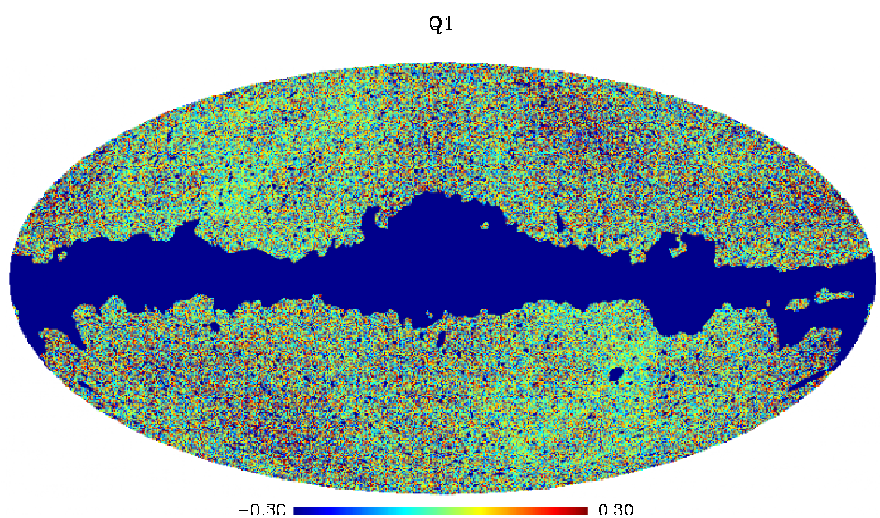
$$a_{1m} = a_{1m}^{KSZ} + a_{1m}^{TSZ} + a_{1m}^{CMB} + \sigma_{noise}/\sqrt{N}$$

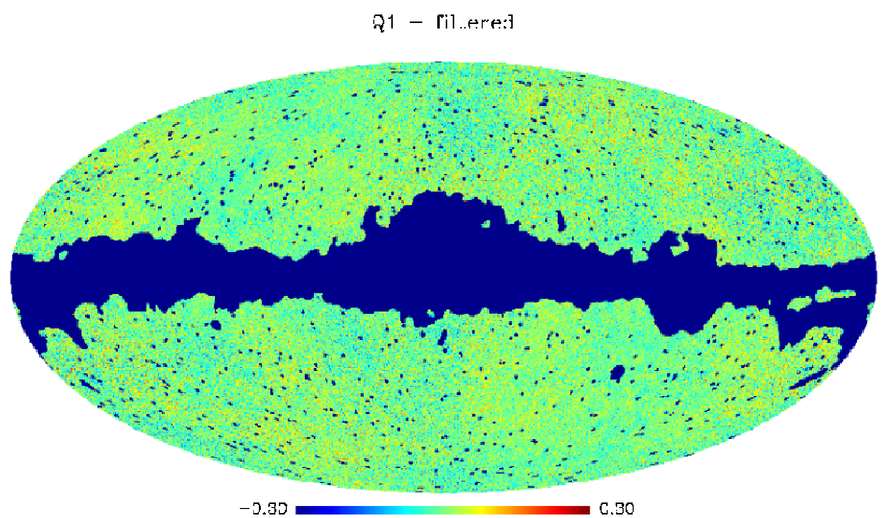
Hence, if N>>1 clusters move coherently, one can isolate the KSZ term through the cumulative dipole measurement.

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

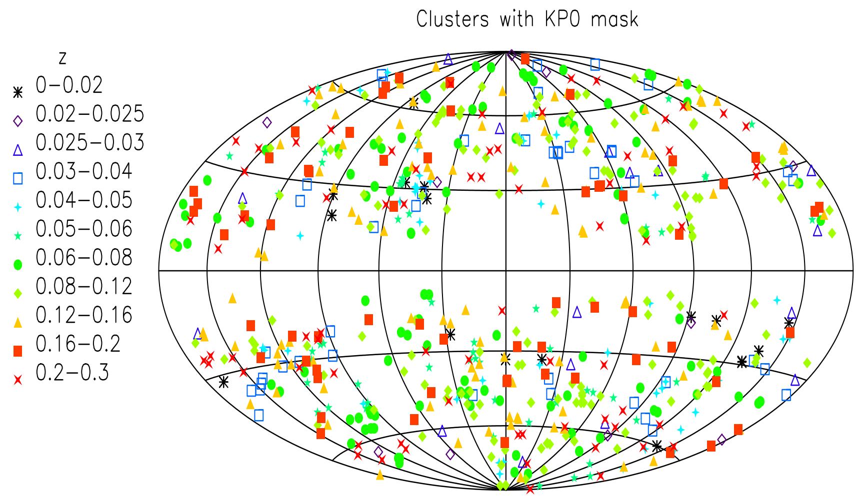
$$F_\ell = \frac{C_\ell(sky) - C_\ell^{\Lambda CDM} B_\ell^2}{C_\ell(sky)}$$



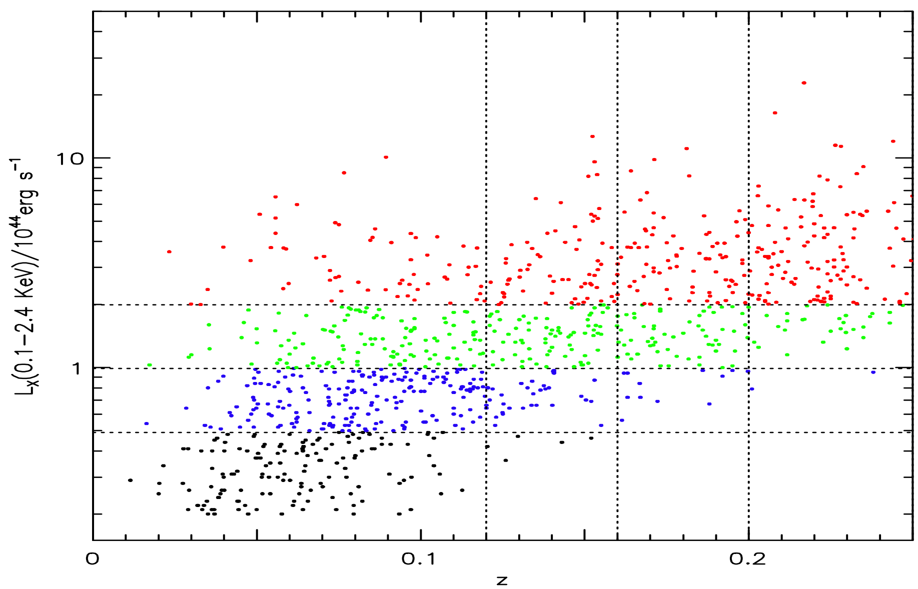


2. *X-ray cluster data*

- 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

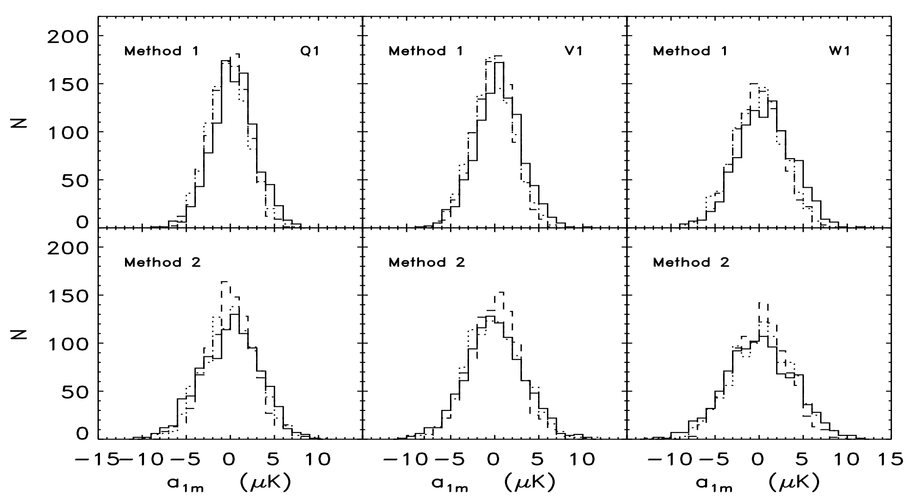


2010 – KAEEK (985 clusters)
L_X-limited

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%.

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

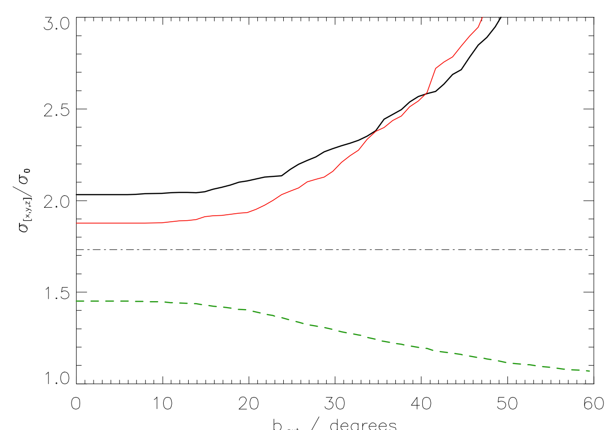
PROOF:

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:

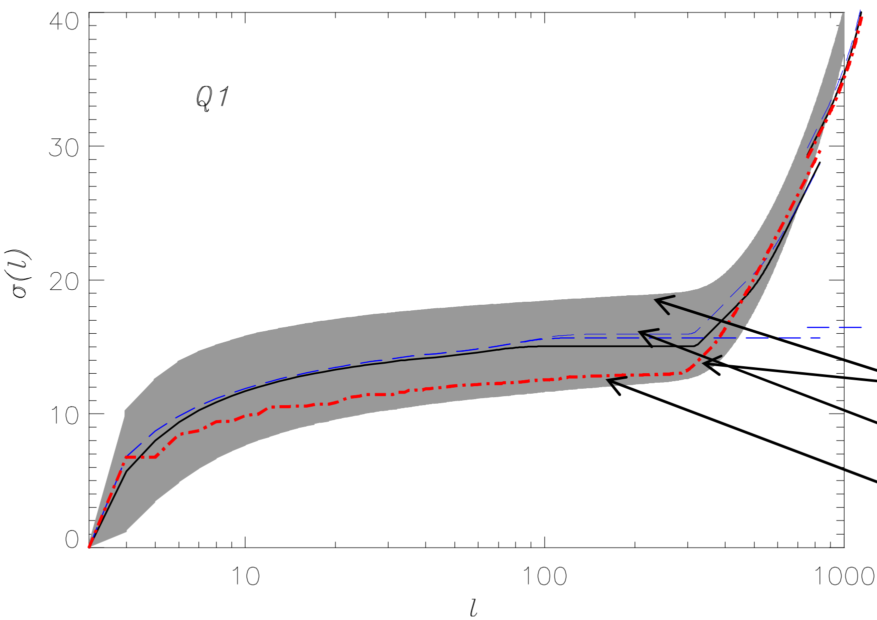
$$\sigma_{fil}^2=\frac{1}{4\pi}\Sigma(2l+1)\left[\frac{\Delta_l^2}{C_l^{theor}+\Delta_l+N_l}+\frac{N_l^2}{C_l^{theor}+\Delta_l+N_l}\right]=\sigma_{CV,fil}^2+\sigma_{N,fil}^2(t_{obs})$$

6. Contribution to dipole from1[st] term $\boldsymbol{\sim 15\sqrt{3/N_{cl}}\ \mu K}$; 2[nd] 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 $\boldsymbol{a_0=\langle\Delta T\rangle}$ ***and*** $\boldsymbol{a_{1m}=\langle n_m\Delta T\rangle}$. 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: $\sigma^2(l) \equiv \Sigma_{q=4}^{l}\sigma^2(q)$

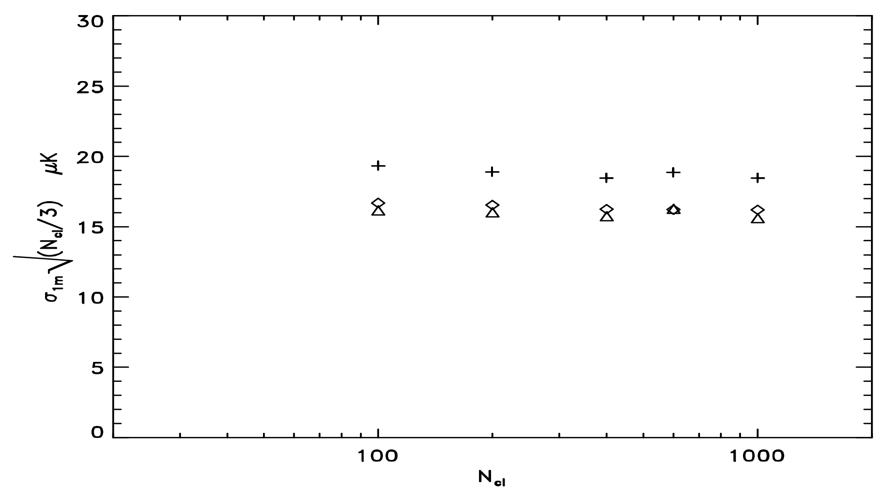
$$\sigma^2_{fil} = \frac{1}{4\pi}\Sigma(2l+1)\left[\frac{\Delta_l^2}{C_l^{theor}+\Delta_l+N_l}\right] \equiv \Sigma_q\sigma^2(q)$$

4000 random ΛCDM universes (1σ range)

mean

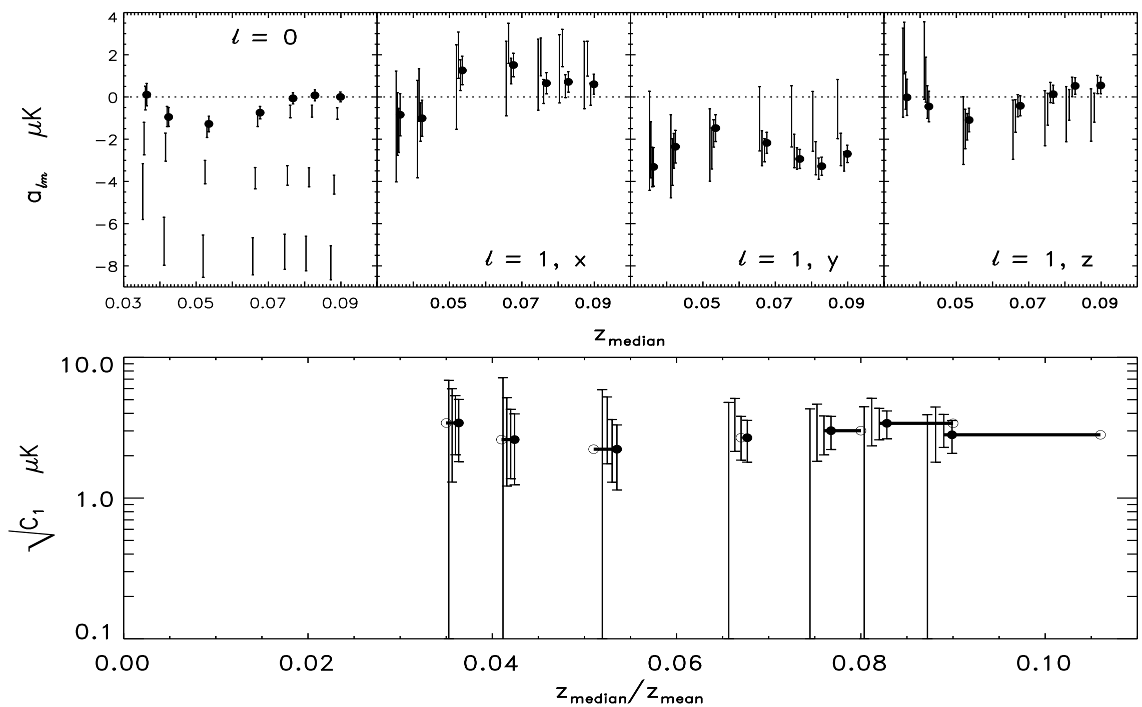
Our Universe:
the *only relevant* realisation

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



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.



From KABKE1,2 (08/09)

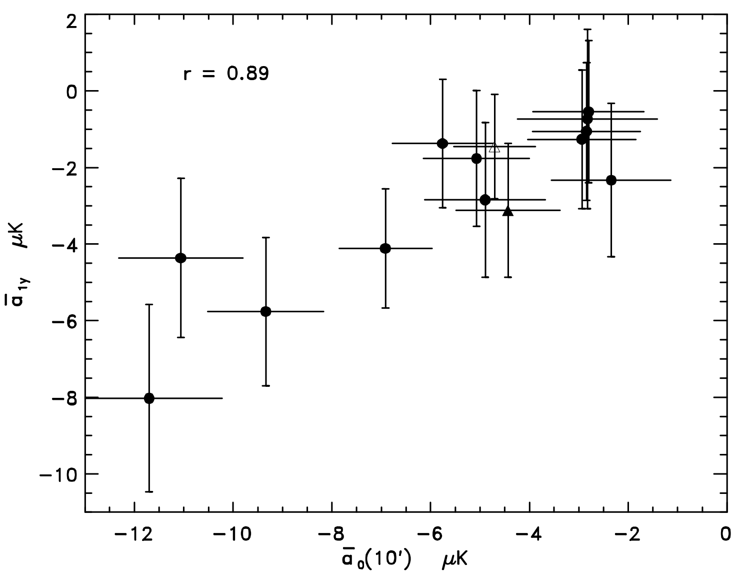
• The dipole appears only at cluster positions.

• Must originate from CMB photons which interacted w cluster gas.

• The final dipole is independent of distance/redshift.

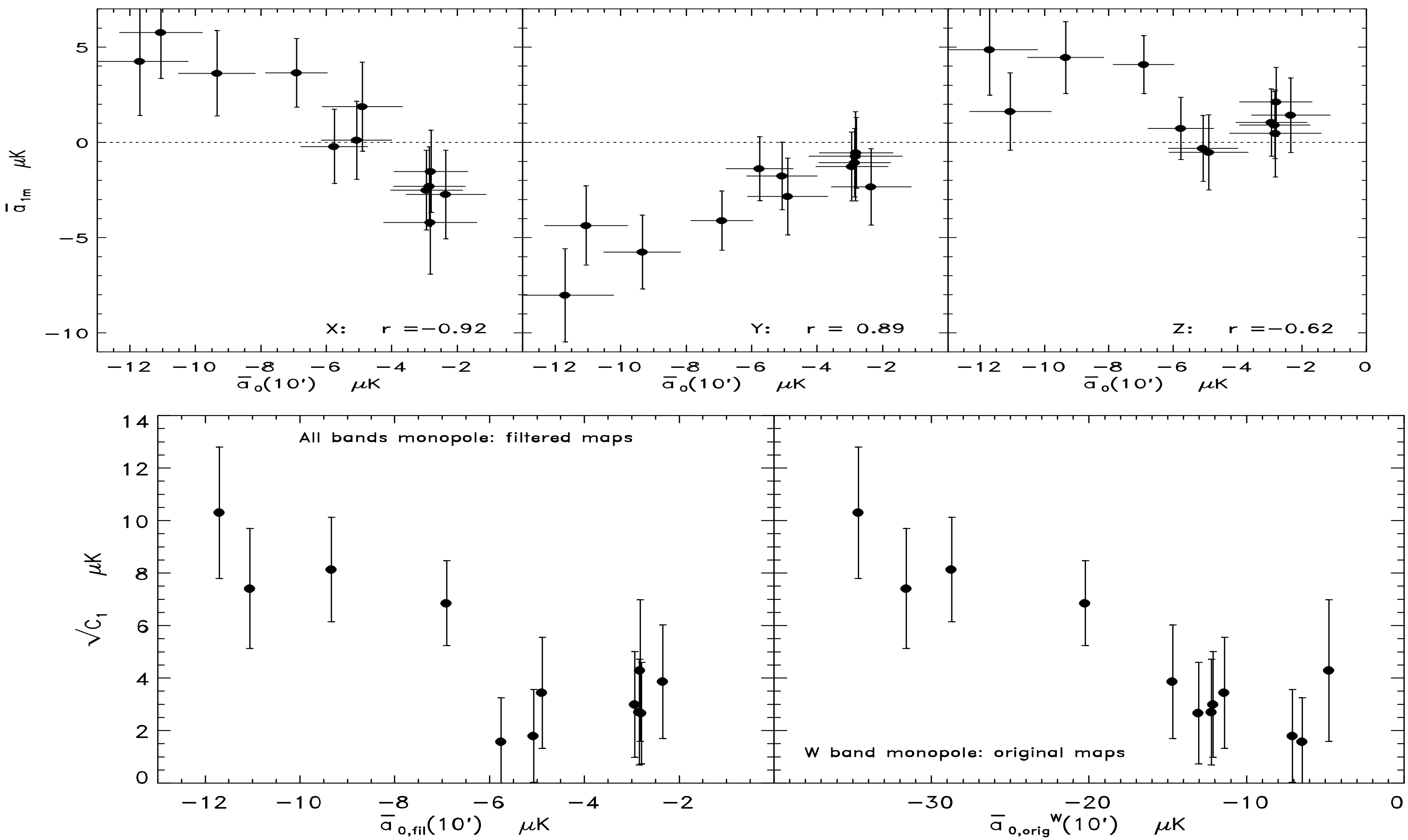
From KAEEK (2010): dipole at zero monopole (30')

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.*

More on dipole – L_X correlation



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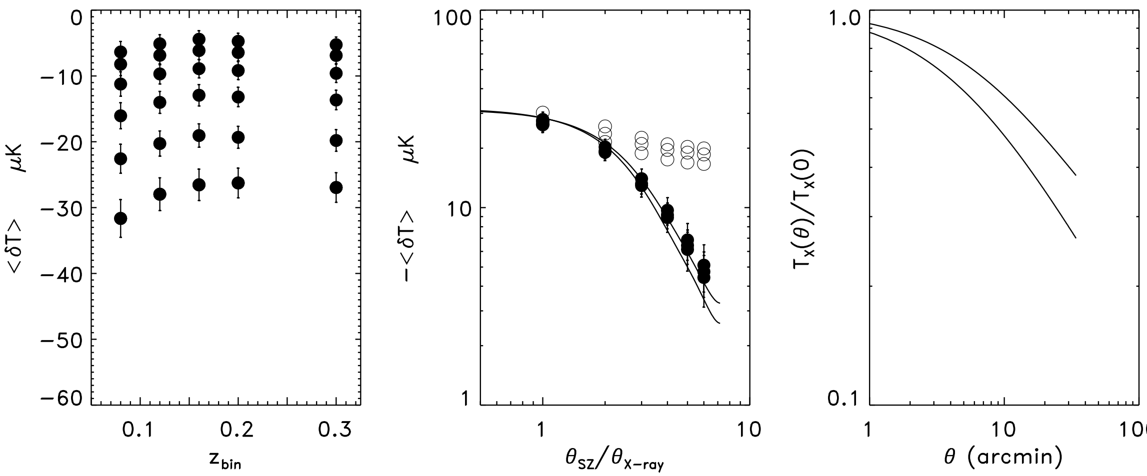
5. More on (negligible) TSZ contribution to dipole

- TSZ goes as $\boldsymbol{\tau} T_X$, whereas KSZ goes as $\boldsymbol{\tau}$
- When T_X decreases w *r* TSZ monopole vanishes as KSZ dipole remains



Open: β-model Lines – NFW profiles

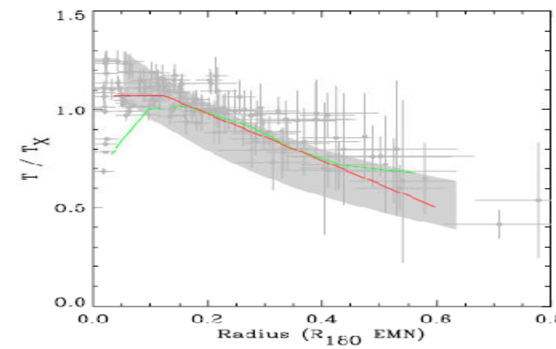


Fig. 5. Scaled projected temperature profiles compared with the average profiles from *ASCA* (Markevitch et al. 1998, grey band), *BeppoSAX* observations of cooling core clusters (De Grandi & Molendi 2002, green line), and *Chandra* observations of cooling core systems (Vikhlinin et al. 2005, red line).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

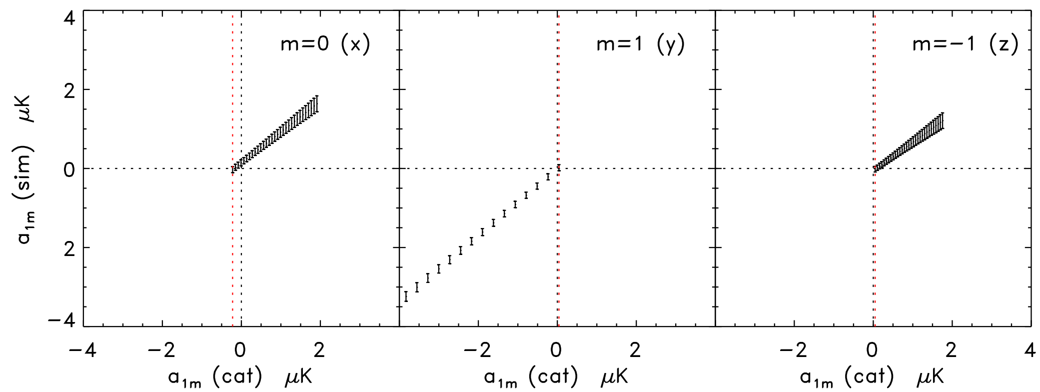
Table 4. TSZ component in filtered maps: observed and modelled.

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

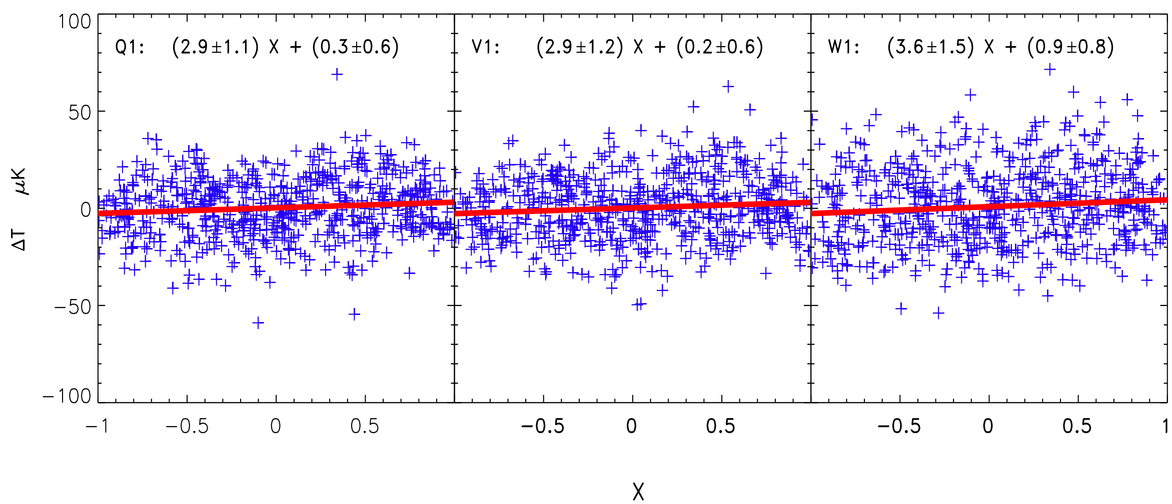
1. TSZ component w fits the measured values well, but
2. Residual TSZ dipole is negligible.

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.
This is the minimal S/N in the measurement!

KSZ dipole etc

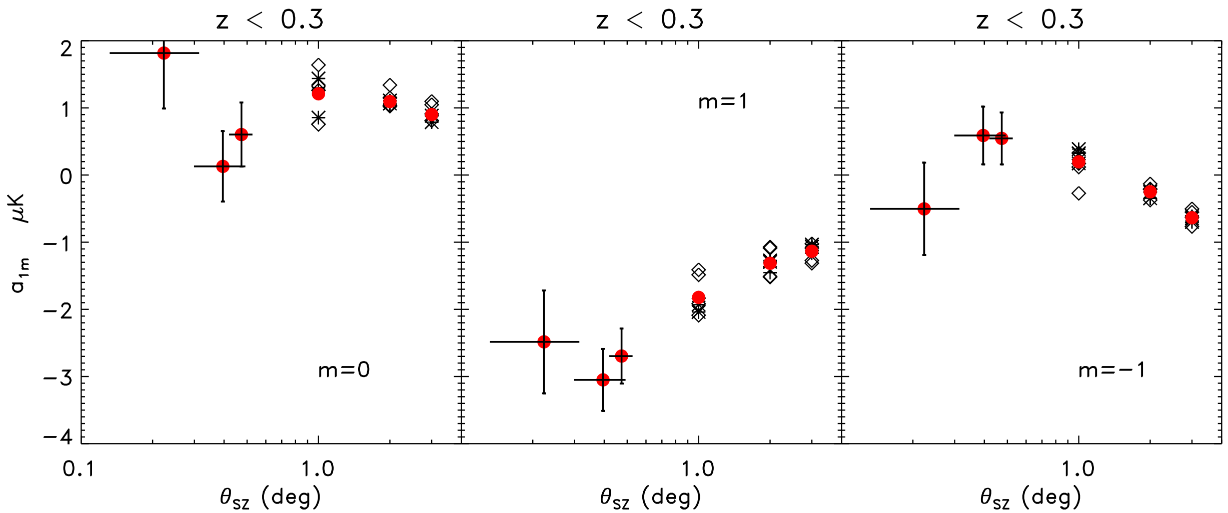
Table 3. TSZ monopole vs KSZ dipole contributions from rings.

Ring	$N_{\rm pixels}$	Monopole (unfiltered)	Dipole components (filtered) $a_{1,x}$	$a_{1,y}$	$a_{1,z}$
		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

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

(1)	(2)	(3)							
	CMB maps	TSZ estimate using catalogs: (a) | (b)							
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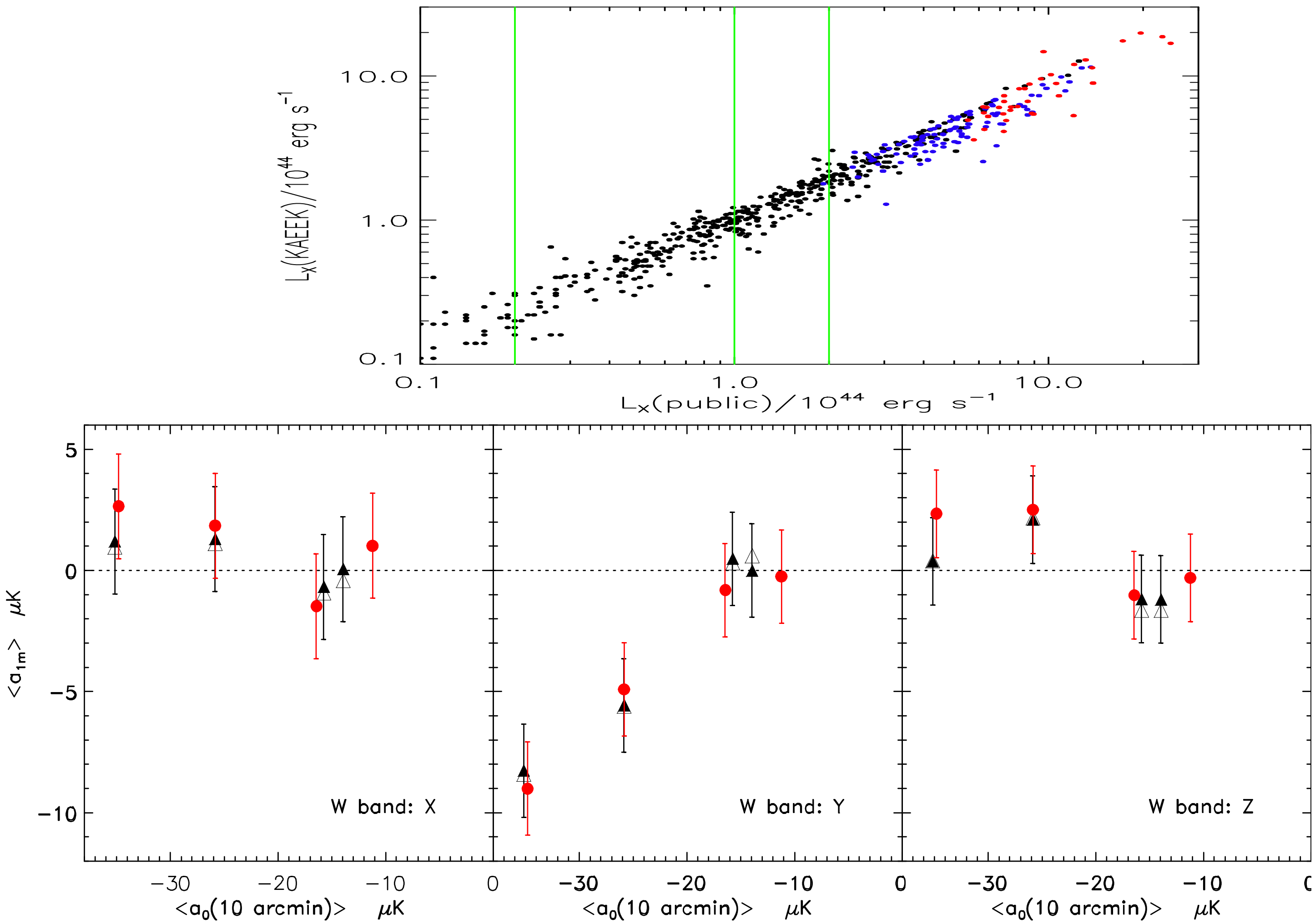
	μK	μK				μK			
0.05	-4.5 ± 1.3	-5.3	0.3	-0.2	-0.2	-5.6	0.2	-0.2	-0.2
0.06	-6.8 ± 1.1	-5.7	0.3	-0.3	-0.2	-6.1	0.3	-0.2	-0.2
0.08	-7.5 ± 1.0	-6.2	0.2	-0.0	-0.1	-6.7	0.2	-0.1	-0.1
0.12	-7.6 ± 0.9	-7.5	0.1	0.0	-0.2	-7.8	0.1	0.1	-0.2
0.16	-7.3 ± 0.8	-7.9	0.2	-0.1	-0.1	-8.6	0.2	-0.0	-0.1
0.20	-7.4 ± 0.8	-8.8	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%

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



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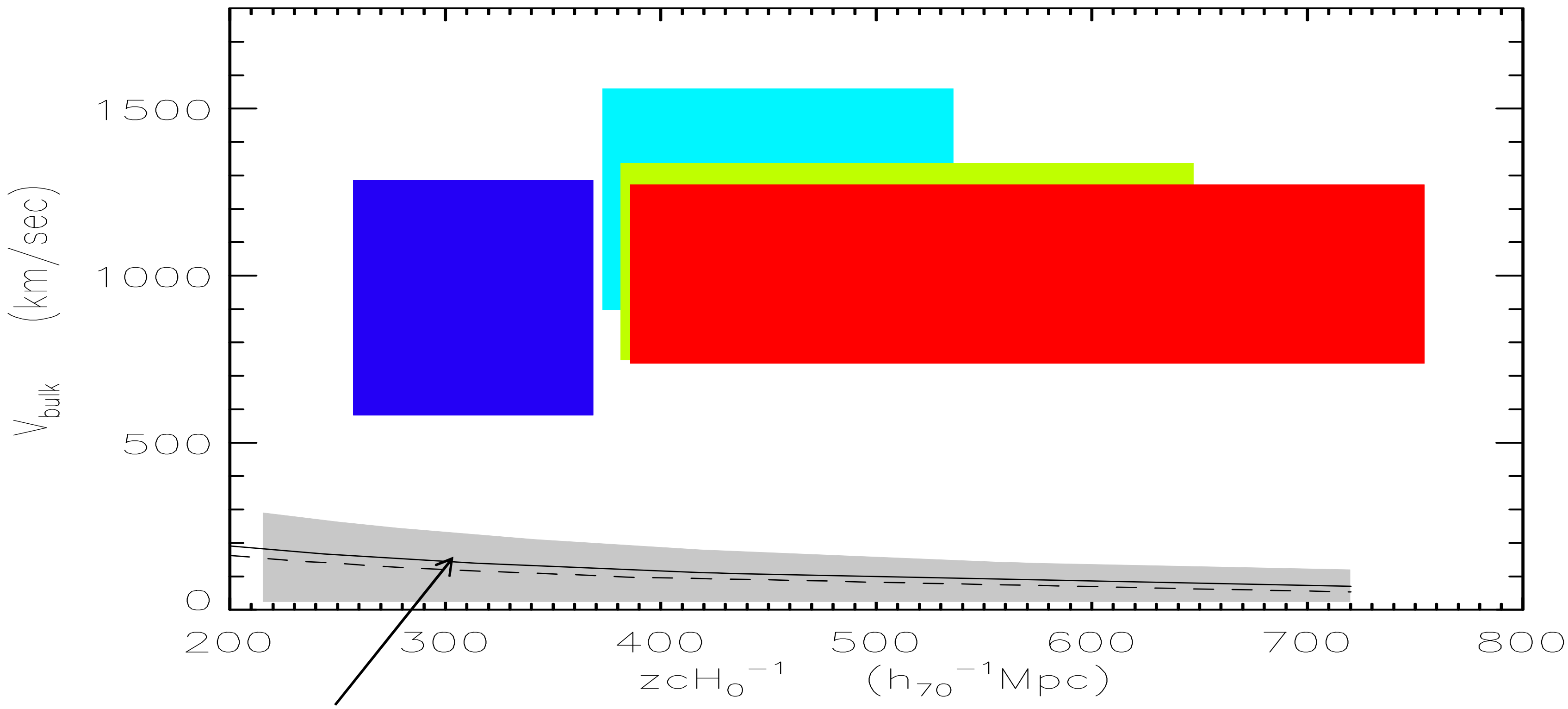
Cosmological implications: ΛCDM

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 $\boldsymbol{V_m}$

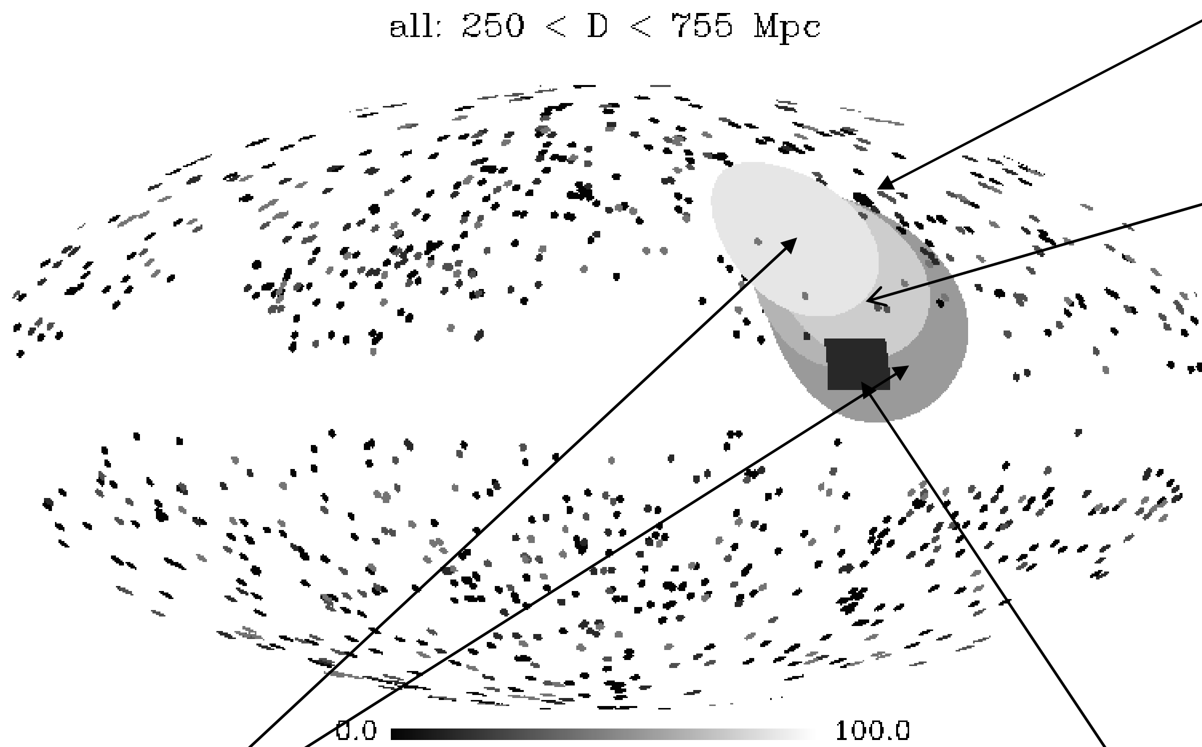


Gravitational instability with concordance ΛCDM model cannot explain the amplitude AND coherence of the flow

Direction of motion

CMB ***local*** dipole
(l,b) = (264.4, 48.4)

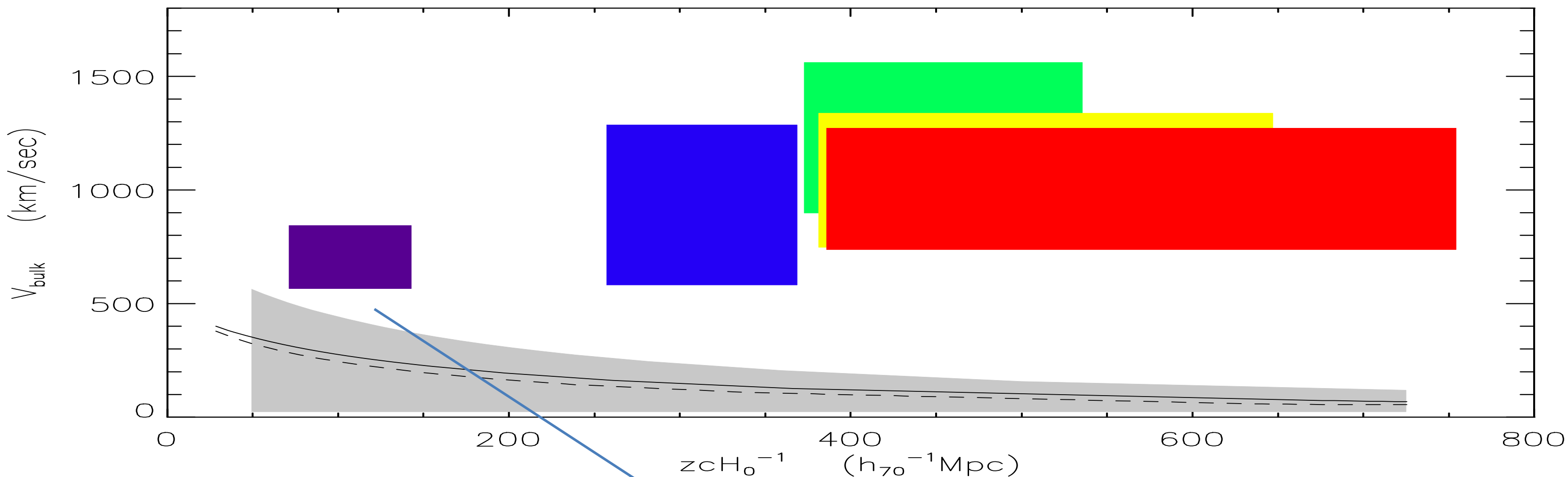
Great Attractor:
Hydra-Centaurus



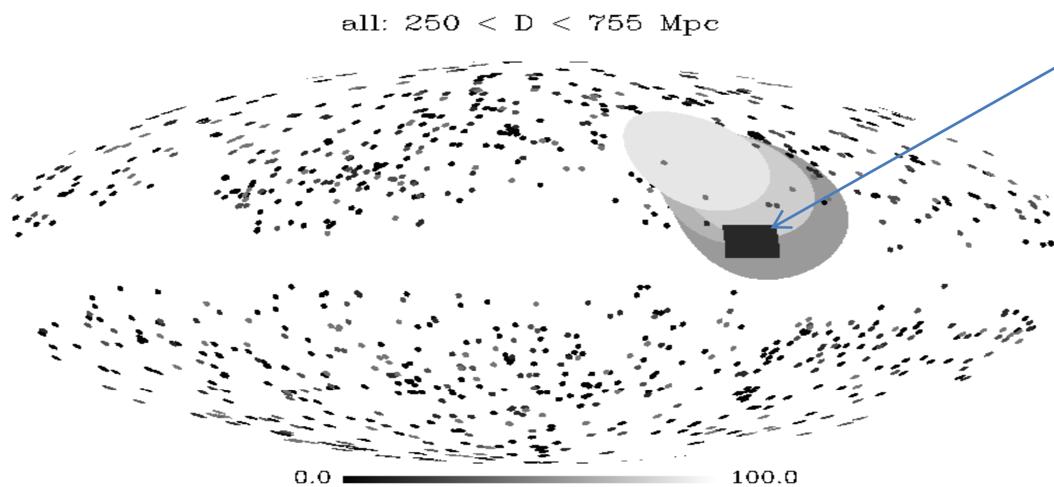
KAEEK: 100 to > ~600 h^{-1} Mpc
coherent flow:
V ~ 600-800 km/sec

Watkins et al (2008) motion
w/n ~ 50-100 h^{-1} Mpc:
(l,b) = (287±9, 8±6) deg
1-dimensional V=407±81 km/sec

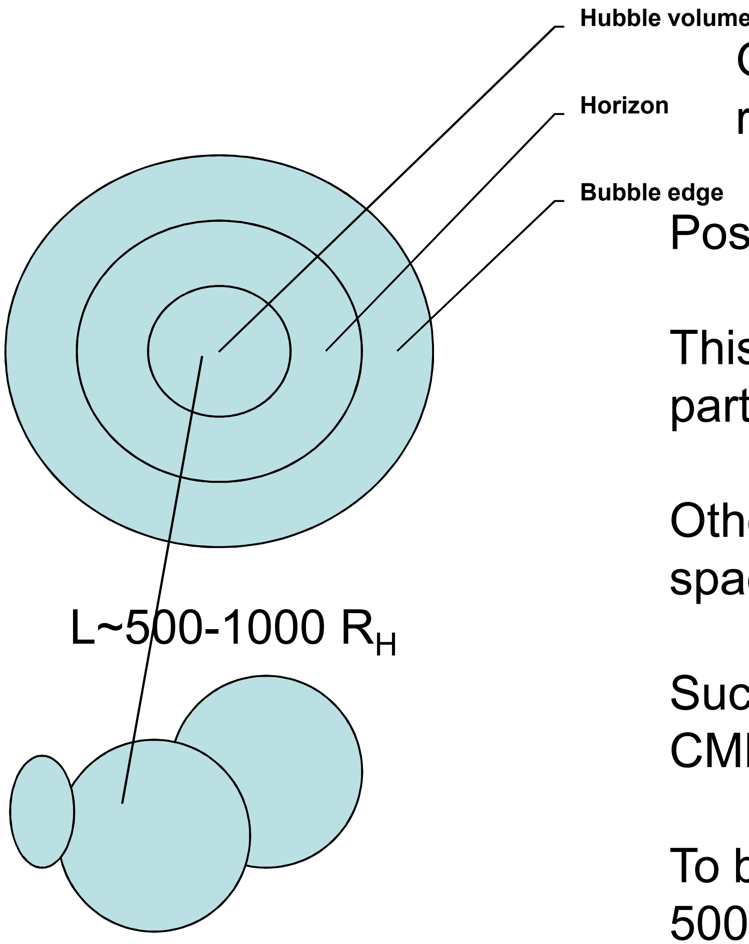
Comparison with other data:



3D from Watkins et al (2008), also Ma et al (2011)



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)

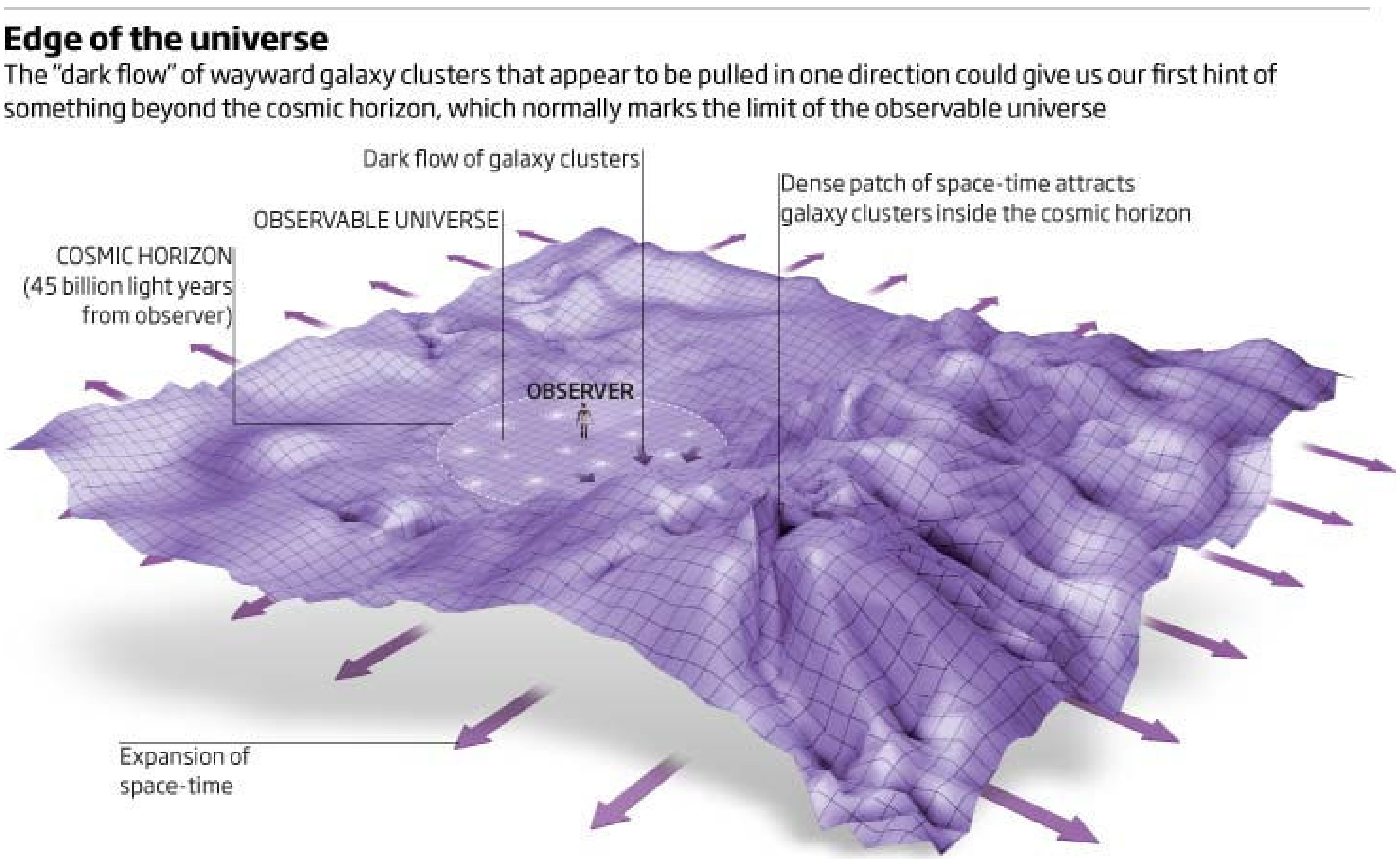
Specific model – an example (Turner 1991)

- 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:

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

- 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)

Dark flow according to *New Scientist*



From Gunn (1988)

Consider for a moment an extreme resolution. The striking feature of the 7S data is the bulk flow. The bulk flow is essentially absent in the IRAS accelerations. The

. . .

inflation theory. Most of the problem, it seems to me, would disappear if the MWB did not, in fact, provide a rest frame. For it not to do so is, of course, not trivially

. . .

any gradient which manifests itself as a gradient in the equation of state, such as any gradient which modulates the entropy, or the baryogenesis, or the early annihilation of the dark matter, would produce a dipole. The probability is only one in ten that it would lie so close to the IRAS dipole as it does, but that does not seem so forbidding.

. . .

of the length of inflation. The idea can be laid to rest if it turns out that a shell at a few thousand $km\ s^{-1}$ distance is in fact at rest with respect to the CMB, but it will become very much more attractive if the bulk flow persists to ever larger distances, and becomes compelling if those distances grow to the order of 10000 $km\ s^{-1}$, since then the potential fluctuations causing the flows could be ruled out by existing observations of the smoothness of the background.

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).

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 2010)

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!

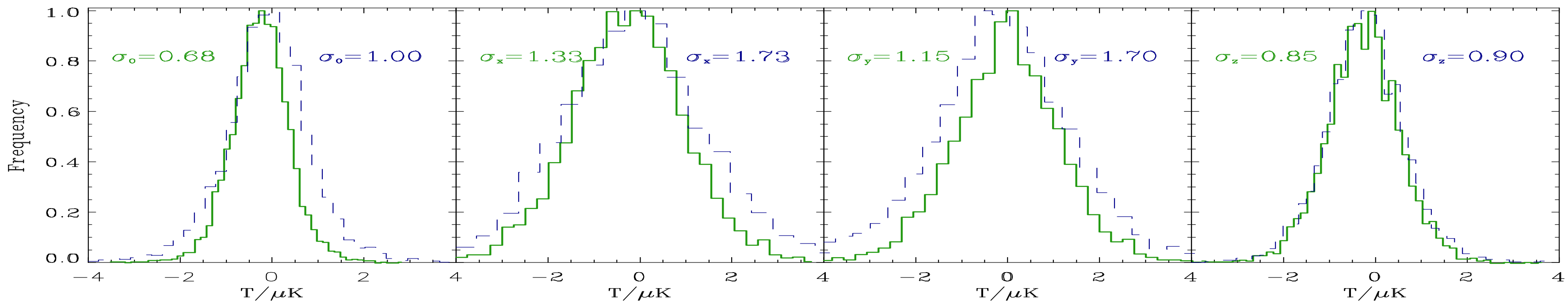
Conclusions

- 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?

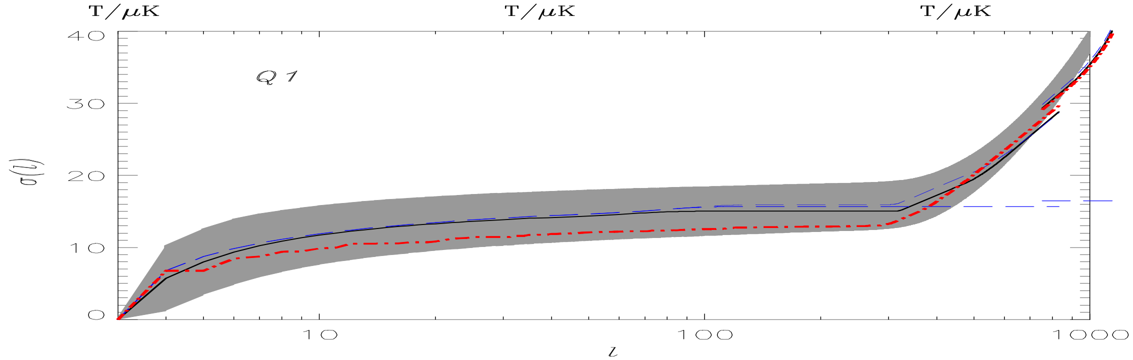
Keisler's claim: reconstructed the catalog of ~ 700+ clusters from public data

- Keisler claims: $(a_{1x}, a_{1y}, a_{1z}) = (1.2\pm1.7, -2.4\pm1.7, 0.2\pm1.1)$ μK
- KABKE1,2 get: $(a_{1x}, a_{1y}, a_{1z}) = (0.7\pm1.2, -3.3\pm1.1, 0.5\pm1.)$ μK at z<0.3 and
  $(0.6\pm1.2, -2.7\pm1.1, 0.6\pm1.)$ μK at z<0.2

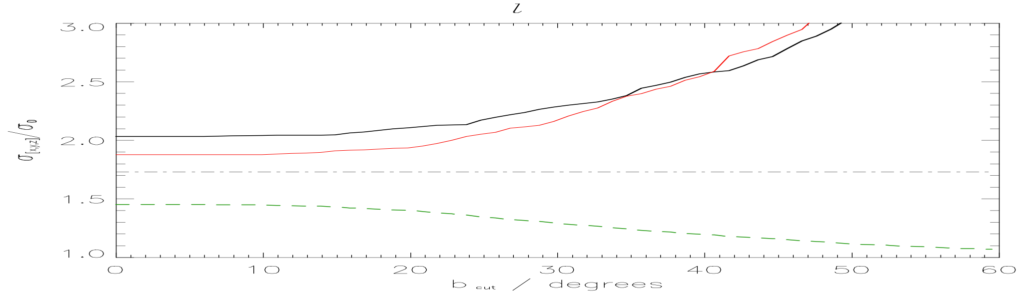
The only way to get such errors and the y/z ratio is when the dipole outside the mask has not been subtracted in simulated maps (Keisler confirmed this dipole-subtraction mistake). ***This is 50% increase in a_{1y}***. AKEKE show:



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:***

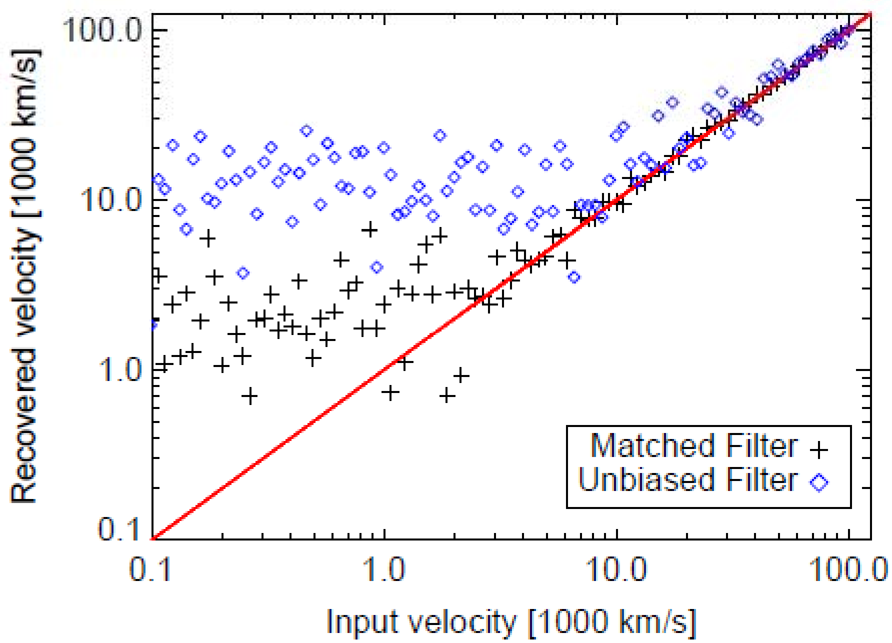


Fig. 13 of OMCP arxiv posting

Their clusters have <τ>~7x10^{-3} – hence:
Where their filters recover *V*, their average clusters should have dT_{KSZ}~ 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.