Constraints on Pre-Inflation Cosmology and Dark Flow

N. Q. Lan (Hanoi National University of Education),
G. J. Mathews (University of Notre Dame),
T. Kajino (National Astronomical Obsevatory Japan)

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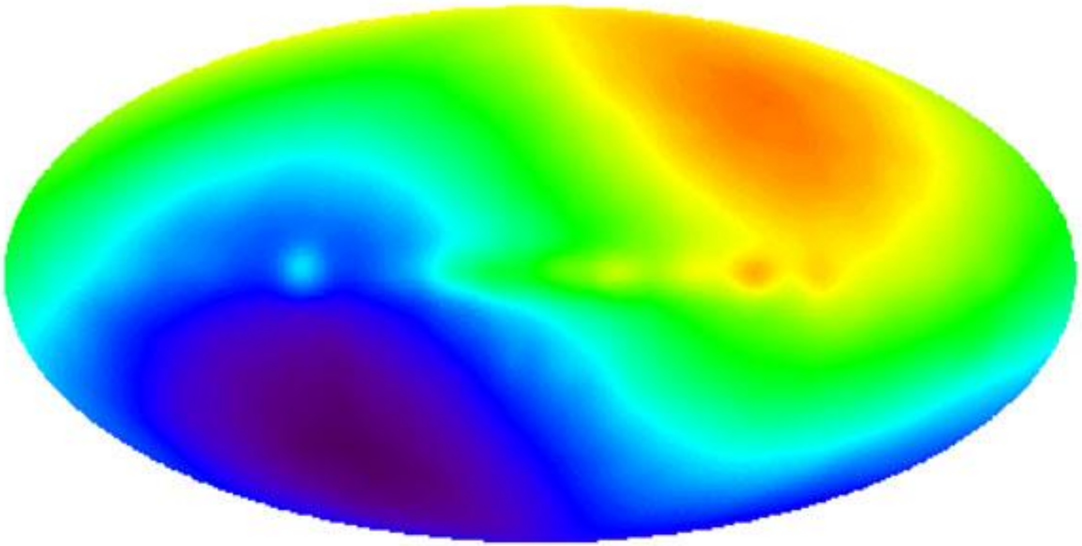
CMB Dipole



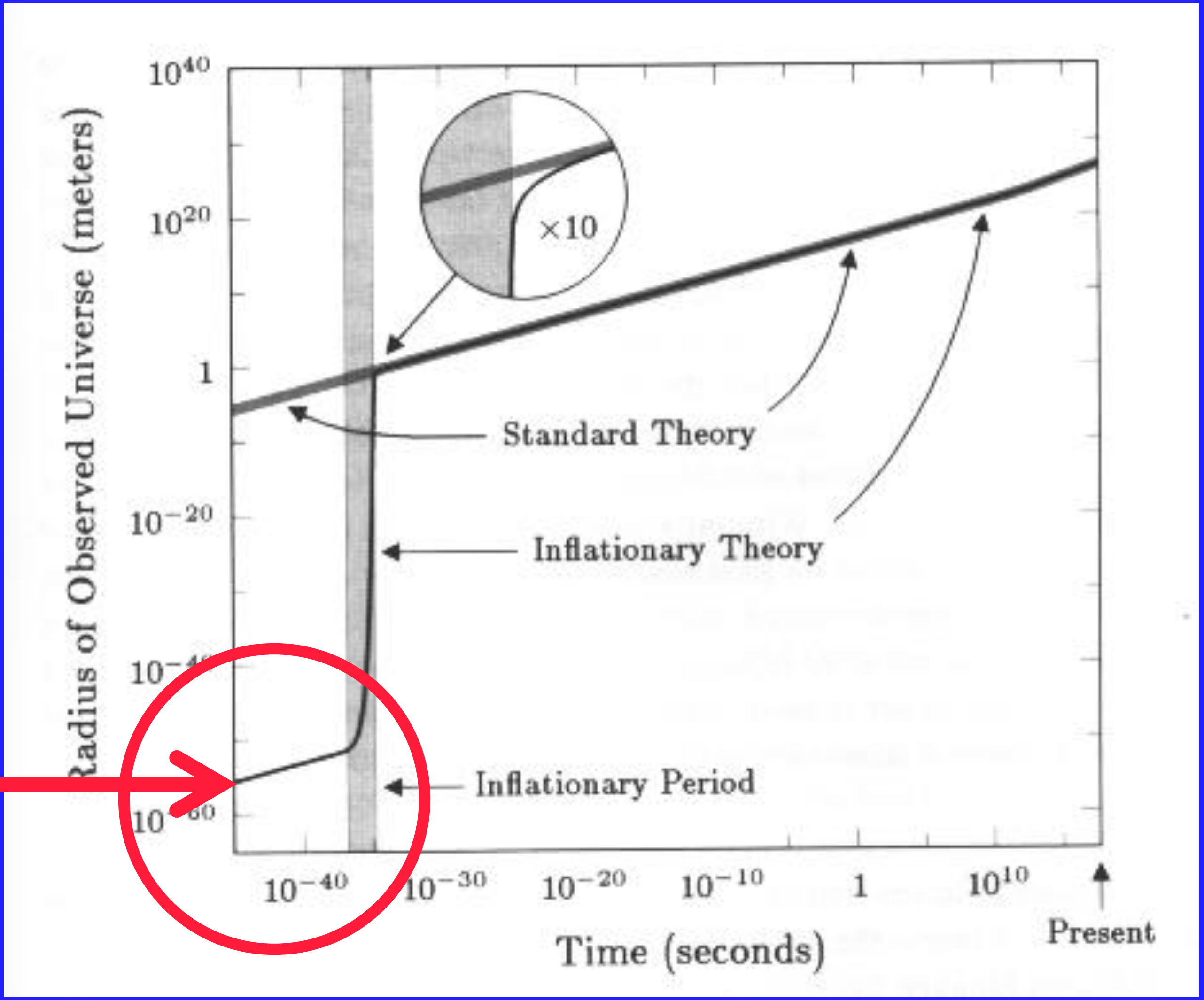
$$T(\theta) = \frac{T_{CMB}}{\sqrt{1-\beta^2}(1-\beta\cos\theta)}$$

$$\beta = V/c$$

	V (km/sec)	$(l_{Gal}, b_{Gal})^\circ$	Refs
Sun-CMB (COBE/DMR-based)	369.5 ± 3.0	$(264.44 \pm 0.3, 48.4 \pm 0.5)$	Kogut et al (1993)
Sun-LSR	20.0 ± 1.4	$(57 \pm 4, 23 \pm 4)$	Kerr & Lynden-Bell (1986)
LSR-GC	222 ± 5	$(91.1 \pm 0.4, 0)$	Fich et al (1989)
GC - CMB	552.2 ± 5.5	$(266.5 \pm 0.3, 29.1 \pm 0.4)$	Kogut et al (1993)
Sun - LG	308 ± 23	$(105 \pm 5, -7 \pm 4)$	Yahil et al (1977)
LG-CMB	627 ± 22	$(276 \pm 3, 30 \pm 3)$	Kogut et al (1993)

Pre-Inflation Cosmology

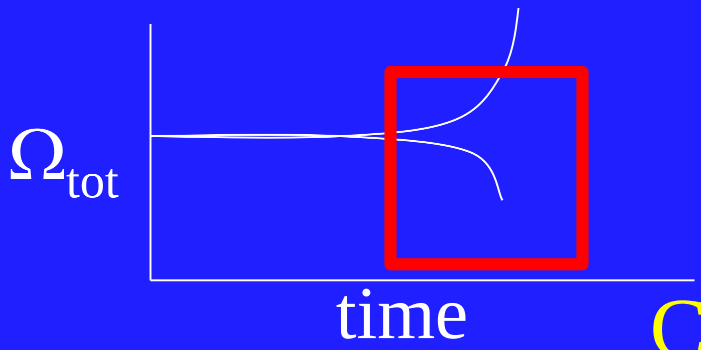
Can we learn anything about physical properties the universe prior to inflation?



Yes, if the universe is slightly open

$$\Omega_{tot} = 1 - \Omega_k = 1 - \frac{k}{[a(t)^2 H(t)^2]}$$

Curvature evolution



k/H^2a^2 should dominate
As universe slows down

Could we be at this epoch?

If Ω_0 is even slightly different than 1.000, then the scale entering the horizon now exhibits pre-inflation curvature fluctuations

The universe may be slightly open

$\Omega_k = 1 - \Omega_{tot} = -0.0005 \pm 0.00065$; -0.0027 ± 0.0004

$$\boxed{\Omega_{tot} > 0.994 \quad (95\% \text{ C.L.})}$$

- Normal matter: $\Omega_B = 0.0463 \pm 0.001$
- $= 0.0482 \pm 0.001$
- Dark Matter: $\Omega_{DM} = 0.240 \pm 0.001$
- $= 0.258 \pm 0.001$
- Dark Energy: $\Omega_\Lambda = 0.714 \pm 0.010$
- $= 0.692 \pm 0.010$

WMAP 9yr data , G. Hinshaw et al ApJ (2013)
Planck Collaboration, 2 yr data, astro-ph: 0675550

If so, then the current visible horizon is just beginning to show the pre-inflation curvature

current horizon

$$\frac{r_l}{a_0} = \frac{1}{H_0}\int_0^1 \frac{dx}{\sqrt{\Omega_\Lambda x^4 + (1-\Omega_0)x^2 + \Omega_m x + \Omega_\gamma}}$$

$$\approx 3.3/H_0$$

Pre-inflation hubble scale = current horizon

$$l\sqrt{(1-\Omega_i)} \approx 3.3\sqrt{(1-\Omega_0)}$$

Models for Pre-Inflation expansion

- Pre-inflation isocurvature fluctuations
  - Kurki-Suonio, Graziani, Mathews (1991); G. J. Mathews, N. Q. Lan, T. Kajino (2015).
- Multiple inflation fields/Open inflation
  - Turner 1981; Sasaki et al.1993, Butcher et al. 1995; Linde et al.1995;1999; Langlois 1996; Chiba and Yamaguchi 1999; Yamauchi et al. 2011; Sugimura et al. 2012
- Pre-inflation landscape – Quantum entanglement of the wave-function for the universe with those of super-horizon modes
  - Mersini-Houghton (2005), Holman & Mersini-Houghton (2006) and Holman, Mersini- Houghton & Takahashi (2008a)

- => CMB dipole ≠ CMB rest frame

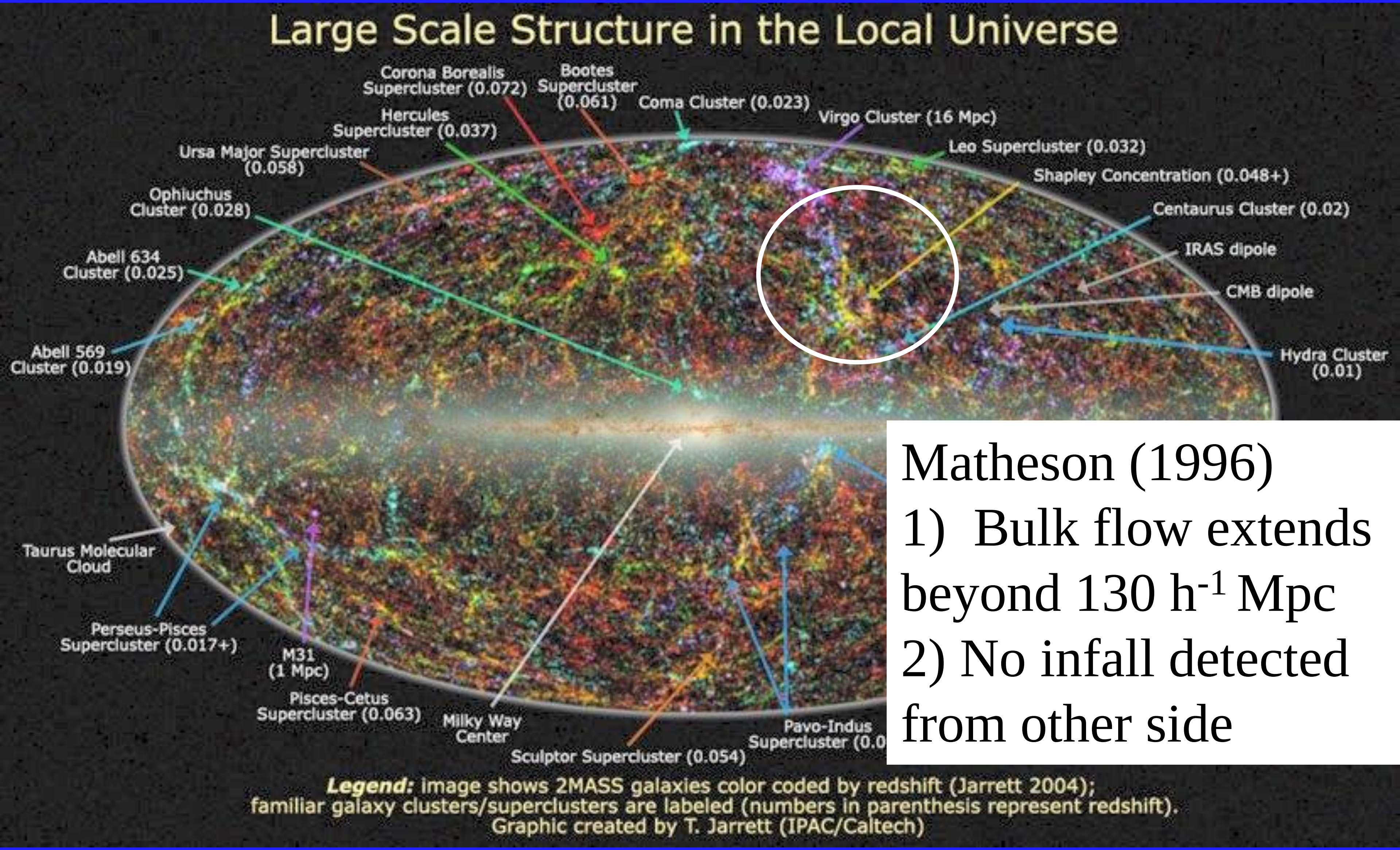
Question:

Is the CMB dipole due to motion of the Local Group or does it extend across the universe?

(Is there a universal cosmic dipole moment?)

Great Attractor: $35h^{-1}$ Mpc

Lynden-Bell (1983)



Matheson (1996)

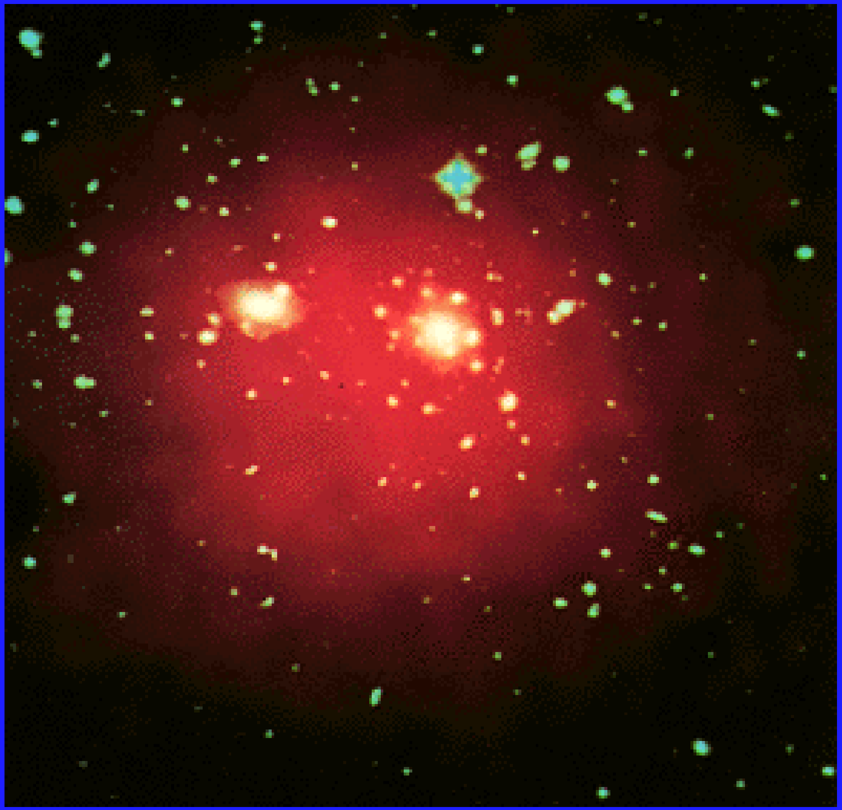
1) Bulk flow extends beyond 130 h^{-1} Mpc

2) No infall detected from other side

Does the dark flow extend to Gpc distances?

Galaxy Clusters+CMB provide a means to study bulk flow at scales > 200 Mpc (Kashlinsky 2012)

Abell 1689



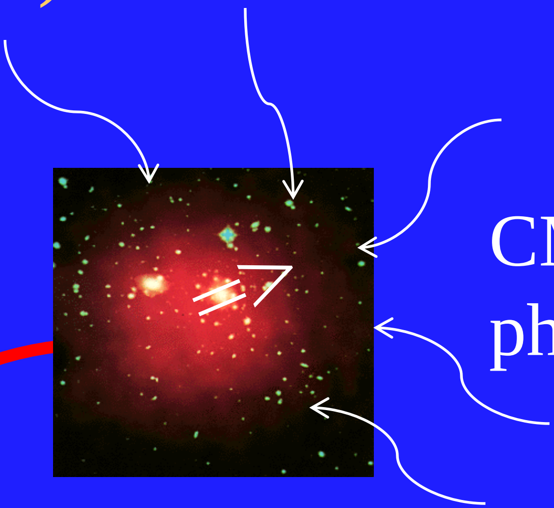
Coma

Kinetic Sunyev-Zeldovich Effect

Kashlinsky (2012)

$$\left\langle T \frac{\Delta V}{V} \right\rangle = -\left\langle T \frac{\vec{V}}{c} \right\rangle \hat{x}_{obs}$$

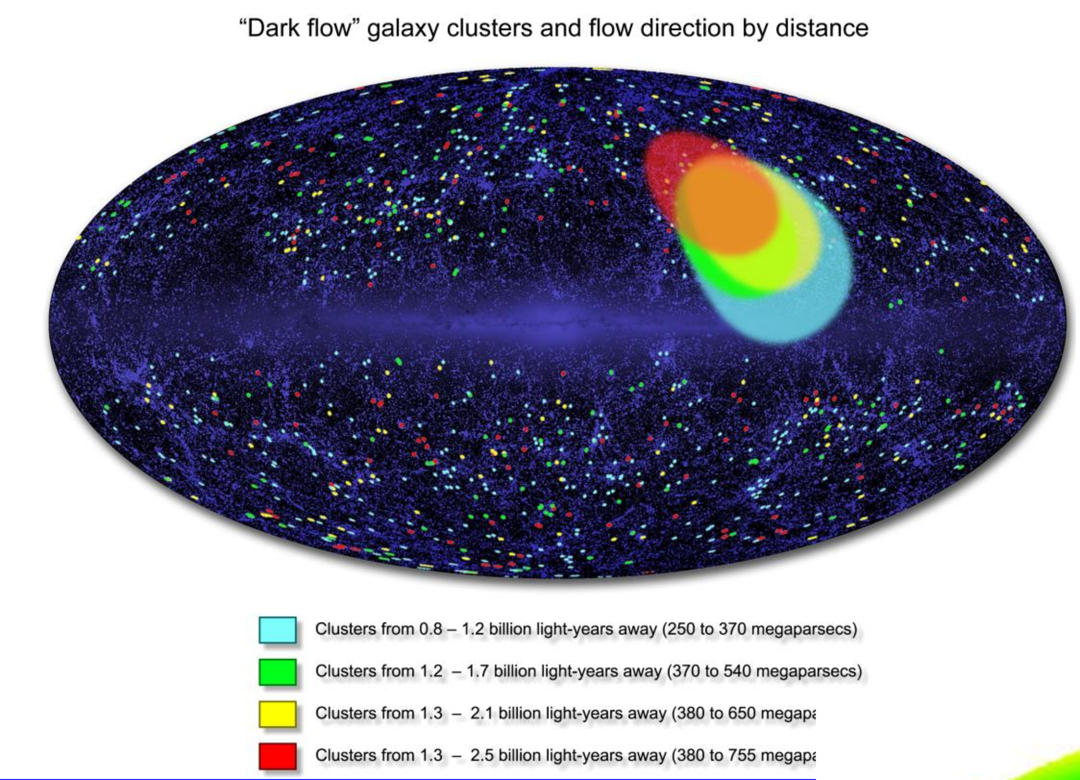
$$\langle \vec{V} \rangle = \overline{T}\, \vec{V}_{cl}$$

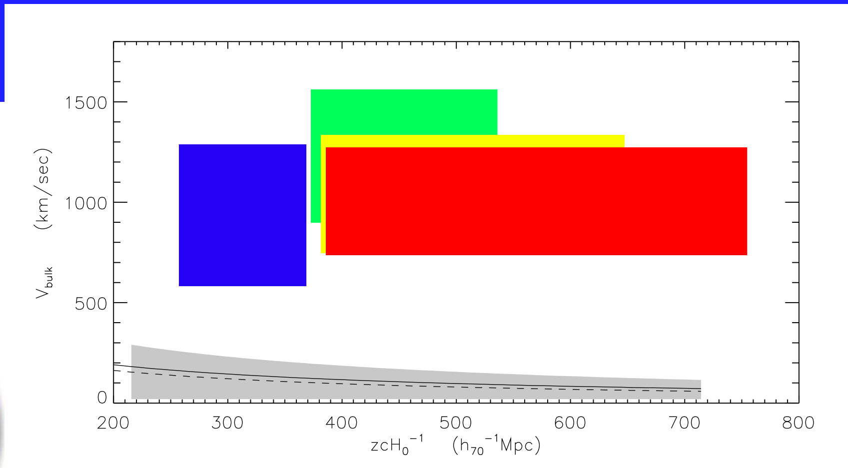


CMB photons

Net effect: Redshift of CMB photons along line of sight to the cluster.

Dark Flow

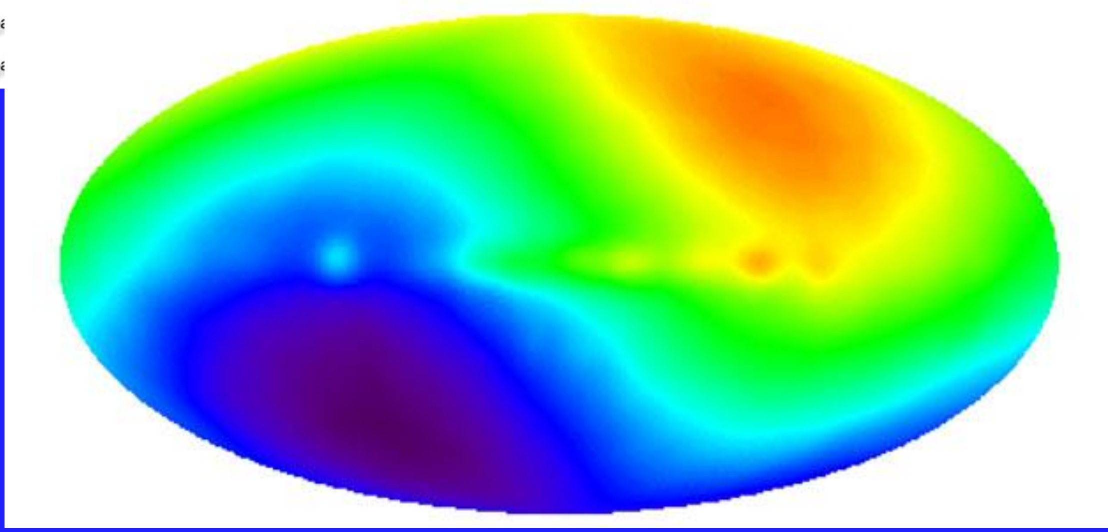




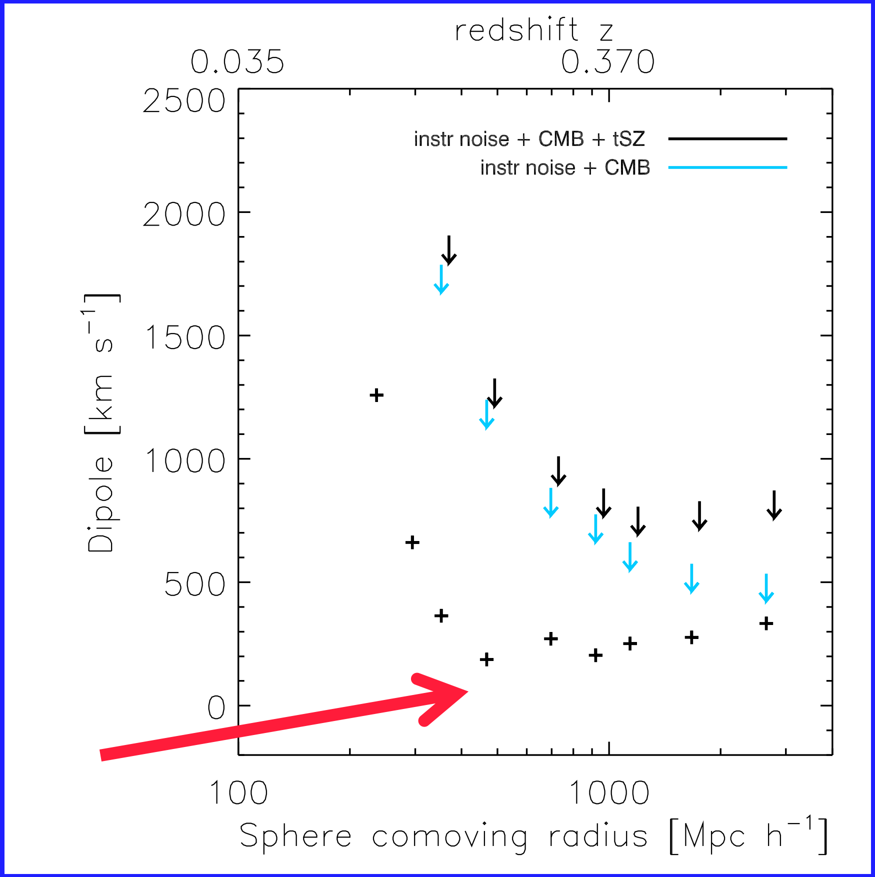
Kashlinsky (2012)

$V_{BF} = 800 \pm 200$ km s^{-1}

$(l,b) = (283 \pm 14, 12 \pm 14)$



But!! Planck Data seem to contradict this: arXive:1303.5090



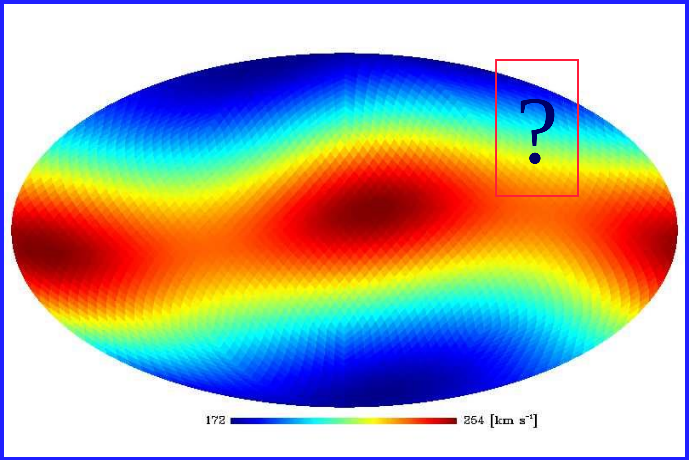


Fig. 8. Mollweide projection in Galactic coordinates of the upper limit (at 95 % C.L.) of the kSZ dipole amplitude from applying the uMMF approach to HFI frequency maps using the whole MCXC cluster sample. In no direction is the dipole detected at more than $2\,\sigma$.

See However: Atrio-Barandela arXive:1303.6614 => detection

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On the Statistical Significance of the Bulk Flow Measured by the PLANCK Satellite

F. Atrio-Barandela

Física Teórica, Universidad de Salamanca, 37008 Salamanca, Spain; atrio@usal.es

ABSTRACT

A recent analysis of data collected by the Planck satellite detected a net dipole at the location of X-ray selected galaxy clusters, corresponding to a large-scale bulk flow extending at least to $z \sim 0.18$, the median redshift of the cluster sample. The amplitude of this flow, as measured with Planck, is consistent with earlier findings based on data from the Wilkinson Microwave Anisotropy Probe (WMAP). However, the uncertainty assigned to the dipole by the Planck team is much larger than that found in the WMAP studies, leading the authors of the Planck study to conclude that the observed bulk flow is not statistically significant.
We here show that two of the three implementations of random sampling used in the error analysis of the Planck study lead to systematic overestimates in the uncertainty of the measured dipole. Random simulations of the sky do not take into account that the actual realization of the sky leads to filtered data that have a 12% lower root-mean-square dispersion than the average simulation. Using rotations around the Galactic pole (the Z axis), increases the uncertainty of the X and Y components of the dipole and artificially reduces the significance of the dipole detection from 98-99% to less than 90% confidence. When either effect is taken into account, the corrected errors agree with those obtained using random distributions of clusters on Planck data, and the resulting statistical significance of the dipole measured by Planck is consistent with that of the WMAP results.

Key words. cosmology: observations – cosmic microwave background – large scale structure of the universe – galaxies: clusters: general

1. Introduction.

The intrinsic difficulty of determining peculiar velocities from galaxy redshifts and distance indicators led Kashlinsky & Atrio-Barandela (2000) to propose an alternative method of probing the velocity field on large scales. Galaxy clusters leave an imprint on the Cosmic Microwave Background (CMB) in the form of distortions in the CMB blackbody spectrum caused by the Sunyaev-Zel'dovich (SZ) effect (Sunyaev & Zel'dovich 1970, 1972). Two different mechanisms contribute to the SZ effect: the thermal component (TSZ) is caused by the thermal motions of electrons in the potential wells of clusters, whereas the kinematic component (KSZ) is due to the motion of the cluster as a whole. We noted that any bulk flow of clusters would produce a dipole in the anisotropy temperature in the direction of clusters. Since this signal is small compared to the sampling variance of the intrinsic CMB dipole at the same positions, we proposed to use the statistical properties of the CMB data to filter out the dominant cosmological component, thereby increasing the signal-to-noise ratio of any contribution from a bulk-flow dipole.

In Atrio-Barandela et al. (2008) and Kashlinsky et al. (2008, 2009) we presented results of our application of this method to Wilkinson Microwave Anisotropy Probe (WMAP) 3-year data, later extended to WMAP 5-year and 7-year data (Kashlinsky et al. 2010; Kashlinsky, Atrio-Barandela & Ebeling 2011). For a sample of ~700 X-ray-selected clusters, we detected a persistent dipole, measured at the cluster positions within apertures (of 25′ radius) that contain zero TSZ monopole. The dipole is roughly aligned with the CMB dipole and can be traced to cluster redshifts exceeding $z \sim 0.2$; its amplitude correlates with that of the monopole within apertures of 10′ radius. We interpreted this signal, associated exclusively with clusters, as evidence of a large-scale flow of amplitude $\simeq 600$–1000 km s^{-1} that could encompass the whole observable horizon. A "Dark Flow" of this amplitude, if real, would be equivalent to the all-sky CMB dipole being primarily of primordial origin, intrinsic to last scattering surface.

Our theoretical and numerical estimates indicated that our dipole detection is significant at the 99.4% confidence level. However, independent confirmation of this result is still lacking, and several studies have challenged our results. Keisler (2009) confirmed the existence of the dipole detected by us, but claimed that it was not statistically significant. It was shown though (Atrio-Barandela et al. 2010) that Keisler neglected to subtract the dipole outside the Galactic mask, causing the error bars of his measurement to be overestimated. More recently, Osborne et al. (2011) and Mody & Hajian (2012) did not find bulk flows in WMAP data using filtering schemes different from ours. However, both teams of authors implicitly assumed that clusters have the same angular extent in the original data as in the filtered maps, and that the electron pressure and the electron density in clusters follow the same radial profile. Both assumptions are incorrect and render these filters insensitive to bulk flows. In Atrio-Barandela et al. (2013) we demonstrated that correct implementation of either of these alternative filtering schemes leads to results that are

An Analytic Formulation of Constraints on Pre-Inflation Fluctuations in a nearly flat Open ΛCDM Cosmology

G. J. Mathews, I. Suh, N. Q. Lan, and T. Kajino Phys. Rev. D92, 123514 (2015), arXiv:1406.3409.

Inhomogeneous inflation

Kurki-Suonio, Graziani, Mathews, PRD 44, 3071(1991)

Mathews, Lan, Kajino PRD (2015) arXiv1406.3409M

al amplitude of the fluctuations.
For simplicity, let us consider
neities in the inflation field:

Preinflation fluctuation of inflaton field

Fluctuation wavelength

r_x, depends on Ω_i. During a curvature-do
ase, $H\lambda$ stays constant. If $\Omega_i \ll 1$, the curvat
gins to dominate the expansion soon and $H\lambda$

Fluctuation amplitude

flation gets going, the uni
ow-rolling solution

$\dot{\phi} = -\frac{V'(\phi)}{}$

MATHEWS

$\Rightarrow$ If $\Omega_0 = 1.002 \pm 0.008$ is slightly less than 1, there is a contribution to the CMB dipole moment from preinflation fluctuations

General Inflaton Field

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2a^2}(\nabla\phi)^2 + V(\phi)$$

$$ds^2 = -dt^2 + a(t)^2\left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right]$$

$$H^2 = \frac{8\pi}{3m_{Pl}^2}(\rho_r + \langle\rho_\phi\rangle) + \frac{1}{a^2} \quad ,$$

$$\ddot{\phi} = \frac{1}{a^2}\nabla^2\phi - 3H\dot{\phi} - V'(\phi)$$

Initial Conditions

$$\phi(t,z) = \phi_i + \delta\phi_i \sin\frac{2\pi}{\lambda_i}(a_i z - t) \qquad 1$$

$$\lambda_i = l H_i^{-1} = \frac{l}{m_{Pl}} = l\sqrt{1-\Omega_i}\, a_i$$

$$\rho_{\phi,i} \equiv f\Omega_i \frac{3m_{Pl}^4}{8\pi} \quad , \quad 0 < \Omega_i < 1 \quad , \quad 0 < f < 1 \quad ,$$

Analytic Model

$$\rho_r + \langle \rho_\phi \rangle \approx A \left(\frac{a_i}{a} \right)^4 + B$$

$$\left(\frac{a_x}{a_i} \right) = \left(\frac{1 - l^2(1 - \Omega_i)}{B l^2} \right)^{1/2}$$

$$\delta\rho_\phi = \frac{1}{2}\delta(\dot{\phi}^2) + \frac{1}{2a^2}\delta(\nabla\phi)^2 + \delta\rho_r + \delta V$$

$$\left. \frac{\delta\rho}{\rho + p} \right|_x \approx \frac{(1/2)\delta(\dot{\phi})_x^2 + \delta V_x}{\dot{\phi}_x^2} \quad .$$

$$\left.\frac{\delta\rho}{\rho+p}\right|_x \approx K \frac{\sqrt{f\Omega_i}\, l^2}{[1-l^2(1-\Omega_i)]^{3/2}} \quad ,$$

where the constant K is given by:

$$K = \left[1+\frac{3}{2\pi}\right] 8\pi\sqrt{2}\, \frac{V(\phi_i)^{3/2}}{V'(\phi_i) m_{Pl}^3} \quad .$$

COBE Normalization

$$K = 5.2 \times 10^{-4} \left[1+\frac{3}{2\pi}\right] 8\pi\sqrt{2} \; = \; 0.0270.$$

CMB Fluctuations

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{l=1}^{\infty}\sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta,\phi)$$

$$\langle |a_{lm}|^2 \rangle = \frac{4\pi}{9}\int \frac{dk}{k}\mathcal{P}_S(k)\mathcal{W}_l^2(k)$$

$$\mathcal{P}_S(k) = \frac{1}{8}\left[\frac{1}{3}\frac{\delta\rho}{\rho+P}\right]^2 \delta(k-k_0)$$

Window Functions

Expand in

$$\epsilon = \sqrt{1-\Omega_0}$$

$$\mathcal{W}_{1k} \approx \frac{10}{3} k\epsilon + \mathcal{O}(\epsilon^3) \quad , \quad \langle |a_1|^2 \rangle^{1/2} \approx \sqrt{\frac{\pi}{2}} \frac{10}{9} \left[\frac{\delta\rho}{\rho + p} \right] \epsilon \sqrt{k_0}$$

$$\mathcal{W}_{2k} \approx \frac{\sqrt{24}}{5\sqrt{3}} k\epsilon^2 + \mathcal{O}(\epsilon^4) \qquad \langle |a_2|^2 \rangle^{1/2} \approx \frac{4}{3} \sqrt{\frac{2\pi}{3}} \left[\frac{\delta\rho}{\rho + p} \right] \epsilon^2 k_0$$

$$k_0 < \frac{1}{1-\Omega_0} \frac{25}{48} \frac{\langle |a_2|^2 \rangle}{\langle |a_1|^2 \rangle}$$

$$C_2 \equiv \frac{1}{5} \sum_m \langle |a_{2m}|^2 \rangle = 157 \ \mu\mathrm{K}^2 \tag{36}$$

from which we obtain $\langle |a_2|^2 \rangle = 785\ \mu\mathrm{K}^2$. Therefore, for $1 - \Omega_0 < 6 \times 10^{-3}$ we deduce

$$k_0 < 0.013 \quad . \tag{37}$$

$$k_0 \ < \ 0.013 \ \ (v_{DF} = 254 \text{ km s}^{-1})$$
$$\quad < \ 8.3 \times 10^{-4} \ \ (v_{DF} = 1{,}000 \text{ km s}^{-1})$$

Constraints on Preinflation Parameters

$$\left.\frac{\delta \dashrightarrow}{\dashrightarrow + p}\right] > 0.068 \quad (v_{DF} = 254 \text{ km s}^{-1})$$

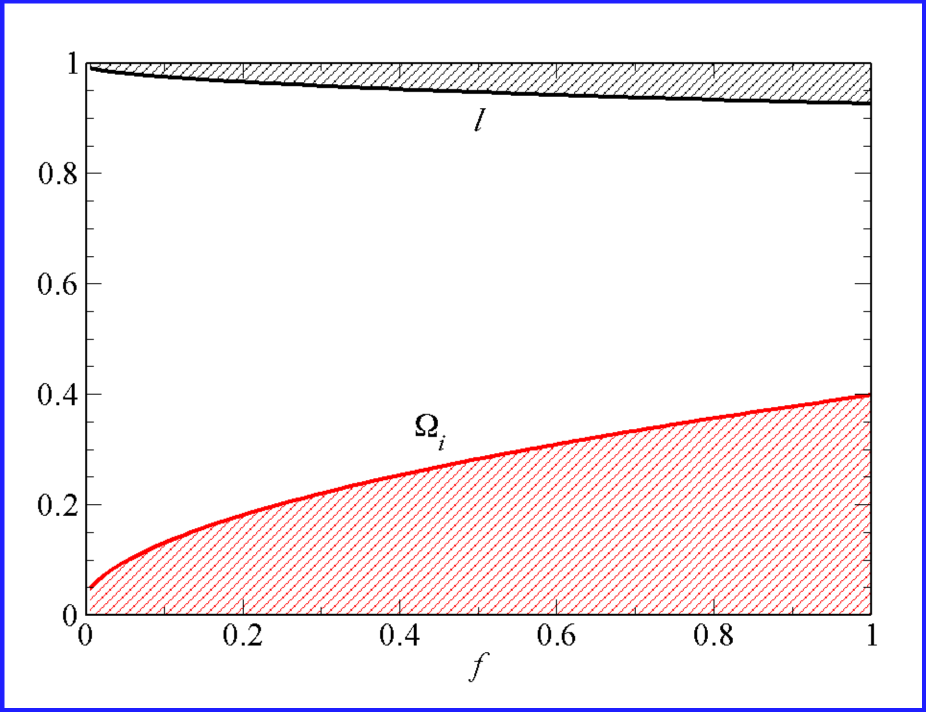
$$> 0.27 \quad (v_{DF} = 1,000 \text{ km s}^{-1})$$

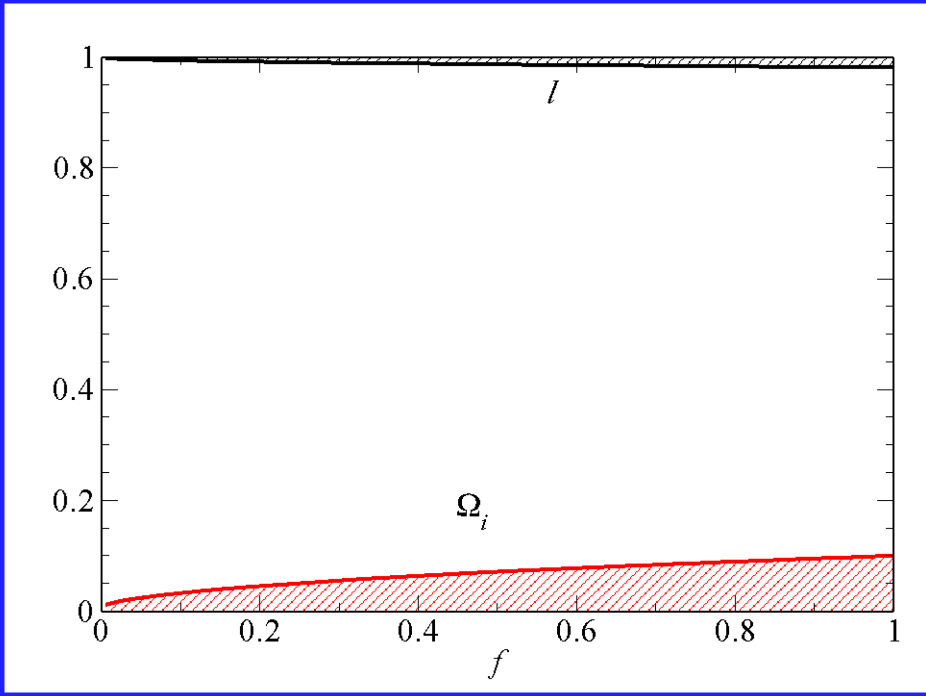
$$f = K^2 \left.\frac{\delta \dashrightarrow}{\dashrightarrow + p}\right]^2 \frac{[1 - l^2(1 - \boxtimes)]^3}{\boxtimes l^4} < 1$$

Solution

V < 254 Km/s

V < 1000 Km/s





Constrains on the preinflation parameter as a function of the fraction f of the initial preinflation energy density in the inflation field for a preinflation fluctuation corresponding to a present till velocity of 254km/s and 1000km/s. Lower shaded region shows allowed value for the initial closure parameter Omega(i).Upper shaded region shows the allowed values of the wavelength parameter l for preinflation isocurvature fluctuation in the inflation field.

Horizon scale

$$\frac{r_l}{a_0} = \frac{1}{H_0}\int_0^1 \frac{dx}{\sqrt{\Omega_\Lambda x^4 + (1-\Omega_0)x^2 + \Omega_m x + \Omega_\gamma}}$$

Present Hubble scale $\qquad r_l / a_0 \simeq 3.3 / H_0$

For fluctuation, (1/k0 > $0.013^{-1} \approx$
77 times Hubble scale
23 times cosmic horizon

Conclusions

We have analyzed a chaotic open inflationary universe characterized by a general inflaton effective potential, but in which there is a plane-wave isocurvature fluctuation in the power spectrum.

We have shown in a simple analytic model that such fluctuations are constrained by the requirement that they not exceed the observed limit on the pre-inflation dipole contribution deduced in the Planck analysis or the magnitude of the quadrupole and higher moments in the CMB power spectrum.

Indeed, from these constraints alone we find that the pre inflation fluctuation in the power spectrum must reside at least $\sim$ 80 times the current Hubble scale.

Also, if there is a pre-inflation component to the current cosmic dipole moment, then the initial pre-inflation closure parameter could have been as large as $\Omega i < 0.4$ ($\Omega k,i > 0.6$). This parameter reduces to $\Omega i < 0.1$ if a dark flow as large as 1000 km s−1 is allowed.

Thank you