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The Consistency of Cosmic Flows on $100 h^{-1}\text{Mpc}$ Scales

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1 Introduction

Dark matter on $100 h^{-1}\text{Mpc}$ scales is accessible to only a couple of techniques. Cosmic Microwave Background (CMB) fluctuations probe dark matter on these scales at $z \sim 1100$, but the anisotropy spectrum is sensitive to other parameters as well as the dark matter power spectrum. Peculiar velocities offer a complementary approach, and have the advantage that the dark matter distribution can be compared directly to the distribution of galaxies in the nearby Universe. The bulk flow statistic measures the mean motion of a sample with respect to the CMB, and thus gives an indication of the level of mass density fluctuations on scales larger than the sample size. Recent large-scale peculiar surveys have measured bulk flows which, *at face value*, appear to be in conflict. The purpose of this paper is to quantify the effect of sparse sampling on the bulk flow statistic and to determine whether recent results are consistent.

2 Consistency of large-scale peculiar velocity surveys

The SMAC cluster sample (Hudson *et al.*¹), with a depth of $\sim 12000 \text{ km s}^{-1}$, has a bulk velocity of $\sim 600 \text{ km s}^{-1}$, with respect to the Cosmic Microwave Background (CMB) frame. Some other surveys (Willick²; Lauer & Postma³, hereafter LP) have also yielded large bulk motions on similarly large scales. However, Dale *et al.*⁴ (hereafter SC) found rather small bulk motions on similar scales. The EFAR survey (Colless *et al.*⁵) was not designed to measure bulk flows but rather to measure peculiar velocities near two distant superclusters. As result its sky coverage is very non-uniform and it is less suitable for bulk flows. We discuss the implications of non-uniform sampling below.

We have recently measured the bulk flow from the SNIa data of Tonry *et al.*⁶. This sample contains a large number of objects nearby ($R < 6000 \text{ km s}^{-1}$), where the bulk flow is known

Table 1: Bulk flows and consistency for large-scale surveys

Survey	Method	N	Depth	\mathbf{V} km/s	l	b	Meas. error km/s	Samp. error km/s	P
LP	BCG	119	8400	832	349	51	252	120	0.06
SC	TF	63	8100	120	295	10	140	170	0.30
SMAC	FP	56	6600	690	260	-1	200	180	0.29
Willick	TF	15	11100	1060	275	28	450	220	0.36
EFAR	FP	49	9500	630	53	6	380	290	0.16
Tonry	SNIa	65	10300	610	311	9	200	130	0.58
STEWS^a	Mixed	248	8200	350	288	8	80	100	

^aSTEWS is SMAC + Tonry + EFAR + Willick + SC

to be in the range $300 - 500 \text{ km s}^{-1}$. To assess the bulk flow on very large scales, beyond local attractors such as the “Great Attractor”, we limit the sample to the distant SNe with $6000 \text{ km s}^{-1} < d < 30000 \text{ km s}^{-1}$. We also exclude SNe with extinction $A_V > 1$. This SN sample yields a bulk flow of $610 \pm 200 \text{ km s}^{-1}$ toward $l = 311 \pm 20^\circ$, $b = 8 \pm 15^\circ$, consistent with the bulk flows from the SMAC and Willick samples.

To address the consistency of cosmic flows, we have reanalyzed in a consistent way the large-scale peculiar velocity samples discussed. The results are given in Table 1. The measurement errors are due to peculiar velocity errors only; these are the values typically quoted when reporting their bulk flow results. It is important to note that these are accurate estimates of the bulk flow of the sparse peculiar velocity samples, but do not necessarily reflect the error in the bulk flow of the *volume*. Based on these errors alone, there appears to be conflict between some of the surveys (e.g. SC vs SMAC).

To calculate the bulk flow of a volume, one must be aware that small-scale (“internal”) flows in a sparse sample do not completely cancel, and will act as an extra source of noise. In order to account for this aliasing effect, it is necessary to have some idea of the expected level of the internal flows. The statistical effect can be calculated exactly if the power spectrum of mass fluctuations is known. Here we outline the main steps of the analysis; a more detailed discussion is given in Hudson *et al.*¹ (see also Colless *et al.*⁵)

For each survey, we calculate the window functions for each Cartesian component of the bulk flow (following Kaiser⁷). The contributions to the bulk flow statistic come from a wide range of scales, with significant contributions from scales as small as $\lambda \sim 30h^{-1} \text{ Mpc}$ ($k \sim 0.2$). To assess the consistency of a given survey with a cosmological model, we compute a total covariance matrix $\mathbf{C} = \mathbf{C}_{\text{cos}} + \mathbf{C}_{\text{pv}}$, where the subscript “cos” denotes the cosmic variance part and “pv” denotes the peculiar velocity errors. To compare two surveys, we generalize this method. We calculate the difference in the sample bulk flows and its total covariance, including the covariance due to random peculiar velocities and the sampling covariance. The latter allows for the fact that two sparse surveys do not trace the same volumes. For further details of this approach, see Watkins & Feldman⁸.

In the penultimate column of Table 1, we present sampling errors for the comparison between the bulk flow of the given survey compared to an idealized dense and uniformly sampled sphere of radius 9000 km s^{-1} , assuming a ΛCDM model with parameters: $\Omega_m = 0.35$, $\Omega_\Lambda = 0.65$, $H_0 = 70 \text{ km/s}$, $\Omega_b = 0.047$. Note that in nearly all cases the sampling errors are comparable to, or larger than, the peculiar velocity errors. The LP and SNIa samples have the highest density of objects and so have the smallest sampling errors. Because of its non-uniform sky coverage, the survey with the highest sampling error is EFAR. The last column indicates the probability that the bulk flow of a given sample is consistent, within the errors, with the bulk flow from the other surveys. When sampling errors are included there is *no conflict* for any survey at the

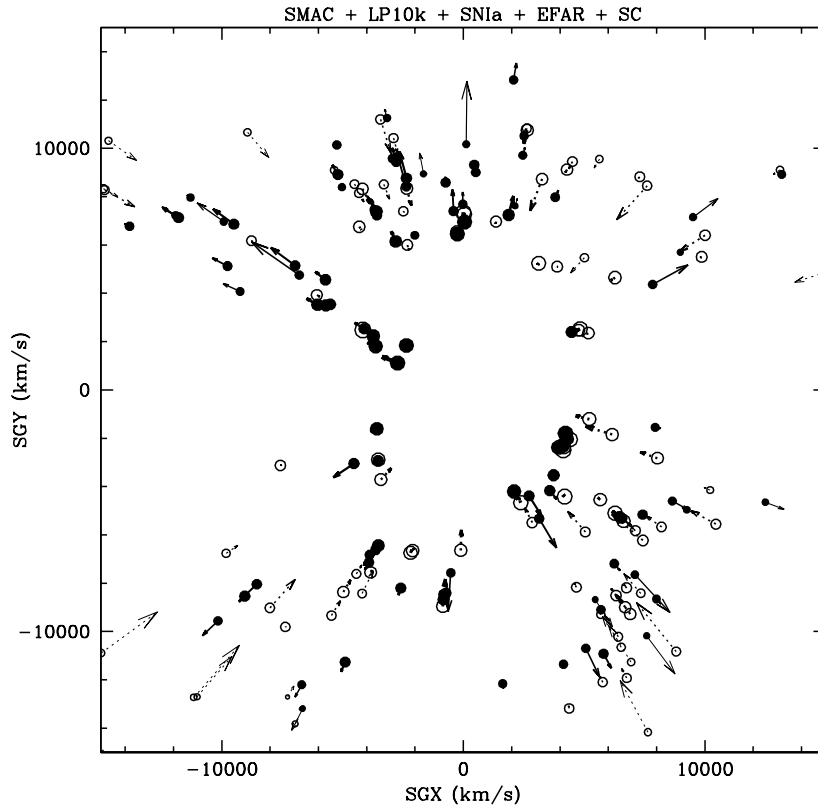


Figure 1: Peculiar velocity diagram for the STEWS sample in the Supergalactic Plane. The circle represents the distance to a cluster and the tip of the vector represents its redshift. Clusters with smaller random errors, and hence greater statistical weight, are indicated by larger circles. Outward flowing objects are solid, inward-flowing ones are open with dotted vectors. Notice the excess of inflowing objects on the right hand side, and the excess of outflowing objects in the upper left quadrant.

2σ level. The sample in poorest agreement is the Lauer & Postman survey, but even there the difference is quite marginal (significant at only the 94% level).

We then throw all the data into the pot to cook. This process yields the STEWS sample (= SMAC + Tonry + EFAR + Willick + SC, but excluding LP) which has a bulk flow of 350 ± 80 km/s toward $l = 288^\circ$, $b = 8^\circ$. A plot of the peculiar velocities for this sample is shown in Fig. 1. For the Λ CDM model used above, the expected rms value of the bulk flow, allowing for the sparse geometry of the STEWS sample is 130 km s^{-1} in each component. Allowing for random peculiar velocity errors, we find that the bulk flow of the STEWS sample is consistent with the Λ CDM model. The STEWS sample is obviously less sparse than the individual surveys of which it is composed. Sampling effects are still non-negligible, however — compared to an ideal densely-sampled survey of radius 9000 km s^{-1} , the sampling error is $\sim 100 \text{ km s}^{-1}$. Although the errors are large, the bulk flow is still significantly different from zero. It thus appears that there are significant contributions to bulk motions arising from scales $\gtrsim 100h^{-1} \text{ Mpc}$.

3 Discussion

These results suggest substantial contributions to the Local Group's motion from large scales. A natural question is whether we can identify the structures responsible. Part of the motion may be due to the Shapley Concentration; the peculiar velocity data favor a substantial mass

for this supercluster complex. If X-ray emitting clusters are used to trace the gravity field, one predicts a very strong contribution to the LG's motion from a distance of $\sim 150h^{-1}$ Mpc (Kocevski *et al.*⁹). One prominent supercluster at this distance in the right direction on the sky is the Shapley Concentration. On the other hand, Saunders and collaborators¹⁰ have extended the IRAS PSCz survey closer to the Galactic Plane. They find that approximately 50% of the Local Group's motion, or $\sim 300 \text{ km s}^{-1}$ in the direction of the negative Galactic Y ($l = 270^\circ$, $b = 0^\circ$) arises from $\sim 200h^{-1}$ Mpc. The structure(s) responsible for this gravity have not been completely identified.

We expect to resolve some of these issues with a new peculiar velocity survey, the NOAO Fundamental Plane Survey (NFPS). The NFPS is a survey of 93 X-ray selected clusters within $200 h^{-1}$ Mpc. For each cluster, we obtain 20 – 70 FP distances per cluster, with a total of 4000 FP cluster galaxies. The NFPS is therefore 4 times the size of the SMAC and EFAR surveys combined. We expect random, systematic and sampling errors each $\lesssim 100 \text{ km s}^{-1}$ and so expect to resolve the question of the amplitude of the large-scale flow. A description of this survey is given by Smith *et al.*¹¹

4 Summary

We have compared the bulk flow of recent large-scale peculiar velocity surveys to each other, allowing for the errors due to sparse sampling. We conclude that, contrary to the current perception, there is no significant conflict between these surveys. The combined STEWS peculiar velocity dataset samples a volume $\sim 100h^{-1}$ Mpc in radius and has a bulk flow of $350 \pm 80 \text{ km s}^{-1}$. Allowing for the sparse sampling, we find that this result is not in conflict with the Λ CDM models. Structure(s) responsible for the large-scale motion have not yet been identified, but some likely suspects are presently under surveillance.

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