A Challenge to the Standard Cosmology from the Large Scale Bulk Flow

Rick Watkins

June 5, 2024

Willamette University
Salem, Oregon

Collaborators

Hume Feldman: University of Kansas

Brent Tully, Ehsan Kourkchi: University of Hawaii

WU undergrads: Trey Allen, CJ Bradford, Albert Ramon, Alexandra Walker

KU undergrads: Rachel Cionitti, Yara Al-Shorma

Bulk Flow Basics

Measuring Peculiar Velocities

The *Peculiar Velocity* is the radial velocity **peculiar** to an individual galaxy, in contrast to the apparent motion of all galaxies away from us (Hubble Flow)

The measured redshift of a galaxy is the sum of the cosmological redshift and the Doppler shift

$$cz = H_o r + v$$

Thus we can estimate a galaxy's peculiar velocity using measurements of it's **redshift** z and **distance** r.

$$v = cz - H_o r$$

Measuring Peculiar Velocities

$$v = cz - H_o r$$

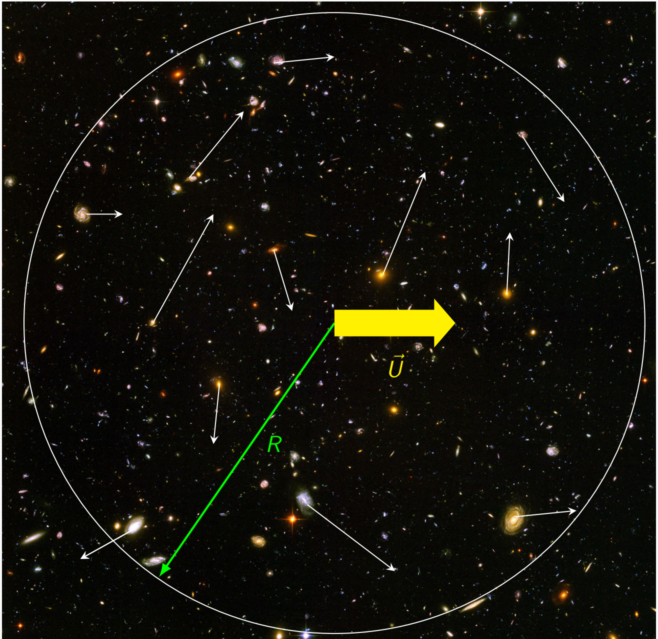
Redshift can be measured very accurately, but distances typically have fractional uncertainties of $5 - 20\%$. This leads to large uncertainties for peculiar velocities, particularly for distant galaxies with $cz \gg v$

Peculiar Velocity Challenges:

- We can only measure the radial component of velocity
  $v_i = \vec{v}_i \cdot \hat{r}_i$
- Individual peculiar velocities have large uncertainties, particularly for objects at large distances
- The velocity field is only linear on large scales $\gtrsim 10h^{-1}$Mpc

Characterizing peculiar velocities via the Bulk Flow gets around these challenges

The Bulk Flow



Bulk Flow

The Bulk Flow is measured for a **specific radius** R. There is not just a single Bulk Flow.

Pros:

- Averages out large measurement errors
- Averages out small-scale nonlinear motions
- Provides a test of the Cosmological Principle
- Can be measured independent of Hubble Constant H_o

Cons:

- Reduces information down to three numbers

Bulk Flow as a Weighted Average

We estimate the Bulk Flow as a weighted average of radial velocities v_n:

$$U_i = \sum_n w_{i,n} \; v_n \tag{1}$$

where i is x, y, or z.

For an IDEAL survey, you can show that if we use weights

$$w_{i,n} = \frac{\hat{r}_n \cdot \hat{x}_i}{r_n^2} \tag{2}$$

then the estimated U_i will match the bulk flow that would be calculated from the **full 3D velocities** $\vec{v}_n$

(This assumes that the velocity field is a gravitational potential flow, i.e. is curl free.)

Bulk Flow as Weighted Average

We estimate the Bulk Flow as a weighted average of radial velocities v_n:

$$U_i = \sum_n w_{i,n} \ v_n \tag{3}$$

where i is x, y, or z.

Real surveys sample the volume unevenly. In particular, there are typically more galaxies with smaller uncertainty nearby.

The Minimum Variance (MV) method of analysis generates weights that result in bulk flow estimates that are as close as possible to those that would come from an ideal survey that samples the volume evenly.

Bulk Flow as Weighted Average

We estimate the Bulk Flow as a weighted average of radial velocities v_n:

$$U_i = \sum_n w_{i,n}\ v_n \tag{4}$$

where i is x, y, or z.

Real surveys sample the volume unevenly. In particular, there are typically more galaxies with smaller uncertainty nearby.

MV weights accounts for measurement uncertainties and object distribution so that the **information** in the volume is effectively sampled evenly as an ideal survey would.

Bulk Flow as Weighted Average

We estimate the Bulk Flow as a weighted average of radial velocities v_n:

$$U_i = \sum_n w_{i,n} \; v_n \tag{5}$$

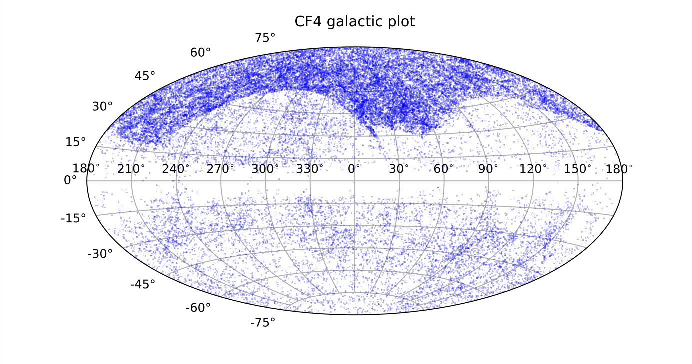
where i is x, y, or z.

Extra Bonus: We can add constraints to the MV method in order to ensure that our bulk flow estimate is independent of the Hubble constant; this flattens out the angular distribution so that the Bulk Flow is independent of phantom radial flows that would arise from using an incorrect value of H_o.

Estimating Bulk Flows using the *CosmicFlows-4* groups catalog

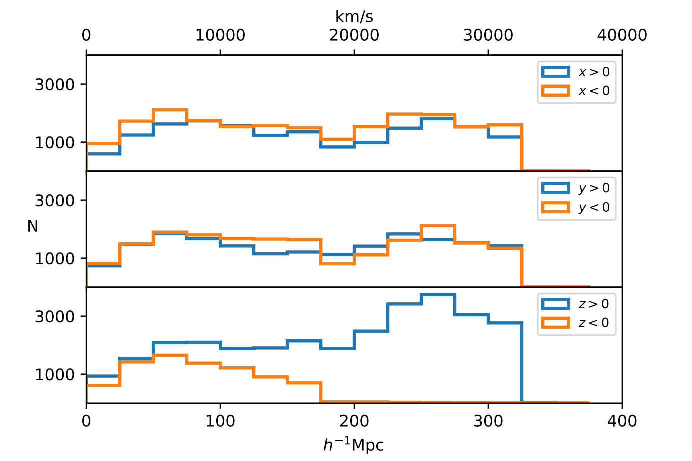
The Data:

- 38,057 individual galaxies and groups of galaxies
- Includes SDSS, 6dFGS, etc. $\Rightarrow$ The Distribution is <u>not</u> isotropic, so it's important to use an analysis like the MV method.



Kourkchi *et al.* , 2020, ApJ, **902**, 145

The Data:



Distributions in x and y are fairly balanced, but z distribution is much deeper on the positive side.

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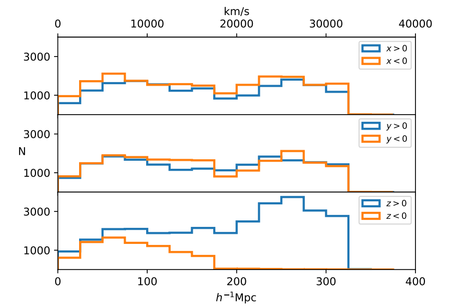


Distributions in x and y are fairly balanced, but z distribution is much deeper on the positive side.

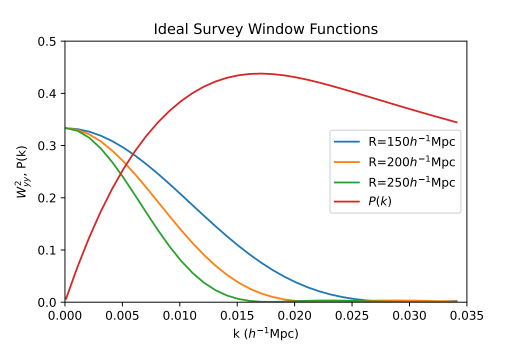
This is important since we find mainly the y-component of the bulk flow to be anomalously large.

Window Functions

Window functions tell us how different scales contribute to the bulk flow components:

$$\langle U_i^2 \rangle \propto \int W_{ii}^2(k) P(k) dk$$

where W_{ii}^2 is the window function and $P(k)$ is the density fluctuation power spectrum.



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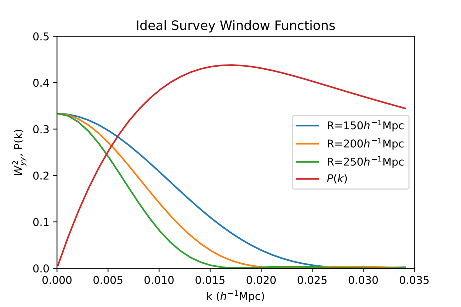
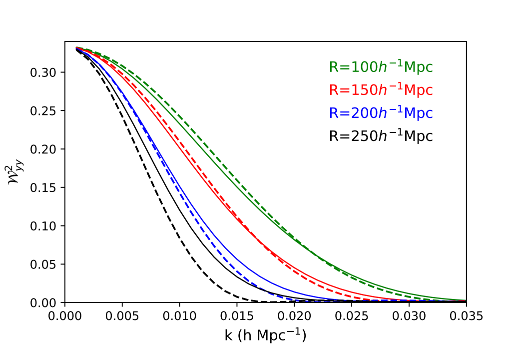


The window function is small on scales smaller than R (large k) indicating that motions on these scales are effectively averaged out.

How large an R can our data support?: Window Functions

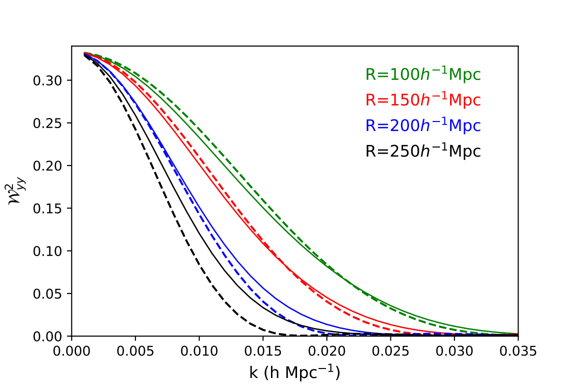


(these are for U_y; U_x and U_z similar)

Solid lines: Real survey Dashed lines: Ideal survey

Window functions tell us how sensitive the bulk flow moments are to different **scales**. The agreement between the Real and Ideal survey window functions indicates that the MV method is working.

How large an R can our data support?: Window Functions

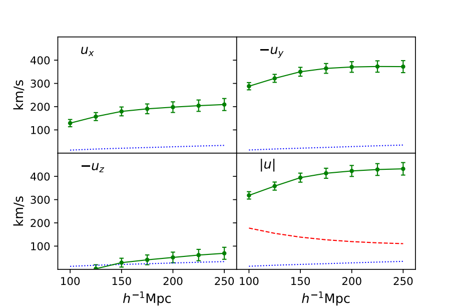


(these are for U_y; U_x and U_z similar)

Solid lines: Real survey Dashed lines: Ideal survey

Beyond $R = 150 - 200h^{-1}$Mpc there's not enough information at large distances to estimate Bulk Flow accurately

CF4 Results



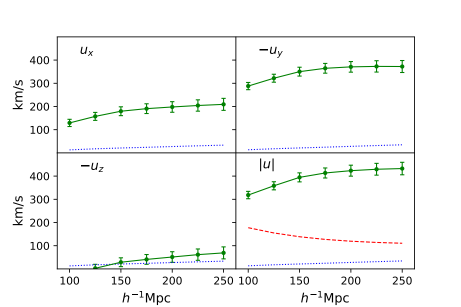
Green lines: Bulk Flow estimates with error bars

Blue dotted line: measurement noise

Red dashed line: Theoretical expectation

How the Bulk Flow changes with radius R is itself interesting information.

CF4 Results



The Bulk Flow:

- increases with radius rather than decreases as expected
- is much larger than expectations from ΛCDM
- is (very) roughly in the direction of the Shapley Supercluster, although the Shapley is not large enough to cause a flow of this magnitude.

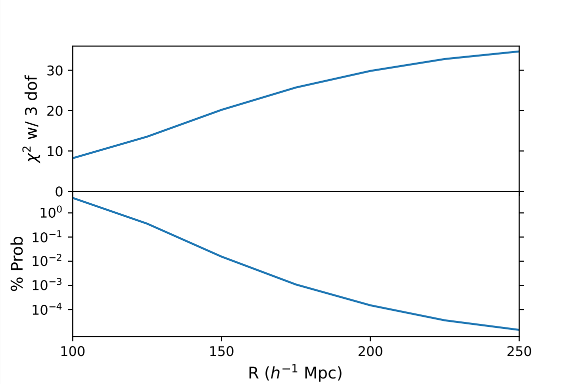
Compare to Cosmological Standard Model

Chi-square analysis with 3 d.o.f.

$$\chi^2 = \sum_{i,j} U_i R_{ij}^{-1} U_j \tag{6}$$

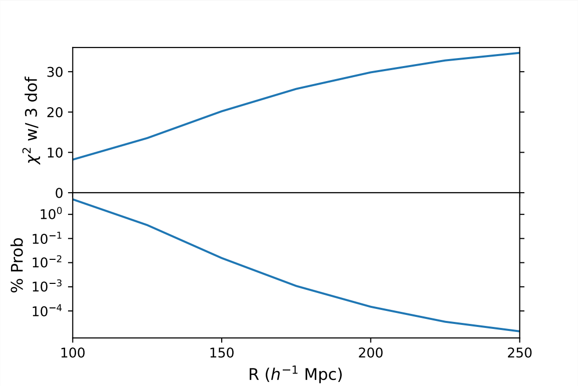
where $R_{ij} = \langle U_i U_j \rangle$ is the theoretical covariance matrix calculated for the Bulk Flow component estimates using Planck CMB cosmological parameters.

χ^2 with 3 d.o.f. as a function of R



As R increases, bulk flow becomes increasingly unlikely

χ^2 with 3 d.o.f. as a function of R



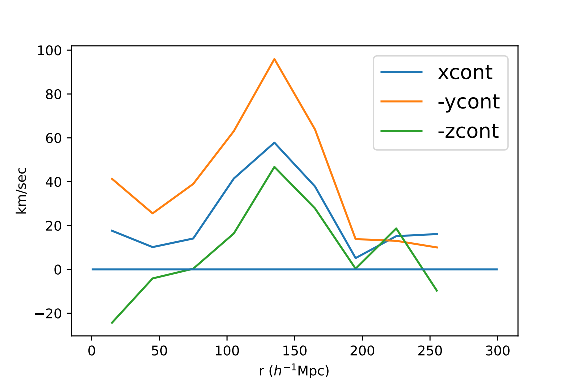
Note that inconsistency with standard model **only** appears at sufficiently large R. Studies that emphasize flows on smaller scales can agree with this work and also the standard model.

Results Summary

	$R = 150h^{-1}$Mpc	$R = 200h^{-1}$Mpc
Expectation (km/s)	139	120
Bulk Flow (km/s)	395 ± 29	427 ± 37
Direction	$l = 297^\circ \pm 4^\circ$	$l = 298^\circ \pm 5^\circ$
	$b = -4^\circ \pm 3^\circ$	$b = -7^\circ \pm 4^\circ$
χ^2 with 3 d.o.f.	20.19	29.84
Probability	1.54×10^{-4}	1.49×10^{-6}

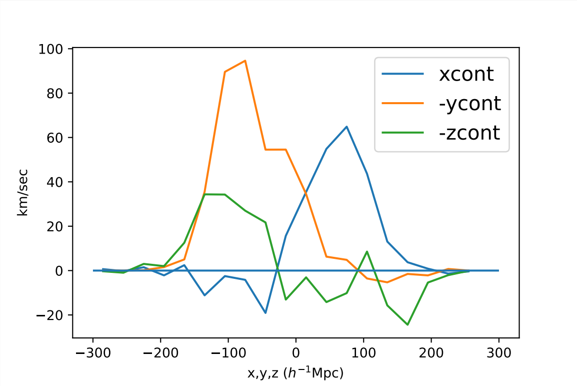
Watkins *et al.* , 2023, MNRAS, **525**, 1885

The Bulk Flow in more detail (preliminary)



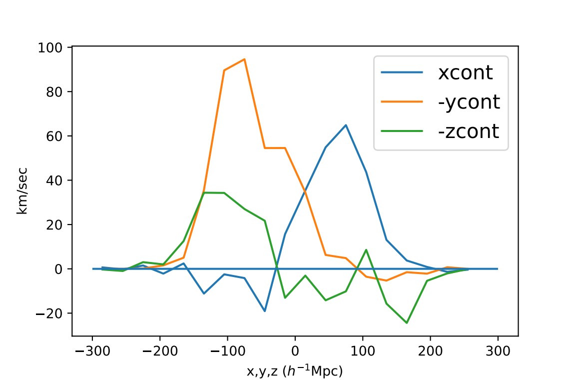
Contributions to U_i ($w_{i,n}\ s_n$) binned in radial distance. The largest contribution to the Bulk Flow is coming from objects between 100-150 h^{-1}Mpc. This explains why the Bulk Flow increases with distance.

The Bulk Flow in more detail (preliminary)



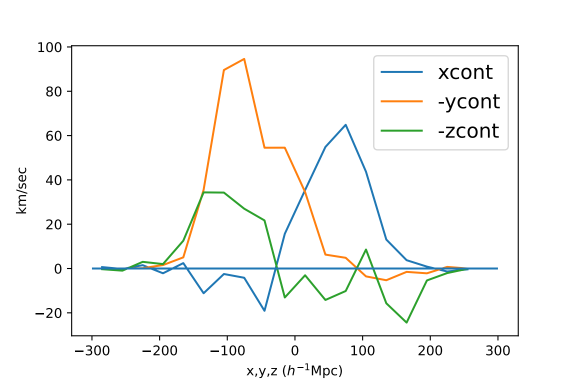
Contributions to U_i ($w_{i,n}\ s_n$) binned in x_i. The largest contribution to the y component of the Bulk Flow is coming from the $-y$ direction at distances between 100-150h^{-1}Mpc.

The Bulk Flow in more detail (preliminary)



Note that much of the volume appears to be at **rest** with respect to the CMB.

The Bulk Flow in more detail (preliminary)



This is suggestive of anomalously large structures vs. violation of the Cosmological Principle.

Related Results

Whitford *et al.* , (2023), MNRAS, **526**, 3051

- MV analysis of CF4 obtained bulk flow of 428$\pm$ 108km/s for $R = 173h^{-1}$Mpc in good agreement with our result
- Tested method with CF4 mocks
- Error bars obtained from mocks somewhat larger than ours ($\pm$30km/s)
- They found 0.11% probability of this Bulk Flow in standard model: smaller tension
- Difficult to understand why mocks would give uncertainties so much larger than linear theory when focussed on large scale motions.

Related Results

Hoffman *et al.* , (2024), MNRAS, **527**, 3788

- Reconstructed velocity field from CF4 catalog using Weiner Filter constrained by ΛCDM.
- Derived Bulk Flow from the reconstructed velocity field.
- They find somewhat a smaller Bulk Flow with similar uncertainty
- They find much smaller tension with the Standard Model (2-3σ)
- Difficult to quantify how the bulk flow calculated using this method probes different scales
- Paper suggests that difference with our result is due to different bias correction schemes, but my research indicates that this is not the case.

Summary:

- We find a tension between the Bulk Flow within a radius $R = 150h^{-1}$Mpc and the standard cosmological model at the 3.8σ level
- At $R = 200h^{-1}$Mpc the tension increases to 4.8σ level
- Evidence for anomalously large structures? A violation of the Cosmological Principle?
- It's important to continue to improve the dataset and the methods.

See Watkins *et al.* , 2023, MNRAS, **525**, 1885 for details

Research supported by National Science Foundation Grants AST-1907365 and AST-1907404