Analyzing the Large-Scale Bulk Flow using CosmicFlows4

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Peculiar Velocities: Basics

A galaxy's redshift is the sum of Doppler shift ($cz = v$) and cosmological redshift ($cz = H_o r$)

If we know measured (total) redshift cz and distance r we can estimate peculiar velocity:

$$v = cz - H_o r$$

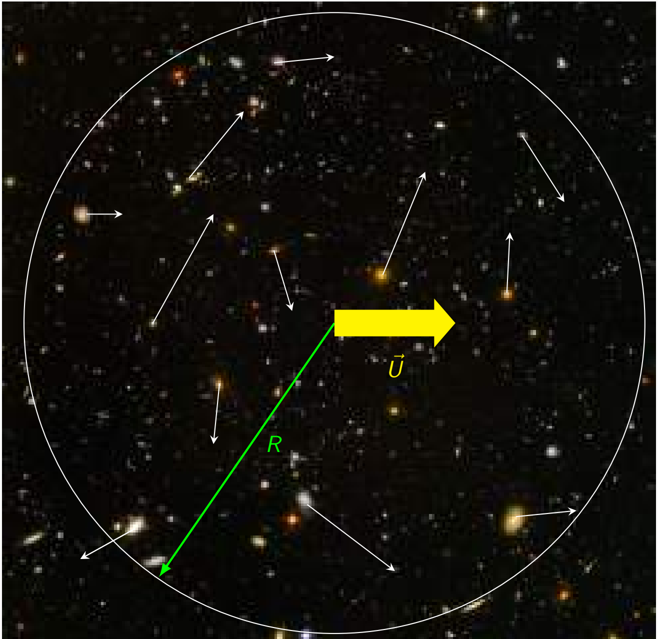
This gives us the component of the galaxy's velocity along the line of sight.

Peculiar Velocity Challenges:

- Can only measure radial component $v_n = \vec{v}_n \cdot \hat{r}_n$
- Distance uncertainties are typically percentage errors, which translate into very large uncertainties for individual peculiar velocities, particularly for objects at large distances
- Velocity field only linear on large scales $\gtrsim 10h^{-1}$Mpc

Characterizing the peculiar velocity field via the large-scale Bulk Flow gets around these challenges

The Bulk Flow



Bulk Flow

Bulk Flow measured for specific radius R

Pros:

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

Cons:

- Reduces information down to three numbers

Bulk Flow as Weighted Average

Estimate Bulk Flow as weighted average of radial velocities v_n:

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

where i is x, y, or z.

For IDEAL survey, can show that if we use weights

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

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 curl-free, as it should be if generated by gravity)

Bulk Flow as Weighted Average

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where i is x, y, or z.

REAL surveys sample volume unevenly. For example, there are more galaxies with smaller uncertainties nearby.

The Minimum Variance (MV) method of analysis generates weights that result in bulk flow estimates that are as close as possible to those of ideal survey; evens out sampling of volume.

Bulk Flow as Weighted Average

Estimate Bulk Flow as weighted average of radial velocities v_n:

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

where i is x, y, or z.

Extra Bonus: Can add constraints to MV method in order to ensure that bulk flow estimates are independent of the Hubble constant; it flattens out angular distribution.

The Data:

Distances to galaxies measured through distance modulus

$$\mu = 5\log_{10}(r) + 25 + \delta$$

where δ is measurement error drawn from Gaussian of width σ_μ

To get r from μ must correct for bias (overestimate)

$$r = 10^{\frac{\mu}{5}-5}\exp(-\ln(10)\sigma_\mu^2/10)$$

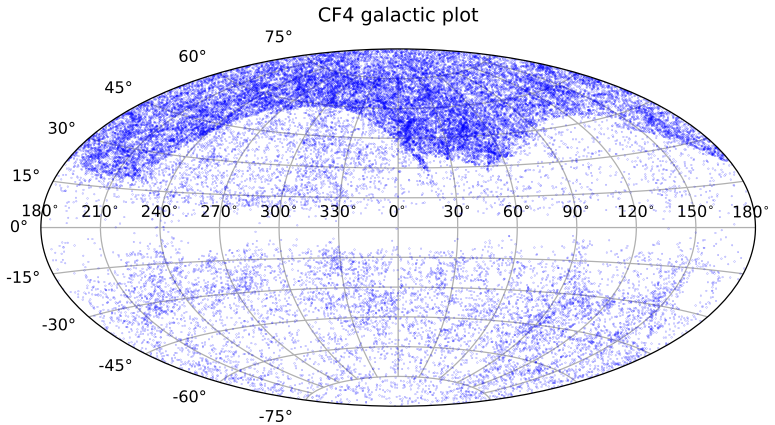
The exponential term corrects for statistical bias introduced by errors when exponentiating the distance modulus. For details see our paper.

The Data:

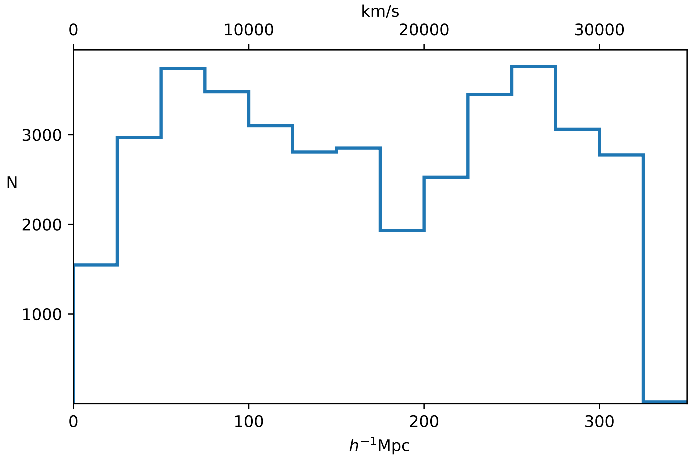
Distance modulus measurements of galaxies known to be in groups is combined in a weighted average to make a single, more accurate, distance modulus for the group as a whole.

The Data:

- cz , μ, and σ_μ measurements for 38,057 individual galaxies and groups of galaxies
- Includes SDSS, 6dFGS, etc. $\Rightarrow$ Distribution not isotropic.



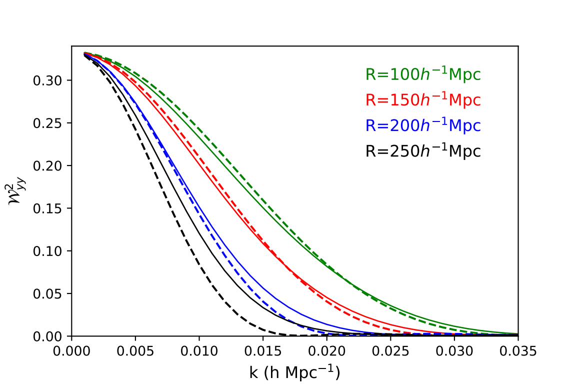
The Data:



Radial distribution of the objects in the CF4

Deeper objects mostly from the Sloan Digital Sky Survey and concentrated in galactic north

How big can we go?: Window Functions

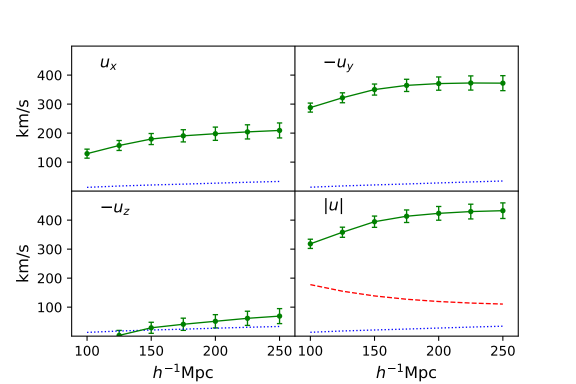


(these are for U_y; U_x and U_z similar)

Solid lines: Real survey   Dashed lines: Ideal survey

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

CF4 Results

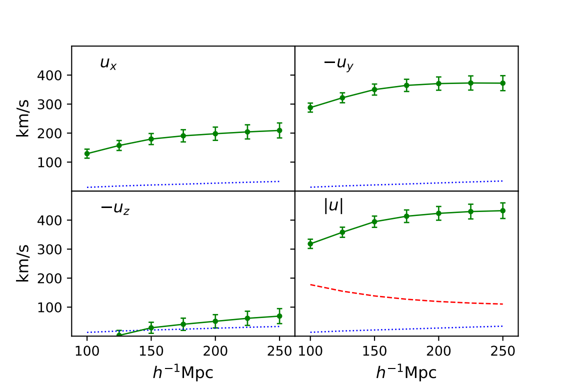


Green lines: bulk flow estimates with error bars

Blue dotted line: Theoretical expectation of difference between ideal and actual survey bulk flow (not including noise)

Red dashed line: Theoretical expectation for bulk flow

CF4: New Results



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The bulk flow

- increases with radius rather than decreases
- is much larger than expectations
- is roughly in the direction of the Shapley Supercluster

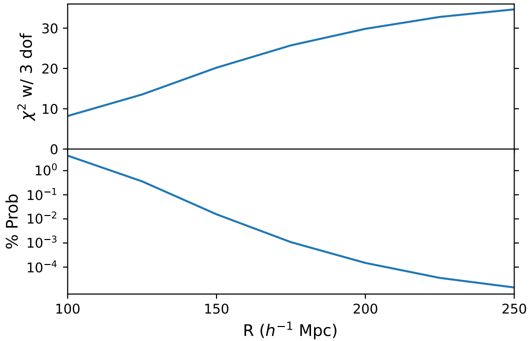
Compare to Cosmological Standard Model

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

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

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

χ^2 with 3 d.o.f. as a function of R



As R increases, bulk flow becomes increasingly unlikely

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}

Discussion:

- Tension of bulk flow ($R = 150h^{-1}$Mpc) with standard cosmological model is at the 3.8σ level
- Tension of bulk flow ($R = 200h^{-1}$Mpc) with standard cosmological model is at the 4.8σ level
- Evidence for violation of Cosmological Principle? (see also the distribution of Quasars)
- It's important to continue to improve dataset and methods.

See arXiv:2302.02028 for details

Discussion:

Questions???

See arXiv:2302.02028 for details

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