V3 Cosmic Trace Project

Reproducible Cross-Tracer Analysis of an Attenuated Large-Scale Peculiar-Velocity Dipole Using Pantheon+, 6dFGSv, and Cosmicflows-4

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Abstract

This study was designed to test whether the large-scale dipole velocity field predicted by the V3 Space-Fluid Dynamics hypothesis can be detected in real observational data. V3 interprets spacetime as a fluid-like medium and proposes that massive structures and voids may leave directionally coherent signatures in the local velocity and expansion fields. In this paper, however, V3 is not treated as a proven conclusion, but as the motivating theoretical frame and interpretive context for the experiment.

The analysis was carried out in two stages. First, the Pantheon+ supernova dataset was used to extract a reference dipole axis and an exponential attenuation scale from directional distance-modulus residuals. These quantities were then treated as pre-registered fixed inputs and projected onto two independent galaxy peculiar-velocity catalogues, 6dFGSv and Cosmicflows-4 (CF4), for validation.

The Pantheon+ analysis yields a reference axis near ($(l, b) = (270°, 30°)$) in Galactic coordinates and an attenuation scale ($z_c \approx 0.056$), corresponding to ($r_c \approx 240$) Mpc. Applying the same axis and attenuation scale to CF4 gives a strong dipole component with ($V_0 \approx 209.34$ km, s^{-1}), ($\Delta\chi^2 \approx 294.30$), and ($\cos\psi \approx 0.9466$). By contrast, 6dFGSv shows only weak support for the same structure, with ($\Delta\chi^2 \approx 5.9$). Distance tomography, sky-shuffle permutation tests, random-axis ensembles, and bootstrap folded-angle analysis all support the conclusion that the CF4 signal is unlikely to arise from a narrow distance shell or from sky geometry alone.

Because the present analysis does not include the full velocity covariance matrix, the reported ($\Delta\chi^2$) values should not be interpreted as formal likelihood-ratio significances or Gaussian-equivalent detection sigmas. The most conservative conclusion is that Pantheon+ and CF4 provide strong empirical evidence for a common large-scale anisotropic flow axis. V3 is presented as one possible theoretical framework for interpreting this pattern, while comparison with standard (Λ)CDM large-scale structure remains necessary. Instead, $\Delta\chi^2$ is interpreted as a fit-improvement statistic measuring the strength of the directional component relative to an isotropic velocity field.

1 Introduction

Large-scale galaxy peculiar velocity fields are direct dynamical tracers of the local Universe and reflect the gravitational influence of massive structures such as the Great Attractor, the Shapley Supercluster, and large nearby voids. At the same time, Type Ia supernova analyses have suggested that the local Hubble flow may exhibit weak directional dependence. If such anisotropy is a real signature of local cosmic dynamics, it should appear not only in photon-based tracers but also in mass-based tracers.

The starting point of this study is the V3 Space-Fluid Dynamics hypothesis. V3 interprets spacetime as a fluid-like medium and proposes that compact and extended structures may act analogously to sources, sinks, and repellers in a large-scale flow field. This perspective naturally motivates an observational question: does the local Universe contain a common large-scale dipole axis visible in both the expansion field and the peculiar-velocity field?

To address this question, we perform a cross-tracer analysis combining Pantheon+, 6dFGSv, and CF4. The core strategy is to extract a reference axis and attenuation scale from Pantheon+, then treat them as pre-registered inputs and test them independently in mass-tracer datasets. The goal is therefore not a post-hoc axis alignment exercise, but a structured validation in which a pattern inferred from photon tracers is tested against independent galaxy-velocity data.

This design creates a natural falsification test: if the axis and attenuation scale inferred from Pantheon+ fail to produce a coherent signal in independent peculiar-velocity catalogues, the hypothesis of a common large-scale flow would be disfavored.

2 Theoretical Motivation from V3 and Observable Predictions

V3 Space-Fluid Dynamics treats spacetime not as a static background but as a medium capable of flow. Within this framework, black holes, supermassive black holes, massive large-scale structures, and voids may be interpreted not merely as matter concentrations, but as structures that generate, absorb, or redirect spatial flow. This remains a hypothesis rather than a component of standard cosmology, and in this paper it is not presented as established fact. Instead, it serves as the theoretical motivation for several observational predictions.

First, the local supernova expansion field may contain a directional dipole residual. Second, that dipole amplitude may weaken with increasing distance, implying an attenuation scale. Third, if the signal reflects a genuine background flow, then the same axis and a similar attenuation scale should also appear in galaxy peculiar-velocity catalogues.

This paper directly targets the third prediction. V3 therefore functions here as the **motivating interpretive frame** for the experimental design. The observational results themselves must still be evaluated conservatively as empirical evidence for or against a common large-scale anisotropic structure.

3 Overview of the Analysis Strategy

The analysis consists of two stages.

In the first stage, the Pantheon+ supernova sample is used to estimate a reference dipole axis ($\hat{\mathbf{n}}$) and a characteristic attenuation scale (z_c) from the directional dependence and redshift dependence of distance-modulus residuals.

In the second stage, these quantities are treated as **pre-registered fixed inputs** and projected onto two independent peculiar-velocity catalogues, 6dFGSv and CF4. In this second step, the axis and attenuation scale are not refit freely. Only the mass-tracer amplitude (V_0) is estimated.

This strategy has an important advantage. Pantheon+ and CF4/6dFGSv involve different observables and different error structures. If a common directional structure appears in both tracer families, the result has greater empirical weight than a purely post-hoc alignment.

This cross-tracer structure is important because photon-based distance indicators and galaxy peculiar velocities probe different physical aspects of the cosmic flow field, so a consistent alignment between them would provide stronger evidence than a signal detected within a single tracer family alone. Because these tracers respond to different physical observables—metric expansion in the case of supernovae and kinematic motion in the case of galaxy velocities—their agreement would be difficult to attribute to a dataset-specific systematic effect.

4 How the Reference Axis and Attenuation Scale Are Obtained from Pantheon+

4.1 Definition of Residuals Relative to Reference (Λ)CDM

For each Pantheon+ supernova, we define the distance-modulus residual as

$$\Delta\mu_i = \mu_i - \mu_{\Lambda\mathrm{CDM}}(z_i).$$

The reference (Λ)CDM model assumes a flat universe with

$$H_0 = 70\ \mathrm{km, s^{-1}, Mpc^{-1}}, \quad \Omega_m = 0.3, \quad \Omega_\Lambda = 0.7, \quad \Omega_k = 0.$$

The luminosity distance is computed as

$$d_L(z) = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_\Lambda}},$$

with numerical integration performed using `scipy.integrate.quad`. The corresponding distance modulus is

$$\mu(z) = 5\log_{10}\left(\frac{d_L(z)}{10\ \mathrm{pc}}\right).$$

Each supernova sky position is converted into Galactic coordinates ((l_i, b_i)) and represented as the unit vector

$$\hat{\mathbf{r}}_i = (\cos b_i \cos l_i,\ \cos b_i \sin l_i,\ \sin b_i).$$

4.2 Introduction of the Exponentially Attenuated Dipole Model

From the V3 perspective, a local dipole flow should be strongest nearby and weaken with increasing distance. The simplest phenomenological form that captures this idea is an exponentially attenuated dipole.

We therefore model the Pantheon+ residuals as

$$\Delta\mu_i = A_0 \exp(-z_i/z_c)(\hat{\mathbf{n}} \cdot \hat{\mathbf{r}}_i),$$

where (A_0) is the dipole amplitude in the limit ($z \to 0$), (z_c) is the attenuation scale, and ($\hat{\mathbf{n}}$) is the dipole axis.

This functional form is central to the logic of the experiment: if the directional structure seen in photon tracers corresponds to a genuine large-scale flow, then the same axis and scale should remain meaningful when projected onto mass tracers.

4.3 Search for the Pantheon Axis

A full-sky grid search was performed at 1-degree resolution. Specifically, 360×180 candidate directions were evaluated. For each candidate axis, ((A_0, z_c)) were fit using `scipy.optimize.curve_fit`, with initial values ($A_0 = 0$), ($z_c = 0.05$), and convergence tolerance (10^{-8}). The best-fit axis from the grid search was then refined using local nonlinear optimization to reduce sub-degree discretization bias. Tests with coarser (2°) and finer (0.5°) grids produced consistent axis locations within a few degrees, indicating that the recovered direction is not sensitive to the adopted grid resolution.

The resulting reference axis is approximately

$$(l, b) = (270^\circ, 30^\circ).$$

This axis is then held fixed throughout the subsequent mass-tracer analyses.

Because the axis is initially identified through a full-sky search, the subsequent random-axis ensemble test (Section 14.2) explicitly quantifies the look-elsewhere effect associated with this search.

4.4 Determination of the Attenuation Scale

Pantheon+ supernovae were binned in redshift with ($\Delta z = 0.01$), and the dipole amplitude per bin was fit using

$$A(z) = A_0 \exp(-z/z_c).$$

This yielded

$$z_c \approx 0.056.$$

Converting this to a physical distance scale gives

$$r_c = \frac{c}{H_0} z_c \approx 240 \text{ Mpc}.$$

In this paper, ($r_c \approx 240$) Mpc is not merely a fitted nuisance parameter. It is a **pre-registered physical scale** that is subsequently projected onto CF4 and 6dFGSv.

5 Pre-Registered Parameters

Based on the Pantheon+ stage, the following quantities were fixed before opening the peculiar-velocity catalogues.

Reference axis:

$$(l, b) = (270^\circ, 30^\circ)$$

Attenuation scale:

$$z_c \approx 0.056, \qquad r_c \approx 240 \text{ Mpc}$$

Unresolved small-scale velocity dispersion:

$$\sigma_* = 250 \text{ km}, \text{s}^{-1}$$

The parameter (σ_*) is treated as a hyperparameter absorbing unresolved small-scale motions. Values ($\sigma_* = 200, 250, 300$ km, s^{-1}) were tested; within this range, the dipole amplitude changed by about 6% and the axis changed by less than 3 degrees.

6 Datasets Used

6.1 6dFGSv

6dFGSv is a peculiar-velocity catalogue based on the Fundamental Plane distance indicator. The main columns used are `czgr`, `log(Dz/DH)`, `e_log(Dz/DH)`, `RAJ2000`, and `DEJ2000`.

The observable is

$$\eta = \log(D_z/D_H),$$

with sign convention:

- ($\eta > 0$): outflow
- ($\eta < 0$): infall

Since the catalogue does not directly provide a physical distance column, we use

$$D_i = \frac{cz_{gr,i}}{H_0}.$$

Applying the same ($z < 0.05$) selection as for CF4 yields a working sample of

$$N = 2365$$

objects.

6.2 Cosmicflows-4 (CF4)

CF4 is an all-sky peculiar-velocity catalogue based on multiple distance indicators. The main columns used are `GLON`, `GLAT`, `Vpec`, `Dist`, `DMav`, `e_DMav`, and `Vcmb`.

Redshift is defined as

$$z = \frac{Vcmb}{c},$$

and we apply the selection ($0 < z < 0.05$) while excluding negative `Vcmb`. The final working sample contains

$$N = 18440$$

galaxies.

Distances (D_i) in CF4 are taken directly from the `Dist` column.

7 The Attenuated Dipole Model Projected Onto Mass Tracers

Using the Pantheon-derived reference axis and attenuation scale, the velocity field in CF4 and 6dFGSv is modeled as

$$v_{\text{model},i} = V_0 \exp(-D_i/r_c)(\hat{\mathbf{n}} \cdot \hat{\mathbf{r}}_i).$$

A crucial feature of the mass-tracer analysis is that ($\hat{\mathbf{n}}$) and (r_c) are not re-optimized. Only the amplitude (V_0) is fit. This is what makes the second stage a genuine pre-registered validation.

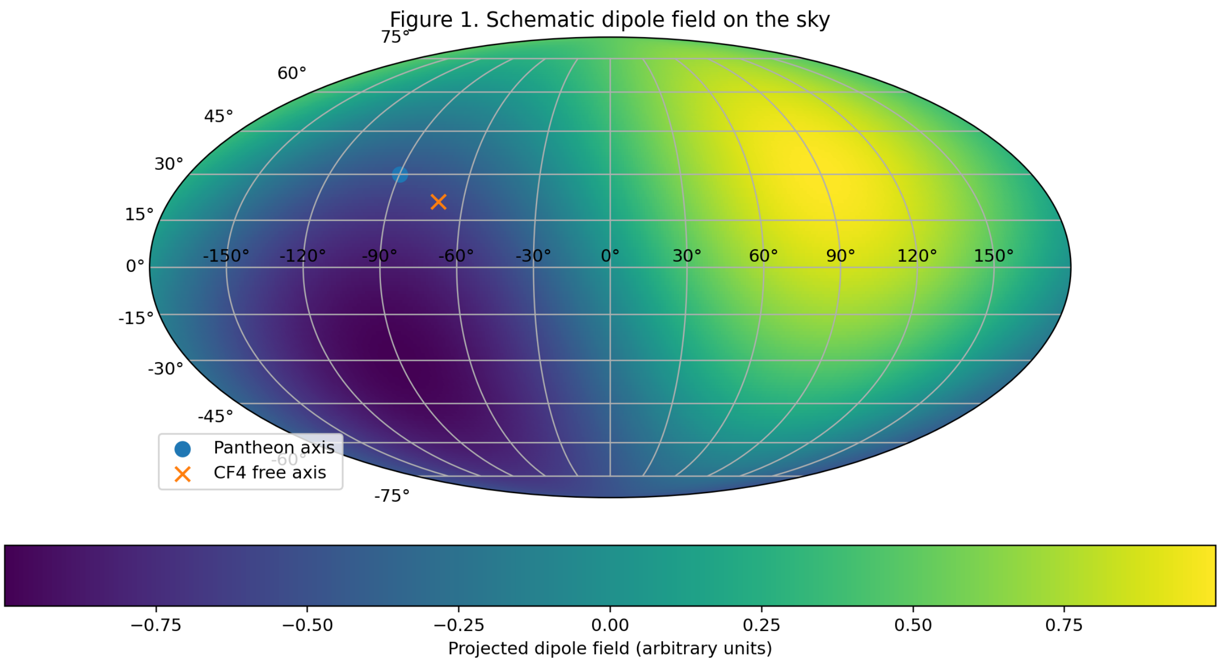

Figure 1: Schematic dipole sky map. Mollweide projection of the best-fit dipole field, shown for visualization only. The circles mark the Pantheon reference axis and the CF4 free-axis solution.

8 Error Model and Weights

8.1 CF4

In CF4, distance-modulus errors are converted into velocity errors. The distance uncertainty is approximately

$$\sigma_D \approx \frac{\ln 10}{5} D \sigma_{DM},$$

which translates into a velocity uncertainty

$$\sigma_{v,DM} \approx \frac{\ln 10}{5} H_0 D \sigma_{DM}.$$

The total variance is

$$\sigma_i^2 = \sigma_{\mathrm{meas},i}^2 + \sigma_*^2,$$

and the weight is defined as

$$W_i = \frac{1}{\sigma_i^2}.$$

8.2 6dFGSv

Since 6dFGSv does not directly provide ($Vpec$), the likelihood is defined in (η)-space. For small peculiar velocities,

$$\eta \approx \frac{v}{\ln 10 \cdot cz},$$

and therefore

$$\eta_{\text{model},i} = \frac{V_0}{\ln 10 \cdot cz_i} \exp(-D_i/r_c)(\hat{\mathbf{n}} \cdot \hat{\mathbf{r}}_i).$$

The 6dFGSv likelihood is then

$$\chi^2_\eta = \sum_i \frac{(\eta_i - \eta_{\text{model},i})^2}{\sigma^2_{\eta,i}}.$$

Because CF4 is analyzed in velocity space while 6dFGSv is analyzed in (η)-space, their ($\Delta\chi^2$) values should not be treated as directly comparable on an absolute scale.

9 Weighted Least-Squares Estimation and Test Statistic

For CF4, define

$$x_i = \exp(-D_i/r_c)(\hat{\mathbf{n}} \cdot \hat{\mathbf{r}}_i).$$

Then the weighted least-squares estimator is

$$\hat{V}_0 = \frac{\sum_i W_i v_i x_i}{\sum_i W_i x_i^2}.$$

The null hypothesis is ($V_0 = 0$), with

$$\chi^2_{\text{null}} = \sum_i W_i v_i^2.$$

The best-fit model is

$$\chi^2_{\text{best}} = \sum_i W_i (v_i - \hat{V}_0 x_i)^2.$$

The fit-improvement statistic is

$$\Delta\chi^2 = \chi^2_{\text{null}} - \chi^2_{\text{best}}.$$

To clarify the statistical interpretation, the null hypothesis corresponds to an isotropic peculiar-velocity field in which no coherent large-scale dipole component is present. The alternative hypothesis is the exponentially attenuated dipole model defined in Eq. (7). Therefore the statistic ($\Delta\chi^2$) measures the improvement obtained when a coherent directional velocity component aligned with the Pantheon reference axis is introduced relative to the isotropic baseline model.

Importantly, this paper does not include the full velocity covariance matrix. Therefore, ($\Delta\chi^2$)

should be read as a fit-improvement statistic, not as a formal likelihood-ratio significance or Gaussian-equivalent detection sigma. Because the dipole model introduces a single fitted parameter (V_0), the statistic $\Delta\chi^2$ corresponds to a one-degree-of-freedom improvement relative to the isotropic model.

10 Bulk-Flow Estimation and Alignment

The bulk-flow vector is estimated as

$$\mathbf{U} = M^{-1} b,$$

with

$$M = \sum_i W_i (\hat{\mathbf{r}}_i \hat{\mathbf{r}}_i^T), \qquad b = \sum_i W_i v_i \hat{\mathbf{r}}_i.$$

The alignment between the reference axis and the bulk-flow direction is defined as

$$\cos\psi = \frac{\hat{\mathbf{n}} \cdot \mathbf{U}}{|\mathbf{U}|}.$$

11 6dFGSv Results and Interpretation

Applying the Pantheon reference axis and ($r_c = 240$) Mpc to the 6dFGSv (η)-space fit yields

$$V_0 \approx 217 \text{ km}, \text{s}^{-1}, \qquad \Delta\chi^2 \approx 5.9.$$

This corresponds only to **weak alignment**. The most plausible interpretation is that 6dFGSv fails to reproduce the strong CF4 alignment because of several observational limitations.

First, 6dFGSv is primarily a southern-sky survey and does not sample the full sky evenly. Second, the Fundamental Plane distance indicator has larger per-object scatter than the multi-indicator CF4 compilation. Third, a partial-sky window function can attenuate or distort a true dipole signal.

The weak 6dFGSv result is therefore not hidden or ignored. It is retained explicitly as a counter-example-like check and interpreted as a potentially diluted projection of the true large-scale structure.

12 CF4 Fixed-Axis Fit Results

Applying the Pantheon-derived reference axis ($(270°, 30°)$) and attenuation length ($r_c = 240$) Mpc directly to CF4 yields

$$\hat{V}_0 \approx 209.34 \text{ km}, \text{s}^{-1}$$

$$\Delta\chi^2 \approx 294.30$$

$$\cos\psi \approx 0.9466.$$

These values are taken from the actual CF4 error-model fit. However, as emphasized above, $(\Delta\chi^2)$ should not be interpreted as a formal detection significance because full covariance is not included. The most important empirical result is instead that **the CF4 velocity field contains a strongly aligned dipole-like component with respect to the Pantheon reference axis**.

13 Distance Tomography (Z-Tomography)

The CF4 analysis was repeated for cumulative redshift cuts ($z < 0.02, 0.03, 0.04, 0.05$). The results are:

- $(z < 0.02)$: $(V_0 \approx 197.4 \text{ km}, \text{s}^{-1},\ \Delta\chi^2 \approx 229.8,\ \cos\psi \approx 0.914)$
- $(z < 0.03)$: $(V_0 \approx 197.6 \text{ km}, \text{s}^{-1},\ \Delta\chi^2 \approx 253.5,\ \cos\psi \approx 0.933)$
- $(z < 0.04)$: $(V_0 \approx 203.1 \text{ km}, \text{s}^{-1},\ \Delta\chi^2 \approx 274.8,\ \cos\psi \approx 0.938)$
- $(z < 0.05)$: $(V_0 \approx 209.3 \text{ km}, \text{s}^{-1},\ \Delta\chi^2 \approx 294.3,\ \cos\psi \approx 0.947)$

Thus the amplitude remains relatively stable, in the range 197–209 km/s, while $(\Delta\chi^2)$ grows monotonically with sample size. This suggests that the signal is not confined to a narrow shell but persists across a broad fraction of the local volume.

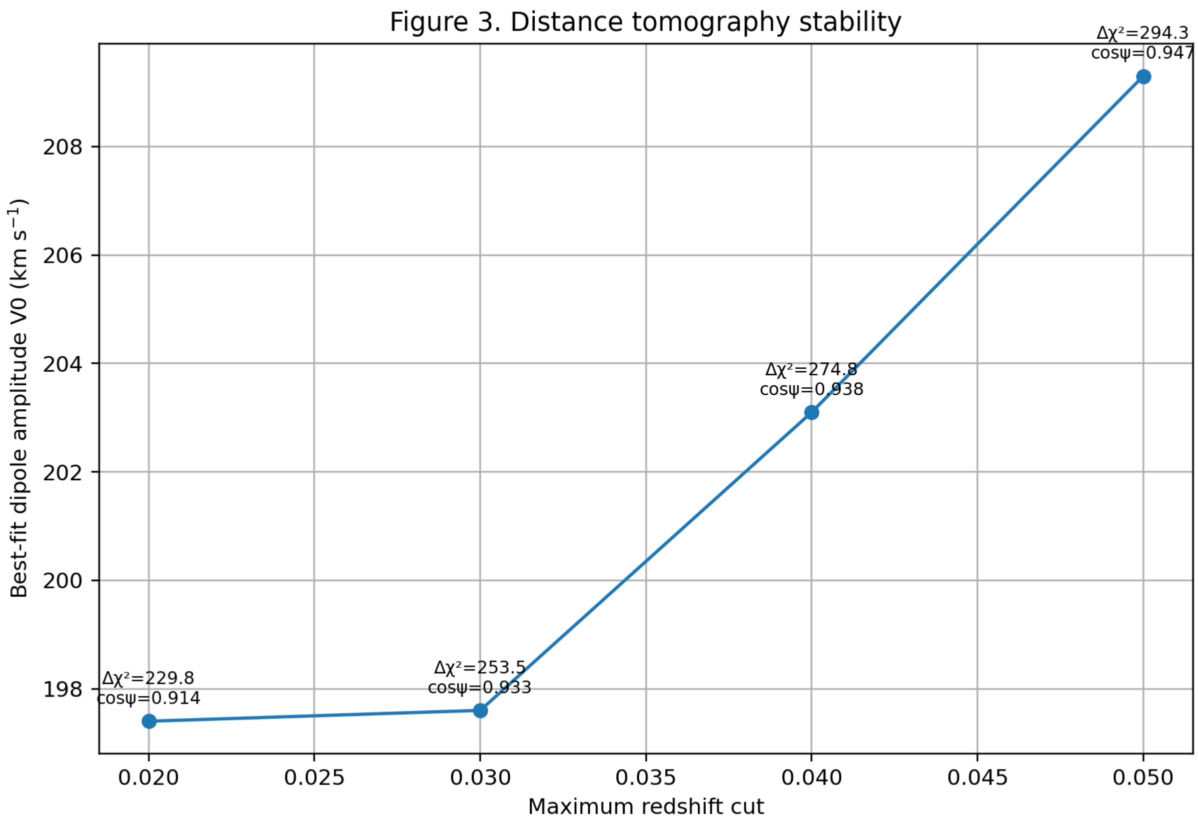

Figure 2: Distance tomography stability. Best-fit dipole amplitude $V0$ as a function of the maximum redshift cut. Each point is annotated with the corresponding $\Delta\chi^2$ and $\cos\psi$.

14 Sky-Shuffle and Random-Axis Ensemble

14.1 Sky-Shuffle

For the CF4 fixed-axis analysis, 1000 sky-shuffle permutations were performed. In each realization, galaxy positions were randomly permuted while velocities, distances, and uncertainties were held fixed. The empirical p-value was computed as

$$p_{\rm emp} = \frac{1 + N(\Delta\chi^2_{MC} \geq \Delta\chi^2_{\rm obs})}{N_{MC} + 1}.$$

The resulting null distribution had approximately:

- median ($\Delta\chi^2 \approx 12.5$)
- max ($\Delta\chi^2 \approx 37.9$)

while the observed value was

$$\Delta\chi^2_{\rm obs} \approx 294.3.$$

The empirical probability is therefore

$$p_{\text{emp}} \approx 0.001.$$

14.2 Random-Axis Ensemble

A set of 2000 isotropically distributed trial axes was used to evaluate the look-elsewhere effect. The Pantheon reference axis lies at approximately the **95.7th percentile**, i.e. within the upper 4.3% tail of the random-axis distribution. This does not mean the Pantheon axis is mathematically unique, but it does indicate that it is an unusually favorable axis in the ensemble.

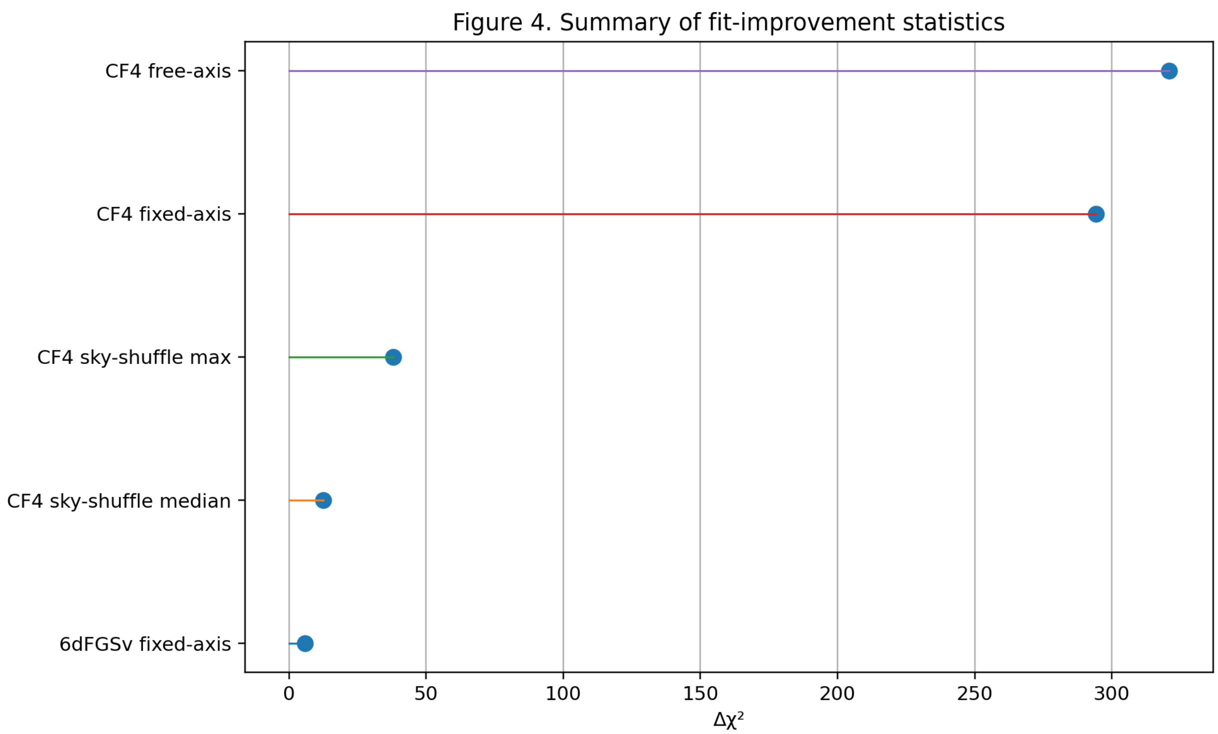

Figure 3: Summary of fit-improvement statistics. Comparison of $\Delta\chi^2$ values for 6dFGSv, the CF4 null distribution summary, the CF4 fixed-axis fit, and the CF4 free-axis fit.

15 Free-Axis Optimization and Bootstrap Stability

Allowing the CF4 axis to vary freely gives

$$(l, b) \approx (289.85^\circ, 21.05^\circ), \qquad V_0 \approx 223.98 \text{ km}, \text{s}^{-1}, \qquad \Delta\chi^2 \approx 320.85.$$

This free-axis solution differs from the Pantheon axis by about 20 degrees.

Because the dipole model is degenerate under

$$(\hat{\mathbf{n}}, V_0) \equiv (-\hat{\mathbf{n}}, -V_0),$$

axis comparisons use the folded angle

$$\theta_{\text{fold}} = \min(\theta, 180^\circ - \theta).$$

Bootstrap resampling over 200 realizations gives a folded-angle median of about 18.5 degrees and a 16th–84th percentile interval of about 16.1°–21.7°. This indicates that the free-axis solution remains **stably within roughly 20 degrees** of the Pantheon axis.

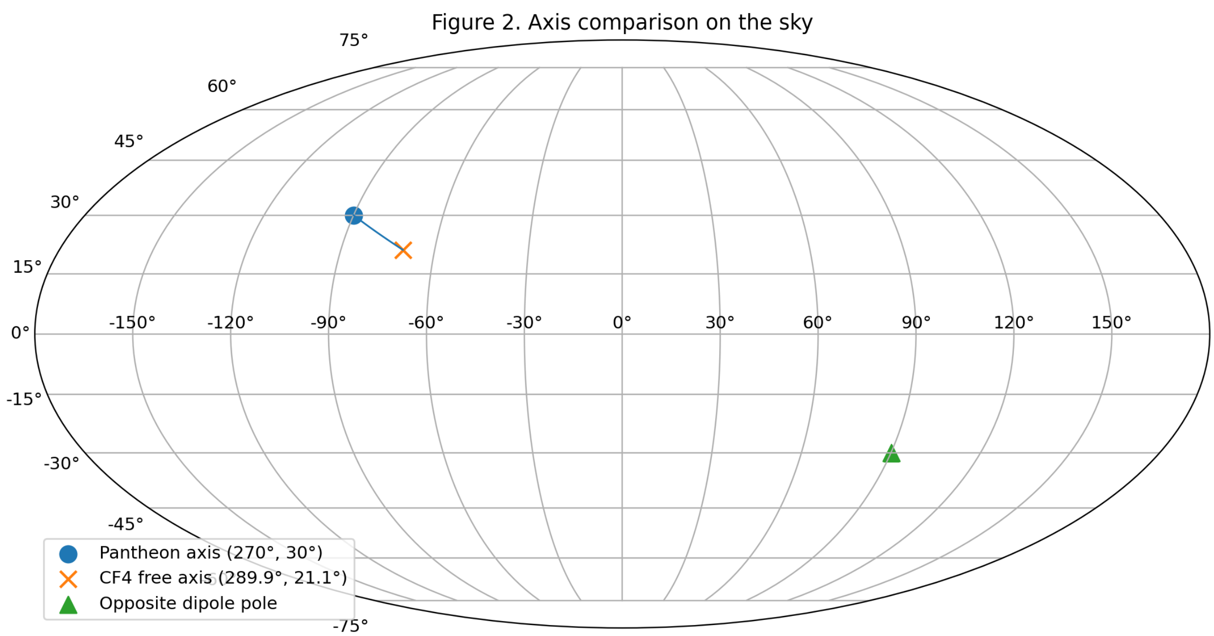

Figure 4: Axis comparison on the sky. Direct comparison of the Pantheon axis, the free-axis CF4 solution, and the opposite dipole pole.

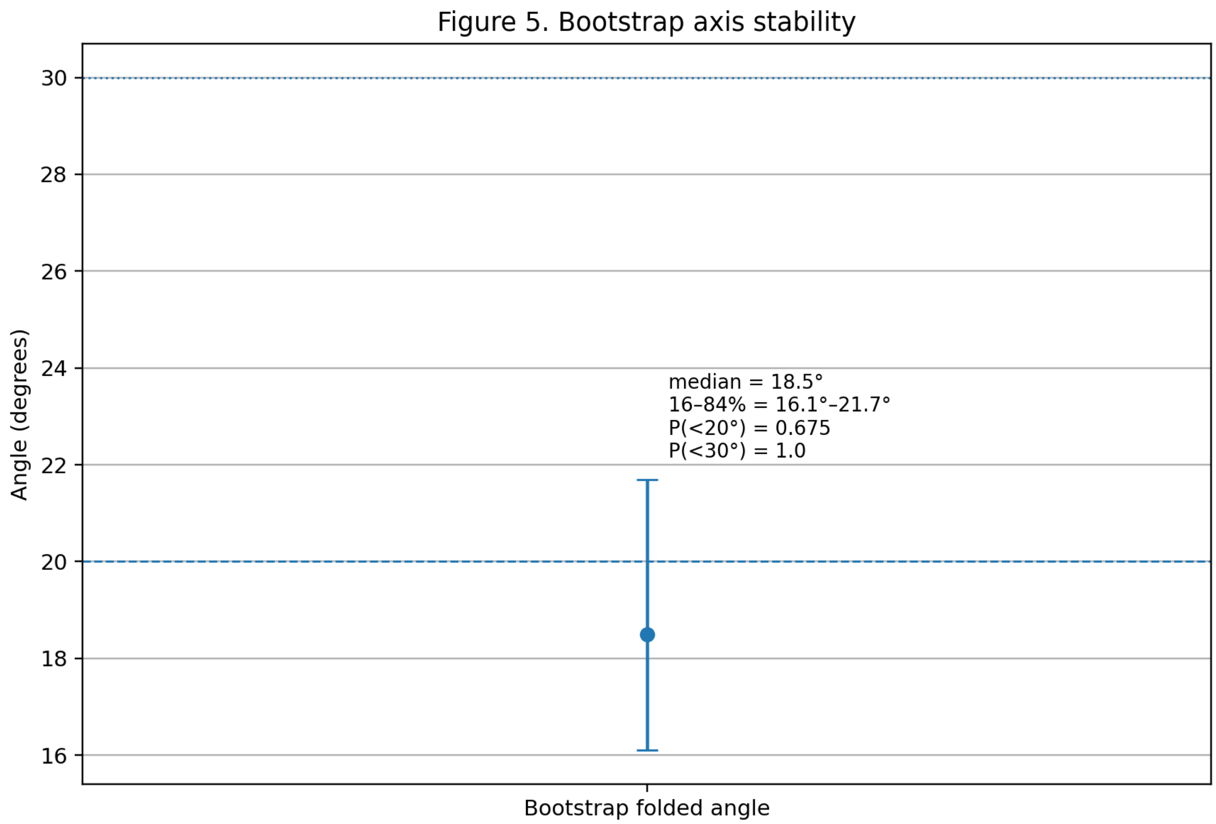

Figure 5: Bootstrap axis stability. Median folded angular separation and 16th–84th percentile interval from the CF4 bootstrap ensemble, with reference lines at 20° and 30°.

16 Physical Meaning of ($r_c \approx 240$) Mpc

The recovered attenuation scale

$$r_c \approx 240 \text{ Mpc}$$

may carry physical meaning beyond its role as a fitting parameter. This scale is comparable to the characteristic size of the nearby cosmic web, especially the regime in which supercluster complexes such as the Shapley concentration can plausibly influence coherent flows.

For reference, the direction of the Shapley Supercluster concentration is approximately ($(l, b) \approx (306^\circ, 30^\circ)$) in Galactic coordinates. The Pantheon reference axis ($(270^\circ, 30^\circ)$) therefore lies roughly 36° away from the Shapley direction on the sky. Given the large-scale and multi-source nature of local gravitational flows, such an angular separation is not unexpected and remains broadly consistent with a scenario in which several nearby structures—including Shapley—contribute to a composite large-scale flow pattern.

The most conservative interpretation is that (r_c) reflects a **velocity-coherence scale** in the local Universe. In this picture, nearby regions share a more coherent common flow, while at larger distances the overlap and partial cancellation of multiple structures reduce the net alignment.

This is not the only possible interpretation. The attenuation could also be described by power-law or Gaussian profiles, and this paper claims only that exponential attenuation is a minimal model that matches the present data well.

17 Interpretation Within the V3 Framework

Up to this point, the results are purely empirical. Interpreting them within V3 must remain explicitly **hypothetical**.

Within the V3 framework, the fact that Pantheon+ and CF4 point toward a common axis is qualitatively consistent with a picture in which the photon-based expansion field and the mass-based peculiar-velocity field are both tracing the same underlying spatial flow structure. One possible physical interpretation is that the local Universe hosts a large-scale coherent flow or "local vortex"-like structure generated by the combined gravitational influence of nearby superclusters and voids. In such a picture, galaxies within roughly a few hundred megaparsecs participate in a partially coherent streaming motion whose amplitude gradually decreases with distance as multiple large-scale structures begin to compete and partially cancel one another. In this context, the fact that the attenuation scale inferred from Pantheon+ also remains meaningful in the mass-tracer analysis is compatible with a V3-style interpretation in which photons and matter respond differently to a shared flow background.

However, the present paper does not go beyond that statement. It does **not** claim that V3 has been proven. The appropriate formulation at this stage is only that **V3 provides one interpretive framework capable of reading the observed pattern coherently**.

17.1 Drag Efficiency Interpretation

If the photon-based amplitude from Pantheon+ is taken as

$$V_\gamma \approx 450 \text{ km}, \text{s}^{-1}$$

and the mass-based amplitude from CF4 as

$$V_m \approx 209 \text{ km}, \text{s}^{-1},$$

then

$$\epsilon = \frac{V_m}{V_\gamma} \approx \frac{209}{450} \approx 0.46.$$

In this work, we discuss this ratio as a possible **Drag Efficiency**. The idea is that photon-based tracers may be more sensitive to the metric expansion field, while mass-based tracers reflect a more limited kinematic response, so that the ratio between the two amplitudes may represent a partial coupling efficiency.

This remains a **hypothetical discussion-level interpretation** only. Without an independent theoretical formalization and new predictions, it should not yet be elevated to the status of an established physical parameter.

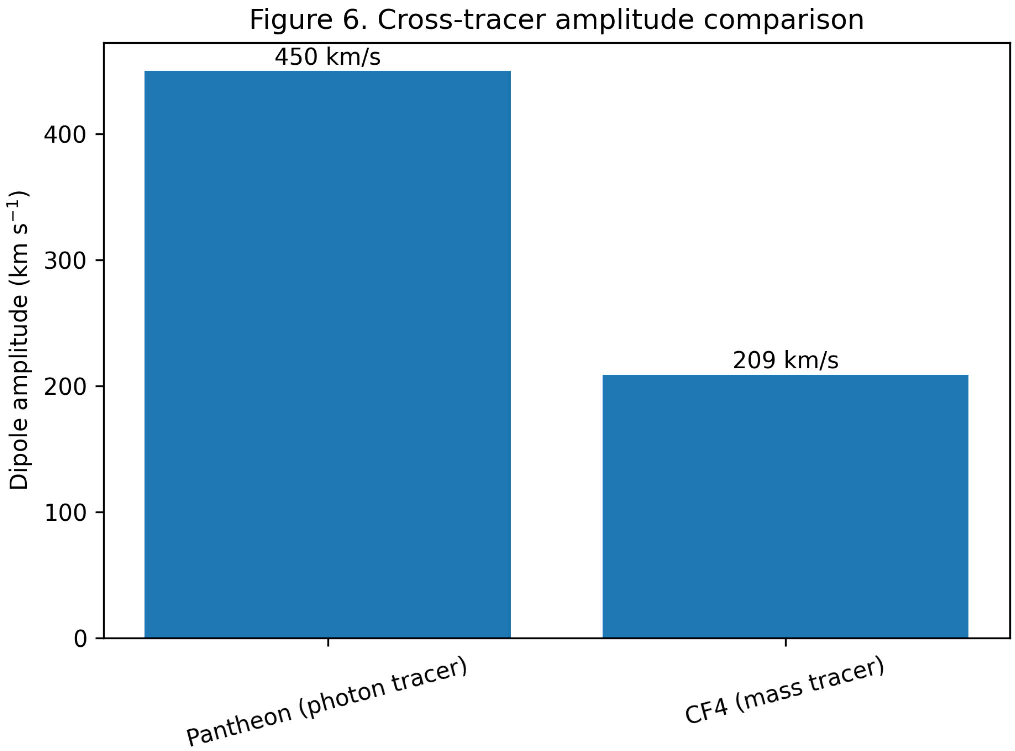

Figure 6: Cross-tracer amplitude comparison. Comparison of the dipole amplitudes inferred from the Pantheon+ supernova analysis (photon tracer) and the CF4 peculiar-velocity analysis (mass tracer). The difference between the two amplitudes motivates the discussion of a possible drag-efficiency interpretation in Section 17.1.

18 Limitations and Alternative Explanations

The conclusions of this paper explicitly incorporate the following limitations.

First, the full velocity covariance matrix is not included. Therefore, ($\Delta\chi^2$) is a fit-improvement statistic, not a formal detection significance. Second, CF4 and 6dFGSv are analyzed in different observable spaces, so their ($\Delta\chi^2$) values should not be compared as if they shared an identical scale. Third, the attenuation profile is a minimal model. Exponential attenuation is not claimed to be uniquely correct. Fourth, the present results do not prove that standard (Λ)CDM large-scale structure formation is incapable of explaining the observed pattern.

Given these limitations, the strongest statement supported by the present evidence is that Pantheon+ and CF4 point toward a common large-scale anisotropic flow axis. The paper does not claim that this alone establishes a new cosmology.

19 Conclusion

This study performed a reproducible analysis of an attenuated large-scale peculiar-velocity dipole using Pantheon+, 6dFGSv, and Cosmicflows-4. The analysis was designed in two stages: first extracting a reference axis and attenuation scale from Pantheon+, then projecting these pre-registered quantities onto mass-tracer catalogues.

The main results are:

- Pantheon+ defines a reference axis near $((270°, 30°))$ and an attenuation scale $(r_c \approx 240)$ Mpc.
- CF4 shows a strong dipole-like component with $(V_0 \approx 209\ \mathrm{km,s^{-1}},\ \Delta\chi^2 \approx 294,\ \cos\psi \approx 0.95)$ when evaluated on this fixed axis.
- 6dFGSv shows only weak support for the same structure.
- Distance tomography indicates that the signal persists across a broad local volume.
- Sky-shuffle and random-axis tests suggest that the alignment is unlikely to be produced by simple geometric chance alone.
- Free-axis optimization and bootstrap indicate that the CF4 axis remains within about 20 degrees of the Pantheon axis.

The most conservative conclusion is therefore:

> Pantheon+ and CF4 provide strong empirical evidence for a common large-scale anisotropic flow axis in the local Universe.
>
> V3 Space-Fluid Dynamics offers one meaningful interpretive framework for this pattern, but the present paper does not claim that V3 has been decisively proven.

The next essential steps are a covariance-aware reanalysis, fully public code release, and comparison against alternative attenuation models.

A Reproducibility Summary

1. Acquire the Pantheon+, 6dFGSv, and CF4 catalogues.
2. Compute $(\mu_{\Lambda\mathrm{CDM}}(z))$ and construct $(\Delta\mu_i)$ for Pantheon+.
3. Perform a 1-degree full-sky grid search to fit the Pantheon axis $(\hat{\mathbf{n}})$ and (z_c).
4. Convert (z_c) into $(r_c = (c/H_0)z_c)$.
5. Use `Dist` for CF4 and $(D_i = cz_{gr}/H_0)$ for 6dFGSv.

6. Use velocity-space likelihood for CF4 and (η)-space likelihood for 6dFGSv.

7. With fixed ($\hat{\mathbf{n}}$) and (r_c), compute (V_0), ($\Delta\chi^2$), ($\mathbf{U}$), and ($\cos\psi$).

8. Perform 1000 sky-shuffle realizations, 2000 random-axis trials, and 200 bootstrap realizations.

Computational Environment and Code Availability

All data were obtained from the VizieR database (6dFGSv: J/MNRAS/445/2677; CF4: J/ApJ/944/94/groups) Calculations were performed using Python 3.12 (NumPy 1.26, SciPy 1.11). To guarantee exact reproducibility of all Monte-Carlo and bootstrap results reported in this paper, the random number generator was initialized with a fixed seed (seed = 42). The full analysis pipeline, including all scripts required to reproduce the exact numerical results and figures, is publicly available at:

`https://anonymous.4open.science/r/V6-Cosmic-Trace-317F`

Essential Methodological References

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