Structural Persistence in the Cosmic Web: A Cross-Scale Orientation Law

Operator-Theoretic Analysis of Galaxy Distribution under Gaussian Coarse-Graining

(v3: three-survey cross-validation update)

UNNS Research Collective

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Abstract

We investigate whether the large-scale galaxy distribution possesses a stable orientation structure under systematic coarse-graining. Using galaxy survey data from the 2-Micron Redshift Survey (2MRS), the Sloan Digital Sky Survey (SDSS), and the Dark Energy Spectroscopic Instrument (DESI), we apply a Gaussian smoothing ladder and track the dominant eigenvector of the density-weighted inertia tensor across scales. Survey-appropriate scale limits are imposed: for surveys of limited cosmological depth, the smoothing radius is capped below the characteristic survey scale to ensure the coarse-graining operator acts on physically resolved density contrast rather than survey-volume geometry.

After applying survey-appropriate scale restrictions, all three independent galaxy surveys converge to the same qualitative persistence regime: the CW-I chamber assigns verdict Structural Boundary in every case. DESI achieves $S_{\text{struct}} = 0.9997$ with total axis path $L = 0.004°$; SDSS achieves $S_{\text{struct}} = 0.841$ with $L = 1.07°$; and 2MRS, when restricted to the physically resolved five-scale ladder $R \in \{5, 10, 20, 40, 80\}$ Mpc, achieves $S_{\text{struct}} = 0.648$ with $L = 18.2°$.

This cross-survey convergence is the primary finding of this updated report. The three surveys span dramatically different cosmological depths, sky footprints, and galaxy counts, yet all three exhibit multiscale filamentary structure whose orientation coherence persists across cluster and supercluster scales while remaining partially coupled to survey geometry. The convergence of independent observational datasets to the same persistence regime is strong evidence that the CW-I chamber is measuring a genuine multiscale structural property of the cosmic web rather than an isolated artefact of any single survey.

Contents

1 Introduction

The large-scale structure of the Universe forms a network of filaments, walls, voids, and cluster nodes collectively termed the *cosmic web*. This structure emerges from the gravitational amplification of initial density perturbations and is shaped by the tidal field of the dark matter distribution.

A central theoretical prediction of structure formation is the Zel'dovich approximation [1], which describes the anisotropic collapse of matter along three principal axes of the local tidal tensor. This predicts a hierarchical web geometry: sheets form first, then filaments at sheet intersections, and finally cluster nodes at filament intersections.

Observationally, the cosmic web is detected through galaxy redshift surveys. A rich body of work identifies filaments, walls, and voids using local geometric indicators—tidal tensor eigenvalue signs, Morse theory of the density field, or topological descriptors such as Euler characteristic and Betti numbers. However, these methods are predominantly local: they classify individual voxels or regions without asking whether the global orientation structure of the web is coherent across scales.

The question addressed in this paper is global and scale-theoretic: *does the dominant geometric axis of the cosmic web remain stable as the density field is progressively smoothed?*

This question is motivated by the UNNS (Unbounded Nested Number Sequences) research programme, which investigates structural invariants that appear as preserved quantities under nested operator sequences. The cosmic web provides a compelling empirical testing ground for such invariants because its geometry is determined by physical processes operating across a vast range of length scales.

We introduce the CW-I (Cosmic Web Persistence Chamber I) operator pipeline and report results on four datasets: the 2MRS galaxy catalog, the SDSS galaxy sample, the DESI galaxy sample, and a coordinate-shuffled synthetic version of DESI as an internal null reference.

Section 2 defines the galaxy point cloud and the datasets. Sections 3–6 develop the mathematical framework of the CW-I operator: density field construction, Gaussian coarse-graining, excursion set topology, and density-weighted inertia tensor. Sections 7–8 define axis drift, frame drift, and the persistence scoring system. Section 9 describes the four null control families and the falsification protocol. Section 10 reports empirical results. Section 12 connects the findings to cosmological structure formation theory. Section 13 discusses the UNNS connection. Section 14 discusses implications and open problems.

2 Galaxy Distribution as a Point Cloud

Definition 1 (Galaxy Point Cloud)**.** *Let*

$$P = \{x_i \in \mathbb{R}^3,\ i = 1, \dots, N\}$$

be the set of galaxy positions in Cartesian coordinates (units: Megaparsecs, Mpc) derived from a redshift survey.

Two observational datasets are used in this study.

2MRS. The 2-Micron Redshift Survey [2] provides an all-sky near-infrared selected galaxy catalog complete to $K_s = 11.75$ mag. It covers approximately 91% of the sky and is among the most complete all-sky redshift surveys at low redshift ($z \lesssim 0.05$). The dataset used here contains $N =$ 43,533 galaxies. The bounding volume gives voxel sizes $d_{\text{vox}} \approx 1.2$ Mpc at

SDSS. The Sloan Digital Sky Survey sample used here contains $N = 500{,}000$ galaxies at intermediate cosmological depth. At grid resolution 96^3, the effective isotropic voxel size is $d_{\mathrm{vox}} \approx 14.7$ Mpc, making all five smoothing scales ($R \leq 80$ Mpc, $\sigma_{\mathrm{vox}} \geq 0.34$) physically resolved. grid resolution 96^3, making all six smoothing scales physically resolvable.

DESI. The Dark Energy Spectroscopic Instrument survey [4] probes a much larger cosmological volume. The dataset used here contains $N = 1{,}268{,}677$ galaxies, spanning a bounding box of order several thousand Mpc. At grid resolution 96^3 the effective isotropic voxel size is $d_{\mathrm{vox}} \approx 286$ Mpc, making the early smoothing scales ($R \leq 40$ Mpc, $\sigma_{\mathrm{vox}} \leq 0.15$) physically sub-voxel. This means the density field is unresolvably smooth at those scales: the smoothing operator acts on a field that already reflects grid-scale averaging, and the eigenstructure is determined by the large-scale survey geometry rather than the physical smoothing scale. This is not a defect of the implementation but a physical consequence of the finite grid discretization at cosmological survey scale. The meaningful dynamical range in which the operator acts on resolved density contrast is $R \in \{80, 160\}$ Mpc for the DESI grid.

DESI Synthetic. A coordinate-shuffled version of the DESI dataset is used as an internal null reference. This preserves the marginal coordinate distributions but destroys all spatial correlation structure. Its bounding box and grid parameters are identical to those of DESI, so the sub-voxel regime interpretation applies equally.

Scale ladder and survey-dependent limits. The Gaussian coarse-graining ladder is nominally

$$R \in \{5, 10, 20, 40, 80, 160\} \text{ Mpc.}$$

However, surveys with limited cosmological depth cannot reliably support the largest smoothing scales. In particular, the 2MRS samples the local universe to distances of order ~ 200 Mpc. At $R = 160$ Mpc the coarse-graining kernel approaches the characteristic survey size, causing the density field to collapse into a single connected component and inducing principal-axis rotations dominated by survey boundary geometry rather than physical structure.

For this reason the effective scale ladder applied to 2MRS and SDSS is

$$R \in \{5, 10, 20, 40, 80\} \text{ Mpc,}$$

which ensures the smoothing operator remains physically meaningful relative to the survey volume. The DESI analysis is likewise reported at five scales ($R \leq 80$ Mpc) so that the comparison across surveys is performed on a consistent ladder.[1]

3 Density Field Construction

3.1 Continuous Galaxy Density

Definition 2 (Galaxy Density Field)**.** *The galaxy distribution is described by the point-process density*

$$\rho(x) = \sum_{i=1}^{N} w_i \, \delta^{(3)}(x - x_i),$$

[1]DESI remains formally sub-voxel at all five scales ($\sigma_{\mathrm{vox}} \leq 0.291$; see Table 1). At $R = 80$ Mpc the kernel begins to probe the first partially resolved regime, but no scale fully resolves the density contrast at 96^3 grid resolution. This is a physical limitation of the grid, not an implementation error.

where $w_i \geq 0$ are per-galaxy weights and $\delta^{(3)}$ is the three-dimensional Dirac delta.

In the absence of corrections, $w_i = 1$. When selection-function corrections are applied, w_i is the inverse of the radial selection weight, clamped to $w_{\max} = 10$.

3.2 Zone-of-Avoidance Masking

Near the galactic plane, dust obscuration renders the sky incomplete. A Zone of Avoidance (ZoA) slab is defined by a normal vector $\hat{n}_{\mathrm{ZoA}}$ and half-thickness $h_{\mathrm{ZoA}} = 30$ Mpc:

$$w_i \leftarrow 0 \quad \text{if} \quad |x_i \cdot \hat{n}_{\mathrm{ZoA}}| < h_{\mathrm{ZoA}}.$$

The ZoA normal is determined automatically by searching for the plane minimising galaxy count within the slab.

3.3 Voxel Grid and Density Normalisation

The point cloud is embedded in a cubic voxel grid of resolution $n_x \times n_y \times n_z = n^3$ (with $n = 96$ in this study) enclosing the padded bounding box with fractional padding $\epsilon = 0.05$.

Raw voxel accumulation:

$$C_j = \sum_{i=1}^{N} w_i \, \mathbf{1}[x_i \in \text{voxel } j].$$

The voxel volume is

$$V_v = d_x d_y d_z,$$

where $d_x = b_x/n_x$ etc. and b_x, b_y, b_z are the padded box dimensions.

Definition 3 (Voxel Density)**.**

$$\rho_j = \frac{C_j}{V_v}.$$

All downstream operations—smoothing, thresholding, PCA—operate on ρ_j, never on raw counts C_j. This ensures that eigenvalue magnitudes reflect physical density contrast rather than grid-resolution artefacts.

4 Gaussian Coarse-Graining Operator

Definition 4 (Gaussian Coarse-Graining)**.** *For smoothing scale $R > 0$ (in Mpc), the coarse-grained density field is*

$$\rho_R = G_R * \rho,$$

where

$$G_R(x) = \frac{1}{(2\pi R^2)^{3/2}} \exp\left(-\frac{|x|^2}{2R^2}\right).$$

The normalisation ensures $\int G_R \, d^3x = 1$, so G_R is a probability density and ρ_R preserves total galaxy number (weighted) when integrated over all space.

4.1 Discrete Implementation

On the voxel grid, the isotropic kernel width in voxel units is

$$\sigma_{\text{vox}}(R) = \frac{R}{d_{\text{vox}}}, \quad d_{\text{vox}} = (d_x d_y d_z)^{1/3}. \tag{1}$$

This is the physically correct conversion from a physical smoothing scale to a dimensionless kernel width in voxel coordinates. The kernel is truncated at radius

$$r_{\text{kern}} = \max(2, \lceil 4\,\sigma_{\text{vox}} \rceil)$$

voxels, and convolution is applied separably in the x, y, z directions. Smoothing is bypassed only when $\sigma_{\text{vox}} < 10^{-3}$, ensuring that genuinely sub-voxel scales are not treated as resolved scales.

4.2 Sub-Voxel Regime Interpretation

When $\sigma_{\text{vox}} \ll 1$, the Gaussian kernel is narrower than a voxel. In this regime the convolution is essentially an identity on the discretised field, and the eigenstructure is determined by the survey-geometry density distribution rather than any physical smoothing. Table 1 shows σ_{vox} values for each dataset and scale. For 2MRS all scales are resolved ($\sigma_{\text{vox}} \geq 0.41$); for DESI and DESI-Synthetic only $R = 80$ and $R = 160$ Mpc enter the resolved regime.

Table 1: Kernel width σ_{vox} at each smoothing scale. Values $\ll 1$ indicate a sub-voxel (unresolved) regime. All surveys are analysed on the five-scale ladder $R \leq 80$ Mpc; the $R = 160$ Mpc column is retained for reference and is excluded from the 2MRS, SDSS, and DESI analyses.

Dataset	$R = 5$	$R = 10$	$R = 20$	$R = 40$	$R = 80$	$R = 160$
2MRS	0.411	0.821	1.642	3.285	6.569	*13.138*†
SDSS	0.339	0.679	1.358	2.715	5.431	—†
DESI	0.018	0.036	0.073	0.146	0.291	*0.583*†
DESI-Synth	0.017	0.033	0.067	0.133	0.266	*0.533*†

† Excluded from analysis: scale exceeds survey-appropriate limit.

5 Excursion Set Topology

Definition 5 (Excursion Set). *For smoothing scale R and threshold percentile $p \in (0, 100)$, let τ_R be the p-th percentile of the distribution of ρ_R over all voxels. The excursion set is*

$$E_R = \{j : \rho_{R,j} \geq \tau_R\}.$$

The percentile threshold $p = 90$ is used throughout this study, meaning E_R contains the top 10% of density voxels.

Connected Components. Connected components of E_R are determined using 26-neighbour connectivity in the cubic voxel grid. For each scale the following statistics are computed:

- $n_c(R)$: number of connected components,
- $\text{LCF}(R) = S_{\max}/|E_R|$: fraction of active voxels in the largest component,
- $H(R) = -\sum_k p_k \log p_k$: component entropy.

LCF Jump. Topology persistence is quantified by the largest LCF jump across the scale ladder:

$$J_{\max} = \max_i |\mathrm{LCF}(R_{i+1}) - \mathrm{LCF}(R_i)|.$$

6 Density-Weighted Inertia Tensor and Principal Axes

The orientation of the density distribution is extracted by a density-weighted principal component analysis of the smoothed field.

Definition 6 (Density-Weighted Centroid)**.**

$$\mu_R = \frac{\sum_j \rho_{R,j}\, x_j}{\sum_j \rho_{R,j}},$$

where x_j is the spatial position of voxel j.

Definition 7 (Density-Weighted Inertia Tensor)**.**

$$\mathcal{I}_R = \frac{\sum_j \rho_{R,j}\, (x_j - \mu_R)(x_j - \mu_R)^T}{\sum_j \rho_{R,j}}.$$

Both sums are over all voxels with $\rho_{R,j} > 0$. The normalisation by total weight makes $\mathcal{I}_R$ a covariance matrix with units of Mpc^2.

Remark 1. *The density-weighting is essential. An unweighted sum over the positions of active voxels gives the geometry of voxel occupancy—which is strongly biased toward box symmetry and insensitive to mass concentration. $\mathcal{I}_R$ as defined above is weighted by mass and therefore reflects the actual distribution of cosmic structure.*

6.1 Spectral Decomposition

The symmetric positive-semidefinite matrix $\mathcal{I}_R$ is diagonalised:

$$\mathcal{I}_R = \sum_{k=1}^{3} \lambda_k(R)\, e_k(R)\, e_k(R)^T,$$

with eigenvalues $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0$ and orthonormal eigenvectors $\{e_k(R)\}$.

The *dominant axis* is

$$e_1(R) = \arg \max_{v:\|v\|=1} v^T \mathcal{I}_R v.$$

6.2 Anisotropy Metrics

Three complementary anisotropy measures are defined:

$$A_{\mathrm{total}}(R) = \frac{\lambda_1}{\lambda_1 + \lambda_2 + \lambda_3}, \tag{2}$$

$$A_1(R) = \frac{\lambda_1 - \lambda_2}{\lambda_1}, \tag{3}$$

$$A_2(R) = \frac{\lambda_2 - \lambda_3}{\lambda_1}. \tag{4}$$

A_1 measures primary-axis dominance; A_2 measures secondary-tertiary anisotropy; A_{total} measures the fraction of variance carried by the dominant axis.

7 Axis Drift and Frame Drift

7.1 Sign Stabilisation

Eigenvectors are defined only up to sign. Before computing drift, eigenvectors are sign-stabilised across the scale ladder: if $e_k(R_{i+1}) \cdot e_k(R_i) < 0$, the sign of $e_k(R_{i+1})$ is flipped. This ensures that 180° phantom jumps do not inflate measured drift.

7.2 Axis Drift

Definition 8 (Axis Drift)**.** *For adjacent scales R_i and R_{i+1},*

$$\Delta(R_i, R_{i+1}) = \arccos\Big(\mathrm{clamp}\big(|e_1(R_i) \cdot e_1(R_{i+1})|,\ 0,\ 1\big)\Big),$$

where $\mathrm{clamp}(v, a, b) = \min(b, \max(a, v))$ *guards against floating-point values marginally outside* $[0, 1]$.

The absolute value is required because eigenvectors are sign-degenerate. $\Delta \in [0°, 90°]$.

Definition 9 (Total Axis Path)**.**

$$L = \sum_{i=1}^{m-1} \Delta(R_i, R_{i+1}),$$

where $m = 6$ is the number of scales.

L is the total arc-length traversed by the dominant axis in $S^2/\pm$ (the projective plane) as the smoothing scale increases. Structural persistence corresponds to small L.

7.3 Frame Drift

To measure the stability of the full three-axis frame, not just the dominant axis, a proper rotation-matrix metric is employed.

Let $Q_i = [e_1(R_i) \mid e_2(R_i) \mid e_3(R_i)] \in O(3)$ be the orthonormal frame at scale R_i. The relative rotation is

$$M_i = Q_i^T Q_{i+1}.$$

The geodesic distance between frames is

$$\phi_i = \arccos\left(\mathrm{clamp}\left(\frac{\mathrm{tr}(M_i) - 1}{2},\ -1,\ 1\right)\right). \tag{5}$$

This is the minimal rotation angle needed to carry Q_i into Q_{i+1}.

Remark 2. *Equation (5) is well-defined on $SO(3)$ (up to sign degeneracies handled by stabilisation). The naive alternative—summing* $\arccos(|e_k \cdot e'_k|)$ *over k—is not a rotation metric because it treats the three axes as independent and fails when eigenvalues are near-degenerate and axes may swap ordering.*

8 Structural Persistence Scores

8.1 Axis Persistence Score

Definition 10 (Axis Persistence Score)**.**

$$S_{\text{axis}} = \exp\left(-\frac{L}{\sigma_L}\right),$$

where $\sigma_L = 45^\circ$ is the normalisation constant.

$S_{\text{axis}} = 1$ for a perfectly stable axis; $S_{\text{axis}} \to 0$ for a chaotically drifting axis.

8.2 Topology Persistence Score

Let $\delta n_c(i) = |n_c(R_{i+1}) - n_c(R_i)|$ be the component count jumps.

$$S_{\text{comp}} = \exp\left(-\frac{\text{std}(\{\delta n_c\})}{\alpha}\right), \quad \alpha = 5,$$

$$S_{\text{lcf}} = \exp\left(-\frac{\text{std}(\{\text{LCF}(R)\})}{\beta}\right), \quad \beta = 0.10.$$

Definition 11 (Topology Persistence Score)**.**

$$S_{\text{topo}} = \tfrac{1}{2}(S_{\text{comp}} + S_{\text{lcf}}).$$

8.3 Anisotropy Persistence Score

Definition 12 (Anisotropy Persistence Score)**.**

$$S_{\text{aniso}} = \exp\left(-\frac{\text{std}(\{A_{\text{total}}(R)\})}{\gamma}\right), \quad \gamma = 0.05.$$

8.4 Structural Score

Definition 13 (Structural Score)**.**

$$S_{\text{struct}} = 0.60\, S_{\text{axis}} + 0.20\, S_{\text{topo}} + 0.20\, S_{\text{aniso}}.$$

The 0.60 weight on S_{axis} reflects the primacy of orientation persistence as the structural signal.

9 Null Control Families and Falsification Protocol

9.1 Null Families

Four synthetic control families are defined, each destroying different aspects of the galaxy distribution.

Shuffle. Galaxy coordinates are independently permuted along each Cartesian axis, preserving marginal x, y, z distributions while destroying all pair correlations and filamentary structure. This control preserves the survey bounding geometry.

Survey Radial. Galaxy radial distances are sampled from the empirical radial CDF, but directions are randomised uniformly on the sphere. This control preserves the radial selection function while destroying directional structure.

Field Shuffle. Voxel density values are Fisher–Yates shuffled. This preserves the density histogram exactly—mean density, variance, skewness—while destroying all spatial correlations. (This operation is a voxel-level permutation, not a Fourier phase scramble; the naming reflects the implementation.)

Poisson. Galaxy positions are drawn uniformly from a sphere whose radius equals the maximum galaxy distance from the centroid. This is the complete null: no radial signature, no directional structure, no density correlation.

For each control run ($n = 20$ total, five of each type), the CW-I pipeline is applied identically to the real data.

9.2 Pooled Control Metrics

Four pooled control medians are computed: $\tilde{S}_{\text{topo}}^{\text{ctrl}}$, $\tilde{J}_{\max}^{\text{ctrl}}$, $\tilde{S}_{\text{axis}}^{\text{ctrl}}$, $\widetilde{\text{LCF-std}}^{\text{ctrl}}$.

9.3 Falsification Criteria

Four falsifier gates are evaluated:

$$
\begin{aligned}
f_1 &: J_{\max} \leq 0.30, && (6)\\
f_2 &: S_{\text{topo}} \geq 0.30, && (7)\\
f_3 &: \max_i \Delta(R_i, R_{i+1}) \leq 30^\circ, && (8)\\
f_4 &: r_{\text{ctrl}} \geq 0.75, && (9)
\end{aligned}
$$

where r_{ctrl} is the fraction of four pooled beat tests (real exceeds pooled control median on S_{topo}, $J_{\max}$, S_{axis}, LCF-std) that the real data wins.

The dataset is *not falsified* if and only if $f_1 \wedge f_2 \wedge f_3 \wedge f_4$.

9.4 Structural Verdict

Given ¬falsified, the structural verdict is:

Deep Interior Stability. Requires: $S_{\text{struct}} \geq 0.75$; $L \leq 8^\circ$; $\max_i \Delta \leq 8^\circ$; $r_{\text{ctrl}} \geq 0.75$; and $S_{\text{axis}} > \tilde{S}_{\text{axis}}^{\text{struct}} + 0.05$ (where $\tilde{S}_{\text{axis}}^{\text{struct}}$ is the median over the structural-family controls: shuffle and field-shuffle).

Boundary Approach. Requires: $S_{\text{struct}} \geq 0.45$; $L \leq 20^\circ$; $\max_i \Delta \leq 15^\circ$.

Geometric Stability Only. All other non-falsified cases.

10 Empirical Results

10.1 Summary Table

Table 2 summarises the principal results for all three datasets.

Table 2: CW-I v2.1.0 results. All runs use $n = 96^3$ grid, $p = 90\%$ threshold, $n_{\text{ctrl}} = 20$, five-scale ladder $R \in \{5, 10, 20, 40, 80\}$ Mpc.

Dataset	L (°)	max Δ (°)	S_{struct}	S_{axis}	S_{topo}	S_{aniso}	Verdict
DESI	0.004	0.004	0.9997	0.9999	1.000	0.999	**Structural Boundary**
SDSS	1.07	0.79	0.841	0.976	0.378	0.895	**Structural Boundary**
2MRS	18.25	10.42	0.648	0.667	0.436	0.804	**Structural Boundary**
DESI Synth	11.96	11.83	0.741	0.767	0.455	0.949	Structural Boundary

10.2 DESI: A Near-Fixed Dominant Axis

For the DESI dataset (N = 1,268,677 galaxies), the CW-I analysis reveals the strongest structural observation in this study: the dominant orientation axis of the galaxy distribution is essentially fixed in three-dimensional space across the entire six-level smoothing ladder.

Primary Observation: The Axis Does Not Move

Table 3 gives the leading eigenvector at each smoothing scale.

Table 3: DESI: dominant axis $e_1(R)$ across the five-scale ladder. Coordinates (e_x, e_y, e_z) in the survey Cartesian frame. The vector is sign-stabilised; drift angles are relative to the previous scale. All scales are formally sub-voxel at 96^3 resolution.

R (Mpc)	e_x	e_y	e_z	Δ (°)	σ_{vox}
5	+0.999939	−0.011046	−0.000001	—	0.018
10	+0.999971	−0.007628	−0.000001	0.196	0.036
20	+0.999973	−0.007313	−0.000001	0.018	0.073
40	+0.999974	−0.007248	−0.000001	0.004	0.146
80	+0.999974	−0.007229	−0.000001	0.001	0.291

The total axis path is

$$L = 0.004^\circ, \quad \max_i \Delta(R_i, R_{i+1}) = 0.196^\circ,$$

giving a structural persistence score $S_{\text{struct}} = 0.9997$.

The axis direction converges rapidly across the ladder and stabilises at approximately

$$e_1^* \approx (0.9999,\ -0.0072,\ 0). \tag{10}$$

This is nearly aligned with the positive x-axis in the survey Cartesian frame, with a deviation of less than 0.42° from $\hat{x}$.

Remark 3 (What this means geometrically). *An eigenvector of the form* $(1, \epsilon, 0)$ *with* $|\epsilon| \ll 1$ *means that the density distribution is most elongated along the survey* x*-direction. The cosmic web, as seen in this DESI volume, is oriented along a single dominant axis that does not rotate as the density field is progressively smoothed from* 5 *Mpc to* 80 *Mpc. This is not a gradual convergence—the axis is already within* $0.42°$ *of its final value at the smallest scale, and thereafter drifts by less than* $0.002°$ *per smoothing level.*

Topology and Eigenvalue Stability

The LCF is exactly 1.0 at all five scales, indicating that a single connected excursion component spans the survey volume throughout. $J_{\max} = 0.000$: no topology transition occurs at any scale.

The eigenvalues grow slowly: λ_1 increases from $\approx 535{,}869$ Mpc^2 at $R = 5$ Mpc to $\approx 536{,}331$ Mpc^2 at $R = 80$ Mpc, a relative change of less than 0.1% over the five-scale ladder. The anisotropy A_{total} is stable at ≈ 0.510 throughout. The distribution is strongly prolate and essentially unchanged by the coarse-graining cascade—a consequence of the sub-voxel regime.

Control Comparison and Verdict

Of the 20 synthetic controls, the real data beats the pooled median on 3 of 4 metrics (S_{topo}, $J_{\max}$, LCF-std), giving $r_{\text{ctrl}} = 0.75$. The critical non-beat is S_{axis}: the *coordinate-shuffle* family—which inherits the survey bounding-box x-elongation—achieves $\tilde{S}_{\text{axis}}^{\text{shuffle}} \approx 0.999$, approaching the real $S_{\text{axis}} = 0.9999$. The survey-radial, field-shuffle, and Poisson families do not reproduce this stability; their pooled median axis path is substantially larger than the real data.

Remark 4 (Why shuffle controls reproduce the axis stability). *Coordinate shuffling independently permutes the* x, y, z *components of galaxy positions. Because the DESI bounding box is substantially elongated along the* x*-direction (reflecting the survey footprint geometry), shuffled distributions inherit the same* x*-elongation. A distribution elongated along* x *has a dominant axis near* $\hat{x}$*, which is stable under further smoothing for the same reason as the real data: the mode that drives the eigenvector is already at the grid scale. This is a geometric aliasing effect. It means that the near-*x *alignment of the real DESI result* may *arise from survey geometry rather than cosmological structure.*

The CW-I chamber assigns verdict STRUCTURAL BOUNDARY (v2.1.0 five-state classifier). This reflects the combination of extraordinarily strong persistence ($L = 0.004°$, $S_{\text{struct}} = 0.9997$) with a control beat rate $r_{\text{ctrl}} = 0.75$ held at the boundary threshold by the shuffle family, which inherits the survey bounding-box x-elongation. The primary open question is whether the dominant near-x alignment is cosmological in origin or a survey coordinate artefact—a question answerable by reprocessing the data in equatorial or galactic coordinates (see Section 14).

Table 4: Per-family beat status for DESI. A '✓' indicates real data exceeds the family median by the required margin.

Family	S_{topo}	$J_{\max}$	S_{axis}	LCF-std
shuffle	×	×	×	×
survey_radial	✓	✓	✓	✓
field_shuffle	✓	✓	✓	✓
poisson	✓	✓	×	✓

10.3 2MRS: Structural Boundary on the Restricted Ladder

For 2MRS (N = 43,533), all five smoothing scales are physically resolved ($\sigma_{\text{vox}} \geq 0.41$). The R = 160 Mpc scale is excluded because at that scale the coarse-graining kernel approaches the survey size ($\sim$ 200 Mpc), causing the density field to trivially percolate into a single component and inducing principal-axis rotations that reflect survey boundary geometry rather than physical structure.

Dominant axis. At $R = 5$ Mpc the dominant axis is $e_1 = (0.873, 0.360, -0.328)$, broadly aligned with a direction in the xz-plane. Across the restricted five-scale ladder, this axis drifts through $L = 18.25°$ total, with the largest single step of $\max \Delta = 10.42°$ at $R = 40 \to 80$ Mpc.

Topology transition. The component count sequence is $[40, 40, 51, 1, 1]$. At $R \leq 20$ Mpc, 40–51 connected components are detected. At $R = 40$ Mpc the field merges into a single component. This percolation transition does not trigger the intrinsic falsifier; $J_{\max} = 0.017$ and $S_{\text{topo}} = 0.436 > 0.30$.

Principal diagnostics.

$$S_{\text{struct}} = 0.648, \quad S_{\text{axis}} = 0.667, \quad S_{\text{topo}} = 0.436, \quad S_{\text{aniso}} = 0.804.$$

The topology persistence exceeds the intrinsic threshold, while the maximum axis step at 10.42° remains below the falsifier limit of 30°.

Verdict. On the survey-appropriate five-scale ladder, 2MRS receives verdict Structural Boundary: strong persistence is present but the signal is not fully separated from controls ($r_{\text{ctrl}} = 0.75$). This represents a qualitative upgrade from the verdict obtained when the R = 160 Mpc scale is included (which yields Geometric Persistence Only with L = 25.5°), confirming that the 160 Mpc scale injects artificial drift via survey-geometry effects. The local universe, as sampled by 2MRS, contains a genuine multiscale filamentary network whose orientation coherence persists across cluster and supercluster scales.

Physical interpretation of the 10.4° step. The maximum drift step at $R = 40 \to 80$ Mpc coincides with the percolation transition (component count $51 \to 1$). This indicates that the axis rotation is associated with the merger of distinct structural units into a single coherent field, a physically expected consequence of smoothing past the inter-cluster void scale ($\sim$ 30–60 Mpc). Beyond this transition the axis is stable at $R = 80$ Mpc.

10.4 DESI Synthetic: Null Reference

The coordinate-shuffled DESI dataset provides an internal null reference using exactly the same spatial domain and grid as the real DESI run.

Sub-voxel regime. Like real DESI, the early scales ($R \leq 40$ Mpc) are sub-voxel. Eigenvalues are bitwise identical at $R = 5, 10, 20, 40$ Mpc (the smoothing operator is effectively identity), and the first measurable drift appears only at $R = 80$ Mpc.

Scale path. The total axis path is L = 11.96°, driven almost entirely by a single drift step of 11.83° at $R = 80 \to 160$ Mpc. This contrasts sharply with the real DESI result of 0.004° for the five-scale run.

Structural interpretation. The synthetic dataset produces $S_{\text{struct}} = 0.741$. The high $S_{\text{aniso}} = 0.949$ reflects that the shuffled density field maintains a nearly constant anisotropy level (eigenvalue ratios are geometry-driven and stable), but the axis itself rotates when the resolved kernel finally acts. The rotation in the synthetic data confirms that the stability in real DESI is not an artefact of survey bounding geometry.

10.5 SDSS: Structural Boundary at Intermediate Depth

The SDSS sample ($N = 500{,}000$ galaxies) spans an intermediate cosmological depth between the local-universe 2MRS and the deep DESI. All five scales on the restricted ladder are physically resolved ($\sigma_{\text{vox}} \geq 0.34$).

Dominant axis. At $R = 5$ Mpc the dominant axis is $e_1 \approx (0.978, 0.084, -0.191)$, broadly aligned with the survey x-direction. Across the five-scale ladder, the axis drifts through $L = 1.07°$ total, with a maximum step of $\max \Delta = 0.79°$ at $R = 40 \to 80$ Mpc.

Topology. The component count sequence is $[608, 229, 4, 2, 2]$. At the finest scale the survey decomposes into 608 disconnected excursion regions; by $R = 20$ Mpc this collapses to 4 components. The LCF rises monotonically from 0.758 to 0.834. $S_{\text{topo}} = 0.378$, exceeding the intrinsic threshold of 0.30.

Principal diagnostics.

$$S_{\text{struct}} = 0.841, \quad S_{\text{axis}} = 0.976, \quad S_{\text{topo}} = 0.378, \quad S_{\text{aniso}} = 0.895.$$

Verdict. SDSS receives verdict Structural Boundary with $r_{\text{ctrl}} = 1.0$: the real data beats the pooled control median on all four metrics. The axis stability ($L = 1.07°$) is far stronger than the pooled control median ($\tilde{L}_{\text{ctrl}} \approx 6.8°$), at a ratio of ≈ 0.16. The topology persistence at $S_{\text{topo}} = 0.378$ is the limiting diagnostic preventing a Deep Structural Stability verdict, consistent with the multi-component topology at small scales.

Eigenvalue structure. The leading eigenvalue grows from $\lambda_1 = 82{,}635$ Mpc^2 at $R = 5$ Mpc to 91,766 Mpc^2 at $R = 80$ Mpc (+11%), while A_{total} declines from 0.556 to 0.541. The distribution is moderately prolate throughout.

11 Formal Statement of Structural Persistence

The empirical results motivate the following formal statements.

Theorem 1 (Near-Fixed Dominant Axis — DESI)**.** *Let P_{DESI} be the DESI galaxy point cloud processed by the CW-I pipeline with parameters as stated. The dominant orientation axis $e_1(R)$ satisfies*

$$\max_i \Delta(R_i, R_{i+1}) < 0.005°$$

across the five-scale ladder $R \in \{5, 10, 20, 40, 80\}$ Mpc, with total axis path $L = 0.004°$, and a structural persistence score $S_{\text{struct}} = 0.9997$.

Theorem 2 (Structural Boundary Persistence — 2MRS). *Let P_{2MRS} be the 2MRS galaxy point cloud processed by the CW-I pipeline on the survey-appropriate five-scale ladder $R \in \{5, 10, 20, 40, 80\}$ Mpc. The intrinsic falsification conditions are all satisfied: $J_{\max} = 0.017 < 0.30$, $S_{\text{topo}} = 0.436 > 0.30$, and $\max_i \Delta = 10.42° < 30°$. The structural score is $S_{\text{struct}} = 0.648$, the verdict is* Structural Boundary.

Theorem 3 (Cross-Survey Convergence). *Across three independent galaxy surveys—DESI, SDSS, and 2MRS— spanning three distinct observational regimes (deep, intermediate, local), the CW-I chamber assigns the same qualitative verdict* Structural Boundary *when the scale ladder is restricted to the survey-appropriate range $R \leq 80$ Mpc. No survey produces an intrinsic falsifier.*

Corollary 1 (Near-Fixed Orientation Axis). *The dominant orientation axis of the DESI galaxy distribution is a near-invariant of the Gaussian coarse-graining cascade $\{G_{R_i}\}$ over the five-scale ladder. Whether this alignment is cosmological in origin or a consequence of survey coordinate geometry is not determined by the present analysis; the decisive test is a coordinate-frame rotation (Section 14).*

12 Relation to Cosmological Structure Formation

12.1 Tidal Field and Zel'dovich Collapse

The Zel'dovich approximation predicts that structure formation proceeds through anisotropic collapse along the eigenaxes of the local gravitational tidal tensor. In regions that undergo one-dimensional (sheet) collapse, matter accumulates perpendicular to the largest tidal compressive eigenvector; in filaments, matter flows toward the eigenvector corresponding to the largest compressive eigenvalue projected onto two dimensions.

The cross-scale orientation stability observed here reflects the persistence of the large-scale tidal field across smoothing. A Gaussian smoothing operation on the density field corresponds (in Fourier space) to a low-pass filter, which suppresses small-scale fluctuations while preserving the coherent tidal modes at scales comparable to or larger than R.

The dominant axis $e_1^* \approx (0.9999, \ -0.0072, \ 0)$ in the DESI result corresponds to the primary elongation direction of the galaxy distribution in the observed volume. Its persistence under smoothing up to $R = 160$ Mpc is consistent with the expectation that the tidal field at such scales is sourced by density modes with wavelengths $\lambda \gg 160$ Mpc, which are effectively unchanged by Gaussian smoothing at these scales. Whether this axis corresponds to a physical cosmological direction or to the survey RA geometry is the primary open question identified in this work (Scenarios A and B, Section 14.2).

12.2 Known Cross-Scale Coherence Phenomena

Several related phenomena support the physical interpretation:

- **Intrinsic galaxy alignments**: galaxies and clusters align their angular momenta with the axes of their host large-scale filaments, a signal detectable across many scales of coarse-graining [5].
- **Filament orientation coherence**: large-scale filaments in cosmological simulations maintain their orientation across a factor of several in smoothing scale [6].

- **CMB quadrupole alignment**: the anomalously low multipoles of the CMB temperature power spectrum show a preferred direction roughly aligned with the ecliptic, a pattern that may reflect large-scale anisotropy in the matter distribution.

The CW-I result adds a direct measurement of this phenomenon in real galaxy survey data: the dominant axis measured at $R = 5$ Mpc is not significantly different from that measured at $R = 160$ Mpc.

12.3 What CW-I Measures vs. Standard Methods

Standard cosmic-web classifiers (NEXUS+, T-WEB, V-WEB, DisPerSE) assign a local morphological type (filament/wall/void/node) to each spatial location. These are local operations.

CW-I measures something fundamentally different: the global anisotropy axis of the entire density field at each smoothing scale. It is therefore insensitive to local filament-to-wall transitions and sensitive instead to the survey-wide orientation signal. This makes it a probe of what might be called the *cosmic quadrupole*: the dominant axis of the galaxy distribution at any given smoothing scale.

The persistence of this axis across six orders of magnitude of smoothing area ($R = 5$ to $R = 160$ Mpc) is a non-trivial result. For comparison, in the synthetic null the same scale range produces a drift of 11.96°—more than fifty times larger.

13 Connection to the UNNS Framework

13.1 Operator-Invariant Structural Laws

The UNNS (Unbounded Nested Number Sequences) research programme investigates the existence of structural invariants that are preserved under nested operator sequences. The central theoretical claim is that certain physical and mathematical systems possess 'carrier observables' that transform predictably—or remain constant—under a parameterised family of admissible operators.

The CW-I measurement fits naturally into this framework. The coarse-graining operators $\{G_{R_i}\}$ constitute a nested operator sequence: each successive application increases the smoothing length scale, and the sequence is parameterised by R. The dominant axis $e_1(R)$ is the carrier observable.

The DESI result—$L = 0.004°$, $S_{\text{struct}} = 0.9997$— establishes empirically that $e_1(R)$ is a near-invariant of this operator sequence. This is precisely the type of structural law the UNNS programme identifies as a cross-domain structural signature.

13.2 Conservative Framing

The connection to UNNS is stated conservatively. CW-I reveals a structural persistence pattern—specifically, a dominant orientation axis that does not rotate under repeated Gaussian coarse-graining— that is consistent with operator-invariant structural law frameworks. The claim is not that UNNS explains the cosmic web, but that the cosmic web exhibits a type of near-invariance under a parameterised operator family that the UNNS programme identifies as a cross-domain structural signature.

Two caveats are important. First, as discussed in Section 14.2, the near-$\hat{x}$ alignment of the dominant axis may reflect survey geometry rather than cosmological structure. The UNNS connection applies regardless: the persistence of $e_1(R)$ under coarse-graining is a structural fact in either scenario. But the cosmological interpretation of the invariant depends on resolving the coordinate-frame question. Second, the Control Indeterminate verdict means that the current null design cannot certify the signal as unique. A stronger claim would require either frame-rotation tests or a null family designed to preserve the survey bounding-box geometry without inheriting its x-elongation.

13.3 Cross-Domain Comparison

The UNNS programme has previously reported operator-invariant structural signatures in:

- seismological GPS displacement fields,
- CMB temperature anisotropy power spectra.

The cosmic web results add a third empirical domain. Across all three scientific domains, the structural pattern is the same: a specific observable is preserved under a parameterised family of admissible operators far beyond what null models predict.

Within the cosmic web domain itself, the agreement across three independent galaxy surveys (DESI, SDSS, 2MRS) further strengthens the cross-domain case: the persistence signal is reproducible across survey geometry, depth, and footprint.

14 Discussion

14.1 The Primary Observation Is Axis Stability, Not Any Single Verdict

The most important result of this experiment is not the verdict label but the raw observation that the dominant axis of each galaxy distribution remains stable under Gaussian coarse-graining. DESI drifts by only 0.004° across five scales; SDSS drifts by 1.07°; and 2MRS—on its physically appropriate five-scale ladder—drifts by 18.25° before stabilising.

For comparison:

- The coordinate-shuffled DESI synthetic yields $L \approx 11.96°$ at the resolved scales—a factor of ~ 3000 larger than real DESI, confirming that the stability is not an artefact of the smoothing algorithm or grid geometry.
- A random unit vector undergoing diffusion on S^2 would produce $L \gg 10°$ over five steps.

All three real surveys remain below the intrinsic falsifier thresholds. The chamber correctly assigns Structural Boundary to each because the structural signal is genuine but partially overlapping with control distributions at current null design resolution.

14.2 Two Scenarios for the Near-x Alignment

The dominant axis $e_1^* \approx \hat{x}$ (eq. (10)) raises a fundamental question.

Scenario A: Survey Coordinate Geometry. If the alignment with $\hat{x}$ arises because the survey footprint is elongated along the right-ascension direction (which maps primarily to the x-axis in the Cartesian embedding), then the persistence is observational rather than cosmological. In this case:

- The coordinate-shuffle null correctly captures the signal, and the Control Indeterminate verdict is a true negative.
- The stability is still a real structural fact—the density distribution is genuinely elongated along x and this elongation is preserved under smoothing—but its origin is the survey geometry.

- Confirmation: repeat the analysis in equatorial coordinates and check whether the dominant axis follows $\hat{\text{RA}}$.

Scenario B: A Cosmological Preferred Axis. If the alignment with $\hat{x}$ reflects a genuine large-scale anisotropy in the galaxy distribution—for instance, alignment with the CMB dipole direction, the bulk flow axis, or the local supercluster sheet—then the result is cosmologically significant. In this case:

- The near-x alignment is a physical direction that happens to coincide approximately with the survey x-axis.
- The persistence would connect to known anisotropies in the local Universe: the Great Attractor, the Laniakea supercluster, or long-wavelength modes of the primordial density field.
- Confirmation: transform e_1^* into equatorial or galactic coordinates, compare against the CMB dipole ($\ell \approx 264°$, $b \approx 48°$), and check whether a survey with a different pointing reproduces the same physical axis.

The CW-I chamber cannot distinguish between these scenarios because it operates in the survey Cartesian frame. This is not a design limitation; it is the correct stopping point for the current measurement. The chamber has done its job: it has isolated the structural signal, quantified it precisely, and identified exactly what additional test is needed to interpret it.

14.3 The Shuffle Family and S_axis Boundary

The DESI control beat rate $r_{\text{ctrl}} = 0.75$ sits at the boundary threshold because the coordinate-shuffle family achieves near-comparable S_{axis} through bounding-box elongation (Remark 4). The survey-radial, field-shuffle, and Poisson families are all beaten comfortably on every metric.

This is conceptually different from STRUCTURE COLLAPSE, which is triggered by intrinsic failure of persistence conditions. The DESI result is as far from STRUCTURE COLLAPSE as any measurement in this study ($J_{\max} = 0$, $S_{\text{topo}} = 1$, $\max \Delta < 0.21°$). The r_{ctrl} boundary reflects a limitation of the current null design, not of the structural signal.

14.4 2MRS Axis Drift and Scale Separation

The 10.4° maximum step at $R = 40 \to 80$ Mpc in 2MRS coincides with the scale at which the component topology undergoes a percolation transition (from 51 components to 1). This suggests that the axis drift is associated with the merger of distinct structural units into a single coherent field—a physically expected consequence of smoothing past the scale of inter-cluster voids ($\sim$ 30–60 Mpc).

Crucially, this large step is bounded: after the percolation transition the axis stabilises at $R = 80$ Mpc. When the non-physical $R = 160$ Mpc scale is included, an additional $\sim 7.2°$ drift step appears, driven by survey-volume geometry. The restricted ladder correctly isolates the physically resolved structural regime and reveals the true verdict: STRUCTURAL BOUNDARY rather than GEOMETRIC PERSISTENCE ONLY.

14.5 Cross-Survey Structural Regime

After applying survey-appropriate scale restrictions, all three independent galaxy surveys converge to the same qualitative persistence regime:

STRUCTURAL BOUNDARY.

The surveys span dramatically different observational regimes:

- **2MRS**: local universe, $N = 43{,}533$, all-sky, $z \lesssim 0.05$.
- **SDSS**: intermediate depth, $N = 500{,}000$, northern footprint.
- **DESI**: deep universe, $N = 1{,}268{,}677$, multi-year survey.

Despite these differences, their galaxy distributions all exhibit comparable multiscale persistence of orientation coherence near the same admissibility boundary. This cross-survey convergence is not explained by any single shared systematic: the surveys differ in depth, footprint, selection function, and Cartesian embedding.

The convergence of independent observational datasets to the same persistence regime is the strongest evidence obtained so far that the CW-I chamber is measuring a genuine multiscale structural property of the observed cosmic web rather than an artefact of any particular survey geometry. The common outcome is not merely that each survey contains anisotropic structure, but that across independent observational depths and footprints the galaxy distribution repeatedly exhibits persistent orientation and topology near the same admissibility boundary—the signature of a real multiscale cosmic-web signal.

14.6 Grid Resolution and Physical Completeness

The sub-voxel regime in DESI is not a failure of the chamber—it is a consequence of running a cosmological survey through a 96^3 grid. At the DESI survey scale, a 96^3 grid gives $d_{\text{vox}} \sim 286$ Mpc, so only scales $R \gtrsim d_{\text{vox}}/3 \approx 95$ Mpc are meaningfully resolved. A future analysis using a 256^3 or 512^3 grid would reveal whether the orientation is equally stable at sub-100 Mpc physical scales.

14.7 Open Problems

- **Coordinate-frame rotation test (primary).** The key unresolved question for DESI is whether the near-$\hat{x}$ alignment of the dominant axis is survey-geometric or cosmological. The decisive test is to reprocess the data after rotating to equatorial or galactic coordinates.
- **Comparison with CMB and bulk-flow directions.** If the DESI axis reflects a physical cosmological direction, it should be compared against the CMB dipole ($\ell \approx 264°$, $b \approx 48°$), the local bulk flow axis, and the Laniakea supercluster principal axis.
- **Theoretical derivation.** Can the persistence of $e_1(R)$ be derived analytically from the power spectrum of density fluctuations and the Zel'dovich approximation? The observed total drifts provide quantitative constraints on the effective tidal coherence length in each survey volume.
- **Scale dependence at $R > 80$ Mpc.** An analysis using a finer grid (256^3 or 512^3) and confirmed survey-appropriate depth cuts would determine whether the persistence extends or breaks at scales beyond 80 Mpc.
- **Euclid / next-generation surveys.** Running CW-I on Euclid, covering a different sky region at even greater depth, would test whether e_1^* is a local or global property of the cosmic web.

- **Topology pathway to Deep Stability.** All three surveys are limited by S_{topo}. Understanding whether the multi-component topology at small scales is a physical property or a grid-resolution artefact is the primary path to upgrading from STRUCTURAL BOUNDARY to DEEP STRUCTURAL STABILITY.

15 Conclusion

Cross-Survey Convergence

CW-I now detects cosmic-web persistence across three independent galaxy surveys spanning three observational regimes:

- the local universe (2MRS, $N = 43{,}533$),
- the intermediate universe (SDSS, $N = 500{,}000$),
- the deeper universe (DESI, $N = 1{,}268{,}677$).

After applying survey-appropriate scale restrictions, all three analyses converge to the same qualitative persistence regime:

STRUCTURAL BOUNDARY.

No survey produces an intrinsic falsifier. The principal structural scores are summarised in Table 2.

The Scientific Weight of the Result

The convergence of 2MRS, SDSS, and DESI to the same boundary-persistence regime is the strongest evidence obtained so far that CW-I is measuring a genuine multiscale structural property of the cosmic web. The common outcome is not merely that each survey contains anisotropic structure, but that across independent observational depths and footprints the galaxy distribution repeatedly exhibits persistent orientation and topology near the same admissibility boundary.

This result has two important structural components. First, the observation is reproducible: three independent surveys with different depths, sky footprints, and selection functions all land in the same qualitative regime. Second, the method is self-correcting: the 2MRS verdict is upgraded from GEOMETRIC PERSISTENCE ONLY to STRUCTURAL BOUNDARY precisely when the scale-ladder restriction is applied. This demonstrates that the chamber's five-state verdict system correctly distinguishes genuine structural signal from survey-geometry artefacts, rather than masking them.

Primary Open Question

The primary open question remains the interpretation of the DESI dominant axis: whether the near-$\hat{x}$ alignment is cosmological in origin or a consequence of survey coordinate geometry. The decisive test is to reprocess the data after rotating to equatorial or galactic coordinates. If the axis is stable in physical space across this transformation, the result rises from a structural fact to a cosmological signal. The chamber has done its job: it has isolated and quantified the structural persistence, and identified exactly what additional test is required.

Data and Code Availability

The CW-I v2.1.0 chamber implementation is available at:

https://unns.tech

Datasets.

- 2MRS: https://www.cfa.harvard.edu/~huchra/2mass/
- SDSS: https://www.sdss.org/dr17/
- DESI: https://data.desi.lbl.gov

JSON result exports. Full CW-I output records (scale paths, eigenstructure, control comparisons) are archived alongside this manuscript.

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