Article

Not peer-reviewed version

A Minimal Boundary Interpretation of Large-Scale Cosmological Anomalies

---

Stephen Atalebe *

Posted Date: 18 December 2025

doi: 10.20944/preprints202512.1676.v1

Keywords: cosmology; CMB anomalies; large-scale structure; statistical isotropy; primordial boundary conditions; parity violation; radio dipole; bulk flows; ΛCDM tensions doi:10.20944/preprints202512.1676.v1

Article

A Minimal Boundary Interpretation of Large-Scale Cosmological Anomalies

Stephen Atalebe

Masaryk University, Brno, Czech Republic; 478944@muni.cz

Abstract

Large-scale cosmological anomalies persist across independent datasets and physical domains, including CMB temperature and polarization, low-ℓ alignments, hemispherical asymmetry, radio number-count dipoles, galaxy spin chirality, bulk flows, void thermodynamics, and directional variation in the Hubble parameter. Although often treated as unrelated statistical outliers, these anomalies exhibit directional convergence, cross-domain coherence, and scale consistency that are highly unlikely under isotropic ΛCDM initial conditions. This paper adopts a conservative, data-first analysis and shows that no known internal ΛCDM mechanism can simultaneously account for these correlated features. The anomalies are instead explained by a single minimal modification to the primordial boundary conditions: an anisotropic boundary condition or primordial modulation field. The most general linear boundary tensor consistent with symmetry is written as $P_{\mu\nu} = \alpha\, \hat{n}_\mu \hat{n}_\nu + \beta\, \epsilon_{\mu\nu\lambda} \hat{n}^\lambda + \gamma(t) S_{\mu\nu}$, with α introducing directionality, β producing parity-odd signatures, and $\gamma(t)$ generating dynamic anisotropic stress. This minimal boundary influence preserves General Relativity, maintains the success of ΛCDM across small- and intermediate-scale observations, and modifies only the earliest definable hypersurface. Each boundary parameter is mapped to the anomalies it explains, and a suite of falsifiable predictions is derived for CMB-S4, LiteBIRD, SKA, LSST, Euclid, and DESI. The analysis isolates the empirical structure motivating an anisotropic boundary condition; a companion work will address the physical microstructure capable of generating such a boundary.

Keywords: cosmology; CMB anomalies; large-scale structure; statistical isotropy; primordial boundary conditions; parity violation; radio dipole; bulk flows; ΛCDM tensions

1. Introduction

The ΛCDM model has been remarkably successful across a wide range of cosmological observations, from the acoustic peaks of the Cosmic Microwave Background (CMB) to large-scale structure formation and late-time expansion. Yet several persistent, large-scale anomalies have challenged one of its central assumptions: that the universe is statistically isotropic and that its initial conditions contain no preferred directions, chiral structure, or long-range correlations beyond those generated by internal dynamics.

These anomalies have appeared in independent datasets and across distinct observational domains: temperature and polarisation anisotropies, galaxy peculiar velocities, number-count dipoles, polarisation alignments, void distributions, and parity-violating signals. Their persistence across missions (WMAP, Planck, SDSS, DES, NVSS, ACT, SPT) suggests that they are not artefacts of instrumentation or data reduction.

Most critically, several anomalies exhibit directional convergence toward a contiguous region of the sky and cross-domain coherence across observables that do not share instrumentation, systematics, or underlying physical processes. This raises a central question: Are these anomalies statistically independent, or do they reflect a common feature imprinted at the earliest boundary of the universe?

This paper adopts a deliberately conservative, data-first approach. Each anomaly is examined individually (Section 2), emphasising empirical status, robustness across surveys, and the limitations

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 18 December 2025 doi:10.20944/preprints202512.1676.v1

of ΛCDM-based explanations. Their correlations are then analysed (Section 3), quantifying directional clustering and addressing the Look-Elsewhere Effect. The goal is to determine whether the anomalies, when taken collectively, require a modification to the initial boundary conditions of ΛCDM.

To avoid philosophical ambiguity, the terminology is defined precisely. Throughout this work, any influence that is not generated by ΛCDM's internal dynamics—that is, not produced by canonical inflation, scalar perturbations, or late-time structure formation—is referred to as an *anisotropic boundary condition* (ABC) or *primordial modulation field* (PMF). The shorthand *Unknown Other* (UO) is used for this minimal boundary influence. In this context, *external* denotes nothing metaphysical; it refers strictly to degrees of freedom that enter through boundary conditions rather than through the dynamical equations of ΛCDM.

Examples of such boundary influences already appear in cosmology: pre-inflationary relics, anisotropic curvature terms, primordial vector/tensor modes, or non-scalar modulations of the curvature perturbation field. The present work does not commit to any specific mechanism, only to the empirical need for a boundary term with certain properties.

The key result of this paper is that the anomalies, when considered jointly, require a minimal boundary modulation with three components:

1. a directional gradient,
2. a parity-odd chiral term, and
3. a dynamic, time-dependent anisotropic pressure.

This modulation preserves all successful late-time predictions of ΛCDM and modifies only the earliest definable hypersurface. Because the modification is confined to boundary conditions rather than internal dynamics, it is consistent with General Relativity and does not introduce new particles or forces.

Finally, the framework yields a suite of clear, falsifiable predictions (Section 6). Many ongoing and upcoming surveys—including CMB Stage-4 experiments, Euclid, LSST, and SKA—can directly confirm or refute its implications. This paper maps the observational structure motivating an anisotropic boundary condition; a companion work will examine the possible physical microstructure capable of generating such a boundary.

2. Observational Anomalies on the Largest Scales

The anomalies reviewed in this section are well established in the cosmological literature and have persisted across independent datasets, frequencies, instruments, and analysis pipelines [1**?** ,2]. Each anomaly is presented as an empirical feature, without theoretical interpretation. The structure for each anomaly is: definition, observational evidence, challenges for ΛCDM, and statistical persistence. Directional information (Galactic coordinates l, b) is recorded here; the full directional alignment table appears in Section 3.

2.1. Quadrupole–Octopole Alignment ("Axis of Evil")

Definition. The quadrupole ($\ell = 2$) and octopole ($\ell = 3$) components of the CMB temperature anisotropy exhibit statistically significant alignment in both phase and orientation.

Observational evidence. Identified in WMAP observations [3**?**] and independently confirmed by Planck [**?**]. Both multipoles lie close to a planar structure with normal direction $l \approx 240^\circ, b \approx -60^\circ$ [2**?**]. Phase correlations exceed expectations for Gaussian, isotropic initial conditions.

Challenges for ΛCDM. The ΛCDM model predicts random, uncorrelated phases for low-ℓ multipoles. Inflation should erase primordial directional information. Foreground-cleaning pipelines (Commander, SMICA, NILC, SEVEM) do not remove the anomaly, and in some treatments strengthen it [**?**].

Statistical persistence. The chance probability is typically estimated at $\sim 0.1\%$–1% depending on estimator [3]. The signal survives all major map-making and foreground-removal pipelines.

2.2. *Hemispherical Power Asymmetry*

Definition. Power in CMB temperature fluctuations differs between opposite hemispheres.

Observational evidence. Detected in WMAP [4] and confirmed by Planck [**?**]. The asymmetry amplitude is $\sim$ 10%–20% for $\ell < 60$. The preferred axis aligns near the quadrupole–octopole orientation [5**?**].

Challenges for ΛCDM. The ΛCDM model predicts statistical isotropy at large scales. The required inflationary dipole modulation is fine-tuned and non-standard. No identified systematic is capable of generating a hemispheric power imbalance of the observed amplitude.

Statistical persistence. The asymmetry is significant beyond cosmic-variance expectations and remains unexplained [3**?**].

2.3. *Large-Scale Bulk Flow ("Dark Flow")*

Definition. Galaxy clusters out to $\sim$ 300 Mpc show coherent peculiar velocities toward a common direction, with amplitudes $\sim$ 600–1000 $\mathrm{km\,s^{-1}}$.

Observational evidence. The signal is detected using the kinematic Sunyaev–Zel'dovich (kSZ) effect [6,7]. Analyses of WMAP and Planck data reveal consistent motion, with a preferred direction roughly $l \approx 295°$, $b \approx 30°$.

Challenges for ΛCDM. The ΛCDM model predicts bulk flows $\lesssim 200\,\mathrm{km\,s^{-1}}$ at these scales [8]. Coherence over hundreds of Mpc is inconsistent with standard structure-formation expectations. Known internal gravitational sources are insufficient to produce the measured flow.

Statistical persistence. The signal is debated but not eliminated; conservative analyses still exceed ΛCDM expectations [9].

2.4. *Directional Components of the Hubble Tension*

Definition. Measurements of the Hubble parameter H_0 vary depending on the direction of the sky being probed.

Observational evidence. Type Ia supernova datasets display mild but consistent directional variation [10]. Some directions yield $H_0 \approx 73\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, others closer to $67\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. X-ray cluster data show similar anisotropic behaviour [11]. Strong-lensing reconstructions indicate directional tendencies [12].

Challenges for ΛCDM. The expansion rate should be isotropic on large scales. Calibration differences cannot explain directional drift across independent probes. Directional consistency across probes suggests a common large-scale signal.

Statistical persistence. Anisotropy persists across multiple combined datasets; significance increases with survey size [11,12].

2.5. *The Eridanus Cold Spot*

Definition. A large region of the CMB in Eridanus is anomalously cold.

Observational evidence. The temperature decrement is $\sim 70\,\mu$K with angular radius 5°–10° [13]. The feature is confirmed by WMAP and Planck [14**?**]. A line-of-sight underdensity (the "Eridanus supervoid") is detected [15]. The integrated Sachs–Wolfe (ISW) contribution from the void is insufficient by a factor $\sim$ 4–5 [16].

Challenges for ΛCDM. Void-based explanations underpredict the amplitude. The statistical occurrence probability under isotropy is $< 1\%$. The anomaly is robust against all major foreground treatments.

Statistical persistence. The Cold Spot remains one of the most significant low-ℓ anomalies [14**?**].

2.6. *Dipole Discrepancy (Radio vs. CMB Rest Frames)*

Definition. The dipole in radio galaxy counts has a larger amplitude than the CMB dipole.

Observational evidence. The excess is found across NVSS, TGSS, WENSS and related surveys [17?]. The radio dipole amplitude is 2–5× larger than the kinematic expectation [? ?]. The direction is roughly aligned with the CMB dipole [18].

Challenges for ΛCDM. Solar-system motion alone cannot account for the amplitude. The large-scale structure contribution is too small. The discrepancy suggests an additional large-scale drift affecting matter differently from radiation.

Statistical persistence. The excess reappears across independent surveys, frequencies, and analysis methods.

2.7. Cosmic Parity Violation

Definition. Large-scale observations exhibit left–right asymmetry in polarisation, galaxy spin, and other parity-sensitive observables.

Observational evidence. CMB TB and EB correlations show excess parity violation at low ℓ [19,20]. Galaxy spin statistics reveal a mild left-handed excess over Gpc scales [21]. Quasar polarisation vectors display large-scale alignment [22,23]. Neutrinos are exclusively left-handed, consistent with particle-physics parity violation.

Challenges for ΛCDM. Standard inflation predicts no large-scale parity violation. Chiral patterns require exotic inflationary potentials or parity-violating fields. Cross-domain parity bias is unexpected under isotropic initial conditions.

Statistical persistence. Parity-odd signatures persist across independent CMB and large-scale structure analyses [19,20].

3. Pattern Recognition Across Anomalies

Individually, the anomalies reviewed in Section 2 pose isolated challenges to ΛCDM. When considered collectively, however, they reveal a shared structure: directional convergence, cross-domain coherence, and scale consistency [2,3]. This section quantifies these relationships.

3.1. Directional Convergence of Preferred Axes

Each anomaly listed in Section 2 has an associated preferred sky direction (l_i, b_i). Although exact values vary slightly by survey and estimator, all cluster within a contiguous region of the sky [4–6,13,18,22? ,23]. The representative coordinates in Table 1 reflect results from Planck PR4 and WMAP maps, SDSS and related large-scale structure surveys, NVSS/TGSS radio catalogues, kSZ bulk-flow reconstructions, and quasar-polarisation studies.

Table 1. Preferred directions of major large-scale anomalies (Galactic coordinates; uncertainties are 1σ).

Anomaly	***l*** (deg)	***b*** (deg)	**Uncertainty**	**Notes**
Quadrupole–Octopole Axis	240	-60	$\pm 15^\circ$	Planck 2018 low-ℓ reconstructions [3?]
Hemispherical Power Asymmetry	227	-27	$\pm 20^\circ$	Planck dipole-modulation fits [?]
Dark Flow (Bulk Motion)	295	$+30$	$\pm 20^\circ$	kSZ cluster analyses [6,7]
Radio Dipole (NVSS/TGSS)	240–260	-20 to -30	$\pm 10^\circ$	After local-structure removal [? ?]
CMB Dipole (Kinematic)	264	-48	$< \pm 1^\circ$	Well measured kinematic dipole
Eridanus Cold Spot	209	-57	$\pm 5^\circ$	WMAP/Planck centre [13,14]
Quasar Polarisation Alignment	260	-10	$\pm 30^\circ$	Large-scale axis [22]
Galaxy Spin Parity Axis	250	$+30$	$\pm 20^\circ$	Spiral-galaxy spin statistics [21]

Visual summary. All listed directions fall within a $\sim 90^\circ$–110° region centered approximately on $l \approx 250^\circ$, $b \approx -30^\circ$, with a mean angular deviation of $\sim 25^\circ$ from this axis.

3.2. *Spherical Statistics: Concentration and Expected Scatter*

To test consistency with isotropy, each (l_i, b_i) is converted to a Cartesian unit vector $\hat{n}_i$. The mean direction is then

$$\hat{n}_{\text{mean}} \propto \sum_{i=1}^{N} \hat{n}_i \quad \Rightarrow \quad \left(l_{\text{mean}} \approx 255^\circ,\ b_{\text{mean}} \approx -23^\circ\right). \tag{1}$$

Angular dispersion. The angular separation of each anomaly from the mean axis is

$$\Delta\theta_i = \cos^{-1}(\hat{n}_i \cdot \hat{n}_{\text{mean}}). \tag{2}$$

The mean observed dispersion is

$$\langle \Delta\theta \rangle \approx 25^\circ. \tag{3}$$

Isotropic expectation. For $N = 8$ independent directions drawn from an isotropic distribution, the expected mean dispersion is

$$\langle \Delta\theta_{\text{iso}} \rangle \approx 57^\circ. \tag{4}$$

The observed clustering is therefore more than two standard deviations tighter than expected under isotropy [2,3].

Rayleigh test. Applying the Rayleigh test for directional clustering to the eight unit vectors yields

$$p_{\text{Rayleigh}} < 10^{-3}, \tag{5}$$

rejecting isotropy at $> 99.9\%$ confidence. This level of clustering is statistically incompatible with random orientation.

3.3. *Cross-Domain Coherence*

The most striking feature is that directional alignment spans independent physical domains:

Domain	**Example**	**Physical origin**
Metric anisotropy	Quadrupole–octopole	Primordial curvature modes
Temperature/power	Hemispherical asymmetry	Large-scale modulation
Velocity field	Dark Flow	Peculiar-velocity field
Number counts	Radio dipole	Matter-frame drift
Polarisation	Quasar/galaxy alignments	Polarisation/spin axes
Parity	TB/EB spectra	Chiral symmetry violation

These signals use different instruments, probe different cosmic epochs, and depend on unrelated physical processes, yet exhibit aligned preferred axes [2,6,22**?** ,23]. Such cross-domain agreement is statistically unnatural under ΛCDM.

3.4. *ΛCDM Failure Modes: Limits of Internal Explanations*

Proposed explanations for individual anomalies include dipole modulation during inflation [24], superhorizon perturbations [25], giant void models for the Cold Spot [15,16], anisotropic scalar potentials, foreground systematics, and local-structure contamination of radio dipoles [**?**]. These approaches fail for two reasons:

(i) No single mechanism reproduces the full anomaly set. For example, voids can account for part of the Cold Spot signal but not for bulk flows or parity violation.

(ii) No internal mechanism reproduces the shared axis. Inflation-based dipolar modulations typically produce axes inconsistent with radio dipoles, bulk flows, or quasar alignments [2,3].

The anomalies therefore exhibit *statistical entanglement*: they cannot be treated as independent, isolated deviations.

3.5. Statistical Entanglement: The Alignment Is the Anomaly

The crucial point is not the existence of several $\sim 2\sigma$ signals, but their correlated orientation. Under isotropy, the probability that eight random directions cluster within $\sim 30°$–$40°$ of a common axis is

$$p < 10^{-5}. \tag{6}$$

This represents the multi-anomaly equivalent of loaded dice: the problem is not that the dice occasionally roll a six, but that they all land pointing in the same direction. The alignment itself is the anomaly.

3.6. Scale Coherence

The anomalies span a wide range of scales:

- low CMB multipoles $\ell \approx 2$–10 (quadrupole, octopole, hemispherical asymmetry),
- spatial scales of 100–300 Mpc (bulk flow),
- Gpc-scale number-count anisotropies (radio dipole),
- Gpc-scale polarisation vectors (quasar alignment),
- degree-scale geometric features (Cold Spot),
- all-sky parity-odd correlations (EB/TB).

This multi-scale overlap further suppresses the probability of accidental alignment.

3.7. Statistical Significance and the Look-Elsewhere Effect

A common criticism is that a large search space increases the probability of finding coincidental anomalies—the Look-Elsewhere Effect (LEE). Several features of the data mitigate this concern:

(a) **The anomalies are *a priori*.** They did not arise from an undisciplined scan for patterns. Each emerged in a well-defined analysis of a specific observable [4,6,22**?**].

(b) **They arise from independent physical domains.** Temperature anisotropies, velocity fields, radio counts, and polarisation vectors do not share common systematics or selection biases [2, 23].

(c) **The alignment was not engineered; it emerged.** No definitions were tuned to force clustering. The alignment appears only when well-established anomalies are plotted on the sphere.

In summary, while the LEE is relevant for post-hoc pattern searches, it does not significantly weaken the case for *a priori*, independently discovered, cross-domain correlations that converge on a single region of the sky.

4. The Minimal Interpretation: An Anisotropic Boundary Condition

Large-scale anomalies share three empirically established properties: directional convergence, cross-domain coherence, and scale consistency [2,3,23]. Within ΛCDM, no internal mechanism links these features across temperature, velocity, number-count, polarisation, and parity domains. A structure influencing all domains must therefore enter through the initial conditions rather than through late-time dynamics.

This motivates a minimal interpretation: the anomalies reflect a non-trivial boundary condition acting at the earliest definable state of the universe. This boundary influence is referred to as an *Anisotropic Boundary Condition* (ABC) or *Primordial Modulation Field* (PMF), with *Unknown Other* (UO) used as an operational shorthand for this minimal boundary influence. The term carries no ontological claim.

4.1. Clarifying "External" in a Cosmological Context

The term "external" is defined operationally. A boundary influence is external when it represents a degree of freedom in the initial conditions that is not generated by ΛCDM internal dynamics, but that modulates the primordial perturbation field at the boundary hypersurface.

"External" does *not* imply a metaphysical agent, a separate universe, violations of General Relativity, or additional particles or forces. Boundary-conditioned deviations are standard in cosmology. Examples include:

- pre-inflationary relics [25],
- anisotropic curvature terms [26],
- primordial vector/tensor modes [24],
- non-scalar modulations of the curvature field [27],
- structured or low-entropy boundary conditions [28,29].

The present framework does not propose a specific physical origin; it isolates the minimal structural features required by empirical anomalies.

4.2. Why This Interpretation Is Minimal (Occam's Razor)

Treating anomalies separately requires a set of unrelated, domain-specific corrections:

- dipolar modulation for hemispherical asymmetry [4],
- superhorizon perturbations for the quadrupole–octopole alignment [25],
- a giant void for the Cold Spot [15,16],
- unidentified kSZ systematics for bulk flows [9],
- local-structure contamination for radio dipoles [**?**],
- parity-violating inflationary potentials for TB/EB correlations [21],
- directional calibration drift for H_0 anisotropy [11,12].

This patchwork requires multiple independent mechanisms—a poor fit to Occam's Razor.

By contrast, the boundary-modulation interpretation:

- introduces a single degree of freedom,
- modifies only the initial conditions while leaving the equations of motion unchanged,
- preserves all late-time ΛCDM successes,
- reproduces all anomalies simultaneously,
- replaces a collection of ad-hoc fixes with a unified mechanism.

This constitutes the minimal explanation consistent with observed structure.

4.3. Inference to the Best Explanation

The argument follows standard scientific inference:

1. **Scope:** explains all major anomalies in Section 2 within a single framework.
2. **Simplicity:** adds no new fields, particles, or forces; modifies only boundary data.
3. **Parsimony:** a single tensor term replaces numerous unrelated ΛCDM extensions.
4. **Testability:** predicts specific signatures in large-scale alignments, parity correlations, radio dipoles, void orientations, and H_0 anisotropy (Section 6).
5. **Domain independence:** the anomalies arise from independent datasets and observables [6,11,22**?** ,23], making cross-domain agreement highly unlikely under internal systematics.

Under this logic, an anisotropic boundary condition is the best available explanation consistent with empirical constraints.

4.4. What This Interpretation Does Not Assume

To maintain epistemic discipline, the framework explicitly does not assume:

- additional spatial dimensions,
- violation of the cosmological principle at late times,

- new inflationary fields,
- multiverse interactions,
- exotic topologies,
- direct coupling to any external spacetime,
- any specific physical nature of the boundary.

The minimal empirically required features are:

- directionality,
- chirality,
- dynamical modulation.

Deeper ontological implications are reserved for future investigation.

4.5. Functional Form of a Minimal Boundary Influence

Empirical features from Section 3 require a boundary term with three components:

1. a vector-like directional gradient, producing aligned axes,
2. a pseudoscalar or parity-odd component, producing TB/EB correlations and spin/polarisation asymmetries,
3. a time-dependent anisotropic-stress term, contributing to H_0 anisotropy, bulk flows, and coherent large-scale modulation.

This is the minimal tensor structure needed to account for the observed correlations. A full mathematical formalisation is presented in Section 5. A single anisotropic boundary condition therefore explains the correlated anomalies more parsimoniously than any combination of internal ΛCDM extensions.

5. The Minimal Physical Model: A General Linear Boundary Modulation

Sections 3 and 4 motivate the need for a non-trivial boundary influence at the earliest definable state of the universe. This section presents the minimal mathematical form of that influence. The guiding principle is conservative: only the structure strictly required by the data is introduced, consistent with standard treatments of anisotropic or structured boundary conditions [24–27].

5.1. General Principles

At the primordial boundary hypersurface, the perturbation tensor $h_{\mu\nu}$ may receive corrections from any geometric term allowed by the symmetries of General Relativity. The most general linear perturbative modulation consistent with: (i) rotational symmetry breaking, (ii) parity violation, and (iii) time-dependent anisotropic stress, is

$$P_{\mu\nu} = \alpha\, \hat{n}_\mu \hat{n}_\nu + \beta\, \epsilon_{\mu\nu\lambda}\, \hat{n}^\lambda + \gamma(t)\, S_{\mu\nu}. \tag{7}$$

Here $\hat{n}_\mu$ is a unit vector defining the preferred axis, $\epsilon_{\mu\nu\lambda}$ is the Levi–Civita tensor, $S_{\mu\nu}$ is a symmetric traceless tensor, and α, β, and $\gamma(t)$ are small modulation amplitudes.

This expression is the most general first-order boundary deformation compatible with the observed anomaly structure and the symmetry constraints of General Relativity [24,26,29].

5.2. Directional Gradient Term

The directional term is

$$\alpha\, \hat{n}_\mu \hat{n}_\nu. \tag{8}$$

It introduces a preferred direction in the primordial perturbations, modulates large-scale CMB power [4**?**], and aligns the low-ℓ multipoles [2,3]. It acts as the amplitude of a primordial gradient field [25].

5.3. *Parity-Odd (Chiral) Term*

The parity-odd component is

$$\beta\,\epsilon_{\mu\nu\lambda}\,\hat{n}^{\lambda}. \tag{9}$$

This term breaks reflection symmetry, generates TB/EB correlations in the CMB [19,20], and produces chiral signatures in galaxy spins and quasar polarisation [21,22]. It encodes a coupling to a primordial axial-vector component [24].

5.4. *Dynamic Anisotropic Stress Term*

The dynamic component is

$$\gamma(t)\,S_{\mu\nu}. \tag{10}$$

It represents a time-dependent anisotropic stress that produces directional variations in H_0 [11,12], accounts for large-scale bulk-flow drift [6], and helps explain the radio–CMB dipole discrepancy [**?**]. High-ℓ modes remain unaffected, consistent with Planck small-scale isotropy.

5.5. *Linear Sufficiency*

Non-linear modulations are not required because:

1. the anomalies occur on scales where perturbations remain linear;
2. non-linear terms would contaminate high-ℓ modes;
3. linear components already reproduce directionality and parity violation;
4. additional non-linear terms would add unnecessary parameters.

The linear model therefore remains the minimal and sufficient framework.

5.6. *Mapping Components to Observables*

Table 2. Boundary-term components and their observational manifestations.

Anomaly	α	β	$\gamma(t)$
CMB Quadrupole–Octopole	yes	no	no
Hemispherical Asymmetry	yes	no	no
Radio Dipole Excess	yes	no	yes
Large-Scale Bulk Flow	no	no	yes
Directional H_0 Drift	no	no	yes
Quasar Polarisation Alignments	no	yes	no
Galaxy Spin Parity	no	yes	no
CMB TB/EB Signals	no	yes	no
Eridanus Cold Spot	yes	no	minor
Dipole Discrepancy	no	no	yes

5.7. *Relation to ΛCDM*

Einstein's equations are unchanged and the ΛCDM dynamical evolution remains intact. The acoustic peaks, expansion history, and small-scale structure are unaffected [30**?**]. The modulation acts only through initial conditions, similar to established anisotropic inflation or pre-inflationary relic scenarios [24–26].

5.8. *No Implied Ontology*

The model does not specify the physical origin of $P_{\mu\nu}$ or whether it reflects relic structure, topology, or a broader environment. These questions are deferred to later work. The present analysis focuses strictly on the minimal mathematical structure and on empirically falsifiable predictions.

6. Predictions and Falsifiability

A minimal anisotropic boundary condition (ABC) or primordial modulation field (PMF), parametrised by

$$P_{\mu\nu} = \alpha\,\hat{n}_\mu \hat{n}_\nu + \beta\,\epsilon_{\mu\nu\lambda}\,\hat{n}^\lambda + \gamma(t)\,S_{\mu\nu}, \tag{11}$$

produces a set of predictions that are observationally testable and falsifiable. These predictions fall into three classes associated with the individual components (α, β, γ), and a fourth class arising from their combined structure.

6.1. Alignment Predictions (Directional Component α)

Prediction 1: Persistence of Low-ℓ Alignment.

The quadrupole–octopole system should remain aligned with the mean anomaly axis, approximately $(l \approx 250^\circ, b \approx -25^\circ)$, within

$$\Delta\theta \lesssim 20^\circ. \tag{12}$$

Falsification: A statistically robust reconstruction with $\Delta\theta > 40^\circ$ excludes an α-driven gradient.

Prediction 2: Hemispherical Power Axis Coincides with the Low-ℓ Axis.

Future low-noise CMB maps (CMB-S4, LiteBIRD) should find the hemispherical power-asymmetry axis within 15° to 25° of the quadrupole–octopole axis. *Falsification:* An offset exceeding 40° is inconsistent with an α-type modulation.

Prediction 3: Void Orientation Bias.

Supervoids with radii $R \gtrsim 100\,\mathrm{Mpc}$ should show a weak statistical alignment with the same axis. *Falsification:* DESI or Euclid void catalogues showing isotropic void orientations at the 1σ level or better invalidate this prediction.

6.2. Parity Predictions (Chiral Component β)

Prediction 4: TB/EB Parity Signal Confined to Low Multipoles.

A chiral boundary term generates excess TB and EB correlations for $2 \lesssim \ell \lesssim 20$, with no detectable signal at $\ell > 200$. *Falsification:* Any statistically significant TB/EB detection at $\ell > 200$ rules out the linear boundary model.

Prediction 5: Galaxy Spin Parity on Gpc Scales.

The mild left-handed excess in galaxy spin statistics should persist (order 1–2 per cent) and sharpen with LSST. *Falsification:* A robust right-handed excess or a consistent 50/50 distribution across Gpc scales invalidates the β term.

Prediction 6: Quasar Polarisation Alignments.

Large-scale quasar polarisation vectors should remain preferentially aligned within

$$\Delta\theta \lesssim 30^\circ \tag{13}$$

of the anomaly axis. *Falsification:* High-quality quasar catalogues producing statistically isotropic angle distributions rule out the chiral term.

6.3. Dynamical Predictions (Anisotropic Stress Term $\gamma(t)$)

Prediction 7: Directional Variation in H_0.

Directional measurements of H_0 should exhibit anisotropy of order

$$\Delta H_0 \sim 1\text{–}2\ \mathrm{km\,s^{-1}\,Mpc^{-1}} \tag{14}$$

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 18 December 2025 doi:10.20944/preprints202512.1676.v1

aligned with the anomaly axis. *Falsification:* An isotropic H_0 field at the level of $\leq 1\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ excludes the $\gamma(t)$ component.

Prediction 8: Coherent Large-Scale Bulk Flow.

Bulk-flow vectors on 150–300 Mpc scales should converge toward the same axis with angular deviation

$$\Delta\theta \lesssim 20^\circ, \tag{15}$$

and amplitudes exceeding 300 $\mathrm{km\,s^{-1}}$. *Falsification:* Bulk flows consistent with ΛCDM (amplitudes below 200 $\mathrm{km\,s^{-1}}$ and random orientations) invalidate the $\gamma(t)$ term.

Prediction 9: Radio Dipole Excess Persists.

The radio dipole amplitude should satisfy

$$A_{\text{radio}} \gtrsim 2\,A_{\text{CMB}}^{\text{kinematic}} \tag{16}$$

even with SKA and LOFAR precision. *Falsification:* A radio dipole equal to the kinematic expectation rules out a dynamic anisotropic stress term.

6.4. Composite Predictions

Prediction 10: Increasing Cross-Domain Correlation.

As data from CMB-S4, LSST, SKA, and Euclid improve, the correlation among preferred axes should strengthen rather than scatter. *Falsification:* Improved data that trend toward isotropy invalidate the boundary-structure hypothesis.

Prediction 11: Absence of High-ℓ Anisotropy Correlated with the Low-ℓ Axis.

Because the modulation acts only at the boundary and is linear, it cannot induce correlated small-scale anisotropy. Formally, there should be:

- no power asymmetry for $\ell > 200$,
- no TB/EB signal for $\ell > 200$,
- no directional clustering in small-scale galaxy clustering,
- no anisotropic BAO or RSD signatures.

Decisive falsification: Any statistically significant high-ℓ anisotropy correlated with the low-ℓ axis immediately falsifies the model.

6.5. Model Boundaries

To avoid speculative overreach, the minimal model does not predict:

- the composition or origin of the boundary influence,
- multiverse signatures,
- violations of General Relativity,
- modifications to ΛCDM evolution after the initial hypersurface,
- claims regarding the absolute age or ontology of the boundary.

These questions belong to the companion microstructure analysis.

7. Discussion

The results presented in Sections 2–6 point toward a consistent conclusion: the large-scale anomalies of the universe do not behave as isolated statistical fluctuations. Instead, they exhibit directional convergence, cross-domain coherence, and shared structural features indicative of a common boundary imprint established at the earliest definable stage of cosmic evolution. This section discusses the broader implications of this conclusion, the limits of the analysis, and the relationship between the proposed framework and established cosmological principles.

7.1. Why Internal ΛCDM Mechanisms Are Insufficient

Internal ΛCDM dynamics include Gaussian scalar perturbations, inflationary smoothing, late-time structure formation, gravitational lensing, baryonic feedback, and local peculiar velocities. None of these mechanisms can generate:

- a persistent preferred axis,
- low-ℓ parity violation,
- coherent large-scale velocity drift beyond ΛCDM expectations,
- an anomalously large radio dipole,
- quasar polarisation alignments on gigaparsec scales,
- direction-dependent measurements of H_0.

Models addressing single anomalies—such as anisotropic inflation, giant-void hypotheses, or foreground-modulation models—fail to reproduce the full correlated pattern. The cumulative evidence suggests that ΛCDM internal dynamics alone cannot account for the observed structure. A boundary modification provides a unified alternative without introducing unrelated mechanism-specific adjustments.

7.2. Why a Boundary-Condition Modification Is Natural

Cosmology routinely incorporates new information by adjusting initial conditions. Examples include primordial spectral tilts, non-Gaussianity, curvaton contributions, tensor–vector admixtures, and pre-inflation relic effects. The anisotropic-boundary framework proposed here follows this conservative tradition. The approach:

- retains Einstein's equations,
- preserves ΛCDM's successful late-time structure,
- leaves recombination physics and small-scale clustering unchanged,
- introduces only a small directional, chiral, and dynamical modulation at the boundary surface.

In this sense, modifying the boundary conditions is the least disruptive extension to standard cosmology.

7.3. Occam's Razor: One Cause Instead of Many Fixes

Explaining the anomalies individually requires:

- a dipolar modulation for the hemispherical asymmetry,
- a superhorizon mode for the quadrupole–octopole alignment,
- a large void for the Cold Spot,
- unidentified kSZ systematics for bulk flow,
- catalogue-incompleteness corrections for the radio dipole,
- exotic parity-breaking inflation for TB/EB modes,
- directional calibration effects for H_0.

This patchwork introduces multiple unrelated mechanisms. In contrast, a single anisotropic boundary condition introduces three components:

- α: directional gradient $\rightarrow$ alignment and hemispherical asymmetry,
- β: chiral term $\rightarrow$ parity violation, spin and polarisation alignments,
- $\gamma(t)$: dynamic anisotropic stress $\rightarrow$ bulk flow, radio-dipole excess, and H_0 drift.

Together these three components account for the entire anomaly set. The boundary interpretation is therefore simpler, not more complex, than fragmented alternatives.

7.4. Epistemic Modesty

The present framework does not claim:

- the physical nature of the boundary,
- the dimensionality or structure beyond the boundary,

- whether the modulation arises from topology, relic fields, or pre-inflationary dynamics,
- whether the boundary corresponds to a broader cosmological environment.

None of these questions can be answered from the anomalies considered here. Only the minimal structural features demanded by data are inferred. The boundary is treated strictly as an empirical requirement, not an ontological entity. This epistemic modesty prevents misinterpretation.

7.5. Compatibility with the Cosmological Principle

The cosmological principle asserts large-scale homogeneity and statistical isotropy. The anisotropic-boundary framework respects this principle:

- high multipoles ($\ell > 200$) remain isotropic,
- BAO, RSD, and large-scale structure statistics remain isotropic,
- homogeneity is preserved,
- only the largest scales carry anisotropic signatures.

Isotropy emerges at small scales exactly as in standard cosmology. The boundary influence modifies only the initial surface and not the subsequent evolution.

7.6. Future Precision Tests

Several upcoming observational programmes will sharply test the predictions outlined in Section 6:

- CMB-S4: low-ℓ TB/EB signals, ISW anisotropies,
- LiteBIRD: primordial polarisation,
- SKA: radio-dipole amplitude and number-count anisotropies,
- LSST: galaxy spin statistics and shear correlations,
- Euclid: void orientations and bulk-flow mapping,
- DESI: refined peculiar-velocity fields,
- GAIA: stellar-stream anisotropies.

Many of these tests could confirm or falsify the minimal boundary model within the next decade.

7.7. Connection to the Forthcoming Microstructure Paper

This paper intentionally avoids addressing the physical origin of the boundary influence. The forthcoming microstructure analysis will explore:

- possible pre-inflation relics,
- anisotropic topological constraints,
- parity-selective fields,
- whether the modulation is continuous or discrete,
- how such a boundary might arise within a larger cosmological environment.

The present work provides the empirical and statistical foundation for that deeper investigation.

7.8. Summary

The large-scale anomalies are real, persistent across datasets, cross-domain in nature, and statistically inconsistent with isotropic ΛCDM initial conditions. A minimal anisotropic boundary condition accounts for these features without altering the universe's internal dynamics. The interpretation is conservative, falsifiable, and fully compatible with established cosmological practice.

8. Conclusions

This work has reviewed the major large-scale cosmological anomalies observed in CMB temperature and polarisation, galaxy peculiar velocities, radio number counts, quasar polarisation vectors, parity-sensitive observables, and the thermodynamic behaviour of cosmic voids. These anomalies persist across independent instruments, frequencies, surveys, and analysis pipelines. Most importantly, they exhibit directional convergence, cross-domain coherence, and scale consistency that cannot be produced by ΛCDM internal dynamics alone.

A unified directional-alignment table, spherical statistical tests, and an explicit treatment of the Look-Elsewhere Effect demonstrate that the anomalies do not behave as independent outliers. Instead, they form a correlated pattern concentrated in a contiguous region of the sky. Under statistically isotropic initial conditions, such a configuration is highly improbable.

The minimal explanation consistent with the data is a non-trivial boundary condition acting on the earliest definable hypersurface of the universe. This influence has been formalised as an Anisotropic Boundary Condition (ABC) or Primordial Modulation Field (PMF), with “Unknown Other” (UO) used as shorthand for its observational fingerprint. No ontological assumptions accompany this terminology. The boundary influence must contain three empirically required components:

- a directional gradient,
- a parity-odd chiral term,
- a dynamic anisotropic stress.

A general linear modulation tensor $P_{\mu\nu}$ incorporating these components was introduced and mapped to the anomalies it reproduces. This formulation preserves General Relativity and all successful ΛCDM predictions, altering only the initial conditions rather than the governing dynamics.

The model yields a series of sharp, falsifiable predictions. It forbids high-ℓ anisotropy, requires alignment among low-ℓ modes, predicts specific TB/EB signatures, and links bulk flows, radio-dipole amplitudes, and directional variations in H_0 to the same preferred axis. Future observations from CMB-S4, LiteBIRD, Euclid, LSST, DESI, GAIA, and SKA will test these predictions decisively. Several of these experiments may confirm or falsify the model within the coming decade.

The purpose of this paper has been to identify the observational fingerprints that necessitate a minimal anisotropic boundary condition. The forthcoming microstructure paper will investigate the possible physical origins of this boundary influence and assess whether the directional, chiral, and dynamical signatures constrain any pre-inflationary relics, topological features, or external environments.

For now, the evidence is clear: the universe carries large-scale, correlated signatures that do not arise from its internal dynamics. These signatures require a minimal anisotropic boundary condition. This paper has mapped the fingerprints; the next will investigate the hand.

Author Contributions: Conceptualization, S.A.; methodology, S.A.; formal analysis, S.A.; investigation, S.A.; writing—original draft preparation, S.A.; writing—review and editing, S.A.; visualization, S.A.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Acknowledgments: The author thanks colleagues and anonymous reviewers for critical feedback that helped refine the statistical and conceptual structure of this work. All outputs were reviewed and fully validated by the author, who takes full responsibility for the final content.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ABC	Anisotropic Boundary Condition
CMB	Cosmic Microwave Background
GR	General Relativity
KSZ	Kinematic Sunyaev–Zel'dovich
LEE	Look-Elsewhere Effect
LSS	Large-Scale Structure
PMF	Primordial Modulation Field
UO	Unknown Other
ΛCDM	Lambda Cold Dark Matter

References

1. Bennett, C.L.; et al. Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Are There Cosmic Microwave Background Anomalies? *ApJS* **2011**, *192*, 17.
2. Schwarz, D.J.; et al. CMB Anomalies after Planck. *Class. Quant. Grav.* **2016**, *33*, 184001.
3. Copi, C.J.; Huterer, D.; Schwarz, D.J.; Starkman, G.D. Large-Angle Anomalies in the CMB. *MNRAS* **2015**, *451*, 2978.
4. Eriksen, H.K.; et al. Asymmetries in the CMB. *ApJ* **2004**, *605*, 14.
5. Hansen, F.K.; Banday, A.J.; Gorski, K.M. Testing the CMB theories of the early universe. *MNRAS* **2004**, *354*, 641.
6. Kashlinsky, A.; et al. A Measurement of Large-Scale Peculiar Velocities of Galaxy Clusters. *ApJL* **2008**, *686*, L49.
7. Kashlinsky, A.; et al. Large-Scale Coherent Motions in the Universe. *ApJL* **2010**, *712*, L81.
8. Watkins, R.; Feldman, H.A.; Hudson, M.J. Consistently Large Cosmic Flows on Scales of 100 Mpc. *MNRAS* **2009**, *392*, 743.
9. Atrio-Barandela, F. On the Statistical Significance of the Dark Flow. *A&A* **2013**, *557*, A116.
10. Colin, J.; et al. Evidence for Anisotropy in the Hubble Expansion. *A&A* **2019**, *631*, L13.
11. Migkas, K.; et al. Probing Cosmic Isotropy with X-ray Galaxy Clusters. *A&A* **2020**, *636*, A15.
12. Krishnan, C.; et al. Hints of Anisotropic Expansion from H0 Measurements. *PRD* **2021**, *103*, 103509.
13. Vielva, P.; et al. Detection of the Cold Spot in the WMAP Data. *ApJ* **2004**, *609*, 22.
14. Cruz, M.; Martinez-Gonzalez, E.; et al. The Non-Gaussian Cold Spot. *MNRAS* **2006**, *369*, 57.
15. Kovacs, A.; Garcia-Bellido, J. The Cold Spot as a Supervoid. *MNRAS* **2016**, *462*, 1882.
16. Nadathur, S.; et al. Supervoids and the CMB Cold Spot. *MNRAS* **2014**, *440*, 18.
17. Singal, A.K. Large Excess Radio Dipole in the NVSS Data. *ApJL* **2011**, *742*, L23.
18. Bengaly, C.A.P.; Maartens, R.; Santos, M.G. Testing the Cosmological Principle with Radio Surveys. *JCAP* **2018**, *04*, 031.
19. Kim, J.; Naselsky, P. Anomalous Parity Asymmetry of the CMB. *ApJL* **2011**, *739*, L38.
20. Collaboration, P. Planck 2018 results. VII. Isotropy and Statistics of the CMB Polarization. *A&A* **2020**, *641*, A7.
21. Contaldi, C.; Magueijo, J.; Smolin, L. Anomalous Gravitational Waves and Parity Violation. *PRL* **2008**, *101*, 141101.
22. Hutsemekers, D.; et al. Confirmation of Quasar Polarization Alignments. *A&A* **2005**, *441*, 915.
23. Pelgrims, V. Polarization Alignments over Gigaparsec Scales. *A&A* **2016**, *590*, A53.
24. Ackerman, L.; Carroll, S.M.; Wise, M.B. Imprints of a Primordial Preferred Direction on the Microwave Background. *PRD* **2007**, *75*, 083502.
25. Contaldi, C.R.; Peloso, M.; Sorbo, L. Anisotropies from Pre-Inflation Dynamics. *JCAP* **2014**, *07*, 014.
26. Barrow, J.D.; Hervik, S. Anisotropic Inflation. *PRD* **2006**, *73*, 023007.
27. Ferreira, P.G.; Quartin, M. Isotropy Breaking and Cosmic Tensions. *MNRAS* **2020**, *493*, L60.
28. Carroll, S.M.; Chen, J. Spontaneous Inflation and the Low-Entropy Past. *arXiv:hep-th/0410270* **2004**.
29. Ellis, G.F.R. The Arrow of Time and Boundary Conditions. *Stud. Hist. Phil. Mod. Phys.* **2013**, *44*, 242.
30. Dodelson, S. *Modern Cosmology*; Academic Press, 2003.