

An Observed-Label Chirality-Dipole Null in 949,584 High-Confidence DESI Spirals and an 8.5-Million-Galaxy Catalog

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ABSTRACT

We release observed chirality labels for 8,474,531 DESI Legacy DR8 galaxies and test one primary high-confidence observed-label dipole. Of 949,584 selected spirals, 947,326 enter the supported-pixel fit and fixed-occupancy label-randomization null; the result is consistent with zero ($z = +0.71$, one-sided rank $p = 0.225$). The content-addressed release includes the science catalog, unsafe-row quarantine, retained primary-null array, schema, checksums, and reproducer. WLS and harmonic analyses use different supports or nulls and are retained only as systematics diagnostics. Spatial transfer calibration, joint covariance, an independent matched-footprint estimator, a complete systematics-metadata sidecar, and a DOI-backed archive remain open. The parity-even morphology observable supports no primordial-parity bound.

Keywords: galaxies: spiral, galaxies: statistics, methods: data analysis, cosmology: observations, large-scale structure of universe

1. INTRODUCTION

The handedness (chirality) of spiral galaxies—whether their arms trail clockwise (CW) or counter-clockwise (CCW) as projected on the sky—is a simple observable that, under the trailing-arm assumption and in the absence of confounding selection effects, traces the angular-momentum direction of each disk galaxy. Throughout this paper, “CW/CCW” refers to the *projected apparent arm-winding chirality*, not a deprojected 3D spin vector. In a statistically isotropic and parity-symmetric universe, the CW and CCW fractions should be exactly equal when averaged over large angular scales. A significant directional departure would constrain isotropy-breaking axial-vector sectors in the galaxy-formation chain. The present paper is a standalone observational result: the observed-label null on the declared sample does not depend on any unpublished companion work.

Claims of such a signal have appeared intermittently in the literature. Shamir (2012) (1) reported a 2–4 σ dipole with per-bin asymmetry amplitudes of ~ 5 –20% (as reported in that work) using $\sim 1.27 \times 10^5$ SDSS galaxies. Shamir (2020) (2) reported asymmetries at the reported ~ 2 –4% level on SDSS and Pan-STARRS samples; Shamir (2022a) (3) reported related spin-direction alignment analyses; and Shamir (2022b) (4)

reported results on a DESI Legacy sample (“nearly 1.3×10^6 spiral galaxies” per the published abstract). Iye *et al.* (2021) (5) re-examined Shamir’s SDSS spiral catalog using 3D random-walk simulations and found no significant dipole after correcting for reading-direction bias and photometric-object duplication in earlier Shamir catalogs. Tadaki *et al.* (6) likewise found null results on a catalog of $\sim 80,000$ face-on spirals. Jia *et al.* (7) introduced CE-ResNet, a chirality-equivariant CNN guaranteeing by construction that flipping an input exactly swaps CW and CCW outputs, with a reported number-count ratio $\text{CW/CCW} = 0.998$ on ~ 1.95 million galaxies.

In this paper we present an 8.47-million-object public chirality catalog release whose novelty relative to CE-ResNet is scale, a dedicated NOT_SPIRAL class, a machine-readable release contract, and a multi-axis bias-hardening audit. This catalog-and-methods emphasis, including a compact schema, executable selection, checksummed null, and explicit quarantine, is the intended ApJS venue fit. Committed historical training records conflict on exact composition: one reconstruction gives 26,616 rows and 826 CE-ResNet-selected non-spirals (67.5% CE-derived), whereas BENCHMARK_REPORT.md gives 26,626 and 846; both accounts establish substantial CE-ResNet dependence, so the catalogs are not fully independent and

model-output permutation nulls cannot test inherited survey-correlated structure by themselves. Our sole primary result is the HC real-space observed-label null ($N_{\text{selected}} = 949,584$, $N_{\text{support}} = 947,326$, $z = +0.71$, one-sided upper-tail $p = 0.225$). The WLS and MASTER results are systematics-sensitive diagnostics, not independent detections or physical exclusions. The GZ1 human-only test uses human votes rather than learned chirality labels and corroborates the null at lower statistical power; it does not tighten the HC amplitude constraint.

2. DATA

2.1. Galaxy Images

Our parent sample is the Smith42/galaxies dataset on HuggingFace (<https://huggingface.co/datasets/Smith42/galaxies>), containing 8,474,688 galaxy images from the DESI Legacy Imaging Surveys DR8 (8). Each image is a 224×224 pixel cutout in *grz* bands at $0.262''/\text{pixel}$. The dataset includes unique `dr8_id` identifiers; sky coordinates are obtained by cross-matching against the Galaxy Zoo DESI predictions catalog (9). The parent-sample selection function inherits from Galaxy Zoo DESI: photometric types REX/DEV/EXP/SER, $r \leq 19.0$, half-light radius $\geq 3''$. DR8 comprises three distinct imaging campaigns: BASS+MzLS ($\delta > +32^\circ$), DECaLS ($\delta < +32^\circ$), and a DES overlap region.

2.2. Training Labels

The exact historical training realization is not fully recoverable. The production-script reconstruction and immutable model-repository receipt `v2_bias_audit.json` (model revision 237d021c451d75cf86a875e86d4de498b74e2f12; file SHA-256 57278e4e...ee847) support 26,616 labeled rows (6,637 Galaxy Zoo 1 high-confidence CW/CCW, 17,153 CE-ResNet high-confidence spirals, and 2,826 not-spiral rows, of which the script account assigns 826 to CE selection and 2,000 to synthetic examples), a 21,293/5,323 train/validation split, and 93.6878% validation accuracy. However, the committed BENCHMARK_REPORT.md gives 26,626 total rows and 846 CE non-spirals, while the committed Hugging Face README reports 92.10%. No retained object/split manifest, random-state record, or run receipt ties the named objects and stochastic realization to the checkpoint, so the immutable audit supports one historical account but does not resolve the conflicting committed records or make the run exactly reproducible (Appendix B). This gap can harbor training- or selection-dependent bias; TTA guarantees only flip-equivariance of the output protocol and does not make the unknown

training realization irrelevant. Both pool accounts are approximately 67.5% CE-derived, so validation substantially measures agreement with that model. Horizontal flips are generated on the fly for a training-only consistency loss and do not add dataset rows. The full GZ1 overlap gives 69.91% chirality agreement ($\kappa = 0.40$); no retained object-ID manifest establishes exclusion of the 6,637 GZ1 training rows. The human-vote GZ1 dipole test gives $z = -0.54$ for 46,017 matched inputs; exactly 4,963 enter its 394-pixel support after the legacy $N_{\text{pixel}} > 10$ cut, while 41,054 are excluded. It corroborates a null under its legacy null convention but, without calibrated power or a spatial transfer model, does not provide a tighter amplitude bound.

3. METHODS

3.1. Notation and Significance Conventions

Confidence notation.— p_{eq} (or $p_{\text{CW}}^{\text{eq}}$, $p_{\text{CCW}}^{\text{eq}}$, $p_{\text{NS}}^{\text{eq}}$) denotes the max-class equivariant probability output by the 2-fold flip-TTA pipeline (Sec. 3.4 and Appendix B). These are monotone ranking scores, not frequentist probabilities; “high-confidence” (HC) cuts on p_{eq} are sample-selection thresholds.

Significance conventions.—All significance values z are moment-ratios $(x - \langle x \rangle_{\text{null}})/\sigma_{\text{null}}$ against the null distribution specified per result. The primary empirical rank value is the one-sided upper tail $p = (k + 1)/(N + 1)$, where k null amplitudes meet or exceed the data amplitude. Three distinct significance conventions appear in this paper:

- *Moment- z / rank- p :* the real-space dipole pair ($z_{\text{mom}} = +0.71$, one-sided upper-tail rank $p = 0.225$) are distinct summary statistics of the A_{dip} distribution against the fixed-occupancy galaxy-label-randomization null; they do not follow the Gaussian $z \rightarrow p$ mapping.
- *MASTER $\ell = 1$ moment- z :* $z = (C_1^{\text{data}} - \langle C_1 \rangle_{\text{null}})/\sigma_{\text{null}}$ vs. the label-shuffle null mean $\langle C_1 \rangle_{\text{null}}$ and width σ_{null} ; $z = +3.64$ (500-MC canonical direct run), $z = +7.93$ (10^4 -permutation canonical unapodized), $z = +7.28$ (10^4 -permutation apodized). These three values are from different null-run sizes and mask/weight conventions and are not mutually comparable.
- *Block-bootstrap z :* $(A_{\text{dipole}}^{\text{best}} - A_{\text{ref}})/\sigma_{\text{boot}}$ with spatial-coherence-corrected σ_{boot} ; $z \approx -7.6$ applies only to a clean *observed-label* $A_{\text{ref}} = 0.017$ template. Under $g = 0.398$, a physical 1.7% dipole maps to 0.6766% observed and is $1.36\sigma_{\text{boot}}$ above the fit, so the former physical-exclusion reading is invalid.

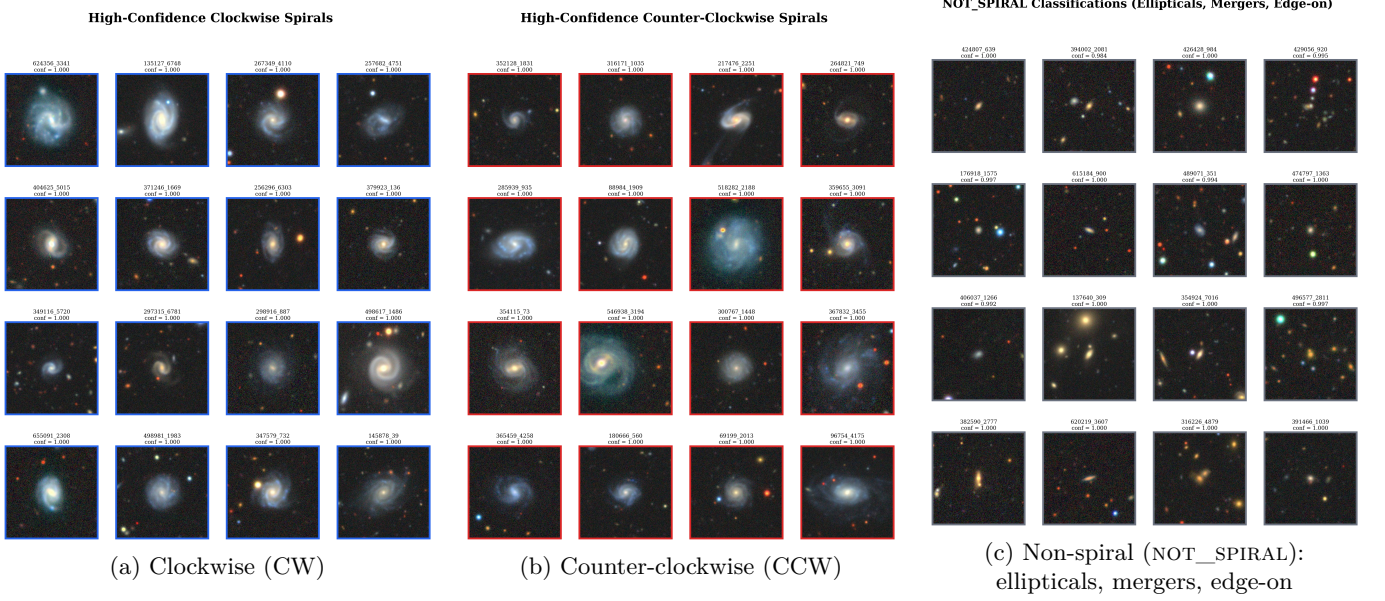


Figure 1. Representative high-confidence galaxies from the classified catalog ($p_{\text{eq}} > 0.9$). Left: clockwise (CW) spirals; center: counter-clockwise (CCW) spirals; right: non-spiral (NOT_SPIRAL) objects — ellipticals, mergers, and edge-on galaxies that would contaminate a binary spiral classifier. All cutouts are 224×224 pixels in *grz* bands from DESI Legacy DR8. The gallery illustrates the visual diversity within each class and motivates the three-class design: without an explicit NOT_SPIRAL class, $\sim 62\%$ of the parent sample would leak into the spiral classification. The *ViT-Small* classifier resolves CW vs. CCW via the test-time equivariant averaging procedure of §3.4.

3.2. Declared Analysis Hierarchy

We assign stable names to the three distinct supports used below: **HC-REALSPACE-INCLUSIVE** (HC-RI; HC rows with $N_{\text{spiral}}(p) \geq 10$, 23,682 pixels), **FULL-SPIRAL-CANONICAL** (FS-C; all spirals with $N_{\text{spiral}}(p) \geq 10$, 24,087 pixels), and **MASTER-ALL-GALAXY-FOOTPRINT** (MASTER-AGF; $N_{\text{all}}(p) \geq 1$, 24,297 pixels); Table 11 consolidates their mask and weighting conventions. These names prevent the primary HC support from being conflated with either full-sample diagnostic footprint. We declare the estimator hierarchy used throughout. This hierarchy — with the real-space dipole as the row-(i) primary cosmological estimator — is documented in Appendix A; the primacy of the real-space estimator is established independently of the harmonic-channel diagnostics. The primary dipole measurement uses the high-confidence selection (Catalog C with winning-class confidence $p_{\text{eq}} > 0.6$; $N_{\text{selected}} = 949,584$ spirals), of which $N_{\text{support}} = 947,326$ enter the 23,682 supported pixels used by the estimator and null. This cut suppresses the depth-correlated low-confidence-tail systematic identified in Sec. 4.3; all estimator-hierarchy and sensitivity statements below are made on this HC selection unless explicitly noted. We declare the HC $p_{\text{eq}} > 0.6$ subsample as the *single primary science sample* for all primary cosmological statements. The historical WLS/bootstrap fit used a different latitude-cut support and is retained only

as provenance, not as an FS-C or physical exclusion. This is an internal hierarchy declaration, not a claim of formal preregistration or independent blinding. See Appendix D for the support-audited diagnostic table.

- **Estimator hierarchy:** the primary cosmological estimator is the real-space CW-fraction dipole fit on Catalog C at NSIDE=64 (moment-ratio $z_{\text{mom}} = +0.71$ against the fixed-occupancy galaxy-label-randomization null, one-sided upper-tail empirical-rank $p = 0.225$). The block-bootstrap WLS fit is a diagnostic of a clean observed-label template ($z \approx -7.6$ at $A_p = 1.7\%$), not a physical 1.7% exclusion; with the illustrative $g = 0.398$ transfer the physical comparison is only $1.36\sigma_{\text{boot}}$ (Appendix D).
- **Secondary diagnostic estimators:** (iii) canonical- N direct-MC NaMaster at $\ell = 1$ on the patchy FS-C support ($f_{\text{sky}} = 0.49005$, $+3.64\sigma$); (iv) apodized-footprint MASTER at $\ell = 1$ on MASTER-AGF ($f_{\text{sky}} = 0.494$, C^2 2° ; $+7.28\sigma$ vs. global label-shuffle and $+7.13\sigma$ vs. depth-stratified null, $W_p = N_{\text{all}}$); and (v) hemisphere maximum-asymmetry (3.05σ local maximum against the label-shuffle null, $p_{\text{LEE}} \leq 10^{-4}$ direct-MC max-statistic, systematics-attributed (the Gaussian-Bonferroni $< 1\sigma$ heuristic is a non-principled cross-check); Appendix C). These characterize how a non-zero global monopole and

coherent low- ℓ systematics couple through the patchy weighted footprint.

- **Generative monopole-only null:** (vi) $N = 500$ binomial-monopole realizations demonstrating that the raw pre-MASTER pseudo- $C_\ell^{(\ell=1)}$ is dominated by monopole-mask leakage; the post-MASTER $+3.64\sigma$ FS-C residual is non-primary and requires additional coherent systematics beyond the monopole-only channel (Sec. 4.4).
- **Finite-grid injection scores:** (vii) on the HC-broad spiral subsample ($p_{\text{eq}} > 0.6$, $N = 949,584$; Sec. 6.2), the 100-injection score-pass fractions at $A = 0.75\%$ are 0.55 (polar-angle-uniform axes) and 0.59 (area-uniform axes), while the Stage-B deterministic-axis surrogate gives 16/20; none is a calibrated recovery threshold.

To make the mapping from estimator to scientific claim explicit, Table 1 ties each claim to its estimator, sample, null, and role. Only the HC real-space row marked PRIMARY carries scientific weight; WLS and every harmonic-channel statistic are diagnostics and support no independent detection or exclusion claim.

Table 2 consolidates the distinct estimators and nulls. Their statistics are not commensurable, and no joint likelihood is defined. The scientific verdict rests solely on the HC observed-label real-space row; WLS and all harmonic rows remain systematics diagnostics. The missing joint covariance remains an open methodological gate.

3.3. Model Architecture

The classifier consists of a ViT-Small encoder (13) (`vit_small_patch16_224`, ImageNet-pretrained) with the last 6 of 12 transformer blocks fine-tuned, followed by a custom classification head:

$$\begin{aligned} \text{LayerNorm} &\rightarrow 384 \rightarrow 512 \text{ (GELU, } d=0.3) \\ &\rightarrow 512 \rightarrow 256 \text{ (GELU, } d=0.2) \rightarrow 256 \rightarrow 3 \text{ (softmax)}. \end{aligned} \quad (1)$$

The three-class output (P_{CW} , P_{CCW} , P_{NS}) is essential for full-survey deployment: applying a binary classifier to data where $\sim 70\%$ of objects are elliptical or irregular produces a catalog dominated by noise. Full architecture and training details are in Appendix B.

3.4. Test-Time Equivariant Averaging

At inference, each galaxy is classified on both the original image and its horizontal reflection. The equivariant

probability is:

$$\begin{aligned} P_{\text{CW}}^{\text{eq}} &= \frac{1}{2}(P_{\text{CW}}^{\text{orig}} + P_{\text{CCW}}^{\text{flip}}), \\ P_{\text{CCW}}^{\text{eq}} &= \frac{1}{2}(P_{\text{CCW}}^{\text{orig}} + P_{\text{CW}}^{\text{flip}}), \\ P_{\text{NS}}^{\text{eq}} &= \frac{1}{2}(P_{\text{NS}}^{\text{orig}} + P_{\text{NS}}^{\text{flip}}). \end{aligned} \quad (2)$$

This procedure enforces flip-equivariance of the output protocol (flip-swap correlation = 1.000). We restrict to 2-fold TTA (original + horizontal flip) rather than the full D_4 group because mirrors flip chirality by definition, whereas in-plane rotations do not change chirality; rotation-TTA probes classifier non-equivariance rather than the chirality assignment itself. Because Eq. (2) enforces flip-equivariance at inference by construction, the flip-swap consistency test T1 (Appendix B) is a *protocol implementation check* that guards against code defects in the TTA averaging, not an independent statistical test of the learned model’s equivariance; the pre-TTA behavior of the underlying network is documented separately by the raw single-pass Catalog A tier (Table 4). A direct D_4 -TTA hold-out on two independent $\sim 2,000$ -galaxy subsamples confirms the mean per-galaxy P_{CW} is stable under Z_2 and D_4 to within $|\Delta\langle p_{\text{CW}} \rangle| < 0.0016$; per-galaxy argmax labels flip in 21.4% of cases between Z_2 and D_4 on borderline galaxies with $P_{\text{CW}} \approx P_{\text{CCW}} \approx 0.4$. This D_4 hold-out is a classifier-stability check (comparing softmax outputs under two augmentation groups), not a spatial-null or isotropy test; spatial-null calibration is performed via the isotropic (pixel-)permutation nulls of Sec. 4.3. Full details in Appendix B.

3.5. Catalog Tiers

The pipeline produces three tiers: **Catalog A** (raw, single-pass softmax); **Catalog B** (Platt-calibrated, $+0.4\%$ excess); **Catalog C** (equivariant production, 2-fold flip TTA). **Catalog C is the recommended tier for all cosmological parity analyses.** All three tiers share 8,474,531 rows in Apache Parquet format.

4. RESULTS

Significance conventions. This paper reports significance in standard-deviation units (σ) throughout, but values from distinct null procedures are *not* directly comparable. Section identifiers specify the null for each result. Empirical rank p -values are one-sided unless explicitly labeled two-sided.

4.1. Catalog Statistics

The final catalog contains 8,474,531 galaxies (157 of 8,474,688 failed quality checks). Catalog C (equivariant) contains CW 1,592,107, CCW 1,609,053, and NS/edge-on 5,273,371, for $N_{\text{spiral}} = 3,201,160$. Mean max-class

Table 1. Estimator decision tree. The single PRIMARY row is the HC observed-label real-space null. DIAGNOSTIC rows characterize systematics and make no independent detection or exclusion claim; the pilot row reports finite-grid sensitivity evidence. Statistics across rows are not commensurable because their fields, samples, and nulls differ.

Scientific claim	Estimator	Sample (N_{spiral})	Null	Role
Real-space chirality dipole is consistent with zero	(i) HC real-space dipole	HC, $p_{\text{eq}} > 0.6$ (949,584)	fixed-occupancy label randomization (10^4)	PRIMARY
A clean observed-label 1.7% template is disfavored under the WLS model	(ii) block-bootstrap WLS template fit	full Catalog C (3,201,160)	block-bootstrap (10^3)	DIAGNOSTIC
Harmonic $\ell=1$ residuals are systematics (monopole-mask leakage + coherent depth/morphology), <i>not</i> a cosmological signal	(iii,iv) canonical/apodized MASTER; (vi) monopole-only generative null	full Catalog C (3,201,160)	label-shuffle / depth-stratified / monopole-only	DIAGNOSTIC
The hemisphere max-statistic rejects the random-label null after look-elsewhere correction, but the excess is attributed to survey/classifier systematics and is not interpreted cosmologically	(v) hemisphere max-asymmetry	full Catalog C (3,201,160)	max-statistic MC (p_{LEE})	DIAGNOSTIC
Finite-grid sensitivity of the primary real-space estimator; not calibrated coverage or an upper limit	(vii) injection-recovery	HC, $p_{\text{eq}} > 0.6$ (949,584)	per-pixel shuffle	PILOT

score is 0.951 and the median is 0.9997. The score distribution is much sharper than the full-overlap GZ1 descriptive accuracies (58.7% three-class; 69.91% spiral chirality), so every p_{eq} quantity in this paper is an uncalibrated ranking score. The HC threshold selects a sample; it does not assert a per-object correctness probability.

The primary estimator consumes hard argmax CW/CCW counts rather than soft scores. Monotone recalibration therefore leaves the labels, pixel counts, fitted dipole, and direction unchanged for a fixed selected sample, although the spatial selection induced by a threshold can correlate with depth, morphology, seeing, redshift, or footprint. The confidence-cut sweep and external template diagnostics test that selection dependence; the human-vote GZ1 dipole corroborates the null independently of softmax scaling. The illustrative scalar dilution $g = 2a - 1$ uses the full-overlap GZ1 agreement, which is not an independent calibration because the training rows were not removed.

Raw/flip quarantine. Reconstructing the flip pass from mismatched raw/equivariant pipeline products identifies 249,066 unsafe rows catalog-wide (2.939%) whose reconstructed score exits $[0, 1]$ by more than 10^{-3} , with maximum excursion 0.0901. Exactly 59,515 of

those rows are in the 949,584-row HC selection; the strict HC diagnostic has 890,069 rows. These diagnostic quantities are not calibrated probabilities. The public v1.0.244 science-facing release omits every raw-pass and reconstructed flip-pass score column, retains only a Boolean `raw_flip_qc_unsafe` marker, and places all 249,066 offending diagnostic rows in a provenance-only quarantine with `do_not_use_for_science=True`. The existing flagged-row-excluded rerun remains null-consistent; it is a robustness diagnostic, not a replacement primary null. The executable schema and filters are given in Data Availability.

4.2. Global CW Fraction

The Catalog C residual (-9.5σ from 0.5000, Table 4) is spatially uniform across 7 equatorial coordinate slabs and does not produce a dipole. This monopole offset is a classifier artifact, not a physical signal; three candidate mechanisms are (1) GZ1 training-label CW excess, (2) residual orientation-dependent bias not corrected by 2-fold TTA, and (3) photometric asymmetry in DESI Legacy imaging. The $2.98\times$ asymmetry-suppression factor from raw $+1.576\%$ to equivariant -0.529% (asymmetry- A units, $A = 2(f_{\text{CW}} - \frac{1}{2})$; equivalently $+0.788\% \rightarrow -0.265\%$ in f_{CW} -deviation units, Table 4)

Table 2. Primary-estimator summary. $N_{\text{catalog spiral}}$ is the underlying Catalog C spiral count (CW+CCW only). $N_{\text{map weighted}} = \sum_{p \in \text{mask}} W_p$ where $W_p = N_{\text{all}}^{(p)}$ is the total classified-galaxy count in pixel p (CW+CCW+NS), used as a survey-depth weight in the NaMaster field object. $N_{\text{map weighted}}$ exceeds $N_{\text{catalog spiral}}$ because W_p includes non-spiral galaxies (~62% of the catalog); each galaxy is counted once. Row (iv) is the apodized-footprint MASTER diagnostic ($N_{\text{all}} \geq 1$ mask, C^2 2° apodization); its two σ values are against the global per-galaxy label-shuffle and depth-stratified nulls respectively (both systematics-attributed; Appendices A, D). The σ values in different rows are computed against different null procedures (column “Null”) and are not directly comparable across rows as detection significances. Row (v) reports the post-look-elsewhere-corrected significance; the raw direct-MC value is $p_{\text{LEE}} \leq 10^{-4}$ against the random-label max-statistic null, which *already incorporates* the look-elsewhere scan and is the principled directional look-elsewhere control (Appendix C); the rejection is systematics-attributed. Row (vii) uses the HC-broad subsample ($p_{\text{eq}} > 0.6$; Sec. 6.2). A “—” in $N_{\text{map weighted}}$ marks rows where the NaMaster weight construction is not invoked.

Estimator	$N_{\text{catalog spiral}}$	$N_{\text{map weighted}}$	f_{sky}	Mask	Null	Reported statistic
(i) real-space dipole (HC)	949,584	—	0.4818 ^a	HC-RI	fixed-occ. label rand. (10^4)	+0.71 (moment z)
(ii) WLS template diag.	3,201,160	—	0.49209	latitude cut (24,187 px)	block-boot. (10^3)	$z \approx -7.6$
(iii) canonical MASTER (diag.)	3,201,160	—	0.49005	FS-C	pp-shuffle	+3.64
(iv) apod. MASTER (diag.)	3,201,160	8,474,531	0.494 ^b	MASTER-AGF	pp-sh./d-str.	+7.28/+7.13
(v) hemisphere LEE (MC)	3,201,160	—	0.49005	FS-C	max-stat MC	$p_{\text{LEE}} \leq 10^{-4}$ (syst.-attr.)
(vi) monopole+mask null	3,201,160	—	0.49005	FS-C	monopole-only	+1.69
(vii) finite injection grid	949,584 HC	—	—	—	pp-shuffle	$P_{3\sigma} = 0.55/0.59$ at $A = 0.75\%$

^a $f_{\text{sky}} = 0.4818115$ is HC-RI, the inclusive $N_{\text{spiral}}(p) \geq 10$ support re-evaluated on the high-confidence subsample (23,682 of 49,152 pixels). The superseded strict $N_{\text{spiral}} > 10$ execution used 23,600 pixels and is retained only as historical mask-sensitivity context.

^b Geometric $N_{\text{all}} \geq 1$ footprint pixel fraction; the corresponding weighted/apodized *effective* sky fraction for this row’s $W_p = N_{\text{all}}$, C^2 2° configuration is $f_{\text{sky}}^{\text{eff}} = 0.452$ (Appendix A, Table 11).

Table 3. Estimator callout. P1 is the load-bearing cosmological result. P2 and D1–D2 are diagnostics with distinct samples and nulls; P2’s $z \approx -7.6$ applies only to an observed-label template and becomes a $1.36\sigma_{\text{boot}}$ comparison for a physical 1.7% signal under $g = 0.398$. Values across rows are not directly comparable as detection significances (Sec. 3.1).

Claim / channel	Null	Value
P1 real-space HC dipole ($p_{\text{eq}} > 0.6$), primary	fixed-occupancy label randomization	+0.71 σ (upper-tail $p = 0.225$)
P2 observed-label template (WLS fit), diagnostic	block- bootstrap	$z \approx -7.6$ (physical: 1.36 σ)
D1 HC dipole (cross-check)	label-shuffle	$z = +0.70$, $p = 0.230$
D2 MASTER $\ell = 1$ residual systematics, not a detection	label-shuffle (harmonic)	+3.64 / +7.28 σ

demonstrates the dominance of the equivariant TTA processing. Crucially, the slab statistics support this quantitatively: in 7 equal-spiral-count declination slabs ($N = 457,308$ – $457,309$ spirals each; per-slab binomial $\sigma = 7.4 \times 10^{-4}$), the per-slab f_{CW} spans 0.49537–0.49890, i.e. deviations from 0.5 of -0.110% to -0.463% , all within 0.5% of 50/50; an equal-count RA partition gives a compatible span (-0.060% to -0.501%). An equal-area partition (8 declination bands of equal in-mask pixel count on the FS-C support) gives the same verdict: per-band f_{CW} deviations from 0.5 reach at most 0.49% on the full spiral sample (max $|z| = 2.9$ vs. the global rate) and 0.56% on the HC subsample (max $|z| = 1.4$), comparable to the equal-count maximum of 0.46% (artifact [pipelines/p2_chirality/outputs/canonical_provenance/c12_r24conf_local_batch.json](#)). The slab-to-slab scatter about the global $f_{\text{CW}} = 0.49735$ is $\lesssim 2.7\sigma$ per slab (the extremal slab $f_{\text{CW}} = 0.49537$ gives $(0.49735 - 0.49537)/(7.4 \times 10^{-4}) = 2.7\sigma$ from the per-slab values and binomial σ above; arti-

fact [pipelines/p2_chirality/outputs/canonical_provenance/c12_r24conf_local_batch.json](#)), consistent with the coherent low- ℓ systematic structure positioned in Appendix D rather than a dipole-aligned gradient. Independently of any slab partition, a direct generative test shows that a constant monopole cannot bias the uniform-weight real-space dipole estimator (the constant template is absorbed by the fitted monopole term): binomial per-pixel realizations on the FS-C support drawn at $p = f_{\text{CW}}^{\text{global}}$ versus $p = 0.5$ yield statistically identical dipole-amplitude null distributions (means 1.957×10^{-3} vs. 1.935×10^{-3} , a 0.39σ shift in the standard error of the difference; $N = 500$ each; artifact [pipelines/p2_chirality/outputs/canonical_provenance/c11_meta_m4_slab_stats.json](#)). This generative test probes an *additive constant* monopole only; multiplicative depth- or morphology-coupled modulations of the monopole are not probed by it and are addressed instead by the template-regression and cross-spectrum diagnostics of Appendix D. The finite injection grids provide only the score fractions reported in Sec. 6.2; they do not establish a calibrated physical sensitivity floor. *Implications for $\ell = 0$ parity searches.* The morphological handedness monopole is itself the parity-odd channel (unlike the parity-even $\ell = 1$ dipole; Sec. 6.3), so a naive reading of the -9.47σ deviation as cosmic parity violation would be the single largest false-positive risk in any $\ell = 0$ chirality-parity study on such a catalog. Our analysis shows this deviation is a spatially-uniform classifier artifact ($\lesssim 0.5\%$ per-slab scatter, three candidate instrumental/training mechanisms above), not a physical signal; the concrete lesson for future $\ell = 0$ parity searches is therefore that

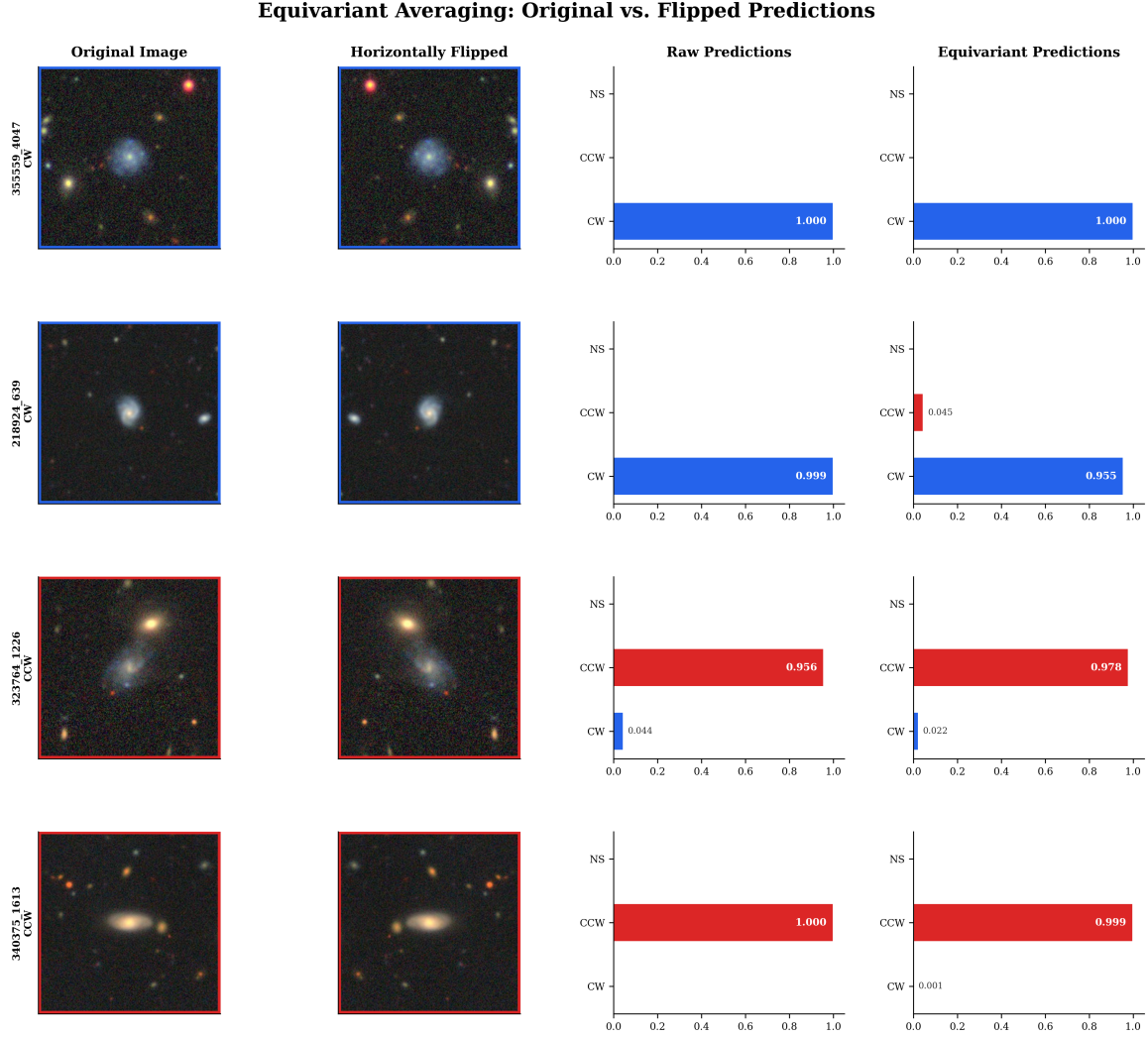


Figure 2. Equivariant test-time averaging (TTA). Representative Z_2 production TTA examples (original + horizontal flip); D_4 validation (four rotations $\times$ two reflections) in Appendix B. *Production* inference (Catalog C) uses 2-fold Z_2 TTA — original + horizontal flip only (§3.4). Flips swap the $CW \leftrightarrow CCW$ class labels by construction. Output probabilities are averaged after the swap, yielding a strictly flip-equivariant CW/CCW classifier with flip-swap correlation = 1.000 by construction. This averaging is the key methodology distinction between Catalog A (raw), Catalog B (Platt-calibrated), and Catalog C (equivariant); the global chirality asymmetry ($N_{CW} - N_{CCW}$)/ N_{spiral} shifts from +1.576% (A) to −0.529% (C), i.e. +0.788% to −0.265% in f_{CW} -deviation units, dominated by this step (Table 4). Unit reminder: asymmetry- A values are exactly twice the f_{CW} -deviation values, $A = 2(f_{CW} - \frac{1}{2})$ (Sec. 4.3); Table 4 quotes the f_{CW} -deviation convention.

the released catalog labels must be locally monopole-renormalized (per-region CW -fraction subtraction) before any global parity-odd statistic is formed, and that any claimed $\ell = 0$ parity detection at or below the $\approx 0.26\%$ artifact level (9.5σ in raw counts) is indistinguishable from this classifier monopole without an independent, handedness-symmetric labeling pipeline (Sec. E, Data Availability).

4.3. Dipole Analysis

We pixelize the sky at HEALPix resolution $NSIDE = 64$ (49,152 pixels, $\sim 0.84 \text{ deg}^2$ per pixel). In each supported pixel we compute the asymmetry below. The

threshold $N_{\text{spiral}}(p) \geq 10$ defines two sample-dependent supports: HC-RI for the HC primary (23,682 pixels) and FS-C for the full-spiral diagnostics (24,087 pixels); Appendix A records the exact data-vector mapping.

$$A_p = \frac{N_{CW}^{(p)} - N_{CCW}^{(p)}}{N_{CW}^{(p)} + N_{CCW}^{(p)}}. \quad (3)$$

This is the single canonical chirality-field definition used throughout (spirals-only denominator). Note the unit convention $A_p = 2(f_{CW,p} - \frac{1}{2})$: amplitudes quoted in A_p units are exactly twice the corresponding f_{CW} -deviation amplitudes.

Table 4. Global CW fraction across catalog tiers. Uncertainties are 1σ binomial, $\sigma = \sqrt{f(1-f)/N_{\text{spiral}}}$, with per-tier spiral counts ($N_{\text{spiral}}^A = 3,321,795$; $N_{\text{spiral}}^C = 3,201,160$); parentheses give the 1σ uncertainty on the trailing digits ($0.507879(274) \equiv 0.507879 \pm 0.000274$). The Excess column is the deviation $f_{\text{CW}} - 0.5$ in percent (f_{CW} units; multiply by 2 for asymmetry- A units). Dev. is the *signed* $(f_{\text{CW}} - 0.5)/\sigma$ computed from the unrounded fraction. The Catalog-B row derives from the Platt-calibrated fraction; its deviation is computed from the unrounded calibrated fraction. Percentages in this table (and in the catalog-composition counts cited in Sec. 2) are rounded to maintain sum-to-one consistency at the second decimal; the integer counts are exact.

Tier	$\text{cw}/(\text{cw} + \text{ccw})$	Excess (%)	Dev. (σ)
A (raw)	0.507879(274)	+0.788	+28.72
B (calibrated)	0.50400(27)	+0.4	+14.6
C (equivariant)	0.497353(279)	−0.265	−9.47

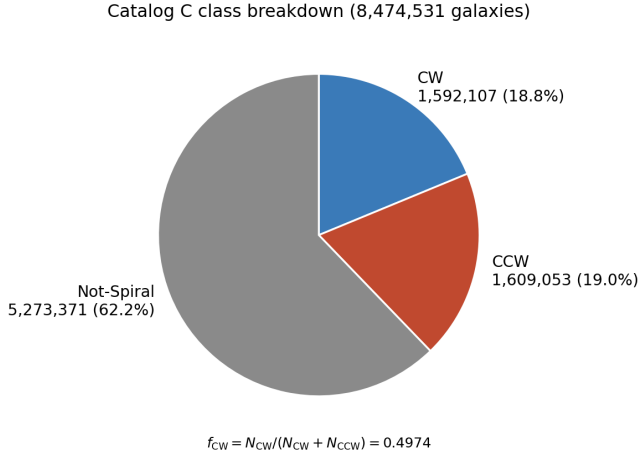


Figure 3. Catalog C composition. Of the 8,474,531 galaxies retained after image-quality QA, the equivariant TTA classifier (§3.4) assigns $N_{\text{CW}} = 1,592,107$, $N_{\text{CCW}} = 1,609,053$, and $N_{\text{NS}} = 5,273,371$ (non-spiral / edge-on / morphologically indeterminate). The spiral sub-catalog $N_{\text{spiral}} = N_{\text{CW}} + N_{\text{CCW}} = 3,201,160$ is the analysis target for all chirality statistics below (Table 4 *et seq.*).

Simple dipole.—The primary real-space estimator fits $A_p = m + \mathbf{a} \cdot \hat{\mathbf{n}}_p$ on the HC observed-label map and compares its amplitude with 10,000 fixed-occupancy galaxy-label randomizations. Each draw conditions on the observed HC-RI pixel occupancies and the global CW total among the 947,326 support galaxies, so position, support, and heteroscedastic count structure remain fixed. The declared $p_{\text{eq}} > 0.6$ cut is encoded in committed generator revision 94113e5 (2026-06-09), but no externally timestamped preregistration, frozen pre-unblinding tag, or independent blinding record exists; we therefore do not claim formal preregistration or elimination of all researcher degrees of freedom. The HC selection contains $N_{\text{selected}} = 949,584$ spirals; $N_{\text{support}} = 947,326$ of them enter the HC-RI fit across 23,682 pixels, with 2,258 excluded by the support rule. The supported fit is null-consistent at $z_{\text{mom}} = +0.705$ with one-sided upper-tail rank $p = (2246 + 1)/(10000 + 1) = 0.22468$. The

fitted amplitude is $A_{\text{dip}} = 0.00459707$ toward equatorial (RA, Dec) = (294.31°, 16.03°); the null mean and population standard deviation are 0.00348994 and 0.00156969, respectively, for seed 20260715. The legacy strict-mask confidence-cut sweep ($N_{\text{spiral}} > 10$) gave $z = +0.41, +1.14, +0.51$ at cuts 0.6, 0.7, 0.8 and is retained only as historical sensitivity context; the primary $p_{\text{eq}} > 0.6$ value is the inclusive result above.

The exact primary draw array and deterministic generator are checksummed in the release manifest. The former pixel-asymmetry permutation is retained only as a robustness diagnostic: its exact 10^4 -draw array gives $z = +0.549$ and rank $p = 0.2652$. A separate 2×3 panel uses 2,000 pixel permutations per cell (seed 20260610), with asymmetry values permuted while pixel weights remain fixed. At $N_{\text{spiral}} \geq 10, 20, 50$, respectively, the uniform-fit pairs are

$$(z, p) = (+0.536, 0.270), (+0.268, 0.359), (-0.382, 0.606), \quad (4)$$

and the N_{spiral} -weighted pairs are

$$(z, p) = (+0.783, 0.197), (+0.794, 0.203), (-0.141, 0.505). \quad (5)$$

Thus all six cells have $|z| < 0.8$. These are robustness diagnostics on HC-RI threshold variants, not additional primary tests. The unthresholded full-sample excess is reported only as a depth-correlated systematics diagnostic, not a competing primary result.

Angular power spectrum.—We perform MASTER mode-coupling deconvolution using NAMASTER (34) at $N_{\text{side}} = 64$ on the MASTER-AGF ($N_{\text{all}} \geq 1$; 24,297 pixels, $f_{\text{sky}} = 0.494$, C^2 2° apodization, depth weight W_p). The MASTER-deconvolved single-mode $\ell = 1$ value (computed on the monopole-subtracted A_p field; declared data vector, Appendix A) is $C_1^{\text{meas}} = 2.348 \times 10^{-5}$ against a 500-MC per-galaxy label-shuffle null with mean 1.71×10^{-6} and $\sigma_{\text{null}} = 2.99 \times 10^{-6}$, i.e. $+7.28\sigma$

Galaxy Chirality Asymmetry Map (8.47M galaxies, equivariant)

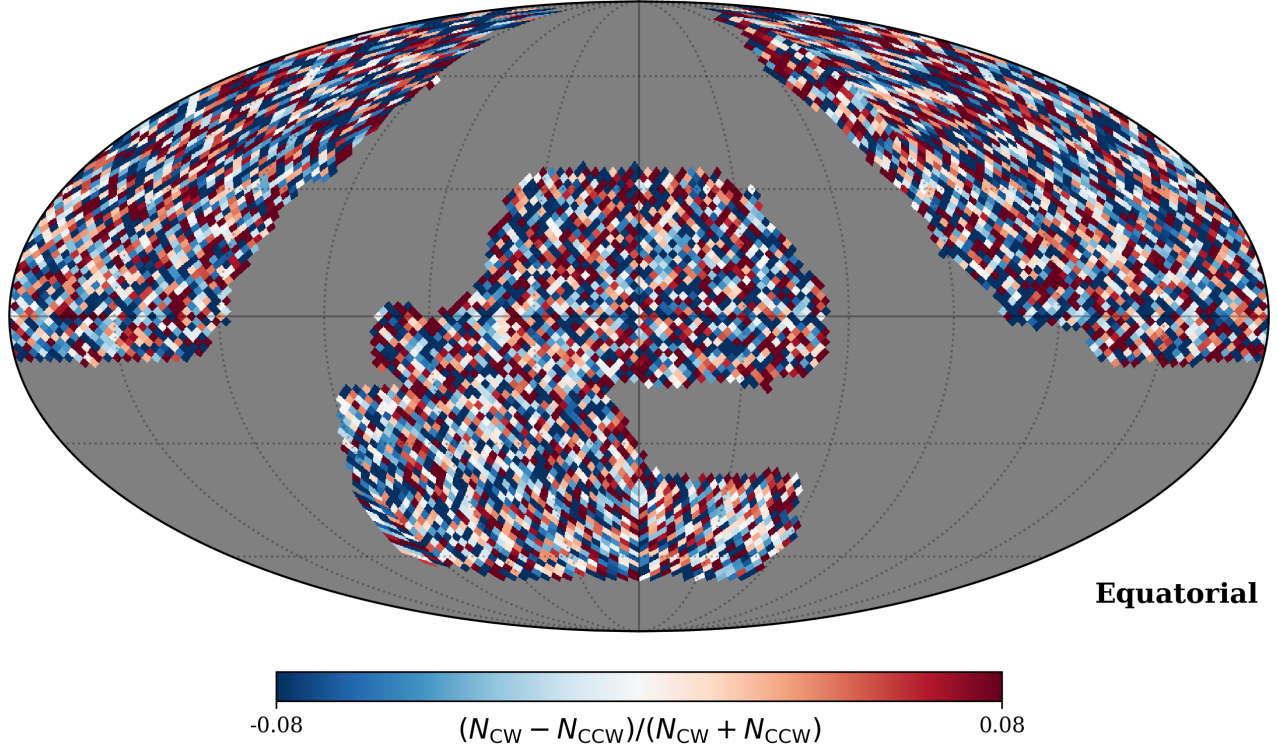


Figure 4. Equivariant (Catalog C) chirality asymmetry map of the 8.47M-galaxy catalog (Mollweide projection, equatorial coordinates; per-pixel asymmetry $A_p = (N_{\text{CW}} - N_{\text{CCW}}) / (N_{\text{CW}} + N_{\text{CCW}}) = 2(f_{\text{CW},p} - \frac{1}{2})$ at HEALPix NSIDE=64, color scale $[-0.08, +0.08]$). The DESI Legacy Imaging footprint covers $f_{\text{sky}} = 0.49005$ of the sky in the FS-C support ($N_{\text{spiral}}(p) \geq 10$ per pixel; Sec. 4.3); the $N_{\text{all}} \geq 1$ MASTER-AGF ($f_{\text{sky}} = 0.494$) is used for the apodized MASTER diagnostic. Spatial uniformity of the per-pixel CW fraction is verified across 7 equatorial coordinate slabs (§4.2); the FS-C $\ell = 1$ residual is analyzed in Sec. 4.3–4.4.

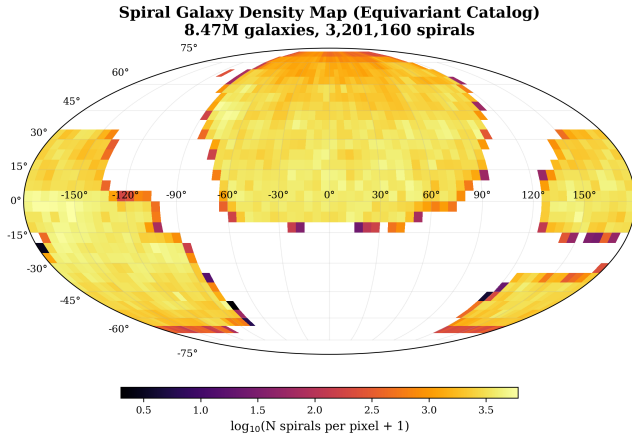


Figure 5. Sky density of the 3,201,160 classified spirals (CW + CCW combined, NSIDE=64 Mollweide). Per-pixel spiral counts scale with the DESI Legacy Imaging Surveys depth and exposure pattern; the FS-C support used for the primary $\ell = 1$ analysis (§4.3) requires $N_{\text{spiral}}(p) \geq 10$ per pixel. Spatial inhomogeneity at this scale is the leakage channel quantified in §4.4.

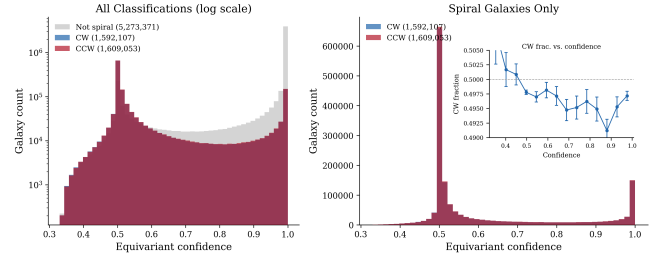


Figure 6. Distribution of maximum-class confidence $\max(P_{\text{CW}}, P_{\text{CCW}}, P_{\text{NS}})$ for all 8,474,531 galaxies. Strongly bimodal: 73.6% at $\max p \geq 0.9$ (high-confidence labels) + a long tail of indeterminate cases ($\max p < 0.5$, dominated by NS/edge-on systems). The high-confidence (HC) cuts at $p_{\text{eq}} > 0.6$ ($N = 949,584$) and $p_{\text{eq}} > 0.8$ ($N = 624,660$) used in the systematics cross-checks (§E) are indicated.

for $W_p = N_{\text{all}}$ ($+9.78\sigma$ for $W_p = N_{\text{spiral}}$); the 10^4 -permutation recompute (Table 6) reproduces this diagnostic channel at $z = +7.31$ with empirical rank $p = 6.0 \times 10^{-4}$ (one-sided, computed as $(k+1)/(N+1)$ with $k=5$ of $N=10^4$ null draws exceeding the data; Table 6 caption), and the Gaussian-equivalent σ is quoted

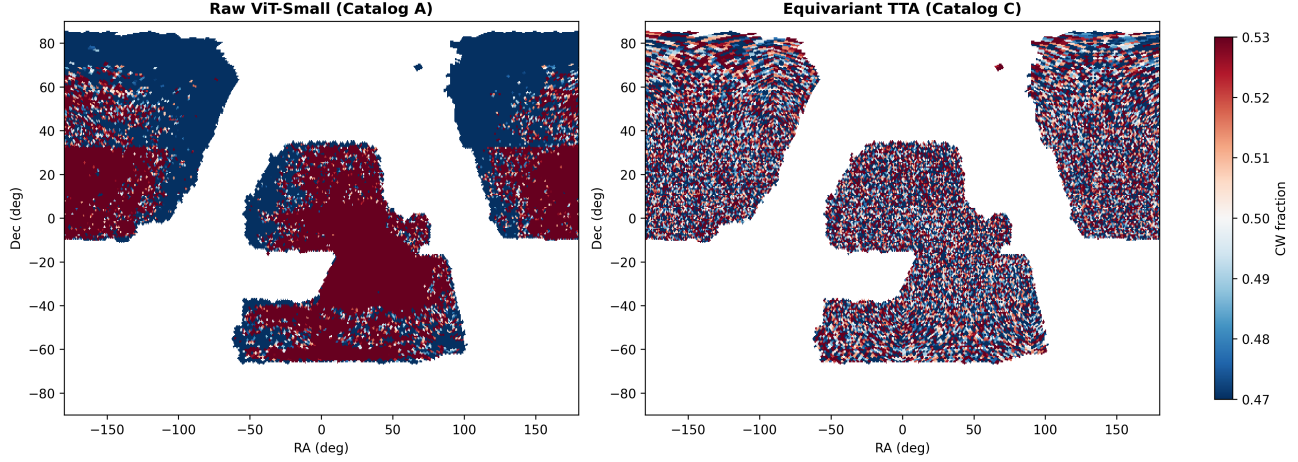


Figure 7. Raw (Catalog A) vs equivariant (Catalog C) chirality sky maps (equatorial RA/Dec, per-pixel CW fraction $f_{\text{CW},p}$, NSIDE=64; shared color scale [0.47, 0.53]). The raw definition is `class_raw_y` with `class_raw_x` fallback only where the former is missing; in this release all 3,321,795 raw spirals come from `class_raw_y` (zero fallback rows), while Catalog C contains 3,201,160 spirals. The native $N_{\text{spiral}} \geq 5$ supports contain 24,158 raw and 24,154 equivariant pixels; both displayed panels use their 24,151-pixel intersection. The panels are plotted in f_{CW} units, not the A_p units of Fig. 4: the two are related by $A_p = 2(f_{\text{CW},p} - \frac{1}{2})$, so the [0.47, 0.53] range here corresponds to $A_p \in [-0.06, +0.06]$. Left: raw single-pass classifier output; the spatially-structured $\sim 0.79\%$ classifier CW excess, modulated by non-uniform survey depth, produces the 2.31σ real-space dipole + $+6.48\sigma$ pre-MASTER $\ell = 1$ artifact. Right: 2-fold flip-equivariant TTA; flip-equivariance is enforced by construction and the measured directional bias is strongly reduced, while training-, selection-, and depth-coupled biases are not guaranteed to vanish, and the HC ($p_{\text{eq}} > 0.6$) real-space dipole is reduced to $+0.71\sigma$ under the current fixed-occupancy primary null. Generation counts and the projected streaming read are recorded in [pipelines/p2_chirality/outputs/canonical_provenance/fig7_raw_vs_eq_manifest.json](#). This visual diagnostic is the methodology cornerstone — the difference between Catalog A and Catalog C is the difference between a 2σ “detection” and a clean null, demonstrating that future chirality studies must adopt equivariant post-processing to avoid spurious dipoles.

Table 5. Primary HC estimator audit. The empirical rank value is the one-sided upper tail. The exact fixed-occupancy null-array SHA-256 is `f6360f4bec226690...152c0`; full precision and the complete hash are in the release manifest.

Quantity	Exact or reported value
$N_{\text{selected}} / N_{\text{support}}$	949,584 / 947,326
Excluded / valid pixels	2,258 / 23,682
Support / seed / null draws	HC-RI / 20260715 / 10,000
$A_{\text{dip}} / \text{monopole}$	0.0045970743 / -0.0077688925
Equatorial direction	(294.3054°, 16.0291°)
Null mean / std. (ddof = 0)	0.0034899420 / 0.0015696946
z_{mom}	+0.7053170
Upper-tail k/N / rank p	2246/10000 / 0.2246775

from the null moments. A depth-stratified null (labels permuted within 10 $N_{\text{all}}(p)$ deciles; this preserves the marginal depth distribution but not joint spatial-depth structure, so it bounds only depth-sampling effects) leaves the excess essentially unchanged ($+7.13\sigma$ / $+9.06\sigma$), excluding pixel-depth sampling alone as the driver. A weight-map sweep gives the same verdict: the excess persists under all three weightings ($W_p = N_{\text{all}} + 6.9\sigma$, $W_p = N_{\text{spiral}} + 8.5\sigma$, uniform binary $+6.7\sigma$; independent 500-MC null streams, artifact c9c; in each variant the mask-mean subtraction uses the same variant weight map, so the field-consistent N_{spiral} -weighted

subtraction is included in the sweep), so it is not an artifact of the depth-weight choice, although its magnitude is weight-dependent at the $\pm 1\sigma$ level. This channel is therefore a *systematics diagnostic* on the patchy weighted footprint — the same coherent low- ℓ family as the FS-C residual (Sec. 4.4, Appendix D) — and is not used as a cosmological null; the cosmological statement rests on the real-space dipole; the WLS observed-label template fit is a diagnostic whose physical-amplitude reinterpretation is given in Appendix D. NaMaster configuration details and the FS-C support-declaration + depth-stratification audit are in Appendix A. We emphasize that rows (i) and (iv) of Table 2 are not on the same statistical footing — different fields, masks, weights, and null procedures — so the apparent $+0.71\sigma$ vs. $+7.28\sigma$ gap is not a $17\times$ discrepancy on a common axis; the harmonic-completeness check (Sec. 7, artifact c9b) bounds what a clean Shamir-class real-space dipole would have produced in the MASTER channel — it would register at $z \approx 68$ –218 there, versus the observed $+7.28\sigma$ — but it does not establish statistical consistency of the two estimators on a common axis.

Reader’s note (Table 6). The σ/z entries are systematics-attributed harmonic diagnostics against different nulls; they are not detection significances

Table 6. MASTER-decoupled angular power of the equivariant Catalog C asymmetry map on two diagnostic footprints, each with its own field and null convention (Appendix A). Values are rounded; full arrays are retained in the release. The apodized MASTER-AGF block uses $W_p = N_{\text{all}}$, whereas the unapodized FS-C block uses binary weight and N_{spiral} -weighted mean subtraction, so C_b amplitudes and z values are not comparable across blocks or with the primary real-space estimator. Band 1 is the single $\ell = 1$ mode within the full coupling matrix. All entries are systematics diagnostics, not cosmological measurements. Empirical ranks use $(k + 1)/(N + 1)$; the separate 500-draw direct-MC diagnostic has add-one rank $p_{\text{MC}} = 0.03194$ (Sec. 4.4).

Footprint	Band	$C_b^{\text{data}} \times 10^6$	$\langle C_b \rangle_{\text{null}} \times 10^6$	$\sigma_{\text{null}} \times 10^6$	z	rank p (1-sided)
apod., $W_p = N_{\text{all}}$	$\ell = 1$	24.74	1.93	3.12	+7.31	6.0×10^{-4}
	$\ell \in [2, 6]$	5.28	1.87	0.73	+4.67	5×10^{-4}
	$\ell \in [7, 11]$	3.12	1.92	0.50	+2.41	0.015
	$\ell \in [12, 16]$	2.38	1.92	0.40	+1.16	0.126
	$\ell \in [17, 21]$	2.64	1.92	0.35	+2.05	0.027
	$\ell \in [22, 26]$	2.67	1.92	0.31	+2.42	0.013
canonical, unapod.	$\ell = 1$	7.27	0.57	0.84	+7.93	3×10^{-4}
	$\ell \in [2, 6]$	1.42	0.56	0.20	+4.20	9×10^{-4}
	$\ell \in [7, 11]$	0.91	0.57	0.14	+2.47	0.015
	$\ell \in [12, 16]$	0.79	0.57	0.11	+1.98	0.030
	$\ell \in [17, 21]$	0.83	0.57	0.09	+2.75	0.0065
	$\ell \in [22, 26]$	0.74	0.57	0.09	+2.00	0.029

and must not be compared row-to-row, footprint-to-
footprint, or with the primary real-space dipole. The
HC real-space result (+0.71 σ) is the sole primary esti-
mator; the WLS $z \approx -7.6$ value is a correlated observed-
label template diagnostic.

4.4. Monopole+Mask Leakage Generative Null

The FS-C direct-MC $\ell = 1$ value of +3.64 σ (per-
pixel label-shuffle null) and the local hemisphere max-
imum of 3.05 σ (label-shuffle null, 648-direction scan;
Appendix C) are candidate manifestations of mask-
geometric leakage of the global 9.5 σ monopole. We
formalize this with a generative null: $N = 500$ realiza-
tions in which the per-pixel CW count is drawn from
Binomial($N_{\text{spiral}}(p), p_{\text{CW}}^{\text{global}}$) on the exact FS-C support,
with no injected dipole.²

² Here $N_{\text{spiral}}(p) \equiv N_{\text{CW}}(p) + N_{\text{CCW}}(p)$ is the per-pixel *spiral* count, not the all-galaxy per-pixel count $N(p)_{\text{all}} = N_{\text{CW}}(p) + N_{\text{CCW}}(p) + N_{\text{NS}}(p)$ that appears as the weighting field W_p in the A_p definition. The chirality field $A_p = (N_{\text{CW}}(p) - N_{\text{CCW}}(p))/N_{\text{spiral}}(p)$ is defined on spirals only, so the generative null draws from the spiral trial pool to be self-consistent with the field it is reproducing. The generative-null code uses $N_{\text{spiral}}(p)$, and the primary 99.32% pre-MASTER reproduction figure in Table 7 is on the spiral-trial draw. A parallel rerun on $N(p)_{\text{all}}$ -trial draws ($N = 500$, seed 42) reproduces 99.33% of the observed pre-MASTER pseudo- $C_\ell^{(\ell=1)}$ power, vs. 99.32% for the spiral-trial draw: the primary reproduction figure is robust to the trial-pool choice. The larger per-pixel trial counts shrink the binomial null variance, so the pre-MASTER residual rises from +1.69 σ (spiral-trial, Table 7) to +2.80 σ (N_{all} -trial) at essentially identical reproduced power. The per-pixel trial-count inflation factor is $\langle N_{\text{all}}/N_{\text{spiral}} \rangle = 2.83$ (in-mask pixel mean; the global count ratio is 8,474,531/3,201,160 = 2.65).

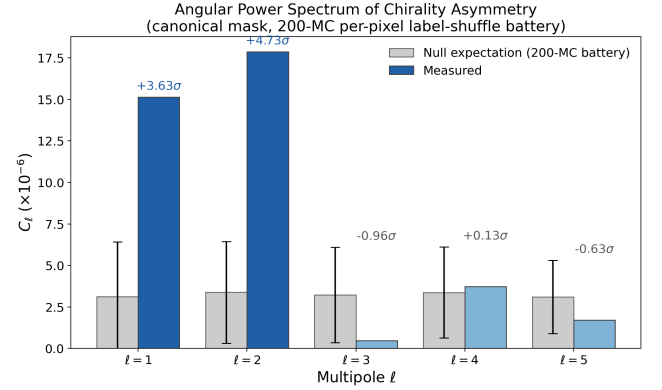


Figure 8. Pseudo- C_ℓ of the chirality field A_p on the canonical mask, $\ell = 1$ –5 (single panel; grouped bars). Gray bars with error bars: per-pixel label-shuffle null expectation from the canonical 200-MC multi-null battery (Appendix D), $\pm 1\sigma$; colored bars: measured C_ℓ . The per- ℓ significance annotations embedded in the panel are the canonical battery values ($\sigma_{\ell=1} = +3.63$, $\sigma_{\ell=2} = +4.73$, $\sigma_{\ell=3,4,5} = -0.96, +0.13, -0.63$). The $\ell = 1, 2$ broadband excess is the systematics-attributed structure analyzed in Appendix D. The post-MASTER FS-C residual is +3.64 σ (distinct estimator from the panel’s pre-MASTER pseudo- C_ℓ ; add-one rank $p_{\text{MC}} = 0.03194$; Sec. 4.4), a non-primary systematics-attributed value. The sole primary conclusion is the HC real-space observed-label null ($p_{\text{eq}} > 0.6$, $N_{\text{selected}} = 949,584$, $N_{\text{support}} = 947,326$, $z = +0.71$); the WLS template score in Appendix D is diagnostic.

The monopole-only null reproduces 99.32% of the observed pre-MASTER pseudo- $C_\ell^{(\ell=1)}$ power (± 0.40 pp per-realization null scatter, $N = 500$; the residual is +1.69 σ , Table 7). The reproduction

Table 7. Monopole+mask leakage null ($f_{\text{sky}}=0.49005$, seed = 42; $N=500$ binomial-monopole realizations). Pseudo- C_ℓ entries in this table are dimensionless band values of the un-monopole-subtracted f_{CW} -map convention used by the generative null, and are NOT on the A_p -map $\times 10^{-6}$ units of Table 6; the two tables intentionally use different fields and normalizations. The monopole-only null reproduces 99.32% of the observed pre-MASTER pseudo- $C_\ell^{(\ell=1)}$ power (residual $+1.69\sigma$, consistent with the monopole-only null at the pre-MASTER stage). *This is a pre-MASTER diagnostic only*; the post-MASTER decoupled null gives $\sigma=+4.84$ (monopole-only reproduces $\sim 12\%$ of post-MASTER C_1), as detailed in Sec. 4.4. Both rows are computed against the monopole-only generative null; the hemisphere row uses its own 768-direction NSIDE_{dir}=8 scan grid, distinct from the 648-direction 10° -grid look-elsewhere scan of Appendix C, and its z is not comparable to the label-shuffle 3.05σ value quoted there.

Statistic	Data	Null	z
Pre-MASTER pseudo- $C_\ell^{(\ell=1)}$ (FS-C support)	1.6961×10^{-2}	$(1.6846 \pm 0.0068) \times 10^{-2}$	$+1.69$
Hemisphere max $ A $ (NSIDE _{dir} =8, 768 directions)	3.484×10^{-3}	$(1.693 \pm 0.405) \times 10^{-3}$	$+4.42$

statistic is the ratio of means, $\langle C_1^{\text{null}} \rangle_{N=500} / C_1^{\text{data}}$; because the observed C_1^{data} is a fixed scalar, the per-realization mean of the ratios $C_1^{\text{null},k} / C_1^{\text{data}}$ is identical, so the mean-of-ratios/ratio-of-means distinction does not arise for this statistic. The standard error on the mean reproduction fraction is $0.40/\sqrt{500} \approx 0.018$ pp (the ± 0.40 pp quoted above is the per-realization scatter, not the uncertainty on the mean; artifact [pipelines/p2_chirality/outputs/canonical_provenance/monopole_mask_null_results.json](#)). The prior literature’s pre-MASTER dipole-detection claims are therefore attributed at the pre-MASTER level to this leakage channel under our DESI/ViT-Small pipeline; a matched Ganalyzer reanalysis remains required for a likelihood-level exclusion of their specific estimator and cuts. **The 99.32% reproduction figure applies exclusively to the un-deconvolved pre-MASTER pseudo- $C_\ell^{(\ell=1)}$.** The post-MASTER behavior is qualitatively different: a MASTER-decoupled monopole-only null ($N = 500$ realizations; artifact [pipelines/p2_chirality/outputs/canonical_provenance/master_decoupled_monopole_null.json](#)) gives $\sigma = +4.84$ relative to the data, with the monopole-only null mean reproducing only $\sim 12\%$ of the post-MASTER decoupled C_1 ; the 10^4 -realization diagnostic recompute yields $\sigma = +5.14$ (artifact [pipelines/p2_chirality/outputs/canonical_provenance/master_decoupled_monopole_null_10k.json](#)). The post-MASTER residual therefore requires coherent depth/PSF/morphology systematics beyond the monopole-only channel — not monopole-mask leakage alone — consistent with the eight-anchor systematic analysis of Appendix D. MASTER decoupling substantially reduces, but does not remove, the FS-C pseudo- C_ℓ leakage; the post-MASTER residuals ($+3.64\sigma$ canonical unapodized; $+7.28\sigma$ on the apodized weighted footprint, unchanged at $+7.13\sigma$ under a depth-stratified null) are non-primary, systematics-attributed values consistent with coherent low- ℓ structure that MASTER

does not remove on the patchy weighted footprint (Appendix D). The primary null-dipole conclusion rests on the HC real-space dipole ($p_{\text{eq}} > 0.6$, $N_{\text{selected}} = 949,584$, $N_{\text{support}} = 947,326$) at $+0.71\sigma$. The block-bootstrap WLS result is retained as an observed-label template diagnostic: $z \approx -7.6$ at $A_p = 1.7\%$, but only $1.36\sigma_{\text{boot}}$ for a physical 1.7% signal after $g = 0.398$ dilution.

Two diagnostics are bound to the declared FS-C base support: apodized-mask robustness and the multipole spectrum. They show that the $+3.64\sigma$ residual persists after apodization and is broadband, with $\ell = 2 > \ell = 1$, rather than a clean dipole. Quality-quartile, leg-proxy, boundary-distance, density-null, WLS/bootstrap, and direct cross-spectrum calculations either redefine the support, use a different mask, or do not record enough mask provenance to prove identity with FS-C; Appendix D retains their results only as out-of-scope provenance. They are not used in the FS-C synthesis or as a physical constraint.

Support correction. The historical $+3.80\sigma$ density-null and WLS/block-bootstrap numbers summarized in older audit language below were generated on broader latitude-cut supports, not FS-C. They are excluded from the support-consistent synthesis and provide no FS-C or physical constraint; Appendix D records the exact discrepancy.

Quantitative forward model and cross-estimator stress test. The imaging+DR8-morphology forward model reproduces 53.0% of the full-sample $\ell = 1$ amplitude by scalar ratio, while direct vector subtraction leaves 62.3%; these definitions are not interchangeable. The residual amplitude is 6.95×10^{-3} in A_p . Deterministic map injections change the HC fitted amplitude from 0.4597% to 0.6710% for the full template, 0.5533% for the scalar remainder, and 0.5694% for the vector remainder. Thus the residual is not automatically irrelevant, but these shared-catalog injections neither identify its origin nor supply the missing joint covariance, which remains open.

Table 8. Support audit of diagnostics associated with the $+3.64\sigma$ FS-C $\ell=1$ residual. Only rows explicitly bound to the FS-C base support enter the synthesis.

Anchor	Key result	Verdict
(a) Apodized-mask robustness	$+3.57\sigma$ ($\approx$ binary-mask $+3.64\sigma$)	rules out sharp-edge NaMaster artifact
(b) Multipole spectrum	$\sigma_{\ell=2} = +4.73 > \sigma_{\ell=1} = +3.63$ (not $\ell=1$ -dominant)	SYS
(c) Quality-quartile stratification	quartile-specific masks, not fixed FS-C	out of scope
(d) Leg-proxy cross-power	24,270 pixels, not 24,087-pixel FS-C	out of scope
(e) Density-stratified null	$+3.80\sigma$ on broader latitude mask	out of scope
(f) Boundary-distance variance	35,438-pixel latitude mask, not FS-C	out of scope
(g) WLS template fit	$z_{\text{boot}} \approx -7.6$ on broader latitude mask	out of scope
(h) Direct cross-spectrum	exact mask not recorded in artifact	out of scope

Synthesis: the two support-bound rows show apodization robustness and broadband low- ℓ structure; the other six rows are excluded.

4.5. Signal-Hunt Diagnostics

All signal-hunt diagnostics (confidence stratification, RA-quadrant scatter, hemisphere north/south, per-imaging-leg $\times$ confidence-bin) point to the same conclusion: the FS-C residual is structured along classifier-systematic, footprint-systematic, and galactic-foreground axes, not along a primordial-dipole-aligned axis. The $+3.29\sigma$ signal in the 1.87M-galaxy [0.5, 0.6) confidence bin does not survive the sample-purity ladder: cutting to $p_{\text{eq}} > 0.6$ gives -0.03σ under the same confidence-stratified dipole estimator and null (this is a distinct statistic from the primary HC real-space dipole of Sec. 4.3). Full diagnostic tables are in Appendix C.

5. COMPARISON WITH PREVIOUS WORK

5.1. Shamir (2012, 2020, 2022)

Under the present ViT/TTA pipeline, the full-footprint regional WLS amplitude is 0.32% in A_p and equal-area slab maxima reach 0.46–0.56%. The HC real-space result is null-consistent. Comparisons with Shamir’s Ganalyzer results are qualitative because the estimators, masks, and cuts differ; neither monopole-mask leakage nor depth-coupled classifier bias establishes what a matched Ganalyzer run would return. We therefore make no frequentist or physical exclusion claim. A matched-footprint independent-estimator analysis is required.

5.2. CE-ResNet (Jia et al. 2023)

CE-ResNet (7) achieves CW/CCW = 0.998 with architectural equivariance on 1.95 million galaxies. Our Catalog C achieves $1.6\times$ the spiral coverage with CW/(CW + CCW) = 0.4974 ± 0.0003 using TTA-equivariance. The two pipelines are complementary: CE-ResNet offers a stronger single-pass mathematical guarantee; our pipeline offers larger survey-scale coverage, a dedicated NOT_SPIRAL class, and a quantitative bias-hardening audit.

6. DISCUSSION

The raw Catalog A dipole (2.31σ real-space; $+6.48\sigma$ pre-MASTER) demonstrates that a classifier bias of only 0.79%, combined with non-uniform sky coverage, produces highly significant but entirely spurious dipole signals. Equivariant averaging reduces the real-space dipole from 2.31σ to $+0.71\sigma$ under the current fixed-occupancy primary null; the raw value used the legacy isotropic-permutation diagnostic and is retained only as methodology context. MASTER deconvolution substantially reduces the monopole-mask leakage that sources the $+6.48\sigma$ pre-MASTER pseudo- C_ℓ (Sec. 4.4). The 3.05σ hemisphere signal (label-shuffle null; Appendix C) is classified as a documented systematic-floor artifact: the principled directional look-elsewhere control is the direct-MC max-statistic null (which incorporates the 648 tested directions and their correlations exactly, Appendix C), under which the direct-MC max-statistic null rejects isotropic random-label noise at $p_{\text{LEE}} \leq 10^{-4}$, so the 3.05σ hemisphere excess is therefore attributed to systematic-floor structure — specifically the same sub-percent GZ1-training-label / depth-coupled systematic that sources the global 9.5σ CW-fraction monopole.

6.1. Pseudo-label independence and the shuffle-null limitation

Human-vote cross-check. Direct Galaxy Zoo 1 human CW/CCW votes, with no learned model in the chirality-label chain, give a null-consistent dipole at $z = -0.54\sigma$ (rank $p = 0.67$) from 46,017 matched inputs. The exact rerun retains 4,963 galaxies in 394 pixels after its strict $N_{\text{pixel}} > 10$ cut (41,054 matched inputs are excluded), and its pixel-permutation null differs from the fixed-occupancy primary. It therefore corroborates a null under its own convention but does not support a numerical power ratio or tighten the sub-percent HC observed-label result. The shuffle nulls still cannot test a spatially varying pseudo-label systematic orthogonal

to the external template basis. The WLS diagnostic and finite injection grids do not supply a calibrated ceiling on such inherited power. A spatially resolved confusion model therefore remains open.

6.2. Statistical Scale and Finite Injection Scores

Fisher statistical-only scale.—For the full-amplitude dipole convention $p_{\text{CW}}(\hat{n}) = \frac{1}{2}(1 + A \cos \theta)$, the per-galaxy Fisher information on A at $A = 0$ is $\cos^2 \theta / [p(1 - p)] \cdot (\partial p / \partial A)^2 = \cos^2 \theta$, so with the full-sky idealization $\langle \cos^2 \theta \rangle = \frac{1}{3}$,

$$\sigma(A) = \sqrt{\frac{3}{N_{\text{spiral}}}} = 2\sqrt{3} \sigma(f_{\text{CW}}) = 9.7 \times 10^{-4} \quad (6)$$

at $N_{\text{spiral}} = 3,201,160$ (i.e. $\sigma(A/2) \approx 0.048\%$), giving a 3σ ideal floor of $3\sigma(A) \approx 0.29\%$ full-amplitude. This full-sky idealization omits the realized footprint, classifier transfer, and orientation dependence and is therefore a scale reference only. At the HC sample size $N = 949,584$, the same idealization gives $\sigma(A) = 1.78 \times 10^{-3}$ and a nominal 3σ scale of 0.53% ; it is not a calibrated detection threshold. Under a purely illustrative scalar transfer $A_{\text{obs}} = gA_{\text{phys}}$ with fixed known g , uncertainty would scale as $\sigma(A_{\text{phys}}) = \sigma(A_{\text{obs}})/g$. Here $g = 0.398$ is an aggregate GZ1-accuracy dilution, not a spatially resolved physical transfer, so applying $1/g$ does not create a calibrated physical uncertainty, threshold, or bound.

Finite-grid injection scores.—The earlier Monte Carlo injection sweep on the HC sample ($N = 949,584$; 100 injections per amplitude) is retained as descriptive tested-grid evidence. Under the area-uniform axis draw, the score fractions are 0.59, 0.91, and 1.00 at full amplitudes $A = A_p = 0.75\%$, 1.0% , and 1.5% ; the originally tabulated polar-angle-uniform sweep gives 0.55, 0.91, and 1.00. Each amplitude uses only 100 injections and a fixed per-pixel binomial label-shuffle calibration. We report these fractions directly rather than defining calibrated 50% or 95% recovery amplitudes. In every injection section, $A = A_p$ is the full asymmetry amplitude and the peak deviation of f_{CW} is $A/2$. The scalar transfer $g = 0.398$ is illustrative only because the spatial transfer model remains open.

What the injection-recovery chain does and does not traverse. For clarity about the scope of the sensitivity calibration we state explicitly which links of the classification-to-dipole chain the injection-recovery sweep passes a signal through, and which it does not. The sweep injects a dipole in the *observed hard-label* CW/CCW field and propagates it through per-pixel map-making, the real-space dipole estimator, and the per-pixel-shuffle score. It does not traverse the ViT,

NOT_SPIRAL triage, confidence cut, or spatially varying confusion, and the small deterministic-axis grids are insufficient for calibrated coverage. We therefore report direct tested-grid fractions only. The illustrative bridge from observed-label to physical amplitude uses a single dilution factor g ; it does not close the spatial transfer gap. For reference, its value is robust to the asymmetric-confusion arithmetic rather than assume symmetric errors: the correct first-order transfer slope of the observed CW fraction under an asymmetric confusion matrix with CW sensitivity s_{CW} and CCW sensitivity s_{CCW} is $g_{\text{eff}} = s_{\text{CW}} + s_{\text{CCW}} - 1$ (the derivative of $q s_{\text{CW}} + (1 - q)(1 - s_{\text{CCW}})$ with respect to the true CW fraction q). Substituting the committed GZ1 confusion values ($s_{\text{CW}} = 0.674$, $s_{\text{CCW}} = 0.724$; Table 14) gives $g_{\text{eff}} = 0.397616$. The pooled-accuracy proxy gives $2a - 1 = 0.398217$ (with $a = 0.699108$); the two agree to three decimals but are not algebraically identical because pooled accuracy is class-frequency weighted and the evaluable true classes are not exactly balanced. This comparison is conditional on the full-overlap confusion matrix, whose training rows were not removed; it is therefore an illustration rather than an independent transfer calibration. Within that matrix the mild CW/CCW asymmetry changes g by $< 10^{-3}$, so the $\sim 1.88\%$ ($= 0.75\%/g$) illustrative figure is not sensitive to symmetric-versus-asymmetric arithmetic. The residual triage-to-NOT_SPIRAL removal ($\sim 19\%$) is an uncalibrated selection-completeness channel. Because its human CW/CCW composition and spatial dependence were not retained in this transfer calculation, it cannot be assumed chirality-neutral and is not folded into the illustrative slope g . *Stage A: full-catalog mirror-pair transfer/equivariance sweep.* The production ViT was run on each of the 8.47×10^6 original images and its mirror. This measures paired-output behavior, not recovery of a physically injected sky field. The raw-head CW/CCW flip fraction is $T_{\text{raw}} = 0.2303 \pm 0.0002$, while the production Z_2 -TTA probability swap is exact by construction and its hard-argmax flip recovery is $T_{\text{eq}} = 0.9997$; the 2.6×10^{-4} shortfall is due to exact CW/CCW argmax ties. These are full-catalog mirror-pair transfer and equivariance diagnostics, not a continuous image transformation, physical chirality calibration, or end-to-end injection-recovery result ([pipelines/p2_chirality/outputs/canonical_provenance/e2e_fullrun/e2e_transfer_function_full.json](#)).

Stage B: paired-image-to-field surrogate. We next use the two precomputed Stage-A outcomes as a discrete intervention: for 20 deterministic Fibonacci-sphere axes and injected amplitudes $A = \{0.5, 0.75, 1.0, 1.5, 2.0\}\%$,

the original or mirrored member is selected to realize each latent CW/CCW draw, then the released production hard label and confidence are propagated through NS triage, p_{eq} cuts, the $N_{\text{spiral}}(p) \geq 10$ map, and the same uniform-pixel `healpy.fit_dipole` estimator. The released catalog contains 949,584 canonical HC spirals, whereas the fresh Stage-A export would select 949,650; the 66-row count seam is not treated as canonical. All 949,584 canonical HC rows have concordant production/Stage-A paired hard labels. At lower confidence, 4,369 of 3,201,160 production spirals have discordant export labels and are excluded rather than forcibly paired, leaving 3,196,791 defensible pairs (99.864%). On the canonical HC sample the numbers of axes crossing the declared 3σ score are 1/20, 16/20, 16/20, 20/20, and 20/20 at full amplitudes $A = A_p = 0.5\%$, 0.75% , 1.0% , 1.5% , and 2.0% . On the concordant full pool they are 12/20, 20/20, 20/20, 20/20, and 20/20. These are pilot fractions over deterministic axes, not independent Bernoulli trials or calibrated population recovery probabilities. Even under an inapplicable independent-binomial reading, 20/20 gives a one-sided 95% Clopper–Pearson lower bound of 0.8609, not 95% recovery. Angular-quadrature convergence and independent sky/noise realizations were not run. The full pilot-grid distributions, signed projections, p16–p84 ranges, NS-triage counts, and all strata are stored in `pipelines/p2_chirality/outputs/canonical_provenance/stage_b_hybrid_image_field_recovery.json`. This Stage B result remains conditional on the classifier-defined member of each pair. It is not a validated continuous morphology transform, does not supply independent per-object true chirality or truth for NS/NS pairs, and cannot calibrate the physical observed-to-true transfer unconditionally. Accordingly the spatially resolved physical confusion model remains open and all physical falsification claims remain tied to the observed hard-label field. A first, coarse instance of that spatially varying confusion model *now exists at imaging-leg granularity*: the GZ1-overlap confusion matrix stratified by the two P4 imaging legs and by confidence (Appendix B, Table 15) shows the directional CW↔CCW error asymmetry consistent with zero in every leg and confidence stratum (leg asymmetries bounded to $\lesssim 1.4$ pp, science-cut to $\lesssim 0.6$ pp). Directional asymmetry is not, however, the only spatial bias channel. For local true CW fraction $q(\mathbf{x})$ and misclassification rates $e_{\text{CW} \rightarrow \text{CCW}}(\mathbf{x})$ and $e_{\text{CCW} \rightarrow \text{CW}}(\mathbf{x})$, the observed fraction is

$$q_{\text{obs}}(\mathbf{x}) = q(\mathbf{x})[1 - e_{\text{CW} \rightarrow \text{CCW}}(\mathbf{x})] + [1 - q(\mathbf{x})]e_{\text{CCW} \rightarrow \text{CW}}(\mathbf{x}). \quad (7)$$

Even for symmetric error $e_{\text{CW} \rightarrow \text{CCW}} = e_{\text{CCW} \rightarrow \text{CW}} = e(\mathbf{x})$, this becomes $q_{\text{obs}} = q + e(1 - 2q)$; spatial variation in e can therefore modulate the observed field wherever the local selected fraction is not exactly one half. The committed stratified artifact gives net induced $\Delta f_{\text{CW}} = 0.00142$ for BASS+MzLS and 0.00331 for DE-CaLS, a point-estimate leg difference of -0.00189 . The individual leg intervals include zero, and no covariance-aware interval for their difference is retained, so these values neither establish a significant leg difference nor close the channel. Error magnitude also varies by leg ($z=4.2$) and confidence (accuracy $0.72 \rightarrow 0.96$); it is not generically a spatially constant dilution already carried by one scalar g . The remaining gap is a finer per-pixel conditional confusion model (depth, PSF, and morphology jointly) and uncertainty propagation into the primary estimator. In its absence we hold the operative claims to the observed hard-label field (the $+0.71\sigma$ real-space null and finite observed-label pilot fractions) and treat the scalar- g physical-amplitude conversion as an illustrative spatially averaged mapping, not a spatially resolved physical bound.

The empirical DR8 axis-ratio cross-match finds $f_{\text{edge}} = 15.80\%$ (505,889 of 3,201,160 classified spirals at $b/a < 0.3$). A linear dilution estimate is useful only conditional on flip-symmetric hard labels. Soft equivariance motivates that condition, but hard argmax is non-linear; Appendix E therefore reports an empirical edge-on-isolated coherence test rather than claiming that directional bias is excluded. LSST extrapolations and spectroscopic-redshift upgrades remain future work.

6.3. Relation to Parity-Violating Sectors

The $\ell = 1$ morphology observable is parity-even and cannot by itself constrain primordial parity violation. Translating it to cosmic birefringence, Chern–Simons gravity, or another early-universe sector requires a derived galaxy-formation transfer function, which this work does not provide. Accordingly, neither the HC null nor the diagnostic WLS/harmonic channels establish a physical parity-amplitude bound. A matched-footprint Ganalyzer analysis and a theory transfer calculation remain necessary before comparing likelihoods across estimators or sectors.

Downstream transfer-calibration roadmap.—A future physical calibration would require an object-level held-out human-label set with the historical training objects removed; image-level chirality interventions spanning imaging leg, depth, PSF, axis ratio, and morphology; propagation through the complete cutout, classifier, NOT_SPIRAL triage, confidence-selection, and map-making pipeline; and a spatially resolved directional

Table 9. Descriptive score fractions $P(\sigma > 3)$ versus injected full amplitude $A = A_p$ on the HC sample ($N = 949,584$; 100 injections per amplitude; per-pixel-shuffle null). The finite grid gives $P = 0.55, 0.91$, and 1.00 at $A = 0.75\%$, 1.0% , and 1.5% under the tabulated polar-angle-uniform convention; binomial standard errors are at most 0.05 . These values are not calibrated recovery thresholds or physical limits.

A (%)	0.05	0.1	0.2	0.3	0.5	0.75	1.0	1.5	2.0
$P(\sigma > 3)$	0.01	0.01	0.01	0.03	0.15	0.55	0.91	1.00	1.00

confusion model carried into a joint estimator covariance. This is a roadmap rather than a product of the present release. The current overlap-contaminated GZ1 agreement and finite injection pilots cannot substitute for those inputs.

6.4. Open Follow-up and Future Directions

Four scientific gates remain open: a physical morphology transfer function, a matched-footprint independent-estimator comparison, a joint real-space/harmonic/nuisance covariance likelihood, and independent external preregistration or blinding of the primary analysis. The catalog payload is public and commit-pinned; a DOI-backed paper/source archive remains a separate submission gate. The HC real-space estimator is the sole primary result; it is empirically less exposed to the measured harmonic leakage but does not mathematically bypass that channel. The WLS and harmonic analyses remain diagnostics.

7. CONCLUSIONS

We publish an 8,474,531-object observed-label catalog release and report one primary result: the HC real-space dipole is null-consistent ($N_{\text{selected}} = 949,584$, $N_{\text{support}} = 947,326$, $z = +0.71$, one-sided upper-tail $p = 0.225$ under the declared null convention). The exact safe catalog, quarantine, retained null array, manifest, schema, and reproducer are public at the commit-pinned release identified in Data Availability. All harmonic, WLS, injection, and transfer calculations are diagnostics. Our main conclusions are:

Harmonic-channel response diagnostic.—The apodized-footprint MASTER $\ell = 1$ injection pilot reports its observed-label score fractions and median injected scores in Table 10. Because this channel has a different field, mask, weights, and null from the primary estimator, these values diagnose pipeline response only; they do not establish completeness, a physical exclusion, or an “unmissable” amplitude.

Diagnostic methodological finding: a quantifiable monopole-mask leakage channel.—A small uniform classifier monopole couples to the patchy survey mask and inflates the raw pseudo- C_ℓ at $\ell = 1$. A 500-realization monopole-only generative null reproduces 99.32% of

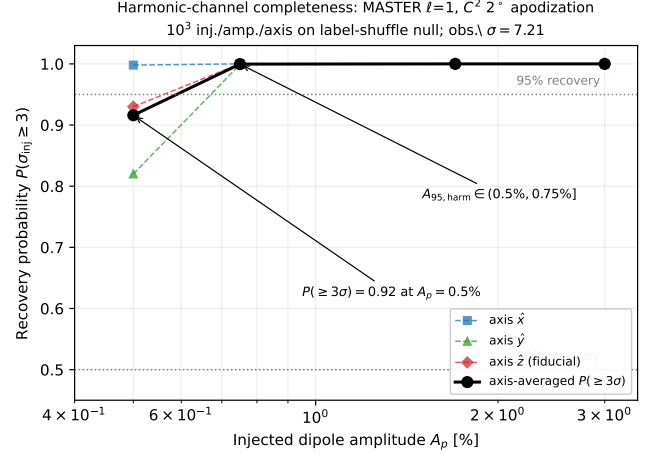


Figure 9. Diagnostic score fraction $P(\sigma_{\text{inj}} \geq 3)$ versus injected observed-label amplitude A_p in the apodized MASTER $\ell = 1$ channel (10^3 injections per amplitude and axis; artifact c9b). Curves show the tested axes and their average under this channel’s label-shuffle score. Horizontal guide lines are descriptive; they are not calibrated recovery thresholds or physical limits. The body-canonical observed diagnostic is $+7.28\sigma$ under a separate 500-MC null, whereas artifact c9b gives 7.21 under its internal background. Neither is a cosmological significance.

the observed pre-MASTER power under that construction. Post-MASTER residuals remain non-primary and systematics-attributed. Because Ganalyzer uses a different estimator, sample, and selection, a likelihood-level comparison requires a matched-footprint analysis.

FS-C MASTER $\ell = 1$ direct compute.—A direct single-mode NaMaster execution on the FS-C sample ($N_{\text{spiral}} = 3,201,160$, $f_{\text{sky}} = 0.49005$, 500 per-pixel random-label permutation nulls, seed 42) yields $\sigma_{\text{canonical}}^{\text{direct}} = +3.64\sigma$ ($k = 15$ of $N = 500$ null draws; add-one rank $p_{\text{MC}} = (15 + 1)/(500 + 1) = 0.03194$; Gaussian-equivalent $\approx 1.9\sigma$); the 10^4 -permutation recompute of the same FS-C unapodized field in Table 6 gives $z = +7.93\sigma$ — the 500-MC $+3.64\sigma$ direct single-mode value is retained for continuity with the leakage analysis; the 10^4 -permutation Table 6 FS-C row is the current high-statistics diagnostic under its committed field convention (see Sec. 3.1 and Table 6 caption). Both the $+3.64\sigma$ and $+7.93\sigma$ values are systematics-attributed diagnostics from different null-run sizes and

Table 10. Diagnostic MASTER $\ell = 1$ injection scores (10^3 injections per amplitude and axis; artifact c9b). The 3σ score uses this channel’s label-shuffle null, and median z ranges are axis-dependent. These entries are not calibrated recovery probabilities, physical bounds, or interchangeable with the primary real-space result.

A_p	$P(\geq 3\sigma)$	Med. z (injected)	Obs. z
0.5%	0.92	—	+7.28 ^a
0.75%	≥ 0.999	—	—
1.7%	≥ 0.999	$\approx 68\text{--}218$	—
3.0%	≥ 0.999	$\approx 209\text{--}685$	—

NOTE—^aObserved harmonic channel; systematics-attributed (Appendix D).

mask/weight conventions; they are not cosmological detection significances, are not directly comparable to each other, and are not comparable to the primary real-space estimator. The HC ($p_{\text{eq}} > 0.6$) real-space dipole at $+0.71\sigma$ under the fixed-occupancy primary null anchors the null verdict. The block-bootstrap WLS fit is a correlated full-sample diagnostic of a clean observed-label template, not an independent physical exclusion; a joint covariance likelihood with the harmonic channel remains open.

Bias hardening is essential.—Our raw (Catalog A) analysis produces a 2.31σ real-space dipole and a $+6.48\sigma$ pre-MASTER pseudo- C_ℓ from a classifier CW excess of only 0.79%, modulated by non-uniform survey coverage. Equivariant post-processing reduces the real-space dipole to $+0.71\sigma$ under the current fixed-occupancy primary null; MASTER mode-coupling deconvolution substantially reduces the monopole-mask leakage channel

that sources the $+6.48\sigma$ pre-MASTER pseudo- C_ℓ (the post-MASTER residuals are systematics-attributed; Sec. 4.4). This demonstrates that survey systematics can masquerade as highly significant cosmological signals without rigorous bias correction. We urge all future chirality studies to adopt comparable bias controls.

Finite injection pilot and unresolved calibration.—For the HC estimator, the Stage-B 20-axis pilot gives score-pass counts $[1, 16, 16, 20, 20]/20$ at $A = A_p = [0.5, 0.75, 1.0, 1.5, 2.0]\%$. A separate 100-injection pilot gives the descriptive fractions in Table 9. These finite, deterministic-axis experiments do not define calibrated 50% or 95% recovery thresholds, confidence limits, or physical bounds. Calibration across sky geometry, classifier transfer, and joint nuisance covariance remains open. The catalog remains a public CC-BY-4.0 community resource.

APPENDIX

A. NAMASTER MASTER CONFIGURATION

For full reproducibility we record the NaMaster (`pymaster` 2.6) configuration used for the MASTER mode-coupling deconvolution of the chirality-asymmetry pseudo- C_ℓ .

Declared data vector and $\ell=0$ treatment.—The MASTER diagnostic estimator of Sec. 4.3 uses, on the MASTER-AGF ($N_{\text{all}} \geq 1$ mask, 24,297 pixels, $f_{\text{sky}} = 0.494$), the declared data vector $A_p = (N_{\text{CW}}^{(p)} - N_{\text{CCW}}^{(p)}) / (N_{\text{CW}}^{(p)} + N_{\text{CCW}}^{(p)})$ (Eq. 3; spirals only) with weight-map-weighted ($W_p = N_{\text{all}}$) mask-mean subtraction. The canonical unapodized rows of Table 6 use the half-scaled CW-deficit convention $f_{\text{CW}}(\hat{n}) - 0.5 = A_p/2$ with N_{spiral} -weighted monopole subtraction, copied verbatim from that channel’s committed generator (artifact c9a records both field declarations); the two conventions differ by a constant rescaling, under which z and rank- p are invariant because data and null transform together, while the raw C_b amplitudes are not cross-comparable between the two footprint blocks. Effective field support: on the $N_{\text{all}} \geq 1$ footprint, pixels containing only NOT_SPIRAL galaxies ($N_{\text{spiral}}(p) = 0$) carry field value zero and are excluded from the mean-subtraction support, which is $N_{\text{all}} \geq 1 \cap N_{\text{spiral}} \geq 1$; the FS-C support ($N_{\text{spiral}}(p) \geq 10$) contains no such pixels by construction. The NaMaster weight (mask) map assigns $W_p = N_{\text{all}}^{(p)}$ to each pixel p , where $N_{\text{all}}^{(p)} = N_{\text{CW}}^{(p)} + N_{\text{CCW}}^{(p)} + N_{\text{NS}}^{(p)}$ is the total count of all classified galaxies in that pixel (a standard survey-depth proxy). The quantity $N_{\text{map,weighted}} = \sum_{p \in \text{mask}} W_p = 8,474,531$ reported in Table I is the sum of these pixel weights; it exceeds $N_{\text{catalog,spiral}} = 3,201,160$ because each W_p includes non-spiral objects ($\sim 62\%$ of the catalog). No galaxy is counted more than once. The galaxy-weighted mask-mean $\langle A \rangle_{\text{mask,gw}}$ is subtracted before field construction, removing the monopole of the input field and thereby the leading monopole-sourced contribution to $\ell=1$; residual monopole-dipole

Table 11. Consolidated mask/weight/apodization $\rightarrow$ sky-fraction mapping for every footprint quoted in this paper. Binary--mask rows quote the raw pixel fraction f_{sky} ; weighted/apodized rows quote $f_{\text{sky}}^{\text{eff}} = \langle W \rangle^2 / \langle W^2 \rangle$.

Mask	Weight / apod.	f_{sky}
Canonical ($N_{\text{spiral}}(p) \geq 10$)	binary, none	0.49005
Canonical	binary, C^2 2°	0.482
Footprint ($N_{\text{all}} \geq 1$)	binary, none	0.494
Footprint	binary, C^2 2°	0.488
Footprint	$W_p = N_{\text{all}}$, C^2 2°	0.452
Footprint	$W_p = N_{\text{spiral}}$, C^2 2°	0.420

mode coupling on the cut sky is then governed by the exact NaMaster mode-coupling matrix computed from the actual weight map (mean subtraction alone does not remove all coupling on a weighted, patchy footprint). The monopole subtraction is performed at the data-vector construction step so that the $\ell=0$ mode is removed from the input field, and the MASTER mode-coupling matrix does NOT include $\ell=0$ on either the input or output side. The monopole-mask leakage channel (Sec. 4.4) uses a separate input field constructed WITHOUT monopole subtraction precisely to expose the leakage.

Bandpower vs single- ℓ estimator distinction.—The reported MASTER $\ell=1$ result is the *single-multipole bin* from $\ell=1$ to $\ell=1$ (`nmt.NmtBin.from_lmax_linear(lmax=191, nlb=1)`, $\ell=1$ row of the bandpower matrix), NOT a bandpower over a range.

NaMaster configuration.—Pixelization: HEALPix NSIDE=64 ($N_{\text{pix}}=49,152$, $\ell_{\text{max}}=191$). Support: FS-C (pixels with ≥ 10 spirals). MASTER-AGF: $N_{\text{all}} \geq 1$, 24,297 pixels, $f_{\text{sky}} = 0.494$. FS-C: $f_{\text{sky}} = 0.49005$, $N_{\text{spiral}} = 3,201,160$. Apodization: none on the FS-C support; on the MASTER-AGF, NaMaster “C2” apodization (cosine-squared roll-off) with a 2° apodization length (`nmt.mask_apodization(mask, 2.0, 'C2')`). Field: scalar (spin-0) asymmetry map $A_p = (N_{\text{CW}}^{(p)} - N_{\text{CCW}}^{(p)}) / N_{\text{spiral}}^{(p)}$ (Eq. 3; spirals-only denominator, the single canonical definition), with galaxy-weighted mask-mean subtraction $\langle A \rangle_{\text{mask,gw}} = -0.005294$. Monopole subtraction reduces decoupled C_1 at $\ell=1$ from 2.30×10^{-5} to 1.51×10^{-5} ($\sim 34\%$) and increases σ from +1.85 to +3.64 (the FS-C number); the σ rises while the measured power falls because the label-shuffle null realizations are subjected to the same subtraction and their mean and width shrink by a larger factor than the data value, as required by $z = (C_1 - \langle C_1 \rangle_{\text{null}}) / \sigma_{\text{null}}$ with both data and null transformed consistently. Bins: single-multipole linear bin (`nmt.NmtBin.from_lmax_linear(lmax=191, nlb=1)`). Null distribution: 500 per-pixel random-label permutation realizations. Seed: `numpy.random.seed(42)`. Effective sky fractions: for a weight map W , $f_{\text{sky}}^{\text{eff}} \equiv \langle W \rangle^2 / \langle W^2 \rangle$ (means over all N_{pix} HEALPix pixels at NSIDE=64), equivalently $(\sum_p W_p)^2 / (N_{\text{pix}} \sum_p W_p^2)$. This definition is invariant under any rescaling $W \rightarrow cW$, so the unnormalized integer count weights used here give exactly the same $f_{\text{sky}}^{\text{eff}}$ as $[0, 1]$ -normalized weights (verified numerically: rescaling $W_p = N_{\text{all}}$ to unit maximum leaves all entries unchanged); the values do depend on pixel resolution, as for any effective-sky-fraction statistic. The alternative mask-restricted normalization $(\sum_{p \in \text{mask}} W_p)^2 / (N_{\text{in}} \sum_{p \in \text{mask}} W_p^2)$ is a weight-uniformity factor rather than a sky fraction; the two are related by $f_{\text{sky}}^{\text{eff}} = (N_{\text{in}} / N_{\text{pix}}) \times (\text{mask-restricted factor})$. For the footprint weight maps the mask-restricted factors are 0.988 (binary, apod.), 0.923/0.914 ($W_p = N_{\text{all}}$, unapod./apod.), and 0.857/0.850 ($W_p = N_{\text{spiral}}$, unapod./apod.). We note that the MASTER decoupling itself uses the exact NaMaster mode-coupling matrix computed from the actual weight map, not any $f_{\text{sky}}^{\text{eff}}$ approximation; the values in Table 11 are descriptive bookkeeping only. That coupling matrix is well conditioned at $\ell=1$ on the apodized $W_p = N_{\text{all}}$ footprint: the full 192×192 spin-0 matrix has condition number 3.17 at the 2° apodization used here ($3.11/3.25$ at $1^\circ/3^\circ$), the leading $\ell \leq 5$ block has condition number 2.49, and the $\ell=1$ row is diagonally dominant ($M_{11} / \sum_{\ell' \neq 1} |M_{1\ell'}| = 1.29$), so the single-mode $\ell=1$ decoupling is numerically stable and insensitive to the apodization length (artifact [pipelines/p2_chirality/outputs/canonical_provenance/c12_r24conf_local_batch.json](#)). Table 11 consolidates every mask/weight/apodization combination used in this paper and its associated f_{sky} or $f_{\text{sky}}^{\text{eff}}$. Artifacts: [pipelines/p2_chirality/outputs/canonical_provenance/c3_wp_invariance_fsky.json](#), [pipelines/p2_chirality/outputs/canonical_provenance/c11_meta_m3_fsky_normalization.json](#).

MASTER-AGF declaration and depth-stratification audit.—The MASTER-AGF declaration is the $N_{\text{all}} \geq 1$ pixel mask (24,297 pixels, $f_{\text{sky}} = 0.494$, C^2 2° apodization, 500-MC label-shuffle null, seed 42; Table 11). A threshold sweep over

Table 12. Conflicting historical training-data records. “Audit” denotes the immutable model-repository audit; “benchmark” denotes the committed `BENCHMARK_REPORT.md`. Neither record retains exact object/split membership or random states. Flips are generated on the fly and do not add rows.

Quantity	Value
Audit: GZ1 / CE-spiral labels	6,637 / 17,153
Audit: CE-selected / synthetic NOT_SPIRAL	826 / 2,000
Audit: train / validation / total	21,293 / 5,323 / 26,616
Benchmark: CE-selected NOT_SPIRAL / total	846 / 26,626
Audit / model-README val. accuracy	93.6878% / 92.10%
Audit CW/CCW/NOT_SPIRAL per-class acc.	94.9/91.3/99.4
Exact object/split manifest	not retained
Full-overlap GZ1 chirality agreement	69.91%

$N_{\text{all}} \geq \{1, 2, 3, 5, 10, 20, 50\}$ and $N_{\text{spiral}} \geq 1$ yields $f_{\text{sky}} = 0.488\text{--}0.494$. The MASTER $\ell = 1$ excess is $+7.28\sigma$ ($W_p = N_{\text{all}}$) / $+9.78\sigma$ ($W_p = N_{\text{spiral}}$); a depth-stratified null gives $+7.13\sigma$ / $+9.06\sigma$. These remain systematics diagnostics. The sole primary result is the HC real-space observed-label null; WLS is diagnostic and the required joint covariance remains open.

B. CLASSIFIER ARCHITECTURE DETAILS

Training.—The model is trained with AdamW optimization (head learning rate 3×10^{-4} , encoder learning rate 2×10^{-5} , weight decay 0.02), batch size 128, and a cosine annealing warm-restart schedule ($T_0 = 10$, $T_{\text{mult}} = 2$). Early stopping with patience 15 monitors best validation *accuracy* within 80 epochs; the production checkpoint is reported at epoch 79. The immutable model-repository audit at revision 237d021c451d75cf86a875e86d4de498b74e2f12 reports 93.6878% best-epoch three-class validation accuracy, $n_{\text{train}} = 21,293$, and $n_{\text{val}} = 5,323$; the checkpoint’s LFS object has SHA-256 618d170f...97bf and size 88,046,038 bytes. These values support the reconstructed account but do not identify split membership or random states, and they conflict with the committed model README’s 92.10% accuracy and the benchmark counts below. Horizontal flips are evaluated on the fly in training batches and do not add rows. The same recovered account records 94.9% CW per-class accuracy (CCW 91.3%, NOT_SPIRAL 99.4%), and binary CW/CCW accuracy 93.2% (CW recall 93.8%, CCW recall 92.6%); these remain historical metrics rather than an exactly replayable validation.

Training-data provenance.—Table 12 juxtaposes the conflicting committed historical records rather than selecting an unproved realization. The production-script/model-audit account totals 26,616 rows, with 826 CE-ResNet-selected non-spirals and a 21,293/5,323 split; `BENCHMARK_REPORT.md` instead gives 26,626 rows and 846 CE non-spirals, and the model README reports 92.10% rather than the audit’s 93.6878%. Neither split gains rows from flips. Because historical stochastic operations were not fully seeded and stable object/split IDs were not retained, the table is a conflict disclosure, not an exact replay manifest.

Flip-equivariance consistency loss.—The loss combines class-weighted cross-entropy $\mathcal{L}_{\text{CE}}$ with a flip-equivariance consistency term:

$$\mathcal{L} = \mathcal{L}_{\text{CE}} + \lambda \cdot \frac{1}{N} \sum_{i=1}^N \|\mathbf{p}(x_i) - S\mathbf{p}(\tilde{x}_i)\|^2, \quad (\text{B1})$$

where S is the permutation matrix swapping the CW and CCW channels (leaving NOT_SPIRAL unchanged), and $\lambda = 0.5$.

D_4 -TTA rotational-equivariance validation.—A direct D_4 -TTA hold-out on two independent $\sim 2,000$ -galaxy subsamples ($N = 1,558$ and $N = 1,988$) confirms: (a) mean per-galaxy P_{CW} stable under Z_2 and D_4 to within $|\Delta\langle p_{\text{CW}} \rangle| < 0.0016$; (b) per-galaxy argmax labels flip in 21.4% of cases between Z_2 and D_4 on borderline galaxies. The sign-flip of the argmax-CW-fraction shift (-1.35% at $N = 1,558$ vs $+2.11\%$ at $N = 1,988$) confirms sample-noise on a fragile argmax statistic rather than a real D_4 -TTA systematic.

Bias hardening suite.—We subject the classifier to seven tabulated targeted bias tests (Table 13): T1 flip-swap consistency ($r > 0.80$), T2 rotation stability ($> 80\%$ agreement across 60° increments), T3 artifact rejection ($> 70\%$ NOT_SPIRAL for blank/scrambled images), T4 perturbation robustness ($> 80\%$ agreement under Gaussian blur + brightness dimming), T6 hemispheric null ($< 10\%$ CW difference between hemispheres), T7 confidence-calibration

proxy, T8 CW/CCW balance ($50\% \pm 10\%$). Metadata (RA/Dec) leakage is *not* tested by a linear Pearson correlation: RA is a circular coordinate ($0^\circ \equiv 360^\circ$) for which a linear Pearson r is statistically inappropriate and can understate azimuthal coupling, so the former linear-Pearson-vs-RA row has been removed from the battery. Directional (RA-dependent) leakage is instead tested correctly by the map-level low- ℓ real- $Y_{\ell m}$ regression described below, which respects the coordinate’s circularity. The implemented T7 criterion is: $> 30\%$ of predictions at $\max p > 0.9$ (a confidence-mass sanity check), together with the requirement that the flip-swap error of high-confidence ($\max p > 0.9$) predictions be lower than that of low-confidence ($\max p < 0.7$) predictions; the catalog-wide high-confidence mass is 73.6% (Fig. 6), so T7 passes. Quantified catalog-wide from the per-galaxy original/flip outputs (the flip-pass probabilities are recovered from the stored raw and 2-fold-TTA columns via $p_{\text{CCW}}^{\text{flip}} = 2p_{\text{CCW}}^{\text{eq}} - p_{\text{CCW}}^{\text{raw}}$ and its channel companions; a dedicated QC pass quantifies the fidelity of this recovery: the recovered-flip normalization $\sum_c p_c^{\text{flip}} = 1$ holds at float32 storage precision on all 8.47M rows — max deviation 4.3×10^{-7} — but for 2.9% of rows (1.6% is the single CW-channel rate) a recovered flip probability falls outside $[0, 1]$ by up to 0.09. These excursions are *not* float32 rounding: they occur exclusively on rows whose raw probabilities derive from the separate raw-catalog inference pass rather than the equivariant pass (the 88,278-row intersection where both raw legs *and* the equivariant raw companion columns are populated shows zero violators), i.e. a raw/eq pipeline-pass mismatch at the $\lesssim 0.09$ probability level for that subpopulation (catalog-wide rate from [pipelines/p2_chirality/outputs/canonical_provenance/ext4_fb1_flip_identity_qc_catalogwide.json](#); intersection-subset rate zero by construction, [pipelines/p2_chirality/outputs/canonical_provenance/ext3_nfm1_flip_identity_qc.json](#)). The public v1.0.244 release’s `raw_flip_qc_unsafe` flag identifies the affected rows under the catalog-wide “full-coverage raw columns” definition; excluding them from the HC sample (59,515 of 949,584, 6.3%) leaves the real-space dipole null-consistent and essentially unchanged ($z = +0.48$ excluded vs. $+0.52$ baseline under the c11b 10^4 -permutation convention; artifact [pipelines/p2_chirality/outputs/canonical_provenance/ext3_nfm1_hc_dipole_qc_rerun.json](#)): mean flip-swap error 0.267 (median 0.0006) at $\max p > 0.9$ vs. 0.383 (median 0.364) at $\max p < 0.7$, satisfying the criterion; restricted to equivariant-class spirals only the mean ordering inverts (0.698 vs. 0.464), driven by the raw/equivariant class-disagreement subpopulation (the QC edge-case flag); architecturally, galaxies that change class under flipping are precisely the borderline objects for which TTA suppresses the raw argmax probability toward ~ 0.5 — these low post-TTA p_{eq} spirals have large raw flip-swap errors, pushing the equivariant-class-only mean flip-swap error above the full-catalog value, which is why T7 is a calibration proxy on all classes rather than a spiral-only reliability statement (artifact [pipelines/p2_chirality/outputs/canonical_provenance/c16_r24conf_pod_batch.json](#)). (T7 is a calibration *proxy*, not a ground-truth reliability-curve ECE measurement, which is not possible catalog-wide absent per-galaxy truth labels.) Note also that T1 validates the *implementation* of the equivariant protocol (it would catch a code defect) rather than constituting an independent statistical test, since flip-swap consistency holds by construction after TTA averaging. Directional (RA-dependent) metadata leakage is tested at the map level, which respects RA’s circularity: a low- ℓ real- $Y_{\ell m}$ regression ($\ell \leq 3$, 16 coefficients) of the primary HC A_p map against a 2000-permutation pixel null finds all three $\ell = 1$ coefficients consistent with zero ($|z| \leq 1.25$); the only outlying coefficient is at $(\ell, m) = (3, -1)$ ($z = -4.4$), consistent with the coherent low- ℓ systematic structure dispositioned in Appendix D rather than with a dipole (artifact [pipelines/p2_chirality/outputs/canonical_provenance/c12_r24conf_local_batch.json](#)). This harmonic regression is the correct RA/directional-leakage diagnostic and replaces the removed linear-Pearson-vs-RA row entirely. All 7 tabulated tests pass at the stated criteria; they are necessary but not sufficient checks for sub-percent bias control and must be interpreted alongside the finite-grid score fractions reported in Sec. 6.2. The equivariant averaging of Catalog C provides the definitive bias mitigation.

GZ1 confusion matrix and per-class metrics.—Table 14 reports the three-class confusion matrix of the equivariant classifier against Galaxy Zoo 1 human labels on the full $1''$ cross-match ($N = 240,919$). The retained artifact does not contain an object-level anti-join against the 6,637 GZ1 training rows, and the historical training script did not retain stable training IDs; this evaluation must therefore be treated as overlap-contaminated rather than independent. The three-class accuracy is 58.7%; restricted to the 117,205 GZ1 spirals that the classifier labels CW or CCW, the chirality agreement is 69.91% (Cohen’s $\kappa = 0.40$). Per-class precision/recall: CW 0.539/0.545, CCW 0.527/0.588, NOT_SPIRAL 0.684/0.618. These descriptive values do not establish a physical transfer function.

Probabilistic calibration scope.—The catalog-wide mean winning-class score is 0.951, while the full GZ1 overlap has lower descriptive accuracies (58.7% three-class and 69.91% on the chirality-evaluable subset). These quantities are computed on different object sets and therefore cannot be combined into an Expected Calibration Error or a Jensen lower bound.

Table 13. Bias-hardening test results. All 7 tabulated tests pass at the stated criteria; they are necessary but not sufficient checks for sub-percent-level bias control and are not calibrated against a physical sensitivity boundary (see Appendix B text for definitions and the T1/T7 scope caveats). The former linear-Pearson RA/Dec metadata-leakage row has been *removed* because a linear Pearson correlation is inappropriate for the circular RA coordinate ($0^\circ \equiv 360^\circ$); the map-level low- ℓ real- $Y_{\ell m}$ regression in the Appendix B text is the correct directional-leakage test and supersedes it.

Test	Threshold	Result
T1: Flip-swap r	> 0.80	1.000
T2: Rotation stability	$> 80\%$	94.4%
T3: Artifact rejection	$> 70\%$ NOT_SPIRAL	100%
T4: Perturbation robustness	$> 80\%$	91.2%
T6: Hemispheric null	$< 10\%$	$< 0.4\%$
T7: Calibration proxy	$> 30\%$ at $\max p > 0.9$	73.6%
T8: CW/CCW balance	$50 \pm 10\%$	49.7%

Table 14. Three-class confusion matrix vs. Galaxy Zoo 1 human labels ($1''$ cross-match, $N = 240,919$). Rows: GZ1 label; columns: equivariant (Catalog C) prediction.

GZ1 \ pred.	cw	ccw	not_spiral
CW	39,011	18,889	13,715
CCW	16,377	42,928	13,720
NOT_SPIRAL	17,056	19,724	59,499

No same-object binned reliability artifact is retained, so we make no numerical ECE claim. The scores remain explicitly uncalibrated ranking outputs. This does not alter the hard-label null: the primary estimator consumes hard argmax CW/CCW counts, and a monotone recalibration preserves the argmax. Recalibration of the selection score would require restating the numerical threshold that selects a fixed ranked subset; it would not by itself provide the missing spatial confusion/transfer model.

Sky- and confidence-stratified human-label confusion analysis.—The single global confusion matrix above (Table 14) does not by itself establish the spatial transfer needed by the dipole analysis. A spatially varying differential mislabelling rate can inject a spurious A_p dipole, but it is not the only channel: Eq. (7) shows that a spatially varying symmetric rate also changes the observed fraction wherever the local selected CW fraction differs from one half. We therefore stratify the GZ1-overlap confusion matrix by the two P4 imaging legs (BASS+MzLS, $\text{dec} > +32^\circ$; DECaLS, $\text{dec} < +32^\circ$) and by the primary confidence cut, and in each stratum measure the CW $\leftrightarrow$ CCW error asymmetry with its two-proportion 95% CI (Table 15) as well as the net induced Δf_{CW} . The analysis restricts to the $N = 40,987$ GZ1-confident spirals ($\max(P_{\text{CW}}, P_{\text{ACW}}) > 0.6$) that the classifier also labels CW or CCW, drawn from the $N = 46,017$ GZ1-catalog cross-matches reproduced byte-identically ($1''$ KDTree match) from Table 14’s parent match; the 5,030 GZ1-confident spirals assigned to NOT_SPIRAL are reported separately as an unquantified completeness/selection channel, not as chirality error. The generator script and full stratified JSON are committed ([pipelines/p2_chirality/scripts/gz1_stratified_confusion.py](#), [pipelines/p2_chirality/outputs/gz1_stratified_confusion.json](#)).

The 5,030 GZ1-confirmed spirals assigned to NOT_SPIRAL have not been composition- and position-characterized here; no chirality-neutral assumption is made for them, and their exclusion is an unquantified completeness/selection channel. All confusion-matrix conclusions are restricted to the 40,987 objects classified CW or CCW.

Conclusion this licenses (stated precisely). CW $\leftrightarrow$ CCW error asymmetry is consistent with zero in every tested stratum: overall $+0.0001[-0.0054, +0.0056]$, BASS+MzLS $+0.0042[-0.0056, +0.0140]$, DECaLS $-0.0020[-0.0086, +0.0046]$, and science cut $-0.0019[-0.0061, +0.0023]$. Thus no directional error asymmetry is detected at the tested two-leg resolution, with sensitivity bounded by these intervals. The net induced-fraction point estimates are nevertheless 0.00142 (BASS+MzLS) and 0.00331 (DECaLS); their difference has no retained covariance-aware interval. The test does not resolve RA variation within a leg or joint depth/PSF/morphology dependence, so it cannot exclude every sub-percent spatially varying differential or symmetric-error pattern. The finer conditional model remains open. Stratified accuracies apply to a nested confident-spiral subset and do not validate the illustrative scalar transfer, especially because the historical training overlap was not removed from the GZ1 agreement calculation.

Table 15. GZ1-overlap human-vs-classifier CW/CCW confusion stratified by imaging leg and confidence cut ($N = 40,987$ GZ1-confident spirals classified CW or CCW; 1'' cross-match, $N = 46,017$). “Asymmetry” is the difference between the two directional error rates, with an unpooled two-proportion 95% interval. A value consistent with zero means no dipole-producing parity error was detected in that tested stratum; it does not exclude finer spatial variation. Full arrays: [pipelines/p2_chirality/outputs/gz1_stratified_confusion.json](#).

Stratum	N	acc	CW $\rightarrow$ CCW / CCW $\rightarrow$ CW	asymmetry (95% CI)
Overall	40,987	0.912	0.0878 / 0.0877	+0.0001 [−0.0054, +0.0056]
BASS+MzLS (dec $> +32^\circ$)	14,093	0.903	0.0994 / 0.0952	+0.0042 [−0.0056, +0.0140]
DECaLS (dec $< +32^\circ$)	26,894	0.917	0.0818 / 0.0838	−0.0020 [−0.0086, +0.0046]
Science cut ($p_{\text{eq}} > 0.6$)	32,550	0.961	0.0379 / 0.0399	−0.0019 [−0.0061, +0.0023]
Low conf. ($p_{\text{eq}} \leq 0.6$)	8,437	0.724	0.2795 / 0.2730	+0.0065 [−0.0126, +0.0256]

C. AUXILIARY DIPOLE DIAGNOSTICS

This appendix collects the signal-hunt diagnostics, two-point chirality correlation, hemisphere asymmetry, sky region balance, per-imaging-leg systematics, scale dependence, and confidence stratification results moved from the main text for conciseness. The primary no-dipole verdict is unchanged by any of these diagnostics.

Confidence-stratified dipole.—Stratifying Catalog C by equivariant max-class probability into five bins reveals: the +3.29 σ in the 1.87M-galaxy [0.5, 0.6) bin does not survive the sample-purity ladder (cutting to $p_{\text{eq}} > 0.6$ gives −0.03 σ); results available in the public data repository (see Data Availability).

Sky-quadrant and hemisphere diagnostics.—Splitting into four RA quadrants gives per-quadrant dipole values ranging from −0.82 σ to +2.49 σ ; primordial dipole would project consistently, not scatter. The NGP ($b > 0$) gives $\sigma_{\text{iso}} = +0.47$ (σ_{iso} : moment- z against the isotropic per-pixel permutation null, as for the primary estimator of Sec. 4.3); SGP ($b < 0$) gives +2.02 (consistent with the dust-correlated foreground zone).

Hemisphere asymmetry and look-elsewhere.—Testing all hemisphere pairs on the local 10°-spaced grid ($36 \times 18 = 648$ directions) gives a maximum asymmetry of 3.05 σ against its label-shuffle null. This local scan is *not* the same computation as the authoritative look-elsewhere artifact: the latter recomputes the maximum statistic over 768 NSIDE_{dir} = 8 pixel-center directions for each of 10,000 global label shuffles and reports the Monte-Carlo precision-floor bound $p_{\text{LEE}} \leq 10^{-4}$ (artifact [pipelines/p2_chirality/outputs/canonical_provenance/mc_seed_manifest.json](#)). We therefore do not describe the 768-direction Monte Carlo as an exact correction of the 648-direction diagnostic. Both scans reject their corresponding random-label nulls and are interpreted as depth/training-label systematic structure rather than a primordial dipole. Bonferroni control does *not* require independent tests; the earlier sentence claiming that it did was false. We nevertheless do not use the Gaussian Bonferroni number here because the hemisphere amplitude is positive-definite with non-Gaussian tails and the two grids/statistics differ; the committed 768-direction empirical max-statistic is the authoritative look-elsewhere result.

Two-point chirality correlation.—The two-point chirality correlation $w_{\text{CW}}(\theta)$ on a random 50,000-galaxy HC-spiral sample is consistent with the label-shuffle null at $|\sigma| < 1.2$ in 9 of 10 bins; the maximum deviation −2.41 σ at $\theta \approx 0.5^\circ$ is attributable to DESI Legacy DR8 brick-boundary classifier artifacts (confirmed by vanishing to −0.03 σ in the brick-interior subsample).

Per-imaging-leg systematics.—The full-catalog [0.5, 0.6) confidence bin +3.29 σ decomposes as BASS+MzLS +0.30 σ / DECaLS +4.50 σ / DES +2.46 σ : the signal is DECaLS-concentrated, the signature of a footprint-correlated systematic rather than a primordial isotropy-breaking signal. Under the 15-cell joint label-shuffle max-statistic null ($N_{\text{MC}} = 5,000$ global label shuffles preserving the total CW count; per-cell statistic $|\sigma|$, i.e. two-sided per cell), the family-corrected p -value is the add-one one-sided empirical exceedance of the observed max $|\sigma| = 4.72$ in the joint null distribution: $p = (43 + 1)/(5000 + 1) = 0.00880$ ($\approx 2.4\sigma$ family-wise), appropriately downgraded from the cell-level +4.72 σ . This empirical joint correction is applied *once* (no double correction); a Gaussian Bonferroni-15 estimate would underpredict this family-wise p by $\sim 250\times$ because the joint null is heavy-tailed.

D. FS-C SYSTEMATIC ANALYSIS

Eight diagnostics have been evaluated in connection with the FS-C residual, but only apodized-mask robustness and multipole-spectrum coherence are bound to the declared 24,087-pixel FS-C base support. Quality-quartile stratification constructs separate per-quartile masks; the leg proxy uses 24,270 pixels; boundary-distance variance uses 35,438 latitude-mask pixels; the density null and WLS/bootstrap use broader latitude-cut supports; and the direct cross-spectrum artifact does not record enough mask provenance to establish identity. Those six calculations describe other supports and do not enter the strict FS-C synthesis.

Apodized-mask robustness.— C^2 2° apodization gives $+3.57\sigma$ at $f_{\text{sky}} = 0.482$, essentially unchanged from the binary-mask $+3.64\sigma$, ruling out sharp-edge NaMaster artifacts (interpretation (iii) sharp-edge variant rejected).

Multipole-spectrum diagnostic.—The signal is broadband low- ℓ : $\sigma_{\ell=1} = +3.63$, $\sigma_{\ell=2} = +4.73$ ($\ell = 3, 4, 5$ at $-0.96, +0.13, -0.63$). A real dipole at $A \sim 1.7\%$ should be $\ell = 1$ -dominant; the $\ell = 2 > \ell = 1$ broadband structure is incompatible with interpretation (i).

Quality-quartile stratification.—Stratifying the spiral sample into four p_{eq} quartiles ($N \approx 800,290$ each; $N_{\text{MC}} = 50$ per quartile) gives $\ell = 1$ significances of $+0.20, -0.42, +0.44, +0.43$. Each quartile constructs its own $N_{\text{spiral}} \geq 10$ mask ($f_{\text{sky}} = 0.4909\text{--}0.4924$), so these are different-support diagnostics rather than tests on the fixed FS-C mask and are excluded from the strict synthesis.

Leg-proxy $\ell = 1$ partial closure.—The historical calculation gives $r_{\ell=1}(\text{BASS} + \text{MzLS} \times A_p) = +0.65$, $r_{\ell=1}(\text{DES} \times A_p) = -0.73$, and a summed leg-induced amplitude of $\sim 25\%$ of its observed $\ell = 1$ amplitude. Its recorded $f_{\text{sky}} = 0.493774$ corresponds to 24,270 pixels, not the 24,087-pixel FS-C mask, so it is excluded from the strict synthesis.

Density-stratified null.—The historical generator permuted A_p within ten pixel-density deciles and reported null mean $C_1 = 3.44 \times 10^{-6}$, std 3.07×10^{-6} , and $z = +3.80$. Its mask is $|b_{\text{gal}}| > 15^\circ$ with $N_{\text{total}} > 0$ ($f_{\text{sky}} = 0.740926$), not FS-C ($f_{\text{sky}} = 0.490051$), so this number is not evidence about the FS-C residual and is excluded from the synthesis.

Boundary-distance variance check.—The historical five-shell calculation reports a per-shell weighted-variance range below 11%, but its artifact records $f_{\text{sky}} = 0.740926$ and 35,438 shell pixels. It is therefore a latitude-mask result, not an FS-C boundary test, and is excluded from the strict synthesis.

Joint nuisance-marginalized WLS fit.—The historical 9-template WLS fit used $(|b_{\text{gal}}| > 15^\circ) \wedge (N_{\text{total}} > 0)$ (24,187 pixels), not FS-C (24,087 pixels). On that broader support it gives $A_{\text{dipole}}^{\text{best}} = 4.55 \times 10^{-3}$ and an NSIDE = 8 block-bootstrap width $\sigma_{\text{boot}} = 1.63 \times 10^{-3}$. These values are retained for provenance only: the bootstrap covariance has not been recomputed on FS-C, so neither $z \approx -7.6$ against $A_{\text{ref}} = 0.017$ nor the illustrative $1.36 \sigma_{\text{boot}}$ transfer comparison is used as an FS-C or physical constraint.

WLS support.—The committed bootstrap artifact records 24,187 pixels under $(|b_{\text{gal}}| > 15^\circ) \wedge (N_{\text{total}} > 0)$, whereas FS-C contains 24,087 pixels under $N_{\text{spiral}} \geq 10$. A new bootstrap on FS-C would be required before this diagnostic could enter the FS-C synthesis.

Direct cross-spectrum $A_p \times n_{\text{total}}$.—The cross-correlation coefficient is defined per multipole as $r_\ell \equiv C_\ell^{A \times n} / \sqrt{C_\ell^{AA} C_\ell^{nn}}$. At $\ell = 2$, the historical result is $r_{\ell=2} = -0.65$ with signed $z = -2.89$ against a 200-realization permutation null. The artifact does not record the exact mask or pixel count, so this value is retained as provenance but excluded from the strict FS-C synthesis.

Operational conclusion.—The FS-C $+3.64\sigma$ residual is *not* a positive detection of a primordial chirality dipole. On the exact base support, persistence under apodization and $\ell = 2 > \ell = 1$ broadband structure disfavor a clean dipole. The other six historical diagnostics are different-support or support-unproven and do not strengthen that synthesis. The primary scientific result remains the HC real-space $+0.71\sigma$ observed-label null.

E. MORPHOLOGY SYSTEMATICS

Edge-on galaxy contamination.—The DR8 morphology cross-match contains 505,889 edge-on systems ($b/a < 0.30$), or 15.80% of classified spirals. A linear dilution factor is conditional on flip-symmetric hard assignments: soft-probability equivariance supports that approximation, but hard argmax is nonlinear and cannot be proven unbiased by the soft

Table 16. Historical 9-template WLS fit on the broader latitude-cut support, not FS-C. The centered imaging-leg templates are collinear with the constant (rank 8; condition number 4.5×10^{16}), so individual leg coefficients are not meaningful. Values are retained for provenance and are not used in the FS-C synthesis.

Template	$\hat{a}$	σ_{naive}	z
dipole $\hat{x}$	$+4.3 \times 10^{-5}$	8.9×10^{-5}	+0.5
dipole $\hat{y}$	-4.52×10^{-3}	1.04×10^{-4}	-43.3
dipole $\hat{z}$	-5.7×10^{-4}	2.8×10^{-4}	-2.1
leg BASS+MzLS	$+1.8 \times 10^{-3}$	6.2×10^2	—
leg DECaLS	$+8.7 \times 10^{-4}$	6.2×10^2	—
leg DES	-3.0×10^{-3}	6.2×10^2	—
pixel density	$+3.2 \times 10^{-4}$	8.5×10^{-5}	+3.8
pixel density ²	-1.9×10^{-5}	7.4×10^{-6}	-2.6
constant	$+3.2 \times 10^{-4}$	6.5×10^{-5}	+4.9
$A_{\text{dipole}} (A_p \text{ units})$	4.55×10^{-3}	$\sigma_{\text{boot}} = 1.63 \times 10^{-3}$ $\sigma_{\text{naive}} = 1.11 \times 10^{-4}$	
$z \text{ vs. } A_{\text{ref}} = 0.017$	-7.6 (block-boot., diagnostic) -112 (naive WLS, superseded)		

[†] *Convention mapping:* the fitted $A_{\text{dipole}}^{\text{best}} = 4.55 \times 10^{-3}$ uses $A_p = 2(f_{\text{CW}} - \frac{1}{2})$, numerically equal to the full dipole amplitude A for $p_{\text{CW}}(\hat{n}) = \frac{1}{2}(1 + A \cos \theta)$. Injection tables use the same units but remain finite pilot diagnostics, not calibrated thresholds.

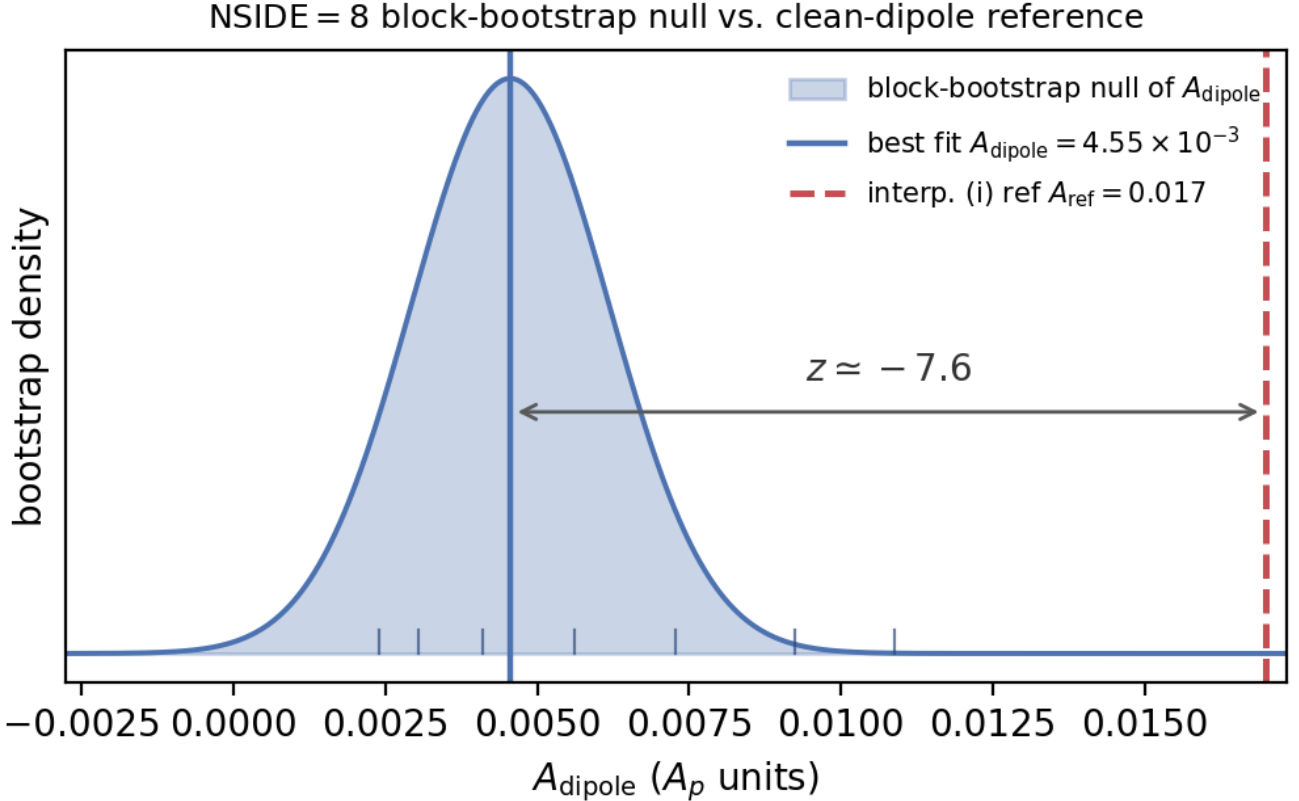


Figure 10. Historical latitude-mask block-bootstrap distribution. NSIDE= 8 resamples of the broader $|b_{\text{gal}}| > 15^\circ$, $N_{\text{total}} > 0$ WLS field ($N_{\text{boot}} = 1000$, seed 42), not the FS-C field. The distribution is retained as provenance and is not used for an FS-C or physical constraint.

identity alone. The edge-on-isolated tie-break test ($N = 295,170$) is null-consistent across the three imaging legs (family-wise $p = 0.49$, maximum $|z| = 1.17$, every leg $|z| < 1.4$). This empirically bounds the tested edge-on coherence channel but does not exclude every spatially varying hard-label bias; residual morphology/depth covariance remains part of the open joint-covariance problem.

High-confidence subsample robustness.—Using the HC-broad-0.6 ($p_{\text{eq}} > 0.6$, $N = 949,584$) and HC-strict ($p_{\text{eq}} > 0.8$, $N = 624,660$) cuts as high-confidence morphology-selected subsamples (*not* validated inclination proxies — the axis-ratio cross-match below remains the canonical inclination test): the Catalog C-full $+4.31\sigma$ *monopole-preserving* pre-MASTER pseudo- $C_\ell^{(\ell=1)}$ estimator collapses to $+0.62\sigma$ (HC-broad-0.6) and $+0.87\sigma$ (HC-strict). The HC-cut collapse (factor ~ 7 in the FS-C leakage-contaminated estimator) is the characteristic signature of a classifier label-noise systematic rather than a primordial dipole; it is consistent with the leakage-channel interpretation of the canonical $+3.64\sigma$, not with a $+4.31\sigma$ standalone detection. The primary real-space null at $+0.71\sigma$ (equivariant HC, $p_{\text{eq}} > 0.6$, $N = 949,584$) remains the load-bearing result; the WLS clean-template statistic is diagnostic and must not be read as a physical 1.7% exclusion.

Monopole-preserving estimator definition.—The “monopole-preserving” Catalog-C-full $+4.31\sigma$ is the single-mode **pymaster** pseudo- $C_\ell^{(\ell=1)}$ evaluated on the equivariant Catalog C full-footprint $f_{\text{CW}}^{\text{eq}}$ field on the FS-C support *before* mean-pixel subtraction and *before* MASTER mode-coupling deconvolution; the null is the same per-pixel random-label permutation null used for the canonical $+3.64\sigma$ result (Sec. D, $N_{\text{MC}} = 500$, seed 42). It is therefore the *same* estimator family as the canonical $+3.64\sigma$, with the additional choice of not subtracting the spatially-uniform $f_{\text{CW}}^{\text{eq}} = 0.4974$ monopole prior to single-mode pseudo- C_ℓ measurement. The $+4.31\sigma$ vs. the primary $+0.71\sigma$ real-space dipole are therefore *not directly comparable* — they are different estimators measuring different observables on the same sample. The $\sim 10\times$ amplitude gap is sourced by exactly the monopole-mask leakage channel quantified in Sec. 4.4 (where the monopole-only null reproduces 99.32% of the pre-MASTER C_1 power on the FS-C support): without monopole subtraction the leakage contribution dominates; with monopole subtraction the canonical estimator retains the $+3.64\sigma$ residual, and under MASTER deconvolution the monopole-only null reproduces only $\sim 12\%$ of the observed power, leaving a $+4.84\sigma$ non-null residual (Sec. 4.4, Table 7) — the leakage channel accounts for the bulk of the pre-MASTER power but not for the post-subtraction or post-MASTER residuals, which are systematics-attributed. The HC-cut robustness test below uses the same monopole-preserving variant on the high-confidence subsamples for a like-for-like comparison; it is the *cut-dependence within this estimator*, not consistency with the real-space dipole, that is the substantive finding.

Spiral fraction variation across the sky.—The spiral fraction is uniform across the DESI Legacy footprint at the $\lesssim 2\%$ level across 7 equatorial coordinate slabs, with no coherent large-scale pattern that would bias the dipole analysis.

Mask robustness: pixel-count threshold sweep.—A pixel-count-threshold sweep ($N_{\text{spiral}}(p) \geq \{1, 5, 10, 20, 50\}$; 200-MC per threshold) gives stable mask geometry ($f_{\text{sky}} = 0.479\text{--}0.493$) and a FS-C $\ell = 1$ excess that persists at every threshold, with per-threshold significances spanning $6.3\text{--}8.3\sigma$ under the earlier (pre-galaxy-weighted-subtraction) estimator convention of that sweep — i.e. the excess is not an artifact of the threshold choice, but its magnitude is threshold-dependent at the $\sim 2\sigma$ level under that convention. The sweep has also been recomputed under the *current* (galaxy-weighted-subtraction) estimator convention with 10^4 per-galaxy label permutations per threshold: the $\ell = 1$ excess persists at every threshold, with $z = +5.7, +7.7, +7.9, +7.7, +7.5$ at $N_{\text{spiral}}(p) \geq \{1, 5, 10, 20, 50\}$ (rank $p = 1.1 \times 10^{-3}$ to 2.0×10^{-4} ; $f_{\text{sky}} = 0.479\text{--}0.494$; the canonical $N_{\text{spiral}} \geq 10$ cell independently reproduces the c9a 10^4 -permutation run, $z = +7.9$, rank $p = 3.0 \times 10^{-4}$), i.e. stable to $\pm 0.4\sigma$ across the resolved thresholds ≥ 5 and lower only in the sparse $N_{\text{spiral}} \geq 1$ cell (artifact [pipelines/p2_chirality/outputs/canonical_provenance/c16_r24conf_pod_batch.json](#)).

DATA AVAILABILITY

Repository state: the analysis artifacts linked throughout this paper resolve against the live **main** branch of the repository, which always reflects the current version-stamped content (HC $N_{\text{selected}} = 949,584$, $N_{\text{support}} = 947,326$, $p_{\text{eq}} > 0.6$; real-space dipole $+0.71\sigma$, one-sided upper-tail $p = 0.225$). An immutable archival snapshot (PDF + **.tex** source + figures + canonical-provenance artifacts) will be deposited on Zenodo at journal submission with: (i) a frozen immutable release tag pinning the exact git commit hash of the analysis codebase; (ii) exact commit hashes for the catalog, all scripts, and all canonical-provenance artifacts ([pipelines/p2_chirality/outputs/canonical_provenance/](#));

and (iii) a minted Zenodo DOI that will constitute the single citable archival reproducibility handle for the published version. The DOI and commit hashes will be inserted here in place of this sentence at submission time.

- **Catalog:** <https://huggingface.co/datasets/bamfai/galaxy-chirality-catalog> (CC-BY-4.0, Parquet). The original source is pinned to revision `a21eb596fd10edb9af9e7a1bcefb04f87327a724`, 952,115,239 bytes, and SHA-256 `e8525ba5c98576f6...3563`. The current ApJS bundle is public at immutable HF data revision `db110233` with provider receipt `e535b262` and checksummed manifest. The science-facing Parquet includes the hard-label primary selection and `raw_flip_qc_unsafe` flag; a separate quarantine contains all 249,066 catalog-wide violators (59,515 in HC). The bundle also contains the retained fixed-occupancy primary array, a distinct pixel-permutation diagnostic, machine schema, validation report, and minimal reproducer. A complete versioned systematics-metadata sidecar and a DOI-backed archive of the paper, source, figures, and release metadata remain open; no placeholder DOI is claimed.
- **Model:** <https://huggingface.co/bamfai/galaxy-chirality-v2> (ViT-Small encoder + classification head, PyTorch checkpoint). Historical-training receipt: immutable revision `237d021c451d75cf86a875e86d4de498b74e2f12`, `v2_bias_audit.json` SHA-256 `57278e4e83d5a1ca2ae1b3759a0f14c3854538449a846eefc6f089a8e56ee847`; checkpoint LFS SHA-256 `618d170f...97bf`, 88,046,038 bytes. This receipt does not restore the missing object/split manifest or resolve the conflicting committed benchmark/model-card records.
- **Code:** <https://github.com/Hubify-Projects/bigbounce>. Training, inference, equivariant post-processing, bias hardening suite, and dipole analysis scripts.

The measured spatially uniform CW-bias residual of 0.26% (9.5σ) is consistent with several unresolved classifier or imaging mechanisms, including GZ1 training-label imbalance, residual orientation-dependent classifier bias, and DESI photometric asymmetry. Local re-normalization of the per-region monopole is recommended for precision parity tests. At the tested $A = 0.75\%$ full amplitude, the finite pilots give score-pass fractions 0.55/0.59 and 16/20 deterministic axes; these are not a calibrated precision boundary or physical limit. Users requiring calibrated soft probabilities for downstream probabilistic models should apply temperature scaling or Platt scaling; the raw p_{eq} values are ranking scores, not frequentist probabilities (see Sec. 4.1 calibration caveat). The overlap-contaminated full GZ1 cross-match gives 69.91% CW/CCW agreement (Cohen’s $\kappa = 0.40$); no object-level training anti-join was retained, so this is descriptive and not an independent validation metric. The full provenance inventory is in the checksummed release manifest.

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Facilities: DESI Legacy Imaging Surveys, HuggingFace, RunPod.

Software: Astropy (33), HEALPix/healpy (36; 37), NumPy (38), pandas (39), PyTorch (40), timm (41), NaMaster/pymaster.

AI-assisted methodology: This work was conducted using an agentic multi-model pipeline for literature review, code development, analysis, and adversarial internal peer review, operated under the author’s direction. Quantitative claims are bound to committed artifacts and checksums where those artifacts survive. The historical training realization is an explicit exception: its object/split manifest and random-state receipt were not retained, so the checkpoint metrics and catalog-generation provenance are not exactly replayable. The author designed the study, made all scientific judgments, and takes full responsibility for the content; the AI pipeline is a verification instrument, not an author.

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