Edge-Anchored Coherence at "The Cliff": A Model-Agnostic RCFT/UMCP Reanalysis

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Abstract

We present a measurement-first model-agnostic reanalysis of the ultracompact source 'The Cliff' using *Recursive Collapse Field Theory* (RCFT) and *Unified Mathematics & Collapse Platform* (UMCP). Eight independent windows—Balmer-edge strength, metal-line quietness, Hα breadth, He I 10830 S/N, effective radius, mid-IR color, X-ray quietness, and Balmer absorption—are mapped to survey-quantile channel confidences, with the Balmer edge serving as a double-weighted hinge. From ranks alone we compute edge-weighted invariants—fidelity F, curvature C, entropy S, integrity κ, and re-entry margin τ_R—that adjudicate cross-window coherence without template fitting. Using the measurements of de Graaff *et al.* (2025a), the object already lies in a high-coherence regime ($F = 0.965$, $C = 0.099$, $S = 0.168$, $\kappa = -0.336$, $\tau_R \approx 1.3\sigma$). A minimal tightening—doubling He I 10830 S/N, pushing the [O III]/Hβ upper limit, and securing the Balmer edge at $R \approx 2700$—drives the invariants to ($F = 0.983$, $C = 0.081$, $S = 0.118$, $\kappa = -0.189$, $\tau_R \approx 2.0\sigma$) and yields a formally *Stable*, single-generator state. We also provide an observing calculus (expected ΔF per hour) and a twin-ranking protocol that scales from one object to a population with straightforward transfer across instruments.

1 Introduction

The source nicknamed "The Cliff" shows an extreme, sharp Balmer break, weak metal lines, broad Balmer emission with a narrow redshifted absorption notch, ultra-compact morphology, cool mid-IR color, and non-detections of X-rays (de Graaff *et al.*, 2025a). Template-based SED fits can reproduce individual bands, but only by invoking window-specific tweaks that do not cohere under fixed, cross-window criteria.

We therefore pose a measurement-first question: *do the measured windows re-enter a single generator?* Within *Recursive Collapse Field Theory* (RCFT) and the *Unified Mathematics & Collapse Platform* (UMCP), each observable is mapped to a survey-quantile channel confidence $c_i \in [0,1]$, with the Balmer-edge channel serving as a double weighted hinge. From ranks alone, we compute invariant summaries—fidelity F, curvature C, entropy S, integrity κ, and reentry margin τ_R—that deliver a physics-agnostic verdict on cross-window coherence. In this frame, the Cliff-like source is an *edge-anchored, high-coherence state*; modest, targeted tightening moves it into the *Stable* region under preregistered gates.

Contributions (measurement-first). We do not fit causal templates. We formalize the observation set and report invariant statements about cross-window agreement:

(i) survey–quantile mapping of eight independent windows into confidences $c_i \in [0,1]$ (ranks only; no priors, no fitted parameters);

(ii) edge-weighted invariants $(F, C, S, \kappa, \tau_R)$ as functions of $\{c_i\}$, with a double-weighted Balmer-edge hinge;

(iii) a minimal tightening plan via expected gain $\Delta F_i = \dfrac{w_i(1-c_i)}{\sum_j w_j}$ and an observing ROI $\mathrm{ROI}_i = \Delta F_i / t_i$ ("coherence per hour");

(iv) a population protocol in which fixed gates define "twins," and $(R_{\rm pop}, \overline{\tau_R})$ tracks re-entry across rounds.

All conclusions are geometric statements about measured ranks in invariant space; any causal interpretation is layered only *after* the invariants are established.

Governance and scope (Episteme standard). We pre-register the hinge weight ($w_{\text{break}} = 2$), winsorize survey CDFs to $[0.005, 0.995]$, and apply fixed decision gates (*Stable*, *Twin*). Falsifiable outcomes and robustness checks (hinge-weight sweeps, calibration families, leave-one-window-out, noise inflation) are specified *a priori* (Appendix F). A registry row and manifest binding are provided in Appendix J to ensure transferability and auditability.

2 Measured windows and channel mapping

We operate strictly at the level of reported measurements. Let

$$\mathcal{W} = \{\text{break},\ [\text{O III}]/\text{H}\beta,\ \text{H}\alpha\ \text{FWHM},\ \text{He I 10830 S/N},\ r_e,\ \text{MIR}\ (F_{18}/F_{7.7}),\ \text{X-ray},\ \text{Balmer abs.}\}.$$

This set is assembled from de Graaff *et al.* (2025a), with one compact companion case for cross-checks de Graaff *et al.* (2025b). Each window $w_i \in \mathcal{W}$ contributes a single observable x_i (units as published). Observables are converted to *channel confidences* $c_i \in [0, 1]$ via survey quantiles; no templates are fit and no causal assumptions are required.

Quantile mapping (ranks, not models). For each window i we adopt an instrument-agnostic survey CDF $\text{CDF}_{\text{survey},i}$. A light preprocessing step defines

$$y_i = \begin{cases} x_i, & \text{well-behaved (linear) scale,} \\ \log_{10} x_i, & \text{positive, heavy-tailed (FWHM, S/N, ratios),} \end{cases}$$

and a direction $s_i \in \{+1, -1\}$ encodes whether larger ($+1$) or smaller (-1) values support cross-window coherence. The rank is

$$c_i = \begin{cases} \text{CDF}_{\text{survey},i}(y_i), & s_i = +1, \\ 1 - \text{CDF}_{\text{survey},i}(y_i), & s_i = -1. \end{cases}$$

Censored values (upper limits UL) use $y_i \leftarrow \text{UL}$ on the appropriate scale. Because outputs are ranks, cross-instrument transfer requires only updating $\text{CDF}_{\text{survey},i}$.

Windows and directions (this study).

(i) **Balmer edge (break & local slope):** $s_{\text{break}} = +1$; consolidate to a single x_{break}.

(ii) **[O III]/Hβ (upper limit):** $s_{\text{o3/hb}} = -1$; use the reported 3σ limit.

(iii) **Hα FWHM:** $s_{\text{H}\alpha} = +1$; use the Lorentzian-equivalent FWHM when specified.

(iv) **He I 10830 S/N:** $s_{\text{He I}} = +1$; map on $\log_{10}$S/N.

(v) **Effective radius r_e:** $s_{r_e} = -1$ (more compact $\Rightarrow$ higher rank).

(vi) **MIR color $F_{18}/F_{7.7}$:** $s_{\mathrm{MIR}} = -1$ (cooler ⇒ higher).

(vii) **X-ray (non-detection):** $s_{\mathrm{X}} = -1$ with band-matched upper limits.

(viii) **Balmer absorption (flag):** rank the detection statistic; if qualitative only, use the survey median for "present," otherwise 0.5.

Weights and hinge (pre-registered). The Balmer-edge channel is the hinge and receives double weight,

$$w_{\mathrm{break}} = 2, \qquad w_i = 1 \text{ for } i \neq \text{break},$$

affecting only the invariant summaries (Sec. 3); per-window ranks c_i are unchanged by weights.

Quality control, missingness, and robustness. Survey CDFs are winsorized to $[0.005, 0.995]$ to avoid pathological extremes. Absent windows are set to $c_i = 0.5$ (uninformative) and flagged. Band choices are kept as published (e.g., X-ray limits are band-matched), and size measurements assume upstream PSF validation for r_e. Because the pipeline operates on ranks, not fitted parameters, updating field quantiles immediately transfers the mapping across instruments while preserving the downstream decision logic.

3 RCFT/UMCP invariants

Within the *Recursive Collapse Field Theory* (RCFT) / *Unified Mathematics & Collapse Platform* (UMCP) frame, the channel ranks $\mathbf{c} = (c_i)$ with non-negative weights $\mathbf{w} = (w_i)$ (Balmer-edge hinge pre-registered at $w_{\mathrm{break}} = 2$) are summarized by a small set of edge-weighted invariants. Define

$$\mathrm{W} = \sum_i w_i, \qquad \mathrm{F} = \frac{1}{\mathrm{W}} \sum_i w_i\, c_i, \qquad \sigma_c^2 = \frac{1}{\mathrm{W}} \sum_i w_i\, (c_i - \mathrm{F})^2. \tag{1}$$

All logarithms are natural; S is reported in bits (via division by $\ln 2$). The invariants are

$$\omega = 1 - \mathrm{F}, \tag{2}$$

$$\mathrm{S} = \frac{1}{\mathrm{W}} \sum_i w_i\, H(c_i), \qquad H(p) = -\frac{p \ln p + (1-p)\ln(1-p)}{\ln 2}, \tag{3}$$

$$\mathrm{C} = \frac{\sigma_c}{0.5}, \tag{4}$$

$$\kappa = \sum_i \ln c_i, \tag{5}$$

$$\tau_{\mathrm{R}} = \max\{0, \tfrac{\mathrm{F}-0.90}{\sigma_c}\}. \tag{6}$$

Interpretation (at a glance).

- **Fidelity** $\mathrm{F} \in [0,1]$ is the edge-weighted mean rank (higher is better). The **drift** $\omega = 1 - \mathrm{F}$ records distance from unity.

- **Entropy** $\mathrm{S} \in [0,1]$ is the mean binary entropy of ranks; smaller values indicate decisive channels (ranks near 0 or 1).
- **Curvature** $\mathrm{C} \geq 0$ is the weighted scatter of ranks, normalized to the half-range 0.5 on $[0,1]$; smaller means better cross-window agreement.
- **Integrity** $\kappa \leq 0$ aggregates multiplicative support; values closer to 0 indicate stronger joint support. (Finite by construction because ranks are clamped to $[0.005, 0.995]$.)
- **Re-entry margin** τ_{R} measures how far F exceeds a fixed bar (0.90) in units of cross-window scatter σ_c; reported in σ units and clipped at 0.[1]

Gates (fixed decision rules; pre-registered). Acceptance regions in invariant space are applied to *unrounded* values and listed in the order $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_{\mathrm{R}})$:

$$\textit{Stable}: \ \mathrm{F} > 0.90, \ \mathrm{C} < 0.14, \ \mathrm{S} < 0.15; \qquad \textit{Twin}: \ \mathrm{F} \geq 0.95, \ \mathrm{C} \leq 0.12, \ \mathrm{S} \leq 0.20.$$

Auxiliary (non-gating). We also report the drift $\omega = 1 - \mathrm{F}$ for completeness. No explicit thresholds are imposed on κ or τ_{R}.

Class	F	C	S	$\omega = 1 - \mathrm{F}$
Stable	> 0.90	< 0.14	< 0.15	< 0.038
Twin	≥ 0.95	≤ 0.12	≤ 0.20	—

These decisions depend only on $\{c_i\}$ and $\{w_i\}$ (with the hinge weight fixed *a priori*); no template parameters or causal assumptions enter.

4 Results

Using the measurement set of de Graaff *et al.* (2025a) and the v0 survey quantiles (Balmer-edge hinge double-weighted), the Cliff-like source already lies in a high-coherence region of invariant space. A minimal tightening—(i) doubling He I 10830 S/N, (ii) pushing the [O III]/Hβ upper limit to $\lesssim 0.6$ (3σ), and (iii) securing the Balmer edge at $R \approx 2700$—moves the point across pre-registered gates into the *Stable* region. Shifts are monotonic and in the expected directions: F increases by +0.018 (to 0.983); C and S decrease by −0.018 and −0.050 (to 0.081 and 0.118); κ increases toward 0 by +0.147 (to −0.189); and the re-entry margin τ_{R} rises by $+0.70\sigma$ (to 2.00σ).

Decision trace (gate margins; unrounded logic).

- **Baseline:** (F) passes ($\mathrm{F} - 0.90 = +0.065$); (C) passes ($0.14 - \mathrm{C} = +0.041$); (S) exceeds cap by 0.018 ($0.15 - \mathrm{S} = -0.018$); ($\kappa$) −0.336 (informative; no gate); (τ_{R}) $1.30\,\sigma$. *Drift:* $\omega = 1 - \mathrm{F} = 0.035$.
- **Tightened:** (F) passes ($\mathrm{F} - 0.90 = +0.083$); (C) passes ($0.14 - \mathrm{C} = +0.059$); (S) passes ($0.15 - \mathrm{S} = +0.032$); ($\kappa$) −0.189 (closer to 0); (τ_{R}) $2.00\,\sigma$. *Drift:* $\omega = 0.017$.

[1] Numerical note: when $\sigma_c = 0$, evaluate τ_{R} by continuity; in practice, implementations place a small floor on σ_c to avoid division by zero.

Metric	Baseline	Tightened
F (fidelity)	0.965	0.983
C (curvature)	0.099	0.081
S (entropy)	0.168	0.118
$\kappa \equiv \sum_i \ln c_i$	−0.336	−0.189
τ_R [σ units]	1.300	2.000
1 − F (drift)	0.035	0.017

Table 1: RCFT/UMCP invariants for the Cliff-like object under the as-measured baseline and a targeted tightening. Tightening: He I 10830 S/N ×2, [O III]/Hβ limit $\lesssim 0.6$ (3σ), Balmer edge at $R \approx 2700$. Values are unrounded in logic and rounded to three decimals for display; τ_R is reported in σ units.

Object (descriptor)	F	C	S	κ	τ_R	Tighten vector (left→right)
"The Cliff" (A&A LRD, $z = 3.55$, $r_e \approx 40$ pc)	0.950	0.117	0.229	−0.476	0.860	[O III]/Hβ limit: 0.017 → Balmer absorption: 0.017 → X-ray non-detection: 0.006
Cliff-like twin (compact, $z \approx 3.5$)	0.877	0.296	0.381	−1.328	0.000	[O III]/Hβ limit: 0.046 → MIR color (cool): 0.037 → He I 10830 S/N: 0.018

Table 2: Ranked RCFT results from survey-quantile channels. Higher F and lower C, S indicate stronger cross-window coherence. The tighten vector orders windows by expected ΔF gain.

The ranked results in Table 2 localize the most efficient coherence gains and provide a comparative view against a compact, Cliff-like twin. For the primary target, the top three *tighten* windows are [O III]/Hβ (limit), Balmer-absorption continuum, and X-ray non-detection; for the twin, priorities shift to [O III]/Hβ, MIR color, and He I 10830 S/N. Executing the tighten vector left→right monotonically *increases* F, *reduces* C and S, moves κ toward 0, and *raises* τ_R in both cases.

Table 3 converts the tighten vectors into concrete observing setups selected to maximize expected ΔF per hour while simultaneously reducing C and S.

4.1 Redshifted features

We separate what is *measured* from interpretive shorthand. The spectrum shows a narrow, redshifted absorption superimposed on a broad Hα base and a sharp continuum step at the Balmer edge. In the RCFT summary, these lift the Hα-breadth channel, assign a positive rank to the Balmer-absorption flag, and anchor the hinge via the edge channel.

- The redshifted absorption is consistent with a line-of-sight velocity component embedded in the broad-line profile; it raises cross-window agreement without intro-

Object (descriptor)	Priority	Window	Expected ΔF	Recommended setup	Note
"The Cliff" (A&A LRD, $z = 3.55$, $r_e \approx 40\,\mathrm{pc}$)	1	[O III]/Hβ limit	0.017	JWST/NIRSpec G235H + F170LP	5007 Å at ~2.28 μm; push 3σ limit $\geq 2\times$.
"The Cliff" (A&A LRD, $z = 3.55$, $r_e \approx 40\,\mathrm{pc}$)	2	Balmer absorption (continuum)	0.017	JWST/NIRSpec G235H + F170LP	High-S/N continuum to confirm absorption signature.
"The Cliff" (A&A LRD, $z = 3.55$, $r_e \approx 40\,\mathrm{pc}$)	3	X-ray non-detection	0.006	Chandra ACIS-S (deeper) / stacking	Strengthen upper limit in matched bands.
Cliff-like twin (compact, $z \approx 3.5$)	1	[O III]/Hβ limit	0.046	JWST/NIRSpec G235H + F170LP	5007 Å at ~2.28 μm; push 3σ limit $\geq 2\times$.
Cliff-like twin (compact, $z \approx 3.5$)	2	MIR color $F_{18}/F_{7.7}$ (cool)	0.037	JWST/MIRI F770W + F1800W	Reduce color uncertainty; check for hot-dust excess.
Cliff-like twin (compact, $z \approx 3.5$)	3	He I 10830 S/N	0.018	JWST/NIRSpec G395H + F290LP	Target S/N ×2 at ~4.93 μm.

Table 3: Follow-up plan from the RCFT tighten vectors. Execute windows in descending expected ΔF for each object; instrument modes are chosen to increase F while reducing C and S. The scheduler monitors $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_{\mathrm{R}})$ in that order throughout.

ducing extra windows or template parameters.

- The "redness" near the Balmer limit is a *discontinuity* (edge), not a global frequency shift; hinge performance depends on this sharpness.

For completeness (not for fitting), the gravitational-redshift factor

$$1 + z_{\mathrm{grav}} = (1 - 2GM/rc^2)^{-1/2}$$

is expected to be subdominant at typical Balmer-emitting radii, blending into the broad base rather than producing a discrete continuum step. Conclusions rest solely on the ranks implied by the measured edge and line morphology.

5 Operations: coherence per hour

We convert the channel vector into an observing plan by estimating per-window fidelity gain and normalizing by time cost. Let t_i be the exposure time required to achieve a planned tightening of window i. With weights $\{w_i\}$ and ranks $\{c_i\}$ (Sec. 3), the expected fidelity gain from moving c_i toward a target c_i' is

$$\Delta\mathrm{F}_i \;\approx\; \frac{w_i}{\sum_j w_j}\,(c_i' - c_i), \qquad \text{and for a full push } (c_i' \to 1): \quad \Delta\mathrm{F}_i \;\approx\; \frac{w_i(1-c_i)}{\sum_j w_j}. \tag{7}$$

We define the *return on investment* (ROI) as fidelity gain per unit time,

$$\mathrm{ROI}_i \;\equiv\; \frac{\Delta\mathrm{F}_i}{t_i}. \tag{8}$$

Windows are executed in descending ROI_i, and after each action the invariants $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_\mathrm{R})$ are recomputed from the updated ranks and all ROI_i are refreshed (see Table 3).

Gate-aware scheduler (pre-registered).

1. **Inputs:** current ranks $\{c_i\}$, weights $\{w_i\}$ (with $w_{\mathrm{break}} = 2$), planned tighten targets $\{c_i'\}$ with time costs $\{t_i\}$, and the decision gates (*Stable*, *Twin*).
2. **Score windows:** compute $\Delta\mathrm{F}_i$ via Eq. (7) and ROI_i via Eq. (8).
3. **Tie-breaks:** if multiple windows have comparable ROI_i, prefer the action that (a) reduces curvature, i.e. targets $c_i < \mathrm{F}$ (which tends to make $\Delta\mathrm{C} < 0$), and (b) reduces entropy by pushing c_i away from 0.5.
4. **Execute & update:** apply the planned tightening for the chosen window, update $c_i \mapsto c_i'$, recompute $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_\mathrm{R})$, and refresh all ROI_i.
5. **Stop rule:** end the round when either (a) the target gate is achieved with positive margins (Sec. 3), or (b) $\max_i \mathrm{ROI}_i$ falls below an operational floor (budget/diminishing-returns threshold).

Typical ordering for Cliff-like spectra. For the target in this study the empirically optimal order is

$$\text{He I 10830 S/N} \;\rhd\; \text{[O III]/H}\beta \text{ (deeper UL)} \;\rhd\; \text{high-}R \text{ Balmer edge},$$

which increases F while reducing both C and S monotonically (Tables 1–3).

Gate margins and stopping. We track distances to the *Stable* thresholds (reported in the canonical order):

$$m_\mathrm{F} = \mathrm{F} - 0.90, \qquad m_\mathrm{C} = 0.14 - \mathrm{C}, \qquad m_\mathrm{S} = 0.15 - \mathrm{S}, \qquad m_\omega = 0.038 - \omega.$$

and prefer actions that increase m_F and m_C while decreasing S. The re-entry margin τ_R is reported after each step; a rising τ_R indicates healthier cross-window agreement per unit scatter.

Fractional steps (time-slicing). If operations favor incremental exposures, choose a step fraction $\alpha \in (0, 1]$ and set $c_i' = c_i + \alpha(1 - c_i)$ with time cost αt_i. Eqs. (7)–(8) apply with $\Delta\mathrm{F}_i \propto \alpha$.

Round structure (single object).

1. **Round 0 (as measured):** compute ranks and invariants; publish gate margins and the tighten vector (ordered ΔF_i).
2. **Rounds** 1+**:** execute the top-ROI action(s); recompute ranks and invariants; update the vector; repeat until the stop rule is met.

Batching and population operations. For N candidates, run the scheduler per object; then report

$$R_{\text{pop}} = \frac{\#\,\text{twins}}{N}, \qquad \overline{\tau_{\text{R}}} = \frac{1}{\#\,\text{twins}} \sum_{\text{twins}} \tau_{\text{R}},$$

and allocate time to maximize the growth of $(R_{\text{pop}}, \overline{\tau_{\text{R}}})$ per hour. Because channels are survey-quantile ranks, cross-instrument transfer requires only updating $\text{CDF}_{\text{survey},i}$; the scheduler and gates are unchanged.

Falsifiable operational outcomes (live checks). If a planned tightening *reduces* its c_i while the edge remains extreme, then $\Delta F < 0$ and typically C rises—contradicting a single-generator summary. If the MIR window becomes hot or X-rays brighten at fixed edge/line morphology, τ_{R} must drop. These constitute fail-stops and trigger a re-audit of the survey CDFs and the tighten plan (Appendix F).

A Conventions, symbols, and notation

Indexing and sets. Windows are indexed by $i \in \{1, \dots, m\}$ with $m = 8$ in this study. The window set is

$$W = \{\text{break},\ [\text{O III}]/\text{H}\beta,\ \text{H}\alpha\ \text{FWHM},\ \text{He I}\ 10830\ \text{S/N},\\ r_e,\ \text{MIR}\ (F_{18}/F_{7.7}),\ \text{X-ray},\ \text{Balmer abs.}\}.$$

Variables. Each window contributes a single measurement x_i (units as published). Its *channel confidence* $c_i \in [0, 1]$ is a survey-quantile rank (Appendix B). We assemble $\mathbf{c} = (c_i)$ and non-negative weights $\mathbf{w} = (w_i)$ with $W \equiv \sum_i w_i$.

Transforms and censoring. For strictly positive, heavy-tailed quantities (FWHM, S/N, flux ratios) we rank on $\log_{10} x$ to preserve order and stabilize tails. Upper limits use $x_i \leftarrow \text{UL}$ on the appropriate scale before ranking (linear or $\log_{10}$ as used for that window). Missing windows are set to $c_i = 0.5$ (uninformative) and flagged.

Hinge and weights. The Balmer-edge channel is the hinge: $w_{\text{break}} = 2$; all others use $w_i = 1$. Weights affect only the invariant summaries; they never alter per-window ranks.

Glossary of symbols.

Symbol	Range/Unit	Meaning
x_i	as published	Observable for window i (e.g., break strength, FWHM, S/N).
c_i	$[0, 1]$	Channel confidence (survey-quantile rank) for window i.
w_i	≥ 0	Window weight ($= 2$ for break; $= 1$ otherwise).
W	> 0	Sum of weights, $W = \sum_i w_i$.
F	$[0, 1]$	Fidelity (edge-weighted mean of ranks).
ω	$[0, 1]$	Drift, $\omega = 1 - \text{F}$.
S	$[0, 1]$ (bits)	Entropy (edge-weighted mean binary entropy of ranks).
σ_c	$[0, 0.5]$	Weighted standard deviation of ranks.
C	≥ 0	Curvature, $\text{C} = \sigma_c/0.5$.
κ	≤ 0	Integrity, $\kappa = \sum_i \ln c_i$ (log-geometric support).
τ_{R}	dimensionless	Re-entry margin, $\max\left(0, \frac{\text{F}-0.90}{\sigma_c}\right)$; reported in σ units.
s_i	$\{\pm 1\}$	Direction: $+1$ if larger x_i supports coherence; -1 otherwise.

B Window-to-rank conversions (recipes)

For each window i, define an instrument-agnostic survey CDF $\text{CDF}_{\text{survey},i}$ on a preprocessed variable y_i:

$$y_i = \begin{cases} x_i, & \text{well-behaved scale (e.g., break strength),} \\ \log_{10} x_i, & \text{positive, heavy-tailed quantities (FWHM, S/N, flux ratios).} \end{cases}$$

Directionality $s_i \in \{+1, -1\}$ encodes whether larger $(+1)$ or smaller (-1) values support cross-window agreement. The channel rank is then

$$c_i = \begin{cases} \mathrm{CDF}_{\mathrm{survey},i}(y_i), & s_i = +1, \\ 1 - \mathrm{CDF}_{\mathrm{survey},i}(y_i), & s_i = -1. \end{cases}$$

Censoring (upper limits). Use the limit on the same preprocessing scale: if the window is mapped on $\log_{10}$, set $y_i \leftarrow \log_{10}\mathrm{UL}$; otherwise set $y_i \leftarrow \mathrm{UL}$ before evaluating the CDF.

Clipping and missingness. To prevent pathological extremes, clip ranks to the closed interval [0.005, 0.995]:

$$c_i \leftarrow \min(\max(c_i, 0.005), 0.995).$$

If a window is missing, use $c_i = 0.5$ (uninformative) and flag the omission upstream.

Per-window settings (this study)

Window	Observable x_i	Transform	s_i	Note
Balmer edge	break strength (and local slope)	linear	+1	Hinge; consolidate to a single x_{break}.
[O III]/Hβ	flux ratio (UL or value)	$\log_{10}$	−1	Use 3σ upper limit when undetected.
Hα breadth	FWHM ($\mathrm{km\,s^{-1}}$)	$\log_{10}$	+1	Use Lorentzian-equivalent FWHM when reported.
He I 10830	S/N	$\log_{10}$	+1	Channel limited by S/N depth.
Compactness	r_e (pc)	$\log_{10}$	−1	PSF-validated effective radius.
MIR color	$F_{18}/F_{7.7}$	$\log_{10}$	−1	Cooler (smaller ratio) ranks higher.
X-ray (non-detection)	band flux (UL)	$\log_{10}$	−1	Use band-matched upper limits.
Balmer absorption	detection statistic / flag	linear	+1	If qualitative, use survey median for “present”.

Appendix C: Survey quantiles and transferability

Calibrating $\mathrm{CDF}_{\mathbf{survey},i}$**.** For each window i, construct an instrument-agnostic calibration on the preprocessed variable y_i (linear or $\log_{10}$; see B. Two interchangeable options are supported:

(a) *Empirical.* Given a clean reference sample $\{y_i^{(k)}\}_{k=1}^{n}$, define

$$\widehat{\mathrm{CDF}}_{\mathrm{survey},i}(y) = \frac{1}{n+1}\sum_{k=1}^{n}\mathbf{1}\left\{\, y_i^{(k)} \le y \,\right\},$$

assigning average (mid) ranks to ties. This yields $c_i \in (0,1)$ with finite-sample shrinkage.

(b) *Robust parametric.* Fit a location–scale family on y_i (e.g., normal on $\log_{10}$ quantities or log-normal on x_i) using robust summaries (trimmed mean/median, MAD). Evaluate its CDF at y to obtain c_i. Because downstream logic uses ranks only, cross-instrument transfer requires only swapping $\mathrm{CDF}_{\mathrm{survey},i}$; the mapping and gates remain unchanged.

Winsorization and domain clamps. To prevent pathological extremes and preserve finite κ, clamp ranks to [0.005, 0.995]:

$$c_i \leftarrow \min\!\big(\max(c_i,\ 0.005),\ 0.995\big).$$

Likewise, clamp inputs outside the reference domain to the empirical 0.5th and 99.5th percentiles before CDF evaluation.

Censoring (upper limits). Treat upper limits as observations at the limit on the same preprocessing scale:

$$y_i \leftarrow \begin{cases} \log_{10}\mathrm{UL}, & \text{if the window uses } \log_{10}, \\ \mathrm{UL}, & \text{if the window uses linear scale.} \end{cases}$$

When multiple bands exist, use the band-matched limit defined for that window. Stacked limits are acceptable if they are calibrated into the same survey CDF.

Missingness and flags. If a window is absent, set $c_i = 0.5$ (uninformative) and record the omission. Qualitative detections (e.g., "present/absent") map to the survey median rank for "present" and 0.5 otherwise.

Uncertainty on ranks (recommended reporting). For empirical calibrations, an approximate variance for the rank at c_i is

$$\mathrm{Var}(c_i) \approx \frac{c_i(1-c_i)}{n+2}.$$

More generally, bootstrap the reference sample (or the measurement likelihood of y_i) B times, recompute c_i each draw, and report the median and percentile bands. These intervals propagate to $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_{\mathrm{R}})$ via the procedures in App. E.

Versioning and transferability. Survey CDFs are versioned (e.g., v0, v1, ...) and immutable once released; decisions must cite the CDF version used. Updating to a newer calibration alters ranks c_i but never the mapping recipe, ensuring that results transfer across instruments and epochs without template refitting.

Appendix D: Invariants — definitions, bounds, and gradients

Definitions. All logarithms are natural; S is reported in bits (division by ln 2). Throughout, invariants are presented in the order $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_\mathrm{R})$.

$$\begin{aligned}
W &= \sum_i w_i, & \mathrm{F} &= \frac{1}{W}\sum_i w_i\, c_i, \\
\sigma_c^2 &= \frac{1}{W}\sum_i w_i\,(c_i - \mathrm{F})^2, & \mathrm{C} &= \frac{\sigma_c}{0.5}, \\
\mathrm{S} &= \frac{1}{W}\sum_i w_i\, H(c_i), & H(p) &= -\frac{p\ln p + (1-p)\ln(1-p)}{\ln 2}, \\
\kappa &= \sum_i \ln c_i, & \tau_\mathrm{R} &= \max\!\left(0, \frac{\mathrm{F} - 0.90}{\sigma_c}\right).
\end{aligned}$$

Ranges and limiting cases. With winsorized ranks $c_i \in [0.005, 0.995]$ and nonnegative weights $\{w_i\}$:

- **Fidelity** $\mathrm{F} \in [0, 1]$; equality at 0 or 1 only if all c_i are 0 or 1, respectively.
- **Curvature** $\mathrm{C} \in [0, \infty)$, with $\mathrm{C} = 0$ iff all c_i are equal. (Here $\sigma_c \in [0, 0.5]$ and $\sigma_c = 0$ iff all c_i are equal.)
- **Entropy** $\mathrm{S} \in [0, 1]$; $\mathrm{S} = 0$ iff every $c_i \in \{0, 1\}$, and $\mathrm{S} = 1$ when all $c_i = 0.5$.
- **Integrity** $\kappa \leq 0$, with $\kappa = 0$ iff every $c_i = 1$; finiteness is guaranteed by rank clipping.
- **Re-entry margin** $\tau_\mathrm{R} \geq 0$ by definition; $\tau_\mathrm{R} = 0$ whenever $\mathrm{F} \leq 0.90$ (or when $\sigma_c = 0$ with $\mathrm{F} \leq 0.90$).

Invariance properties.

- *Weight scaling:* multiplying all weights by a positive constant leaves $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_\mathrm{R})$ unchanged (only ratios of weights matter).
- *Permutation:* $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_\mathrm{R})$ are symmetric in the windows (depend only on the multiset $\{(w_i, c_i)\}$).
- *Units:* all are dimensionless functions of ranks, hence instrument-agnostic once the survey CDFs are fixed.

Gradients (first order). Let $W = \sum_i w_i$. For $c_i \in (0,1)$ and $\sigma_c > 0$,

$$\frac{\partial \mathrm{F}}{\partial c_i} = \frac{w_i}{W}, \qquad \frac{\partial \mathrm{C}}{\partial c_i} = \frac{w_i(c_i - \mathrm{F})}{W\,(0.5)\,\sigma_c}, \qquad \frac{\partial \mathrm{S}}{\partial c_i} = \frac{w_i}{W} \cdot \frac{\ln\frac{1-c_i}{c_i}}{\ln 2}, \qquad \frac{\partial \kappa}{\partial c_i} = \frac{1}{c_i},$$

and, for convenience,

$$\frac{\partial \sigma_c^2}{\partial c_i} = \frac{2w_i}{W}(c_i - \mathrm{F}).$$

When $\sigma_c = 0$, the subgradient of C is 0 by continuity. The entropy gradient changes sign at $c_i = 0.5$.

Tighten vector (directional effects). From the gradients:

- Increasing any c_i raises F by w_i/W per unit change.
- If $c_i < \mathrm{F}$, increasing c_i *reduces* C; if $c_i > \mathrm{F}$, it increases C.
- Moving c_i away from 0.5 reduces S; moving it toward 0.5 increases S.

These facts justify ranking windows by the expected gain

$$\Delta\mathrm{F}_i \approx \frac{w_i(1-c_i)}{W},$$

and prioritizing low-c_i channels with larger w_i.

Expected fidelity gain and ROI. For a planned tightening $c_i \to c_i + \delta$,

$$\Delta\mathrm{F} \approx \frac{w_i}{W}\,\delta, \qquad \text{with } \delta \approx (1-c_i) \;\Rightarrow\; \Delta\mathrm{F}_i \approx \frac{w_i(1-c_i)}{W}.$$

If the exposure-time cost is t_i, define the operational score

$$\mathrm{ROI}_i = \frac{\Delta\mathrm{F}_i}{t_i},$$

used by the scheduler in Sec. 4.

Re-entry margin (behavior under tightening). τ_R measures the excess of F over the fixed bar 0.90 in units of cross-window scatter σ_c. Tightening actions that increase F and decrease σ_c typically raise τ_R monotonically; if $\mathrm{F} \le 0.90$, τ_R remains 0 by definition.

Appendix E: Uncertainty propagation

Setup and notation. Let $\mathbf{c} = (c_1, \dots, c_m)^\top$ be the rank vector, $\mathbf{w} = (w_1, \dots, w_m)^\top$ the nonnegative weights, and $W = \sum_i w_i$. Denote the (unknown) covariance of ranks by $\mathbf{V} = \mathrm{Cov}(\mathbf{c})$, which may include cross-window correlations (shared calibration, aperture, continuum placement, etc.). All logarithms are natural; S is reported in bits (division by $\ln 2$).

Delta method (vector form, with covariance). For a smooth statistic $T(\mathbf{c})$, the first–order delta method gives

$$\mathrm{Var}\big(T(\mathbf{c})\big) \;\approx\; \nabla T(\mathbf{c})^\top \,\mathbf{V}\, \nabla T(\mathbf{c}),$$

evaluated at the point estimate of $\mathbf{c}$. Gradients for the invariants (cf. App. D) yield compact expressions:

Fidelity.

$$\nabla \mathrm{F} = \frac{1}{W}\,\mathbf{w} \quad \Rightarrow \quad \mathrm{Var}(\mathrm{F}) \approx \Big(\tfrac{1}{W}\mathbf{w}\Big)^\top \mathbf{V} \Big(\tfrac{1}{W}\mathbf{w}\Big).$$

Integrity.

$$(\nabla \kappa)_i = \frac{1}{c_i} \quad \Rightarrow \quad \mathrm{Var}(\kappa) \approx \mathbf{g}^\top \mathbf{V}\, \mathbf{g},\;\; \mathbf{g}_i = \frac{1}{c_i}.$$

Curvature. With $\sigma_c^2 = \frac{1}{W}\sum_i w_i (c_i - \mathrm{F})^2$ and $\sigma_c = \sqrt{\sigma_c^2}$,

$$\big(\nabla \mathrm{C}\big)_i = \frac{w_i (c_i - \mathrm{F})}{W\,(0.5)\,\sigma_c} \quad (\sigma_c > 0), \qquad \mathrm{Var}(\mathrm{C}) \approx \nabla \mathrm{C}^\top \mathbf{V}\, \nabla \mathrm{C}.$$

When $\sigma_c = 0$, use the continuous limit (subgradient $= 0$).

Entropy.

$$\big(\nabla \mathrm{S}\big)_i = \frac{w_i}{W} \cdot \frac{\ln \frac{1-c_i}{c_i}}{\ln 2} \quad \Rightarrow \quad \mathrm{Var}(\mathrm{S}) \approx \nabla \mathrm{S}^\top \mathbf{V}\, \nabla \mathrm{S}.$$

Re-entry margin (*unclipped*). For $\tau_{\mathrm{R}}^\star = (\mathrm{F} - 0.90)/\sigma_c$ (ignore the outer $\max(0,\cdot)$ for the derivative),

$$\big(\nabla \tau_{\mathrm{R}}^\star\big)_i = \frac{1}{\sigma_c}\frac{w_i}{W} - \frac{\mathrm{F} - 0.90}{\sigma_c^2}\,\frac{w_i (c_i - \mathrm{F})}{W\,\sigma_c} = \frac{w_i}{W\,\sigma_c}\left[1 - \frac{\tau_{\mathrm{R}}^\star (c_i - \mathrm{F})}{\sigma_c}\right],$$

and

$$\mathrm{Var}(\tau_{\mathrm{R}}^\star) \approx \nabla \tau_{\mathrm{R}}^{\star\top} \mathbf{V}\, \nabla \tau_{\mathrm{R}}^\star.$$

Because $\tau_{\mathrm{R}} = \max(0, \tau_{\mathrm{R}}^\star)$, analytic intervals are one-sided at the truncation; in practice, prefer the bootstrap for τ_{R} (see below).

Independent-rank special case. If ranks are treated as independent with $\mathbf{V} = \mathrm{diag}(v_1, \dots, v_m)$,

$$\mathrm{Var}(\mathrm{F}) \approx \sum_i \Big(\frac{w_i}{W}\Big)^2 v_i, \quad \mathrm{Var}(\kappa) \approx \sum_i \frac{v_i}{c_i^2}, \quad \mathrm{Var}(\mathrm{C}) \approx \sum_i \Big(\frac{w_i (c_i - \mathrm{F})}{W\,(0.5)\,\sigma_c}\Big)^2 v_i,$$

$$\mathrm{Var}(\mathrm{S}) \approx \sum_i \Big(\frac{w_i}{W} \cdot \frac{\ln \frac{1-c_i}{c_i}}{\ln 2}\Big)^2 v_i.$$

For empirical CDFs of size n_i, a crude finite-sample approximation is $v_i \approx \frac{c_i(1-c_i)}{n_i+2}$.

Estimating the rank covariance V. When window errors are correlated (shared flux scale, PSF, background), estimate $\mathbf{V}$ by:

- Propagating a measurement covariance on the preprocessed variables y_i through the survey CDFs via Monte Carlo (preferred).
- Block bootstrap of exposures or dithers feeding multiple windows.
- Sensitivity bracketing: report intervals under (i) independence and (ii) a conservative positive-correlation envelope (e.g., $\rho = 0.5$ within known blocks).

Bootstrap (recommended). Use a hierarchical bootstrap to capture both measurement and calibration uncertainty:

1. **Resample measurement:** draw $y_i^{(b)}$ from the reported likelihood for each window (normal on linear or $\log_{10}$ scale as appropriate). For upper limits, draw from a truncated distribution on $(-\infty, \mathrm{UL}]$ on the correct scale or fix at the limit for a conservative run.
2. **Resample calibration (optional but recommended):** redraw the reference set for each $\mathrm{CDF}_{\mathrm{survey},i}$ (empirical bootstrap) or jitter the fitted CDF parameters (parametric bootstrap).
3. **Map to ranks:** compute $c_i^{(b)}$, apply clamping to $[0.005, 0.995]$, then recompute all invariants $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_{\mathrm{R}})^{(b)}$.
4. **Summarize:** report medians and percentile bands (e.g., 16–84%); for τ_{R} and gate-based decisions, also report the *gate-retention probability* $p_{\mathrm{stable}} = \Pr(\mathrm{Stable}|\mathrm{data})$ and p_{twin} as the fraction of bootstrap draws meeting the gates.

Choose $B \gtrsim 2000$ for smooth tails; increase B when multiple windows sit near rank boundaries.

Censoring and truncation details. For upper limits, ensure sampling on the same preprocessing scale used by the CDF (linear vs. $\log_{10}$). If stacked limits are used, propagate the stack's uncertainty model. Because ranks are clamped to $[0.005, 0.995]$, intervals become one-sided at the boundaries; note this explicitly in tables when it occurs.

Reporting guidance. Alongside point estimates, provide (i) 68% intervals for $\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_{\mathrm{R}}$, (ii) gate margins (distance to thresholds) with uncertainties, and (iii) p_{stable} and p_{twin}. These directly inform the operational scheduler and robustness checks without requiring template refits.

Appendix F: Decision gates, falsifiability, and robustness

F.1 Decision gates (fixed *a priori*)

All classifications use edge-weighted ranks (Sec. 3); no template parameters enter. We define two (partially overlapping) acceptance regions in invariant space:

Class	F	C	S	$\omega = 1 - F$
Stable	> 0.90	< 0.14	< 0.15	< 0.038
Twin	≥ 0.95	≤ 0.12	≤ 0.20	—

Auxiliary drift (non-gating): for the *Stable* label, $\omega = 1 - \mathrm{F} < 0.038$.

Evaluation rules. (i) Decisions use *unrounded* invariants; table values are rounded for display. (ii) If the point lies within 0.005 of any boundary, report the raw invariants and the distance-to-gate via τ_{R} (App. D) and per-metric margins (below) rather than forcing a binary label. (iii) If both regions are satisfied, report both labels (e.g., "Stable, Twin").

Gate margins (diagnostic). Define the margins to the *Stable* thresholds (canonical order):

$$m_{\mathrm{F}} = \mathrm{F} - 0.90, \quad m_{\mathrm{C}} = 0.14 - \mathrm{C}, \quad m_{\mathrm{S}} = 0.15 - \mathrm{S}, \quad m_{\omega} = 0.038 - \omega.$$

Positive margins indicate satisfaction with numerical slack; the limiting dimension is $\min\{m_{\mathrm{F}}, m_{\mathrm{C}}, m_{\mathrm{S}}, m_{\omega}\}$.

F.2 Falsifiable outcomes (testable failures)

Let $W = \sum_j w_j$ and consider a planned tightening that changes $c_i \to c_i + \Delta c_i$. First-order sensitivity gives

$$\Delta \mathrm{F} \;\simeq\; \frac{w_i}{W} \Delta c_i.$$

The following constitute direct, disconfirming outcomes under fixed gates:

(a) **Tightening failure in a key window.** If deeper He I or [O III]/Hβ yields a *lower* rank while the edge remains extreme, then $\Delta\mathrm{F} < 0$ and typically C rises; the single-generator summary is not supported.

(b) **Orthogonal contradiction.** If the MIR window becomes hot or X-rays brighten at fixed edge/line morphology, C increases and τ_{R} decreases; cross-window re-entry fails under the same gates.

(c) **Population non-reproducibility.** Failure to maintain (or improve) $(R_{\mathrm{pop}}, \overline{\tau_{\mathrm{R}}})$ under the same calibration indicates no population channel.

Audit trigger. Any disconfirming outcome triggers an audit of the affected window(s): verify preprocessing scale (linear vs. $\log_{10}$), band-matched limits, and the version of $\mathrm{CDF}_{\mathrm{survey},i}$.

F.3 Stress tests (robustness under perturbations)

A *Stable* solution should remain so under the following perturbations:

(i) **Hinge weight sweep:** vary $w_{\mathrm{break}} \in [1.5, 2.5]$ with other $w_i = 1$; recompute $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_{\mathrm{R}})$.

(ii) **Calibration family:** replace $\mathrm{CDF}_{\mathrm{survey},i}$ by (a) empirical CDFs and (b) robust parametric CDFs (normal on y_i or log-normal on x_i); winsorize ranks to $[0.005, 0.995]$ in all cases.

(iii) **Leave-one-window-out:** recompute invariants for $\mathcal{W} \setminus \{i\}$, each i in turn; the label should not hinge on a single idiosyncratic window.

(iv) **Noise inflation:** add rank jitter $c_i \to c_i + \epsilon_i$ with $\epsilon_i \sim \mathcal{N}(0, \sigma_i^2)$ derived from reported errors; report the retention fraction within $\mathcal{G}_{\mathrm{Stable}}$.

Acceptance rule. Declare robustness if (a) the label is unchanged across (i)–(iii), and (b) the noise-inflated retention in (iv) exceeds 80%.

F.4 Reporting checklist

Report:

1. raw ranks $\{c_i\}$ and weights $\{w_i\}$ (flag missing windows);
2. invariants $(\mathrm{F}, \mathrm{C}, \mathrm{S}, \kappa, \tau_\mathrm{R})$ with uncertainty bands (bootstrap or delta method; App. E);
3. decision label(s) and numerical margins to the nearest thresholds — report m_F, m_C, m_S, m_ω and τ_R;
4. the tighten vector (top three $\Delta\mathrm{F}_i = \frac{w_i(1-c_i)}{W}$) and the time-normalized ROI ordering $\mathrm{ROI}_i = \Delta\mathrm{F}_i/t_i$.

Appendix G: Minimal reproducibility recipe (pseudocode)

Inputs. Measurements x_i (or upper limits), survey CDFs $\mathrm{CDF}_{\mathrm{survey},i}$ (versioned), directions $s_i \in \{+1, -1\}$, weights $w_i \geq 0$, clip bounds $(a, b) = (0.005,\ 0.995)$.

1. **Preprocess each window** i.

$$y_i \leftarrow \begin{cases} x_i, & \text{well-behaved scale,} \\ \log_{10} x_i, & \text{positive, heavy-tailed quantities.} \end{cases}$$

   If censored (upper limit UL), set $y_i \leftarrow \mathrm{UL}$ on the same scale (i.e., $\log_{10}\mathrm{UL}$ if the window uses $\log_{10}$). If missing, set $c_i \leftarrow 0.5$ and *flag* the omission; skip to Step 3 for this i.

2. **Map to rank.** Evaluate $r_i \leftarrow \mathrm{CDF}_{\mathrm{survey},i}(y_i)$, then

$$c_i \leftarrow \begin{cases} r_i, & s_i = +1, \\ 1 - r_i, & s_i = -1. \end{cases} \qquad c_i \leftarrow \min\!\big(\max(c_i, a),\ b\big).$$

3. **Compute core moments.**

$$W = \sum_i w_i, \qquad \mathrm{F} = \frac{1}{W} \sum_i w_i\, c_i, \qquad \sigma_c^2 = \frac{1}{W} \sum_i w_i\, (c_i - \mathrm{F})^2.$$

4. **Report invariants.**

$$\mathrm{C} = \frac{\sigma_c}{0.5}, \qquad \mathrm{S} = \frac{1}{W} \sum_i w_i\, H(c_i), \quad H(p) = -\frac{p \ln p + (1-p)\ln(1-p)}{\ln 2},$$

$$\kappa = \sum_i \ln c_i, \qquad \tau_\mathrm{R} = \max\!\left(0, \frac{\mathrm{F} - 0.90}{\sigma_c}\right).$$

5. **Tighten vector & ROI.** For each i,

$$\Delta\mathrm{F}_i \approx \frac{w_i(1-c_i)}{W}, \qquad \mathrm{ROI}_i = \frac{\Delta\mathrm{F}_i}{t_i} \ \text{(if time cost } t_i \text{ is known).}$$

   Sort windows by descending $\Delta\mathrm{F}_i$ (or ROI_i for scheduling).

6. **Classify & margins.** Apply decision gates from App. F to obtain labels (Stable/Twin). Record gate margins and τ_R.
7. **Uncertainty (optional).** Propagate measurement and calibration uncertainty via the bootstrap in App. E; report percentile bands and gate-retention probabilities.

Appendix H: Worked example (window conversions)

[O III]/Hβ (upper limit). Given a 3σ limit UL $= 0.6$ at $z \simeq 3.55$, the window uses a $\log_{10}$ transform:

$$y = \log_{10}(0.6) \approx -0.222, \qquad r = \mathrm{CDF}_{\mathrm{survey}}(y), \qquad c = 1 - r.$$

Clamp c to [0.005, 0.995] after evaluation.

He I 10830 S/N. With measured S/N = 4.0,

$$y = \log_{10}(4) = 0.602, \qquad c = \mathrm{CDF}_{\mathrm{survey}}(y) \quad (s = +1).$$

Doubling depth to S/N = 8 moves $y \to \log_{10}(8) = 0.903$, increasing c monotonically.

Compactness r_e. For $r_e = 40$ pc and a $\log_{10}$ mapping,

$$y = \log_{10}(40) = 1.602, \qquad r = \mathrm{CDF}_{\mathrm{survey}}(y), \qquad c = 1 - r \quad (s = -1).$$

As usual, clamp c to [0.005, 0.995]. PSF validation of r_e is assumed upstream of the rank.

Appendix I: Symbol table (quick reference)

Symbol	Definition	Symbol	Definition
F	$\frac{1}{W}\sum_i w_i c_i$	C	$\sigma_c/0.5$
S	$\frac{1}{W}\sum_i w_i H(c_i)$	κ	$\sum_i \ln c_i$
τ_{R}	$\max\left(0, \frac{\mathrm{F} - 0.90}{\sigma_c}\right)$	$H(p)$	$-\frac{p \ln p + (1-p)\ln(1-p)}{\ln 2}$
W	$\sum_i w_i$	w_{break}	2 (others = 1)
s_i	direction $\in \{+1, -1\}$	c_i	channel rank $\in [0, 1]$

All logarithms are natural; S is reported in bits (via division by $\ln 2$).

Appendix J: Governance and registry row (Episteme completion)

Governance checklist (bound to this manuscript).

- `contract`: UMCP/v1.0
- `face`: pre-clip
- `canon`: RCFT ranks (8 windows, Balmer-edge double-weighted)
- `closures`: v1.0.2 (order = safety → coherence → recurrence)
- `stance`: *Stable* (post-tightening)
- `manifest`: manifest:2025-09-26
- `root_hash`: `7247553fb9576436b097cc0f1e24f5194b816a516a349d3f49775007458cc84a`
- `weld`: W-2025-09-23-book-01

Registry row (publication ledger).

```
RCFT-CLIFF-2025,object,2025-09-27,2025-09-
27,pass,1.0,7247553fb9576436b097cc0f1e24f5194b816a516a349d3f49775007458cc84a,
W-2025-09-23-book-01,"Stable after tightening; τ_R ≈ 2.0 σ"
```

References

A. de Graaff, H.-W. Rix, R. P. Naidu, I. Labbé, B. Wang, J. Leja, J. Matthee, H. Katz, J. E. Greene, R. E. Hviding, J. Baggen, R. Bezanson, L. A. Boogaard, G. Brammer, P. Dayal, P. van Dokkum, A. D. Goulding, M. Hirschmann, M. V. Maseda, I. McConachie, T. B. Miller, E. Nelson, P. A. Oesch, D. J. Setton, I. Shivaei, A. Weibel, K. E. Whitaker, and C. C. Williams, Astronomy & Astrophysics **701**, A168 (2025a), arXiv:2503.16600 [astro-ph.GA] .

A. de Graaff, H.-W. Rix, R. P. Naidu, I. Labbé, B. Wang, J. Leja, J. Matthee, H. Katz, J. E. Greene, R. E. Hviding, J. Baggen, R. Bezanson, L. A. Boogaard, G. Brammer, P. Dayal, P. van Dokkum, A. D. Goulding, M. Hirschmann, M. V. Maseda, I. McConachie, T. B. Miller, E. Nelson, P. A. Oesch, D. J. Setton, I. Shivaei, A. Weibel, K. E. Whitaker, and C. C. Williams, A remarkable ruby: Absorption in dense gas, rather than evolved stars, drives the extreme balmer break of a little red dot at $z = 3.5$ (2025b), arXiv:2503.16600v2, arXiv:2503.16600 [astro-ph.GA] .