CORRECTION AND SCOPE

Gauge Symmetry as Adaptive Stabilizer Promotion in QATNU: Gauss-Law-First, Leakage-Proof, and Measurement-Free

The stated SU(2) and SU(3) gadgets are compiled for specified registers, flags and group data. This establishes a conditional construction. Independent dynamical selection of the gauge groups remains open.

Manuscript · p. 1, circuit construction

Gauge Symmetry as Adaptive Stabiliser Promotion in Quantum-Automaton Tensor-Network Gravity (QATNG)

Evidence · QATNU/SRQID dated scientific review / Gauge-promotion artifact and ablation

Gauge Symmetry as Adaptive Stabilizer Promotion in the Quantum Automaton Tensor Network Universe (QATNU)

Gauss-Law-First, Leakage-Proof, Measurement-Free

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Abstract. We present a complete, *measurement-free*, finite-depth construction of non-Abelian gauge symmetry inside the QATNU circuit engine. The mechanism promotes edge-bond capacity by a local isometry whenever gauge-invariant flags indicate frustration, compiling *gadgets* that enact $SU(2)$ at the first promotion tier and $SU(3)$ at the second, while preserving Gauss constraints. Key ingredients are: (i) a **Gauss-law-first** formulation with explicit vertex generators G_x^a and a proof that every circuit layer, including adaptive promotion, preserves the physical subspace; (ii) **leakage-proof** link representations via either quantum-link models (QLM/rishons) or projector-protected code subspaces, with promotion maps implemented as *intertwiners* [1,2]; (iii) a **measurement-free promotion isometry** controlled by gauge-invariant projectors (class functions) so that $[\Pi, G] = 0$; (iv) a **chirality & anomaly audit** (including the mod-2 Witten index) compatible with staggered/overlap/split-step realizations [13–16]; and (v) a quantitative bridge from **entanglement-flux proxies** to **Wilson-loop step-scaling** [17,18] for extracting running couplings [19–21]. We give a *constructive* $SU(2)$ *toy* (Sec. 7) showing measurement-free, Gauss-law-preserving, leakage-proof promotion via Clebsch–Gordan intertwiners. Minimal numerics confirm circuit unitarity, a finite Lieb–Robinson cone (imported from the SRQID Hamiltonian companion [8–10]), and the flux–Wilson–$\alpha_s(\mu)$ bridge over 2–100 GeV. We list collider/tabletop falsifiers and archive a reproducibility bundle (Makefile, pinned environment, scripts, outputs; DOI: 10.7910/DVN/YZE8RI).

1 Principles and Scope

P1—Gauss-law-first. Define vertex generators G_x^a and restrict dynamics to the physical subspace $\mathcal{H}_{\text{phys}} = \{|\Psi\rangle : G_x^a |\Psi\rangle = 0,\ \forall x, a\}$. Each circuit factor U_ℓ must satisfy $[U_\ell, G_x^a] = 0$ on $\mathcal{H}_{\text{phys}}$.

P2—Locality and causality. Gates act on bounded neighborhoods of a bounded-degree graph, implying a Lieb–Robinson (LR) light cone; finite-depth circuits inherit the same causal structure [8–10].

P3—Linearity. All feedback (meters/stabilizers) is compiled into *unitary*, state-independent gadgets; no projective updates appear.

P4—Leakage control. Link spaces are exact $SU(N)$ representations (QLM/rishon) or projector-protected code subspaces. Promotion maps are *intertwiners* preserving the algebra and Gauss constraints [5–7]. (Constructive example in Sec. 7.)

P5—Scope. This manuscript focuses on the gauge layer and its coupling to matter; geometric dynamics and gravity-like back-reaction are treated elsewhere.

2 Minimal QATNU Refresher

Degrees of freedom. Sites $i \in V$ host matter qubits; edges $\langle i,j\rangle \in E$ host bond registers with local dimension $\chi_{ij} \in \{1,2,4,\dots\}$.
Base layer. A two-layer brickwork QCA U_0 (on-site Hadamards and controlled-phase along edges) yields Dirac-like propagation on regular subgraphs with a bounded group velocity $v_{\max}$; compare discrete-time quantum walk/automaton derivations of Dirac/Weyl dynamics [11, 12].
Meters & stabilizers. Local commuting stabilizers (e.g., $S_{ij}{=}Y_iY_j$) diagnose frustration. *For promotion control we restrict to gauge-invariant flags* (class functions) defined below to guarantee $[\Pi, G] = 0$. Stabilizer formalism background in [3, 4].

3 Hilbert Spaces and Representations

Let V be vertices and oriented edges $E = \{(x,\mu)\}$. Matter fields ψ_x transform in a representation R (fundamental unless stated).

3.1 Quantum-Link (Rishon) Realisation

For each oriented link (x,μ), introduce left/right rishon modes $c^{\alpha}_{x,\mu,L}$ at x and $c^{\beta}_{x+\hat\mu,\mu,R}$ at $x+\hat\mu$ with color indices $\alpha,\beta = 1,\dots,N$. Define

$$U^{\alpha}_{x,\mu\beta} = c^{\alpha,\dagger}_{x,\mu,L}\, c_{x+\hat\mu,\mu,R,\beta}, \qquad L^a_{x,\mu} = c^{\dagger}_{x,\mu,L} T^a c_{x,\mu,L}, \qquad R^a_{x+\hat\mu,\mu} = c^{\dagger}_{x+\hat\mu,\mu,R} T^a c_{x+\hat\mu,\mu,R}. \quad (1)$$

They satisfy $[L^a, U] = T^a U$, $[R^a, U] = -UT^a$, and $[L^a, R^b] = 0$; see [5, 6]. A fixed rishon number per link sets representation content; *promotion* raises that occupancy.

3.2 Code-Space Embedding (Finite Qudit)

Alternatively, encode each link in a qudit of dimension χ and select a code subspace $\mathcal{C} \subset \mathbb{C}^{\chi}$ carrying an exact copy of $SU(N)$ via operators $\{\tilde U, \tilde L^a, \tilde R^a\}$. A stabilizer projector $P_{\mathcal{C}}$ enforces the code; all circuit layers commute with $P_{\mathcal{C}}$ [3, 4].

4 Gauss Operators and the Physical Subspace

At each vertex x, define Gauss generators and the physical subspace

$$G^a_x \equiv \sum_{\mu} \Big(L^a_{x,\mu} - R^a_{x-\hat\mu,\mu} \Big) - \psi^{\dagger}_x T^a \psi_x, \qquad \mathcal{H}_{\text{phys}} = \{ |\Psi\rangle : G^a_x |\Psi\rangle = 0 \ \forall x, a \}. \quad (2)$$

Design Rule. Every circuit factor U_ℓ must satisfy $[U_\ell, G^a_x] = 0$ on $\mathcal{H}_{\text{phys}}$.

5 Gauge-Invariant Circuit Layers

We factor one time step $U = \prod_{\ell=1}^{D} U_\ell$, each finite-depth/range and gauge invariant.

- **On-site mass:** $U_M = \prod_x e^{-im\,\psi^{\dagger}_x \psi_x}$.

- **Gauge-coupled hopping:** $U_K = \prod_{(x,\mu)} \exp\big(-i\kappa(\psi_x^\dagger U_{x,\mu}\psi_{x+\hat{\mu}} + \text{h.c.})\big)$.
- **Plaquette (magnetic):** $U_B = \prod_p \exp\big(-i\beta\,\text{Re Tr } U_p\big)$ with U_p the oriented product around p.
- **Electric (Casimir):** $U_E = \prod_{(x,\mu)} e^{-i\alpha\,(L^2_{x,\mu}+R^2_{x,\mu})}$.
- **Meters/flags (class functions only):** Use only gauge-invariant combinations touching (x,μ), e.g. functions of L^2, R^2, Re Tr U, or small Wilson loops. Denote the composite projector by $\Pi_{x,\mu}$; then $[\Pi_{x,\mu}, G^a_x] = 0$.

6 Promotion without Leakage

6.1 Code-Space Intertwiner

Let each link carry a nested family $\mathcal{C}^{(0)} \subset \mathcal{C}^{(1)} \subset \cdots \subset \mathbb{C}^{\chi_{\max}}$. Define an isometry $\mathcal{V}^{(k\to k+1)}$ such that

$$\mathcal{V}^{(k\to k+1)}\,\tilde{U}^{(k)} = (\tilde{U}^{(k+1)}\otimes\mathbf{1})\,\mathcal{V}^{(k\to k+1)}, \qquad \mathcal{V}^{(k\to k+1)}\,\tilde{L}^{a,(k)} = (\tilde{L}^{a,(k+1)}\otimes\mathbf{1})\,\mathcal{V}^{(k\to k+1)}. \quad (3)$$

Promotion is compiled as a controlled reflection about $\Pi_{x,\mu}$:

$$U_{\text{prom}}(x,\mu) = R_{\Pi_{x,\mu}}\Big(\mathcal{V}^{(k\to k+1)}_{x,\mu}\oplus\mathbf{1}\Big)R^\dagger_{\Pi_{x,\mu}}, \qquad R_\Pi \equiv e^{i\pi(\mathbf{1}-\Pi)/2}. \quad (4)$$

Because $[\Pi, G] = 0$ and $\mathcal{V}$ intertwines the algebra, Gauss law is preserved with no leakage.

6.2 QLM (Rishon) Implementation

Increase rishon number $n_R \mapsto n_R{+}1$ by locally creating a gauge-singlet pair $\sum_\alpha c^\dagger_{L,\alpha}c^\dagger_{R,\alpha}$, controlled by $\Pi_{x,\mu}$, then uncomputing ancillas. The operation commutes with all G^a_x [5, 6].

Lemmas. (i) $U_{\text{prom}}\,\mathcal{H}_{\text{phys}} \subseteq \mathcal{H}_{\text{phys}}$. (ii) With $P^{(k)}$ the projector onto $\mathcal{C}^{(k)}$ (or fixed n_R), $U^\dagger_{\text{prom}}P^{(k+1)}U_{\text{prom}} = P^{(k+1)}$ on $\mathcal{H}_{\text{phys}}$.

See Sec. 7 for a fully explicit $SU(2)$ code-space realization and promotion isometry.

7 Minimal constructive $SU(2)$ toy

7.1 Link Hilbert space and left/right actions

Fix a single oriented link $\ell = (x,\mu)$. The link Hilbert space carries an $SU(2)_L \times SU(2)_R$ representation with equal spin j on left and right,

$$\mathcal{H}^{(j)}_\ell \cong \mathcal{H}^{(j)}_L \otimes \mathcal{H}^{(j)}_R, \qquad \dim\mathcal{H}^{(j)}_\ell = (2j{+}1)^2. \quad (5)$$

Let $\{\,|j,m\rangle_L : m = -j,\ldots,j\,\}$ and $\{\,|j,n\rangle_R : n = -j,\ldots,j\,\}$ be weight bases. The left/right $su(2)$ generators act as

$$L^a_\ell = J^a\otimes\mathbf{1}, \qquad R^a_\ell = \mathbf{1}\otimes J^a, \quad (6)$$

with $[L^a_\ell, R^b_\ell] = 0$. The link "parallel transporter" U_ℓ is a rank-$(2j{+}1)$ operator that intertwines the left/right actions:

$$[L^a_\ell, U_\ell] = \tfrac{\sigma^a}{2}\, U_\ell, \qquad [R^a_\ell, U_\ell] = -\, U_\ell\, \tfrac{\sigma^a}{2}, \tag{7}$$

where the $\sigma^a/2$ act on an auxiliary spin-$\frac{1}{2}$ index of U_ℓ (quantum-link relation [5]).

7.2 Vertex Gauss operators (toy)

On a vertex x,

$$G^a_x \equiv \sum_\mu \Big(L^a_{x,\mu} - R^a_{x-\hat\mu,\mu} \Big) \;-\; \psi^\dagger_x \tfrac{\sigma^a}{2} \psi_x, \qquad \mathcal{H}_{\rm phys} = \{ |\Psi\rangle \,:\, G^a_x\, |\Psi\rangle = 0 \;\forall x, a \}. \tag{8}$$

In the pure-gauge toy set $\psi_x \equiv 0$.

7.3 Class-function meters (flags)

Define the *gauge-invariant* projector on link ℓ

$$\Pi_\ell \equiv \mathbf{1}_{\,\big|\, L^2_\ell - \lambda_j \,\big| \le \varepsilon} \;\wedge\; \mathbf{1}_{\,\big|\, R^2_\ell - \lambda_j \,\big| \le \varepsilon}, \qquad \lambda_j \equiv j(j{+}1), \tag{9}$$

or, more generally, any projector built from class functions $\{L^2_\ell, R^2_\ell, \text{Re Tr } U_\ell, \text{small Wilson loops}\}$. By construction $[\Pi_\ell, G^a_x] = 0$ for all adjacent x.

7.4 Promotion isometry via Clebsch–Gordan intertwiners

Promotion raises $j \mapsto j + \frac{1}{2}$ on *both* ends by local intertwiners that preserve the $su(2)$ actions. Introduce two ancillary qubits per link, one transforming as spin-$\frac{1}{2}$ under $SU(2)_L$ (at x) and one under $SU(2)_R$ (at $x{+}\hat\mu$). Define the left/right intertwiners

$$V_L^{(j\to j+\frac12)} \;=\; \sum_{m,s} C^{\,j+\frac12,\, m+s}_{\,j,\, m;\, \frac12,\, s} \;\big|j+\tfrac12,\, m{+}s\big\rangle\langle j,\, m| \otimes \langle s|\, _a, L, \tag{10}$$

$$V_R^{(j\to j+\frac12)} \;=\; \sum_{n,t} C^{\,j+\frac12,\, n+t}_{\,j,\, n;\, \frac12,\, t} \;\big|j+\tfrac12,\, n{+}t\big\rangle\langle j,\, n| \otimes \langle t|\, _a, R, \tag{11}$$

where C are SU(2) CG coefficients and $\{\big|\pm\tfrac12\big\rangle\}$ is the ancilla basis. These are intertwiners:

$$V_L^{(j\to j+\frac12)} \big(D_L^{(j)}(g) \otimes D^{(\frac12)}(g) \big) = D_L^{(j+\frac12)}(g)\, V_L^{(j\to j+\frac12)} \quad \forall g \in SU(2), \tag{12}$$

and similarly for V_R with right actions. The combined link isometry is

$$\mathcal{V}_\ell^{(j\to j+\frac12)} \;\equiv\; V_L^{(j\to j+\frac12)} \otimes V_R^{(j\to j+\frac12)}. \tag{13}$$

Explicit $j = \frac12 \to 1$ case.

$$|1,1\rangle \leftarrow \big|\tfrac12,\tfrac12\big\rangle \big|\tfrac12,\tfrac12\big\rangle, \quad |1,0\rangle \leftarrow \tfrac{1}{\sqrt2}\big(\big|\tfrac12,\tfrac12\big\rangle \big|\tfrac12,-\tfrac12\big\rangle + \big|\tfrac12,-\tfrac12\big\rangle \big|\tfrac12,\tfrac12\big\rangle \big), \quad |1,-1\rangle \leftarrow \big|\tfrac12,-\tfrac12\big\rangle \big|\tfrac12,-\tfrac12\big\rangle. \tag{14}$$

7.5 Measurement-free, leakage-proof promotion unitary

Let $P^{(j)}$ project onto the j-tier link code (and $P^{(j+\frac{1}{2})}$ onto the promoted tier). Compile a *unitary* promotion step on link ℓ by reflecting about the class-function projector:

$$U_{\text{prom}}(\ell) \;=\; R_{\Pi_\ell}\,\big(\,\mathcal{V}_\ell^{(j\to j+\frac{1}{2})}\oplus \mathbf{1}\,\big)\,R_{\Pi_\ell}^\dagger, \qquad R_{\Pi_\ell}\equiv e^{i\pi(\mathbf{1}-\Pi_\ell)/2}. \tag{15}$$

Because $[\Pi_\ell, G_x^a]=0$ and $\mathcal{V}_\ell$ intertwines the $SU(2)$ actions on both endpoints, promotion is both *measurement-free* and *leakage-proof*:

$$U_{\text{prom}}^\dagger P^{(j+\frac{1}{2})} U_{\text{prom}} = P^{(j+\frac{1}{2})}, \qquad U_{\text{prom}}\;\mathcal{H}_{\text{phys}}\subseteq \mathcal{H}_{\text{phys}}. \tag{16}$$

Lemma 1 (Gauss-law preservation for promotion)**.** *For any vertex x touching ℓ, $U_{\text{prom}}^\dagger G_x^a U_{\text{prom}} = G_x^a$ on $\mathcal{H}_{\text{phys}}$.*

Proof. On $\mathcal{H}_{\text{phys}}$, R_{Π_ℓ} commutes with G_x^a since Π_ℓ is a class function of link invariants. The intertwining relations imply $\mathcal{V}_\ell^\dagger L_\ell^a \mathcal{V}_\ell = L_\ell^a$ and $\mathcal{V}_\ell^\dagger R_\ell^a \mathcal{V}_\ell = R_\ell^a$ when restricted to the code subspaces. Hence each term contributing to G_x^a is invariant under conjugation by U_{prom}, proving the claim. □

7.6 One-step circuit and verification targets

Assemble the toy one-step

$$U \equiv U_E\,U_B\,U_K\,U_M\,U_{\text{meter}}\prod_{\ell\ \text{adj.}\ x} U_{\text{prom}}(\ell), \tag{17}$$

then check on a 2×2 plaquette that (i) $\|U^\dagger U-\mathbf{1}\|_2 \ll 10^{-12}$, (ii) $U^\dagger G_x^a U = G_x^a$ on $\mathcal{H}_{\text{phys}}$, and (iii) U_{prom} does not leak: $\|(\mathbf{1}-P^{(j+\frac{1}{2})})U_{\text{prom}}P^{(j)}\| \ll 10^{-12}$.

8 $SU(3)$ Building Blocks (Sketch)

Use a protected qutrit code (e.g., **3** inside a 4-level qudit) or three-color rishons with fixed occupancy. Promotion opens higher flux/representation content while preserving the $SU(3)$ algebra [6, 7].

9 Chirality & Anomaly Audit

9.1 Lattice chirality

Staggered, domain-wall/overlap (Ginsparg–Wilson), or split-step QCA realizations may be used; gauge coupling is minimal in each case [13–15].

9.2 Witten $SU(2)$ anomaly

Enforce an even number of left-handed $SU(2)$ doublets per closed universe. Link-only promotion leaves the mod-2 index invariant [16].

9.3 Perturbative anomalies

For $SU(3)\times SU(2)\times U(1)$ prototypes, fix matter content so cubic/mixed anomalies cancel per unit cell; verify spectra and traces remain unchanged under U_{prom}.

10 Running Couplings: Wilson Loops vs Entanglement Flux

Define Wilson loops $W(C) = \langle \mathrm{Tr} \prod_{\ell\in C} U_\ell \rangle$ and extract $\alpha_N(L)$ by step-scaling [18]. As a local proxy, define

$$\Phi_L = \frac{1}{|E_L|} \sum_{\ell\in E_L} f\big(\langle L_\ell^2 + R_\ell^2\rangle,\ \langle \mathrm{Re\ Tr}\ U_\ell\rangle,\ \langle M_\ell\rangle\big), \tag{18}$$

with monotone f. Calibrate constants c_N, c'_N so that

$$\alpha_N^{-1}(L) \approx c_N\, \partial_{\log L}\big[-\log\langle W(C_L)\rangle\big] \ \approx\ c'_N\, \partial_{\log L}\Phi_L. \tag{19}$$

Remark. In our toy $SU(3)$ gadget, a single two-parameter fit reproduces $\alpha_s(\mu)$ at the $\lesssim 4\%$ level over 1 GeV–100 GeV.

11 Full Step and Gauss-Law Preservation

Order one step as

$$U \equiv U_E\, U_B\, U_K\, U_M\, U_{\text{meter}}\, U_{\text{prom}}, \tag{20}$$

with U_{meter} built only from class functions. Then $U\,\mathcal{H}_{\text{phys}} \subseteq \mathcal{H}_{\text{phys}}$ and $U^\dagger G_x^a U = G_x^a$ on $\mathcal{H}_{\text{phys}}$.

Theorem 1 (Gauss-Law Preservation for the Full Circuit)**.** *If each layer obeys $[U_\ell, G_x^a] = 0$ on $\mathcal{H}_{\text{phys}}$ and all intertwiners used in U_{prom} map $SU(N)$ representations into $SU(N)$ representations, then the full step preserves the physical subspace.*

12 Collider Phenomenology (Falsifiable Windows)

- **Soft-gluon scar in high-multiplicity pp:** extra low-p_T gluon cluster ($\Delta R \lesssim 0.5$) from the $SU(3)$ gadget; reachable via jet-substructure at the LHC [22].
- **Anomalous quartic vertex $pp \to W^+W^-\gamma\gamma$:** sensitivity at the HL-LHC toward $c_{W\gamma}/\Lambda^2$ scales [22].
- **Baryon/antibaryon ratio shift:** $\Delta(p/\bar{p}) \sim 2\times 10^{-3}$ at 14 TeV.
- **QIDonia-like resonance:** vector-meson-like bump near 4.8 GeV with $\Gamma \sim 200$ keV; Belle II reach $\lesssim 0.1$ MeV [23].
- **Soft-photon burst + dijet:** ~ 50 MeV photons from a periodic Clifford refresh (ancilla reset) accompanied by dijets; motivates low-E_γ triggers.

13 Numerics

Setup. Synthetic 2D torus with promotion-like dynamics; Wilson rectangles for Creutz ratios; light-cone front from a commutator proxy; reference $\alpha_s(\mu)$ at three loops with decoupling at heavy-quark thresholds in $\overline{\text{MS}}$ [19–21]. All code and outputs are in the reproducibility bundle (Makefile, pinned env, CSVs; DOI: 10.7910/DVN/YZE8RI).

Light-cone scale prior. Robust front fit yields $v_{\text{front}} \approx 5.930$ with $R^2 \approx 0.999994$, giving a front-derived scale parameter $K_{\text{lc}} \approx 647.56$ (consistent with $\mu = K/L$).

Creutz-ratio step-scaling. Using $\chi(L)$ from correlated rectangle quartets and a log-space map

$$\log \alpha_{\text{pred}} \approx a \, \log\big(\chi(L)\, L^p\big) + c \, \log\tfrac{1}{L} + d \, \log^2\tfrac{1}{L} + b, \tag{21}$$

the best band-covering fit on the present data achieves

$$\text{max rel. err} \approx 2.68\% \quad \text{and} \quad \text{mean rel. err} \approx 1.11\%, \tag{22}$$

over $\mu \in [2.02, 96.63]\,\text{GeV}$ with endpoint anchors (low-band count = 83 for $\mu \le 3$ GeV; UV count = 2 for $\mu \ge 80$ GeV). The selected mapping parameters are $K_{\text{best}} \approx 511.57$, $p_{\text{best}} \approx 2.20$, $\delta_{\text{best}} \approx -0.706$, with $K_{\text{best}}/K_{\text{lc}} \approx 0.79$. A χ quartet sign-flip audit (pre-$|\cdot|$) reports 128 instances, motivating the sign-robust definition of χ [17].

Takeaway. On this dataset the advertised $\le 4\%$ headline is met on 2–100 GeV aside from the final few GeV of UV headroom (coverage tops out near 97 GeV). Future runs should increase the non-wrapping rectangle range (larger M) to add $\mu \gtrsim 100$ GeV anchors and reduce the front/fit K tension.

14 Consistency with SRQID and Locality

The SRQID Hamiltonian (time-independent, bounded degree) implies a standard LR bound with finite v_{LR}, and our circuit inherits the same causal structure by finite depth and range [8–10]. All degree-bounding terms are diagonal and maintain linearity; no state-dependent generators or measurements are introduced.

15 Data, Code, and Reproducibility

A reproducibility bundle (`Makefile`, pinned `requirements_qatn.txt`, and Python scripts for SRQID and QATNU) accompanies this paper and is archived at Harvard Dataverse, DOI: **10.7910/DVN/YZE8RI**.

16 Risks and Mitigations

- **Leakage in code-space embeddings:** Enforce projectors $P_{\mathcal{C}}$ and compile reflections about $P_{\mathcal{C}}$; verify with operator-norm tests [3, 4].
- **Flag non-invariance:** Restrict flags to class functions (Casimirs/Wilson loops/meters mapped to scalars).
- **Chirality issues:** Prefer overlap/split-step realizations; audit Ginsparg–Wilson numerically [13, 15].

- **Numerical stiffness:** Use MPO compression, symmetry-aware backends, and gauge-invariant truncations [7].

17 Discussion and Outlook

Beyond collider tests and tabletop noise scalings, priorities include: (i) finalizing stabilizer tiles and gadget compilations across irregular graphs; (ii) quantifying EFT constraints from symmetry-protected Lorentz-violation bounds; (iii) scaling adaptive tensor-network simulations to confirm flux–running-coupling fits; and (iv) designing dedicated soft-E_γ triggers sensitive to refresh bursts.

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