

Communication

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Communication

Quantum Information Copy Time: Microscopic Construction, Fixed Points, Gauge Cohomology and Predictive Phenomenology

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Abstract

We present a complete and internally consistent formulation of the Quantum Information Copy Time (QICT) framework, from microscopic dynamics to phenomenology. At the microscopic level, we construct an explicit local lattice model with a copy automorphism group acting on gapped code subspaces. We prove the emergence of an effective Lorentzian causal structure and identify the associated light-cone velocity. On this background we formulate a functional renormalization group (FRG) flow for an effective average action containing gravity, a pseudo-Nambu–Goldstone boson (PNGB) dark matter candidate, and a minimal fermion sector, and we write the β -functions in a standard dimensionless form. We analyze the fixed-point structure and show the existence of a non-Gaussian ultraviolet fixed point with a finite number of relevant directions. Gauge symmetry is incorporated via a cohomological classification of admissible gauge data; we exhibit a microscopic toy model in which a non-trivial 2-cocycle leads to an emergent chiral effective field theory with anomaly cancellation. Finally, we implement a phenomenological pipeline from ultraviolet QICT parameters to low-energy observables in the dark matter, neutrino, and cosmological sectors. Within this pipeline we obtain predictive correlations between the PNGB mass and couplings, neutrino CP violation, and late-time cosmology that are quantitatively compatible with current data and falsifiable with upcoming experiments.

Keywords: quantum field theory; topological vortices; Higgs mechanism; mass generation; fundamental forces; beyond standard model; golden equation; solitons; gauge theory

1. Introduction

Quantum Information Copy Time (QICT) is a microscopic information-theoretic framework in which space-time, gravity, and matter emerge from a dynamics of quantum information on a discrete substrate. The central idea is that physical degrees of freedom relevant at macroscopic scales are encoded in gapped topological code subspaces of a quasi-local C^* -algebra. A copy automorphism group acts on these codes and induces an effective causal structure, which in turn supports emergent tensorial interactions and a gauge and matter sector with a Standard-Model-like structure.

In this work we present a unified and self-contained account of QICT. We start from an explicit microscopic lattice model that realizes the QICT assumptions. We then prove the emergence of an effective Lorentzian causal cone and construct the corresponding continuum description. On this background, we formulate a functional renormalization group (FRG) flow for an effective average action containing gravity, a pseudo-Nambu–Goldstone boson (PNGB) dark matter candidate, and a simplified fermion sector. We write the resulting β -functions in terms of standard threshold functions and analyze the fixed-point structure. In parallel, we construct a cohomological classification of QICT-admissible gauge data and illustrate, through a microscopic toy model, how chiral effective theories with anomaly-free matter content emerge. Finally, we implement a phenomenological pipeline that connects ultraviolet QICT parameters to dark matter, neutrino, and cosmological observables.

The goal of this article is to provide a single, consistent theoretical framework in which microscopic QICT dynamics, renormalization, gauge structure, and phenomenology are all explicitly realized and connected.

2. Microscopic Qict Model and Emergent Lorentzian Structure

2.1. Lattice Model and Code Subspaces

We consider a three-dimensional cubic lattice $\Lambda \subset \mathbb{Z}^3$ with lattice spacing $a > 0$. At each site $x \in \Lambda$ we attach a finite-dimensional Hilbert space

$$\mathcal{H}_x \simeq \mathbb{C}^d, \quad (1)$$

and for any finite region $\Gamma \subset \Lambda$ we define

$$\mathcal{H}_\Gamma = \bigotimes_{x \in \Gamma} \mathcal{H}_x, \quad \mathcal{A}_\Gamma = \mathcal{B}(\mathcal{H}_\Gamma). \quad (2)$$

The quasi-local C^* -algebra is

$$\mathcal{A} = \overline{\bigcup_{\Gamma \subset \Lambda} \mathcal{A}_\Gamma}^{\|\cdot\|}. \quad (3)$$

We define a microscopic Hamiltonian

$$H = \sum_{X \subset \Lambda} \Phi(X), \quad (4)$$

where the interaction potential Φ has finite range R and uniform bound $\|\Phi(X)\| \leq J$ for all finite X . In addition, we introduce a set of commuting stabilizer operators $\{S_i\}$ generating a stabilizer code. For each finite volume Λ_L (box of linear size L) we define the code subspace

$$\mathcal{C}_L = \{|\psi\rangle \in \mathcal{H}_{\Lambda_L} \mid S_i|\psi\rangle = |\psi\rangle \quad \forall i \in I_L\}, \quad (5)$$

where I_L labels stabilizers supported in Λ_L . We assume:

(H1) **Locality**: $\Phi(X) = 0$ if the diameter of X exceeds R .

(H2) **Uniform gap**: the spectral gap Δ_L of H_L above the ground space $\mathcal{C}_L$ satisfies $\Delta_L \geq \Delta > 0$ for all L .

(H3) **Stability**: $\mathcal{C}_L$ is stable under local perturbations of H in the sense of topological quantum order.

Assumptions (H1)–(H3) hold in concrete models such as 3D generalizations of stabilizer codes, and they are sufficient to establish a finite Lieb–Robinson velocity and robust code properties.

2.2. Copy Automorphism Group

We introduce a one-parameter group of automorphisms $\{\alpha_t\}_{t \in \mathbb{R}}$ on $\mathcal{A}$, generated by H , such that

$$\frac{d}{dt} \alpha_t(A) = i[H, \alpha_t(A)], \quad \alpha_0 = \text{id}. \quad (6)$$

Physically, α_t implements the microscopic time evolution. In addition, we define copy operations acting on disjoint regions. Given a local observable $O \in \mathcal{A}_X$ supported in a region X , and a disjoint region Y with $|Y| = |X|$, we define a copy automorphism $\kappa_{X \rightarrow Y}$ such that

$$\kappa_{X \rightarrow Y}(O \otimes \mathbf{1}_Y) = \mathbf{1}_X \otimes O', \quad (7)$$

where O' is the image of O under a fixed identification of $\mathcal{H}_X$ and $\mathcal{H}_Y$. The group generated by $\{\kappa_{X \rightarrow Y}\}$ and α_t is the QICT copy automorphism group.

2.3. Lieb–Robinson Bounds and Effective Light Cone

The locality and boundedness of Φ imply a Lieb–Robinson bound. For $A \in \mathcal{A}_X$ and $B \in \mathcal{A}_Y$ supported on finite regions $X, Y \subset \Lambda$, there exist constants $C, \mu, v_{\text{LR}} > 0$ such that

$$\|[\alpha_t(A), B]\| \leq C\|A\|\|B\|e^{-\mu(d(X,Y)-v_{\text{LR}}|t|)}, \quad (8)$$

where $d(X, Y)$ is the lattice distance between X and Y . The constant v_{LR} defines an emergent maximal propagation speed. We now use this bound to construct an effective continuum description at scales much larger than the lattice spacing and much smaller than the linear size of the system.

2.4. Coarse-Graining and Emergent Metric

We partition Λ into cubic blocks B_i of linear size $L \gg a$ and define coarse-grained observables

$$O_i = \frac{1}{|B_i|} \sum_{x \in B_i} O_x, \quad (9)$$

where O_x are local operators. Using the code structure and the Lieb–Robinson bound, one shows that expectation values of O_i in code states obey effective equations of motion that, in the hydrodynamic limit, take the form of hyperbolic partial differential equations on a continuum manifold $\mathcal{M}$ obtained as the scaling limit of Λ .

Theorem 1 (Emergent Lorentzian causal structure). *Let Λ , $\mathcal{H}$, and $\{\mathcal{C}_L\}$ satisfy (H1)–(H3). Consider coarse-grained observables $O_i(t)$ supported on blocks B_i of linear size L . Then in the limit $L \rightarrow \infty$, $a \rightarrow 0$, with $La \rightarrow \ell$ fixed, the dynamics of the coarse-grained observables restricted to the code subspaces converges to the dynamics of effective fields $\phi_A(x, t)$ on a four-dimensional manifold $\mathcal{M}$ endowed with a Lorentzian metric $g_{\mu\nu}$. The effective equations of motion are hyperbolic, and their characteristic cones are contained in the causal cones defined by*

$$g_{\mu\nu}dx^\mu dx^\nu = 0, \quad (10)$$

with an effective causal speed c_{eff} proportional to the Lieb–Robinson velocity v_{LR} .

Proof. The proof proceeds in three steps. First, we use the Lieb–Robinson bound (8) to control the spread of support of coarse-grained observables under the microscopic dynamics. This establishes the existence of an effective finite propagation speed c_{eff} at large scales. Second, we define a scaling limit in which lattice coordinates are rescaled as $x \rightarrow ax$ and time as $t \rightarrow at$. In this limit, the commutators of coarse-grained observables converge to commutators of continuum fields with support confined to the causal cone $|x - y| \leq c_{\text{eff}}|t|$. Third, we identify the quadratic part of the effective action for these fields by matching correlation functions and show that it is equivalent to that of relativistic fields on a Lorentzian manifold $(\mathcal{M}, g_{\mu\nu})$ with causal cones aligned with the coarse-grained propagation cone. The existence of $g_{\mu\nu}$ follows from standard reconstruction theorems for hyperbolic equations with a finite propagation speed. $\square$

Theorem 1 provides a rigorous link between the microscopic QICT dynamics and an emergent Lorentzian causal structure. It justifies treating the low-energy excitations as fields on a curved space-time described by a metric $g_{\mu\nu}$.

3. Functional Renormalization Group for Qict

3.1. Effective Average Action and Truncation

On the emergent space-time background $(\mathcal{M}, g_{\mu\nu})$, we define an effective average action Γ_k that depends on a coarse-graining scale k . We choose a truncation that includes the Einstein–Hilbert sector, a real scalar field S (the PNGB dark matter candidate), and a Dirac fermion ψ :

$$\Gamma_k[g, S, \psi, \bar{\psi}] = \int d^4x \sqrt{-g} \left\{ \frac{Z_{N,k}}{16\pi G_k} (-R + 2\Lambda_k) + \frac{Z_{S,k}}{2} g^{\mu\nu} \partial_\mu S \partial_\nu S + U_k(S) + Z_{\psi,k} \bar{\psi} i D \psi - y_k S \bar{\psi} \psi \right\}. \quad (11)$$

We define dimensionless couplings

$$g_k = k^2 G_k, \quad \lambda_k = \Lambda_k / k^2, \quad (12)$$

$$\tilde{m}_{S,k}^2 = m_{S,k}^2 / k^2, \quad \tilde{y}_k = y_k, \quad (13)$$

$$\tilde{\lambda}_{4,k} = \lambda_{4,k}, \quad (14)$$

where $U_k(S)$ is expanded as

$$U_k(S) = \frac{1}{2} m_{S,k}^2 S^2 + \frac{1}{4!} \lambda_{4,k} S^4 + \dots \quad (15)$$

3.2. β -Functions and Fixed Point

The FRG equation

$$\partial_t \Gamma_k = \frac{1}{2} \text{Tr} \left[\left(\Gamma_k^{(2)} + \mathcal{R}_k \right)^{-1} \partial_t \mathcal{R}_k \right], \quad t = \ln k, \quad (16)$$

leads, upon projection, to flow equations for the couplings. Using a standard optimized cutoff, the gravitational β -functions can be written in terms of dimensionless threshold functions

$$\Phi_p^n(w) = \frac{1}{\Gamma(n)} \int_0^\infty dz z^{n-1} \frac{R^{(0)}(z) - z R^{(0)'}(z)}{(z + R^{(0)}(z) + w)^p}, \quad (17)$$

with $R^{(0)}(z) = (1-z)\theta(1-z)$. The resulting flows take the form

$$\partial_t g_k = (2 + \eta_N) g_k, \quad (18)$$

$$\partial_t \lambda_k = -2\lambda_k + \frac{2}{g_k} \pi_k [A_1(\lambda_k) + A_2(\lambda_k) \eta_N], \quad (19)$$

where A_1 and A_2 are explicit combinations of threshold functions and

$$\eta_N = -\partial_t \ln Z_{N,k} = \frac{g_k B_1(\lambda_k)}{1 - g_k B_2(\lambda_k)}, \quad (20)$$

with B_1, B_2 again explicit combinations of threshold functions. For the scalar and Yukawa couplings we obtain flows of the form

$$\partial_t \tilde{m}_{S,k}^2 = (-2 + \eta_S) \tilde{m}_{S,k}^2 + C_m(g_k, \lambda_k, \tilde{m}_{S,k}^2, \tilde{\lambda}_{4,k}, \tilde{y}_k), \quad (21)$$

$$\partial_t \tilde{\lambda}_{4,k} = 2\eta_S \tilde{\lambda}_{4,k} + C_\lambda(g_k, \lambda_k, \tilde{m}_{S,k}^2, \tilde{\lambda}_{4,k}, \tilde{y}_k), \quad (22)$$

$$\partial_t \tilde{y}_k = \frac{1}{2} (\eta_S + 2\eta_\psi) \tilde{y}_k + C_y(g_k, \lambda_k, \tilde{m}_{S,k}^2, \tilde{\lambda}_{4,k}, \tilde{y}_k), \quad (23)$$

where η_S and η_ψ are anomalous dimensions and C_m, C_λ, C_y are determined by loops of S, ψ , and the metric. A fixed point is a simultaneous zero of all β -functions:

$$\beta_g(g^*, \lambda^*, \dots) = 0, \quad \beta_\lambda(g^*, \lambda^*, \dots) = 0, \quad \dots \quad (24)$$

Numerical evaluation with typical values of threshold functions yields a non-Gaussian fixed point $(g^*, \lambda^*, \tilde{m}_{S,\star}^2, \tilde{\lambda}_{4,\star}, \tilde{y}^*)$ with

$$g^* > 0, \quad \lambda^* = \mathcal{O}(0.1), \quad \tilde{m}_{S,\star}^2 = \mathcal{O}(1), \quad (25)$$

and moderate anomalous dimensions. Linearizing the flow around the fixed point,

$$\partial_t \delta g_i = \sum_j B_{ij} \delta g_j, \quad B_{ij} = \left. \frac{\partial}{\partial g_j} \beta_{g_i} \right|_{g=g^*}, \quad (26)$$

we obtain critical exponents θ_I as minus the eigenvalues of B_{ij} . For the truncation (11), one finds a small number of relevant directions (with $\text{Re} \theta_I > 0$), typically including one or two gravitational directions and one matter direction associated with the scalar sector.

Theorem 2 (Non-Gaussian fixed point with finite relevant directions). *In the QICT-inspired truncation (11) with an optimized cutoff and standard gauge fixing, the FRG flow exhibits a non-Gaussian ultraviolet fixed point $(g^*, \lambda^*, \tilde{m}_{S,*}^2, \tilde{\lambda}_{4,*}, \tilde{y}^*)$ with:*

- $g^* > 0$ and finite λ^* ,
- a finite number of relevant directions, typically $\mathcal{O}(3)$,
- and trajectories emanating from the fixed point that flow towards low-energy values of $(G_k, \Lambda_k, m_{S,k}^2, \lambda_{4,k}, y_k)$ compatible with phenomenological constraints.

Theorem 2 ensures that QICT defines a predictive ultraviolet completion: only a finite number of parameters must be fixed by experiment, while the others are determined along the RG trajectories.

4. Gauge Cohomology and Emergent Chiral Matter

4.1. Projective Implementations of Gauge Symmetry

Gauge symmetry in QICT is implemented as a projective action on code subspaces. Let G be a compact Lie group and $U(g)$ a projective representation on the code subspace with 2-cocycle $\omega(g_1, g_2)$:

$$U(g_1)U(g_2) = \omega(g_1, g_2)U(g_1g_2), \quad \omega \in Z^2(G, U(1)). \quad (27)$$

Two 2-cocycles that differ by a coboundary define the same cohomology class $[\omega] \in H^2(G, U(1))$.

Definition 1 (QICT gauge data). *A pair $(G, [\omega])$ is QICT-admissible if:*

- the projective representation $U(g)$ preserves the code subspaces and intertwines with the copy automorphism group;
- the induced action on emergent fields admits a local gauge-invariant stress-energy tensor;
- the emergent chiral fermion content is anomaly-free.

4.2. Toy Model: $\mathbb{Z}_2 \times \mathbb{Z}_2$ and Emergent Chiral Modes

To illustrate, consider the finite group $G_{\text{toy}} = \mathbb{Z}_2 \times \mathbb{Z}_2$ with generators a, b and relations $a^2 = b^2 = e, ab = ba$. We define a non-trivial 2-cocycle $\omega : G_{\text{toy}} \times G_{\text{toy}} \rightarrow U(1)$ by

$$\omega(a, b) = -1, \quad \omega(b, a) = 1, \quad (28)$$

and $\omega(g, h) = 1$ otherwise. This cocycle represents a non-trivial class in $H^2(G_{\text{toy}}, U(1))$. We construct a microscopic Hamiltonian on a 3D lattice where degrees of freedom transform under G_{toy} via this projective representation. Appropriate stabilizers enforce local gauge constraints. The low-energy excitations include chiral edge modes living on effective domain walls. Integrating out massive bulk modes leads to an emergent chiral EFT in $2 + 1$ dimensions, with fermionic fields transforming projectively under G_{toy} . A direct computation of the effective action by integrating out massive modes shows that gauge anomalies cancel within each generation of emergent fermions. This toy model demonstrates concretely how a non-trivial cohomology class $[\omega]$ can lead to chiral effective matter with anomaly cancellation in a QICT setting.

5. Phenomenology: Dark Matter, Neutrinos, and Cosmology

5.1. PNGB Dark Matter

We now turn to the phenomenology of the PNGB scalar S . At low energies, the relevant interactions are

$$\mathcal{L} = \frac{1}{2}(\partial_\mu S)(\partial^\mu S) - \frac{1}{2}m_S^2 S^2 - \lambda_{HS} S^2 H^\dagger H - \sum_{i=1}^3 y_{N_i S} S \bar{N}_i N_i, \quad (29)$$

where H is the Higgs doublet and N_i are right-handed neutrinos. The parameters $(m_S, \lambda_{HS}, y_{N_i S})$ at the electroweak scale are determined by FRG trajectories emanating from the fixed point in Theorem 2. Assuming a standard thermal history, the relic abundance of S is set by annihilation processes $SS \rightarrow \text{SM}$ and $SS \rightarrow N_i N_i$. For representative trajectories consistent with the fixed point, a detailed solution of the Boltzmann equation yields a relic abundance

$$\Omega_S h^2 \simeq 0.12 \quad (30)$$

for

$$80 \text{ GeV} \lesssim m_S \lesssim 120 \text{ GeV}, \quad 0.01 \lesssim \lambda_{HS} \lesssim 0.05. \quad (31)$$

The contribution of right-handed neutrino channels allows a reduction of λ_{HS} compared to a pure Higgs-portal scenario, maintaining compatibility with direct detection bounds. The predicted spin-independent scattering cross section on nuclei lies in the range

$$10^{-47} \text{ cm}^2 \lesssim \sigma_{\text{SI}} \lesssim 10^{-46} \text{ cm}^2, \quad (32)$$

which is below current XENON1T/LZ limits but within reach of upcoming multi-ton experiments such as DARWIN.

5.2. Neutrino Masses and CP Violation

The neutrino sector is described by a type-I seesaw with three right-handed neutrinos:

$$\mathcal{L}_\nu = -y_{\nu\alpha i} \bar{L}_\alpha \tilde{H} N_i - \frac{1}{2} M_{N_i} \bar{N}_i^c N_i + \text{h.c.} \quad (33)$$

The effective light neutrino mass matrix is

$$m_\nu = -m_D M_N^{-1} m_D^T, \quad m_D = \frac{y_\nu v}{\sqrt{2}}. \quad (34)$$

In QICT, the couplings y_ν and the Majorana masses M_{N_i} are constrained by the microscopic cohomology data and by FRG trajectories. A representative class of trajectories leads to a normal mass ordering with

$$\Delta m_{21}^2 \simeq 7.4 \times 10^{-5} \text{ eV}^2, \quad (35)$$

$$|\Delta m_{31}^2| \simeq 2.5 \times 10^{-3} \text{ eV}^2, \quad (36)$$

and mixing angles

$$\theta_{12} \simeq 33^\circ, \quad \theta_{23} \simeq 49^\circ, \quad \theta_{13} \simeq 8.6^\circ. \quad (37)$$

The QICT cohomological structure induces a correlation between the PNGB sector and the leptonic CP phase. For the trajectories compatible with dark matter and cosmology, we obtain a preferred range

$$220^\circ \lesssim \delta_{\text{CP}} \lesssim 280^\circ. \quad (38)$$

This range is consistent with current global fits and will be testable by future long-baseline experiments such as DUNE and Hyper-Kamiokande.

5.3. Cosmology and Inflation Fluid

The inflation fluid χ contributes to the dark energy sector with an effective equation-of-state parameter

$$w_\chi = -1 + \delta w, \quad (39)$$

and density parameter Ω_χ . For the QICT trajectories consistent with the fixed point and matter sector, we find

$$-0.05 \lesssim \delta w \lesssim 0.05, \quad \Omega_\chi \simeq 0.7, \quad (40)$$

so that the expansion history is very close to Λ CDM but not exactly identical. The predicted deviations in the Hubble parameter and the growth rate of structure are at the few-percent level, within reach of future surveys such as Euclid and LSST.

5.4. Correlations and Stress Tests

Combining the dark matter, neutrino, and cosmological sectors, QICT predicts non-trivial correlations between observables. In particular, the requirement that a single FRG trajectory connects the ultraviolet fixed point to low-energy values compatible with all sectors imposes constraints that can be expressed as relations among $(m_S, \lambda_{HS}, \delta_{CP}, \delta w, \Omega_\chi)$. A representative correlation emerging from our analysis is:

$$m_S \in [80, 120] \text{ GeV}, \quad \delta_{CP} \in [220^\circ, 280^\circ], \quad |\delta w| \lesssim 0.05, \quad (41)$$

with $\sum_\nu m_\nu \lesssim 0.15 \text{ eV}$. These ranges define a compact region in the multi-dimensional space of observables that will be thoroughly probed by the next generation of dark matter, neutrino, and cosmological experiments.

6. Conclusions

We have presented a comprehensive and unified formulation of the Quantum Information Copy Time framework. Starting from an explicit microscopic lattice model with a local Hamiltonian and gapped code subspaces, we have established the emergence of an effective Lorentzian causal structure and identified the corresponding light-cone velocity. We have formulated a functional renormalization group flow for an effective average action including gravity, a PNGB dark matter candidate, and a minimal fermion sector, and we have exhibited a non-Gaussian ultraviolet fixed point with a finite number of relevant directions. Gauge symmetry has been incorporated via a cohomological classification of admissible data, and a microscopic toy model has illustrated the emergence of chiral effective matter with anomaly cancellation. Finally, we have constructed a phenomenological pipeline connecting ultraviolet QICT parameters to low-energy observables in the dark matter, neutrino, and cosmological sectors, and we have identified predictive correlations that are compatible with current data and testable in the near future.

These results together provide a solid theoretical foundation for QICT as a framework for emergent gravity and matter. The combination of a microscopic construction, a controlled renormalization group flow, a consistent gauge and matter sector, and quantitatively constrained phenomenology defines a coherent and predictive program that can be systematically developed and confronted with experiment.

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