Emergent Mass Hierarchies and the Strong Gravity Scale from an Error-Correcting Tensor Network

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Abstract

We present a framework in which spacetime and gravity are not fundamental continuum geometries, but emergent thermodynamic properties of a discrete, $[8, 4, 4]$ quantum error-correcting tensor network. By applying topological parity constraints to a 65,536-dimensional bipartite supercell, the lattice natively reproduces key structural features of the Standard Model without phenomenological insertion: exactly three fermion generations, an exponential mass hierarchy scaled by the reciprocal of the Golden Ratio $(1/\phi)$, and geometric CP-violation generating the CKM mixing matrix. Evaluating the lattice's response to mechanical strain reveals a spontaneous symmetry breaking to a period-4 vacuum, isolating a spin-2 E_g graviton mode with a bare "strong gravity" scale of **1.3 GeV**. To investigate the Equivalence Principle, we evaluate the metric strain of topologically confined composite states. We demonstrate via exact Octahedral (O_h) group theory that a purely scalar representation of the strong force (A_{1g}) is mathematically invisible to the E_g graviton projector, forcing a collapse of gravitational universality. This constitutes a no-go theorem: macroscopic gravity strictly requires the QCD flux tube to be modeled as an extended topological string possessing transverse shear components. Finally, we frame the 10^{19} gap between the bare lattice scale and the physical Planck mass as a thermodynamic consistency check. Applying holographic scaling to distribute the local metric strain requires an entanglement horizon of $\mathbf{10^{38}}$ nodes, aligning the discrete lattice geometry with Dirac's Large Number Hypothesis and the emergent physical weakness of Newton's constant, G.

1 Introduction: The $[8, 4, 4]$ Lattice Vacuum

The fundamental incompatibility between General Relativity and the Standard Model of particle physics stems from a foundational assumption: the treatment of the quantum vacuum as a continuous, smooth spacetime manifold. At the Planck scale, quantum fluctuations render this continuum computationally and physically unstable. In recent years, holographic duality and the "It from Qubit" paradigm [1, 2] have suggested that spacetime and gravity are not fundamental, but rather emergent phenomena arising from the quantum entanglement of discrete, underlying degrees of freedom.

In this paper, we formalise this paradigm by modelling the quantum vacuum not as a passive continuum background, but as an active, discrete, topological tensor network governed strictly by quantum error correction. Specifically, we propose that the local geometry of spacetime is isomorphic to the extended $[8, 4, 4]$ Hamming code.

Rather than embedding particles into a pre-existing space, we define the vacuum as a network of localised supercells, each possessing 8 binary degrees of freedom. By applying the logical

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parity checks of the $[8, 4, 4]$ code as fundamental superselection rules, this 256-dimensional space naturally partitions into states satisfying specific topological parity constraints. Remarkably, these parity-protected valid states map precisely onto the fermion and boson particle content of the Standard Model. The purpose of this paper is to demonstrate how generation hierarchies, chiral mixing, and the Strong Gravity scale natively emerge from the geometric deformation of this error-correcting vacuum.

2 Standard Model Emergence (The Microscopic Scale)

2.1 The Topological Generation Lock

Particle propagation through the vacuum is modelled as a discrete quantum walk governed by controlled-NOT (CNOT) operations acting on the qubit registers. By constructing the full adjacency matrix of the valid subspace under these operations, we observe a strict topological partitioning. The Hilbert space factorises into exactly three disjoint sub-graphs. This demonstrates that the existence of exactly three generations of matter is a topological "generation lock" mandated by the routing architecture of the 8-bit quantum vacuum.

2.2 The Golden Mass Hierarchy

The generation mass hierarchy follows a Boltzmann-weighted thermodynamic cost of propagating a frustrated codeword through the error-correcting vacuum. Each valid codeword possesses a frustration count F—the number of edges on the Q_3 face-adjacency graph connecting faces with differing bit values—and the effective mass scales exponentially:

$$M(\mathbf{c}) = \exp\left(\frac{F(\mathbf{c})}{2\varphi}\right) \tag{1}$$

where $\varphi = (\sqrt{5} - 1)/2 \approx 0.618$ is the reciprocal of the Golden Ratio. To leading order, this reduces to $m_n \approx E_0\, e^{\kappa n}$ where $n \in \{0, 1, 2\}$ is the generation index and $\kappa = 1/\phi$, providing a purely geometric origin for the observed hierarchical gap between quark masses [9].

2.3 Geometric CP Violation and the CKM Matrix

To break time-reversal symmetry on a rigid lattice, a geometric chiral phase ($e^{i\pi/4}$) is introduced into the non-commuting off-diagonal components of the weak hopping matrix. This phase arises naturally from the C_4 rotational symmetry of the octahedral lattice, whose fundamental phase quantum is $2\pi/4 = \pi/2$; the half-quantum $\pi/4$ is the minimal phase that breaks time-reversal while preserving the lattice symmetry group. Diagonalising the total Hamiltonian cleanly extracts a 3×3 unitary mixing matrix [3, 4]. The resulting lattice-derived $|V_{\mathrm{CKM}}|$ matrix successfully replicates the phenomenological hierarchy of the physical universe, yielding a strictly non-zero Jarlskog invariant ($J \neq 0$).

3 Emergence of Strong Gravity (The Mesoscopic Scale)

3.1 The E_g Graviton Tensor Mode

On a discrete 3D octahedral (O_h) lattice, continuous rotational symmetry is broken. The closest analogue to the traceless, symmetric spin-2 metric distortion of General Relativity is the E_g tensor representation of the octahedral point group. To isolate the gravitational response, we construct the exact E_g Clebsch–Gordan projection operator (P_{E_g}) using the character-weighted sum over all 48 elements of O_h:

$$P_{E_g} = \frac{2}{48} \sum_{g \in O_h} \chi_{E_g}(g)^* \, R_g \tag{2}$$

where $\chi_{E_g}(g)$ is the E_g character of group element g and R_g is the corresponding 256-dimensional representation matrix acting on the codeword space. The mechanical strain derivative of the Hamiltonian $(\partial H/\partial \epsilon)$ is filtered through this projector to isolate the gravitational sector:

$$\left(\frac{\partial H}{\partial \epsilon}\right)_{E_g} = P_{E_g} \frac{\partial H}{\partial \epsilon} P_{E_g} \tag{3}$$

3.2 Tachyonic Instability and Spontaneous Symmetry Breaking

Evaluation of the E_g band structure reveals that the flat $k = 0$ state is physically unstable (tachyonic: negative curvature at the Γ point). This instability triggers a spontaneous symmetry breaking, with the vacuum state rolling into a stable global minimum at $k = \pi/2$. In lattice physics, this corresponds to a spatial wavelength of exactly 4 lattice units, suggesting a connection between the gravitational vacuum structure and the 4-bit logical depth of the $[8, 4, 4]$ code.

3.3 Metric Elasticity and the "Strong Gravity" Scale

Following Sakharov's paradigm of induced gravity [5], the gravitational constant is inversely proportional to the stiffness of the vacuum. By computing the second derivative of the E_g tensor band at the stable minimum, we extract a strictly positive bare geometric stiffness:

$$K_{E_g} \approx 1.29 \tag{4}$$

This yields a bare Planck mass governed entirely by the strong force scale:

$$M_{P,\text{bare}} = \sqrt{4\pi \, K_{E_g}} \, \Lambda_{\text{QCD}} \approx 1.3 \text{ GeV} \tag{5}$$

4 The Equivalence Principle and the Trace Anomaly

4.1 The Failure of the Bare Lattice

When metric strain is applied solely to the bare kinetic hopping operators, the resulting effective gravitational constants reveal a catastrophic violation of universality. The gravitational coupling across the three bare quark generations varies by over two orders of magnitude ($G_3/G_1 \sim 10^{-2}$ to 10^2 depending on the generation), precisely because the strain derivative couples to the *spatial extent* of the wavefunction (which favours delocalised light states) rather than to the *energy density* (which should favour heavy states proportionally to their mass).

4.2 The "Stretchy Glue" and the Virial Theorem

In physical QCD, quarks are strictly confined into colour-singlet hadrons. To model macroscopic gravity, the metric strain must couple to both the kinetic tunnelling and the geometric tension of the confinement energy:

$$\frac{\partial H_{2P}}{\partial \epsilon} = \frac{\partial H_{\text{kin}}}{\partial \epsilon} + \frac{\partial V_{\text{glue}}}{\partial \epsilon} \tag{6}$$

This is the discrete lattice analogue of the Virial Theorem: the total gravitational response is the sum of kinetic and potential strain responses, not the kinetic response alone.

4.3 A No-Go Theorem for Scalar Confinement

To satisfy the Equivalence Principle, the macroscopic binding energy must successfully couple to the graviton field. Crucially, the *geometry* of this binding energy determines its visibility to the graviton.

Computational sweeps utilising a purely scalar on-site confinement potential ($V_{\text{glue}} \propto A_{1g}$) demonstrate that the gravitational ratio G_3/G_1 collapses toward zero in the strong-coupling limit ($G_3/G_1 \approx 0.003$ at $g_s = 20$). Because the joint E_g projector strictly annihilates the A_{1g} trace, the scalar binding energy becomes completely invisible to the graviton, leaving only the sub-dominant kinetic hopping to source the gravitational field. As the scalar binding mass grows, the numerator of the effective gravitational coupling freezes while the denominator expands, forcing the ratio to vanish.

Theorem 1 (No-Go for Scalar Confinement)**.** *On the octahedral lattice with E_g graviton projection, a purely scalar (A_{1g}) confinement potential cannot produce gravitational universality. In the strong-coupling limit $g_s \to \infty$, the effective gravitational constant of confined states satisfies $G_{\text{eff}} \to 0$, because the dominant energy component ($V_{\text{glue}} \propto A_{1g}$) is annihilated by the E_g projector.*

The Equivalence Principle therefore dictates that the physical QCD flux tube must possess intrinsic E_g shear components—transverse quantum fluctuations that transform as the spin-2 tensor representation and are therefore visible to the graviton [6]. Pure group theory dictates that a uniaxial mechanical strain decomposes into the O_h representations with strict coefficients:

$$\text{diag}(1,0,0) = \frac{1}{3}A_{1g} + \frac{1}{2}E_{g,u} + \frac{1}{6}E_{g,v} \tag{7}$$

Thus, an extended uniaxial flux tube would contribute exactly 1/6 of its tension to the E_g channel, providing a specific, mathematically exact prediction for the gravitational coupling fraction of an extended confining string.

5 Holographic Scaling and the Dirac Large Number

5.1 The Holographic Scaling Limit

The mesoscopic evaluation of the lattice yielded a bare Planck mass of $M_{P,\text{bare}} \approx 1.3$ GeV (Eq. 5). While this successfully derives the local metric stiffness of the vacuum, it sits 19 orders of magnitude below the macroscopic cosmological Planck mass ($\sim 10^{19}$ GeV).

In the holographic paradigm, macroscopic gravity is a collective thermodynamic phenomenon. The local stiffness must scale with the entanglement entropy (N) of the causal horizon [7], yielding an effective macroscopic mass of:

$$M_{P,\text{macro}} = M_{P,\text{bare}}\sqrt{N} \tag{8}$$

5.2 The Dirac Large Number Consistency

To bridge the gap between the lattice's 1.3 GeV local scale and the observed physical vacuum, the scaling relation (Eq. 8) requires an entanglement factor of $N \approx 10^{38}$.

This requirement acts as a consistency check for the lattice framework. The value 10^{38} is precisely the square root of the Eddington number ($\sim 10^{76}$), representing the expected number of coherent nucleonic degrees of freedom within a typical cosmological horizon. We emphasise that N is determined here by requiring consistency with the observed Planck mass, not derived independently from the lattice geometry. An independent derivation of N—whether from the entanglement entropy of the cosmological horizon or from the number of coherent lattice cells within the Hubble volume—would promote this consistency check to a fundamental prediction. Nonetheless, the framework naturally accommodates Dirac's Large Number Hypothesis [8], demonstrating that the macroscopic weakness of Newton's constant (G) behaves precisely as a thermodynamic dilution of the $O(1)$ GeV lattice stiffness across a vast 10^{38}-node cosmic entanglement web.

6 Conclusion and Open Problems

We have demonstrated that treating the quantum vacuum as a discrete, $[8,4,4]$ error-correcting tensor network naturally resolves critical phenomenological features of the Standard Model and provides concrete results in the gravitational sector. The principal results are:

1. **Generation hierarchy:** The $[8,4,4]$ code admits exactly 48 valid codewords partitioned into three generations by an exact $\mathbb{Z}_2$ topological lock on the G_0 bit, with an exponential mass hierarchy governed by the reciprocal Golden Ratio ($\kappa = 1/\phi$).

2. **CKM mixing:** Geometric CP violation through a chiral phase in the weak hopping matrix produces a unitary 3×3 mixing matrix with the correct phenomenological hierarchy and non-zero Jarlskog invariant.

3. **Spin-2 metric elasticity:** The E_g tensor branch of the band structure provides a spin-2 graviton mode propagating at the speed of light, with a tachyonic instability at $k = 0$ condensing to a period-4 vacuum at $k = \pi/2$.

4. **Strong gravity scale:** The bare E_g stiffness $K_{E_g} \approx 1.29$ yields a bare Planck mass of 1.3 GeV, the "strong gravity" scale at which the tensor mode operates within a single lattice cell.

5. **No-go theorem:** Scalar (A_{1g}) confinement is gravitationally sterile on the octahedral lattice. The Equivalence Principle requires the QCD flux tube to possess intrinsic E_g transverse shear components, with a predicted coupling fraction of $1/6$ from the O_h Clebsch–Gordan decomposition.

6. **Dirac Large Number consistency:** The 10^{19} gap between the bare and macroscopic Planck masses is consistent with holographic entanglement scaling across $N \approx 10^{38}$ horizon degrees of freedom.

Open Problems. The immediate priorities are: (a) rigorous derivation of the complete 3D composite stress-energy tensor ($T_{\mu\nu}$), explicitly coupling the E_g metric projector to the transverse quantum fluctuations of the macroscopic hadronic state to achieve perfect macroscopic gravitational universality; (b) independent derivation of the entanglement factor N from the lattice geometry, which would promote the Dirac Large Number consistency to a prediction of G; and (c) extraction of the quantitative value of Newton's constant from the lattice's E_g stiffness combined with the holographic scaling, requiring the extended flux tube calculation described in Section 4.3.

Code and Data Availability

The complete Python implementation of all calculations reported in this paper—the single-particle walk operator (256D), O_h projection, E_g band structure, two-particle meson space (2,304D), confinement sweep, and strain-derivative analysis—is publicly available at:

https://github.com/neusym/ckm-lattice

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