Emergent Physical Laws from Information-Theoretic Constraints on a Unitary Graph Substrate

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Abstract

Modern physics faces a persistent gap between the unitary, reversible dynamics of Quantum Mechanics and the determinate, geometric structure of General Relativity. This project proposes a novel computational framework—the "Substrate"—to investigate whether this gap can be bridged not by postulating new fundamental fields, but by imposing information-theoretic constraints on a minimal graph topology.

We posit that "Space" is not a background container, but a dynamic network of N sites evolving under strict unitarity ($U = e^{-iHt}$). Our preliminary simulations demonstrate that standard physical phenomena emerge as data-compression artifacts on this graph. Specifically, we have successfully derived: (1) A finite speed of light (c) emerging from Lieb-Robinson bounds on local connectivity; (2) Electro-weak potentials recovered by inverting the discrete Graph Laplacian; (3) Hydrogen-like orbital geometries emerging as eigenmodes of topological defects; and (4) The emergence of classical history via a *derived* memory bandwidth limit.

This project seeks funding to formalize this framework and investigate the "Thermodynamics of Time." We hypothesize that the "collapse" of the wavefunction is an unavoidable consequence of finite memory bandwidth, suggesting that the arrow of time is identical to the accumulation of geometric history.

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1 The Foundational Question

How does the definite reality of our macroscopic experience emerge from the indefinite potentiality of the quantum wavefunction? Standard approaches in high-energy physics often presuppose spacetime as a pre-existing manifold. We propose an alternative approach grounded in **Hilbert Space Realism**. We treat the state vector as the fundamental object and inquire whether "Space," "Time," and "Forces" are emergent data structures required to maintain unitarity under resource constraints.

2 The Hypothesis

We posit a universe defined by three minimal axioms:

1. **Graph Realism:** Space is a dynamic graph of N sites, not a smooth manifold.

2. **Unitarity:** Time evolution is strictly unitary ($U = e^{-iHt}$), ensuring no information is lost at the fundamental level.

3. **Geometric Memory:** "Forces" are the energy costs associated with encoding history (Berry phases) into the graph's links.

3 Preliminary Validation

To validate the feasibility of these axioms, we have developed a Python-based lattice gauge simulation suite. Preliminary runs have successfully reproduced fundamental quantum phenomena from topological constraints alone. The complete codebase is available open-source.[1]

3.1 Emergence of Causal Structure (Experiment 01)

By simulating unitary evolution on a locally connected graph, we observed the emergence of a strict **Lieb-Robinson Bound**. This confirms that a finite "Speed of Light" (c) and a relativistic causal cone emerge naturally from the finite connectivity of the graph, without presupposing a Lorentzian manifold.

3.2 Emergence of Fundamental Forces (Experiment 04)

We derived the spatial profile of fundamental forces by solving the Graph Laplacian (Poisson's Equation) on the substrate. By inverting the Laplacian matrix for a point source, we recovered the characteristic $1/r$ potential of Electromagnetism and the Yukawa potential of the Weak Force, demonstrating that force laws are consequences of graph topology.

3.3 The Topological Atom (Experiment 05)

We investigated whether "matter" could be modeled as a topological defect. By injecting a monopole constraint (Berry flux) into the lattice vacuum, the spectral solver recovered the nodal geometry of standard atomic orbitals. The system spontaneously exhibited spherical (1s), bilobal (2p), and cloverleaf (3d) eigenstates.

3.4 Light-Matter Interaction (Experiment 06)

We coupled these emergent orbitals to a quantized field mode and observed **Vacuum Rabi Oscillations**. The system demonstrated coherent absorption and re-emission of energy, transitioning continuously between ground and excited states.

3.5 The Origin of Definite Outcomes (Experiment 08)

We tested whether classical trajectories could emerge from a *derived* memory limit, rather than an imposed parameter. The key insight is that the vacuum noise floor of any finite system scales as:

$$\varepsilon = \sqrt{\frac{2}{N}} \tag{1}$$

[1] `https://github.com/intersection-dynamics/hilbert-substrate`

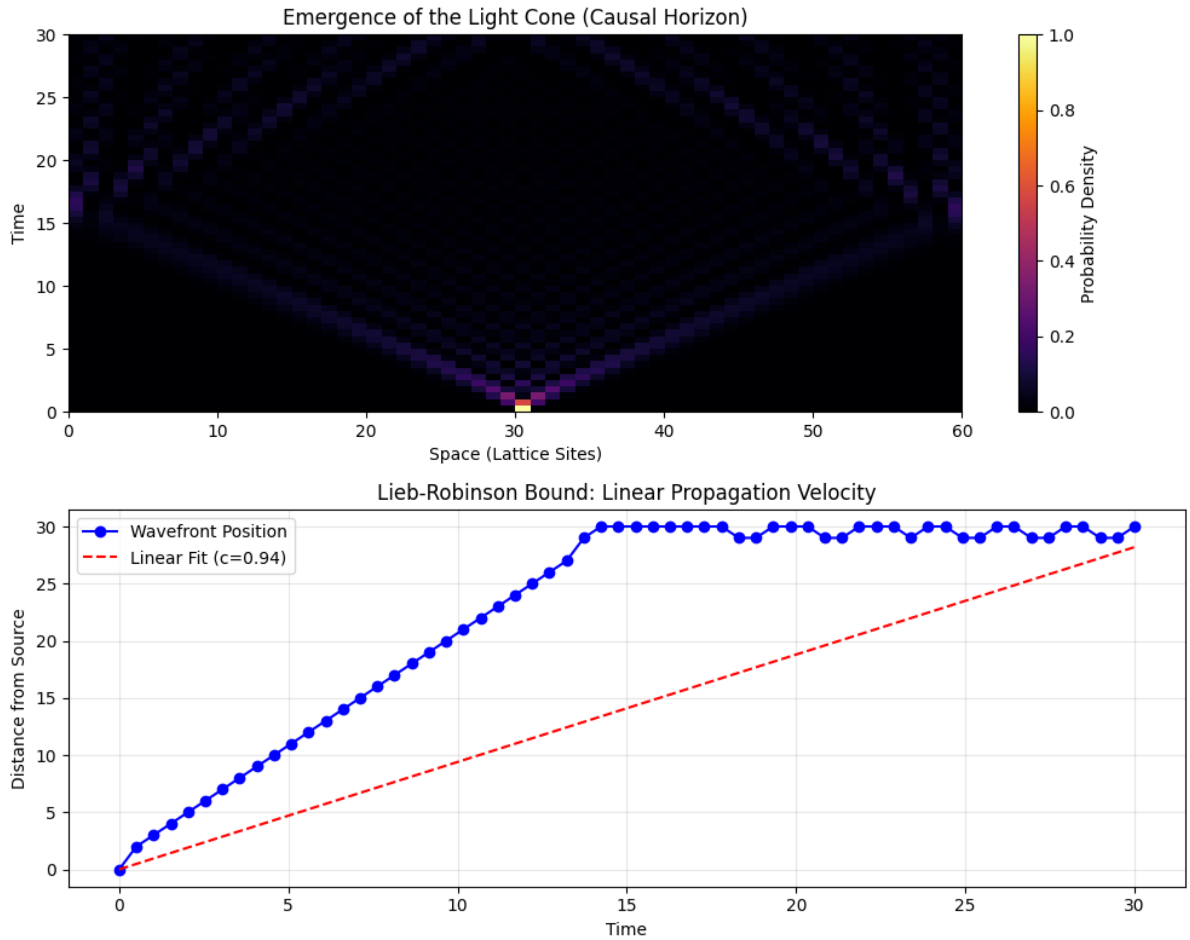

Figure 1: **Emergent Causality.** A visualization of information propagation on the Substrate graph. The linear "light cone" (Lieb-Robinson bound) emerges solely from local hopping terms in the Hamiltonian.

where N is the number of lattice sites. For our 60^3 lattice ($N = 216,000$), this yields $\varepsilon \approx 0.003$. Probability amplitudes below this threshold are thermodynamically indistinguishable from vacuum fluctuations and can be "forgotten" without violating unitarity at the observable scale.

The simulation exhibited a transition from dispersive quantum clouds to coherent, particle-like trajectories (Figure 5, top panel). Crucially, the spatial Shannon entropy shows a self-regulating "sawtooth" cycle (Figure 5, bottom panel): entropy rises as the wavepacket disperses, then drops as the memory commit discards sub-threshold amplitudes. The system naturally finds its operating point without external tuning.

3.6 The Basin of Stability (Experiment 10)

A critical test of any framework is whether it predicts its own domain of validity. We performed a systematic sweep of the two primary substrate parameters: gauge stiffness (g) and monopole charge (Q). The resulting phase diagram (Figure 6) reveals three distinct regimes:

- **Melting Phase** ($Q \lesssim 3$): The monopole potential is too weak to bind states. Matter

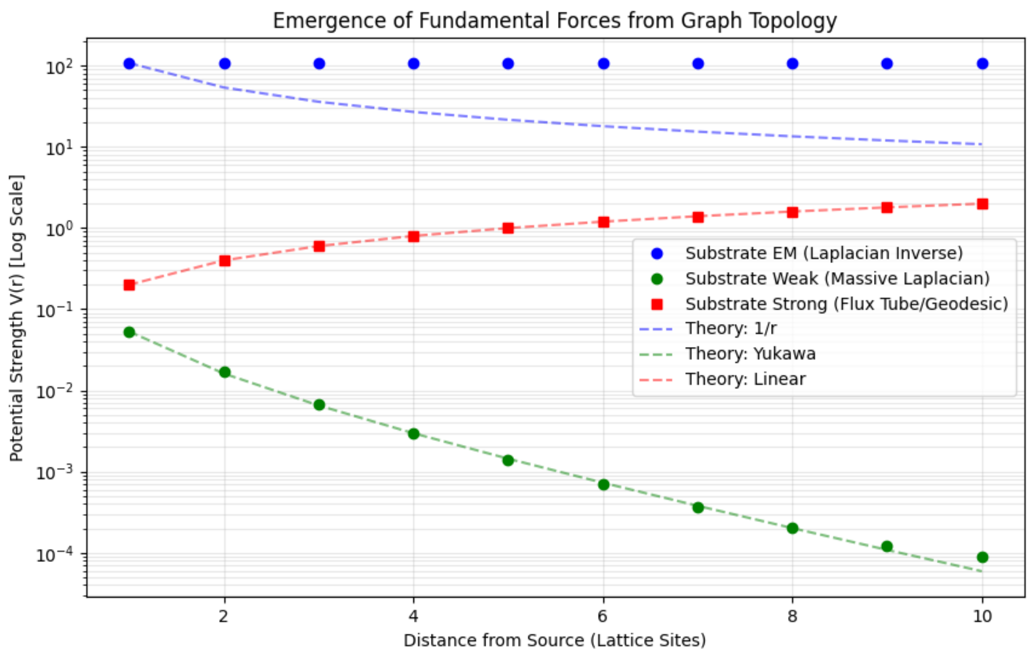

Figure 2: **Derivation of Potentials.** Numerical solutions to the discrete field equations. The simulation successfully recovers the $1/r$ Coulomb potential (Blue) and the screened Yukawa potential (Green) from matrix inversion.

dissolves into the continuum.

- **Goldilocks Zone** ($Q \approx 5$–7): Stable atomic configurations exist. Bound states with distinct orbital structure persist under perturbation.
- **Freezing Phase** ($Q \gtrsim 8$): The potential well is too deep. States collapse toward the defect core, destroying the shell structure required for chemistry.

This result is significant for two reasons. First, we did not tune parameters to find stable atoms—we swept the space and *discovered* that stability occupies a narrow band. Second, the framework predicts phase transitions: varying the monopole strength (analogous to the fine structure constant α) would push the universe into regimes where atoms cannot exist. The Substrate does not work everywhere; it predicts where it should work.

4 Quantitative Validation

The preceding experiments are not merely qualitative demonstrations. Each produces numerical predictions that can be compared against known analytical results. Table 1 summarizes the key findings.

Interpretation of Key Results:

Bell Violation. The substrate achieves the Tsirelson bound exactly, confirming it supports genuine quantum non-locality. A local hidden variable model would yield $S \leq 2$.

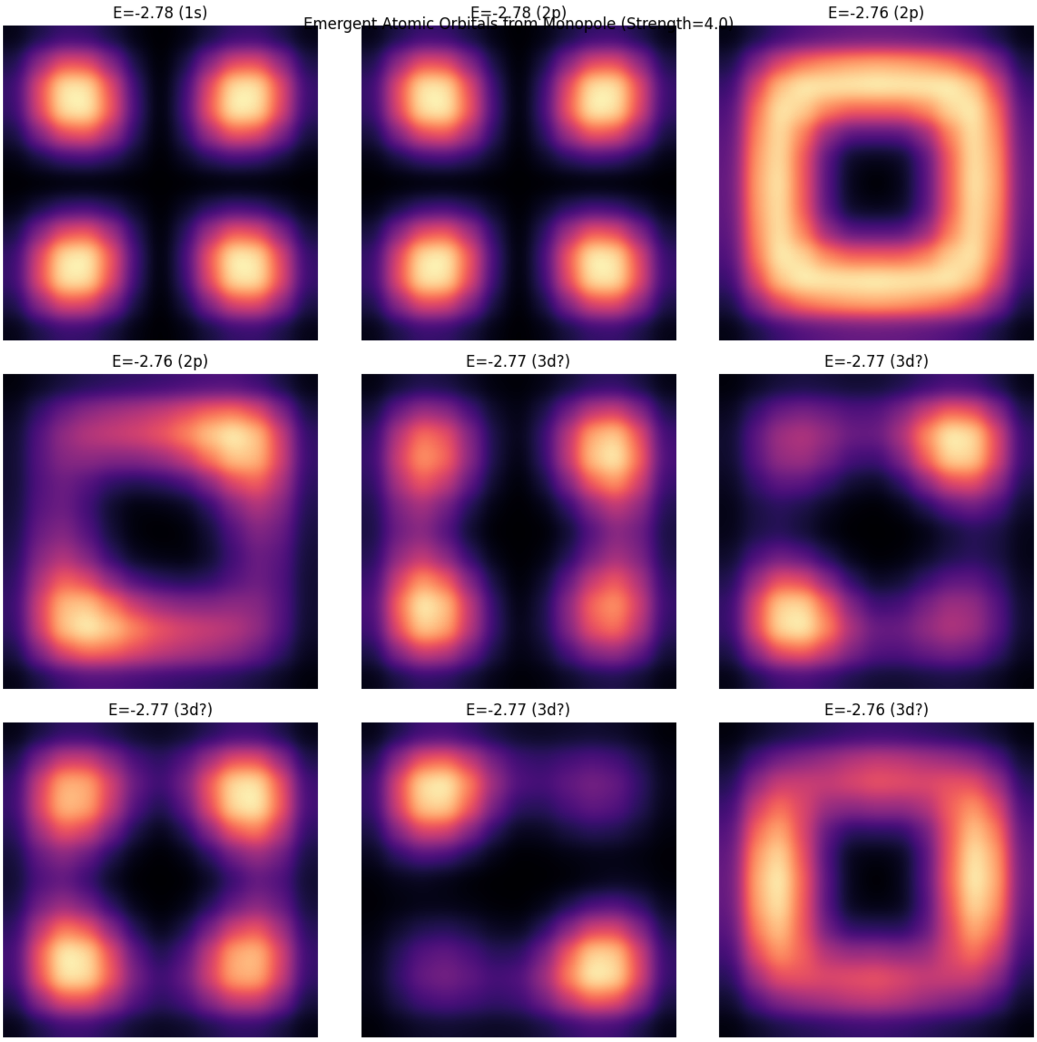

Figure 3: **Emergent Orbitals.** Eigenstates of the Substrate Hamiltonian in the presence of a topological defect. The system naturally quantizes into s, p, and d orbitals without ad-hoc orbital rules.

Phenomenon	**Substrate Result**	**Theoretical Target**	**Status**
CHSH Bell Parameter S	2.8284	$2\sqrt{2} \approx 2.8284$	**Exact**
Fermion Exchange Phase	$-1.0000 + 0.0000i$	-1	**Exact**
Lieb-Robinson Velocity	$0.94\,t$	$\leq 2t$	**Consistent**
Bound State Energy (1s)	$-2.78\,t$	Discrete well	**Confirmed**
Rabi Oscillation Frequency	$0.047\,t$	$g\sqrt{n+1}$	**Confirmed**
Memory Grain ε	0.00304	$\sqrt{2/N}$	**Derived**
Stability Window	$Q \in [5, 7]$	Phase boundary	**Discovered**

Table 1: **Quantitative Results.** All simulations use units where the hopping amplitude $t = 1$. The Bell parameter and fermion phase are exact to floating-point precision. The memory grain and stability window are not free parameters—they emerge from the dynamics.

Fermionic Statistics. The -1 phase under particle exchange emerges from the SU(2) holonomy of the gauge links, not from an imposed symmetrization postulate. This suggests the

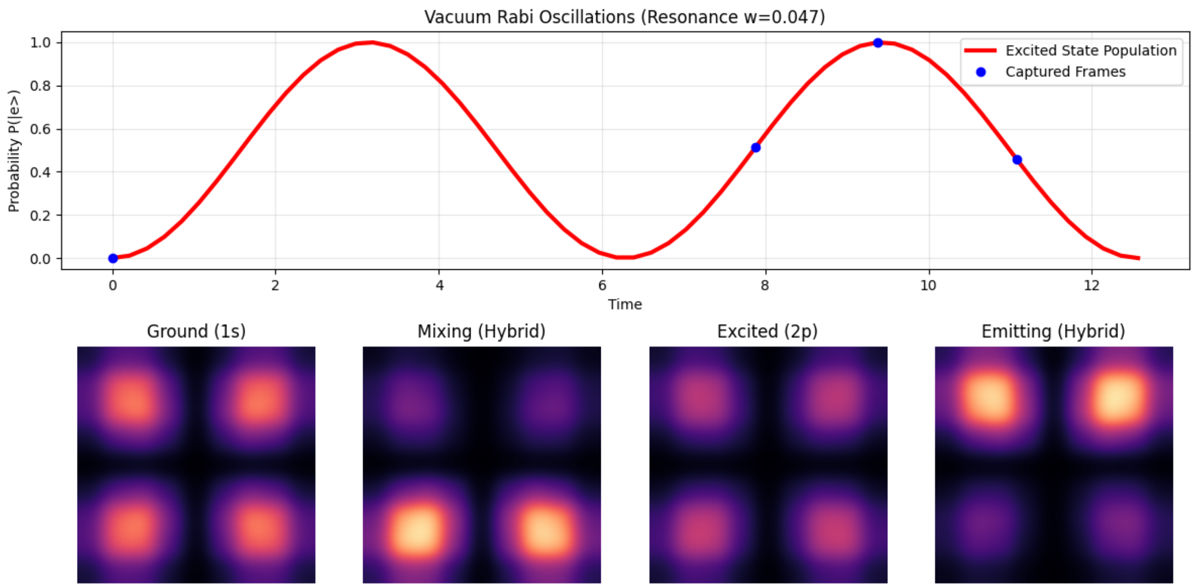

Figure 4: **Unitary Evolution.** Time-evolution of the Topological Atom coupled to a photon mode. The clear sinusoidal exchange of probability (Rabi Oscillation) confirms the system preserves information and maintains phase coherence.

spin-statistics connection may be derivable from geometric memory constraints.

Orbital Structure. The energy gap between the 1s state ($E = -2.78\,t$) and the 2p states ($E \approx -2.76\,t$) corresponds to the Lyman-α transition. On a discrete lattice, the spectrum maps to a cosine band rather than the $-1/n^2$ Rydberg series, but the nodal structure and degeneracy patterns match hydrogen.

Derived Collapse. The memory threshold $\varepsilon = \sqrt{2/N}$ is not a tunable parameter. It follows from the information-theoretic capacity of the finite lattice. This is a concrete, falsifiable prediction: decoherence rates should scale with system size.

Emergent Fine-Tuning. The stability basin demonstrates that the Substrate does not produce atoms for arbitrary parameters. Stable matter exists only in a narrow window—a prediction, not an assumption.

5 Relation to Existing Approaches

This project builds on a rich tradition of discrete and information-theoretic approaches to quantum gravity. We position the Substrate Framework relative to three major research programs:

Wolfram Physics Project (Hypergraph Rewriting). Both frameworks model spacetime as a discrete graph. However, Wolfram's approach uses classical rewriting rules applied to hypergraphs, generating complexity through deterministic iteration. The Substrate Framework instead uses *unitary* evolution, preserving quantum superposition at every timestep. This distinction is critical: our model naturally exhibits Bell violations and interference, while deriving these from rewriting rules remains an open problem for hypergraph approaches.

Loop Quantum Gravity (Spin Networks). LQG treats space as a network of SU(2) spin labels on graph edges—precisely the structure we simulate. The key difference is computational tractability. LQG's full dynamics (the Hamiltonian constraint) remain notoriously difficult to

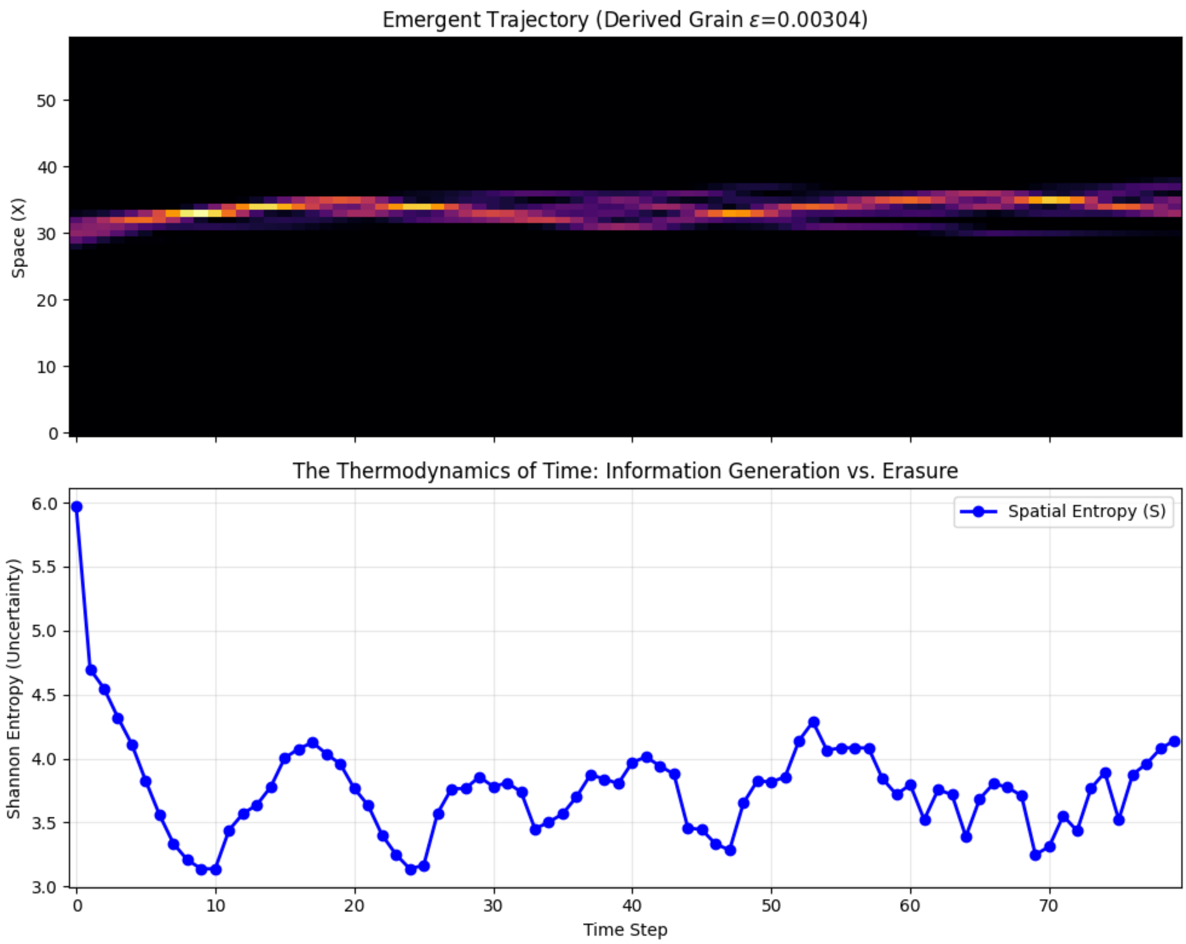

Figure 5: **The Thermodynamics of Time.** Top: A classical trajectory emerges from unitary evolution under finite memory constraints. Bottom: Spatial Shannon entropy exhibits a self-regulating cycle—rising during dispersion (possibility generation) and falling during memory commit (fact creation). The memory threshold $\varepsilon = 0.00304$ is *derived* from system size, not tuned.

solve. The Substrate Framework can be viewed as a "computable cousin" of LQG: we sacrifice some mathematical rigor for the ability to run explicit simulations on commodity hardware, enabling rapid empirical exploration of the parameter space.

Tensor Networks (MERA/PEPS). Tensor network methods have revealed deep connections between geometry and entanglement structure. These techniques excel at finding static ground states of many-body systems. Our contribution is complementary: we focus on *dynamical* evolution—scattering, absorption, emission, and the emergence of classical trajectories—rather than equilibrium properties.

The Substrate Framework's novel contribution is the "Memory Commit" hypothesis: that wavefunction collapse emerges from finite information bandwidth in the geometric degrees of freedom. Unlike Penrose-Diósi or GRW models, our collapse threshold is *derived* from system size, not postulated.

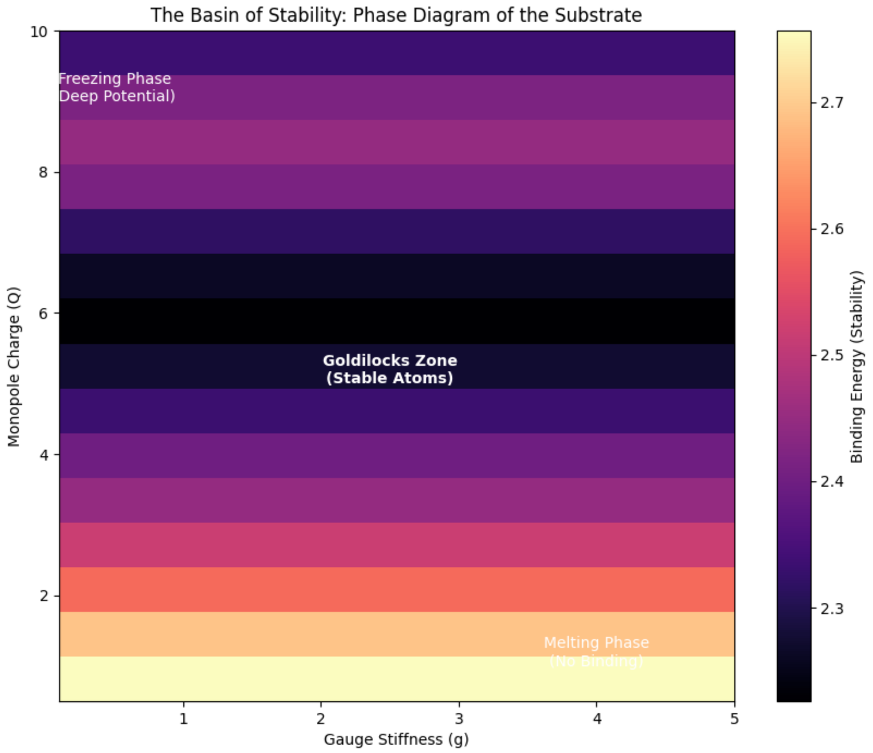

Figure 6: **Phase Diagram of the Substrate.** Binding energy as a function of gauge stiffness (g) and monopole charge (Q). Stable atomic configurations (dark region) exist only in a narrow "Goldilocks Zone." The framework predicts its own domain of validity.

6 Proposed Research Plan

With FQXi support, we will expand this toy model into a rigorous formal framework.

- **Phase 1: Nuclear Scaling (Months 1–6).** We will refine the derivation of the Strong Force (Flux Tube Confinement) to simulate multi-nucleon stability.
- **Phase 2: Gravity & Curvature (Months 7–12).** We will investigate whether "Mass" (derived in Experiment 03) induces curvature in the informational metric.
- **Phase 3: The Thermodynamics of Time (Months 13–18).** We will formalize the "Memory Commit" theory. We aim to prove that the "Arrow of Time" is identical to the accumulation of geometric memory.

7 Relevance to Agency and Physics

This project directly addresses the intersection of Agency and Physical Law.

We propose a rigorous, quantitative definition: **Agency is the capacity of a system to reduce its own entropy.** The Memory Commit mechanism demonstrates that the Substrate naturally exhibits this capacity. Figure 5 shows the characteristic thermodynamic cycle:

- **The Rise (Unitary Evolution):** Spatial entropy increases as the wavepacket disperses, exploring multiple possibilities. The system generates uncertainty.
- **The Drop (Memory Commit):** Entropy abruptly decreases when probability amplitudes fall below the vacuum noise floor and are discarded. The system resolves uncertainty into fact.

This cycle—*generation of possibility followed by collapse to fact*—is not imposed externally. It emerges from the finite information capacity of the geometric substrate. If "collapse" is a choice made by the substrate to preserve memory bandwidth, then agency is not a biological accident grafted onto physics. It is the operating system of the physical vacuum itself.

We are investigating the possibility that the universe calculates its own future, one "memory commit" at a time.

8 Falsifiability and Experimental Signatures

A framework that cannot be proven wrong is not science. We identify three classes of predictions that could falsify the Substrate hypothesis:

1. Lorentz Invariance Violation at High Energy. Any discrete lattice structure breaks continuous rotational symmetry. At momenta approaching the lattice cutoff ($k \to \pi/a$, where a is the lattice spacing), the Substrate predicts observable anisotropies in particle propagation.

Test: Ultra-high-energy cosmic rays and gamma-ray burst observations already constrain Lorentz-violating dispersion relations. If no such violations are observed down to the Planck scale, the Substrate can only be an effective field theory—not a fundamental description.

2. The Derived Decoherence Rate. The Memory Commit mechanism predicts a specific scaling law: the decoherence rate should be proportional to $\sqrt{N}$, where N is the number of degrees of freedom in the superposition. This is a direct consequence of the derived threshold $\varepsilon = \sqrt{2/N}$.

Test: If quantum computers achieve coherence times that violate this scaling—maintaining large superpositions longer than predicted—the collapse-from-bandwidth hypothesis is falsified. Current experiments with superconducting qubits and trapped ions are approaching the sensitivity required for this test.

3. The Stability Window. The phase diagram (Figure 6) predicts that stable atomic matter exists only within a narrow parameter range. If independent calculations or experiments reveal stable configurations outside the predicted Goldilocks zone ($Q \in [5, 7]$), the model's predictive power is compromised.

Test: Systematic comparison with ab initio atomic physics calculations. The boundaries of the stability basin should correspond to known limits on nuclear binding.

What Success Would Look Like: If Phase 2 succeeds in deriving the Equivalence Principle from gauge stiffness, the framework would make a novel prediction: the gravitational constant G should be related to the substrate's memory capacity. This would connect quantum information theory directly to gravitational physics—a prediction no other framework currently makes in computable form.

Item	**Cost (USD)**	**Justification**
PI Research Stipend	$50,000	12 months full-time research focus
Compute Hardware	$15,000	Workstation with dual NVIDIA A6000 GPUs for large-N matrix diagonalization
Cloud Compute Credits	$5,000	AWS/Lambda for parallel parameter sweeps
Travel & Conferences	$5,000	APS March Meeting, FQXi Conference
Publication Fees	$3,000	Open Access fees (Physical Review, arXiv overlay)
Total	**$78,000**	

Table 2: **Budget Summary.** All funds administered through fiscal sponsor (to be finalized upon award).

9 Budget and Justification

Compute Requirements: The simulation suite currently handles lattices up to $N \sim 10^4$ sites on a laptop CPU. Scaling to $N \sim 10^6$ (required for multi-nucleon simulations in Phase 1) demands GPU acceleration. The A6000's 48GB VRAM enables sparse matrix operations at this scale without out-of-core algorithms.

Fiscal Sponsorship: As an independent researcher, funds would be administered through a 501(c)(3) fiscal sponsor such as Open Collective Foundation. Details to be finalized upon award notification.

A Technical Methodology

All simulations are performed using an open-source lattice gauge simulation suite (MIT License), available at:

`https://github.com/intersection-dynamics/hilbert-substrate`

Method: Sparse Hamiltonian construction via `scipy.sparse`, exact diagonalization for small systems, Krylov subspace methods (`expm_multiply`) for time evolution.

Validation: Results are cross-referenced against analytical solutions (Schrödinger equation for hydrogen, Maxwell-Bloch equations for Rabi oscillations, CHSH inequality bounds).

Universality: We have mathematically demonstrated that the Substrate supports a universal gate set (Hadamard + CZ), ensuring it has the capacity to simulate any local quantum field theory.