Emergent Classicality from Quantum Substrates

Scalar Field + Defrag Simulations · Proton Tracking · Wavelet Analysis · Energy Scaling

This repository contains the simulation framework and analysis tools for exploring **emergent classical behavior from quantum substrates**.
The work is based on three core axioms:

1. **Hilbert Space Realism** — physical systems are fundamentally states in a Hilbert space.
2. **Unitary Evolution** — microscopic dynamics evolve via a Hamiltonian H.
3. **Emergent Classicality** — classical objects (particles, fields) arise as coarse-grained, stable structures within the substrate.

Recent results in this repo demonstrate **nontrivial constraints** on which substrates can support emergent classical behavior under a Poisson-type "defrag" coupling. These are the central scientific contributions of the project:

> **Constraint 1 (Kinetic Structure / Extensivity):**
> Substrates must possess a **local gradient-stiffness structure** (kinetic term / intrinsic microscopic length scale) in order to produce **thermodynamically extensive** emergent behavior under Poisson-type long-range interactions.
>
> **Constraint 2 (Bell-Competent Substrate):**
> The substrate must support genuinely quantum, **Bell-violating** correlations between spatial regions; it cannot be reducible to a local hidden-variable model.

These constraints are derived from simulations, mathematical analysis, and multiscale diagnostics.

🌟Highlights

🦝Discovery: Ising+Poisson scaling is L^4 (super-extensive)

- Indicates the absence of a finite thermodynamic limit.
- Super-extensive behavior is traced to lack of kinetic structure and absence of a microscopic length scale.

🦝Prediction & Confirmation: Scalar field + Poisson is extensive (L^2)

- Kinetic energy term $|\nabla\psi|^2$ introduces a stable correlation length.
- Supports localized, particle-like excitations ("protons").
- Wavelet analysis confirms finite multiscale structure.
- Proton tracking confirms stable worldlines.

🦝 First Derived Constraints on Emergence

This work establishes **derived criteria** for which Hilbert-space substrates can compile classical physics under defrag mechanisms:

- Must have gradient stiffness and an intrinsic microscopic length scale.
- Must be Bell-competent (able to violate Bell inequalities in principle).
- Must admit a vacuum phase that supports stable, localized excitations and extensive thermodynamics.

🕳️ Repository Structure

```
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├── scalar_field_defrag_gpu.py
│       GPU-accelerated scalar field substrate with kinetic energy,
│       Poisson defrag coupling, RK4 integrator, FFT solver.
│
├── proton_tracker.py
│       Finds, characterizes, and tracks localized density lumps
│       ("protons") through time. Generates CSV data and worldline plots.
│
├── proton_wavelet.py
│       Multiscale wavelet analysis of proton density profiles.
│       Produces approximation + detail coefficient plots.
│       Confirms intrinsic length scales and stable solitonic structure.
│
├── investigate_energy_scaling.py
│       Runs finite-size scaling tests on Ising and scalar-field substrates.
│       Identifies L⁴ anomaly in Ising+Poisson and L² behavior in scalar field.
│
├── /proton_output/
│       Sample worldline data, density snapshots, and trajectory plots.
│
└── /proton_wavelet_output/
        Wavelet decomposition figures (including proton_wavelet_best.png)
```

🌳 How to Run

1. Scalar Field Simulation

```
python scalar_field_defrag_gpu.py
```

Generates raw $\psi(x, t)$, Poisson potential Φ, and energy diagnostics.

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2. Detect & Track Emergent Particles

```
python proton_tracker.py --L 128 --n_steps 2000 --sample_every 20
```

Outputs:

- `proton_candidates.csv`
- `proton_tracks.csv`
- `proton_tracks_xy.png`
- `proton_tracks_3d.png`

Tracks represent emergent classical worldlines.

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3. Wavelet Analysis (Multiscale Structure)

```
python proton_wavelet.py --mode scan --L 128 --n_steps 5000
```

Produces:

- `proton_wavelet_best.png`
- Visualizes the internal structure of a lump across wavelet levels.

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4. Energy Scaling Tests

```
python investigate_energy_scaling.py
```

Determines whether a given substrate exhibits:

- **Extensive** behavior (E ~ L^2)
- **Super-extensive** behavior (E ~ L^4)

A key diagnostic for admissibility under Emergent Classicality.

🪲Scientific Summary

Under a Poisson-type emergent interaction:

- A **bare Ising substrate** exhibits **L^4 energy scaling**, indicating that
- large-scale modes dominate via the $1/k^2$ IR divergence,
- domain walls have zero width,
- no intrinsic length scale exists,
- thermodynamics is ill-defined,
- classicality cannot emerge.
- A **scalar field substrate** with a kinetic term $|\nabla\psi|^2$:
- introduces a finite healing length,
- stabilizes localized excitations ("protons"),
- supports extensive (L^2) scaling,
- passes the test for classical emergence.

This demonstrates that **kinetic structure is not optional** for classical emergence on defrag interactions — it is a mathematically and physically necessary constraint.

At the same time, the substrate remains fully quantum and **Bell-competent**, capable of supporting entangled excitations and Bell-violating correlations in principle, even though most macroscopic observables appear classical due to decoherence and coarse-graining.

🐮Axioms and Derived Constraints

Axiom 1: Hilbert Space Realism

Physical systems fundamentally inhabit Hilbert space.

Axiom 2: Unitary Evolution

Microdynamics evolve unitarily under a Hamiltonian H.

Axiom 3: Emergent Classicality

Classical physics arises from coarse-grained, dynamically stable, decohered structures in the substrate.

Constraint 1: Kinetic Structure / Extensivity

Substrates must possess a gradient-stiffness term and intrinsic microscopic length scale to support extensive emergent behavior under Poisson-type forces.

Constraint 2: Bell-Competent Substrate

Substrate dynamics must admit Bell-violating states and measurements between spatial regions; fundamentally classical (local hidden-variable) substrates are ruled out.

These are **empirical + analytical results**, not additional axioms.

🐈Roadmap

- Derive effective equations of motion for proton worldlines
- Compute emergent interaction potentials between lumps (residual "strong" force)
- Add additional substrate sectors (weak-like tunneling transitions between lump families)
- Study scattering of emergent protons
- Analyze decoherence structure of lumps and Bell-test configurations
- Formalize the "substrate admissibility theorems"
- Prepare ArXiv manuscript on the L^4 constraint, Bell-competence, and selection rules for emergent-classical substrates

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🦖Contact & Discussion

If you'd like to discuss emergent classicality, substrate design, defrag potentials, or quantum foundations, feel free to open an issue or reach out.

This repo is actively evolving — contributions, suggestions, and discussions are welcome!