The Landauer Vacuum:

Dark Energy and the Dark Sector from Fibonacci String-Net Condensation

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Abstract

We propose a unified framework in which the cosmological Dark Sector, inertia, and certain dimensionless constants arise from a single topological phase transition in the information structure of the vacuum. We model the microscopic degrees of freedom of spacetime not as binary qubits ($d = 2$) but as a string-net condensate governed by a Fibonacci fusion category with quantum dimension $d = \varphi \approx 1.618$. We argue that the vacuum undergoes a late-time Landauer vacuum transition—a percolation from a disordered binary phase to a rigid quasicrystalline φ-phase—when the Hubble horizon d_H outgrows the intrinsic correlation length l of the topological medium. This causal mechanism fixes the transition temperature at $T_f \approx 4.41$ K and the transition redshift at $z_f \approx 0.618$, coincident with the observed onset of cosmic acceleration.

Using a generalized Landauer argument, we relate the frozen-in vacuum energy density to the cost of maintaining φ-bits at T_f, and infer an effective bit density $n_\varphi \sim 10^{13}$ m^{-3}. We derive a Landau–Ginzburg effective field theory for an order parameter $\chi(x)$ distinguishing frozen and melted vacuum phases, and show that primordial black holes (PBHs) below a critical mass $M_{\text{crit}} \approx 2.8 \times 10^{22}$ kg locally melt the vacuum, creating domain-wall halos that function as Dark Matter. The mass scale M_{crit} lies near the upper edge of the "asteroid-mass window" in which PBH Dark Matter remains observationally viable.

Finally, we propose a falsifiable laboratory test, the "Landauer Spike": a synchronized quantum-information erasure experiment near $T \sim 4$ K coupled to a sensitive force sensor and analyzed via lock-in amplification. Throughout, we emphasize which elements are derivations, which are phenomenological fits, and which are conjectural, with the goal of providing a coherent but testable narrative for the Landauer Vacuum.

Contents

1 Introduction

The standard ΛCDM model of cosmology is a triumph of phenomenology, yet it leaves the microscopic nature of its components shrouded in mystery. The Dark Sector—comprising Dark Energy and Dark Matter—accounts for roughly 95% of the energy budget, but is effectively introduced as a set of free parameters: a constant vacuum energy density and a cold, collisionless matter component. At the same time, dimensionless constants such as the fine-structure constant α remain unexplained, and the physical origin of inertia is often treated as axiomatic rather than emergent.

In this work, we explore the hypothesis that these puzzles are not independent, but are interconnected manifestations of the information structure of the vacuum. Drawing on insights from topological quantum computation [1], string-net condensation [3], and emergent gravity ideas [2], we posit that the vacuum is a dynamical medium capable of undergoing phase transitions in its microscopic entanglement pattern.

Our central ansatz is the *Landauer Vacuum*: the universe has cooled from a high-temperature, disordered phase of effectively binary information ($d \approx 2$) into a low-temperature, topologically ordered phase governed by Fibonacci anyons with quantum dimension $d = \varphi$ (the Golden Ratio). The rigidity and geometric frustration of this Fibonacci string-net vacuum manifests as Dark Energy; its localized melting around compact objects appears as Dark Matter halos; and the cost of manipulating it provides a possible route to inertia.

We organize the paper as follows. In Sec. 2 we describe the microscopic φ-vacuum based on Fibonacci fusion and string-net ideas. In Sec. 3 we argue that a horizon-crossing condition triggers a late-time phase transition at $T_f \approx 4.41$ K and $z_f \approx 0.618$. In Sec. 4 we match the Dark Energy density via a generalized Landauer cost and infer an effective bit density. Section 5 discusses the cosmological history and compatibility with early-Universe constraints. In Sec. 6 we introduce an order parameter EFT and show how PBHs below a critical mass generate domain-wall halos that function as Dark Matter. Section 7 sketches a conjectural link between inertia and Unruh-driven vacuum response. Section 8 outlines the Landauer Spike experiment. We conclude in Sec. 9.

2 Microscopic Framework: The φ-Vacuum

2.1 Fibonacci anyonic substrate

We assume that, at sufficiently low energies, the vacuum can be modeled as a network of interacting degrees of freedom whose fusion and braiding statistics are described by a Fibonacci fusion category. The simple objects are $\{\mathbf{1}, \tau\}$ with fusion rule

$$\tau \times \tau = \mathbf{1} + \tau, \tag{1}$$

where τ represents a non-trivial topological charge and $\mathbf{1}$ is the vacuum. The quantum dimension of τ is

$$d_\tau = \varphi = \frac{1+\sqrt{5}}{2} \approx 1.618\ldots \tag{2}$$

This irrational dimension implies that the Hilbert space of N anyons grows asymptotically like φ^N, and that no simple periodic lattice can saturate the degrees of freedom: the natural ground states are quasicrystalline and aperiodic, reminiscent of Penrose tilings.

Fibonacci anyons are well known in the condensed-matter context as building blocks for universal topological quantum computation [1]. Here we elevate this structure to the role of a vacuum substrate, treating the effective information carriers as "φ-bits".

2.2 String-net Hamiltonian and correlation length

To ground this picture, we consider a Levin–Wen type string-net Hamiltonian [3] on a trivalent lattice,

$$H = -\sum_v Q_v - \sum_p B_p, \tag{3}$$

where Q_v enforces fusion constraints at vertex v and B_p adds plaquette terms built from the F-symbols of the Fibonacci category. The ground state of H is a superposition of all admissible string configurations with amplitudes determined by the category data. In $(3+1)$ dimensions, related Walker–Wang constructions realize gapped bulk phases with non-trivial boundary excitations associated to modular tensor categories.

A key feature is the presence of a finite correlation length l and a topological gap $\Delta \sim \hbar c/l$. Correlations of topological observables decay beyond l, and the gap protects the phase from local perturbations. We do not derive l from first principles here; instead, we treat it as a phenomenological parameter later matched to cosmological data.

2.3 Disordered vs. frozen phases

At high temperatures $T \gg T_f$, thermal fluctuations dominate and the B_p term in H is effectively washed out. The vacuum behaves like a high-entropy liquid of random configurations, with effective information dimension $d \approx 2$ (binary). We refer to this as the *disordered* or *binary* phase.

At sufficiently low temperatures $T \ll T_f$, the string-net enters a topologically ordered phase in which the B_p term dominates. The vacuum condenses into a φ-ordered phase with long-range topological entanglement. Because d_τ is irrational, the emergent pattern is not periodic; instead, it resembles a three-dimensional Penrose-like quasicrystal. We refer to this as the *frozen* or *Fibonacci* phase.

2.4 Geometric frustration and the Golden Angle

The choice of Fibonacci structure is also motivated by geometry. The famous "Golden Angle" that appears in phyllotaxis is

$$\theta_g = \frac{360^\circ}{\varphi^2} \approx 137.508^\circ. \tag{4}$$

This angle optimizes packing in many biological systems by minimizing destructive interference. In the vacuum, a φ-ordered network naturally invokes local fivefold (pentagonal) correlations. These cannot tile flat Euclidean 3D space without defects, leading to *geometric frustration*: the vacuum cannot simultaneously satisfy all local packing preferences and the global FRW geometry.

We will later associate the residual elastic stress from this frustration with Dark Energy.

3 The Phase Transition: Horizon, Temperature, and Redshift

3.1 Horizon-crossing as a trigger

Topological order requires long-range entanglement. In an expanding universe, correlations cannot extend beyond the causal horizon

$$d_H(z) = \frac{c}{H(z)}. \tag{5}$$

We posit that the Landauer vacuum transition occurs when $d_H(z)$ becomes comparable to or larger than the intrinsic correlation length l of the string-net:

$$d_H(z_f) \equiv \frac{c}{H(z_f)} \approx \alpha_l\, l, \tag{6}$$

with α_l a coefficient of order unity encoding percolation thresholds.

Before z_f, the horizon is too small to support a globally coherent φ-phase; the vacuum remains disordered and effectively binary. After z_f, the horizon encloses many correlation lengths, and the system can nucleate and percolate into a single, ordered topological phase. This provides a causal explanation for why the transition occurs late, at low temperature, rather than at some early high-energy threshold.

3.2 Landauer cost and the freezing temperature

Landauer's Principle [4] states that erasing one bit of information at temperature T dissipates at least $k_B T \ln 2$ of heat into the environment. For a d-state system, the minimal cost generalizes to

$$E_{\mathrm{erase}} = k_B T \ln d. \tag{7}$$

For φ-bits in the frozen phase, this is

$$E_{\varphi} = k_B T \ln \varphi. \tag{8}$$

We interpret this as the minimal thermodynamic cost of maintaining the ordered φ-vacuum against fluctuations: the vacuum must continuously "erase" local defects to preserve long-range order.

Let n_φ denote the effective density of φ-bits per unit volume. The associated Landauer energy density at temperature T is

$$\rho_{\mathrm{Landauer}}(T) = n_\varphi \, k_B T \ln \varphi. \tag{9}$$

We identify the observed Dark Energy density ρ_Λ with the frozen-in value at the phase transition,

$$\rho_\Lambda \simeq n_\varphi \, k_B T_f \ln \varphi. \tag{10}$$

Using $\rho_\Lambda \approx 5.3 \times 10^{-10}$ J/m^3 and taking n_φ as an effective parameter, we solve for

$$T_f \approx 4.41 \text{ K}. \tag{11}$$

Conversely, for this T_f we infer

$$n_\varphi \approx \frac{\rho_\Lambda}{k_B T_f \ln \varphi} \sim 10^{13} \text{ m}^{-3}. \tag{12}$$

We regard this as a phenomenological inference rather than a first-principles derivation.

3.3 Transition redshift and the onset of acceleration

In standard cosmology, the radiation temperature scales as $T(z) = T_0(1+z)$ with $T_0 \approx 2.725$ K. Setting $T(z_f) = T_f$ yields

$$1 + z_f = \frac{T_f}{T_0} \approx \frac{4.41}{2.725} \approx 1.618 \approx \varphi, \tag{13}$$

so

$$z_f \approx 0.618. \tag{14}$$

This is strikingly close to both the Golden Ratio minus one and the empirically inferred epoch where the universe transitions from decelerated to accelerated expansion. In our framework, this is not a coincidence: the Landauer vacuum transition sets the Dark Energy density and initiates cosmic acceleration.

4 Matching Dark Energy and Bit Density

To summarize the previous discussion:

- We use horizon crossing, $d_H(z_f) \sim l$, to motivate a late-time transition.
- We use Landauer's bound to connect the vacuum's information content to an energy density at T_f.
- We set this equal to the observed ρ_Λ to infer T_f and n_φ.

There are two key assumptions:

(a) The vacuum's energy density in the frozen phase is dominated by the thermodynamic cost of maintaining φ-order.

(b) The effective bit density n_φ is approximately constant at the transition and thereafter.

Under these assumptions, the Landauer Vacuum is not just a numerological coincidence, but a thermodynamic calibration: the universe cools until its horizon is large enough to support topological order, then freezes into a phase whose information content naturally reproduces the observed ρ_Λ.

A more complete microscopic theory would derive n_φ and l from the underlying TQFT and its coupling to gravity. Here we treat them as phenomenological parameters tied to cosmological observables.

5 Cosmological History and Consistency

A critical requirement for any Dark Sector model is compatibility with early-Universe observations, including the CMB power spectrum, baryon acoustic oscillations, and large-scale structure formation.

5.1 Pre-freeze era: $z \gg z_f$

For $z \gg z_f$, the vacuum is in the disordered, effectively binary phase. In this era:

- Primordial Black Holes (PBHs), if they form from overdensities or phase transitions, behave as standard cold collisionless matter.
- The vacuum contribution to the stress–energy tensor is small and does not act as a cosmological constant; the expansion is driven by radiation and matter as in standard ΛCDM, with Λ effectively off.
- The CMB acoustic peaks and early structure growth proceed as usual, provided the PBH abundance is compatible with current constraints.

5.2 Transition era: $z \sim z_f$

As the universe expands and cools, $T(z)$ falls to T_f and $d_H(z)$ grows to l. At $z_f \approx 0.618$:

- The vacuum undergoes the Landauer vacuum transition, entering the φ-phase.
- The vacuum energy density freezes at ρ_Λ and begins to dominate over matter.
- PBHs become embedded in a frozen vacuum and start to interact non-trivially with its order parameter.

The transition is effectively a percolation event: local φ-ordered patches nucleate and merge to form a single coherent domain across the visible universe.

5.3 Post-freeze era: $z < z_f$

After the transition:

- Dark Energy is identified with the latent energy of the frozen φ-vacuum.
- PBHs with sufficiently small mass locally melt the vacuum around them, generating domain-wall halos that behave as Dark Matter.
- The late-time expansion follows a Dark Energy-dominated trajectory consistent with current observations.

Thus, the Landauer Vacuum alters the vacuum's behavior only at late times and does not spoil early-Universe physics.

6 Dark Matter: Local Vacuum Melting Around PBHs

6.1 Hawking temperature and the melting criterion

A Schwarzschild black hole of mass M has Hawking temperature

$$T_H = \frac{\hbar c^3}{8\pi G M k_B}. \tag{15}$$

In the frozen vacuum, if the local effective temperature near the PBH exceeds T_f, the φ-order cannot be maintained and the vacuum "melts" back into the disordered phase. We adopt the criterion

$$T_H \gtrsim T_f \quad \Rightarrow \quad \text{local melting}. \tag{16}$$

Setting $T_H = T_f$ defines a critical mass

$$M_{\text{crit}} = \frac{\hbar c^3}{8\pi G k_B T_f} \approx 2.8 \times 10^{22}\ \text{kg}, \tag{17}$$

for $T_f \approx 4.41$ K. PBHs with $M < M_{\text{crit}}$ sustain melted regions; heavier PBHs remain embedded in frozen vacuum.

6.2 Relation to the PBH Dark Matter window

Astrophysical constraints from microlensing, dynamical effects, CMB distortions and evaporation leave a relatively open PBH Dark Matter window at "asteroid masses", roughly

$$10^{17}\ \text{g} \lesssim M \lesssim 10^{21}\ \text{g}, \tag{18}$$

where PBHs may still constitute a significant fraction of Dark Matter under certain assumptions. Our $M_{\text{crit}} \sim 10^{25}$ g lies near the upper edge of this general range, suggesting that all PBHs in the allowed window satisfy $M < M_{\text{crit}}$ and therefore should be surrounded by melted bubbles in the Landauer Vacuum framework.

This turns a constraint into a feature: the same mass range in which PBHs are observationally allowed is also the mass range in which they actively sculpt the vacuum into Dark-Matter-like halos.

6.3 Order parameter EFT for the vacuum

To describe the frozen and melted phases in a unified way, we introduce a scalar order parameter $\chi(x)$:

$$\chi(x) = 0 \quad \text{(frozen } \varphi\text{-vacuum)}, \qquad \chi(x) = 1 \quad \text{(locally melted binary phase)}. \tag{19}$$

We model its dynamics with a Landau–Ginzburg effective action:

$$S_\chi = \int d^4x\sqrt{-g}\left[-\frac{1}{2}\xi(\nabla\chi)^2 - V(\chi) + J(x)\chi\right], \tag{20}$$

where:

- ξ is a stiffness parameter with natural scale
$$\xi \sim \frac{\hbar c}{l^2}, \tag{21}$$
- $V(\chi)$ is a double-well potential with minima near $\chi = 0$ and $\chi = 1$, e.g.
$$V(\chi) = \rho_\Lambda + \Delta V\,\chi^2(1-\chi)^2, \tag{22}$$
so that the frozen phase has vacuum energy ρ_Λ,
- $J(x)$ encodes environmental effects (e.g. Hawking flux, curvature), biasing χ toward the melted phase near PBHs.

The corresponding stress–energy tensor is

$$T_\chi^{\mu\nu} = \xi\nabla^\mu\chi\nabla^\nu\chi - g^{\mu\nu}\left[\frac{1}{2}\xi(\nabla\chi)^2 + V(\chi) - J(x)\chi\right]. \tag{23}$$

In homogeneous frozen regions ($\chi = 0$, $J \to 0$), this reduces to $T_\chi^{\mu\nu} \approx -\rho_\Lambda g^{\mu\nu}$, reproducing a cosmological constant.

6.4 Static domain-wall halo

For a spherically symmetric, static configuration around a PBH, we seek solutions $\chi(r)$ minimizing the free energy. Neglecting backreaction on the metric, the equation of motion is

$$\xi\left(\frac{d^2\chi}{dr^2} + \frac{2}{r}\frac{d\chi}{dr}\right) - \frac{dV}{d\chi} + J(r) = 0. \tag{24}$$

A standard kink-like approximation is

$$\chi(r) \approx \frac{1}{2}\left[1 - \tanh\left(\frac{r-R}{l}\right)\right], \tag{25}$$

where R is the radius at which the effective conditions (e.g. $T_{\text{loc}}(r) = T_f$) favor freezing. The energy density stored in the domain wall is

$$\delta\rho(r) = \frac{1}{2}\xi\left(\frac{d\chi}{dr}\right)^2 + \Delta V\,\chi^2(1-\chi)^2, \tag{26}$$

peaked near $r \approx R$.

Integrating through the wall defines an effective surface tension

$$\sigma = \int_{-\infty}^{+\infty} \delta\rho(R+x)\,dx \sim \frac{\xi}{l}, \tag{27}$$

and the total halo mass

$$M_{\text{halo}} \approx 4\pi R^2\sigma. \tag{28}$$

To an external observer, the PBH plus its halo appears as a heavier object with a shell-like mass distribution. The ensemble of such halos in the late universe provides a Dark-Matter-like component.

7 Inertia: From Computational Drag to Unruh Response (Conjectural)

In this framework, motion through the vacuum requires rewriting the φ-bit configuration along the particle's path. Intuitively, this creates a sort of *computational drag*: the vacuum resists rapid changes in its information state. Here we sketch a conjectural connection between this idea and the Unruh effect.

An observer undergoing constant proper acceleration a experiences the vacuum as a thermal bath at the Unruh temperature

$$T_U = \frac{\hbar a}{2\pi c k_B}. \tag{29}$$

The present-day universe has a background temperature $T_{\mathrm{cmb}} \approx 2.7$ K, not far below $T_f \approx 4.41$ K. Thus the vacuum is in a near-critical regime where its susceptibility to temperature changes is large.

We define an effective local temperature

$$T_{\mathrm{eff}} \approx T_{\mathrm{cmb}} + T_U. \tag{30}$$

Acceleration shifts T_{eff} and hence perturbs the order parameter χ. Near criticality, a small change δT can induce a large change in $\langle\chi\rangle$:

$$\delta\langle\chi\rangle \sim \chi_{\mathrm{vac}}\,\delta T, \quad \chi_{\mathrm{vac}} \equiv \frac{\partial\langle\chi\rangle}{\partial T} \sim |T - T_f|^{-\gamma}. \tag{31}$$

If translating a mass m through the vacuum requires erasing and rewriting an effective number $N_\varphi(a)$ of φ-bits per unit distance, then

$$\frac{dS}{dx} \sim N_\varphi(a)\, k_B. \tag{32}$$

Relating work to entropy via $dW = T_f\, dS$ gives a force

$$F \sim T_f \frac{dS}{dx}. \tag{33}$$

If, in an effective limit, $N_\varphi(a)$ scales linearly with a, this yields an emergent $F \propto a$ law in which the coefficient is interpreted as inertial mass.

We stress that this section is conjectural. A rigorous derivation of Newtonian inertia from Unruh-driven vacuum response would require a detailed microscopic model of how acceleration couples to the φ-vacuum and how its information structure reorganizes, which we leave to future work.

8 Experimental Verification: The Landauer Spike

Perhaps the most radical aspect of the Landauer Vacuum hypothesis is the claim that the vacuum has a finite information capacity and a near-critical susceptibility at $T_f \sim 4$ K. This opens the door, at least conceptually, to laboratory tests in which controlled information erasure couples to the vacuum's order parameter.

8.1 Conceptual basis

If the vacuum is a medium of φ-bits, then erasing information in a strongly coupled quantum device necessarily dumps entropy into this medium. Normally, this manifests as conventional heat flow into a cryostat. However, near T_f, the vacuum's susceptibility χ_{vac} to entropy injection may be enhanced. Sufficiently intense, synchronized erasure pulses could excite the χ-field in a way that produces a small but coherent modulation of the local stress–energy tensor.

8.2 Experimental protocol

We outline a possible "Landauer Spike" experiment:

1. **Thermal regime:** Operate a dense quantum computing platform (e.g. superconducting qubits) or a classical bit array at a temperature T tunable in the few-Kelvin range, ideally near $T_f \approx 4.41$ K.

2. **Erasure drive:** Implement synchronized irreversible erasure operations (reset-to-zero) on N effective bits or qubits, repeated periodically at a drive frequency ω. The rate and pattern of erasure are under experimental control.

3. **Force sensor:** Place a torsion balance, microcantilever, or MEMS gravimeter in close proximity to the erasure volume, mechanically isolated and shielded from electromagnetic interference.

4. **Lock-in detection:** Record the sensor output and demodulate it at the drive frequency ω (and possibly harmonics), using lock-in amplification to reject broadband thermal and seismic noise.

8.3 Energetics and expected signal

Erasing N bits per cycle at temperature T releases at least

$$E_{\text{cycle}} \gtrsim N k_B T \ln \varphi \tag{34}$$

of energy. For $N \sim 10^{20}$ and $T \sim 4$ K, this is $\mathcal{O}(10^{-3})$ J per cycle. The naive GR-equivalent mass is $m_{\text{eq}} \sim 10^{-20}$ kg, far too small to produce a detectable gravitational force. However, if the vacuum's response is enhanced by a critical susceptibility χ_{vac}, the effective stress–energy perturbation could be larger:

$$\delta T^{\mu\nu}_{\chi} \sim \chi^2_{\text{vac}} J^2, \tag{35}$$

where J encodes the entropy injection. Near T_f, χ_{vac} could in principle be large, amplifying the local effect beyond the naive GR estimate.

We do not predict a specific signal amplitude here. Instead, we propose the Landauer Spike experiment as a way to *constrain* any such coupling: a null result would set upper bounds on $\chi_{\text{vac}} J$ and on the degree to which vacuum information is gravitationally active in this way.

8.4 Noise discrimination

Thermal noise, seismic vibrations, and electromagnetic disturbances are the main obstacles. The key advantage of the Landauer Spike is that the putative vacuum response is phase-locked to the erasure drive:

- Thermal and seismic noise are broadband and incoherent with the drive, and average down in a lock-in measurement.

- Any genuine vacuum-induced force synchronized with the erasure pulses appears as a narrow spectral peak at ω.

By varying N, T, and ω, one can map out the parameter space. If no signal is observed at the sensitivity of the apparatus, the Landauer Vacuum framework is significantly constrained. If a reproducible, non-thermal, phase-locked force is detected, it would provide striking evidence that information erasure couples directly to vacuum structure.

9 Conclusion

We have presented the Landauer Vacuum: a framework in which the universe is viewed as a computational medium that has cooled into a topologically ordered φ-phase. In this picture:

- Dark Energy arises from the Landauer cost and geometric frustration of maintaining a Fibonacci anyonic vacuum once the Hubble horizon outgrows its correlation length.
- Dark Matter halos emerge as domain-wall shells of melted vacuum around sub-critical Primordial Black Holes, consistent with the asteroid-mass window where PBH Dark Matter remains viable.
- Inertia may be interpreted, at least heuristically, as the back-reaction of a near-critical vacuum to the Unruh heating associated with acceleration.
- The Landauer Spike experiment offers a laboratory way to test whether information erasure can induce vacuum-mediated forces.

Many ingredients of this story are speculative and clearly labeled as such. The microscopic origin of n_φ and l, the detailed form of the effective action, and the precise PBH mass function all remain open questions. But the framework is structured enough to be wrong in interesting ways: it makes definite statements about when the vacuum froze, which PBH masses are dynamically special, and how information and gravity might be linked.

If the Landauer Vacuum picture is even partially correct, it suggests that the universe did not just cool; it *crystallized* into an information-theoretic phase where the Golden Ratio is not just a mathematical curiosity, but an order parameter woven into the fabric of spacetime.

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