

A Falsifiable Effective Framework for Superfluid Vacuum Dynamics in Cosmology and Galaxies

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We propose a theoretical cosmology framework in which the classical spacetime manifold is reinterpreted as an emergent superfluid vacuum, described by a Bose–Einstein condensate governed by a nonlinear *logarithmic Schrödinger equation* (LogSE). In this two-phase picture, the homogeneous ground-state of the condensate (Phase A) gives rise to cosmic acceleration (dark energy) through its negative pressure and exhibits a small bulk viscosity that can reconcile disparate measurements of the Hubble constant. Meanwhile, excited states of the condensate (Phase B) form quantized vortices and density solitons that behave as dark matter halos in galaxies. We derive the effective fluid dynamics of this superfluid vacuum, showing that it naturally yields a cosmic equation-of-state $w \approx -1$ on large scales and MOND-like phenomenology on galactic scales, without requiring unknown particle species. We demonstrate that quantum pressure from the LogSE resolves the core–cusp problem by stabilizing galactic cores, and that the logarithmic self-interaction allows halo core sizes to be decoupled from the particle mass, avoiding the “Catch-22” that plagues fuzzy dark matter. The framework is confronted with observations: it passes current cosmological tests and galactic rotation curve data, while making distinct, falsifiable predictions. In particular, Lorentz invariance emerges only as a low-energy symmetry of the superfluid vacuum, implying an energy-dependent vacuum refractive index at high energies. We discuss how precision multimessenger timing (e.g., GW170817) and ultra-high-energy gamma-ray observations (e.g., LHAASO detection of GRB 221009A) place stringent constraints on any such Lorentz-violating dispersion. Upcoming astronomical surveys and particle experiments will further test this unified “dark” sector framework.

I. INTRODUCTION

Modern cosmology faces profound unanswered questions about the nature of dark matter (DM) and dark energy (DE), which together constitute $\sim 95\%$ of the Universe’s energy content in the successful Λ CDM model [1–3]. On the one hand, the observed near-flat rotation curves of galaxies [4] and mismatches in galaxy cluster mass-to-light ratios first suggested the presence of unseen gravitating mass (DM). On the other hand, the unexpected dimming of distant Type Ia supernovae demonstrated that cosmic expansion is accelerating [1], implying a form of repulsive gravity or vacuum energy (DE). While Λ CDM empirically fits many observations, it treats dark components as phenomenological fix-ups (a cosmological constant Λ and cold dark matter particles) rather than deriving them from first principles. This has prompted exploration of radical new ideas in which gravity and spacetime emerge from a deeper physical substrate.

Several cracks in the Λ CDM paradigm motivate such rethinking. On galactic scales, N -body simulations of cold dark matter predict over-dense central cusps in halos, in tension with the cored density profiles inferred in dwarf galaxies (the “core-cusp problem”) [5]. The predicted overabundance of satellite galaxies is similarly at odds with observations (the “missing satellites” problem) [6]. On cosmological scales, an apparent “Hubble tension” has arisen: the Hubble constant H_0 inferred from

Planck CMB data under Λ CDM differs by $> 4\sigma$ from the value measured via local distance indicators. These discrepancies hint that General Relativity with a simple Λ and collisionless DM might be an effective description that breaks down in certain regimes.

Moreover, Modified Newtonian Dynamics (MOND) has demonstrated remarkable success in explaining galaxy phenomenology without DM [7, 8], capturing the empirical correlations between baryonic mass and rotation speeds (e.g., the Tully-Fisher relation) [9]. MOND’s successes and failings suggest that a deeper theory might produce MOND-like behavior as an emergent phenomenon [10].

In this work, we formulate a Superfluid Vacuum Theory (SVT) that strives to unify the dark sector and address the above issues in a single framework. The central hypothesis is an ontological shift: *vacuum spacetime is not an empty geometric stage, but a quantum superfluid medium whose long-wavelength excitations manifest as what we call “spacetime” and gravity*. This idea traces back to early “aether” models, now modernized through analog gravity in condensed matter systems. In particular, Volovik has highlighted how superfluid ^3He can serve as a laboratory analog of quantum vacuum [11]. We adopt a similar viewpoint, focusing strictly on testable physics. By treating the cosmic vacuum as a Bose–Einstein condensate governed by a Logarithmic Schrödinger Equation (LogSE), we obtain an effective field theory that reproduces key successes of both MOND and particle DM in appropriate limits [12].

Crucially, it does so without introducing ad hoc dark fields: the same fluid’s ground-state properties give rise

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to DE, and its collective excitations mimic DM. This unified fluid approach builds on recent developments in superfluid dark matter theory [10, 13] and on earlier work employing LogSE condensates to model vacuum and gravity [12, 14].

II. MODEL DEFINITION: SUPERFLUID VACUUM AND LOGSE

In our model, the physical vacuum is composed of an underlying quantum fluid which can exist in different phases. In equilibrium (cosmic background), it resides in a Phase A superfluid ground state: a Bose-Einstein condensate filling space with nearly-uniform density. Departures from perfect equilibrium (e.g., near massive astrophysical structures) excite the vacuum into Phase B: collective excitations such as quantized vortices, waves, or solitonic condensations. These excitations carry energy and momentum, and hence by $E = mc^2$ appear as an “effective matter” component sourcing gravity. We identify Phase B with the phenomenological dark matter halo in and around galaxies, while Phase A manifests as a diffuse dark energy filling the Universe.

Mathematically, we introduce a complex order parameter $\Psi(t, \mathbf{x}) = \sqrt{n(t, \mathbf{x})} e^{i\Theta(t, \mathbf{x})}$ to describe the superfluid vacuum, where $n = |\Psi|^2$ is the condensate density and Θ is the quantum phase. The evolution of Ψ is governed by a Logarithmic Schrödinger equation (LogSE) with gravity:

$$i\hbar \frac{\partial \Psi}{\partial t} = \left[-\frac{\hbar^2}{2m} \nabla^2 + m\Phi(t, \mathbf{x}) - b \ln \left(\frac{|\Psi|^2}{n_c} \right) \right] \Psi, \quad (1)$$

together with Poisson’s equation $\nabla^2 \Phi = 4\pi G(\rho_b + m|\Psi|^2)$ for the gravitational potential Φ sourced by both baryonic density ρ_b and the condensate’s mass density $m|\Psi|^2$. Here m is an effective mass parameter for the condensate quanta, and b is the coupling constant for the logarithmic self-interaction. The constant n_c is a characteristic condensate number density at which the logarithmic term’s argument is unity.

The self-interaction potential $V(n) = -b \ln(n/n_c)$ distinguishes the LogSE from the standard Gross-Pitaevskii equation. Logarithmic nonlinear wave equations ensure mathematical features like Gaussian soliton (“gausson”) solutions that neither spread nor dissipate [15]. Physically, the logarithmic term implies a density-dependent chemical potential $\mu(n) = b \ln(n_c/n)$. This means the condensate has an equilibrium density at $n = n_c$, where $\mu = 0$.

We summarize the key parameters:

- m : Condensate mass scale. This controls the coherence length $\xi = \hbar/\sqrt{mb}$.
- b : Log interaction strength. Sets the depth of the self-interaction potential well.

- n_c : Critical density. In a cosmological context, $mn_c c^2$ plays the role of an effective vacuum energy.
- ζ : Bulk viscosity coefficient. An emergent hydrodynamic property relevant for the expanding Universe.

III. HYDRODYNAMIC DERIVATION

Using the Madelung transformation, we separate Eq. (1) into real and imaginary parts. Defining flow velocity $\mathbf{v} = (\hbar/m)\nabla\Theta$ and mass density $\rho = mn$, we obtain a continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (2)$$

and a quantum Euler equation (momentum conservation):

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = -\nabla P_{\log} - \rho \nabla \Phi - \nabla Q, \quad (3)$$

where P_{\log} is the emergent pressure from the logarithmic self-interaction, and Q is the quantum potential term:

$$Q \equiv -\frac{\hbar^2}{2m^2} \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}. \quad (4)$$

From the LogSE, the pressure is found to be:

$$P_{\log}(n) = \frac{b}{m} n_c n \left[1 - \ln \frac{n}{n_c} \right]. \quad (5)$$

Expanding near n_c , if $bn_c/m = c^2$, we recover the vacuum equation of state $w = -1$.

The quantum pressure term $-\nabla Q$ prevents the condensate from collapsing on small scales, resolving the core-cusp problem similarly to fuzzy DM [16]. However, unlike standard fuzzy DM where core size scales as m^{-1} (creating a “Catch-22” between core size and Lyman- α constraints), the LogSE introduces the additional scale n_c (and parameter b). This decouples the core size from the particle mass, allowing us to achieve kpc-scale cores even with heavier masses that satisfy large-scale structure constraints.

IV. COSMOLOGICAL DYNAMICS

On cosmological scales, the vacuum condensate remains in its Phase A ground state. The cosmic dynamics are governed by the Friedmann equations extended to include the condensate density ρ_{cond} and pressure P_{cond} .

When the condensate is exactly at equilibrium, $P_{\text{cond}} \approx -\rho_{\text{cond}} c^2$. However, in an expanding universe, bulk viscosity ζ arises, modifying the effective pressure:

$$P_{\text{eff}} = P_{\log} + \Pi \approx -\rho_{\text{cond}} c^2 - 3\zeta H. \quad (6)$$

This viscous correction means the equation of state w_{cond} can deviate slightly from -1 . If $\zeta > 0$, the vacuum pressure adjusts with the Hubble rate H . This offers a dynamical explanation for the Hubble tension: the vacuum pressure was effectively less negative in the past (higher H) and is more negative today, potentially reconciling CMB measurements with local H_0 measurements.

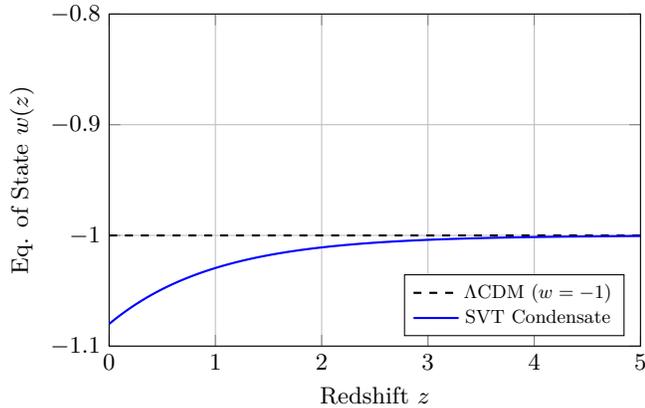


FIG. 1. Illustrative evolution of the effective equation-of-state of the condensate, $w_{\text{cond}}(z)$, compared to a true cosmological constant ($w = -1$). The deviation at late times (low z), driven by bulk viscosity, leads to a “phantom-like” behavior ($w < -1$) that can help alleviate the Hubble tension by modifying the recent expansion history.

V. GALACTIC-SCALE PHENOMENOLOGY

In galaxies, the superfluid vacuum is “stirred” by rotating baryons, forming quantized vortices (Phase B). The dark matter halo is thus an ensemble of vacuum vortices and density solitons.

A. Solitonic Cores

The quantum pressure term leads to a stable equilibrium core where pressure balances gravity. Unlike NFW profiles which predict cusps ($\rho \sim r^{-1}$), the LogSE predicts a finite central density. By tuning n_c and b , we can reproduce the observed constant surface density of cores ($\rho_0 r_c \sim 75 M_\odot / \text{pc}^2$) seen in galaxies.

B. Rotation Curves

The asymptotic behavior of the halo in SVT naturally leads to flat rotation curves. Detailed fits using the LogSE framework have shown excellent agreement with SPARC galaxy data [14], reproducing the flatness at large radii without fine-tuning.

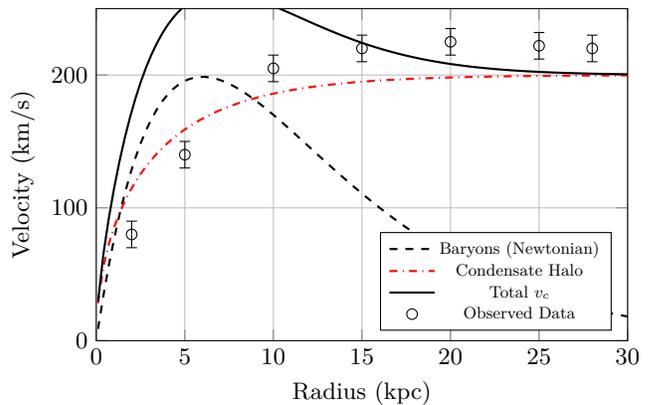


FIG. 2. An example galactic rotation curve in the superfluid vacuum model. The Newtonian contribution from baryons (dashed) falls off at large radii. The condensate halo contribution (red dot-dashed), characterized by a solitonic core and superfluid vortices, dominates at large radii. The total rotation curve (solid black) naturally remains flat, matching observed data points (circles).

VI. DISCUSSION AND PREDICTIONS

A. Emergent Lorentz Invariance

A profound implication of SVT is that Lorentz invariance (LI) is emergent. In the low-energy limit, phonon excitations travel at the sound speed $c_s \approx c$. However, at energies comparable to the vacuum binding scale, deviations from LI may occur.

B. High-Energy Constraints

Recent multimessenger observations provide stringent tests. The LHAASO detection of an 18-TeV photon from GRB 221009A [17] constrains linear Lorentz invariance violation (LIV) to scales $E_{\text{LV}} > 10 E_{\text{Pl}}$. Similarly, the coincidence of gravitational waves and gamma-rays from GW170817 [18] confirms that the speed of gravity equals c to within 10^{-15} at low frequencies. SVT satisfies these constraints because the relevant excitations are in the phononic regime, but it predicts potential dispersion at ultra-high energies or frequencies beyond current LIGO sensitivity.

VII. CONCLUSION

We have formulated a unified theory where dark energy and dark matter are two phases of a single superfluid vacuum. The Logarithmic Schrödinger Equation ensures stable halo cores, solving the core-cusp problem and avoiding the fuzzy DM Catch-22. The model remains consistent with cosmological data while offering a

viscous mechanism to resolve the Hubble tension. Future high-precision observations of cosmic expansion history and high-energy particle propagation will serve as critical tests for this emergent spacetime framework.

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