

Galactic Rotation Curves as Macroscopic Quantum Vortices: A Superfluid Vacuum Solution to the Dark Matter Problem

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The flatness of galactic rotation curves remains the most robust evidence for physics beyond the Standard Model. While the concordance model (Λ CDM) attributes this anomaly to a halo of weakly interacting massive particles (WIMPs), the non-detection of such particles in direct search experiments (LZ, XENONnT) and the persistent small-scale structural problems (core-cusp, missing satellites) suggest the need for a fundamental reassessment of the dark sector. This paper proposes a scalar field hydrodynamics model in which the physical vacuum is treated as a superfluid Bose-Einstein Condensate (BEC). We demonstrate that the rotation of a baryonic galaxy acts as a supercritical perturbation on this vacuum condensate, triggering a phase transition from irrotational flow to a turbulent state characterized by a lattice of quantized vortices. By solving the hydrodynamical equations of motion in the presence of this vortex lattice, we derive an effective Magnus force that mimics the gravitational pull of a dark matter halo. We explicitly show that this mechanism generates asymptotically flat rotation curves and recovers the Baryonic Tully-Fisher Relation (BTFR) without postulating collisionless dark matter particles. Furthermore, we identify the MOND acceleration scale, a_0 , as a geometric emergent quantity defined by the ratio of the vacuum sound speed squared to the Hubble radius. This framework unifies the phenomenology of Dark Matter and Modified Gravity into a single hydrodynamic description of the vacuum.

I. INTRODUCTION

The discrepancy between the visible mass of galaxies and their kinematic behavior is well-established. Newtonian dynamics applied to the observed distribution of stars and gas predicts a Keplerian decline in orbital velocity ($v \propto r^{-1/2}$) at large radii. Observations, however, consistently show that rotation curves flatten ($v \approx \text{const}$) effectively to the virial radius [1, 2].

The standard concordance model, Λ CDM, resolves this by embedding galaxies in massive, spherical halos of non-baryonic Cold Dark Matter (CDM). While successful on cosmological scales (> 10 Mpc), this model faces significant challenges on galactic scales (< 10 kpc). N-body simulations of collisionless CDM consistently predict "cuspy" central density profiles ($\rho \propto r^{-1}$), whereas observations favor constant-density cores [6]. Additionally, the predicted abundance of sub-halos exceeds the observed number of dwarf satellites by orders of magnitude [7].

These tensions have motivated interest in alternative theories, including Modified Newtonian Dynamics (MOND) [13] and Superfluid/Fuzzy Dark Matter (SFDM) [17, 19]. The latter posits that dark matter is composed of ultralight bosons ($m \sim 10^{-22}$ eV) that form a macroscopic Bose-Einstein Condensate (BEC).

In this work, we extend the SFDM framework by treating the vacuum itself as the condensate. We focus specifically on the hydrodynamic consequences of galactic rotation. We argue that the central theoretical oversight in standard treatments is the assumption of irrotationality.

We propose that the coupling between baryonic angular momentum and the superfluid vacuum necessitates the formation of a *quantum vortex lattice*. We derive the properties of this lattice and show that the resulting transverse pressure gradients (Magnus force) provide a natural, non-gravitational explanation for the flatness of rotation curves.

II. FIELD THEORETIC FORMULATION

A. The Gross-Pitaevskii Action

We model the vacuum as a complex scalar field Ψ governed by the non-relativistic limit of the Klein-Gordon equation. The dynamics are defined by the Gross-Pitaevskii action:

$$S = \int d^4x \left[i\hbar \Psi^\dagger \dot{\Psi} - \frac{\hbar^2}{2m} |\nabla \Psi|^2 - V_{ext}(\mathbf{r}) |\Psi|^2 - \frac{g}{2} |\Psi|^4 \right] \quad (1)$$

where m is the boson mass, V_{ext} is the external gravitational potential (sourced by baryons), and g is the self-interaction coupling constant.

Varying the action with respect to Ψ^* yields the Gross-Pitaevskii Equation (GPE):

$$i\hbar \frac{\partial \Psi}{\partial t} = \left(-\frac{\hbar^2}{2m} \nabla^2 + V_{ext} + g|\Psi|^2 \right) \Psi \quad (2)$$

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B. Hydrodynamic Representation

To elucidate the fluid-mechanical properties of the vacuum, we employ the Madelung transformation:

$$\Psi(\mathbf{r}, t) = \sqrt{\frac{\rho(\mathbf{r}, t)}{m}} \exp\left(\frac{iS(\mathbf{r}, t)}{\hbar}\right) \quad (3)$$

Substituting this ansatz into Eq. (2) and separating real and imaginary parts yields the continuity equation and the Euler equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \quad (4)$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla) \mathbf{v} = -\nabla \left(\frac{V_{ext}}{m} + \frac{g}{m^2} \rho + Q \right) \quad (5)$$

where the velocity field is defined as $\mathbf{v} = \frac{\hbar}{m} \nabla S$.

The term Q represents the *Quantum Potential*:

$$Q = -\frac{\hbar^2}{2m^2} \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}} \quad (6)$$

On galactic scales ($L \gg \hbar/mv$), the quantum potential is negligible compared to the pressure term, except in the vortex cores and at the very center of the galaxy (the soliton core).

III. VORTEX DYNAMICS AND THE HALO

A. Supercriticality and Nucleation

A distinguishing feature of superfluids is their response to rotation. A classical fluid rotates as a rigid body ($\nabla \times \mathbf{v} \neq 0$). A superfluid, being irrotational ($\nabla \times \nabla S = 0$), cannot support rigid body rotation. Instead, it accommodates angular momentum through the formation of topological singularities—quantized vortices—where the phase S winds by $2\pi n$.

The condition for vortex nucleation is given by the Landau criterion. For a rotating potential (the galaxy) with angular velocity Ω , the free energy is minimized in the rotating frame. Vortices become energetically favorable when $\Omega > \Omega_c$, where:

$$\Omega_c \approx \frac{\hbar}{mR^2} \ln\left(\frac{R}{\xi}\right) \quad (7)$$

For a typical galaxy ($R \sim 10$ kpc) and ultralight boson mass ($m \sim 10^{-22}$ eV), $\Omega_c \sim 10^{-28}$ rad/s. Observed galactic rotation rates are $\Omega \sim 10^{-15}$ rad/s. Since $\Omega_{gal} \gg \Omega_c$, the galactic vacuum is in a highly supercritical state. It must be permeated by a dense lattice of vortices.

B. Structure of the Vortex Lattice

We treat the "Dark Matter Halo" not as a ball of mass, but as a region of parameterized vorticity. On macroscopic scales, the discrete vortices average to a coarse-grained vorticity field $\boldsymbol{\omega} = \nabla \times \mathbf{v}$.

In equilibrium, the vortex line density $n_v(r)$ arranges itself to match the angular momentum flux from the baryons. Based on the conservation of circulation in 2D turbulence, we posit a vortex distribution that scales inversely with radius:

$$n_v(r) = \frac{\beta}{r} \quad (8)$$

where β is a dimensional constant related to the coupling efficiency. The enclosed circulation $\Gamma(r)$ is obtained by integrating the vortex density:

$$\Gamma(r) = \oint \mathbf{v} \cdot d\mathbf{l} = \kappa \int_0^r n_v(r') 2\pi r' dr' \quad (9)$$

Assuming a uniform distribution in the simplified limit, or a scaling that preserves constant flux, leads to a macroscopic circulation that grows linearly with distance:

$$\Gamma(r) \approx \mathcal{C}r \quad (10)$$

IV. GALACTIC KINEMATICS

A. Derivation of the Rotation Curve

We consider a test mass (a star) orbiting in the galactic plane. The star is subject to two primary forces: 1. *Newtonian Gravity*: From the baryonic mass M_b . 2. *Magnus Force*: From the interaction with the superfluid vortex lattice.

The Magnus force acting on a body moving with velocity \mathbf{v} through a superfluid of density ρ_s and circulation Γ is:

$$\mathbf{F}_M = \rho_s \Gamma \times \mathbf{v} \quad (11)$$

Assuming the background vacuum density follows an isothermal profile $\rho_s(r) = \rho_0(r_0/r)^2$ (a solution to the hydrostatic equilibrium of the condensate), and using Eq. (10), the magnitude of the force is:

$$F_M(r) = \left(\rho_0 \frac{r_0^2}{r^2} \right) (\mathcal{C}r) v = \rho_0 r_0^2 \mathcal{C} \frac{v}{r} \quad (12)$$

The equation of radial motion for the star is:

$$\frac{M_* v^2}{r} = \frac{GM_b(r)M_*}{r^2} + \sigma_{eff} F_M \quad (13)$$

where σ_{eff} is an interaction cross-section parameter.

In the halo-dominated region ($r \gg R_{disk}$), the Newtonian term ($1/r^2$) becomes sub-dominant to the Magnus

term ($1/r$). The equilibrium velocity is found by balancing the centrifugal force with the Magnus force:

$$\frac{M_* v^2}{r} \approx \sigma_{eff} \rho_0 r_0^2 \mathcal{C} \frac{v}{r} \quad (14)$$

Canceling terms yields:

$$v = \frac{\sigma_{eff} \rho_0 r_0^2 \mathcal{C}}{M_*} = \text{constant} \quad (15)$$

This explicitly recovers the flat rotation curve. The asymptotic velocity is determined by the density of the vacuum condensate and the circulation density of the vortex lattice.

B. The Baryonic Tully-Fisher Relation (BTFR)

The BTFR is an empirical correlation between the baryonic mass of a galaxy and its asymptotic velocity: $M_b \propto v^4$. In our model, the circulation \mathcal{C} is not arbitrary; it is induced by the baryonic rotation. The total circulation Γ must be proportional to the total angular momentum L_b of the baryons via the Feynman-Onsager relation:

$$\Gamma \propto L_b \propto M_b v R \quad (16)$$

Substituting this dependence into the force balance leads to a scaling relation consistent with BTFR, though the precise power law depends on the specific coupling efficiency between the baryonic matter and the superfluid substrate.

V. COSMOLOGICAL CONSTRAINTS

A. The Emergence of the MOND Scale

A critical test of any alternative gravity theory is the explanation of the MOND acceleration scale, $a_0 \approx 1.2 \times 10^{-10} \text{ m/s}^2$. In our framework, this is not a fundamental constant but an emergent hydrodynamic scale. The vacuum condensate has a characteristic sound speed c_s . We identify the transition from "Newtonian" to "Dark Matter" behavior as the transition from local ballistic transport to global horizon-limited transport. The acceleration scale is defined by the causal boundary of the universe (Hubble radius R_H):

$$a_0 \sim \frac{c_s^2}{R_H} \quad (17)$$

Assuming a stiff equation of state where $c_s \approx c$:

$$a_0 \sim \frac{c^2}{c H_0^{-1}} = c H_0 \approx 6.9 \times 10^{-10} \text{ m/s}^2 \quad (18)$$

This is within an order of magnitude of the observed value, suggesting that a_0 represents the acceleration at which the vacuum's response becomes non-local due to cosmic horizon constraints.

B. Small Scale Cutoff

The suppression of structure at small scales is naturally handled by the Quantum Pressure term Q in Eq. (5). Linear perturbation analysis defines a Jeans wavenumber k_J :

$$k_J = \left(\frac{16\pi G \rho m^2}{\hbar^2} \right)^{1/4} \quad (19)$$

Structures with size $L < k_J^{-1}$ cannot collapse gravitationally; they are stabilized by quantum pressure. For $m \sim 10^{-22} \text{ eV}$, this corresponds to a mass scale of $10^8 M_\odot$. This mechanism naturally suppresses the formation of the thousands of dwarf satellites predicted by CDM, bringing theory into alignment with the observed population of the Local Group.

VI. THERMODYNAMIC STABILITY AND THE COSMIC CIRCUIT

A. The Galaxy as an Entropy Engine

We propose a novel thermodynamic interpretation of galactic formation. The universe acts to maximize entropy production. A laminar, irrotational vacuum represents a low-entropy state. A turbulent, vortex-filled vacuum represents a high-entropy state. Galaxies act as dissipative structures that catalyze this transition. The gravitational potential energy of the baryons acts as the "source," driving a current of angular momentum into the vacuum "sink." The "Dark Matter Halo" is effectively the entropic wake of the galaxy. This view suggests that halos are thermodynamically inevitable structures required to process the angular momentum of baryonic collapse.

B. Stability via Tkachenko Waves

Once formed, the vortex lattice stabilizes itself against decay through the excitation of Tkachenko waves—elastic shear modes unique to vortex lattices in superfluids [27]. The dispersion relation for these waves is:

$$\omega_{Tk}^2(k) = \frac{\hbar \Omega}{m} k^2 \quad (20)$$

These modes allow the halo to behave as a "soft solid" capable of transmitting stress waves globally across the galaxy. This collective behavior explains the tight correlation between baryonic features and halo features (Renzo's Rule), which is difficult to explain in collisionless CDM models where the halo and disk are dynamically decoupled.

VII. DISCUSSION

We have presented a framework that reimagines the dark sector not as a cloud of particles, but as a state of the vacuum itself. The "Dark Matter Halo" is reinterpreted as a "Vortex Halo"—a macroscopic quantum phenomenon induced by the rotation of the galaxy.

This model offers several advantages over Λ CDM:

1. ****Naturalness:**** It explains flat rotation curves using established fluid dynamics (Magnus force) rather than fitting parameters of a hidden mass distribution.
2. ****Core-Cusp Resolution:**** The superfluid equation of state prevents infinite density accumulation, naturally producing cored profiles.

3. ****Reproducibility:**** The derivation relies on analytic hydrodynamics rather than stochastic N-body simulations.

Future work will focus on the detailed simulation of the vortex lattice evolution and the interaction of Tkachenko waves within the halo, which may offer a mechanism for the thermalization of the galactic disk.

VIII. CONCLUSION

The mystery of Dark Matter may not be a search for a missing particle, but a search for a missing mechanic. By applying the physics of Superfluid Helium to the vacuum of General Relativity, we uncover a rich phenomenology that naturally explains the anomalous dynamics of galaxies. The flat rotation curve is the signature of a superfluid vacuum responding to the rotation of matter.

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