Gravity as Acoustic Radiation Pressure

The Secondary Bjerknes Force in the Superfluid Vacuum

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Overview for Non-Specialists

Rethinking Empty Space

Most of us learn that space is nothingness, an inert backdrop in which planets and particles drift. Modern physics shows that this 'emptiness' behaves more like a frictionless ocean. Quantum field theory assigns every point in space a restless energy, and a century of experiments have revealed waves, fluctuations and vacuum pressures arising from that energy. This paper takes that intuition seriously: it treats empty space as a superfluid—a medium with no viscosity that supports waves and vortices but offers no drag to moving objects. In such a medium, matter is not a collection of solid particles but a pattern of persistent vibrations, like standing waves on a string.

Gravity as a Pressure Wave

When two sources oscillate in the same fluid, they influence one another through pressure waves. Vilhelm Bjerknes discovered in 1906 that pulsating bubbles in water can attract each other through what he called the Secondary Bjerknes force. This attraction is not mystical; it comes from the way each bubble's vibrations create zones of higher and lower pressure that push its neighbour.

In the framework proposed here, gravity is the vacuum analogue of this acoustic radiation pressure. Each 'particle' of matter is modelled as an oscillon—a tiny region where the superfluid vacuum vibrates in a self-sustaining way. Two oscillons in the same medium exchange pressure waves. If they oscillate in phase, the waves pull them together, reproducing Newton's inverse–square law simply because spherical waves spread out with distance. When viewed from inside the medium, this mutual attraction appears as the curvature of spacetime described by Einstein's general relativity.

Not a Revival of the Old Æther

Calling the vacuum a 'medium' evokes nineteenth-century ether theories, which experiments famously falsified. The key difference is viscosity. The classical ether was thought to behave like a gas or syrup that objects could plough through, which would have created drag that Michelson and Morley would have detected. A superfluid has no internal friction. It can carry waves and vortices but provides no preferred frame of reference. Inside such a medium, internal observers—composed of the medium's own excitations—experience Lorentz invariance and cannot detect absolute motion. This is not a metaphor but a mathematical statement: decades of research in analogue gravity have shown that the equations governing small disturbances in a moving superfluid map exactly onto the equations of a relativistic scalar field on a curved spacetime [1–3].

Building on Solid Foundations

The proposal unifies several well-established research programmes. The analogue gravity programme, developed by Unruh, Visser and Barceló [1–3], demonstrated that sound waves in a fluid obey the same differential equations as fields in curved spacetime; properties such as horizons, Hawking-like radiation and effective metrics arise naturally from fluid dynamics. Volovik [4] extended this by showing that quasiparticles in the superfluid helium-3A (^{3}He-A) phase obey relativistic dispersion relations and experience emergent gauge fields, reproducing many features of the Standard Model and suggesting that Lorentz invariance and gauge symmetries could be emergent rather than fundamental. Finally, nonlinear wave theory provides the mechanism for matter itself: oscillons and ponderomotive trapping show that self-sustaining 'breathers' can form when the time-averaged radiation pressure balances dispersive spreading—and in this picture, those breathers become the building blocks of matter.

By combining these elements, the paper derives gravitational attraction as a manifestation of acoustic pressure without modifying the successful predictions of general relativity. It shows that inertial and gravitational mass become the same quantity (the equivalence principle), and that gravity's relative weakness compared with other forces follows from how little of the vacuum's energy is locked into an oscillon.

Why This Matters

Understanding gravity as emergent opens new avenues for both theory and experiment. The hydrodynamic picture explains why the cosmological constant is small and why Lorentz symmetry is so robust. It also makes five testable predictions, ranging from subtle modifications to gravitational wave polarisation to possible deviations in high-frequency oscillators. Because these predictions use existing or near-term technology, the theory is falsifiable: a single failed test could rule it out. Conversely, confirming any of these signatures would point toward a deeper unity between condensed-matter physics and cosmology.

In essence, the paper invites readers to imagine the vacuum not as emptiness but as a perfectly smooth sea, where matter is a pattern of waves and gravity is the subtle pressure those waves *exert on one another. This view does not overturn the mathematics of Einstein or the quantum field theorists; rather, it asks what physical mechanisms might lie beneath those equations and offers concrete ways to find out.*

Abstract

This manuscript is a preprint and has not been peer reviewed. We derive Newtonian gravity as an emergent phenomenon arising from the Secondary Bjerknes Force between oscillating structures in a superfluid vacuum. Building on the analogue gravity programme of Unruh, Visser, and Barceló, and the superfluid vacuum theory of Volovik, we show that if matter consists of self-sustaining oscillations (oscillons) in a medium belonging to the ^{3}He-A universality class, then gravitational attraction arises as acoustic radiation pressure between in-phase oscillators. The framework reproduces the Newtonian inverse-square law as a geometric consequence of spherical wave propagation, renders the equivalence of inertial and gravitational mass tautological rather than coincidental, and offers a route to reinterpreting the vacuum-energy ("cosmological constant") problem via the Gibbs–Duhem relation for a self-sustained condensate. The tensor polarisation of gravitational waves—observed by LIGO—is addressed through the emergent metric formalism: the effective spacetime metric, constructed as a rank-2 symmetric tensor from the order parameter triad of the chiral superfluid, supports tensor perturbations by construction. The identification of the specific propagating spin-2 collective mode remains an open theoretical task, with recent experimental observation of chiral graviton modes in fractional quantum Hall liquids and theoretical work on spin-nematic Goldstone bosons establishing that condensed matter systems can host the required spin-2 physics. We present five falsifiable predictions that distinguish this framework from standard General Relativity and discuss open problems including the phase-locking mechanism and the spin-2 mode identification. The mathematical structure of GR is preserved as the acoustic metric of the underlying hydrodynamics.

1. Introduction

The analogue gravity programme, initiated by Unruh [1] and developed extensively by Visser [2] and Barceló *et al.* [3], demonstrated that the equations governing small perturbations in a moving fluid are mathematically identical to those of a scalar field propagating on a curved spacetime. This is not metaphor but mathematical isomorphism: linearising the continuity and Euler equations for an inviscid barotropic fluid yields an effective metric—the acoustic metric—that captures the causal structure experienced by phononic excitations. Sonic horizons, Hawking-like radiation, and effective curvature all emerge from classical fluid dynamics.

Separately, Volovik [4] showed that superfluid Helium-3A (^{3}He-A) provides a more complete analogue: its low-energy quasiparticle spectrum contains Fermi points where excitation energy vanishes linearly with momentum, producing an effective dispersion relation $E^2 = c_s^2(p - qA)^2$ that is identical to the relativistic relation for a massless Weyl fermion. The Lorentz invariance observed in particle physics emerges from the topology of these Fermi points, not from fundamental spacetime symmetry. Volovik's work established that the Standard Model's gauge structure, chiral anomalies, and Lorentz symmetry all have precise counterparts in the low-energy physics of ^{3}He-A.

This paper takes the next step: if the vacuum belongs to the ^{3}He-A universality class, and if matter consists of localised self-sustaining oscillations (oscillons) within this medium, then gravity emerges as the Secondary Bjerknes Force—the acoustic radiation pressure between oscillating bodies in a fluid, first described by Bjerknes [5] in 1906.

We do not propose to replace General Relativity. GR is the acoustic metric of this framework—the effective geometry experienced by low-energy excitations. What we propose is a physical mechanism underlying the geometric description: gravity is not spacetime curvature *per se*, but the acoustic radiation pressure between resonant structures that manifests as effective curvature for internal observers.

Two axioms constrain the derivation:

Axiom 1 (Relative Motion). There is no experimentally accessible absolute reference frame within the medium for internal observers. While the substrate may possess an ontological rest frame, this frame remains hidden from any entity composed of the medium's own excitations.

Axiom 2 (Trapped Oscillation). Oscillation is the fundamental mechanism for trapping energy into stable configurations. Matter is not a static defect but a dynamic, self-sustaining resonance—an oscillon maintained by the ponderomotive balance between internal radiation pressure and external vacuum elasticity.

From these axioms, we derive the emergence of Lorentz invariance from Fermi point topology (Section 2), the identification of matter as oscillons (Section 3), gravity as Bjerknes force (Section 4), the recovery of known gravitational phenomenology (Section 5), the tensor polarisation challenge and gravitational waves (Section 6), falsifiable predictions (Section 7), and open problems (Section 8).

A critical clarification is necessary throughout: this framework does not propose that space contains a substance. Space is genuinely empty. However, empty space has dynamic properties—it permits movement, carries energy, supports wave propagation. These properties are mathematically identical to those of a superfluid. When we use terms such as 'superfluid vacuum' or 'medium,' we describe how space behaves, not what it is made of. The analogy is behavioural, not ontological. The term 'non-viscous ether' captures this precisely: 'ether' because space has properties and supports dynamics; 'non-viscous' because there is no drag, no resistance, no substance. This is why Michelson and Morley found nothing: there is no substance to detect motion through. Yet the mathematics of superfluids correctly describes vacuum dynamics because space exhibits the same behavioural properties—zero viscosity, wave propagation, topological defects, emergent Lorentz invariance.

2. The Medium and Emergent Relativity

2.1 Fermi Point Topology and Lorentz Invariance

In Volovik's analysis [4], the ground state of ^{3}He-A is a Bose–Einstein condensate of Cooper pairs with non-zero angular momentum. The energy spectrum of low-energy quasiparticle excitations contains topologically protected singularities—Fermi points—where quasiparticle energy vanishes linearly with momentum. Near a Fermi point, the dispersion relation takes the form:

$$E^2 = c^2_s(p - qA)^2$$

where c_s is the speed of sound and A is an effective gauge field corresponding to displacement of the Fermi point in momentum space. This equation is mathematically identical to the relativistic dispersion relation for a massless Weyl fermion with limiting speed $c = c_s$.

The topological protection is essential. Because the Fermi point topology is stable under continuous deformation of the Hamiltonian, the linear dispersion—and therefore the emergent Lorentz symmetry—is robust against perturbation. All matter and measuring instruments composed of quasiparticles are governed by the effective acoustic metric, not the underlying Galilean metric of the substrate. An observer moving through the fluid experiences length contraction and time dilation exactly as Special Relativity predicts. Axiom 1 is satisfied: the absolute rest frame exists ontologically but remains operationally inaccessible to internal observers.

2.2 The Acoustic Metric

Linearising the continuity and Euler equations for an inviscid barotropic fluid, Unruh [1] and Visser [2] showed that phase fluctuations of the condensate satisfy a wave equation in curved effective spacetime. The acoustic metric $G_{\mu\nu}$ captures the causal structure experienced by quasiparticles. In a stationary, homogeneous background, $G_{\mu\nu}$ reduces to the Minkowski metric $\eta_{\mu\nu}$—flat spacetime emerges.

If the fluid accelerates or rotates, the Riemann curvature tensor becomes non-zero. To internal observers, this curvature is indistinguishable from gravity. A radial inflow toward a sink creates geometry mathematically equivalent to the Schwarzschild metric, complete with an event horizon where flow velocity equals sound speed. General Relativity is not replaced but recovered—as the effective geometry of the acoustic metric.

3. Matter as Oscillons

3.1 Ponderomotive Trapping

Axiom 2 requires a mechanism for energy self-trapping. In nonlinear media, the ponderomotive force—the time-averaged force exerted by oscillating fields on the medium—

provides this mechanism. For an oscillating field of amplitude E and frequency ω, the ponderomotive force is:

$$F_p = -(e^2/4m\omega^2)\,\nabla\langle E^2\rangle$$

This force pushes the medium away from regions of high field intensity, creating a localised density deficit. The oscillation digs its own potential well in the vacuum density. When nonlinear self-focusing balances dispersive spreading, a stable solitary wave—an oscillon or breather—forms. The oscillon's stability is maintained by the balance between internal radiation pressure (pushing outward) and the elastic pressure of the surrounding vacuum (pushing inward).

Particles are therefore not static defects but active, breathing structures—dynamic equilibria maintained by continuous oscillation. Different particles correspond to different resonant modes of the vacuum substrate, with masses determined by the energy content of each self-sustaining oscillation pattern. This aligns with the Haisch–Rueda–Puthoff model in Stochastic Electrodynamics [6], where inertia arises from the resistance of charged structures to acceleration through the electromagnetic zero-point field.

3.2 The Causal Sequence

From the two axioms, phenomena emerge in a specific causal order:

Movement → Pressure → Oscillation → Density → Mass

Relative motion creates pressure gradients (force fields). Self-reinforcing pressure patterns form oscillations. Persistent oscillation creates stable density structure. Trapped oscillation manifests as inertial mass. This sequence is identical to classical sound theory—because the underlying mathematics is the same.

4. Gravity as the Secondary Bjerknes Force

4.1 The Bjerknes Mechanism

In 1906, Vilhelm Bjerknes [5] investigated the forces between pulsating bodies immersed in a fluid. He derived that two spheres oscillating at frequency ω in an incompressible fluid exert a mutual force—the Secondary Bjerknes Force—through acoustic radiation pressure.

The mechanism is straightforward. Sphere 1 pulsates, creating a spherical pressure wave that propagates through the surrounding fluid. This wave reaches Sphere 2, which is also pulsating. Depending on the phase relationship between the two oscillators, the time-averaged interaction is either attractive or repulsive.

The time-averaged force between two oscillons with volume pulsation rates $\dot{V}_1$ and $\dot{V}_2$ is:

$$\langle F^1\rangle = -(\rho\,/\,4\pi r^2)\,\langle \dot{V}_1\dot{V}_2\rangle$$

where ρ is the fluid density and r is the separation between the oscillators.

4.2 Recovery of Newtonian Gravity

Three features of this expression are immediately significant.

Inverse-square dependence. The $1/r^2$ factor is not postulated but derived: it is a geometric consequence of spherical wave spreading in three-dimensional space. The energy of the pressure wave spreads over surface area $4\pi r^2$, producing the characteristic inverse-square falloff. Newton's gravitational law emerges from geometry, not from an imposed force law.

Phase-dependent sign. The sign of the force depends on the product $\langle \dot{V}_1 \dot{V}_2 \rangle$. For in-phase oscillators ($\Delta\varphi = 0$), the product is positive and the force is attractive. For anti-phase oscillators ($\Delta\varphi = \pi$), the product is negative and the force is repulsive. For gravity to be universally attractive, all matter must oscillate in a common temporal phase. This phase coherence is a known phenomenon in coupled oscillator systems, and its mechanism in the vacuum is discussed in Section 8 as an open problem.

Mass coupling. The pulsation amplitude $\dot{V}$ is proportional to the energy content of the oscillon—its mass. The product $\dot{V}_1 \dot{V}_2$ therefore scales as $m_1 m_2$, recovering the mass-mass coupling of Newtonian gravity. Newton's gravitational equation $F = Gm_1m_2/r^2$ is recovered with G identified as the coupling constant relating oscillon pulsation amplitude to the fluid's acoustic properties.

4.3 The Equivalence Principle

The equivalence of inertial and gravitational mass—the deepest unexplained symmetry in physics—becomes tautological in this framework.

Gravitational mass is the magnitude of the vacuum pressure deficit created by the oscillon: how much field energy the oscillation displaces. This is the static property—the depth of the well.

Inertial mass is the resistance to acceleration through the vacuum pressure field: the added mass the oscillon drags through the medium, plus the zero-point field reaction force. This is the dynamic property—the response to applied force.

Both measure the same physical parameter: the displacement volume of the oscillon. A larger oscillon displaces more vacuum (creating a deeper gravitational well) and presents a larger cross-section to the zero-point field (creating more inertia). The equivalence is not coincidental—it is physically mandated by the hydrodynamics. There is only one 'mass,' and it manifests as both gravity and inertia depending on context.

5. Recovery of Known Gravitational Phenomenology

5.1 Light Bending and Shapiro Delay

If the vacuum has variable energy density, light passing through it experiences different acoustic impedances at different points. Near mass (where the vacuum is denser due to field redistribution around the oscillon deficit), light propagates more slowly. This is mathematically equivalent to a variable refractive index:

$$n(r) = 1 + 2GM/rc^2$$

This is Puthoff's Polarisable Vacuum representation [7], which reproduces the predictions of General Relativity for light bending and Shapiro delay to all currently measurable precision. The curvature interpretation and the refractive interpretation produce identical observational predictions—they are mathematically equivalent descriptions of the same physics. What the hydrodynamic framework adds is mechanism: the field is denser near mass because mass has displaced it, and light slows in the denser region.

5.2 The Vacuum Catastrophe

Quantum Field Theory predicts a vacuum energy density of approximately 10^{13} J/m^3. According to the Equivalence Principle, this energy should gravitate, curving the universe into a singularity. Yet observations reveal a cosmological constant 120 orders of magnitude smaller—the largest failed prediction in the history of physics.

In this framework, the paradox is addressed by treating the vacuum as a self-sustained condensate in equilibrium. According to the Gibbs–Duhem relation for a self-sustained condensate at equilibrium [4]:

$$P_{va}{}^{u} = -\varepsilon_{va}{}^{u} + \mu n = 0$$

The immense microscopic energy density is exactly cancelled by the chemical potential term. The vacuum energy exists but is weightless—it does not gravitate because it is uniform and in equilibrium. Only perturbations from equilibrium (matter, oscillons) create local pressure gradients that manifest as gravitational effects. The effective cosmological constant $\Lambda \approx 0$ is the natural consequence of vacuum being a self-sustained fluid in equilibrium, not a fine-tuned cancellation.

5.3 The Hierarchy Problem

Why is gravity 10^{36} times weaker than electromagnetism? In this framework, electromagnetism involves direct field interaction at the resonant scale of matter—electron shells, atomic bonds—where the coupling is strong because the interaction scale matches the oscillon's characteristic frequency. Gravity involves the residual pressure differential from matter displacing vacuum energy. Since matter represents an infinitesimal displacement of the vacuum's enormous energy density, the gravitational gradient is correspondingly tiny.

The hierarchy is not fine-tuned but geometrically determined by the ratio of oscillon energy to vacuum energy—like the ratio of a cup of water to the ocean. Gravity is weak because matter is a tiny disturbance in an enormous medium.

6. Gravitational Waves and the Tensor Polarisation Challenge

A critical challenge for any fluid-based gravity model is the LIGO observation of gravitational waves with tensor (spin-2, quadrupole) polarisation. A classical inviscid fluid—the simplest interpretation of the non-viscous ether—supports only longitudinal (compressive) waves: density oscillations propagating as scalar perturbations. Such waves would produce monopolar or dipolar strain patterns, not the transverse quadrupole signature that LIGO observes. If the vacuum were a classical fluid, this framework would be falsified by existing data.

The vacuum, however, is not a classical fluid. As established in Section 2, the non-viscous ether belongs to the same universality class as the A-phase of superfluid Helium-3 (^{3}He-A)—a chiral superfluid whose ground state is a Bose–Einstein condensate of Cooper pairs with non-zero orbital angular momentum. The order parameter of ^{3}He-A is not a scalar. It is a complex 3×3 matrix constructed from the orthonormal triad ($\hat{e}_1$, $\hat{e}_2$, $\hat{l} = \hat{e}_1 \times \hat{e}_2$) and the spin vector $\hat{d}$, encoding both orbital and spin degrees of freedom. This internal structure is vastly richer than anything a classical fluid possesses, and it is from this structure that the emergent spacetime metric arises.

6.1 The Emergent Metric and Its Perturbations

In Volovik's framework [4], the effective spacetime metric experienced by low-energy quasiparticles is constructed from the order parameter triad:

$$g_{\mu\nu} = e^a{}_\mu \, e^b{}_\nu \, \eta_a{}^b$$

where $e^a{}_\mu$ is the emergent tetrad (vierbein) built from the ^{3}He-A order parameter fields and $\eta_a{}^b$ is the flat Minkowski metric. This construction is bilinear in the tetrad—it is inherently a rank-2 symmetric tensor. Perturbations of the metric, $\delta g_{\mu\nu}$, are therefore tensor perturbations by construction. They arise not from density fluctuations (which would be scalar) but from fluctuations of the order parameter triad—oscillations of $\hat{e}_1$, $\hat{e}_2$, and $\hat{l}$ that deform the local geometry without changing the local density.

This is the mechanism by which the non-viscous ether supports gravitational radiation. The vacuum is scalar in its bulk density but tensorial in its geometric structure, because the emergent metric carries more information than the density alone. Gravitational waves correspond to propagating disturbances in this geometric structure—perturbations of $g_{\mu\nu}$ that travel through the vacuum at the limiting speed c (identified with the Fermi velocity at the Fermi points). To internal observers, these perturbations are indistinguishable from the gravitational waves predicted by General Relativity, because GR is the effective field theory of the acoustic metric.

6.2 Why Classical Fluid Objections Do Not Apply

The objection that 'a fluid cannot support transverse waves' applies strictly to classical fluids characterised by a single scalar field (density) and a vector field (velocity). Such fluids lack the internal degrees of freedom required for tensor perturbations.

The non-viscous ether is not such a fluid. Three features distinguish it.

First, the order parameter is a matrix, not a scalar. The ^{3}He-A order parameter encodes orientation (the $\hat{l}$-vector), chirality (the handedness of $\hat{e}_1 \times \hat{e}_2 = \hat{l}$), and superfluid phase. Fluctuations of these fields produce perturbations with vector and tensor character, not merely scalar.

Second, the Pauli exclusion principle provides a mechanism for transverse rigidity absent in classical fluids. In a Fermi system, the occupied quantum states resist deformation of the Fermi surface, creating an effective shear stiffness in the collisionless regime even though the medium is a fluid. This rigidity is not classical viscosity—it arises from quantum statistics and vanishes in the hydrodynamic (collision-dominated) limit.

Third, superfluid ^{3}He experimentally supports transverse, polarised acoustic modes. The Acoustic Faraday Effect, observed by Avenel, Varoquaux, and Ebisawa in superfluid ^{3}He-B [9], demonstrates rotation of acoustic polarisation analogous to electromagnetic Faraday rotation—confirming that real quantum superfluids possess the internal degrees of freedom necessary for polarised transverse wave propagation. While this specific observation occurs in the B-phase rather than the A-phase, it establishes the principle that quantum superfluids are categorically different from classical fluids in their wave-propagation properties.

6.3 The Open Problem: Identifying the Specific Spin-2 Mode

The framework establishes that the non-viscous ether possesses the order parameter structure required to support tensor metric perturbations. What has not yet been achieved is the identification of a specific propagating spin-2 collective mode within the ^{3}He-A universality class whose dispersion relation, coupling to matter, and radiation formula reproduce the quantitative predictions of General Relativity for gravitational wave emission—most critically, the quadrupole formula that governs energy loss in binary pulsar systems.

This is a genuine open problem, not a hidden weakness, and its difficulty is worth stating plainly.

Transverse Zero Sound (TZS), predicted by Landau [8] for Fermi liquids in the collisionless regime, has been considered as a candidate for the gravitational radiation carrier. However, TZS is governed by the $\ell = 1$ (dipolar) Landau parameter F^s_1, making it a spin-1 vector mode—a 'material photon' in the terminology of Valentinis, Zaanen, and van der Marel [15]—rather than the spin-2 tensor mode required for gravitational radiation. Furthermore, experimental searches for TZS in normal liquid ^{3}He have yielded null results, with attenuation exceeding 2000 cm^{-1} [16]. TZS is therefore not the gravitational wave analogue.

The graviton analogue, in Volovik's framework, is not any single collective mode but a composite perturbation of the emergent metric—a correlated fluctuation of the tetrad fields that produces a propagating disturbance in $g_{\mu\nu}$ with the correct tensor symmetry. Deriving the effective action for these composite perturbations, extracting the propagating degrees of freedom, and computing the radiation formula from binary oscillon sources remains an open calculation. This calculation would need to recover the quadrupole emission formula to within the precision established by binary pulsar observations—currently 0.013% for the double pulsar PSR J0737−3039 [17].

Recent developments in condensed matter physics provide grounds for optimism that this programme is achievable. Liang *et al.* [18] have experimentally observed chiral graviton modes—spin-2 collective excitations—in fractional quantum Hall liquids, confirming that quantum fluids can support modes with the correct tensor character. Chojnacki, Shannon, and Penc [19] have demonstrated theoretically that spin-nematic phases host massless, relativistically dispersing spin-2 Goldstone bosons whose effective field theory maps onto linearised gravity. These results establish that condensed matter systems are capable of producing the spin-2 physics required for gravitational radiation—the outstanding task is to identify or derive the analogous mode within the specific universality class of the non-viscous ether.

6.4 What Is Established and What Remains

The situation may be summarised as follows. The non-viscous ether, understood as a chiral superfluid with the topological structure of ^{3}He-A, possesses an emergent spacetime metric that is a rank-2 symmetric tensor constructed from the order parameter triad. Perturbations of this metric are tensor perturbations by construction. The medium supports transverse, polarised wave propagation as demonstrated experimentally in superfluid Helium-3. The mathematical framework of General Relativity—the Einstein field equations—describes the dynamics of this emergent metric, as established by the analogue gravity programme.

What remains is the derivation: starting from the microscopic dynamics of the order parameter, computing the propagating spin-2 degrees of freedom and their coupling to oscillon sources, and demonstrating quantitative agreement with observed gravitational wave phenomenology. This is a well-defined theoretical programme with clear success criteria, and the recent experimental and theoretical progress in condensed matter spin-2 physics suggests it is within reach.

7. Falsifiable Predictions

The framework generates predictions that distinguish it from standard General Relativity. If any of the following are observed and are inconsistent with the predicted forms, the framework is falsified.

7.1 Gravitational Wave Echoes

If the objects currently identified as black holes are in fact gravastars—dense superfluid condensates with physical surfaces rather than event horizons—then binary merger ringdowns should exhibit echo signatures: secondary pulses arriving at characteristic time delays after the primary signal, caused by wave reflection from the dense surface. Analysis of existing LIGO/Virgo data can test this prediction [10].

7.2 Mass Modulation from Oscillation

If mass is the energy content of self-sustaining oscillation, then externally driven oscillation at frequencies near a material's fundamental resonance should produce measurable mass modulation. A high-frequency mechanical oscillator placed on a precision gravimeter should show periodic weight variation correlated with driving frequency, distinguishable from vibrational artefacts by its frequency spectrum.

7.3 Vacuum Electrostatic Potential

If gravity and electrostatic phenomena are inverse expressions of the same energy gradient, then evacuating a Faraday-shielded chamber should produce a measurable shift in internal electrostatic potential as field energy redistributes into the matter-free volume. A grounded chamber would dissipate this instantaneously; an isolated chamber should show a transient positive shift during pumpdown.

7.4 Gravitational Wave Polarisation

If gravitational waves are propagating tensor perturbations of the emergent metric, their polarisation structure should exhibit subtle deviations from GR predictions at frequencies approaching the dispersive regime where the emergent metric approximation breaks down. In the analogue gravity framework, the effective Lorentz invariance is exact only at low energies; at higher energies, quasiparticles begin to probe the underlying structure of the non-viscous ether, leading to frequency-dependent corrections. Next-generation detectors (LISA, Einstein Telescope) operating at different frequency bands may detect frequency-dependent polarisation effects absent from standard GR.

7.5 Warm Lightning Pressure Correlation

If electrostatic fields are the inverse expression of gravitational energy gradients, then lightning should correlate with rate of local pressure change (dP/dt) independently of ice crystal content. This prediction is most testable in tropical oceanic thunderstorms where cloud-top temperatures remain above freezing and the conventional graupel mechanism cannot function efficiently.

8. Open Problems

Intellectual honesty requires explicit acknowledgement of unresolved issues.

Phase locking. For gravity to be universally attractive via the Bjerknes mechanism, all matter must oscillate in temporal phase coherence. While coupled oscillator systems naturally synchronise (the Kuramoto model provides the mathematical framework), the mechanism by which approximately 10^{80} particles achieve and maintain coherence has not been derived from first principles. This remains one of the most significant open problems in the framework.

Several physically motivated candidates exist, however, suggesting this is a tractable problem rather than a fundamental obstacle. First, the zero-point field itself may serve as a universal driving oscillation that entrains all oscillons into common phase—analogous to Huygens' observation that pendulum clocks mounted on a shared wall spontaneously synchronise through mechanical coupling via the wall's vibrations. In this picture, the vacuum's stochastic background is the 'shared wall,' and phase coherence is not something that must be achieved across 10^{80} independent oscillators but something inherited from a common bath. Second, if all matter condensed from the same cosmological phase transition, initial phase coherence may have been established at formation and subsequently maintained by the coupling. The relevant question then shifts from 'how do particles synchronise?' to 'what mechanism could de-synchronise oscillators that share a common driving field?'—a substantially easier problem to constrain.

Spin-2 mode identification. As discussed in Section 6.3, the non-viscous ether possesses the order parameter structure to support tensor metric perturbations, but the specific propagating spin-2 collective mode has not yet been identified within the ^{3}He-A universality class. The derivation of the gravitational radiation formula from the microscopic dynamics of the order parameter—and its quantitative comparison with binary pulsar observations—is an essential open calculation.

Absolute mass scale. The framework explains why particles have discrete masses (resonance conditions) and why mass ratios take specific values (eigenvalue structure), but does not yet derive the absolute scale—why the electron mass is 0.511 MeV specifically.

Full LIGO waveform. A complete inspiral-merger-ringdown waveform template derived from superfluid dynamics has not yet been calculated. This would require numerical simulation of oscillon mergers in a chiral superfluid medium and identification of the spin-2 radiation channel.

CP violation. The origin of matter–antimatter asymmetry within the hydrodynamic framework remains an open question. The framework identifies antimatter as matter with opposite topological winding, but does not yet explain the cosmological preference for one winding sense.

Relationship to quantum gravity. This framework derives gravity as emergent from condensed matter physics and makes no claims about Planck-scale phenomena. Whether the superfluid description extends beyond the effective field theory regime, or whether new physics appears at the Planck scale, is deliberately left open.

9. Discussion

9.1 The Non-Viscous Ether and the Nature of Empty Space

The framework presented here synthesises three independent research programmes—analogue gravity, superfluid vacuum theory, and stochastic electrodynamics—into a single derivation of Newtonian gravity from acoustic radiation pressure. A recurring question, both historical and contemporary, is the ontological status of the medium invoked by this derivation. We address it directly.

The term 'ether' was discredited, rightly, when Michelson and Morley demonstrated that no drag-producing luminiferous medium permeates space. The rigid, crystalline ether of the nineteenth century predicted preferred reference frames, velocity-dependent forces, and detectable motion through the substrate. None of these predictions survived experimental scrutiny, and the concept was abandoned in favour of Einstein's postulate that the laws of physics take the same form in all inertial frames.

Yet Einstein himself, in his 1920 Leiden address, drew a distinction that the subsequent century has largely overlooked: 'According to the general theory of relativity, space is endowed with physical qualities; in this sense, therefore, there exists an ether... But this ether may not be thought of as endowed with the quality characteristic of ponderable media, as consisting of parts which may be tracked through time.'

This distinction—between a medium containing substance and a medium possessing properties—is precisely the one on which the present framework rests. Space is genuinely empty: it contains no particles, no lattice, no material substrate. Yet empty space demonstrably possesses dynamic properties. It permits movement. It carries energy. It supports wave propagation. It exhibits vacuum fluctuations measurable via the Casimir effect and the Lamb shift. It sustains topological defects. These are not the properties of 'nothing.' They are the properties of a medium—specifically, properties mathematically identical to those of a superfluid.

We use the term *non-viscous ether* to capture this ontological status with precision. 'Ether' because space has properties and supports dynamics; 'non-viscous' because there is no drag, no resistance, no detectable substance. This is why Michelson and Morley found nothing: there is nothing to find. The medium has no internal structure against which motion could be measured. It has no viscosity that would create drag. It has no crystalline order that would define a preferred orientation. It has only the behavioural properties of a superfluid—zero viscosity, quantised circulation, topological defects, and emergent Lorentz invariance—without the substance.

In the formal derivation presented in Sections 2–6, we employ the precise technical language of the analogue gravity programme: the vacuum belongs to the same universality class as the A-phase of superfluid Helium-3 (^{3}He-A), characterised by topologically protected Fermi points from which Lorentz invariance, gauge fields, and the effective metric emerge at low energies. This identification, due to Volovik, is supported by the mathematical isomorphism between the quasiparticle spectrum of ^{3}He-A and the Standard Model's chiral fermion content. The non-viscous ether is the conceptual description of what this mathematical framework physically represents: empty space whose dynamic behaviour is governed by the equations of superfluid hydrodynamics.

Robert Laughlin, in his 2005 monograph, stated the point with characteristic directness: 'The modern concept of the vacuum of space, confirmed every day by experiment, is a relativistic ether. But we do not call it this because it is taboo.' Frank Wilczek titled his popular exposition *Mass, Ether, and the Unification of Forces*, describing the quantum vacuum as 'highly evolved ether.' Volovik opens *The Universe in a Helium Droplet* by declaring it 'the new ether of the 21st century.' The present work follows these precedents while insisting on a terminological clarity they sometimes leave implicit: the ether is non-viscous, non-substantial, and non-detectable as a substance. It is defined entirely by its behavioural properties, which happen to be those of a quantum liquid.

9.2 Nested Motion and the Absence of Absolute Rest

The framework's first axiom—that no experimentally accessible absolute reference frame exists within the medium—is not merely a theoretical postulate. It is an empirical observation confirmed at every physical scale accessible to measurement.

Consider the hierarchy of motion that characterises the observable universe. An electron orbits within an atom. The atom oscillates within a molecule. The molecule participates in the thermal motion of a macroscopic body. That body rests on the surface of the Earth, which rotates on its axis at approximately 460 m/s at the equator. The Earth orbits the Sun at 30 km/s. The Sun orbits the galactic centre at approximately 220 km/s. The Milky Way falls toward the Virgo Cluster. The local supercluster participates in larger-scale flows at approximately 600 km/s relative to the cosmic microwave background rest frame.

At no point in this hierarchy does the universe reveal a preferred rest state. Every frame that appears stationary at one scale is found to be in motion when examined from the next scale up. The pattern does not terminate. There is no largest container that sits still while everything within it moves. This is not an artefact of observational limitation but a structural feature of physical reality: motion is relative at every accessible scale, from the subatomic to the cosmological.

This observation constitutes direct empirical support for Axiom 1. In a superfluid vacuum—a medium with zero viscosity and no internal lattice—there is no structure against which absolute motion could be defined. Unlike a crystal, which possesses a rest frame defined by its lattice (detectable through diffraction, phonon spectra, and other internal measurements), a superfluid at zero temperature has no rigid internal order that would distinguish one velocity from another. The nested hierarchy of relative motion is therefore not merely consistent with a superfluid vacuum—it is the *expected signature* of such a medium. A crystalline vacuum would exhibit a preferred frame. A viscous medium would produce observable drag over cosmological timescales. Only a superfluid permits the frictionless, frame-independent, endlessly nested motion that the universe displays.

Volovik's analysis formalises this observation. In his framework, the vacuum substrate may possess an ontological rest frame in the sense that the mathematical description admits a preferred foliation. However, this frame remains operationally inaccessible to any entity composed of the medium's own excitations. All measuring instruments—rods, clocks, interferometers—are themselves made of quasiparticles governed by the emergent acoustic metric. They undergo physical Lorentz–Fitzgerald contraction and physical time dilation that automatically compensate for any motion relative to the substrate. The result is what Volovik terms a 'bi-metric' system: the underlying Galilean metric of the substrate coexists with the emergent Lorentzian metric experienced by all low-energy physics, and no experiment accessible to internal observers can distinguish between them.

9.3 The Cosmic Microwave Background and Cosmological Context

A potential objection to the claim that no preferred rest state exists is the cosmic microwave background (CMB). The CMB defines, in practice, a cosmological frame: the frame in which the radiation field is isotropic. Our motion relative to this frame (approximately 370 km/s toward the constellation Leo) is measurable via the CMB dipole anisotropy.

This observation does not contradict Axiom 1. The CMB frame is a property of a particular cosmological configuration—the specific distribution of radiation and matter in the observable universe—not a property of the vacuum's fundamental laws. In the hydrodynamic framework, it is analogous to the bulk flow pattern of a river. A river has a measurable flow direction and velocity, but the equations of fluid dynamics themselves contain no preferred direction. The flow is an initial condition, not a law of nature.

The framework presented here makes no commitment to a specific cosmological model for the origin of the CMB or the large-scale structure of the universe. The causal sequence Movement → Pressure → Oscillation → Density → Mass describes how stable structures emerge from vacuum dynamics at any epoch and any scale. Whether this process operated in a singular initial event, in a gradual cosmological evolution, or through mechanisms not yet identified is a question orthogonal to the gravitational physics derived in this paper. The CMB's existence as an empirical datum is acknowledged and accommodated; its cosmological interpretation lies outside the scope of the present work.

What the framework does predict is that any cosmological model compatible with it must respect two constraints: (i) the vacuum equations admit no preferred frame, so any apparent frame (such as the CMB frame) must arise from boundary or initial conditions rather than from the dynamics; and (ii) the vacuum is a self-sustained condensate in thermodynamic equilibrium (Section 5.2), so the effective cosmological constant is naturally small. These constraints are consistent with observation but do not, by themselves, select a unique cosmological history.

9.4 The Causal Sequence and Emergent Structure

A distinctive feature of this framework is the causal sequence from which all physical phenomena derive:

Movement → Pressure → Oscillation → Density → Mass

This sequence is not imposed as an additional axiom but follows directly from the two foundational axioms. Axiom 1 (relativity of motion) establishes that relative motion exists and is the primitive physical quantity. Axiom 2 (oscillation traps energy) establishes that self-reinforcing patterns of motion persist while transient disturbances dissipate.

From relative motion, pressure gradients arise—this is the definition of a force field in fluid dynamics. From pressure gradients, oscillating patterns can form when boundary conditions or nonlinear feedback create standing or self-reinforcing waves. From oscillation, persistent density structure emerges as the time-averaged effect of the ponderomotive force. From density structure, inertial mass manifests as the resistance of a localised oscillation pattern to acceleration through the surrounding medium.

This sequence is identical in mathematical form to classical acoustics, and deliberately so. The framework proposes that the identity is not coincidental but fundamental: the mathematics of sound in a medium correctly describes the physics of matter in a vacuum because both are instances of the same hydrodynamic process operating at different scales.

The nested motion hierarchy discussed in Section 9.2 provides observational support for this picture. At every scale, we observe the same sequence in operation. Pressure waves in the interstellar medium compress gas into self-gravitating clouds. Gravitational collapse produces rotating, oscillating structures (protostars, accretion discs). Stable oscillation produces persistent density configurations (stars, planets). The process repeats at larger scales: galaxies form from the gravitational interaction of stellar-scale structures, galaxy clusters from the interaction of galactic-scale structures, and so on. The universe builds complexity through the same causal sequence at every accessible scale—precisely as expected if the sequence reflects the fundamental dynamics of the medium rather than scale-specific mechanisms.

9.5 What the Framework Achieves and What Remains Open

Several features of the framework are worth emphasising. First, it resolves long-standing puzzles without introducing new entities. The hierarchy problem, the vacuum catastrophe, and the equivalence principle all find natural explanations within the hydrodynamics—no extra dimensions, no fine-tuning, no new particles. Second, it is falsifiable: each prediction in Section 7 can be tested with existing or near-future technology. Third, it is conservative: it accepts the mathematical structure of both General Relativity and quantum mechanics while proposing a deeper physical substrate from which both emerge.

The framework does not claim to be complete. The most significant open problems—the phase-locking mechanism, the absolute mass scale, the identification of the specific spin-2 collective mode that carries gravitational radiation in the vacuum—are acknowledged explicitly in Section 8. These are genuine gaps, not hidden weaknesses. The framework's value lies not in resolving every question but in providing a physically motivated, mathematically grounded, and experimentally testable starting point for understanding gravity as an emergent phenomenon.

Newton described what gravity does. Einstein described what gravity looks like. This framework proposes what gravity *is*: acoustic radiation pressure between oscillating structures in a medium whose properties are described by the mathematics of superfluid hydrodynamics—the non-viscous ether of the twenty-first century.

10. Conclusion

We have derived Newtonian gravity as the Secondary Bjerknes Force between oscillating defects in a superfluid vacuum belonging to the ^{3}He-A universality class. The derivation rests on two axioms (relative motion and trapped oscillation) and produces the inverse-square law as a geometric consequence, the equivalence principle as a tautology, and the weakness of gravity as the natural ratio of oscillon energy to vacuum energy. The emergent spacetime metric—a rank-2 symmetric tensor constructed from the order parameter triad—possesses the tensor structure required for gravitational radiation, though the identification of the specific propagating spin-2 mode remains an open theoretical programme informed by recent experimental and theoretical advances in condensed matter spin-2 physics. The framework preserves the mathematical structure of General Relativity as an acoustic metric while providing the physical mechanism that GR's geometric description lacks.

Five falsifiable predictions are presented, several testable with existing data or near-term experiments. Open problems are acknowledged explicitly, including the phase-locking mechanism, the spin-2 mode identification, and the absolute mass scale. The framework represents a specific, testable proposal within the broader analogue gravity programme, and invites both theoretical scrutiny and experimental investigation.

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