

# Gravity as Pressure Gradient

## A Superfluid Vacuum Mechanics

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### Abstract

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This companion paper reformulates the same underlying premise as the primary preprint (“Gravity as Acoustic Radiation Pressure”) in a pressure-gradient language: if the vacuum is treated as an effective, self-sustained medium, then static gravitation corresponds to a spatial pressure gradient and gravitational radiation corresponds to propagating compressional disturbances of that medium. The aim here is not to claim experimental confirmation, but to provide a transparent mapping between a hydrodynamic/acoustic description and standard gravitational observables under clearly stated assumptions.

Using Lighthill’s acoustic analogy and the standard quadrupole framework, the paper derives an energy-loss expression with the same leading-order mass, separation, and frequency dependence as the Peters–Mathews result for compact binaries. The numerical coefficient can be matched through the model’s mapping between Newton’s constant and an effective background density scale; this fixes a single correspondence constant rather than constituting an independent prediction. The analysis highlights one sharp point of potential discrimination from General Relativity: the angular distribution and polarisation content of the radiated field in the medium description.

Explicit open problems are stated, including the mechanism by which a pure spin-2 mode would emerge (or be selected) from the medium’s collective excitations, and how phase-locking is maintained for long-lived sources. The paper closes with testable implications and clarifies which claims are derivations within the model and which are speculative extensions that require additional work.

### Overview for Non-Specialists

This paper is a technical companion to “Gravity as Acoustic Radiation Pressure.” The core idea is simple: if the vacuum can be modelled as an effective medium, then gravity can be described in two equivalent ways—either as a radiation-pressure interaction between oscillating structures, or as a macroscopic pressure gradient in that medium.

The value of this companion paper is practical. It shows how standard results that are normally derived in General Relativity can be approached from hydrodynamics/acoustics, using well-known tools such as Lighthill’s acoustic analogy. In particular, it derives a quadrupole power-loss law for binaries with the

same leading-order dependence as the Peters–Mathews formula, and it identifies a concrete observational handle: differences in the angular distribution and polarisation content of the emitted radiation.

The paper is written as a preprint. It is not a claim of experimental validation. Where the analysis requires an identification between the model’s medium parameters and Newton’s constant, that identification is stated explicitly. Where a result depends on an assumption (e.g., the nature of the relevant collective mode), the assumption is flagged as an open problem. The goal is to make the framework easy to critique, test, and either improve or falsify.

## 1. Introduction

Modern gravitational physics describes spacetime as dynamical geometry. In parallel, a long tradition of analogue-gravity research has shown that, under appropriate conditions, the equations governing perturbations in fluids and condensed-matter systems can be written in an effective-metric form. This paper adopts that programme as a methodological starting point: it treats the vacuum as an effective, inviscid medium and asks what aspects of gravitational phenomenology can be reproduced as medium dynamics under clearly stated assumptions.

The primary preprint (“Gravity as Acoustic Radiation Pressure”) develops a force-law picture based on radiation pressure between oscillatory structures. The present companion paper develops the complementary pressure-gradient picture. In a hydrodynamic description, a static attractive interaction corresponds to a pressure gradient around a persistent source configuration; time-dependent source motion generates propagating disturbances that carry energy and momentum away as radiation.

This paper focuses on two goals. First, it outlines how a pressure-gradient model can reproduce Newtonian scaling at the level of an effective theory. Second, it uses Lighthill’s acoustic analogy to derive a quadrupole power-loss expression for binary systems. The resulting scaling matches the familiar Peters–Mathews dependence, while the overall coefficient is tied to the mapping between Newton’s constant and a background medium density scale; this fixes a single correspondence constant within the framework.

Importantly, the goal is not to claim that the medium model has already been empirically confirmed. The goal is to present a transparent derivation pathway, highlight where the framework aligns with established results, and identify discriminating tests—especially those involving angular distribution and polarisation content—where a medium description may diverge from standard General Relativity templates.

For clarity and reviewer-friendliness, the paper distinguishes (i) derivations that follow from the stated assumptions, (ii) parameter identifications required to connect to measured quantities, and (iii) speculative extensions (e.g., deeper links to electromagnetism or cosmology) that are outside the scope of the present derivations and are not required for the main results presented here.

## 2. The Medium

The vacuum has measurable mechanical properties. This is not a theoretical claim but an experimental fact. Maxwell (1865) showed that the speed of electromagnetic propagation is determined by two constants of the vacuum: the electric permittivity  $\epsilon_0$  and the magnetic permeability  $\mu_0$ , through the relation  $c = 1/\sqrt{(\epsilon_0\mu_0)}$ . These are properties of the vacuum, not of light. Maxwell himself concluded that light must be a disturbance propagating through whatever medium those properties describe.

The term “speed of light” is misleading. The complete expression is the speed of light *in a vacuum*. There is no fixed speed of light as such. Light and electromagnetic energy travel at different speeds depending on the medium through which the waves propagate. What is fixed is the propagation speed determined by the medium’s properties. In this framework, that speed is the sound speed of the vacuum:

$$c^2 = dP/d\rho$$

This is the standard expression for the speed of sound in any medium — the ratio of pressure change to density change. Maxwell’s relation expresses this same fact in electromagnetic language. The vacuum has a density ( $\rho_0$ ), a compressibility, and a thermodynamic equation of state. The speed of light is fixed by these mechanical properties, just as the speed of sound in air is fixed by the density and compressibility of air. The sound wave has no say in the matter. It propagates at whatever speed the medium permits.

This explains why  $c$  is invariant for all observers. An entity made of patterns within a medium cannot outrun the medium’s disturbance speed. Lorentz invariance is not a postulate about reference frames but a consequence of being embedded in a medium whose propagation speed is  $c$ . Volovik (2003) demonstrated this rigorously: in superfluid helium-3 A-phase, quasiparticles near the Fermi points experience emergent Lorentz invariance with the speed of transverse sound playing the role of  $c$ . The symmetry is exact at low energies and breaks down at the medium’s microscopic scale — a prediction with no counterpart in Special Relativity.

The specific equation of state of the vacuum remains an open question. Zloshchastiev (2011) proposed a logarithmic superfluid described by the Logarithmic Schrödinger Equation, which uniquely produces a density-independent sound speed — essential for compatibility with relativity. Volovik's  $^3\text{He-A}$  programme derives Lorentz invariance from topological protection of Fermi points. These may represent complementary descriptions at different scales. The gravitational mechanism presented here depends only on the vacuum being a medium with mechanical properties and a well-defined sound speed equal to  $c$ . It does not depend on which equation of state is correct.

### **3. Matter as Reconfigured Vacuum Energy**

Matter is a region where vacuum energy has been reconfigured into a stable standing pattern, reducing the local contribution to ambient vacuum pressure and creating a radial pressure deficit.

This is best understood through the physics of Chladni plates. When a metal plate is vibrated at a resonant frequency, sand scattered on its surface collects at the nodes — the places where the plate has zero displacement. But these nodes are not regions of zero energy. They are regions where the energy has changed character. Kinetic energy of displacement is zero at the node, but elastic strain energy is at its peak. The sand marks where energy has changed form, not where energy is absent.

A particle in this framework is the same kind of phenomenon. Vacuum energy in the region occupied by the particle has not been removed — it has been reconfigured from propagating modes into a trapped, self-sustaining standing pattern. The energy is present, but it no longer contributes to the ambient vacuum pressure. The surrounding vacuum, still carrying its energy in the form that generates pressure, therefore has higher pressure than the region occupied by the particle. This asymmetry — this deficit — is what produces gravity.

The specific mechanism of stability — whether particles are oscillons, topological defects, solitons, or some other self-sustaining configuration — is a separate question. The gravitational physics depends only on the existence of the deficit and its magnitude, not on what sustains it internally. This separation is essential. It means

the gravitational framework is not contingent on any particular theory of particle structure.

Both inertial mass and gravitational mass measure the same quantity: the amount of vacuum energy locked into the standing pattern. Inertial mass measures resistance to acceleration — how much reconfigured energy must be set in motion through the medium. Gravitational mass measures the depth of the pressure deficit — how much vacuum energy has been displaced from the ambient pressure field. These are the same number because they refer to the same physical quantity. The equivalence principle is therefore tautological within this framework, not a coincidence requiring explanation.

The permitted configurations are not arbitrary. Solutions to the Schrödinger equation in a central potential — spherical harmonics — yield the periodicity numbers 2, 8, 18, 32 as the only patterns where energy can stably configure itself at each harmonic level. The periodic table of elements is the catalogue of these permitted reconfigurations. It maps not what elements are, but which standing wave patterns the medium supports (Harrison, 2024). The elements exist because the field permits them. They repeat because stability comes in quantised forms.

## **4. Static Gravity: The Pressure Gradient**

Matter displaces vacuum energy from its occupied volume. The surrounding vacuum, at higher pressure, presses inward along the resulting gradient. This is gravity.

The mechanism is identical in structure to several established physical principles. Archimedes' principle: the buoyant force on a submerged body equals the weight of displaced fluid, arising entirely from the pre-existing pressure gradient in the surrounding fluid acting on the body's surface. The body responds to the gradient; it does not create a new kind of force. The Casimir effect: conducting plates restrict vacuum modes between them, reducing the local energy density, so that external vacuum pressure exceeds internal — producing a measurable inward force, experimentally verified to 1%. This demonstrates that vacuum pressure differentials generate real forces. Osmotic pressure: a solute's presence creates a pressure deficit in the solvent's chemical potential, and the surrounding solvent flows inward to equalise. The solute does not pull the solvent. Its presence creates a deficit and the medium

responds. Debye (1923) showed that this is a mechanical pressure effect, not diffusion — a structural correction recently confirmed (Bhatt and Bhatt, 2023).

In each case, a deficit or asymmetry in a medium's energy density produces a real, measurable force directed inward toward the region of lower pressure. In each case, the force arises from the medium's properties, not from direct interaction between objects. Gravity, in this framework, is the same phenomenon operating in the vacuum.

The inverse-square law follows from Gauss's theorem. A pressure deficit spreading spherically through three-dimensional space produces a flux that falls as  $1/r^2$  by geometric necessity — the same total deficit distributed over a spherical surface whose area grows as  $4\pi r^2$ . This is not a property of any specific interaction. It is a consequence of three-dimensional geometry and conservation. Any conserved quantity emanating from a point source in three dimensions obeys an inverse-square law.

Mass coupling follows from the same physics. The depth of the pressure deficit is proportional to the energy content of the source — how much vacuum energy has been reconfigured. The response of a second body is proportional to its own displacement volume. The force therefore scales as the product  $m_1 m_2$ , recovering Newton's gravitational law.

The gravitational constant  $G$  relates the measured force to the vacuum's microscopic density:

$$G = K / (4\pi\rho_0)$$

where  $K$  is a dimensionless geometric factor and  $\rho_0$  is the vacuum density. Since  $G$  is measured empirically and  $\rho_0$  is not independently measurable,  $K$  is absorbed into the measurement of  $G$ . The value  $K = 2/3$  is established by the gravitational radiation calculation in Section 5.

Le Chatelier's principle provides the thermodynamic reason the gradient exists at all. The vacuum in thermodynamic equilibrium is perturbed by the presence of a mass — a region where energy has changed form. Le Chatelier's principle states that a system at equilibrium, when perturbed, responds to counteract the perturbation. The vacuum generates a restoring pressure gradient directed inward, attempting to fill the deficit. That restoring gradient is gravity. Gravity is a thermodynamic necessity.

Superposition follows because pressure gradients are linear: the gradient from two sources is the vector sum of the individual gradients. The shell theorem follows from the cancellation of gradients by symmetry inside a uniform spherical shell. Tidal forces follow from the variation of the gradient across an extended body. Every feature of Newtonian gravity is recovered from the single premise that matter creates a pressure deficit in a medium.

## 5. Gravitational Radiation: The Acoustic Quadrupole

This section presents the central quantitative result of the paper. Scalar pressure waves with quadrupolar source geometry, propagating through the vacuum medium, reproduce the Peters (1964) formula for total gravitational radiation power at leading order. The calculation matches the Hulse-Taylor binary pulsar's orbital decay rate. However, the angular distribution of this radiation differs from General Relativity's tensor prediction, providing a specific falsifiable test of the framework.

### 5.1 The Source

Two masses orbiting their common centre of mass create a time-varying pattern of pressure deficits. Each mass displaces vacuum energy; the combined deficit pattern is asymmetric and rotates with the orbital frequency. As the orbit evolves, changes in the deficit pattern propagate outward through the vacuum at the sound speed  $c$ .

The total mass (monopole moment) is conserved. The centre of mass (dipole moment) does not accelerate for an isolated system – conservation of momentum forbids it. The leading-order radiation is therefore quadrupolar, by elimination. This is a geometric property of the source, not of the wave's intrinsic spin.

### 5.2 The Lighthill Acoustic Quadrupole

Lighthill (1952) derived the power radiated by acoustic quadrupole sources in a fluid medium. The radiated power per unit solid angle is:

$$dP/d\Omega = (1 / 16\pi^2\rho_0c^5) |n_i n_j d^3Q_{ij}/dt^3|^2$$

where  $n_i$  is the unit direction vector,  $Q_{ij}$  is the mass quadrupole moment tensor, and the third time derivative is taken. Integrating over all solid angles using the standard angular integral for rank-4 direction cosines:

$$\int n_i n_j n_k n_l d\Omega = (4\pi/15)(\delta_{ij}\delta_{kl} + \delta_{ik}\delta_{jl} + \delta_{il}\delta_{jk})$$

Contracting with the symmetric quadrupole moment tensors yields three terms. Two are identical by the symmetry  $Q_{ij} = Q_{ji}$ , giving the total acoustic power:

$$P_{ac} = (1/60\pi\rho_0 c^5) [(d^3 Q_{kk}/dt^3)^2 + 2(d^3 Q_{ij}/dt^3)(d^3 Q_{ij}/dt^3)]$$

### 5.3 Trace Elimination

For an isolated binary system conserving total mass, the monopole moment (the trace  $Q_{kk}$ ) is constant to leading order. Its third time derivative vanishes. The trace-squared term drops out:

$$P_{ac} = (1/30\pi\rho_0 c^5) (d^3 Q_{ij}/dt^3)(d^3 Q_{ij}/dt^3)$$

Mass conservation eliminates monopole radiation. Momentum conservation eliminates dipole radiation. The surviving radiation is quadrupolar. The resulting expression has the same mathematical structure as General Relativity's transverse-traceless quadrupole output. Whether this structural correspondence constitutes a full physical equivalence with the TT projection — particularly regarding polarisation content and angular distribution — is addressed in Section 5.6.

### 5.4 Comparison with General Relativity

The GR quadrupole formula (Peters, 1964) gives the gravitational radiation power as:

$$P_{GR} = (G/5c^5) \langle (d^3 Q_{ij}^{TT}/dt^3)(d^3 Q_{ij}^{TT}/dt^3) \rangle$$

Substituting  $G = K/(4\pi\rho_0)$ :

$$P_{GR} = (K/20\pi\rho_0 c^5) \langle (d^3 Q_{ij}/dt^3)(d^3 Q_{ij}/dt^3) \rangle$$

Comparing the acoustic and GR expressions:

$$P_{ac}/P_{GR} = (1/30\pi) / (K/20\pi) = 2/3K$$

Setting  $P_{ac} = P_{GR}$  requires  $K = 2/3$ . The structural form of the two expressions is identical: both depend on the third time derivative of the quadrupole moment squared, both scale with  $c^{-5}$ , and both carry the same mass, orbital parameter, and eccentricity dependence. The coefficient equality is obtained under the identification  $G = K/(4\pi\rho_0)$  with  $K = 2/3$ , a standard geometric factor in continuum mechanics.  $K$  is not a free parameter tuned to observational data — it is the coupling constant between

the macroscopic observable  $G$  and the microscopic vacuum density  $\rho_0$ , absorbed into every empirical measurement of  $G$ :

$$G = 1 / (6\pi\rho_0)$$

No observation can independently distinguish  $K = 2/3$  from any other value, because  $G$  is always measured with  $K$  already absorbed. The factor refines the predicted vacuum density, not any observable quantity.

## 5.5 The Hulse-Taylor Binary Pulsar

PSR B1913+16 provides the most precise test of gravitational radiation energy loss in physics. The system parameters are:  $m_1 = 1.4408 M_\odot$ ,  $m_2 = 1.3886 M_\odot$ , orbital period  $P = 27906.98$  s, eccentricity  $e = 0.6171334$ . The observed orbital period derivative is  $dP/dt = -2.423 \times 10^{-12}$  s/s. After correcting for galactic acceleration, the GR prediction is  $-2.4025 \times 10^{-12}$  s/s. Agreement is within 0.2%.

The Hulse-Taylor measurement constrains total radiated power integrated over all solid angles. Since the acoustic quadrupole formula with  $K = 2/3$  reproduces the GR power formula in its entirety — same functional form, same dependence on all orbital parameters — it predicts the same orbital decay rate. This match is a necessary condition for viability and is now established.

## 5.6 Angular Distribution and Polarisation

While the total radiated power is identical between the acoustic and GR formulations, the angular distribution of that power is not. This difference constitutes the framework's sharpest falsifiable prediction.

The acoustic quadrupole radiates power predominantly in the orbital plane. For a circular binary in the  $xy$ -plane, the Lighthill formula yields an angular power distribution proportional to  $\sin^4\theta$ , where  $\theta$  is the polar angle from the orbital axis. Power vanishes along the orbital axis ( $\theta = 0$ ) and peaks in the equatorial plane ( $\theta = \pi/2$ ).

General Relativity's tensor quadrupole predicts a different pattern. The two GR polarisation modes ( $h_+$  and  $h_\times$ ) combine to give a total power distribution that peaks along the orbital axis and is minimised in the orbital plane. A detector viewing a binary

face-on (along the orbital axis) receives maximum signal in GR and minimum signal in the acoustic framework.

The total power integrated over all angles is the same in both cases — this is why the Hulse-Taylor calculation matches. But the directional distribution is qualitatively different. This has consequences for interferometric detection.

Current LIGO/Virgo observations cannot cleanly distinguish these angular patterns for most events, because the binary's inclination angle is not measured independently — it is inferred from the signal amplitude and waveform using General Relativity's antenna pattern as a template. If the underlying physics differs from GR, the same signal would be interpreted as a different inclination angle. There is a model dependence in current analyses that has not been resolved.

The exception is multi-messenger events where electromagnetic observations independently constrain the source geometry. GW170817 — the binary neutron star merger detected in both gravitational waves and across the electromagnetic spectrum — had its viewing angle independently constrained to approximately 20–30 degrees from face-on by jet observations and kilonova modelling. The gravitational wave signal was strong, consistent with GR's prediction that near-face-on binaries produce large signals. In the acoustic framework, a binary viewed at 20–30 degrees from the orbital axis would produce a significantly weaker signal than GR predicts, though not zero. This represents tension with the acoustic prediction, but the uncertainties in the independently measured inclination — and the fact that this is a single event — prevent definitive conclusions.

This angular distribution difference is the most discriminating near-term test of the framework. As the gravitational wave detector network expands — with LIGO-India, the Einstein Telescope, and Cosmic Explorer providing greater angular diversity — and as more multi-messenger events accumulate with independently measured inclination angles, a statistical analysis of detected signal amplitudes versus source geometry will be decisive. If the distribution follows GR's tensor pattern, the purely scalar acoustic hypothesis is falsified. If it follows the  $\sin^4\theta$  acoustic pattern, tensor gravity is falsified. The data will decide.

It should be noted that if the vacuum possesses internal degrees of freedom beyond scalar compressibility — as both Volovik's topological superfluid and Zlochastiev's

emergent metric programme suggest — then the radiation may carry transverse polarisation through collective modes of the vacuum’s order parameter, potentially reproducing GR’s angular pattern while retaining the pressure gradient as the mechanism for static gravity. The relationship between the static pressure gradient (which requires only scalar density) and the dynamic radiation pattern (which may require the vacuum’s full internal structure) is an open question of fundamental importance.

## **5.7 Limitations and Future Work**

This is a leading-order calculation. General Relativity’s prediction for the Hulse-Taylor pulsar includes post-Newtonian corrections — higher-order terms in  $v/c$  — up to 2.5 post-Newtonian order. These corrections are essential for accurate orbital phase matching in LIGO inspiral waveforms. Extending the acoustic calculation to the same post-Newtonian order is the highest-priority future calculation for this programme. The leading-order structural identity established here is a necessary condition for viability. It is not sufficient to claim full equivalence with GR’s radiative predictions.

The Lighthill formalism was derived for ordinary viscous fluids. A superfluid has no viscosity, which simplifies the calculation by eliminating dissipative terms. However, the retarded Green’s function for a superfluid may differ subtly from the ordinary fluid case. Verification by researchers working in superfluid acoustics would strengthen this result.

## **6. Variable Gravity: The Effective Metric**

A mass does not merely create a pressure gradient. It changes the local vacuum density. Changed density means changed sound speed. Changed sound speed means light bends, clocks run at different rates, and signals experience delays.

Since  $c^2_{\text{local}} = dP/d\rho$  evaluated at the local vacuum density near a mass, the propagation speed varies with position. A spatially varying propagation speed is mathematically equivalent to a spatially varying refractive index. Light passing through a region of reduced vacuum density follows a curved path — not because spacetime is curved, but because the medium’s properties vary, exactly as light curves when passing through glass of varying density.

This produces an effective metric identical to the Schwarzschild solution in the weak-field limit. Gravitational lensing is refraction. Time dilation is the slowing of all oscillatory processes in a region of altered propagation speed. The Shapiro delay is the increased transit time through a region of higher effective refractive index. The Pound-Rebka experiment measures the frequency shift of photons climbing out of a refractive index gradient.

Barceló, Liberati and Visser (2005) formalised this correspondence, demonstrating that any barotropic, irrotational, inviscid fluid flow produces an effective spacetime metric for acoustic perturbations. This correspondence is exact for linear perturbations in certain fluid configurations and does not by itself prove that spacetime is a fluid. It demonstrates that the mathematical structure of curved spacetime can emerge from fluid mechanics, and the present framework proposes that this emergence is physical rather than merely analogical.

## **7. Frame-Dragging: Superfluid Vorticity**

A static pressure deficit is spherically symmetric and cannot produce frame-dragging, which requires the surrounding medium to be dragged into co-rotation with a spinning mass. However, a rotating mass in this framework is not a static cavity. It is a rotating pattern of energy displacement.

A rotating body embedded in a superfluid creates quantised vortex lines. Superfluids cannot rotate continuously like normal fluids — they have no viscosity and cannot sustain shear. Instead, they nucleate arrays of quantised vortex filaments that collectively carry angular momentum through the medium. This is observed experimentally in superfluid helium and in Bose-Einstein condensates. Rotating the container does not spin the fluid smoothly; it generates a vortex lattice that mimics solid-body rotation.

A rotating mass in the superfluid vacuum would nucleate the same structures. The vortex lines carry angular momentum outward into the surrounding medium. Matter and light passing through this vortex-threaded region are carried along by the circulation. This is the effect General Relativity describes as frame-dragging — not spacetime geometry twisting, but the medium itself transporting angular momentum through quantised vorticity.

Gravity Probe B confirmed frame-dragging around Earth at 37 milliarcseconds per year. Quantitative prediction within this framework requires knowledge of the vacuum's vortex nucleation threshold, which is future work. The mechanism is grounded in established superfluid phenomenology and requires no additional postulates.

## **8. Dark Matter: The Long-Range Tail**

Galaxies rotate too fast. The outer stars in spiral galaxies orbit at speeds that should disperse them if the only gravity comes from visible matter. The rotation curves are flat where Newtonian gravity predicts they should decline. This observation, established by Rubin and Ford (1970) and confirmed for every galaxy measured since, is among the most robust in astrophysics.

The standard interpretation — dark matter — assumes that invisible massive particles provide the additional gravitational effect. Despite decades of direct detection experiments and collider searches, no dark matter particle has been found.

The entire dark matter hypothesis rests on a single premise: that space is empty. Stars are objects moving through a void, held in orbit solely by the gravitational pull of visible matter interior to their orbit. If visible mass is insufficient, invisible mass is required. Remove the premise, and the requirement dissolves.

If space is a medium, objects embedded in it are coupled to the medium. The medium has its own pressure, density, and dynamical response. A galaxy in a superfluid vacuum is a structure *in* a medium, not a collection of independent objects orbiting through nothing. The medium's pressure gradient, shaped by the collective energy displacement of the entire galaxy, governs the dynamics at all radii.

If the vacuum's equation of state includes logarithmic corrections — as Zloshchastiev's logarithmic superfluid predicts — the pressure gradient does not fall off as pure  $1/r^2$  at galactic scales. It retains a long-range tail. Stars at the galactic edge experience more inward pressure than Newtonian gravity predicts, not because invisible matter is present, but because the medium's response extends further than a point-source model assumes. Zloshchastiev (2020) published galaxy rotation curve fits using this

mechanism, obtaining agreement with observed flat rotation curves without dark matter particles.

*The galactic rotation anomaly is an artefact of applying vacuum dynamics to a medium.*

## **9. Dark Energy: Residual Vacuum Tension**

The universe's expansion is accelerating (Riess et al., 1998; Perlmutter et al., 1999). The standard interpretation attributes this to a cosmological constant  $\Lambda$  — an intrinsic energy density of empty space acting as negative pressure. Nobody knows why the vacuum should have this energy density, or why it has the specific value observed. Naive quantum field theory estimates exceed the observed value by approximately 120 orders of magnitude.

In the present framework, the vacuum is a thermodynamic system with an equation of state. If it is not perfectly at equilibrium — carrying a residual tension from whatever process created or shaped it — that tension acts as negative pressure driving expansion. The vacuum is slowly relaxing toward equilibrium, and the current epoch falls during that relaxation.

This reframes the cosmological constant problem. The question is not why  $\Lambda$  has its value, but how far the vacuum has relaxed toward equilibrium and what determines the relaxation timescale. The “cosmological constant” may not be constant at all but slowly evolving — a prediction distinguishable from  $\Lambda$ CDM through precision cosmological measurements. Zloshchastiev's logarithmic equation of state resolves this naturally through the Gibbs-Duhem relation, which constrains the vacuum's pressure and energy density simultaneously.

## **10. Electromagnetism: The Second Mode**

Electromagnetic phenomena represent a second class of vacuum excitation, already fully described by Maxwell's equations. The identification of  $\epsilon_0$  and  $\mu_0$  as mechanical properties of the vacuum medium places electromagnetism within the same physical substrate as gravity.

Both are pressure gradient phenomena. Gravity operates through gradients in the vacuum's energy density. Electromagnetism operates through gradients in the vacuum's permittivity and permeability. Voltage is pressure — not by analogy but by definition: energy per unit charge, force per unit charge over distance. Current flows from high voltage to low voltage as fluid flows from high pressure to low pressure. The hydraulic analogy taught in introductory circuit theory works because it describes the same physics in the same medium.

This framework does not unify gravity and electromagnetism. It identifies their shared medium. Maxwell already provided the complete mathematical description of the electromagnetic mode. The present contribution answers the question Maxwell himself posed: what is the medium whose properties  $\epsilon_0$  and  $\mu_0$  determine the speed of light? It is the same superfluid vacuum whose pressure gradients produce gravity. Formal unification — explaining why one manifests as spin-1 and the other as quadrupolar radiation — remains open. The claim here is limited and defensible: they share a substrate.

## 11. Falsifiable Predictions

A framework that explains everything predicts nothing. The following predictions distinguish this model from General Relativity and are testable with current or near-future technology.

**Angular distribution of gravitational radiation.** This is the framework's sharpest near-term prediction. The acoustic quadrupole radiates power predominantly in the orbital plane ( $\sin^4\theta$ ), while GR's tensor quadrupole radiates predominantly along the orbital axis. For multi-messenger events where the source inclination is independently constrained by electromagnetic observations, the distribution of detected gravitational wave amplitudes as a function of viewing angle will follow one pattern or the other. A statistical analysis across many events with independently measured inclinations — enabled by the expanding detector network — will be decisive. This test requires no new technology, only more events and more detectors.

**Gravitational wave dispersion at high frequency.** An acoustic medium has a microscopic structure imposing a cutoff frequency where the continuum

approximation breaks down. General Relativity predicts gravitational waves are non-dispersive at all frequencies. If the vacuum is a medium, gravitational waves at sufficiently high frequency should show dispersion — a frequency-dependent propagation speed detectable in binary merger signals.

**Modified gravity at galactic scales without dark matter particles.** The framework predicts that galaxy rotation curves are explained by the vacuum's equation of state, not by invisible particles. Continued null results from direct detection experiments (LZ, XENONnT, DARWIN) would be consistent. A positive detection of a dark matter particle would falsify this prediction.

**Anomalous orbital velocities in wide binary stars.** The logarithmic correction to the vacuum's pressure gradient predicts deviation from strict  $1/r^2$  Newtonian gravity at specific macroscopic scales. Precision astrometry of ultra-wide binary star systems using European Space Agency Gaia data should reveal slight anomalous orbital velocities matching the theoretical logarithmic coefficient. This test is achievable with existing data.

**Gravitational wave echoes from compact objects.** If the vacuum is a superfluid, extreme density gradients near compact objects may produce a phase boundary rather than a classical event horizon. Gravitational waves reflecting from this boundary would produce post-merger echoes at specific time delays. Tentative evidence has been reported (Abedi, Dykaar and Afshordi, 2017), though statistical significance remains debated.

**Casimir force variation in different gravitational potentials.** If the vacuum is a compressible medium rather than an invariant quantum field, its local properties should vary with the ambient gravitational potential. The Casimir force between conducting plates measured in deep space should differ minutely from the same measurement conducted on Earth's surface. This contradicts the standard assumption of invariant vacuum zero-point energy and is in principle testable with precision experiments at different altitudes or orbital positions.

**Dark energy evolution.** If the cosmological “constant” is a residual vacuum tension rather than a fundamental constant, it may be slowly evolving. Precision measurements of the dark energy equation of state parameter  $w$  and its time derivative

by surveys such as DESI, Euclid, and the Vera Rubin Observatory could detect departure from  $w = -1$ , consistent with this prediction.

**Speed of gravity in extreme environments.** In General Relativity, gravitational waves travel at exactly  $c$  by construction. In this framework, both light and gravitational disturbances propagate at the local sound speed of the vacuum. In regions of extreme density variation — near neutron stars or black hole candidates — the local speed may differ from the flat-space value. A measurable difference in arrival times of gravitational and electromagnetic signals from the same event would test this prediction.

## 12. Open Problems

Intellectual honesty requires explicit acknowledgement of what the framework does not yet explain. The following problems are open and their resolution is not guaranteed.

**Spin-2 mode identification.** LIGO has detected gravitational waves with tensor polarisation — two transverse modes ( $h_+$  and  $h_\times$ ) consistent with a spin-2 field. The Lighthill calculation in Section 5 produces scalar pressure waves with quadrupolar source geometry. The total radiated power matches, but the angular distribution and polarisation content differ. Section 5.6 identifies the vacuum’s internal degrees of freedom as the mechanism that could produce transverse modes, and both Volovik’s topological superfluid and recent experimental observation of chiral graviton modes in fractional quantum Hall systems establish that condensed matter systems can host spin-2 physics. However, the specific propagating spin-2 collective mode within the vacuum’s order parameter has not been identified. This is the framework’s most important open theoretical problem.

**Post-Newtonian extension.** The gravitational radiation calculation matches the Peters (1964) formula at leading order. General Relativity’s prediction for the Hulse-Taylor pulsar and for LIGO inspiral waveforms includes corrections up to 2.5 post-Newtonian order in  $v/c$ . Extending the acoustic calculation to the same order is essential for quantitative comparison with LIGO phase data and is the highest-priority future calculation.

**Phase locking.** For gravity to be universally attractive, the pressure deficit mechanism requires all matter to couple coherently to the vacuum medium. While Section 4 derives gravity from pressure gradients without requiring oscillatory phase coherence, the deeper question of how approximately  $10^{80}$  particles maintain coherent coupling to a single medium has not been derived from first principles. The Kuramoto model of coupled oscillators provides a mathematical framework for synchronisation, but the physical mechanism in the vacuum context remains unspecified.

**Absolute mass scale.** The framework explains why particles have discrete masses (resonance conditions in the medium) 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. This requires knowledge of the vacuum’s microscopic density and equation of state that is not currently available.

**Full inspiral-merger-ringdown waveform.** A complete waveform template derived from superfluid vacuum dynamics — covering the inspiral, merger and ringdown phases of a binary coalescence — has not been calculated. This would require numerical simulation of interacting energy configurations in a compressible superfluid medium and is computationally demanding.

**Vacuum equation of state.** Multiple equations of state can produce the same effective metric at leading order. The gravitational mechanism depends only on the vacuum being a medium with sound speed  $c$ , but the dark matter and dark energy predictions (Sections 8 and 9) depend on the specific equation of state. Zloshchastiev’s logarithmic superfluid and Volovik’s  $^3\text{He-A}$  universality class may represent complementary descriptions, but uniquely determining the vacuum’s equation of state from gravitational observations alone may not be possible — an inherent degeneracy that limits the framework’s predictive specificity at cosmological scales.

### **13. Relationship to Existing Work**

This framework builds on and extends several established research programmes.

**Analogue gravity** (Unruh, 1981; Barceló, Liberati and Visser, 2005). The mathematical correspondence between fluid mechanics and curved spacetime is

established for linear perturbations in certain fluid configurations. Acoustic metrics in moving fluids reproduce the Schwarzschild geometry, Hawking radiation analogues, and ergoregion effects. This correspondence demonstrates that curved spacetime geometry can emerge from fluid mechanics. The present paper proposes that this emergence is physical: the vacuum is the fluid, and the acoustic metric reflects the physical propagation conditions of the medium.

**Volovik's  $^3\text{He-A}$  programme** (Volovik, 2003). Superfluid helium-3 A-phase demonstrates that a quantum liquid with a chiral order parameter can produce emergent Lorentz invariance, gauge fields, gravity, and chiral fermions as collective phenomena. The present framework adopts the physical conclusion — that the vacuum belongs to the universality class of such quantum liquids — without committing to the Fermi liquid specifics. Volovik's demonstration that transverse collective modes in topological superfluids can carry spin-2 characteristics is particularly relevant to the polarisation question raised in Section 5.6.

**Zloshchastiev's logarithmic superfluid** (Zloshchastiev, 2011, 2020, 2023). The Logarithmic Schrödinger Equation provides a rigorous equation of state for a superfluid vacuum, derives a density-independent sound speed, resolves the cosmological constant via the Gibbs-Duhem relation, and fits galaxy rotation curves. The present paper shares these thermodynamic foundations and draws on them for Sections 8 and 9. However, a substantive divergence exists regarding the nature of the effective metric. Zloshchastiev's programme derives an emergent pseudo-Riemannian metric tensor from the superfluid dynamics, treating this metric as a genuine geometric structure induced by the quantum liquid. The present paper takes a different position, treating the effective geometry as refractive index variation in a medium rather than genuine spacetime curvature. This is an honest disagreement, not a contradiction in the cited literature: both frameworks share the same thermodynamic substrate but differ on the ontological status of the emergent metric. If the metric possesses independent dynamical degrees of freedom beyond what refractive index variation produces, strong-field observations will reveal the difference. The acoustic quadrupole calculation presented here and the emergent metric programme are complementary approaches, and the relationship between them — particularly regarding gravitational wave polarisation — is an open question of significant importance.

**Lighthill aeroacoustics** (Lighthill, 1952). The acoustic quadrupole radiation formula, developed for jet noise analysis, provides the mathematical framework for computing gravitational radiation power in this model. The application of Lighthill's formalism to gravitational physics appears to be novel.

**Modified gravity and MOND** (Milgrom, 1983). MOND modifies Newton's law below a critical acceleration scale. The present framework predicts modified gravity at galactic scales from the vacuum's equation of state, which may reproduce MOND phenomenology as an effective description. The relationship between the logarithmic correction and Milgrom's acceleration scale is an open question.

## 14. Conclusion

The vacuum is a medium. Matter is energy reconfigured within that medium. Gravity is the medium's pressure response to the resulting energy deficit.

These statements, combined with standard fluid mechanics and thermodynamics, reproduce Newtonian gravity, weak-field General Relativity, and the total gravitational radiation power measured by the Hulse-Taylor binary pulsar. Dark matter is reinterpreted as a long-range tail in the vacuum's pressure gradient. Dark energy is residual vacuum tension. Electromagnetism is a second excitation mode of the same medium. Frame-dragging is superfluid vorticity. The speed of light is the sound speed of the vacuum.

The framework makes specific, falsifiable predictions that distinguish it from General Relativity. The sharpest is the angular distribution of gravitational radiation: the acoustic quadrupole predicts power concentrated in the orbital plane, while GR's tensor quadrupole predicts power concentrated along the orbital axis. Multi-messenger gravitational wave observations with independently measured source geometries will be decisive. If the vacuum possesses internal degrees of freedom supporting transverse modes — as both Volovik's and Zlochastiev's programmes suggest — the radiation may carry tensor-like polarisation while retaining the pressure gradient as the mechanism for static gravity. Resolving this question is the framework's most important open problem.

The framework is quantitative, falsifiable, and grounded in established principles of continuum mechanics, thermodynamics, and acoustic radiation theory. It proposes no new particles, no extra dimensions, and no modifications to observed physics. It proposes only that the vacuum is a physical medium — a proposition supported by the Casimir effect, by Maxwell’s identification of vacuum permittivity and permeability, and by the entire analogue gravity programme.

General Relativity describes how spacetime geometry responds to matter. This framework describes *why*: the geometry that matter appears to curve is the pressure field of the medium in which matter exists. The equations are the same. The understanding is different.

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