Gravitational Pressure Model—–The "Rippling Universe" and Its Observable Evidence

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Abstract

General relativity faces fundamental conceptual and theoretical challenges in explaining dark matter, dark energy, and black hole singularities. This paper proposes a new paradigm termed the "Gravitational Pressure Model" that seeks to provide a unified resolution to these issues. The model postulates the existence of a dark matter superfluid background (Ψ-medium) as a fundamental physical entity in the universe. We argue that spacetime geometry is not fundamental, but rather an emergent collective variable of the macroscopic quantum state of the Ψ-medium; and that gravity is an emergent force experienced by objects within the stress gradient field of this medium. This framework can precisely reproduce all successful predictions of general relativity and Newtonian gravity in the low-energy limit. More importantly, based on the microscopic properties of the medium, the model puts forward three distinctive predictions testable in next-generation experiments: (1) the energy dispersion relation of high-energy gravitational waves; (2) tiny corrections to the Hubble expansion history of the late-time universe; (3) possible extremely weak violations of the equivalence principle between different matter components. This model reinterprets black holes as extreme physical phases of the medium, thereby offering a novel physical picture for resolving the singularity problem and information paradox.

Full Text

Preamble

Gravitational Pressure Model – "The Rippling Universe" and Its Observable Evidence

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Abstract: General relativity faces fundamental conceptual and theoretical challenges in explaining dark matter, dark energy, and black hole singularities. This paper proposes a new paradigm called the "Gravitational Pressure Model" that attempts to provide a unified solution to these problems. The model postulates the existence of a dark matter superfluid background (Ψ-medium) as a fundamental physical entity in the universe. We argue that spacetime geometry is not fundamental but rather an emergent collective variable of the macroscopic quantum state of the Ψ-medium; gravity, in turn, is an emergent force experienced by objects within the stress gradient field of this medium. This framework can precisely reproduce all successful predictions of general relativity and Newtonian gravity in the low-energy limit. More importantly, based on the microscopic properties of the medium, the model proposes three unique predictions testable in next-generation experiments: (1) energy dispersion relations for high-energy gravitational waves; (2) tiny corrections to the Hubble expansion history of the late universe; and (3) extremely weak violations of the equivalence principle between different types of matter. The model reinterprets black holes as limiting physical phases of the medium, thereby providing a novel physical picture for resolving the singularity problem and information paradox.

Keywords: emergent gravity, dark matter superfluid, gravitational pressure model, Ψ-medium, testable predictions, black hole information paradox

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1. Introduction: Toward an Emergent Paradigm of Gravity

The success of general relativity is undeniable, yet its geometric interpretation reifies spacetime itself, facing ontological circularity at the conceptual level and leading to insurmountable divergences in quantization at the technical level. A fundamental question arises: if spacetime does not "exist" fundamentally but rather "emerges," where does it come from?

This paper develops an alternative framework based on matter interactions, whose core thesis is that the spacetime geometry we perceive is a collective manifestation of the macroscopic quantum state of a dark matter superfluid (Ψ-medium) at cosmic scales. The model rests on three foundational principles:

1.1 Medium Ontology Principle

The Ψ-medium is a physical entity whose ground state constitutes the quantum vacuum, and its inertia (i.e., coupling to the metric) is defined by this medium.

1.2 Induced Geometry Principle

The stress-energy of visible matter perturbs the equilibrium state of the medium, and this perturbed state is precisely characterized by an emergent effective metric $g_{\mu\nu}$, namely the stress operator of the medium.

1.3 Dynamics Emergence Principle

The dynamical laws of the effective metric $g_{\mu\nu}$ constitute the low-energy effective theory of the Ψ-medium in the long-wavelength limit, rather than fundamental laws.

2.1 Microscopic Description and Induced Metric

We assume the Ψ-medium can be described by a relativistic quantum field theory defined on a microscopically flat background $\eta_{\mu\nu}$. The visible matter field ϕ_{vis} couples to the medium field Ξ through a tiny interaction term $\mathcal{L}_{\text{int}}$:

$$\mathcal{L}_{\text{int}} = \lambda \int d^{4x}\, \phi_{\text{vis}}(x)\mathcal{O}(x)\Xi(x)$$

where $\mathcal{O}$ is the corresponding operator. By integrating out the medium degrees of freedom via path integration, we obtain an effective action for the visible matter:

$$S_{\text{eff}}[\phi_{\text{vis}}] = S_{\text{vis}}[\phi_{\text{vis}}] + \Gamma[g_{\mu\nu}]$$

The key step is that we define the emergent metric $g_{\mu\nu}$ as a functional of the expectation value of the medium' s stress tensor:

$$g_{\mu\nu} \equiv \eta_{\mu\nu} + \frac{\lambda}{\rho_{\text{DM}}}\langle T^{\Xi}_{\mu\nu}\rangle$$

After integrating out the medium field, the effective action is rewritten as the visible matter action in this emergent metric $g_{\mu\nu}$:

$$S_{\text{eff}}[\phi_{\text{vis}}; g_{\mu\nu}] = S_{\text{vis}}[\phi_{\text{vis}}, g_{\mu\nu}] + \Gamma[g_{\mu\nu}]$$

where $\Gamma[g]$ is the quantum effective action of the medium.

2.2 Einstein Equations as Low-Energy Equation of State

We assume the Ψ-medium is a quantum phase in topological order, whose long-wavelength, low-energy dynamics is dominated by massless spin-2 excitations. Under this assumption, its quantum effective action $\Gamma[g]$ must take the Einstein-Hilbert form at the lowest order of the derivative expansion:

$$\Gamma[g] = \frac{1}{16\pi G_N} \int d^{4x} \sqrt{-g}(R - 2\Lambda)$$

where Λ is the ground state energy of the medium (i.e., dark energy). By varying the total effective action S_{eff}, we obtain the emergent Einstein field equations:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G_N T^{\text{vis}}_{\mu\nu}$$

Thus, the core equations of general relativity emerge as an emergent, macroscopic "equation of state."

2.3 Newtonian Limit and Pressure Gradient Force

In the static weak-field approximation, $g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu}$. In our framework, the Newtonian potential Φ is directly related to pressure perturbations δP within the medium:

$$\Phi = \frac{\delta P}{\rho_{\text{DM}}}$$

where ρ_{DM} is the static mass density of the medium. The equation of motion for test particles $\ddot{\mathbf{x}} = -\nabla\Phi$ is therefore interpreted as a net force in the medium' s pressure gradient field: $\mathbf{F} = -(m/\rho_{\text{DM}})\nabla(\delta P)$. Inertia corresponds to the symmetry of pressure distribution when moving uniformly through a homogeneous medium.

3. Correspondence Principle with Classical Gravitational Theories

To establish the reliability of this framework, we first demonstrate that under appropriate limits, it can fully reproduce all classical predictions of general relativity (GR) and Newtonian gravity that have been repeatedly verified experimentally.

3.1 Exact Reproduction of Newton' s Law of Universal Gravitation

Under static, weak-field, and low-velocity conditions, the reduction path of our model proceeds as follows: **Reduction of field equations:** In static conditions, our model's core field equations reduce to Laplace's equation $\nabla^2\Phi = 0$ in vacuum and Poisson' s equation $\nabla^2\Phi = 4\pi G_N \rho_{\text{vis}}$ in the presence of sources. This is completely consistent with the field equations for Newtonian gravitational potential. **Reduction of equations of motion:** As described in Section 2.3, the equation of motion for test particles manifests as $\mathbf{a} = -\nabla\Phi$, directly corresponding to Newton' s second law in a gravitational field. **Interpretation of Newton' s constant:** The emergent Newtonian constant G_N is explicitly expressed as a composite constant related to the fundamental properties of the Ψ-medium:

$$G_N = \frac{\lambda^2}{K\rho_{\text{DM}}}$$

where K is the bulk modulus of the medium, λ is the coupling constant, and ρ_{DM} is the medium density. This does not affect its constant value at low energies but provides a physical explanation for its origin. Therefore, in all scenarios where Newtonian gravity applies—such as planetary orbits and terrestrial gravity—this model is mathematically and observationally equivalent to Newtonian theory.

3.2 Passing Classical Tests of General Relativity

Our framework naturally inherits all successes of GR through its emergent Einstein field equations. The following illustrates this through GR' s three classic tests: **Gravitational redshift:** The gravitational time dilation effect predicted by GR is reproduced by the emergent metric $g_{00} = 1 + 2\Phi/c^2$, yielding identical predictions. **Light deflection:** The bending angle of light passing near the Sun, $\Delta\phi = 4GM/(c^2R)$, is derived from null geodesics in the emergent metric, matching GR' s prediction. **Perihelion precession:** The anomalous precession of Mercury' s orbit, $43''$ per century, is obtained by solving the geodesic equation in the post-Newtonian expansion of our model, identical to GR' s result.

3.3 Compatibility with Modern Precision Observations

This model is also compatible with more modern GR validations: **Shapiro time delay:** The time delay of radar echoes in gravitational fields is determined by null geodesics of the emergent metric, consistent with GR predictions. **Geodetic effect and frame-dragging:** Measurements from the GP-B satellite and other experiments of geodetic precession and frame-dragging verify GR' s predictions at higher-order approximations. In our model, these effects are interpreted as the response of test objects in a moving medium background (dragged by rotating masses), with the same geodesic equation governing motion, thus yielding identical predictions. **Gravitational waves:** Starting from linearized Einstein field equations, our model also predicts transverse tensor perturbations propagating at the speed of light, with the same quadrupole formula as GR, completely consistent with black hole merger events observed by LIGO/Virgo.

Summary: This framework becomes a theory empirically equivalent to GR by emergently producing the same metric $g_{\mu\nu}$ and dynamical equations in the low-energy, weak-field limit. It not only covers all of GR’ s successes but, more importantly, provides a different physical ontology underlying these achievements—gravity is not geometry but arises from interactions within a dark matter superfluid medium.

4. Unique Predictions and Quantifiable Test Paths

The equivalence between this model and GR is a conclusion of the low-energy approximation. The microscopic structure of the Ψ-medium manifests at the Planck scale Λ_{DM}, leading to observable deviations from GR.

4.1 Gravitational Wave Dispersion Relations

In energy regions above Λ_{DM}, gravitons as quasiparticles may exhibit dispersion, modifying their propagation: $\omega^2 \approx c^2k^2 + \xi(k/\Lambda_{\text{DM}})^2$. The sign and magnitude of parameter ξ serve as a fingerprint of the model and can be constrained through future space-based gravitational wave detectors (such as LISA) observing intermediate-mass black hole merger events.

4.2 Modified Cosmological Expansion History

The equation of state of the Ψ-medium may deviate from $w = -1$ under early-universe high-energy conditions, leading to a modified Hubble expansion rate $H(z)$. This can be probed through next-generation cosmological observations (such as the Euclid satellite and SKA radio array) via precision measurements of baryon acoustic oscillations and weak gravitational lensing.

4.3 Potential Violation of the Equivalence Principle

Coupling strengths between different components of visible matter and the Ψ-medium may exhibit tiny differences at the part-per-million level, leading to weak equivalence principle violations. This can be tested through follow-up missions to MICROSCOPE or ultra-high-precision atom interferometer experiments.

5.1 Superfluidity and Dissipation

We propose that the superfluid order parameter of the Ψ-medium is coherent on cosmological scales. Uniform motion of celestial bodies does not excite dissipative quasiparticles (such as rotons) because their velocities are far below the Landau critical velocity $v_c \sim \min(\Delta/p)$, where Δ is the energy gap of the medium. For extreme celestial objects (such as rapidly rotating neutron stars), approaching v_c may produce observable dissipative effects.

5.2 Lorentz Invariance

The ground state of the medium is Lorentz invariant. The emergent metric $g_{\mu\nu}$ reduces to $\eta_{\mu\nu}$ in the absence of matter perturbations. Any potential Lorentz-violating operators are suppressed by the energy gap Δ at low energies, consistent with existing stringent constraints.

5.3 Quantization Pathway

This framework provides a natural background-dependent perturbative scheme for quantum gravity. On a fixed medium background $\eta_{\mu\nu}$, standard quantization can be performed on metric fluctuations $h_{\mu\nu}$, with the graviton as a spin-2 quasiparticle of the Ψ-medium. The UV divergence problem is naturally cut off by the medium' s microscopic physics at the scale Λ_{DM}.

6. Toward Quantum Gravity: A Novel Resolution to Black Hole Puzzles

Black holes, as the most extreme predictions of general relativity, become sites where the theory breaks down, spawning some of the most fundamental puzzles in modern physics. The "Dark Matter Pressure Model" (i.e., the Ψ-medium model) provides a fresh and unified perspective on these problems by redefining the nature of gravity.

6.1 From Spacetime Singularities to Medium Limiting States: Dissolving the Singularity Problem

General relativity predicts a "singularity" of infinite density and spacetime curvature at black hole centers, where all physical laws fail—marking the collapse of classical gravitational theory.

Traditional dilemma: Whether string theory, loop quantum gravity, or recent schemes attempting to produce "regular black holes" through higher-order pure gravity corrections, one core goal is eliminating this unpleasant singularity.

Model resolution: Within the dark matter pressure model framework, the singularity problem is naturally dissolved. A black hole is not a monster compressing matter to an infinitesimal point. Instead, it is a celestial object whose gravity is so strong that it compresses the surrounding Ψ-medium to a limiting state.

One can imagine that as matter collapses, the compression of the Ψ-medium approaches a critical point. At this juncture, the medium itself generates enormous, nonlinear internal pressure (or quantum effects) to resist further compression.

Therefore, the black hole center is not a mathematical singularity but a bounded, extremely dense core composed of Ψ-medium in a new state of matter. This avoids infinities, aligning in spirit with current quantum gravity research directions attempting to resolve singularity issues.

Theoretical advantage: This picture transforms the black hole from a geometric monster that invalidates physics into a physical phase of cosmic medium under extreme conditions, fundamentally removing the singularity.

6.2 Information Paradox and Rescue of Quantum Unitarity

Hawking radiation' s "information paradox" sharply highlights the deep contradiction between general relativity and quantum mechanics.

Traditional dilemma: According to Hawking' s calculations, black hole evaporation leads to permanent loss of information about infalling matter, violating the "unitarity" principle of quantum mechanics requiring information conservation. Recent research using concepts like "Quantum Extremal Surfaces" has theoretically inclined toward information conservation, but the specific physical mechanism remains to be elucidated.

Model resolution: The model provides an intuitive physical carrier for information conservation. Without singularities, information of infalling matter is not destroyed. During infall, through its mass and energy, matter creates specific perturbation patterns in the Ψ-medium, which can be encoded or stored in the structure of the medium core inside the black hole.

During Hawking evaporation, as the black hole mass decreases, the state of the medium core evolves accordingly. Previously encoded information can be gradually released to the external universe through Hawking radiation (interpretable as quantum or thermodynamic fluctuations near the event horizon, this "critical pressure surface").

Theoretical advantage: This picture naturally maintains quantum unitarity without introducing unresolved assumptions, offering a physically intuitive solution to the information paradox.

6.3 Physical Picture of Event Horizons and Black Hole Thermodynamics

The dark matter pressure model also provides clearer physical interpretations for event horizons and black hole thermodynamics.

New interpretation of event horizons: The event horizon is no longer an abstract geometric boundary of "no return." In the model, it is the surface where the Ψ-medium' s pressure gradient reaches a critical value. On this surface, the "effective gravity" produced by the pressure gradient is so strong that even light cannot escape. It can be regarded as a phase transition boundary of the medium from an escapable phase to an inescapable phase.

Emergence of thermodynamics: The thermodynamic properties of black holes—temperature and entropy—can be understood in this model as macroscopic emergent phenomena from microscopic quantum fluctuations and statistical behavior of the Ψ-medium near this critical surface. This aligns with mainstream theories linking black hole entropy to horizon area but provides a different physical foundation—entropy is associated with the number of microscopic states of the medium.

6.4 Dialogue and Transcendence with Contemporary Quantum Gravity Research

The dark matter pressure model resonates with multiple frontier efforts in quantum gravity and demonstrates unique simplicity and unity.

Resonance with "regular black hole" research: The model intrinsically predicts black holes without singularities, consistent with research goals of constructing "regular black holes"through quantum gravity corrections, but provides a more fundamental physical mechanism (medium pressure) rather than pure mathematical modification.

Providing a potential quantization path: String theory unifies all forces and matter through extra dimensions and one-dimensional string vibrations; loop quantum gravity attempts to directly quantize spacetime geometry itself. Both paths are exceptionally complex and face experimental verification challenges. The dark matter pressure model takes a different approach: if gravity is an excitation propagating on the Ψ-medium background (analogous to phonons), then quantizing gravity transforms into quantizing excitations on this background. This bypasses the difficulty of directly quantizing spacetime geometry and may be a more technically feasible path.

Through its fresh examination of black hole puzzles, the "dark matter pressure model" demonstrates extraordinary potential as a candidate quantum gravity theory: it physically eliminates singularities by introducing medium limiting states; it resolves the information paradox through information encoding and release in the medium core structure; and it reduces event horizons and black hole thermodynamics to more fundamental medium critical behavior and statistical physics.

7. Toward a Dynamic Universe: Dark Matter Ripples and the Fate of the Cosmos

The preceding chapters constructed a theoretical framework unifying gravity, dark matter, and dark energy within the Ψ-medium. However, a complete cosmological theory must answer not only "what the universe is" but also "why it evolves as it does."

This chapter proposes the "dark matter ripples" model, elevating the static medium picture to an intrinsically dynamic system, aiming to provide a novel, self-consistent dynamical mechanism for cosmic expansion, structure formation, and ultimate fate.

7.1 From Static Geometry to Dynamic Medium: The Necessity of Paradigm Shift

The standard cosmological model (ΛCDM) attributes cosmic expansion to an eternal, unchanging cosmological constant Λ. While enormously successful, its core harbors profound physical dilemmas:

The cosmological constant problem: Quantum field theory predictions for vacuum energy density differ from observed values by more than 60 orders of magnitude, representing one of physics' most severe fine-tuning problems.

Absence of dynamics: Λ as a static background cannot explain why the universe transitioned from decelerating to accelerating expansion, nor provide possible dynamic correlations between cosmic evolution and matter distribution.

This model proposes that what drives cosmic evolution is not an abstract constant but the dynamic processes of the cosmic background entity itself—the Ψ-medium. We vividly term this process "dark matter ripples," representing the medium' s own grand, cosmic-scale density fluctuations or volume oscillations.

7.2 Dual-Engine Driving Mechanism of Ripples

The "ripples" are not sourceless; their power originates from an exquisite "dual-engine" system that tightly couples the medium' s intrinsic properties with feedback from cosmic contents.

Engine One: Natural Frequency ("The Universe' s Heartbeat") The Ψ-medium, as a fundamental physical entity, possesses one or more characteristic frequencies or eigenmodes determined by its microscopic structure or intrinsic quantum field-theoretic properties. This natural frequency is an inherent property of the medium, independent of matter' s existence.

Physical connotation: This can be analogized to an enormous, elastic cosmic "drumhead" with specific vibrational modes. These vibrations originate from quantum fluctuations in the medium' s ground state or some yet-to-be-revealed self-interaction.

Cosmological role: This natural vibration is the initial driving force and fundamental rhythm of cosmic expansion. It drives the universe' s most basic background expansion-contraction motion. The accelerating expansion we currently observe may correspond to an extremely long "expansion phase."

Engine Two: Gravitational Squeezing ("Matter Feedback") Matter in the universe (visible matter) continuously squeezes and perturbs the Ψ-medium through its gravity. This squeezing is not a passive background but an active feedback mechanism driving ripple evolution.

Physical connotation: During structure formation (galaxies, clusters) under gravitational collapse, enormous gravitational potential energy is released. This energy does not disappear but is transferred and stored in the compressed Ψ-medium.

Cosmological role: Gravitational squeezing achieves two key functions: **Energy injection:** Provides a continuous energy source for the universe's "ripples," sustaining its dynamical process. **Mode modulation:** The inhomogeneity of matter distribution, like countless stones thrown into water, excites specific ripples in the medium, modulating the fundamental ripple pattern and creating profound dynamical correlations between cosmic expansion history and internal structure formation.

These two engines work together, forming a self-consistent feedback system: the medium' s natural vibrations set the basic rhythm for cosmic evolution, while matter' s gravitational feedback injects energy into this process and modulates its details, jointly composing the dynamical epic of the universe.

7.3 The Nature of Time: From Geometric Parameter to Intrinsic Measure of Medium Evolution

In general relativity, time is a dimension of spacetime geometry, but its intrinsic nature and origin remain unanswered by the theory itself. Our model provides an answer based on physical entities:

Time is the measure of sequence and rhythm in the internal state evolution of the Ψ-medium.

From background to process: Time is no longer an abstract stage for events but the medium' s dynamical process itself. Just as sound is the process of air vibration rather than an entity, time is the process of "state change" of the Ψ-medium.

Origin of time' s arrow: The irreversibility of past and future (time' s arrow) is not an initial condition but directly stems from the intrinsic irreversibility of Ψ-medium dynamics. The medium's one-way relaxation from a non-equilibrium state (such as a highly coherent, low-entropy "ripple" starting point) toward global equilibrium provides the universe' s most fundamental direction of time. Local entropy increase laws are the inevitable result of this macroscopic dynamical arrow.

7.4 Redefinition of Entropy: From Information Abstraction to Function of Medium State

In standard thermodynamics, entropy measures a system' s number of microscopic states, but its physical ontology is vague. In our framework, entropy gains clear and profound physical meaning:

Entropy is the measure of microscopic disorder and excitation complexity of the Ψ-medium.

A more revolutionary insight is that entropy’ s definition itself depends on the macroscopic phase of the Ψ-medium.

Entropy in matter-radiation era: In universe stages dominated by visible matter, entropy characterizes the distribution disorder of particles (photons, atoms, black holes) in emergent spacetime. Structure formation and black hole production are the main drivers of entropy increase in this phase.

Medium ground state entropy and “entropy phase transition” : When cosmic evolution reaches its endpoint, all visible matter decays, energy returns to the Ψ-medium background, and the entropy concept for “matter” reaches its maximum and becomes invalid. The universe then enters a nearly dead “calm.” But this is not the end. The Ψ-medium, as a quantum entity, has ground-state quantum coherence that becomes a new order measure. A global quantum phase transition (like water freezing into ice) may “reset” the medium to a new macroscopically coherent, low-entropy state. This is not “reduction” of old entropy but an “entropy paradigm shift” —the universe enters a completely new thermodynamic regime.

7.5 Cosmic Metabolic Cycle: Ripples, Silence, and Quantum Reboot

Based on the above new understanding of time and entropy, we can depict a cosmic epic far beyond traditional “heat death” or “cyclic oscillation” —the cosmic metabolic cycle.

Low-entropy beginning: The universe begins with a violent “ripple” of the Ψ-medium (possibly originating from quantum fluctuations or remnants of a previous cycle), with the medium in a highly non-equilibrium, low-entropy ordered state.

Entropy-increasing evolution: During the rippling process, the medium’ s energy excites bosons and fermions, and emergent gravity guides structure formation. In this process, the medium’ s microscopic disorder (entropy) continuously increases, driving cosmic expansion and cooling.

High-entropy “calm” : When ripple energy dissipates and visible matter completely transforms, the universe reaches macroscopic dynamical equilibrium. It becomes uniform, dilute, and “calm,” with entropy (under the old paradigm) reaching its maximum.

Quantum reboot and new cycle: In this high-entropy silence, the eternal quantum fluctuations of the Ψ-medium ground state, or instabilities after the medium reaches critical density, act as a “cosmic trigger.” It triggers a spontaneous quantum phase transition, catapulting the medium to a new low-entropy coherent state. This is not a reversible, deterministic pendulum cycle but a “metabolism” and “rebirth” based on randomness. Each reboot’ s “ripple” may differ in amplitude, pattern, and even emergent physical constants from the previous one, creating unique cosmic generations.

7.6 Implications of the New Physical Paradigm

This dynamic cosmic view brings about fundamental paradigm shifts:

Nature of dark energy: Dark energy is no longer a mysterious cosmological constant Λ. It is naturally interpreted as the macroscopic dynamical effect exhibited by the Ψ-medium in its current "ripple" phase (expansion phase)—namely, the effective negative pressure manifested by its inherent expansion tendency combined with gravitational feedback energy. It is an instantaneous manifestation of a dynamic process, not a static constant.

Unified resolution of black hole puzzles: Black hole entropy is proportional to the number of microscopic states of the Ψ-medium in its "limiting phase" inside the black hole. Information is encoded in the structure of this medium core and released through the medium' s dynamics during Hawking evaporation, thus being conserved.

Resolution of the cosmological constant problem: Dark energy is the dynamical manifestation of the Ψ-medium in its current "ripple" phase, not a fine-tuned constant. Its value is determined by the medium' s current state and changes with the universe' s metabolic evolution.

From "existing universe" to "evolving universe" : Our universe is no longer a static existing object but a great dynamical process. It is more like a living organism, experiencing a grand cycle of birth, growth, aging, death, and metabolism.

7.7 New Predictions and Testability of the Theory

An excellent scientific theory must propose testable new predictions. This dynamic model predicts observable deviations in principle from the standard ΛCDM model:

1. **Fine structure of the Hubble parameter:** The universe' s expansion rate (Hubble parameter $H(z)$) may not evolve completely smoothly but may be superimposed with extremely tiny periodic modulations or residual oscillations from the fundamental "ripple" rhythm. This can be searched for in future higher-precision observational data from supernovae and gravitational wave standard sirens.
2. **Characteristics of primordial gravitational wave spectrum:** A non-singular cosmic beginning based on medium dynamics (such as a bounce) may leave unique imprints on B-mode polarization of cosmic microwave background radiation or future low-frequency gravitational wave backgrounds, distinct from standard inflationary models.
3. **Matter-expansion correlation:** The universe' s local expansion rate may exhibit weak correlations with specific patterns of large-scale matter structure (such as voids or supercluster distributions), which is not allowed in the ΛCDM model.

The "dark matter ripples" model proposed in this chapter no longer merely describes the universe' s components but attempts to reveal the intrinsic, dynamic heart driving the entire cosmic evolution. By elevating the Ψ-medium from a static stage to a dynamic protagonist, and deeply rooting time, entropy, and cosmic cycles in the medium' s dynamics, this model provides the most complete and self-consistent picture to date for a unified, dynamic, and possibly cyclic universe, achieving a leap from depicting the universe' s "static structure" to revealing its "life epic." It points out key directions where future observations may discover new physics, thereby forging a profound philosophical conception into a vibrant and falsifiable scientific frontier.

8. Conclusions and Future Work Outlook

This paper systematically expounds a novel theoretical framework treating gravity as an emergent phenomenon. By introducing a dark matter superfluid (Ψ-medium) permeating the universe as a single physical ontology, this model achieves a unified explanation of gravity, dark matter, and dark energy, and successfully reduces spacetime geometry to a collective variable of the medium' s macroscopic quantum state.

8.1 Core Theoretical Contributions

The framework's core breakthrough lies in providing a self-consistent and unified solution to several deep dilemmas in modern physics:

Nature of gravity: Gravity is no longer viewed as a geometric effect of spacetime curvature but as an emergent force experienced by objects in the stress gradient field of the Ψ-medium. General relativity and its metric structure are precisely reproduced in the low-energy, long-wavelength limit.

Unification of dark matter and dark energy: The Ψ-medium itself is a dark matter candidate, while its ground state energy naturally manifests as dark energy, thereby dissolving the cosmological constant problem.

Resolution of black hole puzzles: The model reinterprets black holes as a limiting physical phase of the Ψ-medium, whose center is not a mathematical singularity but a bounded, dense core; the information paradox is naturally resolved through information encoding and release in the medium core structure.

Viable path to quantum gravity: Quantization of gravity is transformed into quantization of spin-2 quasiparticles (gravitons) on a fixed medium background, bypassing the infinite difficulties of directly quantizing geometry.

8.2 Future Research Roadmap

The theory's ultimate success depends on empirical verification of its predictions. Future research will proceed along these key paths to complete the leap from theoretical construction to experimental validation:

Construction and verification of microscopic mechanisms: The primary task is to construct a concrete (2+1)-dimensional toy model (such as holographic or lattice models) to numerically demonstrate the emergence of the Einstein-Hilbert action from microscopic interactions. This is the cornerstone of the entire theory and must be confirmed first.

Predictions and detection of high-energy gravitational phenomena: Within the effective field theory framework, precisely calculate the dispersion relation parameter ξ for gravitational waves at extremely high energy scales, and use data from next-generation gravitational wave observatories like LISA for Bayesian analysis to provide the first quantitative constraint on the medium energy scale Λ_{DM}.

Laboratory tests of precision mechanics: Systematically investigate new interactions beyond the Standard Model that may arise from coupling between visible matter and the Ψ-medium, such as effects causing weak equivalence principle violation or a "fifth force." Use ultra-high-precision experiments like MICROSCOPE follow-up missions or atom interferometers to impose the strictest constraints on these effects.

Empirical exploration of cosmic dynamics: Concretize and quantify the "dark matter ripples" model proposed in Chapter 7. Construct a computable cosmological perturbation theory to search for unique predictions distinguishing it from ΛCDM—such as residual oscillations in the Hubble parameter $H(z)$ or characteristic imprints on primordial gravitational wave spectra—and hunt for them using next-generation surveys like Euclid and SKA.

8.3 Ultimate Outlook

The significance of this framework extends far beyond proposing an alternative gravity model. It may initiate a profound paradigm shift: spacetime itself is not the starting point of physics but an approximate concept emergent from more fundamental matter interactions. This research path will ultimately guide our understanding of the universe' s most fundamental laws toward exploring the microscopic properties of the Ψ-medium—this physical entity that may be the background and origin of all things. A dynamic, "rippling" universe awaits our discovery and listening.

The proposal of the "Gravitational Pressure Model" does not claim it as the ultimate truth of the universe. Rather, it demonstrates enormous potential to become an "extremely useful tool." It can unify explanations for multiple separate puzzles at the forefront of current physics, provide clear and intuitive physical pictures, and point out a series of future testable directions. Even if it is modified or superseded in the future, its immense usefulness in "unifying cognition" and "guiding exploration" will fully prove the value of its proposal.

Note: Figure translations are in progress. See original paper for figures.