Cosmic Vacuum Scalar Field Driven Gravitational Geometry Model

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Abstract

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Full Text

Preamble

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Abstract

This paper proposes a theory of gravity based on a preferred cosmic vacuum scalar field, aiming to provide a unified field-theoretic mechanism explaining the origin of the equivalence principle and spacetime geometry. The model assumes the existence of a vacuum scalar field ϕ coupled to rest mass m, establishing the equivalence between inertial and gravitational mass through the energy relation E = mϕ. Under static spherical symmetry, based on the geometric emergence and self-consistency constraints of the scalar field distribution, the Schwarzschild metric is rigorously derived via effective field theory methods, reproducing the classical pre- dictions of general relativity. Furthermore, in linear perturbation analysis, beyond tensor gravitational waves, this theory predicts the existence of scalar transverse polarization modes (breathing modes) of gravitational waves, providing clear field- theoretic predictions and observational prospects. Additionally, this framework in- terprets cosmic expansion as the dynamical evolution of the background scalar field $ $0(t), offering a novel theoretical approach to unify descriptions of local gravity and cosmic dynamics.

Keywords: preferred vacuum scalar field; equivalence principle; Schwarzschild metric; scalar gravitational waves; geometric emergence of gravity; cosmological dynamics.

Contents

1.1 Research Background

General Relativity (GR) has been extensively experimentally validated from solar system scales to cosmological scales [1]. However, GR still faces several fundamental theoretical questions, such as: the physical origin of the equivalence principle, the microscopic in- terpretation of vacuum energy (cosmological constant) [2], and the fusion of gravity with quantum theory.

This work proposes an Effective Field Theory (EFT) model based on a preferred vacuum scalar field, aiming to provide a field-theoretic mechanism with clear physical content for the equivalence principle, inertial effects, and static spherically symmetric gravitational fields.

1. Scalar-Tensor Theories of Gravity

Brans-Dicke theory and its generalizations introduce dynamical scalar fields into grav- itational geometry to adjust the gravitational constant or coupling strength [3]. In our model, the ϕ field is not a scalar field with gravitational coupling in the traditional sense, but directly couples to the particle energy scale, and its background value $ $0 = c2 is constant, not playing the role of adjusting coupling strength. The geometric emergence in our model originates from the distribution of the ϕ field itself, rather than through non-minimal coupling between the scalar field and the Ricci scalar.

2. Lorentz Violation and Preferred Frame Theories

Theories such as Einstein-Aether theory [4] or Bumblebee models [5] achieve dynam- ical breaking of Lorentz symmetry through the introduction of background vector or tensor fields. In our model, the preferred reference frame originates from a cosmologi- cally uniform background ϕ field, rather than through dynamical spontaneous breaking; this field remains consistent with special relativity in local inertial frames, only exhibiting preferredness at the global cosmological background level, and is compatible with existing high-precision clock comparison experiments through dynamical damping.

3. Vacuum Energy and Modified Newtonian Dynamics (MOND)

Certain models attempting to explain inertia or gravity from vacuum fluctuations or inhomogeneous vacuum energy [6] often introduce acceleration-scale modifications in the low-velocity weak-field regime. Our model strictly returns to Newtonian gravity in the weak-field limit, introducing no new acceleration scales; the proportionality relation between vacuum energy density ρ and scalar field ϕ (ρ ϕ) results from vacuum redistribution due to mass coupling, not from dynamical assumptions.

4. Emergent Spacetime and Analog Models

Condensed matter or optical analogies often simulate curved spacetime through ef- fective metrics [7]. Our model differs in that the ϕ field is a fundamental classical field, not an effective low-energy excitation; its coupling rule with matter, (E = mϕ), derives directly from energy scale considerations, and the model construction follows the EFT paradigm, requiring observational self-consistency with GR.

5. Cosmological Constant and Vacuum Scalar Field

Interpreting the cosmological constant as the potential energy of a uniform scalar field is common in cosmology (e.g., quintessence). In our model, the background part \$ \$0 of the ϕ field corresponds to the vacuum energy background, but its dynamical equation in vacuum simplifies to (cid:3)(\$ \$2) = 0. This equation possesses a different dynamical structure from typical quintessence fields [8].

By unifying inertia and gravity as different manifestations of the same vacuum scalar field, this model provides a mechanistic explanation of the equivalence principle and rig- orously derives the Schwarzschild metric from effective field theory without introducing additional dynamical degrees of freedom. Its new predictions primarily concern gravita- tional wave polarization modes (scalar-dominated) and the field-theoretic interpretation of cosmological expansion, providing clear windows for future experimental tests.

2 Equivalence Principle of the Vacuum Field

This model follows the paradigm of Effective Field Theory (EFT), aiming to provide a field-theoretic interpretation based on explicit physical mechanisms for the classical successes of General Relativity (GR). The core of the model unifies inertial effects and gravitational interactions through a preferred vacuum scalar field ϕ, thereby providing a mechanistic explanation for the physical origin of the equivalence principle.

2.1 Postulate System

A. Boundary Condition Postulates A.1 Local Lorentz Invariance: Within sufficiently small local spacetime regions, the form of physical laws is consistent for all inertial observers, with the speed of light c being a universal constant.

A.2 Empirical Cornerstone of General Relativity: In solar system-scale weak-field, static gravitational fields, the predictions of this theory must be consistent with the high-precision, validated predictions of General Relativity (GR).

A.3 Non-zero Vacuum Energy Background: Cosmological observations support the existence of a uniform, isotropic non-zero vacuum energy density $ $0.

B. Core Construct Postulates (New Physics Core of the Theory) B.4 Preferred Vacuum Scalar Field: There exists a classical real scalar field ϕ asso- ciated with the cosmic vacuum structure. At cosmological scales, it defines a preferred global reference frame S0, in which its background value is constant $ $0.

B.5 Energy Scale Relation: For a particle with rest mass m, its total energy E (in- cluding rest energy) is determined by the fundamental coupling between this mass and the local ϕ field:

E = mϕ. (2.1) B.6 Matter-Vacuum Scalar Field Coupling and Geometric Emergence Principle: All matter fields Ψm couple fundamentally to the preferred vacuum scalar field ϕ. All physical effects arising from this coupling (including inertial motion and gravitational interactions) are equivalent to that, matter follows minimal coupling in an emergent metric gμν[ϕ] uniquely determined by the ϕ field. The concrete realization and verification of this principle will be completed in Section 3 through the rigorous derivation of the metric.

2.2 Key Corollaries and Kinematic Transformations

The following corollaries are derived from the above postulate system to satisfy theoretical self-consistency (particularly self-consistency with special relativity and GR experimental predictions).

1. Scalar Field Background Value:

To satisfy self-consistency with GR empirical predictions (Postulate A.2), the back- ground value of the preferred vacuum scalar field $ $0 must be the fundamental physical constant c2; that is: $ $0 = c2. (2.2) This conclusion is independently and consistently obtained from Appendix B (weak- field limit vacuum energy flow model) and Section 3.3 (self-consistency analysis of energy-time scale relations).

2. Derivation of Scalar Field Transformation Rules

In this model, the kinematic transformation rule of the scalar field ϕ (Corollary 8) is not an independent postulate but can be derived from more fundamental pictures.

This derivation is a key step connecting classical kinematics with the new field-theoretic framework, with the following logical chain: (a) Special Relativistic Kinematics Input: We accept the conclusions of special rela- tivity regarding kinematic effects. In particular, for an inertial observer Oν moving with velocity ν relative to the S0 frame, when measuring a spatial region at rest in the S0 frame with proper volume V0, due to the relativity of simultaneity, the measured scale along the motion direction undergoes Lorentz contraction while transverse scales remain unchanged; therefore, the measured volume of this region is Vν = V0/γ, where γ is the Lorentz factor: (cid:18) (cid:19)−1/2 (b) Key Assumption of Vacuum Field Energy: To connect the above kinematic effects with the vacuum scalar field ϕ, we introduce an ontological assumption about vacuum field energy: the total energy E0 = $ $0V0 of the vacuum field contained within volume V0 in the S0 frame is a Lorentz invariant. (Note: This assumption differs from the transformation properties of energy as a component of the energy-momentum tensor in standard quantum field theory, reflecting the specificity of the ϕ field as a classical preferred field in this model.) (2.3) (c) Based on the above two points, the moving observer Ov measures the vacuum energy density of this region as: = $\gamma$$ $0. (2.4) (d) According to the relation derived in Appendix B under the weak-field, static limit, ρ ϕ, i.e. there exists a universal constant κ such that ρ = $\kappa\phi$. We assume that this local proportionality relation originating from static matter coupling also holds for measurements in different inertial frames due to relative motion. (e) Derivation of Field Potential Transformation: Applying the proportionality rela- in the S0 frame, $ $0 = $\kappa$$ $0; in the Ov frame, tion to the S0 frame and the Ov frame: ρv = $\kappa\phi$v. Combining with equation (2.4), we obtain:

Since κ (cid:54)= 0, according to equation (2.2), $\kappa\phi$v = $\gamma$$ $0 = γ($\kappa$$ $0). ϕv = $\gamma$$ $0 = γc2. (2.5) (2.6)

3. Energy Expression for a Moving Particle

For a particle with rest mass m, when it moves with velocity v relative to S0, according to the energy scale relation (2.1), its total energy is determined by the local field potential at the particle' s location. Since in the particle' s own instantaneous rest inertial frame, the local field potential is precisely ϕv given by the transformation rule (2.6), the energy of this particle is:

E = mϕv = mγc2. This expression is completely consistent with the energy expression for moving particles in special relativity. It shows that the increase of energy with velocity for inertial particles in special relativity is interpreted in this model as the result of the particle' s rest mass coupling to a local vacuum field potential ϕv that increases with velocity. (2.7)

2.3 Field-Theoretic Derivation and Mechanistic Interpretation of

Inertial Force

2.3.1 Establishment of Dynamical Equation

Consider a test particle with rest mass m0, initially at rest in the preferred frame S0 or moving with constant velocity v0 along the x direction. An external force Fext is applied along its motion direction (x direction), parallel to the instantaneous velocity, giving it an instantaneous acceleration a = dv/dt. At any time t, the particle velocity v(t) = v0 + at.

According to (2.7): = m0c2 dγ (2.8) Using the differential relation of the Lorentz factor dγ tivistic kinematics result), we obtain: dt = $ $3vc2a(standardspecialrela— = m0$ $3va. (2.9) From power balance Fextv = dE/dt, taking v (cid:54)= 0, we obtain the relation between external force and acceleration:

Fext = m0$ $3a. According to Newton' s third law, the particle must experience a resistive force equal in magnitude and opposite in direction to this external force, which is the inertial force Finert.

In the next section, we will prove that this inertial force originates from the reaction force generated by the vacuum field gradient induced by the particle' s own acceleration. To maintain dynamical equilibrium, we have: (2.10) Finert = −Fext = −m0$ $3a. (2.11) Equation (2.10) is mathematically identical to the dynamical equation for longitudinal force in special relativity, and provides a different physical interpretation space for inertial force, detailed in the next section.

2.3.2 Field Gradient Interpretation of Inertial Force (Field-Theoretic Mech-

anism of the Equivalence Principle) The spatial gradient of the vacuum scalar field is the direct physical cause acting on particle mass and producing acceleration. In the gravitational case (Appendix B), this gradient $\nabla\phi$(r) is generated by the static mass source M and leads to gravitational acceleration ag = $-\nabla\phi$. The inertial force shown in equation (2.11) is precisely the reaction force generated by the equivalent vacuum field gradient induced by the particle' s own acceleration.

1. Acceleration-Induced Equivalent Vacuum Field Gradient

According to equation (2.6), the vacuum field potential measured locally by a particle at instantaneous velocity v(t) is ϕv(t) = γ(v(t))c2. The accelerated motion of the particle causes its locally measured field potential ϕv to change.

Within an infinitesimally short time dt, the velocity increment is dv = adt, and the particle displacement is dx = vdt. The resulting change in local field potential is: dϕv = dv = c2 · (2.12) d$\phi\nu$ = $ 3 d $.

Therefore, along the particle' s motion path, its acceleration a induces an equivalent vac- uum field gradient: (2.13) $\nabla\phi$ind = = ($ 3 $a) · = $ $3a. (2.14) Equation (2.14) is the first key conclusion: acceleration a leads to an equivalent field gradient $\nabla\phi$ind along the direction of motion, with magnitude $ $3a.

2. Relation Between Vacuum Field Gradient and Acceleration

According to the energy scale relation E = mϕ (2.1), when a particle' s energy varies with position in the vacuum scalar field, the force it experiences is directly defined by the negative gradient of energy with respect to coordinates:

F = − (2.15) According to equation (2.10), in the weak-field, low-velocity approximation (ν (cid:28) c), γ 1, equation (2.10) reduces to:

This naturally yields Newton' s second law. Combining equations (2.16) and (2.15):

F = ma. a = − (2.16) (2.17) Equation (2.17) is the core dynamical principle of this model: the vacuum field gradient is the direct cause of acceleration, with the magnitude of acceleration equal to the negative of the field gradient. Equation (2.17) is already explicitly manifested in the gravitational case: the steady-state field gradient $\nabla\phi$(r) produced by a static mass source M leads to gravitational acceleration ag = $-\nabla\phi$ (see Appendix B).

3. Reverse Acceleration Produced by Induced Gradient and Inertial Force

Applying equation (2.17) to the equivalent vacuum field gradient $\nabla\phi$ind = \$ $3a(equa-tion(2.14))inducedbytheparticle\text{'}sownacceleration.Thisgradientactingontheparticle\text{'}sownmassm$
a \$ = $-\nabla\phi$ind = $-$\$ \$3a. (2.18) This acceleration is opposite in direction to the original acceleration a. According to Newton' s second law derived in the low-velocity limit of this model, equation (2.16), the force corresponding to this acceleration (i.e., the inertial force) is:

Finert = m0aϕ = $-$m0\$ $3a.(2.19)Thisexpressioniscompletelyconsistentwithequation(2.11)derivedfromdyna$
$tionforceproducedbytheequivalentvacuumeldgradientinducedbytheparticle\text{'}sownacceleration, accordingtoth$
$consistentlyderiveddynamicalrelationsa = -d$ \$/dx and F = ma in this model. The work done by the external force Fext is precisely used to overcome this reaction force to maintain the particle' s accelerated motion.

If the particle remains at rest or in uniform rectilinear motion in the preferred frame S0 (i.e., a = 0), then its local field potential $\phi\nu = \gamma$c2 is constant (γ unchanged), so there is no field reaction force (Finert = 0), and no external force is required to maintain its state of motion (Fext = 0), naturally yielding Newton' s first law of motion.

2.4 Field-Theoretic Unification of Gravitational Acceleration and

the Equivalence Principle Extending equation (2.17) to three-dimensional vector form gives: a = $-\nabla\phi$. (2.20) Equation (2.20) originates from the energy scale relation E = mϕ (2.1) and Newton's second law F = ma (2.16) derived from it in the low-velocity limit, and is a universal principle pervading both gravitational and inertial forces: the spatial gradient of the vacuum scalar field is the direct physical cause of acceleration, with the acceleration direction pointing toward decreasing field potential.

Gravitational Acceleration: The static mass source M , through coupling with the preferred vacuum scalar field ϕ, excites a steady-state vacuum field distribution in its vicinity. Under the weak-field approximation (Appendix B): ϕ(r) = c2 $-$ (2.21) substituting into the universal relation (2.20) yields the specific form of gravitational acceleration: agrav(r) = $-\nabla\phi$ = $-$ (2.22) Gravitational acceleration originates from the static vacuum field gradient $\nabla\phi$(r) pro- duced by the coupling between the mass source and the vacuum field.

Inertial Force: When a particle accelerates under an external force, the change in its own state of motion induces an equivalent vacuum field gradient $\nabla\phi$ind = \$ $3a(three-dimensionalgeneralizationofequation(2.14)1).Accordingtoequation(2.20), thisyieldsthereversea$
= $-\nabla\phi$ind = $-$\$ $3a, andthecorrespondingforceistheinertialforceFinert$ = $m0a$ \$ = $-$m0\$ \$3a (2.19).

Unified Mechanism of the Equivalence Principle: Gravitational acceleration and inertial acceleration (resistance) are locally indistinguishable; their physical origins 1Three-dimensional generalization of equation (2.14). are unified in this model through: - Gravitational acceleration: originates from the real, static vacuum field gradient excited by the coupling between an external static mass source and the vacuum field $ $0; - Inertial force: originates from the equivalent vacuum field gradient induced by the particle' s own accelerated motion.

Both follow the identical dynamical relation a $= -\nabla\phi$, both act on the particle' s rest mass m, and both use the vacuum scalar field ϕ as the interaction medium. The equivalence of inertial and gravitational mass thus becomes a natural corollary.

3 EFT Derivation of Spacetime Metric Based on the

Preferred Vacuum Scalar Field In this section, within the framework of the preferred vacuum scalar field established in Section 2, starting from the geometric emergence principle (Postulate B.3), combined with static spherical symmetry and dynamical requirements self-consistent with general relativity, we rigorously derive the emergent metric for static spherically symmetric grav- itational fields, ultimately reproducing the Schwarzschild metric.

3.1 Derivation Prerequisites

The following prerequisites are specific to Section 3, numbered continuously following the postulates in Section 2.

Postulate 7 (Vacuum Dynamical Self-Consistency Requirement) To ensure the model is phenomenologically consistent with the extremely high-precision validated General Relativity (GR) in vacuum regions, the metric gμ$\nu[\phi]$ emergent from the ϕ field must satisfy the GR vacuum field equations Rμ$\nu = 0$ in source-free regions. The gravita- tional constant G appears as an integration constant under this condition [1].

Postulate 8 (Integrability of Continuous Lorentz Transformations) In a static spherically symmetric gravitational field, infinitesimal Boost transformations between radially stacked local inertial frames must commute with each other. Due to the strict spherical symmetry in this model, the equivalent relative velocities between ad- jacent static observers are all radial, satisfying this commutativity; thus the rapidity $\eta =$ artanh(v/c) differential is an exact differential, allowing path integration to obtain finite transformations [9]. This condition provides the mathematical foundation for the geometric constraint T (r)S(r) = 1 [10, 11].

Geometric Setup: From static spherical symmetry, the line element can be generally written as: ds2 = T (r)2c2dt2 − S(r)2dr2 − r2dΩ2, dΩ2 = d$ $2 + sin2 θd$ $2, (3.1) where T (r) = (cid:112)g00(r), S(r) = (cid:112)−grr(r), and t is the coordinate time synchronized with stationary clocks at infinity. The transverse spatial geometry maintains the stan- dard spherical form. The physical reason is: according to the vacuum energy flow model established in

Appendix B, the vacuum energy flow excited by a static spherically sym- metric mass source is purely radial; there is no net vacuum energy flow in transverse directions, so the angular part of the metric is unaffected by the inhomogeneity of the ϕ field, preserving the standard spherical geometry of Euclidean space. This conclusion is guaranteed jointly by Postulate B.3 (Geometric Emergence Principle) and static spherical symmetry.

3.2 Geometric Constraint of the Vacuum Field

Consider two adjacent static observers Or and Or+dr. According to the equivalence prin- ciple (guaranteed by the universal relation $a = -\nabla\phi$ from Sec. 2.3.2 and the unified mechanism of gravity and inertia) and Postulate 8, there exists an equivalent relative velocity dv along the radial direction between their local inertial frames, corresponding to a Lorentz factor γ(dv).

3.2.1 Time Dilation Effect

In the local inertial frame of Or, the clock of Or+dr moves with velocity dv and undergoes time dilation: dτr = γ(dv) dτr+dr.

From the line element, dτr = T (r)dt and dτr+dr = T (r + dr)dt. Substituting into (3.2) yields (3.2) T (r + dr) T (r) γ(dv) (3.3)

3.2.2 Length Contraction Effect

The proper length at Or+dr is dlr+dr = S(r + dr)dr. In the frame of Or, this moving ruler is length-contracted: dlr = dlr+dr γ(dv) S(r + dr)dr γ(dv) (3.4) Meanwhile, the same coordinate interval dr corresponds to a proper length dlr = S(r)dr at Or. Self-consistency requires these two expressions to be equal, giving S(r + dr) = γ(dv).

Integral Constraint Multiplying (3.3) and (3.5) we obtain T (r + dr) T (r) S(r + dr) (3.5) (3.6) In the continuous limit, this leads to the differential equation d dr ln[T (r)S(r)] = 0. Inte- grating and applying the boundary condition T (∞) = S(∞) = 1 as r $\to \infty$, we arrive at the core geometric constraint:

T (r)S(r) = 1. (3.7)

3.3 Derivation of Spacetime Metric –Physical Scaling Condi-

In the weak-field, low-velocity limit, Newtonian gravity should hold. According to the energy scale relation (2.1), the total energy of a particle with rest mass m in a gravitational field is E = mϕ(r). In Newtonian gravity, the total energy of a particle is ENewton = mc2 + mVN (r) = mc2 (cid:104) , where VN (r) = − GM [1]. Comparing gives: 1 + VN (r) (cid:105) ϕ(r) = c2 (cid:20) (cid:21) VN (r) = c2 − (3.8) From experimental validations of general relativity, under the weak-field approximation, [1]. According to the line element the time dilation factor is dτ c2 = 1 − GM form dτ = T (r)dt, we have: dt 1 + VN (r) T (r) 1 + VN (r) c2 = 1 − (3.9) Comparing (3.8) and (3.9) yields the weak-field relation T (r) = ϕ(r)/c2. Based on theo- retical self-consistency, extending this to the strong-field region gives the physical scaling condition:

T (r) = (3.10) This condition directly associates time geometry with the physical potential, embodying the energy scale relation and equivalence principle at the geometric level.

Combining the geometric constraint (3.7) with the physical scaling condition (3.10):

S(r) = T (r) (3.11) Substituting into the line element form, we obtain the emergent metric for static spheri- cally symmetric gravitational fields: ds2 = (cid:21)2 (cid:20) ϕ(r) c2dt2 − (cid:21)2 (cid:20) c2 dr2 − r2dΩ2. (3.12)

3.4 Schwarzschild Metric Verification and Vacuum Dynamical

Equation Define the dimensionless field Ψ(r) ϕ(r) ; then the metric (3.12) simplifies to: ds2 = \$ \$2c2dt2 − Ψ−2dr2 − r2dΩ2. (3.13)

3.4.1 Ricci Tensor Calculation and Vacuum Field Equation

For the metric (3.13), according to the standard derivation of static spherically symmetric metrics in general relativity (see [10,11]), the vacuum field equations Rμν = 0 can be reduced to a differential equation for \$ \$2:

This equation is equivalent to the three-dimensional flat space Laplacian form: (cid:0)r\$ 2$(cid:1) = 1.(3.14)(cid:18)r2d($2) (cid:19) = 0 \$ 2(2) = 0.(3.15)$IntegrationandConstantDeterminationIntegratingequation(3.17)yieldsr$ \$2 = r + C, where C is an integration constant.

Rearranging gives: \$ \$2(r) = 1 + (3.16) Boundary conditions:

2. Newtonian limit matching: In the weak field, g00 = \$ \$2 1+ C

, while the weak-field [1]. Comparison yields prediction of general relativity is g00 1 + 2VN C = − 2GM , i.e., the Schwarzschild radius rs = 2GM c2 = 1 − 2GM Therefore: (cid:114) ϕ(r) = c2 (3.17)

3.4.3 Reproduction of the Schwarzschild Metric

Substituting (3.20) into (3.12) gives the exact Schwarzschild metric: ds2 = (cid:18) (cid:19) c2dt2 − (cid:18) (cid:19)−1 dr2 − r2dΩ2. (3.18) Direct verification confirms that this metric satisfies Rμν = 0, fully consistent with Postulate 7 [10].

3.5 Scalar Gravitational Waves: Linearized Predictions from the

Vacuum Dynamical Equation and Observational Tests

3.5.1 Vacuum Dynamical Equation and Its Core Implications

The fundamental dynamical equation of this model in vacuum is rigorously derived from the metric emergence principle and the vacuum dynamical self-consistency require- ment (Postulate 7). Under static spherical symmetry, the vanishing Ricci tensor gives \$ 2($2/c4) = 0. Covariantlygeneralizingtogeneralspacetimeyields:$ (cid : 3)(\$2) = 0, (3.19) where (cid:3) = ∂μ∂μ is the d' Alembert operator in Minkowski spacetime (in the full theory, the covariant form under the emergent metric should be used, but the background Minkowski metric is applicable in the lowest-order perturbation analysis).

This equation has four core physical implications:

1. Self-consistent derivation of nonlinear field equations: The vacuum dynam-

ics is completely determined by the quadratic combination \$ \$2 of the ϕ field, requiring no additional potential terms or coupling parameters. This is a key distinguishing feature of this model from general scalar-tensor theories.

2. Non-standard dynamical characteristics of the scalar field: Traditional

scalar field theories follow the Klein-Gordon equation ((cid:3) + m2)ϕ = 0. This model satisfies the wave equation for \$ \$2. In the weak-field approximation, setting ϕ = c2+$\delta\phi$ and linearizing yields (cid:3)($\delta\phi$) = 0, so the perturbation $\delta\phi$ satisfies the massless wave equation. However, in the strong-field region, nonlinear effects are significant, and ϕ itself does not satisfy the linear wave equation. This feature is qualitatively consistent with the behavior of Horndeski theory in the zero-mass limit: longitudinal modes vanish while breathing modes persist [12].

3. Dynamical foundation for metric emergence: From the emergent metric re-

lation g00 = (ϕ/c2)2, we have \$ \$2/c4 = g00. Thus, equation (3.19) under the back- ground Minkowski metric is equivalent to (cid:3)g00 = 0. This reveals that the geometric quantity g00 obeys a linear wave equation in vacuum, providing a clear mathematical starting point for gravitational wave analysis.

4. Theoretical window for cosmological evolution: Extending the equation to

a time-dependent background \$ \$0(t) allows studying the evolution of \$ \$2 0(t) on cos- mic scales, providing a field-theoretic framework for interpreting cosmic expansion dynamics.

3.5.2 Linearized Wave Equation and Metric Perturbations

Consider small perturbations on the flat background \$ \$0 = c2: ϕ = c2 + $\delta\phi$. Expanding equation (3.19) to first order: (cid:3)(c4 + 2c2$\delta\phi$) = 2c2(cid:3)($\delta\phi$) = 0 (cid:3)$\delta\phi$ = 0. (3.20) That is, the perturbation $\delta\phi$ propagates at the speed of light c, satisfying the massless scalar wave equation.

Linearizing the metric emergence relation (Postulate 6) yields the metric perturba- tions: h00 = hrr = − h$\theta\theta$ = h$\phi\phi$ = 0. (3.21)

3.5.3 Polarization Mode Analysis: Scalar Breathing Mode Dominance

In four-dimensional spacetime, these metric perturbations excite only scalar transverse polarization modes (breathing modes). Decomposing in the transverse-traceless (TT) gauge, the polarization tensor takes the form [12]: eij = diag(1, 1, 0) (propagation direction z), (3.22) i.e., both transverse directions stretch and contract in phase, with area change but shape preservation. This mode does not contain the independent tensor transverse-traceless polarization modes ("+" and "×"). This feature is consistent with the polarization analysis of scalar-tensor theories in the massless limit: longitudinal modes vanish, with only breathing modes persisting as additional polarization states [12].

3.5.4 Observational Constraints and Test Strategies

(1) Existing Observational Constraints Polarization analysis of the binary neutron star merger event GW170817 with multiple detectors indicates that the observational data are highly consistent with general relativity predictions, with the relative amplitude of additional polarization modes constrained to within approximately 30% of tensor modes [15,16].

In the minimal prediction of this model, the scalar breathing mode amplitude is comparable to tensor modes, so this constraint sets a clear upper limit on possible nonlinear corrections or couplings beyond the minimal framework in this model. (2) Theoretical Compatibility Pathways To make the theory compatible with the observed dominance of tensor gravitational wave signals, the following physical mechanisms may be considered: • High-order self-coupling of the scalar field or interactions with non-trivial back- grounds, inducing high-order tensor-type responses within the effective field theory framework [17]; • In strong-field, dynamic spacetimes (e.g., binary mergers), the metric emergence re- lation g$\mu\nu[\phi]$ may contain nonlinear corrections, causing waveforms in the radiation zone to be dominated by tensor components.

Such mechanisms are widespread in scalar-tensor theories, typically predicting mixed radiation spectra dominated by tensor modes with subdominant scalar modes, consistent with current observations [12,18].

3.6 Preferred Reference Frame Tests with Atomic Clocks

At large scales satisfying the cosmological principle, the background distribution of the ϕ field is uniform and isotropic, with gradient ∇$ $0 0 [24]. The center of mass of local bound systems (such as the solar system) is not subject to directional net forces from ϕ field gradients, and any initial peculiar velocity is damped within the framework of cosmic expansion dynamics, naturally causing the system to be comoving with the lo- cal ϕ field background (relative velocity v0 $\to$ 0). This naturally suppresses observable effects of "preferred frame absolute motion" locally, making this model automatically and fundamentally compatible with null results from all high-precision atomic clock com- parison experiments (frequency ratio stability at 10−18 level showing no preferred frame modulation signals) [25].

3.7 Extended Discussion on Cosmological Issues

This model attributes the sole source of gravity to the spatial gradient of the vacuum scalar field: a = $-\nabla\phi$. At local scales, this gradient is excited by static mass sources, successfully returning to Newtonian gravity and the Schwarzschild metric. The follow- ing provides conceptual extensions at cosmological scales: (1) proposing a decoupling mechanism between gravity and vacuum energy, offering a new potential solution to the cosmological constant problem; (2) revealing that the background field evolution in this model can be qualitatively mapped to dynamical features suggested by current dark en- ergy observations; (3) deriving several testable windows qualitatively distinguishable from ΛCDM based on its pure Doppler redshift picture.

The cosmological modeling of this model, self-consistent construction of the emergent metric, and quantitative comparison with observational data all await systematic follow- up research.

3.7.1 The Cosmological Constant Problem: Decoupling Mechanism Between

Gravity and Vacuum Energy The core dilemma of the cosmological constant problem is: the vacuum energy density ρvac predicted by quantum field theory exceeds the observed effective value $\rho\Lambda$ (10−3eV)4 by dozens of orders of magnitude (discrepancy up to 10123 times at the Planck scale), and in the general relativity framework, any form of vacuum energy directly couples to gravitational geometry [2]. This model offers a different solution path: the vacuum energy density $ $0 itself does not participate in gravitational coupling. Gravity originates entirely from $\nabla\phi$, not from the absolute value of $ $0; the background field value $ $0 = c2 is uniquely determined by the self-consistency requirement between the weak-field limit and general relativity, independent of the vacuum energy numerical value predicted by quantum field theory. This gravity-vacuum energy decoupling mechanism requires no fine-tuning, no cancellation terms, and does not negate the reasonableness of quantum field theory vacuum energy estimates, fundamentally severing the causal chain between vacuum energy density and observable gravitational effects.

3.7.2 Dark Energy Observational Indications and Dynamical Correlation

with This Model In recent years, high-precision cosmological survey observations have accumulated pre- liminary evidence supporting dynamical dark energy evolution. The DESI collaboration, using first-year Baryon Acoustic Oscillation (BAO) measurements combined with CMB and supernova samples, found that the time evolution of the dark energy equation of state parameter exhibits characteristics of w0 > -1, wa < 0, with deviation confidence from the flat ΛCDM model reaching 2.6σ to 3.9σ (depending on the supernova sample), indicating that the cosmological constant null hypothesis w $= -1$ faces serious challenges [27]. The latest DESI analysis further reports that the signal-to-noise ratio for dark en- ergy equation of state evolution exceeds 4σ, showing significant "crossing - 1" behavior during evolution, qualitatively consistent with theoretical predictions of Quintom dark energy models [28]. Additionally, studies on coupled dark matter-dark energy models indicate that effective equation of state crossing the phantom divide (weff $= -1$) can be naturally realized around redshift z 0.5, providing concrete dynamical realization pathways for DESI observations [29].

Within this model's framework, if the background scalar field $ 0$(t) undergoesslowmonotonicevolutionovercosm$
˙ 0/ 0.$Mappingthisdynamicstotheeectivedarkenergyequationofstateintheemergent FLRW representationyie$
$dependent formsqualitativelyconsistentwith DESI observationalcharacteristics. Thismodelprovidesadynami$
3)($2) = 0, independent of potential function slow-roll assumptions. It should be made clear that this model currently cannot provide quantitative predictions directly fitted to observa- tional data; only qualitative dynamical analogies exist between this model and DESI observations.

3.7.3 Testable Qualitative Predictions: Observational Windows Distinguish-

ing This Model from ΛCDM The pure Doppler redshift picture of this model yields a series of testable characteristics qualitatively distinguishable from

ΛCDM. These characteristics do not depend on specific parameterizations but arise from structural differences in the framework itself, potentially providing decisive tests for future high-precision observations.

Anisotropy of the Hubble Flow The ΛCDM framework, based on the cosmo- logical principle, predicts that the Hubble flow should be isotropic at sufficiently large scales; any observed anisotropy must be attributed to local structure or observational selection effects [24]. This model, however, allows for intrinsic dipole Hubble flow: if the ϕ field possesses a large-scale dipole gradient, the Hubble flow can exhibit directional dependence. Recent analysis based on the Pantheon+ supernova sample indicates that within the redshift range 0.023 < z < 0.15, the Hubble expansion rate exhibits statisti- cally significant dipole variation, with amplitude exceeding 1.5kms−1Mpc−1, greater than the 1% uncertainty claimed in SH0ES measurements; the deceleration parameter also shows redshift-dependent dipole modulation, with confidence exceeding 5σ [26]. This study further suggests that the inferred cosmic acceleration cannot be due to a cosmolog- ical constant and is likely a general relativistic effect caused by anomalous bulk flow in the local universe [26]. This observational characteristic highly aligns with this model' s picture: dipole Hubble flow can provide independent evidence for the existence of large- scale ϕ field gradients, with its amplitude and direction imposing strict constraints on the model' s parameter space.

4 Conclusion

This study constructs a theory of gravity centered on a preferred vacuum scalar field, suc- cessfully incorporating the equivalence principle and spacetime geometry into a unified field-theoretic framework. The theory self-consistently derives the Schwarzschild metric in static spherically symmetric vacuum and predicts scalar polarization modes of gravita- tional waves under linear perturbations. This model not only is compatible with existing high-precision experimental constraints but also proposes new physical perspectives for understanding gravity and cosmic expansion from scalar field dynamics. Future gravita- tional wave detection and precision cosmological observations, particularly discriminating between polarization modes and measurement of Hubble parameter evolution, will be- come key pathways for testing this theory.

A Geometric Properties of Scalar Field Distribution and Boundary Condition Analysis Analysis Prerequisites:

1. Known solution: employing the exact solution ϕ(r) = c2(cid:112)1 − rs/r already derived

from theoretical self-consistency requirements (consistency with general relativity empirical results).

2. Metric background: to reveal the geometric characteristics of this solution relative

to the flat background spacetime, we first compute its gradient and flux under the background Minkowski spacetime ηµν. This is a purely mathematical comparative analysis intended to visually display the inhomogeneity of the field. True physi- cal conservation laws should be discussed through covariant divergence under the theory' s own emergent metric gµ$\nu[\phi]$.

A.1 Scalar Field Gradient and Flux Calculation From the solution ϕ(r) = c2(cid:112)1 − rs/r, compute its radial coordinate derivative: (cid:17)−1/2 (cid:17)−1/2 (cid:16) (cid:17) (cid:16) = c2 · (cid:16) rs (A.1) Under the background Minkowski metric ηµν = diag(+1, −1, −r2, −r2 sin2 θ), the raised radial component of its gradient is: (cid:18) dϕ where we have substituted rs = 2GM/c2. The negative sign indicates that under the flat background, this scalar field gradient points toward the origin. ∇rϕ ηrr∂rϕ = (−1) · (A.2) (cid:17)−1/2 (cid:19) (cid:16) The total flux Φϕ through a spherical surface of radius r (with area element dA = r2 sin θdθdϕ in the background flat space) is: (cid:73) Φϕ(r) = (cid:90) 2π (cid:90) π (cid:20) ∇rϕdA = sphere (cid:16) (cid:17)−1/2(cid:21) r2 sin θdθdϕ. (A.3) Completing the angular integration (area 4πr2) yields: Φϕ(r) = −4πGM (cid:16) (cid:17)−1/2 (A.4) This flux explicitly depends on radius r and is negative (inward centripetal). Under the flat spacetime background, this clearly reveals that the ϕ field distribution possesses non- trivial source characteristics, with non-conserved flux. This non-conservation is a key feature for understanding energy transfer behavior in curved geometry. In the complete physical picture of the theory, the energy-momentum tensor of the scalar field coupled to matter should satisfy covariant conservation under the emergent metric gµ$\nu[\phi]$.

A.2 Classical Boundary Conditions at the Schwarzschild Radius From the solution ϕ(r) = c2(cid:112)1 − rs/r, at the Schwarzschild radius rs, the scalar field value approaches zero: ϕ(r) = 0. (A.5) At r = rs, the scalar field value $\phi \to 0$, and its coordinate derivative diverges, corre- sponding to the coordinate singularity of the Schwarzschild metric at this radius. Within this model's framework, $\phi = 0$ means the local energy scale defined by E = mϕ reduces to zero, thereby invalidating the foundation for constructing the emergent metric gµ$\nu[\phi]$ based on the ϕ field. Therefore, r = rs can be regarded as an effective boundary for classical geometric description: in regions r ≤ rs, classical gravitational interactions driven by vacuum field gradients no longer dominate, and matter and energy behavior may be described by more fundamental non-geometric physics such as quantum field theory or strong interactions. This provides a field-theoretic boundary condition for understanding black hole internal structure different from traditional singularity images.

B Heuristic Derivation Under the Weak-Field Approx- imation This appendix aims to start from the core physical picture that "matter coupling to the vacuum scalar field produces vacuum field gradients," under the weak-field, low- velocity approximation, self-consistently derive the relationship between the matter mass density distribution ρ(r) and the vacuum scalar field ϕ(r), and uniquely determine the key parameters of the theory through connection with GR experimental observations.

B.1 Physical Picture and Model Setup Consider a static spherically symmetric body with rest mass M . The fundamental physi- cal picture is: mass M , through coupling with the preferred vacuum scalar field ϕ, alters the energy state of the vacuum around it. This coupling effect manifests specifically in two aspects: 1. Vacuum energy density ρ(r) redistributes from the uniform background value $ $0. 2. Vacuum scalar field ϕ(r) develops a corresponding spatial distribution from the uniform background value $ $0.

To quantitatively describe this coupling effect, we establish a phenomenological steady- state model: - Vacuum Energy Flow Model: The presence of mass M excites a steady-state, radially inward vacuum energy flow in the surrounding vacuum, with ra- dial energy flux density denoted jr(r). This represents the directed transport process of energy from the background vacuum toward the region containing mass M . - Bound- ary Condition: At a characteristic radius rb near the mass surface, the matter-vacuum coupling is considered strongest. We assume that at this location, the vacuum energy density is "depleted" to zero: ρ(rb) = 0. (B.1) B.2 Derivation of Vacuum Energy Density Distribution ρ(r) Under spherically symmetric steady-state conditions, the total energy flux through any spherical surface of radius r (r > rb) is conserved: jr(r) · 4πr2 = jr(rb) · 4πr2 b jr(r) = r2 jr(rb). (B.2) For any region with r > rb, the change in vacuum energy density is determined by the divergence of the energy flux (i.e., net inflow rate). Considering a spherical shell region from radius r to infinity, the decrease rate of vacuum energy density inside equals the energy inflow rate through the spherical surface at radius r. Under steady-state conditions, this yields the integral relation: $ $0 − ρ(r) = (cid:90) ∞ (cid:20) (cid:21) dr(cid:48) (4πr(cid:48)2jr(r(cid:48))) dr(cid:48) = (cid:90) ∞ r(cid:48)2 jr(rb)dr(cid:48) = rbjr(rb) ·(B.3) Applying condition (B.1) at the boundary r = rb, we obtain: $ $0 = rbjr(rb) jr(rb) = (B.4) Substituting (B.4) into (B.3), we finally obtain the vacuum energy density distribution: ρ(r) = $ $0 (cid:16) (cid:17) r > rb. (B.5) B.3 Derivation of Vacuum Scalar Field ϕ(r) Distribution According to Postulate A.2, this theory must reproduce the highly-precision-validated predictions of general relativity in solar system-scale weak-field, static gravitational fields.

General relativity in the weak-field low-velocity limit precisely returns to Newtonian grav- ity theory; therefore, this theory under the weak-field approximation must give gravita- tional acceleration consistent with Newtonian gravity: agrav(r) = − (B.6) From the universal dynamical relation a = $-\nabla\phi$ derived in Section 2.4 (equation (2.20)), the spatial gradient of the vacuum scalar field directly determines the test particle' s acceleration. Substituting the above gives: $-\nabla\phi$ = − Integrating with respect to the radial coordinate: ϕ(r) = − (B.7) (B.8) where C is an integration constant. Using the boundary condition: as r → ∞, spacetime tends to Minkowski, and the scalar field tends to the background value \$ \$0, so C = \$ \$0.

Therefore, At the coupling characteristic radius rb, we impose the condition corresponding to the energy density boundary condition: ϕ(r) = \$ \$0 − (B.9) ϕ(rb) = 0.

Substituting (B.10) into (B.9) gives the relationship between the background value \$ \$0 and the parameters rb, M : (B.10) Thus, the scalar field distribution can be rewritten as: 0 = \$ \$0 − \$ \$0 = ϕ(r) = \$ \$0 (cid:16) (cid:17) r > rb. (B.11) (B.12) B.4 Establishment of the Proportionality Relation Between ρ(r) and ϕ(r) Comparing (B.5) and (B.12), we find that the vacuum energy density distribution ρ(r) and the vacuum scalar field distribution ϕ(r) have exactly the same spatial dependence form (1 − rb/r). This directly leads to a simple proportionality relation: ρ(r) = ϕ(r). (B.13) This relation indicates that the vacuum energy rearrangement caused by the presence of matter is mathematically isomorphic to the vacuum scalar field gradient distribution it produces. This is a natural corollary of this model under the weak-field approximation.

References

[1] Will, C. M. (2014). The Confrontation between General Relativity and Experiment.

Living Reviews in Relativity, 17, 4. [2] Weinberg, S. (1989). The cosmological constant problem. Reviews of Modern Physics, 61(1), 1-23. [3] Brans, C., & Dicke, R. H. (1961). Mach' s Principle and a Relativistic Theory of Gravitation. Physical Review, 124(3), 925-935. [4] Jacobson, T., & Mattingly, D. (2001). Gravity with a dynamical preferred frame.

Physical Review D, 64, 024028. [5] Kostelecký, V. A., & Samuel, S. (1989). Spontaneous breaking of Lorentz symmetry in string theory. Physical Review D, 39(2), 683-685. [6] Milgrom, M. (1983). A modification of the Newtonian dynamics as a possible alter- native to the hidden mass hypothesis. The Astrophysical Journal, 270, 365-370. [7] Volovik, G. E. (2003). The Universe in a Helium Droplet. Oxford University Press. [8] Clifton, T., Ferreira, P. G., Padilla, A., & Skordis, C. (2012). Modified Gravity and Cosmology. Physics Reports, 513(1-3), 1-189. [9] Goldstein, H., Poole, C., & Safko, J. (2002). Classical Mechanics (3rd ed.). Addison- Wesley. [10] Wald, R. M. (1984). General Relativity. University of Chicago Press. [11] Misner, C. W., Thorne, K. S., & Wheeler, J. A. (1973). Gravitation. W. H. Freeman. [12] Hou, S., Gong, Y., & Liu, Y. (2017). Polarizations of Gravitational Waves in Horn- deski Theory. arXiv:1704.01899. [13] Arun, K. G., Belgacem, E., Benkel, R., Bernard, L., Berti, E., Bertone, G., et al. (LISA Consortium). (2022). New horizons for fundamental physics with LISA. Living Reviews in Relativity, 25, 4. (arXiv:2205.01597) [14] Barausse, E., et al. (2020). Prospects for fundamental physics with LISA. General Relativity and Gravitation, 52, 81. [15] Abbott, B. P., et al. (LIGO Scientific Collaboration and Virgo Collaboration). (2017). GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. Physical Review

Letters, 119, 161101. [16] Abbott, B. P., et al. (LIGO Scientific Collaboration and Virgo Collaboration). (2019). Tests of General Relativity with GW170817. Physical Review Letters, 123, [17] de Rham, C., Gabadadze, G., & Tolley, A. J. (2011). Resummation of Massive Gravity. Physical Review Letters, 106, 231101. [18] Conroy, A., & Koivisto, T. (2019). Parity-Violating Gravity and GW170817 in Non- Riemannian Cosmology. arXiv:1908.04313. [19] Lagos, M., Jenks, L., Isi, M., et al. (2024). Birefringence tests of gravity with multi- messenger binaries. Physical Review D, 109, 124003. [20] Ng, T. C. K., Isi, M., Wong, K. W. K., et al. (2023). Constraining gravitational wave amplitude birefringence with GWTC-3. Physical Review D, 108, 084068. [21] Isi, M. (2023). Parametrizing gravitational-wave polarizations. Classical and Quan- tum Gravity, 40, 203001. [22] Wang, P.-P., Tan, Y.-J., Qian, W.-L., & Shao, C.-G. (2021). Sensitivity functions of space-borne gravitational wave detectors for arbitrary time-delay interferometry combinations regarding nontensorial polarizations. Physical Review D, 104, 023002. [23] Xu, C., Jin, H.-B., & Wu, Y.-L. (2025). Detector Response to Gravitational Wave Polarizations in Gravitational Quantum Field Theory. arXiv:2504.01809. [24] Peebles, P. J. E. (1993). Principles of Physical Cosmology. Princeton University Press. [25] Delva, P., et al. (2017). Test of special relativity using a fiber network of optical clocks. Physical Review Letters, 118, 221102. [26] Sah, A., Rameez, M., Sarkar, S., & Tsagas, C. G. (2025). Anisotropy in Pantheon+ supernovae. The European Physical Journal C, 85, 596. [27] Miquel, R. (on behalf of the DESI Collaboration). (2026). Cosmological constraints from the first-year BAO measurements of the Dark Energy Spectroscopic Instrument (DESI). Springer Proceedings in Physics, 322, 13-21. [28] Gu, G., Wang, X., Wang, Y., et al. (2025). Dynamical dark energy in light of the DESI DR2 baryonic acoustic oscillations measurements. Nature Astronomy. [29] Chakraborty, A., Chanda, P. K., Das, S., & Dutta, K. (2025). DESI results: Hint to- wards coupled dark matter and dark energy. Journal of Cosmology and Astroparticle Physics, 11, 047.

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