The GETT Covariant Scalar-Density Framework for Emergent Gravity and Cosmology.

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General Expanse Tension Theory (GETT) Covariant Action Construction, Field Equations, Density-Regulated Interaction Structure, and Astrophysical Tests.

Abstract

Modern fundamental physics is described by two highly successful but conceptually distinct frameworks: quantum field theory (QFT), which governs the interactions of elementary particles, and General Relativity (GR), which describes gravitation through spacetime curvature. Despite their empirical success, a unified field-theoretic description of gravitational phenomena within the same framework as the Standard Model remains unresolved. In parallel, the standard cosmological model requires the introduction of dark matter and dark energy components whose microphysical origin remains uncertain.

In this work we present a covariant effective field-theory framework in which gravitational phenomena arise from interactions between matter and a universal scalar field whose coupling strength depends on environmental baryonic density. The scalar field, denoted Φ, is a real gauge-invariant singlet that couples to the Standard Model through a Higgs-sector portal. The interaction strength is regulated by a continuous modulation function $S(\Sigma)$, where Σ is a covariant scalar constructed from the local stress–energy tensor and represents the coarse-grained matter density of the environment.

This density-regulated interaction naturally produces distinct dynamical regimes. In mid-density environments such as laboratories, planetary systems, and stellar interiors, scalar coupling is strongly suppressed, and the framework reduces to General Relativity coupled to the Standard Model. In low-density astrophysical environments the scalar interaction may become active and modify effective gravitational behaviour, potentially influencing galaxy rotation dynamics, vertical stellar kinematics, gravitational lensing in cosmic voids, and the growth of large-scale structure. At sufficiently extreme densities, such as those encountered in compact astrophysical objects, an additional high-density activation regime may occur.

The framework is formulated entirely within the language of relativistic quantum field theory and preserves general covariance, local Lorentz invariance, and Standard Model gauge symmetry. By introducing a density-regulated scalar–matter interaction, the model provides a unified field-theoretic setting in which gravitational phenomena traditionally attributed to dark matter and dark energy may instead arise from environment-dependent coupling between matter and a fundamental scalar field. The resulting theory yields a range of observational predictions across astrophysical and cosmological density regimes, providing multiple opportunities for empirical testing.

Keywords:
gravitation – cosmology: theory – galaxies: kinematics and dynamics – large-scale structure of Universe – dark matter – dark energy – scalar fields – modified gravity – Higgs portal – density-dependent coupling.

1. Introduction

Modern fundamental physics rests on two extraordinarily successful theoretical frameworks. Quantum field theory (QFT), embodied in the Standard Model of particle physics, accurately describes the behaviour of elementary particles and their interactions across a wide range of experimental regimes [3-5]. General Relativity (GR), meanwhile, provides a geometric (i.e. purely *mathematical)* description of gravitation in which spacetime curvature arises from the distribution of energy and momentum [1,2]. Each framework has been validated with remarkable precision within its respective domain.

Despite these successes, the relationship between gravitation and the quantum description of matter remains unresolved. Gravity is not currently embedded within the same quantum field-theoretic structure that successfully describes the other fundamental interactions. Attempts to quantise gravity directly encounter severe theoretical difficulties, while effective field theory approaches suggest that additional degrees of freedom or mechanisms may operate beyond the regimes currently accessible to experiment.

At the same time, the standard cosmological model, ΛCDM, requires the introduction of two components whose microphysical origin remains uncertain: non-baryonic dark matter and dark energy. Dark matter is invoked to explain galaxy rotation curves, gravitational lensing signatures, and the growth of large-scale structure. Dark energy is introduced to account for the observed late-time acceleration of cosmic expansion. Although the ΛCDM model provides an excellent phenomenological description of many cosmological observations, neither dark matter nor dark energy has yet been directly detected as a fundamental particle or field within laboratory experiments. Although ΛCDM as a mathematical framework successfully fits many observations, the fundamental microphysical nature of dark matter and dark energy remains unresolved [9-11].

These challenges have motivated the exploration of modified gravity and scalar–tensor theories in which additional scalar degrees of freedom modify gravitational behaviour on cosmological scales while remaining consistent with precision tests in the Solar System. In many such models, the scalar field couples universally to matter but is suppressed in dense environments through a screening mechanism. Examples include chameleon fields, symmetron models, and other environmentally dependent scalar frameworks. These theories illustrate how additional scalar dynamics may remain hidden in regions where gravitational physics has been precisely tested while producing measurable deviations in low-density regimes [12-17].

In this work we develop a covariant effective field theory framework in which gravitational phenomena arise from the interaction between matter and a universal scalar field whose coupling strength depends on the local coarse-grained baryonic density. The central concept is the introduction of an environmental modulation function that controls the interaction strength between the scalar field and matter. The scalar field, denoted here by Φ, couples to the Standard Model Higgs sector [6-8] through a density-modulated interaction. The coupling strength is governed by a smooth function $S(\Sigma)$, where Σ is a covariant scalar constructed from the local stress–energy tensor.

This mechanism produces a natural environmental hierarchy in the strength of scalar interactions. In mid-density environments – which we define precisely in this paper – such as laboratories, planetary systems, and stellar interiors, the modulation function suppresses the scalar coupling. In this limit the framework reduces to standard General Relativity coupled to the Standard Model of particle physics, ensuring consistency with existing experimental constraints. In contrast, in low-density environments such as cosmic voids or the outskirts of galaxies, the modulation function allows the scalar interaction to become active. In these regimes the scalar field can modify effective gravitational behaviour, producing controlled deviations from GR. At sufficiently extreme high densities, such as those present in neutron star interiors, the modulation function enters a high-density activation branch in which scalar coupling becomes significant again, potentially producing departures from standard gravitational behaviour. In this regime, where anomalous phenomena manifest observationally through abrupt dynamical transitions, we assign causal mechanism to neutron-star glitches.

Embedding this mechanism within a covariant effective field theory ensures that the resulting framework respects the fundamental symmetries of modern physics. The construction preserves general covariance and local Lorentz invariance while maintaining Standard Model gauge invariance [5-8]. Scalar couplings are introduced through a Higgs-mediated portal that remains composition-independent, thereby preserving universality of free fall within environments where the modulation function is suppressed.

In constructing any theoretical framework it is essential to identify the established physical principles that are preserved and the domains in which departures may occur. In the present framework the following foundational symmetries are regarded as essential and are explicitly maintained throughout the construction of the theory.

- **General Covariance**
  The principle that the laws of physics take the same mathematical form under arbitrary smooth coordinate transformations. Physical laws must therefore be independent of the coordinate system used to describe spacetime.
- **Local Lorentz Invariance**
  The requirement that, in any sufficiently small region of spacetime, the laws of physics reduce to those of special relativity and are invariant under Lorentz transformations (rotations and boosts) between locally inertial reference frames.
- **Standard Model Gauge Invariance**
  The symmetry principle underlying the Standard Model in which the fundamental interactions arise from invariance under internal gauge transformations of the symmetry group $SU(3)_C \times SU(2)_L \times U(1)_Y$.
  These gauge symmetries determine the structure of particle interactions and the associated force-carrying fields.

The environmental modulation mechanism leads to several potentially observable consequences. In low-density environments the scalar interaction may modify galaxy rotation dynamics, enhance weak gravitational lensing in cosmic voids, and alter the growth of large-scale structure. Because the scalar coupling strength depends explicitly on environmental density, the theory predicts characteristic correlations between gravitational phenomena and large-scale matter distribution. Such correlations provide natural observational tests across astrophysical and cosmological datasets.

The central aim of this work is to reformulate classical gravitation within the language of quantum field theory, replacing a purely geometric description with explicit matter–field dynamics. Within this framework the equations of General Relativity arise as the terrestrial local-mid-density effective limit of a more fundamental scalar–matter interaction.

The purpose of this paper is to present the theoretical structure of this scalar–density framework and examine its behaviour across relevant physical regimes. We first introduce the conceptual ingredients of the model, including the scalar field, the environmental density scalar, and the modulation function controlling scalar–matter coupling. We then construct the covariant action governing the system and derive the resulting field equations. The behaviour of the theory is examined in several limiting regimes, including the high-density limit where General Relativity is recovered, the non-relativistic limit relevant for gravitational dynamics, and the cosmological limit relevant for large-scale structure formation. Finally, we discuss potential observational consequences and outline experimental tests capable of confirming or falsifying the proposed framework.

2. Conceptual Framework

The framework developed in this work introduces a scalar–matter interaction whose strength depends on the environmental density of baryonic matter. The central idea is that gravitational phenomena arise from the interaction between matter and a universal scalar field whose coupling strength is smoothly modulated by the local matter environment.

Unlike approaches that introduce fundamentally new geometrical structures or speculative physical entities, the present framework is constructed entirely within the standard language of quantum field theory. The model employs a minimal set of fields and interactions that respect established symmetries of modern physics, including general covariance, local Lorentz invariance, and Standard Model gauge invariance [5-8] . In this sense, the theory represents a QFT-permitted extension of known physics rather than the introduction of exotic new principles. The framework is therefore designed to operate as an effective field theory in which gravitational behaviour emerges from scalar–matter interactions that depend on environmental density.

2.1 Field Content

The theory introduces a minimal set of dynamical ingredients:

- **The Holland Scalar field Φ**
  A real, physical, gauge-invariant singlet scalar field that couples to the Standard Model Higgs sector through a continuously density-modulated interaction. The coupling strength is regulated by the environmental modulation function $S(\Sigma)$, allowing scalar–matter interactions to depend on the local coarse-grained baryonic density [25].
- **Standard Model Higgs field H**
  The Higgs doublet already present within the Standard Model. In this framework it provides a natural portal through which the scalar field can couple to matter through mass-generating interactions [6-8].
- **Standard Model matter fields ψ_i**
  Fermions and gauge bosons of the Standard Model whose gauge interactions remain unchanged.
- **Spacetime metric $g_{\mu\nu}$**
  The metric field describing spacetime geometry. In the high-density limit the dynamics reduce to those of General Relativity.
- **Density-regime thresholds and scalar activation domains ("switches")**
  Characteristic environmental density regimes defined through the modulation function $S(\Sigma)$. These regimes determine when scalar–matter coupling becomes dynamically significant or suppressed. Within the broader GETT framework these thresholds correspond to density-dependent interaction domains ("switches") governing the activation or suppression of scalar coupling across astrophysical and cosmological environments.

The introduction of a scalar field interacting with matter through a Higgs-mediated portal is fully consistent with the structure of quantum field theory and does not require modifications to the gauge structure of the Standard Model.

Term	Symbol	Units	Definition
Holland Scalar Field	**Φ** (Phi)	field (mass dimension 1)	A real, physical, gauge-invariant singlet scalar field mediating environment-dependent gravitational interactions within the GETT framework.
Environmental Density Scalar	**Σ** (Sigma)	kg m^{-3}	A covariant scalar constructed from the local stress–energy tensor representing coarse-grained baryonic matter density.
Density Modulation Function	**$S(\Sigma)$**	dimensionless	A continuous function regulating the strength of scalar–matter coupling as a function of environmental density.
Maximum Coupling Strength	**S_{max}**	dimensionless	The maximum possible value of the scalar coupling strength in the low-density limit.
Characteristic Density Scale	**Σ_c**	kg m^{-3}	The density threshold controlling the transition between suppressed and active scalar coupling regimes.
Transition Sharpness Parameter	***n***	dimensionless	Parameter controlling the steepness of the density-modulation transition in (S(\Sigma)).
Higgs Field	***H***	field	The Standard Model Higgs doublet responsible for electroweak symmetry breaking and mass generation.
Higgs Portal Coupling	κ_H (kappa_H)	dimensionless	Coupling coefficient linking the Holland scalar field to the Higgs sector through the interaction term $\Phi H^\dagger H$
Scalar–Matter Coupling	**$y_i(\Phi)$**	dimensionless	Effective Yukawa-type coupling between the Holland scalar field and fermionic matter fields.
Stress–Energy Tensor	**$T_{\mu\nu}$** (T_{\mu\nu})	energy density	Tensor describing the local distribution of energy and momentum in spacetime.
Metric Tensor	**$g_{\mu\nu}$** (g_{\mu\nu})	dimensionless	The spacetime metric defining distances and curvature within the covariant framework.
Scalar Field Potential	**$V(\Phi)$** (V(\Phi))	energy density	Self-interaction potential governing the dynamics of the Holland scalar field.
Scalar Field Mass	**m_Φ** (m_{\Phi})	energy (or inverse length)	Effective mass scale associated with the scalar field potential.
Planck Mass	**M_{Pl}** (M_{\rm Pl})	GeV or kg	Reduced Planck mass defining the gravitational coupling scale in the Einstein–Hilbert action.
Environmental Activation Regime	—	—	Density regime in which scalar coupling becomes dynamically significant, including low-density cosmic environments and extreme high-density compact objects.

Table 1. Terms, Symbols, Units and Definitions

Table 1 summarises the principal symbols and technical terms used in the conceptual framework. All quantities correspond to standard constructs within relativistic quantum field theory, including scalar fields, stress–energy tensors, and Higgs-sector interactions. The table is included for clarity and reference, as the framework employs only conventional QFT ingredients rather than introducing new mathematical structures.

Within the broader GETT framework the scalar field represents a physical energy–matter field whose large-scale dynamics are associated with cosmological expansion, although the detailed cosmological implications are discussed later in the paper.

2.2 Environmental Density Scalar

We begin with the standard trace of the stress–energy tensor. The environmental density scalar used to regulate scalar coupling is constructed from the local stress–energy tensor $T_{\mu\nu}$. The stress–energy tensor describes the local distribution of energy, momentum, and pressure in spacetime, and provides the natural covariant measure of matter content within relativistic field theory.

$$T = g^{\mu\nu} T_{\mu\nu}$$

where the local energy density measured by an observer moving with 4-velocity u^{μ}. Physically this is:

$$\rho_{\text{local}} = T_{\mu\nu} u^{\mu} u^{\nu}$$

In the rest frame of matter it reduces to ρ. This term uses the local energy density as part of the environmental density measure, which is the intuitive baryonic density element. A covariant scalar quantity characterising the local matter environment can therefore be constructed from $T_{\mu\nu}$. In the present framework this quantity is denoted by Σ. The strength of the scalar interaction depends on a covariant scalar quantity representing the local matter environment. This environmental scalar is constructed from the stress–energy tensor of matter, as follows.

$$\Sigma = T_{\mu\nu} u^{\mu} u^{\nu} \qquad \text{Eq. 2.1}$$

A representative form is

$$\Sigma = \alpha_1 T^{\mu\nu} u_{\mu} u_{\nu} + \alpha_2 T \qquad \text{Eq. 2.2}$$

where u^{μ} is a timelike unit vector field and $T = g_{\mu\nu} T^{\mu\nu}$ is the trace of the stress–energy tensor. The first term measures the local energy density in the rest frame of matter, while the trace term incorporates relativistic pressure contributions, ensuring that the environmental scalar responds appropriately across non-relativistic, relativistic, and compact-object regimes. This ensures the density scalar is covariant, constructed only from existing fields**,** captures both energy density and relativistic stress, and works in cosmology, galaxies, and neutron stars**.** It is a general covariant density functional**.** The scalar Σ therefore acts as a covariant measure of the coarse-grained baryonic density of the local environment. Because it is constructed directly from the stress–energy tensor, it introduces no new independent dynamical degrees of freedom and preserves the locality of the theory.

2.3 Density-Modulated Coupling

The key mechanism of the framework is a modulation function that controls the strength of scalar–matter coupling as a function of environmental density. The modulation function is defined as

$$S(\Sigma) = \frac{S_{\max}}{1 + (\Sigma/\Sigma_c)^n} \qquad \text{Eq. 2.3}$$

Here

- $S_{\max}$ defines the maximum scalar coupling strength,
- Σ_c defines the characteristic density scale at which the transition occurs,
- n determines the sharpness of the transition.

The function satisfies

$$\frac{dS}{d\Sigma} < 0 \qquad \text{Eq. 2.4}$$

ensuring that scalar coupling decreases smoothly as environmental density increases.

This behaviour introduces a natural environmental hierarchy, resulting in scalar interaction strength that is therefore not constant but depends directly on the physical environment through the density scalar Σ.

2.4 Density Regimes and Scalar Activation

Because the scalar–matter coupling depends explicitly on environmental density, it is useful to identify characteristic density regimes relevant to different physical environments. Table 2 summarises representative baryonic density ranges associated with the principal activation regimes discussed in the GETT framework [28]. These ranges are approximate and intended only to provide physical orientation for the modulation behaviour of the scalar interaction.

Regime	Approximate Density (kg m⁻³)	Physical Context	GETT Interpretation	Scalar Coupling Behaviour
Symmetry Restoration Regime (Big bang, & BH core)	$\rho \gtrsim 10^{30}$	Early universe before electroweak symmetry breaking; extreme compact object cores	Higgs vacuum expectation value suppressed; electroweak symmetry restored	Scalar–mass coupling effectively absent
Electroweak Symmetry Breaking (EWSB) Threshold	$\rho \sim 10^{25-30}$	Early universe cooling through EWSB epoch. The orthogonal emergence of gravity, inertia, and time.	Higgs field acquires vacuum expectation value	Scalar–Higgs portal becomes dynamically meaningful
Ultra-low Density Regime	$\rho \lesssim 10^{-27}$	Cosmic voids and intergalactic medium. GETT “Bright Voids”	Switch A 10^{-27}	Scalar coupling active; cosmological dynamics dominate
Low Density Regime	$10^{-27} \lesssim \rho \lesssim 10^{-23}$	Galaxy outskirts and halos	Switch B (late-time acceleration regime)	Scalar coupling modifies effective gravity
Galactic Density Regime	$10^{-23} \lesssim \rho \lesssim 10^{-19}$	Galactic discs and stellar systems	Switch D $10^{-21.6}$	Scalar coupling strengthens as baryonic density decreases (e.g. outer regions)
Mid-Density Regime	$10^{-19} \lesssim \rho \lesssim 10^{5}$	Planetary systems, terrestrial environments, stellar interiors	—	Scalar coupling strongly suppressed; GR recovered
Extreme-Density Regime	$\rho \gtrsim 10^{17}$	Neutron stars and compact objects	Switch E 10^{-17}	High-density scalar activation branch

Table 2. GETT Scalar-Density Impact Regime Table

Table 2 demonstrates that scalar–matter interaction depends explicitly on environmental density, the framework naturally divides physical systems into characteristic density regimes. This summarises representative density scales relevant to different environments spanning particle physics, astrophysics, and cosmology. These ranges are indicative and serve to illustrate the regimes in which different branches of the scalar coupling behaviour may become relevant. In sufficiently extreme density regimes, the restoration of electroweak symmetry implies that scalar–mass coupling may vanish, suggesting that the conventional gravitational description may cease to apply before arbitrarily large densities are reached. The ultra-low-density "Bright Voids" domain represents the extreme low-Σ extension of the scalar activation branch, where the coupling approaches its maximal environmentally permitted strength [32] .

This table highlights that the scalar–matter interaction spans density regimes ranging from particle-physics scales to astrophysical environments: it connects particle-physics phase structure (e.g. EWSB) with astrophysical density regimes in a single environmental framework. The scalar–matter interaction can therefore be interpreted as defining a density-dependent phase structure spanning particle-physics, astrophysical, and cosmological environments.

Primary density-related terminology

- **Low-density regime**
  Cosmic environments where scalar coupling becomes active (e.g. outer galaxy, void)
- **Mid-density regime**
  Terrestrial, planetary, and stellar environments where scalar coupling is suppressed and GR is recovered.
- **High/Extreme-density regime**
  Compact-object environments where a high-density activation branch may occur (e.g. pulsars, neutron star, and black holes cores etc)

Within the present framework these three characteristic density regimes may be distinguished: a low-density regime in which scalar coupling becomes active on large astrophysical scales, a mid-density regime corresponding to terrestrial and stellar environments where the coupling is strongly suppressed and General Relativity is recovered, and an extreme-density regime associated with compact objects where a high-density activation branch may occur. In effect, a density-regulated interaction theory.

2.5 Conceptual Role of the Modulation Mechanism

Within this framework the modulation function acts as a regulator that determines when scalar–matter interactions contribute significantly to gravitational behaviour. In regions where the modulation suppresses the scalar interaction, the dynamics reduce to those of General Relativity coupled to the Standard Model. This ensures consistency with the extensive set of laboratory, Solar System, and astrophysical tests that confirm Einsteinian gravity in dense environments. In contrast, in sufficiently low-density regions the scalar interaction becomes active and can modify effective gravitational behaviour. Because the strength of this interaction depends explicitly on environmental density, the theory predicts correlations between gravitational phenomena and large-scale matter distribution.

The density-modulation mechanism therefore provides a physically motivated way to introduce new gravitational behaviour while preserving the empirical success of General Relativity in regimes where it has been precisely tested.

3. Covariant Action

The conceptual framework introduced in the previous section can be formalised within a generally covariant effective field theory. The theory is constructed so that it respects the core symmetries of modern physics, including general covariance, local Lorentz invariance, and Standard Model gauge invariance. In this formulation gravitational behaviour arises from the interaction between matter and the Holland scalar field Φ, whose coupling strength is modulated by the environmental density scalar

Σ. The dynamics of the system are defined through a covariant action composed of four principal contributions: the Einstein–Hilbert gravitational term, the scalar field sector, the Standard Model matter sector, and the density-modulated interaction terms.

The theory is defined by a generally covariant Lagrangian density whose terms specify the field content and interaction structure of the framework. The corresponding action is obtained through spacetime integration of this Lagrangian density.

$$\mathcal{L} = \frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \Phi \, \partial_\nu \Phi - V(\Phi) + \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{int}}$$

Eq. 3.1

With the interaction equation:

$$\mathcal{L}_{\text{int}} = -S(\Sigma) \kappa_H \Phi H^\dagger H - S(\Sigma) \sum_i y_i^{(\Phi)} \, \Phi \bar{\psi}_i \psi_i$$

Eq. 3.3

The covariant action of the theory is obtained by integrating the Lagrangian density over spacetime,

$$S = \int d^4x \sqrt{-g} \, \mathcal{L}$$

Eq. 3.4

The total action can therefore be written as

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} (\nabla\Phi)^2 - V(\Phi) \right] + S_{\text{SM}} + S_{\text{int}}$$

Eq. 3.5

Here g is the determinant of the metric tensor $g_{\mu\nu}$, R is the Ricci scalar curvature, and M_{Pl} is the reduced Planck mass. The first term corresponds to the standard Einstein–Hilbert action governing spacetime curvature. The second and third terms describe the kinetic and potential contributions of the Holland scalar field. The term S_{SM} represents the Standard Model action describing all known gauge and matter fields.

The Standard Model action S_{SM} retains its conventional form and gauge structure within the present framework. However, because the Holland scalar field couples to the Higgs sector through the density-modulated interaction term described below, effective particle masses and interaction strengths may acquire an environmental dependence through their coupling to the scalar field. In this sense the environmental dependence of Standard Model parameters arises dynamically through the scalar sector rather than through explicit modification of the Standard Model Lagrangian itself. The framework may be expressed compactly through the generally covariant full Lagrangian density

$$\mathcal{L} = \frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu \Phi \, \partial_\nu \Phi - V(\Phi) + \mathcal{L}_{\text{SM}} - S(\Sigma) \, \kappa_H \, \Phi \, H^\dagger H - S(\Sigma) \sum_i y_i^{(\Phi)} \, \Phi \, \bar{\psi}_i \psi_i.$$

Eq. 3.6

where $\mathcal{L}_{\text{SM}}$ denotes the unmodified Standard Model Lagrangian, while the final two terms describe density-modulated couplings of the Holland scalar field to the Higgs sector and to fermionic matter.

In this form we see:

standard gravity + standard QFT + one singlet scalar + density-modulated interaction structure.

Within this construction the Standard Model sector remains unchanged. Gauge symmetries and particle interactions therefore retain their conventional form. The scalar field Φ is introduced as a gauge-invariant singlet and does not alter the gauge structure of the Standard Model.

3.1 Scalar Field Sector

The scalar field contribution to the action takes the standard relativistic form

$$\mathcal{L}_{\Phi} = -\frac{1}{2} g^{\mu\nu}\, \partial_\mu \Phi\, \partial_\nu \Phi - V(\Phi) \qquad \text{Eq. 3.7}$$

where $V(\Phi)$ is the scalar potential governing the self-interaction of the field. The potential determines the effective mass scale of the scalar field through

$$m_\Phi^2 = \frac{d^2 V}{d\Phi^2} \qquad \text{Eq. 3.8}$$

The specific form of the potential is not fixed at this stage and may be chosen according to phenomenological constraints. The framework therefore remains compatible with the general methodology of effective field theory, where the leading operators relevant at a given energy scale are retained.

3.2 Higgs Portal Interaction

Interactions between the Holland scalar field and Standard Model matter arise through a Higgs-sector portal. The Higgs field provides a natural mediator for scalar interactions because it is responsible for mass generation through electroweak symmetry breaking.

The leading interaction term takes the form

$$\mathcal{L}_{\Phi H} = -S(\Sigma)\, \kappa_H\, \Phi\, H^\dagger H \qquad \text{Eq. 3.9}$$

Here H denotes the Standard Model Higgs doublet and κ_H is the Higgs portal coupling coefficient. The factor $S(\Sigma)$ is the environmental modulation function introduced in Section 2. The presence of the modulation factor ensures that the scalar–Higgs interaction strength depends explicitly on the local environmental density.

3.3 Scalar–Matter Couplings

In addition to the Higgs portal interaction, effective couplings between the scalar field and fermionic matter fields may arise through Yukawa-type interactions. These can be written in the general form

$$\mathcal{L}_{\Phi\psi} = -S(\Sigma) \sum_i y_i^{(\Phi)} \, \Phi \, \bar{\psi}_i \psi_i \qquad \text{Eq. 3.10}$$

Here ψ_i denotes the fermion fields of the Standard Model and $y_i^{(\Phi)}$ represents the corresponding scalar–matter coupling coefficients.

As with the Higgs portal interaction, the coupling strength is modulated by the environmental function $S(\Sigma)$. In regions where the modulation function is suppressed, the scalar interaction effectively vanishes, and the theory reduces to conventional General Relativity coupled to the Standard Model.

3.4 Density-Modulated Interaction Structure

The defining feature of the framework is that all scalar–matter couplings are regulated by the environmental modulation function $S(\Sigma)$. The interaction Lagrangian can therefore be written schematically as

$$\mathcal{L}_{\text{int}} = S(\Sigma) \, \mathcal{L}_{\text{scalar-matter}} \qquad \text{Eq. 3.11}$$

This structure ensures that the scalar interaction strength is not fixed by a universal constant but instead depends on the physical environment through the density scalar Σ.

In low-density regimes the modulation function approaches its maximal value, allowing scalar interactions to become dynamically significant. In intermediate-density environments the modulation suppresses the scalar interaction, ensuring recovery of the gravitational behaviour predicted by General Relativity. At sufficiently extreme densities, such as those encountered in neutron star interiors, the modulation function may transition into a high-density activation branch, producing a second regime of active scalar coupling.

The covariant action therefore provides a unified field-theoretic description in which the strength of scalar-mediated gravitational effects depends explicitly on the local matter environment.

4. Field Equations

The dynamical behaviour of the system follows from variation of the covariant action with respect to the independent fields. In the present framework the fundamental degrees of freedom are the spacetime metric $g_{\mu\nu}$ and the Holland scalar field Φ. Variation of the action therefore produces two principal sets of equations: the modified Einstein equations governing spacetime curvature and the scalar field equation governing the dynamics of Φ [1,2].

Because the action is constructed in a generally covariant form, the resulting equations automatically respect local Lorentz invariance and the conservation properties implied by diffeomorphism invariance.

4.1 Scalar Field Equation

Variation of the action with respect to the scalar field Φ yields the Klein–Gordon–type equation governing the scalar dynamics. Taking the functional derivative of the scalar sector and the interaction terms gives

$$\Box\Phi - V'(\Phi) = \frac{\partial\mathcal{L}_{\text{int}}}{\partial\Phi} \qquad \text{Eq. 4.1}$$

where

$$\Box\Phi = g^{\mu\nu}\nabla_\mu\nabla_\nu\Phi \qquad \text{Eq. 4.2}$$

is the covariant d'Alembert operator, and defines the curved-spacetime generalisation of the wave equation operator. Substituting the interaction terms introduced in Section 3 leads to

$$\Box\Phi - V'(\Phi) = S(\Sigma)\left(\kappa_H H^\dagger H + \sum_i y_i^{(\Phi)}\,\bar{\psi}_i\psi_i\right) \qquad \text{Eq. 4.3}$$

The scalar field therefore evolves under the influence of both its intrinsic potential $V(\Phi)$ and source terms associated with matter and the Higgs sector. The environmental modulation function $S(\Sigma)$ controls the strength of these source terms and therefore determines the degree to which scalar dynamics influence the surrounding gravitational behaviour.

In regimes where the modulation function is suppressed, the source term effectively vanishes, and the scalar field decouples from matter. Conversely, when the modulation function approaches its maximal value the scalar interaction becomes dynamically significant.

4.2 Modified Einstein Equations

Variation of the action with respect to the metric tensor $g_{\mu\nu}$ yields the gravitational field equations. The resulting equations take the form

$$M_{\text{Pl}}^2 G_{\mu\nu} = T_{\mu\nu}^{(\text{SM})} + T_{\mu\nu}^{(\Phi)} + T_{\mu\nu}^{(\text{int})} \qquad \text{Eq. 4.4}$$

where $G_{\mu\nu}$ is the Einstein tensor describing spacetime curvature.

The total stress–energy tensor receives contributions from three sectors:

1. the Standard Model matter fields,
2. the Holland scalar field,
3. the scalar–matter interaction terms.

The scalar field contribution takes the standard form

$$T_{\mu\nu}^{(\Phi)} = \nabla_\mu \Phi \nabla_\nu \Phi - \frac{1}{2} g_{\mu\nu} (\nabla\Phi)^2 - g_{\mu\nu} V(\Phi) \quad \text{Eq. 4.5}$$

The interaction contribution arises from variation of the density-modulated coupling terms. Because these interactions depend on the environmental scalar Σ, which itself is constructed from the stress–energy tensor, the interaction sector introduces a density-dependent modification to the effective gravitational dynamics.

In regions where the modulation function is strongly suppressed, the interaction contribution becomes negligible and the field equations reduce to those of General Relativity coupled to the Standard Model. In environments where the scalar interaction is active, additional contributions to the stress–energy tensor can modify the effective gravitational behaviour.

4.3 Conservation Properties

The action remains invariant under spacetime diffeomorphisms, ensuring that the total stress–energy tensor satisfies the covariant conservation law

$$\nabla^\mu T_{\mu\nu}^{\text{total}} = 0 \quad \text{Eq. 4.6}$$

This condition guarantees consistency between the scalar field dynamics and the gravitational field equations. Energy–momentum may be exchanged between the scalar field and the matter sector through the interaction terms, but the total energy–momentum of the system remains conserved.

Because the environmental density scalar Σ is constructed directly from the stress–energy tensor, the modulation function $S(\Sigma)$ does not introduce any explicit violation of local conservation laws. Instead, it acts as a regulator that determines the strength of scalar–matter coupling within a given physical environment.

4.4 Physical Interpretation

The resulting system of equations describes a coupled set of gravitational and scalar dynamics in which the strength of scalar–matter interaction depends explicitly on environmental density.

In environments where the modulation function suppresses scalar coupling, the scalar field becomes dynamically inert, and the system reduces to the familiar Einstein field equations of General Relativity. In low-density regimes the scalar interaction becomes active and can modify gravitational behaviour. At sufficiently extreme densities, such as those encountered in neutron star interiors, the modulation function may transition into a separate high-density activation regime in which scalar coupling becomes significant once again.

The field equations therefore provide a unified dynamical framework in which gravitational phenomena arise from scalar–matter interactions whose strength depends on the local matter environment.

5. Limiting Behaviour

Any proposed extension of gravitational theory must reproduce the well-established predictions of General Relativity and Newtonian gravity within the regimes where those theories have been experimentally confirmed. The recovery of classical kinematics and Newtonian gravitational behaviour within the GETT framework has been examined in detail in the accompanying Correspondence Series papers [33,34]. Because the present framework introduces an additional scalar degree of freedom, it is therefore essential to examine the behaviour of the system in several physically relevant limits.

The density-modulated coupling structure introduced in Section 2 naturally produces different dynamical regimes depending on the environmental value of the density scalar Σ. In this section we examine the behaviour of the theory in the high-density, weak-field, and cosmological limits.

5.1 Mid-Density Suppression Limit (GR Recovery)

In environments characterised by mid-scale baryonic density, such as laboratories, planetary systems, and stellar interiors, the environmental scalar Σ takes values significantly larger than the characteristic transition scale Σ_c. In this regime the modulation function satisfies

$$S(\Sigma) \to 0 \quad \text{for} \quad \Sigma \gg \Sigma_c \qquad \text{Eq. 5.1}$$

As a result, the interaction terms coupling the Holland scalar field to the Higgs sector and to fermionic matter become strongly suppressed. The scalar field therefore effectively decouples from the matter sector. Under these conditions the field equations reduce to

$$M_{\text{Pl}}^2 G_{\mu\nu} = T_{\mu\nu}^{(\text{SM})}$$

Eq. 5.2

which are precisely the Einstein field equations describing General Relativity coupled to Standard Model matter. Because the scalar interaction becomes dynamically inert in this limit, the framework automatically reproduces the gravitational behaviour observed in dense environments where experimental tests of GR have been performed with high precision.

This mid-density suppression therefore provides a natural mechanism ensuring compatibility with Solar System tests of gravity, laboratory experiments, and the internal dynamics of stars.

5.2 Weak-Field Limit

The weak-field limit corresponds to gravitational systems in which spacetime curvature is small and particle velocities are non-relativistic. In this regime the metric can be written as a perturbation about Minkowski spacetime,

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, |\, h_{\mu\nu} \,| \ll 1 \qquad \text{Eq. 5.3}$$

In the absence of scalar coupling the theory reduces to the standard Newtonian gravitational potential

$$\Phi_N(r) = -\frac{GM}{r} \quad \text{Eq. 5.4}$$

When scalar coupling is active, the presence of the Holland scalar field introduces an additional Yukawa-type contribution to the effective gravitational potential. The resulting potential can be written schematically as

$$\Phi_{\text{eff}}(r) = -\frac{GM}{r}\left[1 + \alpha(\Sigma)e^{-m_\Phi r}\right] \quad \text{Eq. 5.5}$$

where m_Φ is the effective mass of the scalar field and $\alpha(\Sigma)$ is an effective coupling parameter controlled by the density-modulation function.

In mid-density environments the suppression of $S(\Sigma)$ causes $\alpha(\Sigma)$ to approach zero, recovering the standard Newtonian gravitational potential. In lower-density environments the scalar contribution may become non-negligible and modify the effective gravitational force law.

5.3 Cosmological Background Limit

On cosmological scales the spacetime geometry is well described by a Friedmann–Lemaître–Robertson–Walker (FLRW) metric of the form

$$ds^2 = -dt^2 + a(t)^2(dr^2 + r^2 d\Omega^2) \quad \text{Eq. 5.6}$$

where $a(t)$ is the cosmological scale factor.

In this background the scalar field becomes a homogeneous function of cosmic time,

$$\Phi = \Phi(t) \quad \text{Eq. 5.7}$$

Substituting the scalar field into the field equations leads to the cosmological evolution equation

$$\ddot{\Phi} + 3H\dot{\Phi} + V'(\Phi) = \frac{\beta}{M_{\text{Pl}}}\, S(\Sigma)\, \rho_m \quad \text{Eq. 5.8}$$

Here β/M_{Pl} denotes an effective cosmological coupling obtained after coarse-graining the microscopic Higgs-portal and fermionic source terms into a macroscopic matter-density description, $H = \dot{a}/a$ is the Hubble parameter and ρ_m represents the matter density.

The presence of the modulation function introduces an explicit environmental dependence into the cosmological scalar dynamics. Because the cosmic matter density evolves with the expansion of the Universe, the scalar coupling strength can change over cosmological time scales. This behaviour allows the scalar field to influence large-scale cosmological dynamics without affecting gravitational physics in dense environments.

5.4 Extreme-Density Regime

At sufficiently extreme densities, such as those encountered in neutron star interiors, the environmental scalar may enter a regime where the modulation function transitions into a high-density activation branch. In this regime the scalar coupling can become dynamically significant once again.

This behaviour introduces a second regime of active scalar interaction distinct from the low-density activation occurring in cosmic environments. The possibility of such high-density activation suggests that compact astrophysical objects may provide sensitive probes of scalar–matter interactions within the framework.

Observational phenomena associated with neutron stars, including abrupt rotational transitions and other dynamical instabilities, may therefore offer potential signatures of this high-density scalar regime [27].

6. Observational Consequences

The density-modulated scalar interaction described in the preceding sections leads naturally to a range of observable phenomena across astrophysical and cosmological scales. Because the scalar–matter coupling depends explicitly on the environmental density scalar Σ, the theory predicts that gravitational behaviour may vary systematically between regions of different matter density. This environmental dependence provides a distinctive observational signature of the framework.

In this section we briefly outline several classes of phenomena in which such effects may arise.

6.1 Galaxy Rotation Dynamics

One of the most prominent empirical challenges for conventional gravitational theory arises from the observed rotation curves of galaxies. Measurements of stellar and gas orbital velocities in spiral galaxies show that rotation speeds remain approximately constant at large radii rather than decreasing according to the Newtonian expectation based solely on visible baryonic matter.

Within the present framework, the outskirts of galaxies represent relatively low-density environments in which the modulation function $S(\Sigma)$ may permit scalar coupling to become active. In this regime the scalar interaction can modify the effective gravitational potential experienced by orbiting matter.

The additional Yukawa-type contribution described in the weak-field limit therefore provides a mechanism through which effective gravitational forces may be enhanced in low-density galactic environments without altering gravitational behaviour in dense stellar systems. Because the strength of this modification depends on environmental density rather than a universal parameter, the framework predicts correlations between rotation curve behaviour and the local baryonic density distribution.

An empirical study of the SPARC galaxy database has highlighted the strong potential for the onset of anomalous rotation velocity at $\log_{10}\rho \sim -21.6\ \mathrm{kg\,m^{-3}}$ [19,29] consistent with the GETT galactic transition regime ("Switch D") [28]. Coarse-grained baryonic mass density was *the* onset defining factor.

6.2 Vertical Stellar Velocity Dispersion

In addition to rotational dynamics within galactic discs, the vertical motion of stars relative to the galactic midplane provides an important probe of the gravitational potential. Measurements of stellar velocity dispersion perpendicular to the disc are widely used to infer the mass distribution within galaxies, particularly in the Solar neighbourhood of the Milky Way.

In conventional analyses based on Newtonian gravity or General Relativity, the observed vertical velocity dispersion of stellar populations is often interpreted as requiring the presence of an additional unseen mass component associated with a dark matter halo. This interpretation arises because the restoring gravitational force inferred from stellar motions appears larger than that predicted from visible baryonic matter alone.

Within the scalar–density framework proposed here, the vertical gravitational potential experienced by stars depends not only on baryonic mass but also on the environmental scalar Σ that regulates scalar–matter coupling. In regions where the local density approaches the transition regime of the modulation function $S(\Sigma)$, scalar-mediated interactions can modify the effective gravitational restoring force perpendicular to the galactic plane. This mechanism provides a natural explanation for enhanced vertical velocity dispersion without requiring the introduction of non-baryonic dark matter. Because the scalar coupling strength depends explicitly on the local density distribution of baryonic matter, the theory predicts that vertical stellar kinematics should correlate with the environmental density profile of the galactic disc.

Vertical velocity measurements therefore provide a complementary observational probe to galaxy rotation curves. While rotation curves measure gravitational dynamics within the plane of the disc, vertical stellar motions probe the gradient of the gravitational potential perpendicular to the plane. Agreement between these two independent diagnostics would provide strong evidence for any proposed gravitational mechanism.

A detailed investigation of vertical stellar kinematics within the Milky Way has been conducted separately using Gaia DR3 data [20] . That analysis examines the relationship between vertical velocity dispersion and the local baryonic density distribution across the galactic disc. The results provide a direct empirical test of the density-dependent gravitational behaviour predicted by the scalar–density framework [44,45].

Together with rotation-curve analyses of external galaxies, including those derived from the SPARC database [29], these studies provide complementary observational bridges linking the theoretical framework presented here with measurable astrophysical phenomena.

6.3 Gravitational Lensing

Gravitational lensing provides an independent probe of gravitational dynamics that does not rely on assumptions about the dynamical state of matter. Weak lensing surveys map the distribution of mass in the Universe by measuring the distortion of background galaxy images caused by intervening gravitational fields.

If scalar-mediated interactions become active in low-density environments, the effective gravitational potential responsible for light deflection may differ slightly from the prediction of General Relativity in those regions. This effect could manifest as subtle modifications to lensing signals in cosmic voids or in the outskirts of galaxy clusters.

Because lensing directly probes spacetime curvature rather than particle dynamics, such observations provide a valuable test of any theory that modifies gravitational interactions.

6.4 Void Lensing

Cosmic voids provide an important observational environment in which the baryonic density falls to extremely low values. In standard cosmological models, weak gravitational lensing signals associated with voids arise primarily from the relative deficit of matter compared to the cosmic mean density.

Within the scalar–density framework proposed here, cosmic voids represent environments in which the environmental density scalar Σ approaches the ultra-low regime described in Section 2.4. In this limit the modulation function $S(\Sigma)$ permits the scalar coupling to approach its maximal activation strength. As a consequence, gravitational potentials in deep cosmic voids may differ systematically from those predicted by General Relativity in the absence of scalar coupling. Weak lensing measurements of background galaxies around voids therefore provide a particularly sensitive probe of the density-dependent interaction mechanism [16,17, 29].

Large observational surveys capable of mapping void lensing signals across wide cosmological volumes, including Euclid and LSST, may therefore offer a direct test of the ultra-low-density behaviour predicted by the scalar–density framework [22,23]. In this context, deep void environments – sometimes referred to as "bright voids" due to the prominence of background galaxy fields – represent a promising regime in which the scalar coupling may become most strongly expressed.

6.5 Large-Scale Structure Formation

The growth of cosmic structure provides another sensitive probe of gravitational physics. The formation of galaxies, clusters, and large-scale filaments results from the gravitational amplification of small primordial density perturbations.

In the present framework the scalar field dynamics are coupled to matter through the density-modulated interaction described earlier. As the cosmic matter density evolves with time, the effective strength of scalar coupling may also evolve. This can influence the rate at which matter perturbations grow during the formation of large-scale structure.

Such effects may appear observationally as modifications to the growth rate of cosmic structures or as environment-dependent variations in clustering statistics.

6.6 Cosmological Expansion Behaviour

On the largest scales the scalar field may contribute to the overall dynamical evolution of the Universe. Because the scalar coupling strength depends on environmental density, the scalar field can influence cosmological dynamics in a manner that evolves over cosmic time.

Observations of distant Type Ia supernovae, baryon acoustic oscillations, and cosmic microwave background measurements indicate that the expansion of the Universe has previously been accelerating. Within the standard cosmological model this phenomenon is attributed to a uniform dark energy component, often represented by a cosmological constant Λ. More recent observations suggest that the expansion rate of the Universe may be evolving in a manner not fully captured by a constant cosmological constant. The DESI DR2 (March 2025) observed *evolution* of dark energy signatures (weakening w) is precisely what a density-regulated scalar mechanism predicts: as mean cosmic density continues to decrease, the rate of change of S(Σ) itself slows, naturally producing a decelerating dark energy effect without requiring any additional tuning.

In particular, as the average matter density of the Universe decreases during cosmic expansion, the modulation function may permit scalar interactions to become increasingly active. This behaviour could contribute to large-scale dynamical effects that influence the expansion history of the Universe.

Within the scalar–density framework proposed here, the phenomenon commonly described as dark energy may instead arise from the activation of scalar–matter coupling in the ultra-low-density regime of the Universe. As the mean cosmic density decreases during cosmic expansion, the environmental scalar Σ approaches the low-density domain in which the modulation function $S(\Sigma)$ permits scalar interactions to become dynamically significant [35]. In this interpretation, the apparent dark energy component is not a fundamental cosmological constant but an emergent large-scale dynamical effect arising from density-regulated scalar interactions. The opportunity for GETT within this regime to resolve the Hubble tension has been explored in detailed analysis [38], and the scope to apply scalar density and phase modulation to recover theoretical cyclical universe models [43]. A detailed treatment of these cosmological implications lies beyond the scope of the present work but represents a promising direction for future investigation.

6.7 Extreme-Density Astrophysical Systems

Compact astrophysical objects such as neutron stars provide environments in which matter densities far exceed those found in ordinary stellar systems. As discussed in Section 5, such extreme conditions may activate a high-density branch of the scalar interaction.

In this regime the scalar field may influence the internal dynamics of compact objects, potentially affecting rotational evolution, stability properties, or other dynamical phenomena. Observational signatures associated with neutron stars may therefore offer additional tests of scalar–matter coupling in the high-density regime [27,36,40].

6.8 Additional Astrophysical Phenomena

Beyond the principal observational tests discussed above, a number of astrophysical observations have been reported in recent years that appear difficult to reconcile with conventional gravitational and cosmological expectations. These include, for example, the presence of massive and highly evolved galactic structures in the early Universe, unusually bright stellar populations at high redshift, extended shell structures observed around red supergiant stars, extreme high-energy particle events such as the Amaterasu cosmic ray, episodic rotational behaviour in neutron stars, and unusual nebular morphologies including bipolar or hourglass-shaped outflows. Public discussions of several of these phenomena are available in the author's "*Solving Science*" lecture series.

The scalar–density framework presented here suggests that gravitational behaviour may vary across environments characterised by very different baryonic density regimes. It is therefore conceivable that some of these phenomena may ultimately be connected to transitions between density-regulated interaction regimes of the scalar field. While no specific claims are made in this work regarding these individual observations, they represent potentially valuable domains in which density-dependent gravitational behaviour could be investigated further.

A systematic examination of such phenomena may therefore provide additional opportunities to test the broader implications of the density–scalar framework across a wide range of astrophysical environments.

7. Experimental Tests and Observational Programme

The scalar–density framework described in this work predicts that gravitational behaviour depends explicitly on the environmental baryonic density through the modulation function $S(\Sigma)$. This environmental dependence leads to several observational signatures that may be tested using current and forthcoming astronomical datasets. Because the scalar coupling strength varies systematically across density regimes, the most sensitive tests of the framework arise in environments where the environmental scalar approaches the transition domains identified in Section 2.4.

A comprehensive experimental programme therefore involves examining gravitational behaviour across a wide range of astrophysical density environments.

7.1 Galaxy Rotation Curve Surveys

Galaxy rotation curves provide one of the most direct probes of gravitational dynamics in low-density environments. Measurements of stellar and gas orbital velocities at large galactocentric radii allow the gravitational potential of galaxies to be inferred independently of assumptions regarding non-luminous matter.

The scalar–density framework predicts that deviations from Newtonian gravitational behaviour should correlate with the environmental baryonic density distribution rather than with an unseen dark matter component. Large rotation curve datasets such as the SPARC database provide high-quality measurements of galaxy rotation profiles and baryonic mass distributions across a wide range of galaxy morphologies.

Statistical analysis of rotation curves as a function of local baryonic density therefore provides a direct empirical test of the density-modulated interaction mechanism proposed here.

7.2 Vertical Stellar Kinematics

The vertical motion of stars relative to the galactic midplane provides an independent dynamical probe of gravitational potential gradients perpendicular to galactic discs. In conventional analyses, the vertical velocity dispersion of stellar populations is often interpreted as evidence for additional gravitational mass associated with dark matter halos.

Within the scalar–density framework, vertical stellar kinematics depend on the local density-dependent coupling between matter and the scalar field [44]. Regions of the galactic disc that approach the transition density regime may therefore exhibit modified vertical restoring forces [45]. High-precision stellar velocity measurements from the Gaia mission provide a powerful dataset for testing such predictions. In particular, correlations between vertical velocity dispersion and the baryonic density structure of galactic discs offer a direct observational test of density-regulated gravitational behaviour.

7.3 Weak Gravitational Lensing

Weak gravitational lensing surveys provide a complementary probe of gravitational potentials that does not rely on the dynamical state of matter. Large imaging surveys map the distribution of gravitational fields through statistical distortions in the shapes of background galaxies.

If scalar-mediated interactions become active in low-density environments, gravitational potentials inferred from lensing measurements may exhibit systematic differences relative to predictions based solely on baryonic mass distributions. Ongoing and forthcoming surveys such as Euclid, the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST), and the Dark Energy Survey therefore offer valuable observational datasets for testing density-dependent gravitational behaviour.

7.4 Void Lensing

Cosmic voids represent environments in which the baryonic density approaches the ultra-low regime described in Section 2.4. In such environments the modulation function $S(\Sigma)$ permits the scalar coupling to approach its maximal activation strength.

Weak gravitational lensing measurements around cosmic voids therefore provide a particularly sensitive probe of the ultra-low-density limit of the framework. Measurements of void lensing signals across large cosmological volumes may reveal systematic deviations from predictions of conventional gravitational models if scalar-mediated interactions become dynamically significant in these environments.

7.5 Large-Scale Structure Growth

The growth of cosmic structure provides another sensitive test of gravitational physics. Measurements of galaxy clustering, redshift-space distortions, and large-scale matter distribution provide constraints on the rate at which density perturbations grow over cosmic time.

Because the scalar coupling strength depends on environmental density, the framework predicts that the growth of cosmic structures may depend on local density conditions rather than solely on universal gravitational constants. Large spectroscopic surveys such as DESI provide the statistical precision required to test such effects [21].

7.6 Compact Object Observations

Extreme-density astrophysical systems offer complementary tests of the high-density regime discussed in Section 5. In neutron stars and other compact objects, the environmental density scalar may reach the regime in which scalar coupling becomes dynamically significant once again.

Observations of neutron star rotational behaviour, pulsar timing irregularities, and gravitational-wave signals from compact object mergers therefore provide potential tests of scalar–matter interactions in extreme-density environments. Precision pulsar timing arrays and gravitational-wave observatories including LIGO and Virgo may therefore offer valuable constraints on the high-density behaviour of the scalar interaction.

7.7 Falsifiability

The scalar–density framework makes a clear qualitative prediction: gravitational behaviour should correlate with environmental baryonic density rather than requiring an additional non-baryonic dark matter component.

If observational studies across galaxy dynamics, gravitational lensing, and large-scale structure formation reveal no correlation between gravitational phenomena and baryonic density environment, the density-modulated scalar interaction proposed here would be strongly constrained or potentially ruled out. Conversely, systematic correlations between gravitational behaviour and environmental density would provide empirical support for the density–scalar mechanism introduced in this work.

8. Discussion

The scalar–density framework presented in this work belongs to the broader class of scalar–tensor theories in which gravitational behaviour is influenced by additional scalar degrees of freedom. Scalar fields have long been studied in cosmology and gravitational physics, appearing in models of inflation, quintessence, and modified gravity. In many such theories the scalar field interacts with matter through coupling functions that may vary with local environmental conditions.

Several existing frameworks employ environmental screening mechanisms to suppress scalar interactions in high-density environments. Examples include chameleon theories, symmetron models, and other scalar–tensor constructions in which scalar coupling strength depends on local matter density. These models are designed to ensure consistency with precision gravitational tests in the Solar System while allowing modified behaviour on cosmological scales.

The framework developed here shares certain conceptual features with these approaches but differs in several important respects. In particular, the scalar field introduced in this work is constructed as a gauge-invariant singlet that couples to the Standard Model through the Higgs sector. This Higgs-portal interaction provides a natural mechanism by which scalar–matter coupling can arise within a conventional quantum field theory setting without introducing exotic particle content.

A second distinctive feature of the framework is the explicit use of a covariant environmental density scalar Σ, constructed from the stress–energy tensor, to regulate scalar coupling. Because this quantity is derived directly from local physical fields, the modulation mechanism remains compatible with general covariance and with the principles of effective field theory.

The resulting interaction structure leads naturally to a density-dependent phase structure in which different gravitational behaviours emerge across distinct environmental regimes. In mid-density environments such as terrestrial laboratories and ordinary stellar systems, scalar coupling is strongly suppressed and the theory reduces smoothly to General Relativity coupled to the Standard Model. In lower-density astrophysical environments, scalar interactions may become dynamically relevant and modify effective gravitational behaviour. At sufficiently extreme densities, such as those encountered in compact astrophysical objects, additional activation regimes may arise.

An additional conceptual aspect of the framework is the connection between scalar–matter coupling and the electroweak sector of the Standard Model. Because the scalar interacts with the Higgs field, the emergence of particle masses through electroweak symmetry breaking naturally influences the structure of scalar–matter interactions. This connection suggests that density-dependent gravitational behaviour may ultimately be linked to the same physical processes responsible for mass generation in particle physics.

The framework therefore provides a unified theoretical setting in which gravitational phenomena across a wide range of density environments may be interpreted as manifestations of a single density-regulated interaction mechanism. While the present work focuses primarily on establishing the theoretical consistency of the scalar–density construction, the observational consequences discussed in the preceding sections indicate several promising directions for empirical investigation.

In the GETT framework the Holland scalar field is interpreted as a physical energy–matter field whose dynamics were established during the early expansion of the Universe. Following the initial high-energy state associated with the Big Bang, the scalar field evolves within an expanding regime in which the field naturally tends toward expansion while coupling intermittently to matter through the density-modulated interaction described earlier. This behaviour produces a dynamical cosmological environment in which expansion, structure formation, and local gravitational phenomena are governed by the interaction between matter and the evolving scalar field.

Further work will be required to explore the detailed cosmological evolution of the scalar field, to study the stability properties of the theory across different density regimes, and to examine the implications of the framework for compact-object physics and large-scale structure formation.

To the author's knowledge, no previous framework in the literature has proposed the specific combination of ingredients developed here: a covariant effective field theory in which a gauge-invariant singlet scalar field couples to the Standard Model through a Higgs-sector portal whose interaction strength is continuously modulated by a covariant environmental density scalar constructed from the stress–energy tensor. While scalar–tensor theories and environmentally screened scalar models have been widely explored, the precise structure of a density-regulated Higgs-portal coupling controlling scalar–matter interactions across astrophysical density regimes does not appear in existing formulations surveyed during the development of this work. The framework presented here therefore represents a distinct theoretical construction within the broader landscape of scalar-mediated gravitational models.

9. Conclusions

This work has presented a covariant scalar–density framework in which gravitational behaviour arises from density-regulated interactions between matter and a gauge-invariant singlet scalar field. The framework is constructed within the language of relativistic quantum field theory and incorporates a scalar field Φcoupled to the Standard Model through the Higgs sector. A covariant environmental density scalar Σ, derived from the stress–energy tensor, regulates the strength of scalar–matter coupling through a modulation function $S(\Sigma)$.

Within this formulation gravitational phenomena may be interpreted as emerging from a density-dependent interaction structure rather than from a fixed universal gravitational coupling alone. In mid-density environments, including terrestrial laboratories, planetary systems, and ordinary stellar interiors, the modulation function suppresses scalar coupling and the theory reduces smoothly to General Relativity coupled to the Standard Model. In lower-density astrophysical environments the scalar interaction may become dynamically significant, potentially influencing galactic dynamics and large-scale cosmological behaviour. At sufficiently extreme densities additional activation regimes may arise, suggesting possible implications for compact astrophysical objects.

The framework therefore provides a theoretical setting in which gravitational phenomena across a wide range of physical environments may be interpreted within a single density-regulated interaction mechanism. Because the scalar field couples through the Higgs sector, the structure of scalar–matter interactions is naturally connected to the emergence of particle masses through electroweak symmetry breaking.

A key feature of the framework is that it produces observational consequences that may be tested empirically. Galaxy rotation curves, vertical stellar kinematics, gravitational lensing, cosmic void dynamics, large-scale structure formation, and compact-object observations provide complementary probes of gravitational behaviour across different density regimes. Systematic correlations between gravitational phenomena and environmental baryonic density would provide support for the density-modulated interaction mechanism, while the absence of such correlations would place strong constraints on the framework.

The present work has focused on establishing the theoretical structure of the scalar–density interaction and outlining its principal observational consequences. Further work will be required to investigate the detailed cosmological evolution of the scalar field, to explore the behaviour of the theory across the full range of density regimes identified in this study, and to examine the implications of the framework for early-universe physics and compact-object dynamics.

If confirmed observationally, the density-regulated scalar interaction proposed here would suggest that gravitational phenomena traditionally attributed to dark matter and dark energy may instead arise from environment-dependent coupling between matter and a fundamental scalar field.

This paper establishes, for the first time in the literature, a fully covariant effective field theory in which a gauge-invariant singlet scalar field couples to all Standard Model matter through a Higgs-sector portal whose interaction strength is continuously and covariantly modulated by the local baryonic density – a construction that unifies the gravitational behaviour of cosmic voids, galactic discs, stellar interiors, and neutron star cores within a single density-regulated scalar mechanism, and in doing so offers not an alternative to General Relativity but its derivation as the inevitable, emergent, mid-density limit of a more fundamental field-theoretic reality.

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