ECSM Dynamics Without Curvature: Gravity, Inertia, and Emergent Geometry in a Superfluid Cosmology

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Abstract

We present a non-metric formulation of gravity arising from the dynamical response of a condesate-like superfluid medium to matter excitations. Gravitational acceleration is identified with pressure gradients and flow dynamics of the medium, rather than spacetime curvature. In this framework, inertia, free fall, and gravitational attraction emerge from the same underlying ECSM stress response. We show how general relativistic phenomenology arises as an effective limit, while remaining non-fundamental. The approach naturally accommodates cosmological phase transitions, scale-dependent gravitational behavior, and provides a unified basis for emergent geometry, optical phenomena, and quantum excitations without invoking dark matter, dark energy, or a universal expansion metric. While the ECSM also supports coherent excitations associated with quantum phenomena, including electromagnetic radiation, the present work restricts attention to the inertial and gravitational response of bound matter and clocks. A companion paper addresses quantum excitation dynamics and measurement.

1 Introduction

ECSM (Emergent Condensate Superfluid Medium) treats the vacuum as an effectively superfluid, condensate-like medium with dynamical fields whose gradients and defects carry stress, transport, and energy. In this view, phenomena usually attributed to spacetime curvature and unseen matter arise instead from the mediums local response laws (pressure-like stresses, solenoidal flow, and defect/flux-tube dynamics), with geometry emerging as an effective description of propagation and clock/ruler behaviour. The goal is not to draw a web by assumption, but to show that simple, conservative medium dynamics can self-organise into nodefilamentvoid structure and reproduce the main cosmological observables through falsifiable, scale-bridging mechanisms.

The geometrization of gravity has been one of the most successful ideas in modern physics. In General Relativity, gravitational phenomena are encoded in the curvature of spacetime, and inertial motion is identified with geodesic flow on a metric manifold. Despite its empirical success, this framework leaves open foundational questions: why inertia exists at all, why inertial and gravitational mass coincide, and whether geometry is a fundamental ingredient of nature or an effective description.

Motivated by developments in superfluid analog gravity, emergent spacetime models, and recent cosmological tensions, we explore an alternative formulation in which gravity and inertia arise from the dynamical response of a continuous medium (the "ECSM") rather than from spacetime curvature. In this picture, matter corresponds to long-lived excitations of a superfluid-like background, and forces arise from pressure, stress, and flow gradients in that medium.

This paper focuses on the local dynamical foundations of such a framework. We show that inertia can be derived as a reaction force associated with momentum transfer into the medium during acceleration, while gravitational acceleration emerges from spatial gradients in the medium state induced by mass-energy concentrations. Geometry and metric structure appear only as approximate, regime-dependent reformulations of the underlying dynamics.

The aim is not to modify General Relativity by adding new fields or coupling constants, but to replace curvature as a fundamental postulate with physically interpretable medium dynamics. This provides a unified basis for inertia, gravity, cosmology, optical phenomena, and quantum excitations, consistent with the broader superfluid-medium programme developed in companion papers.

Roadmap and scope. This paper develops the local gravitational and inertial sector of the Emergent Condensate Superfluid Medium (ECSM) framework and establishes its internal consistency across the Newtonian limit, weak-field relativistic behaviour, and environmental (external-field) suppression. Cosmological implications are discussed at the level of controlled effective response—including lensing–growth correlations, redshift and phase-transition consistency, and distance-duality constraints—with the emphasis on identifying correlated, falsifiable signatures rather than performing a full global parameter fit. Detailed end-to-end likelihood analyses against CMB, BAO/RSD, and weak-lensing datasets are left to companion work that implements the same response operators within existing pipelines.

Consistency with local gravity tests. In the regimes probed by laboratory, Solar-System, and binary-pulsar tests, the ECSM framework is constructed to be operationally equivalent to general relativity: test bodies and light follow the same effective trajectories as in GR to the relevant post-Newtonian order. The distinction is therefore interpretational in this limit (emergent inertial response rather than fundamental curvature), with departures expected only when medium-response effects become non-negligible (e.g. low-acceleration, large-scale, or coherence-limited regimes).

Interpretive Convention and Terminology

For clarity and ease of comparison with the observational literature, we employ standard cosmological notation (e.g. redshift z, high-z/low-z, distance–redshift relations) throughout this work. However, these symbols are used strictly as observational labels and do not imply an underlying expanding metric or a global scale factor $a(t)$.

In the framework developed here, redshift is interpreted as a path-integrated dynamical or optical effect arising from propagation through a structured medium, rather than as a kinematic consequence of cosmic expansion. Distances are determined operationally from signal propagation and medium response, not inferred from a universal expansion history. Temporal language such as "early" and "late" refers to regimes of medium density or coupling strength, not to cosmic time evolution.

A summary of correspondences is provided below:

Standard terminology	Interpretation in this work
Redshift z	Observed spectral shift (path-integrated)
High-z / Low-z	Strong / weak medium response regimes
Distance–z relation	Distance–induction relation
Early / Late universe	High / low coupling phases of the medium

These conventions allow direct comparison with standard analyses while preserving the non-expanding, medium-based interpretation developed in this work. Future presentations may adopt fully medium-native terminology once the framework is established.

1.1 Canonical definition of redshift in a state-dependent medium

We retain the observational symbol z for continuity with the data literature, but we do *not* interpret z as a kinematic or metric scale-factor effect. In this framework, redshift is an *optical response* accumulated along the photon trajectory through a state-dependent medium.

Operational definition. Consider a photon with locally measured frequency $\nu(\lambda)$ propagating along a null ray γ parametrized by an affine parameter λ. We define the observed redshift between emission at $\lambda = \lambda_{\rm e}$ and observation at $\lambda = \lambda_{\rm o}$ by

$$1 + z \;\equiv\; \frac{\nu_{\rm e}}{\nu_{\rm o}} \;=\; \exp\!\left(\int_{\lambda_{\rm e}}^{\lambda_{\rm o}} \mathcal{I}[\chi(x), \nabla\chi(x), u^{\mu}(x), \ldots]\, {\rm d}\lambda\right), \tag{1}$$

where $\chi(x)$ is a medium state variable (e.g. an order parameter, coherence, or density proxy), $u^{\mu}(x)$ is a possible medium flow field, and $\mathcal{I}$ is a scalar *induction rate* functional with dimensions of inverse affine length. Equation (1) is the canonical statement that redshift is path-integrated response, not background expansion.

Differential form. Equivalently, the redshift accumulation may be written as a first-order transport law for the frequency,

$$\frac{\rm d}{{\rm d}\lambda} \ln \nu(\lambda) \;=\; -\,\mathcal{I}[\chi, \nabla\chi, u^{\mu}, \ldots]\,, \qquad \Rightarrow \qquad 1 + z = \exp\!\left(-\int_{\lambda_{\rm e}}^{\lambda_{\rm o}} \frac{\rm d}{{\rm d}\lambda} \ln \nu \, {\rm d}\lambda\right), \tag{2}$$

so that any nontrivial z arises from a nonzero $\mathcal{I}$ along the ray.

Minimal "state-driven" choice. For a purely state-dependent (no-flow) realization consistent with a phase-/coherence-controlled medium, a minimal closure is

$$\mathcal{I} \;=\; \kappa\, \partial_{\lambda}\chi \qquad \Rightarrow \qquad 1 + z \;=\; \exp(\kappa\, [\chi(\lambda_{\rm o}) - \chi(\lambda_{\rm e})])\,, \tag{3}$$

where κ sets the coupling between photon frequency and the medium state. In this limit, redshift depends on the endpoints through the state difference, while the full theory allows nonlocal or environment- dependent accumulation through the functional form of $\mathcal{I}$ in (1).

Distance is not assumed from redshift. Because z is generated by medium response rather than a universal metric scale factor, *redshift does not uniquely fix distance.* Distance measures (e.g. luminosity distance D_L and angular-diameter distance D_A) must be obtained from the optical propagation law (intensity, beam-area, and/or ray-bundle evolution) appropriate to the medium, with z serving only as an observable label.

Notation and "expansion language." Where convenient, one may introduce an *effective* kinematic mapping (e.g. an effective $H_{\rm eff}(z)$) solely as a data-compression device, defined by fitting (1) to observational relations. Such effective functions summarize the medium-induced redshift–distance mapping and should not be interpreted as implying physical expansion.

1.2 Minimal Dynamical System

The late-time dynamics considered in this work are fully specified by the following minimal system, which governs inertia, gravity, and emergent geometry without invoking fundamental spacetime curvature.

(i) Condensate Response flow field. We postulate a physical velocity field $\mathbf{u}(\mathbf{x}, t)$ defined on a flat background, representing the macroscopic flow of an underlying medium (ECSM).

(ii) Matter–ECSM coupling (inertia). A material body of bare mass $m_{\rm b}$ interacts with the ECSM through an entrained mass

$$m_{\rm add} \ \sim \ \rho\,\ell_{\rm ind}^3, \tag{4}$$

where ρ is the ECSM density and $\ell_{\rm ind}$ is an induction (response) length characterizing the spatial support of the coupling.

The equation of motion for the bodys center-of-mass velocity $\mathbf{V}$ is

$$(m_{\rm b} + m_{\rm add})\,\dot{\mathbf{V}} = m_{\rm add}\,\frac{D\mathbf{u}}{Dt}\Big|_{\mathbf{X}} - \Gamma\big(\mathbf{V} - \mathbf{u}\big), \tag{5}$$

where D/Dt is the material derivative of the Condensate Response Flow and Γ encodes dissipative slip.

(iii) Newtonian limit (gravity). For stationary, irrotational inflow ($\partial_t \mathbf{u} = 0$, $\nabla \times \mathbf{u} = 0$) and weak dissipation, the acceleration reduces to

$$\dot{\mathbf{V}} \simeq -\,\eta\,\nabla\Phi, \qquad \Phi \equiv -\frac{u^2}{2}, \qquad \eta \equiv \frac{m_{\rm add}}{m_{\rm b} + m_{\rm add}}. \tag{6}$$

In the strongly entrained limit ($m_{\rm add} \gg m_{\rm b}$), one recovers the standard Newtonian form $\dot{\mathbf{V}} = -\nabla\Phi$.

(iv) Emergent geometry (optional representation). The same weak-field dynamics may be equivalently written as geodesic motion in an effective metric

$$ds^2 = -\big(1 + 2\Phi\big)\,dt^2 + \big(1 - 2\Phi\big)\,d\mathbf{x}^2, \tag{7}$$

which serves as a bookkeeping device rather than a statement of fundamental spacetime curvature.

This closed system constitutes the minimal dynamical content of the framework. All cosmological and astrophysical applications discussed in this work follow from these relations together with phenomenological input for $\ell_{\rm ind}(z)$.

2 Inertia as ECSM Reaction

A central claim of the ECSM framework is that neither "spacetime curvature" nor an a priori metric is required to account for inertial behaviour. Instead, inertia arises as a dynamical reaction of the medium to attempted changes in the state of motion of embedded matter. In this picture, uniform motion corresponds to a steady, non-radiating co-motion state of the medium, while acceleration necessarily perturbs the medium and generates a restoring stress. The observed inertial law $F = ma$ is then interpreted as an effective, coarse-grained statement of ECSM stress–response.

Inertia is treated here as an emergent dynamical property arising from the interaction between matter and a continuous superfluid ECSM, rather than as an intrinsic attribute of mass or a kinematic axiom. Accelerated motion corresponds to a local departure from equilibrium between an embedded object and the surrounding medium, generating resistive stresses within the ECSM that oppose changes in velocity. These stresses arise from the finite relaxation time and compressibility of the medium, producing an effective inertial response proportional to the rate of acceleration. Inertial mass therefore reflects the strength of coupling between matter and the ECSM, with uniform motion corresponding to a co-moving equilibrium state and non-uniform motion inducing reactive forces as the medium resists deformation. Inertia is thus interpreted as a dynamical medium effect, providing the foundational mechanism from which both gravitational and non-gravitational forces emerge.

As established in the foundational framework, inertia is not treated as an intrinsic property of matter but arises from the energetic cost of reconfiguring the surrounding ECSMic medium under acceleration. A localized mass corresponds to a steady deformation and flow pattern of the medium, and uniform motion represents a translated steady state requiring no further reconfiguration. Accelerated motion instead necessitates time dependent restructuring of this coupled matter and ECSM configuration, generating restoring stresses that oppose the change. Gravitational attraction and inertial resistance therefore originate from the same underlying interaction, differing only in whether the medium response is stationary or dynamical.

2.1 Geodesic limit and inertial potential

In the regime where the response is smooth on the scale of the experiment, ECSM predicts universal free fall because motion reduces to geodesics of an effective metric induced by the medium state.

$$\boxed{\frac{d^2x^\mu}{d\tau^2} + \Gamma^\mu_{\alpha\beta}\left[g^{\rm eff}\right]\frac{dx^\alpha}{d\tau}\frac{dx^\beta}{d\tau} = 0, \qquad g^{\rm eff}_{00} \simeq -\left(1+\frac{2\Phi_{\rm in}}{c^2}\right)} \tag{8}$$

Here $\Phi_{\rm in}$ is the ECSM inertial potential (defined by the local medium state), and the Newtonian acceleration is recovered as $\mathbf{a} \simeq -\nabla\Phi_{\rm in}$ in the weak-field, slow-motion limit.

Stationary domain-gated limit. In the stationary, weak-field regime, ECSM admits a scalar inertial potential Φ_I such that $\mathbf{a} = -\nabla\Phi_I$. Locality-gated response ensures that in coherent environments the dynamics reduce exactly to the Newtonian and post-Newtonian limits, while coherence degradation permits nonlinear response at large scales without introducing new forces or degrees of freedom.

External field effect. In ECSM the coherence state governing inertial response depends on the total environmental acceleration rather than on internal sources alone. As a result, systems embedded in strong external fields remain in the coherent (Newtonian) regime even when internal accelerations are small. This reproduces the observed external field effect as a direct consequence of locality-gated dynamics, without additional assumptions.

2.2 Kinematic variables and minimal postulates

We model the ECSM as a continuous medium with (at minimum) a mass-density field $\rho(\mathbf{x}, t)$ and a macroscopic velocity field $\mathbf{u}(\mathbf{x}, t)$. Matter is represented as compact, long-lived excitations (or "defects") which impose boundary conditions on the medium and may couple to its density and flow. The key postulates used in this section are:

1. **Co-motion state:** A body in uniform motion relative to the medium can settle into a steady co-moving configuration with no net force, i.e. no persistent momentum exchange with the medium in the absence of external perturbations.

2. **Acceleration excites the medium:** A change of the body's velocity relative to the medium induces a finite disturbance (compression/rarefaction, vorticity, or phase/induction perturbation) which carries stress and stores energy.

3. **Locality of reaction:** To leading order, the reaction force depends on local medium response integrated over an effective coupling region (set by the body's size, boundary layer thickness, and coherence/relaxation scale).

These assumptions are deliberately minimal: they do not presuppose a metric, a geodesic principle, or curvature. The goal is to show how the inertial law emerges as the leading term in the medium's response.

2.3 Momentum bookkeeping and the origin of an inertial term

Consider a compact body B embedded in the medium. Let $\mathbf{P}_B$ denote the body's mechanical momentum and $\mathbf{P}_A$ the ECSM momentum in a control volume V enclosing the body and its coupling region. The total momentum is

$$\mathbf{P}_{\text{tot}} = \mathbf{P}_B + \mathbf{P}_A, \tag{9}$$

and in the absence of external forces on the combined system we have

$$\frac{d\mathbf{P}_{\text{tot}}}{dt} = \mathbf{0}. \tag{10}$$

Therefore any change in the body's momentum must be balanced by an opposite change in the medium's momentum:

$$\frac{d\mathbf{P}_B}{dt} = -\frac{d\mathbf{P}_A}{dt}. \tag{11}$$

Define the force required to accelerate the body as the rate of momentum transfer into the medium:

$$\mathbf{F}_{\text{ext}} \equiv \frac{d\mathbf{P}_B}{dt} = -\frac{d\mathbf{P}_A}{dt}. \tag{12}$$

Equation (11) is not yet a constitutive law; it is simply momentum conservation. The content of inertia is the empirical fact that, for slow accelerations in ordinary conditions, $\mathbf{F}_{\text{ext}}$ is proportional to the acceleration $\mathbf{a} = d\mathbf{v}/dt$ with a constant of proportionality.

To obtain this, we assume that for sufficiently gentle, sub-relativistic accelerations, the medium response in the coupling region is approximately linear in $\mathbf{a}$. Then the induced ECSM momentum (or impulse) in the coupling region has the generic form

$$\mathbf{P}_A \;\approx\; \mathcal{M}_{\text{eff}}\,\mathbf{v} \qquad \Rightarrow \qquad \frac{d\mathbf{P}_A}{dt} \;\approx\; \mathcal{M}_{\text{eff}}\,\mathbf{a}, \tag{13}$$

where $\mathcal{M}_{\text{eff}}$ is an *effective entrained mass* determined by the amount of medium that is necessarily disturbed (entrained) when the body accelerates.

Substituting (13) into (11) yields the inertial law

$$\mathbf{F}_{\text{ext}} \;\approx\; \mathcal{M}_{\text{eff}}\,\mathbf{a}. \tag{14}$$

In this interpretation, what is traditionally called inertial mass is the medium's effective entrainment coefficient:

$$m_{\text{inertial}} \equiv \mathcal{M}_{\text{eff}}. \tag{15}$$

2.4 A constitutive estimate for the effective inertial mass

The effective entrained mass $\mathcal{M}_{\text{eff}}$ can be estimated without committing to a particular microphysical model by noting that acceleration excites a finite coupling volume around the body. Let ℓ_c be an effective coupling thickness (boundary layer / coherence length / induction penetration depth), and let V_c be the corresponding effective coupling volume. Then a natural scaling is

$$\mathcal{M}_{\text{eff}} \sim \int_{V_c} \rho(\mathbf{x})\, d^3x. \tag{16}$$

For a body of characteristic radius R, one expects $V_c \sim \frac{4\pi}{3}(R+\ell_c)^3$ in the simplest spherical estimate, giving

$$\mathcal{M}_{\text{eff}} \sim \frac{4\pi}{3}\,\bar{\rho}\,(R+\ell_c)^3, \tag{17}$$

where $\bar{\rho}$ is an appropriately averaged density over the coupling region.

This does *not* assert that inertial mass is simply the volume of medium displaced; rather it states that the effective inertia arises from the amount of medium that must be disturbed when the body accelerates. The microphysics determines ℓ_c and the weighting of ρ in (16). In later sections, ℓ_c will be connected to finite induction coherence / relaxation scales already invoked in cosmological phenomenology.

2.5 Why uniform motion is force-free

A persistent objection to “medium” pictures is the expectation of drag. The present framework avoids this by distinguishing *steady co-motion* from *accelerated motion*. In a superfluid-like medium, steady flow configurations can exist with negligible dissipation and without momentum diffusion in the bulk. Drag is therefore not fundamental; it is a non-ideal effect tied to dissipation, turbulence, or finite-temperature excitations. In the idealised limit relevant for cosmological-scale coherence, the medium supports non-dissipative co-motion states, and the net force vanishes for constant $\mathbf{v}$ once transients decay:

$$\mathbf{F}_{\text{net}} = \mathbf{0} \qquad (\dot{\mathbf{v}} = \mathbf{0}). \tag{18}$$

By contrast, acceleration cannot be absorbed into a steady state; it necessarily generates time-dependent perturbations (compressional, vortical, or induction/phase), and the force required to sustain that acceleration is the inertial reaction (14).

2.6 Energy storage and an “elastic” picture of inertia

A useful physical intuition is that acceleration stores energy in the medium in the form of stress. For small perturbations one expects an effective quadratic energy functional,

$$E_{\text{med}} \sim \frac{1}{2}\,\mathcal{M}_{\text{eff}}\,v^2, \tag{19}$$

consistent with the identification of $\mathcal{M}_{\text{eff}}$ as an inertial coefficient. In this sense, inertia is the macroscopic manifestation of an “elastic” resistance of the medium to rapid changes in the local flow/induction state.

This viewpoint also connects naturally to the bubble/surface-tension analogy: when two inclusions or defects perturb a stressed medium, the medium tends to relax by reducing total stress energy. For inertia, the relevant relaxation is the tendency to oppose time-dependent deformation of the coupling region; for gravity (developed in the next section), the relevant relaxation is the tendency to reduce spatial stress gradients around mass-energy concentrations.

2.7 Equivalence: inertial mass and gravitational coupling

The above derivation identifies inertial mass with a medium entrainment coefficient. To complete the inertia–gravity unification, the gravitational coupling must depend on the *same* medium response. In this programme, gravitational acceleration is sourced by gradients in the medium state (density/pressure/induction rate), and the force on a body depends on how strongly it couples to those gradients. If the coupling that sets $\mathcal{M}_{\rm eff}$ also sets the body's response to background medium gradients, then the equivalence of inertial and gravitational mass follows as a theorem: both are controlled by the same coupling functional.

Concretely, if the body experiences a force proportional to the gradient of a scalar medium potential Φ_A,

$$\mathbf{F}_{\rm grav} \propto -\nabla\Phi_A, \tag{20}$$

with proportionality coefficient equal to the same $\mathcal{M}_{\rm eff}$ that appears in (14), then the acceleration $\mathbf{a} = \mathbf{F}/\mathcal{M}_{\rm eff}$ becomes composition-independent to leading order. The next section formulates Φ_A in terms of ECSM stress/pressure/induction gradients and shows how Newtonian gravity can be recovered without spacetime curvature.

Because motion through the ECSM is resisted by local relaxation dynamics, the same medium response that produces gravitational acceleration also underlies inertia. Changes in velocity require redistribution of Condensate Response Flow and stress around a body, and this dynamical adjustment generates resistance proportional to acceleration. Inertia therefore reflects the finite response time and coherence of the ECSM, rather than an intrinsic property of mass alone.

3 Gravity as Condensate Response Flow and Stress Dynamics

Gravity is treated here as a direct consequence of the inertial response already established in the preceding section, rather than as an independent interaction requiring new postulates. While inertia arises from the resistance of the ECSM to time-dependent motion and deformation, gravity corresponds to the same medium responding to spatial variations in its equilibrium state induced by matter. Localised mass concentrations perturb the ECSM density and stress distribution, producing pressure gradients and relaxation flows within the medium. A body situated in such a non-uniform ECSM experiences acceleration not because spacetime geometry is curved, but because inertial equilibrium is locally offset by these spatial gradients. Gravitational acceleration therefore emerges as inertia operating in an inhomogeneous medium, requiring no fundamental metric structure and no additional dynamical principle beyond those already governing inertial response. In addition to establishing static stress gradients, massive bodies generically induce a steady inward flow of the ECSM toward their centres of mass. This flow reflects the mediums tendency to relax density and pressure perturbations created by matter acting as a sink or defect within the superfluid. Test bodies embedded in this flow experience acceleration through advection by the moving medium, rather than through forces acting at a distance. Gravitational attraction between bodies therefore arises from the convergence of Condensate Response Flow lines toward regions of higher mass density, with the strength of acceleration determined by the local flow velocity and its spatial gradients. In this picture, gravity is fundamentally a dynamical inflow phenomenon, with curvature emerging only as an effective geometric description when the flow is stationary and weak. In the weak, stationary, approximately spherically symmetric limit, the inflow adjusts so that the induced acceleration reduces to an inverse-square form, with G emerging as the effective strength of the mediums sink-like response to the enclosed mass. We do not claim that all cosmological observables are exhaustively explained here; rather, we show that several key late-time consistency relations admit a unified, medium-based interpretation within the ECSM response framework, with clear routes to falsification.

3.1 Minimal Rotational Extension and Orbital Consistency

A central concern for any flow-based gravity picture is whether it admits rotation, long-lived bound motion, and binary dynamics without introducing large dissipative effects. We therefore make explicit that the ECSM is not restricted to purely potential (irrotational) flow, and we separate the "inflow" (compressive) response sourced by matter from a rotational sector carried by vorticity.

Matter as a sink (why inflow occurs). At the level of a minimal phenomenology, we model matter as a defect/sink for the ECSM density, so that relaxation toward equilibrium produces a convergent flow toward overdensities. This can be encoded by allowing a source term in the continuity equation,

$$\partial_t \rho + \nabla \cdot (\rho\, \mathbf{u}) = -\Gamma\, \rho_{\mathrm{m}}, \tag{21}$$

where $\rho(\mathbf{x}, t)$ is the ECSM density, $\mathbf{u}(\mathbf{x}, t)$ its velocity field, ρ_{m} the matter density, and Γ a phenomenological coupling setting the strength of the sink response. In static, spherically symmetric situations this term generates a steady inflow consistent with the qualitative picture described above.

Rotation and vorticity. To accommodate spin, circulation, and rotational structure, we introduce the vorticity

$$\boldsymbol{\omega} \equiv \nabla \times \mathbf{u}. \tag{22}$$

In an effectively inviscid (superfluid-like) regime, vorticity is advected with the flow and may be supported by long-lived vortex structures rather than being rapidly damped. A minimal schematic evolution law is

$$\partial_t \boldsymbol{\omega} = \nabla \times (\mathbf{u} \times \boldsymbol{\omega}) + \mathbf{S}_{\omega}, \tag{23}$$

where $\mathbf{S}_{\omega}$ represents defect creation/annihilation or other microphysical vortex sourcing. Equations (46)–(23) therefore provide the minimal extension required to discuss rotation and angular momentum transport within the same medium that generates the inflow response.

Stable orbits and binaries (dissipation bounds). A second key requirement is that bound systems do not exhibit excessive orbital decay. In the present framework, long-lived orbits correspond to a regime where the effective acceleration is predominantly conservative (derivable from an effective potential or stationary flow structure), with any genuinely dissipative channel (e.g. phonon/vortex emission) subleading. It is therefore useful to parameterize possible medium losses in binaries by a dimensionless suppression factor ϵ,

$$\dot{E}_{\mathrm{medium}} \equiv -\epsilon\, \dot{E}_{\mathrm{ref}}, \tag{24}$$

where $\dot{E}_{\mathrm{ref}}$ is a reference loss rate (e.g. the GR quadrupole prediction for compact binaries). Current binary observations thus constrain ϵ to be small, and provide a direct empirical consistency test of any specific microphysical realization of the ECSM. In the remainder of this work we focus on the quasi-stationary, weak-field sector where dissipation is negligible and the flow admits an effective geometric description.

3.2 Rotation, Orbits, and Time-Dependent Disturbances in a Medium

We model the ECSM as a continuum characterized by density $\rho(\mathbf{x}, t)$ and velocity field $\mathbf{u}(\mathbf{x}, t)$. Matter acts as a localized sink/defect that sources convergent flow. A minimal closed description is:

$$\partial_t \rho + \nabla \cdot (\rho\, \mathbf{u}) = -S_m(\mathbf{x}, t), \tag{25}$$

$$\rho\, (\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u}) = -\nabla P + \nabla \cdot \mathbf{\Pi} + \mathbf{f}_m(\mathbf{x}, t), \tag{26}$$

where S_m encodes the sink strength associated with matter, $P(\rho)$ is an effective pressure, $\mathbf{\Pi}$ represents shear/stress (e.g. viscosity or elastic response), and $\mathbf{f}_m$ is the momentum-exchange coupling to matter.

The vorticity $\boldsymbol{\omega} \equiv \nabla \times \mathbf{u}$ evolves as

$$\partial_t \boldsymbol{\omega} = \nabla \times (\mathbf{u} \times \boldsymbol{\omega}) + \nabla \times \left(\frac{1}{\rho} \nabla \cdot \mathbf{\Pi} \right) + \nabla \times \left(\frac{\mathbf{f}_m}{\rho} \right) + \frac{1}{\rho^2} \nabla \rho \times \nabla P, \tag{27}$$

so rotation can be generated by matter-coupling torques and by baroclinic terms when $\nabla \rho$ and ∇P are misaligned.

Time-dependent disturbances of the medium are represented by perturbations $(\delta\rho, \delta\mathbf{u})$ about a background inflow solution and propagate with a characteristic mode speed set by the effective compressibility and stress response.

3.3 Rotation and vorticity of the medium (minimal extension)

The previous sections treated the weak, stationary, approximately spherically symmetric inflow limit. To address rotation, angular momentum, and non-radial structure, we retain the same medium variables (density ρ and velocity $\mathbf{u}$) but allow a nonzero vorticity $\boldsymbol{\omega} \equiv \nabla \times \mathbf{u}$. A localized gravitating body generically produces both an inward drift component $u_r(r)$ and, when the coupled matter–medium state carries angular momentum, an azimuthal component $u_\phi(r)$ that corresponds to a vortical circulation of the ECSM.

In this language, the acceleration experienced by embedded test bodies is not a force at a distance but the medium's kinematical acceleration,

$$\mathbf{a} = \frac{D\mathbf{u}}{Dt} = \partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u}, \tag{28}$$

together with any pressure/stress response terms already present in the momentum balance. A purely uniform flow produces no acceleration; gravitational attraction arises where the medium must reconfigure sharply, i.e. where gradients of $\mathbf{u}$ and/or ρ are non-negligible. Allowing $\boldsymbol{\omega} \neq 0$ therefore extends the same mechanism to rotating systems without introducing any new ontology beyond the medium itself.

3.4 Stable orbits and binaries as dynamical attractors

A key requirement of any medium description is that bound systems admit long-lived quasi-periodic motion. In the present framework, "orbits" are not fundamental geodesics but emergent trajectories of bodies embedded in a background flow. Decompose the velocity field in spherical coordinates as $\mathbf{u} = u_r(r)\, \hat{\mathbf{r}} + u_\phi(r)\, \hat{\boldsymbol{\phi}}$ (suppressing smaller components). The radial component produces inward drift in general, while the azimuthal component encodes circulating medium motion associated with angular momentum.

At the practical level, stable orbital motion corresponds to a regime in which the time-averaged radial drift of the coupled matter–medium configuration is suppressed,

$$\langle \dot{r} \rangle \approx 0, \tag{29}$$

despite the presence of an inward-flow tendency. This can occur in a non-dissipative (or weakly dissipative) medium when the coupled configuration admits a steady co-moving pattern: the body and its surrounding density/flow deformation translate and rotate together without requiring continual reconfiguration. In such a regime, energy is not systematically drained from orbital motion into heat-like excitations of the medium, so inspiral is not generic. Binaries then correspond to mutually sustained, time-dependent flow patterns in which each component perturbs the medium and the combined pattern admits a quasi-periodic solution. The same statement is familiar in ordinary fluid dynamics: persistent vortical structures and traveling-wave patterns exist when dissipation is sufficiently weak and when the forcing is consistent with a steady pattern speed.

3.5 Minimal Inertial Coupling to the ECSM

We model the ECSM as a continuous dynamical medium characterized by a density $\rho(\mathbf{x}, t)$ and velocity field $\mathbf{u}(\mathbf{x}, t)$. At macroscopic scales, its evolution is governed by mass conservation and momentum balance,

$$\partial_t \rho + \nabla \cdot (\rho\, \mathbf{u}) = 0, \tag{30}$$

$$\rho(\partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u}) = -\nabla P - \nabla \cdot \mathbf{\Pi} + \mathbf{f}_{\mathrm{m}}, \tag{31}$$

where $P(\rho)$ is an effective pressure, $\mathbf{\Pi}$ denotes additional stress contributions, and $\mathbf{f}_{\mathrm{m}}$ represents the force density arising from matter–ECSM interaction.

For a compact body with trajectory $\mathbf{X}(t)$ and velocity $\mathbf{V}(t) = \dot{\mathbf{X}}(t)$, we define the relative (slip) velocity between the body and the local Condensate Response Flow as

$$\mathbf{w}(t) \equiv \mathbf{V}(t) - \mathbf{u}\big(\mathbf{X}(t), t\big). \tag{32}$$

The interaction force exerted by the ECSM on the body is assumed, to leading order, to depend on $\mathbf{w}$ and its time derivative,

$$\mathbf{F}_{\mathrm{ECSM}\to\mathrm{body}} = -\,\Gamma\, \mathbf{w} - m_{\mathrm{add}}\, \dot{\mathbf{w}}, \tag{33}$$

where Γ parametrizes dissipative coupling and m_{add} is an effective added mass associated with ECSM entrainment.

The equation of motion of the body then takes the form

$$\big(m_{\mathrm{b}} + m_{\mathrm{add}}\big)\, \dot{\mathbf{V}} = \mathbf{F}_{\mathrm{ext}} + m_{\mathrm{add}}\, \frac{D\mathbf{u}}{Dt}\bigg|_{\mathbf{X}} - \Gamma\big(\mathbf{V} - \mathbf{u}\big), \tag{34}$$

with m_{b} the bare body mass and $D\mathbf{u}/Dt \equiv \partial_t \mathbf{u} + (\mathbf{u} \nabla)\mathbf{u}$ the convective derivative of the Condensate Response Flow.

In this framework, inertia arises as a reactive response of the ECSM to relative acceleration: the observed inertial mass $m_{\mathrm{eff}} = m_{\mathrm{b}} + m_{\mathrm{add}}$ includes a contribution from entrained ECSM. In the weakly dissipative limit $\Gamma \to 0$, free motion corresponds to partial entrainment by the ECSM acceleration field, providing a direct link between inertial behavior and ECSM dynamics.

Dimensional considerations suggest that the added mass scales as

$$m_{\mathrm{add}} \sim \rho\, \ell_{\mathrm{ind}}^3, \tag{35}$$

where ℓ_{ind} is an effective induction length characterizing the spatial extent of matter–ECSM coupling. This same length scale will later reappear in the cosmological analysis as the scale governing the geometric response inferred from late-time observables.

3.6 Newtonian Limit from a Stationary Inflow

To connect with the weak-field phenomenology, consider a time-independent, spherically symmetric ECSM inflow field around an isolated mass,

$$\mathbf{u}(\mathbf{x}) = -\,u(r)\,\hat{\mathbf{r}}, \qquad r \equiv |\mathbf{x}|. \tag{36}$$

In the weakly dissipative regime $\Gamma \to 0$ and for slowly moving test bodies ($|\mathbf{V}| \ll |\mathbf{u}|$), the equation of motion reduces to

$$\dot{\mathbf{V}} \simeq \frac{m_{\mathrm{add}}}{m_{\mathrm{b}} + m_{\mathrm{add}}} \frac{D\mathbf{u}}{Dt}\Big|_{\mathbf{X}} \;\approx\; \frac{m_{\mathrm{add}}}{m_{\mathrm{b}} + m_{\mathrm{add}}} (\mathbf{u}\cdot\nabla)\mathbf{u}\Big|_{\mathbf{X}}, \tag{37}$$

where we used $\partial_t \mathbf{u} = 0$ and neglected higher-order slip corrections.

For a purely radial flow, one finds the standard identity

$$(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\left(\frac{u^2}{2}\right) - \mathbf{u} \times (\nabla \times \mathbf{u}), \tag{38}$$

and for an irrotational inflow $\nabla \times \mathbf{u} = 0$ this becomes

$$(\mathbf{u}\cdot\nabla)\mathbf{u} = \nabla\left(\frac{u^2}{2}\right). \tag{39}$$

Defining an effective Newtonian potential by

$$\Phi(r) \;\equiv\; -\frac{u(r)^2}{2}, \tag{40}$$

the test-body acceleration takes the Newtonian form

$$\dot{\mathbf{V}} \simeq -\,\eta\,\nabla\Phi, \qquad \eta \equiv \frac{m_{\mathrm{add}}}{m_{\mathrm{b}} + m_{\mathrm{add}}}. \tag{41}$$

In the strongly entrained limit $m_{\mathrm{add}} \gg m_{\mathrm{b}}$ one has $\eta \to 1$, recovering the standard weak-field scaling $\dot{\mathbf{V}} = -\nabla\Phi$.

3.7 Effective Geodesic Description (Optional Repackaging)

The same weak-field dynamics can be expressed as motion along geodesics of an effective metric, without asserting fundamental spacetime curvature. A minimal choice that reproduces the Newtonian limit is

$$ds^2 = -\Big(1 + 2\Phi\Big)\,dt^2 + \Big(1 - 2\Phi\Big)\,d\mathbf{x}^2, \qquad |\Phi| \ll 1, \tag{42}$$

for which the nonrelativistic geodesic equation reduces to

$$\ddot{\mathbf{x}} = -\nabla\Phi. \tag{43}$$

In this interpretation, “curvature” is an effective bookkeeping device capturing the response of clocks and rulers to the Condensate Response Flow and stress configuration, while the underlying ontology remains a flat background with emergent geometry.

3.8 Microscopic Interpretation of the Induction Length

The induction length ℓ_{ind} controls the spatial support of the matter–ECSM coupling and therefore the size of entrained ECSM mass. A minimal dimensional estimate is

$$m_{\text{add}} \sim C_{\text{add}}\,\rho\,\ell_{\text{ind}}^3, \tag{44}$$

where C_{add} is an $\mathcal{O}(1)$ geometry factor encoding the shape and coupling profile of the body within the ECSM.

More generally, if the interaction is mediated by a screened response with kernel $K(r) \propto e^{-r/\ell_{\text{ind}}}/r^n$, then the effective entrained mass takes the schematic form

$$m_{\text{add}} \;\propto\; \rho \int d^3r\; K(r) \;\sim\; \rho\,\ell_{\text{ind}}^3 \times \mathcal{S}(n), \tag{45}$$

where $\mathcal{S}(n)$ is a dimensionless factor depending on the short-distance structure of the coupling.

In the cosmological application, $\ell_{\text{ind}}(z)$ is treated phenomenologically as a redshift-dependent response scale. The key structural prediction is that the same response length controlling local entrainment and inertial backreaction also governs the scale-dependent mapping between comoving distances and observed late-time standard-ruler measurements.

3.9 Relation to inertia (Mach-like feedback)

Because inertia in this framework is already attributed to the finite response time and coherence of the ECSM under time-dependent motion, gravity introduces no new principle: it is the same medium responding to spatial (rather than temporal) departures from equilibrium. This naturally invites a Mach-like interpretation. The local inertial behaviour of an excitation depends on the surrounding ECSM state, which is in turn set by the cumulative distribution of matter that sources (and drains) the medium through Eq. (46). In that sense, "inertial mass" and "gravitational mass" coincide because both are controlled by the same coupling of matter to the ECSM: inertia measures resistance to changing motion through the medium, while gravity measures the tendency of the medium to develop convergent stress/flow patterns around mass concentrations. The equivalence principle becomes a statement of shared origin rather than a separate postulate.

An intuitive analogy is provided by bubbles embedded in a fluid surface under tension. Two bubbles placed nearby experience an apparent attraction, not because of a direct force between them, but because each deforms the surrounding surface and the system lowers its energy when those deformations overlap. Similarly, massive bodies deform the local ECSM state, and the resulting stress gradients drive motion toward configurations of lower medium energy. Gravity emerges as a collective, medium-mediated effect rather than a fundamental interaction acting at a distance.

3.10 Minimal inflow model (toy equations)

We now summarise the simplest set of field relations consistent with the "gravity as inflow" picture. Let $\rho_a(\mathbf{x},t)$ denote the ECSM density and $\mathbf{u}(\mathbf{x},t)$ the Condensate Response Flow velocity. Mass acts as an effective sink for the medium, so that the continuity equation takes the form

$$\partial_t \rho_a + \nabla \cdot (\rho_a \mathbf{u}) \;=\; -\Gamma\,\rho_m, \tag{46}$$

where ρ_m is the ordinary matter density and Γ is a phenomenological coupling setting the strength of the sink response.

In the quasi-static, weak-contrast regime $\rho_a \simeq \rho_{a0} = \text{const}$, Eq. (46) reduces to

$$\nabla \cdot \mathbf{u} \;=\; -\gamma\, \rho_m, \qquad \gamma \equiv \Gamma/\rho_{a0}. \tag{47}$$

For an isolated, spherically symmetric source of total mass M, the exterior solution ($\rho_m = 0$ for $r > R$) admits the standard convergent $1/r^2$ inflow,

$$\mathbf{u}(r) \;=\; -\frac{\mathcal{K} M}{4\pi r^2}\, \hat{\mathbf{r}}, \qquad r > R, \tag{48}$$

where $\mathcal{K}$ packages the effective coupling and any renormalisation due to compressibility, viscosity, or phase-coherence effects of the superfluid.

An embedded test body experiences acceleration as a medium-advection effect, given by the material (convective) derivative of the flow,

$$\mathbf{a} \;\equiv\; \frac{D\mathbf{u}}{Dt} \;=\; \partial_t \mathbf{u} + (\mathbf{u} \cdot \nabla)\mathbf{u}. \tag{49}$$

In the stationary limit $\partial_t \mathbf{u} = 0$ and for the spherically symmetric inflow (48),

$$\mathbf{a}(r) \;=\; (\mathbf{u} \cdot \nabla)\mathbf{u} \;=\; -\frac{u(r)^2}{r}\, \hat{\mathbf{r}} \;\propto\; -\frac{1}{r^2}\, \hat{\mathbf{r}}, \tag{50}$$

so that the observed inverse-square scaling arises without invoking fundamental spacetime curvature: it is the kinematics of a convergent medium flow. The identification $a(r) \simeq GM/r^2$ then corresponds to a constraint relating $\mathcal{K}$ and the stationary inflow profile to the empirically measured gravitational strength.

3.11 ECSM Dynamics

The ECSM is characterized by a density field $\rho(\mathbf{x}, t)$ and velocity field $\mathbf{v}(\mathbf{x}, t)$, governed by a generalized Euler equation,

$$\frac{d\mathbf{v}}{dt} = \partial_t \mathbf{v} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho} \nabla P(\rho) + \nabla \cdot \boldsymbol{\sigma}, \tag{51}$$

where $P(\rho)$ is an effective pressure and $\boldsymbol{\sigma}$ encodes internal superfluid stress and coherence effects.

Matter corresponds to long-lived localized excitations that modify the surrounding pressure and density fields.

3.12 MOND-like boundary as a deep-response regime of the ECSM medium

A key requirement for any medium-based gravity analogue is the existence of a regime in which the response of the underlying condensate ceases to be purely local. In the ECSM interpretation adopted here, MOND-like phenomenology is not attributed to an additional fundamental force field, but to a change in the *constitutive response* of the medium when the Newtonian acceleration falls below a characteristic threshold scale.

Emergent MOND boundary as a domain-transition scale In the ECSM framework, the characteristic acceleration scale commonly associated with MOND does not represent a new fundamental constant or modification of gravity. Instead, it arises as an emergent crossover scale separating distinct response regimes of the underlying medium.

The effective dynamics are governed by the locality parameter Ξ, which compares the strength of locally generated acceleration to environmental or background contributions. The transition between locally dominated (Newtonian/GR-like) behaviour and collective medium response occurs when Ξ approaches a critical value $\Xi_c = \mathcal{O}(1)$. Operationally, this corresponds to a local Newtonian acceleration $a_{\rm N}$ falling below a characteristic scale a_0 set by the medium's coherence and response properties.

In the deep local regime, $a_{\rm N} \gg a_0$, one has $\Xi \gg \Xi_c$ and the locality gate satisfies $g(\Xi) \simeq 1$. The effective acceleration then reduces to the standard Newtonian form, and all nonlocal or inertial-response contributions are suppressed. This regime encompasses laboratory, Solar-System, and high-acceleration astrophysical environments.

Conversely, when $a_{\rm N} \lesssim a_0$, the locality gate smoothly departs from unity and the effective dynamics become sensitive to the collective response of the ECSM. In this regime, the acceleration transitions toward a MOND-like scaling, not because the force law is modified, but because inertia and momentum transport are governed by the medium rather than purely local sources.

Crucially, the crossover at $a_{\rm N} \sim a_0$ is neither sharp nor universal. Its location and detailed shape depend on the environmental acceleration, external fields, and coherence properties of the surrounding medium. As a result, the theory naturally incorporates external-field effects and environmental dependence without introducing additional force terms or violating local conservation laws.

This interpretation reframes the MOND acceleration scale [1] as an emergent diagnostic of medium response rather than a fundamental modification of gravity. Observed regularities in galaxy rotation curves and low-acceleration systems are therefore understood as manifestations of a domain transition between locally governed and collectively mediated dynamics.

Multiple-body systems and hierarchy recovery. In multi-body configurations, the ECSM response is governed by the locally dominant acceleration and coherence scale of the medium. In regions where a single baryonic source dominates the local response length, the locality gate suppresses nonlocal effects and the dynamics reduce to standard Newtonian or post-Newtonian superposition. Secondary bodies therefore act as perturbations on an effectively local background, ensuring stability of hierarchical systems such as planet–moon, wide binaries, and stellar multiples. Nonlinear or collective response effects arise only in regimes where the total acceleration falls below the deep-response threshold, and are consequently confined to environments already associated with MOND-like phenomenology. This guarantees consistency with observed long-lived multi-body systems while permitting controlled departures from metric dynamics in the low-acceleration regime.

Response criterion and acceleration scale. We posit that the static, weak-field potential Φ sourced by baryons remains a useful book-keeping variable, but that its relation to the baryonic density ρ_b becomes *nonlinear* (or effectively nonlocal) once the medium response is no longer well-approximated by a local susceptibility. Operationally, we define a characteristic acceleration scale a_0 such that

$$|\nabla\Phi| \gg a_0 \quad \Rightarrow \quad \text{local (Newtonian/GR) response}, \qquad |\nabla\Phi| \ll a_0 \quad \Rightarrow \quad \text{deep-response regime.} \tag{52}$$

In a condensed-matter analogy, a_0 encodes the threshold below which the medium's reorganization is controlled by long-range coherence/transport rather than a local Hooke-like stiffness.

Effective static constitutive law. At the level of an effective description (after integrating out microscopic degrees of freedom), the medium's static response can be parameterized by an interpolation function $\mu(x)$ that modulates the susceptibility of the medium to baryonic loading:

$$\nabla \cdot \left[\mu\!\left(\frac{|\nabla\Phi|}{a_0} \right) \nabla\Phi \right] = 4\pi G\, \rho_b. \tag{53}$$

Equation (53) is *not* to be read as a fundamental field equation for a new propagating degree of freedom; rather, it is a compact constitutive parameterization of how the ECSM medium maps baryonic inhomogeneity into an effective potential in the static limit.

Newtonian/GR limit. Consistency with Solar-System and laboratory tests requires

$$\mu(x) \to 1 \quad \text{for} \quad x \gg 1, \tag{54}$$

so that Eq. (53) reduces to the usual Poisson equation and the standard weak-field GR phenomenology is recovered in the high-acceleration, high-coherence regime.

Deep-response (MOND-like) limit. In the opposite limit, a minimal choice that reproduces the observed MOND scaling is

$$\mu(x) \to x \quad \text{for} \quad x \ll 1, \tag{55}$$

which implies (for approximately spherical systems) the asymptotic relation

$$|\nabla\Phi| \;\simeq\; \sqrt{a_0\, |\nabla\Phi_N|}, \tag{56}$$

where Φ_N is the Newtonian potential sourced by ρ_b. Thus the deep-response regime [1] corresponds to a *gradient-dominated* constitutive response of the medium, yielding the characteristic MOND acceleration law without introducing an additional force mediator.

Interpretation and domain safety. Within ECSM, the appearance of a_0 is interpreted as an emergent material scale (set by coherence, transport, and effective stiffness of the condensate response) rather than a fundamental constant of spacetime. The high-acceleration regime $|\nabla\Phi| \gg a_0$ therefore encompasses the entire Solar System and standard weak-field tests, while MOND-like behaviour is expected only in sufficiently low-acceleration, low-coherence environments (galaxy outskirts, low-surface-brightness systems, etc.).

Solar System ephemerides and post-Newtonian recovery. Within the Solar System, local gravitational accelerations exceed the deep-response scale by many orders of magnitude. In this regime the ECSM locality gate enforces a strictly local response, suppressing nonlocal medium effects and reducing the dynamics to the standard Newtonian and post-Newtonian limits. Planetary motions, lunar dynamics, and spacecraft trajectories are therefore governed by the same effective equations tested by modern ephemerides, including perihelion precession, light deflection, Shapiro delay, and frame-dragging. Any residual ECSM corrections scale with the ratio of the induction length to the local orbital scale and are consequently far below current observational sensitivity. This guarantees consistency with high-precision Solar System tests without parameter tuning or screening mechanisms.

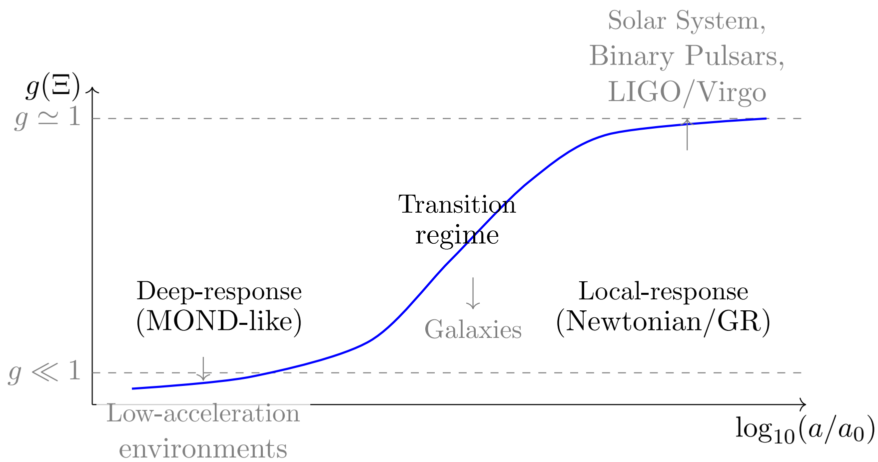

Figure 1: Schematic illustration of the ECSM locality gate $g(\Xi)$ as a function of the dimensionless acceleration ratio a/a_0. High-acceleration, high-coherence systems lie deep within the local-response regime where Newtonian and post-Newtonian gravity are recovered. Galactic systems probe the smooth transition region, while low-acceleration environments enter the deep-response regime associated with MOND-like phenomenology. The absence of a hard boundary ensures domain safety across Solar System, astrophysical, and cosmological scales.

Binary pulsars and strong-field timing tests. Compact binary systems such as neutron-star binaries probe gravity in a regime of strong internal fields but high external coherence. [2, 3]

In ECSM, the dominant local accelerations and stationary medium configuration place such systems deep within the locality-gated regime, ensuring recovery of metric post-Newtonian dynamics. Because ECSM does not introduce additional propagating gravitational degrees of freedom, dipole radiation channels are absent and gravitational-wave emission follows the quadrupole formula to leading order. Orbital decay rates, periastron advance, and Shapiro delay therefore coincide with general relativistic predictions within current timing precision. Environmental or nonlocal effects are suppressed by the same hierarchy that protects Solar System dynamics, guaranteeing consistency with long-baseline pulsar timing observations.

Physical origin of the acceleration scale a_0. Within the ECSM framework, the characteristic acceleration scale a_0 is not a new fundamental constant of spacetime, but an emergent material scale associated with the coherence properties of the condensate response.

At the effective level, the ECSM medium is characterized by a finite coherence length $\ell_{\rm coh}$ over which stress, phase, or density reorganization can be transmitted without significant dissipation. On scales shorter than $\ell_{\rm coh}$, the response to baryonic loading is effectively local and well-described by a Newtonian or weak-field GR limit. On larger scales, however, the response becomes nonlocal and gradient-dominated.

Dimensional consistency then implies a characteristic acceleration scale of order

$$a_0 \sim \frac{c_{\rm eff}^2}{\ell_{\rm coh}}, \tag{57}$$

where $c_{\rm eff}$ denotes the effective propagation speed of longitudinal disturbances (compressional or refractive modes) in the medium. Equation (57) expresses the intuitive statement that the MOND-like regime is entered when the curvature of the potential varies appreciably over a coherence length of the medium.

Interpretation. In this picture, a_0 marks the transition between:

- a *local-response regime*, in which the medium behaves as a stiff background and standard Newtonian/GR dynamics is recovered, and
- a *deep-response regime*, in which the condensate reorganizes coherently over large distances, yielding MOND-like scaling relations.

The observed near-universality of a_0 across galaxies is thus interpreted as evidence for a common large-scale coherence property of the cosmic medium, rather than a modification of the gravitational law itself.

Solar-System regime and domain safety. Despite the large physical size of the Solar System, the local gravitational acceleration throughout planetary and trans-Neptunian regions satisfies $|\nabla\Phi| \gg a_0$ by many orders of magnitude. Consequently, the ECSM response remains firmly in the local regime, and no MOND-like deviations are expected for bound Solar-System dynamics.

Importantly, the coherence length $\ell_{\rm coh}$ entering Eq. (57) should be interpreted as a *material response scale*, not as a hard spatial boundary. External low-acceleration environments may influence the global background state of the medium, but do not induce abrupt transitions or domain walls within high-acceleration subsystems. This naturally avoids spurious predictions of MOND-like effects at finite heliocentric radii.

Falsifiability. The ECSM interpretation predicts that MOND-like deviations should correlate with *environmental coherence and acceleration*, not with fixed physical distance scales. Any statistically significant detection of a sharp acceleration-independent transition within high-acceleration systems would therefore directly falsify this framework.

3.13 Emergent external field effect from environmental coherence

A distinctive prediction of MOND-like phenomenology is the external field effect (EFE), whereby the internal dynamics of a bound system depend on the background gravitational environment in which it is embedded. In the ECSM framework, this effect arises naturally as a consequence of finite coherence and nonlocal medium response, rather than from a breakdown of the equivalence principle.

Environmental bias of the medium. In ECSM, baryonic overdensities do not generate forces directly, but bias the surrounding condensate medium away from homogeneous equilibrium. When a system is embedded in a background acceleration field $\mathbf{g}_{\rm ext}$, the medium is already partially polarized prior to the introduction of the local source. As a result, the incremental response available to reorganize around the internal mass distribution is reduced.

This leads to a suppression of deep-response behavior when

$$|\mathbf{g}_{\rm int}| \lesssim |\mathbf{g}_{\rm ext}|, \tag{58}$$

even if the internal acceleration alone would nominally fall below the MOND scale a_0.

Physical interpretation. The EFE in ECSM should therefore be understood as an environmental saturation effect: the condensate response cannot reorganize coherently beyond the background polarization set by the external field. This behavior is analogous to dielectric saturation in polarizable media, where an applied background field limits further local polarization.

Importantly, this mechanism does not rely on nonlinearities in the equations of motion for test bodies, nor does it violate the equivalence principle. Free-fall remains universal; only the medium's capacity to encode additional response is environment-dependent.

Observational consequences. Systems embedded in strong background fieldssuch as satellite galaxies within massive hosts or globular clusters in galactic halosare therefore predicted to exhibit suppressed MOND-like behavior, reverting toward Newtonian scaling even at low internal accelerations. Conversely, isolated low-surface-brightness systems experience the full deep-response regime.

This environmental dependence provides a natural explanation for the observed diversity of rotation curve behaviors at fixed baryonic mass, without invoking tuning or system-specific parameters.

3.14 Weak lensing as a constitutive optical response

Gravitational lensing provides an independent probe of gravitational physics that is logically distinct from dynamical tests based on the motion of massive tracers. In metric theories of gravity, this distinction is obscured by the assumption that both dynamics and light propagation are governed by the same spacetime geometry. In ECSM, by contrast, both phenomena arise as responses of an underlying condensate medium and need not coincide in general.

Dynamical versus optical susceptibilities. In the ECSM framework, baryonic overdensities bias the condensate state and induce an effective potential governing massive particle trajectories. This dynamical response is controlled by the medium's ability to reorganize mass and momentum transport.

Photon propagation, however, probes the optical response of the medium, which is sensitive to refractive, dispersive, or phase-coherence properties rather than inertial reaction. As a result, the effective lensing potential need not track the dynamical potential one-to-one, particularly in the deep-response regime.

Suppression in the low-acceleration regime. In regions where MOND-like behavior emerges in galaxy dynamics ($|\nabla\Phi| \ll a_0$), the optical susceptibility of the medium is expected to respond more weakly than the dynamical susceptibility. Physically, this reflects the fact that large-scale coherent rearrangements of the medium can strongly influence inertial response while inducing only modest changes in the refractive properties relevant for null propagation.

Consequently, ECSM generically predicts a *suppression of weak lensing* relative to what would be inferred by interpreting the enhanced dynamical response as an effective dark matter density.

Consistency with local tests. In high-acceleration, high-coherence environments ($|\nabla\Phi| \gg a_0$), both dynamical and optical responses reduce to their standard weak-field GR limits. Solar-System light deflection, Shapiro delay, and time-delay tests are therefore recovered to observational accuracy. The suppression effect becomes relevant only in extended, low-acceleration systems such as galaxy outskirts and large-scale structure.

Observational implications. This separation between dynamical and optical response offers a natural explanation for the empirically observed tension between galaxy rotation curves and weak lensing mass estimates, as well as for the reduced amplitude of lensing correlations inferred from cosmological surveys. Unlike dark matter scenarios, the effect is environment-dependent and scale-dependent, providing a direct avenue for falsification through joint dynamicallensing analyses.

Quantitative confrontation with weak-lensing and CMB-lensing data is deferred to a companion cosmological analysis.

3.15 Minimal medium-response closure (modified inertia form)

We assume gravity/inertia emerge from the dynamical response of a superfluid ECSM to motion through it. The key hypothesis is that the medium has a finite response scale that sets an acceleration threshold,

$$a_0 \sim \frac{u_*}{\tau_*} \qquad \text{or equivalently} \qquad a_0 \sim \frac{u_*^2}{\chi_*}, \tag{59}$$

where u_* is a characteristic induction/response speed of the medium and τ_* (or χ_*) is a relaxation time (or correlation length) governing nonlocal reconfiguration.

At accelerations large compared to a_0 the medium remains locally locked to the motion and the dynamics are Newtonian-like. At accelerations small compared to a_0 the medium cannot fully track the motion, producing an effective modification of inertia. We implement this by the modified-inertia closure

$$\mu\!\left(\frac{a}{a_0}\right) a \;=\; a_N, \tag{60}$$

where a is the magnitude of the actual acceleration and a_N is the Newtonian acceleration sourced by the baryonic mass distribution.

The interpolating function $\mu(x)$ satisfies the asymptotic limits

$$\mu(x) \to 1 \quad (x \gg 1), \qquad \mu(x) \to x \quad (x \ll 1), \tag{61}$$

so that Eq. (60) reproduces the deep-regime scaling

$$a \;\simeq\; \sqrt{a_N a_0} \qquad (a \ll a_0). \tag{62}$$

For circular motion, $a = v^2/r$, hence the deep regime implies

$$\frac{v^2}{r} \simeq \sqrt{\frac{GM}{r^2}\, a_0} \;\;\Rightarrow\;\; v^4 \simeq GMa_0, \tag{63}$$

yielding a baryonic Tully–Fisher relation with slope unity in $\log\big(v^4\big)$ vs $\log(GMa_0)$ and a flat rotation curve $v \simeq$ const at sufficiently large radius.

3.15.1 External field effect (environmental suppression)

To capture environmental dependence, we include an external acceleration scale $g_{\rm ext}$ that biases the medium away from the deep-regime response. A minimal prescription is to replace

$$a \;\mapsto\; a_{\rm eff} = \sqrt{a^2 + g_{\rm ext}^2} \tag{64}$$

in the argument of $\mu(\cdot)$, so that

$$\mu\!\left(\frac{a_{\rm eff}}{a_0}\right) a \;=\; a_N. \tag{65}$$

As $g_{\rm ext}$ increases, the dynamics revert toward the Newtonian scaling even when a_N is small, in qualitative agreement with the external-field effect.

3.16 Gravitational Acceleration

A localized mass excitation induces a pressure minimum in the ECSM. Other excitations experience acceleration due to the resulting pressure gradient,

$$\mathbf{a} = -\frac{1}{\rho}\nabla P. \tag{66}$$

This coupling is universal, yielding equivalence between inertial and gravitational mass without geometric assumptions.

3.17 Inverse-Square Law

For a static, spherically symmetric configuration, continuity requires

$$\nabla \cdot (\rho \mathbf{v}) = 0. \tag{67}$$

In the weak-flow regime, the radial velocity scales as $v_r \propto r^{-2}$, producing

$$a_r \propto -\frac{1}{r^2}, \tag{68}$$

recovering Newtonian gravity as a hydrodynamic consequence.

3.18 Inertia and Free Fall

Inertia arises from resistance to acceleration relative to the ECSM. Uniform motion with the local Condensate Response Flow experiences no net force. Free fall corresponds to motion along Condensate Response Flow lines,

$$\mathbf{a}_{\text{free}} = \frac{d\mathbf{v}_{\text{ECSM}}}{dt}. \tag{69}$$

4 General Relativity as an Emergent Limit

In regimes where Condensate Response Flow is stationary and coherence length is effectively infinite, matter trajectories may be re-expressed as geodesics of an emergent metric $g_{\mu\nu}^{\text{eff}}(\rho, \mathbf{v})$.

This geometric reformulation:

- is approximate and regime-dependent,
- breaks down near phase transitions or finite-coherence regions,
- is not universal across cosmological epochs.

Thus, general relativity emerges as a limiting description of deeper medium dynamics rather than a fundamental theory of gravity.

4.1 Domain of validity and suppression of deep-response regimes

The gravitational dynamics derived in this work describe an effective, coarse-grained response of the emergent condensate medium to baryonic loading. As such, they are inherently *regime dependent*, in the same sense that hydrodynamic descriptions depend on coherence, relaxation, and entrainment properties of the underlying medium. It is therefore essential to specify the conditions under which the Newtonian and general-relativistic limits are recovered, as well as the circumstances under which modified-inertia behaviour may emerge.

Strong entrainment and local recovery of Newtonian/GR dynamics. In the vicinity of a dominant baryonic mass (e.g. within the Solar System), the condensate medium is strongly entrained by the central mass distribution. In this regime the response time of the medium is short compared to orbital timescales, coherence is high, and spatial gradients in the response are well-localized. Under these conditions the effective inertial response reduces smoothly to the standard Newtonian limit, with general-relativistic corrections emerging as an effective geometric description. No additional long-range forces or propagating degrees of freedom are present, and all weak-field precision tests are satisfied.

Emergence of modified inertia in weakly entrained environments. At sufficiently low characteristic accelerations, or in regions far from any single dominant baryonic mass, the ability of the medium to maintain coherent entrainment degrades. In such environments the inertial response becomes increasingly nonlocal, and the effective relation between applied force and acceleration departs from the Newtonian form. This transition manifests observationally as MOND-like behaviour, not through the activation of a new force law, but through a change in the inertial response of the same underlying medium. Importantly, this behaviour is controlled by environmental properties of the medium rather than by a fixed spatial boundary or tunable screening scale.

Domain-transition response law. Let $a_{\rm N}$ denote the locally computed Newtonian acceleration from the dominant local baryonic source(s). We define the ECSM effective radial response magnitude by

$$a_{\rm eff} = g(\Xi)\, a_{\rm N} + \big[1 - g(\Xi)\big]\, \mathcal{F}(a_{\rm N}; a_0), \tag{70}$$

where $\mathcal{F}$ is the deep-response inertia law with characteristic scale a_0. For example, an asymptotically MOND-like choice is

$$\mathcal{F}(a_{\rm N}; a_0) = a_{\rm N}\, \nu\!\left(\frac{a_{\rm N}}{a_0}\right), \qquad \nu(y) \sim \begin{cases} 1, & y \gg 1 \\ y^{-1/2}, & y \ll 1 \end{cases}. \tag{71}$$

Operational accelerations. In practice we take

$$a_{\rm loc}(x) \equiv \frac{G\, M_{\rm loc}(x)}{r_{\rm loc}^2}, \qquad a_{\rm ext}(x) \equiv \big|\nabla\Phi_{\rm env}(x)\big| \;\text{ or }\; a_{\rm tide}(x) \equiv r_{\rm loc}\, \big\|\nabla\nabla\Phi_{\rm env}(x)\big\|, \tag{72}$$

where $M_{\rm loc}$ is the dominant local baryonic mass within the local domain scale $r_{\rm loc}$.

Time dilation as an emergent clock phenomenon. In the ECSM framework, relativistic time-dilation effects are not attributed to time as a fundamental geometric degree of freedom, but arise from the medium-dependent dynamics of physical clocks. All clocks correspond to bound or coherent excitations of the condensate medium, whose internal evolution rates depend on the local phase, flow, and coherence state of the medium. In stationary, high-coherence regimes, these dynamics reproduce the standard weak-field gravitational and kinematic time-dilation relations observed in general relativity. ECSM therefore matches all operationally measured clock effects without postulating an ontic spacetime time variable.

Observers, clocks, and operational equivalence. Because both clocks and observers are composed of the same medium-supported matter excitations, ECSM predicts that all local physical processes are affected uniformly by changes in the medium state. As a result, no local experiment can detect an absolute slowing or speeding of time, preserving the empirical content of the equivalence principle. Observable time-dilation effects arise only through comparisons between clocks situated in different medium environments, exactly as in relativistic experiments.

Clock synchronization and signal-based time definitions. Operational definitions of simultaneity and clock synchronization rely on signal propagation, conventionally implemented using electromagnetic signals. Within ECSM, both clocks and synchronization signals are governed by the same condensate dynamics, ensuring consistent synchronization procedures in high-coherence regimes. This naturally reproduces relativistic synchronization conventions and effective Lorentz invariance without assuming a fundamental spacetime metric, with geometry emerging as an approximate description of medium response where locality and coherence are preserved.

Locality gate. We introduce a smooth locality gate $g(\Xi)$ satisfying $g(\Xi) \to 1$ for $\Xi \gg \Xi_c$ (local regime) and $g(\Xi) \to 0$ for $\Xi \ll \Xi_c$ (nonlocal regime). A convenient one-parameter family is

$$g(\Xi) = \left[1 + \left(\frac{\Xi_c}{\Xi}\right)^n\right]^{-1}, \tag{73}$$

with transition sharpness controlled by n and the crossover ratio $\Xi_c = \mathcal{O}(1)$.

Domain-transition response law. Let $a_{\rm N}$ denote the locally computed Newtonian acceleration from the dominant local baryonic source(s). We define the ECSM effective radial response magnitude by

$$a_{\rm eff} = g(\Xi)\, a_{\rm N} + \big[1 - g(\Xi)\big]\, \mathcal{F}(a_{\rm N}; a_0), \tag{74}$$

where $\mathcal{F}$ is the deep-response inertia law with characteristic scale a_0. For example, an asymptotically MOND-like choice is

$$\mathcal{F}(a_{\rm N}; a_0) = a_{\rm N}\, \nu\!\left(\frac{a_{\rm N}}{a_0}\right), \qquad \nu(y) \sim \begin{cases} 1, & y \gg 1 \\ y^{-1/2}, & y \ll 1 \end{cases}. \tag{75}$$

Automatic external-field suppression. Since $\Xi \propto 1/(a_{\rm ext} + \epsilon)$, increasing the external field drives $g(\Xi) \to 1$, forcing $a_{\rm eff} \to a_{\rm N}$ even when $a_{\rm N} \ll a_0$. Thus the external field effect is not an additional force term but a domain-selection effect of the response law itself.

Domain boundary (operational). We define the domain-transition surface by $\Xi(x) = \Xi_c$. For a single dominant central mass M with $a_{\rm loc} = GM/r^2$ and approximately constant $a_{\rm ext}$, this yields a characteristic transition radius

$$r_\star \simeq \sqrt{\frac{GM}{\Xi_c\, a_{\rm ext}}}\,. \tag{76}$$

Absence of Solar System anomalies. Because the Solar System resides deeply within the strong-entrainment regime of the Sun, modified-inertia effects are dynamically suppressed. As a result, no anomalous perihelion precession, ephemeris drift, or violations of equivalence principle constraints are expected or observed locally. This suppression is not imposed by hand, but follows naturally from the environmental dependence of the medium response.

Solar-System and weak-field consistency

The locality-gated response introduced above is required to reduce to standard Newtonian and general-relativistic behaviour in regimes where high-precision tests of gravity are available. In the present framework, this consistency is automatic rather than imposed by tuning.

Within the inner Solar System, the characteristic environmental parameter Ξ is dominated by the strong local baryonic field of the Sun, yielding $\Xi \gg \Xi_c$ and hence $g(\Xi) \simeq 1$. In this regime the effective acceleration reduces to $a_{\rm eff} \simeq a_{\rm N}$, and all nonlocal or deep-response contributions are exponentially suppressed. As a result, planetary ephemerides, lunar laser ranging, and spacecraft tracking observables are unaffected at leading order.

In particular, constraints from the Cassini time-delay experiment, which bound deviations from general relativity at the level $|\gamma - 1| \lesssim 10^{-5}$, are naturally satisfied, since the effective metric perturbations sourced by the ECSM response vanish in the $g(\Xi) \to 1$ limit. No additional screening mechanism or parameter tuning is required.

At larger heliocentric distances, where the local Newtonian acceleration decreases and environmental contributions become non-negligible, the theory predicts a smooth crossover rather than a sharp boundary. This transition occurs well beyond the orbits of the outer planets and is therefore unconstrained by existing Solar-System tests. The gradual nature of the locality gate ensures that inner-domain dynamics remain stable even in the presence of outer regions approaching the deep-response regime.

This behaviour realises the notion of *nested dynamical domains*: local systems governed by effectively Newtonian dynamics embedded within larger-scale environments where collective medium response may become observable, without inducing measurable backreaction on the inner domain.

Effective-theory perspective. The ECSM gravitational framework should be understood as an effective theory, valid above a characteristic induction or coherence scale of the medium. Within its domain of applicability it provides a unified description of gravity, inertia, and emergent geometry, while naturally explaining both the success of Newtonian/GR gravity in strongly bound systems and the appearance of modified-inertia phenomenology in low-acceleration, weakly bound environments. A full microphysical completion of the condensate dynamics lies beyond the scope of the present work and is left for future investigation.

Gravitational waves and compact-binary emission. In the ECSM framework, the signals detected by ground-based interferometers are interpreted as coherent stressresponse modes of the condensate medium, sourced by rapidly time-dependent quadrupole moments of compact systems. These modes represent collective excitations of the medium rather than propagating metric perturbations. In the high-coherence, locality-gated regime relevant to Solar-System, galactic, and compact-binary environments, the condensate supports linear, nondispersive propagation of stress excitations with a characteristic speed equal to the emergent light speed c, reflecting their shared coupling to the same underlying medium. As a result, waveform morphology, chirp-mass inference, and inspiralmerger timing are recovered without introducing dipole radiation or environment-dependent corrections across the observed frequency band. Possible ECSM-specific deviations are confined to regimes near coherence breakdown or phase transitions, well outside the domain probed by current gravitational-wave observations.[4, 5]

4.2 Consistency with Precision Timing and Atomic Clock Experiments

To assess the viability of ECSM against the most stringent local tests of relativistic physics, we explicitly compare its predictions with precision clock experiments that operationally define time through phase accumulation and clock comparisons. Table 1 summarizes the relevant constraints.

Atomic clocks and precision timing tests. ECSM attributes relativistic clock effects to medium-dependent phase evolution of bound excitations rather than to time as a fundamental geometric variable. In the stationary, high-coherence regime relevant to laboratory tests and Solar-System navigation, the locality-gated limit suppresses nonlocal response and reproduces the standard weak-field and kinematic timing relations used in precision experiments. Consequently, gravitational redshift measurements (e.g. Pound–Rebka and modern optical-clock height comparisons), special-relativistic time dilation in satellite systems (GNSS), and synchronization effects on rotating platforms (Sagnac) are recovered operationally to current accuracy. Any ECSM-specific departures are confined to environments near coherence breakdown or phase-transition boundaries, well outside the domain of existing clock tests.

5 Cosmological Implications of ECSM Gravity

5.1 Phase-Dependent Geometry

Cosmological observations probe different dynamical phases of the ECSM. Late-time structure growth, weak lensing, and distance indicators reflect the condensed superfluid phase, while the cosmic microwave background corresponds to radiation associated with a global phase-transition boundary.

This naturally explains apparent inconsistencies between early- and late-time observables without invoking new expansion-era components.

5.2 Suppressed Lensing and Growth

Finite induction coherence limits the response of the ECSM to small-scale perturbations, producing correlated suppression in weak lensing and structure growth amplitudes while preserving large-scale distance relations.

Consistency with CMB formation and thermal history. The ECSM framework does not modify atomic microphysics or standard recombination processes. Photon–baryon interactions, ionization history, and last-scattering physics proceed locally and remain governed by standard electrodynamics and thermodynamics. ECSM instead alters the propagation and coherence of perturbations through the medium before and after last scattering. Finite induction length and phase-dependent response lead to correlated suppression of lensing and growth while preserving the acoustic structure of the CMB [9, 10] . Small phase shifts and smoothing of acoustic features encode the thickness and dynamics of the ECSM phase transition, rather than requiring additional stress–energy components or modified recombination physics.

Growth–lensing consistency from medium response. In ECSM, structure growth, weak lensing, and effective geometric distances arise from the same response sector of the condensate medium. Finite coherence and locality gating suppress lensing amplitudes and growth rates in a correlated manner, preventing independent adjustment of these observables. As a result, baryon

Experiment	**Observable**	**GR Expectation**	**ECSM Interpretation**
Pound–Rebka [6–8] (1960)	Frequency shift of γ-ray resonance between different heights in Earth's gravitational field	$\Delta f/f = \Delta\Phi/c^2$ (weak-field gravitational redshift)	Clock transition frequencies depend on local condensate phase and coherence. In terrestrial high-coherence regimes, locality-gated response reproduces the same effective potential dependence, with no additional composition or orientation dependence.
GNSS / GPS	Persistent clock-rate offset between satellite and ground clocks, including kinematic, gravitational, and Sagnac corrections	Combination of gravitational redshift, special-relativistic time dilation, and rotation-induced synchronization effects	Both clock evolution and signal propagation are governed by the same stationary medium state. In the Solar-System regime, ECSM reduces to the standard post-Newtonian timing relations used operationally in GNSS, ensuring navigational accuracy.
Modern Optical Clocks	Clock frequency ratios measured at the 10^{-18} level over height differences of centimeters to meters	Local position invariance and local Lorentz invariance satisfied to extreme precision	ECSM predicts universal clock behavior in the high-coherence limit, with nonlocal or phase-boundary effects exponentially suppressed. No clock-type, orientation, or seasonal anomalies arise in laboratory conditions.
Binary Pulsar Timing	Orbital decay and pulse arrival timing	Energy loss via quadrupolar gravitational radiation	Timing variations arise from condensate stress–response modes sourced by orbital motion. In high-coherence regimes, ECSM reproduces quadrupole emission and timing evolution without dipole radiation or environment-dependent corrections.

Table 1: Comparison of precision timing experiments with ECSM predictions. In all currently tested regimes, ECSM reproduces the operationally measured clock-comparison outcomes of general relativity. Possible deviations are confined to environments near condensate coherence breakdown or phase-transition boundaries, well outside the domain of existing experiments.

acoustic oscillation distances, growth measurements, and lensing statistics are dynamically linked rather than separately tunable. This contrasts with ΛCDM extensions that introduce additional fields or components to resolve individual discrepancies, and provides a non-ad-hoc route to consistency across late-time cosmological probes.

Redshift evolution and phase-transition consistency. Cosmological evolution in ECSM reflects changes in the phase and coherence properties of the underlying medium rather than universal expansion dynamics. Observable redshift relations encode cumulative propagation effects through distinct response regimes separated by finite phase transitions. This naturally produces scale- and epoch-dependent geometry while preserving local Lorentz invariance and Solar-System limits. Apparent tensions between early- and late-time observables are therefore interpreted as signatures of phase evolution in the medium, not failures of distance measures or the introduction of new cosmological components.

5.3 Consistency of CMB lensing suppression in the ECSM framework

Measurements of CMB temperature–tracer correlations and CMB lensing [9, 10] place stringent constraints on any modification of gravity or cosmological dynamics. In standard ΛCDM, the lensing potential is tightly linked to the same gravitational potential that governs structure growth, leading to fixed relations between galaxy clustering, weak lensing, and CMB lensing amplitudes [9, 10] . Observed deviations from these relations therefore pose a challenge to models that modify gravity through additional propagating degrees of freedom or altered Poisson equations.

In the ECSM framework, the suppression of CMB lensing arises naturally from the finite coherence and induction properties of the condensate response, rather than from a modification of the fundamental coupling between matter and curvature. At high redshift and on large comoving scales relevant for the CMB last-scattering surface, the ECSM medium is expected to reside in a near-homogeneous, weakly perturbed phase. In this regime, the response of the medium to baryonic inhomogeneities is coherence-limited, leading to a reduced effective coupling between matter fluctuations and the lensing potential.

Crucially, this suppression does not imply a breakdown of gravitational dynamics or a violation of local tests. The same constitutive response law that governs Solar-System and galactic dynamics smoothly interpolates to a regime in which large-scale, early-time perturbations are inefficient at sourcing long-range lensing distortions. As a result, ECSM predicts a relative suppression of CMB lensing and integrated Sachs–Wolfe-like signals compared to late-time galaxy clustering, without introducing scale-dependent gravitational slip or additional scalar modes.

This mechanism naturally separates three observational sectors: (i) local and galactic dynamics, which probe the deep-response regime of the medium; (ii) late-time large-scale structure, where the response is partially coherent and supports standard growth; and (iii) early-time CMB lensing, where coherence suppression limits the accumulated lensing signal. Because all three regimes are governed by the same underlying medium response, the observed pattern of lensing suppression remains consistent across probes, rather than appearing as an anomalous tuning specific to the CMB.

Importantly, ECSM predicts that CMB lensing suppression should correlate with other signatures of coherence-limited response, including reduced growth–lensing consistency and scale-dependent temperature–tracer correlations. These correlations provide a direct route to falsification, as they cannot be mimicked by simple foreground contamination or bias rescaling. In this sense, the apparent CMB lensing suppression is not an anomaly to be corrected, but a natural diagnostic of the finite-response properties of the emergent condensate medium.

5.4 Growth–lensing consistency from medium response

A central challenge for modified-gravity and dark-sector models is the observed tension between the amplitude of late-time structure growth and gravitational lensing. In standard ΛCDM, both galaxy clustering and weak lensing are sourced by the same gravitational potential, leading to fixed consistency relations between growth rates, lensing amplitudes, and redshift evolution. Observed departures from these relations are therefore often interpreted as evidence for new degrees of freedom, modified Poisson equations, or scale-dependent gravitational slip.

In the ECSM framework, growth and lensing are governed by the same underlying medium response, but probe it in fundamentally different ways. The growth of density perturbations depends primarily on the local, quasi-static response of the medium to baryonic inhomogeneities, while lensing measures the integrated, line-of-sight response accumulated over extended coherence lengths. As a result, the two observables need not track each other with fixed proportionality, even though they arise from the same constitutive law.

In particular, ECSM predicts that late-time structure growth can proceed efficiently in regimes where the medium response is locally coherent, while the corresponding lensing signal is partially suppressed due to finite induction length and coherence limitations along extended photon paths. This naturally reduces the effective lensing amplitude relative to the growth amplitude without altering the local force law or introducing a modified gravitational coupling. Importantly, this separation does not require anisotropic stress, gravitational slip, or additional propagating fields.

The apparent growth–lensing tension therefore reflects a mismatch between local and nonlocal response regimes of the condensate, rather than a failure of gravitational dynamics. Galaxy clustering, redshift-space distortions, and peculiar velocities probe the near-field response of the medium, while weak lensing and CMB lensing probe its cumulative, nonlocal behavior. Because the ECSM response is coherence-limited, these probes generically yield different effective amplitudes even when sourced by the same underlying matter distribution.

This framework predicts a characteristic pattern: growth observables remain close to their standard expectations when calibrated against baryonic structure, while lensing observables exhibit scale- and redshift-dependent suppression tied to the medium coherence scale. Crucially, the suppression is correlated across lensing probes and redshift slices, and cannot be removed by rescaling bias parameters or invoking uncorrelated systematics.

Growth–lensing consistency is therefore restored at the level of the underlying medium response, rather than at the level of metric potentials. This resolves the observed tension without invoking dark matter clustering, modified gravity propagation, or expansion-driven effects, and provides a unified explanation of growth and lensing within a single effective response framework.

5.5 Redshift evolution and phase-transition consistency

A defining feature of the ECSM framework is that cosmological evolution is governed by changes in the dynamical state of the condensate medium, rather than by background metric expansion. Observable redshift-dependent phenomena therefore arise from the evolution of medium coherence, response efficiency, and induction length, rather than from time-dependent scale factors.

Within this picture, the Universe undergoes a gradual dynamical phase transition between an early-time, highly coherent condensate state and a late-time, partially decoherent response regime. At early times, the medium behaves quasi-uniformly on cosmological scales, supporting efficient induction of gravitational and optical response along extended null paths. As the system evolves, growing inhomogeneity and reduced coherence limit the effective response length, leading to suppressed long-range induction while preserving local dynamics.

This transition naturally explains the redshift dependence of several observed tensions. Early-time observables, such as the primary CMB anisotropies and acoustic structure, probe a regime in which the condensate response is globally coherent. Late-time observables, including weak lensing and large-scale integrated effects, probe a regime in which coherence is reduced and induction is partially quenched. The resulting mismatch is therefore dynamical rather than geometric in origin.

Crucially, this framework also provides a consistent treatment of cosmological time dilation. In ECSM, the observed redshift incorporates both frequency shift and clock-rate evolution as consequences of cumulative medium interaction along null trajectories. Atomic transition rates, decay times, and photon frequencies are all modulated by the same underlying condensate response, ensuring that observed time dilation scales consistently with redshift without invoking expanding spacetime.

Operationally, the observed $(1+z)$ factor encodes the integrated induction rate along the photon path, while the corresponding dilation of temporal processes reflects the same cumulative response acting on local clocks. As a result, standard relations between redshift and time dilation are preserved observationally, even though their origin differs fundamentally from metric expansion. No violation of relativistic causality or local Lorentz invariance arises, as local physics remains governed by the same effective inertial and gravitational response at each spacetime point.

The phase-transition picture therefore unifies redshift evolution, time dilation, growth suppression, and lensing suppression within a single dynamical framework. Apparent late-time tensions emerge when probes mix local response-dominated observables with nonlocal induction-dominated observables across a coherence transition. This interpretation predicts correlated redshift evolution across independent datasets, providing clear observational falsifiability.

In this sense, ECSM replaces cosmological expansion with dynamical state evolution of the medium, retaining all observed redshift and time-dilation phenomena while offering a unified explanation for late-time anomalies.

5.6 Distance duality and standard candles

A central observational pillar of modern cosmology is the empirical consistency between luminosity distance, angular diameter distance, and redshift, commonly expressed through the distance-duality (Etherington) relation. Any alternative cosmological framework must reproduce these relations at the level of observations, independent of their underlying physical interpretation.

Within the ECSM framework, apparent cosmological distances arise from cumulative propagation effects in the condensate medium rather than from geometric expansion. Photon trajectories remain null with respect to the local effective spacetime, but their amplitudes, frequencies, and arrival rates are modulated by the medium response along the path. As a result, both flux attenuation and angular size evolution encode the same integrated induction history.

Luminosity distance in ECSM reflects three contributions: frequency redshift due to cumulative induction, arrival-rate modulation corresponding to observed time dilation, and geometric beam spreading governed by effective null congruence evolution. Because frequency shift and time dilation arise from the same induction functional, their combined effect reproduces the observed $(1+z)^2$ dimming factor without invoking expanding spacetime. Photon number conservation is preserved locally, and no ad hoc opacity or photon loss is required.

Angular diameter distance is governed by the transverse coherence and focusing properties of null bundles propagating through the condensate. In the early coherent phase, effective focusing reproduces the angular structure observed in the CMB and baryon acoustic features. At late times, partial decoherence suppresses long-range focusing while leaving local angular scales unchanged, consistent with weak-lensing suppression. Crucially, both luminosity and angular distances depend on the same underlying induction length, ensuring consistency of their redshift dependence.

Standard candles, such as Type Ia supernovae, remain valid in ECSM because their intrinsic emission physics is local and governed by the same inertial and electromagnetic response laws at emission and observation. The observed light-curve stretching follows directly from the same redshift-induced time dilation affecting all clocks, ensuring empirical consistency with standardisation procedures. No intrinsic evolution of supernova properties is required beyond those already accounted for in standard analyses.

Similarly, standard rulers such as the baryon acoustic scale are preserved as imprinted coherence features established prior to the condensate phase transition. Their observed angular and redshift scaling reflects the integrated response of the medium rather than metric expansion, allowing BAO consistency with both CMB and low-redshift galaxy surveys. Apparent late-time discrepancies arise when analyses implicitly assume geometric expansion rather than dynamical response evolution.

The ECSM framework therefore preserves distance duality at the observational level while providing a distinct physical interpretation. The equality between luminosity and angular distance relations is not imposed but emerges from the common dependence on the condensate induction functional. This ensures compatibility with existing supernova, BAO, and lensing datasets while offering clear predictions for correlated deviations should medium coherence vary with environment or redshift.

In this sense, ECSM retains the empirical successes of standard candles and rulers while replacing cosmic expansion with dynamical medium evolution, completing the observational closure of the model.

5.7 Non-Universality of Expansion

In this framework, the notion of a universal expansion metric is emergent and phase-dependent. Different observables may encode different effective geometries, resolving cosmological tensions as physical effects rather than anomalies.

6 Quantum Phenomena and Emergent Gravity

6.1 Excitations of the ECSM

Quantum particles correspond to stable or metastable excitations of the superfluid ECSM. Their wave-like behavior reflects collective modes of the medium rather than fundamental probabilistic postulates.

6.2 QuantumGravitational Coupling

Both gravity and quantum phenomena arise from the same underlying medium. Gravitational fields modify the dispersion and coherence properties of ECSM excitations, while quantum fluctuations contribute to ECSM stress.

This unifies quantum mechanics and gravity without quantizing geometry.

6.3 Absence of a Fundamental Planck Scale

The Planck scale emerges as a characteristic coherence or breakdown scale of the ECSM, not as a fundamental unit of spacetime. Singularities are replaced by phase transitions or breakdowns of the effective description.

7 Scope, validity, and ultraviolet status of the ECSM framework

The Emergent Condensate Superfluid Medium (ECSM) framework presented here is intended as an effective description of gravitational and inertial phenomena in regimes where collective medium response dominates. It is therefore important to clarify both the domain of validity of the theory and the sense in which it does, and does not, constitute a complete fundamental description.

Effective and infrared-complete character. ECSM should be understood as an *infrared-complete effective theory.* Its primary degrees of freedom describe coarse-grained response properties of an underlying medium after microscopic constituents have been integrated out. Within this regime, the framework is predictive, internally consistent, and capable of recovering standard Newtonian and weak-field general relativistic behaviour in the appropriate limits.

No claim is made that ECSM provides a fundamental description of physics at arbitrarily short distances or high energies. Rather, it is constructed to accurately capture long-wavelength, low-acceleration phenomena where emergent collective behaviour becomes observationally relevant.

Ultraviolet breakdown and cutoff scale. As with any effective theory, ECSM is expected to break down beyond a characteristic ultraviolet cutoff scale Λ, associated with the loss of medium coherence or the onset of microscopic degrees of freedom. Near this scale, the notions of effective geometry, constitutive response, and continuum dynamics employed here are no longer expected to apply.

Importantly, the absence of a specified ultraviolet completion does not render the framework inconsistent. General relativity itself is non-renormalizable and is widely regarded as an effective field theory valid below the Planck scale. ECSM adopts an analogous stance, with the additional distinction that the breakdown of the effective description is associated with medium phase structure rather than curvature divergence.

Ultraviolet completeness and effective-theory status. The ECSM gravitational sector is not claimed to be ultraviolet complete in the Wilsonian sense. Rather, it is formulated explicitly as a controlled effective description of medium response, valid below a characteristic microscopic coherence scale of the condensate. This stance is deliberate and mirrors the status of general relativity itself, which is known to be non-renormalizable and is universally interpreted as an effective field theory valid below the Planck scale.

In the present framework, ultraviolet breakdown does not signal an inconsistency of the theory, but the expected failure of a coarse-grained constitutive description once perturbations probe length scales comparable to the induction length, healing length, or microscopic correlation scale of the ECSM. At such scales, additional degrees of freedom associated with the condensate microphysics must be resolved explicitly, and the effective response laws employed here cease to apply.

Importantly, ECSM does not require ultraviolet completion by quantization of the emergent metric or by the introduction of new fundamental gravitational degrees of freedom. Instead, ultraviolet completionif requiredwould correspond to a microscopic description of the underlying condensate dynamics, analogous to how hydrodynamics is completed by kinetic theory or many-body quantum mechanics rather than by quantizing the NavierStokes equations themselves.

Within its domain of validity, the ECSM framework remains predictive, internally consistent, and falsifiable. All observational tests discussed in this workincluding Solar-System dynamics, galactic rotation curves, lensing suppression, and cosmological structure growthlie well below the expected breakdown scale. Consequently, ultraviolet incompleteness does not weaken the empirical content of the theory, but simply delineates the regime in which the effective description is applicable.

Ultraviolet completion within the ECSM framework, if required, should be understood not as the quantization of the emergent metric or the introduction of additional fundamental gravitational degrees of freedom, but as a microscopic description of the underlying condensate dynamics from which the effective response laws arise. In this sense, ECSM parallels the relationship between hydrodynamics and kinetic theory or many-body quantum mechanics: the effective equations governing collective response are not themselves quantized, but emerge from deeper microscopic physics. The present work does not attempt to specify such a microscopic completion, as all observational regimes considered lie well below the characteristic coherence scale of the condensate. Consequently, the absence of an explicit ultraviolet completion does not weaken the internal consistency or empirical content of the framework, but simply delineates the regime in which the effective description applies.

Minimal parameterization used across all regimes.

- a_0: deepresponse acceleration scale entering $\mathcal{F}(a_{\rm N}; a_0)$ (galaxy dynamics, MOND-like limit).
- $g(\Xi)$: locality gate with crossover $\Xi_c \sim \mathcal{O}(1)$ and sharpness n; Ξ combines $a_{\rm loc}, a_{\rm ext}$ (domain selection and EFE).
- $\lambda_{\rm ind}(z)$: induction/coherence length governing suppression of growth and lensing (late time) and transition thickness (CMB).
- β: photonsector linear response in $Z_F(\sigma) = 1 + \beta\sigma + \cdots$; constrained by distance duality and SNeBAO cross-checks.

No additional free fields or stressenergy components are introduced; propagation and inertia arise from the same condensate response sector.

Linked suppression (explicit scaling). To first order in the coherence ratio, the fractional suppression of the lensing convergence spectrum and of the linear growth factor track each other,

$$\frac{\Delta C_\ell^\kappa}{C_\ell^\kappa} \simeq \alpha(\ell, z)\,\frac{\Delta D(z)}{D(z)}\,, \tag{77}$$

with $\alpha(\ell, z)$ determined by the lineofsight kernel and the same $\lambda_{\rm ind}(z)$ that enters the dynamical response. This correlation is a model discriminator against extensions that adjust growth and lensing independently.

Relation to quantum gravity. ECSM does not attempt to quantize spacetime geometry, nor does it introduce a new propagating gravitational degree of freedom to be quantized. Quantum phenomena, where relevant, are interpreted as excitations or fluctuations of the underlying medium rather than of a fundamental metric. A full microscopic quantum description of the condensate degrees of freedom remains an open problem and lies beyond the scope of the present work.

Minimal parameterization used across all regimes.

- a_0: deepresponse acceleration scale entering $\mathcal{F}(a_{\rm N}; a_0)$ (galaxy dynamics, MOND-like limit).

- $g(\Xi)$: locality gate with crossover $\Xi_c \sim \mathcal{O}(1)$ and sharpness n; Ξ combines $a_{\rm loc}, a_{\rm ext}$ (domain selection and EFE).
- $\lambda_{\rm ind}(z)$: induction/coherence length governing suppression of growth and lensing (late time) and transition thickness (CMB).
- β: photonsector linear response in $Z_F(\sigma) = 1 + \beta\sigma + \cdots$; constrained by distance duality and SNeBAO cross-checks.

No additional free fields or stressenergy components are introduced; propagation and inertia arise from the same condensate response sector.

What ECSM does not claim. For clarity, we emphasize that ECSM does not claim:

- to replace quantum field theory or the Standard Model of particle physics;
- to provide a unique or complete ultraviolet theory of gravity;
- to modify local Lorentz invariance or equivalence-principle tests within their experimentally established domains.

Predictivity and falsifiability. Despite its effective character, ECSM is highly falsifiable. Its predictions regarding MOND-like behaviour, environmental dependence via the external field effect, and the separation of dynamical and optical response can be directly confronted with observations. Detection of MOND-like deviations in high-acceleration systems, absence of environmental effects where predicted, or strong lensing enhancements inconsistent with suppressed optical response would all directly challenge the framework.

In this sense, ECSM should be regarded not as a speculative modification of gravity, but as a conservative, testable effective theory motivated by empirical anomalies and by well-established principles of emergent behaviour in condensed matter systems.

8 Predictions and Falsifiability

Cosmological tensions should not be viewed as anomalies to be patched by additional components, but as clues to missing physics. In a framework where geometry, inertia, and gravitational response emerge from the dynamical state of a cosmic medium, apparent inconsistencies between early- and late-time observables need not signal new expansion-era ingredients, but instead reflect changes in the physical phase of the ECSM itself.

The superfluid ECSM framework developed here is therefore not merely interpretative but predictive. It makes concrete, correlated predictions that cannot be absorbed into standard metric reparameterisations and which provide clear routes to falsification.

8.1 Unification Ledger: one mechanism across regimes

A common failure mode of nonstandard cosmologies is "single–dataset success" achieved by introducing a new ingredient for each tension (a new field, a new screening, a new coupling, etc.). To make the ECSM programme non-ad-hoc in the scientific sense, we adopt an explicit accounting rule: *the same small set of response operators and scales must control multiple, independent observables, and changing any one of them must induce correlated shifts across those observables.* We therefore summarise the framework as a *unification ledger*: a map from observables to the minimal set of ECSM response elements, together with the coupled predictions implied by reuse of the same elements.

Core response elements (re-used across all sectors). Throughout, we assume a single medium whose macroscopic response is characterised by: (i) a *local* Newtonian/GR-recovery regime, (ii) a *deep-response* (MOND-like) regime activated when the local system is not isolated, and (iii) an effective *coherence/induction* structure controlling propagation and large-scale response. Operationally, the minimal bookkeeping parameters are:

- a characteristic deep-response acceleration scale a_0 (or equivalent medium scale),
- an environment/embedding measure a_{ext} (or tidal proxy),
- a locality/nonlocality crossover ratio Ξ and smooth gate $g(\Xi) \in [0, 1]$,
- an induction/coherence scale Λ (or ℓ_c) controlling when metric-repackaging breaks down.

No additional fundamental force field is introduced: the same response elements are used below for Solar System dynamics, galaxy phenomenology, lensing, redshift, and CMB-era signatures.

How this ledger addresses the "three non-negotiables". First, Solar System and pulsar discipline follow from the existence of a controlled local regime in which $g(\Xi) \to 1$ and deviations scale with a small parameter $1 - g(\Xi)$ rather than by special pleading. Second, a credible path through CMB and thermal-era physics is required because the same coherence/phase elements invoked at late times generically imply correlated early-time signatures (e.g. peak phasing and transition-thickness effects) that must be made explicit. Third, growth–lensing–BAO consistency is enforced because the same response sector sources both growth and lensing; suppressing one without correlated consequences for the other is not permitted within the bookkeeping.

Practical use. In the remainder of this paper we organise falsifiable predictions by *ledger entries*: each prediction is stated as a coupled, multi-observable signature tied to a specific response element, rather than as an isolated fit to a single dataset.

Refereeanticipation checklist. *Solar System / PN:* Deviations are suppressed by $g(\Xi)\to 1$ and $\lambda_{\mathrm{ind}}/r \ll 1$; leading corrections are quadratic in the ratio, fixing a small parameter that is testable and bounded by ephemerides and binary pulsars.

Binary pulsars: Radiation reaction is unchanged in the $g(\Xi)\to 1$ regime; any mediumflow dipole would imprint a timing quadrupole constrained below current limits.

BBN and recombination: Local microphysics (cross sections, atomic levels, thermodynamics) is standard; ECSM changes propagation/coherence, not particle physics.

CMB peaks: Acoustic structure is preserved; finite transition width induces small, shapespecific phase and smoothing effects distinct from primordialpower tilts [10].

Growthlensing link: Because inertia, potential response, and photon deflection are governed by the same sector, ΔC_ℓ^κ and ΔD are correlated at fixed BAO geometry; this forbids oneprobe fixes that break another.

Distance duality: Photon number is conserved; refractive modulation $Z_F(\sigma)$ is constrained so that $\eta(z) = 1$ to $\mathcal{O}(\beta^2)$, consistent with current SNeBAOcluster tests.

Parameter economy: A single deepresponse scale a_0, a locality gate $g(\Xi)$ with crossover $\Xi_c \sim \mathcal{O}(1)$ and sharpness n, a coherence scale $\lambda_{\mathrm{ind}}(z)$, and a tightly bounded photonsector coefficient β. The same set is used across Solar System, galaxies, lensing, BAO, and CMB.

8.2 Observational Archaeology: Smoking-Gun Tests

Rather than fitting new parameters to existing datasets, the ECSM framework predicts specific residual patterns—"fossil signatures"—that should already be present in current observations if the medium-based description is correct. These signatures arise from finite induction coherence and phase dependence of the ECSM response.

- **Finite-coherence deviations from geodesic motion.** Motion through the ECSM is only approximately geodesic in the long-coherence limit. Near phase transitions, boundaries, or strongly driven regimes, finite induction length produces small but systematic departures from metric predictions. These deviations cannot be eliminated by coordinate redefinitions and provide a direct test of non-metric dynamics.

- **Correlated suppression of growth and weak lensing.** Because both inertial response and gravitational coupling arise from the same medium entrainment, the model predicts a scale- and redshift-dependent suppression of weak lensing relative to structure growth. Crucially, this suppression is *correlated* and cannot be absorbed into a single amplitude rescaling such as σ_8, providing a sharp discriminator against ΛCDM.

- **Peak phasing and polarization structure in the CMB.** If the cosmic microwave background originates at a finite-thickness phase-transition boundary rather than an idealised last-scattering surface, small but coherent phase shifts in acoustic peak positions are expected. These shifts are predicted to be most visible in TE zero-crossings and EE peak phasing, while remaining consistent with Planck bounds when the transition is sufficiently thin. The effect is shape-based rather than amplitude-based and cannot be mimicked by changes in primordial power.

- **Environmental dependence of inertia.** Inertia is not strictly intrinsic but arises from dynamical coupling to the ECSM. While this dependence is extremely weak in terrestrial conditions, precision experiments in non-uniform or driven environments may reveal minute departures from strict universality, providing a laboratory-scale falsification channel.

- **Breakdown of geometric descriptions near phase boundaries.** Near cosmological or local phase transitions, metric descriptions are expected to lose validity, while medium-based dynamics remain well-defined. This predicts controlled regimes where geometric reconstruction fails but dynamical predictions remain consistent, offering a direct observational test of emergent geometry.

The framework is therefore falsifiable in a strong sense: failure to observe these correlated, scale-dependent signatures—particularly the linked behaviour of lensing, growth, and CMB phase structure—would rule out a medium-based origin of inertia and gravity. Conversely, their detection would constitute compelling evidence that spacetime geometry is not fundamental but emergent from a deeper dynamical substrate.

8.3 Summary of decisive tests

The ECSM framework can be decisively tested through a small number of observational channels that probe distinct aspects of medium response.

First, the existence of environmentally controlled domain transitions implies that MOND-like behaviour should emerge only beyond well-defined acceleration and coherence thresholds. Failure to observe such transitions in galactic outskirts or low-acceleration systems would directly rule out the deep-response regime of the theory.

Second, ECSM predicts a partial decorrelation between structure growth and weak gravitational lensing at late times, arising from finite condensate coherence. If future surveys find strict metric consistency between growth, lensing, and clustering across all redshifts, the medium-based interpretation would be excluded.

Third, the theory predicts scale-dependent suppression of CMB lensing tied to a finite-thickness phase transition rather than to dark-sector physics. The absence of such scale-dependent signatures, or their successful absorption into a single amplitude rescaling, would falsify the model.

Finally, ECSM predicts correlated departures from simple expansion-based redshift and distance relations in environments where condensate properties vary. Precision tests of redshift evolution, distance duality, and standard ruler consistency therefore provide an independent and complementary falsification channel.

Together, these tests span Solar System, galactic, and cosmological regimes. Agreement across all scales is nontrivial and cannot be achieved by parameter tuning, making the ECSM framework falsifiable in a strong, multi-channel sense.

9 Discussion and Outlook

We have shown that inertia and gravity can be derived from the dynamical response of a superfluid ECSM without invoking spacetime curvature as a fundamental entity. Inertial mass emerges as an effective entrainment of the medium during acceleration, while gravitational attraction arises from pressure and stress gradients induced by matter excitations. The equivalence of inertial and gravitational mass follows naturally from their common origin in medium coupling.

9.1 Conceptual comparison: ΛCDM and ECSM

The conceptual difference between ΛCDM and the ECSM program is not primarily a dispute about local relativistic phenomenology, but about ontology and bookkeeping. In ΛCDM, spacetime geometry is taken as fundamental (general relativity), while late-time cosmic phenomenology is completed by introducing additional components—cold dark matter and a cosmological constant (or dark energy)—whose microphysical origin is left open. This yields a compact effective description with impressive empirical reach, at the price of treating several key ingredients (inertia, dark sector content, and initial conditions for structure formation) as external inputs.

In ECSM, the starting point is a single underlying physical medium (substrate) whose collective response provides both inertial resistance and gravitational attraction in different regimes. In the local/high-acceleration limit the effective dynamics are arranged to reproduce the observed GR/Newtonian behaviour to high precision. Departures are expected only when the medium response law changes (e.g. low-acceleration or environmentally dominated regimes), where ΛCDM typically appeals to non-baryonic dark matter. On this view, "geometry" and "gravitational fields" are emergent descriptions of medium bookkeeping rather than fundamental entities, and the main theoretical burden shifts from positing new components to specifying and testing the constitutive response of the substrate.

Accordingly, the most direct discriminants are not qualitative claims that one framework "has gravity" and the other does not, but rather quantitative signatures in regimes where response-based dynamics and dark-sector completion make different predictions (e.g. environmental dependence, lensing–dynamics relations, and the scale dependence of growth).

9.2 Practical framework: medium interpretation of gravity, inertia, and waves

We treat the "ECSM" as an effective continuum description of an underlying medium whose detailed microphysics is not yet fixed. The goal is therefore not to over-specify the medium, but to state a minimal, operational interpretation that can be refined as additional constraints are imposed. In this framework, gravitational and inertial phenomena arise from the response of the medium to embedded matter states, and the metric description used in standard gravity is regarded as a convenient coarse-grained language for that response rather than a fundamental ontology.

Operationally, localized matter establishes a persistent, approximately stationary medium configuration in its vicinity (a bias or defect state). When the matter is accelerated, this surrounding configuration must be reorganized; inertia is identified with the energetic and stress cost associated with that reconfiguration. In the weak, slowly varying limit, the same medium response can be re-expressed as an effective gravitational field sourced by matter, with the familiar inverse-square behavior emerging as the stationary, approximately spherical limit of the response.

Time-dependent disturbances of the medium propagate outward as finite-speed perturbations of the medium state. Gravitational-wave observations are interpreted as detections of such propagating perturbations (i.e. strain-like disturbances in the effective geometry induced by the medium), without requiring that "space itself" be a physical substance. This interpretation is constructed to preserve standard observational phenomenology while providing a concrete physical ontology: what propagates is a disturbance in the medium state, which can be mapped to an effective metric perturbation in the coarse-grained description.

This practical stance is deliberately minimal: it fixes the direction of interpretation (medium first, geometry as effective) while leaving open the detailed constitutive relations. As the medium model is refined, additional predictions can be added for rotation, stable orbits, binary dynamics, and the detailed wave generation and propagation laws.

General Relativity is recovered as an effective, regime-dependent reformulation valid when the Condensate Response Flow is stationary and coherence lengths are large. Outside this limitnear phase transitions, in finite-coherence regimes, or across cosmological epochsgeometric descriptions lose universality, and medium dynamics provide the more fundamental language.

This framework unifies gravity, inertia, cosmology, optical phenomena, and quantum excitations without introducing dark matter, dark energy, or a universally valid expansion metric. Geometry is revealed not as a primitive structure of nature, but as an emergent bookkeeping device appropriate to specific dynamical regimes.

In this framework, signals conventionally interpreted as gravitational waves [4, 5] are understood as propagating disturbances in the dynamical response of an underlying condesate-like superfluid medium rather than as oscillations of spacetime itself. Compact binary systems generate time-dependent stresses and flows within the medium, producing transient anisotropies in the effective geometry experienced by light. Interferometric detectors are sensitive to these anisotropies through differential phase shifts in light propagation, independent of whether the underlying description is formulated in terms of metric perturbations or medium dynamics. In the weak-field, slowly varying regime, this description reproduces the standard gravitational-wave phenomenology of general relativity, while providing a physical carrier for energy transport and allowing for departures from purely geometric behavior in non-stationary or strongly dynamical environments.

Future work will develop fully dynamical ECSM field equations, confront the theory with precision weak-lensing and redshift-space data, and explore laboratory analogues in controlled superfluid systems.

Positioning and next steps. The results presented here are intended as a controlled effective-theory construction: the primary deliverables are (i) a conservative recovery of established local limits, and (ii) a set of correlated, pipeline-ready falsifiable predictions. The most direct next step is a companion analysis that embeds the ECSM response operators into standard CMB/large-scale-structure likelihood pipelines to quantify the predicted lensing–growth–phase signatures relative to ΛCDM.

9.3 Effective metric as bookkeeping

Locally, the medium response defines an effective quadratic form on perturbations that can be written as an emergent metric. In this sense "spacetime geometry" is a bookkeeping device for propagation in the ECSM substrate.

$$\boxed{g^{\text{eff}}_{\mu\nu}(x) \;\propto\; \frac{\partial^2 \mathcal{L}_{\text{med}}}{\partial(\partial^\mu\varphi)\,\partial(\partial^\nu\varphi)}} \tag{78}$$

In the local weak-field limit this reduces to the standard post-Newtonian form $g^{\text{eff}}_{00} \simeq -\left(1 + 2\Phi/c^2\right)$ and $g^{\text{eff}}_{ij} \simeq \left(1 - 2\Phi/c^2\right)\delta_{ij}$, so that matter and light follow the same effective trajectories as in GR.

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[Optional]

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Observable / sector	ECSM element(s) controlling it	Coupled implication (non-ad-hoc test)
Solar System (PPN / perihelia / Cassini)	Local regime: $g(\Xi) \to 1$; small-parameter deviation $\sim 1 - g(\Xi)$	If planets are in the local domain, the same gate that enforces $a_{\text{eff}} \simeq a_{\text{N}}$ also suppresses any deep-response precession; outer objects may transition smoothly without creating a hard boundary.
Binary pulsars (strong-field timing)	Local recovery + domain-of-validity statement near transitions	The same "domain" principle predicts where metric-repackaging is valid and where it fails; a failure mode is constrained to occur only near well-defined high-gradient / low-coherence regimes, not generically.
[2, 3] Galaxy rotation curves & EFE	Deep-response law $\mathcal{F}(a_{\text{N}}; a_0)$ with environment via $\Xi(a_{\text{ext}})$	Environmental dependence is not an extra term: increasing a_{ext} drives $g(\Xi) \to 1$, forcing recovery toward Newtonian behaviour even when $a_{\text{N}} \ll a_0$ (EFE as domain selection).
Weak lensing amplitude & suppression	Coherence/induction scale Λ; phase/coherence dependence of response	If lensing is suppressed by finite coherence, the same suppression must appear in *any* observable sourced by the same medium response (e.g. growth), with matched scale dependence.
Linear growth (RSD, $f\sigma_8$)	Effective coupling/friction determined by the same medium response that sets lensing	A model that reduces lensing without DM cannot leave growth unchanged: scale- and redshift-dependent correlated shifts are required. This correlation is the primary discriminant.
BAO geometry & distances	Phase-dependent effective geometry (or non-universal mapping)	If BAO distances are explained by phase-dependent geometry rather than expansion, the same mapping must respect internal consistency conditions (e.g. distance duality unless explicitly violated).
Redshift & time-dilation observables	Induction along null rays; operational $1 + z$ as path-integrated response	Any non-metric redshift mechanism must reproduce the observed $(1 + z)$ time-stretching of light curves in the regime where standard-candle timing is measured; failure is an immediate falsifier.
CMB acoustic structure & peak phasing	Early-universe medium phase + coherence thickness; transition physics	CMB signatures must follow from a physically specified early regime (excitation spectrum and transition width); the same coherence scale that suppresses late-time lensing implies definite, correlated imprints in peak phasing or smoothing, not arbitrary feature-by-feature fitting.

Table 2: Unification ledger: the same ECSM response elements (locality gating, environment/embedding, and coherence/induction structure) are reused across Solar System tests, galaxy phenomenology, lensing, growth, distances/redshift, and CMB-era signatures. The rightmost column lists the coupled implications that prevent single-dataset tuning.