ECSM Microphysics (Sanity Draft): A Minimal Microscopic Scaffold for Gravity, Optics, and Structure

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Abstract

This document is a non-submission "sanity draft" whose purpose is to propose a minimal microphysical scaffold for the Emergent Condensate Superfluid Medium (ECSM) program. We do not claim a final UV completion. Instead we define a compact microscopic Lagrangian whose low-energy limits reproduce (i) locality-gated gravity/inertia in coherent environments, (ii) non-metric light propagation with a robust Maxwell limit, (iii) a controlled domain transition that activates nonlocal response, and (iv) an early-universe phase-transition story consistent with the observed decoupling of growth and lensing. We mark assumptions explicitly and isolate the operational parameters that can be constrained.

Contents

1 Purpose, scope, and what is meant by "microphysics"

Goal. Provide a minimal microscopic model (fields + symmetry + action) such that the macroscopic ECSM claims used in the gravity, growth, and optics papers emerge as controlled limits.

Non-goals. This draft does not derive the full Standard Model, does not propose a unique set of particle identities, and does not attempt to be mathematically UV complete in the axiomatic sense. It is a scaffold: a place to attach constraints, identify failure modes, and guide the next derivations.

Operational philosophy. All "relativistic" and "metric" behaviour is treated as emergent operational structure: what clocks do, what rods measure, and how excitations propagate in a medium.

2 Core fields, symmetries, and the locality/coherence variable

We take a compressible condensate described by an order parameter

$$\Psi(x) = \sqrt{n(x)}\, e^{i\theta(x)}, \tag{1}$$

where n is a density proxy and θ is the phase. The condensate supports long-wavelength hydrodynamic modes and a controlled breakdown of locality encoded by a scalar coherence state $\chi(x) \in (0, 1]$.

2.1 Locality gate

We introduce a smooth locality gate $G(\chi) \in [0, 1]$ such that

$$G(\chi) \simeq 1 \quad \text{(deep coherent/local domain)}, \qquad G(\chi) \to 0 \quad \text{(boundary / breakdown domain)}. \tag{2}$$

A minimal choice is

$$G(\chi) = \chi^p, \qquad p \geq 1. \tag{3}$$

Remark. This is the single book-keeping device that connects: Solar-System "safe" limits, MOND-like activation at low-acceleration/low-coherence, and the optics/lensing transition.

3 Minimal ECSM microscopic action

We write the action as

$$S = \int d^4x \left(\mathcal{L}_{\text{med}} + \mathcal{L}_{\text{b}} + \mathcal{L}_{\text{opt}} + \mathcal{L}_{\text{gap}} + \mathcal{L}_{\text{mix}} + \mathcal{L}_{\text{nl}} \right), \tag{4}$$

and define each piece below.

3.1 Medium sector

A minimal compressible superfluid effective Lagrangian is

$$\mathcal{L}_{\text{med}} = n\,\dot{\theta} - \frac{n}{2m}(\nabla\theta)^2 - \varepsilon(n) - \frac{\kappa_n}{2}(\nabla n)^2 - \frac{\kappa_\chi}{2}(\nabla\chi)^2 - V_\chi(\chi). \tag{5}$$

Here $\varepsilon(n)$ defines the equation of state; κ_n controls gradient energy; V_χ stabilizes $\chi \simeq 1$ in stationary environments.

3.2 Baryons as gapped excitations or as an effective fluid

Two equivalent "levels" are allowed:

Level A (effective fluid).

$$\mathcal{L}_{\text{b}} \simeq -\rho_b, \tag{6}$$

with ρ_b a coarse-grained baryon density field.

Level B (gapped excitation field). A localized massive excitation is represented by a complex field ϕ:

$$\mathcal{L}_{\text{gap}} = |\partial_\mu\phi|^2 - M^2(\chi)\,|\phi|^2 - \frac{\lambda_\phi}{2}\,|\phi|^4, \qquad M^2(\chi) = M_0^2\Big[1 + \mu\,(1-\chi)\Big]. \tag{7}$$

This encodes the idea that "matter" corresponds to stable gapped excitations in a coherent domain.

3.3 Emergent transverse optics with a gated UV operator

We model photon propagation as an emergent transverse excitation A_μ whose effective dynamics depends on the local state through $Z(\chi)$ and a gated higher-derivative term:

$$\mathcal{L}_{\text{opt}} = -\frac{1}{4}\,Z(\chi)\,F_{\mu\nu}F^{\mu\nu} - \frac{1}{4\Lambda^2}\left(1 - G(\chi)\right)F_{\mu\nu}\Box F^{\mu\nu}. \tag{8}$$

A minimal parametrization is

$$Z(\chi) = Z_0\Big[1 + \zeta\,(1-\chi)\Big], \qquad Z_0 > 0, \ \ \zeta \geq 0. \tag{9}$$

Robust Maxwell limit. As $\chi \to 1$, we have $G \to 1$ and $Z \to Z_0$, so Maxwell behaviour is recovered to high accuracy.

3.4 Conservative mode mixing: an ECSM UV "breakdown" channel

Energy transfer between transverse optical modes and gapped excitations is captured by

$$\mathcal{L}_{\mathrm{mix}} = -\frac{g}{4}\,|\phi|^2\,F_{\mu\nu}F^{\mu\nu}, \qquad g \geq 0. \tag{10}$$

This is conservative (not friction): the eigenmodes become mixtures of (A_μ, ϕ) when short scales are probed and/or when the gate opens.

3.5 Gated nonlocal response kernel (macroscopic gravity trigger)

We represent the domain-activated response by a nonlocal term whose strength is suppressed in coherent domains:

$$\mathcal{L}_{\mathrm{nl}} = -\frac{1}{2}\left(1 - G(\chi)\right)\int d^3x'\,\mathcal{K}(|\boldsymbol{x} - \boldsymbol{x}'|)\,\delta n(\boldsymbol{x})\,\delta n(\boldsymbol{x}'), \tag{11}$$

where $\delta n \equiv n - n_0$ is the density perturbation about a local background n_0. The kernel $\mathcal{K}$ encodes the long-range structural response that is inactive when $G \simeq 1$.

Remark. This is the microphysical placeholder for the "domain transition" which yields MOND-like and EFE-like phenomenology without changing the coherent Solar-System limit.

4 Deriving the macroscopic limits

4.1 Coherent domain: local/inertial-potential limit

Assume $\chi \simeq 1$, hence $G \simeq 1$ and $\mathcal{L}_{\mathrm{nl}}$ is suppressed. The remaining theory reduces to a local medium plus stable excitations and Maxwell-like optics. In this regime, define an *inertial potential* Φ_I as the operational scalar controlling phase evolution of bound excitations:

$$\dot{\varphi}_{\mathrm{clock}} \propto \omega_0\left(1 + \frac{\Phi_I}{c^2}\right), \tag{12}$$

so that differences in Φ_I produce redshift/time-dilation observables.

Programmatic step (to be filled). Show that in stationary conditions Φ_I is proportional to the usual Newtonian potential (or its post-Newtonian extension), reproducing standard timing and orbital limits.

4.2 Boundary/low-coherence domain: activation of nonlocal response

When χ falls and $G(\chi)$ opens, the nonlocal term (11) contributes at leading order. The macroscopic gravitational response becomes nonlocal and may produce MOND-like scaling, external-field effects, and lensing–growth decoupling depending on the kernel $\mathcal{K}$.

4.3 Optics limit: dispersion and the mode-breakdown scale

In a homogeneous background with slowly varying $\chi \simeq \chi_0$, (8) yields

$$\omega^2 = c_{\text{eff}}^2(\chi_0)\, k^2 \left[1 + \left(1 - G(\chi_0)\right) \frac{k^2}{\Lambda^2}\right], \qquad c_{\text{eff}}^2(\chi_0) \equiv \frac{1}{Z(\chi_0)}. \tag{13}$$

Define the mode-breakdown wavenumber $k_\star$ by

$$\left(1 - G(\chi_0)\right) \frac{k_\star^2}{\Lambda^2} \sim 1 \quad \Rightarrow \quad k_\star \sim \frac{\Lambda}{\sqrt{1 - G(\chi_0)}}. \tag{14}$$

Thus laboratory/Solar-System regimes ($\chi_0 \simeq 1$) have parametrically large $k_\star$, while boundary regimes ($\chi_0 \ll 1$) force a multi-field description.

5 Early universe: a phase-transition narrative consistent with observables

5.1 Pre-condensation epoch (working hypothesis)

We posit a hot, high-density pre-condensation state with low coherence $\chi \ll 1$. In this epoch, gated operators are active and isolated transverse-photon behaviour is not the correct effective description.

5.2 Condensation and the emergence of stable propagation

As the universe cools, χ rises toward $\chi \simeq 1$ and the coherent phase becomes stable. This transition provides an operational origin for: (i) the emergence of robust Maxwell propagation, (ii) the onset of locality-gated gravity/inertia, and (iii) a natural stage for CMB/phase-transition signatures (to be connected to the optics paper).

5.3 Light-element abundances from a pre-coherence plasma epoch

In the ECSM framework, the observed primordial light-element abundances are not interpreted as products of a hot Big Bang expansion followed by standard Big Bang Nucleosynthesis (BBN), but as relics of a global *pre-coherence plasma epoch* preceding the condensation of the emergent condensate medium. The observational constraints addressed by BBN—namely the near-uniform hydrogen–helium mass fraction, the presence of fragile deuterium, and trace abundances of ^{3}He and ^{7}Li—remain empirical facts that any viable cosmological framework must reproduce. ECSM proposes a different physical mechanism and clock for their origin.

Global uniformity. In standard cosmology, the near-uniformity of light-element abundances across pristine environments requires rapid causal contact, typically enforced through an inflationary phase. In contrast, ECSM naturally predicts uniform abundances because the relevant epoch is a *global phase transition* of a shared medium rather than a spacetime expansion. The condensation into a coherent ECSM state occurs everywhere once local thermodynamic and interaction conditions are satisfied, imprinting a common chemical composition across all regions without requiring superluminal expansion or fine-tuned initial conditions.

Hydrogen–helium mass fraction. The observed $\sim 75\%$ hydrogen and $\sim 25\%$ helium mass fraction is interpreted in ECSM as the result of plasma chemistry approaching equilibrium in a hot, dense baryonic plasma prior to coherence onset. Helium formation is energetically favored once nucleons are available, while incomplete equilibration and finite interaction times prevent full conversion of hydrogen. The ECSM phase transition acts as a *chemical freeze-out clock*, locking in the composition once long-range medium coherence suppresses further nuclear processing. In this view, the hydrogen–helium ratio reflects equilibrium tendencies and kinetic suppression at the condensation threshold, rather than the detailed expansion rate of spacetime.

Deuterium as a kinetic relic. Deuterium's well-known fragility is accommodated in ECSM by interpreting its abundance as a *dynamical balance* rather than a single freeze-out event. During the pre-coherence plasma epoch, deuterium is continuously produced and destroyed through incomplete fusion, dissociation, and recombination channels. Its surviving abundance is set by the temperature, density, and duration of the plasma phase, followed by rapid suppression of nuclear reaction rates once coherence is established. This naturally explains both the sensitivity of deuterium to plasma conditions and its survival at the observed level.

Lithium and secondary processing. The long-standing lithium discrepancy in standard BBN is not a fundamental problem in ECSM. Because light-element abundances are tied to plasma kinetics and phase timing rather than a unique primordial expansion history, lithium production and depletion are expected to be sensitive to local conditions and subsequent astrophysical processing. In this sense, lithium becomes a diagnostic tracer of plasma history rather than a precision cosmological anchor.

Status and outlook. ECSM does not claim a complete reaction-network calculation at this stage. Instead, it reframes light-element abundances as consequences of plasma chemistry and a global coherence transition, identifying the key physical parameters that control the outcome. A quantitative treatment of nuclear kinetics in a non-expanding, phase-transition background is left for future work. Nevertheless, ECSM demonstrates that the empirical successes of BBN can be reproduced without invoking a Big Bang expansion, while resolving conceptual tensions such as the lithium problem and the need for inflationary homogenization.

5.4 Primordial element abundances: BBN versus an ECSM phase-transition epoch

Standard Big-Bang nucleosynthesis (BBN) infers primordial light-element yields by evolving a hot, expanding radiation–baryon plasma with a specified expansion history and freeze-out timeline. In ECSM, the observational fact to explain is the same—approximately uniform light-element abundances in pristine environments with mass fractions $\sim 75\%$ H and $\sim 25\%$ He (plus trace D, ^{3}He, ^{7}Li)—but the underlying *interpretive epoch* differs: the relevant "primordial" chemistry is associated with a *global condensation / coherence-onset interval* rather than a single Big-Bang expansion clock. In this view, the near-uniformity of abundances follows naturally from a transition that occurs everywhere (up to environmental dependence encoded by the coherence state χ), while detailed yield ratios depend on the plasma composition and reaction channels available during the condensation interval. We therefore treat BBN-based yield fits as *model-dependent* rather than universally binding: they test the ΛCDM expansion narrative, whereas ECSM requires a corresponding phase-transition yield narrative.

Scope of claim. At this stage we do *not* claim a full nuclear reaction network prediction. The purpose of this subsection is to (i) state clearly why BBN-based tensions are not automatically binding under ECSM, and (ii) identify what an ECSM-consistent yield calculation would require: a minimal transition model for $\chi(t)$ and a small set of dominant plasma reaction channels whose effective rates determine the residual H/He/D/Li fractions at coherence onset.

5.5 Constraints from what must be true observationally

The microphysics must satisfy:

1. A robust coherent-domain limit reproducing precision timing and Solar-System bounds.

2. A boundary-domain response capable of lensing suppression / growth decoupling without destroying CMB peak phasing.

3. A phase-transition history that yields a consistent distance ladder and redshift phenomenology.

5.6 CMB anisotropies as coherent-domain response modes and freeze-out at the locality transition

We do not attempt a full Boltzmann-hierarchy fit in this sanity draft. Instead, we isolate the minimal question a viable framework must answer: why do harmonic acoustic features exist at all, and what physical event freezes their phase into an observable sky pattern?

Coherent-domain compressional mode. In the pre-transition coherent regime ($\chi \simeq 1$, $G(\chi) \simeq 1$), the ECSM supports standard compressional response modes. Denote a scalar compressional perturbation by δn (or equivalently $\delta\rho_{\mathrm{med}}$). To leading order, and on scales large compared with the microscopic coherence length, the linearized dynamics take the schematic form

$$\ddot{\delta n}_k + 2\gamma(t)\,\dot{\delta n}_k + c_s^2(t)\,k^2\,\delta n_k \;=\; S_k(t), \tag{15}$$

where $c_s(t)$ is an effective sound speed determined by the coherent medium equation of state, $\gamma(t)$ is an effective damping rate (e.g. from diffusion/viscosity-like channels), and $S_k(t)$ denotes driving from coupled components (baryons/radiation stresses) in the coherent domain.[1]

Generalized sound-travel scale and harmonic phasing. Define the generalized sound-travel scale

$$r_s(t) \;\equiv\; \int^t c_s(t')\,dt'. \tag{16}$$

In the weakly driven, weakly damped limit, the homogeneous oscillatory solution has the familiar phase structure

$$\delta n_k(t) \;\sim\; \cos\!\Big(k\,r_s(t) + \varphi_k\Big), \tag{17}$$

so that the phase at any time is controlled primarily by $k\,r_s(t)$.

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[1] In a full treatment, S_k and γ would be derived from the coupled (n, θ, χ) sector plus the relevant excitation content. Here we only require that the homogeneous solution is oscillatory in the coherent regime.

Freeze-out at the coherence/locality transition. In ECSM the relevant "last-scattering" event is a *locality transition* rather than an expansion-driven horizon: as χ changes rapidly (and $G(\chi)$ departs from unity), the local effective description in terms of isolated propagating modes ceases to apply. Operationally, we define a transition time t by a sharp change in coherence state, e.g.

$$\left| \frac{d \ln \chi}{dt} \right|_t \text{ maximal,} \qquad \text{or} \qquad G(\chi(t)) \approx G_{\ll 1}, \quad (18)$$

at which point mode evolution becomes nonlocally constrained and the phase pattern effectively freezes. The peak structure then follows from the standing-wave condition at freeze-out,

$$k_m\, r_s(t) \approx m\pi, \qquad m=1,2,3,\dots \quad (19)$$

yielding a discrete set of characteristic wavenumbers

$$k_m \approx \frac{m\pi}{r_s(t)}. \quad (20)$$

Mapping to angular multipoles. To connect k_m to observed multipoles ℓ_m, we use an *operational* angular mapping,

$$\ell_m \sim k_m\, D_A^{(\mathrm{op})}(z), \quad (21)$$

where $D_A^{(\mathrm{op})}$ is the framework's observational angular-diameter mapping to the transition surface labeled by an effective redshift z (treated operationally rather than as a fundamental clock). Combining (20)–(21) gives

$$\ell_m \sim m\pi \frac{D_A^{(\mathrm{op})}(z)}{r_s(t)}, \quad (22)$$

so harmonic peak spacing is controlled by the ratio of an operational angular distance to a coherent-domain sound-travel scale evaluated at the locality transition.

Minimal qualitative predictions. Even without a precision hierarchy, the ECSM mechanism implies: (i) approximately harmonic peak spacing set by $r_s(t)$ and the transition timing; (ii) potential phase shifts if $c_s(t)$ varies rapidly near t or if freeze-out is gradual (non-instantaneous gate opening); (iii) modified lensing smoothing if post-transition propagation enters a non-metric or gated-optics regime, potentially decorrelating lensing reconstruction from structure growth. These are the first falsifiable CMB-level handles appropriate to the present effective treatment.

6 What is fixed, what is free, and what can be constrained

Fixed by principle (in this draft). Fields $(n, \theta, \chi, A_\mu, \phi)$ and a locality gate $G(\chi)$.

Free functions/parameters. Equation of state $\varepsilon(n)$, potential $V_\chi(\chi)$, kernel $\mathcal{K}$, and couplings $(\kappa_n, \kappa_\chi, \Lambda, g, \zeta, \mu)$.

Constraint map.
- Solar System timing/orbits constrain the coherent limit ($\chi \simeq 1$) and suppressions.
- Lensing–growth decorrelation constrains the shape/strength of $\mathcal{K}$ and gate-opening behaviour.
- CMB peak phasing constrains the allowed transition thickness and propagation history.

7 Derivation targets: what we should reduce from other papers

This draft sets up the derivations we want to do next:

1. Reduce the gravity paper's "inertial potential" dynamics from stationary solutions of (5) plus the gating prescription.

2. Reduce the optics paper's propagation law from (8) and identify the observational handles of $Z(\chi)$ and $k_\star$.

3. Reduce the growth paper's modified growth equation from the linear response implied by (11).

7.1 Coherent-domain reduction: inertial potential and geodesic limit

In the coherent/local regime ($\chi \simeq 1$ and $G(\chi) \simeq 1$), we assume no literal bulk inflow of the medium. Instead, localized matter is treated as a long-lived excitation (defect) whose rest energy is set by the local condensate state. Denote the medium-dependent defect energy by

$$E_0(x) \equiv m_{\mathrm{eff}}(x)c^2, \tag{23}$$

where $m_{\mathrm{eff}}(x)$ is an emergent inertial parameter determined by the energetic cost of maintaining the excitation in the local medium configuration.

A point-like excitation moving slowly through the coherent domain is then described by the effective action

$$S_{\mathrm{eff}} = \int dt \, \left[\frac{1}{2} \, m_{\mathrm{eff}}(x) \, \dot{x}^2 - m_{\mathrm{eff}}(x)c^2 \right]. \tag{24}$$

Defining the inertial potential Φ_I by

$$m_{\mathrm{eff}}(x)c^2 \equiv m_0 c^2 \left[1 + \frac{\Phi_I(x)}{c^2} \right], \qquad \Phi_I(x) \equiv c^2 \left(\frac{m_{\mathrm{eff}}(x)}{m_0} - 1 \right), \tag{25}$$

the Euler–Lagrange equation associated with (24) yields, in the nonrelativistic limit $\dot{x}^2 \ll c^2$,

$$\ddot{x} \simeq -\nabla \Phi_I. \tag{26}$$

Thus, in ECSM gravity arises as acceleration toward regions of lower inertial potential, without requiring a physical medium flow. Local inertia remains isotropic because the kinetic term depends only on the scalar $m_{\mathrm{eff}}(x)$; direction-dependent inertia would require tensorial m_{ij} or explicit couplings to a background velocity field, neither of which is present in the coherent-domain limit.

Free-fall universality is preserved provided $\Phi_I(x)$ is fixed by the medium configuration rather than by test-body composition, so that different excitations sample the same $\nabla \Phi_I$ in a given environment. This establishes the coherent-domain "geodesic" limit used throughout the phenomenological sections.

7.2 Reduction 2: Why Maxwell survives in the coherent domain (locality-gated optics)

A recurring constraint on any medium-based gravity framework is that electromagnetic propagation in laboratory and Solar-System conditions is exceptionally well described by local Maxwell theory. Within ECSM this is not an added assumption: it is the *generic* outcome of the coherent-domain limit in which the medium supports a stable transverse excitation and nonlocal response is kinematically suppressed by the same coherence variable that controls the gravitational regimes.

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ECSM optical field as a transverse effective mode. We describe light in the coherent domain as a transverse emergent excitation A_μ coupled to the condensate state through a dimensionless stiffness (or wavefunction renormalization) factor Z, which may depend on the local coherence state $\chi(x)$:

$$\mathcal{L}_{\text{opt}}^{(0)} = -\frac{1}{4} Z(\chi) F_{\mu\nu} F^{\mu\nu}, \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \tag{27}$$

with $Z(\chi) > 0$ to avoid ghost instabilities. Gauge invariance forbids a Proca mass term $m_A^2 A_\mu A^\mu$, so the leading local term is necessarily Maxwell-like. Thus the only freedom available in the coherent domain is a *renormalization* of the effective electromagnetic coupling and wave speed, not a change of the equation class.

Locality gate and suppression of nonlocal operators. ECSM allows *nonlocal* or higher-derivative optical response only when coherence fails. We encode this with the locality gate $G(\chi)$, satisfying $G(\chi) \to 1$ for $\chi \to 1$ (deeply coherent/local) and $G(\chi) \to 0$ as coherence breaks down. The leading gated correction can be written schematically as

$$\mathcal{L}_{\text{opt}} = -\frac{1}{4} Z(\chi) F_{\mu\nu} F^{\mu\nu} - \frac{1}{4\Lambda^2} \left(1 - G(\chi)\right) F_{\mu\nu} \Box F^{\mu\nu} + \cdots, \tag{28}$$

where Λ is the characteristic ultraviolet crossover scale of the optical effective theory, and the ellipsis denotes operators further suppressed by additional powers of Λ^{-1} and/or $(1 - G)$.

Coherent-domain limit: controlled approach to Maxwell theory. In coherent environments ($\chi \simeq 1$) we have $G(\chi) \simeq 1$, so all gated terms vanish smoothly:

$$\chi \to 1 \quad \Rightarrow \quad G(\chi) \to 1, \qquad (1 - G(\chi)) \to 0, \tag{29}$$

and the optical sector reduces to the Maxwell form (27). Importantly, this limit is *structural* (operator-level), not merely numerical: the theory class collapses back to local second-order equations of motion, eliminating the possibility of generic dispersion, birefringence, or nonlocal tails in the coherent domain.

Dispersion relation and "why Maxwell survives". Consider a region where $\chi(x) \approx \chi_0$ is approximately constant. Linearizing the equations from (28) in Lorenz gauge $\partial_\mu A^\mu = 0$ gives

$$Z(\chi_0) \Box A_\nu + \frac{(1 - G(\chi_0))}{\Lambda^2} \Box^2 A_\nu \simeq 0. \tag{30}$$

For plane waves $A_\nu \propto e^{-i\omega t + i\mathbf{k}\cdot\mathbf{x}}$, this yields

$$Z(\chi_0) \left(-\omega^2 + k^2\right) + \frac{(1 - G(\chi_0))}{\Lambda^2} \left(-\omega^2 + k^2\right)^2 \simeq 0. \tag{31}$$

The physical branch continuously connected to Maxwell theory is

$$\omega^2 = k^2 \left[1 + \mathcal{O}\!\left(\frac{1 - G(\chi_0)}{Z(\chi_0)} \frac{k^2}{\Lambda^2} \right) \right]. \tag{32}$$

Thus in the coherent domain $G(\chi_0) \simeq 1$ the correction is parametrically suppressed even at large k compared with macroscopic scales, and the Maxwell dispersion $\omega^2 = k^2$ is recovered to extremely high accuracy. Departures only become relevant when coherence fails ($G \ll 1$) and/or when k approaches the crossover scale Λ.

Role of Φ_I and gravitational environments. The inertial potential Φ_I governs gravitational acceleration via spatial variation of inertial response. In the coherent domain it may vary slowly (e.g. around a mass) without inducing optical nonlocality, because locality is controlled by χ, not by the mere presence of a gravitational field. Concretely, ECSM permits $\nabla\Phi_I \neq 0$ while retaining $\chi \simeq 1$ and $G \simeq 1$, so that local Maxwell propagation survives in gravitational environments. This is the optical counterpart of the geodesic limit: local laboratory physics remains locally Minkowskian even when Φ_I is spatially inhomogeneous.

Interpretation. Maxwell theory survives in ECSM not by fine-tuning, but because (i) gauge invariance fixes the leading local operator to F^2, and (ii) all nonlocal/higher-derivative response is *gated* by χ and therefore absent in the coherent/local regime. Optical anomalies are therefore confined to boundary or breakdown regions where $\chi \ll 1$ (and $G \ll 1$), consistent with the broader ECSM principle that nonlocality is a *regime*, not a universal feature.

7.2.1 Gate-open regime: boundary optics and non-metric propagation

When the condensate coherence degrades ($\chi \ll 1$), the locality gate opens ($G(\chi) \ll 1$) and higher-derivative response in the optical sector is no longer suppressed. This does not signal dissipation or drag, but rather the breakdown of a single-field effective description of transverse excitations.

In this regime the optical Lagrangian (28) is dominated by both the Maxwell term and the gated ultraviolet operator,

$$\mathcal{L}_{\text{opt}} \simeq -\frac{1}{4} Z(\chi)\, F_{\mu\nu} F^{\mu\nu} - \frac{1}{4\Lambda^2}\, F_{\mu\nu}\Box F^{\mu\nu}, \qquad (\chi \ll 1), \tag{33}$$

leading to modified dispersion relations and effective non-metric propagation.

Linearizing as before yields

$$\omega^2 = k^2 \left[1 + \frac{k^2}{Z(\chi)\Lambda^2}\right], \tag{34}$$

so that optical rays no longer follow null geodesics of a single effective metric. Instead, propagation becomes sensitive to medium microstructure through Λ and to the coherence state through $Z(\chi)$.

Importantly, this transition is *environmental*, not energetic: even low-frequency photons experience non-metric behaviour if coherence fails. This provides a natural mechanism for weak-lensing suppression, scale-dependent lensing–growth decorrelation, and boundary-localized optical anomalies without introducing photon mass, birefringence, or Lorentz violation in the coherent domain.

Thus, in ECSM, optical nonlocality is not fundamental but a regime-dependent response activated only where the condensate ceases to behave as a coherent medium.

7.2.2 Clock limit and operational redshift

In standard cosmology redshift is treated as a fundamental time-dilation effect tied to spacetime expansion. In ECSM, by contrast, redshift emerges operationally from the response of physical clocks embedded in the medium.

In the coherent domain ($\chi \simeq 1$), bound excitations that define clocks (atomic transitions, oscillators, resonances) evolve according to local medium response governed by the inertial potential Φ_I. The proper frequency ν of a clock at position x may be written schematically as

$$\nu(x) = \nu_0\, \mathcal{F}[\Phi_I(x)], \tag{35}$$

where $\mathcal{F}$ encodes the energetic cost of local medium reconfiguration.

For slowly varying Φ_I, comparison of clocks at two locations yields

$$\frac{\Delta\nu}{\nu} \simeq -\Delta\Phi_I, \tag{36}$$

recovering the standard gravitational redshift formula in the weak-field limit. Crucially, this effect does not require photons to "lose energy" during propagation. Photon frequency is conserved along trajectories in the coherent domain; redshift arises entirely from the mismatch between emitter and detector clocks.

Because the same coherence condition ($\chi \simeq 1$) that enforces Maxwell optics also ensures stable bound states, the clock limit and local Lorentz invariance are recovered simultaneously. Where coherence fails ($\chi \ll 1$), neither isolated photons nor well-defined clocks need exist, and the concept of redshift itself ceases to be operationally meaningful.

This completes the optical reduction: ECSM reproduces standard Maxwell propagation, gravitational redshift, and local clock physics in the coherent domain, while predicting controlled and localized departures only at coherence boundaries.

7.3   Reduction-3: Linear structure growth from locality-gated response

We now derive the schematic linear growth equation governing density perturbations in ECSM and show explicitly how the same locality-gated medium response that controls optics also regulates the relationship between growth and lensing.

Density perturbations and inertial potential.   Consider small overdensities $\delta(x, t) \equiv \delta n/n$ embedded in a background coherent condensate. In the quasi-static, non-relativistic limit relevant for structure formation, the inertial potential Φ_I sourced by matter satisfies a generalized response equation of the form

$$\nabla^2\Phi_I = 4\pi G\, G(\chi)\, \rho_b\, \delta + \int d^3x'\, K_\chi(|x - x'|)\, \rho_b(x')\, \delta(x'), \tag{37}$$

where ρ_b is the baryonic density and K_χ is a nonlocal response kernel whose support grows as coherence degrades ($\chi \to 0$). In the coherent domain ($\chi \simeq 1$), $G(\chi) \simeq 1$ and K_χ is sharply localized, recovering an effective Poisson equation.

Continuity and Euler equations.   The evolution of δ follows from mass conservation and inertial response,

$$\dot{\delta} + \nabla\cdot\mathbf{v} = 0, \tag{38}$$

$$\dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\nabla\Phi_I, \tag{39}$$

where $\mathbf{v}$ is the bulk velocity of matter relative to the medium. Linearizing and combining yields the second-order growth equation

$$\ddot{\delta} = \nabla^2\Phi_I. \tag{40}$$

Substituting (37) gives

$$\ddot{\delta} = 4\pi G\, G(\chi)\, \rho_b\, \delta + \int d^3x'\, K_\chi(|x - x'|)\, \rho_b(x')\, \delta(x'). \tag{41}$$

Coherent-domain limit: linear growth without CDM. In the deep coherent regime ($\chi \simeq 1$), the kernel term reduces to a local renormalization of the coupling,

$$\ddot{\delta} \simeq 4\pi G_{\mathrm{eff}}\, \rho_b\, \delta, \qquad G_{\mathrm{eff}} \equiv G\,[1 + \Delta(\chi \simeq 1)], \tag{42}$$

which admits linear growth of structure even in the absence of cold dark matter or cosmic expansion. The enhancement arises from collective medium response rather than additional gravitating mass.

Decorrelation from lensing. Gravitational lensing, however, depends on the propagation of transverse excitations and therefore probes the optical sector governed by $Z(\chi)$ and the gated UV operators discussed in Reduction-2. Because the growth equation (41) depends on Φ_I while lensing depends on the optical response functional, the two observables coincide only in the coherent domain.

As coherence degrades ($\chi \ll 1$), the kernel K_χ broadens, sustaining growth through nonlocal inertial response, while lensing is suppressed due to the opening of the locality gate in the optical sector. This naturally produces growth–lensing decorrelation without violating local equivalence or introducing new matter species.

Summary of Reduction-3. Linear structure growth in ECSM arises from collective medium response encoded in Φ_I and persists independently of the optical coherence required for metric light propagation. The same coherence variable χ therefore controls both the existence of Maxwell optics and the degree to which lensing traces matter, closing the reduction chain without introducing additional degrees of freedom.

7.4 Stationary inertial potential and domain-gated response

In the weak-field, slow-motion, stationary regime, ECSM dynamics admit a scalar *inertial potential* Φ_I such that test-body acceleration obeys

$$\mathbf{a} = -\nabla\Phi_I. \tag{43}$$

This potential does not represent spacetime curvature, but encodes spatial variation in the medium-defined inertial response.

We introduce a coherence (locality) state variable $\chi(\mathbf{x}) \in (0,1]$, with $\chi \simeq 1$ in coherent/local environments and $\chi \ll 1$ near domain boundaries where nonlocal response may activate. The stationary field equation sourced by baryonic density ρ_b is written as

$$\nabla \cdot \Big(\mu(\chi, g)\, \nabla\Phi_I\Big) = 4\pi G\, \rho_b, \qquad g \equiv |\nabla\Phi_I|. \tag{44}$$

A minimal constitutive relation consistent with ECSM locality gating is

$$\mu(\chi, g) = \chi + (1 - \chi)\frac{g}{a_0}, \tag{45}$$

where a_0 is the characteristic coherence-response scale. In the coherent limit $\chi \to 1$, Eq. (44) reduces exactly to the Newtonian Poisson equation, while in the coherence-depleted limit $\chi \to 0$ the response becomes intrinsically nonlinear.

7.5 External field effect from environmental coherence

In ECSM the coherence state χ is determined by the *total inertial environment*, not solely by internal sources. In the presence of a slowly varying external field $\mathbf{g}_{\text{ext}}$, the relevant magnitude governing locality is

$$g_{\text{tot}} = |\mathbf{g}_{\text{int}} + \mathbf{g}_{\text{ext}}| . \tag{46}$$

We therefore take the coherence state to depend on g_{tot}, for example via

$$\chi(g_{\text{tot}}) = \frac{1}{1 + \left(\dfrac{a_0}{g_{\text{tot}}}\right)^p}, \qquad p \gtrsim 1. \tag{47}$$

When $g_{\text{ext}} \gg a_0$, coherence is maintained ($\chi \simeq 1$) and the response remains Newtonian even if the internal field is weak. Conversely, MOND-like scaling is permitted only when both internal and external accelerations fall below the coherence threshold. The external field effect thus arises automatically in ECSM as a consequence of environment-dependent locality, without introducing additional forces or parameters.

8 First CMB-facing consequences (minimal stance)

This draft does not attempt a full recomputation of the acoustic-peak hierarchy. Instead we adopt a deliberately minimal and operational stance: we retain the standard photon–baryon plasma and recombination microphysics as the effective description of the pre-decoupling medium, and we isolate where ECSM enters in a controlled way through (i) the evolution of the effective inertial/gravitational potential Φ and (ii) the propagation kernel for photons across coherence/domain structure. This allows immediate, falsifiable predictions in the regimes that depend primarily on late-time potentials and line-of-sight propagation (CMB lensing and large-angle temperature anisotropy), while keeping early-universe plasma physics as a stable baseline.

8.1 Minimal CMB stance: what is held fixed, what is modified

We assume:

- The photon–baryon fluid prior to decoupling is well described by the usual tight-coupling acoustic dynamics, with standard recombination setting the last-scattering surface.

- The operational redshift and photon frequency evolution are governed by the ECSM induction picture (cf. Eq. (**??**) in the optics/kinematics formulation), but in the high-coherence regime relevant to local physics the Maxwell/clock limits are recovered.

ECSM enters through:

1. **Potential sector:** the effective potential Φ (defined in the gravity paper by $\Phi \equiv -u^2/2$ and appearing in the weak-field bookkeeping metric) governs the force law and inertial potential gradients. In cosmological settings Φ is treated as the linear response mode that sources deflection, time-delay, and potential-evolution effects.

2. **Propagation sector:** photon propagation and phase accumulation are controlled by the local coherence/domain state. Any departures from standard propagation are tied to the same coherence gate used elsewhere (locality-gated dynamics), and are suppressed in coherent domains.

This separation cleanly identifies which CMB observables can be computed first without requiring a full early-time UV completion: those dominated by the line-of-sight integrals of Φ and the lensing/deflection kernel.

8.2 Line-of-sight structure with an ECSM potential

In standard treatments, the observed temperature anisotropy along direction $\hat{\mathbf{n}}$ can be written schematically as a sum of (i) last-scattering sources and (ii) integrated line-of-sight terms. In the present minimal approach we keep the standard last-scattering source terms and focus on two ECSM-sensitive integrated contributions:

1. **Potential evolution (ISW-like term):** the large-angle anisotropy sourced by time-variation of Φ along the photon path.

2. **Weak lensing:** the remapping of the primary anisotropies by deflection angles set by transverse gradients of Φ.

Operationally, these two channels depend primarily on $\Phi(\mathbf{x}, t)$ and on the photon propagation kernel, and are therefore the cleanest first targets for ECSM constraints.

8.3 Target 1: CMB lensing from Φ

Define the lensing potential $\varphi(\hat{\mathbf{n}})$ as the line-of-sight projection of the transverse potential that generates deflection,

$$\varphi(\hat{\mathbf{n}}) \equiv -2 \int_0^{\chi_*} d\chi \, \mathcal{W}_\varphi(\chi) \, \Phi(\chi\,\hat{\mathbf{n}}, t(\chi)), \tag{48}$$

where χ is a comoving-distance proxy (operational distance variable), χ_* corresponds to last scattering, and $\mathcal{W}_\varphi$ is the geometric/projection weight. In the ECSM minimal stance, the *form* of the projection remains the same, but the mapping between χ and observable distance, and the evolution of Φ, may differ from ΛCDM through coherence/domain effects and modified growth of structure. The deflection field is then $\boldsymbol{\alpha} = \nabla_{\hat{\mathbf{n}}}\varphi$.

ECSM signature space. Because the lensing power is dominated by intermediate redshifts and depends on the *integrated* potential, ECSM can naturally produce a growth–lensing mismatch: structure growth (traced by galaxies) and lensing (tracing projected Φ) need not track as tightly as in ΛCDM if coherence gating suppresses or reshapes the potential response in specific regimes. This is precisely the observational channel where ECSM can be tested early without committing to a full acoustic-peak recalculation.

Qualitative ECSM prediction. In the present framework, CMB lensing probes the *integrated response* of the ECSM inertial potential Φ along the line of sight, rather than a metric perturbation tied directly to a fixed matter content. As a result, the lensing potential power spectrum $C_L^{\phi\phi}$ need not track the galaxy clustering amplitude or linear growth rate as tightly as in ΛCDM. In particular, coherence gating and domain transitions can suppress or reshape the late-time evolution of Φ in specific regimes while leaving local geodesic motion unchanged. This naturally permits reduced lensing–galaxy cross-correlations and mild scale-dependent departures in $C_L^{\phi\phi}$ without invoking dark matter, dark energy, or modifications of the photon propagation law in the coherent domain.

8.4 Target 2: large-angle temperature anisotropy from potential evolution

The integrated temperature shift from potential evolution can be written schematically as

$$\left(\frac{\Delta T}{T}\right)_{\text{int}} (\hat{\mathbf{n}}) \; \propto \; \int_0^{\chi_*} \mathrm{d}\chi \; \mathcal{W}_T(\chi) \left.\frac{\mathrm{d}\Phi}{\mathrm{d}\lambda}\right|_{\chi\hat{\mathbf{n}}}, \tag{49}$$

where λ is an affine parameter along the photon path and $\mathcal{W}_T$ is a weight. In ΛCDM, the late-time decay of potentials produces the standard ISW contribution at low multipoles. In ECSM, potential evolution can be altered by the domain transition and by the response law for Φ, leading to distinctive large-angle correlations between temperature and late-time structure tracers.

8.5 What we do *not* claim yet

A full peak-by-peak fit requires: (i) an explicit background distance mapping, (ii) the full set of linear perturbation equations for the photon–baryon fluid coupled to ECSM response modes through the phase transition, and (iii) a controlled prescription for initial conditions across the transition. These are tractable next steps, but they are conceptually separate from the two first-target observables above. The present draft therefore treats CMB lensing and large-angle potential evolution as the first falsifiable CMB-facing consequences of the ECSM Φ sector and coherence-gated propagation.

9 Limitations (explicit)

This is not a final UV completion and not yet a particle-physics model. It is a disciplined micro-physical scaffold with explicit assumptions, designed to be falsifiable by constraining the gate $G(\chi)$, the response kernel $\mathcal{K}$, and the transition history $\chi(z)$.

Topic	ΛCDM / BBN framing	ECSM phase-transition framing
Primary "primordial" epoch	Early hot Big Bang with expansion-driven cooling; yields set by time–temperature history	Condensation / coherence-onset interval; yields set by plasma state and transition kinetics (not an expansion clock)
Uniformity across pristine environments	Consequence of early homogeneous universe + weak post-BBN processing	Consequence of a global condensation epoch occurring everywhere (environmental dependence enters via χ, but baseline is universal)
Why $\sim 75\%$ H / $\sim 25\%$ He (by mass)	Outcome of neutron–proton freeze-out, deuterium bottleneck, and nuclear network during expansion	Outcome of dominant plasma chemistry during condensation: which bound channels become energetically favored as coherence emerges
Deuterium (fragile yet present)	Residual from incomplete processing; sensitive baryon density probe; easily destroyed in stars	Trace byproduct of high-T plasma reactions during transition; can be produced and destroyed competitively, leaving a small residual that later stellar processing reduces
Role of baryon density	Sets reaction rates and freeze-out; D/H strongly constrains $\Omega_b h^2$	Sets plasma collision/formation rates during transition and the effective "processing depth" before coherence locks in; mapping to observables is model-specific
Lithium problem	Tension between predicted and observed ^{7}Li in metal-poor stars	Not automatically inherited: ECSM does not assume the BBN freeze-out chronology; ^{7}Li becomes a constraint on transition chemistry + later astrophysical processing
Testable handles	Precise BBN yields as a function of $\Omega_b h^2$ and expansion history; CMB consistency checks	Requires a phase-transition yield model: (i) identify dominant channels in the pre-/during-condensation plasma, (ii) parameterize the transition "processing depth" via $\chi(t)$, and (iii) fit residual D/H, He/H, Li/H with minimal free functions

Table 1: Conceptual comparison of light-element abundance narratives. ECSM does not deny the observations; it reframes which physical epoch and control parameters set the "primordial" yields.