Emergent Spacetime Optics and Cosmological Phase Transitions from a Superfluid medium

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Abstract

Cosmological tensions are not anomalies to be patched, but clues to missing physics. We present a unified framework in which spacetime geometry, gravitational response, and cosmological observables emerge from the collective dynamics of a condensed superfluid medium.

In this picture, late-time distance indicators, structure growth, and weak lensing arise as effective responses of a coherent medium with finite induction length, while the cosmic microwave background is reinterpreted as radiation associated with a global phase-transition boundary. This resolves the apparent BAO–CMB tension without invoking inflation, dark matter, or a universally valid expansion metric.

The framework is predictive and falsifiable: finite induction coherence produces correlated, scale- and redshift-dependent signatures in weak lensing, growth, and CMB peak phasing that cannot be absorbed into a single amplitude rescaling. Upcoming tomographic lensing and polarization measurements therefore provide decisive tests of whether cosmic geometry is fundamental or emergent.

1 Introduction

Modern cosmology is confronted by a growing set of internal tensions: discrepant inferences of cosmic distances, structure growth rates, weak lensing amplitudes, and early-time angular scales. These discrepancies are typically addressed by adding new components to an assumed expansion history, such as dark matter, dark energy, or early-universe inflation.

In this work we pursue a different strategy. Rather than modifying the contents of the universe, we reconsider the status of spacetime geometry itself. We propose that geometry is not fundamental, but an emergent, phase-dependent description arising from the collective dynamics of a cosmic superfluid medium.

This perspective naturally unifies late-time phenomenology, weak lensing suppression, and CMB structure within a single physical scale: the induction coherence length of the medium.

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 medium's 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 node–filament–void structure and reproduce the main cosmological observables through falsifiable, scale-bridging mechanisms.

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 $\lambda = \lambda_\mathrm{e}$ and observation at $\lambda = \lambda_\mathrm{o}$ by

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

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,

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

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.

2 Redshift as an Inertial Clock Effect in the Emergent Condensate Superfluid Medium

2.1 Conceptual framework

In standard cosmology, redshift is interpreted as a kinematic consequence of metric expansion. Within the Emergent Condensate Superfluid Medium (ECSM) framework, no spacetime expansion is assumed. Instead, redshift arises operationally from the response of physical clocks embedded in a structured medium.

Photon propagation corresponds to transverse excitations of the condensate and conserves frequency along the trajectory in coherent domains. Redshift therefore cannot arise from photon energy loss or dispersion. Instead, it reflects a mismatch between the emission and detection clock rates induced by spatial and temporal variations in the medium.

2.2 Clock frequency dependence on the inertial potential

The proper frequency of a physical clock at spacetime position x^μ is determined by the local inertial response of the condensate and may be written as

$$\nu(x) = \nu_0\,\mathcal{F}[\Phi_I(x)]\,, \tag{4}$$

where Φ_I is the inertial potential associated with the medium.

For slowly varying fields, the fractional frequency gradient satisfies

$$\partial_\mu \ln\nu = \frac{d\ln\mathcal{F}}{d\Phi_I}\,\partial_\mu\Phi_I. \tag{5}$$

In ECSM, the inertial potential is defined via the effective inertial mass of localized excitations,

$$\Phi_I(x) = c^2\left(\frac{m_{\rm eff}(x)}{m_0}-1\right), \tag{6}$$

where $m_{\rm eff}$ depends on the local coherence state of the condensate.

2.3 Coherence-controlled inertial response

The condensate coherence is described by a dimensionless scalar field $\chi \in (0, 1]$. Variations in χ modify the inertial response according to

$$\frac{d \ln m_{\mathrm{eff}}}{d \ln \chi} \equiv \mathcal{K}(\chi), \tag{7}$$

where $\mathcal{K}(\chi)$ is a dimensionless response function fixed by the condensate microphysics.

The gradient of the inertial potential may therefore be written as

$$\partial_\mu \Phi_I = c^2 \, \mathcal{K}(\chi) \, \frac{\partial_\mu \chi}{\chi}. \tag{8}$$

No additional degrees of freedom are introduced: $\mathcal{K}(\chi)$ is determined by the same condensate energetics that govern gravitational and optical responses in ECSM.

2.4 ECSM redshift accumulation law

Photon trajectories are parameterized by an affine parameter λ along null rays. The evolution of photon frequency relative to detector clocks follows

$$\frac{d}{d\lambda} \ln \nu = -\mathcal{K}(\chi) \, \frac{u^\mu \nabla_\mu \chi}{\chi}, \tag{9}$$

where u^μ is the four-velocity of the medium rest frame.

Integrating from emission to observation yields the ECSM redshift law

$$\boxed{1 + z = \exp \left[\int_{\mathrm{em}}^{\mathrm{obs}} \mathcal{K}(\chi) \frac{u^\mu \nabla_\mu \chi}{\chi} \, d\lambda \right].} \tag{10}$$

Redshift in ECSM is therefore a path-integrated inertial clock effect, not a kinematic Doppler shift and not a consequence of metric expansion.

2.5 Limiting cases

- **Gravitational redshift**: χ varies only between emitter and observer.
- **Cosmological analogue**: χ varies slowly along the propagation path.
- **Local Lorentz limit**: $\chi \approx$ const implies $z = 0$.
- **Coherence breakdown**: $\chi \to 0$ corresponds to loss of a well-defined clock concept.

The ECSM redshift mechanism is thus fully operational, medium-based, and does not require spacetime expansion.

3 ECSM Framework

We model the cosmic medium as a non-relativistic, Galilean-invariant superfluid characterized by a density ρ, velocity field $\mathbf{v}$, and an induction response governing long-range interactions.

In the coherent regime, perturbations in the medium give rise to an effective Newtonian potential. However, this description breaks down when the coherence length becomes finite, leading to scale-dependent departures from metric gravity.

4 Ray Propagation and Emergent Spacetime Optics

Light propagation in the condesate-like superfluid medium is governed not by null geodesics of a fundamental metric, but by induction gradients and density-dependent response functions.

Rays experience refraction and deflection analogous to propagation through a dispersive medium. In the long-wavelength limit, this reproduces standard lensing relations, while at smaller scales finite coherence suppresses deflection efficiency.

This mechanism naturally explains weak lensing suppression without altering structure growth.

5 Phase Transition Dynamics and the CMB

We identify the cosmic microwave background as radiation associated with a global phase transition in the ECSM, occurring when the induction coherence length diverges.

The finite relaxation time of the medium produces a geometrically thin but nonzero emission layer, yielding small, correlated phase shifts in acoustic peaks and polarization spectra.

These effects remain consistent with Planck constraints while breaking the assumption of a universal expansion metric.

6 Microphysical Origin of the Coherence Scale

The induction coherence length χ arises from microscopic interactions within the superfluid medium. At high temperatures or densities, scattering between collective excitations limits long-range induction.

As the universe cools, coherence grows until a condensation threshold is reached. The scale χ is set by the balance between interaction strength, density, and relaxation time, analogous to coherence lengths in terrestrial superfluids.

Importantly, χ need not track any metric expansion variable; it is a physical property of the medium itself.

7 Analogue Systems and Laboratory Connections

The proposed dynamics admit direct analogues in laboratory superfluids, including Bose–Einstein condensates and helium-II systems.

In these media, phonon propagation, vortex formation, and refractive effects exhibit scale-dependent behavior governed by coherence length and healing scales. Optical analogues demonstrate that effective geometries can emerge without underlying spacetime curvature.

These systems provide experimental intuition and, in principle, testbeds for aspects of emergent spacetime optics.

8 Predictions and Falsifiability

The framework yields several distinctive predictions:

- Scale-dependent weak lensing suppression correlated with growth rate.
- Small, non-uniform CMB peak phasing across TT, TE, and EE spectra.
- Breakdown of metric consistency relations at scales comparable to χ.

- Environmental dependence of effective gravitational response.

These signatures cannot be mimicked by a single parameter adjustment in ΛCDM and will be decisively tested by upcoming surveys.

9 Conclusion

By treating geometry as emergent and phase-dependent, we have shown that cosmological tensions need not signal missing components, but rather changes in the physical state of the cosmic medium itself.

A condensate-like superfluid medium with finite induction coherence provides a unified, predictive, and falsifiable framework that naturally accounts for late-time structure, weak lensing suppression, and the origin of the CMB.

If confirmed, this perspective would represent a shift comparable to the transition from ether theories to field theory—this time revealing spacetime itself as an emergent phenomenon.