Fractional Action, Refractive Vacuum, and Testable Memory Signatures in the Light Sector

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We develop a nonlocal, memory-based framework for the light sector in which dissipation, retardation, and hysteresis emerge from a fractional action rather than being inserted phenomenologically at the level of the equations of motion. The construction begins with a Caputo-type fractional extension of the kinetic action, yielding a generalized Euler-Lagrange equation with hereditary temporal structure and recovering the standard local theory in the $\alpha \to 1$ limit. This provides a controlled route from local vacuum propagation to an effective refractive vacuum, in which light behaves as if traversing a medium with delayed constitutive response rather than an exactly instantaneous background. Within this framework, the effective refractive index becomes history-dependent, leading to observable signatures including phase lag, hysteresis under cyclic driving, long-tail relaxation, and protocol-dependent damping. We show that these effects define a falsifiable hierarchy of predictions that distinguishes the local vacuum, an exponential-memory closure, and a fractional-memory extension. We then identify two immediate observational pathways: fast radio bursts (FRBs), where a hereditary vacuum contribution would appear as a residual dispersion law beyond the standard plasma ω^{-2} term, and gamma-ray bursts (GRBs), where the same framework predicts cumulative, non-instantaneous propagation effects beyond standard local Lorentz-invariance-violation templates. In this sense, the proposal is not a metaphysical reinterpretation of light propagation but a concrete testable program. The result is a minimal MetaTime realization in which memory replaces ad hoc damping, the vacuum acquires an effective refractive character, and existing FRB/GRB catalogs become immediate laboratories for falsification.

I. INTRODUCTION

A central lesson of modern theoretical physics is that highly successful formalisms may still remain structurally incomplete in specific regimes. Classical mechanics, quantum theory, statistical physics, and cosmology all provide extraordinarily accurate descriptions across vast domains; yet in several important contexts, effective terms, closure prescriptions, or phenomenological additions are introduced without a fully unified underlying principle. Dissipation is often appended at the level of equations of motion rather than derived from a fundamental variational structure. Memory effects are frequently reduced to Markovian or short-memory approximations. In cosmology, dark-sector phenomenology and perturbative closures are often parameterized effectively, even when their deeper microphysical origin remains unclear. These are not failures of established physics, but indications that the mathematical language currently employed may be too restrictive in situations where hereditary response, nonlocality in time, and coarse-grained informational dynamics become essential.

This work is motivated by the possibility that some of these apparently distinct shortcomings may share a common structural origin. In particular, we explore whether dissipative response, long-memory effects, hysteresis, and part of the effective inertial behavior observed in open or coarse-grained systems can be described within a unified framework based on temporal nonlocality. The guiding idea is modest but consequential: rather than inserting damping, relaxation, or closure terms by hand, one may seek an extended dynamical formalism in which such features emerge from memory-bearing degrees of freedom that have been integrated out of the macroscopic description. In this sense, the problem is not to replace successful local theories where they already work, but to generalize them in those regimes where hereditary effects are physically expected and phenomenological patches become recurrent.

A natural mathematical arena for this program is provided by nonlocal kernels, distributed-memory equations, and fractional calculus. These tools have long appeared in the theory of anomalous transport, viscoelasticity, generalized response theory, and non-Markovian open systems [1–3]. Their relevance lies in the fact that they encode, in a controlled way, the dependence of the present state on an extended temporal history. An exponential memory kernel corresponds to the minimal implementable extension beyond strictly local dynamics, introducing a single relaxation timescale and yielding equations readily adaptable to standard numerical solvers. More general kernels, including multi-scale distributions or fractional operators of Caputo type, allow one to represent long-tail relaxation, hereditary response, and scale-free memory.

The specific hypothesis investigated in this line of work is that several terms commonly treated as effective additions may admit a common reinterpretation as manifestations of memory. We do not assume, *a priori*, that mass, inertia, friction, and irreversibility are identical concepts; such a claim would be premature and unjustified. Rather, we ask a more controlled question: can an extended nonlocal temporal dynamics produce, in suitable limits, effective damping, retarded response, hysteresis loops, and modified perturbative behavior in a way that recovers the standard local theory when the memory scale is removed? Framed this way, the task becomes technically precise. One must define the generalized dynamical variables, specify the memory kernel or fractional operator, derive the effective equations of motion, identify the parameter regime in which the standard theory is recovered, and extract at least one observable consequence by which the extension could in principle be falsified.

This viewpoint is especially attractive in cosmological and dark-sector applications. In those settings, effective fluids, interaction terms, and perturbative prescriptions often serve as practical closures without necessarily revealing the dynamical origin of the response. A causal memory variable, whether implemented through a single-timescale kernel or through a more general distributed-memory operator, provides a concrete way to encode delayed or inherited response of the effective medium. Such a construction may naturally generate damping or phase-lag effects, alter perturbation growth, and produce hysteretic behavior under cyclic or quasi-cyclic protocols. None of these consequences by itself establishes a replacement for the standard cosmological model; however, together they suggest a disciplined pathway toward models in which non-Markovianity is structural rather than phenomenological.

The methodological stance of this work is therefore conservative in its standards, even if ambitious in scope. Any proposed extension must satisfy four requirements. First, it must target a clearly identifiable insufficiency of the local formalism rather than merely add complexity. Second, it must reduce continuously to the standard theory in the appropriate limit, such as vanishing memory scale or integer-order differentiation. Third, it must produce a concrete observable signature, for example in relaxation laws, perturbation damping, hysteresis measures, or effective refractive behavior. Fourth, it must remain computationally implementable and open to numerical and observational falsification. These requirements are essential if one wishes to avoid replacing one phenomenology with another of greater mathematical sophistication but no greater physical content.

In this paper, we adopt this program in its minimal form. We begin from the simplest causal memory closure capable of extending a local theory into a non-Markovian one, and we then indicate how this structure may be generalized toward distributed-memory or fractional formulations. The aim is not to claim a final ontology of time, matter, or information, but to provide a technically controlled framework in which hereditary effects can be treated as first-class dynamical ingredients. If successful, such a framework would offer a unified way to discuss dissipation, retardation, and hysteresis across otherwise disconnected problems, while preserving the standard description as the appropriate short-memory limit.

II. FRACTIONAL ACTION AND TEMPORALLY NONLOCAL EFFECTIVE DYNAMICS

A. Minimal fractional extension of the action

To make the role of temporal memory explicit, we begin from the standard local action for a single degree of freedom $x(t)$,

$$S_0[x] = \int_{t_0}^{t_f} dt \left[\frac{1}{2} M\dot{x}^2 - V(x)\right], \tag{1}$$

where M is the inertial parameter and $V(x)$ is a potential. The corresponding Euler-Lagrange equation yields the familiar local dynamics,

$$M\ddot{x} + \frac{\partial V}{\partial x} = 0. \tag{2}$$

A natural extension is obtained by replacing the local velocity $\dot{x}$ with a causal fractional derivative of Caputo type,

$${}^{C}_{t_0}D^{\alpha}_{t} x(t) = \frac{1}{\Gamma(1-\alpha)} \int_{t_0}^{t} \frac{\dot{x}(\tau)}{(t-\tau)^{\alpha}}\, d\tau, \qquad 0 < \alpha < 1. \tag{3}$$

This operator depends on the full past history of the trajectory on the interval $[t_0, t]$, thus providing a controlled implementation of temporal memory. The Caputo choice is convenient because it admits standard initial conditions and reduces smoothly to the ordinary derivative in the limit $\alpha \to 1$.

We therefore consider the minimal nonlocal extension

$$S_\alpha[x] = \int_{t_0}^{t_f} dt \left[\frac{1}{2} M \left({}^{C}_{t_0}D^{\alpha}_{t} x\right)^2 - V(x)\right], \qquad 0 < \alpha \le 1. \tag{4}$$

For $\alpha = 1$, this expression reduces exactly to the local action $S_0[x]$. For $0 < \alpha < 1$, the dynamics becomes nonlocal in time, and the present state depends on the accumulated temporal history of the trajectory.

B. Fractional variational principle and generalized Euler-Lagrange equation

The extremization of $S_\alpha[x]$ proceeds through the fractional calculus of variations [1, 2]. Let $x(t) \to x(t) + \varepsilon\eta(t)$, with $\eta(t_0) = \eta(t_f) = 0$, and consider the first variation of the action. Because the Caputo derivative is linear,

$$\delta\left({}^{C}_{t_0}D^{\alpha}_{t} x\right) = {}^{C}_{t_0}D^{\alpha}_{t} (\delta x). \tag{5}$$

Hence,

$$\delta S_\alpha = \int_{t_0}^{t_f} dt \left[M \left({}^{C}_{t_0}D^{\alpha}_{t} x\right) \left({}^{C}_{t_0}D^{\alpha}_{t} \eta\right) - \frac{\partial V}{\partial x}\eta\right]. \tag{6}$$

Using fractional integration by parts on a finite interval introduces the adjoint right-sided derivative. Denoting this operator by ${}_tD^\alpha_{t_f}$, the stationarity condition $\delta S_\alpha = 0$ yields the generalized Euler-Lagrange equation

$$M\,{}_tD^\alpha_{t_f}\left({}^C_{t_0}D^\alpha_t x\right) + \frac{\partial V}{\partial x} = 0. \tag{7}$$

The appearance of the right-sided operator is a standard consequence of fractional variational calculus and reflects the nonlocal structure of the action functional. By itself, it does not imply microscopic acausality.

C. Recovery of the local theory in the classical limit

Any extension of the local formalism is only acceptable if it recovers the standard dynamics in the appropriate limit. For Caputo derivatives,

$$\lim_{\alpha\to 1} {}^C_{t_0}D^\alpha_t x(t) = \dot{x}(t). \tag{8}$$

Correspondingly, the associated adjoint operator reduces to the ordinary derivative structure required by standard variational calculus on a finite interval. Thus, in the limit $\alpha \to 1$, Eq. (7) becomes

$$M\ddot{x} + \frac{\partial V}{\partial x} = 0, \tag{9}$$

which is exactly the usual Newtonian equation obtained from the local action $S_0[x]$.

D. Near-local expansion and emergent damping

For $0 < \alpha < 1$, Eq. (7) remains genuinely nonlocal in time. Nevertheless, in regimes where the nonlocality is weak, or when one is interested in a coarse-grained or low-frequency description, the temporally nonlocal operator can often be approximated by an effective local expansion plus residual memory corrections. Schematically, one may write

$$M\ddot{x} + \gamma_{\text{eff}}\dot{x} + \frac{\partial V}{\partial x} + \mathcal{M}[x] = 0, \tag{10}$$

where γ_{eff} is an effective damping coefficient generated by the underlying memory structure, and $\mathcal{M}[x]$ denotes higher-order or residual nonlocal contributions. In this framework, dissipation is reinterpreted as an effective consequence of hereditary response.

III. OBSERVABLE CONSEQUENCES: HYSTERESIS, RETARDATION, AND EFFECTIVE DAMPING

A temporally nonlocal dynamics is only physically relevant if it leads to consequences that can, at least in principle, be distinguished from those of a purely local theory. We focus on three generic consequences: hysteresis under cyclic driving, retardation in the response to time-dependent forcing, and effective damping in coarse-grained regimes.

A. Hysteresis as a signature of memory

Let $\hat{\Pi}(t)$ denote a generalized driving variable and let $\eta_{\text{eff}}(t)$ represent an effective response function. In the presence of memory, $\eta_{\text{eff}}(t)$ is generally a functional of the full prior history,

$$\eta_{\text{eff}}(t) = \mathcal{F}\big[\hat{\Pi}(\tau)\,;\,\tau \le t\big]. \tag{11}$$

If the system is subjected to a cyclic protocol in $\hat{\Pi}(t)$, the trajectory in the $(\hat{\Pi}, \eta_{\text{eff}})$ plane need not retrace itself. A natural measure of the memory-induced loop is therefore

$$\mathcal{H}_\eta \equiv \oint \eta_{\text{eff}}\, d\hat{\Pi}. \tag{12}$$

In a local reversible response, $\mathcal{H}_\eta = 0$. A nonzero value signals path dependence and thus provides a direct observable of temporal nonlocality.

B. Retardation and phase lag

Consider a harmonic driving protocol,

$$\hat{\Pi}(t) = \Pi_0 \cos(\omega t). \tag{13}$$

If the response is governed by a causal memory kernel $K(t-\tau)$, then

$$\eta_{\text{eff}}(t) = \int_{t_0}^{t} K(t-\tau)\,\hat{\Pi}(\tau)\,d\tau. \tag{14}$$

In Fourier or Laplace space, the convolution structure implies a frequency-dependent response,

$$\tilde{\eta}_{\text{eff}}(\omega) = \tilde{K}(\omega)\,\tilde{\Pi}(\omega). \tag{15}$$

The complex phase of $\tilde{K}(\omega)$ then determines the phase lag between forcing and response.

C. Effective damping in the near-local regime

When the hereditary dynamics is approximated in a coarse-grained or near-local regime, the dynamics can often be expressed approximately as a local equation supplemented by an effective damping term. The observed γ_{eff} may itself encode information about unresolved memory structure. A purely local fit may remain adequate over a narrow range of conditions, while a wider scan in frequency or time could reveal departures from constant damping and expose the underlying hereditary kernel.

IV. REFRACTIVE VACUUM AND THE LIGHT SECTOR

The general framework developed above becomes particularly suggestive when applied to the propagation of light in an effective vacuum medium. In standard relativistic field theory, the vacuum is treated as the baseline arena in which electromagnetic disturbances propagate locally at the invariant speed c. This description is extraordinarily successful and must remain the reference limit of any extension. However, if the vacuum is regarded as an effective medium with unresolved internal structure, coarse-grained informational degrees of freedom, or temporally nonlocal response, then the propagation of light may acquire a weak hereditary character without immediately violating the local limit in regimes where standard tests are already satisfied.

A. Effective refractive response as a constitutive description

The central quantity in this sector is an effective refractive parameter, denoted η_{eff}, which summarizes the delayed response of the medium to the relevant driving or state variables. At the phenomenological level, we write

$$\eta_{\text{eff}}(t) = 1 + \delta\eta(t), \qquad |\delta\eta| \ll 1, \tag{16}$$

so that the standard vacuum limit is recovered when $\delta\eta \to 0$. The associated effective propagation speed is then

$$c_{\text{eff}}(t) = \frac{c}{\eta_{\text{eff}}(t)} \approx c\,(1 - \delta\eta(t)), \tag{17}$$

to leading order in the deviation.

To express the hereditary character of this response, we assume that η_{eff} depends not only on the instantaneous value of a source variable $\hat{\Pi}(t)$, but on its temporal history:

$$\eta_{\text{eff}}(t) = 1 + \int_{t_0}^{t} K_\eta(t-\tau)\,\hat{\Pi}(\tau)\,d\tau. \tag{18}$$

B. Exponential and fractional closures in the light sector

The simplest implementation of the refractive vacuum idea is obtained with an exponential kernel,

$$K_\eta^{\text{exp}}(t-\tau) = \frac{1}{\tau_\eta} e^{-(t-\tau)/\tau_\eta}\Theta(t-\tau), \tag{19}$$

which yields a single-timescale memory law. Equivalently, one may introduce a latent refractive variable $m_\eta(t)$ satisfying

$$\dot{m}_\eta = \frac{\hat{\Pi}(t) - m_\eta}{\tau_\eta}, \qquad \eta_{\text{eff}}(t) = 1 + \chi_\eta\, m_\eta(t), \tag{20}$$

where χ_η sets the coupling strength.

A more general realization is obtained when the vacuum response is assumed to involve a hierarchy of relaxation scales. In that case one is led naturally to a fractional constitutive law,

$${}^{C}_{t_0}D_t^{\alpha} m_\eta(t) = \frac{1}{\tau_\alpha^{\alpha}}\left[\hat{\Pi}(t) - m_\eta(t)\right], \qquad 0<\alpha<1, \tag{21}$$

with

$$\eta_{\text{eff}}(t) = 1 + \chi_\eta\, m_\eta(t). \tag{22}$$

C. Propagation delay and effective optical path

If the vacuum admits a weak effective refractive response, then light propagation over a path length L acquires a corresponding retardation. In the simplest one-dimensional picture,

$$t_{\text{flight}} = \int_0^L \frac{\eta_{\text{eff}}(x,t)}{c}\,dx. \tag{23}$$

In the homogeneous approximation,

$$t_{\text{flight}} \approx \frac{L}{c}\,\eta_{\text{eff}}(t), \tag{24}$$

so that the excess delay relative to the standard vacuum value is

$$\Delta t = t_{\text{flight}} - \frac{L}{c} \approx \frac{L}{c}\,\delta\eta(t). \tag{25}$$

V. TESTABLE PREDICTIONS FOR THE LIGHT SECTOR

A refractive-vacuum framework only becomes physically meaningful if it produces signatures that are empirically distinguishable from those of a strictly local vacuum. The emphasis is not on any single experimental platform, but on model-independent signatures that follow from the existence of temporal memory in the effective optical response.

A. Prediction I: time-of-flight residuals with memory dependence

The most direct signature of a refractive vacuum is a small deviation in propagation time relative to the standard null baseline. If light propagates over an effective path length L, then

$$t_{\text{flight}} = \int_0^L \frac{\eta_{\text{eff}}(x,t)}{c}\,dx, \tag{26}$$

and the excess delay is

$$\Delta t = t_{\text{flight}} - \frac{L}{c} \approx \frac{1}{c}\int_0^L \delta\eta(x,t)\,dx. \tag{27}$$

If η_{eff} is hereditary, then two signals traversing the same baseline under identical instantaneous conditions but different prior driving histories may accumulate different delays.

B. Prediction II: phase lag under modulated driving

Consider a periodic modulation,

$$\hat{\Pi}(t) = \Pi_0 \cos(\omega t). \tag{28}$$

In a memory-bearing medium, the refractive response will generally take the form

$$\eta_{\text{eff}}(t) = 1 + \eta_0(\omega)\cos\big(\omega t - \phi(\omega)\big), \tag{29}$$

where $\phi(\omega)$ is the frequency-dependent phase lag.

C. Prediction III: hysteresis under cyclic protocols

If the system is driven through a cyclic protocol and the effective refractive response depends on prior history, the trajectory need not retrace itself. The natural loop observable is

$$\mathcal{H}_\eta = \oint \eta_{\text{eff}}\, d\hat{\Pi}. \tag{30}$$

A nonzero quasi-static loop is therefore a particularly strong indicator of genuine hereditary behavior.

D. Prediction IV: protocol-dependent effective damping

When the exact memory dynamics is projected onto a near-local description, one infers an effective optical damping coefficient γ_{opt}. A crucial prediction of the present framework is that this inferred coefficient need not be constant. Instead, it may depend on the probing protocol, frequency window, or temporal range used in the fit,

$$\gamma_{\text{opt}} = \gamma_{\text{opt}}(\omega, T_{\text{obs}}, \mathcal{P}), \tag{31}$$

where T_{obs} is the observation window and $\mathcal{P}$ denotes the driving protocol.

E. Prediction V: departure from single-timescale relaxation

Suppose the system is driven out of equilibrium and then released. The response $\delta\eta(t)$ will relax back toward zero. The form of that relaxation is diagnostic. Exponential-memory closure predicts

$$\delta\eta(t) \propto e^{-t/\tau_\eta}, \tag{32}$$

whereas a fractional-memory closure predicts a broader relaxation law, often expressible through Mittag-Leffler or power-law tails,

$$\delta\eta(t) \propto E_\alpha[-(t/\tau_\alpha)^\alpha]\,. \tag{33}$$

VI. EXPERIMENTAL AND OBSERVATIONAL PATHWAYS

The predictive framework outlined above becomes scientifically compelling only if it can be confronted with data that already exist. In the light sector, this is possible today because two mature observational ecosystems already probe frequency-dependent propagation effects over cosmological baselines: fast radio bursts (FRBs), for which public CHIME/FRB catalogs now provide large samples with measured dispersion properties, and gamma-ray bursts (GRBs), for which Fermi-LAT and Fermi-GBM data have been extensively used to test energy-dependent propagation and Lorentz-invariance-violation scenarios. CHIME/FRB publicly serves catalog data including Catalog 1 and Catalog 2, while Catalog 1 contains 536 FRBs [4, 5]. On the GRB side, the Fermi-LAT second GRB catalog is available through HEASARC and has been supplemented beyond its original 10-year sample using the same analysis procedure [7].

A. Pathway I: Fast radio bursts and anomalous dispersion-measure residuals

FRB observations provide the most direct current pathway because the data analysis pipeline already revolves around frequency-dependent arrival-time delays. In standard radio propagation through ionized plasma, the dispersive delay scales as ω^{-2}, and the inferred dispersion measure is interpreted as the integrated free-electron column along the line of sight. CHIME/FRB baseband and catalog analyses explicitly treat dispersion in exactly these terms [6]. Within the present framework, the proposal is not to discard the plasma contribution, but to test whether an additional hereditary vacuum contribution survives in the residuals after the best-fit plasma law is removed. The minimal phenomenological form is

$$\Delta t_{\text{obs}}(\omega) = A_{\text{DM}}\,\omega^{-2} + A_{\text{mem}}\,\omega^{-\alpha}, \qquad 0 < \alpha < 2, \tag{34}$$

where the first term is the standard plasma delay and the second is an effective memory-induced residual.

A concrete analysis strategy is therefore as follows. For each burst, one first fits the standard cold-plasma law and records the post-fit timing residuals as a function of frequency. One then compares three nested models: pure plasma, plasma plus exponential-memory correction, and plasma plus fractional-memory correction. A particularly strong signature would be the repeated appearance of similar α values across independent FRBs after controlling for known local propagation effects such as scattering, host contribution, or local plasma complexity. Catalog 1 includes 474 one-off bursts and 62 repeat bursts from 18 repeaters, which already permits a first clustered comparison [4].

B. Pathway II: Gamma-ray bursts and re-interpretation of LIV timing tests

The second pathway uses the existing GRB timing infrastructure built around Fermi-LAT and Fermi-GBM. These datasets have long been used to search for Lorentz-invariance-violation-like energy-dependent speed variations by comparing the arrival of high-energy and low-energy photons over cosmological baselines. GRB 090510 remains the canonical case: in the Fermi analysis, a ~ 31 GeV photon was detected 0.829 s after the GBM trigger, and Fermi-based studies used GRB 090510 and additional LAT bursts to set strong constraints on linear and quadratic LIV-induced vacuum dispersion [8, 9].

In the standard LIV interpretation, one often writes a local kinematic propagation delay of the schematic form

$$\Delta t_{\mathrm{LIV}} \propto E^n, \tag{35}$$

with $n = 1$ or 2. The refractive-vacuum alternative proposed here is different in structure. The delay is not assumed to be purely instantaneous and kinematic. Instead, the effective propagation correction is treated as cumulative and hereditary,

$$\Delta t_{\mathrm{mem}}(E) = \int_0^D \mathcal{G}(E, z(s))\, ds, \tag{36}$$

where $\mathcal{G}$ depends not only on photon energy but also on the temporally extended response of the effective medium along the trajectory. In a fractional-memory realization, the key prediction is not simply a different power of E, but a long-tail temporal structure and phase asymmetry that standard LIV templates are not optimized to detect.

C. Complementarity and falsifiability

FRBs and GRBs probe different frequency regimes, different source classes, and different dominant nuisance terms. That is precisely why they are powerful together. In the FRB pathway, the target signature is a non-plasma residual,

$$\delta\Delta t_{\mathrm{FRB}}(\omega) \propto \omega^{-\alpha}, \tag{37}$$

superposed on the usual ω^{-2} law. In the GRB pathway, the target signature is a non-instantaneous propagation residual with long-tail or asymmetric temporal structure,

$$\delta\Delta t_{\mathrm{GRB}}(E, t) \neq \delta\Delta t_{\mathrm{local}}(E). \tag{38}$$

Accordingly, the refractive-vacuum program stands or falls on immediate re-analysis questions: after removal of the standard plasma law, do FRB residuals prefer a coherent $\omega^{-\alpha}$ component across events? After marginalizing source-intrinsic timing structure, do LAT/GBM light curves contain long-tail or phase-asymmetric residuals better fit by a hereditary propagation kernel than by a purely local LIV template?

VII. CONCLUSIONS AND OUTLOOK

In this work we have developed a minimal but coherent framework in which temporally nonlocal dynamics is elevated from a phenomenological correction to a structural principle. The central achievement of the construction is methodological: damping, retardation, and hysteresis are not appended by hand at the level of the effective equations of motion, but arise from a memory-bearing action. By replacing the strictly local kinetic sector with a Caputo-type fractional extension, we obtained a generalized variational formalism in which hereditary response is built into the dynamics itself, while the standard local theory is recovered continuously in the appropriate limit.

The framework does not attempt to overthrow the successful local description of light propagation where that description already works. Instead, it targets precisely those regimes in which local constitutive closure may be incomplete. In that sense, the refractive-vacuum picture introduced here is conservative in its standards but ambitious in its scope. The vacuum is not treated as a naive varying-c arena, nor is Lorentz structure discarded by fiat. Rather, the observable light sector is modeled as if it were coupled to an effective medium with memory, so that small deviations from purely instantaneous propagation can emerge at the coarse-grained level without sacrificing the standard transparent-vacuum limit.

The second major result is that this formulation is falsifiable now. The theory does not merely produce abstract formal consequences; it yields concrete observational signatures. In the radio domain, the framework predicts that fast radio burst propagation may contain a residual dispersive component beyond the standard cold-plasma ω^{-2} law, with a fractional-memory contribution naturally parameterized by a nontrivial $\omega^{-\alpha}$ scaling. In the high-energy domain, it predicts that gamma-ray burst timing residuals may contain long-tail relaxation and phase-asymmetric propagation structure that are not well captured by standard instantaneous Lorentz-invariance-violation templates. These are present-tense re-analysis questions for CHIME/FRB and Fermi-LAT/GBM data products.

The conceptual message is therefore sharper than a purely formal exercise. By encoding memory at the level of the action, we avoid the standard practice of patching the equations with friction-like or closure-like terms whose deeper origin remains unspecified. In the MetaTime interpretation, what appears macroscopically as damping or delayed response can be read as the projected consequence of unresolved temporal structure. The theory does not yet claim that inertia, dissipation, and irreversibility are strictly identical. What it does claim is that they can be studied within a single controlled language of hereditary dynamics, rather than as disconnected phenomenological additions.

This paper should therefore be read as a foundational light-sector realization of a broader MetaTime program. The refractive-vacuum sector provides the cleanest first arena because it translates nonlocal temporal structure into immediately testable observables: delay, phase lag, hysteresis, dispersive response, and protocol dependence. But the formal logic is not confined to optics. The same strategy can be extended to the gravitational sector, where temporally nonlocal response may modify effective propagation, retardation, or coupling structure in weak-field and cosmological regimes. It can also be extended to dark-energy and dark-sector phenomenology, where memory variables and distributed kernels may provide a more structural alternative to purely ad hoc closure prescriptions and interaction terms.

In summary, the present work establishes a disciplined alternative to patchwork phenomenology. It shows that one can formulate a light-sector theory in which memory, not manual damping, generates effective retardation; in which the vacuum, not as ontology but as phenomenology, acquires a refractive response; and in which the MetaTime program becomes scientifically meaningful only by risking immediate observational failure. A new framework must not merely sound profound. It must be precise enough to be wrong.

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