Edge-Time Theory Quantized (ETTQ) Field Equations:

A Decoherence-Frontier Effective Theory for Temporal Ordering, Classical Record Formation, and the Dark Sector

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1. Abstract

Edge-Time Theory Quantized (ETTQ) is the later, more formal development of the earlier QTET program. In its strongest defensible form, ETTQ does **not** treat time as a mere coordinate convention, nor does it rely on the literal identity "time = energy." Instead, it proposes that the experienced arrow of time is the macroscopic imprint of a **dynamical ordering sector** that helps determine when physical alternatives become stable classical records. This paper presents a publication-oriented formulation built around three linked claims: (i) a low-energy ordering field can be represented covariantly by a scalar foliation field $\tau(x)$ or, equivalently where appropriate, a unit time-like field u_μ; (ii) the "edge of now" is best interpreted as a **local decoherence-and-record frontier**, not as a universal simultaneity surface; and (iii) the homogeneous stress of the ordering sector can be vacuum-like at late times, while its inhomogeneous excitations may generate only weak, tightly constrained dark-sector response. The resulting framework is formulated as an effective theory rather than a complete ultraviolet completion, and it is explicitly constrained by decoherence theory, no-signalling, multimessenger gravity, cosmology, and laboratory precision measurement [1], [2], [3], [4], [5], [6], [7].

The manuscript also resolves several recurring weaknesses in earlier formulations. ETTQ is here stated in a way that is compatible with the relativity of simultaneity, with the no-signalling structure of entanglement, and with the empirical requirement that any preferred-ordering sector must reduce to general relativity plus ordinary quantum theory to very high precision in tested regimes [8], [9], [10], [11], [12]. The theory is therefore advanced not as a declaration that foundational physics has al-ready been solved, but as a **testable research program**: one that connects tempo-ral ordering, irreversible record formation, and dark-sector phenomenology within a single effective scaffold. We derive the background continuity solution for a mildly dynamical ordering sector, formalize a phenomenological record-formation quantity (DEIQ), introduce a threshold criterion for the operational "edge of now," and iso-late concrete observational targets in cosmology, gravitational-wave constraints, and cross-correlated quantum-clock searches. The central claim is that ETTQ becomes strongest when its speculative language is disciplined into explicit mathematical objects, narrow falsifiable claims, and experimentally legible signatures.

Keywords: arrow of time; decoherence; Quantum Darwinism; dark energy; dark matter; preferred foliation; quantum gravity; cosmology; quantum clocks; entanglement.

2. Introduction

Time enters modern physics in at least three logically distinct ways. First, **coordinate time** labels events in a chosen chart. Second, **proper time** is what clocks measure along timelike worldlines. Third, there is **physical time-as-process**: the observed asymmetry between past and future, expressed through irreversibility, entropy production, and the accumulation of durable records. Many conceptual tensions in quantum gravity arise because these three uses of "time" are not identical, yet are routinely spoken about as though they were [8], [9]. ETTQ is aimed at the third usage. Its concern is not to replace coordinate time or proper time, but to ask whether the **arrow** and **experienced passage** of time can be attached to a physically meaningful ordering process.

That question is not metaphysically optional. Special relativity denies a frame-invariant global simultaneity slice, so any literal universal present is immediately suspect. Standard quantum theory, meanwhile, treats time differently from observables such as position and momentum. Decoherence theory explains why classical appearances emerge, but does not by itself say how an observer should speak about the "present" unless one supplements it with an operational criterion for what has become a stable record [1], [2]. In earlier QTET drafts, the moving present was described more poetically as a "time edge." The later ETTQ draft sharpened that image into something closer to a publishable claim: the present is best treated as a **local frontier of decoherence and record formation**.

This paper carries that refinement through consistently. It preserves the motivating intuition of QTET - that time's passage is tied to physical activity rather than passive bookkeeping - but translates that intuition into a narrower and more legible framework. The result is a version of ETTQ that distinguishes carefully between (a) established physics, (b) phenomenological ansatz, and (c) speculative extension. That distinction matters. A theory about time becomes weaker, not stronger, when its most dramatic claims outrun its mathematical content. Accordingly, the present manuscript makes the strongest case for ETTQ by narrowing the claims to those that can be stated with explicit variables, equations, and observational filters.

A minimal publication-grade ETTQ paper therefore makes three negative commitments as well:

- it does **not** infer controllable faster-than-light signalling from entanglement;
- it does **not** claim that energy-time uncertainty alone proves a time operator or a fundamental chronon;
- it does **not** claim that weak wake structure can already replace the entire clustering dark matter sector required by lensing and large-scale structure.

These constraints do not impoverish the theory. They clarify its actual novelty. ETTQ becomes distinctive when it combines (i) a covariant ordering sector, (ii) a local decoherence-frontier interpretation of the present, and (iii) a hybrid dark-sector phenomenology with precise falsifiability conditions. The remainder of the paper develops that core.

Table 1: *Translating the early QTET intuition into publication-grade ETTQ statements.*

Early QTET intuition	ETTQ statement	Immediate empirical burden
"Time is the kinetic driver of the universe."	Temporal ordering is represented by a dynamical low-energy sector whose stress-energy can be vacuum-like in the background and weakly responsive in perturbations.	Must reduce to GR plus standard cosmology where tested.
"The edge of now is physically advancing."	The present is a **local decoherence frontier** where redundantly accessible records cross operational thresholds.	Must be compatible with relativity of simultaneity and open-system quantum theory.
"Sub-space communication" through entanglement may exist.	Entanglement reveals hidden correlation architecture, but not controllable superluminal signalling.	Must satisfy no-signalling and relativistic causality.
"Dark matter may be turbulence behind time's edge."	Ordering-sector inhomogeneities may contribute only weak wake/response terms; the clustering dark matter component is retained unless and until data say otherwise.	Must respect Bullet Cluster, CMB, lensing, and null direct-detection limits.
"Quantized updates" or chronons may underlie rendering.	A microscopic update scale can be introduced only as a phenomenological ultraviolet parameter, not as a deduction from elementary uncertainty slogans.	Must avoid conflict with Lorentz tests and spacetime-foam bounds.

3. The minimal publishable core of ETTQ

The strongest version of ETTQ can be stated as four postulates.

Postulate A (ordering sector). The low-energy theory contains a field that locally defines a timelike ordering direction. At the effective level this can be represented by a scalar $\tau(x)$ with timelike gradient, or by the associated normalized vector field u_μ.

Postulate B (local present). The "edge of now" is not a universal simultaneity hypersurface. It is an operational boundary at which coherent alternatives become stable records accessible to multiple observers.

Postulate C (vacuum-like background). The homogeneous component of the ordering sector can contribute a late-time stress that is approximately vacuum-like, with $w \approx -1$ or mildly dynamical deviations from it.

Postulate D (weak inhomogeneous response). Perturbations of the ordering sector can source only small, tightly constrained gravitational response, strongest at late times and on large or low-acceleration scales if present at all.

These postulates are deliberately sparse. They do not define a complete theory; they define the **minimum scientific kernel** that can be developed without immediately contradicting established results. Figure 1 summarizes that kernel visually.

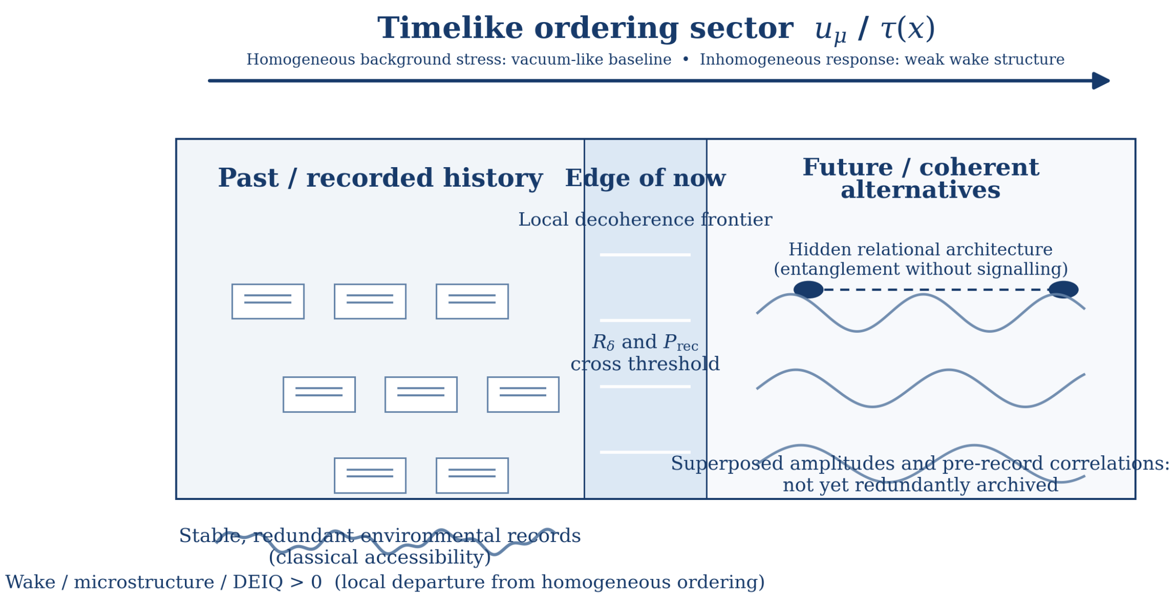

Figure 1: *Graphical abstract of the revised ETTQ framework. A homogeneous timelike ordering sector provides the background arrow, the edge of now is a local decoherence frontier, the past is the domain of stable records, and the future remains a domain of coherent alternatives and hidden pre-record correlations. Weak wake structure is shown only as a local departure from the homogeneous background, not as a complete substitute for the dark sector.*

The most important consequence of this formulation is methodological. ETTQ should be read neither as a purely interpretive gloss on existing theory nor as a claim that every cosmological anomaly already has a temporal explanation. It is better understood as an effective-theory program with two layers. The first layer is **conceptual but disciplined**: it provides a precise operational account of the present in terms of record formation. The second is **dynamical and testable**: it proposes that the sector associated with temporal ordering may itself contribute a small amount of stress-energy and a weak response function. That two-layer structure is what allows ETTQ to preserve its original ambition without detaching from the current evidentiary landscape.

4. Covariant ordering sector

4.1 Scalar-clock and unit-timelike-field formulations

The cleanest low-energy starting point is a scalar ordering field $\tau(x)$ with

$$X \equiv -\frac{1}{2}\nabla_\mu\tau\,\nabla^\mu\tau > 0,$$

so that the associated normalized timelike direction is

$$u_\mu \equiv \frac{\nabla_\mu\tau}{\sqrt{2X}}, \qquad u_\mu u^\mu = -1.$$

This move converts loose language about a preferred temporal direction into a covariant field statement. A broad class of effective ordering-sector models can then be written as

$$S = \int d^4x\,\sqrt{-g}\left[\frac{M_{\rm Pl}^2}{2}R + P(X,\tau) + \mathcal{L}_m\right],$$

where $P(X,\tau)$ is a k-essence-like Lagrangian density and $\mathcal{L}_m$ denotes the matter sector. Varying with respect to τ yields

$$\nabla_\mu\left(P_{,X}\,\nabla^\mu\tau\right) + P_{,\tau} = 0,$$

and the ordering-sector stress tensor is

$$T^{(\tau)}_{\mu\nu} = P_{,X}\,\nabla_\mu\tau\,\nabla_\nu\tau + P\,g_{\mu\nu}.$$

In a homogeneous Friedmann-Lemaitre-Robertson-Walker (FLRW) background, these imply

$$\rho_\tau = 2XP_{,X} - P, \qquad p_\tau = P,$$

alongside the background Einstein equations

$$3M_{\rm Pl}^2H^2 = \rho_r + \rho_m + \rho_\tau,$$

$$-2M_{\rm Pl}^2\dot{H} = \frac{4}{3}\rho_r + \rho_m + \rho_\tau + p_\tau.$$

The canonical scalar limit $P(X, \tau) = X - V(\tau)$ is especially useful because it makes the logic transparent. In that limit,

$$\rho_\tau = \frac{1}{2}\dot{\tau}^2 + V(\tau), \qquad p_\tau = \frac{1}{2}\dot{\tau}^2 - V(\tau),$$

so the equation-of-state parameter is

$$w_\tau = \frac{p_\tau}{\rho_\tau} = \frac{\frac{1}{2}\dot{\tau}^2 - V}{\frac{1}{2}\dot{\tau}^2 + V}.$$

When potential energy dominates, $\dot{\tau}^2 \ll V$, one obtains $w_\tau \to -1$. This is the technically disciplined version of the old QTET slogan that time continues to “drive” cosmic expansion. The correct statement is not that time is identical to kinetic energy. It is that a timelike ordering sector can carry stress-energy, and its homogeneous stress can look vacuum-like in the infrared.

4.2 Relation to preferred-foliation effective theories

The scalar-clock language is not the only possible formulation. ETTQ can also be embedded, at least phenomenologically, in the language of preferred-foliation vector-tensor theories, especially Einstein-aether or khronometric models [10], [11], [12]. In that language one writes

$$\mathcal{L}_{\text{aet}} = -M_{\text{aet}}^2 \left[c_1 \nabla_\mu u_\nu \nabla^\mu u^\nu + c_2 (\nabla_\mu u^\mu)^2 + c_3 \nabla_\mu u_\nu \nabla^\nu u^\mu + c_4 a_\mu a^\mu\right] + \lambda(u_\mu u^\mu + 1),$$

with

$$a_\mu \equiv u^\nu \nabla_\nu u_\mu.$$

ETTQ does **not** claim identity with Einstein-aether gravity. The point of writing this Lagrangian is narrower: it shows that an ordering sector can be cast in a referee-legible covariant form and that existing constraints on preferred timelike structure can be imported immediately. Those constraints are severe. Gravitational-wave multi-messenger observations after GW170817 and pulsar-timing analyses sharply restrict departures from luminal propagation and low-energy Lorentz violation [5], [11], [12], [13]. Any viable ETTQ realization must therefore satisfy a non-negotiable requirement: the ordering sector must be **effectively hidden** in the regimes already probed with high precision.

That result is not a weakness. It is a filter. It tells us that the only publishable versions of ETTQ are those that behave almost exactly like ordinary gravity and quantum theory except in carefully defined infrared or record-formation observables. In other words, the theory cannot be casual about its couplings.

5. The edge of now as a decoherence frontier

The heart of ETTQ is not the background cosmology. It is the claim that the experienced present should be attached to **record formation**. In open quantum systems, a system S interacting with an environment E is described locally by the reduced state

$$\rho_S = \mathrm{Tr}_E \, \rho_{SE}.$$

Decoherence suppresses off-diagonal terms in selected bases, producing effectively classical behavior for certain observables [1], [2]. In many simple models one can write the damping of off-diagonal terms schematically as

$$\rho_S(x, x', t) \approx \rho_S(x, x', 0) \exp\left[-\Lambda(x - x')^2 t\right],$$

where Λ is an environment-dependent decoherence scale. This, however, is only the first step. Decoherence suppresses interference; it does not by itself define objective classical facts.

Quantum Darwinism sharpens the picture by emphasizing **redundancy**. A record becomes effectively objective when many fragments of the environment independently carry the same information about a system pointer state [3], [14]. If f_δ denotes the fraction of the environment required to recover a fraction $1 - \delta$ of the relevant classical information, then the redundancy is

$$R_\delta = \frac{1}{f_\delta}.$$

This leads naturally to an operational definition.

Definition 1 (record-frontier event). An event e is said to have entered the **classical past** when both of the following hold:

$$R_\delta(e) \geq R_\star,$$

$$P_{\mathrm{rec}}(e) \geq P_c,$$

where $R_\star$ is a redundancy threshold, P_{rec} is the effective probability that the event has been durably recorded, and P_c is a chosen operational cut close to unity.

This is where the DEIQ idea becomes useful. In earlier drafts DEIQ was suggestive but underdefined. Here it is made explicit as a phenomenological coupling between the ordinary environment and an ETTQ-specific record-formation channel.

Definition 2 (DEIQ field). The Dynamic Edge Interaction Quotient, $\chi_{\mathrm{DEIQ}}(x, t)$, is a bounded phenomenological field satisfying

$$0 \leq \chi_{\mathrm{DEIQ}}(x, t) \leq 1,$$

and entering the effective record-formation rate through

$$\Gamma_{\text{eff}}(x,t) = \Gamma_{\text{env}}(x,t) + \Gamma_0\,\chi_{\text{DEIQ}}(x,t).$$

A minimal record-dynamics model is then

$$\dot{P}_{\text{rec}} = \Gamma_{\text{eff}}(1 - P_{\text{rec}}),$$

with solution

$$P_{\text{rec}}(t) = 1 - \exp\left[-\int_0^t \Gamma_{\text{eff}}(t')\,dt'\right].$$

If Γ_{eff} is approximately constant over a relevant interval, then the crossing time for a threshold P_c is explicit:

$$t_P = -\frac{\ln(1 - P_c)}{\Gamma_{\text{eff}}}.$$

This is an example of how ETTQ gains strength when its language is turned into resolved differential structure rather than metaphor. Figure 2 illustrates the resulting record-frontier picture.

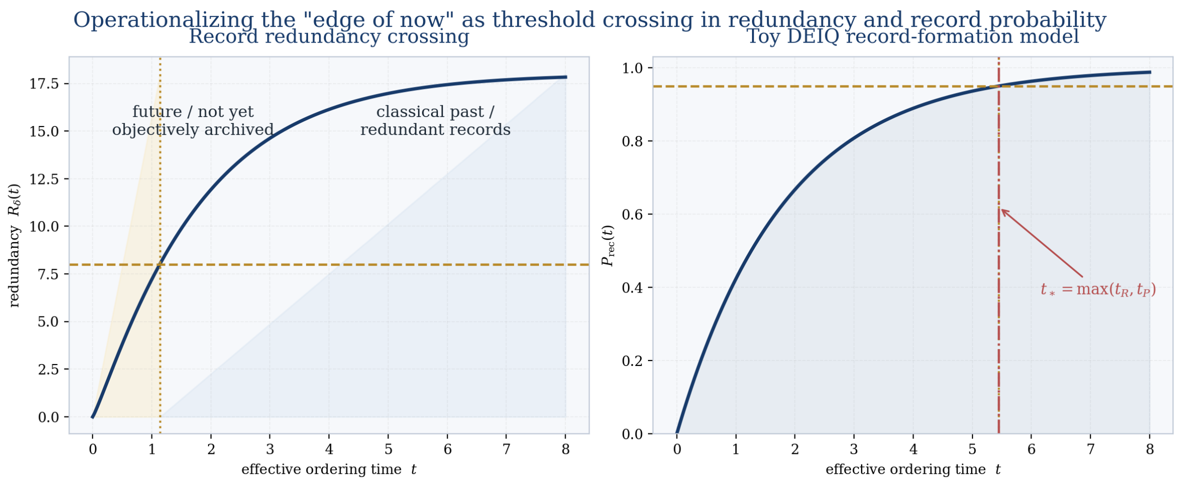

Figure 2: *Illustrative record-frontier dynamics. Left: redundancy $R_\delta(t)$ crossing a threshold for objective accessibility. Right: a toy DEIQ-driven record probability approaching unity. The operational edge of now is identified with the latest time at which both thresholds have been crossed. The curves are phenomenological and intended only to visualize the criterion introduced in the text.*

The benefit of this formulation is twofold. First, it makes the "present" local and operational, avoiding direct conflict with relativity. Second, it suggests a laboratory signature: if the ordering sector is real, then in addition to ordinary environmental decoherence there may exist a tiny, universal, cross-platform contribution to record formation or phase noise. That possibility is developed in Section 8.

6. Entanglement, relational structure, and no-signalling

One of the most vulnerable features of the early QTET language was the suggestion that entanglement might open a genuine signalling channel through a hidden temporal substrate. That is too strong. The correct reading is subtler. Entanglement may reveal a **pre-record relational structure**, but it does not enable controllable superluminal communication [4].

Take the Bell singlet,

$$|\Psi^-\rangle = \frac{|01\rangle - |10\rangle}{\sqrt{2}}.$$

The reduced state of subsystem B is maximally mixed:

$$\rho_B = \mathrm{Tr}_A\left(|\Psi^-\rangle\langle\Psi^-|\right) = \frac{I}{2}.$$

For any local completely positive trace-preserving operation $\mathcal{E}_A$ acting on subsystem A,

$$\rho_B' = \mathrm{Tr}_A\left[(\mathcal{E}_A \otimes I_B)\rho_{AB}\right] = \rho_B.$$

That is the operational content of no-signalling. ETTQ therefore cannot use entanglement as evidence for practical faster-than-light communication. What it *can* say is that the future domain - the domain before stable record formation - contains non-classical relational structure that is not well represented by classical local variables alone.

This is one reason ETTQ fits more comfortably with relational or emergent-time ideas than with literal collapse mysticism. In the Page-Wootters picture, dynamics can be read conditionally relative to a clock subsystem inside a stationary total state [15], [16]:

$$(H_C + H_S)|\Psi_{CS}\rangle = 0,$$

$$|\psi_S(t)\rangle \propto \langle t|\Psi_{CS}\rangle.$$

ETTQ does not reduce to the Page-Wootters mechanism, but it shares a useful lesson: temporal behavior can emerge operationally from correlations. Likewise, entanglement-geometry programs - for example the Ryu-Takayanagi relation, Van Raamsdonk's "entanglement builds spacetime" argument, and the ER = EPR conjecture - motivate the idea that relational quantum structure and spacetime organization may be deeply linked, even though they do not by themselves validate any particular ETTQ dynamics [17], [18], [19].

The right conclusion is therefore restrained. ETTQ may interpret the pre-record domain as a hidden architecture of correlations, but it must do so in a way that preserves no-signalling exactly. Any future experimental claim that appears to violate that principle would count not as confirmation of ETTQ, but as a falsification of the version developed here.

7. Cosmological background dynamics

The most promising empirical interface for ETTQ is late-time cosmology. If the ordering sector contributes a nearly homogeneous stress, then its cleanest manifestation is dark-energy-like expansion. This section resolves the basic background differential equations into a form suitable for phenomenology.

The continuity equation for a homogeneous component with equation-of-state parameter $w_\tau(a)$ is

$$\dot{\rho}_\tau + 3H(1 + w_\tau)\rho_\tau = 0.$$

A standard and observationally convenient parameterization is the Chevallier-Polarski-Linder (CPL) form,

$$w_\tau(a) = w_0 + w_a(1 - a).$$

Substituting into the continuity equation and integrating gives the closed-form solution

$$\rho_\tau(a) = \rho_{\tau 0}\, a^{-3(1+w_0+w_a)} \exp[-3w_a(1 - a)]\,.$$

This is one of the core "resolved differentials" needed to move ETTQ beyond rhetoric. It provides a direct bridge between the theory's vacuum-like ordering sector and the form in which dark-energy data are actually constrained.

The normalized Hubble function is then

$$E(a)^2 \equiv \frac{H(a)^2}{H_0^2} = \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_{\tau 0}\, a^{-3(1+w_0+w_a)} \exp[-3w_a(1 - a)]\,.$$

In the ΛCDM limit $(w_0, w_a) = (-1, 0)$, this reduces to a constant late-time density. For canonical slow-roll ordering dynamics, one also has approximately

$$w_\tau + 1 \approx \frac{\dot{\tau}^2}{V(\tau)} \ll 1.$$

This background picture is the correct place to interpret the old QTET claim that temporal ordering continues to "fuel" expansion. The more precise statement is that the ordering sector can behave as an almost undiluted vacuum-like component. That interpretation is consistent with standard conservation laws because it is the negative pressure, not a violation of conservation, that keeps the late-time density nearly constant [20], [21].

The observational context is suggestive but not decisive. Planck remains well fit by flat ΛCDM in its baseline analysis [6]. Pantheon+ and the first-year DESI BAO analyses did not overturn that conclusion, though they motivated wider exploration of mildly dynamical dark-energy histories [22], [23]. The three-year DESI DR2 BAO analysis is more provocative: the abstract reports that flat ΛCDM remains a good fit, but that some combinations with CMB and supernova data prefer dynamical dark energy, with significance ranging from roughly 2.8σ to 4.2σ depending on the supernova sample, and with a favored region in the quadrant $w_0 > -1$, $w_a < 0$ [7]. The correct inference for ETTQ is cautious. These data do **not** establish a time-ordering sector. They do, however, keep open the possibility that a mildly dynamical vacuum-like component is phenomenologically relevant.

Figure 3 visualizes the background solutions used in this paper. The curves are illustrative, not fitted.

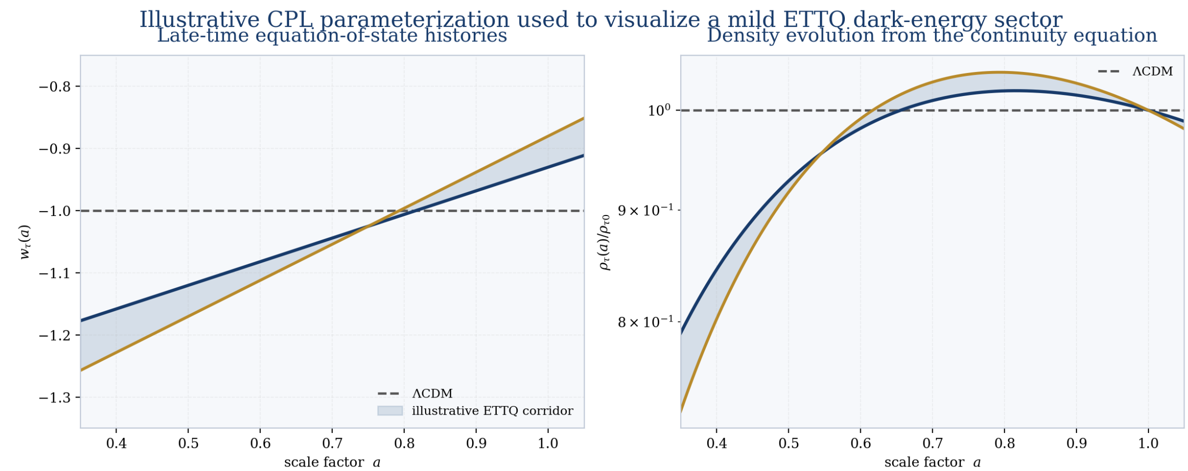

Figure 3: *Illustrative late-time cosmology for an ETTQ ordering sector modeled in CPL form. Left: equation-of-state histories lying close to, but not identical with, ΛCDM. Right: the corresponding density evolution obtained by integrating the continuity equation. These curves are schematic guides to the phenomenological corridor suggested by current data combinations; they are not direct fits.*

The stronger claim is thus not "ETTQ has already explained dark energy." It is that ETTQ identifies the correct observational dial: if the theory is more than an interpretive overlay, then it should appear first as a tightly constrained deviation from a pure cosmological constant, not as a wild departure from precision cosmology.

8. Perturbations, wake response, and the hybrid dark sector

Early QTET drafts entertained the possibility that dark matter might be entirely replaced by turbulence, eddies, or hidden structure behind the temporal frontier. Current evidence makes that too aggressive. The Bullet Cluster remains strong evidence that a large fraction of gravitating mass does not track the dominant baryonic plasma [24]. Direct-detection experiments continue to report null results in wide WIMP parameter ranges, but these nulls do not erase the gravitational evidence for an unseen clustering component [25]. At the same time, galaxy-scale regularities such as the radial acceleration relation continue to motivate careful scrutiny of low-acceleration phenomenology [26].

ETTQ is strongest here when it adopts a **hybrid** stance: the ordering sector may contribute weak response or wake terms, but it does not claim full replacement of the clustering dark matter sector.

In longitudinal gauge one writes

$$ds^2 = -(1+2\Psi)dt^2 + a(t)^2(1-2\Phi)\delta_{ij}dx^i dx^j.$$

For a general k-essence-like ordering field, the perturbation sound speed is

$$c_s^2 = \frac{P_{,X}}{P_{,X} + 2XP_{,XX}}.$$

A schematic linearized perturbation equation for the Fourier mode $\delta\tau_k$ is then

$$\delta\ddot{\tau}_k + 3H\,\delta\dot{\tau}_k + \left(c_s^2\frac{k^2}{a^2} + m_{\text{eff}}^2\right)\delta\tau_k = S_k[\Phi, \Psi, \delta\rho_m],$$

where S_k denotes metric and matter sourcing terms. Rather than claim a complete perturbation theory at this stage, ETTQ can be carried into data analysis through standard response functions,

$$k^2\Phi = 4\pi G a^2 \rho_m \delta_m\, \mu(k, a),$$

$$\eta(k, a) \equiv \frac{\Psi}{\Phi}.$$

A conservative ETTQ ansatz is

$$\mu_{\text{ETTQ}}(k, a) = 1 + \frac{\alpha_0 a^s}{1 + (k/k_\star)^2},$$

$$\eta_{\text{ETTQ}}(k, a) = 1 + \frac{\beta_0 a^s}{1 + (k/k_\eta)^2},$$

with $|\alpha_0|, |\beta_0| \ll 1$. This form enforces two desirable limits: recovery of GR at high k and suppression of the response at early times. It is not a unique prediction of ETTQ, but it is a useful example of how the theory can be represented in actual parameter-estimation pipelines.

The astrophysical burden is substantial. Any nonzero wake sector must coexist with the strong lensing and merger evidence usually attributed to collisionless dark matter, with the CMB damping and peak structure, and with large-scale structure growth.

That is why ETTQ should not be advertised as a fully alternative dark-matter theory at present. Its more defensible ambition is narrower: to determine whether a small additional response associated with temporal ordering can account for part of the low-acceleration or late-time phenomenology without breaking the rest of cosmology.

Figure 4 shows the type of weak response corridor that the theory can reasonably target.

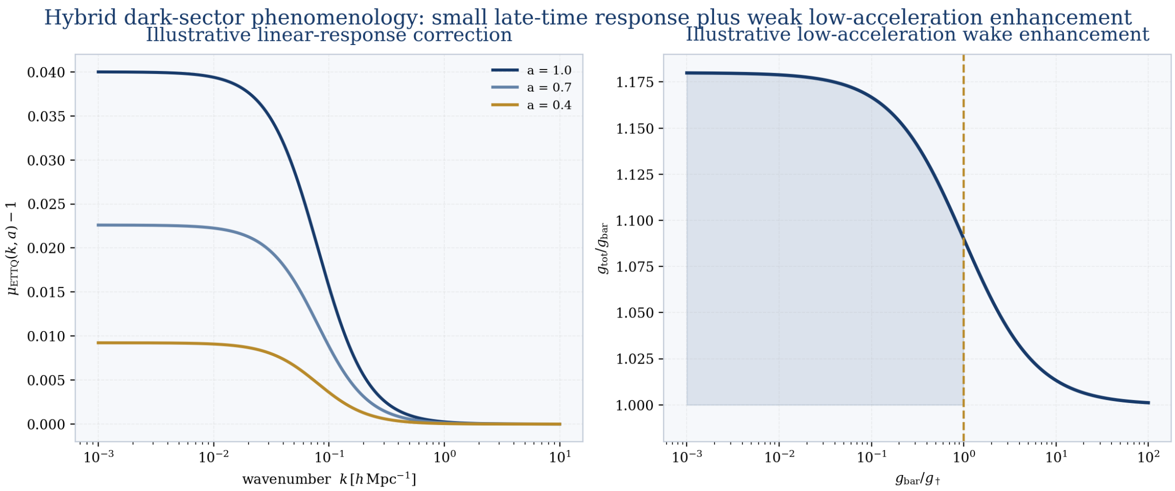

Figure 4: *Illustrative hybrid dark-sector phenomenology. Left: a small ETTQ linear-response correction that is largest at low wavenumber and late times. Right: a weak low-acceleration enhancement that could supplement, but not replace, the ordinary dark sector. Both panels are phenomenological ansatz, displayed to show the scale and shape of the response a viable ETTQ model would need.*

This section also clarifies the status of the "turbulence" metaphor. If ETTQ invokes microstructure, it must do so in a way that respects stringent limits on naive spacetime-foam or Lorentz-violating effects. High-resolution astrophysical imaging and gamma-ray burst timing place strong bounds on simple Planck-scale dispersion models [27], [28]. Mature quantum-gravity programs such as causal sets and loop quantum gravity are relevant here because they demonstrate that discrete or nontrivial microstructure need not imply crude low-energy Lorentz violation [29], [30]. Again, the burden of proof falls on the ETTQ model-builder: any microstructure must be either symmetry-protected, statistically hidden, or coupled only to specially chosen observables such as record formation.

9. Experimental program and publication-grade falsifiability

A theory about time is scientifically meaningful only if it can fail. The present formulation of ETTQ makes its strongest case through a hierarchy of tests.

9.1 Cosmological filters

The first filter is straightforward: the background and perturbation sectors must be fitted directly to data. That means embedding the ordering-sector equation of state and response functions into Boltzmann and structure-formation pipelines and confronting them with Planck, supernova, and BAO likelihoods [6], [7], [22], [23]. A viable ETTQ realization should satisfy four conditions simultaneously:

1. recover the ΛCDM limit continuously;
2. allow only small late-time dynamical deviations unless data demand more;
3. preserve growth and lensing observables within current bounds;
4. produce a parameter region that survives multimessenger gravity constraints.

This is the correct way to turn the dark-energy portion of ETTQ into a statistical question rather than a philosophical one.

9.2 Multimessenger gravity and pulsars

The second filter is preferred-foliation consistency. Gravitational-wave speed measurements and binary pulsars sharply restrict any ordering sector that couples directly to gravity in a Lorentz-violating way [5], [11], [12], [13]. These data do not force ETTQ to zero, but they do force it into a narrow corridor. Any model that predicts appreciable low-energy deviations in the propagation speed of gravitational waves, dipolar radiation, or large preferred-frame effects is already excluded.

9.3 Record-frontier searches in quantum platforms

The third filter is where ETTQ becomes experimentally distinctive. If the edge of now is associated with record formation, and if the ordering sector carries its own weak fluctuations, then one may expect a universal but tiny extra contribution to phase noise or decoherence that is **correlated across spatially separated systems** after ordinary environmental channels are removed. A generic open-system model for this is

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \mathcal{L}_{\text{env}}[\rho] + \gamma_\tau\, \mathcal{D}[A]\rho,$$

where $\mathcal{D}[A]\rho = A\rho A^\dagger - \frac{1}{2}\{A^\dagger A, \rho\}$ and γ_τ is the ETTQ-specific contribution. For networked clocks or interferometers one then searches not just for excess local noise, but for a cross-spectrum

$$C_{ij}(f) = \langle \tilde{y}_i(f)\tilde{y}_j^*(f)\rangle = H_i(f)H_j^*(f)S_\tau(f) + N_{ij}(f),$$

in which a common residual spectrum $S_\tau(f)$ survives environmental vetoes. That is a concrete, publication-legible prediction strategy. The signal need not be large; it must be **structured** and shared.

The experimental motivation is realistic. Quantum-clock theory now treats proper time operationally even in regimes involving quantum superpositions [31]. Space-based and long-baseline entanglement platforms already distribute coherence across thousand-kilometer scales [32]. In parallel, gravitationally mediated entanglement witness proposals illustrate how small, carefully isolated quantum-gravitational effects can be targeted without pretending that macroscopic quantum gravity has already been observed [33], [34]. ETTQ can profit from that methodology even if its mechanism differs.

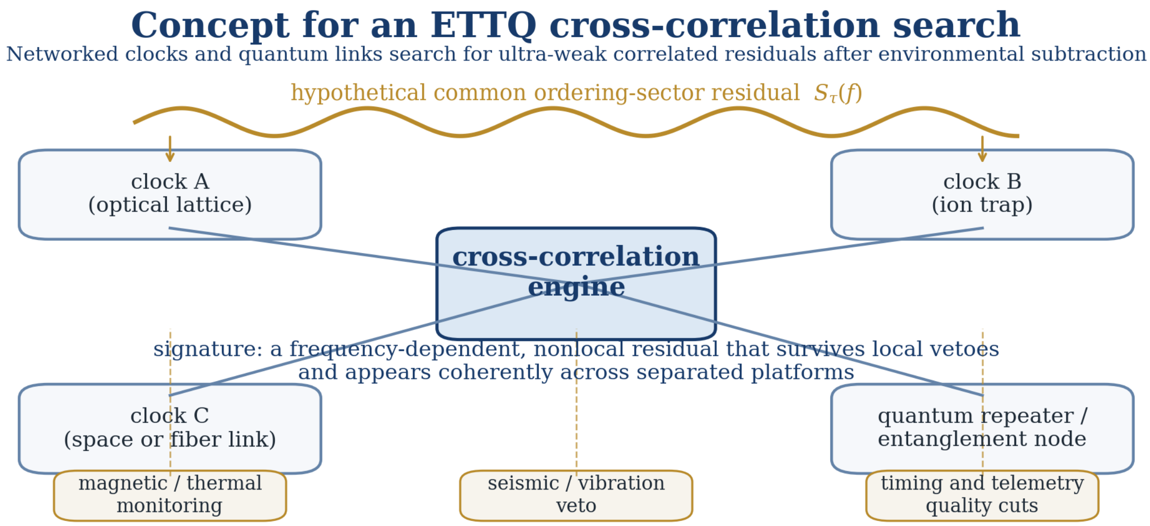

Figure 5: *Schematic of a possible ETTQ cross-correlation search. Networked clocks and quantum links are monitored together with environmental veto channels. The target signature is not generic local excess noise but a structured, weak, nonlocal residual that remains coherent across separated platforms after conventional subtraction.*

9.4 What is outside the minimal core

Finally, publication-grade discipline requires saying what is *not* currently part of the minimal ETTQ theory. Extra time dimensions, engineered wormholes, warp-like vacuum control, and macroscopic manipulation of the "time edge" are not needed to state the core theory, and introducing them too early weakens the paper. The dynamical Casimir effect is a legitimate example of time-dependent boundary modulation in a quantum vacuum [35], but that fact does not make wormhole engineering or warp drives close technological consequences [36], [37], [38]. The strongest case for ETTQ is made by **leaving these ideas in the outlook** until the minimal ordering-sector physics survives basic tests.

Table 2: *Observational and theoretical filters for a viable ETTQ realization.*

Filter	Quantity or observable	What would support ETTQ	What would kill the present formulation
Background cosmology	w_0, w_a, $E(a)$	Mild, data-improving late-time deviation from ΛCDM consistent with Planck and supernovae	Large deviation already excluded by CMB/BAO/SNe fits

Filter	Quantity or observable	What would support ETTQ	What would kill the present formulation
Perturbations	$\mu(k, a)$, $\eta(k, a)$	Small late-time response that improves low-acceleration or growth phenomenology without breaking lensing/CMB	Order-unity departure or early-time growth mismatch
Multimessenger gravity	GW speed, pulsar damping, preferred-frame tests	Couplings small enough to remain hidden in current precision tests	Any appreciable low-energy Lorentz-violating propagation effect
Quantum record frontier	Cross-correlated residual decoherence or phase noise	Shared residual surviving environmental vetoes across separated platforms	No residual beyond shrinking upper bounds in regimes where ETTQ predicts one
Entanglement sector	No-signalling, conditional-time interpretation	Exact consistency with no-signalling and relational-time analogies	Any claim or result requiring controllable FTL signalling

10. Discussion

The point of this manuscript is not merely to rewrite earlier ETTQ/QTET materials in more cautious language. It is to identify the version of the theory that is most likely to survive professional scrutiny.

That version has a clear shape. It separates three different notions of time. It represents temporal ordering with an explicit field rather than with metaphor alone. It treats the present as a local decoherence frontier defined by stable record formation. It allows the ordering sector to behave as a nearly vacuum-like component in cosmology. It keeps any dark-matter replacement claim narrow and provisional. And it proposes a distinct laboratory program centered on cross-correlated record-formation residuals.

What remains original in that package is substantial. Standard cosmology has no dedicated dynamical sector whose *interpretive role* is to underwrite temporal ordering and record formation. Standard decoherence theory does not normally speak of the "present." Standard dark-energy parameterizations are agnostic about why an almost vacuum-like late-time component should exist. ETTQ tries to link these three domains - arrow of time, classical record formation, and dark-sector phenomenology - within a single effective language. That is an unusual synthesis, and it is worth testing.

But the limits are equally important. The theory is not yet complete. It does not derive a unique ultraviolet completion. It does not solve the cosmological constant problem. It does not replace quantum measurement theory wholesale. It does not establish a hidden signalling substrate. And it does not eliminate the conventional dark sector. Those are not embarrassments; they are the honest boundaries of the current framework.

The strongest concluding statement is therefore the following: **ETTQ should be judged as a constrained research program, not as a finished theory**. If future cosmological fits favor mild dynamical dark energy, if preferred-foliation couplings can be made technically natural while remaining observationally hidden, and if precision quantum networks begin to show unexplained correlated record-formation residuals, then ETTQ will have earned a much stronger status. If those conditions fail, the present formulation should be discarded or narrowed further. That is the correct scientific standard.

11. Appendix A. Variation of the ordering-field action

For completeness, this appendix records the main variation steps for the k-essence-like ordering action. Starting from

$$S_\tau = \int d^4x\,\sqrt{-g}\,P(X,\tau), \qquad X = -\frac{1}{2}\nabla_\mu\tau\nabla^\mu\tau,$$

one has

$$\delta X = -\nabla_\mu\tau\,\nabla^\mu(\delta\tau).$$

Therefore,

$$\delta S_\tau = \int d^4x\,\sqrt{-g}\,\left[P_{,X}\delta X + P_{,\tau}\delta\tau\right] = \int d^4x\,\sqrt{-g}\,\left[-P_{,X}\nabla_\mu\tau\,\nabla^\mu(\delta\tau) + P_{,\tau}\delta\tau\right].$$

Integrating by parts and discarding the boundary term yields

$$\delta S_\tau = \int d^4x\,\sqrt{-g}\,\left[\nabla_\mu\left(P_{,X}\nabla^\mu\tau\right) + P_{,\tau}\right]\delta\tau,$$

so the Euler-Lagrange equation is

$$\nabla_\mu\left(P_{,X}\nabla^\mu\tau\right) + P_{,\tau} = 0.$$

For the canonical limit $P = X - V(\tau)$, this becomes

$$\Box\tau - V_{,\tau} = 0.$$

In FLRW, where $\tau = \tau(t)$, the equation reduces to

$$\ddot{\tau} + 3H\dot{\tau} + V_{,\tau} = 0.$$

The slow-roll condition $\ddot{\tau} \ll 3H\dot{\tau}$ gives the useful approximation

$$3H\dot{\tau} \approx -V_{,\tau},$$

which makes explicit how the ordering field can remain nearly vacuum-like while still evolving.

12. Appendix B. Closed-form solutions used in the figures

For the CPL parameterization,

$$\frac{d\ln\rho_\tau}{d\ln a} = -3\big[1 + w_0 + w_a(1-a)\big].$$

Integrating from $a = 1$ to a general a gives

$$\ln\frac{\rho_\tau(a)}{\rho_{\tau 0}} = -3(1 + w_0 + w_a)\ln a - 3w_a(1-a),$$

hence

$$\rho_\tau(a) = \rho_{\tau 0}\, a^{-3(1+w_0+w_a)} \exp[-3w_a(1-a)]\,.$$

For constant $\Gamma_{\rm eff}$, the DEIQ record equation

$$\dot{P}_{\rm rec} = \Gamma_{\rm eff}(1 - P_{\rm rec})$$

integrates to

$$P_{\rm rec}(t) = 1 - (1 - P_0)e^{-\Gamma_{\rm eff} t}.$$

The time to reach threshold P_c is therefore

$$t_P = \frac{1}{\Gamma_{\rm eff}} \ln\left(\frac{1-P_0}{1-P_c}\right).$$

In the figures of the main text we take $P_0 = 0$ for simplicity, so $t_P = -\ln(1-P_c)/\Gamma_{\rm eff}$.

13. Appendix C. Scope note on speculative extensions

The broader QTET manuscript family discussed extra temporal dimensions, sub-space transport, and future vacuum-engineering technologies. Those ideas may remain heuristically interesting, but they are not required for the minimal ETTQ core developed here. The present paper therefore treats them as **downstream possibilities only**. A complete theory that survives the cosmological, multimessenger, and quantum-network tests described above could later revisit such questions. At the current stage, however, the strongest publication strategy is to keep the theory anchored to its narrowest nontrivial claims.

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