Research Article

A Field-Theoretic Approach to the Problem of Time: From Frozen Formalism to Dynamical Evolution

Md. Tasruzzaman Babu[1]

1. Louisiana Tech University, United States

The ontological status of time represents a fundamental impasse in theoretical physics. General relativity treats it as a dynamical component of spacetime, while quantum mechanics requires it as an external parameter. This incompatibility culminates in the Wheeler-DeWitt equation, which describes a static universe—a "frozen formalism" starkly at odds with experienced reality. We propose a radical resolution: time is not fundamental but emerges as a quantum phenomenon. We introduce the *Tempon field*, Φ, a new fundamental scalar that serves as the universal mediator of temporal flow. Its interaction with matter via the stress-energy trace provides a physical substrate for time, transforming it from a background parameter into a dynamical quantum entity. This framework naturally resolves the Problem of Time by promoting Φ to an internal clock variable, recovering evolution from a timeless quantum state.

Crucially, this model is not mere philosophy but yields a definitive, falsifiable signature. It predicts a universal, coherent oscillation in the fractional frequency of all atomic clocks, characterized by a narrow spectral line accompanied by daily and annual Doppler sidebands—a "smoking gun" pattern that cannot be replicated by axions, dark photons, or conventional modified gravity. We derive this signature, demonstrate its uniqueness, and detail complementary tests in gravitational wave polarizations and collider searches. By providing a direct experimental pathway, this work elevates the question of time's origin from metaphysical speculation to the domain of testable physics, with discovery potential within the next decade.

Corresponding author: Tasruzzaman Babu, mba068@latech.edu

1. Introduction

Time is the most familiar yet most mysterious dimension of physical reality. Its treatment represents a fundamental schism between our two most successful physical theories. In quantum mechanics, time is an absolute, external parameter—a static stage upon which the drama of wavefunction evolution unfolds. The Schrödinger equation is unthinkable without this pre-existing temporal background. In stark contrast, general relativity demotes time from its privileged status, weaving it into a dynamic, mutable spacetime fabric that curves and ripples in response to matter and energy [1]. This is more than a mere technicality; it is a profound ontological divide.

The conceptual incompatibility becomes mathematically acute in any attempt to quantize gravity. The Wheeler-DeWitt equation, $\widehat{H}|\Psi\rangle=0$, which arises from a canonical quantization of the gravitational field, describes a static universe [2]. This "frozen formalism" presents a universe without time, a cosmic photograph where nothing ever happens. This conclusion is sharply at odds not only with our experience of temporal flow but with the very premise of physics as the study of dynamical change. This is the notorious "Problem of Time" in quantum gravity [3]: the apparent disappearance of time at the fundamental level.

This problem is more than a technical puzzle; it is a fundamental impasse that existing strategies have been unable to fully resolve. The Page-Wootters mechanism [4] and relational approaches championed by Rovelli [5] offer profound insights by suggesting that time emerges from correlations between subsystems within the universe. However, these frameworks share a critical limitation: they treat time as a convenient correlation, lacking a *physical substrate*. The "clock" in these models is an arbitrary quantum degree of freedom—a photon, a spin, or a gravitational mode—that is itself subject to quantum uncertainty, superposition, and decoherence. This leads to a circular "Measurement Problem of Time": to measure the evolution of a quantum universe, one needs a classical clock, but any clock *inside* the universe isitself quantum. This paradox cannot be solved by simply selecting a different quantum variable; it demands a more radical solution—the introduction of a *fundamental clock* that is not composed of other quantum degrees of freedom.

It is crucial to distinguish this new approach from a historical proposal with a superficially similar name. The "Tempon" field introduced here is fundamentally distinct from the concept of the "chronon [6]," which posits a discrete, minimal unit of time. Our framework is not concerned with the potential granular *structure* of time, but with the ontological *origin* of its continuous flow. We seek the physical mechanism that enables "becoming" from a state of "being."

In this work, we propose such a mechanism. We introduce the "Tempon field" (from Latin *tempus*), a new fundamental scalar field Φ that serves as the physical substrate for time. The conceptual shift is analogous to the Higgs mechanism [7]: just as the Higgs field reconceptualized mass from an intrinsic property to an emergent phenomenon arising from interaction, we propose that temporal flow emerges from the interaction of matter with the Tempon field. Its vacuum expectation value defines a universal clock, and its excitations mediate the physical process of temporal evolution itself.

The novelty of this work, therefore, is not the abstract idea of an internal clock, but its concrete implementation as a new fundamental field with a mandatory universal coupling to the stress-energy tensor. This specific, physical implementation leads directly to the theory's most powerful feature: a unique, non-generic, and falsifiable experimental signature. We predict a coherent, monochromatic modulation in the fractional frequency of all atomic clocks, characterized by a central spectral line accompanied by daily and annual Doppler sidebands—a "smoking gun" pattern that cannot be reproduced by any known dark matter candidate [8] or modified gravity model [9]. This paper develops this conceptual framework, demonstrates its theoretical consistency, and details the clear experimental pathway it provides, thereby elevating the problem of time from a philosophical conundrum to a question of empirical science.

2. Theoretical Foundation: From Concept to Field Theory

2.1. The Conceptual Shift: Time as a Relational Property

The Tempon framework initiates a profound conceptual shift: what we experience as the flow of time is not a fundamental background structure, but a relational property that emerges from the interaction between physical systems and a universal field. In this view, temporal evolution is not described with respect to an abstract parameter t, but is instead a measure of correlation between the state of matter and gravity and the dynamical state of the Tempon field Φ. This transforms time from a stage into a participant—a dynamical quantum entity whose behavior can be quantified, measured, and potentially manipulated.

2.2. The Mandatory Properties of the Tempon Field

For a field to serve as the universal mediator of time, its properties must be severely constrained by both theoretical consistency and phenomenological requirements:

- **Spin-0 (Scalar):** Proper time in relativity is a Lorentz invariant quantity—its value is agreed upon by all observers, regardless of their state of motion. This isotropy and frame-independence necessitates that the field mediating its flow must also be invariant under Lorentz transformations, ruling out vector or tensor fields that would introduce preferred directions. A scalar (spin-0) field is the only mathematically consistent choice.
- **Electrically Neutral & Colorless:** Time affects all particles universally, independent of their electric charge, quark color, or other quantum numbers. A charged or colored field would couple selectively, violating the observed universality of time dilation and contradicting precision tests of equivalence principles.
- **Couples to the Trace of the Stress-Energy Tensor (*T*):** This is the defining interaction. In General Relativity, the stress-energy tensor $T_{\mu\nu}$ informs spacetime how to curve. Its trace, $T=g^{\mu\nu}T_{\mu\nu}$, is a Lorentz scalar that fundamentally represents a system's mass-energy content in its rest frame. By coupling universally as $\alpha\Phi T$, the Tempon field modulates the rate of proper time in proportion to local energy density, providing a natural field-theoretic origin for gravitational time dilation. This coupling ensures that all forms of mass-energy "experience" time through their interaction with Φ.

2.3. The Theoretically Favored Scalar Model

The minimal, self-consistent implementation is an Effective Field Theory (EFT) for a real scalar field Φ, formulated in the Einstein frame to preserve the established successes of General Relativity. The action is:

$$S = \int d^4x\sqrt{-g}\,[\frac{M_{Pl}^2}{2}R + \frac{1}{2}(\partial\Phi)^2 - V(\Phi) - \alpha\Phi T + L_{int}\,]$$

where:

- $\frac{M_{Pl}^2}{2}R$ is the standard Einstein-Hilbert term for gravity.
- $\frac{1}{2}(\partial\Phi)^2 - V(\Phi)$ is the canonical kinetic and potential energy for the Tempon field.
- $\alpha\Phi T$ is the universal linear coupling to the trace of the stress-energy tensor.
- *Lint* represents possible higher-dimensional portal interactions (e.g., with the gluon and photon field strength tensors, suppressed by a high-energy cutoff scale Λ).

doi.org/10.32388/O98SG2

This formulation inherently respects Lorentz invariance (as all terms are Lorentz scalars) and general covariance (as it is constructed from diffeomorphism-invariant quantities within a curved spacetime). For a constant field value $\Phi \approx \Phi_0$ and a small coupling $\alpha \ll 1$, the theory smoothly recovers all tested predictions of General Relativity and the Standard Model.

2.4. Distinction from Conventional Scalar-Tensor Theories

While the Tempon framework mathematically resembles a scalar-tensor theory, its physical interpretation and fundamental goal are categorically different, as summarized in Table 1.

Aspect	**Conventional Scalar-Tensor (e.g., Brans-Dicke)**	**Tempon Field Theory**
Primary Role	Dynamical gravitational coupling; a modified theory of gravity.	Fundamental mediator of temporal evolution; a theory of time.
Core Question	"Is the gravitational constant G fundamentally a field?"	"Is the flow of time fundamentally mediated by a field?"
Coupling Focus	Modifies the kinetic term of the gravity sector (ΦR).	Couples directly to the matter sector ($\alpha \Phi T$).
Relationship to GR	A rival theory proposing an alternative mechanism for gravity.	A completion that provides a physical substrate for time within GR's geometric framework.
Key Signature	Time-varying G, violations of Strong Equivalence Principle.	Universal modulation of all clock rates, coherent across different technologies.

Table 1. Distinction between the Tempon Field and Conventional Scalar-Tensor Theories

This distinction is crucial: the Tempon framework is not a modified theory of gravity, but rather a theory of time that is *implemented within* the gravitational framework. It leaves the geometric description of gravity intact while providing a dynamical origin for the temporal aspect of spacetime.

doi.org/10.32388/O98SG2

3. Resolving the Problem of Time

3.1. The Tempon as the Internal Clock Variable

The fundamental challenge of quantum gravity is encapsulated in the Wheeler-DeWitt equation: $\widehat{H}_{\text{total}}$ $|\Psi\rangle=0$. This constraint asserts that the wavefunction of the universe $|\Psi\rangle$ is static, yielding the infamous "frozen formalism" where no evolution occurs. The Tempon field Φ resolves this impasse by providing a physical degree of freedom that can be promoted to the role of a time parameter.

In the canonical quantization of the coupled system, the total Hamiltonian constraint incorporates the Tempon field:

$$\widehat{H}_{total} = \widehat{H}_{gravity} + \widehat{H}_{matter} + \widehat{H}_{\Phi} \approx 0.$$

While this equation remains formally timeless, the presence of the monotonic Tempon field allows us to re-interpret the dynamics. We can choose the value of Φ itself as a clock variable, asking how the rest of the universe changes as Φ changes.

This leads to a relational formulation where the state of the universe is expressed as $\Psi[g_{\mu\nu}$,matter;$\Phi]$, a function of geometry, matter fields, *and* the Tempon field. The timeless constraint can then be recast into a Schrödinger-like equation of motion:

$$i\hbar\frac{\partial}{\partial\Phi}\Psi\left[g_{\mu\nu}, matter; \Phi\right] = \widehat{H}_{phys}\Psi\left[g_{\mu\nu}, matter; \Phi\right].$$

The "Movie and Internal Clock" Analogy: Imagine the quantum state of the universe as a complete, unordered stack of all possible frames of a movie—this is the frozen $|\Psi\rangle$ of the Wheeler-DeWitt equation. The Tempon field Φ is a clock visible in every frame. By sorting these frames according to the reading on this internal clock, we recover the sequence of the movie. The equation $i\hbar\frac{\partial}{\partial\Phi}\Psi = \widehat{H}_{\text{phys}}$ $\Psi$is the directorial rule that tells us how the scene changes from one frame to the next. Time is no longer an external parameter imposed on the film; it is the progression of the story as measured by the clock within the story itself.

3.2. From Static Being to Dynamic Becoming

The derivation of the Schrödinger-like equation represents the crucial transition from static description to dynamic evolution. The left-hand side, $i\hbar\frac{\partial}{\partial\Phi}$, generates the change in the universal wavefunction with

 doi.org/10.32388/O98SG2

respect to the Tempon field. The right-hand side, $\widehat{H}_{phys}$, contains the operators that generate genuine physical changes in the gravitational and matter fields relative to this clock.

This framework successfully bridges the gap between:

- **Being:** The static, four-dimensional geometric view of reality described by the Wheeler-DeWitt constraint.
- **Becoming:** Our experienced reality of temporal flow and successive events.

When the Tempon field assumes a classical background value that increases monotonically (e.g.,$\langle\Phi\rangle \sim t$), the formalism reduces to the familiar time-dependent Schrödinger equation in a fixed spacetime background. However, in the full quantum regime, Φ itself can fluctuate and entangle with other degrees of freedom, revealing a more complex, fundamentally relational nature of time.The Tempon field thus does not just parameterize time—it quantum-mechanically *mediates* it, providing a physical substrate that transforms the frozen landscape of quantum gravity into a dynamic universe that evolves.

4. Experimental Signatures and Falsifiability

The Tempon framework also generates specific, quantitative predictions across multiple experimental domains, any of which could definitively confirm or rule it out.

4.1. The Universal Signature in Precision Clocks

The most direct and sensitive test of the Tempon hypothesis involves using atomic clocks—devices that measure the flow of time—to search for the field that constitutes it [10].

Derivation of the Signature: A coherent oscillation of the Temponfield, $\Phi(t,\mathbf{x})=\Phi_0+\Phi_1\cos(\omega_T t-\mathbf{k}T\cdot\mathbf{x}+\phi)$, acts as a modulating background. Through its universal coupling to the trace of the stress-energy tensor, $\alpha\Phi T\alpha\Phi T$, this oscillation induces a periodic modulation in the rate of proper time itself. This manifests as a fractional frequency shift in every atomic clock:

$$\frac{\delta\nu}{\nu} = \alpha\kappa\Phi_1 cos(\omega_T t + \varphi),$$

where $\omega_T = \frac{m_T c^2}{\hbar}$ is the angular frequency of the Tempon field determined by its m_T, and κ is an O(1) factor. The minuscule coupling $\alpha\Phi 1 \ll 1$ ensures the effect is a perturbative modulation.

The "Smoking Gun" Triplet: A true Tempon signal would be unmistakable, characterized by three correlated phenomena in the cross-power spectrum of a global clock network:

1. **A Narrow Central Spectral Line**: A Narrow Central SpectralLine at $fT = \omega T/2\pi$, will be found reflecting the coherent, monochromatic nature of the field oscillation.
2. **Daily and Annual Doppler Sidebands**: Daily and Annual Doppler Sidebands atfrequencies $f_T \pm f_{\text{day}}$ and $f_T \pm f_{\text{year}}$ will be created, caused by the motion of the Earth's clocks through the oscillating Tempon field background. These sidebands are a hallmark of a coherent, astrophysical field [11].
3. **Species-Independent Response**: Species-Independent Response will befound where the phase and amplitude of the modulation are identical, to within a small tolerance ϵ, across all types of clocks (e.g., Sr, Yb, Al^+), regardless of their underlying atomic structure.

The Universality Proof: The species-independent response is a direct consequence of the universal coupling to T. While different clock atoms have varying sensitivities (Q_X^i) to different fundamental forces (electromagnetic, gluonic, etc.), the Tempon coupling is to the total mass-energy. The fractional difference in response between two clock species i and j is bounded by $\epsilon \lesssim 10^{-3}$, as shown by representative sensitivity coefficients [12]:

Clock	Q^γ	Q^g	Q^e
Sr	0.064	0.008	0.00
Yb	0.065	0.009	0.00
Al^+	0.065	0.007	0.00

Table 2. Sensitivity Coefficients for Optical Lattice and Ion Clocks

This near-perfect universality cannot be replicated by axions, dark photons, or other dilatonic fields, which inherently produce species-dependent shifts [8][13].

The characteristic spectral pattern expected from the Tempon field is illustrated schematically in Fig. 1, showing the predicted cross-power spectrum that a global atomic-clock network would exhibit if such a field exists. The plot shows a sharp central line corresponding to the coherent field oscillation and symmetric annual and daily Doppler sidebands (±1/year, ±1/day) arising from Earth’s motion.

doi.org/10.32388/O98SG2

4.2. Complementary Tests and Particle Identification

Gravitational Wave Astronomy: The Tempon field, as a scalar coupled to gravity, would introduce an additional polarization mode in gravitational waves. Beyond the two transverse-tensor (+ and ×) modes of General Relativity, a scalar "breathing" mode would be present with an amplitude $\epsilon_b \sim \alpha^2 \Xi(f)$. Current LIGO-Virgo-KAGRA constraints of $\epsilon b < 0.1$ already limit the coupling strength [14], while next-generation detectors (Einstein Telescope, Cosmic Explorer) could probe down to $\epsilon_b \sim 10^{-3} (\alpha \lesssim 0.03)$, providing a direct, independent test.

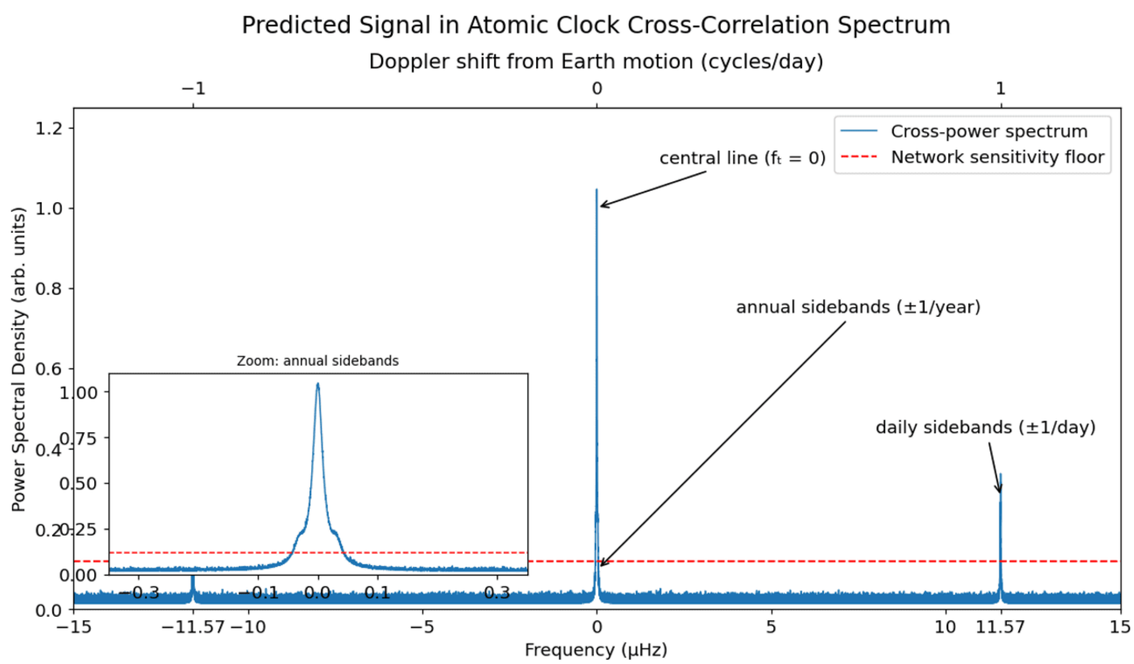

Figure 1. Predicted signal in atomic-clock cross-correlation spectrum.

Collider Searches and Particle Identification: At high-energy colliders like the LHC, the Tempon particle could be produced via gluon fusion or photon fusion, analogous to the Higgs boson but with a different coupling structure. Its defining signature would be a democratic decay pattern into a wide range of final states:

- Diphotons ($\gamma\gamma$)
- Dileptons ($e^+e^-, \mu^+\mu^-$)
- Dijets ($gg, q\bar{q}$)

doi.org/10.32388/O98SG2

This pattern is the fingerprint of its universal coupling to the stress-energy tensor. A particle observed to decay *only* to photons would be an axion-like particle; one decaying *only* to muons would be a different vector. The Tempon's simultaneous appearance in multiple decay channels with rates determined by the mass-energy of the final states would be its unique identifier. Current null results at the LHC imply a lower bound on the effective scale $\Lambda/c_g \gtrsim 300$ TeV [15].

5. Discussion: Synthesis and Distinction

5.1. Why This is Not "Just Another Scalar-Tensor Theory"

While the Tempon framework employs scalar-tensor mathematics, it represents a fundamental departure in physical interpretation and objective. Conventional scalar-tensor theories, such as Brans-Dicke theory [16], are fundamentally modified theories of gravity. Their primary goal is to alter how spacetime responds to matter, typically by making the gravitational constant G a dynamical field. The scalar field in these theories couples directly to the Ricci scalar (ΦR), modifying the geometric sector of the action.

In stark contrast, the Tempon framework is a theory of time implemented *within* gravity. It fully retains the geometric structure of General Relativity but provides a physical substrate for the temporal dimension. The Tempon field Φ couples not to curvature, but universally to the matter sector via the stress-energy trace ($\alpha\Phi T$). Its role is not to change how matter tells spacetime to curve, but to provide the dynamical medium through which temporal evolution for all matter occurs. This conceptual distinction —between modifying gravity and explaining time—is categorical and fundamental.

5.2. Comparison with Other New Physics

The unique, multi-faceted signature of the Tempon field allows for clear experimental discrimination from other proposed light, weakly-coupled fields. The coordinated pattern predicted in atomic clock networks serves as an unreproducible fingerprint.

 doi.org/10.32388/O98SG2

Feature	Tempon (Scalar)	Axion/ALP	Dark Photon	Chronon
Fundamental Role	Mediator of time	Solution to Strong CP problem; dark matter [17]	Vector portal to dark matter [18]	Hypothetical discrete time unit
Universal Clock Response	Yes (identical phase/amplitude)	No (species-dependent couplings) [8]	No (charge-dependent couplings) [13]	Not applicable (concept of continuous signal does not apply)
Doppler Sidebands	Yes (intrinsic signature)	Possible (if coherent DM) but with random phase	Possible (if coherent DM) but with random phase	No
GW Polarization	Yes (breathing mode)	No	Yes (longitudinal mode) [19]	No
Collider Signature	Democratic decays ($\gamma\gamma$, $\ell\ell$, jets)	Predominantly $\gamma\gamma$[20]	Predominantly $\ell\ell$ [18]	Not applicable

Table 3. Distinguishing the Tempon Field from Other New Physics Candidates.

This unique combination of signatures, summarized in Table 3, produces the unmistakable spectral fingerprint shown in Fig. 2. From the figure it is evident that Tempon field produces a sharp, single-frequency peak (solid line) with smaller, symmetric side-peaks caused by Earth's motion. In contrast, a dark matter signal appears as a broad, noisy hump (dashed line) with no such structure.

doi.org/10.32388/O98SG2

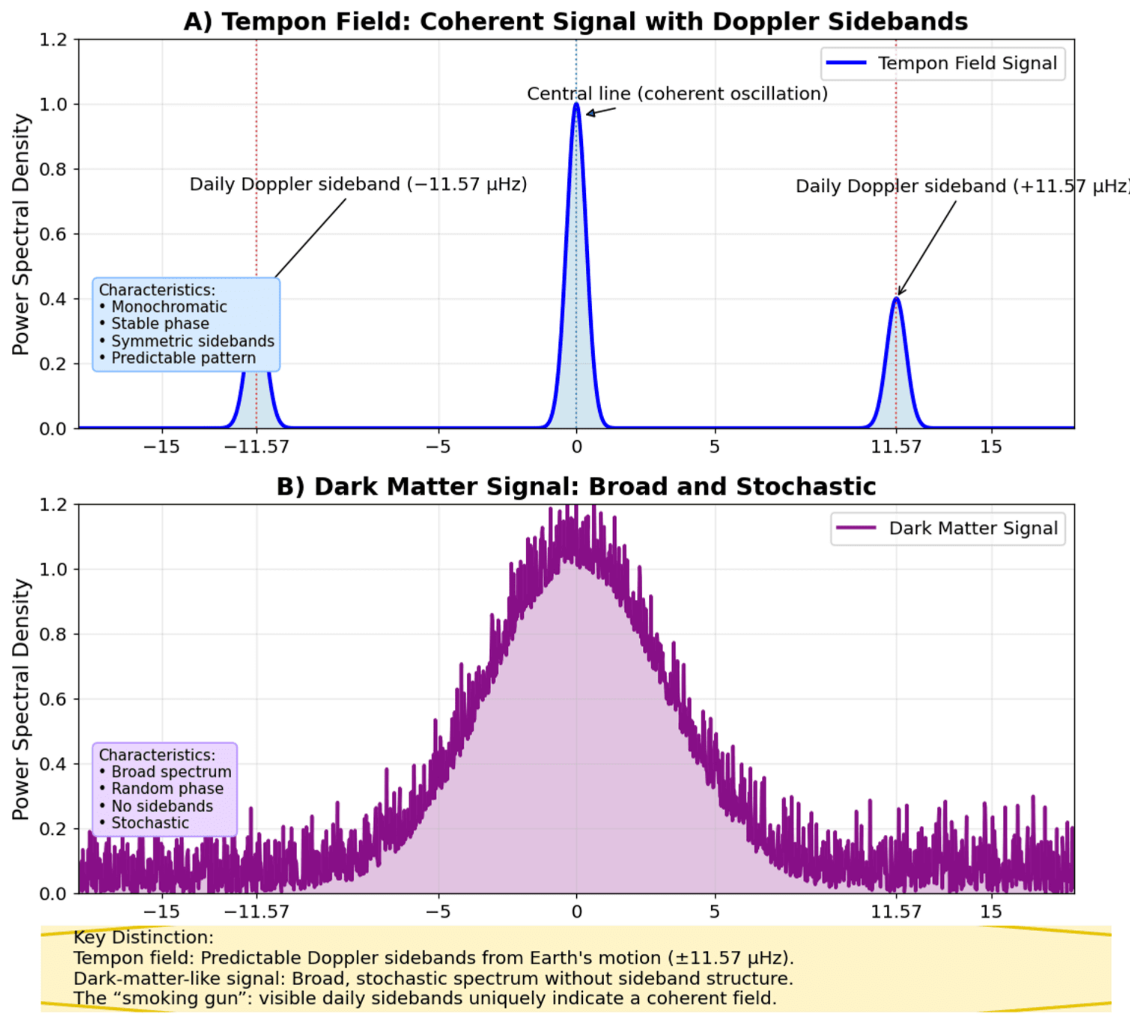

Figure 2. Predicted spectral signature of the Tempon field compared to dark matter.

5.3. Falsifiability Statement

It is falsified if, after a comprehensive and conclusive experimental campaign, the following null results are obtained:

1. **Precision Metrology:** A cross-correlated analysis of a global network of optical atomic clocks (e.g., Sr, Yb, Al$^+$), with a combined fractional frequency sensitivity surpassing $\delta\nu/\nu < 10^{-21}$integrated over the theoretically viable mass range ($f_T \in \left[10^{-8}, 1\right]$ Hz), detects no evidence of a coherent, narrow-band signal exhibiting the characteristic Doppler sideband structure and universal response.

 doi.org/10.32388/O98SG2

2. **Gravitational Waves:** Next-generation gravitational wave observatories, capable of constraining the amplitude of the scalar breathing mode to $\epsilon_b < 10^{-3}$, find no deviation from the pure tensor polarizations predicted by General Relativity.
3. **Collider Searches:** High-energy collider experiments, such as the high-luminosity LHC and future colliders, probing energy scales corresponding to Λ/c_g>1000 TeV, find no evidence of a new scalar resonance with a democratic decay pattern.

The fulfillment of any one of these null results would severely constrain the parameter space, while the conjunction of all three would effectively exclude the simplest realization of the Tempon field as a viable physical theory. This clear falsifiability demarcation elevates the proposal from philosophical speculation to rigorous science.

5.4. Future Outlook: Toward an Emergent Relativity

Furthermore, the Tempon framework suggests a profound conceptual shift—it provides a physical substrate not only for quantum evolution but also for *relativistic* time dilation itself. The universal coupling $\alpha\Phi T$ naturally reproduces gravitational time dilation, as regions of higher energy density modify the local amplitude of the Tempon field. More speculatively, velocity-dependent interactions with the Tempon vacuum could furnish a *mechanistic origin* for Lorentz invariance, whereby relative motion modulates the effective rate of temporal exchange with the field's condensate. In this view, the familiar Lorentz γ-factor may emerge dynamically from field interactions rather than serving as an a priori postulate. If confirmed, this would recast special relativity as a low-energy phenomenology of a deeper field-theoretic symmetry—an enticing direction for future investigation.

6. Conclusion

This work has undertaken a journey from one of physics' most profound conceptual impasses—the Problem of Time—to the formulation of a concrete, testable quantum field theory. We began with the stark incompatibility between the timeless, static picture of the universe dictated by the Wheeler-DeWitt equation in quantum gravity and the dynamic, temporal reality we experience. Existing relational strategies, while insightful, were shown to lack a specific physical mechanism, trapped by the circularity of needing a classical clock to measure a quantum universe.

The Tempon framework resolves this by proposing a fundamental shift: time is not a background stage but an emergent property arising from interaction with a new quantum field, Φ. By establishing the

doi.org/10.32388/O98SG2

mandatory properties of this field—its scalar nature, neutrality, and universal coupling to the stress-energy tensor—we have built a consistent Effective Field Theory that seamlessly integrates with General Relativity while reinterpreting its temporal sector. Crucially, this framework provides the physical pathway to break the "frozen formalism," promoting the Tempon field itself to the role of an internal clock variable. This transforms the static quantum state of the universe into a dynamic one, governed by a Schrödinger-like equation, $i\hbar\frac{\partial}{\partial\Phi}\Psi = \widehat{H}_{\text{phys}}$. In essence, the Tempon field acts as the "projector" that animates the timeless film reel of the cosmos into the movie of evolving reality.

Ultimately, this work moves the ancient question "What is time?" from the realm of metaphysical philosophy into the domain of empirical, experimental physics. It provides a clear, falsifiable roadmap. The predicted signature—a universal, correlated modulation in atomic clock networks with a specific spectral fingerprint—offers a near-term opportunity for discovery. Complementary tests in gravitational-wave polarizations and collider searches provide independent avenues for verification. Whether ultimately confirmed or refuted, the Tempon framwork demonstrates that the nature of time can be subjected to the rigorous scrutiny of experimental science, with the potential for a definitive answer within the coming decade.

References

1. ^Einstein A (1916). *"The Foundation of the General Theory of Relativity." Annalen der Physik [Annals of Physics].* ***354****(7):769–822. doi:10.1002/andp.19163540702.*
2. ^DeWitt BS (1967). *"Quantum Theory of Gravity. I. The Canonical Theory." Phys Rev.* ***160****(5):1113–1148. doi:10.1103/PhysRev.160.1113.*
3. ^Anderson E (2017). *The Problem of Time: Quantum Mechanics Versus General Relativity. Cham, Switzerland: Springer. doi:10.1007/978-3-319-58848-3.*
4. ^Page DN, Wootters WK (1983). *"Evolution Without Evolution: Dynamics Described by Stationary Observables." Phys Rev D.* ***27****(12):2885–2892. doi:10.1103/PhysRevD.27.2885.*
5. ^Rovelli C (1990). *"Quantum Mechanics Without Time: A Model." Phys Rev D.* ***42****(8):2638–2646. doi:10.1103/PhysRevD.42.2638.*
6. ^Caldirola P (1956). *"A New Model of Classical Electron." Nuovo Cim.* ***3****(suppl 2):297–343. doi:10.1007/BF02743686.*

7. ^Englert F, Brout R (1964). "Broken Symmetry and the Mass of Gauge Vector Mesons." Phys Rev Lett. **13**(9):321–323. doi:10.1103/PhysRevLett.13.321.
8. a, b, cWcisło P, Ablewski P, Beloy K, et al. (2018). "New Bounds on Dark Matter Coupling From a Global Network of Optical Atomic Clocks." Sci Adv. **4**(12):eaau4869. doi:10.1126/sciadv.aau4869.
9. ^Abbott BP, Abbott R, Abbott TD, et al. (LIGO Scientific and Virgo Collaborations) (2016). "Tests of General Relativity With GW150914." Phys Rev Lett. **116**:221101. doi:10.1103/PhysRevLett.116.221101.
10. ^Derevianko A, Pospelov M (2014). "Hunting for Topological Dark Matter With Atomic Clocks." Nat Phys. **10**:933–936. doi:10.1038/nphys3137.
11. ^Roberts BM, Blewitt G, Dailey C, Pospelov M (2017). "Search for Domain Wall Dark Matter With Atomic Clocks on Board Global Positioning System Satellites." Nat Commun. **8**:1195. doi:10.1038/s41467-017-01440-4.
12. ^Wcisło P, Ablewski P, Beloy K, et al. (2016). "Experimental Constraint on Dark Matter Detection With Optical Atomic Clocks." Nat Astron. **1**:0009. doi:10.1038/s41550-016-0009.
13. a, bTang Z, Wang B, Chen Y, et al. (SHANHE Collaboration) (2024). "First Scan Search for Dark Photon Dark Matter With a Tunable Superconducting Radio-Frequency Cavity." Phys Rev Lett. **133**:021005. doi:10.1103/PhysRevLett.133.021005.
14. ^Abbott R, Abbott TD, Abraham S, et al. (2021). "Constraints on Cosmic Strings Using Data From the Third Advanced LIGO–Virgo Observing Run." Phys Rev Lett. **126**(24):241102. doi:10.1103/PhysRevLett.126.241102.
15. ^Aaboud M, Aad G, Abbott B, et al. (ATLAS Collaboration) (2017). "Search for New Phenomena in High-Mass Diphoton Final States Using 37 fb^{-1} of Proton–Proton Collisions Collected at $\sqrt{s} = 13$ TeV With the ATLAS Detector." Phys Lett B. **775**:105–125. doi:10.1016/j.physletb.2017.10.039.
16. ^Brans C, Dicke RH (1961). "Mach's Principle and a Relativistic Theory of Gravitation." Phys Rev. **124**(3):925–935. doi:10.1103/PhysRev.124.925.
17. ^Peccei RD, Quinn HR (1977). "CP Conservation in the Presence of Pseudoparticles." Phys Rev Lett. **38**(25):1440–1443. doi:10.1103/PhysRevLett.38.1440.
18. a, bFabbrichesi M, Gabrielli E, Lanfranchi G (2021). The Physics of the Dark Photon: A Primer. Cham, Switzerland: Springer. doi:10.1007/978-3-030-62519-1.
19. ^Yunes N, Pretorius F (2009). "Fundamental Theoretical Bias in Gravitational Wave Astrophysics and the Parametrized Post-Einsteinian Framework." Phys Rev D. **80**(12):122003. doi:10.1103/PhysRevD.80.122003.
20. ^Jaeckel J, Ringwald A (2010). "The Low-Energy Frontier of Particle Physics." Annu Rev Nucl Part Sci. **60**:405–437. doi:10.1146/annurev.nucl.012809.104433.

Declarations

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.