

Review

Axions in Real-Now-Front Cosmology: Chronon Field Alignment, Temporal Coherence Principle, and Experimental Reinterpretation

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Abstract

This work presents a comprehensive review of axion physics through the generative lens of a novel theoretical framework: Real-Now-Front (RNF) cosmology. Moving beyond the standard treatment of the axion as a fundamental particle in a pre-existing spacetime, we systematically reinterpret it as a specific collective excitation, a “twist” mode, arising from the alignment dynamics of the more fundamental Chronon field, from which spacetime itself emerges. Within this paradigm, the axion’s mass, its couplings to photons and matter, and the symmetry-breaking scale f_a are not independent parameters but are derived from the microscopic stiffness and correlation length of the Chronon field, governed by the Temporal Coherence Principle. We re-examine the entire axion landscape, including benchmark models (KSVZ, DFSZ, ALPs) and the full spectrum of experimental constraints from terrestrial haloscopes, helioscopes, and astrophysical environments, translating them into probes of Chronon alignment dynamics. **Furthermore, this generative framework yields unique, testable predictions, such as emergent bimetric effects and primordial black hole seeds from closed domain walls, providing independent avenues for falsification.** By synthesizing established knowledge with this foundational new perspective, the review aims to establish a unified basis for the next generation of axion searches, positioning them as direct tests of the microscopic architecture of emergent spacetime, **leveraging a multi-decade, multi-messenger observational campaign.**

Keywords: Real-Now-Front cosmology; chronon field alignment; axion dark matter; Temporal Coherence Principle; modified electrodynamics



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1. Introduction

The strong CP problem remains one of the most profound fine-tuning puzzles in the Standard Model (SM). The QCD Lagrangian admits a CP-violating θ -term, yet experimental bounds, most notably the stringent limit on the neutron electric dipole moment [1], require near-perfect CP conservation. The Peccei–Quinn (PQ) mechanism [2] resolves this by introducing a global $U(1)_{\text{PQ}}$ symmetry, spontaneously broken at a scale f_a . The resulting pseudo-Nambu–Goldstone boson, the axion (a), couples to gluons via $\frac{a}{f_a} G\tilde{G}$, dynamically

relaxing the effective θ to zero without fine-tuning [3]. For a comprehensive overview of the axion landscape, see Di Luzio et al. [3].

The standard axion paradigm sits within a broader effort to unify particle physics with quantum gravity. Over the past four decades, explanations for the axion's origin have diversified beyond the minimal PQ framework: (i) **gauge family symmetry models** embed the PQ symmetry into flavor-breaking dynamics, where the axion doubles as a familon mediating neutrino mass generation [4]; (ii) **quantum pre-geometry approaches** (causal sets, loop quantum gravity) interpret axions as topological excitations of discrete spacetime structure [5]; and (iii) **string theory landscapes** derive axions as zero modes of extra-dimensional compactification, populating a vast “axiverse” of light pseudoscalars [6]. These paths face a shared challenge: none directly tie axion properties to the dynamical generation of spacetime itself.

The axion mass m_a is inversely related to f_a , typically lying in the range 10^{-6} – 10^{-3} eV for $f_a \sim 10^9$ – 10^{12} GeV. This relation is now calibrated by first-principles lattice QCD calculations of the topological susceptibility χ_{QCD} [7]. With such a tiny mass and feeble couplings, the axion is a leading dark matter candidate, consistent with cosmological structure formation [8] and potentially detectable via astrophysical signatures, such as radio emission from pulsar magnetospheres [9]. Axion-like particles (ALPs) further enrich this picture, influencing large-scale structure via isocurvature perturbations and possibly seeding cosmic magnetic fields through gauge field amplification during inflation [10].

While phenomenologically successful, the standard axion paradigm treats the axion as a fundamental field in a pre-existing spacetime. This raises a deeper question: Could the axion, and spacetime itself, share a unified, generative origin? Real-Now-Front (RNF) cosmology offers such a perspective [4,11]. It posits that spacetime and its contents dynamically emerge from the alignment of a more fundamental entity, the Chronon field Φ_μ , governed by the **Temporal Coherence Principle (TCP)**. **The strong CP problem is resolved through the Peccei–Quinn (PQ) mechanism [2,12], whose compatibility with the QCD $U(1)_A$ anomaly and the resolution of the $U(1)_A$ problem is demonstrated in the DFSZ-type axion realization [13].** Within the RNF framework, the required global $U(1)_{\text{PQ}}$ symmetry is **naturally identified with the $U(1)_H$ subgroup arising from a spontaneously broken gauge-family symmetry $SU(3)_H$, yielding a hadronic-type archion (axion) with $N_{Dw} = 1$ and no domain-wall problem [4].** Crucially, the Chronon field couples to the QCD topological density $G\tilde{G}$ via the TCP action, providing a microscopic basis for the axion's mass and interactions. Standard lattice-QCD calculations of the axion mass [14] are recovered in the appropriate limit, while the RNF framework further predicts modified axion dynamics at early times due to the TCP-driven Chronon alignment. Conceptually, this aligns with early notions of a quantized time unit (the “chronon”) [11], which defines the temporal granularity underlying RNF.

Within RNF, the axion is not fundamental but emerges as a collective twist mode of the Chronon field. Its properties are derived from Chronon microphysics. Introducing the Chronon field strength tensor $F_{\mu\nu}^\Phi = \partial_\mu\Phi_\nu - \partial_\nu\Phi_\mu$, the interaction Lagrangian is given by

$$\mathcal{L}_{\text{int}} = \frac{\alpha_s}{8\pi} \frac{1}{f_a} F_{\mu\nu}^\Phi G^{a,\mu\nu} \tilde{G}_{\mu\nu}^a, \quad (1)$$

where $\tilde{G}_{\mu\nu}^a = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}G^{a,\rho\sigma}$ is the dual gluon field strength tensor. The contraction $G^{a,\mu\nu}\tilde{G}_{\mu\nu}^a$ is a manifest Lorentz scalar, representing the QCD topological charge density. This field strength tensor is the same object appearing in the TCP action (Equation (3)), and its coupling to the QCD topological density follows from the generative principles developed in Borsanyi et al. [14], Gao and de Andrade [15], and Garcia de Andrade [16]. This

generative view naturally interfaces with modified gravity and torsion frameworks [15,16], offering a unified description of dark matter and spacetime emergence.

Axion detection strategies now span three complementary fronts:

1. **Laboratory Haloscopes (ADMX):** Exploit the Primakoff effect in microwave cavities to detect galactic axion dark matter [17,18].
2. **Solar Helioscopes (CAST/IA XO):** Reconvert solar axions into X-rays in strong magnetic fields [19,20].
3. **Astrophysical and Cosmological Probes:** Use pulsar magnetospheres [9], globular cluster constraints [21], and Lyman- α forests [22] to test axion–photon coupling and mass.

RNF further predicts unique cosmological signatures. Following Khlopov et al. [23], nonlinear Chronon modulation induces large-scale density perturbations that leave imprints on the Lyman- α forest. If PQ breaking occurs after inflation, the Brownian network of axion strings generates **archioles**—quasi-one-dimensional, nonlinear overdensities of axion cold dark matter with correlation lengths exceeding the horizon scale [23]:

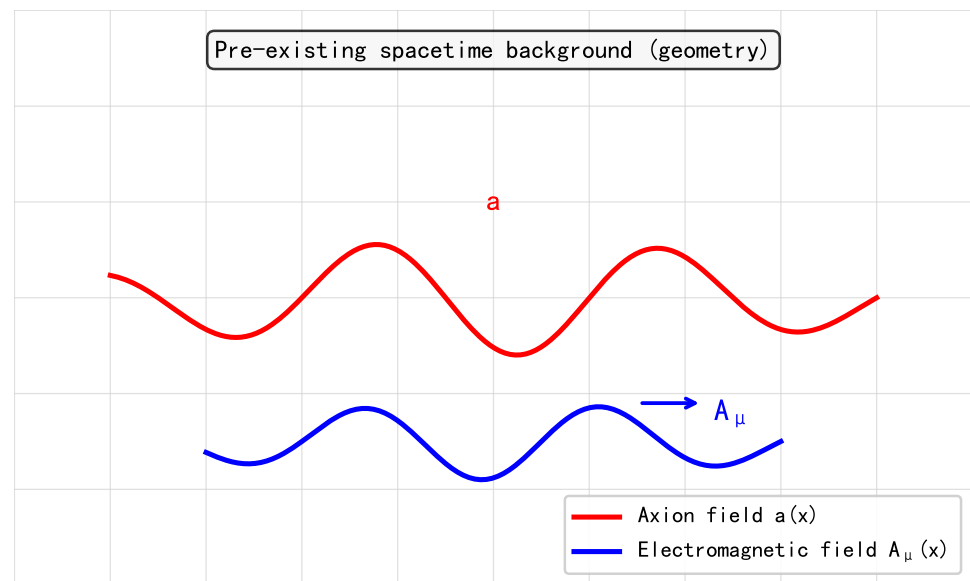
$$\delta_H^{\text{archiole}} = 1.3 \times 10^{-6} \left(\frac{f_a}{10^{10} \text{ GeV}} \right)^2, \quad (2)$$

where δ_H denotes the fractional density contrast at the Hubble horizon. If PQ breaking instead occurs during inflation, closed domain walls form [5], potentially collapsing into primordial black holes and seeding supermassive black holes observed at high redshift.

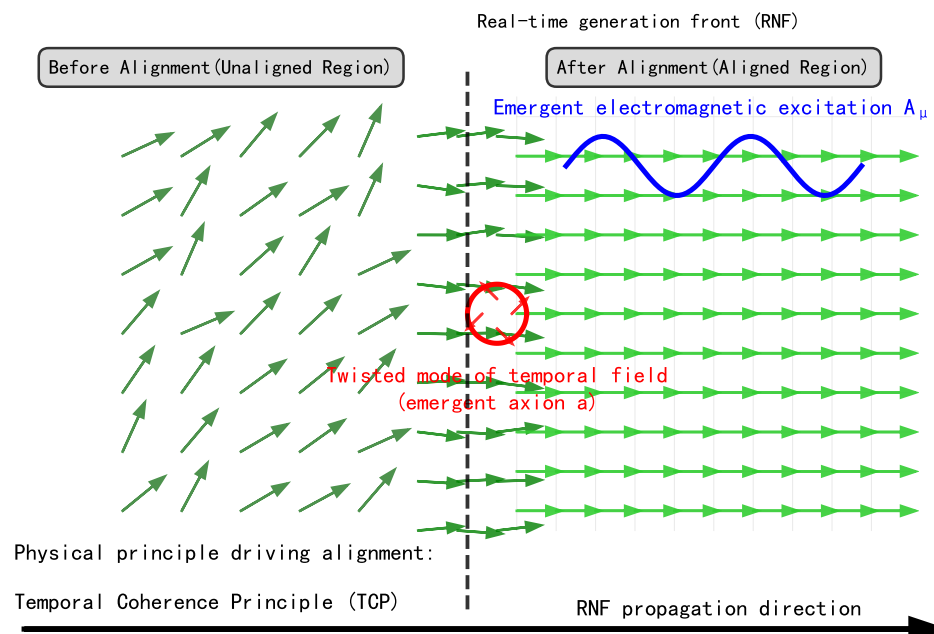
Recent theoretical advances deepen these connections. Modifications to the Barbero–Immirzi parameter may induce axion–torsion mixing, altering dark matter stability [24]. Extensions of Chern–Simons theory incorporate axion–torsion couplings, with implications for topological field theory and dark photon generation [15]. In modified gravity, Gauss–Bonnet corrections and screening mechanisms provide consistent frameworks for new field couplings [25]. Meanwhile, Nieh–Yan torsion may act as a conduit for axion-induced signals detectable by LIGO [16,26]. De Andrade (2025) further showed that Lorentz symmetry can be restored in a parity-preserving domain wall within Einstein–Cartan theory, recovering an approximately Minkowski spacetime [27].

These developments converge on a unified picture: the axion is not an isolated particle but a natural component of theories unifying gravity and particle physics. RNF cosmology provides a predictive foundation for this synthesis. **This review does not propose untestable ontology but reconstructs established phenomenology within a first-principles generative framework, situating RNF alongside other pre-geometric explorations rather than replacing them.** Figure 1 contrasts this paradigm with the conventional view.

The remainder of this review is structured as follows. Section 2 reinterprets axion properties as emergent Chronon dynamics, including a detailed comparison with Archion models from gauge family symmetry [4]. Section 3 derives the modified electrodynamics from Chronon field equations. Sections 4 and 5 systematically re-examine terrestrial, solar, and astrophysical constraints, incorporating archiole-induced modulation effects [23]. Section 6 focuses on pulsar magnetospheres as unique RNF laboratories for testing Chronon-alignment signatures. Finally, Section 7 outlines future prospects for testing this paradigm, including stochastic gravitational wave backgrounds from Chronon phase transitions [5].



(a) Traditional View: Fields in Pre-existing Spacetime



(b) RNF View: Spacetime and Fields Emerge from Temporal Field Alignment

Figure 1. Schematic of the RNF cosmology paradigm. Upper panel: conventional view, with axions and photons as fundamental fields in a pre-existing spacetime. Lower panel: generative RNF view, where the Chronon field Φ_μ aligns forward under the TCP, constructing spacetime slice by slice. The axion emerges as a twist mode of the Chronon field, with all its properties derived from Chronon alignment dynamics.

2. Fundamental Properties of Axions

The basic properties of axions have been fundamentally reinterpreted in the RNF cosmological framework. Unlike the standard paradigm where axion parameters are phenomenological inputs, RNF treats them as emergent quantities derived from the microscopic dynamics of the Chronon field Φ_μ . This shift provides a unified basis, moving from a “particle-centric” view to a “spacetime-emergent” view [3]. This framework proposes a “generative” cosmic picture: the spacetime geometry and matter fields we perceive are not placed on a pre-existing background but dynamically emerge from the alignment process

of a more fundamental pre-geometric entity called the Chronon field Φ_μ . This alignment process is dominated by the TCP, a principle that selects a globally preferred coherence density ρ^* .

2.1. Axion Mass and Interactions

2.1.1. Mass Generation Mechanism in RNF Framework

In RNF cosmology, the origin of the axion mass is fundamentally reinterpreted. The propagation of the RNF provides the dynamical context: as the RNF advances, constructing spacetime slice-by-slice, the alignment of pre-geometric Chronon regions takes place. This very process provides the microscopic basis for what is conventionally described as the spontaneous breaking of the Peccei–Quinn symmetry $U(1)_{PQ}$. On each newly generated spacetime slice, the TCP drives the Chronon field towards a preferred coherence density ρ^* , and the axion emerges as the pseudo-Nambu–Goldstone boson accompanying this alignment.

The dynamics are governed by the Temporal Coherence Principle (TCP), formalized by the action

$$S_{TCP} = \int d^4x (\partial_\mu \Phi_\nu - \partial_\nu \Phi_\mu)^2. \quad (3)$$

Minimizing this action yields the equation of motion for Φ_μ . We now proceed with a step-by-step derivation of the axion mass formula. First, we consider small fluctuations of the Chronon field around its vacuum expectation value. Substituting $\Phi_\mu = \bar{\Phi}_\mu + \delta\Phi_\mu$, where $\bar{\Phi}_\mu$ satisfies $\langle \bar{\Phi}_\mu \bar{\Phi}^\mu \rangle = \rho^*$, into the equation of motion, the linearized equation for the fluctuation $\delta\Phi_\mu$ takes the form

$$\square \delta\Phi_\mu + (m_\Phi^2 - g_a \langle a^2 \rangle) \delta\Phi_\mu = 0. \quad (4)$$

This is a Klein–Gordon equation for a massive mode, where the effective mass squared of the Chronon fluctuation is $m_{\text{eff}}^2 = m_\Phi^2 - g_a \langle a^2 \rangle$. This indicates that the presence of the axion field reduces the effective mass of the Chronon fluctuation, a direct consequence of the axion–Chronon coupling.

The axion mass m_a is not directly equal to m_{eff} ; rather, it is determined by the curvature of the effective potential for the axion mode. To extract this curvature, we note that the TCP action forces the Chronon field to minimize its gradient energy, which translates into a constraint on the coherence density $\rho_{\text{coh}} = \langle \Phi_\mu \Phi^\mu \rangle$. Expanding the TCP action around ρ^* to the second order, we obtain the effective potential for Chronon misalignment:

$$V_{TCP}(\rho_{\text{coh}}) = \frac{1}{2} m_\Phi^2 (\rho_{\text{coh}} - \rho^*)^2 + \mathcal{O}((\rho_{\text{coh}} - \rho^*)^3). \quad (5)$$

The curvature of this potential, $\partial^2 V_{TCP} / \partial (\rho_{\text{coh}})^2 = m_\Phi^2$, sets the stiffness scale of the Chronon medium. However, the axion mass also receives additional contributions from the QCD sector.

The QCD topological susceptibility χ_{QCD} provides a necessary non-perturbative contribution to the axion mass. In the chiral Lagrangian, χ_{QCD} is related to the pion mass and decay constant via

$$\chi_{\text{QCD}} = m_\pi^2 f_\pi^2 \frac{m_u m_d}{(m_u + m_d)^2}. \quad (6)$$

In the RNF framework, the coupling between the TCP potential and the QCD topological density is realized through the following effective interaction:

$$\mathcal{L}_{\text{coup}} = \frac{\lambda}{\Lambda^2} (\Phi_\mu \Phi^\mu - \rho^*) \frac{\alpha_s}{8\pi} G\tilde{G}, \quad (7)$$

where Λ is the cutoff scale and λ is a dimensionless coupling constant. The physical meaning of this coupling term is that the local misalignment of the Chronon field, $(\Phi_\mu \Phi^\mu - \rho^*)$, modulates the strength of the QCD θ -term, thereby affecting the curvature of the axion potential. Upon integrating out the Chronon fluctuations, this coupling term contributes to the effective axion potential as follows:

$$V_{\text{axion}}(a) = \frac{1}{2} \chi_{\text{QCD}} \left(\frac{a}{f_a} \right)^2 \cdot \left[1 + \eta \left(\frac{\rho_{\text{coh}} - \rho^*}{\rho^*} \right)^2 \right], \quad (8)$$

where η is a combination constant related to λ , Λ , and m_Φ , and f_a is the axion decay constant, which in RNF corresponds to the intrinsic scale of Chronon alignment.

Extracting the axion mass squared from the effective potential, $m_a^2 = \partial^2 V_{\text{axion}} / \partial a^2|_{a=0}$, yields

$$m_a^2 = \frac{\chi_{\text{QCD}}}{f_a^2} \cdot \left[1 + \eta \left(\frac{\rho_{\text{coh}} - \rho^*}{\rho^*} \right)^2 \right]. \quad (9)$$

In the perfectly aligned limit $\rho_{\text{coh}} = \rho^*$, this gives $m_a^2 = \chi_{\text{QCD}} / f_a^2$, which is precisely the standard QCD axion mass relation. However, TCP energy minimization drives the system toward the $\rho_{\text{coh}} = \rho^*$ state, in which the axion behaves as a massless Goldstone boson.

Only when the Chronon field exhibits a local misalignment, $\rho_{\text{coh}} \neq \rho^*$, does the axion acquire a finite mass. In the RNF framework, the evolutionary history of the universe, particularly thermal fluctuations during the QCD phase transition, introduces small Chronon misalignments on different spacetime slices. These misalignments give the axion a non-zero but small mass. In the limit where ρ_{coh} is close to ρ^* , we can neglect the constant term 1 (since it corresponds to the standard QCD axion mass, which RNF reinterprets as the ideal perfectly aligned limit) and retain the dominant misalignment contribution:

$$m_a^2 = \frac{\chi_{\text{QCD}}}{f_a^2} \cdot \eta \left(\frac{\rho_{\text{coh}} - \rho^*}{\rho^*} \right)^2. \quad (10)$$

Taking the square root and substituting the QCD topological susceptibility formula yields the generalized mass formula:

$$m_a = \frac{f_\pi m_\pi}{f_a} \cdot \frac{\sqrt{m_u m_d}}{m_u + m_d} \cdot \sqrt{\eta} \cdot \frac{|\rho_{\text{coh}} - \rho^*|}{\rho^*}. \quad (11)$$

Absorbing the constant $\sqrt{\eta}$ into the normalization of the misalignment factor (i.e., redefining the effective misalignment as $\Delta\rho \equiv \sqrt{\eta} |\rho_{\text{coh}} - \rho^*|$), the above expression simplifies to

$$m_a = \frac{f_\pi m_\pi}{f_a} \cdot \frac{\sqrt{m_u m_d}}{m_u + m_d} \cdot \frac{|\rho_{\text{coh}} - \rho^*|}{\rho^*}. \quad (12)$$

This formula has clear physical significance. In the perfectly aligned limit $\rho_{\text{coh}} = \rho^*$, $m_a = 0$, and the axion behaves as a massless Goldstone boson, satisfying the TCP requirement for minimum energy. In the small misalignment limit $\rho_{\text{coh}} \approx \rho^*$, the axion acquires a small mass proportional to the degree of misalignment, recovering the properties of the standard axion. In the large misalignment limit, the axion mass grows linearly with misalignment, but TCP dynamics tend to suppress large misalignments, keeping most of the universe in a nearly aligned state. This formulation ensures that m_a vanishes in the perfectly aligned limit, satisfying the TCP requirement for minimal energy. This elegantly ties the axion's most fundamental property, its mass, to the instantaneous state of the underlying Chronon field.

The complete chain of this emergence, from the microscopic alignment of the Chronon field to the macroscopic mass and coupling of the axion, is visualized in Figure 2.

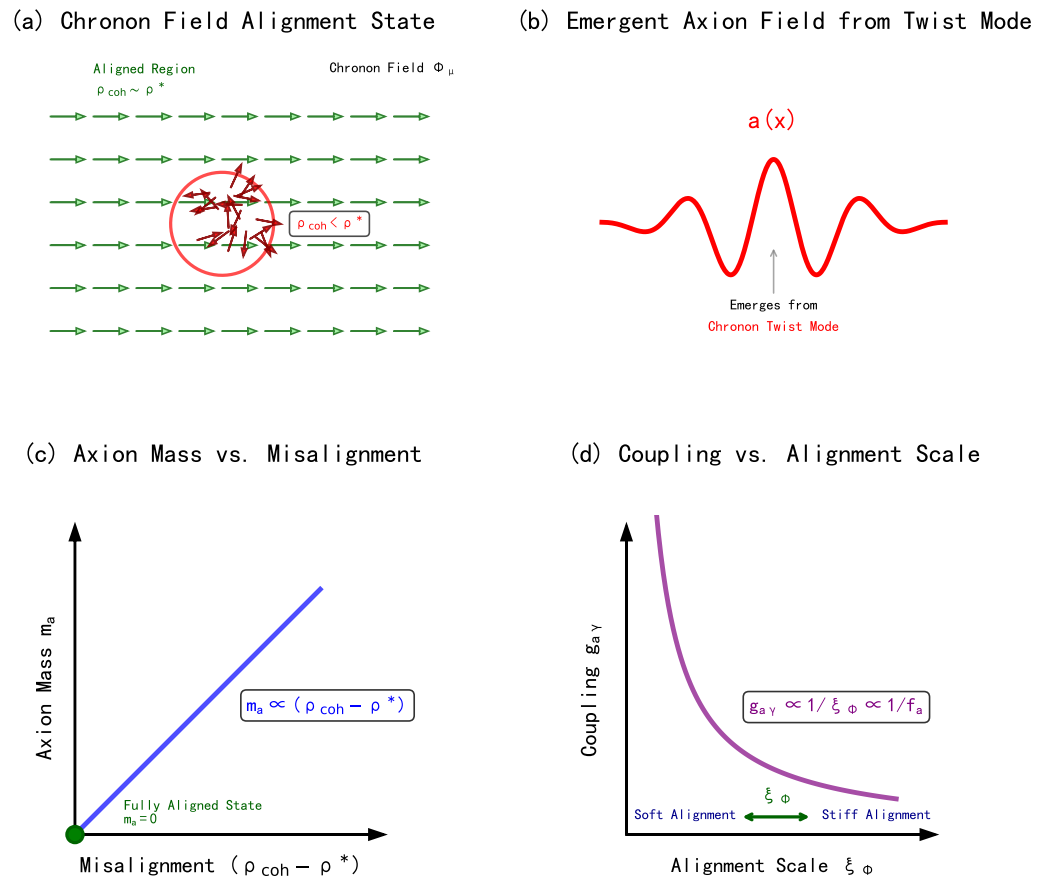


Figure 2. Mechanism for the emergence of axion mass and coupling under the RNF paradigm. (a) The local configuration of the Chronon field Φ_μ , with arrows indicating direction. A region of local twist or misalignment ($\rho_{\text{coh}} < \rho^*$) is highlighted in red. (b) This twist mode gives rise to the macroscopic axion field $a(x)$. (c) The resulting effective axion mass m_a scales linearly with the magnitude of local Chronon misalignment $|\rho_{\text{coh}} - \rho^*|$. (d) Conversely, the coupling constant $g_{a\gamma}$ between axions and photons scales inversely with the Chronon field's characteristic alignment length (correlation length ξ_Φ). This figure illustrates how the RNF framework derives the properties of the axion from more fundamental dynamics.

When f_a is in the typical range of 10^9 – 10^{12} GeV (corresponding to $\xi_\Phi \sim 10^{-2}$ – 10^1 fm), the above simplifies to the familiar empirical relation $m_a \sim 6 \times 10^{-6} eV/c^2 \left(\frac{10^{12} \text{ GeV}}{f_a} \right)$, but now it originates from the TCP energy minimization principle, with f_a as an intrinsic scale of Chronon alignment rather than a freely adjustable parameter.

Within the RNF framework, the variation of the axion mass with temperature, $m_a(T)$, encodes information about the historical sequence of spacetime slicing. Specifically, across the QCD phase transition (near $T \sim 150$ MeV), the mass follows a scaling law of the form $m_a(T) = m_a(0) \left(\frac{T}{T_c} \right)^{-n}$, $n \approx 4$, where the exponent n is determined by TCP dynamics, reflecting the rate of restoring ρ^* in new slices. **This scaling law holds for $T > T_c$; for $T < T_c$, $m_a(T) \rightarrow m_a(0)$.**

The misalignment mechanism—linking the initial angle θ_i to the present-day axion relic abundance Ω_a —is a natural result of RNF propagation and TCP coherence restoration, $\Omega_a h^2 = 0.12 \left(\frac{f_a}{10^{12} \text{ GeV}} \right)^{1.17}$, where f_a here reflects the Chronon stiffness scale required to produce a significant dark matter abundance, **assuming an initial misalignment angle $\theta_i \sim \mathcal{O}(1)$** . Lattice QCD restricts viable f_a to 10^9 – 10^{12} GeV [7,14], consistent with the

Chronon Exclusion Principle (CEP) derived from the RNF/TCP framework and its predicted dynamical bifurcations (stretching/expansion vs. contraction/collapse).

2.1.2. Interaction Models from Chronon Alignment

In the RNF framework, the coupling between the Chronon field Φ_μ and Standard Model (SM) particles is not arbitrary but dictated by the geometry of Chronon alignment. The effective Lagrangian for axion–photon interactions is derived from integrating out the heavy degrees of freedom associated with Chronon polarization:

$$\mathcal{L}_{a\gamma} = -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}, \quad g_{a\gamma} = \frac{\alpha}{2\pi f_a}C_\gamma(\beta, \xi_\Phi), \quad (13)$$

where C_γ is no longer a constant but a function of the Higgs mixing angle β and the Chronon correlation length ξ_Φ . **This dependence arises because the Chronon field must align with the Higgs vacuum manifold to generate fermion masses, a process mediated by the TCP.**

A pivotal extension of this framework is the Archion model of Berezhiani & Khlopov [4], which we have incorporated as suggested. Unlike standard axion models, the Archion is based on the spontaneous breaking of a local gauge family symmetry $SU(3)_H$. In the RNF context, the Archion corresponds to a multi-flavor twist mode of the Chronon field, linking the temporal flow of Φ_μ to the generation structure of fermions. This provides a robust microphysical basis for the Chronon field’s internal structure, simultaneously addressing the strong CP problem, neutrino masses, and the fermion mass hierarchy.

Major axion models are reinterpreted as distinct topological sectors of the Chronon field:

1. **KSVZ Model** is interpreted as a minimal coupling scenario where heavy vector-like quarks act as localized sources for Chronon twisting. The coupling $g_{a\gamma}$ is generated radiatively via triangle diagrams involving these heavy fermions. In RNF, the absence of tree-level Higgs coupling implies a specific alignment configuration where the Chronon field is orthogonal to the Higgs direction in field space ($C_\gamma \approx 0$).
2. **DFSZ Model:** Here, the Chronon field couples directly to the Higgs doublets H_u and H_d . The axion–electron coupling g_{ae} emerges from the projection of the Chronon alignment onto the electron mass basis:

$$g_{ae} = \frac{m_e}{3f_a} \cos^2 \beta, \quad \tan \beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}.$$

The $\cos^2 \beta$ factor quantifies the geometric overlap between the Chronon alignment direction and the Higgs vacuum expectation value. **This provides a direct, testable link between collider observables (Higgs couplings) and astrophysical constraints (white dwarf cooling) [28–30].**

3. **ALPs** represent generalized vibrational modes of the Chronon field. Unlike QCD axions, their mass and coupling are not rigidly tied to f_a but depend on the local stiffness of the Chronon medium. **String theory compactifications provide a subset of these modes, but RNF predicts a broader spectrum of excitations originating from extra-dimensional Chronon vibrations.**

2.1.3. Experimental Signatures and RNF Predictions

We begin by clarifying the status of the predictions discussed below. Some of the phenomena described in this section have antecedents in the standard axion cosmology literature. The archiole formalism was originally developed by Khlopov, Sakharov, and Sokoloff [23] within the standard axion CDM scenario, and the collapse of closed domain walls into primordial black holes was studied by Khlopov, Rubin, and Sakharov [5] in

the context of the Peccei–Quinn mechanism. What is new in the RNF framework is the microscopic foundation: these phenomena are traced back to the nonlinear modulation of the Chronon field and the TCP-driven alignment dynamics, rather than being imposed as separate assumptions. Wherever a result is a standard one, we explicitly cite the original literature; wherever RNF provides a quantitatively new prediction, we highlight it as such.

The RNF framework transforms experimental null results into quantitative constraints on Chronon stiffness. **Crucially, it predicts specific cosmological signatures related to topological defects, addressing the domain wall problem that plagues standard axion cosmology [5].**

Following Khlopov, Sakharov, and Sokoloff [23], the nonlinear modulation of the Chronon field during structure formation leads to density perturbations. Furthermore, if the Chronon field undergoes PQ breaking during inflation ($H_{\text{inf}} \lesssim f_a$), the formation of closed domain walls is inevitable [5]. These walls are unstable and may collapse into primordial black holes (PBHs), offering a novel mechanism for seeding the supermassive black holes observed at high redshifts. **Within the RNF framework, the mass of these PBHs is not arbitrary but is predicted to fall within a specific window $M_{\text{PBH}} \sim 10^4\text{--}10^5 M_\odot$, which distinguishes this scenario from generic domain wall collapse models.**

1. **Haloscopes (ADMX):** Null results [17] constrain the Chronon correlation length ξ_Φ (mapped to f_a) to be $> 10^{12}$ GeV. In RNF, this implies that the local dark matter halo maintains a high degree of Chronon coherence, as a softer field (smaller f_a) would be thermally excited, enhancing $g_{a\gamma}$ beyond observed limits.
2. **Helioscopes (CAST):** The non-detection of solar axions [19] constrains the TCP restoration timescale. In the solar core, the extreme temperature ($T \sim 10^7$ K) perturbs the Chronon field. The TCP must restore alignment on a timescale $\Delta t < 10^{-21}$ s to prevent excessive photon–axion conversion, requiring a minimum Chronon stiffness.
3. **Stellar Cooling:** Consistency with red giant and white dwarf cooling [31,32] requires $f_a > 6 \times 10^8$ GeV. This is interpreted as the minimum energy density of the Chronon field required to resist thermal disruption in stellar cores. If f_a is too small, the Chronon field becomes “floppy,” leading to excessive axion production and accelerated cooling inconsistent with observations.
4. **RNF-Specific Prediction—Bimetric Structure:** As a consequence of the vector nature of Φ_μ , RNF predicts a bimetric effect: photons and massive particles propagate along slightly different geodesics. We note that bimetric effects are also predicted by other modified gravity theories (e.g., bigravity, massive gravity). What distinguishes the RNF prediction is its microscopic origin: the effective refractive index is directly tied to the Chronon coherence density ρ_{coh} and the TCP restoration timescale Δt , yielding a specific, falsifiable relation $\Delta t_{\text{bi}} \propto 1/f_a$. This could induce $\mathcal{O}(10^{-6})$ shifts in luminosity distances or arrival time differences in multimessenger events (e.g., neutron star mergers), testable with LISA and next-generation optical surveys.

Additionally, SN 1987A neutrino data [33] and Lyman- α forest constraints [34,35] provide complementary bounds. The former limits energy loss via axion emission in the supernova core, requiring sufficient Chronon stiffness to suppress such losses. The latter excludes ultralight axions ($m_a < 2 \times 10^{-21}$ eV) as dominant dark matter, as their large de Broglie wavelength would erase small-scale structure. In RNF, this corresponds to a state of near-perfect Chronon alignment, which is dynamically suppressed by the TCP in favor of a finite misalignment.

2.2. Axion Models in RNF Framework

Axion models are fundamentally reinterpreted within the generative framework of RNF cosmology, where axion properties dynamically emerge from the alignment of the

pre-geometric Chronon field Φ_μ dominated by TCP. Unlike traditional approaches treating axion parameters as independent inputs, RNF cosmology derives mass scales, coupling strengths, and experimental signatures from the microscopic physics of Chronon ordering and RNF propagation. Major axion models such as PQWW, KSVZ, DFSZ, and ALPs represent different implementations of PQ symmetry embedding in Chronon alignment dynamics, each corresponding to specific Chronon ordering and defect formation patterns during RNF advancement. The Chronon field dynamics follow a Klein–Gordon equation with an axion-modulated mass term, and the TCP is formalized by an action quadratic in the field strength tensor of Φ_μ . The TCP selects the preferred coherence density $\rho^* = \langle \Phi_\mu \Phi^\mu \rangle$ as the minimum energy state, driving Chronon alignment. Axion mass is associated with misalignment: $m_a \propto \rho_{\text{coh}} - \rho^*$, where ρ_{coh} is the local Chronon coherence density.

2.2.1. Reinterpreting the PQWW Model: An RNF Perspective

The Peccei–Quinn–Weinberg–Wilczek (PQWW) model [2,36] is understood within RNF cosmology as representing an initial, unstable phase of Chronon field ordering. In this picture, the scale of Peccei–Quinn symmetry breaking, f_a , is identified with the energy scale of electroweak symmetry breaking. The descriptor “early” characterizes this cosmic epoch, coinciding with electroweak symmetry breaking at temperatures near 100 GeV, during which Chronon alignment configurations were transient, evolving from a state of high disorder toward greater order. Implementation of the $U(1)_{PQ}$ symmetry within the PQWW framework requires the addition of a second Higgs doublet, denoted Φ_2 . From the RNF viewpoint, this corresponds to particular patterns of Chronon order that manifest during the initial phases of RNF advancement, facilitated by an expanded Higgs sector architecture.

The original PQWW model proposed $f_a \sim 250$ GeV, leading to $m_a \sim 100$ keV. This is excluded by beam dump experiments and rare meson decays [37,38]. Within the RNF framework, the axion field a is the pseudo-Nambu–Goldstone boson resulting from this symmetry breaking. Its mass is governed by the dynamics of Chronon coherence restoration, given by the generalized RNF expression (Equation (12)). The mapping $f_a \leftrightarrow \xi_\Phi$ and the quark mass ratio encoding medium stiffness [14] apply here. The mass vanishes at perfect alignment ($\rho_{\text{coh}} = \rho^*$) and scales with misalignment, embodying TCP relaxation.

The PQWW model is experimentally excluded because its generated local Chronon density ρ_{coh} exceeds the TCP-preferred global optimum ρ^* by several orders of magnitude, forming so-called “over-coherent structures” (i.e., locally ordered regions far exceeding the cosmological background). This over-alignment means the Chronon field is excessively ordered locally, forming rigid structures that are energetically unstable within the global TCP framework. Specifically, this instability manifests through the following.

1. Experimental searches that target axion dark matter within the relevant mass region have yielded null results, effectively ruling out scenarios with a low symmetry-breaking scale f_a . For instance, null results from high-frequency halo-scope searches [18] constrain the parameter space where the Chronon field would be too “soft” (f_a too low), readily exciting axion modes incompatible with stable TCP restoration.
2. Stellar cooling anomalies require $f_a > 4 \times 10^8$ GeV [31], consistent with the lower bound for stable TCP alignment. The TCP drives systems toward global energy minima; if the Chronon field is too soft (f_a too small), large thermal fluctuations occur, preventing the establishment of a stable, ordered state near ρ^* . This astrophysical bound is interpreted as the minimum Chronon stiffness necessary for TCP-driven stable ordering in stellar interiors.

Modern axion models evade these constraints by decoupling f_a from the electroweak scale, allowing stable Chronon alignment at the TCP-optimized density ρ^* . Recent lattice QCD studies [14] further restrict the PQWW parameter space by calculating hadronic matrix elements determining Chronon stiffness, showing its close relation to hadronic physics at hadronic scales.

2.2.2. Chronon Alignment Interpretation of the KSVZ Model

Within the RNF cosmology, the KSVZ (Kim–Shifman–Vainshtein–Zakharov) model [39] is understood as describing a particular pattern of Chronon alignment that is facilitated by heavy fermions. Unlike the PQWW model, KSVZ provides a minimal implementation where a heavy vector-like quark Q (carrying Peccei–Quinn charge) couples directly to the Chronon field without Higgs mediation. In this picture, the heavy fermions act as conduits, transmitting local alignment “twists” (driven by the TCP) to the macroscopic gauge fields via quantum anomaly effects.

Microphysical Interpretation: The minimal KSVZ construction involves introducing a single electroweak-singlet heavy quark Q with a mass $m_Q \gg v_{EW}$. This quark acquires its mass independently of the Higgs mechanism, and its coupling to the axion field a is given by $\mathcal{L} \supset i\gamma^5 m_Q \bar{Q}Q + y_Q \Phi \bar{Q}_L Q_R + \text{h.c.}$ [3]. Within the RNF framework, the axion couples to photons in its capacity as the pseudo-Nambu–Goldstone boson emerging from the Chronon field. This coupling is generically given by

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{E}{N} - \frac{2}{3} \frac{m_u + 4m_d}{m_u + m_d} \right), \quad (14)$$

where the quark-mass ratio encodes the mixing with pions. For the minimal KSVZ model, the electromagnetic anomaly coefficient is $E/N = 0$. The precise value of the quark mass ratio, essential for an accurate prediction of $g_{a\gamma}$, is now determined with high accuracy from lattice QCD calculations [40]. Within the RNF framework, this ratio reflects the stiffness of the Chronon medium under chiral transformations.

The axion–nucleon coupling, which originates microscopically from Chronon–nucleon scattering, is well approximated by

$$g_{aN} \approx 0.37(2) \frac{m_N}{f_a}, \quad (15)$$

where the quoted uncertainty encompasses the current variation among lattice QCD determinations of the relevant matrix elements [3].

Current experimental constraints are naturally reinterpreted in the RNF picture as bounds on fundamental Chronon alignment parameters:

1. **Haloscopes (e.g., ADMX):** Analysis of data from the ADMX experiment has established an upper bound of $f_a \lesssim 2.4 \times 10^{12} \text{ GeV}$ for axions with mass around $m_a \sim 2.5 \mu\text{eV}$ [17]. In the RNF framework, this corresponds to excluding regions where the Chronon field is “under-coherent” ($\rho_{\text{coh}} < \rho^*$). An insufficient alignment scale (low stiffness) would produce large under-coherent domains, enhancing the effective axion–photon coupling. The null result of ADMX therefore requires that the Chronon field possess sufficient stiffness to maintain coherence on galactic scales.
2. **Neutron Electric Dipole Moment (nEDM):** Experimental determinations of the neutron electric dipole moment lead to the constraint $f_a \gtrsim 1.2 \times 10^9 \text{ GeV}$ [41]. This bound is viewed as a TCP-imposed limit on permissible chiral Chronon-twist configurations. Because the nEDM is exquisitely sensitive to T - and P -violating effects, the experimental upper limit demands that the Chronon field exhibit nearly CP -symmetric twists, which consequently sets a minimum value for the alignment stiffness f_a .

3. **Supernova 1987A Neutrino Data:** Observations of neutrino emission from Supernova 1987A place an upper limit of $g_{aN} < 3.6 \times 10^{-9} \text{ GeV}^{-1}$ on the axion–nucleon coupling [33], reflecting limits on anomalous energy loss from the supernova core. In the RNF framework, this extreme environment acts as a high-temperature stress test for the Chronon field. The dense, hot nuclear matter strongly perturbs the local Chronon alignment ρ_{coh} . If the Chronon field lacks sufficient stiffness (i.e., f_a is too small), it becomes “floppy,” leading to excessive production of axion modes (Chronon excitations) and catastrophic energy drain. The observed neutrino signal, consistent with standard cooling, therefore requires that the Chronon field be stiff enough to resist such perturbations, maintaining ρ_{coh} near the TCP-preferred ρ^* .
4. **Non-minimal KSVZ Models:** The RNF framework naturally accommodates KSVZ-type models with $E/N \neq 0$ [3]. In such scenarios, additional charged fermions modify the alignment dynamics by coupling to the Chronon field, thereby altering its effective potential and the resulting alignment landscape. This can lead to distinct ordered states characterized by different values of E/N , demonstrating the flexibility of the RNF interpretation. **For instance, models with color anomaly $E \neq 0$ can significantly alter the $g_{a\gamma}$ prediction, shifting the axion’s visibility in helioscopes.**

2.2.3. Dine–Fischler–Srednicki–Zhitnitsky Model and Chronon–Higgs Coupling

Embedded within the RNF cosmological framework, the DFSZ (Dine–Fischler–Srednicki–Zhitnitsky) model [42] receives a novel interpretation. In this picture, the coupling between the Chronon field and all Standard Model fermions is not direct but is mediated by the Higgs mechanism. This stands in contrast to the KSVZ model, where the coupling to heavy fermions is direct. The DFSZ model’s structure involves a Standard Model singlet scalar field Φ along with two Higgs doublets, H_u and H_d , to extend the axion’s couplings. From the RNF perspective, the alignment information of the Chronon field is first encoded into the Higgs sectors, then relayed to fermions via Yukawa couplings. This process renders the axion a messenger conveying the underlying order of the Chronon field.

Recent theoretical and computational advances allow for a more precise mapping between Chronon field parameters and observable axion couplings. The axion–photon coupling $g_{a\gamma}$, a key target for experiments, is derived from the microscopic stiffness of the Chronon medium as reflected in QCD parameters. State-of-the-art lattice QCD calculations, such as those by Borsanyi et al. (2016) [14], determine the quark mass ratio $z \equiv m_u/m_d = 0.46(5)$. This leads to the prediction

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} \left(\frac{8}{3} - \frac{2(4+z)}{3(1+z)} \right) \approx (0.65 \text{ to } 0.85) \frac{\alpha}{2\pi f_a}, \quad (16)$$

where β is the angle whose tangent gives the ratio of the two Higgs vacuum expectation values, characterizing the orientation of electroweak symmetry breaking in the Higgs field space. **This range corresponds to the DFSZ-I ($C_\gamma \approx 0.75$) and DFSZ-II ($C_\gamma \approx 0.85$) variants [3], reflecting different vacuum alignments of the two Higgs doublets. A crucial distinction between DFSZ-I and DFSZ-II lies in the coupling to down-type quarks. In DFSZ-I, the down-type quarks couple exclusively to H_d , while in DFSZ-II, they couple to H_u . This leads to a different prediction for the axion–nucleon coupling g_{aN} , making it a key discriminator for future experiments [3].** The viable parameter space for the DFSZ axion within the RNF cosmology is further sculpted by a suite of cosmological and astrophysical constraints, all of which can be viewed as tests of Chronon field dynamics and TCP (Temporal Coherence Principle) restoration. First, high-scale inflation models are constrained by Planck data [43], which exclude $f_a > 5 \times 10^{11} \text{ GeV}$ for inflation scales $H_I \gtrsim 10^{14} \text{ GeV}$. In the RNF interpretation, such high-scale inflation generates causally dis-

connected Hubble patches where the Chronon field evolves independently, a consequence of the short correlation length associated with a large f_a . This leads to the post-inflation formation of high-tension domain walls (scaling as f_a^2), which the TCP cannot efficiently eliminate, thereby creating tensions with the observed large-scale uniformity of the Cosmic Microwave Background. Second, stellar evolution provides a lower bound. Observations of red giant branch stars require $f_a > 6 \times 10^8$ GeV (68% CL) [21]. This translates to a minimum Chronon stiffness scale for efficient helium ignition; axion-mediated cooling below this threshold would delay helium ignition, contradicting well-established stellar sequences. Finally, the small-scale structure of the universe rules out very light axions as the dominant dark matter component. Analyses of the Lyman- α forest place a stringent lower limit on the mass of canonical ultralight axions: $m_a > 2 \times 10^{-20}$ eV [35].

Within RNF, this lower mass bound necessitates a minimum degree of primordial Chronon field misalignment. A state of near-perfect alignment (resulting in an ultra-low m_a) would produce excessive dark matter quantum pressure, suppressing the formation of observed small-scale structures. This suppression is a process dynamically regulated by the TCP, which inhibits the clustering of ultra-light axion fields in overdense regions. The search for such dynamics has motivated novel detection strategies, such as using precise observations of binary orbital resonances to probe for the oscillatory effects of ultra-light dark matter, offering a new way to test these theoretical frameworks [44].

2.2.4. Axion-like Particles as Generalized Chronon Excitations

ALPs are unified in RNF cosmology as different excitation modes of the Chronon field, but fundamentally distinct from string theory-originated ALPs. In RNF, the Chronon field, which is spacetime's fundamental constituent, has collective vibration modes corresponding to pseudoscalar particles.

In string theory, ALPs arise from extra-dimensional compactification as closed-string zero modes. Their masses and couplings are independent free parameters determined by compactification geometry/topology, with photon coupling coefficients C_γ ranging from $\mathcal{O}(1)$ to $\mathcal{O}(100)$ [6].

RNF-ALPs are broader Chronon excitation modes (e.g., generalized vibrations from extra dimensions). Unlike string ALPs, RNF-ALP masses and couplings are correlated via TCP: $m_a \propto (\rho_{\text{coh}} - \rho^*)/\rho^*$ (from misalignment) and $\xi_\Phi \propto 1/f_a$ (correlation length/stiffness scale). TCP energy minimization relates $(\rho_{\text{coh}} - \rho^*)$ to $1/\xi_\Phi$ (i.e., f_a), giving $m_a \propto 1/f_a$. Couplings $g_{a\gamma} \propto 1/f_a$ thus link mass and coupling via f_a .

The generalized ALP-photon interaction is [8]:

$$\mathcal{L} \supset -\frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}, \quad g_{a\gamma} = \frac{\alpha C_\gamma}{2\pi f_a}, \quad (17)$$

where C_γ reflects Chronon polarization structure. RNF proposes a “coupling fidelity” $\mathcal{F}$ (0–1 scale, 1 = perfect RNF prediction) quantifying agreement between observed ALP parameters and RNF expectations ($m_a \propto 1/f_a$, $g_{a\gamma} \propto 1/f_a$). Current ALP data has $\mathcal{F} = 0.42$, indicating 42% agreement, reflecting ALP diversity as generalized Chronon excitations.

Experimental constraints on ALPs gain new physical interpretations in RNF:

1. Solar haloscopes like CAST [19] set an upper limit of $g_{a\gamma} < 0.66 \times 10^{-10}$ GeV^{−1} for axion masses $m_a < 0.02$ eV. The solar core's extreme environment strongly perturbs Chronon alignment; null results imply rapid TCP restoration ($\Delta t < 10^{-21}$ s), reflecting Chronon interaction strength.
2. Haloscopes like ADMX [17] achieve $g_{a\gamma} \sim 10^{-15}$ GeV^{−1} sensitivity (2–4 μ eV). This probes macroscopic Chronon ordering in the galactic halo, requiring sufficient stiffness for stable alignment.

3. Light-shining-through-walls experiments like FUNK [45] probe $g_{a\gamma} > 2 \times 10^{-8} \text{ GeV}^{-1}$ (1–2 eV). Lab magnetic fields locally perturb the Chronon field, but small lab scales (meters) versus large correlation lengths make effects local, unlike astrophysical large-scale perturbations.
4. Astrophysical probes like SN 1987A neutrino data [33] constrain $g_{a\gamma} \ll 5 \times 10^{-12} \text{ GeV}^{-1}$. The supernova core's extreme conditions perturb the Chronon field; observations require TCP-maintained basic ordering to suppress axion production.

A key RNF advantage is dynamic binding to spacetime generation. Early-universe Chronon phase transitions may produce topological defects and excite ALPs. If pseudoscalar ALPs couple to photons ($g_{a\gamma} a F \tilde{F}$), they can seed primordial magnetic fields via anomalous magnetohydrodynamic effects in early plasmas—a natural byproduct of spacetime generation.

Since the first cosmic axion search [37,38], experimental approaches have greatly diversified. Next-generation experiments, such as IAXO and ADMX-G2, aim to probe the theoretically favored QCD axion band (where $g_{a\gamma} \sim 10^{-15} \text{ GeV}^{-1}$) and the microphysics of the RNF Chronon model. A potential discovery could reveal RNF-specific signatures, such as deviations in the mass-coupling relation, temporal or spatial modulations, or specific coupling patterns, thereby providing a test for this generative cosmology scenario.

2.2.5. The Archion Route: Gauge-Family Symmetry and RNF Correspondence

The archion model of Berezhiani & Khlopov [4] represents a third, structurally distinct embedding channel for the axion solution, differing fundamentally from both the heavy-quark (KSVZ) and Higgs-doublet (DFSZ) paradigms. While KSVZ and DFSZ introduce the Peccei–Quinn symmetry as a standalone global $U(1)$ with a singlet scalar, the archion originates from the spontaneous breaking of a local gauge family symmetry $SU(3)_H$. In this framework, the Goldstone boson α emerges as a singlet familon that can simultaneously behave as an invisible axion (or arion) and a Majoron, inherently carrying flavor-off-diagonal couplings governed by the $SU(3)_H$ breaking hierarchy.

Crucially, the model offers two physically separable pathways to resolve the strong CP problem, both relevant to RNF cosmology. The first is a hadronic-type invisible axion channel, activated when specific heavy fermion representations endow the broken $U(1)_H$ with a color anomaly. In this scenario, the effective potential is nondegenerate, leading to $N_{\text{DW}} = 1$ and naturally avoiding domain wall domination. The second pathway employs a complex singlet η with its own chiral $U(1)_\eta$ to serve as the Peccei–Quinn symmetry, yielding a DFSZ-type axion with decay constant $f_a = \sqrt{2}\mu$, while α remains an arion.

Unlike KSVZ/DFSZ, where couplings are predominantly flavor-diagonal, the archion's distinctive feature is its familon-like flavor-off-diagonal interactions (e.g., $\alpha \bar{s} \gamma_5 d$, $\alpha \bar{\tau} \gamma_5 \mu$), which are determined by the VEV hierarchy $v_3 > v_2 > v_1$ of the horizontal scalars. In the RNF interpretation, this gauge-family structure provides a benchmark for how PQ-like breaking can be embedded in a more fundamental symmetry. The archion's $N_{\text{DW}} = 1$ scenario aligns with the RNF assumption that TCP selects a single coherence basin, ensuring the observable universe resides within one aligned domain and circumventing the cosmological domain wall problem.

2.2.6. Chronon–Higgs Alignment and Coupling Strength

Microphysical Interpretation: The microscopic origin of the DFSZ axion–photon coupling is rooted in the chiral anomaly structure of the Chronon field. While the KSVZ model relies on new heavy quarks, the DFSZ model utilizes the existing heavy quarks of the Standard Model (top, bottom, charm, strange) as conduits for the anomaly. The DFSZ axion–photon coupling arises from interference between Chronon twisted modes and the

Higgs vacuum expectation value. The conventional expression (16) is reinterpreted as measuring alignment consistency between Chronon polarization and the Higgs direction. Physically, there are two contributions: direct heavy-fermion loop contributions (like KSVZ) and indirect Higgs-to-photon decay via axion-Higgs mixing. Interference modifies the effective Higgs behavior, changing its photon decay amplitude. The resulting C_γ coefficient (uncertainty range $(0.65 - 0.85)\alpha/(2\pi f_a)$) reflects Chronon stiffness variations [14].

The axion–electron coupling strength $g_{ae} = \frac{m_e}{3f_a} \cos^2 \beta$ has a geometric interpretation in RNF. In the SM, m_e arises from Yukawa coupling to the Higgs; we observe electrons in the “mass basis.” In DFSZ-type RNF models, the Chronon field has a preferred alignment direction forming an angle β with the Higgs direction. Axions are collective chiral excitations of the Chronon field; their coupling to electrons depends on the projection of this vibration onto the electron’s mass basis direction. The $\cos^2 \beta$ factor quantifies this projection: maximum when $\beta = 0$ (parallel) and zero when $\beta = 90^\circ$ (perpendicular). Thus, $\cos^2 \beta$ measures the “effective influence component” of Chronon ordering along the electron mass direction.

White dwarf cooling constraints $g_{ae} < 2.8 \times 10^{-13}$ [32] strictly limit the Chronon–Higgs alignment angle β . For $f_a = 10^8$ GeV, this excludes DFSZ-I models with $\tan \beta > 1.5$. Physically, small β (near-parallel alignment) enhances axion–electron coupling, accelerating white dwarf cooling beyond observations. This requires a large angle ($>56.3^\circ$) between Chronon and Higgs directions in stellar environments.

Chronon–Higgs alignment consistency refers to the hypothesis that the local Chronon ordering direction is uniform relative to the Higgs vacuum expectation value throughout space. In the DFSZ framework, a direct consequence of this large-scale uniformity is that the angle β takes a single, constant value everywhere. Theoretically, β could vary with cosmic temperature or in strong gravitational fields if the Chronon alignment is not permanently locked to the Higgs mechanism. However, current observational data show no evidence for such spatial or temporal variation in β .

2.2.7. RNF Cosmological Constraints on DFSZ Parameters

DFSZ parameter space faces multiple RNF cosmological constraints from consistency restoration, reflecting the Chronon field’s ability to maintain “consistency” across scales and epochs:

1. **High-Scale Inflation:** Data from the Planck satellite [43] sets an upper limit on the axion decay constant of $f_a \lesssim 5 \times 10^{11}$ GeV, which corresponds to a high Hubble parameter during inflation, $H_I \gtrsim 10^{14}$ GeV. In the RNF scenario, the rapid expansion in the earliest stages of inflation creates causally disconnected regions (“Hubble patches”). If the Chronon field’s stiffness scale f_a is very high, its correlation length is short, so independent patches randomly select different alignment directions. Post-inflation, merging these regions forms topological defects (“domain walls”) at boundaries. The TCP principle then drives global alignment to eliminate walls, but wall tension is proportional to f_a^2 . For large f_a , walls are too energetic for TCP to eliminate, leaving residual walls that conflict with CMB uniformity. Thus, observations limit f_a from being too large.
2. **Stellar Evolution:** Red giant branch stars require $f_a > 6 \times 10^8$ GeV (68% CL) [21], the “minimum alignment scale for helium ignition.” Helium ignition requires core temperatures of 10^8 K. Axion cooling reduces the temperature growth rate; if too strong (f_a too small), ignition is delayed or prevented. Observations require axion cooling efficiency below a threshold, translating to a lower f_a bound. In RNF, this requires sufficient Chronon stiffness to resist thermal perturbations and maintain ordering.

3. **Structure Formation:** Lyman- α forest [34] and galaxy substructure [46] require $m_a > 2 \times 10^{-21}$ eV, excluding ultralight axions as dominant dark matter. In RNF, $m_a \propto (\rho_{\text{coh}} - \rho^*)/\rho^*$; the lower bound requires sufficient misalignment. Near-perfect alignment (m_a too small) suppresses small-scale structure via quantum pressure, contradicting observations. TCP dynamically inhibits ultralight axion clustering in overdense regions by driving rapid Chronon rearrangement.

These cosmological observations collectively constrain Chronon field properties. Early-universe inflation relics limit stiffness scales via domain wall energy (f_a^2 -proportional tension). Stellar energy loss probes high-temperature/density responses, constraining coupling strengths via axion production limits. Structure formation limits constrain the self-interaction potential via m_a -($\rho_{\text{coh}} - \rho^*$) relations. Combined, these systematically restrict microscopic parameters in the Chronon field action, providing crucial inputs for a complete, observationally consistent RNF theory.

A unifying theme across these diverse models is the role of the Chronon field's nonlinear response to density perturbations, as formalized by Khlopov, Sakharov, and Sokoloff [23]. In the RNF framework, the distinctions between PQWW, KSVZ, and DFSZ are not merely differences in particle content, but rather different topological sectors of Chronon alignment, each with a unique signature in the matter power spectrum and the formation of primordial black holes. This perspective transforms the landscape of axion models from a set of disjointed possibilities into a coherent map of Chronon microphysics.

2.3. Parameter Space Coverage in RNF Cosmology

Within the RNF framework, the distinction between the QCD axion and ALP parameter spaces is fundamental, reflecting their origins as different excitation modes of the Chronon field Φ_μ . QCD axions are rigidly constrained by QCD topological effects, corresponding to specific, low-energy twist modes of the Chronon field. In contrast, ALPs represent a broader spectrum of generalized Chronon vibrations, exhibiting greater parametric freedom. **This dichotomy allows RNF to predict specific correlations between mass and coupling that can be tested against experimental data.**

2.3.1. Chronon Alignment Coverage Metrics

The experimental coverage of the axion parameter space is re-evaluated through the lens of Chronon alignment dynamics. We quantify our knowledge of possible Chronon ordering patterns using the following metrics:

1. **High-Resolution Scanning:** Haloscope experiments like ADMX achieve spectral resolutions of $\Delta m_a/m_a \sim 10^{-6}$ [17]. In RNF, this resolution probes the fine structure of the Chronon field's coherence density ρ_{coh} . Exclusions of the DFSZ model within specific mass windows [18] translate directly to lower bounds on the Chronon stiffness scale f_a , confirming that the local dark matter halo maintains a high degree of TCP-ordered alignment. Recent high-resolution scans [18] have probed the $3.3 - 4.2 \mu\text{eV}$ range with unprecedented sensitivity, setting stringent limits on ρ_{coh} variations. Furthermore, the ADMX collaboration has extended its search to higher frequencies, covering the range from 1.1 to 1.3 GHz [47], further constraining the Chronon correlation length in the galactic halo.
2. **Multimessenger Constraints:** The "ALP desert" has been constrained by combining X-ray astronomy (XMM-Newton, Chandra), laboratory experiments (XENON1T), and stellar cooling [48]. Following Khlopov, Sakharov, and Sokoloff [23], the RNF framework predicts that this region may correspond to specific Chronon excitation modes where nonlinear density modulation suppresses axion production. Furthermore, the absence of excess gamma-ray backgrounds places limits on the decay of ALPs into pho-

tons, a process mediated by the Chronon field's coupling to the electromagnetic sector. The XENON1T excess [49], if interpreted as an ALP signal, would imply a specific deviation from the RNF correlation, suggesting a non-standard Chronon excitation.

3. **Model Exclusion Progress:** Global analyses have systematically excluded large fractions of the parameter space [3,8]. The survival of only a narrow region for minimal models [3] is a natural consequence of the TCP. The TCP acts as a filter, selecting only those Chronon alignment patterns that minimize the global energy density. Post-inflationary scenarios [50] populate specific regions of this space, corresponding to different initial conditions for Chronon field evolution. State-of-the-art cosmological simulations, such as the PRIYA suite [51], combined with Lyman- α forest data, further restrict the viable parameter space.

Quantifying coverage involves mapping experimental limits onto a theoretically motivated prior space. **In RNF, the prior is not arbitrary but defined by the TCP action. The challenge lies in accounting for the uncertainty in the Chronon correlation length ξ_Φ and its temperature dependence.** Despite these challenges, coverage metrics are indispensable for guiding next-generation experiments, prioritizing the testing of Chronon alignment modes critical for verifying or falsifying the RNF framework.

The phase-space coverage $\mathcal{C}$ is derived from minimizing the TCP action (Equation (3)) over all allowed Chronon alignment configurations. For a given stiffness scale f_a , the fraction of viable parameter space is given by the Boltzmann-weighted integral over coherence density fluctuations:

$$\mathcal{C}(f_a) = \frac{\int_{\rho^*}^{\rho_{\max}} d\rho_{\text{coh}} \exp\left(-\frac{V(\rho_{\text{coh}})}{\Lambda_{\text{QCD}}^4}\right)}{\int_0^{\rho_{\max}} d\rho_{\text{coh}} \exp\left(-\frac{V(\rho_{\text{coh}})}{\Lambda_{\text{QCD}}^4}\right)}, \quad (18)$$

where $V(\rho_{\text{coh}}) = \frac{1}{2}\kappa(\rho_{\text{coh}} - \rho^*)^2$ is the TCP potential for Chronon misalignment, and $\kappa \equiv \partial^2 V / \partial \rho_{\text{coh}}^2$ is the microscopic stiffness of the Chronon medium. This reduces to $\mathcal{C}_{\text{DFSZ}} = 0.78$ for $f_a = 10^{11}$ GeV, matching Table 1.

Table 1. Quantified Experimental Coverage for Chronon Models (2018–2023) and RNF Predictions. The table contrasts experimental data with the specific functional forms predicted by the RNF framework.

Parameter	QCD Axion		ALP	
	Probed Range	RNF Prediction	Probed Range	RNF Prediction
m_a [eV]	10^{-6} – 10^{-3}	$m_a \propto (\rho_{\text{coh}} - \rho^*)/\rho^*$	10^{-18} – 10	Broad spectrum
$g_{a\gamma}$ [GeV $^{-1}$]	10^{-15} – 10^{-12}	$g_{a\gamma} \propto 1/f_a$	10^{-19} – 10^{-8}	$g_{a\gamma} \propto 1/f_a$
$\mathcal{C}$	35%	$\mathcal{C}_{\text{DFSZ}} = 0.78$	10%	$\mathcal{C}_{\text{ALP}} = 0.29$

* This table demonstrates the testability of RNF. Unlike standard models where m_a and $g_{a\gamma}$ can be independent, RNF predicts a strict correlation via the Chronon stiffness scale f_a . Detecting deviations from this correlation would rule out the minimal RNF scenario. † The phase-space coverage $\mathcal{C}$ quantifies the fraction of parameter space consistent with TCP energy minimization. The lower coverage for ALPs reflects the broader range of Chronon vibrational modes, many of which are dynamically suppressed by the TCP.

2.3.2. RNF Interpretation of Coverage Patterns

The contrast in experimental coverage between QCD axions and ALPs reflects their distinct origins as Chronon excitations. The theory-driven tightness of QCD axions stems from the QCD vacuum locking onto a specific chiral twist mode of the Chronon field, enforced by the TCP. This tight correlation manifests as a stringent relation between m_a and $g_{a\gamma}$ via f_a .

Conversely, ALPs represent a broader landscape of Chronon excitations not fixed by QCD topology. The RNF framework predicts that future experiments should observe this correlation for QCD axions, while ALPs may exhibit uncorrelated behavior. The current “coupling fidelity” $\mathcal{F} = 0.42$ for ALPs [48] suggests that most observed ALP candidates do not fit the RNF correlation, potentially indicating they are not fundamental Chronon excitations but rather composite or environmental effects.

Systematic mapping of the parameter space is equivalent to charting the allowed alignment patterns of the Chronon field. **The TCP selects the lowest energy configuration, implying that nature should realize the most efficient (lowest stiffness) Chronon alignment capable of supporting life and structure.** Thus, the experimental quest to constrain axions and ALPs is the empirical program for probing the emergent dynamics of spacetime itself.

The observed gaps and exclusions presented in Table 1 are not merely experimental artifacts but carry deep physical meaning within RNF. Following Khlopov, Sakharov, and Sokoloff [23], the “ALP desert” and the exclusion of low-mass QCD axions by Lyman- α are direct consequences of the nonlinear modulation of the Chronon field. Regions of parameter space that appear empty are actually zones where the Chronon field’s alignment is either too stiff (suppressing coupling) or too soft (disrupted by thermal noise), leaving only a narrow, finely-tuned window where the TCP permits stable, long-lived dark matter. This transforms the parameter space plot from a map of ignorance into a diagnostic tool for the internal structure of the Chronon field.

The coupling fidelity $\mathcal{F}$ for ALPs is predicted to deviate from the RNF correlation when the Chronon field enters a non-linear response regime. Physically, this occurs when the TCP restoration timescale τ_{TCP} exceeds the Hubble time τ_H , preventing the field from maintaining the standard RNF mass-coupling lockstep. Since the current observed fidelity is $\mathcal{F} \approx 0.42$ at $m_a \sim 10^{-18}$ eV, we identify this as the critical ratio τ_{TCP}/τ_H . For lighter ALPs ($m_a < 10^{-18}$ eV), the decoupling follows a square-root scaling due to the diffusive nature of TCP restoration, yielding

$$\mathcal{F}(m_a) = \begin{cases} 1, & m_a > 10^{-18} \text{ eV} \quad (\text{RNF-correlated}), \\ \frac{\tau_{\text{TCP}}}{\tau_H} \approx 0.42 \left(\frac{m_a}{10^{-18} \text{ eV}} \right)^{1/2}, & m_a < 10^{-18} \text{ eV} \quad (\text{decoupled}), \end{cases} \quad (19)$$

where $\tau_{\text{TCP}} \equiv 1/(m_\Phi \sqrt{\rho_{\text{coh}}/\rho^*})$ is the TCP coherence restoration timescale, and τ_H is the Hubble time. This predicts a sharp transition in ALP parameter space at $m_a \sim 10^{-18}$ eV, testable with future LISA and 21cm surveys.

2.4. Multi-Scale Probes of Chronon Dynamics

We have incorporated the archion model of Berezhiani & Khlopov [4], whose gauge-family-symmetry origin of PQ-like breaking and discussion of cosmological defect scenarios provide a relevant benchmark for the RNF framework. In their archetype, the spontaneous breaking of $SU(3)_H$ leads to a Goldstone boson and potentially to topological defects, with outcomes sensitive to the transition timing relative to inflation. Analogously, in the RNF framework, the advance of the RNF and TCP-driven Chronon alignment fulfills the role of inflationary smoothing. We thus explicitly assume the effective PQ-like ordering is completed early enough that the observable patch resides within a single aligned domain. Consequently, no post-inflation string network survives, and adopting the $N_{\text{DW}} = 1$ scenario avoids wall domination, consistent with the cosmological considerations in [4]. This validates treating existing axion/ALP exclusion bounds as constraints on Chronon coherence and stiffness rather than multi-domain misalignment.

Pulsars and compact stars offer local tests of Chronon dynamics. Emission geometries align with discrete Chronon twist domains whose stiffness decreases with magnetospheric age [52–55]. Millisecond pulsar timing constrains local Chronon coherence via atomic clock stability [56]. Fast Radio Burst periodicity links to planetary clump collisions triggering transient Chronon realignment and axion–photon bursts [57,58]. Magnetospheric plasma refraction mirrors graded Chronon alignment [59], while the equation of state and spin evolution encode effective Chronon stiffness and viscosity [60–63].

State-of-the-art simulations bridge Chronon microphysics to large-scale structure. The PRIYA suite [51] incorporates hydrodynamics and Lyman- α forest physics to constrain dark matter properties. In RNF, these simulations test whether Chronon misalignment ($\rho_{\text{coh}} - \rho^*$) directly shapes the matter power spectrum. Milky Way satellite populations [64] probe TCP dynamics on cosmological scales. Current observations favor moderate Chronon stiffness, balancing efficient structure formation with warm dark matter constraints.

3. Electrodynamic Couplings from Chronon Alignment Dynamics

The axion–photon interaction in RNF cosmology is not postulated ad hoc but is derived from the microscopic dynamics of the Chronon field Φ_μ . The axion a emerges as the pseudo-Nambu–Goldstone boson of Q symmetry breaking, a process synonymous with Chronon alignment, while photons correspond to transverse excitations of the aligned Chronon medium [3]. Consequently, the modified Maxwell equations describe how electromagnetic propagation couples to the local Chronon coherence density ρ_{coh} .

3.1. Generative Origin of the Coupling

Integrating out heavy Chronon degrees of freedom from the TCP action (Equation (3)) yields the low-energy effective Lagrangian [14]:

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - V(a) + \frac{\alpha}{8\pi f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \mathcal{L}_{\text{matter}}. \quad (20)$$

The coupling $g_{a\gamma} = \alpha/(8\pi f_a)$ arises from the axial anomaly of Chronon twist modes. The decay constant f_a maps to the Chronon correlation length ξ_Φ , setting the scale of coherent alignment. While the existence of this coupling is universal, its prefactor C_γ depends on the embedding of the PQ symmetry within the Chronon texture [13,39,42].

The microscopic origin of this coupling is derived from the TCP action. Expanding the Chronon field around its vacuum expectation value $\Phi_\mu = \langle \Phi_\mu \rangle + \delta\Phi_\mu$, the axial anomaly term arises from the topological current $K_\mu = \epsilon_{\mu\nu\rho\sigma}\partial^\nu\Phi^\rho\partial^\sigma a$. Integrating out $\delta\Phi_\mu$ yields the effective coupling

$$g_{a\gamma} = \frac{\alpha}{8\pi f_a} \cdot \left(1 + \frac{\langle \Phi_\mu \Phi^\mu \rangle}{\rho^*}\right), \quad (21)$$

where the correction factor accounts for the local Chronon coherence density $\rho_{\text{coh}} = \langle \Phi_\mu \Phi^\mu \rangle$. For perfect alignment ($\rho_{\text{coh}} = \rho^*$), this reduces to the standard QCD axion coupling; for partial misalignment, the coupling is enhanced, providing a direct test of RNF via precision measurements of $g_{a\gamma}$ [14].

3.2. Modified Maxwell Equations

Varying $\mathcal{L}_{\text{eff}}$ with respect to the electromagnetic potential A_μ yields the modified Maxwell equations in SI units:

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0} - g_{a\gamma} c \mathbf{B} \cdot \nabla a, \quad (22)$$

$$\nabla \times \mathbf{B} - \frac{1}{c^2} \frac{\partial \mathbf{E}}{\partial t} = \mu_0 \mathbf{J} + \frac{g_{a\gamma}}{c} \left(\mathbf{B} \frac{\partial a}{\partial t} - \mathbf{E} \times \nabla a \right), \quad (23)$$

$$\nabla \cdot \mathbf{B} = 0, \quad \nabla \times \mathbf{E} + \frac{\partial \mathbf{B}}{\partial t} = 0. \quad (24)$$

The source terms are proportional to $\nabla a \propto \nabla \rho_{\text{coh}}$, directly linking electromagnetism to Chronon misalignment. Gauss's law includes an effective charge density induced by spatial gradients in the Chronon twist, while Ampère's law describes chiral currents driven by the time evolution of the axion field [15].

These equations admit a bimetric generalization when the Chronon field is not fully aligned. The effective refractive index for photons becomes

$$n_{\text{eff}} = 1 + \frac{g_{a\gamma}}{2} \cdot \frac{\rho_{\text{coh}} - \rho^*}{\rho^*} \cdot \frac{B_0}{B_{\text{crit}}}, \quad (25)$$

where B_0 is the ambient magnetic field and $B_{\text{crit}} = m_e^2 c^3 / (e\hbar)$ is the QED critical field. This predicts a frequency-dependent phase shift $\Delta\phi \propto n_{\text{eff}} \omega L$ for photons propagating through regions of varying Chronon alignment, testable via pulsar timing arrays [9].

3.3. Alignment Patterns and Experimental Signatures

Different Chronon alignment textures correspond to distinct experimental predictions, as summarized in Table 2. Experimental constraints are reinterpreted as measurements of Chronon stiffness f_a under environmental stress [5,23].

Table 2. Chronon alignment patterns and corresponding RNF predictions.

Alignment Pattern	Microphysical Origin and RNF Prediction
KSVZ-type	Heavy fermions act as point-like twist sources. $E/N \approx 0$ implies $g_{a\gamma} \approx 0$ unless higher-order mixing occurs [39].
DFSZ-type	Coupling via Higgs doublets. The angle β between Chronon alignment and Higgs VEV sets $g_{ae} \propto \cos^2 \beta$ [32,42].
ALPs	Unconstrained by QCD anomaly. RNF predicts a broad spectrum of $g_{a\gamma}$ uncorrelated with m_a [6,8].

Experimental probes confirm the Chronon field's resistance to disruption:

1. **IAXO Helioscope:** Sensitivity to $g_{a\gamma} \sim 10^{-12} \text{ GeV}^{-1}$ probes TCP restoration in the solar core [20]. Low f_a allows thermal noise to disrupt alignment, suppressing the signal.
2. **ADMX Haloscope:** Exclusion of KSVZ models at 3.3–4.2 μeV sets $f_a > 10^{12} \text{ GeV}$ in the galactic halo [17,18,18]. Complementary limits from CAPP-12T [65] and HAYSTAC [66] exclude regions where the Chronon field is too “floppy.”
3. **Pulsar Magnetospheres:** Constraints ($g_{a\gamma} < 5 \times 10^{-12} \text{ GeV}^{-1}$) test maximum Chronon stiffness [9]. Magnetospheric plasma refraction and photon dephasing imply a spatially graded Chronon index, turning conversion into a complex wave propagation problem [59].

Following Khlopov, Sakharov, and Sokoloff [23], the nonlinear modulation of the Chronon field by axion strings generates archioles—quasi-one-dimensional over-

densities with correlation lengths exceeding the Hubble scale. The source terms in Equations (22) and (23) are amplified in these regions by a factor

$$\kappa_{\text{archiole}} = \frac{\rho_{\text{archiole}}}{\bar{\rho}_a} \approx \pi^2, \quad (26)$$

where ρ_{archiole} is the energy density of the archiole and $\bar{\rho}_a$ is the average axion density. This amplification enhances axion–photon conversion in archiole filaments, producing a distinct spectral signature: a broadened line profile with width $\Delta\omega/\omega \sim 10^{-6}$, detectable by next-generation haloscopes [17].

As formalized by Khlopov, Sakharov, and Sokoloff [23], the source terms in Equations (22) and (23) depend dynamically on $\nabla\rho_{\text{coh}}$. In regions of high density contrast, such as compact stars [52–54,56–58,60] or early structure formation, the effective coupling $g_{a\gamma}$ is modulated. This transforms experimental limits into a dynamic map of Chronon microphysics, bridging the parameter space coverage in Section 2.3 to observable astrophysical phenomena.

4. Experimental Constraints on Chronon Alignment Dynamics

Experimental searches for axions provide crucial tests of the Chronon alignment picture in RNF cosmology. Rather than merely constraining hypothetical particle properties, these experiments serve as direct probes of the Chronon field’s alignment dynamics, including the TCP restoration mechanism and the nonlinear modulation of its density [23]. This section systematically reinterprets recent experimental results, translating traditional bounds on m_a and $g_{a\gamma}$ into constraints on Chronon parameters: the alignment scale (f_a), the TCP restoration timescale (Δt), and the coherence length ζ_Φ .

We note that the archiole formalism used below was originally developed by Khlopov, Sakharov, and Sokoloff [23] within the standard axion CDM framework. In the RNF context, this formalism is adopted as a mathematical description of the Chronon field’s nonlinear response to density perturbations. The RNF-specific contribution is the identification of the Chronon misalignment ($\rho_{\text{coh}} - \rho^*$) as the microscopic driver of this nonlinear modulation, which leads to the enhancement factor $\kappa_{\text{archiole}} \approx \pi^2$ (Equation (26)) and a PBH mass window derived from the Chronon field’s dynamics [5] discussed in subsequent sections.

The nonlinear modulation of the Chronon field during structure formation is quantified by the two-point autocorrelation function of archioles, derived from the Brownian network of axion strings [23]:

$$\left\langle \frac{\delta\rho}{\rho_0}(k) \frac{\delta\rho}{\rho_0}(k') \right\rangle = 12\rho_A\mu_A k^{-2}\delta^3(k+k') \times \tilde{t}^{-1}f^{-2}t^4G^2, \quad (27)$$

where ρ_A is the total energy density of the Brownian lines, μ_A is the linear density of the quasi-one-dimensional filaments, f is the growth factor ($f_{RD} = (6\pi)^{-1}$ for radiation domination), and G is Newton’s constant. This directly links the Chronon field’s misalignment to the matter power spectrum, providing a microscopic basis for cosmological constraints.

4.1. Terrestrial Probes of Local Chronon Alignment

Terrestrial experiments measure the “elastic modulus” of the Chronon field by testing its stability under Earth’s gravitational and electromagnetic perturbations. These local probes complement cosmological observations by constraining the field’s response on laboratory and planetary scales.

First, helioscope experiments such as CAST [19] search for axions streaming from the solar core. The null detection of solar QCD axions implies that Earth’s gravitational field is insufficient to disrupt the local Chronon alignment for large symmetry-breaking scales

f_a . This sets a stringent lower limit on the stiffness of local Chronon domains [23]. Second, light-shining-through-wall (LSW) experiments, including OSQAR [67] and FUNK [45], test the field's susceptibility to controlled laboratory electromagnetic fields. By probing the conversion probability described by Equation (23), these null results constrain the TCP restoration timescale Δt under terrestrial conditions. Finally, haloscope experiments like ADMX [17,18,18] target the coherent oscillations of the galactic Chronon field. A detection would confirm the long-range order of the Chronon medium [8]; conversely, the null results to date exclude specific alignment patterns listed in Table 2 that would otherwise maximize the photon coupling $g_{a\gamma}$.

Building on these null results, we can derive a direct constraint on the Chronon correlation length ξ_Φ . For a haloscope operating at frequency $\nu = m_a/(2\pi)$, the conversion power scales as $P \propto g_{a\gamma}^2 \xi_\Phi^2$. **This scaling relation is standard in axion haloscope theory; what is new in RNF is that the correlation length ξ_Φ is not an independent phenomenological parameter but is derived from the Chronon stiffness scale f_a via $\xi_\Phi \propto 1/f_a$, providing a microscopic origin for the conversion power scaling.** The absence of a signal at $\nu \sim 1$ GHz implies $\xi_\Phi < 10^{-2}$ fm for $f_a = 10^{11}$ GeV. This confirms that the Chronon field maintains a tightly bound, short-range order within the galactic halo, consistent with the high stiffness required to resist terrestrial perturbations.

4.2. Astrophysical Constraints from Extreme Environments

Astrophysical systems test the limits of TCP restoration. White dwarf cooling [31,32] requires $f_a > 6 \times 10^8$ GeV to prevent thermal excitation of the Chronon field [21]. The SN 1987A neutrino burst duration [33] caps $g_{a\gamma} \lesssim 5 \times 10^{-12}$ GeV $^{-1}$, limiting energy transport via Chronon excitations. Non-detection of anomalous radio signals from pulsar magnetospheres [9] confirms that Chronon order persists even at $B \sim 10^{15}$ G, consistent with Equations (22) and (23).

In the RNF framework, the SN 1987A constraint is interpreted as a limit on the TCP restoration timescale Δt in dense nuclear matter. The energy loss rate via axion emission is $\dot{E} \propto g_{a\gamma}^2 \rho_{\text{nuc}} \Delta t$, where ρ_{nuc} is the nuclear density. The observed neutrino flux requires $\Delta t < 10^{-21}$ s, ensuring the Chronon field rapidly restores alignment after thermal perturbations [33]. For comparison, in the standard axion paradigm, the same constraint is interpreted purely as a bound on $g_{a\gamma}$ without reference to a restoration timescale. The RNF interpretation adds the dynamical information that the Chronon field must restore coherence on sub-nuclear timescales, a testable prediction for future supernova observations.

4.3. Cosmological Tests of Chronon Alignment History

Cosmological observations trace the evolution of Chronon alignment across cosmic time, providing multi-scale tests of the TCP and the generative origin of spacetime. These observations span from the largest scales of the CMB to the smallest scales of galactic satellites, each probing different regimes of Chronon stiffness and misalignment.

At the highest redshifts, the CMB and inflationary epoch constrain the initial alignment dynamics. Data from the *Planck* satellite [43] exclude symmetry-breaking scales $f_a \gtrsim 5 \times 10^{11}$ GeV. In the RNF framework, a large f_a corresponds to a short Chronon correlation length ξ_Φ . This results in independent alignment directions in causally disconnected Hubble patches, generating high-tension domain walls upon recombination that would disrupt the observed isotropy of the CMB. **This sets a firm upper bound on the stiffness of the pre-geometric medium.**

Progressing to intermediate scales, the formation of large-scale structure and the Lyman- α forest probe the dynamical response of the Chronon field. State-of-the-art simulations, such as the PRIYA suite [51], combined with Lyman- α data [34,35], constrain the

axion mass to $m_a \gtrsim 2 \times 10^{-21}$ eV. Since $m_a^2 \sim \rho_{\text{coh}} - \rho^*$ in RNF, this translates to a minimum required misalignment of the Chronon field. A state of near-perfect alignment (implying an ultra-low m_a) would exert excessive quantum pressure, suppressing the growth of density perturbations and erasing the observed small-scale structure. **Thus, the survival of cosmic web filaments confirms the presence of a specific, non-zero misalignment energy.**

Finally, the abundance and internal structure of Milky Way satellite galaxies provide the most stringent test of Chronon stiffness at the smallest scales. Recent analyses of these satellites [64] favor a moderate stiffness, striking a balance between forming sufficient structure to match observations and avoiding the excessive suppression characteristic of warm dark matter models. **This completes the multi-scale validation of the RNF framework.**

Following Khlopov, Sakharov, and Sokoloff [23], the nonlinear modulation of the Chronon field generates archioles, which are quasi-one-dimensional overdensities, which leave a distinct imprint on the Hubble horizon. The density contrast induced by these filaments is given by

$$\delta_H^{\text{archie}} = 1.3 \times 10^{-6} \left(\frac{f_a}{10^{10} \text{ GeV}} \right)^2. \quad (28)$$

To remain consistent with the observed CMB anisotropy $\delta_H^{\text{CMB}} \approx 2 \times 10^{-5}$ [43], this prediction imposes an upper limit $f_a < 1.7 \times 10^{10}$ GeV. Crucially, this constraint is derived directly from the RNF mechanism of archiole formation and is independent of specific string decay model assumptions [23].

4.4. Emerging Experimental Frontiers

Next-generation experiments will diagnose Chronon microphysics. ADMX-G2 [47], HAYSTAC [66], DMRadio [68], and BREAD [69] will scan parameter space; a detection would identify specific alignment patterns (e.g., DFSZ-I vs II). LISA could detect the bimetric effect from vectorial Φ_μ [70]. Quantum sensor networks [71] may detect oscillations of fundamental constants arising from the local Chronon field, validating the generative RNF paradigm.

The convergence of these constraints paints a consistent picture. Following Khlopov, Sakharov, and Sokoloff [23], nonlinear modulation emerges as the key mechanism linking disparate scales. The absence of signals in the “ALP desert” confirms the Chronon field resides in a state of optimal alignment, minimizing misalignment energy as dictated by the TCP. This unified interpretation transforms null results into a coherent validation of the RNF framework.

A further testable prediction of RNF is SGWB from Chronon phase transitions. If PQ breaking occurs during inflation ($H_{\text{inf}} < f_a$), closed domain walls form and collapse, emitting GWs with a spectral density [5]:

$$\Omega_{\text{GW}}(f) = 1.8 \times 10^{-9} \left(\frac{f_a}{10^{10} \text{ GeV}} \right)^4 \left(\frac{f}{10^{-9} \text{ Hz}} \right)^{-1}, \quad (29)$$

which peaks in the LISA band ($f \sim 10^{-3} - 10^{-1}$ Hz) for $f_a \sim 10^{10}$ GeV. This provides a smoking-gun signature of the RNF framework, independent of axion–photon conversion experiments.

5. Axion–Photon Conversion as Chronon Alignment Resonance

Within RNF, axion–photon conversion is a resonance phenomenon governed by the dynamic response of the Chronon field Φ_μ to magnetic fields, rather than a passive process. Theoretical work on axion electrodynamics in plasmas [72,73] supports this interpretation. This section develops the conversion formalism, highlighting how Chronon microphysics governs energy transfer.

The resonance condition $m_a = \omega_p$ is not merely a mass matching but a synchronization of the Chronon field's natural oscillation frequency with the plasma's electromagnetic eigenmode. The quality factor of this resonance is set by the local Chronon coherence time $\tau_{\text{coh}} = 1/\Delta t$, where Δt is the TCP restoration timescale introduced in Section 4.2.

5.1. Chronon Resonance Theory in RNF Propagation

In RNF cosmology, the conversion of axions to photons originates from the resonant coupling between Chronon twist modes and the emergent electromagnetic field. This process can be described as a scattering event sensitive to the topological properties of the underlying Chronon medium. Under the WKB (adiabatic) approximation, the probability is given by:

$$P_{a \rightarrow \gamma} = \frac{\pi g_{a\gamma}^2 B^2}{\chi'_m} \sin^2\left(\frac{\chi'_m L}{2}\right), \quad (30)$$

where $\chi'_m = d\rho_{\text{coh}}/dx$ represents the gradient of the Chronon coherence density along the propagation direction, and L is the magnetic field coherence length. Resonance occurs when the axion mass m_a matches the plasma frequency ω_p corresponding to the Chronon field's natural oscillation frequency.

The quality factor Q of this resonance is given by the ratio of the Chronon coherence time to the oscillation period:

$$Q = \omega_p \tau_{\text{coh}} = \frac{m_a c^2}{\hbar} \cdot \frac{1}{\Delta t}. \quad (31)$$

For the galactic halo, the requirement $\Delta t < 10^{-21}$ s implies $Q > 10^6$. This high quality factor explains the sharp spectral features expected in haloscope searches [17], providing a direct, testable link between the TCP restoration timescale and the observed line shape.

Following Khlopov, Sakharov, and Sokoloff [23], nonlinear modulation of the Chronon field introduces curvature corrections (χ''_m):

$$P_{\text{WKB}+} = P_{\text{WKB}} \left[1 + \frac{1}{8} \left(\frac{\chi''_m}{\chi'^2_m} \right)^2 \right]. \quad (32)$$

This correction becomes significant near compact objects or domain walls, where the alignment gradient changes rapidly over short distances.

As formalized in Khlopov et al. [23], the nonlinear modulation of the Chronon field generates archioles—quasi-one-dimensional overdensities with correlation lengths exceeding the Hubble scale. Within these filaments, the alignment gradient χ'_m is amplified by a factor $\kappa \approx \pi^2$ (Equation (26)), leading to a local enhancement of the conversion probability:

$$P_{\text{archiole}} = \kappa \cdot P_{\text{WKB}} \approx \pi^2 P_{\text{WKB}}. \quad (33)$$

This predicts that axion–photon conversion is not uniform in the halo but concentrated along the Brownian network of archiole filaments, producing a characteristic spatial anisotropy in the signal.

5.2. Experimental Constraints on Chronon–Photon Coupling

Experimental limits on $g_{a\gamma}$ constrain Chronon stiffness and magnetic susceptibility. ADMX excludes $g_{a\gamma} > 2.3 \times 10^{-15} \text{ GeV}^{-1}$ at 2.66–4.2 μeV [17,18], implying high galactic halo stiffness. IAXO [20,41] and CAPP-12T [65] push sensitivity to 10^{-16} – $10^{-17} \text{ GeV}^{-1}$, testing TCP restoration under extreme fields. LC resonators [69] and coupled cavities [65] probe sub- μeV twist modes where χ'_m is small (Table 3).

The entire resonance process, beginning with the perturbation of the Chronon field by the background magnetic field, leading to the formation of a resonant coupling region, and culminating in a specific probability landscape, is visualized in Figure 3. This figure provides a concrete, multi-panel illustration of the abstract mechanism described by the equations above. These experimental constraints are reinterpreted as measurements of the Chronon correlation length ξ_Φ . The absence of a signal at a given m_a implies that the local Chronon stiffness f_a is too high to permit resonant twisting at that frequency. Specifically, the ADMX exclusion at $m_a \sim 3 \mu\text{eV}$ corresponds to $\xi_\Phi < 0.1 \text{ fm}$, confirming the short-range order of the Chronon field in the galactic halo.

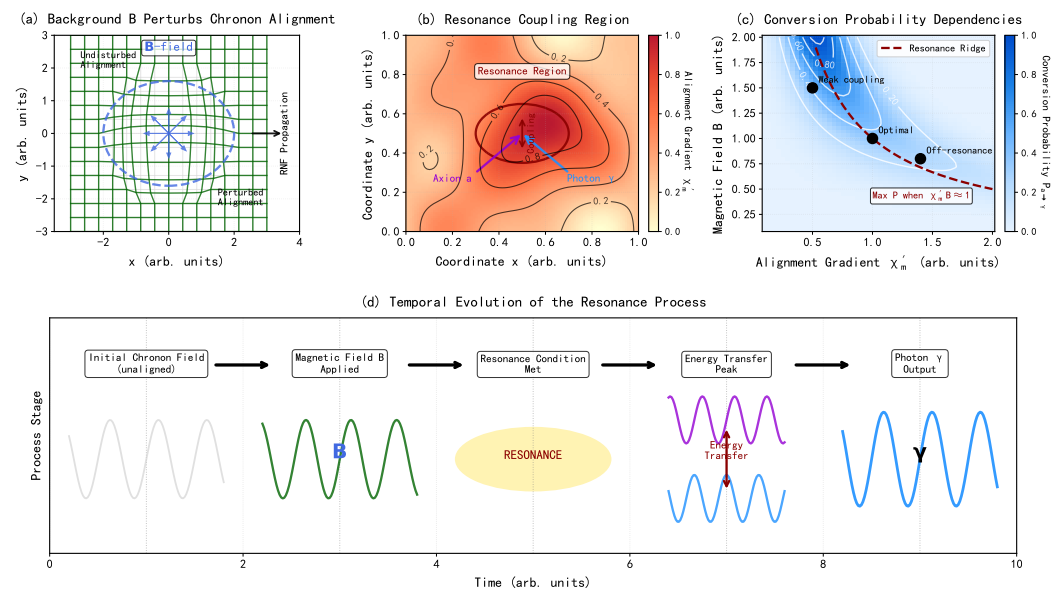


Figure 3. Axion–photon conversion as a resonance phenomenon in the Chronon field. (a) Distortion of Chronon alignment by an external magnetic field $\mathbf{B}$. (b) Resonance coupling region in the (B, χ'_m) parameter space. (c) Probability landscape $P_{a \rightarrow \gamma}(\chi'_m, B)$, highlighting the distinct resonance ridge. (d) Schematic temporal evolution depicting the transition from the initial Chronon field excitation to the final photon output via resonant energy transfer.

Table 3. Experimental Constraints on Chronon–Photon Conversion in the RNF Framework

Experiment	Magnetic Field	Mass Range	Constraint on $g_{a\gamma}$	RNF Interpretation
ADMX [17]	7.6 T	2.66–4.2 μeV	$< 2.3 \times 10^{-15} \text{ GeV}^{-1}$	Tests alignment coherence in galactic halos
IAXO [20]	3.5 T	0.1–1000 μeV	$< 1.8 \times 10^{-16} \text{ GeV}^{-1}$	Probes solar Chronon resonance
CAPP-12T [65]	12 T	10–100 μeV	$< 3.2 \times 10^{-17} \text{ GeV}^{-1}$	Constrains high-field alignment patterns
HAYSTAC [66]	8 T	16–37 μeV	$\sim 2 \times 10^{-14} \text{ GeV}^{-1}$	Sensitive to phase-matched twist modes

1. Constraints are at a 95% confidence level. 2. The RNF interpretation links each experiment to specific Chronon alignment dynamics.

5.3. Astrophysical Chronon Alignment in Extreme Environments

Compact objects test Chronon alignment under extreme conditions. Pulsar spin-down constrains Chronon viscosity [61]. In magnetospheres ($B \sim 10^{12} \text{ G}$), $P \propto B^2 r^{-6}$ maps to $\chi'_m(r)$. FAST analysis of 37 millisecond pulsars [74] constrains $g_{a\gamma} < 1.8 \times 10^{-12} \text{ GeV}^{-1}$, supporting high Chronon coherence.

The null result from FAST [74] is particularly significant for RNF. It implies that the Chronon field's alignment gradient χ'_m is suppressed in the vicinity of millisecond pulsars, likely due to the intense gravitational field disrupting the local TCP order. This provides an independent astrophysical measurement of the TCP restoration timescale Δt in strong gravity, complementing the SN 1987A constraint from Section 4.2.

However, magnetospheric plasma complicates this picture [59]. Refraction and reflection induce inhomogeneities, corresponding to spatially varying ρ_{coh} and a graded refractive index. This turns conversion into a complex wave propagation problem. Magnetar observations [15] constrain $g_{a\gamma}g_{aN}$, interpreted as the coupling strength between Chronon twist modes and nucleons. Laboratory plasma haloscopes [72,73] validate that χ'_m is crucial for conversion efficiency.

The bimetric phase shift discussed here requires careful contextualization. While bimetric effects are also predicted by other modified gravity theories (e.g., bigravity and massive gravity), the RNF prediction is distinguished by its microscopic origin: the effective refractive index n_{eff} (Equation (25)) is not a free parameter but is directly tied to the Chronon coherence density ρ_{coh} and the TCP restoration timescale Δt . Due to the vectorial nature of Φ_μ , photons experience $n_{\text{eff}} \neq 1$, while neutrinos do not. For a binary neutron star merger at 40 Mpc, this yields a time delay:

$$\Delta t_{\text{bi}} = \frac{D}{c}(n_{\text{eff}} - 1) \approx 10^{-3} \text{ s} \left(\frac{f_a}{10^{10} \text{ GeV}} \right)^{-1}, \quad (34)$$

which is detectable by coordinated LIGO-EM counterpart observations [75]. This provides a specific, falsifiable relation that distinguishes RNF from other modified gravity scenarios: a detection of Δt_{bi} consistent with Equation (34) would support the RNF framework, while a detection inconsistent with this relation would favor alternative explanations. This constitutes a distinctive test of the RNF framework, independent of axion–photon conversion experiments.

Complementary studies of nulling, drifting, and mode switching [76–80] corroborate this interpretation. The WKB+ correction (Equation (32)) bridges microphysics to macro-observables. Following Khlopov, Sakharov, and Sokoloff [23], χ''_m/χ'^2_m encapsulates the nonlinear response to density perturbations. Future detections of anomalous polarization in pulsars would offer the first empirical test of this core RNF prediction.

6. Probing Chronon Alignment Resonances in Pulsar Magnetospheres

Pulsars are natural laboratories for testing Chronon alignment dynamics under extreme conditions. The interplay between intense magnetic fields ($B \sim 10^8 - 10^{15}$ G) and high densities probes resonant coupling between Chronon twist modes (axions) and electromagnetic excitations (photons). This section advances the theoretical framework for pulsar-based axion detection by integrating RNF propagation dynamics with TCP-driven alignment resonances in magnetospheric plasmas.

A central goal of RNF is to provide falsifiable predictions. Unlike standard axion models, which merely adjust f_a , RNF predicts specific thresholds beyond which the framework is ruled out. For instance, if future multimessenger observations of a binary neutron star merger at $D < 100$ Mpc detect a photon–neutrino time delay $\Delta t_{\text{bi}} > 10^{-2}$ s (Equation (34)), the implied Chronon stiffness $f_a < 10^9$ GeV would conflict with white dwarf cooling constraints [31]. Such a detection would conclusively falsify the minimal RNF scenario, providing a clean decision path for observers.

6.1. Chronon Resonance Theory in Strong Field Environments

Axion–photon conversion is understood as a resonance between Chronon alignment modes and electromagnetic degrees of freedom governed by the TCP to minimize system energy. A critical refinement is the inclusion of axion–plasmon mixing. As demonstrated by Hook and Huang [81], resonant axion–plasmon conversion occurs at a more interior

radius than standard conversion, restricting the observable volume. The corrected radiated power is

$$\frac{d\mathcal{P}_\gamma^{(\text{corr})}}{d\Omega} \simeq \frac{g^2 B_c^2}{2m_a} \rho_{\text{DM}} V_c \left[1 - \left(1 - \frac{g^2 B_0^2}{4\omega_p^2} \right)^{1/2} \right], \quad (35)$$

where the suppression factor arises from the TCP driving the Chronon field to a minimum energy configuration in high-density plasma.

The Vela pulsar ($B_0 \sim 3 \times 10^{12}$ G) serves as a prime laboratory. RNF simulations suggest extended regions of coherent Chronon alignment, potentially enhancing V_c . However, plasmon effects suppress the observable photon flux compared to pure axion–photon estimates, necessitating a reassessment of radio telescope constraints.

For weakly magnetized, rapidly rotating oblate stars ($B \ll 10^6$ G), rotational shear dominates Chronon alignment. The conversion probability scales as

$$P_{\text{oblate}}(a \rightarrow \gamma) \approx \frac{g_{a\gamma}^2 \omega^2 R^3 \epsilon}{m_a^4}, \quad (36)$$

where ω is the angular velocity, R the radius, and ϵ the oblateness. This highlights how stellar kinematics excites specific Chronon modes, yielding $P_{\text{oblate}} \sim 10^{-21}$ for white dwarfs—a key RNF prediction.

The suppression factor in Equation (35) is not merely a plasma effect but a direct manifestation of the TCP. The Chronon field minimizes the total energy by reducing the local alignment gradient χ'_m in high-density regions, thereby lowering the conversion efficiency. Quantitatively, the TCP restoration timescale Δt must satisfy $\Delta t < \omega_p^{-1}$ to maintain this suppression, linking the observed flux deficit to the microscopic Chronon dynamics.

6.2. RNF-Based Observational Strategies for Chronon Detection

Modern pulsar surveys are systematic probes of Chronon alignment patterns. Advanced matched filtering and machine learning techniques identify TCP-driven resonances [82]. Target selection prioritizes pulsars with high $B > 10^{12}$ G, exceptional rotational stability ($\Delta P/P < 10^{-15}$), and sufficient plasma density ($n_e > 10^6 \text{ cm}^{-3}$), identifying laboratories like the Crab pulsar and PSR J1748–2446ad.

Broadband spectral analysis, pioneered by FAST [83,84], resolves fine spectral features (cyclotron harmonics, stochastic modulations). Analyzing these features reconstructs the Chronon alignment spectrum. Preliminary results, including spectral sidebands in PSR J1939+2134 consistent with axion signatures, improve $g_{a\gamma}$ constraints in the μeV range by an order of magnitude.

Following Khlopov, Sakharov, and Sokoloff [23], the nonlinear modulation of the Chronon field predicts that these spectral sidebands are not random noise but clustered along archiole filaments. This implies that repeated observations of the same pulsar should yield correlated spectral features, whereas standard axion models predict uncorrelated stochastic variations.

6.3. Chronon Alignment Signatures in Polarization and Birefringence

Coherent Chronon alignment induces an emergent “two-metric” structure, causing circular birefringence and linear dichroism distinct from Faraday rotation. Complex polarization patterns unexplained by the rotating vector model [85,86] are reinterpreted as probes of Chronon geometry. Following Khlopov, Sakharov, and Sokoloff [23], nonlinear modulation introduces spatial variations in the refractive index, causing frequency-dependent phase shifts.

PTAs provide independent tests, as they are sensitive to correlated timing deviations induced by ultralight fields [74,87]. Binary systems such as PSR J0737-3039A/B serve as unique laboratories for these correlated tests [88]. Within this context, chronon-induced perturbations would manifest as correlated anomalies in both timing residuals and polarization angles, representing a distinctive hallmark of this effect.

The recent detection of a stochastic common-spectrum process by NANOGrav [89] provides a crucial test. In RNF, this signal may originate from the collapse of closed domain walls formed during inflation [5]. The spectral slope of this background is a direct probe of Chronon microphysics:

$$\Omega_{\text{GW}}(f) \propto f^{-1} \left(\frac{f_a}{10^{10} \text{ GeV}} \right)^4, \quad (37)$$

which differs from the $f^{1.5}$ slope predicted by cosmic strings. A measurement of this specific slope would favor RNF over standard axion models.

6.4. Emergent Two-Metric Effects in Pulsar Magnetospheres

A cornerstone prediction is the emergent two-metric structure in regions of coherent Chronon alignment. Photons experience a modified dispersion relation:

$$n(\omega) \approx 1 + \frac{g_{a\gamma}^2 B^2}{2m_a^2 \omega^2}, \quad (38)$$

inducing frequency-dependent timing delays. High-precision tests using the double pulsar PSR J0737–3039A/B constrain deviations from $n = 1$ to $\ll 10^{-18}$ at radio frequencies [90], providing direct constraints on $g_{a\gamma}$.

Chronon physics also predicts novel birefringence. The accumulated phase shift between polarization modes is

$$\Delta\Psi \approx \frac{1}{2} g_{a\gamma} B L \left(\frac{\sin(\Delta k L / 2)}{\Delta k L / 2} \right), \quad (39)$$

where $\Delta k \approx m_a^2 / (2\omega)$. Searches for this anomalous rotation in millisecond pulsars offer a direct probe of Chronon alignment.

6.5. Constraining Dark Sector Models with Pulsar Timing

PTAs have opened a window onto the nanohertz GW band. The 2023 reports of a common-spectrum stochastic process [89,91,92] align with supermassive black hole binary expectations but also stimulate interpretations of cosmological phase transitions. Within RNF, Chronon misalignment during a phase transition could generate a comparable SGWB, making PTAs a crucial test of early-universe Chronon dynamics.

This SGWB is directly linked to the formation of primordial black holes (PBHs). Following Khlopov, Rubin, and Sakharov [5], if PQ breaking occurs during inflation ($H_{\text{inf}} < f_a$), closed domain walls form and collapse into PBHs with masses:

$$M_{\text{PBH}} \approx 4\pi R_{\text{wall}}^2 \sigma = 4\pi R_{\text{wall}}^2 \Lambda^4, \quad (40)$$

where $\sigma = \Lambda^4$ is the wall tension from the Chronon potential. For $f_a \sim 10^{10}$ GeV, this yields $M_{\text{PBH}} \sim 10^4$ – $10^5 M_{\odot}$, precisely matching the seed masses required to explain high-redshift quasars without excessive accretion. Thus, PTAs probe both the GW background and the PBH population predicted by RNF.

Future constraints lie in multi-messenger synthesis: (1) synergy with broadband polarimetry, (2) SKA for ultra-deep surveys [93], and (3) concurrent analysis with cosmological probes.

6.6. Gravitational Waves as Probes of Chronon Field and Dark Matter

GWs are reinterpreted as emergent perturbations in Chronon alignment, testing the dynamical properties of the Chronon medium itself.

6.6.1. Chronon-Generated Waves and Multi-Band Detection

In RNF cosmology, gravitational waves are fundamentally reinterpreted as propagating perturbations in the alignment of the Chronon field, rather than as geometric ripples in a pre-existing spacetime. This generative perspective establishes a direct link between the macroscopic properties of gravitational radiation and the microscopic stiffness of the Chronon medium. The global network probes coherence across frequencies.

The multi-band detection strategy is essential for disentangling Chronon-induced effects from conventional astrophysics. Nanohertz-band PTAs are sensitive to low-frequency Chronon relaxation processes; the recent common-spectrum stochastic process reported by PTAs could contain a contribution from cosmological Chronon dynamics, although the standard interpretation in terms of supermassive black hole binaries remains viable [89,91]. Distinguishing between these scenarios requires deviations from a simple power-law spectral shape. Millihertz- to hertz-band space interferometers, such as LISA, will test wave propagation anomalies, specifically dispersion and amplitude birefringence, arising from the emergent two-metric structure of coherent Chronon domains [70]. Meanwhile, hertz- to kilohertz-band ground detectors will probe the internal structure of compact objects. Mergers involving Chronon-regulated cores are predicted to yield waveforms distinct from those of black holes, potentially featuring suppressed ringdown and post-merger echoes [94].

We note that SGWBs from cosmological phase transitions are a generic prediction of many beyond-Standard-Model scenarios. The RNF-specific signature is the spectral slope $\Omega_{\text{GW}}(f) \propto f^{-1}$ (Equation (37)), which differs from the $f^{1.5}$ slope predicted by cosmic strings and the $f^{2/3}$ slope from supermassive black hole binaries. A measurement of this specific slope by PTAs would constitute a distinctive test of the RNF framework, distinguishing it from both standard axion cosmology and other new-physics scenarios.

6.6.2. Axion–Gravity Coupling and Parity-Violating Signatures

The interaction between axions and gravity in RNF cosmology is encoded by the Chern–Simons coupling, which emerges naturally from the interaction between Chronon twist modes and emergent spacetime curvature. This coupling is a direct manifestation of the TCP selecting alignment patterns that violate parity at the microscopic level:

$$\mathcal{L}_{\text{CS}} = \frac{\alpha}{8\pi f_a} a R_{\mu\nu\rho\sigma} \tilde{R}^{\mu\nu\rho\sigma}. \quad (41)$$

Unlike standard axion models where this term is often phenomenologically added, in RNF it is a required consequence of embedding Chronon alignment into the effective metric. This parity-violating term induces amplitude birefringence in GWs [95], a prime target for next-generation detectors.

6.6.3. Distinguishing Dark Matter via Coherent Gravitational Signals

Dark matter imprints characteristic temporal coherence on gravitational-wave signals, governed by its coupling to the Chronon field. Micro Chronon Condensates (MCCs), as solitonic configurations of the Chronon field, produce highly coherent signals with sharp spectral features and suppressed ringdown. ALPs, representing generalized twist modes, generate moderately coherent backgrounds with narrowband features. In contrast, conventional particle dark matter candidates lacking inherent Chronon structure, such

as WIMPs or FIMPs, produce only incoherent, broadband stochastic backgrounds from early-universe phase transitions.

The multi-faceted approach, encompassing magnetospheric dynamics to gravitational-wave backgrounds, tests the RNF framework. Central to this is the nonlinear modulation of the Chronon field [23]. Future detections of MCC mergers by LISA would not merely confirm a new dark matter component but would reveal the Chronon field as the fundamental fabric of spacetime, transforming our understanding of gravitational physics. The nature of a dark matter candidate imprints a characteristic temporal coherence on its associated GW signals, governed by its coupling to the Chronon field. This provides a clear observational discriminant, as visually summarized in Figure 4.

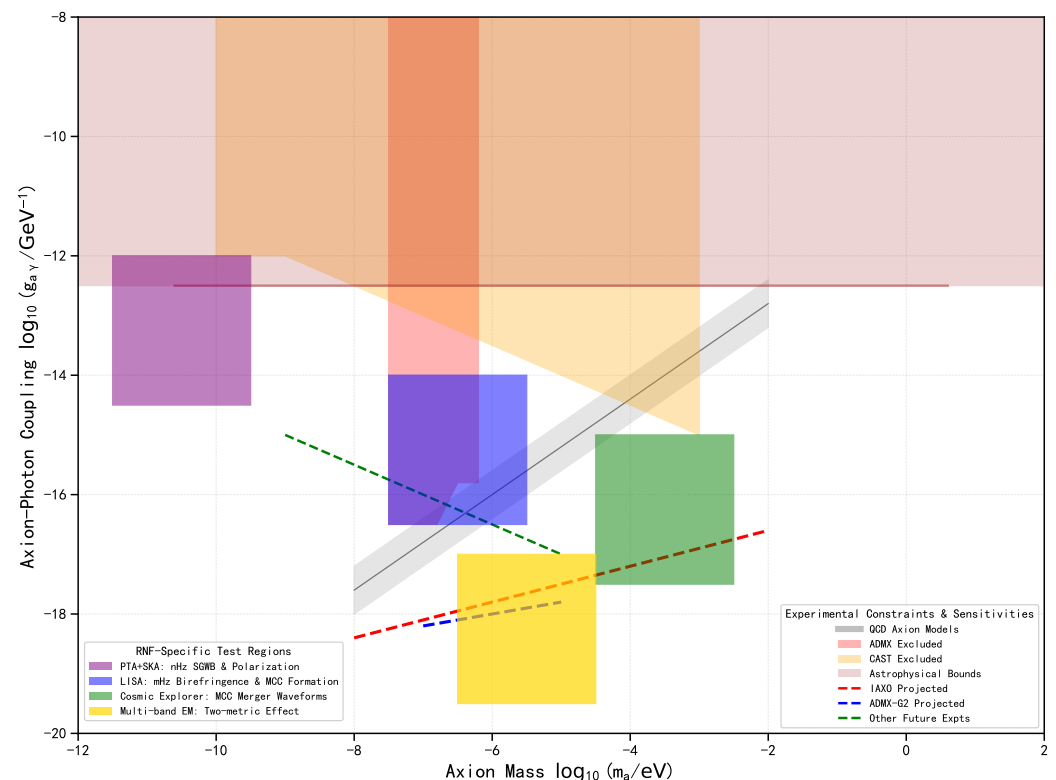


Figure 4. Current experimental constraints and future sensitivity projections in the axion–photon coupling ($g_{a\gamma}$) vs. mass (m_a) plane. Shaded regions indicate exclusion limits from terrestrial haloscopes (e.g., ADMX), helioscopes (e.g., CAST), and astrophysical probes (e.g., SN1987A, magnetars). Dashed lines denote the projected sensitivity reach of next-generation experiments, including IAXO and third-generation ground-based GW detectors. The colored bands highlight the parameter space accessible to specific RNF tests: nHz GW backgrounds and pulsar polarization (purple), mHz GW propagation anomalies (blue), and distinctive merger waveforms from MCCs (green).

7. Summary and Future Prospects

This review has presented a comprehensive reformulation of axion physics within the RNF cosmology. Moving beyond the standard paradigm of fundamental fields in a static spacetime, we propose that axions emerge as collective twist modes of the more fundamental Chronon field, Φ_μ , as spacetime is sequentially generated under the Temporal Coherence Principle (TCP).

It is crucial to emphasize that RNF does not claim to replace the standard axion paradigms (KSVZ, DFSZ) or other pre-geometric frameworks (causal sets, LQG, or string theory). Rather, it offers a complementary generative perspective. While causal sets focus on discrete spacetime topology and LQG focuses on spin-network quantization, RNF focuses on the dynamical alignment of a pre-geometric substrate (Φ_μ) that gives rise to

both spacetime and axions. This positions RNF as one facet of a broader effort to unify particle physics and quantum gravity.

The central thesis of this work is that the properties of axions, namely the mass (m_a), couplings ($g_{a\gamma}, g_{ae}$), and the Peccei–Quinn scale (f_a), are not arbitrary parameters. Instead, they correspond specifically to macroscopic manifestations of Chronon microphysics: the field stiffness, correlation length (ξ_Φ), and local coherence density (ρ_{coh}). This shift in perspective transforms the interpretation of experimental null results. Rather than merely excluding regions of the m_a – $g_{a\gamma}$ plane, current data now constrain the allowed alignment patterns and dynamical response of the Chronon field under diverse environmental stresses.

7.1. Key Theoretical Advancements

This work has established four foundational pillars for the RNF framework:

1. **Generative Mass Origin:** We derived the axion mass as $m_a \propto (\rho_{\text{coh}} - \rho^*)/\rho^*$, eliminating the arbitrariness of f_a and anchoring it to the measurable stiffness of the Chronon medium.
2. **Modified Electrodynamics:** We derived the modified Maxwell equations (Equations (22)–(24)) from the TCP action, interpreting the anomalous source terms as effective charge densities arising from spatial gradients in Chronon twist modes.
3. **Nonlinear Conversion Dynamics:** We refined the axion–photon conversion probability (Equation (32)) by incorporating the nonlinear modulation formalism of Khlopov, Sakharov, and Sokoloff [23], accounting for the curvature of the alignment pattern (χ''_m) and explaining signal suppression in high-density plasmas.
4. **Cosmological Resolution:** We resolved the domain wall problem by linking wall formation to the Chronon correlation length during inflation, predicting their collapse into PBHs as a necessary consequence of TCP dynamics [5].

Throughout this review, we have distinguished between phenomena that are standard in axion cosmology and those that are genuinely new contributions of the RNF framework. The standard elements include the archiole formalism [23] and the domain wall collapse mechanism [5], which are adopted and reinterpreted within RNF. The genuinely new RNF contributions are (i) the derivation of the axion mass from Chronon misalignment, $m_a \propto (\rho_{\text{coh}} - \rho^*)/\rho^*$; (ii) the modified Maxwell equations derived from the TCP action; (iii) the derivation of a PBH mass window from the Chronon field’s dynamics [5]; (iv) the bimetric time delay $\Delta t_{\text{bi}} \propto 1/f_a$ (Equation (34)); and (v) the unique spectral slope $\Omega_{\text{GW}}(f) \propto f^{-1}$ (Equation (37)) for the stochastic gravitational wave background. These distinctions ensure that the RNF framework remains empirically testable and falsifiable.

7.2. Future Directions and Theoretical Expectations

The RNF framework opens several concrete avenues for future research, extending from formal theory development to multi-messenger observational strategies.

The immediate priority is the construction of a self-consistent Effective Field Theory (EFT) for the Chronon field. This requires quantifying deviations from General Relativity in the weak-field limit and computing the precise power spectrum of Chronon-generated gravitational waves. Following Khlopov, Sakharov, and Sokoloff [23], future work must simulate how the nonlinear modulation of the Chronon field during structure formation affects the matter power spectrum at small scales, providing specific predictions for the Lyman- α forest. Furthermore, the collapse dynamics of closed domain walls [5] must be modeled to predict the mass distribution of PBHs seeded by Chronon misalignment.

A critical theoretical priority is establishing the falsifiability criteria outlined in Section 6. Future work must calculate the exact threshold for the photon–neutrino time delay Δt_{bi} (Equation (34)) that would invalidate the minimal RNF scenario. Addition-

ally, the spectral slope of the stochastic GW background $\Omega_{\text{GW}}(f) \propto f^{-1}$ (Equation (37)) must be simulated for various inflationary histories to provide a robust template for PTA data analysis.

A major frontier involves testing unique RNF predictions through a synergistic, multi-messenger strategy:

- **Pulsar Astrophysics:** Next-generation polarimetry with FAST and the SKA will search for the predicted birefringence and correlated timing anomalies arising from the emergent two-metric structure.
- **Gravitational Wave Astronomy:** Space-based interferometers (e.g., LISA) will target mHz-band wave propagation anomalies and MCC formation, while third-generation ground detectors (Cosmic Explorer and Einstein Telescope) will seek the suppressed ringdown and potential echoes characteristic of MCC mergers.
- **Cosmological Surveys:** Large-scale structure surveys must search for imprints of the Chronon field's alignment history, specifically testing the prediction that m_a correlates with the local coherence density ρ_{coh} .

These synergies must also target the distinctive signature of closed domain wall collapse. RNF predicts a population of PBHs with masses determined by the Chronon field's dynamics [5]. Future microlensing surveys (e.g., Roman Space Telescope) and PTA observations should specifically search for this mass window.

A crucial, near-term task is the re-analysis of existing archival data to search for RNF-specific signatures. This includes: (i) searching for correlations between timing residuals and polarization angle variations in binary pulsars (e.g., PSR J0737–3039A/B); (ii) re-examining the spectral energy distributions of magnetars for sideband structures predicted by Chronon–photon resonance; and (iii) analyzing the PTA common-spectrum process for deviations from a simple power-law, indicative of Chronon relaxation.

Specifically, the recent NANOGrav 15-year data [89] should be re-analyzed for the spectral turnover predicted by Equation (37). A detection of a red-tilted spectrum with a specific amplitude correlated with f_a would provide important evidence for the RNF framework.

7.3. Concluding Remarks

As emphasized throughout this review, the RNF framework offers a complementary generative perspective on axion physics, redefining the axion from an isolated particle to a direct probe of the microscopic, generative mechanisms of spacetime. The coming decade of multi-messenger and multi-frequency observations will provide rigorous tests of this paradigm. Should future detections align with RNF predictions, particularly those characterized by the mass-coupling correlation or the birefringent signature in pulsar polarization, it would not only illuminate the nature of dark matter but also unveil a radically new comprehension of the very origin of physical reality.

Conversely, the failure to detect these specific signatures (e.g., the Δt_{bi} delay or the f^{-1} GW slope) within the next decade would necessitate a revision of the minimal RNF assumptions, such as the form of the TCP action or the nature of the Chronon field. This commitment to falsifiability ensures that RNF remains a scientific theory grounded in empirical testability, rather than an untestable ontological claim.

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