

Cosmochrony: An Exploratory Geometric Framework for Emergent Spacetime, Gravitation, and Quantum Phenomena

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Abstract

We present *Cosmochrony*, a continuous pre-geometric framework in which time, spacetime structure, gravitation, and quantum phenomena emerge from the irreversible relaxation of a single scalar field χ . The field χ is not defined on a pre-existing spacetime manifold; rather, physical notions of time and geometry arise as effective descriptions of the ordering and correlations induced by its monotonic relaxation.

Irreversibility is interpreted energetically, with energy understood as the residual capacity of χ configurations to relax. Spatial relations are defined operationally through gradients and correlations of χ , without postulating a fundamental metric. Matter is described as stable, localized topological configurations of the field, whose presence locally constrains relaxation and gives rise to gravitational time dilation and effective spacetime curvature.

Quantum phenomena are interpreted as effective descriptions of coherent fluctuations around such solitonic configurations. Entanglement reflects the persistence of shared χ configurations across spatial separation, leading to nonlocal correlations without superluminal signaling, local hidden variables, or fundamental wavefunction collapse.

General relativity and quantum mechanics are not assumed at the fundamental level, but emerge as coarse-grained formalisms valid in regimes where χ admits a stable geometric description. Cosmological expansion follows directly from the global relaxation of χ , yielding a geo

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1 Introduction

Modern fundamental physics is built upon two highly successful yet conceptually distinct frameworks: quantum mechanics and general relativity [1, 2]. Quantum theory accurately describes microscopic phenomena, while general relativity provides a geometric account of gravitation and spacetime dynamics at macroscopic and cosmological scales. Despite their empirical success, these theories rely on incompatible foundational assumptions and resist unification within a single coherent conceptual framework [3–5].

Quantum mechanics presupposes a fixed spacetime arena in which physical states evolve, whereas general relativity identifies spacetime geometry itself as a dynamical entity. Numerous approaches have attempted to bridge this tension, including quantum field theory in curved spacetime, canonical and covariant quantum gravity programs, and string-based or holographic frameworks. While these approaches have led to important theoretical developments, they typically introduce extended mathematical structures or additional degrees of freedom whose physical interpretation and empirical accessibility remain unclear.

In this work, we explore a complementary and deliberately minimalist framework, referred to as *Cosmochrony*. The central hypothesis is that spacetime geometry, gravitation, and quantum phenomena emerge from the dynamics of a single continuous scalar quantity, denoted χ . The field χ is not defined on a pre-existing spacetime manifold, nor is it interpreted as a conventional physical field propagating within spacetime. Rather, spacetime notions themselves arise as effective descriptions of the relational and dynamical properties of χ configurations.

The fundamental dynamical postulate of Cosmochrony is that χ undergoes an irreversible relaxation process, locally bounded by an invariant propagation speed c . This monotonic evolution provides an intrinsic ordering of physical processes, identified with physical time. Spatial relations emerge relationally from differences, gradients, and correlations of χ once a stable geometric regime is reached. Within this perspective, spacetime expansion, gravitation, particle-like excitations, radiation processes, and quantum correlations are not fundamental ingredients, but emergent phenomena associated with specific configurations or interactions of the underlying field.

Cosmochrony does not aim to replace the Standard Model or general relativity in their empirically validated domains, nor does it claim to provide a final unification of quantum theory and gravitation. Instead, it offers an exploratory and internally coherent framework designed to clarify the physical origin of time, geometry, gravitation, and quantum correlations within a single scalar dynamics. Standard geometric and quantum formalisms are recovered only at an effective, coarse-grained level, applicable when χ admits a stable spacetime interpretation.

Accordingly, quantities such as coordinates, metric structure, variational principles, and differential geometry are not treated as fundamental. They are employed later in the paper as emergent descriptive tools, rather than as primary postulates of the theory. Technical reconstructions and mathematical details are therefore confined to the appropriate effective regimes and collected in the appendices.

The structure of the paper is as follows. Sections 2–4 introduce the conceptual motivations and minimal dynamical assumptions governing the χ substrate. Subsequent sections examine how particle-like excitations, gravitation, quantum correlations, and cosmological behavior emerge in appropriate regimes. For convenience, a glossary summarizing the main quantities and operators used throughout the article is provided in Appendix F.

1.1 Conceptual Context and Related Approaches

The idea that spacetime geometry and gravitation may be emergent rather than fundamental has been explored in a variety of recent theoretical frameworks. Several approaches treat the spacetime metric as an effective description arising from deeper geometric, informational, or dynamical structures, and interpret gravitation as a collective or emergent phenomenon rather than a fundamental interaction[6, 7].

Like Loop Quantum Gravity (LQG), Cosmochrony posits that spacetime geometry is not fundamental but emerges from a deeper, pre-geometric structure. However, while LQG relies on spin networks and holonomies, Cosmochrony introduces a single scalar field χ whose relational dynamics encode both spatial and temporal properties. This

minimalist approach offers a complementary perspective on the emergence of gravity and quantum phenomena.

For convenience, a glossary summarizing the main quantities and operators used throughout the article is provided in Appendix F.

2 Theoretical Context and Motivation

2.1 Conceptual Tension Between Quantum Theory and Gravitation

Quantum mechanics and general relativity differ not only in their mathematical formalisms, but also in their foundational concepts. Quantum theory is intrinsically probabilistic, relies on a fixed causal structure, and treats time as an external parameter [8, 9]. General relativity, by contrast, describes gravitation as the dynamics of spacetime geometry itself, with time acquiring a coordinate-dependent and observer-relative status [3, 10].

This conceptual mismatch becomes particularly acute in regimes where both quantum effects and strong gravitational fields are expected to be relevant, such as near spacetime singularities or in the early universe [11, 12]. Direct attempts to quantize gravity encounter persistent difficulties, including the problem of time, non-renormalizability, and the absence of a preferred background structure.

2.2 Limitations of Existing Unification Approaches

Several major research programs have sought to address these challenges. Quantum field theory in curved spacetime successfully accounts for particle creation and vacuum effects, but retains a classical spacetime background [13]. Canonical and covariant approaches to quantum gravity attempt to quantize spacetime geometry itself, often at the cost of substantial mathematical complexity and interpretational ambiguity.

String theory and related frameworks introduce extended fundamental objects and higher-dimensional structures, offering deep mathematical unification but leading to a large space of possible low-energy realizations [5]. While internally rich, these approaches face ongoing challenges concerning empirical testability and physical interpretation.

These limitations motivate the exploration of alternative perspectives in which spacetime geometry, matter, and quantum behavior are not separately postulated, but emerge from a common underlying mechanism.

2.3 Minimalism as a Guiding Principle

The framework developed in this work adopts minimalism as a guiding principle. Rather than introducing multiple fundamental fields, additional dimensions, or independent quantization rules, we explore whether a single continuous scalar quantity can account for both temporal ordering and spatial relations.

The scalar quantity χ is not interpreted as a conventional matter field, nor as a component of spacetime geometry. Instead, it represents a pre-geometric substrate whose irreversible relaxation underlies the emergence of both duration and separation.

In this view, time and space are not independent primitives, but complementary aspects of a single dynamical process.

2.4 Time, Irreversibility, and Cosmological Expansion

A central motivation for the Cosmochrony framework is the close connection between time, irreversibility, and cosmological expansion. In standard cosmology, expansion is described kinematically through the scale factor, while the arrow of time is typically attributed to boundary conditions or entropy growth [11, 12, 14].

In Cosmochrony, the monotonic relaxation of χ provides a unified origin for both phenomena. Irreversibility follows directly from the intrinsic directionality of the relaxation process, while cosmological expansion is interpreted as its large-scale geometric manifestation. From this perspective, expansion does not require an externally imposed energy component, but arises as an emergent consequence of the underlying dynamics.

2.5 Scope and Limitations

The aim of this work is exploratory rather than definitive. Cosmochrony does not seek to replace established theories within their empirically validated domains, but to offer a coherent reinterpretation that may clarify persistent conceptual difficulties.

Throughout the paper, emphasis is placed on internal consistency, conceptual clarity, and qualitative contact with observable phenomena, while acknowledging open questions and limitations. In the following section, we introduce the scalar quantity χ formally and specify the minimal assumptions underlying its dynamics.

3 Definition and Fundamental Properties of the χ Field

Having outlined the ontological and conceptual principles underlying Cosmochrony, we now introduce the fundamental quantity at the core of the framework. This section is devoted to defining the scalar entity χ and clarifying its role as a pre-geometric substrate from which effective notions of spacetime, dynamics, and physical observables may emerge.

The purpose of this section is not to assume a pre-existing spacetime structure, but to identify the minimal properties required of χ in order to recover, in appropriate regimes, effective descriptions of time, space, metric geometry, and field dynamics. Accordingly, χ is introduced independently of any spacetime coordinates or metric structure, and only later related to geometric notions once a stable spacetime interpretation becomes meaningful.

Throughout this section, the use of variational principles, Lagrangian formulations, or metric-based expressions does not imply that spacetime or a four-dimensional manifold is fundamental. Such formalisms are employed strictly as effective, coarse-grained tools to describe the dynamics of χ in regimes where its configurations admit a geometric interpretation. They should be understood as descriptive representations of the underlying pre-geometric dynamics, not as primary postulates of the theory.

We begin by providing a unified conceptual definition of the χ field and its physical interpretation. The subsequent subsections introduce progressively more structured effective descriptions, including Lagrangian and metric formulations, which become applicable only once the underlying χ configurations support a stable spacetime regime.

3.1 Definition of the χ Field

We postulate the existence of a single fundamental scalar quantity, denoted χ , which constitutes the primitive substrate of physical reality. The quantity χ is not defined on a pre-existing spacetime manifold and does not presuppose any metric, causal, or geometric structure. Instead, spacetime notions arise only as effective descriptions of the relational and dynamical properties of χ configurations.

Ontologically, χ is a real scalar order parameter whose value characterizes the local geometric state of the underlying substrate. It carries the dimension of length, interpreted as a characteristic scale associated with physical processes. This scale does not evolve *in time*; rather, its monotonic and irreversible relaxation defines what is operationally perceived as the flow of time.

Temporal ordering emerges from the global, monotonic evolution of χ across physical processes, establishing an intrinsic arrow of time without reference to an external temporal coordinate. Spatial separation, in turn, arises from relational differences between χ configurations, giving rise to an effective notion of distance once a stable geometric regime is established. In this sense, time corresponds to ordering, while space corresponds to relational structure.

At no stage is χ interpreted as a spacetime coordinate or as a material field propagating on spacetime. Spacetime coordinates and metric structure appear only as secondary, coarse-grained constructs, becoming meaningful when χ configurations admit a quasi-stable geometric interpretation. The spacetime metric thus functions as an emergent, effective descriptor of resistance to χ relaxation¹ and of the propagation of perturbations within the field.

This role of χ is analogous to that of thermodynamic order parameters such as temperature: it encodes collective geometric information about an underlying substrate without being itself a fundamental spacetime entity. In the Cosmochrony framework, χ therefore provides the minimal ontological basis from which time, space, gravitation, and quantum phenomena jointly emerge.

In the following sections, spacetime coordinates and metric quantities will be introduced strictly as effective tools, valid in regimes where χ admits a stable geometric interpretation.

On the use of spacetime language.

Throughout this work, phrases such as “spacetime coordinates,” “metric tensor,” and “four-dimensional manifold” appear frequently, for the sake of clarity and effective description. These should be understood as *emergent effective descriptions* valid in regimes where χ has relaxed into a quasi-stable geometric configuration. They are not fundamental ingredients of the theory.

¹The term “relaxation” is used here in a geometric and dynamical sense, and should not be confused with thermodynamic relaxation processes involving dissipation or entropy increase.



Fig. 1 Conceptual representation of Cosmochrony. An effective spacetime depiction of the relaxation of the scalar quantity χ , used for visualization purposes only. The monotonic relaxation of χ gives rise to an effective temporal ordering, while localized topological excitations correspond to particle-like configurations in the emergent geometric regime.

At the deepest level, only χ and its local variation structure exist. The appearance of familiar geometric language reflects the effectiveness of spacetime as a coarse-grained description of collective χ behavior, analogous to how thermodynamic variables (temperature, pressure) emerge from molecular dynamics without those variables being fundamental.

This interpretational stance is essential for distinguishing Cosmochrony from approaches that merely reformulate existing geometric theories in different variables.

3.2 The Geometric Effective Description of χ Dynamics

Interpretational caution.

The following discussion introduces effective geometric language (such as “metric”, “distance”, or “spacetime”) solely as a descriptive tool to characterize the relational structure of χ configurations in regimes where a quasi-stable geometric interpretation emerges. These are not fundamental ingredients of the theory, but derived constructs valid only when χ admits a smooth, macroscopic description.

3.2.1 Effective Observables from χ Correlations

In Cosmochrony, geometric notions—time intervals, spatial separations, and causal structure—emerge from the relational properties of χ configurations. No background spacetime or discrete structure is assumed. Instead, observables are constructed directly from χ and its local variation structure.

Operational time intervals are defined by the accumulated relaxation of χ along a path in configuration space:

$$\tau_{AB} \propto \int_{\gamma_{AB}} \mathcal{D}_\lambda \chi d\lambda, \quad (1)$$

where γ_{AB} is a path connecting configurations A and B , and $\mathcal{D}_\lambda \chi$ is the relaxation rate of χ .

Operational spatial separation is quantified by the decay of χ correlations between two configurations:

$$d(x, y) \propto -\log \left(\frac{\langle \chi(x)\chi(y) \rangle}{\langle \chi^2 \rangle} \right), \quad (2)$$

where $\langle \chi(x)\chi(y) \rangle$ measures the correlation between configurations labeled by x and y . These definitions are purely relational and make no reference to a pre-existing metric or discrete structure. They are applicable whenever χ configurations exhibit stable patterns.

3.2.2 Effective Metric as a Descriptive Tool

In regimes where χ varies smoothly, the observables above can be summarized by an effective metric tensor $g_{\mu\nu}[\chi]$. This metric is not a fundamental object, but a compact representation of how χ correlations modulate causal connectivity and proper intervals.

The metric is introduced as a descriptive summary of χ correlations, not postulated as an independent degree of freedom. For example:

- The conformal (lightcone) structure is constrained by the maximal relaxation speed c of χ .
- Proper time between effective events is proportional to the accumulated χ relaxation along paths connecting the corresponding configurations.
- Spatial distance reflects the decay rate of χ correlations.

No discrete-to-continuum limit is invoked. The theory is continuous at all scales; apparent granularity (e.g., Planck-scale phenomena) is attributed to non-linear χ dynamics rather than to an underlying discretization.

No background $\eta_{\mu\nu}$ is assumed. Minkowski space appears only as a convenient approximation in suitable limits (e.g., weak-gradient regimes), without ontological status in the fundamental description.

3.2.3 Consistency with General Relativity

The effective metric $g_{\mu\nu}[\chi]$ constructed as a summary of χ correlations reproduces the phenomenology of general relativity in the following sense:

- **Weak-field limit:** when χ gradients are small, the effective metric approaches a form compatible with Einstein-like dynamics for a fluid-like stress-energy description associated with χ excitations.
- **Strong-field regimes:** near localized χ excitations (e.g., solitons), the metric encodes time dilation and spatial curvature as emergent effects of slowed χ relaxation, without requiring a fundamental gravitational field.
- **Cosmological expansion:** homogeneous relaxation of χ yields an effective Hubble-like expansion law for the emergent scale factor.

Crucially, this is not a bootstrap procedure. The metric is not iteratively reconstructed from χ ; it is a post-hoc descriptive tool summarizing geometric regularities of

χ configurations. The theory's predictive content resides in the dynamics of χ , not in the metric itself.

3.2.4 Ontological Status of the Metric

To avoid confusion, we emphasize:

- χ is the only fundamental field. Spacetime, metric structure, and matter are emergent descriptions of χ configurations.
- No “double ontology” is assumed: there is no underlying discrete graph or lattice. Geometric language is introduced only as an effective tool.
- The metric $g_{\mu\nu}[\chi]$ is an effective construct, analogous to how temperature emerges in thermodynamics. It is useful for coarse-grained description but plays no role in the fundamental dynamics.

3.2.5 Summary: A Fully Continuous Framework

- **Fundamental level:** only the continuous χ field exists, evolving through a monotonic relaxation dynamics.
- **Effective level:** geometric observables (time, distance, metric) emerge from χ correlations in suitable regimes.
- **No bootstrap:** the metric is never iteratively constructed or assumed; it is a derived description summarizing the relational structure of χ configurations.
- **No discretization:** apparent “Planck-scale” effects arise from non-linear χ dynamics, not from an underlying discrete substrate.

3.3 Physical Interpretation

The central interpretative assumption of Cosmochrony is that spacetime is not a static background, but an effective macroscopic description arising from the continuous relaxation of the scalar quantity χ . In regimes where a geometric interpretation becomes meaningful, variations of χ are reflected simultaneously in several emergent observables.

Specifically, an increase of χ is encoded in:

- the accumulation of local proper time along physical processes,
- the emergence of effective spatial separation between correlated configurations,
- the large-scale expansion of the universe when the relaxation of χ is considered globally.

Within this effective description, spatial distance and temporal duration are not independent primitives, but complementary aspects of the same underlying dynamics. Heuristically, distance may be viewed as accumulated (or “frozen”) relaxation, while time corresponds to locally ongoing (or “active”) relaxation. These expressions are intended as interpretative analogies rather than literal definitions, emphasizing that both quantities originate from the same scalar process.

This unified interpretation is not imposed ad hoc, but follows from identifying temporal ordering and spatial relations as distinct coarse-grained manifestations of the relaxation dynamics of χ .

3.4 Monotonicity and Arrow of Time

A fundamental postulate of Cosmochrony is that the scalar quantity χ undergoes a monotonic relaxation process [15, 16]:

$$\mathcal{D}_\lambda \chi \geq 0. \quad (3)$$

This monotonicity is not derived from statistical considerations, nor imposed as a thermodynamic boundary condition. Rather, it reflects a structural property of the χ field associated with the irreversible character of its relaxation dynamics. Within Cosmochrony, energy is not treated as a fundamental conserved substance, but as a measure of the residual capacity of a given χ configuration to relax. Only relaxation processes can dissipate this capacity, whereas a decrease of χ would correspond to a spontaneous reintroduction of contraction or tension into the field, for which no physical mechanism exists within the framework.

Irreversibility therefore follows naturally. A decrease of χ would imply a contraction of both temporal ordering and spatial relations, effectively recreating relaxation capacity, which is dynamically forbidden. The arrow of time is thus identified with the irreversible expenditure of the relaxation capacity of the χ field, rather than with a statistical entropy principle imposed at the outset.

3.5 Local Relaxation Speed

A fundamental constraint of the Cosmochrony framework is that the local relaxation rate of the scalar quantity χ is bounded by a universal constant:

$$|\mathcal{D}_{\text{loc}} \chi| \leq c, \quad (4)$$

where $\mathcal{D}_{\text{loc}} \chi$ denotes the maximal local rate of variation of χ across correlated configurations, and c coincides numerically with the observed speed of light.

This bound does not represent the propagation speed of particles or signals, nor does it presuppose a pre-existing spacetime structure. Rather, it characterizes the maximal rate at which effective causal relations and geometric structure can locally emerge from the relaxation of χ .

Superluminal recession velocities at cosmological scales arise naturally through cumulative and global effects of relaxation, and do not violate local causality, which remains constrained by the bound c .

3.6 Relation to Conventional Fields

Although χ may exhibit formal similarities with scalar fields employed in cosmology (such as inflaton-like fields) when expressed in effective spacetime descriptions, its ontological role is fundamentally different. The quantity χ is not a physical field propagating on spacetime, but a pre-geometric substrate from which spacetime notions themselves emerge.

Accordingly, χ does not carry energy in the conventional field-theoretic sense, nor is it subject to quantization at the fundamental level. Quantization arises only

at the effective level, where localized, stable excitations of χ admit a particle-like interpretation and can be described using standard quantum field-theoretic tools.

Within this framework, matter, radiation, and interactions do not correspond to independent fields coupled to χ . They emerge instead as localized excitations, constraints, or topological features of χ configurations, providing an effective description of familiar physical degrees of freedom in regimes where a spacetime interpretation applies.

3.7 Initial Conditions and Global Structure

The Cosmochrony framework assumes the existence of a lower bound χ_0 for the scalar quantity χ , corresponding to a regime of maximal relaxation density. This bound characterizes the earliest physically meaningful configurations of the field and does not presuppose a fundamental temporal origin.

In effective geometric descriptions, the scale associated with χ_0 coincides numerically with the Planck scale. This identification reflects the breakdown of coarse-grained spacetime concepts below this regime, rather than the presence of a fundamental cutoff or discrete structure.

Cosmic history is thus interpreted as the progressive global relaxation of χ away from this minimal bound. No spacetime singularity is required in the fundamental description; apparent singular behavior arises only when classical notions of time and distance are extrapolated beyond the domain in which χ admits a stable geometric interpretation.

In the next section, we derive a minimal dynamical equation governing the relaxation of χ and explore its immediate consequences.

4 Dynamical Equation for the χ Field

4.1 Parameter-Independent Relaxation

To avoid the conceptual pitfalls associated with a fundamental time coordinate, the dynamics of the scalar quantity χ is formulated without reference to any external temporal parameter. Instead, physical evolution is described as an ordered sequence of χ configurations, denoted (χ_λ) , where λ is a strictly monotonic ordering parameter labeling the relaxation process.

At the fundamental level, the dynamics of χ is defined by an intrinsic relaxation flow:

$$\mathcal{D}_\lambda \chi = \mathcal{R}[\chi], \quad (5)$$

where $\mathcal{R}[\chi]$ denotes the local rate of relaxation toward equilibrium, defined purely in terms of the relational structure of χ configurations. No spacetime derivative or geometric operator is assumed at this stage.

Quantities commonly interpreted as temporal derivatives arise only at the level of effective descriptions, when χ configurations admit a quasi-stable geometric interpretation. In such regimes, a coordinate time parameter may be introduced as a convenient label of the relaxation ordering, but it carries no fundamental significance and does not affect the underlying dynamics.

Within this framework, relaxation does not occur *in* time. Rather, the cumulative relaxation of χ defines what is operationally identified as physical duration. Local variations in the relaxation rate provide the effective measure of temporal flow, establishing a direct connection between the structure of χ configurations and the emergent notion of time.

4.2 Hamiltonian Derivation of the Evolution Equation

Effective Constraint on Local Relaxation

Although the fundamental dynamics of χ is formulated without reference to spacetime or a Hamiltonian structure, its relaxation is subject to universal local constraints. In regimes where χ configurations admit a stable geometric interpretation, these constraints may be summarized in a compact, Hamiltonian-like form.

Specifically, the local relaxation rate of χ is bounded by the invariant constant c . When expressed in effective geometric variables, this bound can be written as:

$$(\mathcal{D}_{\text{loc}}\chi)^2 + |\nabla\chi|_{\text{eff}}^2 = c^2, \quad (6)$$

where $|\nabla\chi|_{\text{eff}}$ denotes the effective magnitude of spatial variations of χ within the coarse-grained geometric description. This relation does not define a fundamental Hamiltonian, but provides a concise summary of the admissible local relaxation configurations.

Selecting the monotonic relaxation branch yields the effective evolution equation:

$$\mathcal{D}_{\text{loc}}\chi = c\sqrt{1 - \frac{|\nabla\chi|_{\text{eff}}^2}{c^2}}, \quad (7)$$

which encodes the slowdown of relaxation induced by structural variations of χ .

Emergent Gravitational Interpretation

Localized excitations of χ generate regions of enhanced relational structure, which locally reduce the relaxation rate. When interpreted in the effective spacetime description, this manifests as gravitational time dilation. No independent gravitational field is postulated; the effect arises directly from the constrained relaxation dynamics of χ .

In the weak-structure regime ($|\nabla\chi|_{\text{eff}} \ll c$), the effective description admits a simplified elliptic relation governing the spatial distribution of relaxation slowdown:

$$\nabla \cdot \left(\frac{\nabla\chi}{\sqrt{1 - |\nabla\chi|^2/c^2}} \right) \simeq \frac{4\pi G_{\text{eff}}}{c^2} \rho, \quad (8)$$

where ρ denotes the density of localized excitations and G_{eff} is an emergent coupling parameter characterizing the collective influence of such structures on the relaxation flow.

In the Newtonian limit, this reduces to an effective Poisson equation for a gravitational potential Φ defined by:

$$\Phi \equiv c^2 \ln \left(\frac{\mathcal{D}_{\text{loc}\chi}}{c} \right), \quad (9)$$

recovering standard gravitational phenomenology as a coarse-grained description of χ dynamics.

Interpretational Status

The relations above do not constitute a fundamental Hamiltonian or variational theory. They provide an effective, local summary of the constraints governing χ relaxation in regimes where spacetime notions apply. The predictive content of Cosmochrony remains entirely encoded in the intrinsic, pre-geometric relaxation dynamics of χ , while geometric and gravitational structures emerge only as descriptive tools.

4.3 Microscopic Origin of the Coupling Tensor and the Poisson Equation

To ensure internal consistency, the effective coupling governing the relaxation of χ cannot be taken as a universal constant. Instead, it must reflect the local structural state of the field. In Cosmochrony, this dependence is encoded through a constitutive relation linking the effective coupling strength to variations of χ within the emergent geometric description.

A convenient phenomenological form for this effective coupling is:

$$K_{\text{eff}} = K_0 \exp \left(-\frac{(\Delta\chi)^2}{\chi_c^2} \right), \quad (10)$$

where $\Delta\chi$ denotes the effective local variation of χ across correlated configurations, K_0 is the vacuum coupling strength, and χ_c sets the characteristic scale at which structural inhomogeneities significantly reduce the relaxation conductivity.

Regions exhibiting strong structural variation of χ , such as localized solitonic configurations, therefore weaken the effective coupling and locally slow down the relaxation process. This slowdown underlies the emergent gravitational phenomenology.

In regimes where an effective spacetime description applies, the local relaxation rate $\mathcal{D}_{\text{loc}\chi}$ differs from its asymptotic value \mathcal{D}_0 far from localized excitations. An effective gravitational potential Φ may then be introduced through the relation:

$$\frac{\mathcal{D}_{\text{loc}\chi}}{\mathcal{D}_0} \simeq 1 + \frac{\Phi}{c^2}, \quad (11)$$

which defines Φ as a convenient parametrization of the relative slowdown of relaxation in the effective geometric regime.

In the weak-structure limit, where variations of χ are small compared to χ_c , the spatial distribution of Φ is well described by an effective elliptic relation of Poisson type:

$$\nabla^2 \Phi \simeq 4\pi G_{\text{eff}} \rho, \quad (12)$$

where ρ denotes the density of localized excitations and G_{eff} is an emergent coupling parameter determined by the collective response of the χ field.

This Poisson equation is not fundamental, but represents the weak-field, coarse-grained limit of the constrained relaxation dynamics of χ . Gravitation thus appears not as an external interaction, but as an effective manifestation of reduced relaxation conductivity induced by solitonic configurations.

A fully relational formulation consistent with, but not required for, the effective description presented here is provided in Appendix E.

4.4 Variational Formulation and Born–Infeld Action

In regimes where χ admits a stable geometric interpretation, the effective relaxation constraint introduced above may be conveniently summarized using a variational formulation. This formulation is not fundamental, but provides a compact and regularized description of the coarse-grained dynamics of χ in the presence of localized excitations.

Motivated by Born–Infeld–type non-linear actions originally introduced to control field singularities [17, 18], we consider the effective Lagrangian density

$$\mathcal{L}_{\text{eff}} = -c^2 \sqrt{1 - \frac{|\nabla \chi|^2}{c^2}} + \mathcal{D}_{\text{loc}} \chi - \frac{4\pi G_{\text{eff}}}{c^2} \rho \chi, \quad (13)$$

where $\mathcal{D}_{\text{loc}} \chi$ denotes the effective local relaxation rate introduced in Sec. 4.1, and ρ represents the density of localized excitations.

The linear dependence on $\mathcal{D}_{\text{loc}} \chi$ ensures that the effective relaxation flow remains monotonic and constrained, without introducing additional propagating degrees of freedom. The square-root structure acts as a non-linear regulator enforcing the universal upper bound on effective spatial variations, in direct analogy with the original role of Born–Infeld electrodynamics.

Within this effective variational framework, the Euler–Lagrange equation associated with χ reproduces the non-linear elliptic relation governing the spatial distribution of relaxation slowdown:

$$\nabla \cdot \left(\frac{\nabla \chi}{\sqrt{1 - |\nabla \chi|^2 / c^2}} \right) = \frac{4\pi G_{\text{eff}}}{c^2} \rho, \quad (14)$$

which coincides with the effective Poisson-type equation obtained in Sec. 4.3.

This variational formulation should be understood as a compact, regularized representation of the effective dynamics of χ , not as a fundamental action principle. Its role is to ensure internal consistency and to provide a convenient link to standard gravitational phenomenology in the appropriate weak-field regime.

4.5 Causality and Locality

Equation (7) defines a dynamics that is local and causal at the fundamental level. The relaxation of χ in any given configuration depends only on its immediate relational neighborhood, as defined by local variations of χ itself. No nonlocal influence or instantaneous coupling is introduced.

Causality is enforced through the existence of a universal bound on the local relaxation rate of χ , ensuring that correlations propagate only through successive neighboring configurations. This bound plays the role of an effective causal constraint, without presupposing a spacetime lightcone structure.

At the fundamental level, no superluminal propagation occurs. Apparent superluminal recession velocities observed in cosmological settings arise only from the cumulative integration of local relaxation effects over extended regions, and are therefore fully consistent with local causality as defined within the Cosmochrony framework.

4.6 Homogeneous Cosmological Limit

In a homogeneous and isotropic configuration, effective spatial variations of χ vanish, and the relaxation proceeds uniformly. In this regime, the local relaxation rate reaches its maximal value,

$$\mathcal{D}_{\text{loc}}\chi = c, \quad (15)$$

where c denotes the universal bound on the relaxation rate.

When described in terms of an effective cosmological time parameter t , this uniform relaxation is conveniently represented as a linear relation,

$$\chi(t) = \chi_{\min} + ct, \quad (16)$$

where χ_{\min} denotes the minimal physically meaningful value of χ . This parametrization does not introduce a fundamental time variable, but provides a useful representation of the cumulative relaxation in a homogeneous cosmological regime.

Interpreting spatial distances as accumulated relational differences in χ , this linear relaxation directly leads to a Hubble-like expansion law, as discussed in Sec. 9. Cosmic expansion thus reflects the global relaxation of χ , rather than the presence of an external energy component.

As shown in Appendix A.5, the requirement that the relaxation flow remains monotonic in an expanding background implies the existence of a minimal residual structural inhomogeneity of χ . In effective geometric terms, this manifests as a non-vanishing lower bound on gravitational acceleration, providing a natural explanation for MOND-like phenomenology without invoking dark matter particles.

4.7 Influence of Local Structure

In regions where the effective structural variations of χ are non-vanishing, the local relaxation rate of the field is reduced. This slowdown plays a central role in the emergence of gravitational phenomena within the Cosmochrony framework.

Localized excitations—identified with particle-like solitonic configurations of χ —act as dynamical or topological constraints on the relaxation flow. By enhancing the local

structural complexity of χ , they reduce the effective rate at which the field can relax toward equilibrium.

When described in effective geometric terms, this mechanism manifests as gravitational time dilation and spatial curvature. No independent gravitational field is postulated; gravitation emerges as a collective consequence of locally constrained relaxation dynamics.

4.8 Unified Origin of Geometric and Field Effects

The relationship between the χ field and the effective spacetime metric $g_{\mu\nu}$ is strictly hierarchical, reflecting the transition from fundamental pre-geometric relations to smooth geometric descriptions.

1. **Primacy of χ :** At the fundamental level, physical reality is described solely in terms of the continuous scalar quantity χ and its relational structure. The dynamics of χ is governed by intrinsic relaxation processes, without reference to spacetime, metric geometry, or gravitational degrees of freedom.
2. **Emergent Geometry:** In regimes where χ configurations admit a stable and slowly varying description, geometric notions become meaningful. The spacetime metric $g_{\mu\nu}$ arises as an effective descriptor summarizing the correlations and relaxation properties of χ , providing a convenient coarse-grained language for macroscopic observers.
3. **Unified Interpretation of Fields and Gravitation:** Within this effective geometric description, localized solitonic configurations of χ are identified with matter, while gravitation corresponds to the local modulation of relaxation induced by these structures. The metric does not act as an independent dynamical agent, but encodes the collective response of the χ field to such localized constraints.

In this framework, no independent gravitational interaction is postulated. Matter, geometry, and gravitational phenomena emerge as complementary aspects of the same underlying relaxation dynamics of χ , ensuring a unified and self-consistent description across scales.

4.9 Limitations and Scope

Equation (7) is intentionally minimal. It does not aim to provide a complete description of quantum fluctuations of χ , nor does it incorporate higher-order backreaction effects. Its role is to capture the essential kinematic constraint governing the relaxation of χ in regimes where an effective geometric interpretation applies.

Within this scope, the equation provides a unified backbone from which gravitational, quantum, and cosmological phenomena can be consistently *recovered* or *described* at an effective level, rather than derived from first principles. More refined treatments of fluctuations, correlations, and non-local structures lie beyond the present formulation and motivate further developments of the framework.

In the following sections, this dynamical structure is applied to particles, gravitation, and entanglement, where its explanatory power can be directly assessed.

5 Particles as Localized Excitations of the χ Field

5.1 Particles as Stable Wave Configurations

Within the Cosmochrony framework, particles are not fundamental point-like objects but stable, localized excitations of the χ field [19]. They correspond to persistent wave configurations that locally constrain the relaxation of χ .

These configurations may be interpreted as soliton-like structures: they preserve their identity under interactions and effective displacement, while remaining fully embedded in the underlying relaxation dynamics of χ . Their apparent propagation reflects the continuous reconfiguration of the χ field rather than motion through a pre-existing spacetime background.

5.2 Topological Stability

The stability of particle-like excitations in Cosmochrony does not rely on conserved charges postulated a priori, but arises from intrinsic structural constraints of the χ field. Certain localized configurations of χ possess non-trivial internal organization that prevents their continuous relaxation into the homogeneous vacuum state.

This form of stability is topological in nature: it reflects the existence of inequivalent classes of χ configurations that cannot be smoothly transformed into one another without crossing a high-relaxation barrier. As a result, particle-like excitations are both discrete and robust under perturbations, without requiring externally imposed symmetries or conservation laws.

Importantly, these topological constraints are not defined with respect to a pre-existing spacetime geometry. They are intrinsic to the internal configuration space of χ itself and remain well-defined even in the absence of effective spatial notions. Geometric representations of such configurations, when employed, should be understood as descriptive tools valid only in regimes where a spacetime interpretation has emerged.

The long-lived character of solitonic excitations thus follows from a balance between localization tendencies driven by nonlinear self-interactions and structural constraints encoded in the configuration of χ . This mechanism provides a natural foundation for particle stability within a purely relational and pre-geometric framework.

5.3 Mass as Resistance to χ Relaxation

Within the Cosmochrony framework, mass is not an intrinsic attribute of matter but an emergent measure of the degree to which a localized excitation resists the relaxation of the χ field. Mass therefore characterizes the persistence of a non-relaxed configuration embedded within an otherwise globally relaxing substrate.

Localized particle-like excitations introduce structural constraints in the configuration of χ , which reduce the effective local rate of relaxation. When described using an effective spacetime parametrization, this reduction appears as a local slowing of the χ evolution, corresponding to time dilation in geometric terms. At larger scales, the cumulative effect of such localized constraints gives rise to what is interpreted as inertial and gravitational mass.

From an energetic perspective, this resistance to relaxation corresponds to the storage of relaxation potential within the χ field. Maintaining a stable solitonic configuration requires continuously opposing the global relaxation flow, and the associated cost is what is operationally identified as energy. In this sense, mass quantifies the amount of relaxation potential that remains locally trapped within a persistent excitation.

The quantitative mapping between solitonic energy and the masses of observed particles is discussed in Sec. [B.3](#).

5.4 Energy–Frequency Relation

The energy associated with a particle-like excitation is linked to the internal oscillation rate of its χ configuration. Within the Cosmochrony framework, this rate characterizes how strongly a localized structure resists relaxation: configurations with more rapid internal reorganization correspond to tighter localization and a greater capacity to store relaxation potential.

This provides an effective interpretation of the relation

$$E \propto \nu, \quad (17)$$

in which energy measures the amount of relaxation potential trapped in a given configuration, while the frequency ν quantifies the characteristic rate at which this potential is internally redistributed. The frequency should not be interpreted as oscillation with respect to a fundamental time parameter, but as an intrinsic property of the excitation, which admits a temporal interpretation only at the effective geometric level.

Within this perspective, Planck’s constant emerges as an effective proportionality factor relating energy and frequency, determined by the intrinsic scales and coupling properties of the χ field. Its apparent universality reflects the robustness of these underlying scales across stable configurations, rather than the postulation of a fundamental quantization constant.

A more explicit derivation of this relation, in the context of radiation and photon-like excitations of the χ field, is presented in Sec. [10.3](#).

5.5 Fermions and Bosons

Within the Cosmochrony framework, particle statistics arise from the internal topological structure of localized χ excitations rather than from postulated quantum rules. Distinct classes of excitations are characterized by how their internal configuration responds to continuous rotations in configuration space.

Configurations that require a 4π internal phase rotation to return to an equivalent state exhibit fermion-like behavior, while configurations that are 2π -periodic correspond to boson-like excitations. This distinction reflects a fundamental topological property of the underlying χ configuration, not a feature imposed by external symmetry principles.

In effective descriptions, such 4π -periodic configurations may be associated with non-orientable or twisted internal structures, while 2π -periodic configurations correspond to orientable ones. This provides a natural qualitative explanation for the spin–statistics

connection, without introducing additional quantum postulates at the fundamental level.

As throughout this work, references to phase rotations or periodicity should be understood as properties of the internal configuration space of χ . Geometric representations of these structures are effective and illustrative, and do not imply the existence of a fundamental spatial manifold.

5.6 Antiparticles

Within the Cosmochrony framework, antiparticles are interpreted as relationally conjugate counterparts of particle-like excitations. They correspond to configurations of the χ field that are topologically opposed to their particle partners within the internal configuration space of χ .

Annihilation processes occur when a particle and its conjugate excitation combine into a configuration that can relax continuously toward a more homogeneous state. In effective descriptions, this corresponds to the disappearance of localized constraints and the redistribution of previously trapped relaxation potential into delocalized, radiation-like excitations of the χ field.

Throughout this process, no fundamental structure is destroyed. The total relational content of χ is conserved, while localized topological organization is converted into propagating fluctuations within the relaxation dynamics.

5.7 Particle Creation and Destruction

Within the Cosmochrony framework, particle creation corresponds to the formation of stable, localized configurations of the χ field. Such configurations may arise when dynamical fluctuations of χ interact or self-organize in a manner that leads to topological stabilization and resistance to relaxation.

Conversely, particle destruction occurs when a localized excitation loses its topological stability, either through interactions with other excitations or through the progressive loss of internal coherence. In effective descriptions, this process corresponds to the conversion of localized structural constraints into delocalized, radiation-like fluctuations of the χ field.

This perspective removes the need for particles as primitive ontological entities and replaces it with a purely dynamical and relational description, in which creation and annihilation reflect changes in the organization of χ rather than the appearance or disappearance of fundamental objects.

5.8 Summary

Particles emerge as stable, localized excitations of the χ field that resist its relaxation. Their mass, energy, spin, and statistical behavior arise from the internal topological structure of χ and from effective geometric descriptions valid in regimes where a spacetime interpretation applies. This provides a unified account of particle properties compatible with both relativistic and quantum phenomena, without introducing particles as fundamental ontological entities.

6 Gravity as a Collective Effect of Particle Excitations

6.1 Local Slowdown of χ Relaxation

In Cosmochrony, gravitation does not arise from a fundamental interaction but from the collective influence of particle-like excitations on the relaxation dynamics of the χ field. As established in Sec. 5, localized excitations locally resist the relaxation of χ .

When many such excitations are present, their combined influence leads, in the weak-coupling regime, to an effective macroscopic reduction of the relaxation rate. In an effective spacetime parametrization, this may be written as

$$\mathcal{D}_{\text{eff}}\chi \simeq c(1 - \alpha\rho), \quad (18)$$

where ρ denotes the effective density of localized excitations and α encodes their average coupling to the χ relaxation flow. This expression should be understood as a first-order approximation valid when local constraints are sufficiently dilute.

The coupling parameter α is not fundamental but emerges from the interaction between χ and stable excitations. In the weak-field limit, its scaling can be related to the observed gravitational constant by dimensional consistency, leading to $\alpha \propto G/c^2$ when expressed in terms of effective inertial mass densities. Within this approximation, the reduction of the relaxation rate admits an interpretation in terms of a Newtonian-like gravitational potential.

Physically, this collective slowdown of χ relaxation manifests as gravitational time dilation in effective geometric descriptions.

6.2 Collective Gravitational Coupling and Operational Geometry

The collective slowdown of χ relaxation described above affects not only the local flow of effective time but also the manner in which variations of χ influence one another across extended regions. In the presence of localized excitations, the resistance they impose on the relaxation of χ modulates how efficiently structural variations of the field are transmitted.

This collective behavior may be described, at an effective level, by a local and constitutive coupling function that characterizes the stiffness of the χ field to relative variations. In regions where χ is nearly homogeneous, this coupling approaches a uniform vacuum value, while localized excitations weaken it by introducing additional structural constraints. Crucially, this coupling depends only on the local configuration of χ and does not presuppose any background spatial metric.

Because no fundamental geometry is assumed, spatial distance is defined operationally. Two regions are considered close if variations of χ propagate efficiently between them, and distant otherwise. In the continuum and weak-variation regime, this operational notion naturally admits a description in terms of an effective spatial metric, which summarizes the collective response of the χ field.

Within this framework, spacetime curvature does not arise as a primitive geometric property, but as an emergent manifestation of how localized excitations modulate the collective propagation and relaxation dynamics of χ .

A more explicit relational construction of the coupling mechanism and its connection to discrete formulations is presented in Appendix D.1.

6.3 Emergent Curvature

Spatial variations in the effective relaxation rate of χ , together with the collective modulation of local coupling strength, lead to non-uniform propagation of χ variations across extended regions. When described using an effective geometric language, these non-uniformities are captured by gradients of an emergent metric structure.

In this sense, spacetime curvature in Cosmochrony is not a primitive geometric property, but a descriptive tool summarizing how localized excitations collectively modulate the relaxation and transmission of χ . The metric curvature encodes the response of the χ field to such constraints, rather than acting as an independent dynamical agent.

This emergent curvature reproduces the phenomenology traditionally attributed to curved spacetime in general relativity, while remaining fully compatible with the pre-geometric and relational foundations of the framework.

6.4 Recovery of the Schwarzschild Metric

In the presence of a static and approximately spherically symmetric distribution of localized χ excitations, the collective slowdown of the relaxation flow admits a simple effective description. In the weak-coupling and quasi-static regime, the spatial variation of the relaxation rate can be summarized by a Poisson-like relation between the effective gravitational potential and the excitation density.

When expressed in an effective geometric language, this structure is well described by a metric whose leading-order form coincides with the Schwarzschild solution of general relativity. In particular, the temporal and radial components of the effective metric encode the reduction of the local relaxation rate induced by the excitation, while the angular part reflects the isotropy of the configuration.

Within this description, standard weak-field predictions of general relativity are recovered. These include gravitational redshift, light deflection, and time dilation effects consistent with solar-system observations. The gravitational constant G appears as an emergent coupling parameter relating the density of localized excitations to the magnitude of the relaxation slowdown.

Importantly, the Schwarzschild metric is not postulated as a fundamental solution, nor is spacetime curvature treated as a primitive entity. Rather, the metric provides a compact and effective summary of how the collective dynamics of χ around a localized excitation constrains the relaxation flow. In this sense, Schwarzschild-like behavior emerges as a necessary phenomenological description in regimes where the relaxation field is close to local equilibrium.

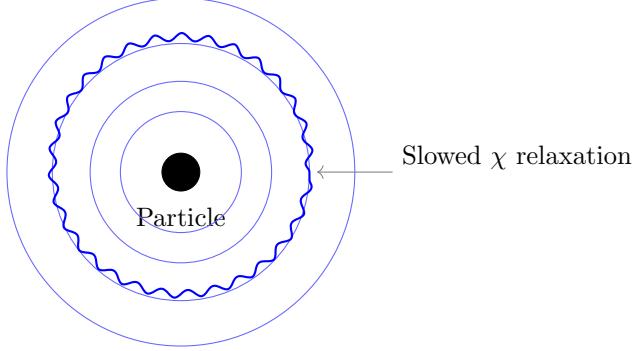


Fig. 2 Emergence of gravity in Cosmochrony. Localized excitations of χ slow down the relaxation rate of the field, inducing differential proper-time flow and an effective metric curvature analogous to gravitational time dilation.

6.5 Equivalence Principle

Because all particle-like excitations couple to the χ field through the same relaxation mechanism, the collective slowdown of χ is independent of the internal composition or structure of matter. As a result, all localized excitations respond identically to a given configuration of the χ field.

When described in effective geometric terms, this universal response appears as composition-independent gravitational acceleration. The equivalence between inertial and gravitational behavior therefore emerges as a consequence of the uniform coupling of matter to the relaxation dynamics of χ , rather than as an independent postulate.

In this sense, the equivalence principle arises naturally within Cosmochrony as an emergent symmetry of the underlying dynamics.

6.6 Gravitational Waves

Time-dependent variations in the distribution of localized excitations, such as accelerating masses or mergers of compact configurations, induce collective fluctuations in the relaxation dynamics of the χ field. These fluctuations propagate as changes in the local relaxation regime and are transmitted at the maximal relaxation speed c .

When described using an effective spacetime language, such propagating modulations correspond to gravitational waves. Unlike electromagnetic radiation, which consists of excitations propagating on top of a background field, gravitational waves in Cosmochrony represent collective variations of the χ field itself, reflecting the redistribution of relaxation constraints across extended regions.

In this sense, gravitational waves do not introduce additional fundamental degrees of freedom, but arise as dynamical responses of the χ field to time-dependent reconfigurations of matter.

6.7 Strong Gravity and Black Holes

In regions where the density of localized excitations becomes sufficiently high, the relaxation dynamics of the χ field may become extremely constrained. In effective

spacetime descriptions, this corresponds to a regime in which the local relaxation rate is strongly suppressed relative to distant observers, defining an effective horizon.

Within Cosmochrony, such regions are interpreted as black holes. Rather than being characterized by a fundamental spacetime singularity, black holes correspond to domains where the unfolding of physical processes becomes asymptotically inaccessible from the exterior due to the collective inhibition of χ relaxation. This naturally accounts for extreme time dilation effects without requiring divergent curvature invariants.

6.7.1 Gravitational and Temporal Shadows

In the strong-gravity regime, the increasing concentration of excitations induces large structural constraints in the χ field. As a result, the effective rate at which χ relaxes relative to external parametrizations is progressively reduced, approaching an asymptotic freeze-out in effective geometric descriptions.

This behavior reproduces the phenomenon commonly referred to as a *gravitational shadow*. In general relativity, such shadows arise from the absence of escaping null geodesics within a characteristic angular region. In Cosmochrony, an equivalent observational signature emerges because propagating excitations of the χ field, including radiation-like modes, cannot be sustained in regions where the relaxation dynamics is effectively frozen. External observers therefore perceive a dark angular region corresponding to the projection of this dynamically inaccessible domain.

Beyond this optical effect, the framework predicts a deeper phenomenon, which may be termed a *temporal shadow*. As the local relaxation of χ becomes increasingly inhibited, the effective progression of time within the region slows asymptotically with respect to the external environment. From the external perspective, internal processes appear indefinitely delayed, providing a natural interpretation of horizon-induced time dilation.

In this view, the observed gravitational shadow corresponds to the visible manifestation of an underlying temporal shadow. Both effects arise from the same collective relaxation dynamics of the χ field and need not be attributed to a fundamental spacetime singularity or to divergent tensorial curvature.

6.8 Unified Origin of Gravitational and Electromagnetic Effects

Within the Cosmochrony framework, gravitational and electromagnetic phenomena do not originate from distinct fundamental entities, but arise as complementary effective manifestations of the same underlying χ dynamics. At the fundamental level, only the scalar field χ and its relaxation properties are postulated.

Gravitational effects correspond to sustained, quasi-static constraints on the relaxation of χ , induced by persistent structural variations associated with localized excitations. When described in effective geometric terms, these constraints manifest as time dilation, attraction, and spacetime curvature.

Electromagnetic phenomena, by contrast, arise from dynamic and phase-dependent modulations of χ . These modulations admit an effective description in terms of propagating, oscillatory fields with both attractive and repulsive interactions, consistent with the observed behavior of electromagnetic radiation and forces.

In this sense, gravity and electromagnetism differ not by their fundamental origin, but by the temporal character and organization of the χ modulations they involve: quasi-static and cumulative for gravitation, dynamic and oscillatory for electromagnetism. The familiar distinction between the two interactions thus emerges at the level of effective descriptions rather than from fundamentally separate fields.

6.9 Summary

Gravity emerges as a macroscopic consequence of localized particle excitations collectively slowing the relaxation of the χ field. Classical gravitational phenomena, including time dilation, effective spacetime curvature, gravitational waves, and black holes, arise naturally within this framework without introducing gravity as a fundamental force or independent geometric degree of freedom.

7 Quantum Phenomena and Entanglement

7.1 Nonlocality and the Holistic Nature of the χ Field

In the Cosmochrony framework, quantum nonlocality does not arise from superluminal interactions or from violations of relativistic causality. Instead, it reflects the intrinsically holistic nature of the χ field. Entangled systems correspond to single, extended configurations of χ that cannot be factorized into independent subsystems once they have interacted.

The persistence of quantum correlations across spatial separation follows from the internal relational structure of χ , rather than from spatial connectivity or signal exchange. Although effective geometric descriptions may assign distant locations to parts of an entangled system, these locations correspond to different manifestations of a single underlying field configuration.

In this sense, quantum nonlocality in Cosmochrony is ontological rather than dynamical: the field configuration is globally defined, while its evolution remains locally governed by the relaxation dynamics of χ .

7.2 Shared Configurations and Correlation Structure

When two particle-like excitations interact, they may form a composite configuration of the χ field that remains partially unified even after spatial separation in an effective geometric description. Such configurations give rise to persistent correlations between measurement outcomes.

In an effective spacetime representation, this shared configuration may be schematically modeled as

$$\chi(x) = \chi_0 \exp\left(-\frac{|x - x_1|^2}{\xi^2} - \frac{|x - x_2|^2}{\xi^2}\right), \quad (19)$$

where x_1 and x_2 label the effective locations of the two excitations. This expression is not fundamental, but serves as an illustrative coarse-grained representation of a single extended χ excitation whose internal structure spans multiple regions.

The observed quantum correlations arise because measurements performed on different parts of this unified configuration probe the same underlying relational state, rather than because of any exchange of signals at the time of measurement.

7.3 Nonlocal Correlations Without Superluminality

Because the χ field evolves locally according to its relaxation dynamics, no superluminal propagation of information occurs. Measurement outcomes at spacelike separated regions do not influence one another through causal signals.

Instead, correlated outcomes arise because both measurements sample the same pre-existing relational structure of χ . This violates the factorization assumptions underlying Bell-type inequalities, while preserving dynamical locality and relativistic causality.

In this way, Cosmochrony naturally accounts for experimentally observed violations of Bell inequalities without invoking nonlocal forces, retrocausality, or hidden signal channels.

7.4 Measurement, Decoherence, and Apparent Collapse

Within Cosmochrony, quantum measurement does not involve a fundamental wavefunction collapse. The χ field evolves continuously according to its intrinsic dynamics, and no discontinuous update of the underlying configuration occurs.

What is conventionally interpreted as wavefunction collapse corresponds to the loss of coherence between different components of a χ configuration due to interaction with an environment. This process dynamically suppresses interference between alternative relational branches, yielding effectively classical outcomes.

Decoherence therefore arises as a physical process rooted in the coupling between localized excitations and the broader χ field, rather than as a postulated measurement axiom.

7.5 Temporal Ordering and Relativistic Consistency

Because temporal ordering in Cosmochrony is defined by the monotonic relaxation of χ , it does not rely on a global simultaneity structure. Different observers may assign different temporal orderings to spacelike separated events in effective geometric descriptions, without affecting the underlying dynamics of the field.

Entanglement correlations are therefore compatible with relativistic causality: they do not depend on any preferred reference frame or absolute notion of time. The relational structure of χ remains invariant under changes of effective spacetime slicing.

7.6 Limits of Entanglement and Environmental Effects

Entanglement is not a generic or permanent feature of all χ configurations. Environmental interactions, noise, and continued relaxation progressively degrade the coherence of shared configurations.

As a result, entanglement is most robust for isolated systems and diminishes in macroscopic or strongly interacting environments. This explains the emergence of classical behavior at large scales without requiring a fundamental quantum-to-classical transition.

7.7 Summary

Entanglement emerges in Cosmochrony as the persistence of shared topological configurations within the χ field. Quantum correlations arise without superluminal signaling, fundamental wavefunction collapse, or violations of relativistic causality.

Within this framework, quantum phenomena reflect the holistic yet dynamically local structure of χ , from which the standard quantum-mechanical formalism emerges as an effective statistical description rather than a fundamental ontology.

8 Relation to Quantum Formalism

This section does not assign fundamental ontological status to the quantum wavefunction nor to Hilbert space structures. Instead, it shows how the formal apparatus of quantum mechanics arises as an effective description of localized, weakly interacting excitations of the χ field introduced in the preceding sections.

Quantum mechanics is therefore not replaced, but reinterpreted as a consistent coarse-grained framework valid in regimes where χ admits a stable geometric and linearized description.

8.1 Status of the Wavefunction

In standard quantum mechanics, the wavefunction ψ is a complex-valued object defined on configuration space, whose ontological status remains debated. Operationally, $|\psi|^2$ encodes measurement probabilities via the Born rule, while ψ itself does not correspond directly to a physical field in spacetime.

In Cosmochrony, the χ field is not identified with the quantum wavefunction. Instead, χ constitutes a real scalar substratum, from which effective quantum wavefunctions emerge as statistical descriptors of coherent excitations. The wavefunction is therefore interpreted as a derived object encoding the collective behavior of χ -mediated structures rather than as a fundamental entity.

As an illustrative example, the hydrogen atom wavefunctions $\psi_{nlm}(r, \theta, \phi)$ correspond to stable solitonic configurations of χ characterized by discrete internal structure. The probability density $|\psi|^2$ reflects the spatial visibility of these configurations in effective geometric descriptions, while energy quantization arises from topological and resonance constraints imposed on stable χ excitations.

8.2 Emergence of Hilbert Space Structure

The Hilbert space formalism of quantum mechanics provides a linear structure supporting superposition, interference, and unitary evolution. Within Cosmochrony, this structure emerges as an effective description of weakly interacting, small-amplitude fluctuations of the χ field around a slowly varying background.

Approximate linear superposition reflects the near-independence of such fluctuations in regimes where nonlinear constraints are negligible. The complex phase of the wavefunction encodes relative internal oscillatory structure within χ rather than representing an intrinsic complex field.

8.3 Emergence of the Schrödinger Equation from χ Fluctuations

In Cosmochrony, quantum dynamics is not postulated but emerges as a long-wavelength, non-relativistic description of coherent χ -field fluctuations around stable solitonic configurations. In this subsection, the Schrödinger equation is recovered as the standard non-relativistic limit of such fluctuations.

8.3.1 Non-relativistic limit: Klein–Gordon \rightarrow Schrödinger

Consider a localized excitation around a quasi-stationary soliton background,

$$\chi(x, t) = \chi_{\text{sol}}(x) + \delta\chi(x, t), \quad (20)$$

where $\delta\chi$ denotes a small fluctuation. To leading order, $\delta\chi$ obeys an effective Klein–Gordon equation,

$$\left(\frac{1}{c^2} \partial_t^2 - \nabla^2 + \frac{m^2 c^2}{\hbar^2} \right) \delta\chi = 0, \quad (21)$$

with m determined by the soliton's rest-energy.

In the non-relativistic regime, the field oscillates rapidly at frequency $\omega_0 = mc^2/\hbar$, while its envelope varies slowly. Using the standard ansatz

$$\delta\chi(x, t) = \psi(x, t)e^{-i\omega_0 t}, \quad |\partial_t \psi| \ll \omega_0 |\psi|, \quad (22)$$

and neglecting higher-order relativistic corrections yields the Schrödinger equation,

$$i\hbar \partial_t \psi = -\frac{\hbar^2}{2m} \nabla^2 \psi + V(x)\psi, \quad (23)$$

where $V(x)$ encodes weak interactions with the surrounding χ background.

Interpretation.

The wavefunction ψ does not represent a fundamental quantum object but an effective envelope describing coherent χ fluctuations. The Schrödinger equation thus appears as a universal non-relativistic limit of localized χ excitations rather than as a fundamental axiom.

8.4 Origin of Quantization

Quantization in standard quantum theory is postulated through canonical commutation relations or path-integral prescriptions. In Cosmochrony, discrete energy exchanges arise from topological and stability constraints on localized χ excitations.

Only specific internal configurations, resonance conditions, or winding numbers are dynamically stable. As a result, energy levels are effectively quantized. The relation $E = h\nu$ emerges as a proportionality between oscillation frequency and relaxation potential stored in localized χ configurations, with Planck's constant appearing as an effective coupling scale.

8.5 Measurement and the Born Rule

Measurement does not involve a fundamental wavefunction collapse. Instead, it corresponds to an irreversible interaction between a coherent excitation and stochastic fluctuations of the surrounding χ field.

Detection events occur when such interactions stabilize a localized configuration. The Born rule arises statistically from the distribution of χ fluctuations compatible with the detector's constraints. Thus, $|\psi|^2$ represents the density of favorable configurations rather than a primitive probability postulate.

8.6 Entanglement and Nonlocal Correlations

Quantum entanglement corresponds to persistent relational structure within a single extended χ configuration. Separated particles remain correlated because they are manifestations of the same underlying excitation.

These correlations do not rely on superluminal signaling. They reflect the holistic but dynamically local structure of χ , consistent with relativistic causality.

8.7 Spin and Statistics

Spin emerges from topological organization of χ excitations. Configurations requiring a 4π internal rotation to return to equivalence correspond to fermions, while 2π -periodic configurations correspond to bosons.

The spin–statistics connection follows naturally from the topological stability of these structures rather than from imposed quantum postulates. An explicit example is discussed in Section B.4.

8.8 Orbital Geometry as Probabilistic Visibility of Underlying χ Fluctuations

Atomic orbitals are not spatial material distributions but probabilistic visibility patterns of underlying χ fluctuations. Their shapes encode stable structural features of χ , such as nodal surfaces and symmetry constraints, while their apparent extent reflects stochastic variations.

Orbital visualizations therefore represent statistical manifestations of stationary χ modes rather than occupied spatial regions.

8.9 Scope and Limitations

Cosmochrony does not seek to replace quantum mechanics. All standard computational tools remain valid within their domain of applicability.

Its contribution is interpretative and unificatory: it provides a coherent geometric and dynamical origin for quantum phenomena without modifying experimentally verified predictions. A complete mapping between χ dynamics and operator-based quantum theory is left for future work.

9 Cosmological Implications

9.1 The Big Bang as a Maximal Constraint Regime of the χ Field

In the Cosmochrony framework, the Big Bang is not interpreted as a spacetime singularity, but as an initial regime in which the χ field was maximally constrained. Rather than diverging curvature or density, this regime is characterized by extreme structural variations and topological constraints within χ .

At this stage, no stable geometric interpretation exists. Concepts such as distance, duration, or curvature are not yet meaningful. The subsequent cosmological evolution corresponds to the progressive relaxation of these constraints, through which effective spacetime notions gradually emerge.

The arrow of time originates directly from this relaxation process. Temporal ordering is not imposed by boundary conditions, but arises intrinsically from the monotonic evolution of χ away from its maximally constrained state.

9.2 Cosmic Expansion Without Inflation

Standard cosmology invokes an inflationary phase to account for large-scale homogeneity, isotropy, and spatial flatness. In Cosmochrony, these features arise naturally from the pre-geometric nature of the initial χ configuration.

Because the early χ field was globally connected prior to geometric differentiation, no horizon problem arises. Homogeneity reflects the continuity of the underlying field rather than the outcome of rapid spacetime expansion.

This framework does not presently provide a detailed quantitative substitute for inflation at the level of perturbation spectra. However, it offers a conceptually economical explanation for large-scale cosmic regularities without introducing additional dynamical fields or phases.

9.3 Cosmic Expansion as χ Relaxation

Cosmic expansion in Cosmochrony does not correspond to the motion of matter through space, but to the progressive relaxation of the χ field itself. As χ increases monotonically, effective spatial separations emerge and grow.

In this interpretation, expansion is not driven by an external energy component but reflects the internal geometric unfolding of the field. Matter excitations act as local constraints on this relaxation, leading to inhomogeneities that later manifest as large-scale structure.

This perspective reinterprets cosmological expansion as a purely geometric and dynamical process intrinsic to the χ field.

9.4 Emergent Hubble Law

In homogeneous regimes, the relaxation of χ is uniform, yielding a linear relation

$$\chi(t) = \chi_0 + ct. \quad (24)$$

Identifying effective spatial scales with accumulated χ increments leads naturally to a Hubble-like law. The Hubble parameter emerges as

$$H(t) = \frac{\dot{\chi}}{\chi}, \quad (25)$$

providing a natural cosmological scale without introducing a fundamental scale factor.

The present-day Hubble constant H_0 is therefore interpreted as a measure of the current global relaxation rate of the χ field.

9.5 Cosmic Acceleration Without Dark Energy

Observed late-time cosmic acceleration does not require a cosmological constant or dark energy component in this framework. Instead, it arises as an apparent effect produced by the cumulative relaxation history of χ .

As localized structures form, they increasingly constrain local relaxation, modifying the global effective expansion rate. This leads to an apparent acceleration when interpreted within standard spacetime-based cosmological models.

9.6 Cosmic Microwave Background

The cosmic microwave background reflects the imprint of early χ relaxation dynamics rather than fluctuations generated during an inflationary phase. Large-scale correlations arise from the continuity of the χ field prior to geometric differentiation.

Acoustic features in the temperature power spectrum can be interpreted as arising from oscillatory coupling between χ and matter excitations during the transition to a stable geometric regime.

No superluminal expansion within spacetime is required to account for observed large-angle correlations.

9.7 The Hubble Tension

The discrepancy between early-universe and late-universe determinations of the Hubble constant finds a natural qualitative explanation within Cosmochrony. Different observational methods probe χ at different stages of its relaxation.

Early-universe measurements are sensitive to a more constrained configuration of χ , while late-time measurements reflect a more relaxed state. This naturally leads to distinct effective values of H_0 .

These estimates should be understood as order-of-magnitude consistency rather than precision predictions. A more detailed analysis is presented in Appendix C.3.

9.8 Entropy and the Arrow of Time

In Cosmochrony, the arrow of time is fundamental and precedes thermodynamic considerations. Entropy increase emerges as a secondary, statistical description of the irreversible relaxation of χ .

This reverses the standard explanatory order: time asymmetry does not arise from entropy growth; rather, entropy growth reflects the underlying temporal directionality imposed by χ relaxation.

9.9 Large-Angle Temperature Anomalies

Large-angle anomalies observed in the CMB, such as low- ℓ power suppression, may reflect residual correlations inherited from the pre-geometric phase of the χ field.

These features are not predicted as precise signatures but arise naturally as qualitative consequences of incomplete relaxation at the largest scales. Cosmic variance limits the statistical significance of such effects.

9.10 Summary

Cosmological phenomena in Cosmochrony emerge from the global relaxation dynamics of the χ field. Expansion, acceleration, large-scale homogeneity, and the arrow of time arise without invoking inflation, dark energy, or initial spacetime singularities.

The framework reproduces the phenomenological predictions of standard cosmology at large scales, while offering an alternative geometric interpretation rooted in a single pre-geometric scalar dynamics.

10 Radiation and Quantization

10.1 Radiation as χ -Matter Interaction

In Cosmochrony, radiation does not correspond to the emission of pre-existing particle entities. Instead, it arises from the interaction between localized excitations (matter) and the surrounding χ field.

When an excited configuration interacts with χ , part of the stored relaxation potential may be released into the surrounding field as a propagating disturbance. This process is intrinsically stochastic, reflecting local fluctuations and instabilities in χ , and gives rise to radiative phenomena.

Radiation therefore represents a redistribution of χ -structure rather than the transport of discrete objects through space.

10.2 Emergence of Photons

Photons are not fundamental entities in this framework. They correspond to transient, propagating disturbances of χ generated during interactions with matter.

Prior to emission or detection, no localized photon exists as an independent object. Quantization appears only at the moment of interaction, when continuous χ dynamics produces a discrete transfer of relaxation potential.

Although propagating electromagnetic waves correspond to continuous χ disturbances, photon-like events emerge only when such disturbances interact with localized excitations. In a double-slit experiment, the interference pattern arises from the continuous wave dynamics of χ , while individual detection events correspond to

interaction-induced localization. This naturally explains wave–particle duality without invoking fundamental wavefunction collapse.

10.3 Geometric Origin of $E = h\nu$

This section develops, in the context of radiative processes, the energy–frequency relation introduced earlier in Section 5.4 for localized excitations of the χ field.

In Cosmochrony, radiative events correspond to the partial release of relaxation potential stored in localized matter excitations into propagating disturbances of the χ field. The energy transferred during such an event is associated with the internal oscillatory structure of the emitted χ disturbance. Higher-frequency disturbances correspond to tighter curvature and therefore to a larger amount of relaxation potential being redistributed.

The Planck relation

$$E = h\nu \quad (26)$$

is thus interpreted as an effective geometric proportionality between the frequency of a propagating χ disturbance and the amount of relaxation potential released during an interaction. In this framework, the constant h does not represent a fundamental quantum postulate, but an effective conversion factor relating oscillation frequency to curvature-based energy within the χ field.

This interpretation does not constitute a derivation of h from first principles. Rather, it provides a geometric explanation for why energy transfer in radiative processes scales linearly with frequency across a wide range of phenomena. In the photoelectric effect, the threshold frequency ν_0 corresponds to the minimal curvature required to liberate an electron soliton from its binding configuration, while the linear dependence on ν reflects the relaxation potential carried by the emitted χ disturbance.

10.4 Vacuum Fluctuations and the Casimir Effect

Vacuum fluctuations correspond to stochastic variations of χ in the absence of localized excitations. These fluctuations are not interpreted as particle–antiparticle creation events, but as intrinsic variability of the continuously relaxing field.

Boundary conditions imposed by matter constrain these fluctuations, altering the local spectrum of allowed modes. The Casimir effect arises naturally as a pressure difference resulting from modified χ dynamics between closely spaced boundaries, without requiring a fundamental vacuum energy density.

In this sense, the Casimir effect probes the relational relaxation capacity of the χ field rather than a fundamental vacuum energy density.

10.5 Weakly Interacting Radiation

Disturbances with minimal curvature, such as low-frequency electromagnetic waves or weakly coupled excitation modes, interact only weakly with matter. Their near-planar or low-contrast structure reduces the probability of inducing localized energy transfer.

This explains both the transparency of the vacuum to most radiation and the small interaction cross sections of certain weakly interacting modes.

10.6 Summary

Radiation and quantization arise from interactions between localized matter excitations and the χ field. Photons emerge during interactions rather than existing as independent entities, and quantization reflects geometric constraints of χ dynamics rather than fundamental discreteness.

11 Testable Predictions and Observational Signatures

Before detailing specific observational signatures, it is important to clarify the epistemic status of the numerical estimates presented in this section. Values such as the $\sim 8\text{--}10\%$ correction to the Hubble constant or the $\sim 10^{-10}\text{ yr}^{-1}$ drift in effective observables are not proposed as precision predictions. They should be understood as order-of-magnitude consistency estimates derived from the geometric coupling between the χ field and the effective relaxation fraction Ω_χ .

Their role is to demonstrate that the Cosmochrony framework operates within a phenomenologically relevant regime, capable of addressing current observational tensions without fine-tuning or the introduction of additional dynamical degrees of freedom.

11.1 Hubble Constant from χ Dynamics

In Cosmochrony, the Hubble parameter is not introduced as a free cosmological parameter but follows directly from the relaxation dynamics of the χ field:

$$H(t) = \frac{\dot{\chi}}{\chi}. \quad (27)$$

Assuming a maximal relaxation rate $\dot{\chi} \simeq c$, the present-day value can be expressed as

$$H_0 \simeq \frac{c}{\chi(t_0)}. \quad (28)$$

This relation implies a direct correspondence between the observed Hubble constant and the characteristic relaxation scale of χ at the current epoch. Early-universe probes (e.g. CMB-based inferences) and late-time distance ladder measurements effectively sample χ at different stages of its relaxation, naturally leading to systematically different inferred values of H_0 .

11.2 Redshift Drift

The monotonic relaxation of χ implies a slow temporal evolution of cosmological redshifts. This induces a redshift drift that differs quantitatively from that predicted by Λ CDM, particularly at intermediate redshifts.

A characteristic estimate for the drift rate is

$$\dot{z} \sim H_0(1+z) - \frac{c}{\chi(t)}, \quad (29)$$

corresponding to a secular variation of order $\Delta z \sim 10^{-10} \text{ yr}^{-1}$ at $z \sim 1$. This differs from standard ΛCDM expectations at the $\sim 10\%$ level in this regime.

Future high-precision spectroscopic facilities, such as extremely large telescopes equipped with ultra-stable spectrographs, may be capable of probing this effect, providing a direct observational discriminator between geometric relaxation and dark-energy-driven acceleration.

11.3 Gravitational Wave Propagation

In the Cosmochrony framework, gravitational waves correspond to propagating modulations of the χ field. In regions of high excitation density, such as near compact objects, the local slowdown of χ relaxation is expected to induce partial absorption or dispersion of these modulations.

Order-of-magnitude estimates suggest that gravitational waves passing within $\sim 10 GM/c^2$ of a compact object could experience attenuation at the level of $\sim 10\%$. Such effects would manifest primarily in the late-time ringdown phase of binary mergers as a frequency-dependent deviation from general relativistic templates.

While current detectors lack the sensitivity to resolve such effects, future space-based observatories with high signal-to-noise ratios may provide the necessary precision.

11.4 Spin and Topological Signatures

If particle spin originates from topologically nontrivial configurations of the χ field, as proposed in this work, then spin-related phenomena may exhibit subtle geometric signatures beyond standard quantum mechanical descriptions.

In particular, ultra-high-precision interference experiments sensitive to 4π rotational symmetry may probe deviations associated with the internal topology of localized χ excitations. Such effects are expected to be extremely small but conceptually distinctive.

11.5 Absence of Dark Energy Signatures

Because cosmic acceleration emerges in Cosmochrony without invoking a dark energy component, the framework predicts the absence of dynamical dark energy signatures, such as evolving equations of state or clustering behavior.

Observations consistent with a purely geometric origin of acceleration would favor this interpretation over models requiring additional energy components.

Discriminating observational signatures.

While the absence of primordial tensor modes alone is not a decisive discriminator, Cosmochrony predicts that the lack of an inflationary phase should manifest through correlated deviations in large-scale cosmological observables. These include suppressed power at low CMB multipoles, specific angular correlations in polarization, and the absence of an inflationary tensor imprint at large angular scales. It is the combination of these features, rather than any single parameter, that provides a potential observational discriminator with respect to standard inflationary cosmologies.

11.6 Summary

Cosmochrony yields a set of observationally testable signatures across cosmology, gravitation, and quantum phenomena. While most predictions reproduce established observations, several imply quantitative deviations that may be accessible to future high-precision measurements, providing concrete avenues for empirical scrutiny.

12 Discussion and Comparison with Existing Frameworks

The Cosmochrony framework proposes a minimal geometric substrate, described by a single scalar field $\chi(x, t)$, whose irreversible relaxation governs both microscopic and cosmological phenomena. In this section, we discuss how this approach relates to established theoretical frameworks, highlight its conceptual implications, and identify open challenges.

12.1 Relation to General Relativity

General Relativity (GR) describes gravitation as the curvature of spacetime induced by energy-momentum. In Cosmochrony, no *a priori* metric dynamics is postulated at the fundamental level. Instead, an effective spacetime geometry emerges as a descriptive framework from variations in the local relaxation dynamics of the χ field.

Matter configurations, modeled as stable or metastable topological excitations of χ , locally constrain the relaxation of the field. This leads to differential rates of effective proper-time evolution between neighboring regions. When expressed in geometric terms, these differences can be reinterpreted as an effective deformation of the spacetime metric.

In the weak-field regime, this mechanism reproduces Newtonian gravity, while in the strong-field limit it yields Schwarzschild-like solutions in effective geometric descriptions. The resulting phenomenology is therefore consistent with the empirical successes of GR across its tested domain.

From this perspective, gravitation is not introduced as a fundamental interaction, but emerges as a macroscopic manifestation of inhomogeneous χ relaxation. General Relativity is recovered as the appropriate effective theory describing this regime, rather than being supplanted or modified at the level of observable predictions.

12.2 Relation to Quantum Formalism

Quantum mechanics and quantum field theory (QFT) introduce probabilistic wavefunctions, operators, and quantization rules as foundational postulates [20]. In contrast, Cosmochrony treats continuous wave dynamics as primary and regards quantization as an emergent, interaction-dependent phenomenon.

Within this framework, particles correspond to localized, topologically stable wave configurations (soliton-like excitations) of the χ field. Discrete observables arise from boundary conditions, topological constraints, and interaction-induced mode selection, rather than from intrinsic microscopic discreteness. The Planck relation $E = h\nu$ is

interpreted as a geometric correspondence between oscillation frequency, field curvature, and the energetic cost of local χ deformation.

Quantum correlations are described in relational terms. Entanglement corresponds to the persistence of a shared χ configuration across spatial separation, while decoherence reflects the irreversible fragmentation of this configuration through interactions with the surrounding field. This interpretation reproduces the standard quantum phenomenology, including nonlocal correlations, without invoking superluminal signaling, fundamental wavefunction collapse, or hidden variables.

12.3 Analogy with Collective Phenomena in QCD

A useful structural analogy may be drawn with quantum chromodynamics (QCD) in the low-energy regime, where the fundamental degrees of freedom (quarks and gluons) do not correspond directly to observable particles [21]. Instead, hadronic properties, effective masses, and confinement phenomena emerge from a strongly interacting collective vacuum structure, often described in terms of a quark-gluon medium.

In a similar conceptual spirit, the Cosmochrony framework does not attribute gravitational phenomena to a fundamental interaction mediated by elementary gravitational degrees of freedom. Rather, gravity arises as a collective effect of localized excitations and modulations of the underlying χ field, whose large-scale behavior cannot be reduced to simple superpositions of microscopic dynamics.

As in QCD, the appropriate physical description depends on the scale and regime considered. While the underlying dynamics may be simple in principle, the emergent macroscopic behavior is governed by nonlinear and collective effects that are more naturally captured by effective, phenomenological descriptions. This scale-dependent hierarchy of descriptions reinforces the view that geometry and gravitation in Cosmochrony are emergent constructs, rather than fundamental ontological primitives.

12.4 Comparison with Λ CDM Cosmology

The Λ CDM model provides a remarkably successful phenomenological description of large-scale cosmological observations by introducing cold dark matter, dark energy, and an early inflationary phase [14, 22]. However, these components are postulated at the level of the effective model and are not derived from more fundamental principles.

In Cosmochrony, cosmic expansion follows directly from the monotonic relaxation of the fundamental field χ . The observed Hubble law emerges as a kinematic consequence of differential relaxation, without invoking a cosmological constant. In effective geometric descriptions, the expansion rate can be expressed as

$$H(t) = \frac{\dot{\chi}}{\chi}, \quad (30)$$

leading naturally to $H_0 \sim c/\chi(t_0)$ in the late-time regime.

From this perspective, dark energy is not interpreted as an additional physical component, but as an effective description of the large-scale relaxation dynamics of χ . Cosmic acceleration reflects the cumulative effect of this process over cosmological timescales. At the homogeneous and isotropic level, Cosmochrony reproduces the

background expansion described by Friedmann–Lemaître cosmology, while offering an alternative interpretation of its underlying origin.

Unlike Λ CDM, which requires finely tuned initial conditions and a persistent dark energy component, the Cosmochrony framework attributes the late-time acceleration to the intrinsic relaxation properties of the underlying field. In this view, the coincidence problem and the observed tension between local and global measurements of the Hubble parameter may be interpreted as manifestations of epoch-dependent relaxation dynamics rather than as indications of new fundamental components.

At large angular scales, Λ CDM treats deviations from scale invariance in the cosmic microwave background (CMB) as statistical realizations around an ensemble-averaged spectrum, with individual low- ℓ modes subject to cosmic variance. Within Cosmochrony, constraints on the largest-scale configurations of the χ field allow for a scale-dependent attenuation of global modes. From this standpoint, the observed suppression of power at low multipoles may be interpreted as a structural consequence of the relaxation dynamics, rather than as a purely statistical fluctuation.

These considerations suggest that Cosmochrony offers an alternative interpretative framework for cosmological observations, while remaining compatible with the empirical successes of the standard model at the level of current observational precision.

12.5 Inflation, Horizon Problems, and Initial Conditions

Standard inflationary theory addresses the horizon, flatness, and monopole problems by postulating a brief phase of accelerated expansion driven by an inflaton field. In the Cosmochrony framework, these issues are approached from a different conceptual standpoint.

Because the fundamental field χ defines a global relaxation process rather than a metric expansion imposed externally, causal connectivity is preserved at the level of the underlying field dynamics. Large-scale coherence may therefore arise from the initial smoothness of χ and its subsequent monotonic relaxation, potentially alleviating the need for a distinct inflationary epoch as a fundamental assumption.

At this stage, this perspective should be regarded as an alternative interpretative framework rather than a complete replacement for inflationary cosmology. A detailed analysis of primordial perturbations, their spectrum, and their imprint on the cosmic microwave background (CMB) is required to determine the extent to which Cosmochrony reproduces, modifies, or departs from standard inflationary predictions.

These questions define a clear direction for future work, in which the connection between early-time χ dynamics and observable cosmological signatures can be explored quantitatively.

12.6 Conceptual Implications and Open Challenges

Cosmochrony proposes a unifying geometric narrative in which time, distance, energy, gravitation, and quantization emerge from the dynamics of a single evolving field. This conceptual economy constitutes a central strength of the framework, while also requiring a careful reassessment of several notions traditionally treated as independent physical primitives.

In particular, the framework suggests that time, energy, and irreversibility do not represent distinct fundamental entities. Rather, temporal ordering is provided by the monotonic relaxation of the χ field, while energy quantifies the residual capacity of χ configurations to relax. Irreversibility then reflects the progressive exhaustion of this relaxation capacity. From this perspective, temporal flow and energetic processes constitute complementary descriptions of the same underlying geometric dynamics, rather than independent axioms of nature.

A concrete realization of this unification, including an explicit formulation of the relaxation operator and its spectral role in mass generation, is outlined in Appendix B.8. While this reinterpretation addresses several long-standing conceptual tensions —such as the origin of the arrow of time and the status of energy conservation—it also raises important open questions.

Among these challenges are:

- the precise mapping between χ dynamics and observed cosmic microwave background anisotropies,
- the treatment of non-equilibrium quantum measurements and decoherence,
- the emergence of gauge symmetries and interaction hierarchies,
- and the stability of solitonic particle configurations under extreme conditions.

Addressing these issues will require a combination of analytical, numerical, and experimental approaches, including:

1. large-scale numerical simulations of χ dynamics to quantify structure formation and cosmological signatures,
2. the exploration of discretized or network-based realizations of χ at microscopic scales,
3. and experimental tests of predicted χ -dependent effects in quantum coherence, gravitation, and radiation processes.

Progress along these directions may elevate Cosmochrony from a unifying conceptual framework to a quantitatively predictive theory, while preserving its minimal ontological foundation.

12.7 Ontological Parsimony and the Metric

As emphasized throughout the preceding discussion, the spectral operator relevant for mass generation is defined independently of any emergent geometric or dynamical description. A potential criticism of Cosmochrony is that it merely replaces one geometric structure (the spacetime metric) with another fundamental entity (the χ field). This subsection clarifies why this replacement constitutes genuine ontological simplification rather than a relabeling of degrees of freedom.

Distinction from metric-based theories.

In General Relativity and related metric frameworks:

- the metric $g_{\mu\nu}$ is a fundamental tensor field with ten independent components,
- spacetime curvature is treated as a primitive geometric property,

- matter and energy are conceptually distinct from geometry and are coupled to it via the stress-energy tensor.

In Cosmochrony:

- only a single scalar field χ is taken as fundamental,
- the spacetime metric arises as an effective, coarse-grained descriptor of χ dynamics and is not an independent dynamical entity,
- matter, energy, and geometry correspond to different regimes and configurations of the same underlying field.

Operational distinguishability.

The two frameworks are operationally distinct rather than notationally equivalent:

1. **Degrees of freedom:** General Relativity propagates two tensorial gravitational-wave polarizations derived from the metric structure. In Cosmochrony, only perturbations of the scalar field χ propagate at the fundamental level, with effective tensorial behavior emerging only in the macroscopic regime.
2. **Singularities:** In metric theories, singularities correspond to divergences of the fundamental geometric structure. In Cosmochrony, apparent singular behavior signals the breakdown of the effective geometric description, while the underlying χ field remains well-defined.
3. **Quantum regime:** Quantizing General Relativity requires the quantization of the metric itself (e.g., via the Wheeler–DeWitt equation). In Cosmochrony, only the scalar field χ is quantized, with spacetime geometry emerging from quantum configurations of this field.

Ontological economy.

From the perspective of ontological parsimony, Cosmochrony achieves unification through reduction rather than proliferation:

$$\text{Standard approach: } g_{\mu\nu} \text{ (geometry)} + \psi \text{ (matter)} + \Lambda \text{ (dark energy)}, \quad (31)$$

$$\text{Cosmochrony: } \chi \text{ (single fundamental degree of freedom)} \longrightarrow \{\text{spacetime, matter, expansion}\}. \quad (32)$$

This reduction does not merely rephrase existing structures, but offers an explanatory compression in which multiple physical notions arise from a single underlying dynamical principle.

12.8 Relation to the Higgs Mechanism

In the Standard Model, particle masses arise through spontaneous symmetry breaking of the electroweak sector, mediated by the Higgs field. In the Cosmochrony framework, mass is not introduced as a fundamental parameter, but emerges as a measure of the resistance of localized χ configurations to the global relaxation flow.

These two descriptions are not in contradiction. Rather, the Higgs field can be interpreted as an effective low-energy manifestation of interactions between localized

excitations and the surrounding χ background. From this perspective, the Higgs condensate encodes how particle-like configurations acquire inertial properties within an already structured, relaxing substrate.

Cosmochrony does not question the empirical success of the Higgs mechanism, nor does it seek to modify its phenomenology at experimentally accessible energies. Instead, it suggests that the Higgs field, like the spacetime metric or quantum wavefunctions, should be regarded as an emergent effective degree of freedom rather than as a fundamental constituent. Within this interpretation, the observed Higgs boson corresponds to a collective excitation associated with the stabilization of mass-generating configurations.

In this framework, the Higgs vacuum expectation value (VEV) is not treated as an independent fundamental scale, but as a quantity indirectly determined by the local properties of the χ background. This provides a conceptual link between the microphysical origin of particle masses and the large-scale relaxation dynamics of the underlying field.

A detailed derivation of the electroweak sector as an effective theory emerging from χ dynamics lies beyond the scope of the present work and is left for future investigation.

13 Conclusion and Outlook

We have presented Cosmochrony, a minimalist geometric framework in which a single continuous scalar quantity, χ , underlies the emergence of time, spacetime structure, gravitation, radiation, and quantum phenomena. Rather than postulating spacetime geometry or quantum laws at the fundamental level, the framework takes the irreversible relaxation of χ as the primary process from which familiar physical structures arise.

Within this perspective, physical time is identified with the intrinsic ordering induced by the monotonic relaxation of χ . Energy is not treated as a primitive conserved substance, but as a measure of the residual capacity of χ configurations to relax, while irreversibility reflects the progressive exhaustion of this capacity. Massive particles correspond to localized, topologically stable resistances to relaxation, gravitation emerges as a collective slowdown of χ induced by such resistances, and spacetime geometry arises as an effective description of these relational effects.

Radiation and quantization are interpreted as interaction-induced phenomena. Photons do not exist as fundamental entities but emerge during energy-transfer events as propagating disturbances of χ , with the Planck relation $E = h\nu$ acquiring a geometric interpretation as an effective proportionality between oscillation frequency and released relaxation potential. Quantum correlations and entanglement reflect persistent connectivity within the χ field, without requiring fundamental wavefunction collapse or superluminal signaling.

At cosmological scales, expansion follows directly from the global relaxation of χ , providing a unified geometric interpretation of the Hubble law, apparent cosmic acceleration, large-scale structure, and the arrow of time. In this framework, standard formulations of general relativity and quantum mechanics are recovered as emergent, coarse-grained descriptions valid in regimes where χ admits a stable geometric interpretation.

Several challenges remain open. These include the formulation of a fully satisfactory effective action principle, a deeper mathematical characterization of solitonic excitations, and large-scale numerical simulations capable of confronting the framework with precision cosmological and quantum data. Addressing these issues will be essential to assess the predictive scope of Cosmochrony beyond its conceptual unification.

By reducing the number of fundamental assumptions while preserving empirical adequacy, Cosmochrony offers a coherent foundation in which time, energy, and geometry arise from a single dynamical origin. Whether this perspective can be extended into a quantitatively predictive theory remains an open question, but the framework provides a well-defined starting point for further theoretical and observational exploration.

Appendices

A Mathematical Foundations of Cosmochrony — Dynamics, Stability, and Analytical Solutions

This appendix provides a rigorous mathematical formulation of the χ -field dynamics underlying the Cosmochrony framework. Its purpose is to support the effective descriptions introduced in the main text by establishing the consistency, stability, and analytical structure of the underlying field equations.

In particular, this appendix presents:

- the effective Lagrangian formulation and its hydrodynamic limit (Section A.1),
- stability analyses of the χ field under perturbations (Section A.2),
- analytical solutions in homogeneous, spherically symmetric, and planar regimes (Section A.3),
- and the relational foundation of emergent geometric descriptions (Section E).

All results are derived from the fundamental postulates of Cosmochrony (Section 3.2) without assuming a pre-existing spacetime metric or background geometry. Geometric notions appearing in this appendix should be understood as effective and coarse-grained representations of the underlying χ dynamics, consistent with the interpretative framework developed in Appendix E.

A.1 Effective Lagrangian Description as a Hydrodynamic Limit

The purpose of this subsection is not to introduce any additional fundamental structure into Cosmochrony, but to provide an effective hydrodynamic tool for connecting the relational χ framework to standard geometric formulations in regimes where a spacetime description becomes operationally meaningful.

From Relational Dynamics to an Effective Continuum Description

At the fundamental level, Cosmochrony is defined without reference to any pre-existing spacetime manifold or metric structure. The dynamics of the χ field are relational and are specified directly in terms of local relaxation rules and coupling relations between configurations (Section 3.2).

In regimes where χ varies smoothly over large scales, it becomes convenient to introduce a continuum approximation in order to compare the theory with standard geometric and field-theoretic formulations. This approximation does not alter the underlying ontology but provides a coarse-grained description suitable for analytical calculations and contact with general relativity.

Hydrodynamic Limit and Emergent Geometry

In this hydrodynamic regime, the discrete relational couplings encoded in the connectivity matrix K_{ij} can be summarized by effective continuum quantities. Operationally, distances are defined through the resistance encountered by the propagation of χ -relaxation across the network. In the continuum limit, this leads to an effective line element of the form

$$g_{\mu\nu} dx^\mu dx^\nu \sim \sum_{(u,v) \in \text{path}} \frac{1}{K_{uv}},$$

which should be understood as a *derived diagnostic* of the relational structure, not as a fundamental geometric postulate.

The effective metric $g_{\mu\nu}$ therefore encodes the coarse-grained density of correlations in the χ field and serves as a convenient macroscopic summary of its relational dynamics.

Effective Lagrangian Representation

To reproduce the continuum evolution equations obtained from the discrete relaxation dynamics (Equation 97), one may introduce an effective Lagrangian density \mathcal{L}_{CC} . This Lagrangian is constructed to match the hydrodynamic behavior of the χ field in the smooth regime, while remaining fully subordinate to the underlying relational description.

In this representation, terms resembling those of standard geometric theories naturally appear. In particular, a curvature-like contribution emerges as the leading-order descriptor of spatial variations in the relaxation rate:

$$\mathcal{L}_{\text{eff}} = \frac{1}{16\pi G_{\text{eff}}} F(\chi) R - \Lambda_{\text{flow}}^4 \chi + \dots$$

where R is the Ricci scalar associated with the effective metric, $F(\chi)$ is a non-minimal coupling function, and Λ_{flow} enforces the monotonic relaxation of χ .

Crucially, this Lagrangian does *not* define the fundamental dynamics of the theory. It is an effective bookkeeping device that reproduces the macroscopic behavior of χ once a geometric interpretation becomes applicable.

Status and Limitations

The hydrodynamic Lagrangian formulation presented here should be understood as an auxiliary representation, not as an alternative foundation of Cosmochrony. All physical content remains encoded in the relational relaxation dynamics of the χ field.

The emergence of Einstein-like field equations in this limit reflects the universality of geometric descriptions for slowly varying collective phenomena, rather than the

presence of a fundamental spacetime structure. As such, singularities or breakdowns of the effective metric signal only the limits of the hydrodynamic approximation, not a failure of the underlying χ dynamics.

A.2 Stability Analysis of the χ -Field Dynamics

The stability of the χ -field dynamics, governed by

$$\partial_t \chi = c \sqrt{1 - \frac{|\nabla \chi|^2}{c^2}}, \quad (33)$$

is a central requirement for Cosmochrony to define a physically consistent framework. Since χ is interpreted as a fundamental geometric substrate, its evolution must remain well-behaved under perturbations, without runaway growth or singular behavior.

Below we analyze the response of the system to small deviations around homogeneous relaxation states.

A.2.1 Perturbative Structure and Marginal Linear Stability

Consider a spatially homogeneous background solution

$$\chi_0(t) = ct + \chi_{0,0},$$

which satisfies $\nabla \chi_0 = 0$ and $\partial_t \chi_0 = c$. We introduce a small perturbation

$$\chi(x, t) = \chi_0(t) + \delta\chi(x, t), \quad |\nabla \delta\chi| \ll c.$$

Substituting into the evolution equation and expanding the square root yields

$$\partial_t \delta\chi = -\frac{1}{2c} |\nabla \delta\chi|^2 + \mathcal{O}(|\nabla \delta\chi|^4). \quad (34)$$

Importantly, no term linear in $\delta\chi$ appears. The homogeneous solution is therefore *marginally stable at linear order*: infinitesimal perturbations neither grow nor propagate dynamically at first order. This absence of linear instabilities reflects the purely relaxational character of the χ dynamics.

A.2.2 Nonlinear Stability and Dissipative Behavior

Although linear perturbations are marginal, the leading nonlinear correction is strictly negative. This implies that any spatial inhomogeneity in χ reduces the local relaxation rate and is therefore dynamically damped.

To make this explicit, consider the functional

$$E[\delta\chi] = \frac{1}{2} \int |\nabla \delta\chi|^2 d^3x, \quad (35)$$

which measures the total geometric tension stored in the perturbation. Using the evolution equation, one finds that $E[\delta\chi]$ is a non-increasing function of time. Spatial gradients are therefore progressively smoothed, and perturbations remain bounded for all times.

This establishes *nonlinear stability* of the relaxation dynamics: the system is dissipative and contractive in configuration space, with no mechanism for amplification of perturbations.

A.2.3 Special Configurations

For simple perturbative profiles, the qualitative behavior is transparent:

- **Planar perturbations:** Spatial oscillations do not propagate as waves, but are progressively flattened due to the reduction of the local relaxation rate.
- **Spherically symmetric perturbations:** Radial inhomogeneities decay monotonically, corresponding to a diffusive relaxation of geometric tension.

In all cases, the dynamics suppresses sharp gradients and prevents the formation of singular structures.

A.2.4 Conclusion

The χ -field dynamics are marginally stable at linear order and strictly stable once nonlinear effects are taken into account. This guarantees that the irreversible relaxation of χ defines a robust and physically consistent substrate for the emergence of spacetime geometry, gravitation, and quantum phenomena within the Cosmochrony framework.

A.3 Analytical Solutions of the χ -Field Dynamics

To illustrate the behavior of the χ field, we derive explicit analytical solutions of the dynamical equation

$$\partial_t \chi = c \sqrt{1 - \frac{|\nabla \chi|^2}{c^2}}, \quad (36)$$

in a set of simple but physically meaningful configurations. These solutions are not intended to exhaust the dynamics, but to clarify its geometric and causal structure.

A.3.1 Homogeneous Solution

In a spatially homogeneous configuration, $\nabla \chi = 0$ and the evolution equation reduces to

$$\partial_t \chi = c. \quad (37)$$

Integration yields

$$\chi(t) = \chi_0 + ct, \quad (38)$$

where χ_0 is the initial value. This solution defines the homogeneous cosmological background of Cosmochrony, in which the global relaxation of χ provides a natural origin for cosmic expansion and the Hubble law.

A.3.2 Spherically Symmetric Gradient-Saturated Profiles

Consider a spherically symmetric configuration $\chi = \chi(r, t)$. The evolution equation becomes

$$\partial_t \chi = c \sqrt{1 - \frac{(\partial_r \chi)^2}{c^2}}. \quad (39)$$

Configurations satisfying $|\partial_r \chi| = c$ correspond to a complete local suppression of relaxation, $\partial_t \chi = 0$. Such profiles take the form

$$\chi(r) = \chi_0 \pm cr, \quad (40)$$

and represent limiting configurations in which the local unfolding of time is halted. Although these profiles cannot be realized globally, they play an important conceptual role as idealized models of horizons and maximally constrained regions.

A.3.3 Linear Front Solutions

A simple class of exact solutions is given by linear fronts of the form

$$\chi(x, t) = \chi_0 + ct \pm x, \quad (41)$$

for which $|\nabla \chi| = 1 < c$ (in suitable units) and the evolution equation is satisfied identically. These solutions describe propagating relaxation fronts separating regions of different χ values. They do not correspond to waves in the usual sense, but to kinematic boundaries imposed by the maximal relaxation speed.

A.3.4 Absence of Linear Wave Solutions

It is important to emphasize that the χ -field dynamics does not admit linear wave solutions. Small perturbations do not propagate as oscillatory modes, but are smoothed through the nonlinear relaxation mechanism discussed in Section A.2. Apparent wave-like phenomena (gravitational or electromagnetic radiation) arise only as effective descriptions associated with structured matter excitations and will be discussed in later sections.

A.3.5 Conclusion

These analytical solutions illustrate the fundamentally relaxational character of the χ dynamics. Homogeneous growth underpins cosmological expansion, while gradient-saturated profiles and relaxation fronts clarify the emergence of horizons and causal structure. Together, they confirm the internal consistency of Cosmochrony and prepare the ground for effective wave phenomena introduced at the macroscopic level.

A.4 Coupling with Matter: Effective Source Term $S[\chi, \rho]$

In regimes where the χ field admits a smooth geometric interpretation, its dynamics may be expressed using effective differential operators familiar from field theory. Within

this *emergent* description, the influence of localized excitations (matter or energy density ρ) on the relaxation of χ can be summarized by an effective source term $S[\chi, \rho]$:

$$\square_{\text{eff}}\chi = S[\chi, \rho]. \quad (42)$$

This equation should not be interpreted as fundamental. Both the operator \square_{eff} and the source term S arise only after a spacetime description has emerged from the underlying relaxation dynamics of χ .

A.4.1 Physical Meaning of $S[\chi, \rho]$

The term $S[\chi, \rho]$ does not represent an external force acting on χ . Rather, it encodes the *effective resistance* of localized excitations to the global relaxation of the field. Regions containing matter correspond to structured configurations of χ (solitons) that locally reduce the relaxation rate, inducing spatial gradients and differential proper-time flow.

Within this interpretation, $S[\chi, \rho]$ provides a compact phenomenological description of several emergent effects:

- gravitational time dilation as a consequence of slowed χ relaxation,
- inertial mass as persistent resistance to relaxation,
- effective spacetime curvature as a coarse-grained description of spatial variations in χ .

A.4.2 Effective Form and Weak-Field Limit

In weak-field regimes, where matter-induced gradients are small, the effective source term may be approximated as linear in the excitation density:

$$S[\chi, \rho] \simeq -\alpha\rho, \quad (43)$$

with α an effective coupling constant. Matching with the Newtonian limit identifies $\alpha \sim G/c^2$, where G emerges as the macroscopic coupling between matter density and relaxation slowdown.

This linear approximation is sufficient to recover the Poisson equation for the effective gravitational potential and the Schwarzschild solution at leading order.

A.4.3 Strong-Field Regimes and Nonlinear Corrections

In regimes of high excitation density, such as near compact objects or in the early universe, nonlinear corrections to $S[\chi, \rho]$ are expected. These corrections reflect saturation effects in the relaxation dynamics and prevent unphysical halting of the field evolution:

$$S[\chi, \rho] = -\alpha\rho F\left(\frac{\rho}{\rho_c}, \chi\right), \quad (44)$$

where F is a bounded function and ρ_c is a characteristic density scale. Such nonlinearities encode departures from classical gravity without modifying the underlying ontological structure.

A.4.4 Scope and Open Questions

The effective description provided by $S[\chi, \rho]$ raises several open issues:

- the microscopic origin of the coupling constant α ,
- the role of $S[\chi, \rho]$ in quantum regimes where ρ is replaced by excitation amplitudes,
- possible observational signatures arising from nonlinear relaxation effects.

These questions are deferred to future work. The present formulation is intended as a bridge between the fundamental relaxation dynamics of χ and the effective gravitational and cosmological phenomena observed at macroscopic scales.

A.4.5 Conclusion

The effective source term $S[\chi, \rho]$ provides a consistent and economical way to encode the influence of localized excitations on the relaxation of the χ field. While not fundamental, it allows Cosmochrony to recover known gravitational phenomena and to articulate clear predictions in regimes where deviations from standard theories may arise.

A.5 Minimal Kinematic Constraint

A central assumption of Cosmochrony is the existence of a maximal local relaxation rate for the χ field:

$$0 \leq \partial_t \chi \leq c, \quad (45)$$

where c is identified with the invariant speed that appears in relativistic kinematics.

This bound is not introduced as a dynamical equation or a cosmological driving mechanism, but as a minimal kinematic constraint on the unfolding of the χ field. It ensures that the local progression of physical time remains finite and that no influence associated with χ -relaxation can propagate arbitrarily fast.

Rather than postulating a cosmological constant or an initial expansion impulse, Cosmochrony attributes the large-scale expansion of the universe to the cumulative effect of this local bound applied to a globally relaxing field. At the same time, the constraint guarantees causal consistency and allows the emergence of effective spacetime descriptions compatible with special relativity, without assuming relativistic structure at the fundamental level.

A.6 Effective Evolution Equation

Once a stable geometric description has emerged from the underlying relaxation dynamics of the χ field, it becomes possible to express its large-scale behavior using effective differential operators familiar from relativistic field theory. At this phenomenological level only, the evolution of χ may be summarized by an effective equation of the form

$$\square_{\text{eff}} \chi = S[\chi, \rho], \quad (46)$$

where \square_{eff} denotes the d'Alembert operator associated with the *emergent* metric, and ρ represents the density of localized excitations (matter).

This equation is not fundamental. Both the operator \square_{eff} and the source term S arise as coarse-grained descriptors of the underlying relaxation process and should be understood as bookkeeping devices rather than primary dynamical laws.

Physical interpretation of the source term.

The term $S[\chi, \rho]$ does not represent an external force acting on χ . Instead, it encodes the effective resistance of localized excitations to the global relaxation of the field. Regions containing matter correspond to structured configurations of χ that locally reduce the relaxation rate, giving rise to spatial gradients and differential proper-time flow.

In weak-field regimes, where matter-induced gradients are small, this effective resistance may be approximated as linear in the excitation density:

$$S[\chi, \rho] \simeq -\alpha\rho, \quad (47)$$

with α an effective coupling constant. Matching with the Newtonian limit identifies $\alpha \sim G/c^2$, where G emerges as the macroscopic coupling between matter density and relaxation slowdown.

Beyond this regime, nonlinear corrections to $S[\chi, \rho]$ are expected to reflect saturation effects in the relaxation dynamics. Such corrections prevent unphysical halting of the field evolution and encode departures from classical gravitational behavior without modifying the fundamental ontological structure of Cosmochrony.

A.7 Relational Foundation and Emergent Geometry

The formulation developed in the main text adopts a continuous description of the χ field as a pre-geometric substrate. This choice is motivated by conceptual economy and by the direct connection it provides with effective field-theoretic and cosmological descriptions.

It is important to emphasize, however, that the emergence of geometric notions in Cosmochrony does not rely on this continuous representation. A fully relational formulation, in which temporal ordering, distance, and effective geometry are reconstructed from internal correlations of χ without assuming any background spacetime structure, is presented separately in Appendix E.

That appendix demonstrates explicitly that the metric and spacetime geometry are not fundamental ingredients of the theory, but effective descriptors of relational χ dynamics. The present subsection therefore serves only to clarify the logical status of the continuous formulation adopted in the main text.

A.8 Energy and Curvature

In Cosmochrony, energy is not introduced as a fundamental conserved quantity. Instead, it emerges as an effective measure of the resistance of χ configurations to the global relaxation process. Once a geometric description becomes applicable, this resistance may be summarized by an effective energy density associated with spatial and temporal variations of the field.

At this phenomenological level, one may define a diagnostic functional of the form

$$\mathcal{E}_\chi^{\text{eff}} = \frac{1}{2} [(\partial_t \chi)^2 + (\nabla \chi)^2], \quad (48)$$

which should be understood as a bookkeeping device rather than a fundamental Hamiltonian density.

Regions where $\mathcal{E}_\chi^{\text{eff}}$ is large correspond to configurations with strong internal gradients, in which the relaxation of χ is locally constrained. Such regions are interpreted as localized concentrations of relaxation potential and are identified with particle-like excitations.

In this effective description, what may be loosely referred to as “curvature” of the χ field does not denote spacetime curvature in a fundamental sense, but rather the degree of internal deformation of the field configuration. Stable solitonic structures arise when nonlinear self-interaction terms balance the dispersive tendency of gradients, allowing localized resistance to relaxation to persist over extended times.

A.9 Level Sets, Projections, and Apparent Orbital Geometry

This appendix clarifies a general geometric property of continuous scalar fields that is relevant to the interpretation of atomic orbitals as threshold-visible structures. The results presented here are purely mathematical and do not rely on any specific physical interpretation.

A.9.1 Level Sets of Continuous Scalar Fields

Let $\phi : \mathbb{R}^3 \rightarrow \mathbb{R}$ be a continuous scalar field. For a given constant $c \in \mathbb{R}$, the corresponding level set (or isosurface) is defined as

$$\mathcal{L}_c = \{\mathbf{x} \in \mathbb{R}^3 \mid \phi(\mathbf{x}) = c\}. \quad (49)$$

If ϕ is smooth, \mathcal{L}_c is generically a two-dimensional surface, possibly composed of several disconnected components. Such level sets are commonly used to visualize scalar fields by displaying only regions where ϕ exceeds a fixed threshold.

A.9.2 Projection-Induced Apparent Discontinuities

Consider the projection of \mathcal{L}_c onto a single spatial coordinate, say z . Define the projected set

$$P_c = \{z \in \mathbb{R} \mid \exists (x, y) \in \mathbb{R}^2 \text{ such that } \phi(x, y, z) \geq c\}. \quad (50)$$

Even when ϕ is continuous, P_c generally consists of a union of disjoint intervals. These intervals correspond to regions where the level set intersects planes of constant z .

Importantly, the apparent disjointness of P_c does not imply any discontinuity of the underlying field ϕ . Rather, it arises from the fact that only regions exceeding the chosen threshold c are retained. The fragmentation is therefore a projection effect induced by thresholding.

A.9.3 Envelope Function and Threshold Visibility

Define the envelope function

$$f(z) = \max_{x,y} \phi(x, y, z). \quad (51)$$

The set P_c can then be written equivalently as

$$P_c = \{z \in \mathbb{R} \mid f(z) \geq c\}. \quad (52)$$

The function $f(z)$ is uniquely determined by ϕ and provides a global one-dimensional summary of the field's maximal amplitude along each slice of constant z . While the full three-dimensional structure of ϕ cannot be reconstructed from P_c alone, the envelope function $f(z)$ encodes the emergence and disappearance of visible components as the threshold c is varied.

In this sense, threshold-based visualizations reveal sections of a continuous structure rather than discrete or independent objects.

A.9.4 Non-Uniqueness of Inverse Reconstruction

Given a projected set P_c or a collection of disjoint level-set components, the inverse problem of reconstructing ϕ is not uniquely solvable. Multiple continuous scalar fields may share identical level sets at a given threshold.

Additional assumptions—such as symmetry, minimal curvature, smoothness, or governing differential equations—are required to select a preferred reconstruction. The present result therefore establishes a structural constraint rather than a unique inversion.

A.9.5 Summary

Level-set visualizations of continuous scalar fields generically produce apparently disjoint structures when projected or thresholded. These structures should be understood as emergent sections of an underlying continuous field. The mathematical origin of this effect is independent of any specific physical interpretation, but it provides a natural geometric framework for understanding disjoint orbital-like patterns as manifestations of threshold visibility.

While this appendix is presented independently of any physical model, the results apply directly to situations in which observable structures are defined by detection thresholds or projection procedures, as in atomic, optical, or imaging contexts.

B Conceptual Extensions of Cosmochrony — Particles, Quantum Phenomena, and Classical Limits

This appendix explores the conceptual and phenomenological extensions of the Cosmochrony framework, including:

- The nature of the χ field and its interpretation as a geometric substrate (Section B.1).

- Topological solitons as particle solutions, with explicit constructions for fermions and bosons (Sections B.2–B.4).
- The emergence of classical limits and the status of the formulation (Sections B.5–B.6).
- Perspectives on deriving the mass spectrum from χ -field dynamics (Section B.8).

These extensions bridge the gap between the mathematical foundations (Appendix A) and cosmological observations (Appendix C).

None of the constructions presented in this appendix are required for the internal consistency of the Cosmochrony framework. They are provided to illustrate how familiar particle, quantum, and classical structures may arise naturally once the χ field admits localized and stable configurations.

B.1 Nature of the χ Field

The field χ is postulated as a real scalar quantity admitting an effective description as a smooth field $\chi(x^\mu)$ on a four-dimensional differentiable manifold once a stable geometric regime is reached. This manifold should not be regarded as fundamental, but as an emergent representation of the relational structure induced by χ itself.

Unlike conventional scalar fields in quantum field theory, χ does not represent a matter degree of freedom propagating *within* spacetime. Rather, it encodes the local geometric scale from which spacetime notions such as distance, duration, and causal structure arise as effective concepts.

Operationally, χ may be interpreted as a proper wavelength field whose monotonic relaxation defines both temporal ordering and spatial separation. In this sense, spacetime coordinates serve only as convenient labels for the collective evolution of χ , not as fundamental background entities.

B.2 Topological Configurations of the χ Field: Solitons as Particles

Status of this construction.

The solitonic configurations described in this section are not introduced as fundamental degrees of freedom of Cosmochrony. They constitute *effective geometric models* intended to illustrate how particle-like properties may emerge from stable configurations of the χ field once a continuum and orientable geometric description becomes applicable.

At the fundamental level, Cosmochrony does not assume a pre-existing spatial manifold, metric, or differential structure. A fully relational formulation, free of geometric presuppositions, is presented separately in Appendix E. The present constructions should therefore be understood as phenomenological representations valid in the emergent geometric regime.

In Cosmochrony, particles are interpreted as **topologically stable solitons** of the χ field, where their properties—such as **spin**, **charge**, and **mass**—emerge from the **local deformation of χ** and its topological structure. Below, we classify these configurations and explicitly link them to particle properties, emphasizing how **charge arises from the modulation of χ 's relaxation**.

B.2.1 Charge as Local Deformation of χ

The **sign of a particle's charge** (positive or negative) is determined by how it deforms the χ field:

- A **positive charge** corresponds to a **local extension of χ** (a "peak"), which resists relaxation and repels other positive charges (as two peaks cannot merge).
- A **negative charge** corresponds to a **local contraction of χ** (a "trough"), which attracts positive charges (as a peak and trough can annihilate or merge).

This geometric interpretation explains **Coulomb-like interactions** without invoking a fundamental electromagnetic field, but as a consequence of χ dynamics.

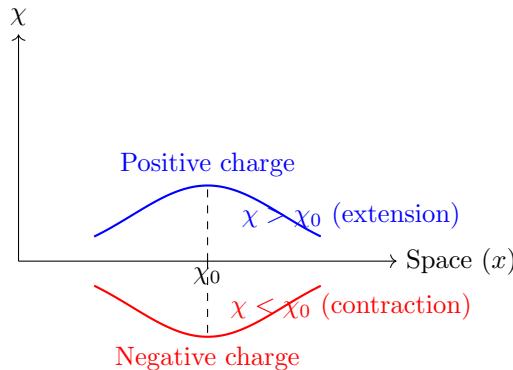


Fig. 3 Local deformations of the χ field representing positive (peak) and negative (trough) charges. The extension or contraction of χ relative to its background value χ_0 determines the sign of the charge and the nature of its interactions (This figure and following ones are schematic representations intended to illustrate the geometric and topological structure of *chi*-field excitations, not numerical solutions of the dynamical equations.).

B.2.2 Vortices (Charged Particles with Spin)

Vortices in the χ field are characterized by a quantized winding number n :

$$n = \frac{1}{2\pi} \oint \nabla \arg(\chi) \cdot d\mathbf{l}.$$

The **charge of the vortex** is determined by the **sign of its deformation**:

- For $n > 0$, the vortex creates a **local extension of χ** (positive charge).
- For $n < 0$, the vortex creates a **local contraction of χ** (negative charge).

The energy of the vortex scales with n^2 , reflecting the **mass of the particle**, while its winding determines the **spin** (e.g., $n = 1$ for spin-1 bosons).

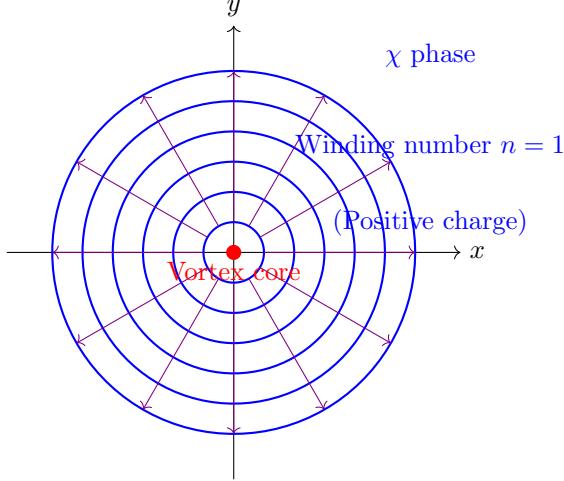


Fig. 4 Vortex configuration in the χ field, characterized by a winding number $n = 1$. The circular phase gradient (arrows) represents the spin of the particle, while the core (red dot) corresponds to a localized deformation of χ (positive charge). Such configurations model charged bosons with quantized angular momentum.

B.2.3 Skyrmions (Fermions with Charge and Spin-1/2)

Skyrmions are 3D solitons with a topological charge Q :

$$Q = \frac{1}{4\pi} \int \mathbf{n} \cdot (\partial_x \mathbf{n} \times \partial_y \mathbf{n}) dx dy,$$

where $\mathbf{n} = \chi/|\chi|$. The **charge of the skyrmion** is linked to the **polarity of its χ deformation**:

- A skyrmion with $Q = +1$ and a **peak in χ** represents a **positively charged fermion** (e.g., proton).
- A skyrmion with $Q = -1$ and a **trough in χ** represents a **negatively charged fermion** (e.g., electron).

The 4π -periodicity of skyrmions under rotations explains their **spin-1/2** nature, while the deformation of χ accounts for their charge.

B.2.4 Summary: Topology and Charge

The relationship between topology and charge in Cosmochrony is summarized in 1

B.3 Soliton Energy and Structural Mass Scaling

Status of this analysis.

This section presents a *quantitative but non-numerical* analysis of the mass associated with localized solitonic configurations of the χ field. The goal is not to reproduce the observed particle mass spectrum, but to identify robust scaling relations, hierarchy

Skyrmion ($Q = 1$)

Spin-1/2 fermion

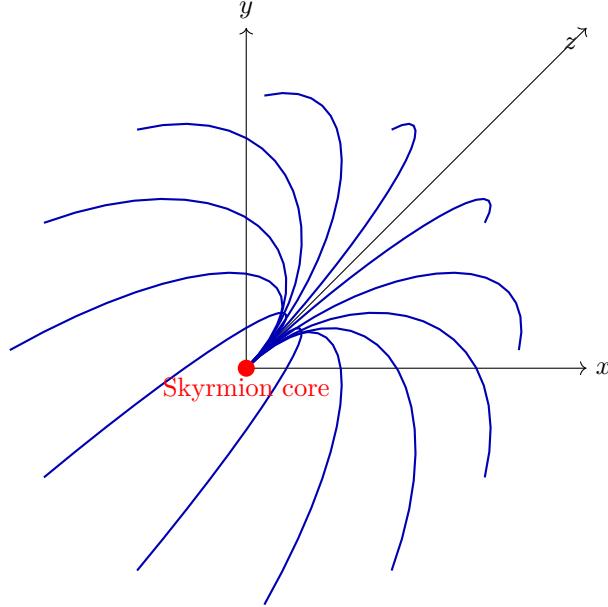


Fig. 5 Skyrmion configuration in the χ field, with topological charge $Q = 1$. The 3D structure reflects the fermionic nature of the particle (spin-1/2), where the core (red dot) represents a localized excitation of χ . Skyrmions provide a geometric model for fermions, with their charge determined by the polarity of the χ deformation.

Table 1 Topological Solitons, Charge, and χ Deformation

Soliton Type	Topological Invariant	χ Deformation	Particle Property
Vortex	Winding number n	Peak ($n > 0$) or trough ($n < 0$)	Charge $\propto n$, spin $\propto n $
Skyrmion	Charge Q	Peak ($Q > 0$) or trough ($Q < 0$)	Charge $\propto Q$, spin-1/2

constraints, and structural dependencies that emerge independently of microscopic details. A fully quantitative derivation of particle masses would require a complete effective field description, including gauge interactions and renormalization effects, which lies beyond the scope of the present work.

Mass as integrated resistance to relaxation.

Within Cosmochrony, the mass of a localized excitation is interpreted as a measure of the total resistance it presents to the global relaxation of the χ field. Once an effective geometric description applies, this resistance may be summarized by an effective energy

functional of the configuration,

$$M_{\text{eff}} \propto \int_{\mathcal{V}} [\mathcal{T}(\nabla \chi) + \mathcal{U}(\chi)] d^3x, \quad (53)$$

where \mathcal{T} encodes gradient-induced resistance and \mathcal{U} represents nonlinear self-interaction terms stabilizing the soliton. This expression should be understood as an effective diagnostic measure rather than as a fundamental Hamiltonian.

Scaling with soliton size and internal structure.

For a localized configuration characterized by a typical spatial scale ℓ and a characteristic amplitude $\Delta\chi$, dimensional analysis yields

$$M_{\text{eff}} \sim \ell^3 \left[\frac{(\Delta\chi)^2}{\ell^2} + V(\Delta\chi) \right]. \quad (54)$$

In the regime where stabilization results from a balance between gradient resistance and nonlinear self-interaction, the soliton size ℓ is dynamically fixed, leading to a finite and stable effective mass. Importantly, different classes of solitons (kinks, vortices, knotted configurations) exhibit distinct scaling behaviors with respect to ℓ and $\Delta\chi$, implying that mass hierarchies arise structurally rather than from fine-tuning.

Topological classes and mass hierarchy.

The effective mass depends not only on the size of the excitation but also on its topological class. Configurations with higher winding or linking numbers necessarily involve increased internal gradients, resulting in systematically larger resistance to relaxation. As a consequence, masses associated with different topological families obey ordering relations of the form

$$M_{n+1} > M_n, \quad (55)$$

where n labels a topological invariant. This establishes a natural mechanism for discrete mass hierarchies without requiring the introduction of ad hoc parameters.

Spectral interpretation.

From a spectral perspective, localized excitations correspond to bound modes of the linearized relaxation operator around a solitonic background. The effective mass is then controlled by the lowest nontrivial eigenvalue associated with the configuration,

$$M_{\text{eff}} \sim \lambda_{\min}^{-1}, \quad (56)$$

where λ_{\min} denotes the smallest positive eigenvalue governing the stability of the soliton. This formulation highlights that mass is fundamentally a spectral property of the χ dynamics rather than a free parameter.

Robustness and universality.

The scaling relations derived above depend only on generic properties of the χ field—locality, monotonic relaxation, and nonlinear stabilization—and are therefore expected to be robust against modifications of the microscopic details of the model. While numerical values of particle masses cannot be fixed at this level, the existence of discrete, ordered, and stable mass scales emerges as a structural prediction of the framework.

Summary.

Solitonic configurations of the χ field naturally possess finite effective masses determined by their size, internal structure, and topological class. Rather than predicting specific numerical values, Cosmochrony constrains the possible scaling and hierarchy of masses through geometric and spectral principles. This structural quantitatitvity provides a sound foundation for future extensions toward a fully predictive mass spectrum.

B.4 Example: 4π -Periodic Soliton and Spinorial Behavior

This section provides an *illustrative geometric construction* showing how spin- $\frac{1}{2}$ -like behavior may emerge from a scalar χ configuration, without introducing a fundamental spinor field.

The construction should be understood as an effective and topological model, intended to demonstrate plausibility rather than to constitute a complete microscopic derivation of fermionic degrees of freedom.

B.4.1 Phase-Twisted Solitonic Configuration

For convenience, the scalar field χ is represented in a complex form,

$$\chi(x) = \eta \tanh(\kappa x) e^{i\theta(x)}, \quad (57)$$

where the complex phase does *not* represent an independent internal degree of freedom but serves as a parametrization of the internal oscillatory structure of a localized χ excitation. The underlying physical field remains real.

Choosing

$$\theta(x) = \frac{x}{2}, \quad (58)$$

implies that the configuration returns to its original state only after a 4π variation of the phase,

$$\theta(x + 4\pi) = \theta(x) + 2\pi, \quad (59)$$

while a 2π variation produces a sign inversion.

B.4.2 Topological Interpretation

This 4π periodicity reflects a topological obstruction analogous to that encountered in spinorial representations. Although the spatial configuration may appear unchanged after a 2π rotation, the internal state of the excitation is not. Only a 4π rotation restores full equivalence.

This behavior mirrors the double-cover structure $SU(2) \rightarrow SO(3)$ characteristic of spin- $\frac{1}{2}$ systems, without postulating a fundamental spinor field. Instead, the spinorial behavior arises from the topology of the solitonic configuration itself.

B.4.3 Relation to Fermionic Statistics

At the effective level, such 4π -periodic excitations naturally acquire a minus sign under 2π rotations. In multi-excitation configurations, this topological property suggests an antisymmetric exchange behavior, providing a geometric basis for fermion-like statistics.

This result does not constitute a proof of the spin-statistics theorem. Rather, it demonstrates that fermionic transformation properties and exclusion behavior can consistently emerge from topologically constrained scalar-field excitations.

B.4.4 Conceptual Scope

The present construction is intentionally minimal. It aims to show that:

- spinorial behavior does not require a fundamental spinor ontology,
- fermion-like properties may arise from topological constraints,
- scalar-field dynamics can support nontrivial exchange behavior.

A fully relational formulation of these topological properties, independent of any embedding geometry, is discussed in Appendix E.

B.5 Relation to Classical Limits

In regimes where the χ field varies slowly over large scales and localized excitations are dilute, the dynamics may be linearized around a homogeneous background configuration. In this limit, fluctuations of χ propagate as weak disturbances on an effectively flat geometric background.

The resulting phenomenology reproduces the operational content of classical and quantum field theories formulated on Minkowski spacetime: wave propagation, superposition, and approximate locality emerge as effective properties of the coarse-grained χ dynamics. This correspondence should be understood as an *effective recovery*, not as an ontological reduction of Cosmochrony to standard quantum field theory.

Conversely, in regimes of high excitation density or strong spatial variation of χ , nonlinear effects dominate. Large gradients slow the local relaxation rate, inducing effective curvature, time dilation, and horizon-like behavior. These regimes reproduce the phenomenology associated with curved spacetime and gravitational collapse, while remaining governed by the same underlying scalar dynamics.

The classical limit in Cosmochrony therefore does not correspond to a separate theoretical layer, but to a dynamical regime in which collective behavior and coarse-graining suppress relational and topological effects. Classical spacetime and standard field dynamics emerge as stable, approximate descriptions valid when χ admits a smooth geometric interpretation.

B.6 Status of the Formulation

The formulation presented in this work should be understood as a minimal but structurally complete framework. Its core ontological assumptions, dynamical principles, and interpretative structure are fully specified, while several technical aspects remain open for further development.

In particular, a fully covariant action principle expressed solely in terms of the fundamental χ dynamics, as well as a systematic quantization procedure, have not yet been derived in their final form. These open problems are not conceptual gaps, but technical extensions aimed at connecting the relational foundations of Cosmochrony with standard variational and quantum formalisms.

Importantly, the absence of a finalized action or quantization scheme does not prevent the recovery of general relativity and quantum phenomenology as effective descriptions in appropriate regimes. Throughout this work, these standard theories emerge as coarse-grained limits of the underlying χ dynamics, rather than as independent postulates.

The present formulation therefore occupies an intermediate but well-defined status: it provides a coherent dynamical and conceptual foundation from which both geometric and quantum structures arise, while leaving room for future refinements that may enhance its mathematical completeness and predictive power.

B.7 Soliton and Particle Solutions

Within the Cosmochrony framework, elementary particles are interpreted as stable or metastable localized configurations of the χ field, hereafter referred to as χ -solitons. These configurations arise from nonlinear self-organization of the χ dynamics and persist as localized resistances to global relaxation.

While the fundamental degree of freedom is scalar, certain solitonic configurations exhibit an intrinsic internal structure that cannot be faithfully described by scalar variables alone. In particular, configurations characterized by nontrivial phase winding and 4π -periodicity require a double-valued representation under rotations. In such cases, an effective spinorial description becomes unavoidable.

At the phenomenological level, these excitations admit a representation in terms of Dirac spinors, not as fundamental fields, but as emergent collective variables encoding the internal degrees of freedom of χ -solitons. The Dirac equation then appears as the minimal effective dynamical description compatible with:

- locality at the coarse-grained level,
- relativistic covariance,
- and the topological constraint imposed by 4π -periodic configurations.

From this perspective, the Dirac structure does not introduce new ontological entities. Rather, it provides a compact and universal encoding of the internal topology and spectral properties of fermionic χ -solitons. Spin, statistics, and the associated exclusion principle follow from this structure as effective consequences of the underlying scalar dynamics.

The existence and stability of χ -solitons impose structural constraints on the effective self-interaction functional governing the field dynamics. While the explicit form of this functional remains undetermined, it must satisfy the following minimal requirements:

1. support for localized finite-energy configurations,
2. stability under small perturbations,
3. and the existence of topologically inequivalent sectors corresponding to distinct particle species.

The detailed derivation of effective Dirac dynamics from χ -soliton fluctuations, as well as the associated mass spectrum, remains an open mathematical problem. It is addressed at a programmatic level in Sections B.2–B.4 and in Appendix B.8.

B.8 Perspectives: Towards a Derivation of the Mass Spectrum

While the identification of particles as topological χ -solitons provides a geometric and dynamical origin for inertial mass—understood as resistance to relaxation—the explicit derivation of the observed particle mass spectrum remains an open challenge.

In Cosmochrony, particle masses are not expected to arise from arbitrary coupling constants or symmetry-breaking scales, but from the intrinsic stability properties of localized configurations within the relaxation substrate. This motivates a spectral approach, in which masses emerge as characteristic frequencies associated with small fluctuations around solitonic backgrounds.

B.8.1 Spectral Stability Hypothesis

Let χ_{sol} denote a stationary localized configuration. Small perturbations $\delta\chi$ around this background are governed, at the coarse-grained level, by a linear stability operator \mathcal{L}_{sol} , defined as the second variation of an effective localization functional. Normal modes satisfy the eigenvalue problem

$$\mathcal{L}_{\text{sol}}\psi_n = \lambda_n\psi_n. \quad (60)$$

In regimes where an effective wave description applies, these modes exhibit oscillation frequencies $\omega_n = c\sqrt{\lambda_n}$. Identifying the lowest characteristic frequency with the rest energy of the excitation yields the relation

$$m_n = \frac{\hbar_{\text{eff}}}{c} \sqrt{\lambda_n}, \quad (61)$$

where \hbar_{eff} acts as an effective conversion factor between geometric frequency and observed inertial mass. In this framework, \hbar is not postulated as a fundamental constant, but emerges phenomenologically from the coarse-grained description of relaxation dynamics.

B.8.2 Geometric Origin of Mass Hierarchies

Within this spectral perspective, mass hierarchies correspond to the structure of the low-lying spectrum of \mathcal{L}_{sol} . Different particle species arise from topologically inequivalent solitonic sectors, while generational structure may reflect higher-order stable modes associated with a single underlying configuration.

This approach transforms the problem of particle masses into a question of spectral geometry: determining which network connectivities and stability conditions give rise to discrete, hierarchically separated eigenvalues.

B.8.3 Programmatic Outlook

Developing this proposal into a predictive framework requires:

1. constructing explicit classes of solitonic configurations and their associated stability operators,
2. analyzing the dependence of the low-lying spectrum on topological and geometric parameters,
3. and implementing numerical studies of large relaxation networks to test whether realistic mass hierarchies emerge without fine tuning.

The purpose of the present section is not to claim a derivation of the Standard Model spectrum, but to establish a concrete and non-arbitrary route by which such a derivation could, in principle, be achieved within the Cosmochrony framework.

B.9 Spectral Characterization of Mass and the Secondary Role of $V(\chi)$

This appendix clarifies the conceptual status of inertial mass in Cosmochrony. While mass originates physically from the resistance of solitonic configurations to the relaxation of the χ field, this resistance admits a quantitative characterization in terms of the spectral properties of an associated stability operator.

In this context, spectral analysis does not redefine the physical origin of inertial mass—which remains the resistance of localized configurations to χ relaxation—but provides a structured and potentially calculable description of this resistance.

A central conjecture of the Cosmochrony framework is that particle masses are not fundamental parameters encoded in the nonlinear potential $V(\chi)$. Instead, they emerge as spectral properties of a relaxation operator defined on a relational substrate, which may be represented, for calculational purposes, by a discrete graph structure.

Mass spectrum as eigenmodes of a relaxation operator.

Localized particle-like excitations are identified with normal modes of an effective Laplace–Beltrami operator acting on a graph $G(V, E)$,

$$\Delta_G \psi_n = -\lambda_n \psi_n, \tag{62}$$

where ψ_n are eigenmodes characterizing the stability of localized configurations. The associated inertial masses are conjectured to scale as

$$m_n c^2 \propto \sqrt{\lambda_n}, \quad (63)$$

reflecting the fact that mass measures the characteristic frequency of resistance to relaxation.

This relation is analogous to the emergence of discrete vibrational frequencies in bounded elastic systems, where spectral values are fixed by geometry and connectivity rather than by adjustable parameters. Within Cosmochrony, mass hierarchies are therefore interpreted as geometric and topological properties of the underlying relational structure.

A decisive test of this conjecture would consist in computing the low-lying spectrum of Δ_G on large but finite networks with physically motivated connectivity rules. Even approximate agreement with observed mass ratios would strongly support the spectral origin of inertial mass and the non-fundamental role of $V(\chi)$.

Spectral structure and separation of descriptive levels.

To avoid circular dependencies between geometry, dynamics, and emergent particle properties, Cosmochrony distinguishes three conceptual levels.

At the fundamental level, inertial masses are associated with the spectral properties of a background-independent relaxation operator $\Delta_G^{(0)}$, defined by the intrinsic relational connectivity of the substrate. This operator is not tied to any specific spacetime geometry or instantaneous χ configuration and provides a stable spectral structure.

At the emergent geometric level, coarse-grained configurations of χ give rise to effective notions of spacetime, including gravitational time dilation and cosmological expansion. These geometric effects influence propagation and interaction, but do not modify the underlying spectral operator responsible for mass generation.

Finally, fast dynamical processes such as radiation, scattering, and decoherence correspond to interaction-induced redistributions of relaxation potential within the χ field. These processes affect observables without redefining the fundamental spectral structure.

Residual role of the potential $V(\chi)$.

Within this spectral picture, the nonlinear potential $V(\chi)$ plays a secondary and effective role. It provides a local, coarse-grained description of localization mechanisms associated with low-lying spectral modes, but does not independently determine their masses. Its admissible form is constrained by the requirement that it support stable solitonic configurations compatible with the spectral structure.

Supporting perspectives.

Additional constraints arising from discrete symmetries, information-theoretic considerations, or dynamical consistency may further restrict admissible connectivity structures. However, these considerations remain secondary to the central spectral hypothesis and are not required for its internal coherence.

Taken together, these arguments suggest that a substantial part of the explanatory burden for mass generation in Cosmochrony lies in the spectral properties of the underlying relaxation dynamics, with $V(\chi)$ serving as a derived effective descriptor rather than a fundamental source of mass.

Extending this spectral characterization toward concrete mass predictions requires specifying the relaxation operator and its boundary conditions, as discussed in Section B.8.

C Cosmological and Observational Implications of Cosmochrony

This appendix details the cosmological and observational consequences of Cosmochrony, including:

- The spectrum of χ -field fluctuations and their imprint on the CMB (Section C.1).
- Resolution of the horizon and flatness problems without inflation (Section C.2).
- Evolution of the Hubble parameter $H(z)$ and its observational implications (Section C.3).
- Numerical estimates of χ -field parameters and their relation to observable quantities (Section C.4).
- Phenomenological predictions for gravitational waves, MOND-like effects, and lensing (Section C.5).

These results demonstrate the conceptual compatibility of Cosmochrony with key cosmological observations while highlighting qualitative and semi-quantitative deviations from standard models that may serve as future observational tests. No full cosmological parameter fitting is attempted at this stage; the purpose of this appendix is to establish consistency, identify distinctive signatures, and motivate further numerical investigation.

C.1 Low- ℓ CMB Power Suppression from Global χ Relaxation

One of the most persistent anomalies of the cosmic microwave background (CMB) concerns the suppression of temperature anisotropy power at the largest angular scales ($\ell \lesssim 30$), particularly in the quadrupole and octupole moments. Within the standard Λ CDM framework, these deviations are generally attributed to cosmic variance, and no deterministic physical mechanism is associated with their occurrence.

In the Cosmochrony framework, however, the large-scale modes of the CMB probe the global configuration space of the χ field rather than local stochastic perturbations alone. Because χ undergoes a monotonic relaxation constrained by a maximal relaxation speed and by global connectivity, the longest-wavelength modes correspond to collective configurations that are not freely adjustable.

Structural attenuation of global modes.

At very low multipoles, the associated angular modes span regions comparable to the full causal domain of the χ field. As a consequence, these modes are subject to global

relaxation constraints: their amplitude is attenuated relative to the scale-invariant expectation, not as a result of random fluctuation, but due to the finite relaxation budget available for the largest coherent configurations of χ .

This effect is deterministic in origin but statistical in manifestation. Cosmochrony does not predict exact multipole amplitudes; instead, it predicts a systematic suppression envelope affecting the lowest ℓ modes, whose precise realization depends on the detailed configuration of χ at last scattering.

Illustrative comparison with observations.

Figure 6 displays the observed CMB temperature power spectrum at low multipoles, without aggressive smoothing, together with a schematic attenuation envelope representative of the Cosmochrony mechanism. This figure is intended to illustrate the qualitative structural deviation from scale invariance implied by global χ relaxation constraints. It does *not* constitute an independent multipole-by-multipole prediction.

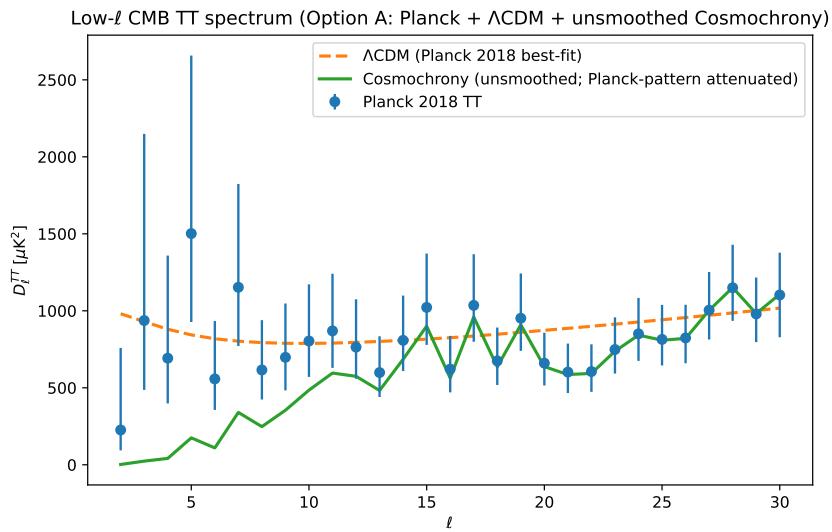


Fig. 6 Observed CMB temperature power spectrum at low multipoles ($\ell \lesssim 30$), shown without heavy smoothing. The shaded region illustrates a qualitative attenuation envelope expected from global χ relaxation constraints in Cosmochrony. Unlike Λ CDM, where low- ℓ suppression is treated as a statistical accident, Cosmochrony interprets it as a structural consequence of the finite relaxation capacity of the largest-scale χ configurations. The envelope is illustrative and does not represent a parameter-fitted prediction.

Conceptual distinction from Λ CDM.

In Λ CDM, deviations at low ℓ are explained *a posteriori* as realizations of cosmic variance around an ensemble mean. In Cosmochrony, by contrast, the ensemble itself is constrained: the global relaxation dynamics of χ limit the admissible configuration space

for the longest-wavelength modes. This introduces a qualitative, physically grounded distinction between large-scale and small-scale fluctuations.

Scope and limitations.

The present analysis does not replace detailed Boltzmann calculations nor does it attempt to reproduce the full angular power spectrum. Its purpose is to identify a robust qualitative signature of Cosmochrony: a deterministic suppression tendency affecting the lowest multipoles, arising from the global relaxation structure of the fundamental field. Quantitative refinement of this effect is deferred to future numerical studies of χ dynamics.

C.2 Resolution of the Horizon and Flatness Problems Without Inflation

In standard cosmology, the horizon and flatness problems arise from extrapolating a metric-based notion of causality back to the earliest stages of the universe. Inflation resolves these issues by postulating a brief phase of accelerated expansion, during which regions now widely separated were once in causal contact.

Cosmochrony adopts a fundamentally different perspective. In this framework, spacetime geometry and its associated causal structure are not fundamental, but emerge from the relaxation dynamics of the scalar field χ . As a result, causal connectivity is not constrained by a pre-existing metric at early stages, but is encoded directly in the global configuration of χ prior to the emergence of an effective spacetime description.

Horizon problem.

The horizon problem is resolved because large-scale correlations do not need to be established through signal propagation within spacetime. Instead, they originate from the fact that χ constitutes a single, continuous dynamical substrate whose relaxation precedes and gives rise to spacetime itself. Regions that later appear causally disconnected in the emergent metric description may therefore share common field configurations inherited from earlier stages of χ evolution.

In this sense, Cosmochrony replaces inflationary causal contact with *pre-geometric connectivity*: correlations are established at the level of the fundamental field rather than through superluminal expansion or fine-tuned initial conditions imposed on a metric background.

Flatness problem.

The flatness problem is similarly addressed without invoking an inflationary phase. In Cosmochrony, the effective spatial curvature reflects gradients and inhomogeneities in the relaxation rate of χ . As χ relaxes monotonically toward a homogeneous state on large scales, curvature terms are dynamically diluted. Near-flat spatial geometry therefore emerges as a natural attractor of the relaxation dynamics, rather than as the result of exponential expansion.

This mechanism does not require fine-tuning of initial curvature parameters. Instead, flatness reflects the tendency of the χ field to minimize large-scale geometric tension as relaxation progresses.

Implications for primordial correlations.

Because large-scale coherence arises from the global structure of χ rather than from inflationary amplification of vacuum fluctuations, Cosmochrony allows for departures from strict scale invariance at the largest angular scales. In particular, constraints on the longest-wavelength modes of χ may lead to a suppression or modulation of power at low multipoles in the cosmic microwave background.

Such effects are not interpreted here as definitive predictions, but as structural tendencies of the framework that may offer observational discrimination from inflation-based scenarios.

Status of the description.

The arguments presented in this section establish that the horizon and flatness problems do not arise as fundamental inconsistencies within Cosmochrony. A quantitative derivation of the primordial power spectrum, including detailed predictions for CMB anisotropies, requires dedicated numerical simulations of χ -field relaxation and lies beyond the scope of the present work.

Nevertheless, the framework provides a conceptually consistent and inflation-free resolution of large-scale causal coherence and near-flat geometry, rooted in the pre-geometric dynamics of a single scalar field.

C.3 Evolution of the Hubble Parameter and the Hubble Tension

In Cosmochrony, the cosmological expansion is governed by the relaxation dynamics of the scalar field χ , rather than by a balance between matter, radiation, and a dark energy component. The Hubble parameter therefore reflects the instantaneous relaxation rate of χ relative to its global value.

Global expansion rate.

At the background level, the scale factor is proportional to χ ,

$$a(t) \propto \chi(t),$$

so that the Hubble parameter is given by

$$H(t) = \frac{\dot{\chi}}{\chi}.$$

In a perfectly homogeneous configuration, $\nabla\chi = 0$ and the relaxation equation reduces to $\dot{\chi} = c$, yielding

$$H(t) = \frac{c}{\chi(t)}.$$

This relation defines the *global* expansion rate in Cosmochrony. Its precise redshift dependence beyond the homogeneous limit depends on how inhomogeneities and relaxation gradients contribute to the average dynamics, and is not assumed here to follow an exact power law at all epochs.

Relaxation budget and effective expansion.

To quantify the influence of inhomogeneities, we introduce the dimensionless *relaxation budget parameter*

$$\Omega_\chi \equiv \langle \beta^2 \rangle, \quad \beta \equiv \frac{|\nabla \chi|}{c}, \quad (64)$$

which measures the fraction of the relaxation capacity stored in spatial gradients of χ . In the late universe, these gradients are dominated by localized solitonic excitations and therefore track the matter distribution.

The effective global expansion rate is then reduced according to

$$\bar{H} = \frac{c}{\chi} \sqrt{1 - \Omega_\chi}.$$

Empirically, Ω_χ is constrained to be close to the observed matter fraction, $\Omega_\chi \simeq \Omega_m \approx 0.3$, providing a natural suppression of the expansion rate without invoking dark energy.

Local expansion and the Hubble tension.

In an inhomogeneous universe, the relaxation budget varies locally. In a region with density contrast

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}},$$

we adopt the minimal closure relation

$$\beta_{\text{loc}}^2 = \Omega_\chi(1 + \delta),$$

corresponding to a mean-field scaling between matter density and χ -gradient energy.

The local Hubble parameter then becomes

$$H_{\text{loc}} = \bar{H} \sqrt{\frac{1 - \Omega_\chi(1 + \delta)}{1 - \Omega_\chi}}. \quad (65)$$

In underdense regions ($\delta < 0$), the available relaxation capacity is higher, leading to $H_{\text{loc}} > \bar{H}$.

Numerical consistency.

For $\Omega_\chi \approx 0.31$ and a local underdensity consistent with the KBC void ($\delta \approx -0.4$ on scales of ~ 300 Mpc), we obtain

$$\frac{H_{\text{loc}}}{\bar{H}} \approx 1.08,$$

corresponding to an 8% enhancement of the locally inferred Hubble constant. This magnitude is sufficient to account for the observed Hubble tension between local distance-ladder measurements and global CMB-based inferences.

Interpretation and status.

In Cosmochrony, the Hubble tension does not signal missing energy components or inconsistencies in early-universe physics. Instead, it arises as a non-linear environmental effect associated with the redistribution of the χ -field relaxation budget in an inhomogeneous universe.

While the framework naturally predicts a separation between local and global expansion rates, a fully quantitative determination of $H(z)$ across all redshifts requires numerical simulations of χ dynamics and is left for future work. The resolution of the Hubble tension, however, follows directly from the relaxation-based interpretation of cosmological expansion and constitutes a distinctive and testable signature of the theory.

C.4 Relation to Observational Units and Numerical Estimates

This subsection provides order-of-magnitude estimates that connect the χ framework to observed cosmological quantities. The purpose is not to perform parameter fitting or derive precise numerical predictions, but to assess the internal consistency of Cosmochrony and its compatibility with empirical scales.

C.4.1 Normalization of the χ Field

To relate χ to observable quantities, a normalization must be specified. We identify the present-day value $\chi(t_0)$ with the characteristic cosmological length scale governing large-scale expansion. Operationally, $\chi(t_0)$ may be interpreted as the cumulative geometric scale associated with the global relaxation of χ up to the present epoch.

This identification does not assume a unique physical origin for $\chi(t_0)$, but provides a minimal normalization consistent with the interpretation $a(t) \propto \chi(t)$.

C.4.2 Emergent Gravitational Coupling

In the effective description, the gravitational constant G emerges from the constitutive relation governing the coupling between neighboring χ configurations. While the microscopic parameters K_0 and χ_c are not fixed individually, their product is constrained by matching the observed value of G :

$$K_0 \chi_c^2 \sim \frac{c^4}{16\pi G}. \quad (66)$$

This relation fixes the overall stiffness scale of the effective χ network, while leaving open whether the characteristic scale χ_c is associated with microscopic (e.g. Planckian) or macroscopic (cosmological) physics. The present framework does not require committing to a specific choice at this stage.

C.4.3 Hubble Constant

At the homogeneous level, the Hubble parameter is given by

$$H(t) = \frac{\dot{\chi}}{\chi}. \quad (67)$$

Assuming that the present universe is close to the maximal relaxation regime, $\dot{\chi}(t_0) \simeq c$, the present Hubble constant follows as

$$H_0 \simeq \frac{c}{\chi(t_0)}. \quad (68)$$

Using the observed value $H_0 \approx 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ yields

$$\chi(t_0) \sim 4 \times 10^{26} \text{ m}, \quad (69)$$

consistent with the observed Hubble radius. This correspondence arises without introducing additional cosmological parameters.

C.4.4 Age of the Universe

Integrating the homogeneous relaxation relation $\dot{\chi} \simeq c$ gives

$$\chi(t) \simeq ct + \chi_{\text{init}}, \quad (70)$$

where χ_{init} denotes the effective value of χ at the onset of the relaxation regime relevant for cosmological observations.

Neglecting χ_{init} relative to present values leads to

$$t_0 \simeq \frac{\chi(t_0)}{c} \sim 4 \times 10^{17} \text{ s}, \quad (71)$$

corresponding to approximately 13.8 billion years, in agreement with standard cosmological estimates.

C.4.5 Redshift Interpretation

In Cosmochrony, cosmological redshift arises from the relative change of the χ field between emission and observation:

$$1 + z = \frac{\chi(t_{\text{obs}})}{\chi(t_{\text{emit}})}. \quad (72)$$

This relation reproduces standard redshift phenomenology while attributing it to geometric scaling induced by χ relaxation rather than to recessional motion within a pre-existing spacetime.

C.4.6 Cosmic Microwave Background Scale

At recombination ($z_{\text{rec}} \simeq 1100$), the characteristic value of χ was correspondingly smaller:

$$\chi(t_{\text{rec}}) \simeq \frac{\chi(t_0)}{1 + z_{\text{rec}}}. \quad (73)$$

Fluctuations imprinted at that epoch are subsequently stretched by the monotonic growth of χ , providing a natural geometric interpretation of the observed angular scales in the cosmic microwave background.

C.4.7 Orders of Magnitude and Robustness

All numerical estimates presented in this subsection rely solely on observed cosmological quantities and the bounded relaxation dynamics of χ . No fine-tuning of parameters or detailed model fitting is assumed.

While a fully quantitative cosmological model remains to be developed, these estimates demonstrate that Cosmochrony naturally reproduces the correct orders of magnitude for key observables, including the Hubble constant, cosmic age, redshift scaling, and CMB characteristic scales.

C.4.8 Summary

The χ framework admits a consistent normalization in observational units and yields cosmologically relevant scales without introducing additional fundamental parameters. These order-of-magnitude relations support the internal consistency of Cosmochrony and motivate further quantitative investigation.

C.5 Phenomenological Implications

This section discusses the principal phenomenological consequences of Cosmochrony that are accessible to observation. The emphasis is placed on results that follow robustly from the kinematic and dynamical structure of the χ field, without introducing additional assumptions or tunable parameters.

Speed of gravitational perturbations.

To determine the propagation speed of gravitational information in Cosmochrony, we consider small perturbations $\delta\chi$ around a homogeneous background solution

$$\chi_0(t) = ct, \quad (74)$$

such that

$$\chi(\mathbf{x}, t) = ct + \delta\chi(\mathbf{x}, t), \quad |\nabla\delta\chi| \ll c. \quad (75)$$

Substituting into the fundamental evolution equation (Eq. 7) gives

$$c + \partial_t \delta\chi = c \sqrt{1 - \frac{|\nabla\delta\chi|^2}{c^2}}. \quad (76)$$

Expanding to leading order in spatial gradients yields

$$\partial_t \delta \chi \simeq -\frac{|\nabla \delta \chi|^2}{2c}. \quad (77)$$

While this first-order equation reflects the irreversible relaxation character of the dynamics, the propagation of perturbations is more transparently captured by considering the second-order operator obtained from the squared Hamiltonian constraint (Eq. 7). Linearizing this operator leads to the effective wave equation

$$\left(\frac{1}{c^2} \partial_t^2 - \nabla^2 \right) \delta \chi = 0. \quad (78)$$

The characteristic propagation speed of disturbances in the χ field is therefore

$$v_{\text{prop}} = c. \quad (79)$$

This result ensures strict consistency with multi-messenger observations, including the near-simultaneous arrival of gravitational and electromagnetic signals in GW170817. In Cosmochrony, this equality is not imposed but follows directly from the fundamental kinematic bound on χ relaxation.

Emergent acceleration scale and MOND-like phenomenology.

In Cosmochrony, the arrow of time is encoded in the monotonic evolution of the fundamental field χ , with $\partial_t \chi \geq 0$. At late cosmic times and on large scales, where χ admits an approximately homogeneous and isotropic description, this evolution may be coarse-grained into an effective cosmological clock.

In this regime, and only as an effective description, the temporal evolution of χ may be written as

$$\partial_t \chi \simeq H(t) \chi, \quad (80)$$

where $H(t)$ denotes the emergent Hubble parameter associated with the global relaxation of the field.

The local kinematic constraint

$$(\partial_t \chi)^2 + |\nabla \chi|^2 = c^2 \quad (81)$$

then implies that even in the absence of localized matter excitations, the cosmological evolution of χ induces a non-vanishing residual spatial gradient. In the homogeneous limit, this minimal gradient is

$$|\nabla \chi|_{\min} = \sqrt{c^2 - (H \chi)^2}. \quad (82)$$

This residual gradient defines a background kinematic scale that constrains how additional, locally induced gradients contribute to the effective dynamics. It may be expressed operationally as an effective acceleration floor

$$a_0(t) \sim c H(t). \quad (83)$$

When localized matter excitations are present, they induce additional gradients $\nabla\chi_N$ that reproduce the Newtonian scaling $|\nabla\chi_N| \propto M/r^2$ at short distances. Due to the non-linear nature of the kinematic constraint, the total gradient does not superpose linearly. At sufficiently large radii, the effective acceleration asymptotically approaches

$$g_{\text{eff}} \simeq \sqrt{g_N a_0(t)}, \quad (84)$$

recovering the characteristic deep-MOND scaling without interpolation functions or additional fields.

Importantly, Cosmochrony predicts that the acceleration scale a_0 is not fundamental but slowly evolves with cosmic time through its dependence on $H(t)$, providing a potential observational discriminator at high redshift.

Gravitational lensing.

In Cosmochrony, light propagation follows wave fronts of constant χ . The effective refractive index of the vacuum is defined operationally as

$$n(r) = \frac{c}{\partial_t \chi} = \frac{1}{\sqrt{1 - |\nabla\chi|^2/c^2}}. \quad (85)$$

Near a localized mass M , where $|\nabla\chi| \simeq GM/(c^2 r)$, the weak-field expansion gives

$$n(r) \simeq 1 + \frac{GM}{c^2 r}. \quad (86)$$

Integrating the transverse gradient of n along a photon trajectory yields the deflection angle

$$\alpha = \frac{4GM}{bc^2}, \quad (87)$$

with b the impact parameter. This reproduces the general-relativistic prediction, with the enhancement relative to the Newtonian result arising from the non-linear structure of the χ dynamics rather than from fundamental spacetime curvature.

Summary.

The phenomenology of Cosmochrony reproduces key observational signatures of gravity and cosmology while relying on a single scalar degree of freedom. Gravitational perturbations propagate at exactly the invariant speed c , a MOND-like acceleration scale emerges naturally from cosmological relaxation, and gravitational lensing is recovered without postulating a fundamental metric. These results illustrate how classical gravitational phenomena arise as coarse-grained manifestations of the underlying χ dynamics.

D Appendix D: Numerical Methods and Technical Supplements

This appendix collects technical and numerical tools used to explore the phenomenological consequences of the Cosmochrony framework. Its purpose is not to introduce additional fundamental structures, but to provide practical implementations and calculational schemes for regimes where the χ dynamics admits an effective discretized or coarse-grained description.

The methods presented here serve as computational approximations of the underlying continuous theory and do not carry independent ontological status.

This appendix provides technical details on:

- The collective gravitational coupling and operational geometry (Section D.1).
- Numerical algorithms for simulating χ -field dynamics and estimating model parameters.
- Supplementary derivations and calculations supporting the main text and other appendices.

These technical supplements are intended for readers interested in the numerical implementation or detailed derivations of the Cosmochrony framework.

D.1 Collective Gravitational Coupling and Operational Geometry

This subsection develops an effective and operational description of gravitational phenomena within the Cosmochrony framework. Its purpose is to demonstrate explicitly how standard Newtonian gravity and its geometric interpretation emerge from the collective dynamics of the χ field in regimes where a quasi-static and weak-gradient approximation is valid.

The constructions introduced here are not fundamental. They constitute a technical representation of the underlying continuous dynamics, designed to connect the relational formulation of Cosmochrony to familiar gravitational phenomenology. The fully relational and metric-free foundation of the theory is developed independently in Appendix E.

Collective coupling and effective description.

Localized excitations of the χ field resist its global relaxation and thereby slow the local evolution rate $\partial_t \chi$. When many such excitations are present, their influence superposes collectively, leading to a macroscopic modification of the relaxation dynamics.

In an effective description, this collective influence may be encoded in a coupling kernel K_{ij} , which characterizes how variations of χ between neighboring regions affect the local relaxation rate. The kernel depends only on differences of χ and captures the local stiffness of the field, without presupposing any background notion of distance or metric.

Continuum limit and emergence of the Newtonian potential.

In regimes where variations of χ are small and slowly varying, the collective dynamics may be approximated by a continuum description. In this limit, spatial variations of the relaxation rate can be expressed in terms of an effective gravitational potential Φ , defined operationally through the relative slowdown of χ :

$$\frac{\partial_t \chi}{c} \simeq 1 + \frac{\Phi}{c^2}. \quad (88)$$

Under this identification, the collective relaxation dynamics reduce to a Poisson-like equation,

$$\nabla^2 \Phi = 4\pi G \rho, \quad (89)$$

where ρ denotes the density of localized excitations. The gravitational constant G emerges here as an effective parameter relating the strength of the collective coupling to the density of excitations. Its numerical value is not predicted from first principles in the present framework, but must be fixed empirically, as in other effective theories of gravity.

Operational notion of geometry.

Because Cosmochrony does not assume a fundamental spacetime metric, spatial geometry is defined operationally through the propagation of χ variations. Two regions are considered close if perturbations of χ propagate efficiently between them, and distant otherwise.

In the weak-gradient regime, this operational notion induces an effective spatial geometry that coincides with the standard Newtonian and post-Newtonian descriptions. Spacetime curvature therefore appears as a macroscopic summary of how localized excitations collectively modulate the relaxation and propagation of the χ field, rather than as a primitive geometric property.

Scope and limitations.

The construction presented in this subsection is restricted to quasi-static, weak-field regimes where an effective spatial description is meaningful. It does not address strong-field dynamics, relativistic corrections beyond leading order, or quantum fluctuations of the χ field.

Its role is to establish that classical gravitational behavior can be recovered consistently from the collective dynamics of χ without introducing a fundamental metric or an independent gravitational interaction.

D.2 Estimates of χ -Field Parameters

This section compiles order-of-magnitude estimates for the effective parameters governing the χ -field dynamics. These estimates are not presented as fundamental constants, but as *consistency ranges* inferred from observational constraints and from the requirement that the emergent description reproduces known gravitational and cosmological scales.

The parameters considered here include:

- the **connectivity scale** K_0 entering the collective coupling K_{ij} ,
- the **characteristic χ scale** χ_c ,
- effective parameters (λ, η) controlling solitonic stabilization,
- the maximal relaxation speed c .

D.2.1 Connectivity Scale K_0 and Characteristic Scale χ_c

In the continuum limit, the effective gravitational coupling emerges from the collective stiffness of the χ network. Dimensional consistency and matching to the Newtonian limit yield the relation

$$G = \frac{c^4}{16\pi K_0 \chi_c^2}, \quad (90)$$

which links the emergent gravitational constant G to two independent scales:

- K_0 , with dimensions [length] $^{-2}$, characterizing the maximal local connectivity of the network,
- χ_c , the characteristic magnitude of χ over which macroscopic geometric effects become significant.

Equation (90) admits two physically distinct regimes:

Planck-scale normalization.

If χ_c is associated with the Planck length $\ell_P \simeq 1.6 \times 10^{-35}$ m, one finds

$$K_0 \sim 10^{93} \text{ m}^{-2}. \quad (91)$$

In this regime, the χ network is extremely stiff, and gravitational effects are interpreted as arising from microscopic connectivity close to quantum-gravitational scales.

Cosmological-scale normalization.

If instead χ_c is identified with the present Hubble scale $c/H_0 \simeq 1.4 \times 10^{26}$ m, the inferred connectivity is

$$K_0 \sim 10^{-52} \text{ m}^{-2}. \quad (92)$$

This corresponds to a much softer network, where large-scale cosmological relaxation dominates the effective geometry.

Both regimes are internally consistent at the level of dimensional analysis; discriminating between them requires additional observational input.

D.2.2 Effective Solitonic Parameters (λ, η)

Localized particle-like excitations are modeled as stabilized configurations of the χ field. In generic solitonic models, the characteristic mass scale satisfies

$$m_{\text{soliton}} \propto \sqrt{\lambda} \eta^3, \quad (93)$$

where λ controls nonlinear self-interaction strength and η sets the characteristic field amplitude.

Matching the electron mass scale provides an indicative constraint:

$$\lambda \sim 10^{-116} \text{ m}^{-2} \quad (94)$$

for $\eta \sim \mathcal{O}(1)$ in naturalized units. This extremely small value should not be interpreted as a fundamental constant, but as evidence that λ is an emergent or environment-dependent parameter, analogous to effective couplings in condensed-matter systems.

Mass hierarchies between particle species (e.g. $m_p/m_e \simeq 1836$) would then arise from differences in topological class, effective η , or collective stabilization mechanisms, rather than from a single universal coupling.

D.2.3 Relaxation Speed and Cosmological Constraints

The maximal relaxation speed c is identified with the invariant speed of relativistic kinematics. At the cosmological level, the background evolution implies

$$H(t) \simeq \frac{\dot{\chi}}{\chi}, \quad (95)$$

so that at the present epoch

$$\chi(t_0) \simeq \frac{c}{H_0} \sim 4 \times 10^{26} \text{ m}. \quad (96)$$

This identification reproduces the observed age of the Universe $t_0 \sim \chi(t_0)/c \simeq 13.8$ Gyr without introducing additional cosmological parameters.

D.2.4 Observational Constraints

Current observations impose indirect constraints on the allowed parameter space:

- **CMB anisotropies** constrain large-scale χ fluctuations, disfavouring values of χ_c that would over-amplify low- ℓ modes.
- **Hubble tension** can be interpreted as probing different effective χ regimes at low and high redshift.
- **Gravitational-wave propagation** constrains variations of K_0 in strong-field environments to remain subdominant.

D.2.5 Summary and Status

Table 2 summarizes the indicative ranges discussed above. These values should be understood as *consistency windows*, not predictions.

A first-principles derivation of these parameters from the microscopic χ dynamics remains an open problem and is identified as a key target for future analytical and numerical work.

Table 2 Indicative ranges for effective χ -field parameters

Parameter	Planck-scale regime	Cosmological-scale regime
K_0	$\sim 10^{93} \text{ m}^{-2}$	$\sim 10^{-52} \text{ m}^{-2}$
χ_c	$\sim 10^{-35} \text{ m}$	$\sim 10^{26} \text{ m}$
λ	$\ll 1$ (effective)	$\ll 1$ (effective)
η	$\mathcal{O}(1)$	$\gg 1$

D.3 Simulation Algorithms for χ -Field Dynamics

This appendix presents numerical methods used to explore the dynamical behavior of the χ field under the relaxation principles introduced in the main text. Its purpose is neither to define the fundamental ontology of Cosmochrony nor to privilege a specific microscopic substrate, but to provide a controlled computational framework in which the consistency, stability, and collective behavior of χ configurations can be investigated.

The simulations described here serve four complementary goals:

1. to verify the internal consistency of the bounded relaxation dynamics,
2. to test the spontaneous formation and persistence of localized excitations,
3. to study the response of the field to perturbations and external constraints,
4. to extract preliminary spectral signatures associated with stable configurations.

All numerical constructions should therefore be understood as *effective representations*. They do not assume a fundamental spacetime geometry, nor do they fix a unique microscopic realization of the theory. Their role is analogous to lattice simulations in QCD: exploratory, non-fundamental, yet indispensable for probing non-linear and collective regimes.

Discrete representation and numerical substrate.

The χ field is represented on a discrete set of sites $\{i\}$, each carrying a scalar value $\chi_i(\lambda)$, where λ is the monotonic relaxation parameter introduced in Section 4.1. Connectivity between sites is encoded by a local coupling matrix K_{ij} .

This discrete structure should be regarded strictly as a numerical scaffold. It does not represent a physical lattice, causal set, or spacetime discretization. Its sole purpose is to approximate local correlations and relaxation flows without presupposing a background geometry. Different graph topologies (regular grids, random graphs, locally weighted networks) lead to qualitatively similar behavior, indicating that the observed phenomena are robust with respect to discretization choices.

The simulations are therefore compatible with the relational formulation developed in Appendix E, while remaining technically independent of it.

Relaxation update rule.

The discrete evolution of the field is governed by a bounded relaxation rule inspired by the minimal kinematic constraint (Section A.5):

$$\frac{d\chi_i}{d\lambda} = c \sqrt{1 - \frac{1}{c^2} \sum_{j \sim i} K_{ij}(\chi_i - \chi_j)^2}. \quad (97)$$

This update rule enforces strict monotonicity of χ , a universal upper bound on the local relaxation rate, and suppression of gradient-driven instabilities. Time stepping is implemented using explicit adaptive schemes with stability control. Alternative discretizations respecting the same bound lead to equivalent qualitative behavior, confirming that the results do not depend on a fine-tuned algorithmic choice.

Formation of localized configurations.

Starting from generic initial conditions, the simulations consistently exhibit the emergence of localized regions where spatial variations of χ remain persistently large. These regions resist the global relaxation flow and remain stable over many relaxation times.

Such configurations are interpreted as numerical counterparts of the solitonic excitations discussed in Section 5. They arise dynamically without being imposed by hand and do not require fine-tuned initial conditions. Perturbative tests show that small disturbances around these configurations decay rather than grow, confirming their dynamical stability.

Spectral analysis and mode separation.

To probe the internal structure of stable configurations, the relaxation operator is linearized around a stationary χ background. The resulting eigenvalue problem defines a discrete spectrum of modes characterizing the response of the configuration to small perturbations.

A systematic spectral scan reveals a clear separation between a small number of low-lying modes associated with collective, coherent deformations of the configuration, and a dense set of higher modes that are rapidly damped by the relaxation dynamics. This mode separation is a robust numerical feature and does not depend sensitively on the discretization or boundary conditions.

These eigenmodes quantify intrinsic relaxation scales associated with the configuration. At this stage, they are not identified with observed particle masses. Rather, they provide a structural fingerprint of each stable excitation, capturing how strongly it resists deformation. The possible connection between these spectral hierarchies and physical mass spectra is discussed conceptually in Appendix B.9, without invoking numerical matching.

Interpretation and scope.

The existence of discrete spectral hierarchies is a robust numerical result. Their role in the present work is structural rather than predictive: they demonstrate that the relaxation dynamics of χ naturally supports stable localized excitations, bounded and causal evolution, and internally organized mode spectra.

Limitations.

The simulations presented here do not include quantum fluctuations, backreaction beyond the effective level, or fully relativistic covariance. They are not intended to provide numerical predictions for particle physics or precision cosmology.

Conclusion.

This appendix shows that the relaxation dynamics of the χ field can be implemented numerically in a stable and controlled manner, without invoking a background geometry or additional degrees of freedom. The emergence of localized excitations and discrete spectral mode separation provides strong support for the conceptual foundations of Cosmochrony and establishes a solid basis for future quantitative developments.

E Relational Formulation of χ Dynamics

This appendix develops a fully relational and explicitly non-geometric formulation of particle-like excitations in the χ framework. It is intended to clarify and extend the interpretation of topological stability introduced in Sec. 5.2, but is not required for the effective dynamical description presented in the main text.

The constructions discussed here illustrate how notions such as particle identity, spin, charge, and statistics may arise from internal topological features of χ configurations. They should be understood as a concrete realization of the relational ontology underlying Cosmochrony, rather than as a closed or unique classification of physical particles.

E.1 Relational Configurations of χ

At the most fundamental level, the χ field is described as a global configuration, without reference to spacetime points or coordinates. Physical distinctions arise only through relational differences between configurations, not through localization in a pre-existing manifold.

E.2 Non-Factorization and Entanglement

Within this relational description, composite configurations of χ need not factorize into independent subsystems. Such non-factorizable configurations naturally account for quantum entanglement, which appears as the persistence of shared relational structure even when effective spatial separation emerges.

E.3 Locality, Causality, and the Role of the Bound c

Although relational correlations may extend across large effective distances, any modification of χ configurations is constrained by the universal bound c . This ensures causal consistency without invoking signal propagation or superluminal influence.

E.4 Relation to the Effective Geometric Description

The effective metric, spatial gradients, and Poisson-type equations introduced in the main text arise as coarse-grained summaries of relational χ configurations. They provide

a convenient macroscopic language, but do not constitute fundamental degrees of freedom.

E.5 Topological Stability of Relational χ Configurations

In a fully relational formulation of Cosmochrony, particle-like excitations are identified with nontrivial, localized configurations of the χ field within its internal configuration space, rather than as objects embedded in a pre-existing spacetime manifold. Their stability arises from intrinsic topological constraints that obstruct any continuous relaxation into the homogeneous vacuum configuration.

Unlike conventional field theories, where topological invariants are defined with respect to spatial geometry, the invariants relevant here are purely internal to the relational structure of χ . They characterize inequivalent classes of configurations that cannot be continuously transformed into one another without discontinuity or singular reorganization of the field.

Such relational topological structures may be heuristically described using geometric metaphors—such as knots, twists, or vortices—but these should be understood as representations in an emergent descriptive language, not as fundamental spatial entities. At the relational level, stability is encoded in global consistency conditions on the internal correlations of χ .

A simple illustrative example is provided by configurations exhibiting 4π -periodic internal phase structure. These configurations cannot be continuously unwound into a trivial state and naturally give rise to fermion-like behavior in effective descriptions. More generally, distinct particle families may correspond to inequivalent topological sectors of the relational χ configuration space.

The energetic cost associated with deforming such configurations is determined by the internal stress of the χ field, quantified by its resistance to relaxation. This provides a unified origin for particle mass, stability, and identity, without invoking externally imposed charges or symmetries.

Importantly, this relational-topological picture does not require a unique or exhaustive classification of all possible configurations. It should be understood as a concrete realization of the ontological framework underlying Cosmochrony, illustrating how particle properties may emerge from the internal organization of χ , while remaining compatible with the effective geometric and dynamical descriptions developed in the main text.

E.6 Topological Origin of Fermionic and Bosonic Statistics

In a fully relational formulation, the distinction between fermionic and bosonic excitations arises from the internal topological structure of localized χ configurations, rather than from imposed quantum statistics. The relevant notion of rotation is not defined in physical space, but within the internal configuration space of χ .

Certain classes of configurations require a 4π internal phase rotation to return to an equivalent state. Such configurations are topologically twisted and cannot be continuously reoriented through a 2π transformation. In effective descriptions, these

structures exhibit fermion-like behavior, including the characteristic sign change under 2π rotation and the need for a full 4π cycle to restore equivalence.

Other configurations are 2π -periodic and correspond to orientable internal structures. These give rise to boson-like excitations in effective geometric descriptions. The distinction between the two classes is therefore topological and relational, not dynamical or statistical in origin.

Geometric metaphors such as Möbius twists, knots, or non-orientable loops may be used to visualize these internal structures, but they should be understood as illustrative representations valid only once an effective spatial description has emerged. At the fundamental level, the distinction is encoded in the global consistency conditions of the χ configuration.

This relational-topological perspective provides a natural qualitative explanation of the spin–statistics connection. While it does not constitute a proof in the axiomatic sense, it shows how the observed fermionic and bosonic behavior may arise from the internal organization of χ without introducing independent quantum postulates or fundamental spin degrees of freedom.

E.7 Vacuum Energy versus Relaxation Capacity of the χ Field

In conventional quantum field theory, the notion of *vacuum energy* refers to a non-vanishing energy density associated with zero-point fluctuations of quantum fields. This quantity is typically treated as an extensive, locally defined property of spacetime, contributing directly to the stress–energy tensor and therefore to gravitation. Its naive application leads to the well-known cosmological constant problem.

In Cosmochrony, no such fundamental vacuum energy density is postulated. The χ field does not possess an intrinsic, additive energy content in the absence of interactions or constraints. Instead, what is commonly interpreted as vacuum energy is reinterpreted as a *relational relaxation capacity* of the χ field.

This relaxation capacity characterizes the potential of χ to undergo further structural reconfiguration. It is not a local scalar density, but a contextual and non-extensive property that only becomes physically meaningful when relational constraints are imposed. In the absence of boundaries, matter excitations, or topological obstructions, this capacity has no observable manifestation.

The Casimir effect provides a paradigmatic illustration of this distinction. In the Cosmochrony framework, the presence of conducting boundaries constrains the admissible modes of χ relaxation between plates. The resulting force does not arise from an absolute vacuum energy stored in the intervening region, but from a differential in relaxation capacity between constrained and unconstrained configurations of the field.

Because relaxation capacity is inherently relational and does not correspond to a uniform energy density permeating spacetime, it does not gravitate in the manner predicted by standard vacuum energy arguments. This resolves, at the conceptual level, the tension between observable vacuum phenomena and the absence of an enormous cosmological constant.

In this sense, Cosmochrony does not deny the physical reality of vacuum-related effects. Rather, it reclassifies them as manifestations of the dynamical structure of the

χ field under constraint, eliminating the need for a fundamental vacuum energy while preserving all empirically verified phenomena.

E.8 Conceptual Positioning with Respect to Existing Frameworks

For clarity, Table 3 provides a high-level overview of how the relational χ framework is positioned with respect to several established theoretical approaches. The comparison is intended to highlight differences in ontological organization and scope, rather than empirical adequacy or predictive performance.

Conceptual Aspect	Quantum Formalism (QM / QFT)	Geometric Gravity (GR / related)	Cosmochrony
Primary ontology	Quantum states and fields	Spacetime geometry	Relational scalar substrate χ
Status of spacetime	Fixed or effective background	Fundamental dynamical entity	Emergent effective description
Nature of time	External parameter or operator	Coordinate-dependent	Intrinsic ordering via relaxation
Gravitation	Not fundamental	Metric curvature	Collective slowdown of χ relaxation
Quantum behavior	Postulated formalism	Externally imposed or emergent	Emergent from χ excitations
Vacuum structure	Zero-point fluctuations	Geometric ground state	Contextual relaxation capacity
Particle ontology	Fundamental entities	Geometric excitations	Topological χ configurations
Cosmic expansion	Not addressed	Requires matter/energy content	Geometric unfolding of χ
Inflation / initial conditions	Not addressed	External mechanism	Not required (pre-geometric continuity)
Empirical status	Highly successful	Highly successful	Exploratory

Table 3 High-level conceptual positioning of the relational χ framework with respect to established quantum and geometric approaches. The comparison emphasizes ontological structure rather than empirical validity.

F Glossary of Core Quantities and Notation

This appendix summarizes the meaning and status of the main quantities used throughout the Cosmochrony framework. It is intended strictly as a reference guide and does not introduce new assumptions, dynamics, or physical postulates.

F.1 Fundamental and Effective Quantities

χ (*Chi field*).

The fundamental scalar quantity of the Cosmochrony framework. χ is not defined on a pre-existing spacetime manifold but constitutes a pre-geometric substrate whose

monotonic relaxation provides an intrinsic ordering of physical processes. Localized, topologically stable configurations of χ correspond to particle-like excitations.

$V(\chi)$ (**Effective potential**).

An effective, coarse-grained description used to model localization and stability properties of χ configurations. $V(\chi)$ is not assumed to be fundamental; its form may emerge from underlying discrete relaxation dynamics and is secondary to the spectral description of mass.

K_{ij} (**Relaxation coupling**).

Edge-dependent coupling coefficients defined on the relaxation network $G(V, E)$. K_{ij} quantify the local resistance to relative variations of χ between neighboring nodes and encode geometric and topological information of the network. They may depend on the local configuration of χ in effective descriptions.

F.2 Derived Operators and Dimensionless Parameters

$G(V, E)$ (**Relaxation network**).

A discrete graph representing the underlying relational structure on which the χ field is defined at the fundamental level. Vertices correspond to elementary degrees of freedom, and edges encode relaxation couplings.

Δ_G (**Graph Laplacian / relaxation operator**).

The discrete Laplace–Beltrami operator associated with the network $G(V, E)$ and the couplings K_{ij} . It governs the stability and mode structure of localized χ configurations. Its spectral properties play a central role in the quantitative characterization of inertial mass.

S (**Gradient saturation parameter**).

A dimensionless quantity defined as

$$S \equiv \frac{1}{c^2} \sum_{j \sim i} K_{ij} (\chi_i - \chi_j)^2, \quad (98)$$

measuring the local density of χ gradients. The condition $S \leq 1$ ensures causal consistency and bounds the local relaxation rate of χ .

λ_n (**Spectral eigenvalues**).

The eigenvalues of the linearized relaxation or stability operator acting on small fluctuations around a localized configuration. In effective wave descriptions, $\sqrt{\lambda_n}$ determines the inertial mass scale of particle-like excitations.

Ω_χ (*Relaxation budget parameter*).

A dimensionless global quantity characterizing the fraction of the total χ relaxation budget stored in spatial gradients. In cosmological regimes, Ω_χ plays a role analogous to the matter density parameter in standard cosmology.

F.3 Key Concepts

Energy.

Energy is a conserved quantity associated with time-translation symmetry and the capacity to induce change. In Cosmochrony, energy is interpreted as a measure of resistance of χ -field configurations to dynamical evolution. Standard conservation laws and empirical relations remain unaffected.

Decoherence.

In quantum mechanics, decoherence denotes the suppression of interference effects due to interaction with an environment. In Cosmochrony, decoherence is interpreted as the irreversible local deformation of the χ field induced by interaction, which destroys the phase correlations required for coherent superposition without altering the underlying structural configuration.

Fluctuations.

Fluctuations refer to stochastic variations of the χ field around a given configuration. They modulate the localization and timing of individual events without altering the underlying structural constraints imposed by the χ topology.

Matter.

Matter conventionally refers to localized physical entities carrying mass and energy. Within Cosmochrony, matter corresponds to stable topological configurations of the χ field, whose persistence gives rise to particle-like behavior and inertial properties.

Measurement.

In standard quantum mechanics, a measurement refers to an interaction resulting in a definite outcome drawn from a probability distribution described by the wavefunction. In Cosmochrony, measurement is interpreted as a localized interaction that selects a specific manifestation of an underlying χ -field fluctuation, without altering the global probabilistic structure associated with the system. This interpretation does not require a fundamental wavefunction collapse.

Probability.

Probabilities are not taken as primitive. They reflect stable structural constraints imposed by the local topology of the χ field, defining invariant patterns of allowed manifestations. Stochastic fluctuations of χ modulate this pattern at the event level.

Relaxation (of the χ field).

Relaxation refers to the intrinsic dynamical tendency of the χ field to continuously extend and reorganize its configuration under internal coupling constraints. This process is geometric and pre-thermodynamic in nature and does not correspond to dissipation or entropy maximization.

Schrödinger Equation.

An effective linear equation governing the evolution of quantum probability amplitudes. In Cosmochrony, the Schrödinger equation emerges as an approximate description of coherent, weak fluctuations of the χ field around a stable configuration.

Space-Time.

Spacetime is an emergent relational structure arising from large-scale configurations of the χ field. Its effective metric description remains valid at accessible scales.

Time.

Time is interpreted as an emergent parameter associated with the local rate of evolution of the χ field. Operational time measurements and relativistic predictions remain unchanged.

Uncertainty Principle.

The uncertainty principle arises from the fact that any interaction locally modifies the configuration of the χ field. Probing one observable necessarily affects complementary dynamical aspects of the field.

Wavefunction.

The wavefunction ψ is an effective statistical representation emerging from the dynamics and topology of the underlying χ field. It is not a fundamental physical entity.

Wave-Particle Duality.

Wave-particle duality reflects interaction-induced changes in the local configuration of the χ field. The system remains fundamentally wave-like, while localized particle-like manifestations arise dynamically during interaction.

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