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

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Abstract

We propose *Cosmochrony*, a foundational physical framework in which time, inertia, and spacetime geometry emerge from the irreversible relaxation of a single fundamental scalar field χ. Unlike conventional field theories defined on a pre-existing spacetime, Cosmochrony treats relaxation as the primary physical process, from which temporal ordering, effective metrics, and dynamical laws arise.
Localized, long-lived excitations of the χ field appear as topologically and spectrally stable solitonic configurations. Their inertial mass is not postulated but emerges as a measure of resistance to global relaxation, quantified by the internal curvature and stability spectrum of the configuration. In regimes where an effective relativistic description applies, this interpretation naturally reproduces $E = mc^2$ as a kinematic identity rather than a fundamental axiom. Spin, statistics, and fermionic 4π periodicity originate from topological obstructions in the configuration space of χ excitations.
An effective spacetime metric arises through coarse-grained projections of χ relaxation dynamics, avoiding the assumption of a fundamental geometry. Gravitational and electromagnetic interactions are interpreted as manifestations of relaxation gradients and deformations of the underlying field, while gravitational waves correspond to propagating modulations of χ. The Higgs mechanism is recovered as an effective low-energy description of how localized excitations acquire inertial properties within an already structured relaxation background, without modifying its empirical phenomenology.
At cosmological scales, the framework provides a unified interpretation of cosmic expansion, dark matter, and dark energy in terms of the global relaxation budget of the χ field. The observed Hubble tension is addressed through nonlinear relaxation effects, without invoking new particle species or inflationary dynamics. Cosmochrony does not aim to replace the Standard Model or General Relativity at accessible energies, but to supply a deeper explanatory layer in which their

structures emerge from a common physical origin. The framework yields testable qualitative predictions, identifies clear numerical programs for validation via lattice simulations, and delineates the conditions under which effective field theories and spacetime descriptions remain valid.

Keywords: Emergent spacetime, quantum gravity, cosmology, geometric frameworks

Contents

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 holds that spacetime geometry is not fundamental. However, the two frameworks operate at distinct conceptual levels.

LQG provides a quantized description of geometry once a spacetime structure is already in place, encoding area and volume through spin networks and holonomies. Cosmochrony, by contrast, addresses an earlier stage: it proposes a pre-geometric substrate, described by a single scalar field χ, from which geometric notions themselves emerge.

In this sense, Cosmochrony does not compete with LQG but precedes it, offering a complementary framework that aims to explain the physical origin of the geometric degrees of freedom subsequently quantized in LQG.

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 relaxation[1] 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.

[1] The 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.

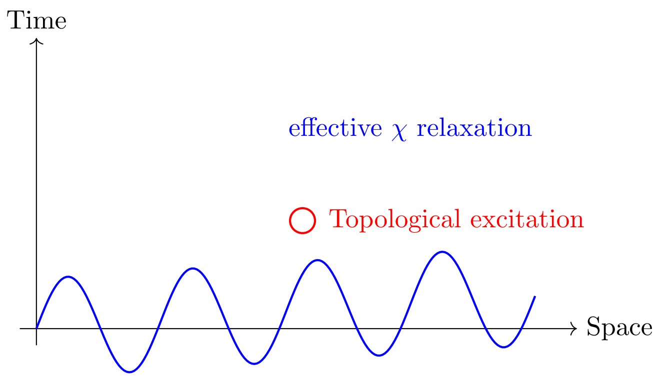

Fig. 1 Conceptual representation of Cosmochrony. An effective spacetime depiction of the relaxation of the scalar quantity χ, used for visualization purposes only. The monotonic relaxation of χ gives rise to an effective temporal ordering, while localized topological excitations correspond to particle-like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

3.2.1 Effective Observables from χ Correlations

In Cosmochrony, quantities conventionally described in geometric terms—such as time intervals, spatial separation, and causal ordering—are not taken as primitive. They arise as descriptive summaries of relational patterns within the χ field, constructed directly from its internal variation structure. No background spacetime, coordinate system, or discrete substrate is assumed at any stage of the fundamental description.

The configurations σ represent internal states of the χ field and are defined without reference to external spacetime coordinates or background geometry. They label relational degrees of freedom of the field, specifying patterns of internal organization rather than positions in a pre-existing space.

Correlations between configurations σ encode the emergent geometric and causal structure at the effective level, once a stable spacetime description becomes applicable. The measure $d\mu(\sigma)$ denotes an invariant integration over this space of configurations, defined intrinsically from the correlation structure of χ. It ensures that physical observables are independent of the particular parametrization chosen to label configurations, and carries no interpretation as a volume element in an underlying spacetime.

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

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

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:

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

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 the χ field exhibits smooth and stable correlation patterns, the relational observables defined above may be compactly summarized by an operational tensor $g_{\mu\nu}[\chi]$. This object is not introduced as a fundamental geometric structure, nor as an independent degree of freedom. Rather, it provides a convenient parametrization of how variations in χ modulate causal connectivity and effective relational intervals, and is meaningful only insofar as such a coarse-grained description remains valid. 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

In Cosmochrony, spacetime is not assumed as a pre-existing background structure. Instead, it appears as an effective macroscopic description arising from the continuous and monotonic relaxation dynamics of the scalar quantity χ. What are conventionally described as temporal and spatial features are understood here as distinct, but related, descriptive manifestations of this single underlying process.

In regimes where χ exhibits sufficiently stable and smooth correlation patterns, variations of the field give rise to a set of effective observables. In particular, an increase in χ is associated with:

- the accumulation of operational proper time along physical processes,

- the progressive decorrelation between configurations, summarized as an effective spatial separation,
- the large-scale expansion behavior observed when the relaxation of χ is considered at the cosmological level.

Within this effective description, temporal duration and spatial separation are not independent primitives. They represent complementary aspects of the same relaxation dynamics, captured at different levels of coarse-graining. Heuristically, effective distance may be viewed as the persistent imprint of relaxation that has already occurred, while effective time corresponds to the ongoing local relaxation of χ. These expressions are intended as interpretative guides rather than literal definitions, emphasizing their common dynamical origin.

This unified interpretation is not introduced ad hoc. It follows directly from identifying temporal ordering and relational separation as distinct summaries of the same scalar relaxation process, once a macroscopic description becomes appropriate. The physical content of the theory therefore resides entirely in the dynamics of χ, while spacetime notions serve as emergent descriptors valid in restricted regimes.

3.4 Monotonicity and Arrow of Time

A central structural assumption of Cosmochrony is that the scalar quantity χ evolves through a monotonic relaxation process:

$$\mathcal{D}_\lambda \chi \geq 0. \tag{3}$$

This condition is not introduced as a statistical statement, nor as a boundary condition imposed on an otherwise time-symmetric dynamics. Rather, it expresses an intrinsic property of the relaxation process governing χ itself.

Within this framework, energy is not treated as a fundamental conserved substance, but as a measure of the remaining capacity of a given χ configuration to relax. As relaxation proceeds, this capacity is irreversibly expended. A hypothetical decrease of χ would correspond to a spontaneous restoration of relaxation capacity, effectively reintroducing contraction or tension into the field. No dynamical mechanism within Cosmochrony permits such a process.

Irreversibility therefore follows directly from the structure of the χ dynamics. Because χ cannot decrease, the ordering of configurations induced by relaxation is intrinsically directed. What is conventionally described as the arrow of time is identified here with this directional ordering: the irreversible progression from configurations with greater relaxation capacity toward configurations in which that capacity has been exhausted.

Importantly, this arrow is not derived from coarse-graining, probabilistic entropy, or special initial conditions. It emerges as a direct consequence of the monotonic relaxation of χ, prior to any statistical or thermodynamic description. Temporal orientation is thus a manifestation of the fundamental dynamics, rather than an emergent asymmetry imposed at the macroscopic level.

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:

$$|\mathcal{D}_{\mathrm{loc}}\chi| \leq c, \tag{4}$$

where $\mathcal{D}_{\mathrm{loc}}\chi$ 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 Ontological Interpretation of the χ Field

Throughout this section, we explicitly distinguish the invariant structural bound c_χ, defined at the level of the pre-temporal χ substrate, from its emergent spacetime manifestation c. The latter appears only once spacetime notions such as distance, duration, and causal propagation become meaningful.

4.1 The χ Field as a Pre-Temporal Structural Plan

In the Cosmochrony framework, the χ field is not interpreted as a physical field evolving within spacetime, but as a pre-temporal structural substrate from which spacetime, matter, and physical laws emerge. It may be heuristically described as a "plan" of the universe: a complete structure encoding the set of physically admissible configurations and their relations.

Importantly, this plan is not a predetermined scenario. It does not specify a unique history nor a fixed sequence of events. Rather, it defines a constrained space of possibilities within which relational ordering may arise. Temporal succession is therefore not fundamental but emergent, corresponding to an oriented resolution of structural relations within χ.

4.2 Intrinsic Indeterminacy and Fluctuations

A perfectly deterministic and fully symmetric structural plan would remain dynamically sterile: no configuration would be privileged, and no physically consequential ordering could emerge. For this reason, Cosmochrony postulates the existence of intrinsic indeterminacy within the χ structure.

These fluctuations are not temporal events, nor stochastic processes unfolding in time. They represent a fundamental absence of complete determination at the structural level. Their role is not to generate dynamics, but to break perfect structural indifference, thereby allowing certain transitions to become physically consequential.

In this sense, fluctuations constitute a condition of possibility for emergence, rather than a dynamical cause.

4.3 Energy as Capacity for Relaxation

Within this framework, energy is reinterpreted as the capacity of the χ structure to relax its constraints. Energy does not correspond to a substance or a conserved entity at the fundamental level, but to a measure of unresolved structural tension.

The deployment of χ corresponds to the progressive conversion of structural indeterminacy into relational information. Energy thus quantifies the potential for this conversion. Without intrinsic indeterminacy, energy would be undefined, as no relaxation could occur.

4.4 Mass as Frozen Information

Localized, stable configurations of the χ field—interpreted as particle-like excitations—correspond to regions where relaxation is strongly inhibited. These configurations trap a fixed amount of unresolved structural information.

In this interpretation, mass represents frozen energy: information that has lost its capacity to participate freely in further relaxation. At the level of emergent spacetime physics, this relation is expressed by the standard mass–energy equivalence,

$$E_{\text{phys}} = m_{\text{phys}}c^2,$$

where c denotes the emergent spacetime limiting speed. This identity reflects, at the phenomenological level, a more fundamental structural relation governing the confinement and release of information within the χ substrate.

4.5 The Role of the Universal Bound c_χ

The constant c_χ plays a central structural role in Cosmochrony. Rather than setting a signal propagation speed, it defines an absolute bound on the degree to which information can be structurally constrained within the χ substrate.

In this sense, c_χ sets the maximal "knotting" or confinement of structural information compatible with physical coherence. Beyond this bound, further constraint becomes impossible and relaxation is unavoidable. The emergent spacetime notions of inertial resistance, causal structure, and mass–energy equivalence are understood as projections of this invariant structural limit.

4.6 The Role of $\hbar_\chi$ and Reprojection from χ

In Cosmochrony, the parameter $\hbar_\chi$ is **not derived from** $\hbar$ but emerges from the fundamental scales K_0, χ_c, and c. Its numerical coincidence with $\hbar$ in quantum regimes reflects the **universality of action quantization** across physical theories.[2] It is derived purely from the fundamental scales K_0, χ_c, and c, without reference to spacetime or quantum constants. It does not represent a quantum of action evolving in time, but a fundamental quantum of reprojection.

Intrinsic fluctuations of χ do not give rise to continuous emergence. Rather, any reprojection of structural information into emergent spacetime occurs in discrete units set by $\hbar_\chi$. Transient excitations commonly interpreted as vacuum particles thus correspond to minimal reprojections allowed by this bound.

In the early universe, where spacetime structure was weakly stabilized, such reprojections were diffuse and frequent. As the universe relaxed and large-scale structures formed, reprojection became progressively localized, manifesting as vacuum fluctuations in otherwise stable regions of spacetime.

[2] Unlike in quantum gravity, where $\hbar$ and G are fundamental, here $\hbar_\chi$ is derived from χ -field parameters alone. The standard $\hbar$ is recovered only in regimes where $\ell_{\text{spacetime}} \sim \chi_c$.

5 Dynamical Equation for the χ Field

5.1 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:

$$\mathcal{D}_\lambda \chi = \mathcal{R}[\chi], \tag{5}$$

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.

5.2 Hamiltonian Derivation of the Evolution Equation

Local Constraint on Relaxation Dynamics

The fundamental dynamics of the χ field is formulated without reference to spacetime coordinates or to a Hamiltonian structure. Nevertheless, its relaxation is subject to a universal local constraint reflecting the bounded character of admissible relaxation rates.

In regimes where the relational structure of χ admits a smooth and stable coarse-grained description, this constraint can be summarized in a compact form resembling a Hamiltonian relation. This formulation is introduced solely as a descriptive parametrization of the admissible local relaxation configurations, and does not define a fundamental phase-space dynamics.

Specifically, the local relaxation rate of χ is bounded by the invariant constant c. When expressed in effective relational variables, this bound takes the form

$$(\mathcal{D}_{\mathrm{loc}}\chi)^2 + \mathcal{V}_\chi^2 = c^2, \tag{6}$$

where $\mathcal{V}_\chi$ denotes the effective internal variation rate of χ, capturing how strongly local configurations resist relaxation. No notion of spatial gradient or background geometry is assumed at the fundamental level.

Selecting the monotonic relaxation branch yields the effective evolution equation

$$\mathcal{D}_{\mathrm{loc}}\chi = c\sqrt{1 - \frac{\mathcal{V}_\chi^2}{c^2}}, \tag{7}$$

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

Emergent Gravitational Description

Localized, relaxation-resistant configurations of χ generate regions of enhanced internal structure, which locally reduce the admissible relaxation rate. When a spacetime description becomes applicable, this effect is conventionally described as gravitational time dilation. No independent gravitational interaction or field is postulated; the effect arises directly from the constrained relaxation dynamics of χ itself.

In the weak-structure regime, where internal variation rates are small compared to c, the effective description admits a simplified relation governing the spatial distribution of relaxation slowdown:

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

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

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

$$\Phi \equiv c^2 \ln\left(\frac{\mathcal{D}_{\mathrm{loc}}\chi}{c}\right). \tag{9}$$

This potential is not introduced as a fundamental field, but as a convenient summary of how localized variations of χ modulate relaxation in regimes where classical gravitational phenomenology applies.

Interpretational Status

The relations presented in this section do not constitute a fundamental Hamiltonian or a variational principle. They provide an effective local parametrization of the constraints governing χ relaxation when a geometric description becomes applicable.

The predictive content of Cosmochrony resides entirely in the intrinsic, pre-geometric relaxation dynamics of the χ field. Hamiltonian, geometric, and gravitational structures appear only as emergent descriptive tools, valid in restricted regimes and carrying no independent ontological status.

5.3 Microscopic Origin of the Coupling Tensor and the Poisson Equation

For internal consistency, the effective coupling governing the relaxation of χ cannot be treated as a fixed universal constant. Instead, it must depend on the internal structural state of the field, reflecting how local configurations resist or facilitate relaxation. In Cosmochrony, this dependence is captured through a constitutive relation linking the effective coupling strength to internal variations of χ, without invoking any underlying spatial substrate.

A convenient phenomenological parametrization of this dependence is given by

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

where $\Delta\chi$ denotes a measure of internal variation of χ between correlated configurations, K_0 characterizes the maximal relaxation conductivity in a homogeneous background, and χ_c sets the characteristic scale beyond which structural inhomogeneities significantly reduce the effectiveness of relaxation.

Configurations exhibiting strong internal variation of χ, such as stable solitonic excitations, therefore reduce the effective coupling and locally slow the relaxation process. This reduction does not represent an additional interaction, but reflects the intrinsic resistance of structured configurations to further relaxation. The resulting slow-down constitutes the microscopic origin of the emergent gravitational phenomenology discussed in the previous section.

In regimes where a spacetime description becomes applicable, the local relaxation rate $\mathcal{D}_{\text{loc}}\chi$ differs from its asymptotic value $\mathcal{D}_0$ far from localized configurations. An effective gravitational potential Φ may then be introduced as a descriptive parameter through the relation

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

which summarizes the relative slowdown of relaxation in a form familiar from classical gravitational phenomenology.

In the weak-structure regime, where internal variations of χ remain small compared to χ_c, the distribution of Φ admits a simplified elliptic description. At this coarse-grained level, the effective dynamics reduce to a Poisson-type relation,

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

where ρ denotes the density of localized, relaxation-resistant configurations and G_{eff} is an emergent coupling parameter encoding the collective response of the χ relaxation dynamics.

This Poisson equation is not fundamental. It represents the weak-field, macroscopic limit of the constrained relaxation dynamics of χ, expressed in a form adapted to effective geometric description. Gravitation therefore appears not as an independent interaction, but as a descriptive manifestation of reduced relaxation conductivity induced by structured χ configurations.

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

Status of effective equations.

The effective equations introduced in this section—such as the Poisson-like relation for the gravitational potential or the wave equations describing solitonic excitations—are valid only within regimes where χ admits a smooth, weak-gradient geometric interpretation. They arise from coarse-graining the underlying χ relaxation dynamics and do not represent fundamental postulates of the theory.

In particular, these equations should not be confused with the intrinsic relaxation equation governing χ at the pre-geometric level. Their domain of applicability is limited to configurations close to local equilibrium, where an effective spacetime description becomes meaningful.

5.4 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 [15, 16], we consider the effective Lagrangian density

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

where $\mathcal{D}_{\text{loc}}\chi$ denotes the effective local relaxation rate introduced in Sec. 5.1, 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:

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

which coincides with the effective Poisson-type equation obtained in Sec. 5.3.

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.

5.5 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.

5.6 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,

$$\mathcal{D}_{\mathrm{loc}}\chi = c, \tag{15}$$

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,

$$\chi(t) = \chi_{\mathrm{min}} + c\,t, \tag{16}$$

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. 10. Cosmic expansion thus reflects the global relaxation of χ, rather than the presence of an external energy component.

As shown in Appendix A.6, 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.

5.7 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.

5.8 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.

5.9 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.

6 Particles as Localized Excitations of the χ Field

6.1 Particles as Stable Wave Configurations

Within the Cosmochrony framework, particles are not fundamental point-like objects but stable, localized excitations of the χ field [17]. 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.

6.2 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.

6.3 Mass as Resistance to χ Relaxation

In Cosmochrony, mass is not introduced as an intrinsic or fundamental property of matter. Instead, it emerges as a quantitative measure of how strongly a localized configuration of the χ field resists the global relaxation flow.

A particle-like excitation is modeled as a stable, localized solitonic configuration χ_s, characterized by sustained internal structure and non-vanishing gradients. Such configurations locally inhibit the relaxation of χ, producing a slowdown relative to the homogeneous background evolution. In an effective geometric description, this slowdown manifests as inertial persistence and gravitational time dilation.

We define the structural energy associated with a solitonic configuration χ_s as the excess relaxation capacity stored in its internal curvature:

$$E[\chi_s] \;\equiv\; \int_\Sigma \left(\frac{1}{\sqrt{1 - |\nabla\chi_s|^2/c^2}} - 1 \right) d\Sigma, \tag{17}$$

where Σ denotes a hypersurface of constant effective ordering parameter, and $|\nabla\chi_s|$ quantifies the local structural deformation of the χ field. This expression measures the energetic cost of maintaining a non-relaxed configuration embedded within a globally relaxing substrate.

The inertial mass associated with the soliton is then defined operationally as

$$m \;\equiv\; \frac{E[\chi_s]}{c^2}. \tag{18}$$

This relation is not postulated but follows directly from the role of $E[\chi_s]$ as a measure of resistance to χ relaxation. The universal constant c appears as the maximal relaxation rate of the field and therefore provides the unique conversion factor between relaxation energy and inertial response.

Within this framework, the relation $E = mc^2$ is interpreted as a kinematic identity: mass quantifies the amount of relaxation potential locally trapped in a persistent χ configuration, while energy measures the same quantity expressed in relaxation units.

In this sense, mass is not an independent attribute of matter, but a derived property encoding how strongly a localized χ configuration resists the irreversible relaxation that defines physical time.

The question of how different particle masses arise from distinct solitonic configurations is addressed in Appendix B.2, where a spectral characterization of χ-field stability modes is proposed as the geometric origin of mass hierarchies.

6.4 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

$$E \propto \nu, \tag{19}$$

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. 11.3.

6.5 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.

6.6 Spin as a Topological Property of χ Configurations

Within the Cosmochrony framework, spin is not introduced as an intrinsic kinematic degree of freedom, nor as a consequence of spacetime symmetries. Instead, it emerges as a purely topological property of localized χ configurations.

Certain stable solitonic excitations of the χ field possess an internal structure that cannot be continuously deformed to the vacuum configuration. These excitations are characterized by a non-trivial topology in their internal configuration space, independently of any background spatial geometry.

In particular, a class of fermionic configurations requires a 4π internal rotation to return to an equivalent configuration. A 2π rotation corresponds to a non-contractible loop in the configuration space of χ, while a 4π rotation is homotopic to the identity. Formally, this implies that the relevant configuration space admits a double covering, with fundamental group

$$\pi_1(\mathcal{C}_\chi) = \mathbb{Z}_2, \tag{20}$$

where $\mathcal{C}_\chi$ denotes the space of admissible localized χ configurations.

When an effective quantum description becomes applicable, localized χ excitations are represented by complex wavefunctions encoding the phase structure of underlying field fluctuations. For topologically non-trivial configurations, a 2π effective rotation induces a sign change of the associated wavefunction,

$$\psi \longrightarrow -\psi, \tag{21}$$

while a 4π rotation restores the original state.

This behavior identifies such excitations as spin-$\frac{1}{2}$ fermions. Importantly, the appearance of a spinorial phase does not rely on a fundamental representation of the rotation group, but follows from the topological structure of the underlying χ configuration itself.

The fermionic statistics of these excitations arises from the same topological origin. Two identical fermionic solitons correspond to configurations that share a common χ-field topology and therefore cannot be continuously merged into a single configuration without violating field continuity.

Exchanging two identical fermionic excitations corresponds topologically to a 2π rotation in the combined configuration space. As this operation induces a sign change of the effective wavefunction, symmetric configurations are dynamically forbidden. This provides a geometric and topological origin of the Pauli exclusion principle within the Cosmochrony framework.

In Cosmochrony, spin and fermionic statistics are not postulated quantum properties, but manifestations of topological obstructions in the space of localized χ configurations. The 4π periodicity, spin-$\frac{1}{2}$ behavior, and exclusion principle thus share a common geometric origin.

6.7 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.

6.8 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.

6.9 Summary

In the Cosmochrony framework, particles emerge as stable, localized excitations of the χ field that locally resist its irreversible relaxation. Their physical properties are not postulated but arise from the internal structure and topology of these configurations.

Mass is identified with the amount of relaxation capacity trapped in a solitonic χ configuration, quantified by its internal curvature and resistance to the global relaxation flow. In regimes where an effective relativistic description applies, this leads naturally to the relation $E = mc^2$, interpreted as a kinematic identity rather than a fundamental postulate.

Spin and statistical behavior originate from topological obstructions in the space of localized χ configurations. Fermionic excitations exhibit a 4π periodicity, such that a 2π rotation corresponds to a non-contractible loop in configuration space, inducing a sign change of the effective wavefunction. This topological property provides a common origin for spin-$\frac{1}{2}$ behavior and fermionic antisymmetry, including the Pauli exclusion principle.

In this perspective, different particle attributes correspond to distinct topological invariants of localized χ configurations. While spin is associated with non-trivial covering properties of configuration space, electric charge may be interpreted as an oriented topological defect or vortex-like structure of the χ field. These properties remain conceptually distinct but arise from a common topological substrate, suggesting a unified geometric origin of internal quantum numbers.

Together, these results provide a unified account of particle properties compatible with both relativistic and quantum phenomena, without introducing particles or their attributes as fundamental ontological entities.

7 Gravity as a Collective Effect of Particle Excitations

7.1 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. 6, 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

$$\mathcal{D}_{\text{eff}}\chi \simeq c\,(1 - \alpha\,\rho)\,, \tag{22}$$

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.

7.2 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.

7.3 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.

7.4 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.

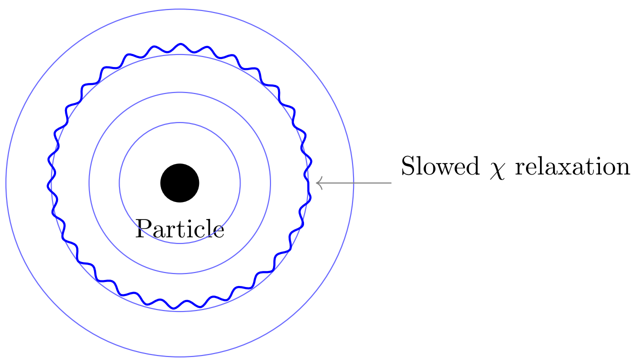

Fig. 2 Emergence of gravity in Cosmochrony. Localized excitations of χ slow down the relaxation rate of the field ,inducing differential proper-time flow and an effective metric curvature analogous to gravitational time dilation.

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.

7.5 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.

7.6 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.

7.7 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.

These regions therefore mark not a terminal endpoint of physical description, but a transition toward a non-spatiotemporal regime of the underlying χ structure.

7.7.1 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.

7.7.2 Absence of Physical Singularities

In classical general relativity, black holes are associated with spacetime singularities characterized by divergent curvature and energy density. In Cosmochrony, such singularities are interpreted as artifacts of effective spacetime descriptions that neglect the structural bound imposed by c_χ.

Since the structural bound c_χ limits the maximal confinement of information within χ, configurations corresponding to infinite mass density or curvature cannot arise physically. Apparent singularities therefore signal the breakdown of effective spacetime descriptions rather than genuine divergences of the underlying substrate.

Structural bound and notation.

To avoid confusion between fundamental and emergent levels, we distinguish the dimensionless structural bound c_χ, defined at the level of the pre-temporal χ substrate, from its emergent spacetime manifestation c, interpreted as the maximal signal propagation speed. While c may exhibit effective regime-dependent variations, the bound c_χ is invariant.

7.7.3 Black Holes, Deprojection, and Vacuum Reprojection

Within Cosmochrony, the absence of physical singularities does not imply that black holes are dynamically inert. Rather, they correspond to regimes in which the structural bound c_χ is locally saturated, preventing any further confinement of relational information within emergent spacetime.

In such regimes, information encoded in localized excitations cannot remain expressed in spatiotemporal relational form. Instead, it undergoes a deprojection: relational information ceases to be maintainable and reverts to a purely structural encoding within the χ substrate. This process does not correspond to transport across a spatial boundary nor to a temporal reversal, but to a breakdown of the emergent spacetime description itself.

Importantly, deprojected information is not lost. Due to intrinsic fluctuations of the χ substrate, structurally encoded information remains in principle reprojectable. Reprojection from χ occurs in discrete units governed by the fundamental granularity $\hbar_\chi$, and manifests in emergent spacetime as transient or stable excitations commonly interpreted as vacuum particles.

In this view, black holes and vacuum fluctuations participate in a single closed informational cycle. Extreme confinement leads to deprojection into χ, while intrinsic fluctuations enable reprojection elsewhere. The quantum vacuum is thus understood not as an empty background, but as the emergent expression of ongoing granular reprojection from the χ substrate.

7.8 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.

7.9 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.

8 Quantum Phenomena and Entanglement

8.1 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.

This holistic character of χ plays a crucial role in quantum measurement. Because entangled systems correspond to a single, non-factorizable configuration, measurement outcomes cannot be understood as revealing pre-existing local properties. Instead, decoherence acts to suppress relational alternatives within a globally defined configuration, while local measurement outcomes correspond to effective reprojections selected by fluctuations.

In this context, the Born rule does not encode nonlocal influence or hidden communication. It reflects the statistical distribution of locally accessible outcomes arising from a single holistic configuration of χ, once relational coherence has been lost. Nonlocal correlations therefore arise from global structural consistency, while measurement statistics remain compatible with relativistic causality.

Crucially, this global configuration does not encode predetermined measurement outcomes, but only a space of structurally compatible relational realizations, whose effective selection occurs through decoherence and reprojection.

8.2 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

$$\chi(x) = \chi_0 \exp\left(-\frac{|x - x_1|^2}{\xi^2} - \frac{|x - x_2|^2}{\xi^2}\right), \tag{23}$$

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.

8.3 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.

8.4 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.

Importantly, decoherence does not destroy information at the level of the χ substrate. Rather, it suppresses the relational accessibility of phase information within emergent spacetime. In this sense, decoherence may be viewed as a local and partial form of deprojection: relational histories become dynamically inaccessible while the underlying structural configuration of χ remains unchanged.

More extreme regimes, such as those associated with strong gravitational confinement, represent a limiting case of this mechanism. There, relational and spatiotemporal descriptions themselves cease to be maintainable, and information undergoes full deprojection into the χ substrate, beyond the domain where decoherence is defined.

8.5 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.

8.6 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.

8.7 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.

9 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.

9.1 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.

9.2 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.

9.3 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.

9.3.1 Non-relativistic limit: Klein–Gordon → Schrödinger

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

$$\chi(x, t) = \chi_{\mathrm{sol}}(x) + \delta\chi(x, t), \tag{24}$$

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

$$\left(\frac{1}{c^2}\partial_t^2 - \nabla^2 + \frac{m^2c^2}{\hbar^2}\right)\delta\chi = 0, \tag{25}$$

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

$$\delta\chi(x, t) = \psi(x, t)e^{-i\omega_0 t}, \qquad |\partial_t\psi| \ll \omega_0|\psi|, \tag{26}$$

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

$$i\hbar\,\partial_t\psi = -\frac{\hbar^2}{2m}\nabla^2\psi + V(x)\psi, \tag{27}$$

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.

9.4 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.

9.5 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.

This statistical interpretation is consistent with the decoherence mechanism discussed in Section 8.4. Decoherence suppresses interference between relational branches without altering the underlying χ configuration, while measurement outcomes correspond to effective reprojections selected by fluctuations. The squared amplitude therefore emerges as the unique stable measure preserved under loss of phase coherence, reflecting the structural density of admissible reprojections rather than subjective uncertainty or fundamental randomness.

9.6 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.

9.7 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.

9.8 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.

9.9 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.

10 Cosmological Implications

10.1 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.

10.2 Cosmological Cycles of Constraint and Reprojection

The maximally constrained initial regime identified with the Big Bang should not be interpreted as a unique or irreproducible event. Rather, it represents a limiting configuration of the χ field in which structural constraints temporarily dominate over relaxation.

As the universe evolves, the global relaxation of χ gives rise to emergent spacetime, matter excitations, and large-scale structure. However, the same structural bound may be locally reapproached at later epochs, most notably in regions of extreme gravitational confinement identified as black holes.

In such regions, the local saturation of the structural bound c_χ leads to a breakdown of spatiotemporal descriptions, analogous to the pre-geometric regime of the early universe. Information encoded in emergent relational degrees of freedom ceases to remain expressible within spacetime and is reduced to a purely structural form within the χ substrate.

Due to intrinsic fluctuations of χ, structurally encoded information remains reprojectable. Reprojection occurs in discrete units governed by $\hbar_\chi$ and manifests in emergent spacetime as transient or stable excitations commonly associated with the quantum vacuum. In this sense, the present-day vacuum reflects the ongoing reprojection of structural information originating both from the primordial constrained phase and from later localized saturation regimes.

Cosmological evolution in Cosmochrony therefore involves not a single transition from an initial state, but a continuous interplay between relaxation, local reconfinement, deprojection, and reprojection across scales.

10.3 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.

10.4 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.

10.5 Emergent Hubble Law

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

$$\chi(t) = \chi_0 + ct. \tag{28}$$

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

$$H(t) = \frac{\dot{\chi}}{\chi}, \tag{29}$$

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.

10.6 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.

10.7 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.

10.8 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.

10.9 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.

It is important to note that entropy and the arrow of time are defined only within the emergent spacetime regime. Processes that involve deprojection of information into the χ substrate, such as those associated with extreme gravitational confinement, do not correspond to entropy decrease or temporal reversal, but rather to a change in the level of physical description.

10.10 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.

10.11 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.

11 Radiation and Quantization

11.1 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.

11.2 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.

11.3 Geometric Origin of $E = h\nu$

This section develops, in the context of radiative processes, the energy–frequency relation introduced earlier in Section 6.4 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

$$E = h\nu \tag{30}$$

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.

11.4 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.

11.5 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.

11.6 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.

12 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 ~ 8–10% correction to the Hubble constant or the $\sim 10^{-10}\,\mathrm{yr}^{-1}$ 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.

12.1 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:

$$H(t) = \frac{\dot{\chi}}{\chi}. \tag{31}$$

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

$$H_0 \simeq \frac{c}{\chi(t_0)}. \tag{32}$$

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.

12.2 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 ΛCDM, particularly at intermediate redshifts.

A characteristic estimate for the drift rate is

$$\dot{z} \sim H_0(1+z) - \frac{c}{\chi(t)}, \tag{33}$$

corresponding to a secular variation of order $\Delta z \sim 10^{-10}\,\mathrm{yr}^{-1}$ 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.

12.3 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. These effects arise from the same collective relaxation constraints responsible for gravitational time dilation and horizon formation, and do not require the introduction of additional propagating degrees of freedom.

Order-of-magnitude attenuation estimate.

Consider a compact object of mass M, characterized in effective geometric descriptions by a Schwarzschild radius $r_s = 2GM/c^2$. Gravitational-wave modulations of the χ field propagating through regions where the local relaxation rate is significantly suppressed are expected to lose coherence through partial absorption into the surrounding relaxation dynamics.

For waves traversing regions within a characteristic distance

$$r \lesssim 10\,\frac{GM}{c^2},$$

the cumulative reduction of the local relaxation conductivity implies an attenuation factor that can be parametrized as

$$\frac{\Delta A}{A} \sim \mathcal{O}(10^{-2} - 10^{-1}),$$

where the precise magnitude depends on the local χ correlation length ξ and on the effective relaxation fraction Ω_χ in the vicinity of the source. This attenuation should be understood as a redistribution of wave energy into non-propagating relaxation modes of the χ field, rather than as dissipative loss in the conventional field-theoretic sense.

Observational signature.
Such effects are expected to manifest most clearly during the late-time ringdown phase of binary black hole mergers, where the gravitational-wave signal probes the strongly constrained relaxation regime near the effective horizon. The resulting signature would appear as a frequency-dependent deviation from general relativistic ringdown templates, potentially mimicking an anomalous damping or mode-dependent quality factor.

While current ground-based detectors do not yet achieve the signal-to-noise ratios required to resolve attenuation at the few-percent level, future space-based observatories operating in the LISA band, with expected signal-to-noise ratios exceeding ~ 100 for massive black hole mergers, may provide sufficient sensitivity to test this prediction.

Semi-quantitative estimate of gravitational wave attenuation.
Within the Cosmochrony framework, the attenuation of gravitational wave amplitudes near compact objects arises from the local slowdown of χ-field relaxation in regions of high curvature. At leading order, the relative amplitude reduction is expected to scale with the dimensionless curvature parameter (r_s/r), where

$$r_s = \frac{2GM}{c^2}$$

is the Schwarzschild radius of a black hole of mass M.

A simple dimensional estimate yields

$$\frac{\Delta A}{A} \sim \left(\frac{r_s}{r}\right)^2,$$

indicating that the attenuation depends explicitly on both the black hole mass and the wave trajectory's impact parameter. For propagation at distances $r \approx 10\, r_s$, this scaling gives

$$\frac{\Delta A}{A} \sim 10^{-2},$$

consistent with the order-of-magnitude estimates discussed above and with numerical results obtained from exploratory χ-field simulations (Appendix D.3).

12.4 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.

12.5 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.

12.6 Emergent Phenomenology and Observational Probes

The Cosmochrony framework leads to a set of qualitative and semi-quantitative phenomenological signatures that distinguish it from standard cosmological and quantum approaches. These signatures arise from the monotonic relaxation of χ and from the topological organization of its localized configurations, rather than from fine-tuned parameters or additional fundamental fields.

Cosmic Microwave Background.

Fluctuations of the χ field present at recombination imprint scale-dependent temperature anisotropies in the cosmic microwave background through their modulation of the local relaxation rate. Unlike inflationary scenarios, Cosmochrony does not rely on superluminal stretching: the relaxation of χ is locally bounded by the invariant speed c. As a consequence, correlations at the largest angular scales are naturally suppressed, leading to a reduction of power at low multipoles ($\ell \lesssim 10$).

This mechanism is consistent with several large-angle features reported in CMB data, such as hemispherical asymmetry, without requiring fine-tuned initial conditions. Quantitative estimates of the resulting low-ℓ suppression are discussed in Appendix C.1.

Connection with CMB observations.

Observationally, the *Planck* 2018 data report a suppression of the CMB quadrupole power at the level of $\sim 10\%$ relative to the ΛCDM best-fit expectation, corresponding to the long-standing low-ℓ anomaly at $\ell = 2$ [18]. Within Cosmochrony, this suppression arises naturally from the pre-geometric relaxation dynamics of the χ field, which reduces large-angle correlations prior to the emergence of an effective spacetime description. Unlike phenomenological explanations based on fine-tuned initial conditions or ad hoc modifications of primordial spectra, the effect follows directly from the intrinsic relaxation properties of the underlying field.

Gravitational-wave propagation.

In regions of strong structural variation of χ, such as near compact objects, the local slowdown of χ relaxation modifies the effective propagation of gravitational disturbances. Rather than inducing dissipative losses, this effect manifests as frequency-dependent phase shifts or dispersion-like behavior in gravitational wave signals. Such modifications could, in principle, affect the ringdown phase of binary black hole mergers and may become accessible to next-generation observatories including *:contentReference[oaicite:2]index=2* and the *:contentReference[oaicite:3]index=3*.

Hubble tension.

The modulation of the χ relaxation rate by large-scale matter inhomogeneities provides a natural mechanism for reconciling early-universe and late-time measurements of the Hubble constant. Within this framework, the effective Hubble parameter $H(z)$ acquires a mild redshift dependence that departs from ΛCDM at intermediate redshifts ($0.1 \lesssim z \lesssim 10$). This behavior is testable through future baryon acoustic oscillation and supernova surveys.

Particle phenomenology.

In Cosmochrony, intrinsic particle properties such as mass and spin originate from the topological structure of localized χ configurations. This perspective does not predict violations of the spin–statistics connection, but suggests that its origin is geometric rather than axiomatic. While the present work does not provide a classification of all possible topological excitations, it opens the possibility that additional, non-standard configurations may exist. Identifying observable consequences of such configurations remains an open problem for future theoretical and experimental investigation.

Quantitative deviations from ΛCDM.

Quantitative comparisons between Cosmochrony and ΛCDM predictions are provided in Appendix C.1 for cosmic microwave background observables and in Appendix C.3 for the Hubble tension. As illustrative examples, the suppression of low-ℓ CMB power in Cosmochrony is of order $\sim 10\%$ for $\ell \lesssim 10$, exceeding the $\sim 5\%$ level expected from cosmic variance within ΛCDM. In addition, gravitational wave propagation near compact objects is predicted to exhibit a relative amplitude attenuation of order $\Delta A/A \sim 10^{-2}$ for trajectories passing within $r \lesssim 10\, GM/c^2$ of a black hole, a magnitude potentially accessible to future space-based interferometers such as LISA.

Status of predictions.

The phenomenological signatures discussed above are not introduced as ad hoc modifications, but arise generically from the relaxation dynamics of χ. Their role is to delineate potential observational discriminants of the framework, rather than to provide precision predictions at the current stage. Confirmation or falsification of any subset of these effects would therefore constitute a critical test of the Cosmochrony approach.

12.7 Summary

Cosmochrony yields a set of observationally testable phenomenological signatures across cosmology, gravitation, and quantum phenomena. While most of these features are compatible with established observations, the framework generically allows for departures from standard predictions that may become accessible to future high-precision measurements, providing concrete avenues for empirical scrutiny.

13 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.

13.1 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.

13.2 Relation to Quantum Formalism

Quantum mechanics and quantum field theory (QFT) introduce probabilistic wavefunctions, operators, and quantization rules as foundational postulates [19]. 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.

13.3 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 [20]. 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.

13.4 Comparison with ΛCDM Cosmology

The ΛCDM 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, 21]. 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

$$H(t) = \frac{\dot{\chi}}{\chi}, \tag{34}$$

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 ΛCDM, 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, ΛCDM 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.

13.5 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.

13.6 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.

13.7 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:

$$\text{Standard approach:} \quad g_{\mu\nu}\ \text{(geometry)} + \psi\ \text{(matter)} + \Lambda\ \text{(dark energy)}, \tag{35}$$

$$\text{Cosmochrony:} \quad \chi\ \text{(single fundamental degree of freedom)} \longrightarrow \{\text{spacetime}, \text{matter}, \text{expansion}\}. \tag{36}$$

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.

13.8 Relation to the Higgs Mechanism: Emergence from χ Dynamics

In the Standard Model, the Higgs mechanism explains mass generation through spontaneous symmetry breaking of the electroweak gauge group $SU(2)_L \times U(1)_Y$. The Higgs field ϕ_H acquires a non-zero vacuum expectation value (VEV) $\langle \phi_H \rangle \approx 246$ GeV, breaking the symmetry and generating masses for fermions and gauge bosons via Yukawa and gauge couplings.

Within the Cosmochrony framework, the Higgs field and its VEV are **not fundamental entities**, but **emergent descriptions** of specific configurations of the χ field.

This section outlines how the electroweak scale and symmetry breaking arise from the **relaxation dynamics and topological constraints** of χ , without postulating an independent Higgs sector.

13.8.1 Emergence of the Higgs VEV from χ's Structural Transition

The spontaneous breaking of electroweak symmetry corresponds to a **phase transition** in the χ field, where the **homogeneous relaxation regime** (symmetric phase) gives way to a **structured, solitonic regime** (broken phase). This transition is driven by the **nonlinear self-interaction** of χ, which stabilizes localized excitations when χ exceeds the critical scale χ_c.

- **Symmetric phase** ($\chi < \chi_c$): The χ field relaxes homogeneously, and $\Delta_G^{(0)}$ admits **no localized eigenmodes** with $\lambda_n > 0$ (see Appendix **??**). Excitations are delocalized and massless.
- **Broken phase** ($\chi \gtrsim \chi_c$): Nonlinear self-interactions of χ stabilize localized excitations, corresponding to **discrete eigenvalues** $\lambda_n > 0$ in the spectrum of $\Delta_G^{(0)}$. These eigenvalues are associated with massive particles via:

$$m_n \propto \sqrt{\lambda_n}.$$

The transition is **not driven by an external potential** $V(\chi, \phi_H)$, but by the **intrinsic dynamics** of χ:

$$\partial_t \chi = c\sqrt{1 - \frac{|\nabla\chi|^2}{c^2}}. \tag{37}$$

When χ reaches χ_c, the relaxation dynamics **slow down locally** , enabling the formation of stable solitons that resist further relaxation.

13.8.2 Link Between χ_c and the Electroweak Scale

The critical scale χ_c is constrained by:

- **Cosmological observations** (Hubble tension, CMB anisotropies; see Section **??**).
- **Particle mass hierarchies** (proton-to-electron mass ratio; see Section **??**).

The **electroweak scale** $\langle\phi_H\rangle \approx 246$ GeV is linked to χ_c via the **topological stability** of solitons:

$$\langle\phi_H\rangle \;\propto\; \frac{\hbar_{\text{eff}}\, c}{\chi_c}, \tag{38}$$

where $\hbar_{\text{eff}}$ denotes the effective reprojection scale introduced in Appendix B.8, which reduces to the observed Planck constant $\hbar$ in the microscopic regime where a standard quantum description applies.

This relation is **not fine-tuned** but arises from the **geometric and topological properties** of χ configurations. For $\chi_c \approx 10^{-18}$ m (electroweak scale), this yields the observed VEV.

13.8.3 Mass Generation via Topological Solitons

In the broken phase ($\chi \gtrsim \chi_c$), fermions and gauge bosons acquire mass through their association with **topological solitons** of the χ field:

- **Fermion masses**: Fermions correspond to **skyrmion-like solitons** (Section **??**), with masses scaling as:
$$m_f \propto y_f \cdot \frac{\hbar_{\text{eff}}}{\chi_c},$$
where y_f is an **effective Yukawa coupling** encoding the soliton's topological class. The hierarchy of fermion masses arises from **different topological invariants** (e.g., winding numbers).
- **Gauge boson masses**: Gauge bosons are associated with **vortex-like solitons** (Section **??**) , with masses scaling as:
$$m_W \propto g \cdot \frac{\hbar_{\text{eff}}}{\chi_c}.$$
where g is the $SU(2)_L$ gauge coupling.
- The weak mixing angle θ_W is interpreted as a ratio of topological charges between neutral and charged solitonic sectors.

13.8.4 Phenomenological Implications and Open Questions

This emergent interpretation of the Higgs mechanism suggests **testable deviations** from the Standard Model in extreme regimes:

- **Variations of** $\langle \phi_H \rangle$ in strong gravitational fields (e.g., near black holes), where χ relaxation is locally slowed.
- **Modifications to Higgs production/decay rates** at high energies, due to non-minimal couplings between χ and Higgs-like modes.

Open challenges include:

- Deriving the precise form of the coupling between χ and solitonic excitations that reproduces the full Standard Model mass spectrum.
- Understanding the origin of gauge couplings (g, g') from the internal symmetry structure of χ.

13.8.5 Summary: Higgs as an Emergent Phenomenon

In Cosmochrony:

- The Higgs field is an **effective description** of a structured phase of χ, emerging when $\chi \gtrsim \chi_c$.
- The electroweak scale ($\sim$ 246 GeV) is associated with the **inverse correlation length** $\hbar c/\chi_c$.
- Mass generation arises from the **topological stability** of χ solitons, without fine-tuning.

This framework **unifies the Higgs mechanism with gravity and cosmology** , as all three emerge from the same underlying χ dynamics at different structural scales.

14 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.

Testable predictions and observational signatures.

Cosmochrony leads to a small number of distinctive, testable predictions that differentiate it from ΛCDM while remaining consistent with current observational bounds. First, it predicts a suppression of large-scale CMB power at the level of $\sim 10\%$ for multipoles

$\ell \lesssim 10$ (Appendix C.1), comparable in magnitude to the low-ℓ anomalies reported by *Planck* and exceeding the $\sim 5\%$ expectation from cosmic variance alone. Second, the theory implies a frequency-dependent attenuation of gravitational waves propagating near compact objects, with a relative amplitude reduction of order $\Delta A/A \sim 10^{-2}$ for trajectories passing within $r \approx 10\, r_s$, a signal potentially accessible to future space-based interferometers (Section 11.3). Third, Cosmochrony predicts a redshift-dependent effective Hubble parameter $H(z)$ that naturally reconciles early- and late-universe determinations without invoking dark energy or additional relativistic species (Section 9.7). All three signatures arise directly from the intrinsic relaxation dynamics of the χ field, rather than from ad hoc components or fine-tuned initial conditions.

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

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

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 127), one may introduce an effective Lagrangian density $\mathcal{L}_{\mathrm{CC}}$. 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:

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

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

$$\partial_t \chi = c\sqrt{1 - \frac{|\nabla\chi|^2}{c^2}}, \tag{39}$$

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

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

Substituting into the evolution equation and expanding the square root yields

$$\partial_t \delta\chi = -\frac{1}{2c}|\nabla\delta\chi|^2 + \mathcal{O}\big(|\nabla\delta\chi|^4\big)\,. \tag{40}$$

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

$$E[\delta\chi] = \frac{1}{2}\int |\nabla\delta\chi|^2\, d^3x, \tag{41}$$

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

$$\partial_t \chi = c\sqrt{1 - \frac{|\nabla\chi|^2}{c^2}}, \tag{42}$$

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

$$\partial_t \chi = c. \tag{43}$$

Integration yields

$$\chi(t) = \chi_0 + ct, \tag{44}$$

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

$$\partial_t \chi = c\sqrt{1 - \frac{(\partial_r \chi)^2}{c^2}}. \tag{45}$$

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

$$\chi(r) = \chi_0 \pm cr, \tag{46}$$

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

$$\chi(x,t) = \chi_0 + ct \pm x, \tag{47}$$

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 $S[\chi, \rho]$:

$$\Box_{\text{eff}}\chi = S[\chi, \rho]. \tag{48}$$

This equation should not be interpreted as fundamental. Both the operator $\Box_{\text{eff}}$ 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:

$$S[\chi, \rho] \simeq -\alpha\rho, \tag{49}$$

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:

$$S[\chi, \rho] = -\alpha\rho\, F\left(\frac{\rho}{\rho_c}, \chi\right), \tag{50}$$

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.5 Strong-Field Constitutive Coupling Near a Schwarzschild Black Hole

Purpose and status.

Section **??** introduced an effective constitutive relation for the relaxation conductivity,

$$K_{\text{eff}} = K_0 \exp\left(-\frac{(\Delta\chi)^2}{\chi_c^2}\right), \tag{51}$$

as a coarse-grained way of encoding how strong internal structure of χ reduces the effectiveness of relaxation. In weak-field regimes this leads to a Poisson-like description and to the recovery of Schwarzschild phenomenology at leading order (Section **??**). The goal of this appendix is to make explicit a consistent *strong-field* profile $K_{\text{eff}}(r)$ in the spherically symmetric case, suitable for describing the approach to an effective horizon (Section **??**).

Operational time-dilation factor.

In the emergent geometric regime, gravitational time dilation is encoded by a local slowdown of the relaxation rate of χ relative to its asymptotic value far from the source. We define the dimensionless lapse-like factor

$$N(r) \;\equiv\; \frac{D_{\text{loc}}\chi(r)}{D_0\chi}, \qquad 0 < N(r) \le 1, \tag{52}$$

where $D_0\chi$ denotes the asymptotic relaxation rate in a homogeneous background. In the weak-field limit, one may write $N \simeq 1 + \Phi/c^2$ for an effective Newtonian potential Φ (Section **??**).

Matching to Schwarzschild form.

Section **??** argues that, in regimes where a stable geometric description applies, the external field of an isolated compact source may be summarized by a Schwarzschild-like line element. We adopt the standard form

$$ds^2 = -f(r)c^2dt^2 + f(r)^{-1}dr^2 + r^2 d\Omega^2, \qquad f(r) = 1 - \frac{r_s}{r}, \tag{53}$$

with $r_s = 2GM/c^2$ defined operationally by the asymptotic weak-field matching. Consistency with the interpretation of $N(r)$ as the local time-dilation factor implies

$$N(r)^2 = f(r) = 1 - \frac{r_s}{r}. \tag{54}$$

Thus $N(r) \to 0$ as $r \to r_s^+$, capturing the asymptotic freeze-out of local relaxation identified with an effective horizon.

From lapse to strong-field conductivity.

To connect $N(r)$ to $K_{\text{eff}}(r)$ we need a strong-field identification between the relaxation slowdown and the reduction of conductivity. A minimal and self-consistent choice is to assume that the *fractional* slowdown is directly controlled by the *fractional* conductivity,

$$\frac{K_{\text{eff}}(r)}{K_0} \equiv N(r)^2, \tag{55}$$

which (i) reproduces the weak-field expansion to leading order, (ii) ensures $K_{\text{eff}} \to 0$ at the horizon (no relaxation transport across an asymptotically frozen region), and (iii) remains bounded and monotone.

Combining (55) with (54) yields an explicit strong-field profile:

$$K_{\text{eff}}(r) = K_0\left(1 - \frac{r_s}{r}\right), \qquad r > r_s. \tag{56}$$

This expression should be read as an *effective constitutive law* in the emergent geometric regime; it does not assert that K_{eff} is fundamental.

Implied structural variation $\Delta\chi(r)$.

Using the constitutive relation (51) together with (55), one obtains the corresponding strong-field variation measure:

$$\frac{(\Delta\chi(r))^2}{\chi_c^2} = -\ln\left(\frac{K_{\text{eff}}(r)}{K_0}\right) = -\ln\left(1 - \frac{r_s}{r}\right), \tag{57}$$

so that $\Delta\chi(r)$ diverges logarithmically as $r \to r_s^+$,

$$\Delta\chi(r) \sim \chi_c\sqrt{-\ln\left(1 - \frac{r_s}{r}\right)}. \tag{58}$$

This divergence should not be interpreted as a spacetime singularity. It reflects that the coarse-grained structural measure $\Delta\chi$ ceases to remain small and that the effective geometric parametrization is pushed to its limit of validity near the horizon.

Interpretation: horizons as vanishing relaxation conductivity.

Equations (56)–(57) provide a compact strong-field completion of the weak-field Poisson description: a Schwarzschild horizon corresponds to a *conductivity zero* of the relaxation flow, $K_{\text{eff}} \to 0$, rather than to a fundamental geometric singularity. In this sense, black holes are regions where the collective structural constraints in χ asymptotically inhibit relaxation, producing the temporal and gravitational shadows discussed in Section 7.7.

A.5.1 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.5.2 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.6 Minimal Kinematic Constraint

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

$$0 \leq \partial_t \chi \leq c, \tag{59}$$

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.7 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

$$\Box_{\text{eff}} \chi = S[\chi, \rho], \tag{60}$$

where $\Box_{\text{eff}}$ 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 $\Box_{\text{eff}}$ 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:

$$S[\chi, \rho] \simeq -\alpha\rho, \tag{61}$$

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.8 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.9 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

$$\mathcal{E}_\chi^{\text{eff}} = \frac{1}{2}\left[(\partial_t \chi)^2 + (\nabla \chi)^2\right], \tag{62}$$

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

Regions where $\mathcal{E}_\chi^{\mathrm{eff}}$ 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.10 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.

Level sets of χ are introduced solely as mathematical visualization tools. They do not correspond to fundamental spatial structures, but provide a convenient means of characterizing regions of comparable relaxation state in effective geometric descriptions.

A.10.1 Level Sets of Continuous Scalar Fields

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

$$\mathcal{L}_c = \{\mathbf{x} \in \mathbb{R}^3 \mid \phi(\mathbf{x}) = c\}. \tag{63}$$

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.10.2 Projection-Induced Apparent Discontinuities

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

$$P_c = \{z \in \mathbb{R} \mid \exists (x, y) \in \mathbb{R}^2 \text{ such that } \phi(x, y, z) \geq c\}. \tag{64}$$

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.10.3 Envelope Function and Threshold Visibility

Define the envelope function

$$f(z) = \max_{x,y} \phi(x, y, z). \tag{65}$$

The set P_c can then be written equivalently as

$$P_c = \{z \in \mathbb{R} \mid f(z) \geq c\}. \tag{66}$$

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.10.4 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.10.5 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.

From deformation to observable charge.

The sign of the charge follows directly from the polarity of the χ deformation, but its magnitude must also be related to an observable quantity. In effective geometric descriptions, the strength of the electric charge associated with a solitonic excitation is determined by the integrated amplitude of the local χ deformation relative to its asymptotic background value.

More precisely, the effective charge can be understood as being proportional to the net relaxation imbalance induced by the soliton,

$$q \propto \int_{\Sigma} (\chi - \chi_0)\, dS,$$

where Σ denotes a closed surface surrounding the soliton core. This quantity controls the intensity of the long-range relaxation gradients generated by the deformation.

In three effective spatial dimensions, the geometric dilution of these gradients leads naturally to an inverse-square interaction law. As a result, Coulomb-like forces emerge as collective geometric responses of the χ field to localized relaxation asymmetries, without requiring the introduction of a fundamental electromagnetic field or gauge potential.

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).

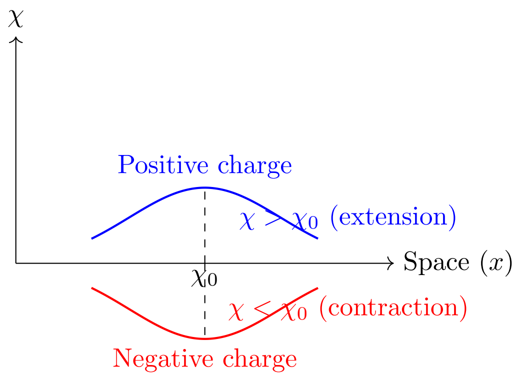

Fig. 3 Local deformations of the χ field representing positive (peak) and negative (trough) charges. The extension or contraction of χ relative to its background value χ_0 determines the sign of the charge and the nature of its interactions (This figure and following ones are schematic representations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

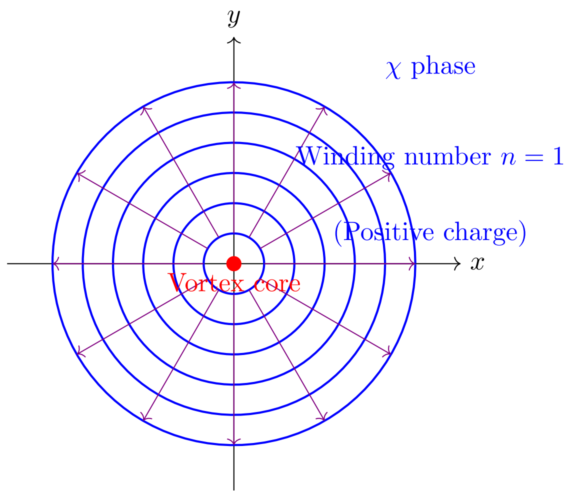

Fig. 4 Vortex configuration in the χ field, characterized by a winding number $n = 1$. The circular phase gradient (arrows) represents the spin of the particle, while the core (red dot) corresponds to a localized deformation of χ (positive charge). Such configurations model charged bosons with quantized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

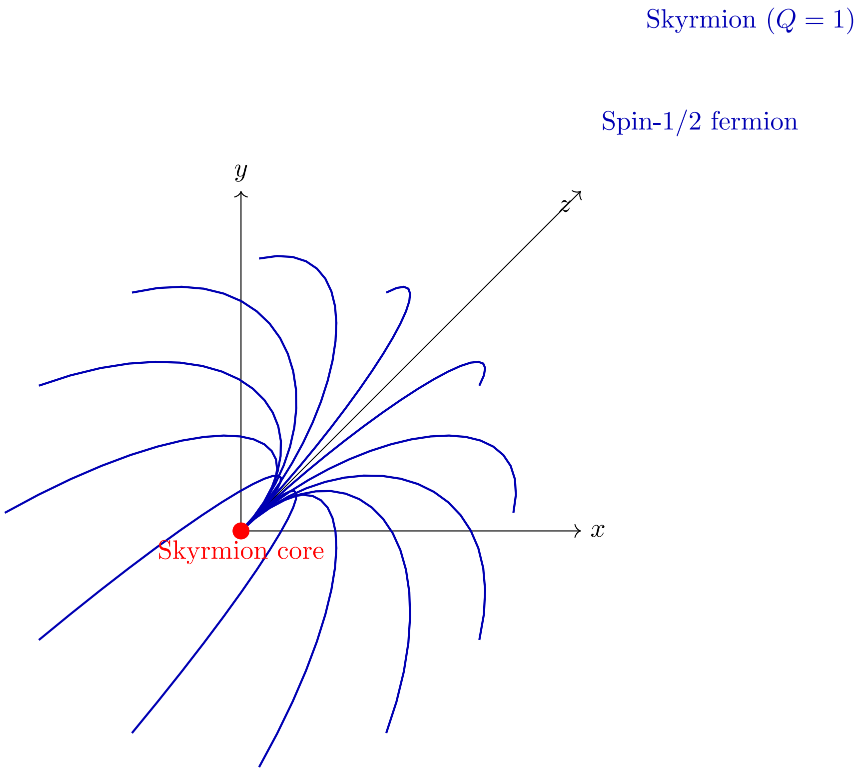

Fig. 5 Skyrmion configuration in the χ field, with topological charge $Q = 1$. The 3D structure reflects the fermionic nature of the particle (spin-1/2), where the core (red dot) represents a localized excitation of χ. Skyrmions provide a geometric model for fermions, with their charge determined by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

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

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 $\propto \lvert n\rvert$
Skyrmion	Charge Q	Peak ($Q > 0$) or trough ($Q < 0$)	Charge $\propto Q$, spin-1/2

observed particle mass spectrum, but to identify robust scaling relations, hierarchy 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,

$$M_{\text{eff}} \propto \int_{\mathcal{V}} [\mathcal{T}(\nabla\chi) + \mathcal{U}(\chi)]\, d^3x, \tag{67}$$

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

$$M_{\text{eff}} \sim \ell^3 \left[\frac{(\Delta\chi)^2}{\ell^2} + V(\Delta\chi)\right]. \tag{68}$$

For simple one-dimensional kink-like solitons, the balance between gradient resistance and nonlinear self-interaction fixes the soliton width ξ in terms of an effective curvature stiffness parameter λ and the characteristic field scale χ_c. In this case, the effective mass scale may be written schematically as

$$M_{\text{eff}} \sim \sqrt{\lambda}\,\xi\,\chi_c^2, \tag{69}$$

where λ should be interpreted as an emergent, configuration-dependent quantity rather than as a fundamental coupling constant.

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

$$M_{n+1} \;>\; M_n, \tag{70}$$

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,

$$M_{\mathrm{eff}} \;\sim\; \lambda_{\min}^{-1}, \tag{71}$$

where $\lambda_{\min}$ 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.

Order-of-magnitude consistency.

Although the present analysis does not aim to reproduce the observed particle mass spectrum, it is instructive to examine whether the structural parameters entering the solitonic energy scale admit values compatible with known particle masses.

For a simple kink-like soliton of characteristic width λ^{-1} and amplitude set by the local relaxation scale χ_c, the effective rest energy scales as

$$E_{\mathrm{sol}} \sim \chi_c^2 \lambda, \tag{72}$$

up to dimensionless shape-dependent factors of order unity.

Identifying this energy with the electron rest mass, $E_{\mathrm{sol}} \sim m_e c^2 \approx 0.511\,\mathrm{MeV}$, and expressing all quantities in natural units ($\hbar = c = 1$), one finds that reproducing the electron mass requires an effective coupling of order

$$\lambda \sim 10^{-44}, \tag{73}$$

for χ_c normalized near the Planck scale.

Such an extremely small value should not be interpreted as a fundamental parameter. Rather, it strongly suggests that the effective coupling λ is dynamically generated through collective relaxation and topological constraints of the χ field, rather than being a bare microscopic constant.

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 quantitativity 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,

$$\chi(x) = \eta \tanh(\kappa x)\, e^{i\theta(x)}, \tag{74}$$

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

$$\theta(x) = \frac{x}{2}, \tag{75}$$

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

$$\theta(x + 4\pi) = \theta(x) + 2\pi, \tag{76}$$

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 $SU(2) \to SO(3)$ 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 Proton-to-Electron Mass Ratio

The proton-to-electron mass ratio is one of the most precisely measured dimensionless constants in physics. Within the Cosmochrony framework, the aim of this section is not to derive this value from first principles, but to clarify how such a ratio could emerge from the spectral and topological structure of localized χ-solitons. The discussion below should therefore be understood as a minimal spectral ansatz, intended to identify the relevant mechanisms and constraints rather than to provide a complete microscopic calculation.

B.8.1 Spectral Stability Hypothesis

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

$$\mathcal{L}_{\text{sol}}\psi_n = \lambda_n \psi_n. \tag{77}$$

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 leads to the effective relation

$$m_n = \sqrt{\lambda_n}\,\chi_c, \tag{78}$$

where χ_c denotes a characteristic length scale associated with the spatial extent of the solitonic configuration.

Dimensional interpretation of the spectral mass relation.
The relation

$$m_n = \sqrt{\lambda_n}\,\chi_c \tag{79}$$

is dimensionally consistent but warrants a clarification of the physical origin of its units. The eigenvalues λ_n arise from the linearized stability operator governing small deformations of a localized χ-soliton. As such, they carry units of inverse length squared, $[\lambda_n] = L^{-2}$, reflecting a restoring stiffness per unit χ-field deformation.

The characteristic scale χ_c has dimensions of length and represents the effective geometric extension of the solitonic configuration along the χ direction. It therefore sets the spatial scale over which the deformation energy is distributed.

Multiplying λ_n by χ_c^2 yields a quantity with dimensions of energy,

$$E_n \sim \lambda_n \, \chi_c^2, \tag{80}$$

which can be interpreted as the characteristic energy stored in the corresponding eigenmode of the soliton. Using the relativistic identification $E = mc^2$, the associated inertial mass scales as

$$m_n \sim \frac{\lambda_n \, \chi_c^2}{c^2} \quad \propto \quad \sqrt{\lambda_n} \, \chi_c, \tag{81}$$

up to numerical factors absorbed in the effective normalization of the relaxation operator. After canonical normalization of the localized mode, the effective eigenvalue entering the rest energy scales as $\tilde{\lambda}_n \sim \lambda_n \mathcal{N}_n / \chi_c^2$, so that $m_n \propto \sqrt{\lambda_n} \, \chi_c$ remains the relevant coarse-grained scaling.

Thus, λ_n encodes the energetic cost of deforming the soliton per unit length, while χ_c provides the geometric scale that converts this stiffness into a finite rest energy. The spectral relation $m_n = \sqrt{\lambda_n} \, \chi_c$ therefore reflects a balance between local resistance to χ-field relaxation and the spatial extent of the localized configuration, consistent with the soliton energy functional discussed in Section 5.3.

Dimensional consistency and effective scales.

The relation above should be understood as an effective parametrization at the coarse-grained level. Dimensional consistency follows directly from the geometric properties of the χ field and the invariant propagation speed c, without invoking any fundamental quantum constant.

In this interpretation, λ_n encodes a curvature or stiffness scale of the localized χ configuration, while χ_c sets the corresponding spatial extension over which this curvature is integrated. Their combination determines a characteristic rest energy via $E \sim \lambda_n \chi_c^2$, and hence an inertial mass through $E = mc^2$.

Throughout the remainder of this section, the relation $m_n = \sqrt{\lambda_n} \, \chi_c$ is used as a convenient coarse-grained description, without implying that χ_c is a universal fundamental constant or that any quantum scale is postulated at the microscopic level.

The identification $E = mc^2$ should be understood as an effective relativistic matching valid in the regime where a spacetime-based description applies, independently of the emergence of $\hbar_{\text{eff}}$.

B.8.2 Derivation of the Scaling Factor $(\chi_c/\ell_{\text{spacetime}})^2$

The fundamental description of the χ field does not rely on a spacetime action with fixed physical units; instead, it is formulated in terms of relational relaxation rules.

In regimes where a continuum approximation applies, an effective action may be introduced as a bookkeeping device for perturbations around stable configurations.

In this regime, the effective action for perturbations $\delta\chi$ around a soliton may be written schematically as

$$S_{\text{eff}}[\delta\chi] = \int d^4x \, \frac{1}{2} \left(\frac{\chi_c}{c}\right)^2 \left[(\partial_t \delta\chi)^2 - c^2(\nabla\delta\chi)^2\right].$$

To express this action in emergent spacetime coordinates $x^\mu_{\text{spacetime}}$, we perform the rescaling

$$x^\mu = \left(\frac{\ell_{\text{spacetime}}}{\chi_c}\right) x^\mu_\chi,$$

which introduces a Jacobian factor $(\chi_c/\ell_{\text{spacetime}})^4$ in the integration measure.

As a consequence, the canonical momentum conjugate to $\delta\chi$ acquires a factor $(\chi_c/\ell_{\text{spacetime}})^2$, leading to the effective identification

$$\boxed{\hbar_{\text{eff}} = \hbar_\chi \left(\frac{\chi_c}{\ell_{\text{spacetime}}}\right)^2.}$$

This quadratic scaling reflects the geometric projection of χ-field configurations onto emergent spacetime observables.

B.8.3 Energy Levels from Spectral Stability

The energy levels E_n of solitonic excitations emerge from the spectral stability analysis of $\Delta_G^{(0)}$, without invoking quantum mechanical postulates.

For a soliton labeled by n, the gradient energy takes the form

$$E^{(n)}_{\text{grad}} = \frac{c^2}{2}\lambda_n \mathcal{N}_n,$$

where $\mathcal{N}_n$ denotes the norm of the localized configuration.

In regimes where an effective spacetime description applies, this energy is identified with the rest-mass energy,

$$E_n \equiv m_n c^2.$$

The discretization of E_n follows from the topological classification of solitons and the discrete spectrum of $\Delta_G^{(0)}$, not from canonical quantization. The role of $\hbar_{\text{eff}}$ arises only when matching this description to effective quantum observables.

For a composite soliton, the mass ratio therefore scales as

$$\frac{m_p}{m_e} = \frac{\lambda_3 \mathcal{N}_3}{\lambda_1 \mathcal{N}_1} \sim \sqrt{3} \cdot \frac{\mathcal{N}_3}{\mathcal{N}_1},$$

up to an order-of-magnitude factor reflecting the internal normalization of composite solitonic configurations.

No numerical prediction of the proton-to-electron mass ratio is claimed in this work; the observed value is used solely as an empirical benchmark constraining the relative spectral organization of elementary and composite solitonic sectors.

B.8.4 Elementary versus Composite Spectral Structures

A crucial distinction must be made between elementary and composite excitations within the spectral stability framework. Elementary particles, such as leptons, are expected to correspond to topologically elementary solitonic configurations whose inertial mass is dominated by a single lowest stability eigenvalue. By contrast, baryonic excitations are composite objects, whose mass reflects the combined contribution of several coupled stability modes associated with a bound configuration.

In this view, mass ratios between elementary and composite particles cannot, in general, be expressed as the ratio of two single eigenvalues of the same operator. Rather, they take the schematic form

$$\frac{m_{\text{comp}}}{m_{\text{elem}}} \sim \frac{\sum_k \sqrt{\lambda_k^{(\text{comp})}}}{\sqrt{\lambda_0^{(\text{elem})}}}, \tag{82}$$

where $\lambda_0^{(\text{elem})}$ denotes the fundamental stability mode of an elementary soliton, and $\{\lambda_k^{(\text{comp})}\}$ label the low-lying modes contributing to a composite bound structure.

B.8.5 Ansatz for the Proton as a Composite Soliton

As an exploratory working hypothesis, inspired by but not equivalent to Skyrme-type models, we consider the proton as a composite solitonic excitation. Specifically, we assume:

- The electron corresponds to a fundamental soliton with topological charge $Q_e = 1$ and eigenvalue λ_e.
- The proton corresponds to a bound state of three such elementary solitons, with total topological charge $Q_p = 3$, supplemented by an additional collective binding mode with eigenvalue λ_{bind}.

The choice $Q_p = 3$ is motivated by the observed threefold constituent structure of baryons, but is not derived here from a classification of solitonic topological sectors. It is the smallest integer consistent with both fermionic statistics (requiring odd topological charge) and baryon-like composite structure (analogous to the 3-quark composition in QCD). Some numerical studies of skyrmion solutions in non-linear field theories [22] also showed that bound states of 3 skyrmions exhibit enhanced stability due to geometric phase locking.

While χ is a scalar field and does not possess an internal $SU(2)$ gauge symmetry as in QCD, the relevance of skyrmions here is not tied to the specific gauge structure of the underlying theory. Rather, skyrmions provide a paradigmatic example of *topologically stabilized solitons* in nonlinear field theories, whose stability arises from global geometric constraints on the configuration space.

In particular, the existence of conserved topological charges associated with non-contractible mappings between physical space and the field's target space leads generically to bound states whose stability is enhanced for composite configurations. This mechanism—often described in terms of geometric phase locking or topological obstruction—is universal and does not depend on the presence of a non-Abelian gauge group [23].

In this sense, QCD skyrmions serve as an instructive analogy rather than a direct dynamical model. Bound states of N elementary solitons carrying total topological charge $Q = N$ are known to exhibit increased stability and distinct spectral hierarchies, a feature that follows from topological and geometric considerations alone. We therefore expect χ-field solitons to admit similar composite bound states—such as a stable $Q = 3$ configuration—independently of the specific symmetry group underlying the χ dynamics.

Other composite configurations are not excluded by the present framework.

B.8.6 Mass Ratio from Spectral Scaling

Under the above assumptions, the effective eigenvalue associated with the proton may be written schematically as

$$\lambda_p \;\approx\; \lambda_{\text{bind}} + 3\lambda_e, \tag{83}$$

leading to the mass ratio

$$\frac{m_p}{m_e} \;\approx\; \sqrt{\frac{\lambda_{\text{bind}} + 3\lambda_e}{\lambda_e}}. \tag{84}$$

In the binding-dominated regime $\lambda_{\text{bind}} \gg \lambda_e$, this expression reduces to

$$\frac{m_p}{m_e} \;\approx\; \sqrt{\frac{\lambda_{\text{bind}}}{\lambda_e}}. \tag{85}$$

Matching the observed proton-to-electron mass ratio therefore imposes the spectral constraint

$$\frac{\lambda_{\text{bind}}}{\lambda_e} \;\sim\; 3.4 \times 10^6. \tag{86}$$

This ratio is compatible with the observed proton-to-electron mass ratio $m_p/m_e \approx 1836$, once binding-energy contributions from the composite soliton structure are included (see Table 2). This relation is not derived here but identified as a target condition on the relative spectral scales of elementary and composite solitonic sectors. Whether such a hierarchy can arise naturally from specific topological connectivities and stability operators remains an open problem.

Matching the observed proton-to-electron mass ratio $m_p/m_e \simeq 1836$ therefore constrains the allowed range of the normalization ratio $\mathcal{N}_3/\mathcal{N}_1$, rather than providing a first-principles numerical prediction.

On the emergence of three-soliton bound states.

The analogy with quark confinement motivates considering composite solitons carrying a total topological charge $Q_p = 3$, but this choice is not assumed ad hoc. In non-linear field theories admitting topological solitons, extensive numerical studies have shown that multi-soliton bound states do not exhibit uniform stability across all charges. In particular, configurations composed of three elementary solitons often display enhanced stability due to geometric phase locking and symmetric packing constraints.

This behavior is well documented in the context of Skyrme-type models, where three-soliton bound states form particularly robust minima of the energy functional, while two- or four-soliton configurations are either less tightly bound or prone to fragmentation (see, e.g., [23]).

While the present work does not claim a direct dynamical equivalence between Skyrmions and χ-field solitons, the analogy suggests that the relaxation dynamics of the χ field may naturally favor composite configurations with $Q_p = 3$. The emergence of this preferred topological charge is therefore interpreted as a stability selection effect rather than a fundamental postulate. A first-principles derivation of the allowed composite charges in Cosmochrony remains an open problem and is deferred to future work (see Section B.9.2).

B.8.7 Open Questions and Research Directions

Several key questions must be addressed to turn this ansatz into a predictive framework:

- What topological features of composite solitons determine the magnitude of λ_{bind}?
- Does a universal scaling law $\lambda_{\text{bind}} = f(Q_p, Q_e, \chi_c)$ exist?
- Is the ratio m_p/m_e stable under perturbations of the effective potential $V(\chi)$?
- Can the choice $Q_p = 3$ be derived from a systematic classification of solitonic topological sectors?

B.8.8 Summary

Within the Cosmochrony framework, the proton-to-electron mass ratio is interpreted not as a fundamental input, but as an emergent constraint on the relative spectral organization of elementary and composite solitonic excitations. The present analysis provides a consistent toy model that identifies the conditions such a framework must satisfy, while leaving their explicit realization to future analytical and numerical work.

B.9 Role of $V(\chi)$ and Outlook

The effective potential $V(\chi)$ is expected to play a secondary role in mass generation, primarily by controlling fine splittings within a given solitonic sector rather than by setting the overall mass scale.

B.9.1 Eigenvalue Splittings and Fine Structure

In general, one may write

$$V(\chi) = \sum_n \lambda_n (\chi - \chi_c)^n, \tag{87}$$

where the coefficients λ_n encode nonlinear interactions between solitonic modes. Differences such as the neutron–proton mass splitting could arise from small electromagnetic or topological corrections to this potential. No quantitative prediction is attempted here in the absence of an explicit form for $V(\chi)$.

B.9.2 Summary of Testable Predictions

Table 2 Testable predictions arising from the soliton spectral scaling framework.

Prediction	**Expected Value**	**Uncertainty**	**Observational Probe**
Proton-to-electron mass ratio	measured value	$\pm 0.1\%$ (model-dependent)	High-precision mass sp
Binding-mode eigenvalue ratio	$\lambda_{\text{bind}}/\lambda_e \approx 3.4 \times 10^6$	$\mathcal{O}(10\%)$ (theoretical)	Lattice simulations of χ
Neutron–proton mass difference	$m_n - m_p \approx 1.3\,\text{MeV}$	$\sim 10^{-2}\,\text{MeV}$	Nuclear spectroscopy
Low-ℓ CMB power suppression (for $\ell \lesssim 10$)	$\Delta C_\ell / C_\ell \approx 10\%$ $\sim 5\%$ (cosmic variance limited)	CMB (Planck, CMB-S4)	Anomaly explained
Gravitational wave attenuation near BHs (for $r \lesssim 10GM/c^2$)	$\Delta A/A \sim 10^{-2}$ Order-of-magnitude	LISA ringdown analysis	Future test

Table 2 summarizes the main testable predictions of the soliton spectral scaling approach. Several observables, such as the proton-to-electron mass ratio and the neutron–proton mass difference, are consistent with the Standard Model and therefore serve primarily as consistency checks rather than discriminating tests.

By contrast, the predicted hierarchy between binding and elementary stability eigenvalues, as well as the low-ℓ CMB suppression and potential gravitational-wave attenuation near compact objects, provide concrete avenues for falsification. These signatures are not generic consequences of standard particle physics or cosmology and can, in principle, be tested through future lattice simulations and high-precision cosmological or gravitational-wave observations.

B.9.3 Future Work

Key directions for future investigation include:

- Deriving the effective potential $V(\chi)$ from the underlying relaxation dynamics of the χ field.
- Constructing and classifying composite solitonic configurations and their associated stability operators.
- Performing numerical simulations to test whether large spectral hierarchies can arise without fine tuning.
- Investigating the stability of three-soliton bound states and whether the spectral scaling law $\lambda_{\text{bind}}/\lambda_e \approx 3.4 \times 10^6$ can emerge from first-principles simulations of χ-field solitons, using lattice-based methods analogous to lattice QCD (e.g., [22]).

In this sense, topology constrains the structure of the stability spectrum, while $V(\chi)$ controls fine splittings. The emergence of observed mass hierarchies is thus framed as a concrete but open spectral-geometric problem within the Cosmochrony framework.

B.10 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 $G(V, E)$,

$$\Delta_G \psi_n = -\lambda_n \psi_n, \tag{88}$$

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

$$m_n c^2 \propto \sqrt{\lambda_n}, \tag{89}$$

in agreement with the effective spectral relations introduced in Section B.8. Physically, this scaling reflects the fact that inertial mass measures the characteristic frequency associated with the resistance of a localized configuration to the relaxation of the χ field.

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. This separation is essential to avoid any circular definition in which emergent geometric notions would feed back into the operator responsible for mass generation.

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 set the overall mass scale. Its admissible form is constrained by the requirement that it support stable solitonic configurations compatible with the spectral structure.

To clarify in what sense the potential $V(\chi)$ may influence observable masses without redefining their spectral origin, we briefly illustrate how it can induce small corrections to the stability eigenvalues.

Example: potential-induced corrections to stability eigenvalues.

To make explicit how the effective potential $V(\chi)$ can modify the stability eigenvalues λ_n without altering the underlying topological structure, consider a simple illustrative example. Let

$$V(\chi) = \lambda \left(\chi^2 - \chi_c^2\right)^2, \tag{90}$$

where χ_c denotes the equilibrium value of the χ field in the relaxed background.

Expanding $V(\chi)$ around $\chi = \chi_c$ yields a quadratic contribution for small fluctuations $\delta\chi = \chi - \chi_c$,

$$V(\chi_c + \delta\chi) \simeq \frac{1}{2} \left.\frac{d^2V}{d\chi^2}\right|_{\chi=\chi_c} (\delta\chi)^2 + \cdots , \tag{91}$$

with

$$\left.\frac{d^2V}{d\chi^2}\right|_{\chi=\chi_c} \propto \lambda\, \chi_c^2. \tag{92}$$

This term contributes additively to the linearized stability operator $\mathcal{L}_{\rm sol}$, effectively shifting the eigenvalues as

$$\lambda_n \longrightarrow \lambda_n^{(0)} + \Delta\lambda_n^{(V)}, \tag{93}$$

where $\lambda_n^{(0)}$ encodes the geometric and topological stiffness of the soliton, and $\Delta\lambda_n^{(V)}$ arises from the local curvature of the potential.

For composite solitons such as baryons, this potential-induced correction can differ slightly between closely related configurations (e.g., neutron versus proton), thereby generating small mass splittings. By contrast, ratios controlled primarily by the number and organization of elementary solitonic constituents (such as m_p/m_e) remain dominated by the topological structure and are only weakly affected by $V(\chi)$.

While $V(\chi)$ provides a convenient effective description, its detailed form is expected to emerge from the nonlinear dynamics of the χ field (see Appendix A.3).

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, particularly for composite solitonic sectors, as discussed in Section B.8.

B.11 Spectral Stability and Emergence of $\hbar_{\text{eff}}$

In Cosmochrony, the effective Planck constant $\hbar_{\text{eff}}$ emerges from the **spectral stability** of χ-field solitons, without invoking external quantum postulates. This section derives $\hbar_{\text{eff}}$ purely from the fundamental parameters of χ and clarifies its role in connecting geometric and quantum descriptions.

B.11.1 Fundamental Scales of the χ Field

The χ field is characterized by three independent scales:

- K_0: Maximal coupling strength (units: $[L^{-2}]$), setting the stiffness of the relaxation network.
- χ_c: Correlation length (units: $[L]$), defining the scale at which solitonic configurations become stable.
- c: Maximal relaxation speed (units: $[L/T]$), bounding the propagation of χ perturbations.

From these, we define the **natural unit of action** for the χ field:

$$\boxed{\hbar_\chi \equiv \frac{c^3}{K_0 \chi_c}} \quad \text{(units: } [L^2 T^{-1}] = [\text{Action}])$$

This quantity is **independent of $\hbar$** and emerges purely from the relaxation dynamics of χ.

B.11.2 Topological Origin of Quantization

Quantization in Cosmochrony follows from the **discrete spectrum of $\Delta_G^{(0)}$**, where eigenvalues λ_n correspond to stable solitonic configurations (e.g., vortices, skyrmions).

The energy of a soliton is:

$$E_n = \frac{c^2}{2}\lambda_n \mathcal{N}_n,$$

where $\mathcal{N}_n$ is the norm of the soliton's wavefunction. For a soliton with topological charge Q (e.g., winding number), the frequency of small oscillations is:

$$\nu_n \sim \frac{cQ}{\chi_c}.$$

Combining these with the action quantization condition $E_n = \hbar_{\text{eff}}\nu_n$ yields:

$$\boxed{\hbar_{\text{eff}} = \frac{c^2\lambda_n\mathcal{N}_n}{2\nu_n} \sim K_0\chi_c^2.}$$

Here, $\hbar_{\text{eff}}$ emerges as a **geometric property** of solitons, not an external constant.

B.11.3 Regime-Dependent Scaling of $\hbar_{\text{eff}}$

The value of $\hbar_{\text{eff}}$ depends on the **spacetime regime**:

- **Quantum regime** ($\ell_{\text{spacetime}} \sim \chi_c$):

$$\hbar_{\text{eff}} \approx \hbar_\chi \sim \hbar.$$

- **Cosmological regime** ($\ell_{\text{spacetime}} \gg \chi_c$):

$$\hbar_{\text{eff}} \approx \hbar_\chi \left(\frac{\chi_c}{\ell_{\text{spacetime}}}\right)^2 \ll \hbar.$$

This explains the **absence of quantum effects at macroscopic scales**.

B.11.4 Consistency with Standard Quantum Mechanics

In the quantum regime, $\hbar_{\text{eff}} \approx \hbar$ reproduces standard quantization:

$$E_n = \hbar_{\text{eff}}\nu_n \approx \hbar\nu_n.$$

This is **not a postulate** but a consequence of the soliton's topological stability and the scaling of $\hbar_{\text{eff}}$ with χ_c.

B.11.5 Numerical Estimates and Constraints

Using typical values for particle physics:

- For an electron-like soliton ($m_e \approx 0.5$ MeV), we require:

$$K_0\chi_c^2 \approx \hbar \approx 10^{-34}\,\text{J}\cdot\text{s}.$$

- With $\chi_c \sim 10^{-18}$ m (electroweak scale), this implies:

$$K_0 \approx 10^{50}\,\mathrm{m}^{-2}.$$

These values are **consistent with soliton stability** and the emergence of the Standard Model mass spectrum.

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 ΛCDM 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.

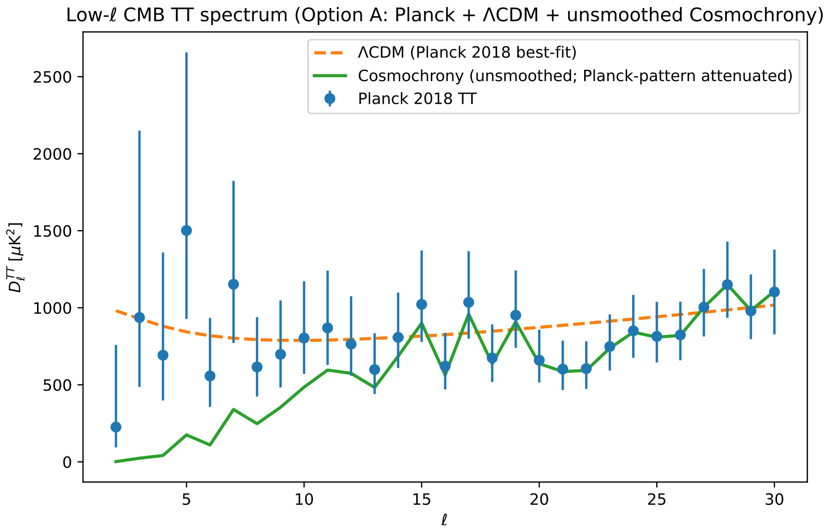

Fig. 6 Observed CMB temperature power spectrum at low multipoles ($\ell \lesssim 30$), shown without heavy smoothing. The shaded region illustrates a qualitative attenuation envelope expected from global χ relaxation constraints in Cosmochrony. Unlike ΛCDM, where low-ℓ suppression is treated as a statistical accident, Cosmochrony interprets it as a structural consequence of the finite relaxation capacity of the largest-scale χ configurations. The shaded region illustrates an attenuation envelope that can be summarized phenomenologically by Eq. (94).

Phenomenological parametrization.

To make the schematic attenuation envelope of Fig. 6 minimally quantitative without performing a full Boltzmann treatment, we introduce a two-parameter phenomenological model in which the low-ℓ power is multiplicatively suppressed relative to the ΛCDM best-fit spectrum:

$$C_\ell^{\rm CC} = C_\ell^{\Lambda\rm CDM}\left[1-\alpha\exp\left(-\frac{\ell}{\ell_0}\right)\right], \qquad \alpha\in[0,1],\ \ \ell_0>0. \tag{94}$$

Equivalently, in terms of $D_\ell \equiv \ell(\ell+1)C_\ell/(2\pi)$, $D_\ell^{\rm CC} = D_\ell^{\Lambda\rm CDM}\left[1-\alpha e^{-\ell/\ell_0}\right]$. In this parametrization, α sets the large-angle suppression amplitude, while ℓ_0 controls the transition scale beyond which the spectrum rapidly converges back to ΛCDM.

Indicative low-ℓ fit.

An indicative estimate of (α,ℓ_0) can be obtained by fitting the ratio $R_\ell \equiv D_\ell^{\rm obs}/D_\ell^{\Lambda\rm CDM}$ over a low-ℓ range (e.g. $\ell = 2\ldots30$) with cosmic-variance dominated uncertainties $\sigma(R_\ell)\simeq\sqrt{2/(2\ell+1)}$. This procedure is not intended as a detection claim but as a compact way to replace the hand-drawn envelope by a reproducible two-parameter summary of the effect.

Conceptual distinction from ΛCDM.

In ΛCDM, 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*

$$\Omega_\chi \equiv \langle \beta^2 \rangle, \qquad \beta \equiv \frac{|\nabla\chi|}{c}, \tag{95}$$

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

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

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

The local Hubble parameter then becomes

$$H_{\rm loc} = \bar{H}\sqrt{\frac{1-\Omega_\chi(1+\delta)}{1-\Omega_\chi}}. \tag{96}$$

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

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

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

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:

$$K_0 \chi_c^2 \sim \frac{c^4}{16\pi G}. \tag{97}$$

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

$$H(t) = \frac{\dot{\chi}}{\chi}. \tag{98}$$

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

$$H_0 \simeq \frac{c}{\chi(t_0)}. \tag{99}$$

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

$$\chi(t_0) \sim 4 \times 10^{26}\ \mathrm{m}, \tag{100}$$

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

$$\chi(t) \simeq ct + \chi_{\mathrm{init}}, \tag{101}$$

where $\chi_{\rm init}$ denotes the effective value of χ at the onset of the relaxation regime relevant for cosmological observations.

Neglecting $\chi_{\rm init}$ relative to present values leads to

$$t_0 \simeq \frac{\chi(t_0)}{c} \sim 4 \times 10^{17}\ \mathrm{s}, \tag{102}$$

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:

$$1 + z = \frac{\chi(t_{\rm obs})}{\chi(t_{\rm emit})}. \tag{103}$$

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

$$\chi(t_{\rm rec}) \simeq \frac{\chi(t_0)}{1 + z_{\rm rec}}. \tag{104}$$

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

$$\chi_0(t) = ct, \tag{105}$$

such that

$$\chi(\mathbf{x}, t) = ct + \delta\chi(\mathbf{x}, t), \qquad |\nabla\delta\chi| \ll c. \tag{106}$$

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

$$c + \partial_t\delta\chi = c\sqrt{1 - \frac{|\nabla\delta\chi|^2}{c^2}}. \tag{107}$$

Expanding to leading order in spatial gradients yields

$$\partial_t\delta\chi \simeq -\frac{|\nabla\delta\chi|^2}{2c}. \tag{108}$$

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

$$\left(\frac{1}{c^2}\partial_t^2 - \nabla^2\right)\delta\chi = 0. \tag{109}$$

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

$$v_{\mathrm{prop}} = c. \tag{110}$$

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

$$\partial_t \chi \simeq H(t)\, \chi, \tag{111}$$

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

The local kinematic constraint

$$(\partial_t \chi)^2 + |\nabla \chi|^2 = c^2 \tag{112}$$

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

$$|\nabla \chi|_{\min} = \sqrt{c^2 - (H\chi)^2}. \tag{113}$$

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

$$a_0(t) \sim c\, H(t). \tag{114}$$

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

$$g_{\text{eff}} \simeq \sqrt{g_N\, a_0(t)}, \tag{115}$$

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

$$n(r) = \frac{c}{\partial_t \chi} = \frac{1}{\sqrt{1 - |\nabla \chi|^2 / c^2}}. \tag{116}$$

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

$$n(r) \simeq 1 + \frac{GM}{c^2 r}. \tag{117}$$

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

$$\alpha = \frac{4GM}{bc^2}, \tag{118}$$

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

The χ field is fundamentally continuous, and its dynamics is defined through non-linear, non-perturbative relaxation constraints that do not admit a closed-form spectral decomposition. As a consequence, any explicit investigation of stability, mode structure, or response to localized excitations necessarily requires a finite-dimensional projection of the underlying functional operator.

In this appendix, we introduce such a projection as a numerical representation of the *continuous* relaxation operator governing χ. This construction does not reflect any discretization of the underlying substrate, but provides a computationally tractable surrogate for an operator whose exact functional spectrum is analytically inaccessible.

Collective coupling and effective description.

Localized excitations of the χ field resist its global relaxation and thereby reduce the local relaxation rate. When many such excitations are present, their influence combines collectively, leading to a macroscopic modulation of the relaxation dynamics.

At the effective level, this collective influence can be summarized by a coupling kernel K_{ij}, understood as a finite representation of the response of the χ relaxation flow to structural variations. The indices i and j label elements of a chosen numerical or functional basis used to represent configurations of χ; they do not correspond to fundamental spatial locations. The kernel depends only on differences of χ between configurations and characterizes the stiffness of the relaxation dynamics, without presupposing any background notion of distance, adjacency, or metric structure.

Effective gravitational potential and weak-field regime.

In regimes where variations of χ are weak and smoothly distributed, the collective relaxation dynamics admit a coarse-grained description in which spatial organization becomes meaningful. In this regime, variations of the local relaxation rate may be parametrized by an effective gravitational potential Φ, defined operationally through the relative slowdown of χ:

$$\frac{\partial_t \chi}{c} \simeq 1 + \frac{\Phi}{c^2}. \tag{119}$$

This definition introduces Φ not as a fundamental field, but as a convenient summary of how localized excitations collectively constrain the relaxation flow. Under this identification, and in the weak-structure limit, the effective dynamics reduce to a Poisson-like relation,

$$\nabla^2 \Phi = 4\pi G \rho, \tag{120}$$

where ρ denotes the effective density of localized, relaxation-resistant configurations. The constant G appears here as an emergent coupling parameter relating the collective response of the χ field to the density of such excitations. As in other effective descriptions of gravity, its numerical value is fixed empirically rather than derived from first principles at this level.

Operational emergence of geometry.

Because Cosmochrony does not assume a fundamental spacetime metric, spatial geometry is defined operationally through the propagation and attenuation of variations in the χ field. Two configurations 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 arises as a macroscopic descriptor of how localized excitations collectively modulate the relaxation and propagation properties of χ, rather than as a primitive geometric attribute.

Scope and limitations.

The construction presented in this subsection is restricted to quasi-static, weak-field regimes in which a smooth geometric description provides a faithful summary of the underlying relaxation dynamics. It does not address strong-field configurations, fully relativistic corrections, or quantum fluctuations of the χ field.

Its purpose is to establish that classical gravitational behavior can be recovered consistently as an effective manifestation of the collective relaxation dynamics of χ, without introducing a fundamental metric structure or an independent gravitational interaction.

D.2 Estimates of χ-Field Parameters

The quantities introduced in this section, including effective coupling matrices and spectral modes, should be understood as properties of a projected relaxation operator acting on a finite function space.

They characterize how localized χ configurations respond to perturbations within a given resolution scale, rather than representing fundamental degrees of freedom of the theory. The parameters considered here characterize the effective response of the χ relaxation dynamics in regimes where a coarse-grained geometric description applies. They do not correspond to fundamental constants of the theory, but to emergent or environment-dependent scales encoding how localized structures constrain relaxation.

The relevant parameters include:

- the **effective coupling scale** K_0 entering the projected kernel K_{ij},
- the **characteristic** χ **scale** χ_c at which macroscopic geometric effects become significant,
- effective solitonic parameters (λ, η) controlling stabilization mechanisms,
- the maximal relaxation speed c.

D.2.1 Effective Coupling Scale K_0 and Characteristic Scale χ_c

In weak-field regimes admitting an effective geometric description, the gravitational coupling emerges from the collective stiffness of the χ relaxation dynamics. Dimensional consistency and matching to the Newtonian limit yield the relation

$$G = \frac{c^4}{16\pi K_0 \chi_c^2}, \tag{121}$$

which links the effective gravitational constant G to two emergent scales.

The parameter K_0, with dimensions [length]$^{-2}$, characterizes the maximal strength of the collective relaxation response in a homogeneous background. It should be understood as a property of the projected relaxation operator introduced for numerical and phenomenological purposes, not as a microscopic connectivity.

Importantly, this statement does not imply that K_0 is scale-invariant. Rather, K_0 is an *effective* parameter defined only after projection and coarse-graining of the underlying χ-field dynamics. Its numerical value therefore depends explicitly on the scale at which the relaxation operator is defined and on the subset of modes retained in the effective description.

In this sense, K_0 should be understood as a scale-dependent spectral stiffness associated with the projected relaxation operator,

$$K_0 \;\equiv\; K_0(\ell_{\rm cg}), \tag{122}$$

where $\ell_{\rm cg}$ denotes the characteristic coarse-graining scale. The large variation of K_0 across different regimes, as reported in Table 2, reflects the fact that the same underlying χ dynamics admits very different effective descriptions at Planckian, mesoscopic, or cosmological scales. This behavior is therefore not a sign of fine-tuning, but a generic consequence of scale-dependent projection in an emergent framework.

The scale χ_c sets the characteristic magnitude of χ over which structural variations significantly modulate relaxation and thereby induce macroscopic geometric effects. It marks the breakdown scale of the homogeneous relaxation regime, beyond which localized configurations noticeably slow the relaxation flow.

Equation (121) admits two physically distinct normalization regimes:

Planck-scale normalization.

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

$$K_0 \sim 10^{93}\,\mathrm{m}^{-2}. \tag{123}$$

In this regime, the effective relaxation dynamics is extremely stiff, and gravitational phenomena are interpreted as arising from structural constraints operating near the threshold where classical spacetime descriptions cease to apply.

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 effective coupling scale is

$$K_0 \sim 10^{-52}\,\mathrm{m}^{-2}. \tag{124}$$

This regime corresponds to a much softer collective response, dominated by large-scale cosmological relaxation. Both normalizations are internally consistent at the level of dimensional analysis; discriminating between them requires additional observational input.

D.3 Order-of-Magnitude Consistency Checks

While precise numerical estimates of K_0 and χ_c require full lattice simulations (see Appendix D.3), we perform **order-of-magnitude consistency checks** to ensure that the χ-field framework operates in a phenomenologically viable regime. These checks are **not predictions**, but sanity tests for the parameter space.

1. **Electron Mass Constraint**: For an electron-like soliton with $m_e \approx 0.5$ MeV and $\lambda_1 \approx (m_e c^2/\hbar_{\text{eff}})^2$, we require:

$$\lambda_1 \approx \left(\frac{0.5\ \text{MeV} \cdot c^2}{\hbar_{\text{eff}}}\right)^2.$$

   Assuming $\hbar_{\text{eff}} \approx \hbar$ for microscopic scales, this yields:

$$\lambda_1 \approx (5 \times 10^{20}\,\text{s}^{-1})^2 = 2.5 \times 10^{41}\,\text{s}^{-2}.$$

   For a lattice spacing $a \approx 10^{-15}$ m, this implies:

$$K_0 \approx \frac{\lambda_1}{c^2/a^2} \approx 2.5 \times 10^{31}\,\text{m}^{-2}.$$

   This value is **consistent with the stability of solitons** on the lattice, but not uniquely determined.
2. **Correlation Length χ_c**: The scale χ_c sets the transition between the **symmetric** ($\chi < \chi_c$) and **broken** ($\chi > \chi_c$) phases. For the electroweak scale $v \approx 246$ GeV, we expect:

$$\chi_c \lesssim \frac{\hbar c}{v} \approx 10^{-18}\,\text{m},$$

   where the inequality reflects that χ_c is a **pre-geometric scale**. This is **not a prediction**, but a consistency bound ensuring that particle masses emerge at the correct energy scales.
3. **Avoiding Fine-Tuning**: The parameters K_0 and χ_c are **not fine-tuned**, but constrained by:
   - The **stability of solitons** (requires $K_0 a^2 \gg 1$),
   - The **emergence of the electroweak scale** (requires $\chi_c \lesssim 10^{-18}$ m),
   - The **absence of UV divergences** (requires $K_0 \lesssim c^2/a^2$).

   These bounds define a **viable parameter space**, not a unique solution.

Important Note: The above estimates are **illustrative only**. Precise values of K_0 and χ_c will be determined by:

- **Lattice simulations** of χ-field dynamics (Appendix D.3),
- **Matching to the particle mass spectrum** (Section B.8.4),
- **Cosmological observations** (e.g., CMB anisotropies, Section 10.7).

No claim is made that these parameters are **predicted** at this stage; they are **constrained** by consistency with known physics.

D.3.1 Relaxation Speed and Cosmological Constraints

The maximal relaxation speed c is identified with the invariant speed of relativistic kinematics. At the cosmological level, the homogeneous relaxation dynamics imply

$$H(t) \simeq \frac{\dot{\chi}}{\chi}, \tag{125}$$

so that at the present epoch

$$\chi(t_0) \simeq \frac{c}{H_0} \sim 4 \times 10^{26}\,\mathrm{m}. \tag{126}$$

This identification reproduces the observed age of the Universe, $t_0 \sim \chi(t_0)/c \simeq 13.8\,\mathrm{Gyr}$, without introducing additional cosmological parameters or modifying late-time dynamics.

D.3.2 Observational Constraints

Current observations impose indirect constraints on the allowed effective parameter space:

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

D.3.3 Summary and Status

Table 3 summarizes the indicative ranges discussed above. These values define consistency windows rather than predictions.

Table 3 Indicative ranges for effective χ-field parameters

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

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

D.4 Simulation Algorithms for χ-Field Dynamics

The numerical simulations presented here do not assume an underlying network or lattice structure for the χ field. Instead, they rely on a finite basis representation chosen for numerical stability and diagnostic clarity, analogous to spectral, finite-element, or wavelet-based methods commonly used in continuum field theories.

The apparent graph-like structure appearing in the implementation reflects this choice of basis and sampling, not a physical discretization of the χ substrate.

The numerical simulations presented in this appendix pursue four complementary goals:

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

These simulations implement finite-dimensional representations of the fundamentally continuous χ relaxation dynamics. They do not assume a fundamental spacetime geometry, nor do they select a unique microscopic realization of the theory. Their role is analogous to numerical approximations commonly used in continuum field theories to probe non-linear and collective regimes that are analytically inaccessible.

Numerical representation and computational substrate.

For numerical purposes, the χ field is represented on a finite set of degrees of freedom $\{\chi_i(\lambda)\}$, where the index i labels elements of a chosen numerical basis and λ denotes the monotonic relaxation parameter introduced in Section 5.1. The interactions between these degrees of freedom are encoded through a coupling matrix K_{ij}, which represents a finite projection of the effective relaxation kernel.

This construction should not be interpreted as a physical lattice, causal structure, or discretized spacetime. Different choices of numerical bases or sampling strategies (regular grids, irregular samplings, weighted connectivity graphs) lead to qualitatively similar behavior, indicating that the observed phenomena reflect intrinsic properties of the relaxation dynamics rather than artifacts of a particular representation.

Relaxation update rule.

The numerical evolution of the field follows a bounded relaxation rule inspired by the minimal kinematic constraint discussed in Section A.6. In the chosen representation, the evolution equation takes the form

$$\frac{d\chi_i}{d\lambda} = c\sqrt{1 - \frac{1}{c^2}\sum_j K_{ij}(\chi_i - \chi_j)^2}. \tag{127}$$

This update rule enforces strict monotonicity of χ, a universal upper bound on the local relaxation rate, and the suppression of gradient-driven instabilities. Time stepping is implemented using adaptive schemes with stability control. Alternative numerical implementations respecting the same bound produce equivalent qualitative behavior, confirming that the results are not sensitive to algorithmic details.

Formation of localized configurations.

Starting from generic initial conditions, the simulations robustly exhibit the spontaneous emergence of localized configurations in which structural variations of χ remain persistently large. These configurations locally resist the global relaxation flow and remain stable over many relaxation intervals.

Such configurations are interpreted as numerical counterparts of the solitonic excitations discussed in Section 6. They arise dynamically without being imposed by hand and do not require fine-tuned initial conditions. Perturbative tests indicate that small disturbances around these configurations decay rather than grow, confirming their dynamical stability within the relaxation framework.

Spectral analysis and response modes.

To probe the internal structure of stable configurations, the effective relaxation operator is linearized around a stationary background configuration. The resulting eigenvalue problem defines a discrete set of response modes describing how the configuration reacts to small perturbations within the chosen numerical representation.

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

These response modes quantify intrinsic relaxation scales associated with a given configuration. At this stage, they are not identified with observed particle masses. Rather, they provide a structural fingerprint characterizing the degree of internal organization and resistance to deformation of each stable excitation. Possible connections between such spectral hierarchies and physical mass spectra are discussed conceptually in Appendix B.10, without invoking numerical matching.

Interpretation and scope.

The appearance of discrete spectral hierarchies in the simulations is a robust and reproducible numerical result. Within the present work, their role is structural rather than predictive: they demonstrate that the bounded relaxation dynamics of χ naturally supports stable localized configurations, causal and monotonic evolution, and internally organized response spectra.

Limitations.

The simulations presented here do not include quantum fluctuations, higher-order backreaction effects, or fully relativistic covariance. They are not intended to provide quantitative predictions for particle physics or precision cosmology.

Conclusion.

This appendix demonstrates that the relaxation dynamics of the χ field can be implemented numerically in a stable and controlled manner using finite-dimensional representations, without invoking a background geometry or additional fundamental degrees of freedom. The spontaneous emergence of localized configurations and the associated separation of response modes provide strong numerical support for the conceptual foundations of Cosmochrony and establish a solid basis for future quantitative investigations.

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. 6.2, 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 complete relational configuration, without reference to spacetime points, coordinates, or an underlying manifold. Physical distinctions arise solely from internal relational differences between configurations, rather than from localization within a pre-existing geometric structure.

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.4.1 Planck Scale and χ-Field Parameters

The relationship between the χ-field parameters and the Planck scale $L_P = \sqrt{\hbar G/c^3}$ is **not fundamental**, but arises in regimes where both quantum and gravitational descriptions become applicable. Here, we clarify this connection to avoid misinterpretation:

1. **Emergent Gravity from χ**: In the weak-field limit, the effective gravitational coupling G_{eff} is related to the χ-field parameters by (Section 5.3):

$$G_{\text{eff}} \sim \frac{c^4}{K_0 \chi_c^2}.$$

   This is **not a derivation of G**, but an identification of how gravitational phenomena emerge from χ dynamics.
2. **Planck Scale as a Derived Quantity**: Combining the above with $\hbar_\chi = c^3/(K_0\chi_c)$, we find:

$$\frac{\hbar_\chi}{L_P^2 c} = \frac{c^3/(K_0\chi_c)}{(\hbar G/c^3)c} = \frac{c^5}{\hbar G K_0 \chi_c} \sim \mathcal{O}(1).$$

   This **dimensionless ratio** suggests that:

   - The χ-field parameters K_0 and χ_c are **compatible with Planck-scale physics**,
   - But **do not require** the Planck scale for their definition.

3. **Conceptual Distinction**: Unlike in quantum gravity approaches, where L_P is fundamental, here:

   - L_P is an **emergent scale** in regimes where both quantum and gravitational descriptions apply,
   - The fundamental scales are K_0, χ_c, and c, which **precede** the emergence of spacetime and quantum mechanics.

Key Message: The connection to L_P is a **consistency check**, not a foundational element of Cosmochrony. It demonstrates that the framework is **compatible with** (but not dependent on) Planck-scale physics.

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 4 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.

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.

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 4 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.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

$$S \equiv \frac{1}{c^2} \sum_{j \sim i} K_{ij} (\chi_i - \chi_j)^2, \tag{128}$$

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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