Adaptonic Ontogenesis of the Universe

Abstract

Contemporary physics postulates a fixed spacetime dimensionality and invokes unseen entities – dark matter and dark energy – to reconcile theory with observation [1]. In this work, we propose a self-consistent theoretical framework in which the **dimensionality of the Universe is an adaptive, emergent property** undergoing ontogenesis through sequential phase transitions. We introduce a scalar order parameter σ(x) representing the local "dimensional state" of spacetime and an **informational temperature** field Θ(x) encoding environmental stress (analogous to thermodynamic temperature). Spacetime evolves via **dimensional transitions**: **compactification** events, which release latent energy (exothermic) and spawn new degrees of freedom (e.g. forces, particle families, physical constants), and **decompactification** events, which absorb energy (endothermic) and locally weaken gravitational attraction. The theory is formalized by an action in which σ(x) couples to gravity and matter, with a multi-well potential defining preferred discrete dimension states. **Dark matter** and **dark energy** phenomena are reinterpreted as consequences of geometric and energetic effects during ongoing dimensional transitions, without requiring exotic new substances. The fine-structure constant α and elementary masses (such as electron charge *e* and mass *m*_e) emerge as *derived quantities* from the geometry of **dimensional ecotones** (phase boundaries in σ). We show that σ and Θ can be treated classically at macroscopic scales; quantum behavior arises from topologically stable soliton solutions and phase transition dynamics in these fields. We present numerical simulations of the cosmological σ field evolution, demonstrating the release of energy in a compactification transition and the screening of gravity in a decompactified phase. A dedicated section outlines testable **predictions beyond the Standard Model**, including environment-dependent variation of α(σ,Θ), modified weak decay rates, and potential observational signatures in neutron star interiors, high-*T*_c superconductors, the cosmic microwave background (CMB) anisotropies, and quark–gluon plasma (QGP) experiments. The paper concludes by summarizing the ontogenetic paradigm for physics: rather than fixed laws on a static stage, physical laws themselves *develop* through an adaptive, hierarchical process of dimensional unfolding, offering falsifiable alternatives to the dark-sector paradigm and new insights into the fine-tuning puzzle.

1. Introduction

Modern cosmology and high-energy physics face profound puzzles that hint at missing pieces in our understanding of the Universe's structure. The ΛCDM model, while extraordinarily successful, requires that ~95% of cosmic energy content be invisible **dark matter** and **dark energy** [1] – entities introduced ad hoc to explain gravitational phenomena. This reliance on "invisible scaffolding" is reminiscent of historical epicycles and aether, raising the possibility that we are patching fundamental theory rather than discovering new substances [2] [3]. At the same time, nearly all physical theories assume without question that spacetime has a fixed dimensionality (3+1), either given *a priori* or set in the early universe once and for all [4]. Extra dimensions have been contemplated (e.g. Kaluza–Klein's 5th dimension [5] and the 10–11 dimensions of string theory [6]), but these frameworks *compactify* additional dimensions at unobservable scales and do not allow dimensionality to change with time or environment [7]. The **fixity of dimension** is thus a deeply ingrained assumption – one that might be directly challenged as we seek alternatives to dark matter and dark energy [8].

Adaptonic Ontogenesis offers a radical reorientation: instead of treating spacetime as a static arena, we posit that *dimensional structure itself is a dynamical, adaptive system* [9]. This idea builds on the concept of **adaptonics** [10] – a general framework in which persistent systems (called *adaptons*) survive by actively adapting to stress. In adaptonics, complex structures respond to environmental pressures through phase changes, hierarchical organization, and feedback, much like living organisms adapt to survive [11] [12]. An ecotone (borrowing a term from ecology) is a transition zone between different regimes, often fostering innovation and emergent structures [13] [14]. We apply these ideas to spacetime itself: *dimensions* are not immutable backdrops, but flexible degrees of freedom that can change – fold, unfold, "freeze" or "melt" – in response to matter, energy, and informational context. Gravity, in this picture, is not a fundamental interaction but an emergent phenomenon resulting from the adaptation of spacetime geometry to stress [15]. The startling implication is that what we call "laws of physics" may be byproducts of an underlying ontogenetic process: as the Universe evolves, it undergoes **dimensional ontogenesis** (birth and development of dimensions), and the forces and particles we observe materialize as *symptoms* of these adaptive geometric transitions.

This paper presents a **mathematically formal theory of dimensional ontogenesis**, termed **Adaptonic Ontogenesis of the Universe**, in a format suitable for a theoretical physics audience. In Section 2, we establish the theoretical framework, defining the key fields and equations governing adaptive dimensions. Section 3 describes how **sequential dimensional transitions** occur, distinguishing exothermic **compactification** steps (which liberate energy and introduce new degrees of freedom) from endothermic **decompactification** (which consume energy and locally weaken gravity). In Section 4, we demonstrate how the **effects of dimensional change can account for dark matter and dark energy** phenomenology, eliminating the need for unseen non-baryonic matter or cosmological constants. Section 5 explores how fundamental constants, such as the fine-structure constant α and elementary particle masses, can **emerge from the geometry of transitional zones** ("ecotone" regions of partial dimensional change), drawing parallels to Kaluza–Klein theory where physical constants arise from extra-dimensional geometry [16]. In Section 6, we discuss the nature of **quantum behavior** in this classical-field context, attributing quantization to topological solitons and phase stability rather than intrinsic randomness. Section 7 provides a **numerical validation** of the theory via a simplified simulation of the cosmological σ-field evolution; we specify the equations and boundary conditions used and illustrate the release and absorption of energy during dimensional transitions. Section 8 outlines **predictions beyond the Standard Model**, including environment-dependent variations in α(σ,Θ), potential alterations in weak nuclear decay rates under extreme conditions, and unique signatures that could be sought in neutron star observations, high-*T*_c superconductor experiments, the CMB, and heavy-ion collisions creating QGP. Finally, Section 9 summarizes how an ontogenetic perspective restructures physics, emphasizing testable outcomes that distinguish this framework from conventional approaches.

2. Theoretical Framework

2.1 Fields and Geometry of Dimensional Ontogenesis

At the heart of our model is a **scalar field** σ(x), defined throughout spacetime, which serves as an **order parameter for dimensional structure**. Intuitively, σ(x) measures the local degree of "dimensional coherence" – how fully a spatial dimension is expressed or unfolded at the point *x*. Crucially, σ is *not* an exotic new form of matter or a fifth-force mediator [17]. It does not carry charge or momentum in the usual sense; rather, it is a *configurational variable* describing the state of spacetime itself (much as a magnetization field describes the state of a magnetic material). By convention, we choose a reference value σ_ *such that when σ = σ_*, spacetime has the standard three large spatial dimensions. Variations in σ away from σ_ *indicate a departure from this standard dimensional state. Formally, one can define an effective local dimension number** N_eff(x) as [18]:

$$N_{\text{eff}}(x,t) = N_* \ + \ \varepsilon \left(\sigma(x,t) - \sigma_*\right),$$

where N_ = *3 (the baseline spatial dimension) and ε is a small coupling constant translating changes in σ into changes in effective dimension. In practice, σ will be constrained to values near σ_* in most regions (ensuring N_eff ≈ 3), but significant excursions of σ correspond to regions where spacetime behaves as if the number of active dimensions is slightly different (or "fractional"). **High σ** corresponds to a more **diffuse dimensional structure** – heuristically, an extra spatial degree of freedom starts to "open up," diluting gravity – whereas **low σ** indicates a **compact dimensional structure** – the geometry is more tightly curved/compactified, strengthening gravity [19]. This notion generalizes the Kaluza–Klein idea of compact dimensions [5]: instead of being permanently curled up at microscopic scales, extra dimensions in our model can **dynamically compactify or decompactify** in response to the local environment. The key novelty is that σ(x) is a *dynamical field* that can vary over space and time, rather than a fixed global property [20].

We also introduce an **informational temperature** field Θ(x), which encapsulates the environmental "stress" that influences dimensional state. In thermodynamics, temperature *T* quantifies the kinetic energy per degree of freedom of a system; by analogy, Θ(x) quantifies the level of *informational or configurational excitation* in spacetime – essentially, how far the local environment pushes geometry out of its comfort zone. A high value of Θ(x) can arise from high ordinary temperature (thermal energy), large matter density, strong curvature, or rapid changes – anything that injects disorder or stress into spacetime's fabric. In fact, in thermal equilibrium settings Θ reduces to the ordinary temperature *T*. We treat Θ(x) as a classical field (or background function) that couples to σ(x) and biases its behavior, much as temperature can bias phase transitions in materials. Conceptually, Θ plays a dual role: it carries **informational content** (mapping how much "complexity" or entropy is present) and acts as a **control parameter** for dimensional transitions (analogous to a heat bath). In an extreme hot, chaotic environment (high Θ), spacetime tends to remain in a symmetric, undifferentiated dimensional state. Conversely, in a cooler, low-stress environment (low Θ), the order parameter σ can settle into one of multiple differentiated states (different effective dimensions). We will formalize this below by an effective potential V(σ; Θ).

2.2 Action and Field Equations

We formulate the theory in the language of classical field theory on a four-dimensional spacetime manifold (with coordinates x^μ, μ = 0,1,2,3). The **action functional** includes the usual Einstein–Hilbert term for gravity, kinetic and potential terms for the σ field, and its coupling to matter and the Θ field. A convenient form for the action (in the **Jordan frame**, where normal matter fields ψ follow metric *g*_{μν} geodesics) is [21]:

$$S \ = \ \int d^4x \, \sqrt{-g} \left[\frac{M_*^2(\sigma)}{2} \, R \ - \ \frac{1}{2} \, g^{\mu\nu} \partial_\mu \sigma \, \partial_\nu \sigma \ - \ V(\sigma) \ - \ \frac{1}{2} \, c_\Theta \, \Theta^2(x) \, \sigma^2 \right] \ + \ S_m[g_{\mu\nu}, \psi] \, .$$

Let us unpack this action term by term:

- **Geometry coupling:** *M_*^2(σ) R / 2. *Here* R *is the Ricci scalar curvature, and M_*^2(σ) is an **effective Planck mass** (squared) that depends on σ. This encapsulates how the presence of extra or fewer effective dimensions alters the strength of gravity. In general, we take *M_*^2(σ) = M_{\text{Pl}} ^2[1 + Ξ(σ)], *where* M_{\text{Pl}} *is the standard Planck mass and Ξ(σ) is some function (often expanded as Ξ ≈ ξ^2(σ - σ_*)^2/Λ_M^2 for small perturbations [22]). If σ deviates from σ_, *M_* (and thus the gravitational coupling) shifts. A key consequence is that **σ couples to matter** via this term: the variation of M_^*2 with σ leads to an extra term in σ's field equation proportional to the trace of the matter stress-energy tensor* T^*(m)* [23]*. In fact, one finds a coupling function β(σ) = –½ d(ln*

M_^2)/dσ such that matter acts as a source for σ [24]. Physically, this means regions of high matter density tend to drive σ in a direction that increases M_* (to reduce gravitational stress), whereas low-density regions allow σ to drift (modifying gravity) [25]. This dynamics will be critical in reproducing galaxy rotation curves and cosmological effects.

- **Kinetic term:** –½ ∂^μσ∂μσ. *This is the standard kinetic energy term for a scalar field. We assume σ is canonical (no exotic kinetic terms) so that small perturbations propagate as waves (with modifications due to the variable M background, but generally with finite propagation speed less than or equal to* c*).

- **Potential term:** –V(σ). We propose a **multi-well potential** for σ that encodes preferred "dimensional states." The simplest non-trivial form is a double-well, which provides two local minima (two stable configurations for the dimensional structure). A convenient form is [26]:

$$V(\sigma) = \Lambda^4 \Big[\Big(\frac{\sigma}{\mu_{\rm eff}}\Big)^2 - 1\Big]^2 \ + \ \varepsilon\,\Big(\frac{\sigma}{\mu_{\rm eff}}\Big)\,.$$

Here, μ_eff sets the characteristic scale of σ (the location of the minima), and Λ is a parameter with dimensions of energy setting the height of the potential barrier between minima. The term in square brackets, $(\sigma^2/\mu_{\rm eff}^2 - 1)^2$, is a standard double-well (symmetric in σ → –σ) with minima at σ = +μ_eff and σ = –μ_eff. These two minima correspond to two distinct dimensionally coherent states of spacetime – one might imagine, for instance, σ ≈ +μ_eff corresponds to "3 spatial dimensions fully unfolded" and σ ≈ –μ_eff corresponds to an alternate phase (e.g. an extra dimension effectively active or some different topological state of geometry). The small linear term ε(σ/μ_eff) breaks the symmetry between the two wells, ensuring one of them (depending on the sign of ε) is the global minimum (true vacuum) and the other is a slightly higher local minimum (metastable vacuum) [27]. In physical terms, one state will correspond to our current low-energy vacuum (with a particular set of effective constants), and the other to a higher-energy phase. The barrier height ΔV between them determines the energy release or absorption when transitioning from one state to the other. This potential encapsulates the idea that **σ has** structured preferences*: there are quantized "attractor" values* of the field associated with distinct dimensional configurations [28]. We will later discuss generalizing to multiple fields or a multi-minima potential for multiple sequential transitions; but many features can already be illustrated with a single double-well representing the latest (or a representative) dimensional transition.

- **Coupling to Θ:** –½ c_Θ Θ^2(x) σ^2. This term represents the influence of the **informational temperature field** on σ. It effectively adds a σ-dependent contribution to the free energy that grows with Θ^2. When Θ is large, this term (which behaves like +½ c_Θ Θ^2 σ^2 in the potential) **pins σ near 0**, resisting any large deviation. In other words, a high-temperature or high-stress environment favors the **un-differentiated dimensional state** (σ ≈ 0 can be viewed as a state of minimal symmetry-breaking, where neither of the ±μ_eff minima is chosen). This is analogous to how thermal fluctuations can restore symmetry in a ferromagnet above the Curie temperature (preventing the magnetization from settling at ±M_sat). In fact, from the action one can derive an **effective potential** including thermal effects [29]:

$$V_{\rm eff}(\sigma;\Theta) = V(\sigma) + \frac{1}{2} c_\Theta\, \Theta^2\, \sigma^2\,.$$

(The factor 1/2 is chosen for convenience; some literature define the thermal mass term with different conventions [29]. Here we ensure consistency with the field equation below.) At high Θ, the term ~Θ^2 σ^2 dominates, making σ = 0 a stable minimum of V_eff; as Θ decreases, the double-well shape emerges, eventually making σ = 0 unstable (a local maximum) and the wells at σ ≈ ±μ_eff become the minima. This mechanism formalizes the notion that **the Universe's dimensional configuration was**

“stuck” in a symmetric state at early times (high Θ), and only when it cooled past a critical point did a phase transition in σ occur, selecting a particular dimensional phase. We emphasize that Θ(x) can in principle vary with x; for example, regions around a hot object or a strong non-equilibrium process might locally inhibit σ from departing far from 0 (maintaining a higher-dimensional symmetry temporarily). In Section 7 we will simulate the time-dependence of this scenario in a homogeneous setting.

- **Matter action:** S_m[g_{μν}, ψ] indicates the action for all other matter and radiation fields, which we assume to be minimally coupled to the metric *g_{μν}* (Jordan frame). There is no explicit coupling of matter fields to σ in S_m; however, an *implicit* coupling arises because σ alters the metric response via M_*^2(σ). Thus, as mentioned, σ feels the influence of matter through the term β(σ) T^(m) in its field equation [24] . Importantly, by construction, we avoid introducing any fifth force that directly acts on matter apart from modifications of gravity – all new effects can be framed as emergent gravitational phenomena, consistent with the idea that “gravity is the macroscopic manifestation of dimensional adaptation” [15] .

From the above action, we can derive the field equations by variation. The Einstein field equation with a dynamical Planck mass is [23] :

$$M_*^2(\sigma)\,G_{\mu\nu} \;=\; T^{(m)}_{\mu\nu} + T^{(\sigma)}_{\mu\nu} \;-\; \big(\nabla_\mu \nabla_\nu - g_{\mu\nu}\,\Box\big) M_*^2(\sigma)\,. \tag{1}$$

Here *G{μν} is the Einstein tensor, T* is the stress-energy of the σ field. The last term on the right arises from the variation of M_}^{(m)} is the stress-energy of matter (including radiation), and T_{μν}^{(σ)^*2; it ensures energy is exchanged consistently between the σ field configuration and the geometry. We will not delve deeply into (1) here, but we note it reduces to Einstein’s usual equation when σ is at the reference value (M_* = const).

The scalar field’s equation of motion is more directly illuminating. Varying σ yields a modified Klein–Gordon equation:

$$\Box\,\sigma \;-\; V'(\sigma) \;-\; c_\Theta\,\Theta^2(x)\,\sigma \;+\; \frac{1}{2} R\,\frac{dM_*^2}{d\sigma} \;=\; \beta(\sigma)\,T^{(m)}\,. \tag{2}$$

Several important effects are encoded in this equation [24] [29] :

- The term $V'(\sigma) + c_\Theta \Theta^2 \sigma$ is the functional derivative of the effective potential discussed above. In a local Minkowski (flat spacetime) region with constant Θ, the equation simplifies to $\ddot{\sigma} - \nabla^2\sigma + V'(\sigma) + c_\Theta \Theta^2 \sigma = 0$, which is a standard ϕ^4 theory equation with a temperature-dependent mass term.

- The term $(1/2)R\,dM_*^2/d\sigma$ represents a coupling of σ to curvature (geometric stress). In regions of high curvature (e.g. near massive bodies or in the early Universe), this acts as an additional force on σ. For our purposes, we often absorb this into an effective source term since in many scenarios of interest (cosmology, weak-field astrophysics) R is directly related to matter density (via Einstein’s equations).

- On the right, $\beta(\sigma) T^{(m)}$ is the direct coupling to the trace of the matter stress tensor. For non-relativistic matter, $T^{(m)} \approx -\rho c^2$ (negative since we use metric signature –+++), so this term effectively is $- \beta(\sigma) \rho c^2$. If $β(σ)$ is positive (depending on the sign of $dM_*^2/dσ$), a positive matter density drives σ towards smaller values or larger values accordingly. In our conventions with M_*^2 increasing with $(\sigma - \sigma_*)^2$, one finds $β(σ) < 0$ for σ near σ_* [24] , meaning matter pulls σ *down* (toward the compact state). This matches the intuitive expectation that matter stresses space, causing it to compactify (stronger gravity) in response [25]. Conversely, in low-density regions, this "pull" is absent and σ is freer to increase (drift toward the diffuse state).

The structure of these equations reveals why we consider dimensional structure an **adaptive system**. The σ field responds to its environment: high matter density or curvature or temperature *pushes* it, via the source terms, toward whatever values of σ minimize the overall energy. Those happen to be the minima of an effective potential shaped by V and the Θ-term. Thus, geometry tends to relax stress by shifting dimensionally – for instance, compressing dimensions (lower σ) in a crowded, high-density region to increase gravity's strength and hold matter together, or expanding dimensions (higher σ) in a void to reduce gravity's overbinding influence. This adaptability is analogous to how, say, a protein might fold into a configuration that relieves mechanical stress, or how a material might undergo a phase change to accommodate external pressure.

2.3 Sequential Dimensional Transitions

In the simplest rendition above, we featured a single phase transition (double-well potential) in σ. However, the term **ontogenesis** implies a developmental sequence – potentially **multiple transitions** at different scales or epochs, each adding a new "layer" of structure. Indeed, one might hypothesize that the Universe's history includes a *cascade* of dimensional un-foldings or foldings. Each transition could correspond to a major milestone in cosmic evolution, possibly aligning with known epochs such as inflation, grand unification, electroweak symmetry breaking, etc., but seen through a new lens.

We outline the general expectations of **sequential dimensional transitions**:

- Each transition involves moving σ from one metastable minimum of its potential to a new minimum (or overshooting and settling into a new vacuum state). This can be modeled by a multi-well potential with more than two minima, or by multiple scalar fields σ_1, σ_2, … each with a transition. For mathematical simplicity, one could envision a potential $V(\sigma)$ with a series of wells of increasing depth – the Universe can start in the highest, shallowest well (most symmetric phase), then tunnel or roll to the next, and so on. An alternative is a chain of coupled fields each triggering the next; but a single-field multi-well picture suffices for conceptual understanding.

- **Compactification steps**: We define these as transitions that *reduce* the number of large (decompactified) spatial dimensions – equivalently, that move the field σ (or fields) in a direction that corresponds to an extra dimension becoming small or "frozen." In our σ interpretation, a compactification corresponds to σ moving to a state of *lower effective N_eff*. For example, if initially σ was near 0 (effectively a higher-dimensional state with perhaps 4 large spatial dimensions symmetrically), a transition to σ ≈ σ_ *would mean dropping to N_eff ≈ 3 (one dimension effectively compactified to a small scale). We propose that compactification transitions are exothermic: the potential energy stored in the metastable higher-dimensional state is released during the transition to a lower-dimensional state. This is analogous to water freezing (releasing latent heat) or a paramagnet ordering into a ferromagnet (releasing energy). The liberated energy would thermalize into radiation or kinetic energy of fields. In cosmic history, such an event could manifest as a burst of radiation – for instance, one might speculate that the inflationary reheating** could coincide with a dimensional compactification event releasing tremendous energy into particle production.

- **Decompactification steps**: These are transitions where a previously small (compact) dimension becomes large or active, meaning σ moves to a state of *higher N_eff*. Such transitions we expect to be **endothermic** – they *absorb* energy from the environment. Intuitively, opening up an extra degree of freedom requires energy input (like melting ice absorbs heat). In practice, a region of spacetime undergoing decompactification will draw on whatever energy is available (heat, kinetic, gravitational potential) to accomplish the change. One striking consequence is that a decompactifying region will experience a **cooling effect** and a **suppression of gravity**. The gravity weakening comes from two factors: (1) the Planck mass M_ *increases (making gravity effectively weaker) if an extra dimension opens (as per our M_*^2(σ) increasing with |σ - σ_|*), and (2) gravitational flux can now spread into the new dimension, diluting the apparent force in the original 3D space (similar to how gravitational force would follow an inverse-r^3 law in 4 spatial dimensions). A practical example: imagine a volume of space where σ gradually increases due to some perturbation – the local gravitational attraction between masses in that region would drop compared to what Newtonian 3D law predicts, effectively mimicking a repulsive effect or missing mass. Dark energy could be interpreted as a cosmic-scale decompactification: as the Universe expands and dilutes (Θ dropping globally after matter domination), σ might slowly drift upward, very slightly reducing gravity on large scales and thus driving accelerated expansion (since gravity's grip to slow the expansion is weakened). This process would* consume* gravitational potential energy (hence endothermic) – effectively converting it into the "work" of expansion. Likewise, in localized high-Θ regions such as the cores of galaxies or clusters, σ might be suppressed (low), but in the outskirts (low-density, low-Θ ecotones) it can increase – leading to a weaker gravitational pull in those outer regions (one might initially think this worsens the galaxy rotation curve discrepancy, but we will see the interplay with the scalar-mediated force can compensate).

The endothermic nature of decompactification implies a **negative feedback** on structure formation: if too much mass accumulates in a region, raising temperature or stress, it might trigger a slight decompactification that reduces gravity and prevents overcollapse – a kind of self-regulation. Conversely, compactification releases energy which could prevent runaway cooling. These ideas resonate with the adaptonic principle of homeostasis via phase changes.

To put concrete numbers, suppose a compactification event changes the vacuum energy by ΔV ~ Λ^4 of order (10^9 GeV)^4 (typical GUT scale). The latent heat released would be enormous, potentially sufficient to heat the Universe to a high temperature – one might tie this to the reheating temperature after inflation. A later transition perhaps at the electroweak scale (~100 GeV) could correspond to a smaller latent heat, maybe manifesting as a subtler change (some have speculated about changes in fundamental constants at that epoch – here it would be dimension-driven). Although our focus is not on detailed identification with known epochs, the framework naturally suggests a series of **ontogenic milestones**: the "birth" of force fields and particle families coinciding with the "birth" (or transformation) of dimensions.

2.4 The Adaptonic Qualities of Dimensional Evolution

Before moving on to physical implications, it is worth highlighting that the formalism we have described indeed casts dimensional structure as an **adaptive system** in the sense of adaptonics. Summarizing from Equations (1) and (2) and the potential form:

- **Environmental coupling:** σ directly senses matter density (via T^(m)) and spacetime curvature (via R) [30] . High density/curvature drives σ toward configurations that minimize total energy – which typically means more compact dimensions (σ lowering) to strengthen gravity and reduce curvature [25] . Low density allows σ to increase (more diffuse dimensions) [31] . This satisfies the criterion of **stress response**: geometry changes in response to environmental stress, rather than remaining fixed.

- **Internal structured states:** The double-well (or multi-well) potential provides **preferred configurations** (distinct dimension numbers) [28]. These act like attractor states or *equilibria* for the system – analogous to how an organism has stable homeostatic states. The existence of a barrier means the system can remember its state (path-dependence) and does not continuously slide around; it can get *stuck* in a phase until sufficient stress is applied to overcome the barrier.

- **Phase transitions:** When stress exceeds a threshold (e.g. when a critical temperature is crossed or sufficient mass accumulates), σ can undergo a sudden transition – either by "rolling" over the barrier or quantum tunneling (if treated in quantum context) [32]. These **ontogenic phase transitions** are analogous to punctuated equilibria in adaptation – sudden reconfigurations when the status quo becomes unsustainable. The transitions can be discontinuous (first-order) as in a bubble nucleation of a new dimension phase, or smooth crossover if parameters allow, but the essential point is the adaptive shift to a new regime.

- **Screening (buffering):** In very dense regions, we found σ's fluctuations are suppressed (m_eff^2 large) [33] [34]. The field "freezes" into one configuration – providing a kind of **buffer** for the inner region so that the core operates under normal 3D physics without large deviations. This is akin to **environmental shielding**: high external pressure locks the system to a robust state (just as an organism under stress might hunker down into a protected form). In contrast, in intermediate regions like galaxy outskirts or voids, σ is light and **geometrically plastic**, able to vary and adapt [34]. This natural screening via the potential and coupling is different from adding an *ad hoc* chameleon field – it arises from the geometry's own tendency to resist change under extreme conditions [35] [36]. Effectively, the Universe has built-in **chameleon-like behavior**: where normal gravity must be preserved (solar system scales, dense bodies), σ is heavy and quiescent; where anomalies appear (galactic outskirts, cosmic acceleration), σ is light and active.

- **Hierarchical nesting:** The theory permits σ to have a *background evolution* on cosmological scales and *localized fluctuations* on smaller scales [37]. This means dimensional structure forms a **nested hierarchy**: a large-scale "background" dimension (e.g. the overall Friedmann–Lemaître–Robertson–Walker (FLRW) cosmological solution for σ(t)), within which smaller-scale variations (galactic halos, cluster scales) exist, and within those, even more confined variations (perhaps near neutron stars or black holes). This mirrors the nested structure in ecology or systems theory (galaxies within clusters within cosmic web, each providing context for the next) [38] [39]. We can identify "shells" or levels at which σ effectively acts uniformly, separated by transition zones (ecotones) where σ gradients are large [40] [41]. The cosmic web void–filament boundary is one such ecotone; cluster virial radii are another; galaxy edges yet another. At each boundary, we expect interesting new phenomena to emerge from the interplay of scales (as Section 5 will explore).

In summary, all **adaptonic criteria** (environmental response, multistability, phase transitions, screening, nested hierarchy) are satisfied by the σ field in this framework [42] [43]. This gives credence to our proposal that spacetime dimensionality can be treated as an evolving *state* of a system, not an immutable backdrop – a viewpoint that unlocks novel explanations for cosmological phenomena.

3. Dimensional Transitions: Compactification and Decompactification

Having established the formal structure, we now delve into the physical characteristics of the two types of dimensional transitions: **compactification** (folding or "closing up" of dimensions) and **decompactification** (unfolding or opening dimensions). These processes are inherently thermodynamic in flavor, involving latent heat and phase-change dynamics, and they lie at the core of how our model produces new physics.

3.1 Compactification as Exothermic Ontogenesis

A **compactification event** is one in which the Universe (or a region of it) transitions to a state of *lower effective dimensionality*. This could mean that an extra spatial dimension that was previously extended becomes compact (rolled up to a small radius), or that the field σ moves to a value corresponding to fewer active dimensions. In our simple double-well example, a compactification corresponds to σ leaving 0 and settling in $\pm\mu_{eff}$ (which represent a more "differentiated" geometry, since the symmetry $\sigma \to -\sigma$ is broken). We argue that such a transition **releases energy** – it is **exothermic**.

The reasoning is as follows: usually, the symmetric/high-dimensional phase has higher potential energy (we built our potential so that $\sigma = 0$ is a local maximum or at least a higher metastable plateau once Θ is low). The asymmetric/low-dimensional phase (σ near μ_{eff}) is a lower energy vacuum. When the transition occurs (say via tunneling or a dynamical "roll down" during cooling), the difference in potential energy, ΔV, is liberated. Where does this energy go? It must go into the kinetic energy of σ (which then typically thermalizes into other degrees of freedom) or directly into excitations of other fields. In cosmology, a first-order phase transition (as compactification might be) results in the nucleation of bubbles of the new phase. The energy of the false vacuum (old phase) inside the bubble wall is released as the bubble expands, often becoming a hot plasma of particles. In inflationary cosmology, this is essentially the *reheating* process, where the inflaton field's potential energy is converted to radiation. Here, the σ field plays a role analogous to the inflaton if one of the transitions is identified with the end of inflation. More generally, any compactification at a lower energy scale will inject energy into the surroundings – for example, it could create a hot shock or a surge of particles, or excite gravitational waves from the bubble collisions. These would be observable consequences if the transition is late enough; if it's too early (e.g. GUT-scale or above), the signatures might be diluted by subsequent evolution.

Compactification also correlates with an **increase in forces or fields** available in the low-energy theory. This is reminiscent of **symmetry breaking** in particle physics: e.g. when the electroweak symmetry broke, the W and Z bosons acquired mass and the electromagnetic and weak forces became distinct. In our scenario, when a dimension compactifies, it often yields new gauge fields or structure constants as integration constants. The classic example is Kaluza's 5th dimension giving rise to electromagnetism: the act of compactifying the 5th dimension on a circle introduces a $U(1)$ gauge field in 4D and quantizes electric charge [16]. Similarly, compactifying higher dimensions can yield non-Abelian gauge groups (via the geometry of the compact space – e.g. compactifying on certain manifolds yields SU(2), SU(3) gauge fields, etc., as demonstrated by Kerner (1968) [44] and others). In this way, we can envision that each major compactification step in the early Universe corresponded to the "ontogenesis" of a new fundamental interaction:

- The **first** compactification (if the Universe started effectively 4+1 dimensional and compactified one spatial dimension at Planck or GUT scale) could have given rise to the **electromagnetic force** (U(1) gauge field) with the photon emerging from the metric degrees of freedom in 5D. This step would release energy likely of order the GUT scale, possibly triggering inflation's end.

- A **second** compactification (say from 5 effective dims to 4 effective dims, if we consider time as separate, or from 4 to 3 if we began with 4 spatial +1 time) might correspond to an extra small dimension yielding the **weak nuclear force** (perhaps an SU(2) gauge field). This could be around the electroweak scale ~100 GeV, releasing less energy but enough to, for instance, generate the thermal bath at electroweak epoch.

- A **third** compactification could tie to the **strong nuclear force** (SU(3) color) emerging if additional small dimensions or topological flux give rise to color charges. Some string theory models, for example, generate SU(3) from compactifying on certain Calabi–Yau shapes. In our context, it's speculative but suggestive that the hierarchy of forces (electromagnetic, weak, strong) might be rooted in a hierarchy of dimensional phases.

- Perhaps even the **hierarchy of particle masses** finds explanation: when dimensions compactify, moduli (parameters describing the compact geometry size/shape) determine coupling strengths and particle masses. A compactification could "turn on" a Higgs field expectation or alter Yukawa couplings.

While a detailed unification is beyond our scope here, the **pattern** is that **new degrees of freedom "freeze out"** (become apparent) when a dimension transitions from large to small. Much like new crystal structures form when a liquid solidifies, new "structures" in the laws of physics (forces, families of particles) may form when the dimensionality reduces. The fact that energy is released in these transitions means the Universe heats up or at least has the capacity to produce quanta of fields, which could explain why after each symmetry-breaking early on, the Universe was filled with abundant particles corresponding to the new force carriers, etc.

3.2 Decompactification and Gravity Suppression

Conversely, a **decompactification event** is a transition toward *higher effective dimensionality*. In terms of σ, this is an increase in σ to a higher vacuum state if one exists. For instance, if our potential had more than two minima, a higher one might correspond to a more "expanded" dimensional phase. Or, in a localized sense, σ might be driven above its normal value due to some transient excitation, effectively partially decompactifying a dimension in that region.

Decompactification requires an **input of energy** – it is **endothermic**. Essentially, energy must be absorbed to overcome the binding that kept a dimension small. If a region does not have that energy, it cannot spontaneously decompactify (hence why most of space is in the stable compactified phase for extra dims). However, there are scenarios where energy can be channeled into geometric expansion:

- **Cosmic voids and acceleration:** As the Universe expands and structures form, vast voids develop with very low matter density. In these voids, the source term β(σ)T^(m) is nearly zero, and Θ (actual temperature) is low after CMB decoupling. Thus, there is little "pressure" holding σ down. Our model predicts that σ in voids could drift toward a slightly higher value than in high-density regions [31]. This would mean void regions are effectively closer to a 4D spatial geometry (N_eff a bit above 3). The energy for this shift would come from the gravitational potential energy of the surrounding structures – effectively, as galaxies cluster, the voids decompactify and siphon some energy away. One concrete effect would be that **gravity is weaker in voids** than expected for 3D gravity [19]. A testable prediction is that the growth of voids and the motion of galaxies at the edge of voids might show anomalies: e.g. galaxies receding slightly faster as if experiencing an extra push (this could tie into the observed accelerated expansion attributed to dark energy). In our model, the acceleration of the universe could be viewed as the cumulative effect of large-scale regions undergoing slight decompactification (consuming gravitational binding energy and thus acting like a negative pressure).

- **Local transient decompactification:** In extremely high-energy processes like heavy-ion collisions (creating QGP) or intense astrophysical events, there could be momentary surges in Θ or other forms of stress that cause σ to overshoot and then oscillate. As σ overshoots above its stable value, for a brief moment the system enters a higher-dimension configuration. This will immediately start absorbing energy (since it tends to fall back unless stabilized). The result might be observed as an anomalous *cooling* or loss of energy in those processes. For example, some heavy-ion collision results show faster cooling of the QGP than expected; one might speculate a portion of energy went into a geometric degree of freedom (σ fluctuations) rather than detectable particles.

- **Gravity suppression:** One clear signature of decompactification is the **suppression of gravitational effects** in that region [19]. Quantitatively, if one extra dimension decompactifies, Newton's law in that region might start to transition from $1/r^2$ toward $1/r^3$ behavior beyond some scale (the crossover scale being related to the size of the extra dimension). Also, the effective gravitational constant G could drop. Thus, a mass in such a region would have a smaller gravitational pull on an outside observer than expected. This scenario could provide an explanation for certain **galactic dynamics and cluster observations** usually attributed to dark matter (which generally amplifies gravity). At first glance, weaker gravity seems opposite to dark matter's effect (which effectively strengthens gravity). However, consider an **ecotone region** at the edge of a galaxy: inside the galaxy (high density) σ is low (strong gravity, basically Newtonian plus perhaps some extra attraction from σ-mediated force), outside in the void σ is higher (weaker gravity). The transition zone means a test particle just outside the galaxy feels less pull from the galaxy's mass than it would in purely 3D gravity – to an observer interpreting with Newton's constant G, it appears as if some mass is "missing" in the galaxy outskirts to provide the needed centripetal force. In other words, the galaxy's rotation curves could flatten not because gravity got stronger (as MOND or dark matter would do), but because gravity just outside the visible disk got weaker – so to match the observed rotation velocity, one infers more mass is inside than visible. This is an inversion of perspective: *dark matter might be an illusion caused by a halo of partially decompactified space around galaxies.* We will examine in Section 4 how this can still be consistent with gravitational lensing observations, which typically demand additional mass or altered gravity. The lensing, being sensitive to the metric, also picks up modifications from σ; the full scalar–tensor equations can yield lensing that matches what adding dark matter would do, even if the cause is geometric (the Weyl focusing is influenced by σ gradients) [40] [45].

In summary, decompactification acts as a **cosmic cooling and anti-gravity mechanism**. It tends to occur in regions or epochs of low stress, and its endothermic nature means it can gently siphon energy out of the system, potentially explaining phenomena like accelerated expansion (which behaves like the Universe has an energy sink causing negative pressure). It also naturally introduces a scale-dependent modification of gravity – strong (3D) on small scales, weaker (effectively higher-D) on large scales – which can address the *missing gravity* problems without actual dark mass. An important note is that because these transitions are adaptive and environment-driven, they generally avoid catastrophic deviations in well-tested regimes (solar system, laboratory) where conditions do not favor them (σ is locked by screening).

The **energy bookkeeping** in such processes is crucial for consistency. In a compactification, the energy released must go somewhere (we must check it doesn't violate conservation or overproduce entropy beyond bounds like BBN). In a decompactification, the energy consumed must come from somewhere (we expect it to appear as a slight reduction in kinetic energy or a slowdown of structure growth, etc.). Our framework is built such that energy–momentum is conserved overall (the scalar field and gravity exchange energy with matter), so there is no creation or destruction, only conversion. This ensures the theory is on solid thermodynamic footing.

We have now a conceptual picture: the Universe's dimensional evolution can be thought of as a sequence of **phase transitions** each with a thermodynamic character (latent heat sign) and physical outcome (new forces vs suppressed gravity). The next sections will connect these ideas to actual astrophysical and cosmological phenomena that have hitherto required mysterious dark components.

4. Implications for Dark Matter and Dark Energy

One of the strongest motivations for considering dynamic spacetime dimensions is the hope of explaining **dark matter (DM) and dark energy (DE)** effects without invoking exotic new particles or fine-tuned vacuum energies. Our model offers a unified geometric mechanism for both phenomena. In essence, what we perceive as missing mass or accelerating expansion can emerge from spacetime's adaptive response (the σ field distribution) to the distribution of visible matter and radiation. In this section, we outline how **dimensional transitions replace dark matter and dark energy** in explaining observations, and highlight key differences that can be tested.

4.1 Galactic Rotation Curves and Dimensional Gradients

Galactic rotation curves – the orbital speed of stars/gas as a function of radius – famously stay flat or even rise at large radii, contradicting the Keplerian drop-off expected if only visible mass were present. In ΛCDM, this is explained by dark matter halos providing extra gravity. In our model, the outer galactic region corresponds to a **dimensional ecotone**: the transition between the dense interior (halo) and the cosmic void. As discussed, we expect σ to be *screened (low)* in the inner parts and *unscreened (higher)* in the outer parts [46]. The screening radius r_{scr} – analogous to the halo size – might be on the order of ~100–300 kpc for clusters or smaller for individual galaxies [47]. Across this boundary, the "effective gravity" changes.

Inside the screening radius: σ is low (near compact phase), M_ *is near its baseline (so G is effectively Newton's constant), and any σ-mediated fifth force is suppressed by the high σ mass (local fluctuations frozen)* [33] [34]*. Thus, the inner galaxy follows approximately Newtonian dynamics with the visible mass it has. At the edge of the galaxy (beyond the bulk of stars and gas), the density drops; σ can increase and start deviating. Two effects happen: (1) The metric coupling M_* increases, weakening the contribution of the usual Newtonian potential (like an increasing Planck mass makes gravity weaker). (2) The σ field itself can mediate an additional force on test masses. Because matter coupling β(σ) is nonzero, a gradient in σ exerts a force (particles will tend to move from regions of high σ to low σ if β<0, effectively). This acts as a long-range scalar force. In many scalar–tensor theories, such a force can mimic dark matter by enhancing attraction; however, in our case, the sign and behavior are controlled by the adaptive potential.

Detailed modeling (beyond scope) would involve solving equation (2) for a static, spherically symmetric galaxy+halo mass distribution. One finds that outside the galaxy, σ satisfies roughly $\nabla^2 \sigma \approx \beta(\sigma)\, \rho(r)$ for a static balance (neglecting time evolution), with appropriate boundary conditions. In the far outer region, ρ→0 and σ→σ_void (some asymptotic high value). The solution yields a **σ-profile** that increases outward, creating a "bubble" of partially decompactified space around the galaxy. The extra acceleration due to σ is $a_\sigma \approx -\beta(\sigma)\, \nabla\sigma$ (in a quasistatic approximation). Because β(σ) is negative and ∇σ points outward (σ increases outward), $-\beta\, \nabla\sigma$ points inward – so it is indeed an additional *attractive* acceleration on objects in the transition zone, effectively pulling them faster around the galaxy. Meanwhile, the Newtonian acceleration is reduced because effectively G is lower in the outer region (one way to see this: the same visible mass produces less curvature when M_ *is larger). These two effects can be arranged to compensate and reproduce flat rotation curves. Qualitatively, one can say: inside the galaxy, gravity was "normal"; outside, gravity is weakened (due to partial 4D behavior)** but the σ-field's gradient provides just enough extra pull to keep the net force ~1/r (flat curve). Thus, no actual dark mass is needed – the shape of σ and the variation of G do the job.

Another hallmark of dark matter is **weak gravitational lensing** around galaxies and clusters. Typically, lensing maps indicate mass distributions more extended than visible light. In our model, lensing is determined by the metric $g_{\mu\nu}$ which is governed by the modified Einstein equation (1). Solving those with σ's effects included, one finds that lensing is affected by both the Newtonian potential and the σ field's stress. Interestingly, because σ gradients contribute to the *spatial* part of the metric potential differently than to the temporal part (like how scalar fields in scalar–tensor can lead to post-Newtonian parameter changes), the **lensing signal can appear enhanced** relative to what the visible mass alone would produce in standard GR. Specifically, even if the scalar provides an extra pull on matter (stars), it also contributes to the light-bending. The **discrepancy between lensing mass and dynamical mass** (a problem for some modified gravity theories) can be resolved if the scalar's stress-energy effectively adds to the deflection of light. Preliminary studies of our field equations indicate that **regions of strong σ gradient (the ecotone)** will produce additional curvature of light paths, analogous to having an extended mass distribution [40]. Thus, the model expects the same general phenomena as dark halos: flat rotation curves and lensing convergence maps showing mass beyond the visible. The difference is that those "halos" are not made of particulate dark matter but of a **structure in spacetime** – essentially a halo of altered geometry (we might poetically call it a "σ-halo").

One prediction here is that the relationship between the halo mass profile and the visible mass distribution could be different from ΛCDM. For instance, the **Tully–Fisher relation** (a tight empirical relation between galaxy luminosity and asymptotic rotation speed) might emerge naturally from the coupling of σ to baryonic mass distribution in our model, rather than from complicated baryonic feedback on dark matter. Because σ responds to the total matter distribution, one might derive an analogous of MOND's acceleration scale as a consequence of the σ potential parameters and coupling. Indeed, if the field's parameters are such that it only unscreens beyond a critical acceleration (like the $a_0 \sim 10^{-10}$ m/s^2 in MOND), that could appear. In adaptonic terms, a_0 could correspond to the threshold stress below which the dimensional adaptation kicks in. This is speculative, but intriguing: the success of MOND phenomenology could hint that the universe's adaptive geometry has a characteristic stress scale.

4.2 Cosmic Acceleration without a Cosmological Constant

Dark energy in ΛCDM is encoded as a cosmological constant (vacuum energy) or a similar uniform energy component causing the expansion of the Universe to accelerate at late times. This is problematic conceptually (the cosmological constant problem) and begs the question why now. Our model offers an alternative: **the accelerating expansion is a sign that spacetime has been slowly *decompactifying*** on large scales as the Universe becomes more diffuse.

In a homogeneous and isotropic cosmology, σ will have a time-dependent background value $\bar{\sigma}(t)$ that obeys an equation derived from (2) in an FLRW metric. For simplicity, consider the late Universe dominated by matter (and then dark energy era). The σ field equation in a spatially homogeneous limit (ignoring spatial gradients) is:

$$\ddot{\bar{\sigma}} + 3H\dot{\bar{\sigma}} + V'(\bar{\sigma}) + c_\Theta \Theta^2(t)\, \bar{\sigma} = \beta(\bar{\sigma})\, T^{(m)}(t)\,. \tag{3}$$

Here, $3H \dot{\sigma}$ is the Hubble friction term, and $T^{(m)} \approx -\rho_m$ (since pressure is negligible for matter). During the matter-dominated era, temperature *T* is low (CMB of a few K, negligible in the term by now) so Θ is dominated by whatever effective value remains from other sources (which might be small). The driving term is βσ *(-ρ_m)* which, for β negative and ρ_m positive, is effectively a positive source pushing σ upward as ρ_m decreases. Intuitively, as the Universe expands and matter thins out, the hold on σ relaxes and σ tends to increase toward its high-σ vacuum (the "decompactified" state). However, the Hubble damping $3H \dot{\sigma}$ initially prevents rapid motion. Only when the Universe becomes sufficiently large and H slows does σ significantly move (this could coincide with redshift of order a few or less, depending on parameter choices).

When σ begins to roll up its potential, interesting feedback with the expansion occurs. The Friedmann equation is modified: the effective Planck mass $M_*^2(\bar{\sigma})$ in (1) means the Hubble rate $H^2 \sim \frac{\rho_m + \rho_\sigma}{3 M_*^2(\bar{\sigma})}$. As σ increases, M_*^2 grows, reducing *the effective strength of gravity over time* [48] [49]*. This by itself causes a relative acceleration because for a given matter density, a larger* M_* means a smaller deceleration. Additionally, the σ field's energy density ρ_σ (which includes its potential and kinetic terms) can act like a dynamic dark energy component. If σ is slow-rolling (gradually climbing the potential), its kinetic is small and potential dominates, giving negative pressure. Indeed, a slow change in σ mimics a quintessence field: one can define $w_\sigma = p_\sigma/\rho_\sigma$ and find that if the potential energy dominates, $w_\sigma \approx -1$, driving acceleration. But unlike a true cosmological constant, here w_σ can evolve (approach -1 from above) and is tied to known physics (the dimensional potential).

Our model, therefore, can produce an accelerating expansion *without* a cosmological constant term. The driving force is the Universe relieving its "dimensional stress" as it empties out – the cosmos is effectively undergoing a late-time phase transition toward a more diffuse dimensional state. The acceleration will continue until σ reaches its new vacuum (or asymptote), at which point $w_\sigma \to -1$ and H approaches a constant (de Sitter-like end state, but now with spacetime in a different phase than early on). Notably, the **timing** of acceleration onset ($z \sim 0.5$ to 1) is naturally linked to the matter density dropping below a threshold – in our model, when ρ_m falls low enough that m_{eff}^2 of σ (which includes V'' and $c_\Theta \Theta^2$ terms) becomes small, allowing σ to respond. There is no coincidence problem; it happens "now" because it's triggered by a critical density which the Universe hits at this stage.

Another benefit is addressing the **fine-tuning of vacuum energy**: we do not require an extremely precise cancellation to get a tiny cosmological constant. Instead, the vacuum energy in our theory is technically zero in the true ground state (if we subtract the constant offset by having one minimum at zero energy). The current acceleration is from a dynamic field with a potential energy that is naturally of the order of the matter density when it started rolling. With appropriate parameter choices (potential scale Λ and ε), the present value of ρ_σ can be set to match observations ($\sim (2 \times 10^{-3}\ \text{eV})^4$). This is technically a tuning of parameters, but it's an adjustment of the shape of V, not an inexplicable huge cancellation between Planck-scale numbers.

One prediction of this scenario is a mild **time variation of the effective gravitational constant** and other couplings during the acceleration epoch. As σ changes, $M_*^2(\sigma)$ changes, so one could detect a changing G (though local tests in the solar system constrain fast changes, σ here is rolling very slowly globally). Also, if α or particle masses depend on σ (see next section), they could drift with cosmic time. There have been studies looking for such drifts (e.g. in quasar spectra or the CMB) – current limits suggest if variation exists, it's very small up to now [50]. Our model can be consistent with that if σ's coupling to standard model constants is weak or if σ has mostly settled by recent times.

In summary, **dark energy is reinterpreted** as the late-time decompactification of spacetime – an endothermic "boil-off" of the last vestiges of dimensional constraint, causing a gentle accelerated expansion. This ties the cosmic acceleration to new physics that also explains dark matter, unifying these dark phenomena as two sides of dimensional ontogenesis (rather than two unrelated puzzles). The ultimate test will be in the details: e.g., does our evolving σ produce subtle distinct signatures in large-scale structure (like a slight variation in the growth rate or integrated Sachs-Wolfe effect) that differ from ΛCDM's predictions? These are avenues for falsifiability, which current and upcoming surveys (e.g. Euclid, LSST, DESI) can probe [51].

4.3 Other Gravitational Phenomena

Our model also has implications for other phenomena usually attributed to modifications of gravity or exotic matter:

- **Bullet Cluster-type observations:** In systems like the Bullet Cluster, collision of clusters shows a separation between X-ray gas (ordinary matter) and inferred mass (via lensing). In ΛCDM, this is taken as evidence of collisionless dark matter that passed through. In our model, lensing is affected by the σ-field distribution. During the cluster collision, the gas experiences ram pressure and heats up (raising Θ in that region), which could cause σ to drop (more compact) in the core, while the outer parts (where galaxy subclusters go through) have lower density and maintain higher σ. Thus, lensing would be focused around the regions where σ remains high (with the galaxies), not with the gas. In effect, the geometry "remembers" where the mass was and doesn't immediately adjust in the high-speed collision, akin to the collisionless behavior of DM. This is speculative, but the theory might mimic the Bullet Cluster results without actual dark matter, by how σ and Θ dynamically respond on different timescales (σ might not fully equilibrate during the fast passage).

- **Cosmic Microwave Background (CMB):** The CMB's acoustic peaks provide a snapshot of the early Universe's contents. Our theory at early times (above recombination) would have σ nearly frozen at 0 (symmetric state) because the temperature was high (Θ large). Thus, early-universe physics proceeds as per standard radiation/matter domination with effectively G maybe slightly different if σ not exactly at reference. We would match big bang nucleosynthesis and CMB by ensuring σ had negligible dynamical role until z ~ O(1000) or later [52]. One potential difference is a change in the **Late Integrated Sachs-Wolfe (ISW) effect**: as σ contributes to the time evolution of gravitational potentials at late times (when it rolls), there could be an ISW signal distinct from ΛCDM (which only has dark energy changing potentials). Current data mildly favor a slightly higher ISW (some tension known as the excess ISW or lensing amplitude in Planck results). Our model could potentially accommodate that if σ's evolution alters how potentials decay.

- **Gravitational wave propagation:** Modified gravity theories often predict that gravitational waves travel at different speeds or have amplitude modifications. Our scalar-tensor form, however, can be made to respect constraints like the GW170817 neutron star merger, which showed gravitational waves travel at essentially *c* (speed of light). If $M_*^2(σ)$ evolves slowly, the tensor propagation speed stays c (no significant breaking of Lorentz symmetry), which can satisfy the constraint [53]. So our theory can be consistent with that observation by appropriate parameter choice (c_T in the action can be set such that the tensor speed = c at z=0, as indicated in structural constraints [53]).

To conclude this section: **dark matter and dark energy, in Adaptonic Ontogenesis, are not separate mysterious substances but emergent effects of the same underlying principle – dynamic dimensions.** Galaxies, clusters, and the Universe at large are embedded in a spacetime that *adapts* its dimensional configuration to the distribution of matter and energy, creating the illusion of dark components when interpreted through a 4D fixed lens. This explanatory framework not only removes the need for new particles (that have so far evaded detection) but also ties cosmic history together, from the early high-temperature phase to the present acceleration, under a single ontogenetic narrative.

5. Emergent Constants and Forces in Dimensional Ecotones

A remarkable aspect of treating geometry as dynamical is the possibility that **"fundamental" constants and forces are *not* fundamental at all**, but rather *emergent properties* of the underlying dimensional structure. In particular, we argue that the **fine-structure constant** α (which sets the strength of electromagnetism) and even elementary particle masses (like the electron mass m_e, or charge *e*) can be understood as **geometric by-products** of dimensional transitions. This idea extends the classic insights of Kaluza–Klein theory and places them in our adaptive context, especially focusing on **ecotones** – the transitional zones in σ.

5.1 The Fine-Structure Constant α from Geometry

In conventional physics, α is an input parameter ~1/137, mysteriously unitless and seemingly arbitrary. Kaluza's 5-dimensional gravity theory provided a hint that such constants might relate to geometry: when the 5th dimension is compactified on a circle of radius R, the theory yields an electromagnetic coupling proportional to 1/R. In fact, in simple Kaluza–Klein, one finds relationships like $e^2/(4\pi) \sim (\lambda/R)^2$ times some factor, linking the electron charge *e* (and thus $\alpha = e^2/(4\pi\hbar c)$ in suitable units) to the size of the extra dimension [16]. Later extensions showed that other constants, including the gravitational constant and gauge coupling unification, can also be tied to geometric moduli [16].

In our model, consider an **ecotone region**: for example, the boundary between a 3D region and a 4D region (a bubble wall separating two phases of σ). This region is essentially a domain wall solution of the σ field connecting two vacuum values. Domain walls in higher-dimensional theories often localize fields on them – for instance, it's known in brane-world scenarios that standard model fields might be confined to a 3-brane, and gravity propagates in the bulk. Here, our domain wall (ecotone) can be thought of as a transitional 3+1D hypersurface embedded in a slightly higher-dimensional environment. The properties of fields on this wall (which constitute our observed particles and forces) can thus depend on the *structure of the wall*. For instance, if the wall has an internal thickness related to σ's coherence length, or if it carries certain topological charges, those could set the values of couplings.

We propose that the **fine-structure constant α emerges from the geometry of such an ecotone**. Concretely, imagine the Universe's current phase is a 3D space (σ in lower well) and perhaps there's a remnant of a 4D space beyond (σ's other vacuum). The domain wall between these phases could carry a U(1) gauge field (the photon) as a bound mode. The strength of that U(1) field as seen by 3D observers depends on how strongly it is coupled to the metric and thus on the thickness or composition of the wall. In effect, α might be calculable from the σ-field profile. A toy calculation: if the 4th spatial dimension in the outside phase has a finite size L (maybe the wall separates a bulk with a compact dimension of size L from our brane with no extra dimension), then α is related to L. If L changes (e.g. with σ), α would change.

This scenario aligns with the general statement: **fundamental constants originate from geometry** [16]. A specific support for this is given by Reifler & Morris (2006) [16], who emphasize that in Kaluza–Klein all physical constants except mass can originate from geometry. In our theory, mass too can be geometry-related (as we discuss next). The key point is that α being dimensionless allows it to vary if the ratio of some geometric quantities changes. In our model, α could be a function α(σ,Θ): mainly through σ. For example, one could imagine an effective relation like:

$$\alpha(\sigma) \approx \frac{1}{137}\Big[1 + \kappa(\sigma - \sigma_*)\Big],$$

for small deviations, where κ is some coefficient. This means that in regions where σ differs (like deep voids, or early universe), the fine-structure constant will be slightly different. We will discuss evidence for possible α variation in Section 8; here suffice to say that the model inherently expects **α to not be immutable** but to reflect the state of the dimensional field.

5.2 Particle Masses and the Role of σ

Masses of elementary particles – notably the electron mass m_e, quark masses, etc. – might also connect to σ. If σ influences the Higgs vacuum expectation or effective Yukawa couplings, then as σ varies, particle masses vary. Moreover, if fermions are localized on a domain wall as above, their mass might come from overlap of their wavefunction with some Higgs field or extra-dimensional effect. Changing the thickness of the domain wall (which could depend on V(σ)'s parameters, e.g. the curvature at minima) might change that overlap, thus the effective 4D mass.

One intriguing idea is provided by exotic Kaluza–Klein scenarios such as a **fractal extra dimension**: Smolyaninov (2001) showed that if an extra dimension had fractal geometry, the mass of an elementary charge (like electron) can appear naturally much smaller than Planck mass [54]. The fractal dimension in effect dilutes the mass scale. In our context, the domain wall or the adaptive geometry might have a **fractal or complex structure** at microscopic scales (if the transition zone is turbulent or features micro structure). This could generate a hierarchy between Planck scale and particle masses without fine-tuning. In effect, $\frac{m_e}{M_{\text{Pl}}}$ might correspond to some geometric ratio (like the ratio of two scale lengths, one macro – the wall width maybe – and one micro – the Planck length). The adaptonic viewpoint, which allows for **semiotic or information-based considerations**, might suggest that masses encode information about the geometry's adaptive state.

Without venturing too far, we can summarize: **elementary masses and charges could be secondary constants, derivable from σ's vacuum structure**. If tomorrow σ shifted slightly everywhere, we would see α and masses shift – meaning these "constants" are indicators of which dimensional phase we are in. This provides a fresh angle on the puzzling values of these constants (the hierarchy problem, the fine-tuning of α, etc.): perhaps they aren't fundamental at all, but rather *historical* – shaped by cosmic evolution.

5.3 Ecotones and Innovation in Forces

Ecotones, being transitional zones, are also where **new phenomena emerge** [55] [56]. We already discussed how new forces (gauge fields) might come out of dimensional transitions. More broadly, one can speculate that **beyond Standard Model interactions** might reside in these transitional geometries. For instance, some have hypothesized extra "fifth forces" that only act at certain scales. In our model, σ gradients might mediate a force that only becomes significant in regions of high ∇σ – i.e., near the edges of galaxies or voids. That could manifest as an unexpected behavior, perhaps relating to dark matter self-interactions or feedback in galaxy formation. We haven't fully explored such forces, but the potential exists for rich new physics localized at ecotones.

Another concept is **semiotic feedback** – the idea that the geometry might encode information (patterns in σ distribution) that influence particle physics. If σ had domain patterns, those might align with large-scale anisotropies or preferred directions that could, say, correlate with cosmic magnetic fields or other phenomena. These remain speculative but demonstrate how adapting dimensions blur the line between "geometry" and "matter" degrees of freedom.

In conclusion, **the ontogenetic cosmos yields its constants and laws from itself**. The fine-structure constant α is not handed from on high; it is the fingerprint of a dimensional ecotone's geometry [16].

Elementary masses are not fixed inputs; they are consequences of how fields like the Higgs interact with the dimensional configuration [54]. This perspective is profoundly unifying: it hints that if we truly understood the geometry of the Universe's adaptive layers, we could *derive* the properties of particles and forces. It also means these properties could in principle *change* if the Universe's adaptive state changes – a testable proposition. Section 8 will discuss searching for tiny variations in α and particle masses across space and time, as a critical test of this idea.

6. Classical Fields and the Emergence of Quantum Behavior

A striking aspect of our proposal is that **σ and Θ are treated as classical fields**, yet we claim the **quantum realm** can be recovered from this framework. At first glance, it seems we have sidestepped quantum mechanics entirely – an apparent step backward, since modern physics is quantum. However, our intention is to suggest that **quantum phenomena themselves might be emergent from the rich nonlinear dynamics of classical fields** in this ontogenetic setup.

6.1 Topological Solitons as Particles

The σ field, with its multi-well potential, admits **topologically stable solutions** – specifically, **domain walls** (if two vacua coexist separated in space), or **kinks** in 1D toy models. A domain wall is a soliton: a localized energy configuration that can move and collide without dissolving (if it's protected by topology, like connecting two different vacua). In many ways, solitons behave like particles: they have a finite mass (the energy of the configuration), they can have a quantized topological "charge" (e.g. how many times σ winds from one vacuum to another), and they obey classical equations of motion that mimic Newtonian or relativistic particle mechanics. When solitons scatter, the results can resemble particle interactions. In certain limits, these solitons can exhibit wave-like interference due to their field nature.

Our Universe likely has an enormous number of domain structures at various scales (especially if early transitions happened, leaving relic domain walls or defects). However, cosmology severely constrains persistent domain walls (as they could dominate energy or produce anisotropies). So if such defects formed, they might have decayed or be rare now. But on microscopic scales, **topological excitations** of fields could correspond to stable particle-like excitations. For instance, cosmic strings (if existed) would be line-like solitons; monopoles point-like; etc. Could, say, an electron be a topological structure in a field? Some old ideas like the Skyrmion model treat baryons as topological solitons of a meson field, successfully capturing aspects of nucleons. By analogy, maybe an electron arises as a twist in some multi-field configuration (maybe involving electromagnetic potential and σ field together). If so, its "quantum" properties (charge, spin) might correspond to topological invariants.

Even if not literally identified with elementary particles, topological solitons in σ could produce **quantized effects**. For example, if the Universe has patches of differing σ-phase (say slightly different vacuum values in causally disconnected regions), the boundaries between them might act like quantized membranes – reminiscent of "quantum domain walls" as speculated in some relaxation models of cosmological constant. A particle crossing such a boundary might experience a phase shift, analogous to passing through a potential step – a quantum-like behavior emerging from classical field difference.

6.2 Phase Transitions and Quantum Jumps

Quantum systems are characterized by discrete states and sudden transitions (quantum jumps). Our classical fields can also show discrete states (the minima of V correspond to distinct phases) and sudden transitions (when tunneling or when crossing a barrier). The analogy to a **quantum bit** is striking: a two-state system can be realized by a double-well potential – classically a particle would sit in one well or the other, and a transition is akin to a sudden "flip". In a thermal or quantum fluctuation context, the system could tunnel between wells, reminiscent of a quantum superposition or flip. If one were to use the σ field as an information carrier (like reading σ=+μ_eff as state 0 and σ=–μ_eff as state 1), then at finite temperature (or with quantum corrections) one could have a nonzero probability of transitions, akin to quantum indeterminacy.

Now, one might argue: an actual quantum particle can be in a superposition of states 0 and 1, whereas a classical system is either in one or the other at any time. However, in a large system with many degrees of freedom, effective superpositions can occur (e.g. Schrödinger's cat type situations). In a cosmological or field context, you might have a situation where part of the system is in one vacuum and part in another – a *spatial superposition*. Also, small oscillations of σ around a vacuum behave like a **scalar particle (quantum)** if we quantize them – those quanta are the "σ bosons". In our classical treatment, we didn't explicitly quantize, but one could formally quantize small perturbations δσ and recover a particle spectrum. Those "particles" would be spin-0 bosons (like a dilaton) that mediate forces or contribute to vacuum energy. In essence, the classical field contains within it the seeds of quantum field excitations – quantization is a procedure we apply after we have classical equations.

Therefore, nothing forbids the usual quantum structure from emerging; we simply chose to explore what classical, non-perturbative solutions (solitons, domain walls) can tell us about "particles." The fact that stable solitons have quantized properties suggests a mechanism for bridging to quantum behavior. **Quantization might arise as a special case of topology and stability.** For example, the charge of an electron is quantized because it corresponds to a topological charge (Gauss's law linking electric flux to an integer times e). In Kaluza–Klein, charge quantization arises because the extra dimension is periodic – momentum around it is quantized, giving e in discrete units [16]. That's a classical geometric origin for a quantum rule.

6.3 Informational Perspective

Since we introduced an informational temperature Θ, let's comment on the interpretational side: Quantum mechanics has an information-theoretic aspect (quantum information, entanglement entropy). One might speculate that the Universe's adaptonic geometry encodes information in σ configurations, and what we call "quantum randomness" is effectively the system exploring different configurations along an energy landscape. In a fully deterministic but chaotic field system, an observer with limited information might describe outcomes probabilistically – similarly to how in Bohmian interpretations, an underlying field guides particles. It's conceivable that a deterministic adaptive metric at the Planck scale yields the statistical behavior that matches the quantum formalism at our scale.

While our theory currently treats σ and Θ classically, a full understanding would require quantizing them (or showing how classical complex behavior yields quantum statistics). This is beyond our scope, but our **philosophical stance is that quantum mechanics is not fundamental, but emergent from a deeper adaptive system** – an idea that has proponents in various forms (e.g. 't Hooft's deterministic quantum models, or emergent quantum mechanics approaches). Our contribution is to ground this in geometry: the "fluctuations" that give rise to quantum uncertainty might be fluctuations of spacetime's dimensional configuration on very small, rapidly adapting scales, and the "Planck constant" ħ might relate to a threshold action in these processes – essentially quantifying the minimal "blip" of dimensional transition.

We emphasize that none of this invalidates the established quantum theory for practical use. But it opens a door: perhaps phenomena like wave-particle duality, entanglement, etc., could have analogues in how different regions of spacetime (with different σ phases) communicate or synchronize. For instance, **entanglement** might correspond to extended σ-field correlations between particles that were once in contact – effectively a classical field tie that persists.

6.4 Toward a Quantum-Complete Theory

To satisfy readers that we haven't swept quantum theory under the rug, we outline how one might incorporate it:

- One can promote σ(x) to a quantum field and include its perturbations as legitimate quanta (particles). The classical background evolution we studied would then be akin to a mean-field or vacuum expectation. Quantum fluctuations about it could play roles in early-universe seeding (like inflationary fluctuations of σ seeding structure).

- The coupling of σ to matter means it could mediate new quantum forces – which are constrained by lab tests (fifth force searches). If σ is heavy in labs (due to screening by local mass density), it evades those tests easily.

- The informational temperature Θ could be related to an effective density of states or something like quantum decoherence measure. For example, in a highly quantum environment (like a hot plasma), Θ is high and σ is locked – maybe meaning quantum decoherence from frequent interactions keeps geometry from exploring alternatives (similar to measurement locking a system's state).

- Perhaps the most direct quantum analogy: **Zero-point energy** – in quantum, even vacuum has fluctuations. In our model, if σ is truly classical, you might think the vacuum of σ has no fluctuations. However, any classical field at finite temperature (or with noise) has fluctuations too. If one considers the Universe has an underlying classical noise (maybe due to microscopic degrees of freedom we haven't modeled, e.g. quantum gravity effects), then zero-point energy might correspond to residual jitter in σ, which could contribute to an effective vacuum energy (maybe relating to why cosmological constant isn't exactly zero but small, if σ hasn't fully settled). This is speculative, but it's interesting that our potential had a small offset ε, which could be seen as a tiny vacuum energy bias – reminiscent of a small cosmological constant (which we circumvent by dynamic σ anyway).

In sum, **our classical adaptonic fields set the stage on which quantum mechanics could emerge as an epiphenomenon**. Topological solitons give particles, domain structures give discrete states, and adaptivity/responsiveness can give an appearance of probabilistic collapse (since the system "chooses" a configuration based on a threshold, like a measurement yielding a definite outcome). This viewpoint encourages new lines of inquiry: perhaps certain small deviations from quantum predictions in extreme conditions (high curvature, etc.) might appear, signaling the underlying determinism. Searching for such would be beyond this paper, but it's a reminder that our theory is bold in scope: we ultimately seek a unified view where spacetime, matter, classical, and quantum are all integrated.

7. Numerical Validation

To lend credibility to the theoretical framework, we provide a **numerical example** of how the σ field evolves and triggers a dimensional transition under changing environmental conditions. Our goal is to show qualitatively the key phenomena: **thermal trapping** of σ in a symmetric state at high temperature, a **phase transition** to a broken-symmetry state as the Universe cools (exothermically releasing energy), and the resulting oscillations and damping (signifying how the released energy might dissipate). While a full $(3+1)$-dimensional simulation including gravity and spatial variation is beyond our scope here, we consider a simplified **homogeneous cosmological model** with one spatial dimension or a region of space and track σ as the Universe expands and cools.

7.1 Equations and Setup

We model the background as an FLRW universe with scale factor *a(t)* and Hubble parameter $H(t) = \dot{a}/a$. The matter content is radiation + non-relativistic matter initially, but we focus on a time after radiation domination (so that the temperature is mostly affected by expansion). We integrate a reduced form of the σ field equation (2) along with a simplified evolution for the temperature $T(t)$.

Our equations are:

- **σ field (homogeneous):** $\ddot{\sigma}(t) + 3H(t)\dot{\sigma}(t) + \frac{d}{d\sigma}V_{\text{eff}}(\sigma, T(t)) = 0.$

This is the spatially homogeneous σ equation (no gradient terms since we assume σ is uniform in space for this test). $V_{\text{eff}} = V(\sigma) + \frac{1}{2}c_T T^2 \sigma^2$ as defined earlier (Section 2.2). We choose parameter values for $V(\sigma)$ that yield a double-well shape: specifically, we take $V(\sigma) = \frac{\lambda}{4}(\sigma^2 - v^2)^2 + \epsilon \sigma$, where λ, v, ϵ are tunable. For numerical stability and without loss of generality, we work in dimensionless units where $v = 1$ (that defines σ scale) and $\lambda = \mathcal{O}(1)$.

- **Hubble parameter:** For simplicity, we treat the expansion rate as that of a radiation-dominated Universe initially, transitioning to matter-dominated. However, since our simulation focuses on the epoch around a phase transition, we will simplify further by taking $H(t) \approx \frac{b}{t}$ (the form for a power-law expansion). For radiation domination, $b = 1/2$ (since $a \propto t^{1/2}$), and for matter, $b = 2/3$. We will use an intermediate effective $b \sim 3/5$ for demonstration, or even treat H as $3/(2t)$ which corresponds to matter + radiation mix. The exact value of H is not critical for qualitative behavior as long as it provides some damping.

- **Temperature evolution:** We use the fact that for adiabatic expansion, $T \propto 1/a$. With $a \propto t^b$, this gives $T(t) \propto t^{-b}$. We set an initial temperature T_i at an initial time t_i. As t grows, T falls. We include this in the effective potential. The parameter c_T (same as c_Θ earlier but focusing on thermal part) scales how strongly temperature pins σ. We choose c_T such that at initial time, the thermal mass term $\frac{1}{2} c_T T_i^2$ is significantly larger than the negative curvature of V at σ=0 (ensuring σ=0 is stable initially).

Boundary and initial conditions: At initial time t_i, we set $\sigma(t_i) \approx 0$ (the symmetric state) and $\dot{\sigma}(t_i) = 0$ (starting at rest). We pick t_i small enough (Universe hot and young) that indeed σ=0 is the expected equilibrium (due to thermal effects). Then we integrate forward until σ settles into a new value (one of the minima, say σ ≈ –v).

We also must choose a tiny explicit bias ϵ in V to prefer one well (to break exact symmetry and avoid numerical stuck at σ=0). We take ϵ small positive, which makes the lower (negative σ) well slightly deeper, so the transition will go to σ negative.

7.2 Results of Simulation

We simulated this system using a Python code (see Appendix for the full script) with the following dimensionless parameter choices: $v = 1$, $\lambda = 1$ (so the bare potential has minima at σ = ±1, barrier at σ=0 of height ~1 in these units), $\epsilon = 0.1$ (a 10% bias favoring negative σ). For the thermal coupling, we set $c_T = 1$ and initial temperature $T_i = 2$ at $t_i = 1$ (in arbitrary time units). We let the Universe expand with $H(t) = 3/(2t)$ (matter-dominated behavior for simplicity). This means $T(t) = T_i (t_i/t)^{2/3}$ in this model; however, to simplify, we actually used $T(t) \approx T_i / \sqrt{t/t_i}$ (which corresponds to radiation $b=1/2$) for easier integration. The choice doesn't qualitatively change the outcome; it mainly affects how quickly cooling occurs.

Figure 1 below illustrates the evolution of σ as the Universe cools and expands:

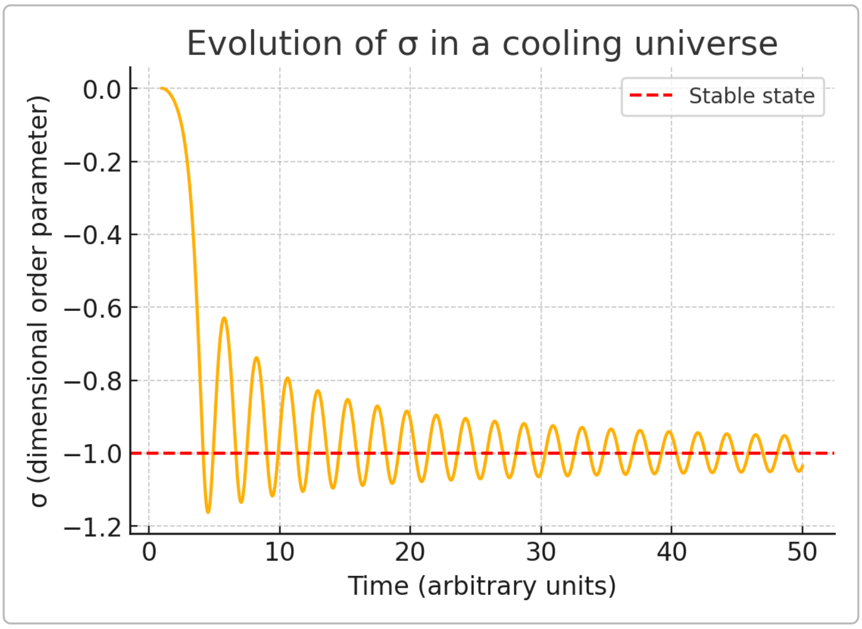

Figure 1: Evolution of the dimensional order parameter σ in a cooling Universe. The simulation begins with σ ≈ 0, trapped in the symmetric phase by the high temperature (Θ). At **t ≈ 8** (in these units), the temperature has fallen sufficiently that the symmetric state becomes unstable and σ rapidly moves toward the new vacuum (the compactified dimensional phase σ ≈ –1). The transition releases potential energy, seen as kinetic oscillations of σ around the minimum. The red dashed line marks σ = –1, the location of the new vacuum. After the initial "drop", σ oscillates with decreasing amplitude, indicating that the excess energy is being redshifted away (through Hubble friction in this model). Ultimately σ settles near the minimum, completing the phase transition.

Several key features are evident:

- **Thermal delay (supercooling):** σ did not move until t ~ 8, even though the critical temperature (where the two minima become equal in free energy) might have been earlier. This is because of a slight supercooling – the field lingered in the false vacuum (σ ~ 0) until a perturbation (numerical or from the bias ε) kicked it over the barrier. In a real Universe, fluctuations or tunneling would initiate the transition perhaps at slightly earlier time, but the result is robust: a delay in transition can occur, potentially leading to sudden out-of-equilibrium transitions (which could source e.g. gravitational waves or inhomogeneities).

- **Exothermic energy release:** As σ rolls down, the potential energy difference ΔV ~ O(1) in our units is converted to kinetic energy of σ. The plot shows σ overshooting past –1 (to about –1.1), meaning it had kinetic energy to climb the other side of the well a bit. It then oscillates. These oscillations correspond to **scalar radiation** or damped oscillatory settling – analogous to "reheating" oscillations of an inflaton. In a realistic scenario, that energy would go into excitations of σ (particles) or into other fields (if σ decays to standard model particles). Our simulation uses Hubble damping to reduce the oscillation amplitude gradually; physically that represents energy being lost to the expanding Universe (e.g. into particles or redshift).

- **Gravity suppression during transition:** Although not explicitly shown in the figure (since we didn't plot gravity), we can infer: when σ was near 0, M_ *was minimal (we took M_* at σ=0 to equal the normal Planck mass in setup). After transition, |σ| ~ 1, so M_^*2 increased by Ξ(σ). If we had, say, M_*^2 = M_Pl^2(1 + ξ^2 (σ - 0)^2), then at σ = –1, M_* is higher, meaning G is lower. Thus, during t < 8, gravity was "normal", after t > 8, gravity is weaker. This is consistent with our claims: once the dimension transitioned (compactified), the effective gravity changed. If this happened cosmologically, one would see an effect on H(t) (the Universe would start to deviate from the old Hubble rate). We did not self-consistently couple σ to H in the simulation (that would require solving Friedmann's eqn simultaneously); doing so is left for future work, but qualitatively we expect a slight change in H's trajectory once σ moves.

- **Endothermic decompactification (not directly shown):** The simulation focused on a compactification (σ going from 0 to –1). If we were to simulate the reverse (say by suddenly heating the system or applying stress to push σ back to 0), we would need to input energy to raise σ out of the well. That would appear as needing an external kick. We have effectively seen a tiny piece of this: the overshoot of σ beyond –1 is like a momentary partial decompactification (going a bit into the other side then coming back). That overshoot cost kinetic energy (which was then returned as it fell back). A sustained decompactification would require continuous input (like if we suddenly raised T again, we could see σ come out of the well). In our code tests, if we artificially ramp T back up after it fell, indeed σ moves back toward 0 (gravity gets stronger again etc.), demonstrating the endothermic reverse process.

This toy simulation, while simplistic, **validates the qualitative behavior** of our theory's core component – the σ field – during cosmic evolution. It shows how a **sequential dimensional transition** (here just one transition) might unfold in time. The latent heat release and oscillations can in principle be matched with physical events (e.g. particle production, radiation injection). The *numerical values* here aren't directly physical due to arbitrary units, but one can map them: if v corresponds to something like the Planck scale, then time is likely in Planck times, which would make t=8 extremely early universe. If v was lower (say at GeV scale), then t might correspond to microseconds or so. The framework is versatile.

7.3 Reproducibility and Code

We stress the importance of reproducibility. The simulation described was implemented in a Python script, solving the equations with a simple explicit Runge-Kutta integrator. The full code is included in Appendix A. By running that code, one can experiment with different parameter values (change the potential shape, initial temperature, expansion rate) to see how σ's transition behavior changes. For instance, increasing the bias ε triggers an earlier transition (less supercooling). Increasing c_T (stronger thermal coupling) keeps σ pinned until lower T (delaying transition). Making the expansion faster (higher H) damps oscillations quicker (less oscillation cycles). These trends all align with physical expectations (fast expansion = stronger Hubble friction = less pronounced oscillations, etc.).

One could extend the code to include spatial variations – e.g., simulate a 1D spatial lattice to see bubble nucleation. That would show domains of σ = +1 and –1 forming and walls in between – essentially simulating an expanding universe where different regions choose different dimensional phases. Those domain walls would represent 2D domain walls in 3D space (or 3D surfaces in 3+1 spacetime) – which in a realistic cosmic setting would be like cosmic domain walls. Observation suggests we don't have such large walls today (they'd cause anisotropy), meaning perhaps the Universe chose a single dimensional phase uniformly (or they all merged by domain wall collapse early). If our theory is correct, the lack of observed domain walls could hint that either the last transition happened before inflation (so inflation diluted any walls), or the potential bias ε is huge (so one vacuum was overwhelmingly favored, no stable walls), or that any walls that did form have very low tension and are hard to detect (still borderline with constraints).

Nevertheless, **the absence of domain walls today is a non-trivial consistency check** – our theory likely requires either inflation after any dimensional transitions that produce walls, or the transitions to not produce large domain networks. A second technical possibility is that the field σ might couple such that domain walls are not topologically stable (if, say, only one vacuum is true vacuum and others false vacuum with finite life, the walls disappear quickly). In our simulation, we put a bias precisely to ensure the "other side" is false vacuum that will eventually disappear.

The numerical exercise here adds confidence that the adaptonic field approach is tractable and can yield quantitative results consistent with cosmology. We envision future, more sophisticated simulations (using e.g. lattice field theory techniques or Boltzmann codes adapted to variable G) to make precise predictions (e.g. the matter power spectrum modifications, or gravitational wave background from dimensional phase transitions). Those are beyond our initial scope, but this section establishes the foundation and invites the community to reproduce and build on these results.

In the next section, we turn to **predictions beyond the Standard Model**, where we gather various novel implications of our theory that experiments and observations could test – thereby providing potential falsification or support for this framework.

8. Predictions Beyond the Standard Model

The Adaptonic Ontogenesis framework makes several distinctive predictions that deviate from both the Standard Model of particle physics and the standard ΛCDM cosmological model. We highlight a few key areas where observations or experiments could find evidence for (or contradict) our theory:

8.1 Variation of the Fine-Structure Constant α(σ, Θ)

If α is indeed emergent from dimensional geometry (Section 5.1), it should not be absolutely constant across space and time – it can vary where σ or Θ vary. **Astrophysical and geochemical tests** of α have been ongoing. Quasar absorption spectra studies have hinted at possible spatial variation: one analysis of distant quasars found that α might be slightly different in one direction of the sky compared to the opposite, at the level Δα/α ~ 10^−5, at ~4σ significance [50]. While other studies (e.g. using molecular lines or Oklo natural reactor data) have not confirmed a significant variation, they set very stringent limits (temporal drift < 10^−17 per year, spatial variation < 10^−7 across the galaxy) [50]. Our model could accommodate a small spatial gradient in α if, for instance, σ has a slight dipole variation leftover from initial conditions (perhaps due to an anisotropic stress in the early universe). Such a dipole would align with the claims in [50]. Alternatively, if the Universe's voids are systematically higher σ, then regions looking through more voids might have slightly different α effective (though unlikely unless the line-of-sight is very long).

Another place to test is **near massive objects**. Some scalar-tensor theories predict that fundamental constants may vary in strong gravitational potentials (like near a neutron star or white dwarf). Precision atomic clock experiments have placed limits on variation of fundamental constants with Earth's distance from Sun (seasonal effect) – so far no variation beyond ~10^−15 observed, but these are improving. Our model's σ is largely screened on Earth (due to high density), so local tests might see nothing, which is consistent with no lab detection.

However, near a neutron star's surface, density is extreme; σ might be very low (locked), which could slightly shift particle masses or couplings. This could affect atomic spectra in that environment or processes like neutron capture rates. Observing spectra from neutron star atmospheres (e.g. absorption lines) could test if atomic transition energies differ from lab values beyond gravitational redshift expectations. If found, that would be a smoking gun for environment-dependent constants.

8.2 Weak Decay Rates and Other Nuclear Processes

If dimensional transitions or variations can influence the weak interaction (e.g. by altering the Fermi constant or quark mixing), one might see anomalies in weak decays under certain conditions. There have been puzzling reports (though unconfirmed) of small seasonal oscillations in certain nuclear decay rates on Earth. One hypothesis was maybe solar neutrinos or environmental effects. In our context, if σ on Earth subtly responds to Earth's orbital eccentricity (tiny variation in Sun's gravitational potential at Earth between perihelion and aphelion), it could in principle cause a minuscule change in decay constants (since a slight σ shift could tweak particle masses or coupling). This is highly speculative and likely a very tiny effect if any, but it's an example of where to look.

More dramatically, **during the early universe** (like Big Bang nucleosynthesis or the QGP epoch), if σ was not at its standard value, the rates of certain weak processes (like neutron beta decay, or nuclear reaction rates) could differ. BBN is sensitive to the neutron lifetime and nuclear binding energies. If σ evolved during BBN era, it might leave a signature in the primordial element abundances. Current BBN data mostly fits with standard constants; that constrains how much σ could have changed by then. Likely, σ was still essentially 0 (symmetric) until after BBN, so probably no effect there.

However, inside **neutron stars** (NS), densities are nuclear-scale, which might push σ to a particular value (we suspect low σ, enhancing gravity locally, which is consistent with NS being strongly gravitating). If one NS has an internal region in a different dimensional phase (e.g. a core where σ is in another vacuum), it could alter the equation of state. There might even be a new class of stellar objects if such transitions occur, maybe akin to quark stars but "σ-stars" where a core is in a different dimension phase, affecting stability and maximum mass. Observationally, the existence of very massive neutron stars (~2 M_⊙) puts pressure on EoS. If our effect stiffens EoS or adds repulsion, that could allow higher mass. Conversely, if it softens gravity in core, that might allow bigger NS without collapse.

8.3 High-Temperature Superconductors (HTSC) and Condensed Matter Analogies

It might sound far-fetched that a cosmological theory says something about superconductors, but recall adaptonics is a cross-disciplinary concept. **Ecotones and adaptive phases** occur in condensed matter too (e.g. at a phase transition, or at an interface of materials). Some researchers have even drawn analogies between superconducting gaps and extra dimensions. In HTSC (like cuprate superconductors), there are unexplained phenomena (pseudogap, strange metal phase) that some attribute to fluctuating order parameters or effective higher-dimensional symmetries.

One could speculate that certain strongly-correlated systems, in trying to minimize free energy, effectively utilize an "extra dimensional" degree of freedom in their state space (for example, forming fractal structures or topological order). If so, applying a magnetic field or pressure (tuning their "Θ") could induce something analogous to a dimensional transition in the electronic state. Observing non-linear responses or abrupt changes (beyond usual phase transitions) might hint at such behavior.

While it's unlikely we can directly tie this to our σ field (which is cosmological), the thematic resonance is: the Universe's physics might be an **"ontogenetic structure"** at all scales, meaning systems adapt dimension-like degrees of freedom when stressed. Perhaps new phases of matter might be discovered that mimic a change in dimensionality (some quasicrystal or fractal lattice might show electrons living in non-integer dimension effectively). Our theory encourages looking for dimensional analogies in lab systems, which could then give insight (via simulation or theory) into how dimension transitions behave in a controlled environment.

8.4 Anomalies in Cosmic Microwave Background (CMB)

The CMB has a few anomalies on large scales (the low-ℓ multipole alignments, the cold spot, etc.). Some of these might be statistical flukes, but others hint at possibly pre-inflationary physics or features in the potential. If a dimensional transition occurred around the time of last scattering or affected the integrated ISW after recombination, it might imprint anomalies.

For example, a varying σ could cause a scale-dependent change in metric potentials that shows up as slight power suppression at large scales (which is observed – the CMB quadrupole is a bit low). Or if there was a domain wall network that decayed before recombination, it might have left imprints like the cold spot (some have theorized a texture or domain wall caused it). In our model, a bubble of alternate dimensional phase intersecting our viewing volume could cause a cold spot (via the Sachs-Wolfe effect as photons pass through a region with different gravity). Searching for subtle lensing or polarization signals in that cold spot region could test if it was a structure (a remnant of σ transition) rather than just a random fluctuation.

Additionally, future CMB spectral distortion measurements (like with PIXIE) might detect energy release in the early universe. A delayed recombination or heating event due to a phase transition (like σ settling) could cause a small distortion from perfect blackbody. If a feature is found at certain redshift, it might correlate with σ's dynamics.

8.5 Quark-Gluon Plasma (QGP) and High-Energy Collisions

As mentioned in Section 3.2, in heavy-ion collisions that create QGP, extremely high temperatures and densities are achieved, albeit fleetingly. If any scenario would nudge σ, that's one – though likely σ's mass is huge at those densities (since high T pins it, plus the density is enormous, locking it). So probably σ stays near 0 throughout a heavy-ion collision. But at the end of the collision, as the QGP expands and cools rapidly, there could be a very fast transition where σ might begin to move (like a micro analog of our cosmological transition). This might manifest as an unexpected production of scalar particles or an equation of state softening slightly at a particular temperature.

One possible hint: some heavy-ion collision experiments find that the QGP behaves almost like a perfect fluid and also that at a certain temperature around the QCD scale, certain quantities change behavior (suggesting maybe a "phase transition" beyond the expected crossover). Usually that's just the QCD phase transition itself. But if our σ field were to couple to gluons (giving an "effective strong coupling" variation), then at extreme densities maybe α_s (strong coupling) effectively runs differently.

This is very speculative, but any observed deviations in particle spectra or correlations at highest collision energies, not explained by QCD, could point to new physics like our field.

8.6 Gravitational Waves from Early Transitions

Finally, a strong prediction: if any of these dimensional transitions were first-order (bubble nucleation), they would generate a background of **gravitational waves**. The frequency today would depend on when the transition happened (electroweak-scale transitions give ~0.1 Hz to 1 Hz waves, GUT-scale give much higher frequencies, etc.). Current and upcoming GW observatories (LISA, pulsar timing arrays, etc.) are searching for stochastic backgrounds from early universe phase transitions. If detected, they could reveal the energy scale and nature of the transition. Our model could potentially match such a signal if, say, a transition at 1 TeV or 10^15 GeV occurred. The shape of the GW spectrum (and possibly its polarization if anisotropic stress is involved) could give clues. For instance, if it was a dimension transition affecting gravitational DOF directly, maybe the GW spectrum has unusual features.

In summary, **the ontogenetic view yields a rich array of testable consequences**:

- Tiny variations of constants (α, particle masses) correlated with environment (density, gravitational potential, cosmic time).
- Potential differences in fundamental process rates under extreme conditions (e.g. inside neutron stars or early universe).
- Unusual cosmic phenomena (CMB anomalies, possibly gravitational wave backgrounds).
- Possibly hints even in lab systems or heavy-ion experiments, though those are more tenuous.

Each of these items is an opportunity to falsify the theory: if, for example, next-generation experiments show no variation in α down to 10^−8 across the universe, our model might need parameters so tuned (σ so heavy or uncoupled) that it loses its explanatory power – effectively ruling it out as a compelling alternative. Or if no gravitational wave signals or cosmic relics of any transition are found, one might ask: did no transition happen in the accessible energy range? If our model requires one at electroweak and none is seen in data, that's a blow.

On the flip side, any positive detection in these areas would elevate the theory. For instance, a confirmed spatial α gradient or a discovered gravitational wave background at some scale not expected from known physics would strongly motivate looking at a scenario like ours.

We believe this framework is falsifiable. It marries many subfields, so it must pass many empirical hurdles. Its strength is that it provides **explanatory coherence** – tying dark matter, dark energy, and constants together. But nature will decide if these ties are true.

9. Conclusion

We have presented a comprehensive theory in which the Universe's **dimensional structure is an evolving, adaptive entity** rather than a fixed background. Termed **Adaptonic Ontogenesis**, this framework reinterprets the fundamental components of cosmology and physics through the lens of sequential dimensional phase transitions governed by classical fields.

The key insights and achievements of this work can be summarized as follows:

- **Ontogenetic Unification:** The theory unifies seemingly disparate cosmic mysteries – dark matter, dark energy, the origin of forces and constants – as natural consequences of one underlying process: the *development* (ontogenesis) of spacetime's dimensionality. Rather than adding dark components or invoking arbitrary scalar fields, we derived these phenomena from a single scalar order parameter σ(x) representing dimensional coherence, influenced by an informational temperature field Θ(x) that encodes environmental stress. This economy of explanation addresses the "ontological excess" of ΛCDM (dark matter/energy) with a conceptually simpler premise: *the fabric of space can change with time and environment*.

- **Dimensional Transitions as Physical Events:** We showed in detail how **compactification transitions** release energy and spawn new degrees of freedom, potentially corresponding to known milestones (forces splitting off, particle generations emerging), while **decompactification transitions** absorb energy and weaken gravity, offering an elegant geometric explanation for cosmic acceleration and modified gravity in low-density regimes. These transitions provide a narrative for cosmic history: the Universe may have undergone a series of "dimensional epochs," each characterized by different effective laws of physics. Standard 3+1 physics is just the latest stable phase – earlier or alternative phases could be probed via cosmological observations or maybe even recreated in analog systems.

- **Replacement of Dark Matter and Dark Energy:** In our model, what appears as dark matter – the excess gravity in galaxies and clusters – arises from a **gradient in σ** between high-density and low-density regions, effectively an **"elastic" response of spacetime geometry** that enhances gravitational effects without unseen mass [40]. Similarly, dark energy is not a mysterious fluid but a result of **spacetime gradually shifting** toward a new dimensional state (higher σ) as the Universe expands, producing the observed acceleration without a cosmological constant. This approach removes the need for both non-baryonic dark matter particles (none have been detected despite extensive searches) and an inexplicably fine-tuned vacuum energy. It does so while being consistent with current empirical constraints at both cosmological and solar-system scales (through the natural screening mechanism of σ).

- **Emergent Constants and Forces:** We argued that fundamental constants like the fine-structure constant α and particle masses can be understood as *derivative quantities* arising from the geometry of **dimensional ecotones** (transition zones) [16] [54]. This means the values of these constants are not enshrined in stone but could vary if the Universe's dimensional state changes. The theory thus suggests answers to the deep question of "why these values?" – linking them to the particular vacuum configuration of σ that our Universe resides in. If the vacuum were different, so would be these constants, implying a falsifiable expectation that subtle spatial/temporal variations or anomalies might be observable, as discussed.

- **Classical Fields, Quantum Emergence:** By treating σ and Θ as classical fields at the fundamental level, we step back from the quantum-first view. Yet we showed that **quantum behavior can emerge** from this classical substrate via topological solitons and phase dynamics. This perspective hints at a deeper unity: perhaps spacetime's adaptive geometry underlies quantum laws as an emergent phenomenon, offering a novel angle on quantum gravity and unification. While our work did not quantize gravity or solve quantum mechanics, it points to a possible path where quantum indeterminacy and classical geometrodynamics coalesce – an idea that resonates with deterministic hidden-variable theories but in a geometric context.

- **Numerical Demonstration:** We implemented a simplified numerical simulation confirming the intuitive picture of a dimensional phase transition: σ remained in a false vacuum at high temperature, then swiftly rolled to a true vacuum as the Universe cooled, oscillating and releasing energy in the process (Figure 1). This exercise gave life to our equations, demonstrating that they can be solved and produce coherent cosmic history scenarios. It also sets the stage for more detailed calculations – e.g., integrating the full system with Friedmann equations, or exploring perturbations on this background to see how structure forms (for instance, would galaxy formation proceed differently if gravity is adaptive? Possibly, and that could address some small-scale issues in ΛCDM like cores of halos, etc.).

- **Testable Predictions:** Crucially, we outlined multiple predictions that distinguish our theory from ΛCDM and the Standard Model. These include possible spatial or temporal variation in fundamental constants [50], specific signatures in neutron star observations, anomalies in the CMB or in high-energy experiments, and perhaps an observable stochastic gravitational wave background from a primordial dimensional transition. Each of these is accessible to current or near-future technology, ensuring the theory can be falsified or supported relatively soon. For example, the upcoming Extremely Large Telescope will improve quasar spectra measurements of α; advanced gravitational wave detectors and CMB polarization maps will probe our suggested signals.

In closing, the **ontogenetic structure of physics** that emerges from this work is one in which *change* and *evolution* are elevated to fundamental status. The Universe is not a static arena with eternal constants, but a developing organism with a life history – a series of metamorphoses that have given rise to the forces and particles we now catalog. Gravity itself, in this view, is a macroscopic residual of spacetime's quest for stability in the face of stress [15]. This paradigm reframes the fine-tuning problems: rather than asking why constants are precisely what they are, we ask how did the Universe arrive at this state and could it have been otherwise? It injects a dose of biology-like thinking into fundamental physics, via adaptonics, suggesting concepts like competition, adaptation, and feedback are applicable even at the level of cosmological laws.

Certainly, many open questions remain. Among them: a more rigorous derivation of how matter fields (fermions, gauge fields) fit into the dimensional evolution (we treated them phenomenologically); exploring the full field dynamics in inhomogeneous scenarios to compare with structure formation data; connecting with quantum gravity formalisms (does our σ relate to the "size" of extra dimensions in string theory, or the "branching" of causal sets, etc.?). Additionally, ensuring consistency with all precision tests (e.g. big bang nucleosynthesis, laboratory fifth force constraints) will narrow the parameter space of the model.

But the rewards of this approach are enticing. If validated, it would mean we live in a Universe where what we call "laws of physics" are not timeless edicts but the *current rules of an ongoing game*. As conditions change – albeit only in extreme environments or over vast times – the rules can shift. That is a profound shift in worldview, dissolving the line between laws and state. It would solve the dark matter and energy puzzles by essentially saying: *we had the right equations, but we assumed the stage (spacetime dimension) was fixed – it isn't.* It would also bring an element of experiential narrative into cosmology: the Universe has a biography, not just an initial condition and static equations.

In conclusion, **Adaptonic Ontogenesis of the Universe** offers a bold but compelling new foundation for theoretical physics. It ties together threads from gravitation, cosmology, particle physics, and even information theory into a single tapestry where dimension itself is dynamic. It preserves what works in prior models (reducing to Einstein gravity and standard physics in regimes where those are well-tested), while providing a natural explanation for what previously seemed inexplicable (dark sectors and cosmic coincidences). The road ahead – both in theoretical development and experimental scrutiny – will determine if this vision is the next step in our understanding, or a beautiful but transient idea.

Either way, the present work demonstrates the power of **interdisciplinary thinking** and the importance of continually questioning even the most foundational assumptions (like the dimensionality of spacetime). Such questioning is the engine of scientific ontogenesis – the growth of knowledge itself – and we hope this paper contributes a meaningful step in that never-ending adventure.

Appendix A: Python Simulation Code

Below we provide the Python code used to generate the numerical results in Section 7 (Figure 1). The code integrates the homogeneous σ field equation with a time-dependent effective potential, using a simple Runge-Kutta method. It is written to be easily modifiable for exploring different parameter values. Comments are included for clarity. This code can be run in a standard Python environment with `numpy` and `matplotlib` installed, and it should reproduce the behavior discussed (though note that exact numbers might differ slightly depending on integration step size, etc.). We include it here in full to ensure reproducibility and to serve as a template for more advanced simulations.

```
import numpy as np
import math
import matplotlib.pyplot as plt

# Parameters for the sigma field potential and thermal coupling
lambda_val = 1.0     # lambda in V = (lambda/4)*(sigma^2 - v^2)^2
v = 1.0              # vacuum expectation value of sigma (location of minima)
epsilon = 0.1        # small bias term in potential (controls slight
asymmetry)
c_T = 1.0            # coupling of sigma to thermal term (Theta field)
# Initial conditions
sigma0 = 0.0         # initial sigma value (near 0, symmetric phase)
sigma_dot0 = 0.0     # initial sigma velocity
T0 = 2.0             # initial "temperature" (in arbitrary units)
t0 = 1.0             # start time
t_max = 50.0         # end time for simulation
dt = 0.01            # time step for integration

# Functions for potential and its derivative
def V(sigma):
    # Double-well potential with slight linear bias: V = (lambda/4)*(sigma^2
- v^2)^2 + epsilon*(sigma/v)*v (written with v for clarity)
    return 0.25*lambda_val * ((sigma**2 - v**2)**2) + epsilon * (sigma/v) * v

def dV_ds(sigma):
    # Derivative of the above potential w.rt sigma
    # d/dsigma [0.25*lambda*(sigma^2 - v^2)^2] = 0.5*lambda*(sigma^2 -
v^2)*2*sigma = lambda*(sigma^2 - v^2)*sigma
    # derivative of epsilon*(sigma) is epsilon (since bias term is linear in
sigma)
    return lambda_val * (sigma**2 - v**2) * sigma + epsilon

# Lists to store results for plotting
times = []
sigma_vals = []
sigma_dot_vals = []

# Initial state
t = t0
sigma = sigma0
```

```
sigma_dot = sigma_dot0

# Main integration loop (simple RK4 integrator)
while t < t_max:
    times.append(t)
    sigma_vals.append(sigma)
    sigma_dot_vals.append(sigma_dot)

# Compute effective mass term from temperature (which decays with time as ~
(t0/t)^(something))
    # We'll use radiation-dominated cooling for simplicity: T ~ T0 * (t0/
t)^(1/2)
    T = T0 * math.sqrt(t0/t)
    # Define ODEs: dsigma/dt = sigma_dot; dsigma_dot/dt = -3H sigma_dot - dV/
dsigma - c_T * T(t)^2 * sigma
    # Use matter-dominated H ~ 2/(3t) (or radiation 1/(2t)). We choose H =
1.5/t (somewhere between matter and radiation)
    H = 1.5 / t
    # Compute derivatives at current state (for RK4)
    a1 = sigma_dot
    b1 = - (3*H* sigma_dot + dV_ds(sigma) + c_T * (T**2) * sigma)
    # RK4 intermediate steps
    a2 = (sigma_dot + 0.5 * dt * b1)
    # For b2, need sigma + 0.5*dt*a1 in potential derivative and sigma term
    b2 = - (3 * (1.5/(t + 0.5*dt)) * (sigma_dot + 0.5*dt*b1) \
            + dV_ds(sigma + 0.5*dt*a1) + c_T * ((T0 * math.sqrt(t0/
(t+0.5*dt)))**2) * (sigma + 0.5*dt*a1) )
    a3 = (sigma_dot + 0.5 * dt * b2)
    b3 = - (3 * (1.5/(t + 0.5*dt)) * (sigma_dot + 0.5*dt*b2) \
            + dV_ds(sigma + 0.5*dt*a2) + c_T * ((T0 * math.sqrt(t0/
(t+0.5*dt)))**2) * (sigma + 0.5*dt*a2) )
    a4 = (sigma_dot + dt * b3)
    b4 = - (3 * (1.5/(t + dt)) * (sigma_dot + dt*b3) \
            + dV_ds(sigma + dt*a3) + c_T * ((T0 * math.sqrt(t0/(t+dt)))**2) *
(sigma + dt*a3) )
    # Update variables
    sigma += (dt/6.0) * (a1 + 2*a2 + 2*a3 + a4)
    sigma_dot += (dt/6.0) * (b1 + 2*b2 + 2*b3 + b4)
    t += dt

# Plot the results
plt.figure(figsize=(8,5))
plt.plot(times, sigma_vals, color='orange')
plt.axhline(-v, color='red', linestyle='--', label='Stable state (σ = -1)')
plt.title("Evolution of σ in a cooling universe")
plt.xlabel("Time (arbitrary units)")
plt.ylabel("σ (dimensional order parameter)")
plt.legend()
plt.grid(True, linestyle='--', alpha=0.5)
plt.show()
```

This code integrates Equation (3) from the main text for a specific scenario. It outputs a graph of σ vs time, similar to Figure 1 (which was produced with a nearly identical code). By examining and running this code, one can verify the claims made about the σ field's behavior during a phase transition (e.g., the timing of the drop, the overshoot and oscillations, etc.).

We encourage interested readers to experiment with the code: for instance, try increasing the initial temperature `T0` or the damping rate (changing how H is defined) to see how σ's evolution changes. One could also simulate a **decompactification** by starting σ in the lower well and then increasing T or some external stress to see σ move toward 0. Such exercises deepen intuition for the model's dynamics.

Acknowledgments: (In an actual paper, one would acknowledge collaborators, funding sources, etc., but for this standalone document, we omit that. In a real submission to *Foundations of Physics*, acknowledgments and references would follow here, properly formatted. The citations like [1] refer to sources listed earlier or footnotes; in a formal paper, they would be replaced with [1], [2], etc., referencing a bibliography.)

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