Coherence Cosmology and Friedmann-Like Dynamics

Homogeneous Coherence Branches in an FRW Background

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March 28, 2026

Abstract

The Taiji–Skyrme framework augments an $SU(2)$ Skyrme-type field with a coherence scalar derived from a Taiji spinor, leading to a dimensionless coherence field $\psi(x)$ governed by an effective potential $V_{\text{eff}}(\psi)$ with multiple minima. At the classical level, this scalar sector admits distinct vacuum branches, domain walls, and parameter-dependent bifurcations. In the present document we examine the implications of the coherence field for homogeneous and isotropic cosmology within general relativity.

We embed the coherence scalar into a Friedmann–Robertson–Walker (FRW) spacetime, derive the homogeneous field equation, and obtain the modified Friedmann equations with coherence contributions to the total energy density and pressure. Each vacuum branch defines an effective cosmological fluid with an equation of state determined by the local structure of $V_{\text{eff}}(\psi)$ and by the kinetic energy of ψ. We outline how branch transitions and large-scale domain-wall networks may alter the expansion history in a controlled way, and we discuss qualitative scenarios in which coherence branches play roles analogous to dark energy or dark matter. Throughout, gravity is treated strictly within general relativity; coherence influences cosmology solely via its contribution to the stress–energy tensor. We conclude by listing the observational constraints that any coherence-based cosmological scenario must satisfy, including cosmic microwave background, large-scale structure, and background expansion data.

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1 Introduction

The Taiji–Skyrme theory couples an $SU(2)$ field $U(x)$, representing structured internal degrees of freedom, to a coherence sector encoded in a real, dimensionless scalar field $\psi(x)$. The scalar arises from the norm of a Taiji spinor and is governed by an effective potential $V_{\text{eff}}(\psi)$ constructed to admit multiple local minima. These minima define coherence vacuum branches, while domain-wall solutions interpolate between neighbouring branches. The vacuum and interface structure of the coherence field have been analysed in a flat-space setting in terms of an effective scalar Lagrangian and multi-vacuum potential.

On cosmological scales, the relevant spacetime is well approximated by a Friedmann–Robertson–Walker (FRW) geometry, with large-scale homogeneity and isotropy. In such a background, the coherence field may be treated, to leading order, as spatially homogeneous, $\psi(x) \approx \psi(t)$, and its dynamics contribute to the total energy density and pressure that drive the expansion of the universe. The question addressed in this document is how the coherence scalar modifies the standard Friedmann equations and what qualitative cosmological behaviours can be generated by its multi-branch structure.

We work strictly within general relativity: the Einstein equations

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu} \tag{1}$$

relate spacetime curvature to the total stress–energy tensor $T_{\mu\nu}$, which includes contributions from:

- conventional matter components (radiation, baryons, and any additional matter),
- the Skyrme sector,
- and the coherence scalar ψ.

No independent coherence-based gravitational force is introduced. The role of the coherence field is exclusively to modify the energy density and pressure budget through its kinetic and potential terms.

The structure of this document is as follows. In Section 2 we introduce the FRW metric, specialise the coherence Lagrangian to a spatially homogeneous field, and derive the scalar-field equation of motion and the associated energy density and pressure. In Section 3 we describe how each vacuum branch defines an effective cosmological fluid with a characteristic equation of state and discuss the role of branch transitions and domain-wall networks at large scales. Section 4 presents qualitative cosmological scenarios based on early- and late-time branch occupancy and outlines their possible impact on expansion history and structure formation. Section 5 summarises the main constraints and observational tests that any coherence-based cosmology must satisfy.

2 Homogeneous Coherence Field in FRW

2.1 FRW background

We consider a spatially homogeneous and isotropic universe described by the FRW metric

$$ds^2 = -dt^2 + a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2) \right], \tag{2}$$

where $a(t)$ is the scale factor and $k = 0, \pm 1$ encodes the spatial curvature. The Hubble parameter is $H(t) = \dot{a}(t)/a(t)$, where a dot denotes differentiation with respect to cosmic time t.

In this background, homogeneity and isotropy imply that the coherence field can be taken to be a function of time only,

$$\psi(x) = \psi(t), \tag{3}$$

at the level of the background cosmology. Spatial variations, including domain walls and inhomogeneities, can be treated as perturbations around this homogeneous configuration and will be discussed structurally in Section 3.

2.2 Effective Lagrangian and scalar equation

The effective coherence Lagrangian density in a general spacetime is

$$\mathcal{L}_{\rm coh} = \frac{1}{2}\partial_\mu\psi\,\partial^\mu\psi - V_{\rm eff}(\psi) - \alpha\,\psi\,K(U), \tag{4}$$

where $V_{\rm eff}(\psi)$ is the multi-vacuum potential and $K(U)$ is a scalar functional of the Skyrme field measuring its local activity. On cosmological scales, it is convenient to absorb the averaged effect of $K(U)$ into an effective potential,

$$V_{\cos}(\psi; t) = V_{\rm eff}(\psi) + \alpha\,\psi\,\bar{K}(t), \tag{5}$$

where $\bar{K}(t)$ denotes a spatial average of $K(U)$ on constant-time hypersurfaces. In regimes where $\bar{K}(t)$ is slowly varying or approximately constant, one can treat $V_{\cos}(\psi)$ as a time-independent effective potential with shifted minima. For simplicity, and to emphasise the structural features, we shall treat $V_{\cos}(\psi)$ as a given effective potential and suppress its possible weak time dependence.

In the FRW background with homogeneous $\psi(t)$, the kinetic term reduces to

$$\partial_\mu\psi\,\partial^\mu\psi = -\dot{\psi}^2, \tag{6}$$

and the coherence part of the action is

$$S_{\rm coh} = \int d^4x\sqrt{-g}\,\left[\frac{1}{2}\partial_\mu\psi\,\partial^\mu\psi - V_{\cos}(\psi)\right] = \int dt\,a(t)^3\left[\frac{1}{2}\dot{\psi}^2 - V_{\cos}(\psi)\right]. \tag{7}$$

Varying with respect to ψ yields the homogeneous scalar-field equation of motion,

$$\ddot{\psi} + 3H\dot{\psi} + \frac{dV_{\cos}}{d\psi}(\psi) = 0. \tag{8}$$

This is the standard Klein–Gordon equation in an expanding universe, with a Hubble friction term $3H\dot{\psi}$ and force term given by the derivative of the effective potential. The multi-vacuum structure and branch dependence are encoded in the shape of $V_{\cos}(\psi)$.

2.3 Energy density and pressure of the coherence field

The stress–energy tensor of the coherence field is obtained by varying the action with respect to the metric,

$$T^{(\psi)}_{\mu\nu} = \partial_\mu\psi\,\partial_\nu\psi - g_{\mu\nu}\left[\frac{1}{2}\partial_\alpha\psi\,\partial^\alpha\psi - V_{\cos}(\psi)\right]. \tag{9}$$

For a homogeneous field in FRW, this reduces to a perfect-fluid form with energy density and pressure

$$\rho_\psi = T^{(\psi)}_{00} = \frac{1}{2}\dot{\psi}^2 + V_{\cos}(\psi), \tag{10}$$

$$p_\psi = \frac{1}{3}\sum_{i=1}^{3} T^{(\psi)}_{ii}/a^2 = \frac{1}{2}\dot{\psi}^2 - V_{\cos}(\psi), \tag{11}$$

and an equation-of-state parameter

$$w_\psi = \frac{p_\psi}{\rho_\psi} = \frac{\frac{1}{2}\dot{\psi}^2 - V_{\cos}(\psi)}{\frac{1}{2}\dot{\psi}^2 + V_{\cos}(\psi)}. \tag{12}$$

In the limit where the field is slowly rolling or sitting near a minimum, $\dot{\psi}^2 \ll V_{\cos}(\psi)$, one has $w_\psi \approx -1$, while in the opposite, kinetic-dominated regime, $\dot{\psi}^2 \gg V_{\cos}(\psi)$, one has $w_\psi \approx +1$.

2.3 Modified Friedmann equations

Let $\rho_{\rm tot}$ and $p_{\rm tot}$ denote the total energy density and pressure,

$$\rho_{\rm tot} = \rho_\psi + \rho_{\rm other}, \qquad p_{\rm tot} = p_\psi + p_{\rm other}, \tag{13}$$

where $\rho_{\rm other}$ and $p_{\rm other}$ include the contributions from radiation, baryons, and any additional components, including the Skyrme sector treated as an effective fluid at cosmological scales. The Einstein equations for the FRW metric then yield the Friedmann equations

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_{\rm tot} - \frac{k}{a^2}, \tag{14}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_{\rm tot} + 3p_{\rm tot}). \tag{15}$$

The coherence scalar modifies $\rho_{\rm tot}$ and $p_{\rm tot}$ through (10) and (11), thereby altering the expansion history. Energy–momentum conservation,

$$\dot{\rho}_{\rm tot} + 3H(\rho_{\rm tot} + p_{\rm tot}) = 0, \tag{16}$$

is automatically ensured by the Bianchi identities and the field equations, provided that the coherence sector and the other components exchange energy only through explicitly included interaction terms. In the absence of direct coupling between ψ and other fluids at the background level, ρ_ψ and $\rho_{\rm other}$ each satisfy their own continuity equations.

2.4 Standard cosmological components and the Maxwell radiation sector

For cosmological applications it is convenient to make the decomposition of the total energy density and pressure explicit. In the Taiji–Skyrme framework we distinguish standard matter and radiation components from the coherence sector, which itself is resolved into a small effective set of coherence branches on cosmological scales.

We write the total background energy density as

$$\rho_{\rm tot}(a) = \rho_m(a) + \rho_r(a) + \sum_{b\in\mathcal{B}_{\rm eff,cos}} \rho_b(a) + \rho_\Lambda(a) + \rho_{\rm extra}(a), \tag{17}$$

where

- $\rho_m(a)$ collects non-relativistic matter (baryons and any additional cold matter),
- $\rho_r(a)$ denotes the radiation component,
- $\rho_b(a)$ is the homogeneous energy density associated with coherence branch b in the effective cosmological branch set $\mathcal{B}_{\rm eff,cos}$,
- $\rho_\Lambda(a)$ represents any explicit cosmological-constant term,
- and $\rho_{\rm extra}(a)$ accounts for any additional sectors treated as effective fluids.

For each branch b we define the corresponding pressure $p_b(a)$ and equation-of-state parameter

$$w_b(a) \equiv \frac{p_b(a)}{\rho_b(a)}. \tag{18}$$

Branches whose dynamics make them behave as halo-like matter satisfy $w_b(a) \simeq 0$; branches whose dynamics freeze them near a high plateau or minimum of $V_{\rm cos}(\psi)$ satisfy $w_b(a) \simeq -1$ and can drive accelerated expansion; transitional branches exhibit a time-dependent $w_b(a)$ interpolating between these regimes.

The single-fluid description of the coherence sector in terms of $(\rho_\psi(a), p_\psi(a))$ is recovered by summing over the effective cosmological branch set,

$$\rho_\psi(a) \equiv \sum_{b\in\mathcal{B}_{\rm eff,cos}} \rho_b(a), \qquad p_\psi(a) \equiv \sum_{b\in\mathcal{B}_{\rm eff,cos}} p_b(a). \tag{19}$$

In formulas that do not need to resolve individual branches, only ρ_ψ and p_ψ appear explicitly.

In the extended Skyrme–Taiji framework, the radiation density $\rho_r(a)$ includes the electromagnetic energy density $\rho_{\rm EM}(a)$ associated with the Maxwell sector of the coherence connection, together with any additional relativistic degrees of freedom:

$$\rho_r(a) = \rho_{\rm EM}(a) + \rho_{\rm rel,\ other}(a). \tag{20}$$

At the level of background cosmology, this combined radiation component is well approximated as a perfect fluid with equation of state

$$p_r(a) = \frac{1}{3}\,\rho_r(a), \tag{21}$$

corresponding to $w_r = 1/3$. Non-relativistic matter is characterised by $p_m \simeq 0$.

The symbols $\rho_\Lambda(a)$ and $p_\Lambda(a)$ denote an explicit cosmological-constant term obeying

$$p_\Lambda(a) = -\rho_\Lambda(a). \tag{22}$$

In the *baseline* Taiji coherence cosmology one typically sets $\rho_\Lambda(a) = 0$ and attributes any late-time acceleration to one or more coherence branches in the sum $\sum_b \rho_b(a)$. The term $\rho_\Lambda(a)$ is kept in the formulas mainly to allow direct comparison with standard ΛCDM fits when desired.

With this decomposition, the Friedmann equations (14) and (15) retain their standard GR form; the coherence sector enters only through the branch-resolved contribution $\sum_b \rho_b(a)$ and its associated pressures $\sum_b p_b(a)$, while the Maxwell sector is contained in $\rho_r(a)$.

3 Branch-Dependent Effective Cosmological Fluids

3.1 Vacuum branches as effective fluids

The multi-vacuum potential $V_{\cos}(\psi)$ admits minima at field values ψ_i, each associated with a coherence vacuum branch. Near a minimum, the potential may be expanded as

$$V_{\cos}(\psi) \approx V_i + \frac{1}{2} m_i^2 (\psi - \psi_i)^2 + \cdots, \tag{23}$$

where $V_i = V_{\cos}(\psi_i)$ and $m_i^2 = V''_{\cos}(\psi_i)$. If the field is trapped in a given minimum and oscillations around it are negligible, the energy density and pressure are approximately

$$\rho_\psi \approx V_i, \qquad p_\psi \approx -V_i, \tag{24}$$

so that the branch behaves as an effective cosmological constant with equation-of-state parameter $w_\psi \approx -1$.

If the field oscillates around the minimum or rolls slowly towards it, the equation of state can deviate from -1. For small oscillations in a quadratic minimum, the time-averaged equation of state approaches that of pressureless matter, $w_\psi \approx 0$, while for more general potentials the effective w_ψ depends on the shape of $V_{\cos}(\psi)$ and the amplitude of oscillations. Thus, different branches and dynamical states of the coherence field can mimic distinct cosmological fluids:

- vacuum-energy-like behaviour ($w \approx -1$) when the field is frozen near a minimum,
- matter-like behaviour ($w \approx 0$) for certain oscillatory regimes,
- and potentially other intermediate behaviours for more complex potentials.

In this document, the term "branch" refers exclusively to coherence vacuum branches arising from the multi-minima structure of $V_{\cos}(\psi)$. The electromagnetic sector associated with the Maxwell field A_μ is treated as part of the standard radiation component $\rho_r(a)$ with equation of state $w_r = 1/3$ and does not introduce additional branch structure at the level of the homogeneous background.

3.2 Branch fluids, late-time acceleration, and DESI DR2

Recent baryon acoustic oscillation (BAO) measurements from the DESI Collaboration (DESI 2024 Data Release 2, as summarised for example in the APS Physics Viewpoint "Rethinking Our Place in the Universe") probe the expansion history $H(z)$ with high precision over a wide redshift range. When these data are analysed within standard GR+FLRW and the usual fluid decomposition of ΛCDM, the results are often phrased as hints that the component driving late-time acceleration (the so-called *dark energy* sector) may have an equation-of-state parameter $w(a)$ that deviates mildly from a strict cosmological constant value $w = -1$.

In the Taiji–Skyrme framework we do *not* introduce a separate fundamental dark-energy substance. The phrase "dark energy" is used only as an observational shorthand for whatever combination of fields or branches drives late-time acceleration in GR. In our baseline cosmology we set

$$\rho_\Lambda(a) = 0, \tag{25}$$

and attribute any accelerated expansion entirely to the effective behaviour of one or more coherence branches in the sum $\sum_{b\in\mathcal{B}_{\rm eff,cos}} \rho_b(a)$.

Within this branch-fluid picture, the role usually assigned to dark energy is played by those coherence branches whose equation of state satisfies $w_b(a) \simeq -1$ over the relevant range of scale factor. A mild deviation of the observationally inferred "dark-energy" equation of state from -1 can then arise in two structurally natural ways:

- *Single-branch behaviour.* A single branch $b_\star$ dominates the late-time coherence sector, with $\rho_{b_\star}(a)$ and $p_{b_\star}(a)$ slowly evolving as ψ moves in a region of $V_{\rm cos}(\psi)$ that is nearly but not exactly flat. The corresponding $w_{b_\star}(a)$ remains close to -1 but may acquire a gentle time dependence.

- *Multi-branch sharing.* Two or more branches with slightly different equations of state w_{b_1}, w_{b_2}, … contribute comparably to $\sum_b \rho_b(a)$, and their relative energy fractions evolve slowly with a. Even if each w_b is individually almost constant, the weighted average over branches can drift in time.

At the level of background cosmology it is convenient to define an effective equation-of-state parameter for the coherence sector playing the role usually labelled as "dark energy":

$$w_{\rm coh,eff}(a) \equiv \frac{\displaystyle\sum_{b\in\mathcal{B}_{\rm eff,cos}} p_b(a)}{\displaystyle\sum_{b\in\mathcal{B}_{\rm eff,cos}} \rho_b(a)}. \tag{26}$$

In standard ΛCDM language this quantity would be called the dark-energy equation of state $w_{\rm DE}(a)$; here it is explicitly a derived property of the populated coherence branches, with ρ_Λ set to zero in the baseline model.

Determining whether a specific Taiji branch history can reproduce DESI-like reconstructions of $w(a)$ is a quantitative question that requires:

- specifying the cosmological coherence potential $V_{\rm cos}(\psi)$ and the relevant branch set $\mathcal{B}_{\rm eff,cos}$,

- solving the coupled background equations for $\psi(t)$ and the branch energy densities $\rho_b(a)$,
- and comparing the resulting $H(a)$ and $w_{\rm coh,eff}(a)$ with DESI-based reconstructions.

These steps are deliberately left for future numerical and statistical work. The present subsection only fixes the structural mapping between observational statements about "dark energy" and the coherence branch-fluid description employed in this framework.

3.3 Early-time high-energy coherence branch as an inflationary sector

Bertacca, Jimenez, Matarrese and Ricciardone have proposed an "inflation without an inflaton" scenario (*Physical Review Research*, 2025), in which an early inflationary phase is realised without introducing a new fundamental inflaton scalar. The basic idea is that an effective high vacuum-energy density in GR can drive a quasi-de Sitter phase, with tensor perturbations sourced by quantum vacuum fluctuations of the metric.

In the Taiji coherence framework, an analogous mechanism can be implemented structurally by using a high-energy branch of the same effective potential $V_{\rm eff}(\psi)$ that governs late-time coherence dynamics. Concretely, consider a branch $b_{\rm inf} \in \mathcal{B}$ and a field region $\psi \in \mathcal{I}_{\rm inf}$ such that:

- $V_{\rm eff}(\psi)$ is large and slowly varying over $\mathcal{I}_{\rm inf}$, so that the branch energy density

  $$\rho_{b_{\rm inf}}(a) \simeq V_{\rm eff}(\psi)$$

  dominates the total $\rho_{\rm tot}$ and yields an effective $w_{b_{\rm inf}} \simeq -1$;
- the slope and curvature of the potential in this region are sufficiently small to support a slow-roll-type evolution of $\psi(t)$, leading to an extended quasi-de Sitter phase;
- there exists an exit mechanism by which the field leaves $\mathcal{I}_{\rm inf}$ (for example by rolling towards a lower-lying branch or tunnelling followed by classical relaxation), so that the Universe reheats and transitions to a radiation-dominated era.

No additional scalar field is introduced: the same coherence order parameter ψ and its multi-branch potential $V_{\rm eff}(\psi)$ provide both the early inflationary and any late-time acceleration sectors, depending on which branch or field region is populated. At the level of the Friedmann equations, the inflationary phase corresponds to a branch fluid with

$$\rho_{b_{\rm inf}}(a) \approx \text{const}, \qquad w_{b_{\rm inf}} \approx -1, \tag{27}$$

temporarily dominating the sum in $\rho_{\rm tot}(a)$.

At this stage we only specify the structural role of a high-energy coherence branch as a candidate inflationary sector. A full inflationary model would require:

- specifying $V_{\rm eff}(\psi)$ in the relevant high-energy regime,
- checking slow-roll conditions and computing the duration of the quasi-de Sitter phase,

- and deriving the spectrum and statistics of primordial perturbations for comparison with CMB data.

These steps are flagged as a separate line of investigation and are not assumed to be satisfied by default.

3.4 Branch transitions

As the universe expands and the Hubble rate decreases, the effective friction term $3H\dot{\psi}$ in (8) weakens, allowing the coherence field to move more freely in the potential landscape. If the parameters of $V_{\cos}(\psi)$ are such that multiple minima exist, the field may undergo transitions between branches, either through classical evolution over barriers (if the barriers are low enough), quantum tunnelling, or a combination of both mechanisms.

At the level of the background cosmology, a branch transition corresponds to the coherence field shifting from one minimum ψ_i to another ψ_j, changing the vacuum energy density from V_i to V_j and thereby altering the effective equation of state and the expansion rate. In a coarse-grained description, one may characterise these transitions by:

- the difference in vacuum energies $\Delta V_{ij} = V_j - V_i$,
- the relative timing of the transition with respect to other cosmological epochs,
- and the degree to which the new branch is populated across space.

Rapid transitions with large ΔV_{ij} can have dramatic effects on the expansion history, whereas slow or partial transitions may be interpreted as smooth crossovers between effective fluids.

3.5 Domain-wall networks at cosmological scales

If different regions of the universe settle into different coherence branches, domain walls form at the interfaces between them. On sufficiently large scales, a network of such walls contributes to the total energy density and pressure with characteristic equation-of-state properties. For thin, relativistic domain walls, the effective equation of state tends to be negative, with w between -1 and $-1/3$, depending on the network geometry and dynamics.

The Taiji coherence sector provides a natural setting for such domain-wall networks, since the multi-vacuum potential is constructed explicitly from the coherence field. However, the cosmological viability of substantial domain-wall networks is tightly constrained: large wall energy densities can lead to excessive anisotropies and conflicts with observed homogeneity. In any realistic coherence-based cosmology, one must therefore ensure that:

- either the domain walls are sufficiently diluted or short-lived,
- or their energy density remains subdominant compared to other components at all observationally relevant epochs.

In the present document we restrict ourselves to structural remarks: the detailed dynamics and observational constraints on domain-wall networks will require a dedicated analysis.

4 Qualitative Cosmological Scenarios

To illustrate the potential cosmological roles of coherence branches, we outline a few simple scenarios at a qualitative level. These are not fully developed models, but they demonstrate how the branch structure of $V_{\cos}(\psi)$ can enter the expansion history.

4.1 Early high-coherence branch

Suppose that at very early times the coherence field occupies a branch with relatively high vacuum energy V_{early} and that the field is effectively frozen near this minimum due to strong Hubble friction. In this regime, $\rho_\psi \approx V_{\text{early}}$ and $w_\psi \approx -1$, so the coherence field behaves like an early dark-energy component. Depending on the magnitude of V_{early}, this could drive an accelerated expansion phase or contribute a significant fraction of the total energy density alongside radiation.

As the universe expands and H decreases, the field may eventually become unstable in the early branch or transition to a lower-energy branch. The timing and nature of this transition would determine whether the coherence scalar plays a role analogous to inflation, early dark energy, or a transient dark component that leaves imprints on the cosmic microwave background and structure formation.

4.2 Late-time low-coherence branch

At late times, after radiation and matter have diluted, the coherence field may relax into a lower-energy branch with vacuum energy V_{late}. If V_{late} is small but nonzero, the coherence scalar can act as a late-time dark-energy component with $w_\psi \approx -1$, driving the observed accelerated expansion. In this case, the value of V_{late} would have to be tuned or dynamically selected to match the observed dark-energy density.

Alternatively, if the field oscillates around the late-time minimum in a way that yields a time-averaged w_ψ close to zero, the coherence component could mimic an additional pressureless matter component, contributing to the total dark matter density. Mixed scenarios, where coherence contributes both dark-matter-like and dark-energy-like components, are also conceivable, depending on the shape of $V_{\cos}(\psi)$ and the initial conditions.

4.3 Branch transitions and structure formation

Branch transitions can influence the growth of cosmological perturbations and the formation of structure. For example:

- A transition from a high-energy branch to a lower-energy branch can alter the expansion rate and hence the growth factor for density perturbations.
- Spatial variations in the timing of the transition can seed isocurvature perturbations or lead to residual domain-wall structures.
- If certain branches couple more strongly to the Skyrme sector or to other matter components, transitions between these branches can change the effective gravitational clustering properties of the coherence field.

A full treatment of these effects would require perturbation theory around the FRW background with coherence fluctuations included. Here we note only that the multi-branch structure introduces new degrees of freedom in the expansion history and the growth of structure, which can in principle be constrained by observations.

5 Outlook and Constraints

Any coherence-based cosmological scenario must confront a range of observational and theoretical constraints. We list the main classes of constraints and briefly indicate the role of the coherence field in each.

5.1 Background expansion history

The modified Friedmann equations (14) and (15), with ρ_ψ and p_ψ given by (10) and (11), determine the background expansion history. Observations of supernovae, baryon acoustic oscillations, and cosmic chronometers constrain the Hubble parameter $H(z)$ and the effective equation-of-state parameter of the dark sector. Coherence-based models must:

- reproduce the observed late-time accelerated expansion if the coherence field plays the role of dark energy,
- and avoid introducing large deviations from the standard expansion history at earlier epochs unless these are compensated by other effects.

5.2 Cosmic microwave background

The cosmic microwave background (CMB) provides sensitive probes of both the background cosmology and the evolution of perturbations. The presence of coherence branches, branch transitions, or domain-wall networks can affect:

- the angular diameter distance to recombination,
- the relative heights and positions of acoustic peaks,
- and the integrated Sachs–Wolfe effect at late times.

Any significant early or intermediate contribution of the coherence field to the energy density must be consistent with CMB observations. This places constraints on the timing and magnitude of branch transitions and on the allowed equation-of-state history $w_\psi(z)$.

In the present framework, the cosmic microwave background is the thermal relic of the Maxwell photon sector. At the level of the homogeneous FRW background we treat this sector as part of the radiation fluid $\rho_r(a)$ introduced in Sec. 2.4, with equation of state $w_r = 1/3$. The detailed angular power spectrum and acoustic features therefore encode both the standard photon–baryon plasma physics and any modifications to the expansion history induced by the coherence component.

5.3 Large-scale structure and growth of perturbations

The growth of matter perturbations is influenced by the expansion rate and by the clustering properties of the dark components. If the coherence field behaves as a smooth dark-energy component with $w_\psi \approx -1$ and negligible perturbations, its impact is similar to that of a cosmological constant. If, however, coherence exhibits nontrivial clustering or acts as an additional matter-like component, it will affect:

- the growth rate of structure,
- the shape of the matter power spectrum,
- and the abundance of galaxy clusters.

These observables can therefore constrain both the equation of state and the perturbative behaviour of the coherence field, as well as any couplings to other sectors.

5.4 Domain-wall constraints

Persistent domain-wall networks with significant energy density are strongly constrained by both CMB anisotropies and large-scale isotropy. A coherence-based cosmology that produces domain walls must ensure that:

- either the walls are inflated away or diluted to negligible levels,
- or they decay sufficiently early so as not to conflict with observations.

The multi-vacuum structure of $V_{\cos}(\psi)$ must therefore be compatible with a cosmological history in which domain walls are not observationally dominant at late times.

5.5 Theoretical consistency

Finally, the coherence cosmology must remain consistent with the rest of the Taiji–Skyrme framework:

- the form of $V_{\cos}(\psi)$ and its branches should be compatible with the vacuum and domain-wall analysis in flat space,
- the identification of coherence branches with effective cosmological fluids must align with the parameter mapping used in galaxy phenomenology and other applications,
- and the treatment of the coherence field as a classical scalar must be justified as an appropriate limit of the underlying quantum-coherence operator.

These requirements ensure that the cosmological sector is not introduced ad hoc but arises as a consistent extension of the core theory.

Summary

We have embedded the coherence scalar of the Taiji–Skyrme framework into an FRW cosmological background and derived the homogeneous field equation and modified Friedmann equations. Each vacuum branch of the multi-vacuum potential defines an effective cosmological fluid with an equation of state determined by the local form of $V_{\cos}(\psi)$ and the kinetic energy of the field. Branch transitions and domain-wall networks introduce additional structural possibilities, potentially influencing both the background expansion history and the growth of structure.

The analysis here is intentionally structural and qualitative. Making quantitative contact with observations will require:

1. specifying concrete forms of $V_{\cos}(\psi)$ and initial conditions for ψ,
2. solving the coupled system of background and perturbation equations,
3. and confronting the resulting predictions with data from supernovae, the CMB, large-scale structure, and other cosmological probes.

Nevertheless, the present formulation provides a consistent and general-relativistically compatible framework for exploring coherence-based cosmological scenarios, fully integrated with the vacuum, domain-wall, and galaxy-phenomenology sectors of the Taiji–Skyrme theory.