Psi–Continuum Cosmology v3: Response–Field Interpretation of Late–Time Cosmic Expansion

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A macroscopic response-field interpretation of late-time cosmic acceleration

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Abstract

Recent cosmological observations indicate that the late-time expansion of the Universe is accelerating, a phenomenon conventionally attributed to a cosmological constant or an exotic dark energy component. While this description is empirically successful, it leaves unresolved conceptual questions concerning the physical origin, natural scale, and timing of cosmic acceleration.

In this work we propose a phenomenological physical interpretation of late-time acceleration, in which the observed effect can be viewed as a macroscopic response of spacetime geometry to the integrated history of cosmic expansion. Building upon the Psi–Continuum framework established in previous work, we interpret the Ψ term not as a new energy component nor as a modification of gravitational dynamics, but as an effective response field encoding delayed geometric adjustment to the expansion history.

Within this perspective, the standard ΛCDM model corresponds to the instantaneous response limit, while the ΨCDM extension represents the leading-order correction associated with a finite geometric response time. The single deformation parameter ε_0, previously constrained by supernova, cosmic chronometer, and baryon acoustic oscillation data, acquires a natural effective meaning as a low-frequency susceptibility of spacetime to its expansion history.

The response-field interpretation provides a consistent macroscopic description of background expansion data without introducing additional dynamical degrees of freedom, scalar potentials, or violations of general covariance. The framework is formulated at an effective level, analogous to linear response theory in non-equilibrium statistical physics, and remains fully consistent with the geometric structure of general relativity.

We discuss conceptual implications of this interpretation, its relation to existing approaches such as bulk viscosity, backreaction, and modified gravity, and highlight testable phenomenological signatures that can be probed by upcoming precision cosmological surveys.

Contents

1 Introduction

The discovery of the late-time acceleration of cosmic expansion remains one of the central challenges of modern cosmology. Observational evidence from Type Ia supernovae, baryon acoustic oscillations, and cosmic chronometers consistently indicates that the expansion rate of the Universe has entered an accelerated phase at low redshifts. Within the standard cosmological framework, this phenomenon is successfully described by the ΛCDM model, in which acceleration is attributed to a cosmological constant Λ.

Despite its remarkable phenomenological success, the physical interpretation of Λ remains conceptually challenging. The cosmological constant introduces a fundamental energy scale that is vastly separated from expectations based on quantum field theory, and it provides no dynamical explanation for the observed coincidence between the onset of acceleration and the present cosmological epoch. Moreover, persistent tensions between early- and late-time measurements of the Hubble parameter suggest that a purely instantaneous description of cosmic expansion may be incomplete.

These conceptual difficulties have motivated a wide range of alternative approaches, including dynamical dark energy, modified gravity, nonlocal extensions of general relativity, backreaction effects, and phenomenological extensions of the Friedmann equations Gubitosi et al. [2013], Deser and Woodard [2007], Buchert [2000]. While many of these frameworks introduce additional degrees of freedom or modify the underlying gravitational dynamics, an alternative possibility is that the geometry of spacetime itself exhibits a nontrivial macroscopic response to the history of cosmic expansion.

In this work we explore such a possibility within the Psi–Continuum framework. Rather than postulating a new energy component or altering the field equations of general relativity, we interpret the observed acceleration as an emergent response phenomenon, conceptually distinct from dynamical dark energy or modified gravity approaches Gubitosi et al. [2013]. In this picture, spacetime behaves as a macroscopic medium with a finite response time, adjusting to changes in the expansion rate in a history-dependent manner. The effective acceleration observed at late times is then understood as a delayed geometric response to earlier phases of cosmic expansion.

This interpretation builds upon the phenomenological ΨCDM model introduced in previous work Klimov [2025a,b], where the background expansion history was extended by a single deformation parameter ε_0. That analysis demonstrated that a minimal, percent-level modification of the late-time Hubble flow remains statistically consistent with ΛCDM across current supernova, cosmic chronometer, and baryon acoustic oscillation datasets. In the present paper, this phenomenological viability is taken as an empirical input rather than as a subject of further parameter fitting.

The primary objective of this work is to provide a physical interpretation of the Ψ term as a macroscopic response field associated with the expansion history of the Universe. We argue that ε_0 can be naturally reinterpreted as an effective susceptibility characterizing the low-frequency response of spacetime geometry to changes in the expansion rate. In the instantaneous-response limit, this susceptibility vanishes and the standard ΛCDM model is recovered as a special case.

This work is intended as a conceptual and interpretational extension of the Psi–Continuum phenomenology, rather than as a complete fundamental theory. We deliberately restrict our analysis to the background-level description and effective macroscopic considerations.

By framing cosmic acceleration as a response phenomenon, the Psi–Continuum approach offers a conceptually economical perspective that preserves general covariance, avoids the introduction of new dynamical fields, and remains fully compatible with the geometric structure of general relativity. At the same time, it provides a natural phenomenological interpretation of the late onset of acceleration and suggests a unified macroscopic description of background expansion data.

The structure of this paper is as follows. In Section 2 we develop the response-field interpretation of the Ψ term and establish its formal analogy with linear response theory. Section 3 presents the geometric formulation of the effective response contribution. Section 5 discusses the phenomenological implications of this framework and its relation to existing approaches. We conclude in Section 7 with a summary and an outlook for future developments.

2 The Response–Field Interpretation of Ψ

2.1 Motivation: beyond instantaneous expansion

In the standard ΛCDM framework, the expansion history of the Universe is fully characterized by instantaneous relations between the Hubble parameter and the energy content at a given cosmic time. The Friedmann equations encode this assumption explicitly, implying that the geometry of spacetime reacts immediately to changes in the matter–energy distribution Planck Collaboration [2020]. While this picture is sufficient for describing a wide range of cosmological phenomena, it does not address the possibility that the expansion of the Universe may represent a non-equilibrium process at macroscopic scales.

In many physical systems, instantaneous response constitutes an idealized limit. Real macroscopic media typically exhibit finite response times, leading to history-dependent behavior described by memory kernels and response functions Onsager [1931]. This observation motivates the consideration of a similar description for cosmic expansion, in which spacetime geometry responds to changes in the expansion rate in a delayed and cumulative manner.

2.2 Spacetime as a responding medium

We adopt the viewpoint that spacetime, at cosmological scales, can be treated as an effective macroscopic medium characterized by response properties rather than microscopic degrees of freedom. Within this perspective, the Hubble expansion rate $H(t)$ plays the role of a macroscopic driving variable, while the observed late-time acceleration represents the response of the geometry to its prior evolution.

At leading order, such a response may be expressed through a linear history-dependent relation,

$$\delta H(t) = \int_{-\infty}^{t} \chi(t-t')\, \dot{H}(t')\, dt', \tag{1}$$

where $\chi(t-t')$ is a causal response kernel encoding the memory of the expansion history. This form is formally analogous to linear response relations encountered in non-equilibrium thermodynamics and condensed matter systems Onsager [1931].

The key assumption underlying Eq. (1) is that the late-time expansion of the Universe can be treated as a weakly non-equilibrium process, allowing the response to be described by a linear functional of the expansion history. Importantly, no additional dynamical degrees of freedom are introduced; the response kernel χ represents an effective macroscopic property of spacetime.

2.3 The Ψ field as an effective response variable

Within the Psi–Continuum framework, the response contribution to the expansion rate is encapsulated by the effective scalar quantity $\Psi(t)$, defined schematically as

$$\Psi(t) \equiv \int_{-\infty}^{t} \chi(t-t')\, \dot{H}(t')\, dt'. \tag{2}$$

The Ψ term thus represents an accumulated geometric response to the integrated expansion history, rather than a fundamental energy density or a dynamical scalar field.

In the phenomenological implementation developed in previous work Klimov [2025b], the leading-order effect of this response manifests as a deformation of the late-time Hubble flow parameterized by a single constant ε_0. From the present perspective, ε_0 acquires a clear physical meaning as the low-frequency limit of the response function,

$$\varepsilon_0 \;\propto\; \lim_{\omega \to 0} \chi(\omega), \tag{3}$$

where $\chi(\omega)$ denotes the Fourier transform of the response kernel. The ΛCDM model is recovered in the instantaneous-response limit $\chi(\omega) \to 0$, corresponding to vanishing susceptibility.

2.4 Relation to effective Friedmann dynamics

The response-field contribution Ψ enters the cosmological dynamics through an effective modification of the background expansion equations,

$$H^2 = \frac{8\pi G}{3}\rho + \Psi, \tag{4}$$

where Ψ should be interpreted as a geometric response term rather than an independent source of stress–energy. This formulation preserves general covariance at the level of the field equations while allowing for history-dependent behavior in the background evolution.

Crucially, Ψ does not correspond to a conserved energy component and does not require the introduction of an equation of state or sound speed. Its role is purely to encode the macroscopic adjustment of spacetime geometry to the expansion history. As a result, the framework avoids the instabilities and fine-tuning issues commonly associated with dynamical dark energy models Planck Collaboration [2020].

2.5 Conceptual status of the response description

The response-field interpretation presented here is intended as an effective macroscopic description, analogous to constitutive relations in continuum physics. No assumptions are made regarding the microscopic origin of the response kernel χ, which may ultimately be related to coarse-grained gravitational degrees of freedom or emergent properties of spacetime.

At this level, the Psi–Continuum framework should be viewed as an effective theory of cosmic expansion, valid at late times and large scales. Its minimal parameterization reflects the leading-order response of spacetime geometry and provides a physically transparent reinterpretation of cosmic acceleration as a memory-driven phenomenon rather than a fundamental energy source.

3 Geometric formulation of the response term

3.1 Response contribution as a geometric modification

In order to consistently interpret the Ψ term as a macroscopic response rather than an additional energy component, it is essential to formulate its role directly at the level of spacetime geometry. In the standard formulation of general relativity, the Einstein equations relate the curvature of spacetime to the stress–energy content via

$$G_{\mu\nu} = 8\pi G\, T_{\mu\nu}, \tag{5}$$

where $G_{\mu\nu}$ is the Einstein tensor and $T_{\mu\nu}$ denotes the energy–momentum tensor of matter and radiation. Within the ΛCDM model, the cosmological constant enters as a purely geometric term proportional to the metric,

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\, T_{\mu\nu}, \tag{6}$$

effectively shifting the vacuum curvature without introducing additional dynamical degrees of freedom Planck Collaboration [2020].

The response-field interpretation of the Ψ term follows a closely related geometric logic. Rather than attributing Ψ to a conserved stress–energy tensor, we treat it as an effective, history-dependent contribution to the curvature sector,

$$G_{\mu\nu} + \Psi\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu}, \tag{7}$$

where Ψ is a scalar functional of the expansion history, as defined in Section 2. Importantly, Ψ is not constant and does not represent vacuum energy; instead, it encodes a macroscopic geometric response of spacetime to its prior evolution.

3.2 Covariance and consistency

At the level of homogeneous and isotropic cosmology, the modification (7) leads directly to the effective Friedmann equation

$$H^2 = \frac{8\pi G}{3}\rho + \Psi, \tag{8}$$

used throughout the phenomenological analysis of the Psi–Continuum framework. Because the response term is proportional to the metric, general covariance is preserved explicitly, and no preferred frame or direction is introduced.

The time dependence of Ψ reflects the nonlocal-in-time nature of the response, rather than a violation of diffeomorphism invariance. In particular, the framework does not alter the local geometric structure of spacetime or the propagation of matter and radiation. In this sense, the Psi–Continuum framework remains fully compatible with the geometric principles of general relativity, while extending the standard description to include memory effects at the level of background expansion.

Because Ψ is treated as an effective geometric contribution at the level of background cosmology, its time dependence does not imply a violation of the contracted Bianchi identities, which continue to hold for the full geometric sector.

3.3 Distinction from effective stress–energy sources

Although Eq. (7) is formally similar to introducing an effective vacuum stress–energy tensor, the physical interpretation is fundamentally different. The Ψ term does not correspond to a locally conserved energy–momentum tensor and therefore does not admit an equation of state, sound speed, or perturbative clustering properties.

This distinction is crucial. Interpreting Ψ as a geometric response avoids the conceptual difficulties commonly associated with dark energy fluids or scalar-field models, such as fine-tuned potentials, dynamical instabilities, or violations of causality Planck Collaboration [2020]. The response term modifies only the homogeneous background evolution, while leaving the local dynamics of matter and radiation unaffected.

3.4 Relation to curvature and expansion history

From a geometric standpoint, the response interpretation suggests that the spacetime curvature at a given epoch depends not only on the instantaneous matter content but also on the integrated history of the expansion rate. This perspective departs from the strictly local-in-time character of the classical Friedmann equations and introduces a controlled form of temporal nonlocality, encoded entirely in the scalar quantity Ψ.

In this sense, Ψ may be viewed as a measure of accumulated geometric response associated with the cosmic expansion. The late-time acceleration then arises naturally as the relaxation of this strain, rather than as the effect of a new energy source. The smallness of the deformation parameter ε_0 reflects the weakness of the response, consistent with the near-equilibrium nature of the late-time Universe.

3.5 Geometric limit and recovery of ΛCDM

In the limit of instantaneous response, the memory kernel introduced in Section 2 collapses to a delta function, and the response term Ψ vanishes identically. In this case, the standard ΛCDM framework is recovered, with cosmic acceleration attributed entirely to a constant geometric offset.

The Psi–Continuum framework thus embeds ΛCDM as a special limiting case within a broader geometric description, in which cosmic acceleration reflects the macroscopic response properties of spacetime rather than the presence of a fundamental vacuum energy density.

4 Memory, causality, and the origin of delayed expansion

4.1 Causality and temporal nonlocality

The introduction of a history-dependent response naturally raises questions concerning causality and locality. In particular, any modification of the cosmological expansion that depends on past evolution must be shown to respect the causal structure of spacetime and avoid acausal propagation of information.

In the Psi–Continuum framework, causality is preserved by construction. The response kernel $\chi(t - t')$ introduced in Section 2 is assumed to be causal, vanishing identically for $t' > t$. As a result, the response term $\Psi(t)$ depends only on the past expansion history and does not anticipate future dynamics. This form of temporal nonlocality is therefore fully consistent with the causal ordering of events in general relativity.

Temporal nonlocality of this kind is a familiar feature of effective macroscopic descriptions. In continuum physics and non-equilibrium statistical mechanics, memory effects arise naturally when microscopic relaxation times are coarse-grained over, leading to constitutive relations that depend on the integrated history of the system Onsager [1931]. The Psi–Continuum framework adopts an analogous viewpoint at cosmological scales.

4.2 Memory effects in geometric evolution

From a geometric perspective, the expansion of the Universe represents a large-scale deformation of spacetime. If spacetime is treated as an effective medium, it is natural to expect that such deformation may not relax instantaneously. Instead, residual geometric strain can accumulate and relax over cosmological timescales.

In this interpretation, the Ψ term quantifies the memory of past expansion encoded in the geometry itself. The observed late-time acceleration then corresponds to a relaxation process, in which spacetime responds to earlier periods of more rapid expansion. The delayed onset of acceleration emerges as a direct consequence of this memory, without the need to invoke new energy sources.

4.3 Origin of the delayed response

The physical origin of the delayed response can be understood at an effective level without specifying a microscopic model. The rapid expansion of the early Universe, followed by a long quasi-equilibrium matter-dominated era, provides a natural setting for the accumulation of geometric memory. As the expansion rate slows, the response of spacetime geometry lags behind, leading to an effective enhancement of the late-time expansion rate.

This picture is consistent with the small magnitude of the deformation parameter ε_0, which indicates that the response is weak and that spacetime remains close to equilibrium throughout most of cosmic history. The late-time acceleration thus reflects a cumulative effect rather than a sudden dynamical transition.

4.4 Absence of superluminal effects

A crucial consequence of the response interpretation is that no superluminal signal propagation is introduced. The response term Ψ modifies only the homogeneous background evolution and does not correspond to a propagating field with an associated characteristic speed. As a result, local physics, including the propagation of light and gravitational waves, remains governed by the standard causal structure of general relativity Planck Collaboration [2020].

This distinguishes the Psi–Continuum framework from models in which dark energy perturbations or modified gravity effects can introduce superluminal modes or instabilities. In the present framework, all response effects are encoded in the background geometry and manifest only on cosmological timescales.

4.5 History-dependent geometric response as an emergent phenomenon

Taken together, these considerations suggest that cosmic acceleration may be understood as an emergent, memory-driven phenomenon. Rather than signaling the presence of a fundamental energy component, the late-time acceleration reflects the macroscopic response of spacetime to its own expansion history.

This interpretation provides a unified explanation for both the timing and the magnitude of the observed acceleration, while remaining fully compatible with the causal and geometric foundations of general relativity. In this sense, the Psi–Continuum framework offers a minimal and physically transparent extension of the standard cosmological model.

5 Phenomenological implications

5.1 Implications for the H_0 tension

One of the most persistent anomalies in contemporary cosmology is the tension between early-time and late-time measurements of the Hubble parameter Planck Collaboration [2020]. While cosmic microwave background observations constrain H_0 through an integrated history of expansion, local distance ladder measurements probe the expansion rate in the recent Universe. Within the standard ΛCDM framework, these two determinations are expected to agree.

In the Psi–Continuum framework, this expectation is relaxed. Because the observed expansion rate includes a response contribution that depends on the recent expansion history, locally inferred values of H_0 are naturally sensitive to the delayed geometric response encoded in Ψ. As a result, late-time measurements effectively probe

$$H_{\rm local} = H_{\rm bare} + \delta H_{\Psi}, \tag{9}$$

while early-time probes remain primarily sensitive to the bare expansion history.

This separation provides a plausible qualitative explanation for the observed H_0 tension, without invoking additional relativistic species, early dark energy, or modifications of recombination physics. In this interpretation, the tension emerges as a manifestation of geometric memory rather than as evidence for new fundamental components.

5.2 Effective equation of state

Although the Ψ term does not correspond to a physical energy component, it is often convenient to characterize its impact in terms of an effective equation-of-state parameter $w_{\rm eff}(z)$. In the response interpretation, this quantity should be regarded as a diagnostic tool rather than a fundamental property.

Because Ψ arises from a delayed geometric response rather than a dynamical fluid, $w_{\text{eff}}(z)$ is expected to remain close to -1 at late times, with only mild redshift dependence. In particular, the framework does not predict phantom behavior or rapid evolution of the effective equation of state. This behavior is consistent with current observational constraints, which favor models close to ΛCDM while allowing small deviations at low redshift Planck Collaboration [2020].

5.3 Absence of clustering and perturbative effects

A distinctive feature of the Psi–Continuum framework is the absence of perturbative degrees of freedom associated with the response term. Since Ψ does not correspond to a propagating field or a stress–energy component, it does not cluster and does not contribute to density or velocity perturbations.

Consequently, the growth of large-scale structure proceeds as in standard general relativity, with matter and radiation perturbations evolving under the usual gravitational dynamics Alam et al. [2017]. This property ensures compatibility with large-scale structure observations and avoids the instabilities and scale-dependent effects that often arise in models with dynamical dark energy or modified gravity.

5.4 Predictions for future observations

The response-field interpretation leads to several qualitative predictions that can be tested with future precision cosmological data. These include:

- a smooth, percent-level deviation from ΛCDM in the late-time expansion history, without sharp transitions or oscillatory behavior;
- mild redshift dependence in reconstructed expansion parameters at $z \lesssim 1$, consistent with a memory-driven response;
- consistency between background expansion probes, accompanied by a systematic offset between early- and late-time determinations of the Hubble parameter;
- absence of scale-dependent modifications in structure growth or gravitational wave propagation.

Upcoming surveys such as DESI, *Euclid*, and the *Roman Space Telescope* will significantly improve constraints on the late-time expansion history and provide a sensitive test of the response-based interpretation of cosmic acceleration DESI Collaboration [2024].

5.5 Observational status

At present, the Psi–Continuum framework remains fully consistent with existing background expansion data, while offering a coherent physical interpretation of small deviations from the standard cosmological model. The phenomenological viability established in earlier analyses Klimov [2025b] serves as a motivation for further exploration of the response-field perspective, rather than as a claim of definitive observational preference.

A concrete and falsifiable observational signature of the response-based interpretation is summarized in Appendix B.

6 Discussion and relation to other approaches

The response-field interpretation of cosmic acceleration presented in this work occupies a distinct conceptual position within the landscape of contemporary cosmological models. Rather than introducing new fundamental components or modifying the dynamical laws of gravity, the Psi–Continuum framework reinterprets late-time acceleration as an emergent macroscopic property of spacetime geometry.

6.1 Comparison with dynamical dark energy

Models of dynamical dark energy typically invoke scalar fields with specified potentials to generate time-dependent acceleration Gubitosi et al. [2013]. While such models offer a rich phenomenology, they introduce additional degrees of freedom, require fine-tuned potentials, and may lead to instabilities or violations of energy conditions Planck Collaboration [2020]. By contrast, the Psi–Continuum framework does not postulate a new dynamical field or an equation of state. The response term Ψ modifies only the background expansion and does not propagate or cluster, thereby avoiding many of the theoretical challenges associated with scalar-field models.

6.2 Relation to bulk viscosity and effective fluids

Cosmological models incorporating bulk viscosity or effective imperfect fluids also generate accelerated expansion through non-equilibrium effects Brevik and Gorbunova [2005]. Although there is a superficial similarity to the response-based interpretation, the Psi–Continuum framework differs in both formulation and physical meaning. Bulk viscosity models introduce dissipative stress–energy components and entropy production at the level of matter sources, whereas the response term Ψ is geometric in nature and does not correspond to a physical fluid or dissipative process.

6.3 Backreaction and averaging approaches

The possibility that cosmic acceleration arises from backreaction effects due to inhomogeneities has been extensively studied Buchert [2000]. Such approaches typically rely on spatial averaging and the nonlinear coupling between structure formation and background expansion. In contrast, the Psi–Continuum framework operates at the level of homogeneous geometry and introduces temporal nonlocality rather than spatial averaging. The response interpretation is therefore complementary to, rather than a reformulation of, backreaction scenarios.

6.4 Modified gravity and effective field theories

Modified gravity models, including $f(R)$ theories and scalar–tensor extensions, alter the gravitational action and introduce new propagating modes. Effective field theory approaches to dark energy similarly parameterize deviations from general relativity through additional operators and fields Gubitosi et al. [2013], Deser and Woodard [2007], Planck Collaboration [2020]. The Psi–Continuum framework remains fully within the geometric structure of general relativity and does not modify the underlying field equations. Instead, it introduces an effective response term at the level of background dynamics, placing it conceptually closer to an effective macroscopic description than to a fundamental modification of gravity.

6.5 Conceptual positioning

The Psi–Continuum approach may be viewed as an effective theory of cosmic response, analogous to constitutive relations in continuum physics. It embeds ΛCDM as a limiting case corresponding to instantaneous geometric response, while allowing for weak, history-dependent corrections at late times. In this sense, the framework does not compete with existing models on a microscopic level, but offers a complementary macroscopic interpretation of cosmic acceleration grounded in geometric response and memory effects.

7 Conclusions and outlook

In this work we have presented a physical interpretation of the Psi–Continuum framework in which late-time cosmic acceleration arises as a macroscopic response of spacetime geometry to the integrated history of cosmic expansion. Building upon the phenomenological viability of the ΨCDM model, we have shown that the Ψ term can be consistently understood as a response field rather than as a new energy component or a modification of gravitational dynamics.

By formulating the response at the level of spacetime geometry, we have demonstrated that general covariance and causal structure are preserved. The introduction of temporal nonlocality through a causal memory kernel provides a natural explanation for the delayed onset of acceleration, while avoiding the conceptual and technical challenges commonly associated with dynamical dark energy, modified gravity, or additional propagating fields.

Within this perspective, the standard ΛCDM model emerges as the instantaneous-response limit of a more general geometric description. The small magnitude of the deformation parameter ε_0, constrained by current observations, reflects the near-equilibrium nature of the late-time Universe and supports the interpretation of cosmic acceleration as a weak, cumulative response effect.

The response-field framework offers a unified and economical explanation for several key features of the observed expansion history, including the smooth late-time acceleration and the qualitative origin of the H_0 tension, while remaining fully compatible with existing background and structure formation constraints. Importantly, it achieves this without introducing new dynamical degrees of freedom or invoking finely tuned energy scales.

Looking forward, the Psi–Continuum approach opens several avenues for further investigation. A more detailed characterization of the response kernel and its connection to fundamental geometric or thermodynamic principles may provide deeper insight into the origin of cosmic memory effects. Future high-precision cosmological surveys will enable increasingly sensitive tests of subtle deviations from instantaneous expansion and will allow the response-based interpretation to be further constrained or falsified.

More broadly, this work suggests that cosmic acceleration need not signal the presence of an unknown energy component, but may instead reflect an emergent property of spacetime itself. Interpreting the expansion of the Universe as a non-equilibrium geometric process with memory offers a conceptually coherent alternative perspective on one of the most profound phenomena in modern cosmology.

A Response kernel and Onsager-type formulation

A.1 Linear response framework

The response-field interpretation of the Ψ term can be naturally formulated within the general framework of linear response theory. In this approach, the macroscopic evolution of a system close to equilibrium is described by a linear relation between generalized forces and generalized fluxes, as formalized by Onsager Onsager [1931]. While the original formulation applies to thermodynamic systems, the underlying structure is sufficiently general to admit an effective geometric extension.

We consider the cosmic expansion rate $H(t)$ as a macroscopic variable describing the state of spacetime at cosmological scales. Deviations from instantaneous equilibrium are characterized by the time derivative $\dot{H}(t)$, which plays the role of a generalized driving force in the response formulation.

A.2 Geometric response relation

Within this framework, the response of spacetime geometry may be written in the form

$$\delta H(t) = \int_{-\infty}^{t} \chi(t - t')\, \dot{H}(t')\, dt', \tag{10}$$

where $\chi(t - t')$ is a causal response kernel encoding the relaxation properties of the effective geometric degrees of freedom. This expression represents a direct generalization of Onsager-type linear response relations to the cosmological expansion.

Causality requires $\chi(\tau) = 0$ for $\tau < 0$, ensuring that the response at time t depends only on the past evolution of the system. The specific form of χ is not fixed by the formalism and reflects effective macroscopic properties of spacetime rather than microscopic dynamics.

A.3 Low-frequency limit and effective susceptibility

The phenomenological parameter ε_0 introduced in the Psi–Continuum model corresponds to the low-frequency limit of the response function. Taking the Fourier transform of Eq. (10), one obtains

$$\delta H(\omega) = i\omega\, \chi(\omega)\, H(\omega), \tag{11}$$

where $\chi(\omega)$ denotes the frequency-dependent susceptibility associated with the geometric response.

In the limit $\omega \to 0$, the response is governed by

$$\varepsilon_0 \;\equiv\; \lim_{\omega \to 0} \chi(\omega), \tag{12}$$

which characterizes the strength of the delayed geometric response on cosmological timescales. The small observed value of ε_0 implies that spacetime responds weakly and smoothly to the expansion history, consistent with a near-equilibrium interpretation of late-time cosmic evolution.

A.4 Interpretational remarks

The Onsager-type formulation presented here should be understood as an effective macroscopic description rather than a fundamental microscopic theory. No assumption is made regarding the underlying degrees of freedom responsible for the response kernel. Instead, the formalism provides a compact and physically transparent way to encode memory effects in the geometric evolution of the Universe.

Within this viewpoint, the Psi–Continuum framework may be regarded as the leading-order term in an expansion of the geometric response around the instantaneous limit, analogous to linear constitutive relations in continuum physics. Higher-order or nonlinear response effects, while conceivable, are expected to be subdominant at late times and are beyond the scope of the present work.

B Idealized response signature at low redshift

For practical confrontation with future low-redshift expansion data, it is useful to introduce the dimensionless response signature

$$\Delta_\Psi(z) \equiv \frac{H_\Psi(z) - H_\Lambda(z)}{H_\Lambda(z)}. \tag{13}$$

Within the minimal Psi–Continuum deformation adopted as the phenomenological baseline, the modified expansion rate is

$$H_\Psi(z) = H_\Lambda(z)\left(1 + \frac{\varepsilon_0}{1+z}\right), \tag{14}$$

which yields the analytic response signature

$$\Delta_\Psi(z) = \frac{\varepsilon_0}{1+z}. \tag{15}$$

Equation (15) defines a distinctive and highly constrained low-redshift pattern: a smooth, monotonic, percent-level enhancement of $H(z)$ localized to $z \lesssim 1$. The amplitude is controlled by the single susceptibility-like parameter ε_0, while the functional form is fixed entirely by the response ansatz.

This analytic form enables a direct and falsifiable observational test of the response-based interpretation of cosmic acceleration.

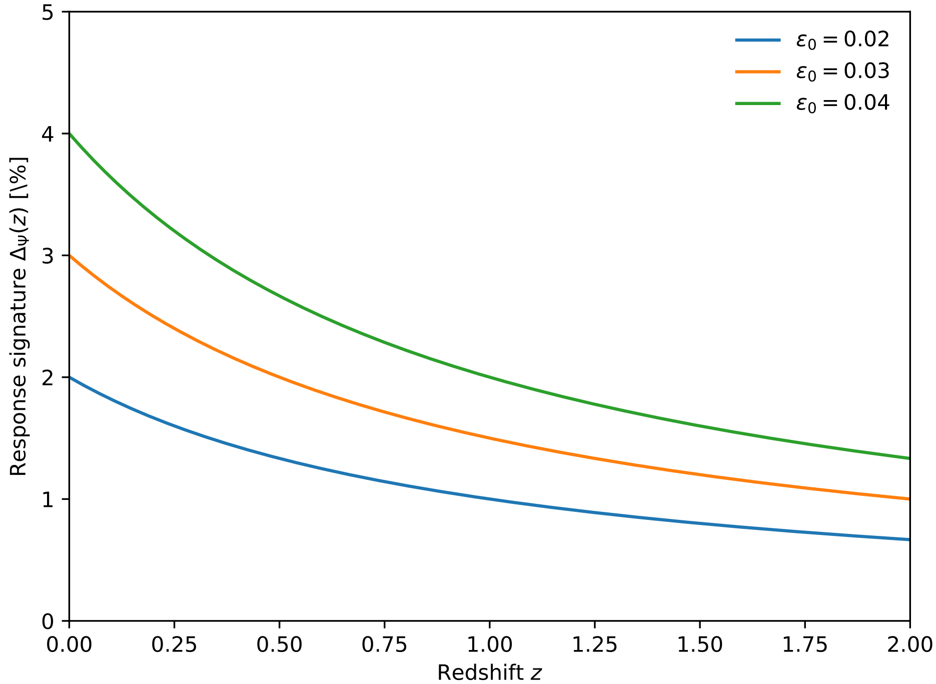

Figure 1: Idealized Psi–Continuum response signature $\Delta_\Psi(z)$ defined in Eq. (13), shown for representative values of the response parameter ε_0. The pattern is smooth and monotonic, with percent-level enhancement localized to $z \lesssim 1$ and no sharp transitions.

Ψ–Continuum prediction (response signature).
If cosmic acceleration arises from a delayed geometric response of spacetime, the late-time expansion rate must exhibit a smooth, monotonic enhancement relative to ΛCDM at low redshifts,

$$\frac{H(z)}{H_\Lambda(z)} - 1 \;\simeq\; \mathcal{O}(1\text{–}4\%) \quad \text{for} \quad z \lesssim 1,$$

with no corresponding modifications at early times, no clustering of the response term, and no scale-dependent effects in structure formation.
The absence of such a low-redshift enhancement would falsify the response-based interpretation of cosmic acceleration within the minimal Psi–Continuum framework.

Recent BAO and cosmic chronometer measurements have begun to probe the low-redshift expansion history with percent-level precision Alam et al. [2017]. Several analyses report mild preferences for slightly elevated values of $H(z)$ at $z \lesssim 1$ relative to the best-fit ΛCDM prediction, although the statistical significance remains limited.

Within the Psi–Continuum framework, such deviations are naturally interpreted as early indications of a delayed geometric response. Upcoming high-precision data will be decisive in determining whether this pattern persists or is attributable to statistical fluctuations.

Fig. 1 was generated using a Python implementation of Eq. (15).

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