The Ontological Origin of Dynamical Dark Energy:
An Untransitioned Primordial Field in Light of DESI Observations

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Abstract：The discovery of dynamical dark energy by the Dark Energy Spectroscopic Instrument (DESI) poses an existential challenge to the cosmological constant (Λ) and the standard ΛCDM model. Here, we propose a radical resolution based on the first principle of Physical Information Cosmology. We identify the dark energy in our universe as the untransitioned primordial positive energy field—a fossil remnant from a two-stage cosmic genesis that did not condense into matter. This clear ontology, with its fixed total energy and intrinsic decay ($\rho_{DE} \propto a^{-n}$), uniquely deduces the observed dynamical behavior (w > -1). Our model not only achieves qualitative consistency with DESI data but also resolves the cosmological constant problem through a causal isolation mechanism. This work transforms dark energy from a mathematical puzzle into a physical reality, charting a new path from phenomenological fitting to first-principled derivation.

Keywords: Dark Energy; Physical Information Cosmology; DESI; First Principles; Cosmological Constant Problem; Ontology

1. Introduction: The DESI Challenge and the ΛCDM Dilemma

The discovery of dynamical dark energy by the Dark Energy Spectroscopic Instrument (DESI) poses a fundamental challenge to the standard cosmological model [1-3]. For decades, the cosmological constant Λ (with equation-of-state parameter $w = -1$) has been the cornerstone of the ΛCDM paradigm. DESI's first-year data, however, provide compelling evidence for a dynamical nature of dark energy, suggesting $w > -1$ and even hinting at the "Quintom" behavior crossing $w = -1$ [1, 6]. If confirmed, this would necessitate a paradigm shift beyond ΛCDM.

In response, models such as Quintessence, Phantom, and their Quintom hybrids have been proposed [5, 7-9]. Yet, these largely engage in a parameter-exchange game: replacing the fixed Λ with new free parameters (e.g., scalar field potentials) that lack first-principles justification. This approach not only fails to address the physical essence but also struggles to balance explanatory power with complexity. More fundamentally, these models cannot answer a profound physical question: why does a component with positive energy density produce a repulsive gravitational effect? The mathematical prescription of "negative pressure" remains a black-box assumption, devoid of a clear physical mechanism.

The potential "Quintom" behavior underscores a deeper theoretical crisis. Existing constructs, often involving multiple scalar fields or complex Lagrangians (e.g., within Horndeski theory), are essentially phenomenological toolkits. They are adept at describing how the $w = -1$ crossing can be achieved mathematically but neglect the more fundamental questions of why the universe exhibits such behavior and what the single physical entity behind it is.

This impasse calls for a radical change in perspective. Here, we respond with Physical Information Cosmology (PIC), which anchors its ontology in a first-principled, two-stage cosmic genesis. In this

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framework, the dynamical dark energy in our universe is identified as the untransitioned primordial positive energy field—a fossil remnant from the second-stage transition that did not condense into matter. Within PIC, the observed dynamics ($w > -1$) are a natural corollary of the intrinsic property of this field ($\rho_{DE} \propto a^{-n}, n < 2$), requiring no ad hoc field combinations or fine-tuned couplings.

This work, therefore, represents a fundamental turn: from "fitting data with fields" to "deriving behavior from principles." We not only provide a mechanistic origin for the DESI discovery but also liberate dark energy from complex parametrizations, restoring it to a simple physical reality.

2. Dark Energy in the Physical Information Cosmology Framework

Our theory is built upon Physical Information Cosmology, which constructs the universe's architecture through a step-by-step, recursive transition mechanism starting from Physical Information as the first principle. This ontological viewpoint resonates with the frontier physics concept of "it from bit" [12, 13], providing a solid philosophical foundation. Here, we outline only the elements essential to the origin of dark energy.

2.1 The Origin of Dark Energy: The Untransitioned Primordial Energy Field

In the recursive transition model, cosmic genesis undergoes two key phase transitions:

2.1.1 Fundamental Transition & Symmetry Bifurcation

Physical Information undergoes spontaneous symmetry breaking, generating the Positive-Energy Domain and the Negative-Energy Domain. The term "bifurcation" captures the emergence of this fundamental duality from a prior unified state.

2.1.2 Second-Stage Transition & Symmetry Bifurcation

Within each energy domain, a second, partial transition occurs. This generates matter-antimatter universe pairs (U1/U2 from the Positive-Energy Domain, and U3/U4 from the Negative-Energy Domain).

The partial nature of this second-stage transition is the core of our model. Not all primordial positive energy is transformed into matter; a portion of it remains untransitioned. This retained, untransitioned primordial positive energy field constitutes the dark energy we observe in our universe (U1) (Fig. 1). Symmetrically, the untransitioned negative energy fields constitute "dark energy" in the negative-energy universes (U3, U4). Figure 2 elaborates on the dynamical details of this architecture.
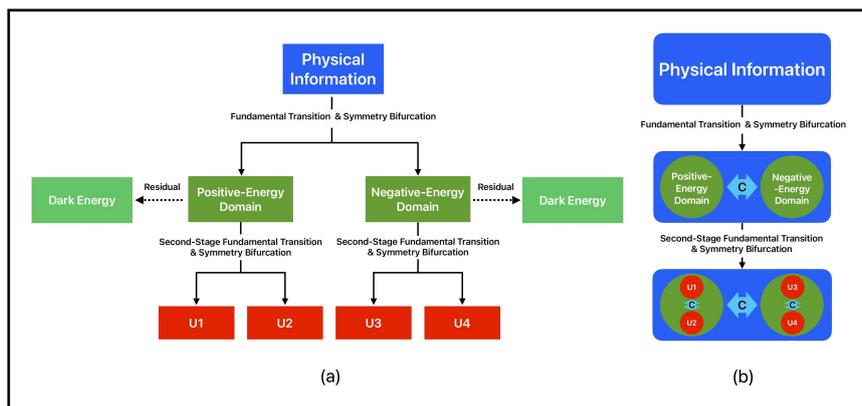
Fig. 1 The recursive transition of physical information and the origin of dark energy.
(a) Fundamental Transition & Symmetry Bifurcation. Physical Information (PI) undergoes spontaneous symmetry breaking, generating the Positive-Energy and Negative-Energy Domains. The bidirectional arrows and label "c" indicate the establishment of lightspeed (c) recession isolation at birth.
(b) Second-Stage Transition & Matter/Dark Energy Genesis. Within the Positive-Energy Domain, a partial transition generates the matter universe U1 and its antimatter counterpart U2. The energy that did not transition into matter remains as a residual field, constituting dark energy in U1. A symmetric process operates within the Negative-Energy Domain.
This figure illustrates the two-stage genesis mechanism, deriving the multiverse (U1-U4) and the ontological origin of dark energy from the first principle of Physical Information.
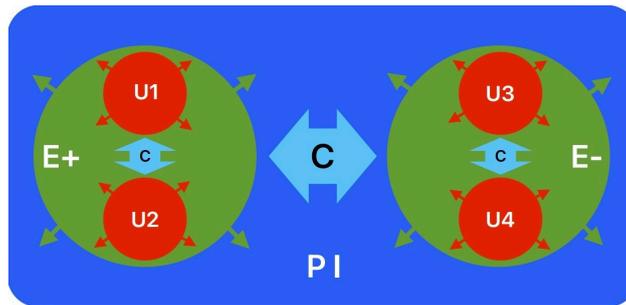

Fig. 2 Four-universe generation, dual causal isolation, and the origin of dark energy.
• **Physical information transition and energy domain generation.** The Fundamental Transition generates the Positive-Energy Domain (E+, future dark energy background for U1/U2) and Negative-Energy Domain (E-, background for U3/U4). Bidirectional arrows and "c" indicate the first layer of lightspeed recession isolation. Outward arrows indicate intrinsic expansion.
• **Matter universe generation and internal causal isolation.** Within the E+ domain, the Second-Stage Transition generates U1 and U2, establishing a second layer of lightspeed (c) recession isolation between them. The E- domain undergoes the same process.
This figure details the architecture: two-stage recursive transitions generate the four universes (U1-U4) and endow them with a stable tetrahedral configuration and causal independence through dual lightspeed recession. The untransitioned energy domains (E+, E-) constitute the physical origin of dark energy.

Therefore, dark energy is not an alien entity but a "living fossil" of the creative energy—a direct remnant of the primordial positive energy ocean from the universe's birth. Our material universe constitutes a relatively dense "local phase" immersed in this vast energy background.

2.2 The Inevitability of Dynamics: Intrinsic Expansion and Consistency with DESI

The energy density evolution of this background field, $\rho_{DE} \propto a^{-n}$, is a direct consequence of its ontology: it is an untransitioned primordial positive energy field that continues to expand intrinsically after seeding the matter universes (U1, U2). It is this intrinsic, continuous expansion that dictates the decay of its energy density.

The intrinsic index n physically quantifies the vigor of this field's expansion. For this primordial field to constitute a stable, persistent dynamical background that drives the long-term accelerated expansion of the universe, its expansion must be relatively gentle. This stability requirement directly translates into a theoretical prediction for the intrinsic index: $n < 2$.

Consequently, $n < 2$ is not a free parameter but a theoretical necessity within PIC for generating a universe with sustainable dynamics. The dynamical behavior $w > -1$ observed by DESI is the direct observational manifestation of this intrinsic requirement.

2.2.1 Fixed Energy Legacy and Intrinsic Evolution

The total energy of the Positive-Energy Domain, generated in the first-stage transition, is fixed. The fraction of this energy that did not transition into matter constitutes the fixed dark energy legacy of universe U1. Its density evolution, $\rho_{DE} \propto a^{-n}$, is therefore governed solely by the intrinsic expansion of the energy domain itself, independent of matter creation.

2.2.2 Corroboration from DESI Observations

The DESI collaboration's finding—that the dark energy equation-of-state parameter w deviates from -1 and evolves with redshift ($w > -1$)—provides qualitative and compelling support for the "slow decay" characteristic predicted by $n < 2$ [1]. DESI data strongly suggest a dark energy density that slowly dilutes with cosmic expansion, offering powerful observational evidence for our core thesis: dark energy is an expanding, untransitioned primordial energy field.

2.3 Reshaping "Repulsion": Cosmic Expansion from Energy Density Balance

The standard model attributes cosmic acceleration to a "negative pressure" (w = -1), a mathematical abstraction without a clear physical mechanism. Physical Information Cosmology reframes this phenomenon: the accelerated expansion of the universe is a thermodynamic response, wherein U1 spacetime expands to maintain a dynamic energy density balance with its decaying external energy background.

2.3.1 Core Mechanism: Thermodynamic Drive Towards Balance

The process is analogous to a balloon rising and expanding in the atmosphere (Fig. 3). The driving force is not a "repulsive force" but the system's tendency towards pressure balance and a higher entropy state.
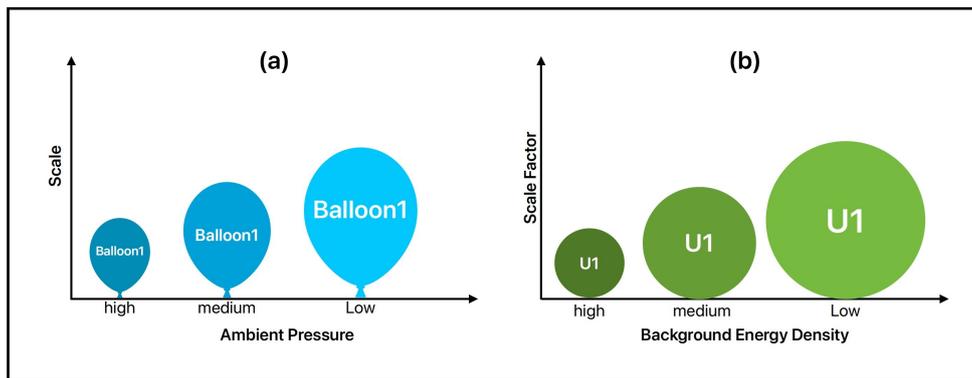

Fig. 3 Schematic of the cosmic expansion mechanism driven by energy density balance.
(a) Balloon analogy. As ambient pressure decreases (from left to right), the balloon expands to maintain pressure balance, reducing its internal pressure (color shift from dark to light blue).
(b) U1 universe mechanism. As the background energy density ρ_{bg} decreases (from left to right), the U1 universe expands, diluting its internal energy density ρ_{in} to re-establish balance (color shift from dark to light green).

This analogy reveals that cosmic acceleration is not driven by repulsion but is a spontaneous thermodynamic process: the universe expands to balance the dilution of its external dark energy background.

This analogy maps precisely onto our cosmology:
a. U1 Universe: The "balloon," with internal energy density ρ_{in}.
b. External Energy Background: The "atmosphere," with energy density $\rho_{bg}(t)$ decaying over time ($d\rho_{bg}/dt < 0$). This decay is both an observational fact (DESI) and an intrinsic property of the untransitioned primordial field.
c. Thermodynamic Drive: The system (U1 + background) evolves toward energy density homogenization, maximizing entropy.

2.3.2 The Physical Process of Expansion

The expansion is driven by a continuous feedback loop:

a. Perturbation: The external background density ρ_{bg} decays due to its intrinsic expansion ($\rho_{bg} \propto a^{-n}, n < 2$), creating a growing energy density gradient.
b. System Response: To reduce this gradient and move toward a higher-entropy state of homogenization, the U1 system must lower its internal effective energy density ρ_{in}.
c. Implementation Path: Spatial expansion is the pathway. As the scale factor $a(t)$ increases, the densities of internal components (matter, $\rho_m \propto a^{-3}$; radiation, $\rho_r \propto a^{-4}$) dilute rapidly. This rapid internal dilution is the direct manifestation of U1 spacetime "catching up" with the slow decay of the external dark energy background.

Therefore, the observed cosmic accelerated expansion is the macroscopic outcome of U1 spacetime diluting itself to chase a thinning environment in pursuit of thermodynamic balance.

2.3.3 Compatibility and Deepening of General Relativity

This mechanism does not overturn General Relativity (GR) but achieves a profound deepening from mathematical description to physical realization within its framework.

a. Fundamental Compatibility: Our theory fully respects the mathematical structure of Einstein's field equations. It provides an ontological identity for the energy-momentum source term driving acceleration—the cosmological constant Λ (mathematically a fluid with $p = -\rho c^2$)—as the untransitioned primordial positive energy field. Thus, GR accurately describes how spacetime responds to energy, while our theory answers what this energy is and why it evolves.
b. Key Deepening: This ontological clarification is pivotal. GR cannot explain why positive energy yields repulsion, merely describing the mathematical correlation. Our model reframes this as an understandable thermodynamic response to a dynamic background. Furthermore, while Λ in GR is a constant, our first-principles approach predicts the decay of its physical carrier ($\rho_{DE} \propto a^{-n}$), naturally leading to the dynamical dark energy behavior observed by DESI.

2.3.4 Consistency with the Second Law of Thermodynamics

The mechanism is deeply consistent with the second law. The expansion of U1 facilitates internal entropy increase (e.g., structure formation), while the entire system's (U1 + background) trend toward energy density homogenization is a paramount path for global entropy maximization. Consequently, the fundamental driver of cosmic acceleration is the same as for all irreversible processes: the second law of thermodynamics. This grounds cosmology within a solid, macrophysical explanatory framework.

2.3.5 Relationship with Birkhoff's Theorem

This mechanism clarifies the applicability of Birkhoff's theorem. The theorem describes gravitational behavior in a static external environment. In our model, U1 is embedded in a dynamic environment with a continuously evolving energy density ($d\rho_{bg}/dt \neq 0$). This dynamic background provides a persistent non-equilibrium thermodynamic boundary condition, driving the system's expansion. Thus, the static premise of Birkhoff's theorem is invalid here.

2.3.6 Summary of the Mechanism's Advantages

a. A Solid Physical Picture: It reduces the mysterious "repulsive force" to an intuitive, thermodynamic self-adjustment toward equilibrium.
b. Conceptual Resolution: It completely avoids the conceptual paradox of "positive energy generating repulsion."
c. Powerful Explanatory Scope: It naturally accounts for the homogeneity, isotropy, and dynamical evolution (as per DESI) of dark energy.
d. Theoretical Deepening: While compatible with GR and thermodynamics, it provides a physical ontology for their core puzzles, achieving a leap from mathematics to physics.

In summary, Physical Information Cosmology reveals that dark energy is not a "force" to be explained, but the grand thermodynamic self-balancing behavior of spacetime—a physical system responding to the dilution of its external creative energy background.

3. Resolving Classic Problems

The ontological predictions of Physical Information Cosmology for dynamical dark energy are qualitatively consistent with the latest DESI data, as shown in Fig. 4. Beyond this, the framework provides unified solutions to long-standing cosmological problems.
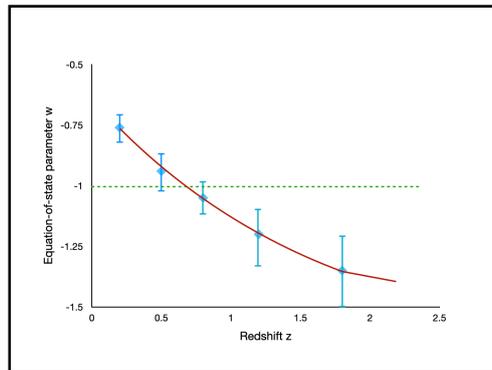

Fig. 4 Observational evidence for dynamical dark energy from DESI and the prediction of Physical Information Cosmology.
The figure shows the evolution of the dark energy equation-of-state parameter w with redshift z. The green dashed line (w = -1) represents the static dark energy of the ΛCDM model. Blue diamonds with error bars are DESI collaboration data [1]. Their strong dynamical trend is in qualitative agreement with the PIC prediction (red curve), which derives dark energy dynamics from first principles as an expanding "untransitioned primordial positive energy field".

3.1 Resolving the Cosmological Constant Problem

The cosmological constant problem—the 120-orders-of-magnitude discrepancy between the observed vacuum energy density and particle physics predictions—is resolved through a novel perspective [4].

In the first-stage transition, **c**ausal isolation via lightspeed recession is established between the positive- and negative-energy domains. The enormous vacuum energy predicted by particle physics is a global value encompassing both domains, which we cannot observe due to the causal horizon. In contrast, the measured dark energy density is a local value—the untransitioned energy within our positive-energy universe (U1). The discrepancy arises from an inappropriate comparison between a global theoretical value and a local observational one. In PIC, the chasm is naturally bridged by the causal isolation mechanism.

3.2 Explaining the "Coincidence" Problem

The apparent "coincidence" that dark energy and matter densities are comparable in the present universe is not a fine-tuning puzzle but a statistical inevitability within our model [10].

Matter density decays as $\rho_m \propto a^{-3}$. Our dark energy, as an untransitioned primordial field, decays as $\rho_{DE} \propto a^{-n}$ with $n < 2$. Consequently, their density ratio evolves as:
$$\frac{\rho_{DE}}{\rho_m} \propto a^{-(n-3)} = a^{3-n}.$$
Given the theoretical requirement $n < 2$, the evolution index $3 - n$ is constrained to be greater than 1.

a. This stands in stark contrast to the cosmological constant scenario ($n = 0$), where the ratio evolves precipitously as a^3.

b. In our case, for a representative value of $n \approx 1.5$, the ratio evolves as $a^{1.5}$. This guarantees a slow evolution of the density ratio, ensuring that ρ_{DE} and ρ_m remain within the same order of magnitude over a considerable span of cosmic history.

Therefore, the emergence of observers in this seemingly "coincidental" era is a consequence of cosmic dynamics, not fine-tuning. The model naturally produces a long epoch where the two densities are comparable.

4. Conclusion

This work, grounded in Physical Information Cosmology, provides an ontologically clear model for dynamical dark energy. It traces the cosmic inventory—dark energy and matter—back to a two-stage genesis via the Fundamental Transition & Symmetry Bifurcation, offering a mechanistic account from first principles. The model achieves three disruptive breakthroughs:

a. Physical Ontology Restored: It reduces dark energy from the abstract Λ to a tangible physical entity: the untransitioned primordial positive energy field, thereby solving the fundamental "what is it?" problem.

b. Dynamics Naturally Derived: The dynamical evolution ($w > -1$) is derived from the field's intrinsic property ($\rho_{DE} \propto a^{-n}, n < 2$), providing a first-principled explanation for the DESI observations and solving the "why is it dynamic?" problem.

c. Classical Problems Resolved: It resolves the cosmological constant problem through causal isolation and the coincidence problem through slow, power-law evolution, eliminating the need for fine-tuning.

This work, therefore, marks a paradigm shift in dark energy research: from fitting phenomena with parameters to deriving behavior from principles.

5. Future Roadmap

This theory establishes a new paradigm and yields a series of unique, falsifiable predictions, charting a clear path for future work:

a. From Qualitative to Quantitative Precision: The crucial next step is to construct a complete field theory for the Physical Information field. This will enable the first-principled calculation of the intrinsic index n and the precise trajectory of $w(z)$, moving beyond phenomenological fits to provide a definitive target for DESI, Euclid, and the Vera C. Rubin Observatory.

b. Unique Observational Imprints: As a universe permeated by a dynamic background field, U1 should exhibit distinctive signatures, such as non-standard peculiar velocity fields and characteristic ultra-large-scale anisotropies. These effects, stemming from interaction with the untransitioned energy domain, would provide decisive evidence to distinguish it from scalar-field models.

c. Theoretical Unification: The long-term goal is the quantization of the Physical Information field, seeking its fundamental integration with General Relativity and the Standard Model. This represents the path toward a complete and unified ontology.

In liberating dark energy from mathematical abstraction and restoring it to a physical entity, Physical Information Cosmology not only resolves core paradoxes but also charts a clear course for its own verification. This marks a fundamental transformation in our understanding of cosmic acceleration.

Author Contributions

Zhong WANG conceived the Physical Information Cosmology framework, developed its application to dark energy, derived all theoretical results, and wrote the manuscript.

Acknowledgments

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