

# The Ontological Origin of Dynamical Dark Energy: A Primordial Field Consistent with DESI

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## Abstract

The cosmological constant ( $\Lambda$ ) is the cornerstone of the standard  $\Lambda$ CDM model, but the Dark Energy Spectroscopic Instrument (DESI) has found evidence for dynamical dark energy that challenges this paradigm. Here, we propose a radical resolution based on the first principle of “Physical Information,” which underpins a new cosmological paradigm wherein the universe’s contents arise through recursive phase transitions. We show that dark energy is the untransitioned remnant of the primordial positive energy field—a fossil from cosmic genesis. This ontology, with its fixed total energy and intrinsic decay ( $\rho_{DE} \propto a^{-n}$ ), naturally yields dynamical behavior in which the equation of state  $w(z)$  evolves and crosses the phantom divide ( $w = -1$ ), providing a first-principled account for the quintom-like behavior reported by DESI. Moreover, it resolves the cosmological constant problem through a causal isolation mechanism rooted in the multi-sector geometry of the universe. This work transforms dark energy from a mathematical puzzle into a physical reality, charting a new path from phenomenological fitting to first-principled ontological derivation.

**Keywords:** Dark Energy; Physical Information; Cosmological Constant Problem; DESI Survey; First Principles; Ontology; Cosmological Paradigm

## 1. Introduction: The DESI Challenge and the $\Lambda$ CDM Dilemma

The discovery of dynamical dark energy by the Dark Energy Spectroscopic Instrument (DESI) challenges the cornerstone of modern cosmology: the cosmological constant  $\Lambda$  (with  $w = -1$ ) of the standard  $\Lambda$ CDM model [1-3]. DESI data provide compelling evidence for a dynamical nature, indicating that the dark energy equation of state  $w(z)$  evolves across the cosmological constant boundary ( $w = -1$ ), as seen in quintom-like behavior [1, 6], necessitating a paradigm shift.

In response, phenomenological models like Quintessence, Phantom, and Quintom hybrids have been proposed [5, 7-9]. Yet, these largely engage in a parameter-exchange game, replacing  $\Lambda$  with new free parameters that lack first-principles justification. This approach fails to address the physical essence or answer a profound question: why does positive energy density produce repulsive gravity? The “negative pressure” prescription remains a black-box assumption. This impasse highlights the limitation of prevailing approaches, which remain within the realm of parameterized dark energy or modified gravity, without addressing the ontological origin of the phenomenon.

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This theoretical impasse underscores a deeper crisis. Existing constructs are essentially phenomenological toolkits, adept at describing how  $w = -1$  can be crossed mathematically but neglecting why and what single physical entity drives it.

Here, we respond with a fundamentally different paradigm: Physical Information Cosmology (PIC). Unlike phenomenological extensions, PIC anchors its ontology in a first-principled, two-stage cosmic genesis. In this framework, dark energy is the untransitioned primordial positive energy field—a fossil remnant from creation. The observed dynamics in which  $w(z)$  evolves and crosses the cosmological constant boundary ( $w = -1$ ) are a natural corollary of its intrinsic property ( $\rho_{DE} \propto a^{-n}$ ,  $n < 2$ ), requiring no ad hoc fields or fine-tuning.

This work, therefore, represents a fundamental turn: from "fitting data with fields" to "deriving behavior from principles," restoring dark energy to a simple physical reality. Critically, PIC is not a modification of gravity but a reconstruction of cosmic ontology from the symmetry and phase transitions of physical information, offering a unified ontological ground for both dark energy and the inferred dark matter effects.

## 2. Dark Energy in the Physical Information Cosmology Framework

Physical Information Cosmology constructs the universe's architecture through a recursive transition from Physical Information as the first principle [12, 13]. Here, we outline only the elements essential to dark energy's origin.

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

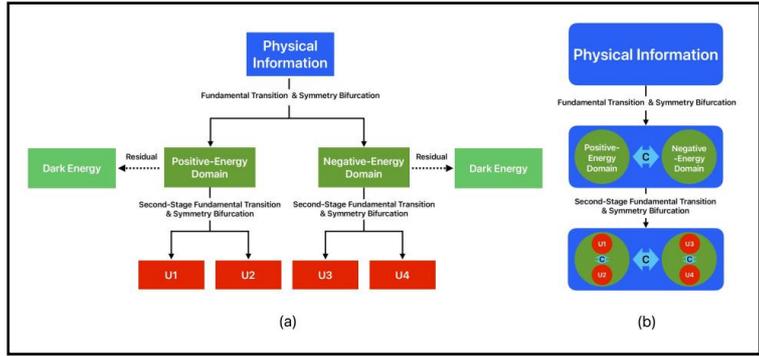
Cosmic genesis in our model undergoes two key phase transitions:

**a. Fundamental Transition & Symmetry Bifurcation:** Physical Information undergoes spontaneous symmetry breaking, generating the Positive-Energy Domain and the Negative-Energy Domain.

**b. Second-Stage Transition & Symmetry Bifurcation:** A second, partial transition within each domain generates matter-antimatter universe pairs (U1/U2 from Positive-Energy; U3/U4 from Negative-Energy).

The partial nature of this second transition is core to our model. Not all primordial positive energy transforms into matter; a portion remains untransitioned. This retained primordial positive energy field constitutes the dark energy in our universe (U1) (Fig. 1). Symmetrically, untransitioned negative energy constitutes "dark energy" in U3/U4. Fig. 2 elaborates the dynamical architecture.

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.

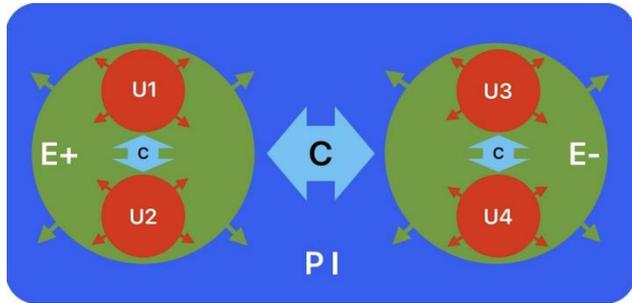


**Fig. 1 The recursive transition of physical information and the origin of dark energy.**

**(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 fig. 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 fig. 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. Our material universe is a relatively dense "local phase" immersed in this vast background.

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

The “fixed total energy” stems from the conservation of information during the first-stage symmetry breaking. The ‘intrinsic decay’ ( $n < 2$ ), characterizing a gentle expansion, is mandated by the stability criterion of the post-transition configuration: a larger  $n$  would imply overly rapid dilution, destabilizing the embedding of matter universes.

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 of  $w(z)$  evolving across the phantom divide ( $w = -1$ ), as reported 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  $w(z)$  evolves across the cosmological constant boundary ( $w = -1$ ) — provides direct qualitative support for the “slow decay” dynamics ( $n < 2$ ) inherent to our framework. 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 whose intrinsic decay naturally produces the observed quintom-like evolution. This conclusion is corroborated by the official DESI DR2 parameter constraints, which for the DESI+CMB+DESY5 combination yield  $w_0 = -0.752 \pm 0.057$  and  $w_a = -0.86_{-0.20}^{+0.23}$ , firmly favoring  $w_0 > -1$  and  $w_a < 0$  — a robust, model-dependent indicator of the described crossing behavior [1, Sec. VII].

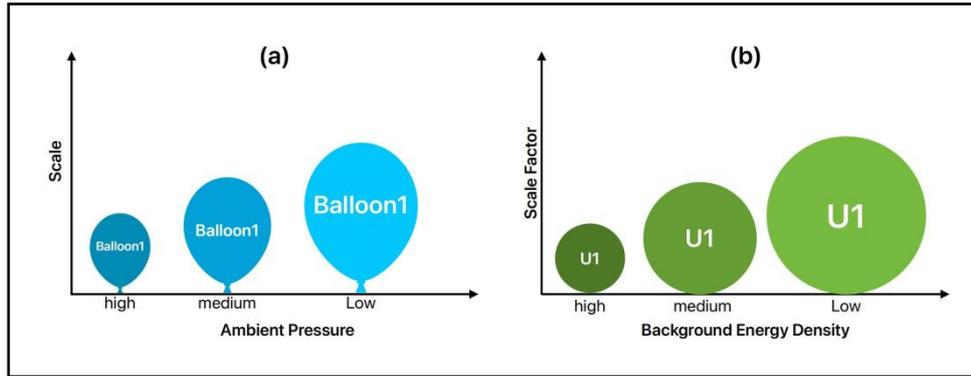
## 2.3 Reshaping "Repulsion": Cosmic Expansion from Energy Density Balance

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  $\rho_{bg}$  decreases (from left to right), the U1 universe expands, diluting its internal energy density  $\rho_{in}$  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  $\rho_{in}$ .

**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  $\rho_{bg}$  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  $\rho_{in}$ .

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  $\Lambda$  (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. Thus, GR accurately describes how spacetime responds to energy, while our theory provides the missing physical ontology for what this energy is and why it evolves, reframing cosmic acceleration as an understandable thermodynamic response to a dynamic background. Furthermore, while  $\Lambda$  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, macro-physical 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. Beyond this, the framework provides unified solutions to long-standing cosmological problems.

#### 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, causal 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 comparable densities of dark energy and matter in the present era are not a fine-tuning coincidence but a statistical inevitability in our model [10]. Matter and dark energy densities evolve as  $\rho_m \propto a^{-3}$  and  $\rho_{DE} \propto a^{-n}(n < 2)$ , respectively. Consequently, their ratio  $\frac{\rho_{DE}}{\rho_m} \propto a^{3-n}$  evolves slowly because the index  $3 - n > 1$ .

This gentle evolution starkly contrasts with the cosmological constant scenario ( $n = 0$ ), where the ratio scales as  $a^3$ . For a representative value  $n \approx 1.5$ , the ratio grows as  $a^{1.5}$ , ensuring  $\rho_{DE}$  and  $\rho_m$  remain within the same order of magnitude across a vast cosmic epoch.

Thus, the emergence of observers in this "coincidental" era is a natural consequence of cosmic dynamics, not fine-tuning.

## 4. Conclusion and Outlook

This work establishes a new paradigm for dynamical dark energy within Physical Information Cosmology. By tracing the cosmic inventory to a two-stage genesis, we provide a mechanistic account from first principles, achieving three fundamental breakthroughs:

- a. Physical Ontology Restored**, reducing dark energy from the abstract  $\Lambda$  to the tangible untransitioned primordial positive energy field.
- b. Dynamics Naturally Derived**, explaining the reported quintom-like evolution ( $w(z)$  crossing  $-1$ ) from the field's intrinsic property ( $\rho_{DE} \propto a^{-n}$ ,  $n < 2$ ), providing a first-principled physical picture for the trend indicated by DESI data.
- c. Classical Problems Resolved**, addressing the cosmological constant problem via causal isolation and the coincidence problem via slow, power-law evolution.

This marks a shift from fitting phenomena with parameters to deriving behavior from principles.

This foundation charts a clear path for future work, yielding unique, falsifiable predictions. The immediate task is a complete field theory for Physical Information to calculate the index  $n$  and the precise  $w(z)$  trajectory. Observational signatures, such as non-standard peculiar velocities and ultra-large-scale anisotropies from interaction with the energy domain, will provide decisive tests against scalar-field models. The long-term goal of unifying this framework with General Relativity and the Standard Model through quantization points toward a complete and unified ontology.

Thus, by restoring dark energy to a physical entity, this work not only resolves core paradoxes but also initiates a verifiable and expansive research programme, transforming 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.

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