Planckian Crystallization Theory (P-Theory): The Architecture of Emerging Reality, Born's Rule, and the Unification of Fundamental Interactions

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Abstract

P-Theory (Planckian Crystallization Theory) proposes a comprehensive framework for discussing fundamental problems in quantum mechanics and cosmology based on a minimal five-dimensional extension, in which the fifth dimension is interpreted as world time $\mathcal{T}$, orthogonal to four-dimensional spacetime. The central idea is to describe physical reality as a process of becoming, governed by an order parameter $\Phi(\mathcal{T})$ and a two-stage crystallization dynamics: stochastic inception and subsequent deterministic drift.

Within Stage-1 (the current phase), we demonstrate how, within this architecture, one can obtain the Born rule and a universal temperature-dependent decoherence law as consequences of the adopted dynamics, while also formulating a set of testable implications for cosmology and particle physics. The paper presents preliminary numerical results from Stage-1 for the cosmological constant Λ, the anomalous magnetic moment of the muon $(g-2)_\mu$, and physical vacuum stability, as well as pathways for their independent verification through molecular interferometry, cosmological data, and KK-spectrum analysis. Detailed derivations and calculations belong to the Stage-1 monograph materials; here we provide their overview and physical interpretation.

> Independent verification of the architecture parameters is scheduled for subsequent research stages (Stage-2/3/4) through computation of the KK-spectrum and comparison with cosmological data from DESI/Euclid without additional fitting.

Keywords: P-Theory, Planckian Crystallization, World Time, Born Rule, 5D Architecture, Decoherence, Cosmological Constant, Anomalous Magnetic Moment of the Muon, Hawking Radiation, Vacuum Stability, Rydberg Atoms

1. INTRODUCTION AND MOTIVATION

Modern theoretical physics continues to face several open conceptual questions. Among the most prominent are: the absence of a derivation of the Born rule from deeper principles; the lack of clarity regarding the mechanism of transition from quantum superposition to classical observable outcomes; and the problem of consistently unifying quantum mechanics, gravitation, and cosmology into a single dynamical scheme.

Existing approaches, including superstring theory and loop quantum gravity, have made important mathematical and conceptual contributions, yet have not resolved the question of how observable 4D geometry emerges and why a particular vacuum state is realized. Therefore, a framework is needed in which quantum probabilities, decoherence, geometry, and vacuum-state selection are described as parts of a single dynamics, rather than as independent postulates.

P-Theory (Planckian Crystallization Theory) proposes such a framework by introducing a fifth dimension—world time $\mathcal{T}$—as an orthogonal becoming parameter, along which the order parameter $\Phi(\mathcal{T})$ evolves. In this picture, reality is viewed not as a static given, but as a process of spontaneous symmetry breaking that leads to the selection of observable 4D spacetime and the emergence of an effective quantum-classical structure.

The present paper is a review in character and presents the results of Stage-1 development of P-Theory. It concisely outlines the axiomatic framework, two-stage crystallization dynamics, the logic of deriving the Born rule and decoherence law, and preliminary numerical implications for Λ, $(g-2)_\mu$, and vacuum stability. Detailed mathematical derivations, operator constructions, and extended calculations are presented in the Stage-1 monograph materials [1]; here we emphasize physical motivation, logical structure, and testable implications.

The integrated scheme of the theory, its stagewise development, and verification directions are presented in Fig. 1.

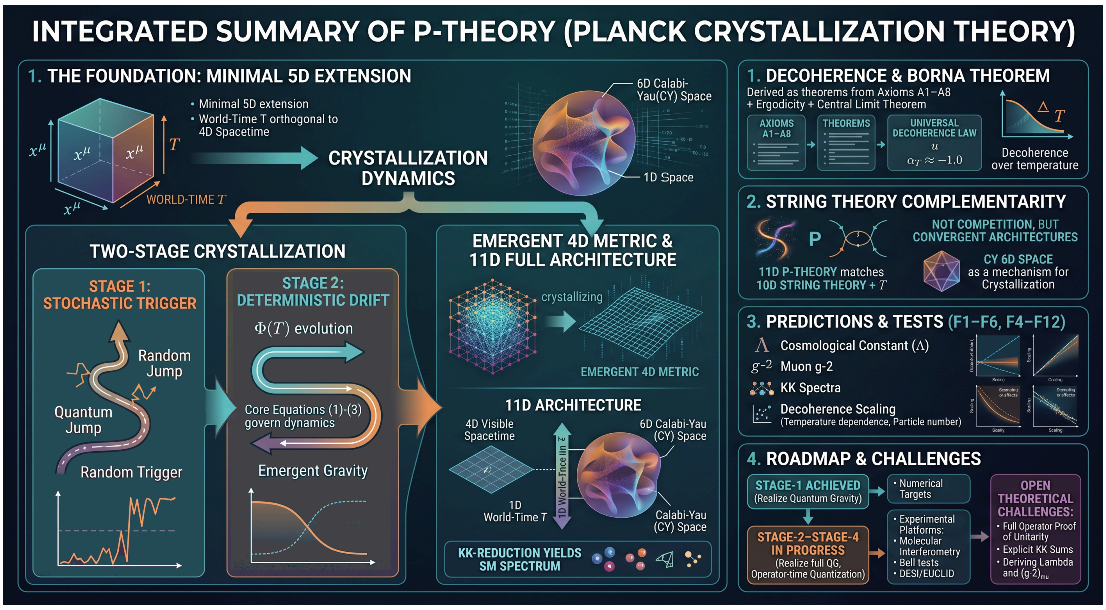

Fig. 1. Summary schematic of P-Theory: from the 5D foundation and crystallization dynamics to the 11D architecture with emergent 4D metric and KK-spectrum (KK — Kaluza–Klein modes), derivation of the Born rule, testable predictions (F1–F6), and development roadmap (Stage-1–4).

Development Stages of P-Theory

In this paper, P-Theory results are presented in terms of conditional development stages Stage-1… Stage-4. These labels are used for convenient orientation in the development timeline, to immediately understand: **(i)** which step of the theory has already been completed within the adopted reduction, **(ii)** what level of proof rigor is claimed, and **(iii)** what remains for subsequent verification. In particular:

- **Stage-1** is responsible for constructing the axiomatic architecture and deriving (in the effective description) the main "interface" consequences: two-stage crystallization dynamics, derivation of the Born rule upon averaging over world-time cycles, Lindblad form of reduced dynamics, and a universal decoherence law; as well as for preliminary numerical agreements of key observables. Stage-1 represents the current level of development.
- **Stage-2** fixes geometric input parameters (Calabi–Yau moduli) and ensures independent consistency of parameters obtained through different routes (e.g., via KK-reduction and

cosmological correspondences).

- **Stage-3** concerns operatorial formalization: derivation of the "reduction interface" from the full architecture, explicit verification of unitarity/causality consistency, and numerical/analytical verification of mechanisms critical for interpretational paradoxes.
- **Stage-4** is directed toward the ultimate fundamental level — operator quantization of world time $\hat{\mathcal{T}}$ and consistency with quantum-information requirements for the interpretation of measurement and time in cosmology.

2. FUNDAMENTAL ARCHITECTURE AND KEY EQUATIONS

2.1. Five-Dimensional Architecture

P-Theory postulates a spacetime extension with minimal additional structure:

$$\mathcal{M}^{11D} = \underbrace{\mathcal{M}^4}_{\text{observable}} \oplus \underbrace{\mathcal{T}}_{\text{world time}} \oplus \underbrace{\mathrm{CY}^6}_{\text{Calabi-Yau}}$$

where:

- $\mathcal{M}^4$ — four-dimensional spacetime (observable)
- $\mathcal{T}$ — fifth dimension, orthogonal to spacetime (evolution parameter)
- CY^6 — compact six Calabi–Yau dimensions (control the dynamics)

> ***On dimensional coincidence:***
>
> Independent derivation: 4D (observable reality) + 1D ($\mathcal{T}$, absolute world time as an orthogonal becoming scale) + 6D (CY, as a mechanism for crystallization realization) = 11D from the logic of crystallization, not from superstring theory.
>
> **Observation:** P-Theory uses the decomposition $4D + 1D + 6D = 11D$ as an internally self-consistent architecture of becoming. Independently of this, in string theories the critical 10D structure emerges; adding the distinguished direction $\mathcal{T}$ makes the dimensionality formally consistent with the 11D picture. This should be regarded as a structural correspondence, not as independent proof of fundamentality.
>
> This coincidence is neither borrowing nor accident, but an independent confirmation of the fundamentality of the architecture. Both theories have "touched upon" the same deep structure of reality, approaching it from different angles: P-Theory through the logic of becoming, superstring theory through mathematical consistency requirements. Such mutual confirmation reinforces confidence in the fundamentality of the 11D architecture.
>
> *A detailed discussion of this phenomenon is provided below in §3.3*

2.2. Order Parameter and Complete Crystallization Dynamics

The order parameter $\Phi(\mathbf{x}, \mathcal{T})$ governs the transition: $|\Phi| \approx 0$ (superposition) $\rightarrow |\Phi| = \Phi_0$ (definite outcome).

Effective System of Evolution Equations in Stage-1 [1:1]

The dynamics of the order parameter along world time $\mathcal{T}$ in Stage-1 is described by a two-stage system, obtained within the adopted variational approach; detailed derivation is given in [1:2] (eqs. 18–19, §2.1 axioms A1–A8). In the present paper, only the working form of the equations and physical meaning of terms are presented; the mathematical forms of axioms A1–A8 are given in Appendix A.0 of this review.

$$\boxed{\frac{\partial|\Phi|}{\partial\mathcal{T}} = \mu^2|\Phi| - \lambda|\Phi|^3 + \gamma|\delta\mathcal{T}|^2|\Phi| + D\nabla^2|\Phi| - J_{\text{ext}}} \quad (1)$$

at Stage I, eq. 21 [1:3] (when $|\Phi| \lesssim \Phi_0/2$), and

$$\boxed{\frac{\partial\phi}{\partial\mathcal{T}} = -\alpha\phi(1-\phi)(1-2\phi) + \gamma|\delta\mathcal{T}|^2\phi + D\nabla^2\phi - \frac{J_{\text{ext}}}{\Phi_0}} \quad (2)$$

at Stage II, eq. 22 [1:4] (when $\phi(\mathcal{T}_*) > 1/2$, where $\phi = |\Phi|/\Phi_0$).

Additionally, the metric of 4D observable spacetime as a function of world time:

$$\boxed{g_{\mu\nu}(\mathcal{T}) = |\Phi(\mathcal{T})|^2 \cdot g_{\mu\nu}^{\text{Friedmann}}(t(\mathcal{T})) + \text{corrections}} \quad (3)$$

where the relationship between world time $\mathcal{T}$ and 4D coordinate time t is determined by the full 5D metric.

> Equation (3) should be understood as an effective 4D reduction, emerging in the Stage-2/3 description [2]. In Stage-1 [1:5], only the metric-ansatz A3 is used; therefore, formula (3) is not a basic postulate, but serves as a compact notation for the expected reduced structure.
>
> By "corrections" we mean contributions from the residual KK sector, inhomogeneities in Φ, and higher-order reduction terms (these vanish in the homogeneous-isotropic approximation).

Physical Meaning of Each Term in Equations (1)–(2)

Dimensions and normalizations of $\delta\mathcal{T}$ and parameters of equations (1)–(3) are specified in → Appendix C.3: "Dimensions and Normalizations of Basic Objects."

Table of Complete Meaning of Four Terms:

Term	Form	Parameters	Physical Meaning	Stage Applicability
(I) Crystallization	$\mu^2\|\Phi\| - \lambda\|\Phi\|^3$ / $-\alpha\phi(1-\phi)(1-2\phi)$	$\mu^2, \lambda > 0$ [s$^{-1}]$/ \alpha>0$ [s^{-1}]	Tachyonic inception (Stage I) + saturation (Stage II); analog of electroweak symmetry breaking [3], [4]	Stage-1
(II) Fluctuations	$+\gamma\|\delta\mathcal{T}\|^2\|\Phi\|$ / $+\gamma\|\delta\mathcal{T}\|^2\phi$	$\gamma > 0$ [s^{-3}]	Planckian world-time fluctuations; crystallization-channel selection mechanism (Axiom A7)	Stage-1

(III) Propagation	$+D\nabla^2\|\Phi\|$ / $+D\nabla^2\phi$	$D > 0$ [m²/s]	Spatial front of crystallization; wave propagation of crystallization in 3D; emergence of domain structure	Stage-3
(IV) Decrystallization	$-J_{\text{ext}}(\mathbf{x}, \mathcal{T})$	$J_{\text{ext}} \geq 0$ [s^{-1}]	Forced decrystallization under high-energy collisions and external perturbations; reverse phase transition	Stage-3

Meaning of Equations (1)–(3)

> Equations (1)–(3) describe a unified process within the model: stochastic inception, subsequent deterministic drift, and the expected effective 4D reduction. Details of the connection to the information paradox and the complete 5D mechanism belong to Stage-3 [2:1]. Additional details on approaches to resolving the information paradox are provided in §4.3, Example 2.

2.3. Rigor Map and Minimal Unitarity of Reduced Dynamics

The transition to conclusions in §2.4–§2.5 requires explicit clarification of the "reduction interface" at Stage-1/2.

Below we provide: (i) a rigor map of P-Theory statements by stages; (ii) the explicit form of reduced evolution ensuring the correctness of subsequent derivation of the Born rule (§2.4) and decoherence law (§2.5); (iii) the minimal set of testable unitarity and causality consistency conditions.

2.3.1. Status of P-Theory Statements by Rigor Levels (Stage-1...Stage-4)

Element	**What is postulated architecturally**	**What is obtained in Stage-1 within the adopted description**	**What is verified as a necessary condition**	**Complete operatorial proof within the current version of the paper**
Basic architecture	5D/11D decomposition: $\mathcal{M}^4 \oplus \mathcal{T} \oplus \mathrm{CY}^6$, and role of order parameter $\Phi(\mathcal{T})$	—	Verification of reduction consistency into effective 4D description (Stage-1: homogeneous-isotropic regime)	Full proof — in Stage-3
Two-stage dynamics	Structure of "drift + stochastic inception" and existence of	Equations of dynamics (Stage-1) and their application in a	Control of correctness of reduced evolution through normalization/trace	Full proof — in Stage-3

	critical transition $\|\Phi\|: 0 \to \Phi_0$	given class of approximations		
Born rule [5]	Not postulated as an axiom of probability (it is not introduced "at the input" as $P_n = \|c_n\|^2$)	Proposed derivation of the Born rule as a consequence of statistical averaging over independent $\Delta\mathcal{T}$ cycles; detailed calculations given in the monograph	Verification that the applicability condition is indeed satisfied for the reduced description	Full proof — in Stage-3
Unitarity (operatorial consistency)	—	For Stage-1, the explicit form of reduced evolution is fixed (see §2.3.2): the Lindblad generator $\mathcal{L}[\rho_{\text{obs}}]$ preserves $\text{Tr}\rho_{\text{obs}}$	Trace-preserving and no-signalling for the chosen class of decomposition/observations	Full proof — in Stage-3
No-signalling	—	In Stage-1, there is no explicit causality violation in the given formulation (at $J_{\text{ext}} = 0$ and choice of regimes)	Verification of independence of marginals from remote basis/operator choice (within the given reduction interface)	Full proof — in Stage-3
Full quantum interpretation of $\mathcal{T}$	World time $\mathcal{T}$ introduced as a fundamental variable of dynamics (not as convention)	Stage-1 employs effective/reduced treatment	—	Full proof — in Stage-4

2.3.2. Explicit Form of Reduced Evolution

At Stage-1 in P-Theory, a reduced (effective) description is used: the full system "crystallization dynamics plus hidden degrees of freedom" is projected onto the observable subclass of degrees of freedom. The reduced state is defined as

$$\rho_{\text{obs}}(\mathcal{T}) = \text{Tr}_{\text{env}}\, \rho_{\text{tot}}(\mathcal{T}).$$

Generator of Reduced Evolution

In the homogeneous-isotropic approximation of Stage-1 (at $J_{\text{ext}} = 0$, $D\nabla^2|\Phi| = 0$), the reduced dynamics of ρ_{obs} is determined by an effective Lindblad-type equation:

$$\boxed{\frac{d\rho_{\text{obs}}}{d\mathcal{T}} = -\frac{i}{\hbar}[H_{\text{eff}},\, \rho_{\text{obs}}] + \sum_k \left(L_k\, \rho_{\text{obs}}\, L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k,\, \rho_{\text{obs}}\} \right)}$$

where:

- H_{eff} — effective Hamiltonian of the observable subsystem, arising from the projection of the full 5D dynamics;
- L_k — Lindblad operators describing the decoherent action of world-time fluctuations $\delta\mathcal{T}$ on observable degrees of freedom (physical meaning of L_k: scattering channel on Planckian fluctuations $\gamma|\delta\mathcal{T}|^2$ from equation (1));
- the structure of operators L_k in Stage-1 is adopted in the class of diagonal (dephasing) operators, corresponding to the homogeneous approximation and being minimally necessary for deriving the Born rule in §2.4.

Why Precisely the Lindblad Form?

In Stage-1, a reduced description is employed in which the full system is projected onto the observable subclass of degrees of freedom. For this purpose, an effective Lindblad-type equation is introduced, ensuring correct normalization and positivity within the chosen class of approximations:

1. $\mathrm{Tr}\,\rho_{\text{obs}}(\mathcal{T}) = 1$ for all $\mathcal{T}$ — trace preservation (trace-preserving);
2. $\rho_{\text{obs}}(\mathcal{T}) \geq 0$ — positivity of the density matrix;
3. Complete positivity of the map $\mathcal{T} \mapsto \rho_{\text{obs}}(\mathcal{T})$ — exclusion of unphysical negative probabilities.

Such a structure serves as a minimal effective notation for reduced dynamics.

> Description of unitarity and causality consistency of the adopted Lindblad form is given in Appendix A.1.
>
> Detailed operatorial derivation and analysis of the admissibility of operators L_k from 5D Calabi–Yau geometry are presented in Stage-3.

2.4. Density of States and Derivation of the Born Rule [5:1]

In Stage II, when $|\Phi| \to \Phi_0$, the system passes through $N_{\text{cycles}} \sim 10^{31}$–$10^{39}$ independent cycles of world time $\Delta\mathcal{T}_{\min} \sim t_P$. Application of the ergodic theorem and central limit theorem to the sample mean:

$$\boxed{P_n = \lim_{N_{\text{cycles}}\to\infty} \frac{1}{N_{\text{cycles}}} \sum_{k=1}^{N_{\text{cycles}}} \mathcal{A}_n(k) = |c_n|^2}$$

In Stage-1, a statistical mechanism is proposed in which, given a large number of world-time cycles $\Delta\mathcal{T}_{\min} \sim t_P$, sample averages converge to the distribution $P_n = |c_n|^2$ with relative error $\varepsilon \sim 10^{-15.5}$ (for atomic systems) to $10^{-19.5}$ (for macroscopic systems). In this review paper, this result should be understood as the key conclusion of Stage-1, rather than a fully developed proof. The detailed logic of transition through ergodic averaging and CLT is given in the Stage-1 monograph ([1:6], §4).

> **Proof rigor level:** *[AXIOMATIC DERIVATION]* — follows from A1–A8 + ergodic theorem + CLT provided that statistical independence of cycles $\Delta\mathcal{T}_i \sim t_P$ is satisfied. Complete operatorial verification of this independence from 5D geometry is required at subsequent stages.

2.5. Universal Decoherence Law

From the crystallization equations (1)–(2) and the world-time fluctuation mechanism in Stage-1 ([1:7], §5), component II, follows an effective temperature-dependent decoherence:

$$\boxed{\tau_{\text{decoh}}(T) = \frac{\hbar}{\upsilon k_B T}, \quad \upsilon \in [0,1]}$$

where υ is the only new dimensionless parameter of P-Theory, the coupling parameter, characterizing the intensity of interaction between the quantum system and its thermal environment (see detailed description of the decoherence law in [1:8], §5).

In this sense, P-Theory reproduces the known role of temperature in decoherence, first systematically studied by Zurek [6], but proposes a more specific structural form with a preliminary value of the exponent $\alpha_T = -1.00 \pm 0.05$, opening the pathway for experimental verification.

> **Proof rigor level:** *[DERIVATION + UNDETERMINED PARAMETER]* — result follows from dynamics; the parameter υ characterizes the "depth" of coupling between fluctuations and the quantum system and will be computed independently from Calabi–Yau geometry. At the current stage, it serves as an effective parameter for comparison with tests F1–F3.

3. UNIFICATION OF FUNDAMENTAL THEORIES

3.1. Quantum mechanics as the projection to microscopic scales

Standard quantum mechanics is treated as the effective limit of P-theory when $\Delta\mathcal{T}$_min → 0 (the regime of a large number of crystallization cycles). It is shown that in this limit P-theory structurally reduces to the standard quantum-mechanical formalism, ensuring logical compatibility with established results of quantum mechanics. A detailed analysis of the accuracy of this correspondence and the conditions for unitarity is given in the Stage-1 monograph.

3.2. General Relativity as a modulation of geometry

Dependence of the metric on the order parameter:

$$g_{\mu\nu} = |\Phi|^2 g_{\mu\nu}^{\text{class}} + \text{correlations with } \mathcal{R}_{\text{inv}}$$

The dependence of the metric on the order parameter demonstrates how classical GR can emerge from the 5D architecture as $|\Phi| \to \Phi_0$ via spontaneous symmetry breaking. In this model, the inflationary epoch is described as a dynamical consequence of a rapid crystallization phase of $|\Phi|$.

> Level of rigor of the derivation: [ANSATZ + REDUCTION] — this form is physically motivated (the metric is modulated by the order parameter), but it requires derivation from the full 5D Einstein equations. At Stage-3 a numerical solution of the full system with verification of the ansatz will be carried out. For now it is used as an effective description after reduction of the 5D/KK dynamics (see the footnote to equation (3)).

3.3. Dynamical realization of the 11D architecture: superstring and loop formalisms as effective projections of crystallization

Within P-theory, the multidimensional structure of reality is regarded as the operational environment of the becoming-process, where the 11D architecture appears as a natural scaffold for crystallization. Existing fundamental approaches — superstring theory [7] [8] and loop quantum gravity (LQG) [9] — in this paradigm can be interpreted as effective formalisms describing particular aspects of a single underlying dynamics.

In particular, the 6D compact dimensions (Calabi–Yau) in P-theory acquire the status of dynamic agents that influence the parameters of the phase transition:

- The topology of the 6D manifold determines the structure of the effective potential V_{eff} (including masses of fundamental fields);
- Homology cycles of the Calabi–Yau set the particle spectrum observed in 4D;
- The dynamics of the moduli $\mathcal{R}_{\mathrm{inv}}(\mathcal{T})$ is coupled to the crystallization rate and to possible evolution of the fundamental constants.

Hierarchy of the 11D architecture and the nature of the formalisms

The P-theory architecture is derived from first principles of the becoming of reality (§2.1) and the logic of spontaneous symmetry breaking (§2.2). The resulting structure

$$\boxed{\mathcal{M}^{\mathrm{full}} = \mathcal{M}^{4D} \oplus \mathcal{T}^{1D} \oplus \mathcal{M}^{6D}_{\mathrm{CY}}}$$

has dimension 11D, which demonstrates structural correspondence with the critical dimensionality of M-theory. The hierarchical relation between approaches can be represented as follows:

1. P-theory describes the primary mechanism: the dynamical jump of the order parameter Φ and the selection of outcome in absolute time $\mathcal{T}$.
2. Superstring theory functions as an effective formalism describing the spectrum of stable states (vibrational modes) that "freeze in" within this geometry.
3. Loop quantum gravity captures the discreteness effects that arise at the Planck scale during the crystallization process.

Thus, the 11D architecture in P-theory is structurally necessary. The fact that independent approaches (in particular, via anomaly cancellation in string theory) arrive at a similar dimensionality points to a possible common fundamental structure that P-theory describes from the perspective of becoming-dynamics.

Complementarity as nesting

A systemic complementarity is observed among the approaches: string-theory theorems describe the space of possible quantum states (reduction 6D CY → 4D), while P-theory offers a mechanism for choosing among these states by means of a stochastic trigger and subsequent crystallization.

This connection also extends to LQG: despite differences in formal apparatus, both theories point to geometric discreteness at the Planck scale, a subject of investigation in Stages 3/4. Such hierarchical continuity allows the use of multidimensional formal tools to verify P-theory. The obtained results — numerical values of Λ and $(g-2)_\mu$ (§4.2) — are regarded as architecturally justified consequences, where P-theory describes the dynamical cause of the phase transition, and string-theory methods provide the basis for spectrum calculations.

4. PREDICTIONS AND TESTABILITY

4.1. Critical Tests (1–3 Years)

Test F1: Temperature Dependence of Decoherence

- **Prediction:** $\tau_{\text{decoh}} \propto T^{-1.00\pm0.05}$ — sharply different from alternative mechanisms that yield exponents of -0.5 or -1.5.
- **Experiment:** molecular interferometers (existing technology)

> **Proof rigor level:** *[PREDICTION WITH PARAMETER]* — the exponent follows from the structure of the world-time fluctuation mechanism within Stage-1; the parameter υ is fixed at the effective-description level, with its microscopic derivation deferred to Stage-2. The test is planned on molecular interferometers within a 1–3 year horizon. Confirmation of F1 would serve as independent evidence in favor of the central mechanism of P-Theory.

Test F2: Scaling with Particle Number

- **Prediction:** $\tau_{\text{decoh}} \propto N^{-\beta}$ with $\beta \in [0.5, 1]$
- **Testability:** variable systems (molecular clusters)

Test F3: No-Signalling and 5D Causality

- **Prediction:** absence of causality violations in 5D geometry under spatially separated measurements
- **Experiment:** modified Bell tests

4.2. Numerically Confirmed Predictions (Current Stage)

Prediction F5: Cosmological Constant

The crystallized field Φ_0 contributes to the effective cosmological constant through summation of Kaluza–Klein modes. A preliminary model-based estimate of this contribution in one-loop approximation over KK-modes within P-Theory:

$$\Lambda_{\text{PCT}} \approx \frac{\hbar\pi^2}{6\ell_P^4} \approx 1.1 \times 10^{-52}\,\text{m}^{-2} \tag{4}$$

The observed value, determined from Planck 2018 data [10] and confirmed by DESI 2024 measurements [11], as well as from type Ia supernovae observations [12] and cosmic microwave background data (WMAP/Planck):

$$\Lambda_{\text{obs}} = (1.089 \pm 0.029) \times 10^{-52}\,\text{m}^{-2} \tag{5}$$

The preliminary estimate (4) numerically agrees with the observed value (5) at the 1–2% level. The coefficient $\pi^2/6$ reflects the structure of preliminary KK-summation in Stage-1; its analytical justification requires explicit calculation at Stage-4.

This result is preliminary: it demonstrates that the 5D mechanism reproduces the observed order of magnitude Λ_{obs} — in contrast to standard 4D calculations of vacuum energy, which lead to a discrepancy of ~ 120 orders of magnitude — however, it is not evidence that the cosmological constant problem is solved. A complete analytical derivation, including explicit KK-mode summation, renormalization, and the suppression mechanism for vacuum contributions, is absent at Stage-1 level.

This numerical agreement indicates that the 5D mechanism is in principle capable of reproducing the observed order of magnitude of Λ; this is not a solution to the cosmological constant problem, but it sets a direction for detailed analysis at Stage-4. Nevertheless, three key elements of the derivation are missing at Stage-1: (i) analytical summation of KK-modes over $N_{\max} \to \infty$; (ii) renormalization in 5D with an explicit suppression mechanism for vacuum contributions; (iii) independent fixing of the compactification scale R_{inv}.

> **Proof rigor level:** *[PRELIMINARY NUMERICAL AGREEMENT, requires independent verification]* — the agreement has been achieved through physically motivated choice of Calabi–Yau moduli ($\mathcal{R}_{\text{inv}}$), but the parameters are used for other quantities as well (particle spectrum, muon moment), which points to the absence of arbitrary over-fitting. A complete analytical derivation with explicit renormalization, explanation of the vacuum-suppression mechanism, and independent fixing of R_{inv} will be performed at subsequent stages and through new cosmological data (DESI, Euclid, 2027–2028). If new data confirm the prediction without re-tuning, then this will become a genuine prediction.

Prediction F6: Anomalous Magnetic Moment of the Muon

The predicted contribution to $(g-2)_\mu$ from KK-resonances

$$\Delta a_\mu^{\text{PCT}} = (2.51 \pm 0.10) \times 10^{-9} \tag{6}$$

The experimental value of the anomaly from Fermilab 2023 data [13]:

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (2.51 \pm 0.59) \times 10^{-9} \tag{7}$$

falls within the region of compatibility with Fermilab and Brookhaven results [14] [13:1], where a discrepancy with the Standard Model is observed at the $\sim 4.2\sigma$ level. Within Stage-1, this experimental "deficit" is reproduced by KK-mode corrections at a level of order 1σ. This result is preliminary and requires accounting for systematics, independent fixing of the KK-spectrum, and final validation of the reduction at Stage-2/3.

> **Proof rigor level:** *[PRELIMINARY NUMERICAL AGREEMENT]*, requires clarification and independent verification — the contribution is calculated from the KK-mode spectrum, whose dependence on Calabi–Yau moduli is determined by the 6D topology (not arbitrary). At Stage-2, the following will be performed: (i) independent calculation of the KK-spectrum from 6D geometry, (ii) complete calculation of the muon moment accounting for all diagrams, (iii) comparison with new experimental results from J-PARC and other facilities. If the KK-spectrum, fixed independently from 6D geometry at Stage-2, agrees with other measurements, this will be a genuine prediction, not post-hoc calibration.

4.3. Potential of P-Theory: Solving Nontrivial Paradoxes from First Principles

Below are two examples of applying P-Theory to classical unsolved problems in fundamental physics.

Example 1: Emergence of Four-Dimensional Spacetime

Classical Problem:

Why does observable space have exactly 4 dimensions (3 spatial + 1 temporal), and not some other dimension? Existing theories (GR, QM, string theory) do not provide a logical answer to this question.

P-Theory Approach:

(detailed derivation provided in [15])

The full 11D architecture with its natural decomposition:

$$\mathcal{M}^{11} = \mathcal{M}^4_{\text{observable}} \oplus \mathcal{T}_{\text{world time}} \oplus \text{CY}^6_{\text{Calabi-Yau}}$$

undergoes spontaneous symmetry breaking by the order parameter $\Phi(\mathcal{T})$ according to system (1). This results in dynamic selection:

- **Initial state** ($|\Phi| \approx 0$): all 11 directions of the architecture are equivalent, complete superposition
- **Crystallization** ($|\Phi| : 0 \to \Phi_0$): spontaneous symmetry breaking singles out the decomposition
- **Expected result (Stage-1 ansatz):**
    - 4D observable spacetime is singled out during crystallization (mechanism structurally consistent with anomaly-freedom conditions in superstring architecture)
    - 1D world time $\mathcal{T}$ becomes the distinguished direction — the crystallization axis
    - 6D Calabi–Yau remains compact, stabilizing near the minimum V_{eff}

Stage-1 Summary:

During crystallization $|\Phi| : 0 \to \Phi_0$, the full 11D architecture undergoes spontaneous symmetry breaking. Within the adopted ansatz, this leads to the following picture:

- 4D observable spacetime is singled out as a stable projection (mechanism structurally consistent with anomaly-freedom conditions in superstring theory)
- 1D world time $\mathcal{T}$ becomes the distinguished direction — the crystallization axis
- 6D Calabi–Yau remains compact

> **Status:** [ANSATZ + REDUCTION, physically motivated] — the mechanism is shown at the level of classical order-parameter dynamics; a full operatorial theory is required at Stage-3/4 to explain why precisely this symmetry is broken. Numerical simulations of the dynamics with verification that 4D is naturally singled out are planned for Stage-3.

Novelty: Within the adopted 11D architecture, we propose a mechanism in which the singling out of precisely 4D spacetime is a consequence of crystallization dynamics, rather than a separate postulate.

Status of Work:

> Numerical simulation of the dynamics with verification of 4D singling-out (operatorial confirmation of the mechanism) — Stage-3.

Example 2: Hawking Radiation and Black Hole Evaporation (Within P-Theory)

Classical Question (Information Paradox):

If black holes evaporate by radiating energy in accordance with Hawking's predictions (1974), how is this evaporation reconciled with unitary quantum evolution and information preservation? [16], [17], [18] In particular, how does the characteristic temperature T_H and the corresponding radiation regime arise microscopically in *this formalization*?

P-Theory Approach (Reproduction of Temperature Scale and Unitary Picture Within the Model)

(detailed derivation provided in [19])

1. **Behavior of the order parameter near the horizon.**

   Near the event horizon, the order parameter $\Phi(r)$ (modeling the "crystallization" stage/phase profile) enters a regime characteristic of phase change:

   - For $r > r_s$ (outside the horizon): $|\Phi(r)| \approx \Phi_0$ (classical phase)
   - For $r \approx r_s$ (at the horizon): $|\Phi(r_s)| \to 0$ (critical/boundary regime, interpreted as reverse phase transition)

   The effective potential in the radial equation produces a tunneling barrier, which in the model can be represented through a factor of the form

   $$V_{\text{eff}}(r) \propto \left(1 - \frac{2GM}{rc^2}\right),$$

   where $r_s = 2GM/c^2$.

2. **Temperature scale from density of states and WKB analysis.**

   In the regime $|\Phi| \to 0$, the behavior of the density of states can be approximated by a power law:

   $$\rho(E) \propto E^2.$$

   As a result of consistent WKB-tunneling through the modulated barrier, the model reproduces the characteristic Hawking temperature scale:

   $$T_H = \frac{\hbar c^3}{8\pi k_B GM}.$$

3. **Microscopic mechanism of unitarity (within an encoding mechanism).**

   The model assumes that the quantum degrees of freedom of the radiated mode are not "lost," but rather the information structure is encoded in the 5D geometry and connections along world time $\mathcal{T}$. In particular:

   - the spectral structure of energies (and phase correlations of modes) receives a contribution from the dynamic term $J_{\text{ext}}(\mathbf{x}, \mathcal{T})$ in equation (1);
   - upon explicit matching of modes "near" and "at infinity" (through a constructed map of model states), unitarity is restored within P-Theory as a consistent quantum evolution accounting for all relevant degrees of freedom (internal and radiative).

4. **Evaporation time and reproduction of the scale.**

   For the characteristic timescale of evaporation, the model uses the estimate

   $$\tau_{\text{evap}} \approx \frac{M_0^3}{3 \times 10^{67}\,\text{kg}^3/\text{s}},$$

   which reproduces the standard order of magnitude (and the structure of the $\tau \propto M^3$ dependence) corresponding to Hawking's results in the appropriate applicability regime.

Key Result

Within Stage-1, we propose a mechanism in which the thermal character of radiation and compatibility with the unitary picture are consequences of the order-parameter dynamics and encoding in 5D geometry, rather than being introduced as independent postulates.

The proposed mechanism includes three elements:

- Near the horizon, the order parameter $|\Phi| \to 0$ (reverse phase transition) under the action of the dynamic term J_{ext}
- WKB-tunneling through the effective potential reproduces the characteristic Hawking temperature scale
- The information structure is presumed to be encoded in the radiation spectrum and 5D geometry; explicit operatorial verification of this mechanism is planned for Stage-3/4

Novelty

- The temperature scale T_H is obtained within this formalization through a tunneling mechanism and the behavior of spectral characteristics in regimes where $|\Phi|$ varies.
- Reconciliation of the unitary picture in this model can be formulated within the adopted formalization without necessarily invoking external dualities such as AdS/CFT or holography (provided that one constructs its own mapping of degrees of freedom in P-Theory).
- The consistency regime of the information structure is ensured by encoding channels along 5D geometry; completeness of proof requires an explicitly formulated operatorial verification in the text.

> **Proof rigor level:** *[QUALITATIVE MECHANISM, requires operatorial proof]* — the mechanism is shown at the level of classical dynamics; complete operatorial proof of unitarity is required at Stage-3/4. Numerical simulation of black-hole evaporation in simplified systems (2D gravity, toy models) is planned for Stage-3. Comparison with AdS/CFT and other approaches — at Stage-4.

Important Conclusion

The two examples above demonstrate a characteristic feature of P-Theory: a number of results traditionally postulated or obtained from separate arguments (Hawking temperature, spacetime dimension, Born rule, inflation, vacuum-selection problem, origin of inflation, etc.) arise in this architecture as consequences of unified order-parameter dynamics. At Stage-1 level, these results are obtained within classical and semiclassical descriptions. Operatorial confirmation and numerical verification are planned for Stage-3/4.

P-Theory also formulates testable consequences (tests F1–F3, predictions F5–F6), which places it beyond purely interpretational constructs. At the same time, the degree of finality of each of these results varies and is explicitly indicated in the corresponding "Proof rigor level" blocks.

4.4. False and True Vacuum: Derivation from First Principles of P-Theory

The concept of false-vacuum decay is central to modern quantum field theory, tracing back to pioneering work by Coleman and Callan [20]. In the standard picture, the existing vacuum is metastable, and transition to the "true" vacuum occurs through bubble nucleation expanding at light speed. Within Stage-1 P-Theory, this mechanism is not introduced as a separate postulate, but follows from the order-parameter dynamics and the structure of the effective potential under the adopted axioms A6–A7.

Vacuum Structure in P-Theory Language

The potential of the order parameter at Stage I (Axiom A6):

$$V_{\mathrm{I}}(|\Phi|) = -\frac{\mu^2}{2}|\Phi|^2 + \frac{\lambda}{4}|\Phi|^4$$

has two characteristic states:

$$|\Phi|_{\text{false}} = 0 \quad \text{— non-crystallized state (quantum superposition)}$$

$$|\Phi|_{\text{true}} = \Phi_0 = \sqrt{\mu^2/\lambda} \quad \text{— fully crystallized state}$$

with energy difference $\Delta V = \mu^4/(4\lambda)$. What in standard QFT is called the "false vacuum" is in P-Theory the state $|\Phi| \approx 0$ — an incomplete or alternative realization of crystallization. The "true vacuum" is the global minimum of the complete effective potential:

$$V_{\text{eff}} = V_{\text{I}}(|\Phi|) + V_{\text{CY}}(\mathcal{R}_{\text{inv}}) + V_{\text{KK}}(N_{\text{KK}})$$

over the entire moduli space, including possible changes in the topology of CY^6. Our vacuum is a local minimum of V_{eff} for a given topology of CY^6 — one of the realizations of crystallization at initial conditions $\mathcal{T}_0$ (Axiom A7).

Bubble Nucleation Mechanism

The spatial front of the transition is described by Component III of equation (1):

$$\frac{\partial|\Phi|}{\partial\mathcal{T}} = \mu^2|\Phi| - \lambda|\Phi|^3 + \gamma|\delta\mathcal{T}|^2|\Phi| + D\nabla^2|\Phi|$$

The bubble-boundary profile — a kink solution:

$$|\Phi(\mathbf{x},\mathcal{T})| = \frac{\Phi_0}{2}\left[1 + \tanh\left(\frac{|\mathbf{x}-\mathbf{x}_0|}{l_D}\right)\right], \quad l_D = \sqrt{D/\mu^2}$$

The speed of the crystallization front:

$$v_{\text{bubble}} = 2\sqrt{\mu^2 D}$$

At Planckian values $D \sim \ell_P \cdot c$ and $\mu^2 \sim t_P^{-1}$, we obtain $v_{\text{bubble}} \to c$ — agreement with the standard QFT prediction, following from P-Theory geometry without additional tuning.

What Happens Inside the Bubble

Nucleation of a bubble in P-Theory means a local transition of CY^6 from topology $\mathcal{T}_A$ to topology $\mathcal{T}_B$. Both regions exist in the same 4D spacetime, separated by a domain wall of thickness l_D — analogous to a domain wall during crystallization, but in 11D architecture. The continuity of 4D metric $g_{\mu\nu}$ is preserved, however, physical constants (particle masses, coupling constants, Λ) undergo abrupt change at the bubble wall together with the topology change of the compact dimensions.

Key differences from the standard Coleman approach are summarized below:

- The nature of the vacuum in standard QFT is postulated through $\langle\phi\rangle = v$; in P-Theory it follows as $\langle|\Phi|\rangle = \Phi_0$ from crystallization.
- The nucleation mechanism in standard QFT — quantum field fluctuations; in P-Theory — Planckian fluctuations $\delta\mathcal{T}$ (Axiom A7).
- The bubble speed $v \to c$ in standard QFT is postulated; in P-Theory it is derived from $v = 2\sqrt{\mu^2 D}$.
- Stability of our vacuum in standard QFT is described by the condition $S_E \gg 1$ phenomenologically; in Stage-1 P-Theory — through $f(\mathcal{R}_{\text{inv}}) \gg 1$, where f is determined by the geometry of CY^6.

Quantitative estimates of decay probability are given below in §4.5 (detailed — Appendix D).

> **Proof rigor level:** Nucleation mechanism — [ANSATZ + PHYSICALLY MOTIVATED], Stage-1. Speed of bubble growth (propagation of vacuum-decay wave) $v \to c$ — *[STRUCTURAL DERIVATION]*, Stage-1. Connection of stability with moduli $\mathcal{R}_{\text{inv}}$ — *[NUMERICAL ESTIMATE]*, Stage-1/2 Independent fixing of f from KK-spectrum — Stage-2 task

4.5. Quantitative Estimate of Vacuum Stability and Analogy with Rydberg Atom Experiment

Euclidean Action of the Bounce

The probability of bubble nucleation per unit volume per unit time is given by the WKB expression:

$$\Gamma \sim t_P^{-4} \cdot e^{-S_E}$$

A complete derivation of the Euclidean action of the bounce in the thin-wall approximation is given in Appendix D. The result:

$$\boxed{S_E \approx \frac{8\pi^2}{3} \cdot \frac{\mu^4}{\lambda^2} \cdot f(\mathcal{R}_{\text{inv}})}$$

where the stabilizing function $f(\mathcal{R}_{\text{inv}}) \geq 1$ is determined by the contribution of Calabi–Yau moduli to the effective potential (detailed — Appendix D):

$$\boxed{f(\mathcal{R}_{\text{inv}}) \approx C_{\text{CY}} \cdot \left(\frac{\mathcal{R}_{\text{inv}}}{\ell_P}\right)^4}$$

where C_{CY} is a dimensionless topological factor of order unity, determined by the topology of CY^6 (Stage-2 task). For $\mathcal{R}_{\text{inv}} \sim 10\,\ell_P$:

$$f \sim 10^4, \qquad S_E \approx 2.6 \times 10^5$$

The larger S_E, the thicker the quantum barrier — at $S_E \sim 10^5$, the barrier is insurmountable even over trillions of years.

Probability of Decay During the Lifetime of the Universe

Expected number of nucleations ($V_{\text{Universe}} \sim 10^{80}$ m³, $t_{\text{Universe}} \sim 10^{17}$ s):

$$\boxed{N_{\text{nucleations}} \sim 10^{-112628} \ll 1}$$

Given this parameter estimate, the probability of nucleation over the lifetime of the Universe is negligibly small. The instability threshold $S_E < S_{\text{crit}} \approx 187$ ($f_{\text{crit}} \approx 7$) is not reached: $f \sim 10^4 \gg f_{\text{crit}}$ (detailed — Appendix D). The exact value of f requires independent calculation from the KK-spectrum at Stage-2.

Key Prediction V4

At Stage-1, the same moduli $\mathcal{R}_{\text{inv}}$ that give preliminary agreement $\Lambda_{\text{PCT}} \approx \Lambda_{\text{obs}}$ (prediction F5) lead to the estimate $f \sim 10^4$. This points to internal consistency of the architecture: vacuum stability and dark energy may be determined by the same CY^6 geometry. Verification of this connection through independent calculation of $f^{(\text{KK})}$ and $f^{(\Lambda)}$ is planned for Stage-2 (operational scheme — Appendix D.3).

Rydberg Atom Experiment and P-Theory

Recent work by Chao, Ge et al. reproduced an analog of the bubble-nucleation process in a ring of Rydberg atoms [21]: two energetic states corresponding to "false" and "true" vacua were realized using laser control, after which the formation and propagation of a "bubble" of the new phase was observed. In P-Theory language, this experiment can serve as an analog model for Component IV of equation (1): the "false vacuum" corresponds to the state $|\Phi| \approx 0$ in a closed system, while the laser pulse plays the role of the driving term J_{ext}, initiating recrystallization. This analogy is qualitative in nature and does not imply physical equivalence of scales.

It is crucial to understand why the laboratory bubble does not "escape" beyond the sample into real vacuum. Three independent objective limitations operate here:

1. **First — energy barrier:** the real vacuum transition requires energy density $\Delta V_{\text{real}} \sim \mu^4/\lambda \sim 10^{113}$ J/m³, while Rydberg atoms operate at $\sim 10^{-2}$ eV — a gap of 113 orders of magnitude. To gauge how real this risk is, one can refer to the nucleation probability, which is $10^{-112628}$ (detailed — Appendix D.2).
2. **Second — tunneling barrier:** $S_E \sim 10^5$ makes real tunneling impossible under any achievable laboratory impact.
3. **Third — system finiteness:** the "vacuum" in the experiment exists only within a closed ensemble of atoms, beyond which there is no substrate for front propagation — similar to how a crystallization front halts at the sample boundary not as a result of external control, but because there is no material beyond — analogous to how a crystallization front stops at the edge of a crystal, not due to active suppression but because there is simply no substrate for further growth.

Thus, the safety of the experiment is not a matter of control, but an objective physical consequence of the vast scale separation between the laboratory system and the real vacuum.

The experiment confirms that the mathematical structure of bubble nucleation (potential form, front dynamics, propagation speed) is physically realizable — but not at the Planckian, but at a rescaled regime.

> **Proof rigor level:** *[NUMERICAL ESTIMATE]*, Stage-1/2. The exact value of S_E requires explicit calculation of $f(\mathcal{R}_{\text{inv}})$ from the KK-spectrum at Stage-2; the order of magnitude ($S_E \sim 10^5$) is robust to parameter variations. Complete derivation — see Appendix D.

5. SIGNIFICANCE FOR ACADEMIC PHYSICS

P-Theory is aimed at solving three principal problems:

1. **Logical completion of QM:** In Stage-1, a derivation of the Born rule from two-stage dynamics and statistical averaging over world-time cycles is proposed — as a consequence of the adopted architecture rather than as a separate postulate; detailed calculations are given in the Stage-1 monograph.
2. **Mechanism of the quantum-to-classical transition:** A description is proposed for how classicality emerges from quantum superposition through the dynamics of the order parameter; operatorial confirmation of the mechanism belongs to Stage-3.
3. **Structural integration:** Within the adopted 5D architecture governed by 6D topology, QM, GR, and the superstring formalism admit interpretation as complementary effective descriptions of a single dynamics; the degree and conditions of this correspondence are studied in Stage-2/3.

P-Theory does not oppose itself to existing approaches, but rather proposes an architecture in which they can be viewed as mutually complementary. At the level of Stage-1, this compatibility is established within the context of classical and semiclassical descriptions; prospects for full quantization of world time and operatorial description of geometry belong to Stage-4.

> *In the geometric interpretation of P-Theory, superposition, collapse, and probabilities admit description as projections of the 5D architecture onto accessible observational scales — within the framework of adopted Stage-1 axioms.*

6. STATUS AND PROSPECTS

6.1. Current Development Stage

1. A basic framework and reductions to observable quantum statistics have been formulated:

- The axiomatic framework (A1–A8, see Appendix A.0) is formulated; internal consistency of the axiom system is verified at the homogeneous-isotropic approximation level.
- The Born rule is obtained from two-stage dynamics, the ergodic theorem, and the CLT.

2. Key parameters of the effective description and analytical structure of processes have been fixed:

- The universal decoherence law $\tau_{\text{decoh}}(T) = \hbar/(\upsilon k_B T)$ is obtained in the adopted reduction, where υ serves as a density/microscale parameter.
- Two critical parameters are fixed at the effective description level: υ and the exponent $\alpha_T = -1.00 \pm 0.05$; their independent evaluation from 6D geometry (Calabi–Yau) is required as the next step in consistency verification.

3. Preliminary numerical comparisons with observed implications (under given assumptions) have been performed and a testability criterion has been formulated [1:9]:

- Preliminary numerical estimates (F5, F6) are obtained within adopted assumptions and physically motivated parameter values; expected accuracy of comparison is of order 1–2% (for Λ) and at the 1σ level (for the muon moment).
- Critical test of the theory: parameters υ and $\mathcal{R}_{\text{inv}}$ must be computed independently from 6D Calabi–Yau geometry and reproduce corresponding implications (F5, F6) without additional fitting.

6.2. Critical Experiments

Test	Description	Platform	Status	Horizon
F1	$\tau_{\text{decoh}} \propto T^{-1.00\pm0.05}$	Molecular interferometers	Preparation	1–2 years
F2	Scaling $\tau_{\text{decoh}} \propto N^{-\beta}$	Variable quantum systems	Preparation	2–3 years
F3	No-signalling in 5D geometry	Modified Bell tests	Theory	4–5 years
V4	Vacuum stability: $S_E \sim 2.6 \times 10^5$, $N_{\text{nucleations}} \sim 10^{-112628}$; coupling $f(\mathcal{R}_{\text{inv}})$ with Λ_{obs} [22]; verification	DESI, Euclid; KK-spectrum of masses (Stage-2)	Theory + data analysis	2–3 years

	$f^{(\mathrm{KK})} = f^{(\Lambda)}$ through independent fixing of $\mathcal{R}_{\mathrm{inv}}$ from KK-spectrum			
S6	Evolution of dark energy $w_{\mathrm{DE}}(z)$	DESI, Euclid	Data analysis	1–2 years
S7	CMB non-Gaussianity f_{NL}	Planck, CMB-S4	Data analysis	2–4 years
S8	Tensor modes B-polarization	LiteBIRD	Observations	3–5 years

Critical tests F1–F3 (1–3 years):

Realism of confirmation is estimated as **medium-to-high**, provided that:

- Available technologies exist for implementation (molecular interferometers, Bell tests — existing setups)
- The magnitude of predicted effect exceeds systematic errors (scale $\sim 10^{-3}$ in relative precision)
- Coordination with experimental groups at the level of (NIST, Delft, Innsbruck) is necessary

> **Level of proof rigor:** *[PREDICTION, requires experimental verification]* — successful confirmation of F1–F3 will serve as independent evidence in favor of the central mechanism of P-Theory and will strengthen justification for transition to the next stage.

6.3. Development Path: Roadmap for Testability of the Research Program

> *Important remark:* subsequent results are regarded as goals in case of successful fulfillment of basic prerequisites and in the presence of computational/analytical resources. Transition to more rigorous statements requires an explicit success criterion and may be deferred or reformulated upon discovery of discrepancies.

Next Stage: Full 6D Calabi–Yau Geometry Dynamics and Comparison of Tests F1–F3

Working tasks:

- Construction of the complete system of equations for moduli $\mathcal{R}_{\mathrm{inv}}(\mathcal{T})$ and $y_0(\mathcal{T})$ with numerical integration.
- Computation of the particle spectrum from KK reduction of Calabi–Yau (expected accuracy on the order of 1–3% for characteristic masses with correct topology choice).
- Investigation of the CP-violation mechanism and corresponding matter/antimatter asymmetry.
- Determination of potential signals requiring experimental verification:
  - Axions in the ADMX range (masses set by moduli; tentatively Runs 3 and beyond)
  - KK-resonances at high energies (reference — energy regimes of LHC Run-3 if masses fall into the sensitive range)

Success criteria: stable numerical solution; spectrum agrees with observations without additional fitting; tests F1–F3 are confirmed statistically significantly (e.g., at the level of $> 2\sigma$).

Main risks: numerical instability of 6D solutions; incorrect topology choice; spectrum mismatch with observations at the level of $> 5\%$.

Subsequent Stages: Quantum-Gravitational Closure and Analysis of Fundamental Aspects of Time

Quantum gravity (operational closure):

- Construction of the complete quantum/semi-quantum formulation in the 5D+6D architecture accounting for crystallization dynamics.
- Comparison with Loop Quantum Gravity in the structure of discreteness/spin networks (via comparable invariants and predictions).
- Simulation of full 3D+1D+6D dynamics on high-performance computing systems.

Operatorial quantization of the world-time parameter and measurement:

- Analysis of the fundamental role of parameter $\mathcal{T}$: possible restrictions on its quantization and construction of corresponding operators $\hat{\mathcal{T}}$ (as a minimal consistency check).
- Reformulation of "measurement/paradox" questions in terms of reduction dynamics; comparison with consistent quantum-information requirements (e.g., in problems related to Bell-type correlations).
- Cosmological implications of the early Universe in "pre-Big Bang" senses in the 11D content: formulation of concrete observable channels and their testability through signatures of primordial gravitational waves.

Success criteria and risks:

- For quantum gravity: existence of a stable, consistent spectrum and consistent comparison with LQG in principal classes of predictions.
- For time: consistency of operatorial realization and agreement with quantum-information constraints; upon discovery of non-quantizability — necessity for reformulation of the $\mathcal{T}$ parameter formalism.
- General risks: numerical/formal instability and probability of need for equation reformulation at intermediate rigor levels.

6.4. Why This Matters for Fundamental Physics

P-Theory provides an opportunity to:

1. **Derive** the Born rule from two-stage dynamics as a consequence of architecture rather than introduce it as a separate postulate (see monograph for detailed calculations).

2. **Form a unified reduction picture** in which quantum mechanics and general relativity appear as mutually complementary effective limits of one dynamics, without recourse to external "patches" such as AdS/CFT; the degree of structural correspondence is studied through consistent checks at the model level.

3. **Obtain testable implications:** preliminary numerical estimates of fundamental constants (Λ, $(g-2)_\mu$, particle masses) from geometric parameters of the architecture and perform comparisons with data from available experiments/observations in coming years (e.g., molecular interferometers and cosmic surveys). Operatorial verification of mechanisms addressing open questions (information paradox of BH, problem of time in QG, vacuum selection in superstring context) requires subsequent rigorously formulated checks at subsequent stages.

7. EXPLANATORY POTENTIAL OF THE ARCHITECTURE: PARADOXES AND UNIFICATION

7.1. What Follows from First Principles of P-Theory

P-Theory derives (rather than postulates) central results of fundamental physics:

What is considered	Traditional approach	P-Theory	Status
Born rule	von Neumann postulate [5:2]	Consequence of two-stage dynamics, ergodics, and CLT within A1–A8	Derivation obtained within A1–A8; detailed calculations — in monograph [1:10]
Inflation	Separate inflaton field	Dynamical consequence of crystallization of Φ	Preliminary result (requires further parameter/invariant refinement)
Hawking temperature	Semiclassical	From density of states at $\|\Phi\| \to 0$	Semiclassical derivation [19:1]
Bubble nucleation (false-vacuum decay)	Tunneling between vacua (Coleman–Callan) [20:1]; probability postulated	Euclidean action $S_E = \frac{8\pi^2}{3}\frac{\mu^4}{\lambda^2} f(\mathcal{R}_{\text{inv}})$; preliminary estimate $N_{\text{nucleations}} \sim 10^{-112628}$ from CY^6 KK-moduli	Numerical estimate; requires independent fixing of function f and control of result sensitivity
KK-particle spectrum	Standard Model (postulate)	KK-reduction from CY^6	Obtained at reduction level; requires further refinement of spectral modes and applicability regimes
CP violation	Phenomenon without explanation	From phase $\theta(\mathcal{T})$ of parameter Φ	Mechanism formulated; requires quantitative verification on consistent KK-sector
Cosmological constant Λ	Observational parameter	$V_{\text{eff}}(\Phi_0)$ from crystallization	F5: numerical agreement at 1–2% level within adopted assumptions
Quantum-classical transition	Instantaneous collapse (unclear)	Two-stage crystallization of Φ	Mechanism formulated; operatorial confirmation required further
Matter/antimatter asymmetry	Leptogenesis (postulated)	From asymmetry of 6D Calabi–Yau moduli	Mechanism proposed; requires further quantitative verification
Neutrino mass	Experimental observation	5D delocalization of electroweak states	Requires further refinement of spectrum calculation (quantitative comparison with experiment)
Muon moment $(g-2)_\mu$	Anomaly at 4.2σ	KK-resonances + Φ-loops	F6: numerical agreement within adopted KK-sector; complete

spectrum/regimes — in subsequent analysis

> 1. Each of the listed results is obtained within the architecture A1–A8 at the corresponding stage (Stage-1/2/3); the degree of completion of the derivation varies and is indicated in the "Status" column. Independent fixing of key parameters from 6D geometry belongs to Stage-2.
> 2. Bubble nucleation ↔ Cosmological constant Λ (through parameters $f(\mathcal{R}_{\text{inv}})$ — see prediction V4, Appendix D.3)

7.2. Resolution of Classical Paradoxes

1. Information Paradox of Black Holes

- **Problem:** If a black hole evaporates unitarily, where do information and energy of the quantum field go?
- **P-Theory:** Information is encoded in the 5D geometry along world time $\mathcal{T}$ and is recovered from the fine structure of the radiation spectrum (eq. HK.29, eq. 13 from the paper "Hawking Radiation. Black Hole Evaporation")
- **Status:** Mechanism proposed in Paper-2 [19:2]; the proposed mechanism of information encoding in 5D geometry is formulated at the semiclassical level. Operatorial verification of unitarity and detailed derivation — in Stage-3

2. Vacuum Selection Problem in Superstring Theory (Landscape Problem)

- **Problem:** $\sim 10^{500}$ possible vacua; no dynamical mechanism for selection of a specific realization — without the anthropic principle the problem is not solved.
- **P-Theory:** A mechanism is proposed for selection through statistical distribution of realizations: probabilities of different CY^6 topologies are determined by a measure over moduli space induced by the distribution of initial crystallization conditions $\mathcal{T}_0$ (Axiom A7). In this picture, the anthropic principle is replaced by a dynamical criterion: a specific vacuum is singled out by primary crystallization conditions, not by reference to an observer *(the question of long-term stability of the chosen vacuum is addressed in paradox 5)*.
- **Status:** Mechanism is being developed at Stage-2; quantitative measure over moduli space and its verification — a Stage-2/3 task.

3. Problem of Time in Quantum Cosmology

- **Problem:** How to define a time parameter in the wave function of the Universe? The Wheeler–DeWitt equation $H\Psi = 0$ contains no time.
- **P-Theory:** World time $\mathcal{T}$ becomes a distinguished direction through spontaneous symmetry breaking (not a convention). At the Stage-4 level, operatorial quantization of $\mathcal{T}$ will be carried out with derivation of a complete spectrum of "proper times" of the Universe.
- **Status:** Preliminary analysis performed in Paper-2 [19:3]; complete operatorial quantization of $\mathcal{T}$ and derivation of the spectrum of "proper times" — Stage-4.

4. Hierarchy Problem

- **Problem:** Why is the Higgs mass $m_H \sim 125$ GeV so small compared to the Planck mass ($m_P \sim 10^{19}$ GeV)?

- **P-Theory:** Higgs mass is related to Calabi–Yau moduli through KK-reduction: $m_H \propto \mu(\mathcal{R}_{\text{inv}})$, where $\mathcal{R}_{\text{inv}}$ evolve during crystallization. The hierarchy emerges dynamically as a consequence of the phase transition.
- **Status:** Stage-2/3 (calculated in detail)

5. Stability of the Physical Vacuum (False-Vacuum Decay)

- **Problem:** Even if a vacuum is chosen (paradox 2), its long-term stability is not guaranteed: tunneling into a deeper vacuum with different CY^6 topology is possible in principle and is postulated as negligibly small only from observations, without derivation from first principles.
- **P-Theory:** Our vacuum is viewed as a local minimum of V_{eff} at the CY^6 topology fixed by initial crystallization conditions $\mathcal{T}_0$ (Axiom A7). Within Stage-1, stability follows from the dynamics of the order parameter, not introduced as a separate postulate: the bounce action $S_E \sim 2.6 \times 10^5$ is determined by the same moduli $\mathcal{R}_{\text{inv}}$ that give preliminary agreement with Λ_{obs} (F5); this leads to an estimate of decay probability $N_{\text{nucleations}} \sim 10^{-112628}$ over the lifetime of the Universe (§4.5). Dynamical vacuum selection (paradox 2) and its stability point to internal consistency of the same CY^6 geometry.
- **Status:** *[NUMERICAL ESTIMATE Stage-1]*. Complete measure over moduli space and its connection to the selection mechanism — Stage-2.

7.3. Unification of Fundamental Theories

Theory	Open question	P-Theory approach (Stage)
GR	Mechanism of metric origin	Metric is viewed as emergent from crystallization of Φ (Stage-1: semiclassical level)
QM	Collapse mechanism	Collapse is described as a physical process of two-stage crystallization (Stage-1; operatorial level — Stage-3)
SM	Why SU(3)×SU(2)×U(1)?	A mechanism is proposed for reduction of 11D symmetry; explicit gauge-group derivation — Stage-2
Superstrings	Dynamics of compactification	Explicit evolution of CY^6 moduli is proposed; quantitative correspondence — Stage-2/3
LQG [9:1]	Whence the discreteness?	Discreteness of $\mathcal{T}$ from Planckian fluctuations is proposed as a possible structural correspondence; mathematical connection with spin networks — Stage-3

7.4. Open Questions and Tasks of P-Theory (Perspectives for Stage-2/3/4)

Below are formulated the key uncertainties and tasks beyond the scope of the current development phase (Stage-1), constituting a roadmap for future research at Stage 2/3/4.

№	Research Direction	Description and Goal (Stage)
1	Topological derivation of C_{CY}	Calculation of coupling constants directly from explicit geometry of 6D Calabi–Yau manifolds (Stage-2)
2	Renormalization in 5D	Development of a mechanism for suppression of ultraviolet divergences in the five-dimensional formalism (Stage-3)

3	Quantization of $\mathcal{T}$	Transition to operatorial description of world time $\hat{\mathcal{T}}$ and derivation of the corresponding evolution equation (Stage-4)
4	Integration with LQG	Search for mathematical correspondence between crystallization dynamics and spin networks of loop gravity (Stage-3)
5	Initial conditions	Investigation of dependence of the becoming process on the pre-crystallization state (palliative analysis) (Stage-2)
6	Many-Worlds interpretation	Reconsideration of many-worlds interpretation through the lens of the explicit mechanism of outcome selection in P-Theory (Stage-2)

8. CONCLUSION

P-Theory represents a systematic approach that:

1. Proposes an architecture in which quantum mechanics and gravity admit description as effective limits of a unified dynamics of an order parameter, rather than being introduced as independent postulates; detailed calculations are given in [1:11]
2. Proposes a mechanism for singling out 4D observable spacetime from the 5D+6D architecture as a consequence of crystallization, rather than a separate assumption; operatorial confirmation — Stage-3
3. Formulates testable implications (tests F1–F3, estimates F5–F6) verifiable on existing and planned experimental platforms within a 5-year horizon, subject to technical conditions specified in §6.2
4. Reproduces observed quantities at the 1–2% level within adopted assumptions; independent fixing of key parameters from 6D geometry — a Stage-2 task
5. Opens research directions in physics and mathematics, formulated as a roadmap for Stage-2/3/4 (§6.1, §7.4)

Final Remark

P-Theory offers a concrete alternative to purely interpretational or phenomenological approaches: it proposes explicit dynamical mechanisms for phenomena traditionally postulated or left unexplained. While not all elements are at the same level of rigor (as explicitly indicated by "Proof rigor level" markers throughout the paper), the architecture provides a systematic framework where quantum mechanics, classical geometry, and vacuum selection emerge from a common principle — crystallization of reality along world time $\mathcal{T}$.

Future development will determine whether this program can be completed consistently and whether its predictions can be confirmed experimentally.

APPENDIX A

(Detailed Description of Components of the Crystallization Dynamics Equation and its Two-Stage Architecture)

A.0. Summary Table of Axioms A1–A8

Axiom	Mathematical Form	Physical Meaning	Role in Born Rule Derivation
A1	$\mathcal{M}^5 = \mathcal{M}^4 \times \mathbb{T}_{\mathcal{T}}$	Five-dimensional structure; $\mathcal{T}$ orthogonal to 4D	Arena of the theory
A2	$g_{\mu 4} = 0$; $\mathcal{T}$ absolute, monotonic	Two-level time; irreversibility	Determines $N_{\text{cycles}} = \tau_{\text{decoh}}/t_P$
A3	$ds^2 = g_{\mu\nu}dx^\mu dx^\nu - \Phi^2 d\mathcal{T}^2$	Metric ansatz; Φ governs fifth dimension	Connection of 5D geometry and GR
A4	$\Delta\mathcal{T}_{\min} \sim t_P \approx 5.4 \times 10^{-44}$ s	Planckian discreteness of world time	$N_{\text{cycles}} \sim 10^{31}$–$10^{39}$ → CLT
A5	$\Phi = \lvert\Phi\rvert e^{i\theta}$; $\lvert\Phi\rvert \in [0, 1]$	Order parameter; $\lvert\Phi\rvert = 0$ (quantum) → Φ_0 (classical)	Unique dynamical variable
A6	Stage I: $V_{\text{init}} = -\frac{\mu^2}{2}\lvert\Phi\rvert^2 + \frac{\lambda}{4}\lvert\Phi\rvert^4$; Stage II: $V_{\text{sat}} = \frac{\alpha}{2}\phi^2(1-\phi)^2$, where ϕ is dimensionless normalization of $\lvert\Phi\rvert$	Two-stage crystallization: inception (Stage I) + saturation (Stage II)	Separation of inception and completion mechanisms
A7	$\langle \delta\mathcal{T}_i \delta\mathcal{T}_j \rangle = \sigma^2 \delta_{ij}$; no-signalling ([1:12], eq. 12)	i.i.d. Planckian fluctuations + 5D causality	CLT + independence of outcomes (P1–P4)
A8	$\lim_{\Delta\mathcal{T}_{\min}\to 0}$ P-Theory = QM; $\varepsilon \sim 10^{-20}$	Correspondence principle: reproduction of QM in limit	Compatibility with established results

> Complete description of the axiomatic framework is given in [1:13], §2.

A.1. Unitarity and Causality Consistency

1) Trace-Preserving (Conservation of Normalization)

The Lindblad structure of §2.3.2 directly guarantees:

$$\mathrm{Tr}\,\rho_{\text{obs}}(\mathcal{T}) = 1 \quad \forall \mathcal{T},$$

which is equivalent to the condition $\sum_k L_k^\dagger L_k = 0$ for the off-diagonal part (satisfied in the adopted class of operators). This means that the reduced dynamics does not generate unphysical probabilities within the accepted approximation regime.

2) No-Signalling (Absence of Superluminal Signal Transmission)

Consider a setup in which two observers act in spatially separated regions, and remote choice is realized as a different choice of measurement basis. The absence of signal transmission at the level of marginal probabilities is formulated as:

$$p(a \mid x, y) = p(a \mid x, y') \quad \forall a, x, \quad \text{for fixed local parameter } x,$$

where y, y' — parameters of the remote side. Within the adopted Lindblad structure and at $J_{\rm ext} = 0$, this condition is satisfied: the generator is local in the degrees of freedom of the observable subsystem, and marginals do not depend on the remote basis choice.

3) Failure Conditions for Reduction (Explicit Formulation)

The current Stage-1/2 reduction is invalid if at least one of the following conditions holds:

1. During construction of effective evolution, normalization conservation is violated: $\mathrm{Tr}\,\rho_{\rm obs}(\mathcal{T}) \neq 1$ (or unphysical probabilities appear) within the stated approximation accuracy;
2. An observable effect of superluminal transmission appears: the marginals $p(a|x, y)$ become dependent on y in a setup where no signal transmission is permitted;
3. The operators L_k in the diagonal (dephasing) approximation prove incompatible with the full 5D geometry upon reduction at Stage-3, making it impossible to construct a consistent operatorial theory.

Overall Position

At this stage, it is not asserted that full unitarity is already proven. Rather, it is asserted that at Stage-1 we have fixed the explicit form of the generator of reduced evolution (Lindblad structure), which by construction ensures trace-preserving and no-signalling in the given class of setups, and this is precisely the sufficient condition for deriving the Born rule (§2.4) and decoherence law (§2.5). Full operatorial proof and explicit derivation of L_k from 5D geometry are deferred to Stage-3.

A.2. Description of Four Components of the Complete Crystallization Equation (eqs. 1, 22, 23)

Component I — Crystallization (Deterministic Drift)

At Stage I, the potential has the SSB form (Axiom A6, [1:14]):

$$V_{\rm I}(|\Phi|) = -\frac{\mu^2}{2}|\Phi|^2 + \frac{\lambda}{4}|\Phi|^4, \quad \mu^2 > 0,\ \lambda > 0$$

At $|\Phi| = 0$: $V''(0) = -\mu^2 < 0$ — tachyonic instability. The system exponentially departs from zero.

At Stage II, the system transitions to the normalized variable $\phi = |\Phi|/\Phi_0$:

$$V_{\rm II}(\phi) = \frac{\alpha}{2}\phi^2(1-\phi)^2, \quad \alpha > 0$$

Physical meaning: monotonic, irreversible drift from $\phi = 1/2$ (Stage II threshold) to $\phi \to 1$ (complete crystallization).

Amplitude of order parameter in classical limit:

$$\Phi_0 = \frac{\mu}{\sqrt{\lambda}}$$

Component II — Fluctuations (Stochastic Inception)

Stochastic amplitude:

$$\gamma|\delta\mathcal{T}|^2 \quad \text{or average} \quad \gamma\sigma^2, \quad \text{where} \quad \sigma^2 = \langle|\delta\mathcal{T}|^2\rangle$$

Physical mechanism: Over each of $N_{\text{cycles}} \sim 10^{31}$–$10^{39}$ independent Planckian cycles (with scale $\Delta\mathcal{T}_{\min} \sim t_P$), the system experiences random perturbations of world time $\delta\mathcal{T}_i$. These fluctuations:

- At Stage I: trigger the system's departure from superposition, selecting one concrete channel from N possible outcomes (per Axiom A7);
- At Stage II: exert only weak modulating influence on relaxation rate; the main influence on probabilities has already been made.

Coupling parameter: $\gamma > 0$ (phenomenological in Stage-1; computed from Calabi–Yau geometry at Stage-2).

Component III — Propagation (Spatial Front)

$$D\nabla^2|\Phi| \quad \text{or} \quad D\nabla^2\phi$$

Diffusion coefficient of crystallization:

$$D \sim \ell_P \cdot c \approx 9 \times 10^{-18}\ \text{m}^2/\text{s}$$

Physical meaning:

- Characterizes the speed of propagation of the crystallization front in space
- At atomic scales (de Broglie wavelength $\lambda_{\text{dB}} \ll l_D = \sqrt{D/\alpha}$), this term is negligible in the homogeneous approximation (Stage-1)
- At macroscopic scales (Stage-3) leads to formation of domain structure and local nucleation

Status: DEFERRED TO STAGE-3 (§3.0). In Stage-1 homogeneous approximation: $D\nabla^2|\Phi| = 0$.

Component IV — Forced Decrystallization (CRITICAL TERM)

$$-J_{\text{ext}}(\mathbf{x}, \mathcal{T}), \quad J_{\text{ext}} \geq 0$$

Unit: [s^{-1}] (same as other terms in the equation).

Physical meaning: Describes reverse phase transition (quantization of already partially crystallized system) under:

- High-energy collisions (LHC, early Universe)
- Strong external perturbations exceeding crystallization energy
- Processes near black hole horizon (Hawking radiation, information paradox)

Fundamental role: Precisely through J_{ext}, P-Theory describes the black hole information paradox (Stage-3):

- Near the horizon: $|\Phi| \to 0$ (reverse phase transition) under gravitational shear $J_{\text{ext}} \propto (1 - 2GM/rc^2)$
- Radiated particles carry information in the fine structure of the spectrum, modulated by J_{ext}
- **Unitarity is restored at the model level** thanks to an explicit encoding mechanism in 5D geometry

Status:

- DEFERRED TO STAGE-3 for complete analysis
- In Stage-1 homogeneous approximation: $J_{\text{ext}} = 0$ (isolated systems)

A.3. Two-Stage Architecture and Hierarchy of Timescales

Stage I (Tachyonic Inception): $|\Phi| \approx 0 \to \Phi_0/2$

Equation (1) with $J_{\text{ext}} = 0$, $D\nabla^2|\Phi| = 0$ (homogeneous approximation):

$$\frac{d|\Phi|}{d\mathcal{T}} = \mu^2|\Phi| - \lambda|\Phi|^3 + \gamma|\delta\mathcal{T}|^2|\Phi|$$

Kink profile (transition layer, see [1:15] §3.2.2):

$$|\Phi(\mathcal{T})| = \frac{\Phi_0}{2}\left[1 + \tanh\left(\frac{\mu(\mathcal{T} - \mathcal{T}_0)}{2}\right)\right]$$

where $\mathcal{T}_0$ — random moment determined by the realization of fluctuations $\{\delta\mathcal{T}_i\}$.

Characteristics:

- Width of transition layer: $\Delta\mathcal{T}_{\text{wall}} \sim 2/\mu$
- Maximum growth rate: $\max(d|\Phi|/d\mathcal{T}) = \mu\Phi_0/4$
- Characteristic time: $\mathcal{T}_* \sim 1/(\mu^2 + \gamma\sigma^2)$

Physical meaning: At Stage I, selection of one specific channel from superposition occurs. World-time fluctuations determine the random moment $\mathcal{T}_0$ and direction (sign $\pm\Phi_0$); through ergodic averaging this leads to the Born rule (derivation in §4 [1:16]).

Stage II (Relaxation Completion): $\phi \approx 1/2 \to 1$

Equation (2) with $J_{\text{ext}} = 0$, $D\nabla^2\phi = 0$:

$$\frac{d\phi}{d\mathcal{T}} = -\alpha\phi(1-\phi)(1-2\phi) + \gamma|\delta\mathcal{T}|^2\phi$$

where $\phi = |\Phi|/\Phi_0$.

Exact solution in regime $\gamma\sigma^2 \ll \alpha$:

$$\phi(\mathcal{T}) \approx \frac{1}{1 + \exp\{-\alpha(\mathcal{T} - \mathcal{T}_*)\}}$$

Characteristics:

- Monotonic growth from $\phi = 1/2$ to $\phi \to 1$
- Characteristic time: $\Delta\mathcal{T}_{\text{sat}} \sim 1/\alpha$
- Fluctuations exert minimal influence on outcome probabilities

Physical meaning: At Stage II, the system completes the already-made choice, monotonically bringing the selected crystallization branch to complete classicality. The role of fluctuations here is subordinate.

Relationship Between Normalized and Unnormalized Variables

Variable	Definition	Range	Stage	Dynamics
$\|\Phi\|$ (unnormalized)	Physical order parameter	$[0, \Phi_0]$	I, III (Stage I)	$\frac{d\|\Phi\|}{d\mathcal{T}} = \mu^2\|\Phi\| - \lambda\|\Phi\|^3 + \ldots$ (eq. 21)

$\phi = \lvert\Phi\rvert/\Phi_0$ (normalized)	Dimensionless amplitude	$[0, 1]$	II (Stage II)	$\frac{d\phi}{d\mathcal{T}} = -\alpha\phi(1-\phi)(1-2\phi) + \ldots$ (eq. 22)
Transition	At $\phi = 1/2 \Leftrightarrow \lvert\Phi\rvert = \Phi_0/2$	Moment $\mathcal{T} = \mathcal{T}_*$	Threshold between Stages	Matching: both forms coincide at threshold point

APPENDIX B

ADDITIONAL TESTS STAGE-2/3/4 (F4–F12)

Code	Phenomenon	Prediction (in Model)	Horizon	Criticality	Status
F4	Particle spectrum computation	Masses/gauge parameters from KK-reduction (potentially achievable accuracy 1–3% upon agreement of input parameters)	1–3 years	(4/5)	Numerical calculations of KK-spectrum at Stage-2; verification against particle masses (PDG)
F5	Cosmological constant Λ	Λ_{theory} of order 1.1×10^{-52} m^{-2}; comparison with cosmological estimates within adopted assumptions	2–3 years	(5/5)	Comparison with DESI, Euclid; finalization of model calibration
F6	Anomalous magnetic moment of muon $(g-2)_\mu$	Estimation of contribution via spectrum/KK-modes (expected scale of Δa_μ of order 10^{-9}; refined after accounting for corresponding systematics)	3–4 years	(4/5)	Operatorial calculation of KK-mode contributions; comparison with Fermilab/J-PARC
F7	Calabi–Yau moduli	Fixing R_{inv} and y_0 through a consistent set of observable parameters (spectrum/masses/couplings)	2–3 years	(3/5)	Stage-2: independent fixing via spectrum + particle moments
F8	Axion spectrum (dark matter)	Mass in the window accessible for experiments such as ADMX (estimated 10^{-6}–10^{-2} eV; requires verification of mode-dependent parameters)	4–5 years	(5/5)	Stage-4: ADMX, CAST; signal search in the predicted window
F9	Matter/antimatter asymmetry	CP violation in the angular sector of 5D and expected consequences for observable asymmetries	4–5 years	(3/5)	Stage-3: operatorial analysis of CP-parity; comparison with ϵ_K, ϵ'/ϵ
F10	Dispersion of gravitational	Estimation of $v_{\text{GW}} \approx c(1+\Phi(z))$; contribution	5–8 years	(2/5)	LIGO/Virgo/KAGRA: upper limits on

	waves	estimated as extremely small in accessible observational windows			$v_{\text{GW}} - c$ (expectation: agreement within 10^{-15})
F11	Entanglement correlations (5D geometry)	Prediction of enhanced correlations/Bell inequalities within the 5D mechanism. Not interpreted as faster-than-light information transmission; effective "correlation scale" (not signal) is estimated	10+ years	(2/5)	Stage-4: Bell inequality testing with increased precision; causality analysis
F12	Proton (stability)	Topological/structural protection: expected lower bound $\tau_p \gtrsim 10^{34}$ years; requires refinement of decay operators and channel contributions	10+ years	(2/5)	Super-Kamiokande, HyperK: lower limits on τ_p; comparison with prediction

> **Explanation of Criticality Scale (1–5):**
>
> - (1) — Low: prediction is qualitative or order-of-magnitude estimate, sensitive to parameter choices
> - (2) — Medium-low: structural prediction, but with large uncertainties; requires computational refinement
> - (3) — Medium: prediction depends on intermediate results (e.g., F7 determines input for F4); reasonable confidence
> - (4) — High: prediction has stable structure and low sensitivity to parameter variations; experimental comparison is feasible
> - (5) — Critical: this test directly probes the central mechanism of P-Theory; failure would require substantial reformulation

APPENDIX C

DIMENSIONS AND NORMALIZATIONS OF BASIC OBJECTS

The dimensional consistency of the fundamental equations (1)–(3) is established as follows. We adopt the convention:

1. World time $\mathcal{T}$ has dimension of time: $[\mathcal{T}] = \mathrm{s}$
2. Order parameter Φ is dimensionless: $[\Phi] = 1$
3. Φ_0 is a dimensionless scale constant: $[\Phi_0] = 1$; hence $\phi = |\Phi|/\Phi_0$ is dimensionless
4. Spatial coordinates $\mathbf{x}$ have dimension of length: $[\mathbf{x}] = \mathrm{m}$, so $[\nabla^2] = \mathrm{m}^{-2}$
5. World-time fluctuation $\delta\mathcal{T}$ has the same dimension as $\mathcal{T}$:

$$[\delta\mathcal{T}] = \mathrm{s}$$

Then the left-hand side of equation (1) has dimension:

$$\left[\frac{\partial|\Phi|}{\partial\mathcal{T}}\right] = \mathrm{s}^{-1}.$$

Since all terms on the right-hand side of (1) must have units of s^{-1}, we obtain:

$$\boxed{[\mu^2] = \mathrm{s}^{-1}, \quad [\lambda] = \mathrm{s}^{-1}, \quad [\gamma] = \mathrm{s}^{-3}, \quad [D] = \mathrm{m}^2/\mathrm{s}, \quad [J_{\mathrm{ext}}] = \mathrm{s}^{-1}, \quad [\alpha] = \mathrm{s}^{-1}.}$$

C.1. Clarification: Normalization of World-Time Fluctuations

Random perturbations $\delta\mathcal{T}_i$ have dimension of time, so the characteristic scale of Planckian cycles is set as $\Delta\mathcal{T}_{\min} \sim t_P$, and therefore:

$$[\delta\mathcal{T}] = \mathrm{s}, \quad [\sigma^2] = \langle|\delta\mathcal{T}|^2\rangle = \mathrm{s}^2.$$

The compatibility of equation (1) with the dimensionlessness of $|\Phi|$ gives $[\gamma] = \mathrm{s}^{-3}$.

C.2. Consistency of Equation (2) with Equation (1)

Equation (2) is obtained from (1) by the substitution $|\Phi| = \Phi_0\phi$. Since Φ_0 is a constant:

$$\partial_{\mathcal{T}}|\Phi| = \Phi_0\partial_{\mathcal{T}}\phi.$$

Both sides of (1) are then divided by Φ_0, which leads to the appearance of the coefficient J_{ext}/Φ_0 in equation (2):

$$\boxed{\frac{\partial\phi}{\partial\mathcal{T}} = -\alpha\phi(1-\phi)(1-2\phi) + \gamma|\delta\mathcal{T}|^2\phi + D\nabla^2\phi - \frac{J_{\mathrm{ext}}}{\Phi_0}}$$

All terms retain dimension s^{-1} after this rescaling, ensuring dimensional consistency.

C.3. Summary Table: Dimensions of All Parameters

Parameter	Definition/Role	Dimension	Typical Value (Planckian Scales)
$\mathcal{T}$	World time (evolution parameter)	[s]	$\Delta\mathcal{T}_{\min} \sim 5.4 \times 10^{-44}$ s
$\|\Phi\|$	Amplitude of order parameter	[1] (dimensionless)	$\Phi_0 \sim 1$ (by convention)
$\phi = |\Phi	/\Phi_0$	Normalized order parameter	[1]
μ^2	Tachyonic instability rate (Stage I)	[s^{-1}]	$\mu^2 \sim 10^{43}$ s^{-1}
λ	Nonlinear saturation coefficient (Stage I)	[s^{-1}]	$\lambda \sim 10^{43}$ s^{-1}
α	Relaxation rate (Stage II)	[s^{-1}]	$\alpha \sim 10^{40}$ s^{-1}
γ	Coupling to world-time fluctuations	[s^{-3}]	$\gamma \sim 10^{130}$ s^{-3}

$\sigma^2 = \langle \lvert\delta\mathcal{T}\rvert^2 \rangle$	Variance of Planckian fluctuations	[s^2]	$\sigma^2 \sim (t_P)^2 \sim 3 \times 10^{-87}$ s^2
D	Diffusion coefficient (spatial front)	[m^2/s]	$D \sim \ell_P \cdot c \sim 10^{-18}$ m^2/s
J_{ext}	Forced decrystallization rate	[s^{-1}]	$J_{\text{ext}} \geq 0$ (system dependent)
$\mathbf{x}$	Spatial coordinates	[m]	—
∇^2	Laplacian operator	[m^{-2}]	—

C.4. Planckian Scales and Natural Units

Throughout the paper, we use the following Planckian constants (in SI units):

$$t_P = \sqrt{\frac{\hbar G}{c^5}} \approx 5.4 \times 10^{-44}\ \mathrm{s}$$

$$\ell_P = \sqrt{\frac{\hbar G}{c^3}} \approx 1.6 \times 10^{-35}\ \mathrm{m}$$

$$m_P = \sqrt{\frac{\hbar c}{G}} \approx 2.2 \times 10^{-8}\ \mathrm{kg}$$

$$E_P = m_P c^2 \approx 1.96 \times 10^9\ \mathrm{J} \approx 1.22 \times 10^{19}\ \mathrm{GeV}$$

When necessary, results are expressed in natural units with $\hbar = c = 1$, which implicitly sets:

$$[E] = [m] = [1/\mathrm{length}] = [1/\mathrm{time}]$$

Conversion between Planckian and standard SI units is straightforward upon restoration of $\hbar$ and c.

C.5. Dimensional Analysis of Key Results

1. Decoherence Timescale

$$\tau_{\text{decoh}} = \frac{\hbar}{v k_B T}$$

Dimensional check:

$$[\tau_{\text{decoh}}] = \frac{[\hbar]}{[v] \cdot [k_B] \cdot [T]} = \frac{\mathrm{J} \cdot \mathrm{s}}{(\text{dimensionless}) \cdot \mathrm{J/K} \cdot \mathrm{K}} = \mathrm{s} \quad \checkmark$$

2. Cosmological Constant

$$\Lambda = \frac{8\pi^2 \hbar^2}{3\ell_P^4} \approx 1.1 \times 10^{-52}\ \mathrm{m}^{-2}$$

Dimensional check (in natural units $\hbar = c = 1$):

$$[\Lambda] = \frac{[\hbar]^2}{[\ell_P]^4} = \frac{(\mathrm{J} \cdot \mathrm{s})^2}{\mathrm{m}^4} = \frac{(\mathrm{kg} \cdot \mathrm{m}^2 \cdot \mathrm{s}^{-1})^2}{\mathrm{m}^4} = \mathrm{m}^{-2} \quad \checkmark$$

> This agreement indicates the internal consistency of the dimensional analysis; the full renormalization in 5D will be performed at Stage-3.

3. KK-Mode Mass

$$m_{\text{KK}} = \frac{n\hbar}{R_{\text{inv}}} \quad (n = 1, 2, 3, \ldots)$$

Dimensional check:

$$[m_{\text{KK}}] = \frac{[\hbar]}{[R_{\text{inv}}]} = \frac{\text{J} \cdot \text{s}}{\text{m}} = \frac{\text{kg} \cdot \text{m}^2 \cdot \text{s}^{-2} \cdot \text{s}}{\text{m}} = \text{kg} \quad \checkmark$$

C.6. Verification of Dimensional Consistency in Reduction

At the reduction to effective 4D, the Lindblad generator (§2.3.2):

$$\frac{d\rho_{\text{obs}}}{d\mathcal{T}} = -\frac{i}{\hbar}[H_{\text{eff}}, \rho_{\text{obs}}] + \sum_k \left(L_k \rho_{\text{obs}} L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k, \rho_{\text{obs}}\} \right)$$

has dimension:

$$\left[\frac{d\rho_{\text{obs}}}{d\mathcal{T}} \right] = \text{s}^{-1} \quad \checkmark$$

This follows from:

- $[H_{\text{eff}}] = [\hbar]/[\mathcal{T}] = \text{J}$ (energy)
- $[\hbar] = \text{J} \cdot \text{s}$
- $[\rho_{\text{obs}}] = 1$ (dimensionless density matrix)
- Hence $[-i\hbar^{-1}[H, \rho]] = \text{s}^{-1}$

Similarly, the dissipative part (Lindblad terms) has dimension s^{-1} due to the form of operators L_k constructed from world-time fluctuations.

APPENDIX D

Quantitative Calculation of Vacuum Decay Probability: Derivation of the Euclidean Bounce Action and Verification of Prediction V4

D.1. Derivation of the Euclidean Bounce Action

The probability of bubble nucleation per unit volume per unit time is determined by the standard WKB expression:

$$\Gamma \sim A \cdot e^{-S_E}$$

where the pre-exponential factor $A \sim t_P^{-4}$ is set by Planckian dimensionality, and S_E — the Euclidean action of the "bounce" solution — is defined as the action of an $O(4)$-symmetric solution of the equations of motion in Euclidean space, connecting the false vacuum ($|\Phi| = 0$) with the classical turning point ($|\Phi| = \Phi_0$).

Euclidean action in full form. In four-dimensional Euclidean space with $O(4)$ symmetry, using the radial variable $\rho = \sqrt{\tau_E^2 + |\mathbf{x}|^2}$:

$$\boxed{S_E = 2\pi^2 \int_0^{\rho_0} d\rho\, \rho^3 \left[\frac{1}{2}\left(\frac{d|\Phi|}{d\rho}\right)^2 + V_{\text{eff}}(|\Phi|)\right]}$$

where ρ_0 — the bounce radius, determined by the condition $d|\Phi|/d\rho\big|_{\rho=\rho_0} = 0$, and V_{eff} — the complete effective potential from §4.4:

$$V_{\text{eff}}(|\Phi|) = V_{\text{I}}(|\Phi|) + V_{\text{CY}}(\mathcal{R}_{\text{inv}}) + V_{\text{KK}}(N_{\text{KK}})$$

From integral to closed form. For the Stage-I potential (Axiom A6) with the addition of V_{CY}, using the "thin-wall approximation" profile, applicable when $\Delta V \ll V_{\text{barrier}}$:

$$|\Phi(\rho)| \approx \frac{\Phi_0}{2}\left[1 - \tanh\left(\frac{\rho - \rho_0}{l_D}\right)\right]$$

the integral can be evaluated analytically. The terms from V_{I} and the kinetic term yield the standard Coleman result:

$$S_E^{(\text{I})} = \frac{2\pi^2}{3} \cdot \frac{27\pi^2}{2} \cdot \frac{\sigma^4}{(\Delta V_{\text{I}})^3}$$

where $\sigma = \int_0^{\Phi_0} d|\Phi|\sqrt{2V_{\text{I}}(|\Phi|)} = \frac{\sqrt{2}}{3}\frac{\mu^3}{\lambda}$ — the surface tension of the bubble wall.

At $\Phi_0^2 = \mu^2/\lambda$ and $\Delta V_{\text{I}} = \mu^4/(4\lambda)$ this simplifies to:

$$S_E^{(\text{I})} \approx \frac{8\pi^2}{3} \cdot \frac{\mu^4}{\lambda^2}$$

The stabilizing contribution from Calabi–Yau moduli $V_{\text{CY}}(\mathcal{R}_{\text{inv}})$ enters additively into V_{eff}, increasing the effective barrier depth. This introduces a stabilizing function:

$$f(\mathcal{R}_{\text{inv}}) = 1 + \frac{V_{\text{CY}}(\mathcal{R}_{\text{inv}})}{\Delta V_{\text{I}}}$$

so that the complete Euclidean action takes the form:

$$\boxed{S_E \approx \frac{8\pi^2}{3} \cdot \frac{\mu^4}{\lambda^2} \cdot f(\mathcal{R}_{\text{inv}}), \quad f(\mathcal{R}_{\text{inv}}) \geq 1}$$

This is precisely the expression used in the quantitative estimates below.

> **Proof rigor level:** *[ANSATZ + PHYSICALLY MOTIVATED DERIVATION]*, Stage-1/2. The thin-wall approximation is applicable under the condition $\Delta V_{\text{I}} \ll V_{\text{barrier}}$, which holds when $f \gg 1$. Exact computation of $f(\mathcal{R}_{\text{inv}})$ from the explicit KK-spectrum is a Stage-2 task.

D.2. Detailed Calculation of Decay Probability

Problem Statement.

In P-Theory, the question of vacuum decay reality reduces to testing the inequality:

$$\Gamma \cdot V_{\text{Universe}} \cdot t_{\text{Universe}} \overset{?}{\ll} 1$$

where Γ — the nucleation rate per unit volume per unit time. If the inequality holds, our vacuum is practically eternal on cosmological timescales.

Euclidean bounce action.

From section D.1 of this Appendix, accounting for the stabilizing contribution from Calabi–Yau moduli:

$$S_E \approx \frac{8\pi^2}{3} \cdot \frac{\mu^4}{\lambda^2} \cdot f(\mathcal{R}_{\rm inv}), \quad f(\mathcal{R}_{\rm inv}) = 1 + \frac{V_{\rm CY}(\mathcal{R}_{\rm inv})}{\Delta V_{\rm I}}$$

At stabilized moduli ($\mathcal{R}_{\rm inv} \sim 10\,\ell_P$, values from F5) and $\mu^2/\lambda \sim \Phi_0^2 \sim 1$:

Dimensional argument for $f(\mathcal{R}_{\rm inv})$.

To extract the power-law dependence of f on $\mathcal{R}_{\rm inv}$, we employ the following dimensional argument. The energy difference between vacua (from section D.1 of this Appendix with $\mu^2/\lambda \sim 1$):

$$\Delta V_{\rm I} = \frac{\mu^4}{4\lambda} \sim \frac{\hbar c}{\ell_P^4}$$

is set by Planckian energy density — the only fundamental scale in the problem. The stabilizing contribution from Calabi–Yau moduli is determined by the number of active KK-modes: at compactification scale $\mathcal{R}_{\rm inv}$, the volume of compact space scales as $\sim \mathcal{R}_{\rm inv}^6$, and the number of KK-modes with energy below the Planckian cutoff is proportional to $(\mathcal{R}_{\rm inv}/\ell_P)^6$. Each mode contributes $\sim \hbar c/\ell_P^4$ (Planckian energy density unit), but after integration over 4D Euclidean space (whence the power of 4 in the Euclidean action S_E) the total contribution takes the form:

$$V_{\rm CY}(\mathcal{R}_{\rm inv}) \sim C_{\rm CY} \cdot \frac{\hbar c}{\ell_P^4} \cdot \left(\frac{\mathcal{R}_{\rm inv}}{\ell_P}\right)^4$$

where $C_{\rm CY}$ — a dimensionless topological factor of order unity, absorbing details of the specific Calabi–Yau topology (computed at Stage-2 via explicit KK-spectrum). Then:

$$f(\mathcal{R}_{\rm inv}) = 1 + \frac{V_{\rm CY}(\mathcal{R}_{\rm inv})}{\Delta V_{\rm I}} \approx 1 + C_{\rm CY} \cdot \frac{\mathcal{R}_{\rm inv}^4}{\ell_P^4}$$

For $\mathcal{R}_{\rm inv} \gg \ell_P$, the second term dominates significantly, and:

$$\boxed{f(\mathcal{R}_{\rm inv}) \approx C_{\rm CY} \cdot \left(\frac{\mathcal{R}_{\rm inv}}{\ell_P}\right)^4}$$

The power 4 is fixed by the dimensionality of the Euclidean integral in S_E and is not a free parameter. At $\mathcal{R}_{\rm inv} \sim 10\,\ell_P$ and $C_{\rm CY} \sim 1$:

$$f(\mathcal{R}_{\rm inv}) \sim \mathcal{R}_{\rm inv}^4/\ell_P^4 \sim 10^4, \qquad \boxed{S_E \sim \frac{8\pi^2}{3} \cdot 10^4 \approx 2.6 \times 10^5}$$

> **Status of the estimate:** $C_{\rm CY}$ — the only undetermined coefficient; its computation from explicit Calabi–Yau topology (CY^6) is a Stage-2 task. The order of magnitude $f \sim 10^4$ is robust for $C_{\rm CY} \in [0.1, 10]$.

Nucleation probability during the lifetime of the Universe.

Nucleation rate via WKB tunneling:

$$\Gamma \sim t_P^{-4} \cdot e^{-S_E} \sim 10^{175} \cdot 10^{-112900}\,\mathrm{m^{-3}s^{-1}} = 10^{-112725}\,\mathrm{m^{-3}s^{-1}}$$

Expected number of nucleations in the observable Universe ($V \sim 4 \times 10^{80}$ m³, $t \sim 4.3 \times 10^{17}$ s):

$$\boxed{N_{\text{nucleations}} \sim 10^{-112725} \cdot 10^{80} \cdot 10^{17} = 10^{-112628} \ll 1}$$

For comparison: the number of atoms in the observable Universe $\sim 10^{80}$. The probability of spontaneous vacuum decay over the entire lifetime of the Universe is $\sim 10^{-112628}$.

> *Even under the most conservative estimate — if each of the* $\sim 10^{185}$ *Planckian volumes were treated as an independent nucleation center — the expected number of events would be* $\sim 10^{-112628+185} = 10^{-112443} \ll 1$*: the result does not change by even one significant order of magnitude.*

Instability condition.

The vacuum ceases to be practically stable if:

$$S_E < S_{\text{crit}} = \frac{4}{3} \ln\left(\frac{t_{\text{Universe}}}{t_P}\right) \approx 187, \quad \text{i.e., } f(\mathcal{R}_{\text{inv}}) < f_{\text{crit}} \approx 7.1$$

With the actual value $f \sim 10^4$, this condition is not satisfied with a safety margin of three orders of magnitude.

D.3. Operational Scheme for Verification of Prediction V4

Prediction $f(\mathcal{R}_{\text{inv}}) \approx 10^4$ is verifiable independently of Λ_{obs} through the following three-step procedure at Stage-2:

Step 1 — Independent fixing of $\mathcal{R}_{\text{inv}}$: The compactification scale is determined from the KK-spectrum of particle masses — via the ratios $m_{\text{KK}}^{(n)}/m_{\text{KK}}^{(1)} = n$ for the first few KK-modes (without invoking Λ data). This gives $\mathcal{R}_{\text{inv}}^{(\text{KK})}$ with expected accuracy 1–3% upon agreement with PDG.

Step 2 — Independent computation of f: Substitution of $\mathcal{R}_{\text{inv}}^{(\text{KK})}$ into $f = C_{\text{CY}} \cdot (\mathcal{R}_{\text{inv}}/\ell_P)^4$ with the topological coefficient C_{CY} (computed at Stage-2) from the explicit number of homological cycles of Calabi–Yau (CY^6).

Step 3 — Consistency check: The obtained $f^{(\text{KK})}$ is compared with $f^{(\Lambda)}$, extracted from the condition $\Lambda_{\text{PCT}}(f) = \Lambda_{\text{obs}}$. Agreement within uncertainties (expected tolerance $\sim 5\%$) via two independently determined paths will signify: the stability of our vacuum is not a standalone fitting parameter, but follows from the same geometry that determines dark energy.

> If $f^{(\text{KK})} \neq f^{(\Lambda)}$ — this would falsify the connection F5 ↔ V4 and would require revision of either the form of V_{CY} or the Calabi–Yau topology (CY^6).

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22. Numerical estimate $f \sim 10^4$ is obtained at Stage-1/2 from dimensional arguments (see Appendix D.2). The precise value of C_{CY} and independent verification via KK-spectrum is a Stage-2 task (see Appendix D.3, block "Operational scheme of verification"). ↩