Phase–Tunneling Cosmogenesis: Structural Origin of a Critical Phase Mass in a Finite–Window Regime

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Abstract

We investigate the emergence of a robust critical phase mass $m_{\phi,\mathrm{crit}} \simeq 1.965$ in the framework of Phase–Bifurcation Cosmogenesis. We show that this threshold is not an asymptotic attractor nor a probabilistic artifact, but a structural property of the phase configuration space defined within a finite cosmological window. We further demonstrate that extending the dynamics to arbitrarily late times yields a trivial asymptotic behavior in which all trajectories synchronize, thereby clarifying the physical meaning of the escape sector as a finite–window phenomenon. Finally, we outline how quantum tunneling can act as a prior on initial phase conditions without altering the position of the classical critical threshold, and how a rotational tilt can catalyze nucleation via a Stark–like reduction of the Euclidean action.

Contents

1 Introduction

A recurring challenge in cosmogenesis models is to explain why non–trivial dynamical histories arise from a pre–dynamical (effectively timeless) regime without invoking external clocks or ad hoc fine–tuning. In the Phase–Bifurcation Cosmogenesis program, the evolution of a relative phase variable $\Delta\phi$ (between coupled sectors, or "twin" components in CPT–symmetric settings [9]) exhibits a striking and persistent numerical feature: a critical phase mass

$$m_{\phi,\mathrm{crit}} \simeq 1.965, \tag{1}$$

marking a sharp transition in the probability of phase synchronization.

The purpose of this paper is threefold. First, we formalize why the observed threshold is intrinsically a *finite–window* phenomenon. Second, we show that pushing the evolution to asymptotically late times yields a *null result* (trivial global synchronization), which does not invalidate the finite–window criticality but instead clarifies its physical meaning. Third, we propose a quantum nucleation mechanism—tunneling in phase configuration space—that provides a principled prior on initial conditions in a timeless ontology (in the spirit of Barbour's Platonia and "time capsules" [1, 2]), without shifting the classical threshold.

Roadmap. Sections 2–4 establish the finite–window dynamics, the operational sector classification and the structural origin of $m_{\phi,\mathrm{crit}}$, and interpret the asymptotic null result. Sections 5–6 introduce tunneling as a prior and connect the finite window to an emergent, local notion of time.

2 Phase Dynamics in a Finite Cosmological Window

The phase evolution considered in Phase–Bifurcation Cosmogenesis is governed by a periodic effective potential of the form

$$V_{\mathrm{eff}}(\Delta\phi) = V_0\,[1 - \cos(\Delta\phi)], \tag{2}$$

together with Hubble friction and a decaying rotational source term. The resulting dynamics is naturally expressed in terms of the number of e–folds $N = \ln a$.

Crucially, the physically relevant evolution occurs within a *finite cosmological window*, corresponding to approximately $\Delta N \simeq 9.2$ e–folds. Within this interval, the rotational source and Hubble damping compete with the periodic potential, giving rise to non–trivial phase trajectories (a phenomenon well–studied in general nonlinear synchronization contexts [10, 11]).

Extending the integration beyond this window is not physically innocent. At late times, the rotational source becomes negligible and the potential term dominates the dynamics, forcing all trajectories toward synchronization. As a consequence, asymptotic evolution inevitably erases the transient phase structure that is relevant for physical observables.

For this reason, all sector classifications and probability estimates in this work are defined *strictly within the finite window.* The notion of "escape" does not refer to divergence at infinite time, but to the failure of a trajectory to relax toward a potential minimum during the finite cosmological epoch under consideration.

Numerical implementation. Throughout, we follow the operational definitions implemented in the public analysis scripts, where trajectories are integrated over the finite window and classified without reference to the asymptotic $N \to \infty$ limit. See Appendix A for the sector classifier and data products.

3 Structural Origin of the Critical Phase Mass

Phase trajectories $\Delta\phi(N)$ are classified into three qualitatively distinct sectors:

- **Sector A (synchronization):** trajectories that relax toward $\Delta\phi \to 0$ within the finite window;
- **Sector B (intermediate peak):** trajectories that develop a maximum but eventually decay without crossing the antipodal point;
- **Sector C (escape / non–relaxation):** trajectories that either cross $\Delta\phi = \pi$ or fail to decay significantly within the window.

Importantly, Sector C is defined operationally by non–relaxation within the finite window, rather than by asymptotic divergence. This definition is robust under numerical refinement and does not rely on late–time behavior.

For fixed values of the phase mass m_ϕ and rotational coupling $k_{\rm rot}$, we define the synchronization probability

$$P_A(m_\phi, k_{\rm rot}) = \frac{N_A}{N_{\rm tot}}, \tag{3}$$

where N_A denotes the number of trajectories classified as Sector A. Marginalizing over the rotational coupling yields

$$P_A(m_\phi) = \langle P_A(m_\phi, k_{\rm rot})\rangle_{k_{\rm rot}}. \tag{4}$$

The critical phase mass is then defined by the condition

$$P_A(m_{\phi,\rm crit}) = 0.5. \tag{5}$$

Applying this procedure over the parameter grid yields the robust value

$$m_{\phi,\rm crit} \simeq 1.965, \tag{6}$$

with only a weak second–order dependence on the rotational coupling.

4 Asymptotic Evolution and the Null Result

As a consistency check, we investigated the behavior of the phase dynamics under asymptotic time evolution, extending the integration well beyond the finite cosmological window.

In this limit, trajectories eventually synchronize toward a potential minimum, and the escape sector disappears entirely. This *null result* is not a failure of the model, but a direct consequence of the dominance of the periodic potential once the rotational source has decayed.

The asymptotic trivialization confirms that Sector C is intrinsically a finite–window phenomenon. Its disappearance at late times demonstrates that the critical phase mass does not correspond to an eternal attractor, but to a structural threshold governing transient cosmological behavior.

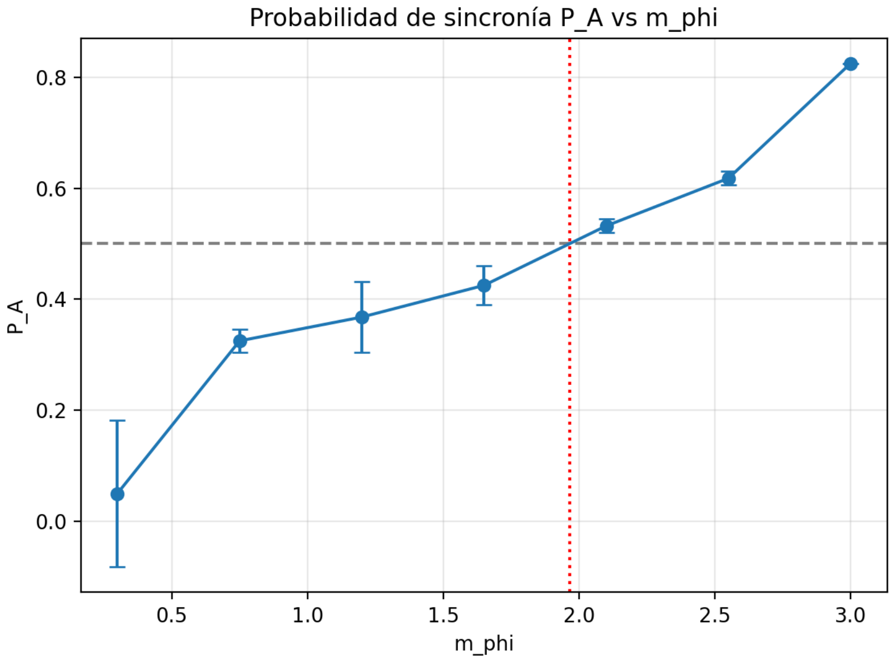


Figure 1: Synchronization probability P_A versus m_ϕ (finite window), with the operational critical threshold defined by $P_A = 0.5$.

5 Quantum Tunneling as a Prior on Phase Initial Conditions

Having established that the critical mass $m_{\phi,\text{crit}}$ is a structural feature of the classical phase space, we now address the selection of initial conditions. In a timeless Barbour–like framework [1, 2], there is no temporal evolution prior to the emergence of the phase. Consequently, the transition from the static vacuum ($\Delta\phi = 0$) to the dynamic regime can be modeled as a quantum nucleation event.

We propose that the initial distribution of the phase difference, $\mathcal{P}(\Delta\phi_{\text{ini}})$, is determined by a semiclassical tunneling probability across the effective barrier, suppressed by the Euclidean action [3, 4, 5, 6, 7]:

$$\mathcal{P}(\Delta\phi_{\text{ini}}) \propto \exp(-S_E(\Delta\phi_{\text{ini}}))\,. \tag{7}$$

5.1 WKB approximation and rotational (Stark–like) catalysis

Near the synchronization point, one may approximate $V_{\text{eff}} \approx \frac{1}{2}m_\phi^2\Delta\phi^2$. A primordial rotational component can introduce a symmetry–breaking tilt to the Euclidean effective potential, analogous (phenomenologically) to a linear Stark term [12]:

$$V_{\text{E}}(\Delta\phi) \approx \frac{1}{2}m_\phi^2\Delta\phi^2 - \epsilon_{\text{rot}}\Delta\phi, \qquad \epsilon_{\text{rot}} \propto k_{\text{rot}}. \tag{8}$$

Under a WKB prescription, the tunneling action to reach an emergence point $\Delta\phi_{\text{ini}}$ may be written as:

$$S_E(\Delta\phi_{\text{ini}}) = \int_0^{\Delta\phi_{\text{ini}}} \sqrt{2\,V_{\text{E}}(\phi)}\,\mathrm{d}\phi. \tag{9}$$

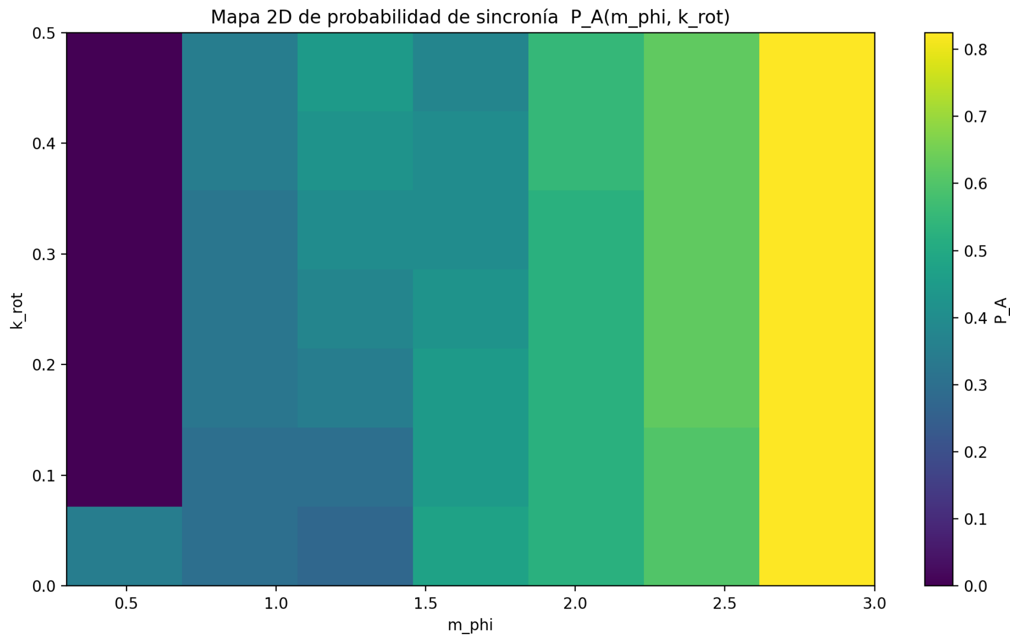


Figure 2: Heatmap of $P_A(m_\phi, k_{\rm rot})$ showing near–vertical transition bands. The weak dependence on $k_{\rm rot}$ indicates that $m_{\phi,\rm crit}$ is primarily controlled by the potential stiffness relative to Hubble damping (finite window).

Two consequences follow: (i) large initial amplitudes are exponentially suppressed; (ii) a non–zero $k_{\rm rot}$ lowers the effective barrier, enhancing nucleation probability (rotational catalysis).

5.2 Interaction with the classical critical threshold

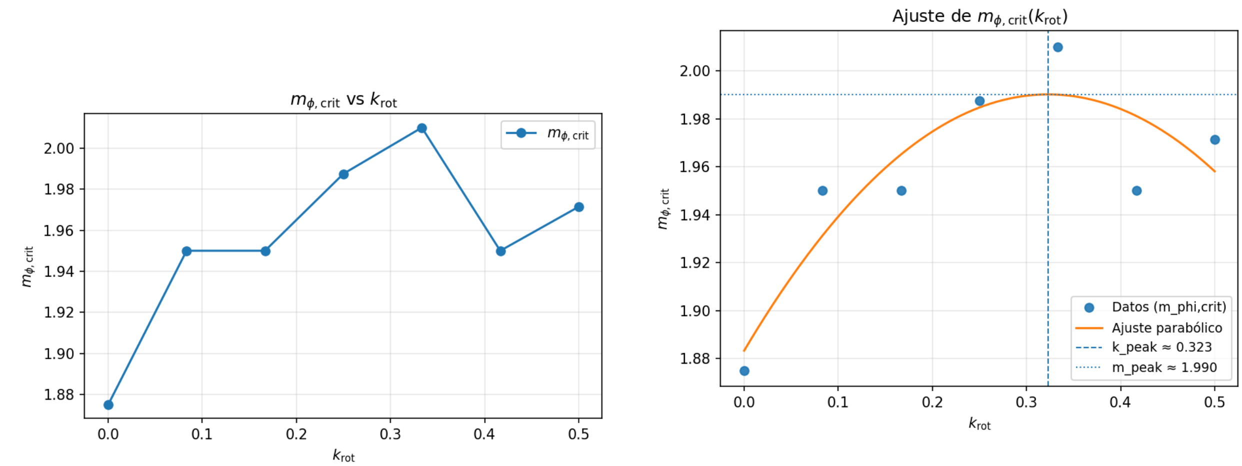
The tunneling prior does not alter the position of the dynamical threshold $m_{\phi,\rm crit} \simeq 1.965$ (Section 3). Instead, it filters which initial conditions are statistically realized. In this view, the classical finite–window dynamics defines the structural boundary, while quantum nucleation biases where the system starts within that boundary.

Crucially, the comparison between the WKB–tilted prior and a flat uniform prior (Fig. 4) reveals no significant shift in the survival probability landscape. The dominance of the classical attractor ensures that the critical mass $m_{\phi,\rm crit}$ remains robust regardless of the specific shape of the initial distribution. The tunneling mechanism explains the *existence* of the excursion, but the finite–window dynamics dictates its *fate*.

6 Discussion

6.1 Finite window as a "time capsule"

Our null result in the asymptotic limit (Section 4) has a direct interpretational consequence: if the escape sector exists only within a finite cosmological window, then "time"—understood as relational phase evolution—is not an eternal background parameter but a transient emergent property. This aligns naturally with Barbour's notion of *time capsules* [1].



(a) $m_{\phi,\mathrm{crit}}$ sampled versus k_{rot}.

(b) Smooth fit highlighting a mild crest near $k_{\mathrm{rot}} \sim 0.33$.

Figure 3: Weak secondary dependence of the operational critical mass on rotational coupling.

6.2 Pre–geometric vacuum viewpoint

The finite–window picture can be sharpened conceptually by adopting a "pre–geometric vacuum" stance. If the underlying excitations of the quantum vacuum are not meaningfully localized prior to classical geometry, then they are not anchored to a spatial metric in the usual sense: they do not distinguish "here" from "there." In an idealized singular regime (or pre–time regime), distance and trajectories cease to be operational notions; the vacuum behaves as a coherent global state rather than "space filled with things."

Within this reading, the synchronized limit $\Delta\phi \to 0$ corresponds to maximal coherence: no direction, no point, and no curvature is privileged at the level of the phase state. The emergence of a dynamical phase excursion is then not merely a story of "evolution in time" but a transition from a globally coherent configuration to a regime where relational differences become stable enough to function as records—precisely the role Barbour assigns to time capsules [1, 2].

6.3 Implications for CPT–symmetric ("Siamese") cosmology

Within CPT–symmetric settings [9], a phase–nucleation event provides a natural origin for a primordial phase offset between twins. Such a seed may then be processed through the same critical filter $m_{\phi,\mathrm{crit}}$, connecting the abstract phase dynamics to phenomenological consequences explored in companion works. (For broader cosmological asymmetry context, see [8].)

7 Conclusion

We have shown that the critical phase mass $m_{\phi,\mathrm{crit}} \simeq 1.965$ is a robust structural feature of Phase–Bifurcation Cosmogenesis when the dynamics is defined within a physically motivated finite window. Extending evolution to asymptotic times yields a null result (universal synchronization), clarifying that the escape sector is intrinsically finite–window and supporting an interpretation of the threshold as a geometric bifurcation in phase configuration space.

We outlined a quantum nucleation mechanism in which tunneling provides a prior over initial phase conditions in a timeless ontology; tunneling does not move the classical threshold but biases

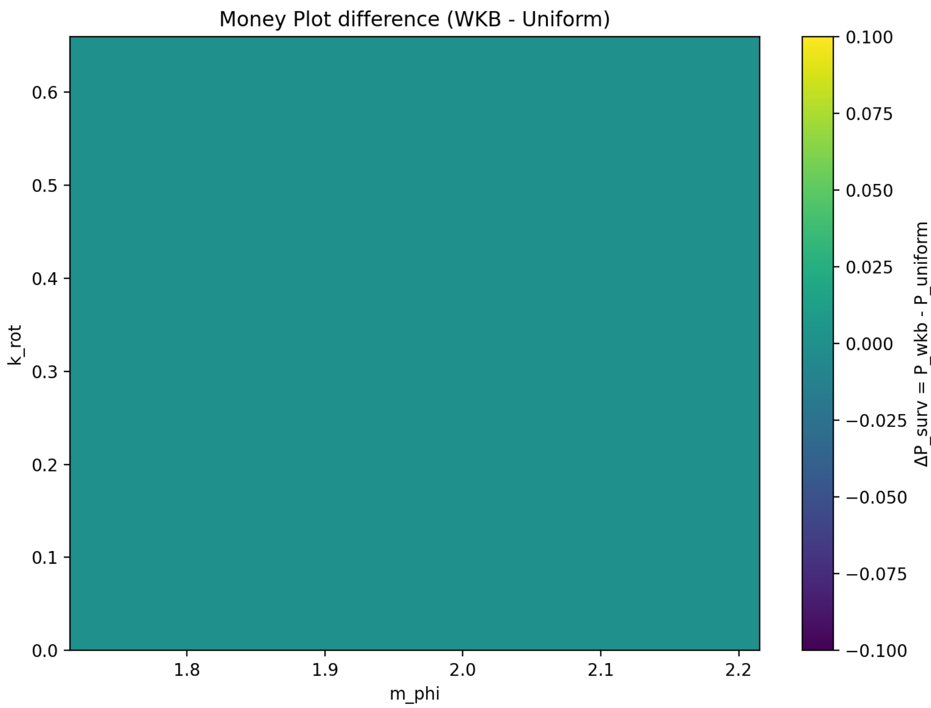


Figure 4: **Robustness against initial conditions.** The differential map $\Delta P_{\mathrm{surv}} = P_{\mathrm{WKB}} - P_{\mathrm{uniform}}$ shows negligible deviation across the parameter space (uniform color indicates $\Delta P \approx 0$). This demonstrates that the critical threshold $m_{\phi,\mathrm{crit}}$ is a structural feature of the classical dynamics, largely insensitive to the specific choice of the quantum prior.

realized initial conditions, while a rotational tilt can catalyze nucleation by lowering the Euclidean action. Together, these ingredients link a timeless "board," a quantum "first move," and a classical finite–window "game."

A Operational Sector Classifier

For transparency and reproducibility, we summarize the operational classifier used throughout the analysis. Given a sampled trajectory $\Delta\phi(N)$ over the finite window, define $\Delta\phi_{\mathrm{final}}$ and $\max(\Delta\phi)$ within the window. A minimal operational definition is:

- Sector A if $\Delta\phi_{\mathrm{final}} < \varepsilon$ (synchronization),
- Sector C if $\max(\Delta\phi) > \pi$ (crosses the antipodal barrier), or if $\Delta\phi_{\mathrm{final}} > 0.8 \max(\Delta\phi)$ (non–relaxation),
- Sector B otherwise (intermediate peak with decay).

This definition encodes the key physical principle emphasized in the main text: Sector C is a finite–window non–relaxation class, not an asymptotic attractor.

B Data and Code Availability

The scripts and datasets required to reproduce the finite–window sector maps and the critical value $m_{\phi,\mathrm{crit}}$ are organized under the repository structure: `src/` (code), `data/` (CSV tables), and `figs/` (figures). Key scripts include an operational sector classifier and utilities to compute $P_A(m_\phi)$ and interpolate the critical threshold.

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