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The branch-cut quantum gravity with a self-coupling inflation scalar field: Dynamical equations

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Abstract

This article focuses on the implications of the recently developed commutative formulation based on branch-cutting cosmology, the Wheeler–DeWitt equation, and Hořava–Lifshitz quantum gravity. Assuming a mini-superspace of variables, we explore the impact of an inflaton-type scalar field $\phi(t)$ on the dynamical equations that describe the trajectories evolution of the scale factor of the Universe, characterized by the dimensionless helix-like function $\ln^{-1}[\beta(t)]$. This scale factor characterizes a Riemannian foliated spacetime that topologically overcomes the big bang and big crunch singularities. Taking the Hořava–Lifshitz action as our starting point, which depends on the scalar curvature of the branched Universe and its derivatives, with running coupling constants denoted as g_i, the commutative quantum gravity approach preserves the diffeomorphism property of General Relativity, maintaining compatibility with the Arnowitt–Deser–Misner formalism. We investigate both chaotic and nonchaotic inflationary scenarios, demonstrating the sensitivity of the branch-cut Universe's dynamics to initial conditions and parameterizations of primordial matter content. The results suggest a continuous connection of Riemann surfaces, overcoming primordial singularities and exhibiting diverse evolutionary behaviors, from big crunch to moderate acceleration.

KEYWORDS

branch cut cosmology, scalar field, inflation

1 | INTRODUCTION

The chronology of the Universe is based on the Big Bang model, which indicates that in primordial times there was an era dominated by inflation, followed by eras dominated by the presence of radiation and matter. At present, the dominant phase would correspond to the dark energy era, which supposedly drives the accelerated expansion of the Universe. The first observed light would then correspond to relics of the cosmic microwave background (CMB), composed of photons that would have originated during the recombination phase, marked by the dissociation between matter and radiation. The recombination era would have occurred approximately 380 million years after cosmic inflation when the Universe reached a temperature of approximately T~0.26 eV.

Branch cut gravity (BCG) corresponds to an extension of the ontological domain of General Relativity to the complex plane (Bodmann et al. 2022; Bodmann et al. 2023a; Bodmann et al. 2023b; de Freitas Pacheco et al. 2022; Einstein 1916, 1917; Hess et al. 2023; Zen Vasconcellos et al. 2019; Zen Vasconcellos et al. 2021a, 2021b; Zen Vasconcellos et al. 2023), having been developed as a theoretical alternative proposal to the inflation model (Guth 1981, 2004). BCG is based on the mathematical technique of augmentation and the notion of closure and existential completeness (Manders 1989), which have proven to be extremely useful in both quantum mechanics (Aharonov & Bohm 1959; Dirac 1937; Wu et al. 2021) and in pseudocomplex general relativity (pc-GR) Hess (2017); Hess & Boller (2020); Hess & Greiner (2009), with direct physical and cosmological manifestations.

In the classical scenario, the universe described by branch-cutting cosmology continually evolves from the negative complex cosmological time sector, prior to a primordial singularity, to the positive sector, continually bypassing a branch-cutting, and no primordial singularities occur in the imaginary sector, only branch points. The branching universe involves a continuous sum of an infinite number of infinitely (originally) separated poles, surrounding a primordial branching point, organized along a line in the complex plane with infinitesimal residues. And just like the primordial branch point singularity, the resulting analytic function argument can be mapped from a single point in the domain to multiple points in the range, characterized by the scale factor, $\ln^{-1}[\beta(t)]$, analytically continued to the complex plane.

In an earlier contribution included in this volume (Weber et al. 2024), on the basis of the branch-cutting cosmology, the Wheeler–DeWitt equation, and the Hořava–Lifshitz quantum gravity, in an environment configured by a mini-superspace structure with an inflaton field, we have analized the evolution of the wave function of the Universe. In this contribution, we investigate the implications of an inflaton-type scalar field (Guth 1981, 2004) on the dynamical equations, which describe the time-evolution of the branch-cut scale factor $\ln^{-1}[\beta(t)]$, which characterizes a topological foliated spacetime structure. Like standard cosmology, its evolution over time can shed some light on understanding a crucial aspect of cosmic evolution, what drives the acceleration of the Universe.

2 | HOŘAVA–LIFSHITZ BRANCH-CUT ACTION

The starting point of our formulation is the action of Hořava–Lifshitz:

$$\begin{aligned} \mathcal{S}_{HL} = \frac{M_P^2}{2}\int d^3x\,dt\,N\sqrt{g}\Big(& K_{ij}K^{ij} - \lambda K^2 - g_0 M_P^2 \\ & - g_1\mathcal{R} - g_2 M_P^{-2}\mathcal{R}^2 - g_3 M_P^{-2}\mathcal{R}_{ij}\mathcal{R}^{ij} - g_4 M_P^{-4}\mathcal{R}^3 \\ & - g_5 M_P^{-4}\mathcal{R}\left(\mathcal{R}^i_j\mathcal{R}^j_i\right) - g_6 M_P^{-4}\mathcal{R}^i_j\mathcal{R}^j_k\mathcal{R}^k_i \\ & - g_7 M_P^{-4}\mathcal{R}\nabla^2\mathcal{R} - g_8 M_P^{-4}\nabla_i\mathcal{R}_{jk}\nabla^i R^{jk}\Big). \end{aligned} \tag{1}$$

This action depends on the scalar curvature, $\mathcal{R}$, of the branched Universe and its derivatives in different orders. Here, g_i represents running coupling constants, M_P is the Planck mass, ∇_i denotes covariant derivatives, and the branching Ricci components of the three-dimensional metrics can be determined by imposing a maximum symmetric surface foliation. In expression (1), $K = K^{ij}g_{ij}$ represents the trace of the extrinsic curvature tensor K_{ij} (see (Abreu et al. 2019; Bertolami & Zarro 2011; Bodmann et al. 2023a; Bodmann et al. 2023b; Cordero et al. 2019; García-Compeán & Mata-Pacheco 2022; Hess et al. 2023; Hořava 2009; Vieira et al. 2020)). The Hořava–Lifshitz approach to commutative quantum gravity preserves the diffeomorphism property of General Relativity (Kiefer 2012), which characterizes an isomorphism of smooth varieties, as well as the usual foliation of the Arnowitt–Deser–Misner (ADM) formalism at the limit of the infrared region of the spectrum (García-Compeán & Mata-Pacheco 2022).

3 | MINI-SUPERSPACE OF VARIABLES

We consider in the following a mini-superspace of variables $(u(t), \phi(t))$, adopting the variable change $u(t) \equiv \ln^{-1}[\beta(t)]$, with $du \equiv d\ln^{-1}[\beta(t)]$, and $\phi(t)$ denoting the scalar-inflaton field minimally coupled to gravity but with a nonlinear self-interaction described by a coupling function $F(\phi)$. The action of the scalar field, S_ϕ, may be written as (Kiritsis & Kofinas 2009; Tavakoli et al. 2021) in homogeneous and isotropic cosmological settings (Kiritsis & Kofinas 2009; Tavakoli et al. 2021; Weber et al. 2024)

$$S_\phi = \int_{\mathcal{M}} d^3x\,dt\,N\sqrt{g}F(\phi)g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi. \tag{2}$$

In the following, from the total action determined by adding the Hořava–Lifshitz and the scalar field actions, the Hamiltonian associated with the mini-superspace of variables may be obtained (for details, see Weber et al. (2024)).

Applying standard canonical quantization procedures, the following super-Hamiltonian results

$$\mathcal{H} = \frac{1}{2}\frac{N}{u}\left[-p_u^2 + g_r - g_m u - g_k u^2 - g_q u^3 + g_\Lambda u^4 + \frac{g_s}{u^2}\right] + \frac{1}{2}\frac{N}{u}\left[\frac{1}{u^{3\omega-1}F(\phi)}p_\phi^2\right]. \tag{3}$$

In this expression, g_k, g_Λ, g_r, and g_s, g_m, and g_q represent, respectively, the curvature, cosmological constant, radiation, stiff matter, and quintessence running coupling constants (Bertolami & Zarro 2011; Maeda et al. 2010; Weber et al. 2024).

3.1 | Hamilton equations

Hamilton equations may be synthesized in the form

$$u' = \frac{\partial \mathcal{H}}{\partial p_u} \quad \text{and} \quad p_u' = -\frac{\partial \mathcal{H}}{\partial u}, \tag{4}$$

and

$$\phi' = \frac{\partial \mathcal{H}}{\partial p_\phi} \quad \text{and} \quad p_\phi' = -\frac{\partial \mathcal{H}}{\partial \phi}. \tag{5}$$

Combining these equations with (3), we obtain the following Hamilton equations:

$$u' = -N\frac{p_u}{u}; \quad \phi' = N\frac{p_\phi}{u^{3\omega}F(\phi)}; \quad p_\phi' = \frac{N}{2}\left[\frac{p_\phi^2}{u^{3\omega}}\frac{F'(\phi)}{F^2(\phi)}\right], \tag{6}$$

with $F'(\phi) = dF(\phi)/d\phi$, and

$$p_u' = -\frac{N}{2}\left[\frac{p_u^2}{u^2} - g_k - 2g_q u + 3g_\Lambda u^2 - \frac{g_r}{u^2} - 3\frac{g_s}{u^4} - \frac{3\omega}{u^{3\omega+1}}\frac{p_\phi^2}{F(\phi)}\right]. \tag{7}$$

From Equations (6), we get:

$$p_\phi = \frac{1}{N}F(\phi)u^{3\omega}(t)\phi'(t) \quad \text{while} \quad p_u = -\frac{u(t)u'(t)}{N}. \tag{8}$$

Adopting $\omega = 1$ and the time gauge $N = u^n(t)$, by eliminating p_ϕ on the ϕ' and p_ϕ' equations above, we obtain

$$\frac{\phi''(t)}{\phi'(t)} - \frac{1}{2}\frac{F'(\phi)}{F(\phi)}\phi'(t) + \frac{F'(\phi)}{F(\phi)} + (3-n)\frac{u'(t)}{u(t)} = 0. \tag{9}$$

Integrating this equation we obtain

$$\log\left(\frac{\phi'}{\sqrt{F(\phi)}}F(\phi)^{\phi'(t)}\right) = \log\left(u(t)^{n-3}\right). \tag{10}$$

Expanding $F(\phi)^{\phi'(t)}$, around $t = 0$, it results

$$F(\phi)^{\phi'(t)} = F(\phi)^{\phi'(0)}\Big\{1 + \log(F(\phi))\phi''(0)F(\phi)) + \frac{1}{2}\log(F(\phi))\left(\log(F(\phi))\phi''(0)^2 + \phi''(0)^{(3)}\right)F^2(\phi)\ \ldots\Big\}. \tag{11}$$

Adopting the boundary condition $\dot{\phi}(0) = 1$, we obtain from the expression above, in first order of $\phi(t)$ time derivative (for convergence reasons) (see for instance Tavakoli et al. (2021)),

$$\phi'^2(t)F(\phi) = \mathcal{K}u(t)^{2(n-3)}, \tag{12}$$

where $\mathcal{K}$ represents an integration constant.

From Equation (6), the following expression follows,

$$p_u = -u(t)^{1-n}u'(t) \ \rightarrow\ p_u' = -(1-n)\frac{u'(t)^2}{u(t)^n} - u(t)^{1-n}u''(t), \tag{13}$$

so

$$-\frac{2}{N}p_u' = 2(1-n)\frac{u'(t)^2}{u(t)^{2n}} + 2\frac{u''(t)}{u(t)^{2n}}. \tag{14}$$

With respect to the p_ϕ-dependent term in Equation (7), from (6) and (12), the following expression holds

$$\frac{3\omega}{u^{3\omega+1}}\frac{p_\phi^2}{F(\phi)} \rightarrow 3u(t)^{2(1-n)}F(\phi)\dot{\phi}(t)^2 = \frac{3\mathcal{K}}{u(t)^4}, \tag{15}$$

with $\omega = 1$.

Using Equation (6) to remove the dependence of the momenta p_u and p_ϕ in Equation (7), in combination with Equations (12), (14), and (15) we obtain

$$(1-2n)u'(t)^2 + 2u(t)u''(t) + u(t)^{2n}\left[g_k + 2g_q u - 3g_\Lambda u^2 + \tfrac{g_r}{u^2} + 3\tfrac{g_s+\mathcal{K}}{u^4}\right] = 0. \tag{16}$$

A common aspect throughout the evolutionary process of the scale factor concerns the origin of the current phase of the branch-cut Universe. BCG successfully addresses the issue of the primordial singularity. It consistently portrays the early Universe as a Riemannian foliation

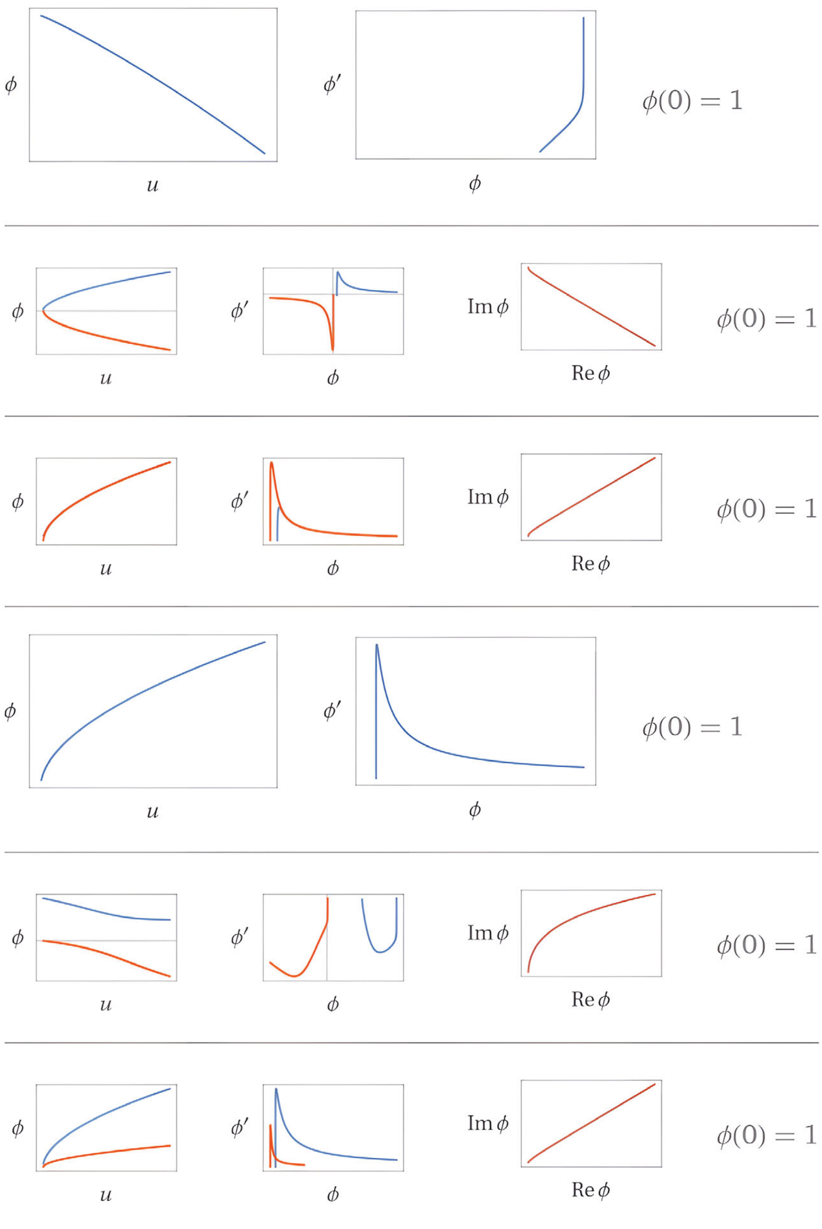

FIGURE 1 Typical $u(t) - \phi(t)$ trajectory solutions of Equation (12) in the case of chaotic inflation.

in which the singularities of the multiverse merge, giving rise to a smooth branching topological structure that resembles continuously connected Riemann surfaces. This structure introduces a new cosmic scale factor that is analytically continued into the complex plane that describes a transition region between the present stage of the Universe and its mirror counterpart. Our findings concerning the dynamics of the scale factor reveal that they are highly sensitive to both the initial conditions and the different parameterizations of the primordial matter content. The branch-cut Universe begins its expansion from a quantum leap in the mirror sector. Depending on the initial conditions, the branch-cut Universe presents an evolutionary behavior of the big crunch or moderate acceleration type.

3.1.1 | Chaotic inflation

In the context of the early universe's evolution, chaotic inflation emerges as a phase positing that this period is a natural and potentially inevitable outcome of the chaotic initial conditions in the early cosmos. To simulate the inflationary field's presence, we employ chaotic inflation to parameterize the coupling function, denoted as $F(\phi)$, expressed as

$$F(\phi) = \frac{1}{2} g_{\phi}^{2} \phi^{2}(t). \tag{17}$$

This choice of chaotic inflation serves as a method for modeling the inflationary phase, capturing the dynamical behavior resulting from quantum fluctuations and

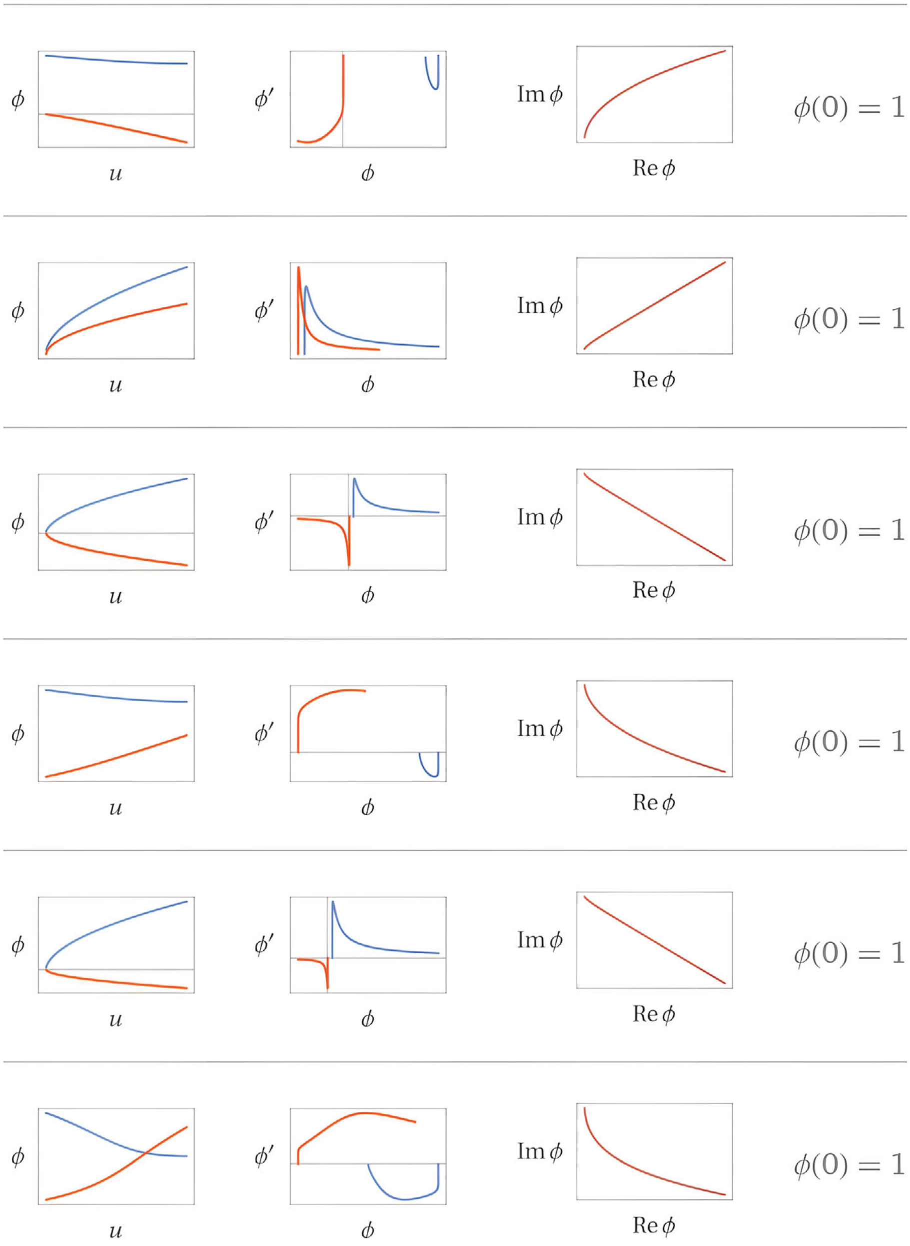

FIGURE 2 Additional typical $u(t) - \phi(t)$ trajectory solutions of Equation (12) in the case of chaotic inflation.

providing insights into the impact of initial conditions on cosmic evolution.

3.1.2 | Modeling inflation with a Fubini-type potential

In an alternative approach, we introduce the Fubini potential to model nonchaotic inflation and establish the coupling function $F(\phi)$. The Fubini potential is defined as

$$F(\phi) = \frac{\beta}{4}(\phi - \phi_c)^4 - \frac{1}{2}g_\phi^2(\phi - \phi_c)^2. \tag{18}$$

This nonchaotic inflationary model adds valuable insights into the analysis of the scalar field's role in the universe's evolution. Utilizing Equation (12), Figures 1 and 2 depict the trajectories in the $u(t) - \phi(t)$ plane for chaotic inflation scenarios, while Figures 3 and 4 show the corresponding nonchaotic inflation trajectories in the $u(t) - \phi(t)$ plane.

The observed patterns shown in Figures 1 and 2 suggest that the scalar field, coupled with the chaotic inflationary potential, facilitates a moderate expansion of the universe. This expansion is driven by the dynamics resulting from quantum fluctuations during the early stages of the cosmos. The trajectories indicate a relatively stable and sustained inflationary phase, portraying a scenario where the universe undergoes a gradual and controlled expansion.

Conversely, in the case of nonchaotic inflation scenarios, as shown in Figures 3 and 4, the trajectories exhibit

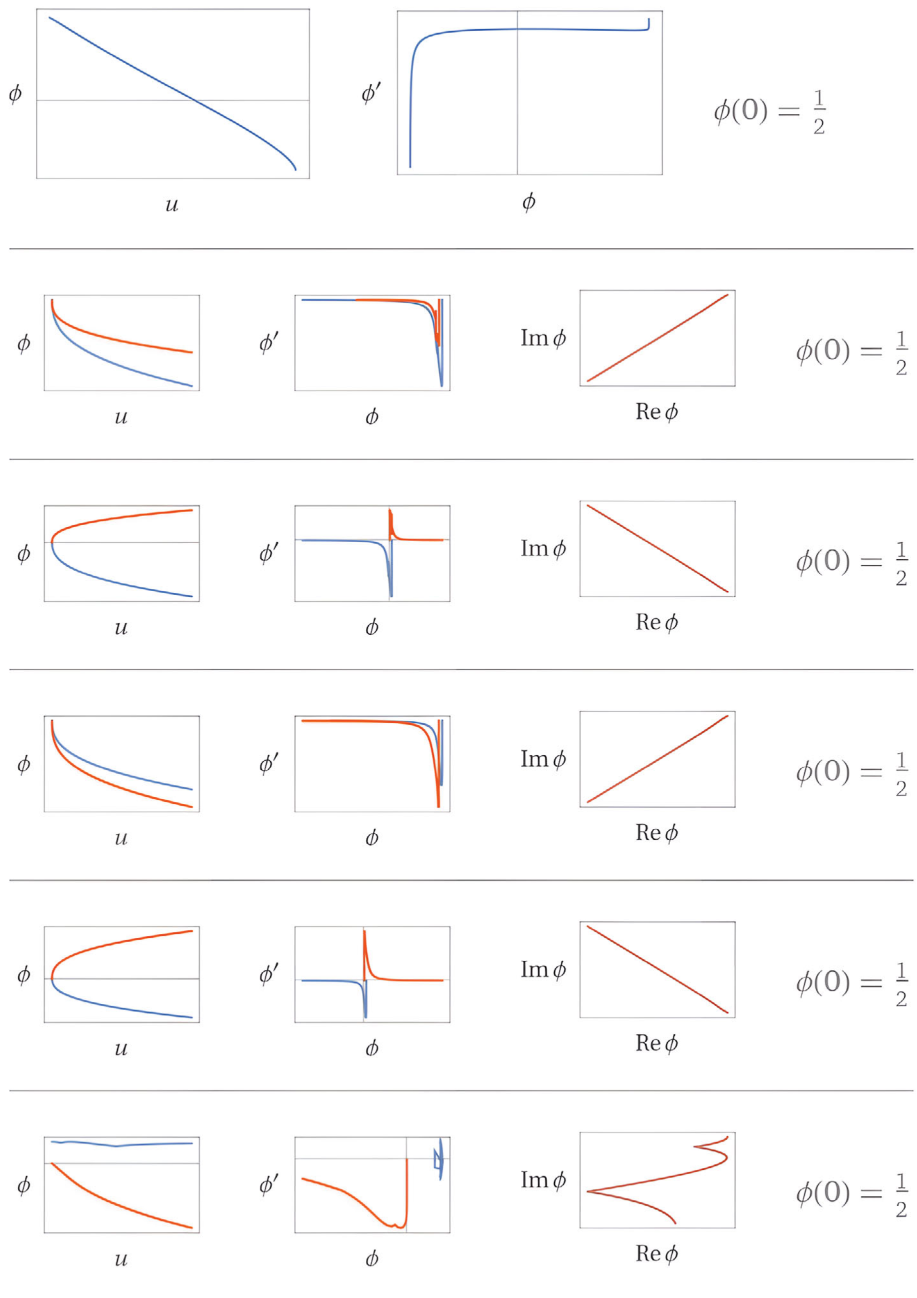

FIGURE 3 Typical $u(t) - \phi(t)$ trajectory solutions of Equation (12) in the case of nonchaotic inflation.

different patterns, indicating distinct behavior compared to chaotic inflation. The scalar field, influenced by the Fubini-type potential, plays a role in driving processes that may lead to outcomes reminiscent of the big crunch. This suggests that nonchaotic inflationary scenarios can result in more varied and potentially dramatic evolutionary paths for the universe. The trajectories in Figure 4 imply that the scalar field, under the influence of specific potentials, may not always lead to a gradual and stable expansion but could contribute to more dynamic and diverse evolutionary outcomes.

The comparison of potential shapes in Figure 5 further emphasizes the differences between chaotic and nonchaotic inflation. On the left, the generic form of the potential for chaotic inflation indicates a relatively smooth and gradual rise. On the right, the Fubini potential (de Alfaro et al. 1976) for nonchaotic inflation shows a more complex shape, suggesting that the scalar field dynamics in nonchaotic scenarios may involve more intricate and nonlinear behavior.

In summary, Figures 1–5 provide a visual representation of the distinct trajectories and potential shapes associated with chaotic and nonchaotic inflation scenarios. The implications extend to our understanding of how the scalar field, coupled with specific potentials, influences the evolution of the universe. This offers valuable insights into

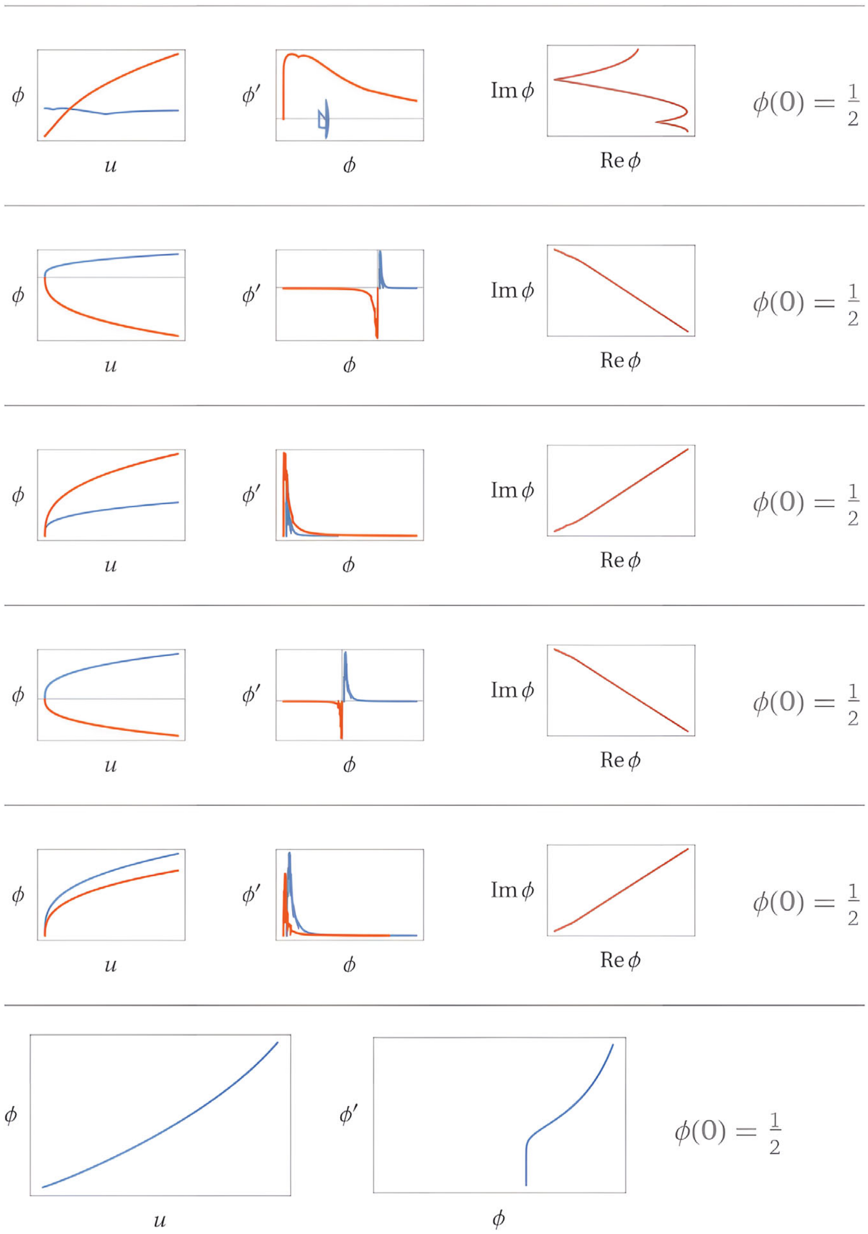

FIGURE 4 Additional typical $u(t) - \phi(t)$ trajectory solutions of Equation (12) in the case of nonchaotic inflation.

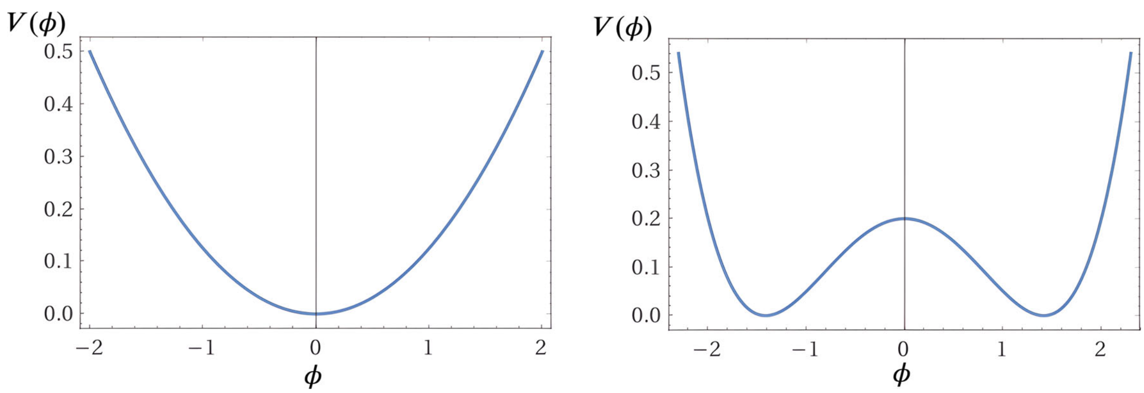

FIGURE 5 On the left, a generic form of the potential for the chaotic inflationary scenario. On the right, a typical form of the potential of the original nonchaotic inflationary model, based on the Fubini formulation.

the range of possible outcomes during the early stages of cosmic evolution.

4 | SUMMARY AND FINAL REMARKS

In this paper, we provide an exploration of the Hořava–Lifshitz Branch-Cut Action, shedding light on the intricate dynamics of the branched Universe, its inflationary scenarios, and the role of the scalar field in shaping cosmic evolution.

The Hořava–Lifshitz Branch-Cut Action encompasses various terms, each dependent on the scalar curvature $\mathcal{R}$ of the branched Universe and its derivatives in different orders. Key components include running coupling constants denoted as g_i, the Planck mass M_P, covariant derivatives ∇_i, and branching Ricci components of three-dimensional metrics. The Hořava–Lifshitz approach maintains the diffeomorphism property of General Relativity and aligns with the Arnowitt–Deser–Misner (ADM) formalism in the infrared limit.

In a mini-superspace of variables $(u(t), \phi(t))$, where $u(t) \equiv \ln^{-1}[\beta(t)]$ and $\phi(t)$ represents the scalar-inflaton field with a nonlinear self-interaction described by the coupling function $F(\phi)$, we formulate the action of the scalar field, S_ϕ. Combining the Hořava–Lifshitz and scalar field actions yields the Hamiltonian associated with this mini-superspace.

Canonical quantization procedures lead to the super-Hamiltonian $\mathcal{H}$, revealing the intricate interplay of terms involving the scale factor $u(t)$ and the scalar field $\phi(t)$. The ensuing Hamilton equations express the dynamical evolution of $u(t)$ and $\phi(t)$, providing insights into the evolution of the branched Universe.

We present a detailed analysis of the trajectories in the $u(t) - \phi(t)$ plane, exploring its solutions for different initial conditions. Figures 1–4 depict the evolution of the trajectories under various scenarios. The branch-cut Universe displays a complex and highly sensitive evolutionary behavior, influenced by both initial conditions and parameterizations of the primordial matter content. The model successfully addresses the issue of the primordial singularity, presenting a smooth branching topological structure that emerges from the merging singularities of the multiverse.

We differentiate between chaotic and nonchaotic inflation scenarios. Chaotic inflation is modeled through the coupling function $F(\phi) = \frac{1}{2}g_\phi^2\phi^2(t)$, while nonchaotic inflation employs the Fubini potential $F(\phi) = \frac{\beta}{4}(\phi - \phi_c)^4 - \frac{1}{2}g_\phi^2(\phi - \phi_c)^2$. Figures 1–4 visualize the $u(t) - \phi(t)$ trajectories for both scenarios. These trajectories illustrate how the scalar field's interplay with the chosen potentials contributes to the evolution of the scale factor, influencing either a moderate expansion or processes reminiscent of the big crunch.

AUTHOR CONTRIBUTIONS

Conceptualization: C.A.Z.V.; *Methodology*: C.A.Z.V., B.A.L.B., P.O.H., J.A.deF.P., D.H., F.W., and M.M.; *Software*: C.A.Z.V., B.A.L.B., M.R., and M.M.; *Validation*: C.A.Z.V., B.A.L.B., D.H., P.O.H., J.A.deF.P., F.W.; *Formal analysis*: C.A.Z.V., B.A.L.B., P.O.H., J.A.deF.P., D.H., F.W.; Investigation: C.A.Z.V., B.A.L.B., P.O.H., J.A.deF.P., M.R., G.A.D., M.M., and F.W.; *Resources*: C.A.Z.V.; *Data curation*: C.A.Z.V. and B.A.L.B.; *Writing–original draft preparation*: C.A.Z.V.; *Writing–review and editing*: C.A.Z.V., B.A.L.B., P.O.H., J.A.deF.P., D.H., G.A.D., M.R., M.M., and F.W.; *Visualization*: C.A.Z.V. and B.A.L.B.; *Supervision*: C.A.Z.V.; *Project administration*: C.A.Z.V. All authors have read and agreed to the published version of the article.

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REFERENCES

Abreu, E., Mendes, A., Oliveira-Neto, G., Ananias Neto, J., Rezende Rodrigues, J., & Silva de Oliveira, M. 2019, *Gen. Relativ. Gravit.*, *51*, 95.

Aharonov, Y., & Bohm, D. 1959, *Phys. Rev.*, *115*(3), 485.

Bertolami, O., & Zarro, C. A. 2011, *Phys. Rev. D*, *84*, 044042.

Bodmann, B., Hadjimichef, D., Hess, P., et al. 2023a, *Universe*, *9*(10), 428.

Bodmann, B., Zen Vasconcellos, C., de Freitas Pacheco, J., Hess, P., & Hadjimichef, D. 2022, *Astron. Nachr.*, *344*(1-2), e220086.

Bodmann, B., Zen Vasconcellos, C., Hess, P., de Freitas Pacheco, J., Hadjimichef, D., Razeira, M., & Degrazia, G. 2023b, *Universe*, *9*(6), 278.

Cordero, R., Garcia-Compean, H., & Turrubiates, F. J. 2019, *Gen. Relativ. Gravit.*, *51*, 138.

de Alfaro, V., Fubini, S., & Furlan, G. 1976, *Nuovo Cimento A*, *34*, 569.

de Freitas Pacheco, J., Zen Vasconcellos, C., Hess, P., Hadjimichef, D., & Bodmann, B. 2022, *Astron. Nachr.*, *344*(1-2), e220070.

Dirac, P. 1937, *Proc. R. Soc. A*, *160*(900), 48.

Einstein, A. 1916, *Ann. Phys.*, *49*, 769.
Einstein, A. 1917, *Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie*, König.-Preuss. Akad. Wiss (Berlin, Germany).
García-Compeán, H., & Mata-Pacheco, D. 2022, *Universe*, *8*(4), 237.
Guth, A. 1981, *Phys. Rev.*, *D23*, 347.
Guth, A. 2004, in: *Measuring and Modeling the Universe*, ed. W. L. Freedman, Vol. *2*, Cambridge Univ. Press, UK (Cambridge).
Hess, P. 2017, in: *Centennial of General Relativity: A Celebration*, ed. C. A. Z. Vasconcellos, World Scientific Pub. Co. (Singapore).
Hess, P., & Boller, T. 2020, in: *Topics on Strong Gravity: A Modern View on Theories and Experiments*, ed. C. A. Z. Vasconcellos, World Scientific Pub. Co. (Singapore).
Hess, P., & Greiner, W. 2009, *Int. J. Mod. Phys. E*, *18*(1), 51.
Hess, P., Vasconcellos, Z., de Freitas Pacheco, J., Hadjimichef, D., & Bodmann, B. 2023, *Astron. Nachr.*, *344*(6), e220101.
Hořava, P. 2009, *Phys. Rev. D*, *79*, 084008.
Kiefer, C. 2012, *Quantum Gravity*, 3rd. ed., Oxford University Press, Ed. (Oxford).
Kiritsis, E., & Kofinas, G. 2009, *Nucl. Phys.*, *821*, 467.
Maeda, K.-i., Misonoh, Y., & Kobayashi, T. 2010, *Phys. Rev. D*, *82*, 064024.
Manders, K. 1989, *J. Philos.*, *86*(10), 553.
Tavakoli, F., Vakili, B., & Ardehali, H. 2021, *Adv. High Energy Phys.*, *2021*, 6617910.
Vieira, H., Bezerra, V., Muniz, C., Cunha, M., & Christiansen, H. 2020, *Phys. Lett. B*, *809*, 135712.
Weber, F., Hess, P., Bodmann, B., et al. 2024, *Astron. Nachr.*, in press.
Wu, K.-D., Kondra, T., Rana, S., et al. 2021, *Phys. Rev. Lett.*, *126*(9), 090401.
Zen Vasconcellos, C., Hadjimichef, D., Razeira, M., Volkmer, G., & Bodmann, B. 2019, *Astron. Nachr.*, *340*, 857.
Zen Vasconcellos, C., Hess, P., de Freitas Pacheco, J., Hadjimichef, D., & Bodmann, B. 2023, *Astron. Nachr.*, *344*(6), e220079.
Zen Vasconcellos, C., Hess, P., Hadjimichef, D., Bodmann, B., Razeira, M., & Volkmer, G. 2021a, *Astron. Nachr.*, *342*(5), 776.
Zen Vasconcellos, C., Hess, P., Hadjimichef, D., Bodmann, B., Razeira, M., & Volkmer, G. 2021b, *Astron. Nachr.*, *342*(5), 765.

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