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学位論文題目 Testing inflation models by primordial black holes,
gravitational wave and the Swampland conjectures

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博士論文の要旨

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論文題目：Testing inflation models by primordial black holes, gravitational wave and the Swampland conjectures

In the past, the standard Big Bang theory described by the cosmological principle and general relativity, had long been believed to provide a theory explaining the origin and evolution of the Universe. However, the standard Big Bang theory suffers from several problems, among which representative examples include the horizon problem, the flatness problem, the monopole problem, and the origin of primordial density perturbations. For instance, taking the flatness problem as an example, in the standard Big Bang theory the Hubble horizon increases monotonically, and hence in the early Universe the Ω parameter of curvature must be fine-tuned to an extremely small value. The origin of these difficulties lies in the fact that the cosmic expansion caused by radiation or matter is decelerated. To address these several fundamental problems in standard Big Bang cosmology, inflation that is accelerated expansion provides elegant resolutions. At present, it is widely accepted as a theory that explains the present Universe from more general initial conditions.

However, revealing the underlying mechanism responsible for inflation still remains one of the most urgent and central issues in modern cosmology. In addition, despite its theoretical successes, the precise nature of the scalar field ϕ , commonly referred to as the inflaton field, has not yet been established. Furthermore, neither the energy scale at which inflation occurred nor its precise epoch in cosmic history has been directly probed by current observational data. Although many inflationary models consistent with observational data, have been proposed, no model has been uniquely identified. Therefore, in order to constrain the precise nature of the inflaton field and, ultimately, to identify a specific inflation model, we impose constraints from both a bottom-up perspective based on observations and a top-down perspective based on UV-complete theories at high energy scales.

We first consider the bottom-up perspective, which is provided by observations of the cosmic microwave background (CMB). Inflation can explain the origin of quantum perturbations. This means inflation generates curvature perturbations, and spatial variations of these curvature perturbations lead to temperature

anisotropies in the CMB. Therefore, comparing the physical quantities theoretically predicted by inflation with current CMB observations provides a means to test inflation. In particular, its temperature anisotropies and polarization patterns have so far yielded only an upper bound on the energy scale of inflation, constraining it to be below approximately 10^{16} GeV. This constraint is rewritten in terms of the tensor-to-scalar ratio r , and the most stringent current bound is $r < 0.036$.

On the other hand, from a top-down perspective, there exist complementary efforts to constrain the energy scale of inflation based on internal consistency relations derived from purely theoretical considerations. One such relation is the Lyth bound, which applies to slow-roll models with super-Planckian field excursions and provides a model-independent lower bound on r . However, even when both the observational bounds and the theoretical lower bounds discussed above are taken into account, substantial uncertainties remain regarding the model-dependent functional form of the inflaton potential $V(\phi)$ and the total field excursion $\Delta\phi$ during inflation.

Furthermore, recent developments in quantum gravity, particularly in string theory, have motivated theoretical constraints on effective field theories through what are known as the Swampland Conjectures. The Swampland Distance Conjecture proposes that effective field theories with trans-Planckian field excursions are incompatible with a consistent UV completion in quantum gravity, and that, in order to remain within the Landscape, which is the regime of EFT control, the Hubble scale H must decrease accordingly. At present, among the Swampland Conjectures, the Swampland Distance Conjecture is supported by a substantial amount of evidence comparing with other conjectures, and if it is valid, it would impose nontrivial theoretical constraints and yield new exclusions that could not be obtained from previous observations. In this paper, unlike previous studies, we successfully impose constraints on the parameter space of the inflationary potential by applying these constraints to concrete inflationary models. The new results obtained from this theoretical perspective are more restrictive than those from Planck2018, and as we will see in the following, they provide a stepping stone toward identifying a inflation model.

In addition to the above constraints on general inflationary models, theoretical models beyond the standard model such as supergravity or superstring theory, generically predict many light scalar fields. Therefore, it is more natural to consider multi-field inflation, in which multiple scalar fields contribute to the inflaton dynamics, rather than single-field inflation. Within such multi-field inflationary scenarios, there exist possibilities that observational signatures

arising during inflation or from transitions may provide specific clues for model discrimination. In several multi-field inflationary scenarios, the Universe undergoes multiple-field transitions during inflation, analogous to phase transitions. Identifying the role of these transitions through observations could provide decisive information about the ultimate theory to describe the early Universe.

In some of these models, interactions between fields can cause resonant field excitations during inflation. A classical example is the so called "Trapped Inflation". But resonances during inflation and their impact on the primordial perturbation had been studied even earlier. Many of the works are based on the mechanism suggested, where moduli fields of string theory are stabilised by the backreaction of resonantly produced particles. As moduli field(s) pass through or close to (in the case of multi-field inflation) a critical point in field space, some real scalar field χ is rendered massless. Thus, this point was naturally denoted by the name "Enhanced Symmetry Point" (ESP). Around ESP the effective mass of χ is changing non-adiabatically, which induces resonant excitations. The excitations backreact onto the motion of the inflaton, modifying its dynamics.

In this work we consider a somewhat modified scenario. Instead of the field χ becoming massless at the critical point, we allow it to become tachyonic, i.e. its mass squared to become negative. Hence, for some parameter values the resonance resembles the one studied, which they called "Tachyonic Resonance". To emphasize this difference, we name the critical point as the "Symmetry Breaking Point" (SBP). The idea for such a scenario is inspired by the tachyonic trap mechanism, employed to provide an alternative method of reheating for non-oscillatory potentials and to prevent the scalar field of the quintessential inflation scenario from reaching superplanckian values.

The current scenario is explored in the context of the supersymmetry-inspired multi-field running-mass model. Augmenting the running-mass-inflation (RMI) with the tachyonic trap mechanism provides a concrete scenario by which inflation can end in a form similar to hybrid inflation. The current treatment, however, differs from the usual considerations of hybrid inflation. First, we take the waterfall phase, i.e. the evolution in the χ direction in field space, to last more than 10 e-folds, which requires a very flat potential. In such a setup, the tachyonic trap becomes essential to redirect the field evolution from the RMI direction into the waterfall one, at least for parameter ranges considered in this work.

The tachyonic resonance at SBP has another important effect: it generates a sharp peak in the spectrum of the primordial perturbation P_ζ at small scales. The amplitude of that peak can be enhanced by several orders of magnitude relative to the slow-roll result on large scales. Combined with the large spectral running of RMI, the spectrum can reach as high values as $P_\zeta \sim 10^{-1.5}$. The resulting large curvature perturbation at the small scales has distinct observational consequences.

Later, upon horizon reentry in the early Universe, the large curvature perturbation can trigger gravitational collapse, leading to the formation of the primordial black holes (PBHs). PBHs with masses in the range 10^{17} g – 10^{23} g can serve as dark matter candidates. This scenario can be constrained or confirmed by future gamma-ray observations and related astrophysical probes. After that, we can see that this multi-field Trapped inflation consistent with observations generates enough amount of PBHs as DM candidates to explain almost DM.

Second, the same perturbations generate stochastic induced gravitational waves (SIGWs) through nonlinear second-order effects. These SIGWs, peaking in the deci-Hz band, provide promising targets for future gravitational-wave detectors such as LISA, DECIGO, and BBO. In the current analysis, we incorporate recent refinements accounting for the dissipation of small-scale fluctuations, yielding state-of-the-art predictions for the SIGW spectrum.

Third, PBHs formed in the early Universe can assemble into binaries through many-body gravitational interactions. The mergers of these binaries also generate a stochastic background of gravitational waves. Remarkably, such merger signals may be detectable not only by DECIGO and BBO but also through resonant cavity experiments exploiting the inverse Gertsenshtein effect, originally proposed in the context of axion searches. In general, in conventional studies of gravitational waves (GWs) generated from binaries, the abundance of PBHs has often been assumed to be nearly 100%. In contrast, in this paper we compute not only the GW spectra generated from PBH binaries arising from generic PBH mass distributions, but also the GW spectra predicted within the specific inflationary model considered here. As mentioned above, these signals may be detectable by future observations, and moreover, since different inflationary models generate distinct GW spectra, they can serve as a means to distinguish inflationary models.

博士論文審査結果

Name in Full

氏 名 古田 悠真

T i t l e

論文題目

Testing inflation models by primordial black holes, gravitational wave and the Swampland conjectures

古田悠真氏の学位論文は、次の 2 編の論文で行われた彼のオリジナルな研究に基づいて書かれている。

- 1) Y. S. Furuta, M. Karčiauskas, K. Kokri, and A. Saez, "Primordial Black Holes as Dark Matter and the Tachyonic Trap During Inflation" arXiv:2511.23182,
- 2) Y.S. Furuta, Y. Hamada, and K. Kohri, "Inflation models selected by the swampland distance conjecture with the Lyth bound", Phys. Rev. D 112 (2025) 10, 103517.

1 つ目の論文では、タキオニックトラップ・インフレーションと呼ばれる、ハイブリッドインフレーションの特殊なモデルにおける、小スケールにおいて大きな曲率ゆらぎが得られるモデルにおいて、誘導重力波の生成、原始ブラックホールの形成と、その連星による合体重力波を議論している。この論文は現在、Physical Review D 誌に投稿中である。2 つ目の論文では、スワンプランド距離予想により、ヒルトップインフレーションなど、インフレーションモデルが選別される場合があることが指摘されている。

学位論文の構成は冒頭にインフレーション宇宙のレビューがあり、引き続き、1 つ目のタキオニックトラップ・インフレーションの解説が書かれている。その中でも新しい研究として、散逸がある場合の誘導重力波の定式化と議論、原始ブラックホール連星による合体重力波についての新しい計算が特徴的である。特に、散逸がある場合の誘導重力波はここ 1 年以内に明らかになってきた現象であり、世界的な競争の中で出願者がいち早く習得して発展させたことは顕著な成果である。また、ダークマターになることができる原始ブラックホール連星からの合体重力波の正確な計算とその予想されるシグナルを明快に示した研究は少なく、極めてオリジナルな研究となっている。学位論文の後半に 2 つ目の論文で議論されたスワンプランド距離予想によるインフレーションモデルの選別についての詳しい解説が記述されており、弦理論と宇宙論を繋ぐ特徴的な内容となっている。

学位論文は平易な英語で書かれている。また、学会発表や普段のセミナーにおいても英語発表を問題なく行っており、総研大経費でリトアニアに単身で研究打ち合わせに渡航するなど、外国人研究者と不自由なく議論する英語能力を有していることが認められる。

これらの結果は学術的に十分な価値が認められるものであり，博士論文の内容として必要な水準を満たしていると判断し，古田氏の博士論文本審査を合格と判定した.