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研究課題名（和文）ヒッグス・ポテンシャルの臨界性とインフレーション

研究課題名（英文）Criticality of Higgs potential and inflation

研究代表者
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研究成果の概要（和文）：2012年のヒッグス粒子の発見後に、我々自身のものを含む多くの研究により、素粒子の標準模型が、量子重力の効果が顕著になるプランク・スケール（現在みているTeVスケールよりさらに千兆倍も上のスケール）まで正しいと仮定しても、理論的な矛盾が生じないことが明らかとなった。一方、宇宙論の分野では素粒子の標準模型では説明のつかない、暗黒物質の存在、および、インフレーションの存在が確実となった。このような状況のもとで、標準模型がプランク・スケールで臨界性を示す、という事実を積極的に取り入れ、ヒッグス場がインフレーションを引き起こす臨界ヒッグス・インフレーションを提唱し、様々な物理的帰結を調べた。

研究成果の概要（英文）：After the discovery of the Higgs particle in 2012, researchers, including ourselves, revealed that the Standard Model of particle physics can be theoretical consistent up to the Planck scale, which is quadrillion times larger than the currently observed TeV scale. On the other hand, the success of the Standard Cosmology has made certain that we need physics beyond the Standard Model such as the dark matter and the inflation. Under this situation, we have proposed the critical Higgs inflation, in which the Higgs field causes the inflation, and studied various physical consequences.

研究分野：　素粒子論

キーワード：　ヒッグス　インフレーション　標準模型　臨界性　暗黒物質　ニュートリノ

１．研究開始当初の背景
2012 年のヒッグス粒子の発見後に、我々自身のものを含む多くの研究により、素粒子の標準模型が、量子重力の効果が顕著になるプランク・スケール（現在みている TeV スケールよりさらに千兆倍も上のスケール）まで正しいと仮定しても、理論的な矛盾が生じないことが明らかとなった。一方、宇宙論の分野では素粒子の標準模型では説明のつかない、暗黒物質の存在、および、インフレーションの存在が確実となった。このような状況のもとで我々は、標準模型がプランク・スケールで臨界性を示す、という事実を積極的に取り入れ、ヒッグス場がインフレーションを引き起こす臨界ヒッグス・インフレーションを提唱した。

２．研究の目的
臨界ヒッグス・インフレーションの宇宙論的帰結を調べ、将来観測可能な理論的予言を行う。

３．研究の方法
理論研究であるので最も重要となるのは議論である。それをもとに必要な計算を行い、論文を書き、国際会議で発表する。

４．研究成果
超弦理論において臨界ヒッグス・インフレーションの仮定がどのような意味を持つかを調べ、ヒッグス場を大きくしていく方向が余剰次元が広がる方向と繋がる可能性を発見した。漸近安全重力の下でヒッグス・インフレーションにつながる非ミニマル結合を含むヒッグス湯川系を調べ、世界で初めてフェルミオンの寄与が非ミニマル結合の紫外極限の振る舞いを逆転させることを発見した。

以下、研究成果のより詳しい英文の概要を記す。

Relativity for games

We present how to implement special relativity in computer games. The resultant relativistic world shows the time dilation and Lorentz contraction exactly, not only for the player but also for all the nonplayer characters, who obey the correct relativistic equation of motion according to their own accelerations. Causality is explicitly maintained in our formulation by use of covariant velocities, proper times, worldlines, and light cones. Faraway relativistic scenes can be accurately projected onto the skydome. We show how to approximate a rigid body consisting of polygons, which is ubiquitous in computer games but itself is not a relativistically invariant object. We also give a simple idea to mimic the Doppler effect within the RGB color scheme.

Eternal Higgs inflation and cosmological constant problem

We investigate the Higgs potential beyond the Planck scale in the superstring theory, under the assumption that the supersymmetry is broken at the string scale. We identify the Higgs field as a massless state of the string, which is indicated by the fact that the bare Higgs mass can be zero around the string scale. We find that, in the large field region, the Higgs potential is connected to a runaway vacuum with vanishing energy, which corresponds to opening up an extra dimension. We verify that such universal behavior indeed follows from the toroidal compactification of the non-supersymmetric $SO(16)\times SO(16)$ heterotic string theory. We show that this behavior fits in the picture that the Higgs field is the source of the eternal inflation. The observed small value of the cosmological constant of our universe may be understood as the degeneracy with this runaway vacuum, which has vanishing energy, as is suggested by the multiple point criticality principle.

Non-minimal coupling in Higgs-Yukawa model with asymptotically safe gravity

We study the fixed point structure of the Higgs-Yukawa model, with its scalar being non-minimally coupled to the asymptotically safe gravity, using the functional renormalization group. We have obtained the renormalization group equations for the cosmological and Newton constants, the scalar mass-squared and quartic coupling constant, and the Yukawa and non-minimal coupling constants, taking into account all the scalar, fermion, and graviton loops. We find that switching on the fermionic quantum fluctuations makes the non-minimal coupling constant irrelevant around the Gaussian-matter fixed point with the asymptotically safe gravity.

Meaning of the field dependence of the renormalization scale in Higgs inflation

We consider the prescription dependence of the Higgs effective potential under the presence of general nonminimal couplings.

We evaluate the fermion loop correction to the effective action in a simplified Higgs-Yukawa model whose path integral measure takes simple form either in the Jordan or Einstein frame. The resultant effective action becomes identical in both cases when we properly take into account the quartically divergent term coming from the change of measure. Working in the counterterm formalism, we clarify that the difference between the prescriptions I and II comes from the counter term to cancel the logarithmic divergence. This difference can be absorbed into the choice of tree-level potential from the infinitely many possibilities, including all the higher-dimensional terms. We also present another mechanism to obtain a flat potential by freezing the running of the effective quartic coupling for large field values, using the nonminimal coupling in the gauge kinetic function.

Di-higgs enhancement by neutral scalar as probe of new colored sector

We study a class of models in which the Higgs pair production is enhanced at hadron colliders by an extra neutral scalar. The scalar particle is produced by the gluon fusion via a loop of new colored particles, and decays into di-Higgs through its mixing with the Standard Model Higgs. Such a colored particle can be the top/bottom partner, such as in the dilaton model, or a colored scalar which can be triplet, sextet, octet, etc., called leptoquark, diquark, coloron, etc., respectively. We examine the experimental constraints from the latest Large Hadron Collider (LHC) data, and discuss the future prospects of the LHC and the Future Circular Collider up to 100TeV. We also point out that the 2.4σ excess in the $bb\gamma\gamma$ final state reported by the ATLAS experiment can be interpreted as the resonance of the neutral scalar at 300GeV.

Hill-climbing Higgs inflation

We propose a realization of cosmic inflation with the Higgs field when the Higgs potential has degenerate vacua by employing the recently proposed idea of hillclimbing inflation. The resultant inflationary predictions exhibit a sizable deviation from those of the ordinary Higgs inflation.

Cosmological implications of Standard Model criticality and Higgs inflation

The observed Higgs mass indicates that the Standard Model can be valid up to near the Planck scale MP. Within this framework, it is important to examine how little modification is necessary to fit the recent experimental results in particle physics and cosmology. As a minimal extension, we consider the possibility that the Higgs field plays the role of inflaton and that the dark matter is the Higgs-portal scalar field. We assume that the extended Standard Model is valid up to the string scale 10^17GeV. (This translates to the assumption that all the non-minimal couplings are not particularly large, $\xi \lesssim 10^2$, as in the critical Higgs inflation.) We find a correlated theoretical bound on the tensor-to-scalar ratio r and the dark matter mass mDM. As a result, the Planck bound $r<0.09$ implies that the dark-matter mass must be smaller than 1.1TeV, while the PandaX-II bound on the dark-matter mass $mDM>0.7\pm0.2$TeV leads to $r\gtrsim 2\times10^{-3}$. Both are within the range of near-future detection. When we include the right-handed neutrinos of mass $M_R \sim 10^{14}$GeV, the allowed region becomes wider, but we still predict $r\gtrsim 10^{-3}$ in the most of the parameter space. The most conservative bound becomes $r>10^{-5}$ if we allow three-parameter tuning of m_{DM}, M_R, and the top-quark mass.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

〔雑誌論文〕（計６件・すべて査読有）

1. Phys.Rev. D97 (2018) 023523
Hill-climbing Higgs inflation
R. Jinno, K. Kaneta, K. Oda

2. Progress of Theoretical and Experimental Physics, Volume 2017, Issue 11, 1 November 2017, 113J01
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3. Eur.Phys.J. C77 (2017) 273
Di-higgs enhancement by neutral scalar as probe of new colored sector
K. Nakamura, K. Nishiwaki, K. Oda, S. C. Park, Y. Yamamoto

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Meaning of the field dependence of the renormalization scale in Higgs inflation

Y. Hamada, H. Kawai, Y. Nakanishi, K. Oda

5. Class.Quant.Grav. 33 (2016) 125011
Non-minimal coupling in Higgs-Yukawa model with asymptotically safe gravity
K. Oda, M. Yamada

6. Phys.Rev. D92 (2015) 045009
Eternal Higgs inflation and cosmological constant problem
Y. Hamada, H. Kawai, K. Oda

〔学会発表〕（計 15 件）
以下では招待講演のみを記す。すべて本人 Kin-ya Oda による発表である。
（うち２件は次の未掲載論文
[arXiv:1709.09350]
Cosmological implications of Standard Model criticality and Higgs inflation
Y. Hamada, H. Kawai, Y. Nakanishi, K. Oda
についての招待講演である。）

1.“Higgs inflation puts lower and upper bounds on tensor-to-scalar ratio and on Higgs-portal-dark-matter mass”
The 7th KIAS Workshop on Particle Physics and Cosmology and The 2nd KEK-NCTS-KIAS Workshop on Particle Physics Phenomenology, 6-10 November 2017, KIAS, Korea

2.“Higgs inflation under SM criticality: Higgs portal dark matter, neutrino and hill- climbing”
International workshop “Energy Frontier in Particle Physics: LHC and Future Colliders,” 29-30, September 2017, National Taiwan Unversity, Taiwan.

3.“Multiple point principle in (non-super) superstring, and Higgs inflation” 3rd RISE Collaboration Meeting, University of Toyama, 6-7 March 2017.

4.“Quantum corrections in Higgs inflation”
IBS-PNU Joint Workshop on Particle Physics and Cosmology, 30 November-2 December 2016, Pusan National University, Korea.

5.“Non-minimal couplings, frame/prescription (in)dependence, and Higgs inflation”
The 1st KEK-KIAS-NCTS Joint Workshop on Particle Physics Phenomenology, 26-28 May 2016, National Tsing Hua University, Taiwan.

6.“Higgs inflation and fate of our universe”
Symposium: New Generation of Quantum Theory—Particle Physics, Cosmology, and Chemistry—, 7-9 March 2016, Kyoto University

7.“Eternal Higgs inflation”
Workshop on Particles and Cosmology, 13-19 September 2015, 15th Hellenic School and Workshops on Elementary Particle Physics and Gravity, Corfu, Greece.

8.「相対論的ゲームを作る」
日本デジタルゲーム学会、2015 年夏季研究発表大会、企画セッション「物理学とゲーム開発」–ゲームにおける物理学の役割と可能性–招待講演、2015 年 8 月 1 日、日本大学 生産工学部 津田沼キャンパス。

〔図書〕（計 0 件）

〔産業財産権〕

○出願状況（計 0 件）

名称：
発明者：
権利者：
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〔その他〕
ホームページ等

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