中国科学院大学物理科学学院

奖学金申请表

学科专业	理论物理	学生姓名	王清扬
导师姓名	汤勇	本人联系方式	18561769501
就读年级	直博第 5 年		
研究方向	宇宙学	攻读学位	理学博士
此次申报奖学金名称		国家奖学金和朱李月华优秀博士生奖	

在学期间学习成绩、科研工作及取得的成果介绍（须附原件或复印件。对于每项科研工作，要求写清楚申请人的科学贡献与价值。）

论文：（请按重要性填写 5 **篇以内**已接收的论文代表作，本人姓名请**标黑并以下划线标注**，论文已接收未发表请标注并在附件中附接收证明）

1. Dark matter production in Weyl R^2 inflation. **Q. Y. Wang**, Y. Tang and Y. L. Wu. *Phys.Rev.D* **106** (2022) 2, 023502. （第一作者）
2. Inflation in Weyl scaling invariant gravity with R^3 extensions. **Q. Y. Wang**, Y. Tang and Y. L. Wu. *Phys.Rev.D* **107** (2023) 8, 083511.（第一作者）

专利：（请按重要性填写申请或授权专利状况，并标注是否被授权，本人姓名请**标黑并以下划线标注**）

无

书籍著作： 1. 翻译图书《宇宙从哪里来：从量子物理学到宇宙结构》，人民邮电出版社，2023.07.
在学期间获奖情况（须附原件或复印件） **国科大优秀学生荣誉称号：** 1. 中国科学院大学 2021-2022 学年三好学生标兵 2. 中国科学院大学 2022-2023 学年三好学生标兵 **其他获奖情况：** 1. 中国科学院大学首届科普科幻作品大赛科普图文组优秀奖
在学期间参加公共服务情况 1. 2020-2021、2021-2022、2022-2023、2023-2024 学年《粒子物理基础》课程助教 2. 2020-2021、2021-2022、2022-2023 学年《规范场理论》课程助教
推荐意见（推荐人原则上应为申请人导师，并佐证申请人对学术成果的科学贡献与价值）： 在以上研究工作中，王清扬作为文章的第一作者，完成了标度不变引力理论下的暴胀理论模型构造和暗物质剩余丰度的理论和数值计算。这些工作为我们理解宇宙起源和早期宇宙演化提供了理论依

据，同时还能解释暗物质的起源，为后续工作提供有意义的参考，得到国际同行的正面引用。 **推荐人签名：** 汤勇 **日期：**2023.09.26
学生郑重承诺以上陈述及提交的全部书面材料真实有效。 学生签字：郑清均　　日期：2023.09.26

注意事项：

1. **表中涉及情况若没有请填写“无”；**
2. **证明材料请按上述填写顺序排列，并将对应序号标注在材料右上角（可铅笔标注）；**

证明材料：

（1）论文

PHYSICAL REVIEW D **106,** 023502 (2022)

Dark matter production in Weyl R^2 inflation

Qing-Yang Wang,[1] Yong Tang,[1,2,3,4,*] and Yue-Liang Wu[1,2,3,5]

[1]*University of Chinese Academy of Sciences (UCAS), Beijing 100049, China*
[2]*School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024, China*
[3]*International Center for Theoretical Physics Asia-Pacific, Beijing/Hangzhou, China*
[4]*National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China*
[5]*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

(Received 6 April 2022; accepted 23 June 2022; published 6 July 2022)

Dark matter and inflation are two key elements to understand the origin of cosmic structures in modern cosmology, and yet their exact physical models remain largely uncertain. The Weyl scaling invariant theory of gravity may provide a feasible scheme to solve these two puzzles jointly, which contains a massive gauge boson playing the role of dark matter candidate and allows the quadratic scalar curvature term, namely R^2, to realize a viable inflationary mechanism in agreement with current observations. We ponder on the production of dark matter in the Weyl R^2 model, including the contribution from the nonperturbative production due to the quantum fluctuations from inflationary vacuum and perturbative ones from scattering. We demonstrate that there are generally three parameter regions for viable dark matter production: (1) If the reheating temperature is larger than 10^3 GeV, then the Weyl gauge boson as dark matter can be produced abundantly with mass larger than the inflation scale $\sim 10^{13}$ GeV. (2) Small mass region with 3×10^{-13} GeV for a higher reheating temperature. (3) Annihilation channel becomes important in the case of higher reheating temperature, which enables the Weyl gauge boson with a mass up to 4×10^{16} GeV to be produced through freeze-in.

DOI: 10.1103/PhysRevD.106.023502

I. INTRODUCTION

Dark matter is an effective paradigm to explain the various observations in galactic rotation curve, cosmic large scale structures, and the gravitational lensing of clusters [1–4]. Studies of the primordial nucleosynthesis [5] and the power spectrum of cosmic microwave background (CMB) [6] also provide strong evidence that there is abundant missing matter whose present total amount is about five times that of visible matter described by the standard model (SM) of particle physics. As for the physical essence of dark matter, however, it still remains obscure. All experiments so far have not identified whether dark matter interacts with SM particles except gravity [7–9].

In this paper, we ponder on a new kind of vector dark matter [10,11] from the Weyl scaling invariant theory of gravity [12,13]. Weyl symmetry with various forms has wide applications in cosmological physics [14–18]. It can naturally introduce a local scaling symmetry associated with a gauge boson (called a Weyl gauge boson or WGB), which acquires a mass from the symmetry breaking. The consideration of Weyl gravity is also motivated by the reasonableness of introducing a quadratic scalar curvature term R^2 into theory [19–21]. It can provide a successful inflationary mechanism with observational conformity, albeit it has a different form under the Weyl geometry [22–25]. Our previous study has discussed Weyl R^2 inflation [21] and briefly the production of dark matter. However, the intrinsic connection between the inflaton and WGBs has not been fully explored. The purposes of this paper are twofold. First, we use the latest cosmological observations to update the preferred parameter space for Weyl R^2 inflation. Second, we identify the viable dark matter mass range by considering all the production channels.

There are several contributions for the production of WGBs. If dark matter is already massive during inflation, there will be an important nonperturbative production mechanism [26–37] that is due to the quantum fluctuations in rapidly expanding background [38–45]. Other important contributions are also present after inflation, such as producing from inflaton decay or the annihilation from particles in thermal bath after reheating [46–59]. The previous study

*Corresponding author.
tangy@ucas.ac.cn

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

Inflation in Weyl scaling invariant gravity with R^3 extensions

Qing-Yang Wang,[1] Yong Tang,[1,2,3,4,*] and Yue-Liang Wu[1,2,3,5]

[1]*University of Chinese Academy of Sciences (UCAS), Beijing 100049, China*
[2]*School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024, China*
[3]*International Center for Theoretical Physics Asia-Pacific, Beijing/Hangzhou, China*
[4]*National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China*
[5]*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

(Received 17 January 2023; accepted 28 March 2023; published 13 April 2023)

The cosmological observations of cosmic microwave background and large-scale structure indicate that our universe has a nearly scaling invariant power spectrum of the primordial perturbation. However, the exact origin for this primordial spectrum is still unclear. Here, we propose the Weyl scaling invariant $R^2 + R^3$ gravity that gives rise to inflation that is responsible for the primordial perturbation in the early universe. We develop both analytic and numerical treatments on inflationary observables, and find this model gives a distinctive scalar potential that can support two different patterns of inflation. The first one is similar to that occurs in the pure R^2 model, but with a wide range of tensor-to-scalar ratio r from $\mathcal{O}(10^{-4})$ to $\mathcal{O}(10^{-2})$. The other one is a new situation with not only slow-roll inflation but also a short stage of oscillation-induced accelerating expansion. Both patterns of inflation have viable parameter spaces that can be probed by future experiments on cosmic microwave background and primordial gravitational waves.

DOI: 10.1103/PhysRevD.107.083511

I. INTRODUCTION

Inflation is a hypothetical epoch of exponential expansion introduced in the very early universe to solve the cosmological horizon and flatness problems [1,2]. It is also a reasonable scheme to explain the origin of primordial density perturbations, which plays the role of the seeds that formed the structure of current universe [3]. In recent years, the precise measurement of cosmic microwave background (CMB) presents us with an almost scale invariant spectrum of primordial perturbations [4]. This result is usually explained by an approximate de Sitter spacetime of the very early universe [5–9]. Moreover, it is theoretically explored that there is a more profound and basic principle behind the phenomenon, namely, local Weyl scaling invariance of the universe. This symmetry is first proposed by H. Weyl in the attempt of understanding gravity and electromagnetism in a unified framework [10,11], and after a century of development, it has been applied extensively to particle physics, cosmology [12–31] and gauge theory of gravity [32–35].

Lately, inflation in the Weyl scaling invariant theory of gravity, especially induced by a quadratic curvature term R^2, has been of many concern [36–46]. Comparing with the conventional R^2 model, which is also called the Starobinsky model [47–50], the scaling invariant version not only allows a viable inflation scenario with good observational agreement, but also provides a framework to comprehend another fundamental puzzles, such as the hierarchy problem [38,41,51] and dark matter candidates [42,46].

However, inflation with only quadratic scalar curvature might be just a simplistic scenario. From the viewpoint of effective field theory, any higher-order curvature effects may exist and play a role in the early universe. Hence it is reasonable to evaluate their impacts on inflation. Generally, the extensions with high-order tensors, like $R_{\mu\nu}R^{\mu\nu}$ or $R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$, can result in unacceptable ghost degrees of freedom [52], while the terms of arbitrary functions of the Ricci scalar are known to be safe. Therefore, in this paper, we consider a minimal extension of Ricci scalar beyond the R^2 model with Weyl scaling invariance, namely a cubic term coupled with an extra scalar field as denominator R^3/φ^2. We will show that even if this term is extremely small, it will have an essential impact on inflation, which even open up a completely different inflationary scenario from Weyl R^2 and conventional $R^2 + R^3$ models.

The paper is organized as follows. In Sec. II, we develop the analytic formalism of Weyl $R^2 + R^3$ model and derive the effective scalar potential. We show that in some cases, the potential has two different kinds of global minima, leading to two distinctive inflationary patterns. In Sec. III, we investigate the inflation in the pattern of evolving to the side minimum. We calculate the spectral index n_s and

*Corresponding author.
tangy@ucas.ac.cn

 © 2023 American Physical Society

（2）获奖

中国科学院大学
University of Chinese Academy of Sciences

授予：王清扬

三好学生标兵

荣誉称号

（2021－2022学年）

校长：

2022年7月1日

No. 12201033

http://www.ucas.ac.cn

中国科学院大学
University of Chinese Academy of Sciences

授予：王清扬

三好学生标兵

荣誉称号

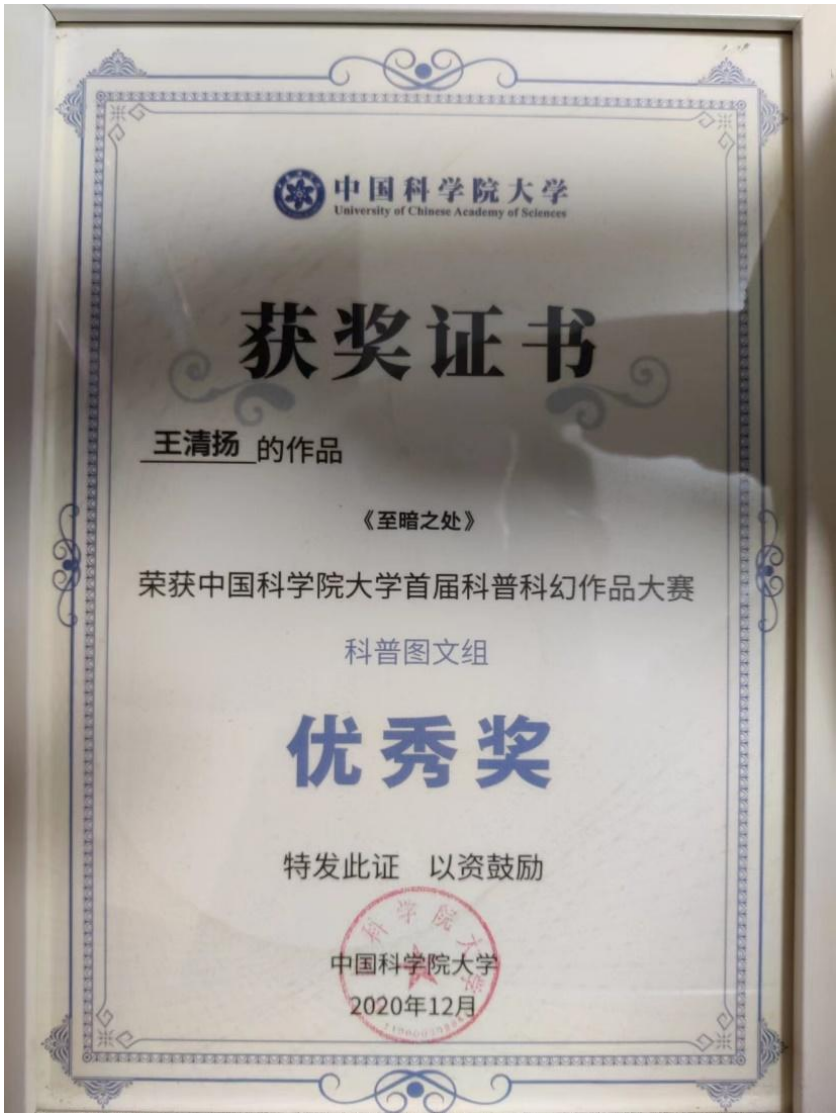
（2022－2023学年）

校长：

2023年6月29日

No. 12300971

http://www.ucas.ac.cn



中国科学院大学
University of Chinese Academy of Sciences

获奖证书

王清扬 的作品

《至暗之处》

荣获中国科学院大学首届科普科幻作品大赛

科普图文组

优秀奖

特发此证　以资鼓励

中国科学院大学

2020年12月