様　式　C－１９、F－１９－１、Z－１９　（共通）

科研費 KAKENHI

科学研究費助成事業　　研究成果報告書

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研究課題名（和文）Probing the early universe by stochastic gravitational wave background

研究課題名（英文）Probing the early universe by stochastic gravitational wave background

研究代表者
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研究者番号：６０８１７５１８

交付決定額（研究期間全体）：（直接経費）　3,200,000円

研究成果の概要（和文）：私は13本の研究論文を完成させ、そのうち10本がすでに出版されています。主な成果は以下の通りです。(1)単一場インフレーションモデルにおける曲率摂動の完全な非線形表現を発見しました。これにより、その統計的性質を明確にするのに非常に役立ちます。 (2)いくつかの一般的な条件の下で、重力波スペクトルがその発生源に関わらず普遍的な赤外f^3スケーリングを持つことを示しました。(3)パルサータイミングアレイ（NANOGravなど）で観測されたnHz重力波信号が、惑星質量の原始ブラックホールの存在を示唆している可能性があることを示しました。

研究成果の学術的意義や社会的意義
この研究は、初期宇宙の謎を解き明かすための重要な進展を遂げました。特に、原初ブラックホールの形成やインフレーション理論の解析において、新たな視点を提供しました。研究者は、曲率摂動の非ガウス性とその統計的性質を明らかにし、ブラックホールの形成率を精密に計算しました。また、これらの計算結果を一般相対性理論の数値シミュレーションで検証し、信頼性を高めました。さらに、次世代の重力波観測（LISAやDECIGO）を通じて、理論的予測と実際の観測データを照らし合わせる試みも行われています。この研究は、宇宙の初期条件や構造形成の理解を深め、現代宇宙論において重要な役割を果たしています。

研究成果の概要（英文）：I completed 13 research papers, of which 10 are already published. The main achievements are as follows. (1) We found a fully nonlinear expression for the curvature perturbation in single-field inflation models, which is very helpful in determining its statistical properties. SP and Sasaki, Phys.Rev.Lett. 131 (2023) 1, 011002. 48 citations. (2) We show that under some general conditions, the GW spectra, no matter what sources they come from, has an universal infrared f^3 scaling. Cai, SP, and Sasaki, Phys.Rev.D 102 (2020) 8, 083528. 141 citations. (3) We show that the nHz GW signal observed by pulsar timing arrays (NANOGrav, etc.) could indicate the presense of planet-mass PBHs. Demenech and SP, Sci.China Phys.Mech.Astron. 65 (2022) 3, 230411. 124 citations.

研究分野：宇宙論

キーワード：初期宇宙論　確率的重力波　インフレーション　原始ブラックホール　宇宙論的摂動理論　スカラー誘導重力波　非ガウス曲率摂動

１．研究開始当初の背景

Besides the yet detected gravitational wave (GW) bursts of binaries, the stochastic background of gravitational waves all over the sky may be the next stirring discovery. Such stochastic background of gravitational waves can be generated by many physical processes in the early universe, for instance the incoherent superpositions of black hole/neutron star binaries, first order phase transitions, reheating after inflation, topological defects, modified gravity, spectator fields during inflation, induced by primordial scalar perturbations, etc. The stochastic gravitational wave is an important scientific goal of the upcoming experiments like LISA, Taiji/Tianqin, DECIGO, BBO, LiteBIRD, and SKA.

In this project I study the physical origin of such stochastic background of gravitational waves, especially the gravitational waves induced by the primordial curvature perturbations at nonlinear level, which may also generate primordial black holes (PBHs), if the power spectrum of the curvature perturbation peak on some small scales. Such induced GWs and the PBHs can be cross-checked to probe the small-scale curvature perturbation. Also, the phenomenology of the PBHs is very fruitful. Depending on their masses, they can be the candidate of dark matter, the origin of the binary black holes detected by LIGO, or the supermassive black holes in the galactic center. Therefore, induced gravitational waves can be used to constrain primordial black holes as dark matter, the merger rate of the primordial black hole binaries, or the seeds for galaxy formation.

２．研究の目的

The stochastic gravitational waves (GWs) carry a huge amount of information of cosmology and high energy physics, which is not transparent to us in the traditional electromagnetic or neutrino observations. Now KAGRA starts to run and join the global network of laser interferometers of LIGO/VIRGO. In the near future LISA and Taiji/Tianqin will be launched, together with SKA and LiteBIRD. On the large frequency band, interesting GW signals might be detected in the near future, and the stochastic gravitational wave background is one of the most important scientific goal of such detectors. The purpose of my research is to probe the physics in the early universe by the stochastic background of gravitational waves. Toward this goal, it is of very much scientific significance to systematically study the stochastic gravitational waves from different sources, try to find their universal feature and different characteristics, and then try to identify and distinguish them in the signals of future detections.

In the induced gravitational wave case, their cross-check with the constraint on abundance of the primordial black holes (PBHs) is crucial evidence, which is connected to another big problem of our universe—the essence of dark matter. This has been done in some simple Gaussian cases, but recent study shows that when the power spectrum of the curvature perturbation is enhances, the non-Gaussianity is also enhanced, which varies the PBH abundance and induced GW spectrum significantly. Along this path, I aim to break the Gaussian statistics usually used in the literature, and try to find robust predictions for induced GWs and PBH abundance when non-Gaussianity is taken into account.

３．研究の方法

I first delve into the statistical properties of the general probability distribution function $P(\mathcal{R})$ that must be satisfied by the curvature perturbation $\mathcal{R}$ in single-field inflation models capable of producing primordial black holes. Next, I employ more relevant methods such as the compact function method and the peak theory of random fields to calculate the abundance of primordial black holes. We will pay particular attention to issues that previous researchers have overlooked, such as the collapse of non-spherically symmetric black holes, primordial black hole clustering, softening of the background equation of state in the early universe, and the collapse of second-type perturbations into primordial black holes. These calculations are quite complicated, primarily involving analytical calculations supplemented by numerical calculations and numerical fitting.

I also used the result of numerical general relativity to verify the primordial black hole formation calculated by the analytical methods. Additionally, I used perturbation theory in general relativity to calculate the secondary gravitational wave background induced by curvature perturbations and search for signals in experimental data from LIGO and NANOGrav. These techniques are already mature, but since there are two many vertices, sometimes numerical integrals will be used.

４．研究成果

My main research achievements during the period of the JSPS Young Scientist Project JP20K14461 is mainly divided into two related directions, which are listed below.

1. Properties of the Stochastic Gravitational Waves

In this project I aim to find universal aspects and characteristic features of the stochastic gravitational wave background from various physical sources. What to be elucidated is the way to distinguish the wave signals from different physical processes, which will be very helpful to both theorists and experimentalist who work for KAGRA, LISA, etc. For specific GW sources, I focus on the scalar induced GWs and its related phenomenology, the generation of Primordial black holes, which have been a frontier of research in cosmology and astrophysics in recent years. The induced GWs can be used to indirectly detect PBHs, particularly those which could constitute all dark matter with asteroid-mass PBHs. I have conducted extensive research in this field, achieving significant progress and proposing new scientific objectives for space GW detection programs. My work can be summarized as follows.

1.1 Infrared Scaling Laws of Stochastic Gravitational Wave Background

I studied the general stochastic GW energy spectrum Ω_{GW} and found that in the infrared frequency domain far from the source, the stochastic GW energy spectrum exhibits a power law, with the spectral index related only to the cosmic equation-of-state parameter *w* at the time of GW generation [Cai, SP, and Sasaki, Phys.Rev.D 102 (2020) 8, 083528]. In the standard cosmological scenario dominated by radiation *w*=1/3, the infrared spectral index is 3. This indicates that the infrared spectral index can be used to probe the equation of state parameter *w* of the hot universe. This result has important significance for both theoretical research and signal detection of stochastic GW background. After publication, it received wide attention and high praise from the international academic community, being cited 141 times.

[Impact] (1) Several scientific target papers from the LISA working group reviewed this result, referring the f^3 scaling as a universal property of the stochastic GW background. (2) Papers by John Ellis et al. [JCAP 10 (2020) 032 and JCAP 11 (2020) 020] and Joseph Silk et al. [JCAP 09 (2022) 016 and JCAP 06 (2022) 008] review our result, and use it as the starting point for their analytical calculations of the GW spectrum. (3) Papers by Tsutomu Yanagida et al. [Phys.Rev.D 101 (2020) 12, 123533] prominently cite and review this paper five times and verify this infrared f^3 scaling in the special case of binary black hole precession.

In a subsequent work, we proposed a specific method for probing the history of cosmic evolution using the infrared spectral index of scalar-induced secondary GWs [Guillem, SP, and Sasaki, JCAP 08 (2020)

017]. This result is considered a new approach to exploring the hot history of the universe and received wide attention from the academic community, being cited 124 times, including comments and extended studies by John Ellis and Joseph Silk.

1.2 Induced GW to explain PTA data

In 2020, the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) announced evidence of nanohertz GWs in their 12.5-year data. Together with Domenech, we first discovered that the induced GW spectrum generated in the early universe with a soft equation of state can explain this signal, and the corresponding planet-mass PBHs can explain the unknown compact objects observed in multiple microlensing experiments like OGLE [Domenech and SP, Sci.China Phys.Mech.Astron. 65 (2022) 3, 230411]. As multiple experimental groups further confirmed strong evidence of the existence of nanohertz GW signals in 2023, our proposed mechanism received more attention and further study, which has 124 citations. In October 2023, it was selected as an ESI highly cited paper. It won the 2023 Best Paper Award of *Science China Physics Mechanics and Astronomy*.

[Impact] Carr et al. categorized our model as a new mechanism of generating PBHs in his review paper [Rept.Prog.Phys. 84 (2021) 11, 116902] and pointed out in another review paper [Phys.Rept. 1054 (2024) 1-68] that our model is the only one predicting the existence of planet-mass PBHs. Dvali et al.'s paper [Phys.Rev.D 104 (2021) 12, 123507] suggested that the potential connection between the GW signal observed by NANOGrav and PBHs is extremely important based on our results. Our paper has also been prominently cited in LIGO group's searches for sub-solar mass PBHs, multiple LISA working group white papers, and review articles. After NANOGrav, EPTA, PPTA, CPTA released their new data in 2023 and confirmed strong evidence for the existence of the nHz GW background, we re-analyzed the new data and fit by our model. This new paper, 2402.18965, was submitted to JCAP and will be published soon.

1.3 Analytical Calculation of Induced Gravitational Wave Spectra

Based on the general properties of inflation models, we proposed that a power spectrum peak of finite width can be well described by a two-parameter log-normal function and provided the first analytical expression for induced GWs, clearly pointing out that induced GWs of a narrow peak show a power-law break from f^3 to f^2 in the infrared band, while induced GWs of a broad peak exhibit a quadratic relationship $\Omega_{GW} \sim 10^{-6}\mathcal{P}_{\mathcal{R}}^2$ near the peak. Our proposed parameterization of the scalar power spectrum and analytical expression of the GW spectrum are useful for signal searches and parameter fitting of stochastic GWs, receiving wide attention and general adoption from the academic community, with 133 citations.

[Impact] NANOGrav's data analysis paper on nanohertz GWs [Astrophys.J.Lett. 951 (2023) 1, L11] used our proposed log-normal form as the starting point for fitting induced GW signals. Colin Hill et al.'s paper [Mon.Not.Roy.Astron.Soc. 528 (2024) 1, 883-897] prominently cites our results, pointing out that this parameterization form can serve as the starting point for their future calculations. Multiple LISA working group and cosmology working group white papers and reports also adopted our proposed spectral shape.

2 Nonlinear Primordial Perturbations and Primordial Black Hole Formation

Research on the non-Gaussianity of primordial perturbations can constrain and discriminate inflation models, helping us understand the physics of the early universe. With the increasingly stringent constraints on large-scale primordial non-Gaussianity from WMAP and Planck, the academic community has shifted its interest towards small-scale (< 1Mpc) primordial non-Gaussianity. This type of non-Gaussianity is not only crucial for the physics related to primordial black holes and scalar-induced gravitational waves but also significantly impacts phenomena such as the number of superclusters and the formation of high-redshift galaxies. In the period of grant, I kept studying the properties of the curvature perturbation power spectrum on small scales and its phenomenological applications, aiming to find a more accurate and robust prediction for the induced GWs.

2.1 Non-perturbative Behavior of Curvature Perturbations

Collaborating with Misao Sasaki, we systematically studied the dynamics of single-field inflation and successfully obtained a non-perturbative expression for the curvature perturbation $\mathcal{R}$ in general single-field inflation models. This expression is precise even up to the tail where $\mathcal{R} \sim O(1)$, thus it can be used for accurate calculations of the mass functions of primordial black holes and dark matter halos. This expression unifies the non-Gaussian relationships in various inflation models, predicts new analytically solvable models, and aligns with the semiclassical limit of quantum diffusion, bearing profound physical significance and broad application prospects. We further proved that when the dynamical evolution of inflation deviates from the attractor solution, the probability density function of the curvature perturbation exhibits an exponential tail rather than a Gaussian tail, a behavior that cannot be explained by the previously popular perturbative expansions. This result lays a solid foundation for further discussions on the origin, evolution, and application of non-Gaussianity. The paper was published in *Physical Review Letters* [SP and Sasaki, Phys.Rev.Lett. 131 (2023) 1, 011002], and received widespread attention from the academic community, being cited 48 times.

[Impact] Reviewer of PRL highly praised this paper: "I believe this is a technically strong, important, and interesting paper that makes significant progress in a major research area. ... In my opinion, this paper is correctly calculated, highly innovative, and far surpasses the previous state-of-the-art, making it a highly impactful result." Dan Hooper et al. [arXiv:2308.00756)] prominently cite this work, using the result that the probability density function of curvature perturbations generated by single-field inflation must have an exponential tail as a starting point for their paper. Based on this result, I was invited to write a chapter of *Non-Gaussianities* for the book *Primordial Black Holes*, to be published by Springer Press in late 2024.

2.2 Non-Gaussianity in the Curvaton Scenario

Collaborating with Misao Sasaki, we constructed an analytically solvable non-minimally coupled curvaton model to produce primordial black holes on small scales. As the energy density of the curvaton increases, the probability distribution of curvature perturbations transitions from a χ^2 distribution to an exponential tail. This is the first multifield model that is analytically solvable up to all orders of curvature perturbations, which avoids the strict observational constraints of single-field inflation. The paper was published as a rapid communication in *Physical Review D* [Phys.Rev.D 108 (2023) 10, L101301] and quickly gained widespread attention and high appreciation in the academic community, being cited 52 times. Recently, it has been discovered that induced gravitational waves with negative non-Gaussianity $f_{\rm NL} \lesssim -1$ is the best fit of the newly released PTA data by pulsar timing arrays, and the curvaton mechanism is currently the only model capable of generating negative non-Gaussianity at the non-perturbative level. The physical significance and theoretical depth behind this remain to be further explored.

[Impact] Dan Hooper et al. extensively studied our model, and extended it to self-interacting curvaton to explain the origin of supermassive black holes [JCAP 04 (2024) 021]. Based on our model, Andrei Linde extended the non-minimally coupled curvaton to a dilaton-coupled axion model and calculated the formation of primordial black holes and induced gravitational waves [JCAP 08 (2022) 08, 037].

５．主な発表論文等

〔雑誌論文〕　計10件（うち査読付論文　10件／うち国際共著　8件／うちオープンアクセス　0件）

１．著者名 Shi Pi, Jianing Wang	４．巻 -
２．論文標題 Primordial Black Hole Formation in Starobinsky's Linear Potential Model	５．発行年 2023年
３．雑誌名 Journal of Cosmology and Astroparticle Physics	６．最初と最後の頁 -
掲載論文のDOI（デジタルオブジェクト識別子） なし	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Domenech Guillem、Pi Shi	４．巻 65
２．論文標題 NANOGrav hints on planet-mass primordial black holes	５．発行年 2022年
３．雑誌名 Science China Physics, Mechanics & Astronomy	６．最初と最後の頁 230411
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s11433-021-1839-6	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Bian Ligong、Cai Rong-Gen、Cao Shuo、Cao Zhoujian、Gao He、Guo Zong-Kuan、Lee Kejia、Li Di、Liu Jing、Lu Youjun、Pi Shi、Wang Jian-Min、Wang Shao-Jiang、Wang Yan、Yang Tao、Yang Xing-Yu、Yu Shenghua、Zhang Xin	４．巻 64
２．論文標題 The Gravitational-wave physics II: Progress	５．発行年 2021年
３．雑誌名 Science China Physics, Mechanics & Astronomy	６．最初と最後の頁 120401
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s11433-021-1781-x	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

１．著者名 Pi Shi	４．巻 64
２．論文標題 Detecting warm dark matter by the stochastic gravitational waves	５．発行年 2021年
３．雑誌名 Science China Physics, Mechanics & Astronomy	６．最初と最後の頁 290431
掲載論文のDOI（デジタルオブジェクト識別子） 10.1007/s11433-021-1733-0	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

1．著者名 Zhou Zihan、Jiang Jie、Cai Yi-Fu、Sasaki Misao、Pi Shi	4．巻 102
2．論文標題 Primordial black holes and gravitational waves from resonant amplification during inflation	5．発行年 2020年
3．雑誌名 Physical Review D	6．最初と最後の頁 103527
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.102.103527	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Tang Chengfeng、Zhang Pierre、Luo Wentao、Li Nan、Cai Yi-Fu、Pi Shi	4．巻 911
2．論文標題 Measuring the Gravitomagnetic Distortion from Rotating Halos. I. Methods	5．発行年 2021年
3．雑誌名 The Astrophysical Journal	6．最初と最後の頁 44～44
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/abe69e	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Pi Shi、Sasaki Misao	4．巻 2020
2．論文標題 Gravitational waves induced by scalar perturbations with a lognormal peak	5．発行年 2020年
3．雑誌名 Journal of Cosmology and Astroparticle Physics	6．最初と最後の頁 037～037
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1475-7516/2020/09/037	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

1．著者名 Domenech Guillem、Pi Shi、Sasaki Misao	4．巻 2020
2．論文標題 Induced gravitational waves as a probe of thermal history of the universe	5．発行年 2020年
3．雑誌名 Journal of Cosmology and Astroparticle Physics	6．最初と最後の頁 017～017
掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1475-7516/2020/08/017	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

1．著者名 Mizuno Shuntaro、Mukohyama Shinji、Pi Shi、Zhang Yun-Long	4．巻 102
2．論文標題 Universal upper bound on the inflationary energy scale from the trans-Planckian censorship conjecture	5．発行年 2020年
3．雑誌名 Physical Review D	6．最初と最後の頁 21301
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.102.021301	査読の有無 有
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1．著者名 Cai Rong-Gen、Pi Shi、Sasaki Misao	4．巻 102
2．論文標題 Universal infrared scaling of gravitational wave background spectra	5．発行年 2020年
3．雑誌名 Physical Review D	6．最初と最後の頁 83528
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.102.083528	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

〔学会発表〕　計11件（うち招待講演　4件／うち国際学会　11件）

1．発表者名 Shi Pi
2．発表標題 Starobinsky ' s linear potential model revisited
3．学会等名 The 31st Workshop on General Relativity and Gravitation in Japan (JGRG31)（国際学会）
4．発表年 2022年

1．発表者名 Shi Pi
2．発表標題 Starobinsky ' s linear potential model revisited
3．学会等名 The 9th Korea-Japan Workshop on Dark Energy, Seoul, Korea（国際学会）
4．発表年 2022年

１．発表者名
Shi Pi

２．発表標題
Logarithmic duality of the curvature perturbation

３．学会等名
Non-linear nature of cosmological perturbations and its observational consequences（招待講演）（国際学会）

４．発表年
2022年

１．発表者名
Shi Pi

２．発表標題
NANOGrav 12.5-yr Result and the Planet-mass PBHs

３．学会等名
2021 Annual Meeting of Division of Gravity and Relativistic Astrophysics, Chinese Physics Society（国際学会）

４．発表年
2021年

１．発表者名
Shi Pi

２．発表標題
NANOGrav 12.5-yr result and induced gravitational waves

３．学会等名
Gravitational-Wave Primordial Cosmology（国際学会）

４．発表年
2021年

１．発表者名
Shi Pi

２．発表標題
Probing the primordial black holes by stochastic gravitational wave background

３．学会等名
SUSY 2021（国際学会）

４．発表年
2021年

１．発表者名
Shi Pi

２．発表標題
Stochastic Gravitational Waves from the Early Universe

３．学会等名
Summer School on GRAVITATIONAL WAVE ASTRONOMY（招待講演）（国際学会）

４．発表年
2021年

１．発表者名
Shi Pi

２．発表標題
Some Properties of Stochastic Gravitational Wave Background

３．学会等名
Spring workshop on gravity and cosmology（招待講演）（国際学会）

４．発表年
2020年

１．発表者名
Shi Pi

２．発表標題
An analytical formula for induced gravitational waves with a lognormal peak

３．学会等名
14th International Conference on Gravitation, Astrophysics and Cosmology (14CGAC)（国際学会）

４．発表年
2020年

１．発表者名
Shi Pi

２．発表標題
NANOGrav 12.5-yr Result and the Planet-mass PBHs

３．学会等名
The Online Workshop on General Relativity and Gravitation in Japan（招待講演）（国際学会）

４．発表年
2020年

1．発表者名 Shi Pi
2．発表標題 NANOGrav 12.5-yr Result and the Planet-mass PBHs
3．学会等名 2020/2021 Annual Meeting of Division of Gravity and Relativistic Astrophysics, Chinese Physics Society（国際学会）
4．発表年 2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関			
中国	Chinese Academy of Sciences	Peking University	University of CAS	
ドイツ	Leibniz University Hannover			