様　式　C－１９、F－１９－１、Z－１９　（共通）

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 cosmology with astrophysical gravitational wave background

研究課題名（英文）Probing cosmology with astrophysical gravitational wave background

研究代表者
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研究成果の概要（和文）：本研究では宇宙論的な側面から重力波について調査することを目的とした。本研究期間中に、研究代表者は重力波と銀河との間に生じる相関関係に基づいた連星赤方偏移を推定するための全く新しい手法を開発した。この新しい手法のほかにも、天体物理的かつ原始的な背景重力波の検出の可能性を評価し、モデル化することにおいても新しい結果が得られることができ、今後のさらなる進展が期待される。

研究成果の学術的意義や社会的意義
The methods developed within this project can be applied to upcoming GW data and our theoretical results can be used for validating future GW-based cosmological measurements. Japanese research community plays an important role in international
GW research and this project adds to such efforts.

研究成果の概要（英文）：I studied gravitational waves (GW) in the cosmological context. I have developed novel approaches for binary redshift estimation based on GW-galaxy correlations. Novel results have also been obtained in modeling and evaluating the detection prospects of astrophysical and primordial GW backgrounds.

研究分野：Cosmology

キーワード：Cosmology　Gravitational Waves　Primordial Black Holes　Cross-Correlations　Multimessenger Astronomy　Large-scale Structure

１．研究開始当初の背景

Gravitational wave observations have enabled a new and important way to map the universe. Active research is being carried out worldwide with the aim to assess the capabilities of current and upcoming gravitational-wave observations in addressing open questions in early and late-time cosmology, as well as the astrophysics of compact binaries. The main motivation for starting this project was the development of robust modeling approaches, with the aim of bringing gravitational wave observations into the ranks of independent and powerful cosmology probes. The project was proposed in a very timely manner since gravitational wave catalogs continue to accumulate new sources, and novel methods will be required in the near future in order to derive robust cosmological constraints from these.

２．研究の目的

In this project, my aim was to focus on the interconnections between gravitational wave sources and galaxies. By leveraging this connection, I proposed to develop methods for statistically comparing the distributions of GW binaries and galaxies both in space and redshift. This allows to develop independent cosmological probes, as well as shed light on the origin of gravitational-wave sources. Importantly, gravitational waves can be observed in two main modalities. The resolved sources originate from heave and/or relatively nearby sources, while weaker and further sources, as well as fundamental physics processes in the early universe, produce unresolved backgrounds. My aim was to make progress in modeling both of the channels and asses their information content regarding cosmology, large-scale tests of gravity, and production channels of gravitational waves.

３．研究の方法

One of the main methods of my research was the measurement of spatial correlations of gravitational-wave sources. Since gravitational-wave sources are expected to reside in galaxies, their spatial distribution in the universe is not uniform but rather exhibits spatial correlations. Importantly, the distribution of gravitational-wave sources is expected to be correlated with that of galaxies. I have developed numerical codes to robustly model such spatial correlations, as well as cross-correlations with galaxy clustering measurements. This equally applies to both resolved sources and GW backgrounds originating from astrophysical or primordial binaries.

Another important methodological challenge was the statistical modeling of data. In order to assess the power of upcoming data, I have leveraged ideas from galaxy clustering studies, and have developed a statistical pipeline that allows for the generation of synthetic mock datasets. This allowed to carried out the complete, end-to-end statistical analysis, from data generation to performing a forecast analysis with Bayesian parameter inference on relevant cosmological and astrophysical parameters. In order to increase the robustness of cosmological constraints from the distribution of gravitational-wave binaries, I have incorporated ideas from machine learning. The Gaussian Process

reconstruction method allows for model-independent reconstructions of cosmological quantities as functions of redshift. I have shown that this method can be successfully incorporated into the statistical modeling of future gravitational-wave observations.
As far as the primordial gravitational-wave backgrounds are concerned, the analysis was performed using a hybrid approach of numerical modeling of the inflationary perturbations in a complex proof-of-concept model and deriving relevant analytical approximations in order to facilitate the interpretation of the results. Additionally, in order to compute relevant CMB observables, Einstein-Boltzmann solvers have been used.

４．研究成果

During my Kekenhi project, I have made significant contributions to the field of gravitational-wave cosmology, especially in the direction of developing the dark-siren approach, as well as modeling gravitational-wave backgrounds in astrophysical and primordial scenarios. I have derived results that significantly clarify the power of clustering measurements in constraining the cosmological parameters, testing models of modified gravity, and constraining the linear clustering bias of gravitational-wave sources. This study has been published in ApJ. An additional important achievement has been the study of population modeling of black hole-neutron star mergers, especially in connection with addressing the question of whether the observed black holes can be of primordial origin. This study has been published in ApJ.
As far as the alternative gravitational-wave binary formation channels are concerned, I have further studied the formation of anisotropies in stochastic gravitational-wave backgrounds in the context of a primordial black hole scenario. I and my colleagues have assessed the prospects of measuring such anisotropic gravitational-wave backgrounds in future experiments, as well as the prospects of such measurements being able to distinguish between primordial and astrophysical black hole scenarios. This study has been published in PRD, and it has extended the results obtained in an earlier paper of mine also published in PRD.
An additional aspect of GW backgrounds is the careful modeling of signals from the early universe, which is important in order to correctly interpret any possible detection in the future. For this, I have led a study of induced GW backgrounds formed during inflation, and have clarified an important open question in inflationary cosmology regarding the possibility to break the Lyth bound. This study has been published in PRL, has been featured as IPMU press release, and has been one of the 9 research highlights of the Kavli IPMU annual report for FY 2021.
In addition to the main theme of the KAKENHI project, I have also worked on projects of indirect relevance to the main theme. Particularly, I have published a paper in PRD exploring the prospects of generating cosmological magnetic fields in the early universe. The proposed mechanism might also be relevant for generating a gravitational-wave background, and therefore is of interest for future gravitational-wave experiments. I have also led a short invited review article covering the main numerical approaches in astrophysical and laboratory tests of General Relativity (accepted for publication in the

journal Universe), as well as have published and submitted additional papers on tests of the LCDM model.

The field of gravitational-wave cosmology in general, and the aspects investigated within this KAKENHI project in particular are being actively developed internationally and within Japan. My main results obtained in this project have been published in leading journals, and have received numerous citations. Additionally, I have presented the achievements in more than 20 talks at international workshops and invited seminars in Europe, US, Canada, and Japan. The obtained results address the objectives of the research proposal. Additionally, several interesting extensions, such as deriving constraints on GW clustering from existing LIGO-Virgo-Kagra data, exploring binary-host connection using numerical simulations, and linking gravitational-wave backgrounds to the reionization history of the universe have been established and some preliminary progress has been made. These and other related topics are beyond the main scope of the current project, and are left to be carefully explored in future research.

５．主な発表論文等

〔雑誌論文〕　計8件（うち査読付論文　8件／うち国際共著　7件／うちオープンアクセス　2件）

１．著者名 Sasaki Misao、Vardanyan Valeri、Yingcharoenrat Vicharit	４．巻 107
２．論文標題 Super-horizon resonant magnetogenesis during inflation	５．発行年 2023年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.107.083517	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 ―

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２．論文標題 Cosmological dynamics of multifield dark energy	５．発行年 2022年
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１．著者名 Wang Sai、Vardanyan Valeri、Kohri Kazunori	４．巻 106
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１．著者名 Canas-Herrera Guadalupe, Contigiani Omar, Vardanyan Valeri (corresponding author)	４．巻 918
２．論文標題 Learning How to Surf: Reconstructing the Propagation and Origin of Gravitational Waves with Gaussian Processes	５．発行年 2021年
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１．著者名 Cai Yi-Fu, Jiang Jie, Sasaki Misao, Vardanyan Valeri (corresponding author), Zhou Zihan	４．巻 127
２．論文標題 Beating the Lyth Bound by Parametric Resonance during Inflation	５．発行年 2021年
３．雑誌名 Physical Review Letters	６．最初と最後の頁 251301
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.127.251301	査読の有無 有
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１．著者名 Sasaki Misao, Volodymyr Takhistov, Vardanyan Valeri (corresponding author), Ying-li Zhang	４．巻 -
２．論文標題 Establishing the Non-Primordial Origin of Black Hole-Neutron Star Mergers	５．発行年 2022年
３．雑誌名 The Astrophysical Journal accepted	６．最初と最後の頁 -
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1088/1475-7516/2021/04/006	査読の有無 有
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掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/universe9070340	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24件（うち招待講演　18件／うち国際学会　19件）

1．発表者名 Valeri Vardanyan	
2．発表標題 AMPLIFICATION OF GRAVITATIONAL WAVES IN THE EARLY UNIVERSE	
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２．発表標題
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１．発表者名
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

Inspire account
inspirehep.net/author/profile/V.Vardanyan.1
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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