様　式　C－１９、F－１９－１、Z－１９　（共通）

科研費 KAKENHI

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研究課題名（和文）Predicting the formation of stars, black holes, and gravitational-wave signals with young galaxy clusters

研究課題名（英文）Predicting the formation of stars, black holes, and gravitational-wave signals with young galaxy clusters

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研究成果の概要（和文）：観測とシミュレーション結果の差を縮めることに成功した。
しかし当初のアイデア（LIGA-VIRGO-KAGRAの周波数帯にある恒星サイズのブラックホールを分解する）が実現不可能であることが判明したため、計画をより一般化して再構築する必要があった。
そこで、私は、超大質量ブラックホールの合体によって発生するナノヘルツ帯の確率的重力波のバックグラウンドに焦点を切り替えた。これらは、大規模な宇宙論シミュレーションで非常に正確に分解することができるため、このプロジェクトは、現在作成している新しい密度マップの理想的な使用事例となっている。

研究成果の学術的意義や社会的意義
The confirmation of the stochastic gravitational wave background by the NANOGrav collaboration last year boosted the significance of this project massively, especially our unique ability to estimate the anisotropies in the stochastic background.

研究成果の概要（英文）：I initially designed this project to utilize high redshift density reconstructions that I was working on at the moment. The idea of using density maps located in the era of maximum star formation is motivated as merging stellar remnants such as neutron stars and black holes, are the astrophysical sources of gravitational waves.
I was able to accomplish to close the gap of observational studies and cosmological simulations, however, I had to restructure the project in a general way. The initial idea to resolve stellar size that lie in the LIGA-VIRGO-KARGA frequency band turned out to be unfeasible. Therefore, I switched the focus to the Stochastic gravitational wave background in the nano-hertz band that is sourced by merging super-massive blackholes. These objects can very accurately be resolved in large-scale cosmological simulations, which makes this project an ideal use-case for the new density maps that I am creating now.

研究分野：Cosmology

キーワード：Large-scale structure　Gravitational waves

様　式　C－１９、F－１９－１、Z－１９（共通）

１．研究開始当初の背景

When I applied for this project, my focus was on constrained simulations, which involve representing a galaxy distribution at fairly high redshifts, specifically between 2 and 2.5. This range corresponds roughly to a cosmic epoch that occurred about 11 billion years ago. This particular era is especially intriguing because it marks the peak of star formation in galaxies.
During this time, the Universe was creating more stars than it had before or would after this period. Recognizing this significant fact, I was motivated to utilize it and combine my ongoing research with the newly emerging and exciting field of gravitational wave astronomy. Just a few years prior, the LIGO-VIRGO collaboration (now including KAGRA as well) had confirmed the first gravitational wave signal.
Even more recently, they achieved a remarkable milestone by measuring and localizing the very first gravitational wave event, known as GW170817. This groundbreaking achievement spurred my interest in studying these phenomena further and integrating them with my ongoing research, as I envisioned numerous beneficial applications. At the time when I delved into the literature, I identified a clear gap in the interplay between time-domain astrophysics, particularly in the study of transient events such as gravitational wave bursts, and the research on large-scale structure formation.
While the localization of gravitational wave sources was being analyzed using random cosmological simulations, there was a noticeable lack of efforts to generalize these analyses to constrained simulations. One possible reason for this could be the scarcity of expertise required to run constrained simulations, a specialized skill possessed by only a very limited number of research groups worldwide.

２．研究の目的

I was inspired by the work of Vitale et al. (2019, ArXiv:1808:00901), where the authors studied a completely new idea to constrain cosmic star formation parameters with the help of gravitational wave measurements. Utilizing gravitational wave observations to constrain parameters that are crucial for cosmological structure formation led me to further investigate a potential synergy with large-scale structure. While Vitale et al. focused on an observational approach, my interest lay in numerical simulations. The key questions that guided my research were multifaceted and aimed at bridging the gap between observational data and theoretical models:

1. Efficiency in Studying Stellar Activities of Protoclusters:
   How can we most efficiently study the stellar activities of protoclusters by applying constrained simulations instead of relying on random initial conditions? This question aimed to improve the accuracy and relevance of simulations by using actual observed data as initial conditions, thereby providing a more realistic framework for understanding the early stages of galaxy formation.

2. Predicting Merging Events of Binary Black Holes:
   How reliably can we predict merging events of binary black holes using simulations? Understanding these events is crucial for interpreting gravitational wave signals and for providing insights into the end stages of stellar evolution. This question focused on enhancing the predictive power of our models to match observational data from gravitational wave detectors.

3. Forecasting the Number and Timing of GW Events:
   How well can we forecast the number counts and timing of gravitational wave events from high-redshift observations, given the merging events of binary black holes or other massive stellar objects? This question aimed to develop robust models that could predict the frequency and distribution of gravitational wave events across cosmic time, helping to refine our understanding of the dynamics of the early Universe.

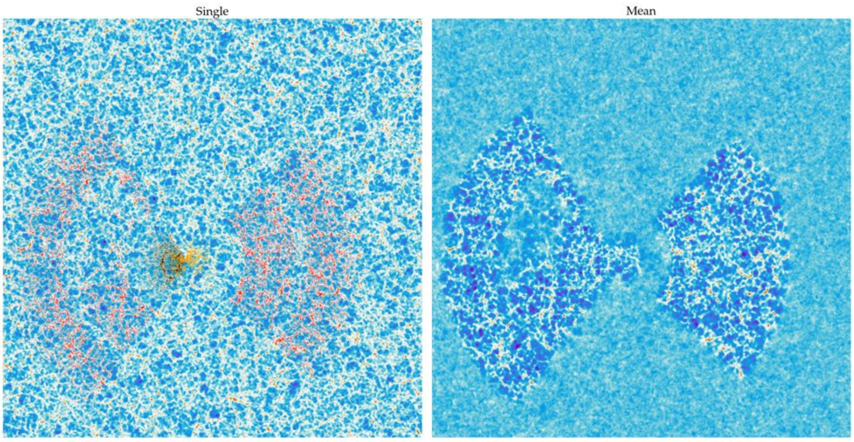
4. Iterative Improvement of Star Formation Models:
   How do we iteratively improve star formation models? This question involved developing a feedback loop where observational data and simulation results continuously inform and refine each other. By integrating new data into existing models, we can enhance their accuracy and predictive capabilities, leading to a deeper understanding of the processes driving star formation.

5. Simulating Young Galaxy Clusters versus Regular Galaxies: How much do we gain from simulating young galaxy clusters compared to regular galaxies? This question explored the benefits of focusing on galaxy clusters, which are dense environments with unique dynamics and interactions that can provide critical insights into the processes of star formation and evolution in the early Universe.

By addressing these questions, my research aimed to create a comprehensive framework that integrates gravitational wave observations with constrained cosmological simulations. This approach not only enhances our understanding of star formation and large-scale structure formation but also bridges the gap between theoretical predictions and observational data. The ultimate goal was to develop more accurate models of the Universe's evolution, leveraging the synergy between different astrophysical phenomena and observational techniques.

３．研究の方法

The key ingredient to my research is the technique known as initial conditions inference. This method allows me to run cosmological simulations that accurately represent the existing observed galaxy distribution. This approach involves several crucial steps and considerations that collectively enhance our understanding of large-scale structure formation. Initial Conditions Inference Initial conditions inference is a powerful technique in cosmology. It enables the reconstruction of the initial density field of the Universe from observed large-scale structures, such as galaxies and clusters of galaxies. This method involves backtracking the evolution of these structures using the laws of physics to their primordial state, providing a detailed map of the initial conditions of the Universe. These inferred initial conditions are crucial for running realistic cosmological simulations that can accurately predict the evolution of cosmic structures.



Cosmological Simulations Using the inferred initial conditions, I perform cosmological simulations that replicate the observed galaxy distribution. These simulations are essential for several reasons: Exact Knowledge of the Galaxy Environment: The simulations provide a precise representation of the environments in which galaxies are embedded. This includes the density and composition of the surrounding medium, which influences galaxy formation and evolution. Dark Matter Distribution: Understanding the distribution of dark matter is critical for studying galaxy formation. Dark matter constitutes a significant portion of the total mass in the Universe and affects the gravitational potential wells in which galaxies form. These simulations offer detailed insights into the dark matter distribution around galaxies. Streaming Velocity Estimation: One of the significant advantages of these simulations is the ability to estimate precise streaming velocities, which are not directly obtainable from galaxy redshift surveys. Streaming velocities influence the movement of galaxies within clusters and the interaction between different cosmic structures. Preparation and Development Over the last two years, I have worked intensively on high-redshift galaxy surveys to gather the necessary data for my simulations. This work involved developing a series of analytical and numerical models to derive the initial conditions accurately. The preparation phase included: Data Collection and Analysis: Conducting comprehensive surveys of high-redshift galaxies to collect data on their positions, velocities, and other relevant properties. Model Development: Creating analytical models to interpret the data and numerical models to process it. These models are crucial for accurately inferring the initial conditions needed for the simulations. Simulation Execution: Performing constrained cosmological simulations using the derived initial conditions. These simulations were run on high-performance computing facilities to ensure they could handle the complexity and scale of the data. Results and Predictions The constrained cosmological simulations generated from these initial conditions allowed me to predict the further evolution of the observed galaxy structures. The results of these simulations are illustrated in Figure 1. The figure showcases the input high-redshift galaxies at the top and the corresponding dark matter distribution, highlighting the intricate interplay between visible matter and dark matter in shaping the Universe's large-scale structure. These simulations have provided several significant insights: Galaxy Formation and Evolution: By accurately replicating the observed galaxy distribution, the simulations have helped us understand the processes driving galaxy formation and evolution at high redshifts. Dark Matter Dynamics: The detailed dark matter maps generated by the simulations have shed light on the role of dark matter in the formation of cosmic structures. Predictive Power: The ability to predict future galaxy distributions based on current observations is a critical outcome of this research. This predictive power can be used to guide future observations and refine our models further. Conclusion In summary, the methods employed in this research proposal combine advanced techniques in initial conditions inference with state-of-the-art cosmological simulations. This approach enables a detailed and accurate study of the large-scale structure formation in the Universe. The work done over the past two years in preparing and developing these methods has laid a solid foundation for future research, promising significant advancements in our understanding of cosmology.

４．研究成果

Initially, the research aimed to resolve the mergers of stellar-sized black holes using the constrained cosmological simulations. However, the attempt to achieve this resolution encountered significant challenges. The primary issue lay in the simulation resolution that could be inferred from the initial conditions. Despite the sophisticated techniques employed, the simulations lacked the granularity needed to accurately resolve these small-scale phenomena. This outcome, although not as anticipated, provided valuable insights and redirected the focus of the research towards more feasible objectives. Shift in Focus: Super-Massive Black Holes Upon realizing the limitations with stellar-sized black holes, the investigation pivoted towards the study of super-massive black holes (SMBHs) residing in the centers of the most massive galaxies. The simulations, even with their current resolution, proved to be highly effective in modeling these colossal entities. This shift opened up new avenues for understanding the dynamics and mergers of SMBHs, which are pivotal in shaping the large-scale structure of the Universe. New Reconstructions and Stochastic Gravitational Wave Background The new reconstructions of the local Universe developed through these simulations are proving to be exceptional tools for studying the resulting stochastic gravitational wave background from SMBH mergers. These mergers generate low-frequency gravitational waves, contributing to the stochastic gravitational wave background. This background is precisely the signal that the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) has recently confirmed exists. Their detection of this background, primarily in the nano-hertz frequency band, marks a significant milestone in gravitational wave astronomy. Implications for NANOGrav and Future Research The results from my simulations have direct implications for NANOGrav's observations. By providing detailed models of SMBH mergers and their gravitational wave emissions, my research offers a valuable framework for interpreting the nano-hertz gravitational wave background. This contribution not only supports the findings of NANOGrav but also enhances our understanding of the sources contributing to this background. Future Directions Building on these findings, I will further focus on the application of our latest simulations to this issue. The next steps involve: Refining Simulation Techniques: Enhancing the resolution and accuracy of the simulations to better capture the dynamics of SMBHs and their mergers. This includes incorporating more detailed initial conditions and utilizing advanced computational methods. Analyzing Gravitational Wave Data: Collaborating with observational teams to compare simulation results with actual gravitational wave data from NANOGrav and other observatories. This synergy will help validate the models and provide deeper insights into the nature of the stochastic gravitational wave background. Exploring Environmental Effects: Investigating the role of the galactic environment on SMBH mergers. Understanding how factors such as galaxy mergers, interactions, and gas dynamics influence the behavior of SMBHs will be crucial for developing comprehensive models. Predictive Modeling: Developing predictive models that can forecast future gravitational wave signals from SMBH mergers. These models will be essential for guiding future observational campaigns and enhancing our ability to detect and analyze gravitational waves. Broadening the Scope: Expanding the research to include other potential sources of gravitational waves, such as intermediate-mass black holes and exotic compact objects. This broader scope will help create a more complete picture of the gravitational wave universe.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　0件／うち国際共著　2件／うちオープンアクセス　0件）

１．著者名 Ata Metin、Lee Khee-Gan、Vecchia Claudio Dalla、Kitaura Francisco-Shu、Cucciati Olga、Lemaux Brian C.、Kashino Daichi、Muller Thomas	４．巻 6
２．論文標題 Predicted future fate of COSMOS galaxy protoclusters over 11 Gyr with constrained simulations	５．発行年 2022年
３．雑誌名 Nature Astronomy	６．最初と最後の頁 857～865
掲載論文のDOI（デジタルオブジェクト識別子） 10.1038/s41550-022-01693-0	査読の有無 無
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 Lee Khee-Gan、Ata Metin、Khrykin Ilya S.、Huang Yuxin、Prochaska J. Xavier、Cooke Jeff、Zhang Jielai、Batten Adam	４．巻 928
２．論文標題 Constraining the Cosmic Baryon Distribution with Fast Radio Burst Foreground Mapping	５．発行年 2022年
３．雑誌名 The Astrophysical Journal	６．最初と最後の頁 9～9
掲載論文のDOI（デジタルオブジェクト識別子） 10.3847/1538-4357/ac4f62	査読の有無 無
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0件

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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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			
スペイン	Astrophysical Institute of the Canaries			
米国	UC Davis	UC Santa Cruz		
イタリア	Osservatorio di Astrofisica e Scienza			
ドイツ	Max Planck Institute for Astronomy,			

共同研究相手国	相手方研究機関			
オーストラリア	Swinburne University of Technology			