Research Center for the Early Universe

Graduate School of Science

University of Tokyo

Annual Report

2022

令和４年度 年次研究報告

東京大学大学院理学系研究科附属

ビッグバン宇宙国際研究センター

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Preface

We are pleased to present the annual report of Research Center for the Early Universe (RESCEU) for the fiscal year of 2022 (from April 2022 to March 2023).

RESCEU was founded in 1999 as an institute belonging to Faculty of Science, the University of Tokyo, led by the first director, Prof. Katsuhiko Sato of Physics Department. In 2015 we reorganized the research projects in RESCEU, and now we have three major projects including (1) Evolution of the universe and cosmic structures (led by Jun'ichi Yokoyama), (2) Gravitational-wave astrophysics and experimental gravity (led by Kipp Cannon), and (3) Formation and characterization of planetary systems (led by Yasushi Suto). Those projects have been supported by a variety of collaboration among our research affiliates in Departments of Physics, Astronomy, and Earth and Planetary Sciences of Faculty of Science, the University of Tokyo.

Due to the pandemic of COVID-19, the activity in RESCEU has been seriously affected for the last couple of years. We had been struggling to advance our projects; weekly seminars and regular discussions have been carried out via zoom, and we organized a summer school online inviting several foreign researchers. Since the latter half of the year, we have been gradually been resuming face-to-face activities such as seminars and workshops.

We are pleased to announce the following awards for our RESCEU members this year. Professor Kenta Hotokezaka received the Yukawa-Kimura Prize, for his research on "Electromagnetic Counterparts of Neutron Star Mergers" in January 2023. Fumihiro Naokawa, a graduate student of Yokoyama group, received the School of Science Encouragement Award (Master program), University of Tokyo in March 2023. The following students of Yokoyama group received presentation awards in the conferences as follows. Jason Kristiano: 2nd International Symposium on Trans-Scale Quantum Science (poster, Nov. 2022) Jun'ya Kume: 26th International Summer Institute on Phenomenology of Elementary Particle Physics and Cosmology (poster, Sep. 2022) Hyun Jeong: Joint workshop on General Relativity and Cosmology (oral, Mar. 2023).

Along with these awards to current members, former director Professor Emeritus Kazuo Makishima received the Order of the Sacred Treasure, Gold Rays with Neck Ribbon in April 2022.

In 2022, two new faculties, Kana Moriwaki and Kentaro Komori (since June), joined as assistant professors. Moriwaki is working on observational cosmology and large scale structures at Yoshida group, while Komori is dedicated to gravitational wave science at Ando group. Two new project assistant professors, namely, Akihiro Suzuki and Ryusuke Jinno (since October) have been hired by RESCEU. Suzuki is an expert of supernovae working with Shigeyama, while Jinno is a particle cosmologist mainly working with members of Yokoyama group. Furthermore, six postdocs joined us, namely, Yuki Takei (JSPS, Shigeyama group), Daichi Tsuna (Shigeyama group), Purnendu Karmakar (JSPS, Cannon group), Kazuya Takahashi (Hotokezaka group), Alessandro Trani (Suto group), and Wang Haoyu (Ando group). On the other hand, several people left RESCEU to a new position: Yuji Chinone to an assistant professor at KEK on October 1, Heather Fong to University of British Columbia as a CITA National Fellow on February 1, Daichi Tsuna to Caltech as Burke Fellow on December 1, and Alessandro Trani to Niels Bohr Institute on December 1.

Finally, Professor Yasushi Suto stepped down from the director after eight years of his service, and I have taken over the directorship. Since COVID-19 has finally turned to normal endemic, we are planning to resume various face-to-face activities this year such as the summer school, international conferences, and inviting visiting professors. We would appreciate your further support for our activities.

May 2023

Director Jun'ichi Yokoyama

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Reports on overall activities at RESCEU in 2022

1 Members

RESCEU members

Yasushi Suto [須藤靖]	Director
Jun'ichi Yokoyama [横山順一]	Professor
Kipp Cannon	Professor
Toshikazu Shigeyama [茂山俊和]	Professor
Kenta Hotokezaka [仏坂健太]	Associate Professor
Kohei Kamada [鎌田耕平]	Assistant Professor
Atsushi Nishizawa [西澤篤志]	Assistant Professor
Kana Moriwaki [森脇可奈]	Assistant Professor
Kentaro Komori [小森健太郎]	Assistant Professor
Akihiro Suzuki [鈴木昭宏]	Project Assitant Professor
Yuji Chinone [茅根裕司]	Project Assitant Professor
Ryusuke Jinno [神野隆介]	Project Assitant Professor
Koh Ueno [上野昴]	Postdoctoral Fellow (Kakenhi Grant of Prof. Yokoyama)
Daisuke Toyouchi [豊内大輔]	Postdoctoral Fellow (RESCEU)
Christopher M. Irwin	Postdoctoral Fellow (Kakenhi Grant of Prof. Hotokezaka)
Kazuya Takahashi [高橋和也]	Postdoctoral Fellow (RESCEU)
Alessandro Trani	Postdoctoral Fellow (RESCEU)
Daichi Tsuna [津名大地]	Postdoctoral Fellow (RESCEU)
Wang Haoyu	Postdoctoral Fellow (Kakenhi Grant of Prof. Michimura)
Yuki Takei [武井勇樹]	Postdoctoral Fellow (JSPS Grant)
Purnendu Karmakar	Postdoctoral Fellow (JSPS Grant)
Heather Fong Kin Yee	Postdoctoral Fellow (Kakenhi Grant of Prof. Cannon)
Chiyo Ueda [上田千代]	Secretary
Naoko Tomioka [富岡直子]	Secretary
Mami Narita [成田満美]	Secretary
Nao Watanabe [渡辺菜穂]	Secretary

RESCEU affiliates

Naoki Yoshida [吉田直紀]	Professor, Dept. of Physics
Tomonori Totani [戸谷友則]	Professor, Dept. of Astronomy
Kotaro Kohno [河野孝太郎]	Professor, Institute of Astronomy
Mamoru Doi [土居守]	Professor, Institute of Astronomy
Motohide Tamura [田村元秀]	Professor, Dept. of Astronomy
Seiji Sugita [杉田精司]	Professor, Dept. of Earth and Planetary Science
Eiichi Tajika [田近英一]	Professor, Dept. of Earth and Planetary Science
Satoshi Yamamoto [山本智]	Professor, Dept. of Physics
Hideo Higuchi [樋口秀男]	Professor, Dept. of Physics
Chikara Furusawa [古澤力]	Professor, Universal Bioligy Institute
Aya Bamba [馬場彩]	Associate Professor, Dept. of Physics
Akito Kusaka [日下暁人]	Associate Professor, Dept. of Physics
Kazuhiro Shimasaku [嶋作一大]	Associate Professor, Dept. of Astronomy
Masaki Ando [安東正樹]	Associate Professor, Dept. of Physics
Hajime Kawahara [河原創]	Assistant Professor, Dept. of Earth and Planetary Science
Nobunari Kashikawa [柏川伸成]	Professor, Dept. of Astronomy

2 Projects

Project 1. Evolution of the Universe and cosmic structures

Name	Research thema
Jun'ichi Yokoyama	Physics of the Early Universe
Toshikazu Shigeyama	Coevolution of galaxies and stars
Naoki Yoshida	Evolution of compact objects and time domain astronomy
Tomonori Totani	Evolution of the Universe probed by gamma-ray bursts and fast radio bursts
Kotaro Kohno	Dust-enshrouded growth of galaxies and supermassive black holes
Aya Bamba	Chemical evolution of the Universe with supernova remnant study
Akito Kusaka	Observational cosmology based on cosmic microwave background radiation
Kazuhiro Shimasaku	Galaxy formation and evolution
Nobunari Kashikawa	Distant objects and early Universe
Kohei Kamada	Particle cosmology
Kana Moriwaki	Machine learning and cosmology

Project 2. Gravitational-wave astrophysics and experimental gravity

Name	Research thema
Kipp Cannon	Detection and interpretation of gravitational waves emitted by the collisions of compact objects
Kenta Hotokezaka	Electromagnetic counterparts of gravitational-wave neutron star mergers
Mamoru Doi	Identifications of gravitational-wave sources by wide-field and multi-color optical observations
Masaki Ando	Gravitational-wave experiment and astrophysics
Kentaro Komori	Gravitational-wave experimental astrophysics
Atsushi Nishizawa	Theories of gravitation and data analysis

Project 3. Formation and characterization of planetary systems

Name	Research thema
Yasushi Suto	Dynamical evolution of orbit and angular momentum of exoplanetary systems
Motohide Tamura	Exoplanet observations and instrumentations
Seiji Sugita	An asteroid sample-return mission and feasibility study for an exoplanet observation satellite
Satoshi Yamamoto	Physics and chemistry of protoplanetary disk formation
Eiichi Tajika	Diversity and evolution of habitable planets
Hajime Kawahara	Exploring instrumentation and methods for characterizing exoplanets
Hideo Higuchi	Universal biology
Chikara Furusawa	Universal biology

3 Symposia and Meetings

RESCEU Summer School 2022

Place: Online
Time: 2021/8/17 (Wed) – 2021/8/19 (Fri)

Program

8/17 (Wed) morning, chair: Kazuya Takahashi

9:50–10:00	Yasushi Suto	Opening remarks
10:00–11:30	(L) Kazunori Akiyama	Photographing Black Holes with the Event Horizon Telescope
11:30–12:00	break	
12:00–12:15	Fumihiro Naokawa	Gravitationally lensed Cosmic Birefringence
12:15–12:30	Hiroto Mitani	Physics of the atmospheric escape driven by EUV photoionization heating

8/17 (Wed) afternoon, chair: Kana Moriwaki

14:00–14:15	Jason Kristiano	One-loop perturbativity bound in single-field inflation
14:15–14:30	Alessandro Trani	A new model of common envelope evolution in binary stars
14:30–14:45	Daiki Watarai	Physically consistent waveform for capturing Beyond-GR effects in the merger phase
14:45–15:00	break	
15:00–15:15	Yurina Nakazato	[OIII] emission lines from high-z galaxies in the Epoch of Reionization
15:15–15:30	Jun'ya Kume	Abelian-Higgs cosmic string model and its multi-messenger signals
15:30–16:00	break	
16:00–17:30	(L) Kirsten Knudsen	High-redshift galaxies and galaxy evolution from an observational perspective

8/18 (Thu) morning, chair: Christopher Irwin

10:00–10:15	Minori Shikauchi	Probing BH population with astrometric satellite Gaia
10:15–10:30	Fumio Uchida	Magneto-hydrodynamic evolution of the cosmological magnetic fields
10:30–11:00	break	
11:00–11:15	Betül Uysal	The effect of the baryonic streaming in the formation of the Milky Way
11:15–11:30	Takuya Tsutsui	Observational constraint on axion dark matter with gravitational waves

8/18 (Thu) afternoon, chair: Kohei Kamada

14:00–14:15	Toshinori Hayashi	Dynamical disruption timescales of hierarchical triple systems: dependence on the orbital configuration
14:15–14:30	Koki Tokeshi	Two-point correlation in primordial black hole formation
14:30–14:45	Takatoshi Ko	Is the remnant J005311 from the white dwarf binary merger SN 1181 remnant?
14:45–15:00	break	
15:00–15:15	Yuta Tarumi	Non-LTE analysis of Helium line in kilonova
15:15–15:30	Rui Lan Zhang	Fast method for generating mock line intensity maps based on hydrodynamical simulations
15:30–16:00	break	
16:00–17:30	(L) David Wands	Primordial black holes from inflation

8/19 (Fri) morning, chair: Purnendu Karmakar

10:00–11:30	(L) Emanuele Berti	Testing gravity with gravitational waves
11:30–12:00	break	
12:00–12:15	Yuta Shiraishi	Searching for blackholes in non-interacting binaries by photometrical surveys
12:15–12:30	Soichiro Kuwahara	The recent status of Cherenkov-like burst search

8/19 (Fri) afternoon, chair: Daisuke Toyouchi

14:00–15:30	(L) Nami Sakai	Astrochemical approach to star and planet formation
15:30–16:00	break	
16:00–16:15	Honori Inaguma	Stellar-mass black hole binary mergers by the Kozai-Lidov mechanism
16:15–16:30	Hiroki Kawai	The core-halo mass relation in fuzzy dark matter halos
16:30–16:40	Jun'ichi Yokoyama	Closing remarks

(L: Lecture)

4 RESCEU colloquia

- RESCEU Colloquium No. 56
  Stefan Ballmer (Syracuse University)
  “The Next Leap in Gravitational-Wave Astronomy”
  June 2, 2022, 16:00-17:00

II

Reports
on the research activities
of each project in 2022

5 Project 1. Evolution of the Universe and cosmic structures

5.1 Activity Report

5.1.1 Lorentzian description of phase transition

Phase transition has been formulated by the path integral in the Euclidian spacetime, but it has a problem such as the ambiguity of the final state or the existence of the multiple negative modes in the presence of gravity. We succeeded in formulating the phase transition with the Lorentzian path integral and in evaluating the transition rate when we take the gravity as a background. We not only reproduced the traditional results of the Euclidean path integral but also evaluated the formation rate of the bubble whose radius is different from that of the critical one, which cannot be done in the traditional formalism. (Yokoyama & Kamada)

5.1.2 Chiral effect in cosmology

Chiral effect, such as the chiral anomaly, plays imprtant roles in cosmology. We succeeded in evaluating the formation rate of a domain-wall system called the chiral soliton lattice, whose stability is energetically favored by the chiral effect, by describing it with the Nambu-Goto-like action. We also studied the coevolution of magnetic field and baryon asymmetry after axion inflation, which are generated with the help of chiral effect. There is a possibility that they annihilate each other, but we found that it can be avoided by the right-handed neutrino and succeeded in construcvting a scenario to explain the present baryon asymmetry of the Universe in the context of axion inflation. (Kamada)

5.1.3 Astrophysical transients: their origins and consequences

The following topics were studied in this project.

- Optical emission immediately after binary neutron star mergers (Shigeyama)
- Observations of the early light from type Ia supernovae (Shigeyama, Doi)
- Influence of Pop III supernova explosions on the companion stars (Shigeyama)
- Rapidly rotating massive white dwarfs as a result of binary white dwarf mergers (Kashiyama, Fujisawa, Ko, Tsuna, Shigeyama, Bamba)
- Emission of type IIn supernovae (Shigeyama, Tsuna, Kashiyama, Takei)
- Eruptive mass loss from a massive star a few years before the core collapse (Shigeyama, Takei, Tsuna, Ko)
- Nuclear burning flash at later evolutionary phases of massive stars (Shigeyama, Hasegawa)
- Accretion of C+O matter onto a neutron star igniting Carbon burning (Shigeyama, Nagarajan)
- Influence of supernova fallback on newborn neutron star magnetospheres (Shigeyama, Kashiyama, Zhong)

- Rotational equilibria on the 2D Lagrange coordinates (Fujisawa)
- The W4 method: a new multi-dimensional root-finding scheme for nonlinear systems of equations (Fujisawa)
- Black hole formation from rotating massive stars (Shigeyama, Kashiyama, Tsuna)
- Emission of type IIn supernovae (Shigeyama, Tsuna, Kashiyama, Takei)
- Influence of supernova fallback on newborn neutron star magnetospheres (Shigeyama, Kashiyama, Zhong)

Here the names of researchers are listed in the parentheses.

5.1.4 Statistical Computational Cosmology

We developed a deep-learning method to detect and classify transient objects in data collected by Tomo-e Gozen. It was implemented in the Tomo-e Gozen pipeline, and the number of transient candidates was reduced to about 40 objects per night, which is a factor of 130 smaller than the previous version, while maintaining the recovery rate of real transients; we obtain a false positive rate of 0.0002 at a true positive rate of 0.9. We also conducted theoretical calculations to detect pair-instability supernovae though the nominal 5-year operation of Euclid satellite. Our model is based on recent observations of LIGO-VIRGO of massive blackhole mergers, and forecast that Euclid detects several hydrogen-poor PISNe. (Yoshida)

5.1.5 Large-Scale Structure of the Universe

Line intensity mapping measures the large-scale distribution of galaxies. We developed a method to generate mock line intensity maps from dark-matter only simulation data. We confirm that the statistical properties of the line intensity maps are properly reproduced with our method. Our new method is faster than detailed cosmological hydrodynamics simulation and thus can produce a large amount of mock data. They will play a critical role in estimating systematic biases and covariances in analysis of future wide-field observational data by, e.g., NASA's SPHEREx. (Moriwaki)

5.1.6 High redshift galaxies

We have launched the Hinotori (star formation History INvestigatiOn TO find RejuvenatIon) project to reveal the nature of rejuvenation galaxies (RGs), galaxies that restarted their star formation after being quiescent. As the first step of Hinotori, we construct the largest RG sample with 1071 sources. These RGs are selected from reconstructed star formation histories of ~ 9000 $z \sim 0$ galaxies. We find that the RGs account for ~ 10 % of the whole sample, and rejuvenation events contribute on average only about 0.1 % of the total stellar mass in those galaxies but 17 % of the cosmic-star formation rate density today. The morphology of the RGs is more disk-like than QGs, suggesting that rejuvenation may occur selectively in disk-like QGs. Our results also suggest that galaxies may have experienced multiple rejuvenation events since $z \sim 1$. (Shimasaku)

It has recently been reported that the quenching of satellite galaxies in clusters depends on the orientation relative to the cluster central galaxies, with satellites along the major axis of centrals being more likely to be quenched than those along the minor axis. We detect such anisotropic quenching up to $z \sim 1$ in a large optically selected cluster catalogue constructed from the Hyper Suprime-Cam Subaru Strategic Program. We then confirm that the observed anisotropy cannot be explained by differences in local galaxy density or stellar mass distribution along the two axes. Finally, we argue that the physical origins of the observed anisotropy should have shorter quenching time-scales than ~ 1 Gyr, like ram-pressure stripping, because, for anisotropic quenching to be observed, satellites must be quenched before their initial orientation angles are significantly changed. (Shimasaku)

5.1.7 High redshift galaxies

The large variation in opacity in the Lyα forest at $z > 5.5$ may indicate that the reionization process is inhomogeneous. Fluctuations in the UV background (Γ model) and IGM gas temperature (T model) have been proposed to explain this large variation, but they predict the correlation between $\tau_{\rm eff}$ and galaxy density inversely. To explore models that could explain the large variation in $\tau_{\rm eff}$, Lyαemitters (LAEs) are searched around the sightlines of two quasar (J1137+3549 and J1602+4228) with $\tau_{\rm eff} \sim 3$ and J1630+4012 with $\tau_{\rm eff} \sim 5.5$. Using narrow-band imaging with Subaru/Hyper Suprime-Cam, LAE density maps were created and their spatial distributions are explored. We found that the low $\tau_{\rm eff}$ region shows excess density within 20 h^{-1} Mpc from the quasar sightlines, while the high $\tau_{\rm eff}$ region is deficient in LAEs. These observed $\tau_{\rm eff}$-galaxy density relations consistently support the Γ model in all three fields. (Kashikawa)

5.1.8 Dust-enshrouded growth of galaxies and supermassive blackholes

We conducted an ALMA-Herschel joint analysis of 180 sources detected in 33 lensing cluster fields by the ALMA Lensing Cluster Survey (ALCS) at 1.2 mm. Our main sample comprised 141 securely detected sources, and we performed far-infrared spectral energy distribution modeling to derive physical properties related to dusty star formation for 125 of these sources. The redshift distribution suggests an increasing fraction of $z \sim 1-2$ galaxies among fainter millimeter sources. The median intrinsic (delensed) star formation rate for the main sample was significantly (~3 times) lower than that of conventional submillimeter galaxies at similar redshifts[67]. We also presented multi-wavelength mosaics and photometric catalogs, constructed from reprocessed archival Hubble Space Telescope (HST) and Spitzer data. The final catalogs contain 218,000 sources, covering a combined area of 690 arcmin^2, a factor of ~ 2 improvement over the currently existing photometry. These serve as valuable tools for future ALMA surveys and follow-ups with JWST. Our multi-wavelength approach will enable better constraints on photometric redshifts and stellar masses, aiding in the identification of high-redshift candidates and contributing to our understanding of the Epoch of Reionization and the formation of the first galaxies[57] (Kohno, Shimasaku).

We utilized ALMA to investigate G09.83808, a strongly-lensed submillimeter galaxy (SMG) at $z = 6.0$. Our observations detected various line emissions such as [N II] 205 μm and [O III] 88 μm, as well as dust continuum emissions. The compact spatial distribution of the dust suggests that G09-83808 could be a progenitor to compact quiescent galaxies observed at $z \sim 4$. We also noted a declining trend in the [N II] line to infrared luminosity ratio, analogous to trends seen in local luminous infrared galaxies. We estimated the gas-phase metallicity of the galaxy to be $Z \sim 0.5 - 0.7 Z_\odot$, indicating that G09.83808 is among the early galaxies to experience chemical enrichment[66]. Furthermore, we detected the CO(12–11) line and investigated the physical properties of the multi-phase interstellar medium in G09.83808. Our findings suggest that the molecular gas is concentrated in the central 0.5 kpc region and is both warm ($T_{\rm kin} \sim 320$ K) and dense. We find the elevated CO luminosity ratio $L_{\rm CO(12-11)}/L_{\rm CO(6-5)} = 1.1 \pm 0.2$, which is consistent with those in local active galactic nuclei and $6 < z < 7$ quasars. We suggest that G09-83808 hosts a dust-obscured growing supermassive black hole, which illuminates the surrounding ISM to form X-ray dominated regions, at the end of cosmic reionization[54] (Kohno).

We investigated the feasibility of [C II] 158 μm line intensity mapping using the integrated superconducting spectrometer (ISS) technology, which has been demonstrated by DESHIMA2.0 on the submillimeter-wave telescope ASTE[55, 56], to obtain new constraints on the [C II] luminosity functions and the roles of dust-obscured star-formation in the epoch of reionization (Kohno, Moriwaki, Yoshida).

5.1.9 X- and γ-ray study of high-energy astrophysics

Our aim is understanding high energy phenomena in the universe, such as supernova explosions and their remnants, compact stars such as neutron stars and blackholes, and active galactic nucleus. Such high energy objects emit X-rays and gamma-rays, thus we observe such high energy photons using balloons and satellites.

This year we studied the shock structure and heating mechanism in supernova remnant (SNR) systems. We have made detailed spatially resolved spectroscopy of young SNRs, SN1006, and found that the temperature of the heated interstellar medium become higher in the scale of ~0.6 pc. The increase is smaller than expected from the Rankine-Hugoniot relation of ideal gas, but we still discuss what makes the descrepancy. The particle acceleration on the SNR shocks are also examined; we found that the enhancement of synchrotron X-rays due to the shock-cloud interaction [83], which is the third sample for such a case. The detailed analysis of an old gamma-ray SNR, G298.6+0.0, and confirmed as one of the oldest sample found ever [93].

The accreting neutron stars are also studied into the detail. We have phase-resolved (both orbital and spin) spectroscopy of Cen X-3, and found that the key parameter of time variability is absorption [94]. Together with same analysis with Her X-1, another accreting neutron star, a toy model of the geometry of accreting pulsars has been constructed, which well explain both models.

We also study on the detector development for the near future missions. For the XRISM, to be launched on the Japanese fiscal year 2023, we fixed the performance verification targets. We also developed the Monte-Carlo based data analysis method for pile-uped data of the X-ray CCD onboard XRISM. For Cipher mission, the first imaging polarimetory cubesat in the hard X-ray band, we developed the new analysis method to increase the sensitivity sensitivity several fold. The GRAMS mission, a new MeV gamma-ray mission, we succeeded to have a chance of the balloon Engineering Demonstration Experiment in the fiscal year of 2023, and started the preparation (Bamba).

5.1.10 Observational cosmology using cosmic microwave background

We conduct cosmology research by observing Cosmic Microwave Background (CMB) through observational projects: Polarbear, Simons Array, and Simons Observatory.

The Polarbear experiment and its successor, Simons Array, are designed to measure both inflationary signature and the gravitational lensing effect in CMB polarization. Polarbear has concluded its observation campaign in 2016, and our focus has been on data analysis. We realized the improvement of the constraint on the tensor-to-scalar ratio r. Recently we are proceeding a new time-domain data analysis of the Polarbear datasets for searching the Axion-like particle (ALP). For Simons Array experiment, we are focusing on both of data analysis and deployment of the telescopes. Science observations are conducted with the first telescope, and we are analyzing the data in parallel with analysis pipeline development to achieve the improved result on the inflationary signature and ALP search. As for the second telescope, test observations and deployment are proceeded. We are providing feedbacks by the analysis of the test observations.

The Simons Observatory experiment is scheduled for the first light in 2023. We are deploying three 0.4-m Small Aperture Telescopes (SATs), which are dedicated for exploring inflationary signature, and a 6-m Large Aperture Telescope (LAT), which will measure (or constrain) the sum of neutrino masses, and the dark content of the universe. We have primarily focused on the development of SATs, especially the cryogenic optics tube, the cryogenic continuously rotating half-wave plate (HWP) system, and the wiregrid calibrator, and made significant progress in fabricating and commissioning. Currently, we also are woking on the deployment work at the Chile site.

We also focus on developing techniques for high-performance computation (HPC) enabling data analysis for Simons Observatory as well as Simons Array, producing order-of-magnitude larger data volume than the previous instruments. While improving computational throughput, we need to improve on the analysis systematics as well. One of our emphasis has been to reduce systematic leakage from the E-modes to B-modes, developing technique to achieve this in a computationally feasible manner. In doing so, we have developed a new pipeline module by taking advantage of GPUs and have validated it with simulated datasets. (Kusaka, Kiuchi, Takeuchi)

5.1.11 Solid grains ejected from terrestrial exoplanets as a probe of the abundance of life in the Milky Way

Searching for extrasolar biosignatures is important to understand life on Earth and its origin. Astronomical observations of exoplanets may find such signatures, but it is difficult and may be impossible to claim unambiguous detection of life by remote sensing of exoplanet atmospheres. Here, another approach is considered: collecting grains ejected by asteroid impacts from exoplanets in the Milky Way and then travelling to the Solar System. The optimal grain size for this purpose is around 1micron, and though uncertainty is large, about 10^5 such grains are expected to be accreting on Earth every year, which may contain biosignatures of life that existed on their home planets. These grains may be collected by detectors placed in space, or extracted from Antarctic ice or deep-sea sediments, depending on future technological developments. (Totani)

5.2 Publication List

[1] T. Hayashi, K. Kamada, N. Oshita and J. Yokoyama, "Vacuum decay in the Lorentzian path integral", Journal of Cosmology and Astroparticle Physics **05** (2022) 041.

[2] J. Kristiano and J. Yokoyama, "Perturbative region on non-Gaussian parameter space in single-field inflation", Journal of Cosmology and Astroparticle Physics **07** (2022) 007.

[3] K. Murai, F. Naokawa, T. Namikawa, E. Komatsu,"Isotropic cosmic birefringence from early dark energy" , Physical Review D **107**(2023) L041302.

[4] S. Hashiba, K. Kamada, H. Nakatsuka, "Gauge field production and Schwinger reheating in runaway axion inflation", Journal of Cosmology and Astroparticle Physics **04** (2022) 058.

[5] K. Fujikura, S. Hashiba, and J. Yokoyama, "Generation of neutrino dark matter, baryon asymmetry, and radiation after quintessential inflation", Physical Review D **107** (2023) 063537.

[6] T. Fujita, J. Kume, K. Mukaida and Y. Tada, "Effective treatment of U(1) gauge field and charged particles in axion inflation", Journal of Cosmology and Astroparticle Physics **09** (2022), 023.

[7] V. Domcke, K. Kamada, K. Mukaida, K. Schmitz, and M. Yamada, "Wash-in leptogenesis after axion inflation", Journal of High Energy Physics **01** (2023) 053.

[8] K. Kamada, N. Yamamoto, and D-L. Yang, "Chiral effects in astrophysics and cosmology", Progress in Particle and Nuclear Physics **129** (2023) 104016.

[9] T. Higaki, K. Kamada, and K. Nishimura, "Formation of a chiral soliton lattice", Physical Review D**106** (2022) 9, 096022.

[10] H. Abe et al. (incl. J. Kume, K. Ueno, J. Yokoyama), "Noise subtraction from KAGRA O3GK data using Independent Component Analysis", Class. Quant. Grav. **40** (2023) 085015.

[11] T. Washimi *et al.* (incl. J. Kume, J. Yokoyama) "Response of the underground environment of the KAGRA observatory against the air pressure disturbance from the Tonga volcanic eruption on January 15, 2022", PTEP **2022** (2022) no.11, 113H02.

[12] M. Hindmarsh and J. Kume, "Multi-messenger constraints on Abelian-Higgs cosmic string networks", [arXiv:2210.06178 [astro-ph.CO]], Journal of Cosmology and Astroparticle Physics in press.

[13] KAGRA collaboration, "Input optics systems of the KAGRA detector during O3GK", PTEP **2023** (2023) no.2, 023F01.

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5.3 International Conference Talks

5.3.1 Contributed talks

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[133] Matsui, S., Shimasaku, K., Ito, K., Ando, M., Tanaka, T., "The average SMBH accretion properties of star-forming galaxies and their cosmic evolution over $4 \lesssim z \lesssim 7$", Galaxy Evolution Workshop 2023, Kyoto University and online, 2023/2/20–2/23

[134] Takumi Tanaka, "SWIMMY Survey: Mining Unique Color Features Buried in Galaxies by Deep Anomaly Detection", Tracing the SMBH growth: outlook beyond the HSC-SSP, and future collaborations, 2022/11/30–12/2, Kagoshima University and online

[135] Tanaka, T., Shimasaku, K., Ando, M., Ito, K., Matsui, S., Tacchella, S., and Yesuf, H., "HINOTORI: A Statistical Study of Rejuvenated Galaxies with the SDSS/MaNGA Sample", 9th Galaxy Evolution Workshop, 2023/2/20–2/23, Kyoto University and online

[136] K. Kohno, "Surveys of dusty galaxies using ALMA and beyond" A half century of millimeter and submillimeter astronomy: Impact on astronomy/astrophysics and the future, Miyakojima, Japan, December 15–18, 2022

[137] K. Kohno, "Integrated superconducting spectrometers for existing and future submillimeter-wave telescopes" Chile-Japan Academic Forum 2022, Astronomy, Astronomical Instrumentation, Microsatellites & Space Imaging, Puerto-Varas, Chile, November 29-30, 2022

[138] K. Kohno, "Near-infrared-dark lensed faint ALMA sources uncovered by the ALMA lensing cluster survey (ALCS)" IAU Symposium 373: Resolving the Rise and Fall of Star Formation in Galaxies, Busan, Korea, August 9-11, 2022 (e-talk)

[139] Masaaki Murata *et al.*, "Development of the Calibration System with a sparse wire grid for Small Aperture Telescope of Simons Observatory," SPIE Astronomical Telescopes + Instrumentation, Montreal, Quebec, Canada (2022/7/17–22)

[140] Kana Sakaguri for POLARBEAR Collaboration, "Preparation fot the Simons Array CMB polarization experiment and development of optical elements," 2nd International Symposium on Trans-Scale Quantum Science (TSQS) 2022, The University of Tokyo (2022/11/8–11)

[141] Atsuto Takeuchi for POLARBEAR Collaboration, "Status of the Simons Array Experiment," International Conference on the Physics of the Two Infinities, Kyoto University (2023/3/27–30)

[142] Kana Sakaguri for POLARBEAR Collaboration, "Preparation for the second telescope of the Simons Array CMB polarization experiment," International Conference on the Physics of the Two Infinities, Kyoto University (2023/3/27–30)

[143] Junna Sugiyama for Simons Observatory collaboration, "Development of a Cryogenic Half-wave Plate for Simons Observatory," International Conference on the Physics of the Two Infinities, Kyoto University (2023/3/27–30)

[144] Bamba, A., Sano, H., Yamazaki, R., Vink, J., "Understanding shock-cloud interaction on the supernova remnant RCW86 with Athena", "The third scientific conference dedicated to the Athena X-ray observatory", Madrid/Hybrid, 2022, Nov. 7-10 (oral)

[145] Odaka, H., "X-ray Imaging Polarimetry using a Fine Pixel CMOS Imager", NDIP20 (Conference on New Development in Photodetection), Troyes, France, 2022, July 4-8 (poster)

[146] Odaka, H., "Unveiling accretion disc winds from supermassive black holes with Monte Carlo X-ray radiative transfer modeling", What Drives the Growth of Black Holes?, Reykjavik, Iceland, 2022, September 26-30 (poster)

[147] Yeung, P.K., Bamba, A., Sano, H., "Gamma-ray and X-ray study of possibly oldest GeV supernova remnant G298.6-0.0", "Particle Acceleration in Astrophysical Objects", Rome/Hybrid, 2022, Sep. 5-7 (oral)

[148] Yeung, P.K., "Multiwavelength studies of G298.6-0.0: Possibly one of the oldest GeV supernova remnants", "XRISM Core-to-Core Science Workshop", Saitama, 2022, Octobar 19-21 (poster)

[149] Tamba, T., Odaka, H., Bamba, A., Murakami, H., Mori, K., Hayashida, K., Teradam Y., Nobukawa, M., MIzuno, T., Yoneyama, T., XRISM MOPT, "Development of a new analysis framework for pile-up data of X-ray CCDs based on Monte-Carlo simulation", IACHEC 2022 Spring Virtual Workshop, online, 2022, May 23-25 (oral)

[150] Takashima, S., Odaka, H., Bamba, A., Yoneda, H., Ichinohe, Y., Aramaki, T., Inoue, Y., "A multi-task neural network model for event reconstruction of large effective area Compton cameras", "ADASS Conference XXXII", online, 2022, October 30-November 4 (poster)

[151] Minami,T., Bamba, A., Terada, Y., "XRISM と NuSTAR の同時観測による強磁場白色矮星の非熱的放射の探査", "XRISM Core-to-Core Science Workshop 2022", Saitama, 2022, October19-21 (poster)

[152] Minami,T.,Katsuragawa,M,Nagasawa,S.,Takeda,S., Takahashi,T.,Tsuzuki,Y.,Watanabe,S., "Study of performance and response of thick CdTe double-sided strip detectors for various fields", "The 4th workshop on quantum beam imaging", Riken Wako, 2022, September26-27 (oral)

[153] Ichihashi, M., Kasuga, T., Odaka, H., Bamba, A., Kato, Y., Katsuda, S., Suzuki, H., Nakazawa, K., "The discovery of spatial variation of electron temperature in the northwestern region of SN1006", "Supernova Remnants and their Progenitors", Harvard/Hybrid, 2022, August 16-18 (oral)

[154] Ichihashi, M., Kasuga, T., Odaka, H., Bamba, A., Kato, Y., Katsuda, S., Suzuki, H., Nakazawa, K., "Understanding the heating mechanism of collisionless shocks with XRISM observations of supernova remnants", "XRISM Core-to-Core Science Workshop", Saitama, 2022, Octobar 19-21 (poster)

[155] Ichihashi, M., Kasuga, T., Odaka, H., Bamba, A., Kato, Y., Katsuda, S., Suzuki, H., Nakazawa, K., "The observation and future prospect of temperature gradient in the shock of SN1006", "Third Athena Scientific Conference 2022: Exploring the Hot and Energetic Universe", Saitama, 2022, November 7-10 (poster)

[156] Iwata, T., Tanimoto, A., Odaka, H., Bamba, A., Inoue, Y.,"Unveiling the origin of hard X-ray emission of Centaurus A with multi-epoch NuSTAR observations: disk or jet?", "What Drives the Growth of Black Holes: A Decade of Reflection", Reykjavik, 2022, September 26-30 (poster)

[157] Iwata, T., Tanimoto, A., Odaka, H., Bamba, A., Inoue, Y., "Unveiling the origin of the iron emission line of Centaurus A with high-resolution X-ray spectroscopy", "XRISM Core-to-Core Science Workshop 2022", Saitama, 2022, October19-21 (poster)

[158] Arai, S., Odaka, H., Bamba, A., "Hunting for jet/wind interactions in Cygnus X-3 with XRISM", "XRISM Core-to-Core Science Workshop 2022", Saitama, 2022, October19-21 (poster)

5.3.2 Invited talks

[159] J. Yokoyama, “Introduction to KAGRA experiment”, Synergies at new frontiers at gamma-rays, neutrinos and gravitational waves, ICRR, The University of Tokyo, 2022/3/24.

[160] J. Yokoyama, “Cooperation in physics in the Asia Pacific Region”, IUPAP centennial symposium, Trieste, Italy, 2022/7/12.

[161] J. Yokoyama, “Cooperation in physics in the Asia Pacific Region through AAPPS”, Global Physics Summit, Yonsei University, Korea 2022/8/22.

[162] J. Yokoyama, “Status of KAGRA in September 2022”, LIGO-Virgo-KAGRA meeting, Cardiff University, UK, 2022/9/14.

[163] J. Yokoyama, “Mid-to-long term future through Asia Pacific physics cooperation”, APCTP basic science forum, Korea, 2022/10/25.

[164] J. Yokoyama, “Closing remarks”, 2nd international symposium on trans-scale quantum science, Trans-Scale Quantum Science Institute, The University of Tokyo, 2022/11/11.

[165] J. Yokoyama, “Status of KAGRA in September 2022”, LIGO-Virgo-KAGRA meeting, Northwestern University, USA, 2023/3/15.

[166] J. Yokoyama, “KAGRA toward O4 and beyond”, 15th Asia Pacific Physics Conference, Korea, online 2022/8/22-25.

[167] K. Kamada, “Wash-in Leptogenesis in the axion inflationary magnetogenesis scenario”, 15th Asia Pacific Physics Conference, Korea, online 2022/8/22-25.

[168] K. Kamada, “Lorentzian Description of the 1st Order Phase Transition”, Online Workshop “Physics of the Early Universe”, Online, 2022/6/16.

[169] J. Kristiano, “Primordial black holes from single-field inflation?”, Cosmology and Particle Astrophysics (CosPA 2022), Online, 2022/11/30.

[170] J. Kristiano, “Ruling out primordial black hole formation from single-field inflation”, Workshop on Dynamics of primordial black hole formation, Rikkyo University, 2023/03/10.

[171] Akihiro Suzuki, “Radiation-hydrodynamics modelings of interaction-powered transients”, 2022/12/14, Exploring the Transient Universe, Tokyo

[172] Naoki Yoshida: “3D density field reconstruction with a sparsity prior”, Cosmology with Weak Lensing: Beyond the Two-point Statistic (Kyoto University, April 15, 2022)

[173] Naoki Yoshida: “Early structure formation and dynamical evolution of star clusters”, Gravitational Wave Constraints on Dark Compact Objects, (Pennsilvania State University, USA, May 19, 2022)

[174] Naoki Yoshida: “First star formation under the influence of baryonic streaming motions”, From Stars to Galaxies II, (Chalmers University of Technology, Sweden, June 24, 2022)

[175] Moriwaki K., “Deep Learning Application for Reconstruction of Large-Scale Structure of the Universe”, SWIFAR Colloquium, Yunnan University, Online (April 21, 2022)

[176] Moriwaki K., “IGM at High Redshifts Probed by 21cm Line”, Galaxy-IGM Workshop 2022, Kushiro Royal Inn, Hokkaido, Japan (Aug 9, 2022)

[177] K. Kohno, “Exploring dark side of galaxy formation in the early Universe” International Conference on the Physics of Two Infinities, Kyoto University, Japan, March 27–30, 2023

[178] K. Kohno, “Unbiased surveys of dust-enshrouded galaxies using ALMA” The 7th Chile-Cologne-Bonn Symposium, Physics and Chemistry of Star Formation – The Dynamical ISM across Time and Spatial Scales, Puerto-Varas, Chile, September 26–30, 2022

[179] K. Kohno, “Galaxy surveys with AtLAST/LST and IFUs” Lorentz Center Workshop, Mapping the Invisible Universe, Leiden University, the Nertherlands, August 29 – September 2, 2022

[180] Akito Kusaka, “Cosmic Microwave Background - challenges and future prospect,” Frontiers in Cosmology, Bangalore, India (2023/2/20–24)

[181] Akito Kusaka, “Exploration of Inflation and Dark Universe through Cosmic Microwave Background,” 2nd International Symposium on Trans-Scale Quantum Science, Tokyo, Japan (2022/11/8–11)

[182] Odaka, H., “X-ray Polarimetry for Astrophysics with CMOS imaging sensors”, Pixel22 (10th International Workshop on Semiconductor Pixel Detectors for Particles and Imaging), Santa Fe, USA, 2022, December 12-16

[183] Yeung, P.K., "Supernova Remnant Kes 79", U.Tokyo/Hybrid, open to Department of Astronomy & Institute of Astronomy of The University of Tokyo Japan, June 2022

[184] Yeung, P.K., "High-Energy Studies of Two Intermediate-Aged/Old Supernova Remnants Kes 79 & G298.6-0.0", Department of Electrical, Electronic and Computer Engineering, Gifu University, Gifu, Japan, August 2022

[185] Yeung, P.K., "Multiwavelength studies of G298.6-0.0: Possibly one of the oldest GeV supernova remnants", Department of Physics, Kindai University, Higashiosaka, Japan, September 2022

[186] Yeung, P.K., "Multiwavelength studies of G298.6-0.0: Possibly one of the oldest GeV supernova remnants", Department of Astronomy, Kyoto University, Japan, September 2022

[187] Yeung, P.K., "Multiwavelength studies of G298.6-0.0: Possibly one of the oldest GeV supernova remnants", Department of Physical Sciences, Aoyama Gakuin University, Japan, October 2022

[188] Yeung, P.K., "Multiwavelength studies of G298.6-0.0: Possibly one of the oldest GeV supernova remnants", The University of Hong Kong, Hong Kong, November 2022

[189] Yeung, P.K., "Multiwavelength studies of G298.6-0.0: Possibly one of the oldest GeV supernova remnants", Kagoshima University, Kagoshima, Japan, November 2022

[190] Yeung, P.K., "Multiwavelength studies of G298.6-0.0: Possibly one of the oldest GeV supernova remnants", Core of Research for the Energetic Universe (CORE-U), Hiroshima University, Higashihiroshima, Japan, November 2022

[191] Yeung, P.K., "Hadronic gamma-rays from the radiative shell & molecular clouds of the old GeV supernova remnant G298.6-0.0", Department of Physics, Nagoya University, Nagoya, Japan, March 2023

[192] Tomonori Totani, "Emergence of life in an inflationary universe", Potential and Limitations of Evolutionary Processes, Israel, May 2022 (online presetation)

6 Project 2. Gravitational-wave astrophysics and experimental gravity

6.1 Activity Report

6.1.1 Kipp Cannon group

Our research group studies black holes, neutron stars, exotic astrophysical objects, and the Universe using gravitational waves, and electromagnetic observations. Gravitational waves are waves of spacetime curvature generated by the movement of mass and momentum. There are many reasons why gravitational waves are an interesting way to explore the sky. Because gravitational waves are generated by physical processes different from those that produce light or radio waves (which are generated by the movement of electric charges and currents), gravitational waves carry different information about their sources than is carried by electromagnetic waves. Gravitational waves interact weakly with matter allowing them to pass through material that would be opaque to radio waves and light. For example we expect that gravitational waves can escape the dense deep cores of supernovæ, and show us the earliest moments of the Big Bang. The Earth, too, is transparent to gravitational waves, so gravitational-wave telescopes can see the sky below them through the Earth as easily as they can see the sky above, allowing gravitational-wave telescopes to monitor the whole sky continuously, day and night. Gravitational waves are the only significant form of energy expected to be radiated by some of the most exotic events in the universe like the collisions of black holes. However, because everything is nearly transparent to gravitational waves, it is very difficult to build a device that can detect them, and the first detection of this form of energy was only achieved in 2015. It is even more difficult to build a device that can generate gravitational waves of any measurable amplitude, and so astronomy, that is the observation of intense naturally occurring sources of these waves like the collisions of black holes, provides our only opportunity to explore this aspect of the natural world.

Our research group's members are members of the LIGO Scientific Collaboration and KAGRA Collaboration, and we analyze data collected by the two LIGO gravitational-wave antennas in the United States, the Virgo antenna in Italy, the GEO600 antenna in Germany, and the KAGRA antenna in Japan.

The Advanced LIGO and Advanced Virgo antennas were not collecting data during FY2022, and had not been doing so since March of 2020 at the start of the pandemic. The fourth observing run for the Advanced detectors, "O4", began shortly after the start of the FY2023 academic year. Nevertheless, analysis of previously recorded data continued during this time, as well as research and development of new techniques for analyzing and extracting information from the data, which we hope to apply in the future. Members of our group are active in all aspects of observational gravitational-wave astronomy, the following are some highlights from FY2022.

Searches for Compact Object Collisions

When heavy stars exhaust their fuel supply they undergo gravitational collapse. The end state of this process can be a neutron star or a black hole. There are many of these in the Universe, and occasionally they collide with one another. These collisions are very powerful sources of gravitational radiation. Since the first detection of gravitational waves from the collision of a pair of black holes in September, 2015, we have been able to study the behaviour of strongly curve spacetime.

This past academic year the LIGO, Virgo, and KAGRA collaborations published the results of a search for collisions of black holes with masses below 1 solar mass (doi:10.48550/arXiv.2212.01477). There are theoretical reasons to believe that the normal life cycle of stars cannot result in such low mass black holes, only exotic processes such as large density fluctuations in the early Universe or some dark matter models could result in such objects existing at all. The discovery of such an object could transform our understanding of nature. The search produced no evidence of such objects, and so constraints on primordial black hole production and dissipative dark matter were inferred.

Overlapping of gravitational-wave signals in the future gravitational-wave detectors

Future terrestrial gravitational wave detectors such as Einstein Telescope and Cosmic Explorer are expected to observe a large number of gravitational wave events (hundreds of thousands of events per year) from binary coalescences of neutron stars and black holes. If the number of events is too large, the gravitational wave signals in the detector data will overlap each other, which might affect the parameter estimation of an individual gravitational wave signal. In the worst case, these signals cannot be separated and make their detections difficult. To study this issue, we first performed a simulation to randomly generate gravitational wave events and estimated how much gravitational wave signals would overlap. Then, it was investigated how much the error of parameter estimation and the estimation bias are degraded when the gravitational wave signals overlap. As a result, it was found that the parameter estimation was hardly affected unless the waveforms of the overlapping gravitational wave signals were very similar. Therefore, our conclusion is that the overlaps of gravitational wave signals can occur frequently but do not cause a problem for parameter estimation in the future gravitational wave detector [17].

Short gamma-ray burst search with the CHIME radio telescope

Short gamma-ray bursts (sGRBs) are energetic and explosive outbursts lasting less than two seconds. sGRBs are thought to originate from compact object mergers such as binary neutron star and black hole-neutron star collisions. Since the collisions of compact objects is also be a source of gravitational waves, the detection of gravitational wave signals associated with sGRBs would impose important constraints on the origin of sGRBs. However, only one gravitational wave signal associated with a sGRB has been observed so far. In this study, in order to increase the samples of sGRBs that are the target of gravitational wave surveys, we will attempt to detect sGRBs where only a faint light can be observed. In FY2022, Ms. Shikauchi visited the University of British Columbia, and in collaboration with the group leading the Canadian Hydrogen Intensity Mapping Experiment (CHIME) experiment developed a search for the synchrotron afterglows of neutron star collisions based on the the work in [20]. The ultimate goal of this work is to use neutron star collision remenants identified with CHIME to constrain a search for gravitational waves from these systems to increase the likelihood of successfully associating a gravitational-wave signal with an electromagnetic counterpart.

6.1.2 Cosmology, Hubble parameter from Black Hole Collisions

Because when two black holes collide their masses can be inferred from the phase evolution of the gravitational waveform, and because the amplitude of the emitted gravitational waves is unambiguously determined by the masses of the two black holes, the phase evolution and the observed amplitude of a gravitational wave, together, reasonably precisely indicate the distance of the source of the waves from Earth. If, in addition, the host galaxy and its red shift can be known, then from a collection of such observations a distance-red shift relationship can be measured quite accurately. This is the so-called "dark sirens" technique for inferring the Hubble parameter. Unfortunately, in practice, a specific host galaxy cannot be identified for a black hole collision observed only with gravitational waves, but one can marginalize over all the galaxies consistent with its location and still infer a Hubble parameter, with the penalty being that many more black hole collisions must be observed to make a measurement with useful precision.

In the past, the black hole collisions used for these studies were selected by hand, by the researchers choosing "good ones". This risks introducing a confirmation bias or self-selection effect into the results. Members of our group are working on generalizing the technique to allow all of the black hole collisions from a gravitational wave catalogue to be used, replacing manual selection of good signals with the P(astro) parameter — using the probability a given signal is of astrophysical origin to weight its contribution to the result.

Origins of Compact Binaries with the Astrometric Satellite Gaia

The astrometric satellite Gaia is able to observe non-interacting black hole-luminous companion (BH-LC) binaries and estimate BH mass by observing the motion of the LCs. Since the orbital period of detectable

BH-LC binaries should be longer than that of BH X-ray binaries in the Milky Way and extragalactic binary BHs, Gaia may reveal a different BH population from X-ray and gravitational wave observations. The next data release was held in June 2022 and included information of binaries, which has attracted a great deal of attention. Up to now, there are about ten papers studies theoretically predicting the number of BH-LC binaries observed with Gaia. Two BH-LC binaries have already been confirmed (El-Badry, et al. 2023a, Tanikawa et al. 2022, El-Badry et al. 2023b). To shed additional light on these observations, in FY2022 we used the binary stellar population synthesis code BSE to model the development of black hole binaries and investigate their properites. We found various correlations among the parameters of the binaries, such as the masses and orbital period, and also with its extrinsic properties like the height of the binary from the galactic plane. We found these correlations differ depending on the binary evolution parameters, suggesting that observations of large numbers of such binary systems with Gaia could be used to constrain these unknown parameters.

Neutron Star Interiors

The interior structure of neutron stars is determined by the laws of nuclear physics, however we don't have a good understanding of the behaviour of matter in the extreme pressure and density conditions found deep in the interior of a neutron star, therefore not much is known about the interior structure of these objects. The gravitational waves emitted during the collisions of neutron stars with one another will carry information about their interior structure. Careful study of gravitational waves from neutron star collisions can, therefore, teach us about the properties of matter in regimes inaccessible to experiments here on Earth. Models of neutron stars can be used to connect theories of the properties of nuclear matter to features found in the gravitational waves emitted during their collisions. In collaboration with Prof. Hotokezaka's neutron star modelling group, and the nuclear physics group at the University of Tokyo, members of our group are making this connection from theory to observation, and investigating the ability of gravitational-wave detectors to detect a hadron-quark phase transition in the core of neutron stars. The specific goal is to determine if the transition is a continuous cross-over or a first-order phase transition.

These two different scenarios predict different gravitational waveforms emitted from binary neutron star mergers, and it has been found that the difference appears mainly in the merger or the post-merger phase rather than in the inspiral phase. The main frequency band of gravitational waves after the coalescence of binary neutron stars is 2 kHz to 4 kHz, which is higher than the most sensitive frequency band of the current detectors, for example LIGO. Even with the extremely high signal-to-noise ratio of GW170817, the highest SNR signal seen, we still saw no evidence of a post-merger signal in that gravitational wave. It was hidden by the detector noise. Therefore, in order to use gravitational wave observations to answer the question how the quark-hadron phase transition takes place, a detector which has better sensitivity in the high frequency range and an appropriate analysis method are needed. The goals of this study are figuring out whether current or currently proposed future detectors can solve this problem, what kind of events are suitable for this purpose, and what kind of analyses are effective. This work formed the basis of Ms. Harada's master's thesis, which she succesfully defended this academic year.

Tests of General Relativity

Only with the observations of black hole and neutron star collisions in recent years have we had access to observational tests of the behaviour of gravitational fields in the strong field regime. There are many theories of gravity besides Einstein's theory of general relativity that are seriously considered, but, unfortunately, there are few predictions of what gravitational waves from black hole collisions might look like if these other theories of gravity are correct. Without specific predictions from alternative theories of gravity, it is difficult to construct tests that might falsify general relativity or its alternatives. One approach is to construct a parameterized phenomenological description of the family of gravitational wave signals from black hole mergers in general relativity, and then introduce perturbations of the parameters, thereby constructing non-GR black hole merger-like waveforms. The signals observed in the gravitational-wave detector data can be compared to these and constraints placed on the values of the perturbation parameters, thereby constraining how much of a deviation from general relativity's predictions is admissible. Members of our group are attempting to construct a novel test of this type. The work is on-going, and might lead to a new constraint on general-relativity, or if not, at least a statement of what sort of future detector would be required to make the measurements required to perform the tests that are being designed.

Test of General Relativity in Strong Gravitational Fields

General Relativity (GR), the standard theory of gravity, is only a low-energy effective theory, although it explains well the observations made so far, and it is bound to break down at some point when we approach the strong gravity region. Specifically, it has difficulties in predicting the singularity at which the laws of physics break down, and in the impossibility of renormalization in terms of quantum theory. In order to construct a theory of gravity that avoids these difficulties, it is essential not only to conduct theoretical research but also to devise an appropriate method to analyze the obtained gravitational wave data and to analyze the actual data in order to extract significant information from the data. Therefore, we are devising a quantitative analysis method for the merge stage of the binary black hole coalescence process, which is the most gravitationally intense region available through observations, and analyzing the actual data with the aim of extracting information that will lead to an understanding of the physics of the strong gravitational field.

Test of gravity with gravitational-wave polarizations

One of the ways to test gravity in the dynamical strong-field regime is to count the polarization modes of gravitational waves. Not all gravity theories predict the same number of polarization modes. There are two tensor modes in general relativity, while three or more polarization modes can be found in extended theories of gravity. In other words, incorrect gravity theories can be ruled out by examining the number of polarization modes in the observed gravitational-wave signals. We constructed the mixed polarization model including a scalar polarization as an additional one beyond general relativity and analyzed the actual observation data of the gravitational wave detectors with the scalar-tensor polarization model. We found no signs of polarizations inconsistent with the prediction of general relativity. Therefore, we obtained a new result that supports the correctness of general relativity.

Observational constraint on axion dark matter with propagating gravitational waves

Most of matter in the Universe is invisible, which is called dark matter. A candidate for dark matter is the axion. If they exist, axions form clouds in a galactic halo and amplify and delay a part of gravitational waves propagating in the clouds. The Milky Way, from within which we observe the Universe, is surrounded by a dark matter halo potentially composed of a number of axion patches. Thus, if an axion cloud comprises our galaxy's dark matter, characteristic secondary gravitational waves are always expected right after a reported gravitational-wave signal from a compact binary merger. We searched for the secondary gravitational waves with a method optimized for the time delay and the amplification. We found no significant signal and constrained the axion coupling to the parity violating sector of gravity, which is at most 10 times improved from a previous study, Gravity Probe B.

Stochastic Gravitational-wave Background

While some gravitational wave sources like GW170817 are close, loud, and infrequent, we also anticipate classes of gravitational wave sources that are distant, quiet, and numerous. Rather than distinct, impulsive, signals being detected from such sources we expect to observe them collectively as a diffuse "glow" of random gravitational radiation coming from all directions on the sky — a stochastic gravitational-wave background. Spacetime fluctuations in the very early Universe are expected to contribute to a cosmological gravitational-wave background, but that is expected to be undetectable with modern equipment. A detectable astrophysical stochastic background of gravitational radiation could come from more recent processes, for example black hole collisions in the early Universe, a population of cosmic strings, and so on. Many of the possible sources of a stochastic gravitational wave background are hypothetical; their discovery would be a tremendous breakthrough. Some sources of stochastic gravitational waves might not be uniformly distributed on the sky, for example if they are confined to galaxies and are close enough that the separation of galaxies on the sky is significant, or if, for example, there are gravitational lenses close to us that magnify and make some parts of the sky appear brighter than others. Members of our group are collaborating with researchers at the California Institute of Technology and Pennsylvania State University to develop and conduct a search for anisotropic stochastic gravitational waves.

Other Gravitational-wave Sources

A number of solutions of Einstein's field equation for gravity are known that allow a vehicle to be transported through the surrounding spacetime at speeds greater than the speed of light. Most such solutions of the field equation share the property of requiring material with negative mass to form the require spacetime curvature. Although anti-gravitating tensile material is believed to exist, and is believed to have been responsible for large scale properties of our Universe today, there is no evidence that anti-gravitating negative energy density material exists, and some hypothesize that its existence is forbidden due to some yet undiscovered law of nature. Another property the solutions all possess is that they quickly decay to flat space in their exteriors, which is usually imposed to simplify the mathematics involved in finding such faster-than-light solutions. What if these two properties are connected? Perhaps faster-than-light solutions can be found that include an out-going radiation component, and perhaps those solutions don't require negative mass. An everyday analogy can be seen: boats exist, boats move faster than the velocity of surface waves in water, but boats that produce no wake while doing that are likely impossible.

Therefore, for fun, members of our group have hypothesized what the gravitational-wave wake from a faster-than-light spacetime bubble might look like, and have conducted a search for these signals in 1 year of data of LIGO and Virgo from O3. Measuring the sensitivity of the search, we can use a null result to put constraints on the rate of near-Earth flybys of faster-than-light vehicles. This work will be published shortly. Although this was conducted for amusement, a bi-product of this work has been the discovery that the waveform model is particularly well suited for identifying a novel class of "glitch" waveforms in the detector data, and we hope to see it help with noise mitigation efforts in the future.

Improvements of gravitational-wave detector sensitivity

Globally correlated magnetic noise

Correlation analysis between data obtained from multiple detectors is essential to detect the stochastic gravitational-wave background. However, when global disturbances affect gravitational wave detectors, correlations due to other than gravitational waves can appear and become a source of noise even in two detectors that are sufficiently far apart. One of the main sources of such a correlation noise is the global magnetic field, called the Schumann resonance. Based on the Fisher analysis, we discuss the impact of the correlated magnetic noise on the detection of the stochastic gravitational-wave background. We show how much the detector sensitivity to the stochastic gravitational-wave background is affected in the presence of the correlated magnetic noise. We furthermore show that a network observation combining more than 3 detectors is quite essential and that KAGRA may play an important role in better separating the correlated noise.

Study on sensitivity improvement for the future space-beased gravitational-wave detectors

The Japanese future space-based gravitational-wave detector, DECIGO, aims at detecting primordial gravitational waves generated by inflation in the early Universe. However, as the prediction for the amplitude of the inflationary gravitational waves is highly uncertain, it is necessary to improve the target sensitivity of DECIGO and enhance the possibility of the detection of the inflationary gravitational waves. The current target sensitivity of DECIGO is limited by quantum noise (shot noise and radiation pressure noise). However, squeezing is not available for DECIGO because of its long arm length and large optical loss. In the case, the quantum locking method that controls main cavity length by feeding back the signal from an external small auxiliary cavity can be used to reduce the radiation pressure noise. We extended the quantum locking by incorporating optical spring and showed that the radiation pressure noise is reduced further and the sensitive frequency band broadens [16].

Searching for short gamma-ray burst afterglows with the radio telescope Canadian Hydrogen Intensity Mapping Experiment (CHIME) (Shikauchi)

The aim of this work is to understand the origin of short gamma-ray bursts (sGRBs), explosive events in the Universe. We are trying to detect sGRB afterglows with the radio telescope CHIME. In the last fiscal years, I spent one year at the University of British Columbia, Canada, and developed a code to remove aliases which can be a cause of false positives. Aliases are also known as folding noise. They appear when we try to digitize higher frequency components than a sampling frequency. CHIME takes a skymap in a day called "ringmap" and aliases are seen as artificial objects with the same brightness as true ones. Thus, true objects are duplicated by aliasing. One of the features of aliases is that their position changes by frequency. If an effect of noise raised by human activities such as mobile phones, TV broadcasts, and airplanes is not negligible in a specific frequency, data in the frequency band will be removed from the analysis. That means brightness of pixels where aliases in a frequency band exist can change day by day. They can induce false positives for searches for sGRB afterglows. Considering the position of aliases move in frequency unlike true objects, we constructed a filter based on linear regression model and applied it to data in wide frequency band so that aliases move large enough to distinguish if they are aliases or not. We successfully reduced brightness of aliases to a few percents of the true sources.

Theoretical estimates of black hole—luminous companion binary search with the astrometric satellite Gaia (Shikauchi)

The astrometric satellite Gaia has been supposed to detect black hole (BH)–luminous companion (LC) binaries by observing LCs in the visible light band. The recent data release in 2022 first revealed information about non-single stars and two BH–LC binaries have been confirmed (El-Badry+2023a, Tanikawa+2022, El-Badry+2023b). As more BH binaries get detected with Gaia, we wondered if we could find correlations between binary parameters seen in X-ray BH binaries. By using binary population synthesis code BSE (Hurley+2000, 2002), we theoretically estimated correlations of binary parameters and spatial parameters, i.e. the distance from the Galactic plane and the velocity perpendicular to the plane, of detectable BH–LC binaries with Gaia. To that end, we first predicted a spatial distribution of detectable BH–LC binaries in the Milky Way by numerically calculating the motion of each binary after BH formation. Finally, we found some significant correlations which could give us a clue for binary evolution models such as supernova models, the strength of BH natal kick (Shikauchi+2023).

On the Testability of the Quark-Hadron Transition Using Gravitational Waves (Harada)

In high-density matter, such as that found at the core of a massive neutron star, the quark degrees of freedom may be liberated. However, it is not known how the transition from hadron matter to quark matter occurs. The maximum density of remnants of the binary neutron star mergers is believed to reach about five times the nuclear saturation density. The gravitational waves emitted from them are sensitive to the equation of state around the quark-hadron transition. However, the frequencies involved are typically above 2 kHz, which is considerably higher than the most sensitive frequency range of current detectors, for example LIGO. In this study, numerical relativity waveforms calculated for two representative quark-hadron transition scenarios were used, and Bayesian model selection was performed to investigate the distinguishability of correct scenarios using future detectors. In the analyses, it was assumed that the relatively low density equation of state around nuclear saturation densities is completely known from accumulated observations. Under this assumption, it was found that determining the correct scenario is challenging with observations with the design sensitivity of Advanced LIGO, but there is a realistic possibility with third-generation detectors or future detectors specialized for post-merger signals.

Test of General Relativity in Strong Gravitational Fields (Watarai)

General Relativity (GR), the standard theory of gravity, is only a low-energy effective theory, although it explains well the observations made so far, and it is bound to break down at some point when we approach the strong gravity region. Specifically, it has difficulties in predicting the singularity at which the laws of physics break down, and in the impossibility of renormalization in terms of quantum theory. In order to construct a theory of gravity that avoids these difficulties, it is essential not only to conduct theoretical research but also to devise an appropriate method to analyze the obtained gravitational wave data and to analyze the actual data in order to extract significant information from the data. Therefore, we are devising a quantitative analysis method for the merge stage of the binary black hole coalescence process, which is the most gravitationally intense region available through observations, and analyzing the actual data with the aim of extracting information that will lead to an understanding of the physics of the strong gravitational field.

Testing Metric Affine gravity (Karmakar)

Despite the phenomenological success of General Relativity (GR), particularly in the small scale, challenges persist in understanding phenomena such as galaxy clusters, cosmological acceleration, quantization, and fermion coupling to gravity. Metric Affine Gravity (MAG) has garnered attention for its potential to address these challenges by offering insights into gravity as a gauge theory, fermion coupling to gravity, and the acceleration of the universe.

In GR, the affine connection is solely expressed through the Levi-Civita connection, which is derived from the metric field, thereby representing the spacetime geometry through the metric alone. However, in Metric Affine Gravity, the affine connection and vierbein are treated as fundamental fields to describe spacetime geometry. Consequently, spacetime can exhibit not only wraps and curves (metric) but also twists (torsion) and disformation (non-metricity). GR can be considered as a subclass of this extended theory of gravity and should be tested against observations.

While the disformation aspect of MAG remains understudied, it holds great potential. However, some parts of the theory exhibit instability. A subclass known as symmetric teleparallel gravity, which incorporates non-metricity, shows greater stability. As a result, it is a promising candidate to be tested against observations, such as on galaxy cluster scales and gravitational waves. Progress is being made in understanding spacetime within this framework.

When handling these theories against observations, caution must be exercised. GR has a strong presence in processed data, which may need to be re-evaluated for general purposes. Therefore, it is crucial to carefully consider the compatibility and implications of these alternative theories with existing observational data.

Axion dark matter search with gravitational waves (Nishizawa, Tsutsui)

Most of the matter present in our universe is composed of unknown dark matter, and there have been many dark matter candidates proposed so far. One of the candidates is the axion, and it is believed that there are multiple axion clouds within the halo of the Milky Way. When gravitational waves propagate through these axion clouds, gravitational waves induce the decay of axions into gravitons, which results in an amplification of the gravitational wave amplitude and a time delay due to the changes of the propagation speed. In other words, such specific gravitational wave signatures should be detected around the observational data of previously detected gravitational waves from compact binary mergers. By searching for such distinctive gravitational wave signals, we have placed constraints on the gravitational coupling constant of axions that are up to about 10 times stronger than previous one [19].

On the other hand, we are also engaged in a collaborative research for tabletop experiments searching for axions conducted in the Ando Laboratory, Graduate School of Science, Department of Physics, participating from the theoretical and data analysis aspects.

Development and application for a Cherenkov radiation-like gravitational wave detection system (Kuwahara)

We assumed the existence of superluminal objects (including artificially engineered superluminal spacecraft by extraterrestrial life forms) emitting transient gravitational waves and developed a detection system to explore them. Assuming gravitational waves are generated in the form of shock waves, we created waveform templates based on electromagnetic Cherenkov radiation. Investigations were conducted on one year of O3 (Observation 3) data. The ranking statistics obtained from this search enabled constraints on parameters such as the power, velocity, and distance of superluminal objects from the observer's location. By chance, the specialized waveform model introduced here was found to match very well with certain transient noise events known as "glitches." We are currently preparing these results for publication.

Exploration of primordial stochastic gravitational waves from the early universe through foreground gravitational wave subtraction (Kuwahara)

We revisited the latest research on subtraction of foreground from neutron star and black hole binaries. To determine the sensitivity of current gravitational wave detectors to each anisotropic mode, we developed code to calculate the Overlap Reduction Function for the spherical harmonic modes of each detector and recalculated the Fisher information matrix based on its definition. Utilizing the aforementioned Overlap Reduction Function, we created the code to calculate this Fisher information matrix.

Stochastic gravitational-wave background search in the presence of globally correlated magnetic noise (Nishizawa)

Once the third-generation gravitational wave (GW) detectors such as Einstein Telescope and Cosmic Explorer are completed, the detection of a GW background from a number of compact binary mergers will be well within reach. Additionally, there is the possibility of detecting a cosmological GW background originating from the early universe.

A cross-correlation of data from multiple detectors is used for the detection of a GW background. However, when disturbances of global origin exist on the Earth and affect the GW detectors, correlations other than GWs may appear even between detectors that are sufficiently far apart. This could lead to false detections of a GW background. Particularly, a global magnetic field known as the Schumann resonances could potentially have a significant impact on GW detectors in the future.

To address this, we conducted research on parameter estimation for GW background searches, considering a correlation noise originating from the Schumann resonances. In the presence of four second-generation detectors (LIGO, Virgo, KAGRA), we performed Fisher analysis with an analytical model of the Schumann resonances. The results showed that if the Schumann resonances can be appropriately modeled, correlation noise would not significantly affect the search sensitivity. However, we also found that inadequate modeling could bias the parameter estimation results. These research findings were published in the paper [21].

Displacement noise-free gravitational wave detector with neutron interferometers (Nishizawa)

Observing primordial gravitational waves (GWs), believed to be a direct evidence of inflation in the early Universe, is an important goal in GW researches. However, the sensitivity of ground-based detectors to primordial GWs is limited by low-frequency noises such as seismic vibrations and thermal fluctuations of mirrors. One solution to this challenge is the concept of a displacement noise-free interferometer (DFI), where displacement noise can be canceled out. In a laser DFI, the displacement noise can be completely eliminated by appropriately combining signals, while retaining the gravitational wave signal. However, a drawback of this approach is that it lacks sensitivity in the low-frequency range ($0.1 - 1$ Hz), which is the frequency band of interest for observations of primordial GWs.

To address this, we proposed the idea of a DFI with neutron interferometers, which can have good sensitivity around 1 Hz, thank to the velocity of neutrons much slower than that of laser light [17]. In the original neutron DFI using Mach-Zehnder interferometers, neutrons were incident from both sides. However, preparing bidirectional neutron sources posed various challenges. To overcome this, we devised a practical improvement: a neutron DFI where neutrons with different velocities are incident from one direction [18, 20]. Currently, we are progressing with the consideration of principle verification experiments using this setup for the neutron DFI.

People and Things

During the 2022 through 2023 academic year, two of our Master's students, Ms. Harada and Mr. Watarai, successfully defended their theses and continued on to the doctoral program. One doctoral student, Dr. Tsutsui, successfully defended his thesis and has found employment in the field of modelling and forecasting of stochastic processes.

6.1.3 Kenta Hotokezaka group

Kilonova is one of the electromagnetic wave-counterparts associated with binary neutron star mergers. The radioactive decay of the neutron-rich material released at the time of coalescence is the energy source of kilonovae. It is important that this phenomenon is particularly related to the origin of heavy elements. We conducted research from both observational and theoretical perspectives on kilonovae [25, 26, 28, 29].

A kilonova enters the nebular phase, where emission lines arising from atomic transitions escape from the ejecta without interaction. Thus, observing the nebular spectrum will provide us valuable information on the elements synthesized in merger ejecta. We developed a model for the kilonova nebular emission including all the r-process elements. With this model, we found that the late-time *Spitzer* observations of the kilonova AT2017gfo can be explained by the emission line of doubly ionized tungsten or selenium [25].

We also continued to study the multi-wavelength behaviour of non-thermal afterglow. In particular, we conducted a VLA observation at 4.5 year after GW170817 [27]. The radio flux was detected at the level of $3\,\mu$Jy. This flux level agrees with the expectation of the jet afterglow. Therefore, we put a constraint on the late-time contribution of the kilonova afterglow.

Gamma-Ray Burst Theory (K. Takahashi, C. M. Irwin)

Gamma-ray bursts (GRBs) and their afterglows are important as a probe of death of massive stars and compact binary mergers. We examined the possibility that the shock breakout theory can explain GRB 060218. In order to do it, we considered non-thermal equilibrium processes and light-travel time effects. We found that a shock breakout model including these effects successfully explain the observed data. We also studied particle acceleration in GRB afterglows. In particular, we showed that the future multi-wavelength observation of neutron star mergers' afterglows can reveal the dependence of the particle spectrum on the shock velocity [32].

Supermassive Black Holes and AGNs (D. Toyouchi)

We studied the chemical evolution of AGN environments [30]. In this work, we focused on the evolution of [Fe/Mg] with a semi-analytic modeling. As a result, we obtained a constraint on the birth rate of massive stars in the AGN environments. We also performed radiation hydrodynamics simulations for first star formation [31].

6.2 Activity report of Affiliates

6.2.1 Masaki Ando

Ando group is working on experimental research for gravitational-wave observation, in particular for large projects such as KAGRA and B-DECIGO. KAGRA is a gravitational-wave antenna at Kamioka, Gifu prefecture in Japan. We are playing a key role since the conceptual study phase before the start of the project in 2010. The installation of the main components have been finished in FY2018, and we are in the phase of commissioning; shakedown, and tuning for the full operation of the interferometer. In FY2020, the KAGRA interferometer started the observation run, named O3GK. Our group members led the commissioning works and operation of the interferometer. We are also working on B-DECIGO, which is a space-borne gravitational wave antenna with an observation band of around 0.1 Hz. We made a theoretical study on science cases by this mission as well as experimental development of critical subsystems, such as laser interferometer, stabilized laser source, drag-free system, and low-noise thruster.

6.2.2 Mamoru Doi

In preparation to the fourth observing run (O4) of the gravitational wave (GW) detectors of the LIGO-Virgo-KAGRA Collaboration (LVK) which begins in 2023, we updated the VOEvent based automated followup system of Tomo-e Gozen that we developed in O3 to adapt the system to the revised alert format which will be used in O4. The pipeline software that searches transient objects from data obtained by Tomo-e Gozen is also upgraded, and will enable us to search optical counterparts of GW events in a timely fashion.

We search for optical counterparts of Fast Radio Bursts (FRBs) using the optical high-speed observing facilities, Tomo-e Gozen on the Kiso Schmidt telescope and TriCCS on the Seimei telescope, in order to understand the nature of the mysterious transient phenomena. The searches target both repeating and non-repeating FRBs. In FY 2022, we published the results (optical upper limits) of the monitoring observation of repeating FRB 20190520B in collaboration with the radio observing groups using the Five-hundred-meter Aperture Spherical radio Telescope (FAST), and conducted further monitoring observations of repeating FRBs. The simultaneous optical–radio survey for non-repeating FRBs using Tomo-e Gozen and the Canadian Hydrogen Intensity Mapping Experiment (CHIME) is also ongoing.

We have discoverd an ultraluminous fast-evolving transient at redshift of 1.063 using the Hyper Suprime-Cam (HSC) on the 8.2 m Subaru telescope. We also found and studied 32 tiny (diameter less than 100 m) near-Earth Objects (NEOs) with Tomo-e Gozen, and discovered that the distribution of tiny NEOs in a diameter and rotational period diagram is truncated around a period of 10 s. We also discovered 22 flares from M3- M5 dwarfs with a rise time of about five to one hundred seconds with Tomo-e Gozen, and studied their properties.

6.3 Publication List

[1] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Model-based Cross-correlation Search for Gravitational Waves from the Low-mass X-Ray Binary Scorpius X-1 in LIGO O3 Data", The Astrophysical Journal Letters, 941, L30 (2022).

[2] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO and Advanced Virgo O3 data", Physical Review D 106, 102008 (2022).

[3] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Search for continuous gravitational wave emission from the Milky Way center in O3 LIGO-Virgo data", Physical Review D 106, 042003 (2022).

[4] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data", Physical Review D 106, 062002 (2022).

[5] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Searches for Gravitational Waves from Known Pulsars at Two Harmonics in the Second and Third LIGO-Virgo Observing Runs", The Astrophysical Journal, 935, 1 (2022).

[6] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Narrowband Searches for Continuous and Long-duration Transient Gravitational Waves from Known Pulsars in the LIGO-Virgo Third Observing Run", The Astrophysical Journal, 932, 133 (2022).

[7] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "All-sky, all-frequency directional search for persistent gravitational waves from Advanced LIGO's and Advanced Virgo's first three observing runs", Physical Review D 105, 122001 (2022).

[8] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "All-sky search for gravitational wave emission from scalar boson clouds around spinning black holes in LIGO O3 data", Physical Review D 105, 102001 (2022).

[9] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "First joint observation by the underground gravitational-wave detector KAGRA with GEO 600", Progress of Theoretical and Experimental Physics, 2022, 063F01 (2022).

[10] B. P. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Search for Gravitational Waves Associated with Gamma-Ray Bursts Detected by Fermi and Swift during the LIGO-Virgo Run O3b", The Astrophysical Journal, 928, 186 (2022).

[11] H. Abe *et al.* (The KAGRA Collaboration), "The Current Status and Future Prospects of KAGRA, the Large-Scale Cryogenic Gravitational Wave Telescope Built in the Kamioka Underground", Galaxies, 10, 63 (2022).

[12] H. Abe *et al.* (The KAGRA Collaboration), "Noise subtraction from KAGRA O3GK data using Independent Component Analysis", Classical and Quantum Gravity, 40, 085015 (2023).

[13] T. Akutsu *et al.* (The KAGRA Collaboration), "Input optics systems of the KAGRA detector during O3GK", Progress of Theoretical and Experimental Physics, 2023, 023F01 (2023).

[14] H. Takeda, S. Morisaki, and A. Nishizawa, "Search for scalar-tensor mixed polarization modes of gravitational waves", Physical Review D 105, 084019 (2022).

[15] A. Nishizawa, S. Iwaguchi, Y. Chen, T. Morimoto, T. Ishikawa, B. Wu, I. Watanabe, Y. Kawasaki, R. Shimizu, H. Shimizu, M. Kitaguchi, Y. Michimura, and S. Kawamura, "Neutron displacement noise-free interferometer for gravitational-wave detection", Physical Review D 105, 124017 (2022).

[16] S. Iwaguchi, A. Nishizawa, Y. Chen, Y. Kawasaki, M. Kitaguchi, T. Morimoto, T. Ishikawa, B. Wu, I. Watanabe, R. Shimizu, H. Shimizu, Y. Michimura, and S. Kawamura, "Displacement-noise-free neutron interferometer for gravitational wave detection using a single Mach-Zehnder configuration", Physics Letters A 441, 128150 (2022).

[17] T. Tsutsui and A. Nishizawa, "Observational constraint on axion dark matter with gravitational waves", Physical Review D 106, L081301 (2022).

[18] S. Iwaguchi, A. Nishizawa, Y. Chen, Y. Kawasaki, T. Ishikawa, M. Kitaguchi, Y. Yamagata, B. Wu, R. Shimizu, K. Umemura, K. Tsuji, H. Shimizu, Y. Michimura, and S. Kawamura, "Displacement-noise-free interferometric gravitational-wave detector using unidirectional neutrons with four speeds", Physics Letters A 458, 128581 (2023).

[19] Y. Himemoto, A. Nishizawa, A. Taruya, "Distinguishing a stochastic gravitational-wave signal from correlated noise with joint parameter estimation: Fisher analysis for ground-based detectors", Physical Review D 107, 064055 (2023).

[20] M. Shikauchi, K. Cannon, H. Lin, T. Totani, J. R. Shaw,"On the use of CHIME to detect long-duration radio transients from neutron star mergers", The Astrophysical Journal, 928, 72 (2022).

[21] Y. Niino, M. Doi, S. Sako et al., "Deep Simultaneous Limits on Optical Emission from FRB 20190520B by 24.4 fps Observations with Tomo-e Gozen", The Astrophysical Journal, 931, 109 (2022).

[22] J. Jiang, N. Yasuda, K. Maeda, N. Tominaga, M. Doi et al., "MUSSES2020J: The Earliest Discovery of a Fast Blue Ultraluminous Transient at Redshift 1.063", The Astrophysical Journal Letters, 933, L36 (2022).

[23] J. Beniyama, S. Sako, S., R. Ohsawa et al., "Video observations of tiny near-Earth objects with Tomo-e Gozen", Publications of the Astronomical Society of Japan, 74, 877 (2022).

[24] M. Aizawa, K. Kawana, K., K. Kashiyama et al., "Fast optical flares from M dwarfs detected by a one-second-cadence survey with Tomo-e Gozen", Publications of the Astronomical Society of Japan, 74, 1069 (2022).

[25] K. Hotokezaka, *et al.*, "Tungsten versus Selenium as a potential source of kilonova nebular emission observed by Spitzer", Monthly Notices of the Royal Astronomical Society ,**515**, L89-L93 (2022).

[26] K. Kawaguchi, *et al.*, "Electromagnetic Counterparts of Binary-neutron-star Mergers Leading to a Strongly Magnetized Long-lived Remnant Neutron Star", Astrophys. J. **933**, 22 (2022).

[27] A. Balasubramanian, *et al.*, "GW170817 4.5 Yr After Merger: Dynamical Ejecta Afterglow Constraints", Astrophys. J. **938**, 12 (2022).

[28] N. Domoto, *et al.*, "Lanthanide Features in Near-infrared Spectra of Kilonovae", Astrophys. J. **939**, 8 (2022).

[29] B. Dorsman, *et al.*, "Prospects of Gravitational-wave Follow-up through a Wide-field Ultraviolet Satellite: A Dorado Case Study", Astrophys. J. **944**, 126 (2023).

[30] D. Toyouchi, *et al.*, "Top-heavy stellar mass distribution in galactic nuclei inferred from the universally high abundance ratio of [Fe/Mg]", Monthly Notices of the Royal Astronomical Society, **512**, 2573-2583 (2022).

[31] D. Toyouchi, *et al.*, "Radiative feedback on supermassive star formation: the massive end of the Population III initial mass function", Monthly Notices of the Royal Astronomical Society, **518**, 1601-1616, (2023).

[32] K. Takahashi, *et al.*, "Probing particle acceleration at trans-relativistic shocks with off-axis gamma-ray burst afterglows", Monthly Notices of the Royal Astronomical Society, **517**, 5541-5559, (2022).

[33] T. Ishikawa, et al. "First-step experiment for sensitivity improvement of DECIGO: Sensitivity optimization for simulated quantum noise by completing the square", Phys. Rev. D 107, 022007 (2023).

[34] M. Croquette, et al. "Recent advances toward mesoscopic quantum optomechanics", AVS Quantum Sci. 5, 014403 (2023).

[35] T. Kawasaki, et al. “Angular trapping of a linear cavity mirror with an optical torsional spring”, Phys. Rev. A 106, 013514 (2022).

[36] T. Shimoda, et al. “Coherent angular signs amplification using an optical cavity”, Appl. Opt. 61, 3901-3911 (2022).

[37] S. Otabe, et al. “Photothermal effect in macroscopic optomechanical systems with an intracavity nonlinear optical crystal”, Opt. Express 30, 42579- 42593 (2022).

6.4 International Conference Talks

6.4.1 Contributed talks

[38] (contributed talk) A. Nishizawa, “Statistically separating the modified effects of GW generation and propagation”, GR23, Beijing, China (hybrid), 2022/7/4-8.

[39] (poster) A. Nishizawa, “Distinguishing the modified generation and propagation of gravitational waves”, Symposium on Gravitational wave physics and astronomy: Genesis, Kyoto Univ., Japan, 2022/4/25-29.

[40] (poster) A. Nishizawa, “Impact of correlated noise on the parameter estimation of stochastic gravitational waves”, The 9th KAGRA International Workshop, online, 2022/6/6-8.

[41] (poster) S. Kuwahara, “Cherenkov radiation-like Gravitational-Wave Search’”, KAGRA Face-to-Face Meeting, The University of Tokyo (hybrid), 2022/8/1-3.

[42] (poster) S. Kuwahara, “Cherenkov radiation-like Gravitational-Wave Search ’’ , LIGO-Virgo-KAGRA Collaboration Meeting, Cardiff University, 2022/9/12-16.

[43] (poster) S. Kuwahara, “Cherenkov radiation-like Gravitational-Wave Search ’’ , LIGO-Virgo-KAGRA Collaboration Meeting, Northwestern University, 2023/3/13-17.

[44] (poster) M. Shikauchi, K. Cannon, H. Lin, T. Totani, R. J. Shaw, “Prospect for blind sGRB afterglow search with CHIME”, Gravitational Wave Physics and Astronomy Workshop (GWPAW), the Sofitel Melbourne on Collins, Melbourne, Australia (hybrid), 2022/12/5-9.

[45] (poster) R. Harada, “Examination of the Testability of the Hadron-Quark Phase Transition using Gravitational Waves”, KAGRA Face-to-Face Meeting, The University of Tokyo (hybrid), 2022/8/1-3.

[46] (poster) R. Harada, “Examination of the Testability of the Hadron-Quark Phase Transition using Gravitational Waves”, LIGO-Virgo-KAGRA Collaboration Meeting, Cardiff University, 2022/9/12-16.

[47] (poster) R. Harada, “Examination of the Testability of the Quark-Hadron Phase Transition Using Gravitational Waves”, KAGRA Face-to-Face Meeting, ICRR, The University of Tokyo (hybrid), 2022/11/30-12/1.

[48] (poster) R. Harada, “On the Testability of the Quark-Hadron Phase Transition Using Gravitational Waves”, LIGO-Virgo-KAGRA Collaboration Meeting, Northwestern University, 2023/3/13-17.

[49] (poster) D. Watarai, “Physically consistent waveform for capturing beyond-GR effects in the merger phase”, KAGRA Face-to-Face Meeting, The University of Tokyo (hybrid), 2022/8/1-3.

[50] (poster) D. Watarai, “Physically consistent waveform for capturing beyond-GR effects in the merger phase”, LIGO-Virgo-KAGRA Collaboration Meeting, Cardiff University, UK, 2022/9/12-15.

[51] (poster) D. Watarai, “Physically consistent waveform for capturing beyond-GR effects in the merger phase”, KAGRA Face-to-Face Meeting, ICRR, The University of Tokyo (hybrid), 2022/11/30-12/1.

[52] (poster) D. Watarai, “Physically consistent waveform for capturing beyond-GR effects in the merger phase”, LIGO-Virgo-KAGRA Collaboration Meeting, Northwestern University, USA, 2023/3/13-16.

[53] (contributed talk) Y. Oshima et al., “First Results of Axion Dark Matter Search with DANCE”, FY2022 ” What is dark matter? - Comprehensive study of the huge discovery space in dark matter ” (Mar. 2023, Kavli IPMU and online).

[54] (contributed talk) H. Fujimoto et al., “Axion dark matter search with optical ring cavity ”, FoPM International Symposium (Feb. 2023, University of Tokyo).

[55] (contributed talk) H. Fujimoto et al., “Latest Status and Sensitivity of DANCE: Dark matter Axion search with riNg Cavity experiment ” , KASHIWA DARK MATTER SYMPOSIUM 2022 (Dec. 2022, University of Tokyo and online).

[56] (contributed talk) C. P. Ooi et al., “Development of a cryogenic suspension system for TOrsion-Bar Antennae (TOBA) ”, The 5th International Forum on Quantum Metrology and Sensing (November 29th, 2022, online).

[57] (contributed talk) Y. Oshima, et al., “Torsion-Bar Antenna for Early Earthquake Alert ”, The 5th International Forum on Quantum Metrology and Sensing (November 29th,2022, online).

[58] (contributed talk) M. Ando, “Future Strategy Committee ”, KAGRA F2F (Nov 30th, 2022, Online).

[59] (contributed talk) Y. Oshima, et al., “Angular Measurement with a Coupled Cavity for Torsion-Bar Antenna ”, KAGRA Future Working Group 2nd open meeting (November 2022, University of Tokyo and online).

[60] (contributed talk) M. Ando, et al., “FWG Open Meeting ”, KAGRA Future Working Group 2nd open meeting (November 2022, University of Tokyo and online).

[61] (contributed talk) H. Wang, et al., “Mirror birefringence in KAGRA ”, LIGO-Virgo-KAGRA Collaboration Meeting (September 2022, Cardiff and online).

[62] (contributed talk) H. Wang, et al., “Current status of birefringence characterization and simulation of KAGRA ITMs ”, The 29th KAGRA Face-to-Face meeting (August 2022, University of Tokyo and online).

[63] (contributed talk) Y. Oshima, et al., “Wavefront Sensing with a Coupled Cavity for Torsion-Bar Antenna ”,, GRAvitational-wave Science & technology Symposium 2022 (June 2022, Padova, Italy).

[64] (contributed talk) M. Ando, “Gravitational Waves: VIRGOKAGRA and Future R&Ds ”, ILANCE Meeting (June 8, 2022, ICRR Kashiwa, Chiba).

[65] (contributed talk) M. Ono, “Control of Dual-Pass Fabry-Perot cavity for space gravitational antennas:DECIGO and B-DECIGO ”, The 9th KAGRA International Workshop (June 2022, online).

[66] (contributed talk) H. Wang, “Birefringence characterization of KAGRA ITMs and simulation with Finesse ”, GWADW2022 (May 2022, online).

[67] (contributed talk) H. Fujimoto et al., “Recent Upgrades and Future Prospects of DANCE ”, FY2022 ”What is dark matter? - Comprehensive study of the huge discovery space in dark matter ” (Mar. 2023, Kavli IPMU and online).

[68] (poster) Y. Oshima et al., “Torsion-Bar Antenna for Low-Frequency Gravity Gradient Observation ”, 2nd International Symposium on Trans-Scale Quantum Science (November 2022, University of Tokyo).

[69] (poster) M. Ono et al., “Control of Dual-Pass FabryPerot Cavity for space gravitational wave antennas: DECIGO and B-DECIGO ”, Gravitational Wave Advanced Detector Workshop 2022 (May 2022, online).

[70] (poster) Y. Oshima et al., “Angular Signal Amplification with a Coupled Cavity for Torsion-Bar Antenna ”, Gravitational Wave Advanced Detector Workshop 2022 (May 2022, online).

[71] (poster) S. Takano et al., “The Current Status of Torsion-Bar Antenna (TOBA) Experiment ”, Gravitational Wave Advanced Detector Workshop 2022 (May 2022, online).

[72] (poster) M. Ando, “Space GW Antennae: DECIGO/BDECIGO ”, Gravitational Wave Advanced Detector Workshop 2022 (May 2022, online).

6.4.2 Invited talks

[73] A. Nishizawa, “Observational tests of gravity with gravitational waves”, The 9th Korea-Japan Workshop on Dark Energy, Yonsei University, Seoul (hybrid), 2022/11/14-18.

[74] K. Hotokezaka, “Progress and challenge in kilonova theory”, Symposium on gravitational wave physics and astronomy:Genesis, Kyoto Japan, 2022/4/25-29.

[75] K. Hotokezaka, “Element identification in kilonova”, GW-EM Workshop, Wiezmann Institute of Science, Rehovot Israel, 2022/6/19-7/1

[76] K. Hotokezaka, “Unsolved issues in EM counterparts of NS mergers”, TCAN22 on binary neutron stars workshop, online, 2022/6/20-24

[77] K. Hotokezaka, “Non-LTE in Kilonova”, NBIA workshop on Radiation Transfer in Astrophysics, Niels Bohr Institute, Copenhagen Denmark, 2022/6/6-10.

[78] M. Ando, “KAGRA: Large Cryogenic Gravitational Wave Telescope”, International Conference on the Physics of Two Infinites (March 30th, 2023, Kyoto, Japan).

[79] H. Fujimoto et al., “Recent Upgrades of Optical System and Data Analysis in DANCE”, Workshop on Very Light Dark Matter 2023 (Mar. 2023, Chino, Japan).

[80] Y. Oshima et al., "First Results of DANCE from Long-Term Observation", Workshop on Very Light Dark Matter 2023 (Mar. 2023, Chino, Japan).

[81] M. Ando, "DECIGO: a space gravitational wave antenna", KIW9: KAGRA International Workshop (June 6, 2022, Online).

7 Project 3. Formation and characterization of planetary systems

7.1 Activity Report

Project 3 “Formation and characterization of planetary systems” approaches the problem both theoretically and observationally through the collaboration with members in Departments of Physics, Astronomy, and Earth and Planetary Sciences. We show several highlights of our research this year.

7.1.1 Architecture of planetary systems predicted from protoplanetary disks observed with ALMA

Starting from the initial configurations of 12 multi-planetary systems deduced from ALMA disks, we carried out two-stage N-body simulation to investigate the evolution of the planetary systems at the disk stage as well as the long term orbital stability after the disk dispersal. At the disk stage, our simulation includes both the orbital migration and pebble/gas accretion effects. We found a variety of planetary systems are produced and can be categorised into distant giant planets, Jupiter-like planets, Neptune-like planets and distant small planets. We found the disk stage evolution as well as the final configurations are sensitive to both the initial mass assignments and viscosity. After the disk stage, we implement only mutual gravity between star and planets and introduce stochastic perturbative forces. All systems are integrated for up to 10Gyr to test their orbital stability. Most planetary systems are found to be stable for at least 10Gyr with perturbative force in a reasonable range. Our result implies that a strong perturbation source such as stellar flybys is required to drive the planetary system unstable.

7.1.2 Analytic model for photometric variation due to starspots on a differentially rotating star

We present an analytic model of the lightcurve variation for stars with non-evolving starspots on a differentially rotating surface. We generate different realizations of multi-spots according to the model, and perform mock observations of the resulting lightcurve modulations. We discuss to what extent one can recover the properties of the spots and the parameters for the differential rotation law from the periodogram analysis. Although our analytical model neglects the evolution of spots on the stellar surface (dynamical motion, creation and annihilation), it provides a basic framework to interpret the photometric variation of stars, in particular from the existing Kepler data and the future space-born mission.

7.1.3 Dynamical disruption timescales of hierarchical triple systems

We examine the stability of hierarchical triple systems using direct N-body simulations without adopting a secular perturbation assumption. We estimate their disruption timescales in addition to the mere stable/unstable criterion, with particular attention to the mutual inclination between the inner and outer orbits. We improve the fit to the dynamical stability criterion that has been widely adopted in the previous literature. Especially, we find that that the stability boundary is very sensitive to the mutual inclination; coplanar retrograde triples and orthogonal triples are much more stable and unstable, respectively, than coplanar prograde triples. We obtain an improved empirical fit to the disruption timescales, which indicates that the coplanar retrograde triples are significantly more stable than the previous prediction. We furthermore find that the dependence on the mutual inclination can be explained by the energy transfer model based on a parabolic encounter approximation. We also show that the disruption timescales of triples are highly sensitive to the tiny change of the initial parameters, reflecting the genuine chaotic nature of the dynamics of those systems.

7.1.4 Photometric variations due to a global inhomogeneity on an obliquely rotating star

We perform intensity variability analyses (photometric analyses: the Lomb-Scargle periodogram, autocorrelation, and wavelet) and asteroseismic analysis of 92 Kepler solar-like main-sequence stars to understand the reliability of the measured stellar rotation periods. We focus on the 70 stars without reported stellar companions, and classify them into four groups according to the quarter-to-quarter variance of the Lomb-Scargle period and the precision of the asteroseismic period. We present detailed individual comparison among photometric and asteroseismic constraints for these stars. We find that most of our targets exhibit significant quarter-to-quarter variances in the photometric periods, suggesting that the photometrically estimated period should be regarded as a simplified characterization of the true stellar rotation period, especially under the presence of the latitudinal differential rotation. On the other hand, there are a fraction of stars with a relatively small quarter-to-quarter variance in the photometric periods, most of which have consistent values for asteroseismically and photometrically estimated rotation periods. We also identify over ten stars whose photometric and asteroseismic periods significantly disagree, which would be potentially interesting targets for further individual investigations.

7.1.5 Lagrange stability of hierarchical triple systems

While there have been many studies examining the stability of hierarchical triple systems, the meaning of "stability" is somewhat vague and has been interpreted differently in previous literatures. The present paper focuses on "Lagrange stability", which roughly refers to the stability against the escape of a body from the system, or "disruption" of the triple system, in contrast to "Lyapunov-like stability" that is related to the chaotic nature of the system dynamics. We compute the evolution of triple systems using direct N-body simulations up to $10^7 P_{\rm out}$, which is significantly longer than previous studies (with $P_{\rm out}$ being the initial orbital period of the outer body). We obtain the resulting disruption timescale $T_{\rm d}$ as a function of the triple orbital parameters with particular attention to the dependence on the mutual inclination between the inner and outer orbits, $i_{\rm mut}$. By doing so, we have clarified explicitly the difference between Lagrange and Lyapunov stabilities in astronomical triples. Furthermore, we find that the von Zeipel-Kozai-Lidov oscillations destabilize significantly inclined triples (roughly with $60^\circ < i_{\rm mut} < 150^\circ$) relative to those with $i_{\rm mut} = 0^\circ$. On the other hand, retrograde triples with $i_{\rm mut} > 160^\circ$ become strongly stabilized with much longer disruption timescales.

7.1.6 A super-Earth orbiting near the inner edge of the habitable zone around the M4.5 dwarf Ross 508

We report the first near-infrared radial velocity (RV) discovery of a super-Earth planet on a 10.77 d orbit around the M4.5 dwarf Ross 508. Using precision RVs from the Subaru Telescope IRD (InfraRed Doppler) instrument, we derive a semi-amplitude of 3.92 ms−1, corresponding to a planet with a minimum mass msini of 4.00 Earth masses. The planet, Ross 508 b, has a semi-major axis of 0.05366 au. This gives an orbit-averaged insolation of 1.4 times the Earth's value, placing Ross 508 b near the inner edge of its star's habitable zone. We have explored the possibility that the planet has a high eccentricity and its host is accompanied by an additional unconfirmed companion on a wide orbit. Our discovery demonstrates that the near-infrared RV search can play a crucial role in finding a low-mass planet around cool M dwarfs like Ross 508.

7.1.7 Direct-imaging Discovery and Dynamical Mass of a Substellar Companion Orbiting an Accelerating Hyades Sun-like Star with SCExAO/CHARIS

We present the direct-imaging discovery of a substellar companion in orbit around a Sun-like star member of the Hyades open cluster. So far, no other substellar companions have been unambiguously confirmed via direct imaging around main-sequence stars in Hyades. The star HIP 21152 is an accelerating star as identified by the astrometry from the Gaia and Hipparcos satellites. We detected the companion, HIP 21152 B, in multiple epochs using the high-contrast imaging from SCExAO/CHARIS and Keck/NIRC2. The CHARIS spectroscopy reveals that HIP 21152 B's spectrum is consistent with the L/T transition, best fit by an early T dwarf. Our orbit modeling determines the semimajor axis and the dynamical mass of HIP 21152 B to be 17.5 au and 27.8 Jupiter masess, respectively. Mass estimates inferred from luminosity-evolution models are slightly higher. With a dynamical mass and a well-constrained age due to the system's Hyades membership, HIP 21152 B will become a critical benchmark in understanding the formation, evolution, and atmosphere of a substellar object as a function of mass and age.

7.1.8 The JWST Early-release Science Program for Direct Observations of Exoplanetary Systems

The direct characterization of exoplanetary systems with high-contrast imaging is among the highest priorities for the broader exoplanet community. As large space missions will be necessary for detecting and characterizing exo-Earth twins, developing the techniques and technology for direct imaging of exoplanets is a driving focus for the community. For the first time, JWST will directly observe extrasolar planets at mid-infrared wavelengths beyond 5 microns, deliver detailed spectroscopy revealing much more precise chemical abundances and atmospheric conditions, and provide sensitivity to analogs of our solar system ice-giant planets at wide orbital separations, an entirely new class of exoplanet. However, in order to maximize the scientific output over the lifetime of the mission, an exquisite understanding of the instrumental performance of JWST is needed as early in the mission as possible.

We describe our 55 hr Early Release Science Program that will utilize all four JWST instruments to extend the characterization of planetary-mass companions to 15 microns as well as image a circumstellar disk in the mid-infrared with unprecedented sensitivity.

We also present the highest fidelity spectrum to date of a planetary-mass object. VHS 1256 b is a <20 Jupiter masses widely separated ($a = 150$ au), young, planetary-mass companion that shares photometric colors and spectroscopic features with the directly imaged exoplanets HR 8799c, d, and e. As an L-to-T transition object, VHS 1256 b exists along the region of the color-magnitude diagram where substellar atmospheres transition from cloudy to clear. We observed VHS 1256 b with JWST's NIRSpec IFU and MIRI MRS modes for coverage from 1 to 20 microns at resolutions of 1000-3700. Water, methane, carbon monoxide, carbon dioxide, sodium, and potassium are observed in several portions of the JWST spectrum based on comparisons from template brown dwarf spectra, molecular opacities, and atmospheric models. The spectral shape of VHS 1256 b is influenced by disequilibrium chemistry and clouds. We directly detect silicate clouds, the first such detection reported for a planetary-mass companion.

7.1.9 Photosynthetic Fluorescence from Earthlike Planets around Sunlike and Cool Stars

Remote sensing of the Earth has demonstrated that photosynthesis is traceable as the vegetation red edge (VRE), which is a steep rise in the reflection spectrum of vegetation, and as solar-induced fluorescence. This study examines the detectability of biological fluorescence from two types of photosynthetic pigments, chlorophylls (Chls) and bacteriochlorophylls (BChls), on Earthlike planets with oxygen-rich/poor and anoxic atmospheres around the Sun and M dwarfs. We find that the BChl-based fluorescence for wavelengths of 1000-1100 nm, assuming the spectrum of BChl b-bearing purple bacteria, could provide a suitable biosignature, but only in the absence of water cloud coverage or other strong absorbers near 1000 nm. The Chl fluorescence is weaker for several reasons. The apparent reflectance excess is greatly increased in both the Chl and BChl cases around TRAPPIST-1, due to the fluorescence and stellar absorption lines. This could be a promising feature for detecting the fluorescence around ultracool red dwarfs using follow-up ground-based observations at high spectral resolution.

7.1.10 An Earth-sized Planet around an M5 Dwarf Star at 22 pc

We report on the discovery of an Earth-sized transiting planet (R=1.015 Earthe radii) in a period of 4.02 day orbit around K2-415, an M5V star at 22 pc. The planet candidate was first identified by analyzing the light-curve data obtained by the K2 mission, and it is here shown to exist in the most recent data from TESS. Combining the light curves with the data secured by our follow-up observations, including high-resolution imaging and near-infrared spectroscopy with IRD, we rule out false-positive scenario. Based on IRD's radial velocities of K2-415, which were sparsely taken over three years, we obtain a planet mass of 3.0 Earth masses for K2-415b. Being one of the lowest-mass stars (0.16 solar masses) known to host an Earth-sized transiting planet, K2-415 will be an interesting target for further follow-up observations, including additional radial velocity monitoring and transit spectroscopy.

7.1.11 Investigation of asteroids Ryugu, Bennu, and Dimorphos with Hayabusa2, OSIRIS-REx, and Hera missions

Samples from asteroid Ryugu brought back to the Earth by JAXA's Hayabusa2 were analyzed extensively throughout 2022. We continued our participation in curation and initial analysis activities of Ryugu samples. These activities have revealed many important properties of Ryugu and its parent body. One important finding is that Ryugu sample experienced extensive aqueous alteration in its parent body and still retain much hydrated minerals [13]. Second, Ryugu materials turned out to be very similar to CI chondrites, one of the most primitive carbonaceous chondrites found on Earth [14]. Because the elemental abundance of CI chondrites is similar to the solar composition, CI has been considered as the standard materials of our solar system. However, because all the CI chondrite samples collected on Earth have been contaminated with Earth's moisture and organics, light element abundances were not considered reliable. Now we have contamination-free CI materials from Ryugu, our knowledge on the light elements in the solar system would be much more accurate. We also observed both noble gas and adsorbed gas in the returned samples, revealing that the surface exposure ages of Ryugu is several million years [15] and that Ryugu materials are rather reducing [16]

Second, we participated in other international planetary missions, such as NASA's OSIRIS-REx mission and ESA's Hera mission. The former is a sample return mission to a carbon-rich asteroid in a near-Earth orbit with aiming at science goals with Hayabusa2. Because of our similar experiences, we participated in science data analysis around OSIRIS-REx sampling campaign on asteroid Bennu [17]. We observed a massive ejecta curtain emerged from the physical disturbance created by sampling activities on Bennu, indicated that its surface materials are extremely mobile with internal cohesion ¡¡ 1 Pa. This further shows that crater chronology curve for Bennu should be very similar to Ryugu. The latter mission is to conduct detailed observations of artificial impact crater created on Dimorphos a satellite of asteroid Didymos. We conducted detailed science and project design with many lessons learned from Hayabusa2 [18].

7.2 Publication List

[1] Shijie Wang, Kazuhiro D. Kanagawa, and Yasushi Suto,"Architecture of planetary systems predicted from protoplanetary disks observed with ALMA II: evolution outcomes and dynamical stability", 2022, ApJ, 932, 31(26pp)

[2] Yasushi Suto, Shin Sasaki, Yuta Nakagawa, and Othman Benomar,"Analytic model for photometric variation due to starspots on a differentially rotating star", 2022, PASJ, 74, 857–876

[3] Toshinori Hayashi, Alessandro Alberto Trani, and Yasushi Suto,"Dynamical disruption timescales and chaotic behavior of hierarchical triple systems",2022, ApJ, 939, 81(20pp) 2022/11/08

[4] Yuting Lu, Othman Benomar, Shoya Kamiaka, and Yasushi Suto, "Meta-analysis of photometric and asteroseismic measurements of stellar rotation periods: the Lomb-Scargle periodogram, autocorrelation function, wavelet and rotational splitting analysis for 92 Kepler asteroseismic targets", 2022, ApJ, 941, 175(39pp)

[5] Yasushi Suto, Shin Sasaki, Masataka Aizawa, Kotaro Fujisawa, and Kazumi Kashiyama, " Modeling photometric variations due to a global inhomogeneity on an obliquely rotating star: application to lightcurves of white dwarfs", 2023, PASJ, 75, 103-119

[6] Toshinori Hayashi, Alessandro Alberto Trani, and Yasushi Suto, "Lagrange vs. Lyapunov stability of hierarchical triple systems: dependence on the inclination between inner and outer orbits", 2023, ApJ, 943, 58(7pp)

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[8] Miles, Brittany E.; Biller, Beth A.; Patapis, Polychronis and 108 more, 2023, " The JWST Early-release Science Program for Direct Observations of Exoplanetary Systems II: A 1 to 20 μm Spectrum of the Planetary-mass Companion VHS 1256-1257 b ", ApJL, 946, id.L6, 19 pp.

[9] Hirano, Teruyuki; Dai, Fei; Livingston, John H. and 46 more " An Earth-sized Planet around an M5 Dwarf Star at 22 pc ", AJ, 165, id.131, 14 pp.

[10] Komatsu, Yu; Hori, Yasunori; Kuzuhara, Masayuki and 8 more " Photosynthetic Fluorescence from Earthlike Planets around Sunlike and Cool Stars ", AJ, 165, id.131, 14 pp.

[11] Hinkley, Sasha; Carter, Aarynn L.; Ray, Shrishmoy and 86 more " The JWST Early Release Science Program for the Direct Imaging and Spectroscopy of Exoplanetary Systems ", PASP, 134, id.095003, 20 pp.

[12] Harakawa, Hiroki; Takarada, Takuya; Kasagi, Yui and 46 more " A super-Earth orbiting near the inner edge of the habitable zone around the M4.5 dwarf Ross 508 ", PASP,74,id.095003, 20 pp.

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III

Reports on the research activities of RESCEU groups in 2022 (in Japanese)

2022年度 RESCEU研究グループ別 研究活動報告

8　横山順一研究室

8.1　横山 (順) 研究室

当研究室は、一般相対性理論、場の量子論、素粒子物理学等の基礎物理学理論に基づいて宇宙論と重力理論の理論的研究を幅広く行うとともに、理学部物理学教室の教育と研究に参画しています。また、大型低温重力波検出器 KAGRA の本格稼働を迎え、ビッグバン宇宙国際研究センターの Cannon 研究室とともに重力波データ解析の研究と人材育成にも携わっています。横山は 2021 年 9 月から KAGRA 科学会議議長を務めるとともに [45, 48, 51, 52]、2022 年末まで 3 年間アジア太平洋物理学会連合会長として域内の物理学の振興に務めました [46, 47, 49]。

8.1.1　宇宙論: 時空構造

真空相転移のローレンツ経路積分による考察

真空相転移はユークリッド化された時空での経路積分により定式化されてきたが、終状態の曖昧さや重力存在下での負モードの唯一性の破れといった問題がある。そこで本研究では、実時間において真空相転移の確率をローレンツ経路積分で直接定式化し、鞍点法により評価することを試みた。その結果、重力を背景時空として扱った場合、ローレンツ経路積分による解析は、従来のユークリッド経路積分で予言される相転移確率を再現した。さらに、ユークリッド経路積分では評価できなかった、臨界半径とは異なる大きさを持つ真空泡の生成についても、その生成確率を評価した [5, 30, 54]。

単一場インフレーション模型における高次量子効果

我々は、単一場インフレーション模型における曲率揺らぎの 2 点相関関数に対する 3 点相互作用からの 1 ループ補正を計算し、それが古典的な寄与より十分小さくなることを要請することにより、原始非ガウス性揺らぎに上限を与えた。特に、観測的に許される非ガウス性の範囲はこの制限を満たすが、1 ループ補正が古典的な寄与の 1 ～ 10 % 程度になる領域もあるので、将来観測がそのような値を示唆した場合、高次のループ補正を考慮することが重要になる [6, 28, 33, 35, 39, 61, 105, 107]。

原始ブラックホール (PBH) 生成機構として最も研究されているものに、単一場インフレーションにおいて作られた大きな振幅を持つ小スケール密度揺らぎの崩壊が挙げられる。我々は、大スケールにおける密度揺らぎのパワースペクトルへの 1 ループ補正を計算し、大量の PBH を作るような小スケール揺らぎは CMB スケールに大きな補正を与え、矛盾を来すことを示した [55, 56, 66, 74, 78, 92, 109, 113, 114, 108]。

初期宇宙の一次相転移と重力波

初期宇宙の一次相転移は音波・乱流等の流体の運動を引き起こし、それによって生成した重力波が宇宙空間干渉計で将来的に観測される可能性がある。我々は音波からの重力波生成のシミュレーションを提案した [84] ほか、相互作用の弱い粒子がこのプロセスに関与した場合に特徴的な重力波シグナルが出現する可能性を指摘し [77, 85, 111]、重力の影響を考慮した場合の原始ブラックホール生成の可能性も議論した [87]。また物理学会で概説を行った [91]。

数理解析と宇宙論

LIGO/Virgo によるブラックホール連星からの重力波初観測以降、連星系の運動を解析的に理解する post-Newtonian 或いは post-Minkowskian 理論が発展している。この際必要となるファインマン積分において、展開の高次になると解析的計算が難しくなるという問題を回避するには、積分を数値的に高精度で評価した結果から解析的表式を推測すると良い。この数値評価に、機械学習を活用した normalizing flow という手法でモンテカルロ積分を行った結果、通常のモンテカルロ積分と比べてどのような改善が見られるか報告した [80, 86]。

Stochastic inflation において、相関関数の e-folding 展開が一般に発散級数となることが知られている。そこで本研究では、発散級数に解析的意味付けを与える Borel 総和の手法を用いてこれを処理し、相関関数の正しい時間発展が得られることを示した。また Borel 空間における特異点の解析から、本研究で扱った $\lambda\phi^4$ 模型では非摂動効果の非存在が示唆された [83, 89]。

我々はグラディエントフローを空間方向に 4 階微分へと拡張した方程式が、場の量子論における鞍点解へ自動的に収束する振る舞いをすることを発見し、報告した [89]。

宇宙複屈折の精密計算

宇宙複屈折とは、宇宙マイクロ波背景放射 (CMB) が伝播中にその偏光面が回転する現象を指し、近年 CMB の観測データからその存在が示唆されている。本研究では、これまで考慮されていなかった重力レンズ効果を取り入れた理論計算を実現し、将来の高精度観測では、その効果が必ずしも無視できないことを示した [7, 22, 25, 37, 41, 43, 75, 81]。

8.1.2 宇宙論: 物質の起源と進化

インフレーション後の宇宙再加熱と物質生成

インフレーション後の宇宙が運動項優勢になるような模型では、宇宙再加熱をどう実現するかに問題があったが、我々はインフラトンが U(1) ゲージ場と Chern-Simons 結合をしている場合、ゲージ場がまず増幅され、そこからシュウィンガー効果により物質粒子が生成されることにより、放射優勢のビッグバン宇宙が再現されることを示した [8] 。

インフレーション後場が振動せず運動項優勢となる理論での再加熱機構として、ヒッグス場に時空曲率との結合を与え、インフレーション後にスピノーダル不安定性を実現する方法も考えられる。われわれは、このような理論に階層的な質量を持つ三世代の右巻きニュートリノを導入することにより、宇宙再加熱、ダークマター、バリオン非対称生成を同時に実現するシナリオを構築した [9]。

また、こうした重い右巻きニュートリノを導入することにより、観測との相性がとても良い R^2 インフレーション理論の再加熱機構がどのように変化し、それがスペクトル指数やバリオン非対称などの観測量にどのような影響を与えるのかを仔細に研究し、定量的に明らかにした [40, 64, 73]。

アクシオンインフレーション

Axionic inflaton と U(1) ゲージ場の間に Chern-Simons 結合があると、偏極に依存したタキオン不安定性によってゲージ場が成長することが知られている。我々はこの系に対する準解析的なアプローチを提案し [10, 29, 57, 58]、荷電粒子生成による反作用を取り入れた場合の電磁場の強度の推定に成功した。この結果は初期磁場やバリオン数、原始重力波や原始ブラックホールの生成等の現象論的帰結に重要な示唆を与えるものである。

また、この Chern-Simons 結合により、インフレーション終了後にヘリシティを持った磁場とバリオン非対称が既に生成されている状況が実現される。その後の時空の発展とともに、磁場とバリオン非対称が対消滅する可能性があるが、我々は、右巻きニュートリノの存在下において完全な対消滅を回避し、最終的に現在の宇宙のバリオン非対称が説明できるシナリオを構築することに成功した [11, 53, 90, 93, 94, 97, 99]

宇宙論におけるカイラル効果

カイラル量子異常に代表されるカイラル効果は、宇宙論においても重要な役割を果たしうる。このテーマに関する総説を書く [12] とともに、我々は、カイラル効果によりエネルギー的にも安定化されるカイラルソリトン格子と呼ばれるドメインウォールの宇宙における量子トンネルによる生成率を南部後藤作用を用いて評価することに成功した [13, 44]。また、宇宙にレプトンの存在量の世代間に大きな非対称があった場合、高温においてカイラルプラズマ不安定と呼ばれる機構によって強い磁場生成が起こることを示し、レプトン非対称にこれまでより強い制限がかかることを明らかにした [79, 100, 102, 103]。

スファレロン脱結合によるバリオン非対称生成機構

近年、素粒子標準模型内で実現できるバリオン数非対称生成のシナリオが新しく提案された。宇宙膨張によるスファレロン脱結合で熱平衡からのずれができると主張し、CP の破れはスファレロン性質のため、従来思われたより多く稼げるという定性的な評価があった。しかし、このシナリオでは、まだ脱結合していないスファレロンによる、できたバリオン数を消す効果を考慮しなかった。本研究でその効果を入れて、このシナリオで生成できるバリオン数が僅少にとどまることを示した [21, 72, 82]。

条件付き確率を用いた原始ブラックホール形成条件

原始ブラックホールの形成判定を行なうにあたって、曲率揺らぎで表される圧縮関数と呼ばれる指標を用いた判定方法がある。圧縮関数は揺らぎの平均的なプロファイルが与えられて具体的に調べられるのが常であるが、本研究では、平均プロファイル近似に頼らない定式化の構築を目的として、条件付確率分布関数を用いる方法を考察した [26, 59, 65]。

初期磁場の時間発展とバリオン等曲率揺らぎ生成

初期宇宙における磁場の時間発展を理解することは、初期磁場研究における定量的な議論の基礎となる。本研究では、近年提案された保存量 Hosking integral に基づいて磁場の時間発展の理論を再構築し、数値計算と整合的に初期磁場の時間発展を記述した [27, 31, 36, 60, 63, 69, 110, 112, 115]。

また、宇宙磁場の起源に関して、とくに電弱対称性が回復した相における磁場生成シナリオについて一般的な議論を行なった。$U(1)_Y$ 磁気ヘリシティがカイラル量子異常を通じて物質反物質非対称性と結びついていることから、磁場のゆらぎに由来するバリオン等曲率揺らぎ生成が帰結される。バリオン等曲率揺らぎに対する宇宙論的制限から、このようなシナリオは観測的に示唆されるボイド磁場の強度を説明できないことを示した [34, 104, 106]。

8.1.3 重力波検出器 KAGRA データ解析

環境モニターを用いた雑音除去手法の開発

我々は独立成分解析 (ICA) と呼ばれる信号処理手法を用いた独自の雑音除去手法の開発に長らく取り組んできた。KAGRA 初の観測データに対して独立

成分解析 (ICA) と呼ばれる信号処理手法を用いた独自の雑音除去手法を適用することで、重力波の観測周波数帯域において影響が顕著であった音響雑音等の削減に成功した [14]。また、この研究を通して培われた解析手法を用いて、2022 年 1 月のフンガ・トンガ噴火時の環境モニターの応答が調べられた [15]。現在は非線形雑音の除去手法を実装し、雑音を人工的に注入した試験データの解析に取り組んでいる。

粒子放射と重力波を用いた宇宙ひもの観測的制限

宇宙ひものループが重力波の放射と素粒子の放射のどちらによって崩壊するかについては決定的な結論は出ていない。そこで本研究では、素粒子と重力波双方の放出を仮定した上での解析を可能とする定式化を行い、近年のパルサータイミングアレイの観測結果等を用いた制限を導出した [16, 24, 32, 38, 88]。

軽量ダークマター探索

サファイア鏡を使っている KAGRA では、干渉計の補助チャンネルを利用した軽量ベクトル場ダークマターのユニークな探索が可能であり、10^{-13} eV 程度以下の質量を持つ B-L ゲージボゾンを、既存の上限値を 1 桁以上上回る感度での探索が可能となる見込みである。現在、KAGRA 初の観測データからの制限を算出するため、軽量ベクトル場ダークマターの統計的性質を明らかにした我々の研究に基づいた解析パイプラインを開発中である [42]。

KAGRA 全著者論文, LVK 論文

KAGRA プロジェクトの認定著者として横山、粂、上野は全著者論文の著者に名を連ねている [17, 18]。また、LIGO, Virgo と KAGRA は協定を結んでいるため、第三観測期の論文は LVK 論文として KAGRA の認定著者は著者になっている。後者については掲載を省略する。

8.1.4 時間領域天文学

Tomo-e Gozen カメラによる赤色矮星フレアの観測

東京大学木曽観測所の 105 センチシュミット望遠鏡に取り付けられた Tomo-e Gozen カメラを用いて、毎秒 2 フレームという高速撮像で取得した多数の天体データを解析し、これまでに観測されたことの無かった高速なものを含む赤色矮星のフレアを 22 件検出することに成功した [19, 118]。

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9 Kipp Cannon研究室

9.1 研究活動報告

私たちの研究グループは、ブラックホール、中性子星、エキゾチックな天体、そして宇宙そのものを重力波観測、時には電波観測も用いて研究しています。重力波は、質量やエネルギーの動きによって生成される時空曲率の波です。重力波が宇宙を探索するの適している理由は沢山あります。重力波は電磁波（電荷の動きによって生成される） を生成する過程とは異なる物理的プロセスによって生成されるため、電磁波とは異なる波源に関する情報を我々にもたらします。また、重力波は物質と非常に弱く相互作用するため、電波や光に対して不透明な物質であっても透過します。例えば、超新星の中心部分やビッグバンの最も初期の瞬間でさえも重力波であれば、観測することができると期待されています。地球も重力波に対しては透明であるため、重力波望遠鏡は昼夜を問わず、常に全天を継続的に観測することができます。重力波は、ブラックホール連星の衝突のような、宇宙で最も激しいイベントで放射される唯一の重要なエネルギーの形です。しかし、重力波に対してはほぼ全てのものが透明であるため、それらを検出できる装置を構築することは非常に困難であり、重力波の検出は 2015 年に初めて達成されました。

私たちの研究グループのメンバーは LIGO と KAGRA コラボレーションのメンバーであり、世界中の重力波検出器、LIGO (アメリカ)、Virgo (イタリア)、GEO600 (ドイツ)、KAGRA (日本) によって収集されたデータを分析してします。それらのデータはほぼ解析し終え、多くの科学的成果が得られました [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15]。現在は 2023 年 5 月から開始される、LIGO, Virgo, KAGRA による第 4 次観測「O4」へ向けて、データ解析の準備を進めています。また、データから得られる科学的成果を最大化するためには様々な理論研究が必要ですが、私たちのグループのメンバーは、重力波を用いた天文学や宇宙論、基礎物理の探索までほぼ全ての分野で活動しています。

9.1.1 重力波データ解析

グローバルな相間磁場雑音を考慮した背景重力波探査

現在稼働中の LIGO・Virgo・KAGRA や Einstein Telescope に代表される第 3 世代の重力波検出器が完成すると、多数のコンパクト連星合体からの重力波が折り重なった天体起源の背景重力波の検出は十分射程圏内となる。さらに、初期宇宙に起源を持つ宇宙論的な背景重力波の検出の可能性も期待できる。背景重力波の検出には複数台の検出器から得られたデータ同士で相関を取る手法が用いられるが、地球規模で存在する擾乱が重力波検出器に影響を与える場合、十分離れた 2 台の検出器間でも重力波以外の相関が現れ、背景重力波を誤検出する恐れがある。特に、シューマン共鳴磁場と呼ばれる大域磁場は将来的に重力波検出器に深刻な影響を及ぼしうる可能性がある。我々は、シューマン共鳴磁場に由来する相関雑音を考慮した背景重力波探査によるパラメーター推定について研究を行った。KAGRA を入れた合計 4 台の第 2 世代検出器を想定した場合で、シューマン共鳴磁場の解析的モデルを用いてフィッシャー解析を行い、シューマン共鳴磁場を適切にモデル化できれば相関雑音は背景重力波探査に影響を与えないということが分かった。しかし、モデル化が不十分な場合にはパラメーター推定結果をバイアスさせてしまうことも分かった。これらの研究成果は論文 [21] として発表した。

前景重力波の分離による初期宇宙由来の背景重力波の探索

前項のように、多数のコンパクト連星合体からの重力波が折り重なった天体起源の背景重力波はインフレーションなどの初期宇宙において生成された原始重力波を覆い隠してしまうと考えられている。したがって、原始重力波を検出するためには、天体起源の重力波信号を適切なデータ解析により取り除く必要がある。我々は、中性子連星及びブラックホール連星由来の前景放射について、個々の連星からの重力波信号を波形テンプレートを用いて除去する方法を再検討した。また、現行の重力波検出器が背景重力波の各異方性モードに対してどれくらいの感度をもって測定できるかを判定するため、各検出器の球面調和モードに対するオーバーラップ関数を計算するコードを作成し、Fisher 情報行列を計算するコードの開発を行なった。

9.1.2 重力波天文学

電波望遠鏡 Canadian Hydrogen Intensity Mapping Experiment（CHIME）によるショートガンマ線バーストからの残光探査

ショートガンマ線バースト（short gamma-ray burst、sGRB）と呼ばれる爆発的突発現象の起源に迫るために。本研究では、電波望遠鏡 CHIME で sGRB からの電波残光を観測することを目指している。昨年度はカナダのブリティッシュコロンビア大学に長期滞在し、今後の解析において偽陽性の原因となりうる『エイリアス』を除去するコードを開発した。エ

イリアスとは、通称『折り返し雑音』とも呼ばれる。サンプリング周波数よりも高周波な成分がデータに含まれている際に生じる雑音で、CHIME の取得する全天マップ上では特定の天体と同じ明るさを持つ光源として見られる。いわば、『同じ天体が複製されている』ような状態である。エイリアスの特徴として、周波数ごとに出現位置が異なるという点が挙げられる。人間の活動（携帯電話、テレビ、飛行機など）に起因する雑音の影響が強いと特定の周波数データが解析から除外されてしまう可能性があるため、ある周波数帯でエイリアスが存在するピクセルの明るさが日によって変化し、残光探査において偽要因を誘発しうる。実際の天体と異なり、エイリアスの位置が周波数ごとに異なることを利用し、十分にエイリアスが動きうるような周波数帯に渡る複数のデータを用いて、線型回帰モデルに基づくフィルターを構築し適用したところ、エイリアスの明るさを実際の天体の数%未満にまで抑えることができた。

位置天文観測衛星 Gaia によるブラックホール連星観測に関する理論予想

位置天文観測衛星 Gaia では、可視光で恒星を観測することで、ブラックホールと恒星からなる連星を検出しうると考えられていた。2022 年 6 月のデータ公開において初めて連星に関するデータが公開され、すでに二つのブラックホール－恒星の連星が確認されている（El-Badry+2023a, Tanikawa+2022, El-Badry+2023b）。今後もブラックホール連星の検出は相次ぐと期待されることから、昨年度は X 線連星の観測で明らかになっている連星パラメータの相関に注目し、『Gaia で観測されるようなブラックホール連星にも連星パラメータ間の相関が見られるのか』を理論予想した。これまで Gaia で観測しうるブラックホール連星に関する理論予想において、連星種族合成コード BSE を用いて、連星進化を追っていた。今回は、X 線連星で見られている相関がブラックホール質量や連星軌道周期といった連星パラメータと銀河面からの高さという空間分布に関するパラメータに関するものであることから、BSE で得られたブラックホール連星が銀河内をどのように運動するかを数値計算で追った。その結果、観測しうるブラックホール連星には様々な相関が見られることが分かり、連星進化パラメータによって相関の様子が異なることも明らかになった。

9.1.3 重力波による基礎物理の探究

重力波偏極モードによる重力理論の検証

一般相対性理論を拡張した重力理論はこれまで多数提案されており、一般相対性理論の正しさを様々な側面からより高精度で検証することは我々の重力に対する理解を深める上で重要である。重力波観測を用いれば、重力波を放射する天体の近傍、つまり、動的かつ非常に強い重力場における重力の性質を調べることが可能である。そのような検証方法の 1 つとして、重力波の偏極モードがある。偏極モードの数は各重力理論に特有であり、一般相対性理論では２つのモードが存在するが、拡張重力理論では 3 つ以上の偏極モードが存在できる。つまり、偏極モードの数を観測データから調べることで正しい重力理論を絞り込むことができる。我々は一般相対性理論における通常の偏極モードに加え、スカラー偏極モードが存在する場合の重力波形をパラメータを導入する形で構築した。そして、その波形を用いて重力波検出器の観測データを解析し、得られた重力波信号が一般相対性理論の予言する偏極モードと矛盾するような兆候は無く、一般相対性理論の正しさを支持する結果を得た [16]。

重力波による強重力場における一般相対論の検証

重力波による強重力場における一般相対論の検証重力の標準理論である一般相対論は、これまでの観測結果を良く説明するが低エネルギー有効理論に過ぎず、強重力領域に迫ればどこかで必ず破綻してしまう。具体的には、物理法則が破綻する特異点の予見や量子論としてくりこみが不可能などの困難を抱えている。これらを回避する重力理論の構築には、理論研究はもとより、得られる重力波データを適切に解析する手法を考案し実データを解析することで、有意な情報を引き出すボトムアップ的なアプローチが不可欠である。そこで我々は, 観測を通じて知ることができる最も重力が強い領域である連星ブラックホール合体過程のマージ段階の定量的な解析法を考案し、実際にデータ解析を行うことで、強重力場の物理の理解に繋がる情報を引き出すことを目的とした研究を行っている。

一般相対性理論を超える一般時空幾何の観測的検証

一般相対性理論はこれまでに様々な実験的検証をパスしているが、重力の量子化や特異点の存在の理解には理論的課題が残っている。計量アフィン重力理論は、重力をゲージ理論として理解し、量子重力理論の構築に向けた取り組みとして近年注目されている。一般相対性理論は計量から導かれるレヴィ・チビタ接続によってのみ表現され、時空の幾何学は単に計量のみによって表される。一方、計量アフィン重力は一般的な接続（アフィン接続）により時空の幾何学が記述される。その結果、時空は曲がり（計量）だけでなく、捩率や非計量性も含むことになる。計量アフィン重力理論の非計量性の側面はまだ研究が進んでおらず、非計量性を取り入れた対称テレパラレル重力と呼ばれるサブクラスは理論的に安定であり、今後観測的検証が期待されている。我々はこれらの理論を重力波の最新観測データを用いて検証しようとしている。

チェレンコフ放射状重力波の検出システムの開発とその探査

超光速天体 (地球外生命体による人工的な超光速宇宙船を含む) の存在と同天体が突発性重力波を発すると仮定し、これを探索する検出システムの開発を行なった。重力波が衝撃波のような形で発生すると想定し、電磁気学によるチェレンコフ放射を元に波形テンプレートを作成した。その波形テンプレートを用い、第 3 期観測 (O3) の 1 年間のデータに対して探索を行った。この探索で得られたランキング統計量によって、超光速天体のパワー、速度、観測者から天体の軌道までの距離などに制限を課した。また、偶然にも、ここで紹介した特殊な波形モデルは、「グリッチ」と呼ばれるある種の過渡的なノイズ事象に非常によくマッチすることが判明した。

重力波を用いたハドロン-クォーク相転移の検証

重い中性子星の中心部に存在するような高密度物質においては、クォークの自由度が顕在化し得ると考えられる。しかし、ハドロン物質からクォーク物質への遷移がどのように起こるのかは分かっていない。連星中性子星合体直後に形成される天体の最大密度は通常の原子核密度の 5 倍程度にも及ぶと考えられ、そこから放出される重力波はクォーク-ハドロン転移周りの状態方程式に敏感である。しかし、その周波数は 2 kHz 以上であり、LIGO 等の現行の検出器の最も感度の良い周波数帯と比べてかなり高い。本研究では、代表的な 2 つのクォーク-ハドロン転移シナリオに対して計算された数値相対論波形を用い、ベイズ統計に基づくモデル選択をシミュレーションすることで、将来の検出器を用いた正しいシナリオの判定可能性調べた。この際、原子核密度周りの比較的低密度の状態方程式は、それまでの観測の蓄積によりよく決まっているものと仮定した。この仮定のもと、Advanced LIGO の設計感度での観測では正しいシナリオの判断が困難であること、逆に第 3 世代の検出器や合体後の信号の観測に特化した将来の検出器では現実的な可能性があることが明らかになった。

重力波によるアクシオン暗黒物質の探査

我々の宇宙に存在するほとんどの物質は未知の暗黒物質であり、その正体がどのような物であるかについて様々な議論がなされてきた。そのような暗黒物質の候補の 1 つとしてアクシオンが考えられており、天の川ハローは複数のアクシオン雲が存在していると考えられている。重力波がアクシオン雲中を伝播すると、アクシオンのグラビトンへの崩壊を誘導することが知られており、重力波の振幅は増幅され、伝播速度の変化による時間遅延が生じることになる。つまり、これまで検出されてきた連星合体由来重力波の周辺には特徴的な重力波が検出されるはずである。我々はそのような特徴的な重力波を探すことで、結合定数（素粒子論における基本的パラメーター） に対して先行研究より最大で約 10 倍強い制限を課した [19]。一方、理学系研究科物理学専攻の安東研究室で行われているアクシオン探査のテーブルトップ実験にも理論・データ解析の方面から参加し、共同研究を行っている。

9.1.4 重力波検出器に関する研究

中性子干渉計を用いた変位雑音フリー重力波検出器

宇宙誕生時のインフレーションの直接証拠であると考えられている原始重力波の観測は、 重力波観測における重要な目標の一つである。地上の検出器によって原始重力波の検出を試みた場合、地面振動や鏡などの熱雑音によって検出器の感度が制限されてしまう。その解決策として、変位雑音をキャンセルできる変位雑音フリー干渉計のアイデアがある。変位雑音フ リーレーザー干渉計では、適切に信号を組み合わせることで重力波信号を残しつつ、感度の妨げとなる変位雑音を完全に消すことができる。しかし、観測対象である低周波数帯 (0.1–1 Hz) に対しては感度を持たないことが問題であった。そこで、我々はレーザー光源ではなく速度を変えることのできる中性子を用いることで、有効周波数が 1 Hz 付近の変位雑音フリー中性子干渉計を提案した [17]。この変位雑音フリー中性子干渉計では Mach-Zehnder 干渉計に両側から中性子を入射していたが、双方向の中性子源の用意には様々な困難が伴う。そこで、その実用的改良版として片方向からの異なる速度の中性子を入射する場合の変位雑音フリー中性子干渉計を考案した [18, 20]。現在、このセットアップを用いた変位雑音フリー中性子干渉計の原理検証実験の検討を進めている。

9.2 業績リスト

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10　茂山俊和研究室

10.1　研究活動報告

私たちの研究室では、突発的に明るくなる天体現象の理論モデルを構築することで、その天体の宇宙史における役割を理解する研究をしています。具体的には超新星爆発や様々な星の合体現象を研究対象にしています。以下では、2022 年度に論文などで成果発表を行なった研究について説明します。

10.1.1　白色矮星合体によって生じた超新星の残骸の理論モデル

白色矮星合体の結果

酸素とネオンからなる白色矮星と炭素と酸素からなる少し軽い白色矮星が合体した結果できたと思われる天体から強い星風が吹いていることが発見され、その観測を説明するモデルを樫山和巳、藤澤幸太郎、両氏と 2019 年に構築した。最近、その天体の星風を取り巻くような広い領域と中心の点状の領域から X 線が観測された。また、吾妻鏡に記録が残っている 1181 年に爆発した超新星とこの天体が結び付けられるという指摘がなされた。私たちは、広い領域からの X 線はこの超新星が星間物質と衝突して生じた衝撃波によって放射され、点状の X 線は星風が超新星に内側からぶつかって生じた衝撃波からの放射と解釈して、モデルを構築している。X 線の解析は馬場研の方々が行ない、その結果を再現する定量的なモデルを作ることが当面の目標。[12, 13, 30, 51]

10.1.2　大質量星からの突発的な質量放出

重力崩壊型超新星を起こす大質量星の中には、その数年前に突発的に増光し、外層を大量に放出するものがあると考えられている。私たちは、その現象論的なモデルを構築し、超新星爆発直前に観測された増光現象と比較することでどの程度の質量が放出されたのかを推測するとともに、放出された物質の密度構造や星の構造の変化を調べてきた。今年度はこの現象の物理的原因を追求するために、球殻状の薄い領域で起きる核燃焼の安定性について調べている。[11, 36, 38, 45]

10.1.3　星周物質と爆発物質の衝突で光る天体

IIn 型超新星光度曲線モデル

星周物質が超新星爆発の数年前に突発的に放出され、超新星爆発で放出された物質と衝突することで光る一連の過程を計算するコードを構築し CHIPS と名づけて公開した。計算コードの詳細を記述した論文を The Astophysical Journal に発表した。このコードを用いて、赤色超巨星の水素外層に注入するエネルギーと注入時間がどのような関係を満たすと星周物質が形成されるかを調べ、The Astrophysical Journal に発表した。[5]

超新星の前兆現象と近傍宇宙での検出可能性

近年の高頻度探索観測によって、超新星の爆発前に濃い星周物質が放出されていることがわかっている。これらが突発的な質量放出によるものである場合、爆発前にどのような放射が期待されるかを CHIPS コードを用いて計算した。最も頻繁に起こると考えられている赤色超巨星による (II 型) 超新星の場合、放射は主に赤外で明るくなり、地球から 10 Mpc 以内の近傍で起こる超新星については次世代可視光・赤外望遠鏡の Rubin Observatory で超新星爆発の数ヶ月前からでも超新星を予言できることを示した。[1, 5, 37]

星周物質の輻射による加速

濃い星周物質が存在する超新星では星周物質起源の狭い水素などの輝線が観測されるが、その輝線幅によって得られる速度は超新星の放射による星周物質の加速によって影響されうる。そこで星周物質を持った赤色超巨星の爆発の輻射流体シミュレーションと解析的モデルの構築を行い、星周物質の広がりや質量によってその加速がどの程度起こるかを調べた。質量の大きく広がりの小さい、すなわち高密度の星周物質の場合、秒速 1000km 程度まで加速できることを示した。そしてこれらの結果を II 型超新星と比較することにより、赤色超巨星での質量放出だけでは説明できなかった観測されている幅広い星周物質の速度を包括的に再現できることを示した [20]。

多次元輻射流体力学シミュレーションコードの開発と応用

星周物質との衝突によって輝く突発天体の力学的進化や熱的放射のメカニズムを解明する目的で、多次元輻射流体力学シミュレーションコードの開発および整備を行っている。このような突発天体では爆発物質の持つ力学的エネルギーが星周物質との衝突によって衝撃波を介して熱エネルギーへと変換され、

光学的に厚い領域において熱放射のエネルギーとなったものが光学的に薄い領域へと解放されることになる。従って、この過程を無矛盾に取り扱うためには輻射流体力学シミュレーションが極めて強力な手段となる。IIn 型超新星をはじめとする、星周物質との衝突をエネルギー源とする突発天体の起源解明を目的として、多次元流体力学と放射輸送を取り入れたシミュレーションコードを開発し、大規模並列シミュレーションを実施することで、様々な突発天体の光度曲線モデリングを進めている [23, 24, 28]。

ガンマ線バーストジェットと星周物質の相互作用

ガンマ線バースト (GRB) は、天球面上においてガンマ線点源が短時間現れる現象で、継続時間が比較的長い GRB(long GRB) は大質量星の重力崩壊に伴って発生することが知られている。 この際に、中心エンジンによって駆動され、ローレンツ因子にして 100 を超える超相対論的ジェットが星を貫き、即時ガンマ線放射を行うとともに、星周物質との衝突によるエネルギー散逸によって幅広い波長域での残光放射で輝く。近年の超新星可視光観測から示唆されているように、GRB 親星においても重力崩壊直前に放出された物質が濃い星周物質として親星周囲に存在している可能性を考え、GRB ジェットが星周物質に衝突し伝搬が妨げられる過程の 3 次元特殊相対論的流体力学シミュレーションを行うことで、どの程度のエネルギーが散逸し、どのような電磁波放射が予想されるのかを調べている [31, 40, 48]。

10.1.4 中性子星に降着する物質からの炭素爆燃波

Ia 型に分類される超新星の中には非常に明るく光るものも見られる。放射性元素 ^{56}Ni の質量が Chandrasekhar limit 1.4 $M_\odot$ を超えているものもあり、爆発物質の質量は 2 $M_\odot$ くらいとこちらも Chandrasekhar limit を超えている。爆発した星として回転している白色矮星を考える場合が多いが、観測の特徴を再現するのは難しい。私たちは、これらの超新星が星形成を続けている銀河で起きていることに着目し、大質量星を起源とするシナリオを考えた。中性子星との近接連星系をなす大質量星は進化するとその外層をほとんど失い CO 中心核のみが残る。重力波を放射しつつ軌道がさらに縮み、ついにはそこに中性子星が飲み込まれ、中性子星に CO が降着する。このときに C+C の核融合反応に点火して爆轟波が発生して星全体を吹き飛ばす可能性を調べることにした。[10]

定常流による解析

中性子星に降着する球対称な定常遷音速流を計算し、C+C→Mg などの核融合反応によるエネルギー供給の影響を調べている。この流れは、周囲のガスの化学組成と比エンタルピーと降着率で規定される。C と O が質量比で半々の蘇生の時に与えられた比エンタルピーに対して降着率がある値より大きい時に降着流が中性子星表面に到達しなくなる現象を見出した。系統的な計算を行い、臨界降着率が中性子星質量と周囲の物質の比エンタルピーにどのように依存するか調べた。[10]

10.1.5 高速回転や磁場を伴った天体の構造と重力波

ブラックホールや白色矮星、中性子星など、恒星がその一生を終えた後に形成されるコンパクト天体は様々な高エネルギー天体現象を起こす。これらは極限的環境における物理過程を探る実験室である。

コンパクト天体の多くは非常に高速な回転や強力な磁場を伴っており、様々な高エネルギー現象と密接に関わっている。そこで、このような高速回転するコンパクト天体を考えるために、ラグランジュ座標に基づく新しい回転星の定式化と計算をニュートン重力と一般相対論でそれぞれ行いその構造を計算した。また、そのために必要な数値計算手法の開発も行った [16, 17, 18]。

また、中性子星は非常にコンパクトであるため、回転軸に対して非軸対称的に歪み高速回転していると重力波を放出すると考えられている、有力な重力波候補天体である。そこで、磁場による中性子星の歪みの新しい解を計算し、理論的に求めた [14, 15]。

10.1.6 極金属欠乏銀河の化学進化

近年の銀河サーベイで発見されはじめた極金属欠乏銀河 (Extremely Metal-Poor Galaxies; EMPGs) は、金属量が太陽組成の数%程度の近傍銀河であり、より始原的な環境での銀河形成を理解する上で重要な天体だと考えられている。EMPGs の中にはガス相の鉄の酸素に対する存在比が太陽組成に比べて高いなど、特異な元素組成を示すものも報告されており、その化学進化がどのようなものであったのかは興味深い問題である。すばる望遠鏡を用いてこれら EMPGs を重点的に観測する intensive program “EMPRESS 3D” (PI: 大内正己) に参加し、種々の超新星による特異な化学組成の説明を試みている [33, 41]。また、同プログラムの一環で、より始原的な環境に近いという EMPGs の性質を利用して、すばる望遠鏡での近赤外分光観測からヘリウムの始原的な質量比 $Y_{\rm P}$ を推定する研究なども行なっている [22]。

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11 仏坂健太研究室

11.1 研究活動報告

当研究室は、白色矮星、中性子星、ブラックホールなどのコンパクト天体に関する宇宙物理学を理論的に研究しています。特にコンパクト連星からの重力波やそれらに付随する電磁波放射に関する研究を観測グループと連携して行っています。

11.1.1 連星中性子星の電磁波対応天体

キロノバの研究

キロノバは連星中性子星合体に付随する電磁波対応天体の一つであり、合体時に放出された中性子過剰物質の放射性崩壊によって輝く現象である。この現象は特に重元素の起源に関連するという重要性がある。我々はキロノバに関する観測・理論の両目から研究を行った。[1, 2, 4, 5]。

キロノバ の研究の中でも特に中性子星合体エジェクタが光学的に薄くなった星雲期の放射は自由電子によって励起された重元素からの放射脱励起の光を直接観測することができるため、中性子星合体に伴って生成され元素を特定するために極めて有用であると考えられている。しかし、キロノバ星雲期は観測的にも理論的も、その性質はほとんどわかっていない。その理由は、星雲期の放射の計算に必要な原子データが欠落しているためである。そこで我々は星雲期の計算に必要な原子データ、特に原子の禁制線に関するデータ（輝線リスト）揃えた。作成した原子データを用いて、GW170817 における Spitzer 衛星によるキロノバ 星雲期の観測データの解釈を行った [2]。我々の理論に基づくと、キロノバ星雲期に観測された 4.5 ミクロンの強い放射はセレン (原子番号 34) もしくはタングステン (原子番号 74) の微細構造線で説明できることがわかった。今回の観測は、Spitzer 衛星による測光観測にとどまっているが、今後、キロノバが観測されればジェームズウェッブ宇宙望遠鏡を使ってより詳細な分光観測が可能であり、これからの発展が期待できる。

中性子星合体は合体後にブラックホールが形成される場合と大質量中性子星が形成される場合がある。大質量中性子星が形成される場合、合体後の中性子星が持つ膨大な回転エネルギーが磁場を介して、解放され合体エジェクタの運動エネルギーに変換されることが予想される。我々は数値流体シミュレーションを用いて、このエネルギーの変換機構やエネルギーが注入されたエジェクタの時間発展およびそのようなエジェクタが生成する電磁波対応天体について調べた [1]。膨張速度とエジェクタ質量の増加によりキロノバ信号が増幅されることや、エジェクタと星間物質の間に形成される衝撃波からのシンクロトロン放射が数桁強くなることを示した。これにより将来の中性子星合体の電磁波対応天体の観測から合体後に形成される天体の性質に迫ることができることを示した。

電波対応天体の研究

中性子星合体は非相対論的なキロノバエジェクタだけなく、相対論的なジェットも駆動する。このジェットと星間物質の間に形成された衝撃波によって加速された非熱的な電子によって放射されるシンクロトロン光が電波から X 線まで幅広い波長で観測される。我々はこのシンクロトロン放射に関する研究を行った [1, 3]

GW170817 の残光は基本的には構造を持った相対論的ジェットで説明できるが、合体後の 3 年後に X 線超過があるという示唆があった。論文 [3] では合体後 4.5 年での電波放射を Very Large Array による観測によって調べた。その結果、電波放射は超過を示さずジェット残光でよく説明できることを示した。このことは X 線超過がもし本当ならばフォールバック円盤など X 線特有の残光とは異なる放射の存在を示唆している。

11.1.2 ガンマ線バーストジェットにおける粒子加速の研究

ガンマ線バースト残光は、連星中性子星合体に伴う電磁波対応天体の１つであり、ジェットの衝撃波によって加速された電子のシンクロトロン放射が電波からX線までの広い波長帯域で観測される現象である。衝撃波における粒子加速メカニズムの解明は高エネルギー天体物理学の重要なテーマであるが、詳細は未解明である。特に、衝撃波速度が相対論・非相対論的な場合で粒子加速効率が変わることが理論的に示唆されているが、直接観測による検証はできていない。ガンマ線バースト残光はジェットが相対論的速度から非相対論的速度に遷移する過程で形成されるため、粒子加速の衝撃波速度依存性を観測的に検証できる可能性があるユニークな天体現象である。我々は、LIGO-Virg-Kagra O4 の連星中性子星合体の検出範囲 200 Mpc の星周物質が比較的濃い環境において、GRB 170817A と同様の構造を持つ off-axis ジェットが形成された場合、ガンマ線バースト残光のスペクトルのベキ指数の時間発展を観測することで粒子加速の衝撃波速度依存性が観測的に検証できることを理論モデルを用いて示した [8] 。

11.1.3 超大質量星および活動銀河核

活動銀河核の金属の化学進化に関する研究を行った[6]。この研究では、活動銀河核広輝線領域の [Fe/Mg] 組成比を化学進化モデルを使って議論した。結果として銀河中心核における 50 太陽質量を超える大質量星の存在比などに制限を与えた。また初代星形成に関する研究も行っている [7]。具体的には初代星形成の輻射流体シミュレーションを実施した。輻射フィードバックの効果について調べ、星形成環境と誕生する星質量の相関関係を導いた。

11.1.4 恒星・ブラックホール連星の探査

恒星とブラックホールからなる連星は、これまで主に質量交換をする X 線連星として発見されおり、現在数１０天体が報告されている。しかし、質量交換は特定の条件が揃った場合のみ生じる現象であり、広い連星パラメータの中でも限られた領域のものに限定される。そこで我々は、系外惑星探査衛星 TESS の測光観測サーベイデータから伴星にブラックホールを持つ天体に特徴的な変光を検出することで質量交換を伴わない恒星・ブラックホール連星を発見することを目指してデータ解析を行っている [10]。

11.2 業績リスト

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