Research Center for the Early Universe
Graduate School of Science
University of Tokyo

Annual Report

2023

令和5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

Version 令和 7 年 3 月 26 日

Preface

We are pleased to present the annual report of Research Center for the Early Universe (RESCEU) for the fiscal year of 2023 (from April 2023 to March 2024).

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.

After suffering for several years from Covid-19, this year's activities were almost restored to pre-pandemic levels. We were also able to conduct our annual summer school, which has traveled around Japan every year, this year at Shinshu University in Nagano City for face-to-face meetings. However, instead of sleeping and eating together, this time each participant stayed at a hotel and commuted to the venue. The international conference in Hongo was also revived, with the RESCEU symposium and several other meetings. We also hosted LIGO-Virgo-KAGRA collaboration meeting at Toyama International Conference Hall jointly with local researchers there.

Furthermore, for the first time in many years, we were able to invite Professor Re'em Sari of the Hebrew University as a visiting professor in the Visiting Professor Division, which is the only division that the Graduate School of Science maintains.

On the other hand, there was very sad news: Prof. Starobinsky, who had been a visiting professor at RESCEU for 12 times since 2000, passed away on December 21 in Moscow due to Covid. He was also a frequent lecturer at our summer school. He had made immortal achievements in many areas of cosmology and gravity theory, including inflationary cosmology, and we were certain he would win the Nobel Prize. We pray for his soul rest in peace.

We are pleased to announce the following awards for our RESCEU members this year. Professor Kenta Hotokezaka was awarded the 38th Nishinomiya-Yukawa Memorial Prize (Oct. 2023) for his "Theoretical Study of Electromagnetic Counterparts Associated with Neutron Star Mergers". Professor Emeritus Katsuhiko Sato was awarded the ICGAC-15 award in July 2023 together with Visiting Professor Alexei Starobinsky for their pioneering contributions to the theory of cosmic inflation, which established the roles of gravitational wave production, and of super-horizon fluctuations in creating the seeds of cosmic structure. Minori Shikauchi, a student of Cannon group, received the excellent award in the final examination of the Forefront Physics and Mathematics Program to Drive Transformation (FoPM) in October. Fumihiro Naokawa (Yokoyama group) and Daiki Watarai (Cannon group) each received the Student Presentation Award of the Physical Society of Japan in June.

In this academic year, Kenneth Wong joined RESCEU as a project assistant professor, and Tomoko Ishida as a secretary. On the other hand, Assistant Professor Atsushi Nishizawa was promoted to an associate professor of Hiroshima University, Assistant Professor Kohei Kamada was promoted to a distinguished researcher at Hangzhou Institute for Advanced Study, and Project Assistant Professor Ryusuke Jinno was promoted to an associate professor at Kobe University. Among our postdocs, Daisuke Toyouchi was promoted to a specially appointed assistant professor at Osaka University, Yuki Takei got a next position at Yukawa Institute for Theoretical Physics, Kyoto University, and Jun'ya Kume moved to University of

Padua. Finally, Professor Yasushi Suto retired from the University of Tokyo in March 2024, and moved to Kochi University of Technology. I have also been serving as Director of Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI) since November 2023.

We would appreciate your further support for our activities.

May 2024

Director Jun'ichi Yokoyama

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I

Reports on overall activities at RESCEU in 2023

1 Members

RESCEU members

Jun'ichi Yokoyama [横山順一]	Director
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
Ryusuke Jinno [神野隆介]	Project Assitant Professor
Kenneth Wong	Project Assistant Professor
Koh Ueno [上野昂]	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)
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)
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
Tomoko Ishida [石田智子]	Secretary

RESCEU affiliates

Yasushi Suto [須藤靖]	Professor, Dept. of Physics
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 2023

Place: Faculty of Engineering, Shinshu University, Nagano, Japan
Time: 2023 August 9 (Wed) – 2023 August 12 (Sat)
Web: https://sites.google.com/view/resceu-ss2023

Program

August 9 (Wed)

12:30–13:00	Registration	
13:00–13:10	Tomoya Kinugawa	Opening remarks

(chair: Kana Moriwaki)

13:10–14:40	(L) Livia Vallini	The interstellar medium of galaxies in the Epoch of Reionization I - Theory & Modelling
15:00–16:30	(L) Livia Vallini	The interstellar medium of galaxies in the Epoch of Reionization II - Observations

(chair: Hiroto Mitani)

17:00–17:15	Yurina Nakazato	Simulations of highII]edshift [OIII] emitters: Chemical evolution and bursty star formation history
17:15–17:30	Yuka Yamada	Target selection of [OII] emission line galaxies with z∼1.6-2.4 for the upcoming PFS observation
17:30–17:45	Jason Kristiano	Primordial black holes from single-field inflation?
17:45–18:00	Minori Shikauchi	Spatial and Binary Parameter Distributions of BH Binaries in the Milky Way Detectable with Gaia

August 10 (Thu)
(chair: Kenta Hotokezaka)

9:00–10:30	(L) Yoshiyuki Inoue	High-Energy Accretion Phenomena Around Black Holes I
10:50–12:20	(L) Yoshiyuki Inoue	High-Energy Accretion Phenomena Around Black Holes II
Lunch		
13:30–17:30	Free Discussions	
18:00–21:00	Dinner	

August 11 (Fri)
(chair: Kipp Cannon)

9:00–10:30	(L) Jocelyn Read	Neutron-star astrophysics with gravitational-wave astronomy I - Source modeling and single-event inference
10:50–12:20	(L) Jocelyn Read	Neutron-star astrophysics with gravitational-wave astronomy II - Population results and future expectations
Lunch		
13:30–15:00	Poster Session	

(chair: Kohei Kamada)

15:30–17:00	(L) Muneto Nitta	Introduction to Topological Solitons and Defects & Application to QCD I

(chair: Akihiro Suzuki)

17:15–17:30	Reiko Harada	On the Testability of the Quark-Hadron Transition Using Gravitational Waves From Merging Binary Neutron Stars
17:30–17:45	Suyog Garg	Convolutional Neural Network for Gravitational-Wave detection from Neutron Star Black Hole Binary
17:45–18:00	Tomoya Kinugawa	Gravitational waves from first star remnants

August 12 (Sat)

(chair: Kohei Kamada)

9:00–10:30	(L) Muneto Nitta	Introduction to Topological Solitons and Defects & Application to QCD II

(chair: Toshikazu Shigeyama)

11:00–11:15	Fumio Uchida	Monopole wrapped by domain walls?
11:15–11:30	Koki Tokeshi	Borel resummation for secular divergences in stochastic inflation
11:30–11:45	Fumihiro Naokawa	The rotation of photon by the rotation of axion
11:45–12:00	Yuta Shiraishi	Compact Star-Luminous Star Search by TESS Photometric Survey
12:00–12:15	Hanchun Jiang	Search for M-dwarf Flares by Machine Learning Method
12:15–12:24	Jun'ichi Yokoyama	Closing remarks

(L: Lecture)

Poster Presentations

Purnendu Karmakar	f(Q) cosmology
Jun'ya Kume	Back-reactions in axion inflation with U(1) gauge field
Soichiro Kuwahara	Recent status of foreground subtraction on the search of stochastic gravitational wave
Tomoya Hasegawa	A light curve model of SN precursor emission - Combining the results of Tsuna et al. (2021) and Matsumoto & Metzger (2022) -
Muzi Hong	Quartic Gradient Flow
Christopher Irwin	Insights on the origin of low-luminosity GRBs from a revised shock breakout picture for GRB 060218
Zhuoxi Liang	The Luminosity Functions of Supernova Host Galaxies
Yuting Liu	Hubble constant from the cluster-lensed quasar system SDSS J1004+4112: investigation of the lens model dependence
Kazuya Takahashi	Imaging jet structures with gamma-ray burst afterglows
Yuki Takei	Simulating hydrogen-poor interaction-powered supernovae
Akihiro Suzuki	Gamma-ray burst jet simulations with massive circum-stellar medium
Soichiro Yamazaki	Quantum algorithm for collisionless Boltzmann equation simulation

The 14th RESCEU International Symposium: From Large to Small Structures in the Universe

Place: Koshiba Hall, University of Tokyo
Time: 2023 October 30 (Mon) – 2023 November 2 (Thu)
Web: https://www.resceu.s.u-tokyo.ac.jp/symposium/resceu_sympo2023/

Program

October 30 (Mon)

9:00–9:30	Registration	
9:30–9:40	Jun'ichi Yokoyama	Opening address
9:40–9:50	Hiroto Mitani	Logistics

Dark Matter Halos and Galaxies (chair: Masamur Oguri)

9:50–10:15	Yipeng Jing	The connection between dark matter halos and emission line galaxies (ELGs) and evidence for galactic conformity
10:15–10:40	Atsushi Taruya	To be or not to be: (non-)universal features in dark matter halos
10:40–10:55	Hyunbae Park	Impact of small-scale structure on reionization
10:55–11:20	Coffee	

Machine learning in Astronomy (chair: Naoki Yoshida)

11:20–11:45	Kana Moriwaki	Deep learning application to large-scale structure of the universe traced by line intensity
11:45–12:10	Pablo Lemos	Machine Learning Powered Inference in Astronomy
12:10–12:35	Ofer Lahav	AI for Cosmological Experiments: Evolution or Revolution?
12:35–14:00	Lunch	

Galaxy Surveys and their cosmological implications (chair: Ofer Lahav)

14:00–14:25	Masahiro Takada	Subaru HSC and PFS
14:25–14:50	Takahiro Nishimichi	Emulator as a theoretical template in cosmological inference
14:50–15:15	Toshiya Namikawa	Probing inflationary gravitational waves with high-precision cosmic microwave background B-modes
15:15–15:30	Yuka Yamada	Target selection of [OII] emission line galaxies for PFS observation
15:30–15:50	Coffee	

Baryonic evolution of cosmic structures (chair: Masahiro Takada)

15:50–16:15	Jia Liu	Effects of baryonic feedback on the cosmic web
16:15–16:40	Renyue Cen	The Missing Pillar In Galaxy Formation
16:40–17:05	Eiichiro Komatsu (online)	The Temperature of Hot Gas in the Universe

October 31 (Tue)

From Fluctuations to Compact Objects (chair: Atsushi Taruya)

9:00–9:25	Jun'ichi Yokoyama	Small to Large-scale fluctuations in the universe
9:25–9:50	Masamune Oguri	Gravitationally lensed supernovae
9:50–10:05	Masahiro Morikawa	The Universality of Astronomical Objects from Low-Frequency Fluctuations
10:05–10:30	Kenta Hotokezaka	Neutron Star Mergers and Kilonovae
10:30–10:50	Coffee	

Black Holes and Gravitational Wave (chair: Kipp Cannon)

10:50–11:15	Re'em Sari	Dynamical Processes around Supermassive Black Holes
11:15–11:30	Soichiro Morisaki	Rapid localization and inference on compact binary coalescences with the Advanced LIGO-VirgoKAGRA gravitational-wave detector network
11:30–11:45	Daiki Watarai	Physically consistent gravitational waveform for capturing beyond-GR effects in the compact binary merger phase
11:45–12:00	Suyog Garg	Deep Convolutional Neural Network for detecting Gravitational Wave signals from Eccentric Compact Binaries
12:00	Conference Photo	
12:20 – 14:00	Lunch	

Numerical Simulations (chair: Kana Moriwaki)

14:00–14:25	Kohji Yoshikawa	Vlasov-Poisson simulation of collisionless self-gravitating systems
14:25–14:50	Naoki Yoshida	Putting the Universe in a computer
14:50–15:15	Michiko Fujii	N-body simulations of star clusters
15:15–15:35	Coffee	

Cosmological Parameters (chair: Yipeng Jing)

15:35–16:00	Changbom Park	Discordance of the flat ΛCDM 'concordance' model: Evidence for the Dark Energy Equation of State Parameter $w > -1$
16:00–16:25	Takahiko Matsubara	Statistics of tensor fields in observational cosmology and nonlinear perturbation theory
16:25–16:40	Jingjing Shi	Galaxy Intrinsic Shape - Challenge and Opportunity
16:40–16:55	Yuting Liu	Hubble constant from the cluster-lensed quasar system SDSS J1004+4112: investigation of the lens model dependence
16:55–17:20	Shun Saito	Prospects from Emission-Line Galaxy Redshift Surveys

November 1 (Wed)

Protoplanetary Disks (chair: Hiroto Mitani)

9:00–9:25	Nami Sakai	Protostellar disks formed in diverse chemical environments
9:25–9:50	Yuri Aikawa	Chemical and Physical Evoution of Protopalnetary Disks
9:50–10:05	Daisuke Takaishi	Formation of unipolar outflow and "protostellar rocket effect" in magnetized and turbulent molecular cloud cores
10:05–10:20	Masataka Aizawa	Revealing faint asymmetric structures in dust continuum emission of proto-planetary disks
10:20–10:35	Anton Feeney-Johansson	Studying the velocity and angular momentum structure of protostellar outflows in the eDisk survey
10:35–11:00	Coffee	

Observations and Modellings of Exoplanets (chair: Konstantin Batygin)

11:00–11:25	Othman Benomar	Asteroseismology as a Tool to Probe Stellar Interiors and Its Contribution to Exoplanet Science
11:25–11:40	Teruyuki Hirano	Chromatic Measurements of RadialVelocity Jitter
11:40–11:55	Shin'ichirou Yoshida	Numerical modeling of rapidly rotating brown dwarfs
11:55–12:10	Hiroto Mitani	Atmospheric escape of hot Jupiters
12:10–12:35	Hajime Kawahara	Initiatives at ISAS for Exploring Habitable Worlds
12:35–14:00	Lunch	

Dynamics of Few-Body and Many-Body Systems (chair: Kenta Hotokezaka)

14:00–14:25	Konstantin Batygin	The Planet 9 hypothesis: a status update
14:25–14:40	Kento Masuda	A planet-planet eclipse in the Kepler-51 system?
14:40–15:05	Alessandro Trani	Three-body encounters in black hole discs around a supermassive black hole
15:05–15:20	Toshinori Hayashi	Constraining the binarity of dark companions in Gaia BH1 and Gaia BH2
15:20–15:35	Hideki Asada	Relativistic three-body problem
15:35–16:25	Yasushi Suto	from N to 3
18:00	Conference banquet	

November 2 (Thu)
Astrophysics of Galaxies and Galaxy Clusters (chair: Erik Reese)

9:30–9:55	Noriko Yamasaki	Understanding the soft-X-ray sky
9:55–10:20	Tetsu Kitayama	High-resolution measurements of the Sunyaev-Zel'dovich effect toward galaxy clusters
10:20–10:45	Sebastien Peirani	BH spin and galaxy orientation from new horizon simulations
10:45–11:00	Kazuya Takahashi	Imaging jet structures with gamma-ray burst afterglows
10:00–11:15	Hiroki Kawai	Analytical model for the statistics of ultra-high magnification events
11:15–11:30	Kenneth Wong	A Measurement of the Hubble Constant from Lensed Quasars
11:30–11:55	Kazuo Makishima	The Missing Last Piece in Understanding the Cluster Evolution
11:55–12:15	Naoki Yoshida & Yasushi Suto	Closing

4 RESCEU colloquia

- RESCEU Colloquium No. 60
  Tsvi Piran (Hebrew University of Jerusalem)
  “Tidal Disruption Events - a being is devoured by a black hole”
  February 19, 2024, 14:00-15:00

- RESCEU Colloquium No. 59
  Stephane Colombi (Institut Astrophysique de Paris/OAR)
  “Vlasov versus N-body”
  November 20, 2023, 14:30-16:00

- RESCEU Colloquium No. 58
  Alfredo Luminari (INAF IAPS/OAR)
  “Time-Evolving Photoionisation in the XRISM era”
  October 12, 2023, 13:00-14:00

- RESCEU Colloquium No. 57
  Ajit Kembhavi (Inter-University Center for Astronomy and Astrophysics)
  “Artificial Intelligence and Machine Learning in Astronomy”
  September 28, 2023, 13:00-14:00

II

Reports
on the research activities
of each project in 2023

5 Project 1. Evolution of the Universe and cosmic structures

5.1 Activity Report

5.1.1 Quantum aspects of inflationary cosmology

We have been working on higher-order quantum corrections to the curvature perturbation spectrum generated during inflation. We have also studied reheating after R^2 inflation in the presence of heavy Majorana neutrinos to explain the origin of radiation and baryon asymmetry simultaneously through leptogenesis. (Yokoyama)

5.1.2 Chiral magnetohydrodynamics

To deal with magnetohydrodynamics in a fluid where the chirality of fermions is a relatively well-conserved quantity, it is necessary to use chiral magnetohydrodynamics, which incorporates chiral anomalies and the chiral magnetic effect. We discovered that in the early universe, under a large lepton flavor asymmetry, the chiral magnetic effect can amplify hypermagnetic fields, leading to a conversion into baryon number. This allowed us to establish an upper limit on the lepton flavor asymmetry in the early Universe. Motivated by axion inflation, we also studied the chiral magnetohydrodynamics numerically with initial conditions where the magnetic helicity of fermions cancels out. We found that the annihilation of chirality and magnetic helicity progresses as a power function of time, which can be explained by the conservation of a quantity known as the Hosking integral. This implies that the possibility of baryon number generation during axion inflation being disrupted by such annihilation is reduced. (Kamada and Yokoyama)

5.1.3 Higgs inflation in the Einstein-Cartan formalism

We studied the behavior of an inflation model at the high-energy scales where the Standard Model Higgs drives inflation in the Einstein-Cartan formalism, where the metric and Palatini formulations can be smoothly connected by adding the Nieh-Yan term. We found that when the Nieh-Yan term is sufficiently small, the behavior of the theory nearly matches that of the Palatini formulation. We also showed that quantum effects lead to the emergence of an R^2 term below the cutoff scale only on the case closer to the metric formulation, ensuring the theory's consistency. (Kamada)

¥subsectionAstrophysical transients: their origins and consequences The following topics were studied in this project. ¥beginitemize ¥item Optical emission immediately after binary neutron star mergers (Shigeyama) ¥item Observations of the early light from type Ia supernovae (Shigeyama, Doi) ¥item Dynamical model of supernova SN 1181 as a result of binary white dwarf mergers (Ko, Shigeyama, Bamba) ¥item Emission of type IIn supernovae (Shigeyama, Takei) ¥item Eruptive mass loss from a massive star a few years before the core collapse (Shigeyama, Takei, Ko) ¥item Nuclear burning flash at later evolutionary phases of massive stars (Shigeyama, Hasegawa) ¥item Influence of nuclear burning on the accretion of Helium rich matter onto a neutron star (Shigeyama) ¥item Influence of supernova fallback on newborn neutron star magnetospheres (Shigeyama, Zhong) ¥enditemize Here the names of researchers at RESCEU are listed in the parentheses.

5.1.4 Statistical Computational Cosmology

Cosmology with ongoing and future wide-field galaxy surveys demands accurate theoretical prediction for statistics of clustering of galaxies and dark matter. We devised a neural network emulator for real-space galaxy clustering trained on data extracted from the DARK QUEST suite of N-body simulations. The emulator achieves sub-percent accuracies at mega-parsec scales, and thus can be readily used to interpret data from future surveys. We combine the emulator with a galaxy-halo connection model to predict the galaxy correlation function through the halo model. We continue working on signal extraction from future line intensity mapping observations. We explore applications of modern generative models, high-order statistics such as void probability function and minimum spanning tree. We contribute the Japan-Netherland project TIFUUN through development of data analysis methods and generating realistic mock catalogues using cosmological simulations. (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)

¥subsectionHigh redshift galaxies

With an X-ray stacking analysis of $\simeq 12,000$ Lyman-break galaxies (LBGs) using the Chandra Legacy Survey image, we investigate average supermassive black hole (SMBH) accretion properties of star-forming galaxies (SFGs) at $4 \lesssim z \lesssim 7$. Although no X-ray signal is detected in any stacked image, we obtain strong 3σ upper limits for the average black hole accretion rate (BHAR) as a function of star formation rate (SFR). At $z \sim 4$ (5) where the stacked image is deeper, the 3σ BHAR upper limits per SFR are ~ 1.5 (1.0) dex lower than the local black hole-to-stellar mass ratio, indicating that the SMBHs of SFGs in the inactive (BHAR $\lesssim 1 M_\odot$ yr^{-1}) phase are growing much more slowly than expected from simultaneous evolution. We obtain a similar result for BHAR per dark halo accretion rate. QSOs from the literature are found to have ~ 1 dex higher SFRs and $\gtrsim 2$ dex higher BHARs than LBGs with the same dark halo mass. We also make a similar comparison for dusty starburst galaxies and quiescent galaxies from the literature. A duty-cycle corrected analysis shows that for a given dark halo, the SMBH mass increase in the QSO phase dominates over that in the much longer inactive phase. Finally, a comparison with the TNG300, TNG100, SIMBA100, and EAGLE100 simulations finds that they overshoot our BHAR upper limits by $\lesssim 1.5$ dex, possibly implying that simulated SMBHs are too massive. (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)

5.1.6 High redshift quasars

The correlation between the stellar mass of galaxies and the mass of supermassive black holes (SMBHs) is known as co-evolution Since both galaxy and SMBH masses are related to the mass of the dark matter halo (DMH), it is important to constrain the DMH mass of quasars at high redshifts in order to understand the co-evolution. Clustering analysis is commonly used to estimate the DMH masses of objects, but has so far been limited to the analysis for $z < 4$ because the number density of quasars decreases rapidly at high redshifts. The HSC-SSP, a large-scale survey utilizing the wide field of view and high sensitivity of the HSC, has produced deep imaging data covering about 1200 square degrees, and the Subaru High-z Exploration of Low-Luminosity quasars (SHELLQs) has discovered 162 new quasars so far by efficiently selecting low-luminosity quasars at $z \sim 6$ using Bayesian statistics and spectroscopic follow-up observations. The number density of high-redshift quasars has been dramatically increased by detecting fainter quasars than ever before. We have performed a clustering analysis of quasars at $z \sim 6$ using quasars detected by SHELLQs and bright quasars detected by SDSS and Pan-STARRS in the HSC-SSP region. In this study, we selected 107 quasars considering the uniformity of the sample, and discussed the typical DMH masses of these quasars. As a result of the clustering analysis, we obtained $M_{halo} = 5.0^{+7.4}_{-4.0} \times 10^12 h^{-1} M_\odot$ as a typical DMH mass of quasar at $z \sim 6$. The mass corresponds to the most massive halo at the time, and its mass evolution by the extended Press-Schechter theory shows that it grows to a mass of $2 \times 10^{14} h^{-1} M_\odot$ at $z = 0$, which is equivalent to the DMH of a galaxy cluster. Furthermore, a comparison with a previous study in which clustering analysis was performed for quasars at $z < 4$ shows that the DMH mass of quasars is almost independent of redshift and is typically distributed in the range of $10^{12-13} h^{-1} M_\odot$. Although a tendency that the quasar DMH masses are independent of redshift had been pointed out for $z < 4$ before, this study reveals, for the first time, that this tendency continues up to $z \sim 6$. This result suggests that the SMBHs require high mass DMHs to accrete enough gas and stars to the accretion disk in order to shine brightly as quasars, while the feedback from the quasar becomes stronger when the DMH mass becomes too large, which prevents the accretion. The results suggest that this mechanism is universally active in all epochs. (Kashikawa)

5.1.7 Dust-enshrouded growth of galaxies and supermassive blackholes

By exploiting the ALMA Lensing Cluster Survey (ALCS), which observed 33 lensing cluster fields at 1.2 mm, we discovered a triply imaged X-ray active galactic nucleus (AGN) at $z = 2.063 \pm 0.005$ lensed by the galaxy cluster MACS J0035.4-2015 ($z = 0.352$)[55]. A stacking analysis of galaxies in cluster fields has been made to investigate the difference of dust properties between galaxies in fields and biased regions[49]. (Kohno)

Dusty star-forming galaxies (DSFGs) are among the most massive and active star-forming galaxies during the cosmic noon. Theoretical studies have proposed various formation mechanisms of DSFGs, including major merger-driven starbursts and secular star-forming disks. Here, we report J0107a, a bright ($\sim$8 mJy at observed-frame 890 μm) DSFG at $z = 2.467$ that appears to be a gas-rich massive disk and might be an extreme case of the secular disk scenario. J0107a has a large stellar mass of 5×10^{11} $M_\odot$ with a large molecular gas mass reservoir $\sim 10^{11}$ $M_\odot$, and an elevated star formation rate of ~ 500 $M_\odot$ yr^{-1}. J0107a does not have a gas-rich companion. The rest-frame 1.28 μm JWST NIRCam image of J0107a shows a grand-design spiral with a prominent stellar bar extending $\sim$15 kpc. The Atacama Large Millimeter/submillimeter Array Band-7 continuum map reveals that the dust emission originates from both the central starburst and the stellar bar. 3D disk modeling of the CO(4-3) emission line indicates a dynamically cold disk with rotation-to-dispersion ratio $V_{\rm max}/\sigma \sim$8. The results suggest a bright DSFG may have a non-merger origin, which is in contrast to a classical SMG formation scenario, and its vigorous star formation may be triggered by the bar and/or rapid gas inflow[50]. (Kohno)

We are leading the international joint development of new millimeter and submillimeter wave spectroscopic devices such as DESHIMA2.0 and its development into a three-dimensional imaging spectrograph, TIFUUN, planning their deployment on Atacama Submillimeter Telescope Experiment (ASTE) in Chile. Based on these new technological developments, we are planning to search for high-redshift dusty starburst galaxies and dust-enshrouded growing super-massive black holes. We are also planning to extract information from less-massive galaxies that have been overlooked by existing telescopes like ALMA, using the sub/millimeter-wave line intensity mapping (LIM) technique, with coordinated theoretical and data-scientific studies of LIM. (Kohno, Moriwaki, Yoshida)

5.1.8 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 environment of efficient acceleration sites in supernova remnant (SNR) systems. We have made detailed spatially resolved spectroscopy of SNRs, HESS J1534-571 and Kepler. We found that there is no enhancement of synchrotron X-rays due to the shock-cloud interaction in both targets [94, 96].

We also study on the detector development for the near future missions. We succeeded to launch the XRISM satellite on Sep. 7, 2023. The satellite is safely operated and made the first light on December 2023, and started the performance verification observations. We expect new results will be published in the next year.

The GRAMS mission, a new MeV gamma-ray mission, we succeeded the balloon Engineering Demonstration Experiment on July 2023. Everything went smoothly and we achieved the safe usage of the Liquid argon detectors at the balloon hight.

We also develop the small satellite mission ipher which aims to detect the polarization of hard X-rays. We utilize the CMOS sensor as the main detector. In order to measure the polarization, we need small pixel size CMOS sensors. With the beam experiment at SPring-8, we successfully demonstrated that 1.5 μm pixel size CMOS sensors have better sensitivity for X-ray polarization than 2.5 μm pixel ones.

5.1.9 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 Simons Observatory experiment has celebrated the first light in 2023. We deployed and started observations with two of the three 0.4-m Small Aperture Telescopes (SATs), which are dedicated for exploring inflationary signature, with the third starting in 2024. Also starting observation in 2024 is 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. We have been the primary contributor of these subsystems in on-site commissioning and data analysis to validate and characterise them. We also played a crucial role in the area of data analysis pipeline to extract scientific result such as the CMB power spectrum.

In achieving the goals enumerated above, we made significant progress in research and development of new instruments. We summarized several of these R&D as journal publications, including the wiregrid calibrator, anti-reflection coating, and the optical and mechanical elements of the cryogenic half-wave plate. We apply some of our microwave experimental technique outside the CMB observation; for example, we develop a concept of light dark-matter search experiment using a magnon-cavity hybrid system.

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 have recntly conducted a re-analysis of the calibration data observing crab nebula daily, and conducted a new time-domain data analysis of the POLARBEAR datasets for searching the Axion-like particle (ALP). For Simons Array experiment, science observations are conducted with the first and second telescopes. (Kusaka, Kiuchi, Takeuchi)

5.1.10 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)

5.1.11 Statistical study on repeating fast radio bursts in comparison with earthquakes and solar flares

The production mechanism of repeating fast radio bursts (FRBs) is still a mystery, and correlations between burst occurrence times and energies may provide important clues to elucidate it. While time correlation studies of FRBs have been mainly performed using wait time distributions, here we report the results of a correlation function analysis of repeating FRBs in the 2D space of time and energy. We analysed nearly 7,000 bursts reported in the literature for the three most active sources of FRB 20121102A, 20201124A, and 20220912A, and found the following characteristics that are universal in the three sources. A clear power-law signal of the correlation function is seen, extending to the typical burst duration (10 msec) towards shorter time intervals (Δt). The correlation function indicates that every single burst has about a 10–60 per cent chance of producing an aftershock at a rate decaying by a power law as $\propto (\Delta t) - -p$ with $p = 1.5$–2.5, like the Omori-Utsu law of earthquakes. The correlated aftershock rate is stable regardless of source activity changes, and there is no correlation between emitted energy and Δt. We demonstrate that all these properties are quantitatively common to earthquakes, but different from solar flares in many aspects, by applying the same analysis method for the data on these phenomena. These results suggest that repeater FRBs are a phenomenon in which energy stored in rigid neutron star crusts is released by seismic activity. This may provide a new opportunity for future studies to explore the physical properties of the neutron star crust. (Totani)

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5.2.1 international conferences

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[2] S. Arai, H. Odaka, K. Hagino, A. Bamba, "Understanding nucleosynthesis by Gamma-Ray and AntiMatter Survey (GRAMS)", The 1st IReNA-Ukakuren Joint Workshop Advancing Professional Development in Nuclear Astrophysics and Beyond・ NAOJ, 2023, August 28-September 1 (poster)

[3] M. Ichihashi, T. Kasuga, H. Odaka, A. Bamba, Y. Kato, S. Katsuda, H. Suzuki, K. Nakazawa, "The evaluation of injection energy to cosmic rays from the gradient of electron temperature near the shock", the 38th International Cosmic Ray Conference 2023, Nagoya, 2023, July 26Aug 3 (poster)

[4] M. Ichihashi, M. Sawada, A. Bamba, K. Hagino, "Post-shock temperature equilibrationto be revealed by spatially resolved spectroscopy of SN 1006 with XRISM/Resolve", The 2nd XRISM Community Workshop, Maryland, 2024, January 17 - 19 (oral)

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[12] K. Tsuge, Y. Fukui, K. Higashino, K. Tokuda, T. Onishi, H. Sano, A. Konishi, K. Tachihara, R. Yamada, K. Muraoka, T. Wong, M. Sewilo, R. Chen, S. Madden, R. Indebetouw, T. Inoue, M. Sasaki, A. Kawamura, V. Lebouteiller, M. Meixner, T. Minamidani, N. Mizuno, O. Nayak, A. Nishimura, K. Saigo,S. Zahorecz,"Massive star formation scenario in the LMC probed by the ALMA ACA Molecular Cloud Survey", "Protostars and Planets VII", kyoto, 2023, April 10–15 (poster)

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5.3 International Conference Talks

5.3.1 Contributed talks

[15] J. Yokoyama, "Developing a New Nonlinear Independent Component Analysis Scheme," 10th KAGRA International Workshop, 2023/5/29 National Tsing Hua University, 2023/8.

[16] J. Yokoyama, "Developing a New Nonlinear Independent Component Analysis Scheme," ICRC 2023 Nagoya University, 2023/8.

[17] K. Kamada, " Baryon (over)production from large lepton flavor asymmetry", PLANCK 2023, 2023/5/25.

[18] Akihiro Suzuki, "Early electromagnetic signals from supernova associated with GRBs", 2024/2/2, Transients down under, Swinburne institute of Technology

[19] Takatoshi Ko, "A dynamical model for IRAS 00500+6713: the remnant of a type Iax supernova SN1181 hosting a double degenerate merger product WD J005311", 2023/7, 3,2,1: Massive Triples, Binaries and Mergers 2023, Leuven

[20] Takatoshi Ko, "A dynamical model for IRAS 00500+6713: the remnant of a type Iax supernova SN1181 hosting a double degenerate merger product WD J005311", 2023/8, 2023 Asia-Pacific Regional IAU Meeting (APRIM 2023), Koriyama

[21] Takatoshi Ko, "The newest unidentified historical supernova SN 1181 with a peculiar white dwarf", 2023/9, Riken Summer School 2023, Wako

[22] Takatoshi Ko, "The newest unidentified historical supernova SN 1181 with a peculiar white dwarf", 2024/2, East Asian Young Astronomers Meeting 2024 (EAYAM2024), Chiang Mai

[23] K. Moriwaki "Deep learning for line intensity mapping: reconstruction of the large-scale structure of the universe " , Astro AI with Fugaku, Tsukuba University (September 2023)

[24] Kei Ito, "A JWST view of the morphology of quiescent galaxies at $z \geq 3$", Resolving Universe, Japan, November 2023

[25] Kei Ito, "Protocluster of Quiescent Galaxies at $z = 2.77$ in the COSMOS field", A journey through galactic environments, Italy, September 2023

[26] Kei Ito, "Galaxy Evolution at the Cosmic Noon with Euclid and H20 survey", Subaru in the era of Euclid, Japan, September 2023

[27] Kei Ito, "Discovery of a protocluster of quiescent galaxies at z = 2.77 in the COSMOS field", GALAXY TRANSFORMATION ACROSS SPACE AND TIME, Australia, September 2023

[28] Kei Ito, "Discovery of a Protocluster of Quiescent Galaxies at z = 2.77", COSMOS 2023 team meeting, USA, May 2023

[29] M. Ando, K. Shimasaku, K. Ito, "Anisotropic quenching...", Journey through Cosmic Environment, Italy, September, 2023

[30] Suin Matsui, Kazuhiro Shimasaku, Kei Ito, Makoto Ando, Takumi S.Tanaka, "The average SMBH accretion properties of star-forming galaxies and their cosmic evolution over $4 \lesssim z \lesssim 7$", HSC-AGN collaboration meeting 2023, Ehime, 11 2023

[31] Tanaka, T. S., Shimasaku, K. et al.: “Image-based deep anomaly detection using Subaru Hyper Suprime-Cam data” The CD3 x Simons Foundation workshop “AI-driven discovery in physics and astrophysics”, Japan, Jan. 2024

[32] K. Kohno, “The Large Submillimeter Telescope: Overview and revised requirements for science cases”, URSI General Assembly and Scientific Symposium 2023, Sapporo, Japan, 2023/08/19–26

[33] T. Totani, “Fast radio bursts trigger aftershocks resembling earthquakes, but not solars”, Observations and theories of neutron stars, Kyoto, 2023/9/7-8

[34] T. Totani, “Fast radio bursts trigger aftershocks resembling earthquakes, but not solars”, Conference “Fast Radio Bursts 2023”, online, Nov. 7-10, 2023

5.3.2 Invited talks

[15] J. Yokoyama, “Closing remarks,” KAGRA International Workshop 10, 2023/5/30, National Tsing Hua University.

[16] J. Yokoyama, “Status of KAGRA,” Siam Physics Congress 2023, 2023/6/15, Chengmai.

[17] J. Yokoyama, “Inflation, Primordial Black Holes, and Gravitational Wave Background,” Gravitational Wave Probes of Physics Beyond Standard Model, 2023/11/6 Osaka Metropolitan University.

[18] J. Yokoyama, “Primordial Black Holes from Single-field Inflation?,” Future Perspectives on PBHs 2023/12/12 Rome

[19] J. Yokoyama, “Primordial Black Holes from Single-field Inflation?,” IBS CTPU-CGA 2024 Workshop on (Primordial) Black Holes and Gravitational Waves 2024/3/18

[20] Akihiro Suzuki, “Radiation-hydrodynamic simulations of supernovae and project ideas with LUMI supercomputer”, 2023/11/21, 2nd Finland-Japan bilateral meeting on extra-galactic transients, Tuorla observatory, Finland

[21] Takatoshi Ko, “Introduction of SNR 1181 and a massive white dwarf in its center”, 2023/7, One Day Meeting with Prof. Roger Blandford, Wako

[22] K. Moriwaki, ”Galaxy formation with cosmological simulation and machine learning”, NECO Summer School, Kyoto University (September 2023)

[23] K. Moriwaki, ”Deep learning application to large-scale structure of the universe traced by line intensity”, The 14th RESCEU Symposium, From Large to Small Structures in the Universe, the University of Tokyo (October 2023)

[24] K. Moriwaki, ”Reconstruction of the Large-Scale Structure of the Universe with Conditional GAN”, AI-driven discovery in physics and astrophysics, the University of Tokyo (January 2024)

[25] K. Moriwaki, ”Machine Learning in Cosmology and Astrophysics”, Third Mini-Workshop on the Early Universe, Ishigaki (February 2024)

[26] Naoki Yoshida: ”Formation of the First Stars and Galaxies”, Neutral Hydrogen as a Cosmological Probe Across Cosmic Time (Nazareth, Israel, May 15, 2023)

[27] Naoki Yoshida: “Putting the Universe in a computer”, From Large to Small Structures in the Universe (University of Tokyo, Tokyo, October 31, 2023)

[28] Naoki Yoshida: “Small-scale density fluctuations and early structure formation”, Multi-Messenger Astronomy - Bridging Transients, Lensing, and Dark Matter (The Chinese University of Hong Kong, China, November 9, 2023)

[29] Naoki Yoshida: “Simulating Cosmic Structure Formation”, International Symposium on Cosmology and Particle Astrophysics (Hong Kong SAR, China, November 12, 2023)

[30] Naoki Yoshida, Masahiro Takada, Masashi Chiba: “Subaru Prime Focus Spectrograph”, 4MOST Science Meeting (Uppsala University, Sweden, February 12, 2024)

[31] K. Kohno, “Investigating the Physical and Chemical Properties of Dust-Enshrouded High-redshift Galaxies Via the Help of Gravitational Lensing” (invited), Kavli-IAU Astrochemistry Symposium, Astrochemistry VIII - From the First Galaxies to the Formation of Habitable Worlds, Traverse City, MI, USA, 2023/07/10–14

[32] K. Kohno, “The Large Submillimeter Telescope (Project overview)” (invited), One-day workshop on structural engineering for sub/millimeter telescopes, Nagoya University, Japan, 2023/08/28

[33] K. Kohno, “Radio to infrared observations with synergies between UNAM and U. Tokyo” (invited), 3rd International Colloquium of Mexican and Japanese Studies: Global Challenges and Divided Societies, University of Tokyo, Komaba, Japan, 2023/09/26-28

[34] K. Kohno, “Key science questions in the next decade and roles of radio, sub/mm, and far-IR observations” (invited), Kavli-IAU Workshop on Global Coordination Probing the Universe From Far-infrared to Millimeter Wavelengths: Future Facilities and their Synergies, Caltech, Pasadena, USA, 2024/03/26–28

[35] A. Bamba, Spectral break of energetic pulsar wind nebulae detected with wideband X-ray observations WN/PeVatron workshop・ Columbia U./online, 2023, July 18-20 (invited)

[36] Tomonori Totani, “Emergence of life in an inflationary universe”, International Symposium on Advanced and Sustainable Science and Technology College of Science, National Chung Hsing University, Taiwan, September 11-13, 2023

[37] Tomonori Totani, “A new “ messenger ” of extrasolar biosignatures / FRBs trigger aftershocks resembling earthquakes ”, Annual Meeting on Multi Messenger Astrophysics, Gero, Gifu, 2023/12/4-5

[38] Tomonori Totani, “Statistical properties of repeating FRBs, in comparison with earthquakes and solars”, The 32nd Texas Symposium on Relativistic Astrophysics, Shanghai, China Dec. 11-15, 2023

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 [2].

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 [1].

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 [17].

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 [19].

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 [2]. 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 [16, 18]. 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).

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[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).

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[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).

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

Analysis of asteroid Ryugu's samples brought back to the Earth by JAXA's Hayabusa2 progressed throughout 2023. Our participation in curation and initial analysis activities of Ryugu samples continued. Furthermore, we developed a new and improved optical measurement systems for the upcoming curation of Bennu samples, which will be delivered from NASA to JAX in 2024. We also participated in Bennu sample measurement activities in the NASA OSIRIS-REx project team. These activities have revealed many important properties of asteroids Ryugu and Bennu. One important finding is on the space weathering processes of Ryugu and Bennu surface materials [1] [2] [7]. Although Ryugu and Bennu share many similar properties, such as low density (∼1.2 g/cc), extremely low albedo (∼0.04), flat spectra without clear 0.7 um absorption feature, low thermal inertia (∼300 J m^{-2} $s^{-0.5}$ K^{-1}), and high boulder abundance, they have been known to have opposite direction of space weathering. More specifically, Ryugu material reddens and darkens with age, and Bennu material blues and brightens with age. Such opposite spectral evolution would play an important role in expanding the spectral variety among C-complex asteroids. Our new analyses have shown that the evolution tracks of the two asteroids follow the single line with a kink in the reflectance-spectral slope space. Such coincidence in evolution track would strongly support that the color change in surface materials on two asteroids is controlled by the same common mechanism. This would be rather inconsistent with two different processes and events on the two asteroids. Although the exact mechanism has not been identified, our analysis show that grain size change on two asteroids would be able to account for the observed spectral changes on the two asteroids.

We also conducted a number of new analyses of Hayabusa2 data obtained both during proximity operation around asteroid Ryugu and after departing from it. One outcome is about distribution of fractures on boulders on Ryugu. Our analysis revealed that boulder fractures are consistent with thermal fatigues caused by diurnal temperature change caused by asteroid spin [3] [9]. Another is observation of dependence of zodiacal light on the distance from the Sun. Continuous measurement in zodiacal light as the Hayabusa2 spacecraft changes its distance r from the Sun, we could detect zodiacal light changes quantitatively. Our new observation allows us to estimate that dust number density is proportional to $r^{1.54\pm0.08}$ [10]. This dependence is lower than the measurements by dust counting in the past.

7.2 Publication List

[1] Yumoto, K., Tatsumi, E., Kouyama, T., Golish, D. R., Cho, Y., Morota, T., ... & Sugita, S. (2024). "Comparison of optical spectra between asteroids Ryugu and Bennu: I. Cross calibration between Hayabusa2/ONC-T and OSIRIS-REx/MapCam". Icarus, 417, 116122.

[2] Yumoto, K., Tatsumi, E., Kouyama, T., Golish, D. R., Cho, Y., Morota, T., ... & Sugita, S. (2024). "Comparison of optical spectra between asteroids Ryugu and Bennu: II. High-precision analysis for space weathering trends". Icarus, 420, 116204.

[3] Schirner, L., Otto, K. A., Delbo, M., Matz, K. D., Sasaki, S., & Sugita, S. (2024). "Aligned fractures on asteroid Ryugu as an indicator of thermal fracturing". Astronomy & Astrophysics, 684, A5.

[4] Mori, S., Cho, Y., Tabata, H., Yumoto, K., B 旦 ttger, U., Buder, M., ... & Sugita, S. (2024). "Fraunhofer line-based wavelength-calibration method without calibration targets for planetary lander instruments". Planetary and Space Science, 240, 105835.

[5] Nishiyama, G., Morota, T., Namiki, N., Inoue, K., & Sugita, S. (2023). “Lunar Low-Titanium Magmatism during Ancient Expansion inferred from Ejecta originating from Linear Gravity Anomalies”. J. Geophys. Res,. 29(10), e2023JE008034.

[6] Nishimura, M., Nakato, A., Abe, M., Nagashima, K., Soejima, H., Yada, T., ... Sugita, S., Ito. M., Okada, T., Tachibana, S. & Usui, T. (2023). “Ryugu Sample Database System (RS-DBS) on the Data Archives and Transmission System (DARTS) by the JAXA curation. Earth, Planets and Space, 75(1), 131.

[7] Matsuoka, M., Kagawa, Ei., Amano, K., T. Nakamura, E. Tatsumi, T. Osawa, T. Hiroi, R. Milliken, D. Domingue, D. Takir, R. Brunetto, A. Barucci, K. Kitazato, S. Sugita, et al. (2023) “Space weathering acts strongly on the uppermost surface of Ryugu”. Commun Earth Environ 4, 335.

[8] Watanabe, S., Arakawa, M., Hirabayashi, M., Sugita, S., Bottke, W. F., Michel, P. (2023) “Exploration-Based Reconstruction of Planetesimals”, Protostars and Planets VII, 993-1029.

[9] Sasaki, S., S. Kanda, H. Kikuchi, T. Michikami, T. Morota, C. Honda, H. Miyamoto, R. Hemmi, S. Sugita, E. Tatsumi, M. Kanamaru, S. Watanabe, N. Namiki, P. Michel, M. Hirabayashi, N. Hirata, T. Nakamura, T. Noguchi, T. Hiroi, N. Sakatani, K. Matsumoto, H. Noda, S. Kameda, T. Kouyama, H. Suzuki, M. Yamada, R. Honda, Y. Cho, K. Yoshioka, M. Hayakawa, M. Matsuoka, R. Noguchi, H. Sawada, Y. Yokota, & M. Yoshikawa (2023), Crack Orientation of Boulders on Ryugu: Meridional Preference and Exfoliation, Journal of Evolving Space Activities 1, 89, pp. 1-7,

[10] Tsumura, K., Shuji Matsuura; Kei Sano; Takahiro Iwata; Kohji Takimoto; Manabu Yamada; Tomokatsu Morota; Toru Kouyama; Masahiko Hayakawa; Yasuhiro Yokota; Eri Tatsumi; Moe Matsuoka; Naoya Sakatani; Rie Honda; Shingo Kameda; Hidehiko Suzuki; Yuichiro Cho; Kazuo Yoshioka; Kazunori Ogawa; Kei Shirai; Hirotaka Sawada; Seiji Sugita (2023), Heliocentric Distance Dependence of Zodiacal Light Observed by Hayabusa2#, Earth, Planets and Space, 75:121

[11] Yumoto, K., Yuichiro Cho, Shingo Kameda, Satoshi Kasahara, Seiji Sugita, In-situ measurement of hydrogen on airless planetary bodies using laser-induced breakdown spectroscopy, Spectrochimica Acta Part B: Atomic Spectroscopy, 106696.

[12] Yumoto, K., Y. Cho, T. Koyaguchi, and S. Sugita (2023), Dynamics of gas-driven eruption on Ceres as a probe to its interior, Icarus,

[13] Clark, B. et al. (2023) Overview of the search for signs of space weathering on the low-albedo asteroid (101955) Bennu, Icarus,

III

Reports
on the research activities
of RESCEU groups in 2023
(in Japanese)

2023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。横山は 2021 年 9 月から 2023 年 9 月まで KAGRA 科学会議議長を、2023 年 4 月よりビッグバン宇宙国際研究センター長を務めていますが、同年 11 月よりカブリ数物連携宇宙研究機構長を併任することとなったため本務はそちらに移り、理学系研究科の業務は兼務教授として続けています。また鎌田助教は中国科学院杭州高等研究院に栄転し、神野特任助教は本年度末を以て神戸大学准教授に栄転しました。

8.1.1 宇宙論: 時空構造

アインシュタイン・カルタン形式のインフレーション

我々はアインシュタイン・カルタン形式においては Nieh-Yan 項を加えることによって計量形式と Palatini 形式が滑らかに接続することに注目し、標準模型のヒッグス場にリッチスカラーとの結合を加えてインフレーションを実現する模型におけるカットオフスケールの振る舞いを評価した [6]。

またこの形式において $f(R)$ 理論は一般的に新たな自由度が存在しないと知られているが、Nieh-Yan 項および Holst 項を導入することにより、新たな自由度が出て、Starobinsky inflation およびその変形が実現できることを示した [49, 72]。

複数場インフレーション由来の B-mode シグナル

複数場インフレーション模型、特にスペクテーター模型においては、単一場インフレーション模型において成り立ついわゆる consistency 関係が成り立たなくなることが知られている。LiteBIRD による宇宙背景放射 (CMB) の B-mode 偏光の観測を通じて、原始テンソル揺らぎの振幅および波数依存性に対して成り立つ consistency 関係を精査することにより、複数場インフレーション模型の検証が可能であることを示した [7]。

連星系の post-Minkowskian 理論計算に対する機械学習の適用可能性

連星系の運動を解析する post-Minkowskian 理論の予言を確定させるには、そこに現れるファインマン積分を次元正則化パラメータ ε の展開として知る必要があるが、一定のループ次数以上においては積分自体の複雑さがボトルネックとなり、この展開を解析的に行うことが難しい。我々はそれを回避する方法として数値ブートストラップ法に注目し、ここに機械学習を用いたモンテカルロ積分のサンプリング手法である normalizing flow を適用する可能性を研究した [9]。

単一場インフレーション中の原始ブラックホール生成における 1-loop 補正

原始ブラックホール (PBH) の種となるような大振幅揺らぎがもたらす、宇宙背景放射 (CMB) の揺らぎに対する 1-loop 補正の研究を、昨年度に引き続いて推進した。以前はスローロールパラメータ η の時間変化が階段関数的であるようなインフレーション模型において 1-loop 補正を計算していたが、本年度はその時間変化が連続的であるような模型を考察した [43, 44, 45, 46, 59, 60]。

インフラトン振動期における原始ブラックホール生成

R^2 インフレーションモデルを代表とする数々のインフレーションモデルにおいて、インフラトン振動期中における原始ブラックホールの過剰生成が指摘されてきたが、我々は、その振動期中における非球対称性の効果が無視できないことに着目して、原始ブラックホールの生成が大きく抑制されることを示した [26, 54, 77]。

8.1.2 宇宙論: 物質の起源と進化

カイラル磁気流体力学

我々は高温の初期宇宙において大きなレプトンフレーバー非対称がある状況下ではカイラル磁気効果によりハイパー磁場の増幅が起こり、そこからバリオン数への転換が生じることを発見し、それにより初期宇宙におけるレプトンフレーバー非対称の上限を定めた [29, 84]。我々はまた、フェルミオンのカイラリティの磁気ヘリシティがちょうど打ち消し合うような初期条件を持つ系の発展を数値的に解き、カイラリティと磁気ヘリシティの対消滅は時間のべき関数で進み、それは Hosking integral という量の保存で説明できることを発見した [3, 5, 82, 83]。

軽いスレプトンの存在下での Affleck-Dine 機構

我々は量子効果と熱的効果を詳しく解析し、超対称性理論の Affleck-Dine 機構が適切に働き、現在の宇宙を実現するような条件を定めた [4]。

一次相転移と重力波生成

宇宙論的一次相転移で生じる重力波の数値計算の新たな手法である Higgsless scheme を提案した [31]。また、一次相転移が一時的なドメインウォール生成を伴う場合、ウォールができない場合と比べて流体の運動が重力波生成を引き起こしやすいことを、3 次元数値シミュレーションの結果とともに指摘した [8]。他にも、相転移に伴って相互作用の弱い粒子が生成される場合があるが、その際の重力波シグナルが特徴的なものになることを指摘した [32, 33, 34]。

渦上のニュートリノゼロモードとトポロジカル不変量

物性理論で用いられる、運動量空間におけるトポロジカル不変量を用いて、Z-string の安定性をより現代的な方法で理解・検証した [67]。

Axion inflation 中の粒子生成による反作用

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。荷電粒子が存在する場合は荷電粒子生成によるゲージ場への反作用 [87] を考慮する必要がある一方、それらが存在しない場合は成長したゲージ場からインフラトンへの反作用が問題となる。我々はこの後者の場合に生成するインフラトン揺らぎの性質を明らかにするため、確率形式のアプローチを開発している [35]。

重力外場によるフェルミオンのカイラリティ生成

一般にフェルミオンのカイラリティには、励起された “粒子” が運ぶものと真空に蓄えられたものの 2 種類が存在しているが、左右非対称な円偏極の重力波の重力場背景のもとでは後者の寄与が卓越するであろう、というこれまでの現象論的研究では見過ごされていた新たな示唆を得た [89]。

初期磁場の時間発展とバリオン等曲率揺らぎ生成問題

我々は、磁気流体力学の保存量 Hosking integral を考慮し、初期磁場の時間発展則を解析的に記述した。さらにこれを応用して、電弱対称性が回復した相における磁場生成シナリオが一般的に抱えるバリオン等曲率揺らぎ生成問題を、ボイド磁場に対する観測的制限と比較して議論した。その結果、ビッグバン元素合成との整合性により、ボイド磁場の起源としては電弱対称性が破れた相における磁場生成シナリオが有望であることが確かめられた [14, 24, 68, 69, 92, 93]。

無衝突ボルツマン方程式の量子アルゴリズム

我々は、量子アルゴリズムと古典計算の併用によって無衝突ボルツマン方程式を効率的に解く手法を二通りのアプローチで提案した [15, 90]。

複合ソリトン

アクシオン電磁気学において、磁場とアクシオン勾配の内積が実効電荷を生じる。われわれは、この実効電場によって安定化し得る解として、トフーフト=ポリャコフモノポールを球殻状のアクシオンドメインウォールが包むような配位の性質と宇宙論的な役割を調べている [39, 91]。

Stochastic inflation の相関関数

Borel 総和の手法を用いて相関関数の発散を処理し、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が存在しないことが示唆された [16, 25, 40, 41, 63, 95]。

インフレーション宇宙における確率選択現象

我々は制約付き確率過程の理論を拡張するとともに、場の配位空間で示される極稀な軌道を解析し、一見相反する理論と観測の隔たりに自然な説明を与えた。すなわち、複数場が存在する状況から出発しても、観測可能な宇宙では単一場による記述に帰着することを示した [1, 25, 42, 70, 94]。

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について、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たところ、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 [17]。

場の配位の鞍点解を計算する数値手法

初期宇宙の現象を考察するとき、場の配位の鞍点解が重要になる場合がある。場の配位の鞍点解の新しい数値手法を研究し、それを用いてバウンス解および sphaleron 解を解いた [18, 30, 47, 48, 66, 71]。

宇宙複屈折

宇宙マイクロ波背景放射 (CMB) の複屈折の重力レンズ効果を取り入れた精密計算結果を報告した [20]。開発された計算ツールによる計算結果と現行の観測結果との比較から、特定の初期暗黒エネルギーモデルに対する制限につながった [19]。

偏光面の回転角には位相不定性があることを考慮すると、物理的に許されるが見過ごされている解が大量にあることを見出した [53, 74]。宇宙複屈折の起源として着目されるアクシオン型粒子 (ALP) について、ポテンシャルを転がり落ちるケースで、宇宙複屈折のシグナルに違いが現れるかどうかを調べた [50, 51, 52, 75]。

インフレーション後の再加熱とバリオン数生成

R^2 インフレーション理論に三世代の重いマヨラナニュートリノを付け加えることで、バリオン非対称とニュートリノ振動実験を同時に説明することができる。マヨラナニュートリノの湯川結合行列の成分に階層性がある場合、マヨラナニュートリノ優勢期が実現することを示し、CMB 観測によるマヨラナニュートリノの探索の可能性を提示した。[26, 21, 76]

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

重力波検出器の感度向上のため、環境チャンネルのデータと重力波信号を含むストレインチャンネルのデータを併用し、それらの分布の非ガウス性を使って信号源を分離する独立成分解析に取り組んでいる。本年度は、変分原理を用いることにより、任意の非線形相互作用をする複数の信号を分離する方法の開発に成功した [22, 27, 28]。

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、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 [10, 88]。

軽量ダークマター探索

近年、干渉計を利用した軽量ダークマター探索実験が盛んになっている [62]。我々は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 [12]、新たに開発したパイプラインを用いて重力波検出器 KAGRA による初の B-L ゲージボゾン探索を執り行った [36, 38]。また、同パイプラインをアクシオン探索実験にも適用し、結合定数への上限値を導出した [11]。

KAGRA 全著者論文, LVK 論文

横山、粂、上野は KAGRA の著者となっています。今年度は LIGO-Virgo-KAGRA のものを含め、5 編の全著者論文を出版しましたが、そのリストは割愛します。

8.1.4 時間領域天文学

Tomo-e Gozen を用いた高空間分解観測

東京大学木曽観測所の 105 センチシュミット望遠鏡に搭載されている Tomo-e Gozen カメラの高い時間分解能を活用することで、高い空間分解を実現する観測をコミュニティに提案した [74]。

＜受賞＞

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(学位論文)

[24] F. Uchida, "Probing the Early Universe with the Evolution of Promordial Magnetic Fields", (博士論文).

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＜学術講演＞

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[79] R. Jinno, “First-order phase transitions and gravitational wave production in the early Universe,” Joint workshop on General Relativity and Cosmology, Chiba, 2024/3/6-8

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[87] Jun’ya Kume, “U(1) gauge field production in axion inflation -backreaction from charged particles-”, Institute for Basic Science, Center for Cosmology, Gravity and Astroparticle physics (CGA), Korea, May 2023.

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(アウトリーチ)

[100] 横山順一 「宇宙：始まりと終わり」 新島学園短期大学創立 40 周年記念講演会 高崎市文化センター 2023/10/14

9 Kipp Cannon研究室

9.1 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 space-time 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 with detectable amplitudes, and so observation of highly energetic astronomical phenomena provides our only opportunity to explore this aspect of the natural world.

Our research group's members are members of the 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. Currently, we are participating in the fourth observation "O4" by LIGO, Virgo, and KAGRA, which started in May 2023. In addition, various theoretical studies are needed to maximize the scientific results obtained from the data, and members of our group are active in almost all areas of the exploration of astronomy, cosmology, and fundamental physics with gravitational waves.

This year our group was joined by one new Master's student. Two of our Master's students graduated to the doctoral program, and one doctoral student graduated with her Ph.D. and has moved to a research scientist position with SPring8. Our postdoctoral fellow's term ended and he is moving to a research position at Tartu University.

9.1.1 Nuclear Physics with Gravitational Waves

Neutron Star Interiors

It is expected that at high enough densities, quarks become free particles and matter becomes a quark plasma. How the phase transition occurs is not known, although a number of possible models have been constructed. Determining which, if any, are correct, and what physical properties the plasma possess would teach us about the properties of quarks and other fundamental particles. It is possible that this phase transition occurs deep in the interior of neutron stars, and, if so, the gravitational waves emitted during the collisions of neutron stars will be affected by the presence of this material. Studying the gravitational waves observed from neutron star collisions is hoped to be able to reveal information about the phase transition to a quark plasma.

Our group recently completed an analysis of this phenomenon and concluded that the best observable is the duration of the post-collision signal, *i.e.*, the time delay from the stars' collision to the collapse of the debris to a black hole. This is in contrast to previous studies which focused on spectroscopy, testing for the presence of specific frequencies in the post-merger signal.

9.1.2 Testing General Relativity with Gravitational Waves

Compact Object Collisions in Alternative Gravity Theories

One challenge confronting people attempting to use observations of gravitational waves to constrain gravity theories is that only for General Relativity — the prevailing theory of gravity — have extensive theoretical and numerical studies of the behaviour of spacetime during compact object collisions been performed. Comparatively little is known about the waves produced by compact object collisions in alternate theories of gravity. The standard approach taken to using gravitational wave observations to test for evidence of non-General Relativity gravity is to introduce *ad hoc* parameterized perturbations to the waveform models, and use observed signals to constrain the value of the perturbation parameters. The difficulty with this is there is often no physical interpretation of the meaning of the perturbation parameters, it's not clear what the inferred constraints are constraining, and it's not understood if it is reasonable to imagine the parameters being varied independently.

Our group is engaged in an effort to translate combinations of perturbation parameters into physically meaningful quantities, for example a "non-conservation of energy" parameter. The goal is to allow, for example in that specific case, one to require that energy be conserved when varying the waveform perturbation parameters. This allows a more refined, careful, analysis of the observed waveforms to be performed and allows smaller departures from general relativity's predictions to be detected.

9.1.3 Cosmology with Gravitational Waves

Inferring the Hubble Parameter from Compact Object Collisions

Gravitational waves from compact object collisions can provide measurements of the Hubble parameter that are independent of the cosmic distance ladders derived from electromagnetic observations, and cosmological probes such as the cosmic microwave background, as demonstrated following the detection of GW170817. However, unlike the case of GW170817, most of the GW candidates observed so far do not have electromagnetic counterparts and thus their host galaxies cannot be identified, *i.e.*, their red-shift information cannot be obtained directly. In recent years, measurements of the Hubble parameter using multiple candidates of those have been made, relying on a galaxy catalogue, spacial and mass distribution of sources, or both. Those studies have typically used only significant events, for example events with a signal-to-noise-ratio of 11 or higher. While efforts have been made in the past to correct for the selection bias, it is expected that using a lower threshold in the event selection and utilizing all candidates detected by detection pipelines reduce the risk that a measurement of the Hubble parameter is affected by human-induced selection bias. Many of the sub-threshold candidates originate from non-Gaussian noise in detectors rather than from compact binary collisions, and they must be properly handled, which makes the analysis more complex. We have formulated an analysis technique that enables such appropriate handling of sub-threshold candidates by utilizing intermediate data products accumulated during the detection process of GWs. We plan to implement this method and analyze actual data obtained during the third observing run of the LIGO-Virgo-KAGRA Collaboration.

9.1.4 Multi-Messenger Astronomy

Triggered Search for Neutron Star Collisions via Long Duration Radio Transients

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) produces daily intensity maps of the sky covering the radio frequency band in which synchrotron radiation should be emitted from the debris of neutron star collisions. In this frequency band the debris from the explosion should exhibit a characteristic brightening and dimming lasting from weeks to months. Previous work has modelled the brightness vs. time curves for such transient radio sources, and we have previously studied the problem of detecting the presence of such a signal in CHIME data. In this past year we conducted the first investigation of the feasibility of such a search in real, rather than synthetic, daily CHIME intensity maps. This is still a work in progress, but we are hopeful that the final sensitivity will be similar to previously published theoretical estimates.

9.1.5 Expanding Compact Object Detection Parameter Space

Synthesizing Eccentric Merger Waveforms with Neural Networks

As mentioned above, searches for gravitational waves from compact object collisions rely on parametric models of the signals. These are constructed using fits to numerical simulations of spacetime and matter during a compact object collision. One weakness of the models that are currently available is their inability to simulate the signals from highly eccentric collisions. There exists eccentric waveform models, but they are slow, requiring integration of many simultaneous differential equations, and that makes it impractical to use such models for Monte Carlo parameter estimation algorithms, which need to evaluate enormous numbers of waveform models. Our group is in the process of experimenting with the use of neural networks to construct accurate eccentric waveform model predictions with comparatively little computational cost. The hope is this will allow tests for the presence of eccentricity in the analysis of future gravitational-wave detections.

9.1.6 Searching for Astrophysical Stochastic Gravitational Waves

Multiple Anisotropic Sources

It is expected that laser interferometric gravitational-wave detectors will detect the presence of an astrophysical stochastic gravitational-wave background in the near future. It is possible that this flux of gravitational waves is composed of multiple distinct components, for example components with different spectral indexes or components with different anisotropic distributions on the sky. Our group is studying the problem of detecting and interpreting such gravitational waves.

9.1.7 List of Achievements

< Awards, etc. >

- Harada, Reiko, JST Support for Pioneering Research Initiated by the Next Generation (SPRING), University of Tokyo "University of Tokyo 'Developing Advanced Human Resources to Lead the Green Transformation (SPRING GX)".
- Kwon, Seonjun, Korea Education Institute In Tokyo Scholarship.
- Garg, Suyog, Embassy?recommended MEXT Scholarship 2023 for doctoral studies at The University of Tokyo.

< Report >

(Refereed Publications)

[1] Abbott, R. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration and KAGRA Collaboration). Constraints on the cosmic expansion history from GWTC-3. *Astrophys. J.*, 949(2):76, Jun 2023. doi:10.3847/1538-4357/ac74bb.

[2] Abbott, R. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration and KAGRA Collaboration). GWTC-3: Compact binary coalescences observed by LIGO and Virgo during the second part of the third observing run. *Phys. Rev. X*, 13(4):041039, Dec 2023. doi:10.1103/PhysRevX.13.041039.

[3] Abbott, R. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration and KAGRA Collaboration). Open data from the third observing run of LIGO, Virgo, KAGRA and GEO. *Astrophys. J., Suppl. Ser.*, 267(2):29, Jul 2023. doi:10.3847/1538-4365/acdc9f.

[4] Abbott, R. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration and KAGRA Collaboration and CHIME/FRB Collaboration). Search for gravitational waves associated with fast radio bursts detected by CHIME/FRB during the LIGO-Virgo observing run O3a. *Astrophys. J.*, 955(2):155, Sep 2023. doi:10.3847/1538-4357/acd770.

[5] Abbott, R. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GWTC-2.1: Deep extended catalog of compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run. *Phys. Rev. D*, 109(2):022001, Jan 2024. doi:10.1103/PhysRevD.109.022001.

[6] Abbott, R. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration and KAGRA Collaboration). Search for gravitational-wave transients associated with magnetar bursts in Advanced LIGO and Advanced Virgo data from the third observing run. *Astrophys. J.*, 966(1):137, Apr 2024. doi:10.3847/1538-4357/ad27d3.

[7] Tanikawa, A. *et al.*. Search for a Black Hole Binary in Gaia DR3 Astrometric Binary Stars with Spectroscopic Data. *Astrophys. J.*, 946(2):79, Apr 2023. doi:10.3847/1538-4357/acbf36.

[8] Shikauchi, M. *et al.*. Spatial and Binary Parameter Distributions of Black Hole Binaries in the Milky Way Detectable with Gaia. *Astrophys. J.*, 953(1):52, Aug 2023. doi:10.3847/1538-4357/acd752.

[9] Tanikawa, A. *et al.*. Compact binary formation in open star clusters — I. High formation efficiency of Gaia BHs and their multiplicities. *Mon. Not. R. Astron. Soc.*, 527(2):4031–4039, Oct 2023. doi:10.1093/mnras/stad3294.

[10] S. Sasaoka, *et al.*, Deep Learning for Detecting Gravitational Waves from Compact Binary Coalescences and Its Visualization by Grad-CAM. In Proceedings of 38th International Cosmic Ray Conference – PoS(ICRC2023), volume 444, page 1498, 2023. doi:10.22323/1.444.1498

[11] S. Sasaoka, *et al.*, Deep Learning Application for Detecting Gravitational Waves from Core-Collapse

Supernovae. In Proceedings of 38th International Cosmic Ray Conference – PoS(ICRC2023), volume 444, page 1499, 2023. doi:10.22323/1.444.1499

[12] S. Garg, *et al.*, Comparison of training methods for Convolutional Neural Network model for Gravitational-Wave detection from Neutron Star − Black Hole Binaries. In Proceedings of 38th International Cosmic Ray Conference – PoS(ICRC2023), volume 444, page 1536, 2023. doi:10.22323/1.444.1536

[13] D. S. Dominguez, *et al.*, Convolutional neural network for continuous gravitational waves detection. In Proceedings of 38th International Cosmic Ray Conference – PoS(ICRC2023), volume 444, page 1519, 2023. doi:10.22323/1.444.1519

(Dissertations)

[14] Harada, R. On the Testability of the Quark-Hadron Phase Transition Using Gravitational Waves (Master's Thesis).

[15] Shikauchi, M. Prospects for Probing Black Hole Populations in the Milky Way with the Gaia Satellite (Doctoral Thesis).

< **Presentations** >

(International Conference)

Talks and Posters

[16] (poster) R. Harada, K. Cannon, Kenta Hotokezaka and Koutarou Kyutoku, "Examination of the Testability of the Hadron-Quark Phase Transition using Gravitational Waves", LIGO-Virgo-KAGRA Collaboration Meeting, Toyama, Japan, 2023/9/11–15.

[17] (contributed talk) R. Harada, K. Cannon, Kenta Hotokezaka and Koutarou Kyutoku, "On the Testability of the Hadron-Quark Phase Transition using Gravitational Waves", RESCEU Summer School 2023, Nagano, Japan, 2023/8/9–12.

[18] (poster) R. Harada, K. Cannon, Kenta Hotokezaka and Koutarou Kyutoku, "On the Testability of the Hadron-Quark Phase Transition using Gravitational Waves", GravityShapePisa 2023, Pisa, Italy, 2023/10/24–27.

[19] (poster) R. Harada and K. Cannon, "Estimation of the Hubble constant from compact object catalogues without threshold", LIGO-Virgo-KAGRA Collaboration Meeting, Baton Rouge, USA, 2024/3/11–14.

[20] (contributed talk) M. Shikauchi, "On the Coincident Detection of Short Gamma?ray Burst Afterglows with CHIME and LIGO/Virgo/KAGRA", The 1st Annual Conference, the creation of multi-messenger astronomy, 2023/12/4–6.

[21] (contributed poster) 今福 隼斗、「重力波観測で探る一般相対論を超えた偏光自由度」、53 回天文・天体物理学若手夏の学校、素粒子・重力・宇宙論分科会 a15、2023 年 8 月 1 日〜 8 月 4 日.

[22] (contributed talk) H. Imafuku, *et al.*, "Search for scalar polarization of gravitational waves", LIGO-Virgo-KAGRA collaboration meeting, 2023/9/11–14.

[23] (contributed poster) H. Imafuku, *et al.*, "Search for scalar polarization of gravitational waves from binary black hole", The 32th KAGRA Face-to-Face meeting, 2023/12/14–15.

[24] (contributed poster) H. Imafuku, *et al.*, "Search for scalar polarization of gravitational waves from binary black hole", Joint workshop on General Relativity and Cosmology, 20243/6–8.

[25] (contributed poster) H. Imafuku, *et al.*, "Search for scalar polarization of gravitational waves from binary black hole", LIGO-Virgo-KAGRA collaboration meetingy, 2023/9/11–15.

[26] (contributed poster) S. Garg, "Gravitational-Waves from Eccentric CBC Sources", LIGO-Virgo-KAGRA Meeting, 2024/03.

[27] (contributed poster) S. Garg, "Deep Convolutional Neural Network for detecting GW signals from Compact Binaries", Machine Learning for Physics workshop, 2023/11/

[28] (contributed poster) S. Garg, "Convolutional Neural Network for detecting GW signals from Compact Binaries", LIGO-Virgo-KAGRA Meeting, 2023/9.

[29] (contributed poster) S. Garg, "Convolutional Neural Network for detecting GW signals from Compact Binaries", International Cosmic Ray Conference, 2023/8.

[30] (contributed poster) S. Garg, "Convolutional Neural Network for detecting GW signals from Compact Binaries", KAGRA International Workshop, 2023/5.

[31] (contributed poster) S. Garg, "Convolutional Neural Network for detecting GW signals from Compact Binaries", Annual Conference on Multi Messenger Astrophysics, 2023/12.

(Domestic Conference)

Talks and Posters

[32] (contributed talk) P. Karmakar, "Testing Nonmetricity Cosmology", JGRG 2023, 2023/11/30.

[33] (contributed talk) S. Garg, "X-Ray Observations of ASASSN-14li", RESCEU-NBIA Workshop, 2023/12.

[34] (contributed talk) S. Garg, "Neural Network model for Gravitational-Wave detection from eccentric Compact Binary sources", RESCEU Symposium, 2023/10.

[35] (contributed talk) S. Garg, “Convolutional Neural Network model for Gravitational-Wave detection from eccentric Compact Binary sources”, RESCEU Summer School, 2023/8.

(Seminars)

[36] (seminar) P. Karmakar, “Testing Non-metricity Cosmology”, University of Tartu, 2023/12/12.

[37] (seminar) P. Karmakar, “Testing Non-metricity Cosmology”, University of Padova, 2023/12/19.

[38] (seminar) P. Karmakar, “Testing Non-metricity Cosmology”, 4th QGG Lecture Series, RIKEN, 2023/8/23.

9.2 Kenta Hotokezaka Group

9.2.1 Electromagnetic Counterparts of Neutron Star Mergers

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 [1, 2, 3, 5].

We develop a model for kilonova nebular emission, where the accurate line list is used. With this model, the synthetic spectra of the nebular emission of GW170817 are obtained. We compared them with the observed data taken by VLT X-Shooter and found that the strong spectral line at 2.1 micron is likely an emission line of doubly-ionized tellurium [1].

The second brightest gamma-ray burst, GRB 230307A, was discovered on March 7th, 2023. Despite the bright prompt emission, the afterglow of this burst is particularly faint. Moreover, the burst was localized in the outskirt of a relatively nearby galaxy, suggesting that the progenitor of this burst is a compact binary merger. We worked on the JWST follow-up observations for this event. We showed that a kilonova modeling explains observed data well and the spectroscopic data exhibit a distinct peak at 2.1 micron consistent with the tellurium emission line [5].

We worked on the afterglow emission of relativistic jets launched in mergers [4, 6]. We develop a numerical code to compute the radio flux and image of afterglows [11, 16, 17]. This code will be useful to constraint the structure of relativistic jets and viewing angle to jets.

9.2.2 Shock Breakout

Shock breakout is the first light from a supernova. Detecting the emission of shock breakout is of considerable interest, as it potentially provides important information about the progenitor star and its immediate circumstellar environment. We found a new regime of shock breakout, where the breakout is initially out-of thermal equilibrium and rapidly thermalized as time goes. We showed that many of the observed features of low-luminosity GRBs can be explained within this regime [9, 12, 13].

9.2.3 Supermassive Stars and Supermassive Black Holes

We studied the evolution of supermassive black holes using the luminosity function of high-redshift quasars [7]. Moreover, we performed a radiation hydrodynamic simulation to reveal the role of the radiation feedback for first star formation [8].

9.2.4 List of Achievements

< **Reports** >

(Refereed Publications)

[1] M. Tanaka, *et al.*, “Cerium Features in Kilonova Near-infrared Spectra: Implication from a Chemically Peculiar Star”, Astrophys. J., **953**, 17 (2023).

[2] N. Domoto, *et al.*, “Transition Probabilities of Near-infrared Ce III Lines from Stellar Spectra: Applications to Kilonovae”, Astrophys. J. **956**, 113 (2023).

[3] K. Hotokezaka, *et al.*, “Tellurium emission line in kilonova AT 2017gfo”, Monthly Notices of the Royal Astronomical Society, **526**, L155 (2023).

[4] M. Brightman, *et al.*, “The high energy X-ray probe (HEX-P): sensitive broadband X-ray observations of transient phenomena in the 2030s”, Frontiers in Astronomy and Space Sciences, **10**, 1292656 (2024).

[5] A. J. Levan, *et al.*, “Heavy-element production in a compact object merger observed by JWST”, Nature **626**, 8000 (2024).

[6] S. Bhattacharjee, *et al.*, “Joint gravitational wave-short GRB detection of binary neutron star mergers with existing and future facilities”, Monthly Notices of the Royal Astronomical Society, **528**, 4255 (2024).

[7] W/ Li, *et al.*, “The Assembly of Black Hole Mass and Luminosity Functions of High-redshift Quasars via Multiple Accretion Episodes”, Astrophys. J. **950**, 85 (2023).

[8] 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).

[9] C. Irwin, "Insights on the origin of low-luminosity GRBs from a revised shock breakout model for GRB 060218", AAS High Energy Astrophysics Division meeting No. 20, **55**, 117.09, (2023).

< **Talks** >

(Contributed)

[10] K. Takahashi, K. Hotokezaka & K. Ioka, "Imaging jet structures with gamma-ray burst afterglows", The 14th RESCEU International Symposium: From Large to Small Structures in the Universe, Tokyo, Japan, 30 Oct. — 2 Nov. 2023.

[11] C. Iarwin, "A Revised Shock Breakout Model for GRB 060218", GRB50, Virginia, August 2023.

[12] C. Irwin, "Insights on the Origin of Low-Luminosity GRBs", Transients Down Under, Melbourne, January 2024.

(Invited)

[13] K. Hotokezaka, "Kilonova Spectrum: Photospheric and Nebular phases", Multi-messenger Modeling of Neutron Star Mergers, May 8 — Jul 10, 2023, Princeton, USA.

[14] K. Hotokezaka, "Kilonova and Neutron Star Merger Plasma", The 14th International Colloquium on Atomic Spectra and Oscillator Strengths for Astrophysical and Laboratory Plasmas, Jul 10 — 14, 2023, Paris, France.

9.3 Affiliates — Atsushi Nishizawa

9.3.1 Circular Polarization of the Astrophysical Gravitational Wave Background

The circular polarization of gravitational waves is a powerful observable to test parity violation in gravity and to distinguish between the primordial or the astrophysical origin of the stochastic background. This property comes from the expected unpolarized nature of the homogeneous and isotropic astrophysical background, contrary to some specific cosmological sources that can produce a polarized background. However, we show that there is a non-negligible amount of circular polarization also in the astrophysical background, generated by Poisson fluctuations in the number of unresolved sources, which is present in the third-generation interferometers with signal-to-noise ratio larger than two [1].

Axion dark matter search with gravitational waves

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. Considering a realistic halo profile of dark matter in the Milky Way and searching for such distinctive gravitational wave signals, we have updated the constraints on the gravitational coupling constant of axions from that obtained with a uniform density profile [2].

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.

< **Reports** >

(Refereed Publications)

[1] L. Valbusa Dall'Armi, A. Nishizawa, A. Ricciardone, S. Matarrese, "Circular Polarization of the Astrophysical Gravitational Wave Background ", Physical Review Letters 131, 041401 (2023).

[2] T. Tsutsui and A. Nishizawa, "Observational constraint on axion dark matter in a realistic halo profile with gravitational waves", Physical Review D, 107, 103516 (2023).

< **Talks** >

(Contributed)

[3] A. Nishizawa, "Observational constraint on axion dark matter with gravitational waves", Kickoff workshop: "Search for new particles using gravitational waves (SNPGW)", Nagoya Univ. (hybrid) (Jun. 12, 2023).

9.4 Affiliates — Mamoru Doi

The former half of the fourth observing run (O4a) of the gravitational wave (GW) detectors of the LIGO-Virgo-KAGRA Collaboration (LVK) has been conducted in May 2023–Jan. 2024. During this period, we have carried out GW event followup observations using Tomo-e Gozen Camera (Tomo-e Gozen) mounted on the 1.05 m Kiso Schmidt telescope, putting the VOEvent based automated followup system and the transient object search pipeline software in operation. Tomo-e Gozen followed up 17 GW events in O4a. Although no promising candidate of an electromagnetic counterpart of a GW event was found during O4a by us or any other observatories, the automated followup system has been working as intended throughout O3 proving the utility of the observation system.

We carried out northern sky survey every clear night using the Tomo-e Gozen, searching for the optical transients and moving objects on the sky. Among the transient objects discovered by Tomo-e Gozen, SN 2024acn drew special attention with its peculiar lightcurve and spectrum. Further followup observations and data analysis for this object are underway. Data taken in the northern sky survey is also utilized to monitor ∼ day scale variability objects on the sky, such as variable stars and active galactic nuclei. One paper (Maeda *et al.* 2023) was published to model early flash of SNeIa, including SN2020hvf which was found by the Tomo-e Gozen northern sky survey.

We also search for optical counterparts of Fast Radio Bursts (FRBs) using the optical high-speed observing facilities, Tomo-e Gozen and TriCCS, in order to understand the nature of the mysterious transient phenomena. The searches target both repeating and non-repeating FRBs. In FY 2023, we analyzed the 98 fps movie data taken in the monitoring observations of repeating FRBs using TriCCS. Although an optical transient associated with a FRB is not found so far, the high sensitivity of the instrument to a flash like event is proved. The simultaneous optical-radio survey for non-repeating FRBs using Tomo-e Gozen and the Canadian Hydrogen Intensity Mapping Experiment (CHIME) is also ongoing.

< **Reports** >

(Refereed Publications)

[1] Kakeru, O., *et al.*, “A search for extragalactic fast optical transients in the Tomo-e Gozen high-cadence survey”, Mon. Not. R. Astron. Soc., 527(1), 334–345, 2024.

9.5 Affiliates — 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.

On December 14th-15th, 2023, our group, together with RESCEU members, hosted the 32th KAGRA Face-to-Face collaboration meeting at the University of Tokyo. There were around 160 participants as well as 27 poster presentations. This meeting was financially supported by RESCEU.

< **Awards** >

[1] 高野哲, 第 78 回年次大会 日本物理学会学生優秀発表賞，日本物理学会 (2023 年 10 月).

[2] 藤本拓希, 2023 年春季大会 日本物理学会学生優秀発表賞，日本物理学会 (2023 年 4 月).

<**報文**>

(Journal Papers)

[3] Y. Michimura, H. Wang, *et al.*, Effects of mirror birefringence and its fluctuations to laser interferometric gravitational wave detectors, Phys. Rev. D 109, 022009 (2024).

[4] Y. Oshima, *et al.*, First results of axion dark matter search with DANCE, Phys. Rev. D 108, 072005 (2023).

[5] K. Tsuji, *et al.*, Optimization of Quantum Noise in Space Gravitational-Wave Antenna DECIGO with Optical-Spring Quantum Locking Considering Mixture of Vacuum Fluctuations in Homodyne Detection, Galaxies 2023, 11, 111 (2023).

[6] R. Sugimoto, *et al.*, Experimental demonstration of back-linked Fabry-Perot interferometer for a space gravitational wave antenna, Phys. Rev. D 109, 022003 (2023).

[7] D. Ganapathy, *et al.*, Broadband Quantum Enhancement of the LIGO Detectors with Frequency-Dependent Squeezing, Phys. Rev. X 13, 041021 (2023).

[8] T. Akutsu, *et al.*, Overview of KAGRA: Data transfer and management, PTEP 2023, 10A102 (2023).

[9] R. Abbott, *et al.*, Open Data from the Third Observing Run of LIGO, Virgo, KAGRA, and GEO, ApJS 267, 29 (2023).

[10] R. Abbott, *et al.*, Constraints on the Cosmic Expansion History from GWTC?3, ApJ 949, 76 (2023).

[11] R. Abbott, *et al.*, Search for Gravitational Waves Associated with Fast Radio Bursts Detected by CHIME/FRB during the LIGO-Virgo Observing Run O3a, ApJ 955, 155 (2023).

[12] R. Abbott, *et al.*, GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo during the Second Part of the Third Observing Run, Phys. Rev. X 13, 041039 (2023).

[13] R. Abbott, *et al.*, GWTC-2.1: Deep extended catalog of compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run, Phys. Rev. D 109, 022001 (2024).

[14] C. Fletcher, *et al.*, A Joint Fermi-GBM and Swift-BAT Analysis of Gravitational-wave Candidates from the Third Gravitational-wave Observing Run, ApJ 964, 149 (2024).

(Thesis)

[15] 瀧寺陽太, アクシオン暗黒物質探索のための s/p 偏光間の反射位相差測定，修士論文 (2024 年 3 月).

< **Presentations** >

(International Meetings)

Invited talks

[16] Masaki Ando, Status of KAGRA, LVK Meeting (March 13th, 2024, Luisiana State University, Baton Rouge, Luisiana, USA).

[17] Masaki Ando, Space Gravitational-Wave Antenna B-DECIGO and DECIGO, LGWA2023 (October 10th, 2023, Catanial, Italy / Online).

[18] Masaki Ando, Space Gravitational-Wave Antenna B-DECIGO and DECIGO, ICGAC15 (July 6th, 2023, Gyeongju, South Korea).

Contributed talks

[19] Hinata Takidera, *et al.*, Laser wavelength tuning for sensitivity improvement of DANCE for axion dark matter search, FY2023 "What is dark matter?" (March 2024, YITP).

[20] Masaki Ando, Prospects on IGWN form KAGRA Point of View, The KAGRA Online Meeting (February 29th, 2024).

[21] Haoyu Wang, *et al.*, Updates of simulation for birefringence, The 32nd KAGRA F2F meeting (December 2023, University of Tokyo).

[22] Masaki Ando, IGWN Formation, 同上.

[23] Masaki Ando, Report from KSC Board, 同上.

[24] Masaki Ando, Future Strategy Committee, 同上.

[25] Masaki Ando, TorPeDO and TOBA for Newtonian Noise Research, KAGRA FWG 3rd Open Meeting (Dec 7th, 2023, NAOJ).

[26] Kentaro Komori, Sotatsu Otabe, Kentaro Somiya, Demonstration of GW signal enhancement by long SRC and the future, 同上.

[27] Masaki Ando, KAGRA Scientific Congress: Old/New KSC board, The 31st KAGRA F2F meeting (September 15th, 2023, Toyama).

[28] Masaki Ando, Future Strategy Committee, 同上.

[29] Satoru Takano, *et al.*, Newtonian Noise Measurement with TOrsion-Bar Antenna, 同上.

[30] Yuka Oshima, *et al.*, Development of Torsion-Bar Antenna for Low-Frequency Gravitational-Wave Observation, 38th International Cosmic Ray Conference (July 2023, Nagoya University).

[31] Haoyu Wang, *et al.*, Birefringence issues in KAGRA, Path to kHz Gravitational-wave Astronomy (July 2023, Tsinghua University).

[32] Hinata Takidera, *et al.*, Current status of Dark matter Axion search with riNg Cavity Experiment (DANCE), Student Fest by SGU-PG (June 2023, Koshiba Hall).

Poster Presentations

[33] Yuka Oshima, *et al.*, Development of Torsion Pendulums and Readout Optics for Gravity Gradient Observation, International Symposium on Quantum Electronics (February 2024, University of Tokyo).

[34] Masaya Ono, *et al.*, Quantum Squeezing Experiment in Gravitational Wave Physics, QuARC 2024 (Jan 2024, New Hampshire, USA).

[35] Hinata Takidera, *et al.*, Measurement of reflection phase difference between s-polarization and p-polarization for DANCE, Quantum Innovation 2023 (November 2023, Tokyo Convention Hall).

[36] Satoru Takano, *et al.*, Cryogenic Monolithic Interferometer for TOrsion-Bar Antenna, LVK meeting September 2023 (September 2023, Toyama).

[37] Hinata Takidera, *et al.*, Improving the sensitivity of Dark matter Axion search with riNg Cavity Experiment (DANCE) with wavelength tunable laser, Amaldi15 (July 2023, online).

[38] Yuka Oshima, *et al.*, Torsion-Bar Antenna and its Angular Sensor, GWADW 2023 (May 2023, Isola d'Elba, Italy).

[39] H. Fujimoto, *et al.*, Dark matter Axion search with riNg Cavity Experiment DANCE: Latest optical system and sensitivity, 同上.

9.6 Affiliates — Kentaro Komori

We worked on KAGRA commissioning, in particular, on the interferometer works to improve the detector stability and sensitivity. We applied feedforward technique to the interferometer control, and reduced the coupling noises from other length degrees of freedom. In addition, we measured mechanical quality factors of the sapphire substrate of the KAGRA test mass, and pointed out that the quality factors are smaller than the designed values so that it might be a fundamental issue for the future KAGRA.

We also worked on several table-top scale experiments. Toward future upgrade of large-scale GW detectors targeting high-frequency sensitivity, a long signal recycling cavity (LSRC) is planned to be installed. We succeeded in an experimental demonstration of the LSRC at the table-top scale interferometer, which will accelerate the installation in the large detectors. Furthermore, we proceeded with optomechanical experiments using mg-scale torsion pendulum to ultimately achieve macroscopic quantum state.

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、2023 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、モデル化を行なっている。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構築した。そのモデルでなされた多波長に関する予言に従い、多波長にわたる観測を試みている。[17, 18, 34, 20, 22, 25, 23, 36, 38, 39, 40, 41]

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。[22, 18, 34]

10.1.3　星周物質と爆発物質の衝突で光る天体

公開コード CHIPS の発展

近年、星周物質との相互作用によって光る超新星のスペクトル中に水素輝線が存在しないものが見つかってきている (Ibn/Icn 型超新星)。これらの超新星のいくつかは前兆現象が数ヶ月から数年前に発見されており、爆発的な質量放出が星周物質形成に寄与している可能性がある。CHIPS コード ver.1 は赤色超巨星にのみ対応していたが、これをヘリウム星やウォルフ・ライエ星の最外層の底にエネルギー注入しても計算が安定に走るように改良した。注入エネルギーと放出される質量などを調査し、The Astrophysical Journal で発表した [7]。

超新星爆発後期に、星周物質との相互作用による寄与が考えられる 2 つめのピークを持つ Ibc 型超新星が何例か報告されている。このピークを説明するために、星周物質が何らかの原因によって親星から切り離されるシナリオを考えた。親星の性質から恒星風は非常に強い動圧を持っていることが想定されるので、これが星周物質の自由落下を阻む。星周物質の殻が形成されるような状況を親星や星周物質の質量を変えて調べ、Publications of the Astronomical Society of Japan Letters にて発表した [6]。また、このシナリオを基に星周物質の殻を親星の周りに置き、超新星光度曲線のモデリングを行った。殻の質量や位置を変えながらピーク光度や立ち上がり時間の変化を調べ、長い時間の立ち上がりを持つ SN Ib 2010al と 2 つめのピークを持つ SN Ic 2022xxf の光度曲線を再現することに成功した。これらの結果をまとめ、The Open Journal of Astrophysics に投稿した [8]。

近傍の超新星 SN 2023ixf の観測と理論解釈

2023 年 5 月、我々の近傍の銀河 M101 に明るい重力崩壊型超新星 SN 2023ixf が出現した。この超新星の親星は近傍にあることから過去に多波長のデータが取られており、大質量星の終末期の活動が詳らかになった貴重なイベントである。我々は観測天文学者と協力しつつ上記の CHIPS コードを活用して爆発前の質量放出を加味した超新星の光度曲線を包括的に計算した。その結果、爆発の 1 年ほど前に 0.3-1 太陽質量程度の外層が放出されていた場合、超新星の明るい光度を再現できることがわかった。[2, 37]

超新星の前兆現象の新たな理論モデル

近年の高頻度探索観測によって、一部の超新星の爆発前に明るい可視光のフレアが前兆現象として検出されている。フレアは大質量星のエディントン限界光度の 100 倍程度と明るく、星の大部分を破壊しないでこの明るい放射を駆動するメカニズムは大きな謎である。私たちは、超高輝度超新星で提唱されている中心エンジン機構を援用し、大質量星と連星

を組んだコンパクト天体が放出物質の一部を降着することで観測されている大きなエネルギーを駆動するシナリオを新たに提唱した。典型的な質量のブラックホールや中性子星が超新星の親星と近い連星を組んでいた場合、前兆現象の明るさと継続時間が自然に説明できることがわかった。[5, 42]

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。本年度は、フィンランドで運用されているスーパーコンピュータ LUMI(https://www.lumi-supercomputer.eu) を利用した大規模シミュレーション研究を現地の共同研究者との協力の下で開始し、星周物質との衝突によって輝く突発天体の多次元モデルグリッドの構築を目指している [21]。

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。[9, 16, 35]

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。

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。与えられた C と O の質量比と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。ヘリウム中心核に中性子星が飲み込まれた場合も想定し，13 の元素のみを取り扱う簡単な核反応ネットワークを組み込んだ同様の計算を行い，この場合にも臨界降着率があることを見出した。この臨界降着率が核反応率の不定性によってどのような影響を受けるかを調べている。

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。

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。そのため、中性子星の磁場構造と歪み方は、中性子星の活動やそこからの重力波の推定にとって非常に重要である。そこで、磁場によって中性子星クラストが弾性的に歪み、どのうなエネルギー解放を行うか求めた [13]。また、一般相対論的重力による定式化のもとで、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]。

10.1.6 天体物理と量子計算

天体物理学を支配する方程式の多くは、解析的に解を求めることができないので数値計算が必要であるが、方程式によっては計算量保が非常に大きくなる。例えば、希薄流体やニュートリノなどを記述するボルツマン方程式は、6 次元位相空間上の分布関数に対する方程式であり、次元が大きく膨大な計算量が必要である。一方で、最近発展の目覚ましい量子計算では、特定の問題に対しては指数関数的な計算速度の向上が期待でき、天体物理学で必要となる方程式への応用することも可能である。

そこで、ボルツマン方程式の衝突項を無視したブラソフ方程式に対して、特定の状況のみではあるが非常に強力な量子アルゴリズムを開発し、その計算量が古典計算に対して優位であることを示した [15]。今後は、量子計算を他の天体物理学の問題へも応用していくことを目指す。

10.1.7 極金属欠乏銀河の性質と化学進化

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。 [10, 11, 12]

10.1.8 大質量星による放射性同位体の合成と核ガンマ線

大質量星の進化段階や超新星爆発で合成される放射性同位体の中には、恒星風や超新星爆発によって星間空間へ供給された後に崩壊して MeV 核ガンマ線として検出が期待できるものが存在する。100 万年程度の半減期を持つ ^{26}Al,^{60}Fe は、COMPTEL による観測などによって銀河面からの放射として既に検出されており、2020 年代後半から 2030 年代にかけて計画されている MeV ガンマ線検出ミッションにおいても期待されているターゲットである。

将来観測での個々の星形成領域を分解した核ガンマ線観測は、恒星風や連星相互作用による質量損失過程やブラックホールといったコンパクト天体形成過程への制限につながることが期待される。現在ない、公開恒星進化コード MESA を用いた、大質量星の進化計算によってこれらの同位体の生成量を調べ、その観測可能性について検討を進めている。[30]

10.1.9 初代銀河のダストの理論モデル構築

ビッグバンから 1 億年以内の初代銀河では、ダストは主に超新星爆発によって作られると考えられている。初代銀河のダストを可視・紫外・赤外の観測を通じて理解することは、初期宇宙の星形成史の大きな指針となる。我々は準解析的銀河形成モデルとして公開されている A-SLOTH (Ancient Stars and Local Observables by Tracing Halos) に、新たにダストの生成、成長および輻射・超新星によるフィードバックなどの物理を実装し、銀河内のダスト質量の時間進化を計算する枠組みを構築した。このモデルをジェームズウェッブ宇宙望遠鏡で近年観測された最遠方の銀河 (候補) に適応した。ダスト減光率・ダスト質量ともに少ないこれらの銀河を説明するには、観測から数千万年以内に爆発的星形成が起こっていて、生成された星々の輻射圧でダストを銀河外に吹き飛ばす機構が必要であることが分かった。[4, 29]

10.1.10 次世代紫外・X 線衛星ミッションのサイエンス検討への参画

JEDI(仮称) は、日本主導で 2030 年代打ち上げを目指した広帯域紫外線・X 線衛星計画である。2030 年代におけるマルチメッセンジャー天文学の発展に寄与するべく、様々な電磁波・ニュートリノ・重力波観測からの突発天体アラートに対応して即応観測を実現するミッションとして計画が進行している。星周物質と衝突して輝く超新星やガンマ線バースト、さらには近年になって存在が明らかとなった Fast blue optical transients (FBOTs) といった突発天体は将来のマルチメッセンジャー天文観測および JEDI による即応観測において想定される重要なターゲットである。JEDI の実現に向けてワーキンググループに参画し、グループ内でのサイエンス検討に主に理論面から貢献している。[31]

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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, 3, 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 VLT X-Shooter による合体後 10 日後のスペクトルデータの解釈を行った [1]。その結果、キロノバの後期に見られる 2.1 ミクロンのピークがテルルの持つ強い輝線でよく説明できることがわかった。この解釈が正しければ、中性子星合体 GW170817 ではテルルが太陽質量の 0.5% 程度生成されたことが示唆される。

これまでに観測されたガンマ線バーストの中で２番目に明るい GRB 230307A にキロノバに酷似した天体が付随した。ジェームズウェッブ宇宙望遠鏡による追観測プログラムに参加し、キロノバのスペクトルの解析を行なったところ、GW170817 で観測されたキロノバと同様に、2.1 ミクロンの輝線が強いピークを作っていることがわかった。これもテルルによる輝線で説明することができることを示した [5]。

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い、現在検討されている X 線衛星による検出可能性を議論した [4]

中性子星合体が駆動するガンマ線バーストも重要な電磁波対応天体の一つである。現在、運用されているガンマ線バースト衛星、また近い将来打ち上げが検討されているガンマ線バースト探査衛星 DAKSHA によるガンマ線対応天体の検出頻度の評価を行なった [6]。

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。GW170817 では、合体後およそい 10 日後から電波、X 線で残光が検出され、150 日後付近でピークを迎え、その後数年間、残光は観測可能であった。このジェットによる残光は、放射源運動や形状などが電波による VLBI 観測によって分解できる可能性がある。実際、GW170817 では放射源の超光速度運動が観測されている。我々は、様々なパラメータで残光の電波イメージを生成する数値コードを開発し、将来の電磁波対応天体の観測に向けた準備を進めている [11, 16, 17]。

11.1.2　大質量星の爆発に伴うショックブレイクアウト研究

大質量星が爆発する際に、衝撃波が星表面を突き破る瞬間に光が放射される。この現象はショックブレイクアウトと呼ばれる。ショックブレイクアウトの性質は、星の質量、半径、爆発エネルギー、衝撃波の速度などに依存する。我々は、これまで考えらていなかったショックブレイクアウトの性質を理論的に発見し、その性質が低光度ガンマ線バースト 060218 の観測的特徴をよく説明できることを導いた [9, 12, **?**]。

11.1.3　超大質量星および超大質量ブラックホール

超大質量ブラックホールの進化に関する研究を行なった [7]。特に高赤方偏移クエーサーの光度関数から、初期宇宙における超大質量ブラックホールがガス降着によって成長する効率を調べた。また初代星形成に関する研究も行っている [8]。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、初代星の初期質量関数のより質量が大きい部分の性質を調べた。

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。

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