Research Center for the Early Universe

Graduate School of Science

University of Tokyo

Annual Report

2020

令和２年度 年次研究報告

東京大学大学院理学系研究科附属

ビッグバン宇宙国際研究センター

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Preface

I am pleased to deliver the annual report of Research Center for the Early Universe (RESCEU) for the fiscal year of 2020 (from April 2020 to March 2021).

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 Prof. Jun'ichi Yokoyama), (2) Gravitational-wave astrophysics and experimental gravity (led by Prof. Kipp Cannon), and (3) Formation and characterization of planetary systems (led by myself). Those projects have been supported by a variety of collaboration among our research affiliates in Departments of Physics, Astronomy, and Earth and Planetary Sciences of Faculty of Science, the University of Tokyo.

Due to the pandemic outbreak of COVID-19, the activity in RESCEU has been seriously affected. We were not able to organize any international meeting nor symposium this year. We had the summer school, but it is entirely online without inviting foreign researchers. Since the official members of RESCEU are mostly working on theoretical projects, however, weekly seminars and regular discussions have been carried out via zoom fortunately.

Finally we are pleased to announce the awards for our RESCEU members. Prof. Jun'ichi Yokoyama received the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology in April 2020. Dr. Masamune Oguri received the PASJ Excellent Paper Award in 2020 as a coauthor of Hikage et al. PASJ 71(2019) id. 43, and Dr. Kazuhiro Kanagawa received the PASJ Excellent Paper Award in 2020 as the first author of Kanagawa et al. PASJ 68(2016) id. 43, in March 2021.

We would like to congratulate all of them for their wonderful achievements.

May 2021

Director Yasushi Suto

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I

Reports on overall activities at RESCEU in 2020

1 Members

RESCEU members

Yasushi Suto [須藤靖]	Director
Jun'ichi Yokoyama [横山順一]	Professor
Kipp Cannon	Professor
Toshikazu Shigeyama [茂山俊和]	Professor
Kenta Hotokezaka [仏坂健太]	Associate Professor
Masamune Oguri [大栗真宗]	Assistant Professor
Kazumi Kashiyama [樫山和己]	Assistant Professor
Kohei Kamada [鎌田耕平]	Assistant Professor
Atsushi Nishizawa [西澤篤志]	Assistant Professor
Yuu Niino [新納悠]	Project Assistant Professor (RESCEU & JSPS Grant of Prof. Shigeyama)
Kotaro Fujisawa [藤澤幸太郎]	Project Assistant Professor (RESCEU)
Haruki Nishino [西野玄記]	Project Assistant Professor (RESCEU & JSPS Grant of Prof. Kusaka)
Yuji Chinone [茅根 裕司]	Project Assistant Professor (RESCEU & JSPS Grant of Prof. Kusaka)
Koh Ueno [上野昂]	Postdoctoral Fellow (JSPS Grant of Prof. Cannon)
Kazuhiro Kanagawa [金川和弘]	Postdoctoral Fellow (RESCEU) (– 2021/01/31)
Yusuke Yamada [山田悠介]	Postdoctoral Fellow (JSPS Fellow)
Tatsuya Matsumoto [松本達矢]	Postdoctoral Fellow (JSPS Fellow)
Keisuke Inomata [猪又敬介]	Postdoctoral Fellow (JSPS Grant of Prof. Yokoyama) (– 2020/08/31)
Heather Fong	Research Fellow (JSPS Fellow)
Sayuri Nagano [永野早百合]	Secretary
Chiyo Ueda [上田千代]	Secretary
Reiko Sugiyama [杉山礼子]	Secretary

RESCEU affiliates

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

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 blackholes
Aya Bamba	Chemical evolution of the universe with supernova remnant study
Kazuhiro Shimasaku	Galaxy Formation and Evolution
Akito Kusaka	Observational cosmology using cosmic microwave background
Masamune Oguri	Unveiling the nature of dark matter and dark energy
Kazumi Kashiyama	Evolution of compact objects and time domain astronomy
Kohei Kamada	Particle 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	Multi-messanger astrophysics of compact binary mergers
Mamoru Doi	Identifications of gravitational-wave sources by wide-field and multi-color optical observations
Masaki Ando	Gravitational-Wave Experiment and Astrophysics

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
Masahiro Ikoma	Diversity and origins of exoplanetary atmospheres
Hajime Kawahara	Exploring instrumentation and methods for characterizing exoplanets
Hideo Higuchi	Universal model on motor proteins
Chikara Furusawa	Evolutionary dynamics of computational cell models

3 Symposia and Meetings

Planet^2 / RESCEU Summer School

Place: Online
Time: 2020/8/17 (Mon) – 2020/8/19 (Wed)

Program

8/17 (Mon) morning

10:00–10:10	Yasushi Suto	Opening remark
10:10–11:30	(L) Nobunari Kashikawa	High-z galaxies and their environment
11:30–11:45	Yuta Tarumi	s-process enrichment and the origin of barium in ultrafaint dwarf galaxies
11:45–12:00	Kana Moriwaki	Component extraction from line intensity maps with conditional GAN
12:00–12:15	Hyunbae Park	Scatter in the reionization history by baryon-dark matter streaming velocity

8/17 (Mon) afternoon

13:15–14:35	(L) Hajime Kawahara	Frontier in Exoplanet Characterization
14:35–14:50	Ayano Komaki	Photoevaporation from protoplanetary disk: dependence on central star spectrum
14:50–15:05	Shijie Wang	Evolution of the multiplanetary systems deduced from six ALMA disks
15:05–15:20	Hiroto Mitani	Effect of Stellar Wind on Atmospheric Escape

8/18 (Tue) morning

10:00–10:40	(T) Seiji Sugita	Topical talk: The Evolution of Ryugu and the Early Solar System Revealed by Hayabusa2 Observations
10:40–10:55	Daichi Tsuna	Transients upon Black Holes Born From Erupting Massive Stars
10:55–11:10	Kojiro Kawana	A variety of emission from tidal disruption events of a white dwarf by a black hole
11:10–11:25	Toshinori Hayashi	A strategy to search for an inner binary black hole from the motion of the tertiary companion: radial-velocity modulations of a star and time-delay effects of a pulsar
11:25–11:40	Tilman Hartwig	Neural Networks can learn periodic data
11:40–11:55	Kipp Cannon	Data Analysis in COVID Days

8/18 (Tue) afternoon

13:00–13:40	(T) Tomonori Totani	Emergence of life in an inflationary universe
13:40–13:55	Yici Zhong	How much supernova fall-back can invade newborn pulsar wind and magnetosphere?
13:55–14:10	Naoto Kuriyama	The features of multiple mass eruptions from progenitors of Type IIn supernovae
14:10–14:25	Yuki Takei	A two-temperature radiative transfer simulation for interaction-powered supernovae
14:25–14:40	Lin Haoxiang	Radio afterglow from Fast Radio Bursts produced by Neutron Star Mergers
14:40–14:55	Minori Shikauchi	On the use of CHIME to Detect Long-Duration Radio Transients from Neutron Star Mergers

8/19 (Wed) morning

10:00–11:20	(L) Masaki Ando	Observation of Gravitational-Wave in Space
11:20–12:00	(T) Mamoru Doi	The Tomo-e Gozen Camera the first wide-field CMOS imager

8/19 (Wed afternoon)

13:00–13:15	Leo Tsukada	Stochastic background from ultralight vectors
13:15–13:30	Takuya Tsutsui	Early warning of third generation gravitational wave detector for precessed compact binary merger
13:30–13:45	Keisuke Inomata	Scalar perturbations induced by scalar perturbations
13:45–14:00	Fumio Uchida	A baryogenesis scenario from helical magnetic fields and constraints on it
14:00–14:15	Minxi He	Tachyonic preheating in the mixed Higgs-R^2 model
14:15–14:25	break	
14:25–14:40	Soichiro Hashiba	Particle production induced by vacuum decay in real time formalism
14:40–14:55	Jun'ya Kume	Quantum correction in gravitational leptogenesis and its renormalization
14:55–15:10	Koki Tokeshi	PBH mass spectrum and window function dependence
15:10–15:25	Takumi Hayashi	Towards Coleman-de Luccia bubble nucleation in the Lorentzian path integral
15:25–15:30	Jun'ichi Yokoyama	closing

(L: Lecture, T: Topical talk)

4 RESCEU colloquia

- RESCEU Colloquium No. 45
  Gilles Ferrand (Astrophysical Big Bang Laboratory (ABBL), Cluster for Pioneering Research, and Interdisciplinary Theoretical and Mathematical Sciences Program (iTHEMS), RIKEN)
  "From the thermonuclear supernova to the supernova remnant"
  November 26, 2020, 10:30-11:30

- RESCEU Colloquium No. 46
  Akira Endo (Delft University of Technology, on behalf of the DESHIMA collaboration)
  "DESHIMA: Integrated Superconducting Spectrometer for Wideband Submillimeter Astronomy"
  December 10, 2020, 17:00-18:00

- RESCEU Colloquium No. 47
  Takaaki Tanaka (Kyoto University)
  "Recent X-ray Studies of Supernova Remnants and Beyond"
  February 18, 2021, 14:00-15:00

- RESCEU Colloquium No. 48
  Hiroki Akamatsu (SRON Netherlands Institute for Space Research)
  "Energetics of galaxy clusters and cryogenic probes for future astronomical applications"
  March 25, 2021, 16:00-17:00

II

Reports on the research activities of each project in 2020

5 Project 1. Evolution of the universe and cosmic structures

5.1 Activity Report

This project aims at clarifying the origin and evolution of both matters and structures of the Universe-based on theoretical and observational studies. It covers physics of the early universe including but not limited to inflation, cosmological phase transition, formation and evolution of density perturbation, as well as formation and evolution of the hierarchical structure of the universe, namely, stars, galaxies, and clusters of galaxies in terms of numerical simulations and optical and X-ray observations. Cosmic microwave background radiation and gravitational waves are also important probe of the Universe and are actively investigated in this project. These studies not only clarifies the evolution of our Universe but also provide us with invaluable informations on the nature of dark matter and dark energy. Below are highlights of the achievements in FY2020 listed in descending scales.

5.1.1 Inflationary cosmology

We studied the realization of the hot Big Bang Universe after inflation, namely, the reheating, in the mixed Higgs-R^2 model. We identified the realization condition of the reported violent particle production mechanism just after inflation, which may lead to quick connection to the hot Big Bang Universe in that model. (Yokoyama, Kamada)

5.1.2 Quantum anomaly in the early Unvierse

There can be interesting phenomena in the early Unvierse induced by background magnetic fields as well as gravitational waves through the chiral anomaly inherent in the quantum theories. It causes the Chern-Simons coupling between the pseudo-scalar and gauge fields or gravitational fields. We studied the magnetic field and gravitational wave production from the dynamics of pseudo-scalar fields through the Chern-Simons coupling, that are identified as inflaton and also the phase of the flat direction in supersymmetric theories, which can result in the generation of matter and antimatter asymmetry of the Universe. Especially we clarified the subtleties in the renormalization of the gravitational wave production. We also studied the baryon isocurvature perturbation generated by the primordial magnetic fields generated at the electroweak symmetry breaking. We found that the intergalactic magnetic fields suggested by the blazar observation cannot be explained by the primordial magnetic fields generated before the electroweak symmetry breaking due to too large isocurvature perturbation. (Kamada)

5.1.3 Statistical Computational Cosmology

We applied a sparsity-based method called adaptive LASSO to reconstruct three-dimensional density distribution in the Universe by gravitational lensing observations. We apply an adaptive LASSO algorithm to perform reconstruction on the assumption that the underlying cosmic density field is represented by a sum of Navarro-Frenk-White halos. We generate realistic mock galaxy shape catalogues by considering the shear distortions from isolated halos for the configurations matched to Subaru Hyper Suprime-Cam Survey with its photometric redshift estimates. Galaxy clusters with mass greater than 10^{14} solar-masses can be detected with 1.5-σ confidence, with an average false detection rate of 0.022 per square-degree. The standard deviation of the redshift estimation is less than 0.1. Our method enables direct three-dimensional cluster detection with accurate redshift estimates. (Yoshida)

5.1.4 Observational cosmology using cosmic microwave background

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

The Polarbear experiment and its successor, Simons Array, are designed to measure both inflationary signature and the gravitational lensing effect in CMB polarization. Polarbear has concluded its observation campaign in 2016, and our focus has been on data analysis. Our recent results from this project include the first demonstration of so-called "de-lensing," a rejection of contamination due to gravitational lensing effect in reconstructing primordial B-mode power spectrum, using CMB polarization data only. We also released several results influential to future CMB projects, including: 1) improved measurement of the gravitational lensing power spectrum measurement, 2) constraint on the tensor-to-scalar ratio r, and 3) the E-mode power spectrum and constraint on the cosmological parameters.

For Simons Array experiment, observation using the first telescope and the deployment of the second telescope were paused due to COVID-19 pandemic; we virtually lost our access to the telescope site in Chile. We managed to gain access to the site toward the end of 2020, and resumed observation at the beginning of 2021 using the first telescope. The deployment of the second telescope is underway toward the first light soon. In parallel, development of the analysis pipeline is actively on-going.

The Simons Observatory experiment is scheduled for the first light in 2022 and 2023. We will deploy three 0.4-m Small Aperture Telescopes (SATs), which are dedicated for exploring inflationary signature, and a 6-m Large Aperture Telescope (LAT), which will measure (or constrain) the sum of neutrino masses, and the dark content of the universe. We have primarily focused on the development of SATs, and delivered the cryogenic optics tube for the first telescope. We also made significant progress in fabricating and commissioning the second and third cryogenic half-wave plate rotation mechanism.

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

5.1.5 Probing Dark Matter with Gravitational Waves

We studied the possibility of using amplitude and phase fluctuations of gravitational waves due to gravitational lensing as a probe of the small-scale matter power spectrum, which contains a wealth of information about the particle nature of dark matter. We showed that the frequency dependence of amplitude and phase fluctuations arise from the wave optics nature of the propagation of gravitational waves. It is predicted that gravitational lensing dispersions of gravitational waves at frequencies of $f \sim 0.1 - 1$ Hz probes the abundance of low-mass dark halos with mass $1h^{-1}M_\odot \lesssim M \lesssim 10^4 h^{-1}M_\odot$ and hence serve as a new test of the cold dark matter paradigm. We pointed out that primordial black holes (PBHs) with $M_{\rm PBH} \gtrsim 0.1\ M_\odot$ can significantly enhance the signal mainly due to their shot noise. The abundance of PBHs can be efficiently probed with gravitational waves at frequencies of $f \sim 10 - 100$ Hz where the enhancement of the signals is large. (Oguri)

5.1.6 ALMA lensing cluster survey: uncovering and characterising highly magnified dust-enshrouded galaxies behind lensing clusters

Recent ALMA observations have unveiled the presence of faint (i.e., sub-mJy at $\lambda \sim$1 mm, significantly fainter than the "classical" bright submillimeter galaxies), dusty star-forming galaxies, which are often invisible in the deepest near-infrared images taken with the *HST* and 8-m-class telescopes. They seem to represent the bulk population of massive galaxies at $z > 3 - 4$ and beyond, which have been completely missed by the Lyman-break galaxy selection using *HST*/WFC3. Due to its faintness, however, detailed physical characterization of the faint dusty star-forming population remains a challenge; even using ALMA, spectroscopic follow-up studies of these faint galaxies can be very expensive. With these backgrounds, we have conducted the ALMA lensing cluster survey (ACLS, PI: K. Kohno. co-PIs: M. Oguri et al.), a 96-hour ALMA large program in cycle-6. It aims at obtaining high-resolution (∼arcsec) 1.2-mm images of high-magnification regions of 33 lensing clusters with a depth of ∼70 μJy (1σ), covering ∼110 arcmin^2 in total. We have two frequency tuning setups, resulting in a total frequency coverage of 15 GHz, which allows us to search for millimeter-wave line emitting galaxies. The sample is taken from the best-studied massive clusters including CLASH, HFF, and RELICS. We have securely detected 129 continuum sources above 5σ, and it will become 113 independent continuum sources even after removing multiple images by cluster lens. We find a significant number of near-infrared-dark, magnified (but intrinsically faint) dusty star-forming galaxies, and follow-up studies of them are on-going. As one of the initial outcomes, we published a discovery of a triple image "*H*-band-dropout" ALMA galaxy, which is associated with a galaxy group at $z = 4.32 - 4.33$, lensed by the massive galaxy cluster ACT-CL J0102-4915 (aka *El Gordo*) at $z = 0.87$ (Caputi, K., Caminha, G., Fujimoto, S., Kohno, K., et al. 2021, ApJ, 908, 146). We also uncover a multiply imaged sub-L* galaxy at $z = 6.072$ behind the massive cluster RXC J0600-2007 at $z = 0.430$ (Fujimoto, S., Oguri, M., Brammer, G., Yoshimura, Y., Laporte, N., Kohno, K., Shimasaku, K., et al., ApJ, 911, 99; Laporte, N., Zitrin, A., Ellis, R. S., Fujimoto, S., Oguri, M., Kohno, K., et al. 2021, MNRAS, in press). It exhibits a surprisingly elevated [CII] 158 μm emission (∼25 mJy) because of its high magnification (μ ∼20 on average). In fact, after careful identification of multiple images and refinement of the mass models led by M. Oguri and our collaborators, we find that this galaxy straddles the caustics at $z = 6.07$ so a part of this galaxy reaches an extremely high magnification up to μ ∼160 (!). The reconstructed [CII] 158 μm line, rest-frame far-infrared continuum (i.e., ALMA band-6 or 1.2 mm continuum), and rest-frame ultraviolet (i.e., *HST*/F160W or near-infrared *H*-band) images reveal the distributions of stars and interstellar medium at 100 - 300 pc scales. Given the uniqueness of the uncovered galaxy as an intrinsically faint (ergo ubiquitous), sub-L* galaxy, an intensive follow-up campaign has been launched, including the approved JWST GO-1 program using NIRCam and NIRSpec IFU (PI. Fujimoto, S.). (Kohno, Oguri, Shimasaku)

5.1.7 High redshift galaxies

We compare the spatial distribution of LAEs at ∼ 2 with that of IGM HI gas, a faithful tracer of matter distribution, finding that LAEs tend to be located on the near (to us) sides of HI dense regions because those on the far sides suffer from heavier Lyα absorption. This result indicates that care is needed when using LAEs to search for overdense regions of matter. We search for bright $z = 7.3$ LAEs using deep HSC/NB1010 imaging data, finding no source. We use this result to obtain a lower limit to the HI neutral fraction to be > 0.28. This indicates that cosmic reionization is still ongoing at $z = 7.3$. (Shimasaku)

5.1.8 Astrophysical transients: their origins and consequences

The following topics were studied in this project.

- Binary neutron star mergers in faint dwarf spheroidal galaxies (Shigeyama)
- Optical emission immediately after binary neutron star mergers (Shigeyama)
- Observations of the early light from type Ia supernovae (Shigeyama; Doi, M.)
- Influence of Pop III supernova explosions on the companion stars (Shigeyama)
- Rapidly rotating massive white dwarfs as a result of binary white dwarf mergers (Kashiyama, Fujisawa, Ko, Shigeyama)
- Emission of type IIn supernovae (Shigeyama, Tsuna, Kashiyama, Takei)
- Eruptive mass loss from a massive star a few years before the core collapse (Shigeyama, Kuriyama)
- Accretion of C+O matter onto a neutron star igniting Carbon burning (Shigeyama, Nagarajan)

- Influence of supernova fallback on newborn neutron star magnetospheres (Shigeyama, Kashiyama, Zhong)
- Rotational equilibria on the 2D Lagrange coordinates (Fujisawa)
- The W4 method: a new multi-dimensional root-finding scheme for nonlinear systems of equations (Fujisawa)

Here the names of researchers are listed in the parentheses.

5.1.9 Probing the origin of compact objects in the universe by theoretical modeling and multi-wavelength observations

We studied radio afterglows from binary neutron star (BNS) mergers, and especially its implications for fast radio bursts (FRBs). If some of FRBs are produced by BNS mergers, radio afterglows may be detected by follow-up radio observations of FRB locations. We made quantitative predictions using a latest afterglow model of BNS mergers. Totani also studied on the origin of the Fermi bubble, which is a giant gamma-ray bubble structure towards the Galactic Center. Structures found in the X-ray and radio diffuse emission in this region were compared in detail, and their origin were discussed. (Totani)

5.1.10 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, so we observe such high energy photons using balloons and satellites.

This year we examined carefully how and when accelerated particles on the shocks of supernova remnants escape to the space and become galactic cosmic rays. With systematic study of a few tens supernova remnants in X-ray and gamma-ray band, it is found that accelerated particles escape from the acceleration sites (shocks of supernova remnants) within $\sim$10 kyrs. This is the first observational measurement of particle escape from the acceleration sites. The acceleration efficiency has diversity within the order of 3, which means that only a few supernova remnants contribute the Galactic cosmic rays.

Torus of active galactic nucleus (AGNs) feed supermassive blackholes and important to understand the co-evolution of galaxy and the blackholes. This year we have made systematic analysis of AGNs hidden by their torus with the X-ray emission model we developed (”XClumpy”), and found that around half of AGNs are hidden type. It is found that the covering fraction by their torus is larger than previously expected. Our result implies that there are more undiscovered AGNs hidden by their torus.

We also study on the detector development for the near future missions. For the XRISM, to be launched on the Japanese fiscal year 2022, we fixed the performance verification targets. For Cipher mission, the first imaging polarimetory cubesat in the hard X-ray band, we tested the X-ray use of infrared CMOS sensor and found that it totally satisfies our requests with good efficiency. We also started GRAMS mission development in this year. (Bamba)

5.2 Publication List

[1] K. Kamada, and C. S. Shin, “Magnetogenesis from a rotating scalar: á la scalar chiral magnetic effect”, Journal of High Energy Physics **04**, 185 (2020).

[2] T. Akutsu *et al.* [KAGRA], “Application of independent component analysis to the iKAGRA data,” Progress of Theoretical and Experimental Physics **2020** (2020) no.5, 053F01.

[3] T. Hayashi, K. Kamada, N. Oshita and J. Yokoyama, “On catalyzed vacuum decay around a radiating black hole and the crisis of the electroweak vacuum”, Journal of High Energy Physics **08**, 088 (2020).

[4] T. Fujita, K. Kamada, and Y. Nakai, “Gravitational waves from primordial magnetic fields via photon-graviton conversion”, Phys. Rev. D **102**, 103501 (2020).

[5] K. Kamada, J. Kume and Y. Yamada: "Renormalization in gravitational leptogenesis with pseudo-scalar-tensor coupling," Journal of Cosmology and Astroparticle Physics **10**, 030 (2020).

[6] K. Tokeshi, K Inomata, and J. Yokoyama, "Window function dependence of the novel mass function of primordial black holes", Journal of Cosmology and Astroparticle Physics **12**, 038 (2020).

[7] M. He, R. Jinno, K. Kamada, A. A. Starobinsky and J. Yokoyama, "Occurrence of tachyonic preheating in the mixed Higgs-R^2 model," Journal of Cosmology and Astroparticle Physics **01**, 066 (2021).

[8] M. Gunaydin, R. Kallosh, A. Linde and Y. Yamada, "M-theory Cosmology, Octonions, Error Correcting Codes," Journal of High Energy Physics **01**, 160 (2021).

[9] Lingyuan Ji, Marc Kamionkowski, Keisuke Inomata, "Standard model prediction for cosmological 21 cm circular polarization", Phys. Rev. D **103**, 023516 (2021).

[10] S. Hashiba, Y. Yamada and J. Yokoyama, "Particle production induced by vacuum decay in real time dynamics", Phys. Rev. D **103**, 045006 (2021).

[11] Keisuke Inomata, "Analytic solutions of scalar perturbations induced by scalar perturbations", Journal of Cosmology and Astroparticle Physics **03**, 013 (2021).

[12] Tsuna, D., Ishii, A., Kuriyama, N., et al. 2020, Astrophys. J. Lett., 897, L44. doi:10.3847/2041-8213/aba0ac

[13] Takei, Y. & Shigeyama, T. 2020, Publ. Astron. Soc. Japan, 72, 67. doi:10.1093/pasj/psaa050

[14] Ohsawa, R., Hirota, A., Morita, K., et al. Shigeyama, T. (35th author) 2020, Planetary Space Science, 194, 105011. doi:10.1016/j.pss.2020.105011

[15] Kuriyama, N. & Shigeyama, T. 2021, Astron. & Astrophys., 646, A118. doi:10.1051/0004-6361/202038637

[16] Suda, T., Saitoh, T. R., Moritani, Y., Shigeyama, T., 2021, Publ. Astron. Soc. Japan. doi:10.1093/pasj/psab02

[17] Kojima, Y., Kisaka, S., & Fujisawa, K. 2021, Mon. Not. R. Astron. Soc., 502, 2097. doi:10.1093/mnras/staa3489

[18] Tsuna, D., Kashiyama, K., & Shigeyama, T. 2021, arXiv:2103.08338, Astrophys. J. in press

[19] Jaelani A. T., *et al.* (incl. Oguri M.), 2020, MNRAS, **494**, 3156

[20] Kikuchihara S., *et al.* (incl. Oguri M.), 2020, ApJ, **893**, 60

[21] Jaelani A. T., More A., Oguri M., *et al.*, 2020, MNRAS, **495**, 1291

[22] Chan J. H. H., *et al.* (incl. Oguri M.), 2020, A&A, **636**, A87

[23] Chiu I.-N., *et al.* (incl. Oguri M.), 2020, MNRAS, **495**, 428

[24] Tampo, Y., Tanaka, M., Maeda, K., *et al.* (incl. Kawana K.) 2020, ApJ, **894**, 27

[25] Bakx T., *et al.* (incl. Yoshida N.), 2020, MN, **493**, 4294

[26] Steinhardt C. L., *et al.* (incl. Oguri M.), 2020, ApJ, **894**, 125

[27] Tarumi Y., Yoshida N., and Inoue S., 2020, MNRAS. **494**, 120

[28] Shirasaki M., Macias O., Ando S., Horiuchi S., Yoshida N., 2020, ApJ, **101**, 3022

[29] Moriwaki K., *et al.*, 2020, MNRAS, **496**, L54

[30] Akahori T., *et al.* (incl. Oguri M.), 2020, PASJ, **72**, 62

[31] Murata R., Sunayama T., Oguri M., *et al.*, 2020, PASJ, **72**, 64

[32] Sunayama T., *et al.* (incl. Oguri M.), 2020, MNRAS, **496**, 4468

[33] Harikane Y., *et al.* (incl. Moriwaki K.), 2020, ApJ, **896**, 93

[34] Whalen D. J., Mezcua M, Meiksin A., Hartwig T., Latif, M. A., 2020, ApJ, **896**, 45

[35] Okabe T., Oguri M., Peirani S., Suto Y., Dubois Y., Pichon C., Kitayama T., Sasaki S. and Nishimichi T., 2020, MNRAS, **496**, 2591

[36] Tsuna D., Ishii A., Kuriyama N., Kashiyama K., Shigeyama T., The Astrophysical Journal Letters, **897**, 2, id.L44

[37] Tarumi Y., Hartwig T., Magg M., 2020, ApJ, **897**, 58

[38] Fukushima H., Hosokawa T., Chiaki G., Omukai K., Yoshida N., Kuiper R., 2020, MN, **497**, 829

[39] Acebron A., *et al.* (incl. Oguri M.), 2020, ApJ, **898**, 6

[40] Chen M. C., *et al.* (incl. Oguri M.), 2020, ApJ, **898**, 81

[41] Seto N., Kashiyama K., 2020, International Journal of Astrobiology, **19**, 4, pp. 308-313

[42] KAGRA Collaboration(incl. Kashiyama K.), Progress of Theoretical and Experimental Physics, ptaa120,

[43] Chao D. C.-Y., *et al.* (incl. Oguri M.), 2020, A&A, **640**, 88

[44] Chiu I.-N., Okumura T., Oguri M., *et al.*, 2020, MNRAS, **498**, 2030

[45] Silverman J. *et al.* (incl. Hartwig T.), 2020, ApJ, **899**, 154

[46] Park H., Ahn K., Yoshida N., Hirano S., 2020, ApJ, **900**, 30

[47] Takahashi I., Suzuki N., Yasuda N., Tanaka M., Kimura A., Ueda N., Tominaga N., Yoshida N., 2020, PASJ, **72**, 89

[48] Okabe N., *et al.* (incl. Oguri M.), 2021, MNRAS, **501**, 1701

[49] Inoue S.,Yoshida N.,Yajima H., MN, **498**, 5960

[50] Tarumi Y. *et al.*, 2020, arXiv. 2009.10096

[51] Oguri M., Takahashi R., 2020, ApJ, **901**, 58

[52] Yoshiura S., Oguri M., Takahashi K., Takahashi T., 2020, Phys. Rev. D, **102**, 083515

[53] Sonnenfeld A., *et al.* (incl. Oguri M.), 2020, A&A, **642**, A148

[54] Li X., Oguri M., *et al.*, 2020, ApJS, **251**, 19

[55] Yoshikawa K., Tanaka S., Yoshida N., Saito S., 2020, ApJ, **905**, 159

[56] Rasmussen K. C. *et al.* (incl. Hartwig T.), 2020, ApJ, **905**, 20

[57] Moriwaki K., Shirasaki M., Yoshida N., 2021, ApJL, **906**, L1

[58] Jaelani A. T., *et al.* (incl. Oguri M.), 2021, MNRAS, **502**, 1487

[59] Tarumi Y., Hotokezaka K., and Beniamini P., 2021, arXiv. 2102.03368

[60] Hilton M., *et al.* (incl. Oguri M.), 2021, ApJS, **253**, 3

[61] Park H., Shapiro P., Ahn K., Yoshida N., Hirano S., 2020, ApJ, **908**, 96

[62] Pierel J. D. R., *et al.* (incl. Oguri M.), 2021, ApJ, **908**, 190

[63] Ghirardini V., *et al.* (incl. Oguri M.), 2021, A&A, **647**, A4

[64] Moriya, T. J., Jiang, J., Yasuda, N., *et al.* (incl. Kawana K.), 2021, ApJ, **908**, 249

[65] Komaki A., Nakatani R., Yoshida N., ApJ, **910**, 51

[66] Lin H., Totani T.: Detectability of radio afterglows from binary neutron star mergers and implications for fast radio bursts, MNRAS, 498, 2384-2390 (2020).

[67] Kataoka J., Yamamoto M., Nakamura Y., Ito S., Sofue Y., Inoue Y., Nakamori T., Totani T.: Origin of Galactic Spurs: New Insight from Radio/X-Ray All-sky Maps, ApJ, 908, (2021).

[68] Lee, M. M., Tanaka, I., Iono, D., et al. (including Kohno, K.): "Revisited Cold Gas Content with Atomic Carbon [C I] in $z = 2.5$ Protocluster Galaxies", 2021, Astrophys. J. , 181, 14

[69] Okabe, N., Simon, D., Dominique, E., et al. (including Oguri, M., Kohno, K.): "Active gas features in three HSC-SSP CAMIRA clusters revealed by high angular resolution analysis of MUSTANG-2 SZE and XXL X-ray observations", 2021, Mon. Not. R. Astron. Soc., 501, 1701

[70] Izumi, T., Onoue, M., Matsuoka, Y., et al. (including Kashikawa, N., Kohno, K.): "Subaru High-z Exploration of Low-luminosity Quasars (SHELLQs). XII. Extended [C II] Structure (Merger or Outflow) in a $z = 6.72$ Red Quasar", 2021, Astrophys. J. , 908, 235

[71] Caputi, K. I., Caminha, G. B., Fujimoto, S., Kohno, K., et al.: "ALMA Lensing Cluster Survey: An ALMA Galaxy Signposting a MUSE Galaxy Group at $z = 4.3$ Behind *El Gordo*", 2021, Astrophys. J. , 908, 146

[72] Tadaki, K., Belli, S., Burkert, A., et al. (including Kohno, K.): "Structural Evolution in Massive Galaxies at $z \sim 2$", 2020, Astrophys. J. , 901, 74

[73] Yamaguchi, Y., Kohno, K., Hatsukade, B., et al.: "ALMA twenty-six arcmin^2 survey of GOODS-S at one millimeter (ASAGAO): Millimeter properties of stellar mass selected galaxies", 2020, Publ. Astron. Soc. Japan, 72, 69

[74] Akahori, T., Kitayama, T., Ueda, S., et al. (including Kohno, K., Oguri, M.): "Discovery of radio jets in the Phoenix galaxy cluster center", 2020, Publ. Astron. Soc. Japan, 72, 62

[75] Silverman, J. D., Tang, S., Lee, K.-G., et al. (including Kashikawa, N., Kohno, K., Oguri, M., Shimasaku, K.): "Dual Supermassive Black Holes at Close Separation Revealed by the Hyper Suprime-Cam Subaru Strategic Program", 2020, Astrophys. J. , 899, 154

[76] Scourfield, M., Viti, S., García-Burillo, S., et al. (including Kohno, K.): "ALMA observations of CS in NGC 1068: chemistry and excitation", 2020, Mon. Not. R. Astron. Soc., 496, 5308

[77] Yamashita, T., Nagao, T., Ikeda, H., et al. (including Kohno, K.): "A Wide and Deep Exploration of Radio Galaxies with Subaru HSC (WERGS). III. Discovery of a $z = 4.72$ Radio Galaxy with the Lyman Break Technique", 2020, Astron. J. , 160, 60

[78] Umehata, H., Smail, I., Swinbank, A. M., Kohno, K., et al.: "ALMA Deep Field in SSA22. A near-infrared-dark submillimeter galaxy at $z = 4.0$", 2020, Astron. & Astrophys., 640, L8

[79] Izumi, T., Nguyen, D. D., Imanishi, M., et al. (including Kohno, K.): "ALMA Observations of Multiple CO and C Lines toward the Active Galactic Nucleus of NGC 7469: An X-Ray-dominated Region Caught in the Act", 2020, Astrophys. J. , 898, 75

[80] Harikane, Y., Ouchi, M., Inoue, A. K., et al. (including Kohno, K.): "Large Population of ALMA Galaxies at $z > 6$ with Very High [O III] 88 μm to [C II] 158 μm Flux Ratios: Evidence of Extremely High Ionization Parameter or PDR Deficit?", 2020, Astrophys. J. , 896, 93

[81] Uno, S., Takekoshi, T., Oshima, T., et al. (including Kohno, K.): "Demonstration of wideband metal mesh filters for submillimeter astrophysics using flexible printed circuits", 2020, Applied Optics, 59, 4143

[82] Kameno, S., Sawada-Sato, S., Impellizzeri, C. M. V., et al. (including Kohno, K.): "A Massive Molecular Torus inside a Gas-poor Circumnuclear Disk in the Radio Galaxy NGC 1052 Discovered with ALMA", 2020, Astrophys. J. , 895, 73

[83] Kitayama, T., Ueda, S., Akahori, T., et al. (including Kohno, K.): "Deeply cooled core of the Phoenix galaxy cluster imaged by ALMA with the Sunyaev-Zel'dovich effect", 2020, Publ. Astron. Soc. Japan, 72, 33

[84] Bakx, T. J. L. C., Tamura, Y., Hashimoto, T., et al. (including Kohno, K.): "ALMA uncovers the [C II] emission and warm dust continuum in a $z = 8.31$ Lyman break galaxy", 2020, Mon. Not. R. Astron. Soc., 493, 4294

[85] M. Saito, S. Yamauchi, K.K. Nobukawa, A. Bamba, T. Pannuti, "X-ray emission from the mixed-morphology supernova remnant HB 9", PASJ, 72, 65 (2020) (doi: 10.1093/pasj/psaa042)

[86] A. Tanimoto, Y. Ueda, H. Odaka, S. Ogawa, S. Yamada, T. Kawaguchi, K, Ichikawa, "Application of X-Ray Clumpy Torus Model (XCLUMPY) to 10 Obscured Active Galactic Nuclei Observed with Suzaku and NuSTAR", ApJ, 897, 2 (2020) (doi: 10.3847/1538-4357/ab96bc)

[87] S. Yamada, Y. Ueda, A. Tanimoto, S. Oda, M. Imanishi, Y. Toba, C. Ricci, "Nature of Compton-thick Active Galactic Nuclei in "Nonmerging" Luminous Infrared Galaxies UGC 2608 and NGC 5135 Revealed with Broadband X-Ray Spectroscopy", ApJ, 897, 107 (2020) (doi: 10.3847/1538-4357/ab94b1)

[88] H. Suzuki, A. Bamba, R. Yamazaki, Y. Ohira, "Study on the escape timescale of high-energy particles from supernova remnants through thermal X-ray properties", PASJ, 72, 72 (2020) (doi: 10.1093/pasj/psaa061)

[89] H. Suzuki, T. Tamba, H. Odaka, A. Bamba, K. Hagino, A. Takeda, K. Mori, T. Hida, M. Yukumoto, Y. Nishioka, T.G. Tsuru, "Development of the detector simulation framework for the Wideband Hybrid X-ray Imager onboard FORCE", NIMA, 979, 164433 (2020) (doi: 0.1016/j.nima.2020.164433)

[90] T. Kasuga, H. Odaka, K. Hatauchi, S. Takashima, T. Tamba, Y. Aizawa, S. Hashiba, A. Bamba, Y. Zhou, T. Tamagawa, "Artifact-less Coded Aperture Imaging in the X-ray Band with Multiple Different Random Patterns", JATIS, 6, 035002 (2020) (doi: 10.1117/1.JATIS.6.3.035002)

[91] W.G. Ho, C.M. Espinoza, Z. Arzoumanian, T. Enoto, T. Tamba, D. Antonopoulou, M. Beiger, S. Guillot, B. Haskell, P.S. Ray, "Return of the Big Glitcher: NICER timing and glitches of PSR J0537-6910", MNRAS, 498, 4605 (2020) (doi: 10.1093/mnras/staa2640)

[92] H. Sano, P.P. Plucinsky, A. Bamba, P. Sharda, M.D. Fillipovic, C.J. Law, R.Z.E. Alsaberi, Y. Yamane, K. Tokuda, F. Acero, M. Sasaki, J. Vink, T. Inoue, S. Inutsuka, J. Shimoda, K. Tsuge, K. Fujii, F. Voisin, N. Maxted, G. Rowell, T. Onishi, A. Kawamura, N. Mizuno, H. Yamamoto, K. Tachihara, Y. Fukui, "ALMA CO Observations of Gamma-Ray Supernova Remnant N132D in the Large Magellanic Cloud: Possible Evidence for Shocked Molecular Cloud Illuminated by Cosmic-Ray Protons", ApJ, 902, 53 (2020) (doi: 10.3847/1538-4357/abb469)

[93] A. Bamba, E. watanabe, K. Mori, S. Shibata, Y. Terada. H. Sano, M.D. Filopovic, "Low X-ray Efficiency of a Young High-B Pulsar PSR J1208-6238 Observed with Chandra", Ap&SS, 365, 178 (2020) (doi: 10.1007/s10509-020-03891-6)

[94] K. Hagino, H. Odaka, G. Sato, T. Sato, H. Suzuki, T. Mizuno, M. Kawaharada, M. Ohno, K. Nakazawa, S.B. Kobayashi, H. Murakami, K. Miyake, M. Asai, T. Koi, G. Madejski, S. Saito, D.H. Wright, T. Enoto, Y.

Fukazawa, K. Hayashi, J. Kataoka, J. Katsuta, M. Kokubun, P. Laurent, F. Lebrun, O. Limousin, D. Maier, K. Makishima, K. Mori, T. Nakamori, T. Nakano, H. Noda, M. Ohta, R. Sato, H. Tajima, H. Takahashi, T. Takahashi, S. Takeda, T. Tanaka, Y. Terada, H. Uchiyama, Y. Uchiyama, S. Watanabe, K. Yamaoka, Y. Yatsu, T. Yuasa, "Origin of the in-orbit instrumental background of the Hard X-ray Imager onboard Hitomi", JATIS, 6, 046003 (2020) (doi: 10.1117/1.JATIS.6.4.046003)

[95] M. Mizumoto, M. Nomura, C. Done, K. Ohsuga, H. Odaka, "UV line driven disc wind as the origin of ultrafast outflows in AGN", MNRAS, 503, 1442 (2021) (doi: 10.1093/mnras/staa3282)

[96] T. Nagayoshi, A. Bamba, S. Katsuda, Y. Terada, "Detection of the hard X-ray non-thermal emission from Kepler's supernova remnant", PASJ, in press

[97] Y. Fujita, A. Bamba, K.K. Nobukawa, H. Matsumoto, "X-ray Emission from the PeVatron-Candidate Supernova Remnant G106.3+2.7", PASJ, in press

[98] S. Ogawa, Y. Ueda, A. Tanimoto, S. Yamada. "Systematic Study of AGN Clumpy Tori with Broadband X-ray Spectroscopy: Updated Unified Picture of AGN Structure", ApJ, 906, 84 (2021) (doi: 10.3847/1538-4357/abccce)

[99] R. Uematsu, Y. Ueda, A. Tanimoto, T. Kawamuro, K. Setoguchi, S. Ogawa, S. Yamada, H. Odaka, "X-ray Constraint on Location of AGN Torus in Circinus Galaxy", ApJ, in press [arxiv]

[100] R. Tomaru, C. Done, K. Ohsuga, H. Odaka, T. Takahashi, "The thermal-radiative wind in low mass X-ray binary H 1743-322: II. iron line predictions from Monte Carlo radiation transfer", MNRAS, 494, 3413 (2020)

[101] R. Tomaru, C. Done, K. Ohsuga, H. Odaka, T. Takahashi, "The thermal-radiative wind in the neutron star low-mass X-ray binary GX 13 + 1", MNRAS, 497, 4970 (2020)

[102] Y. Wada, T. Enoto, K. Nakazawa, H. Odaka, Y. Furuta, H. Tsuchiya, "Photonuclear Reactions in Lightning: 1. Verification and Modeling of Reaction and Propagation Processes", JGR Atmospheres, 125, e2020JD033193 (2020)

[103] Y. Wada, T. Enoto, K. Nakazawa, T. Yuasa, Y. Furuta, H. Odaka, K. Makishima. H. Tsuchiya, "Photonuclear Reactions in Lightning: 2. Comparison Between Observation and Simulation Model", JGR Atmospheres, 125, e2020JD033194 (2020)

[104] K. Makishima, T. Enoto, H. Yoneda, H. Odaka, "A NuSTAR confirmation of the 36 ks hard X-ray pulse-phase modulation in the magnetar 1E 1547.0–5408", MNRAS, 502, 2266 (2021)

[105] Toba, Y. et al. (additional 27 co-authors including Momose. R.), "Search for Optically Dark Infrared Galaxies without Counterparts of Subaru Hyper Suprime-Cam in the AKARI North Ecliptic Pole Wide Survey Field", 2020, ApJ, 899, Issue 1, id.35

[106] Ando, M., Shimasaku, K., Momose, R., "A systematic search for galaxy proto-cluster cores at $z \sim 2$", 2020, MNRAS, 496, pp.3169-3181

[107] Ishimoto, R. et al. (additional 16 co-authors including Momose. R.), "Subaru High-z Exploration of Low-luminosity Quasars (SHELLQs). XI. Proximity Zone Analysis for Faint Quasar Spectra at $z \sim 6$", 2020, ApJ, 903, id.60, 11pp.

[108] Inoue, A. K. et al. (additional 30 co-authors including Shimasaku, K. and Momose. R.), "CHORUS. I. Cosmic HydrOgen Reionization Unveiled with Subaru: Overview", 2020, PASJ, 72, 101, 17pp.

[109] Liang, Y. et al. (additional 13 authors including Kashikawa, N. and Shimasaku, K.), "Statistical Correlation between the Distribution of Lyα Emitters and Intergalactic Medium HI at $z \sim 2.2$ Mapped by the Subaru/Hyper Suprime-Cam", 2021, ApJ, 907, id.3, 21pp.

[110] Silverman, J. D. et al. (additional 32 authors including Kashikawa, N. and Shimasaku, K.), "Dual Supermassive Black Holes at Close Separation Revealed by the Hyper Suprime-Cam Subaru Strategic Program", 2020, ApJ, 899, id.154, 12pp.

[111] Gu, L. et al. (additional 8 authors including Shimasaku, K.), "Implications of the mild gas motion found with Hitomi in the core of the Perseus cluster", 2020, A&A, 638, 138, 15pp.

[112] Ando, M., Shimasaku, K., Momose, R., "A systematic search for galaxy proto-cluster cores at $z \sim 2$", 2021, IAUS, 359, 166

[113] Kim, S. J. et al. (additional 23 co-authors including Momose. R.), "Identification of AKARI infrared sources by the Deep HSC Optical Survey: construction of a new band-merged catalogue in the North Ecliptic Pole Wide field", 2021, MNRAS, 500, pp.4078-4094

[114] Oi, N., Goto, T., Matsuhara, H., Utsumi, Y., Momose, R., Toba, Y., Malkan, M., Takagi, T., Huang, T.-C., Kim, S. J., Ohyama, Y., 2021, "Subaru/HSC deep optical imaging of infrared sources in the AKARI North Ecliptic Pole-Wide field", 2021, MNRAS, 500, pp.5024-5042

[115] Momose, R., Shimasaku, K., Kashikawa, N., Nagamine, K., Shimizu, I., Nakajima, K., Terao, Y., Kusakabe, H., Ando, M., Motohara, K., Spitler, L., 2021, "Environmental Dependence of Galactic Properties Traced by Lyα Forest Absorption: Diversity among Galaxy Populations", 2021, ApJ, 909, id.117, 21pp.

[116] Ono, Y. et al. (additional 27 co-authors including Shimasaku, K. and Momose. R.) "SILVERRUSH X: Machine Learning-aided Selection of 9318 LAEs at $z = 2.2, 3.3, 4.9, 5.7, 6.6, and 7.0$ from the HSC SSP and CHORUS Survey Data", 2021, ApJ, in press.

[117] Momose, R., Shimizu, I., Nagamine, K., Shimasaku, K., Kashikawa, N., Kusakabe, H., "Connection between Galaxies and HI in Circumgalactic and Intergalactic Media: Variation according to Galaxy Stellar Mass and Star Formation Activity", 2021, ApJ, in press.

[118] Momose, R., Shimasaku, K., Nagamine, K., Shimizu, I., Kashikawa, N., Ando, M., Kusakabe, H., "Catch Me if You Can: Biased Distribution of Lyα-emitting Galaxies according to the Viewing Direction", 2021, ApJL, in press.

[119] Shimakawa, R. et al. (additional 10 co-authors including Momose. R.), "Subaru Hyper Suprime-Cam excavates colossal over- and underdense structures over 360 deg^2 out to $z = 1$", 2021, MNRAS, in press.

[120] Zhilei Xu, *et al.*, "The Simons Observatory: metamaterial microwave absorber and its cryogenic applications," Appl. Opt. 60, 864-874 (Feb 2021).

[121] Maximilian H. Abitbol, *et al.*, "The Simons Observatory: Bandpass and polarization-angle calibration requirements for B-mode searches", arXiv:2011.02449 (Nov 2020)

[122] The Polarbear Collaboration, "A measurement of the CMB E-mode angular power spectrum at subdegree scales from 670 square degrees of Polarbear data," Astrophys. J., 904(1):65 (Nov 2020)

[123] Zack Li, *et al.*, "The cross correlation of the ABS and ACT maps," JCAP09(2020)010 (Sep 2020)

[124] The Polarbear Collaboration, "A Measurement of the Degree Scale CMB B-mode Angular Power Spectrum with Polarbear," Astrophys. J., 897(1):55 (Jul 2020)

[125] Masashi Nashimoto, Makoto Hattori, and Yuji Chinone, "CMB Shadows: The Effect of Interstellar Extinction on Cosmic Microwave Background Polarization and Temperature Anisotropy," Astrophys. J. Letter, 895(1):21 (May 2020)

[126] The Polarbear Collaboration, "Measurement of the Cosmic Microwave Background Polarization Lensing Power Spectrum from Two Years of Polarbear Data," Astrophys. J., 893(1):85 (Apr 2020)

[127] The Polarbear Collaboration, "Internal delensing of cosmic microwave background polarization B-modes with the Polarbear experiment," Physical Review Letters, 124(13):131301 (April 2020)

[128] C. A. Hill, A. Kusaka, *et al.*, "A cryogenic continuously rotating half-wave plate mechanism for the POLARBEAR-2b cosmic microwave background receiver," Review of Scientific Instruments 91, 124503 (2020)

5.3 International Conference Talks

5.3.1 Contributed talks

[129] Yoshida N., "Spiral Arm Instability in Primordial Protostellar Disks", UT Joint Workshop on Protoplanetary Disks and Planets, Online(May 5, 2020)

[130] Komaki A., Nakatani R., Yoshida N., "Photoevaporation from Protoplanetary Disk(Hydrodynamical simulation): Dependence on Central Star Spectrum", UT Joint Workshop on Protoplanetary Disks and Planets, Online(May 5, 2020)

[131] Momose, R. et al.: "Systemic investigations for mock observed Lyman-alpha halos", European Astronomical Society Annual Meeting, Online, 2020/06

[132] Lin, H., "Detectability of radio afterglows from FRBs produced by neutron star mergers", Fast Radio Bursts 2020 Thailand Meeting, online, Jul. 6-9, 2020

[133] Kana Moriwaki, "Component extraction from line intensity maps with conditional GAN", RESCEU Summer School, Online(August 17, 2020)

[134] Keisuke Inomata, "Scalar perturbations induced by scalar perturbations", RESCEU Summer School 2020, Online, 2020/8/18.

[135] F. Uchida, “A baryogenesis scenario from helical magnetic fields and constraints on it”, RESCEU Summer School 2020, Online, 2020/8/19.

[136] J. Kume, “Quantum correction in gravitational leptogenesis and its renormalization”, RESCEU Summer School 2020, Online, 2020/8/19.

[137] K. Tokeshi, “PBH mass spectrum and window function dependence”, RESCEU Summer School 2020, Online, 2020/8/19.

[138] M. He, “Tachyonic preheating in the mixed Higgs-R^2 model”, RESCEU summer school 2020, Online, 2020/08/19.

[139] T. Hayashi, “Towards Coleman-de Luccia bubble nucleation in the Lorentzian path integral” RESCEU Summer School, RESCEU summer school 2020, Online, 2020/08/19.

[140] J. Kume, “Towards the offline noise subtraction using Independent Component Analysis”(poster), 25th KAGRA Face-to-Face Meeting, Online, 2020/8/20-22.

[141] Yuji Chinone, “A Null test framework for B-mode measurements with Polarbear,” CMB systematics and calibration focus workshop, Kavli IPMU, Kashiwa, Japan, Online (November 2020)

[142] F. Uchida, “Constraint on the intergalactic magnetic field from baryon isocurvature perturbations at the Big-Bang Nucleosynthesis”, AAPPS-DACG Workshop on Astrophysics, Cosmology and Gravitation, Online, 2020/11/11.

[143] J. Kume, “Renormalization in the minimal model of the gravitational leptogenesis”, AAPPS-DACG Workshop on Astrophysics, Cosmology and Gravitation, Online, 2020/11/11.

[144] T. Hayashi, “The effect of Hawking radiation on BH catalyzed phase transition”, AAPPS-DACG Workshop on Astrophysics, Cosmology and Gravitation, Online, 2020/11/11.

[145] K. Tokeshi, “Primordial black holes and uncertainty of the mass function: window function dependence,” AAPPS-DACG Workshop on Astrophysics, Cosmology and Gravitation, Online, 2020/11/11.

[146] K. Tokeshi, “Primordial black holes, improved mass function, and its window function dependence,” The Online Workshop on General Relativity and Gravitation in Japan (Online JGRG), Online, 2020/11/23.

[147] F. Uchida, “Constraints on baryogenesis from primordial magnetic fields”, The Online Workshop on General Relativity and Gravitation in Japan (Online JGRG), Online, 2020/11/24.

[148] M. He, “Reheating in the mixed Higgs-R^2 model”, The Online Workshop on General Relativity and Gravitation in Japan (Online JGRG), Online, 2020/11/24.

[149] J. Kume, “Offline noise subtraction in KAGRA using independent coomponent analysis”, The Online Workshop on General Relativity and Gravitation in Japan (Online JGRG), Online, 2020/11/27.

[150] Lin, H., “Afterglows from neutron stars and fast radio bursts”, Connecting high-energy astroparticle physics for origins of cosmic rays and future perspectives (CRPHYS2020), YITP, Kyoto University, Japan, Dec. 7-10, 2020

[151] Hiromasa Suzuki, Aya Bamba, Ryo, Yamazaki, Yutaka Ohira, “Observational gamma-ray and X-ray study on cosmic-ray escape from supernova remnants”, YITP workshop, 7-10 December 2020, Kyoto (oral)

[152] Tomoaki Kasuga, Hirokazu Odaka, Tsubasa Tamba, Kosuke Hatauchi, Taihei Watanabe, Atsushi Tanimoto, Satoshi Takashima, Sorato Nanmoku, “cipher: a CubeSat-Based Hard X-ray Imaging Polarimetry Mission”, YITP workshop, 7–10 December 2020, Kyoto (oral)

[153] Satoshi Takashima, Hirokazu Odaka, Aya Bamba, Hiroki Yoneda, Masato Kimura, Masashi Tanaka, Kohei Yorita, ”GRAMS project: A MeV gamma-ray large area telescope using liquid argon and its concept study”, YITP workshop, 7-10 December 2020, Kyoto (poster)

[154] Mitani H.,”Stellar wind effect on the atmospheric escape of hot Jupiters”, AGU Fall Meeting, Online(December 8, 2020)

[155] Kotaro Kohno: “Large format imaging spectrograph for the Large Submillimeter Telescope (LST)”, SPIE digital forum, Astronomical Telescope + Instrumentation 2020 (on-line, Dec.14–18, 2020)

[156] J. Kume, “Noise subtraction in offline data analysis of KAGRA”(poster), 26th KAGRA Face-to-Face Meeting, Online, 2020/12/17-18.

[157] J. Kume, “Noise subtraction in offline analysis of KAGRA using independent component analysis”, The 7th KAGRA International Workshop, National Central U. Taiwan, Online, 2020/12/19.

[158] Kotaro Kohno: “Dust-enshrouded galaxies uncovered by ALMA deep surveys”, CONquest workshop (on-line, Jan.19–22, 2021)

[159] Hiromasa Suzuki, Aya Bamba, Rei Enokiya, Hiroya Yamaguchi, Paul P. Plucinsky, Hirokazu Odaka, "Uniform distribution of the extremely overionized plasma in the SNR G359.1-0.5 and its implication for the SNR evolution", COMMITTEE ON SPACE RESEARCH (COSPAR), 28 January - 4 February, 2021, Sydney, Australia (oral)

[160] Tomoaki Kasuga, Hirokazu Odaka, Tsubasa Tamba, Kosuke Hatauchi, Taihei Watanabe, Atsushi Tanimoto, Satoshi Takashima, Sorato Nanmoku, "Concept of the cipher Mission: a CubeSat for the Imaging Polarimetry in the Hard X-ray Band", 43rd COSPAR Scientific Assembly, 28 January–4 February 2021, On-line (oral)

[161] Kana Moriwaki, "[OIII] line emitters as a probe of galaxy-21 cm cross-correlation signals from the early stage of reionization", SAZERAC The 21-cm Signal from Cosmic Dawn and the Epoch of Reionization, Online(January 29, 2021)

[162] Oguri M., "Summary", Time-domain Cosmology with strong gravitational lensing, Online (January 25–February 2, 2021)

[163] Momose, R. et al.: "The diversity of IGM-galaxy connection at redshift $z = 2-3$", Galaxy Evolution Workshop 2020, Online, 2021/02

[164] Kazumi Kashiyama, "Can repeating fast radio bursts still be rotation powered?", YITP International Molecule-type Workshop : Fast Radio Bursts: A Mystery Being Solved?, Online(February 8–19,2021)

[165] Momose. R. et al.: "Environmental Dependence of Galactic Populations Traced by Lyα Forest Tomography", PFS Collaboration Meeting 2021, Online, 2021/03

[166] Yuji Chinone, "Systematics–POLARBEAR/Simons Array perspective," CMB-S4 Spring 2021 Collaboration meeting, Online (March 2021)

[167] Oguri M., "Wide Imaging with Subaru HSC of the Euclid Sky (WISHES)", Subaru Users Meeting FY2020, Online (March 3–5, 2021)

5.3.2 Invited talks

[168] Yoshida N., "Zooming in onto the origin of heavy elements", First Light Reunion, Online(May 29, 2020)

[169] K. Kamada, "Towards a robust estimate for gravitational leptogenesis", Zooming in on Axions in the Early Universe, Virtual Institute at CERN, Online, 2020/6/24.

[170] J. Yokoyama, "Dark matter and baryon number generation in quintessential inflation," Japan-Netherlands symposium on Gravity and Cosmology, Online, 2020/7/27.

[171] A. Bamba. "Electromagnetic observations of neutron stars", "Workshop on Frontiers of Nuclear Structure and Nuclear Astrophysics", On-line, 2020 Oct. 14-16

[172] Kotaro Kohno: "Broader bandwidth – extragalactic science cases", The ALMA 2030 Vision: Design considerations for Digitizers, Backend and Data Transmission System (on-line, October 14–16, 2020)

[173] J. Yokoyama, "Gravitational waves as a new probe of the universe," 38th SPP conference, Online, 2020/10/19.

[174] Hartwig T., "The First Stars", SAZERAC, Online (October 22, 2020)

[175] Kana Moriwaki, "Deep learning application for line intensity mapping", The 9th KIAS Workshop on Cosmology and Structure Formation, Seoul(November 3, 2020)

[176] Yoshida N., "Distribution of the Cosmic Relic Neutrinos", KIAS Cosmology Conference, Online(November 5, 2020)

[177] J. Yokoyama, "Gravitational waves from the early universe," Korea-Japan joint session of KPS annual meeting, Online, 2020/11/6.

[178] Tomonori Totani, "Gamma-ray bursts as a probe of intergalactic medium and cosmic reionization", Invited talk at workshop "Probing the Extragalactic Universe with High Energy and Very High Energy Sources" Dec. 9-11, 2020, online.

[179] Kazumi Kashiyama, "Fast Radio Bursts and their possible counterparts", Probing the Extragalactic Universe with High Energy and Very High Energy Sources, Online(December7–10, 2020)

[180] K. Kamada, "Primordial magnetic field – Its relationship to cosmology and implication to the IGMF", NECO on-line workshop "Probing the Universe with High and Very High Energy Sources", International Research Network Extragalactic Astrophysics and Cosmology, Online, 2020/12/9.

[181] Kazumi Kashiyama, "Fast Radio Bursts: A Mystery Being Solved?", Connecting high-energy astroparticle physics for origins of cosmic rays and future perspectives, Online(December9–11, 2020)

[182] J. Yokoyama, "Mixed Higgs R^2 inflation," 7th Korea-Japan workshop on dark energy, Online, 2020/12/10.

[183] Kotaro Kohno: "Future plans of KAKENHI program I: DESHIMA2.0 on ASTE campaign 2021", ALMA/45m/ASTE Users Meeting 2020 (on-line, January 5–7, 2021)

[184] Kotaro Kohno: "Uncovering obscured galaxies using Large Millimeter Telescope and ALMA", 2nd International Colloquium of Mexican and Japanese Studies: Distance, Interconnectedness and Sharing (on-line, Jan. 31–Feb. 02, 2021)

[185] Yoshida N., "Statistical Computational Cosmology with Big Astronomical Data", ERCIM Symposium on Data Science, Online(February 19, 2021)

[186] Yoshida N., "The First Generation of Stars and Blackholes in the Universe", Higgs Colloquium, University of Edinburgh, Edinburgh(February 26, 2021)

[187] Yoshida N., "Cosmic Relic Neutrinos and Large-Scale Structure: Nonlinear Clustering and the Neutrino Mass", CfA Colloquium, Harvard-Smithsonian Center for Astrophysics, Cambridge(March 5, 2021)

[188] Oguri M., "Introduction to WISHES", UNIONS Collaboration Meeting 2021, Online (March 9–10, 2021)

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 sometimes also electromagnetic observations as well. 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 evergy was only achieved in 2015.

Our research group's members are members of the LIGO Scientific Collaboration (LSC) 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 conducting their third observational data-taking run, "O3", through the 2019/2020 academic year, and were expected to continue through most of the 2020/2021 academic year, however, due to the pandemic, observations were stopped in late March 2020, and so unfortunately the 2020/2021 academic year saw no new data from the LIGO/Virgo detector network. Members of our group are active in all aspects of observational gravitational-wave astronomy, the following are some highlights from FY2020.

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 saw many new discoveries of black hole and neutron star collisions. Two of these are especially noteworthy. The gravitational wave signal GW190814 (doi:10.3847/2041-8213/ab960f) was the collision of a 23 solar-mass black hole and an object with the unusual mass of about 2.6 solar masses. It's not clear if the lighter object is a neutron star or black hole, and both options are unusual. If a neutron star, it would be the heaviest neutron star known and above the maximum mass allowed by a number of neutron star equation of state models; if a black hole, it might be the smallest known black hole. The signal was discovered by the GstLAL detection system developed by members of RESCEU. A second remarkable discovery was GW190521, a collision of two black holes with a total mass of 150 solar masses. Both of the black holes involved in the collision, and certainly the heavier of the two, have masses above the so-called pair production bound. This refers to a process triggering the collapse of a star when its core reaches a certain mass, and because of this process it's believed that black holes above that mass cannot form during supernovae. These black holes were larger than that limit. They might be the result of earlier collisions of smaller black holes, but in any case their life stories are more complicated than the other black holes we've observed.

Other on-going projects within our group include the development of techniques for removing signals from detector data for the purpose of constructing clean noise models, the development of an ultra high-speed sky mapping system suitable for use in early-warning detection systems, and the development of a system to estimate the sensitivity of a search for gravitational waves mathematically, replacing the current computationally costly technique of hiding fake signals in the data and searching for them with the detection software. Group members have contributed to the search for gravitational-wave echoes from gravitational lenses — waves from compact object collisions that arrive at Earth from multiple directions at different times from having followed more than one path through spacetime. Studies of compact object collisions are in some ways limited by the available computer resources, so the more efficiently we can use them the more knowledge we can obtain, and improving analysis efficiency is a theme in our group. One on-going project in this regard is the development of techniques to reduce the enormous data volume of the detection systems to allow intermediate retained and reused for multiple analyses.

Transients from Newborn Black Holes

The origin of the binary black holes detected by the Advanced LIGO and Virgo detectors is one of the biggest problems in gravitational wave astrophysics. One unique pathway to probe this is to directly observe the formation of black holes. With members of other labs in RESCEU, we are conducting theoretical research on transients following black hole formation. When a black hole forms from a massive star, a fraction of the outer envelope is ejected because gravity from the collapsing core decreases due to emission of neutrinos. We calculated months-long electromagnetic emission from this mass ejection, and found that this can explain the enigmatic intermediate luminosity red transients found by recent transient surveys [15]. We have also researched the possibility of observing black hole formation through gravitational waves. A recent re-analysis of the neutron star merger event GW170817 resulted in a tentative detection of a gravitational-wave signal at 1 second post-merger. We have shown that a phenomenon called gravitational wave echoes, inspired by models of quantum gravity, can explain the amplitude and frequency of this signal. We have also shown that these echo signals, if real, can also be caught by future gravitational-wave detectors when massive stars in nearby galaxies collapse to black holes [16, 17].

Exotica

Cosmic strings are theoretical topological defect structures left over from the cooling process of the early Universe. Although none have been discovered, a broad spectrum of theories of fundamental physics predict their existence. Even if they exist, they might be so rare that none are present in the part of the Universe visible to us. Either way, searching for them and either confirming their existence or putting limits on their number will teach us a great deal about fundamental physics. Members of our group led the development of the LSC and Virgo Collaboration's cosmic string detection pipeline and are currently analyzing the data collected during the O3 observing run, searching for evidence of these signals using a new analysis system developed by RESCEU members. The new system is more computationally efficient than the previous system, and makes use of more sophisticated statistical analyses allowing it to make a confident detection claim should a signal ever be found in the future. The results of this work were published this past year in June 2021 at Physical Review Letters.

Recently we have begun developing a search for Cherenkov radiation-like bursts of gravitational waves. When an electric charge moves through a medium above the speed of light in that medium it generates an optical shock wave — a flash of light known as Cherenkov radiation. This same phenomenon occurs in accoustic systems as a sonic boom, and as the wake behind boats moving through water above the speed of surface waves. It stands to reason that a gravitational charge (a mass) moving at superluminal speeds would generate a gravitational wave flash in a similar way. There is some interest in this phenomenon at the microscopic scale as a symptom of non-Lorenze invariance, but at the macroscopic level there is no known source mechanism. Nevertheless, as an educational exercise for students, developing a search for such signals will be a very productive and entertaining activity.

Test of gravity with gravitational-wave polarizations

Many gravity theories that extend the general theory of relativity have been proposed so far, and it is important to verify the correctness of the theory from various aspects with higher accuracy in order to deepen our understanding of gravity. Since the first detection of gravitational waves, it has become possible to investigate the nature of gravity in the vicinity of celestial bodies that emit gravitational waves, that is, in a dynamical and extremely strong gravitational field. One of the ways for verifying gravity in such a situation is the polarization modes of gravitational waves. The number of polarization modes is unique to each gravity theory. There are two tensor modes in general relativity, while three or more polarization modes in extended theories of gravity. In other words, the true gravity theory can be identified by examining the number of polarization modes from the observation data. We analyzed the actual observation data of the gravitational wave detectors and found no signs of polarizations inconsistent with the prediction of general relativity [26]. Therefore, we obtained a new result that supports the correctness of general relativity. In addition, in order to test the theories of gravity, we study cosmological models in the concrete modified gravity theories and classify them based on the observational properties about gravitational waves [21].

Future Observatories

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 may overlap each other, which may 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.

Study on sensitivity improvement for the future gravitational-wave detectors

Currently operating gravitational wave detectors on the ground are LIGO, Virgo, KAGRA and GEO600, which will be upgraded and more sensitive within the next five years. Since the best way of the upgrade depends on technologies available today and their difficulties to realize, the detailed examination is required. We joined the working group on an upgrade of the Japanese detector KAGRA to KAGRA+ and considered the update plan and the sensitivity optimization [20]. Meanwhile, a space gravitational wave detector is also planned for his future in the 2030s. In particular, the DECIGO project, which is being promoted mainly by Japan, aims to detect primordial gravitational waves originating from inflation, and sensitivity improvement and optimization for that purpose are also being studied [22].

People and Things

One of our Master's students, Mr. Chi-Wai Chan, defended his thesis and continued in our group as a doctoral student, and one of our doctoral students, Dr. Leo Tsukada, successfully defended his thesis and has secured a research position at Pennsylvania State University, where he will continue his work on searches for stochastic gravitational wave backgrounds and for compact object collisions.

6.1.2 Kenta Hotokezaka group

Kilonova, r-process, radio counterpart

Kilonovae are optical-near IR transients associated with binary neutron star mergers and black hole neutron star mergers. In the LIGO/Virgo O3 observing run, the compact binary merger candidates were actively observed in the optical band to find a kilonova. However, no kilonova candidates were found. We highlighted the follow-up campaigns for two neutron star black hole candidates, two binary black hole candidates, and a Mass-Gap binary candidate [1]. We concluded that the follow-up observations are too shallow to catch the canonical kilonova signature.

We studied the turbulent mixing of r-process elements in the interstellar medium [7]. We found that the inhomogeneity of r-process elements inferred from the various measurements such as the chemical abundances of metal poor stars, the geological measurements of short-lived r-process elements supports the neutron star merger scenario of the origin of r-process elements.

We participated in a radio follow-up observations for GW170817 with LOFAR [2]. Unfortunately, no signal was found partly due to the fact that the sky location of GW170817 is not optimal for LOFAR. We also studied the potential that future radio observations can constrain the size of the emission region of the radio counterparts of neutron star mergers [4].

We found that both VLBI measurements and scintillation methods will be powerful to constrain the size and superluminal motion of the merger outflows for events with distance out to $\sim 100\,\mathrm{Mpc}$.

Shock Acceleration of neutrinos in core collapse supernovae

In core collapse supernovae (CCSNe), a huge amount of energy is carried away by neutrinos. Indeed, this picture was confirmed by the direct neutrino observations of SN 1987A. If the next Galactic supernova happens, it is expected that the deep inside of core collapse explosion can be studied in great detail with 10^3 to 10^4 neutrinos, c.f., Kamiokande II detected only a dozen of neutrinos.

We studied the neutrino shock acceleration taking place in core-collapse supernova [6]. The leading players here are heavy leptonic neutrinos, ν_μ and ν_τ; the former and latter potentially gain the energy up to 100 and 200 MeV, respectively, through the shock acceleration because they interact with material mainly through scatterings with nucleons and nuclei. By using a Monte Carlo neutrino transport simulation, we showed that the neutrino shock acceleration commonly occurs in the early post-bounce phase (<50 ms after bounce) for all massive stellar collapse experiencing nuclear bounce and would reoccur in the late phase (>100 ms) for failed CCSNe. This produces a distinctive high energy tail around 100 MeV. We estimated the expected event counts for Hyper(Super)-Kamiokande, DUNE, and JUNO. We found that the event counts with the energy of >80 MeV are a few orders of magnitude higher than that of the thermal neutrinos regardless of the detectors, and muon production may also happen in these detectors by ν_μ with the energy of >100 MeV. Such neutrino signals will provide a precious information on deciphering the inner dynamics of CCSN and placing a constraint on the physics of neutrino oscillation; indeed, the detection of the high energy neutrinos through charged current reaction channels will be a smoking gun evidence of neutrino flavour conversion.

6.2 Activity report of Affiliates

6.2.1 Ando Masaki

The Ando group is working on experimental research for gravitational-wave observations, in particular for large projects such as KAGRA and B-DECIGO. KAGRA is a gravitational-wave antenna at Kamioka, Gifu prefecture in Japan. We have been playing a key role since the conceptual study phase before the start of the project in 2010. The installation of the main components was completed in FY2018, and we are in the commissioning phase; shakedown and tuning for full operation of the interferometer. In FY2020, the KAGRA interferometer started an observation run, named O3GK. Our group members led the commissioning and operation of the interferometer. We are also working on B-DECIGO, which will be a space-borne gravitational wave antenna with observation band around 0.1 Hz. We conducted theoretical studies of science cases for this mission as well as experimental development of critical subsystems, such as laser interferometer, stabilized laser source, drag-free system, and low-noise thruster. In FY2020, we continued a system design study with a company so as to show the feasibility of the full mission. This activity wad financially supported by RESCEU. In addition to these experimental activities, we are also working on theoretical and data-analysis research. The motivation is to test the theory of gravity using polarization information of the observed gravitational-wave signal. We made estimations of test precisions using current and future gravitational-wave antennae.

6.2.2 Doi Mamoru

Two optical instruments are being developed by Doi, Shigeyama and other colleagues, with the goal of studying Kilonovae and other transients.

The first instrument is the Tomo-e Gozen camera (Tomo-e), which is a wide-field optical camera with 84 2k $\times$ 1k CMOS sensors on the prime focus of the 1.05 m Kiso Schmidt telescope. The CMOS array enables us to take consecutive images with a rate of 2 frames per second covering an instantaneous field-of view (FoV) of 20 square degrees. Tomo-e can do very wide ($\sim$one thousand square degree) searches for the optical counterpart of a GW source in one hour. Tomo-e can also search for kilonova by itself with wide surveys. In FY2020 we have carried out a mixed wide survey with a single scan of the $7000\,\mathrm{deg}^2$ sky and a frequent survey of a $2000\,\mathrm{deg}^2$ sky area more than 10 times every night with intervals shorter than 1 hour. In FY2020, about 2 PByte 2 fps data were taken, and 100 TByte data were reserved after stacking images by 6 seconds – 9 seconds. The data have been processed with dedicated pipeline software which searches for transients/moving objects using machine learning techniques. More than 20 newly discovered near-Earth objects were found, and many supernovae have been observed so far. There was no Kilonova candidate found, though we are still improving data analysis, and making better reference images taken by Tomo-e itself.

The second instrument is TriCCS, a three band (g,r,i or z) simultaneous imaging spectrograph for a Nasmyth focus of the Seimei 3.8 m telescope. TriCCS is being developed by Doi, Sako, Niino (UTokyo), Maeda, Matsubayashi, Ohta, Kawabata (Kyoto University), and graduate students. TriCCS adopts high sensitivity CMOS sensors by Canon Co., which can take 100 frames per second. The field of view of TriCCS is about 10' $\times$ 5', which is not very wide, but color or spectral information can be obtained, taking advantage of the 3.8 m telescope aperture. Hence TriCCS is suitable for deep follow-up observations of kilonova and other transients. Commissioning observations were carried out five times in FY2020, and the basic performance for imaging mode was verified, which will be open to the community in 2021B. Preparation of low-resolution spectroscopy mode was also done.

Simultaneous observations of Fast Radio Bursts were also carried out with Tomo-e and CHIME experiment twice in March 2021. Unfortunately there was no FRB during the observation periods.

6.3 Publication List

[1] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Optically targeted search for gravitational waves emitted by core-collapse supernovae during the first and second observing runs of advanced LIGO and advanced Virgo", Physical Review D, 101, 084002 (2020).

[2] R. Hamburg *et al.* (Fermi Gamma-ray Burst Monitor Team and LIGO Scientific Collaboration and Virgo Collaboration), "A joint fermi-GBM and LIGO/Virgo analysis of compact binary mergers from the first and second gravitational-wave observing runs", Astrophysical Journal, 893, 100 (2020).

[3] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "GW190814: Gravitational waves from the coalescence of a 23 solar mass black hole with a 2.6 solar mass compact object", Astrophysical Journal, 896, L44 (2020).

[4] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "GW190412: Observation of a binary-black-hole coalescence with asymmetric masses", Physical Review D, 102, 043015 (2020).

[5] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Prospects for observing and localizing gravitational-wave transients with Advanced LIGO and Advanced Virgo", Living Reviews in Relativity, 23, 3 (2020).

[6] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "GW190521: A binary black hole merger with a total mass of $150\,M_{\odot}$", Physical Review Letters, 125, 101102 (2020).

[7] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Properties and astrophysical implications of the $150\,M_\odot$ binary black hole merger GW190521", Astrophysical Journal Letters, 900, L13 (2020).

[8] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Gravitational-wave constraints on the equatorial ellipticity of millisecond pulsars", Astrophysical Journal Letters, 902, L21 (2020).

[9] T. Akutsu *et al.* (KAGRA Collaboration), "Vibration isolation system with a compact damping system for power recycling mirrors of KAGRA", Classical and Quantum Gravity, 38, 065011 (2021).

[10] T. Akutsu *et al.* (KAGRA Collaboration), "Overview of KAGRA: Calibration, detector characterization, physical environmental monitors, and the geophysics interferometer', Progress of Theoretical and Experimental Physics, ptab018 (2021).

[11] T. Akutsu *et al.* (KAGRA Collaboration), "Overview of KAGRA : Detector design and construction history", Progress of Theoretical and Experimental Physics, ptaa125 (2020).

[12] T. Akutsu *et al.* (KAGRA Collaboration), "Overview of KAGRA : KAGRA science", Progress of Theoretical and Experimental Physics, ptaa120 (2020).

[13] T. Akutsu *et al.* (KAGRA Collaboration), "Application of independent component analysis to the iKAGRA data", Progress of Theoretical and Experimental Physics, 2020, 053F01 (2020).

[14] D. Tsuna, A. Ishii, N. Kuriyama, K. Kashiyama, T. Shigeyama, "Intermediate Luminosity Red Transients by Black Holes Born from Erupting Massive Stars", Astrophysical Journal Letters, 897, L44 (2020).

[15] N. Oshita, D. Tsuna, and N. Afshordi, "Quantum Black Hole Seismology I: Echoes, Ergospheres, and Spectra", Physical Review D, 102, 024045 (2020).

[16] N. Oshita, D. Tsuna, and N. Afshordi, "Quantum Black Hole Seismology II: Applications to Astrophysical Black Holes", Physical Review D, 102, 024046 (2020).

[17] S. Zhu, M. Baryakhtar, M. A. Papa, D. Tsuna, N. Kawanaka, H.-B. Eggenstein, "Characterizing the Continuous Gravitational-Wave Signal from Boson Clouds around Galactic Isolated Black Holes", Physical Review D, 102, 063020 (2020).

[18] S. Sachdev, R. Magee, C. Hanna, K. Cannon, L. Singer, J. R. SK, D. Mukherjee, S. Caudill, C. Chan, J. D. E. Creighton, B. Ewing, H. Fong, P. Godwin, R. Huxford, S. Kapadia, A. K. Y. Li, R. K. L. Lo, D. Meacher, C. Messick, S. R. Mohite, A. Nishizawa, H. Ohta, A. Pace, A. Reza, B. S. Sathyaprakash, M. Shikauchi, D. Singh, L. Tsukada, D. Tsuna, T. Tsutsui, and K. Ueno, "An Early-warning System for Electromagnetic Follow-up of Gravitational-wave Events", Astrophysical Journal Letters, 905, L25 (2020).

[19] Y. Michimura, K. Komori, Y. Enomoto, K. Nagano, A. Nishizawa, E. Hirose, M. Leonardi, E. Capocasa, N. Aritomi, Y. Zhao, R. Flaminio, T. Ushiba, T. Yamada, L.-W. Wei, H. Takeda, S. Tanioka, M. Ando, K. Yamamoto, K. Hayama, S. Haino, and K. Somiya, "Prospects for improving the sensitivity of the cryogenic gravitational wave detector KAGRA", Physical Review D, 102, 022008 (2020).

[20] S. Arai, P. Karmakar, and A. Nishizawa, "Cosmological evolution of viable models in the generalized scalar-tensor theory", Physical Review D, 102, 024003 (2020).

[21] R. Yamada, Y. Enomoto, A. Nishizawa, K. Nagano, S. Kuroyanagi, K. Kokeyama, K. Komori, Y. Michimura, T. Naito, I. Watanabe, T. Morimoto, M. Ando, A. Furusawa, S. Kawamura, "Optimization of quantum noise by completing the square of multiple interferometer outputs in quantum locking for gravitational wave detectors", Physical Letters A 384, 126626 (2020).

[22] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Open data from the first and second observing runs of advanced LIGO and advanced Virgo", SoftwareX, 13, 100658 (2021).

[23] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems", Physical Review D, 103, 064017 (2021).

[24] T. Tsutsui, K. Cannon, L. Tsukada, "High speed source localization in searches for gravitational waves from compact object collisions", Physical Review D, 103, 043011 (2021).

[25] H. Takeda, S. Morisaki, A. Nishizawa, "Pure polarization test of GW170814 and GW170817 using waveforms consistent with modified theories of gravity", Physical Review D, 103, 064037 (2021).

[26] L. Tsukada, R. Brito, W. East, and N. Siemonsen, "Modeling and searching for a stochastic gravitational-wave background from ultralight vector bosons", Physical Review D, 103, 083005 (2021).

[27] M. W. Coughlin, *et al.*,"Implications of the search for optical counterparts during the second part of the Advanced LIGO's and Advanced Virgo's third observing run: lessons learned for future follow-up observations", Monthly Notices of the Royal Astronomical Society **497**, 1181-1196 (2020).

[28] J. W. Broderick, *et al.*, “LOFAR 144-MHz follow-up observations of GW170817” Monthly Notices of the Royal Astronomical Society ,**494**, 5110-5117 (2020).

[29] S. Mukherjee, “Velocity correction for Hubble constant measurements from standard sirens”, Astron. and Astrophys. **646**, A65 (2020). 038 (2020).

[30] D. Dobie, *et al.*,, “Constraining properties of neutron star merger outflows with radio observations”, Monthly Notices of the Royal Astronomical Society **494**, 2449-2464 (2020).

[31] M. Safarzadeh and K. Hotokezaka, “Being Careful with the Field Formation Interpretation of GW190412”, Astrophys. J. Letters **897**, L7 (2020).

[32] H. Nagakura and K. Hotokezaka, “Non-thermal neutrinos created by shock acceleration in successful and failed core-collapse supernova,” Monthly Notices of the Royal Astronomical Society, **502**, 89-107 (2021).

[33] P. Beniamini and K. Hotokezaka, “Turbulent mixing of r-process elements in the Milky Way”, Monthly Notices of the Royal Astronomical Society, **496**, 1891-1901 (2020).

[34] Arima, N. et al. “ Intrinsic color diversity of nearby Type Ia supernovae ” , Publications of the Astronomical Society of Japan, 73, pp.326-337 (2021)

[35] Osawa, R. et al. ”Relationship between radar cross section and optical magnitude based on radar and optical simultaneous observations of faint meteors”, Planetary and Space Science, 194, article id. 105011 (2020)

[36] Niino, Y. et al. “ Optical followup observations of gravitational wave events with the wide-field CMOS camera Tomo-e Gozen ” , Yamada Conference LXXI: Gamma-ray Bursts in the Gravitational Wave Era 2019, proceedings of the conference held 28 October - 1 November 2019 in Yokohama, Kanagawa, Japan. Edited by T. Sakamoto, M. Serino and S. Sugta. pp.199-200 (2020)

[37] KAGRA Collaboration: Application of independent component analysis to the iKAGRA data, PTEP, 053F01 (2020).

[38] Rika Yamada et al.: Optimization of quantum noise by completing the square of multiple interferometer outputs in quantum locking for gravitational wave detectors, Phys. Lett. A 384, 126626 (2020).

[39] Yuta Michimura, Kentaro Komori: Quantum sensing with milligram scale optomechanical systems, The European Physical Journal D 74, 126 (2020).

[40] Yuta Michimura et al.: Prospects for improving the sensitivity of the cryogenic gravitational wave detector KAGRA, Phys. Rev. D 102, 022008 (2020).

[41] KAGRA Collaboration: Overview of KAGRA: KAGRA science, PTEP, ptaa120 (2020).

[42] KAGRA Collaboration: Overview of KAGRA: Detector design and construction history, PTEP, ptaa125 (2020).

[43] Kiwamu Izumi et al.: The current status of contribution activities in Japan for LISA, PTEP 2020, ptaa124 (2020).

[44] KAGRA Collaboration, LIGO Scientific Collaboration and Virgo Collaboration: Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA, Living Reviews in Relativity 23, 3 (2020).

[45] Yuta Michimura, et al.: Ultralight vector dark matter search with auxiliary length channels of gravitational wave detectors, Phys. Rev. D 102, 102001 (2020).

[46] Tomotada Akutsu et al.: Compact integrated optical sensors and electromagnetic actuators for vibration isolation systems in the gravitational-wave detector KAGRA, RSI 91, 115001 (2020).

[47] Takuya Kawasaki, et al.: Optical trapping of the transversal motion for an optically levitated mirror, Phys. Rev. A 102, 053520 (2020).

[48] N. Aritomi et al.: Control of a filter cavity with coherent control sidebands, Phys. Rev. D, 102, 042003 (2020).

[49] T. Shimoda, et al.: Torsion-Bar Antenna: A ground-based mid-frequency and low-frequency gravitational wave detector, IJMPD 29, 1940003 (2020).

[50] Y. Zhao, N. Aritomi et al.: Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors, Phys. Rev. Lett., 124, 171101 (2020).

[51] Hiroki Takeda, et al.: Pure polarization test of GW170814 and GW170817 using waveforms consistent with modified theories of gravity, Phys. Rev. D, 103, 064037 (2021).

[52] Shoki Iwaguchi et al.: Quantum Noise in a Fabry-Perot Interferometer Including the Influence of Diffraction Loss of Light, Galaxies 9, 9 (2021).

[53] Tomohiro Ishikawa et al.: Improvement of the Target Sensitivity in DECIGO by Optimizing Its Parameters for Quantum Noise Including the Effect of Diffraction Loss, Galaxies 9, 14 (2021).

[54] KAGRA Collaboration: Overview of KAGRA: Calibration, detector characterization, physical environmental monitors, and the geophysics interferometer, PTEP 2021, ptab018 (2021).

[55] Seiji Kawamura et al.: Current status of space gravitational wave antenna DECIGO and B-DECIGO, PTEP, ptab019 (2021).

[56] KAGRA Collaboration: Vibration isolation systems for the beam splitter and signal recycling mirrors of the KAGRA gravitational wave detector, Class. Quantum Grav. 38, 065011 (2021).

[57] Soichiro Morisaki, et al.: Improved sensitivity of interferometric gravitational-wave detectors to ultralight vector dark matter from the finite light-traveling time, Phys. Rev. D 103, L051702 (2021).

[58] Takafumi Ushiba et al.: Cryogenic suspension design for a kilometer-scale gravitational-wave detector, Class. Quantum Grav. 38, 085013 (2021).

[59] Koji Nagano, et al.: Demonstration of a dual-pass differential Fabry-Perot interferometer for future interferometric space gravitational wave antennas, Class. Quantum Grav. 38, 085018 (2021).

6.4 International Conference Talks

6.4.1 Contributed talks

[60] Yuta Michimura: Summary of Sensitivity Estimate for O4 in Various Interferometer Configurations, KAGRA 2020 May Telecon (May 2020, Online).

[61] N. Aritomi: Frequency Dependent Squeezing with 300 m filter cavity in TAMA, The 25th KAGRA face-to-face meeting (August 2020, Online).

[62] T. Tsutsui, "An improvement of early warning with 3G detectors by precession effect", JGRG Workshop, Online, 2020/11/23-27.

[63] Yuta Michimura for the KAGRA Collaboration: Future Plans for KAGRA Facility, KAGRA-OzGrav Meeting (November 2020, Online).

[64] Yuka Oshima, et al.: The current status of DANCE: Dark matter Axion search with riNg Cavity Experiment, Kashiwa Dark Matter Symposium 2020 (November 2020, Online).

[65] Miyata, T. et al. "The University of Tokyo Atacama Observatory 6.5m telescope: site development", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[66] Yoshii, Y. et al. "The University of Tokyo Atacama Observatory 6.5m Telescope: overview and construction status", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[67] Minezaki, T. et al. "The University of Tokyo Atacama Observatory 6.5 m telescope: Development of the telescope and the control system", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[68] Yoshikawa, K. et al. "The University of Tokyo Atacama Observatory 6.5m telescope: Permafrost hazards and the high-altitude infrastructures", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[69] Takahashi, H. et al. "The University of Tokyo Atacama Observatory 6.5m Telescope: Design of mirror coating system and its performances II", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[70] Collao, J. et al. "The University of Tokyo Atacama Observatory 6.5m telescope: Safety management at the extremely high altitude at Chajnantor mountain", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[71] Konishi, M. et al. "he University of Tokyo Atacama Observatory 6.5m telescope: On-sky performance of the near-infrared instrument SWIMS on the Subaru telescope", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[72] Kamizuka, T. et al. "The University of Tokyo Atacama Observatory 6.5m telescope: On-sky performance evaluations of the mid-infrared instrument MIMIZUKU on the Subaru telescope", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[73] Asano, K. et al. "The University of Tokyo Atacama Observatory 6.5m telescope: update of the Near-Infrared Echelle Spectrograph NICE as a first light instrument", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[74] L. Tsukada, "Modeling and searching for a stochastic GW background from ultralight bosons", The 7th KAGRA international workshop, Taipei, Taiwan, 2020/12/18-20.

[75] N. Aritomi: Frequency-Dependent Squeezing for Gravitational-Wave Detectors, The 26th KAGRA face-to-face meeting (December 2020, Online, poster).

[76] Hiroki Takeda, et al.: Tests of alternative theories of gravity through gravitational-wave polarization modes, KAGRA The 26th Face to Face Meeting (December 2020, Online, poster).

[77] Yuka Oshima, et al.: Dark matter Axion search with riNg Cavity Experiment DANCE: Signal calibration and sensitivity evaluation, 7th KIW (December 2020, Online).

[78] Hiroki Fujimoto, et al.: Dark matter Axion search with riNg Cavity Experiment DANCE: Development of automated cavity locking system, 7th KIW (December 2020, Online).

[79] N. Aritomi: Frequency-Dependent Squeezing for Gravitational-Wave Detectors, 7th KIW (December 2020, Online).

[80] Yuta Michimura: Expectations for Sensitivity of KAGRA in O4, 7th KIW (December 2020, Online).

[81] Hiroki Takeda, et al.: Polarization tests of GW170814 and GW170817 using waveforms consistent with alternative theories of gravity, 7th KIW (December 2020, Online).

[82] Ching Pin Ooi, et al.: Towards suspension noise measurements of crystalline fibres at cryogenic temperatures for torsion pendulums, 3rd IFQMS (December 2020, Online).

[83] Takuya Kawasaki: Quantum radiation pressure fluctuation in a linear optical cavity, 3rd IFQMS (December 2020, Online).

[84] Satoru Takano, et al.,: Cryogenic Monolithic Torsion Pendulum Made of Silicon for Gravity Gradient Sensing, 3rd IFQMS (December 2020, Online).

[85] Yuta Michimura et al: Laser interferometric searches for ultralight dark matter Transformative Research Area "Dark Matter" Symposium, (February 2021, Online).

[86] (Poster) M. Shikauchi, "On the use of CHIME to Detect Long-Duration Radio Transients from Binary Neutron Star Mergers", Innovative Area Gravitational Wave Physics and Astronomy: Genesis, The Fourth Annual Area Symposium, Online, 2021/2/22-24.

[87] (Poster) T. Tsutsui, "A roll of precession on early warning with 2.5 generation detectors", Innovative Area Gravitational Wave Physics and Astronomy: Genesis, The Fourth Annual Area Symposium, Online, 2021/2/22-24.

[88] (Poster) A. Nishizawa, "Stacking gravitational-wave polarization signals", Innovative Area Gravitational Wave Physics and Astronomy: Genesis, The Fourth Annual Area Symposium, Online, 2021/2/22-24.

[89] Yuta Michimura et al: Levitating Optomechanics: Optical Levitation LVK Meeting (March 2021, Online).

[90] Yuta Michimura for the KAGRA Collaboration: Status of KAGRA: Instrument Updates for O4, LVK Meeting (March 2021, Online).

[91] Hiroki Fujimoto, et al.: Dark matter Axion search with riNg Cavity Experiment DANCE: Development of control system for long-term measurement, Rencontres de Moriond on Gravitation (Mar. 2021, Online, poster).

[92] Yuka Oshima, et al.: Dark matter Axion search with riNg Cavity Experiment DANCE: Current sensitivity, Rencontres de Moriond on Gravitation (Mar. 2021, Online, poster).

6.4.2 Invited talks

[93] Masaki Ando: Observation of Gravitational-Wave in Space, RESCEU Summer School 2020 (Aug 19, 2020, Online).

[94] Masaki Ando: Gravitational-wave Observation and KAGRA, ILC Summer Camp 2020 (Sep 24, 2020, Online).

[95] Kenta Hotokezaka, "Multi-messenger astrophysics of neutron star merger", Workshop on Frontiers of Nuclear Structure and Nuclear Astrophysics, Online, 2020/10/15.

[96] A. Nishizawa, "Tests of gravity with gravitational waves", the APCTP-KPS-JPS meeting, online, 2020/11/6.

[97] Kenta Hotokezaka, "Modeling electromagnetic counterparts of neutron star mergers", AAPPS-DACG Workshop, Online, 2020/11/11.

[98] Kenta Hotokezaka, "Electromagnetic counterparts of neutron star mergers", The extreme Universe viewed in very-high-energy gamma rays 2020, Online, 2020/12/4.

[99] Kenta Hotokezaka, "Radio counterparts of neutron star mergers and VLBI observations", Black Hole Astrophysics with VLBI: Multi-Wavelength and Multi-Messenger Era, Online, 2021/1/19.

[100] L. Tsukada, "Modeling and searching for a stochastic GW background from ultralight bosons", Innovative Area Gravitational Wave Physics and Astronomy: Genesis, The Fourth Annual Area Symposium, Online, 2021/2/22-24

7 Project 3. Formation and characterization of planetary systems

7.1 Activity Report

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

7.1.1 Radial-velocity variation of a tertiary star orbiting a binary black hole in a triple system

A number of ongoing surveys are likely to discover star-black hole binaries in our Galaxy in the near future. A fraction of them may be triple systems comprising an inner binary, instead of a single black hole, which might be progenitors of binary black holes (BBHs) routinely discovered now from the gravitational wave. We extend our previous proposal to locate inner BBHs from the short-term radial-velocity (RV) variation of a tertiary star in coplanar triples, and we consider noncoplanar triples and their long-term RV variations as well. Specifically, we assume coplanar and noncoplanar triples with an inner BBH of the total mass 20 $M_{\odot}$, whose outer and inner orbital periods are 80 days and 10 days, respectively. We perform a series of N-body simulations and compare the results with analytic approximate solutions based on quadrupole perturbation theory. For coplanar triples, the pericenter shift of the outer star can be used to detect the hidden inner BBH. For noncoplanar triples, the total RV semi-amplitude of the outer star is modulated periodically on the order of 100km/s due to its precession over roughly the Kozai-Lidov oscillation timescale. Such long-term modulations would be detectable within a decade, independent of the short-term RV variations on the order of of 100 m/s at roughly twice the orbital frequency of the inner binary.

7.1.2 Search for Alignment of Disk Orientations in Nearby Star-Forming Regions

Spatial correlations among proto-planetary disk orientations carry unique information on physics of multiple star formation processes. We select five nearby star-forming regions that comprise a number of proto-planetary disks with spatially-resolved images with ALMA and HST, and search for the mutual alignment of the disk axes. Specifically, we apply the Kuiper test to examine the statistical uniformity of the position angle (PA: the angle of the major axis of the projected disk ellipse measured counter-clockwise from the north) distribution. The disks located in the star-forming regions, except the Lupus clouds, do not show any signature of the alignment, supporting the random orientation.

Rotational axes of 16 disks with spectroscopic measurement of PA in the Lupus III cloud, a sub-region of the Lupus field, however, exhibit a weak and possible departure from the random distribution at a 2σ level, and the inclination angles of the 16 disks are not uniform as well. Furthermore, the mean direction of the disk PAs in the Lupus III cloud is parallel to the direction of its filament structure, and approximately perpendicular to the magnetic field direction. We also confirm the robustness of the estimated PAs in the Lupus clouds by comparing the different observations and estimators based on three different methods including sparse modeling. The absence of the significant alignment of the disk orientation is consistent with the turbulent origin of the disk angular momentum.

7.1.3 Obliquity of an Earth-like planet from frequency modulation of its direct imaged lightcurve

Direct-imaging techniques of exoplanets have made significant progress recently, and will eventually enable to monitor photometric and spectroscopic signals of earth-like habitable planets in the future. The presence of clouds, however, would remain as one of the most uncertain components in deciphering such direct-imaged signals of planets. We attempt to examine how the planetary obliquity produce different cloud patterns by performing a series of GCM (General Circulation Model) simulation runs using a set of parameters relevant for our Earth. Then we use the simulated photometric lightcurves to compute their frequency modulation due to the planetary spin-orbit coupling over an entire orbital period, and attempt to see to what extent one can estimate the obliquity of an Earth-twin. We find that it is possible to estimate the obliquity of an Earth-twin within the uncertainty of several degrees with a dedicated 4 m space telescope at 10 pc away from the system if the stellar flux is completely blocked.

7.1.4 Photo-evaporation and atmospheric properties of hot rocky exoplanets

The space telescope Kepler, by transit observations, detected a significant number of small-size exoplanets, which are twice as large or small in size than the Earth. Those are thought to include many rocky exoplanets. Because of the observational bias in favor of planets close to their central star, many of those rocky exoplanets have hot enough surfaces to be molten and are theoretically expected to have atmospheres composed of silicate, sodium, potassium and so on. Such exoplanets are sometimes called lava planets or magma planets and their atmospheres are called the mineral atmospheres.

The existence of hot rocky exoplanets is not trivial: Given intense X-ray and UV (XUV) irradiation from their central star, those planets may be subject to substantial mass loss via the escape (or photo-evaporation) of the mineral atmospheres. To investigate the stability of hot rocky exoplanet atmospheres, we have developed a computation code for simulating the hydrodynamic escape of the highly XUV-irradiated mineral atmosphere, including the detailed non-LTE radiative transfer and photochemistry [61]. Our simulations demonstrate that alkali and alkaline-earth elements such as sodium play a crucial role in efficient radiative cooling and thereby slow the atmospheric escape substantially. The heating efficiency of the mineral atmosphere of hot rocky super-Earths is estimated to be smaller by a few orders of magnitude than other types of atmospheres such as hydrogen-rich ones. We conclude that hot rocky super-Earths survive photo-evaporation for billion years.

Detection and characterization of such tenuous atmospheres are challenging, however, with often-used transmission spectroscopic observations during planetary transits. Instead, we have explored the possibility of detection via emission spectroscopic observations via secondary eclipses [62]. We have modeled the chemical structure and emission spectrum of the mineral atmospheres and found that such atmospheres are bright at 4 μm and 10 μm. Such emission features are prominent enough to be detected with the next-generation space telescope for infra-red spectroscopic observations of exoplanets, Ariel [63].

7.1.5 Formation of aqua-planets

An increasing number of low-mass exoplanets have been discovered around low-temperature dwarfs such as M dwarfs [64]. Some include planets with Earth-like insolation, which attract growing interest in how common Earth-like aqua planets are beyond the Solar system. While terrestrial planets are often assumed to capture icy or water-rich planetesimals, a primordial atmosphere of nebular origin itself can produce water through oxidation of the atmospheric hydrogen with oxidizing minerals from incoming planetesimals or the magma ocean. Thermodynamically, normal oxygen buffers produce water comparable in mole number equal to or more than hydrogen. Thus, the primordial atmosphere would likely be highly enriched with water vapor; however, the primordial atmospheres have been always assumed to have the solar abundances.

We integrate the 1D structure of such an enriched atmosphere of sub-Earths embedded in a protoplanetary disc around an M dwarf and investigate the effects of water enrichment on the atmospheric properties with focus on water amount [65]. We find that the well-mixed highly enriched atmosphere is more massive by a few orders of magnitude than the solar-abundance atmosphere, and that even a Mars-mass planet can obtain water comparable to the present Earth ’ s oceans. Although close-in Mars-mass planets likely lose the captured water via disc dispersal and photoevaporation, these results suggest that there are more sub-Earths with Earth-like water contents than previously predicted.

7.1.6 Mapping of Directly Imaged Planets

One of the key issues in astrobiology is how to characterize terrestrial planets in the future when direct imaging from space becomes possible. We have previously proposed Spin-Orbit Tomography, which can estimate the two-dimensional distribution of planetary surfaces by applying an inverse problem to luminosity variations. In this year's project, we have succeeded in extending the application of machine learning technology to Spin-Orbit Tomography. In particular, we introduced three new methods (non-negative matrix factorization, sparse modeling, and Gaussian process) from the field of information science to the mapping method of planetary surfaces, and greatly extended the method ([69, 72, 73]).

7.1.7 Discovery of the runaway dipper

We developed a pipeline to process the full frame data of the first year of TESS, and analyzed 7 million objects. In particular, we searched for dippers that produce irregular dimming due to debris-like material orbiting stars by learning using neural nets. As a result, we found 38 new dippers, including a runaway dipper that seems to have escaped from a molecular cloud, which is in the field and has a velocity of over 70 km/s ([68]). In addition, we found a dipper candidate with a large line-of-sight velocity variation, which may be orbiting a binary star. This is currently under follow-up observation (Kasagi et al. in prep).

7.1.8 New capability for exoplanet characterizaion on Subaru

High-dispersion coronagraphic instrument, REACH science operation started We are developing an instrument at Subaru Telescope to realize HDC, which we proposed in 2014, combining coronagraph with high-dispersion spectroscopy. We have started the scientific operation of this instrument, REACH. In addition, we have detected couple of new molecules in hot jupiters ([67, 70, 74])

7.1.9 First Detection of OH Emission from an Exoplanet Atmosphere: High-dispersion Characterization of WASP-33b Using Subaru/IRD

We have detected a new chemical signature in the atmosphere of an extrasolar planet using the IR Doppler instrument Subaru/IRD. The hydroxyl radical (OH) was found in the dayside of the exoplanet WASP-33b. The planet is a hot-Jupiter, a gas-giant planet orbiting its host star closer than Mercury orbits the Sun and therefore reaching atmospheric temperatures of more than 2000K. Although OH has been detected in the atmosphere of Solar System planets including Earth, Venus, and Mars, this is the first time it has been found in the atmosphere of a planet beyond the Solar System. Our results show not only that we can detect such a molecule in exoplanet atmospheres, but also that we can understand the detailed chemistry of this planetary population.

7.1.10 SCExAO/CHARIS Direct Imaging Discovery of a Close Low-Mass Companion to an Accelerating Sun-like Star

We present the direct imaging discovery of a substellar companion to the nearby Sun-like star, HD 33632 Aa, at a projected separation of $\sim$ 20 au, obtained with SCExAO/CHARIS integral field spectroscopy, complemented by Keck/NIRC2 thermal infrared imaging. The companion, HD 33632 Ab, induces an astrometric acceleration on the star as detected with the Gaia and Hipparcos satellites. Its spectra are best matched by a field L/T transition object and an older, higher-gravity, and less dusty counterpart to HR 8799 cde. We have also measured a dynamical mass based on the astrometry, which turns out to be consistent with that estimated from photo-spectroscopy.

7.1.11 Discovery of exogenic materials on asteroid Ryugu and Bennu

JAXA ’ s Hayabsua2 and NASA ’ s OSIRIS-REx missions observed small rubble-pile asteroids Ryugu and Bennu with similar spectroscopic and morphological properties, respectively. These asteroids belong to C-type asteroids, which may have played important role in delivering both water and organics to terrestrial planets, including Earth. Thus, the origin and evolution of Ryugu and Bennu have important implications for the origin of life.

Our recent joint data analysis between Hayabusa2 and OSIRIS-REx teams found that both asteroids have fragments of exogenic materials from other asteroids; Ryugu has S-type bright boulders, which are likely from one of the most common spectral type of asteroids in the inner main belt, and Bennu has V-type bright boulders, which are likely from one of the rarest spectral type of asteroids, such as Vesta (Tatsumi et al., 2021). This finding show that these similar asteroids are from different parent bodies and experienced different collisional histories. Furthermore, detailed morphological and spectral analyses of Ryugu surface revealed that Ryugu is covered with thin (¡ 1m) reddish surface layer on the top of blueish substrate. Because he top reddish layer is distributed over equatorial and mid-latitude regions, where solar radiation is strong, the reddening is likely due to either solar wind irradiation or solar heating.

Careful crater counting further shows that crater color distribution has a clear bimodal distribution, indicating that surface reddening event terminated rather abruptly. These observations suggest that Ryugu surface may have been reddened by intense solar irradiation during Ryugu ’ s orbital excursion toward the Sun and that the event terminated by a sudden orbital change due to close encounter with a large planet. Because of the success of the first artificial impact experiment on an asteroid, now we have a calibration data point for cratering age on Ryugu (Arakawa et al., 2020). Based on this calibration, we estimate the surface age of the termination of reddening event is between 0.3 - 8.1 Myrs, and Ryugu ’ s topography age is 8.5 Myrs older than the above age.

7.1.12 High-throughput laboratory evolution reveals evolutionary constraints in Escherichia coli

Understanding the constraints that shape the evolutionary dynamics is critical for predicting and controlling evolution. Despite its importance, however, a systematic investigation of evolutionary constraints is lacking. To understand the evolutionary constraint, we perform a high-throughput laboratory evolution of Escherichia coli under the addition of 95 antibacterial chemicals and quantified the transcriptome, resistance, and genomic profiles for the evolved strains [79]. Utilizing machine learning techniques, we analyze the phenotype–genotype data and identified low dimensional phenotypic states among the evolved strains. Further analysis reveals the underlying biological processes responsible for these distinct states, leading to the identification of trade-off relationships associated with drug resistance. These findings bridge the genotypic, gene expression, and drug resistance gap, while contributing to a better understanding of evolutionary constraints. This understanding of the nature of evolutionary constraints will contribute to research exploring extraterrestrial living systems.

7.1.13 Dynamical systems approach to evolution–development congruence

It is acknowledged that embryonic development has a tendency to proceed from common toward specific. Ernst Haeckel raised the question of why that tendency prevailed through evolution, and the question remains unsolved. Here, we revisit Haeckel's recapitulation theory, that is, the parallelism between evolution and development through numerical evolution and dynamical systems theory. By using intracellular gene expression dynamics with cell-to-cell interaction over spatially aligned cells to represent the developmental process, gene regulation networks (GRN) that govern these dynamics evolve under the selection pressure to achieve a prescribed spatial gene expression pattern. For most numerical evolutionary experiments, the evolutionary pattern changes over generations, as well as the developmental pattern changes governed by the evolved GRN exhibit remarkable similarity. Changes in both patterns consisted of several epochs where stripes are formed in a short time, whereas for other temporal regimes, the pattern hardly changes. In evolution, these quasi-stationary generations are needed to achieve relevant mutations, whereas, in development, they are due to some gene expressions that vary slowly and control the pattern change. These successive epochal changes in development and evolution are represented as common bifurcations in dynamical systems theory, regulating working network structure from feedforward subnetwork to those containing feedback loops. The congruence is the correspondence between successive acquisitions of subnetworks through evolution and changes in working subnetworks in development. Consistency of the theory with the segmentation gene-expression dynamics is discussed. Novel outlook on recapitulation and heterochrony are provided, testable experimentally by the transcriptome and network analysis [80].

7.1.14 Thermodynamic trade-off relations and information processing in biochemical system

Chemical reactions are responsible for information processing in living cells, and thermodynamic trade-off relations can explain their accuracy and speed. Based on differential geometric theory of information namely information geometry, we derived several thermodynamic trade-off relations such as thermodynamic speed limits and thermodynamic uncertainty relations in biological systems [88] and chemical systems [91]. We also clarify an information-geometric interpretation of the entropy production based on the projection theorem [89]. By applying the thermodynamic trade-off relation, we proposed a machine-learning method to estimate the entropy production from time series data [87]. We also numerically shows the behavior of information flow near critically in the Ising system [91]. These results would explain information processing and its thermodynamic cost in living systems universally, e.g., astrobiological living systems.

7.1.15 Mechanism of Contraction Rhythm Homeostasis of heart muscle

The heart rhythm is maintained by oscillatory changes in [Ca^{2+}]. However, it has been suggested that the rapid drop in blood pressure that occurs with a slow decrease in [Ca^{2+}] preceding early diastolic filling is related to the mechanism of rapid sarcomere lengthening associated with spontaneous tension oscillation at constant intermediate [Ca^{2+}]. Here, we analyzed a new type of oscillation called hyperthermal sarcomeric oscillation. Sarcomeres in rat neonatal cardiomyocytes that were warmed at 38-42 degree Celicius oscillated at both slow, Ca2+-dependent frequencies and fast, Ca-independent frequencies. Our high-precision experimental observations revealed that the fast sarcomeric oscillation had high and low peak-to-peak amplitude at low and high [Ca^{2+}], respectively; nevertheless, the oscillation period remained constant. Our numerical simulations suggest that this regular rhythm is maintained by the unchanged cooperative binding behavior of myosin molecules during slow oscillatory changes in [Ca^{2+}] [94].

7.1.16 Development of new imaging technology by combination of optics and AI technologies

We are developing imaging technologies to answer the very basic question “What is life”. These technologies are implemented with microscopes for the observation of cells and molecules in the laboratory, but the same technologies can be applied for telescopes as well.

Nearly half year from April, the laboratory works were forced to stop due to the lab closure by COVID-19 in FY2020. “Wet experiments” using protein or living cells were seriously delayed. We, therefore, rather focused on the development of the image processing algorithms using machine learning or deep learning technologies. For example, Kowashi applied deep learning based image processing algotirhms for the processing of the images of interferometric scattering microscope. Two papers were published by former international intern students from Lomonosov Moscow State University through STEPS (Students and Researchers Exchange Program in Sciences with Russian Universities) program. Yakov has developed an image henhancement algorithm for super-resolution microscopy [**?**], and Alex has developed a cell segmentation and tracking algorithm [110]. We also tried to develop “explainable AI” for the cell image classification. Microscope images were first classified by deep learning AI. Then, we extracted the features that AI has used for the classification by using Grad-CAM analysis. As a proof of this concept, we have classified the microscopic cell images for the cell cycle, and the Grad-CAM analysis indicated that AI has classified the cell images by focusing on nucleus and Golgi. We cell biologists expected nucleus would be most informative for the cell cycle classification, but this analysis unexpectedly identified Golgi as another marker for the cell cycle. In fact, we confirmed that Golgi changes its shape and size according to the cell cycle. This would be a primitive but first example that cell biologists learned from AI [97].

7.2 Publication List

[1] Kanagawa K. D., Nomura H., Tsukagoshi T., Muto T., Kawabe R., 2020, ApJ, **892**, 83

[2] Kanagawa K. D., Szuszkiewicz E., 2020, ApJ, **894**, 59

[3] Jiaqing Bi *et al.* (incl. Kanagawa K. D.), 2020, ApJL, **895**, L18

[4] Hayashi T. and Suto Y., 2020, ApJ, **897**, 29

[5] Nakagawa Y., Kodama T., Ishiwatari M., Kawahara H., Suto Y., Takahashi Y.O., Hashimoto G.L., Kuramoto K., Nakajima K., Takehiro S. and Hayashi Y., 2020, ApJ, **898**, 95

[6] Aizawa M., Suto Y., Oya Y., Ikeda S. and Nakazato T., 2020, ApJ, **899**, 55

[7] Hayashi T. and Suto Y., 2021, ApJ, **907**, 48

[8] Kanagawa K. D. *et al.*, 2021, ApJ, **909**, 212

[9] Kandori, Ryo; Tamura, Motohide; Saito, Masao and 9 more. 2020, "Distortion of Magnetic Fields in BHR 71", ApJ, 892, 128.

[10] Gaidos, E.; Hirano, T.; Mann, A. W. and 18 more. 2020, "Zodiacal exoplanets in time - X. The orbit and atmosphere of the young 'neptune desert'-dwelling planet K2-100b", MNRAS, 495, 650.

[11] Tampo, Yusuke; Naoto, Kojiguchi; Isogai, Keisuke and 51 more. 2020, "First detection of two superoutbursts during the rebrightening phase of a WZ Sge-type dwarf nova: TCP J21040470+4631129", PASJ, 72, 49.

[12] Nielsen, L. D.; Brahm, R.; Bouchy, F. and 74 more. 2020, "Three short-period Jupiters from TESS. HIP 65Ab, TOI-157b, and TOI-169b", A & A, 639, 76.

[13] Doi, Yasuo; Hasegawa, Tetsuo; Furuya, Ray S. and 135 more. 2020, "The JCMT BISTRO Survey: Magnetic Fields Associated with a Network of Filaments in NGC 1333", ApJ, 899, 28.

[14] Hirano, Teruyuki; Krishnamurthy, Vigneshwaran; Gaidos, Eric and 19 more. 2020, "Limits on the Spin-Orbit Angle and Atmospheric Escape for the 22 Myr Old Planet AU Mic b", ApJ, 899, L13.

[15] Louie, Dana R.; Narita, Norio; Fukui, Akihiko and 5 more. 2020, "Simulations Predicting the Ability of Multicolor Simultaneous Photometry to Distinguish TESS Candidate Exoplanets from False Positives", PASP, 132, 4403.

[16] Kandori, Ryo; Tamura, Motohide; Saito, Masao and 9 more. 2020, "Distortion of Magnetic Fields in the Dense Core SL 42 (CrA-E) in the Corona Australis Molecular Cloud Complex", ApJ, 900, 20.

[17] Uyama, Taichi; Currie, Thayne; Christiaens, Valentin and 27 more. 2020, "SCExAO/CHARIS High-contrast Imaging of Spirals and Darkening Features in the HD 34700 A Protoplanetary Disk", ApJ, 900, 135.

[18] Luque, R.; Casasayas-Barris, N.; Parviainen, H. and 27 more. 2020, "Obliquity measurement and atmospheric characterisation of the WASP-74 planetary system", A & A, 642, 50.

[19] Nowak, G.; Luque, R.; Parviainen, H. and 97 more. 2020, "The CARMENES search for exoplanets around M dwarfs. Two planets on opposite sides of the radius gap transiting the nearby M dwarf LTT 3780", A & A, 642, 173.

[20] Kemmer, J.; Stock, S.; Kossakowski, D. and 93 more. 2020, "Discovery of a hot, transiting, Earth-sized planet and a second temperate, non-transiting planet around the M4 dwarf GJ 3473 (TOI-488)", A & A, 642, 236.

[21] Luque, R.; Pallé, E.; Kossakowski, D. and 73 more. 2019, "Planetary system around the nearby M dwarf GJ 357 including a transiting, hot, Earth-sized planet optimal for atmospheric characterization", A & A, 628, 39.

[22] Lawson, Kellen; Currie, Thayne; Wisniewski, John P. and 23 more. 2020, "SCExAO/CHARIS Near-infrared Integral Field Spectroscopy of the HD 15115 Debris Disk", AJ, 160, 163.

[23] Uyama, Taichi; Norris, Barnaby; Jovanovic, Nemanja and 7 more. 2020, "High-contrast H α imaging with Subaru/SCExAO + VAMPIRES", JATIS, 6, 045004.

[24] Gaidos, E.; Hirano, T.; Wilson, D. J. and 20 more. 2020, "Zodiacal exoplanets in time - XI. The orbit and radiation environment of the young M dwarf-hosted planet K2-25b", MNRAS, 498, L119.

[25] Currie, Thayne; Brandt, Timothy D.; Kuzuhara, Masayuki and 27 more. 2020, "SCExAO/CHARIS Direct Imaging Discovery of a 20 au Separation, Low-mass Ratio Brown Dwarf Companion to an Accelerating Sun-like Star", ApJ, 904, L25.

[26] Hirano, Teruyuki; Kuzuhara, Masayuki; Kotani, Takayuki and 15 more. 2020, "Precision radial velocity measurements by the forward-modeling technique in the near-infrared", PASJ, 72, 93.

[27] Parviainen, H.; Palle, E.; Zapatero-Osorio, M. R. and 43 more. 2021, "TOI-519 b: A short-period substellar object around an M dwarf validated using multicolour photometry and phase curve analysis", A & A, 645, 16.

[28] Yen, Hsi-Wei; Koch, Patrick M.; Hull, Charles L. H. and 43 more. 2021, "The JCMT BISTRO Survey: Alignment between Outflows and Magnetic Fields in Dense Cores/Clumps", ApJ, 907, 33.

[29] Narang, Mayank; Manoj, P.; Ishwara Chandra, C. H. and 6 more. 2021, "In search of radio emission from exoplanets: GMRT observations of the binary system HD 41004", MNRAS, 500, 4818.

[30] Chen, G.; Pallé, E.; Parviainen, H. and 25 more. 2021, "An enhanced slope in the transmission spectrum of the hot Jupiter WASP-104b", MNRAS, 500, 5420.

[31] Sha, Lizhou; Huang, Chelsea X.; Shporer, Avi and 70 more. 2021, "TOI-954 b and K2-329 b: Short-period Saturn-mass Planets that Test whether Irradiation Leads to Inflation", AJ, 161, 82.

[32] Pattle, Kate; Lai, Shih-Ping; Di Francesco, James and 26 more. 2021, "JCMT POL-2 and BISTRO Survey Observations of Magnetic Fields in the L1689 Molecular Cloud", ApJ, 907, 88.

[33] Ngoc, Nguyen Bich; Diep, Pham Ngoc; Parsons, Harriet and 146 more. 2021, "Observations of Magnetic Fields Surrounding LkHα 101 Taken by the BISTRO Survey with JCMT-POL-2", ApJ, 908, 10.

[34] Arzoumanian, D.; Furuya, R. S.; Hasegawa, T. and 146 more. 2021, "Dust polarized emission observations of NGC 6334. BISTRO reveals the details of the complex but organized magnetic field structure of the high-mass star-forming hub-filament network", A & A, 647, 78.

[35] Nugroho, Stevanus K.; Kawahara, Hajime; Gibson, Neale P. and 23 more. 2021, "First Detection of Hydroxyl Radical Emission from an Exoplanet Atmosphere: High-dispersion Characterization of WASP-33b Using Subaru/IRD", ApJ, 910, L9.

[36] Riu, L., C. Pilorget, R. Milliken, K. Kitazato, T. Nakamura, Y. Cho, M. Matsuoka, S. Sugita, M. Abe, S. Matsuura, M. Ohtake, T. Iwata, E. Tatsumi, S. Kameda, and N. Sakatani (2021), "Spectral characterization of the craters of Ryugu as observed by the NIRS3 instrument on-board Hayabusa2", *Icarus*, 360, 114353.

[37] Nishiyama, G., T. Kawamura, N. Namiki, B. Fernando, K. Leng, K. Onodera, S. Sugita, T. Saiki, H. Imamura, Y. Takagi, H. Yano, M. Hayakawa, C. Okamoto, H. Sawada, Y. Tsuda, K. Ogawa, S. Nakazawa, Y. Iijima (2021), "Simulation of Seismic Wave Propagation on Asteroid Ryugu Induced by The Impact Experiment of The Hayabusa2 Mission: Limited Mass Transport by Low Yield Strength of Porous Regolith", *J. Geophys. Res.*126, e2020JE006594.

[38] Kikuchi, S., N. Ogawa, O.Moria, T. Saikia, Y. Takei, F. Teruia, G. Ono, Y. Mimasu, K. Yoshikaw, S. Van Wal, H. Takeuchia, H. Ikeda, A. Fujiia, Y. Takao, T. Kusumoto, N. Hirata, N. Hirata, K. Shirai, T. Kouyama, S. Kameda, M. Yamada, S. Nakazawa, M. Yoshikawa, S. Tanaka, S. Sugita, S. Watanabe, Y. Tsuda (2020), "Ballistic deployment of the Hayabusa2 artificial landmarks in the microgravity environment of Ryugu", *Icarus*, 358, 114220.

[39] Grott, M. J. Biele, P. Michel, S. Sugita, S. Schröder, N. Sakatani, W. Neumann, S. Kameda, T. Michikami, and C. Honda (2020) "Macroporosity and Grain Density of Rubble Pile Asteroid (162173) Ryugu", *J. Geophys. Res. Journal of Geophysical Research: Planets*, 125, e2020JE006519.

[40] Suzuki, A. et al. (2021), "Experimental study concerning the oblique impact of low- and high-density projectiles on sedimentary rocks", *Plant. Sp. Sci.*, 195, 105141.

[41] K. Kitazato, R. E. Milliken, T. Iwata, M. Abe, M. Ohtake, S. Matsuura, Y. Takagi, T. Nakamura, T. Hiroi, M. Matsuoka, L. Riu, Y. Nakauchi, K. Tsumura, T. Arai, H. Senshu, N. Hirata, M. A. Barucci, R. Brunetto, C. Pilorget, F. Poulet, J.-P. Bibring, D. L. Domingue, F. Vilas, D. Takir, E. Palomba, A. Galiano, D. Perna, T. Osawa, M. Komatsu, A. Nakato, T. Arai, N. Takato, T. Matsunaga, M. Arakawa, T. Saiki, K. Wada, T. Kadono, H. Imamura, H. Yano, K. Shirai, M. Hayakawa, C. Okamoto, H. Sawada, K. Ogawa, Y. Iijima, S. Sugita, R. Honda, T. Morota, S. Kameda, E. Tatsumi, Y. Cho, K. Yoshioka, Y. Yokota, N. Sakatani, M. Yamada, T. Kouyama, H. Suzuki, C. Honda, N. Namiki, T. Mizuno, K. Matsumoto, H. Noda, Y. Ishihara,R. Yamada, K. Yamamoto, F. Yoshida, S. Abe, A. Higuchi, Y. Yamamoto, T. Okada, Y. Shimaki, R. Noguchi, A. Miura, N. Hirata, S. Tachibana, H. Yabuta, M. Ishiguro, H. Ikeda, H. Takeuchi, T. Shimada, O. Mori, S. Hosoda, R. Tsukizaki, S. Soldini, M. Ozaki, F. Terui, N. Ogawa, Y. Mimasu, G. Ono, K. Yoshikawa, C. Hirose, A. Fujii, T. Takahashi, S. Kikuchi, Y. Takei, T. Yamaguchi, S. Nakazawa, S. Tanaka, M. Yoshikawa, S. Watanabe, and Y. Tsuda, (2020) "Thermally altered subsurface material of asteroid (162173) Ryugu", *Nature Astron.*, 5, 246-250.

[42] DellaGiustina, D. N., K. N. Burke, K. J. Walsh, P. H. Smith, D. R. Golish, E. B. Bierhaus, R.-L. Ballouz, T. L. Becker, H. Campins, E. Tatsumi, K. Yumoto, S. Sugita, J. D. Prasanna Deshapriya, E. A. Cloutis, B. E. Clark, A. R. Hendrix, A. Sen, M. M. Al Asad, M. G. Daly, D. M. Applin, C. Avdellidou, M. A. Barucci, K.

J. Becker, C. A. Bennett, W. F. Bottke, J. I. Brodbeck, H. C. Connolly, M. Delbo, J. de Leon, C. Y. Drouet d'Aubigny, K. L. Edmundson, S. Fornasier, V. E. Hamilton, P. H. Hasselmann, C. W. Hergenrother, E. S. Howell, E. R. Jawin, H. H. Kaplan, L. Le Corre, L. F. Lim, J. Y. Li, P. Michel, J. L. Molaro, M. C. Nolan, J. Nolau, M. Pajola, A. Parkinson, M. Popescu, N. A. Porter, B. Rizk, J. L. Rizos, A. J. Ryan, B. Rozitis, N. K. Shultz, A. A. Simon, D. Trang, R. B. Van Auken, C. W. V. Wolner, and D. S. Lauretta (2020) "Variations in color and reflectance on the surface of asteroid (101955) Bennu", *Science*, 370, eabc3660,

[43] Noda, H., H. Senshu, K. Matsumoto, N. Namiki, T. Mizuno, S. Seiji, S. Abe, Hiroshi Araki, K. Asari, Y. Cho, A. Fujii, M. Hayakawa, A. Higuchi, N. Hirata, N. Hirata, C. Honda, R. Honda, Y. Ishihara, S. Kameda, S. Kikuchi, T. Kouyama, M. Matsuoka, Y. Mimasu, T. Morota, S. Nakazawa, K. Ogawa, N. Ogawa, G. Ono, S. Oshigami, T. Saiki, N. Sakatani, S. Sasaki, H. Sawada, Makoto Shizugami, Hidehiko Suzuki, Tadateru Takahashi, Yuto Takei, Satoshi Tanaka, Eri Tatsumi, Fuyuto Terui, M. Tsuda, S. T., S. Watanabe, M. Yamada, R. Yamada, T. Yamaguchi, K. Yamamoto, Y. Yokota, F. Yoshida, K. Yoshikawa, M. Yoshikawa, K. Yoshioka (2020), "Alignment determination of the Hayabusa2 laser altimeter (LIDAR)", *Earth Planet Sci.*, 73, 21 (pp.15).

[44] Kikuchi, S., S. Watanabe, T. Saiki, H. Yabuta, S. Sugita, T. Morota, N. Hirata, N. Hirata, T. Michikami, C. Honda, Y. Yokota, R. Honda, T. Okada, N. Sakatani, Y. Shimaki, K. Matsumoto, R. Noguchi, Y. Takei, F. Terui, N. Ogawa, K. Yoshikawa, G. Ono, Y. Mimasu, H. Sawada, H. Ikeda, C. Hirose, T. Takahashi, A. Fujii, T. Yamaguchi, Y. Ishihara, T. Nakamura, K. Kitazato, K. Wada, S. Tachibana, E. Tatsumi, M. Matsuoka, H. Senshu, S. Kameda, T. Kouyama, M. Yamada, K. Shirai, Y. Cho, K. Ogawa, Y. Yamamoto, A. Miura, T. Iwata, N. Namiki, M. Hayakawa, M. Abe, S. Tanaka, M. Yoshikawa, S. Nakazawa, and Y. Tsuda (2020), "Hayabusa2 Landing Site Selection: Surface Topography of Ryugu and Touchdown Safety", *Space Sci. Rev.*, 216, 116.

[45] Tatsumi, E., C. Sugimoto, L. Riu, S. Sugita, T. Nakamura, T. Hiroi, T. Morota, M. Popescu T. Michikami, K. Kitazato, M. Matsuoka, S. Kameda, R. Honda, M. Yamada, N. Sakatani, T. Kouyama, Y. Yokota, C. Honda, H. Suzuki, Y. Cho, K. Ogawa, M. Hayakawa, H. Sawada, K. Yoshioka, C. Pilorget, M. Ishida, D. Domingue, N. Hirata, S. Sasaki, J. de León, M. A. Barucci, P. Michel, M. Suemitsu, T. Saiki, S. Tanaka, F. Terui, S. Nakazawa, S. Kikuchi, T. Yamaguchi, N. Ogawa, G. Ono, Y. Mimasu, K. Yoshikawa, T. Takahashi, Y. Takei, A. Fujii, Y. Yamamoto, T. Okada, C. Hirose, S. Hosoda, O. Mori, T. Shimada, S. Soldini, R. Tsukizaki, T. Mizuno, T. Iwata, H. Yano, M. Ozaki, M. Abe, M. Ohtake, N. Namiki, S. Tachibana, M. Arakawa, H. Ikeda, M. Ishiguro, K. Wada, H. Yabuta, H. Takeuchi, Y. Shimaki, K. Shirai, N. Hirata, Y. Iijima, Y. Tsuda, S. Watanabe, M. Yoshikawa (2021), "Collisional history of Ryugu's parent body from bright surface boulders", *Nature Astron.*, 4.

[46] Kikuchi, S., F. Terui, N. Ogawa, T. Saiki, G. Ono, K. Yoshikawa, Y. Takei, Y.Mimasu, H.Ikeda, H. Sawada, S. Van Wal, S. Sugita, S. Watanabe, Y. Tsuda (2020), "Design and reconstruction of the Hayabusa2 precision landing on Ryugu", *J. Spacecraft and Rockets*, 1-28.

[47] Miura, Y. N., M. Okuno, Y. Cho, K. Yoshioka, S. Sugita (2020), "Ne-Ar separation using a permeable membrane to measure Ne isotopes for future planetary explorations", *Planet. Sp. Sci.*, 193, # 105046, pp.11

[48] Noguchi, R., N. Hirata, N. Hirata, Y. Shimaki, N. Nishikawa, S. Tanaka, T. Sugiyama, T. Morota, M. Kanamaru e, S. Sugita, Y. Cho, R. Honda, S. Kameda, E. Tatsumi, K. Yoshioka, H. Sawada, Y. Yokota, N. Sakatani, M. Hayakawa, M. Matsuoka, M. Yamada, T. Kouyama, H. Suzuki, C. Honda, K. Ogawa, M. Kanamaru, S. Watanabe (2021), "Crater depth-to-diameter ratios on asteroid 162173 Ryugu", *Icarus* 354, 114016.

[49] Kadono, T., M. Arakawa, R. Honda, K. Ishibashi, K. Ogawa, N. Sakatani, H. Sawada, Y. Shimaki, K. Shirai, S. Sugita, and K. Wada (2020), "Impact Experiment on Asteroid (162173) Ryugu: Structure beneath the Impact Point Revealed by In Situ Observations of the Ejecta Curtain", *Astrophys. J. Lett.*, 899, L22 (6pp).

[50] Hirabayashi, M., Nakano, R., Tatsumi, E., Walsh, K. J., Barnouin, O. S., Michel, P., Christine M. Hartzell, D. T. Britt, S. Sugita, S. Watanabe, W. F. Bottke, D. J. Scheeres, R. Ballouz, Y. Cho, T. Morota c, E. S. Howell, D. S. Lauretta, (2020). "Spin-driven evolution of asteroids' top-shapes at fast and slow spins seen from (101955) Bennu and (162173) Ryugu". *Icarus*, 113946.

[51] Tatsumi, E., D. Domingue, Y. Yokota, S. Schröder, S. Hasegawa, D. Kuroda, M. Ishiguro, T. Hiroi, R. Honda, R. Hemmi, L. Le Corre, N. Sakatani, T. Morota, M. Yamada, S. Kameda, T. Koyama, H. Suzuki, Y. Cho, K. Yoshioka, M. Matsuoka, C. Honda, M. Hayakawa, N. Hirata, N. Hirata, Y. Yamamoto, F. Vilas, N. Takato, M. Yoshikawa, M. Abe, and S. Sugita (2020), "Global photometric properties of (162173) Ryugu", *Astron. & Astrophys.*, 639, A83 pp.19.

[52] Shimaki,Y., H. Senshu, N. Sakatani, T. Okada, T. Fukuhara, S. Tanaka, M. Taguchi, T. Arai, H. Demura, Y. Ogawa, K. Suko, T. Sekiguchi, T. Kouyama, S. Hasegawa, J. Takita, T. Matsunaga, T. Imamura, T. Wada, K. Kitazato, N. Hirata, N. Hirata, R. Noguchi, S. Sugita, S. Kikuchi, T. Yamaguchi, N. Ogawa, G. Ono, Y. Mimasu, K. Yoshikawa, T. Takahashi, Y. Takei, A. Fujii, H. Takeuchi, Y. Yamamoto, M. Yamada, K. Shirai,

Y. Iijima, K. Ogawa, S. Nakazawa, F. Terui, T. Saiki, M. Yoshikawa, Y. Tsuda, S. Watanabe, "Thermophysical properties of the surface of asteroid 162173 Ryugu: Infrared observations and thermal inertia mapping", *Icarus* 348 (2020) 113835, pp.1-15.

[53] Saiki,T., Y. Takei, Y. Mimasu, H. Sawada, N. Ogawa, G. Ono, K. Yoshikawa, F. Terui, M. Arakawa, S. Sugita, S. Watanabe, M. Yoshikawa, S. Nakazawa, and Y. Tsuda (2020), "Hayabusa2's kinetic impact experiment: Operational planning and results", *Acta Astronautica,* 175, 362-374, 2020.

[54] Morota, T., S. Sugita, Y. Cho, M. Kanamaru, E. Tatsumi, N. Sakatani, R. Honda, N. Hirata, H. Kikuchi, M. Yamada, Y. Yokota, S. Kameda, M. Matsuoka, H. Sawada, C. Honda, T. Kouyama, K. Ogawa, H. Suzuki, K. Yoshioka, M. Hayakawa, N. Hirata, M. Hirabayashi, H. Miyamoto, T. Michikami, T. Hiroi, R. Hemmi, O. S. Barnouin, C. M. Ernst, K. Kitazato, T. Nakamura, L. Riu, H. Senshu, H. Kobayashi, S. Sasaki, G. Komatsu, N. Tanabe, Y. Fujii, T. Irie, M. Suemitsu, N. Takaki, C. Sugimoto, K. Yumoto, M. Ishida, H. Kato, K. Moroi, D. Domingue, P. Michel, C. Pilorget, T. Iwata, M. Abe, M. Ohtake, Y. Nakauchi, K. Tsumura, H. Yabuta, Y. Ishihara, R. Noguchi, K. Matsumoto, A. Miura, N. Namiki, S. Tachibana, M. Arakawa, H. Ikeda, K. Wada, T. Mizuno, C. Hirose, S. Hosoda, O. Mori, T. Shimada, S. Soldini, R. Tsukizaki, H. Yano, M. Ozaki, H. Takeuchi, Y. Yamamoto, T. Okada, Y. Shimaki, K. Shirai, Y. Iijima, H. Noda, S. Kikuchi, T. Yamaguchi, N. Ogawa, G. Ono, Y. Mimasu, K. Yoshikawa, T. Takahashi, Y. Takei, A. Fujii, S. Nakazawa, F. Terui, S. Tanaka, M. Yoshikawa, T. Saiki, S. Watanabe, Y. Tsuda (2020), "Sample collection from asteroid (162173) Ryugu by Hayabusa2: Implications for surface evolution", *Science*, 368, 654-659.

[55] Okada, T., T. Fukuhara, S. Tanaka, M. Taguchi, T. Arai, H. Senshu, N. Sakatani, Y. Shimaki, H. Demura, Y. Ogawa, K. Suko, T. Sekiguchi, T. Kouyama, J. Takita, T. Matsunaga, T. Imamura, T. Wada, S. Hasegawa, J. Helbert, T. G. Müller, A. Hagermann, J. Biele, M. Grott, M. Hamm, M. Delbo, N. Hirata, N. Hirata, Y. Yamamoto, S. Sugita, N. Namiki, K. Kitazato, M. Arakawa, S. Tachibana, H. IkedA, M. Ishiguro, K. Wada, C. Honda, R. Honda, Y. Ishihara, K. Matsumoto, M. Matsuoka, T. Michikami, A. Miura, T. Morota, H. Noda, R. Noguchi, K. Ogawa, K. Shirai, E. Tatsumi, H. Yabuta, Y. Yokota, M. Yamada, M. Abe, M. Hayakawa, T. Iwata, M. Ozaki, H. Yano, S. Hosoda, O. Mori, H. Sawada, T. Shimada, H. Takeuchi, R. Tsukizaki, A. Fujii, C. Hirose, S. Kikuchi, Y. Mimasu, N. Ogawa, G. Ono, T. Takahashi, Y. Takei, T. Yamaguchi, K. Yoshikawa, F. Terui, T. Saiki, S. Nakazawa, M. Yoshikawa, S. Watanabe, Y. Tsuda (2020), "Highly porous nature of a primitive asteroid revealed by thermal imaging", *Nature*, 579, 518-522.

[56] Okoda, Y., Oya, Y., Sakai, N., Watanabe, Y., & Yamamoto, S., "Molecular Distributions of the Protostellar Envelope and the Outflow of IRAS 15398–3359: Principal Component Analysis", ApJ, 900, 40 (2020)

[57] Ebisawa, Y., Sakai, N., Menten, K.M., Oya, Y., & Yamamoto, S., "Temperature Structure of the Pipe Nebula Studied by the Intensity Anomaly of the OH 18cm Transition". ApJ, 904, 136 (2020)

[58] Oya, Y. & Yamamoto, S., "Substructures in the Disk-Forming Region of the Class 0 Low-Mass Protostellar Source IRAS 16293–2422 Source A on a 10 au Scale", The Astrophysical Journal, 904, 185 (2020).

[59] Okoda, Y., Oya, Y., Francis, L., Johnstone, D., Inutsuka, S., Yamamoto, S., & FAUST team members, "FAUST II. Discovery of a Secondary Outow in IRAS15398–3359: Variability in Outow Direction during the Earliest Stage of Star Formation?", ApJ, 910, 11 (2021)

[60] T. Tada, R. Tada, P. Chansom, M. Songtham, P. Carling, and E. Tajika, "In-situ Occurrence of Muong Nong-type Australasian Tektite Fragments from the Quaternary Deposits near Huai Om, North-Eastern Thailand", Progress in Earth and Planetary Science, 7:66 https://doi.org/10.1186/s40645-020-00378-4 (2020).

[61] Ito, Y., and Ikoma, M., "Hydrodynamic escape of mineral atmosphere from hot rocky exoplanet. I. Model description", MNRAS 502, 750-771 (2021).

[62] Ito, Y., Changeat, Q., Edwards, B., Al-Refaie, A., Tinetti, G., Ikoma, M., "Detectability of Rocky-Vapour atmospheres on super-Earths with Ariel", Experimental Astronomy (2021).

[63] Tinetti, G. et al., 2021: "Ariel: Enabling planetary science across light-years," Ariel Definition Study Report, 147 pages. Reviewed by ESA Science Advisory Structure in November 2020.

[64] Kemmer, J. et al., "Discovery of a hot, transiting, Earth-sized planet and a second temperate, non-transiting planet around the M4 dwarf GJ 3473 (TOI-488)", A & A, 642, A236 (2020).

[65] Kimura, T. and Ikoma, M., "Formation of aqua planets with water of nebular origin: effects of water enrichment on the structure and mass of captured atmospheres of terrestrial planets", MNRAS 49 3755-3766 (2020).

[66] Hashimoto, J. et al., "Accretion Properties of PDS 70b with MUSE", AJ, 159, 222 (2020).

[67] Ishizuka, Kawahara, Nugurho, Kawashima, Hirano, and Tamura, "Neutral metals in the atmosphere of HD149026b" Astronomical Journal 161, 153 (2021)

[68] Tajiri, Kawahara, Aizawa, Fujii, Hattori, Kasagi, Kotani, Masuda, Momose, Muto, Ohsawa, and Takita "Dippers from the TESS Full-Frame Images I: The Results of the first 1 year data and Discovery of A Runaway dipper" , Astrophysical Journal Supplement 251,2 (2020)

[69] Kawahara and Masuda, "Bayesian Dynamic Mapping of an Exo-Earth from Photometric Variability", Astrophysical Journal, 900, 48, (2020)

[70] Nugroho, Gibson, de Mooij, Herman, Watson, Kawahara, Merrit "Detection of Fe I Emission in the Day-side Spectrum of WASP-33b" Astrophysical Journal Letters 898, L31 (2020),

[71] Nakagawa, Kodama, Ishiwatari, Kawahara, Suto, Takahashi, Hashimoto, Kuramoto, Nakajima, Takehiro, and Hayashi "Obliquity of an Earth-like planet from frequency modulation of its direct imaged lightcurve: mock analysis from general circulation model simulation" Astrophysical Journal, 898, 95 (2020),

[72] Kawahara,, "Global Mapping of the Surface Composition on an Exo-Earth using Color Variability" Astrophysical Journal 894, 58 , (2020)

[73] Aizawa, Kawahara, and Fan, "Global Mapping of an Exo-Earth using Sparse Modeling" Astrophysical Journal 896, 22 (2020),

[74] Nugroho, Gibson, de Mooij, Watson, Kawahara, Merritt "Searching for Thermal Inversion Agents in the Transmission Spectrum of MASCARA-2b/KELT-20b: Detection of Neutral Iron and Ionised Calcium H&K Lines" , Monthly Notices of the Royal Astronomical Society 496, 504, (2020)

[75] C. Furusawa and N. Irie: Toward understanding of evolutionary constraints: experimental and theoretical approaches, Biophys. Rev. 12(5):1155-1161 (2020).

[76] T. Horinouchi, C. Furusawa: Understanding metabolic adaptation by using bacterial laboratory evolution and trans-omics analysis, Biophys. Rev., 12(3):677-682 (2020).

[77] R. Ohbayashi, S. Hirooka, R. Onuma, Y. Kanesaki, Y. Hirose, Y. Kobayashi, T. Fujiwara, C. Furusawa, S-Y Miyagishima: Evolutionary changes in DnaA-dependent chromosomal replication in Cyanobacteria, Front. Microbiol., 11, 786 (2020).

[78] T. Horinouchi, T. Maeda, H. Kotani, C. Furusawa: Suppression of antibiotic resistance evolution by single-gene deletion, Sci. Rep., 10(1):4178 (2020).

[79] T. Maeda, J. Iwasawa, H. Kotani, N. Sakata, M. Kawada, T. Horinouchi, A. Sakai, K. Tanabe, C. Furusawa: High-throughput laboratory evolution and evolutionary constraints in Escherichia coli, Nature Communications, 11(1):5970 (2020).

[80] T. Kohsokabe and K. Kaneko. Dynamical Systems Approach to Evolution-Development Congruence: Revisiting Haeckel's Recapitulation Theory. J Exp. Zoology B, 2021;1-14. (2021).

[81] Q-Y. Tang, T.Hatakeyama, K. Kaneko. Functional Sensitivity and Mutational Robustness of Proteins. Physical Review Research 2 (3), 033452 (2020).

[82] A. Sakata and K. Kaneko. Dimensional reduction in evolving spin-glass model: correlation of phenotypic responses to environmental and mutational changes. Phys.Rev.Lett. 124, 218101 (2020).

[83] T. Kurikawa, O. Barak, K. Kaneko. Repeated sequential learning increases memory capacity via effective decorrelation in a recurrent neural network. Phys. Rev. Research 2, 023307 (2020).

[84] Y. Matsushita, & K. Kaneko. Homeorhesis in Waddington's Landscape by Epigenetic Feedback Regulation. Phys. Rev. Research 2, 023083 (2020).

[85] J.F. Yamagishi and K. Kaneko. Chaos with a High-dimensional Torus. Physical Review Research 2, 023044 (2020)

[86] K. Itao and K. Kaneko. Reply to Read and Parkin: Our model correctly expresses the ethnographic nature of the cultural incest taboo and kinship structures. Proceedings of National Academy of Sciences (USA), Letter 117, 9167-9168 (2020)

[87] Shun Otsubo, Sosuke Ito, Andreas Dechant and Takahiro Sagawa, Estimating entropy production by machine learning of short-time fluctuating currents. Physical Review E, 101, 062106 (2020).

[88] Sosuke Ito and Andreas Dechant, Stochastic time evolution, information geometry, and the Cramér-Rao bound. Physical Review X, 10, 021056 (2020).

[89] Sosuke Ito, Masafumi Oizumi and Shun-ichi Amari, Unified framework for the entropy production and the stochastic interaction based on information geometry. Physical Review Research, 2, 033048 (2020).

[90] Matthijs Meijers, Sosuke Ito and Pieter Rein Ten Wolde, Behavior of information flow near criticality. Physical Review E, 103, L010102 (2021).

[91] Kohei Yoshimura and Sosuke Ito, Information geometric inequalities of chemical thermodynamics. Physical Review Research, 3, 013175 (2021).

[92] Seohyun Lee, Hyuno Kim, Hideo Higuchi and Masatoshi Ishikawa. Visualization Method for the Cell-Level Vesicle Transport Using Optical Flow and a Diverging Colormap. Sensors 2021, 21, 522, 1-13 (2021).

[93] Seine A. Shintani, Takumi Washio and Hideo Higuchi. Mechanism of Contraction Rhythm Homeostasis for Hyperthermal Sarcomeric Oscillations of Neonatal Cardiomyocytes. Sci. Rep. 10:20468, 1-12 (2020).

[94] Seohyun Lee, Hyuno Kim, Hideo Higuchi, Masatoshi Ishikawa. Visualization and Data Analysis for Intracellular Transport using Computer Vision Techniques. 2020 IEEE Sensors Applications Symposium. IEEE Xplore 20055684, 1-6 (2020).

[95] Seohyun Lee, Hyuno Kim, Hideo Higuchi. Extended Dual-Focus Microscopy for Ratiometric-Based 3D Movement Tracking. Appl.Sci. 10,6243;1-12 (2020).

[96] Kohsuke Gonda, Hiroshi Negishi, Mayumi Takano-Kasuya, Narufumi Kitamura, Naoko Furusawa, Yasushi Nakano, Yoh Hamada, Masayuki Tokunaga, Hideo Higuchi, Hiroshi Tada, Takanori Ishida. Heterogeneous drug efficacy of an antibody-drug conjugate visualized using simultaneous imaging of its delivery and intracellular damage in living tumor tissues. Translational Oncology. 13, 100764,1-11 (2020).

[97] Nagao Y, *et al.* Robust Classification of Cell Cycle Phase and Biological Feature Extraction by Image-Based Deep Learning. *Mol Biol Cell* 31: 1346-1354 (2020).

[98] Aoyama-Ishiwatari S, *et al.* NUDT21 links mitochondrial IPS-1 to RLR-containing stress granules and activates host antiviral defense. *J Immunol* 206: 154-163 (2021).

7.3 International Conference Talks

7.3.1 Contributed talks

[99] Watanabe, Y., Tajika, E., Ozaki, K., and Hong, P.K., "Consequence of Hydrocarbon Haze Formation on Global Carbon Cycle under Anoxic and Mildly Oxidized Environment", Goldschmidt 2020, Online, 2020/06/26.

[100] Chang, Y, Kayama, M., Tajika, E., Sekine, Y., Sekine, T., Nishido H., and Kobayashi, T., "Shock-induced vitrification affected on cathodoluminescence of quartz: possibility as a shock barometer and its potential application to natural impact samples", JpGU-AGU Joint Meeting 2020: Virtual, Online, 2020/07/12-16.

[101] Tada, T., Kayama, M., Chang, Y., Miyake, A., Igami, Y., Tada, R., Carling, P. A., Songtham, W., and Tajika, E., "Evaluation of shock deformation of the basement sandstone around the probable impact site of Australasian Tektite Event using synchrotron X-ray diffraction analysis", JpGU-AGU Joint Meeting 2020: Virtual, Online, 2020/07/12-16.

[102] Tada, T., Tada, R., Carling, P. A., Songtham, W., Chansom, P., Kogure, T., Chang, Y., and Tajika, E., "Identification of Ejecta Deposit formed by Australasian Tektite Event based on Discovery of Shocked Quartz and in situ Tektite Fragments in North Eastern Thailand", JpGU-AGU Joint Meeting 2020: Virtual, Online, 2020/07/12-16.

[103] Miki, A., Tajika, E., and Ozaki, K., "Modelling the behaviors of marine carbon isotopic composition after Neoproterozoic snowball Earth event", JpGU-AGU Joint Meeting 2020: Virtual, Online, 2020/07/12-16.

[104] Aoyama, K., Tajika, E., and Ozaki, K., "Variations of burial rates of organic carbon in terrestrial and marine environments during the Phanerozoic", JpGU-AGU Joint Meeting 2020: Virtual, Online, 2020/07/12-16.

[105] Watanabe, Y., Tajika, E., Ozaki, K., and Hong, P.K., "Potential Positive Feedback Mechanisms in an Anoxic Environmental System of a Planet with CO2-CH4 Atmosphere", JpGU-AGU Joint Meeting 2020: Virtual, Online, 2020/07/12-16.

[106] Watanabe, Y., Tajika, E., Ozaki, K., and Hong, P.K., "Effect of Hydrocarbon Haze on Climate Stability under Weakly Oxidized Late-Archean Environment", JpGU-AGU Joint Meeting 2020: Virtual, Online, 2020/07/12-16.

[107] Oya, Y., "Temperature Structure of the Pipe Nebula Studied by the Intensity Anomaly of the OH 18 cm ", The Early Phase of Star Formation 2020, July 12–17, 2020, Germany (Canceled)

[108] Okoda, Y, Oya, Y., Sakai, N., Watanabe, Y., & Yamamoto, S., "Chemical and Physical Structures around the Very Low Mass Protostellar Source IRAS 15398–3359", The Early Phase. of Star Formation 2020, July 12–17, 2020, Germany (Canceled)

[109] Kazuhiro D, Kanagawa, "A fast inward migration of a planet within a protoplanetary disk: Observational signatures from gas morphology", Exoplanet III, Online(July 20, 2020)

[110] Alexandr Y, *et al.* A method for automatic tracking of cell nuclei with weakly-supervised mitosis detection in 2D microscopy image sequences. *The 2020 5th International Conference on Biomedical Signal and Image Processing. Association for Computing Machinery*, August 21-23, 2020, Online

[111] Oya, Y., "Circummultiple/circumstellar Structures and Outflow near its Launching Point: the IRAS 16293–2422 Source A Case", Five years after HL Tau: a new era in planet formation, December 7–11, 2020, Online

[112] Okoda, Y., Oya, Y., Francis, L., Johnstone, D., Inutsuka, S., Yamamoto, S., & FAUST team members, "Dynamic Structure around the Protostar with a Key to Disk Formation", Five years after HL Tau: a new era in planet formation, Virtual conference, Dec 7-11,2020, Online

[113] Kameda, S. et al., "UVSPEX onboard WSO-UV for the upper atmosphere and surface environments of Earth-like exoplanets", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[114] Narita, N. et al., "MuSCAT3: a 4-color simultaneous camera for the 2m Faulkes Telescope North", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[115] Schmider, F. X. et al., "Characteristics and performances of an interferometric Doppler imager installed at the 188 cm telescope of Okayama Observatory", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[116] Kameda, S. et al., "UVSPEX/WSO-UV for Earth-like exoplanetary oxygen exospheres", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[117] Kawahara, H. et al., "LOTUS: wide-field monitoring nanosatellite for finding long-period transiting planets", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[118] Hajime Kawahara: "LOTUS: wide-field monitoring nanosatellite for finding long-period transiting planets", SPIE Astronomical Telescopes + Instrumentation 2020 : Online, United States, December 14-18, 2020.

[119] Oya, Y., "Circummultiple/Circumstellar Structures and Outflow near its Origin Point: the Multiple System IRAS 16293–2422 Source A Case", East Asian ALMA Science Workshop 2021, February 17–19, 2021, Online

[120] Sugita, S., C. Sugimoto, E. Tatsumi, Y. Yokota, T. Morota, R. Honda, S. Kameda, Y. Cho, K. Yoshioka, H. Sawada, N. Sakatani, M. Hayakawa, M. Matsuoka, M. Yamada, T. Kouyama, H. Suzuki, C. Honda, K. Ogawa, ONC team (2021), "Collisional and Thermal Evolution of Ryugu's Parent Body Inferred from Bright Boulders", 52th Lunar and Planetary Science Conference, Mar 16 - 20, Online, # 1399

[121] Yumoto, K., E. Tatsumi, T. Kouyama, D. R. Golish, S. Kameda, H. Sato, B. Rizk, D. N. DellaGiustina, Y. Yokota, H. Suzuki, J. de León, H. Campins, J. Licandro, M. Popescu, J. L. Rizos, R. Honda, M. Yamada, T. Morota, N. Sakatani, Y. Cho, C. Honda, M. Matsuoka, M. Hayakawa, H. Sawada, K. Ogawa, Y. Yamamoto, S. Sugita, D. S. Lauretta (2021), "Cross Calibration Between Hayabusa2 ONC-T and OSIRIS-REx MapCam for Comparative Analyses of Asteroids Ryugu and Bennu", 52th Lunar and Planetary Science Conference, Mar 16 - 20, Online, # 1370

[122] Yokota, Y., R. Honda, E. Tatsumi, D. Domingue, S. E. Schröder, M. Matsuoka, L. Riu, S. Sugita, T. Morota, N. Sakatani, C. Honda, Y. Cho, S. Kameda, T. Kouyama, M. Yamada, M. Hayakawa, H. Senshu, H. Suzuki, K. Yoshioka, H. Sawada, and K. Ogawa (2021) "East-West Comparison of the Photometric Properties on Asteroid Ryugu", 52th Lunar and Planetary Science Conference, Mar 16 - 20, Online, # 2105

[123] Yamada, M., T. Kouyama, K. Yumoto, E. Tatsumi, T. Morota, N. Sakatani, M. Hayakawa, M. Matsuoka, R. Honda, C. Honda, S. Kameda, H. Suzuki, K. Ogawa, K. Shirai, H. Sawada and S. Sugita (2021) "Moon Imaging by Optical Navigation Camera (ONC) During HAYABUSA2 Earth Return", 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1942

[124] Tatsumi, E., M. Matsuoka, S. Sugita, K. Yumoto, N. Takaki, Y. Cho, R. Honda, M. Yamada, T. Morota, N. Sakatani, S. Kameda, T. Kouyama, Y. Yokota, C. Honda, M. Hayakawa, H. Suzuki, K. Yoshioka, H. Sawada, K. Ogawa, N. Hirata, N. Hirata, T. Saiki, H. Imamura, Y. Takagi, H. Yano, K. Shirai, C. Okamoto, Y. Tsuda, S. Nakazawa, Y. Iijima, K. Kitazato, T. Kadono, K. Wada, M. Arakawa, M. Hirabayashi, S. Watanabe (2021) "Surface Flows Mechanism on Asteroid Ryugu Inferred from the Azimuthal Direction of Wake-Like Features on Regolith Around Large Boulders", 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1338

[125] N. Takaki, T. Morota, Y. Cho, E. Tatsumi, R. Honda, S. Kameda, Y. Yokota, N. Sakatani, T. Kouyama, M. Hayakawa, M. Matsuoka, M. Yamada, C. Honda, H. Suzuki, K. Yoshioka, K. Ogawa, H. Sawada, S. Sugita (2021), "Surface Flows Mechanism on Asteroid Ryugu Inferred from the Azimuthal Direction of Wake-Like Features on Regolith Around Large Boulders", 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1432

[126] Y. Takai, T. Morota, K. Yumoto, R. Honda, S. Kameda, E. Tatsumi, Y. Cho, K. Yoshioka, H. Sawada, Y. Yokota, N. Sakatani, M. Hayakawa, M. Matsuoka, M. Yamada, T. Kouyama, H. Suzuki, C. Honda, K. Ogawa, S. Sugita (2021) “Statistics of Small Craters Observed on Boulder Surface of Asteroid Ryugu”, 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 2044

[127] S. Sasaki, S. Kanda,, H. Kikuchi, T. Michikami, T. Morota, C. Honda, H. Miyamoto, R. Henmi, S. Sugita, E. Tatsumi, M. Kanamaru, S. Watanabe, N. Namiki, P. Michel, M. Hirabayashi, N. Hirata, T. Nakamura, T. Noguchi, T. Hiroi, K. Matsumoto, N. Sakatani, S. Kameda, T. Kouyama, H. Suzuki, M. Yamada, R. Honda, Y. Cho, K. Yoshioka, M. Hayakawa, M. Matsuoka, R. Noguchi, H. Sawada, Y. Yokota, and M. Yoshikawa (2021), “Anomalously Porous and Dark Rocks on Asteroid (162173) Ryugu”, 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 2010

[128] N. Sakatani, S. Tanaka, T. Okada, T. Fukuhara, L. Riu, S. Sugita, R. Honda, T. Morota, S. Kameda, Y. Yokota, E. Tatsumi, K. Yumoto, N. Hirata, A. Miura, T. Kouyama, H. Senshu, Y. Shimaki, T. Arai, J. Takita, H. Demura, T. Sekiguchi, T. G. Müller, A. Hagermann, J. Biele, M. Grott, M. Hamm, M. Delbo, W. Neumann, M. Yamada, H. Suzuki, C. Honda, K. Ogawa, M. Hayakawa, K. Yoshioka, M. Matsuoka, Y. Cho, H. Sawada, K. Kitazato, T. Saiki, H. Imamura, Y. Takagi, H. Yano, K. Shirai, S. Nakazawa, M. Arakawa, K. Wada, T. Kadono, K. Ishibashi (2021), “Anomalously Porous and Dark Rocks on Asteroid (162173) Ryugu”, 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1832

[129] A. J. Ogura, K. Yumoto, Y. Cho, T. Niihara, S. Kameda, and S. Sugita (2021), “Elemental Analysis of Lunar Meteorites Using Laser-Induced Breakdown Spectroscopy”, 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1729

[130] G. Nishiyama, T. Kawamura, N. Namiki, B. Fernando, K. Leng, K. Onodera, S. Sugita, T. Saiki, H. Imamura, Y. Takagi, H. Yano, M. Hayakawa, C. Okamoto, H. Sawada, Y. Tsuda, K. Ogawa, S. Nakazawa, Y. Iijima (2021), “A New Model of Seismicity on Asteroids Implied by the SCI Experiment of the Hayabusa2 Mission: Insights from the Existence of Boulders Perched on Other Boulders”, 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1819

[131] T. Morota, S. Sugita, Y. Cho, E. Tatsumi, N. Sakatani, R. Honda, S. Kameda, M. Yamada, Y. Yokota, C. Honda, T. Kouyama, M. Matsuoka, M. Hayakawa, H. Sawada, K. Ogawa, H. Suzuki, K. Yoshioka, M. Kanamaru, M. Hirabayashi, T. Michikami, and Hayabusa2 team (2021), “Impact Strength of Ryugu’s Boulder Inferred from Meter-Sized Crater Statistics”, 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1755.

[132] M. Kanamaru, S. Sasaki, T. Morota, Y. Cho, E. Tatsumi, M. Hirabayashi, N. Hirata, H. Senshu, Y. Shimaki, N. Sakatani, S. Tanaka, T. Okada, T. Usui, S. Sugita, and S. Watanabe (2021), “YORP Effect on Asteroid 162173 Ryugu and Its Spin Evolution”, 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1769.

[133] T. Ebihara, K. Yumoto, S. Sugita, R. Honda, S. Kameda, E. Tatsumi, Y. Cho, K. Yoshioka, H. Sawada, Y. Yokota, N. Sakatani, M. Hayakawa, M. Matsuoka, M. Yamada, T. Kouyama, H. Suzuki, C. Honda, K. Ogawa, T. Michikami, H. Miyamoto, T. Morota (2021), “Investigation of Distribution and Orientations of Boulders on Asteroid Ryugu: Implications for Surface Evolution”, 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1902.

[134] M. Aoki, C. Sugimoto, K. Yumoto, E. Tatsumi, T. Morota, Y. Cho, Y. Yokota, M. Arakawa, R. Honda, S. Kameda, N. Sakatani, T. Kouyama, M. Hayakawa, M. Matsuoka, M. Yamada, C. Honda, H. Suzuki, K. Yoshioka, K. Ogawa, H. Sawada, S. Sugita, SCI team (2021), “Spectroscopic Analysis of Bright Boulders Inside the SCI Crater on Anteroid Ryugu”, 52th Lunar and Planetary Science Conference, Mar 16 - 20. Online, # 1989.

7.3.2 Invited talks

[135] S. Sugita (2020) “Hayabusa missions”, International Space Station Institute Colloquium series “The Game changers”, July 30, Online hosted from Bern Switzerland.

[136] Sugita, S. R. Honda, T. Morota, S. Kameda, E. Tatsumi, S. Tachibana, K. Kitazato, T. Okada, N. Namiki, M. Arakawa, P. Michel, D. Domingue, S. Tanaka, M. Yoshikawa, S. Watanabe, and Y. Tsuda (2020), “Mission Status of Hayabusa2, Science Highlights, and Outlook for Sample Analyses”, EPSC2020-995, Sep 21 - Oct 8, 2020, virtual meeting.

[137] Suto, Y., “Unveiling spin-orbit architectures of exoplanetary systems”, Astronomy Colloquium, Shanghai Jiao Tong University (September 28, 2020)

[138] Suto, Y., "Unveiling the presence of an inner binary black-hole from the tertiary orbiting star", The 9th KIAS workshop on Cosmology and Structure Formation, Korean Institute of Advanced Study (November 2, 2020)

[139] Yamamoto, S., "Organic Molecules in Disk Forming Regions", 43rd COSPAR Scientific Assembly, F3.5, January 28 – February 4, 2021, Online

III

Reports on the research activities of RESCEU groups in 2020 (in Japanese)

2020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 研究活動報告

当研究室は、一般相対性理論、場の量子論、素粒子物理学等の基礎物理学理論に基づいて宇宙論と重力理論の理論的研究を幅広く行うとともに、理学部物理学教室の教育と研究に参画しています。また、大型低温重力波検出器 KAGRA の稼働を迎え、Cannon 研究室とともに重力波データ解析の研究と人材育成にも携わっています。今年度は科学研究費補助金基盤研究（S)「重力波宇宙物理学の包括的研究」の採択により、5376 コアの計算機クラスターの導入が叶い、KAGRA のデータ解析の準備を進めています。

今年度は新型コロナウイルスの蔓延のため、M0 ゼミの一部期間を除き、研究室の全てのセミナーはオンラインでの開催を余儀なくされました。また、毎日 2 時から 1 時間アーカイブチェックの時間を設け、構成員の情報交換と安否確認を行っています。

8.1.1 初期宇宙論

初期宇宙磁場

初期宇宙磁場は、観測されている現在の銀河や銀河団の磁場の起源やブレーザーの観測によって示唆される銀河間ボイド磁場を説明する上で、興味深い研究対象である。我々は初期宇宙磁場の生成およびそれの引き起こす諸現象に関する様々な研究を行った [17, 44, 57, 64]。

電弱対称性が破れる以前の初期宇宙に磁場の存在を仮定すると、標準模型のカイラル量子異常を通じて初期磁場の磁気ヘリシティは局所的な物質反物質非対称を生じるため、電弱相転移期におけるバリオン等曲率揺らぎの生成が一般に避けられない。ところが、ビッグバン元素合成の理論と軽元素の観測量との整合性から、バリオン等曲率揺らぎとその起源たる初期磁場は制限を受ける。とくに初期磁場に対する制限を明らかにし、観測的に示唆されているボイド空間の銀河間磁場強度の起源としては、電弱対称性が破れて以降の磁場生成あるいは増幅機構が必要であることを示した [19, 23, 29, 34, 46, 49, 53, 65, 66, 67, 68, 69, 70, 71]。

また、磁場生成機構として、アフレック=ダイン機構と呼ばれる複素スカラー場がその field space において各運動量を獲得する機構においてその位相とゲージ場が Chern-Simons 結合を持つ可能性に指摘し、この機構における磁場生成を調べた [5] 。その結果、作られたヘリカルな磁場が電弱相転移時に現在の宇宙を説明するのに十分なバリオン非対称を生成しうることが示された。

さらに、磁場と重力波が重力的な結合をすることに注目し、長距離相関の初期磁場があれば、磁場によって初期宇宙において光子が重力波に変換される現象が起こることを指摘し、こうしてできた重力波が GHz scale の背景重力波として現在の宇宙にも満ちていることを示した [8]。

ブラックホール周りの真空相転移現象についての研究

極小のブラックホールの周辺では真空相転移が強く誘発されることが示唆されている。しかし、高温のホーキング放射のもたらす真空安定化の効果を考慮していないため、この効果を取り入れて相転移確率を計算し直した [7, 48, 31]。その結果、極小のブラックホールは依然として真空相転移を強く誘発することが判明した。

重力的レプトン数生成を実現する最小模型における量子補正の繰り込みについて

擬スカラーインフラトンと、Riemann テンソルで与えられる Chern-Pontryagin 密度の結合項を有する模型では、インフレーション中に非ゼロの Chern-Pontryagin 密度、つまりはヘリカルな原始重力波が生成し、重力的カイラルアノマリーの帰結としてレプトン数が同時に生成される。このような機構を重力的レプトン数生成と言い、上記模型はこの機構を実現する最小模型である。しかしながら、生成されるレプトン数が量子効果に由来する紫外発散を有し、先行研究の評価は紫外切断のスケールをどう取るかに強く依存することが懸念されていた。そこで本研究では解析的計算により紫外発散依存性を leading order 以下までも明らかにし、それらの発散を取り除く相殺項を同定した。すると、特定の繰り込み条件の元ではレプトン数が極めて小さくなり、スファレロン過程を経ても観測されている宇宙のバリオン数は到底説明できないことがわかり、本機構の実現性に疑問を投げかける結果となった [9, 24, 30, 43, 45, 51, 58]。

原始ブラックホール改良質量関数の不定性

原始ブラックホールの質量スペクトル関数は、多くの不定性を抱えているのが現状である。我々はこれを克服するための第一歩として、各々の原始ブラックホールの質量スケールを正確に評価する条件を取り入れた改良ピークカウント理論について、その高ピーク極限における解析的な表式を導出するとともに、密度ゆらぎを粗視化する方法に起因する不定性を調べた。特に揺らぎがスケール不変型のパワースペクトルを持つ場合に、原始ブラックホール形成に重要となるスケール周辺では改良の効果がほとんど効かないことを示した [10, 25, 32, 33, 52, 56]。

ヒッグス-R^2 混合模型における再加熱過程

ヒッグス-R^2 混合模型は現在の宇宙背景放射の観測から最も支持されるインフレーション模型の一つである。この模型は複数場インフレーション模型であり、特にその再加熱過程は単一場インフレーション模型とはまったく違った振る舞いを示し、興味深い現象である [59]。特に、模型パラメータの値によっては、インフレーション直後に激しいタキオニックプリヒーティングと呼ばれる現象が起こり、宇宙が瞬間的に熱化されうる。我々はこの現象を解析的および数値的方法によって解析し、この現象が起こり、宇宙を充分に熱化するパラメータの値とその微調整の程度を定量的に定めた [11, 26, 35, 60, 63]。

M-理論における α-attractor の実現に向けて

量子重力を含む統一理論の候補である M-理論の枠組みで観測と整合する初期宇宙のインフレーションを実現することは重要な課題である。M-理論はその理論的構造も含めて未だ完全な理解には至っていないが、その粒子極限は 11 次元超重力理論で記述されることが分かっている。余剰空間に超対称性を保つようなフラックスを導入し、4 次元コンパクト化を考えると安定した真空を持つ 4 次元有効理論が得られる。我々は得られ有効理論に残るモジュライ場が、現在の観測結果と整合する α-attractor インフレーション模型の元となる結合を持つことを示し、特に原始重力波を特徴づけるパラメータ α がフラックスポテンシャルをどのように選ぶことで変化するかを議論し、7 つの離散的な値が得られることを示した [12, 61]。

21cm 線の円偏光

中性水素の超微細構造に起因する 21cm 線は、光子の脱結合の時期から星ができるまでの暗黒時代を調べるための最も重要な観測量の一つとして期待されている。一方で、宇宙背景放射の四重極モーメントをもつ揺らぎは、中性水素のスピンを揃える働きをし、結果として 21cm 線の円偏光が生成される。宇宙背景放射の四重極モーメントは原始重力波によっても生成されるため、21cm 線の円偏光は初期宇宙の情報も含んでいると言える。先行研究では、生成される円偏光の大きさは見積もられていたものの、その角度パワースペクトルはまだ得られていなかった。我々は、先行研究で用いられていた球座標に基づいた計算手法とは異なる、直交座標に基づいた計算手法を用い、21cm 線の円偏光の角度パワースペクトルを求めることに成功した [13]。

真空崩壊に伴う粒子生成の解析

真空崩壊は背景場がトンネル効果によって一次相転移を起こす現象であるが、この際にその場と結合している粒子の有効質量は急激に変化することになる。有効質量が変化した粒子はそれに伴って基底状態が変化するため、生成消滅演算子の定義が変わることになり粒子生成が起こる。我々はこの粒子生成について、近年提唱されているトンネル効果の実時間形式の下でモデル化し、数学的手法としてストークス現象に着目して解析的な評価を求めた。これは相転移に伴う粒子生成の解析であると同時に、トンネル効果の実時間形式そのものについてトンネル確率とは違った側面からその正当性に対して示唆を与える研究でもある [14, 50]。

二次スカラー揺らぎの解析的表式

宇宙論においてスカラー揺らぎは、初期宇宙の理論と現在の観測を結ぶ重要な働きをする。宇宙背景放射の観測から、大スケールのスカラー揺らぎは大きくないことがわかっているが、小スケールのスカラー揺らぎが大きい可能性はまだ残っている。大きなスカラー揺らぎが存在する場合、その非線形効果が重要になるため、その発展を解析的に追うための基礎を築くことには意義がある。このような背景から、我々は一次のスカラー揺らぎが非線形効果を通して生み出す二次のスカラー揺らぎの解析的表式を求めた。さらに、その表式を用いて、二次スカラー揺らぎがどのような時間発展をするのか、及びどのような揺らぎのスペクトルが予言されるのかを明らかにした [15, 22]。

真空相転移のローレンツ経路積分による考察

真空相転移は時空をユークリッド化し、その上でのバウンス解を用いて解析される。ところが重力が存在するときはこの描像は不明瞭になるので、ユークリッド時空ではなくローレンツ時空で直接解析することを目指した。ドジッター時空での真空相転移を考え、重力への反作用を無視するような状況を考えると、従来のバウンスによる解析の結果を再現することができた [27]。

右巻きニュートリノの重力的粒子生成による包括的宇宙論

クインテッセンシャル・インフレーションに 3 世代の右巻きマヨラナニュートリノを導入することで、暗黒物質の存在量、バリオン数生成、再加熱過程、暗黒エネルギーといった宇宙論の諸問題を、インフレーション後の右巻きニュートリノの重力的粒子生成によって包括的に説明する模型を構築した。この模型に於いては、3 世代の右巻きニュートリノの軽い方から順に N_1, N_2, N_3 とおくと、N_1 はステライル・ニュートリノと同様に暗黒物質として振る舞い、N_2 は N_3 との干渉により正味のバリオン数を生成し、N_3 は標準模型の粒子に崩壊することで再加熱過程を実現する。重力的粒子生成は共形対称性からのズレに起因する機構である為、これら N_1, N_2, N_3 の生成

量はその質量によって定まる。我々はこの質量パラメータを上手く選んでやることで、現在得られている観測量を矛盾無く包括的に説明し得ることを示した [47, 62]。

シュウィンガー効果を用いた再加熱過程の検証

アクシオンのような擬スカラーによって駆動されるインフレーション模型において、擬スカラーがインフレーション終了後にポテンシャルの極小点に落ち込まずに転がり続ける場合の再加熱過程を考えた。この場合、インフラトンがポテンシャル極小点周りでコヒーレントに振動して崩壊するという通常の再加熱過程の議論を適用することは出来ない。しかしながら、擬スカラーが運動し続ける際にはヘリカルな電磁場が生成することが知られており、生成した電磁場から更にシュウィンガー効果によって荷電粒子を生成して熱浴を実現することが可能である。一方、状況によっては残存した磁場が観測と矛盾した結果をもたらしてしまうことがある。我々はこうした模型について検討した結果、擬スカラーの運動が速過ぎなければ再加熱過程が上手くいくパラメータ領域が存在することを示した [54]。

8.1.2 重力波検出器 KAGRA のデータ解析

補助モニターを用いたオフライン解析による雑音除去手法の開発

2020 年 4 月に初の本格稼働を実施した KAGRA であるが、現在は 2022 年 6 月以降開始予定の LIGO-Virgo との O4 共同観測に向けた改修作業中である。重力波初検出を達成するためにはさらなる感度向上を実現しなければならず、様々な雑音源に直接対策を講じるとともに、オフラインデータ解析によりデータから雑音を統計的に除去する手法の開発が重要である。本研究では、非ガウス分布に従う信号が混合した際に分離・復元する処理手法である独立成分解析 (ICA) に着目し、補助モニターを用いた雑音除去手法の開発に取り組んだ。これまで、初期稼働時の iKAGRA データに最も単純なモデルの ICA を適用し、地震計を用いることで地面振動雑音を部分的に削減できるという結果が得られていた [6]。本年度はさらに、最新の KAGRA データと補助モニターに対して拡張した ICA モデルを適用することで、重力波の観測周波数帯域において特に影響が顕著であった音響雑音の除去に成功した [28, 36, 37, 38, 55]。

8.2 業績リスト

＜受賞＞

[1] 横山順一, 令和 2 年度 科学技術分野の文部科学大臣表彰　科学技術賞「最も一般的なインフレーション宇宙論の研究」

[2] Jun'ya Kume, 25th KAGRA Face-to-Face Meeting Best Poster Presentation award, 2020/8/22.

[3] 粂 潤哉, 2020 年秋季大会 日本物理学会学生優秀発表賞 宇宙線・宇宙物理領域, 2020/10/10.

[4] Jun'ya Kume, ONLINE JGRG WORKSHOP 2020 Outstanding presentation award, Gold prize, 2020/11/27.

＜報文＞

(原著論文)

[5] K. Kamada, and C. S. Shin, "Magnetogenesis from a rotating scalar: á la scalar chiral magnetic effect", Journal of High Energy Physics **04**, 185 (2020).

[6] T. Akutsu *et al.* [KAGRA], "Application of independent component analysis to the iKAGRA data," Progress of Theoretical and Experimental Physics **2020** (2020) no.5, 053F01.

[7] T. Hayashi, K. Kamada, N. Oshita and J. Yokoyama, "On catalyzed vacuum decay around a radiating black hole and the crisis of the electroweak vacuum", Journal of High Energy Physics **08**, 088 (2020).

[8] T. Fujita, K. Kamada, and Y. Nakai, "Gravitational waves from primordial magnetic fields via photon-graviton conversion", Phys. Rev. D **102**, 103501 (2020).

[9] K. Kamada, J. Kume and Y. Yamada: "Renormalization in gravitational leptogenesis with pseudo-scalar-tensor coupling," Journal of Cosmology and Astroparticle Physics **10**, 030 (2020).

[10] K. Tokeshi, K Inomata, and J. Yokoyama, "Window function dependence of the novel mass function of primordial black holes", Journal of Cosmology and Astroparticle Physics **12**, 038 (2020).

[11] M. He, R. Jinno, K. Kamada, A. A. Starobinsky and J. Yokoyama, "Occurrence of tachyonic preheating in the mixed Higgs-R^2 model," Journal of Cosmology and Astroparticle Physics **01**, 066 (2021).

[12] M. Gunaydin, R. Kallosh, A. Linde and Y. Yamada, "M-theory Cosmology, Octonions, Error Correcting Codes," Journal of High Energy Physics **01**, 160 (2021).

[13] Lingyuan Ji, Marc Kamionkowski, Keisuke Inomata, "Standard model prediction for cosmological 21 cm circular polarization", Phys. Rev. D **103**, 023516 (2021).

[14] S. Hashiba, Y. Yamada and J. Yokoyama, "Particle production induced by vacuum decay in real time dynamics", Phys. Rev. D **103**, 045006 (2021).

[15] Keisuke Inomata, "Analytic solutions of scalar perturbations induced by scalar perturbations", Journal of Cosmology and Astroparticle Physics **03**, 013 (2021).

(会議抄録)

[16] Y. Yamada, "Nonlinearly realized supergravity and its applications," AIP Conf. Proc. **2319**, no.1, 040018 (2021).

(国内雑誌)

[17] 鎌田耕平, 「銀河間ボイドの化石磁場から探る初期宇宙の物理」日本物理学会誌, 2020, 75 巻, 6 号, p.329-334.

[18] 横山順一　「横山教授に聞く科学のふしぎ」　子ども新聞「風っ子」連載, 第 37 回－第 59 回, 上毛新聞社

(学位論文)

[19] 内田経夫、「初期磁場によるバリオン等曲率揺らぎの生成とその宇宙論的帰結」(修士論文).

[20] 渡慶次孝気、「原始ブラックホール質量関数の不定性の克服と精密化に向けた研究」(修士論文).

(編著書)

[21] T. Y. Tou, J. Yokoyama, R. A. Shukor, K. Tanaka, H. J. Choi, R. Matsumoto, O. H. Chin, J. H. Chin and K. Ratnavelu (eds), "Proceedings of 14th Asia-Pacific Physics Conference (APPC2019)," Sarawak, Malaysia, November 17-22, 2019 AIP Conf. Proc. 2319 (2021) 1.

＜学術講演＞

(国際会議)

一般講演

[22] Keisuke Inomata, "Scalar perturbations induced by scalar perturbations", RESCEU Summer School 2020, Online, 2020/8/18.

[23] F. Uchida, "A baryogenesis scenario from helical magnetic fields and constraints on it", RESCEU Summer School 2020, Online, 2020/8/19.

[24] J. Kume, "Quantum correction in gravitational leptogenesis and its renormalization", RESCEU Summer School 2020, Online, 2020/8/19.

[25] K. Tokeshi, "PBH mass spectrum and window function dependence", RESCEU Summer School 2020, Online, 2020/8/19.

[26] M. He, "Tachyonic preheating in the mixed Higgs-R^2 model", RESCEU summer school 2020, Online, 2020/08/19.

[27] T. Hayashi, "Towards Coleman-de Luccia bubble nucleation in the Lorentzian path integral" RESCEU Summer School, RESCEU summer school 2020, Online, 2020/08/19.

[28] J. Kume, "Towards the offline noise subtraction using Independent Component Analysis"(poster), 25th KAGRA Face-to-Face Meeting, Online, 2020/8/20-22.

[29] F. Uchida, "Constraint on the intergalactic magnetic field from baryon isocurvature perturbations at the Big-Bang Nucleosynthesis", AAPPS-DACG Workshop on Astrophysics, Cosmology and Gravitation, Online, 2020/11/11.

[30] J. Kume, "Renormalization in the minimal model of the gravitational leptogenesis", AAPPS-DACG Workshop on Astrophysics, Cosmology and Gravitation, Online, 2020/11/11.

[31] T. Hayashi, "The effect of Hawking radiation on BH catalyzed phase transition", AAPPS-DACG Workshop on Astrophysics, Cosmology and Gravitation, Online, 2020/11/11.

[32] K. Tokeshi, "Primordial black holes and uncertainty of the mass function: window function dependence," AAPPS-DACG Workshop on Astrophysics, Cosmology and Gravitation, Online, 2020/11/11.

[33] K. Tokeshi, "Primordial black holes, improved mass function, and its window function dependence," The Online Workshop on General Relativity and Gravitation in Japan (Online JGRG), Online, 2020/11/23.

[34] F. Uchida, "Constraints on baryogenesis from primordial magnetic fields", The Online Workshop on General Relativity and Gravitation in Japan (Online JGRG), Online, 2020/11/24.

[35] M. He, "Reheating in the mixed Higgs-R^2 model", The Online Workshop on General Relativity and Gravitation in Japan (Online JGRG), Online, 2020/11/24.

[36] J. Kume, "Offline noise subtraction in KAGRA using independent coomponent analysis", The Online Workshop on General Relativity and Gravitation in Japan (Online JGRG), Online, 2020/11/27.

[37] J. Kume, "Noise subtraction in offline data analysis of KAGRA"(poster), 26th KAGRA Face-to-Face Meeting, Online, 2020/12/17-18.

[38] J. Kume, "Noise subtraction in offline analysis of KAGRA using independent component analysis", The 7th KAGRA International Workshop, National Central U. Taiwan, Online, 2020/12/19.

招待講演

[39] J. Yokoyama, "Dark matter and baryon number generation in quintessential inflation," Japan-Netherlands symposium on Gravity and Cosmology, Online, 2020/7/27.

[40] J. Yokoyama, “Gravitational waves as a new probe of the universe,” 38th SPP conference, Online, 2020/10/19.

[41] J. Yokoyama, “Gravitational waves from the early universe,” Korea-Japan joint session of KPS annual meeting, Online, 2020/11/6.

[42] J. Yokoyama, “Mixed Higgs R^2 inflation,” 7th Korea-Japan workshop on dark energy, Online, 2020/12/10.

[43] K. Kamada, “Towards a robust estimate for gravitational leptogenesis”, Zooming in on Axions in the Early Universe, Virtual Institute at CERN, Online, 2020/6/24.

[44] K. Kamada, “Primordial magnetic field – Its relationship to cosmology and implication to the IGMF”, NECO on-line workshop “Probing the Universe with High and Very High Energy Sources”, International Research Network Extragalactic Astrophysics and Cosmology, Online, 2020/12/9.

(国内会議)

一般講演

[45] 条潤哉、“Gravitational leptogenesis and renormalization in a model with pseudo-scalar-tensor coupling”, 基研研究会 素粒子物理学の進展 2020、Online、2020/8/31.

[46] 内田経夫、鎌田耕平、横山順一、“バリオン非対称の起源としての宇宙磁場にバリオン揺らぎが与える制限”、基研研究会 素粒子物理学の進展 2020、ポスター、Online、 2020/8/31-2020/9/4.

[47] 羽柴聡一朗、“右巻きニュートリノの重力的粒子生成によるバリオン数と暗黒物質の生成”、基研研究会 素粒子物理学の進展 2020、ポスター、Online、2020/08/31-09/04.

[48] 林拓未、“The effect of Hawking radiation on vacuum phase transition”、基研研究会 素粒子物理学の進展 2020、ポスター、Online、2020/08/31-09/04.

[49] 内田経夫、鎌田耕平、横山順一、“磁場によるバリオン数生成シナリオに対する、バリオン揺らぎからの制限”、 日本物理学会 2020 年秋季大会、Online, 2020/9/15.

[50] 羽柴聡一朗、山田悠介、横山順一、“ 真空崩壊に伴う粒子生成とその帰結 ” 、日本物理学会 2020 年秋季大会、Online、2020/09/15.

[51] 条潤哉、鎌田耕平、 山田悠介、 “重力的レプトン数生成における量子補正の正則化とその帰結”、 日本物理学会 2020 年秋季大会、Online、2020/9/15.

[52] 渡慶次孝気、猪又敬介、横山順一、“原始ブラックホールの新しい質量関数と密度揺らぎの粗視化に伴うフィルター関数依存性”、日本物理学会 2020 年秋季大会、Online、2020/9/15.

[53] 内田経夫、鎌田耕平、横山順一、“初期磁場のバリオン揺らぎ生成の効果による制限”、 日本物理学会 2021 年第 76 回年次大会、Online, 2021/3/13.

[54] 羽柴聡一朗、中塚洋佑、鎌田耕平、“ 運動項優勢期におけるシュウィンガー効果による再加熱過程 ”、日本物理学会第 76 回年次大会、Online、2021/03/13.

[55] 条潤哉、伊藤洋介、横山順一、鷲見貴生、横澤孝章、“オフライン解析による KAGRA データの雑音除去”、日本物理学会第 76 回年次大会、Online、 2021/3/14.

[56] 渡慶次孝気、猪又敬介、横山順一、“ピークカウント法における球対称密度揺らぎの扱いとその物理的帰結”、日本物理学会第 76 回年次大会、Online、2021/3/14.

(セミナー)

[57] 鎌田耕平, “ 初期宇宙磁場とその (素粒子) 宇宙論的諸現象”, 理論物理学コロキウム (宇宙), 立教大学 (オンライン), 2020/5/26.

[58] J. Kume, “Renormalization in gravitational leptogenesis with pseudo-scalar-tensor coupling”, Virtual Axion Institute, Online, 2020/7/31.

[59] K. Kamada, Special lecture “Pedagogical lectures on recent progress in Higgs inflation”, Yonsei University, Yonsei Lab for Dark Unvierse, Seoul (Online), South Korea, 2020/8/5-7.

[60] M. He, “Preheating in the mixed Higgs-R^2 model”, invited talk at Yonsei University, Online, 2020/08/13.

[61] 山田悠介, “cosmological α-attractor and M-theory”, 東京大学駒場素粒子論研究室セミナー, 東京大学 (オンライン), 2020/10/14.

[62] S. Hashiba, “Gravitational production of right-handed neutrinos after quintessential infaltion”, Hokkaido University (Online), 2020/10/16.

[63] M. He, “Reheating in the mixed Higgs-R^2 model”, Cosmology seminar at Perimeter Institute of Theoretical Physics, Online, 2020/11/06.

[64] 鎌田耕平, “Cosmological hypermagnetic fields: their generation and implication on the baryon asymmetry of the Universe”, 京都大学素粒子論研究室セミナー, 京都大学 (オンライン), 2020/12/23.

[65] F. Uchida, “Baryon isocurvature constraints on the primordial hypermagnetic fields”, IPMU journal club, Online, 2021/1/13.

[66] K. Kamada, “Constraints on the primordial hypermagnetic fields from the baryon isocurvature perturbations”, ASU cosmology seminar, Arizona State Uiversity, Tempe, AZ, USA, Online, 2021/1/28.

[67] K. Kamada,“Universal constraints on primordial magnetogenesis from baryon isocurvature perturbations”, Kavli IPMU APEC seminar, Kavli IPMU, University of Tokyo, Kashiwa, Japan, Online, 2021/2/4.

[68] K. Kamada, “Baryon isocurvature perturbation constrains primordial hypermagnetic fields”, Institute Basic Science - Center for Theoretical Physics of the Universe, Daejeon, South Korea, Online, 2021/2/10.

[69] K. Kamada, “Chiral effects in cosmology”, High Energy Theory Group Seminar, Keio University, Yokohama, Online, Japan, 2021/2/25.

[70] F. Uchida, “Baryon isocurvature constraints on the primordial hypermagnetic fields”, IBS-CTPU journal club, Online, 2021/2/26.

[71] K. Kamada, “Primordial hypermagnetic fields constrained by baryon isocurvature perturbations”, HET seminar, Ecole Polytechinique Federale de Lausanne, Lausanne, Switzerland, Online, 2021/3/29.

(アウトリーチ)

[72] 横山順一, 第 93 回五月祭講演, 「輪廻する宇宙」 オンライン 2020/9/20-21

[73] 横山順一, 立川国際高校講演会, 「コロナ時代に考える宇宙のこと世界のこと」 立川国際高校 2020/12/18

9 Kipp Cannon研究室

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

私たちの研究グループのメンバーは LIGO と KAGRA コラボレーションのメンバーであり、世界中の重力波検出器、LIGO (アメリカ)、Virgo (イタリア)、GEO600 (ドイツ)、KAGRA (日本) によって収集されたデータを分析してします。LIGO と Virgo は、2019 年 3 月下旬に第 3 次観測「O3」を開始し、データ取得は 1 年間ほど継続される予定でした。しかし、コロナウイルスの流行により 2020 年 3 月下旬に観測が中止されてしまったため、残念ながら今年度は LIGO/Virgo の新しいデータは得られませんでした。その代わり、2 週間ほどの短い期間ですが、KAGRA の新しいデータが得られました。私たちのグループのメンバーは、そのデータの解析を通して重力波を用いた天文学や宇宙論のほぼ全ての分野で活動しています。

9.1 研究活動報告

9.1.1 重力波データ解析

重力波信号の統計特性に基づく重力波探索の効率化

重力波信号のみが持つ特性を利用した、信号を検出するのに必要な計算時間をトータルで短縮するための手法を開発している。具体的には連星合体重力波波形テンプレートを用いた整合フィルターによる信号雑音比と、信号雑音比の時系列とテンプレートの自己相関との差異の 2 つの変数が従う確率密度分布をあらかじめ重力波信号と雑音の双方に対して計算しておいて、重力波信号である可能性が非常に低い疑似信号を検出システムの初期段階で捨ててしまうことができれば、従来にない短い時間で重力波を探索できるようになる。重力波が検出されたコンパクト連星がそもそもいつどこでどうやって作られたのかを知るためには様々な宇宙物理学の理論モデルと実際の観測分布とを突き合わせる必要があるが、この手法が実現すると、今までは計算に時間がかかりすぎるために現実的には困難であった多数の理論モデルの検証が一気に行えるようになり、宇宙物理学上のいくつかの長年にわたる難問が解けることが期待される。

重力波探索におけるモデル選択バイアスのモデリング

コンパクト連星合体により生じる重力波の振幅は非常に小さく、ごく限られたものしか観測することができない。これはつまり、重力波の検出率と発生率には違いが存在することを意味している。その違いは観測機器によるハードウェアとデータ解析によるソフトウェアの両面から生じ、その違いの評価は重力波探索全体を踏まえた感度を調べることによって行われる。従来の感度測定は用意した仮想の重力波信号を検出することによって行われていた。この方法は高コストであることに加え、検出器の感度向上に伴い、データに多数の重力波信号が混じり、将来的に精度が低下することが懸念されている。我々はその問題に対して、仮想の重力波信号を検出する際のソフトウェアの振る舞いをモデル化することで解決を試みている。半解析的な感度推定によりコストは大きく削減され、観測データを直接的に扱うことも回避している。この手法を実践的に改良し、現在では通常の解析の中で用いられるようになった。

GstLAL パイプラインによる背景雑音推定の改善

GstLAL パイプラインによる重力波データ解析では尤度比順位統計を用いているが、その雑音モデルの推定には重力波検出器の観測データを必要とする。しかし、重力波信号が含まれたデータは雑音モデル推定に用いるべきではなく、重力波信号の無い観測データを用意することも現実には不可能であるため、重力波信号の影響をなるべく受けないような雑音モ

デル推定法が必要である。我々のグループでは、重力波検出に用いる波形テンプレートを時間的に逆転させて利用することで、連星中性子星からの重力波信号に対して不感であるような雑音モデル推定法を開発した。現在は、この新たに開発した方法を GstLAL パイプラインに実装することを目指している。

重力波源の高速位置特定手法の開発

電磁波及び重力波による共同観測は重要であるが、その成功率を上げる方法として、重力波源の位置を高速で特定するという方法もある [19]。特に、ショートガンマ線バーストなどの短時間イベントを調べようとすると、時間の経過によって失われていく系の情報が重要であるため、高速位置特定の必要性は非常に高い。本研究では、事前に一部の計算を行っておくことで、従来のものより 100 倍程度高速な新手法を開発した [25]。しかしこの高速化のために、いくつかの近似を行っているため、位置の推定精度の低下を招いてしまっている。そこで現在、これらの近似を 1 つずつ取り除いていき、推定精度の向上を図っている。

将来重力波検出器における重力波信号の重なりとパラメータ推定への影響

Einstein Telescope や Cosmic Explorer などの将来の地上重力波検出器は、中性子星やブラックホールの連星合体による重力波イベントを多数 (1 年間に数 10 万イベント) 観測すると期待されている。しかし、イベント数が多すぎると、検出器データ中の重力波信号同士が互いに重なり合ってしまい、重力波信号のパラメータ推定に影響を与える可能性がある。場合によってはそれらの信号を分離できず、検出が困難になることもあり得る。そこで、我々はまず、重力波イベントをランダムに生成するシミュレーションを行い、重力波信号が重なりがどの程度発生するのかを見積もった。そして、重力波信号が重なり合った場合に、パラメータ推定の誤差や推定バイアスがどの程度悪化するのかを調べた。その結果、重なり合う重力波信号の波形が非常に似ていない限りは、パラメータ推定はほとんど影響を受けないことが分かった。つまり、上述の将来地上重力波検出器においては重力波信号の重なりはパラメータ推定に対してほぼ問題にならないことを示した。

9.1.2 重力波天文学

ブラックホール誕生時の突発的天体現象

Advanced LIGO などの重力波干渉計によって発見された連星ブラックホールがどのように形成されたかは天体物理学の大きな謎の一つになっている。その謎を解明するために、ブラックホール誕生の瞬間を観測する可能性に着目し、ブラックホール形成時に付随する突発的天体現象に関する理論的研究を行っている。ブラックホールが大質量星から誕生する際、中心核のニュートリノ放出によって重力が減少するため星の外層の一部が放出される。この質量放出に伴う 100 日程度の電磁波放射を計算し、可視光・赤外線で光る起源のわからない謎の突発天体 intermediate luminosity red transients の観測を説明できることを示した [15]。また近年中性子星合体 GW170817 の再解析により、合体後の残骸ブラックホールからの新たな重力波信号の検出が報告されている。この信号に対する一つの解釈として量子重力理論が予言する重力波エコーと呼ばれる現象に着目し、GW170817 の再解析結果を説明できることを示した。さらに将来近傍銀河の大質量星からブラックホールが形成された場合、このような重力波放射が次世代の重力波干渉計で観測可能であることを示した [16, 17]。

電波望遠鏡 CHIME によるショートガンマ線バーストからの残光観測へ向けて

我々は、ショートガンマ線バーストからの「残光」を電波望遠鏡 CHIME で観測することを目指している。ショートガンマ線バーストとは、二秒以内という短時間に高エネルギーを放出する爆発現象のことである。即時放射と呼ばれる短時間の放射の後に、数ヶ月から数年という長いタイムスケールで微かな光が観測されることがあり、これを「残光」という。即時放射は、ショートガンマ線バーストのエネルギー源である相対論的ジェットと同じ方向に放射されるため、観測者の位置によって観測が困難であることがある。一方、残光はほぼ等方的に放射されるため、指向性による影響を受けにくく、電波観測によって正確なエネルギースケールを推定することも可能である。しかし、電波残光は非常に暗く、望遠鏡に起因する雑音や分解しきれない天体による背景雑音に隠され、十分な S/N 比で検出することが困難である。そこで、本研究では、重力波観測でも用いられる「尤度比統計」を用いて、ショートガンマ線バーストからの残光を検出することを試みる。本研究によってより多くの電波残光が検出されれば、相対論的ジェットに関するパラメータを統計的に議論し、ショートガンマ線バーストの起源に制限を課すことになると期待する。

近未来重力波望遠鏡による歳差運動している連星合体の事前予報

2015 年に重力波が初検出されてから 2020 年まで、多くの連星合体由来の重力波イベントが定期的に検出され、2017 年には電磁波望遠鏡との共同観測にも成功した。電磁波と重力波ではそれぞれ埋め込まれている情報が異なるため、共同観測によって「ショートガンマ線バーストのモデル制限」や「r 過程元素合成の起源確認」などの、より広い物理を展開することができる。しかし、共同観測の成功は 2017 年の

一例のみであり、その成功確率を上げることは重要である。その方法の１つとして、事前に連星合体の発生時刻・方向を予報するというものがあるが、現状の重力波望遠鏡では感度が不十分である。そこで、近未来にその感度向上及び新たな建設が予定されている重力波望遠鏡による事前予報に関する研究が多く存在する。本研究では、連星の歳差運動を考慮することで事前予報の性能が 10-1000 倍程度向上することを評価した。

9.1.3 重力波による基礎物理の探究

重力波偏極モードによる重力理論の検証

一般相対性理論を拡張した重力理論はこれまで多数提案されており、一般相対性理論の正しさを様々な側面からより高精度で検証することは我々の重力に対する理解を深める上で重要である。重力波の初検出以降、重力波を放射する天体の近傍、つまり、動的かつ非常に強い重力場における重力の性質を調べることが可能になった。そのような状況での重力の検証方法の１つとして、重力波の偏極モードがある。偏極モードの数は各重力理論に特有であり、一般相対性理論では ２つのモードが存在するが、拡張重力理論では３つ以上の偏極モードが存在できる。つまり、偏極モードの数を観測データから調べることで正しい重力理論を絞り込むことができる。我々は重力波検出器の実際の観測データを解析し、得られた重力波信号が一般相対性理論の予言する偏極モードの性質と一致しているかどうかの検証を行った。その結果、一般相対性理論と矛盾するような兆候は無く、一般相対性理論の正しさを支持する結果を得た [26]。また、重力理論検証のために、具体的な修正重力理論における宇宙論モデルや重力波に関する観測的予言の研究も行っている [21]。

ブラックホール周りの極軽量ベクトル場から放射される背景重力波の探査

近年、ブラックホール周りの有質量ボゾン場が不安定性から重力波を放出する現象が提唱されている。その中でもベクトル場に着目し、そこから放出される重力波の重ね合わせである「背景重力波」を探査した。この重力波の周波数帯は主にベクトル場の質量によって決まるため、探査を通してボゾン場の質量に対する観測的制限を課すことが重なる目的である。ブラックホールを含む各系から放出される重力波の周波数について、ベクトル場ではブラックホールの質量に関する高次項まで含んで計算しなければならないことがわかっており、数値計算の結果をフィッティングすることで高精度の重力波スペクトルを導いた。この理論スペクトルに基づき、LIGO の観測データを用いてベイズ解析を行った。統計的に有意な検出結果は得られず、その事実からベクトル場の質量 $0.8 \times 10^{-13}\mathrm{eV} \leq m_b \leq 6.0 \times 10^{-13}-13$ に制限をかけた [27]。

重力波チェレンコフ放射の探査

仮に質点が超光速で動いたときに衝撃波のように発生する重力波が存在するか、探査する。具体的には、チェレンコフ放射や衝撃波に共通する、波形・スペクトルの特徴を持つ重力波を探すことを指す。

9.1.4 重力波検出器に関する研究

将来重力波検出器の感度向上のための検討

現在稼働している地上の重力波検出器は LIGO, Virgo, KAGRA, GEO600 であるが、今後 5 年以内にこれらの検出器はアップグレードし、感度を向上させる予定である。しかし、どのようなアップグレードを行うかは利用可能な技術やその実現の難しさなどにも依るため、詳細な検討が必要である。日本の検出器 KAGRA は KAGRA+ へのアップグレードを予定しているが、我々は KAGRA の共同研究者とその検討を行い、アップグレードに伴う感度の最適化を検討した [20]。一方、更に将来の 2030 年代にはスペース重力波検出器も計画されている。特に、日本が中心となって進める DECIGO 計画はインフレーション起源の原始重力波の検出を目的としており、そのための感度向上および最適化の検討もされている [22]。

9.2 業績リスト

＜受賞＞

[1] L. Tsukada, Best presentation award, The 7th KAGRA international workshop, 2020/12/20.

＜報文＞

(原著論文)

[2] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), “Optically targeted search for gravitational waves emitted by core-collapse supernovae during the first and second observing runs of advanced LIGO and advanced Virgo”, Physical Review D, 101, 084002 (2020).

[3] R. Hamburg *et al.* (Fermi Gamma-ray Burst Monitor Team and LIGO Scientific Collaboration and Virgo Collaboration), “A joint fermi-GBM and LIGO/Virgo analysis of compact binary mergers from the first and second gravitational-wave observing runs”, Astrophysical Journal, 893, 100 (2020).

[4] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), “GW190814: Gravitational waves from the coalescence of a 23 solar mass black hole with a 2.6 solar mass compact object”, Astrophysical Journal, 896, L44 (2020).

[5] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "GW190412: Observation of a binary-black-hole coalescence with asymmetric masses", Physical Review D, 102, 043015 (2020).

[6] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Prospects for observing and localizing gravitational-wave transients with Advanced LIGO and Advanced Virgo", Living Reviews in Relativity, 23, 3 (2020).

[7] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "GW190521: A binary black hole merger with a total mass of $150\,M_\odot$", Physical Review Letters, 125, 101102 (2020).

[8] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Properties and astrophysical implications of the $150\,M_\odot$ binary black hole merger GW190521", Astrophysical Journal Letters, 900, L13 (2020).

[9] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Gravitational-wave constraints on the equatorial ellipticity of millisecond pulsars", Astrophysical Journal Letters, 902, L21 (2020).

[10] T. Akutsu *et al.* (KAGRA Collaboration), "Vibration isolation system with a compact damping system for power recycling mirrors of KAGRA", Classical and Quantum Gravity, 38, 065011 (2021).

[11] T. Akutsu *et al.* (KAGRA Collaboration), "Overview of KAGRA: Calibration, detector characterization, physical environmental monitors, and the geophysics interferometer', Progress of Theoretical and Experimental Physics, ptab018 (2021).

[12] T. Akutsu *et al.* (KAGRA Collaboration), "Overview of KAGRA : Detector design and construction history", Progress of Theoretical and Experimental Physics, ptaa125 (2020).

[13] T. Akutsu *et al.* (KAGRA Collaboration), "Overview of KAGRA : KAGRA science", Progress of Theoretical and Experimental Physics, ptaa120 (2020).

[14] T. Akutsu *et al.* (KAGRA Collaboration), "Application of independent component analysis to the iKAGRA data", Progress of Theoretical and Experimental Physics, 2020, 053F01 (2020).

[15] D. Tsuna, A. Ishii, N. Kuriyama, K. Kashiyama, T. Shigeyama, "Intermediate Luminosity Red Transients by Black Holes Born from Erupting Massive Stars", Astrophysical Journal Letters, 897, L44 (2020).

[16] N. Oshita, D. Tsuna, and N. Afshordi, "Quantum Black Hole Seismology I: Echoes, Ergospheres, and Spectra", Physical Review D, 102, 024045 (2020).

[17] N. Oshita, D. Tsuna, and N. Afshordi, "Quantum Black Hole Seismology II: Applications to Astrophysical Black Holes", Physical Review D, 102, 024046 (2020).

[18] S. Zhu, M. Baryakhtar, M. A. Papa, D. Tsuna, N. Kawanaka, H.-B. Eggenstein, "Characterizing the Continuous Gravitational-Wave Signal from Boson Clouds around Galactic Isolated Black Holes", Physical Review D, 102, 063020 (2020).

[19] S. Sachdev, R. Magee, C. Hanna, K. Cannon, L. Singer, J. R. SK, D. Mukherjee, S. Caudill, C. Chan, J. D. E. Creighton, B. Ewing, H. Fong, P. Godwin, R. Huxford, S. Kapadia, A. K. Y. Li, R. K. L. Lo, D. Meacher, C. Messick, S. R. Mohite, A. Nishizawa, H. Ohta, A. Pace, A. Reza, B. S. Sathyaprakash, M. Shikauchi, D. Singh, L. Tsukada, D. Tsuna, T. Tsutsui, and K. Ueno, "An Early-warning System for Electromagnetic Follow-up of Gravitational-wave Events", Astrophysical Journal Letters, 905, L25 (2020).

[20] Y. Michimura, K. Komori, Y. Enomoto, K. Nagano, A. Nishizawa, E. Hirose, M. Leonardi, E. Capocasa, N. Aritomi, Y. Zhao, R. Flaminio, T. Ushiba, T. Yamada, L.-W. Wei, H. Takeda, S. Tanioka, M. Ando, K. Yamamoto, K. Hayama, S. Haino, and K. Somiya, "Prospects for improving the sensitivity of the cryogenic gravitational wave detector KAGRA", Physical Review D, 102, 022008 (2020).

[21] S. Arai, P. Karmakar, and A. Nishizawa, "Cosmological evolution of viable models in the generalized scalar-tensor theory", Physical Review D, 102, 024003 (2020).

[22] R. Yamada, Y. Enomoto, A. Nishizawa, K. Nagano, S. Kuroyanagi, K. Kokeyama, K. Komori, Y. Michimura, T. Naito, I. Watanabe, T. Morimoto, M. Ando, A. Furusawa, S. Kawamura, "Optimization of quantum noise by completing the square of multiple interferometer outputs in quantum locking for gravitational wave detectors", Physical Letters A 384, 126626 (2020).

[23] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Open data from the first and second observing runs of advanced LIGO and advanced Virgo", SoftwareX, 13, 100658 (2021).

[24] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "All-sky search in early O3 LIGO data for continuous gravitational-wave signals from unknown neutron stars in binary systems", Physical Review D, 103, 064017 (2021).

[25] T. Tsutsui, K. Cannon, L. Tsukada, "High speed source localization in searches for gravitational waves from compact object collisions", Physical Review D, 103, 043011 (2021).

[26] H. Takeda, S. Morisaki, A. Nishizawa, "Pure polarization test of GW170814 and GW170817 using waveforms consistent with modified theories of gravity", Physical Review D, 103, 064037 (2021).

[27] L. Tsukada, R. Brito, W. East, and N. Siemonsen, "Modeling and searching for a stochastic

gravitational-wave background from ultralight vector bosons", Physical Review D, 103, 083005 (2021).

(学位論文)

[28] L. Tsukada, "Modeling and Searching for Stochastic Gravitational-waves Backgrounds from Ultralight Boson Particles" (博士論文).

[29] C. Chan, "Improving Background Estimation Technique In GstLAL Inspiral Pipeline" (修士論文).

[30] M. Shikauchi, "On the use of CHIME to Detect Long-Duration Radio Transients from Neutron Star Mergers" (修士論文).

＜学術講演＞

(国際会議)

一般講演

[31] T. Tsutsui, "An improvement of early warning with 3G detectors by precession effect", JGRG Workshop, Online, 2020/11/23-27.

[32] L. Tsukada, "Modeling and searching for a stochastic GW background from ultralight bosons", The 7th KAGRA international workshop, Taipei, Taiwan, 2020/12/18-20.

[33] (ポスター) M. Shikauchi, "On the use of CHIME to Detect Long-Duration Radio Transients from Binary Neutron Star Mergers", Innovative Area Gravitational Wave Physics and Astronomy: Genesis, The Fourth Annual Area Symposium, Online, 2021/2/22-24.

[34] (ポスター) T. Tsutsui, "A roll of precession on early warning with 2.5 generation detectors", Innovative Area Gravitational Wave Physics and Astronomy: Genesis, The Fourth Annual Area Symposium, Online, 2021/2/22-24.

[35] (ポスター) A. Nishizawa, "Stacking gravitational-wave polarization signals", Innovative Area Gravitational Wave Physics and Astronomy: Genesis, The Fourth Annual Area Symposium, Online, 2021/2/22-24.

招待講演

[36] A. Nishizawa, "Tests of gravity with gravitational waves", the APCTP-KPS-JPS meeting, online, 2020/11/6.

[37] L. Tsukada, "Modeling and searching for a stochastic GW background from ultralight bosons", Innovative Area Gravitational Wave Physics and Astronomy: Genesis, The Fourth Annual Area Symposium, Online, 2021/2/22-24

(国内会議)

一般講演

[38] 鹿内みのり、"電波望遠鏡 CHIME による SGRB からの残光観測に向けた解析パイプライン開発"、第 50 回天文・天体物理若手夏の学校、オンライン開催、2020/8/24-27.

[39] 津名大地、"濃い星周物質内でのブラックホール形成と突発天体"、日本天文学会秋季年会、オンライン開催、2020/9/10.

[40] 筒井拓也、"第 3 世代重力波望遠鏡による歳差運動を伴うコンパクト連星合体の事前予報"、 日本物理学会秋季大会、オンライン開催、2020/9/14.

[41] 津名大地、"IIn 型超新星からの X 線放射"、第 4 回 FORCE 研究会、オンライン開催、2021/3/4.

[42] 西澤篤志、"重力波の非テンソル偏極モード探査のための信号積み重ね法"、日本物理学会年次大会, オンライン開催、2021/3/12-15.

[43] 津名大地、"星周物質との衝突で光る超新星のスペクトルエネルギー分布"、日本天文学会春季年会、オンライン開催、2021/3/19.

(セミナー)

[44] A. Nishizawa, "Test of gravity with gravitational wave polarizations", The GW-genesis seminar series, 2020/6/2.

[45] A. Nishizawa, "KAGRA scientific contribution to the global detector network of gravitational waves", The Gravity Seminar at Southampton U, 2021/3/18.

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、2020 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　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、放出されれた物質の密度構造や星の構造の変化を調べた。この現象の物理的原因は問わずに、水素外層の底に一定の熱エネルギーを注入し変化を輻射流体コードを用いて数値計算した。その結果、放出された物質の一部は再び星の重力によって引き戻され、密度が半径の-1.5 乗に比例する構造を持つことを示した。複数回質量放出現象が起きると仮定した時にどのような明るさの変化が見られるかも調べた。これらの結果はすでに 2 編の論文として発表した。[4]

10.1.2　星周物質と爆発物質の衝突で光る天体

ブラックホール形成時の増光現象

大質量星の中心核が重力崩壊を起こすと、ニュートリノによって大量のエネルギーが星の外に持ち出される。その結果、重力が弱くなり外層の静水圧平衡が崩れて、その一部が放出される。それがそれ以前に放出された星周物質に衝突する時にどのように光るかを数値計算によって調べた。その結果、 AT 2017be という突発天体を含む intermediate luminosity red transients (ILRTs) の特徴を備えていることがわかった。この結果は The Astrophysical Journal Letters に発表した。[1, 17]

IIn 型超新星光度曲線モデル

星周物質と爆発物質の衝突で光る IIn 型超新星の光度曲線モデルを構築した。二つの衝撃波に挟まれた領域をそれぞれの衝撃波の静止系での定常解として記述した。この領域では局所熱平衡を仮定してている。衝撃波表面での放射強度を境界条件として、星周物質での輻射輸送のガスと輻射の 2 温度近似を用いて時間発展を解いた。この計算手法を The Publication Astronomical Soceity of Japan に出版した。今後は、突発的に放出されて形成された星周物質と衝突した超新星の光度曲線を系統的に計算して、超新星とともに大質量星の最後の 10 年の進化に焦点を当てて研究を進める予定である。大質量星からの突発的な質量放出から超新星爆発に至る一連の現象を数値計算する計算コードを公開する取り組みを行なっている。[2]

IIn 型超新星多波長スペクトル進化モデル

星周物質と爆発物質の衝突で光る IIn 型超新星では、衝突時に形成される衝撃波ではガスがエックス線を放射するほど非常に高温になる。その後、衝撃波下流で電子が放射するとこで冷却され、主に紫外線・可視光領域で光る。高温の電子は逆 Compton 散乱で輻射とエネルギーのやり取りもする。この過程を取り入れた赤外線から X 線までの熱的放射のスペクトルを計算するコードを開発し、The Astrophysical Journal に発表した。今後の多波長同時観測によって得られる観測結果からより多くの情報を引き出すために使用する予定である。[7, 12]

10.1.3　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。C と O が質量比で半々の蘇生の時に与えられた比エンタルピーに対して降着率がある値より大きい時に降着流が中性子星表面に到達しなくなる現象を見出した。さらに系統的な計算を行う予定である。

10.1.4 連星系中の種族 III 星

銀河系ハローで最初に形成された全く重元素をもたない星のうち、現在まで生き残っているのは質量が 0.8 $M_\odot$ 以下の星である。そのような星が形成時に大質量星との近接連星系をなしていたときに、表面組成が超新星によってどのように変化するかを SPH 法を用いて数値計算した。その結果、大質量星内及び超新星爆発時に合成された多くの重元素を太陽以上にもつ星に変わってしまうことがわかった。それは重元素を全く持たない大質量星は進化しても膨張の度合いが極端に少なく伴星を飲み込むことがないからである。もし、重元素を少しでも含んでいると大質量星は進化して大きく膨らむので、飲みこまれないで現在まで生き残る星は大質量星からはある程度離れていなくてはいけない。そうすると超新星爆発時に汚染される重元素量は劇的に減り、重元素組成は他の銀河系ハローの星と大差がなくなる。この結果をもとに、いわゆる種族 III 星は銀河系ハローに属する重元素量の多い星であるという逆説的な提案を行い、The Publication of Astronomical Soceity of Japan に発表した。[5]

10.1.5 中性子星の磁場と連続重力波

自転軸に対して非軸対称的な構造を持ち高速で回転している中性子星は、自転周期に応じた定常的な重力波、連続重力波を放出していると考えられている。例えば、中性子星が強い磁場を伴っているとすると、中性子星の磁場が非軸対称的な歪みを生み出すと考えられている。中性子星は中心部のコアと表面の殻の部分であるクラストで構成されているが、クラスト部分に磁場によるストレスが蓄積され、変形の弾性限界を超えた場合には可塑性な流れ (plastic flow) が生じると考えられている。この可塑性な流れは比較的速いタイムスケールで起きクラスト内部の磁場構造を変化させるため、クラスト部分の歪み方に影響を与えている可能性がある。そこで、この可塑的な流れを取り入れた磁場構造と歪みの進化計算を行った [6]。その結果、この可塑的な流れのタイムスケールでクラストの磁場は進化し、その磁場構造の変化に応じて歪み方も変わっていくことが分かった。

一方で中性子星が連星系内に存在している場合、表面に降着物質に由来する非軸対称的な「山」が存在し、この「山」連続重力波の放出源となっているかもしれないと考えられている。そこで、中性子星の強磁場で「山」を支える磁気山モデルに着目し、新しい定式化と計算手法の開発を行った [16, 18]。その結果、これまで考慮されていなかった多重極磁場やトロイダル磁場によって支えられる磁気山、エントロピー分布が一様ではない磁気山など、様々な新しい磁気山の構造を系統的に求めることに成功した。

10.2 業績リスト

＜**報文**＞

(原著論文)

[1] Tsuna, D., Ishii, A., Kuriyama, N., et al. 2020, Astrophys. J. Lett., 897, L44. doi:10.3847/2041-8213/aba0ac

[2] Takei, Y. & Shigeyama, T. 2020, Publ. Astron. Soc. Japan, 72, 67. doi:10.1093/pasj/psaa050

[3] Ohsawa, R., Hirota, A., Morita, K., et al. Shigeyama, T.(35 番目) 2020, Planetary Space Science, 194, 105011. doi:10.1016/j.pss.2020.105011

[4] Kuriyama, N. & Shigeyama, T. 2021, Astron. & Astrophys., 646, A118. doi:10.1051/0004-6361/202038637

[5] Suda, T., Saitoh, T. R., Moritani, Y., Shigeyama, T., 2021, Publ. Astron. Soc. Japan. doi:10.1093/pasj/psab02

[6] Kojima, Y., Kisaka, S., & Fujisawa, K. 2021, Mon. Not. R. Astron. Soc., 502, 2097. doi:10.1093/mnras/staa3489

[7] Tsuna, D., Kashiyama, K., & Shigeyama, T. 2021, arXiv:2103.08338, Astrophys. J. in press

(会議抄録)

[8] Hirano, A., Fujisawa, K., Niinuma, K., et al. 2020, Perseus in Sicily: From Black Hole to Cluster Outskirts, 342, 239. doi:10.1017/S1743921318008001

[9] Niino, Y., Morokuma, T., Sako, S., et al. 2020, Gamma-ray Bursts in the Gravitational Wave Era 2019, 199

(その他国際雑誌)

[10] Shigeyama, Toshikazu; Sako, Shigeyuki, "Research of binary neutron star merger phenomenon by high speed sweeping observation", 2020, Impact, Volume 2020, Number 5, pp. 13-15(3), Publisher: Science Impact Ltd, doi:10.21820/23987073.2020.5.13

(学位論文)

修士論文

[11] 栗山直人; 星周物質との相互作用によって輝く IIn/Ibn 型超新星の親星における爆発的質量放出の研究

＜**学術講演**＞

(国内会議)

日本天文学会 2021 年春季年会、東京工業大学、2021/3/16-19

[12] 津名大地、樫山和己、茂山俊和、" 星周物質との衝突で光る超新星のスペクトルエネルギー分布"、2021 年 3 月 19 日、N27a

[13] Yici ZHONG, Kazumi KASHIYAMA, Toshikazu SHIGEYAMA, and Shinsuke TAKASAO, "How much SNR fallback can invade newborn pulsar wind and magnetosphere?", 2021 年 3 月 16 日, W15a

[14] 酒向重行, 大澤亮, 諸隈智貴, 新納悠, 瀧田怜, 土居守, 茂山俊和他、" 木曽 Tomo-e Gozen の広域動画サーベイのデータ公開に向けた開発"、2021 年 3 月 16 日、V208a

日本天文学会 2020 年秋季年会、弘前大学、2020/9/08-10

[15] 酒向重行, 大澤亮, 諸隈智貴, 新納悠, 土居守, 茂山俊和他、" 木曽広視野 CMOS カメラ Tomo-e Gozen による広域動画サーベイ"、2020 年 9 月 10 日、V204a

[16] 藤澤幸太郎、" 中性子星表面の定常的な磁気山の構造"、2020 年 9 月 9 日、W20a

[17] 津名大地, 石井彩子, 栗山直人, 樫山和己, 茂山俊和, " 濃い星周物質内でのブラックホール形成と突発天体", 2020 年 9 月 10 日, W37a

一般講演

[18] 藤澤幸太郎、"Magnetically confined mountain on the neutron star surface"、ポスター、重力波物理学・天文学：創世記第 4 回領域シンポジウム、Online、2021/02/22

(セミナー)

[19] 藤澤幸太郎、"Structures of magnetically confined mountains on neutron stars"、gw-genesis zoom seminar talk、Online、2020/10/20

11 仏坂健太研究室

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 研究活動報告

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, 8, 9, 10, 15]。

2019 年 4 月から 11ヶ月間行われた LIGO-Virgo Observational Run 3 (O3) では、中性子星を含む連星合体からの重力波イベント候補が 14 天体報告された。このうち O3 の後半で報告されたブラックホール・中性子星合体候補 S191205ah と S200105ae、中性子星合体候補 S191213g と S200213t、質量ギャップ天体候補 S200115j に対して行われた可視光追観測の結果についての解析を行い、キロノバが見つかっていないという事実からエジェクタ質量などに対する制限を与えた [1]。その結果、上記の全てのイベントにおいて追観測は対応天体を発見できるほど十分な感度が確保できていないことがわかった。

電波対応天体の研究

中性子星合体は非相対論的なキロノバエジェクタだけなく、相対論的なジェットも駆動する。このジェットと星間物質の間に形成された衝撃波によって加速された非熱的な電子によって放射されるシンクロトロン光が電波から X 線まで幅広い波長で観測される。我々はこのシンクロトロン放射に関する研究を行った [2, 3, 4, 11, 14, 15]。

中性子星合体 GW170817 では合体時に生成された相対論的ジェットからのシンクロトロン放射が合体後 9 日以降、少なくとも 2021 年 3 月まで電波から X 線までで検出されている。我々はヨーロッパの低周波電波望遠鏡 LOFAR を用いて 150MHz での追観測を行った [2]。その結果、LOFAR の感度が十分ではなく検出できなかったが、これは GW170817 の位置の問題もあり、理想的な位置で連星合体の電磁波対応天体が発見された場合、LOFAR によって 150MHz での残光を検出できる見込みがあることを示した。

GW170817 の電波放射は十分明るく距離も比較的近いため、電波源の固有運動が VLBI によって測定されている。この固有運動は超光速度運動を示し、ジェットのローレンツ因子およびジェットに対する見込角がこの観測から測定された。このような観測は中性子星合体に付随するジェットの性質を調べるのに極めて有効であるのみならず、重力波から測定された重力波振幅と見込角を組み合わせることによって天体までの光度距離を精度良く測定することが可能になる。これによって重力波と電磁波を用いたハッブル定数の測定に繋がる [3]。したがって、今後の重力波イベントにおいて、超光速度運動が測れるかどうかはジェットの物理および重力波宇宙論という二つの観点から重要となる。我々は VLBI によるジェットの固有運動の測定、さらに星間空間の密度揺らぎに起因する電波シンチレーションを使ったジェットのサイズの測定が今後のイベントでどの程度実現可能かを調べた [4]。その結果、VLBI による測定は 100Mpc 程度まで、シンチレーションによる測定は数 100Mpc まで可能であることを示した。これらの結果から将来の重力波・電波観測はジェットの性質とハッブル定数の測定に対して重要な手法を与えることが期待できることがわかった。

11.1.2 連星ブラックホール合体の研究

LIGO/Virgo はこれまで 50 天体ほどの連星ブラックホールからの重力波の検出に成功している。しかし、これら連星ブラックホールが宇宙のいつどこでどのように形成されたのかは、いまだにはっきりしていない。その起源の候補として、大質量連星によって作られる連星起源説、球状星団や銀河核のような星の密度の高い領域で力学的捕獲によって作られる捕獲起源説、宇宙初期に生成された原始ブラックホール同士が合体するという原始ブラックホール説などが提唱されている [12]。

我々は、質量比の比較的大きい連星ブラックホール合体 GW190412 に注目して、このような天体が連星起源説から形成可能かどうかを調べた [5]。この天体は質量比が 4 と大きいだけでなく、軌道角運動量方向に揃ったブラックホールスピンも有限の大きさを持っていることがわかっている。これらの性質が連星進化の過程、特に潮汐効果の結果として現れるのかどうかについて宇宙の星形成史および金属量の進化を考慮に入れた計算を行った。その結果、質量比が 4 ほどの場合、10-20%の連星合体は有限のスピンを持って合体に至ることを示した。

11.1.3 超新星爆発におけるミュー・タウニュートリノ加速の研究

超新星爆発では大量のニュートリノが放出される。実際、大マゼラン雲で起こった超新星爆発 1987A では、カミオカンデによって 10 数個のニュートリノが検出された。現在稼働しているスーパーカミオカンデや IceCube、さらに近い将来の稼働するハイパーカミオカンデでは銀河系内で超新星爆発が起これば 1 万から数 10 万個のニュートリノが観測できる。将来的に、そのような観測データから何がわかるのか？という問いは超新星科学を進める上でも重要な課題である。

これまでの研究では、超新星ニュートリノは電子タイプのニュートリノ・反ニュートリノとそれ以外のタイプのニュートリノ・反ニュートリノとして、ミュータイプとタウタイプには違いが現れないとして研究が進められてきた。この仮定はミュータイプ・タウタイプはそれぞれ中性カレントを通じて超新星物質と相互作用するという前提では、非常に良い近似であるが、ニュートリノのエネルギーがミューオンの質量を超える 100MeV 程度以上といった高エネルギー領域ではミューニュートリノの荷電カレントによる相互作用が重要になる。我々は、超新星爆発において中性子星が形成された際に生じる衝撃波をミュー・タウニュートリノが往復することでいわゆるフェルミ加速が起こることを示した [6]。この結果、ミュー・タウニュートリノが 100MeV 以上まで加速されて、ニュートリノスペクトルが極めてハードになることを発見した。この兆候はボルツマン方程式に基づく数値シミュレーションでも見られていたが、モンテカルロ法を使うことによってより定性的にも定量的にも明確な説明を与えた。このような 100MeV 以上のニュートリノは将来的な観測でも十分なターゲットであり、タウ・ミューの間の縮退が解けることによって観測されるニュートリノスペクトルに現れる影響を議論した。

11.1.4 銀河の化学進化における乱流拡散の研究

銀河の化学進化計算は通常、銀河を一つの箱として考える one-zone 的な計算と銀河の発展を 3 次元流体シミュレーションで解くという方法が用いられる。特に、連星中性子星合体が生成する R 過程元素の化学進化を考える上ではそのイベントレートが低いため、one-zone 的な近似は破れ、銀河の非一様性を考慮する必要があり銀河を空間的に分解する手法が必要である。そこで我々は銀河の星間物質中での重元素の非一様性が乱流拡散によって発展するという問題をモンテカルロ的に扱う方法を開発した [7]。さらに、これまで観測されている金属欠乏星の重元素組成の分布や太陽系の隕石などに記憶されている原始太陽系に含まれていた放射性重元素の量などの分布にこの手法を適応した。その結果、重元素は中性子星合体のような極めて稀な現象、具体的には銀河系で 10 万年に 1 度しか起こらない現象によって生成されたという描像によって非常にうまく説明できることを示した。今後、この手法によって、one-zone 的な簡単な研究と流体シミュレーションなどのコストの高い研究との橋渡しが可能になる。

11.2 業績リスト

＜報文＞

(原著論文)

[1] M. W. Coughlin, *et al.*,“Implications of the search for optical counterparts during the second part of the Advanced LIGO’s and Advanced Virgo’s third observing run: lessons learned for future follow-up observations”, Monthly Notices of the Royal Astronomical Society **497**, 1181-1196 (2020).

[2] J. W. Broderick, *et al.*, “LOFAR 144-MHz follow-up observations of GW170817” Monthly Notices of the Royal Astronomical Society ,**494**, 5110-5117 (2020).

[3] S. Mukherjee, “Velocity correction for Hubble constant measurements from standard sirens”, Astron. and Astrophys. **646**, A65 (2020). 038 (2020).

[4] D. Dobie, *et al.*,, “Constraining properties of neutron star merger outflows with radio observations”, Monthly Notices of the Royal Astronomical Society **494**, 2449-2464 (2020).

[5] M. Safarzadeh and K. Hotokezaka, “Being Careful with the Field Formation Interpretation of GW190412”, Astrophys. J. Letters **897**, L7 (2020).

[6] H. Nagakura and K. Hotokezaka, “Non-thermal neutrinos created by shock acceleration in successful and failed core-collapse supernova,” Monthly Notices of the Royal Astronomical Society, **502**, 89-107 (2021).

[7] P. Beniamini and K. Hotokezaka, “Turbulent mixing of r-process elements in the Milky Way”, Monthly Notices of the Royal Astronomical Society, **496**, 1891-1901 (2020).

＜学術講演＞

(国際会議)

招待講演

[8] Kenta Hotokezaka, “Multi-messenger astrophysics of neutron star merger”, Workshop on Frontiers of Nuclear Structure and Nuclear Astrophysics, Online, 2020/10/15.

[9] Kenta Hotokezaka, “Modeling electromagnetic counterparts of neutron star mergers”, AAPPS-DACG Workshop, Online, 2020/11/11.

[10] Kenta Hotokezaka, “Electromagnetic counterparts of neutron star mergers”, The extreme Universe viewed in very-high-energy gamma rays 2020, Online, 2020/12/4.

[11] Kenta Hotokezaka, “Radio counterparts of neutron star mergers and VLBI observations”, Black Hole Astrophysics with VLBI: Multi-Wavelength and Multi-Messenger Era, Online, 2021/1/19.

(国内会議)

招待講演

[12] 仏坂健太、“重力波天文学の進展”、素粒子物理学の進展 2020、Online、2020/8/31.

[13] 仏坂健太、“Neutron Star Mergers and Kilonovae”、星の錬金術から銀河考古学へ、Online、2020/10/26.

[14] 仏坂健太、“ngVLA で拓く重力波天体”、日本天文学会 2021 年春年会、Online、2021/3/19.

(セミナー)

[15] 仏坂健太, “ Astrophysics of compact binary mergers”, NAOJ Science Colloquium), 国立天文台 (オンライン), 2020/12/2.