Research Center for the Early Universe

Graduate School of Science

University of Tokyo

Annual Report

2021

令和3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 2021 (from April 2021 to March 2022).

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 of COVID-19, the activity in RESCEU has been seriously affected for the last couple of years. However, we have been struggling to advance our projects; weekly seminars and regular discussions have been carried out via zoom, and we organized a summer school online with inviting foreign researchers.

We are pleased to announce the following awards for our RESCEU members this year. Prof. Atsushi Nishizawa received the Young Scientists' Award in the Commendation for Science and Technology by the Minister of Education, Culture, Sports, Science and Technology in March 2021. Jun'ya Kume, a graduate student of the Yokoyama group, received Student Presentation Award of the Physical Society of Japan in both October 2021 and March 2021 and he was also awarded JGRG Workshop 2021 Outstanding Presentation Award Gold Prize in December 2021.

In 2021, we have three new post-docs who joined RESCEU including Dr. Daisuke Toyouchi, Dr. Christopher Irwin (hosted by Prof. Hotokezaka), and Dr. Kohei Fujikura (hosted by Prof. Yokoyama). A JSPS Research Fellow, Dr. Heather Fong, became a Research Fellow at RESCEU in June 2021 (hosted by Prof. Cannon). A post-doc, Dr. Tatsuya Matsumoto, moved to Department of Physics and Columbia Astrophysics Laboratory, Columbia University in August 2021 as a JSPS Overseas Research Fellow. A post-doc, Dr. Yusuke Yamada, moved to Waseda Institute for Advanced Study, Waseda University in March 2022 as an Assistant Professor. Dr. Kohei Fujikura, moved to Department of Physics, Kobe University in March 2022 as a JSPS Research Fellow. A project assistant professor, Kotaro Fujisawa, moved to Department of Physics, the University of Tokyo in March 2022, as an assistant professor. Assistant Prof. Masamune Oguri was promoted to a full professor in Center for Frontier Science, Chiba University in February 2022, and Assistant Prof. Kazumi Kashiyama was promoted to an associate professor in Department of Astronomy, Tohoku University in March 2022.

Finally, Sayuri Nagano left RESCEU at the end of this fiscal year. She had been a secretary of RESCEU for last 25 years, and made significant contribution to all aspects in RESCEU, in particular, taking care of graduate students over generations literally. I would like to express the great respect and gratitude to her on behalf of all members of RESCEU since 1997 when she joined RESCEU.

May 2022

Director Yasushi Suto

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I

Reports on overall activities at RESCEU in 2021

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 (– 2022/1/31)
Kazumi Kashiyama [樫山和己]	Assistant Professor (– 2022/3/15)
Kohei Kamada [鎌田耕平]	Assistant Professor
Atsushi Nishizawa [西澤篤志]	Assistant Professor
Kotaro Fujisawa [藤澤幸太郎]	Project Assistant Professor (RESCEU)
Yuji Chinone [茅根裕司]	Project Assistant Professor (RESCEU & JSPS Grant of Prof. Kusaka)
Daisuke Toyouchi [豊内大輔]	Postdoctoral Fellow (RESCEU)
Koh Ueno [上野昂]	Postdoctoral Fellow (JSPS Grant of Prof. Yokoyama)
Heather Fong	Postdoctoral Fellow (JSPS Fellow (– 2021/6/15), Kakenhi Grant of Prof. Cannon (2021/6/16–))
Tatsuya Matsumoto [松本達矢]	Postdoctoral Fellow (JSPS Fellow) (– 2021/08/31)
Yusuke Yamada [山田悠介]	Postdoctoral Fellow (JSPS Fellow)
Kohei Fujikura [藤倉浩平]	Postdoctoral 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 (–2021/6/30)
Nao Watanabe [渡辺菜穂]	Secretary (2021/6/1 –)

RESCEU affiliates

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

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
Atsushi Nishizawa	Gravitational-wave physics and cosmology

Project 3. Formation and characterization of planetary systems

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

3 Symposia and Meetings

RESCEU Summer School 2021

Place: Online
Time: 2021/8/18 (Wed) – 2021/8/20 (Fri)

Program

8/18 (Wed) morning, chair:Kashiyama

9:50–10:00	Yasushi Suto	Opening remark
10:00–11:30	(L) Smadar Naoz	Gravitational Wave Sources at the Hearts of Galaxies
11:30–11:40	break	
11:40–12:00	Yurina Nakazato	The formation of Supersonically Induced Gas Objects(SIGOs) with H2 chemistry
12:00–12:20	Toshinori Hayashi	The dependency of disruption times of hierarchical three-body systems on the orbital parameters

8/18 (Wed) afternoon, chair:Fujisawa

14:00–14:20	Hiroto Mitani	H2 Pumping effect on atmospheric escape of hot Jupiters
14:20–14:40	Koki Tokeshi	On systematic uncertainties of primordial black hole abundance
14:40–15:00	Yici ZHONG	A necessary condition for supernova fallback invading newborn neutron-star magnetosphere
15:00–15:10	break	
15:10–15:30	Fumio Uchida	Dynamics of the magnetized plasma in the early universe
15:30–15:50	Soichiro Hashiba	Schwinger reheating during kination
15:50–16:10	Yuki Takei	CHIPS: an open source code for supernovae interacting with a massive circumstellar medium

8/19 (Thu) morning, chair:Oguri

10:00–11:30	(L) Masahiro Takada	Hyper Suprime-Cam Search of Primordial Black Holes and other topics
11:30–11:40	break	
11:40–12:00	Yuta Tarumi	r-process enrichment of a globular cluster and its implications
12:00–12:20	Kohei Fujikura	Generation of FIMP dark matter and baryon asymmetry in quintessential inflation with right-handed neutrinos

8/19 (Thu) afternoon, chair:Toyouchi

13:50–14:10	Jun'ya Kume	Chiral plasma and birefringent gravitational waves
14:10–14:30	Takuya Tsutsui	Early warning of precessing NSBH mergers with the near-future gravitational wave detectors
14:30–14:50	Minori Shikauchi	The Binary Evolution Parameter Dependence of the Detectablity of BH-LC binaries with Gaia
14:50–15:00	break	
15:00–16:30	(L) Kenta Kiuchi	Recent progress of numerical relativity simulations of compact objects and its application to gravitational wave astrophysics

8/20 (Fri) morning, chair:Kamada

9:00–10:30	(L) Enrico Pajer	A timeless history of time
10:30–10:40	break	
10:40–11:00	Minxi He	Perturbative Reheating after Mixed Higgs-R^2 Inflation
11:00–11:20	Jason Kristiano	Theoretical bound of primordial non-Gaussianity
11:20–11:40	Hiroki Kawai	An analytic model for the sub-galactic matter power spectrum in fuzzy dark matter halo

8/20 (Fri) afternoon, chair:Nishizawa

13:00–14:30	(L) Kunihiko Kaneko	普遍生物学 (Universal biology)
14:30–14:40	break	
14:40–15:00	Tilman Hartwig	A new, unsupervised, non-parametric likelihood test for multi-dimensional data
15:00–15:20	Ayano Komaki	Photoevaporation of Protoplanetary Disk: Dust-to-gas Mass Ratio Dependence
15:20–15:40	Soichiro Kuwahara	Cherenkov radiation like GW search
15:40–15:50	Jun'ichi Yokoyama	closing

(L: Lecture)

4 RESCEU colloquia

- RESCEU Colloquium No. 49
  Kiwamu Izumi (JAXA Institute of Space and Astronautical Science International Top Young Fellow)
  "Experimental activities for space gravitational wave observations"
  April 08, 2021, 13:00-14:00

- RESCEU Colloquium No. 50
  Akira Okumura (ISEE, KMI, Nagoya University)
  "CTA Small-Sized Telescopes for PeVatron Search"
  April 22, 2021, 10:30-11:30

- RESCEU Colloquium No. 51
  Bunyo Hatsukade (Institute of Astronomy, The University of Tokyo)
  "Radio constraints on the nature of superluminous supernovae and their host galaxies"
  May 20, 2021, 15:00-16:00

- RESCEU Colloquium No. 52
  Kazuyuki Sugimura (Astronomical Institute, Tohoku University)
  "Formation of the First-star Binaries"
  October 11, 2021, 10:30-11:30

- RESCEU Colloquium No. 53
  Masaomi Tanaka (Astronomical Institute, Tohoku University)
  "Kilonova: Electromagnetic signature of heavy-element nucleosynthesis"
  December 06, 2021, 10:30-11:30

- RESCEU Colloquium No. 54
  Shingo Kazama (Nagoya University)
  "Direct Dark Matter Search with XENON"
  December 07, 2021, 15:00-16:00

- RESCEU Colloquium No. 55
  Atsush Takada (Kyoto University)
  "Dawn of MeV gamma-ray astronomy with electron-tracking Compton camera"
  February 10, 2022, 13:30-14:30

II

Reports on the research activities of each project in 2021

5 Project 1. Evolution of the Universe and cosmic structures

5.1 Activity Report

5.1.1 One-loop correction to curvature perturbation in single-field inflation

We calculated one-loop quantum corrections to the power spectrum of the curvature fluctuations produced by single-field inflation from the three-point interaction. We computed the one-loop quantum correction from the three-point interaction and found that this correction is large but finite due to the fact that the spectrum should be red tilted as indicated by observation. Furthermore, we found that an upper bound on the non-Gaussianity is given by requiring the one-loop quantum correction to be smaller than the observed curvature fluctuations. This requirement leads to a condition for the consistency of the single-field inflationary model, which is an important condition for the construction of the model of inflation (Yokoyama).

5.1.2 Baryogenesis

In a class of the models of baryogenesis, only B+L asymmetry is generated but no net B-L asymmetry is. Such mechanisms are thought not to work since the asymmetry is washed out by the electroweak sphaleron before the electroweak symmetry breaking. We take advantage of the fact that at high temperature when some of the Yukawa interactions do not in equilibrium some fermion numbers are good conserved quantity and the washout by the electroweak sphaleron does not complete, and propose a new framework of baryogenesis dubbed "wash-in leptogenesis". In this framework we introduce right-handed neutrinos that are once in equilibrium and decouple due to their Majorana mass at the temperature higher than the completion of the washout by the electroweak sphalerons. We find that at the time of the decouple of the right-handed neutrinos, B-L asymmetry, which survives until today, is induced with the CP-violation originated by the B+L asymmetry of the system. This framework is useful to rescue the SU(5) GUT baryogenesis or the baryogenesis from axion inflation. (Kamada)

5.1.3 Quantum anomaly in the early Universe

We study the gravitational counterpart of the Chiral Magnetic Effect, dubbed "Chiral Gravitational Effect (CGE)", where the energy momentum tensor is induced in parallel to the gravitational waves in the presence of the chiral asymmetry. We evaluate its effect in the dynamical chiral asymmetry with the application to cosmology in mind. We find that the birefringence is induced in the gravitational waves in response to the dynamical chiral asymmetry through the CGE. It suggests a possibility that the helicity of the stochastic gravitational background may carry the information of the non-trivial particle dynamics in the early Universe. (Kamada)

5.1.4 Fast Calculation of Gravitational Lensing Properties of Elliptical Navarro-Frenk-White and Hernquist Density Profiles

We proposed a new approach for fast calculation of gravitational lensing properties, including the lens potential, deflection angles, convergence, and shear, of elliptical Navarro-Frenk-White (NFW) and Hernquist density profiles. In this approach, they are approximated by superpositions of elliptical density profiles for which simple analytic expressions of gravitational lensing properties are available. It turned out this model achieves high fractional accuracy better than 10^{-4} in the wide range of the radius normalized by the scale radius of $10^{-4} - 10^{3}$. Remarkably, this new approximation is ~ 300 times faster in solving the lens equation for a point source compared with the traditional approach resorting to expensive numerical integrations. Our work opened up a new avenue for analyzing gravitational lensing with realistic lens mass models. (Oguri)

5.1.5 High redshift galaxies

We use Subaru/Hyper Suprime-Cam (HSC) IB945 imaging data and detect 44 Lyman alpha emitters (LAEs) at $z \sim 6.8$, finding an overdense region with a projected density excess of $\delta \simeq 14$. This large δ value suggests a highly neutral universe, while the Lyα luminosity function from the 44 sources is consistent with full ionization. We are investigating the origin of this discrepancy. We conduct a systematic survey of proto-clusters at $z \sim 1.5$ using wide imaging data from the HSC SSP. We find that the fraction of red (quiescent) galaxies increases with stellar mass, consistent with stellar-mass dependent environmental quenching recently found at $z > 1$. In addition, although the cores with red and blue central galaxies have similar dark halo masses, only those with red centrals show a significant red fraction excess compared to the field, suggesting a conformity effect. We develop a machine-learning (deep anomaly detection) based method that selects rare galaxy populations from a large data set of HSC multiband images. We find that this method can select $\sim 60\%$ of known quasars and extreme emission-line galaxies at $z = 0.05 - 0.2$. (Shimasaku)

5.1.6 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, Tsuna, 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, Takei, Tsuna, Ko)
- Accretion of C+O matter onto a neutron star igniting Carbon burning (Shigeyama, Nagarajan)
- Influence of supernova fallback on newborn neutron star magnetospheres (Shigeyama, Kashiyama, Zhong)
- Rotational equilibria on the 2D Lagrange coordinates (Fujisawa)
- The W4 method: a new multi-dimensional root-finding scheme for nonlinear systems of equations (Fujisawa)
- Black hole formation from rotating massive stars (Shigeyama, Kashiyama, Tsuna)
- Multi-wavelength emission from Galactic black holes (Kashiyama)
- Gravitational wave background from binary black hole mergers (Kashiyama)
- Emission of type IIn supernovae (Shigeyama, Tsuna, Kashiyama, Takei)

- Influence of supernova fallback on newborn neutron star magnetospheres (Shigeyama, Kashiyama, Zhong)
- Multi-wavelength emission from embryonic pulsar wind nebula (Kashiyama)
- Mechanism of the Galactic fast radio burst (Kashiyama)
- Proposing the 56Ni problem for ultra-stripped supernovae (Kashiyama)

Here the names of researchers are listed in the parentheses.

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

Sensitivity of very-high-energy (VHE) gamma-rays would be greatly improved in the near future by the operation of Cherenkov Telescope Array (CTA). We examined the feasibility of VHE detection of binary neutron star (BNS) mergers by using a latest theoretical model of afterglows from BNS mergers, that is consistent with available observations. The number of nearby star-forming galaxies detected in VHE will also be increased by CTA. We examined the nearby galaxy database and predicted VHE gamma-ray luminosities using physical quantities of these galaxies, and then listed up the promising targets for CTA. Comparison between observed VHE flux and our model prediction would give new insight to cosmic acceleration and their interaction in various types of galaxies. (Totani)

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

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

This year we studied the shock structure and heating mechanism in supernova remnant (SNR) systems. We have made detailed spatially resolved spectroscopy of young SNRs, Tycho (SN1572) and resolved three-dimentional expansion structure using Doppler broadening of emission lines. We found that the shock is decelerated by the circumsteller medium. This is the first direct discovery of circumsteller material around Tycho, implying the origin of Tycho is not a double-degenerate but a single-degenerate. We have also done similar analysis of Kepler (SN1604) and found asymmetric circumsteller medium [74].

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 fluction 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. We also developed the Monte-Carlo based data analysis method for pile-uped data of the X-ray CCD onboard XRISM. For Cipher mission, the first imaging polarimetory cubesat in the hard X-ray band, we completed the readout system and also developed the coded mask pattern with lower noise level. We also started GRAMS mission deverlopment in this year (Bamba).

5.1.9 Observational cosmology using cosmic microwave background

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

The 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 result from this project is the improvement of our previous constraint on the tensor-to-scalar ratio r. We started a new time-domain data analysis of the POLARBEAR datasets for searching the Axion-like particle (ALP).

For Simons Array experiment, observation using the first telescope and the deployment of the second telescope were paused due to COVID-19 pandemic. 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. We have been analyzing calibration observations to characterize the first telescope and analyzing CMB observations with the analysis pipeline we have been developing in parallel. The deployment of the second telescope is underway toward the first light in 2022.

The Simons Observatory experiment is scheduled for the first light in 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 developed the cryogenic optics tube, the cryogenic continuously rotating half-wave plate (HWP) system, and the wiregrid calibrator. We also made significant progress in fabricating and commissioning the second and third cryogenic continuously rotating 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 have developed a new pipeline module by taking advantage of GPUs and have validated it with simulated datasets. (Kusaka, Kiuchi, Chinone)

5.1.10 Statistical Computational Cosmology

We applied a deep-learning method called SSD to detect transient objects in data collected by Tomo-e Gozen. The method works in time domain with 2 Hz frequency and identify ordinary astronomical objects such as stars but also time varying ones such as extremely short transients. It is applied to the ongoing wide-field Tomo-e survey. We also developed a real/bogus classifier for Tomo-e by adopting a two-stage training with treating mislabels. The method achieves an area under the curve of 0.9998 and a false positive rate of 0.0002 at a true positive rate of 0.9. (Yoshida)

5.2 Publication List

[1] V. Domcke, K. Kamada, K. Mukaida, K. Schmitz, and M. Yamada, "Wash-In Leptogenesis", Physical Review Letters **126**, 201802 (2021).

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5.3 International Conference Talks

5.3.1 Contributed talks

[128] J. Kume, "Chiral gravitational effect in primordial thermal plasma", 26th International Symposium on Particles, Strings & Cosmology (PASCOS 2021), Online, 2021/6/14.

[129] T. Hayashi, "Vacuum decay in de-Sitter spacetime with the Lorentzian path integral", 26th International Symposium on Particles, Strings & Cosmology (PASCOS 2021), Online, 2021/06/14.

[130] J. Kume, "Ultralight vector dark matter search using KAGRA", 16th Patras Workshop on Axions, WIMPs and WISPs, online, 2021/6/14.

[131] F. Uchida, "Constraints on primordial magnetic fields from baryon isocurvature perturbations", 26th International Symposium on Particles, Strings & Cosmology (PASCOS 2021), Online, 2021/06/17.

[132] M. He, "Reheating in the mixed Higgs-R^2 inflation model", 26th International Symposium on Particles, Strings & Cosmology (PASCOS 2021), Online, 2021/06/18.

[133] K. Kamada, " Wash-in Leptogenesis as a New Framework for Baryogenesis", 26th International Symposium on Particles, Strings & Cosmology (PASCOS 2021), Online, 2021/06/18.

[134] K. Fujikura, "Electroweak-like Baryogenesis with New Chiral Matter", 26th International Symposium on Particles, Strings & Cosmology (PASCOS 2021), Online, 2021/6/18.

[135] F. Uchida, "Baryon isocurvature constraints on the primordial magnetic fields", COSMO21, Online, 2021/8/5.

[136] J. Kume, "Chiral gravitational effect in the primordial plasma" (poster), COSMO'21, Online, 2021/8/2-6

[137] J, Kristiano, "Theoretical bound on primordial non-Gaussianity in single-field inflation" (poster), COSMO'21, Online, 2021/8/2-6.

[138] K. Fujikura, “Electroweak-like Baryogenesis with New Chiral Matter” (poster), COSMO’21,Online, 2021/8/2-6.

[139] K. Tokeshi, “Systematic biases on primordial black hole mass function”, RESCEU summer school, Online, 2021/08/18.

[140] F. Uchida, “Dynamics of the magnetized plasma in the early universe”, RESCEU Summer School, Online, 2021/8/18.

[141] K. Fujikura, “Generation of FIMP dark matter and baryon asymmetry in quintessential inflation with right-handed neutrinos”, RESCEU Summer School, Online, 2021/8/19.

[142] M. He, “Perturbative Reheating after Mixed Higgs-R^2 Inflation”, RESCEU summer school, Online, 2021/08/20.

[143] J. Kume, “Ultralight Vector Dark Matter search with KAGRA”, Workshop on Very Light Dark Matter 2021, online, 2021/9/28.

[144] J. Kristiano, “Theoretical bound on primordial non-Gaussianity in single-field inflation”, Recent Progress of Quantum Cosmology (YITP Workshop), Kyoto University, Japan, Online, 2021/11/8.

[145] T. Hayashi, “Vacuum decay with the Lorentzian path integral”, KIAS-YITP Joint Workshop 2021 String Theory and Quantum Gravity, Online, 2021/11/30.

[146] T. Hayashi, “Vacuum decay with the Lorentzian path integral” (poster), The 30th Workshop on General Relativity and Gravitation in Japan (JGRG30), Online, 2021/12/6-10.

[147] K. Tokeshi, “Primordial black hole abundance from joint formation criteria” (poster), The 30th Workshop on General Relativity and Gravitation in Japan (JGRG30), Online, 2021/12/6-10.

[148] J. Kume, “Gravitational birefringence in the primordial chiral plasma”, The 30th Workshop on General Relativity and Gravitation in Japan (JGRG30), Online, 2021/12/6.

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[151] J. Kume, “Towards offline noise subtraction from the O3GK data”, The 28th KAGRA Face-to-Face meeting, online, 2021/12/21.

[152] J. Kume, “Noise reduction strategies in mid frequencies”, The 28th KAGRA Face-to-Face meeting, online, 2021/12/21.

[153] Zhong Y., “Study on the effect of the outflow from young neutron stars and supernova fallback on the neutron star diversity”; YITP workshop Extreme Outflows in Astrophysical Transients (2021/08/23-2021/0827)

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[159] T. Tamba, H. Odaka, A. Bamba, A. Tanimoto, S. Takashima, and H. Suzuki, “Probing accretion flow structure of the HMXB Centaurus X-3 through X-ray spectral variability”, IAU Symposium 363, online, 2021, Nov. 29–Dec. 3 (oral)

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[161] A. Tanimoto, Y. Ueda, H. Odaka, S. Yamada, and C. Ricci, “NuSTAR Observations of 52 Compton-thick Active Galactic Nucleus Candidates Selected by the Swift/BAT All-sky Hard X-Ray Survey”, East-Asia AGN Workshop 2021, online, October. 11–13 (oral)

[162] K. Yamada, et al., “Development of inductively coupled position and temperature sensors for cryogenic rotating half wave plate,” The 19th International Workshop on Low Temperature Detectors (LTD19), Online (2021/7)

[163] Yume Nishinomiya, et al., "Development of the characterization methods for tes bolometers for cmb measurements," The 19th International Workshop on Low Temperature Detectors (LTD19), Online (2021/7)

[164] Kana Sakaguri, et al, "Broadband multi-layer Anti-reflection coatings with mullite and duroid used for half wave plate and alumina filter for CMB polarimetry," The 19th International Workshop on Low Temperature Detectors (LTD19), Online (2021/7)

[165] Tomoki Terasaki, et al., "Development of Al-Nb hybrid Lumped-Element Kinetic Inductance Detectors for infrared photon detection," The 19th International Workshop on Low Temperature Detectors (LTD19), Online (2021/9)

[166] Hartwig T., " Multiplicity of the first stars confirmed by supervised classification of extremely metal-poor stars " ; GALAH Science Meeting, Online (June 22-24, 2021)

[167] Moriwaki K., " Component extraction from line intensity maps with conditional GAN " ; UChicago/KICP Line Intensity Mapping Workshop 2021 (July 7-9, 2021)

[168] Hayashi T., "A strategy to search for an inner binary black hole from the motion of the tertiary"; COSMO'21, University of Illinois, Online (August 2-6, 2021)

[169] Hartwig T., " A new, unsupervised, non-parametric likelihood test for multidimensional data " ; RESCEU summer school 2021, Online (August 18-20, 2021)

[170] Nakazato Y., " The formation of Supersonically Induced Gas Objects (SIGOs) " ; RESCEU summer school 2021, Online (August 18-20, 2021)

[171] Zhong Y., "A necessary condition for supernova fallback invading newborn neutron-star magnetosphere"; RESCEU summer school 2021, Online (August 18-20, 2021)

[172] Komaki A., " Photoevaporation of Protoplanetary Disk : Dust-to-gas Mass Ratio Dependence"; RESCEU Summer School, Online (August 18-20, 2021)

[173] Kawai H., "An analytic model for the sub-galactic matter power spectrum in fuzzy dark matter halos"; RESCEU Summer School, Online (Aug 18-20, 2021)

[174] Zhong Y., "Study on the effect of the outflow from young neutron stars and supernova fallback on the neutron star diversity"; YITP workshop Extreme Outflows in Astrophysical Transients, Kyoto University(August 23-27, 2021)

[175] Hartwig T., " Machine learning finds hint for multiplicity of the first stars in stellar archaeology data " ; NIC-XVI, Online (September 21-25, 2021)

[176] Kawai H., "An analytic model for the sub-galactic matter power spectrum in fuzzy dark matter halos"; Workshop on Very Light Dark Matter 2021, Online (September 27-29, 2021)

[177] Moriwaki K., " Signal extraction from line intensity data cubes with 3D conditional GAN " : SUBLIME Workshop, Online(October 14, 2021)

[178] Komaki A., " Photoevaporation of Protoplanetary Disks"; IAU Symposium 362 The predictive power of computational astrophysics as a discovery tool, Online (November 8-12, 2021)

[179] Nakazato Y., " The formation of Supersonically Induced Gas Objects (SIGOs) with H2 cooling"; IAU Symposium 362 The predictive power of computational astrophysics as a discovery tool , Online(November 8-12, 2021)

[180] Mitani H., "Stellar wind effects on the atmospheric escape and transit signals of hot Jupiters"; IAU Symposium 362 The predictive power of computational astrophysics as a discovery tool(Online, November 8-12, 2021)

[181] Kawai H., (Poster) "An analytic model for the sub-galactic matter power spectrum in fuzzy dark matter halos"; Kashiwa Dark Matter Symposium 2021, Online (November 29 - December 2, 2021)

[182] Oguri M., "Status report of WISHES"; Subaru Users Meeting FY2021 (NAOJ, January 11-13, 2022)

[183] Moriwaki K., " Deep Learning for Line De-Confusion from Large-Scale Line Intensity Maps " ; SAZERAC learning the high-redshift Universe, Online (February 3-5, 2022)

5.3.2 Invited talks

[184] J. Yokoyama, "Modified gravity in cosmology and gravitational wave physics," Cosmology and Quantum Space Time (CQUeST 2021), Sogan University, Korea, online 2021/8/6

[185] J. Yokoyama, "Quantum aspects of inflationary cosmology," 1st international symposium on trans-scale quantum science, Trans-scale quantum science institute, The University of Tokyo, online 2021/10/29

[186] J. Yokoyama, "Quantum correction to the inflationary power spectrum," 4th LeCosPA symposium, National Taiwan University, online 2021/12/3

[187] J. Yokoyama, "Inflationary cosmology: its quantum nature," International Conference on Frontier of Physics (ICFP)-2022 Nepal Physical Society, online 2022/1/23

[188] J. Yokoyama, "Quest for the smallness of the primordial non-Gaussianity," Theoretical Physics at CQUeST: Past, Present, and Future, Sogan University, Korea, online 2022/2/10

[189] K. Fujikura, "Microlensing constraints on axion stars including finite lens and source size effects", Kagoshima Workshop on Quantum Aspects of Gravitation, face to face, Kagoshima, Japan, 2022/1/5.

[190] Oguri M., "WISHES: Wide Imaging with Subaru HSC of the Euclid Sky"; Euclid Consortium Meeting 2021, Online (May 25–28, 2021)

[191] Kashiyama, K., "Outflows from Dwarfs", YITP workshop Extreme Outflows in Astrophysical Transients (2021/08/23-2021/0827)

[192] Kashiyama, K., "Magnetic fields of compact objects", NAOJ Future Planning Symposium 2021 -Thinking about Future Plans Across Wavelengths (2021/11/9-2021/11/10)

[193] A. Bamba, "Particle acceleration on shocks of supernova remnants", "High-resolution X-ray spectroscopy of cosmic plasmas", online, 2021. Dec. 13–17

[194] A. Bamba, "Understanding the origin of supernova remnants with plasma diagnostics", "50 years astronomical X-ray spectroscopy in the Netherlands", online, 2022, Jan. 17–19

[195] Yuji Chinone, "Synergies between ALMA/LST and wide-field high-cadence CMB surveys," Synergies between ALMA and wide-field high-cadence multi-wavelength surveys, Online (2022/03)

[196] Yuji Chinone, "The search for primordial gravitational waves from cosmic inflation with CMB experiments in the Atacama desert and space," KMI Colloquium, Nagoya University, Nagoya, Japan (2021/12)

[197] Yuji Chinone, "Polarbear/Simons Array," Cosmoglobe Kickoff Meeting, University of Oslo, Online, June 2021

[198] Yoshida N., " Cosmic Relic Neutrinos and Large-Scale Structure: Nonlinear Clustering and the Neutrino Mass "; IAP Colloquium, Online (May 7, 2021)

[199] Oguri M., "WISHES: Wide Imaging with Subaru HSC of the Euclid Sky"; Euclid Consortium Meeting 2021, Online (May 25-28, 2021)

[200] Kashiyama K., "Outflows from Dwarfs"; YITP workshop Extreme Outflows in Astrophysical Transients, Kyoto University (August 23-27, 2021)

[201] Kashiyama K., "Magnetic fields of compact objects"; NAOJ Future Planning Symposium 2021 -Thinking about Future Plans Across Wavelengths, Online (Novermber 9-10, 2021)

[202] Yoshikawa K., Tanaka S., Yoshida N., "A 400-trillion grid Vlasov Simulation on Fugaku Supercomputer "; The International Conference for High Performance Computing, Networking, Storage and Analysis (SC21), Online (November 17, 2021)

[203] Yoshida N., "Cosmology and Fundamental Physics with Big Astronomical Data "; COMDATA21, Online (November 22, 2021)

[204] Yoshida N, "Cosmic density field reconstruction with a sparsity prior using images of distant galaxies "; BASE21, Online (December 7-9, 2021)

[205] Moriwaki K., " Deep Learning Application for Reconstruction of Large-Scale Structure of the Universe "; Big Data Analytics in Science and Engineering (BASE), 9th International Conference Data Models and New Query Languages in Big Data Analytics, Online (December 7-9, 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 electromagnetic observations. Gravitational waves are waves of spacetime curvature generated by the movement of mass and momentum. There are many reasons why gravitational waves are an interesting way to explore the sky. Because gravitational waves are generated by physical processes different from those that produce light or radio waves (which are generated by the movement of electric charges and currents), gravitational waves carry different information about their sources than is carried by electromagnetic waves. Gravitational waves interact weakly with matter allowing them to pass through material that would be opaque to radio waves and light. For example we expect that gravitational waves can escape the dense deep cores of supernovæ, and show us the earliest moments of the Big Bang. The Earth, too, is transparent to gravitational waves, so gravitational-wave telescopes can see the sky below them through the Earth as easily as they can see the sky above, allowing gravitational-wave telescopes to monitor the whole sky continuously, day and night. Gravitational waves are the only significant form of energy expected to be radiated by some of the most exotic events in the universe like the collisions of black holes. However, because everything is nearly transparent to gravitational waves, it is very difficult to build a device that can detect them, and the first detection of this form of energy was only achieved in 2015. It is even more difficult to build a device that can generate gravitational waves of any measurable amplitude, and so astronomy, that is the observation of intense naturally occurring sources of these waves like the collisions of black holes, provides our only opportunity to explore this aspect of the natural world.

Our research group's members are members of the 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 not collecting data during the 2021/2022 academic year, and had not been doing so since March of 2020 at the start of the pandemic. Nevertheless, analysis of previously recorded data continued during this time, as well as research and development of new techniques for analyzing and extracting information from the data, which we hope to use in the future when observations restart. Members of our group are active in all aspects of observational gravitational-wave astronomy, the following are some highlights from FY2021.

Searches for Compact Object Collisions

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

This past academic year 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.

Development of the data analysis software GstLAL (Fong)

I am involved in developing the data analysis software GstLAL that is used to detect gravitational waves, emitted by colliding black holes and neutron stars, that are passing through Earth. The software identifies possible gravitational-wave events, and to each event, we quantify the probability that the event is a false signal (i.e. not a gravitational wave) by assigning it a likelihood-ratio ranking statistic. My work involves improving the accuracy of the ranking statistic by implementing the option to perform source-specific searches, which in turn improves the sensitivity of the data analysis software to the population of interest. I have also been using this method to design an optimal population model to search for strong gravitationally lensed signals in existing LIGO and Virgo data. I am also involved in preparing the data analysis software such that it can be used to analyze data from the KAGRA detector, whose next observation run is scheduled to begin next spring.

Estimating performances of early warning with near-future gravitational wave detectors (Tsutsui)

Since gravitational and electromagnetic waves from a compact binary coalescence carry independent information about the source, the joint observation is important for understanding the physical mechanisms of the emissions. Rapid detection and source localization of a gravitational wave signal are crucial for the joint observation to be successful. For loud signals, it is even possible to detect it before the merger, which is called early warning. We estimated the performances of the early warning for neutron-star black-hole binaries, considering the precession effect of a binary orbit, with the near-future detectors such as A+, Advanced Virgo+, KAGRA+, and Voyager. We find that the precession effect improves about twice the performance [21]. With the third-generation detectors such as Einstein Telescope and Cosmic Explorer, we find that a neutron star-black hole binary at z=0.1 can typically be localized to $100\,\mathrm{deg}^2$ and $10\,\mathrm{deg}^2$ at the time of 12–15 minutes and 50–300 seconds before merger, respectively, which cannot be achieved without the precession effect [20].

Overlapping of gravitational-wave signals in the future gravitational-wave detectors (Nishizawa)

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 [17].

Astrophysical binary population

Short gamma-ray burst search with the CHIME radio telescope (Shikauchi)

Short gamma-ray bursts (sGRBs) are energetic and explosive outbursts lasting less than two seconds. sGRBs are thought to originate from compact object mergers such as binary neutron stars and black hole-neutron star binaries. Since the coalescence of compact object binaries can also be a source of gravitational waves, the detection of gravitational wave signals associated with sGRBs would impose important constraints on the origin of sGRBs. However, only one gravitational wave signal associated with a sGRB has been observed so far. In this study, in order to increase the samples of sGRBs that are the target of gravitational wave surveys, we will attempt to detect sGRBs where only a faint light can be observed. In FY2021, we estimated how many afterglows from sGRBs could be observed with the radio telescope Canadian Hydrogen Intensity Mapping Experiment (CHIME) and concluded that it is effective to search for sGRBs with CHIME, although the number was slightly lower than in the previous study and that most of the detectable afterglows are likely to be "orphan afterglows", afterglows without observable prompt emissions [18]. In the next fiscal year, we will actually analyze CHIME data and conduct afterglow surveys.

Theoretical Researches on the detectable black hole-luminous companion binaries with astrometric satellite Gaia (Shikauchi)

The astrometric satellite Gaia is expected to be able to observe non-interacting black hole-luminous companion (BH-LC) binaries and estimate BH mass by observing a motion of the LCs. Since the orbital period of the detectable BH-LC binaries should be longer than that of BH X-ray binaries in the Milky Way and extragalactic binary BHs, Gaia may reveal a different BH population from X-ray and gravitational wave observations. The next data release was held in June 2022 and included information of binaries, which has attracted a great deal of attention. Up to now, there are about ten papers studies theoretically predicting the number of BH-LC binaries observed with Gaia. In FY2021, we systematically investigated the dependence of the detectability of BH-LC binaries on binary evolution models such as the supernova model and the common envelope evolution model, and showed that observations can constrain binary evolution parameters [19].

Neutron Star Interiors

Because we don't have a detailed understanding of the behaviour of matter in the extreme pressure and density conditions found in the interior of a neutron star, not much is known about the interior structure of these objects. The gravitational waves emitted during the collisions of neutron stars with one another are expected carry information about their interior structure. Since the structure is determined by the laws of nuclear physics, learning about the structure can teach us about the properties of matter in regimes inaccessible to experiments here on Earth. Models of neutron stars can be used to connect theories of the properties of nuclear matter to features found in the gravitational waves emitted during their collisions. In collaboration with Prof. Hotokezaka's neutron star modelling group, and the nuclear physics group at the University of Tokyo, members of our group are making this connection from theory to observation, and investigating the ability of gravitational-wave detectors to validate or falsify modern theories of nuclear physics. Specifically we are studying what properties of future observatories would be most beneficial in answering these kinds of questions.

Examination of the testability of the hadron-quark phase transition using gravitational waves (Harada)

The hadron-quark phase transitions can occur in the core of neutron stars, but whether this phase transition is a continuous crossover or the first order phase transition is one of the questions in nuclear physics. These different two scenarios give the different waveform of gravitational waves emitted from binary neutron star mergers, and it has been found that the difference mainly appears in the merger or the post-merger phase rather than in the inspiral phase. On the other hand, the main frequency band of gravitational waves after the coalescence of binary neutron stars is 2-4 kHz, which is higher than the most sensitive frequency band of the current detectors, for example LIGO. In fact, due to the detector sensitivity issues in the high frequency range, we have not seen the post-merger signal of GW170817, although this event has a higher signal-to-noise ratio than any gravitational wave events observed before it. Therefore, in order to answer the question how the quark-hadron phase transition takes place, using gravitational wave observation, a detector which has better sensitivity in the high frequency range and an appropriate analysis method are needed. The goals of this study are figuring out whether current or currently proposed future detectors can solve this problem, what kind of events are suitable for this purpose, and what kind of analyses are effective.

Tests of General Relativity

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

Test of General Relativity in Strong Gravitational Fields (Watarai)

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

Test of gravity with gravitational-wave polarizations (Nishizawa)

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 constructed the mixed polarization model including a scalar polarization as an additional one beyond general relativity and analyzed the actual observation data of the gravitational wave detectors with the scalar-tensor polarization model. We found no signs of polarizations inconsistent with the prediction of general relativit. Therefore, we obtained a new result that supports the correctness of general relativity.

Observational constraint on axion dark matter with propagating gravitational waves (Tsutsui)

Most of matter in the Universe is invisible, which is called dark matter. A candidate of dark matter is axion. Axions form clouds in a galactic halo and amplify and delay a part of gravitational waves propagating in the clouds. The Milky Way is surrounded by the dark matter halo composed of a number of axion patches. Thus, the characteristic secondary gravitational waves is always expected right after the reported gravitational-wave signals from compact binary mergers. We search the secondary gravitational waves with a method optimized for the time delay and the amplification. Then, we found no significant signal and constrained the axion coupling to the parity violating sector of gravity, which is at most 10 times improved from a previous study, Gravity Probe B.

Stochastic Gravitational-wave Background

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

Other gravitational-wave sources

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

Therefore, for fun, members of our group have hypothesized what the gravitational-wave wake from a faster-than-light spacetime bubble might look like, and have conducted a search for these signals in the data of LIGO and Virgo. Measuring the sensitivity of the search, we can use a null result to put constraints on the rate of near-Earth flybys of faster-than-light vehicles. This work is nearing completion.

Cosmic Strings (Tsuna)

Cosmic strings are one-dimensional high-energy structures proposed to be left over from the cooling process of the early Universe. A broad spectrum of theories of fundamental physics predict their existence, while they have never been discovered. Searching for them and either confirming their existence or putting limits will teach us a great deal about fundamental physics. These strings occasionally form loops, which are predicted to emit gravitational wave signals potentially within the reach of ground-based detectors such as LIGO, Virgo and KAGRA. We led the analysis of data collected during the O3 observing run, searching for evidence of these signals through searches of the burst signal and the stochastic background. While we did not detect a significant signal from both probes, we were able to set strong constraints on the energy scale and morphology of these strings. The results of this work were published in Physical Review Letters

[16].

Development and Application of a Detection System for a Novel Class of Gravitational-Wave Transients (Kuwahara)

We have developed a detection system for a novel class of gravitational- wave transients which is Cherenkov-like gravitational waves. Since we do not know the actual waveform of gravitational Cherenkov radiation, under the assumption that the waveform is similar to the waveform of Cherenkov radiation in Electrodynamics, we conducted the investigation for 1 year data of O3. The ranking statistic obtained for this search can be utilized to make constraints on the power, the velocity of the super-luminous sources, and the distance from an observer to the trajectory of the source. This study can be also further discussed for the Search for Extra-Terrestrial Intelligence assuming that such aliens have super-luminous spacecraft like in Star Trek or Star Wars. Serendipitously, it has been discovered that the ad hoc waveform model introduced here is an excellent match for some classes of transient noise events called "glitches". For the coming fiscal year, we will try improving ranking statistics and make stronger constraints.

Improvements of gravitational-wave detector sensitivity

Globally correlated magnetic noise (Nishizawa)

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

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

The Japanese future space-based gravitational-wave detector, DECIGO, aims at detecting primordial gravitational waves generated by inflation in the early Universe. However, as the prediction for the amplitude of the inflationary gravitational waves is highly uncertain, it is necessary to improve the target sensitivity of DECIGO and enhance the possibility of the detection of the inflationary gravitational waves. The current target sensitivity of DECIGO is limited by quantum noise (shot noise and radiation pressure noise). However, squeezing is not available for DECIGO because of its long arm length and large optical loss. In the case, the quantum locking method that controls main cavity length by feeding back the signal from an external small auxiliary cavity can be used to reduce the radiation pressure noise. We extended the quantum locking by incorporating optical spring and showed that the radiation pressure noise is reduced further and the sensitive frequency band broadens [22].

People and Things

During the 2021 through 2022 academic year, one of our Master's students, Mr. Kuwahara, successfully defended his thesis and continued on to the doctoral program. One doctoral student, Dr. Tsuna, successfully defended his thesis and continued on to a postdoctoral appointment at the California Institute of Technology. And two doctoral students, Mr. Ohta and Mr. Chan, successfully secured employment in industry.

6.1.2 Kenta Hotokezaka group

Kilonova is one of the electromagnetic wave-counterparts associated with binary neutron star mergers. The radioactive decay of the neutron-rich material released at the time of coalescence is the energy source of kilonovae. It is important that this phenomenon is particularly related to the origin of heavy elements. We conducted research from both observational and theoretical perspectives on kilonovae [1, 14, 2].

A kilonova enters the nebular phase, where emission lines arising from atomic transitions escape from the ejecta without interaction. Thus, observing the nebular spectrum will provide us valuable information on the elements synthesized in merger ejecta. We study the physical conditions and emergent spectra in the nebular phase under the assumption that the ejecta is composed of lanthanides [1]. We find that the time evolution of the thermodynamic quantities are roughly constant with time.

We also study the multi-wavelength behaviour of non-thermal afterglow produced by a jet [3, 4, 5, 11]. In particular, we conducted a VLA observation at 3.5 year after GW170817 [3]. The radio flux was detected at the level of $10\,\mu$Jy. This flux level agrees with the expectation of the jet afterglow. Therefore, we put a constraint on the late-time contribution of the kilonova afterglow.

Radio transient

The radio transient sky is known to be somewhat quiet. However, thanks to the recent progress of technology of radio interferometers, we are entering a new-era that astrophysical explosions can be discovered by radio interferometers. We study a peculiar radio transient, VT J121001+495647, which was discovered in the first epoch image of the VLA all sky survey [7]. This transient has a very long time scale, ~ 20 years, and very bright luminosity, suggesting that the progenitor is a supernova explosion with dense circum-stellar medium at 10^{17} cm. Surprisingly, we found that a MAXI unidentified soft-Xray transient at the same location, of which properties can be explained by the existence of mildly relativistic material.

Black holes and neutron stars

We have studied that black holes and neutron stars in the context of the progenitors of gravitational-wave mergers [6]. We showed that it is practically impossible that neutron star mergers in globular clusters result in the second generation mergers, which fill the lower mass gap. This is because the required stellar density and escape velocity are too high in order to have second generation mergers for neutron stars. On the other hand, we have found that the upper mass gap may be filled by dynamical capture of massive black holes in globular clusters.

We have also discussed the possibilities that the upcoming astronomical surveys can find free-floating black holes and neutron stars [10, 12].

Chemical evolution

The origin of r-process elements in the Galaxy remains an astrophysical mystery. In particular, one of the big question is when r-process elements were produced, i.e., recently? or a several billion of years ago? We studied the history of the production of r-process elements through the observed abundances of a stellar stream [8] and field stars [9]. We found that the abundances of extremely metal-poor stars point to that there is some delay between the star formation and the production of r-process. This might be a hint that r-process elements have been predominantly produced by neutron star mergers.

Galactic Nuclei

Last year, we studied the nature of star formation in galactic nuclear regions based on the recent high-z quasar observations. As a result, we found that the extremely high iron to magnesium abundance ratio observed in quasars requires a highly top-heavy stellar mass distribution (Dr. Toyouchi).

6.2 Activity report of Affiliates

6.2.1 Masaki Ando

Ando group is working on experimental research for gravitational-wave observation, in particular for large projects such as KAGRA and B-DECIGO. KAGRA is a gravitational-wave antenna at Kamioka, Gifu prefecture in Japan. We are playing a key role since the conceptual study phase before the start of the project in 2010. The installation of the main components have been finished in FY2018, and we are in the phase of commissioning; shakedown, and tuning for the full operation of the interferometer. In FY2020, the KAGRA interferometer started the observation run, named O3GK. Our group members led the commissioning works and operation of the interferometer. We are also working on B-DECIGO, which is a space-borne gravitational wave antenna with an observation band of around 0.1 Hz. We made a theoretical study on science cases by this mission as well as experimental development of critical subsystems, such as laser interferometer, stabilized laser source, drag-free system, and low-noise thruster. In FY2021, we continued a system design study with a company to show the feasibility of the full mission. This activity was financially supported by RESCEU.

6.2.2 Mamoru Doi

We developed instruments of optical follow-up of gravitational sources. Primary instrument is Tomo-e Gozen (Tomo-e) on the 1-m Kiso Schmidt telescope. We carried out northern sky survey every clear night. The survey area of each night was about 7000 square degrees once, followed by 2000 square with about half hour cadence. We are finding many transients, such as supernovae, Near Earth Objects, variable stars, and so on. We found early flash of a Type-Ia supernova (SN2020hvf) within the half hour cadence area in 2020, and found that the early flash was due to an interaction between the supernova ejecta and the circumstellar matter. Our finding constrains the progenitor of Type-Ia supernova, and the result was published on ApJL, and web press release was carried out. We also submitted a paper on NEO. Another activity was to develop an optical imaging spectrograph, TriCCS on the Seimei 3.8-m telescope under collaboration with Kyoto University. Three band fast ($\leq$ 98 frame per second, fps) simultaneous imaging mode was possible with three CMOS sensor cameras. Low resolution spectroscopy mode was also developed, and the first commissioning observation was carried out in March 2022. Both Tomo-e and TriCCS will be ready to follow GW o4 observations. Also two GW follow-up papers were published, one for GW event S190510g with Subaru/HSC, and the other for J-Gem activities for O3.

In order to get a clue to understand the nature of Fast Radio Bursts (FRBs), we have conducted a search for their optical counterparts using the high-speed observing facilities. Analyzing 24.4 fps optical data of repeating FRB 20190520B obtained by Tomo-e simultaneously with radio observations by the Five-hundred-meter Aperture Spherical radio Telescope (FAST), we obtained deep upper limits on the optical emission from the 11 radio bursts detected by FAST. The result was submitted in March 2022. Further observations of repeating FRBs are ongoing using TriCCS. Simultaneous radio-optical survey of non-repeating FRBs using Tomo-e is also in progress in collaboration with the FRB research group using Canadian Hydrogen Intensity Mapping Experiment (CHIME).

6.3 Publication List

[1] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Search for Lensing Signatures in the Gravitational-Wave Observations from the First Half of LIGO-Virgo's Third Observing Run", The Astrophysical Journal, 923, 14 (2021).

[2] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Search for Gravitational Waves Associated with Gamma-Ray Bursts Detected by Fermi and Swift during the LIGO-Virgo Run O3a", The Astrophysical Journal, 915, 86 (2021).

[3] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog", Physical Review D 103, 122002 (2021).

[4] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "GWTC-2: Compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run", Physical Review X 11, 021053 (2021).

[5] R. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), "Population properties of compact objects from the second LIGO-Virgo gravitational-wave transient catalog", The Astrophysical Journal Letters 913, L7 (2021).

[6] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Constraints on dark photon dark matter using data from LIGO's and Virgo's third observing run", Physical Review D 105, 063030 (2022).

[7] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Search for continuous gravitational waves from 20 accreting millisecond x-ray pulsars in O3 LIGO data", Physical Review D 105, 022002 (2022).

[8] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "All-sky search for short gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run", Physical Review D 104, 122004 (2021).

[9] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "All-sky search for long-duration gravitational-wave bursts in the third Advanced LIGO and Advanced Virgo run", Physical Review D 104, 102001 (2021).

[10] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Upper limits on the isotropic gravitational-wave background from Advanced LIGO and Advanced Virgo's third observing run", Physical Review D 104, 022004 (2021).

[11] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Search for anisotropic gravitational-wave backgrounds using data from Advanced LIGO and Advanced Virgo's first three observing runs", Physical Review D 104, 022005 (2021).

[12] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Diving below the Spin-down Limit: Constraints on Gravitational Waves from the Energetic Young Pulsar PSR J0537-6910", The Astrophysical Journal Letters, 913, L27 (2021).

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[14] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Search for intermediate-mass black hole binaries in the third observing run of Advanced LIGO and Advanced Virgo", Astronomy & Astrophysics, 659, A84 (2022).

[15] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Constraints from LIGO O3 Data on Gravitational-wave Emission Due to R-modes in the Glitching Pulsar PSR J0537–6910", The Astrophysical Journal, 922, 71 (2021).

[16] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Searches for Continuous Gravitational Waves from Young Supernova Remnants in the Early Third Observing Run of Advanced LIGO and Virgo", The Astrophysical Journal, 921, 80 (2021).

[17] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "All-sky search for continuous gravitational waves from isolated neutron stars in the early O3 LIGO data", Physical Review D 104, 082004 (2021).

[18] R. Abbott *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration), "Observation of gravitational waves from two neutron star-black hole coalescences", The Astrophysical Journal Letters 915, L5 (2021).

[19] K. C. Kipp et al., "GstLAL: A software framework for gravitational wave discovery", SoftwareX, 14, 100680 (2021).

[20] T. Tsutsui, A. Nishizawa, S. Morisaki, "Early warning of precessing neutron-star black-hole binary mergers with the near-future gravitational-wave detectors", Monthly Notices of the Royal Astronomical Society 512, 3878 (2022).

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[22] Y. Himemoto, A. Nishizawa, A. Taruya,"Impacts of overlapping gravitational-wave signals on the parameter estimation: Toward the search for cosmological backgrounds", Physical Review D 104, 044010 (2021).

[23] M. Shikauchi, K. Cannon, H. Lin, T. Totani, J. R. Shaw, "On the Use of CHIME to Detect Long-Duration Radio Transients from Neutron Star Mergers", The Astrophysical Journal 928, 72 (2022).

[24] M. Shikauchi, A. Tanikawa, N. Kawanaka, "Detectability of Black Hole Binaries with Gaia: Dependence on Binary Evolution Models", The Astrophysical Journal 928, 13 (2022).

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[26] M. Arimoto et al. (53 co-authors), "Gravitational Wave Physics and Astronomy in the nascent era", Progress of Theoretical and Experimental Physics, ptab042 (2021).

[27] N. Arima, M. Doi, T. Morokuma, and N. Takanashi, "Intrinsic color diversity of nearby Type Ia supernovae", Publications of the Astronomical Society of Japan, 73, 326 (2021).

[28] J. Jiang et al. (31 co-authors), " Discovery of the Fastest Early Optical Emission from Overluminous SN Ia 2020hvf: A Thermonuclear Explosion within a Dense Circumstellar Environment", The Astrophysical Journal Letters 923, L8 (2021).

[29] T. Ohgami et al. (15 co-authors), "Optical follow-up observation for GW event S190510g using Subaru/Hyper Suprime-Cam", Publications of the Astronomical Society of Japan, 73, 350 (2021).

[30] M. Sasada et al. (70 co-authors), "J-GEM optical and near-infrared follow-up of gravitational wave events during LIGO's and Virgo's third observing run", Progress of Theoretical and Experimental Physics, 05A104 (2021).

[31] K. Hotokezaka, *et al.*, "Nebular emission from lanthanide-rich ejecta of neutron star merger" Monthly Notices of the Royal Astronomical Society ,**506**, 5863-5877 (2021).

[32] G. Raaijmakers, *et al.*, "The Challenges Ahead for Multimessenger Analyses of Gravitational Waves and Kilonova: A Case Study on GW190425", Astrophys. J. **922**, 17 (2021).

[33] A. Balasubramanian, *et al.*, "Continued Radio Observations of GW170817 3.5 yr Post-merger", Astrophys. J. Letters **914**, L20 (2021).

[34] S. Makhathini, *et al.*, "The Panchromatic Afterglow of GW170817: The Full Uniform Data Set, Modeling, Comparison with Previous Results, and Implications", Astrophys. J. **922**, 18 (2021).

[35] D. Dobie, *et al.*, "Radio afterglows from compact binary coalescences: prospects for next-generation telescopes", Monthly Notices of the Royal Astronomical Society, **505**, 2647-2661 (2021).

[36] J. Samsing and K. Hotokezaka, "Populating the Black Hole Mass Gaps in Stellar Clusters: General Relations and Upper Limits", Astrophys. J. **923**, 14 (2021).

[37] D. Z. Dong, *et al.* "A transient radio source consistent with a merger-triggered core collapse supern ova", Science. **373**, 1125-1129 (2021). 038 (2020).

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[41] D. Dobie, *et al.*, "A comprehensive search for the radio counterpart of GW190814 with the Australian Square Kilometre Array Pathfinder", Monthly Notices of the Royal Astronomical Society, **510**, 3794-3805 (2022).

[42] D. Toyouchi, *et al.*, "Hunting wide-area optical surveys for high proper motion isolated neutron stars", Monthly Notices of the Royal Astronomical Society, **510**, 611-619 (2022).

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

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[50] R. Yamada et al., Reduction of quantum noise using the quantum locking with an optical spring for gravitational wave detectors, Physics Letters A 402, 127365 (2021).

[51] T. Akutsu et al., Radiative Cooling of the Thermally Isolated System in KAGRA Gravitational Wave Telescope, J. of Phys.: Conf. Ser. 1857, 012002 (2021).

6.4 International Conference Talks

6.4.1 Contributed talks

[52] (poster) S. Kuwahara, “Cherenkov radiation-like Gravitational-Wave Search”, LIGO-Virgo-KAGRA Collaboration Meeting, online, 2021/9/6-10.

[53] (poster) S. Kuwahara, “Cherenkov radiation-like Gravitational-Wave Search”, LIGO-Virgo-KAGRA Collaboration Meeting, online, 2022/3/14-17.

[54] S. Kuwahara, “Development and Application for a novel class of gravitational wave transients”, KAGRA F2F meeting, online, 2021/12/20-21.

[55] S. Kuwahara, “Cherenkov Radiation-like GW Search”, Multi-messenger Astrophysics of Explosive Transients - Gravitational wave physics and astronomy: Genesis, Area Workshop 2021 Autumn -, online, 2021/10/14.

[56] (poster) R. Harada, “What kind of detector will be useful to test the quark phase transition in NS cores?”, LIGO-Virgo-KAGRA Collaboration Meeting, online, 2022/3/14-17.

[57] (poster) M. Shikauchi, K. Cannon, H. Lin, T. Totani, J. R. Shaw, “On the use of CHIME to Detect Long-Duration Radio Transients from Neutron Star Mergers”, Canadian Astronomical Society Annual Meeting, online, 2021/5/10-14.

[58] M. Shikauchi, “Gaia’s Detectability of Black Hole-Main Sequence Star Binaries Formed in Open Clusters”, Nuclear Burning in Massive Stars? - towards the formation of binary black holes -, YITP, Kyoto University & Monash University, online, 2021/7/26-30.

[59] M. Shikauchi, “On the use of CHIME to Detect Long-Duration Radio Transients from Neutron Star Mergers”, Multi-messenger Astrophysics of Explosive Transients - Gravitational wave physics and astronomy: Genesis, Area Workshop 2021 Autumn -, online, 2021/10/14.

[60] (poster) T. Tsutsui, “Early warning for precessing neutron star-black hole binaries with future GW detectors”, Amaldi 14 conference, online, 2021/7/21.

[61] (poster) T. Tsutsui, “Early warning for precessing neutron star-black hole binaries with future GW detectors”, LIGO-Virgo-KAGRA Collaboration Meeting, online, 2021/9/8.

[62] (poster) T. Tsutsui, “Searching for axion dark matter halo with gravitational-wave observations”, GWPAW, online, 2021/12/15.

[63] (poster) T. Tsutsui, “Observational Constriant to Axion Dark Matters with Propagating Gravitational Waves”, LIGO-Virgo-KAGRA Collaboration Meeting, online, 2022/3/14.

[64] T. Tsutsui, “Searching for axion dark matter halo with gravitational-wave observations”, KAGRA F2F meeting, online, 2021/12/20.

[65] A. Nishizawa, “Gravitational-wave polarization test in the strong gravity regime”, Innovative Area Gravitational Wave Physics and Astronomy: Genesis, Group-A Winter Camp, Online, 2022/1/23.

[66] Daisuke Toyouchi, ”Formation of intermediate-mass BHs in metal-free clouds experiencing violent dynamical heating” East-Asia AGN workshop, China (+online),2021/10/13

[67] M. Ando, Future Strategy Committee, KAGRA F2F Collaboration Meeting, 2021/12/20.

[68] H. Wang et al., Updates of birefringence characterization of ITMs and simulation progress, KAGRA F2F Collaboration Meeting, 2021/12/20.

[69] M. Ando, Development of Human Resources for Future Projects, KAGRA F2F Collaboration Meeting, 2021/12/20.

[70] S. Takano, Cryogenic Monolithic Interferometer for Sensing Gravity Gradient, 4th IFQMS (Dec. 2021, online)

[71] Y. Oshima, Angular Sensor with a Coupled Cavity for Gravity Gradient Sensing, 4th IFQMS (Dec. 2021, online)

[72] C. P. Ooi, Suspension Noise measurements of Cryogenic Torsion Pendulums with Crystalline Fibres, 4th IFQMS (Dec. 2021, online)

[73] M. Ando, R&Ds for Future Upgrade and Post-O5 Planning, LIGO-Virgo-KAGRA Collaboration Meeting, online, 2021/9/6-10.

[74] Y. Michimura et al., Vector and Axion Dark Matter Searches with KAGRA, LIGO-Virgo-KAGRA Collaboration Meeting, online, 2021/9/6-10.

[75] Y. Michimura et al., Ultralight dark matter searches with KAGRA gravitational wave telescope, 17th TAUP (Sep. 2021, Online)

[76] Y. Oshima, First observation and analysis of DANCE: Dark matter Axion search with riNg Cavity Experiment, 17th TAUP (Sep. 2021, Online)

[77] H. Fujimoto, DANCE: Searching for Axion-like particle dark matter with optical bow-tie ring cavity, The Workshop on Very Light Dark Matter 2021 (September 2021, online).

[78] M. Ando, Future Strategy Committee, KAGRA F2F Collaboration Meeting, 2021/8/29.

[79] H. Wang et al., Study of birefringence effects with realistic mirror maps, KAGRA F2F Collaboration Meeting, 2021/8/29.

[80] Yuta Michimura et al., Searching for ultralight vector dark matter with the cryogenic gravitational wave telescope KAGRA, 16th MG Meeting, Online, Jul. 2021.

[81] Y. Michimura et al., Searching for Signals from Ultralight Vector Dark Matter with KAGRA, The 8th KAGRA International Workshop, Online, Jul. 2021.

[82] Y. Oshima, First test operation of DANCE: Dark matter Axion search with riNg Cavity Experiment, 16th Patras Workshop on Axions, WIMPs and WISPs, Online, June 2021.

[83] Y. Michimura, Updates on the Optical Levitation Experiment, The 3rd QFilter Workshop, Online Jun. 2021.

[84] (poster) H. Fujimoto, Dark matter Axion search with riNg Cavity Experiment DANCE: Design and development of auxiliary cavity for simultaneous resonance of linear polarizations, 17th TAUP, Online, Sep. 2021.

[85] (poster) Y. Oshima, Design of Coupled Wave Front Sensor for TOrsion-Bar Antenna, GWADW2021, Online, 2021/5/21.

6.4.2 Invited talks

[86] "Models for the kilonova", GWUniverse Inauguration Workshop: Cosmology with gravitational waves, online, 2021/10/8.

[87] Kenta Hotokezaka, "Remnants and jets of neutron star merger", Gravitational-Wave Physics and Astronomy Workshop, Hybrid, Hannover Germany, 2021/12/14-17.

[88] Christopher M. Irwin, "Aspherical Shock Breakout: Observational Signatures", HEAD 19 meeting, Pittsburgh, 2022/3/17.

[89] Masaki Ando, Gravitational Astrophysics with KAGRA and Beyond, YKIS2022a Symposium, Online, 2022/2/16.

[90] Masaki Ando, TOBA: Ground-Based Mid.-Frequency Gravitational-Wave Antenna, 16th Marcel Grossmann Meeting, Online, 2021/7/7.

[91] Masaki Ando, Space GW Antennae: DECIGO/B-DECIGO, GWADW2021, Online, 2021/5/17.

[92] Masaki Ando, Summary of Low-Frequency Workshop, GWADW2021, Online, 2021/5/21.

[93] Satoru Takano, The Current Status of TOBA, GWADW2021, Online, 2021/5/21.

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 A new formation scenario of a counter-rotating circumstellar disk

We find a new formation pathway of a counter-rotating circumstellar disk in a triple protostar system simulated from a turbulent molecular cloud core with no magnetic field. The tertiary protostar forms via the circumbinary disk fragmentation and the initial rotational directions of all the three circumstellar disks are almost parallel to that of the orbital motion of the binary system. Their mutual gravito-hydrodynamical interaction for the subsequent $\sim 10^4$ yr greatly disturbs the orbit of the tertiary, and the rotational directions of the tertiary disk and star are reversed due to the spiral-arm accretion of the circumbinary disk. The counter-rotation of the tertiary circumstellar disk continues to the end of the simulation ($\sim 6.4 \times 10^4$ yr after its formation), implying that the counter-rotating disk is long-lived. This new formation pathway during the disk evolution in Class 0/I Young Stellar Objects possibly explains the counter-rotating disks recently discovered by ALMA.

7.1.2 Disentangling the stellar inclination of transiting planetary systems using the stellar differential rotation

The Rossiter-McLaughlin (RM) effect has been widely used to estimate the *sky-projected* spin-orbit angle, λ, of transiting planetary systems. Most of the previous analysis assume that the host stars are rigid rotators in which the amplitude of the RM velocity anomaly is proportional to $v_\star \sin i_\star$. When their latitudinal differential rotation is taken into account, one can break the degeneracy, and determine separately the equatorial rotation velocity $v_\star$ and the inclination $i_\star$ of the host star. We derive a fully analytic approximate formula for the RM effect adopting a parameterized model for the stellar differential rotation. For those stars that exhibit the differential rotation similar to that of the Sun, the corresponding RM velocity modulation amounts to several m/s. We conclude that the latitudinal differential rotation offers a method to estimate $i_\star$, and thus the full spin-orbit angle ψ, from the RM data analysis alone.

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

Recent ALMA observations have identified a variety of dust gaps in protoplanetary disks, which are commonly interpreted to be generated by unobserved planets. Predicting mass of such embedded planets is of fundamental importance in comparing those disk architectures with the observed diversity of exoplanets. The prediction, however, depends on the assumption that whether the same gap structure exists in the dust component alone or in the gas component as well. We assume a planet can only open a gap in the gas component when its mass exceeds the pebble isolation mass by considering the core accretion scenario. We then propose two criteria to distinguish if a gap is opened in the dust disk alone or the gas gap as well when observation data on the gas profile is not available. We apply the criteria to 35 disk systems with a total of 55 gaps compiled from previous studies, and classify each gap into four different groups. The classification of the observed gaps allows us to predict the mass of embedded planets in a consistent manner with the pebble isolation mass. We find that outer gaps are mostly dust alone, while inner gaps are more likely to be associated with a gas gap as well. The distribution of such embedded planets is very different from the architecture of the observed planetary systems, suggesting that the significant inward migration is required in their evolution.

7.1.4 Auto–differentiable spectral model for full Bayesian analysis of exoplanet spectra

In FY2021, we released ExoJAX, an automatically differentiable spectral model that enables Bayesian modeling of high-dispersion spectra through HMC-NUTS, which can perform Markov chain Monte Carlo on complex models [4]. ExoJAX was constructed using Google's auto–differentiable package, JAX and Uber-AI's Numpyro stochastic programming language.

We tested ExoJAX on brown dwarfs close to exoplanets and were able to model high-dispersion spectra at a level never seen before. In addition, ExoJAX is the world's first spectral model that can calculate everything from molecular databases to observed spectra end-to-end, whereas previous models require a grid-based model of molecular cross sections to be prepared in advance before calculating the spectral model. Because of this first-principles model, ExoJAX is the first spectral model in the world to have the ability to directly compare the effects of molecular databases with observed quantities.

ExoJAX is being developed according to the standard methods of the current open source community (open development via Github, review system via pull request, test environment construction via pytest, extensive documentation via sphinx, pip install, etc.), and several external Several external participants have also started to participate in the development. Although there are still few such examples in the domestic astronomy community, the benefits of introducing an open source development culture for astronomical software are great. We believe that the fact that this has started in Japan is one of the achievements of the satellite center.

7.1.5 First detection of neutral titanium in exoplanet atmospheres

Detection of molecules and atoms in exoplanet atmospheres can also provide information on planet formation. An example of this is the world's first detection of neutral titanium (Ti) in HD 149026b, which is one of the results of this year's study [5]. Since TiO was not detected in this source, the fact that Ti was detected and TiO was non-detected indicates that the C/O ratio is high. Although it is difficult to generalize due to various models, the high C/O ratio in the standard view means that water vapor was not available in the atmosphere at the time of formation, suggesting that water formed far from the snow line, where it is solid, and migrated close to the star.

7.1.6 First Detection of Hydroxyl Radicals in Exoplanet Atmospheres

Astronomers are familiar with the Hydroxyl Radicals (OH), which is also found in trace amounts in Earth's atmosphere. This molecule coexists in the atmosphere via ultraviolet light and thermal divergence when water is present in the atmosphere. Using a high-dispersion technique with the Subaru Telescope IRD, OH was detected in exoplanet atmospheres for the first time in the world. The exoplanet is WASP33b, a hot Jupiter, which was also the first TiO (titanium dioxide) exoplanet to be detected with Subaru HDS. The OH detected in this study also has a bright line signal, and it is certain that WASP33b has a strong temperature inversion layer. Thus, the high-dispersion method is proving to be extremely useful for the characterization of actual planetary atmospheres [6].

7.1.7 Discovery of Close-in dipper

In the first year, TESS big data analysis discovered many dippers in the southern sky – objects that are thought to be in transit (dipping) disks. In the next fiscal year, four of these objects were followed up with Subaru HDS and CAF É /HIDES to investigate their properties[7]. Of particular interest is the discovery of the close-in binary dipper shown in Figure 3. This object was first confirmed to have a strong time-varying H alpha line. Since the dip period of Dipper coincides with the period of the binary star, the dip is expected to be caused by the disk being partially obscured by the rotating binary star. This is the reason why we can understand the formation of a circumstellar planet. This means that Dipper is a good target for understanding the formation of binary planets.

7.1.8 A rich population of free-floating planets in the Upper Scorpius young stellar association

The nature and origin of free-floating planets (FFPs) are still largely unconstrained because of a lack of large homogeneous samples to enable a statistical analysis of their properties. So far, most FFPs have been discovered using indirect methods; microlensing surveys have proved particularly successful to detect these objects down to a few Earth masses. However, the ephemeral nature of microlensing events prevents any follow-up observations and individual characterization. Several studies have identified FFPs in young stellar clusters and the Galactic field but their samples are small or heterogeneous in age and origin. Here we report the discovery of between 70 and 170 FFPs (depending on the assumed age) in the region encompassing Upper Scorpius and Ophiuchus, the closest young OB association to the Sun. We found an excess of FFPs by a factor of up to seven compared with core-collapse model predictions, demonstrating that other formation mechanisms may be at work. We estimate that ejection from planetary systems might have a contribution comparable to that of core collapse in the formation of FFPs. Therefore, ejections due to dynamical instabilities in giant exoplanet systems must be frequent within the first 10 Myr of a system's life.

7.1.9 37 new validated planets in overlapping K2 campaigns

We analysed 68 candidate planetary systems first identified during Campaigns 5 and 6 (C5 and C6) of the NASA K2 mission. We set out to validate these systems by using a suite of follow-up observations, including adaptive optics, speckle imaging, and reconnaissance spectroscopy. The overlap between C5 with C16 and C18, and C6 with C17, yields light curves with long baselines that allow us to measure the transit ephemeris very precisely, revisit single transit candidates identified in earlier campaigns, and search for additional transiting planets with longer periods not detectable in previous works. Using VESPA, we compute false positive probabilities of less than 1 per cent for 37 candidates orbiting 29 unique host stars and hence statistically validate them as planets. These planets have a typical size of 2.2 R(Earth) and orbital periods between 1.99 and 52.71 d. We highlight interesting systems including a sub-Neptune with the longest period detected by K2, sub-Saturns around F stars, several multiplanetary systems in a variety of architectures. These results show that a wealth of planetary systems still remains in the K2 data, some of which can be validated using minimal follow-up observations and taking advantage of analyses presented in previous catalogues.

7.1.10 Rotating Motion of the Outflow of IRAS 16293-2422 A1 at Its Origin Point Near the Protostar

The Class 0 protostar IRAS 16293-2422 Source A is known to be a binary system (A1 and A2) or even a multiple system. We have observed this source in the SO and OCS lines at 3.1 mm with ALMA. The northwest-southeast (NW-SE) outflow is detected in the SO ($J_N = 2_2$-1_1) line. Based on the morphology of the SO distribution, this bipolar outflow structure seems to originate from the protostar A1 and its circumstellar disk, or the circummultiple structure of Source A. The rotation motion of the NW-SE outflow is detected, from which we evaluate the specific angular momentum of the outflowing gas to be (8.6-14.3) $\times$ 10^{-4} km s^{-1} pc. If the driving source of this outflow is the protostar A1 and its circumstellar disk, it can be a potential mechanism to extract the specific angular momentum of the disk structure. These results can be a hint for the outflow launching mechanism in this source.([11])

7.1.11 Molecular Distributions of the Disk/Envelope System of L483: Principal Component Analysis for the Image Cube Data

We have observed 23 molecular lines toward the Class 0 protostellar source L483 with ALMA and have performed principal component analysis (PCA) for their cube data (PCA-3D) to characterize their distributions and velocity structures in the vicinity of the protostar. Most oxygen-bearing complex organic molecule lines have a large correlation with the first principal component (PC1), representing the overall structure of the disk/envelope system around the protostar. Contrary, the $C^{18}O$ and SiO emissions show small and negative correlations with PC1. The NH_2CHO lines stand out conspicuously at the second principal component (PC2), revealing more compact distribution. Thus, PCA-3D enables us to elucidate the similarities and the differences of the distributions and the velocity structures among molecular lines simultaneously, so that the chemical differentiation between the oxygen-bearing complex organic molecules and the nitrogen-bearing ones is revealed in this source.([12])

7.1.12 Exploring the 100 au Scale Structure of the Protobinary System NGC 2264 CMM3 with ALMA

We have observed the young protostellar system NGC 2264 CMM3 in the 1.3 mm and 2.0 mm bands at a resolution of 70 au with ALMA. The structures of two distinct components, CMM3A and CMM3B, are resolved in the continuum images of both bands. The spectral index α between 2.0 and 0.8 mm is derived to be 2.4-2.7 and 2.4-2.6 for CMM3A and CMM3B, respectively, indicating optically thick dust emission and/or grain growth. A velocity gradient in the disk/envelope direction is detected for CMM3A in the CH_3CN, CH_3OH, and $^{13}CH_3OH$ lines detected in the 1.3 mm band, which can be interpreted as the rotation of the disk/envelope system. From this result, the protostellar mass of CMM3A is roughly evaluated to be 0.1-0.5 M_{sun} by assuming Keplerian rotation. The OCS emission line shows a velocity gradient in both outflow direction and disk/envelope direction. A hint of outflow rotation is found, and the specific angular momentum of the outflow is estimated to be comparable to that of the disk.([13])

7.1.13 Primitive nature of Ryugu materials revealed by data from remote sensing, lander, and Earth-returned samples

In Dec. 2020, JAXA ' s Hayabsua2 returned to the Earth and successfully delivered its capsule with samples from asteroid Ryugu. We participated in curation activities of Ryugu samples by building a new spectrophotometric measurement system in our lab and brought it to JAXA curation facility [14]. The results of the measurements show that both albedo and reflectance spectra of Earth-returned samples and those of the global average of Ryugu agree with each other well, suggesting that Earth-returned samples are good representative of asteroid Ryugu [15]. These curation measurements have served as the basis for the ongoing initial detailed geochemical analyses of Ryugu samples.

Such sample measurement activities promoted remote-sensing data analyses particularly regarding materialistic properties of Ryugu materials [16]. We had a number of major findings about Ryugu. First is the discovery of extremely high porosity (>70 percent) boulders on Ryugu [16]. These high porosities are much larger than average porosity (30 - 50 percent) of Ryugu boulders and as high as that for cometary materials. These high-porosity boulders on Ryugu also possess significantly lower reflectance ($\sim$0.016) than the Ryugu average ($\sim$0.019). They are found only on the floors of few fresh small ($\sim$10 m diameter) craters on Ryugu and but not found on all fresh craters including the artificial crater generated by the small carryon impactor SCI brought by Hayabusa2. This observation suggests that the extremely-high-porosity materials found on Ryugu were not resulted from impact comminution of low-porosity materials by likely by excavation of intrinsically high porosity materials at shallow depth. The distribution pattern of these extremely-high-porosity and low-reflectance materials suggests that their small fragments may be spread widely on Ryugu surface and could be contained in returned samples.

Second, an important finding came from thermal infrared multi-band imager MARA on the MASCOT lander carried by Hayabusa2 [17]. MARA has four narrow-band filters (5.5-7, 8-9.5, 9.5-11.5, and 13.5-15.5 µm). Although thermal infrared spectra of carbonaceous chondrites have not been characterized extensively, recent laboratory studies as well as OSIRIS-REx mission results have shown that carbonaceous chondrite samples with high abundance of hydrated minerals have large drop in emissivity from 8-9.5 µm to 9.5-11.5 µm. The MARA data indicate that Ryugu surface exhibits such band-ratio pattern, suggesting that Ryugu materials may have more hydrated minerals than previously thought. This finding turned out to be consistent with the results of the curation measurements of actual returned samples [15]. Such agreement between thermal infrared spectroscopic observations and returned sample analysis supports that thermal infrared spectroscopic observations could be a powerful tool for measuring the hydration state of C-type asteroids.

Third, high-precision observations of the largest and brightest boulder, Otohime Saxon, on the south pole of Ryugu showed that it may have slight but statistically significant depth of absorption band at 0.7 µm, which would occur on iron-rich serpentine [15]. This study further found evidence for 0.7-µm band on smaller boulders on the northern pole. Because 0.7-µm band easily disappears upon space weathering and heating, the presence of this band on a certain type of boulders on Ryugu suggests that at least some materials on Ryugu would have escaped from extensive heating in its parent body or on Ryugu ' s surface. These materials could also be found in Ryugu ' s samples; they could tell us the thermal history of Ryugu materials.

7.1.14 Evolution of phenotypic fluctuation under host-parasite interactions

Different parasite-types attack hosts of certain phenotypes. Through numerical simulations of the evolution of the host genotype-phenotype mapping, we found that hosts increase phenotypic variation by increasing phenotypic fluctuations if the interaction is sufficiently strong [19]. Depending on the degree of noise in gene expression dynamics, there are two distinct strategies for increasing phenotypic variances: stochasticity in gene expression or genetic variances. The former strategy, which can work over a faster time scale, leads to a decline in fitness, whereas the latter reduces the robustness of the fitted state. Our results provide insights into how phenotypic variances are preserved and how hosts can escape being attacked by parasites whose genes mutate to adapt to changes in parasites. These two host strategies, which depend on internal and external conditions, can be verified experimentally via the transcriptome analysis of microorganisms. We investigate how this balance depends on the size of a collective (denoted by N) and the mutation rate of components (m) through mathematical analyses and computer simulations of multiple population genetics models. We first confirm a previous result that increasing N or m accelerates within-collective evolution relative to among-collective evolution, thus promoting the evolution of cheating[22].

7.1.15 A reverse stroke characterizes the force generation of cardiac myofilaments

We measured the force production of cardiac myofilaments using optical tweezers. The measurements revealed that stepwise force generation was associated with a higher frequency of backward steps at lower loads and higher stall forces than those of fast skeletal myofilaments. To understand these unique collective behaviors of cardiac myosin, the dynamic responses of single cardiac and fast skeletal myosin molecules, interacting with actin filaments, were evaluated under load. The cardiac myosin molecules switched among three distinct conformational positions, ranging from pre- to post-power stroke positions, in 1 mM ADP and 0 to 10 mM phosphate solution. In contrast to cardiac myosin, fast skeletal myosin stayed primarily in the post-power stroke position, suggesting that cardiac myosin executes the reverse stroke more frequently than fast skeletal myosin [23]. In cell work, we propose a machine learning approach to categorize the vesicle transport into active transport and random movement, using the features computed from the vector analysis of 3D vesicle transport trajectories. This approach is expected to simplify the process for vesicle transport data analysis [24] [25].

7.1.16 Experimental demonstration of operon formation catalyzed by transposon sequence

Operons are functional units of clustered genes under the control of the same regulatory machinery. These operons are a hallmark of the genomic architecture of prokaryotes, and thus elucidation of operon formation might be important for understanding the regulatory mechanisms of ancient biological systems. However, the mechanism by which two genes placed far apart gradually come close and form operons remains to be elucidated. Here, we propose a new model of the origin of operons: Mobile genetic elements called insertion sequences can facilitate the formation of operons by consecutive insertion-deletion-excision reactions [32]. This mechanism barely leaves traces of insertion sequences and is thus difficult to detect in nature. In this study, as a proof-of-concept, we reproducibly demonstrated operon formation in the laboratory. The insertion sequence IS3 and the insertion sequence excision enhancer are genes found in a broad range of bacterial species. We introduced these genes into insertion sequence-less Escherichia coli and found that supporting our hypothesis, the activity of the two genes altered the expression of genes surrounding IS3 and formed new operons. This study shows how insertion sequences can facilitate the rapid formation of operons through locally increasing the structural mutation rates and highlights how coevolution with mobile elements may shape the organization of prokaryotic genomes and gene regulation.

7.1.17 Development of new imaging technology to measure "living states" of cells.

We have extended the application of our fluorescent probes to visualize cellular states such as transcription and metabolism. We have clarified the timing when transcription of foreign genes starts after transfection [36]. Yaginuma has found the spatial synchronization of metabolic states among adjacent cells [37]. We also developed technologies to quantitatively measure the living state of cells without fluorescent staining. The amount of intracellular biological components (proteins, lipids, nucleic acids, etc.) can be estimated from the phase delay when light passes through a cell. Inuzuka developed a new method to measure phase delay without conventional interferometry. This robust and stable configuration will be beneficial for the application in space exploration, since it is less susceptible to vibration and does not require sophisticated adjustments.

7.1.18 Thermodynamic trade-off relations and relationship to differential geometry

Thermodynamic trade-off relations are universal thermodynamic laws to explain the accuracy and speed of the information processing in biochemical systems. Several thermodynamic trade-off relations, such as thermodynamic uncertainty relations and speed limits, have been found in recent years. Nowadays, a deep understanding of thermodynamic trade-off relations is required based on concrete mathematical theories such as differential geometry. To deepen our understanding of thermodynamic trade-off relations, we generalized thermodynamic trade-off relations in deterministic chemical reaction networks [38] and clarified the relationship to the differential geometric theories such as the optimal transport theory [39, 41] and information geometry [40] in this year. Based on these results, we can geometrically discuss the accuracy of the information processing in biochemical systems.

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III

Reports
on the research activities
of RESCEU groups in 2021
(in Japanese)

2021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

当研究室はビッグバン宇宙国際研究センターを本拠として、一般相対性理論、場の量子論、素粒子物理学等の基礎物理学理論に基づいて宇宙論と重力理論の理論的研究を幅広く行うとともに、理学部物理学教室の教育と研究に参画しています。また、大型低温重力波検出器 KAGRA の本格稼働を迎え、ビッグバン宇宙国際研究センターの Cannon 研究室とともに重力波データ解析の研究と人材育成にも携わっています。横山はアジア太平洋物理学会連合の会長を務めると共に、2021 年 9 月からは KAGRA 科学会議議長を務めています。

8.1.1 宇宙論: 時空構造

超弦理論と α-attractors

α-attractor は現在までの宇宙背景放射観測と矛盾のないインフレーション模型である。比較的簡単なコンパクト化を仮定した超弦理論には、α-attractor が必要とするモジュライ空間の幾何構造を持つスカラー場が 7 つ含まれている。我々は単一場によるインフレーションを実現するために、余剰次元空間中のフラックスによるポテンシャルを用いて余分な 6 つのスカラー場を固定することを考えた [4, 5, 84]。超弦理論の無矛盾条件と整合するフラックスの選び方で 6 つの余分な場に質量を与えられることを示した。また 4 次元有効理論において、固定されたスカラー場は実際に十分重くなることを示し、実行的に単一場インフレーションを実現されうることを明らかにした。超弦理論において α-attractor を完全に実現するには至ってはいないが、この結果はその実現可能性を支持するものになっている。

ローレンツ対称性と超対称性の破れ

超対称模型における加速膨張宇宙の実現には自発的超対称性の破れが不可欠となるが、これまでは超対称性を破る機構として F-項または D-項が真空期待値を獲得すること模型が考えられていた。我々は新しい超対称性の破れの機構としてベクトル場に真空期待値を持たせることで超対称性とローレンツ対称性を同時に破ることを提案した [6, 83]。この機構ではローレンツ対称性の破れと超対称性の破れのスケールの相関により、宇宙論的観測から超対称性の破れのスケールが制限されることが分かり、現在までの観測的制限から超対称粒子の典型的な質量は 100TeV 程度を上限にもつことを示すことができた。この新しい機構は今後の加速器実験のみならず、ローレンツ対称性の破れに対する観測的制限から検証できる興味深いものになっている。

単一場インフレーションが生成する曲率揺らぎの 1 ループ補正

我々は、インフレーションが生成する曲率揺らぎのパワースペクトルの三点相互作用からの 1 ループの量子補正を計算した。この補正はスケール不変なスペクトルのもとでは発散量を与えるが、現実の宇宙のゆらぎのスペクトル指数は 1 より小さく、大波数のゆらぎが抑制されているため、物理的に意味のある大きな有限値を与えることを見いだした。宇宙論的摂動論が適用可能であるためには、ループ補正は最低次量よりも十分小さくなければならないので、このことは非ガウス性の大きさに対して現在の観測的制限より厳しい上限を与えることを示した。[7, 36, 43, 48, 65]。

パルサータイミングアレイ観測の宇宙論的意義

パルサータイミングアレイ観測の一つ NANOGrav チームは先頃、背景重力波に起因するかもしれない有意な信号の存在を報告した。まだ重力波特有の角度相関関数は観測されていないので、決着がつくには暫く時間を要す見込みだが、この観測が示唆する宇宙論的な意義についてさまざまな観点から検討を加えた [8]。

真空相転移のローレンツ経路積分による考察

真空相転移はユークリッド化された時空での経路積分により定式化されてきたが、終状態の曖昧さや重力存在下での負モードの唯一性の破れといった問題がある。そこで本研究では、実時間において真空相転移の確率をローレンツ経路積分で直接定式化し、鞍点法により評価することを試みた。その結果、重力を背景時空として扱った場合、ローレンツ経路積分による解析は、従来のユークリッド経路積分で予言される相転移確率を再現した。さらに、ユークリッド経路積分では評価できなかった、典型的な大きさとは異なる半径を持つ真空泡の生成についても、その生成確率を評価し、その解釈を与えた [28, 45, 44]。

8.1.2 宇宙論: 物質の起源と進化

ヒッグス-R^2 混合模型における再加熱機構

ヒッグス-R^2 混合模型は観測から支持されるインフレーション模型の一つである。さらにこの模型は、

ヒッグスインフレーションにおいて量子補正から R^2 項が現れ、紫外カットオフスケールがプランクスケールに押し上げられることから、その自然な拡張と考えられている。我々のこれまでの研究により、特別なパラメータにおいてはタキオン不安定性により宇宙の再加熱が瞬時に起こることが示されていたが、微調整されない限り多くのパラメータにおいてはその不安定性は不十分であるか全く現れないことがわかっていた。我々は、後者の場合インフラトン場の摂動論的な崩壊によって再加熱過程が進行し、すべてのエネルギーが標準模型粒子に移行されることを示した。主要な崩壊率を評価し、再加熱期の長さと再加熱温度のパラメータ依存性を調べた [9, 25, 31, 41]。

ストークス現象に着目した重力的粒子生成の解析

重力的粒子生成をストークス現象と呼ばれる数学的現象として解析することにより、生成する粒子量を解析的かつ実用的に計算する手法を提唱した。重力的粒子生成は初期時刻と終時刻の真空状態が異なることにより、初期状態では真空状態であっても終状態においては粒子が存在するようになる現象のことである。これは数学的には 2 階微分方程式の 2 つの基本解が混合することを意味し、ストークス現象と呼ばれる現象に相当する。このストークス現象について知られている定理を用いることにより、生成する粒子量を解析的に評価する式を得た [10]。

プレヒーティングの再考

インフレーション後にインフラトン場と結合する粒子が (非) 摂動的な過程により真空から生成される現象 (プレヒーティング) において、二つの特定のパラメータ領域に異なる性質の共鳴現象が知られていた。一つはインフラトン粒子の摂動的な散乱により理解されるが、もう一つの共鳴はインフラトン粒子との散乱という描像では理解できない非摂動的現象であった。一方で真空からの粒子生成現象は数学的にストークス現象として統一的に理解できる。我々はストークス現象の観点からプレヒーティングを再考し、さまざまなパラメータ領域の粒子生成現象が共鳴現象も含めてストークス現象として統一的に記述できることを示した [11, 73, 82]。

初期 $B+L$ 対称性の存在下での右巻きニュートリノの脱結合に伴うレプトン数生成

ある種のバリオン数生成機構においては、バリオン数とレプトン数の差 $(B-L)$ はゼロで、和 $(B+L)$ がゼロでない非対称が生成されるが、この非対称は電弱スファレロンによって消されてしまい、妥当な機構と考えられていなかった。我々は、いくつかの粒子数の保存則が良い近似である高温な時期においては電弱スファレロンによる非対称の消滅が完成せず、完全な消滅は比較的遅い時期に起こることに注目し、右巻きニュートリノの脱結合が $B+L$ の消滅より前に起これば、$B+L$ 対称性を CP の破れの起源として系に $B-L$ 非対称が生じることを発見した [12, 32, 49, 66]。この機構により、SU(5) 大統一理論に基づく模型やアクシオンインフレーションに基づく模型が現在の宇宙を説明しうるバリオン数生成機構として復活することになる。

初期磁場によるバリオン等曲率揺らぎ生成

電弱対称性が破れる以前の初期宇宙における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が局所的な物質反物質非対称を生じるため、一般にバリオン等曲率揺らぎが生成する。これに対して、ビッグバン元素合成の理論と観測された軽元素の存在量との整合性から制限が得られる。結論として、電弱対称性が破れる以前の磁場生成によって観測的に示唆されているボイド空間の銀河間磁場強度を説明することはできないことを示した [13, 30, 34, 68, 70]。

動的なカイラルプラズマ中でのカイラル重力効果

U(1) ゲージ理論におけるカイラル量子異常に由来したカイラル磁気効果は、宇宙論を含む物理学の様々な分野において注目されている。この効果はカイラルなプラズマ中の異常電流を予言し、それが長波長の磁場に不安定性を引き起こすため、例えば宇宙の初期磁場の形成において重要な役割を担った可能性がある。一方で、素粒子標準模型に存在する重力的カイラル量子異常に関連した言わば “カイラル重力効果” も存在し、近年その研究が進められている。先行研究ではプラズマのカイラル非対称性が静的である場合のみが扱われていたが、本研究では宇宙論への応用を見据え、カイラル非対称が動的に変化している状況を有効場理論を用いて計算した。その結果、カイラル非対称性の時間変化によって誘起されたエネルギー・運動量テンソルによって、重力波の複屈折が起こることが分かった。本研究成果は、原始プラズマ中における素粒子の非自明なダイナミクスの痕跡が、重力波の偏光非対称に保存されている可能性を初めて指摘したものである [14, 27, 35, 47, 60, 61, 74, 75, 76, 77, 80, 81]。

初期磁場の時間発展

初期宇宙における磁場のダイナミクスは、磁気流体の一様等方乱流として記述されるものと考えられる。ところが、伝統的な “permanence of large eddies” すなわちエネルギースペクトルの長波長成分は時間発展しないという仮定は、数値計算により誤りであることが示されている。このような不満足な点を修正し、初期磁場の時間発展をより正しく記述する解析的枠組みの完成を目指している [39]。

原始ブラックホール存在量の定式化に起因する不定性

原始ブラックホールの存在量を評価する場合に、どういった定式化を用いるべきかという不定性の問題があることが知られている。我々は、代表的なものとして良く用いられる三種類の評価方法を対象として、採用する定式化が異なることで最終的な原始ブラックホールの存在量が何桁も変化を受けることを再確認し、また原始ブラックホール形成に要求される初期揺らぎの大きさについても、特定の質量帯においては $\mathcal{O}(1)$ 程度の差異が生じてしまうことを明らかにした [38]。また、原始ブラックホールに関する総説を発表した [15]。

条件付き確率を用いた原始ブラックホール存在量の評価

原始ブラックホールの形成に要求される条件にはいくつかの不定性があり、密度揺らぎのピーク条件あるいは適切な半径を持った球内部の圧縮関数を用いた条件が良く採用されている。本研究では、原始ブラックホール存在量をより精密に評価することを目的として、これらの条件を両方とも取り入れる条件付き確率を用いた定式化を提唱した。この結果、最終的な存在量は従来の見積もりと比べて、少なくとも 10 倍以上小さく評価されることが分かった [46, 64]。

アクシオン星の重力マイクロレンズ

アクシオンと呼ばれる非常に軽い擬スカラー粒子は初期宇宙で大量に供給され、暗黒物質の一つの有力な候補となっている。現在の宇宙において、アクシオンは重力の効果によって凝縮し、アクシオン星と呼ばれる非常に重い星を形成する可能性が示唆されている。我々はさまざまな重力マイクロレンズの観測結果を用いて、アクシオン星に対する重力マイクロレンズの制限を、アクシオン星と光源の星の有限サイズ効果を含めた上で導出した [16, 57, 67, 79]。

8.1.3 重力波検出器 KAGRA のデータ解析

環境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。最新の KAGRA データと環境モニターに対して、拡張した線形 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 [17] の除去に成功した [35, 47, 50, 51, 62]。今年度はさらに、非線形雑音を除去する手法の実装に成功した [63]。

超軽量ダークマター探索

ゲージボゾンダークマターは、レーザー干渉計型重力波望遠鏡を構成する懸架鏡に周期的な力を加える。これによって生じる干渉縞の変化を、LIGO や Virgo、KAGRA といった地上の重力波望遠鏡を用いて調べることで、10^{-13} eV 程度の質量を持つ超軽量ゲージボゾンダークマターの高感度な探索が可能となる。特に、サファイア鏡を使っている大型低温重力波望遠鏡 KAGRA では、干渉計の補助チャンネルを利用したユニークな探索が可能であり、10^{-13} eV 程度以下の質量を持つ $B-L$ ゲージボゾンを、これまでの上限値を 1 桁以上上回る感度での探索が可能である。ダークマター探索に向けた解析パイプラインを開発し、2020 年に行われた KAGRA の最初の観測運転からのデータを用いた解析を現在行なっている [22, 29, 42, 62]。

KAGRA 全著者論文, LVK 論文

KAGRA プロジェクトの認定著者として横山、條、上野は全著者論文の著者に名を連ねている [18, 19, 20, 21]。また、LIGO, Virgo と KAGRA は協定を結んでいるため、第三観測期の論文は LVK 論文として KAGRA の認定著者は著者になっている。後者については掲載を省略する。

8.1.4 時間領域天文学

TriCCS カメラによる多バンド高速撮像

近年、可視領域において非常に高い時間分解能での観測が可能な装置が登場している。このような装置による観測には、マルチメッセンジャー天文学の一翼を担うこととともに、短い時間スケールで変動する天体現象に対する理解の進展への寄与が期待される。京都大学せいめい望遠鏡にとりつけられた TriCCS もその一つであり、3 バンドでの同時撮像が秒以下の時間分解能で可能である。2021 年度に本格運用を開始した TriCCS の試験観測に参加し、系外惑星のトランジットをターゲットに毎秒約 10 フレームの観測を g、r、z の 3 バンドで 2 時間同時撮像し、装置の性能評価等を行なった [59]。

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9 Kipp Cannon研究室

9.1 研究活動報告

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

私たちの研究グループのメンバーは LIGO と KAGRA コラボレーションのメンバーであり、世界中の重力波検出器、LIGO (アメリカ)、Virgo (イタリア)、GEO600 (ドイツ)、KAGRA (日本) によって収集されたデータを分析してします。LIGO と Virgo により 2019 年 3 月下旬から 1 年間ほど行われた第 3 次観測「O3」および KAGRA と GEO600 により 2020 年 4 月に 2 週間ほど行われた観測「O3GK」のデータはほぼ解析し終え、多くの科学的成果が得られました [9, 10, 11, 12, 13, 14, 15, 16]。現在は、2022 年 12 月頃から開始される、LIGO, Virgo, KAGRA による第 4 次観測「O4」へ向けて、データ解析の準備を進めています。また、データから得られる科学的成果を最大化するためには様々な理論研究が必要ですが、私たちのグループのメンバーは、重力波を用いた天文学や宇宙論、基礎物理の探索までほぼ全ての分野で活動しています。

9.1.1 重力波データ解析

重力波データ分析ソフトウェアの開発と重力波信号識別精度の向上

ブラックホールと中性子星の衝突によって放出される重力波を検出するためにはデータ分析ソフトウェアが必要である。 そのソフトウェアは、重力波らしき信号をデータから識別し、各イベントに対してそのイベントが本物の重力波信号である確率を決定する。 我々のグループで行っている研究は、各種の重力波源の特徴に基づいて検索を実行し、重力波信号識別の精度を向上させることである。これにより、連星中性子星をターゲットとした検索や強い重力レンズ効果を受けた信号の検索などの感度を向上させることができる。また、今年後半に次の観測を開始する予定の KAGRA 検出器からのデータを分析できるように、データ分析ソフトウェアの準備にも携わっている。

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。

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 [17]。

9.1.2 重力波天文学

電波望遠鏡 CHIME のデータを用いた、ショートガンマ線バーストからの残光探査

ショートガンマ線バースト（short gamma-ray burst、sGRB）は、2 秒以内という短時間で高エネルギーを放出する爆発的突発現象である。sGRB の起源は連星中性子星やブラックホール－中性子星連星といった高密度天体からなる連星の合体であると考えられている。高密度天体連星の合体は重力波源にもなりうるため、sGRB に関連する重力波信号を検出できれば、sGRB の起源に重要な制限を課すことになる。しかし、即時放射が観測された sGRB に関連した重力波信号はこれまでに一つしか観測されていない。本研究では、重力波探査を行う対象である sGRB のサンプル数を増やすために、即時放射よりも指向性の少ない「残光」と呼ばれる淡い光のみが観測できる sGRB（＝即時放射がこちらを向いていなかったり、エネルギーが低く即時放射を検出できない sGRB からの残光、親なし残光）を検出することを試みる。2021 年度は、電波望遠鏡 Canadian Hydrogen Intensity Mapping Experiment (CHIME) によって sGRB からの残光をいくつ観測できるか見積もり、先行研究よりも少ない値となったが「CHIME で sGRB 探査をするのは有効である」と結論づけ、検出可能な残光のほとんどが親なし残光である可能性を示した [18]。次年度からは CHIME のデータを実際に解析し、残光探査を行う。

位置天文観測衛星 Gaia によるブラックホール連星観測に関する理論的予想

位置天文観測衛星 Gaia では、可視光で伴星の動きを観測することによって、見えていないもう一方の星の質量を推定することができると考えられている。Gaia の観測期間は五年以上であるため、数年ほどの軌道周期を持つブラックホール－伴星連星（以下、ブラックホール連星）を検出することも期待されている。Gaia で検出しうるブラックホール連星の軌道周期は、これまでに観測されているブラックホールを含む X 線連星よりも長いため、X 線連星とは異なるブラックホール分布を明らかにしうるとも考えられている。次回のデータ公開が 2022 年 6 月に予定されており、そこには連星の情報も含まれていると考えられているため、Gaia によってブラックホール連星がどれくらい観測されるかを理論的に予想する先行研究がいくつも発表されるなど、非常に注目が集まっている。これまでに、他の星と連星を組む相手を交換しながら進化する「星団起源」のブラックホール連星がいくつ観測できそうか、連星を組む相手以外と相互作用せずに進化する「孤立連星起源」の連星と区別しうるかを議論していた。2021 年度は、超新星モデルや共通外層進化といった連星進化パラメータに対して、ブラックホール連星の検出可能性がどのように依存しているか系統的に調べ、観測によって連星進化パラメータへの制限を課しうることを明らかにした [19]。

将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、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示し、将来に計画されている重力波望遠鏡によって連星合体が起こる前に予報を出せることを示した。

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

重力波による強重力場における一般相対論の検証

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

重力波チェレンコフ放射の探査

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

重力波による宇宙ひもの探査

宇宙ひもは初期宇宙に起こる相転移によって生じると提唱されている一次元の高エネルギーの物体である。宇宙ひもは交差によってループを形成し、重力波を放出する。ループにはカスプ、キンクと呼ばれる特異な構造が存在し、これらの構造から幅広い周波数で重力波が放出される。これらの構造からのバースト重力波放射、および多数のループからの放射が重なった背景放射は、LIGO, Virgo, KAGRA をはじめとする重力波検出器のターゲットの一つと考えられている。我々は O3 の 1 年弱のデータを解析し、理論波形を用いた宇宙ひもからの短時間バースト放射と背景放射の探査を行った。その結果、統計的に有意な宇宙ひも由来の重力波信号は見つからなかった。この未検出から、宇宙ひものエネルギースケールや形状に関するこれまでの観測 (パルサータイミング、宇宙マイクロ波背景放射など) よりも強い制限が得られた [16]。

重力波を用いたハドロン-クォーク相転移の検証

中性子星の内部ではハドロン-クォーク相転移が起こる可能性があるが、この相転移がクロスオーバー的連続なものなのか一次相転移的不連続なものなのかは核物理の一つの問になっている。この 2 つのシナリオの差異は連星中性子星合体から放射される重力波のインスパイラル段階の波形にはほとんど顕れず、合体または合体後の波形において顕著になることが分かっている。一方で、連星中性子星の合体後の重力波の主な周波数帯は 2-4 kHz であり、LIGO 等の現行の検出器の最も感度の良い周波数帯と比べてかなり高い。実際、GW170817 はそれまでに観測された重力波イベントの中で最大の信号雑音比を持つイベントであったが、高周波数域での検出器の感度の問題のために合体後の信号の検出には至らなかった。従って、重力波観測によってこの問いに答えるためには高周波数域でより良い感度をもつ検出器や適切な解析手法の開発が望まれる。現在の、もしくは現在提案されている将来の検出器による観測でこの問題の解決は可能なのか、そのためにはどのようなイベントが適しているのか、またどのような解析手法が有効なのかを明らかにするのが本研究の目標である。

重力波によるアクシオン暗黒物質の探査

我々の宇宙に存在するほとんどの物質は未知の暗黒物質であり、その正体がどのような物であるかについて様々な議論がなされてきた。そのような暗黒物質の候補の 1 つとしてアクシオンが考えられてきた。アクシオンについては興味深い様々な性質が調べられており、例えばアクシオンは雲を形成することが知られている。天の川ハローには暗黒物質が含まれているので、我々は複数のアクシオン雲に囲まれているということになる。さらに、アクシオン雲と重力波との相互作用に関するものは以下である。アクシオン雲中を重力波が通過すると、アクシオンのグラビトンへの崩壊を誘導する。アクシオンから生成された重力波が、元の重力波と重ね合わされることで、元の重力波の一部は遅延・増幅される。つまり、これまで検出されてきた連星合体由来重力波の周辺には、この特徴的な重力波が検出されるはずである。我々はそのような特徴的な重力波を探すことで、結合定数（素粒子論における基本的パラメーター）に対して先行研究より最大で約 10 倍強い制限を課した。一方、理学系研究科物理学専攻の安東研究室で行われているテーブルトップ実験にも理論・データ解析の方面から参加し、共同研究を行っている [24, 25]。

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

将来のスペース重力波検出器である DECIGO はインフレーション起源の原始重力波を検出を主目的

とする日本の将来計画である。しかし、予測される原始重力波の強度には不確定性があるため、DECIGO の目標感度をさらに高め、検出をより確実なものにするのが望ましい。現在の DECIGO の目標感度は、ショットノイズと輻射圧雑音からなる量子雑音で制限されるが、DECIGO の主共振器は 1000 km と長く、回折による光学的ロスが大きいため、主共振器中で光スクイージングを利用することができない。そこで、主共振器の外側にロスの小さい補助共振器を組み制御する量子ロッキングという方法が有効である。量子ロッキングでは、外側の補助共振器で取得した信号を適切に選んだ振幅と位相で主共振器にフィードバックすることにより主共振器の輻射圧雑音を減らすことができる。我々はさらに輻射圧雑音を低減し、周波数広帯域化を図るため、補助共振器に光ばねを組み込んだ量子ロッキングの検討を行った。その結果、従来の方法に比べてさらなる感度の向上が可能であることを示した [22]。

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10　茂山俊和研究室

10.1　研究活動報告

私たちの研究室では、突発的に明るくなる天体現象の理論モデルを構築することで、その天体の宇宙史における役割を理解する研究をしています。具体的には超新星爆発や様々な星の合体現象を研究対象にしています。以下では、2021 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　大質量星との連星系として誕生した第一世代の軽い星の表面組成

大質量星との連星系として誕生した第一世代の軽い星 (Pop III 星) は大質量星が超新星爆発を起こすとその重元素を多く含んだ層を取り込むことで表面組成を変化させる。この星の表面組成の変化を 3 次元数値流体計算によって定量的に調べ、現在銀河ハローで観測されている古い星の表面元素組成と比較し、そのような Pop III 星の存在する可能性を検討した。[2]

10.1.2　重力崩壊型超新星直後の中性子星磁場の活動性

重力崩壊型超新星では、爆発波が分厚い外層を加速する反作用として、一部の物質が減速され、中心にある中性子星の重力圏に捉えられて降り積もる。一方で、中性子星の回転磁場の活動性によって、外向きの力も働く。この二つの効果のせめぎ合いを球対称を仮定して数値流体力学計算コードを用いて調べた。[3]

10.1.3　大質量星からの突発的な質量放出

重力崩壊型超新星を起こす大質量星の中には、その数年前に突発的に増光し、外層を大量に放出するものがあると考えられている。私たちは、その現象論的なモデルを構築し、超新星爆発直前に観測された増光現象と比較することでどの程度の質量が放出されたのかを推測するとともに、放出された物質の密度構造や星の構造の変化を調べてきた。今年度はこの現象の物理的原因を追求するために、球殻状の薄い領域で起きる核燃焼の安定性について調べている。[4]

10.1.4　星周物質と爆発物質の衝突で光る天体

IIn 型超新星光度曲線モデル

星周物質が超新星爆発の数年前に突発的に放出され、超新星爆発で放出された物質と衝突することで光る一連の過程を計算するコードを構築し CHIPS と名づけて公開した。計算コードの詳細を記述した論文を The Astophysical Journal に発表した。このコードを用いて、赤色超巨星の水素外層に注入するエネルギーと注入時間がどのような関係を満たすと星周物質が形成されるかを調べ、The Astrophysical Journal に発表した。[5, 6, 10, 16, 20, 23, 24]

IIn 型超新星多波長光度進化モデル

星周物質と超新星爆発で放出された物質との衝突で生じた衝撃波からの放射を可視光から X 線に至る多波長で計算するモデルを構築した。[1, 26, 27]

白色矮星合体の結果

酸素とネオンからなる白色矮星と炭素と酸素からなる少し軽い白色矮星が合体した結果できたと思われる天体から強い星風が吹いていることが発見され、その観測を説明するモデルを樫山和巳、藤澤幸太郎、両氏と 2019 年に構築した。最近、その天体の星風を取り巻くような広い領域と中心の点状の領域から X 線が観測された。また、吾妻鏡に記録が残っている 1181 年に爆発した超新星とこの天体が結び付けられるという指摘がなされた。私たちは、広い領域からの X 線はこの超新星が星間物質と衝突して生じた衝撃波によって放射され、点状の X 線は星風が超新星に内側からぶつかって生じた衝撃波からの放射と解釈して、モデルを構築している。X 線の解析は馬場研の方々が行ない、その結果を再現する定量的なモデルを作ることが当面の目標。[11, 14, 17, 18]

非常に明るく光り変化の速い天体とブラックホール形成

近年の高頻度探索観測によって、まれに短い期間のみ明るく光る天体も新たに発見されるようになった。ブラックホールは大質量星から形成される。大質量星の中には鉄の中心核の崩壊の直前に外層の一部を放出する活動を見せるものがあるので、この放出された物質にブラックホール形成時に放出される物質が衝突することで明るくなるモデルをこのような天体に適用して、ブラックホール形成との関連性を調べている。[12, 19, 21, 28, 29]

10.1.5 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。[15]

定常流による解析

中性子星に降着する球対称な定常遷音速流を計算し、C+C→Mg などの核融合反応によるエネルギー供給の影響を調べている。この流れは、周囲のガスの化学組成と比エンタルピーと降着率で規定される。C と O が質量比で半々の蘇生の時に与えられた比エンタルピーに対して降着率がある値より大きい時に降着流が中性子星表面に到達しなくなる現象を見出した。系統的な計算を行い、臨界降着率が中性子星質量と周囲の物質の比エンタルピーにどのように依存するか調べた。[15]

10.1.6 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 [7]。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 [8, 9, 13, 22, 25]。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)

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＜**学術講演**＞

(国内会議)

日本天文学会 2022 年春季年会、広島大学、2022/3/2-5

[10] 黄 天鋭 , 津名 大地, 武井 勇樹, 茂山 俊和, " 大質量星の大規模質量放出現象の輻射流体シミュレーション: 親星外層への エネルギー注入の依存性"、2022 年 3 月 4 日、N22a

[11] 黄天鋭, 藤澤幸太郎, 茂山俊和, " 回転しながら中心天体から放出される流体の自己相似解と連星合体時の放出 物質への応用"、2022 年 3 月 2 日、W26b

[12] 津名大地, 樫山和己, 茂山俊和, "突発天体 AT2018lqh のブラックホール形成モデル", 2022 年 3 月 2 日、W07a

日本天文学会 2021 年秋季年会、京都産業大学、2021/9/13-15

[13] 藤澤幸太郎、木坂将大、小嶌康史" 強い多重極磁場を伴った中性子星表面の磁気山の構造"、2021 年 9 月 15 日、W61a

[14] Narenraju Nagarajan, Kazumi Kashiyama, Kotaro Fujisawa, Toshikazu Shigeyama, "Systematic search of optically thick magnetic rotating wind solutions for double white dwarf merger remnants : sub-Chandrasekhar mass case"、2021 年 9 月 14 日、W42c

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[17] 黄天鋭, 藤澤幸太郎, 茂山俊和, "磁気回転風に関する自己相似解", 2021 年 9 月 14 日、W34a

一般講演

[18] 黄天鋭, 藤澤幸太郎, 茂山俊和, " 回転しながら中心天体から放出される流体の自己相似解と連星合体時の放出物質への応用 " , 2022/1/29, 連星・変光星研究会 2022, 鹿児島大学

[19] 津名大地, 樫山和己, 茂山俊和 "ブラックホール形成に付随する突発天体", 2021/12/22, 第 34 回理論懇シンポジウム, Online

[20] 武井勇樹、津名大地、栗山直人、黄天鋭、茂山俊和、" CHIPS: an open-source code for modeling supernovae interacting with a massive circumstellar medium ", 2021/11/19, SuperVirtual 2021, Online

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[22] 藤澤幸太郎、"Magnetically confined mountain on the neutron star surface", 2021/02/22, 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

(セミナー)

[23] 黄 天鋭, 津名 大地, 武井 勇樹, 茂山 俊和, " 大質量星の大規模質量放出現象の輻射流体シミュレーション " , 2022/1/20, 山形大学理学部宇宙理論研究室談話会, オンライン

[24] 武井勇樹、津名大地、栗山直人、黄天鋭、茂山俊和、" 大質量星の爆発間際の大規模な質量放出とその後の超新星の研究 " , 2022/1/20, 山形大学理学部宇宙理論研究室談話会, 山形大学

[25] 藤澤幸太郎、"Structures of magnetically confined mountains on neutron stars", 2021/10/20, gw-genesis zoom seminar talk、Online

[26] 津名大地, , 樫山和己, 茂山俊和 "Multi-wavelength Emissions from Supernovae with Circumstellar Interaction"、2021/10/1, Stockholm University Astronomy Department Seminar, Online

[27] 津名大地, , 樫山和己, 茂山俊和 "Multi-wavelength Emissions from Supernovae with Circumstellar Interaction", 2021/9/22, Penn State University HEPAP/CMA Seminar, Online

[28] 津名大地, , 樫山和己, 茂山俊和"Observing the Traces of Black Hole Formation", 2021/9/4, Ohio State University CCAPP Astroparticle Lunch Seminar, Online

[29] 津名大地, , 樫山和己, 茂山俊和"Peculiar Optical Transients from Newborn Black Holes?", 2021/6/29, Albert Einstein Institute at Potsdam Seminar, Online

11 仏坂健太研究室

11.1 研究活動報告

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

11.1.1 連星中性子星の電磁波対応天体

キロノバの研究

キロノバは連星中性子星合体に付随する電磁波対応天体の一つであり、合体時に放出された中性子過剰物質の放射性崩壊によって輝く現象である。この現象は特に重元素の起源に関連するという重要性がある。我々はキロノバに関する観測・理論の両目から研究を行った。[1, 14, 2]。

キロノバ の研究の中でも特に中性子星合体エジェクタが光学的に薄くなった星雲期の放射は自由電子によって励起された重元素からの放射脱励起の光を直接観測することができるため、中性子星合体に伴って生成され元素を特定するために極めて有用であると考えられている。しかし、理論的にも先行研究が全く存在しないテーマである。その理由は、星雲期の放射の計算に必要な原子データが欠落しているためである。そこで、我々は第一ステップとして、ネオジム原子に注目して、星雲期の計算に必要な原子データを原子コード GRASP2K および Hullac を用いて揃えた。作成した原子データを用いて、キロノバ 星雲期がどのような物理状態をたどるべきか、また放射スペクトルはどのような性質を持つかを明らかにした [1]。また GW170817 における Spitzer 衛星によるキロノバ 星雲期の観測データの解釈を行った [14]。

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 [3, 4, 5, 11]。

GW170817 の残光は基本的には構造を持った相対論的ジェットで説明できるが、合体後の 3 年後に X 線超過があるという示唆があった。論文 [3] では合体後 3.5 年での電波放射を Very Large Array による観測によって調べた。その結果、電波放射は超過を示さずジェット残光でよく説明できることを示した。このことは X 線超過がもし本当ならばフォールバック円盤など X 線特有の残光とは異なる放射の存在を示唆している。

11.1.2 連星ブラックホール合体の研究

LIGO/Virgo はこれまで 100 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。

我々は、球状星団の中で起こる力学的捕獲シナリオに注目し、特に中性子星やブラックホールが球状星団の中で複数回合体することが可能かどうか調べた [6]。この結果、30 太陽質量ほどの質量の大きなブラックホールは長い時間球状星団の中にとどまることができるので複数回合体が可能であることがわかった。一方で、中性子星は複数回合体を経験できないことがわかった。このことは、例えば、軽い質量ギャップを含むコンパクト連星合体は、球状星団の中で中性子星が複数回合体することによっては形成できないことを示した。

11.1.3 電波突発天体の研究

大型干渉計による電波サーベイの高速および角度分解能の向上により、電波突発天体をサーチできる時代が到来した。我々は、VLA All Sky Survey で発見された電波突発天体の中でも特に明るいものに注目し、フォローアップ観測を行った [7]。今回、フォローアップ観測の対象とした天体の中でも特に一つは X 線の MAXI 未同定天体が発見の 3 年前に同じ場所で発生しており、X 線バーストが付随した新種の天体である可能性を示した。この同定が実際に電波突発天体に付随したものであれば、X 線バーストはガンマ線バーストよりはエネルギーが低いが、その発生頻度はより高く一般的な天体であることを予想した。

11.1.4 銀河に存在する恒星質量ブラックホール・中性子星

我々は銀河に大量に存在すると考えられる孤立した中性子星 [12] やブラックホール [10] の観測可能性を検討した。前者は超新星の名残の熱で輝きながら速い速度動いている特徴を使って通常の天体と見分け、後者は星間物質を降着することで円盤が光という性質を使うという手法を提案した。

11.1.5 その他

銀河の重元素の化学進化に関する研究を行った [8, 9]。また豊内研究員は仏坂とは独立に銀河の中心に存在する大質量ブラックホールの成長に関する研究を行った [13]。Irwin 研究員は大質量星からの衝撃波ブレイクアウトが非等方に起こった場合の衝撃波の時間発展と放射に現れる性質の研究を行った [19]。

11.2 業績リスト

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[3] A. Balasubramanian, *et al.*, "Continued Radio Observations of GW170817 3.5 yr Post-merger", Astrophys. J. Letters **914**, L20 (2021).

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[13] K. Inayoshi, *et al.*, "Rapid Growth of Seed Black Holes during Early Bulge Formation", Astrophys. J. **927**, 21 (2022).

[14] M. M. Kasliwal, *et al.*, "Spitzer mid-infrared detections of neutron star merger GW170817 suggests synthesis of the heaviest elements", Monthly Notices of the Royal Astronomical Society Letters, **510**, L7 (2022).

(会議抄録)

(国内雑誌)

(学位論文)

(著書)

[15] パリティ編集委員会編, 物理学, この１年, 2022, 丸善出版, 2022/1

＜学術講演＞

(国際会議)

一般講演

[16] Daisuke Toyouchi, "Formation of intermediate-mass BHs in metal-free clouds experiencing violent dynamical heating" 2021/10/13, East-Asia AGN workshop, China (+online)

招待講演

[17] "Models for the kilonova", GWUniverse Inauguration Workshop: Cosmology with gravitational waves, online, 2021/10/8

[18] Kenta Hotokezaka, "Remnants and jets of neutron star merger", Gravitational-Wave Physics and Astronomy Workshop, Hybrid, Hannover Germany, 2021/12/14-17.

[19] Christopher M. Irwin, "Aspherical Shock Breakout: Observational Signatures", HEAD 19 meeting, Pittsburgh, 2022/3/17

(国内会議)

一般講演

[20] 豊内大輔, "原始銀河内における超大質量星および中間質量ブラックホールの形成", 天文年会秋季年会, online, 2021/9/15

[21] 豊内大輔, "Formation of massive PopIII stars in metal-free clouds experiencing violent dynamical heating" 2021/9/29, 金属欠乏宇宙研究会, online

[22] 豊内大輔, "大質量初代星形成および種ブラックホール質量成長過程における輻射フィードバックの影響" 2021/12/8, 低金属量星・惑星形成研究会, online

[23] 豊内大輔, "Top-heavy IMF in galactic nuclei inferred from the universally high [Fe/Mg] abundance ratio" 2022/2/8, Galaxy evolution workshop, NAOJ (+online)

[24] 豊内大輔, "原始銀河中の種ブラックホール形成および急速成長" 2022/2/17, 初代星研究会, 東京

招待講演

[25] 豊内大輔, "原始銀河中の種ブラックホール形成および急速成長" 2021/12/28, 超巨大 BH 研究会, online

[26] 仏坂健太、"重力波天文学の進展"、初代星研究会、京都大学東京分室、2022/2/15-18.

[27] 仏坂健太、"コンパクト天体"、光赤天連シンポジウム：2030 年代の戦略的中型をどうするのか、Online、2022/2/21.

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[28] 仏坂健太, " 中性子星合体", 談話会, 東北大学, 2021/10/25.

[29] Kenta Hotokezaka, " Role of radioactivity in kilonovae", Astrophysics colloquium, Hebrew University of Jerusalem, 2021/11/2.

[30] Kenta Hotokezaka, " Radio counterparts to neutron star mergers and radio transients", Astrophysics seminar, Albert Einstein Institute, 2021/11/16.

[31] Kenta Hotokezaka, " Astrophysics of compact binary mergers", Astrophysics seminar, IPMU, 2021/12/21.