Report from RESCEU
2012-2019

Prepared for the External Review in February 2020

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

November 30, 2019

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RESCEU

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
Research Center for the Early Universe

Preface

This report is prepared for the external visiting committee review in February 2020, and summarizes the scientific activities of RESCEU (Research Center for the Early Universe) at the University of Tokyo from 2012 through 2019. Chapter 1 provides an overview of RESCEU. RESCEU has three major scientific projects; Project 1, Project 2 and Project 3. They are described in chapters 2, 3 and 4, respectively. Chapter 5 gives personal achievements of three RESCEU core members.

November 30, 2019
Yasushi Suto
The Director of RESCEU

Chapter 1

RESCEU Overview

1.1 Introduction

The Research Center for the Early Universe (RESCEU) at The University of Tokyo's School of Science was founded in April, 1999, by ordinance of the Ministry of Education, Culture, Sports, Science and Technology (MEXT). The research center is the successor of the center with the same name, founded in 1995, based on the MEXT program "Basic Research for COE (Center of Excellence) Development"

The research center began with a professor, an associate professor, and two assistant professors, and now has gown to two professors, two associate professors, and four assistant professors, as well as several research associates, many postdocs and graduate students. Moreover, with the participation of researchers from the Departments of Physics, Astronomy, and Earth and Planetary Science as RESCEU collaborators, we serve as a hub for research in astrophysics in the School of Science. Astrophysics is a rapidly developing area in basic science. In response to the progress, we are organized into three main research themes to explore new horizons of our knowledge and continue to achieve many state-of-the-art research accomplishments.

The birth and evolution of the Universe is an important problem at the heart of research in astrophysics, and has been a research theme of RESCEU from its beginning. We propose theoretical models of the birth and origin of the Universe by combining the latest research results in particle physics and gravitational theory. We also perform multi-wavelength cosmological observations. Moreover, we explore the evolution of structures in the Universe using numerical simulations, taking the observational results as initial conditions.

The direct detection of gravitational waves by LIGO in the USA in 2015 was a breakthrough in the history of physics. It immediately gave birth to the research area of gravitational astrophysics, which is now developing rapidly. The research group at RESCEU made essential contributions to the detection of gravitational waves from black holes and neutron stars in collaboration with gravitational-wave research groups around the world. We expect to play important roles in the data analysis and interpretation for the forthcoming KAGRA experiment in Japan.

Extrasolar planets, or exoplanets, first found in the 1990s are now established as a new area in astronomy. This field includes research into the origin of the solar system, the co-evolution of the stars and planets, as well as astrobiology. RESCEU leads the project to observe exoplanets using the Subaru telescope. A wide range of other research is conducted at RESCEU, such as the radio observation of protoplanetary discs, precise analysis of light curve data of exoplanetary systems, and the exploration of the origin of the solar system with space missions.

Evolution of the universe and cosmic structures, gravitational-wave astrophysics and experimental gravity, and formation and characterization of planetary systems: through these three main projects of RESCEU, we engage in research with a comprehensive point of view in collaboration with those not only in The University of Tokyo but also many other institutes in Japan and around the world.

1.2 Organization

1.2.1 Organization Structure

Figure 1.1 illustrates the structure of RESCEU, as a member of the Graduate School of Science.

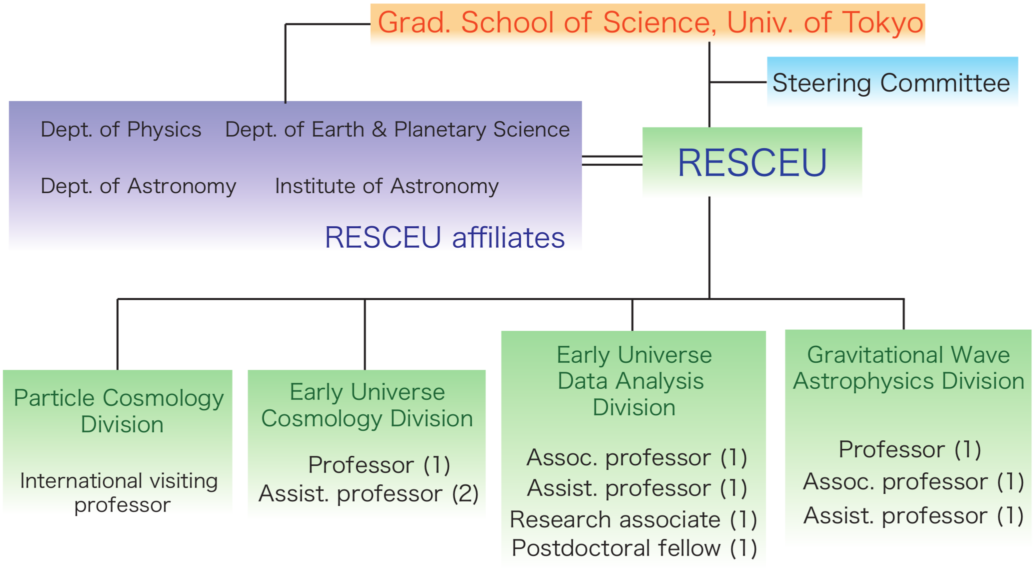

Figure 1.1: The RESCEU organization structure.

1.2.2 RESCEU Members

In Table 1.1, the RESCEU members are given as a function of year. In addition to those shown here, RESCEU is comprised of three secretaries (Ms. Sayuri NAGANO, Ms. Chiyo UEDA and Ms. Reiko SUGIYAMA), and about 20 graduate students in the Department of Physics and the Department of Astronomy.

Table 1.1: RESCEU members. Visiting professors and research fellows are listed separately.

	Director	Professor	Assoc. Prof.	Assist. Prof.	Proj. Assist. Prof.	Postdoctoral Fellow
FY2012	K. Makishima (joint)	J. Yokoyama	T. Shigeyama	T. Suyama J.S. Hiraga A. Taruya N. Sakai	Y. Ito	R. Tsutsui S. Kuroyanagi Y. Watanebe T. Narikawa L. Matthew
FY2013	K. Makishima (joint)	J. Yokoyama	T. Shigeyama	T. Suyama J.S. Hiraga T. Hosokawa	Y. Ito	R. Tsutsui D. Yamauchi Y. Watanabe L. Gu
FY2014	K. Makishima (joint)	J. Yokoyama	T. Shigeyama	T. Suyama J.S. Hiraga M. Oguri T. Hosokawa	Y. Ito T. Suda	D. Yamauchi Y. Watanabe Y. Komiya L. Gu J. White
FY2015	Y. Suto (joint)	J. Yokoyama	T. Shigeyama	T. Suyama M. Oguri T. Hosokawa	Y. Ito T. Suda	T. Nakano D. Yamauchi Y. Komiya
FY2016	Y. Suto (joint)	J. Yokoyama	T. Shigeyama K.Cannon	T. Suyama Y. Ito M. Oguri T. Hosokawa	X. Gao T. Suda	Y. Sakakihara Y.P. Wu Y. Komiya
FY2017	Y. Suto (joint)	J. Yokoyama	T. Shigeyama K. Cannon	T. Suyama Y. Ito M. Oguri K. Kashiyama	T. Suda T. Sekiguchi	A. Ishii Y.P. Wu Y. Komiya
FY2018	Y. Suto (joint)	J. Yokoyama	T. Shigeyama K. Cannon	K. Kamada A. Nishizawa M. Oguri K. Kashiyama	T. Suda T. Sekiguchi Y. Niino	K. Kanagawa A. Ishii Y.P. Wu F. Fong K. Ueno
FY2019	Y. Suto (joint)	J. Yokoyama K. Cannon	T. Shigeyama K. Hotokezaka	K. Kamada A. Nishizawa M. Oguri K. Kashiyama	H. Nishino T. Sekiguchi Y. Niino K. Fujisawa Y. Chinone	K. Kanagawa A. Ishii Y.P. Wu Y. Yamada T. Matsumoto F. Fong K. Ueno

1.2.3 International Visiting Professors and Research Fellows

One of the outstanding features of RESCEU is that it has a position (with a built-in budget) for international visiting professor and research fellow. We can hence invite active overseas researchers to stay at RESCEU and get payed, typical for lengths of 1 through 3 months. Below is the list of these visiting members over the last 8 years. Some of them have repeatedly accepted our invitation, and contributed very much to the RESCEU activity.

Table 1.2: List of international visiting professors and research fellows since 2012.

FY2012	6/25–7/26	Shirley Ho	Carnegie Mellon University, Assistant Professor
	9/18–11/29	Jerome Martin	CNRS (France), Director of Research
	11/1–12/14	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
FY2013	10/1–10/31	Francis Bernardeau	Institut de Physique Théorique de Saclay, Researcher
	10/10–11/29	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
FY2014	11/1–11/30	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
	2/25–3/26	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
FY2015	4/2–4/7	Pisin Chen	National Taiwan University, Professor
	4/13–4/30	Pisin Chen	National Taiwan University, Professor
	4/10–10/31	Thierry Sousbie	Institut d'Astrophysique de Paris, Researcher
	6/28–7/13	Giuseppe Bono	University of Rome Tor Vergata, Associate Professor
	11/4–12/3	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
	2/21–3/5	Chad Hanna	Penn State University, Assistant Professor
FY2016	9/19–11/18	Michael Richmond	Rochester Institute of Technology, Professor
	2/1–2/28	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
FY2017	12/6–12/26	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
	2/10–3/13	Bernard Carr	Queen Mary University of London, Professor
FY2018	10/31–11/21	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
	2/24–3/15	Bernard Carr	Queen Mary University of London, Professor
FY2019	11/18–12/4	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist

1.2.4 RESCEU Affiliates

In addition to the visiting professorship described above, another special and important aspect of RESCEU is the concept of *RESCEU affiliates* illustrated in Fig. 1.2. In addition to the RESCEU members described in § 1.2.2, this program is comprised of about 15 professors, who are mainly affiliated with the Department of Physics, the Department of Astronomy, the Institute of Astronomy, and the department of Earth and Planetary Science. This scheme reinforces the activity of RESCEU, which by itself is a small organization. It will also provide a pilot study for future university restructuring, when we will be even more limited by human and financial resources. This booklet does not provide personal data of the RESCEU affiliates, since their information is already given by their respective Departments.

Under close collaboration with RESCEU members (§ 1.2.2), RESCEU affiliates carry out research as detailed in § 1.3. To accomplish this mission, the RESCEU affiliates are allowed to use part of the RESCEU budget (§ 1.5). The RESCEU affiliates are selected under simple internal rules based on discussion in the *RESCEU meeting*, and are approved by the *steering committee* described in § 1.2.5.

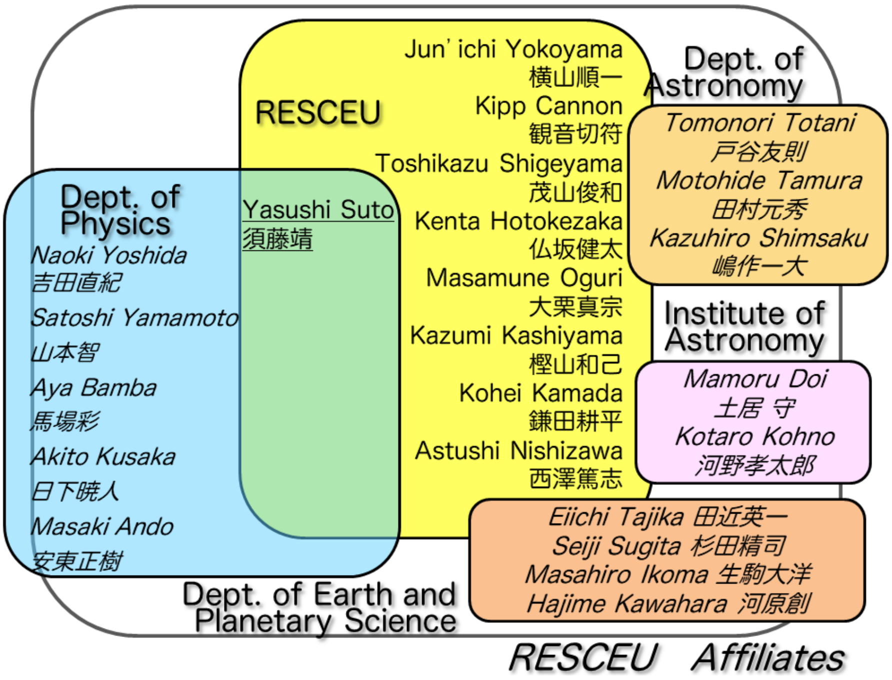

Figure 1.2: RESCEU Affiliates are indicated in *italic*.

1.2.5 Steering Committee

The highest-level decision of RESCEU is done by its *steering committee*, consisting of about 7 members from both inside and outside the Graduate School of Science. The committee approves the use of RESCEU budget, as well as personnel affairs including appointments/unappointments of RESCEU affiliates. The committee also advises as to future plans and directions of RESCEU. The current committee members are given in Table 1.3.

Table 1.3: The RESCEU steering committee as of FY2019.

Name	Title / Position
Hiroyuki TAKEDA 武田洋幸	Dean, Graduate School of Science 東京大学 理学系研究科長・教授
Takaaki KAJITA 梶田隆章	Director, Institute for Cosmic Ray Research 東京大学 宇宙線研究所長・教授
Hideo HIGUCHI 樋口秀男	Professor, Department of Physics 理学系研究科 物理学専攻 教授
Mamoru DOI 土居 守	Director, Institute of Astronomy 理学系研究科 天文学教育研究センター長 ・教授
Motohide TAMURA 田村元秀	Professor, Department of Astronomy 理学系研究科 天文学専攻 教授
Yasushi SUTO 須藤 靖	Director, RESCEU ビッグバン宇宙国際研究センター長 (兼) 理学系研究科 物理学専攻 教授
Jun'ichi YOKOYAMA 横山順一	Professor, RESCEU ビッグバン宇宙国際研究センター 教授

1.3 RESCEU Projects

RESCEU carries out its mission in a number of *projects*. RESCEU was founded in 1999 as an institute belonging to Faculty of Science, the University of Tokyo, led by the first director, Katsuhiko Sato of Physics Department. There had been 7-8 projects, and in 2016 we reorganized the research projects in RESCEU. Now we have three major projects including (1) Evolution of the universe and cosmic structures (led by Jun'ichi Yokoyama), (2) Gravitational-wave astrophysics and experimental gravity (led by Kipp Cannon), and (3) Formation and characterization of planetary systems (led by Yasushi Suto). Those projects have been supported by a variety of collaboration among our research affiliates in the Departments of Physics, Astronomy, and Earth and Planetary Sciences. Their detailed description is given in this booklet.

	2012	2013	2014	2015		2016	2017	2018	2019
Proj. 1	Very Early Universe and Large-scale Structure				Proj. 1	Evolution of the universe and cosmic structures			
Proj. 2	Theory of Galaxy Evolution								
Proj. 3	Formation and Evolution of Galaxies and Clusters of Galaxies								
Proj. 4	Chemical Evolution from Protostellar Cores to Protoplanetary Disks				Proj. 2	Gravitational-wave astrophysics and experimental gravity			
	Formation and Evolution of Massive Galaxies and Super Massive Blackholes								
Proj. 5	Search for Gravitational Waves								
Proj. 6	Direct Search for Dark Matter and Solar Axion				Proj. 3	Formation and characterization of planetary system			
Proj. 7	Cosmic X-ray and Gamma-ray Studies with Scientific Satellites								
	Balloon observations of cosmic anti-protons*								
Proj. 8		Study of Extra-Solar Planets							

*: This sub-project terminated at the end of FY2012.

Figure 1.3: History of the RESCEU projects.

1.4 RESCEU Activity

1.4.1 International Symposia

Table 1.4: Numbered RESCEU international symposia since 2012.

8th	RESCEU/JGRG22 Symposium on General Relativity and Gravitation (12–16 November, 2012)
9th	9th RESCEU International Symposium: Gravitational-Wave Astrophysics in the High Event Rate Regime (5–6 December, 2016)
10th	10th RESCEU/Planet2 Symposium: Planet Formation around Snowline (28–30 November, 2017)
11th	Gravitational-Wave Physics and Astronomy Workshop: GWPAW 2019 (14–17 October, 2019)
12th	12th RESCEU/ 3rd Planet^2 Symposium: From Protoplanetary Disks through Planetary System Architecture to Planetary Atmospheres and Habitability (14–18 October, 2019)

Table 1.5: Other international conferences since 2012.

·	RIKEN-RESCEU-IPMU Joint Meeting 2015 (3–4 March, 2015)
·	RESCEU Workshop: Max's 4 questions in X-ray astronomy to be addressed with ASTRO-H (31 July, 2015)
·	JSPS Core-to-Core Program Planet^2 Symposium 2017: Origin and diversity of planetary systems from the microscope to the telescope (20–23 February, 2017)
·	Space Gravitational-Wave Detection (27–29 March, 2019)

Translated literally, the name of RESCEU in Japanese, ビッグバン宇宙国際研究センター、means *International Research Center for Big-Bang Universe.* As represented by this name, RESCEU is a highly international organization, hosting over the past 8 years many foreign short-term visitors (besides those listed in Table 1.2). This characteristic is also featured by the series of RESCEU international symposia, listed in Table 1.4, and the other international conferences, listed in Table 1.5. Each numbered symposium was attended by 100–200 participants, including a considerable fraction from abroad.

1.4.2 RESCEU Summer Schools

RESCEU is a research, rather than an educational, organization. Nevertheless, the forefront research activity conducted in RESCEU, together with many foreign visitors and guests, endows RESCEU with an ideal environment for graduate education. This is the reason why RESCEU has about 20 graduate students, each pursuing a graduate course in either physics or astronomy. As a highlight of such educational effort, we annually hold a *RESCEU summer school*, often inviting foreign researchers (including the visiting professors) as lecturers. To realize retreat-type environments, the summer schools are held, as shown in Table 1.6, in places away from the busiest city areas.

Table 1.6: Dates, places of and titles of RESCEU summer schools. The numbers indicate numbers of participants.

2012	7/24-7/27	Urabandai	∼30	12th"Dark Energy in the Universe" Summer School
2013	7/24-7/27	Zao	∼40	13th"Dark Energy in the Universe" Summer School
2014	7/31-8/4	Asama	∼80	RESCEU APCosPA Summer School
2015	8/1-8/4	Kinugawa	∼40	RESCEU APCosPA Summer School
2016	8/24-8/28	Hida	∼90	APCosPA-Planet^2 RESCEU Summer School
2017	7/25-7/29	Yamaguchi	∼50	RESCEU Summer School
2018	7/27-7/30	Hakodate	∼50	RESCEU Summer School
2019	8/23-8/26	Kakunodate	∼50	Planet^2/RESCEU Summer School:From the Solar System to the Universe

1.4.3 Outreach Activities

Our research fields, including cosmology, astronomy, and space researches, provide one of the most appealing themes to general public. Being aware of this fact, RESCEU puts great emphasis on outreach activities, mainly in the form of public pictures. As summarized in Table 1.7, we have been conducting the following regular outreach efforts.

1. オープンキャンパス (Open Campus): Usually held in summer, the graduate School of Science always attracts some 4,000 comers who are mostly high school students. We usually provide three lectures, which are so popular that the lecture hall is always standing room only.
2. 公開講演 (Public lecture): We prove one or two lectures. It is aimed mainly for undergraduate students, graduate students, and researches in different research fields. Sometimes we invited guest lectures.

When multiple lectures are presented, we usually plan so that one is from pure theoretical works, another from observational astronomy, and the other from experimental physics. Lecturers are selected from both RESCEU members and RESCEU affiliates.

Table 1.7: Public lectures sponsored by RESCEU.

FY2012	7/7	13th 公開講演	K. Makishima	「天の川にひそむ多くの謎」
	8/7	14th オープンキャンパス	Y. Itoh	「アインシュタインの重力波で宇宙を聴く日」
			T. Shigeyama	「年老いた星が語る銀河の歴史」
			A. Yamamoto$^{\#}$	「南極気球で探る宇宙からの反物質」
	11/19	15th 公開講演	B.P. Schmidt*	「The Accelerating Universe 加速する宇宙」
	12/25	16th 公開講演	T. Suyama	「どんどん広がる宇宙とその仲間たち」
			R. Tsutsui	「星たちが奏でる物語」
FY2013	8/7-8/8	17th オープンキャンパス	J. Yokoyama	「輪廻転生する宇宙」
			M. Ando$^{\#}$	「重力波望遠鏡「かぐら」で探る宇宙」
FY2014	8/6-8/7	18th オープンキャンパス	M. Oguri	「すばる望遠鏡で「見る」暗黒宇宙」
			T. Nakazawa$^{\#}$	「宇宙 X 線衛星「すざく」で見るブラックホールと銀河団」
			T. Hosokawa	「宇宙最初の星の誕生」
FY2015	8/5-8/6	19th オープンキャンパス	T. Shigeyama	「天体の衝突・合体」
			M. Ikoma$^{\#}$	「系外惑星から学んだ太陽系の不思議」
			Y. Ito	「アインシュタインの重力波を捉える：100 年越しの課題提出?」
	11/21	20th 公開講演	J. Yokoyama	「重力波で宇宙を見る」
			M. Ando$^{\#}$	「いよいよ動き出す重力波検出器 KAGRA」
	2/27	21st 公開講演	G. Smoot*	Special Lecture
FY2016	8/2-8/3	22nd オープンキャンパス	J. Yokoyama	「重力波で探る宇宙の始まり」
			K. Cannon	“The first detection of gravitational waves”
			Y. Suto	「太陽系外惑星の世界」
FY2017	8/2-8/3	23rd オープンキャンパス	M. Tamura$^{\#}$	第二の地球に生命を探せ：天文学からアストロバイオロジーへ
			K. Kashiyama	「星の爆発、千紫万紅」
			M. Ando$^{\#}$	「重力波・ブラックホール・宇宙のはじまり」
	12/18	24th 公開講演	J. Yokoyama	「2017 年度ノーベル物理学賞について」
			K. Cannon	“The discovery of gravitational waves by LIGO”
FY2018	8/1-8/2	25th オープンキャンパス	T. Shigeyama	「遥か遠くで起こった天体現象を理解するには」
			A. Bamba$^{\#}$	「X 線で探る宇宙：その熱く激しい姿」
			N. Yoshida$^{\#}$	「宇宙のダークマター」
FY2019	8/7-8/8	26th オープンキャンパス	H. Nishino	「宇宙の始まりを見る」
			K. Fujisawa	「星と宇宙と物理と」
			A. Nishizawa	「重力波天文学」
	12/11	27th 公開講演	Y. Suto	「太陽系外惑星の普遍性と多様性」
			N. Yoshida$^{\#}$	「宇宙論の物理と大規模構造の形成」

$^{\#}$: RESCEU affiliates.

* : Guest lectures.

1.5 Budget

1.5.1 Budget Evolution

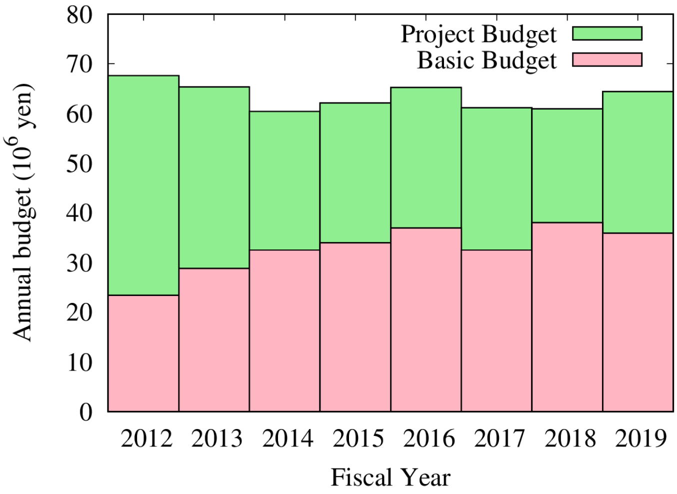

Figure 1.4: Annual RESCEU budget.

RESCEU is principally funded by the University budget. As shown in Fig. 1.4, the budged is divided into basic running costs of the center (pink), and those for the projects (green). The former includes the regular running costs of the Yokoyama, Cannon, Shigeyama, and Hotokezaka Laboratories, personnel expenses for the secretaries and some of the postdocs and project assistant professors, and the costs for electricity, water, as well as for the summer school and other meetings. The salaries for the full, associate, and assistant professors are not included here.

1.5.2 External Funding

As listed in Table 1.8, the RESCEU members have been quite successful in acquiring external funding, particularly Grant-in-Aid for Scientific Research (科研費) from JSPS.

氏名	交付事業区分	事業名	研究代表者	研究期間（年度）	直接経費総額	研究課題名
横山　順一	補助金	基盤研究(B)	研究代表者	2011 – 2014	15,000千円	重力波宇宙論の創成と展開
	補助金	新学術領域研究(研究領域提案型)	研究代表者	2013 – 2014	3,800千円	非ガウスノイズを取り入れた重力波データ解析方法の研究
	補助金	基盤研究(A)	研究代表者	2015 – 2019	32,400千円	多波長重力波宇宙物理学の開拓
	二国間	カナダとの共同研究	研究代表者	2015 – 2017	4,250千円	初期特異性のないインフレーション宇宙創成論
茂山　俊和	補助金	基盤研究(S)	研究代表者	2016—2021	98,300千円	高速掃天観測による連星中性子星合体現象の研究
カンノン　キップ	補助金	研究活動スタート支援	研究代表者	2016 – 2017	2,300千円	Low-Latency Compact Object Searches with LIGO, Virgo and KAGRA in O2 and O3
	補助金	基盤研究(A)	研究代表者	2018 – 2022	32,600千円	Gravitational-wave astrophysics with Advanced LIGO and Virgo's O3 and O4 experiments.
樽家　篤史	科研費	基盤研究（C)	研究代表者	2012～2014	3,900千円	宇宙大規模構造の高速理論計算にもとづく精密宇宙論的データ解析手法の開発
	二国間	日仏共同研究	研究代表者	2011～2012	2,000千円	宇宙大規模構造の宇宙論的観測に向けた精密理論計算
細川　隆史	基金	若手研究(B)	研究代表者	2013 - 2016	2,700千円	宇宙全史にわたる大質量星形成過程の解明
	補助金	新学術領域研究(研究領域提案型)	研究代表者	2014-2015	1,800千円	巨大ブラックホールの起源の理論的研究
須山　輝明	補助金	新学術領域研究(研究領域提案型)	研究代表者	2013-2014	1,800千円	強い重力場での修正重力理論の検証に向けた理論的研究
	補助金	新学術領域研究(研究領域提案型)	研究代表者	2015-2016	1,800千円	修正重力理論におけるコンパクト天体からの重力波
	基金	若手研究(B)	研究代表者	2015-2018	3,200千円	空間的小スケールの原始密度揺らぎを制限する新手法の確立
伊藤　洋介	基金	若手研究(B)	研究代表者	2013 - 2014	3,100千円	GPGPUを用いた効率的な重力波パルサーの探索
	基金	基盤研究(C)	研究代表者	2015 - 2019	3,600千円	パルサーからの重力波の探索
平賀　純子	基金	若手研究(B)	研究代表者	2013 - 2015	3,400千円	CMOSイメージセンサーで切り開くX線撮像分光の新たな地平
	補助金	新学術領域研究(研究領域提案型)	研究代表者	2014 – 2015	2,100千円	密度ゆらぎとその進化の精密測定
須田　拓馬	補助金	成果公開（データベース310）	研究代表者	2015-2017	5,700千円	銀河考古学のための金属欠乏星データベース
	基金	基盤研究(C)	研究代表者	2016 - 2019	7,900千円	連星系での超新星爆発の影響を受けた星の熱進化
大栗　真宗	基金	若手研究(B)	研究代表者	2011 - 2013	3,300千円	宇宙の構造進化から探る暗黒エネルギー
	基金	若手研究(B)	研究代表者	2014 - 2018	2,800千円	密度ゆらぎとその進化の精密測定
	補助金	新学術領域研究(研究領域提案型)	研究代表者	2018 – 2019	1,800千円	ブラックホール連星の起源の解明に向けた統計的手法の研究
	基金	基盤研究(C)	研究代表者	2018 - 2022	3,400千円	広天域撮像サーベイを用いた密度ゆらぎの総量の精密測定
樫山 和己	基金	若手研究(B)	研究代表者	2017 – 2019	3,200千円	パルサー駆動型爆発の多波長観測で探る中性子星形成の多様性
	補助金	新学術領域研究(研究領域提案型)	研究代表者	2018 – 2019	2,000千円	大質量星連星における動的潮汐相互作用
小宮　悠	補助金	新学術領域研究(研究領域提案型)	研究代表者	2018 - 2019	1,200千円	連星中性子星合体によるrプロセス元素宇宙線
関口　豊和	基金	基盤研究(C)	研究代表者	2018 - 2019	1,900千円	数値シミュレーションに基づくアクシオン暗黒物質生成機構の解明
	補助金	新学術領域研究(研究領域提案型)	研究代表者	2018 – 2019	1,400千円	赤方偏移21cm輝線観測を用いたダークエネルギーの解明
鎌田　耕平	補助金	新学術領域研究(研究領域提案型)	研究代表者	2019 - 2020	2,100千円	素粒子標準模型で探る初期宇宙
	基金	基盤研究(C)	研究代表者	2019 - 2021	3,300千円	宇宙磁場から迫る初期宇宙の諸現象
西澤 篤志	補助金	新学術領域研究(研究領域提案型)	研究代表者	2018 – 2019	1,900千円	多様な天体の相関統計解析で迫るブラックホール連星の起源
新納 悠	基金	若手研究(B)	研究代表者	2017–2020	2,800千円	ガンマ線バーストが照らし出す宇宙の進化
西野 玄記	基金	基盤研究(B)	研究代表者	2018 – 2021	13,300千円	宇宙マイクロ波背景放射観測の高感度化を実現する観測システム
筒井　亮	基金	若手研究(B)	研究代表者	2012 - 2015	2,900千円	ガンマ線バーストの新しい観測的分類手法とその統一理論の構築
顧　力意	補助金	研究活動スタート支援	研究代表者	2013 – 2014	2,100千円	Multi-wavelength Investigations of Galaxy-Hot Plasma Interactions in Clusters of Galaxies
金川　和弘	基金	若手研究	研究代表者	2019 - 2021	2,900千円	ガス-ダスト2相流体数値シミュレーションによる惑星移動モデルの再構築
				2016年-2019年 計		
須藤　靖		研究拠点形成事業	協力研究者	2016 – 2021	54,150千円	惑星科学国際研究ネットワークの構築 Core-to-Core Program Planet^2

Table 1.8: External funding acquired by RESCEU member (excluding RESCEU affiliates).

1.5.3 Planet^2: International Network of Planetary Sciences

RESCEU has been awarded a grant for international research collaboration activities from April 2016 through March 2021 by the core-to-core program of the Japan Society of Promotion of Science (JSPS) with US, Swiss, French, and German partners. This program, called "Planet 2 : International Network of Planetary Sciences", is to promote international collaboration on the formation and evolution of planetary systems encompassing both Solar System and exoplanetary systems, with an emphasis on the exchange of young researchers among the participating institutions. The PI of the program is Seiji Sugita, one of the RESCEU associate members, and four co-PI's, Dante Lauretta at the University of Arizona, Patrick Michel at Observatory of Côte d'Azur, Ralf Jaumann at DLR (German Space Agency), and William Benz at PlanetS (University of Bern). The first three of the co-PI's have visited Japan multiple times for the core-to-core program activities. The participating institutions of the program include eleven institutions in Japan including the University of Tokyo, seven in United States, four in France, three in Germany, and four in Switzerland.

For the first three years of its program period (April 2016 to March 2019), Planet 2 organized nine international conferences concerning planets inside and outside our Solar System, as summarized below.

1. "Towards a unified picture for evolution of Solar and extrasolar planetary systems" (Aug. 24-28, 2016) held at Takayama, Japan.
2. "Planet 2 Symposium: Origin and Diversity of Planetary Systems from the Microscope to the Telescope" (Feb. 20–23, 2017) jointly held at Villefranche-sur-Mer France with Observatory of Côte d'Azur.
3. "OSIRIS-REx-Hayabusa2 Joint Science Meeting" (Mar. 23–28, 2017) held at Tucson Arizona, USA with the University of Arizona.
4. "Planet 2 Symposium: Planet Formation around Snowline" (Nov. 28–30, 2017) held at Tokyo Japan.
5. "Hayabusa2 Joint Science Meeting" on Dec. 4–6, 2017 held at Sagamihara, Japan.
6. "Hayabusa2 Joint Science Meeting" on Mar. 20, 2018 held at the Woodlands, Texas, USA with the University of Arizona.
7. "Workshop on Catastrophic Disruption Workshop in the Solar System" (May 13–17, 2018) held at Kobe Japan.
8. "Astrophysics beyond Exoplanets" (July 27–30, 2018) held at Hakodate, Japan.
9. "OSIRIS-REx-Hayabusa2 Joint Science Meeting" on Mar. 20, 2019 held at the Woodlands, Texas, USA with the University of Arizona.

In each year, three lecturers (both foreign and domestic) were invited and gave a series of introductory talks on dark energy mainly for graduate students in Japan.

These international collaborations through the Planet^2 program played an important role in generating science results from asteroid mission, such as JAXA's Hayabusa2 mission including Europe-supplied small lander, MASCOT and NASA's OSIRIS-REx. Initial results of the mission has been published as a special issue in Science journal and special sessions at leading international conferences, such as American Geophysical Union, DPS of American Astronomical Society, and

Lunar and Planetary Science Conference. Furthermore, Planet 2 contributed greatly to exoplanet observation planning for Subaru's InfraRed Doppler (IRD) instrument and science analyses of NASA's Transiting Exoplanet Survey Satellite (TESS) for observing exoplanets. As a result of research cooperation in the Planet 2 program, some of the Japanese members were invited to join the ESA M-class mission, Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL), which was selected March 2019. In the framework of this program, several graduate students and post-docs stayed and worked in foreign participating institutes for one to two months and are writing first-authored papers to report their results in scientific journals. After graduations, some of them have been employed as post-docs in the partner countries.

1.6 Future Plans

It is more than twenty years since RESCEU started as a center in the University of Tokyo. At the time of the last external review in January 2013, we had seven research projects jointly with Departments of Physics and Astronomy in the University of Tokyo, and other universities and institutes in Japan. Given the amazingly rapid progress in the research frontier of astronomy and astrophysics, it is essential for us to reorganize the main research topis on a regular basis. This is why we reorganized the seven projects in 2016 so as to focus on the three major areas; Evolution of the universe and cosmic structures, Gravitational-wave astrophysics and experimental gravity, and Formation and characterization of planetary systems. For the next 10 years, we plan to pursue those three projects, but flexibly explore new important research areas according to the development of astronomy and astrophyics.

The current director of RESCEU (Yasushi Suto) and two senior faculties (Jun'ichi Yokoyama and Toshikazu Shigeyama) will retire in 5 to 10 years from now. Since two new faculties, Kipp Cannon and Kenta Hotokezaka whom we hired in 2016 and 2019, are working mainly on Project 2, we plan to find faculties leading Projects 1 and 3, namely, cosmology and exoplanetary science in a broad sense. Since RESCEU is a relatively small center, it is important to collaborate with various projects, and indeed we are working, and will continue to work, with KAGRA, LiteBird, small-JASMINE, and exoplanet and galaxy surveys with Subaru. Thus we plan to request several faculty positions to the University that will actively participate in those collaborations and lead RESCEU projects.

Chapter 2

Project 1. Evolution of the Universe and Cosmic Structures

2.1 Project Members

Title	Name	Affiliation
Professor	Jun'ichi Yokoyama	RESCEU
Associate Prof.	Toshikazu Shigeyama	RESCEU
Professor	Naoki Yoshida	Department of Physics
Professor	Tomonori Totani	Department of Astronomy
Associate Prof.	Aya Bamba	Department of Physics
Associate Prof.	Kazuhiro Shimasaku	Department of Astronomy
Associate Prof.	Akito Kusaka	Department of Physics
Assistant Prof.	Masamune Oguri	RESCEU
Assistant Prof.	Kohei Kamada	RESCEU

2.2 Objectives of the Project

This project aims at clarifying the creation and evolution of the universe and its large scale structures from both theoretical and observational studies. It covers physics of the early universe including but not limited to inflation, generation of matter and dark matter, cosmological phase transitions, formation and evolution of density perturbations, as well as formation and evolution of the hierarchical structure of the universe, namely, stars, galaxies, and clusters of galaxies in terms of numerical simulations and radio, optical and X-ray observations. These studies not only clarify the evolution of our Universe but also provide us with invaluable information on the nature of dark matter and dark energy. Below are some highlights of project 1.

2.3 Research Highlights

2.3.1 Inflationary Cosmology

Inflation Models with Non-trivial Derivative Interaction

The generalized G-inflation is the most general single-field inflation model with second-order field equations. We have found that this model can naturally accommodate anisotropic inflationary solutions even if the matter content is fully isotropic.

Conventional potential-driven inflation is followed by field oscillation of the inflaton which decays to reheat the universe. In models where inflation is induced by the kinetic energy of the inflaton, such as k-inflation and G-inflation, inflation ends abruptly when the form of the kinetic term changes. In such models reheating takes place through gravitational particle production. We have studied this process in detail and found the condition for sufficient reheating and dark matter formation from conformally coupled massive scalar fields.

We have studied reheating through direct coupling between matter fields and the inflaton field in such a way that shift symmetry is not broken, which requires higher order operator. We have shown that more efficient reheating is possible when the suppression energy scale is below the Planck scale.

Higgs-R^2 Mixed Model

The original Higgs inflation model and Starobinsky model of R^2 inflation are two inflation models whose predictions of the spectral index and the tensor-to-scalar ratio occupy the central region of the observed likelihood contours. We have analyzed the model in which both mechanisms are present and found a simple relation between the Higgs nonmiminal coupling parameter and the scalaron mass. On the reheating stage, it has been known that the cutoff scale of the Higgs-R^2 mixed model in the vacuum can be pushed up to the Planck scale and we showed that the violent particle production observed in the pure nonminimal coupling model can be treated safely. We found that this violent particle production is not efficient enough to complete the reheating of the Universe, contrary to the case of the pure nonminimal coupling model.

Quantum Effects in the Early Universe

Hawking-Moss transition describes phase transition from one de Sitter space to another with a larger cosmological constant. Traditionally it has been interpreted from an energetic point of view. We have shown that the transition rate is given simply by the ratio of the entropy associated with the event horizon using static coordinates. This suggests the importance of gravitational entropy in cosmological phase transitions.

We have proposed a new renormalization scheme appropriate for electromagnetism in de Sitter space where we subtract all the perturbative contributions and studied its consequences.

2.3.2 Particle Cosmology

Cosmological Phase Transition

We consider the cosmological phase transition, especially the electroweak one, in the Twin Higgs model, which is a possible solution for the naturalness problem in the Standard Model of particle physics. We showed that it is impossible to have first order phase transitions in these models for reasonable parameter spaces and we cannot expect gravitational wave production sufficient to be detected by DECIGO and other future gravitational-wave detectors. In other words, we can rule out the model if ever we observe a gravitational-wave background from the cosmological phase transitions.

Axion Dynamics

We have performed a large numerical simulation of formation and evolution of axionic strings, and found a deviation from the scaling solution with a logarithmic increase of the scaling parameter in time.

Dark Matter

We have derived constraints on dark matter annihilation cross section and decay lifetime from cross-correlation analysis of the data from Fermi-LAT and weak lensing surveys by using an updated extragalactic gamma-ray background data. As a result annihilation cross section of $\langle \sigma v \rangle \sim 10^{-23}\mathrm{cm}^3/\mathrm{s}$ is excluded for TeV-scale dark matter depending on channel. The lifetime of $\sim 10^{25}\mathrm{s}$ is also excluded for decaying TeV-scale dark matter.

We examined the possibility that the dark matter consists of charged massive particles (CHAMPs) using CMB anisotropies, tracing the evolution of cosmological perturbations without assuming that CHAMPs and baryons are tightly coupled. As a result we found that CHAMPs leave sizable effects if they are lighter than $10^{11}\mathrm{GeV}$.

As a way to solve the small-scale crisis of the standard cosmology, we considered dark matter interacting with light hidden fermions via well motivated fundamental operators showing the resultant matter power spectrum is suppressed on subgalactic scales.

2.3.3 Observational Cosmology

Observational Cosmology with Gravitational Waves

Following the discovery of gravitational-wave events by LIGO we proposed a new method to reproduce the distance-redshift relation by the cross correlation of galaxies with known redshift and gravitational-wave sources.

Effect of Gravitational Lensing on the Distribution of Gravitational Waves from Distant Binary Black Hole Mergers

Next generation gravitational-wave experiments allow us to observe binary black hole mergers out to very high redshifts, $z > 20$. The redshift distribution of these black hole mergers is expected to provide an important clue to their origin. However, in gravitational-wave observations, redshifts must be inferred from luminosity distance measurements that are affected by gravitational lensing magnifications. We study the expected redshift distribution of binary black hole mergers taking a full account of gravitational lensing effects, and find that highly demagnified images caused by strong lensing produce a high-redshift tail in the observed redshift distribution. Such a demagnified, apparently high-redshift event should be accompanied by a magnified image that is observed typically 10–100 days before the demagnified image. This work highlights the critical important gravitational lensing (de-)magnification on the interpretation of apparently very high redshift gravitational-wave events.

Gravitational Lensing

We have discovered a number of strong gravitational lensing events, including a double source plane event called “Eye of Horus”, and made models of mass distributions using the laser guide AO or spectroscopic data of SDSS-III BOSS survey.

From observations of the massive cluster MACS J1149+2223 with Hubble Space Telescope, we have discovered fast transient events near the critical curve of the cluster. Our careful analysis of the light curve as well as the spectral energy distribution of the transients indicates that these are highly magnified individual stars at redshift $z = 1.5$. For the most prominent event, which are dubbed as Icarus, we estimate that it is magnified by more than a factor of 2000 at the peak. This discovery opens up the possibility of using such highly magnified stars to study distant galaxies as well as the nature of dark matter.

Cosmological Perturbation Theory

We have proposed a new method to calculate the transfer function from the initial to the final power spectra of density fluctuations combining functional derivatives and numerical simulations, to show that observables in the larger scales are relatively insensitive to phenomena on smaller scales so that clean comparison between theories and large-scale observations is possible.

Cosmic Microwave Background

Cosmic microwave background radiation (CMB) is a useful probe of the physics of the early universe. By calculating the three point correlation function of the B-mode polarization of CMB, we have shown that it can be a useful probe of extended gravity theories if and only if there exists a large kinetic coupling of a scalar field to curvature tensor. We further studied the observability of three point function of B-mode polarization of CMB predicted in the generalized G-inflation models and found that while the general relativistic contribution is not observable, the new term associated with G_{5X} may be observed in future.

We studied modulation of the angular power spectrum of CMB anisotropy using the Planck 2015 data and confirmed the existence of oscillatory modulation around the multipole $\ell \sim 120$ observed in WMAP data.

Redshift-Space Distortions

We measured the redshift-space correlation function from a spectroscopic sample of 2783 emission line galaxies from the FastSound survey. The survey, which uses the Subaru Telescope and covers the redshift ranges of $1.19 < z < 1.55$, is the first cosmological study at such high redshifts. We detected clear anisotropy due to redshift-space distortions (RSD) both in the correlation function as a function of separations parallel and perpendicular to the line of sight and its quadrupole moment. RSD has been extensively used to test general relativity on cosmological scales at $z < 1$. Adopting a ΛCDM cosmology with the fixed expansion history, we obtain the first constraint on the growth rate at the redshift, $f(z)\sigma_8(z) = 0.482 \pm 0.116$ at $z \sim 1.4$ after marginalizing over the galaxy bias parameter $b(z)\sigma_8(z)$. This corresponds to 4.2σ detection of RSD. Our constraint is consistent with the prediction of general relativity $f\sigma_8 \sim 0.392$ within the $1-\sigma$ confidence level. We also demonstrate that by combining with the low-z constraints on $f\sigma_8$, high-z galaxy surveys like the FastSound can be useful to distinguish modified gravity models without relying on CMB anisotropy experiments.

Hyper Supreme-Cam

We have published various scientific results from the first year data of the Subaru Hyper Suprime-Cam (HSC) survey. For instance, we have constructed a weak lensing shear catalog from the first-year data, and conducted careful validation tests to make sure that its quality is sufficiently high for first year science. With the weak lensing shear catalog, we have constructed large mass maps and constructed a large sample of mass selected clusters. The comparison of the mass selected cluster sample with X-ray clusters revealed possible selection effects inherent to the X-ray cluster sample. Taking advantage of the photometric redshift information, we have also constructed three-dimensional mass maps, which represent the largest three-dimensional mass maps ever created. From the five band photometry of the HSC survey, we constructed an optically selected cluster catalog that extends out to the redshift of $z = 1.1$.

We used data taken in the Subaru/HSC (Hyper Suprime-Cam) Strategic Survey Program to study various properties of high-redshift galaxies. For example, we obtained the most accurate luminosity functions of bright UV-selected galaxies and bright Lyman α emitters. We also obtained the most accurate stellar-to-halo mass relations for bright UV-selected galaxies. Those studies were published in the PASJ HSC Special Issue in January, 2018.

High Redshift Galaxies

We examine the evolution of galaxy sizes over $z \sim 2 - 9$ using deep Hubble Space Telescope images in general fields and toward gravitational lensing clusters of galaxies. We find that the size of galaxies increases with cosmic time keeping pace with that of host dark matter haloes, with a galaxy-to-dark halo size ratio of ~ 0.03. We also present the most reliable size-luminosity relation of galaxies at $z \sim 6 - 9$. Lyman α emitters (LAEs) are one of the major galaxy populations at high-redshift. We find that LAEs (at $z \sim 2$) are normal star-forming galaxies lying on the star-formation main sequence, except that they are efficiently converting the gas of host haloes into stars. We examine the supermassive black hole (SMBH) mass - host halo mass relation for $z \sim 6$ quasars, finding that their SMBHs are overmassive with respect to the local relation. This indicates that the growth of SMBHs in $z \sim 6$ quasars precedes that of hosting haloes. Spectroscopy of very bright $z \sim 7$ galaxies was carried out to place a constraint on the fraction of neutral gas in the IGM.

2.3.4 Supernova

2D Radiation Hydrodynamics in Supernova Shock Breakout

We have constructed a code to calculate 2D radiation hydrodynamics including the special relativistic effects to investigate supernova shock breakout from stars with stripped envelopes (Wolf-Rayet stars). This project is a collaboration with A. Suzuki and K. Maeda (Kyoto University).

Signature of the Companion Stars in the Early Light of Type Ia supernovæ

Type Ia supernova is thought to be the explosion of a white dwarf in a binary system. There are two scenarios leading to type Ia supernova. One is the double-degenerate scenario in which the companion is also a white dwarf and eventually coalesces to explode without leaving compact remnants. The other is the single-degenerate scenario in which the white dwarf accretes matter from a red-giant or main-sequence companion star. In this scenario, there remains the companion after the supernova explosion and the existence of the companion should affect the dynamics of the ejecta of the explosion. We have been investigating effects of the companion on the dynamics and the radiation by 2D numerical simulations taking into account the finite timescale of thermalization between gas and radiation and pointed out the possibility of the enhancement of blue radiation in the early phase. Our collaborators recently observed such signatures in the early light curves of some supernovæ.

One particular supernova exhibited an enhancement in the light curve with very red color, which cannot be reconciled with the companion interactions. We found that this enhancement is due to He detonation on the surface of a massive white dwarf. We also found that this He detonation explains the observed spectral features due to absorption by Titanium ions. The results were published in Nature. This observation project is a collaboration with M. Doi, J. Jiang, at IoA, and K. Maeda at Kyoto University.

Influence of Supernova Explosions on the Companion Stars

Massive stars are usually formed in multiple stellar systems. Thus a supernova explosion can affect the surface layers of nearby stars. We are focusing on the change of the abundance of Li in solar type stars after the explosion of a nearby star because Li is known to exist only in the surface layer where the temperature is lower than 2.6 million K. This effect may account for the diversity of Li abundances observed in metal-poor dwarf stars. From the theoretical point of view, we are investigating the effects of a supernova on the surface layer of low mass stars by numerical simulations. This part is a collaboration with a researcher at Kobe University. At the same time, we are searching binary systems composed of a massive star and a low mass star by performing spectroscopy observations for known massive stars in our galaxy using 1-m class telescopes. To investigate the population of this kind of binary systems in the current universe, we can infer the population of metal-poor counterparts in the ancient universe. As a bi-product, we found a binary blackhole candidate with a long orbital period of ~ 33 (or 73) days.

Emission of Type IIn Supernovæ

Type IIn supernovæare very bright and could be a useful probe to investigate the activity of star formation in the early universe because this type of supernovae are thought to originate from massive stars. Though the emission of this supernova is believed to come from collisions between ejecta and thick circumstellar matter, there have been no quantitative models to account for spectra and their temporal evolution. This is due to the difficulty to numerically resolve the structure of the shocked matter. To overcome this difficulty, we take two different approaches. First, we are trying to resolve the structure by assuming the shocked ejecta and the shocked circumstellar matter are in stationary states in the rest frames of the shock waves and separated by a contact surface. We have succeeded in obtaining series of such solutions for about a month from the explosion and constructing light curves of some optical bands. Second, we use Chevalier's self-similar solution for the density and velocity structures in the shocked region. We calculate emission from newly shocked matter at each time and radiative transfer equations based on this solution. We have compare these solutions with previous solutions based on the thin shell approximation and with some existing observational data to test our model. The second part is submitted to the Astrophysical Journal.

Machine-Learned Classifier of Supernovæ

We have been developing a machine-learned classifier of supernovæ(Kimura et al. 2017). The classifier has been successfully installed and applied to real data analysis of HSC transient survey started in November 2017. A number of distant Type Ia supernovæwith redshifts greater than 1 were identified, several of which have been sent for follow up observations using Hubble Space Telescope.

Eruptive Mass Loss from a Massive Star a few Years Before the Core Collapse

Sudden Brightening exceeding the Eddington luminosity was observed a few years before some type IIn supernova events. To understand this preceding brightening event, we performed radiation hydrodynamic calculations initiated by injecting some energy at the bottom of the hydrogen-rich envelope of a supergiant with a timescale shorter than the dynamical timescale of the envelope. We found that we can reproduce the observed brightening and that this event ejects about 0.1 $M_{\odot}$ of matter. We will investigate the relation of this ejected matter with the dense CSM required to reproduce the brightness of type IIn supernovae.

2.3.5 Binary Neutron Star Mergers

Origin of r-process Elements in Metal-Poor Stars

To investigate whether r-process elements ejected from binary neutron star mergers (NSMs) can reproduce the abundances of these elements observed in metal-poor stars in the halo of the Milky Way galaxy, we constructed a model to describe the temporal evolution of elemental abundance patterns of metal-poor stars, in which the propagation of r-process elements is treated as cosmic-ray particles. As a result, we found that a significant fraction of r-process elements escape from the host proto-galaxy and pollute the intergalactic matter and other proto-galaxies. Furthermore, we have succeeded in reproducing the observed abundance distribution of r-process elements of metal-poor stars by supplying these elements from NSMs.

r-process Elements in Cosmic Rays

We discuss the difference in the content of r-process elements in cosmic rays if these elements are supplied by supernovæor binary neutron star mergers. We have assumed some different energy distributions for accelerated r-process elements and calculated the transfer of these elements inside our galaxy. We investigate the possibility to distinguish these origins of r-process elements using some meteorites that have long exposures of the order of Myr and satellite with short exposures. The results are published in the Astrophysical Journal.

Faint Dwarf Spheroidal Galaxies

Faint dwarf spheroidal galaxies can be a useful probe to identify the origin of r-process elements, because some of such galaxies have hosted a single NSM in their whole histories. If r-process elements are supplied from NSMs, stars formed before the NSM do not have these elements and can be easily distinguished from younger stars formed from gas polluted by the ejecta of the NSM. Since we have identified such a signature in some faint dwarf spheroidal galaxies from already existing observational data, we have been trying to observe as many stars in such galaxies as possible with the Subaru telescope to strengthen the argument in collaboration with researchers working at NAOJ and IPMU. From such observations for Draco spheroidal galaxy, we obtained a sign of distinct multiple events to enrich the galaxy with r-process elements and published the results in the Astrophysical Journal Letters.

Optical Emission Immediately After Binary Neutron Star Mergers

Gravitational waves from a binary neutron star merger were detected for the first time and the optical counterpart was also detected about 11 hours from the gravitational-wave detection. Follow up observations with electromagnetic waves have revealed that a short gamma-ray burst originates from a binary neutron star merger and heavy elements as much as 1% of the solar mass were ejected. As future transient surveys such as Tomo-e will be able to detect emission earlier than this event, we are investigating what kind of information the emission carries. To this end, we calculated the shock breakout from the merging object and found that this results in ejection of matter composed of free-neutrons with a mass of about $10^{-6}\ M_\odot$ and discussed the emission from this matter. The results were published in the Astrophysical Journal. We are now try to calculate optical spectra emitted within the first few hours of a merger.

2.3.6 X-ray and γ-ray Astrophysics

The radioactive decay of the freshly synthesized r-process nuclei ejected in compact binary mergers power optical/infrared macronovæ(kilonovæ) that follow these events. The light curves depend critically on the energy partition among the different products of the radioactive decay and this plays an important role in estimates of the amount of ejected r-process elements from a given observed signal. We study the energy partition and γ-ray emission of the radioactive decay. We have shown that 20% to 50% of the total radioactive energy is released in γ-rays on timescales from hours to a month.

We observed a nearby cluster CIZA J1358.9-4750 located at the distance 300 Mpc with Suzaku, XMM-Newton, and Chandra to find it is a cluster about to collide with another. The shock wave observed at its center is only 70 million years old and it has a sharp luminosity jump. We have probed physical processes there using X-ray observations.

The universe looks to be quiet and cold world at first glance, but is actually a hot and energetic world. The targets of our group are such high energy phenomena in the universe. Understanding the origin of heavy elements and cosmic rays is one of our main goals.

We have made several achievements on the study of heavy element distribution in young supernova remnants, high energy particle escape from the shocks of supernova remnants, high energy phenomena on compact stars such as white dwarfs, neutron stars, and black holes. We developed a parametrization the uniformity of expansion of supernova remnants. The origin of type Ia SNe is one of the biggest problems, single degenerate (SD) or double degenerate (DD). In the SD case, a dense circum-stellar medium (CSM) makes the expansion highly asymmetric. With excellent spatial resolution and moderate energy resolution of Chandra X-ray observatory, we make Doppler-shift maps of supernova remnants, and found that we will be able to judge the origin of supernova remnants, SD vs. DD, with the symmetric parameters.

For the future missions, we are participating in the the development of the X-ray recovery mission following Hitomi, XRISM, which will be launched in the Japanese fiscal year 2021. We are now making the performance verification target list. We are also developing a hard X-ray polarimeter with CMOS sensor and coded aperture for the future small satellite mission.

2.3.7 Tomo-e Gozen

To search for electro-magnetic counterparts of gravitational wave sources, we have constructed Tomo-e Gozen, a wide field optical camera equipped with 84 CMOS sensors, which is mounted on 1.0-m Schmidt Telescope in Kiso Observatory at the University of Tokyo. Observations started in April 2019. This facility can detect any types of transient sources ranging from comets in the solar system to afterglows of gamma-ray bursts in the distant universe on timescales of seconds.

2.3.8 Fast Radio Bursts etc.

We continued to investigate the origin of mysterious fast radio bursts (FRBs) a new mysterious transient phenomenon lasting only a few ms. Yamasaki et al. (2018) showed that, using a numerical simulation of binary neutron star (BNS) mergers, ejecta formation is a few msec delayed compared with the merged star starts to rapidly rotate, and hence there is a time window for radio signal to escape and become a non-repeating FRB. They also proposed that a repeating FRB is produced by the massive long-lived neutron star left after the BNS merger when the total mass is small enough to survive against collapse for a long time.. They also performed a follow-up observation by Subaru for a FRB, which is reported in Bhandari et al. (2018). Tsuna et al. (2018) predicted the distribution of isolated black holes emitting X-rays by accretion from interstellar medium in the Galaxy and made some predictions for future surveys. Sudoh et al. (2018) investigated the hypothesis that the IceCube neutrinos are generated in star forming galaxies using a state-of-art galaxy formation model, and showed that this population is unlikely to be the main origin of the IceCube neutrinos. We also constructed a new model of nonthermal afterglow emission from BNS mergers, in which a more realistic electron energy distribution is incorporated than previous studies. As a result, we obtained a qualitativley different best-fit solution of the jet model to GW 170817.

2.3.9 Statistical Computational Astrophysics

We applied a popular deep-learning method called Generative Adversarial Network to denoising a two dimensional field. In particular, we devised a set of networks that can estimate and subtract noises from weak-lensing cosmic convergence maps. We trained the networks by using 60,000 mock lensing maps generated from the outputs of cosmological simulations. The trained networks successfully reconstruct 1-point and 2-point statistics of the original, true lensing signals as well as the real space distributions. We have been exploring improvement of cosmological parameter estimation using denoised maps.

2.4 Future Plans

2.4.1 Gravitational-Wave Cosmology and Primordial Black Holes

As disclosed by aLIGO and aVirgo our Universe has unexpectedly many black holes with various masses, and it is becoming more important to investigate the possibility that the primordial black holes (PBHs), have been generated from the large density fluctuation in the early Universe. We will continue to study how to prove the existence of PBHs or to constrain their abundance. To do so we will carefully clarify the relation between the profile of density fluctuation spectrum and the mass function of PBHs. With the improved data of pulsar timing on the gravitational waves, we should be able to rule out the PBH hypothesis in the next five years (or Pulsar Timing Array experiment should discover a nonvanishing residual).

2.4.2 Inflationary Cosmology

We continue our study on model building of inflationary cosmology based on sensible models of particle physics. Particular emphasis will be put on the study of the universe after inflation, namely, how radiation, baryon, and dark matter were created then. The studies include the Higgs-R^2 model and the inflation models followed by the kination regime when the energy density is dominated by the kinetic energy density of a free inflaton field. In the latter case, reheating and matter creation may proceed through gravitational particle production. We also plan to make generic predictions for the B-mode polarization of cosmic microwave background from various inflationary universe models as well as topological defects, to prepare for the forthcoming LiteBIRD satellite which is to be launched in 2027.

2.4.3 Cosmology and Fundamental Physics with Magnetic Fields

Recently the existence of intergalactic magnetic fields is suggested by blazar observations. If they really exist, it would be natural to imagine that it is originated from the early Universe. In this case, such cosmological magnetic fields are one of the key ingredients to explore the early Universe cosmology and fundamental physics, especially its relationship to the Standard Model of particle physics and General Relativity. We will continue to explore the origin, evolution, and observation of cosmological magnetic fields. Especially we will focus on the helicity of magnetic fields since it relates to particle physics through the chiral anomaly in the quantum field theory. Non-trivial phenomena that has not been explored before can play important roles there. These studies include but are not limited to the magnetic field instability in the chiral media, the formulation of magnetohydrodynamics with chiral anomaly, and the detection of helicity of the intergalactic magnetic fields.

2.4.4 Weak Lensing and Cluster Cosmology with Subaru Hyper Suprime-Cam Survey

We plan to continue to work on weak lensing and cluster cosmology with Subaru Hyper Suprime-Cam survey. The full area survey data will be delivered in a few years, from which tight constraints on cosmological parameters can be obtained. These constraints serve as a critical test of possible tension between local and early Universe. The analysis of Hyper Suprime-Cam survey can also be seen as important preparatory work for future wide-field surveys such as Euclid and Large Synoptic Survey Telescope.

2.4.5 Celestial Transient Phenomena

We will search celestial transient phenomena in their early phases with Tomo-e and Subaru Hyper Suprime-Cam in collaboration with observers. This will contribute to identifying the progenitors of type Ia supernovæand the construction of a quantitative model for kilonovæejected from binary neutron star mergers. From theoretical points of view, we will improve our recently published magneto-rotational wind model for merging products of two white dwarfs to predict the range of the total mass for which the merger avoids type Ia supernovæ.

2.4.6 Computational Cosmology and Astrophysics

We pursue a number of topics in theoretical astrophysics from black hole formation to time domain astronomy, from evolution of proto-planetary disks to the particle nature of dark matter. The goal is to understand the formation and evolution of astronomical objects in the cosmological context. A specific science goal is to perform fine calculations of the distribution of cosmic relic neutrinos and to study the effect on the dark matter/galaxy distribution in the universe. We also utilize modern statistical methods and machine learning/AI to analyze data from future galaxy surveys and cosmic microwave background observations. Of particular interest is the so-called intensity mapping observations, both in infrared and submillimeter wave bands, which carry information on the distribution of matter, gas, stars and galaxies. We plan to use machine-learning/deep-learning to analyze the complex data to be obtained from NASA's SPHEREx satellite.

2.4.7 Fast Radio Bursts etc.

We will proceed theoretical studies on the mysterious fast radio bursts, mainly based on the binary neutron star merger scenario. We will also work on the predictions for the observations to test the theories and will be involved in actual observational studies. Additionally, we will continue the studies on the early Universe through the gamma-ray bursts.

2.4.8 High Redshift Galaxies

By combining data from the on-going Hyper Suprime-Cam survey with those from other telescopes, we will conduct the following studies.

(1) Properties of galaxies in the reionization era and constraints on the reionization process.

(2) A systematic survey of proto-clusters of galaxies at $z \gtrsim 2$ and properties of galaxies in them.

(3) Galaxy-IGM connection at $z \gtrsim 2$.

We will also use data from the Prime-Focus Spectrograph (PFS), a new instrument of Subaru, as supplementary data.

2.4.9 X-ray and γ-ray Astrophysics

After the failure of Hitomi, we quickly planned a recover mission now called XRISM. We lead science case study of Galactic diffuse sources: supernova remnants, pulsar wind nebulae, interstellar medium, Galactic center, planetary targets such as Jupiter an comets. We are also in charge of developing tools for analyzing very bright objects. We aim to launch XRISM in the Japanese fiscal year 2021.

2.4.10 Cosmic Microwave Background

In the next several years, we will deepen our insight toward the beginning, dark content, and the evolution of the universe by advancing the experimental projects observing cosmic microwave background (CMB). The Simons Array will complete the deployment of all three telescopes, and start observation with its full capability. Using the acquired dataset, we will put new constraints on the inflationary energy scale, or the tensor-to-scalar ratio r, as well as the sum of the neutrino mass. We will also exploit the dataset combining it with external data, such as those from the Subaru telescope. We will continue the construction of the Simons Observatory instrument, making indispensable contribution to the small aperture telescopes. We plan to start observation early 2020s, and expect early results to be published mid-2020s. This will include significantly improved constraint on inflation, neutrino mass measurements, evolution of the universe and constraint on dark energy through survey of galaxy clusters, and constraint on relativistic species beyond the standard model. In parallel with these research, we will continue development of cutting edge technologies. We will improve maturity of our Microwave Kinetic Inductance Detectors technology; they would find applications for not only CMB observation, but also for other applications such as dark matter search and neutrinoless double-beta decays. For cryogenic half-wave plate technology we develop, we will make further improvements based on field data.

2.5 Publication List

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Chapter 3

Project 2. Gravitational-Wave Astrophysics and Experimental Gravity

3.1 Project Members

Title	Name	Affiliation
Professor	Kipp Cannon	RESCEU
Professor	Mamoru Doi	Institute of Astronomy
Professor	Kotaro Kohno	Institute of Astronomy
Associate Prof.	Masaki Ando	Department of Physics
Assistant Prof.	Kazumi Kashiyama	RESCEU
Assistant Prof.	Atsushi Nishizawa	RESCEU

3.2 Objectives of the Project

Gravitational waves were discovered in 2015 with the observation of a signal from the collision of a pair of black holes. The signal has been named GW150914 after the date of its discovery. Since then we have found dozens more gravitational-wave signals, also all from the collisions of compact objects. Project 2 is active in several areas in this exciting new field. Members of project 2 participate in both the KAGRA Collaboration and LIGO Scientific Collaboration, and we work with data collected from all interferometer detectors: KAGRA, Geo600, both LIGO detectors, and Virgo. Project 2 studies black holes, neutron stars, exotic astrophysical objects, and the Universe using gravitational waves. We show several highlights of project 2.

3.3 Research Highlights

3.3.1 Gravitational-Wave Data Analysis

Compact Objects

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 the release of the first catalogue of gravitational-wave signals, GWTC-1 [arXiv:1811.12907]. The GstLAL detection system developed by our group contributed the bulk of the discoveries to that list. During O3, our group has made significant contributions to several major discoveries of the LSC and Virgo Collaboration. A new neutron star merger was discovered, S190425z, and just as happened in O2 the GstLAL detection system developed by our group was the only system to identify it. Unfortunately not all gravitational-wave detectors were operating, so the location of the source could not be determined precisely, and attempts to identify an optical counterpart have not been successful. We are hopeful that future discoveries will repeat the experience of GW170817. We have also identified what might be the first neutron star-black hole merger, S190426c.

Following these detections, our group contributed to the interpretation of the signals, performing the parameter estimation. Because of the high event rate anticipated during the O3 run, members of our group have worked to automate the parameter estimation system, and this effort has been quite successful. In addition, improvements to the Monte Carlo sampling algorithms have been developed and are undergoing internal review that are expected to lead to an enormous performance improvement over the existing system.

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.

Other Exotica

Cosmic strings are theoretical topological defect structures left over from the cooling process of the early Universe. Although none have been discovered, a broad spectrum of theories of fundamental physics predict their existence. Even if they exist, they might be so rare that none are present in the part of the Universe visible to us. Either way, searching for them and either confirming their existence or putting limits on their number will teach us a great deal about fundamental physics. Members of our group led the development of the LSC and Virgo Collaboration's cosmic string detection pipeline and are currently working to significantly improve the sensitivity and performance of the system to make it easier to use and more effective in the future.

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. One possible source are clouds of bosonic particles condensed around spinning black holes. Such a cloud, if it exists, is expected to extract rotational energy from the hole via the super-radiant instability. This past year members of our group completed a search for gravitational waves generated by this mechanism using stochastic gravitational-wave detection techniques.

Infrastructure for Future Observations

As gravitational-wave detectors are becoming more sensitive, the rate of detections is increasing, and we are quickly reaching the point at which it is no longer possible for people to manually study gravitational-wave candidates one at a time. It is critical to the progress of the field to automate the statistical analysis of signals to understand their properties, and our group is working to ensure we are ready for the "O3" and future observing runs of the Advanced LIGO, Advanced Virgo, and KAGRA detectors.

3.3.2 Gravitational-Wave Experiments

KAGRA Instruments

We are working on KAGRA, a gravitational-wave antenna at Kamioka, Gifu prefecture. The installation of main components has been finished in FY2018, and we are in the phase of commissioning; shakedown and tuning for the full operation of the interferometer. KAGRA is planning to start observation run in the end of 2019. Our group is contributing to this project in the management (Executive Office and Systems Engineering Office), subsystems (Main interferometer and Commissioning), and the community (KSC: KAGRA Scientific Congress).

DECIGO Development

We are also working on B-DECIGO, which is a space-borne gravitational-wave antenna with observation band around 0.1 Hz. We made 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 addition, we are preparing for a proposal of a small-scale space demonstration mission.

3.3.3 The Tomo-e Gozen Camera

The Tomo-e Gozen Camera (Tomo-e) is a new CMOS camera developed for the 105 cm Kiso Schdmit telescope. In total 84 $2\,\mathrm{k} \times 1\,\mathrm{k}$ CMOS sensors with large pixel format ($19\,\mu$m/pixel) will cover 20 deg^2, and the dedicated electronics can achieve two frames per second with low readout noise ($\sim 2\,e^-$). We have started commissioning observations with all 84 sensors at the prime focus of the Kiso Schmidt telescope from October 2019.

The wide field of view and the fast readout speed of Tomo-e enable us to quickly search for optical counterparts of GW events in their large localization errors (typically a few 100 deg^2). During an observing run of the gravitational-wave detectors which continues for about a year, GW event alerts may arrive anytime 24 hours a day. To dynamically perform follow-up observations reacting those alerts, we have developed an automated observation system which starts follow-up observations triggered by electronic alerts. Images obtained in the follow-up observations are automatically processed by a pipeline software, which performs image subtractions with reference images and find transient events. Although the gravitational-wave detectors have not detected any GW event during the engineering runs conducted in ER13 (December 2018) and

ER14 (March 2019), the functionality of the automated observation system has been confirmed by test observations using mock alerts.

3.4 Future Plans

3.4.1 Gravitational-Wave Data Analysis

As the Japanese KAGRA GW detector comes online, we are looking forward to adding the additional data to the global network of GW detectors. Our group is leading the effort to expand the GstLAL detection system to include KAGRA data in future GW discoveries.

In the short term, we are developing the next generation of detection systems for GW bursts from cosmic strings. We are focusing on developing a system optimized for making statistically-sound detection claims rather than a system optimized for setting upper limits from null results.

We are developing an ultra high-speed GW source localization system to reduce the latency with which optical telescopes are informed of GW sources. This system will also be suitable for use in early warning applications, where the early part of a GW signal is used to alert optical and radio telescopes of an imminent collision.

Having developed highly successful solutions to the problem of GW signal detection, we are turning our attention to the interpretation of GW signals. We are working to understand the origin of the black holes seen with GW detectors by studying their population's statistical properties, for example their spin distributions and mass distributions. Perhaps the greatest challenge when analyzing the GW signals that we have discovered, uncovering what they can tell us about the universe, is the computational cost. Estimating the intrinsic parameters of the compact objects involved in neutron star collisions, for example, can take months or years of computer time running Markov-Chain Monte Carlo Bayesian parameter estimators; meanwhile, quantifying the selection biases present in the detection system itself currently relies on massive Monte Carlo simulation campaigns. Our group is working to address both of these difficulties, allowing us to lead the field going forward.

3.4.2 Gravitational-Wave Astrophysics

Compact binary merger plays the main role in on-going and up-coming multi-messenger astronomy. Various theoretical predictions proposed past 30 years have been tested by GW 170817. However, some big questions are not answered yet; binary NS merger is really the origin of short GRB? How the relativistic jet is launched? Given that number of GW events will increase significantly in near future, our group will focus on connecting the diversity of binaries (mass, spin, magnetic field, NS or BH) to the diversity of multi-messenger signatures before and after the merger in particular those related to relativistic jet.

We are also investigating the astrophysical origin of stellar-mass black-hole binaries. To distinguish astrophysical scenarios, we need to measure the distributions of binary parameters, the spatial distribution and time evolution of binaries, and the properties of host galaxies. We will develop the theoretical framework to deal with these physical information of stellar-mass black-hole binaries, combining GW observational data with data from galaxy and high-energy transient source surveys.

3.4.3 Tests of Gravity with Gravitational Waves

We will keep working on the tests of gravity with GW to probe for a strong regime of gravity and gravity at cosmological distances, which have been tested well so far and may give us implications on quantum gravity and the origin of the cosmic accelerating expansion. We extend the generalized framework to test GW propagation by including also GW generation and constructing the more general framework from GW generation to GW detection. On the other hand, we develop a new method that can treat multiple GW event data statistically to utilize the existing data optimally and prepare for the routine detection era of GW.

3.4.4 Gravitational-Wave Experiments

As for the experimental side, we will continue to contribute to the KAGRA gravitational-wave antenna, on the commissioning to improve sensitivity and stability of the operation, as well as on the planning and development for the upgrade. RESCEU is supporting the the space gravitational-wave mission. In particular we will work to realize the B-DECIGO mission.

3.4.5 The Tomo-e Gozen Camera

Tomo-e is almost ready to carry out the follow-up observations of GW events automatically, though it is still necessary to improve the data analysis pipeline to find the optical counterpart quickly and efficiently. In order to identify the candidates, we are going to collaborate with other telescopes. Especially, a three band CMOS imaging spectrograph for the 3.8-m Seimei telescope is being developed by grants with colleagues in Kyoto University, which should be powerful for the identification during the same night. Data archive is another important issue for Tomo-e, and fast internet connection to Tokyo (Mitaka, Hongo, Kashiwa) is being prepared so that we can archive the raw data.

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Chapter 4

Project 3. Formation and Characterization of Planetary Systems

4.1 Project Members

Title	Name	Affiliation
Professor	Yasushi Suto	Department of Physics
Professor	Motohide Tamura	Department of Astronomy
Professor	Seiji Sugita	Department of Earth and Planetary Science
Professor	Satoshi Yamamoto	Department of Physics
Professor	Eiichi Tajika	Department of Earth and Planetary Science
Associate Prof.	Masahiro Ikoma	Department of Earth and Planetary Science
Assistant Prof.	Hajime Kawahara	Department of Earth and Planetary Science

4.2 Objectives of the Project

One of the universal goals of research in astrophysics is to explore to the unseen ends of the Universe we have never seen. The end of the Universe and its origin, as well as the image of the Universe seen by the gravitational waves are clear examples. The researches on the exploration of the primordial matter in the solar system we live, observation of the stars and planets just after their birth, and exploration of diversity of the exoplanets share awareness of these problems. Moreover, it leads to the supreme scientific problem on the origin of life in the Universe.

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.

4.3 Research Highlights

4.3.1 Application of Asteroseismology to Explore the Spin-Orbit Architecture of Exoplanetary Systems

A significant fraction of exoplanetary systems is known to exhibit spin-orbit misalignments. This surprising fact has been mainly revealed by a spectroscopic method, known as the Rossiter-McLaughlin effect for transiting planetary systems. This method measures the projected angle between the stellar spin and the planetary orbital axes, but is insensitive to the obliquity of the stellar spin with respect to the observer. Asteroseismology offers a unique method to infer the stellar obliquity in a complementary fashion.

We analyzed and measured the stellar inclination of 94 Kepler main-sequence solar-like stars, among which 33 are planetary hosts. Among the 33 stars, we found that the stellar inclination of Kepler-408 is 42^{+5}_{-4} degrees, and thus Kepler-408b is, by far, the smallest planet known to have a significantly misaligned orbit.

We also measured the rotation periods of 19 stars in the Kepler transiting planetary systems, obtaining $P_{\mathrm{rot,astero}}$ from asteroseismology and $P_{\mathrm{rot,phot}}$ from photometric variation of their lightcurve. Two stars exhibit two clear peaks in the Lomb-Scargle periodogram, neither of which agrees with the seismic rotation period. Another four systems do not show any clear peak, and so their stellar rotation period is impossible to estimate reliably from photometric variation. For the remaining 13 systems, $P_{\mathrm{rot,astero}}$ and $P_{\mathrm{rot,phot}}$ agree within 30%. Interestingly, 3 out of the 13 systems are in the spin-orbit resonant state in which $P_{\mathrm{orb,b}}/P_{\mathrm{rot,astero}} \approx 1$ with $P_{\mathrm{orb,b}}$ being the orbital period of the inner-most planet of each system. While further analysis of stars with reliable rotation periods is required to examine the statistical significance, the spin-orbit resonance between the star and planets, if confirmed, have important implications for the star-planet tidal interaction, in addition to the origin of the spin-orbit (mis-)alignment of transiting planetary systems.

4.3.2 Solar System Exploration

We are engaged in missions for both small and large bodies in the solar system. In FY2018, however, we were focused on small-body mission activities because Hayabusa2 arrived at the target asteroid Ryugu at the beginning of FY2018.

We conducted a variety of observations and analyses for images obtained with a multi-band telescopic camera and panchromatic wide-angle cameras on Hayabusa2 in FY2018. The observed spectral characteristics of Ryugu turned out to be consistent with the dynamically most probable source asteroid families for Ryugu: Eulalia and Polana families. They are among the most widely dispersed C-complex families in the inner main belt, which can deliver fragments at very high flux rate to the resonance zones ($\nu6$ and 3:1), the dominant sources of near-Earth objects (NEO's).

Furthermore, a very high abundance (about twice Itokawa) of boulders are seen on Ryugu. Many lines of evidence for mass wasting observed on Ryugu indicates that its surface is mechanically unconsolidated, allowing boulders to move easily. The morphologies of impact craters on Ryugu are consistent with gravity-regime formation, in which impact events produce large ejecta masses. These three lines of evidence suggests that large mass of boulders and pebbles should be ejected from Ryugu to space over time.

Consequently, a large number of macroscopic objects of Ryugu-like materials should arrive at Earth, implying that there should be counterparts in our meteorite collection. One class of such candidates is moderately dehydrated carbonaceous chondrites, which exhibit very low albedo and flat spectra. They are also found with high abundance in Antarctica, which has sampled the long-term average flux of infalling meteorites on Earth. Another class of candidates is interplanetary dust particles (IDPs), which also exhibit low albedos and account for large influx of extraterrestrial material to Earth.

Although a decisive conclusion may not be obtained before Ryugu samples returned to Earth are analyzed, currently available observational evidence, such as high boulder abundance on Ryugu, favors that its composition may be similar to moderately dehydrated carbonaceous chondrites. This would further suggest that Ryugu's relatively low abundance of hydrated minerals may be due to partial dehydration on Ryugu's parent body.

4.3.3 Transiting Planets near the Snow Line from Kepler

While astronomers have confirmed 4,000 exoplanets so far, it is still difficult to directly compare exoplanets with solar planets because most of the transiting exoplanets discovered so far have an orbital period shorter than one year. Using graphic processing unit (GPU) computing and techniques in machine learning, we surveyed 200,000 stars observed by the Kepler spacecraft for signals of transiting planets whose orbital period is larger than two years [127]. Most of these signals were overlooked because only one or two transits occurred in four-year light curves, and they were difficult to identify through standard periodic analysis of the detection pipelines. We identified dozens of long-period transiting exoplanets and finally published the catalog of these planets including Jupiter-like gas giants. Also, we found that Neptunian-sized planets around the snow line (at a few au) are common around FGK stars. It is difficult to explain this population using the current formation theory.

4.3.4 Exo Jasmine

The M-class IR satellite for astrometry in Japan, JASMINE (Japan Astrometry Satellite Mission for INfrared Exploration), plans to observe the galactic bulge. This FY, we started a scientific project, Exo JASMINE, which plans to survey transiting planets around late M-type stars during about half of the observation period when JASMINE cannot observe the budge. We aim to detect habitable transiting planets around such stars, which should be the best targets for characterization by ground-based large telescopes such as TMT and the space observatory such as JWST and Ariel.

4.3.5 Self-Lensing Discovery of an Unusually Small White Dwarf in an Wide Orbit Around a Sun-Like-Star

A self-lensing binary (SLB) is the periodic magnification of a star due to gravitational lensing by a compact star companion, which was predicted by Kip Thorne in 1969. After the serendipitous detection of the first SLB, we performed a systematic survey of SLBs in the Kepler data in international collaboration with Harvard-Smithsonian Center for Astrophysics *et al.* Using GPU computing, we found four of the five known SLBs. We discovered that these SLBs, which are a white dwarf and a normal star binary, have features similar to field blue stragglers (FBS). But, we found that the white dwarf mass of one of them, KIC 8145411, is only 0.2 solar mass despite its wide nearly circular orbit (1.28 au) (Masuda, Kawahara *et al.* in press). It is difficult to explain KIC 8145411 using the current binary formation theory. The SLB-FBS connection that we found will provide an excellent test for models of interacting binaries.

4.3.6 LOTUS

Known exoplanets near the snow line are located too far to study in detail, even given their high masses. Nearby targets are crucial for further study by large ground-based telescopes or the space observatory. To find such nearby systems, we are developing the nanosatellite mission LOTUS (long-period transiting exoplanet surveyor) in a collaboration involving the University of Tokyo (Nakasuka lab), NAOJ, and Princeton University. LOTUS has a very wide (33 degree × 33 degree) 7.5 cm telescope in a nanosatellite bus system (20 kg) and plans to observe north and south poles continuously.

4.3.7 Physical and Chemical Evolution of a Disk/Envelope System of Solar-Type Protostars

Physical and chemical evolution during formation processes of solar-type protostars has been studied with Atacama Large Millimeter/submillimeter Array (ALMA). A protostellar disk is a birthplace of a planetary system, and observations of its physical and chemical structure are of fundamental importance in understandings the diversity of planetary systems. By taking advantage of unprecedented spatial resolution and sensitivity of ALMA, we are observing nearby protostellar sources in various molecular lines. Highlights for the last year are summarized as follows.

Okoda *et al.* (2018) have detected the Keplerian motion around the low-mass protostar, IRAS 15398-3359, in Lupus by a high angular resolution observation of the SO line with ALMA. Based on this result, this protostar has been found to have a very low mass (0.007 solar mass). Since this source is deeply embedded in a parent core, the very low mass means the extreme youth of the protostar ($\sim$1000 years). Nevertheless, it has already harbored a Keplerian disk with a size of 40 au in radius. This result provides us with the first observational evidence of “co-evolution” of a protostar and a disk in the earliest phase of star formation.

It is known that the chemical composition of the protostellar source has significant diversity. So far, the chemical diversity is classified by the relative abundances of saturated and unsaturated organic molecules. Oya *et al.* (2019) have found another type of the diversity in the protostellar source, Elias 29, in Ophiuchus. In this source, SO and SO_2 are very abundant, whereas both saturated and unsaturated organic molecules are deficient. Thus, the sulfur chemistry appears as a new “axis” of chemical diversity.

For thoroughly understanding the physical and chemical evolution of solar-type protostars, systematic observations of more protostellar sources are needed. With this in mind, we are now conducting the ALMA large program, FAUST, in which we aim at revealing the chemical composition of 13 representative protostellar sources.

4.4 Future Plans

Starting a new project of exoplanet research was identified in the future plan of RESCEU in the previous external review in 2012. Indeed we started one in 2013, which has evolved into the current Project 3 “Formation and Characterization of Planetary Systems”. This project is supported by several groups in Departments of Physics, Astronomy, and Earth and Planetary Science that are working on solar planets, exoplanets, and star formation both theoretically and observationally in a complementary fashion.

For the last decade, we have enjoyed a huge amount of revolutionary observational data from both space missions (Kepler, Hubble, Spitzer, and Hayabusa) and ground telescopes (Subaru, Keck, ALMA). This is expected to continue in the next decade as well, including the ongoing

GAIA, TESS, Hayabusa 2, CHEOPS, and Subaru IRD (infra-red Doppler spectrograph), and upcoming missions like JWST, ARIEL, and WFIRST among others.

Unfortunately some of the RESCEU affiliates in Project 3 will retire in the next 5 to 10 years. We continue to co-operate with Departments of Physics, Astronomy, and Earth and Planetary Science, and to play a leading role in Japanese Subaru and small-Jasmine project in addition to participating in other international collaborations. For that purpose, we plan to request a couple of associate and assistant professor positions from the University, maybe jointly with Departments of Physics, Astronomy, and Earth and Planetary Science.

RESCEU succeeded in obtaining one permanent professor position for gravitational-wave astrophysics (Kipp Cannon), and an associate professor position (for ten-year term, but takes over one professor position after current professors retire. In addition, one current professor position for exoplanet in Department of Astronomy was offered from the University as a result of our joint application among Departments of Astronomy, RESCEU, and Department of Earth and Planetary Science. Therefore, we expect to obtain a couple of new positions in RESCEU within next several years.

4.5 Publication List

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Chapter 5

Personal Achievement of RESCEU Core Members

5.1 横山順一 Jun'ichi Yokoyama

5.1.1 Education and Professional Experiences

Education

1985	B.S. (Physics)	The University of Tokyo
1987	MSc. (Physics)	The University of Tokyo
1989		Left graduate school to be appointed as a research associate
1990	D.Sc. (Physics)	The University of Tokyo

Professional Appointments

1989−1991	Research Associate	The University of Tokyo
1991−1992	JSPS fellow	Fermi National Accelerator Laboratory (on leave from Tokyo)
1992−1999	Asscociate Professor	Yukawa Institute for Theoretical Physics, Kyoto University
1997−1997	Visiting Researcher	Stanford University (on leave from Kyoto)
1999−2005	Associate Professor	Osaka University
2005−	Professor	The University of Tokyo

5.1.2 Research Highlights

Highlights of my research in the past six years are 1) Cosmology of generalized scalar-tensor theories 2) Novel scenarios for the creation of the universe 3) Gravitational-wave data analysis 4) inflation and reheating in the early universe 5) evolution of axionic strings, and 6) physics of primordial black holes.

1) We have shown that all the known Higgs inflation models can be described as a subclass of the generalized G-inflation and also discovered another mechanism of Higgs inflation. We have also shown that the generalized G-inflation can realize anisotropic inflationary solutions without introducing any vector degrees of freedom.

2) We have worked out two novel scenarios of the creation of the Universe. One is a model making use of the generalized galileon which can violate the null energy condition without causing instabilities and therefore we may start with an asymptotically Minkowski spacetime in the infinite past and start cosmic expansion without the singularity problem. The other is based on the observation that in the final fate of a black hole due to the Hawking evaporation an environment similar to the hot early universe is realized in the vicinity of the black hole horizon. This means that a symmetry may be restored near the horizon due to the thermal effect. We have investigated

a phase transition of such a bubble to show that a wormholelike configuration may be quantum mechanically created beyond whose throat is a domain filled with a false vacuum energy which drives inflation. This means that our universe may have been created by the final fate of a black hole in the other universe

3) Since 2012 we have been working on fundamental research on the data analysis of gravitational waves focusing on the non-Gaussian nature of noise. I have considered possible ways to quantify and deal with non-Gaussian noise and published an invited paper in Proceedings of the Japan Academy. Later on we have realized that it would be better to make use of the non-Gaussianities to separate noise and gravitational-wave signals, we formulated an independent component analysis which has the desired property. We have applied it to the actual data of iKAGRA and confirmed that it effectively removes non-Gaussian seismic noise by combining the data of seismeters.

4) Currently, two inflation models, namely, Starobinsky's R^2 model and the original Higgs inflation model are known to fit the observational data of cosmic microwave background the best. We have considered the mixed model of Higgs-R^2 model and analyzed the curvature perturbaitons and reheating process. In partucular, we have studied the effects of violent preheating on the thermal history of the Universe.

There are a number of models where inflation is followed by a kination regime when the cosmic energy density is dominated by the kinetic energy of a free massless scalar field. We have studied gravitational particle production in such models to show the condition for sufficient reheating and generation of baryon asymmetry and cold dark matter.

5) We have updated a numerical simulation of the evolution of axionic strings in an expanding universe, to find that their number per horizon increases with time and does not obey the scaling solution.

6) We have performed detailed numerical simulations of formation of primordial black holes (PBHs) to identify the most relevant parameters that control their formation. We have also studied a number of cosmological consequences of PBHs such as galactic gamma-ray background and micro black hole dark matter.

5.1.3 Selected Papers

- H. Motohashi, A. A. Starobinsky and J. Yokoyama, "Cosmology Based on f(R) Gravity Admits 1 eV Sterile Neutrinos," Phys. Rev. Lett. **110** (2013) no.12, 121302 Editor's choice

- K. Kamada, T. Kobayashi, T. Takahashi, M. Yamaguchi and J. Yokoyama, "Generalized Higgs inflation," Phys. Rev. D **86** (2012) 023504 75 citations

- H. Motohashi, A. A. Starobinsky and J. Yokoyama, "Inflation with a constant rate of roll," JCAP **1509** (2015) 018 87 citations

- N. Oshita and J. Yokoyama, "Creation of an inflationary universe out of a black hole," Phys. Lett. B **785** (2018) 197 Proposed a novel creation mechanism of the universe.

- J. Yokoyama,"Toward the detection of gravitational waves under non-Gaussian noises I. Locally optimal statistic," Proceedings of the Japan Academy ser B **90** (2014) 422–432. Invited paper.

5.1.4 Honors, Awards and Professional Society Memberships

29th Inoue Research Award (2013)

19th Outstanding Paper Award of the Physical Society of Japan (2014)
Member of Physical Society of Japan, Astronomical Society of Japan, and International Astronomy Union.

5.1.5 Research Plan

I plan to continue my studies on cosmology of the early universe and gravitational waves. Below are the specific research plans.

1) Application of independent component analysis to bKAGRA data. KAGRA will start cryogenic observations in December 2019 to join O3 (Third observation period) of advanced LIGO and advanced Virgo but with a limited sensitivity. In this circumstance, first I plan to use the data of aLIGO and aVirgo to predict the waveform KAGRA would detect. I will treat it like an injected signal to perform independent component analysis to improve the signal-to-noise ratio. Thus we aim at the first detection of gravitational waves by KAGRA with a sufficient SN ratio. Then KAGRA will have engineering works for about one and half years after which O4 joint observation will start. We hope that KAGRA will have reached a useful sensitivity. We will then use the independent component analysis on equal footing among KAGRA, aLIGO, and aVirgo, to determine the number of polarization modes of gravitational waves which is important to prove the general relativity.

2) Ruling out the PBH hypothesis of LIGO black holes. As disclosed by aLIGO and aVirgo our Universe has unexpectedly many black holes with various masses. There are two competent explanations of their origin, one is stellar origin and the other is the primordial origin, namely, PBHs which are created when a large amplitude density fluctuations enter thee Hubble radius. I have shown that this process is associated with production of second-order tensor perturbations or long-wave gravitational waves that can be observed by space-based laser interferometers or precision measurement of pulsar timing. So far the latter has constrained the abundance of PBHs with sub-solar masses but as the observation period gets longer, we will be able to constrain PBHs with larger masses. To do so I will carefully clarify the relation between the profile of density fluctuation spectrum and the mass function of PBHs. With the improved data of pulsar timing, I should be able to rule out the PBH hypothesis in the next five years (or Pulsar Timing Array experiment should discover a nonvanishing residual!)

3) Inflationary cosmology. I plan to continue my research on inflationary cosmology to build sensible models which both account for observations and are well motivated in particle physics. In particular, creation of matter and radiation after inflation will be an active topic of further study by investigating the gravitational production of right-handed massive neutrinos and its consequences for generation of baryon asymmetry and cold dark matter as well as radiation.

I also plan to make generic predictions for the B-mode polarization of cosmic microwave background from various inflationary universe models as well as topological defects, to prepare for the forthcoming LiteBIRD satellite which is to be launched in 2027.

5.1.6 Publications and Patents

< Refereed Original Papers >

[1] S. Hashiba and J. Yokoyama, “Dark matter and baryon-number generation in quintessential inflation via hierarchical right-handed neutrinos,“ Phys. Lett. B **798** (2019) 135024 [arXiv:1905.12423 [hep-ph]].

[2] T. Akutsu *et al.* [KAGRA Collaboration], “First cryogenic test operation of underground km-scale gravitational-wave observatory KAGRA,“ Class. Quant. Grav. **36** (2019) no.16, 165008 [arXiv:1901.03569 [astro-ph.IM]].

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5.1.7 Invited Presentations at International Conferences

[1] J. Yokoyama, “Higgs condensation as an unwanted curvaton” International conference on string cosmology (Makubetsu, 2012/8/7).

[2] J. Yokoyama “Gravitational modulated reheating in R^2 inflation” Cosmological perturbation in the post Planck era (University of Helsinki, 2013/6/4).

[3] J. Yokoyama “Toward the quest for the ultimate theory of the universe by CMB” CMB2013 (OIST, 2013/6/13).

[4] J. Yokoyama “ALMA and variation of the fundamental constants of physics” Todai Forum (University of Chile, 2013/11/8).

[5] J. Yokoyama “Gravitational modulated reheating “ CosPA2013 (University of Hawaii, 2013/11/14).

[6] J. Yokoyama “Cosmology of the Higgs field” PASCOS2013 (National Taiwan University, 2013/11/22).

[7] J. Yokoyama “Cosmic strings and inflation” Cosmic Strings Workshop (Arizona State University, 2014/2/4).

[8] J. Yokoyama “Gravitational Waves: Near Future, Far Future” CosPA2014 (Auckland University, 2014/12/11).

[9] J. Yokoyama “Inflationary Magnetogenesis” Primordial Universe After Planck (IAP, 2014/12/17).

[10] J. Yokoyama “Galiean Genesis of the Inflationary Universe” COSMO15 (University of Warsaw, 2015/9/11).

[11] J. Yokoyama “Gravitational waves from the early universe” CosPA2015 (IBS, 2015/10/16).

[12] J. Yokoyama “Birth of the inflationary universe and tensor perturbations” 2nd LeCosPA Symposium (LeCosPA, 2015/12/17).

[13] J. Yokoyama “Gravitational radiation and CMB anisotropy from cosmic strings created during inflation” Cosmic Strings@Brazil (University of Sao Paulo, San Carlos campus, 2016/2/16).

[14] J. Yokoyama “Approaches to inflationary cosmology” 1st CORE-U Conference (Hiroshima University, 2016/3/7).

[15] J. Yokoyama “SUSY inflation? What else?” SUSY2016 (University of Melbourne, 2016/7/6).

[16] J. Yokoyama “Creation of the inflationary universe out of a black hole” International Conference on Garvitation and Cosmology (Ehwa Women’s University, 2017/7/5).

[17] J. Yokoyama “The Universe after G-inflation” Dark Side of the Universe (IBS, 2017/7/13).

[18] J. Yokoyama “Inflation (and dark energy) : Large or Small?” 4th Korea-Japan joint workshop on Dark Energy (Nagoya University, 2017/8/28).

[19] J. Yokoyama “The creation of inflationary universe out of a black hole” First Symposium of the BRICS Association on Gravity, Astrophysics, and Cosmology (Yangzhou University, 2017/10/19).

[20] J. Yokoyama “Spontaneous genesis after G inflation” 3rd LeCosPA symposium: Cosmic Prospects (LeCosPA, 2017/11/28).

[21] J. Yokoyama “Approaches to inflationary cosmology” IMFP2017 (Pulman Kuala Lumpur, 2017/12/5).

[22] J. Yokoyama “Creation of an inflationary universe in the final stage of black hole evaporation” PACIFIC2018 (Kiroro resort, 2018/2/14).

[23] J. Yokoyama “Self-anisotropizing inflationary universe in Horndeski theory and beyond” ICNFP2018 (Greek Orthodox Academy, Creta, 2018/7/10).

[24] J. Yokoyama “Cosmology of the Higgs field” 5th Korea-Japan workshop on dark energy (KASI, 2018/8/7).

[25] J. Yokoyama “Micro black hole remnant and Planckian interacting dark matter” CosPA2018 (Yangzhou University, 2018/11/22).

[26] J. Yokoyama “Micro black hole and purely gravitational dark matter” Japan-Korea workshop on cosmology (Ishigaki, 2019/6/16).

5.1.8 Teaching Accomplishment

Hayato Motohashi, Kazunari Eda, and Naritaka Oshita received dean's promotion prize. Kohei Kamada received the young scientist promotion award of the Physical Society of Japan.
Lecture courses taught:
The University of Tokyo (2010-13, 2017-2019) General Relativity
The University of Tokyo (2014) Electromagnetism
The University of Tokyo (2016) Analytical mechanics
National Taiwan University (2010-13) Inflationary Cosmology and Gravitational Waves
Okayama University (2016) Basics of General Relativity
Democritos Institute (2018) Inflationary Cosmology

5.1.9 Contribution to Academic Community

Editorial Activities

Associate Editor, Journal of Physical Society of Japan (2000–2016)
Editor, AAPPS Bulletin (2011–2014)
Deputy Editor-in-chief, AAPPS Bulletin (2014–2017)
Editor, Reports on Progress in Physics (2016–)

Organization of Professional Societies

Vice President, Asia Pacific Organization for Cosmology and Particle Astrophysics (2010–2013)
President, Asia Pacific Organization for Cosmology and Particle Astrophysics (2014–2017)
Secretary General, Division of Astrophysics, Cosmology, and Gravitation, AAPPS (2015–)
Secretary, Association of Asia Pacific Physical Societies (AAPPS) (2017–)

Organization and Advisory of Conferences

Steering committee member, COSMO conference series (2011–)
International organizing committee member, CosPA conference series (2010–)
Chair, RESCEU Symposium on General Relativity and Gravitation (2012)
Secretariat, CosPA2017 at Yukawa Institute for Theoretical Physics, Kyoto University (2017)
Chair, RESCEU Workshop on Space Gravitational-Wave Detection (2019)
LOC Chair, Gravitatioanal Wave Physics and Astrophysics Workshop (2019)
Deputy Chair, Asia Pacific Physics Conference (2019)

5.1.10 Outreach

Talks for high school students: 8
Outreach talks for general public: 12
Articles for children's news paper (上毛新聞子供版　科学のふしぎ): 32

5.1.11 Committee Service

External Committees

Member of C19, International Union for Pure and Applied Physics (2012- 2014, 2018–)
General Council member, Asia Pacific Center for Theoretical Physics (2013–2016)

Council member, Yukawa Institute for Theoretical Physics, Kyoto University (2010-2013, 2015-2017)
Member, Research Promotion Committee, IPNP, KEK (2017–)
Member, AAPPS Committee, Physical Society of Japan and JSAP (2015–)
Council member, Association of Asia Pacific Physical Societies (AAPPS) (2017–)

University Committees

理学部 4 号館長
理学系研究科国際交流委員

5.1.12 Internationalization Statistics

	Number	Country
Foreign students advised		
Bachelor Course	0	
Master Course	3	Switzerland, China, Indonesia
Doctor Course	2	China
Foreign researchers hosted	0	
Students sent abroad	2	USA, Germany
Researchers sent abroad	0	
Foreign visitors	> 200	including participants of the conferences I organized

5.2 観音切符, Kipp Cannon

5.2.1 Education and Professional Experiences

Education

1996	Specialized Honours Bachelor of Science in Physics	York University, Toronto
2003	Doctor of Philosophy in Physics	University of Alberta, Edmonton

Professional Appointments

2004–2007	Postdoctoral Researcher	University of Wisconsin-Milwaukee
2007–2010	Senior Postdoctoral Scholar	California Institute of Technology
2010–2016	Senior Research Associate	Canadian Institute for Theoretical Astrophysics
2016–2019	Associate Professor	The University of Tokyo
2019–	Professor	The University of Tokyo

5.2.2 Research Highlights

My group conducts research in the field of gravitational-wave (GW) astronomy. We have been focused on addressing the problem of the detection of signals in noisy data, specifically GW bursts from cosmic strings, the chirping signals from colliding neutron stars and black holes, and persistent stochastic GWs from distant, numerous, astrophysical sources. In collaboration with other research groups around the world, we have led the development of the GstLAL detection system.

Since joining the faculty of the Research Center for the Early Universe, the field of GW astronomy has undergone a tremendous transformation. Within days of starting my appointment, the first direct detection of GWs was announced by the LIGO Scientific Collaboration and Virgo Collaboration, with the discovery of the signal named GW150914. The GstLAL detection system provided the highest confidence for the detection claim. Three months later the GstLAL detection system identified the second high-confidence gravitational-wave signal, GW151226, the "boxing day" signal.

In the second observing run of the Advanced LIGO and Advanced Virgo detectors, the GstLAL system discovered GW170814, the first signal seen with the Advanced Virgo detector. This was the first signal seen with three detectors, it established Virgo to be a fully operational GW detector, and marked the first independent confirmation of LIGO's signal detection claims.

Three days later, the GstLAL system again make a unique discovery when it identified GW170817 in the LIGO data stream. This was the signal from a neutron star collision, and was followed 1.7 s later by a gamma ray burst identified by Fermi. A massive follow-up campaign discovered an optical transient counterpart, thereby pinpointing the precise location, allowing detailed observation across the entire electromagnetic spectrum, with associated searches for neutrinos and additional GWs. Although a very simple part of the observation of this signal, the short time difference between the arrival of the gamma rays and GWs implies gravity travels at the speed of light, differing by no more than one part in 10^{15}, and that has placed profound constraints on our understanding of gravity and the nature of space and time.

5.2.3 Selected Papers

- Abbott, B. P. et al. (LIGO Scientific Collaboration and Virgo Collaboration). Observation of gravitational waves from a binary black hole merger. Phys. Rev. Lett., 116(6):061102, February 2016. doi:10.1103/PhysRevLett.116.061102. (140th author of 1011), arXiv:1602.03837

[gr-qc].
This work reports the first direct detection of gravitational radiation, confirming General Relativity's predictions for the behaviour of merging black holes and the generation of a detectable flux of gravitational waves at astronomical distances, while revealing a significant population of high stellar mass black holes.

- Abbott, B. P. et al. (LIGO Scientific Collaboration and Virgo Collaboration). Binary black hole mergers in the first Advanced LIGO observing run. Phys. Rev., X6(4):041015, October 2016. doi:10.1103/PhysRevX.6.041015. (133rd author of 973), arXiv:1606.04856 [gr-qc].
  Summary of the discoveries of gravitational waves during the first observing run of Advanced LIGO.

- Abbott, B. P. et al. (LIGO Scientific Collaboration and Virgo Collaboration). GW170817: Observation of gravitational waves from a binary neutron star inspiral. Phys. Rev. Lett., 119(16):161101, October 2017. doi:10.1103/PhysRevLett.119.161101. (159th author of 1144), arXiv:1710.05832 [gr-qc].
  This work reports the discovery of GW170817, the gravitational waves from a neutron star collision in the galaxy NGC 4993.

- Abbott, B. P. et al. (LIGO Scientific Collaboration, Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The InsightHxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GWEM Collaboration, the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, JGEM, GROWTH, JAGWAR, Caltech NRAO, TTUNRAO, NuSTAR Collaborations, PanSTARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Wide-field Array, The CALET Collaboration, IKIGW Followup Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger 5Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS, RATIR, SKA South Africa/MeerKAT). Multimessenger observations of a binary neutron star merger. Astrophys. J., 848(2):L12, October 2017. doi:10.3847/20418213/aa91c9. (157th author of 3673), arXiv:1710.05833 [astro-ph.HE].
  This work reports analysis of the neutron star collision originally reported as GW170817. This paper has over 3000 authors, approximately 1/3 of the membership of the International Astronomical Union.

- Abbott, B. P. et al. (LIGO Scientific Collaboration, Virgo Collaboration, Fermi GammayRay Burst Monitor, and INTEGRAL). Gravitational waves and gammarays from a binary neutron star merger: GW170817 and GRB 170817A. Astrophys. J., 848(2):L13, October 2017. doi: 10.3847/20418213/aa920c. (157th author of 1177), arXiv:1710.05834 [astro-ph.HE].
  This work reports confirmation of the speed of gravity, constraining it to be c to better than one part in 10^{15}, strongly constraining our understanding of the nature of gravity.

5.2.4 Honors, Awards and Professional Society Memberships

Academic Honours

Name	Duration	Level
Dunlap Award for Innovation in Astronomical Research Tools[a]	2018	International
Princess of Asturias Award for Technical and Scientific Research[b]	2017	International
UK Royal Astronomical Society Group Achievement Award in Astronomy[c]	2017	International
American Astronomical Society Bruno Rossi Prize[d]	2017	International
Special Breakthrough Prize in Fundamental Physics[e]	2016	International
Gruber Prize in Cosmology[f]	2016	International

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[a] `http://www.dunlap.utoronto.ca/about/dunlap-award`

[b] `https://tinyurl.com/y9ker9k4`

[c] `https://tinyurl.com/y76krgvs`

[d] `https://tinyurl.com/y722h7dn`

[e] `https://breakthroughprize.org/Laureates/1/P4`

[f] `http://gruber.yale.edu/cosmology/2016/ligo-discovery-team`

Professional Society Memberships

- Canadian Astronomical Society (CASCA)
- Canadian Physical Society (CAP)

5.2.5 Research Plan

As the Japanese KAGRA GW detector comes online, we are looking forward to adding the additional data to the global network of GW detectors. Our group is leading the effort to expand the GstLAL detection system to include KAGRA data in future GW discoveries.

In the short term, we are developing the next generation of detection systems for GW bursts from cosmic strings. We are focusing on developing a system optimized for making statistically-sound detection claims rather than a system optimized for setting upper limits from null results.

We are developing an ultra high-speed GW source localization system to reduce the latency with which optical telescopes are informed of GW sources. This system will also be suitable for use in early warning applications, where the early part of a GW signal is used to alert optical and radio telescopes of an imminent collision.

Having developed highly successful solutions to the problem of GW signal detection, we are turning our attention to the interpretation of GW signals. We are working to understand the origin of the black holes seen with GW detectors by studying their population's statistical properties, for example their spin distributions and mass distributions. Perhaps the greatest challenge when analyzing the GW signals that we have discovered, uncovering what they can tell us about the universe, is the computational cost. Estimating the intrinsic parameters of the compact objects involved in neutron star collisions, for example, can take months or years of computer time running Markov-Chain Monte Carlo Bayesian parameter estimators; meanwhile, quantifying the selection biases present in the detection system itself currently relies on massive Monte Carlo simulation campaigns. Our group is working to address both of these difficulties, allowing us to lead the field going forward.

5.2.6 Publications and Patents

< Refereed Original Papers >

[1] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). All-sky search for long-duration gravitational wave transients with initial LIGO. *Phys. Rev.*, D93(4):042005, February 2016. doi:10.1103/PhysRevD.93.042005. (130th author of 934), `arXiv:1511.04398[gr-qc]`.

[2] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Astrophysical implications of the binary black-hole merger GW150914. *Astrophys. J. Lett.*, 818(2):L22, February 2016. doi:10.3847/2041-8205/818/2/L22. (137th author of 985), `arXiv:1602.03846[astro-ph.HE]`.

[3] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). The basic physics of the binary black hole merger GW150914. *Ann. Phys. (Berlin)*, 529(1-2):1600209, October 2016. doi:10.1002/andp.201600209. (130th author of 955), `arXiv:1608.01940[gr-qc]`.

[4] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Binary black hole mergers in the first Advanced LIGO observing run. *Phys. Rev.*, X6(4):041015, October 2016. doi: 10.1103/PhysRevX.6.041015. (133rd author of 973), `arXiv:1606.04856[gr-qc]`.

[5] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Characterization of transient noise in Advanced LIGO relevant to gravitational wave signal GW150914. *Class. Quant. Grav.*, 33(13):134001, June 2016. doi:10.1088/0264-9381/33/13/134001. (138th author of 987), `arXiv:1602.03844[gr-qc]`.

[6] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Comprehensive all-sky search for periodic gravitational waves in the sixth science run LIGO data. *Phys. Rev.*, D94(4):042002, August 2016. doi:10.1103/PhysRevD.94.042002. (132nd author of 960), `arXiv:1605.03233[gr-qc]`.

[7] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Directly comparing GW150914 with numerical solutions of Einstein's equations for binary black hole coalescence. *Phys. Rev.*, D94(6):064035, September 2016. doi:10.1103/PhysRevD.94.064035. (132nd author of 977), `arXiv:1606.01262[gr-qc]`.

[8] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). First low frequency all-sky search for continuous gravitational wave signals. *Phys. Rev.*, D93(4):042007, February 2016. doi:10.1103/PhysRevD.93.042007. (123rd author of 922), `arXiv:1510.03621[astro-ph.IM]`.

[9] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). A first targeted search for gravitational-wave bursts from core-collapse supernovae in data of first-generation laser interferometer detectors. *Phys. Rev.*, D94(10):102001, November 2016. doi:10.1103/PhysRevD.94.102001. (134th author of 967), `arXiv:1605.01785[gr-qc]`.

[10] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GW150914: First results from the search for binary black hole coalescence with Advanced LIGO. *Phys. Rev.*, D93(12):122003, June 2016. doi:10.1103/PhysRevD.93.122003. (136th author of 980), `arXiv:1602.03839[gr-qc]`.

[11] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GW150914: Implications for the stochastic gravitational-wave background from binary black holes. *Phys. Rev. Lett.*, 116(13):131102, March 2016. doi:10.1103/PhysRevLett.116.131102. (133rd author of 957), `arXiv:1602.03847[gr-qc]`.

[12] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GW150914: The Advanced LIGO detectors in the era of first discoveries. *Phys. Rev. Lett.*, 116(13):131103, March 2016. doi:10.1103/PhysRevLett.116.131103. (134th author of 959), `arXiv:1602.03838[gr-qc]`.

[13] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). GW151226: Observation of gravitational waves from a 22-solar-mass binary black hole coalescence. *Phys. Rev. Lett.*, 116(24):241103, June 2016. doi:10.1103/PhysRevLett.116.241103. (133rd author of 977), `arXiv:1606.04855[gr-qc]`.

[14] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). An improved analysis of GW150914 using a fully spin-precessing waveform model. *Phys. Rev.*, X6(4):041014, October 2016. doi:10.1103/PhysRevX.6.041014. (133rd author of 989), `arXiv:1606.01210[gr-qc]`.

[15] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration, ASKAP Collaboration, BOOTES Collaboration, Dark Energy Survey and Dark Energy Camera GW-EM Collaborations, Fermi GBM Collaboration, Fermi LAT Collaboration, Integral Collaboration, iPTF Collaboration, J-GEM Collaboration, Liverpool Telescope Collaboration, LOFAR Collaboration, MASTER Collaboration, MAXI Collaboration, MWA Collaboration, Pan-STARRS Collaboration, PESSTO Collaboration, Pi of the Sky Collaboration, SkyMapper Collaboration, Swift Collaboration, TAROT, Zadko, Algerian National Observatory and C2PU Collaboration, TOROS Collaboration, and VISTA Collaboration). Localization and broadband follow-up of the gravitational-wave transient GW150914. *Astrophys. J. Lett.*, 826(1):L13, July 2016. doi:10.3847/2041-8205/826/1/L13. (137th author of 1590), `arXiv:1602.08492[astro-ph.HE]`.

[16] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Observation of gravitational waves from a binary black hole merger. *Phys. Rev. Lett.*, 116(6):061102, February 2016. doi:10.1103/PhysRevLett.116.061102. (140th author of 1011), `arXiv:1602.03837[gr-qc]`.

[17] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Observing gravitational-wave transient GW150914 with minimal assumptions. *Phys. Rev.*, D93(12):122004, June 2016. doi:10.1103/PhysRevD.93.122004. (135th author of 969), `arXiv:1602.03843[gr-qc]`.

[18] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Properties of the binary black hole merger GW150914. *Phys. Rev. Lett.*, 116(24):241102, June 2016. doi:10.1103/PhysRevLett.116.241102. (135th author of 988), `arXiv:1602.03840[gr-qc]`.

[19] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Prospects for observing and localizing gravitational-wave transients with Advanced LIGO and Advanced Virgo. *Living Rev. Relat.*, 19(1):1, February 2016. doi:10.1007/lrr-2016-1. (130th author of 943), `arXiv:1304.0670[gr-qc]`.

[20] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). The rate of binary black hole mergers inferred from Advanced LIGO observations surrounding GW150914. *Astrophys. J. Lett.*, 833(1):L1, November 2016. doi:10.3847/2041-8205/833/1/L1. (134th author of 965), `arXiv:1602.03842[astro-ph.HE]`.

[21] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Results of the deepest all-sky survey for continuous gravitational waves on LIGO S6 data running on the Einstein@Home volunteer distributed computing project. *Phys. Rev.*, D94(10):102002, November 2016. doi:10.1103/PhysRevD.94.102002. (131st author of 956), `arXiv:1606.09619[gr-qc]`.

[22] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Search for transient gravitational waves in coincidence with short-duration radio transients during 2007–2013. *Phys. Rev.*, D93(12):122008, June 2016. doi:10.1103/PhysRevD.93.122008. (134th author of 998), `arXiv:1605.01707[astro-ph.HE]`.

[23] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Search of the Orion spur for continuous gravitational waves using a loosely coherent algorithm on data from LIGO interferometers. *Phys. Rev.*, D93(4):042006, February 2016. doi:10.1103/PhysRevD.93.042006. (123rd author of 921), `arXiv:1510.03474[gr-qc]`.

[24] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Tests of general relativity with GW150914. *Phys. Rev. Lett.*, 116(22):221101, May 2016. doi:10.1103/PhysRevLett.116.221101. (135th author of 980), `arXiv:1602.03841[gr-qc]`.

[25] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Upper limits on the rates of binary neutron star and neutron-star–black-hole mergers from Advanced LIGO's first observing run. *Astrophys. J. Lett.*, 832(2):L21, November 2016. doi:10.3847/2041-8205/832/2/L21. (132nd author of 958), `arXiv:1607.07456[astro-ph.HE]`.

[26] Adrián-Martínez, S. *et al.* (Antares Collaboration and IceCube Collaboration and LIGO Scientific Collaboration and Virgo Collaboration). High-energy neutrino follow-up search of gravitational wave event GW150914 with ANTARES and IceCube. *Phys. Rev.*, D93(12):122010, June 2016. doi:10.1103/PhysRevD.93.122010. (571st author of 1400), `arXiv:1602.05411[astro-ph.HE]`.

[27] Farr, B., Berry, C. P. L., Farr, W. M., Haster, C.-J., Middleton, H., Cannon, K., Graff, P. B., Hanna, C., Mandel, I., Pankow, C., Price, L. R., Sidery, T., Singer, L. P., Urban, A. L., Vecchio, A., Veitch, J., and Vitale, S. Parameter estimation on gravitational waves from neutron-star binaries with spinning components. *Ap. J.*, 825(2):116, July 2016. `LIGO-P1500117`.

[28] Abbot, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). All-sky search for periodic gravitational waves in the O1 LIGO data. *Phys. Rev.*, D96(6):062002, September 2017. doi:10.1103/PhysRevD.96.062002. (147th author of 1068), `arXiv:1707.02667[gr-qc]`.

[29] Abbot, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). First low-frequency Einstein@Home all-sky search for continuous gravitational waves in Advanced LIGO data. *Phys. Rev.*, D96(12):122004, December 2017. doi:10.1103/PhysRevD.96.122004. (146th author of 1061), `arXiv:1707.02669[gr-qc]`.

[30] Abbot, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). First narrow-band search for continuous gravitational waves from known pulsars in advanced detector data. *Phys. Rev.*, D96(12):122006, December 2017. doi:10.1103/PhysRevD.96.122006. (154th author of 1117), `arXiv:1710.02327[gr-qc]`.

[31] Abbot, B. P. *et al.* (LIGO Scientific Collaboration, Virgo Collaboration, 1M2H Collaboration, Dark Energy Camera GW-EM Collaboration and the DES Collaboration, DLT40 Collaboration, Las Cumbres Observatory Collaboration, VINROUGE Collaboration, MASTER Collaboration). A gravitational-wave standard siren measurement of the Hubble constant. *Nature*, 551:85–88, November 2017. doi:10.1038/nature24471. (167th author of 1422), `arXiv:1710.05835[astro-ph.CO]`.

[32] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). All-sky search for short gravitational-wave bursts in the first Advanced LIGO run. *Phys. Rev.*, D95(4):042003, February 2017. doi:10.1103/PhysRevD.95.042003. (138th author of 986), `arXiv:1611.02972[gr-qc]`.

[33] Abbott, B. P. *et al.* (LIGO Scientific Collaboration). Calibration of the Advanced LIGO detectors for the discovery of the binary black-hole merger GW150914. *Phys. Rev.*, D95(6):062003, March 2017. doi:10.1103/PhysRevD.95.062003. (91st author of 722), `arXiv:1602.03845[gr-qc]`.

[34] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Directional limits on persistent gravitational waves from Advanced LIGO 's first observing run. *Phys. Rev. Lett.*, 118(12):121102, March 2017. doi:10.1103/PhysRevLett.118.121102. (141st author of 996), `arXiv:1612.02030[gr-qc]`.

[35] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Effects of waveform model systematics on the interpretation of GW150914. *Class. Quant. Grav.*, 34(10):104002, April 2017. doi:10.1088/1361-6382/aa6854. (138th author of 990), `arXiv:1611.07531[gr-qc]`.

[36] Abbott, B. P. *et al.* (LIGO Scientific Collaboration and Virgo Collaboration). Erratum: Upper limits on the stochastic gravitational-wave background from Advanced LIGO 's first observing run [Phys. Rev. Lett. 118, 121101 (2017)]. *Phys. Rev. Lett.*, 119(12):029901, July 2017. doi:10.1103/PhysRevLett.119.029901. (141st author of 995).

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< Conference Proceedings >

< Review Papers >

< Books >

< Patent Applications >

5.2.7 Invited Presentations at International Conferences

2016-02-08, Research Center for the Early Universe, University of Tokyo, “Searching for Compact Object Collisions with Latencies of Seconds.”

2016-02-12, Department of Physics, University of Tokyo, “Summary of Advanced LIGO’s Observation of GW150914, a Binary Black Hole Merger.”

2016-02-18, 4th Annual Symposium of the Innovative Area on Multi-messenger Study of Gravitational Wave Sources, IPMU, “Initial Results From Advanced LIGO’s First Science Run.”

2016-02-21, KAGRA Face-to-face, University of Tokyo, “Initial Results From Advanced LIGO’s First Science Run.”

2016-02-23, KEK, Tsukuba, “Initial Results From Advanced LIGO’s First Science Run.”

2016-03-07, RIKEN, Wakoshi, “Initial Results From Advanced LIGO’s First Science Run.”

2016-03-29, Canadian Insitute for Theoretical Astrophysics, Toronto, “Initial Results From Advanced LIGO’s First Science Run.”

2016-05-20, NAOJ, Tokyo, “Initial Results From Advanced LIGO’s First Science Run.”

2016-06-15, Perimeter Institute, Waterloo, “GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence.”

2016-06-29, Kavli IPMU, “GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence.”

2016-09-23, Japan Physical Society Meeting, Miyazaki, “Latest Results from Advanced LIGO’s First Observing Run.”

2016-10-30, Gravitation and the Universe, Hanoi, “Latest Results from Advanced LIGO’s First Observing Run.”

2016-11-01, Irago, University of Electro-Communications Tokyo, “Latest Results from Advanced LIGO’s First Observing Run.”

2017-07-12, Dark Side of the Universe, Daejeon, “Status of LIGO and Virgo and Future Prospects.”

2017-11-09, Astrophysical Big Bangs, RIKEN, Wakoshi, “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral.”

2017-11-15, RIKEN, Wakoshi, “Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA.”

2017-11-20, University of Tokyo, “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral.”

2017-12-15, CosPA, Kyoto University, “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral.”

2017-12-19, Cherenkov Telescope Array Meeting, University of Tokyo, “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral.”

2018-02-05, Physics and Astronomy at the eXtreme (PAX), Pennsylvania State University, “Low-Latency Compact Object Detection: Technical Summary.”

2018-03-24, Japan Physics Society Meeting, Kashiwa, “Back story of GW170817 and Electromagnetic Follow-up Observations.”

2018-05-22, Dunlap Prize lecture, Canadian Astronomical Society Annual Meeting, “The Unlikely Dawn of Joint Gravitational-Wave and Electromagnetic Astronomy.”

2018-10-07, Taipei Gravitational-Wave Group Conference, “Identification and Significance Assessment of Compact Object Merger Candidates.”

5.2.8 Teaching Accomplishment

Student and Postdoctoral Supervision

	Supervision		Co-supervision		Defence committee
	In progress	Completed	In progress	Completed	
Undergraduate:	.	.	.	.	—
Master's:	3	3	.	.	2
Doctoral:	4	.	.	.	4
Postdoctoral:	2	.	.	.	—

Postdoctoral Fellows

- (2018/11–) Dr. Heather Fong. JSPS Postdoctoral Fellowship for Research in Japan.
- (2018/04–) Dr. Koh Ueno (上野昂).

Doctoral Students

- (2019/04–) Mr. Hiroaki Ohta (太田博章).
- (2019/04–) Mr. Daichi Tsuna (津名大地).
- (2018/04–) Mr. Leo Tsukada (塚田怜央).
- (2017/06–) Mr. Soichiro Morisaki (森崎宗一郎).

Master's Students

- (2019/04–) Ms. Minori Shikauchi (鹿内みのり).
- (2018/09–) Mr. Chan Chi-Wai.
- (2018/04–) Mr. Takuya Tsutsui (筒井拓也).
- (2017/06–2018/04) Mr. Leo Tsukada (塚田怜央).
- (2017/04–2019/04) Mr. Hiroaki Ohta (太田博章).
- (2017/04–2019/04) Mr. Daichi Tsuna (津名大地).

5.2.9 Contribution to Academic Community

Editorial Activities

Organization of Professional Societies

Organization and Advisory of Conferences

- Chair of Scientific Organizing Committee for Gravitational-Wave Astrophysics in the High Event Rate Regime 2016, Tokyo, Japan.
- Scientific Organizing Committee for Gravitational Wave Physics and Astronomy Workshop (GWPAW) 2017, Annecy, France.
- Scientific Organizing Committee for GWPAW 2018, Maryland, USA.
- Chair of Scientific Organizing Committee for GWPAW 2019, Tokyo, Japan.

5.2.10 Outreach

- 2016-10-02, Presentation to Japanese high school teachers at Toyama University, “The Significance of the Detection of Gravitational Waves.”
- 2017-09-19, High school student seminar at Ryerson University, Toronto, “The Significance of the Detection of Gravitational Waves.”
- 2017-10-17, Press Conference at The University of Tokyo, “Discovery of a new kind of gravitational wave source.”
- 2017-10-20, Nerd Nite Tokyo, “Gravitational Radiation, or: How I Learned to Stop Worrying and Love Black Hole Collisions.”
- NHK’s コズミック　フロント☆ＮＥＸＴ (Cosmic Front NEXT) episode titled “重力波　天文学を変えた奇跡の２週間” (Gravitational Waves: 2 Weeks That Changed Astronomy)
- 2018-03-27, The 30th Open Lecture at The University of Tokyo (第30回東京大学理学部公開講演会), “Discovery of Gravitational Waves from a Neutron Star Collision.”

5.2.11 Committee Service

External Committees

University Committees

5.2.12 Internationalization Statistics

	Number	Country
Foreign students advised		
Bachelor Course	0	
Master Course	1	
Doctor Course	0	
Foreign researchers hosted	1	Canada
Students sent abroad	3	France, UK, USA
Researchers sent abroad	0	
Foreign visitors	27	Canada, USA

5.3 茂山俊和, Toshikazu Shigeyama

5.3.1 Education and Professional Experiences

Education

1984	B.S. (Astronomy)	The University of Tokyo
1986	MSc. (Astronomy)	The University of Tokyo
1989	Ph. D. (Astronomy)	The University of Tokyo

Professional Appointments

1989−1991	Postdoctoral Fellow	Japan Society for the Promotion of Science (PD)
1991−1992	Postdoctoral Fellow	Max-Planck Institute for Astronomy and Astrophysics
1992−1998	Assistant Professor	The University of Tokyo
1999−	Associate Professor	The University of Tokyo

5.3.2 Research Highlights

I have been investigating dynamical aspects of astrophysical transient phenomena including supernovae, novae, and gamma-ray bursts from theoretical points of view. I will pick up two high lights from these activities in the following paragraphs. In addition to these activities, for these 4 years, I have had a collaboration with observers who have been developing very unique Tomo-e camera installed on the Kiso Schmidt telescope [36, 37, 43, 44] and contributed to its construction as the PI of a JSPS Kakenhi Grant-in-Aid for Scientific Research(S) (Study of neutron star merger by high cadence optical observations) by providing funds for CMOS chips.

Though we have a consensus that type Ia supernova is a thermonuclear explosion of a massive white dwarf composed of carbon and oxygen, we do not know how a massive white dwarf explodes as observed. There are two major scenarios to be tested. The single degenerate (SD) scenario, in which a white dwarf in a binary system accretes matter from the companion star to increase its mass close to the Chandrasekhar limit and ignites carbon fusion reactions near the center. The other scenario referred to as the double degenerate (DD) scenario involves two white dwarfs in a close binary system. The two stars eventually merge due to the energy loss by emitting gravitational waves and ignite helium and/or carbon burning. One of the possible tests is to use emission from type Ia supernovae in the early phases (the first few days). According to the SD scenario, some parts of the supernova ejecta must collide with the companion star. This collision should emit additional UV and optical photons in directions that are not covered by the ejecta. We constructed a 2-D radiation hydrodynamic code to calculate this process and were ready to quantitatively test this scenario by actual observations [20, 23]. The supernova survey using the Hyper Suprime Camera (HSC) mounted on the Subaru telescope found a type Ia supernova with additional emission in its early light curve in 2014 [11]. We tried to fit the observed light curve with this companion interaction model and found that the emission is too red to be compatible with the model prediction. We concluded that this supernova added extra emission due to radio active elements produced by detonation triggered by helium burning on the surface of the white dwarf. This helium detonation is expected to produce a shock wave propagating inward and the shock eventually ignites carbon burning near the central region. Though this explanation can reproduce all the observational features of this phenomenon, we could not specify which of the two scenarios actually worked.

The Hubble Space Telescope detected very red emission in the afterglow of a short duration gamma-ray burst GRB130603B in 2013. This detection was consistent with a prediction from the so called kilo-nova model. Kilo-nova is thought to be high speed matter ejected as a result of binary neutron star merger. The ejecta are exclusively composed of extremely neutron rich radioactive elements synthesized by rapid neutron capture reactions. Since these heavy elements heat up the ejecta and their first ionized ions are much more opaque to optical photons than any other elements, kilo-nova becomes bright only in the infrared after the ejecta cool down. If a neutron star merger is the origin of these elements, we need only one neutron star merger event per every 100,000 yrs to explain the amount of r-process elements in our galaxy. I noticed that if we look into a dwarf galaxy 100,000 times less massive (fainter) than our galaxy, we may be able to extract the information provided by a single event in spectra of stars in the dwarf galaxy. We found such a signature in the existing data of stars in the Draco spheroidal dwarf galaxy and a few others[25, 22]. In addition, we successfully predicted the rate of neutron star mergers from the observed abundance correlation of an r-process element Eu with Fe of stars in more massive dwarf galaxies before the detection of gravitational wave from a neutron star merger event GW180817. To confirm the origin of r-process elements, we performed spectroscopic observations for stars in some dwarf spheroidal galaxies[10]. We also constructed a chemical evolution model of r-process elements originating from neutron star mergers[15] and calculated their contributions to heavy element cosmic rays[12].

5.3.3 Selected Papers

- Tsujimoto, T., & Shigeyama, T. 2014, Astronomy & Astrophysics, 565, L5
  This paper was selected as one of editor's choices in Astronomy & Astrophysics.

- Jiang, J.-A., Doi, M., Maeda, K., Shigeyama, T., et al. 2017, Nature, 550, 80
  This work captured the smoking gun of the trigger that led to the explosion of a white dwarf for the first time.

- Kutsuna, M., & Shigeyama, T. 2015, Publications of the Astronomical Society of Japan, 67, 54
  This work presented an observational test for the SD scenario of type Ia supernovae and motivated supernova surveys using the Subaru telescope.

- Komiya, Y., & Shigeyama, T. 2016, The Astrophysical Journal, 830, 76
  This is the first paper that comprehensively discusses a role of neutron star mergers as the origin of r-process elements in our galaxy.

- Kashiyama, K., Fujisawa, K., & Shigeyama, T. 2019, arXiv e-prints, arXiv:1907.12317, accepted for publication in The Astrophysical Journal
  This work provides a basis for one of our future projects.

5.3.4 Honors, Awards and Professional Society Memberships

Member of the Astronomical Society of Japan
Member of the Physical Society of Japan
Member of the International Astronomical Union

5.3.5 Research Plan

Test the Scenarios for Type Ia Supernovae

To test the SD and DD scenarios for type Ia supernovae, we will continue to search type Ia supernovae in the early phases with Tomo-e and Subaru HSC in collaboration with observers [5, 11]. This mainly tests the SD scenario. My contribution will be to examine whether observed light curves show blue components originating from the collision between the companion and ejecta by using our theoretical 2D model[20]. In addition, we will take a different approach. Using a model for rotating objects produced as a result of double white dwarf merger recently constructed by Kashiyama, Fujisawa, and Shigeyama [1], we will try to derive the maximum value of the initial total mass for all the possible combinations of white dwarf pairs. This approach can test the DD scenario (at least constrain the range of the total mass of merging white dwarfs that will result in a type Ia supernova) from a theoretical point of view. A blind survey with Tomo-e will find rapidly rotating white dwarfs (with spin periods of a few seconds) by using a pipe line developed by a team led by Kashiyama. Some of these objects must be nascent merger products. We will also try to measure spin rates of known possible merger products like R Coronae Borealis stars and Sakurai's objects with Tomo-e. Accumulation of such data will enable us to construct an observational view for the evolution of merging products of double white dwarf.

Origin of r-process Elements in Connection with Transient Astrophysical Phenomena

I will continue to explore the abundances of r-process elements on the surfaces of old stars in the Milky Way halo and local dwarf spheroidal galaxies [10, 19, 22, 25]. These are key observations to derive the rate of events that produce these elements. At the same time, I would like to contribute to optical follow up observations for binary neutron star mergers (and black hole neutron star mergers). Tomo-e will certainly be one of the best instruments to localize these events immediately after the gravitational-wave detections especially for nearby events. Tomo-e will be able to send alerts to other bigger telescopes to perform scientific observations. I will theoretically explore emission in the very early phase of the events and try to develop a method to extract some information on dynamics of ejecta from observed spectra. At present, the only available spectra observed from GW180817 lacks resolved line features probably due to too many lines of r-process elements in the optical bands. I would like to focus on theoretical prediction of spectra emitted from the outermost ejecta where only free neutrons are supposed to decay protons. Our rough estimates suggest that this emission can be observed within a few tens of minutes from nearby sources [10]. Because the ejecta include only hydrogen, we can expect some spectral features like Balmer series from this emission and extract information on the dynamics.

Other Targets of Time-Domain Astronomy Possible by Tomo-e Observations

Other targets for which Tomo-e will be able to search are failed supernovae, pulsars, shock breakout in supernovae, etc. and many other phenomena outside of my expertise. I have worked on some of these targets and will be able to make a certain contribution to the development of this field with Tomo-e and other facilities devoted to high cadence observations for transient objects.

5.3.6 Publications

< Refereed Original Papers >

[1] Kashiyama, K., Fujisawa, K., & Shigeyama, T. 2019, arXiv e-prints, arXiv:1907.12317, accepted for publication in The Astrophysical Journal

[2] Tsuna, D., Kashiyama, K., & Shigeyama, T., 2019, The Astrophysical Journal, 884, 87

[3] Suzuki, A., Maeda, K., & Shigeyama, T. 2019, The Astrophysical Journal, 870, 38

[4] Shigeyama, T., & Kashiyama, K. 2018, Publications of the Astronomical Society of Japan, 70, 107

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[6] Maeda, K., Jiang, J.-. an ., Shigeyama, T., et al. 2018, The Astrophysical Journal, 861, 78

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[14] Suzuki, A., Maeda, K., & Shigeyama, T. 2017, The Astrophysical Journal, 834, 32

[15] Komiya, Y., & Shigeyama, T. 2016, The Astrophysical Journal, 830, 76

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[17] Masuyama, M., Shigeyama, T., & Tsuboki, Y. 2016, Publications of the Astronomical Society of Japan, 68, 22

[18] Noda, K., Suda, T., & Shigeyama, T. 2016, Publications of the Astronomical Society of Japan, 68, 11

[19] Tsujimoto, T., Ishigaki, M. N., Shigeyama, T., et al. 2015, Publications of the Astronomical Society of Japan, 67, L3

[20] Kutsuna, M., & Shigeyama, T. 2015, Publications of the Astronomical Society of Japan, 67, 54

[21] Suzuki, A., & Shigeyama, T. 2014, The Astrophysical Journal, 796, 30

[22] Tsujimoto, T., & Shigeyama, T. 2014, The Astrophysical Journal Letters, 795, L18

[23] Maeda, K., Kutsuna, M., & Shigeyama, T. 2014, The Astrophysical Journal, 794, 37

[24] Ohtani, Y., Morii, M., & Shigeyama, T. 2014, The Astrophysical Journal, 787, 165

[25] Tsujimoto, T., & Shigeyama, T. 2014, Astronomy & Astrophysics, 565, L5

[26] Yasutake, N., Kotake, K., Kutsuna, M., & Shigeyama, T. 2014, Publications of the Astronomical Society of Japan, 66, 50

[27] Tsutsui, R., & Shigeyama, T. 2014, Publications of the Astronomical Society of Japan, 66, 42

[28] Ohtani, Y., Suzuki, A., & Shigeyama, T. 2013, The Astrophysical Journal, 777, 113

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[31] Bekki, K., Shigeyama, T., & Tsujimoto, T. 2013, Monthly Notices of the Royal Astronomical Society: Letters, 428, L31

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< Conference Proceedings >

[36] Kojima, Y., Sako, S., Ohsawa, R., et al. 2018, Proceedings of the SPIE 107091T

[37] Sako, S., Ohsawa, R., Takahashi, H., et al. 2018, Proceedings of the SPIE 107020J

[38] Kamae, T., Lee, S. H., Makishima, K., et al. 2017, Proceedings of the 7th International Fermi Symposium, 145

[39] Ohtani, Y., Suzuki, A., Shigeyama, T., et al. 2017, Supernova 1987A:30 Years Later - Cosmic Rays and Nuclei from Supernovae and Their Aftermaths, 51

[40] Shigeyama, T., Wada, K., & Ohtani, Y. 2017, 7 Years of MAXI: Monitoring X-ray Transients, 49

[41] Yasutake, N., Noda, T., Fujisawa, K., et al. 2017, 14th International Symposium on Nuclei in the Cosmos (NIC2016), 020616

[42] Komiya, Y., & Shigeyama, T. 2017, 14th International Symposium on Nuclei in the Cosmos (NIC2016), 020207

[43] Ohsawa, R., Sako, S., Takahashi, H., et al. 2016, Proceedings of the SPIE 991339

[44] Sako, S., Osawa, R., Takahashi, H., et al. 2016, Proceedings of the SPIE 99083P

[45] Komiya, Y., & Shigeyama, T. 2016, The General Assembly of Galaxy Halos: Structure, Origin and Evolution, 318

[46] Ishigaki, M. N., Tsujimoto, T., Shigeyama, T., et al. 2016, The General Assembly of Galaxy Halos: Structure, Origin and Evolution, 310

[47] Ohtani, Y., Suzuki, A., & Shigeyama, T. 2015, IAU General Assembly 29, 2256376

[48] Nitta Ishigaki, M., Tsujimoto, T., Shigeyama, T., et al. 2015, IAU General Assembly 29, 2254525

[49] Suzuki, A., Maeda, K., & Shigeyama, T. 2014, Proceedings of Swift: 10 Years of Discovery (SWIFT 10, 110

[50] Ohtani, Y., Suzuki, A., & Shigeyama, T. 2014, Proceedings of Swift: 10 Years of Discovery (SWIFT 10, 95

[51] Ohtani, Y., Morii, M., & Shigeyama, T. 2014, Suzaku-maxi 2014: Expanding the Frontiers of the X-ray Universe, 337

[52] Hamano, S., Kobayashi, N., Kondo, S., et al. 2014, American Institute of Physics Conference Series, 117

[53] Suzuki, A., & Shigeyama, T. 2012, Death of Massive Stars: Supernovae and Gamma-ray Bursts, 285

[54] Hamano, S., Kobayashi, N., Kondo, S., et al. 2012, Galactic Archaeology: Near-field Cosmology and the Formation of the Milky Way, 129

5.3.7 Invited Presentations at International Conferences

[1] Shigeyama, T. “Origin of r-process elements in dwarf spheroidal galaxies”, 2017,Workshop “Theories of Astrophysical Big Bangs”, 2017/11/10 at RIKEN

[2] Shigeyama, T., Wada, K., and Ohtani, Y.: “Bright novae - Indications of the spectrum of MAXI J0158-744”, 7 years of MAXI: Monitoring X-ray Transients (Wako, Japan, December 5-7, 2016)

5.3.8 Teaching Accomplishment

5.3.9 Contribution to Academic Community

Editorial Activities

Managing editor of Publications of the Astronomical Society of Japan 2011−2015

Organization of Professional Societies

Member of the board of directors 2011−2015
PASJ Board of Editors 2015−

Organization and Advisory of Conferences

Member of Organizing Committees of 14th International Symposium on Nuclei in the Cosmos XIV 2016

5.3.10 Outreach

2016年度仁科記念講演会「いかにして天然元素は合成されたか」茂山　俊和　2016年12月5日 東京大学安田講堂

5.3.11 Committee Service

External Committees

Member of External Committee of National Astronomical Observatory Japan 2012−2016

University Committees

5.3.12 Internationalization Statistics

	Number	Country
Foreign students advised		
Bachelor Course	0	
Master Course	0	
Doctor Course	0	
Foreign researchers hosted	0	
Students sent abroad	3	USA
Researchers sent abroad	4	USA
Foreign visitors	2	USA, India