Report on RESCEU
2005 –2012

Prepared for the External Review in January 2013

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

November 30, 2012

•RESCEU office & secretaries
Mailing Address: Research Center for the Early Universe
Graduate School of Science
The University of Tokyo
Bunkyo-ku, Tokyo 113-0033
Japan
Phone: +81-3-5841-4169
FAX: +81-3-5841-7638
e-mail address: resceu-sec@resceu.s.u-tokyo.ac.jp
WWW: http://www.resceu.s.u-tokyo.ac.jp

•Director; K. Makishima
Phone: +81-3-5841-4207
FAX: +81-3-5689-0465
e-mail address: maxima@phys.s.u-tokyo.ac.jp

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$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 8\pi G T_{\mu\nu}$

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 booklet provides an overview of RESCEU (Research Center for the Early Universe; ビッグバン宇宙国際研究センター), a member of the Graduate School of Science of the University of Tokyo, and describes its scientific activities, since 2005 when the last external review was held. It consists of the following three parts. The RESEU overview is given in Section 0 (zero). Sections 1 through 7 are devoted to 8-year records of seven RESCEU projects, as well as their future prospects. Finally, personal achievements of two RESCEU core members are given in Sections 8 and 9.

November 30, 2012
Kazuo Makishima
The Director of RESCEU

0 RESCEU OVERVIEW

0.1 History

RESCEU, Research Center for the Early Universe (ビッグバン宇宙国際研究センター), was established in April 1999, in the Graduate School of Science at the University of Tokyo. It is a successor to a more informal research organization with the same name (和名は初期宇宙研究センター), which was selected in 1995 by the Center-of-Excellence (COE) program of the Japan's Ministry of Education, Science, Sports and Culture. RESCEU is the last research center of the Graduate School of Science that was established before the University became a corporation.

RESCEU performs theoretical and observational researches of the early Universe, toward the construction of a unified picture of its origin and evolution. We combine "top down" approaches starting from first-principle theories, including in particular Big Bang and Inflationary cosmology (Early Universe Cosmology Division and Particle Cosmology Division; Fig. 2), with "bottom-up" ones using data from the forefront experiments and observatories, including wide coverage of all electromagnetic frequencies (in Early Universe Data Analysis Division; Fig. 2). In addition, we invite a limited number of researchers, mainly from the Department of Physics, the Department of Astronomy, and the Institute of Astronomy, to join us as *associate members* (§ 0.3.4).

In the fiscal year (FY) of 2009 when RESCEU became 10 years old, we made some major rearrangement of *projects* (§ 0.4), together with some updates in *associate RESCEU members* (§ 0.3.4). Late in the same FY, Junko S. HIRAGA joined us (Fig. 3) through a high competition, as one of the three new feminine assistant professors recruited by the Graduate School of Science. Thanks to the help by the Department of Physics, we have also succeeded in obtaining a new assistant professor position in FY2012, to which Teruaki SUYAMA was appointed (Fig. 3).

0.2 Research Objectives

In conducting our mission described above, RESCEU currently has the following two slogans. The meaning of the first one is given in Fig. 1.

1. To understand the universe through three domains, namely, baryons, dark matter, and dark energy.
2. To serve as an Eastern-Hemisphere Hub for astrophysics and cosmology.

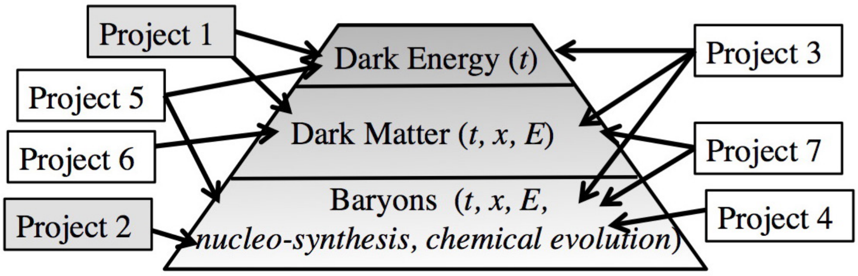


図 1: The research strategy of RESCEU, where t and x mean time and space, respectively. See § 0.4 for projects; gray boxes are theoretical, while white ones are observational and/or experimental.

0.3 Organization

0.3.1 Organization structure

Figure 2 illustrates the structure of RESCEU, as a member of the Graduate School of Science.

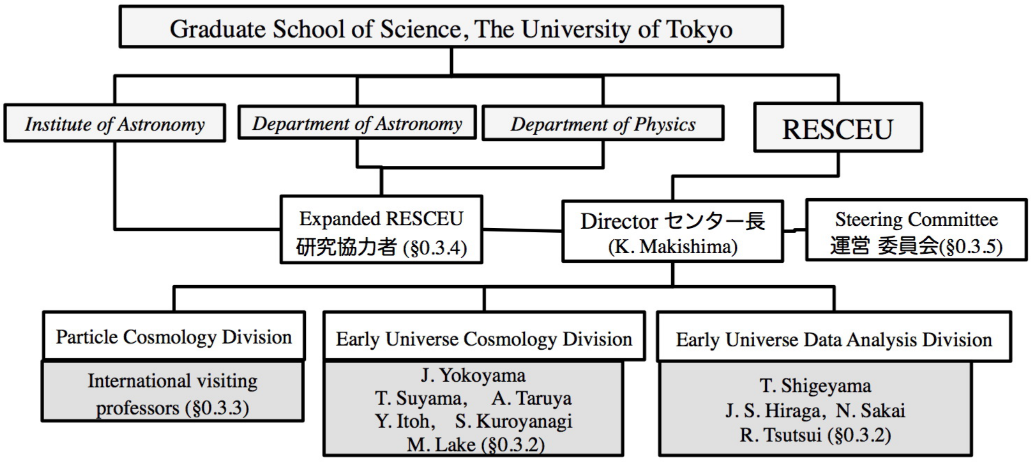


図 2: The RESCEU organization structure.

0.3.2 RESCEU members (staff)

In Fig. 3, the RESCEU staff members (called *proper members* to distinguish from *associate members* described in § 0.3.4) are given as a function of year. In addition to those shown here, RESCEU comprises two secretaries (Ms. Sayuri NAGANO and Ms. Mieko MINAMISAWA), and about 10 graduate students in the Department of Physics and the Department of Astronomy.

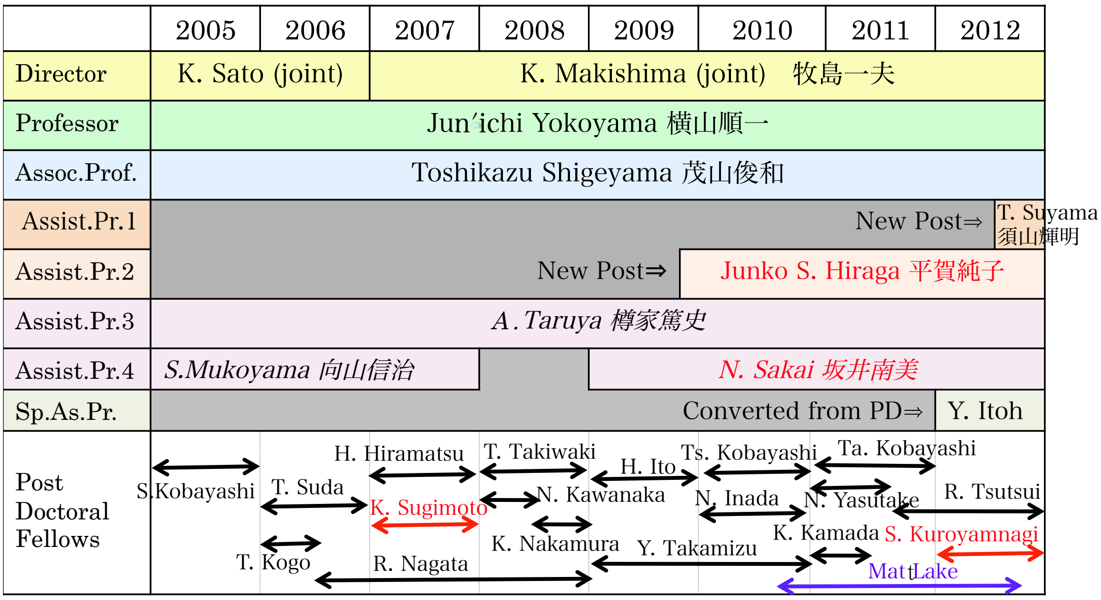


図 3: The RESCEU members. *Italics* indicate those working essentially in Physics department. Red means women, and blue international members. Visiting professors are listed separately in § 0.3.3.

0.3.3 International visiting professors

One of the outstanding features of RESCEU is that it has a position (with a built-in budget) for an international visiting professor. We can hence invite active overseas researchers to stay at RESCEU and get payed, for typical lengths of 1 through 3 months. Since FY2007, the use of this budget has become rather flexible. 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. They also serve, if available, as lectures for our summer school (§ 0.5.3).

表 1: List of international visiting professors since 2005.

FY2005	9/22–1/17	Bernard Carr	Queen Mary London Univ., Professor
FY2006	9/1–11/30	Sergey I. Blinnikov	Inst. Theor. & Exp. Phys. Moscow, Head Scientist
FY2007	9/1–9/30	Nemanja Kaloper	California Univ. Davis, Professor
	10/1–12/25	Sergey I. Blinnikov	Inst. Theor. & Exp. Phys. Moscow, Head Scientist
	1/7–3/31	Paolo Alberto Mazzali	Osservato rio Astronomico di Trieste, Professor
FY2008	4/25–5/24	Ewald Mueller	Max-Planck Inst. Astrophys,, Director of research
	5/21–6/20	Veniamin Berezinsky	Laboratori Nazionali del Gran Sasso, Director
	12/5–3/30	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
FY2009	6/15–8/14	徐 海光 Haiguang Xu	Shanghai Jiao Tong University, Professor
	3/30–9/5	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
	10/31–11/3	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
	1/4–3/31	Bernard Carr	Queen Mary London Univ., Professor
FY2010	8/1–9/29	Massimo Meneghetti	Bologna University, AssociateProfessor
	10/1–11/10	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
	1/18–3/30	Alexei A. Starobinsky	Landau Inst. for Theor. Phys., Major Research Scientist
	1/21–3/4	Edwin L. Turner	Princeton University, Professor
FY2011	4/18–6/6	Alexander Polnarev	Queen Mary London Univ., Reader in Math & Astr.
	5/12–6/15	Edwin L. Turner	Princeton University, Professor
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

0.3.4 Expanded RESCEU (研究協力者集団)

In addition to the visiting professorship described above, another special and important aspect of RESCEU is the concept of *expanded RESCEU* (研究協力者集団) illustrated in Fig. 4. In addition to the proper RESCEU members described in § 0.3.2, it comprises about 10 full/associate/assistant professors, to be called *associate RESCEU members* (研究協力者), who are mainly affiliated to the Department of Physics , the Department of Astronomy, and the Institute of Astronomy. This scheme reinforces the activity of RESCEU, which by itself is a very 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 associate RESCEU members, since their information is already given by their respective Departments.

Under close collaboration with the proper RESCEU members (§ 0.3.2; Fig. 3), the associated members carry out the overall research as detailed in § 0.4. To accomplish this mission, the associate members are allowed to use part of the RESCEU budget (§ 0.6). The associate members are selected under simple internal rules based on discussion in the *expanded RESCEU*, and are approved by the *steering committee* (運営委員会) described in § 0.3.5. Former associate members are given in § 0.4.

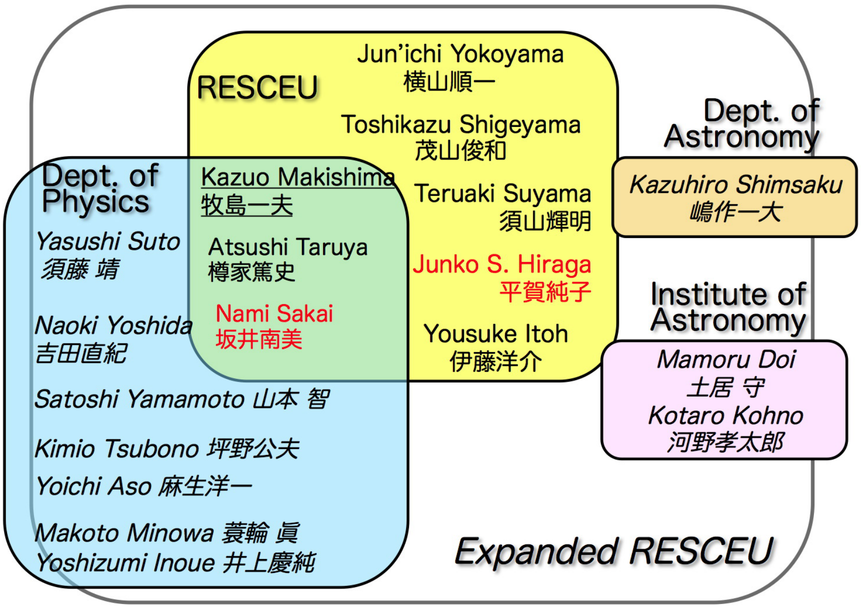


図 4: The expanded RESCEU structure. Associate members are indicated in *italic*. Red indicates women.

0.3.5 Steering committee (運営委員会)

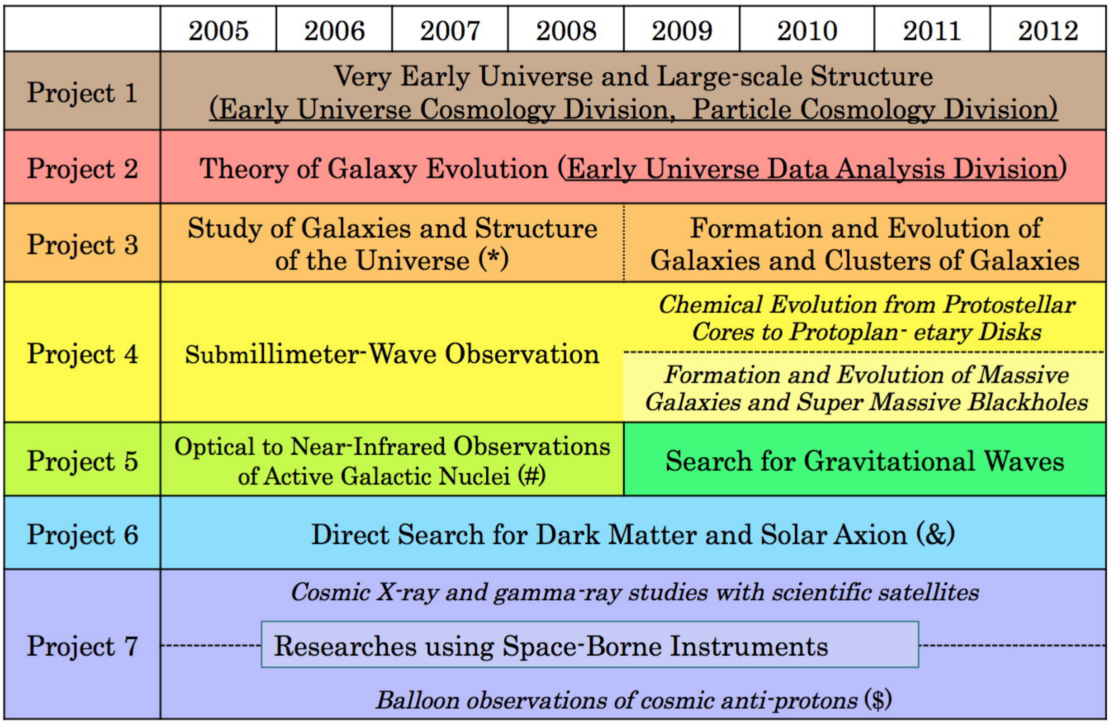
The highest-level decision of RESCEU is done by its *steering committee* (運営委員会), consisting of about 7 members from both inside and outside the Graduate School of Science. The committee approves the use of RESCEU budget, as well as personnel affairs including appointments/disappointments of associate RESCEU members. The committee also give advices as to future plans and directions of RESCEU. The current committee members are given in Table 2.

表 2: The RESCEU steering committee as of FY2012.

Name	Title / Position	Term (FY)
Hiroaki AIHARA 相原博昭	Dean, Graduate School of Science 東京大学 理学系研究科長・教授	2012-2013 *ex officio*
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	2011-2012
Ryugo HAYANO 早野龍五	Professor, Department of Physics 理学系研究科 物理学専攻 教授	2012-2013
Yuzuru YOSHII 吉井 譲	Director, Institute of Astronomy 理学系研究科 天文学教育研究センター長 ・教授	2012-2013
Kei ONAKA 尾中 敬	Professor, Department of Astronomy 理学系研究科 天文学専攻 教授	2012-2013
Kazuo MAKISHIMA 牧島一夫	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	2011-2012
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	2012-2013

0.4 RESCEU projects

RESCEU, in its *expanded* form, carries out its mission in a certain number of *projects*. As shown in Fig. 5, so far there have been 7 projects. Their detailed description is given in § 1 through § 7 of this booklet. From late FY2012 or the beginning of FY2013, we will add another project, on the study of extra-solar Pplanets (project title tentative; § 0.7.2). Former associate members (full and associated professors only) are listed in table 3.



	2005	2006	2007	2008	2009	2010	2011	2012
Project 1	Very Early Universe and Large-scale Structure (Early Universe Cosmology Division, Particle Cosmology Division)							
Project 2	Theory of Galaxy Evolution (Early Universe Data Analysis Division)							
Project 3	Study of Galaxies and Structure of the Universe (*)				Formation and Evolution of Galaxies and Clusters of Galaxies			
Project 4	Submillimeter-Wave Observation				*Chemical Evolution from Protostellar Cores to Protoplan- etary Disks* *Formation and Evolution of Massive Galaxies and Super Massive Blackholes*			
Project 5	Optical to Near-Infrared Observations of Active Galactic Nuclei (#)				Search for Gravitational Waves			
Project 6	Direct Search for Dark Matter and Solar Axion (&)							
Project 7	*Cosmic X-ray and gamma-ray studies with scientific satellites* Researches using Space-Borne Instruments *Balloon observations of cosmic anti-protons* ($)							

*: It was actually Project 6, but shown in this way because its continuation has become Project 3 since 2009.
#: It was actually Project 3, but shown at this position to make the figure simpler.
&: It was called Project 5 till 2009.
$: This sub-project will terminate at the end of FY2012.

図 5: History of the RESCEU projects. *Italics* show sub-project names, and underlines indicate the corresponding Division names in Fig. 2.

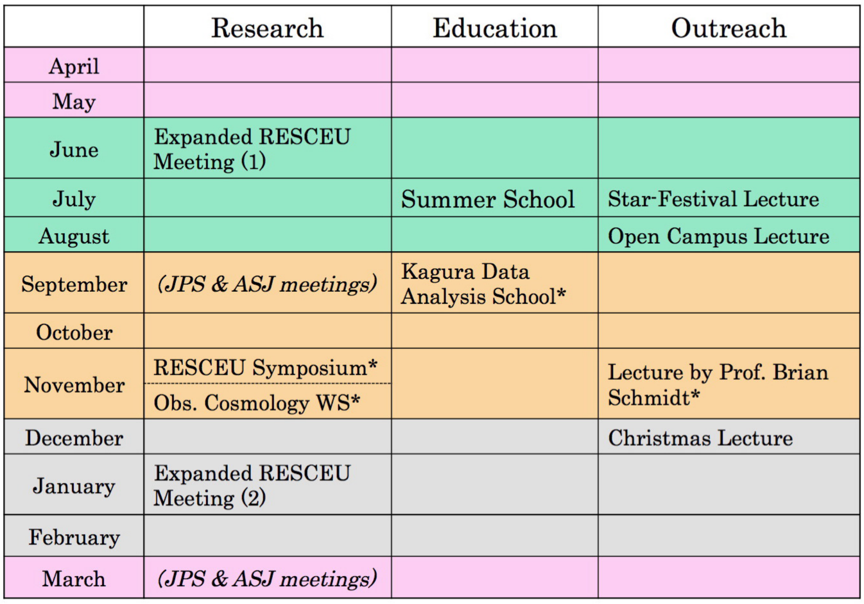
表 3: Former associate RESCEU members.

Ken'ichi NOMOTO	Dept. Astronomy	1999–2007	
Tsutomu YANAGIDA	Dept. Physics	1999–2007	
Yuzuru YOSHII	Inst. Astronomy	1999–2008	
Katsuhiko SATO	Dept. Physics	1999–2008	former Director
Sadanori OKAMURA	Dept. Astronomy	1999–2011	

0.5 RESCEU Activity

0.5.1 Annual activities

To represent annual RESCEU activities, Fig. 6 shows those in FY2012. Like the seven projects, these activities are mostly conducted on the scale of the *expanded RESCEU*.



	Research	Education	Outreach
April			
May			
June	Expanded RESCEU Meeting (1)		
July		Summer School	Star-Festival Lecture
August			Open Campus Lecture
September	*(JPS & ASJ meetings)*	Kagura Data Analysis School*	
October			
November	RESCEU Symposium* Obs. Cosmology WS*		Lecture by Prof. Brian Schmidt*
December			Christmas Lecture
January	Expanded RESCEU Meeting (2)		
February			
March	*(JPS & ASJ meetings)*		

図 6: Annual activities of RESCEU in 2012. Stars indicate non-regular ones, while *italics* show Japan Physical Society and Astronomical Society of Japan annual meetings to which many RESCEUmembers attend.

1. “The Cosmological Constant and the Evolution of the Universe” (7-10 November, 1995)
2. “Dark Matter in the Universe and its Direct Detection” (26-28 November, 1996)
3. “Particle Cosmology” (11-13 November, 1997)
4. “The Birth and Evolution of the Universe” (16-19 November, 1999)
5. “New Trends in Theoretical and Observational Cosmology” (13-16 November, 2001)
6. “Frontier in Astroparticle Physics and Cosmology” (4-7 November, 2003)
7. “Astroparticle Physics and Cosmology” (11-14 November, 2008)
8. “Resceu/JGRG22 Symp. on General Relativity and Gravitation” (12-16 November, 2012)

表 4: List of the RESCEU international symposia.

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0.5.2 International symposia

Exactly speaking, 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 approximately 200 foreign short-term visitors (besides those listed in Table 1). This characteristic is also featured by the series of RESCEU international symposia, listed in Table 4. Each symposium was attended typically by 100–200 participants, including a considerable fraction from abroad.

図 7: A group photo on the occasion of the 7th RESCEU Internatinoal Symposium, co-sponsored by the JSPS Core-to-Core program “DENET” (§ 0.6.3). This particular symposium commemorated the retirement of professor Katsuhiko Sato, the former RESCEU director.

0.5.3 RESCEU summer schools

RESCEU is a research, rather than an educational, organization. Nevertheless, the forefront research activity conducted in (the expanded) 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 10 graduate students, each belonging to 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 Fig. 8, in places away from the busiest city areas.

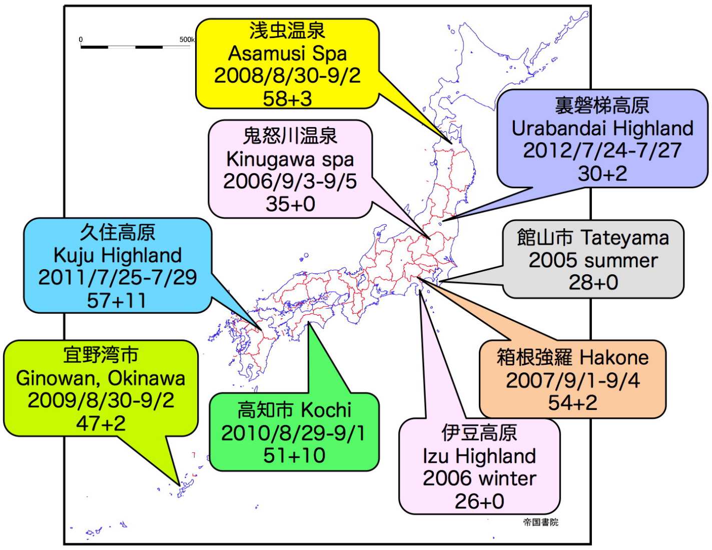


図 8: Locations and dates of the RESCEU summer school. The numbers indicate domestic and overseas participants. The 2012 location was purposely chosen to be in Fukushima prefecture, to help early recovery.


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第５回公開講演会

ビッグバンセンター
クリスマス講演会 2009 & Party
～Astrophysics, Astro-Chemistry, Astro-Biology～

12月25日（金）14:00-16:30
◎場所：東京大学理学部１号館中央棟２階 小柴ホール
◎講演者と演題（各30分＋質疑応答10分）
横山順一：「ビッグバンは見えてきたか」
坂井南美：「星の誕生と化学進化」
須藤　靖：「太陽系外惑星から宇宙生物学へ」
◎講演会終了後に小柴ホール前ホワイエにてパーティーが開かれます
◎問い合わせ先：toiawase@resceu.s.u-tokyo.ac.jp

入場無料
事前登録不要

credit: NASA

図 9: The poster for the first RESCEU Christmas Lecture, created by Dr. M. Nakashima (then a graduate student at RESCEU).

0.5.4 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 5, we have been conducting the following three regular outreach efforts.

1. Participation to the annual Star-Festival Lecture Campaign (全国同時七夕講演会), which is an event of near-simultaneous lectures all over Japan. It started as a part of "International Year of Astronomy 2009", and continues afterwards. Our lectures on this occasion are meant for young generation, particularly junior-high-school students.

2. The University 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 always becomes full to the doors.

3. Christmas lecture. This is a unique RESCEU attempt, which started in 2009. It is aimed mainly for under-graduate students in nearby universities, including of course our own. Figure 9 show the poster used to announce the first Christmas Lecture.

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

表 5: Public lectures sponsored by RESCEU. *Italic* means future plans.

2008	7.31	Open Campus	Y. Suto [#]	「宇宙は何からできている？」
			J. Yokoyama	「宇宙をあやつる暗黒エネルギー」
2009	7.7	Star Festival	Y. Suto [#]	「ガリレオが見た宇宙，見なかった宇宙」
	8.6	Open Campus[*]	Y. Suto [#]	「宇宙は何からできている？」
			T. Shigeyama	「元素はいつどこで出来たのか」
			J. Yokoyama	「宇宙をあやつる暗黒エネルギー」
			K. Makishima	「科学衛星でブラックホールを探る」
	12.25	Christmas	J. Yokoyama	「ビッグバンは見えてきたか」
			Nami Sakai	「星の誕生と化学進化」
			Y. Suto [#]	「太陽系外惑星から宇宙生物学へ」
2010	7.7	Star Festival	S. Okamura[#]	「宇宙ってなんだか知っていますか？」
	8.4	Open Campus[*]	J. Yokoyama	「宇宙をあやつる暗黒エネルギー」
			K. Kohno[#]	「観測により迫る宇宙の謎」
			K. Tsubono[#]	「重力波で宇宙を見る–検出実験の現状–」
	12. 22	Christmas	A. Taruya	「宇宙のものさし、バリオン音響振動」
			T. Shigeyama	「地球と恒星の密接な関係」
			Junko S. Hiraga	「X 線で観る宇宙」
20011	7.7	Star Festival	Nami Sakai	「星の誕生 – 太陽系の奇跡–」
	12.23	Open Campus[*]	J. Yokoyama	「重力波で探る宇宙の始まり」
			K. Shimasaku[#]	「銀河宇宙と私たち」
			M. Minowa[#]	「ニュートリノ–さまざまな実験方法–」
2012	7.7	Star Festival	K. Makishima	「天の川にひそむ多くの謎」
	8.7	Open Campus	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」
	12.25	*Christmas*	*T. Suyama*	*TBD*
			R. Tsutsui	*TBD*

[#] : Associate RESCEU members.
[*] : Merged with the Christmas Lecture because the Open Campus was shifted to December.
[&] : These lectures were given twice in the same day.

0.6 Budget

0.6.1 Budget evolution

RESCEU is run basically on the University budget (運営費交付金). As shown in Fig. 10, it is divided into basic running costs of the center (yellow), and those for the projects (blue). The former includes regular running costs of Yokoyama and Shigeyama Laboratories, personnel expenses for the secretaries and some of the PDs, and the costs for electricity, water, as well as for the summer school and other meetings. The salaries for the full/associate/assistant professors are not included here. Till FY2009, the expenses for the international visiting professors had been provided additionally, while it is included in the graph from FY2010. Pink in Fig. 10 is external funds acquired by the *proper* RESCEU members, which is detailed in the next subsection.

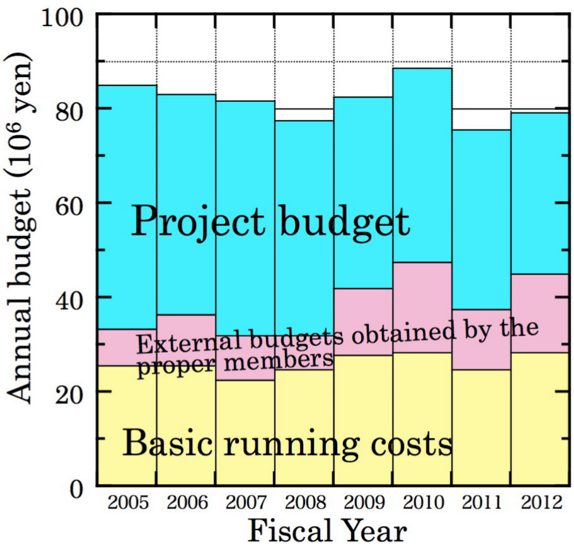


図 10: Annual RESCEU budget.

0.6.2 External funds

As listed in Table 6, the RESCEU members have been quite successful in acquiring external funds, particularly Grant-in-Aid for Scientific Research (科研費) from JSPS.

氏名	制度	種目	研究代表者	実施期間	直接経費総額（千円）	研究課題
横山　順一	科研費	基盤研究（B）	研究代表者	2004～2006	11,700	精細観測データに基づく宇宙進化史の研究
	科研費	基盤研究（B）	研究代表者	2007～2010	13,700	コズミックバリアンスを超克した次世代精細宇宙論の研究
	科研費	基盤研究（B）	研究代表者	2011～2014	15,000	重力波宇宙論の創成と展開
	科研費	新学術領域研究(分担	小玉　英雄	2010～2012	3,100	宇宙初期進化の直接観測に基づく究極理論探査
	二国間	日仏共同研究	研究代表者	2007～2008	5,000	精細観測データによる素粒子的初期宇宙進化史の解明
	二国間	日英共同研究	研究代表者	2009～2010	5,000	ブラックホール等でさぐる加速膨張宇宙の物理
	二国間	エジプトとのセミナー	研究代表者	2011	1,500	素粒子天体物理学でさぐる初期宇宙の進化
茂山　俊和	科研費	基盤研究（C）	研究代表者	2004～2007	2,100	超新星における相対論的輻射流体力学の研究
	科研費	特定領域研究	研究代表者	2009～2010	2,300	星の元素組成から探るガンマ線バースト母天体と矮小銀河の進化
	科研費	基盤研究（S）（分担）	青木　和光	2011～2015	1,100	宇宙初代星誕生から銀河系形成期における恒星進化と物質循環
向山　信治	科研費	若手研究（B）	研究代表者	2005～2007	2,300	高次元理論における初期宇宙論
樽家　篤史	科研費	若手研究（B）	研究代表者	2006～2008	2,900	宇宙背景重力波で探る宇宙の進化の探求
	科研費	若手研究（B）	研究代表者	2009～2011	2,800	宇宙大規模構造の高精度ル論テンプレートから探る精密宇宙論の研究
	科研費	基盤研究（C）	研究代表者	2012～2014	3,900	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	宇宙大規模構造の宇宙論的観測に向けた精密理論計算
坂井　南美	科研費	若手研究（B）	研究代表者	2009～2012	6,900	星形成領域の物理・科学的多様性とその惑星系円盤への伝播の解明
平賀　純子	科研費	基盤研究（C）	研究代表者	2010	600	アナログASICを用いた次世代厚型CCD検出器システムの開発
	科研費	基盤研究（S）（分担）	牧島　一夫	2010	1,000	銀河と銀河団プラズマの相互作用の研究
佐藤　勝彦	科研費	基盤研究（S）	研究代表者	2010～2011	23,300	超新星の爆発機構とガンマ線バースト源エンジンの統一的解明
須藤　靖	先端研究拠点事業		研究代表者	2007～2011	107,350	暗黒エネルギー研究国際ネットワーク

表 6: External funds acquired by the RESCEU staff (excluding the associate members).

0.6.3 DENET: International Research Network for Dark Energy

For 2007 through 2012, RESCEU has been aided by DENET (International Research Network for Dark Energy), which is a core-to-core program funded by JSPS (Japan Society of Promotion of Science) with French, British and US partners. PI of the program is Yasushi Suto, one of the associate RESCEU members, and three co-PI's include Edwin Turner at Princeton University, Jerome Martin at Institut d'Astrophysique de Paris, and John Peacock at The University of Edinburgh. The first two of them have actually stayed at RESCEU as international visiting professors (Table 1). The participating institutions of the program include, among others, The University of Tokyo, 4 other Japanese institutions, 5 United States organizations, 4 British universities, and two French ones.

The main purpose of DENET was to promote international collaborations on the study of dark energy in the universe, with particular emphasis on the exchange of young researchers among the participating institutions. As summarized below, DENET organized, from 2007 to 2012, five international conferences concerning dark energy in the universe.

1. "Decrypting the universe; Large Surveys for Cosmology" (October 24 to 26, 2007), jointly held with Royal Observatory Edinburgh.
2. "Cosmology Near and Far; Science with WFMOS" (May 19 to 21, 2008), held at Kona Marriot Hotel, Hawaii, as the first Subaru-Gemini Joint Science conference.
3. "Science Opportunities with Wide-Field Imaging and Spectroscopy of the Distant Universe" (November 9 to 11, 2009), jointly organized with Department of Astrophysical Sciences, Princeton University.
4. "The Observational Pursuit of Dark Energy after Astro2010" (October 7 to 9, 2010), held at Cahill Center for Astronomy and Astrophysics, Caltech.
5. "The Accelerating Universe" (24 to 26, 2011), held at Institut d'Astrophysique de Paris, in a timely fashion just after the 2011 Nobel Prize in Physics on exactly the same subject.

In addition to those international conferences, DENET cooperated with RESCEU for five years to jointly organized the summer schools described in § 0.5.3. 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.

The activities of DENET played a significant role in establishing the next generation wide-field imaging camera, Hyper-Suprime Cam (HSC), on Subaru telescope, as a collaboration among Japan, Princeton, and Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) at Taiwan. RESCEU (Project 3; § 3.3.7) is an important participant to the HSC project. In addition, the collaboration with Taiwan is in line with our second slogan presented in § 0.2.

0.7 Future Plans

Before national universities were reformed into corporations in 2004, a research center like RESCEU was supposed to have a typical duration of 10 years, at which point a scrap-and-build process was mandatory. Although this requirement is no longer applicable, we still believe that we need to re-structure ourselves continually. Thus, as described at the beginning (§ 0.1), RESCEU, foundation in 1999, has made moderate changes from FY2008 to FY2009. We will continue our effort of such self check and improvements, under the two leading principles given in § 0.2.

0.7.1 What is unique with RESCEU?

Even in Japan, RESCEU is not the only organization that is dedicated to the research of cosmology and astrophysics. We must be cooperating and competing with, for exmple, a few national research institutions like KEK and National Astronomical Observatory, and a considerable number of major universities. Even within the University of Tokyo, there are the Institute for Cosmic Ray Research, the Kavli Institute for the Physics and Mathematics of the Universe (IPMU), and the closest one, the Institute of Astronomy in the Graduate School of Science. To plan our future, a good exercise may be given by reviewing our uniqueness, which may be summarized below.

1. From the beginning in 1995 in its predecessor form, RESCEU has been configured as a flexible collaboration among *leaders in Japan-led international researches*, ranging from theoretical studies (Project 1, Project 2), to non-accelerator experiments (Project 6; § 6) and “big-science” type projects. The *expanded RESCEU* actually comprises leaders, e.g., in the world-renowned Subaru telescope (Project 3; § 3.3.1), the truly international ALMA telescope (Project 4; § 4.3, § 4.4), the Kagura Gravitational Wave detector under construction (Project 5; § 5.4), and the *Suzaku* and *ASTRO-H* X-ray Observatories (Project 7-1; § 7.3).
2. The built-in international visiting professor position (§ 0.3.3) is one of valuable advantages of RESCEU; such a positions is quite limited even all over the University of Tokyo, and is the only one in the Graduate School of Science. RESCEU is also playing an important role in astrophysics/cosmology research in the Asian-Pacific region.
3. The concept of *expanded RESCEU* has been

   enhancing flexible interactions and fusions among neighboring disciplines, including astronomy, astrophysics, cosmology, and particle physics. It will also serve as a cradle for novel sciences, including astrobiology and physics of spontaneous structure formation.
4. Thanks to the structural position of RESCEU, its research activity is closely connected with, and actually much enhanced by, the graduate education in physics and astronomy.
5. Among the competing research organizations, RESCEU is one of the few that have direct access to space technology provided by JAXA (Japan Aerospace Exploration Agency), including balloons, sounding rockets, artificial satellites, and the International Space Station. Although limited to Project 7 at present, this unique capability allows RESEU to potentially leads some future space experiments, including in particular the space gravitational wave experiments DECIGO and DPF (§ 1.4.1, § 5.3).

Having reviewed our uniqueness, below we describe our future strategy, considering a typical time span of 5 years.

0.7.2 Study of extra-solar planets

In the expanded RESCEU meeting held in June 2012 (Fig. 6), it was agreed among the proper and associate members that a new project, Project 8, dedicated to the study of extra-solar planes, should be created. This will take place within FY2012, or from the beginning of FY2013. Since such "exoplanet" studies have already been conducted by Y. Suto as part of Project 1 (§ 1.4.3), he will then move from Project 1 to Project 8 to lead it. The researches in Project 8 will have direct connections to those in Project 4-1 (S. Yamamoto and N. Sakai) using ALMA and other means, namely, studies of chemical and physical evolutions of molecular clouds, and formation of young stars therein.

To much enhance the education and research of extra-solar planets, RESCEU has also been collaborating with the Astronomy, Earth and Planetary Science, and Physics departments, as well as the Institute of Astronomy, asking for a new full-professor position from the University's contingency reservoir (定員再配分). Fortunately, we have succeeded in this effort, and a new professor will arrive in April 2013. Although he/she will formally belong to the Department of Astronomy, we will invite him/her, as a new associate member, to join RESCEU Project 8.

0.7.3 Gravitational waves

Another priority area of the RESCEU's near-future research is the search for Gravitational Waves (GW). Theoretically in Project 1, a certain form of background GW radiation is predicted by inflationary cosmology being studied by J. Yokoyama, and its detection would provide one of few direct means to diagnose truly "early" universe. Various cases of GW emission are calculated by Y. Itoh and S. Kuroyanagi. Experimentally, K. Tsubono (Project 5) is one of the Japan's leaders in gravitational-wave experiments (§ 5), and is deeply involved both in the Kagura (§ 5.4) and DECIGO/DPF (§ 5.3) projects, the latter having close relevance to Project 1.

The GW investigation is expected to enhance cross-project interactions, beyond those between Project 1 and Project 5. Studies of gamma-ray bursts in Project 2 (T. Shigeyama and R. Tsusui) and magnetars (T. Shigeyama in Project 2 and K. Makishima in Project 7) have close connections to the GW signals expected from mergers between two neutron stars. The DECIGO/DPF projects (§ 5.3) will profit from technical heritages accumulated in Project 7.

0.7.4 Other ross-project researches

As listed below, we may further identify a few additional research subjects that are suited to enhance cross-project interactions, and hence should be promoted with particular emphasis.

1. Optical deep surveys with Subaru. The term "Early Universe" may have dual meanings, one implying an early epoch before the "photon vs. matter decoupling" which took place at an age of 0.38 million years, while the other before the event of "cosmic reionization"

which occurred at a rough age of 0.25 billion years. While the GW background (§ 0.7.3) provides a powerful diagnostic for the epoch in the first meaning, the period between the two time-marking events may be studied by various deep surveys including in particular with the Subaru HSC (see § 0.6.3). This age, often called "dark age", is of high importance, because then the structure formation (mainly detectable with baryons) proceeded under the dominant role of dark matter, and the effects of dark energy gradually emerged. In view of Fig. 1, this is clearly one of the priority areas of RESCEU, and can be promoted through a collaboration between Project 3 and Project 1. Project 7 is also partially involved, because the key instrument, the Subaru HSC, uses the same CCD chips as used for *ASTRO-H* (Project 7-1; § 7.3.8) in the X-ray range, for which J. Hiraga is an important player.

2. Neutron-star (NS) magnetism and magnetars. As being studied theoretically in Project 2 (§ 2.5.1) and observationally in Project 7 (§ 7.3.4), magnetars are a special type of NSs with extreme magnetic fields reaching 10^{14-15} Gauss. Under a unique hypothesis that the magnetic field of NSs is a manifestation of nuclear ferromagnetism (Makishima et al. 1999), RESCEU can promote unique investigations of magnetars and the NS magnetism. We may even be collaborating with nuclear physicists and condensed-matter physicists. These subjects also have connections to Project 1 and Project 5, because NSs are expected to be the most promising GW emitters.

3. Interactions between galaxies and hot plasmas. As described in § 7.3.6, Project 7-1 (K. Makishima and collaborators) is discovering, with a help by Project 3 (K. Shimasaku), that galaxies in clusters have been falling to the cluster centers over the Hubble time. As predicted by Makishima et al. (2000), the driving force of this infall is considered to be magneto-hydrodynamical interactions between these galaxies and the X-ray emitting hot plasmas filling the cluster volume. This research subject will provide one of the best examples of the vital importance of joint efforts among different wavelengths.

1 PROJECT 1: Very Early Universe and Large-scale Structure

1.1 Project Members

Title	Name	Affiliation
Professor	Jun'ichi Yokoyama	RESCEU
Professor	Yasushi Suto	Department of Physics
Professor	Naoki Yoshida	Department of Physics
Assistant Prof.	Atsushi Taruya	RESCEU
Assistant Prof.	Teruaki Suyama	RESCEU
Research Associate	Yousuke Itoh	RESCEU

1.2 Objectives of the Project

The ultimate goal of this project is to clarify the birth and evolution of the Universe in terms of theories of fundamental physics as well as cosmological observations.

Over the last decades, cosmological observations using new technologies have developed greatly, and our fundamental view of the Universe has significantly advanced to establish the new standard model of the Universe, which incorporates cosmic inflation with the classical Big Bang model and the concordance values of the cosmological parameters, namely, 4% baryon, 23% dark matter, and 73% dark energy. In this model, inflation in the early Universe not only gives rise to the homogeneous, isotropic, and spatially flat background spacetime but also generates density and curvature fluctuations of quantum origin, thereby predicting the initial condition for the formation of the cosmic structure. While this model successfully reproduces the observed anisotropy of the cosmic microwave background radiation and large-scale structures, there remain fundamental questions such as the specific mechanism of inflation in the particle-physics context as well as the identities of dark matter and dark energy. Among them, the origin of the dark energy, which causes the accelerated cosmic expansion today, is the most serious question, delving into diverse fields of fundamental sciences ranging from astronomy to particle physics.

We grapple with the above-mentioned fundamental problems through bidirectional approaches as explained below.

1.3 Research Method

One is the top-down approach based on the theory of fundamental physics; this approach is used to construct a consistent scenario for cosmic history from the early Universe to the observed Universe. The other approach is the bottom-up approach aimed at revealing with high precision the current status of the Universe through observational data, which makes extensive use of the computer clusters at RESCEU. In connection with the latter approach, we are in close collaboration with Project 3 which is conducting wide-field optical surveys using the Subaru telescope, as well as Project 5 performing gravitational wave experiments.

1.4 Research Highlights

Here we describe our research highlights in the past six years from cosmology of the early Universe to the research on exoplanets.

1.4.1 Early Universe

Inflation in the most general single-field theory with second-order evolution equations

We proposed the generalized G-inflation model which is the most general single-field inflation model with its scalar and gravitational field equations being of second-order. Although our formulation was based on the generalized Galileon, we have shown that the underlying theory is equivalent with that proposed by Horndeski in 1974, that is, we have proved the uniqueness of the most general inflation theory even if apparently different description is possible. This model includes and can describe all the previously known single-field inflation models including the standard potential-driven inflation, k-inflation, G-inflation, DBI inflation, non-minimally coupled Higgs inflation, new Higgs inflation, and even R^2 inflation via conformal transformation. We have calculated power spectrum and bispectrum of primordial curvature and tensor perturbations and provided generic formulae, which are applicable to any inflation models with second-order field equations and hence greatly saves time to analyze each model. We have also constructed an explicit model to realize a large tensor-to-scalar ratio and large non-Gaussianity at the same time. Furthermore we have shown that all three known Higgs inflation models can be unified to the generalized G-inflation model and further discovered two more mechanisms to make the standard Higgs field the inflaton.

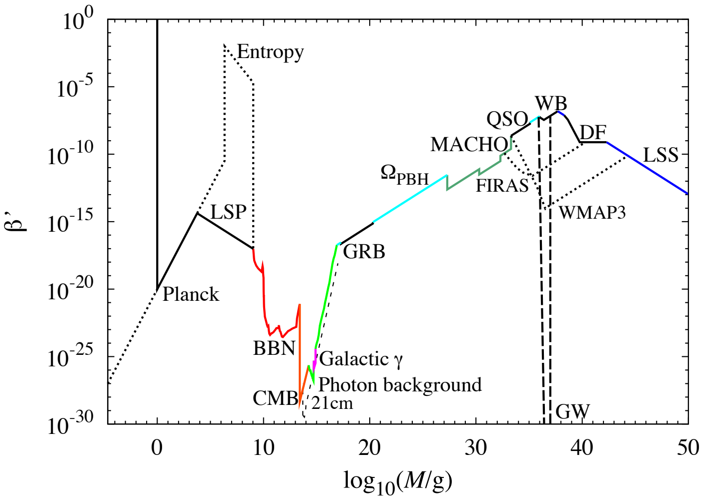
Proposal of the gravitational-wave cosmology

Gravitational waves are the most promising observational means which have the highest transmissivity to convey information of the earliest epoch of the Universe. We have shown that the future space laser interferometer DECIGO can measure the reheating temperature after inflation by observing the modulation of the spectrum of primordial tensor perturbations produced by inflation. If they are also measured by the B-mode polarization of the cosmic microwave background radiation (CMB), we can also determine the amount of entropy production after that, essentially fixing the thermal history of the post-inflationary Universe.

Another important consequence of the gravitational-wave cosmology is that it can act as a probe of the black-hole dark matter. Black holes can account for the cold dark matter if their mass is in the range $10^{20} - 10^{26}$g. Such holes can only be created as PBHs from large-amplitude density fluctuations in the early Universe when the horizon mass corresponds to these mass scales. We have shown that tensor perturbations generated from these large curvature perturbations as a second-order effect is also observable by DECIGO—in fact the amplitude would be larger than any other candidate sources so that the verification or falsification of PBH dark matter hypothesis will be the first scientific result of DECIGO.

Primordial Black Holes

We studied cosmological consequences of evaporating PBHs for the first time incorporating the effects of quark-gluon jets on the big bang nucleosynthesis as well as cosmological gamma ray background. We have also updated various other constraints imposed by gravitational lensing, accretion effects on the CMB through reionization etc. The master figure of this work, which shows the constraint on the mass fraction of the Universe that may collapse into PBHs with mass M shown here, has been quoted as the standard reference on PBH physics now.



1.4.2 Formation and Evolution of Large Scale Structures

Precision calculation for cosmological large-scale structure observations

The large-scale structure of the Universe has been one of the leading subject in cosmology, and in the era of precision cosmology, the precision measurement of power spectrum and/or correlation function would be a strong science driver to clarify the nature of dark energy as well as to constrain the infrared modification to the gravity. This is one of the main reasons why the on-going and upcoming galaxy redshift surveys, including the Subaru Measurement of Imaging and Redshifts, plan to observe the large-scale structure with an unprecedented huge volume. With the advent of such wealth of observations, of particular importance is a high-precision theoretical template, taking full account of the tiny but non-negligible systematics. This is what we have been investigating based on the perturbation theory. Applying the renormalization technique which partially resums a class of infinite series of perturbative expansion, we developed an efficient perturbation scheme which dramatically improves the predictions over a wide range of wavenumber (or separation) far beyond linear scales. Further, an algorithm that allows us to accelerate the power spectrum calculation has been also proposed, and we are now able to apply our methodology to the practical cosmological data analysis.

Neutrino mass constraint from the large-scale structure based on perturbation theory

Cosmological observations with large-scale structure survey is a very powerful probe for neutrino masses, since they cause a characteristic suppression in the growth of structure formation on scales below the neutrino free-streaming scale. In fact, stringent constraints, $m_{\nu,\mathrm{tot}} < 0.2 - 0.6\mathrm{eV}$, have been derived from the galaxy power spectrum and the Lyman-α forest power spectrum. However, most of these previous studies has been based on the linear perturbation theory of large-scale structure formation, and due to a limited applicable range of linear theory, it is very hard to further put a tighter constraint.

We have developed a new formalism to analytically treat the power spectrum beyond the linear order. Based on the perturbation theory, we simultaneously incorporate the non-linear effects of both the gravitational clustering and galaxy bias into the theoretical template of power spectrum. The template we proposed has been actually applied to the luminous red galaxy catalog in the data release 7 of the SDSS-II. Combining with the CMB measurement (WMAP5), we obtained a robust neutrino mass constraint, $m_{\nu,\mathrm{tot}} < 0.81\mathrm{eV}(95\%\mathrm{C.L.})$, which is listed as one of the cosmological constraints on the public data in the particle physics group.

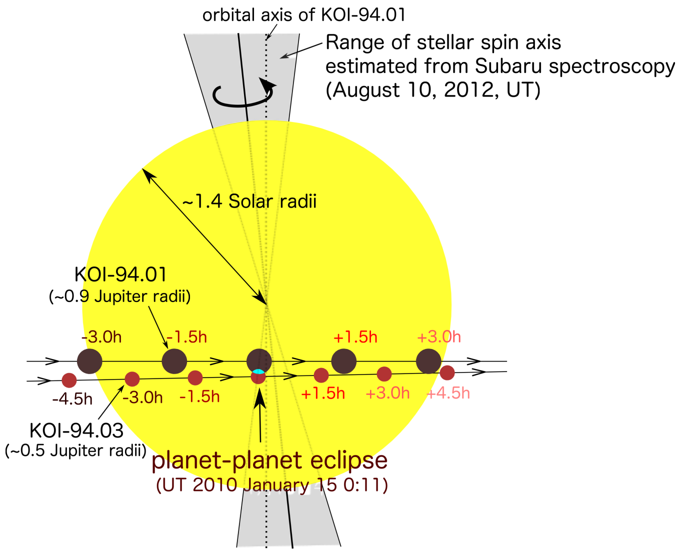
1.4.3 Extrasolar Planets

Towards a remote-sensing of exo-Earths: beyond a pale blue dot

Given the rapid progress of direct imaging techniques of exoplanets, it is just a matter of time to discover a candidate for a second Earth. In that case, what should we do ? Naturally we would like to ask if the planet is covered by ocean, land, and/or vegetation. This is a sort of remote-sensing that is routinely performed for our Earth, but the exo-Earth observation will be observed just by a point source (as Carl Segan phased our Earth observed from space as a pale blue dot). In reality, however, the rotation of the Earth will add a small modulation of colors. Thus an accurate multi-color photometric monitoring of ex-Earth will enable to identify its characteristic surface components. This is what we considered seriously, and we proposed a methodology and showed its feasibility for the first time. We concluded that it is possible to identify ocean and land fairly robustly. If there were no clouds covering an exo-Earth, we could even detect a signature of vegetation from its typical reflection spectrum known as red-edge. This would be a new path way to astrobiology via space astronomy.

Discovery of a planet-planet eclipse in a multiple transiting planetary system

Now more than 250 transiting systems have been identified in which a planet transits in front of the host star. The KOI-94 system is known to have four transiting planets. In carrying out the spectroscopy observation of the RM effect for one of the planets, we found from the archive data of the Kepler mission that the two planets showed a transit simultaneously, and even overlapped each other during that transit.



Multi-transiting planetary system KOI-94

This is the first ever discovery of a planet-planet eclipse, and indicates the amazing degree of the alignment of the orbital planes of the two planets. In addition, our Subaru observation proved that the orbital axis is well aligned with the spin axis of the host star. This places a stringent constraint on the physics of the angular momentum transfer during the formation and evolution of planetary systems.

1.5 International cooperation

In order to promote international collaborations we have organized a number of international conferences and workshops as well as conducting bi- and multi-lateral projects. We conducted JSPS core-to-core program entitled "International Research Network on Dark Energy (DENET)" from 2006 to 2011 whose partners were Princeton University in USA, Royal Observatory in Edinburough, UK, and Institut d'Astrophysique de Paris in France. The Japanese PI was Yasushi Suto.

The list of bilateral projects conducted in the last 6 years is shown below. They are all supported by JSPS.

Partner Institution	Country	PI	PI in Japan
Institut d'Astrophysique de Paris	France	Jerome Martin	Jun'ichi Yokoyama
Queen Mary, University of London	UK	Bernard J. Carr	Jun'ichi Yokoyama
MTI University	Egypt	Abdel Tawfik	Jun'ichi Yokoyama
Institut de Physique Theorique	France	Fransis Bernardeau	Atsushi Taruya

As for the international conferences, in the past five years we organized two RESCEU symposia, namely, 7th RESCEU Symposium on Astroparticle Physics and Cosmology on 11–14, November 2008, and 8th RESCEU Symposium which was held as Horiba International Conference "COSMO/CosPA 2010" from September 27 to October 1, 2010. This conference was attended by 300 participants with more than 160 people from abroad covering all the five continents.

During this conference a new international organization aiming at promotion of researches on the relevant fields in Asia Pacific was established and named "Asia Pacific Organization for Cosmology and Particle Astrophysics (APCosPA)." Pauchy W.H. Hwang at National Taiwan University was elected as the President of the organization, and Jun'ichi Yokoyama was elected as the vise President (President elect) . Since then we have been organizing APCosPA winter school every year in Taiwan and we are supposed to take it over in Japan after 2014.

Another arena for the international collaboration in Asia Pacific is the Asia Pacific Center for Theoretical Physics in Korea. After reformation of the Japan committee for the Center in October 2012, RESCEU has been requested to send a member for the committee as a representative institution for cosmology and astrophysics, together with other institutes representing other fields of physics, namely, KEK, Yukawa Institute, ISSP, and RCNP.

1.6 Future research plans

We plan to continue researches on Inflationary cosmology, Gravitational-wave cosmology, Large-scale structures, and Dark energy and modified gravity. We are also planning to start Basic research towards the data analysis of gravitational wave experiments, to expand the data analysis group of the KAGRA collaboration. On the other hand, the studies on exoplanets will be conducted as a new project of RESCEU.

Inflationary cosmology and birth of the Universe

In G-inflation model, it is possible to violate the null energy condition without any instabilities. Making use of this fact, I plan to construct a new model of the creation of the universe which starts with the Minkowski spacetime and spontaneously initiates cosmic expansion to avoid the initial singularity.

Toward a precision test of gravity on cosmological scales with redshift-space distortion

The observed large-scale structure via spectroscopic measurement of galaxies is apparently distorted due to the peculiar velocity of galaxies, known as the redshift-space distortion (RSD). While this complicates the interpretation of the galaxy clustering data, a measurement of clustering anisotropies offers an exciting opportunity to quantify the growth of structure, which can be used as the cosmological test of gravity. In this respect, accurate theoretical modeling of RSD is crucial and needs to be developed toward a future precision measurement of RSD. Based on the perturbation theory, we are continuously investigating the framework to accurately treat the RSD, and will present an improved prescription for power spectrum and/or correlation function in redshift space, taking account of non-linear gravity and galaxy bias.

A complete description of large-scale structure formation in the presence of massive neutrinos in weakly non-linear regime

While weighing the mass of neutrinos is one of the most important cosmological sciences in upcoming observations of large-scale structure, in the presence of massive neutrinos, theoretical understanding of the gravitational clustering of large-scale structure is yet far from complete. Although we have developed the perturbation theory formalism beyond the linear order, the applicable range of this treatment is not fully satisfactory. Applying the renormalization technique, we are trying to improve the perturbation theory prediction in the presence of massive neutrinos, and will present a prescription which has a widely applicable range, relevant for future surveys.

Modified gravity and massive neutrinos

We plan to continue analysis of the observational constraints on modified gravity model of accelerated expansion, in particular, using the cluster abundance. This issue is closely related with the question if one or two species of sterile neutrinos exist as favored by recent reactor neutrino experiments, because with such neutrinos the standard Λ CDM model cannot reproduce the observed amplitude of small-scale density fluctuations.

Data analysis of gravitational wave experiments
In accordance with the start of the construction of KAGRA, We are trying to help enhance the data analysis group of KAGRA. For this purpose we have recruited one of the (only!) six members of the analysis team to RESCEU and organized a data analysis school. We plan to continue these efforts and hope to establish a data analysis group here at RESCEU.

図 11: The KAGRA data analysis school.

1.7 Major publications

[1] Teruyuki Hirano, Norio Narita, Bun'ei Sato, Yasuhiro H. Takahashi, Kento Masuda, Yoichi Takeda, Wako Aoki, Motohide Tamura, and Yasushi Suto, "Planet-Planet Eclipse and the Rossiter-McLaughlin Effect of a Multiple Transiting System: Joint Analysis of the Subaru Spectroscopy and the Kepler Photometry", The Astrophysical Journal Letters **759**(2012) L36(5pp).

[2] Tsutomu Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama, "Generalized G-inflation: Inflation with the most general second-order field equations," Prog. Theor. Phys. 126 (2011) 511-529.

[3] Tsutomu Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama, "Inflation driven by the Galileon field," Phys. Rev. Lett. 105 (2010) 231302.

[4] B.J. Carr, Kazunori Kohri, Yuuiti Sendouda, Jun'ichi Yokoyama, "New cosmological constraints on primordial black holes," Phys. Rev. D81 (2010) 104019.

[5] Kiyotomo Ichiki, Ryo Nagata, Jun'ichi Yokoyama, "Cosmic Discordance: Detection of a modulation in the primordial fluctuation spectrum," Phys. Rev. D81 (2010) 083010.

[6] Yuka Fujii, Hajime Kawahara, Yasushi Suto, Atsushi Taruya, Satoru Fukuda, Teruyuki Nakajima, and Edwin L. Turner, "Colors of a Second Earth: Estimating the fractional areas of ocean, land and vegetation of Earth-like exoplanets", The Astrophysical Journal **715**(2010) 866–880

[7] By Ryo Saito, Jun'ichi Yokoyama. "Gravitational wave background as a probe of the primordial black hole abundance" Phys. Rev. Lett. 102 (2009) 161101, 107 (2011) 069901(E).

[8] Kazunori Nakayama, Shun Saito, Yudai Suwa, Jun'ichi Yokoyama, "Space laser interferometers can determine the thermal history of the early Universe," Phys. Rev. D77 (2008) 124001.

[9] Shun Saito, Masahiro Takada, and Atsushi Taruya, "Impact of massive neutrinos on nonlinear matter power spectrum", Physical Review Letters **100** (2008) 191301.

[10] Atsushi Taruya, and Takashi Hiramatsu "A Closure Theory for Non-linear Evolution of Cosmological Power Spectra", The Astrophysical Journal **674**(2008) 617–635.

2 PROJECT 2: Theory of Galaxy Evolution

2.1 Project Members

Title	Name	Affiliation
Associate Professor	Toshikazu Shigeyama	RESCEU

2.2 Objectives of the Project

The objective of this project is to construct a quantitative model to describe the dynamical and chemical evolution of galaxies. Quasars at cosmological distances emit photons including information on the early universe. In addition, there are many stars older than the sun in our galaxy. Emissions of these stars also contain fossil information on the galaxy when these stars formed. In particular, emissions both from quasars and old stars encode fruitful information on how elements were synthesized by nuclear fusion operating in stars. In our project, we will simulate the evolution of galaxies by numerical models. The processes to be calculated include the formation of galaxies in the early universe, the evolution of the first stars formed from the gas with the primordial elemental abundances, supernova explosion, the subsequent evolution of a supernova, the formation of stars of the next generation, and the recycle of these processes. By comparing results of the simulations with information in emissions from quasars and old stars, we will explore the origin of elements in the universe. Through these studies, we will learn how a supernova explodes and differences between nearby celestial objects and those at cosmological distances. It will help to probe the geometry of the universe with distant supernovae, for example.

2.3 Explosive events responsible for nucleosynthesis

2.3.1 Origin of type Ia supernovae

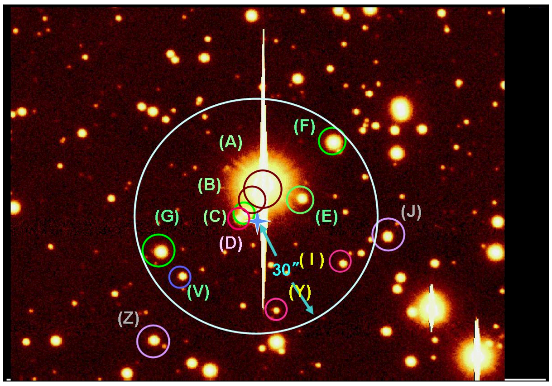


図 12: Optical image of the central region of Tycho's supernova remnant taken by SUBARU.

Type Ia supernova has been thought to be an explosion of an accreting white dwarf composed of carbon and oxygen in a binary system where the companion star is a normal star or also a white dwarf. If the companion star is a white dwarf, the less massive component will be entirely disrupted and resultant merging of the white dwarfs is thought to lead to explosion. On the other hand, if the companion is a normal star, then the white dwarf accreting matter from the companion increases its mass to the limit, beyond which no equilibrium configuration exists, ignites carbon at the center and ends up with a thermonuclear explosion of the entire star. Thus the companion star must be left behind. We have tried to search this ex-companion star in the remnant of Tycho's type Ia supernova with the SUBARU telescope. Our strategy was to find asymmetric absorption lines due to neutral Fe atoms in the ejecta exclusively with blue-shifted components in the optical spectrum of a star inside the remnant. The asymmetric lines are the proof of the existence of the absorbing matter on the line of sight moving toward us, at the same time, show that few absorbing matter moves away from us on the line of sight, and thus identifies the ex-companion star at the center of the remnant. Using FOCAS, we took spectra of more than 30 stars located near the geometrical center of the remnant on the celestial sphere and found two such candidates. However low statistics prevented us from concluding which was the real ex-companion or none of them was [6].

2.3.2 Origin of carbon enhanced metal-poor stars

There are metal-poor stars with enhanced carbon abundance in the halo of the Milky Way galaxy. We argued that all these carbon enhanced metal-poor stars were in originally members of binary systems where the primary star had already evolved to Asymptotic giant branch star blowing carbon rich wind toward the companion. Thus the surfaces of the companion stars are polluted by carbon-rich matter. We discussed the evolution of orbital parameters of binary systems [7].

2.3.3 Light element synthesis in type Ic supernovae

We present a new site for the origin of Li isotopes, Boron, and Beryllium in metal-poor stars. We argue that these elements are produced in the circumstellar matter around Wolf-Rayet stars when the stars explode as type Ic supernovae. We showed that a substantial amount of the ejecta composed of oxygen and carbon are accelerated above 10 MeV/nucleon and collisions with the protons and/or α nuclei in the circumstellar matter produce these light elements with sufficient amounts [8].

2.4 Gamma-ray bursts

2.4.1 Self-similar solutions for ultra-relativistic explosion

We have presented three self-similar solutions in the context of ultra-relativistic explosion of stars. The first one describes the flow when the shock breaks out of the surface of a star [10]. The other two concern with the interaction of ejecta expanding at ultra-relativistic speeds with the circumstellar matter [9, 1]. These solutions are useful to explore the prompt emission from gamma-ray bursts. I hope that many researchers in the related fields will use these solutions to calibrate their numerical codes treating ultra-relativistic fluid dynamics. Note also that the work [10] was done when one of the authors Nakayama was an undergraduate student. He is now an assistant professor in the department of physics.

2.5 Future Research Plans

2.5.1 Magnetar-Supernova relation

The first topic is the influence of extremely strong magnetic fields of a magnetar to supernova explosion. Magnetar is a neutron star spinning at the period of a few seconds to 20 seconds with a large time derivative of the period compared with normal pulsars. This large time derivative of the spin period is ascribed to magnetic braking by extremely strong dipole magnetic fields with the axis misaligned with the spin axis. Thus a magnetar loses its rotational energy. The rate of the associated loss of rotational energy is not enough to explain the observed emission. Thus the energy source is suggested to be magnetic. Therefore if dating back to the time when the supernova explosion just began, the spin period must be far shorter than the observed one and the magnetic field strength be far stronger. If the spin period is as short as a few ms, then the rotational energy becomes of the order of 10^{52} erg and if the field strength is 10^{16} G, the time scale of the spin down is 1000 s. Then we can expect that the energy supply from the magnetar might contribute supernova explosion to some extent because the energy supply is in the form of electromagnetic waves rather than neutrinos. By performing multi-dimensional numerical fluid dynamical calculations, we plan to investigate if this kind of energy supply can reproduce supernova explosions of massive stars observed as either of type II, Ib, or Ic.

2.5.2 Sign of Ex-companion star in emission of type Ia supernova

By performing 2-D radiation hydrodynamical calculations, we will investigate if Hα lines can be seen in spectra of type Ia supernovae. If the companion star was a normal star, a considerable amount of hydrogen exist in the supernova ejecta because it is stripped from the outer layer of the companion star by collision of the ejecta. Calculating spectra taken from different angles at different epochs, we will estimate the fraction of type Ia supernovae that show Hα line.

Asphericity due to the existence of the companion star may lead to different light curves from different observing angle. There is a well known correlation between the peak luminosities of type Ia supernovae and the time scale of the luminosity decay afterward. We investigate if the light curves with different observing angles can reproduce this correlation.

2.5.3 3D stellar evolution models

Existing stellar evolution models assume spherical symmetry. This assumption needs an ad hoc parameter called mixing length to treat the energy transfer due to convection. Though this parametrization has been successful in many respects, there remain many problems that cannot be addressed especially in the evolved phases because of this simplification. Another issue caused by spherical symmetry is the treatment of rotation. Even though some models incorporate effects of rotation and the associated mixing process, the configuration remains spherical symmetry. Therefore supernova explosions from rotating stars cannot be studied self-consistently at present. All these issues could be addressed if 3D stellar evolution models are available. At the moment, there are 3D stellar models that trace hydrodynamical phenomena at some specific epoch of the star. These models cannot trace the entire evolution of a star. These difficulties are rooted in the evolutionary time scale many orders of magnitude longer than the hydrodynamical time scale in a star. Therefore stellar evolution models should trace a series of the equilibrium configurations with gradually changing compositions rather than follow the hydrodynamical behavior. As a first step, we will construct a scheme to obtain equilibrium figures of rotating self-gravitational stars in

3D by using a kind of multi-domain pseudo-spectral methods. The methods have been developed to construct initial setups of simulations for binary neutron star mergers. Rieutord and Espinosa Lara (2012) has recently succeeded in constructing 2D axisymmetric configuration of rotating stars in radiative equilibrium using this method. Though previous methods need to assume the rotation law, this method can derive the rotation law for a given total angular momentum by solving the stationary Navier-Stokes equation. We will do the same thing in 3D. The methodology is rather straight forward. Next step is to incorporate nuclear reaction network to calculate the stellar evolution. By using this 3D stellar evolution code, we will reinvestigate the entire picture of stellar evolution that has been constructed by specifying the mixing length parameter. A final goal is to incorporate the mass loss to follow the evolutionary phases of massive stars. Then we will investigate the supernova mechanism in massive rotating stars in a self-consistent manner.

2.6 Major Publications

[1] Early Evolution of Spherical Ejecta Expanding into the CircumStellar Matter at Ultra-Relativistic Speeds, T. Shigeyama, A. Suzuki, and K. Nakamura, Publications of the Astronomical Society of Japan, 2012, Vol.64, No.4, Article No.87, 5 pages

[2] Type Ia Supernova Remnant Shell at z = 3.5 Seen in the Three Sightlines toward the Gravitationally Lensed QSO B1422+231, S. Hamano, N. Kobayashi, S. Kondo, T. Tsujimoto, K. Okoshi, T. Shigeyama, The Astrophysical Journal, 2012, Volume 754, Issue 2, article id. 88

[3] Non-thermal Photon Production via Bulk Comptonization at Supernova Shock Breakout, A. Suzuki and T. Shigeyama, The Astrophysical Journal, 2010, Volume 719, Issue 1, pp. 881-889

[4] Probing Explosion Geometry of Core-collapse Supernovae with Light Curves of the Shock Breakout, A. Suzuki and T. Shigeyama, The Astrophysical Journal Letters, 2010, Volume 717, Issue 2, pp. L154-L158

[5] A novel method to construct stationary solutions of the Vlasov-Maxwell system, A. Suzuki and T. Shigeyama, Physics of Plasmas, 2008, Volume 15, Issue 4, pp. 042107-042107-5

[6] Searching for a Companion Star of Tycho Type Ia Supernova with Optical Spectroscopic Observations, Ihara, J. Ozaki, M. Doi, T. Shigeyama, N. Kashikawa, K. Komiyama, and T. Hattori, Publications of the Astronomical Society of Japan, 2007, Vol.59, No.4, pp.811-826

[7] The Origin of Carbon Enhancement and the Initial Mass Function of Extremely Metal-poor Stars in the Galactic Halo, Y. Komiya, T. Suda, H. Minaguchi, T. Shigeyama, W. Aoki, and M. Y. Fujimoto, The Astrophysical Journal, 2007, Vol. 658, pp. 367-390

[8] Light-Element Production in the Circumstellar Matter of Energetic Type Ic Supernovae, K. Nakamura, S. Inoue, S. Wanajo, and T. Shigeyama, The Astrophysical Journal (Letters), 2006, Vol. 643, pp. L115-L118

[9] Self-similar Solutions for the Interaction of Relativistic Ejecta with an Ambient Medium, K. Nakamura and T. Shigeyama, The Astrophysical Journal (Letters), 2006, Vol. 643, pp. L115-L118

[10] Self-similar Evolution of Relativistic Shock Waves Emerging from Plane-parallel Atmospheres, Nakayama and T. Shigeyama, The Astrophysical Journal, 2005, Vol. 627, pp. 310-318

3 PROJECT 3: Formation and Evolution of Galaxies and Clusters of Galaxies

3.1 Project Members

Title	Name	Affiliation
Professor	Mamoru Doi	Institute of Astronomy
Associate Prof.	Kazuhiro Shimasaku	Department of Astronomy

3.2 Objectives of the Project

The formation and evolution of galaxies are a complex process. While the growth of galaxies as self-gravitating systems is described well in the framework of hierarchical clustering of dark matter, baryonic processes such as gas cooling/heating and star formation are so complex that they have not yet been fully understood. Because individual baryonic processes are thought to be time and environment dependent, observations of galaxies in the past universe at different environments are essential. The purpose of this Project is to observe the universe at different cosmic times and environments to decipher the formation and evolution of galaxies and their groups. Our research area also includes observational cosmology because galaxy formation and evolution are closely related to the history of the universe itself. By thus studying the history of galaxies and the universe, we are contributing significantly to the "Baryon domain" of RESCEU.

3.3 Research Item 1: High Redshift Galaxies

3.3.1 Research methods

We study galaxies primarily based on optical and infrared observations. Our basic strategy is to search for distant galaxies with Suprime-Cam, a wide-field optical camera on the Subaru Telescope, and carry out followup observations with other instruments and telescopes to study their detailed properties. Among the cameras on 8-10 m class telescopes, Suprime-Cam is most capable of detecting distant galaxies, which are rare and faint. Making the best use of this camera since its commissioning phase (we were members of the developing team), we have been one of the world's leading groups in this research field. A successor to this camera, Hyper Suprime-Cam, will be available in 2013, and Shimasaku is a leader of a planned large program.

3.3.2 Properties of Lyα emitters

Lyα emitters (LAEs), galaxies with strong Lyα emission, are a galaxy population commonly seen at high redshift. Unveiling the nature of LAEs is important not only for the understanding of galaxy evolution but also for the study of cosmic reionization, because LAEs are a promising probe of the neutral fraction of cosmic hydrogen. We have constructed the largest LAE samples over $z \sim 2-7$ from Suprime-Cam narrow-band surveys to investigate LAEs. We have shown that LAEs are on average low-mass galaxies with relatively low metallicities, indicating that they are 'building blocks' of larger galaxies [2, 7]. We have also found that some LAEs have primordial features such as very large Lyα equivalent widths [12]. We have also found, from the most reliable Lyα luminosity functions, that LAEs become more dominant at earlier cosmic times [10].

3.3.3 Epoch of cosmic reionization

Cosmic reionization is a transition of the hydrogen in the intergalactic space from fully neutral to highly ionized states, due probably to ionizing photons from very young galaxies. In spite of its importance for cosmology and galaxy evolution, exactly when it occurred, between $z \sim 10$ and 6, has not been identified. LAEs can be used to measure the neutral fraction, because Lyα luminosities of LAEs in a neutral universe are dimmed due to resonant scattering by hydrogen atoms. Since the first detection of a dimming of the Lyα luminosity function of $z = 6.6$ LAEs [11], we have significantly improved measurements [4, 5]. Our inference that reionization may not have been completed at $z = 6.6$ seems to be supported by a finding that the fraction of FUV-selected galaxies with strong Lyα emission suddenly drops beyond $z \sim 6$ [3]. Identifying ionizing sources is also an important aspect of the reionization problem. We have found that in order for the universe at $z \sim 7$ to be fully ionized, galaxies at that time must have very different properties from those at lower redshifts, e.g., higher escape fractions of ionizing photons and/or population III like stellar populations [8].

3.3.4 Spectroscopic confirmation of three $z \sim 7$ galaxies

Ono et al. (2012) have identified three galaxies at $z = 6.844$, 6.965, and 7.213 from Keck/DEIMOS spectroscopy of candidate galaxies detected with Suprime-Cam [3] (Fig. 13). The $z = 7.213$ galaxy is the second distant galaxy with a confirmed redshift; the most distant one is at $z = 7.215$ and Shimasaku is a co-author of the paper reporting the discovery of this galaxy.

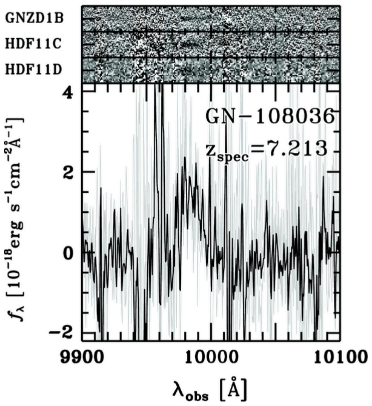


図 13: The galaxy GN-108036 at $z = 7.213$. Asymmetric Lyα emission is seen around 9980Å.

3.3.5 Metallicities of high-redshift galaxies

We have measured metallicities for K-band selected galaxies at $z \sim 2$, to find that they do not obey the mass-metallicity relation established by FUV-selected galaxies at similar redshifts [9]. This suggests that unlike the previous claim, the chemical enrichment of high-redshift galaxies is not solely determined by mass but also depends on, e.g., age.

3.3.6 Galaxy evolution at intermediate redshifts

In order to identify the origin of the environmental dependence of galaxies seen in the present-day universe, we have been conducting wide-area surveys of clusters of galaxies and their surrounding fields at $z < 2$. We have found many red star-forming galaxies in groups of galaxies [6]. This may suggest that galaxies experience a dusty star-formation phase due to some mechanisms related to group environment before falling into clusters as passive galaxies.

3.3.7 Future research plans

High-redshift galaxies

We will extend the research of high-redshift galaxies using existing and future facilities in the world. So far our research has given priority to statistical properties of galaxies like the luminosity function to outline the evolution of galaxies. A next step will be to measure various physical quantities of galaxies and use them to study the physics at work in galaxy evolution. Indeed, we have started such studies for a small number of bright galaxies by measuring metallicites and gas motions etc.

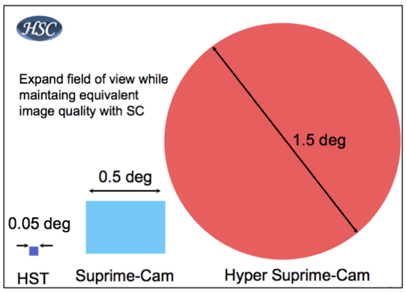


図 14: Hyper Suprime-Cam has an overwhelmingly large field of view.

Hyper Suprime-Cam

With a seven times larger field of view than Suprime-Cam (Fig. 14), Hyper Suprime-Cam is expected to make a breakthrough in the research field of galaxies and cosmology. As a leading member of the large survey project of Hyper Suprime-Cam, Shimasaku will carry out this long-term survey and address important issues in galaxy evolution and cosmic reionization.

Cosmology with Type Ia supernovae

Doi will continue the study of the cosmological parameters using distant type Ia supernovae, taking advantage of Hyper Suprime-Cam. To determine the cosmological parameters and thus the expanding history of the universe is also beneficial to the understanding of galaxy formation and evolution. Doi will also study the star forming history of nearby galaxies to study supernova progenitors. This is also closely related to the study of high redshift galaxies.

3.4 Research Item 2: Cosmology and Galaxy Evolution using SNe Ia

Prof. Mamoru Doi, whose major research field is observational cosmology, joined the project in 2012. He has been studying the cosmological parameters, including the nature of dark energy, by searching for a large number of type Ia supernovae and measuring their luminosity distances [1].

Studying distant type Ia supernovae, including cosmological studies as well as rate studies, will be carried out under the international collaboration with Supernova Cosmology Project team (leader: Dr. Saul Perlmutter), taking advantage of Hyper Suprime-Cam.

Improving the accuracy of distance measurements would be the key for the next decade cosmology. Studying the environment of supernova progenitors in nearby galaxies will be an important activity in this research item. Since the time scale from the star fromation to the explosion of SNe Ia supernova is broadly distributed ($\sim$ 10 Myr - $\sim$ 1 Gyr), the environmental study is closely coupled with understanding the star formation history of the galaxy. A new spectrograph which can carry out optical narrow-band imaging of nearby galaxies will be used. The spectrograph has a Fabry-Perot type imaging mode as well as the standard long-slit spectroscopy mode. The spectrograph successfully obtained its first light in late September 2012 at the Pirika telescope (aperture 1.6m) at Nayoro city in Hokkaido. With this spectrograph, short-time scale ($\sim$10 Myr) star forming activities as well as the metallicity distribution of nearby galaxies will be studied with Balmer and forbidden lines. Accurate absolute flux calibration of SNe Ia will also be an important activity. Preliminary negotiations to calibrate a couple of instruments which have been used for supernova studies have started with US and French researchers.

3.5 Major publications

[1] Suzuki, N. et al. (66 authors including Doi, M.: "The Hubble Space Telescope Cluster Supernova Survey. V. Improving the Dark-energy Constraints above z ¿ 1 and Building an Early-type-hosted Supernova Sample", *Astrophys. J.* **746**, id.85 (2012).

[2] Nakajima, K., Ouchi, M., Shimasaku, K., Ono, Y., Lee, J. C., Foucaud, S., Ly, C., Dale, D. A., Salim, S., Finn, R., Almaini, O., & Okamura, S.: "Average Metallicity and Star Formation Rate of Lyα Emitters Probed by a Triple Narrowband Survey", *Astrophys. J.* **745**, id.12 (2012).

[3] Ono, Y., Ouchi, M., Mobasher, B., Dickinson, M., Penner, K., Shimasaku, K., Weiner, B., Kartaltepe, J. S., Nakajima, K., Nayyeri, H., Stern, D., Kashikawa, N., & Spinrad, H.: "Spectroscopic Confirmation of Three z-dropout Galaxies at z = 6.844-7.213: Demographics of Lyα Emission in $z \sim 7$ Galaxies", *Astrophys. J.* **744**, id.83 (2012).

[4] Kashikawa, N., Shimasaku, K., Matsuda, Y., Egami, E., Jiang, L., Nagao, T., Ouchi, M., Malkan, M. A., Hattori, T., Ota, K., Taniguchi, Y., Okamura, S., Ly, C., Iye, M., Furusawa, H., Shioya, Y., Shibuya, T., Ishizaki, Y., & Toshikawa, J.: "Completing the Census of Lyα Emitters at the Reionization Epoch", *Astrophys. J.* **734**, id.119 (2011).

[5] Ouchi, M., Shimasaku, K., Furusawa, H., Saito, T., Yoshida, M., Akiyama, M., Ono, Y., Yamada, T., Ota, K., Kashikawa, N., Iye, M., Kodama, T., Okamura, S., Simpson, C., & Yoshida, M.: "Statistics of 207 Lyα Emitters at a Redshift Near 7: Constraints on Reionization and Galaxy Formation Models", *Astrophys. J.*, **723**, 869–894 (2010).

[6] Koyama, Y., Kodama, T., Shimasaku, K., Hayashi, M., Okamura, S., Tanaka, I., & Tokoku, C.: "Panoramic Hα and mid-infrared mapping of star formation in a $z = 0.8$ cluster", *Monthly Notices Roy. Astron. Soc.,* **403**, 1611–1624 (2010).

[7] Ono, Y., Ouchi, M., Shimasaku, K., Akiyama, M., Dunlop, J., Farrah, D., Lee, J. C., McLure, R., Okamura, S., & Yoshida, M.: "Stellar populations of Lyα emitters at $z = 3 - 4$ based on deep large area surveys in the Subaru-SXDS/UKIDSS-UDS Field", *Monthly Notices Roy. Astron. Soc.,* **402**, 1580–1598 (2010).

[8] Ouchi, M., Mobasher, B., Shimasaku, K., Ferguson, H. C., Fall, S. M., Ono, Y., Kashikawa, N., Saito, T., Nakajima, K., Okamura, S., Dickinson, M., GIavalisco, M., & Ohta, K.: "Large Area Survey for $z = 7$ Galaxies in SDF and GOODS-N: Implications for Galaxy Formation and Cosmic Reionization", *Astrophys. J.*, **706**, 1136–1151 (2009).

[9] Hayashi, M., Motohara, K., Shimasaku, K., Onodera, M., Uchimoto, K. Y., Kashikawa, N., Yoshida, M., Okamura, S., Ly, C., Malkan, M. A.: "Star Formation Rates and Metallicities of K-Selected Star-Forming Galaxies at z 2", *Astrophys. J.*, **691**, 140–151 (2009).

[10] Ouchi, M., Shimasaku, K., Akiyama, M., Simpson, C., Saito, T., Ueda, Y., Furusawa, H., Sekiguchi, K., Yamada, T., Kodama, T., Kashikawa, N., Okamura, S., Iye, M., Takata, T., Yoshida, M., & Yoshida, M.: "The Subaru/XMM-Newton Deep Survey (SXDS). IV. Evolution of Lyα Emitters from $z = 3.1$ to 5.7 in the 1 deg^2 Field: Luminosity Functions and AGN", *Astrophys. J. Suppl.*, **176**, 301–330 (2008).

[11] Kashikawa, N., Shimasaku, K., Malkan, M. A., Doi, M., Matsuda, Y., Ouchi, M., Taniguchi, Y., Ly, C., Nagao, T., Iye, M., Motohara, K., Murayama, T., Murozono, K., Nariai, K., Ohta, K., Okamura, S., Sasaki, T., Shioya, Y., & Umemura, M.: "The End of the Reionization Epoch Probed by Lyα Emitters at $z = 6.5$ in the Subaru Deep Field", *Astrophys. J.*, **648**, 7–22 (2006).

[12] Shimasaku, K., Kashikawa, N., Doi, M., Ly, C., Malkan, M. A., Matsuda, Y., Ouchi, M., Hayashino, T., Iye, M., Motohara, K., Murayama, T., Nagao, T., Ohta, K., Okamura, S., Sasaki, T., Shioya, Y., & Taniguchi, Y.: "Lyα Emitters at $z = 5.7$ in the Subaru Deep Field", *Publ. Astr. Soc. Japan* **58**, 313–334 (2006).

4 PROJECT 4: Submillimeter-Wave Observation

4.1 Project Members

Title	Name	Affiliation
Professor	Satoshi Yamamoto	Department of Physics
Professor	Kotaro Kohno	Institute of Astronomy
Assistant Prof.	Nami Sakai	RESCEU

4.2 Objectives of the Project

The submillimeter-wave and terahertz-wave region of electromagnetic waves (ν = 300 GHz − 3 THz; λ = 1 mm − 0.1 mm) is relatively unexplored in astronomy and astrophysics, mainly because of technical and observational difficulties. However, it is a very important frequency region for investigating distributions of cold baryons in the universe. Thermal spectral line and continuum emissions in this region can be used as sensitive tracers for cold gas and dust (10 - 100 K). Furthermore, the submillimeter-wave and terahertz-wave radiation is less absorbed and scattered by interstellar matter than infrared, optical and X-ray radiations, and hence, we can study essential parts of structure formation processes of baryons deeply embedded in thick matter. By making a full use of these two advantages, we are exploring (1) galaxy formation in the early universe and (2) star and planet formation in dense molecular clouds.

Our project consists of the two subprojects tackling the above two fundamental structure formation processes of baryons with the ground-based submillimeter telescopes. In particular, we are operating the ASTE (Atacama Submillimeter Telescope Experiment) 10 m telescope in collaboration with National Astronomical Observatory of Japan. We are developing a heterodyne mixer receiver for spectroscopic observations and a submillimeter-wave camera for continuum imaging observations in house. The major objective of our project is to explore fundamental physics and chemistry in the galaxy formation and the star formation by use of these newly developed instruments.

4.3 Sub-project 1: Chemical Evolution from Protostellar Cores to Protoplanetary Disks

4.3.1 Overview

Formation of stars is the most fundamental structure formation process in the universe. At the same time, it is an evolutionary process of interstellar matter toward planets. In this subproject, we are studying the chemical evolution during the star formation process on the basis of the submillimeter-wave and terahertz-wave observation. In the submillimter-wave and terahertz(THz)-wave region, there exist various important spectral lines of fundamental atoms and molecules, including C, C^+, N^+, CH, HDO, D_2O, and H_2D^+. Their observation will provide us with important information for understanding the essential part of chemical processes. From 1998 to 2005, we operated the Mount Fuji submillimeter-wave telescope to explore molecular cloud formation with the large scale survey of the atomic carbon line (0.5 THz). We accomplished the initial purpose with this telescope, and hence, we closed it in 2005. Then we are going up to higher frequencies to trace other fundamental species.

We are now developing a sensitive receiver for the THz observation, which is installed on the ASTE 10 m submillimeter-wave telescope in Chile. For this purpose, we have been fabricating superconducting hot electron bolometer (HEB) mixers in house. In contrast to the superconductor-insulator-superconductor (SIS) mixer whose operation frequency is limited by the superconducting gap frequency, the HEB mixer has no such high-frequency limit. Hence, it has extensively been studied as the most promising sensitive heterodyne device above 1.3 THz. So far, the quasi-optical HEB mixer has mainly been developed for easy fabrication. In contrast, we are developing the waveguide-type HEB mixer. Although the waveguide- type HEB mixer is more difficult in fabrication, it has a well-defined beam pattern which is important for astronomical applications. Furthermore, it can be applied to more sophisticated mixers such as double balanced mixers and single-side-band mixers. We started this project in 2002, and we have recently achieved the best noise performance at 1.5 THz in the world. The 0.9 THz/1.5 THz dual band receiver has then been assembled and installed on the ASTE 10 m submillimeter-wave telescope. We have succeeded in detecting the ^{13}CO($J = 8 - 7$) line (0.9 THz) toward the Orion molecular cloud.

In addition to the above effort, we are also conducting the observational studies of chemical evolution of protostellar cores with various large radiotelescopes including the ASTE 10 m submillimeter-wave telescope and ALMA (Atacama Large Millimeter/submillimeter Array). We have found the significant chemical diversity of protostellar cores, and have been studying its evolution to protoplanetary disks.

4.3.2 Research highlights 1; development of low noise HEB mixer at 1.5 THz

We are fabricating the superconducting HEB mixer device for astronomical applications. By using the NbTiN film with thickness of 10.8 nm, we realized a wave-guide type HEB mixer with very low-noise performance at 1.5 THz. The receiver noise temperature is 470 K, which is about 6 times the quantum noise. This is the world lowest noise performance of the HEB mixer at this frequency. It is rather surprising that such a good performance is obtained with a relatively thick NbTiN film.

In the HEB mixer, a recovery time of superconductivity should be faster than the intermediate frequency. It becomes shorter for a thinner film for the phonon-cooled HEB mixers using NbN or NbTiN as superconducting material, since the heat of hot electrons is transferred more efficiently to the substrate through an interaction with phonons for a thinner film. For a full use of this mechanism, most of the phonon-cooled HEB mixers usually employ a superconducting film with a thickness of a few nm. On the other hand, our result means that a diffusion cooling of hot electrons to the electrodes also plays an important role in our HEB mixer using a relatively thick NbTiN film. In fact, a shorter bridge size (i.e. a shorter distance between electrodes) gives a better performance. Since the superconducting film and the electrodes are successively deposited on the quartz substrate without breaking the vacuum in our fabrication process, formation of the oxidation layer between the superconducting film and the electrodes is suppressed, which ensures a good condition for hot electrons to escape to the electrodes. It is thus demonstrated that a combination cooling (phonon cooling and diffusion cooling) would be a promising direction to achieve a better performance of the NbTiN HEB mixer.

4.3.3 Research highlights 2; Successful commissioning of the THz reciever on ASTE

Since our HEB mixers show good performance, they are used for the 0.9 THz/1.5 THz dual band heterodyne receiver for the ASTE 10 m submillimeter-wave telescope. The receiver is a cartridge-type one, which is compatible to the ALMA cartridge receiver. The incident beam from the antenna is split into two beams with the orthogonal linear polarization by a wire grid. One is fed into the 0.9 THz mixer, while the other is fed into the 1.5 THz mixer. Hence, we can simultaneously observe the two bands. Local oscillator sources are frequency multiplier chains driven by a microwave synthesizer.

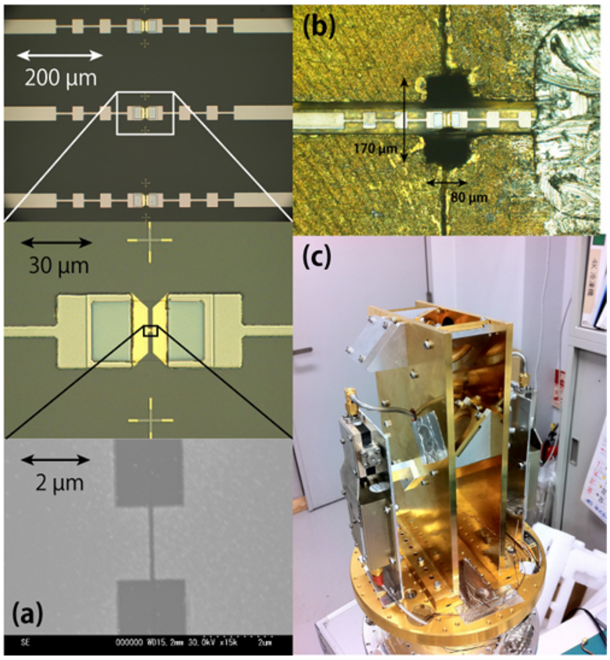


図 15: A THz HEB mixer device and a receiver cartridge for the ASTE 10 m telescope.

In 2011 September to October, we installed this receiver on the ASTE 10 m telescope in Chile. Our receiver worked almost perfectly on the telescope, and we succeeded in the test observation. We detected the continuum emission from the Moon and Jupiter at 0.9 THz. Furthermore, we detected the ^{13}CO ($J = 8 - 7$) line at 0.9 THz toward the Orion A molecular cloud. Although the observation at 1.5 THz was not possible due to poor atmospheric conditions, we were able to demonstrate high potential of our THz receiver installed on the ASTE 10 m telescope.

4.3.4 Research highlights 3; Chemical diversity of low-mass protostellar cores

We have recently established that the chemical composition of low-mass protostellar cores shows significant chemical diversity. One distinct case is the hot corino chemistry characterized by rich existence of saturated complex organic molecules such as $HCOOCH_3$ and C_2H_5CN. Representative sources are IRAS 16293-2422 and NGC1333 IRAS4A/B. Another distinct case is the warm carbon-chain chemistry characterized by rich existence of unsaturated complex organic molecules such as carbon-chain molecules. Representative sources are L1527 and IRAS 15398-3359. The chemical diversity of protostellar cores seems to reflect some differences in past physical processes which each protostar has experienced, and hence, it could be a novel source for tracing the past formation process of each protostar. Furthermore, the discovery of the chemical diversity raised an important question how the chemical diversity is brought into the later stages. If the chemical diversity can be seen even in the protoplanetary disk stage, chemical compositions of the planets could be different from planetary system to planetary system. This is deeply related to the origin of our Solar system. Considering importance of the chemical diversity, we are extending our observation to study chemical compositions of various protostellar cores with the ASTE 10 m submillimeter-wave telescope and the Nobeyama 45 m telescope.

4.3.5 Future research plans

On the basis of the success in the previous commissioning run of our THz HEB mixer receiver on the ASTE 10 m submillimeter-wave telescope, we would like to conduct a full science operation of this receiver. We are planning to observe the fundamental molecules which are responsible to the deuterium fractionation in molecular clouds, HDO, D_2O, H_2D^+, and HD_2^+. Since the deuterium fractionation ratio is a good indicator of chemical evolutionary stages of dense cores, its full characterization is very important for astrochemistry. Particularly, we would like to discriminate the deuterium fractionation in the gas phase and that in the solid phase in the THz observation. Indeed, we tried to conduct the science operation in 2012. Although the receiver system worked very well, we could not perform any science operation because of the trouble of the ASTE telescope. Hence, we would like to try it again in 2013.

In parallel to the above study, we are planning to expand our observational studies on the chemical diversity of protostellar cores. In particular, we are interested in the evolution of the chemical diversity to the protoplanetary disk stage. Fortunately, ALMA will be in its full operation from 2014. This will be a powerful instrument to solve the problem.

4.3.6 Major publications

[1] Nami Sakai, Yancy L. Shirley, Takeshi Sakai, Tomoya Hirota, Yoshimasa Watanabe, and Satoshi Yamamoto, Tentative Detection of Deuterated Methane toward the Low-Mass Protostar IRAS 04368+2557 in L1527h, *Astrophys. J*, **758**, L4 (4 pages) (2012).

[2] Yoshimasa Watanabe, Nami Sakai, Johan E. Lindberg, Jes K. Jorgensen, Suzanne E. Bisschop, and Satoshi Yamamoto, An Unbiased Spectral Line Survey toward R CrA IRS7B in the 345 GHz Window with ASTEh, *Astrophys. J.*, **745**, 126 (23 pages) (2012).

[3] Shoichi Shiba, Yoshihisa Irimajiri, Tetsuya Yamakura, Hiroyuki Maezawa, Norihiko Sekine, Iwao Hosako, and Satoshi Yamamoto, 3.1-THz Heterodyne Receiver Using an NbTiN Hot-Electron Bolometer Mixer and a Quantum Cascade Laserh, *IEEE Trans. Terahertz Sci. Technol.*, **2**, 22-27 (2012).

[4] Osamu Saruwatari, Nami Sakai, Sheng-Yuan Liu, Yu-Nung Su, Takeshi Sakai, and Satoshi Yamamoto, Compact Molecular Outflow from NGC2264 CMM3: A Candidate for Very Young High-Mass Protostarh, *Astrophys. J.*, **729**, 147 (7 pages) (2011).

[5] Tatsuya Shiino, Shoichi Shiba, Nami Sakai, Tetsuya Yamakura, Ling Jiang, Yoshinori Uzawa, Hiroyuki Maezawa, and Satoshi Yamamoto, Improvement of the Critical Temperature of Superconducting NbTiN and NbN Thin Films Using the AlN Buffer Layerh, *Supercond Sci. Technol.*, **23**, 045044 (5 pages) (2010).

[6] Nami Sakai, Tatsuya Shiino, Tomoya Hirota, Takeshi Sakai, and Satoshi Yamamoto, Long Carbon-Chain Molecules and Their Anions, in the Starless Core, Lupus-1Ah, *Astrophys. J.*, **718**, L49-L52 (2010).

[7] Ling Jiang, Shoichi Shiba, Ken Shimbo, Nami Sakai, Tetsuya Yamakura, Mika Sugimura, P.G. Ananthasubramanian, Hiroyuki Maezawa, Yoshihisa Irimajiri, and Satoshi Yamamoto, Development of THz Waveguide NbTiN HEB Mixersh, *IEEE Trans. Appl. Supercond.*, **19**, 301-304 (2009).

[8] Nami Sakai, Takeshi Sakai, Tomoya Hirota, Michael Burton, and Satoshi Yamamoto, Discovery of the Second Warm Carbon Chain Chemistry Source, IRAS15398-3359 in Lupush, *Astrophys. J.*, **697**, 769-786 (2009).

[9] Nami Sakai, Takeshi Sakai, Tomoya Hirota, and Satoshi Yamamoto, Abundant Carbon-Chain Molecules toward the Low-Mass Protostar IRAS04368+2557 in L1527h, *Astrophysical Journal*, **672**, 371-381 (2008).

[10] Nami Sakai, Takeshi Sakai, Yoshihiro Osamura, and Satoshi Yamamoto, Detection of C_6H^- toward Low-Mass Protostar IRAS 04368+2557 in L1527h, *Astrophys. J.*, **667**, L65-L68 (2007).

4.4 Sub-project 2: Formation and Evolution of Massive Galaxies and Super Massive Blackholes

4.4.1 Research method

This project consists of the following research elements.

- Mm/submm continuum survey of dusty massive starburst galaxies in the early universe: In order to study the formation and evolution processes of massive galaxies, we conduct deep and wide surveys at mm and submm wavelengths using ASTE 10 m dish equipped with bolometer arrays. Because of the strong negative K-correction caused by the shape of spectral energy distribution of dusty galaxies, mm and submm wavelengths are best suited for the survey of dusty extreme starburst galaxies, which are violently forming stars with a star formation rate (SFR) of a few 100 - 1000 $M_\odot$ yr^{-1}. ASTE is operated in a close partnership with the sub-project 1 above.

- Multi-wavelengths study of the detected dusty starburst galaxies: By means of SED analysis as well as hard X-ray observations of these dusty starburst galaxies, we investigate the presence of a hidden active galactic nucleus (AGN) within these dusty galaxies. High-z dusty massive starbursts are expected to host growing super massive black holes (SMBHs) accoring to the putative co-evolution of galaxies and SMBHs. This can be closely related to other projects in RESCEU, such as project 3 (Formation and Evolution of Galaxies and Clusters of Galaxies) and 7 (Researches using Space-Borne Instruments).

- Mm/submm spectroscopy as a new diagnostic of energy sources at the centers of dusty galaxies: The nuclear region of galaxies can often be hearvily enshrouded by dust, and conventional diagnostics such as UV/optical/IR spectroscopy and hard X-ray observations can not work. However, molecular lines at mm/submm wavelengths can penetrate into the heart of dusty galaxies, and the presence of a strong hard X-ray source (i.e., AGN) can be revealed by the characteristic spectral features at these wavelengths caused by the effects of high-ionization rate and/or high temperature. Once we establish the new diagnostic methods, we can apply them to the uncovered dusty high-z galaxies in order to address the presence of dust-obscured AGNs. This is intimately conducted with sub-project 1.

- Detailed imaging study of high-J CO and dust emission of nearby gas-rich galaxies: Spatially resolved high-J CO and dust continuum observations give templates for the interpretation of spatially unresolved high-z gas-rich galaxies. Study of underlying physics is also conducted by this category of observations.

- Study of ISM and star-formation in the host galaxies of long-duration Gamma-ray bursts (GRBs): This is complementary to the study of dusty extreme starburst galaxies, because long GRBs tend to be in the less dusty star-forming galaxies. Collaboration with the project 2 (Theory of Galaxy Evolution) can be expected eventually.

4.4.2 Research highlights 1; deep mm/submm surveys of dusty extreme starburst galaxies in the early Universe

We conducted deep and wide area surveys of known blank and biased fields at 1.1 mm in order to uncover dusty extreme starburst galaxy population in the early universe, based on the collaboration including the Univ. of Tokyo, NAOJ, UMASS, INAOE, Cardiff, Univ. of Chile. Major blank fields which are visible from Chile, i.e., ADF-S [6], GOODS-S, COSMOS, SXDF, SDF, and biased regions/proto-clusters such as SSA 22 at $z \sim 3.1$ [9] and 4C 23.56 at $z \sim 2.5$, have been extensively observed down to 1σ noise levels of 0.4 - 2.0 mJy, which are equal/close to the source confusion limit. The total surveyed area is larger than 3 deg^2, yielding > 1400 new detections. Due to a strong negative K-correction, these surveys are already sensitive enough to detect bright ULIRGs over a wide redshift range of $1 < z < 10$. This is complementarly to other extensive surveys with SPIRE/Herschel, SPT, and LABOCA. In fact, our survey is more sensitive than SPIRE/Herschel 0.25 - 0.5 mm surveys such as HerMES and H-ATLAS for unlensed $z > 3$ ULIRGs. SPT 1.4 mm surveys are much wider than us but 10x or shallower for high-z starbursts. LABOCA 0.87 mm surveys have comparable sensitivity, but narrower in area than AzTEC/ASTE surveys.

Our unique surveys have already been producing interesting scientific outcomes. For instance, it gives the most statistically significant number counts of $\lambda \sim 1$ mm selected sources to date. The contribution of 1.1 mm population to the cosmic SFR density is found to be significant [6]. The relationship between SMGs and large scale structures (LSS) has been also uncovered [9]. A proto-quasar grown at the bottom of a LSS has also been identified [8]. Unprecedentedly deep constraint on the dusty star-formation in Lymanα brobs has also been obtained. Ultra-bright submillimeter galaxies have been detected [7], resulting in a discorvey of a new population of high-z galaxies. New ultra wide band spectrometers such as Z-Spec on CSO and Zpectrometer on GBT have also been used to measure the redshift of these ultra-bright SMGs [7]. We have also made extensive efforts on building a new redshift machine for NRO 45m telescope [3].

Based on the success of the AzTEC deep surveys, we have developed a new multi-color mm/submm camera for ASTE. Transition Edge Sensors (TES) have been employed to built a 400 pixel array for 270 GHz and 350 GHz band [2], under the close collaboration with NAOJ, UC Berkeley, McGill Univ., Cardiff, and Hokkaido Univ. The first light has already been obtained on ASTE on June 2012, and improvement of the overall performance in laboratory is now on-going.

4.4.3 Research highlights 2; A new energy diagnostic of dusty galactic nuclei based on mm/submm spectroscopy

We have conducted extensive extragalactic line surveyss toward nearby Seyfert and starburst galaxies using Nobeyama 45 m telescope. Isotope of HCN, i.e., $H^{13}CN$, and two carbon-chain molecules, C_2H and Cyclic-C_3H_2, have been detected for the first time at the center of the type-2 AGN in NGC 1068 [5]. We found that C_2H abundance relative to CS in NGC 1068 is similar to those in starburst galaxies, suggesting that C_2H is not sensitive to the presence of AGN. Nobeyama Millimeter Array has also been extensively used to map HCN(1-0) and HCO^+(1-0) lines in nearby Seyfert and starburst galaxies and the ratio is suggested to be a possible indicator of AGN.

We have awarded two ALMA cycle 0 programs on this research topic (2011.0.00108.S, PI = K. Kohno; 2011.0.00061.S, PI = S. Takano), and a part of the ALMA data has already been delivered. The data analysis is in progress, but unprecedentedly high sensitivity and imaging quality immediately result in a discovery of striking features, e.g., HCN(4-3)/HCO^+(4-3) ratio exeeding unity, and extremely elevated HCN(4-3)/CS(7-6) ratio up to ~10 in the low-luminosity type-1 AGN of NGC 1097, shown in Figure 16.

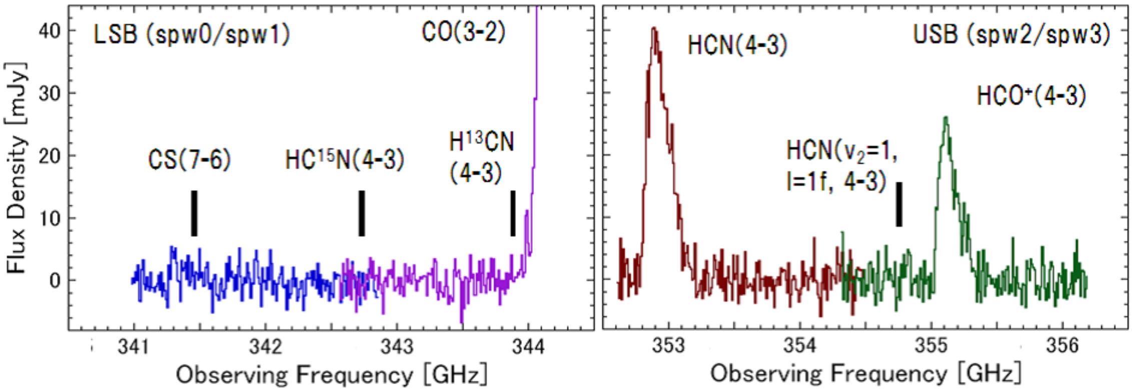


図 16: ALMA Band 7 spectrum of the low-luminosity type-1 active galactic nuclei in the nearby barred spiral galaxy NGC 1097. Underlying λ 860 μm continuum emission has been subtracted in this spectrum. Just one hour observation achieved a noise level of ~ 2 mJy for a velocity resolution of ~ 8 km s^{-1}, which is tremendously great if we compare the typical noise levels expected from existing submm interferometers such as SMA.

4.4.4 Research highlights 3; Interstellar medium and star formation in the (long) gamma-ray burst host galaxies

In order to investigate the true star foramtion rates in the host galaxies of long-duration Gamma-ray bursts (GRBs hereafter), we have conducted extensive search for molecular gas and radio continuum emission toward GRB host galaxies with a hint of dust-obscured star formation. Four GRB host galaxies, 990705, 021211, 041006, and 051022, have been observed with ATCA and no 20 cm radio continuum has been detected. The radio-based SFRs are less than about 10 times those derived from UV/optical observations, suggesting that they have no significant dust-obscured star formation. [4] A sensitive CO spectroscopy was also conducted to constrain the dust-obscured star formation in GRB 000418 at $z = 1.1$ using PdB interferometer.

4.4.5 Research highlights 4; Dense molecular gas, dust, and star-formation in mearby galaxies

Giant molecular clouds have been identified based on the wide and most sensitive CO(3-2) observations of M33 using CATS345 receiver (which is developed by our group) mounted on ASTE, and their evolutionally states have been identified [1]. Similary, sensitive and widest CO(3-2) mapping of several southern star-forming galaxies such as M83 and NGC 986 [10] have been made using ASTE, demonstrating a good spatial coincidence between the dense molecular gas and massive star formation traced by Hα and/or IRAC 8μm continuum. A large scale dust temperature gradient in M33 has been discovered based on the whole area 1.1 mm dust continuum mapping using AzTEC on ASTE, suggesting that intermediate-mass stars, not massive stars, play a major role on the heating of dust clouds.

4.4.6 Future research plans

Based on the achivements so far, we plan to obtain ALMA observing time in order to explore the new discovery space for dusty galaxies and dusty nuclei of galaxies in the universe. Although the oversubscription rate exceeds 9 for the ALMA cycle 0 programs, we belive that the uniqueness of our studies can allow us to be successful on obtaining ALMA observing time. Here are some specific research plans.

1. Multi-color surveys of dusty extreme starbursts in the early universe: We have built 400 pixel multi-color TES bolometer arrays for ASTE. We will conduct multi-band deep surveys including existing AzTEC deep survey fields in order to obtain redshift constraints on the AzTEC sources. Extensive surveys will be made for the Hyper Suprime Cam (HSC) ultra deep fields, i.e., SXDF and COSMOS. The synergies with HSC (i.e., with the project 3 in RESCEU) will be crutial to identify unique and important targets for detailed follow up studies using ALMA. The TES arrays will be eventually upgraded to 0.85 and 0.45 mm bands with 1000 pixels in total, giving further capability to obtain constraint on the redshift distributions of SMGs. Some of the interesting targets, such as SPIRE-drop 1.1 mm sources and 1.1 mm sources associated with 500 μm risers, will be perfect targets of ALMA.

2. Spectroscopic follow up of SMGs: CO observations of SMGs using a new Z-machine on NRO 45m telescope (TZ100/SAM45) will be conducted after the successful science verification programs [3]. We have also discussed with the use of CSO, which will be equipped with ultra wide band spectrometers such as Z-Spec and ZEUS, with Caltech. This is a part of the contribution to the CSO operation from University of Tokyo (grant-based). With these collaboration between CSO and Univ. of Tokyo, we would like to explore the possibilities for the participation to CCAT and/or collaboration for future 30-50m class mm/submm telescope project discussed in Japan. We have also started collaboration with Delft, which

are proposing a novel spectrometer employing MKIDs technology with integrated filter banks (DESHIMA). This will bring another breakthrough of mm/submm technology, and it will be possible to install DESHIMA to ASTE to demonstrate the feasibility of integrated filter bank on-chip spectrometer in 2015-2017, hopefully.

These innovative ultra wide band mm/submm spectrometers are crutial for the redshift determination of SMGs based on detection of [CII] 158μm. This line is known to be the brightest for this waveband, and the existing 10 m class telescope including ASTE is already sensitive enough to detect [CII]158μm lines from bright ULIRGs/HyLIRGs at $2 < z < 6$ (or higher). One we determine the redshift of SMGs, it will be then very suitable for the detailed follow up study using ALMA.

3. ALMA studies of galactic nuclei: Based on our successful ALMA cycle 0 programs on nearby AGNs and starbursts (i.e., NGC 1097, NGC 1068, and NGC 253), we will conduct extensive analysis of molecular abundances, excitations, and kinematics at the very center of active nuclei. We have also submitted further follow up programs of these galaxies, including 10 pc resolution imaging of HCN(4-3) at the center of NGC 1097. We have also successfully obtained ATCA observing time for a follow up study of the lowest-J CS emission in NGC 253. Collaobration with theoretical studies of chemical properties of dense molecular gas (e.g., Harada et al., Nomura et al.) is also underway, in order to understand the observed characteristics of dense molecular medium.

4.4.7 Major publications

[1] Miura, R. E., Kohno, K., Tosaki, T., Espada, D., Hwang, N., Kuno, N., et al., "GMC Evolutions in the Nearby Spiral Galaxy M33", *Astrophys. J.*, in press.

[2] Takekoshi, T., Minamidani, T., Nakatsubo, S., Oshima, T., Kawamura, M., Matsuo, H., Sato, T., Halverson, N. W., Lee, A. T., Holzapfel, W. L., Tamura, Y., Hirota, A., Suzuki, K., Izumi, T., Sorai, K., Kohno, K., Kawabe, R., "Optics Design and Optimizations of the Multi-color TES Bolometer Camera for the ASTE Telescope", *IEEE Trans. Terahertz Sci. Technol.*, in press.

[3] Iono, D., Hatsukade, B., Kohno, K., Kawabe, R., Tamura, Y., et al., "Initial Results from Nobeyama Molecular Gas Observations of Distant Bright Galaxies", *Publ. Astron. Soc. Japan*, **64**, L2 (2012)

[4] Hatsukade, B., Hashimoto, T., Ohta, K., Nakanishi, K., Tamura, Y., and Kohno, K., "Constraints on Obscured Star Formation in Host Galaxies of Gamma-Ray Bursts", *Astrophys. J.*, **748**, id.108 (2012).

[5] Nakajima, T., Takano, S., Kohno, K., and Inoue, H., "Detections of C_2H, Cyclic-C_3H_2, and $H^{13}CN$ in NGC 1068", *Astrophys. J.*, **728**, id.L38 (2011).

[6] Hatsukade, B., Kohno, K., Aretxaga, I., Austermann, J. E., Ezawa, H., Hughes, D. H., et al., "AzTEC/ASTE 1.1-mm survey of the AKARI Deep Field South: source catalogue and number counts", *Mon. Not. Roy. Astron. Soc.*, **411**, 102-116 (2011)

[7] Ikarashi, S., Kohno, K., Aguirre, J. E., Aretxaga, I., Arumugam, V., Austermann, J. E., Bock, J. J., Bradford, C. M., Cirasuolo, M., Earle, L., Ezawa, H., Furusawa, H., Furusawa, J., Glenn, J., Hatsukade, B., Hughes, D. H., Iono, D., Ivison, R. J., Johnson, S., Kamenetzky, J., Kawabe, R., Lupu, R., Maloney, P., Matsuhara, H., Mauskopf, P. D., Motohara, K., Murphy, E. J., Nakajima, K., Nakanishi, K., Naylor, B. J., Nguyen, H. T., Perera, T. A., Scott, K. S., Shimasaku, K., Takagi, T., Takata, T., Tamura, Y., et al., "Detection of an ultrabright submillimetre galaxy in the Subaru/XMM-Newton Deep Field using AzTEC/ASTE", *Mon. Not. Roy. Astron. Soc.*, **415**, 3081-3096 (2011)

[8] Tamura, Y., Iono, D., Wilner, D. J., Kajisawa, M., Uchimoto, Y. K., Alexander, D. M., Chung, A., Ezawa, H., Hatsukade, B., Hayashino, T., Hughes, D. H., Ichikawa, T., Ikarashi, S., Kawabe, R., Kohno, K., et al., "Submillimeter Array Identification of the Millimeter-selected Galaxy SSA22-AzTEC1: A Protoquasar in a Protocluster?", *Astrophys. J.*, **724**, 1270-1282 (2010)

[9] Tamura, Y., Kohno, K., Nakanishi, K., Hatsukade, B., Iono, D., Wilson, G. W., et al., "Spatial correlation between submillimetre and Lyman-α galaxies in the SSA 22 protocluster", *Nature*, **459**, 61-63 (2009)

[10] Kohno, K., Tosaki, T., Miura, R., Muraoka, K., Sawada, T., Nakanishi, K., et al. "ASTE CO(3 2) Observations of the Southern Barred Spiral Galaxy NGC 986: a Large Gaseous Bar Filled with a Dense Molecular Medium", *Publ. Astron. Soc. Japan*, **60**, 457-464 (2008)

5 PROJECT 5: Search for Gravitational Waves

5.1 Project Members

Title	Name	Affiliation
Professor	Kimio Tsubono	Department of Physics
Assistant Professor	Yoich Aso	Department of Physics

5.2 Objectives of the Project

The objectives of the current gravitational wave (GW) search are to open a new window of observation for gravitational wave astronomy and to obtain insight into significant areas of science, such as understanding the physics of neutron stars, verifying and characterizing inflation (related to Project 1), determining the thermal history of the universe, characterizing dark energy, describing the formation mechanism of supermassive black holes in the center of galaxies, testing alternative theories of gravity, and seeking black hole dark matter.

5.3 Space Gravitational Wave Detector, DECIGO

5.3.1 Overview

DECIGO is a Japanese space project aiming at the detection of low-frequency gravitational waves at around 0.1Hz. A space gravitational-wave antenna, DECIGO (DECI-hertz interferometer Gravitational wave Observatory), will provide fruitful insights into the universe, particularly on the formation mechanism of supermassive black holes, dark energy and the inflation of the universe. In the current pre-conceptual design, DECIGO will be comprising four interferometer units; each interferometer unit will be formed by three drag-free spacecraft with 1000 km separation. Since DECIGO will be an extremely challenging mission with high-precision formation flight with long baseline, it is important to increase the technical feasibility before its planned launch in 2027. Thus, we are planning to launch two milestone missions. DECIGO pathfinder (DPF) is the first milestone mission, and key components for DPF are being tested on ground and in orbit.

5.3.2 Scientific targets

With DECIGO sensitivity, a merger event of $10^3 M_\odot$ black holes at $z \sim 1$ will be observed with a signal-to-noise ratio of 6000. Observation by DECIGO could reveal the mechanism of the formation of super-massive black holes at the center of galaxies. DECIGO also targets at GWs from neutron-star binaries; GW signals will be in the DECIGO band a few months

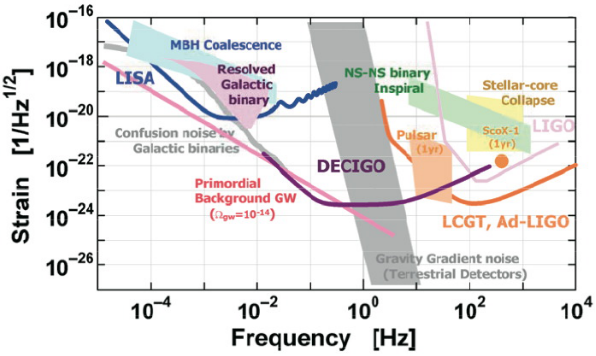


図 17: DECIGO sensitivity goal with expected GW sources.

to 5 years before merger. Thus, DECIGO can be a predictor for these merger events, which would be helpful for observations by ground-based detectors. The most exciting target of DECIGO will be the stochastic background GWs from the early Universe; GWs could be originated from inflation, primordial black holes, astrophysical objects and so on. It will be hard to observe these targets by electromagnetic waves directly because of scattering in high-energy plasma in the early Universe. So as to distinguish the stochastic background GWs from detector noises, DECIGO has multiple interferometer units for cross-correlation observation.

5.3.3 DECIGO conceptual design

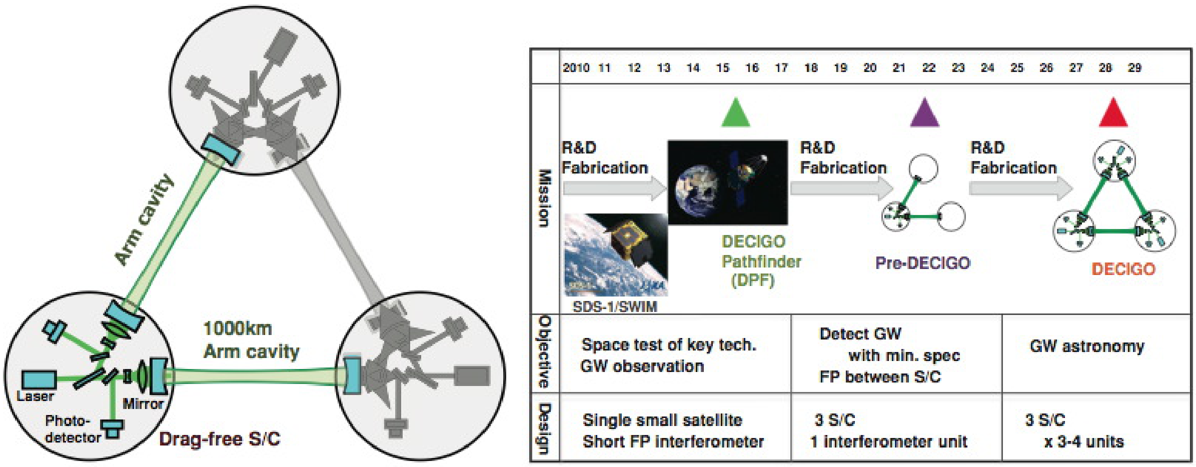


図 18: Conceptual design of DECIGO (left) and roadmap to realize DECIGO (right).

In the current pre-conceptual design, a unit of DECIGO is formed by three drag-free spacecraft, 1000 km apart from one another. These spacecraft have test mass mirrors inside them, which form long-baseline Fabry-Perot (FP) cavities; gravitational waves will be observed as changes in the cavity lengths. We adopted an FP interferometer configuration because it provides a better sensitivity at 0.1 Hz band than an optical transponder configuration used in LISA. The distance between spacecraft (FP cavity arm length) was chosen to be 1000 km so as to be short enough to avoid diffraction losses of laser power, and to store sufficient laser power inside the cavities, and yet to be long enough to ensure the high sensitivity for GW signals. The mirrors forming the cavities have a diameter of 1 m with moderate reflectivity to realize the cavity finesse of 10. The mass of mirror (about 100 kg) was chosen to be the largest we would fabricate and handle. The laser source of DECIGO will have an effective power of 10 W with a wavelength of 532 nm. The orbit and constellation of DECIGO are to be determined, considering the gravity disturbances by the sun and planets, durability of the thruster fuels, solar power supply and the required angle resolution for the GW source, and so on. One of the candidates of the orbit is a record-disk orbit around the sun, along the earth orbit.

5.3.4 DECIGO pathfinder, DPF

DECIGO pathfinder (DPF) will be a small satellite orbiting the earth. The mission payload part of DPF is designed to be a prototype of DECIGO and to test the key technologies of DECIGO, comprising a short Fabry-Perot (FP) cavity, a stabilized laser source and a drag-free control system. In addition, DPF has its own scientific goals: observation of gravitational waves and the gravity of the earth, and demonstrations of advanced space technologies. DPF is selected as one of the candidates of small satellite missions of JAXA.

DPF conceptual design: Conceptual design of DPF is shown in figure 19; DPF will be a single satellite with weight of about 350 kg, orbiting the earth with an altitude of 500 km. DPF will be launched by a next-generation solid propellant rocket, which is being developed as a successor of the M-V launch vehicle of JAXA. The mission payload part of DPF will have a size of 950 × 950 × 900 mm, and a mast structure for gravity-gradient attitude stabilization will be attached at the top of the module. The mission payload of DPF is designed to be a prototype of DECIGO, comprising a short FP cavity, a stabilized laser source and a drag-free control system (figure 19, right).

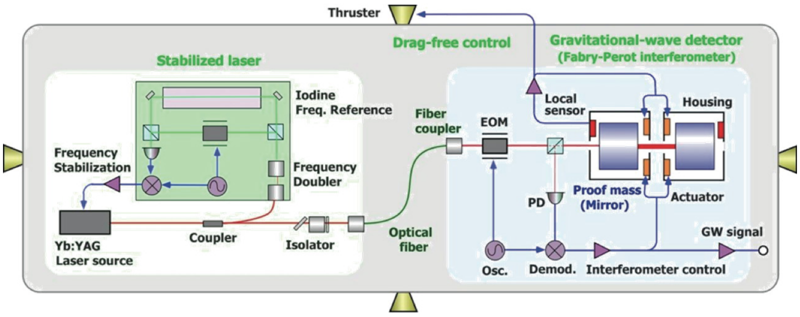


図 19: Conceptual design of DPF.

Objectives of DPF: DPF has its own scientific objectives as well as technical tests for DECIGO. One is observation of gravitational waves and gravity of the earth, and another is space demonstration of advanced precision-measurement techniques. DPF has a potential to detect gravitational-wave signals, if there is an inspiral-and-merger event with $10^3 \sim 4 \times 10^5 M_\odot$ black holes in our galaxy. Although the probability of having such events is considered to be rare, data obtained by DPF observations will have importance because this observation band is difficult to access by ground-based gravitational-wave detectors and other space-based detection methods. Observation of the gravity of the earth is another scientific objective of DPF. Since the proof masses orbit the earth almost freely, gravity distributions of the earth would be observed from the trajectories of the proof masses. In order to cancel the drag force by air and solar radiation, the relative displacements between the proof masses and the satellite frame are to be measured by small Michelson-interferometer-type laser sensors with an acceleration sensitivity of $10^{-11}\mathrm{ms}^{-2}$.

Current status of DPF: Research and development are underway with the support of JAXA and RESCEU, mainly concerning a mission studies including satellite design and drag-free control topology, and tests of key devices, such as a housing system for a proof mass, a stabilized laser and thrusters.

5.3.5 SWIM

A small demonstration module, named SWIM (SpaceWire Interface demonstration Module), has been developed and launched on 23 January 2009 in SDS-1, a JAXA's technology demonstration satellite. SWIM contains a space-qualified data processor and recorder with the SpaceWire interface, and a tiny gravitational-wave detector module with a size of 160 × 80 × 80 mm. SWIM has been operated in orbit successfully for a year, providing heritages for DPF on a SpaceWire-based data processing system and on sensing and control of proof masses in a space environment.

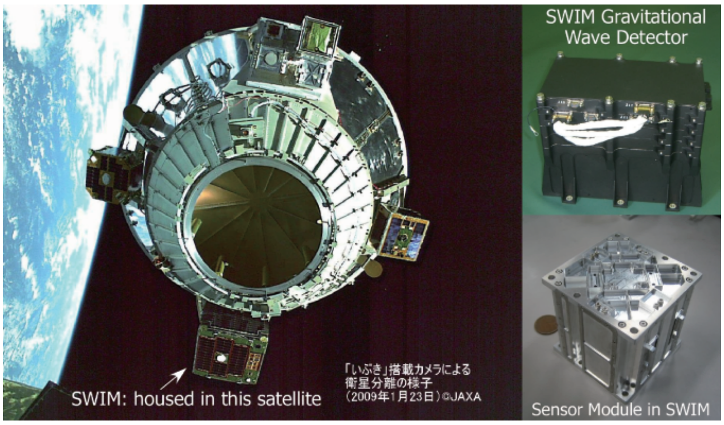


図 20: SWIM on the small satellites SDS-1.

5.4 KAGRA project

KAGRA, previously called LCGT (Large Cryogenic Gravitational-Wave Antenna), is a 3-km laser interferometric gravitational wave antenna built at Kamioka underground site in Japan. With characteristic features of stable environment of the underground site and cryogenic technologies, KAGRA will be one of the most sensitive gravitational-wave telescopes in the world when it starts observation run in the year 2017. For a coalescence of binary neutron stars, KAGRA will have an observation range more than 200 Mpc. With this range, it is estimated that KAGRA will detect multiple gravitational-wave events in one-year observation run. Along with the other telescopes, such as aLIGO in U.S.A. and Advanced VIRGO in Europe, KAGRA will open a new field of gravitational-wave astronomy.

図 21: Conceptual picture of KAGRA. A 3-km 'L'-shaped interferometer is placed in the Kamioka underground site.

KAGRA project was started in 2010 with a support by MEXT (Ministry of Education, Culture, Sports, Science, and Technology) of Japan. KAGRA is hosted by Institute of Cosmic-Ray Research (ICRR), the University of Tokyo, and is co-hosted by High Energy Accelerator Research Organization (KEK) and National Astronomical Observatory of Japan (NAOJ). KAGRA is built by a collaboration of more than 50 institutions and universities, or more than 150 research individuals. Now, KAGRA is in the first construction phase called iKAGRA (initial KAGRA), in which a simplified 3-km interferometer will be constructed in the underground facility. The tunnel and facility will be ready in FY2013, and the first observation run will start with simplified configuration in 2015. After that, KAGRA will be upgraded to bKAGRA (baseline KAGRA). The interferometer configuration will be upgraded to RSE (Resonant-Sideband Extraction), and cryogenic system will be implemented. The first observation run with the full configuration is planned by the end of 2017.

図 22: Construction status of KAGRA. Left: The excavated hall for the Y-end room at the Kamioka underground site. Middle: A Facility to test the installation procedure for the 3-km arm ducts. About 70% of the arm duct has been completed. Right: Cryostats to house the KAGRA main mirrors.

5.5 Future Research Plans

Gravitational waves (GWs) are expected to play a crucial role in the development of multi-messenger astrophysics. The combination of GW observations with other astrophysical triggers, such as from gamma-ray and X-ray satellites (collaborate with Project 7), optical/radio telescopes (related to Project 4), and neutrino detectors allows us to decipher science that would otherwise be inaccessible.

5.6 Major Publications

[1] Ayaka Shoda, Masaki Ando, Kenshi Okada, Koji Ishidoshiro, Wataru Kokuyama, Yoichi Aso, Kimio Tsubono: Search for a stochastic gravitational-wave background with torsion-bar antennas, J. Phys. Conf. Ser. 363 (2012) 012017.

[2] Seiji Kawamura, Masaki Ando, Naoki Seto, Shuichi Sato, Takashi Nakamura, Kimio Tsubono *et al.*, and the DECIGO working group: The Japanese space gravitational wave antenna: DECIGO, Class. Quantum Grav. **28** (2011) 094011.

[3] Koji Ishidoshiro, Masaki Ando, Akiteru Takamori, Hirotaka Takahashi, Kenshi Okada, Nobuyuki Matsumoto, Wataru Kokuyama, Nobuyuki Kanda, Yoichi Aso, and Kimio Tsubono: First Observational Upper Limit on Gravitational Wave Backgrounds at 0.2 Hz with a Torsion-Bar Antenna, Phys. Rev. Lett. **106** (2011) 161101.

[4] Masaki Ando, Koji Ishidoshiro, Kazuhiro Yamamoto, Kent Yagi, Wataru Kokuyama, Kimio Tsubono, and Akiteru Takamori: Torsion-Bar Antenna for Low-Frequency Gravitational-Wave Observations, Phys. Rev. Lett. **105** (2010) 161101.

[5] Masaki Ando, et al.: DECIGO and DECIGO pathfinder, Class. Quantum Grav. **27** (2010) 084010.

[6] Masaki Ando, et al.: DECIGO pathfinder, Class. Quantum Grav. **26** (2009) 9 094019.

[7] S Kawamura, et al.: The Japanese space gravitational wave antenna - DECIGO, Journal of Physics: Conference Series **122** (2008) 012006.

[8] S Kawamura, et al.: The Japanese space gravitational wave antenna; DECIGO, Journal of Physics: Conference Series **120** (2008) 032004.

[9] M Ando, et al.: DECIGO pathfinder, Journal of Physics: Conference Series **120** (2008) 032005.

[10] S. Kawamura, et al.: The Japanese space gravitational wave antenna.DECIGO, Class. Quantum Grav. **23**-8 (2006) S125-S131.

6 PROJECT 6: Direct Search for Dark Matter and Solar Axions

6.1 Project Members

Title	Name	Affiliation
Professor	Makoto Minowa	Department of Physics
Assistant Professor	Yoshizumi Inoue	International Center for Elementary Particle Physics

6.2 Objectives of the Project

Our research projects are based on the search or the observation of supersymmetric neutralinos, axions and neutrinos using techniques of the elementary particle physics experiment. The purpose of the projects is to discover or clarify the detailed nature of these particles which are essential keys to understand the whole picture of the evolution of the Universe from its creation up to the present.

6.3 Direct search for dark matter and solar axions

Various kinds of non-accelerator particle physics experiments and astroparticle physics experiments have been performed in our research group.

The oldest project is the direct experimental search for supersymmetric neutralino dark matter which was running in an underground cell in the Kamioka Observatory. We employed LiF cryogenic bolometers and a $\mathrm{CaF_2(Eu)}$ scintillator for the search experiment. The choice of the detector material is based on the fact that the fluorine is one of the best nuclides for the detection of spin-dependently interacting neutralinos. The fluorine for the dark matter search is complementary to the widely used sodium(of e.g. NaI) when their sensitivity is represented in the parameter plane of the neutralino-proton spin-dependent coupling(a_p) and neutralino-neutron spin-dependent coupling(a_n).

On the basis of the sveral measurements in Kamioka, limits were obtained which overrode the exclusion limits at that time to parameter regions for the spin-dependently interacting neutralinos.

We published our last paper[5] on the direct dark matter search experiment at the Kamioka underground cell in 2006. Our results excluded a part of the parameter region which was allowed at the time of our publication by the positive result by the DAMA NaI experiment. Our dark matter search experiment in the Kamioka Observatory was then closed.

We are also running an experiment to search for axions, light neutral pseudoscalar particles yet to be discovered. Its existence is implied to solve the so-called strong CP problem. The axion would be produced in the solar core through the Primakoff effect. It can be converted back to an x-ray in a strong magnetic field in the laboratory by the inverse process. The conversion process is coherent when the axion and photon remain in phase over the length of the magnetic field if the axion is almost massless. Coherence can be maintained even for higher mass axions if the conversion region is filled with a low-Z buffer gas like helium. We search for such x-rays coming from the direction of the sun with the Tokyo axion helioscope, also known as Sumico(Fig.23).

Sumico was the world's first dedicated axion helioscope except for the pioneering experiment with a fixed surplus accelerator magnet by Lazarus et al.

We started the construction of Tokyo axion helioscope in 1995, and the phase 1 result was published in 1998 without a buffer gas in the manetic field region. Then, phase 2 measurement for the axion mass less than 0.27 eV with a helium gas was made and result was published in 2002.

In the mean time, CERN Axion Solar Telescope(CAST) experiment was getting started in CERN and published their result for measurements with vacuum magnetic field region. The third phase of Tokyo axion helioscope was then prepared, and the result was published for the axion mass region between 0.84 eV and 1.00 eV in 2008. It is the world's first result to search for the axion in the $g_{\mathrm{a}\gamma\gamma} - m_{\mathrm{a}}$ parameter region of the preferred QCD axion models with a magnetic helioscope.

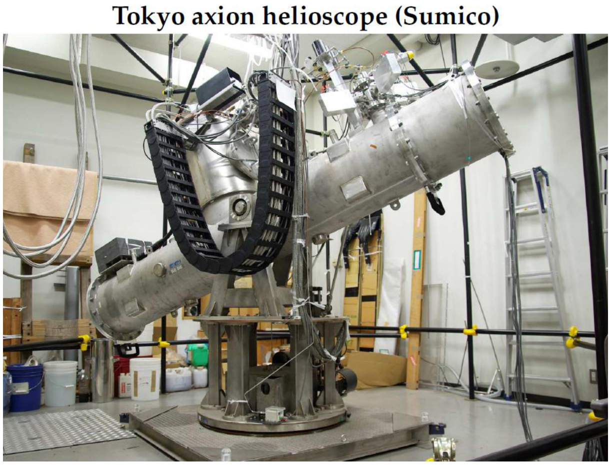


図 23: Tokyo Axion Heloscope (Sumico)

Sumico consists of a cryogen-free 4 T superconducting magnet with an effective length of 2300 mm and PIN photodiodes as x-ray detectors. By now, we put upper limits of $g_{a\gamma\gamma} < (5.6\text{–}13.4) \times 10^{-10}\mathrm{GeV}^{-1}$ to axion - photon coupling constant for the axion mass $m_a < 0.27$ eV and $0.84\ \mathrm{eV} < \mathrm{m_a} < 1.00$ eV. The latter is a newly explored mass region which CAST group that started later has not reached yet(Fig.24).

We started a new R and D study of a compact mobile anti-electron neutrino detector with plastic scintillators to be used at a nuclear reactor station, for the purpose of monitoring the power and plutonium content of the nuclear fuel. It can be used to monitor a reactor from outside of the reactor containment with no disruption of day-to-day operations at the reactor site. This unique capability may be of interest for the reactor safeguard program of the International Atomic Energy Agency(IAEA).

We propose a segmented antineutrino detector made of plastic scintillators called PANDA, Plastic Anti-Neutrino Detector Array. A small prototype was built and deployed for two months at Ohi Power Station in Fukui, Japan. A satisfactory unmanned field operation of the detector system was demonstrated there. The prototype detector consists of a 360-kg plastic scintillator array into which gadolinium-containing sheets are introduced. It is installed on a van, transported to the site, and held in the van outside of the reactor building during the measurement. We observed a difference in neutrino-like event rate before and after the shutdown of the reactor although cosmic-ray induced background events are predominant because of aboveground operation and small detector size. This is the world's first result to detect reactor antineutrinos with an aboveground detector.

Although the present phase of PANDA is dedicated to the applied neutrino science, PANDA could eventually be used to verify the existense of the sterile neutrino, which is implied by the recent cosmological data and invoked for the explanation of short-baseline reactor antineutrino

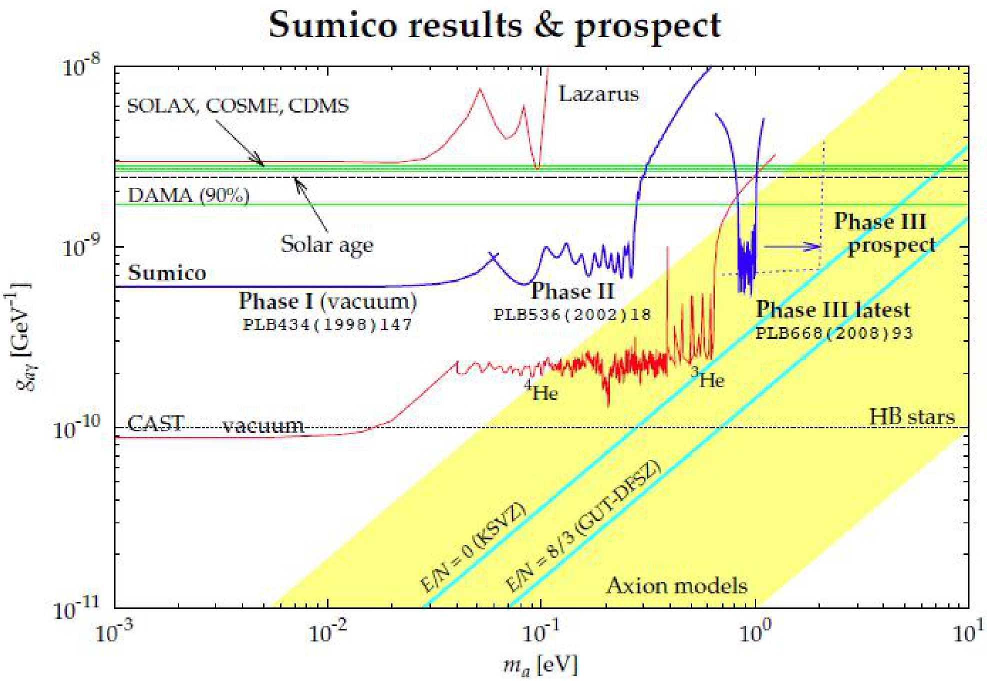


図 24: Exclusion plots in the parameter plane of $g_{a\gamma\gamma} - m_a$.

anomalies as well as the gallium and LSND/MiniBooNE anomalies. We shall bring PANDA into a compact-core research reactor which fits the short oscillation length of the proposed sterile neutrinos. Its mobility and compactness help the deployment in any sites.

6.4 Future Research Plans

We would continue our major research projects, Sumico, the Tokyo axion helioscope and PANDA, the mobile antineutrino detector.

A possible extension of the Tokyo axion helioscope experiment is to search for a point axion source in a certain celestial bodies besides the sun. They include supernova remnants, the galactic center, gamma ray bursts and others. Sumico is able to scan almost all the celestial sphere while only a part is reachable by CAST.

Another project to use Sumico is a search for hidden sector photons kinetically mixing with the ordinary photons. The existence of the hidden sector photons is predicted by extensions of the Standard Model, notably the ones based on the string theory. The hidden sector photon is expected to come from the direction of the sun. It would be produced in the solar core or in the space by oscillation of the ordinary photon, and can transmute into the photon again in a long vacuum chamber in the laboratory. A photon sensor in the chamber would readily detects the ordinary photon. A prototype detector is piggybacked onto the Sumico helioscope. We have let the detector track the sun to search for the hidden sector photons coming from the sun and found no significant signal for the hidden sector photon. We put upper limits to the mixing angle χ of the normal photon and the hidden sector photon in the unexplored parameter region around the hidden sector photon mass of a few millielectron volts. With the satisfactory prototype result in mind, we will construct a larger detector with higher sensitivity to the hidden photon.

As for the PANDA project, our primary goal is to finish the reactor monitor application which satisfies IAEA's requirements. There is yet another motivation of PANDA. With its mobility and compactness, PANDA could be used to verify the existense of sterile neutrinos. The existing cosmological data indicate that the energy density of the Universe may contain dark radiation composed of one or two sterile neutrinos, which have been invoked for the explanation of short-baseline reactor antineutrino anomalies as well as the gallium and LSND/MiniBooNE anomalies. We shall bring PANDA into a compact-core research reactor which fits the short oscillation length of the proposed sterile neutrinos. While almost all the compact-core reactors in Japan are in shutdown, we might consider foreign reactors as possible sites of the experiment.

6.5 Major Publications

[1] Yasuhiro Kuroda, Shugo Oguri, Yo Kato, Ryoko Nakata, Yoshizumi Inoue, Chikara Ito, Makoto Minowa: A mobile antineutrino detector with plastic scintillators,
arXiv:1206.6566v1 [physics.ins-det],
Nuclear Inst. and Methods in Physics Research, A **690** (2012), 41–47.

[2] R. Ohta, Y. Akimoto, Y. Inoue, M. Minowa, T. Mizumoto, S. Moriyama, T. Namba, Y. Takasu, A. Yamamoto: The Tokyo Axion Helioscope,
arXiv:1201.4622v1 [astro-ph.IM],
Nuclear Inst. and Methods in Physics Research, A **670** (2012), 73–78.

[3] S. Oguri, Y. Inoue, M. Minowa: Pulse-shape discrimination of CaF_2(Eu),
arXiv:1007.4750v2 [physics.ins-det],
Nucl. Instr. and Meth. in Phys. Research A **662** (2010), 588–591.

[4] Y. Inoue, Y. Akimoto, R. Ohta, T. Mizumoto, A. Yamamoto, M. Minowa: Search for solar axions with mass around 1 eV using coherent conversion of axions into photons,
RESCEU-55/08, arXiv:0806.2230v2 [astro-ph],
Physics Letters B **668** (2008) 93–97.

[5] Y. Shimizu, M. Minowa, W. Suganuma, Y. Inoue: Dark matter search experiment with CaF_2(Eu) scintillator at Kamioka Observatory,
arXiv:astro-ph/0510390v1,
Physics Letters B **663** (2006) 195 – 200.

7 PROJECT 7: Researches using Space-Borne Instruments

7.1 Project Members

Title	Name	Affiliation
Professor	Kazuo Makishima	Department of Physics / RESCEU
Professor	Akira Yamamoto	The High Energy Accelerator Research Organization
Assistant Prof.	Junko S. Hiraga	RESCEU

7.2 Objectives of the Project

Some important aspects of astrophysics and cosmology can be studied only from outside the Earth's atmosphere. The purpose of this Project is to promote such *researches from space*, based on our close and successful collaboration with the Japan Aerospace Exploration Agency (JAXA). Our research activities include R&D for satellite-borne instruments, implementation of forefront balloon experiments, and scientific analysis of the obtained data. This unique capability provides an important basis for the RESCEU's future growth, covering, e.g., space gravitational wave experiments (Project 5). The two Sub-Projects both probe into energetic radiation that is strongly attenuated by the Earth's atmosphere. By thus studying the most energetiic part of cosmic baryons, we are hence contributing significantly to the "Baryon domain" of RESCEU.

7.3 Sub-Project 1: Cosmic X-ray/Gamma-ray Studies with Scientific Satellites

7.3.1 Research methods

We develop novel instruments for cosmic X-ray/gamma-ray satellites, and use them to observe high-energy celestial sources. Generally, these instruments detect signal photons, and provide their individual energies, sky positions, and arrival times. The data allow us to *simultaneously* perform the X-ray photometry, imagery, and spectroscopy. Our research is guided by the following principles.

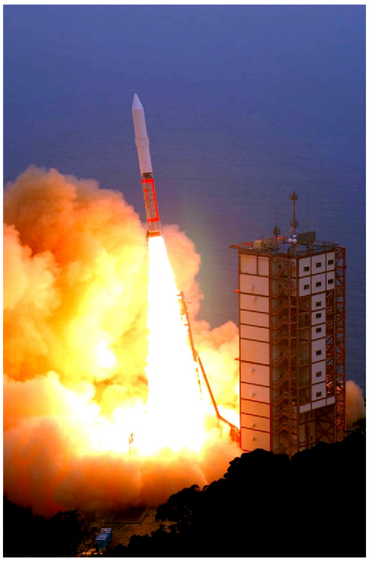


図 25: The launch of *Suzaku*.

- To simultaneously carry out both the hardware developments and the forefront astrophysics.
- To conduct all the research activities in full collaboration with graduate education, mainly in Physics department.
- To make the best use of the knowledge continuation, from preceding satellites to their successors.
- Always attempt to create new research trends, instead of following those ideas which are becoming popular worldwide.
- To collaborate closely with the other RESCEU Projects: with Project 2 in our quest for the origin of magnetars, with Project 3 in establish our plasma physics view of clusters of galaxies, and in a broad sense with Project 5 in space technology.

7.3.2 Launch of the *Suzaku* satellite

On 2005 July 7, the 5th Japanese cosmic X-ray satellite *Suzaku* (*Astro-E2*) was launched by JAXA from the Uchinoura Space Center (Fig.25) [7]. Together with JAXA, RIKEN, Hiroshima University, Saitama University, Stanford University and a few institutinos, we developed the Hard X-ray Detector (HXD) [6] onboard *Suzaku.* Though without imaging capability, the HXD provide unprecedented sensitivity to hard X-rays in the 10–600 keV (usually up to 200 keV) band.

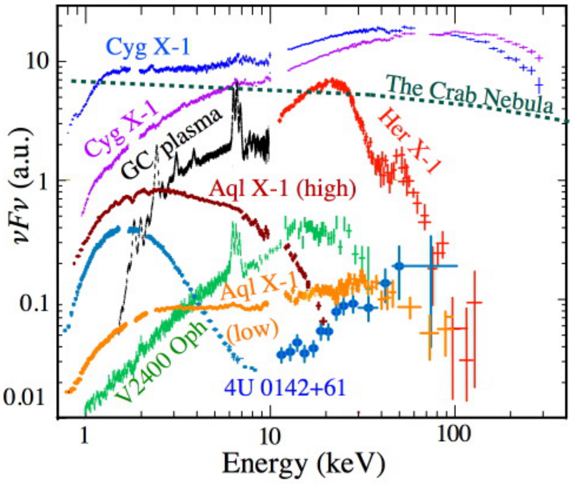


図 26: *Suzaku* spectra of typical X-ray sources.

7.3.3 Mass-accreting black holes

As shown in Fig. 26, *Suzaku* provided the highest-quality wide band spectra of Cyg X-1. We found [5] that the "central engine" of this leading stellar-mass black hole has multiple zones where seed photons from an accretion disk is thermally Comptonized. As a result, the primary continuum of Cyg X-1 (and of other accreting black holes, too) is more complex than a single power-law. This view also applies to some Active Galactic Nuclei [3].

7.3.4 Neutron stars

With *Suzaku*, we study various types of neutron stars, including "magnetars" with ultra-strong magnetic fields of 10^{14-15} Gauss. As represented by 4U 0142+61 in Fig. 26, we established that magnetars all exhibit peculiar two-component spectra, consisting of a soft thermal component and a mysterious very hard component [4]. We propose that the hard component is produced when 511 keV gamma-ray photons, created in the magnetosphere, cascade down to softer photons, through quantum-electro-dynamical (QED) "photon splitting" process under the extreme magnetic fields. We collaborate with Project 2, trying to clarify how magnetars are created.

7.3.5 Accreting white dwarfs

We successfully modeled broad-band *Suzaku* spectra of accreting white dwarfs (WD; green in Fig. 26), which consist of hot thermal Bremsstrahlung continua and ionized Fe-K lines. This allowed us to estimate the mass-to-radius ratios of these degenerate stars. Convolving the spectral model with a plausible WD mass function, we have shown that the mysterious Galactic ridge X-ray emission is explained, in energies above 10 keV, as collection of numerous accreting WDs [1].

7.3.6 Clusters of galaxies

Our research using *Suzaku* and other X-ray missions [2]. reinforced a full plasma-physics view of central regions of clusters of galaxies, which we proposed in 2001 based on observations with *ASCA*, the *Suzaku*'s predecessor. Further extensively employing optical data of some 30 clusters obtained with the University of Hawaii's 88 inch telescope, we have made a novel discovery, that member galaxies in clusters were falling to the potential center over the Hubble. This is considered due to magneto-hydro-dynamical interactions between the moving galaxies and the X-ray emitting hot plasma. In this research, we are collaborating closely with Project 3.

7.3.7 Development for the *ASTRO-H* mission

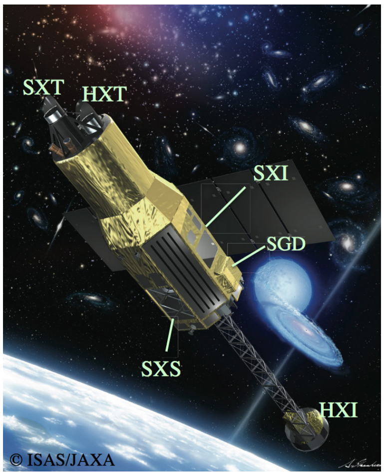


図 27: The *ASTRO-H* mission.

Developed under an extensive international collaboration, *ASTRO-H* is the 6th Japanese X-ray mission with its sensitivity extending into low-energy gamma-rays (up to 600 keV). As the successor to *Suzaku*, it is scheduled for launch in 2014 with an H2A rocket. It carries onboard six instruments, and we At RESCEU participate in the development of three of them. These are; the Soft X-ray Imager (SXI) utilizing the Japan-made CCDs; the Hard X-ray Imager (HXI) employing Silicon and CdTe strip detectors; and the Soft Gamma-ray Detector (SGD) which uses the concept of Compton camera. The HXI and SGD fully utilize heritages from the *Suzaku* HXD, including tight active shields made of BGO scintillators.

7.3.8 Future research plans

The most important research plan for us is to construct *ASTRO-H*, put it into orbit (probably in 2014), and relay important findings with *Suzaku* to this powerful new successor. We plan to use it for a large number of investigations, including the floowing.

- Search magnetar signals with the SGD for the predicted QED effects at > 511 keV.
- Search for aged magnetars with the HXI, to establish their expected prevalence.
- Through studies of neutron stars, give tight constraints on the nuclear equation of state.
- Verify that “ULX objects” seen in nearby galaxies are indeed intermediate-mass black holes.
- Clarify the structure, geometry and function of the central engines in AGNs.
- Measure turbulence and “galaxy drag” in the X-ray emitting plasmas in clusters of galaxies.

7.3.9 Major publications

[1] Yuasa, T., Makishima, K., & Nakazawa, K: “Broadband Spectral Analysis of the Galactic Ridge X-Ray Emission, *Astrophys. J.* **754**, id.129 (2012).

[2] Gu, L. Y., Inada, N., Konami, S., Kodama, T., Nakazawa, K., Kawaharada, M. & Makishima, K: “Two-phase ICM in the Central Region of the Rich Cluster of Galaxies A1795: A Joint *Chandra, XMM-Newton*, and *Suzaku* View”, *Astrophys. J.* **749**, id.186 (2012).

[3] Noda, H., Makishima, K., Yamada, S., Torii, S., Sakurai, S. & Nakazawa, K: “Suzaku Studies of Wide-Band Spectral Variability of the Bright Type I Seyfert Galaxy Markarian 509, *Publ. Astr. Soc. Japan* **63**, 925-936 (2011).

[4] Enoto, T., Nakazawa, K., Makishima, K., Rea, N., Hurley, K. & Shibata, S.: “Broadband Study with *Suzaku* of the Magnetar Class”, *Astrophys. J. Lett.*, **722**, L162–167 (2010).

[5] Makishima, K., Takahashi, H., Yamada, S., Done, C., Kubota, A., Dotani, T., Ebisawa, K., Itoh, T., Kitamoto, S., Negoro, H., Ueda, Y., & Yamaoka, K.: “Suzaku Results on Cygnus X-1 in the Low/Hard State”, *Publ. Astr. Soc. Japan* **60**, 585-604 (2008).

[6] Kokubun, M., Makishima, K., *et al.*: “In-Orbit Performance of the Hard X-Ray Detector on Board Suzaku”, *Publ. Astr. Soc. Japan* **59**, S53-S76 (2007).

[7] Mitsuda, K., Makishima, K.,Hiraga, J. (49 名): “The X-Ray Observatory Suzaku”, *Publ. Astr. Soc. Japan* **59**, S1-S7 (2007).

7.4 Sub-project 2: Balloon Observations of Cosmic Anti-Protons

7.4.1 Research objectives and methods: the BESS project

The Balloon-borne Experiment with a Superconducting Spectrometer (BESS) has performed cosmic-ray observations by using scientific ballooning. to study elementary particle phenomena in the early Universe [1, 2, 3, 4]. BESS has focused on the measurement of low-energy antiproton spectra and the solar modulation dependence, to search for signatures of possible primary origins such as dark matter candidates or primordial black holes (PBHs). BESS has also searched for heavier antinuclei such as anti-helium that might reach Earth from antimatter domains formed in the early Universe. BESS uses a superconducting magnetic-rigidity spectrometer, for clear identification of negative and positively charged particles, with a time-of-flight (TOF) system, and an aerogel Cherenkov counter (ACC) to fully identify incident particles by charge, charge sign, rigidity, and velocity as the spectrometer concept shown in Fig. 28.

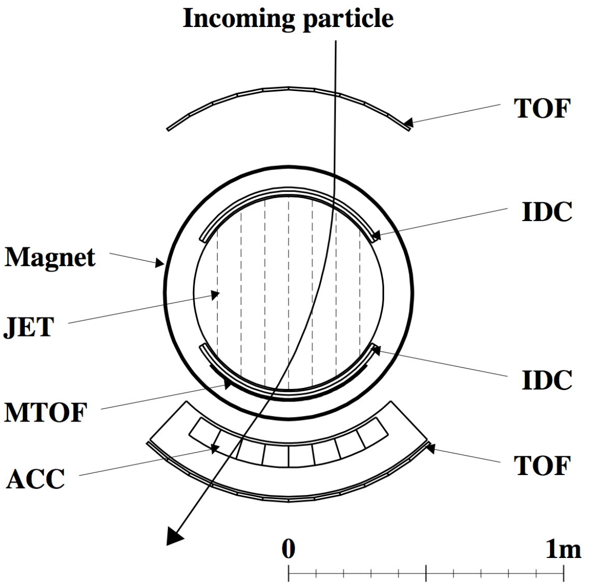


図 28: Cross-section and concept of the BESS spectrometer.

表 7: Progress of the BESS and BESS-Polar balloon flight and observation [1, 4].

	1993	1994	1995	1997	1998	1999	2000	2001	2002	2004	2007
Location	——Canada——							US	C.	Antarctic	
Float time (h)	17.5	17	19.5	20.5	22.0	34.5	44.5	1.0	16.5	205	730
Obse. time, float (h)	14	15	17.5	18.3	20.0	31.3	32.5	1	11.3	180	588
Obs. time, asc./des.(h)						2.8	2.5	12.8	2.3	3.3	3.5
Recorded events (×10^6)	4.0	4.2	4.5	16.2	19.0	19.1	17.0	N/A	13.7	900	4700
Data volume (GB)	4.5	6.5	8.0	31	38	41	38	N/A	56	2,140	13,500
Event filtering	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Magnetic field (T)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.8
MDR (GV)	200	200	200	200	200	200	200	1,400	1,400	240	240
TOF resolution (ps)	300	300	100	75	75	75	75	75	75	160	120
ACC index	–	–	–	1.03	1.02	1.02	1.02	1.02	1.02	1.02	1.03
$\bar{p}$ events observed	6	2	43	415	384	668	558	N/A	147	1,520	7886
$\bar{p}$ energy (GeV)	< 0.5	< 0.5	< 3.6	< 3.6	< 3.6	< 3.6	< 4.2	*N/A*	< 4.2	< 4.2	< 3.5
Anti-He upper limit*	22	4.3	2.4	1.4	1.0	0.8	0.68	N/A	0.65	0.27	0.07

*: Anti-He/He ratios in units of 1×10^{-6}.

7.4.2 Summary of balloon flights

The BESS scientific ballooning program, supported by JAXA/ISAS and NASA, performed eleven successful scientific balloon flights from 1993 through 2008; nine approximately one-day northern-latitude flights and two long-duration Antarctic flights, as summarized in Table 1. The apex of the BESS program was reached with the Antarctic flight of BESS-Polar II, during the 2007- 2008 Austral Summer. It obtained over 4.7 billion cosmic-ray events from 24.5 days of observation. The flight took place at the expected solar minimum, when the sensitivity of the low-energy antiproton measurements to a possible primary source is greatest. These have collectively recorded more than 10,000 cosmic-ray low-energy antiproton candidates. It has also progressed to search for anti-nuclei resulting the most stringent upper limits to the existence of antihelium and antideuterium, as discussed below.

7.4.3 Research highlights

BESS has achieved two major milestones in its program to study the early Universe with the highest-precision measurements, ever achieved, of the cosmic-ray antiproton spectrum and stringent limits on the abundance of cosmological antihelium nuclei from the 2007-2008 Austral Summer flight of BESS-Polar II. The antiproton spectrum has probed to seek for possible exotic primary sources, such as PBHs. The search for antihelium has examined the possibility that antimatter domains remain in the cosmological neighborhood from symmetry breaking processes in the early Universe.

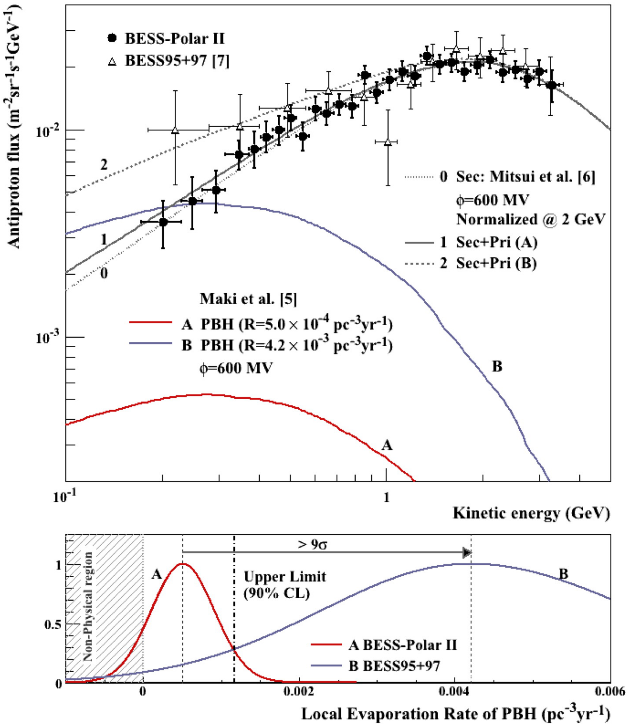


図 29: Antiproton spectrum measured in BESS-Polar II experiment compared with the BESS95+97 and secondary production models, and possible primary fluxes from PBH evaporations calculated for BESS Polar II and BESS(95+97) experiments : (Top) Possible primary antiproton fluxes from PBH evaporation calculated for (A) BESS-Polar II and (B) BESS95+97 by fitting differences of the measured spectra from the Mitsui secondary antiproton spectrum. (Bottom) PBH evaporation rate (R) distributions. Values of $R < 0$ are nonphysical [2].

BESS-Polar II recorded over 4.7 billion cosmic-ray events during 24.5 days of data-taking over Antarctica, as described above. This dataset more than doubled the combined data from all earlier BESS flights. Most important, the flight was at a period of very low, near minimum, Solar activity when the sensitivity of low-energy antiproton measurements to a primary source is greatest. The 7,886 antiprotons identified by BESSPolar II give 10-20 times statistics, depending on energy, of BESS data from 1995 and 1997 during the previous Solar minimum. This shows good consistency with the secondary antiproton flux calculations. Figure 29 shows the BESS-Polar II antiproton spectrum compared with the measured results from BESS95 +97 and with solar-minimum secondary calculations. Comparing the models shown to the measurements, and using the a PBH model calculated by Maki et al., with force-field modulation, we obtained a model-dependent evaporation rate, R, determined by fitting a PBH model spectrum to the difference of a secondary calculation from the measured flux. This excludes by more than 9 sigma the slight possibility of primary antiprotons suggested by the BESS95+97 data with the same models and modulation. As a result, we find a 90% confidence level upper limit of $R = 1.2 \times 10^{-3}$ pc^{-3} yr^{-1}. This is almost insensitive to modulation in this energy/rigidity region. Within statistics, the BESS-Polar II data show no evidence of primary antiprotons from PBH evaporation.

In long-duration balloon flights over Antarctica, BESS has searched for antihelium in the cosmic radiation with the highest sensitivity ever reported. Figure 3 shows the progress of the search for antihelium with the BESS experiment in comparison with previous experiments published. No antihelium candidate was found in BESS-Polar II data among 4.0×10^7 $\|Z\| = 2$ nuclei from 1.0 to 14 GV during the 24.5 days observation. Assuming antihelium to have the same spectral shape as helium, a 95% confidence upper limit to the possible abundance of antihelium relative to helium of 9.4×10^{-8} was determined with the BESS-Polar II data, and 6.9×10^{-8} was determined combining all BESS data, including the BESS-Polar flights. The most conservative upper limit is obtained if no shape is assumed for the antihelium spectrum and the lowest overall antihelium efficiency within the search range is applied to any hypothetical He. With no assumed antihelium spectrum and a weighted average of the lowest antihelium efficiencies for each flight, an upper limit of 1.0×10^{-7} from 1.6 to 14 GV was determined for the combined BESS-Polar data. Under both antihelium spectral assumptions, these are the lowest limits obtained to date. The limit has been lowered by three orders of magnitude over the first reported limit.

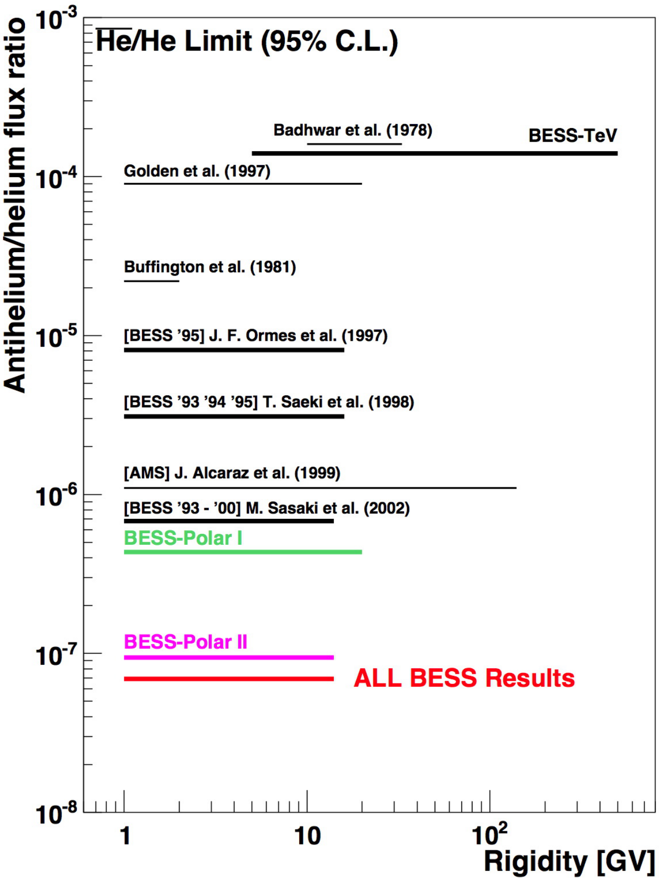


図 30: The new upper limits of antiherlium/herlium ratio at the TOA calculated assuming the same energy spectrum for antiherlium as for helium with previous experimental results. The limit calculated with no spectral assumption is about 25% [3].

7.4.4 Summary of the BESS project

The Balloon-borne Experiment with a Superconducting Spectrometer (BESS) has performed cosmic-ray observations by using scientific ballooning, aiming at study of elementary particle phenomena in the early Universe. The energy spectrum of cosmic-ray antiprotons from 0.17 to 3.5 GeV has been measured using 7,886 antiprotons detected by BESS-Polar II during a long-duration flight for 24.5 days over Antarctica near solar minimum in December 2007 through January 2008. This shows good consistency with secondary antiproton calculations. Cosmologically primary antiprotons have been investigated by comparing measured and calculated antiproton spectra. BESS-Polar II data show no evidence of primary antiprotons from the evaporation of primordial black holes. BESS has searched for antihelium in the cosmic radiation with the highest sensitivity ever reported.

No antihelium candidate was found in BESS-Polar II data among 4×10^7 $\|Z\|$ nuclei from 1.0 to 14 GV. Assuming antihelium to have the same spectral shape as helium, a 95% confidence upper limit to the possible abundance of antihelium relative to helium of 6.9×10^{-8} was determined combining all BESS data, including the two BESS-Polar flights. With no assumed antihelium spectrum and a weighted average of the lowest antihelium efficiencies for each flight, an upper limit of 1×10^{-7} from 1.6 to 14 GV was determined for the combined BESS-Polar data. Under both antihelium spectral assumptions. The BESS-Polar established the lowest limits to date on the possible presence of antihelium in the cosmic radiation, and this limit is lowered by three orders of magnitude over the first reported limit.

7.4.5 Major publications

[1] Yamamoto, A., Abe, K., Fuke, H., Haino, S., Hams, T., Hasegawa, M., Horikoshi, A., Itazaki, A., Kim, Kumazawa, T., Kusumoto, A., Lee, M.H., Makida, Y., Matsuda, S., Matsukawa, Y., Matsumoto, K., Mitchell, J.W., Myers, Z., Nishimura, J., Nozaki, M., Orito, R., Ormes, J.F., Sakai, K., Sasaki, M., Seo, E.S., Shikaze, Y., Shinoda, R., Streitmatter, R.E., Suzuki, J., Takasugi, Y., Takeuchi, K., Tanaka, K., Thakur, N., Yamagami, T., Yoshida, T., and Yoshimura, K.: "Search for Cosmic-ray Antiproton Origins and for Cosmological Antimatter with BESS", *Proc.of COSPAR 2010*, and in printing for *Advances in Space Research.*

[2] Abe, K., Fuke, H., Haino, S., Hams, T., Hasegawa, M., Horikoshi, A., Kim, Kusumoto, A., Lee, M.H., Makida, Y., Matsuda, S., Matsukawa, Y., Mitchell, J.W., Nishimura, J., Nozaki, M., Orito, R., Ormes, J.F., Sakai, K., Sasaki, M., Seo, E.S., Shinoda, R., Streitmatter, R.E., Suzuki, J., Tanaka, K., Thakur, N., Yamagami, T., Yamamoto, A., Yoshida, T., and Yoshimura, K.: "Measurement of the Cosmic-Ray Antiproton Spectrum at Solar Minimum with a Long-duration Balloon Flight over Antarctica", *Phys. Rev. Lett.* **108**, 051102 (2012).

[3] Abe, K., Fuke, H., Haino, S., Hams, T., Hasegawa, M., Horikoshi, A., Itazaki, A., Kim, Kumazawa, T., Kusumoto, A., Lee, M.H., Makida, Y., Matsuda, S., Matsukawa, Y., Matsumoto, K., Mitchell, J.W., Myers, Z., Nishimura, J., Nozaki, M., Orito, R., Ormes, J.F., Sakai, K., Sasaki, M., Seo, E.S., Shikaze, Y., Shinoda, R., Streitmatter, R.E., Suzuki, J., Takasugi, Y., Takeuchi, K., Tanaka, K., Thakur, N., Yamagami, T., Yamamoto, A., Yoshida, T., and Yoshimura, K.: "Search for Antihelium with the BESS-Polar Spectrometer", *Phys. Rev. Lett.* **108**, 131301 (2012).

[4] Yoshimura, K., Yamamoto, A., et al.: "Search for Antideuteron with BESS-Polar", *Proceedings of the 32nd International Cosmic Ray Conference*, Beijing, Aug., 2011.

8 横山 順一、 Jun’ichi Yokoyama

8.1 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	Associate 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

8.2 Research Highlights

Highlights of my research in the past five years are 1) proposal of the generalized G-inflation model, 2) gravitational-wave cosmology, 3) reconstruction of primordial perturbation spectrum from CMB anisotropy, and 4) studies on primordial black holes (PBHs).

1) The generalized G-inflation model we proposed is the most general single-field inflation model whose scalar and gravitational field equations are of second-order. Although our formulation was based on the generalized Galileon, we have shown that the underlying theory is equivalent with that proposed by Horndeski in 1974, that is, we have proved the uniqueness of the most general inflation theory even if apparently different description is possible. This model includes and can describe all the previously known single-field inflation models including the standard potential-driven inflation, k-inflation, G-inflation, DBI inflation, non-minimally coupled Higgs inflation, new Higgs inflation, and even R^2 inflation via conformal transformation. We have calculated power spectrum and bispectrum of primordial curvature and tensor perturbations and provided generic formulae, which are applicable to any inflation models with second-order field equation and hence greatly saves time to analyze each model. We have also constructed an explicit model to realize a large tensor-to-scalar ratio and large non-Gaussianity at the same time. Furthermore we have shown that all three known Higgs inflation models can be unified to the generalized G-inflation model and further discovered two more mechanisms to make the standard Higgs field the inflaton.

2) Gravitational waves are the most promising observational means which have the highest transmissivity to convey information of the earliest epoch of the Universe. I have shown that the future space laser interferometer DECIGO can measure the reheating temperature after inflation by observing the modulation of the spectrum of primordial tensor perturbations

produced by inflation. If they are also measured by the B-mode polarization of the cosmic microwave background radiation (CMB), we can also determine the amount of entropy production after that, essentially fixing the thermal history of the post-inflationary Universe.

Another important consequence of the gravitational-wave cosmology is that it can act as a probe of the black-hole dark matter. Black holes can account for the cold dark matter if their mass is in the range $10^{20} - 10^{26}$g. Such holes can only be created as PBHs from large-amplitude density fluctuations in the early Universe when the horizon mass corresponds to these mass scales. I have shown that tensor perturbations generated from these large curvature perturbations as a second-order effect is also observable by DECIGO—in fact the amplitude would be larger than any other candidate sources so that the verification or falsification of PBH dark matter hypothesis will be the first scientific result of DECIGO.

3) We developed an inversion method to calculate the primordial power spectrum of curvature perturbations from the observed angular power spectrum of CMB anisotropy. We applied it to the WMAP data and found a modulation from a simple power-law spectrum. We then performed forward analysis using Markov Chain Monte Carlo method to test the statistical significance of such a modulation. As a result we confirmed it at 99.995% confidence level using both temperature data and E-mode polarization data. Although the underlying theory to realize it is yet to be explored, in order to calculate cosmological parameters with the predicted accuracy of Planck, one must incorporate such a modulation in the analysis.

4) We studied cosmological consequences of evaporating PBHs for the first time incorporating the effects of quark-gluon jets on the big bang nucleosynthesis as well as cosmological gamma ray background. We have also updated various other constraints imposed by gravitational lensing, accretion effects on the CMB through reionization etc. This work has been quoted as the standard reference on PBH physics now.

   We constructed a double inflation model to reproduce the observed running of the spectral index by WMAP. In the field oscillation regime between two inflation, parametric resonance occurs to enhance the amplitude of curvature perturbation on a narrow wavenumber band, which result in formation of PBHs on a specific mass scale naturally.

8.3 Selected Papers

- Tsutomu Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama, "Generalized G-inflation: Inflation with the most general second-order field equations," Prog.Theor.Phys. 126 (2011) 511-529. This work formulated the most general inflation model with second-order field equations. Cited by 57 papers.

- Tsutomu Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama, "Inflation driven by the Galileon field," Phys.Rev.Lett. 105 (2010) 231302. This work proposed a novel class of inflation models based on Galileon. Cited by 88 papers.

- B.J. Carr, Kazunori Kohri, Yuuiti Sendouda, Jun'ichi Yokoyama, "New cosmological constraints on primordial black holes," Phys.Rev. D81 (2010) 104019. In this paper constraints on the abundance of primordial black holes were extensively revised taking all the effects from Big-Bang nucleosynthesis, gamma-ray backgrounds, gravitational lensing, etc. into account. All the papers on PBHs written after this cite it as the standard reference of the field. Cited by 72 papers.

- Kiyotomo Ichiki, Ryo Nagata, Jun'ichi Yokoyama, "Cosmic Discordance: Detection of a modulation in the primordial fluctuation spectrum," Phys.Rev. D81 (2010) 083010. This paper reports discovery of a 4σ deviation from the simple power-law power spectrum of primordial fluctuations from CMB data. Cited by 17 papers.
- Kazunori Nakayama, Shun Saito, Yudai Suwa, Jun'ichi Yokoyama, "Space laser interferometers can determine the thermal history of the early Universe," Phys.Rev. D77 (2008) 124001. This is a pioneering paper on gravitational-wave cosmology where it was shown that future space laser interferometers can measure the reheating temperature after inflation. Cited by 24 papers.

8.4 Research Plan

I plan to continue my research on 1) Inflationary cosmology and 2) Gravitational-wave cosmology, and 3) Dark energy and modified gravity. I am also planning to start 4) Basic research towards the data analysis of gravitational wave experiments, to expand the data analysis group of the KAGRA collaboration. For the latter purpose, we recently organized a data analysis school for KAGRA at RESCEU.

1) I plan to study the post-inflationary evolution of the universe in the generalized G-inflation model, to clarify how the universe is reheated. The evolution of the universe after inflation can be classified to two distinct possibilities; one is the standard case inflation is followed by field oscillation, the other is the case inflation ends abruptly without being followed by field oscillation. In the former case, it is important to preserve the positivity of the square sound speed during the field oscillation regime. In the latter case, the effect of possible direct coupling between the inflaton and the matter fields on particle production should be carefully investigated besides gravitational particle production. I study these issues to constrain the theory space for viable cosmology.

   In G-inflation model, it is possible to violate the null energy condition without any instabilities. Making use of this fact, I plan to construct a new model of the creation of the universe which starts with the Minkowski spacetime and spontaneously initiates cosmic expansion to avoid the initial singularity.

2) Besides the quantum mechanically generated tensor perturbations from inflation, there are a number of different mechanisms to create almost scale-invariant stochastic background of gravitational radiation, such as scalar-field rearrangements after a global phase transition and cosmic (super) strings. I plan to study evolution of these systems numerically to clarify the features of the stochastic gravitational-wave background thereby generated, in particular, the imprints of reheating processes after inflation.

Another possible source of cosmological gravitational wave is that from a first-order phase transition. Of particular interest among them is that associated with thermal inflation which naturally solves the cosmological moduli problem. It has been claimed that thermal inflation is associated by bubble nucleation of first-order phase transition and that their collisions generate gravitational waves. To see if it is the phase transition is of first order, however, one must carefully apply thermal field theory in nonequilibrium environments. We plan to do this analysis to clarify if indeed observable amount of gravitational waves are generated.

3) I plan to continue analysis of the observational constraints on modified gravity model of accelerated expansion, in particular, using the cluster abundance. This issue is closely related with the question if one or two species of sterile neutrinos exist as favored by recent reactor neutrino experiments, because with such neutrinos the standard Λ CDM model cannot reproduce the observed amplitude of small-scale density fluctuations.

   I would also like to attack the more fundamental problem that why the vacuum energy density is tiny if not equal to zero from fundamental point of view without resorting to the anthropic consideration nor string landscape picture.

4) In accordance with the start of the construction of KAGRA, I am trying to help enhance the data analysis group of KAGRA. For this purpose I have recruited one of the (only!) six members of the analysis team to RESCEU and organized a data analysis school. I plan to continue these efforts and also start basic research on the data analysis method by myself, too. The first problem I wish to study is the effects of non-Gaussian statistics of the noise distribution. I study the properties of the actual statistical distributions of the noises using the data from CLIO and then make an appropriate matched filter. Both linear and nonlinear filters will be considered.

8.5 Publications and Patents

< Refereed Original Papers >

[1] Cosmic strings with twisted magnetic flux lines and wound-strings in extra dimensions
By Matthew Lake, Jun'ichi Yokoyama. arXiv:1207.4891 [gr-qc]. JCAP 1209 (2012) 030.

[2] Self-consistent initial conditions for primordial black hole formation
By A.G. Polnarev, Tomohiro Nakama, Jun'ichi Yokoyama. arXiv:1204.6601 [gr-qc]. JCAP 1209 (2012) 027.

[3] Metric perturbation from inflationary magnetic field and generic bound on inflation models
By Teruaki Suyama, Jun'ichi Yokoyama. arXiv:1204.3976 [astro-ph.CO]. Phys.Rev. D86 (2012) 023512.

[4] Generalized Higgs inflation
By Kohei Kamada, Tsutomu Kobayashi, Tomo Takahashi, Masahide Yamaguchi, Jun'ichi Yokoyama. arXiv:1203.4059 [hep-ph]. Phys.Rev. D86 (2012) 023504.

[5] Phase transition and monopole production in supergravity inflation
By Kohei Kamada, Kazunori Nakayama, Jun'ichi Yokoyama. arXiv:1110.3904 [hep-ph]. Phys.Rev. D85 (2012) 043503.

[6] Primordial non-Gaussianities of gravitational waves in the most general single-field inflation model
By Xian Gao, Tsutomu Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama. arXiv:1108.3513 [astro-ph.CO]. Phys.Rev.Lett. 107 (2011) 211301.

[7] Temporal enhancement of super-horizon curvature perturbations from decays of two curvatons and its cosmological consequences
By Teruaki Suyama, Jun'ichi Yokoyama. arXiv:1106.5983 [astro-ph.CO]. Phys.Rev. D84 (2011) 083511.

[8] Generalized G-inflation: Inflation with the most general second-order field equations
By Tsutomu Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama. arXiv:1105.5723 [hep-th]. Prog.Theor.Phys. 126 (2011) 511-529.

[9] Primordial non-Gaussianity from G-inflation
By Tsutomu Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama. arXiv:1103.1740 [hep-th]. Phys.Rev. D83 (2011) 103524.

[10] Future Oscillations around Phantom Divide in f(R) Gravity
By Hayato Motohashi, Alexei A. Starobinsky, Jun'ichi Yokoyama. arXiv:1101.0744 [astro-ph.CO]. JCAP 1106 (2011) 006.

[11] Improved estimation of radiated axions from cosmological axionic strings
By Takashi Hiramatsu, Masahiro Kawasaki, Toyokazu Sekiguchi, Masahide Yamaguchi, Jun'ichi Yokoyama. arXiv:1012.5502 [hep-ph]. Phys.Rev. D83 (2011) 123531.

[12] Higgs G-inflation
By Kohei Kamada, Tsutomu Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama. arXiv:1012.4238 [astro-ph.CO]. Phys.Rev. D83 (2011) 083515.

[13] Full nonlinear growing and decaying modes of superhorizon curvature perturbations
By Yu-ichi Takamizu, Jun'ichi Yokoyama. arXiv:1011.4566 [astro-ph.CO]. Phys.Rev. D83 (2011) 043504.

[14] The effect of varying sound velocity on primordial curvature perturbations
By Masahiro Nakashima, Ryo Saito, Yu-ichi Takamizu, Jun'ichi Yokoyama. arXiv:1009.4394 [astro-ph.CO]. Prog.Theor.Phys. 125 (2011) 1035-1052.

[15] G-inflation: Inflation driven by the Galileon field
By Tsutomu Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama. arXiv:1008.0603 [hep-th]. Phys.Rev.Lett. 105 (2010) 231302.

[16] Matter power spectrum in f(R) gravity with massive neutrinos
By Hayato Motohashi, Alexei A. Starobinsky, Jun'ichi Yokoyama. arXiv:1005.1171 [astro-ph.CO]. Prog.Theor.Phys. 124 (2010) 541-546.

[17] Geometrically Consistent Approach to Stochastic DBI Inflation
By Larissa Lorenz, Jerome Martin, Jun'ichi Yokoyama. arXiv:1004.3734 [hep-th]. Phys.Rev. D82 (2010) 023515.

[18] Phantom boundary crossing and anomalous growth index of fluctuations in viable f(R) models of cosmic acceleration
By Hayato Motohashi, Alexei A. Starobinsky, Jun'ichi Yokoyama. arXiv:1002.1141 [astro-ph.CO]. Prog.Theor.Phys. 123 (2010) 887-902.

[19] Gravitational-Wave Constraints on the Abundance of Primordial Black Holes
By Ryo Saito, Jun'ichi Yokoyama. arXiv:0912.5317 [astro-ph.CO]. Prog.Theor.Phys. 123 (2010) 867-886, 126 (2011) 351-352(E).

[20] New cosmological constraints on primordial black holes
By B.J. Carr, Kazunori Kohri, Yuuiti Sendouda, Jun'ichi Yokoyama. arXiv:0912.5297 [astro-ph.CO]. Phys.Rev. D81 (2010) 104019.

[21] Cosmic Discordance: Detection of a modulation in the primordial fluctuation spectrum
By Kiyotomo Ichiki, Ryo Nagata, Jun'ichi Yokoyama. arXiv:0911.5108 [astro-ph.CO]. Phys.Rev. D81 (2010) 083010.

[22] Constraining the time variation of the coupling constants from cosmic microwave background: effect of Λ_{QCD}
By Masahiro Nakashima, Kazuhide Ichikawa, Ryo Nagata, Jun'ichi Yokoyama. arXiv:0910.0742 [astro-ph.CO]. JCAP 1001 (2010) 030.

[23] Gravitational Wave Background and Non-Gaussianity as a Probe of the Curvaton Scenario
By Kazunori Nakayama, Jun'ichi Yokoyama. arXiv:0910.0715 [astro-ph.CO]. JCAP 1001 (2010) 010.

[24] On the realization of the MSSM inflation
By Kohei Kamada, J. Yokoyama. arXiv:0906.3402 [hep-ph]. Prog.Theor.Phys. 122 (2010) 969-986.

[25] The moduli problem at the perturbative level
By Martin Lemoine, Jerome Martin, Jun'ichi Yokoyama. arXiv:0903.5428 [astro-ph.CO]. Europhys.Lett. 89 (2010) 29001.

[26] Analytic solution for matter density perturbations in a class of viable cosmological f(R) models
By Hayato Motohashi, Alexei A. Starobinsky, Jun'ichi Yokoyama. arXiv:0905.0730 [astro-ph.CO]. Int.J.Mod.Phys. D18 (2009) 1731-1740.

[27] Gravitino Dark Matter and Non-Gaussianity
By Tomo Takahashi, Masahide Yamaguchi, Jun'ichi Yokoyama, Shuichiro Yokoyama. arXiv:0905.0240 [astro-ph.CO]. Phys.Lett. B678 (2009) 15-19.

[28] Constraints on moduli cosmology from the production of dark matter and baryon isocurvature fluctuations
By Martin Lemoine, Jerome Martin, Jun'ichi Yokoyama. arXiv:0904.0126 [astro-ph.CO]. Phys.Rev. D80 (2009) 123514.

[29] Band-power reconstruction of the primordial fluctuation spectrum by the maximum likelihood reconstruction method
By Ryo Nagata, Jun'ichi Yokoyama. arXiv:0812.4585 [astro-ph]. Phys.Rev. D79 (2009) 043010.

[30] Gravitational wave background as a probe of the primordial black hole abundance
By Ryo Saito, Jun'ichi Yokoyama. arXiv:0812.4339 [astro-ph]. Phys.Rev.Lett. 102 (2009) 161101, 107 (2011) 069901(E).

[31] Constraints on the time variation of the fine structure constant by the 5-year WMAP data
By Masahiro Nakashima, Ryo Nagata, Jun'ichi Yokoyama. arXiv:0810.1098 [astro-ph]. Prog.Theor.Phys. 120 (2008) 1207-1215.

[32] Reconstruction of the primordial fluctuation spectrum from the five-year WMAP data by the cosmic inversion method with band-power decorrelation analysis
By Ryo Nagata, Jun'ichi Yokoyama. arXiv:0809.4537 [astro-ph]. Phys.Rev. D78 (2008) 123002.

[33] Single-field inflation, anomalous enhancement of superhorizon fluctuations, and non-Gaussianity in primordial black hole formation
By Ryo Saito, Jun'ichi Yokoyama, Ryo Nagata. arXiv:0804.3470 [astro-ph]. JCAP 0806 (2008) 024.

[34] Probing reheating temperature of the universe with gravitational wave background
By Kazunori Nakayama, Shun Saito, Yudai Suwa, Jun'ichi Yokoyama. arXiv:0804.1827 [astro-ph]. JCAP 0806 (2008) 020.

[35] Inflation at the GUT scale in a Higgsless universe
By Nemanja Kaloper, Lorenzo Sorbo, Jun'ichi Yokoyama. arXiv:0803.3809 [hep-ph]. Phys.Rev. D78 (2008) 043527.

[36] Affleck Dine leptogenesis via multiple flat directions
By Kohei Kamada, Jun'ichi Yokoyama. arXiv:0803.3146 [hep-ph]. Phys.Rev. D78 (2008) 043502.

[37] Constraints on scalar-tensor models of dark energy from observational and local gravity tests
By Shinji Tsujikawa, Kotub Uddin, Shuntaro Mizuno, Reza Tavakol, Jun'ichi Yokoyama. arXiv:0803.1106 [astro-ph]. Phys.Rev. D77 (2008) 103009.

[38] Space laser interferometers can determine the thermal history of the early Universe
By Kazunori Nakayama, Shun Saito, Yudai Suwa, Jun'ichi Yokoyama. arXiv:0802.2452 [hep-ph]. Phys.Rev. D77 (2008) 124001.

[39] Generation of Large-Scale Magnetic Fields in Single-Field Inflation
By Jerome Martin, Jun'ichi Yokoyama. arXiv:0711.4307 [astro-ph]. JCAP 0801 (2008) 025.

[40] Formation of intermediate-mass black holes as primordial black holes in the inflationary cosmology with running spectral index
By Toshihiro Kawaguchi, Masahiro Kawasaki, Tsutomu Takayama, Masahide Yamaguchi, Jun'ichi Yokoyama. arXiv:0711.3886 [astro-ph]. Mon.Not.Roy.Astron.Soc. 388 (2008) 1426-1432.

[41] Effective search templates for a primordial stochastic gravitational wave background
By Takeshi Chiba, Yoshiaki Himemoto, Masahide Yamaguchi, Jun'ichi Yokoyama. arXiv:0705.2851 [gr-qc]. Phys.Rev. D76 (2007) 043516.

[42] Lepton asymmetry in the primordial gravitational wave spectrum
By Kiyotomo Ichiki, Masahide Yamaguchi, Jun'Ichi Yokoyama. hep-ph/0611121. Phys.Rev. D75 (2007) 084017.

[43] Time variation of proton-electron mass ratio and fine structure constant with runaway dilaton
By Takeshi Chiba, Tatsuo Kobayashi, Masahide Yamaguchi, Jun'ichi Yokoyama. hep-ph/0610027. Phys.Rev. D75 (2007) 043516.

[44] Scale dependence of the primordial spectrum from combining the three-year WMAP, Galaxy Clustering, Supernovae, and Lyman-alpha forests
By Bo Feng, Jun-Qing Xia, Jun'ichi Yokoyama. astro-ph/0608365. JCAP 0705 (2007) 020.

[45] Results of the search for inspiraling compact star binaries from TAMA300's observation in 2000-2004
By TAMA Collaboration (Tomomi Akutsu et al.). gr-qc/0610064. Phys.Rev. D74 (2006) 122002.

[46] Weighing neutrinos in the presence of a running primordial spectral index
By Bo Feng, Jun-Qing Xia, Jun'ichi Yokoyama, Xinmin Zhang, Gong-Bo Zhao. astro-ph/0605742. JCAP 0612 (2006) 011.

[47] Power Spectrum of the Density Perturbations From Smooth Hybrid New Inflation Model
By Masahiro Kawasaki, Tsutomu Takayama, Masahide Yamaguchi, Jun'ichi Yokoyama. hep-ph/0605271. Phys.Rev. D74 (2006) 043525.

[48] Thermal background can solve the cosmological moduli problem
By Jun'ichi Yokoyama. hep-ph/0601067. Phys.Rev.Lett. 96 (2006) 171301, 98 (2007) 039902(E).

[49] Density fluctuations in one-field inflation
By Masahide Yamaguchi, Jun'ichi Yokoyama. hep-ph/0512318. Phys.Rev. D74 (2006) 043523.

[50] D-term inflation and leptogenesis by right-handed sneutrino
By Kenji Kadota, J. Yokoyama. hep-ph/0512221. Phys.Rev. D73 (2006) 043507.

[51] Joint LIGO and TAMA300 search for gravitational waves from inspiralling neutron star binaries
By LIGO Scientific and TAMA Collaborations (B. Abbott et al.). gr-qc/0512078. Phys.Rev. D73 (2006) 102002.

[52] Can oscillating scalar fields decay into particles with a large thermal mass?
By Jun'ichi Yokoyama. hep-ph/0510091. Phys.Lett. B635 (2006) 66-71.

[53] Hiding cosmic strings in supergravity D-term inflation
By Osamu Seto, Jun'ichi Yokoyama. hep-ph/0508172. Phys.Rev. D73 (2006) 023508.

[54] Upper limits from the LIGO and TAMA detectors on the rate of gravitational-wave bursts
By TAMA Collaboration (B. Abbott et al.). gr-qc/0507081. Phys.Rev. D72 (2005) 122004.

[55] Constraining cosmological parameters by the cosmic inversion method
By Noriyuki Kogo, Misao Sasaki, Jun'ichi Yokoyama. astro-ph/0504471. Prog.Theor.Phys. 114 (2005) 555-572.

[56] Neutralino dark matter from heavy gravitino decay
By Kazunori Kohri, Masahiro Yamaguchi, Jun'ichi Yokoyama. hep-ph/0502211. Phys.Rev. D72 (2005) 083510.

[57] Observation results by the TAMA300 detector on gravitational wave bursts from stellar-core collapses
By Masaki Ando, Koji Arai, Youichi Aso, Peter Beyersdorf, Kazuhiro Hayama, Yukiyoshi Iida, Nobuyuki Kanda, Seiji Kawamura et al.. gr-qc/0411027. Phys.Rev. D71 (2005) 082002.

< **Conference Proceedings** >

[58] The Japanese space gravitational wave antenna: DECIGO By Seiji Kawamura, Masaki Ando, Naoki Seto, Shuichi Sato, Takashi Nakamura, Kimio Tsubono, Nobuyuki Kanda, Takahiro Tanaka et al.. Class.Quant.Grav. 28 (2011) 094011.

[59] f(R) Gravity and its Cosmological Implications
By Hayato Motohashi, Alexei A. Starobinsky, Jun'ichi Yokoyama. arXiv:1101.0716 [astro-ph.CO]. Int.J.Mod.Phys. D20 (2011) 1347-1355.

[60] New constraint on the varying fine structure constant
By M. Nakashima, K. Ichikawa, R. Nagata, J. Yokoyama. AIP Conf.Proc. 1241 (2010) 252-258.

[61] DECIGO and DECIGO pathfinder
By Masaki Ando, Seiji Kawamura, Naoki Seto, Shuichi Sato, Takashi Nakamura, Kimio Tsubono, Takeshi Takashima, Ikkoh Funaki et al.. Class.Quant.Grav. 27 (2010) 084010.

[62] DECIGO pathfinder
By Masaki Ando, Seiji Kawamura, Shuichi Sato, Takashi Nakamura, Kimio Tsubono, Akito Araya, Ikkoh Funaki, Kunihito Ioka et al.. Class.Quant.Grav. 26 (2009) 094019.

[63] Probing the early Universe with multichannel observations
By Jun'ichi Yokoyama. AIP Conf.Proc. 1040 (2008) 23-31.

[64] Band-power reconstruction of primordial perturbation spectrum from CMB anisotropy
By Ryo Nagata, Jun'ichi Yokoyama. Mod.Phys.Lett. A23 (2008) 1478-1488.

[65] DECIGO pathfinder
By Masaki Ando, Seiji Kawamura, Takashi Nakamura, Kimio Tsubono, Takahiro Tanaka, Ikkoh Funaki, Naoki Seto, Kenji Numata et al.. J.Phys.Conf.Ser. 120 (2008) 032005.

[66] The Japanese space gravitational wave antenna: DECIGO
By Seiji Kawamura, Masaki Ando, Takashi Nakamura, Kimio Tsubono, Takahiro Tanaka, Ikkoh Funaki, Naoki Seto, Kenji Numata et al.. J.Phys.Conf.Ser. 120 (2008) 032004.

[67] The Japanese space gravitational wave antenna - DECIGO
By Seiji Kawamura, Masaki Ando, Takashi Nakamura, Kimio Tsubono, Takahiro Tanaka, Ikkoh Funaki, Naoki Seto, Kenji Numata et al.. J.Phys.Conf.Ser. 122 (2008) 012006.

[68] Perturbations from D-term inflation
By Osamu Seto, Jun'ichi Yokoyama. Mod.Phys.Lett. A22 (2007) 2035-2038.

[69] Features in the primordial power spectrum: A running spectral index and formation of primordial black holes
By Masahiro Kawasaki, Tsutomu Takayama, Masahide Yamaguchi, Jun'ichi Yokoyama. Mod.Phys.Lett. A22 (2007) 1911-1920.

[70] D-term inflation with suppressed cosmic strings and lowered n(s)
By Osamu Seto, Jun'ichi Yokoyama. J.Phys. A40 (2007) 7121-7125.

[71] Decaying into the thermal medium in the early Universe
By J. Yokoyama. AIP Conf.Proc. 805 (2006) 82-86. Proceedings

< **Review Papers** >

< **Books** >

[72] 「宇宙　地球　地震と火山」（古今書院 2006 年）第一部。

[73] 「宇宙論 I　宇宙の始まり」（日本評論社 2007 年）　分担執筆。

[74] 「宇宙の向こう側」（青土社 2008 年）198 ページ　竹内薫と共著。

[75] 「電磁気学」　（講談社 2009 年）278 ページ

[76] 「現代物理学の世界 トップ研究者からのメッセージ」16 章（講談社 2010 年）二宮正夫編集。

[77] 「知っておきたい物理の疑問 55」　（講談社ブルーバックス　2011 年）日本物理学会編　編集・執筆。

< **Patent Applications** >

8.6 Presentations at Conferences

< **Invited talks at international conferences** >

[1] Jun'ichi Yokoyama "Can oscillating scalar field decay into a particle with a large thermal mass?" Post-YKIS symposium on gravitation and cosmology (Kyoto University, July 2005).

[2] J. Yokoyama: "Inflation with a running spectral index in supergravity," Workshop on Inflation+25, Institut d'Astrophysique de Paris, France, July 2006.

[3] J. Yokoyama: "Inflation with a running spectral index in supergravity," APCTP General Relativity and Gravitation Miniworkshop, Jeju Island, Korea, September 2006.

[4] J. Yokoyama: "Features in the primordial power spectrum: a running spectral index and formation of primordial black holes," Galileo Galilei Institute, Astroparticle physics and cosmology program, Florence, Italy, October 2006.

[5] J. Yokoyama: "Time variation of the proton-electron mass ratio and fine structure constant in runaway dilaton," Galileo Galilei Institute, Astroparticle physics and cosmology program, Florence, Italy, November 2006.

[6] J. Yokoyama: "Features in the primordial power spectrum: a running spectral index and formation of primordial black holes," 2006 International Symposium on Cosmology and Particle Astrophysics (CosPa 2006,), presented at National Taiwan University, Taipei, Taiwan, November 15-17, 2006

[7] J. Yokoyama: "Cosmological creation of supermassive particles," Astronomy and astrophysics in the extreme universe, RIKEN, March 2007.

[8] J. Yokoyama: "Probing the early Universe with a space laser interferometer," APCTP mini workshop on dark energy and gravitational waves (Pohang, July 2007)

[9] J. Yokoyama: "Probing the early Universe with multichannnel cosmological observations," Accelerators in the Universe 2008 (KEK, Tsukuba, Japan, March 12-14, 2008)

[10] J. Yokoyama: "Reconstruction of primordial power spectrum from CMB anisotropy," CosPA 2007 National Taiwan University, (Taipei, November 2007)

[11] Jun'ichi Yokoyama "Primordial fluctuation spectrum: anomaly found from CMB temperature and polarization data" CosPA2008 (October 28- November 1, APCTP, Pohang, Korea)

[12] Jun'ichi Yokoyama: "What can we learn about cosmophysics by observing only one Universe?" The 7th RESCEU International Symposium on Astroparticle Physics and Cosmology (Nov. 12-14, 2008, The University of Tokyo, Tokyo, Japan)

[13] J. Yokoyama, "Gravitational waves and the early Universe," PASCOS 2009 (July 9, 2009, DESY, Hamburg, Germany)

[14] J. Yokoyama, "Cosmology with stochastic gravitational waves," CosPA 2009 (November 20, 2009, University of Melbourne, Australia)

[15] J. Yokoyama, "Phantom crossing and anomalous growth index of density fluctuations in $f(R)$ gravity" Hot topics in modern cosmology Cargese, France, May 10, 2010

[16] J. Yokoyama, "Cosmological constraints on time variation of the fundamental constants" Fundamental Physics using Atoms 2010, Osaka University, August 8, 2010

[17] J. Yokoyama, "w_{eff} and m_ν in $f(R)$ gravity" The observational pursuit of dark energy after Astro2010, Pasadena, October 7-8, 2010

[18] J. Yokoyama, "Gravitational waves as a probe of the early Universe" Gravitational Waves 2010, University of Minnesota, October 15, 2010

[19] J. Yokoyama, "G-inflation" Beyond Standard Models and Dark Sides of Our Universe, Shanghai, November 19, 2010

[20] J. Yokoyama "G-inflation and generalized G-inflation" Solvay/APC/PI conference, Paris, France June 15, 2011

[21] J. Yokoyama "Generalized G-inflation" Preplanckian inflation workshop, University of Minnesota, Minneapolis, U.S.A.

[22] J. Yokoyama "w_{eff} and m_ν in f(R) gravity" CosPA 2011, Beijing University, Beijing, China October 1, 2011.

[23] J. Yokoyama "Primordial Black Holes" Egypt-Japan joint workshop on cosmology (Modern University for technology and information, Egypt, 12/1-12/4, 2011)

[24] J. Yokoyama "Generalized G-inflation" First LeCosPA symposium, National Taiwan University, Taipei, February 6-9, 2012

< Contributed talks at international conferences >

[25] Jun'ichi Yokoyama "Decaying into thermal medium in the early universe," PASCOS05 (Kyonju, Korea, May 2005)

[26] Jun'ichi Yokoyama "A new solution to the cosmological moduli problem" CICHEPII (Cairo, Egypt, January, 2006)

[27] Jun'ichi Yokoyama "Higgs inflation and Higgs condensation," Superstring Cosmophysics workshop (Makubetsu, Japan, August 7, 2012)

[28] Jun'ichi Yokoyama "Higgs condensation as an unwanted curvaton," COSMO2012 (Beijing, China, September 13, 2012)

< Invited talks at domestic conferences >

[29] 横山順一 「始めも終わりもインフレーション」日本物理学会 2005 年秋季大会 宇宙項シンポジウム（大阪市立大学、2005 年 9 月）

[30] 横山順一 「宇宙初期の熱的非平衡過程」東北大学 21 世紀 COE「物質階層融合科学の構築」素粒子・天文合同研究会「初期宇宙の解明と新たな自然像」

[31] 横山順一： "Cosmic Inversion 宇宙背景輻射の非等方性による初期ゆらぎのスペクトルの再構築" 東京大学天文学研究教育センター談話会 (2005 年 6 月 9 日)

[32] 横山順一： “Cosmic Inversion 宇宙背景輻射の非等方性による初期ゆらぎのスペクトルの再構築” 東京大学理学部天文学教室談話会　（2006年1月31日）

[33] 横山順一：「宇宙から素粒子へ」　日本物理学会年次大会シンポジウム (2007年9月22日)

[34] 横山順一：「CMB観測によるDECIGO帯重力波バックグラウンドの推定」DECIGO研究会（国立天文台、2008年4月16日）

[35] 横山順一：“Dark Energy” サマーインスティテュート2008 (経団連研修所、富士吉田、2008年8月）

[36] 横山順一：「インフレーションと重力波」　日本物理学会年次大会シンポジウム (2010年3月22日)

[37] 横山順一： “重力波でさぐろう初期宇宙” 名古屋大学談話会　名古屋大学物理学教室　2011年9月13日

[38] 横山順一： “宇宙創生論　現状と課題” 京都大学国際シンポジウム　知の統合　京都大学百周年記念館　2011年10月15日

[39] 横山順一：「ダークエネルギー問題」　HSC研究会　国立天文台　2012年9月26日

< Contributed talks at domestic conferences >

[40] 横山順一：”Higgsflation” ビッグバン宇宙国際研究センターサマースクール（青森市　2008年8月31日）

[41] 横山順一：“Gravitational waves and the early universe” サマーインスティテュート2009 (経団連研修所、富士吉田、2009年8月5日）

[42] 横山順一：「原始ブラックホールの質量スペクトル」 ビッグバン宇宙国際研究センターサマースクール（宜野湾市　2009年8月30日）

[43] 横山順一：「スペース重力波アンテナDECIGO計画（２１）サイエンス1」日本物理学会秋期大会　(甲南大学　2009年9月10日)

[44] 横山順一：「ゆらぎの減衰」 ビッグバン宇宙国際研究センターサマースクール（南小国町　2011年7月25日）

[45] 横山順一：「ヒッグス場によるインフレーション」 ビッグバン宇宙国際研究センターサマースクール（北塩原村　2012年7月27日）

8.7 Teaching Accomplishment

Besides teaching normal courses at the University of Tokyo, I have given series of lectures at Waseda University, Nagoya University, Tokyo Institute of Technology, Kyoto University, and National Taiwan University in the past five years.

8.8 Contribution to Academic Community

8.8.1 Editorial activities

- Associate editor, Journal of the Physical Society of Japan (2000–)
- Editor, Publications of the Astronomical Society of Japan (2003–2007)
- Editor, AAPPS Bulletin (2011–)

8.8.2 Organization of professional societies

- Member, Executive board, Physical Society of Japan (2008-10)

8.8.3 Organization and advisory of conferences

- Chair, France-Japan Joint Workshop on the Early Universe (Nikko-Kirifuri Convention Hall, Nikko, Japan, May 14-16, 2008)
- Co-chair, RESCEU Symposium on Astroparticle Physics and Cosmology (Koshiba Hall, The University of Tokyo, Japan, November 11-14, 2008)
- Chair, Horiba International Conference COSMO/CosPA 2010 (Ichijo Hall, The University of Tokyo, Japan, September 27-October 1, 2010)
- Member of international organizing committee, JGRG workshop series (2005-2011)
- Member of organizing committee, CosPA conference series (2008-2011)
- Member of international steering committee, COSMO conference series (2011-)

8.9 Outreach

[1] 横山順一：金沢大学公開講座　サイエンストーク　「宇宙の科学」（2005年10月1日）

[2] 横山順一：　東大ビッグバンセンター公開講演会宇宙最大のなぞ：ダークエネルギー「始めも終わりもインフレーション」(小柴ホール、2006年12月22日）

[3] 横山順一: 「宇宙の創生とインフレーション」日本大学公開講座 (2007年5月19日)

[4] 横山順一: 「宇宙論入門」スーパーサイエンスハイスクール講演会日比谷高校　(2007年2月7日)

[5] 横山順一：「宇宙のはじまる前」; 河合塾エンリッチ講座　（河合塾本郷校、2008年6月2日）

[6] 横山順一: 「宇宙をあやつるダークエネルギー」; ビッグバン宇宙国際研究センター　第3回公開講演会「暗黒エネルギーと宇宙の未来」(東京大学、2008年7月31日）

[7] 横山順一：「宇宙への旅立ち」; 大阪大学 Saturday Afternoon Physics　（大阪大学、2008年11月22日）

[8] 横山順一：「相対論を学ぶための数学 II」; 日比谷高校ＳＳＨ講演会（日比谷高校、2009年1月20日）

[9] 横山順一：「研究者のしごと」; 新島学園高等学校進路講座（新島学園、2009年1月24日）

[10] 横山順一：「宇宙のはじまる前」; 新島学園講演会（新島学園、2009年1月24日）

[11] 横山順一：「宇宙のはじまり」; 藤島高校見学会（2009年8月10日）

[12] 横山順一：「宇宙のはじまり」; 日比谷高校見学会（2009年9月25日）

[13] 横山順一: “元素の起源” 日比谷高校 SSH 講演会　(2010年3月5日)

[14] 横山順一： “宇宙最大の謎　ダークエネルギー” 東京大学オープンキャンパス講演会 (2010年8月1日)

[15] 横山順一: “重力波で探る宇宙” 日比谷高校 SSH 講演会　(2011年3月8日)

[16] 横山順一: “重力波で探る宇宙” 小松高校見学会　2011年8月2日

[17] 横山順一: “東大への数理科学:物理と微分方程式” 日比谷高校 SSH 講演会　2011年12月20日

[18] 横山順一: “重力波でさぐる初期宇宙” 東京大学オープンキャンパス講演会　2011年12月23日

[19] 横山順一 :「加速する宇宙」東京大学理学部公開講演会　2012年4月22日

[20] 横山順一：「宇宙のはじまり」成蹊高校見学会（2012年7月10日）

8.10 Committee Service

8.10.1 External committees

- Chair, Joint use management committee, Yukawa Institute for Theoretical Physics, Kyoto University (2007-8)
- Member, Advisory board, Yukawa Institute for Theoretical Physics, Kyoto University (2009-13)
- Member, Japanese committee, Asia Pacific Center for Theoretical Physics (2002–)

8.10.2 University committees

理学系研究科男女共同参画委員会 委員　2007年 –2009年

8.11 Internationalization Statistics

	Number	Country
Foreign students advised		
Bachelor Course	0	
Master Course	0	
Doctor Course	0	
Foreign researchers hosted	9	Russia, UK, China, France, USA
Students sent abroad	7	Taiwan, UK, USA
Researchers sent abroad	13	France, UK, Egypt
Foreign visitors	>200	including participants of the conferences I organized

- PI of France-Japan bilateral project "The early Universe : a precision laboratory for high energy physics" supported by JSPS and CNRS. (2007-2009)
- PI of UK-Japan bilateral project "Black holes and other probes of accelerating phases in the Universe" supported by JSPS and Royal Society. (2009-2011)
- PI of Egypt-Japan bilateral seminar "First Egypt-Japan Workshop on Astroparticle Cosmology" supported by JSPS and MHESR. (2011)

9　茂山　俊和、 Toshikazu Shigeyama

9.1　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	Fellow	Japanese Society for the Promotion of Science for Japanese Junior Scientists
1991−1992	Guest Researcher	the Max-Planck-Institut für Physik und Astrophysik Institut für Astrophysik
1992−1999	Assistant Professor	The University of Tokyo
1999−	Associate Professor	The University of Tokyo

9.2　Highlights of Current Research Sctivities

Type Ia supernova has been thought to be an explosion of an accreting white dwarf composed of carbon and oxygen in a binary system where the companion star is a normal star or is also a white dwarf. If the companion star is a white dwarf, the less massive component will entirely disrupted and merging of the white dwarfs is thought to lead to explosion. On the other hand, if the companion is a normal star, then the white dwarf accreting matter from the companion increases its mass to the limit beyond which no equilibrium configuration exists, ignites carbon at the center and end up with a thermonuclear explosion of the entire star. Thus the companion star must be left behind. We have tried to search this ex-companion star in the remnant of Tycho's type Ia supernova. Our strategy was to find asymmetric absorption lines due to neutral Fe atoms in the ejecta exclusively with blue-shifted components in the optical spectrum of a star inside the remnant. The asymmetric lines are the proof of the existence of the absorbing matter on the line of sight moving toward us, at the same time, show that few absorbing matter moves away from us on the line of sight, and thus identifies the ex-companion star at the center of the remnant. We took spectra of more than 30 stars located near the geometrical center of the remnant on the celestial sphere and found two such candidates. However low statistics prevented us from concluding which was the real ex-companion or none of them was [10].

There are metal-poor stars with enhanced carbon abundance in the halo of the Milky Way galaxy. We argued that all these carbon enhanced metal-poor stars were in originally members of binary systems where the primary star had already evolved to Asymptotic giant branch stars blowing carbon rich wind toward the companion. Thus the surfaces of the companion stars are polluted by carbon-rich matter. We discussed the evolution of orbital parameters of binary systems [8]. We also discuss the origin of Li isotopes, Boron, and Beryllium in metal-poor stars. We argue that these elements are produced in the circumstellar matter around Wolf-Rayet stars when the stars explode as type Ic supernovae. We showed that a substantial amount of the ejecta composed of oxygen and carbon are accelerated above 10 MeV/nucleon and collisions with the protons and/or α nuclei in the circumstellar matter produce these light elements with sufficient amounts [3].

We have presented three self-similar solutions in the context of ultra-relativistic explosion of stars. The first one describes the flow when the shock breaks out of the surface of a star [1]. The other two concern with the interaction of ejecta expanding at ultra-relativistic speeds with the circumstellar matter [5, 22]. These solutions are useful to explore the prompt emission from gamma-ray bursts. I hope that many researchers in the related fields will use these solutions to calibrate their numerical codes treating ultra-relativistic fluid dynamics. Note also that the work [1] was done when one of the author Nakayama was an undergraduate student. He is now an assistant professor in the department of physics.

9.3 Selected Papers

- Searching for a Companion Star of Tycho ' s Type Ia Supernova with Optical Spectroscopic Observations, Ihara, J. Ozaki, M. Doi, T. Shigeyama, N. Kashikawa, K. Komiyama, and T. Hattori, Publications of the Astronomical Society of Japan, 2007, Vol.59, No.4, pp.811-826
- The Origin of Carbon Enhancement and the Initial Mass Function of Extremely Metal-poor Stars in the Galactic Halo, Y. Komiya, T. Suda, H. Minaguchi, T. Shigeyama, W. Aoki, and M. Y. Fujimoto, The Astrophysical Journal, 2007, Vol. 658, pp. 367-390
- Light-Element Production in the Circumstellar Matter of Energetic Type Ic Supernovae, K. Nakamura, S. Inoue, S. Wanajo, and T. Shigeyama, The Astrophysical Journal (Letters), 2006, Vol. 643, pp. L115-L118
- Self-similar Solutions for the Interaction of Relativistic Ejecta with an Ambient Medium, K. Nakamura and T. Shigeyama, The Astrophysical Journal (Letters), 2006, Vol. 643, pp. L115-L118
- Self-similar Evolution of Relativistic Shock Waves Emerging from Plane-parallel Atmospheres, Nakayama and T. Shigeyama, The Astrophysical Journal, 2005, Vol. 627, pp. 310-318

9.4 Research Plan

9.4.1 Magnetar-supernova relation

The first topic is the influence of extremely strong magnetic fields of a magnetar to supernova explosion. Magnetar is a neutron star spinning at the period of a few seconds to 20 seconds with a large time derivative of the period compared with normal pulsars. This large time derivative of the spin period is ascribed to magnetic braking by extremely strong dipole magnetic fields with the axis misaligned with the spin axis. Thus a magnetar loses its rotational energy. The rate of the associated loss of rotational energy is not enough to explain the observed emission. Thus the energy source is suggested to be magnetic. Therefore if dating back to the time when the supernova explosion just began, the spin period must be far shorter than the observed one and the magnetic field strength be far stronger. If the spin period is as short as a few ms, then the rotational energy becomes of the order of 10^{52} erg and if the field strength is 10^{16} G, the time scale of the spin down is 1000 s. Then we can expect that the energy supply from the magnetar might contribute supernova explosion to some extent because the energy supply is in the form of electromagnetic waves rather than neutrinos. By performing multi-dimensional numerical fluid dynamical calculations, we plan to investigate if this kind of energy supply can reproduce supernova explosions of massive stars observed as either of type II, Ib, or Ic.

9.4.2 Sign of Ex-companion star in emission of type Ia supernova

By performing 2-D radiation hydrodynamical calculations, we will investigate if Hα lines can be seen in spectra of type Ia supernovae. If the companion star was a normal star, a considerable amount of hydrogen exist in the supernova ejecta because it is stripped from the outer layer of the companion star by collision of the ejecta. Calculating spectra taken from different angles at different epochs, we will estimate the fraction of type Ia supernovae that show Hα line.

Asphericity due to the existence of the companion star may lead to different light curves from different observing angle. There is a well known correlation between the peak luminosities of type Ia supernovae and the time scale of the luminosity decay afterward. We investigate if the light curves with different observing angles can reproduce this correlation.

9.4.3 3D stellar evolution models

Existing stellar evolution models assume spherical symmetry. This assumption needs an ad hoc parameter called mixing length to treat the energy transfer due to convection. Though this parametrization has been successful in many respects, there remain many problems that cannot be addressed especially in the evolved phases because of this simplification. Another issue caused by spherical symmetry is the treatment of rotation. Even though some models incorporate effects of rotation and the associated mixing process, the configuration remains spherical symmetry. Therefore supernova explosions from rotating stars cannot be studied self-consistently at present. All these issues could be addressed if 3D stellar evolution models are available. At the moment, there are 3D stellar models that trace hydrodynamical phenomena at some specific epoch of the star. These models cannot trace the entire evolution of a star. These are rooted in the evolutionary time scale many orders of magnitude longer than the hydrodynamical time scale in a star. Therefore stellar evolution models should trace a series of the equilibrium configurations with gradually changing compositions rather than follow the hydrodynamical behavior. As a first step, we will construct a scheme to obtain equilibrium figures of rotating self-gravitational stars in 3D by using a kind of multi-domain pseudo-spectral methods. The methods have been developed to construct initial setups of simulations for binary neutron star mergers. Rieutord and Espinosa Lara (2012) has recently succeeded in constructing 2D axisymmetric configuration of rotating stars in radiative equilibrium using this method. Though previous methods need to assume the rotation law, this method can derive the rotation law for a given total angular momentum by solving the stationary Navier-Stokes equation. We will do the same thing in 3D. The methodology is rather straight forward. Next step is to incorporate nuclear reaction network to calculate the stellar evolution. By using this 3D stellar evolution code, we will reinvestigate the entire picture of stellar evolution that has been constructed by specifying the mixing length parameter. A final goal is to incorporate the mass loss to follow the evolutionary phases of massive stars. Then we will investigate the supernova mechanism in massive rotating stars in a self-consistent manner.

9.5 Publications and Patents

< Refereed Original Papers >

[1] Self-similar Evolution of Relativistic Shock Waves Emerging from Plane-parallel Atmospheres, Nakayama and T. Shigeyama, The Astrophysical Journal, 2005, Vol. 627, pp. 310-318

[2] Relics of Metal-free Low-Mass Stars Exploding as Thermonuclear Supernovae, T. Tsujimoto and T. Shigeyama, The Astrophysical Journal (Letters), 2006, Vol. 638, pp. L109-L112

[3] Light-Element Production in the Circumstellar Matter of Energetic Type Ic Supernovae, K. Nakamura, S. Inoue, S. Wana jo, and T. Shigeyama, The Astrophysical Journal (Letters), 2006, Vol. 643, pp. L115-L118

[4] A Method to Identify the Companion Stars of Type Ia Supernovae in Young Supernova Remnants, Ozaki and T. Shigeyama, The Astrophysical Journal, 2006, Vol. 644, pp. 954- 958

[5] Self-similar Solutions for the Interaction of Relativistic Ejecta with an Ambient Medium, K. Nakamura and T. Shigeyama, The Astrophysical Journal, 2006, Vol. 645, Issue 1, pp. 431-435

[6] Surface Pollution of Main-Sequence Stars through Encounters with AGB Ejecta in ω Centauri, Tsujimoto, T. Shigeyama, and T. Suda, The Astrophysical Journal, 2007, Vol. 654, pp. L139-L142

[7] Relativistic Flows after Shock Emergence, R. Kikuchi and T. Shigeyama, The Astrophysical Journal, 2007, Vol. 657, pp. 860-869

[8] The Origin of Carbon Enhancement and the Initial Mass Function of Extremely Metal-poor Stars in the Galactic Halo, Y. Komiya, T. Suda, H. Minaguchi, T. Shigeyama, W. Aoki, and M. Y. Fujimoto, The Astrophysical Journal, 2007, Vol. 658, pp. 367-390

[9] Self-similar Solutions for the Emergence of Energy-varying Shock Waves from Plane-parallel Atmospheres, A. Suzuki and T. Shigeyama, The Astrophysical Journal, 2007, Vol. 661, pp. 385-393

[10] Searching for a Companion Star of Tycho’s Type Ia Supernova with Optical Spectroscopic Observations, Ihara, J. Ozaki, M. Doi, T. Shigeyama, N. Kashikawa, K. Komiyama, and T. Hattori, Publications of the Astronomical Society of Japan, 2007, Vol.59, No.4, pp.811-826

[11] Highly He-rich Matter Dredged Up by Extra Mixing through Stellar Encounters in Globular Clusters, Suda, T. Tsujimoto, T. Shigeyama, and M. Y. Fujimoto, The Astrophysical Journal, 2007, Vol. 671, pp. L129-L132

[12] A novel method to construct stationary solutions of the Vlasov-Maxwell system, A. Suzuki and T. Shigeyama, Physics of Plasmas, 2008, Vol. 15, Issue 4, pp. 042107-042107-5

[13] Detailed Analysis of Filamentary Structure in the Weibel Instability, A. Suzuki and T. Shigeyama, The Astrophysical Journal, 2009, Vol. 695, pp. 1550-1558

[14] Multiple main sequence of globular clusters as a result of inhomogeneous big bang nucleosyn- thesis, T. Moriya and T. Shigeyama, Physical Review D, 2010, vol. 81, Issue 4, id. 043004

[15] Probing Explosion Geometry of Core-collapse Supernovae with Light Curves of the Shock Breakout, A. Suzuki and T. Shigeyama, The Astrophysical Journal Letters, 2010, Volume 717, Issue 2, pp. L154-L158

[16] A conservative scheme for the relativistic Vlasov-Maxwell system, A. Suzuki and T. Shigeyama, Journal of Computational Physics, Volume 229, Issue 5, p. 1643-1660

[17] Boron Synthesis in Type Ic Supernovae, K. Nakamura, T. Yoshida, T. Shigeyama, and T. Kajino, The Astrophysical Journal Letters, 2010, Volume 718, Issue 2, pp. L137-L140

[18] Non-thermal Photon Production via Bulk Comptonization at Supernova Shock Breakout, A. Suzuki and T. Shigeyama, The Astrophysical Journal, 2010, Volume 719, Issue 1, pp. 881-889

[19] Compton Degradation of Gamma-Ray Line Emission from Radioactive Isotopes in The Clas- sical Nova V2491 Cygni, Suzuki and T. Shigeyama, The Astrophysical Journal Letters, 2010, Volume 723, Issue 1, pp. L84-L88

[20] Effects of magnetic fields on the propagation of nuclear flames in magnetic white dwarfs, M. Kutsuna and T. Shigeyama, The Astrophysical Journal, 2012,Volume 749, 51

[21] Type Ia Supernova Remnant Shell at z = 3.5 Seen in the Three Sightlines toward the Gravitationally Lensed QSO B1422+231 S. Hamano, N. Kobayashi, S. Konod, T. Tsujimoto, K. Okoshi, and T. Shigeyama

[22] Early evolution of spherical ejecta expanding into the circumstellar matter at ultra-relativistic speeds T. Shigeyama, A. Suzuki, and K. Nakamura, Publication of Astronomical Society of Japan, 2012, Volume 4, 87

< **Conference Proceedings** >

[23] Light Element Production in the Circumstellar Matter of Type Ic Supernovae at Low Metallicity, K. Nakamura, S. Inoue, S. Wana jo, and T. Shigeyama, Proceedings of the International Symposium on Nuclear Astrophysics - Nuclei in the Cosmos - IX., (CERN), 2006, p.148

[24] Light Element Production in Type Ic Supernovae, T. Shigeyama, K. Nakamura, S. Wanajo, and S. Inoue, ORIGIN OF MATTER AND EVOLUTION OF GALAXIES (AIP Conference Proceedings), 2006, Vol. 847, pp. 105-110

[25] Light Elements Produced by Nitrogen-rich Type Ic Supernovae, K. Nakamura, S. Inoue, S. Wanajo, T. Suzuki, and T. Shigeyama, ORIGIN OF MATTER AND EVOLUTION OF GALAXIES (AIP Conference Proceedings), 2006, Vol. 847, pp. 446-448

[26] Type Ic Supernovae as Sources of Cosmic Rays, K. Nakamura and T. Shigeyama, Cosmic Particle Acceleration, 26th meeting of the IAU, Joint Discussion 1, 16-17 August, 2006, Prague, Czech Republic, JD01, #35

[27] Searching For A Companion Star Of Tycho'S Type Ia Supernova With Optical Spectroscopic Observations, Ihara, J. Ozaki, M. Doi, T. Shigeyama, N. Kashikawa, and K. Komiyama, Supernovae: One Millennium After SN1006, 26th meeting of the IAU, Joint Discussion 9, 17-18 August 2006, Prague, Czech Republic, JD09, #27

[28] The neutrino-process and light element production, K. Nakamura, T. Yoshida, T. Shigeyama, and T. Kajnio, Proceedings of the 11th Symposium on Nuclei in the Cosmos. 19-23 July 2010. Heidelberg, Germany. Published online at Published online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=100, id.63

[29] Lithium, beryllium, and boron production in core-collapse supernovae Nakamura, T. Yoshida, T. Shigeyama, and T. Kajnio, Light Elements in the Universe, Proceedings of the International Astronomical Union, IAU Symposium, 2010, Volume 268, p. 463-468

[30] Light elements from core-collapse supernovae: the neutrino-process and spallation reactions, Nakamura, T. Yoshida, T. Shigeyama, and T. Kajnio, THE 10TH INTERNATIONAL SYMPOSIUM ON ORIGIN OF MATTER AND EVOLUTION OF GALAXIES: OMEG-2010. AIP Conference Proceedings, Volume 1269, pp. 309-314 (2010)

[31] GRB Nucleosynthesis in Dwarf Galaxies, Shigeyama, K. Nakamura, T. Tsujimoto, and T. Moriya, DECIPHERING THE ANCIENT UNIVERSE WITH GAMMA-RAY BURSTS. AIP Conference Proceedings, Volume 1279, pp. 415-417 (2010)

[32] Bulk Comptonization at the emergence of shock waves from stellar atmospheres, A. Suzuki and T. Shigeyama, DECIPHERING THE ANCIENT UNIVERSE WITH GAMMA-RAY BURSTS. AIP Conference Proceedings, Volume 1279, pp. 424-426 (2010)

[33] Probing explosion geometry of core-collapse supernovae with light curves of the shock breakout, A. Suzuki and T. Shigeyama, Death of Massive Stars: Supernovae and Gamma-Ray Bursts, Proceedings of the International Astronomical Union, IAU Symposium, Volume 279, p. 285-288 (2012)

9.6 Invited Presentations at International Conferences

[1] Light Element Production in Type Ic Supernovae, T. Shigeyama, K. Nakamura, S. Wanajo, and S. Inoue, International Symposium on ORIGIN OF MATTER AND EVOLUTION OF GALAXIES 2005: New Horizon of Nuclear Astrophysics and Cosmology, Tokyo, Japan 8-11 November 2005

9.7 Teaching Accomplishment

研究奨励賞　修士課程 鈴木昭宏 2010
研究奨励賞　博士課程 鈴木昭宏 2012

9.8 Contribution to Academic Community

9.8.1 Editorial activities

- Editor of Publication of Astronomical Society of Japan 2007−2008
- Managing Editor of Publication of Astronomical Society of Japan 2011−

9.8.2 Organization of professional societies

A board member of Astronomical Society of Japan 2000−2002, 2011−

9.8.3 Organization and advisory of conferences

- Advisory Committee of Center for Planetary Science 7th International School of Planetary Sciences “Theory of Stellar Evolution and Its Applications ? From the First Stars to Planet-Hosting Stars and Gas Giant Planets”, 2011
- Scientific Organizing Committee Chair of the 3rd Subaru International Conference GALACTIC ARCHAEOLOGY, 2011

9.9 Outreach

- 第 14 回理学部公開講演会『過去を知る理学』長老の星が語る宇宙錬金術 2008
- 第 60 回東レ科学振興会科学講演会『進化と起源の謎』宇宙の起源と進化 – 星が作った多様な宇宙 – 2010

9.10 Internationalization Statistics

	Number	Country
Foreign students advised		
Bachelor Course	0	
Master Course	0	
Doctor Course	0	
Foreign researchers hosted	0	
Students sent abroad	0	
Researchers sent abroad	0	
Foreign visitors	0	