The Center for Physics of the Universe

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ABSTRACT

The Center for Theoretical Physics of the Universe (CTPU) is a research center of the Institute for Basics Science (IBS). CTPU is at the forefront of research exploring the fundamental nature of the universe. The particle theory and cosmology group (PTC) is at present the most developed subdivision of CTPU. The research of the PTC group ranges from particle physics to cosmology, linking the smallest to the largest scales of our Universe. While our field of study is broad, we emphasize new physics beyond the Standard Model and the associated phenomena at the energy, intensity and cosmic frontiers.

INTRODUCTION

About CTPU

The Institute for Basics Science (IBS), a Korean government-funded research institute for fundamental sciences, was established in 2011. The Center for Theoretical Physics of the Universe (CTPU) was the first theoretical physics center among the 28 research centers of IBS. There are two kinds of research centers at IBS; headquarter (HQ) research centers and campus research centers. The campus research centers are installed in major universities throughout Korea, whereas the HQ research centers are located at the main campus of IBS, which is in Daejeon. CTPU belongs to an HQ research center of IBS. Experimental research centers, such as the Center for the Underground Physics, have one director with several group leaders. However, the theoretical physics centers of IBS are adopting a co-director system. Currently, there are two groups at CTPU; the particle theory and cosmology group (PTC), and the field, string and gravity group (FSG). Each group has its own director. Since there was only one group, i.e. the PTC group, at CTPU at the very beginning, the director of PTC group acted as the director of CTPU. The FSG group is not fully established and a third group has not yet been created. If three groups become established at CTPU, then the position of director of CTPU would rotate among the co-directors of the groups. Currently, as the PTC group is the most fully established at CTPU, we will limit our focus to the PTC group in this article.

About the PTC Group

While the Standard Model (SM) of particle physics has passed all experimental tests performed so far, including the discovery of a Higgs like particle [1], there are many outstanding issues that cannot be explained within the SM, for instance dark matter, matter-antimatter asymmetry in the Universe, and the inflationary expansion in the early Universe, which now all have convincing observational evidence regarding their existence. Together with the theoretical incompleteness of the SM, e.g. the lack of unification and the missing theory for quantum gravity, the observation of these phenomena motivates us to seek a more fundamental theory underlying the SM. There are also many ongoing or planned experiments that explore physics beyond the SM. The Large Hadron Collider (LHC) experiments have released a large amount of data and continue running with increased luminosity, and ongoing or planned precision experiments at the intensity and cosmic frontiers will release new data soon. The historic discovery of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory (LIGO) [2] has opened a new era of multi-messenger cosmology.

With unprecedented amounts of data at hand and the prospect of even more in the near future, particle physics and cosmology have been presented with an extraordinary chance to unveil a new physics beyond the SM. In this potentially ripe moment, the CTPU-PTC group is aiming to play a world-leading role in the theoretical efforts to understand the fundamental laws of nature and the origin of our Universe.

Fig. 1: Institute for Basic Science HQ in Daejeon.

CTPU-PTC GROUP

Facts and Figures

As of 2018, the CTPU-PTC group consists of 22 research scientists in various areas of particle physics and cosmology, 3 intern graduate students, 4 associate member scholars, and 4 administrative staff members. The research of the CTPU-PTC group is mainly organized by the director, Dr. Kiwoon Choi, who was a professor at KAIST before he joined IBS in 2013. All research members, except for the director, are officially categorized as research scientists. Internally, several of these research scientists are also called faculty members, who act as leaders of the research groups. The others are called postdocs. The initial term for a typical postdoc is two years, with the possibility for an extension of another year. A few senior members have a three year plus two year contract.

Prior to the construction of the main campus of IBS, the center was located at KAIST Munji Campus, Daejeon until the end of 2017. In 2018, the new main campus of IBS was built at the Daejeon Expo Science Park, and CTPU moved into the theory building of the main campus of IBS (IBS HQ) in Daejeon.

The facility has 18 offices for research scientists, students and visitors. There are two seminar rooms, three discussion rooms for both small group meetings to medium-sized workshops, and two relatively large discussion spaces for other activities. In addition, the facility has its own library and a computer server room for small size computing servers and a NAS data storage server. There are also common facilities shared by all centers at IBS HQ. The IBS Science and Culture Center has an auditorium and several seminar rooms which can host an international conference such as COSMO. It has a fitness room, a cafeteria, and dormitory for IBS members and visitors, and a large computer server room where the clusters for CTPU and other centers have been installed.

With these facilities, CTPU is an ideal place for both new and experienced researchers, from Korea and from overseas. There are always active discussions and collaboration within the PTC group. Also, many exciting international collaborations have been established in small workshops and focus programs hosted by the PTC group annually.

Fig. 2: A discussion space at CTPU.

Working Groups

The PTC group is divided into two smaller groups, particle phenomenology and cosmology, but there is no clear distinction between different groups. Many researchers join both groups and there are active discussions and collaborations between the two groups. There are regular internal and external seminars, journal clubs and working group meetings every week.

The diverse areas of expertise of the approximately 30 group members create an ideal environment for collaboration between different subjects, such as the search for dark matter and probing a new physics beyond the SM in high energy colliders, limiting the inflation models and other early Universe models through gravitational wave experiments, and testing the validity of a physics beyond the standard model with computer simulations.

There are also collaborations between theoretical physicists and experimental physicists at the IBS centers. The presence of other IBS centers, like the Center for Underground Physics (CUP) and the Center for Axion and Precision Physics Research (CAPP), that are working on the search for dark matter and conducting other particle physics experiments at the same location opens up the possibility for collaboration between theory and experimentalists, especially regarding neutrino physics and the search for axion dark matter.

We have built computing facilities for intense computer simulations or for heavy calculations for both cosmology and collider physics. We have several high-performance computers with multicore CPUs and GPUs. There are two cluster machines with a combined 1200 physical computing cores. Every year there is a plan to upgrade the cluster by adding more units with about 200-300 cores. Our plan is to a build computing cluster with more than 2000 physical cores exclusively for the PTC group.

Since its establishment in 2014, the CTPU-PTC group has published more than 120 papers in SCI journals. Some of the notable works are listed as follows; a pioneering work on relaxion/clockwork [3], an explanation of the diverse galactic rotation curves by a self-interacting dark matter model [4], the suggestion of a portal connecting axion and dark photons [5], a new model of gravitational waves from the first order phase transition [6], and spectral decomposition of missing transverse energy at hadron colliders [7].

Nature magazine noticed the fast growth of research at CTPU; CTPU is ranked the 2nd among the "Top 10 institutes in Daejeon", in their 2017 article [8].

Mission

Our ultimate objective is to achieve a deeper understanding of the fundamental laws of nature and the origin of our Universe. To this end, we use the most recent data from pioneering experiments such as the LHC, and also a variety of observational data from astrophysical and cosmological experiments such as the search for dark matter and gravitational waves. As is well known, there are various cosmological and astrophysical observations demanding new physics beyond the SM. It is of particular importance to understand the nature of dark matter and the mechanism to generate the matter-antimatter asymmetry, which are among the biggest unresolved problems in fundamental physics. Another important question is how our Universe evolved in its very early stages, and in particular, to understand the origin of inflationary expansion in the early Universe.

For theorists, one essential mission is to develop models of new physics beyond the SM to explain the phenomena not addressed by the SM, while making further predictions to scrutinize the model. We are studying various new physics models, in particular those addressing dark matter, early Universe inflation, baryogenesis, the weak scale hierarchy problem, and the strong CP problem, along with their observable consequences in the ongoing and forth-coming experiments. To find a clue for new physics, it is crucial to combine expertise covering a wide range of energy scales and complimentary research topics. The CTPU-PTC group makes a unique and significant contribution in searching for new physics by providing multidisciplinary studies, which is possible due to the broadness and depth of the research backgrounds of our group members, crossing the traditional boundaries of particle physics and cosmology.

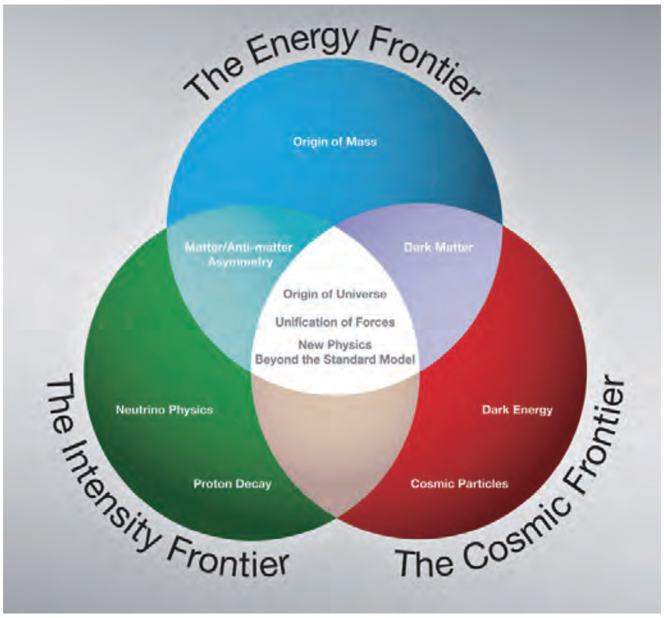

Fig. 3: Three Frontiers of Particle Physics (Courtesy of the US Department of Energy).

RESEARCH AT CTPU-PTC

There are three pillars of research areas in fundamental physics: the energy frontier, the intensity frontier, and the cosmic frontier. Our group is aiming to perform multidisciplinary research in these research areas with a hope to create new research field.

Research in the Energy Frontier

There are good reasons to expect that new physics exists around the TeV scale, which can be probed by the ongoing LHC Run2 experiments. The LHC experiments continue to provide an enormous amount of data at the energy frontier, testing new physics at the TeV scale. Our immediate goal in this crucial and timely frontier is to use the LHC Run2 data to analyze whether nature has new TeV scale particles, and whether these new particles reveal new fundamental symmetries or new dynamical principles of nature. Of particular interest are extra Higgs scalars or other particles associated with the electroweak symmetry breaking sector, supersymmetric particles, top-partners, dark matter candidates, and new heavy gauge bosons or scalars.

Studying the physics potential of future colliders such as the Future Circular Collider (FCC) or the International Linear Collider (ILC) is also an important task, which represents another direction of our energy frontier research.

Finally, with the large amount of data collected at the LHC, high energy physics enters a precision era for Higgs and TeV scale physics. To match the precision which is in reach of current experiments, higher-order perturbative QCD studies, studies of highly energetic jet physics and jet-substructure techniques become increasingly important at the energy frontier, to which CTPU-PTC will contribute.

Research in the Intensity Frontier

There are proposed long-baseline neutrino experiments such as DUNE and T2HKK. As neutrino physics is the least explored area in the electroweak sector, such experiments will be able to test and uncover new physics related to neutrino physics, such as sterile neutrinos or feeble gauge interactions that can affect neutrino oscillations. Our goal in this area is a feasibility study of these experiments for testing new physics, which will provide a timely and important view on what to expect from these experiments.

There are also active searches for new light particles such as light dark matter, dark photons, or axion-like particles. Ongoing and proposed experiments – including many beam-dump experiments around the world– will probe these new particles using unprecedented levels of luminosity and new techniques. We are studying various models and search methods of these new light particles, which are complementary to the energy frontier's searches of new TeV scale particles using the LHC.

Furthermore, we investigate CP violations associated with beyond the SM physics and their implications for electric dipole moments of electrons, neutrons and atoms. In the near future, the experimental sensitivity of electric dipole moment searches will be further improved by one order of magnitude. For many models, this improvement implies a reach in indirect searches up to scales of the order of 100 TeV, i.e. competitive in reach but complementary to direct searches at the LHC, with important implications for baryogenesis, which is one of the key subjects in the cosmic frontier research.

Research in the Cosmic Frontier

For new and extremely light particles, the cosmic frontier, with cosmological and astroparticle observations, can be the most suitable direction to investigate them. Our immediate goal in this direction includes exploiting new data such as the Cosmological Microwave Background (CMB) anisotropy measured by the Planck satellite experiments or data on gravitational waves as recently detected by the Advanced LIGO experiments, which continue to increase their data samples.

Gravitational waves also have important implications for models of inflation. Recent proposals in model building for clockwork and cosmic relaxation scenarios have opened new avenues for models of inflation, and we plan to further explore their implications for gravitational wave physics. Finally, gravitational waves allow us to test models of baryogenesis with first-order electroweak phase transitions, and work on this topic is in progress at CTPU-PTC.

Data from direct and indirect dark matter detection experiments also play a critical part in the cosmic frontier. Analyzing the most recent data to probe the dark sector of the Universe is always one of the highest priorities in our group, so that we can shed new light on our understanding of the nature of dark matter.

Table I. Research subjects of CTPU-PTC group.

Energy Frontier	Intensity Frontier	Cosmic Frontier
• New physics searches at colliders and model building • QCD and jet physics at the LHC • Probing extended Higgs sectors • Developing new computational methods for collider physics	• New physics in light dark sectors • Electric dipole moments and rare flavor changing processes • Low energy precision measurements for dark sector particles • Neutrino oscillations for non-standard interactions	• Cosmological studies of dark matter • CMB / matter power spectrum inflation • Baryogenesis • Large scale structure of the Universe • Connecting cosmology to collider physics • Gravitational waves as a probe of BSM physics

OTHER ACTIVITIES

The CTPU-PTC group hosted and cohosted several prestigious international workshops on cosmology and astroparticle physics. CTPU-PTC was a main host for the 12th CosPA (Conference in the Symposium on Cosmology and Particle Astrophysics) series (2015) [9], the 13th DSU, (Dark Side of the Universe) workshop (2017), and the 1st IBS Conference on the Dark World (2017). In August 2018, the PTC group will host the 22nd COSMO (International Conference on Particle Physics and Cosmology), at IBS HQ. CTPU-PTC was the cohost for the MulitDark workshop for the past three years and is a cohost of the 39th ICHEP (International Conference on High Energy Physics) in 2018.

Fig. 4: IBS conference on the Dark World (2017).

The PTC group also hosts several annual mini-workshops and focus programs on recent issues in particle physics and cosmology. In 2016, many scholars from overseas and domestic institutes participated in programs such as an “Overview of the recent di-photon excess at the LHC Run 2”, the “Focus workshop on particle physics and cosmology”, and the “Focus meeting on collider phenomenology”. In 2017, the “Focus meeting on fundamental composite dynamics” and the “Focus meeting on new perspectives on light particles” were hosted and these meetings initiated many collaborations between PTC group members and scholars from outside the group. CTPU hosted several joint workshops with other institutes in Korea, such as the Korea Astronomy and Space Science Institute (KASI), the Korea Institute for Advanced Study (KIAS), the Asia Pacific Center for Theoretical Physics (APCTP), as well as academic institutes such as Seoul National University, KAIST, Pusan National University, Konkuk University, and Chonbuk National University.

There are programs for graduate students and young postdocs at CTPU, such as the annual summer school on particle physics and cosmology, special lecture series. The aim of the annual summer school is to train and encourage the young students who want to become theoretical particle physicists or cosmologists. Many universities in Korea do not have many professors in particle physics, especially in cosmology. Graduate students in Korea usually struggle to find lectures about these subjects at their own institutes. The CTPU-PTC summer school and lecture series can offer graduate students in Korea the opportunity to learn and discuss basic knowledge and current issues in particle physics and cosmology. There has been much positive feedback from the participants of the previously mentioned programs.

Many young physicists and students who worked at CTPU have moved on to other prestigious institutes after the end of their respective terms. Some of these individuals received tenure track positions at major universities. They have become vital members of the particle

Fig. 5: A Focus meeting at CTPU.

physics and cosmology community. We expect that more collaborations will be established through these former members.

PROSPECTS

Korean government-funded institutes are heavily influenced by both the political and economic environment. This might give the impression that all IBS centers, including CTPU, have an uncertain future. However, IBS became one of the largest and most active research institutes for basic science in Korea in a very short time. International recognition regarding research conducted by and affiliated with IBS also has helped to encourage continuous support for IBS centers. CTPU is a theory group and, compared with experimental centers, is probably less influenced by budget policy.

So far, IBS has not pressured individual researchers to produce short-term achievements. IBS has tightly managed the use of its budget but has given substantial intellectual freedom to its researchers. If this policy stands, then regardless of the changes in the Korean government, CTPU and other IBS centers will grow into internationally prominent research centers.

In summary, the Particle Theory and Cosmology (PTC) group of CTPU is aiming to become an internationally renowned research group in theoretical particle physics and cosmology, through the confluent spectrum of research backgrounds of its group members. The CTPU-PTC group is a young center, now just a little more than four years old. During the past several years, we have successfully recruited young faculty members who have competitively performed research, as well as young postdocs who were eager to broaden and strengthen their research abilities at CTPU. Having established a vivid atmosphere for research, we have identified challenging and outstanding problems and are conducting cutting edge research in theoretical particle physics and cosmology. We expect that CTPU will continue to mature and become one of the core centers for theoretical fundamental physics, both in Korea and internationally.

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