FEATURE

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Research Area : Theoretical Physics

Dark Matter Study as a Bridgehead for New Physics Exploration

Where Can We Find New Physics ?

In past decades, people tried to develop the field of particle physics based on the so-called electroweak naturalness, namely how the electroweak scale (the energy scale creating the electromagnetic and weak forces from more fundamental ones; about the masses of the weak bosons, W and Z, which mediate the weak interaction, 10^{11} eV = 100 GeV) should be naturally explained. In fact, many new physics scenarios such as supersymmetry, extra-dimension and composite Higgs have been proposed in this context, and have been and are still being tested by various experiments and observations including the large hadron collider (LHC). However, people have recently started doubting this guiding principle, the electroweak naturalness, because new physics signals predicted by those scenarios have not been detected there at all. To be more precise, the doubt is that, although the electroweak scale should be naturally explained, it may be achieved by some other mechanisms (or ideas) which are totally different from what we have thought about thus far. People have very recently started seeking new mechanisms based on this consideration, but no one has yet succeeded in proposing a critical mechanism that many people agree with.

Uncovering the Nature of Dark Matter Attracts Attention

Under these circumstances, people start taking a new strategy: developing particle physics by resolving the cosmic dark matter problem. Dark matter was proposed by Fritz Zwicky in 1934 in order to explain the motion of galaxies inside the Coma Cluster, and its existence was established at the beginning of this century thanks to cosmological observations such as the fluctuation of the cosmic microwave background. Its detailed nature, however, is unknown. Moreover, it is known that no dark matter candidate exists in the standard model. As a result, once the nature of dark matter is clarified, it can be used as a bridgehead to launch out into an exploration of new physics. In other words, the strategy is that we first determine the nature of dark matter and then explore new physics beyond the standard model.

Next, let me summarize what we know about dark matter. First, dark matter is electrically neutral. In fact, dark matter can have a very tiny electric charge, or O(1) charge if it is vastly heavy; however we do not consider such special cases in this article. Next, dark matter has, at least, a non-zero mass and moves non-relativistically in the present universe; namely its speed is much slower than that of light in the present universe. Third, its lifetime should be much longer than the age of the universe (13 billion years). Moreover, dark matter hardly interacts with ordinary matter like nuclei. Finally, as quantitative knowledge, it is known that the averaged mass density of dark matter in the universe, which is sometimes called dark matter abundance, is about 2×10^{-30} g/cm^3.

In spite of this knowledge, it is still difficult to say that we have enough information about dark matter. For instance, even if we assume that dark matter is an elementary particle, its mass is merely predicted to be in a range between 10^{-55} g and 10^{-5} g; namely there is uncertainty of fifty orders of magnitude. Since such huge uncertainty makes it impossible to perform a comprehensive search of dark matter experimentally, we are currently trying to detect dark matter based on several influential hypotheses such as the thermal dark matter, axion, sterile neutrino, and primordial black hole hypotheses. Among these, the search for dark matter based on the thermal dark matter hypothesis is more developed than the others. I would therefore like to focus on this hypothesis and describe its present status and prospects in this article.

Thermal Dark Matter Hypothesis

The thermal dark matter hypothesis is as follows: dark matter is an (undiscovered) elementary particle and its abundance observed today was produced by the so-called freeze-out mechanism. In the freeze-out mechanism, dark matter is assumed to be in chemical and kinematical equilibrium with the thermal bath composed of standard model particles during a very early epoch of the universe. However, it eventually decoupled from the bath because the reaction rate which was maintaining the equilibrium becomes smaller than the expansion rate of the universe. After the decoupling, the amount of dark matter in the universe becomes constant, determining dark matter abundance today. Fig. 1 shows typical behavior of the amount as a function of m/T, with m and T being dark matter mass and the temperature of the universe, respectively. Dark matter abundance is seen to coincide with that of equilibrium when $m/T \sim O(1)$, while it deviates from the equilibrium at $m/T \sim O(10)$ and eventually becomes constant. This mechanism is also applied to other phenomena of cosmology (big-bang nucleosynthesis and recombination) and explains observational results successfully. Because of this fact, the thermal dark matter hypothesis is regarded as one of the natural hypotheses about dark matter. When dark matter mass is around the electroweak scale, the thermal dark matter is called

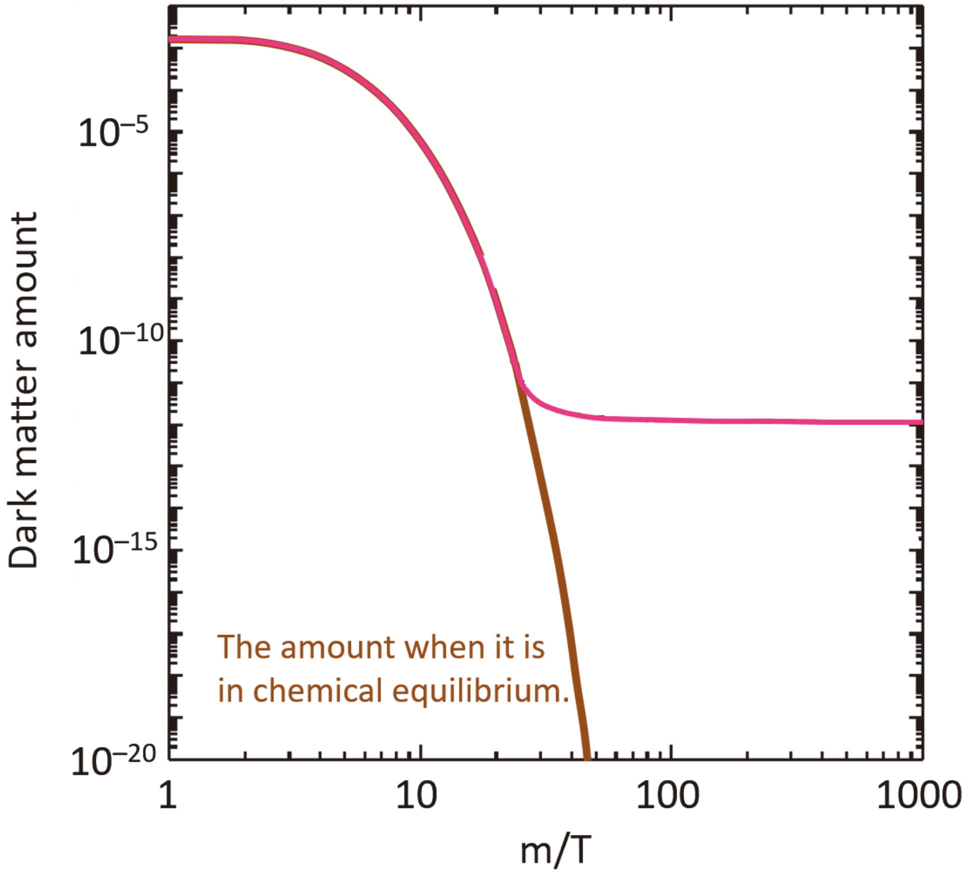

Figure 1. Typical behavior of the dark matter amount (the ratio of the number density of dark matter to the number density of radiation). Here, *m* is the mass of the dark-matter particle and *T* is the temperature of the universe, both expressed in units of energy.

WIMP (Weakly Interacting Massive Particle), and it is intensively discussed in various new physics scenarios beyond the standard model.

Since thermal dark matter is assumed to be in equilibrium in the early universe, it inevitably interacts with standard model particles. The detection of the thermal dark matter relies on this fact, and the important question here is which standard model particle the dark matter interacts with. The strategy of dark matter detection depends strongly on the answer to this question. Hence, the thermal dark matter is classified based on its quantum numbers in order to search for it systematically and comprehensively. The quantum number is nothing but a charge associated with a force, for instance, the electric charge of the electromagnetic force. Dark matter is electrically neutral as mentioned above, and it should not carry a charge of the strong interaction, a color charge; otherwise it would already have been discovered by various experiments. As a result, the quantum numbers we should focus on are those of the weak and gravitational forces. The quantum number of the weak force is called a weak charge, while one of those of the gravitational force is a spin. Another quantum number of the gravitational force is nothing but mass, and it is determined by requiring that the abundance of dark matter,

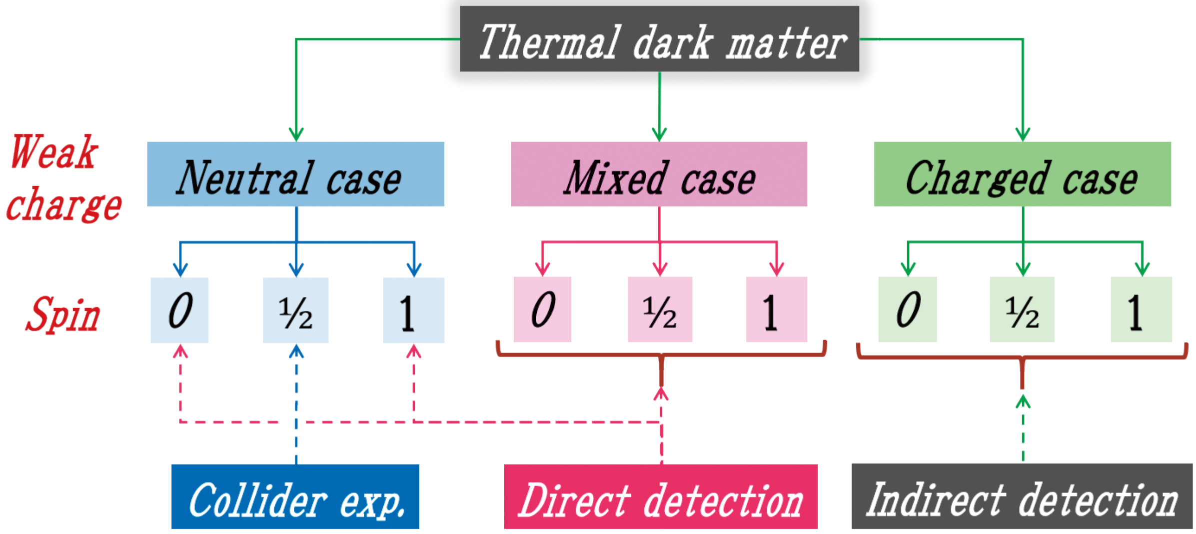

Figure 2. Classification of the thermal dark matter and the most efficient detection method for each case.

which is computed after fixing its weak charge and spin, coincides with the result of cosmological observation. In other words, the mass becomes a derived quantum number.

Classification of Thermal Dark Matter

This classification is summarized in Fig. 2. First, thermal dark matter has a weak charge in the unit of 1/2, namely, 0, 1/2, 1, ···. There is, however, an exception: dark matter may be described by the mixing (linear combination) of states which have different weak charges. Within the familiar electromagnetic dynamics, it corresponds to the case that we consider the particle whose electric charge is given by the mixing of, e.g., 0 and 1. Of course, such a mixing occurs only for the weak force because of the electroweak symmetry breaking, and never occurs for other forces. As a result, dark matter can be classified into three categories: it has no weak charge (neutral under the weak force), has a non-zero weak charge, or has mixed weak charges. Next, if we restrict ourselves considering a renormalizable theory to guarantee enough magnitude of interactions between dark matter and standard model particles, the spin of dark matter is restricted to be either 0, 1/2, or 1. Thanks to the nature of the relativistic quantum field theory, once the weak charge and the spin of dark matter are fixed, all interactions between dark matter and standard model particles are uniquely determined, which allows us to discuss physics of the thermal dark matter quantitatively.

How to Find Thermal Dark Matter Based on Its Classification

The above classification of thermal dark matter has indeed been proposed by us (researchers studying particle phenomenology at the Kavli IPMU), and we are now comprehensively studying how dark matter in all the categories can be detected in the near future based on various collaborations with experimental and observational researchers. Some results of our study concerning the type of experiment, seeming to be the most efficient for detection in each category, are also shown in Fig. 2.

First, in the case where dark matter has mixed weak charges, the scattering cross section between dark matter and a nucleus is always predicted to be large, for its origin is the same as those of the mixing. As a result, direct dark matter detection in underground laboratories is very efficient for detecting such dark matter, and indeed many experiments are now being conducted around the world. Moreover, various future projects such as the XENONnT,[1] where it was decided that the XMASS group (in which some of our colleagues in our institute are involved) would join, have been proposed and approved. When dark matter is actually in this category, it will be detected in the near future.

Next, when dark matter has a non-zero weak charge, its mass is generally predicted to be in the TeV scale, which makes difficult to detect it in the near future at collider experiments. On the other hand, we pointed out that its annihilation cross section is significantly enhanced thanks to the Sommerfeld effect,[2] which makes indirect dark matter detection very efficient. In particular, the observation of gamma-rays from Milky Way satellites[3] by the CTA collaboration[4] is expected to play an important role; however, in order to maximize its sensitivity, we also need to know precisely how dark matter is distributed in each satellite. Fortunately, this problem will be overcome by the PFS project at the Subaru telescope organized mainly by Kavli IPMU. Moreover, when third generation direct dark matter detection experiments such as the DARWIN project,[5] the successor of XENONnT, become available, it will be possible to detect the TeV-scale dark matter. Here, it is important to address the fact that such TeV-scale dark matter is predicted by the so-called anomaly mediated SUSY breaking scenario[6] (Pure Gravity Mediation model, etc.), the one attracting the most attention after the discovery of the Higgs boson, and thus detecting the TeV scale dark matter is now regarded as an urgent issue of particle physics. In addition, some new physics models predict dark matter having a non-zero weak charge is produced not only by the freeze-out mechanism but also by some other non-thermal ones. In such cases, the mass region around the electroweak scale also becomes important to search for. The future LHC (HL-LHC) and lepton collider such as the international linear collider (ILC) experiments will play an important role in searching for such electroweak dark matter.

Finally, we consider the case in which the thermal dark matter is neutral under the weak force. When the spin of dark matter is 0 or 1, its scattering cross section off a nucleus is predicted to be large in general. Hence, the direct dark matter detection is again efficient, as in the case of dark matter having mixed weak charges. On the other hand, when the spin is 1/2, the scattering cross section does not necessarily become large. In particular, when dark matter interacts mainly with leptons (leptophilic dark matter), mainly with the Higgs boson by the pseudo-scalar coupling (CP violating Higgs portal dark matter) or is lighter than the proton (light

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[1] XENONnT is a direct dark-matter search experiment to be conducted at the Gran Sasso underground laboratory LNGS in Italy, using 8 tons of liquid xenon. The experiment aims at detecting dark matter particles through measurement of nuclear recoil events due to scattering of dark-matter particles with xenon nuclei.

[2] The Sommerfeld effect is the effect in which a long-range force between the initial-state particles significantly changes the inelastic-scattering cross section between them compared to that without a long-range force. It is known that if the dark matter particle is sufficiently heavier than the particles that mediate the weak force (W and Z bosons), it will act as a long-range force for dark-matter particles and significantly enhances their annihilation cross section.

[3] Among satellite galaxies, those called dwarf spheroidal galaxies have particularly low luminosity and small mass. As their masses are considered to be dark-matter dominated, they are included in the main objectives of dark-matter search with gamma-ray observations.

[4] CTA（Cherenkov Telescope Array）is a gamma-ray observatory in the 20 GeV~100 GeV gamma-ray energy region.

[5] DARWIN (DARk matter WImp search with liquid xenoN) is a direct dark-matter search experiment using 50 tons of liquid xenon.

[6] One of the supersymmetric models which has attracted particular attention since the discovery of the Higgs boson. It is known as the simplest model that, while accounting for the Higgs mass and being compatible with grand unified theories, is free from the problems which often arise in supersymmetric models, i.e., the problems related to flavor and cosmology.

dark matter), most of their parameter regions are experimentally uncharted and new methods that are different from those we have considered so far are required. For former two cases, dark matter production (mono-photon process, etc.) and the precise measurement of the Higgs boson in future lepton colliders such as ILC will play an important role. On the other hand, for the light dark matter, a new light mediator (a scalar or vector particle) is also predicted in addition to dark matter itself because of the nature (renormalizablility) of the relativistic quantum field theory. High luminosity collider experiments such as Belle II and various K meson experiments are mandatory to detect such light but very weakly interacting particles. Recently, it has also been pointed out that the Higgs boson decay to a pair of mediators can be an important method for dark-matter search. In this case, precision measurements of rare Higgs boson decays will become important.

Conclusion

In conclusion, people are currently making great efforts to look for a new physics scale in particle physics after the completion of the standard model (discovery of the Higgs boson) and non-observation of new physics signals. Clarifying the nature of dark matter is certainly expected to play an important role in this context. As mentioned in the latter half of this article, in recent decades, closer collaboration between theorists and experimentalists in various fields has never been more crucial than it is today. The Kavli IPMU provides an ideal environment under these circumstances and I will continue to vigorously develop such dark matter studies.

Tea Break:

What IPMU Stands For?

There is an anecdote that the remarkable German mathematician and mathematical physicist of the late 19th and early 20th centuries David Hilbert once said, upon hearing that one of his students had dropped out to study poetry: "Good, he did not have enough imagination to become a mathematician.”

We would like to appeal to your imagination and announce a competition for the best suggestion on how someone unfamiliar with the meaning of the abbreviation IPMU could guess what it stands for. For instance,

The Institute for the Pretty Much Unknown,
The Infrared in Physics and the Mathematics of the Ultraviolet ...

We will post the best answers on the Kavli IPMU website and on a poster in the tea hall, making it even more appropriate for the Tea Break rubric.

(Contributed by Alexander A. Voronov)