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Overview on Dark Matter Models

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In this short review, we give an overview of dark matter models from the viewpoint of model building.

1. Introduction

Although dark matter of the Universe has been discussed since 1933, very little is known about the nature of dark matter even today. We do not even know its mass, and we only managed to restrict it roughly between 10^{-31} GeV and 10^{60} GeV, which demonstrates our lack of understanding. Several properties we now know are its mass abundance, its null electromagnetic interaction, its coldness enough to cluster by the primordial gravitational potential, and its stability at least over the age of the Universe. Identification of the nature of dark matter is one of the most important challenges of modern particle physics and cosmology (see, e.g., Refs. [1–3] for more comprehensive reviews). In this contribution, we give a brief overview of the models of dark matter from the viewpoint of model building.

2. Models of Dark Matter

So far, there have been many proposals of models that satisfy the properties mentioned above of dark matter. Here, let us classify the models based on the mechanism to make the matter stable.

2.1 Symmetry

The most straightforward mechanism to make dark matter stable is by symmetry. If the dark matter particle is the lightest particle charged under a new symmetry, it is stable as it does not have any channels to decay into. One of the best examples of the dark matter in this class is the weakly interacting massive particle (WIMP), such as the lightest supersymmetric particle (the LSP). The LSP is stable due to the R-parity, which is required by the nucleon stability in the supersymmetric Standard Model (see [4] for review). In general, the dark matter stability due to new symmetry is well-motivated as the physics beyond the Standard Model often involves new symmetry.

The WIMP is particularly attractive since it fits well with the thermal freeze-out scenario to explain the observed dark matter density. In this scenario, the WIMP is in the thermal equilibrium with the Standard Model particles in the early Universe. When the cosmic temperature decreases below the WIMP mass, it annihilates into the Standard Model particles. The annihilation stops when the mean-free path of the WIMP becomes longer than the Hubble length, and the number density of the WIMP per comoving volume is fixed. The correct relic dark matter abundance is obtained when the annihilation cross-section is $\langle \sigma v \rangle \simeq 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$. The mass range of the WIMP mechanism is limited roughly between $\mathcal{O}(10)$ MeV and $\mathcal{O}(100)$ TeV. The lower limit is from the constraints on the massless degrees of freedom during the Big-Bang Nucleosynthesis and on that at the recombination time (see e.g., [5]). The upper limit is from the so-called unitarity limit on the annihilation cross-section [6].

In the WIMP model, we assume that there is no asymmetry between the particle and the anti-particle of dark matter. When the asymmetry is sizable, on the other hand, the asymmetric contribution can dominate the number density after the dark matter annihilation than the symmetric component. Such a scenario is called the asymmetric dark matter (ADM) (see [7–9] for review). The ADM scenario is motivated to explain the so-called baryon-dark matter coincidence puzzle, i.e., the observed closeness of the mass densities of dark matter and the baryon. If independent mechanisms produce the dark matter and the visible matter in the early Universe, it is puzzling why those abundances are close with each other even though the contribution from the matter-antimatter asymmetry dominates the baryon abundance. In the ADM scenario, the number densities of the dark matter and the visible matter correlate with each other. Thus, the baryon-dark matter coincidence puzzle can be solved if there is an appropriate relation between the dark matter mass and the baryon mass. The mass of the ADM is in the $O(1)$ GeV range if the matter-antimatter asymmetries in the dark and the visible sectors have the same origin and are close with each other.

2.2 Feeble Interaction

Another well-discussed approach to make the dark matter candidates stable is to assume a particle with feeble interactions to other particles. A feeble coupling highly suppresses the decay rate of the particle, and hence, its lifetime can be longer than the Universe. This approach is particularly successful for a very light dark matter, since the decay rate is also suppressed by its mass additionally. The best examples of such dark matter candidates are the QCD axion (see [10] for review) and the axion-like particles, including the Fuzzy dark matter [11]. The axion(-like) particle appears as a pseudo-Goldstone particle in physics beyond the Standard Model. There, interactions and mass are suppressed by the energy scale of new physics, which naturally provides a feebly interacting very light particle.

The mass density of the axion(-like) dark matter comes from the coherent oscillation of the axion(-like) field whose initial condition is given by misaligned from its potential minimum. Among them, the QCD axion is highly motivated since it also solves the strong-CP problem. The mass of the QCD axion, which provides the observed dark matter density via the misalignment mechanism, is roughly given by $m_a \sim 6\,\mu\text{eV}\times(10^{12}\,\text{GeV}/f_a)$, where f_a is the axion decay constant.

Another mechanism to explain the observed dark matter density for feebly interacting dark matter is the so-called freeze-in mechanism. In this case, the dark matter particle is not necessarily very light, unlike the axion-like dark matter, and it is called the feebly interacting massive particle (FIMP) (see [12] for review). In this mechanism, the FIMP never attained thermal equilibrium with the thermal bath of the Standard Model. Still, it continues to be produced from the thermal bath until the temperature becomes lower than the FIMP mass. As in the case of the WIMP, the FIMP abundance is independent of the initial condition and is determined by the properties of the interactions between the FIMP and the Standard Model particles.

The sterile neutrino is another example of the feebly interacting particle (see, e.g., [13] for review). The sterile neutrino has a tiny mixing with the neutrinos in the Standard Model. With the tiny mixing, the lifetime of the sterile neutrino can be much longer than the age of the Universe. As an interesting feature of the sterile neutrino, the neutrino oscillation from the neutrinos in the Standard Model can produce it. The sterile neutrino produced by the (resonant) oscillation mechanism explains the observed dark matter density when its mass is in the keV range.

2.3 Primordial Black Hole

Besides the above possibilities, it is also interesting to note the stability of dark matter due to its "super-heaviness". The Schwarzschild radius of a point-like particle heavier than the reduced Planck mass, $M_{\text{Pl}} \simeq 2.4 \times 10^{18}$ GeV, is larger than its Compton length. Such an object is called the primordial black hole (PBH), which is, for example, formed in the early Universe by a large density fluctuation made by cosmic inflation [14]. As the black hole evaporates by the Hawking radiation with the Hawking temperature, $T \sim M_{\rm Pl}^2/m_{\rm DM}$, the lifetime is longer for a heavier PBH. The PBH lifetime becomes longer than the age of the Universe for $m_{\rm DM} \gg 10^{38}$ GeV.

In the case where a large density fluctuation made by cosmic inflation causes the PBH formation, the mass of the PBH is given by the timing at which the $O(1)$ fluctuation enters the Hubble Horizon after inflation. The number density of the PBH is, on the other hand, determined by the probability to have the $O(1)$ density fluctuation. So far, a wide range of the PBH dark matter mass has been tested by astrophysical surveys, which has narrowed the mass range down to $M_{\rm PBH} \sim 10^{-(12-14)} \times M_{\odot}$.

3. Summary

In this short review, we gave an overview of the dark matter models and classified them based on the reasons of its stabilities. The above discussion covers only a tiny fraction of the possibilities, and so far, a plethora of dark matter candidates with various properties have been proposed. n particular, the properties of the self-interaction of dark matter are also important aspects to classify the models (see, e.g., [16] for review). To uncover the nature of dark matter is one of the most important challenges of particle physics and cosmology of this century. Dark matter is a gateway to new physics, and its identification will be an important milestone in our understanding of the fundamental laws of the Universe.

Disclaimer: the list of references is by far incomplete and only provides the readers with a few keys to the literature.

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