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Unconventional dark matter models: a brief review

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Abstract Although weakly interacting massive particle (WIMP) scenario is very well motivated, it is not guaranteed to be the truth. It is important to keep mind open and consider other well-motivated scenarios. In this paper, we briefly review several possible non-WIMP dark matter (DM) candidates. First, we discuss details on asymmetric DM models, in which the baryon asymmetry in standard model sector is related to the asymmetry in DM sector. We discuss how DM relic abundance is determined in such models. Also we cover the possible interesting experimental signatures induced by its asymmetric nature. Then we consider ultralight DM candidates, i.e., axion and dark photon. In such scenarios, DM should be treated as a coherently oscillating background, instead of each individual particle. Searching strategies for such DM candidates is very different than those in conventional DM models. We discuss several interesting experiments looking for these ultralight particles. We also cover interesting subtleties encountered in those experiments.

Keywords Dark matter model · Weakly interacting massive particle (WIMP) · Ultralight DM candidates · Standard model · Axion · Dark photon

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1 Introduction

Weakly interacting massive particle (WIMP) is the best studied dark matter scenario. It is highly motivated since it naturally predicts correct relic abundance. The mass of the dark matter (DM) particles coincides with electroweak symmetry breaking (EWSB) at which one generically expects the appearance of new physics in order to solve gauge hierarchy problem. WIMP scenario has been studied from various prospects experimentally. Several underground direct detection experiments are aiming to look for DM-nucleon/DM-electron elastic scattering. On the other hand, DM annihilation or decay can induce high-energy cosmic ray, such as gamma photons, electrons/positrons, protons/antiprotons. These may be measured by space satellites or ground telescopes. Finally, DM particles may be produced in high-energy colliders, such as the LEP, the LHC or the proposed future high-energy collider [1, 2]. Once produced, they can escape the detectors and contribute as missing energy in the event. Mono-jet and mono-photon channels may thus probe DM sector.

Various searches have been carried out in long time with large amount of efforts devoted. However, most of them return null results. Few of them exhibit anomalies, such as Ref. [3], which may indicate the signal of DM. However, none of them is conclusive, and it is hard to make a definitive claim on the discovery of DM rather than background caused by SM physics.

Although WIMP is a well-motivated scenario, it is not guaranteed to be the nature of DM. So far, the only concrete evidences of DM come from its gravitational effects and it would be important to keep one's mind open. There are several other choices of well-motivated DM candidates. In some of those "unconventional" scenarios, there could be additional signatures beyond the standard DM searches mentioned above. Interestingly, in some of the cases, all conventional DM searches are not suitable and one has to design new experiments instead.

In this short article, we are going to briefly review several other plausible DM candidates. We start with asymmetric DM scenario where the baryon asymmetry in the standard model sector is shared in the DM sector. Then we focus on the possibilities where DM particles are extremely light. The typical examples for such DM candidates are axion and dark photon.

2 Asymmetric dark matter

It is well known that the energy density of DM and that of baryonic matter is comparable, i.e., $\rho_{\rm DM}/\rho_{\rm B} \sim 5$. In WIMP scenario, the energy density of DM is set by the competition between annihilation rate and Hubble expansion. In the meanwhile, the energy density in the baryon sector is set by the complicated processes of baryogenesis. There is no logical reason intrinsically on why such two different mechanisms give comparable energy densities in the Universe.

Asymmetric DM scenario [4–13], on the other hand, links the asymmetry in baryonic sector to DM sector. This is a particularly interesting scenario and we are going to cover some of its important aspects in this paper. For more comprehensive reviews of asymmetric DM models, please see Refs. [14, 15]. Assuming the symmetric part of DM sector efficiently annihilates away, the asymmetry in the DM sector sets the energy density. The way to determine the DM energy density is a direct analogue to what happens in the baryonic sector, and the energy density of the DM sector is not set by DM annihilation cross section anymore.

The asymmetry in the DM sector is related to the asymmetry in the baryonic sector, i.e., $\Delta n_{\rm DM} \sim \Delta n_{\rm B}$. Thus DM mass is expected to be $O(1)$–$O(10)$ GeV , which is a concrete prediction in ADM models (We emphasize here that this prediction is only correct in the simplest version of ADM models. There can be several ways to get around this prediction). The existing ADM models generally fall into two categories, depending on how the asymmetry in the DM sector is related to the baryonic asymmetry:

(1) An asymmetry is firstly generated in either visible or DM sector, then the asymmetry is transferred to the other sector. The transfer process can either be through chemical equilibrium or electroweak sphalerons process. In this scenario, the baryon/lepton number asymmetry stored in the DM sector shares the same sign with that in the SM sector.

(2) The asymmetries in visible and DM sectors can be simultaneously generated via non-equilibrium *CP*-violating dynamics. In contrast to the previous scenario, the baryon/lepton number asymmetry stored in the DM sector is usually opposite to that in the SM sector.

To make physics picture more clear, let us provide one concrete example for each scenario. For the first scenario, we show an example where asymmetry is previously generated and gets transferred between SM and DM sectors through chemical equilibrium. To achieve the chemical equilibrium between DM and SM sectors, one can write an operator, either renormalizable or non-renormalizable, which couples the SM sector to the DM sector [13], i.e.,

$$\mathscr{L} \supset \frac{1}{M^n}\mathcal{O}_{\rm SM}\mathcal{O}_{\rm DM}, \tag{1}$$

where $\mathcal{O}_{\rm SM}$ is a combination of SM fields which is a gauge singlet under SM gauge groups but carries nonzero $(B-L)$ number. For example, $\mathcal{O}_{\rm SM}$ can be $u^c d^c d^c$, qld^c, lle^c or lH. Assuming DM sector is simple, there is only one component of DM, e.g., X, then $\mathcal{O}_{\rm DM}$ can be written as X^m.

In the early time of the Universe, the temperature can be extremely high. The process described by operators in Eq. (1) can induce the chemical equilibrium between DM and SM sectors. If the $(B-L)$ asymmetry has already been introduced in either DM or SM sector, such chemical equilibrium processes will transfer the asymmetry from one sector to the other.

The sphalerons during electroweak phase transition violate $(B+L)$ but preserve $(B-L)$. The effects from electroweak sphalerons have been studied in details. The baryon asymmetry is related to the asymmetry in $(B-L)$ as

$$\frac{B}{B-L} \sim 0.3. \tag{2}$$

To make concrete predictions on the DM mass in order to achieve correct DM relic abundance, one has to specify many details in the model, for example the $(B-L)$ charge of the DM particle, the field content in SM sector, as well as when the DM sector chemically decouples from the SM sector. However, these aspects usually contribute an order one prefactor to the result. Thus the DM mass in ADM models is generically predicted to be $O(1)$–$O(10)$ GeV.

Now let us introduce a typical benchmark model for the second scenario where the asymmetries in the SM and DM sectors are opposite and generated simultaneously through non-equilibrium processes. Suppose we start with the following Lagrangian [16]:

$$\mathscr{L} \supset \frac{\lambda_a}{M^2}\bar{X}_a \bar{u}^c_{\rm R}\bar{d}^c_{\rm R}\bar{d}^c_{\rm R} + \xi_a \bar{X}_a \Psi^c \Phi^* + h.c., \tag{3}$$

where a runs from 1 to 2. There is a physical *CP*-violating phase, $\arg(\lambda_1^* \lambda_2 \xi_1 \xi_2^*)$, which cannot be rotated away. X_1