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Asymmetric Dark Matter in the shear-dominated universe

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ABSTRACT

We explore the relic abundance of asymmetric Dark Matter in shear-dominated universe in which it is assumed the universe is expanded anisotropically. The modified expansion rate leaves its imprint on the relic density of asymmetric Dark Matter particles if the asymmetric Dark Matter particles are decoupled in shear dominated era. We found the relic abundances for particle and anti-particle are increased. The particle and anti-particle abundances are almost in the same amount for the larger value of the shear factor x_e which makes the indirect detection possible for asymmetric Dark Matter. We use the present day Dark Matter density from the observation to find the constraints on the parameter space in this model.

1. Introduction

In addition to the Wilkinson Microwave Anisotropy Probe (WMAP) data [1], the Planck mission provided the value of the Dark Matter relic density with high precision recently [2]. Planck 2015 data gives the present cold Dark Matter relic density as

$$\Omega_{\rm DM}h^2 = 0.1199 \pm 0.0022\,, \tag{1}$$

where $h = 0.673 \pm 0.098$ is the present Hubble expansion rate in units of 100 $\mathrm{km\,s^{-1}\,Mpc^{-1}}$ [2].

Although there are strong evidences for the existence of Dark Matter, the nature of the Dark Matter is still not known. The usual assumption is that the neutral, long-lived or stable Weakly Interacting Massive Particles (WIMPs) are the best motivated candidates for Dark Matter. Neutralino is one example which is appeared in supersymmetry and it is Majorana particle for which its particle and anti-particle are the same. However, there are other possibilities that the Dark Matter can be asymmetric which means the particles and anti-particles are distinct from each other if the particles are fermionic [3,4].

The relic density of asymmetric Dark Matter in the standard cosmological scenarios and non-standard cosmological scenarios like quintessence, scalar-tensor and brane world cosmological scenarios are discussed in [5–10]. In nonstandard cosmological scenarios, the Hubble expansion rate is changed comparing to the standard cosmological scenario. If the asymmetric Dark Matter particles decay during the era in which the expansion rate is changed, both the Dark Matter particle and anti-particle abundance are affected by the modification.

The particle and anti-particle abundances are determined by solving the Boltzmann equations which are the evolution equations of the particles and anti-particles in the expanding universe. Several nonstandard cosmological models [7–10] discussed the effect of the modified expansion rate on the relic density of asymmetric Dark Matter. The characteristic of the nonstandard cosmological models which are discussed in [7–10] is the increase of the particle and anti-particle abundance due to the increased Hubble expansion rate. In nonstandard cosmological scenarios, for appropriate annihilation cross section, the deviation of the abundance between the particle and anti-particle are not large. For asymmetric Dark Matter, in the beginning we assume there are more particles than the anti-particles; in the end the anti-particles are completely annihilated away with the particles and there are no anti-particles left. This makes the indirect detection is impossible for asymmetric Dark Matter in the standard cosmological scenarios. However, it is changed for non-standard cosmological scenarios. The increased annihilation rate for particle and anti-particle provides us the possibility that the that the asymmetric Dark Matter can be detected indirectly.

One of the interesting nonstandard cosmological model is the Bianchi type I model in which it is assumed the expansion of the universe is not isotropic. In this model the effects of the anisotropy on the expansion rate of the universe is quantified by an anisotropy-energy density which decreases as R^{-6} [11–13]. In [14,15], the authors investigated the relic abundance of Dark Matter in Bianchi I cosmological model. In this paper we extend the discussion of [14,15] to the asymmetric Dark Matter case. We in-

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vestigated how the abundance of asymmetric Dark Matter particles can be affected if the asymmetric Dark Matter particles are decayed in shear-dominated universe. We discuss in detail the relic density of asymmetric Dark Matter in shear-dominated universe and then use the present Dark Matter density from the observation to find the constraints on the parameter space in shear-dominated model.

The arrangement of the paper is following. In section 2, we review the shear-dominated universe. The asymmetric Dark Matter relic density is discussed both in numeric and analytic way in shear-dominated universe in section 3. In section 4, the constraints on the parameter space of shear-dominated universe are obtained using the observed Dark Matter relic density. The conclusion and summary are in the final section.

2. Review of the shear-dominated universe

In this section, we review the shear-dominated universe. In the standard cosmological scenario, it is assumed that the universe is isotropic and homogeneous. However before Big Bang Nucleosynthesis (BBN), there is no evidence which shows that the universe should be homogeneous or isotropic. One of the nonstandard cosmological scenarios is Bianchi type I model which is homogeneous but anisotropic cosmological model [11–13]. The expansion rate in this scenario is

$$H^2 = \frac{8\pi G}{3}(\rho_r + \rho_s), \tag{2}$$

where $G = 1/(8\pi M_{\rm Pl}^2)$ with $M_{\rm Pl} = 2.4\times 10^{18}$ GeV, $\rho_r = \pi^2 g_* T^4/30$ is the radiation energy density, here g_* is the effective number of the relativistic degrees of freedom. ρ_s is the shear energy density which is defined to be

$$\rho_s \equiv \frac{1}{48\pi G}[(H_1 - H_2)^2 + (H_1 - H_3)^2 + (H_2 - H_3)^2], \tag{3}$$

where $H_i \equiv \dot{R}_i/R_i$ are the expansion rates for the three principal axes with R_i being the scale factors of the three principal axes of the universe. It is derived that shear energy density is proportional to $\rho_s \propto \bar{R}^{-6}$ [14]. Here $\bar{R}$ is the mean-scale factor as $\bar{R} = V^{1/3}$ with $V = R_1 R_2 R_3$. We need explicit expression for the expansion rate to calculate the asymmetric Dark Matter relic density in this model. Using the conservation of the entropy per co-moving volume $g_* \bar{R}^3 T^3 = $ const, the shear-energy density is expressed as $\rho_s \propto g_*^2 T^6/$const. It is defined at temperature T_e, $\rho_r = \rho_s$. The universe is shear dominated when $T \gg T_e$, in which $H \propto \bar{R}^{-3}$ and $\bar{R} \propto t^{1/3}$; when the temperature falls well below T_e as $T \ll T_e$, the universe is radiation dominated, here the expansion rate $H \propto \bar{R}^{-2}$ and $\bar{R} \propto t^{1/2}$. In terms of the radiation-energy density, the shear-energy density can be written as

$$\rho_s = \rho_r \left[\frac{g_* T^2}{g_*^e T_e^2}\right], \tag{4}$$

where g_*^e is the value of g_* at T_e. The shear-energy density must be sufficiently small in order not to conflict with the successful prediction of BBN. BBN imposed the bounds on $T_e \geq 2.5$ MeV. Then the total energy density in shear dominated universe is

$$\rho = \rho_r + \rho_s = \frac{\pi^2}{30} g_* T^4 \left[1 + \frac{g_* T^2}{g_*^e T_e^2}\right] \tag{5}$$

Finally the modified expansion rate is

$$H = \frac{\pi m_\chi^2}{M_{\rm Pl}\, x^2}\sqrt{\frac{g_*}{90}\left(1 + \frac{x_e^2}{x^2}\right)}, \tag{6}$$

where $x = m_\chi/T$ with m_χ being the mass of Dark Matter particles and the shear factor x_e is defined to be

$$x_e \equiv \frac{m_\chi}{T_e}\left[\frac{g_*}{g_*^e}\right]^{1/2}. \tag{7}$$

3. Freeze-out of asymmetric Dark Matter in shear-dominated universe

The modified Hubble expansion rate has affects on the relic density of asymmetric Dark Matter in shear-dominated universe. In this section we investigate to what extent the relic density of asymmetric Dark Matter is affected if the asymmetric Dark Matter particles freeze-out in shear-dominated era. Dark Matter relic density is obtained by solving the following Boltzmann equations for particle and anti-particle which are written with the modified expansion rate as

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle\sigma_{\chi\bar{\chi}} v\rangle(n_\chi n_{\bar{\chi}} - n_{\chi,\rm eq} n_{\bar{\chi},\rm eq});$$
$$\frac{dn_{\bar{\chi}}}{dt} + 3Hn_{\bar{\chi}} = -\langle\sigma_{\chi\bar{\chi}} v\rangle(n_\chi n_{\bar{\chi}} - n_{\chi,\rm eq} n_{\bar{\chi},\rm eq}), \tag{8}$$

where χ is the Dark Matter particle which is *not* self-conjugate, i.e. the anti-particle $\bar{\chi} \neq \chi$. In our work, we assumed that only $\chi\bar{\chi}$ pairs can annihilate into Standard Model (SM) particles. Therefore $\langle\sigma_{\chi\bar{\chi}} v\rangle$ is the thermal average of the cross section of the annihilating particles χ and anti-particles $\bar{\chi}$ multiplied with the velocity of the annihilating particles. Here n_χ and $n_{\bar{\chi}}$ are the number densities of particle and anti-particle and their equilibrium values are $n_{\chi,\rm eq} = g_\chi\, (m_\chi T/2\pi)^{3/2} e^{(-m_\chi + \mu_\chi)/T}$ and $n_{\bar{\chi},\rm eq} = g_\chi\, (m_\chi T/2\pi)^{3/2} e^{(-m_\chi - \mu_{\bar{\chi}})/T}$. Here we assume that the asymmetric Dark Matter particles were non-relativistic at decoupling. μ_χ, $\mu_{\bar{\chi}}$ are the chemical potential of the particle and anti-particle, $\mu_{\bar{\chi}} = -\mu_\chi$ in equilibrium.

We follow the same method as in [6] and obtain the number densities for particle and anti-particle in shear-dominated universe. We assume the asymmetric Dark Matter particles χ and $\bar{\chi}$ were in thermal equilibrium when the temperature is high in the early universe. When $T \leq m_\chi$, the equilibrium values of the number densities $n_{\chi,\rm eq}$, $n_{\bar{\chi},\rm eq}$ decrease exponentially for $m_\chi > |\mu_\chi|$. Later the interaction rates for particle $\Gamma = n_\chi \langle\sigma_{\chi\bar{\chi}} v\rangle$ and anti-particle $\bar{\Gamma} = n_{\bar{\chi}} \langle\sigma_{\chi\bar{\chi}} v\rangle$ drop below the expansion rate H. This process leads to the decoupling of the particles and anti-particles from the thermal bath and the co-moving number densities are almost fixed from that inverse-scaled freeze-out temperature x_F.

The Boltzmann equations (8) can be rewritten in terms of the dimensionless quantities $Y_\chi = n_\chi/s$, $Y_{\bar{\chi}} = n_{\bar{\chi}}/s$ and $x = m_\chi/T$, where $s = (2\pi^2/45) g_* T^3$ is the entropy density. Inserting Eq. (6) to the Boltzmann equations (8), then

$$\frac{dY_\chi}{dx} = -\frac{\lambda\langle\sigma_{\chi\bar{\chi}} v\rangle}{x\sqrt{x^2 + x_e^2}}\,(Y_\chi\, Y_{\bar{\chi}} - Y_{\chi,\rm eq}\, Y_{\bar{\chi},\rm eq}); \tag{9}$$

$$\frac{dY_{\bar{\chi}}}{dx} = -\frac{\lambda\langle\sigma_{\chi\bar{\chi}} v\rangle}{x\sqrt{x^2 + x_e^2}}\,(Y_\chi\, Y_{\bar{\chi}} - Y_{\chi,\rm eq}\, Y_{\bar{\chi},\rm eq}), \tag{10}$$

where $\lambda = 1.32\, m_\chi M_{\rm Pl}\sqrt{g_*}$. Combining these two equations (9), (10), we obtain

$$Y_\chi - Y_{\bar{\chi}} = \varepsilon, \tag{11}$$

here ε is constant. Then the Boltzmann equations (9) and (10) become