Constraints on the model of dark matter with Coulomb-like interaction explaining positron anomaly

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Abstract. The models of self-interacting dark matter (DM) are popular now, in particular dark matter with Coulomb-like interaction. It leads to enhancement of annihilation in Galaxy what helps to explain cosmic ray puzzles, e.g. positron anomaly. Though such models get constraints from cosmic microwave background (CMB), large scale structure. The constrained region of model parameters can be essentially enlarged if to take into account possibility of much stronger enhanced annihilation of dark matter particles due to their recombination accounted for by a classical dipole radiation. The given constraints are considered for dark disk model with self-interaction.

1. Introduction

The models of self-interacting dark matter (SIDM) became very popular in the last time (e.g. [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]). Such models may avoid several problems of cold dark matter (CDM) scenario [1, 2, 12], such as predicted excess of dwarf galaxies and cuspy density profile in them, the problems with rotation curve and so called "too-big-to-fail". All these problems could be resolved due to collisions of SIDM particles during large scale structure formation. There can be alternative solution for aforementioned problems with SIDM when it becomes "warm" due to heating from a thermal background of the mediators ($y$-photons) of dark interaction ($y$-background). Warm DM may also avoid copious formation of dwarf galaxies and other CDM problems. But one should care here not to get heated so much to become "hot" (i.e. to prevent formation of greater size galaxies). It may restrict the model.

SIDM can have more advantages in implications to cosmic rays (CR). Positron anomaly in CR can be explained with annihilation of DM in Galaxy. If DM has a thermal origin in early Universe then annihilation cross section should be enhanced in Galaxy to provide observed CR excess. It can be done with the help of Gamow-Sommerfeld-Sakharov (GSS) enhancement [27, 28, 29, 30] accounted for by long-range interaction of DM particles. Also one can suppose that DM annihilation has a narrow resonance [31] with long-range ($U(1)$-gauge) interaction being involved, or some other model scenarios. However, such attempts face the problem with excess of gamma-flux over observed gamma-ray background, and model with GSS-effect are also constrained by Cosmic Microwave Background (CMB) data [32].

We suggested a dark disk model [17, 18, 19, 20, 21, 22] to avoid both constraints. It is based on assumption that some fraction of DM, which annihilate or decay, is concentrated in galactic
disk. It allows to suppress gamma. Here we combine this hypothesis with that on Coulomb-like self-interaction (y-interaction), so test a self-interacting dark matter disk model. One more important ingredient of our consideration is a recombination of DM particles due to a classical dipole radiation [23, 24], which is found to be much stronger than that considered on common quantum level. It may change drastically description of such DM and, as a consequence, the constraints on it.

Our current consideration can be applied to other DM models with long-range interaction.

2. Building model and analysis

We need to get in Galaxy two components of DM: the dominant "passive" component and small "active" one concentrating in galactic disk. To realize this one can suppose that we have SIDM consisted of particles $a$, $b$, $\tilde{a}$, $\tilde{b}$ possessing Coulomb-like interaction with different amounts of particles and antiparticles. Particles $a$ and $b$ are assumed to have opposite $y$-charges.

Dark disk must make up $\lesssim 10^{-3}$ of all DM in order not to contradict observations. This limit follows from upper limit on the dark disk density ($\lesssim 0.4 \text{ GeV/sm}^3$) and (our best fit) disk size $\sim 0.4 \text{ kps}$ [17].

We assume that $a$ particles are heavier, have such an initial asymmetry between $a$ and $\tilde{a}$ that in modern epoch $a$ constitutes dominant component of dark matter in the form of bound states and small fraction of $aa$ pairs survived in free states. Particles $b$ and $\tilde{b}$ can be supposed to have the same amounts, i.e. $n_b = n_a$, $n_{\tilde{b}} = n_{\tilde{a}}$. Given so, we expect that the most of $a$ compose bound states with $b$ giving "passive" halo component; remained unbound $a$ and $\tilde{a}$ form dissipative ("active") component of dark disk. Modern number of free $\tilde{b}$ should be strongly suppressed (negligible), since they are light and annihilate with $b$ through recombination faster.

Particles $a$ and $\tilde{a}$ in dark disk annihilate producing fluxes in cosmic rays therefore mass of $a$ is chosen $\sim 400 \text{ GeV}$ to explain positron anomaly. The mass of lighter particle $b$ is to be adjusted to obtain sufficiently compact $ab$-atoms and prevent $\tilde{a}$ annihilation with $a$ due to higher $ab$-recombination cross section.

Important feature of evolution $a$, $b$, $\tilde{a}$, $\tilde{b}$-system is their recombination in two regimes in dependence which approximation works. If common quantum approximation is valid then recombination is slow, and it becomes fast at lower velocity (later in cosmological evolution) when classical approximation is switched on [23]. These two approximations are given by different cross sections of recombination. In quantum case it is (see, e.g. [23, 25])

$$
\sigma = \frac{32 \pi \alpha_y^3 \ln(v^{-1})}{3\sqrt{3} \mu^2 v^2},
$$

and in classical one

$$
\sigma = (4\pi)^{2/5} \frac{\alpha_y^2}{\mu^2} \frac{1}{v^{14/5}}.
$$

Here $\mu$ is the reduced mass of recombining particles, $v$ is their relative velocity, $\alpha_y$ is the $y$-interaction constant. Classical cross section is much bigger than the given quantum one. It is especially worth to note that quantum formula (1) includes enhancing GSS factor. So "classical" recombination is very fast. It is assumed to be on when [23, 25]

$$
v \ll \alpha_y^{5/2},
$$
i.e. at low velocities.

The choice of model parameters (constant $\alpha_y$, the mass of $b$ particle and initial asymmetries) allows to regulate switching on "strong recombination" in different moments. One can obtain the case of "strong recombination" of $aa$-pairs with immediate successive annihilation inside dark galactic disk, where their velocity can be very low ($\lesssim 50 \text{ km/c}$).
Figure 1. Contour plot for $\log_{10}(j/j_{\text{teor}})$ in dependence of $\alpha_y$ and $m_b$ for $M_a = 500$ GeV (left) and 1 TeV (right) with the CMB constraints and HDM constraints. Excluded are the regions above line “HDM” and below line “CDM”.

In all cases of interest classical approach becomes applicable after the moment when $ab$-particles decouple from $y$-background. Starting with this moment $a,b$-particles cool faster and condition (3) comes soon.

Calculations are done following work [23]. Aforementioned initial parameters are set here at the moment when condition (3) is reached. Modern fraction of free $a\bar{a}$ is not obtained to be bigger than $10^{-6}$.

While such a self-interacting dark disk model is built, one needs to consider different constraints. We must not contradict observational data on the anisotropy of the CMB and prevent for DM to be hot (HDM). For the first, we can outline the region of parameters DM particle mass (of $b$) and $\alpha_y$ for which the value of $\sigma/m$ satisfies the CMB constraint [26]. For the second, we require that the temperature of CMB, at which DM particles are decoupled from $y$-background, was $T_{\text{dec}} > 5$ keV. Until DM particles are coupled to the relativistic background they wash out all the inhomogeneities which smaller the current horizon due to Silk dumping [33]. If it exceeds the galaxy scale, DM is hot and forbidden. When temperature $T_{\text{dec}} \sim 5$ keV horizon corresponds to modern galaxy scale.

As to explanation of positron anomaly, we obtained [17] that in the framework of dark disk model it requires for emissivity value to be $j_{\text{teor}} \equiv \frac{1}{2} n_a n_{\bar{a}} < \sigma v >= 1.4 \cdot 10^{-19} \text{cm}^{-3}\text{s}^{-1}$ within factor 3 (we assume that the probability of annihilation in the “visible” particles is 1).

In Fig. 1 you can see the contour plot for emissivity $j$ in terms of the $j_{\text{teor}}$ for two values of $a$ particle mass $M_a$ with the CMB and HDM constraints. Contour line with label ”0” is of our interest. But as one can see, two constraints (CMB and HDM) exclude all $j$ values (at any $m_b$ and $\alpha_y \gtrsim 10^{-5} j_{\text{teor}}$, what makes impossible explanation of positron anomaly. This conclusion is obtained when classical approximation (2) is valid. For galactic velocity it approximately corresponds to $\alpha_y \gtrsim 10^{-6}$, i.e. low borders of the plots in Fig. 1.
3. Conclusion
Dark disk model was suggested to explain positron anomaly. It could be realised assuming that DM possesses Coulomb-like interaction. In this case such model can avoid existing problems of standard CDM scenario. We built here some variant of such self-interacting dark matter disk model, introducing two species if DM particles (a and b) and their antiparticles. We have shown that two types of constraints, coming from CMB and HDM abundance, exclude parameter region where positron anomaly can be explained.

Acknowledgments
The work fulfilled in the framework of MEPhI Academic Excellence Project (contract № 02.a03.21.0005, 27.08.2013). The work of A. A. K. was supported by Russian Science Foundation (№ 15-12-10039). The work of K. M. B. was also funded by the Ministry of Education and Science of the Russia, Project № 3.6760.2017/BY.

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