Physics Letters B 771 (2017) 162–167

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Constraining dark photon model with dark matter from CMB spectral distortions

Ki-Young Choi [a], Kenji Kadota [b], Inwoo Park [c,b,*]

[a] Institute for Universe and Elementary Particles and Department of Physics, Chonnam National University, 77 Yongbong-ro, Buk-gu, Gwangju, 61186, Republic of Korea
[b] Center for Theoretical Physics of the Universe, Institute for Basic Science (IBS), Daejeon, 34051, Republic of Korea
[c] Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon, 34141, Republic of Korea

ARTICLE INFO

Article history:
Received 16 January 2017
Received in revised form 24 April 2017
Accepted 24 April 2017
Available online 19 May 2017
Editor: M. Trodden

Keywords:
Dark matter
Dark photon
CMB distortion

ABSTRACT

Many extensions of Standard Model (SM) include a dark sector which can interact with the SM sector via a light mediator. We explore the possibilities to probe such a dark sector by studying the distortion of the CMB spectrum from the blackbody shape due to the elastic scatterings between the dark matter and baryons through a hidden light mediator. We in particular focus on the model where the dark sector gauge boson kinetically mixes with the SM and present the future experimental prospect for a PIXIE-like experiment along with its comparison to the existing bounds from complementary terrestrial experiments.

1. Introduction

The energy spectrum of the cosmic microwave background (CMB) follows the most perfect blackbody spectrum ever observed. There yet can exist a minuscule deviation from the blackbody when the CMB photons are not in a perfect equilibrium. The number-changing interactions such as Bremsstrahlung and double Compton scatterings are not efficient enough for the redshift $z \lesssim 2 \times 10^6$ and the energy injection/extraction can result in the Bose–Einstein distribution with a non-vanishing μ parameter (rather than the blackbody distribution with $\mu = 0$) [1]. For $z \lesssim 5 \times 10^4$, even the kinetic equilibrium cannot be maintained due to the inefficient Compton scatterings and the spectrum distortion can be characterized by the Compton y-parameter which is given by the line of sight integral of electron pressure [2].

The attempt to measure potential CMB spectral distortion has been made by the Far Infrared Absolute Spectrophotometer (FIRAS) instrument aboard the COBE satellite [3] two decades ago, leading to the upper bounds $|\mu| \lesssim 10^{-4}$ and $|y| \lesssim 10^{-5}$. The next generation space-telescope PIXIE [4] is expected to improve the sensitivity to $|\mu| \sim 5 \times 10^{-8}$ and $|y| \sim 10^{-8}$.

The CMB spectral distortion can, for instance, be induced by the energy injection into the background plasma in many non-standard cosmological scenarios [5]. The examples include the energy release from decaying heavy relics [6,7], evaporating primordial black holes [8], the annihilating dark matter (DM) [9,10] and the dissipation of acoustic waves [11–13].

Even in the standard cosmology, however, the CMB distortion can occur due to the energy transfer between the photons and the "baryons" (protons and electrons) [5,14,15]. The Coulomb interactions of non-relativistic plasma consisting of baryons with photons can extract energy from the CMB and maintain the kinetic equilibrium. The temperature of baryons follows that of photons and decreases inversely proportional to the scale factor of the Universe, $T_b \simeq T_\gamma \sim 1/a$, instead of $1/a^2$ for the decoupled non-relativistic matter. This extraction of energy from the CMB results in the μ-distortion of the order of $\mu \simeq -3 \times 10^{-9}$.

The analogous effects can be induced when the DM is thermally coupled to the photon-baryon plasma by the elastic scatterings, and such effects on the CMB spectral distortions were first discussed in [16] and elaborated on in [17]. The additional energy extraction from CMB into DM enhances the spectral distortion of CMB with a negative μ. Since the DM number density is inversely proportional to its mass, for a given DM mass density, the FIRAS can constrain the DM mass up to $m_\chi \sim 0.1$ GeV and a fu-

* Corresponding author at: Department of Physics, Korea Advanced Institute of Science and Technology, Daejeon, 34141, Republic of Korea.
E-mail addresses: kiyoungchoi@jnu.ac.kr (K.-Y. Choi), kadota@ibs.re.kr (K. Kadota), inwpark@kaist.ac.kr (I. Park).

http://dx.doi.org/10.1016/j.physletb.2017.04.062

ture experiment such as PIXIE can further extend its sensitivity to $m_\chi \sim 1$ GeV. The CMB distortion measurements would complement the other heavy DM searches such as the direct detection experiments which rapidly lose the sensitivity to sub-GeV DM due to the small recoil energy of the nuclear target.

One of the intriguing models which can realize the coupling of the DM to the SM particles is a "dark photon" scenario where there exists a dark sector with a broken U(1) gauge symmetry [18,19]. The phenomenology associated with such a novel dark sector has received considerable attention in recent years and a wide range of experimental searches have been performed in the collider and beam dump experiments such as BarBar, PHENIX, E137 and Charm [20–25]. The constraints on the dark photon model from the cosmological and astrophysical observations have also been discussed recently [26,27].

In this paper, we study the spectral distortion of CMB in the dark photon model, where the DM and baryons can interact via a dark photon, caused by the momentum transfer between CMB and DM via the elastic scatterings. We also illustrate the comparison with the existing constraints on the dark photon model in the laboratory and astrophysical observations. We first review the model in §2 followed by the estimation of CMB distortions in §3. §4 gives our results, followed by the conclusion in §5.

2. Dark photon and DM

We consider the dark sector consisting of the dark photon and DM. We assume that $U(1)_d$ gauge symmetry in the dark sector has a kinetic mixing with $U(1)_Y$ in the SM of $SU(3)_C \times SU(2)_L \times U(1)_Y$ [18,19]. The mixing is parametrized by a small parameter ε as

$$\mathcal{L}_{mixing} = \frac{\varepsilon}{2}\hat{B}_{\mu\nu}\hat{Z}_d^{\mu\nu} \tag{1}$$

where $\hat{B}_{\mu\nu}$ and $\hat{Z}_{d\mu\nu}$ are the field strengths of $U(1)_Y$ and $U(1)_d$ respectively. We also assume that the fermion DM χ has the $U(1)_d$ gauge interaction with the gauge coupling g_d as

$$\mathcal{L}_{int} = -g_d \hat{Z}_{d\mu}\overline{\chi}\gamma^\mu\chi. \tag{2}$$

After the electroweak symmetry breaking, we replace $\hat{B}_{\mu\nu} = -s_W\hat{Z}_{\mu\nu} + c_W\hat{A}_{\mu\nu}$ with $s_W = \sin\theta_W$ and $c_W = \cos\theta_W$ and the mass of $\hat{Z}_{\mu\nu}$, m_Z^0, is generated from the Higgs mechanism. Similarly we assume that the hidden gauge boson has a mass $m_{Z_d}^0$ by $U(1)_d$ symmetry breaking through the hidden sector Higgs mechanism.

The kinetic mixings between the gauge fields can be removed and the kinetic terms can be canonically normalized by the following field re-definition

$$\begin{pmatrix} A_{SM\mu} \\ Z_\mu^0 \\ Z_{d\mu}^0 \end{pmatrix} = \begin{pmatrix} 1 & 0 & -\varepsilon c_W \\ 0 & 1 & \varepsilon s_W \\ 0 & 0 & \sqrt{1-\varepsilon^2} \end{pmatrix} \begin{pmatrix} \hat{A}_\mu \\ \hat{Z}_\mu \\ \hat{Z}_{d\mu} \end{pmatrix} \tag{3}$$

leading to

$$\begin{aligned}\mathcal{L} = &-\frac{1}{4}A_{SM\mu\nu}A_{SM}^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}^0 Z^{0\mu\nu} - \frac{1}{4}Z_{d\mu\nu}^0 Z_d^{0\mu\nu} \\ &+\frac{1}{2}{m_Z^0}^2 Z_\mu^0 Z^{0\mu} - {m_Z^0}^2\frac{\varepsilon s_W}{\sqrt{1-\varepsilon^2}}Z_\mu^0 Z_d^{0\mu} \\ &+\frac{1}{2}\left({m_Z^0}^2\frac{\varepsilon^2 s_W^2}{1-\varepsilon^2} + {m_{Z_d}^0}^2\frac{1}{1-\varepsilon^2}\right)Z_{d\mu}^0 Z_d^{0\mu}\end{aligned} \tag{4}$$

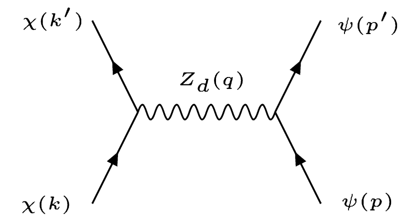

Fig. 1. Elastic scattering between baryon (ψ) and DM (χ) through a dark photon (Z_d) exchange.

The mass matrix of Z_μ^0 and $Z_{d\mu}^0$ can be diagonalized by a mixing parameter θ_X,

$$\begin{pmatrix} Z_{SM\mu} \\ Z_{d\mu} \end{pmatrix} = \begin{pmatrix} \cos\theta_X & -\sin\theta_X \\ \sin\theta_X & \cos\theta_X \end{pmatrix} \begin{pmatrix} Z_\mu^0 \\ Z_{d\mu}^0 \end{pmatrix} \tag{5}$$

where

$$\tan 2\theta_X = \frac{2{m_Z^0}^2\varepsilon s_W/\sqrt{1-\varepsilon^2}}{{m_Z^0}^2 - {m_Z^0}^2\{\varepsilon^2 s_W^2/(1-\varepsilon^2)\} - {m_{Z_d}^0}^2\frac{1}{1-\varepsilon^2}}. \tag{6}$$

The bare gauge fields are consequently related to the mass eigenstates as

$$\begin{aligned}\hat{A}_\mu &= A_{SM\mu} - \frac{\varepsilon c_W s_X}{\sqrt{1-\varepsilon^2}}Z_{SM\mu} + \frac{\varepsilon c_W c_X}{\sqrt{1-\varepsilon^2}}Z_{d\mu}, \\ \hat{Z}_{d\mu} &= -\frac{s_X}{\sqrt{1-\varepsilon^2}}Z_{SM\mu} + \frac{c_X}{\sqrt{1-\varepsilon^2}}Z_{d\mu}, \\ \hat{Z}_\mu &= \left(c_X + \frac{\varepsilon s_W s_X}{\sqrt{1-\varepsilon^2}}\right)Z_{SM\mu} + \left(s_X - \frac{\varepsilon s_W c_X}{\sqrt{1-\varepsilon^2}}\right)Z_{d\mu},\end{aligned} \tag{7}$$

where $s_X = \sin\theta_X$ and $c_X = \cos\theta_X$.

The electromagnetic current hence has the interaction

$$\mathcal{L}_{int} = -eJ_{em}^\mu\left(A_{SM\mu} - \frac{\varepsilon c_W s_X}{\sqrt{1-\varepsilon^2}}Z_{SM\mu} + \frac{\varepsilon c_W c_X}{\sqrt{1-\varepsilon^2}}Z_{d\mu}\right), \tag{8}$$

and the DM interacts with $Z_{d\mu}$ and Z_μ as

$$\mathcal{L}_{int} = -g_d\overline{\chi}\gamma^\mu\chi\left(\frac{c_X}{\sqrt{1-\varepsilon^2}}Z_{d\mu} - \frac{s_X}{\sqrt{1-\varepsilon^2}}Z_{SM\mu}\right). \tag{9}$$

We can therefore see that the electromagnetic current in the SM which couples to $\hat{A}_\mu$ can interact with the dark photon Z_d suppressed by ε. Since we are interested in the parameter range $m_{Z_d} \sim$ GeV $\ll m_Z$, we can represent our dark sector model with two free parameters ε and m_{Z_d} in the following sections. We hence discuss the CMB spectral distortions when the DM interactions with the SM fields ψ_{SM} are mediated by the dark photon, represented by the Lagrangian

$$\mathcal{L}_{int} = -e\varepsilon c_W\overline{\psi}_{SM}\gamma^\mu\psi_{SM}Z_{d\mu} - g_d\overline{\chi}\gamma^\mu\chi Z_{d\mu}. \tag{10}$$

The corresponding Feynman diagram is shown in Fig. 1. We note here that the DM does not interact with the SM photon and only couples to the SM particles by mediating Z_d gauge boson.[1]

3. CMB spectrum distortion from DM-baryon scattering

For the decoupled non-relativistic DM, the temperature decreases as $T_\chi \sim a^{-2}$ (a is the scale factor). When DM is kinetically

[1] The DM coupling to the SM Z is suppressed by $\tan\theta_X$ compared with that to dark photon and hence negligible in the limit of $m_{Z_d} \ll m_Z$ and a small ε.