

# Possible Effects of Dark Energy on the Detection of Dark Matter Particles

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(Dated: April 29, 2021)

## Abstract

We study in this paper the possible influence of the dark energy on the detection of the dark matter particles. In models of dark energy described by a dynamical scalar field such as the Quintessence, its interaction with the dark matter will cause the dark matter particles such as the neutralino vary as a function of space and time. Given a specific model of the Quintessence and its interaction in this paper we calculate numerically the corrections to the neutralino masses and the induced spectrum of the neutrinos from the annihilation of the neutralinos pairs in the core of the Sun. This study gives rise to a possibility of probing for dark energy in the experiments of detecting the dark matter particles.

Recent observational data from supernovae (SN) Ia [1] and cosmic microwave background radiation (CMBR) [2] strongly support for the ‘cosmic concordance’ model, in which the Universe is spatially flat with 4% baryon matter, 23% of cold dark matter (DM) and 73% of dark energy (DE). The baryon matter is well described by the standard model of the particle physics, however the nature of the dark matter and the dark energy remains unknown.

There have been many proposals in the literature for the dark matter candidates theoretically. From the point of view of the particle physics, the leading candidates for cold dark matter are the axion and the neutralino. Various experiments in the search directly or indirectly for these dark matter particles are currently under way.

Regarding dark energy, the simplest candidate seems to be a remnant small cosmological constant. However, many physicists are attracted by the idea that dark energy is due to a dynamical component, such as a canonical scalar field  $Q$ , named *Quintessence* [3]. Being a dynamical component, the scalar field of the dark energy is expected to interact with the other matters [4]. There are many discussions on the explicit couplings of quintessence to baryons, dark matter, photons and neutrinos. These interactions if exist will open up the possibilities of probing non-gravitationally for the dark energy. In this paper we consider the possible effects of the dark energy models which interact with the dark matter in the detection of the dark matter particles. Specifically we will study the influence of the dark energy on the neutralino masses in the Sun, and then calculate the neutrino spectrum annihilated from the neutralino pairs in the core of the Sun.

We start with a coupled system of the interacting dark energy and the dark matter with the Lagrangian generally given by

$$\mathcal{L}_{eff} = \mathcal{L}_{DM} + \mathcal{L}_{\phi} + \mathcal{L}_{int}, \quad (1)$$

where  $\mathcal{L}_{DM}$  and  $\mathcal{L}_{\phi}$  are the free Lagrangian for dark matter and dark energy and the interaction part is given by

$$\begin{aligned} \mathcal{L}_{int} = & -\frac{1}{2}M_{\chi}(\phi)\bar{\chi}\chi - M_{\psi}(\phi)\bar{\psi}\psi - \frac{1}{2}M_S^2(\phi)S^2 - \frac{g_{\chi}}{\Lambda}\partial_{\mu}\phi\bar{\chi}\gamma^{\mu}\gamma^5\chi \\ & - \frac{g_{\psi}}{\Lambda}\partial_{\mu}\phi\bar{\psi}\gamma^{\mu}\psi - \frac{g_S}{\Lambda}\partial_{\mu}\phi S\partial^{\mu}S - \frac{g'_S}{\Lambda}\phi\partial_{\mu}\phi\partial^{\mu}S - \sum \frac{g_i}{\Lambda^2}\mathcal{O}_i, \end{aligned} \quad (2)$$

where the dark matter particles could be the boson( $S$ ), Majorana fermion( $\chi$ ) and(or) Dirac fermion( $\psi$ ). In the detailed discussions below we will consider only the Majorana fermion

such as the neutralino to be the dark matter particle and focus on the interactions which affect the dark matter particles via the mass terms.

Being a function of the quintessence scalar  $\phi$  the mass of the dark matter particle will vary during the evolution of the universe. As shown in Refs. [5, 6, 7] this helps solve the coincidence problem. Furthermore, this type of interactions will affect the cosmic structure formation [8], and the power spectrum of CMB [9]. In this paper we will present a new possible effect of the interacting dark energy with the dark matter in the detection of the dark matter particles.

There are in general two different ways, direct and indirect, in the detections of the dark matter particles. The direct detection records the recoil energy of the detector nuclei when the dark matter particles scatter off them as they pass through the Earth and interact with the matter. The indirect detection observes the annihilation products by the dark matter particles. Obviously the expected detection rates depend on the mass of the dark matter particles. In the presence of the interaction the mass of the dark matter particle will vary as a function of time and also space, and consequently the dark energy will influence the detection.

To determine the mass of neutralino as a function of space we need to know the value of the dark energy scalar field as a function of space. Taking into account the back reaction of the interaction between the dark matter and the dark energy the effective potential of the dark energy scalar as a function of the energy density of the cold dark matter  $\rho_\chi(\phi)$  is given by

$$V_{eff} = \rho_\chi(\phi) + V(\phi). \quad (3)$$

For different dark matter densities the values of dark energy scalar field are expected to be different, and consequently the mass of dark matter particles will also be different. For example, the mass of the dark matter particle in the center of the Milky Way could be different from that in the halo near the solar system. Therefore, the gamma ray spectrum, or the synchrotron radiation spectrum, from the galactic center could be different from that in the nearby halo. Especially for the neutralino dark matter particle its mass measured at the future linear collider (LC) or the large hadron collider (LHC) on the Earth may be different from that measured in other places in the Milky Way, such as in the galactic center. Similarly, the spectrum of the dark matter radiation in the Milky Way might also be different from other galaxies in the local group.

In the following we will consider a specific model of the Quintessence and its interaction with the dark matter particle, the neutralino, and then study its effects on the indirect detection via the process of the neutralinos annihilation into neutrinos.

The dark energy potential which we take is

$$V(\phi) = V_0 e^{\beta\phi/m_p}, \quad (4)$$

and the interaction between the dark energy and the dark matter particle are given by

$$M_\chi(\phi) = M_{\chi_0} \left( 1 + \frac{\lambda_\chi \phi}{m_p} \right). \quad (5)$$

Here  $m_p$  is the reduced Plank mass,  $m_p = 2.436 \times 10^{18}$  GeV. We have numerically solved the evolution of the cosmological model with Quintessence potential (3). And our results show that the cosmological observations are satisfied with a suitable choice of the model parameters such as  $V_0 = 4.2 \times 10^{-47} \text{GeV}^4$ ,  $\beta = 1$  and  $\lambda_\chi = 0.1$ .

In addition to the interactions between the dark matter and the dark energy one expects also a coupling of the Quintessence scalar to the baryon <sup>1</sup> via for instance the quantum gravity effects

$$\mathcal{L}_{\phi qq} = -\lambda_B \frac{\phi}{m_p} (y_q \bar{Q}_L H q_R). \quad (6)$$

The parameter  $\lambda_B$  above characterizing the strength of this type of interaction will be shown below to be strongly constrained. However, since the baryon density inside the Sun is much higher than any other matter densities, this interaction in Eq. (6) will be important to our study in this paper as well as that on the neutrino oscillations [14, 17, 18].

The Eq. (5) shows that the mass of the dark matter particles varies during the evolution of the Universe. At the present time the mass of the neutralino dark matter particle is given by Eq. (5) with the scalar field  $\phi$  evaluated at the present time  $\phi_0$ . This type of physics associated with the mass varying dark matter particles have been proposed and studied in the literature [6, 9, 19], but in these studies the masses of the dark matter particle are constant in space. In this paper we consider the case that neutralino masses vary as a

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<sup>1</sup> The interactions between the dark energy scalar and the neutrinos have been considered in Refs. [10, 11, 12, 13, 14, 15, 16] and related implications of mass varying neutrinos have been studied in neutrino oscillations [14, 17, 18] and gamma ray burst [16].

function of space, for instance the neutralino mass in the Sun differs from that evaluated on the cosmological scale.

The effective potential of the dark energy scalar at the inner of the Sun or the Earth is given by

$$V_{eff} = \rho_B(\phi) + \rho_\chi(\phi) + V(\phi) , \quad (7)$$

where  $\rho_B(\phi)$  is the mass density of the baryon matter and  $\rho_\chi(\phi) = n_\chi M_\chi(\phi)$ . Here it's straightforward to obtain  $\rho_B(\phi) = \rho_{B_0} - \frac{\lambda_B \rho_{B_0} \phi}{m_p}$  from Eq. (6) in terms of the mass density of the baryon matter  $\rho_{B_0}$  in the absence of the interaction (6). We will show later that, by choosing an appropriate parameter  $\lambda_B$ ,  $\rho_B(\phi) \simeq \rho_{B_0}$  is a good approximation in the numerical discussion.

The value of  $\phi$  in the Sun can be obtained by requiring  $\phi$  be at the minimum of the local potential

$$\left. \frac{dV_{eff}}{d\phi} \right|_{\phi=\phi_{min}} = 0 . \quad (8)$$

The contributions to the equation above from the dark matter and baryon are proportional to  $\lambda_B \rho_B$  and  $\lambda_\chi \rho_\chi$  respectively. Since the  $\rho_\chi$  is about 15 orders of magnitude smaller than  $\rho_B$  in the core of the Sun [20], the influence of the dark matter on the effective potential of the dark energy scalar can be safely ignored if

$$\lambda_B \gg \lambda_\chi \frac{\rho_\chi}{\rho_B} \sim 10^{-15} \lambda_\chi , \quad (9)$$

which we will show can be satisfied generally. Given Eq. (8) we have for the value of  $\phi$

$$\phi_{min} = \frac{m_p}{\beta} \ln \frac{\lambda_B \rho_B}{\beta V_0} . \quad (10)$$

From Eqs. (5) and (10) we obtain the ratio of the masses of the dark matter particles in the Sun to that evaluated on the cosmological scale

$$\frac{M_\chi^\odot}{M_\chi^{cos}} = \frac{1 + \frac{\lambda_\chi}{\beta} \ln \frac{\lambda_B \rho_B^\odot}{\beta V_0}}{1 + \lambda_\chi \frac{\phi_0}{m_p}} . \quad (11)$$

In Eq. (11)  $\phi_0$  is the cosmological value of the scalar field at the present time. To satisfy the cosmological observations on the dark energy our numerical results show that  $\phi_0 = -0.51 m_p$ ,  $V_0 = 4.2 \times 10^{-47} \text{GeV}^4$  and  $\beta = 1$  and  $\lambda_\chi = 0.1$  which we have mentioned above.

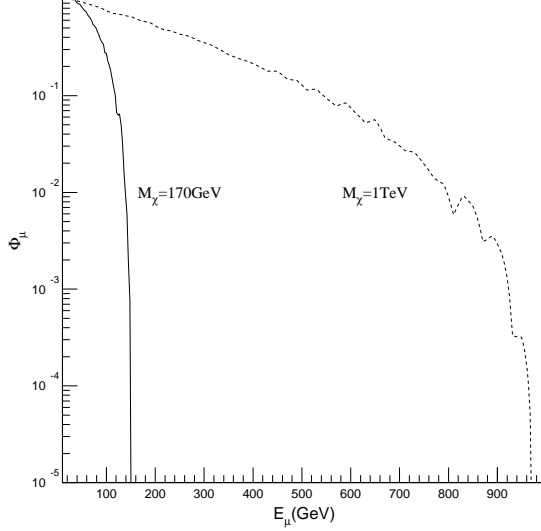


FIG. 1: Spectra of the muons induced by the neutrinos from the annihilation of the neutralino dark matter particles in the core of the Sun with  $m_\chi = 1$  TeV and in the cosmological scale with  $m_\chi = 170$  GeV. The spectra are normalized at 10 GeV and calculated by using the DarkSUSY package [23].

The baryon energy density of the Sun  $\rho_B^\odot$  is about  $2.5 \text{ g/cm}^3$ . However due to the logarithm in Eq. (10), the effect on the dark matter mass is insensitive to the baryon mass density  $\rho_B$ . For example, the baryon density in the Sun  $\rho_B^\odot$  is about a quarter of that in the Earth, which causes that  $M_\chi^\odot$  is about 2% smaller than the value at the Earth in our numerical calculation for  $\lambda_B = 10^{-9}$ .

The parameter  $\lambda_B$  is constrained by the tests on the gravitational inverse square law [21] and the tests on the equivalence principle [22] to be  $\lambda_B \lesssim \mathcal{O}(10^{-2})$ . Here we point out that the presence of the interaction of the dark energy with the baryon in Eq. (6) makes the baryon mass density also vary

$$\frac{\delta\rho_B}{\rho_B} = \frac{\rho_B(\phi_{min}) - \rho_{B0}}{\rho_B} = -\frac{\lambda_B}{\beta} \ln \frac{\lambda_B \rho_B}{\beta V_0}. \quad (12)$$

If taking  $\rho_B(\phi_{min})$  to be the baryon density in the Earth (which is similar to the baryon density of the Sun),  $\delta\rho_B(\phi_{min})$  indicates the correction of the dark energy to baryon mass in the Earth. The proton mass has been measured very precisely on the Earth with an error of  $10^{-8}$ . If we take as an example that  $\delta\rho_B/\rho_B < 10^{-8}$  we obtain an upper limit on  $\lambda_B$ ,  $\lambda_B < 10^{-9}$ , which we use in the numerical calculation.

Now we have  $\phi_{min} \simeq 49m_p$  and consequently  $M_\chi^\odot/M_\chi^{cos} \simeq 6$ . In Fig. 1 we plot the muon

spectra induced by the neutrino from the dark matter annihilation in the center of the Sun and in the cosmological scale. We choose the dark matter mass in the Sun to be 1 TeV, while the dark matter mass in the cosmological scale is about  $1\text{TeV}/6=170$  GeV. From the figure one can see clearly the difference in the neutrino spectra.

On the cosmological scale the dark energy scalar is homogeneously distributed, however in this case it is inhomogeneous, which gives rise to energy density  $\rho_\phi$  in the Sun. From Eqs. (4) and (10) we have

$$\frac{\rho_\phi}{\rho_B} \simeq \frac{V(\phi_{min})}{\rho_B} = \frac{\lambda_B}{\beta} . \quad (13)$$

For  $\lambda_B < 10^{-9}$  and  $\beta = 1$  we have  $\rho_\phi/\rho_B \sim 10^{-9}$  which shows that the dark energy density inside the Sun (or the Earth) can be safely ignored.

In summary, we have in this paper studied the possible effects of interacting dark energy on the detection of the dark matter particles. We have taken a specific model of Quintessence with an exponential potential and interacting with the dark matter mass term, and then discussed numerically the influence of the dark energy on the neutrino spectrum from the annihilation of the neutralino pairs in the Sun. Our results show the possibility of probing for the dark energy in the future experiments of searching for the dark matter particles.

### Acknowledgments

We thank Y. Chen, B. Feng and C. Huang for discussions. This work is supported in part by the NSF of China under the grant No. 10105004,10120130794,19925523, 90303004 and also by the Ministry of Science and Technology of China under grant No. NKBRSF G19990754.

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