Neutrino emission from dark matter annihilation/decay in light of cosmic $e^\pm$ and $\bar{p}$ data

Jie Liu$^a$, Qiang Yuan$^b$, Xiaojun Bi$^b$, Hong Li$^{a,c}$, and Xinmin Zhang$^{a,c}$

$^a$Theoretical Physics Division, Institute of High Energy Physics, Chinese Academy of Science, P.O.Box 918-4, Beijing 100049, P.R.China

$^b$Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Science, P.O.Box 918-3, Beijing 100049, P.R.China and

$^c$Theoretical Physics Center for Science Facilities (TPCSF), Chinese Academy of Science, P.R.China

A self-consistent global fitting method based on the Markov Chain Monte Carlo technique to study the dark matter (DM) property associated with the cosmic ray electron/positron excesses was developed in our previous work. In this work we further improve the previous study to include the hadronic branching ratio of DM annihilation/decay. The PAMELA $\bar{p}/p$ data are employed to constrain the hadronic branching ratio. We find that the 95% (2$\sigma$) upper limits of the quark branching ratio allowed by the PAMELA $\bar{p}/p$ data is $\sim 0.032$ for DM annihilation and $\sim 0.044$ for DM decay respectively. This result shows that the DM coupling to pure leptons is indeed favored by the current data. Based on the global fitting results, we further study the neutrino emission from DM in the Galactic center. Our predicted neutrino flux is some smaller than previous works since the constraint from $\gamma$-rays is involved. However, it is still capable to be detected by the forth-coming neutrino detector such as IceCube. The improved points of the present study compared with previous works include: 1) the DM parameters, both the particle physical ones and astrophysical ones, are derived in a global fitting way, 2) constraints from various species of data sets, including $\gamma$-rays and antiprotons are included, and 3) the expectation of neutrino emission is fully self-consistent.

PACS numbers: 95.35.+d,95.85.Ry,96.50.S-
I. INTRODUCTION

In a previous work ([1], Paper I) we have developed a Markov Chain Monte Carlo (MCMC) code to fit the parameters of dark matter (DM) models, which are proposed to explain the recent reported abnormal excesses of cosmic ray (CR) positrons and electrons by PAMELA [2], ATIC [3], HESS [4, 5] and Fermi-LAT [6]. One assumption adopted in that work is that the DM particles only couple with leptons. To extent the discussion including hadronic channels will be natural and necessary. Actually the non-excess of PAMELA $\bar{p}/p$ data [7] have been studied in many works to set constraints on the hadronic couplings of DM particles (e.g., [8, 9, 10]). However, these studies can only give some illustration constraints on the model parameters instead of a full scan of the possible parameter space. Our MCMC fitting scheme makes it possible to fully scan the high-dimensional parameter space and derive the model-independent constraints from the data directly.

Shortly after the proposal of using DM annihilation to account for the data, the accompanied $\gamma$-ray and radio emission are investigated as constraint and/or future probe of the current models (e.g., [11, 12, 13]). Besides the photon emission, neutrino can also be regarded as an another probe to test the DM interpretation of the data [14, 15, 16]. In Ref. [14] it is shown that Antares and IceCube are promising to detect the neutrino signals of DM annihilation in the Galactic center (GC) or the massive subhalo for models to explain PAMELA and ATIC data, assuming an NFW profile [17] of DM spatial distribution. It is also claimed that for annihilation DM scenario the IceCube/DeepCore detector can explore much of the parameter space to explain the PAMELA and Fermi-LAT $e^\pm$ data, still for an NFW profile [15]. For decaying DM scenario IceCube/DeepCore also has the potential to exclude some of the parameter space, depending on the final states and DM profile [16]. In all of these works, the expectation of neutrino signals will strongly depend on the annihilation/decay final states and DM profile, and the constraints from various kinds of data are not taken into account simultaneously.

Based on the above points, in this work we improve our MCMC code to include the hadronic branching ratio, and then we re-examine the neutrino signals according to the parameter sets derived in MCMC calculations. We include the positron fraction data from PAMELA [2], the electron + positron data from Fermi-LAT and HESS [4, 5, 6], the diffuse $\gamma$-ray data of the GC ridge from HESS [18], and the antiproton-proton ratio data from...
PAMELA in this MCMC study.

The paper is organized as follows. In Sec. II we introduce the production and propagation of the CR electrons/positrons and antiprotons. In Sec. III we give the MCMC fitting results of DM model parameters, for both annihilation and decaying scenarios. The neutrino signals from GC are discussed in Sec. IV. Finally, Sec. V is the summary.

II. PRODUCTION AND PROPAGATION OF $e^\pm$ AND $\bar{p}$

A. Solution of propagation equation

In the Galaxy the transport of charged particles is affected by several processes. The scattering off random magnetic fields will lead to spatial and energy diffusions. The stellar wind may also blow away the CRs from the Galactic plane. In addition, interactions of CR particles with the interstellar radiation field (ISRF) and/or the interstellar medium (ISM) can result in continuous and catastrophic energy losses. Since the detailed processes affect the propagation are species-dependent, the treatments for positrons and antiprotons are separated. For the transport processes we take a spatial independent diffusion coefficient $D(E) = \beta D_0 R^\delta$ (where $R = pc/Z e$ is the rigidity) and a constant wind $V_c$ directed outwards along $z$. CRs are confined within a cylinder halo $L$, i.e. the differential density is bound by $n(z = \pm L, R_{\text{max}}) = 0$ with $R_{\text{max}}$ the scale of the visible Galaxy. The free parameters of the model are the halo size $L$ of the Galaxy, the normalization of the diffusion coefficient $D_0$ and its slope $\delta$, and the constant galactic wind $V_c$.

The propagation equation of CRs can be generally written as

$$-D \Delta N + V_c \frac{\partial N}{\partial z} + 2h \Gamma_{\text{tot}} \delta(z) N + \frac{\partial}{\partial E} \left( \frac{dE}{dt} N \right) = q(x, E),$$

(1)

where $\Gamma_{\text{tot}} = \sum_{i=H,He} n_i \sigma_i v$ is the destruction rate of CRs through interaction with ISM in the thin gas disk with half height $h \approx 0.1$ kpc, $dE/dt$ is the energy loss rate, and $q(x, E)$ is the source function. The solutions for electrons/positrons and antiprotons are presented in the Appendix. More details about the propagation processes and the solutions of propagation equation can be found in Refs. [19, 20, 21, 22, 23].

For the propagation parameters, we use the medium (referred as “MED”) set of parameters which is derived through fitting the observational B/C data given in Ref. [24], i.e.,
\( D_0 = 0.0112 \text{ kpc}^2 \text{ Myr}^{-1}, \delta = 0.70, V_c = 12 \text{ km s}^{-1} \) and the height of the diffusive halo \( L = 4 \text{ kpc} \).

**B. Background**

For all the CRs we consider here, there are backgrounds originated from the traditional astrophysical sources and/or interactions in the Milky Way (MW) or the Earth atmosphere.

The CR proton and Helium spectra are well measured at the Earth. We adopt the parameterizations in Ref. [8] as the interstellar proton and Helium spectra. Then we calculate the positrons (together with a secondary electron component with almost the same flux) and antiprotons produced through interactions between CR protons, Helium and the ISM. The interaction is restricted in a thin disk with half height \( \sim 0.1 \text{ kpc} \) and the average ISM density is adopted as \( \sim 1 \text{ cm}^{-3} \). These parameter choices were shown to be able to give best-fit to the B/C data [25]. The shapes of secondary positrons and antiprotons are fixed to the calculated results, and we further employ two normalization parameters \( c_{e^+} \) and \( c_\bar{p} \) to describe the uncertainties about the inelastic hadronic cross section and propagation effect. \( c_\bar{p} \) is found to be within \( 1 \pm 0.25 \) [8]. For \( c_{e^+} \) we restrict it in a larger range of \( 1 \pm 0.5 \) since the positrons are more sensitively dependent with the propagation [26].

The background of primary electrons is different from that of positrons and antiprotons. Since we do not have exact knowledge of the primary electron injection spectrum from the acceleration source, we adopt a 2-parameter power-law function \( q_{e^-} = a_{e^-}E_e^{-b_{e^-}} \) to describe the injection source of primary electrons. This is similar to the case of GC \( \gamma \)-rays, which are parameterized by \( \phi_{\gamma}^{\text{bkg}} = a_\gamma E_\gamma^{-b_\gamma} \). \( a_{e^-}, b_{e^-}, a_\gamma \) and \( b_\gamma \) are fitted in the MCMC procedure.

There should be two kinds of backgrounds of neutrinos: the atmospheric background and the astrophysical one. For energies smaller \( \sim 100 \text{ TeV} \) the atmospheric background is dominant [27]. Thus we only consider the comparison with atmospheric background in this work. The result of atmospheric neutrino background is adopted as the direction-dependent calculation [28] based on the muon data.
C. DM contribution

The source function (emissivity) of DM annihilation or decay to standard model particles can be written as

\[ q^j(r, E) = \sum_i B_i \langle \sigma v \rangle \left( \frac{1}{2m^2} \right) j^j \rho^2(r), \quad (2) \]

for DM annihilation, or

\[ q^j(r, E) = \sum_i B_i \frac{1}{m\tau} \left( \frac{1}{dE} \right) j^j \rho(r), \quad (3) \]

for DM decay, where \( m_\chi \) is the mass of DM particle, \( \langle \sigma v \rangle \) or \( \tau \) is the annihilation cross section or decay age of DM respectively, \( B_i \) is the branching ratio to final state channel \( i \), \( \frac{dN}{dE} \bigg|_j \) is the yield spectrum of \( j \) species for one annihilation or decay for channel \( i \), and \( \rho(r) \) is DM spatial density in the MW halo. In this work we consider three channels to lepton pairs \( e^+e^- \), \( \mu^+\mu^- \), \( \tau^+\tau^- \) as well as a quark channel \( q\bar{q} \). Since the antiproton production spectra from decay of various quark flavors do not differ much from each other, we do not distinguish quark flavors but use an average result from all the flavors. The spectra \( \frac{dN}{dE} \bigg|_j \) of positrons, antiprotons, \( \gamma \)-photons and neutrinos from decay of the final state particles of various channels are calculated using PYTHIA package [29].

Similar as in Paper I, we take the density profile of the MW halo as the form

\[ \rho(r) = \frac{\rho_s}{(r/r_s)^\gamma(1 + r/r_s)^{3-\gamma}}, \quad (4) \]

where \( \gamma \) represents the central cusp slope of the density profile, \( r_s \) and \( \rho_s \) are scale radius and density respectively. For the MW DM halo, we adopt the total mass to be \( M_{MW} \approx 10^{12} M_\odot \) [30] and the concentration parameter to be \( c_{MW} \approx 13.5 \) [31]. Then we have \( r_s = r_{MW}/c_{MW}(2 - \gamma) \) where \( r_{MW} \approx 260 \) kpc is the virial radius of MW halo. Then \( \rho_s \) can be derived by requiring \( M_{MW} = \int \rho dV \). The local density \( \rho_\odot \) in this process is checked to be within 0.27 to 0.25 GeV cm\(^{-3}\) for \( \gamma \) varying from 0 to 1.5.

Finally there are propagation effects of these particles before being detected by CR detectors. For charged particles such as positrons and antiprotons, we can replace the source term in Eq. (1) with Eqs. (2) (3) and solve the propagation equations to get the propagated fluxes. For neutral particles like \( \gamma \)-ray photons and neutrinos we just need to integrate the contribution along the line-of-sight of given direction. More details of the treatment of \( \gamma \)-rays can refer to Paper I. Note that for neutrinos there will be oscillations between different
flavors. We actually count all flavors of neutrinos from the output of PYTHIA, and multiply a factor $1/3$ to give the result of muon neutrinos.

### III. MCMC STUDY OF DM PARAMETERS

The full parameter space of this MCMC study is

$$\mathbf{P} \equiv (m_\chi, \langle \sigma v \rangle \text{ or } \tau, B_e, B_\mu, B_\tau, B_q, \gamma, a_\gamma, b_\gamma, a_{e^-}, b_{e^-}, c_{e^+}, c_{\bar{p}}).$$

For the branching ratios we have a normalization condition $B_e + B_\mu + B_\tau + B_q \equiv 1$. As a consequence we have 12 free parameters in total.

The probability distribution of the fitting parameters is shown in Fig. 1. The basic fitting results are similar with our previous study in Paper I. What’s new is the constraint on quark branching ratio from PAMELA $\bar{p}/p$ data. We find that the 2$\sigma$ upper limits of $B_q$ is 0.032 for DM annihilation and 0.044 for DM decay respectively. These results show that the DM to explain the recent CR data indeed needs to dominantly couple with leptons instead of hadrons.

FIG. 1: Probability distributions of the model parameters in annihilation (left) and decaying (right) DM scenarios respectively.
IV. NEUTRINO EMISSION

In this section we discuss the neutrino emission of the DM models. For each parameter set in the MCMC samples obtained in the previous calculation, we compute the neutrino flux as a function of energy. The probability distribution of neutrino flux then can be derived for each energy bin.

The predicted fluxes of $\nu_\mu + \bar{\nu}_\mu$ from the GC direction are shown in Fig. 2. Two sky regions, $1^\circ$ and $60^\circ$ (half angle of the cone) around the GC are calculated to show the effects of angular resolution. For comparison we also show the atmospheric background adopted from Ref. [28]. The average results of atmospheric neutrino fluxes are almost the same for $1^\circ$ and $60^\circ$ cones.

![Graph showing predicted fluxes and 1σ uncertainties of muon and anti-muon neutrinos from the GC for annihilation (left) and decaying (right) DM scenarios respectively. The blue solid line shows the atmospheric background.](image)

FIG. 2: Predicted fluxes and 1σ uncertainties of muon and anti-muon neutrinos from the GC for annihilation (left) and decaying (right) DM scenarios respectively. The blue solid line shows the atmospheric background.

It is shown that generally the neutrino fluxes are dominated by the atmospheric background. For the decaying DM scenario the results are almost always lower than the atmospheric background, even for the angular resolution as good as $1^\circ$, which corresponds to the best performance of IceCube [32]. For the annihilation DM case, the neutrino flux from DM will have a chance to exceed the atmospheric background for energies $\sim$TeV, given a very good angular resolution. Otherwise the signal will be still dominated by the background.

However, to better see the detectability of such DM-induced neutrinos, we need to com-
pare the muon events induced by the neutrinos on a detector. Following the method given in Ref. [33] we calculate the expect number of muon events on IceCube. Both the contained and through-going events are included. The size of IceCube detector is adopted as ~1 km$^3$, and the data accumulative time is taken as 3 years. The expected muon events from both the atmospheric and DM-induced muon neutrinos are compiled in Table I. In the calculation we use the mean values of neutrino fluxes shown in Fig. 2. The integral energy for muons is adopted from 0.5 to 2 TeV, which ensures us to include DM-induced signal and exclude atmospheric background as effective as possible. It is shown that for a circle sky region with radius 1° the statistical significance of DM signal is less than 5σ for IceCube running for 3 years. The case of DM annihilation is some better than DM decay. If we enlarge the sky region to about 60° (π sr), the number of events will be much larger, both for atmospheric background and DM signal. The significance of DM signals can reach ~25 − 35σ. However, we should keep in mind that in this case it would be still difficult to pick out signal events from the background events. The information of spatial distribution and energy spectroscopy is necessary.

| cone angle | atm   | DM-ann(σ) | DM-decay(σ) |
|------------|-------|-----------|--------------|
| 1°         | 23.4  | 20.4(4.2) | 6.1(1.3)     |
| 60°        | 7.68 × 10^4 | 9.71 × 10^3(35.0) | 7.07 × 10^3(25.5) |

Compared with the results given in Ref. [14], our predicted neutrino flux for DM annihilation is several times smaller$^1$. This is because in our work the γ-ray constraint is taken into account and a smaller value of the slope of DM central cusp γ is required. Whereas in Ref. [14] NFW profile is adopted. For decaying DM scenario the results do not differ much from each other. Our prediction of neutrino fluxes should be more self-consistent and more reliable.

$^1$ Note this is a rough comparison because the model parameters in Ref. [14] are different from our global fitting ones.
V. SUMMARY

Based on the MCMC code developed in Paper I, we further study the properties of DM models which may connect with the recent CR lepton excesses, after incorporating the hadronic branching ratio and the constraint from PAMELA $\bar{p}/p$ data. Our global fitting results show that DM with annihilation or decay channels dominantly to the combination of $\tau^+\tau^-$ and $\mu^+\mu^-$ can well describe the electron and/or positron data measured by PAMELA, Fermi-LAT and HESS. The $\bar{p}/p$ data from PAMELA limit the branching ratio to quark pairs to be less than 5%. This conclusion is qualitatively consistent with the previous studies [8, 9, 10], but should be regarded as the first quantitative result based on the global fitting method.

We then calculate the neutrino fluxes from the DM annihilation or decay according to the MCMC fitting parameters. Due to the $\gamma$-ray constraint on the DM profile, our expected neutrino flux for DM annihilation scenario is smaller than that in the previous works where the NFW profile is priorly adopted. However, as we have shown in Ref. [34] and Paper I, the NFW profile will be strongly constrained by the diffuse $\gamma$-rays from the GC ridge observed by HESS [18] for DM annihilation scenario. The derived $2\sigma$ upper limit of the slope of DM central profile is $\sim 0.5$ in the MCMC study, which is much smaller than the NFW profile with $\gamma = 1$. Although smaller, the neutrino flux still could be detected by the forthcoming detector such as IceCube. However, a careful analysis about the angular distribution and spectral distribution is necessary to separate the DM-induced signal from the high atmospheric background. For DM decay scenario the constraint from $\gamma$-rays is weaker, and the differences of the neutrino flux between this work and other works are smaller.

APPENDIX: SOLUTIONS OF THE PROPAGATION EQUATIONS OF POSITRONS AND ANTIPROTONS

1. Positrons

The dominant process in the propagation of positrons is energy loss due to synchrotron and inverse Compton scattering for energies higher than $\sim$GeV. In this paper we will neglect the convection and reacceleration of positrons, which is shown to be of little effect for $E \gtrsim 10$
GeV (also the interested energy range here) \[26\]. Then the propagation equation is

\[- D\Delta N + \frac{\partial}{\partial E} \left( \frac{dE}{dt} N \right) = q(x, E), \tag{A.1}\]

in which the second term in the left hand side represents the energy losses. The energy loss rate of positrons due to synchrotron and inverse Compton scattering in the MW can be adopted as \(dE/dt = -\epsilon^2/\tau_\epsilon\), with \(\epsilon = E/1\) GeV and \(\tau_\epsilon \approx 10^{16}\) s \[35\]. We directly write down the propagator for a point source located at \((r, z)\) from the solar location with monochromatic injection energy \(E_S\) \[22, 23\]

\[G^{e^+}_\odot (r, z, E \leftarrow E_S) = \frac{\tau_E}{E_\epsilon} \times \hat{G}_\odot (r, z, \hat{\tau}), \tag{A.2}\]

in which we define a pseudo time \(\hat{\tau}\) as

\[\hat{\tau} = \tau_E \frac{e^{\delta-1} - e^{\delta-1}}{1 - \delta}. \tag{A.3}\]

\(\hat{G}_\odot (r, z, \hat{\tau})\) is the Green’s function for the re-arranged diffusion equation with respect to the pseudo time \(\hat{\tau}\)

\[\hat{G}_\odot (r, z, \hat{\tau}) = \frac{\theta(\hat{\tau})}{4\pi D_0 \hat{\tau}} \exp \left( -\frac{r^2}{4D_0 \hat{\tau}} \right) \times G^{1D}(z, \hat{\tau}). \tag{A.4}\]

The effect of boundaries along \(z = \pm L\) appears in \(G^{1D}\) only. Following Ref. \[22\] we use two distinct regimes to approach \(G^{1D}\):

- for \(\zeta \equiv L^2/4D_0 \hat{\tau} \gg 1\) (the extension of electron sphere \(\lambda \equiv \sqrt{4D_0 \hat{\tau}}\) is small)

\[G^{1D}(z, \hat{\tau}) = \sum_{n=-\infty}^{\infty} (-1)^n \frac{\theta(\hat{\tau})}{\sqrt{4\pi D_0 \hat{\tau}}} \exp \left( -\frac{z_n^2}{4D_0 \hat{\tau}} \right), \tag{A.5}\]

where \(z_n = 2Ln + (\epsilon)^n z\);

- otherwise

\[G^{1D}(z, \hat{\tau}) = \frac{1}{L} \sum_{n=1}^{\infty} \left[ \exp(-D_0 k_n^2 \hat{\tau})\phi_n(0)\phi_n(z) + \exp(-D_0 k_n^2 \hat{\tau})\phi_n'(0)\phi_n'(z) \right], \tag{A.6}\]

where

\[\phi_n(z) = \sin[k_n(L - |z|)]; \quad k_n = (n - 1/2)\pi/L, \tag{A.7}\]

\[\phi_n'(z) = \sin[k_n'(L - \hat{\tau})]; \quad k_n' = n\pi/L. \tag{A.8}\]

For any source function \(q(r, z, \theta; E_S)\) the local observed flux of positrons can be written as

\[\Phi^{e^+}_\odot = \frac{v}{4\pi} \times 2 \int_{0}^{L} dL \int_{0}^{r_{\text{max}}} rdr \int_{E}^{\infty} dE_S G^{e^+}_\odot (r, z, E \leftarrow E_S) \int_{0}^{2\pi} d\theta q(r, z, \theta; E_S). \tag{A.9}\]
2. Antiprotons

It has been shown that for the propagation of antiprotons neglecting the continuous energy losses and reacceleration can provide a good enough approach, especially for energies higher than several GeV [20]. We will also adopt this approximation here. Therefore the relevant processes include the diffusion, convection and the catastrophic losses — inelastic scattering and annihilation in interactions. The propagation equation is

\[- D \Delta N + V_c \frac{\partial N}{\partial z} + 2 \hbar \Gamma_{\text{tot}} \delta(z) N = q(x, E), \] (A.10)

where \( \Gamma_{\text{tot}} = \sum_{i=H,He} n_i \sigma_i^\beta v \) is the destruction rate of antiprotons in the thin gas disk with half height \( h \approx 0.1 \text{ kpc} \) [20], \( q(x, E) \) is the source function. The propagator for a point source located at \( x_S \), expressed in cylindrical coordinates \((r, z)\) (symmetric in \( \theta \)) is [20]

\[ G_0^\beta (r, z, E) = \exp\left(-k_v z\right) \times \sum_{n=0}^{\infty} c_n^{-1} K_0 \left(r \sqrt{k_n^2 + k_v^2}\right) \sin(k_n L) \sin[k_n (L - z)], \] (A.11)

where \( r \) and \( z \) are the radial distance and vertical height of the source, \( K_0(x) \) is the modified Bessel function of the second type, \( k_v = V_c/(2D) \), and \( k_n \) is the solution of the equation

\[ 2k_n \cos(k_n L) = -(2h \Gamma_{\text{tot}} / D + 2k_v) \sin(k_n L), \]

and \( c_n = 1 - \frac{\sin(k_n L) \cos(k_n L)}{k_n L} \). For any source function \( q(r, z; \theta; E) \), the local observed flux is

\[ \Phi_0^\beta (E) = \frac{v}{4\pi} \times 2 \int_0^L \int_0^{R_{\text{max}}} r dr G_0^\beta (r, z, E) \int_0^{2\pi} d\theta q(r, z; \theta; E). \] (A.12)

ACKNOWLEDGEMENTS

The MCMC code is adapted from the released COSMOMC code [36]. We thank Yi-Fu Cai for helpful discussions. This work is supported in part by National Natural Science Foundation of China under Grant Nos. 90303004, 10533010, 10675136 and 10803001 and by the Chinese Academy of Science under Grant No. KJCX3-SYW-N2.

[1] J. Liu, Q. Yuan, X. Bi, H. Li and X. Zhang, arXiv:0906.3858 [astro-ph.CO](Paper I).
[2] O. Adriani et al., Nature 458, 607 (2009) arXiv:0810.4995 [astro-ph]].
[3] J. Chang et al., Nature 456 (2008) 362.
[4] F. Aharonian et al., Phys. Rev. Lett. 101, 261104 (2008) [arXiv:0811.3894 [astro-ph]].
[5] F. Aharonian et al., arXiv:0905.0105 [astro-ph.HE].
[6] A. A. Abdo et al., Phys. Rev. Lett. 102, 181101 (2009) [arXiv:0905.0025 [astro-ph.HE]].
[7] O. Adriani et al., Phys. Rev. Lett. 102, 051101 (2009) [arXiv:0810.4994 [astro-ph]].
[8] F. Donato, D. Maurin, P. Brun, T. Delahaye and P. Salati, Phys. Rev. Lett. 102, 071301 (2009) [arXiv:0810.5292 [astro-ph]].
[9] M. Cirelli, M. Kadastik, M. Raidal and A. Strumia, Nucl. Phys. B 813, 1 (2009) [arXiv:0809.2409 [hep-ph]].
[10] P. F. Yin, Q. Yuan, J. Liu, J. Zhang, X. J. Bi, S. H. Zhu and X. M. Zhang, Phys. Rev. D 79, 023512 (2009) [arXiv:0811.0176 [hep-ph]].
[11] G. Bertone, M. Cirelli, A. Strumia and M. Taoso, JCAP 0903, 009 (2009) [arXiv:0811.3744 [astro-ph]].
[12] J. Zhang, X. J. Bi, J. Liu, S. M. Liu, P. F. Yin, Q. Yuan and S. H. Zhu, Phys. Rev. D 80, 023007 (2009) [arXiv:0812.0522 [astro-ph]].
[13] L. Bergstrom, G. Bertone, T. Bringmann, J. Edsjo and M. Taoso, Phys. Rev. D 79, 081303 (2009) [arXiv:0812.3895 [astro-ph]].
[14] J. Liu, P. F. Yin and S. H. Zhu, Phys. Rev. D 79, 063522 (2009) [arXiv:0812.0964 [astro-ph]].
[15] D. Spolyar, M. Buckley, K. Freese, D. Hooper and H. Murayama, [arXiv:0905.4764 [astro-ph.CO]].
[16] M. R. Buckley, K. Freese, D. Hooper, D. Spolyar and H. Murayama, [arXiv:0907.2385 [astro-ph.HE]].
[17] J. F. Navarro, C. S. Frenk and S. D. M. White, Astrophys. J. 490, 493 (1997).
[18] F. Aharonian et al. [H.E.S.S. Collaboration], Nature 439, 695 (2006) [arXiv:astro-ph/0603021].
[19] D. Maurin, F. Donato, R. Taillet and P. Salati, Astrophys. J. 555, 585 (2001) [arXiv:astro-ph/0101231].
[20] D. Maurin, R. Taillet and C. Combet, [arXiv:astro-ph/0609522].
[21] D. Maurin, R. Taillet and C. Combet, [arXiv:astro-ph/0612714].
[22] J. Lavalle, J. Pochon, P. Salati and R. Taillet, Astron. Astrophys. 462, 827 (2007). [arXiv:astro-ph/0603796].
[23] J. Lavalle, Q. Yuan, D. Maurin and X. J. Bi, Astron. Astrophys. 479, 427 (2008). [arXiv:0709.3634 [astro-ph]] (Paper I).
[24] F. Donato, N. Fornengo, D. Maurin, P. Salati and R. Taillet, Phys. Rev. D 69, 063501 (2004) [arXiv:astro-ph/0306207].

[25] F. Donato, D. Maurin, P. Salati, A. Barrau, G. Boudoul and R. Taillet, Astrophys. J. 563, 172 (2001) [arXiv:astro-ph/0103150].

[26] T. Delahaye, F. Donato, N. Fornengo, J. Lavalle, R. Lineros, P. Salati and R. Taillet, Astron. Astrophys. 501, 821 (2009) [arXiv:0809.5268 [astro-ph]].

[27] C. Evoli, D. Grasso and L. Maccione, JCAP 0706, 003 (2007) [arXiv:astro-ph/0701856].

[28] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa and T. Sanuki, Phys. Rev. D 75, 043006 (2007) [arXiv:astro-ph/0611418].

[29] T. Sjostrand, S. Mrenna and P. Skands, JHEP 0605, 026 (2006) [arXiv:hep-ph/0603175].

[30] X. X. Xue et al., Astrophys. J. 684, 1143 (2008) [arXiv:0801.1232 [astro-ph]].

[31] J. S. Bullock et al., Mon. Not. Roy. Astron. Soc. 321, 559 (2001).

[32] J. Ahrens et al. [IceCube Collaboration], Astropart. Phys. 20, 507 (2004) [arXiv:astro-ph/0305196].

[33] M. D. Kistler and J. F. Beacom, Phys. Rev. D 74, 063007 (2006) [arXiv:astro-ph/0607082].

[34] X. J. Bi, R. Brandenberger, P. Gondolo, T. Li, Q. Yuan and X. Zhang, [arXiv:0905.1253 [hep-ph]].

[35] E. A. Baltz and J. Edsjo, Phys. Rev. D 59, 023511 (1999) [arXiv:astro-ph/9808243].

[36] A. Lewis and S. Bridle, Phys. Rev. D 66, 103511 (2002) [arXiv:astro-ph/0205436].