# LikeDM: likelihood calculator of dark matter detection

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With the large progress in searches for dark matter (DM) particles with indirect and direct methods, we develop a numerical tool that enables fast calculations of the likelihoods of specified DM particle models given a number of observational data, such as charged cosmic rays from space-borne experiments (e.g., PAMELA, AMS-02),  $\gamma$ -rays from the Fermi space telescope, and underground direct detection experiments. The purpose of this tool — LIKEDM, likelihood calculator for dark matter detection — is to bridge the gap between a particle model of DM and the observational data. The intermediate steps between these two, including the astrophysical backgrounds, the propagation of charged particles, the analysis of Fermi  $\gamma$ -ray data, as well as the DM velocity distribution and the nuclear form factor, have been dealt with in the code. We release the first version (v1.0) focusing on the constraints from indirect detection of DM with charged cosmic and gamma rays. Direct detection will be implemented in the next version. This manual describes the framework, usage, and related physics of the code.

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## PROGRAM SUMMARY

Program Title: LIKEDM Licensing provisions: GPLv3 Programming language: FORTRAN 90 and Python Operating system: Linux.

Nature of problem: Dealing with the intermediate steps between a dark matter model and data. Solution method: Fast computation of the likelihood of a given dark matter model (defined by a mass, cross section or decay rate, and annihilation or decay yield spectrum), without digging into the details of cosmic-ray propagation, Fermi-LAT data analysis, or related astrophysical backgrounds.

## I. INTRODUCTION

After the discovery of the 125 GeV Higgs boson at the Large Hadron Collider [1, 2], we have a complete picture of the standard model (SM) of particle physics. The next step beyond the SM could be the identification of the dark matter (DM) particles that were suggested to be widely present in the Universe by a series of astronomical observations. Although the astronomical evidence could be attributed to gravitational interactions between DM and SM particles, we are yet to exclude the possibility of weakly interacting massive particles (WIMPs). The potential weak interactions between DM and SM particles provide us with the opportunity to identify DM, directly via collisions between DM particles and underground targets or indirectly via the products of DM annihilation or decay in the Universe. Many efforts have been made to find a direct signal of DM in an underground detector; however, no convincing evidence has been found till date [3–6]. On the other hand, with the opperation of several new-generation space telescopes and detectors, such as PAMELA, AMS-02, and Fermi, many anomalies have been found in the high-energy sky [7–9]. The uncertainties from astrophysical backgrounds and/or astrophysical sources, however, make the identification of possible DM signals more challenging. Nevertheless, the constraints on

DM models have become more and more stringent with the new direct and indirect data. Some of these constraints depend on certain assumptions about the backgrounds (e.g., the positron anomaly [10, 11]). Since there is no consistent signal of DM present in all observations, we may expect that the assumptions of astrophysical contributions to those anomalies are reasonable. The combination of various kinds of observations is expected to give much improved constraints on DM models, which is one of the motivations for developing this tool for calculating the DM likelihood.

Another motivation is that it is non-trivial to confront DM models with observational data due to the complicated astrophysical backgrounds. First, a proper modeling of the backgrounds, with possible systematic uncertainties (e.g., the cosmic ray (CR) propagation parameters), is necessary when calculating the likelihood of a DM signal. Second, it is better to decouple the DM model inputs from the following astrophysical processes, as it enables our tool to be applied to any DM particle model. Third, we intend to have an efficient computation of the DM signal as well as the backgrounds. With these goals, we develop this likelihood calculator of DM detection, LIKEDM. The basic function of LIKEDM is to deal with the intermediate steps between a DM model and data. To achieve this goal, we 1) calculate the propagation of CR electrons/positrons and antiprotons with Green's functions with respect to energy (e.g., integrated with space and time), 2) model the CR backgrounds with phenomenological forms, 3) model the  $\gamma$ -ray emission with standard Fermi-LAT diffuse emission templates and point sources, and 4) calculate the likelihood map of  $\gamma$ -rays on the "energy-flux" plane for given regions of interest (ROIs). Some works have been published based on parts of these methods [12, 13]. Here we present the first version of this tool and make the code publicly available in the community and summarize the details in this manual. Constraints from direct detection have not been included in this release, and will be added in the subsequent version.

This manual is structured as follows. In Sec. II, we describe the calculation of charged CRs from both the DM signal and the background. The Green's function for fast computation of the propagation of charged CRs is presented. In Sec. III, we describe the likelihood calculation from Fermi-LAT observations of dwarf spheroids (dSphs). We give the energy-flux likelihood map with updated Fermi-LAT data. We introduce the code, installation procedure, and explain the usage of LIKEDM in Sec. IV. Finally, we summarize in Sec. V.

#### II. CHARGED COSMIC RAYS

#### A. Propagation of charged cosmic ray particles

The charged cosmic rays (CRs) propagate diffusively in the random magnetic field of the Milky Way. The interaction with the interstellar medium (ISM) will result in energy losses and/or fragmentation of the primary CRs, as well as the production of secondary CRs. For electrons/positrons, there will be additional energy losses due to radiation in the interstellar radiation field (ISRF) and the magnetic field. The random shocks in the interstellar space may reaccelerate the low-energy CR particles. There may also be convective transport of CRs as evidenced by the wide existence of galactic winds. The general propagation equation of CRs in the Milky Way can be written as [14]

$$\frac{\partial \psi}{\partial t} = Q(\mathbf{x}, p) + \nabla \cdot (D_{xx} \nabla \psi - \mathbf{V}_{\mathbf{c}} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi 
- \frac{\partial}{\partial p} \left[ \dot{p} \psi - \frac{p}{3} (\nabla \cdot \mathbf{V}_{\mathbf{c}} \psi) \right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r},$$
(1)

where  $\psi$  is the CR differential density per unit momentum interval,  $Q(\mathbf{x}, p)$  is the source function,  $D_{xx}$  is the spatial diffusion coefficient,  $\mathbf{V}_{\mathbf{c}}$  is the convection velocity,  $D_{pp}$  is the diffusion coefficient in momentum space,  $\dot{p} \equiv dp/dt$  is the momentum loss rate, and  $\tau_f$ and  $\tau_r$  are timescales for fragmentation and radioactive decay, respectively. A homogeneous spatial diffusion coefficient  $D_{xx}$  is assumed, and the rigidity dependence is assumed to be of a power-law form  $D_{xx} = D_0\beta(R/R_0)^{\delta}$ , with  $\beta$  being the velocity of the particle and  $\delta$ reflecting the property of the ISM turbulence. For Kolmogrov turbulence, we have  $\delta = 1/3$ . The reacceleration is described by diffusion in momentum space. The momentum diffusion coefficient  $D_{pp}$  can be related to the spatial diffusion coefficient  $D_{xx}$  by [15]

$$D_{pp}D_{xx} = \frac{4p^2 v_A^2}{3\delta(4-\delta^2)(4-\delta)w},$$
(2)

where  $v_A$  is the Alfven speed, and w characterizes the level of turbulence which can be absorbed in  $v_A$ . The CRs are assumed to be confined in an extended halo with characteristic height  $z_h$ , beyond which free escape is assumed. Thus, the major propagation parameters are  $D_0$ ,  $\delta$ ,  $v_A$ ,  $V_c$  and  $z_h$ .

The secondary-to-primary ratios, such as B/C and (Sc+Ti+V)/Fe, and the unstableto-stable ratios of secondary particles, such as  ${}^{10}Be/{}^{9}Be$  and  ${}^{26}Al/{}^{27}Al$  are often used to

determine the propagation parameters [15–18]. There are numerical codes to compute CR propagation in the galaxy, such as  $GALPROP^{1}$  [16] and  $DRAGON^{2}$  [19].

In this tool, we adopt GALPROP version  $50^3$  to calculate the propagation of charged particles. We adopt six sets of propagation parameters, with  $z_h$  varying from 2 kpc to 15 kpc, which reflect the major uncertainties in the propagation parameters [20]. All groups are consistent with the B/C data as well as the Fermi diffuse  $\gamma$ -ray emission data [21].

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	$D_0^a$	$z_h$	$v_A$	$\delta$
	$(10^{28} \rm cm^2 s^{-1})$	(kpc)	$\rm (km~s^{-1})$	
1	2.7	2	35.0	0.33
2	5.3	4	33.5	0.33
3	7.1	6	31.1	0.33
4	8.3	8	29.5	0.33
5	9.4	10	28.6	0.33
6	10.0	15	26.3	0.33

TABLE I: Propagation parameters.

<sup>*a*</sup>Diffusion coefficient at R = 4 GV.

#### В. Green's function of charged particle fluxes from DM

The annihilation or decay of DM particles in the Milky Way halo will produce charged CRs such as positrons and antiprotons, which will experience diffusive propagation before reaching the Earth. The fluxes of the charged CRs depend on both the density profile of DM and the propagation parameters (especially the height of the propagation halo  $z_h$ ). We will consider several common forms of DM density profile, including the Navarro-Frenk-White (NFW) profile [22]

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2},\tag{3}$$

<sup>&</sup>lt;sup>1</sup> http://galprop.stanford.edu/
<sup>2</sup> http://www.dragonproject.org/Home.html

<sup>&</sup>lt;sup>3</sup> For the recent updated version 54 please refer to http://sourceforge.net/projects/galprop/.

the Einasto (EIN) profile [23]

$$\rho_{\rm EIN}(r) = \rho_s \cdot \left[ -\frac{2}{\alpha} \left( \left( \frac{r}{r_s} \right) - 1 \right) \right], \tag{4}$$

and the isothermal (ISO) profile [24]

$$\rho_{\rm ISO}(r) = \frac{\rho_s}{1 + (r/r_s)^2}.$$
(5)

The profile parameters are given in Table II [25].

The source function of the charged CRs for DM annihilation or decay is

$$q(E,r) = \begin{cases} \frac{\langle \sigma v \rangle}{2m_{\chi}^2} \frac{dN}{dE} \times \rho^2(r) & \text{for annihilation} \\ \frac{1}{m_{\chi}\tau} \frac{dN}{dE} \times \rho(r) & \text{for decay} \end{cases},$$
(6)

where  $m_{\chi}$  is the mass of the DM particle,  $\langle \sigma v \rangle$  is the annihilation cross section,  $\tau$  is the decay lifetime, and dN/dE is the particle yield spectrum per annihilation or decay.

	$r_s$	$ ho_s$	$\alpha$
	(kpc)	$({\rm GeV~cm^{-3}})$	
NFW	20	0.26	N/A
EIN	20	0.06	0.17
ISO	5	1.16	N/A

TABLE II: DM density profile parameters.

The traditional way to solve the propagation of the DM-induced charged particles is to incorporate the source term for a given DM particle model in the propagation equation (Eq. (1)). In order to isolate the DM particle model from the propagation calculation, we approximate the function dN/dE with a series of Gaussian kernel functions

$$\frac{dN}{dE} \approx \sum_{i} C_i K_i(E, E_i) = \sum_{i} \frac{C_i}{\sqrt{2\pi\sigma_i}} \exp\left[-\frac{(E - E_i)^2}{2\sigma_i^2}\right],\tag{7}$$

where  $E_i$  and  $\sigma_i$  are respectively the central value and width of the *i*th Gaussian kernel. We find that generally  $\sigma_i = 15\% E_i$  results in a good approximation to most of the energy spectrum dN/dE, except when it has very distinct (e.g., monochromatic) spectral structures. The left panel of Fig. 1 shows an illustration of the kernel functions weighted by the coefficients  $C_i$  for a given spectrum. We can then calculate the propagated spectrum of each kernel function,  $G_i(E)$ , which is the approximate Green's function with respect to energy E(dashed lines in the right panel of Fig. 1). The total propagated spectrum can be obtained as

$$\Phi(E) \approx \sum_{i} C_i G_i(E).$$
(8)

As shown in the right panel of Fig. 1, the result from this Green's function method is in good agreement with the direct calculation of the propagation (red dots).

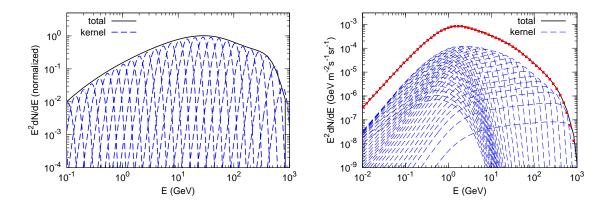


FIG. 1: Illustration of the kernel functions and the sum of the positron spectra, before (left) and after (right) the propagation. The points in the right panel show the direct calculation of the propagated spectrum of positrons with GALPROP. Here we adopt the second setting of the propagation parameters and the NFW profile of DM density. The mass of DM particle is 1 TeV, with an annihilation cross section of  $\langle \sigma v \rangle = 10^{-26} \text{ cm}^3 \text{s}^{-1}$  and  $b\bar{b}$  as the annihilation final state.

Upon applying this method, any DM-induced CR  $e^{\pm}$  and  $\bar{p}$  spectra on Earth can easily be obtained by inserting its source shape. This helps us to significantly reduce the computation time<sup>4</sup> if the predetermined Green's function tables are provided. Users are allowed to generate their own tables of Green's functions if necessary.

## C. Backgrounds

The CR backgrounds relevant for the DM searches include the primary electrons from the CR sources, the secondary positrons and antiprotons from interactions between the primary

 $<sup>^4</sup>$  As a rough example, the computation time of the propagation calculation reduces by a factor of  $\gtrsim 10$  compared with the use of GALPROP.

CR nuclei and the ISM, as well as the possible primary sources of positrons from e.g., pulsars [26]. Instead of using the more physical model which considers the injection/production and propagation of each type of particle [27, 28], we adopt an empirical model to fit the locally observed cosmic ray fluxes following Ref. [11]. This is equivalent to assuming that there is no DM "signal" in the current data and that all the measured events come from CR backgrounds (see also [29, 30]). In contrast to Ref. [11], we assume broken power-law forms to describe the fluxes of the primary electrons, secondary positrons/electrons and secondary antiprotons, with the purpose of reproducing the wide-band data:

$$\phi_{e^{-}} = C_{e^{-}} E^{-\gamma_{1}^{e^{-}}} \left[ 1 + (E/E_{\rm br}^{e^{-}})^{\gamma_{2}^{e^{-}}} \right]^{-1}, \qquad (9)$$

$$\phi_{e^+} = C_{e^+} E^{-\gamma_1^{e^+}} \left[ 1 + (E/E_{\rm br}^{e^+})^{\gamma_2^{e^+}} \right]^{-1}, \qquad (10)$$

$$\phi_{\bar{p}} = C_{\bar{p}} E^{\gamma_1^{\bar{p}}} \left( 1 + E/E_{\rm br}^{\bar{p}} \right)^{-\gamma_2^{\bar{p}}} ..$$
(11)

Note that the form of antiprotons is slightly different from that of electrons and positrons in order to improve the fit to the data. The secondary electron spectrum is assumed to be the same as the secondary positron spectrum, with a normalization factor of 0.6 as expected from the pp collisions [31]. As for the extra source to reproduce the electron/positron excess, a power law with an exponential cut-off is assumed

$$\phi_s = C_s E^{-\gamma_s} \exp(-E/E_c). \tag{12}$$

Therefore the total fluxes of positrons, electrons, and positrons + electrons are

$$\Phi_{e^+} = \phi_{e^+} + \phi_s, \tag{13}$$

$$\Phi_{e^-} = \phi_{e^-} + 0.6\phi_{e^+} + \phi_s, \tag{14}$$

$$\Phi_{e^{\pm}} = \phi_{e^{-}} + 1.6\phi_{e^{+}} + 2\phi_s, \tag{15}$$

respectively, and the positron fraction is  $\Phi_{e^+}/\Phi_{e^{\pm}}$ .

The data used to fit the backgrounds includes the updated AMS-02 positron fraction [32], the AMS-02 spectra of electrons and positrons [33], the AMS-02 total  $e^{\pm}$  spectra [34], and the PAMELA antiproton spectrum [35]. The AMS-02 data below 1 GeV are excluded from the fit [11]. The empirical background model gives a very good description of the data, as shown in Fig. 2. The best-fit  $\chi^2$  value over the number of degrees of freedom (dof) is about 132.8/285 for  $e^+e^-$  and about 11.1/19 for antiprotons. The best-fit parameters are listed in Table III.

TABLE III: Best-fit parameters of the backgrounds.
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	C	$\gamma_1$	$\gamma_2$	$E_{\rm br}$	$E_c$
	$({\rm GeV^{-1}m^{-2}s^{-1}sr^{-1}})$			(GeV)	(GeV)
$\phi_{e^-}$	21.6701	0.9344	2.3734	3.6390	
$\phi_{e^+}$	1.4991	0.9024	2.3647	2.8434	
$\phi_s$	0.6526	2.3390			652.89
$\phi_{\bar{p}}$	0.0995	1.844	5.077	2.849	

When a DM component is added to the model, we should allow for some freedom in the backgrounds to obtain a global best-fit to the data. Therefore, we multiply by factors of  $\alpha_i E^{\beta_i}$ , with  $i = \{e^-, e^+, s, \bar{p}\}$ , on the primary electrons, the secondary positrons/electrons, the extra positrons/electrons and the secondary antiprotons. We adopt the profile likelihood method to manage the nuisance parameters  $\alpha_i$  and  $\beta_i$ , with the scan ranges [0.1, 10] and [-0.5, 0.5], respectively. The code Minuit [36] is used to find the maximum likelihood within the parameter space  $[\alpha_i, \beta_i]$ .

#### D. Solar modulation

The low-energy charged CRs will be modulated by solar activity. We adopt the simple force-field approximation with only one parameter, *viz.* the modulation potential, to calculate the effect of solar modulation [37]. Since our background model is an empirical one instead of a physical model, the solar modulation only applies to the CR fluxes from the DM annihilation or decay.

#### E. The cosmic ray constraints on the DM annihilation parameters space

In this subsection we present some results on the DM model parameter constraints from charged CRs derived with the above method. We adopt a DM annihilation scenario for illustration, and assume that the DM density profile is NFW. Given one set of the DM model parameters, such as the mass, the annihilation cross section, and the branching ratios to each annihilation channel, we calculate the production spectra of positrons and antiprotons

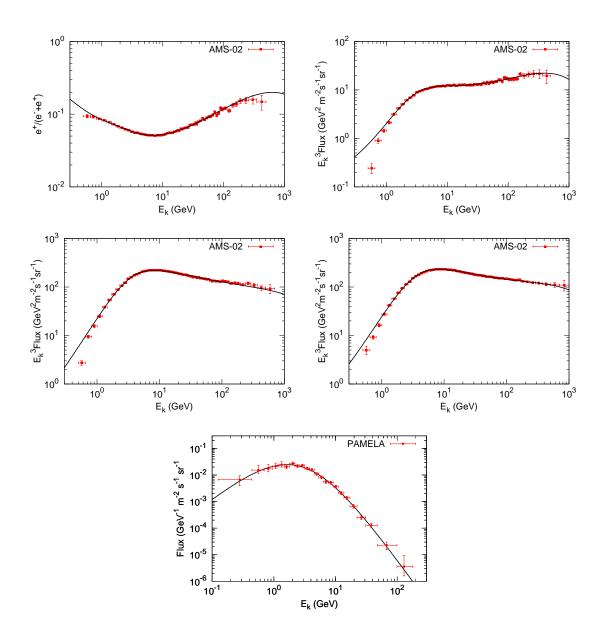


FIG. 2: Background fitting results of the positron fraction (top-left), positron (top-right), electron (middle-left), total  $e^{\pm}$  (middle-right), and antiproton spectra (bottom).

using the tables<sup>5</sup> of Ref. [38]. The propagated fluxes, calculated with the aforementioned Green's function method, together with the backgrounds, are then combined with the data to derive the likelihood,  $\mathcal{L} \propto \exp(-\chi^2/2)$ , of this particular set of DM parameters.

The top-left panel of Fig. 3 shows a map of  $-2\Delta \ln(\mathcal{L}) \equiv -2\ln(\mathcal{L}/\mathcal{L}^0)$ , where  $\mathcal{L}$  is the likelihood of the model with different values of  $\langle \sigma v \rangle$  and  $m_{\chi}$ , and  $\mathcal{L}^0$  is the likelihood for the

<sup>&</sup>lt;sup>5</sup> Only those tables of fluxes at production including EW corrections are used and incorporated in LIKEDM.

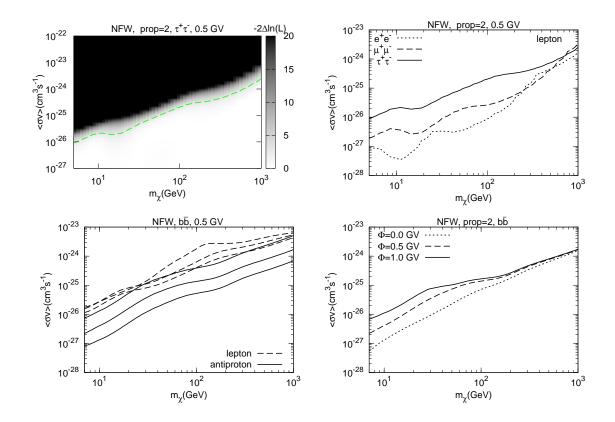


FIG. 3: Figure shows the constraints on the DM annihilation parameters from the charged CR data. The DM density profile is assumed to be NFW, and the solar modulation potential is adopted to be 0.5 GV unless stated elsewhere. Top-left: the map of  $-2\Delta \ln(\mathcal{L})$  on the  $(m_{\chi}, \langle \sigma v \rangle)$  plane from the AMS-02 lepton data, for DM annihilation into  $\tau^+\tau^-$ . The dashed line shows the 95% CL limit. Top-right: 95% upper limits of  $\langle \sigma v \rangle$  from the AMS-02 lepton data, for different DM masses and the annihilation channels of  $e^+e^-$ ,  $\mu^+\mu^-$ , and  $\tau^+\tau^-$ , respectively. Bottom-left: 95% upper limits on  $\langle \sigma v \rangle$  from the AMS-02 lepton data (dashed) and the PAMELA antiproton data (solid), for DM annihilation to  $b\bar{b}$ . The three lines of each group from top to bottom represent the propagation models #1, #2, and #6, respectively. Bottom-right: 95% upper limits on  $\langle \sigma v \rangle$  from the AMS-02 lepton data and the PAMELA antiproton data, for DM annihilation into  $b\bar{b}$ . The three lines of each group from top to bottom represent the propagation models #1, #2, and #6, respectively. Bottom-right: 95% upper limits on  $\langle \sigma v \rangle$  from the AMS-02 lepton data and the PAMELA antiproton data, for DM annihilation into  $b\bar{b}$ . The three lines from top to bottom represent the solar modulation potentials of 1.0, 0.5, and 0 GV, respectively.

null hypothesis (*i.e.*, pure background). The likelihood is calculated using the AMS-02  $e^+e^-$  data. The propagation model is #2, the solar modulation potential is 0.5 GV, and the DM annihilation channel is assumed to be  $\tau^+\tau^-$ . The dashed line shows the 95% confidence level

(CL) upper limit, defined by  $-2\Delta \ln(\mathcal{L}) = 2.71$  for a single-sided probability distribution. Other panels of Fig. 3 illustrate the 95% upper limits of the DM annihilation cross section for different channels (top-right), propagation models (bottom-left), and solar modulation potentials (bottom-right).

### III. GAMMA-RAYS FROM DSPHS

Gamma-rays are another very important messenger for the indirect detection of DM. Gamma-rays travel through space without deflection, thus they can point back to the sources emitting them. It is advantageous to choose regions in the sky with high DM density and low astrophysical background to search for DM. The dSphs in the Milky Way are widely believed to be favorable targets with a high signal-to-noise ratio. Many works have been performed to search for DM-induced  $\gamma$ -rays from dSphs with Fermi-LAT data, yet none of them reported a significant detection [39–43]. Recently, the ongoing Dark Energy Survey (DES) reported some new candidates of dSphs in the southern hemisphere [44, 45]. Several groups had claimed possible weak  $\gamma$ -ray signals from Reticulum 2 [46] and Tucana III [47]. Since there are no reliable kinematic measurements available for these newly-discovered dSphs candidates (hence no reliable DM density profiles), the constraints and implications on DM from them are very uncertain. We adopt the dSphs sample of Ref. [42] in LIKEDM.

#### A. Likelihood Map

To ensure an easy computation of the total likelihood for any given shape of  $\gamma$ -ray spectrum, we take the likelihood map method first proposed in our earlier work [12] and further developed in Refs. [40, 42]. Briefly speaking, the likelihood  $\mathcal{L}_{ij}$  of any flux  $\phi_j$  in each energy bin  $[E_{i-1/2}, E_{i+1/2}]$  is calculated to give a likelihood map on the  $(E, \phi)$  plane. The total likelihood of a given spectrum can be simply obtained through a product of the likelihoods over all energy bins. This method is DM particle model independent, flexible and timesaving. Also, as shown in Ref. [48], it is simple to combine this method with data from other observations.

We describe the method in more detail. DM annihilation in dSphs is adopted for illustra-

tion<sup>6</sup>. The case of DM decay can be easily obtained via proper re-adjustment of the formula (see e.g., Eq. (6)). The  $\gamma$ -ray flux from the annihilation of DM in a dSph is

$$\phi(E) = \frac{\langle \sigma v \rangle}{8\pi m_{\chi}^2} \times \frac{dN_{\gamma}}{dE_{\gamma}} \times J, \tag{16}$$

where  $J = \int dl d\Omega \rho(l)^2$  is the so-called *J*-factor which characterizes the amount of annihilation from a specified direction given the density distribution  $\rho$  of DM. As the bin widths are small, for each energy bin  $[E_{i-1/2}, E_{i+1/2}]$ , we approximate  $dN_{\gamma}/dE_{\gamma}$  with a constant,  $C_i$ . This approximation enables us to calculate the total log-likelihood of the spectrum  $\phi(E)$ from the logarithm of the likelihood map  $\mathcal{L}_{ij}$  as

$$\ln \mathcal{L} = \sum_{i} \ln \mathcal{L}_{ij} |_{\phi_j = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \times J \times C_i}.$$
(17)

We use the standard Fermi Science Tools package [52] version v10r0p5 to analyze the Fermi-LAT data. We use the newly released Fermi Pass 8 data, with four subsets of different point spread function (PSF) levels (i.e., PSF0, PSF1, PSF2 and PSF3), recorded from 4 August 2008 to 4 August 2015. These data are selected from  $10^{\circ} \times 10^{\circ}$  box regions centered on each dSph, and 500 MeV to 500 GeV energies to reduce the impact from the bright Earth limb due to the large PSFs at low energies. The events with zenith angles greater than 100° are also excluded. These selected data are divided into  $100 \times 100$  spatial bins with 0.1° bin size and 24 logarithmically spaced energy bins. Using the suggested diffuse background model<sup>7</sup> including a structured Galactic component and an isotropic component, as well as point sources within 15° of each dSph from the third Fermi catalog (3FGL; [49]) as astrophysical background, we first carry out a standard binned likelihood fitting over the entire energy range to get the best-fitting parameters for each point source and the diffuse components. Then we fix all the parameters of diffuse backgrounds and known point sources in the ROI, and add a point source at the position of the dSph. On varying the flux from the newly added point source, we calculate the  $\ln \mathcal{L}_{ij}^{kl}$  for the kth dSph and lth subset of data in each energy bin and sum over l to obtain the likelihood map  $\mathcal{L}_{ij}^k$  for the kth dSph.

<sup>&</sup>lt;sup>6</sup> The decay case is also included in the code. Since the emission from DM decay is more extended, we use the profile parameters, which could get the median J-factor corresponding to 5° radius integration, from the Markov Chain Monte Carlo (MCMC) fittings to the kinematic data of dSphs [50] to generate normalized two-dimensional **SpatialMap**. Then we calculate the likelihood map for these extended sources. For J-factors and corresponding errors please see Ref. [51].

<sup>7</sup> http://fermi.gsfc.nasa.gov/ssc/data/access/lat/BackgroundModels.html

#### B. Combination of many dSphs

If the *J*-factors of dSphs are known, then we can define a new variable,  $\psi_i = \phi_k(E_i)/J_k = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \times C_i$ , and derive a combined log-likelihood map on the  $(E, \psi)$  plane by adding the log-likelihoods of all dSphs together. Fig. 4 shows a combined log-likelihood map on the  $(E, E^2\psi)$  plane, from the 15 dSphs as listed in Ref. [42]. The *J*-factors of the dSphs are taken from Ref. [50]. The solid line shows the one-sided 95% confidence limit obtained from  $-2\Delta \ln \mathcal{L}_i = -2(\ln \mathcal{L}_i - \ln \mathcal{L}_i^0) = 2.71$ , where  $\mathcal{L}_i^0$  is the likelihood for null-hypothesis (i.e.,  $\psi_i = 0$ ) for the *i*th energy bin. For any spectrum  $\psi(E)$ , the combined log-likelihood can be derived via a sum of log-likelihoods in all energy bins.

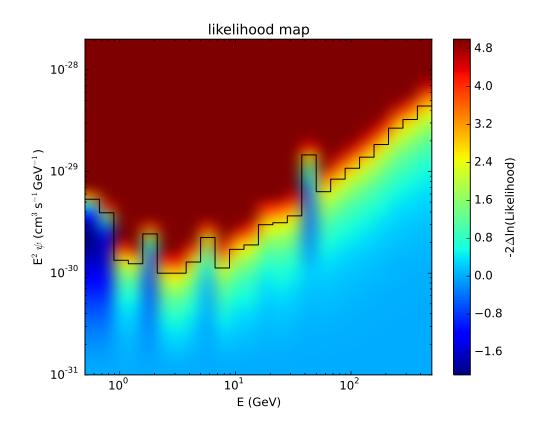


FIG. 4: The log-likelihood map on the  $(E, E^2\psi)$  plane based on 7-year Fermi-LAT data of the 15 dSphs. The colors show the value of  $-2\Delta \ln \mathcal{L}$ , normalized individually for each energy bin (see the text for details). The region above the solid line is excluded at the 95% confidence level.

However, in general the J-factors of dSphs cannot be well determined. If that is the case, we may not be able to have a combined likelihood map (such as that in Fig. 4) which

is independent of J-factors<sup>8</sup>. We can define a likelihood term due to the uncertainties in J-factors as [42]

$$\mathcal{L}_{J,k}(J_{\text{obs},k},\sigma_k) = \frac{1}{\ln(10)J_{\text{obs},k}\sqrt{2\pi}\sigma_k} e^{-[\log_{10}(J_k) - \log_{10}(J_{\text{obs},k})]^2/2\sigma_k^2},$$
(18)

where k represents the kth dSph,  $J_k$  is the "real" value of the J-factor and  $J_{\text{obs},k}$  is the measured J-factor with error  $\sigma_k$ . The joint log-likelihood is then

$$\ln \mathcal{L}(\text{Data}|\phi) = \sum_{k} \left( \sum_{i} \ln \mathcal{L}_{ij} |_{\phi_j = \frac{\langle \sigma v \rangle}{8\pi m_\chi^2} \times J \times C_i} + \ln \mathcal{L}_{J,k} \right).$$
(19)

Maximizing the above joint log-likelihood by varying  $J_k$  for each dSph, we can obtain the final log-likelihood of the spectrum  $\phi(E)$ .

In Fig. 5 we show the combined 95% upper limits for the  $b\bar{b}$  annihilation channel. Here we adopt the *J*-factors given in Ref. [50]. The two solid lines show the differences between the cases with (green) and without (red) uncertainties in *J*-factor measurements. It shows the potential to improve the constraints with better determination of the *J*-factors.

## IV. DESCRIPTION OF THE CODE

In this section we describe the structure of the LIKEDM code. Users can download the source code from Ref. [53] or the batch file from the ancillary files to this paper on the arXiv website. LIKEDM is written in Fortran95, with a Python interface.

### A. Installation

LIKEDM uses the external package Minuit [36] to maximize the likelihoods, which needs to be installed first. To install pyLikeDM, the "f2py" package is required. We provide a BASH script (create\_LikeDM.sh) for quick installation. After running create\_LikeDM.sh, the user is prompted to enter a method of pyminuit installation:

./create\_LikeDM.sh

<sup>&</sup>lt;sup>8</sup> In Ref. [12] we profiled *J*-factors in the likelihood function for each energy bin, and obtained a combined likelihood map. However, this method multi-counts the *J*-factor uncertainties. A proper treatment should first combine likelihoods in different energy bins and then apply the *J*-factor likelihoods [40].

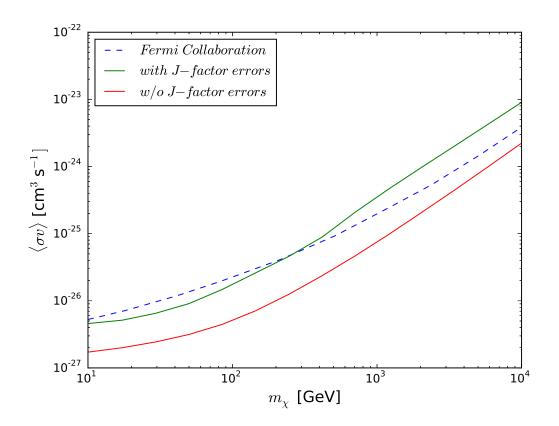


FIG. 5: 95% upper limits on the DM annihilation cross section for the  $b\bar{b}$  annihilation channel, derived from a combined analysis of Fermi-LAT observations of 15 dSphs. The result obtained by Fermi-LAT collaboration with 6 year Pass 8 data is shown for comparison [42]. The two solid lines show the results with (green) and without (red) uncertainties of *J*-factor measurements.

```
start installing pyminuit
start installing pyminuit
# Two ways to install pyminuit:
# (enter "use_pip" or "local" and other keys for doing nothing.)
local
.
.
.
End installing pyLikeDM
Enjoy use!
```

There are three options: use\_pip, local, and any other key. If one chooses use\_pip, sudo authorization is required to install iminuit via pip. If the user does not have pip

installed, he/she can install pyminuit by using the local option. This step can be skipped if pyminuit has already been installed.

LIKEDM has been successfully installed and tested under Scientific Linux, Fedora, and Ubuntu operating systems.

#### B. Running LikeDM

The LIKEDM code can be called by

./pyLikeDM.py LikeDM\_input\_example.ini [dnde.spec]

where LikeDM\_input\_example.ini is an example file of the input parameters (see below part C for details), and the argument dnde.spec is optional, depending on the value of the logical parameter use\_pppc4. If use\_pppc4=T, then the DM annihilation or decay yield spectrum dN/dE is computed using the PPPC4 tables [38]. Otherwise, the file dnde.spec with the spectrum generated by the user needs to be provided. The output looks like

#### C. Inputs and outputs

We provide an example of the input file, LikeDM\_input\_example.ini, in the main folder of LIKEDM:

```
output_name= LikeDM2016
# See all the information?
# 0 for chisq results
# 1 for inputs
# 2 for fitting (alpha, beta)
# 3 for input dNdE
# 4 for propagated fluxes of e+ and pbar
# 5 for individual dSph spectrum
# >=6 for fitting results in each step, very slow!
seebug=0 #debug_level
# Which gamma-ray likelihood MAP you are going to include?
# (The way to generate likelihood map can be found in arxiv 1212.3990)
# optimal likelihood map for annihilation DM
dsphs_map=./dat/GaLikeMap/likelihood_fix_p8_psf0123.dat
# optimal likelihood map for decaying DM
#dsphs_map=./dat/GaLikeMap/likelihood_ext_psf0123.dat
#solor modulation potential
epmod=0.6 #GV, positron
apmod=0.6 #GV, antiproton
# What is the DM halo you want to use during propagation?
WhatHalo=1 #WhatHalo, 1 for NFW, 2 for Einasto and 3 for isothermal
# 6 propagation parameters combination
# See propagation model in 1205.6474.
# 1-6 correspond to Table I from left to right.
WhatGALPROP=2 #propagation parameters combination
use_dSphs=T
                # use_dSphs
use_ep=T
               # use_ep
use_ap=T
                 # use_ap
```

# If users want to compute decaying DM, this flag should be True.

# Then, code will read decay\_time instead of sigmav.

This input format is exactly the same as that in CosmoMC [54] and SuperBayes [55]. The modules to read the input file are src/Read\_parameters.py and alternatively src/inifile.f90. The parameters are explained below:

• output\_name

The name of the prefix of the output files. For the Python interface, this is not used because the output is shown on the screen. However, a user can always modify the subroutine print\_debug\_info to store the output with the name defined by this flag.

• seebug

An integer number to control the debug information shown on the screen. **seebug=0** to 6 will print different kinds of results, for debugging or any interesting outputs such as the pre- or post-propagated particle spectra, and the fitting results of nuisance parameters.

• dsphs\_map

Likelihood map of dSphs. The full path of the map is needed. For the case of decaying DM, the optimal likelihood map is recommended.

• epmod and apmod

Solar modulation potentials in units of GV, for electrons/positrons and protons/antiprotons, respectively.

# • WhatHalo

An integer number to specify the DM halo profile. 1 for NFW, 2 for Einasto and 3 for isothermal.

# • WhatGALPROP

An integer number to determine the propagation parameters. 1 to 6 corresponds to the six sets of propagation parameters given in Ref. [20] (see also Table I of this manual).

# • use\_dSphs, use\_ep, and use\_ap

Logical flags to choose whether or not to use the corresponding data. The current version includes Fermi  $\gamma$ -ray data from dSphs, AMS-02  $e^+e^-$  data, and PAMELA  $\bar{p}$  data.

# • decayDM

Logical flag to determine whether the DM annihilates or decays.

# • DMmass, sigmav, decay\_time

The DM mass in GeV, annihilation cross section in cm<sup>3</sup>s<sup>-1</sup>, and decaying lifetime in s, respectively. sigmav takes effect when decayDM=F, and decay\_time takes effects when decayDM=T.

• use\_pppc4

Logical flag to specify whether to use the PPPC4 table to calculate dN/dE. If F, an external file needs to be provided by the user. The file needs to be 4 columns, with E in GeV,  $\frac{dN}{dE}\Big|_{\gamma}$  in GeV<sup>-1</sup>,  $\frac{dN}{dE}\Big|_{e^+}$  in GeV<sup>-1</sup>, and  $\frac{dN}{dE}\Big|_{\bar{p}}$  in GeV<sup>-1</sup>, respectively.

• BR\_x

Branching ratios for different channels when using the PPPC4 table. The identification numbers can be found either at the PPPC4 website or in the beginning of the file src/PYTHIA\_PPPC4.f90.

The outputs include the computed  $\chi^2$  values on the screen. Users can easily modify the code src/monitorLikeDM.f90 to generate their own favored outputs or store the outputs to a file.

#### D. Package roadmap

The source code of LIKEDM is located in the **src**/ folder. The main routine is **pyLikeDM.py** for the **Python** interface. We introduce the other routines grouped by their functionality:

• Initialization and Reading tables

src/ReadTable.f90 src/PYTHIA\_PPPC4.f90 src/inifile.f90

The routine src/ReadTable.f90 reads the tables of the dSph likelihood map, the Green's functions for the propagation of positrons and antiprotons in the Galaxy, and the DM annihilation/decay spectra dN/dE either from PPPC4 (connected with  $src/PYTHIA_PPPC4.f90$ ) or the user supplied external file.

In addition to reading the tables, we also collect all the initialization subroutines in the src/ReadTable.f90 module and hence this module is the heart of LIKEDM.

The module src/inifile.f90 is taken from CosmoMC. It reads the parameter file and sets default values of the parameters. It is *not* used by default but a user can use this module if they wish to construct their own interface.

• Gamma-rays from dSphs

# src/gamma\_dSphs.f90

This module provides the computation of DM annihilation/decay fluxes from a set of dSphs and their combined likelihood. The *J*-factors of these dSphs have been implemented in the likelihood calculation with a profile likelihood method. By default, a total of 15 dSphs, which are Bootes I, Canes Venatici II, Carina, Coma, Draco, Fornax, Hercules, Leo II, Leo IV, Sculptor, Segue I, Sextans, Ursa Major II, Ursa Minor, and Willman I, are included in the current version of LIKEDM. Users can enable or disable some dSphs likelihood by turning on/off the flags dsphs\_use in the src/ReadTable.f90 module. The *J*-factors are taken from Ref. [50] for both annihilating and decaying DM.

• Charged cosmic rays: background

## src/charge\_bkg.f90

This routine calculates the background fluxes of  $e^+e^-$  and  $\bar{p}$  using the empirical formulae described in Sec. II-C.

• Charged cosmic ray: DM  $e^+$  and  $\bar{p}$ 

src/charge\_lepton.f90
src/charge\_antip.f90

These two routines compute the propagated fluxes of positrons and antiprotons from DM annihilation or decay, using the Green's function method described in Sec. II-B.

• Charged cosmic rays: datasets

# src/charge\_data.f90

This routine gives the cosmic ray data from AMS-02 [11, 32–34] and PAMELA [35], and returns the calculated  $\chi^2$  values for given theoretical fluxes.

```
• Auxiliary module
```

```
src/MathLib.f90
src/monitorLikeDM.f90
src/Main.f90
```

The file src/MathLib.f90 provides some useful mathematical tools such as interpolation and integration. The routine src/monitorLikeDM.f90 gives the outputs controlled by the flag seebug. We also have a main routine, src/Main.f90, which is currently *not* used in the Python version but left as an alternative in the pure Fortran version.

#### V. SUMMARY

We present a publicly-available tool, LIKEDM, for likelihood calculations in DM models. It enables fast computation of the likelihood of a given DM model (defined by mass, cross section or decay rate, and annihilation or decay yield spectrum), without digging into the details of CR propagation, Fermi-LAT data analysis, or related astrophysical backgrounds. This code depends only on the Minuit minimization package, and is easy to install and run. The code LIKEDM also provides an easy framework that can be linked to any particle model or Monte-Carlo code to perform a global study.

The currently released version (v1.0) contains only the indirect detection data, including the electron/positron measurements by AMS-02, the antiproton measurements by PAMELA, and the  $\gamma$ -ray observations from dSphs by Fermi-LAT. Further developments with more data, e.g., from the  $\gamma$ -ray observations of the Galactic center and isotropic background, as well as underground direct detection data, will be carried out soon.

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