Tools for Dark Matter Indirect Detection

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Abstract I discuss ingredients and recipes for computing signals of TeV-scale Dark Matter annihilations and decays in the Galaxy and beyond: the energy spectra of electrons and positrons, antiprotons, antideuterons, gamma rays, neutrinos and antineutrinos e, mu, tau at production, the propagation functions for charged particles in the Galaxy, the energy spectra at the location of the Earth, the gamma ray fluxes from the Galaxy and from beyond. All results discussed here are available in numerical form and ready to be consumed.
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1 Introduction

Cosmology and astrophysics provide several convincing **evidences of the existence of Dark Matter** (DM). The observation that some mass is missing to explain the internal dynamics of galaxy clusters and the rotations of galaxies dates back respectively to the '30s and the '70s. The observations from weak lensing, for instance in the spectacular case of the so-called 'bullet cluster', provide evidence that there is mass where nothing is optically seen. More generally, global fits to a number of cosmological datasets (Cosmic Microwave Background, Large Scale Structure and also Type Ia Supernovae) allow to determine very precisely the amount of DM in the global energy-matter content of the Universe at $\Omega_{\rm DM}h^2 = 0.1123 \pm 0.0035$.

All these signals pertain to the gravitational effects of Dark Matter at the cosmological and extragalactical scale. Searches for explicit manifestation of the DM particles that are supposed to constitute the halo of our own galaxy (and the large scale structures beyond it) have instead so far been giving negative results, but this might be on the point of changing.

Indirect searches for Dark Matter aim at detecting the signatures of the annihilations or decays of DM particles in the fluxes of Cosmic Rays (CRs), intended in a broad sense: charged particles (electrons and positrons, protons and antiprotons, deuterium and antideuterium), photons (gamma rays, X-rays, synchrotron radiation), neutrinos. In general, a key point of all these

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searches is to look for channels and ranges of energy where it is possible to beat the background from ordinary astrophysical processes. This is for instance the basic reason why searches for charged particles focus on fluxes of antiparticles (positrons, antiprotons, antideuterons), much less abundant in the Universe than the corresponding particles, and searches for photons or neutrinos have to look at areas where the DM-signal to astro-noise ratio can be maximized.

Pioneering works have explored indirect detection (ID) as a promising avenue of discovery since the late-70's. Since then, innumerable papers have explored the predicted signatures of countless particle physics DM models. In the past 3 years or so, however, the field has experienced a significant burst of activity, mainly due to the results presented by a few very well performing experiments, above all the PAMELA satellite, the FERMI satellite and the HESS telescope. It is fair to say that the field has passed, for better or for worse, from a theory-driven state to a data-driven phase.

The next few years promise to be even richer of data from Dark Matter Indirect Searches (certainly in terms of further explorations of the parameter spaces, and hopefully even with a positive detection). It will therefore be useful to have at disposal a **set of consistent tools** that can allow to interpret these data in a model independent way and cross-check between different channels. This is what we have aimed at realizing in [1] and that I am going to briefly present in this text. While the complete discussions can be found in [1], here I will focus only on some aspects and on the general infrastructure, leaving most of the formulae outside. All the results are available in numerical form in [2].

2 Fluxes at production

The first ingredients that one needs to compute DM ID signatures are of course the **fluxes of stable Standard Model particles** ($e^\pm, \bar{p}, \bar{d}, \gamma, \overset{(-)}{\nu}_{e,\mu,\tau}$) originating from DM annihilations, or decays. We want to be as model independent as possible and so we consider DM annihilations (parameterized by the DM DM cross section σv) and decays (described by the DM decay rate $\Gamma = 1/\tau$) into a large number of primary channels:

$$\begin{aligned}
&e^+_L e^-_L,\ e^+_R e^-_R,\ \mu^+_L \mu^-_L,\ \mu^+_R \mu^-_R,\ \tau^+_L \tau^-_L,\ \tau^+_R \tau^-_R, q\bar{q},\ c\bar{c},\ b\bar{b},\ t\bar{t},\ \gamma\gamma,\ gg,\\
&W^+_L W^-_L,\ W^+_T W^-_T,\ Z_L Z_L,\ Z_T Z_T,\\
&h_{115}h_{115},\ h_{135}h_{135},\ h_{170}h_{170},\ h_{200}h_{200},\ h_{300}h_{300},\ h_{400}h_{400},\ h_{500}h_{500},\\
&\nu_e\bar{\nu}_e,\ \nu_\mu\bar{\nu}_\mu,\ \nu_\tau\bar{\nu}_\tau, VV \to 4e,\ VV \to 4\mu,\ VV \to 4\tau,
\end{aligned} \tag{1}$$

where $q = u, d, s$ denotes a light quark and h_m is the Standard Model (SM) Higgs boson, with m being its mass in GeV. The last three channels denote models in which the annihilation or decay first happens into some new (light) boson V which then decays into a pair of leptons, along the lines of the models proposed in [3, 4].

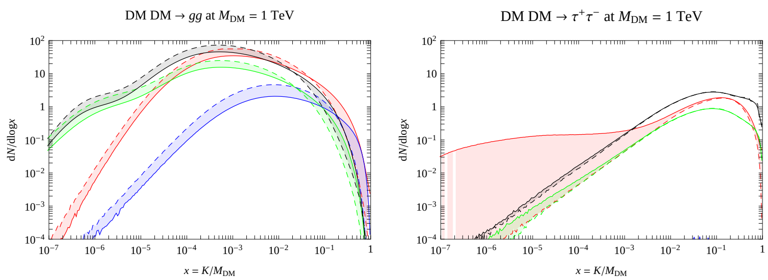

Figure 1: Comparison between Monte Carlo results: PYTHIA is the continuous line, HERWIG is dashed. Photons (red), $e^{\pm}$ (green), $\bar{p}$ (blue), $\nu = \nu_e + \nu_\mu + \nu_\tau$ (black).

All the spectra are available on [2]. Here I want to discuss two general issues: i) the intrinsic uncertainty in computing those spectra with numerical methods and ii) the impact of ElectroWeak radiation.

2.1 MonteCarlo 'uncertainty'

Almost every DM indirect search analysis uses the collider MonteCarlo code PYTHIA to compute the annihilation spectra, despite the fact that other codes are available and that in any case all codes have been designed and calibrated for the collider environment and in an energy range which (until recently) was much lower than the multi-TeV one of interest for some DM models.

In order to get a feeling of the intrinsic uncertainty related to these issues, in [1] we employed the two most widely used MonteCarlo simulation programs: PYTHIA [5] (version 8.135) and HERWIG [6] (version 6.510). In fact, the algorithms implemented in HERWIG and PYTHIA are quite different, in both parton showers and hadronization.

The discrepancies can be tentatively quoted at ±20%, although bigger surprises are possible for some channels. In particular, fig. 1 (right panel) shows a case in which the predictions from HERWIG largely underestimate the flux of photons at low energy. This is due to the fact that the latter does not include photon emission off leptons.

2.2 ElectroWeak radiation

The emission of W's and Z's from the final (or initial!) states is enhanced by one or more powers of $\ln(M/M_{W,Z})$, with $M \gg M_{W,Z}$, not depending on the DM model. For large M, these can be important and lead to significant modifications of the spectra. First, the weak emission entails the presence of further unstable hadrons in the final state, and therefore it significantly modifies the flux of γ's and $e^{\pm}$ at energies $E \ll M$, M being the DM mass. Moreover, W/Z radiation leads to a $\bar{p}$ contribution, even in annihilation channels that would be completely leptonic if EW radiation is neglected. For instance, a DM DM $\to \nu\bar{\nu}$ channel also yield $e^{\pm}$'s, γ's and $\bar{p}$'s, rather counter-intuitively.

3 Propagation of charged cosmic rays

The e^-, e^+ and $\bar{p}$ produced in any given point of the halo **propagate** immersed in the turbulent galactic magnetic field. The field consists of random inhomogeneities that act as scattering centers for charged particles, so that their journey can effectively be described as a diffusion process from an extended source (the DM halo) to some final given point (the location of the Earth, in the case of interest). While diffusing, charged CRs experience several other processes, and in particular energy losses due to synchrotron radiation, Inverse Compton Scattering (ICS) on the low energy photons of the CMB and starlight, Coulomb losses, bremsstrahlung, nuclear spallations... . Quantitatively, the steady-state number density $n_f(\vec{x}, E)$ per unit energy E of the cosmic ray species f $(= e^+, e^-, \bar{p})$ in any given point $\vec{x}$ obeys to a diffusion-loss equation [7]

$$
\begin{aligned}
-\mathcal{K}(E)\cdot\nabla^2 n_f - \frac{\partial}{\partial E}\left(b(E,\vec{x})\, n_f\right) \quad &+ \quad \frac{\partial}{\partial z}\left(\mathrm{sign}(z)\, V_{\rm conv}\, n_f\right) \\
&= \quad Q(E,\vec{x}) - 2h\,\delta(z)\,\Gamma\, n_f\,. \qquad (2)
\end{aligned}
$$

The first term accounts for diffusion, with a coefficient conventionally parameterized as $\mathcal{K}(E) = \mathcal{K}_0(E/\mathrm{GeV})^\delta$. The second term describes energy losses: the coefficient b is position-dependent since the intensity of the magnetic field (which determines losses due to synchrotron radiation) and the distribution of the photon field (which determines losses due to ICS) vary across the galactic halo. It also has a dependence on energy which is equal to E^2 only as long as ICS is approximated with Thomson scattering. It is normalized by the value of the typical loss timescale at 1 GeV at the location of the Earth $\tau_\odot = 5.7\times 10^{15}$ sec. This is illustrated in fig. 2. The third term deals with convection while the last term accounts for nuclear spallations, that occur with rate Γ in the disk of thickness $h \simeq 100$ pc. The source, DM annihilations, is given by $Q = 1/2\,(\rho(\vec{x})/M)^2 \sum_i \mathrm{BR}_i\langle\sigma v\rangle\ (dN^i_f/dE)$, where σv is the total annihilation cross section and the sum runs over all primary channels i in which the cosmic ray species f is produced. $dN^i_f/dE)$ are the spectra discussed in Sec. 2. $\rho(\vec{x})$ is the DM density distribution in the galactic halo. The different processes described above have a different importance depending on the particle species: the journey of electrons and positrons is primarily affected by synchrotron radiation and inverse Compton energy losses, while for antiprotons these losses are negligible and convection and spallation dominate.

Eq. (2) is usually solved numerically in a diffusive region with the shape of a solid flat cylinder that sandwiches the galactic plane, with height $2L$ in the z direction and radius $R = 20\,\mathrm{kpc}$ in the r direction. The location of the solar system corresponds to $\vec{x}_\odot = (r_\odot, z_\odot) = (8.33\,\mathrm{kpc}, 0)$. Boundary conditions are imposed such that the number density n_f vanishes on the surface of

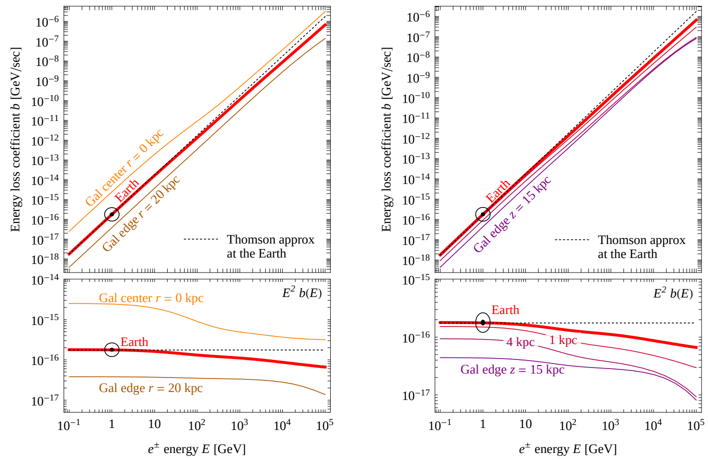

Figure 2: Energy loss coefficient function for electrons and positrons in the Milky Way. Left panel: at several locations along the galactic radial coordinate r, right panel: above (or below) the location of the Earth along the coordinate z. The dot points at the value of $\tau_\odot$.

the cylinder, outside of which the charged cosmic rays freely propagate and escape. The values of the propagation parameters δ, K_0, $V_{\rm conv}$ and L are deduced from a variety of (ordinary) cosmic ray data and modelizations.

In the usual solution scheme, the energy loss coefficient b is considered as constant in space and proportional to E^2. In [1], we improved the numerical solution by including the correct space and energy dependence. This involves defining a set of energy-dependent 'halo functions' (see [1] for more details).

Once the propagation is performed, one obtains the fluxes of charged cosmic rays at the location of the Earth. Depending on the choices for the propagation parameters, the resulting spectra can differ by more than one order of magnitude. Two representative examples can be found in fig. 3: positrons on the left and antiprotons on the right. The MIN, MED, MAX labels refer indeed to different sets of propagation parameters. The positron panel also reports the spectrum obtained by the old approximated propagation method (black line). All numerical spectra are available in [2].

4 Galactic γ rays

Dark Matter produces high energy gamma rays both by direct ('prompt') emission during annihilation or decay and by Inverse Compton Scattering of $e^\pm$ produced by DM on the ambient

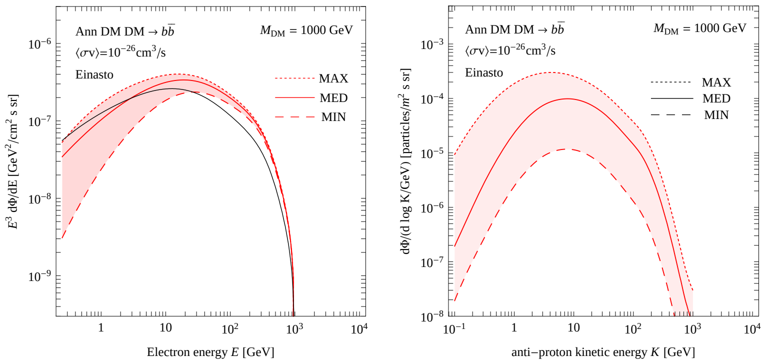

Figure 3: Examples of propagated fluxes of charged CRs at the location of the Earth. Positrons on the left and antiprotons on the right.

light ('secondary'). The former are included in the fluxes discussed in Sec. 2. The latter have to be computed by folding the maps of propagated $e^{\pm}$ with the maps of target light, in particular in the Galaxy.

One of the best features of these fluxes of ICS γ rays as possible signatures of DM is that they originate from 'everywhere' in the diffusion volume of the galactic halo, including regions where the astrophysical background is reduced (e.g. at high latitudes). Moreover, other energy losses (such as synchrotron radiation) are sub-dominant with respect to Inverse Compton energy losses essentially everywhere, so that, thanks to energy conservation, the resulting ICS γ flux suffers only moderate astrophysical uncertainties.

In [1] we presented a compact formalism to compute galactic ICS γ-ray fluxes, employing a set of functions similar to the halo functions that are introduced for the propagation of charged cosmic rays (briefly discussed above). An example of the resulting fluxes is reported in fig. 4, left. This example chooses a specific DM model and a small but not too small observational rectangular window of 5° around the Galactic Center. The fluxes are plotted for different choices of DM profile, showing that variations of two orders of magnitude are possible. Again, all numerical spectra can be computed with the tools available in [2].

5 Extragalactic γ rays

The γ-rays emitted by DM annihilations or decays in all the extragalactic structures and (in principle) all along the history of the Universe reach us in the form of an isotropic contribution to the total γ-ray intensity. In [1] we discuss in detail how to compute it. With respect to the galactic case, there are a few main differences: (i) one has to include the effect of the

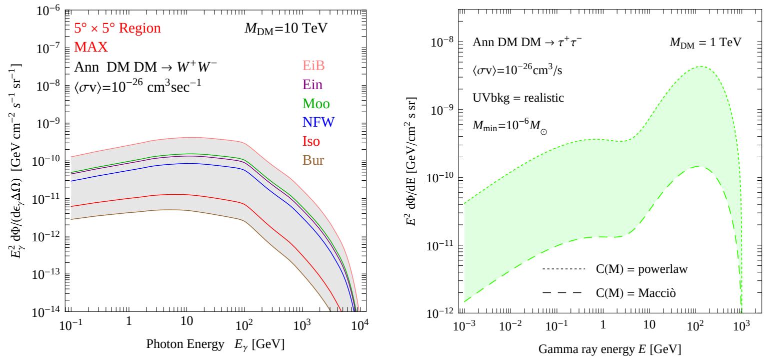

Figure 4: Left: example of fluxes of ICS γ-rays from the Galaxy, for different choices of the DM galactic profile. Right: example of fluxes of extragalactic γ-rays, illustrating the impact of changing the assumption for the concentration parameter.

'cosmological dimming' due to the expansion of the Universe, (ii) one has to include the fact that, unlike in the galactic environment, on cosmologically large distances one can not neglect the absorption of gamma-rays and finally (iii) one has to account for the history of formation of DM structures. Fig. 4, right, shows an example of the resulting fluxes. One also sees that, varying the choice for the concentration function $C(M)$ (one of the parameters associated to the history of halo formation), the spread can be almost 2 orders of magnitude.

6 Conclusions

The next few years will be rich of data in the field of indirect searches for Dark Matter. It will be interesting, from a phenomenological and model-independent point of view, to have at disposal all the tools needed to quickly interpret and cross check them. This is what we aimed at providing in [1]. We make all numerical results downloadable from [2]. The main innovations introduced in the paper are: (i) a comparison between different MCs, (ii) an improved semi-analytical propagation for $e^\pm$ in the Galaxy, (iii) a set of 'halo functions' for computing ICS γ-ray fluxes, (iv) a thorough analysis of the uncertainties that affect extragalactic γ-ray fluxes.

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