INDIRECT DARK MATTER DETECTION*

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Dark matter particles could self-annihilate or decay producing a flux of antimatter particles, gamma-rays or neutrinos which could be observed as an excess over their expected astrophysical backgrounds, opening the possibility of indirectly detecting dark matter. In this paper, we will review the calculation of the expected fluxes of Standard Model particles produced in the annihilation or the decay of dark matter particles, as well as the limits on the dark matter properties which follow from observations.

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1. Introduction

There is mounting evidence that dark matter has been indirectly detected via its gravitational interactions. The first indication was presented by F. Zwicky in his crucial paper from 1937 *On the Masses of Nebulae and of Clusters of Nebulae* [1], where he applied the virial theorem to determine the total mass of the Coma Cluster from his observations of the velocities of the members of the cluster, obtaining the lower limit $M > 9\times10^{46}$ gr. Considering that the Coma Cluster contains approximately 1000 galaxies, it follows that the average mass of each galaxy is $\bar{M} = 9\times10^{43}\,\mathrm{gr} = 4.5\times10^{10}M_{\odot}$, which is, in words of Zwicky, "somewhat unexpected, in view of the fact that the luminosity of an average nebula is equal to that of about 8.5×10^7 suns". From here, Zwicky inferred that in the Coma Cluster there is about 500 times more gravitating matter than luminous matter, which is now believed to be constituted by dark matter.

Another strong indication for dark matter was found by Rubin and Ford [2] from the measurement of the velocities of sixty seven HII regions in the Andromeda Galaxy, finding that the velocities of the regions at large

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distances to the center were much larger than those expected from the Newtonian theory of gravity. This result was confirmed some years later by Rubin, Ford and Thonnard [3] from measurement of the rotation curves of 21 Sc galaxies, concluding that "it is inescapable that non-luminous matter exists beyond the optical galaxy". This strong conclusion was, however, challenged by Milgrom in 1983 [4], who pointed out that a modification of Newtonian dynamics could explain the rotation curves of the galaxies without invoking new kinds of matter. The modification just consists in substituting the well known second Newton's law $m_g\vec{a}=\vec{F}$ by $m_g\mu(a/a_0)\vec{a}=\vec{F}$, where $\mu(x\gg 1)\simeq 1$ and $\mu(x\ll 1)\simeq x$. Hence, the force exerted on a slowly accelerating object is proportional to its acceleration squared, instead of just the acceleration. The critical acceleration can be inferred from observations and takes the value of $a_0\simeq 10^{-8}\,\mathrm{cm\,s^{-2}}$. Nevertheless, observations of the Bullet Cluster by Clowe *et al.* [5] revealed a clear separation between the location of the luminous matter, which was determined by the Chandra X-ray Observatory, and the location of the gravitating matter, which was inferred from weak lensing observations, thus providing strong evidence for particle dark matter.

Lastly, there is evidence for the existence of dark matter not only in distance scales of galaxies and clusters of galaxies, but also at cosmological scales. Namely, the ΛCDM cosmological model, which is currently favored by observations of the angular power spectrum of the cosmic microwave background, requires the 22% of the energy budget of the Universe to be in the form of cold dark matter [6].

The cosmological and astrophysical evidence for dark matter require the dark matter particle to fulfill the following properties:

1. It is dark, namely it does not carry electric charge or color charge. If the dark matter particle carried positive charge, it would form a bound state DM^+e^-, which could be detected in experiments as an anomalously heavy hydrogen atom. Searches for these exotic atoms in sea water exclude abundances of anomalously heavy water with respect to ordinary water larger than $\sim 10^{-29}$ for $m_{\mathrm{DM}}\sim 100\,\mathrm{GeV}$, hence ruling out this possibility. Analogously, if the dark matter particle had negative electric charge, it would bind to nuclei forming anomalously heavy isotopes, which have an abundance also severely constrained by experiments. A review of searches of cosmologically long lived charged particles can be found in [7].

2. It is not made of baryons, as reflected by the fact that the total matter density is $\Omega_{\mathrm{m}}h^2=0.13$ while the baryon density is $\Omega_b h^2=0.022$, six times smaller [6].

3. It moved non-relativistically at the time of the formation of the first structures (see *e.g.* [8]).

4. It exists today, namely it has a lifetime which is longer than the age of the Universe $\tau_{\rm U} \sim 10^{17}$ s.

None of the Standard Model particles fulfills simultaneously all these properties, hence the dark matter particle must belong to a new sector beyond the Standard Model of Particle Physics. One of the most pressing questions in astroparticle physics consists in detecting the dark matter particle and determine its particle physics properties (mass, lifetime, spin, *etc.*). In this paper, we will review the methods proposed to indirectly detect dark matter particles and the limits on the dark matter properties which stem from the, so far, negative searches. We will first postulate that dark matter particles can annihilate or decay producing a flux of antimatter particles, gamma-rays or neutrinos and then, we will derive limits on the annihilation cross section or the decay rate as a function of the mass from the non-observation of an excess in the fluxes with respect to the expected astrophysical backgrounds.

2. The source term

The Milky Way is believed to be embedded in a dark matter halo, although its structure is currently unknown. It is commonly assumed that the dark matter distribution is spherically symmetric, with radial distribution denoted as $\rho(r)$ and which is determined using theoretical models. Some popular choices are the Navarro–Frenk–White (NFW) density profile [9, 10]

$$\rho_{\rm DM}(r) = \frac{\rho_0}{(r/r_{\rm s})[1+(r/r_{\rm s})]^2} \tag{1}$$

with scale radius $r_{\rm s} = 24.42$ kpc, the Einasto profile [11–13]

$$\rho_{\rm DM}(r) = \rho_0 \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_{\rm s}}\right)^{\alpha} - 1\right]\right\} \tag{2}$$

with $\alpha = 0.17$ and $r_{\rm s} = 28.44$ kpc, and the much shallower isothermal profile [14]

$$\rho_{\rm DM}(r) = \frac{\rho_0}{r^2 + r_{\rm s}^2} \tag{3}$$

with $r_{\rm s} = 4.38$ kpc. In all the cases, the overall normalization factor ρ_0 is chosen to reproduce the local dark matter density $\rho_\odot = 0.39$ GeV/cm^3 [15–19] with $r_\odot = 8.5$ kpc.

The annihilation or decay of dark matter particles with mass $m_{\rm DM}$ at the position $\vec{r}$ with respect to the center of the Galaxy produces primary particles with a rate per unit of kinetic energy and unit volume given by

$$Q(T,\vec{r}) = \begin{cases} \dfrac{\rho^2_{\rm DM}(\vec{r})}{2m^2_{\rm DM}} \sum_f \langle\sigma v\rangle_f \dfrac{dN^f}{dT} & \text{(annihilations)}\,, \\ \dfrac{\rho_{\rm DM}(\vec{r})}{m_{\rm DM}} \sum_f \Gamma_f \dfrac{dN^f}{dT} & \text{(decays)}\,, \end{cases} \tag{4}$$

where $\langle\sigma v\rangle_f$ denotes the velocity weighted annihilation cross section, Γ_f the decay rate and dN^f/dT the energy spectrum of the particles produced in the annihilation or decay channel f.

The annihilation or the decay of dark matter particles can produce antiparticles, gamma-rays or neutrinos. We will discuss in the next sections how to calculate the fluxes at the Earth of each messenger as well as the experimental limits.

3. Antimatter fluxes

Antimatter particles, after being produced in the dark matter annihilation or decay, propagate in a complicated way in the Galaxy before reaching the Earth. Antimatter propagation in the Milky Way is commonly described by a stationary two-zone diffusion model with cylindrical boundary conditions [20]. Under this approximation, the number density of antiparticles per unit kinetic energy, $f(T,\vec{r},t)$, satisfies the following transport equation

$$\begin{aligned} 0 \;=\; \frac{\partial f}{\partial t} &= \nabla\cdot[K(T,\vec{r})\nabla f] + \frac{\partial}{\partial T}[b(T,\vec{r})f] - \nabla\cdot\left[\vec{V_c}(\vec{r})f\right] \\ &\quad -2h\delta(z)\Gamma_{\rm ann} f + Q(T,\vec{r})\,. \end{aligned} \tag{5}$$

The boundary conditions require the solution $f(T,\vec{r},t)$ to vanish at the boundary of the diffusion zone, which is approximated by a cylinder with half-height $L = 1$–15 kpc and radius $R = 20$ kpc.

The first term on the right-hand side of the transport equation is the diffusion term, which accounts for the propagation through the tangled Galactic magnetic field. The diffusion coefficient $K(T,\vec{r})$ is assumed to be constant throughout the diffusion zone and is parametrized by

$$K(T) = K_0\,\beta\,\mathcal{R}^\delta\,, \tag{6}$$

where $\beta = v/c$ and $\mathcal{R}$ is the rigidity of the particle, which is defined as the momentum in GeV per unit charge, $\mathcal{R} \equiv p(\mathrm{GeV})/Z$. The normalization K_0

and the spectral index δ of the diffusion coefficient are related to the properties of the interstellar medium and can be determined from the flux measurements of other cosmic ray species, mainly from the boron to carbon (B/C) ratio [21]. The second term accounts for energy losses due to inverse Compton scattering on starlight or the cosmic microwave background, synchrotron radiation and ionization. The third term is the convection term, which accounts for the drift of charged particles away from the disk and which is induced by the Milky Way's Galactic wind. It has axial direction and is also assumed to be constant inside the diffusion region: $\vec{V}_{\rm c}(\vec{r}) = V_{\rm c}\ {\rm sign}(z)\ \vec{k}$. The fourth term accounts for antimatter annihilation with rate $\Gamma_{\rm ann}$, when it interacts with ordinary matter in the Galactic disk, which is assumed to be an infinitely thin disk with half-width $h = 100$ pc. The ranges of the astrophysical parameters that are consistent with the B/C ratio and that produce the minimal (MIN), median (MED) and maximal (MAX) antimatter fluxes were calculated in [21] and are listed in Table I. Lastly, $Q(T, \vec{r})$ is the source term of positrons or antiprotons which was discussed in Sec. 2. In this equation, reacceleration effects and non-annihilating interactions of antimatter in the Galactic disk have been neglected.

TABLE I

Astrophysical parameters compatible with the B/C ratio that yield the minimal (MIN), median (MED) and maximal (MAX) antimatter fluxes.

Model	δ	K_0 (kpc^2/Myr)	L (kpc)	$V_{\rm c}$ (km/s)
MIN	0.85	0.0016	1	13.5
MED	0.70	0.0112	4	12
MAX	0.46	0.0765	15	5

Finally, the flux of primary antiparticles at the Solar System from dark matter annihilations or decays is given by

$$\Phi^{\rm DM}(T) = \frac{v}{4\pi} f(T)\,, \tag{7}$$

where v is the velocity of the antimatter particle.

At energies smaller than ~ 10 GeV the antimatter fluxes at the top of the atmosphere can differ considerably from the interstellar fluxes, due to solar modulation effects. Under the force field approximation [22], the fluxes at the top of the atmosphere are related to the interstellar fluxes by the following simple relation [23]

$$\Phi^{\rm TOA}(T_{\rm TOA}) = \left(\frac{2mT_{\rm TOA} + T_{\rm TOA}^2}{2mT_{\rm IS} + T_{\rm IS}^2}\right) \Phi^{\rm IS}(T_{\rm IS})\,, \tag{8}$$

where m is the mass of the antimatter particle and $T_{\rm IS} = T_{\rm TOA} + \phi_{\rm F}$, with $T_{\rm IS}$ and $T_{\rm TOA}$ being the antimatter particle kinetic energies at the heliospheric boundary and at the top of the Earth's atmosphere, respectively, and $\phi_{\rm F}$ being the Fisk potential, which varies between 500 MV and 1.3 GV over the eleven-year solar cycle.

3.1. Positrons

For the case of the positrons, Galactic convection and annihilations in the disk can be neglected in the transport equation, which is then simplified to

$$\nabla \cdot [K(E,\vec{r}\,)\nabla f_{e^+}] + \frac{\partial}{\partial E}[b(E,\vec{r}\,) f_{e^+}] + Q(E,\vec{r}\,) = 0\,, \tag{9}$$

where the rate of energy loss, $b(E,\vec{r}\,)$, is due to the inverse Compton scattering (ICS) of the positrons on the interstellar radiation field (ISRF) and to the synchrotron losses in the Galactic field: $b = b_{\rm ICS} + b_{\rm syn}$. The part of the energy loss that is due to ICS is given by

$$b_{\rm ICS}(E_e,\vec{r}\,) = \int_0^\infty d\epsilon \int_\epsilon^{E_\gamma^{\rm max}} dE_\gamma\, (E_\gamma - \epsilon)\, \frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma} f_{\rm ISRF}(\epsilon,\vec{r}\,)\,, \tag{10}$$

where $f_{\rm ISRF}(\epsilon,\vec{r}\,)$ is the number density of photons of the interstellar radiation field, which includes the CMB, thermal dust radiation and starlight and which is given in [24]. For electron energies $E_e = 1\,{\rm GeV}$, $b_{\rm ICS}$ ranges between $4.1 \times 10^{-17}\,{\rm GeV\,s^{-1}}$ and $1.9 \times 10^{-15}\,{\rm GeV\,s^{-1}}$, depending on $\vec{r}$. At higher energies, $b_{\rm ICS}$ approximately scales like $\sim E_e^2$. On the other hand, the synchrotron loss part reads

$$b_{\rm syn}(E_e,\vec{r}\,) = \frac{4}{3}\sigma_{\rm T}\gamma_e^2\frac{B^2}{2}\,, \tag{11}$$

where $B^2/2$ is the energy density of the Galactic magnetic field, being $B \simeq 6\,\mu{\rm G}\exp(-|z|/2\,{\rm kpc} - r/10\,{\rm kpc})$ [25]. At the position of the Sun, this yields an energy loss of $b_{\rm syn} \simeq 4.0 \times 10^{-17}(E_e/\,{\rm GeV})^2\,{\rm GeV\,s^{-1}}$. A common simplification consists in assuming that the rate of energy loss is spatially constant and is parametrized by $b(E) = \frac{E^2}{E_0^2\tau_E}$ with $E_0 = 1$ GeV and $\tau_E \simeq 10^{16}$ s.

Rather than measuring the positron flux, most experiments measure the positron fraction, since most sources of systematic error, such as detector acceptance or trigger efficiency, cancel out when computing the ratio of particle fluxes. The positron fraction is defined as the flux of positrons over the flux of electrons plus positrons

$$\mathrm{PF}(E) \;=\; \frac{\Phi^{\mathrm{DM}}_{e^+}(E) + \Phi^{\mathrm{bkg}}_{e^+}(E)}{\Phi^{\mathrm{tot}}(E)}\,, \tag{12}$$

where

$$\Phi^{\mathrm{tot}}(E) \;=\; \Phi^{\mathrm{DM}}_{e^-}(E) + \Phi^{\mathrm{DM}}_{e^+}(E) + k\,\Phi^{\mathrm{bkg}}_{e^-}(E) + \Phi^{\mathrm{bkg}}_{e^+}(E)\,, \tag{13}$$

being $\Phi^{\mathrm{DM}}_{e^\pm}$ and $\Phi^{\mathrm{bkg}}_{e^\pm}$ the $e^\pm$ fluxes from dark matter annihilations or decays and the background fluxes, respectively. The background flux of positrons is constituted by secondary positrons produced in the collision of primary protons and other nuclei with the interstellar medium. On the other hand, the background flux of electrons is constituted by a primary component, presumably produced in supernova remnants, as well as a secondary component, produced by spallation of cosmic rays on the interstellar medium and which is much smaller than the primary component. Whereas the spectrum and normalization of secondary electrons and positrons is calculable in a given propagation model (*e.g.* [26]), the spectrum and normalization of primary electrons is unknown (hence the free normalization parameter k in Eq. (13)). A good parametrization of the interstellar background fluxes in the "model 0" of [27] was derived in [28] and reads:

$$\Phi^{\mathrm{bkg}}_{e^-}(E) \;=\; \left(\frac{82.0\,\epsilon^{-0.28}}{1+0.224\,\epsilon^{2.93}}\right)\mathrm{GeV}^{-1}\mathrm{m}^{-2}\,\mathrm{s}^{-1}\mathrm{sr}^{-1}\,, \tag{14}$$

$$\Phi^{\mathrm{bkg}}_{e^+}(E) \;=\; \left(\frac{38.4\,\epsilon^{-4.78}}{1+0.0002\,\epsilon^{5.63}} + 24.0\,\epsilon^{-3.41}\right)\mathrm{GeV}^{-1}\mathrm{m}^{-2}\,\mathrm{s}^{-1}\mathrm{sr}^{-1}\,, \tag{15}$$

where $\epsilon = E/1\,\mathrm{GeV}$. In the energy range between 2 GeV and 1 TeV, these approximations are better than 5%.

Various experiments have reported in the last few years a series of new results pointing to the existence of a primary source of electrons and positrons. The PAMELA Collaboration reported evidence for a sharp rise of the positron fraction at energies 7–100 GeV [29], possibly extending toward even higher energies, compared to the expectations from spallation of primary cosmic rays on the interstellar medium [26]. This result confirmed previous hints about the existence of a positron excess from HEAT [30], CAPRICE [31] and AMS-01 [32]. Furthermore, the Fermi LAT Collaboration has published measurements of the electron-plus-positron flux from 20 GeV to 1 TeV of unprecedented accuracy [33], revealing an energy spectrum that roughly follows a power law $\propto E^{-3.0}$ without any prominent spectral feature. Simultaneously, the H.E.S.S. Collaboration reported a measurement of the cosmic-ray electron-plus-positron spectrum at energies larger than 340 GeV, confirming the Fermi result of a power-law spectrum with spectral index of $3.0 \pm 0.1(\text{stat.}) \pm 0.3(\text{syst.})$, which furthermore steepens at about 1 TeV [34, 35]. The measured energy spectrum is harder than expected from conventional diffusive models, although it can be accommodated by an appropriate change of the injection spectrum of primary electrons. However, when taken together with the steep rise in the positron fraction as seen by PAMELA up to energies of 100 GeV, the Fermi LAT data suggest the existence of additional Galactic sources of high-energy electrons and positrons with energies up to a few TeV. Furthermore, it should be borne in mind that the determination of the correct Galactic cosmic-ray scenario is still an open problem, and while an electron injection spectrum harder than the conventional could reproduce the Fermi data, fails to account for the AMS-01 and HEAT data below 20 GeV and the H.E.S.S. data above 1 TeV [27].

These results raised a lot of interest in the astrophysics and particle physics communities, leading to many proposals trying to explain this excess. One of the most popular astrophysical interpretations of the positron excess is in terms of the electron–positron pairs produced by the interactions of high-energy photons in the strong magnetic field of pulsars [36–38]. Alternatively, the positrons could be originating from the decay of charged pions which are, in turn, produced by the hadronic interactions of high-energy protons accelerated by nearby sources [39].

An arguably more exciting explanation of the cosmic-ray $e^\pm$ excesses is the possibility that the electrons and positrons are produced in the annihilation or the decay of dark matter particles. Should this interpretation be confirmed by future experiments, then the $e^\pm$ excesses would constitute the first non-gravitational evidence for the existence of dark matter in our Galaxy. The $e^\pm$ excesses can be explained in terms of dark matter annihilations when $\mathrm{DM\,DM} \to \mu^+\mu^-$ provided the dark matter particle has a mass of 1–2 TeV and the annihilation cross section is $\langle\sigma_{\rm ann}v\rangle \sim 10^{-23}\ \mathrm{cm^3\,s^{-1}}$. In the case of annihilations $\mathrm{DM\,DM} \to \tau^+\tau^-$, the dark matter mass must be $\sim 3\,\mathrm{TeV}$ and the annihilation cross section, $\langle\sigma_{\rm ann}v\rangle \sim 10^{-22}\ \mathrm{cm^3\,s^{-1}}$. It is then apparent that interpreting the $e^\pm$ excesses in terms of dark matter annihilations requires very peculiar dark matter properties: *(i)* the dark matter particle should couple predominantly to leptons to avoid overproduction of antiprotons, namely the dark matter particle must be "leptophilic", *(ii)* it must be rather heavy and *(iii)* it must have an unusually large annihilation cross section, about 10^3–10^4 times larger than the maximal annihilation cross section expected for a thermal relic, $\langle\sigma_{\rm ann}v\rangle \sim 3\times10^{-26}\ \mathrm{cm^3\,s^{-1}}$, namely a "boost factor" is required. Furthermore, it has been argued that if dark matter annihilations are the origin of the PAMELA anomaly, then the predicted gamma-ray emission from the center of the Galaxy is in conflict with the H.E.S.S. observations for typical cuspy halo profiles [40–42]. On the other hand, if the positron excess is due to the decay of dark matter particles, the dark matter mass must be in the TeV range and the lifetime must be $\sim 10^{26}$ s. In this case, no boost factors are required and the predicted gamma-ray flux is consistent with present measurements [28, 42, 43]. The electron/positron excesses have attracted a lot of interest in the Particle Physics community and many models have been proposed to explain the data in terms of dark matter annihilations [44–46] or decays [47–50].

3.2. Antiprotons

The general transport equation, Eq. (5), can be simplified for antiprotons by taking into account that in this case energy losses are negligible. Therefore, the transport equation for the antiproton density, $f_{\bar{p}}(T,\vec{r},t)$, is simplified to

$$0 = \frac{\partial f_{\bar{p}}}{\partial t} = \nabla\cdot(K(T,\vec{r})\nabla f_{\bar{p}}) - \nabla\cdot\left(\vec{V}_c(\vec{r}) f_{\bar{p}}\right) - 2h\delta(z)\Gamma_{\mathrm{ann}} f_{\bar{p}} + Q(T,\vec{r})\,, \quad (16)$$

where the annihilation rate, Γ_{ann}, is given by

$$\Gamma_{\mathrm{ann}} = \left(n_{\mathrm{H}} + 4^{2/3} n_{\mathrm{He}}\right) \sigma^{\mathrm{ann}}_{\bar{p}p} v_{\bar{p}}\,. \quad (17)$$

In this expression, it has been assumed that the annihilation cross section between an antiproton and a helium nucleus is related to the annihilation cross section between an antiproton and a proton by the simple geometrical factor $4^{2/3}$. On the other hand, $n_{\mathrm{H}} \sim 1\ \mathrm{cm}^{-3}$ is the number density of hydrogen nuclei in the Milky Way disk, $n_{\mathrm{He}} \sim 0.07\ n_{\mathrm{H}}$ the number density of helium nuclei and $\sigma^{\mathrm{ann}}_{\bar{p}p}$ is the annihilation cross section, which is parametrized by [51]

$$\sigma^{\mathrm{ann}}_{\bar{p}p}(T) = \begin{cases} 661\left(1+0.0115\,T^{-0.774} - 0.948\,T^{0.0151}\right)\ \mathrm{mbarn}\,, & T < 15.5\,\mathrm{GeV}\,, \\ 36\,T^{-0.5}\ \mathrm{mbarn}\,, & T \geq 15.5\,\mathrm{GeV}\,. \end{cases} \quad (18)$$

The PAMELA experiment has measured the cosmic antiproton-to-proton fraction with a fairly high accuracy [52], finding no significant deviation with respect to the expectations from spallations of cosmic rays on the interstellar medium [53]. This allows to set stringent constraints on the annihilation cross section or the decay width of dark matter particles which produce antiprotons in their self-annihilations or decays. Namely, the cross section for the process DM DM $\to W^+W^-$ must be $\langle\sigma_{\mathrm{ann}} v\rangle \leq (3\text{–}270) \times 10^{-26}\mathrm{cm}^3\,\mathrm{s}^{-1}$ and for the process DM DM $\to b\,\bar{b}$, $\langle\sigma_{\mathrm{ann}} v\rangle \leq (4.2\text{–}240) \times 10^{-26}\mathrm{cm}^3\,\mathrm{s}^{-1}$, both for $m_{\rm DM} = 100$–1000 GeV, assuming the Einasto profile and a diffusion model with half width of 4 kpc [54]. The limits on the decay width for the decay DM $\to W^+W^-$ read $\Gamma^{-1} > (20\text{–}3) \times 10^{27}\,$s and for the decay DM $\to b\bar{b}$, $\Gamma^{-1} > (15\text{–}7) \times 10^{27}\,$s [55], in both cases for $m_{\rm DM} = 200$–2000 GeV and for the MED propagation model in Table I.

3.3. Antideuterons

The search for antideuterons is a promising method to detect dark matter annihilations or decays. The antideuteron flux expected from spallations of cosmic rays on the interstellar medium is peaked at a kinetic energy per nucleon $T_{\bar{D}} \sim 5$ GeV$/n$ and rapidly decreases at smaller kinetic energies [56, 57]. In contrast, the spectrum of antideuterons from dark matter annihilations or decays is usually much flatter at low kinetic energies and could easily overcome the astrophysical background [58]. For this reason, it has been argued that the search of antideuterons from dark matter annihilations [58–64] or decays [64, 65] is practically background free and that the observation of one single cosmic antideuteron in the future experiments AMS-02 [66] or GAPS [67] would constitute an evidence for an exotic antideuteron source.

To describe the antideuteron production, it is common to employ the coalescence model [61, 68–70], which postulates that the probability of the formation of an antideuteron out of an antiproton–antineutron pair with given four-momenta $k_{\bar{p}}^\mu$ and $k_{\bar{n}}^\mu$ can be approximated as a narrow step function $\Theta\left(\Delta^2 + p_0^2\right)$, where $\Delta^\mu = k_{\bar{p}}^\mu - k_{\bar{n}}^\mu$. In this model, the coalescence momentum p_0 is the maximal relative momentum of the two antinucleons that still allows the formation of an antideuteron, and depends on the underlying process and on the center of mass energy [64]. One can show that for $|\vec{k}_{\bar{D}}| \gg p_0$, being $\vec{k}_{\bar{D}} = \vec{k}_{\bar{p}} + \vec{k}_{\bar{n}}$, this ansatz leads to the following differential antideuteron yield in momentum space

$$\gamma_{\bar{D}} \frac{d^3 N_{\bar{D}}}{d^3 k_{\bar{D}}} \left(\vec{k}_{\bar{D}}\right) = \frac{1}{8} \frac{4}{3} \pi p_0^3 \cdot \gamma_{\bar{p}} \gamma_{\bar{n}} \frac{d^3 N_{\bar{p}} d^3 N_{\bar{n}}}{d^3 k_{\bar{p}} d^3 k_{\bar{n}}} \left(\frac{\vec{k}_{\bar{D}}}{2}, \frac{\vec{k}_{\bar{D}}}{2}\right) . \tag{19}$$

Since antideuterons are produced by the coalescence of one antiproton and one antineutron, it is apparent that there is a strong correlation between the cosmic antideuteron flux and the cosmic antiproton flux. It has been argued in [64] that the strong limits on the primary antiproton flux from the PAMELA experiment severely constrain the possibility of observing antideuterons from dark matter annihilations or decays at AMS-02 or GAPS, being the expected number too small to unequivocally attribute any possible excess to dark matter annihilations or decays.

4. Gamma-ray searches

The gamma-ray flux from dark matter annihilation or decays is composed of two components: *(i)* the inverse Compton scattering (ICS) radiation of electrons or positrons produced in the annihilation or the decay on the interstellar radiation field and *(ii)* the prompt gamma-ray flux, which is produced directly in the annihilation or the decay. Let us discuss each of them separately.

4.1. Inverse Compton scattering

The electrons and positrons that are generically produced in the annihilation or the decay of dark matter particles also generate a contribution to the total gamma-ray flux through their inverse Compton scattering on the interstellar radiation field (ISRF), which includes the cosmic microwave background, thermal dust radiation and starlight. A pedagogical review can be found in Ref. [71]. Furthermore, the interactions of energetic electrons and positrons with the Galactic magnetic field produce synchrotron radiation in the radio band with frequencies $\mathcal{O}$(0.1–100 GHz), which could also be observed (see *e.g.* Ref. [72, 73]).

The production rate of gamma rays with energy E_γ at the position $\vec{r}$ of the Galaxy, due to inverse Compton scattering of dark matter electrons (or positrons) with number density $f_{e^\pm}(E_e,\vec{r})$ on photons of the ISRF with number density $f_{\rm ISRF}(\epsilon,\vec{r})$ reads

$$\frac{dR_\gamma^{\rm IC}(\vec{r})}{dE_\gamma}=\int\limits_0^\infty d\epsilon\int\limits_{m_e}^\infty dE_e\,\frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma}f_{e^\pm}(E_e,\vec{r})f_{\rm ISRF}(\epsilon,\vec{r})\,. \qquad (20)$$

Here, $d\sigma^{\rm IC}/dE_\gamma$ denotes the differential cross section of inverse Compton scattering of an electron with energy E_e, where an ISRF photon with energy ϵ is up-scattered to energies between E_γ and $E_\gamma+dE_\gamma$. It can be derived from the Klein–Nishina formula and is given by

$$\frac{d\sigma^{\rm IC}(E_e,\epsilon)}{dE_\gamma}=\frac{3}{4}\frac{\sigma_{\rm T}}{\gamma_e^2\,\epsilon}\left[2q\ln q+1+q-2q^2+\frac{1}{2}\frac{(q\Gamma)^2}{1+q\Gamma}(1-q)\right], \qquad (21)$$

where $\sigma_{\rm T}=0.67\,$barn denotes the Compton scattering cross section in the Thomson limit, $\gamma_e\equiv E_e/m_e$ is the Lorentz factor of the electron, $m_e=511\,$keV is the electron mass, and we have defined $\Gamma\equiv 4\gamma_e\epsilon/m_e$ and $q\equiv E_\gamma/\Gamma(E_e-E_\gamma)$. Equation (21) holds in the limit where $\epsilon, m_e\ll E_e$, and kinematics and the neglect of down-scattering require that $\epsilon\le E_\gamma\le(1/E_e+1/4\gamma_e^2\epsilon)^{-1}\equiv E_\gamma^{\rm max}$. On the other hand, the number density of photons of the interstellar radiation field, $f_{\rm ISRF}(\epsilon,\vec{r})$ was given in [24] and the number density of electrons and positrons from dark matter annihilations or decays, $f_{e^\pm}(E_e,\vec{r})$, follows from solving the appropriate transport equation (5). At energies above a few 10 GeV, the transport equation is dominated by the energy loss terms, and the number density of electrons and positrons can be approximated by

$$f_{e^\pm}(E_e,\vec{r}) \simeq \frac{1}{b(E_e,\vec{r})} \int_{E_e}^{\infty} d\tilde{E}_e \, Q\left(\tilde{E}_e,\vec{r}\right) , \tag{22}$$

$Q(E_e,\vec{r})$ being the source term, Eq. (4), and $b(E,\vec{r})=b_{\rm ICS}(E,\vec{r})+b_{\rm syn}(E,\vec{r})$ the rate of energy loss, which was calculated in Eqs. (10), (11).

Finally, the gamma-ray flux from ICS that is received at Earth reads

$$\frac{dJ_{\text{halo-IC}}}{dE_\gamma}(l,b) = 2\,\frac{1}{4\pi}\int_0^\infty ds\,\frac{dR_\gamma^{\rm IC}[r(s,l,b)]}{dE_\gamma}\,, \tag{23}$$

where the factor of 2 takes into account the fact that both dark matter electrons and positrons contribute equally to the total flux of gamma rays.

4.2. Prompt radiation

The prompt gamma-ray flux from dark matter annihilations or decays receives two contributions. The first one stems from the annihilations or the decays of dark matter particles in the Milky Way halo and leads to a differential flux given by

$$\frac{dJ_{\rm halo}}{dE_\gamma}(l,b) = \frac{1}{4\pi}\int_0^\infty Q[E_\gamma, r(s,l,b)]ds\,, \tag{24}$$

where the source term is given in Eq. (4). Explicitly,

$$\frac{dJ_{\rm halo}}{dE_\gamma}(l,b) = \frac{1}{4\pi}\sum_f \frac{\langle\sigma v\rangle_f}{2m_{\rm DM}^2}\frac{dN_\gamma^f}{dE_\gamma}\int_0^\infty \rho_{\rm halo}^2[r(s,l,b)]ds \tag{25}$$

for the case of dark matter annihilations and

$$\frac{dJ_{\rm halo}}{dE_\gamma}(l,b) = \frac{1}{4\pi}\sum_f \frac{\Gamma_f}{m_{\rm DM}}\frac{dN_\gamma^f}{dE_\gamma}\int_0^\infty \rho_{\rm halo}[r(s,l,b)]ds \tag{26}$$

for the case of decays. In these equations, $\rho_{\rm halo}(r)$ is the density profile of dark matter particles in our Galaxy as a function of the distance from the Galactic center, r, and dN_γ^f/dE_γ is the energy spectrum of gamma-rays produced in the annihilation or decay of a dark matter particle in the channel f. Note that the gamma-ray flux received at Earth depends on the Galactic coordinates, longitude l and latitude b, and is given by a line-of-sight integral over the parameter s, which is related to r by

$$r(s,l,b) = \sqrt{s^2 + R_\odot^2 - 2sR_\odot \cos b \cos l}\,, \tag{27}$$

where $R_\odot = 8.5\,\mathrm{kpc}$ is the distance of the Sun to the Galactic center. The angular distribution in the prompt radiation could be exploited to detect dark matter through the anisotropy in the gamma-ray background induced by dark matter annihilations [74] or decays [75].

In addition to the gamma-ray flux that originates from the annihilation or the decay of dark matter particles in the Milky Way halo, there exists a largely isotropic contribution generated by the annihilation or the decay of dark matter particles at cosmological distances. Analogously to the Milky Way component, the latter receives contributions from the direct annihilation or decay of dark matter particles into photons, and from the gamma rays produced by the inverse Compton scattering of dark matter electrons and positrons on the intergalactic radiation field.

The direct decay of dark matter particles at cosmological distances produces a gamma-ray flux that is given by

$$\frac{dJ_{\mathrm{eg}}}{dE_\gamma} = \frac{1}{4\pi}\frac{\Omega_{\mathrm{DM}}^2\rho_{\mathrm{c}}^2}{2m_{\mathrm{DM}}^2}\int_0^\infty \frac{dz}{H(z)}\sum_f \langle\sigma v\rangle_f \frac{dN_\gamma^f}{dE_\gamma}\left[(z+1)E_\gamma\right](1+z)^3\Delta^2(z)\; e^{-\tau(E_\gamma,z)} \tag{28}$$

for the case of annihilations and

$$\frac{dJ_{\mathrm{eg}}}{dE_\gamma} = \frac{1}{4\pi}\frac{\Omega_{\mathrm{DM}}\rho_{\mathrm{c}}}{m_{\mathrm{DM}}}\int_0^\infty dz \sum_f \Gamma_f \frac{dN_\gamma^f}{dE_\gamma}\left[(z+1)E_\gamma\right]\; e^{-\tau(E_\gamma,z)} \tag{29}$$

for the case of decays. In these equations, $\rho_{\mathrm{c}} = 5.5\times 10^{-6}\,\mathrm{GeV/\,cm^3}$ denotes the critical density of the Universe and $H(z) = H_0\sqrt{\Omega_\Lambda + \Omega_{\mathrm{m}}(z+1)^3}$ is the Hubble expansion rate as a function of redshift z; for a ΛCDM cosmology these parameters read $\Omega_\Lambda = 0.73$, $\Omega_{\mathrm{m}} = 0.27$, $\Omega_{\mathrm{DM}} = 0.22$ and $h \equiv H_0/100\,\mathrm{km\ s^{-1}\,Mpc^{-1}} = 0.72$, as derived from the seven-year WMAP data [6]. Furthermore, we have included an attenuation factor for the gamma-ray flux, which incorporates the effects of electron–positron pair production by collisions of gamma rays from dark matter annihilations or decays with the extragalactic background light emitted by galaxies in the ultraviolet, optical and infrared frequencies [76]. The attenuation factor is determined by the optical depth $\tau(E_\gamma, z)$, which was calculated in [77]. Note that in the case of dark matter annihilations we have also included a factor $(1+z)^3\Delta^2(z)$ which accounts for the enhancement of the annihilation signal due to the clustering of dark matter particles at the redshift z. This enhancement factor can be calculated using N-body simulations and ranges between $\sim 10^4$ and 10^7 [78].

In contrast to the inverse Compton scattering radiation, which has a featureless spectrum, the prompt radiation could contain spectral features which may allow the unambiguous identification of dark matter annihilations or decays in the sky. The possibility of observing features in the gamma-ray spectrum will be discussed in detail in the next subsection.

4.3. Gamma-ray features

No known astrophysical source can produce sharp features in the gamma-ray spectrum, therefore, the observation of such feature would constitute an unequivocal sign of dark matter. Conversely, the non-observation of gamma-ray features leads to very strong limits on models, since background subtraction is very efficient. Three possible gamma-ray features have been identified in the literature: gamma-ray lines, gamma ray "boxes" and virtual internal Bremsstrahlung.

4.3.1. Gamma-ray lines

Gamma ray lines are produced in the dark matter annihilations DM DM $\to \gamma(\gamma, Z, h)$ or decays DM $\to \gamma(\nu, h)$ and have a very peculiar spectrum

$$\frac{dN}{dE} = N_\gamma \delta(E - E_0)\,, \tag{30}$$

where N_γ denotes the number of monoenergetic photons produced, and E_0 their energy. For example, for the annihilations DM DM $\to \gamma\gamma$, $N_\gamma = 2$ and $E_0 = m_{\rm DM}$, while for the decays DM $\to \gamma\nu$, $N_\gamma = 1$ and $E_0 = m_{\rm DM}/2$. Gamma-ray lines are predicted to be fairly intense in some concrete models of dark matter annihilations [79–83] or dark matter decays [49, 50, 84–87].

The Fermi LAT Collaboration has conducted a negative search for Galactic gamma-ray lines in the diffuse flux in the energy range from 7 to 200 GeV [88], being the derived limits $\langle\sigma v\rangle_{\gamma\gamma} \lesssim (0.03\text{–}4.6)\times 10^{-27}\,{\rm cm^3\,s^{-1}}$ for $m_{\rm DM} =$ 7–200 GeV, $\langle\sigma v\rangle_{Z\gamma} \lesssim (0.02\text{–}10.1)\times 10^{-27}\,{\rm cm^3\,s^{-1}}$ for $m_{\rm DM} =$ 63–210 GeV. It should be mentioned, though, that it has been reported in [89] the possible existence of a gamma-ray line signal in the Galactic center with a significance of 4.6σ (3.2σ when taking into account the look-elsewhere effect) which, if interpreted in terms of dark matter annihilations, would correspond to $m_{\rm DM} \simeq 130$ GeV and $\langle\sigma v\rangle_{\gamma\gamma} \simeq 1.3\times 10^{-27}\,{\rm cm^3\,s^{-1}}$ when using the Einasto dark matter profile.

For dark matter decays, the negative search by the Fermi LAT translates into $\tau_{\nu\gamma} \gtrsim (3.6\text{–}26.0) \times 10^{28}\,\mathrm{s}$ for $m_{\mathrm{DM}} = 14\text{–}400\,\mathrm{GeV}$ for the NFW profile. The limits on the decay width have been extended in [90] to larger dark matter masses and yield $\tau_{\nu\gamma} \gtrsim 2 \times 10^{25}\,\mathrm{s}$ for $m_{\mathrm{DM}} = 400\text{–}800\,\mathrm{GeV}$ (from the MAGIC limits on the gamma-ray flux from the Perseus galaxy [91]) and $\tau_{\nu\gamma} \gtrsim (3\text{–}20) \times 10^{26}\,\mathrm{s}$ for $m_{\mathrm{DM}} = 800\,\mathrm{GeV}\text{–}7\,\mathrm{TeV}$ (from the measurements of the electron flux by H.E.S.S. Collaboration at TeV energies [34, 35]). In the future, observation of the diffuse background by the Cherenkov Telescope Array (CTA, see Ref. [92] for a recent discussion) might allow to set limits on the dark matter lifetime $\tau_{\nu\gamma} \sim 3\text{–}8 \times 10^{28}\,\mathrm{s}$ for $m_{\mathrm{DM}} = 500\,\mathrm{GeV}\text{–}10\,\mathrm{TeV}$.

The limits on gamma-ray lines are so stringent that are relevant even for models where the gamma-ray line is generated by quantum effects [90]. For example, the decay width for the radiatively induced gamma-ray line, $\Gamma(\psi_{\mathrm{DM}} \to \gamma\nu)$, when the dark matter decays at tree level into muons of the same chirality reads

$$\Gamma(\psi_{\mathrm{DM}} \to \gamma\nu) \simeq \frac{3\alpha_{\mathrm{em}}}{8\pi} \Gamma\left(\psi_{\mathrm{DM}} \to \mu^+_{\mathrm{L,R}}\mu^-_{\mathrm{L,R}}\nu\right) . \tag{31}$$

The limits on the decay width from the PAMELA measurements of the positron fraction read $\Gamma(\psi_{\mathrm{DM}} \to \mu^+_{\mathrm{L,R}}\mu^-_{\mathrm{L,R}}\nu) \gtrsim 10^{-26}\,\mathrm{s}^{-1}$, therefore, Eq. (31) implies $\Gamma(\psi_{\mathrm{DM}} \to \gamma\nu) \gtrsim 10^{-29}\,\mathrm{s}^{-1}$, which is slightly below the sensitivity of present experiments for low dark matter masses and to the projected sensitivity of CTA for larger dark matter masses. In the case that the dark matter decays democratically into all flavours, $\psi_{\mathrm{DM}} \to \ell^+_{\mathrm{L,R}}\ell^-_{\mathrm{L,R}}\nu$, the result is a factor of three larger. Moreover, if the decay is mediated by a heavy vector, the corresponding decay widths must be multiplied by an additional factor of 9. Therefore, the limits on the parameters of these scenarios stemming from the non-observation of loop generated gamma-ray lines are competitive with those stemming from the non-observation of an excess in the electron/positron flux. In specific models, such as when the dark matter is constituted by hidden gauginos of an unbroken U(1), several scalar particles circulate in the loop resulting in a further enhancement of the decay rate into gamma-lines [50].

4.3.2. Gamma-ray boxes

Gamma-ray boxes are produced in scenarios where dark matter particles self-annihilate or decay into intermediate particles which, in turn, decay producing monoenergetic gamma-rays [93]. Consider for definiteness the case of a dark matter particle that self-annihilates into a pair of scalars ϕ that, in turn, decay into a pair of photons. Each of the four photons emitted per annihilation has a monochromatic energy $E'_\gamma = m_\phi/2$ in the rest frame of the corresponding scalar ϕ. In the lab frame — where the dark matter particles are non-relativistic and the scalars have energy $E_\phi = m_{\rm DM}$ — the photon energy reads

$$E_\gamma = \frac{m_\phi^2}{2\,m_{\rm DM}}\left(1 - \cos\theta\sqrt{1 - \frac{m_\phi^2}{m_{\rm DM}^2}}\right)^{-1} \tag{32}$$

with θ the angle between the outgoing photon and the parent scalar in the lab frame. From this equation, it follows that the spectrum has sharp ends defined by the parameters $m_{\rm DM}$ and m_ϕ. The highest (lowest) energy corresponds to a photon emitted at an angle $\theta = 0^\circ$ (180°) with respect to the momentum of the parent scalar. Since the decaying particle is a scalar, the photon emission is isotropic. Hence the resulting spectrum is constant between the energy endpoints and takes a flat, box-shaped form

$$\frac{dN_\gamma}{dE_\gamma} = \frac{4}{\Delta E}\Theta(E - E_-)\Theta(E_+ - E)\,, \tag{33}$$

where Θ is the Heaviside function, $\Delta E = E_+ - E_- = \sqrt{m_{\rm DM}^2 - m_\phi^2}$ is the box width and $E_\pm = (m_{\rm DM}/2)\left(1 \pm \sqrt{1 - m_\phi^2/m_{\rm DM}^2}\right)$. Note that in the limit $\Delta m/m_{\rm DM} \to 0$ (or, effectively, when $\Delta E/E_c$ falls bellow the experimental resolution) the spectrum dN_γ/dE_γ reduces to a line. But, unlike the well-known $\gamma\gamma$ and γZ lines, in this case there are four photons emitted per annihilation and each carries half of the dark matter particle rest-mass energy, or one-fourth for decaying dark matter models.

Interestingly, this model also produces a spectral feature even when the dark matter particle and the intermediate scalar ϕ are not degenerate in mass. In this case, the spectral plateau sits at non-negligible amplitudes and furthermore displays a sharp cut-off, which allows an efficient discrimination from the featureless gamma-ray background. The resulting limits approximately read $\langle\sigma v\rangle_{\phi\phi} \lesssim 10^{-27}$–$10^{-26}\,{\rm cm}^3\,{\rm s}^{-1}$ for $m_{\rm DM} = 5$–$500\,{\rm GeV}$ and $\Gamma_{\phi\phi}^{-1} \gtrsim (5$–$40) \times 10^{27}\,{\rm s}$ for $m_{\rm DM} = 5$–$1000\,{\rm GeV}$, both when $\Delta m/m_{\rm DM} = 1$ and assuming ${\rm BR}(\phi \to \gamma\gamma) = 1$ [93]. The limits are usually more stringent as $\Delta m/m_{\rm DM} \to 0$.

4.3.3. Virtual internal Bremsstrahlung

The signal of virtual internal Bremsstrahlung arises in models, where the dark matter particle is a Majorana fermion or a scalar which annihilates into a fermion–antifermion pair. In this case, the initial state of the annihilation process has zero angular momentum, therefore the annihilation cross section into a light fermion–antifermion pair is helicity suppressed [94, 95]. Nevertheless, the higher order process of emission of a photon (or more generally a vector boson) together with the fermion–antifermion pair lifts the helicity suppression [96, 97]. As a result, the $2 \to 3$ process can have a sizable cross section, even larger than the cross section for the $2 \to 2$ process. Furthermore, under some conditions that we will describe below, the energy spectrum of the emitted photon displays a sharp spectral feature which could be unambiguously attributed to dark matter annihilations if observed in the sky. It can be shown [98] that the differential three-body cross-section, as function of the VIB photon energy $x \equiv E/m_\chi$, is given by

$$v\frac{d\sigma}{dx} \simeq \frac{\alpha_{\rm em} y^4 N_c}{64\pi^2 m_\chi^2}(1-x)\left\{\frac{2x}{(\mu+1)(\mu+1-2x)} - \frac{x}{(\mu+1-x)2} - \frac{(\mu+1)(\mu+1-2x)}{2(\mu+1-x)^3}\ln\left(\frac{\mu+1}{\mu+1-2x}\right)\right\}, \quad (34)$$

where $\mu \equiv (m_\eta/m_\chi)^2$ parametrizes the mass splitting between the DM particle χ and the t-channel mediator η, N_c is a color factor and y is the Yukawa coupling between the Majorana dark matter particle, the fermion and the charged scalar particle which mediates the interaction. As can be checked from Eq. (34), the more degenerate in mass are the dark matter particle and the intermediate scalar, the more prominent is the feature in the gamma-ray spectrum. Interestingly, in the degenerate scenario also the direct detection rate is enhanced in the case of coupling to quarks [99, 100], as well as the antiproton production via the emission of weak gauge bosons or gluons, which also lifts the helicity suppression of the $2 \to 2$ process [101–106].

In [107], it was performed a search of the signature of virtual internal Bremsstrahlung with the Fermi LAT, the resulting limits being in the range $\langle\sigma v\rangle_{2\to3} \lesssim 5$–$60 \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $m_{\rm DM}$ in the range 40–300 GeV. These limits are not strong enough to probe the annihilation rates expected for thermally produced dark matter, however an improvement in sensitivity of one order of magnitude could suffice to test this interesting scenario. One should mention that in [107] it was reported a weak indication for a Bremsstrahlung-like signal in the Fermi LAT data that would correspond to a dark matter mass of ~ 150 GeV with a significance of 4.3σ (3.1σ when taking into account the look-elsewhere effect).

4.4. Targets for dark matter searches

A number of possible targets have been discussed in [108] to detect dark matter annihilations and in [109] to detect dark matter decays. In this subsection, we present a short overview of these targets and the current experimental limits.

4.4.1. Galactic center

The Milky Way center is a primary target for the search for dark matter annihilations or decays since this is the region of the sky where the largest fluxes are expected. Nonetheless, the search for dark matter annihilations in this region is hindered by possible source confusions and by the uncertainty in the modeling of the diffuse galactic background. In order to set conservative limits on the dark matter properties, it can be required that the flux from dark matter annihilations or decays should not exceed the measured flux in the Galactic center. This leads to limits on the annihilation cross section which are of the order of $\langle\sigma v\rangle \lesssim (8\text{–}200) \times 10^{-25}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $\mathrm{DM\,DM} \to \mu^+\mu^-$ and $\langle\sigma v\rangle \lesssim (4\text{–}200) \times 10^{-25}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $\mathrm{DM\,DM} \to b\bar{b}$, both for $m_{\mathrm{DM}} = 100\,\mathrm{GeV}\text{–}10\,\mathrm{TeV}$ and for an Einasto halo profile [110]. For the case of dark matter decays, the limits on the decay width read $\Gamma^{-1} \gtrsim (1\text{–}7) \times 10^{25}\,\mathrm{s}$ for $\mathrm{DM} \to \mu^+\mu^-$ and $\Gamma^{-1} \gtrsim (7\text{–}3) \times 10^{25}\,\mathrm{s}$ for $\mathrm{DM\,DM} \to \tau^+\tau^-$, both for $m_{\mathrm{DM}} = 100\,\mathrm{GeV}\text{–}10\,\mathrm{TeV}$ [110].

4.4.2. Extragalactic background

The diffuse extragalactic gamma-ray background is expected to be perfectly isotropic with a spectrum following a power law. Therefore, the non-observation of a significant deviation from a power law in the diffuse extragalactic gamma-ray spectrum can be used to set limits on the annihilation cross section or decay rate of dark matter particles. In the case of dark matter annihilations, the limits suffer from large uncertainties due to our ignorance on the value of the enhancement factor $(1+z)^3\Delta^2(z)$, *cf.* Eq. (28), and which amounts to three orders of magnitude in the limits. Adopting the recent Millennium II N-body simulations [111], the 90% C.L. limits on the cross section read $\langle\sigma v\rangle \leq (2\text{–}40) \times 10^{-25}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $\mathrm{DM\,DM} \to b\bar{b}$ and $m_{\mathrm{DM}} = 10\,\mathrm{GeV}\text{–}1\,\mathrm{TeV}$, $\langle\sigma v\rangle \leq (3\text{–}40) \times 10^{-24}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $\mathrm{DM\,DM} \to \mu^+\mu^-$ and $m_{\mathrm{DM}} = 70\,\mathrm{GeV}\text{–}7\,\mathrm{TeV}$, and $\langle\sigma v\rangle \leq (3\text{–}20) \times 10^{-27}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $\mathrm{DM\,DM} \to \gamma\gamma$ and $m_{\mathrm{DM}} = 3\text{–}100\,\mathrm{GeV}$ [112]. In the case of dark matter decay, the limits on the decay width are less sensitive to astrophysical uncertainties and read $\Gamma^{-1} > (2\text{–}8)\times 10^{25}\,\mathrm{s}$ for $\mathrm{DM} \to \mu^+\mu^-$ and $m_{\mathrm{DM}} = 10\,\mathrm{GeV}\text{–}10\,\mathrm{TeV}$, $\Gamma^{-1} > (5\text{–}10) \times 10^{25}\,\mathrm{s}$ for $\mathrm{DM} \to \tau^+\tau^-$ and $m_{\mathrm{DM}} = 10\,\mathrm{GeV}\text{–}1\,\mathrm{TeV}$, and $\Gamma^{-1} > (6\text{–}20) \times 10^{25}\,\mathrm{s}$ for $\mathrm{DM} \to b\bar{b}$ and $m_{\mathrm{DM}} = 120\,\mathrm{GeV}\text{–}1\,\mathrm{TeV}$ [113] (see also [114]).

4.4.3. Dwarf spheroidal galaxies

Dwarf spheroidal galaxies are believed to be dark matter dominated systems, due to their very large mass-to-light ratio. For this reason, they constitute excellent targets to search for dark matter annihilations. The Fermi Collaboration has set in [115] limits on the dark matter annihilation cross section from the observation of 14 dwarf spheroidal galaxies, mainly from Draco and Ursa Minor. These limits have been recently improved in [116, 117], excluding the "thermal" annihilation cross section $\langle\sigma v\rangle = 3\times10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $m_{\rm DM} < 40\,\mathrm{GeV}$ in the case of DM DM $\to b\bar{b}$ and $m_{\rm DM} < 10\,\mathrm{GeV}$ in the case of DM DM $\to \tau^+\tau^-$. The dwarf limits on the dark matter decay width read $\Gamma^{-1} > (1\text{–}0.7)\times10^{24}\,\mathrm{s}$ for $m_{\rm DM} = 30\,\mathrm{GeV}$–$1\,\mathrm{TeV}$ when DM $\to b\bar{b}$ and $\Gamma^{-1} > (7\text{–}0.02)\times10^{24}\,\mathrm{s}$ for $m_{\rm DM} = 10\,\mathrm{GeV}$–$10\,\mathrm{TeV}$ when DM $\to \mu^+\mu^-$ [118].

4.4.4. Galaxy clusters

Galaxy clusters are also excellent targets to search for dark matter since they are among the most massive objects in the Universe. The most stringent limits follow from observations by the Fermi LAT of the Fornax galaxy cluster, which require $\langle\sigma v\rangle < (2\text{–}80)\times10^{-24}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $m_{\rm DM} = 30\,\mathrm{GeV}$–$1\,\mathrm{TeV}$ and DM DM $\to b\bar{b}$, and $\langle\sigma v\rangle < (3\text{–}1)\times10^{-22}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$ for $m_{\rm DM} = 300\,\mathrm{GeV}$–$2\,\mathrm{TeV}$ and DM DM $\to \mu^+\mu^-$ [118]. The strongest limits on the dark matter decay width also follow from observations of the Fornax galaxy cluster and read, in the case DM $\to b\bar{b}$, $\Gamma^{-1} > (3\text{–}4)\times10^{26}\,\mathrm{s}$ for $m_{\rm DM} = 10$–$200\,\mathrm{GeV}$ and then decreases $\Gamma^{-1} > (3\text{–}0.6)\times10^{26}\,\mathrm{s}$ for $m_{\rm DM} = 200\,\mathrm{GeV}$–$10\,\mathrm{TeV}$, whereas for the case DM $\to \mu^+\mu^-$ they read $\Gamma^{-1} > (4\text{–}20)\times10^{25}\,\mathrm{s}$ for $m_{\rm DM} = 800\,\mathrm{GeV}$–$10\,\mathrm{TeV}$ [119].

5. Neutrino searches

The calculation of the neutrino flux from dark matter annihilations or decays in the Milky way proceeds along similar lines as for gamma-rays, being the fluxes analogous to those given by Eqs. (25), (26). In contrast to gamma-rays, however, after being produced in the decay or annihilation of dark matter particles, neutrinos undergo flavour oscillations. The neutrino oscillation probabilities in vacuum are given by

$$\begin{aligned} P(\nu_e \leftrightarrow \nu_e) &= 0.54\,, \\ P(\nu_e \leftrightarrow \nu_\mu) &= 0,26\,, & P(\nu_e \leftrightarrow \nu_\tau) = 0.20\,, \\ P(\nu_\mu \leftrightarrow \nu_\mu) &= P(\nu_\mu \leftrightarrow \nu_\tau) = 0.37\,, & P(\nu_\tau \leftrightarrow \nu_\tau) = 0.42 \end{aligned} \tag{35}$$

assuming the present best fit for the oscillation parameters [120]. Thus, a primary neutrino flux in a specific flavour is redistributed almost equally into all neutrino flavours during propagation and any flavour information is lost.

The detection of a neutrino flux at the Earth from dark matter annihilations or decays is hindered by a large atmospheric neutrino background, which is produced in cosmic-ray interactions with the Earth's atmosphere and which was calculated by Honda *et al.* [121]. Other sources of background are tau neutrinos from the decay of charmed particles that are also produced in cosmic-ray collisions with the atmosphere [122], neutrinos produced in cosmic-ray interactions with the solar corona [123] and neutrinos produced in cosmic-ray interactions with the interstellar medium in the Milky Way [124].

The IceCube Collaboration has searched for muon neutrinos from dark matter annihilations in the Galactic Center with the 40-string configuration and has derived 90% limits on the annihilation cross section which read, at $m_{\rm DM} = 1\,{\rm TeV}$, $\langle\sigma v\rangle \lesssim 10^{-23}\,{\rm cm}^3\,{\rm s}^{-1}$ for ${\rm DM\,DM} \to \nu\nu$, $\langle\sigma v\rangle \lesssim 10^{-22}\,{\rm cm}^3\,{\rm s}^{-1}$ for ${\rm DM\,DM} \to \mu^+\mu^-$, $\langle\sigma v\rangle \lesssim 3\times 10^{-22}\,{\rm cm}^3\,{\rm s}^{-1}$ for ${\rm DM\,DM} \to W^+W^-$ and $\langle\sigma v\rangle \lesssim 3\times 10^{-21}\,{\rm cm}^3\,{\rm s}^{-1}$ for ${\rm DM\,DM} \to b\bar{b}$ [125] (see also [126–128]). In the case of decaying dark matter, the limits on the decay width read, for $m_{\rm DM} = 2\,{\rm TeV}$, $\Gamma^{-1} \gtrsim 10^{25}\,{\rm s}$ for ${\rm DM} \to \nu\nu$, $\Gamma^{-1} \gtrsim 2\times 10^{24}\,{\rm s}$ for ${\rm DM} \to \mu^+\mu^-$, $\Gamma^{-1} \gtrsim 5\times 10^{23}\,{\rm s}$ for ${\rm DM} \to W^+W^-$ and $\Gamma^{-1} \gtrsim 5\times 10^{22}\,{\rm s}$ for ${\rm DM} \to b\bar{b}$ [125] (see also [128–131]). This analysis was extended in [132] to heavier dark matter masses, up to the Grand Unification Scale. In general, and except for the processes producing only neutrinos in the final state, the limits on the annihilation cross section or the decay width from a search of an exotic neutrino flux are less stringent than the limits derived using antimatter or gamma-rays.

In the case of dark matter annihilations, there exists a new detection target: the Sun. If the dark matter particles are weakly interacting, they can be captured in the Sun via their scatterings with the nucleons inside the Sun. Dark matter particles are captured inside the Sun at a rate [133]

$$C_{\rm c} \simeq 3.35\times 10^{18}\,{\rm s}^{-1}\left(\frac{\rho}{0.3\,{\rm GeV\,cm}^{-3}}\right)\left(\frac{270\,{\rm km/s}}{\bar{v}}\right)^3\left(\frac{\sigma^{\rm SD}_{\rm DM,p}}{10^{-6}\,{\rm pb}}\right)\left(\frac{1\,{\rm TeV}}{m_{\rm DM}}\right)^2 . \tag{36}$$

At the same time, dark matter particles annihilate and evaporate, thus giving a number of dark matter particles trapped inside the Sun as a function of time which is described by the following differential equation

$$\frac{dN(t)}{dt} = C_{\rm c} - C_{\rm a}N(t)^2 - C_{\rm e}N(t)\,. \tag{37}$$

Neglecting evaporation, one finds that the solution of this equation is given by

$$N(t) = \sqrt{\frac{C_{\rm c}}{C_{\rm a}}}\tanh\left(\frac{t}{\tau}\right)\,, \tag{38}$$

where $\tau \equiv 1/\sqrt{C_{\rm a}C_{\rm c}}$ is the equilibration scale for the process of capture and annihilation. Then, the annihilation rate reads

$$\Gamma_{\rm A} = \frac{C_{\rm a}}{2} N(t)^2 = \frac{C_{\rm c}}{2} \tanh^2\left(\frac{t}{\tau}\right) . \tag{39}$$

For times $t \gg \tau$, $\Gamma_{\rm A} \simeq \frac{C_{\rm a}}{2}$, therefore, the annihilation rate is determined by the capture rate, thus allowing to set limits on the scattering rate of dark matter particles with nucleons as a function of the dark matter mass from the non-observation of an excess in the neutrino flux from the Sun.

The IceCube Collaboration has set limits on the spin-dependent dark matter–proton scattering cross section which are of the order of $10^{-40}\,{\rm cm}^2$ for $m_{\rm DM} = 1\,{\rm TeV}$, assuming annihilations into W^+W^- [134], thus setting the best existing limit on the spin-dependent scattering cross section. For the spin independent scattering cross section, the limits from direct detection experiments such as XENON100 [135] are better, although for large dark matter masses indirect detection experiments give limits which start to be competitive with those from direct detection experiments.

6. Conclusions

In this paper, we have reviewed the possibility of indirectly detecting dark matter through the observation of an excess in the cosmic fluxes of antimatter, gamma-rays or neutrinos which could be produced in the self-annihilation or the decay of the dark matter particles, as well as the limits on the dark matter properties which follow from observations. Whereas present experiments do not rule out many interesting dark matter scenarios, there is a high discovery potential in indirect dark matter searches, as future experiments will start probing regions of the parameter space where a signal could be expected.

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