Physics Letters B 724 (2013) 288–295

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Effective theory of dark matter decay into monochromatic photons and its implications: Constraints from associated cosmic-ray emission

Michael Gustafsson, Thomas Hambye, Tiziana Scarnà *

Service de Physique Théorique, Université Libre de Bruxelles, Boulevard du Triomphe, CP225, 1050 Brussels, Belgium

ARTICLE INFO

Article history:
Received 26 March 2013
Received in revised form 12 June 2013
Accepted 14 June 2013
Available online 19 June 2013
Editor: A. Ringwald

ABSTRACT

We show that there exists only a quite limited number of higher dimensional operators which can naturally lead to a slow decay of dark matter particles into monochromatic photons. As each of these operators inevitably induces decays into particles other than photons, we show that the γ-lines it induces are always accompanied by a continuum flux of cosmic rays. Hence constraints on cosmic-ray fluxes imply constraints on the intensity of γ-lines and *vice versa*. A comparison with up to date observational bounds shows the possibilities to observe or exclude cosmic rays associated to γ-line emission, so that one could better determine the properties of the DM particle, possibly discriminating between some of the operators.

1. Introduction

One of the best "smoking-gun" signals for establishing the existence of an annihilating or decaying dark matter (DM) particle is the possible observation of a cosmic γ-ray line [1]. Forthcoming satellites [2–4] and air Cherenkov telescopes [5–7], but also current instruments like the Fermi large area telescope (Fermi-LAT) [8,9] and the HESS instrument [10,11], will allow to probe this possibility with further sensitivity. From DM particle annihilations the amount of monochromatic γ-rays produced is expected to be limited (even if in some cases it can saturate the present observational bounds) because it is in general loop suppressed with respect to the total annihilation cross section, that is generically constrained by the DM relic density. For a decay, on the contrary, the amount of monochromatic rays emitted could *a priori* be much larger. Even if in many scenarios the DM particle is not expected to decay at all, there exists a well-motivated theoretical framework where DM would naturally decay with a lifetime larger than the age of the Universe: if its stability is due to an accidental low energy symmetry that has no reason to be respected by any ultraviolet (UV) theory, just as expected for the proton in the standard model (SM). In this case the effect of the UV physics causing the decay is suppressed by powers of the UV scale. At low energy, this can be parametrized in full generality by writing down the most general effective theory respecting the low energy symmetries of the model. For a DM particle mass around the electroweak scale (as supported by thermal scenarios), it turns out that a decay suppressed by 4 powers of the grand unified theory (GUT) scale $\Lambda_{GUT} \simeq 10^{15}$ GeV, *i.e.* induced by dimension 6 operators, leads to a lifetime which can give fluxes of cosmic rays (CRs) of the order of current observational sensitivities, $\tau \simeq \Lambda_{GUT}^4/M_{DM}^5 \simeq 10^{26}$ s [12,13]. This is a too nice opportunity to probe the GUT scale to not study it in more detail. For an explicit example of a setup with an accidental symmetry, which can lead to DM decay into γ-lines through dimension 6 operators, see Ref. [13].

The use of an effective theory picture for a DM decay is fully justified because, unlike an annihilation, it necessarily requires a large UV scale (unless one would invoke extremely tiny coefficients). As explained below, this model independent gauge invariant effective operator approach implies that when a DM particle decays, it does so to several final states. It is therefore different from the usual model independent approach of considering indirect detection constraints on separated single decay final states, as *e.g.* Refs. [14]. The amount of CRs that these several final states induce is also in general larger than those from electroweak corrections on a γ-line final state, as considered in Ref. [15]. By allowing a systematic determination of the γ-ray line emission possibilities, and by properly taking care of the low energy symmetries of the theory, the low energy effective operator language is the appropriate one to approach a series of important related questions: What are the theoretical expectations to see a γ-line from a DM decay (including, what effective structure a UV theory must induce to do

* Corresponding author.
E-mail addresses: mgustafs@ulb.ac.be (M. Gustafsson), thambye@ulb.ac.be (T. Hambye), tscarna@ulb.ac.be (T. Scarnà).

0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2013.06.032

so)?[1] What are the possibilities to see a γ-line, given the CR constraints, and conversely to see CRs associated to the observation of a γ-line? And from there, what are the possibilities to discriminate among the various effective radiative operators, hence to have information on the DM particle whose decay would have produced the γ-line, and maybe on the UV physics associated?

2. Full list of radiative operators

To write down the most general effective theory of DM decays is a quite tremendous task, especially if one allows for new particles into which the DM particle could decay. In scenarios of accidentally stable DM, such particles can be expected, see *e.g.* Ref. [13]. However, for the production of monochromatic lines it turns out that this can be done, *i.e.* the number of operators (up to dimension 6) is quite limited.

This is due to the stringent criteria an operator must fulfill in this case:

a) First, obviously the operator must contain the DM field.
b) Secondly, in order for the operator to lead to a two-body decay with a photon, it must not contain too many fields (except eventually scalars that could be replaced by their vacuum expectation values (vev)) and it must contain either a hypercharge $F_Y^{\mu\nu}$ or a $SU(2)_L$ $F_L^{\mu\nu}$ field strength. If the DM particle is neutral, as we will assume here, the photon cannot come from a covariant derivative because in the two-body decays all fields are necessarily neutral. One could eventually have a photon emitted from an operator that contains a new $U(1)$ gauge field that kinematically mix with the hypercharge gauge boson, $\mathcal{L} \ni \varepsilon F_Y^{\mu\nu} F'_{\mu\nu}$ (rendering the various neutral particles to be effectively milli-charged). We will not consider this possibility here. It gives a range of bounds on the emission of γ-ray lines which is similar to the one obtained below (see Ref. [16] for details).
c) Thirdly, some operators can be related to other ones through various relations, equations of motions, shift of a derivative or use of the fact that the commutator of two covariant derivatives D_μ, D_ν gives $F_{\mu\nu}$. However one must be careful in using these relations. The criteria we apply here is that through these relations an operator can be dropped from the list only if in this way there is a one-to-one correspondence between this operator and another one already in the list. Otherwise both operators must be kept because in general they give different ratios of γ-line to CRs.

Applying the criteria above there are only three possible general dimension 5 structures, one for each of the three types of DM particle we consider here, scalar, fermion or vector: $\phi_{DM} F_{\mu\nu} F^{\mu\nu}$, $\bar{\psi}\sigma_{\mu\nu}\psi_{DM} F^{\mu\nu}$, $F^{DM}_{\mu\nu} F^{\mu\nu}\phi$ respectively. By specifying the nature of the $F^{\mu\nu}$ field strengths one obtains 9 possible operators, 5 for a scalar candidate, and 2 each for a fermion and a vector candidate

$$\mathcal{O}^{(5)YY}_{\phi_{DM}} \equiv \phi_{DM} F_{Y\mu\nu} F_Y^{\mu\nu}, \quad \phi_{DM} = (1,0), \qquad A \tag{1}$$

$$\mathcal{O}^{(5)YL}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F_Y^{\mu\nu}, \quad \phi_{DM} = (3,0), \qquad B \tag{2}$$

$$\mathcal{O}^{(5)LL}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F_L^{\mu\nu}, \quad \phi_{DM} = (1/3/5,0), \qquad D_m \tag{3}$$

$$\mathcal{O}^{(5)YY'}_{\phi_{DM}} \equiv \phi_{DM} F_{Y\mu\nu} F_{Y'}^{\mu\nu}, \quad \phi_{DM} = (1,0), \qquad A_x \tag{4}$$

$$\mathcal{O}^{(5)LY'}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F_{Y'}^{\mu\nu}, \quad \phi_{DM} = (3,0), \qquad C_x \tag{5}$$

[1] For this question it is important to keep in mind that the radiative operators we will list below could be induced either directly from the UV physics, or from low energy loop correction to other UV induced DM decay operators.

$$\mathcal{O}^{(5)Y}_{\psi_{DM}} \equiv \bar{\psi}\sigma_{\mu\nu}\psi_{DM} F_Y^{\mu\nu}, \quad \psi_{DM}\cdot\psi = (1,0), \qquad A_x \tag{6}$$

$$\mathcal{O}^{(5)L}_{\psi_{DM}} \equiv \bar{\psi}\sigma_{\mu\nu}\psi_{DM} F_L^{\mu\nu}, \quad \psi_{DM}\cdot\psi = (3,0), \qquad C_{x,m} \tag{7}$$

$$\mathcal{O}^{(5)Y}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F_Y^{\mu\nu}\phi, \quad \phi = (1,0), \qquad A_x \tag{8}$$

$$\mathcal{O}^{(5)L}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F_L^{\mu\nu}\phi, \quad \phi = (3,0), \qquad E_x \tag{9}$$

where ϕ_{DM}/ψ_{DM} denotes the multiplet whose neutral component ϕ^0_{DM}/ψ^0_{DM} is the DM particle. By "(n, Y)" we specify what must be the size n of the $SU(2)_L$ multiplets and their hypercharge Y. $F'^{\mu\nu}$ stands for a new possible low energy gauge field and the vector DM operator $F^{DM}_{\mu\nu}$ stands for an abelian or non-abelian DM field strength (in practice it will not be necessary to make this distinction in the following). ψ and ϕ are meant to be either SM fields when allowed by gauge invariance or new low energy fields. The symbols A–$E_{x,m,v}$ stand for a classification of the operators' possible astrophysical signals, and will be explained in Section 4.

As for the dimension 6 operators the number of possibilities is also remarkably limited. Two general structures are singled out for the scalar case and three for the fermion and vector cases, leading to 7 scalar operators

$$\mathcal{O}^{1YY}_{\phi_{DM}} \equiv \phi_{DM} F_{Y\mu\nu} F_Y^{\mu\nu}\phi, \quad \phi_{DM}\cdot\phi = (1,0), \qquad A \tag{10}$$

$$\mathcal{O}^{1YL}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F_Y^{\mu\nu}\phi, \quad \phi_{DM}\cdot\phi = (3,0), \qquad B \tag{11}$$

$$\mathcal{O}^{1LL}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F_L^{\mu\nu}\phi, \quad \phi_{DM}\cdot\phi = (1/3/5,0), \qquad C_{x,m} \tag{12}$$

$$\mathcal{O}^{1YY'}_{\phi_{DM}} \equiv \phi_{DM} F_{Y\mu\nu} F_{Y'}^{\mu\nu}\phi, \quad \phi_{DM}\cdot\phi = (1,0), \qquad A_x \tag{13}$$

$$\mathcal{O}^{1LY'}_{\phi_{DM}} \equiv \phi_{DM} F_{L\mu\nu} F_{Y'}^{\mu\nu}\phi, \quad \phi_{DM}\cdot\phi = (3,0), \qquad C_x \tag{14}$$

$$\mathcal{O}^{2Y}_{\phi_{DM}} \equiv D_\mu\phi_{DM} D_\nu\phi F_Y^{\mu\nu}, \quad \phi_{DM}\cdot\phi = (1,0), \qquad A_{x,m,v} \tag{15}$$

$$\mathcal{O}^{2L}_{\phi_{DM}} \equiv D_\mu\phi_{DM} D_\nu\phi F_L^{\mu\nu}, \quad \phi_{DM}\cdot\phi = (3,0), \qquad C_{x,m,v} \tag{16}$$

to 6 fermion operators

$$\mathcal{O}^{1Y}_{\psi_{DM}} \equiv \bar{\psi}\sigma_{\mu\nu}\psi_{DM} F_Y^{\mu\nu}\phi, \quad \bar{\psi}\cdot\psi_{DM}\cdot\phi = (1,0), \qquad A_{x,m} \tag{17}$$

$$\mathcal{O}^{1L}_{\psi_{DM}} \equiv \bar{\psi}\sigma_{\mu\nu}\psi_{DM} F_L^{\mu\nu}\phi, \quad \bar{\psi}\cdot\psi_{DM}\cdot\phi = (3,0), \qquad C_{x,m} \tag{18}$$

$$\mathcal{O}^{2Y}_{\psi_{DM}} \equiv D_\mu\bar{\psi}\gamma_\nu\psi_{DM} F_Y^{\mu\nu}, \quad \bar{\psi}\cdot\psi_{DM} = (1,0), \qquad A_x \tag{19}$$

$$\mathcal{O}^{2L}_{\psi_{DM}} \equiv D_\mu\bar{\psi}\gamma_\nu\psi_{DM} F_L^{\mu\nu}, \quad \bar{\psi}\cdot\psi_{DM} = (3,0), \qquad C_{x,m} \tag{20}$$

$$\mathcal{O}^{3Y}_{\psi_{DM}} \equiv \bar{\psi}\gamma_\mu D_\nu\psi_{DM} F_Y^{\mu\nu}, \quad \bar{\psi}\cdot\psi_{DM} = (1,0), \qquad A_x \tag{21}$$

$$\mathcal{O}^{3L}_{\psi_{DM}} \equiv \bar{\psi}\gamma_\mu D_\nu\psi_{DM} F_L^{\mu\nu}, \quad \bar{\psi}\cdot\psi_{DM} = (3,0), \qquad C_{x,m} \tag{22}$$

and to 5 vector operators

$$\mathcal{O}^{1}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F_Y^{\mu\rho} F^{\nu}_{Y'\rho}, \qquad A_x \tag{23}$$

$$\mathcal{O}^{2Y}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F_Y^{\mu\nu}\phi\phi', \quad \phi\cdot\phi' = (1,0), \qquad A_x \tag{24}$$

$$\mathcal{O}^{2L}_{V_{DM}} \equiv F^{DM}_{\mu\nu} F_L^{\mu\nu}\phi\phi', \quad \phi\cdot\phi' = (3,0), \qquad D_{x,m} \tag{25}$$

$$\mathcal{O}^{3YY'}_{V_{DM}} \equiv D^{DM}_\mu\phi D^{DM}_\nu\phi' F_Y^{\mu\nu}, \quad \phi\cdot\phi' = (1,0), \qquad A_{x,m} \tag{26}$$

$$\mathcal{O}^{3LY'}_{V_{DM}} \equiv D^{DM}_\mu\phi D^{DM}_\nu\phi' F_L^{\mu\nu}, \quad \phi\cdot\phi' = (3,0) \qquad D_{x,m} \tag{27}$$

By D^{DM}_μ we mean a covariant derivative that contains the DM vector field.[2]

[2] In Ref. [13] an explicit example can be found of an accidental symmetry setup leading to the operators of Eqs. (24) and (26). Note also that in Ref. [17] there are examples of heavy scalar and heavy vector setups whose exchange induces dimension 6 four fermion interactions that at one loop induce a $\psi_{DM} \to \gamma\nu$ decay. The effective amplitude for this process is the same as the ones that the dimension 5 operators of Eq. (6) or Eq. (7) give. This exemplifies the fact, to keep in mind, that dimension 5 operators for a decay can naturally have a "dimension 6 suppression" of the lifetime.