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Dark Matter and Global Symmetries

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General considerations in general relativity and quantum mechanics rule out global symmetries in the context of any consistent theory of quantum gravity. Motivated by this, we derive stringent and robust bounds from gamma-ray, X-ray, cosmic ray, neutrino and CMB data on models that invoke global symmetries to stabilize the dark matter particle. Under realistic assumptions we are able to rule out fermionic, vector, and scalar dark matter candidates across a broad mass range (keV-TeV), including the WIMP regime. We then specialize our analysis and apply our bounds to specific models such as the Two-Higgs-Doublet, Left-Right, Singlet Fermionic, Zee-Babu, 3-3-1 and Radiative See-Saw models. In the supplemental material we derive robust, updated model-independent limits on the dark matter lifetime.

I. INTRODUCTION

Particle physics models achieve stability for dark matter (DM) particle candidates by advocating the presence of either discrete or global symmetries. Discrete symmetries arise, for example, from broken gauge (local) symmetries, which are respected at the Planck scale [1, 2]. Global symmetries, instead, are generically violated at the Planck scale, leading to important implications on the dark matter phenomenology of the associated models.

There are several reasons why global symmetries are not expected to be present in a consistent theory of quantum gravity, which rely on general facts in gravity and quantum mechanics:

(i) *No-Hair Theorem*: Since local $U(1)$ symmetries are effectively identical to Gauss's law, any observer outside a Black Hole (BH) horizon can determine the BH charge. However, if there existed global symmetries, when a charged particle gets trapped inside the BH there would be no way to assess this from outside the horizon. Thus the charge would appear to be “deleted”, in contradiction to its conservation [3].

(ii) *Hawking Radiation*: The main problem with global symmetries has to do with Hawking radiation [4]. Since there are no gauge interactions associated with global symmetries, one could throw a large amount of charged particles into a BH and increase its charge (Q) indefinitely [4, 5]. However, the theory of Hawking radiation indicates that until $T_{\text{Hawking}} > m$, where m is the mass of the lightest charged particle pair, the BH does not radiate charge. Combining this with the bound on the BH mass, namely $Qm \leq M_{\text{BH}} \leq M_{\text{pl}}^2/m$, where M_{pl} is the Planck mass, we find $Q \leq M_{\text{pl}}^2/m^2$. This limit can however be violated by making Q sufficiently large. Hence, if Q were conserved we could have identical BHs with an infinite number of states labelled by $Q \gg M_{\text{pl}}^2/m^2$.

(iii) *Entropy*: Since an external observer cannot infer a global charge, in order to assign an entropy to a given BH one would have to count all micro-states of all charges, finding an

entropy of order $\sim \log(Q)$. Now, taking Q indefinitely large, one would violate the Bekenstein-Hawking formula, which says that entropy counts the number of states of a BH. Therefore, such objects are ruled out, as are global symmetries [5].

The notion of global symmetries being broken at the Planck scale has profound implications on DM phenomenology. In this study, we assess the possibility of using global symmetries to stabilize DM particles. In order to derive robust results applicable to a variety of particle physics models, we consider Planck-scale suppressed, dimension-five effective operators that mediate the decay of generic DM particles of spin 0, 1/2 and 1; the operators violate global symmetries, and thus induce the decay of DM particles whose stability relies on such global symmetries. The decay of long-lived but metastable DM particles can inform us on the DM particle nature (see e.g. [6, 7]); for example, stringent bounds on the lifetime of electroweak-scale DM stem from the observed diffuse gamma-ray flux [8], which implies lifetime $\tau \gtrsim 10^{26}$ s, thus a billion times longer than the age of the Universe. We emphasize the fact that even though global symmetries might break down to Z_N discrete symmetries at low energies, one can always generically construct Planck-suppressed effective operators that would induce the decay of the DM particle: our results can thus be applied to any global symmetry.

Naively, one might expect that Planck-scale suppression might have a negligible impact on the phenomenology of models which advocate the existence of global symmetries to stabilize the DM particle. Using current cosmic-ray, X-ray, gamma-ray, neutrino and CMB data, spanning the entire keV-TeV energy range, we show that, somewhat surprisingly, global symmetries are not favored as a mechanism to stabilize DM particles. In particular, we rule out a rather large DM mass range, including the classic WIMP mass range around the electroweak scale.

II. OBSERVATIONAL CONSTRAINTS

In this section we summarize how we derived our model-independent limits on the DM lifetime. We employ throughout our analysis an NFW profile [9] with $\rho_{\odot} = 0.4 \text{ GeV/cm}^3$ [10] for the DM density profile.

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A. CMB data

Precise measurements of the Cosmic microwave background (CMB) provide robust limits on DM decays, since the latter alter the ionization and heating history of the CMB as well as its power spectrum. Using combined data from Planck [11], WMAP9 [12], Atacama Telescope [13], South Pole Telescope [14], Hubble Space Telescope [15] and Baryonic Acoustic Oscillations [16], we derive limits on the DM lifetime for several final states as described in the *Supplemental Material* attached to this work. Our results are based on computing the changes in the free electron fraction as a function of redshift induced by the energy injection from DM decays. This scenario was studied in Ref.[17] for the $ee, \mu\mu$ and $\tau\tau$ final states. We follow their approach here, and we additionally derive limits for the bb and WW final states, as shown in the leftmost panel of Fig.1, in the plane defined by the DM particle lifetime versus mass. For more details see the attached *Supplemental Material*.

B. Antiproton Data

Recent measurements of the \bar{p}/p ratio with AMS-02 up to 450 GeV strongly constrain additional primary antiproton sources, including antiprotons possibly originating from DM decays [18]. As a result, restrictive limits can be placed on the DM lifetime. We point out that even decays into charged leptons yield a sizable antiproton flux when electroweak corrections are accounted for. To derive our limits, we solve the transport equation accounting for solar modulation but neglecting energy losses and re-acceleration processes, for $b\bar{b}, WW$ and $\mu\mu$ final states. Our limits are derived requiring the total \bar{p}/p ratio not to exceed the measured one at 95% C.L, using conservative values for the propagation model, as discussed in the *Supplemental Material*. The limits we derive are shown in the second panel of Fig.1.

C. Line Searches

Spectral lines are known as smoking guns DM signals. A multitude of experiments have searched for lines emissions from the keV up to ~ 1 TeV energies. No excess has been found thus far conclusively pointing to an exotic origin. Here, we combine limits from line emission covering energies from 10^{-7} GeV up to ~ 460 GeV, using Chandra, X-ray Multi-Mirror Mission (XMM), High Energy Astronomy Observatory (HEAO), INTERNATIONAL Gamma-Ray Astrophysics Laboratory (INTEGRAL), The Imaging Compton Telescope (COMPTEL), The Energetic Gamma Ray Experiment Telescope (EGRET), and recent Fermi-LAT limits [19–24]. The constraints are summarized in the third panel of Fig.1.

D. Neutrino Data

Neutrino detectors have also been used to constrain DM scenarios. Using AMANDA, Super-K and ICECUBE data several limits were obtained for two-body decaying DM [25–27]. As we shall see further, we will not be interested in this scenario, but, rather, in the three-body final state $f\bar{f}\nu$ instead. Thus, we combine those limits together, and use PYTHIA 6.4 [28] to account for the changes in the energy spectrum to derive new limits, shown in the rightmost panel in Fig.1.

E. Gamma-ray data

Observations of the continuous emission of gamma rays give rise to stringent limits on the DM lifetime. Here we employ limits derived from: (i) the extragalactic gamma-ray background, as derived in Ref.[29], which postulates that the sum of the isotropic component from blazars (making up nearly 70% of the total intensity), star-forming galaxies (SFGs), misaligned active galactic nuclei and DM decays not exceed the measured flux at 95% C.L (Fig.4 of Ref.[29]); (ii) limits from Fermi-LAT observations of eight galaxy clusters at gamma-ray frequencies, in $10^\circ \times 10^\circ$ squared regions centered on the clusters[30]. We do not duplicate those results but we use them in what follows to derive our bounds.

III. BOUNDS ON THE DARK MATTER LIFETIME

As discussed in the previous section, global symmetries are generically violated due to gravitational effects; in the presence of a global symmetry, one should thus consider Planck-suppressed effective operators which break global symmetries, leading to metastable DM particles. Limits on the lifetime of DM particles from observations in a broad range of frequencies thus allow us to derive general constraints on these operators in settings that advocate global symmetries to stabilize DM candidates.

We list in Table I a set of dimension-five gauge and non-gauge invariant operators that violate global symmetries and induce DM decay. We point that our list is not complete, but it serves as a proof of principle since it includes operators mediating several decay modes that produce significant continuum gamma-ray emission, spectral lines, antiproton, charged leptons and neutrino fluxes; in addition, the set we consider encompasses a variety of DM particle quantum numbers. We emphasize that will be focused on the gauge invariant operators though, but in the *supplemental material* we present results for the non-gauge invariant ones.

In the Table, we have introduced the dimensionless couplings $\lambda_i \sim \mathcal{O}(1)$, whose value depends on the unknown mechanism for the quantization of gravity. As we argue below, the precise values of λ_i are irrelevant to our conclusions, but we keep the λ_i 's as free parameters and obtain our limits in the λ vs DM mass plane. For each of the Planck-suppressed operator, we apply the most stringent limit on the DM lifetime for a given particle mass. Our results are collected in Figures

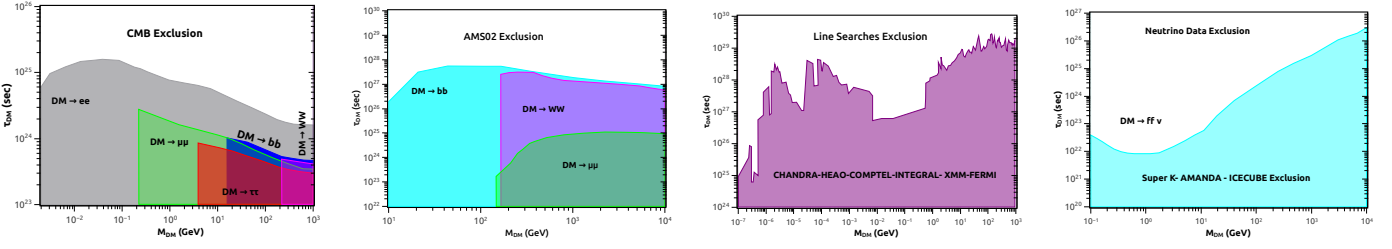


FIG. 1. Model independent bounds on the DM lifetime. *Leftmost*: CMB limits for the ee (gray), $\mu\mu$ (green), $\tau\tau$ (orange), bb (blue) and WW (magenta). *Left/Center*: Limits from AMS-02 using antiproton data for the bb, WW and $\mu\mu$ channels. *Right/Center*: Bounds on the spectral line emission from DM decays. *Right*: Constraints on the three-body $ff\nu$ decays mode using measurements of neutrino detectors.

Name	Interaction Term
O1	$\frac{\lambda_1}{M_{pl}} \bar{f} \gamma^\mu (1 + r_a \gamma_5) f \partial_\mu \mathbf{S}$
O2	$\frac{\lambda_2}{M_{pl}} \mathbf{S} F_{\mu\nu} F^{\mu\nu}$
O3	$\frac{\lambda_3}{M_{pl}} \mathbf{S} \epsilon_{\mu\nu\sigma\lambda} F^{\mu\nu} F^{\sigma\lambda}$
O4	$\frac{\lambda_4}{M_{pl}} \mathbf{S} G_{\mu\nu}^a G^{a,\mu\nu}$
O5	$\frac{\lambda_5}{M_{pl}} \mathbf{S} \epsilon_{\mu\nu\sigma\lambda} G^{a,\mu\nu} G^{a,\sigma\lambda}$
O6	$\frac{\lambda_6 m_Z^2}{M_{pl}} \mathbf{S} Z_\mu Z^\mu$
O7	$\frac{\lambda_7}{M_{pl}} \mathbf{S} Z_{\mu\nu} Z^{\mu\nu}$
O8	$\frac{\lambda_8}{M_{pl}} \mathbf{S} \epsilon_{\mu\nu\sigma\lambda} Z^{\mu\nu} Z^{\sigma\lambda}$
O9	$\frac{\lambda_9 m_W^2}{M_{pl}} \mathbf{S} W_\mu^+ W^{-\mu}$
O10	$\frac{\lambda_{10}}{M_{pl}} \mathbf{S} W_{\mu\nu}^+ W^{-\mu\nu}$
O11	$\frac{\lambda_{11}}{M_{pl}} \mathbf{S} \epsilon_{\mu\nu\sigma\lambda} W^{+\mu\nu} W^{-\sigma\lambda}$
O12	$\frac{\lambda_{12}}{M_{pl}} F^{\mu\nu} Z_\mu \partial_\nu \mathbf{S}$
O13	$\frac{\lambda_{13}}{M_{pl}} \epsilon_{\mu\nu\sigma\lambda} F^{\mu\nu} Z^\sigma \partial^\lambda \mathbf{S}$
O14	$\frac{\lambda_{14}}{M_{pl}} \bar{\psi} \tilde{H}^\dagger (\not{D} L)$
O15	$\frac{\lambda_{15}}{M_{pl}} \mathbf{V}^\mu \bar{f} \partial_\mu f$
O16	$\frac{\lambda_{16}}{M_{pl}} \mathbf{V}_\mu (H^\dagger D_\nu H) F^{\mu\nu}$

TABLE I. Dimension-five Planck-suppressed operators potentially inducing the decay of the DM particle in models with global symmetries. O1-O13 refer to scalar DM (S), O14 to fermion (ψ), and O15-O16 to vector (V) DM particles. In the table, H is the Standard Model Higgs, \tilde{H} the isospin transformation of H , Z and W are the neutral and charged weak gauge bosons, $F_{\mu\nu}$ is the electromagnetic tensor, $G_{\mu\nu}$ is the gluon tensor, f and L represent SM fermions. The list includes both gauge invariant and non-gauge invariant operators that include a DM particle field, but we will restrict our constraints to the gauge invariant ones. See however the *Supplemental Material* for results concerning the non-gauge invariant operators.

2-3. Notice that several bounds are truncated at some DM mass due to the lack of data at lower energies.

Figures 2-3 show that models that advocate the presence of global symmetries to stabilize scalar DM candidates might produce a line emission with a very short lifetime (through operator O2/O3), well below the age of the universe, thus ruling out DM masses larger than 100 keV. It is clear that for any scalar DM operator the whole electroweak WIMP range as well as the large mass range of warm DM is ruled out,

since only for $M_{DM} \lesssim 100$ keV are couplings of order one achieved.

As for fermionic DM candidates stabilized by global symmetries, operator O14 arises naturally at the Planck scale, yielding an appreciable neutrino and cosmic-ray flux. The right panel of Fig.2 shows that we are able to exclude DM masses above 100 MeV. Lastly, in models where vector DM particles are stabilized via the existence of global symmetries, operator O15 would automatically be present at the Planck scale, leading to DM decay into fermion pairs. After employing a combination of the bounds shown in Fig.1, we find that masses larger than 10 MeV induce cosmic-ray and gamma-ray fluxes that exceed the measured values. Conclusions regarding the remaining operators in Table I can be straightforwardly drawn.

In summary, we find that dimension-five effective operators at the Planck scale make global symmetries problematic to stabilize DM particles outside very special, restricted mass ranges. In the next section we show how our bounds highly constrain several well-known models in the literature.

IV. CONCRETE MODELS

In this section we discuss concrete models, widely discussed in the literature, for which our bounds are applicable to. It is important to keep in mind as a caveat that in general global symmetries can be replaced by other symmetries such as discrete symmetries, circumventing our constraints.

Left-Right Model

We consider the left-right mirror symmetric model with the global symmetry $U(1)_{B-L} \otimes U(1)_X$ of Ref. [31]. There, the global symmetry prohibits the term $\bar{L} H \psi_R$, where ψ is a fermionic DM candidate. However, such symmetry is generically violated at the Planck scale and therefore the O14 operator ought to exist, thus ruling out DM masses above 100 MeV. Ref. [31] also invokes the case of WIMP scalar DM protected by the global symmetry, but once again, as we see in the left panel of Fig.2, the entire corresponding WIMP mass range is excluded. As a result, the model described in Ref.[31] does not appear to have a plausible DM candidate. Unless the invoked global symmetry can be replaced by a Z_N discrete

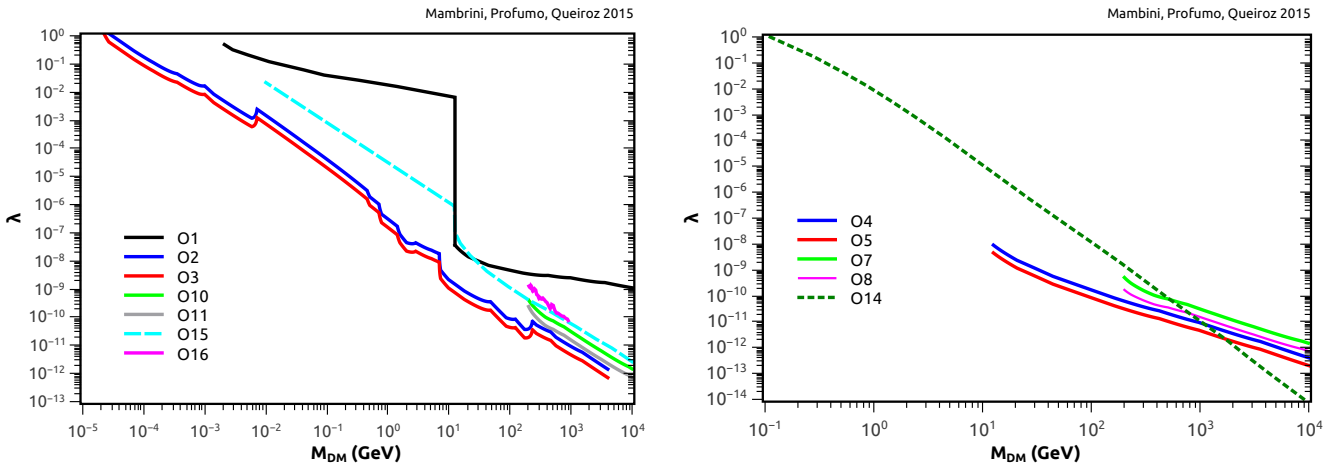


FIG. 2. Limits on the λ as a function of the DM mass by enforcing that the flux induced by DM decays of each individual operator does not exceed the measured values at 90% C.L. These bounds are applicable to any scalar, fermion or vector DM particle stabilized by a global symmetry. From our results one **may** exclude: (i) scalar DM with $M_{DM} > 100$ keV; (ii) fermion DM with $M_{DM} > 100$ MeV; (iii) Vector DM with $M_{DM} > 10$ MeV.

symmetry of some sort, the model is strongly disfavored by data.

Two Higgs Doublet Model

In the original two Higgs doublet model no DM candidate is present. Nevertheless, if the second Higgs doublet is odd under a Z_2 symmetry the CP-even scalar of that doublet can be a DM candidate. This is the case in the so-called Inert Two Higgs Doublet Model (I2HDM) [32]. Recently, a global symmetry has been proposed to replace the Z_2 symmetry [33]. The authors focus on the spontaneous symmetry breaking of the global symmetry through the vev of the second Higgs doublet and comment on the possibility of having an unbroken global symmetry. Despite the interesting Higgs physics implications produced by the use of the global symmetry [33], operator O2 should be present at the Planck scale; thus, from Fig. 2 we conclude that DM masses larger than 100 keV are problematic along with the possibility of having viable WIMP DM candidates in the model.

Singlet Fermion Model

The minimal fermionic DM model studied in Ref.[34] advocates a global symmetry responsible for stabilizing a singlet fermion which yields the desired thermal relic abundance and is consistent with direct searches. The Planck suppressed effective operator O14, however, rules out the entire WIMP mass range. As we mentioned before, in principle one could replace the global symmetry by a discrete symmetry, since Z_N is a subgroup of $U(1)$. However, the necessary discrete symmetry might turn out to imply a rather large and unnatural tuning of the model.

Radiative See-Saw Model

A radiative lepton model in which the charged lepton masses are generated at one-loop level whereas and the neutrino

masses at two-loop level has been proposed in Ref. [35]. In this model the global and Z_2 symmetry have been invoked and two DM candidates postulated. A singlet fermion, referred to as n' in Table I of Ref.[35], is not odd under the Z_2 symmetry, and claimed to be a WIMP due to the presence of a global symmetry. Similarly to the previous model, Planck-suppressed dimension-five operators exclude such possibility.

Zee-Babu Model

The Zee-Babu model adds to the SM a singly-charged and a doubly-charged scalar [36]. Recently, an extension of the Zee-Babu model has been put forth by adding a singlet fermion which is stabilized by a global $U(1)_{B-L}$ symmetry. This global symmetry also forbids terms like $\bar{L}\tilde{H}N$. There, the neutral fermion does not carry a lepton number so it is purely a neutral fermion. Nevertheless, as we discussed, this global symmetry does not hold up to the Planck scale and consequently the operator O14 arises, inducing an excess production of neutrinos, gamma-ray and comic-rays, which results into the exclusion of DM masses below 100 MeV, in tension with what presented in Figs.1-2 of Ref.[36].

3-3-1 Models

3-3-1 models refer to $S(3)_c \otimes S(3)_L \otimes U(1)_N$ gauge extensions of the Standard Model [37]. In Ref.[38] a global symmetry with the purpose of avoiding undesirable mixing among the gauge bosons and of guaranteeing that the lightest particle charged under the global symmetry be stable. Both a complex scalar and a heavy Dirac fermion were studied as potential WIMP DM candidates. In a similar vein to what discussed above, the WIMP mass regime in this model is in jeopardy due to the aforementioned gravity effects. In the urge of preventing the use of global symmetries in the model, Ref.[39] proposed adding an extra gauge symmetry, which would completely change the associated DM phenomenology.

V. CONCLUSIONS

We have studied the phenomenological consequences of a very general lesson from quantum mechanics and general relativity: there can be no global symmetries in a consistent theory of quantum gravity. We have derived, in a model-independent approach, robust gamma-, X-ray, CMB, and cosmic-ray constraints on decaying DM particles, using a large set of data, including data from Fermi-LAT, AMS-02, Super-Kamiokande, Planck, WMAP9, AMANDA, and Icecube among others. We have then applied those bounds to scalar, vector and fermion DM particles decaying through dimension-five Planck-suppressed effective operators, and we have derived the following constraints on the possible mass range:

- (i) scalar DM : $M_{DM} \lesssim 100$ keV ;
- (ii) fermionic DM $M_{DM} \lesssim 100$ MeV ;
- (iii) Vector DM $M_{DM} \lesssim 10$ MeV .

Lastly, we have applied our limits to models such as the Left-Right, Two-Higgs Doublet, Singlet Fermionic, Zee-Babu, 3-3-1 and Radiative See-Saw models to conclude that the presence of DM particles in such models is generically

problematic outside the DM particle mass ranges listed above. In particular, our results basically rule out the entire WIMP mass range. We emphasize again that our results rely on a specific DM halo profile (NFW) and on the fact that λ should not be much smaller than unity. Deviations from these assumptions would quantitatively change the acceptable DM mass ranges, but would leave the overall conclusions unchanged.

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Supplemental Material

We provide here details on the procedures employed to obtain the model-independent bounds on the dark matter (DM) lifetime presented in the main manuscript. The constraints we obtain cover a broad energy spectrum, ranging from 10^{-7} GeV to ~ 10 TeV and are applicable to several decays modes.

I. CMB BOUNDS ON DECAYING DARK MATTER

By precisely measuring the CMB power spectrum, stringent bounds can be placed on the DM lifetime. Typically, those limits come from constraints on new sources of ionization and heating stemming from the products of DM interactions. Here we pay special attention to DM particle decays. Our findings rely on several standard assumptions namely: (i) the DM lifetime is large than the age of the universe; (ii) the DM particle accounts for the DM cosmological abundance; (iii) the DM particle decays fully to SM particles; (iv) the energy fraction which the DM particle deposit into the intergalactic Medium is determined by the transfer functions provided in Ref.[1]. The rate at which a given DM particle decay induces heating and ionization of the baryonic component of the IGM is proportional to

$$\Gamma(z) = \frac{1}{H(z)(1+z)n_H(z)} \left(\frac{dE}{dt dV} \right)_d \quad (1)$$

where $H(z)$ is the Hubble rate and $n_H(z) = n_{H_0}(1+z)^3$ is the number density of hydrogen in the Universe at a given redshift with $n_{H_0} = 1.9 \times 10^{-7} \text{cm}^{-3}$ being the present-day value, and

$$\left(\frac{dE}{dt dV} \right)_d = 13.7 \times 10^{-24} \left(\frac{f_{dec}}{0.1} \right) \left(\frac{n_{H_0}}{1.9 \times 10^{-7}} \right) \left(\frac{\Omega_{DM} h^2}{0.13} \right) \left(\frac{10^{25} \text{s}}{\tau_{DM}} \right) (1+z)^3 \text{eV/s}. \quad (2)$$

where f_{dec} is in general a function of the DM mass and redshift. We closely follow Ref.[2] and average over the redshift dependence to get f_{dec} as a function of the DM mass only, according to Table II of Ref.[3]. We then change the energy deposited into the intergalactic medium by inputting the equation above into the package CosmoRec [4] to later compute deviations on the ionization history, which now depend on the DM mass and lifetime for a given decay final state. We obtained values for f_{dec} for the e^+e^- , $\mu^+\mu^-$, $\tau^+\tau^-$ final states in agreement with Ref.[3], and, in addition, we calculated the efficiencies for decays into quarks and gauge bosons. We used the results of a Markov Chain Monte Carlo simulation using CAMB and CosmoMC packages presented in Ref.[3] and re-scaled them according to our efficiencies to find the limits on the DM lifetime presented in the *Leftmost panel* of Fig.1 of the manuscript.

II. AMS LIMITS ON DECAYING DARK MATTER

Since DM decays produce, in principle, matter and antimatter in equal amount, antiprotons are an interesting target for indirect DM searches, due to the relative rarity of antimatter produced in astrophysical processes. In this section we revisit the procedure to place bounds on the DM lifetime using antiprotons data from AMS-02 [5]. Antiproton data can be used to set stringent limits on the DM lifetime, since DM decays should at some level produce a sizable amount of antiprotons, even for leptonic final states through the inclusion of electroweak corrections (radiation of a gauge boson which decays hadronically)[6].

With recent AMS-02 precise measurements of the antiproton/proton (\bar{p}/p) fraction for energies up to 450 GeV one can derive new restrictive limits on the DM lifetime for several decay modes such as $\bar{b}b$, WW and $\mu\mu$, since no evidence of new sources of antiprotons were found in the data ¹. We follow Ref.[8], where constraints on the DM annihilation cross section were derived using an older data set for the Einasto DM profile based on the total antiproton flux. Here we will instead obtain limits on the DM lifetime with an NFW profile using the latest AMS data on the \bar{p}/p ratio, and compare our finding with existing limits.

The derivation of limits based on antiproton data is subject to large astrophysical uncertainties associated with \bar{p} production, propagation and solar modulation. Here, we employ the standard set of Min-Med-Max propagation models. Min-Med-Max represent values of diffusion parameters which produce a minimum-to-maximum antiproton flux from a DM decay as shown in Table I (See Ref.[9] for a recent review). Current data seem to disfavor the Min propagation model [10, 11] and the Max-model induces arguably overestimated bounds, so we base our limits on the Med propagation model and an NFW DM distribution. To obtain limits on the DM lifetime we first solve the cosmic-ray transport equation in the Galaxy, in a steady state condition for the number density of antiprotons ($f_{\bar{p}}$) per unit of kinetic energy T ,

$$Q_{\bar{p}}(T, \vec{r}) + \vec{\nabla} \cdot [K(T, \vec{r}) \vec{\nabla} f_{\bar{p}} - \vec{V}_c(\vec{r}) f_{\bar{p}}] - 2h\delta(z)\Gamma_{ann} f_{\bar{p}} = 0, \quad (3)$$

where we have neglected energy losses and re-acceleration processes. We describe below the physical meaning of each of those components:

¹ See Ref.[7] where a claim was put forth about excess antiprotons in the PAMELA data.

(i) The first term refers to the primary production of antiproton from DM decays expressed as,

$$Q_{DM} = \frac{\rho}{M_{DM}} \sum_f \Gamma_f \frac{dN_{f\bar{p}}}{dK}, \quad (4)$$

where ρ is the DM halo profile assumed to be NFW,

$$\rho(r) = \frac{\rho_s}{r/r_s(1+r/r_s)}, \quad (5)$$

with $r_s = 24.42$ kpc and $\rho_s = 0.184$, and $dN_{f\bar{p}}/dK$ is the energy spectrum generated using PPCDM [6].

(ii) The second term accounts for the diffusion of cosmic-rays through their propagation in the interstellar medium. It is typically assumed to be constant in the diffusion zone and often parametrized in terms of the particle rigidity (momentum/atomic number) as follows,

$$\mathcal{K}(K) = K_0 (v/c) (p/Z)^\delta, \quad (6)$$

where the normalization (K_0) and the spectral index (δ) are associated with the properties of the interstellar medium and derived from measurements of the primary-to-secondary flux ratios of cosmic-rays such as Boron to Carbon [8], and obviously $Z \equiv 1$ for antiprotons.

(iii) The third term refers to the convection mechanism which accounts for the drift of charged particles away from the disk, assumed to be infinitely thin with a half-height of 100pc [9], induced by the Galactic Wind with a characteristic velocity V_{conv} and spatially constant in the diffusion zone, i.e., $V_{conv} = \text{sing}(z)V_c$. Departures from the thin disk assumption lead to one order of magnitude changes in the final limits as one can see in Fig.6 of Ref.[12].

(iv) The fourth term represents the annihilations of antiprotons with the interstellar gas which is proportional to

$$\Gamma_{\bar{p}p} = (n_H + 4^{2/3}n_{He})\sigma_{\bar{p}p}v_{\bar{p}}, \quad (7)$$

where, $\sigma_{\bar{p}p} = 0.661(1 + 0.0115T^{-0.774} - 0.948T^{0.0151})b$, for $T < 15.5$ GeV and $\sigma_{\bar{p}p} = 0.036T^{-0.5}b$ for $T \geq 15.5$ GeV [13, 14]. In Eq.7 we assumed that the helium-antiproton annihilation cross section is simply a rescaling of the proton-antiproton [12].

We now have all ingredients to solve the transport equation and to compute the astrophysical and DM decay predictions for the antiproton flux. A final physical effect, solar modulation, affects the prediction of the antiproton flux at the Earth's atmosphere at energies below ~ 20 GeV, as result of the solar cosmic-ray wind and magnetic field. We take into account this effect using the force-field approximation, which determines the antiproton flux as a function of the kinetic energy of the antiproton at the atmosphere (T_{at}) by re-scaling the interstellar flux which depends on the antiproton kinetic energy (T_{is}) as follows [15]:

$$\Phi_{at}(T_{at}) = \frac{2m_p T_{at} + T_{at}^2}{2m_p T_{is} + T_{is}^2} \Phi^{is}(T_{is}), \quad (8)$$

with $T_{at} = T_{is} - \phi_F^{\bar{p}}$, where $\phi_F^{\bar{p}}$ is the Fisk potential as given in Table I.

Using a data-driven model to account for the proton flux for the energy range of interest as presented by the PAMELA collaboration [16], which is well fitted by a Fisk potential $\phi_F^p = 0.7$ (see fifth column of Table 1 of [12]), we can finally compute the total \bar{p}/p ratio from primary and secondary production processes, as discussed above, and enforce the condition that the predicted \bar{p}/p ratio does not exceed the ratio measured by AMS-02 data [17] at 95% C.L, for the specific choices of DM lifetime and mass; the bound results in the constraints on the DM lifetime versus mass plane shown in the second panel of Fig.1 of the main manuscript. Our results were obtained with PPCDM code [6].

Notice that our limits are competitive with existing ones derived using PAMELA [9] and AMS-02 [18]. In particular, our limits are mildly similar to Ref.[18] which included several energy loss processes we ignored.

III. NEUTRINO DATA

Neutrino detectors are sensitive to DM decays and have been used to place limits on the DM lifetime. For a NFW profile for $\rho_\odot = 0.4$, the full sky differential neutrino flux from DM decays reads [19],

$$\frac{d\Phi_\nu}{dE_\nu} \simeq 1.7 \times 10^{-5} \left(\frac{100\text{GeV}}{M_{DM}} \right) \left(\frac{10^{24}\text{s}}{\tau_{DM}} \right) \frac{dN_\nu}{dE_\nu} \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}. \quad (9)$$

$$\frac{\text{Antriproton Propagation Model}}{\text{MED } \delta = 0.7 \quad K_0 = 0.0112 \text{Kpc}^2/\text{Myr} \quad V_c = 12 \text{km/s} \quad L = 4 \text{Kpc} \quad \phi_F^p = 0.7 \text{GV}}$$

TABLE I. Propagation model parameters: δ and K_0 are the spectral index and normalization that go into Eq.6; V_c is the wind velocity in Eq.7; L is the half-height of the cylinder with 20Kpc radius which is used to model the antiproton diffusion. We assumed the proton Fisk potential to be equal to the antiproton which is a good approximation as discussed in Ref.[12].

Another source of neutrinos from DM decays stems from cosmological decays of DM particle producing a diffuse neutrino flux from decays at all redshifts which reads:

$$\frac{d\Phi_\nu}{dE_\nu} = \frac{\rho_{DM}}{4\pi M_{DM}} \frac{1}{\tau_{DM}} \int_0^\infty dz \left(\frac{1+z}{H(z)} \right) \left(E_\nu \frac{dN_\nu}{dE_\nu} \right) e^{-s_\nu(E_\nu, z)}, \quad (10)$$

where ρ_{DM} is the cosmological DM density, $H(z) = H_0 \sqrt{\Omega_\Lambda + \Omega_m(1+z)^3}$ is the expansion rate of the universe, and $s(E_\nu, z)$ is the universe opacity to neutrinos obtained in Ref.[20]. The neutrino oscillation probabilities in vacuum is assumed to remain unchanged at the detector. Thus the primary neutrino flux from a specific flavor is redistributed equally into all neutrino flavors, so that the number of expected events is given by,

$$N_{exp} = (\text{time} \times \Delta\Omega) \sum_i \int_{E_{min}}^{E_{max}} \frac{d\Phi_{\nu+\bar{\nu}}}{dE} A_{eff}(E_\nu) dE_\nu. \quad (11)$$

By comparing with the 95% C.L limits on the number of events observed, constraints on the DM lifetime for two body decays were derived: (i) Ref.[21, 22] used AMANDA and Super-K data; (ii) Ref.[23] analyzed recent ICECUBE data; However, operator O14 in Table I of the manuscript induces three body decays ($\bar{f}f\nu$). Hence, we take the limits from those references and use PYTHIA 6.4 [23] to derive the corresponding bounds on three body decay as shown in Fig.1, rightmost panel.

IV. LINE SEARCHES

If bright enough to be distinguishable from background continuum emission, and if morphologically diffuse [24], gamma-ray spectral lines are known as a veritable smoking gun for DM annihilation or decay signals. Several experiments have searched for line emission at energies between 10^{-7} GeV up to 400 GeV: (i) Chandra and X-ray Multi-Mirror Mission (XMM) X-ray telescopes cover the 0.007 keV-12 keV range [25, 26]; (ii) High Energy Astronomy Observatory (HEAO) accounts for the 3-48 keV [27]; (iii) INTERnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) the 20k eV-7 MeV [28]; (iv) The Imaging Compton Telescope (COMPTEL) along with The Energetic Gamma Ray Experiment Telescope (EGRET) screens the MeV-100GeV [29]; (v) Fermi-LAT covering energies up to 462 GeV [30, 31]. Here, we simply combine all of those constraints. We point out that we make use here of the latest Fermi-LAT limits on the flux at 95% C.L for the 180° region centered at the Galactic Center (R180), as described in Ref.[30, 32]. Limits on the DM lifetime are obtained after solving for the DM lifetime using the differential flux equation,

$$\tau_{DM} = 16.7 \times 10^{28} \text{s} \left(\frac{10 \text{GeV}}{m_{DM}} \right) \left(\frac{10^{-9} \text{cm}^{-2} \text{s}^{-1}}{\Phi_{\gamma\gamma}} \right) \times J_{decay}. \quad (12)$$

The combination of the bounds listed above are shown in Fig.1, third panel, of the manuscript. Note that some operators discussed in our work give rise to $Z\gamma$ and $h\gamma$ lines: for those we correct the energy of the gamma-ray line using the relation $E_\gamma = M_{DM}(1 - m_V/M_{DM})$, where m_V is either the Z or Higgs mass, and divide the lifetime by a factor of two since we have one photon in the final state instead. The limits stemming from extragalactic and galaxy cluster studies were taken directly from previous studies, and we do not describe them here again, referring the Reader to Refs.[33–41]. We again thank Alessandro Ibarra, Christoph Weniger, Celine Boehm, Joseph Silk, Juri Smirnov and specially Marco Cirelli for several discussions related to gamma-ray constraints and other topics.

V. DECAY WIDTHS AND NON-GAUGE INVARIANT OPERATORS

In Table I we list the decay width associated with each operator discussed in the main manuscript; in addition we discuss some non-gauge invariant operators (O6-O9-O12-O13) that might appear in more complex setups such as non-Abelian theories [43]. We also show the limits stemming from such operators in Fig.1.

Name	Interaction term	Decay Rate
O1	$\frac{\lambda_1}{M_{pl}} \bar{f} \gamma^\mu (1 + r \gamma_5) f \partial_\mu \mathbf{S}$	$\Gamma(S \rightarrow f \bar{f}) = \frac{\lambda^2 r^2 N_f m_f^2 m_S}{2\pi M_{pl}^2} A^{1/2}$
O2	$\frac{\lambda_2}{M_{pl}} \mathbf{S} F_{\mu\nu} F^{\mu\nu}$	$\Gamma(S \rightarrow \gamma\gamma) = \frac{\lambda^2 m_S^3}{4\pi M_{pl}^2}$
O3	$\frac{\lambda_3}{M_{pl}} \mathbf{S} \epsilon_{\mu\nu\sigma\lambda} F^{\mu\nu} F^{\sigma\lambda}$	$\Gamma(S \rightarrow \gamma\gamma) = \frac{\lambda^2}{\pi M_{pl}^2} m_S^3$
O4	$\frac{\lambda_4}{M_{pl}} \mathbf{S} G_{\mu\nu}^a G^{a,\mu\nu}$	$\Gamma(S \rightarrow gg) = \frac{\lambda^2 m_S^3 N_g}{4\pi M_{pl}^2}$
O5	$\frac{\lambda_5}{M_{pl}} \mathbf{S} \epsilon_{\mu\nu\sigma\lambda} G^{a,\mu\nu} G^{a,\sigma\lambda}$	$\Gamma(S \rightarrow gg) = \frac{\lambda^2}{\pi M_{pl}^2} N_g m_S^3$
O6	$\frac{\lambda_6 m_Z^2}{M_{pl}} \mathbf{S} Z_\mu Z^\mu$	$\Gamma(S \rightarrow ZZ) = \frac{\lambda^2 m_S^3}{32\pi M_{pl}^2} A^{1/2} \times \left(A + 12 \frac{m_Z^4}{m_S^4} \right)$
O7	$\frac{\lambda_7}{M_{pl}} \mathbf{S} Z_{\mu\nu} Z^{\mu\nu}$	$\Gamma(S \rightarrow ZZ) = \frac{\lambda^2 m_S^3}{4\pi M_{pl}^2} A^{1/2} \times \left(A + 6 \frac{m_Z^4}{m_S^4} \right)$
O8	$\frac{\lambda_8}{M_{pl}} \mathbf{S} \epsilon_{\mu\nu\sigma\lambda} Z^{\mu\nu} Z^{\sigma\lambda}$	$\Gamma(S \rightarrow ZZ) = \frac{\lambda^2 m_S^3}{\pi M_{pl}^2} A^{3/2}$
O9	$\frac{\lambda_9 m_W^2}{M_{pl}} \mathbf{S} W_\mu^+ W^{-\mu}$	$\Gamma(S \rightarrow W^+ W^-) = \frac{\lambda^2 m_S^3}{64\pi M_{pl}^2} A^{1/2} \times \left(A + 12 \frac{m_W^4}{m_S^4} \right)$
O10	$\frac{\lambda_{10}}{M_{pl}} \mathbf{S} W_{\mu\nu}^+ W^{-\mu\nu}$	$\Gamma(S \rightarrow W^+ W^-) = \frac{\lambda^2 m_S^3}{4\pi M_{pl}^2} A^{1/2} \times \left(A + 6 \frac{m_W^4}{m_S^4} \right)$
O11	$\frac{\lambda_{11}}{M_{pl}} \mathbf{S} \epsilon_{\mu\nu\sigma\lambda} W^{+\mu\nu} W^{-\sigma\lambda}$	$\Gamma(S \rightarrow W^+ W^-) = \frac{g_{0p}^2 m_S^3}{\pi M_{pl}^2} A^{3/2}$
O12	$\frac{\lambda_{12}}{M_{pl}} F^{\mu\nu} Z_\mu \partial_\nu \mathbf{S}$	$\Gamma(S \rightarrow Z\gamma) = \frac{\lambda^2 m_S^3}{32\pi M_{pl}^2} \left(1 - \frac{m_Z^2}{m_S^2} \right)^3$
O13	$\frac{\lambda_{13}}{M_{pl}} \epsilon_{\mu\nu\sigma\lambda} F^{\mu\nu} Z^\sigma \partial^\lambda \mathbf{S}$	$\Gamma(S \rightarrow Z\gamma) = \frac{\lambda^2 m_S^3}{8\pi M_{pl}^2} \left(1 - \frac{m_Z^2}{m_S^2} \right)^3$
O14	$\frac{\lambda_{14}}{M_{pl}} \bar{\psi} \tilde{H}^\dagger (\not{D} L)$	$\Gamma(\psi \rightarrow f f \nu) = \frac{\lambda^2 v^2 G_f^2 M_\psi^5}{192\pi^3 M_{pl}^2}$
O15	$\frac{\lambda_{15}}{M_{pl}} \mathbf{V}^\mu \bar{f} \partial_\mu f$	$\Gamma(V \rightarrow ff) = \frac{\lambda^2 M_V^3}{64\pi M_{pl}^2} A^{3/2}$
O16	$\frac{\lambda_{16}}{M_{pl}} \mathbf{V}_\mu (H^\dagger D_\nu H) F^{\mu\nu}$	$\Gamma(V \rightarrow H\gamma) = \frac{\lambda^2 v^2 M_V^3}{64\pi M_{pl}^2 m_h^2} \left(1 - \frac{m_h^2}{m_V^2} \right)^3$

TABLE II. Decay width of the dimension five planck suppressed operators, where $A = 1 - 4m^2/M_{DM}^2$ with m being the mass of the final state particle, G_f the fermi constant, m_h higgs mass, and $v = 246$ GeV.

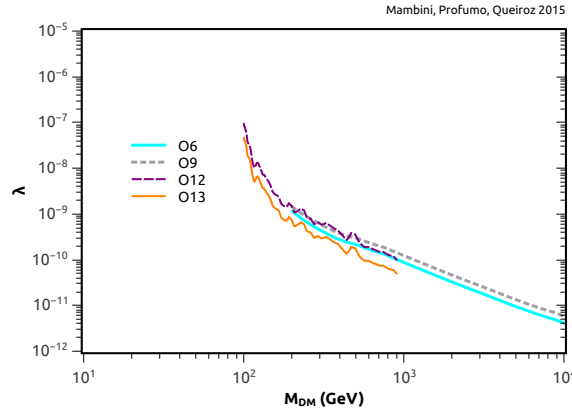


FIG. 1. Limits from non-gauge invariant operators on λ as a function of the DM mass, obtained by enforcing the 95% C.L. bounds from the various observational probes discussed above.

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