

MASSIVE DARK PHOTONS AS HOT DARK MATTER*

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Motivated by the growing interest in the existence of new massive gauge bosons, we suggest that massive dark photons A' can be a consequence of a broken new Abelian symmetry $U(1)'_X$. Such a dark symmetry $U(1)'_D$ is afterwards supposed to be associated with the conservation of the weak number W belonging to the weakly interacting slim particles $U(1)'_W$, being a strong candidate for hot dark matter. The latters correspond then to light dark photons $m'_A \lesssim \text{keV}$ from a weak symmetry breaking scale $\gtrsim 10 \text{ keV}$.

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1. Introduction

During the last decades, a lot of theoretical speculations as well as experimental searches have been driven towards the existence of new particles beyond the Standard Model (SM) of particle physics [1–4]. However, due to the negative results of all these searches and hence the increasing frustration for the failure to discover any of these hypothetical new particles, these attempts have been increasingly challenged. As the prospect of a breakthrough along these routes is dwindling, the interest in a hidden sector — hidden because neutral under the SM gauge symmetries — is mounting: Perhaps no new particles have been observed merely because they do not interact via the SM gauge interactions [5–9].

The hidden sector is supposed to exist as a solution to the problem of the dark side of the universe whose presence is motivated by gravitational physics [10, 11], where the hidden particles serve as possible candidates for the dark sector [6, 12, 13]. Particularly, depending on the model, the hidden sector may contain few or many states, and these can be fermions, bosons or both; and whose existence is believed needful to account for astrophysical data [5–7]. Additionally, these hidden particles can communicate with the visible sector. In particular, other than their gravitational interaction, they can

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communicate through their putative weak interaction, because otherwise, there would be little hope for detecting experimentally particles belonging to the hidden sector as in the direct- and indirect-detection searches of weakly interacting massive particles [14, 15]. For the same purpose, we must focus our prospects on supposing that the hidden and the visible sectors also interact by means of a narrow window, *i.e.*, a portal, in a way that although is weak, it can be (at least in principle) experimentally attainable [6, 16–19].

Among the various candidates for the dark matter (DM), the dark photon (DP) is a popular candidate for the very light DM particles that have been largely dealt with [6, 20, 21]. The DP constitutes a typical example of a spin-1 bosonic light DM. It is associated with the minimal extension of the SM gauge symmetry and is also well-motivated by major esteems [22, 23]. Similarly to other candidates, *i.e.*, QCD axions and axion-like particles (ALPs) [6, 20, 21], DPs are assumed to be produced in the early Universe through certain production channels of inflationary fluctuations, decays or annihilations of earlier fields [6, 17, 18, 20, 21, 24]. Thus, depending on their production history, the resulting DPs vector field may inherit specific properties that can be accessible at present time in the intergalactic medium of our Galaxy. In particular, in addition to the possibility that they can communicate with the visible photons of the electromagnetic field through some portals, the DPs are assumed to belong to the weakly interacting slim particles (WISPs) and have a little mass via a specific mechanism, and hence can bring explanations for some related phenomena, for instance, the hot DM (HDM), which does not appear in the massless visible photons.

The principal goal of the present work is to deal with the massive DPs A' as a candidate for the HDM in the Universe. For that we build a model where the massive DPs consist of particles whose existence belongs to a new symmetry beyond the SM. Concretely, we deal with a simple Abelian symmetry $U(1)'_X$ extension of the SM and show how DPs A' can be readily lodged. Then, we study the breaking of such a dark symmetry $U(1)'_D$ and investigate the associated conserved dark number D , that we further identify with the weak number W associated with the WISPs being a potential candidate for the HDM in the Universe. Next, we discuss how this can be particularly helpful for the breaking scale of this symmetry $U(1)'_W$ and in supporting the case for the massive DPs.

2. Motivation for dark sector

It is now known that the missing mass in the Universe that we call DM is about five times more abundant than the ordinary baryonic matter [14, 25]. Since DM cannot be integrated within the SM, its possible comprehension demands the introduction of new degrees of freedom interacting weakly with

ordinary matter. The introduction of heavy particles $m_X \gtrsim M_{\text{EW}}$ above the energy we have reached so far is the most possible direction. Also, DM could well be explained in terms of light states $m_X \ll 10^2$ GeV that are almost decoupled from the SM particles, the so-called hidden sector. As long as its interaction with the SM particles is weak, the mass scale of the hidden sector m_X could be arbitrary. In this approach, the new physics contribution can be represented as incorporation of two parts: an ultraviolet¹ term responsible for the new heavy degrees of freedom and suppressed by the UV scale Λ_{UV} , and an infrared² term [26]. Thus, roughly, we can write

$$\begin{aligned} L_{\text{SM+NP}} &= L_{\text{SM}} + L_{\text{NP}} \\ &= L_{\text{SM}} + L_{\text{IR}} + L_{\text{UV}} \\ &= L_{\text{SM}} + F_{\text{IR}}(f_{\text{SM}}, X_{\text{IR}}) + \frac{G_{\text{UV}}^n(g_{\text{SM}}, X_{\text{UV}})}{\Lambda_{\text{UV}}^m}, \end{aligned} \quad (1)$$

where the functions f_{SM} and g_{SM} refer to terms involving products of SM fields only, and the functions F_{IR} and G_{UV} refer to the new terms of dimensions four and higher, $d \geq 4$, involving products of SM fields and the new field X_{IR} and X_{UV} , respectively. The values of the n and m numbers are such that the full dimension of the UV contribution is four, *i.e.*,

$$n = 4 + m. \quad (2)$$

However, because no indication of new physics has been observed even with the present highest energy reached at the colliders, the UV contribution in the Lagrangian (1) can be omitted and the full Lagrangian gets simplified to

$$\begin{aligned} L_{\text{SM+NP}} &= L_{\text{SM}} + L_{\text{IR}} \\ &= L_{\text{SM}} + F_{\text{IR}}(f_{\text{SM}}, X_{\text{IR}}) \end{aligned} \quad (3)$$

which is the most general low-energy extension of the SM. It is the so-called hidden sector extension due to its extremely weak interaction with the visible sector. The hidden sector could comprise rich states and phenomenology, but seen that we are interested here in the low-energy scenario which is extensively tested experimentally. We focus mostly on the minimal hidden boson model which has only three unknown parameters: the mass of the new boson $m_{X_{\text{IR}}}$, its direct or indirect coupling ε to the SM, and its decay branching fraction into hidden sector final states $X_{\text{IR}} \rightarrow Y_{\text{IR}}$ which is taken to be either unity or zero depending on whether any invisible dark-sector final states Y_{IR} are kinematically allowed — that is, depending on whether

¹ Short distance.

² Long distance.

$m_{X_{\text{IR}}} > 2m_{Y_{\text{IR}}}$. Here, we focus on the case where the field X_{IR} is the lightest particle in the hidden sector and thus is stable. Therefore, the corresponding parameter space of the minimal hidden boson model is

$$\wp_{\text{SM+IR}} = (m_{X_{\text{IR}}}, \varepsilon) . \quad (4)$$

In addition, we concentrate on X_{IR} masses below the electroweak scale $m_{X_{\text{IR}}} \ll 10^2$ GeV which is the region accessible to accelerator-based experiments, and where the X_{IR} phenomenology is markedly different from supersymmetry and other scenarios that extend the SM. In this view, the existence of a new neutral vector particle

$$X_{\text{IR}} \equiv A' \quad (5)$$

which has a non-vanishing coupling ε to the SM is predicted. Such a hidden photon A' could communicate with the visible sector through a hidden messenger field Z_{IR} but the communication can also be achieved in different processes. Among the constraints on the parameters of this dark photon scenario, the hidden photon must have a light $m_{A'}$ mass and its coupling ε to the SM must be also small so as to guarantee that its possible decay or annihilation processes to the SM sector must not affect the cosmic microwave background radiation. This requirement will be considered in what follows through the direct interaction of the hidden messenger field Z_{IR} with the SM sector.

3. Dark photon model

3.1. Dark photon couplings and mass

The economical model for the low-energy extension of the SM consists of adding an Abelian continuous symmetry; so that the group symmetry of the extended model is

$$\begin{aligned} G_{\text{SM}+X} &= G_{\text{SM}} \times G_X \\ &= \text{SU}(3)_C \times \text{SU}(2)_I \times \text{U}(1)_Y \times \text{U}(1)'_X , \end{aligned} \quad (6)$$

where the additional symmetry $\text{U}(1)'_X$ is related to the conservation of some quantum number X to be determined later on. All SM fields are assumed to be neutral under this additional symmetry so

$$X(q_i) = X(e_i) = X(v_i) = 0 , \quad (7)$$

where the SM fields q_i , e_i , and v_i with i being the family number, refer to the SM quarks, electrons, and left-handed neutrinos, respectively. To allow for

the simplest way of the breaking this additional symmetry, an extra scalar-like field Z_{IR} neutral under G_{SM} but charged under $U(1)'_X$ which restores the longitudinal polarization of the new vector boson X_{IR} is introduced. We call such a singlet scalar field hidden Higgs

$$Z_{\text{IR}} \equiv H' \quad (8)$$

and whose the charges under the group symmetry of the extended model (6) are

$$C(H') = I(H') = Y(H') = 0, \quad (9)$$

$$X(H') \neq 0. \quad (10)$$

Having this hidden Higgs H' added to the SM scalar content, the most general renormalizable scalar potential reads

$$V_{\text{SM}+H'}(H, H') = V_{\text{SM}'}(H) + \mu^2 |H'|^2 + \lambda |H'|^4 + \lambda' |H|^2 |H'|^2, \quad (11)$$

where $V_{\text{SM}'}(H)$ is the standard Higgs potential of the SM, $H = (h^0, h^-)^T$ is the SM Higgs doublet, and μ , λ , and λ' are real constants. More conveniently, it is useful to detach the hidden Higgs field H' into its real and imaginary parts by writing

$$H' = \rho' e^{i\theta'}, \quad (12)$$

where the real fields ρ' and θ' stand for the physical massive field and the massless Goldstone boson, respectively. With this at hand, the scalar potential (11) becomes

$$V_{\text{SM}+H'}(H, H') = V_{\text{SM}'}(H) + \mu^2 \rho'^2 + \lambda \rho'^4 + \lambda' |H|^2 \rho'^2. \quad (13)$$

As it is known, the electroweak symmetry of the SM is surely broken by the non-vanishing vacuum expectation value of the neutral field h^0 at the energy scale of the order of $\langle H \rangle \sim 10^2$ GeV. For the $U(1)'_X$ symmetry, the breaking is ensured if $-(\mu^2 + \lambda' \langle H \rangle^2)/2\lambda > 0$, in such a case, ρ' develops a real vacuum expectation value determined by

$$\langle \rho' \rangle = \sqrt{\frac{m_{\rho'}^2}{2\lambda'}}, \quad (14)$$

$$m_{\rho'} = \sqrt{-(\mu^2 + \lambda' \langle H \rangle^2)}. \quad (15)$$

In this vision, the communication of the physical hidden Higgs ρ' with the SM sector arises indirectly through the scalar portal $\lambda'|H|^2\rho'^2$ parameterizing the size of the interaction between the SM Higgs boson and the hidden Higgs via the coupling constant λ' . However, since the decay properties of the standard Higgs boson with the SM rate expected would be impacted by this interaction [27, 28], such an interaction has to be very small $\lambda' \ll 1$. This corresponds to a weak mixing between the two scalars H and ρ' generating a feeble mixing between the SM weak Z -boson and the new $U(1)'_X$ boson, and, subsequently, no considerable impact on the decays of the Z -boson.

Now, we can go further and investigate the physical meaning of the supposed symmetry $U(1)'_X$. In fact, because there is no locus for a new broken symmetry within the SM, it is then straightforward to think about a symmetry associated with hidden particles feebly interacting with the SM, but likely known to be plentiful in the Universe. We identify these particles with massive dark photons (DPs). Indeed, DPs are believed to be abundant in the Universe with a tiny mass scale. In this picture, one can now assume that the preserved quantum number X associated with the $U(1)'$ symmetry introduced above in Eq. (6) is the dark number D : the number of dark particles minus the number of their anti-particles. This is

$$X \equiv D = \text{DP} - \overline{\text{DP}}. \quad (16)$$

Using the identification $U(1)'_X \equiv U(1)'_D$, we consider the DP fields A' , carrying, along with the dark Higgs field H' , a dark quantum number D whilst all the SM fields are again supposed to be neutral under $U(1)'_D$ as

Fields	SM	H	H'	A'
DP	0	0	2	1
$\overline{\text{DP}}$	0	0	0	0
D	0	0	2	1

According to these field charges, among the new terms involving the dark fields in the most general renormalizable extended Lagrangian, we have

$$L_{\text{SM}+D} \supset \frac{1}{2}\varepsilon^2\rho'^2 A'^2, \quad (17)$$

where ρ' is the physical dark Higgs and ε is the $A' - H'$ coupling constant characterizing the interaction between the dark fields ρ' and A' . Owing to the non-vanishing vacuum expectation value of the dark Higgs (14), the corresponding DP mass is

$$m_{A'} = \frac{\varepsilon}{\sqrt{2}}\sqrt{\frac{m_\rho^2}{2\lambda'}}. \quad (18)$$

Pursuant to the cosmological observations which have directed to a consistent model of the Universe where $\sim 85\%$ of matter is dark, *i.e.*, non-baryonic [14, 25], such massive abundant vector particles are a type of candidates for the HDM and are notably quite favoured by many suggested SM extensions [22, 23]. These particles would inevitably contribute to the HDM of the Universe. Thus, if these massive DPs A' actually form the HDM, the dark number D (16) would then be nothing but the weakly interacting slim number W : the number of WISPs minus the number of their anti-particles, being

$$D \equiv W = \text{WISP} - \overline{\text{WISP}}. \quad (19)$$

Again, using the identification $U(1)'_D \equiv U(1)'_W$, we can say that if these DPs really make up the HDM, they ought to have a local mass density of that supposed in our vicinity to account for the dynamics of our own galaxy. Concretely, they should be spread in a halo bordering our galaxy with a typical relativistic velocity near the speed of light $\sim c$, and would coherently scatter off nuclei in terrestrial detectors [14]. These DPs could be detected indirectly through their self-annihilation $A'\bar{A}' \rightarrow x\bar{x}$ results or directly by investigating their interaction in the detector via their tiny shocks with its nuclei with a typical kinetic energy $K_{A'}$ of tens of keVs, according to the (CDMS II) data [15]. Using this, the DP mass is, roughly, at most

$$m_{A'} \sim \frac{K_{A'}}{c^2} \leq 10^2 \text{ keV} \quad (20)$$

which, in turn, allows to approach the related scales of the model. Indeed, for coupling constants taken at most $\lambda' \sim \varepsilon \sim \vartheta(1)$, we get for the physical dark Higgs mass and its vacuum expectation the values

$$m_{\rho'} \sim \frac{2\sqrt{\lambda'}m_{A'}}{\varepsilon} \geq 10^2 \text{ keV}, \quad (21)$$

$$\langle \rho' \rangle \sim \frac{2m_{A'}}{\varepsilon} \geq 10^2 \text{ keV}, \quad (22)$$

where we see that all the DP involved scales (14), (15), and (18) appear to lie under the well-probed electroweak scale $\sim 10^2 \text{ GeV}$.

3.2. Dark sector decays and productions

In the present model, the DPs A' do not interact directly with the visible sector; but they interact indirectly with the SM via the dark Higgs H' as discussed previously. DPs are assumed to be stable due to their light mass and the conservation of the WISP number associated with the new symmetry $U(1)'_D$. Since the DP is electrically neutral and is its own anti-particle

$A' \equiv \bar{A}'$ and according to its mass range (20), a DP pair in the early Universe can self-annihilate to produce light SM particles, mainly photons A and lighter neutrinos

$$A'A' \rightarrow \gamma\gamma, \nu_e\nu_e. \quad (23)$$

However, as the Universe expands and DPs annihilate without being produced back from lighter particles, their density drops significantly until they are so diluted that they stop interacting with each other. This appealing process leaves a constant population of DPs whose density decreases with the expanding space.

The production as well as the abundance of the DPs can now be discussed. In the present model, the DPs can be produced by dark Higgs via annihilation processes according to some specific modes, depending on the relative mass between A' and ρ' particles. Indeed, because we have $m_{\rho'} > m_{A'}$, DPs can be produced via the dark Higgs annihilation process like

$$\rho'\rho' \rightarrow A'A' \quad (24)$$

as shown in the figure 1.

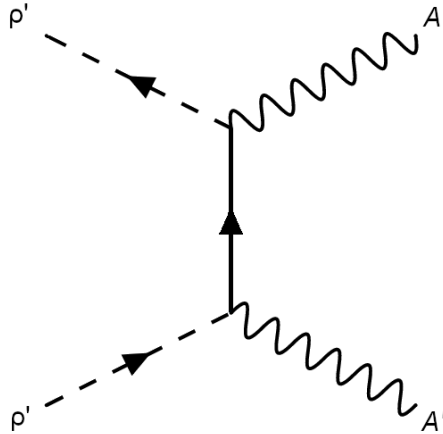


Fig. 1. Production of a dark photon via dark Higgs annihilation.

The corresponding rate of this process scales as

$$\langle\sigma v\rangle_{\rho'\rho'\rightarrow AA'} \sim \frac{\varepsilon^4}{m_{\rho'}^2} \leqslant 10^{-10} \text{ eV}^{-2} \quad (25)$$

which only relies on the dark coupling ε and on the mass of the dark Higgs $m_{\rho'}$ but not on the visible dark Higgs $H - H'$ mixing parameter λ' — which means that the process would be difficult to be detected by a particle physics

experiment. With only the degrees of freedom in the model and based on (18), (21), (22), and (25) and taking into account the dilution of the DPs, straightforward calculations lead to the resulting DPs abundance which can be read, roughly, as

$$\Omega_{A'} \sim 0.2 \left(\frac{\varepsilon}{10^{-8}} \right)^3, \quad (26)$$

where one can see that for a value $\varepsilon \sim 10^{-3}$ of the DP coupling the right abundance of the DM can be obtained.

Although many scenarios and production mechanisms of DP models have been discussed in the literature, DP with a tiny mass below 10^2 keV scale is a motivated candidate for the HDM and its existence remains well motivated from particle physics.

4. Conclusion

WISP candidates for the HDM appear to be a generic possibility as rather minimal model-building choices lead to viable WISPs interacting with ordinary matter through metastable mediators. They are now the target of a growing number and types of experimental searches that are complementary to new physics searches at colliders.

In this work, we have investigated a possible WISP candidate for the HDM in an infrared extension of the SM consisting of an extra symmetry $U(1)'_D$ associated with the new DP A' . The model contained, in addition to the new boson A' , a dark Higgs field H' responsible for the spontaneous breaking of the dark symmetry $U(1)'_D$. The corresponding conserved quantum number D has been associated with the massive DPs A' . Under this coincidence of a conserved dark quantum number D , the dark Higgs H' couples to the DP A' whose mass is generated after the spontaneous breaking of the dark symmetry $U(1)'_D$ by the non-vanishing dark Higgs v.e.v. $\langle \rho' \rangle$. Then, we went even deeper and considered the possibility where the dark symmetry $U(1)'_D$ corresponds to the HDM particles for which the conservation of the dark number D was identified with the WISP number W . With this assessment, the DPs should have a typical speed and interaction with terrestrial detectors according to DM search experiment data which permitted, after investigating the DPs A' kinetic energy, to approximate the involved mass scales of the model, with a DP mass $\leq 10^2$ keV, an energy scale $\geq 10^2$ keV for the dark symmetry $U(1)'_W$ breaking as well as for the associated physical dark Higgs ρ' .

The DP physics still attracts much interest due to the possibilities it provides for the explanation of several phenomena at the same time: the possible indications for DM scattering signals in high purity experiments, the dark matter annihilation mechanism, and more *etc.*

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