Frascati Physics Series Vol. 69 (2019)
PHOTON 2019 - International Conference on the Structure and the Interactions of the Photon
Jun 3-7, 2019

LIGHT DARK STATES ASSOCIATED WITH PHOTONS: AN OVERVIEW OF DARK-SECTOR PHYSICS

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Abstract

There exist various motivations to consider a dark sector beyond the Standard Model (SM). Such a dark sector is assumed to be coupled very weakly, or even feebly, to the known particles via a portal, but can contain its own interaction structures and provide possible candidates for dark matter. Due to its suppressed coupling to the SM particles, the phenomenology and detection strategies of this dark sector are dramatically different from those of conventional new physics, such as TeV supersymmetry and technicolor scenarios. These proceedings review recent developments on dark sector physics, especially those connected to the photon directly, including dark photon, dark current, and axion-like particles.

1 Introduction

With the discovery of the Higgs boson at LHC [1, 2], the SM sector becomes eventually self-contained, to some extent. Still, there are several mysteries in the observed Universe that hint at underlying theories of particle physics. One of them is the existence of dark matter, whose gravitational effects have been observed undoubtedly [3]. Nevertheless, so far the search for non-gravitational signatures of dark matter has not led to any convincingly positive results in direct and indirect searches, and in collider experiments. Thus, a new paradigm of new physics (or more specifically, dark matter physics) has gradually emerged, which suggests that, in contrast to conventional theories beyond SM, there may exist dark particles that only couple to the SM sector via very weaker portals, and, at the same time, are able to explain the dark matter and other observed anomalies. This paradigm is now referred to as dark sector physics.

The possibility of a dark sector is motivated by both UV-scale theories such as string landscape [4], and experimental observations more than just dark matter. For instance, two well-known scenarios in dark sector physics predict the dark photon via kinetic mixing [5] and the axion [6, 7, 8, 9]. The former has attracted a lot of attention recently, because not only such a mixing is theoretically interesting [10], but it can also explain the long-standing anomaly in the muonic anomalous magnetic dipole moment, i.e. the $(g-2)_\mu$, measurements [11, 12], and be relevant for the hypothesis of strongly self-interacting dark matter too [13, 14]. As for the axion, while it was originally proposed to explain the strong CP problem, similar Nambu–Goldstone bosons, namely axion-like particles, can obviously appear in general theories that contain a broken global $U(1)$ symmetry, and thus couple to photons at loop level (or via anomalies).

This review mainly covers the two scenarios of dark sector physics, focusing on recent studies of possible signatures and experimental constraints raised from their interactions with the SM photon.

2 Gauge kinetic mixing

As stated above, a dark photon A', corresponding to a broken or unbroken dark gauge group $U(1)_D$, can couple to the SM photon via gauge kinetic mixing. Without further specifying the UV origin of this mixing, one writes the relevant interactions in terms of renomalizable operators at low energies:

$$\mathcal{L}_D \ni -\frac{\epsilon}{4} F^{\mu\nu} F'_{\mu\nu} + i g_D A'_\mu J^\mu_D \,, \tag{1}$$

where J^μ_D represents the content of dark current, such as $\bar{\chi}\gamma^\mu\chi$ from a dark fermion that charged under the gauge group. Here the kinetic mixing parameter ϵ quantifies the portal interaction between the SM and dark sectors, and thus can be constrained by experimental results once the masses of dark sector particles (A', χ, ...) are presumed.

2.1 Dark photons

In the case of a massive dark photon, A' may be produced on-shell via the photon mixing in laboratory experiments with interacting SM fermions,[1] making its search straightforward, and the signatures depend on its lifetime and decay products. If $m_{A'}$ is above tens of GeV, it only appears in high-energy colliders, such as LEP and LHC, similarly to TeV new physics. In contrast, if A' is lighter than several GeV, low-energy experiments at intensity frontier, including BaBar, Belle and fixed-target experiments, are more competitive, as effectively much larger integrated luminosities can be achieved in these experiments.

If the dark photon decays visibly, which is the case if $m_{A'}$ is larger than twice the electron mass and it does not decay into dark currents with sufficiently high branching fractions, one strategy is to record its decay products ($e^\pm$, $\mu^\pm$, ..) and then reconstruct the invariant mass of the dark photon. The other one is to look for displaced vertices in far-end detectors. In the opposite case, where A' decays invisibly into dark currents or neutrinos, one can only look for the excess of missing-energy/momentum events, especially in electron-beam experiments. Since no signals have been found, all the experiments put constraints on the dark photon, requiring the mixing parameter $\epsilon \leq 10^{-3}$ for $m_{A'}$ below several GeV, as summarized in recent reviews [15, 16, 17].

To address the $(g-2)_\mu$ anomaly, the parameter region of interest is the one corresponding to dark-photon masses in the MeV–GeV range with values of the mixing parameter ϵ around 10^{-3}–10^{-2}. At present, this parameter region has been mostly excluded by NA48/2 if A' decays visibly [18], or by the BaBar results if A' decays invisibly [19]. However, it is still too early to conclude that the dark photon cannot solve the $(g-2)_\mu$ anomaly any more, due to several potential caveats. One is that the bounds on visible mode rely on the reconstruction of the invariant-mass peak under the assumption of two-body decays of the dark photon. More importantly, those experimental bounds can only directly constrain

[1] If $m_{A'} \ll 1\,\mathrm{GeV}$, A' is also produced in supernova and stars, leading to very stringent constraints.

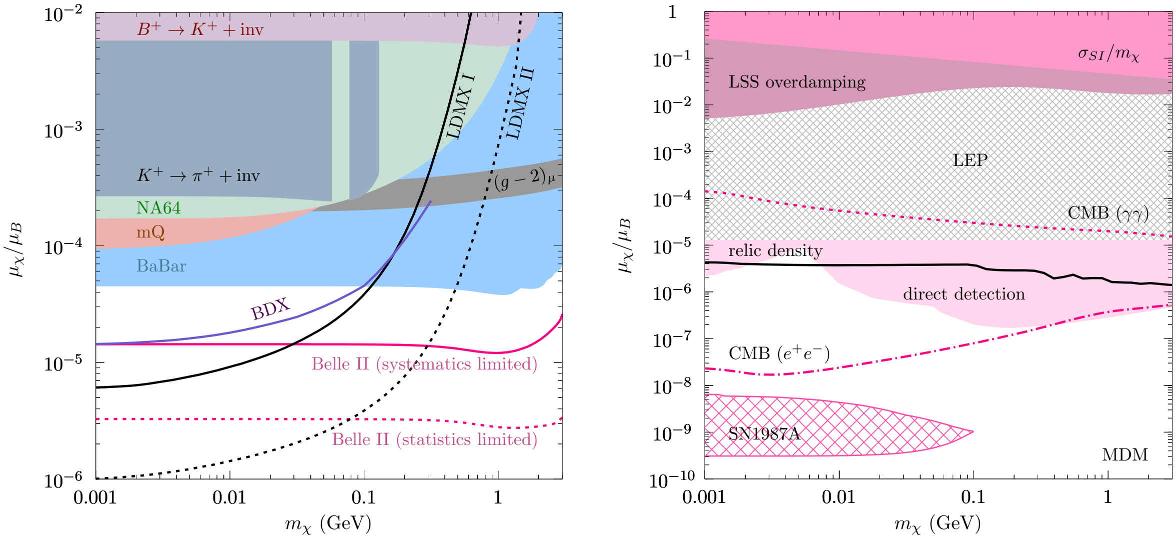

Figure 1: *Constraints on the MDM coupling of a dark Dirac fermion from intensity frontier experiments including projections (left), and conventional dark matter searches and cosmology (right). See* [25].

the coupling of A' to electrons (or nucleons), instead of its coupling to muons. See e.g. [20, 21] and references therein for quantitative studies.

2.2 Dark currents coupled to a photon

If the dark photon is massless, the detection strategy changes conceptually. The reason is that when all four gauge degrees of freedom in the mixing are degenerate/massless, one can always define the two degrees of freedom that couple to the charged SM particles as the *physical* photon so that the *physical* dark photon does not couple to the electromagnetic (EM) current. As a result, it becomes extremely difficult to search for the dark photon, which is not produced directly. Instead, one has to look for signatures caused by dark currents, whose coupling to the EM current is unaffected by the degeneracy.

The associated EM interactions for a Dirac fermion in dark sector can be written as

$$\mathcal{L}_D \ni \epsilon e\, \bar{\chi}\gamma^\mu \chi A_\mu + \frac{1}{2}\mu_\chi\, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu} + \frac{i}{2} d_\chi\, \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu} - a_\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu} + b_\chi\, \bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}\,. \qquad (2)$$

The first term, corresponding to a milli-charged interaction, has been repeatedly studied in the literature. While its current bound is about $\epsilon \leq 10^{-3}$ for $m_\chi \leq 0.1\,\mathrm{GeV}$ and becomes much weaker for higher m_χ, this will be improved by one to two orders of magnitude in future experiments [22, 23]. Meanwhile, we have updated the bounds on other EM form factors, among which the magnetic dipole moment (MDM) interactions is shown in Fig. 1 as an example; for more details see [24, 25, 26].

If the particle content of the dark current contains the dark matter, more constraints can be derived from direct detection experiments, and cosmological/astrophysical considerations, such as observables from large scale structure (LSS). These are also taken into account in right panel of Fig. 1. Notice that the bounds from CMB [27] and Voyager 1 [28] (also the benchmark relic density lines) only apply to symmetric dark matter, as they assume (thermal) pair annihilation.

3 Axion-Like Particles (ALPs)

While the coupling of an axion (or, more generally, an ALP) to photons is model-dependent [29, 30, 31], the interaction term is usually parametrized by a dimension-five operator

$$\mathcal{L}_D \ni -\frac{g_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} \equiv g_{a\gamma\gamma} a \, \mathbf{E} \cdot \mathbf{B} \,, \tag{3}$$

where $g_{a\gamma\gamma}$ is expressed in GeV^{-1} . To be conservative, here we only consider this interaction term while neglecting any other possible portals that connect the ALPs with the SM sector. Again, the detection strategies depend on the mass of the presumed ALP particle.

3.1 Very heavy ALPs

Similarly to the case of dark photons, a heavy ALP can be searched for in both high-energy colliders and low-energy intensity-frontier experiments. One can measure either the decay production of the ALP or the missing energy, according to whether it decays visibly or invisibly. Two main differences from dark-photon searches are the following: 1) There exists a three-photon channel in electron/proton collider searches [32, 33], e.g., $e^- e^+ \to \gamma + a^* \to \gamma\gamma\gamma$; 2) The ALP can be produced in light-by-light scattering with ultra-peripheral nucleus collisions, significantly enhancing its production rate [34]. Therefore, while fixed-target experiments dominate the bounds for m_a from MeV to GeV [35], heavy-ion experiments most likely will provide the strongest bounds for m_a above several GeV, probing the value of $g_{a\gamma\gamma}$ below 10^{-5}–$10^{-4}\,\mathrm{GeV}^{-1}$ in the future.

3.2 Ultra-light ALPs

The most appealing signatures of ultra-light ALPs are the photons from axion-photon conversion in magnetic fields, as suggested by Eq. (3). The source axion can be generated from a high-power laser [36] inside the Sun (i.e. helioscope) or from the dark matter axions of the Milky Way halo (i.e. haloscope). Moreover, the conversion of photons into axions also affects the polarization and energy spectra of cosmic photons during their propagation to our detectors from, e.g., the last scattering surface and high-redshift astrophysical objects. This detection strategy, together with stellar cooling arguments, in general provide the strongest constraints on m_a below MeV or so. For detailed discussions, see e.g. [37, 38, 39].

4 Sterile Neutrino, Light Scalar and More

Another very interesting dark-sector scenario is the so-called ν minimal SM [40]. It introduces three sterile neutrinos of keV–GeV mass scales that mix with the SM neutrinos via tiny mixing angles, in order to obtain both dark matter relic abundance and baryon asymmetry of the Universe. Such sterile neutrinos can decay into a SM neutrino and a photon, leading to observable signatures, although their lifetime can be extremely long due to the small mixing angles.

Also, a light scalar s can couple to the EM field strength via a dimension-five operator $sF^{\mu\nu}F_{\mu\nu}$. The consequence of this operator is the rescaling of the fine-structure constant, whose signatures can be looked for in precision experiments, such as atomic clocks [41].

Before the conclusion, it is worth emphasizing that while this review focuses on the coupling of the dark sector particles to the photon, other kinds of interactions are also very interesting and may lead to different experimental signatures, such as those of Higgs portal, fermionic portal and so on. For more general reviews on dark-sector physics, see [42, 16, 17].

5 Conclusions

There exist both theoretical motivations and experimental hints of the existence of a dark sector, which may contain the dark matter particle and its own interaction structures, but only couples to the SM sector via a very weak portal. Such a new paradigm leads to new detection strategies for physics beyond SM. This paper reviews the recent progress of the experimental efforts to probe the interaction of this dark sector with photons. It shows that astrophysical observations and intensity-frontier experiments can play a very important role in probing light dark particles. Moreover, multi-messenger observations will be crucial to exclude or confirm dark-sector physics scenarios in the future.

6 Acknowledgements

The author thanks Jui-Lin Kuo, Josef Pradler, and Lukas Semmelrock for collaboration on some of the work presented here, which is supported by the New Frontiers program of the Austrian Academy of Sciences. The author also thanks the organizers of PHOTON 2019 for the invitation to give an overview on dark-sector physics.

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