

New Light on Dark Photons

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“Dark Photons”, light new vector particles V_μ kinetically mixed with the photon, are a frequently considered extension of the Standard Model. For masses below 10 keV they are emitted from the solar interior. In the limit of small mass m_V the dark photon flux is strongly peaked at low energies and we demonstrate that the constraint on the atomic ionization rate imposed by the results of the XENON10 Dark Matter experiment sets the to-date most stringent limit on the kinetic mixing parameter of this model: $\kappa \times m_V < 3 \times 10^{-12}$ eV. The result significantly improves previous experimental bounds and surpasses even the most stringent astrophysical and cosmological limits in a seven-decade-wide interval of m_V .

1 Introduction

In the recent years, the model of light vector particles with kinetic mixing to the Standard Model photon has received tremendous attention, theoretically as well as experimentally. Whereas $m_V \gtrsim 1$ MeV is mainly being probed in medium-to-high energy collider experiments, masses in the sub-MeV regime are subject to severe astrophysical and cosmological constraints. Below $m_V < 10$ eV, those limits are complemented by direct laboratory searches for dark photons in non-accelerator type experiments. Among the most prominent are the “light-shining-through-wall” experiments (LSW) [1] and the conversion experiments from the solar dark photon flux, “helioscopes” [2]; a collection of low-energy constraints on dark photons can *e.g.* be found in the recent review [3]. Helioscopes derive their sensitivity from the fact that such light vectors are easily produced in astrophysical environments, such as in the solar interior, covering a wide range of masses up to $m_V \sim$ few keV. In general, stellar astrophysics provides stringent constraints on any type of light, weakly-interacting particles once the state becomes kinematically accessible [4]. Only in a handful of examples does the sensitivity of terrestrial experiments match the stellar energy loss constraints.

Here we review our works [5, 6] in which we have identified a new stellar energy loss mechanism originating from the resonant production of longitudinally polarized dark photons and derived ensuing constraints from underground rare event searches. Limits on dark photons were improved to the extent that previously derived constraints from all LSW and helioscope experiments are now superseded by the revised astrophysical and new experimental limits.

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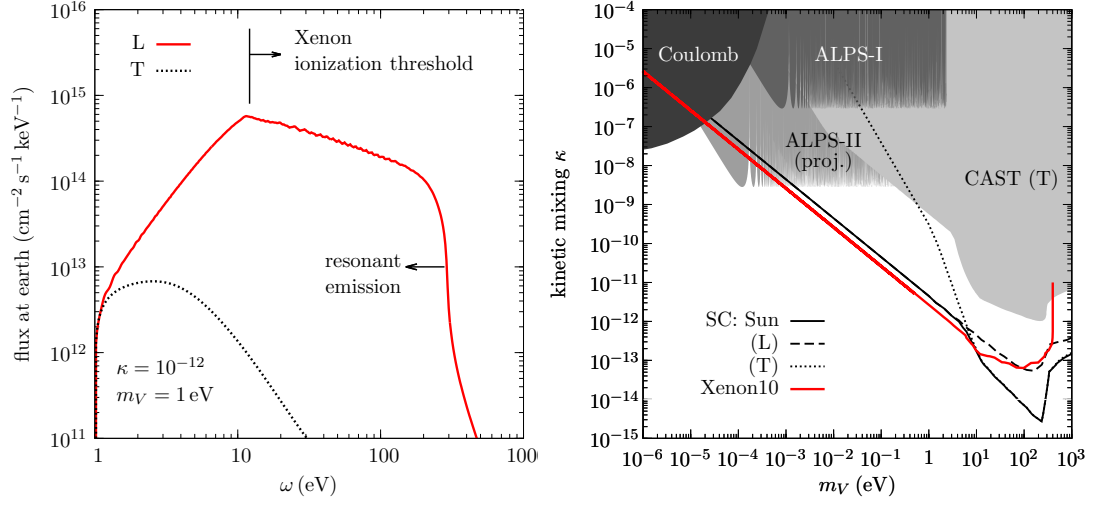


Figure 1: *Left*: Energy differential solar dark photon flux at Earth for $\kappa = 10^{-12}$ and $m_V = 1$ eV. The solid/dotted line shows the longitudinal(L)/transverse(T) contribution. *Right*: Constraints on κ as a function of m_V . The black solid/dashed/dotted curves show the total/longitudinal/transverse energy loss limit of the Sun by requiring that the dark photon luminosity does not exceed 10% of the standard solar luminosity [7]. The red line shows the constraint derived from the XENON10 data. Previous and future (“proj.”) experimental bounds/sensitivities are shown by the shaded regions. From light to dark shading these are from the CAST experiment [8] considering the contributions from only the transverse modes [2], from the ALPS collaboration [9], and from tests of the inverse square law of the Coulomb interaction [10].

2 Dark Photons from the sun: flux and detection

The minimal extension of the SM gauge group by an additional $U(1)_V$ gauge factor yields the following effective Lagrangian well below the electroweak scale,

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}V_{\mu\nu}^2 - \frac{\kappa}{2}F_{\mu\nu}V^{\mu\nu} + \frac{m_V^2}{2}V_\mu V^\mu + eJ_{\text{em}}^\mu A_\mu, \quad (1)$$

where V_μ is the vector field associated with the Abelian factor $U(1)_V$. The field strengths of the photon $F_{\mu\nu}$ and of the dark photon $V_{\mu\nu}$ are connected via the kinetic mixing parameter κ where a dependence on the weak mixing angle was absorbed; J_{em}^μ is the usual electromagnetic current with electric charge e .

Because of the $U(1)$ nature of (1), we must distinguish two cases for the origin of m_V : the Stueckelberg case (SC) with non-dynamical mass, and the Higgs case (HC), where m_V originates through the spontaneous breaking of $U(1)_V$ by a new Higgs field h' . The crucial difference between the two cases comes in the small m_V limit: while all processes of production or absorption of V in SC are suppressed, $\Gamma_{\text{SC}} \sim O(m_V^2)$, in HC there is no decoupling, and $\Gamma_{\text{HC}} \sim O(m_V^0)$. Indeed, in the limit $m_{V,h'} \rightarrow 0$ the interaction resembles one of a mini-charged scalar with the effective EM charge of $e_{\text{eff}} = \kappa e'$ [11, 12, 13, 14]. In the following we discuss the SC and refer the reader to our work [6] as well as to [15] and references therein for HC.

Solar flux The solar flux of dark photons in the SC is thoroughly calculated in Ref. [5]; for further discussion see also [16]. In the small mass region, $m_V \ll \omega_p$ where ω_p is the plasma frequency, the emission of longitudinal modes of V dominates the total flux, and the emission power of dark photons per volume can be approximated as

$$\frac{dP_L}{dV} \approx \frac{1}{4\pi} \frac{\kappa^2 m_V^2 \omega_p^3}{e^{\omega_p/T} - 1}. \quad (2)$$

This formula is most readily obtained by noting that a resonant conversion of longitudinal plasmons into dark photons is possible whenever $\omega^2 = \omega_p^2$. The energy-differential flux of dark photons at the location of the Earth is shown in the left panel of Fig. 1. Resonant emission stops for $\omega \gtrsim 300$ eV since ω_p is limited by the temperature in the sun's core.

Absorption of dark photons In the SC, the ionization of an atom A in the detector can then be schematically described as $V + A \rightarrow A^+ + e^-$. The total dark photon absorption rate is given by,

$$\Gamma_{T,L} = -\frac{\kappa_{T,L}^2 \text{Im} \Pi_{T,L}}{\omega}, \quad \kappa_{T,L}^2 = \frac{\kappa^2 m_V^4}{(m_V^2 - \text{Re} \Pi_{T,L})^2 + (\text{Im} \Pi_{T,L})^2}. \quad (3)$$

$\kappa_{T,L}$ are the effective mixings for the transverse (T) and longitudinal (L) modes respectively. The polarization functions $\Pi_{T,L}$ are found from the in-medium polarization tensor $\Pi^{\mu\nu}$,

$$\Pi^{\mu\nu}(q) = ie^2 \int d^4x e^{iq \cdot x} \langle \Omega | T J_{em}^\mu(x) J_{em}^\nu(0) | \Omega \rangle = -\Pi_T \sum_{i=1,2} \epsilon_i^{T\mu} \epsilon_i^{T\nu} - \Pi_L \epsilon^{L\mu} \epsilon^{L\nu}, \quad (4)$$

where $q = (\omega, \vec{q})$ is the dark photon four momentum and $\epsilon_\mu^{T,L}$ are the polarization vectors for the transverse and longitudinal modes of the dark photon, $\epsilon_\mu^2 = -1$. The first relation (3) is a manifestation of the optical theorem.

The polarization functions $\Pi_{T,L}$ are related to the complex index of refraction, n_{refr} or, equivalently, to the permittivity of the medium $\varepsilon = n_{\text{refr}}^2$. For an isotropic, non-magnetic medium $\Pi_L = (\omega^2 - \vec{q}^2)(1 - n_{\text{refr}}^2)$, and $\Pi_T = \omega^2(1 - n_{\text{refr}}^2)$, so that for an incoming on-shell dark photon with $q^2 = m_V^2$, $\Gamma_L \propto \kappa^2 m_V^2$ indeed holds. We obtain n_{refr} from its relation to the forward scattering amplitude $f(0) = f_1 + if_2$ where the atomic scattering factors $f_{1,2}$ are *e.g.* tabulated in [17]. Close to the ionization threshold we make use of the Kramers-Kronig dispersion relations to relate f_1 and f_2 for estimating n_{refr} . Alternatively, one can solve an integral equation relating $\text{Im} \varepsilon$ and $\text{Re} \varepsilon$ in a self-consistent manner, an approach taken in [6].

Limits from direct detection With flux $d\Phi_{T,L}/d\omega$ and absorption rate $\Gamma_{T,L}$ at hand, the expected number of signal events in a given experiment reads

$$N_{\text{exp}} = VT \int_{\omega_{\text{min}}}^{\omega_{\text{max}}} \frac{\omega d\omega}{|\vec{q}|} \left(\frac{d\Phi_T}{d\omega} \Gamma_T + \frac{d\Phi_L}{d\omega} \Gamma_L \right) \text{Br}, \quad (5)$$

where V and T are the fiducial volume and live time of the experiment, respectively, and Br is the branching ratio of photoionization rate to total absorption rate.

Given the significant infrared enhancement of the solar dark photon spectrum, left panel of Fig. 1, the low-energy ionization signals measured in the XENON10 [18] dark matter experiment

have the best sensitivity to constrain a dark photon flux that is also supported by the Sun. With ~ 12 eV ionization energy in xenon, the absorption of a dark photon with 300 eV energy can produce about 25 electrons. From [18] we estimate a 90% C.L upper limit on the detecting rate to be $r < 19.3$ events $\text{kg}^{-1}\text{day}^{-1}$ (similar to limits deduced in Ref. [19]). In the region $12 \text{ eV} < \omega < 300 \text{ eV}$ the ionization process dominates the absorption, and therefore Br in this region can be set to unity. The 90% C.L. upper limit on κ as a function of m_V is shown by the thick red curve in Fig. 1. As can be seen it surpasses other current experimental limits as well as the solar energy loss bound in a mass interval from $10^{-5} \text{ eV} < m_V \lesssim 10 \text{ eV}$.

Given the enormous amount of experimental progress in the field of direct Dark Matter detection, one can be optimistic that future sensitivity to dark photons, and other light particles is bound to be further improved.

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