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Cosmic Microwave Background Constraints on Very Dark Photons

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Abstract

We analyze the effects of a massive dark photon with $m_V > 1$ MeV on the Cosmic Microwave Background (CMB). We calculate the freeze-in abundance and derive limits on the parameter space from energy injections in the CMB. We find that for dark vectors in the mass range $1 \text{ MeV} < m_V < \lesssim 300 \text{ MeV}$, the model is already ruled out for effective electromagnetic coupling as low as $10^{-34} - 10^{-37}$.

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Dark photons, Hidden sector, Cosmic Microwave Background

1. Introduction

It is well-known that the Standard Model (SM) does not explain all physics. Multiple phenomena, such as dark matter and neutrino oscillations, provide ample motivation to explore phenomenological studies of neutral hidden sectors, weakly coupled to the SM.

The marginal interaction of a kinetic mixing of a new U(1) massive vector V_μ with the electroweak neutral bosons through $B_{\mu\nu}V^{\mu\nu}$ could provide the leading coupling between the hidden sector and the SM. For masses lower than the weak scale, we can only consider the mixing with the photon, and the interaction with the SM is simply

$$\mathcal{L}_V^{\text{int}} = -\frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} = e\kappa V_\mu J_{\text{em}}^\mu. \quad (1)$$

The phenomenology of this model depends on the vector mass m_V and the kinetic coupling κ . For simplicity, we take the mass to be a fundamental parameter, it could instead come from a new Higgs mechanisms [1]. Here, we are interested in the range $m_V > 2 \times 511 \text{ keV}$, so that production from and decays to electron positron pairs are allowed. We first calculate the freeze-in production abundance and then explore its consequences on the Cosmic Microwave Background (CMB). This work, along with Big Bang Nucleosynthesis (BBN) and other cosmological implications, are presented in more details in [2].

The sensitivity of the cosmological probes to this model is quite remarkable. The region of interest is given by lifetimes near the CMB emission epoch, and for $m_V < 220$ MeV is given by

$$\tau_V \simeq \frac{3}{\alpha_{\text{eff}} m_V} = 0.6 \text{ mln yr} \times \frac{10 \text{ MeV}}{m_V} \times \frac{10^{-35}}{\alpha_{\text{eff}}}, \quad (2)$$

where we defined the effective electromagnetic coupling $\alpha_{\text{eff}} = \alpha \kappa^2$. We can estimate the production cross section in $e^+e^- \rightarrow V\gamma$,

$$\sigma_{\text{prod}} \sim \frac{\pi \alpha \alpha_{\text{eff}}}{E_{\text{c.m.}}^2} \sim 10^{-63} \text{ cm}^2, \quad (3)$$

with $E_{\text{c.m.}} \sim 200$ MeV. These extremely low couplings are therefore undetectable in present-day production phenomena and as such we will refer to the dark vectors in this model as Very Dark Photons (VDP).

2. Freeze-in abundance of VDP

As a consequence of the low coupling to the SM, the production rate of the VDP is assumed to be sub-Hubble and V never achieves an equilibrium density. The dominant production channel is via pair coalescence of e^\pm or more generically charged leptons $\bar{l}l \rightarrow V$. The production rate is given by the Boltzmann equation

$$s\dot{Y}_V = \dot{n}_V + 3Hn_V = \prod_{i=l,\bar{l},V} \int \left(\frac{d^3\mathbf{p}_i}{(2\pi)^3 2E_i} \right) N_l N_{\bar{l}} (2\pi)^4 \delta^{(4)}(p_l + p_{\bar{l}} - p_V) \sum |M_{l\bar{l}}|^2, \quad (4)$$

where $Y_V = n_V/s$ is the number density per entropy density, the overdot represents a time derivative, H is the Hubble rate, $N_{l(\bar{l})} = [1 + \exp(-E_{l(\bar{l})}/T)]^{-1}$ is the Fermi-Dirac statistical distribution and

$$\sum |M_{l\bar{l}}|^2 = 16\pi \alpha_{\text{eff}} m_V^2 \left(1 + 2 \frac{m_l^2}{m_V^2} \right) \quad (5)$$

is the matrix element of the interaction, summed both over initial and final spin degrees of freedom. The peak production rate per entropy appears at $T < m_V$ [3] and we can find an analytical result by neglecting the lepton mass and using the Maxwell-Boltzmann distribution instead. We find

$$s\dot{Y}_V^e = \frac{\alpha_{\text{eff}}}{2\pi^2} m_V^3 T K_1(m_V/T), \quad Y_{V,f}^e = 0.24 \frac{\alpha_{\text{eff}} m_V^4}{(Hs)_{T=m_V}} \quad (6)$$

$K_1(m_V/T)$ is the modified Bessel function and in evaluating the final abundance from the electron channel $Y_{V,f}^e$, we have assumed $H(T)s(T)$ to be almost constant in the integration of \dot{Y}_V over time.

Considering the thermal mass of the virtual photon in the reaction $\bar{l}l \rightarrow \gamma^* \rightarrow V$, the production can be enhanced as the longitudinal and transverse mass of the virtual photon generate a resonant production when it can oscillate to an on-shell V [4, 5]. The resonance temperature has a parametrically high lower bound [3] $T_r \geq 3m_V^2/(2\pi\alpha) \simeq (8m_V)^2$, which keeps its contribution sub-dominant, but can reach up to $\sim 30\%$ the value of the bulk production. Working in the same approximations as before, we find the analytic result

$$s\dot{Y} = \frac{\alpha_{\text{eff}}}{2\pi^2} m_V^2 \int_{m_V}^{\infty} d\omega \sqrt{\omega^2 - m_V^2} e^{-\omega/T} \left[\frac{1}{3} \frac{m_V^4}{|m_V^2 - \Pi_L|^2} + \frac{2}{3} \frac{m_V^4}{|m_V^2 - \Pi_T|^2} \right], \quad \Delta Y_{f,r} \simeq \Delta Y_T \simeq 0.06 \frac{\alpha_{\text{eff}} m_V^4}{(Hs)_{T=m_V}}, \quad (7)$$

where we used the narrow-width approximation and the real part of the polarization tensors can be found in [6]. In this limit, the imaginary part of $\Pi_{T(L)}$ is $\text{Im}\Pi_{T(L)} = -\alpha m_V^2 (1 - \exp(-\omega/T))/3$, and the general statement is described in [7]. Due to its much higher resonance temperature, the longitudinal thermal production contribution is completely negligible, a contrasting behaviour with the stellar production, where the L -resonance dominates [4].

The VDPs are long-lived and cool down with the expansion of the Universe until $E_V = m_V$. This rest energy forms an accumulation of energy stored that will be released in the cosmic medium in the decay of the VDPs into e^\pm , μ^\pm , π^\pm pairs and other hadronic states. The energy stored per baryon is therefore

$$E_{\text{p.b.}} = m_V Y_{V,f} \frac{s_0}{n_{b,0}}, \quad (8)$$

with $n_{b,0}/s_0 = 0.9 \times 10^{-10}$, the entropy-to-baryon ratio today. Without using approximations, we numerically calculate the VDP freeze-in abundance from the difference production channels and show the related energy stored in figure 1. The left panel demonstrates the fixed lifetime $\tau_V = 10^{14}$ s, with clear dips at the hadronic resonances from the lower value of α_{eff} to keep τ_V constant [8]. The right panel is for $\alpha_{\text{eff}} = 10^{-35}$. We incorporated charged pions and free quarks by a crude step function at the quantum chromodynamics pseudo-critical temperature for energy density $T_c = 157$ MeV [9]. The charged pions are here treated with scalar quantum electrodynamics, we postpone the ρ -resonance production to [2].

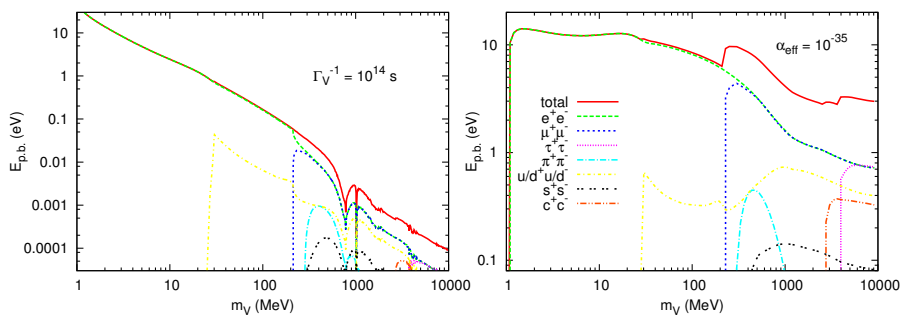


Fig. 1. Total energy stored per baryons with the different contributions for $\Gamma_V^{-1} = 10^{14}$ s and $\alpha_{\text{eff}} = 10^{-35}$.

3. Energy injection in the CMB

If the VDPs decay after the beginning of recombination ($t \approx 10^{13}$ s), the energetic decay products can ionize hydrogen atoms, thus slowing down the recombination process. This modification of the last-scattering surface can have a noticeable imprint in the CMB. The energy injection damps the TT temperature correlations on small scale, while also increasing the TE and EE polarization spectra on the large scales [10, 11]. A generic energy injection from a decaying species can be parametrized as

$$\frac{dE}{dt dV} = 3\zeta m_p \Gamma e^{-\Gamma t}, \quad (9)$$

with the energy output of each decay being $3\zeta m_p$. The energy is thermally distributed, with a fractional amount of $(1 - x_e)/3$ going to ionization, $(1 + 2x_e)/3$ heating the medium and the remainder used in excitations, where x_e is the ionized fraction. Using the codes CLASS [12] and MONTEPYTHON [13], we extracted the 2σ limits on $\Gamma - \zeta$ from the WMAP 7-year [14] and SPT [15] data sets. The resulting constraints are shown on the left in figure 2, along with the WMAP 3-year and Planck forecast for its design precision, including polarization, curves from [11]. The different shape of the curves at small lifetimes comes from the fact that we used the exact cosmic time in the evaluation, as opposed to the matter-dominated approximation in [11].

Remains to determine the efficiency at which the energy stored in the VDPs can be deposited in ionization. The efficiency depends on the species, the decay products, the initial kinetic energy and the redshift [16, 17]. Ref [18] provides transfer functions, solving for the fractional amount of an injection energy deposited at subsequent redshifts. We can therefore compute an effective deposition efficiency f_{eff} by averaging over the range $800 < z < 1000$ [19]. On the right panel of figure 2, we show the overall f_{eff} along

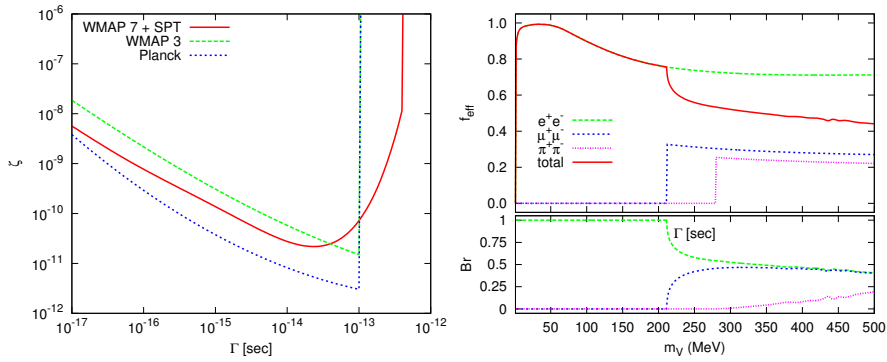


Fig. 2. *Left.* CMB constraints on energy injection parameters ζ and Γ . The WMAP 3 curves also includes large scale structure and together with the Planck forecast including polarization are reproduced from [11]. *Right.* Effective deposition efficiency of each decay channel with the sum weighted by their branching ratios for $\Gamma_V^{-1} = 10^{14}$ s.

its constituents. Both muons and pions contributions are $\sim 1/3$ due to the energy radiated away by the neutrinos.

With this, the $\zeta - \Gamma$ CMB constraints can be related to the VDP parameters with

$$\zeta = \frac{f_{\text{eff}}}{3} \frac{\Omega_V}{\Omega_b} = \frac{f_{\text{eff}}}{3} \frac{E_{\text{p.b.}}}{m_p} \tag{10}$$

and yield the exclusion region shown in figure 3.

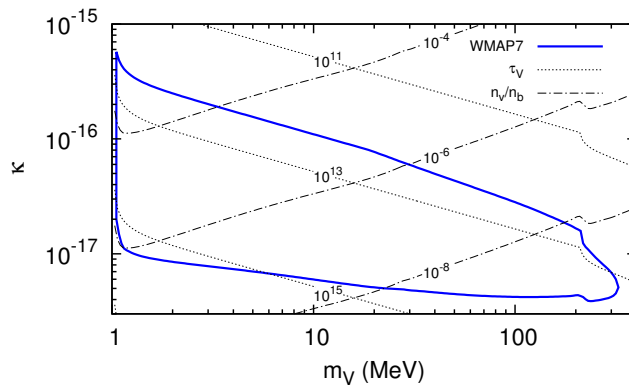


Fig. 3. CMB constraints on VDP. The lifetime in seconds and relative number density of dark photons to baryons prior to their decay is included.

4. Conclusion

We explored the CMB impact of a new U(1) vector kinetically mixing with the photon and mass above the electron threshold. We find a remarkable sensitivity, ruling out a region of parameter space far away from the scope of terrestrial experiments. Dark photons with $m_\nu < 1\text{MeV}$ have a three-photon decay and thus do not require such low couplings to live on cosmological timescales. As such, they have previously been studied as a potential candidate for dark matter [1, 3]. This work will be presented in more details, along with the ρ -resonance production and BBN constraints in [2].

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