Sub-GeV Dark Vector Bosons and their Cosmological Constraints

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Introduction

New forces below the weak scale are allowed by experimental searches if they couple weakly to the Standard Model (SM), but can be tested with cosmology. Dark forces can be introduced into the SM by the following Lagrangian:

$$\mathcal{L}_{eff} = -\frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu$$
$$- \frac{\epsilon}{2}F_{\mu\nu}X^{\mu\nu} - g_V J^\mu_{SM} V_\mu + \mathcal{L}_{\text{SM}}$$

We can ask two important questions:

How do the dark vectors decay?
What is the electromagnetic (EM) energy spectra of the decays?

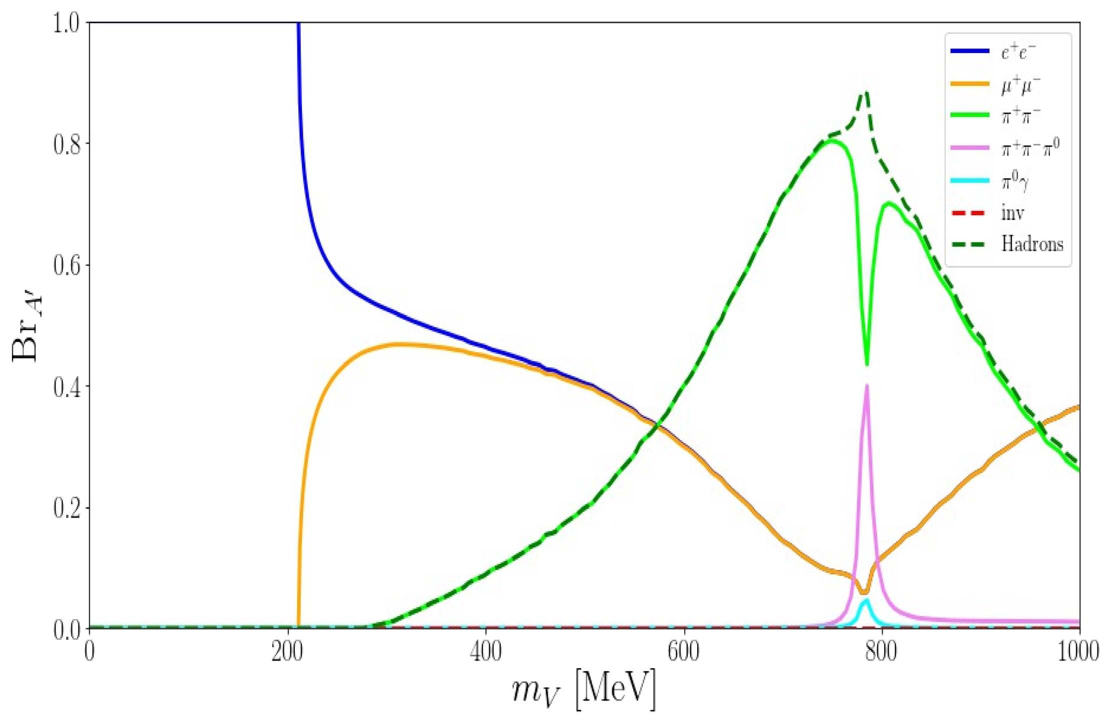

Figure 1: Branching ratio for the dark photon model, where $g_V = 0$ and the only way to interact with the Standard Model is through kinetically mixing with the photon.

Branching Ratios

The main channels in the sub-GeV region that produce electrons and photons are:

e^+e^-, $\mu^+\mu^-$, $\pi^0\gamma$, $\pi^-\pi^+$, $\pi^-\pi^+\pi^0$

The branching ratios were calculated through Feynman rules and the hadronic channels utilized vector meson dominance to determine their coupling.

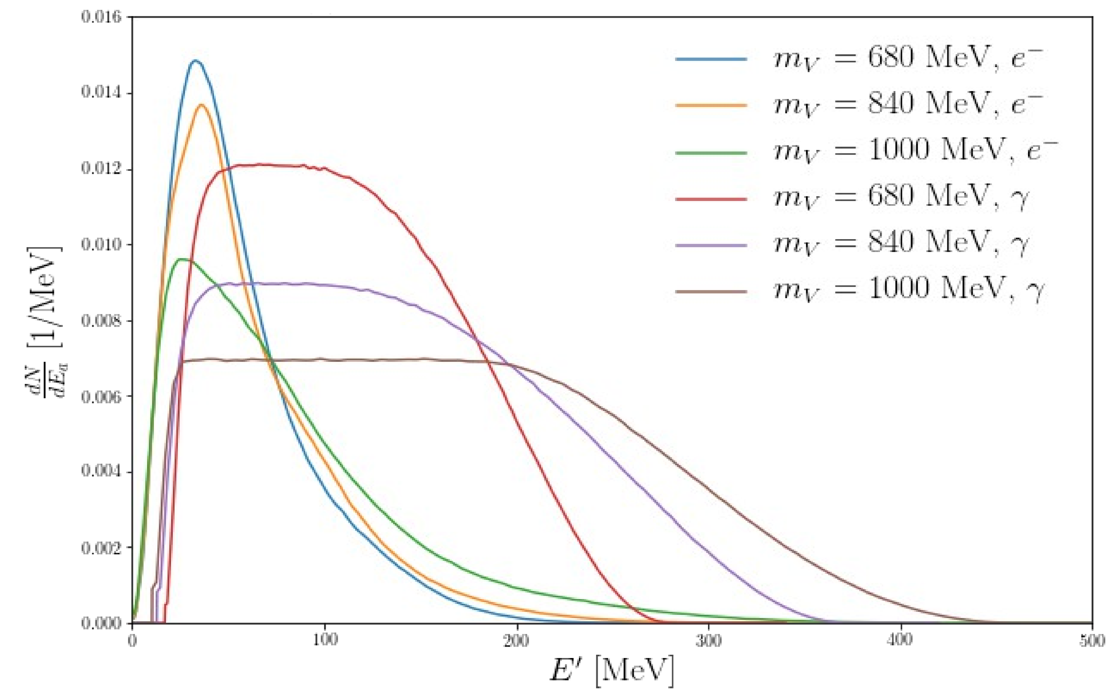

Figure 2: Energy spectra for the decay of V --> $\pi^-\pi^+\pi^0$

Energy Spectra

To find the energy spectra, the final electrons and photons had to be boosted such that they were in the rest frame of the dark vector boson.

Non-leading terms, such as final state radiation, can also produce photons and as such were including in the analysis.

Application to Cosmology

In the early Universe, dark vectors can be created by SM collisions and decay later **(Figure 3)**. These decays can alter Big Bang Nucelosynthesis (BBN) and the Cosmic Microwave Background (CMB).

We can apply the calculated branching ratios and EM energy spectra to determine the total amount of injected EM energy in the early Universe.

- BBN: photodissociation destroys light elements, mainly Helium-4
- CMB: modify recombination, mainly ionization of Hydrogen

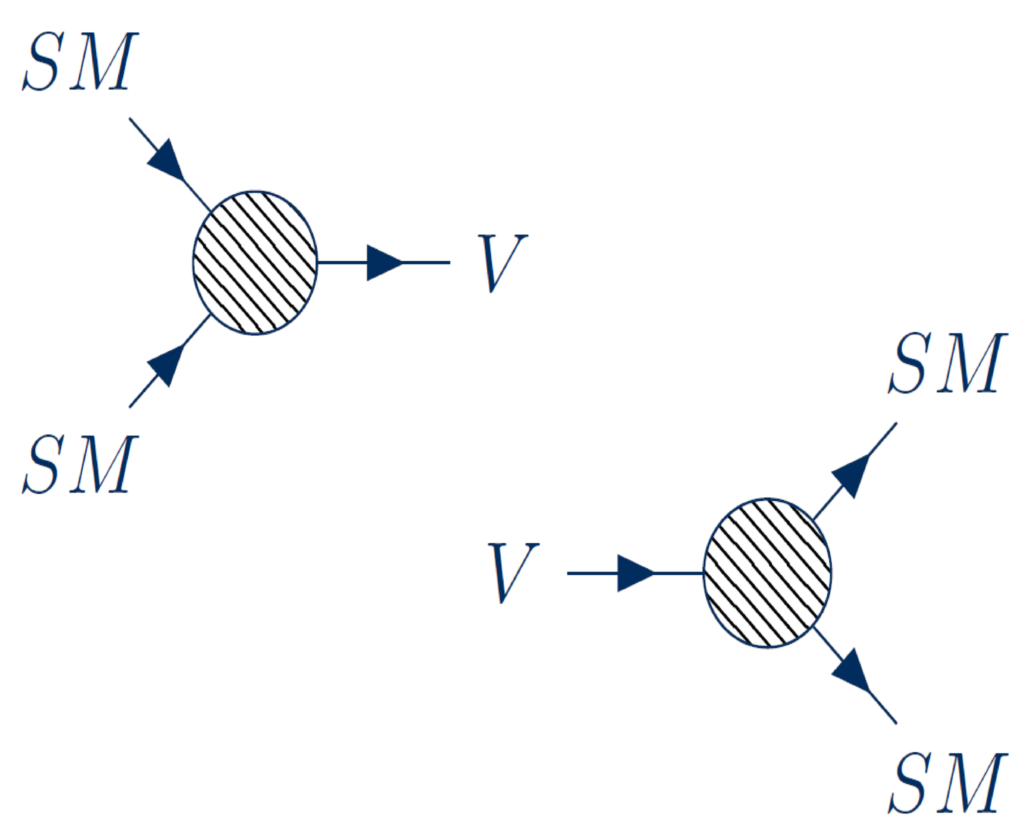

Figure 3: Dark Vectors being created (left) and decaying (right) in the early Universe from Standard Model particles.

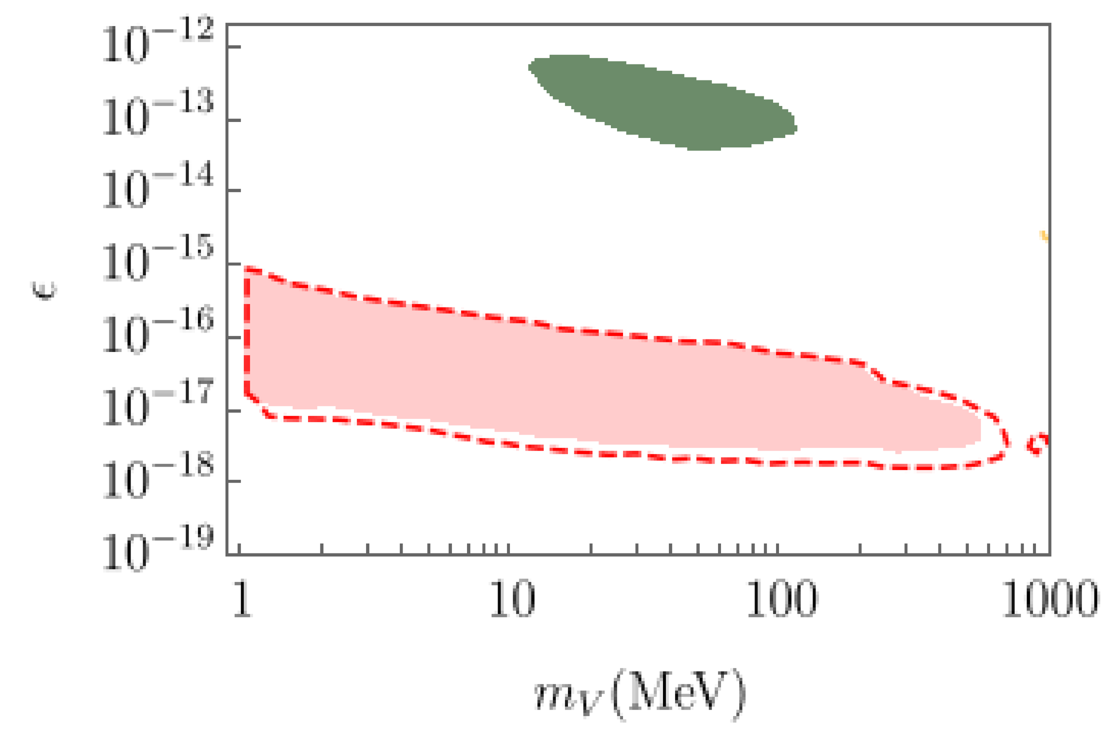

Figure 4: Exclusion plot for the dark photon. The green area is the exclusion from BBN measurements and the red shaded area is the exclusion from CMB. The dotted red line shows projections for a future cosmic variance limited experiment.

Results

In total, four more dark forces were examined alongside the dark photon. Each of the dark forces in the sub-GeV region were explored by calculating the total amount of EM energy injected into the early Universe. The injected energy can alter processes in BBN and CMB. Since measurements of BBN and CMB are precisely measured, they are used to constrain the parameter space of the effective coupling and mass of the dark vector bosons **(Figure 4)**.

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Discovery, accelerated

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