Exploring Dark Photon via Sub-Frequency Laser Search in Gravitational Wave Detectors

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Abstract

We propose a novel idea to detect dark photon in the gravitational wave (GW) experiments. Our setups are capable to perform the whole process of dark photon production, its decay products, and new physics signal discovery. This “mini LHC” is inspired from the recent idea of the dark photon detection using the laser light in light shining through the wall (LSW) experiments such as ALPS II. Taking the sub-frequency light emitted from the laser source as the new physics signal, we show that the sensitivity of our proposal is two order magnitude better than the original idea in the LSW studies.

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1 Introduction

The existence of non-luminous matter dubbed as dark matter (DM) provides the explanations for several astronomy observations, e.g. rotational curves of galaxies. However, except for its gravitational effects, the detail properties, including its spin and mass remain unknown. The DM particle could be a boson or a fermion, and its mass could be as light as below eV or could be heavier than TeV. Even though no conclusive evidence of DM signal has been found in the laboratory, some observations, if interpreted as signals of DM, give us hints about the mass of DM [1–10].

Since the interaction between the Standard Model (SM) particles and DM is very weak, it is usually believed that this interaction is mediated by unknown dark gauge boson known as dark photon. The dark photon is described by the gauge boson of a new dark U(1) gauge group added to the Standard Model (SM) [11,12]. Several proposals have been made to detect dark photon, ranging from laboratory experiments to astronomical observations [1,11,13]. In particular, for laboratory laser experiments, the LSW studies rely on the oscillation of photon into dark photon which is transmitted through the wall then converted back into the photon to be detected at the photodetector (PD) located behind the wall [14–17]. Both signal photon and laser source have the same frequency.

Recently, Ref. [18] proposed a novel idea to detect the dark photon by utilizing a laser source via a different mechanism. Instead of converted back into the photon, the transmitted dark photon decays into an axion and a photon. The proposal relies on the detection of secondary photon, dubbed as sub-frequency photon, originated from dark photon decay. The difference between this scenario and typical LSW experiments is that the frequency of the signal photon is smaller than the original laser frequency. Inspired by this idea, we propose to extend this scenario of dark photon search in gravitational wave experiments. This is possible because the current GW experimental setups are equipped with a laser source and optical cavities to generate a large number of photons. As a result, the GW experiments provide us a suitable environment for dark photon search. Actually, the idea of looking for dark sector particles in GW experiments has been studied in [19–50].

The rest of this paper is organized as follows. In Section 2, we give a brief review on the important aspects of dark photon detection using sub-frequency photon proposed in [18]. In Section 3, we examine the implementation of sub-frequency photon search at GW detectors. We discuss the estimated sensitivity in Section 4. Our summary and conclusions are presented in Section 5.

2 The Model

We briefly review the model and the proposed experimental setup given in [18]. It contains a dark photon $\gamma'$ and an stable axion like particle $a$ residing in the dark sector. The dark photon kinetically mixes with the photon $\gamma$ while the axion couples to both of dark photon and the photon. Due to the mixing, any light sources can be converted into dark photon which subsequently decays into axion like particle and photon when $m_{\gamma'} > m_a$, see Fig.1.

The proposed experimental setup relies on this decay aiming at the detection of the secondary photon whose frequency is smaller than the photon from the light source. This secondary photon is called the sub-frequency photon. In effective Lagrangian language, the
relevant interaction is given by

$$\mathcal{L} \sim - (A_\mu + \epsilon A'_\mu) J_{em}^\mu + \frac{G_{a\gamma\gamma'}}{2} a F_{\mu\nu} \tilde{F}'^{\mu\nu},$$  \hspace{1cm} (2.1)$$

where $J_{em}^\mu$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, and $\tilde{F}'^{\mu\nu}$ stand for the electromagnetic current, the field strength of the photon field $A_\mu$, and of the dark photon field $A'_\mu$, respectively. To determine the number of sub-frequency signal photon, one needs the dark photon decay rate which is given by [51]

$$\Gamma_{\gamma' \to a\gamma} = \frac{G_{a\gamma\gamma'}^2}{96\pi} m_{\gamma'}^3 \left(1 - \frac{m_a^2}{m_{\gamma'}^2}\right)^3.$$  \hspace{1cm} (2.2)$$

Figure 1: The production of dark photon $\gamma'$ via kinetic mixing with the photon followed by its decay into much lighter axion $a$ and subfrequency photon $\gamma$.

For a given light source with the power $P$ and frequency $\omega$, the flux of the sub-frequency signal photon $N_{sub}$ having traversed a distance $L$ is

$$N_{sub} = \epsilon^2 \left(1 - \exp \left[-\frac{m_{\gamma'} \Gamma_{\gamma' \to a\gamma} L}{\sqrt{\omega^2 - m_{\gamma'}^2}}\right]\right) N_\gamma,$$  \hspace{1cm} (2.3)$$

where $N_\gamma = P/\omega$ is the photon number emitted from the source in unit of Hz. In addition, Ref. [18] imposed the following conditions

$$m_a \ll m_{\gamma'} < \omega$$

$$1 \gg \frac{m_{\gamma'} \Gamma_{\gamma' \to a\gamma} L}{\sqrt{\omega^2 - m_{\gamma'}^2}},$$  \hspace{1cm} (2.4)$$

which state that the dark photon is originated from the laser and it decays into a much lighter axion and subfrequency photon. This implies that subfrequency photon would have a sufficient number of events and could be detected using a typical photo detector. If the axion mass is comparable to the dark photon mass $m_a \sim m_{\gamma'}$, the sub-frequency photon would be too feeble to be detected at the optical photodetector considered here [18]. The last condition
is to ensure that the signal photon increases linearly with $L$ which translates into the following bound

$$L \ll \sqrt{\frac{\omega^2 - m_\gamma^2}{m_\gamma^4}} \left( \frac{G^2 a_{\gamma\gamma'}}{96\pi} \right)^{-1}. \quad (2.5)$$

As a result, the relation between the number of signal photon flux $N_{\text{sub}}$ and the number of initial photon flux $N_\gamma$ can be written as

$$\frac{N_{\text{sub}}}{N_\gamma} = \frac{K^2}{96\pi} \frac{m_\gamma^4}{\sqrt{\omega^2 - m_\gamma^2}} L, \quad (2.6)$$

where $K$ is the product of two portal couplings

$$K \equiv \epsilon G_{a_{\gamma\gamma'}}. \quad (2.7)$$

As long as the bound on Eq. (2.5) is satisfied, the number of signal photon scales linearly with $L$.

![Figure 2: The proposed experiment in an optical cavity in [18]. The photon (red line) propagates to the cavity from the laser source. Subsequently, it is reflected by the mirror M1 where only the dark photon (blue line) penetrates the mirror and decay into a sub-frequency photon. The waveguide (dashed line) reflects the scattered sub-frequency photon to be detected at photodetector (PD).](image)

To detect the sub-frequency photon, Ref. [18] suggests the experimental setup shown in Fig. 2. An optical laser is employed as a light source which enters the Fabry-Perot cavity to amplify the laser beam allowing the enhancement of dark photon transition rate with the amplification factor

$$\eta_{\text{cav}} = \frac{N_{\text{pass}} + 1}{2}, \quad (2.8)$$

where $N_{\text{pass}}$ stands for the number of the beam reflection inside the cavity. A mirror M1 placed behind the cavity reflects all the outgoing laser beam from the cavity while the dark photon is transmitted through the mirror. The signal photon resulting from the decay of the dark photon is collected by a photo-detector located behind the mirror. Moreover, a waveguide (WG) is installed between the mirror and the photo-detector to ensure all the signal photon would reach the detector.
Furthermore, the detection of sub-frequency signal photon requires a high efficiency detector as well as low dark counting rate. Photomultiplier tubes (PMT) and transition-edge sensors (TES) are known devices sensitive to low photon counting. In a typical photodetector, the signal to noise ratio (SNR) of the single photon detection is given by

$$\text{SNR} = \frac{N_s \sqrt{t_s}}{\sqrt{N_s + N_d}}, \quad (2.9)$$

where $N_s$, $N_d$, and $t_s$ denote the number of signal photon, the number of dark current noise, and the total measurement time, respectively. For a given detector with the average efficiency $\bar{\eta}_{\text{eff}}$, the number of detectable signal photon is

$$N_s = \eta_{\text{kin}} \eta_{\text{cav}} \bar{\eta}_{\text{eff}} N_{\text{sub}} = \eta_{\text{kin}} \eta_{\text{cav}} \bar{\eta}_{\text{eff}} \frac{K^2}{90 \pi} \frac{m_{\gamma'}^4}{\sqrt{\omega^2 - m_{\gamma'}^2}} L N_{\gamma}. \quad (2.10)$$

Here, $\eta_{\text{kin}}$ stands for the probability of the signal photon arriving at the detector which is optimized by using a waveguide. Several remarks are in order regarding Eq. (2.10). First,

there is no perfect waveguide which collects all the photon. This would cause the loss of the signal photon inside the waveguide. Therefore, the probability of the sub-frequency photon reaching the detector, $\eta_{\text{kin}}$ becomes

$$\eta_{\text{kin}} = \frac{1}{L} \frac{1}{\sqrt{\omega^2 - m_{\gamma'}^2}} \int_0^L d\ell \int_{E(\theta_{\text{lab}}=0)}^{E(\theta_{\text{lab}}=\pi/2)} dE \mathcal{R}(\theta_{\text{lab}}(E), \ell). \quad (2.11)$$

Figure 3: The sensitivity of the ALPS II experiments with different waveguide configurations. The dashed lines indicates $r = 1$ (perfect waveguide) while the solid lines describe $r = 98.5\%$. We set the cut-off at $m_{\gamma'} = 0.99\omega$ which is indicated by vertical dot-dash line. We take 20 days of observation time in all cases.
Here, $R(\theta_{\text{lab}}(E), \ell)$ denotes the surviving fraction of the photon after passing the waveguide given by \[ 2.12 \]

$$R(\theta_{\text{lab}}(E), \ell) = r(E) \frac{1}{2} + r(E)_\tan \theta_{\text{lab}},$$

where $R$ and $r$ are the waveguide’s radius and the reflectivity of the mirror in the waveguide, respectively. We set $R = 8.75$ mm equals to the radius of the lens utilized in ALPS II experiment [15]. The polar angle of the signal photon in the lab frame $\theta_{\text{lab}}$ depends on its energy $E$ [18]

$$\theta_{\text{lab}}(E) = \cos^{-1} \frac{2E\omega - m_\gamma^2}{2E\sqrt{\omega^2 - m_\gamma^2}}.$$ \[ 2.13 \]

Second, the detector efficiency $\eta_{\text{eff}}$ depends on the energy of the incident signal photon [18,52]. Thus, the averaged detector efficiency defined as the ratio between $\eta_{\text{eff}}$ and the probability of the signal photon arriving at the photodetector $\eta_{\text{kin}}$ is given by

$$\bar{\eta}_{\text{eff}} = \frac{1}{\eta_{\text{kin}}} \frac{L}{\omega^2 - m_\gamma^2} \int_{0}^{L} d\ell \int_{E(\theta_{\text{lab}}=0)}^{E(\theta_{\text{lab}}=\pi/2)} dE \eta_{\text{eff}}(E) R(\theta_{\text{lab}}(E), \ell).$$ \[ 2.14 \]

To demonstrate these two effects, we reproduce the sensitivity of ALPS II within the search of subfrequency photon in Fig. 3 [18]. In addition, we also plot the sensitivity of the waveguide with $L = 10$ m. In case of perfect waveguide, the sensitivity scales linearly with $\sqrt{L}$ as can be seen from the three different dashed lines associated with different $L$ and Eq.(2.9). In contrast, for waveguide with $r = 98.5\%$, the sensitivity only improves linearly with $\sqrt{L}$ in low mass region below 0.01 eV where the sensitivity is fairly poor. In the higher mass regime where the sensitivity achieves its maximum value, we see the dependence on $L$ is very weak. The photon loss increases as the waveguide becomes longer. From here on, we take $L = 10$ m in our subsequent calculation to get the sensitivity in GW experiments.

3 The Proposed Setup in GW Detectors

The detection of sub-frequency photon can also be implemented at GW experiments. A typical GW experiment employs the Michelson interferometer to detect the spacetime fluctuation by measuring the differential arm length $\Delta \ell$ induced by the GW. The simplified version of the Michelson interferometer is depicted in Fig. 4.

In GW experiments, a laser beam is used as the light source. The beam splitter divides the laser beam into two perpendicular optical paths in the x and y direction with the same intensity. In the x direction, the beam enters the Fabry-Perrot (FP) cavity formed by intermediate test mass (ITMX) and end test mass (ETMX). Inside the cavity, the laser beam receives power amplification allowing them to produce a large number of photons. For a cavity with finesse $F$, the number of reflection inside the cavity is

$$N_{\text{pass}} = \frac{2F}{\pi}.$$ \[ 3.1 \]

which can also be expressed as $N_{\text{pass}} = P_{\text{arm}}/P_{\text{in}}$. Here, $P_{\text{arm}}$ corresponds to the laser power inside the cavity while $P_{\text{in}}$ is the laser power before entering the FP cavity. The same process
also occurs in the $y$ direction. Subsequently, the amplified beams coming from these cavities interfere each other at the beam splitter producing the interference fringe to be detected at the photo detector (PD), see Fig. 4. The observed interference pattern depends on the difference between these optical paths. Consequently, the measured change of the interference pattern is related to the differential arm length $\Delta \ell$ given by

$$\Delta \ell = \Delta \ell_x - \Delta \ell_y.$$  

(3.2)

Since the GW experiments utilize the Fabry-Perrot cavity, one expects the photon-dark photon conversion to take place inside the cavity. Comparing the setup in Fig. 2 with the GW experimental setup in Fig. 4, one sees that the ETMs play a similar role as M1. Having penetrated the ETM, the dark photon would decay into axion and signal photon after propagation of distance $L$. To detect the signal photon, we propose to install another photodetector (TES) equipped with a waveguide behind the ETM. In this paper, we will use tungsten TES since it was reported to have the best efficiency $\eta_{\text{eff}}$ in the relevant wavelength of sub-frequency photon [18].

Moreover, we suggest to include another cavity in this additional setup to increase the sub-frequency photon signal with amplification factor

$$\eta_{\text{cav}} = \frac{1}{2} \left( \frac{2 \mathcal{F}_{\text{WG}}}{\pi} + 1 \right),$$  

(3.3)

where $\mathcal{F}_{\text{WG}}$ denotes the finesse of the second cavity [53]. It will be placed next to the waveguide along with a lens to focus the signal photon. This is done to prevent the loss of unparalleled sub-frequency photon during the signal amplification if it is installed along with the waveguide.
This slight modification will not disturb the main experimental setup to detect the GWs. Conversely, this would allow GW experiments to perform a search of new physics along with the detection of GWs. Notice that, although there will be a vacuum chamber installed surrounding the ETM, we can still conduct the experiment since only the dark photon signal will leave the main cavity and enter the waveguide. In addition, all the additional instruments should be confined inside a vacuum chamber to minimize the noise.

Taking into account the inclusion of the second cavity, the total detectable number of the sub-frequency signal photon becomes

\[
N_{s}^{\text{tot}} = \eta_{\text{kin}} \eta_{\text{cav}} \eta_{\text{eff}} \eta_{\text{WG}} \left( \frac{K^{2}}{96\pi} \frac{m_{\gamma}^{4}}{\sqrt{\omega^{2} - m_{\gamma}^{2}}} L \right) N_{\gamma},
\]

where in this setup, \(L\) is taken as the distance between the ETM and the end of the waveguide since we consider dark photon decay occurs only inside the waveguide as shown in Fig. 4.

To achieve high sensitivity measurement, the conventional gravitational wave experiments utilize high laser power in their design. A large number of photons allows them to precisely measure the change of the interference pattern. However, having a bunch of photons hitting the mirror would make the position of the mirror become unstable. This is due to the transferred momentum from the photons to the mirror which further limits the ability to precisely determine the differential arm length of the interferometer. This is known as the radiation pressure noise which dominates the experimental sensitivity in low frequency regime.

To overcome this problem, the proposed third generation GW experiment, the Einstein Telescope (ET), plans to combine two separate interferometers. One interferometer is designed to be sensitive at low frequency region (ET-LF) while another one is constructed to achieve high sensitivity at high frequency regime (ET-HF). In ET-LF, a lower laser power is used to suppress the radiation pressure noise. On the other hand, ET-HF exploits higher laser power in its structure. The final sensitivity is reached by combining the sensitivity of these two interferometers. This setup is known as xylophone configuration [58–60].

| Parameters | ALPS II [15] | aLIGO [54] | KAGRA [55–57] | ET-HF [58–60] | ET-LF [58–60] |
|------------|--------------|-------------|----------------|----------------|----------------|
| \(F_{\text{Cav}}\) | 7853 | 450 | 1550 | 880 | 880 |
| \(P_{\text{in}}\) (W) | 30 | 2600 | 412 | 5355 | 32 |
| \(\omega\) (eV) | 1.165 | 1.165 | 1.165 | 1.165 | 0.799 |
| \(L\) (m) | 100 | 10 | 10 | 10 | 10 |
| \(N_{d}\) (Hz) | \(10^{-6}\) | \(10^{-6}\) | \(10^{-6}\) | \(10^{-6}\) | \(10^{-6}\) |
| \(F_{\text{WG}}\) | none | 7853 | 7853 | 7853 | 7853 |

**Table 1:** Parameters of the experiments used in our calculation. The references for the primary FP cavity and laser setup of each experiment are presented in the table. In addition, we adopt the ALPS II cavity finesse to our proposed second cavity for GW experiments.

We collect the optical properties of the interferometer in the current as well as the proposed GW experiments in table [1]. The significant laser power enhancement in their optical cavity plays a crucial role to improve the number of sub-frequency signal photon.
Figure 5: The Sensitivity of GW experiments on dark photon search using subfrequency photon scenario. For all GW detectors, we use waveguide with $L = 10$ m and $r = 98.5\%$. In the case of ALPS II, $L = 100$ m. Both vertical black lines denote the cut-off at $m_{\gamma'} = 0.99\omega$.

### 4 Results and Discussion

We present the projected 1σ sensitivities of our proposal in Fig. 5 where we have taken 20 days of observation time. We set the cutoff $m_{\gamma'} = 0.99\omega$ in these curves to respect the limit in Eq. (2.5). The purple band is the reproduced sensitivity plot proposed by [18] in ALPS II experiment with $L = 100$ m. The additional instruments in their setup consist of a mirror, waveguide and photodetector (TES) as shown in Fig. 2.

Apart from ET-LF, there are more than two order magnitude enhancements in the sensitivity of the existing as well as the proposed GW experiments compared to the ALPS II case. This is due to the higher laser power, higher finesse in the cavity, and the inclusion of additional WG cavity in these experiments. On the other hand, the ET-LF is only one order magnitude better than ALPS II due to the low laser power in their input. Both KAGRA and aLIGO utilize the high laser power as well as high finesse in their FP cavities. However, the radiation pressure noise limits their detector sensitivity at low frequency regime. In contrast, the ET-HF has the best sensitivity since they are able to relieve this noise.

Since the detection method relies on the decay of the dark photon, the sensitivity is optimized when $m_{\gamma'}$ close to the laser frequency $\omega$, cf. Eq. (2.2). Furthermore, the experiments can reach higher dark photon mass by using higher frequency laser source. One can improve the sensitivity by using higher laser power as well as higher finesse cavity which are limited by the damage threshold of the mirror. In addition, suppressing the background noise in the detector, reducing the loss of the waveguide and using the additional cavity with higher finesse in the detection regime would also enhance the sensitivity.
5 Summary and Conclusions

A novel idea to detect dark photon in light shining through the wall (LSW) experiments has been proposed by Ref. [18]. This relies on the notion that any light sources can produce dark photon particles which undergoes decay into sub frequency photon and axion. We propose to extend this idea in the current as well as the proposed GW experiments. We suggest to install additional devices such as photodetector, waveguide, and additional optical cavity in GW detectors that allow us to detect this secondary photon with smaller frequency. The capability of this simple setup to produce new particle and its corresponding decay products as well as detecting new physics signal mimicks high energy collider experiments such as the LHC. The smoking gun of the new physics signal in this "mini LHC" is the detection of secondary photon whose frequency is smaller than the original laser input.

Our proposal is two order magnitudes more sensitive than the original idea to be implemented at the light shining through the wall (LSW) experiments such as ALPS II [18]. We place new limits on the combined portal $K = \epsilon G_{a\gamma\gamma}'$ which are more stringent than the ones given in [18]. As pointed out by Ref. [18], these bounds can not be drawn as a product of $\epsilon$ and $G_{a\gamma\gamma}'$ acquired independently since it is quite model dependent.

In a model where both couplings are available such as Ref. [61], the induced bound on $K$ is less than $10^{-7}$ for $m_{\gamma'} < 10^{-4}$ eV. This is obtained from ALPS I experiment which is sensitive for light dark photon mass below $10^{-3}$ eV. ALPS II would improve this limit by three order magnitudes in the same mass range. From this point of view, our proposal can act as a complementary search of dark photon in higher mass regime ($m_{\gamma'} > 10^{-3}$ eV) compared with ALPS I and ALPS II. As a closing remark, we do not take the induced limits from the sun and horizontal branch (HB) stars since they suffer from astrophysical uncertainties as well as model dependent [62–67]. In contrast, both ALPS I and ALPS II as well as GW experimental setup are purely laboratory experiments operating in well controlled environment.

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