Exploring Dark Photon via Subfrequency Laser Search in Gravitational Wave Detectors

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in collaboration with M. Afif Ismail and Henry Tsz-King Wong

Outline

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Introduction

Dark Photon-SM Interaction

Sub-frequency Photon Signal at GW Detectors

Summary and Conclusion

Universe Pie Chart

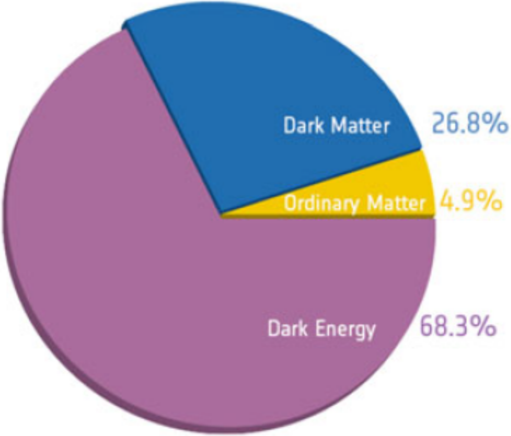
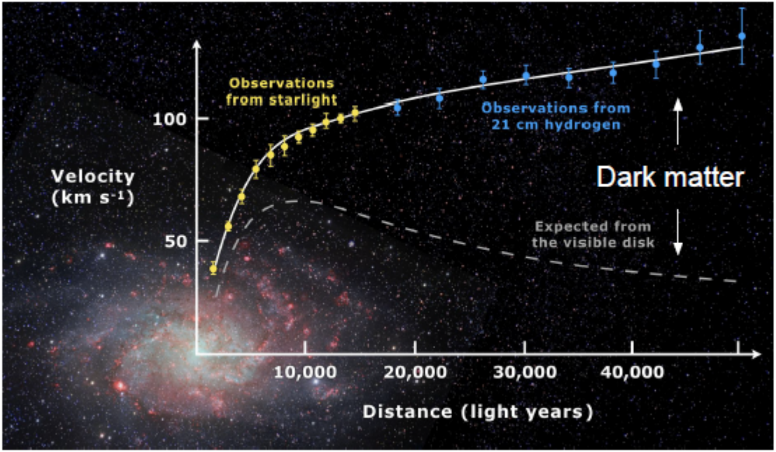


Figure: Composition of the universe extracted from PLANCK (NASA/WMAP Science Team, ESA).

Dark Matter Observation



Galaxy M33 Rotation curve [arXiv:astro-ph/9909252, wikipedia]

Dark Matter Observation

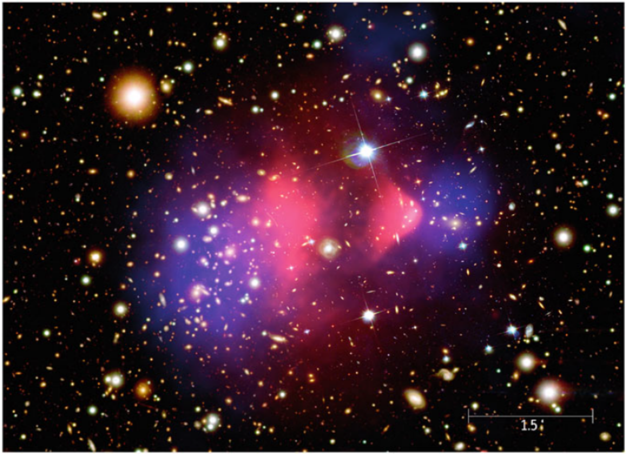
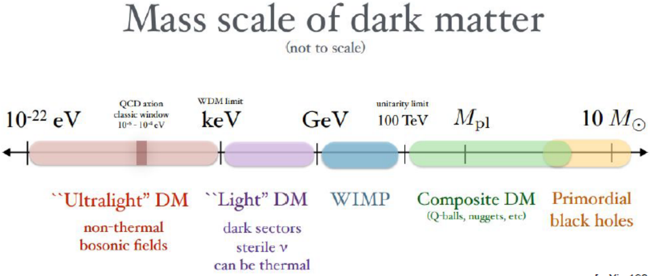


Figure: Two colliding clusters of galaxies or Bullet cluster 1E 0657-558 (NASA/CXC/M. Weiss).

Dark Matter (DM) Properties

- As particle, DM mass and spin remain unknown.
- Other interaction with Standard Model (SM) other than gravitational force? probably yes, but very weakly
- How does DM interact with SM particles?



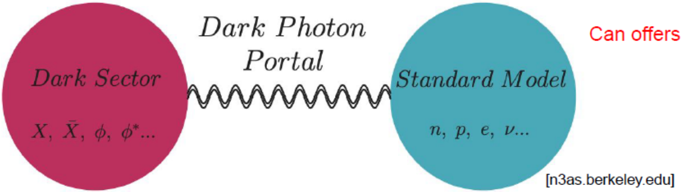
[arXiv:1904.07915v1]

Outline

One Possible DM-SM Interaction

- Dark photon, as a remnant of $U(1)'$ gauge, kinetically mixes with the photon via ϵ.
- It may serve as a portal to connect DM with SM.
- One possible interaction with axion-like particle (ALP) a in dark sector [Kaneta, Lee, Yun '17] :

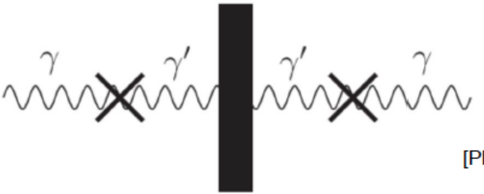
$$\mathcal{L} \supset \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu + \frac{1}{2} \varepsilon F_{\mu\nu} F'^{\mu\nu} - \frac{1}{2} G_{a\gamma\gamma'} a F_{\mu\nu} \tilde{F'}^{\mu\nu} \, .$$



Can offers rich phenomenology

One Possible Phenomenology

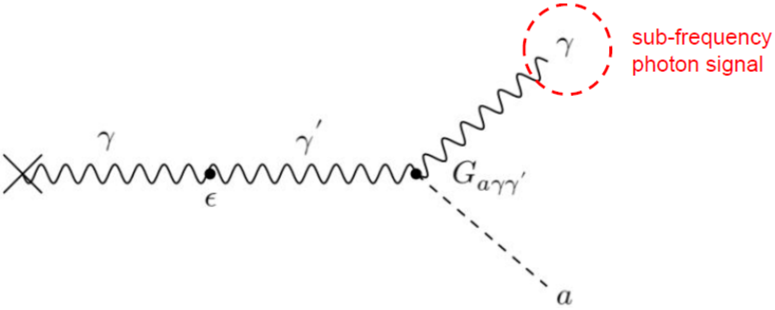
- Light Shining through the Wall (LSW) experiment relies on photon-dark photon oscillation to detect dark photon.
- ALPS II utilizes laser to generate a large photon numbers.



[Phys. Rev. D 76, 115005 (2007)]

Another Phenomenology (Our Focus)

- Photon with frequency ω can oscillate into dark photon.
- When $m_{\gamma'} > m_a$, dark photon decays into axion and secondary photon dubbed as sub-frequency photon with $\omega_{\text{sub}} < \omega$ [Lee, Lee, Yi '22] .



Number of Sub-frequency Photon [Lee, Lee, Yi ’22]

- For $m_{\gamma'} > m_a$, dark photon decays into axion and sub-frequency photon with the rate

$$\Gamma \equiv \Gamma_{\gamma' \to a\gamma} = \frac{G^2_{a\gamma\gamma'}}{96\pi}\, m^3_{\gamma'} \left(1 - \frac{m_a^2}{m^2_{\gamma'}}\right)^3$$

- If $|\gamma\rangle$ denotes photon mass eigenstate and $|\gamma'\rangle$ dark photon mass eigenstate

$$|\gamma(t, L)\rangle = e^{-i(\omega t - \omega L)}\, |\gamma\rangle$$
$$|\gamma'(t, L)\rangle = e^{-i(\omega t - pL)}\; e^{-m_{\gamma'}\Gamma t/2\omega}\, |\gamma'\rangle$$

- $p = \sqrt{\omega^2 - m^2_{\gamma'}}$ is dark photon momentum.

Number of Sub-frequency Photon [Lee, Lee, Yi '22]

- The flavor base photon $|A\rangle$ and its orthonormal pair $|X\rangle$ are related to mass eigenstate via

$$\begin{bmatrix} A \\ X \end{bmatrix} = \begin{bmatrix} \sqrt{1-\varepsilon^2} & \varepsilon \\ -\varepsilon & \sqrt{1-\varepsilon^2} \end{bmatrix} \begin{bmatrix} \gamma \\ \gamma' \end{bmatrix}$$

- If the initial state of the laser $|\Psi(0,0)\rangle = |A\rangle$ then

$$|\Psi(t,L)\rangle = \sqrt{1-\epsilon^2}\, e^{-i\,(\omega t-\omega L)}\,|\gamma\rangle + \epsilon\, e^{-i\,(\omega t-pL)}\; e^{-m_{\gamma'}\Gamma t/2\omega}\;|\gamma'\rangle$$

- The probability of X decay is

$$P_{X\to\text{decay}}(L) = 1 - P_{X\to A}(L) - P_{X\to X}(L)$$

- For a light source with power P and frequency ω, the photon flux is given by $N_\gamma = P/\omega$.
- The number of sub-frequency photon N_{sub} is given by [Lee, Lee, Yi '22] :

$$\frac{N_{\text{sub}}}{N_\gamma} = \frac{K^2}{96\pi} \frac{m_{\gamma'}^4}{\sqrt{\omega^2 - m_{\gamma'}^2}} \mathrm{L}$$

- with the assumptions:
  - $m_a << m_{\gamma'} < \omega$
  - $\frac{m_{\gamma'} \Gamma L}{\sqrt{\omega^2 - m_{\gamma'}^2}} << 1$, the prompt decay of dark photon is $<< 1$
  - $L \Delta p >> 2\pi$, which is satisfied for $L > 1$m
- Here, $K = \epsilon\, G_{a\gamma\gamma'}$ and $\Delta p = \omega - p$

Detection Proposal [Lee, Lee, Yi '22]

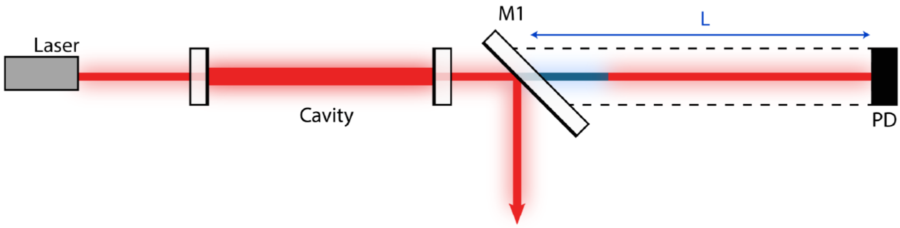
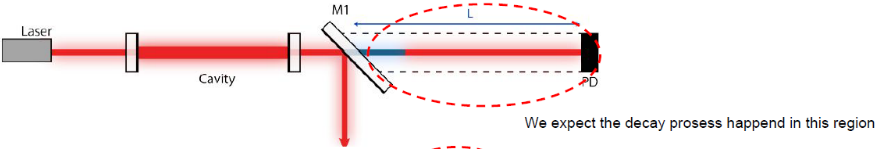


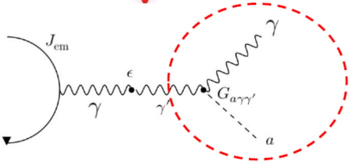
Figure: Proposed setup to detect sub-frequency dark photon in LSW experiment [Lee, Lee, Yi '22] .

Detection Proposal [Lee, Lee, Yi '22]

- The number of detected sub-frequency signal $N_{\rm det}$ depends on the efficiency

$$N_{\rm det} = \eta_{\rm kin}\eta_{\rm cav}\,\bar{\eta}_{\rm eff}\,\frac{K^2}{96\pi}\,\frac{m_{\gamma'}^4}{\sqrt{\omega^2 - m_{\gamma'}^2}}\,\mathrm{L}\,N_\gamma\,.$$





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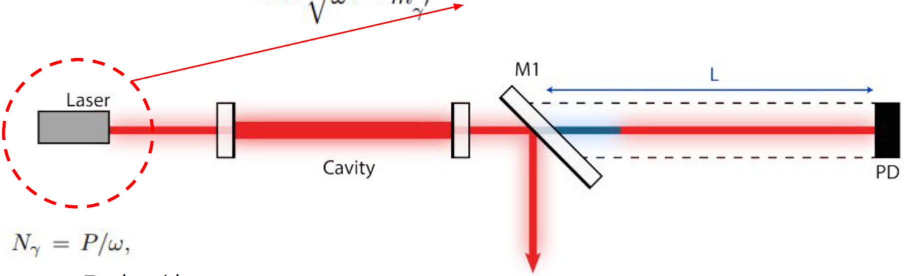
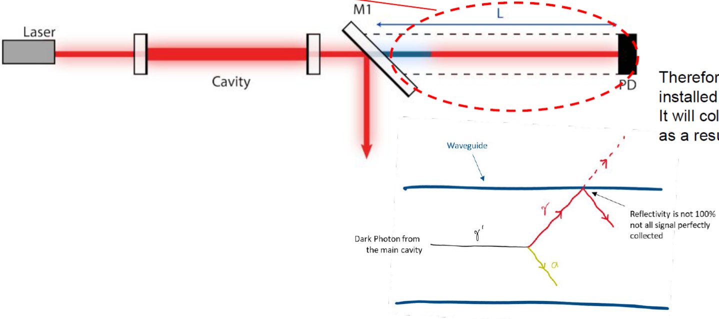


$$N_\gamma = P/\omega,$$

P : input Laser power
ω : input laser frequency

Detection Proposal [Lee, Lee, Yi '22]

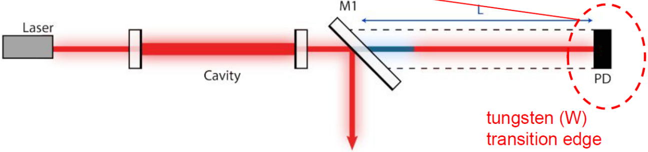
$$N_{\rm det} = \eta_{\rm kin}\eta_{\rm cav}\,\bar{\eta}_{\rm eff}\,\frac{K^2}{96\pi}\,\frac{m^4_{\gamma'}}{\sqrt{\omega^2 - m^2_{\gamma'}}}\,\mathrm{L}\,N_\gamma\,.$$



Therefore, waveguide needs to be installed along the decay region.
It will collect the sub-frequency photon as a result of the decay.

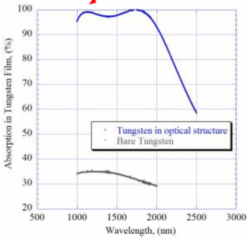
Detection Proposal [Lee, Lee, Yi ’22]

$$N_{\rm det} = \eta_{\rm kin}\eta_{\rm cav}\,\underline{\bar{\eta}_{\rm eff}}\,\frac{K^2}{96\pi}\frac{m^4_{\gamma'}}{\sqrt{\omega^2 - m^2_{\gamma'}}}\,{\rm L}\,N_\gamma\,.$$



tungsten (W) transition edge sensor (TES)

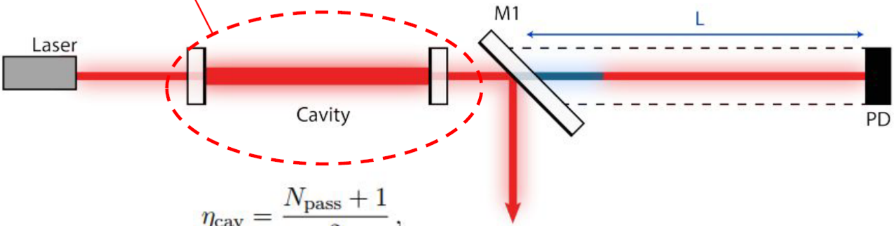
We need a good photo detector with good efficiency around 1064 nm



[Opt. Express 16, 3032 (2008)]

Detection Proposal [Lee, Lee, Yi '22]

$$N_{\rm det} = \eta_{\rm kin}\underline{\eta_{\rm cav}}\,\bar{\eta}_{\rm eff}\,\frac{K^2}{96\pi}\frac{m_{\gamma'}^4}{\sqrt{\omega^2 - m_{\gamma'}^2}}\,\mathrm{L}\,N_\gamma\,.$$



$$\eta_{\rm cav} = \frac{N_{\rm pass}+1}{2},$$

$N_{\rm pass}$: the number of the beam reflection inside the cavity

Outline

Gravitational Wave Observatories

- Current gravitational waves experiments

LIGO Livingston Observatory

LIGO Handford Observatory

KAGRA Observatory

Virgo

[Caltech/MIT/LIGO Lab/Virgo/EGO/ICRR-KAGRA]

Gravitational Wave Observatories

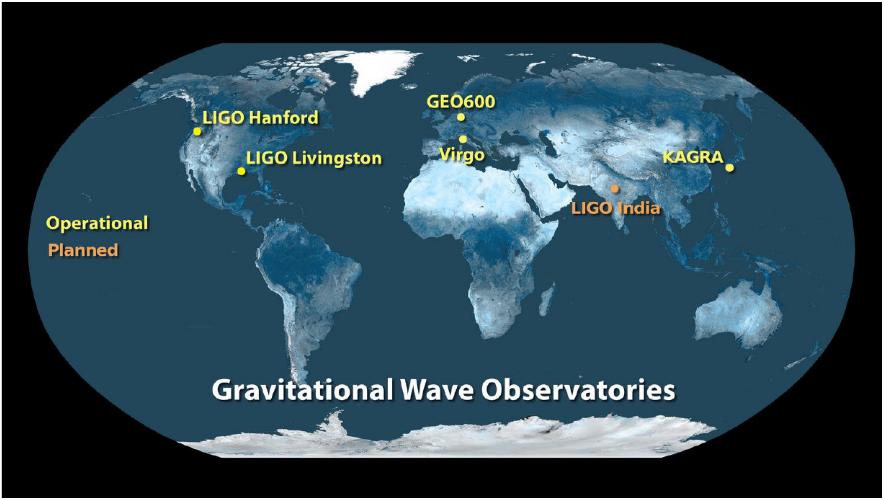
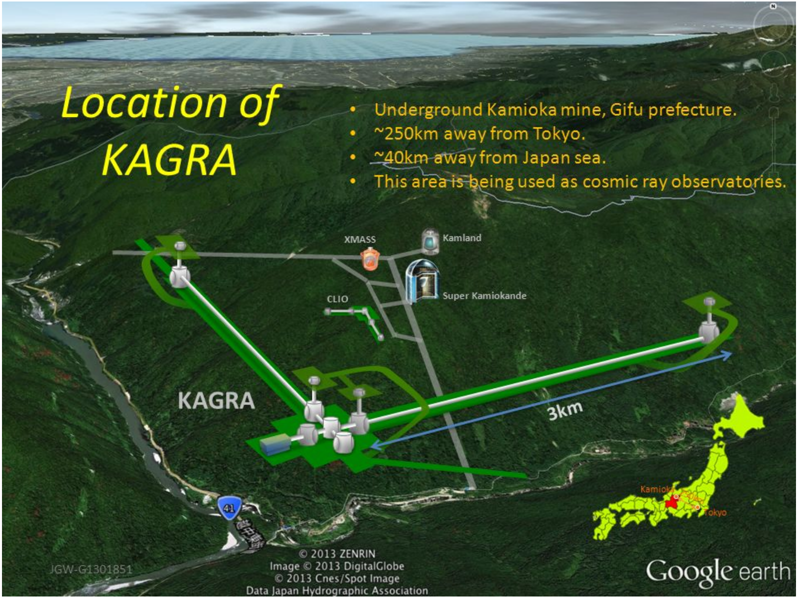


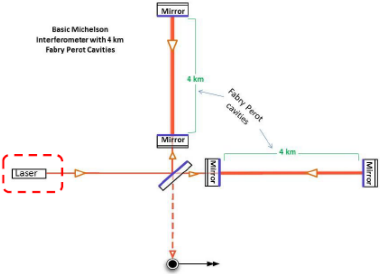
Figure: [LIGO Caltech]

Gravitational Wave Detector



Michelson Interferometer

- A typical GW experiment employs the Michelson interferometer with Fabry Perot cavities
- a laser beam is used as the light source.



[LIGO Caltech]

Michelson Interferometer

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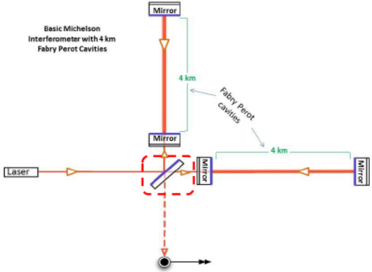
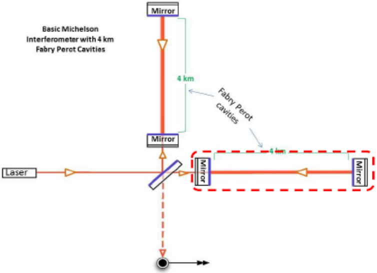
- The beam splitter divides the laser beam into two perpendicular optical paths in the x and y direction with the same intensity.



[LIGO Caltech]

Michelson Interferometer

- A typical GW experiment employs the Michelson interferometer with Fabry Perot cavities
- 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 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
- Subsequently, the amplified beams coming from these cavities interfere with each other at the beam splitter producing the interference fringe to be detected at the photodetector (PD)



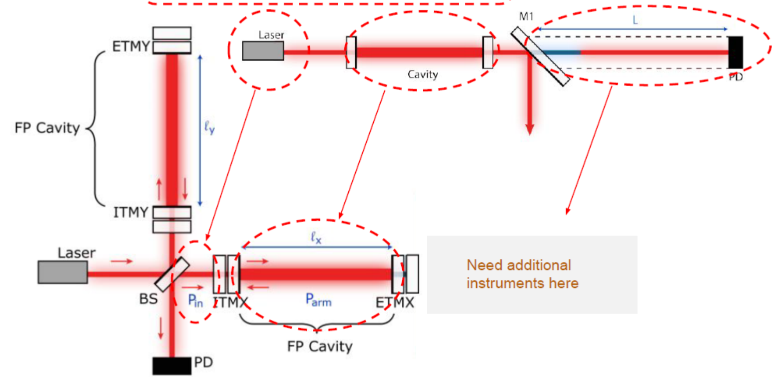
[LIGO Caltech]

Sub-frequency Dark Photon in GW Detectors

- GW experimental setup supports dark photon search.
- High Finesse means high η_{cav} i.e. high number of photons inside cavity.

Parameters	ALPS II	aLIGO [52]	KAGRA [53–55]	ET-HF [56–58]	ET-LF [56–58]
$\mathcal{F}_{\text{Cav}}$	7853	450	1550	880	880
P_{in} (W)	30	2600	412	5355	32
ω (eV)	1.165	1.165	1.165	1.165	0.799

- High reflective cavity
- High number of incoming photon



- We add instruments to GW experiment to fulfill the requirement. Not only that, but we also propose additional instrument (second cavity) beyond previous proposal.

$$N_{\rm det} = \eta_{\rm cav}^{\rm WG}\, \eta_{\rm kin} \eta_{\rm cav}\, \bar{\eta}_{\rm eff}\, \frac{K^2}{96\pi} \frac{m_{\gamma'}^4}{\sqrt{\omega^2 - m_{\gamma'}^2}} L\, N_\gamma\,.$$

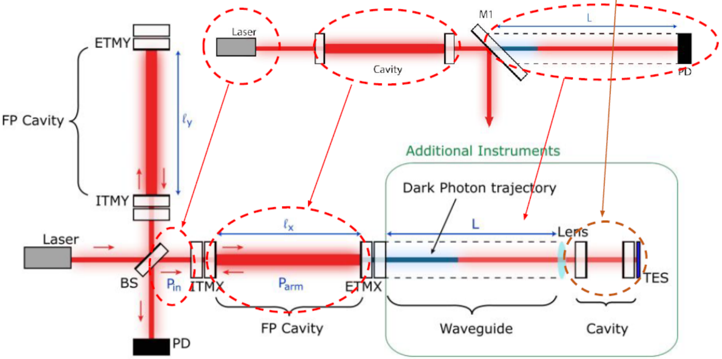


Figure: LSW dark photon search in GW experimental setup based on photon-dark photon oscillation [Ismail, CSN, Wong '23] .

Sub-frequency Dark Photon in GW Detectors

- The signal-to-noise (SNR) is given by

$$\mathrm{SNR} = \frac{N_{\mathrm{det}} \sqrt{t_{\mathrm{det}}}}{\sqrt{N_{\mathrm{det}} + N_d}}$$

- We set the observation time t_{det} = 20 days.
- We put the cut-off $m_{\gamma'} = 0.99\,\omega$.
- The number of noise is 10^{-6} Hz.

TABLE I. 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.

Parameters	ALPS II [14]	aLIGO [62]	KAGRA [63–65]	ET-HF [59–61]	ET-LF [59–61]
$\mathcal{F}_{\mathrm{Cav}}$	7853	450	1550	880	880
P_{in} (W)	30	2600	412	5355	32
ω (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}
$\mathcal{F}_{\mathrm{Cav}}^{\mathrm{WG}}$	...	7853	7853	7853	7853

Sub-frequency Dark Photon in GW Detectors

- We present 1σ exclusion of K vs $m_{\gamma'}$
- Our results are 2 order magnitudes better than ALPS II
- ET-LF only 1 magnitude better due to its lower laser power.

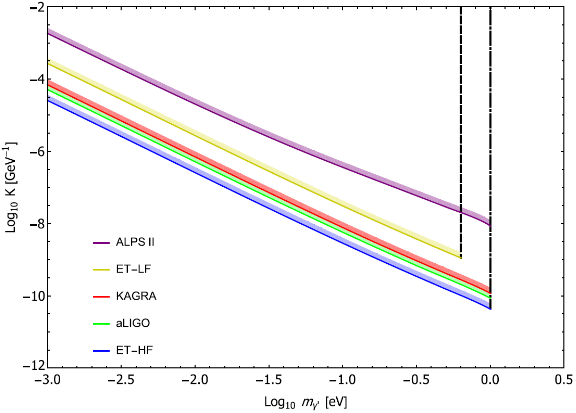


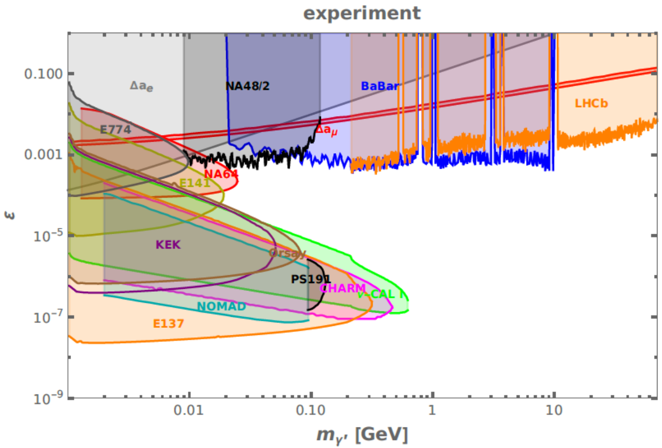
Figure: [Ismail, CSN, Wong '23] .

Outline

Summary and Conclusion

- We propose to implement the detection of sub-frequency photon originating from dark photon decay in GW experiemntal setup.
- The setup is capable to accomodate: dark photon production, its decay product, and its new physics signal similar to those of collider machines.
- The projected sensitivity is two order magnitudes better than the proposed implementation in LSW studies.
- Limit on K can NOT be obtained by multiplying limit on ϵ and $G_{a\gamma\gamma'}$ separately.

- Limit on K can NOT be obtained by multiplying limit on ϵ and $G_{a\gamma\gamma'}$ separately.
- When both coupling exist in a model, ϵ and $G_{a\gamma\gamma'}$ affect each other.



Remarks

- Limit on ϵ is affected by $G_{a\gamma\gamma'}$ if dark photon decays into axion and photon in addition to hadrons and leptons
- The new limit can be recasted using the fact that the number of event N is constant [Chen, Hsieh, CSN '24]

$$\mathcal{L}^{\text{New}} \cdot \sigma_{\text{Prod}}^{\text{New}}(\gamma') \cdot \text{BR}^{\text{New}}(\gamma') \cdot \eta^{\text{New}}(\tau_{\gamma'}) = \mathcal{L}^{\text{Old}} \cdot \sigma_{\text{Prod}}^{\text{Old}}(\gamma') \cdot \text{BR}^{\text{Old}}(\gamma') \cdot \eta^{\text{Old}}(\tau_{\gamma'})$$

Remarks

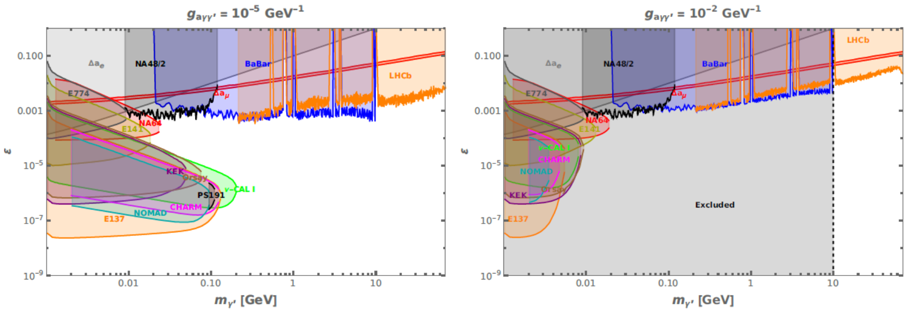


Figure: [Chen, Hsieh, CSN '24] .

Remarks

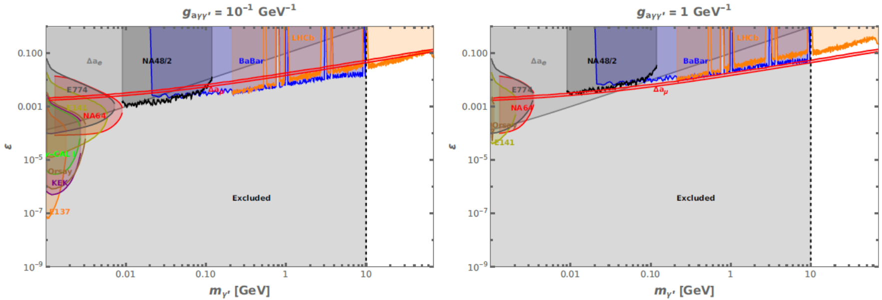


Figure: [Chen, Hsieh, CSN '24] .