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Exploring pseudo-Nambu-Goldstone bosons in the sub-eV to 10 keV mass range with stimulated photon collider

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Abstract
Generic laboratory searches for pseudo-Nambu-Goldstone bosons (pNGBs) in weak-coupling domains beyond the GUT scale are indispensable for understanding the dark components in the universe. We introduce a novel approach to search for resonantly produced pNGBs coupled to two photons in the mass range from sub-eV to 10 keV by colliding plural laser fields to induce the rare scattering process.

Keywords
Nambu-Goldstone Boson, dark matter, dark energy, SAPPHIRES

1 Introduction

Astronomical observations suggest that the universe is occupied by something invisible: dark matter and dark energy via gravitational effects. The Higgs boson has been recently discovered and we are approaching to the completion of the standard model of elemental particles. However, the standard model particles can explain only 5% of the energy density of the universe. What can we do if we want to make something dark visible? Shining intense light on a dark spot in the vacuum is a quite primitive but natural way to see something unseen. The method we introduce in this paper is essentially based on this quit simple concept. If we assume that something dark can be regarded as a kind of particle or *dark field* which respects the basic principle of particle physics, we may generically express the interaction Lagrangian between a standard model particle and a dark field by introducing two independent parameters: the weak coupling strength and the mass of the exchanged dark field. Among possible standard model fields, we choose photons as the probe fields.

A crucial parameter for generic searches is the energy scale, more specifically the center of mass system (CMS) energy of a photon-photon collision. For instance, the Higgs boson is an example of a scalar resonance state at the highest energy scale, 126 GeV which can decay into two photons. The second example is the neutral pion corresponding to a kind of pseudoscalar resonance state at 135 MeV. This particle can also decay into two photons. We now know at least two energy scales in nature where spin-zero neutral resonance states coupling to two photons surely exist. Since these particles have coupling to two photons, in principle, they can be directly created by photon-photon collisions via the inverse processes.

Spontaneous symmetry breaking can be one of the most robust guiding principles for general discussions of dark components in the universe. Whenever a continuous global symmetry is broken, a massless boson may appear as Nambu-Goldstone-Boson (NGB). In nature, however, an NGB emerges as a pseudo-NGB (pNGB) with a finite mass. The neutral pion is such an example of a pNGB via chiral symmetry breaking. Even though a pNGB is close to being massless, its decay into lighter particles such as photons is kinematically allowed. There are several theoretical models that predict low-mass pNGBs coupling to two photons such as dilatons [1], axions [2], and string-theory-based axion-like particles [3],

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[*] On behalf of SAPPHIRES collaboration

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which are relevant to dark components of the universe if the coupling to matter fields is reasonably weak. However, a quantitative prediction on the physical mass of a pNGB in such models is commonly difficult. Indeed, string theories predict pNGBs to be homogeneously distributed on a log scale in the mass range possibly up to 10^8 eV [3]. Therefore, laboratory tests are indispensable for investigating the physical mass as widely as possible in the lower mass range. The above two evidences of spin-zero boson decaying into two photons encourage us to explore similar types of fields via the two-photon coupling in very different energy scales in general. Especially, in order to produce these resonance states at an lower center-of-mass energy, lower energy colliding beams with massless particles, that is, photon colliders have essential roles.

We have previously advocated a novel method [4] for stimulating $\gamma\gamma \to \phi \to \gamma\gamma$ scattering via an s-channel resonant pNGB exchange by utilizing the coherent nature of laser fields. We have first considered a quasi-parallel colliding system (QPS). This colliding system allows us to reach a low CMS energy in the sub-eV range via the small incident angle even if we use a laser field with its photon energy of 1eV. We also have considered an asymmetric-energy head-on collision system (ACS) [5] to access relatively higher CMS energies in order to discuss a possibility to test an unidentified emission line, $\omega \sim 3.5$ keV, in the photon energy spectra from a single galaxy and galaxy clusters [6, 7] (the arguments are still actively ongoing [8]) with an interpretation of a pNGB decaying into two photons [9]. This motivated us to extend the same method up to 10 keV by combining different types of coherent and incoherent light sources in ACS.

In this paper, we review the basic concept of the proposed method and discuss the future prospect toward direct laboratory searches for pNGBs in the mass range from sub-eV to 10 keV as candidates of the dark components of the universe.

2 Generic photon-photon interactions

We assume photon-photon scattering with the following effective Lagrangian in Eq. (1) [4],

$$-L_\phi = gM^{-1}\frac{1}{4}F_{\mu\nu}F^{\mu\nu}\phi, \tag{1}$$

$$-L_\sigma = gM^{-1}\frac{1}{4}F_{\mu\nu}\tilde{F}^{\mu\nu}\sigma, \tag{2}$$

where an effective coupling g/M between two photons and a scalar ϕ or pseudoscalar σ field is introduced. If we are based on the invisible axion scenario [10], a dark field satisfying the dimensional constant $M = 10^{11} - 10^{16}$ GeV and the mass $m =$ meV - μeV can be cold dark matter candidates. If M corresponds to the Planck mass $M_P \sim 10^{18}$ GeV, the interaction is as weak as that of gravity and this case would have a great relevance to explain dark energy if $m \geq$ neV [11].

We may discuss possibilities to exchange scalar and pseudoscalar type of fields by requiring combinations of photon polarization in the initial and final states [4]. The virtue of laser experiments is in the capability of specifying photon spin states both in the initial and final states in the two body photon-photon interaction. This allows us to distinguish types of exchanged fields in general.

3 Concept of stimulated laser colliders

The novelty of the proposed method is in the following two dominant enhancement mechanisms. The first mechanism is the creation of a resonance state via laser-laser collisions by tuning the CMS energy at a pNGB mass, which is the same approach as that in charged particle colliders. The second mechanism is to stimulate the scattering process by adding another background laser field. This feature has never been utilized in high-energy particle colliders, because controllable coherent fields are not available at higher energy scales above 10 keV. We will explain these two mechanisms in the following subsections in detail.

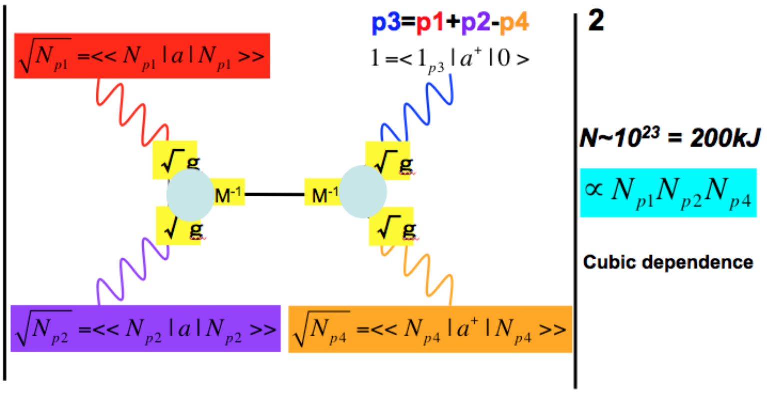

Fig. 1: Concept of stimulated photon collider.

3.1 Inclusion of a resonance state within an energy uncertainty in photon-photon collisions

A CMS energy, E_{cms}, can be generically expressed as

$$E_{cms} = 2\omega \sin\vartheta, \tag{3}$$

where ϑ is defined as a half incident angle between two incoming photons and ω is the beam energy in units of $\hbar = c = 1$. This relation indicates two experimental knobs to adjust E_{cms}. With $\vartheta = \pi/2$, we can realize a CMS collision. A QPS is realized with a small incident angle by focusing a single laser beam, where E_{cms} can be lowered by keeping ω constant. We also consider an asymmetric-energy collision in the head-on geometry in order to relatively increase E_{cms} [5]. Both QPS and ACS correspond to Lorentz boosted systems of CMS. A QPS is realized when a CMS is boosted with respect to the perpendicular direction of head-on collision axis, while a ACS is realized when a CMS is boosted in parallel to the head-on collision axis. Owing to these boosted effects, energies of the final state photons are different from any of incident photon energies. Therefore, frequency shifted photons can be clear signatures of photon-photon scatterings if QPS or ACS are realized as laboratory frames.

We then aim at the direct production of a resonance state via s-channel Feynman amplitude in the photon-photon collisions. The square of the scattering amplitude A proportional to the interaction rate can be expressed as Breit-Wigner resonance function [4]

$$|A|^2 = (4\pi)^2 \frac{W^2}{\chi^2(\vartheta) + W^2}, \tag{4}$$

where χ and the width W are defined as $\chi(\vartheta) \equiv \omega^2 - \omega_r^2(\vartheta)$ and $W \equiv (\omega_r^2/16\pi)(g^2 m/M)^2$, respectively. The energy ω_r satisfying the resonance condition can be defined as ${\omega_r}^2 \equiv m^2/2(1-\cos 2\vartheta_r)$ [4]. If $\chi^2(\vartheta_r) = 0$ is satisfied, $|A|^2$ approaches to $(4\pi)^2$. This feature is independent of any W in mathematics. However, if $M = M_P$, the width W becomes extremely small. This implies that the resonance width is too narrow to directly hit the peak of the Breit-Wigner function by any experimental ability. How can we overcome this situation? In a QPS realized in a focused laser field, the incident angles or incident momenta of laser photons become uncertain maximally at the diffraction limit due to the uncertainty principle. This implies that $|A|^2$ must be averaged over the possible uncertainty on E_{cms}. This unavoidable integration over the possible angular uncertainty results in $W \propto 1/M^2$ dependence of $|A|^2$ compared to the $W^2 \propto 1/M^4$ dependence when no resonance is contained in the energy uncertainty, that is, when $\chi^2(\vartheta) \gg W^2$. In ACS too, a similar uncertainty is expected. We have proposed a ACS with high-intensity pulse lasers [5], where the energy uncertainty is caused by the shortness of the pulse duration time via the uncertainty principle again. In both cases the inclusion of a resonance peak enhances the interaction rate by the huge gain factor of M^2.

3.2 Stimulated scattering by coherent laser fields

In order to reach the sensitivity to the gravitational coupling strength, however, the inclusion of a resonance state within the uncertainty on E_{cms} is still short. We thus need an additional enhancement mechanism. We then consider the stimulation of the Feynman amplitude by replacing the vacuum state $|0\rangle$ with the quantum coherent state $|N\gg$ [4]. A laser field is represented by the quantum coherent state which corresponds to a superposition of different photon number states, characterized by the averaged number of photons N [12]

$$|N\gg \equiv \exp\left(-N/2\right)\sum_{n=0}^{\infty}\frac{N^{n/2}}{\sqrt{n!}}|n>, \tag{5}$$

where $|n>$ is the normalized state of n photons

$$|n>=\frac{1}{\sqrt{n!}}\left(a^{\dagger}\right)^{n}|0>, \tag{6}$$

with $a^{\dagger}$ and a the creation and the annihilation operators of photons specified with momentum and polarization, respectively. The coherent state satisfies the normalization condition

$$\ll N|N\gg=1. \tag{7}$$

We can derive following properties of coherent states $|N\gg$ and $\ll N|$:

$$a|N\gg=\sqrt{N}|N\gg \text{ and } \ll N|a^{\dagger}=\sqrt{N}\ll N| \tag{8}$$

from the familiar relations

$$a^{\dagger}|n\rangle=\sqrt{n+1}|n+1\rangle \text{ and } a|n+1\rangle=\sqrt{n+1}|n\rangle. \tag{9}$$

The property in Eq. (8) gives the expectation value of the annihilation and creation operators to coherent states

$$\ll N|a|N\gg=\sqrt{N} \text{ and } \ll N|a^{\dagger}|N\gg=\sqrt{N}. \tag{10}$$

Figure 1 illustrates how the enhancement of the sensitivity arises due to the coherent laser fields. In the production vertex, two incident photons must annihilate from the incident lasers with the momentum p_1 and p_2, respectively. The expectation values associated with the individual photon legs correspond to the first of Eq. (10). And then if an additional coherent laser field with the momentum p_4 is supplied in advance, the expectation value to create a final state photon p_4 in the sea of the inducing laser field corresponds to the second of Eq. (10). The overall enhancement factor on the interaction rate to have a signal photon with the momentum p_3 is then expressed as

$$(\sqrt{N_{p1}}\sqrt{N_{p2}}\sqrt{1_{p3}}\sqrt{N_{p4}})^2=N_{p1}N_{p2}N_{p4}, \tag{11}$$

where N_i indicate the average numbers of photons with momenta p_i. Because N_{p_i} has no limitation due to the bosonic nature of photons, we can expect a huge enhancement factor by the cubic dependence on the photon numbers. This is in contrast to conventional charged particle colliders where the dependence on the number of particles is quadratic and also there is a physical limitation due to the space charge effect. Compared to the upper number of charged particles, typically 10^{11} particles per collision bunch in conventional colliders, Mega Joule laser, for instance, can provide 10 times of Avogadro's number of visible photons per pulse. The cubic of this number results in a enormous enhancement factor on the interaction rates. Therefore, the stimulated photon collider can provide an extremely high sensitivity to feeble couplings compared to that of particle colliders whose prime missions is, of course, to discover new heavy particles even though sacrificing the quadratic luminosity factor.

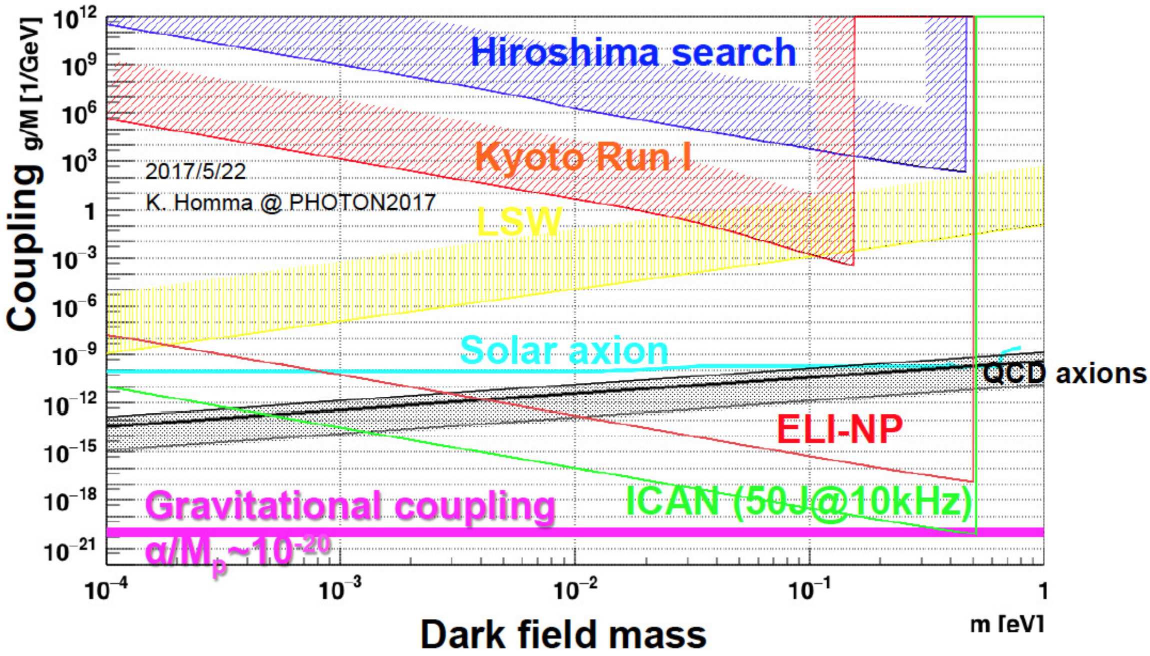

Fig. 2: Sensitivity to the mass–coupling domains in QPS.

4 Future prospect

The first pilot search based on this method has been already performed in [13]. We then have attempted to apply the same method to higher intensity lasers where background signals from the atomic process in residual gas components appeared and they were successfully suppressed in the experiment [14]. We are now in preparation for further upgrades toward the Extreme-Light-Infrastructure project [15] by forming an international collaboration SAPPHIRES (Search for Axion-like Particle via optical Parametric effects with High-Intensity laseRs in Empty Space) [16, 17] based on the concept introduced here. Figure 2 shows the prospect of sensitivity by searches in QPS where the search in Hiroshima [13], the search in Kyoto [14], and the prospect at the Romanian Extreme-Light-Infrastructure site (ELI-NP) are shown. Figure 3 shows the prospect of sensitivity by searches in ACS. The details of the curves are explained in [5]. In both cases, we foresee that the coupling sensitivities can reach the weakness beyond the GUT scale, $M \sim 10^{16}$ GeV, within the currently available laser technology.

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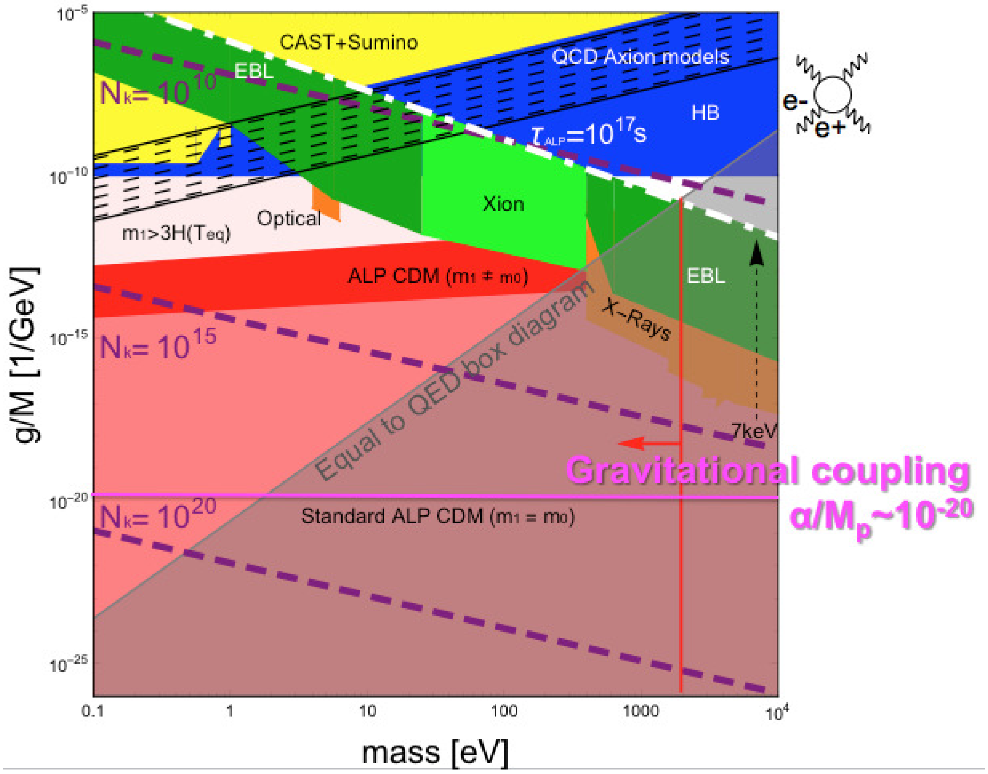

Fig. 3: Sensitivity to the mass–coupling domains in ACS.

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