Searches for pseudo Nambu-Goldstone Bosons by stimulated resonant photon-photon scatterings with high-intensity laser fields

Kensuke Homma[1]

Graduate School of Science Hiroshima University, 1-3-1 Kagami Yama, Higashi-Hiroshima, Japan 739-8526

Abstract

Pseudo Nambu-Goldstone Bosons (pNGB) can be reasonable candidates for dark components in the universe as long as the coupling to matter fields are weak enough. Because of the lightness of pNGBs, it is possible to directly generate low-mass pNGBs via s-channel resonance scattering by colliding low energy massless particles such as lasers. Laser fields are quite useful due to the huge number of photons per pulse and its coherent nature. The stimulated resonant scattering concept can open up an opportunity to access extremely weak coupling domains as weak as the gravitational coupling strength in much lower mass domains compared to the QCD scale, which have not been intensively explored to date. We present the current status and future prospects based on this novel approach.

1 Introduction

Spontaneous symmetry breaking can be one of the most robust guiding principles to naturally explain dark components in the universe. When a continuous global symmetry is broken, a Nambu-Goldstone Boson (NGB) may appear as a massless particle. In nature, however, an NGB emerges as a pseudo-NGB (pNGB) with a finite mass. Even if a pNGB is close to being massless, its decay into massless particles 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]. These are relevant to dark components of the universe if the coupling to matter fields is weak enough. However, the theoretical evaluation of the physical mass of a pNGB 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 necessary to determine the physical masses of pNGBs in a wide mass range. In order to produce pNGBs at an lower center-of-mass (CMS) energy, lower energy colliding beams with massless particles, that is, photon colliders have special 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 above 1eV. We also have considered an asymmetric-energy head-on collision system (ACS) [5] to access relatively higher CMS energies in order to explain 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 [5].

[1]khomma@hiroshima-u.ac.jp

We discuss photon-photon scattering by introducing 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].

In this proceedings, 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 Concept of stimulated laser colliders

The proposed method consists of 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.

2.1 Inclusion of a resonance state in laser-laser 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 head-on 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 would be too narrow to directly hit the peak of the Breit-Wigner function by any experimental effort. 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.

2.2 Stimulated scattering by coherent laser fields

The inclusion of a resonance state within the uncertainty on E_{cms} is still short in order to reach the sensitivity to the gravitational coupling strength. 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

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

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

$$(\sqrt{N_{p_1}}\sqrt{N_{p_2}}\sqrt{1_{p_3}}\sqrt{N_{p_4}})^2 = N_{p_1}N_{p_2}N_{p_4}, \tag{11}$$

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 nature results in a enormous enhancement factor on the interaction rates. Thus, the stimulated photon collider can provide an extremely high sensitivity to feeble couplings.

3 The current status and future prospect

Figure 1 shows the expected 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) [15] are shown. We are now in preparation for the search at ELI-NP by forming an international collaboration SAPPHIRES (Search for Axion-like Particle via optical Parametric effects with High-Intensity laseRs in Empty Space) [16] based on the concept introduced here. Figure 2 shows the prospect of sensitivity by searches in ACS. The details of the curves are explained in [5]. In both collision systems, 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.

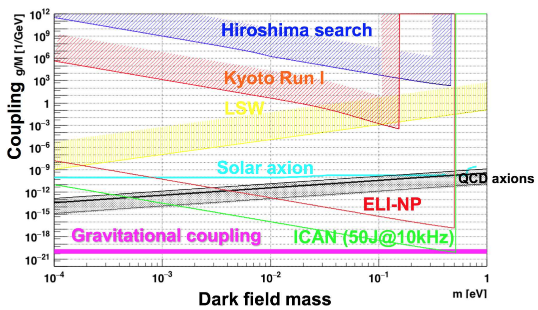

Figure 1: Sensitivity in QPS.

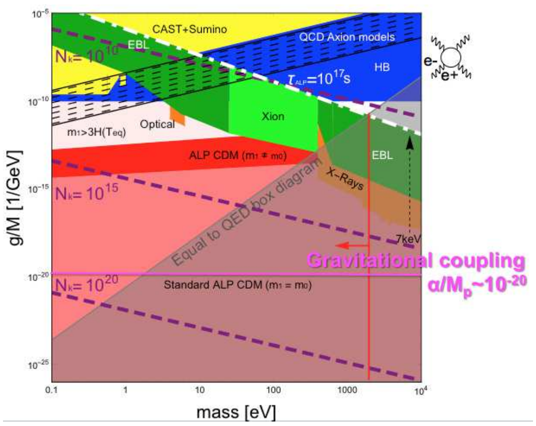

Figure 2: Sensitivity in ACS [5].

Acknowledgements

K. Homma acknowledges the support of the Collaborative Research Program of the Institute for Chemical Research, Kyoto University (Grants Nos. 2017–67 and 2018-83) and the Grants-in-Aid for Scientific Research Nos. 16H01100, 17H02897 and 18H04354 from MEXT of Japan.

References

[1] Y. Fujii and K. Maeda, *The Scalar-Tensor Theory of Gravitation* Cambridge Univ. Press (2003).

[2] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett **38**, 1440 (1977); S. Weinberg, Phys. Rev. Lett **40**, 223 (1978); F. Wilczek, Phys. Rev. Lett **40**, 271 (1978).

[3] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, and J. March-Russell, Phys. Rev. D **81**, 123530 (2010); B. S. Acharya, K. Bobkov, and P. Kumar, J. High Energy Phys. **11**, 105 (2010); M. Cicoli, M. Goodsell, and A. Ringwald, J. High Energy Phys. **10**, 146 (2012).

[4] Y. Fujii and K. Homma, Prog. Theor. Phys **126**, 531 (2011); Prog. Theor. Exp. Phys. 089203 (2014) [erratum].

[5] Kensuke Homma and Yuichi Toyota, Prog. Theor. Exp. Phys. 2017 (2017) no.6, 063C01.

[6] E. Bulbul et al., Astrophys. J. **789**, 13 (2014).

[7] A. Boyarsky, O. Ruchayskiy, D. Iakubovskyi and J. Franse, Phys. Rev. Lett. **113**, 251301 (2014).

[8] E. Bulbul, M. Markevitch, A. Foster, E. Miller, M. Bautz, M. Loewenstein, S. W. Randall and R. K. Smith, Astrophys. J. **831**, 55 (2016) ; F. A. Aharonian *et al.* [Hitomi Collaboration], arXiv:1607.07420 [astro-ph.HE] ; J. P. Conlon, F. Day, N. Jennings, S. Krippendorf and M. Rummel, arXiv:1608.01684 [astro-ph.HE].

[9] J. Jaeckel, J. Redondo and A. Ringwald, Phys.Rev. D **89**, 103511 (2014).

[10] Mark P. Hertzberg, Max Tegmark, and Frank Wilczek, Phys. Rev. D **78**, 083507 (2008); O. Wantz and E. P. S. Shellard, Phys. Rev. D 82, 123508 (2010).

[11] Y. Fujii and K. Maeda, *The Scalar-Tensor Theory of Gravitation* Cambridge Univ. Press (2003).

[12] R. J. Glauber, Phys. Rev. **131** (1963), 2766.

[13] K. Homma, T. Hasebe, and K.Kume, Prog. Theor. Exp. Phys. 083C01 (2014).

[14] T. Hasebe, K. Homma, Y. Nakamiya, K. Matsuura, K. Otani, M. Hashida, S. Inoue, S. Sakabe, Prog. Theor. Exp. Phys. 073C01 (2015).

[15] K. Homma, O. Tesileanu, L. D'Alessi, T. Hasebe, A. Ilderton, T. Moritaka, Y. Nakamiya, K. Seto, H. Utsunomiya, Y. Xu, Romanian Reports in Physics, Vol. 68, Supplement, P. S233-S274 (2016).

[16] http://home.hiroshima-u.ac.jp/spphrs/