Perspective of searching for axion-like particles in the mass range $10^{-7} - 10^3$ eV with stimulated photon-photon collider

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1. pseudo Nambu-Goldstone bosons as candidates for dark components in the Universe  
2. Principle of stimulated resonant photon-photon scattering  
3. Quick overview of experimental activities  
4. Summary
pNGBs can be dark components of the Universe

If $M \sim M_{\text{Planck}}$, dilaton (Dark Energy)

$-\frac{1}{4} \frac{g}{M} F_{\mu \nu} F^{\mu \nu} \phi$

If $M \sim M_{\text{GUT}}$, axion (Cold Dark Matter)

$-\frac{1}{4} \frac{g}{M} F_{\mu \nu} \tilde{F}^{\mu \nu} \sigma$

mass $1.5\text{-}5.9 \times 10^{-7}$ eV

mass $10^{-4}\text{-}10^{-6}$ eV

Scale symmetry breaking

PQ U(1) symmetry breaking

Two-loop self-energy correction

arXiv:1512.01360 [gr-qc]

Y. Fujii

http://en.wikipedia.org/wiki/Dark_energy

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Inflaton (ALP) mass and coupling to photons

\[ \mathcal{L} = \frac{g_{\phi\gamma\gamma}}{4} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \quad \frac{g_{\phi\gamma\gamma}}{\pi f} = \frac{c_\gamma \alpha}{\pi f} \]

\[ c_\gamma = \sum_i q_i Q_i^2 \]

\[ \psi_i \rightarrow e^{i\beta q_i \gamma_5 / 2} \psi_i \]

\[ \phi \rightarrow \phi + \beta f \]

\[ m_\phi \text{ [eV]} \]

\[ g_{\phi\gamma\gamma} \text{ [GeV}^{-1}] \]

CAST

HB

Telescopes

ALPS-II

IAXO

KS\text{\textsc{yz}}

QCD axion

X-ray

CMB \tau

FBL

Successful inflation

Daido, FT, and Yin 1702.03284

Limits taken from Essig et al 1311.0029
Photon-photon collision systems

Quasi-Parallel collision System

Center of Mass System

Asymmetric Head-on collision System

\[ E_{\text{cms}} = 2\omega \sin \theta \]
Low mass search

\[ E_{\text{cms}} = 2\omega \]
High mass search

\[ E_{\text{cms}} = 2\sqrt{\omega_1 \omega_2} \]
High mass search

\[ \beta \]
Lorentz boost

\[ \omega_3 \]
\[ \omega_4 \]
\[ \omega_1 \theta_4 \]
\[ \omega_2 \]
\[ \omega_3 \]
\[ \omega_4 \]

\[ \omega_3 \]
\[ \omega_4 \]
\[ \omega_1 \theta_4 \]
\[ \omega_2 \]
Stimulated photon-photon photon scattering

\[ N_{\text{dark}} \propto N_{\text{creation}} \times N_{\text{creation}} \times N_{\text{induce}} \propto (100J = 10^{20}_{\text{opt.}})^3 \]

\[ (2-u)\omega = 1\omega + 1\omega - u\omega \]

K. Homma et al.
Prog. Theor. Exp. Phys. 2014, 083C01
S-matrix for two-body interactions in stimulated resonant scattering

\[ S^{(2)} = \frac{i^2}{2} \int d^4x \int d^4y T[F_{\mu\nu}(x)F^{\mu\nu}\phi(x)F_{\rho\sigma}(y)F^{\rho\sigma}(y)\phi(y)] \]

\[ N[F_{\mu\nu}(x)F^{\mu\nu}(x)F_{\sigma\rho}(y)F^{\sigma\rho}(y)\langle 0|T[\phi(x)\phi(y)]|0 \rangle] \]

\[ \propto a_i^\dagger a_j^\dagger a_k a_\ell \]

Scalar - propagator

Coherent state:

\[ |N\rangle \equiv \exp(-N/2) \sum_{n=0}^{\infty} \frac{N^{n/2}}{\sqrt{n!}} |n\rangle \quad |n\rangle = \frac{1}{\sqrt{n!}} \left( a^\dagger \right)^n |0\rangle \]

\[ \langle N|N\rangle = 1 \quad \langle N|\left( a^\dagger a \right)|N\rangle = N \quad a|N\rangle = \sqrt{N}|N\rangle, \quad \text{and} \quad \langle N|a^\dagger = \sqrt{N}\langle N| \]

Transition amplitude: \( 1 + 1 \rightarrow 3 + 4 \)

\[ \ll N_1 | \ll N_4 | \ll 1_3 | S^{(2)} | N_1 \gg | N_4 \gg | 0 \gg \]

\[ \propto \ll N_1 | \ll N_4 | \ll 1_3 | a_i^\dagger a_j^\dagger a_k a_\ell | N_1 \gg | N_4 \gg | 0 \gg \]

\[ \propto \sqrt{N_1} \sqrt{N_1} \sqrt{N_4} \ll N_1 |N_1 \gg \ll N_4 |N_4 \gg < 0|0 \gg \]
s-channel propagator cannot be implemented - creation and decay points are spatially apart -

\[
Rate \propto \left(\frac{g}{M}\right)^2_{\text{creation}} \times \left(\frac{g}{M}\right)^2_{\text{decay}}
\]

Solar axion search (CAST)

CAST, Theopisti Dafni, 7th Patras Workshop, Mykonos 2011

Light Shining through a Wall (LSW)


M^4 is huge!
s-channel scattering contains resonance

\[ |\mathcal{M}|^2 \approx (4\pi)^2 \frac{a^2}{\chi^2 + a^2} \]

\[ a = \frac{\omega_r}{16\pi} \left( \frac{gm}{M} \right)^2 \]

\[ \chi = \omega^2 - \omega_r^2 \]

\[ \omega_r^2 = \frac{m^2/2}{1 - \cos 2\vartheta} \]

\[ \chi \gg a \to |\mathcal{M}|^2 \propto a^2 \propto M^{-4} \]

\[ \omega = \omega_r \to |\mathcal{M}|^2 \propto (4\pi)^2 \]

\[ \chi_{\pm} \equiv \pm \eta a \text{ with } \eta \gg 1 \]

\[ |\mathcal{M}|^2 = \frac{1}{\chi_+ - \chi_-} \int_{\chi_-}^{\chi_+} |\mathcal{M}|^2 d\chi \]

\[ = \frac{(4\pi)^2}{2\eta a} 2a \tan^{-1}(\eta) = (4\pi)^2 \eta^{-1} \tan^{-1}(\eta) \]

\[ \approx (4\pi)^2 \eta^{-1} \frac{\pi}{2} = 8\pi^3 a \frac{\eta}{|\chi_{\pm}|} \]

Collision in QPS within momentum-energy uncertainty

e.g. $\gamma-\gamma$ Higgs factory

Gain by $M^2$
The first search for scalar field with FWM
The first search for sub-eV scalar fields via four-wave mixing at a quasi-parallel laser collider

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A search for sub-eV scalar fields coupling to two photons has been performed via four-wave mixing at a quasi-parallel laser collider for the first time. The experiment demonstrates the novel approach of searching for resonantly produced sub-eV scalar fields by combining two-color laser fields in the vacuum. The aim of this paper is to provide the concrete experimental setup and the analysis method based on specific combinations of polarization states between incoming and outgoing photons, which is extendable to higher-intensity laser systems operated at high repetition rates. No significant signal of four-wave mixing was observed by combining a 0.2 \( \mu \)J/0.75 ns pulse laser and a 2 mW CW laser on the same optical axis. Based on the prescription developed for this particular experimental approach, we obtained the upper limit at a confidence level of 95\% on the coupling–mass relation.
Run I at Kyoto-ICR

with atomic Four-Wave Mixing (FWM)
Time structures of the number of photons

POL{1}  POL{2}

Only C

Only I

Pedestal

K. Homma
Pressure dependence of atomic FWM (corrected)

Quadratic pressure dependence is consistent with $\chi^{(3)}$ process
Search for sub-eV scalar and pseudoscalar resonances via four-wave mixing with a laser collider

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Run II with 10 TW at Kyoto-ICR
Extreme-Light-Infrastructure (ELI)

ELI-NP facility (280M€)
Comm. starts from 2019

10 PW x 2
1 PW x 2
0.1 PW x 2

0.2-19.5 MeV gamma beam produced by
~700 MeV e- + laser
Sensitivity below sub-eV mass domain in Quasi-Parallel collision

Hiroshima search
Kyoto Run I
Solar axion
ELI-NP
QCD axions
Gravitational coupling
ICAN (50J@10kHz)

Coupling $g/M [1/\text{GeV}]$

Dark field mass $m [\text{eV}]$
Asymmetric head-on collision for high-mass pNGB search

Coherent beam

Signal photons

Coherent / Incoherent beam

Coherent / Incoherent beam

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Sensitivity in 0.1 eV–10 keV mass domain in Asymmetric Head-on collision

- CAST+Sumino
- QCD Axion models
- EBL
- Xion
- ALP CDM ($m_1 \neq m_0$)

Gravitational coupling $\alpha/M_p \sim 10^{-20}$

K. Homma and Y. Toyota
Prog. Theor. Exp. Phys. 2017, 063C01
Entire scope by this method

Limits shown by Axel Lindner
Axion Dark Matter
2016 in Stockholm
Klystron as a $10^{-5}$ eV photon source

Can we reach dilaton?

\( \frac{g}{M[1/{\text{GeV}}]} \)

\( \alpha_{\text{qcd}}/M_p \)

\( m[\text{eV}] \)

\( g/M[1/{\text{GeV}}] \)

\( \alpha_{\text{qcd}}/M_p \)

K. Homma, Y. Kirita
arXiv:1909.00983
- Charged particle collisions discovered SM particles in extremely strong coupling and high-mass domains over $10^5 – 10^{11}$ eV

- Stimulated photon-photon collider can provide windows in extremely weak coupling and low-mass domains over $10^{-7} – 10^3$ eV

- Current technologies can provide the ways to access gravitational coupling strength in elementary scattering processes!