Optical Ring Cavity Search for Axion Dark Matter

Ippei Obata (ICRR, University of Tokyo)

based on **arXiv: 1805.11753**

Collaborated with
Tomohiro Fujita (Kyoto Univ.)
& Yuta Michimura (KAGRA group, Tokyo Univ.)

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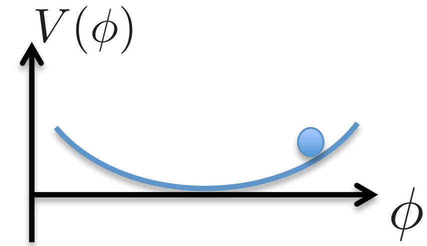
Axion (light scalar field) as Dark Matter



- Axion evolves according to KG equation

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$ (background equation)

- After m > H (oscillation begins), it starts to oscillate and effectively behaves as a pressureless dust

$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m^2\phi^2 \simeq \frac{\rho_0}{a^3}$$

$$P = \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m^2\phi^2 \simeq \frac{P_0}{a^3}\sin(2mt) \sim 0$$ → Axion Dark Matter (ADM)

- Axion dark matter with very low mass can blur the structure on sub-galactic scales.

$$k_J \sim \frac{1}{30\ \mathrm{kpc}}\left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{1/2}$$ →resolve the "small scale problems"?

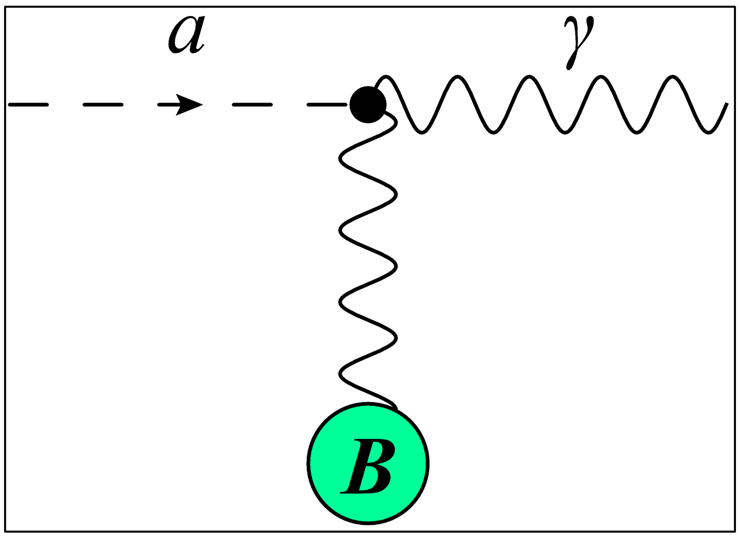
(Jeans length scale)

Search for Axion through photon

(regardless of DM or not)

- Axion generally couples to photons via topological term.

$$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$



Axion-photon conversion (Primakoff effect)

Sikivie 1983,...

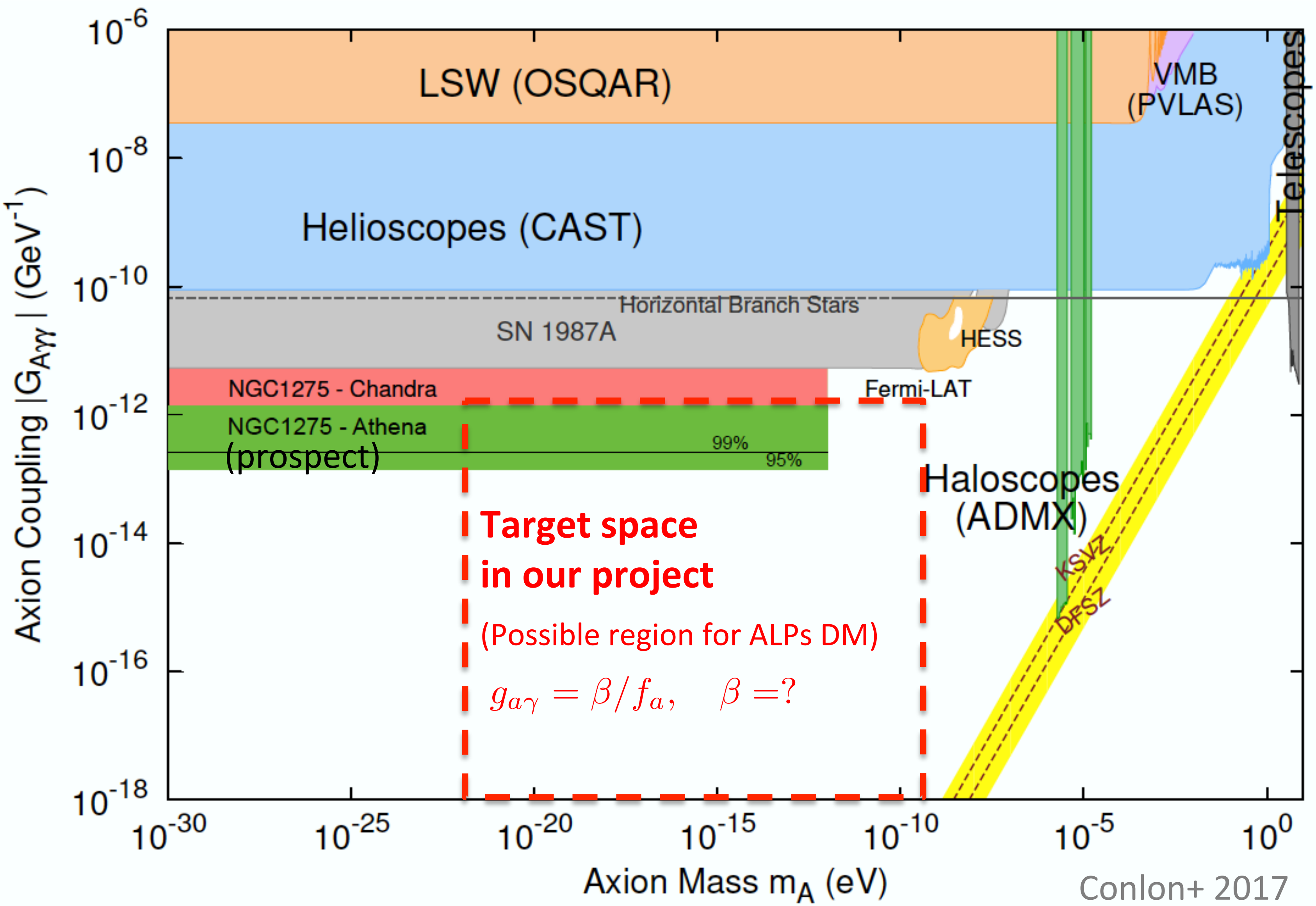
- Axion is converted into photon in the presence of background magnetic field.

→search for axion-photon convertion with

Laboratory experiments

Astrophysical observations

Overview of exclusion limits



Axion DM - Photon Coupling (c=1)

- Rewriting axion-photon couplinng with respect to gauge potential

$$\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} = g_{a\gamma}\dot{a}A_i\epsilon_{ijk}\partial_j A_k + (\text{total derivative})$$

Equation of motion for photon: $\ddot{A}_i - \nabla^2 A_i + g_{a\gamma}\dot{a}\epsilon_{ijk}\partial_j A_k = 0,$

Background axion field: $a(t) = a_0 \cos(mt + \delta_\tau)$

- Decomposing photons into two helicity modes, one can obtain

$$\ddot{A}_k^{\pm} + \omega_{\pm}^2 A_k^{\pm} = 0,$$
$$\omega_{\pm}^2 \equiv k^2 \left(1 \pm \frac{g_{a\gamma} a_0 m}{k} \sin(mt + \delta_\tau)\right)$$

Braking parity symmetry in dispersion relation

$$A_i(t, \boldsymbol{x}) = \sum_{\lambda=\pm} \int \frac{d\boldsymbol{k}}{(2\pi)^3} A_{\boldsymbol{k}}^{\lambda}(t) e_i^{\lambda}(\hat{\boldsymbol{k}}) e^{i\boldsymbol{k}\cdot\boldsymbol{x}}$$

Estimation of Phase Velocity

- Phase velocity of each polarized photon reads

$$c_\pm \equiv \frac{\omega_\pm}{k} = \left(1 \pm \frac{g_{a\gamma} a_0 m}{k} \sin(mt + \delta_\tau)\right)^{1/2}$$

- So we get the difference of phase velocity and its amplitude

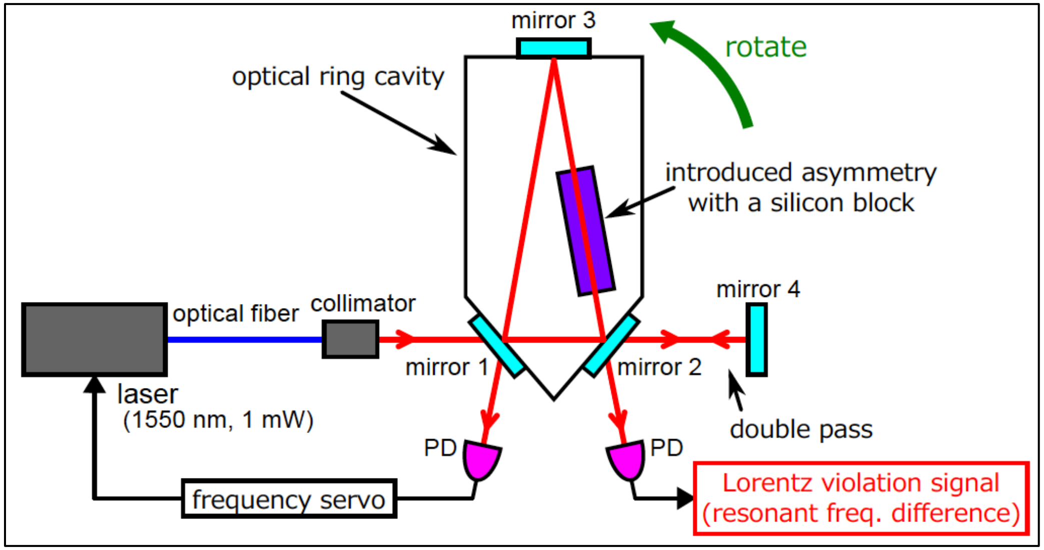
$$\delta c \equiv |c_+ - c_-| = \delta c_0 \sin(mt + \delta_\tau)$$

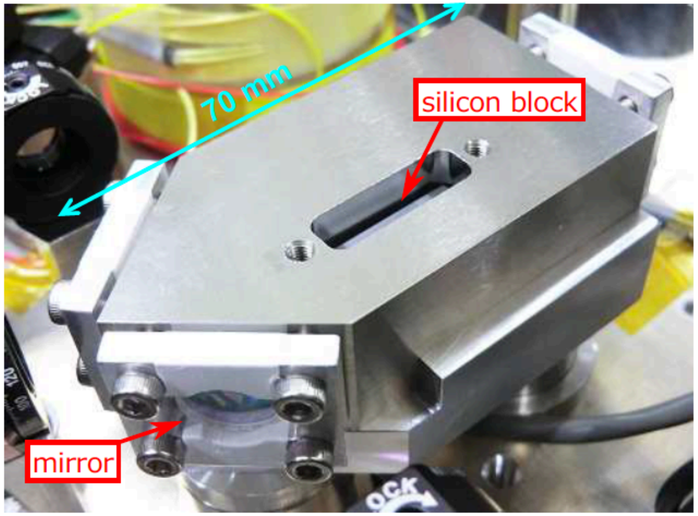
$$\frac{\delta c_0}{c} \simeq 2.7 \times 10^{-24} \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right) \left(\frac{\lambda}{1550\ \mathrm{nm}}\right) \left(\frac{\rho_a}{0.3\ \mathrm{GeV/cm}^3}\right)^{1/2}$$

Is it possible to search for this small difference by using optical methods?

Optical Ring Cavity Experiments

Bayes+ 2011, Michimura+ 2013,…





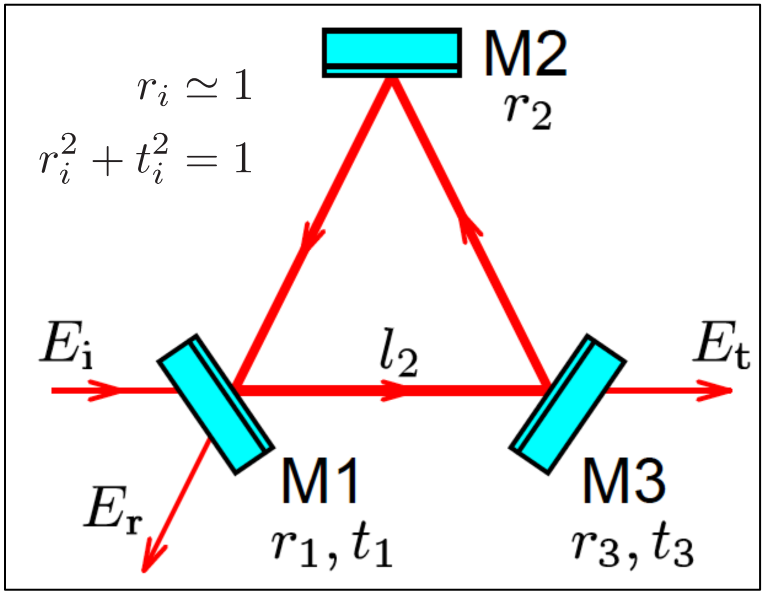
Michimura+ 2016

- It has been proposed to probe the (anisotropic) Lorentz violation signal by measuring the difference of resonant frequency between two optical paths.

- The sensitivity is mainly determined by quantum noise by common noise rejection.

$$\delta c/c \lesssim 10^{-15} \quad (L = 0.1\ \mathrm{m},\ F = 10^2,\ P = 1\ \mathrm{mW})$$ (Michimura+ 2013)

Mechanism of Resonant Cavity



Michimura 2014

■ The transmittance of cavity is given by

$$\phi_2 = l_2\omega/c$$

$$E_t = E_i t_1 t_3 e^{-i\phi_2} + E_i t_1 r_3 r_2 r_1 t_3 e^{-i(\phi+\phi_2)} + \ldots$$
$$= E_i \frac{t_1 t_3 e^{-i\phi_2}}{1 - r_1 r_2 r_3 e^{-i\phi}}$$

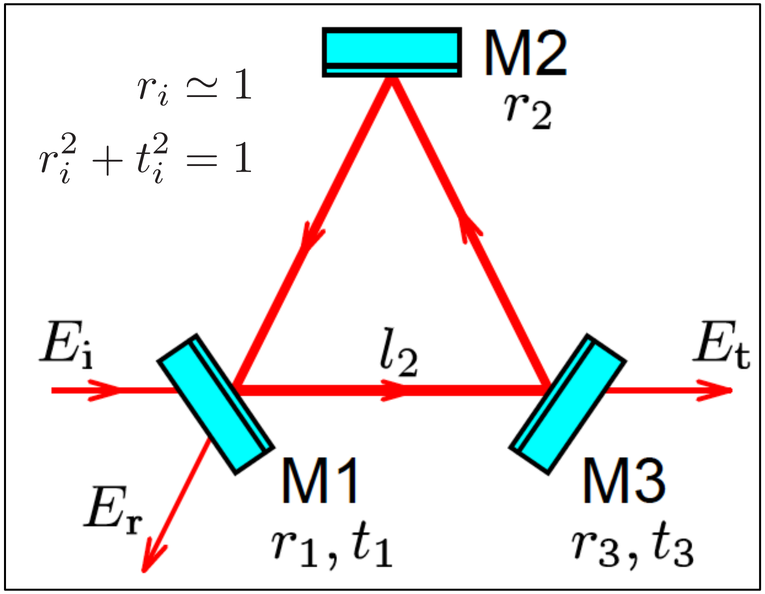
$$P_t = |E_t|^2$$
$$= \frac{(t_1 t_3)^2}{(1 - r_1 r_2 r_3)^2 + 4 r_1 r_2 r_3 \sin^2(\phi/2)} |E_i|^2$$

■ The resonance occurs when the phase of laser beam satisfies

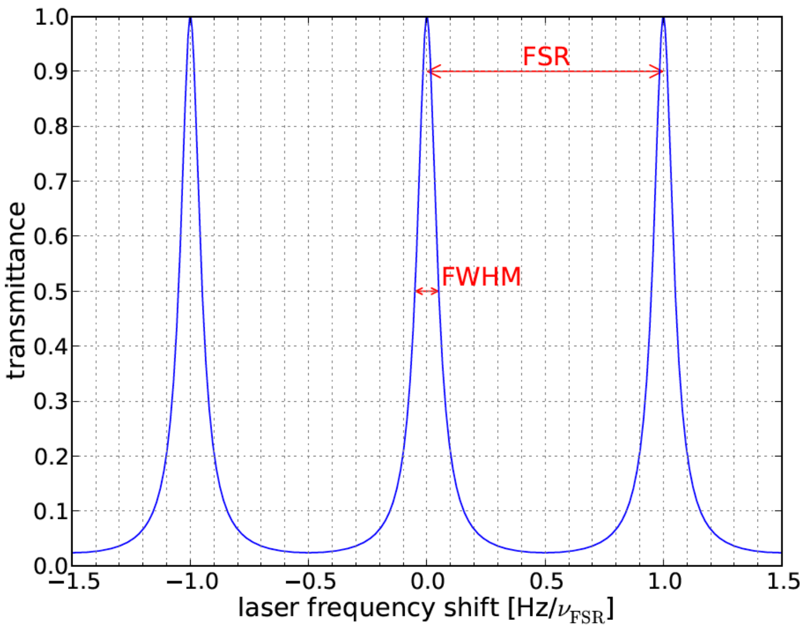
$$\phi = 2\pi m \quad (m = 1, 2, 3, \ldots) \quad \longleftrightarrow \quad \nu = \frac{mc}{L}$$ (resonant frequency)

■ At this time, the phase of reflected photon rapidly changes.

Mechanism of Resonant Cavity



Michimura 2014

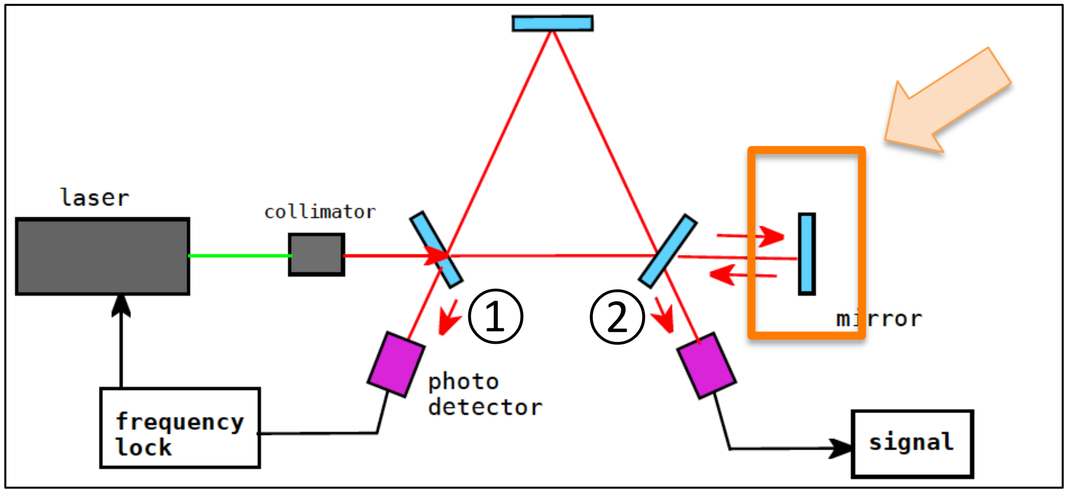


(The sharpness of the peak is characterized by the finesse)

$$\mathcal{F} \equiv \frac{\nu_{\rm FSR}}{\nu_{\rm FWHM}} = \frac{\pi\sqrt{r_1 r_2 r_3}}{1 - r_1 r_2 r_3} \gg 1 \quad (r \to 1)$$

- However, only in the above setup we cannot distinguish the variation of light speed from environmental noises (fluctuations of laser intensity, frequency, cavity length, etc.)

Double Pass Configuration



①-②

- We prepare the mirror at far right.
- The transmitted beam is reflected off and goes back to the cavity.

- We get the signal from two counterpropagating optical paths and measure its difference.

Most environmental noises change two resonant frequencies coherently

→The difference of two signals will reject these common noise fluctuations
(Quantum shot noise becomes the primary source of noise)

Reconsidering AxionDM-Photon…

- Phase velocity of each polarized photon reads

$$c_\pm \equiv \frac{\omega_\pm}{k} = \left(1 \pm \frac{g_{a\gamma} a_0 m}{k} \sin(mt + \delta_\tau)\right)^{1/2}$$

- So we get the difference of phase velocity and its amplitude

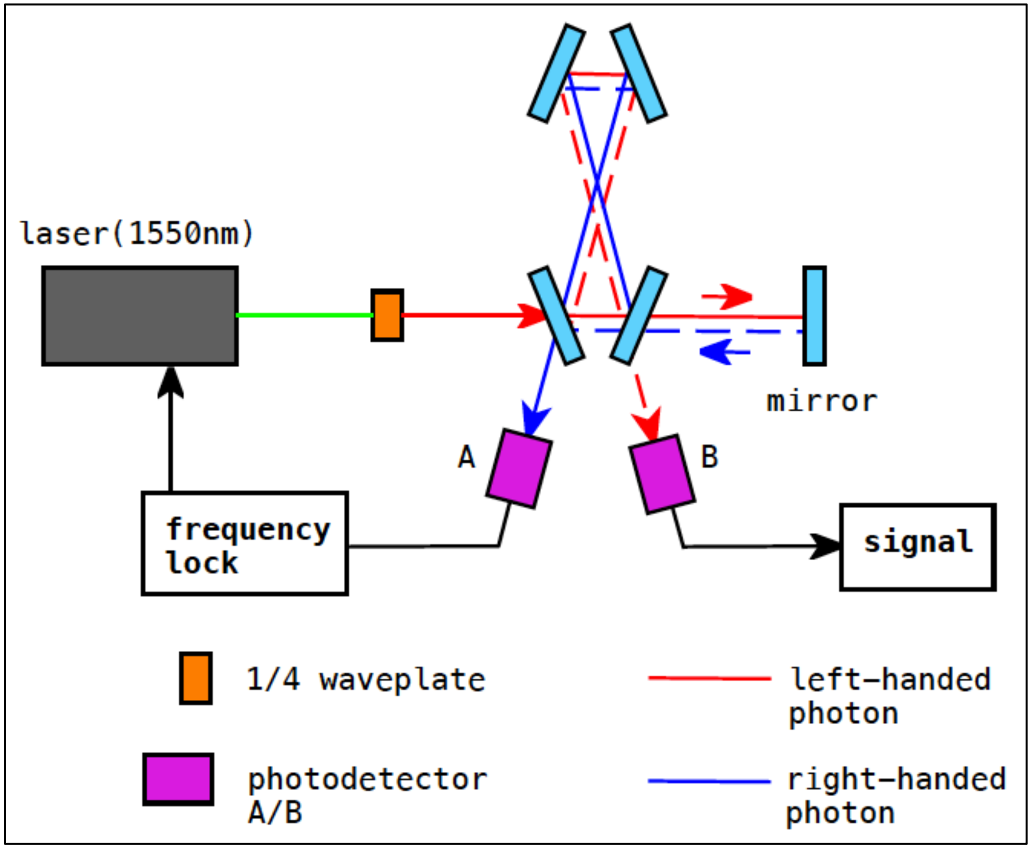
$$\delta c \equiv |c_+ - c_-| = \delta c_0 \sin(mt + \delta_\tau)$$

$$\frac{\delta c_0}{c} \simeq 2.7 \times 10^{-24} \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right) \left(\frac{\lambda}{1550\ \mathrm{nm}}\right) \left(\frac{\rho_a}{0.3\ \mathrm{GeV/cm}^3}\right)^{1/2}$$

✓ **We apply the optical ring cavity measurement to the detection of axion DM-photon coupling by improving previous experimental setup!**

Our Cavity Design

1805.11753



- ✓ This basement can measure the difference of resonant frequencies between left and right-handed polarized photon.

$$\frac{\delta\nu}{\nu} = \frac{\delta c}{c} = 3 \times 10^{-24} \left(\frac{g_{a\gamma}}{10^{-12}\mathrm{GeV}^{-1}} \right) \sin(mt + \delta_\tau)$$

- ✓ A null-experiment sensitive to the axion-photon coupling.
- ✓ Due to a double pass configuration, common fluctuation noises become irrelevant.

Sensitivity curve is primarily given by shot noise :

$$\sqrt{S_{\mathrm{shot}}} = \sqrt{\frac{\lambda}{4\pi P}\left(\frac{1}{t_r^2} + \omega^2\right)}, \quad t_r = \frac{L\mathcal{F}}{\pi}$$

Sensitivity Estimation

- Signal-to-Noise ratio (SNR) is given by $\delta c \equiv |c_+ - c_-| = \delta c_0 \sin(mt + \delta_\tau)$

$$(\mathrm{SNR}) = \frac{\sqrt{T}}{2\sqrt{S_{\mathrm{shot}}}} \frac{\delta c_0}{c} \qquad \sqrt{S_{\mathrm{shot}}} = \sqrt{\frac{\lambda}{4\pi P}\left(\frac{1}{t_r^2} + \omega^2\right)}, \quad t_r = \frac{L\mathcal{F}}{\pi}$$

until $T < \tau = \dfrac{2\pi}{mv^2} \sim 1\mathrm{yr}\left(\dfrac{10^{-16}\mathrm{eV}}{m}\right)$ (coherent time of ADM)

- If T is longer than τ, SNR is modified as $(\mathrm{SNR}) = \dfrac{(T\tau)^{1/4}}{2\sqrt{S_{\mathrm{shot}}}} \dfrac{\delta c_0}{c}$

✓ Finally the sensitivity of axion-photon coupling leads to

$$g_{a\gamma} \lesssim \frac{2}{2.7 \times 10^{-12}} \sqrt{\frac{S_{\mathrm{shot}(\omega)}}{T}}\ (\mathrm{GeV})^{-1} \quad (\mathrm{T} < \tau)$$

$$\lesssim \frac{2}{2.7 \times 10^{-12}} \sqrt{\frac{S_{\mathrm{shot}(\omega)}}{(T\tau)^{1/2}}}\ (\mathrm{GeV})^{-1} \quad (\mathrm{T} \geq \tau)$$

Projected Sensitivity Reach

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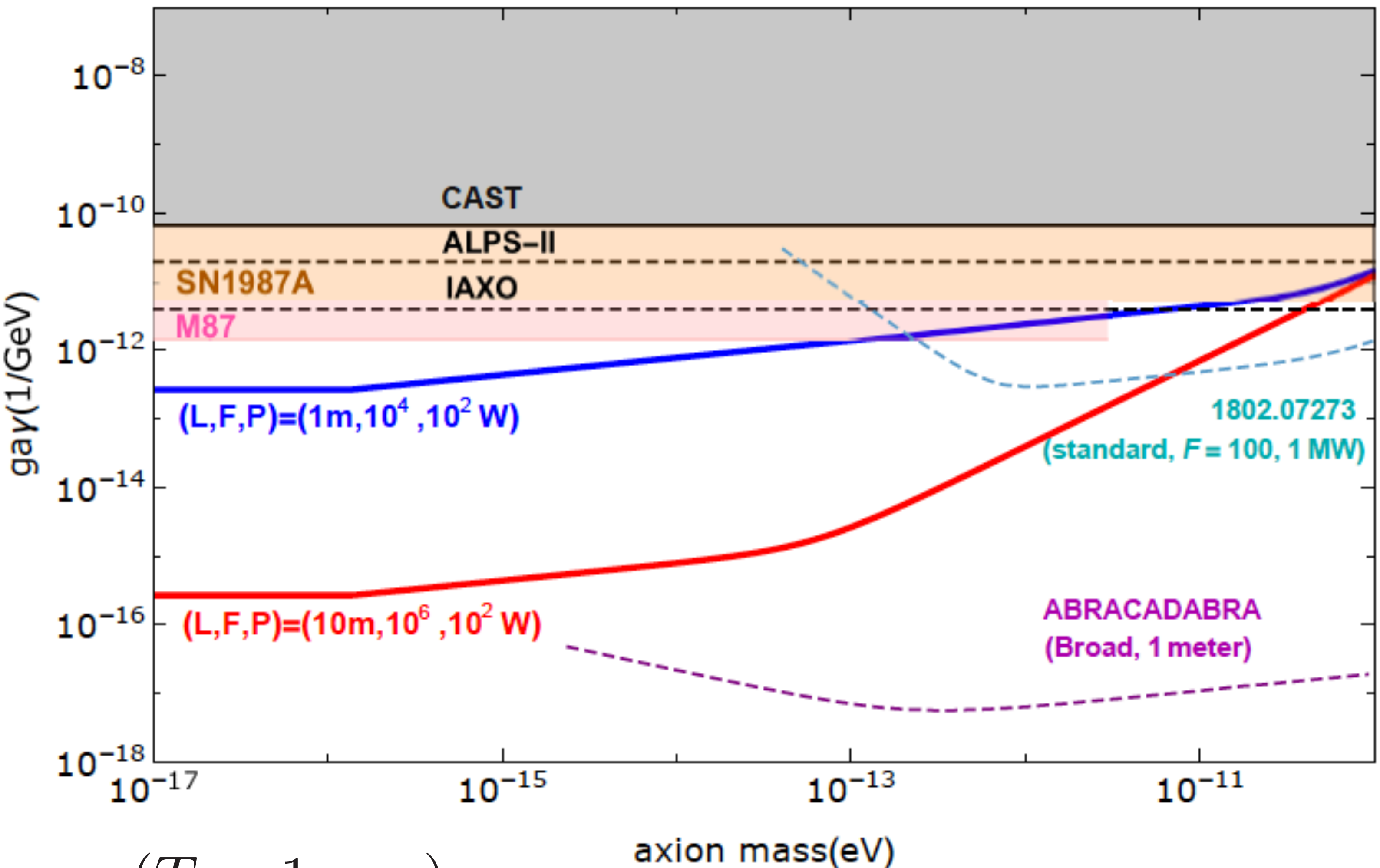

$(T = 1\text{year})$

Summary & Outlook

- ☐ We proposed a novel experiment to probe a coupling of ADM to photon by using optical ring cavity.

- ☐ We prepared two sets of experimental parameters and demonstrated that both of them can reach sensitivities beyond the current constraints.

- ☐ We have to investigate the technical noises at low frequency since the common mode rejection ratio is finite in actually.

- ☐ We're starting to operate the cavity with feasible parameters.