TAUP2019 @ Toyama International Conference Center

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DANCE: Dark matter Axion search with riNg Cavity Experiment

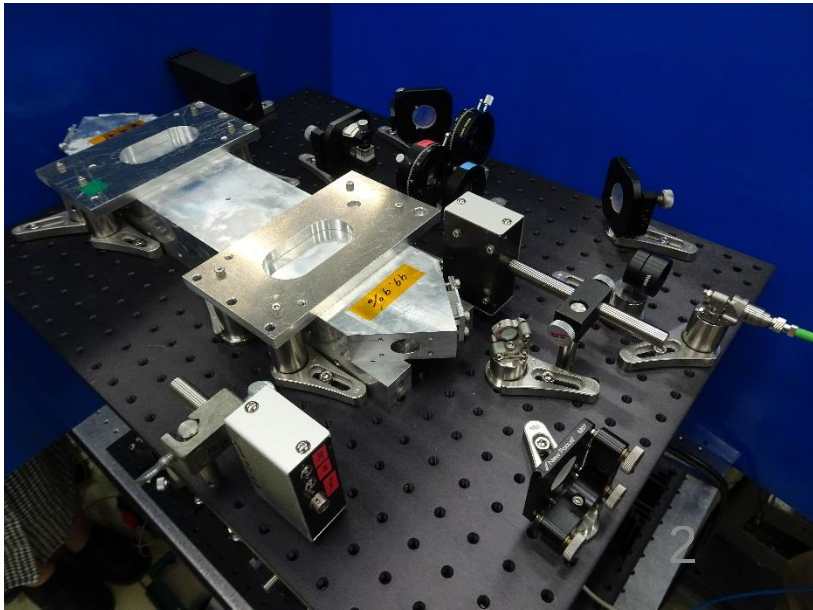
Yuta Michimura

Department of Physics, University of Tokyo

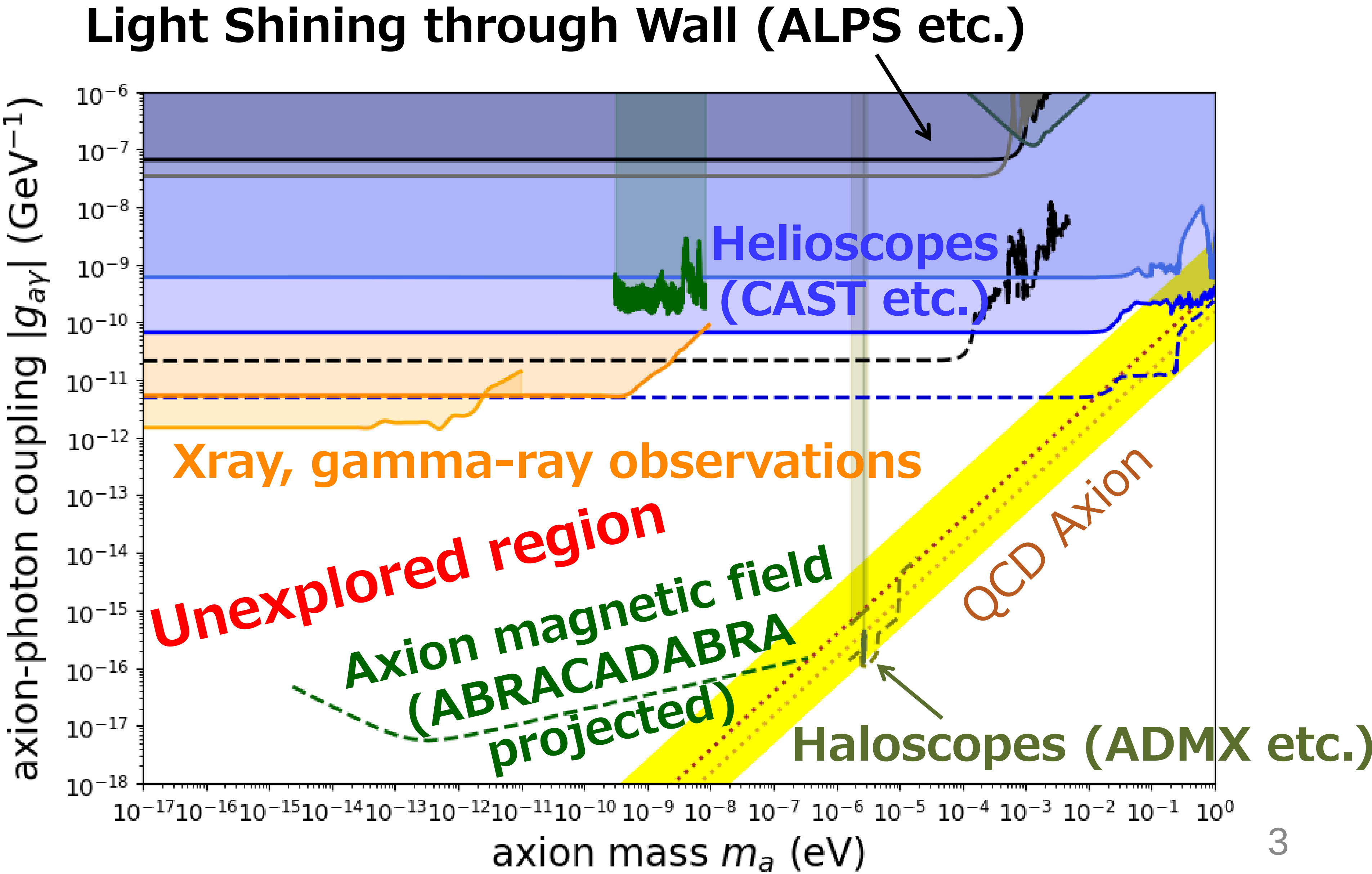
Yuka Oshima, Taihei Watanabe,
Takuya Kawasaki, Hiroki Takeda, Koji Nagano,
Masaki Ando, Ippei Obata, Tomohiro Fujita

Overview

- Proposed a new method to search for dark matter axions using a ring cavity
  I. Obata, T. Fujita, YM, PRL 121, 161301 (2018)
- By measuring phase velocity difference between two circular polarizations
- Prototype experiment is on-going at University of Tokyo



Search for Axion-Photon Coupling



Velocity of Circular Polarizations

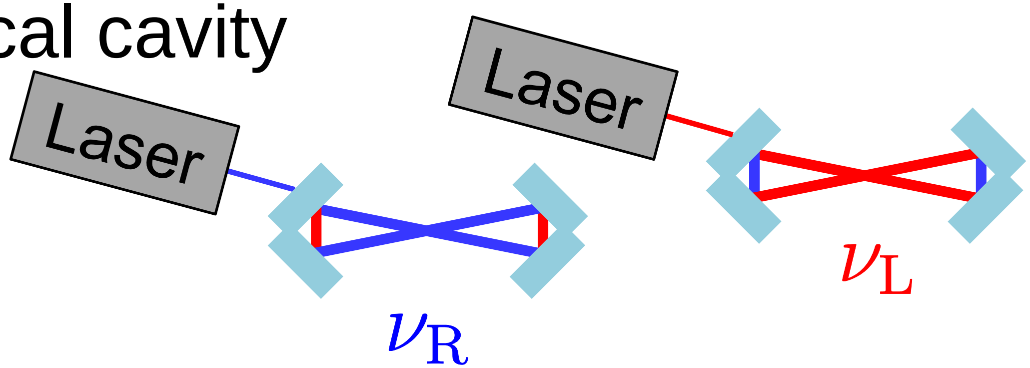
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

coupling constant axion field axion mass

- Measure the difference as resonant frequency difference in an optical cavity

$$\frac{\delta c}{c} = \frac{\nu_{\mathrm{L}} - \nu_{\mathrm{R}}}{\nu}$$

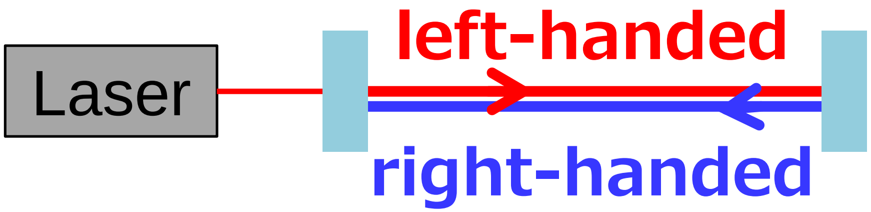


- Search can be done without magnetic field

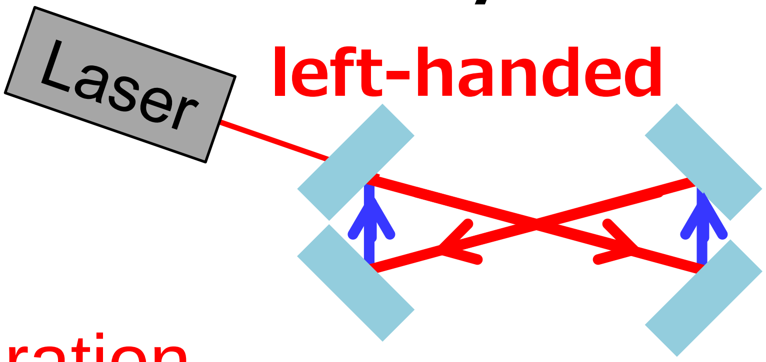
Our Ideas

- Use of bow-tie cavity

The effect is canceled in a linear cavity



Not canceled in a bow-tie cavity



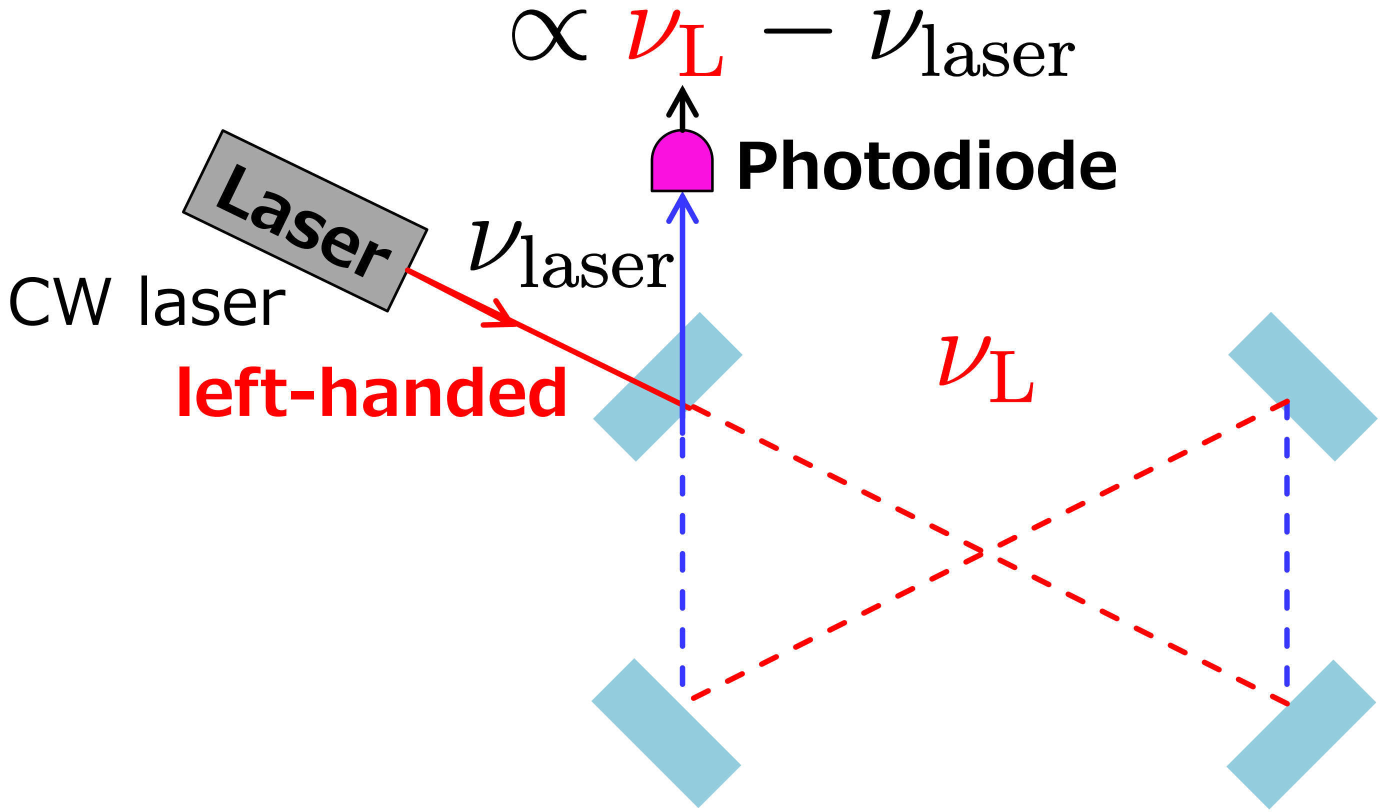
- Use of double-pass configuration

  Transmitted beam is reflected back into the same cavity as different polarization to realize a null measurement of the resonant frequency difference

Y. Michimura+, PRL 110, 200401 (2013)

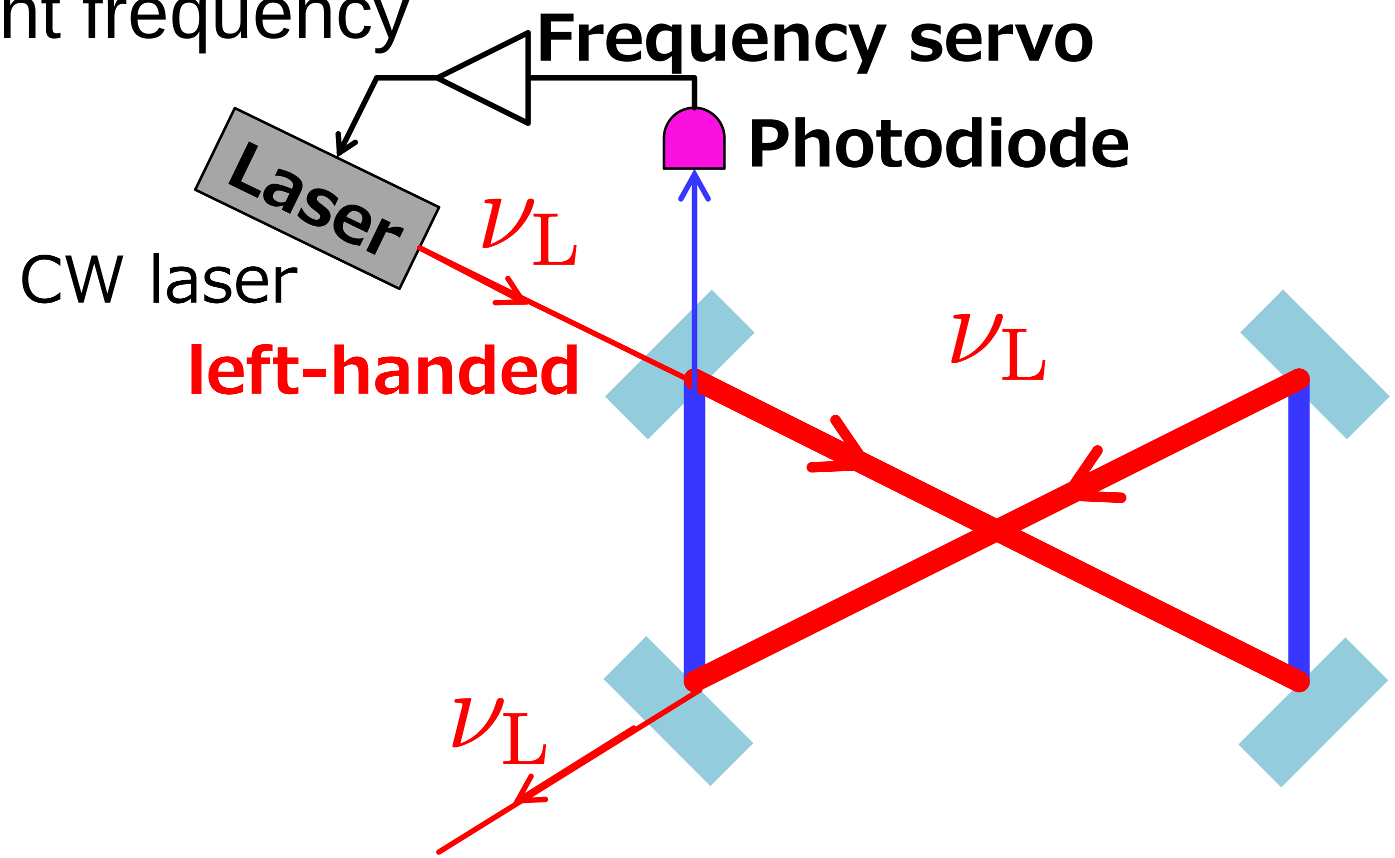
Double-Pass Configuration

- Inject left-handed polarization



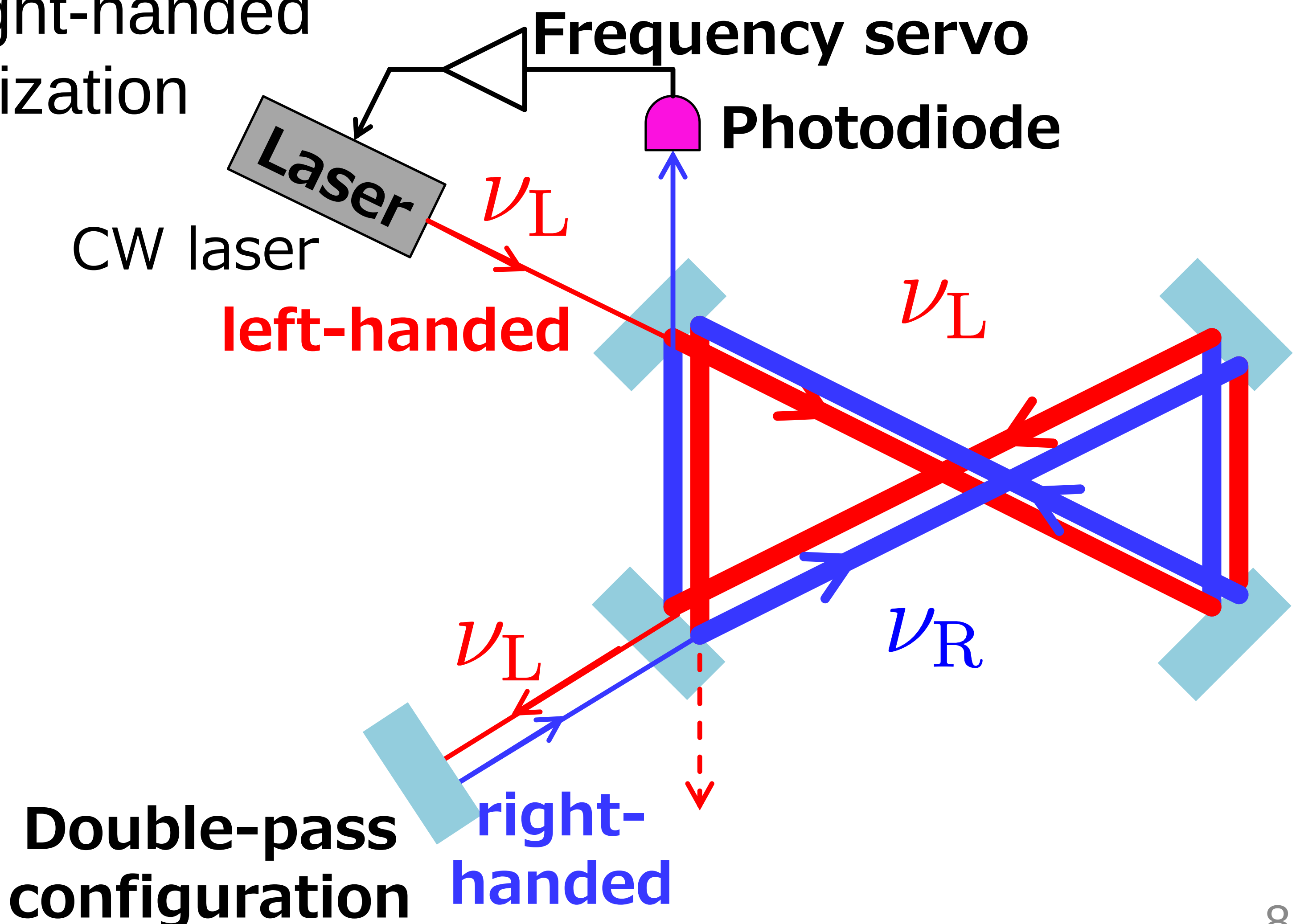
Double-Pass Configuration

- Lock the frequency of the laser to left-handed resonant frequency (ν_L)



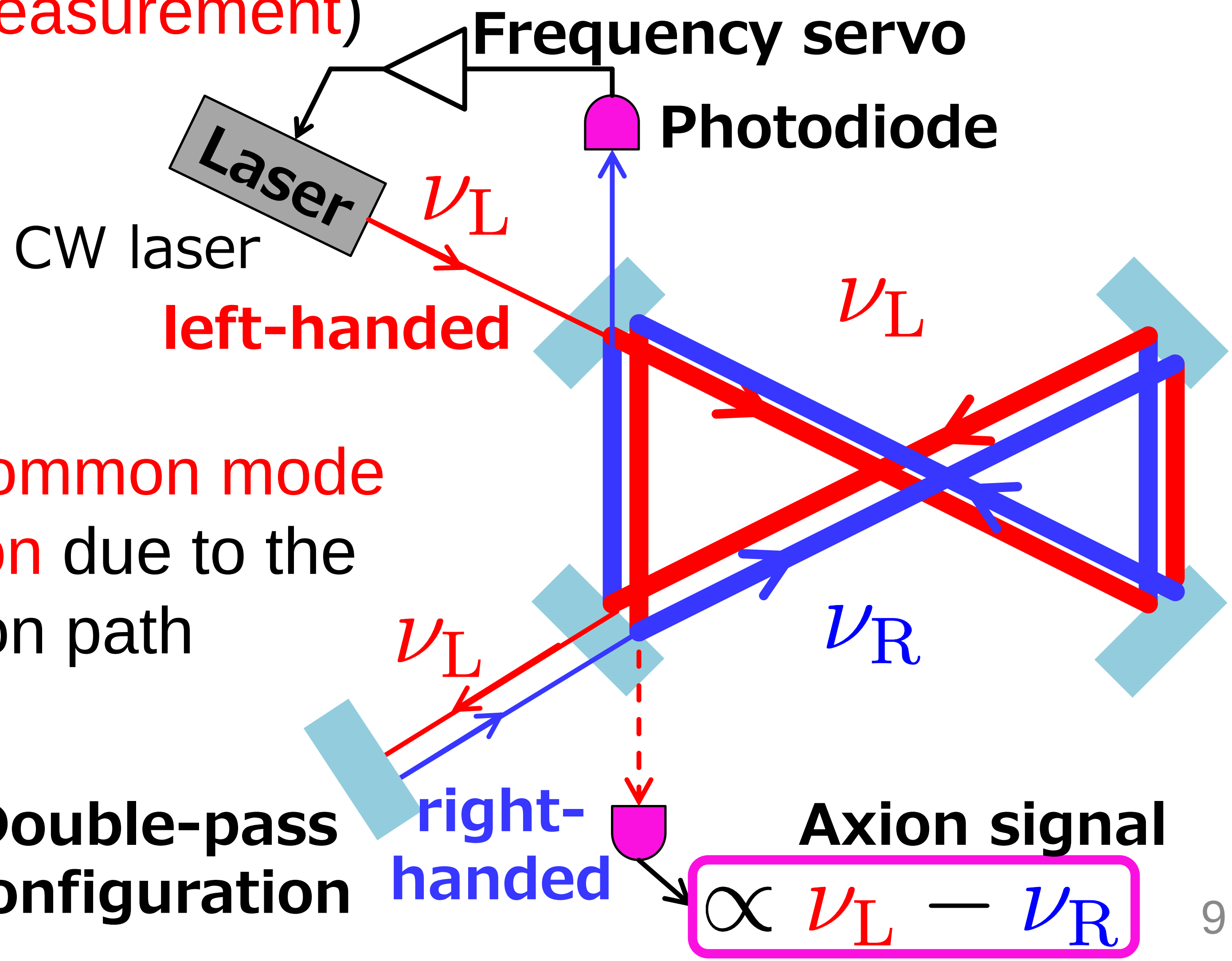
Double-Pass Configuration

- Transmitted beam is reflected back into the cavity as right-handed polarization



Double-Pass Configuration

- Axion signal is extracted from the cavity reflection (null measurement)



- High common mode rejection due to the common path

Sensitivity Calculation

- Cavity length changes (displacement noises) will not be a fundamental noise due to common mode rejection
- Ultimately limited by quantum shot noise

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

axion mass

input laser power

finesse

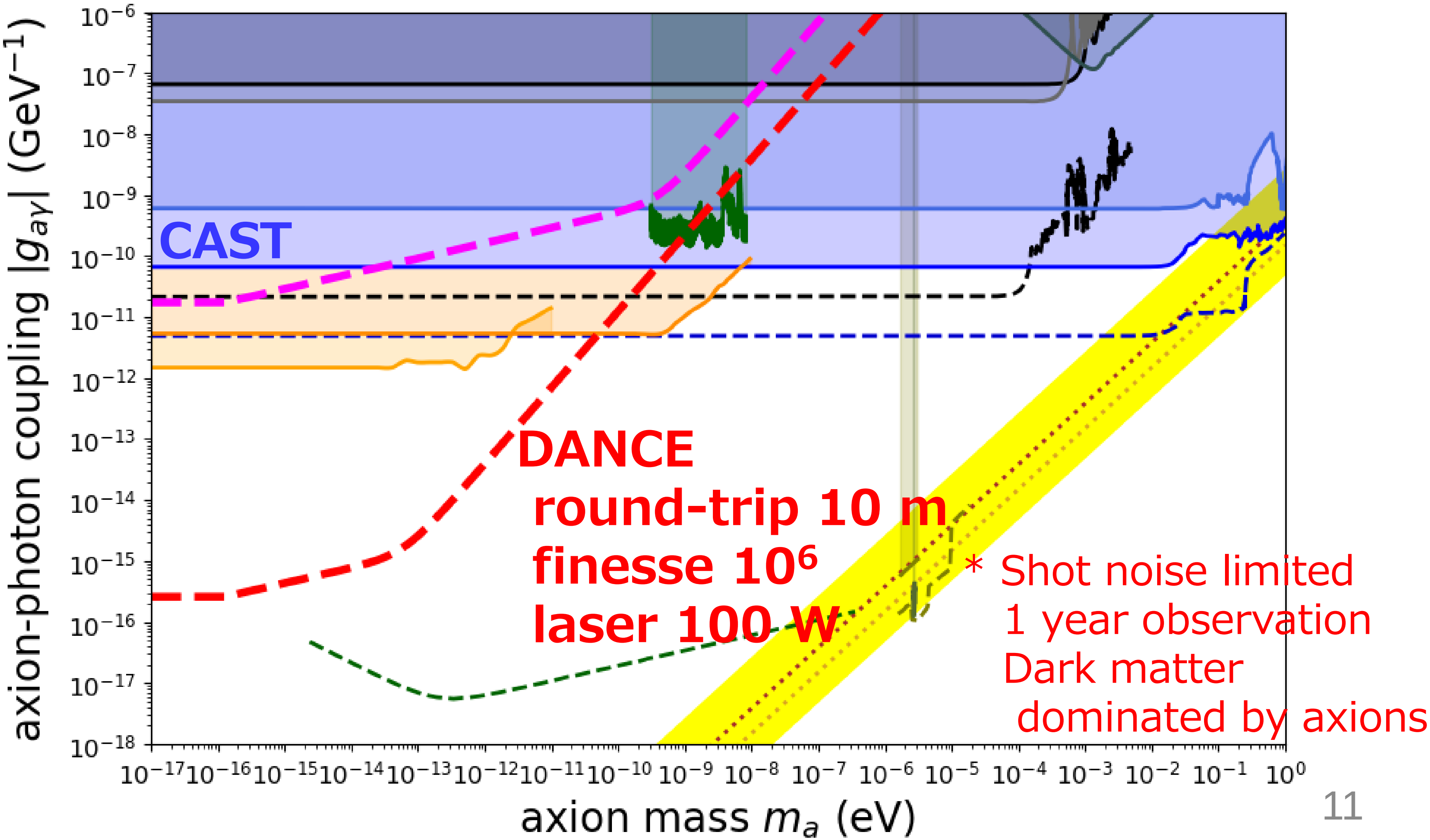
cavity length

- Sensitivity to axion-photon coupling can be calculated by assuming

  axion density = dark matter density

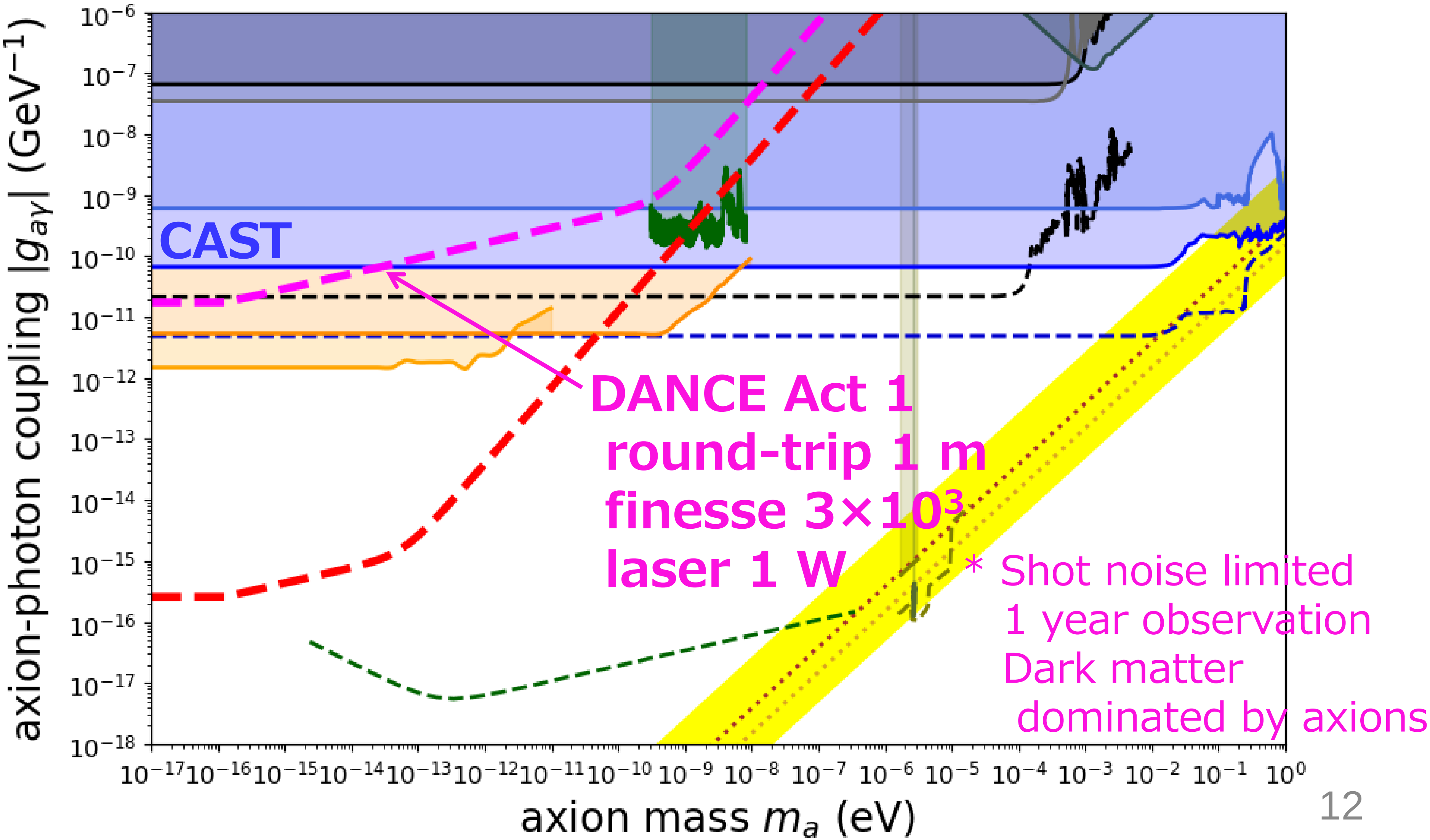
Search for Unexplored Region

Dark matter Axion search with riNg Cavity Experiment

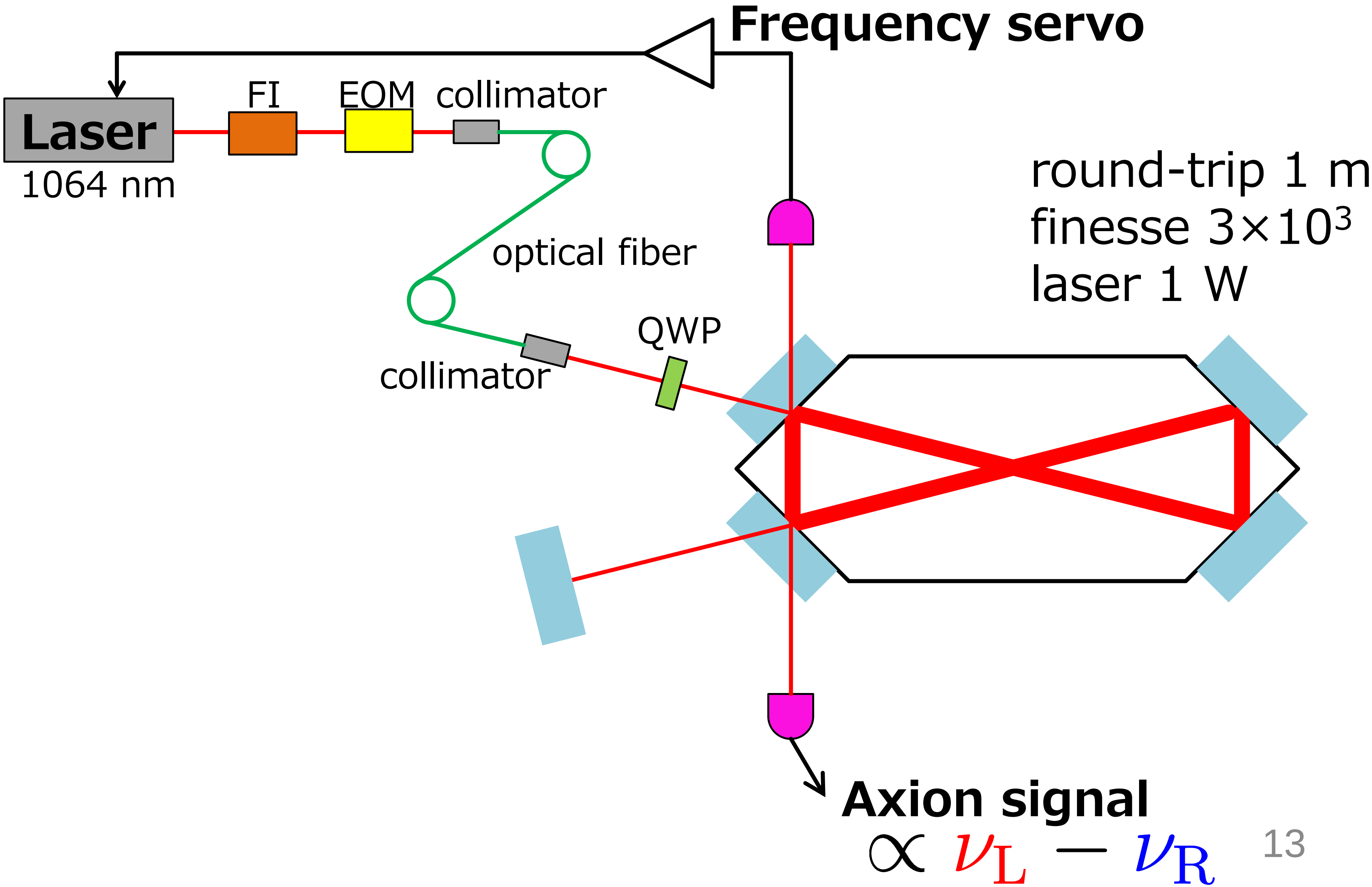


Prototype Experiment

Dark matter Axion search with riNg Cavity Experiment

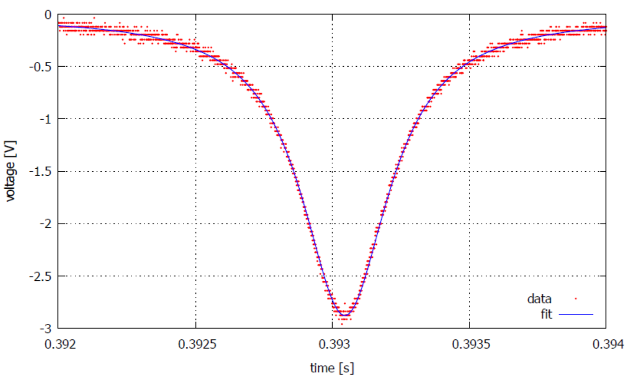


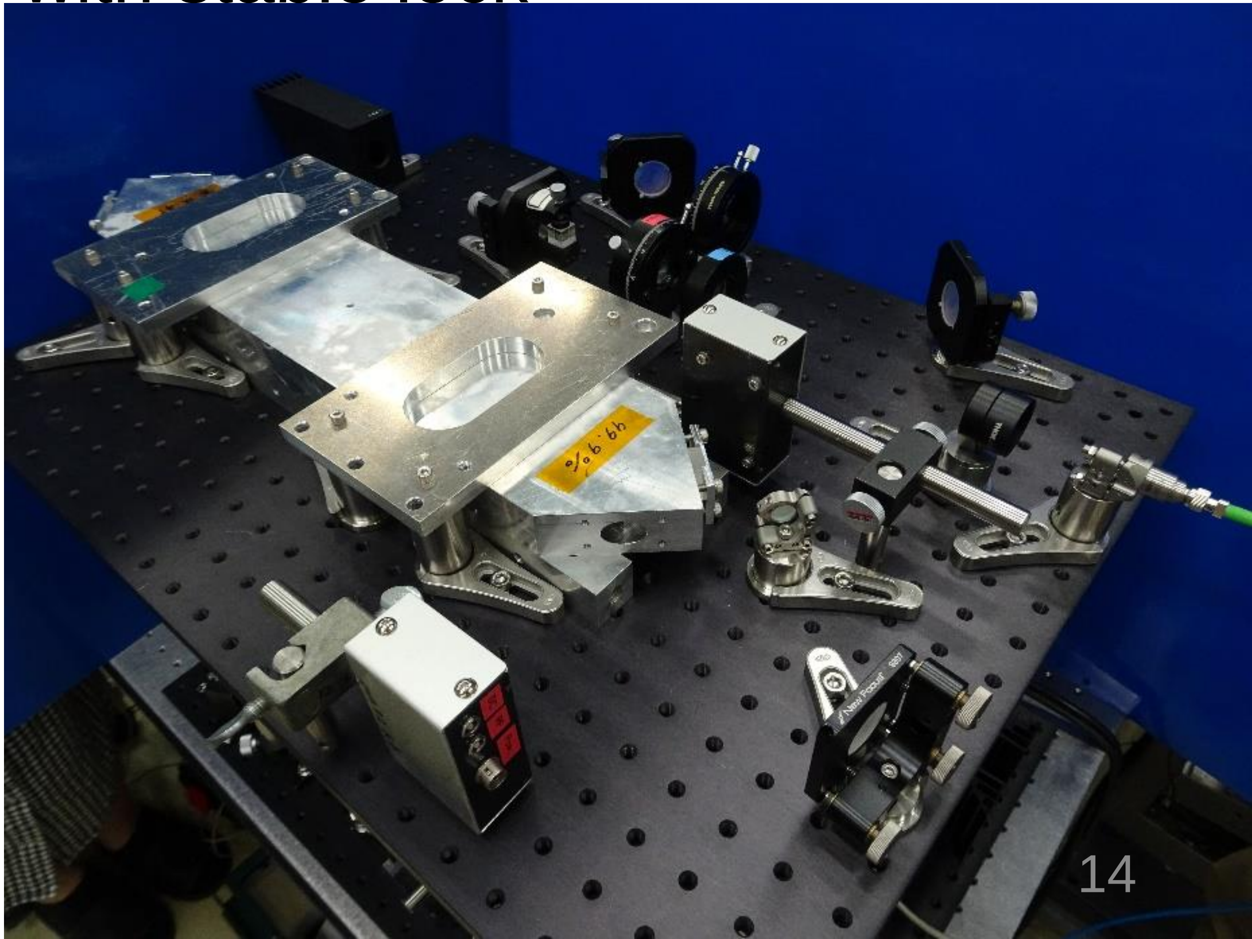
Schematic of DANCE Act 1



DANCE Act 1

- Completed the assembly of optics
- Finesse measured to be 515 +/- 6 (design: 3×10^3)
- Having trouble with stable lock
- Aiming for first run in 2019





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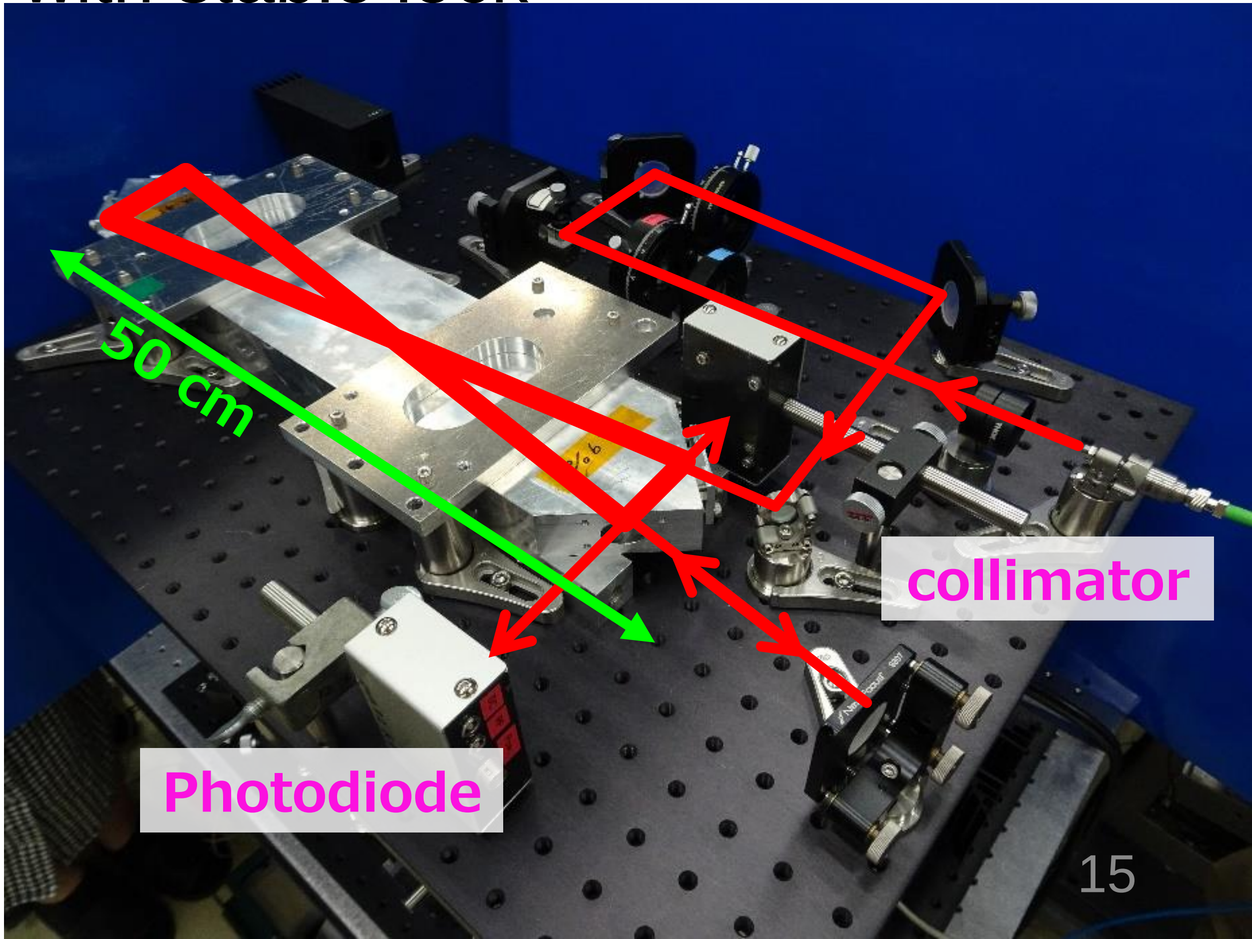
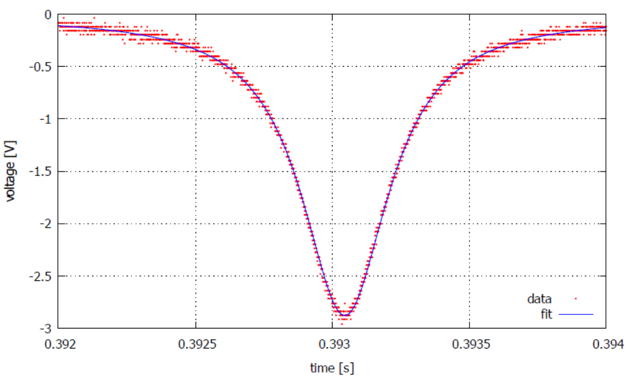


- Aiming for first run in 2019

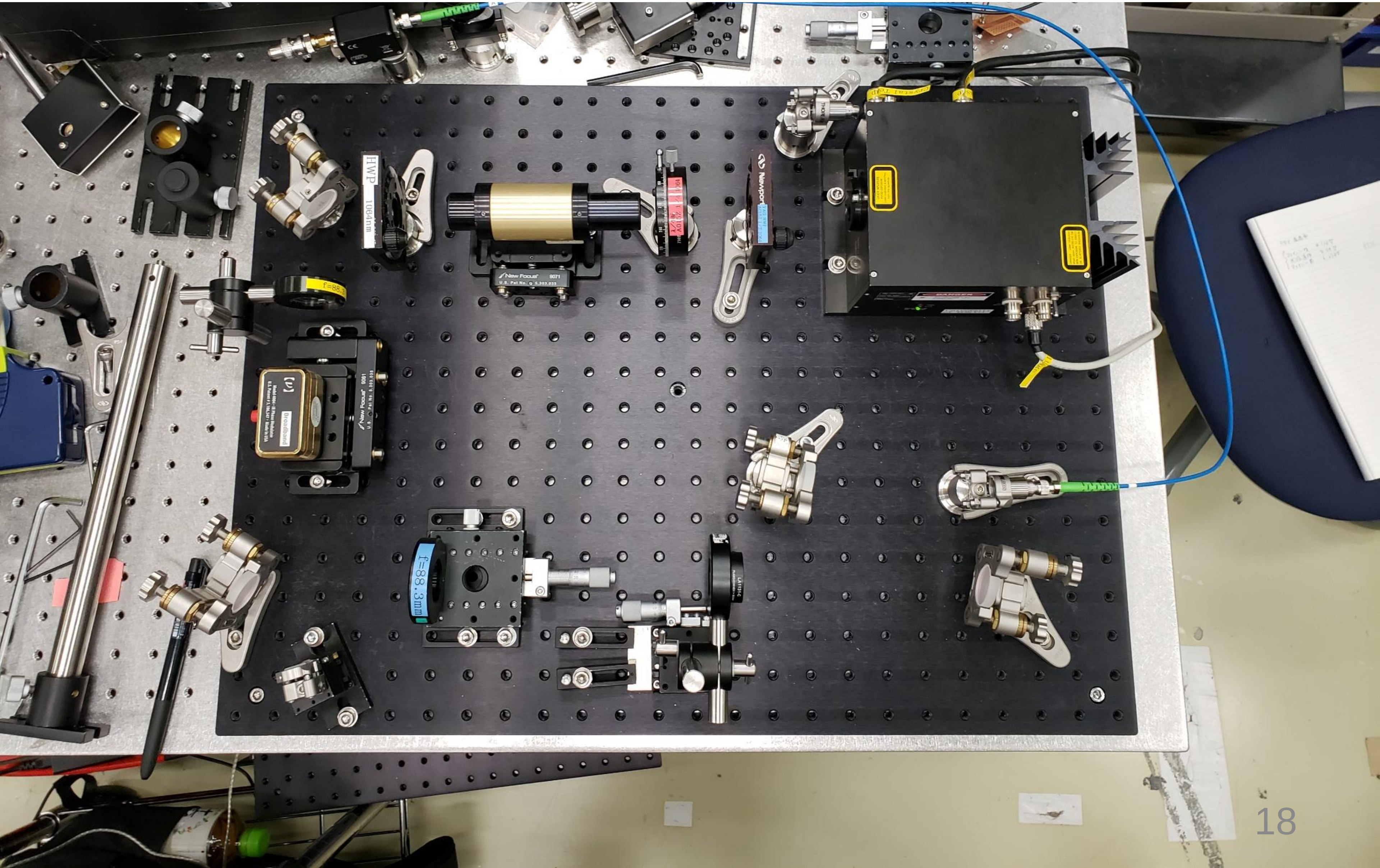


Summary

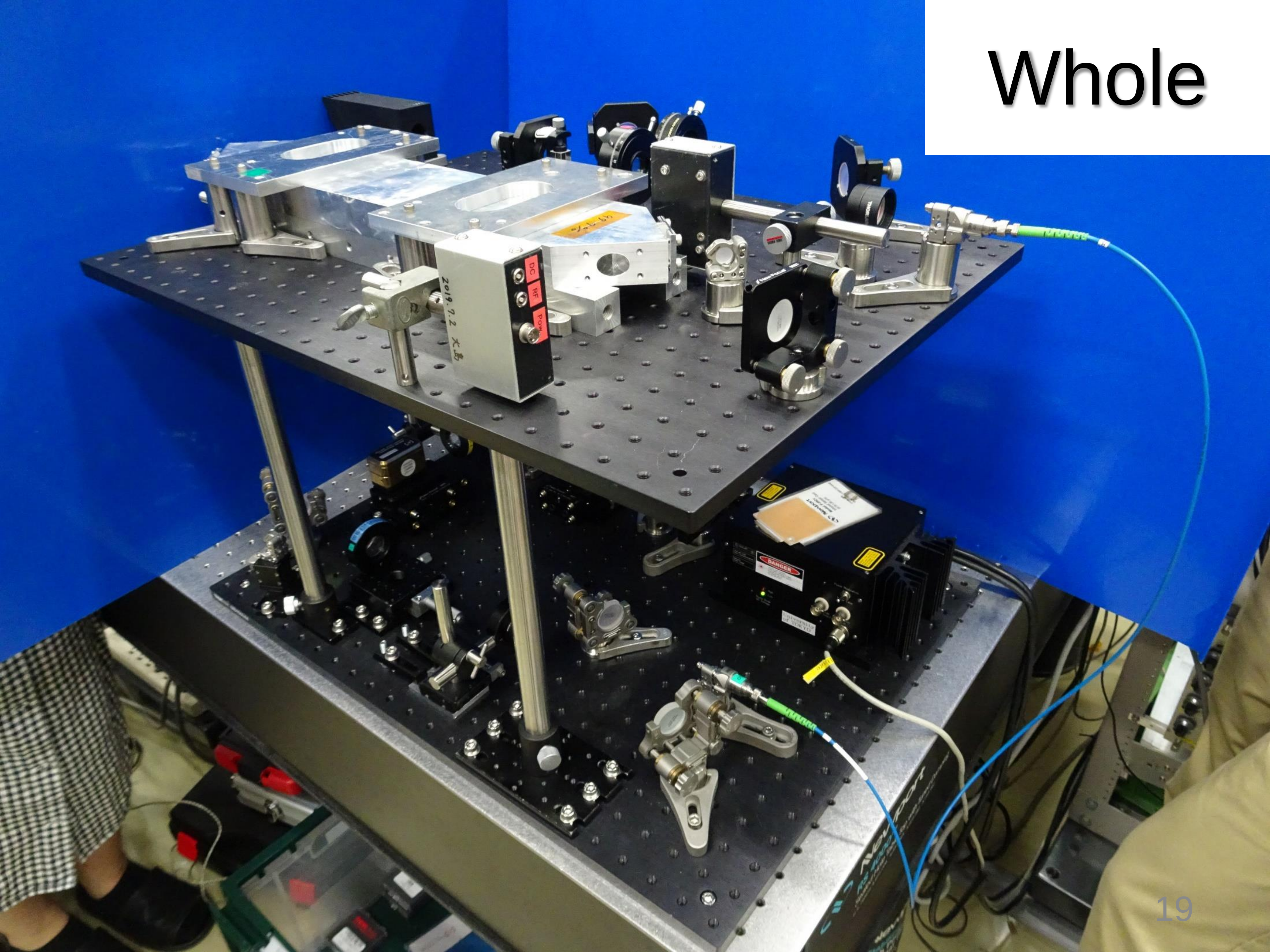
- Proposed a new method to search for axion dark matter using a ring cavity
  I. Obata, T. Fujita, YM, [PRL 121, 161301 (2018)]
- Measure phase velocity difference between two circular polarizations
  Bow-tie cavity and double-pass configuration
- Sensitivity to axion-photon coupling can be improved by several orders of magnitude for axion masses $m_a \lesssim 10^{-10}\,\mathrm{eV}$
- Prototype experiment DANCE Act 1 is on-going
  First run in 2019

Supplemental Slides

Input Optics

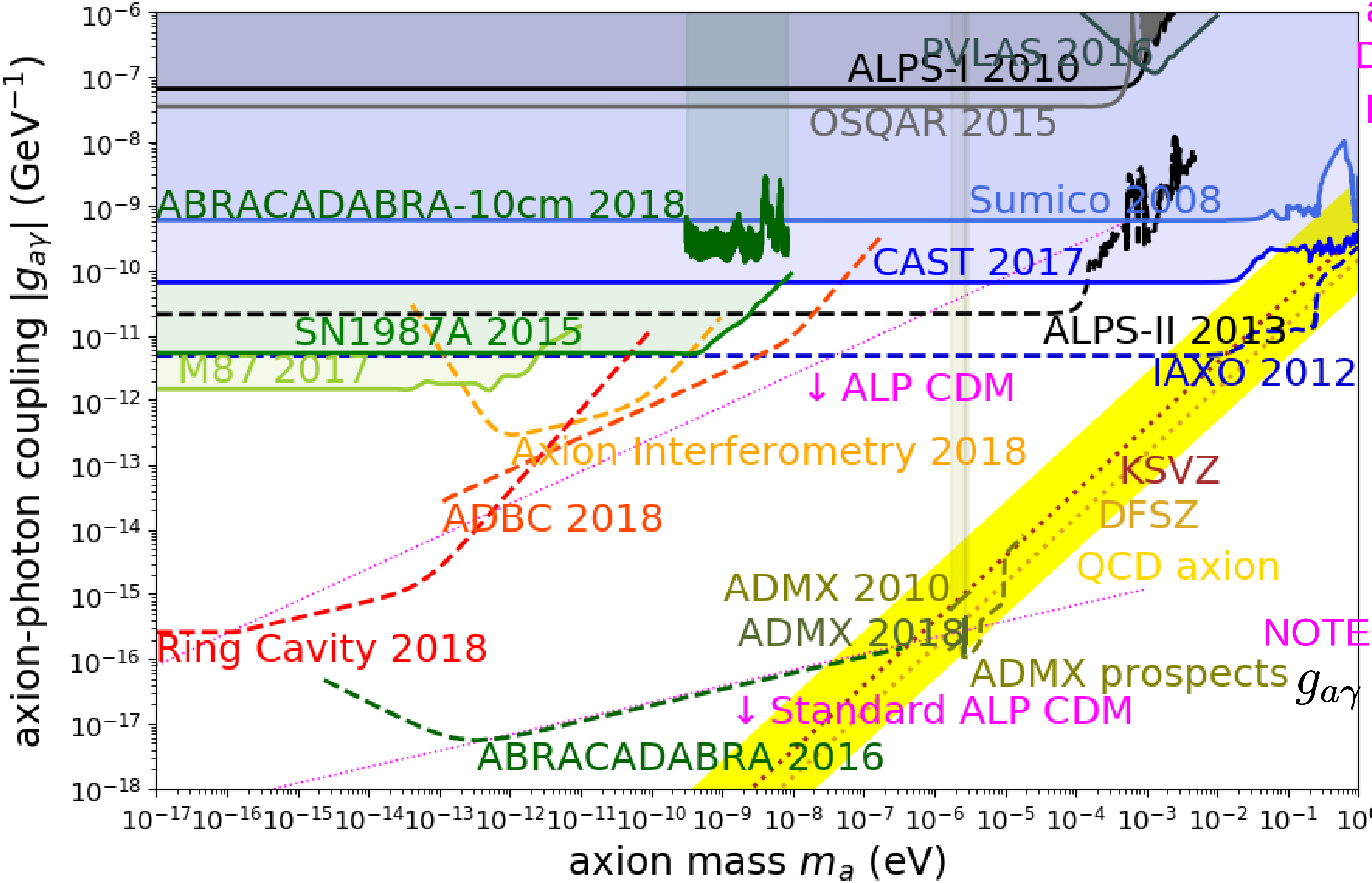


Whole



Bounds on Axion-Photon Coupling

- Extracted some interesting experiments



Solid: achieved
Dashed: proposals

NOTE that $g_{a\gamma} \propto 1/f_a$

Interferometric Searches

- Light speed difference between two circular polarizations

$$c_\pm = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

Can be derived from Maxwell-Axion equations

- If local ALP density = local DM density, $\varrho_a = \frac{m_a^2 a_0^2}{2} = \varrho$

$$\delta c \equiv |c_+ - c_-|$$
$$\simeq 3 \times 10^{-24} \left(\frac{g_{a\gamma}}{10^{-12}\,\mathrm{GeV}} \right) \sin(m_a t + \delta_\tau)$$

local DM density ($0.3\ \mathrm{GeV/cm^3}$)

phase which changes with time scale

- Can be measured with laser interferometers and cavities
- Can be measured without magnets!

$$\tau = \frac{\lambda}{v} = \frac{2\pi}{m_a v^2}$$

de Broglie wavelength

axion velocity (assume dark matter velocity 10^{-3})

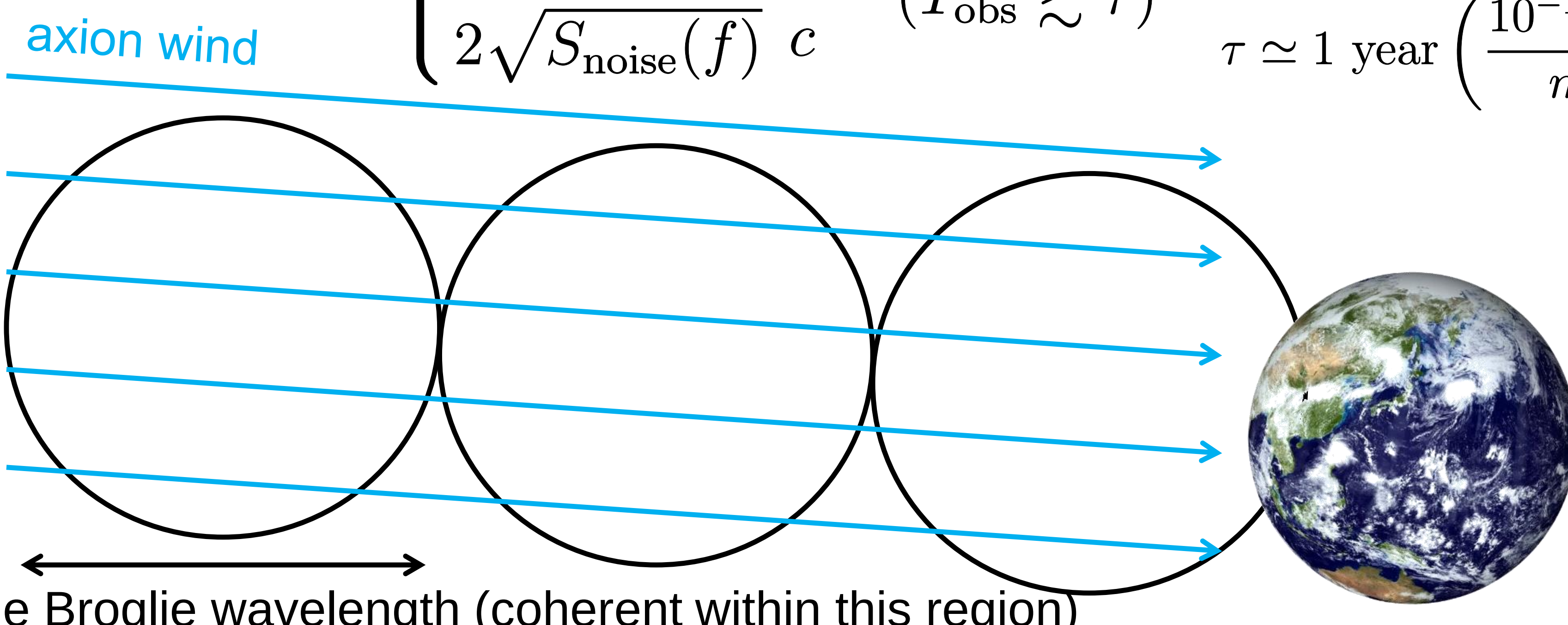
- Also assumes ALP = dark matter

Coherent Time Scale

- SNR grows with $\sqrt{T_{obs}}$ if integration time is shorter than coherent time scale
- SNR grows with $(T_{obs})^{1/4}$ if integration time is longer

$$\mathrm{SNR} = \begin{cases} \dfrac{\sqrt{T_{\mathrm{obs}}}}{2\sqrt{S_{\mathrm{noise}}(f)}} \dfrac{\delta c}{c} & (T_{\mathrm{obs}} \lesssim \tau) \\ \dfrac{(T_{\mathrm{obs}}\tau)^{1/4}}{2\sqrt{S_{\mathrm{noise}}(f)}} \dfrac{\delta c}{c} & (T_{\mathrm{obs}} \gtrsim \tau) \end{cases}$$

$$\tau \simeq 1 \text{ year} \left(\frac{10^{-16} \text{ eV}}{m_a} \right)$$



DeRocco + Hook (2018)

PRD **98**, 035021 (2018)

- Linear cavity with quarter wave plates inside
  mirror reflection flips left-handed to right-handed
- 40 m, finesse 10^6, intra cavity power 1 MW, 30 days integration

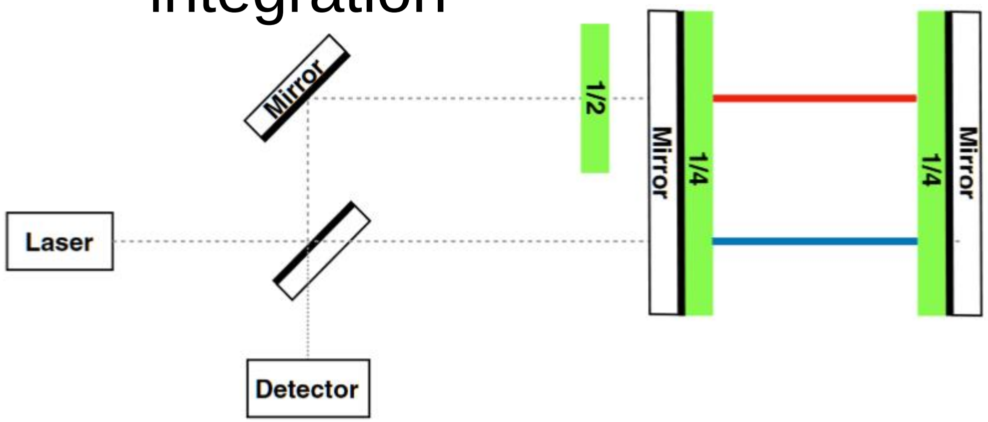


FIG. 3. A diagram of our proposed axion interferometer where the same mirrors are used to form both cavities. The dotted line is linearly polarized light, the red line is ↺ polarized light and the blue line is ↻ polarized light. Two quarter wave plates and a half wave plate are used to maintain the circular polarization of the light. This setup cancels the radiation pressure noise associated with the displacement of the mirror, leaving only noise due to radiation torque. Torque noise in this setup can be several orders of magnitude smaller than the radiation pressure noise experienced by the setup in Fig. 2.

radiation pressure torque noise at low freq.

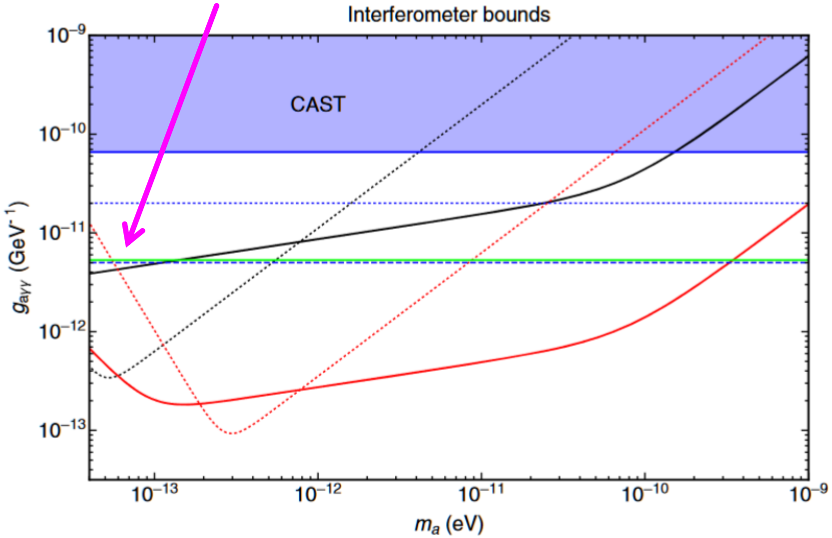
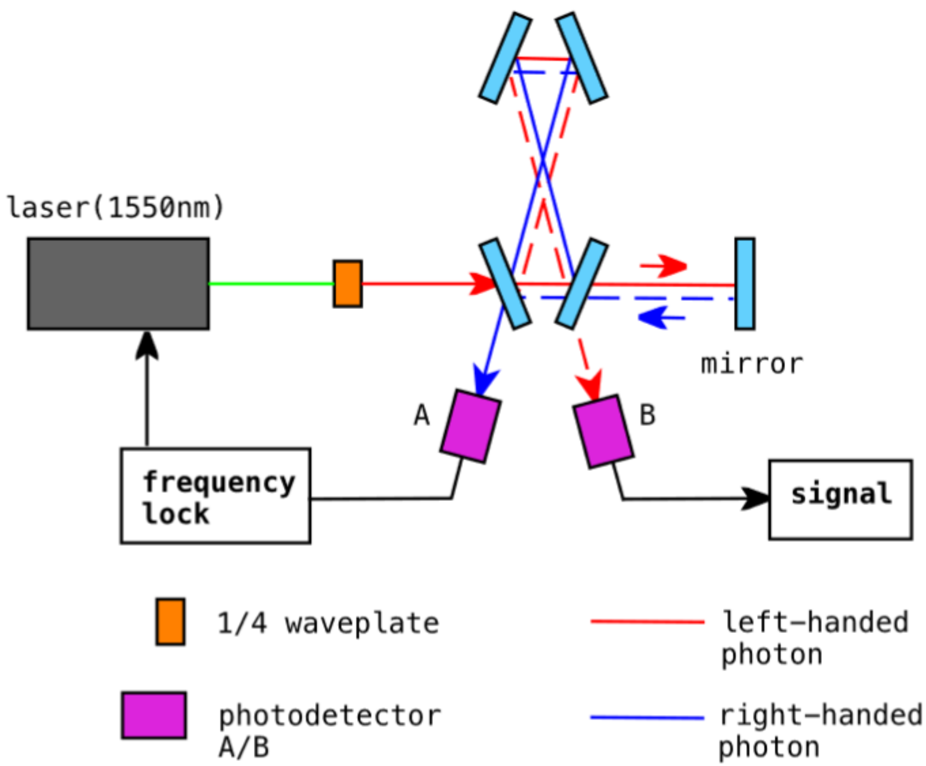


FIG. 5. Same as Fig. 4 but using the configuration shown in Fig. 3. Radiation pressure noise is cancelled leaving only radiation torque noise. We take the beams to be separated by 1 cm and the mirror to be circular and 10 cm in diameter.

Obata + Fujita + Michimura (2018)

[PRL **121**, 161301 (2018)](https://doi.org/10.1103/PhysRevLett.121.161301)

- DARC: Dark matter Axion search with a Ring Cavity (tentative)
- Bow-tie configuration to keep polarization modes
- Double-pass for common mode rejection



research highlights

OPTICAL METROLOGY

Axion sensor

Phys. Rev. Lett. **121**, 161301 (2018)

A current challenge in modern physics is to design experiments for ascertaining the existence of the axion — a proposed dark matter particle found in theories beyond the standard model of particle physics. Now, Ippei Obata and co-workers from the University of Tokyo and Kyoto University, Japan, have investigated the use of an optical ring cavity that makes it possible to search for a tiny difference in the phase velocity of left- and right-handed circularly polarized photons that, in principle, is induced by coupling of photons to axion dark matter. The team used a double-pass bowtie cavity to realize a null experiment with strong rejection from environmental disturbances. Analysis of their set-up suggests that the sensitivity level of the photon–axion coupling constant was estimated to be 3×10^{-16} GeV^{-1} for a low-mass range below 10^{-16} eV, which is beyond the current bound by several orders of magnitude. *NH*

https://doi.org/10.1038/s41566-018-0321-2

Nature Photonics **12**, 719 (2018)

Obata + Fujita + Michimura (2018)

- 10 m, finesse 10^6,
  100 W input,
  1 year integration
  - this means 30 MW intra cavity power

- Note that mirror complex reflectivity difference between p and s polarizations from nonzero incident angle was not considered (incident angle tuning necessary)

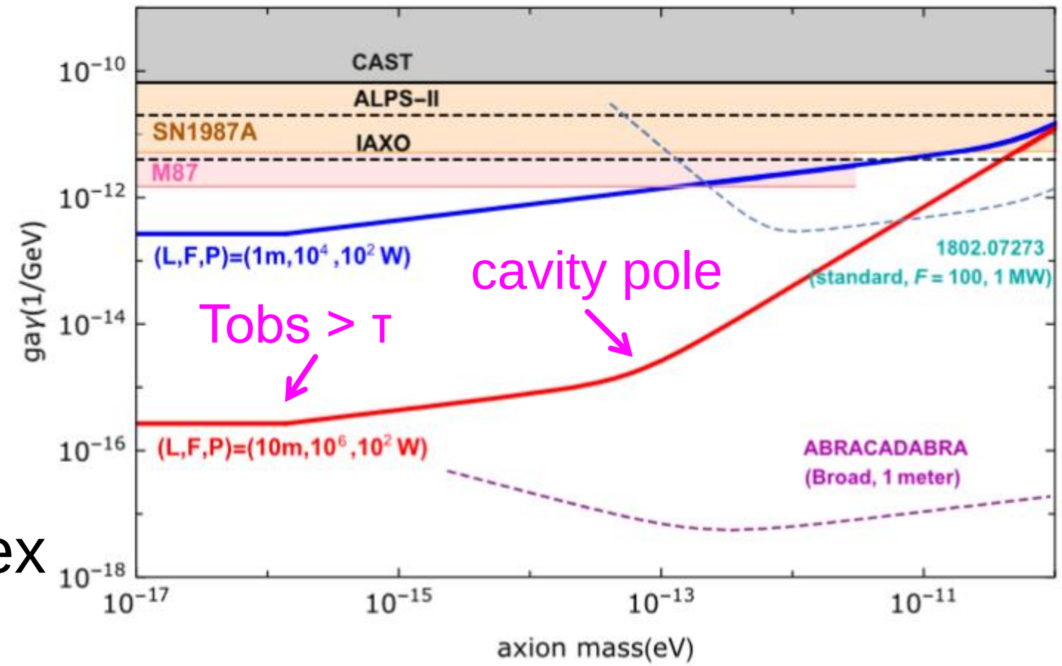
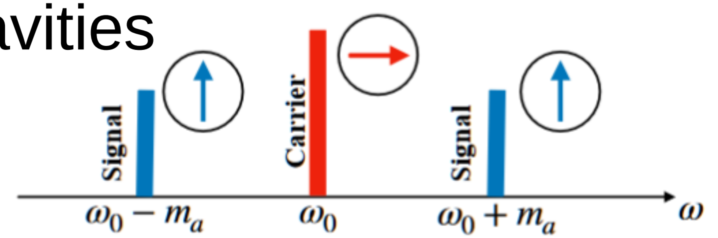


FIG. 2. The sensitivity curves for the axion-photon coupling constant $g_{a\gamma}$ with respect to the axion mass m. The solid blue (red) line shows the sensitivity of our experiment $(L, F, P) = (1(10)\ \mathrm{m}, 10^4(10^6), 10^2(10^2)\ \mathrm{W})$. The gray band represents the current limit from CAST [5]. The dashed black lines are the prospected limits of IAXO [6] and ALPS-II [7] missions. The dashed turquoise blue and purple lines show the proposed reaches of axion optical interferometer suggested in [10] and ABRA-CADABRA magnetometer [12]. The orange and pink bands denote the astrophysical constraints from the cosmic ray observations of SN1987A [15] and radio galaxy M87 [17].

ADBC by MIT Group (2018)

[PRD 100, 023548 (2019)]

- Axion Detection with Birefringent Cavities
- Use linear polarization and detect sidebands of other polarization
- Tune incident angle for resonant detection at high freqs.
- 40 m, finesse 2e5 for → (3e3 for ↑), intra cavity power 1 MW, 30 days integration in total



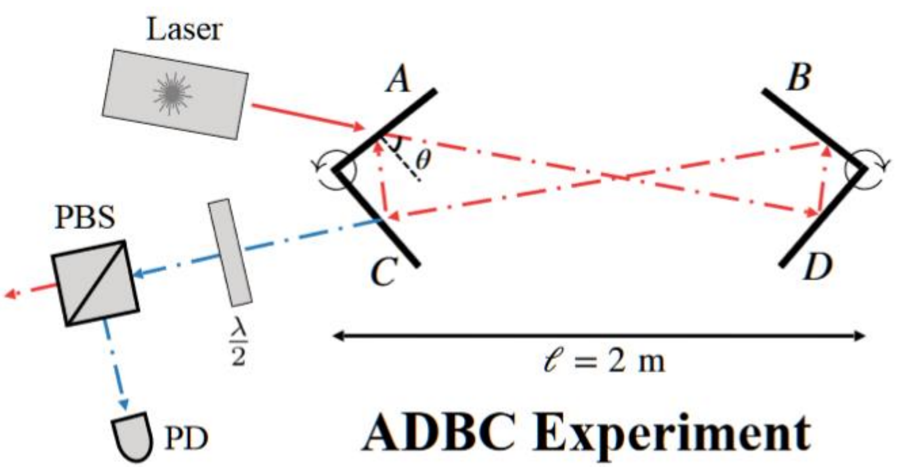
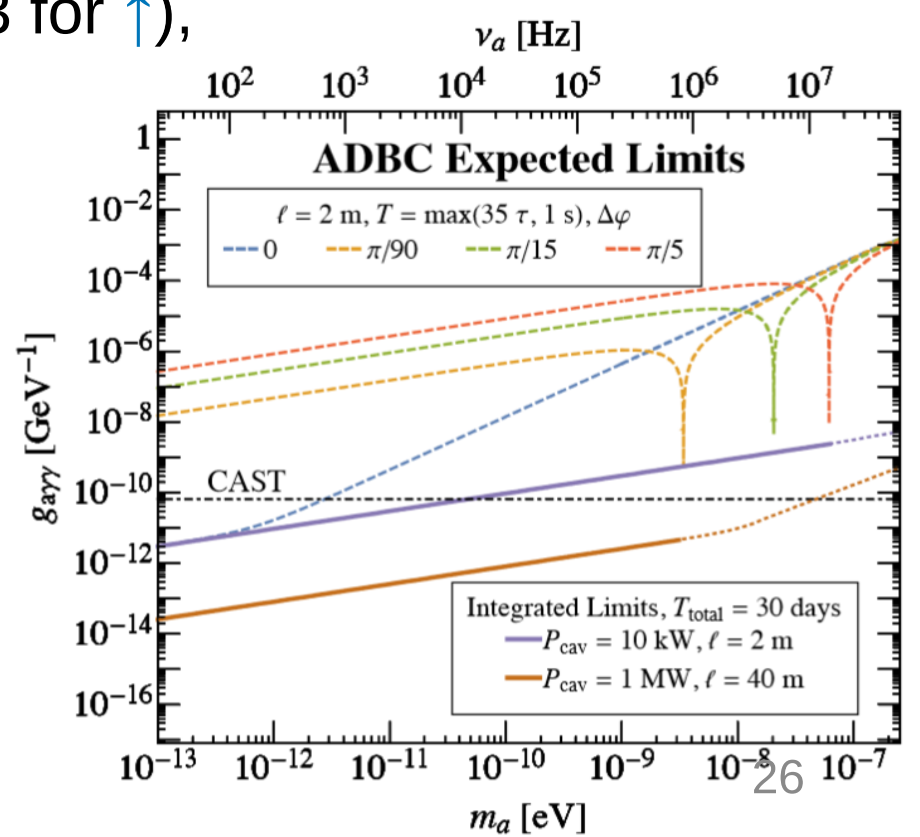


FIG. 2: Schematic of the ADBC experiment. The red optical



Sensitivity Design

- Brute force necessary, you cannot win for free

  NOTE that $\delta c \propto \lambda_{laser}$ and shot noise $\propto\sqrt{\lambda_{laser}}$