Latest results on Dark matter Axion search with riNg Cavity Experiment (DANCE)

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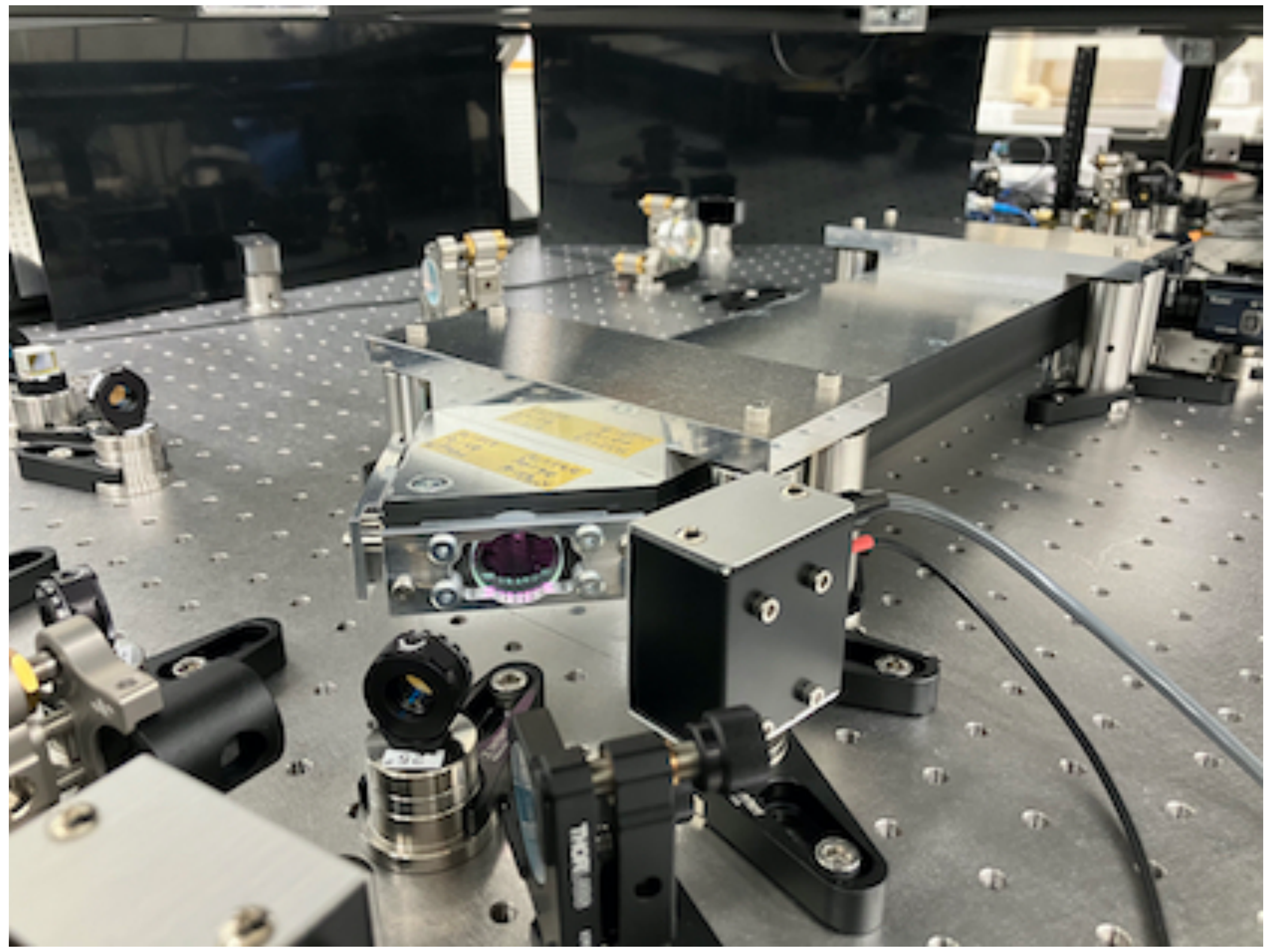
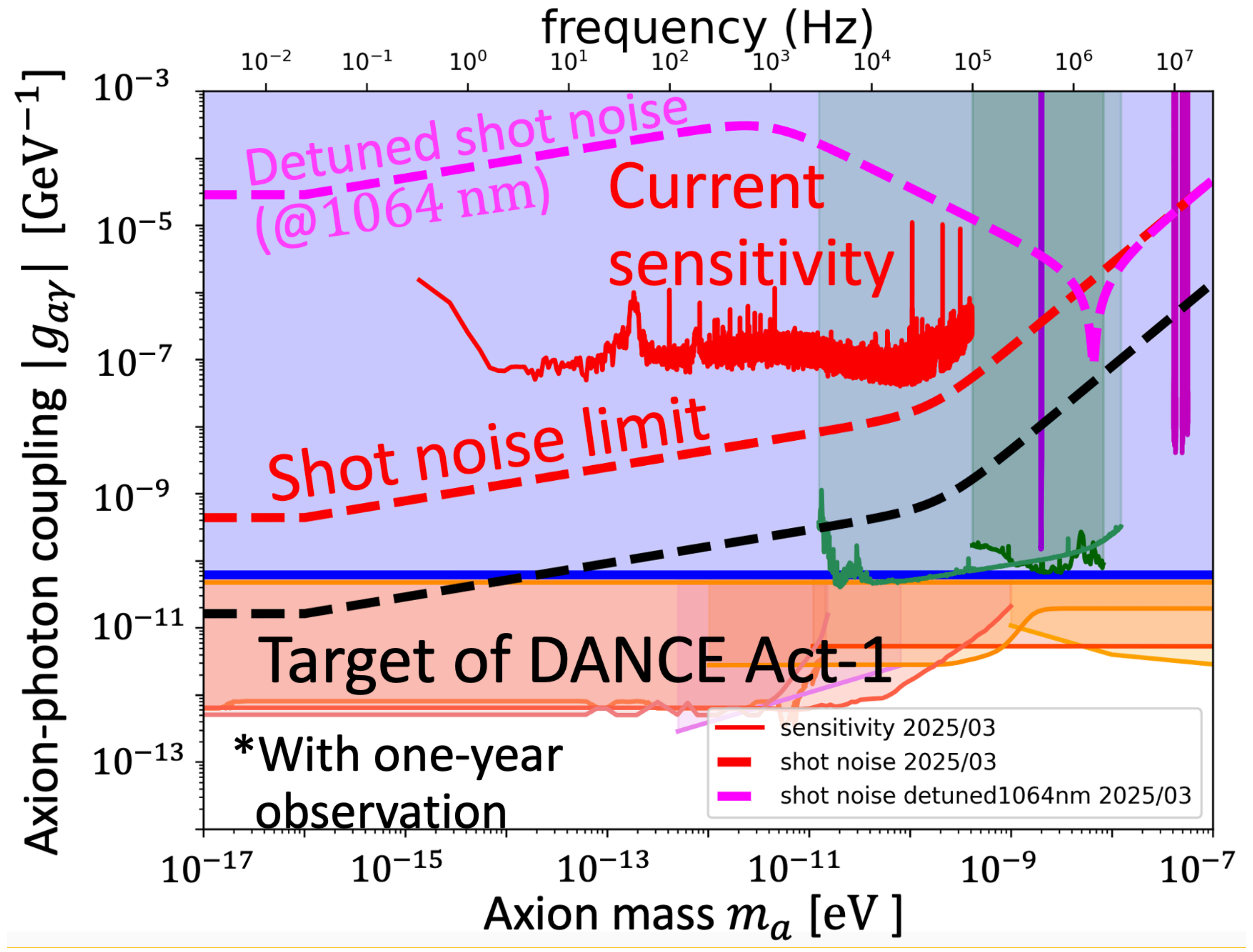
Abstract

DANCE: Dark matter Axion search with riNg Cavity Experiment

- Search for axion-like particles dark matter with an optical cavity
- Prototype experiment: DANCE Act-1 is in progress
  - Non-simultaneous resonance degrades the sensitivity
  - Currently operating for simultaneous resonance to improve the sensitivity

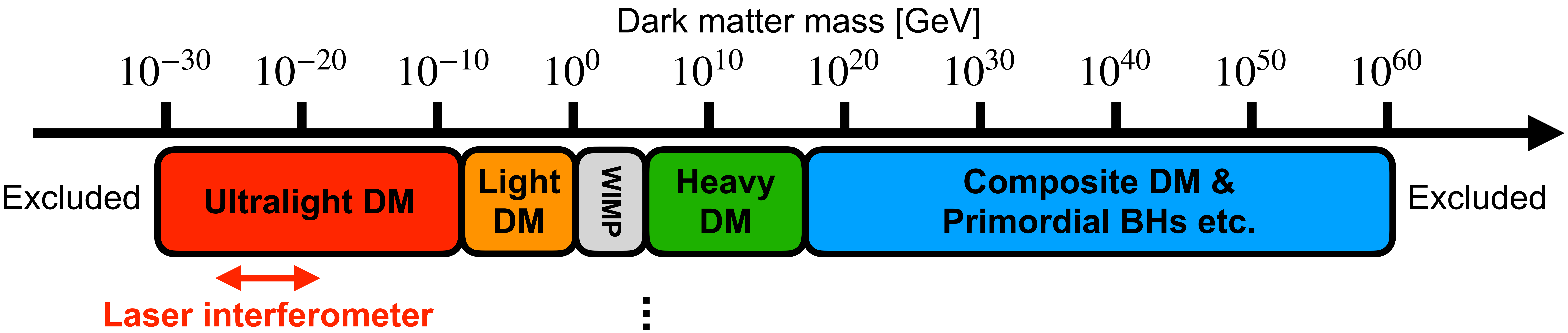


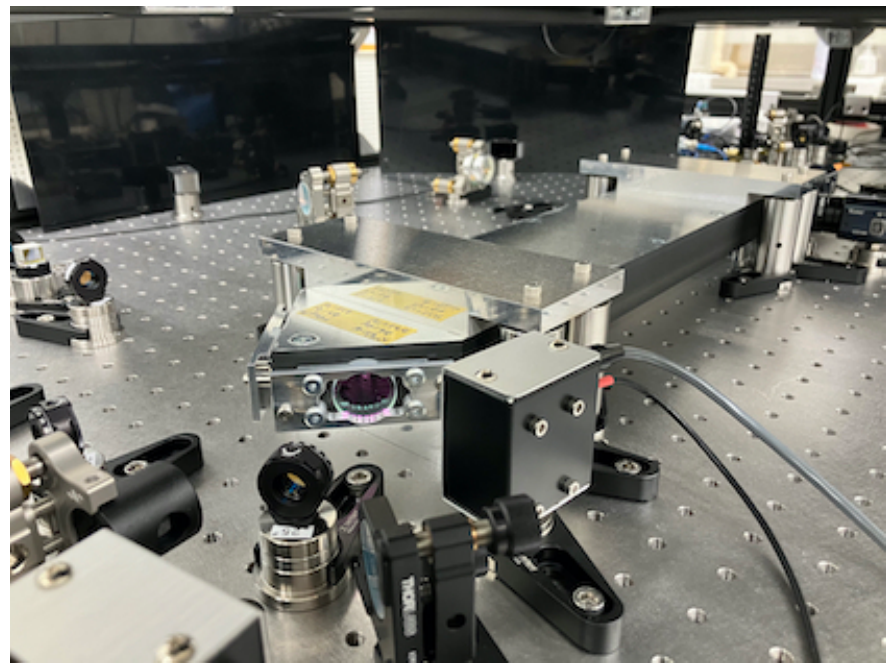
DANCE



Dark matter

- Account for about 80% of all the matter in the universe
- Extensive research is being conducted
- One of the leading candidates of dark matter: Axion

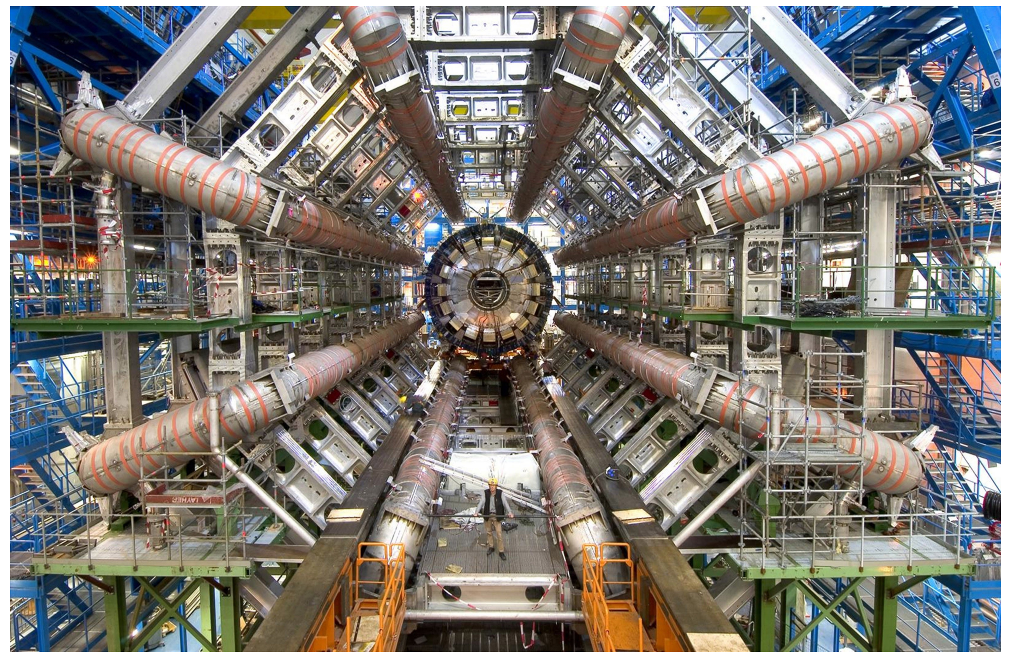




DANCE

KAGRA

XENON



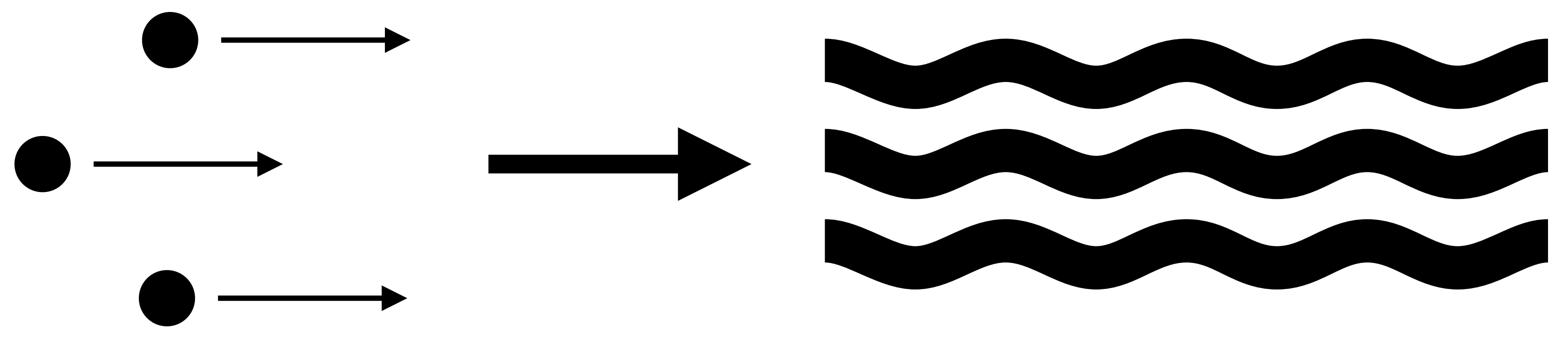
LHC

Subaru telescope

Axion and Axion-Like-Particles (ALPs)

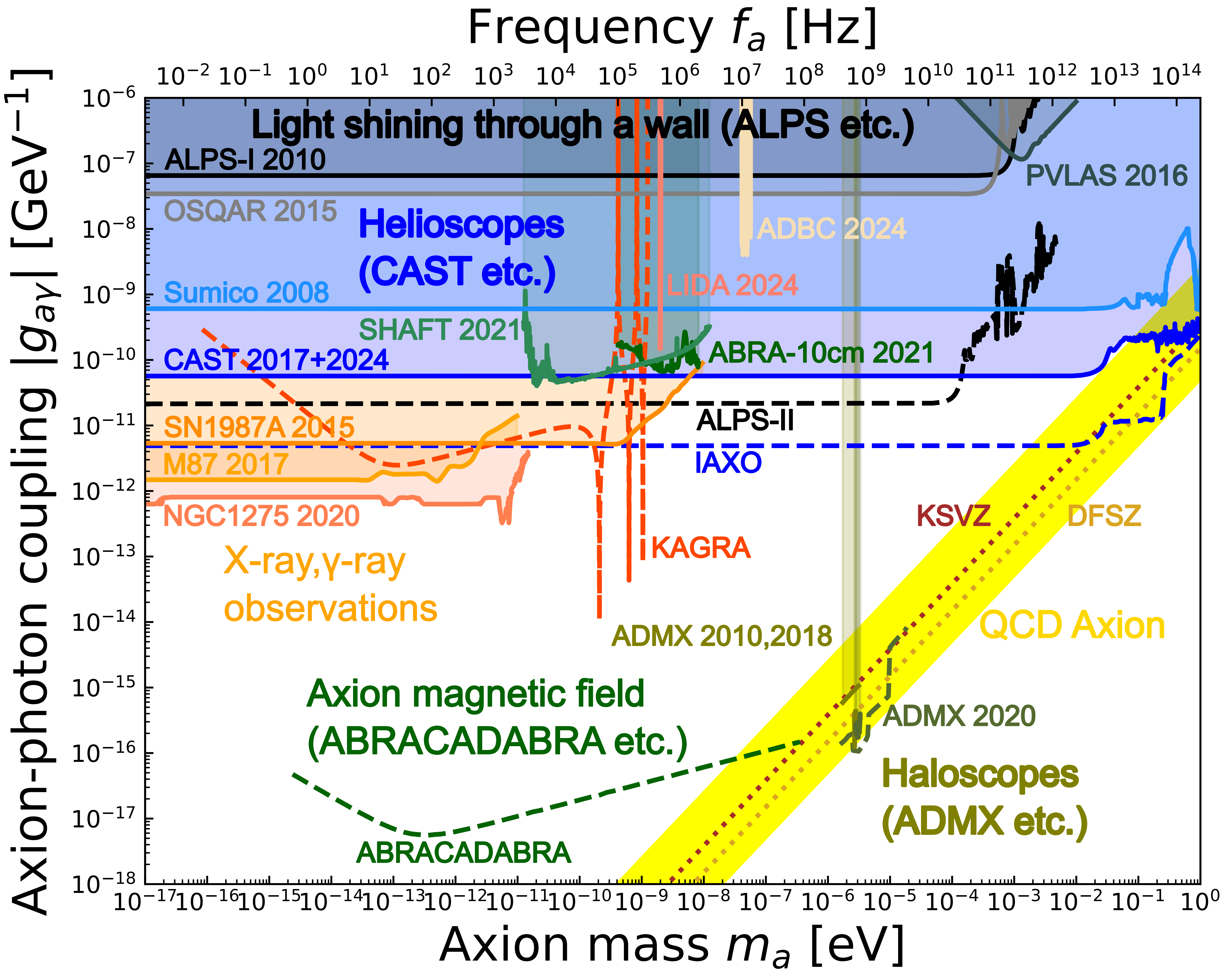
- Axion is suggested to solve strong CP problem on Quantum Chromo Dynamics (QCD)
- Various Axion-Like-Particles (ALPs) is predicted
- Axion weakly interacts with photon, electron, proton, neutron
- Very light particles → Behave like waves

$$f_a = 242 \text{ Hz} \left(\frac{m_a}{10^{-12} \text{ eV}} \right)$$



- Many experiments have utilized the axion-photon conversion under magnetic field (Primakoff effect). However, axion has not been observed yet.

Previous searches



Relation between axion mass and frequency

$$f_a = \frac{m_a}{2\pi\hbar}\ \mathrm{Hz}$$

- Solid line is upper limit
- Dotted line is target sensitivity
- White region is unexplored

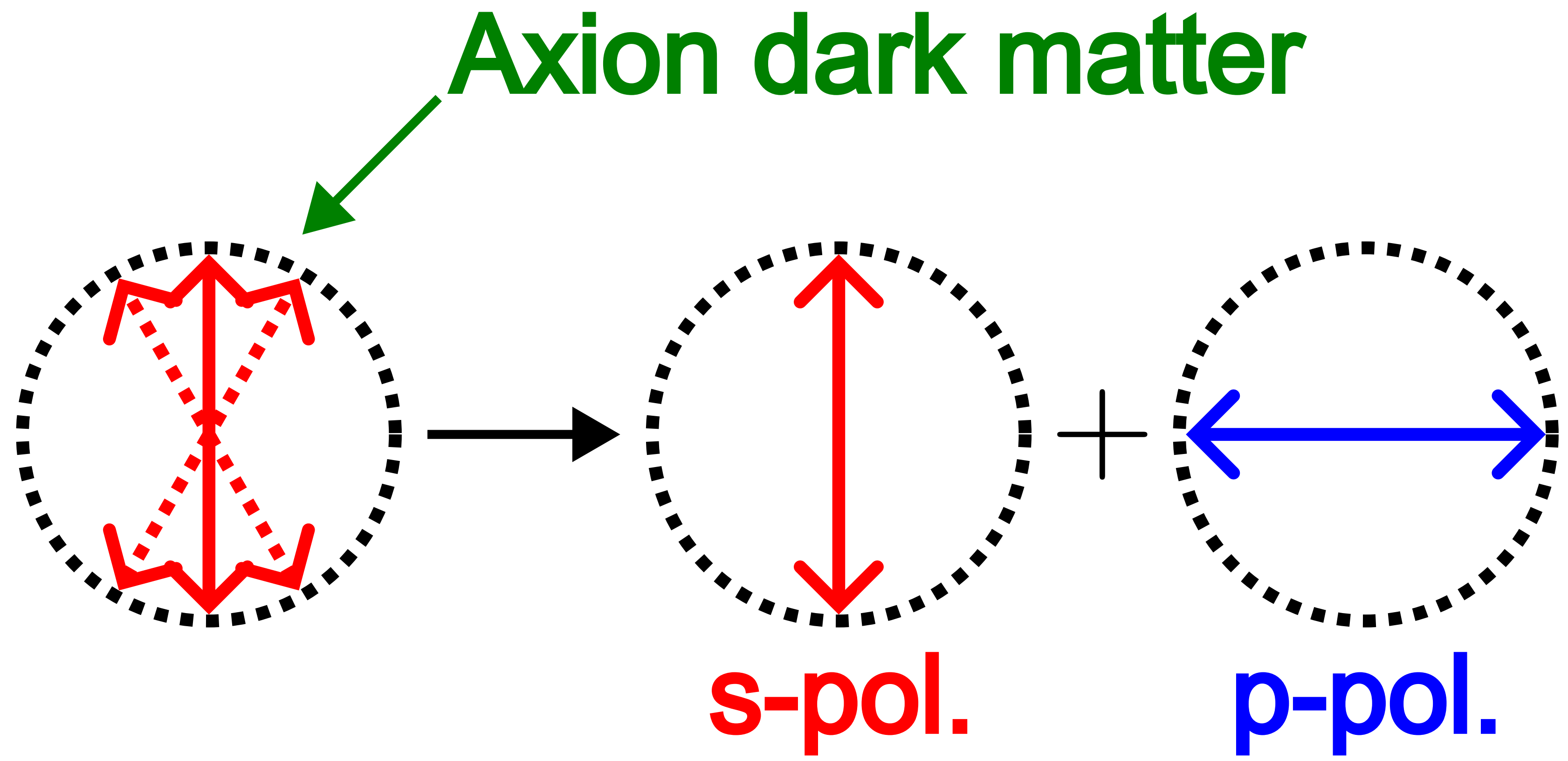
Axion-photon interaction

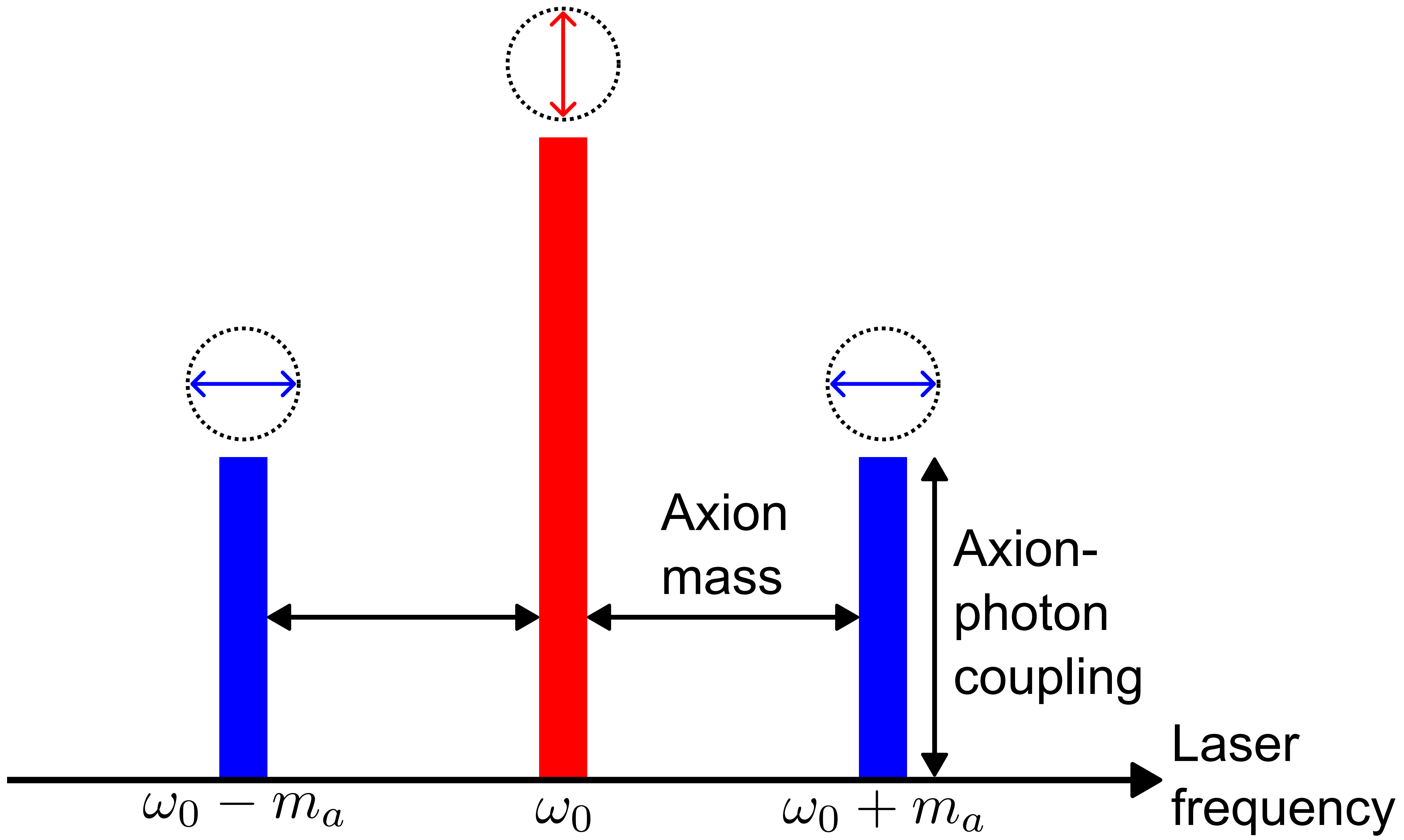
Axion-photon interaction induces phase velocity difference between left- and right-handed circularly polarized light

$$c_{\mathrm{L/R}}(t) = 1 \pm \frac{g_{a\gamma} a_0 m_a}{2k} \sin\left(m_a t + \delta_\tau(t)\right)$$

Phase velocity — **Axion-photon coupling** — **Axion field** — **Axion mass**

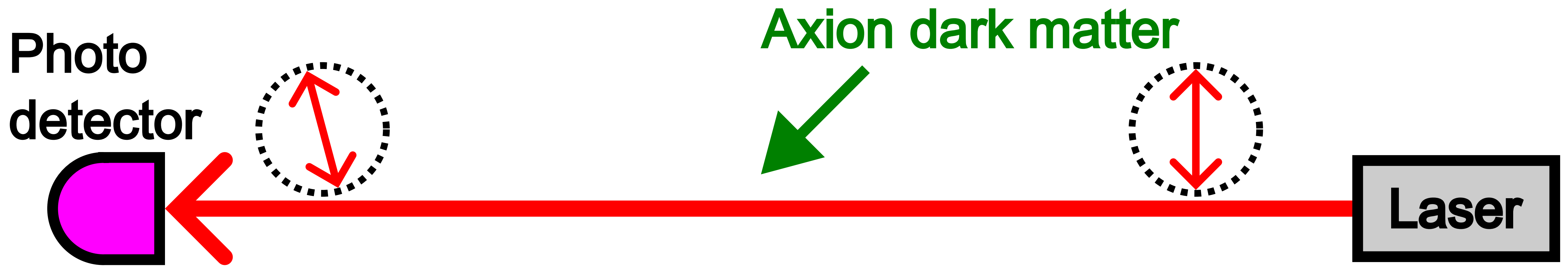
→ Rotation of linearly polarized light





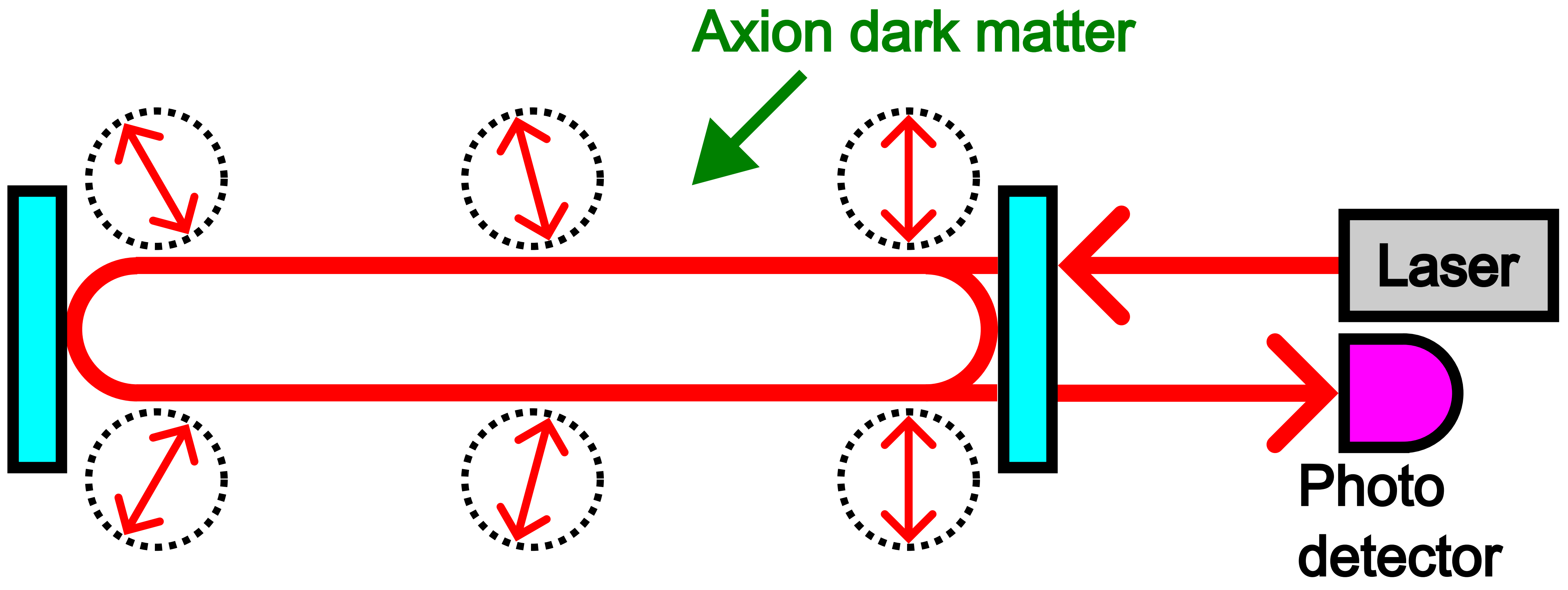
How to amplify the axion signal

Rotation of polarization is small for short optical path



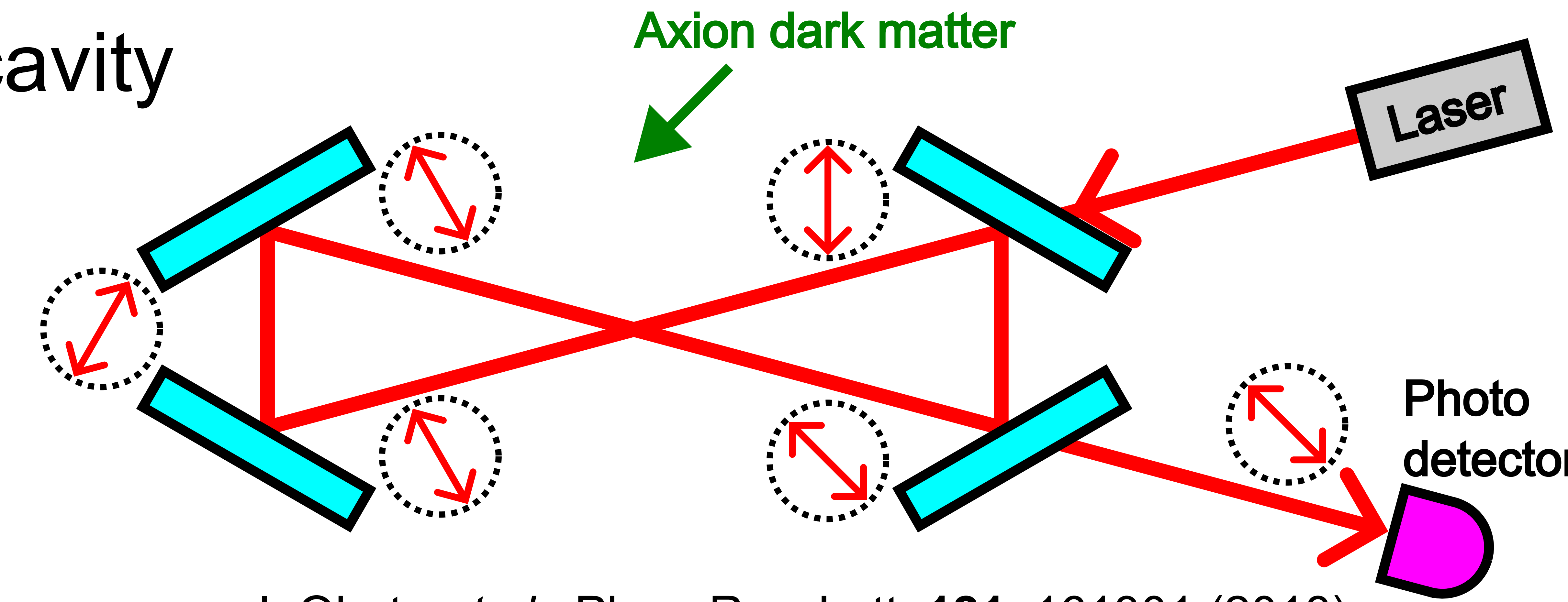
Extend optical path with a linear cavity

However, rotation of polarization can not be amplified because it is flipped by reflections



Extend optical path with a bow-tie ring cavity

Rotation of polarization can be amplified because the flip is canceled upon reflections on both two mirrors

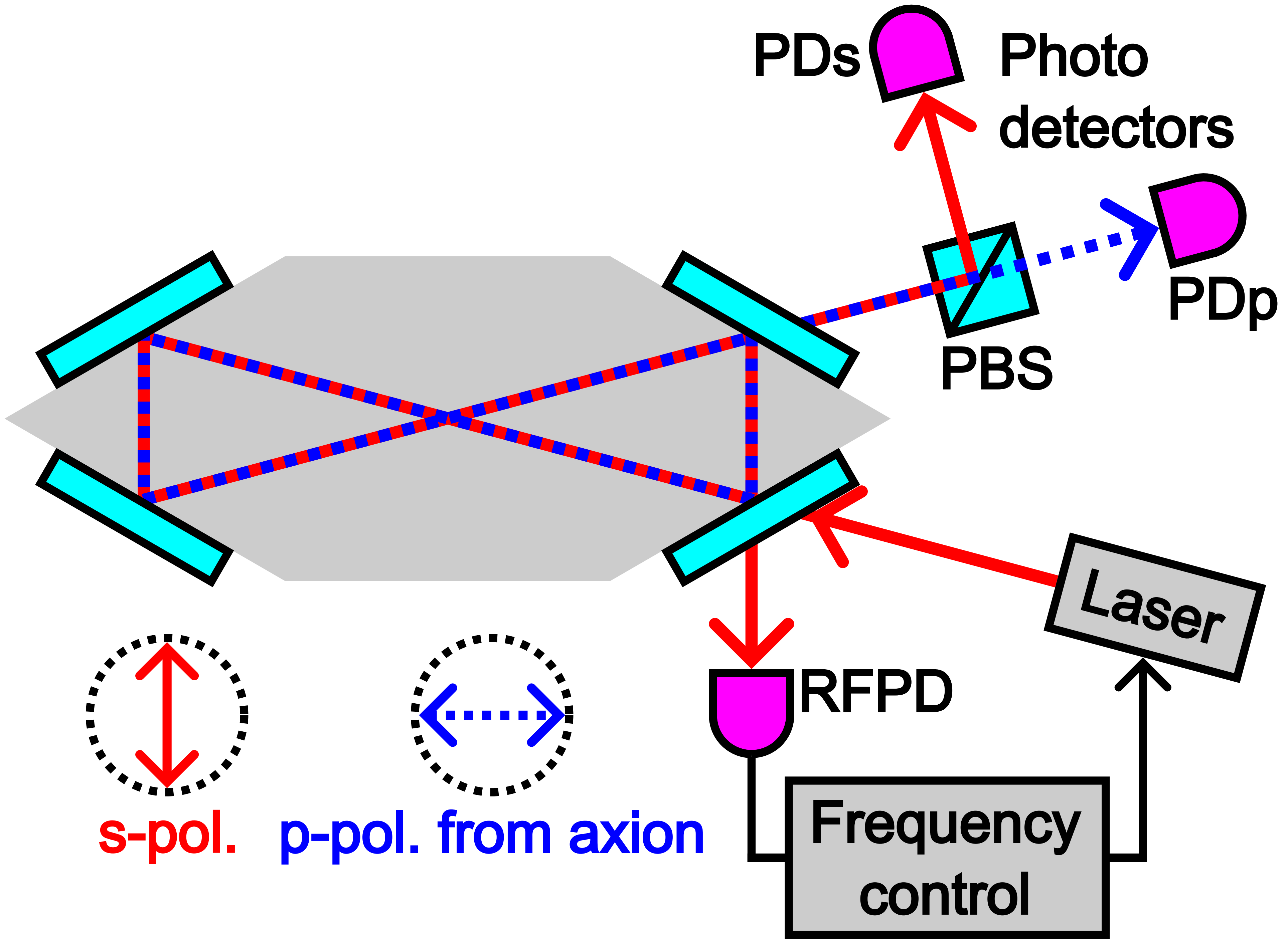


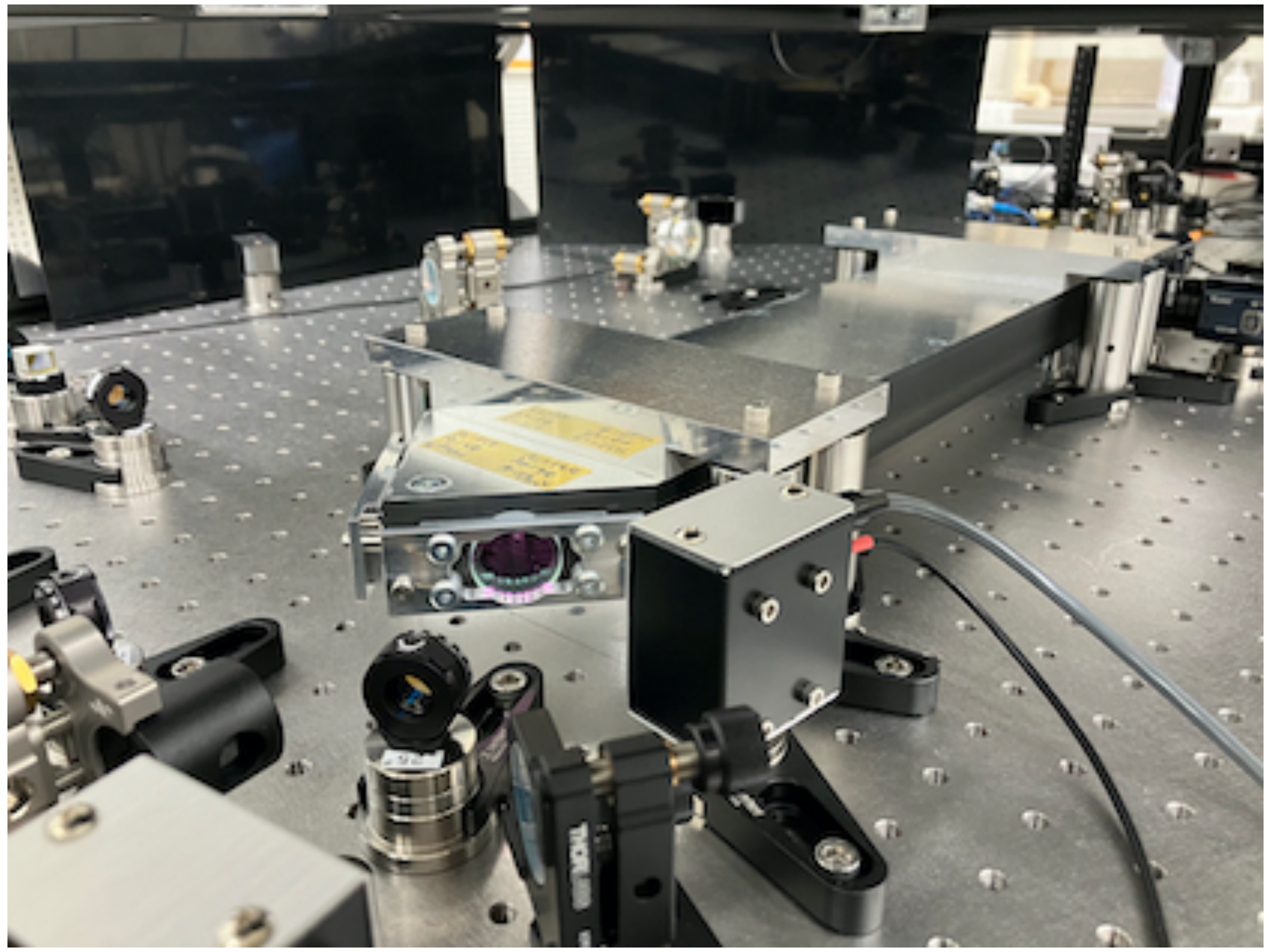
I. Obata *et al.*, Phys. Rev. Lett. **121**, 161301 (2018).

DANCE

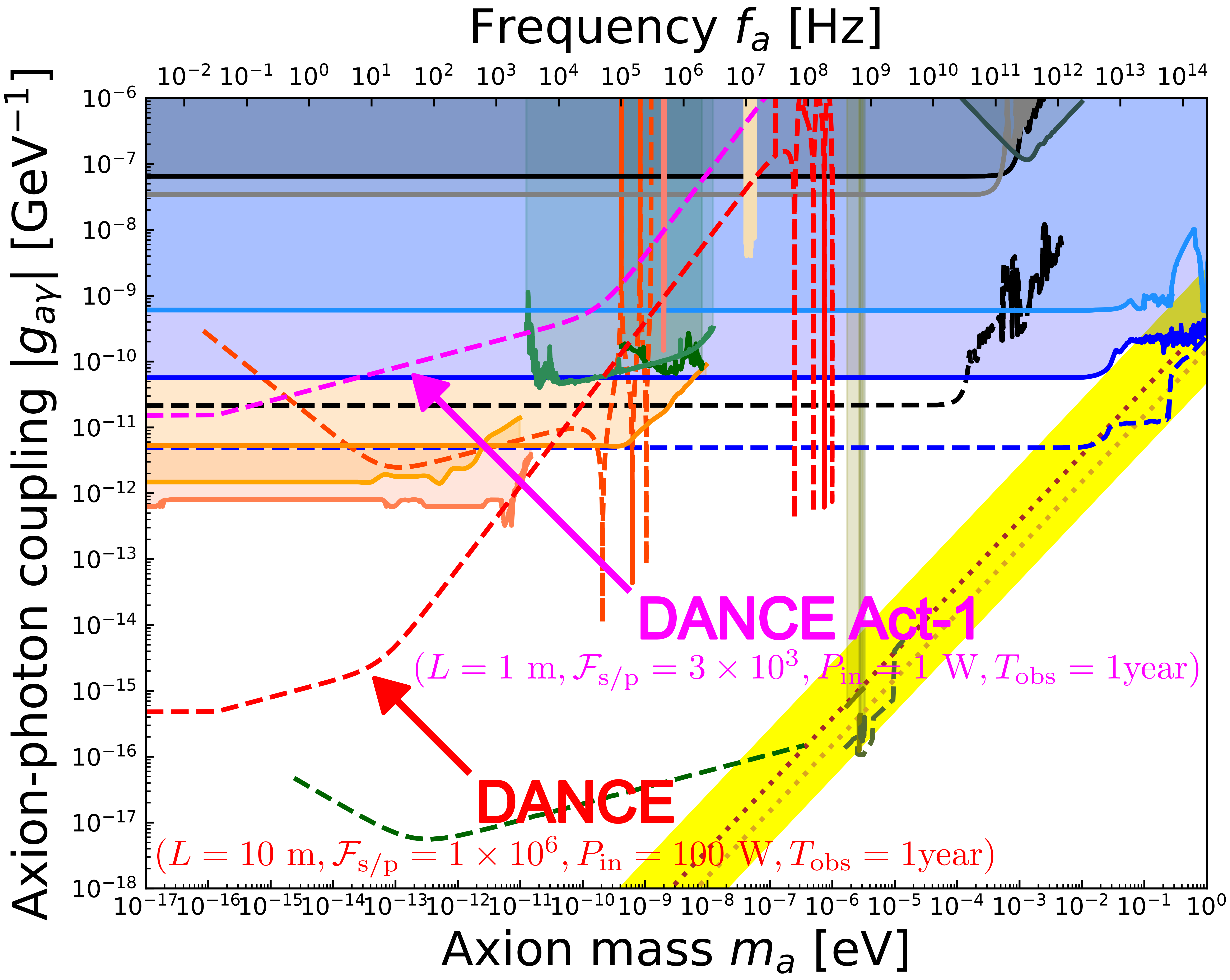
DANCE: Dark matter Axion search with riNg Cavity Experiment

- Amplify p-polarization (Axion signal) generated by the axion-photon coupling
- Prototype experiment: DANCE Act-1 is in progress





Target sensitivity of DANCE



- Shot noise limited
- Assume all dark matter is axion

L : Round-trip

$\mathcal{F}_{\mathrm{s/p}}$: Finesse (s/p-pol.)

P_{in} : Input power

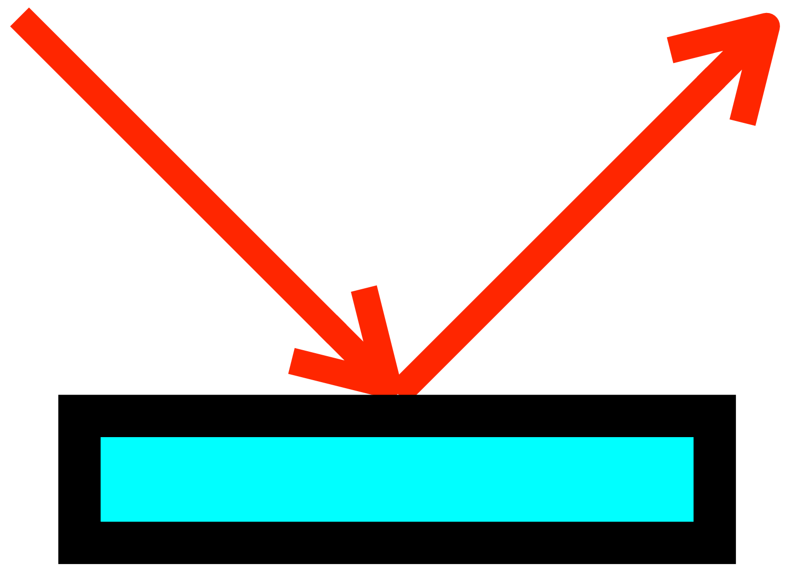
Conduct a sensitive axion search by improving parameters

Simultaneous resonance

Oblique incidence → Resonant frequency difference → Degrades the sensitivity

Reflection phase difference
between s- and p-pol.

$$\Delta\phi = \phi_{\rm s} - \phi_{\rm p} \neq 0 \ \mathrm{deg}$$



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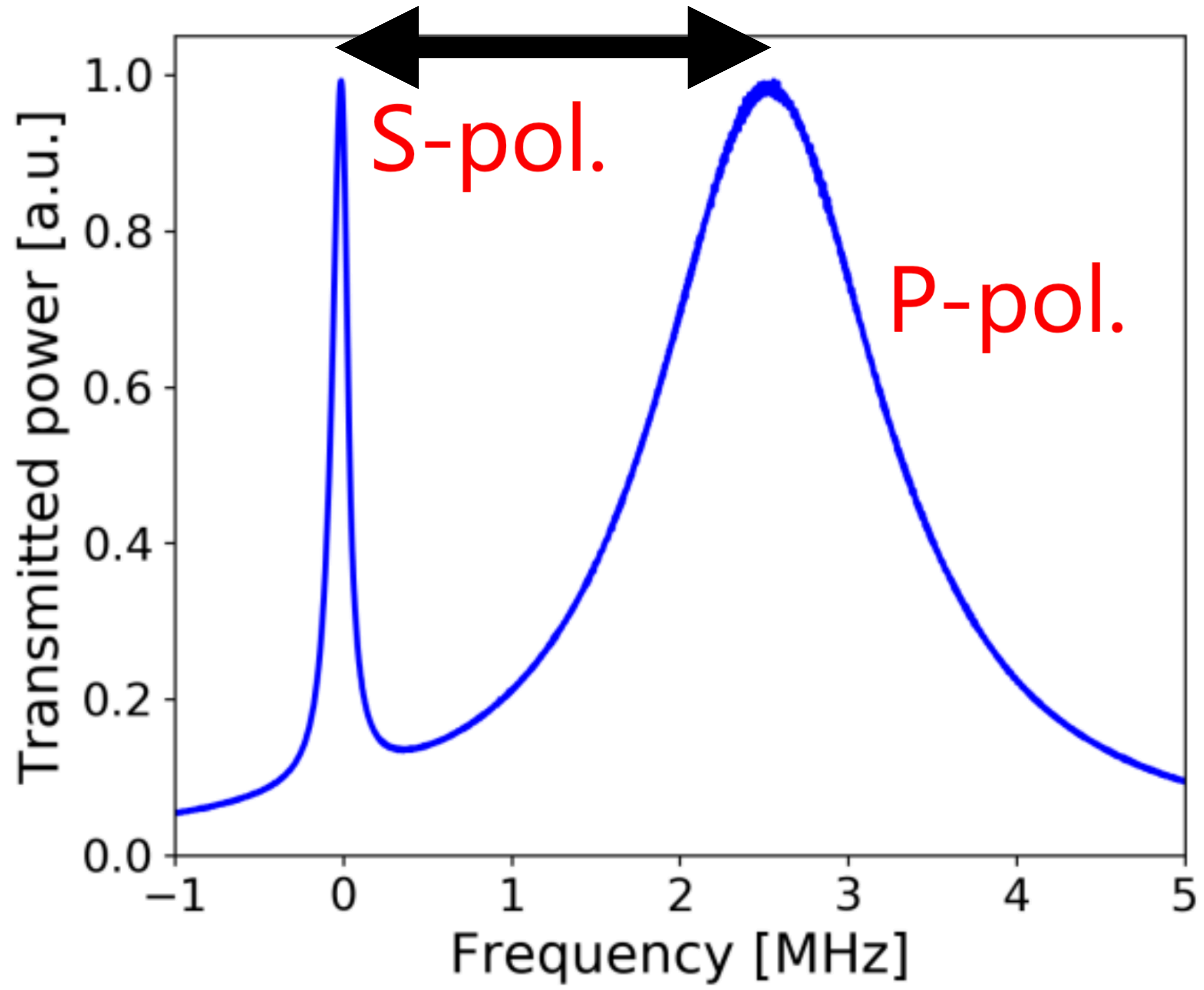

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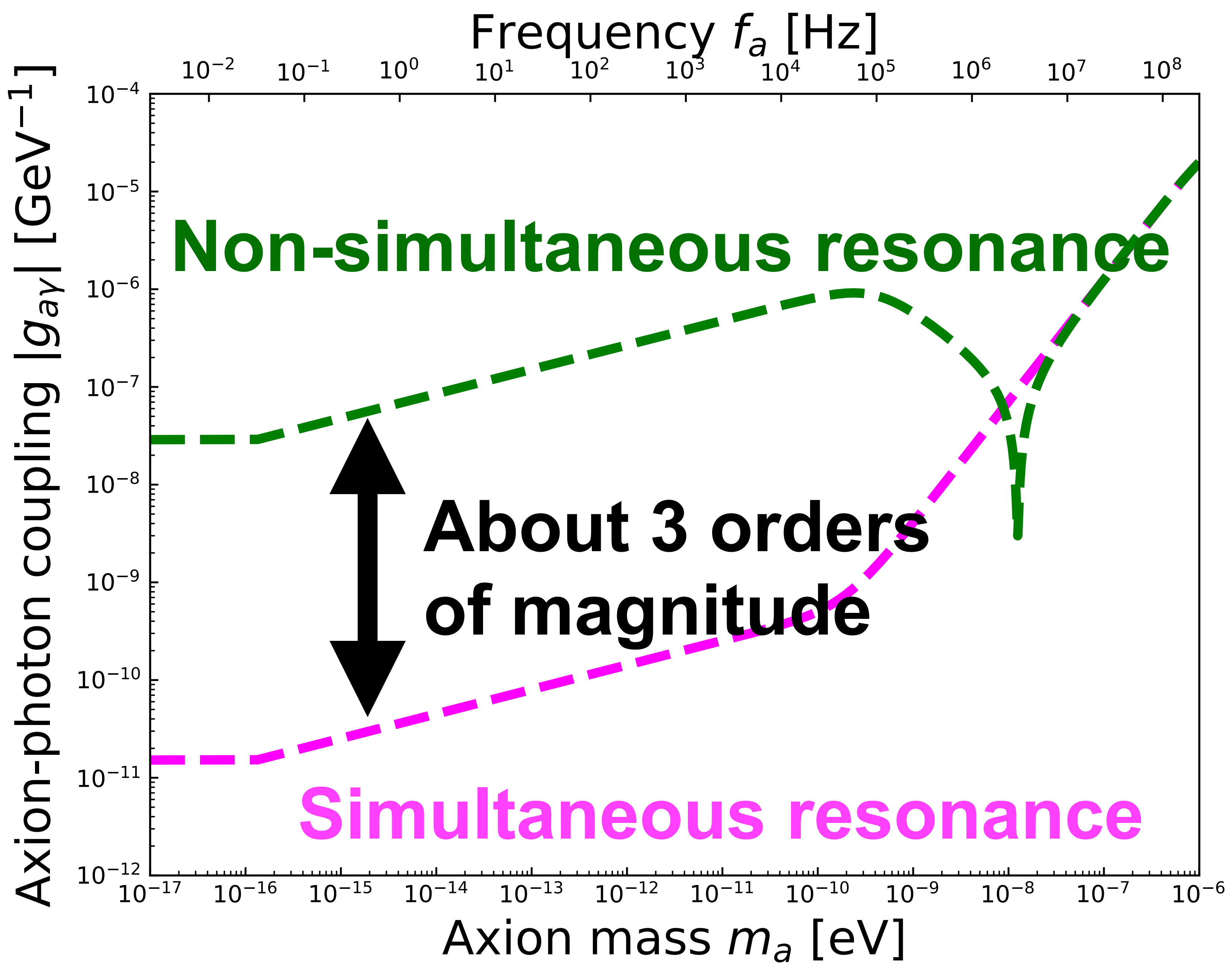
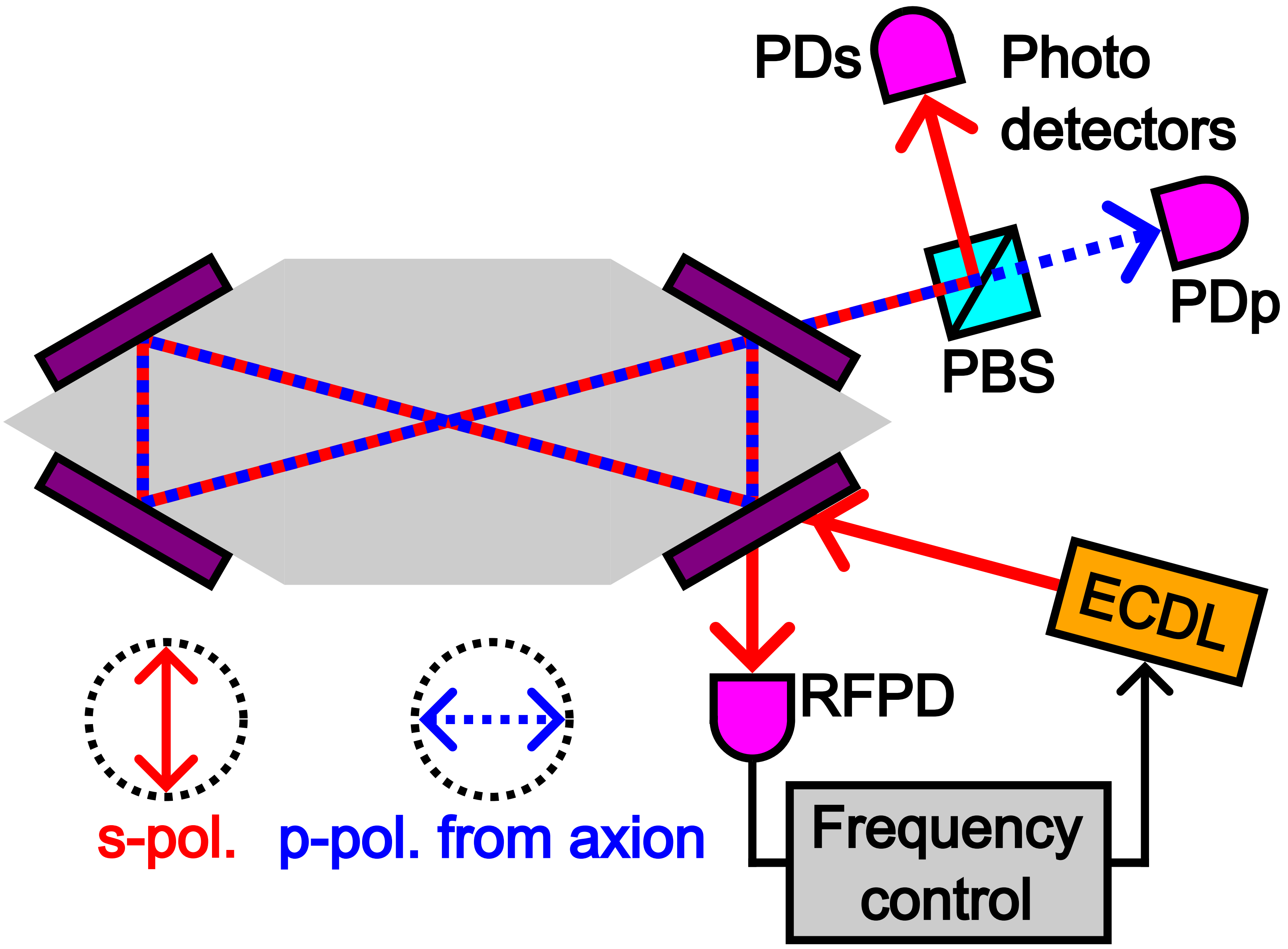
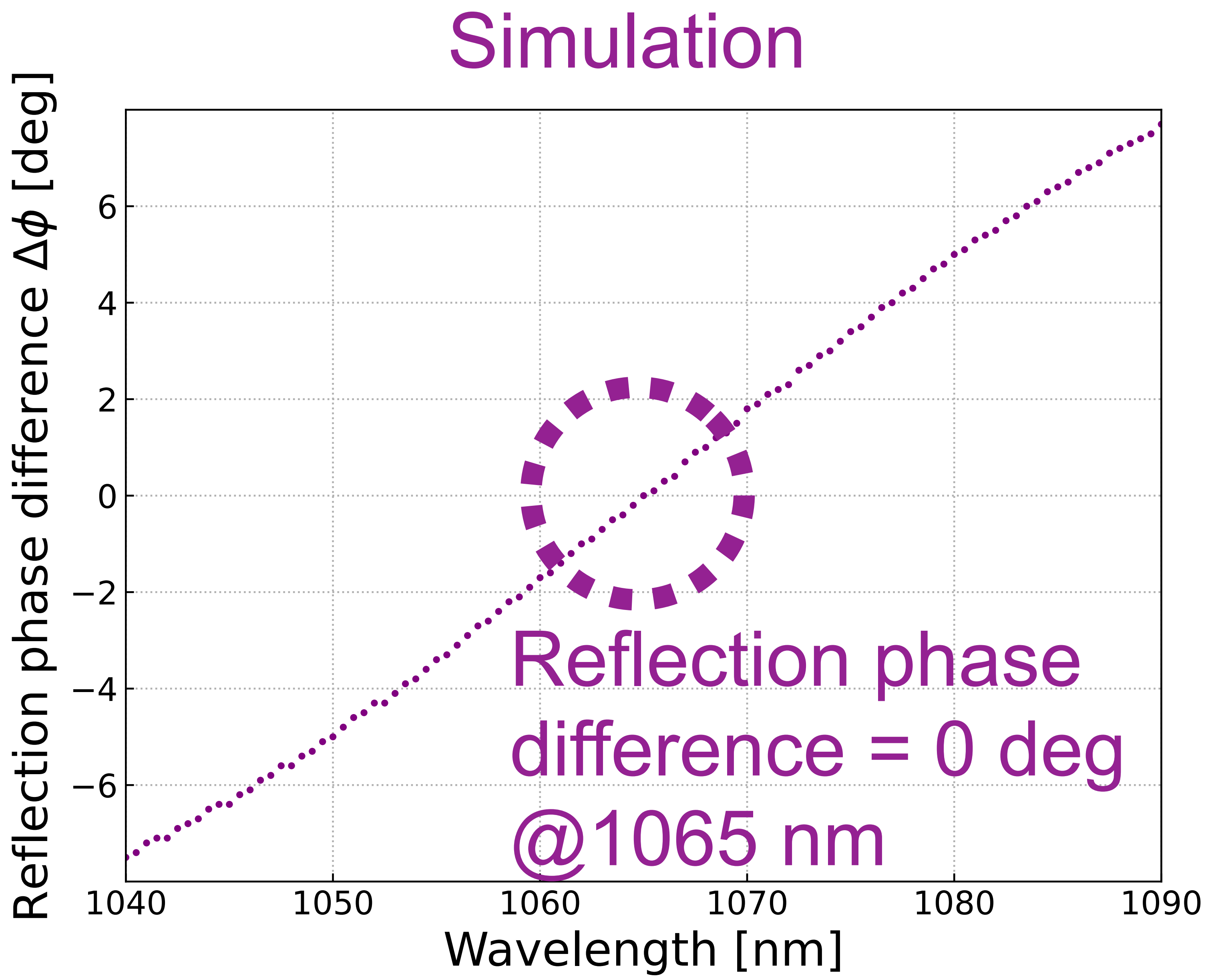


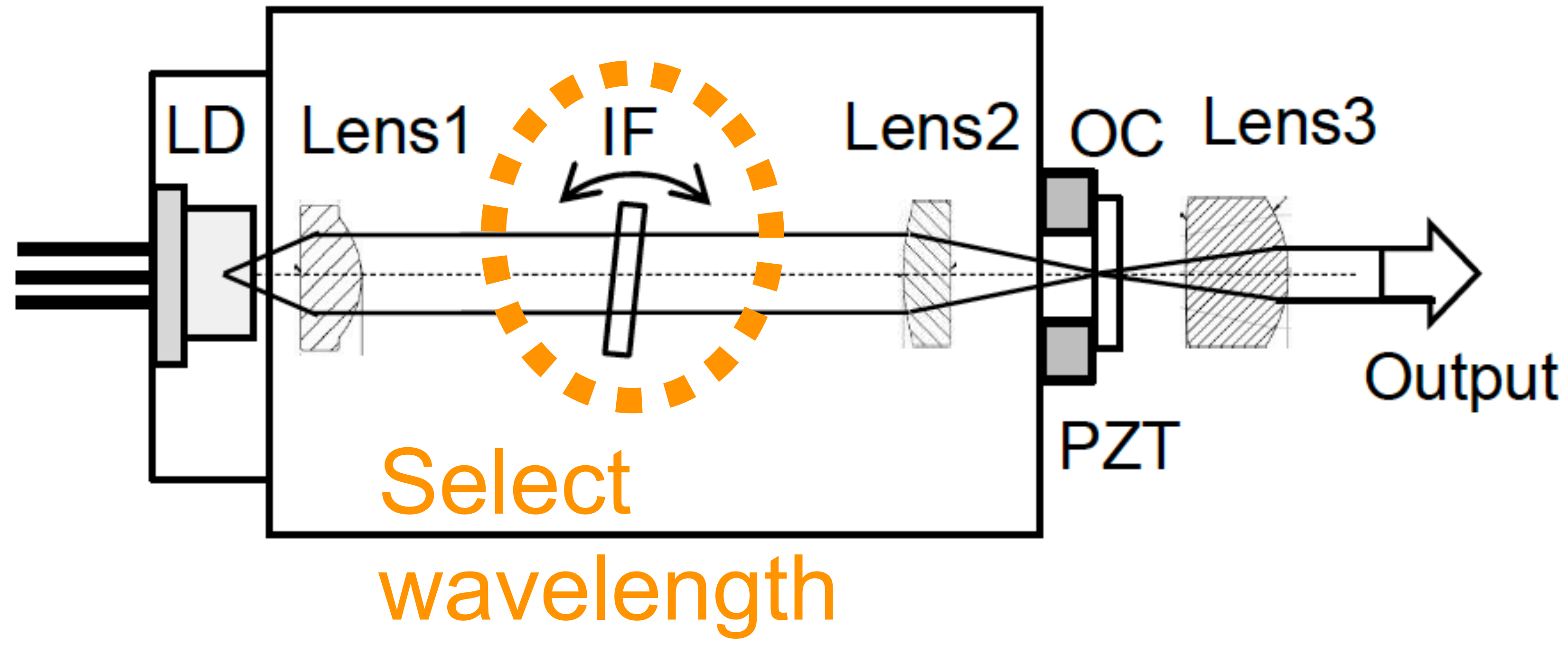
Issue: Degrading the sensitivity due to non-simultaneous resonance
→ Developing new method with zero phase shift mirror and wavelength tunable laser

Y. Oshima *et al.*, Phys. Rev. D **108**, 072005 (2023).

How to achieve simultaneous resonance







ECDL: External Cavity Diode Laser

- Wavelength range: 1038 - 1068 nm
- FWHM: 200 kHz
- Output: 20 - 50 mW

Zero phase shift mirror: Reflection phase difference between s- and p-pol. is 0 deg at specific wavelength

ECDL(Wavelength tunable laser): Select wavelength by changing angle of IF

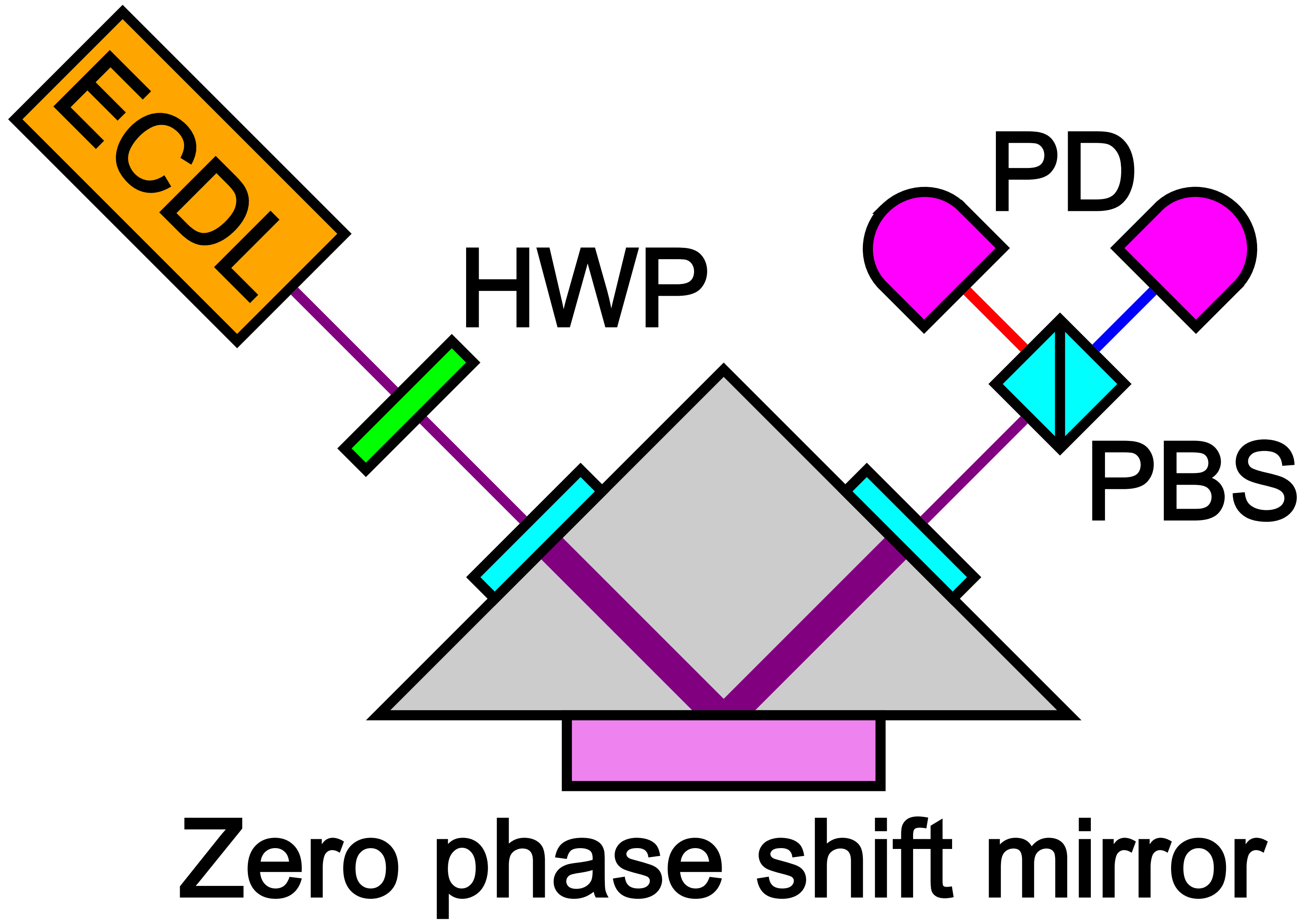
→ Tuning wavelength to cross point of zero phase shift mirror with an ECDL

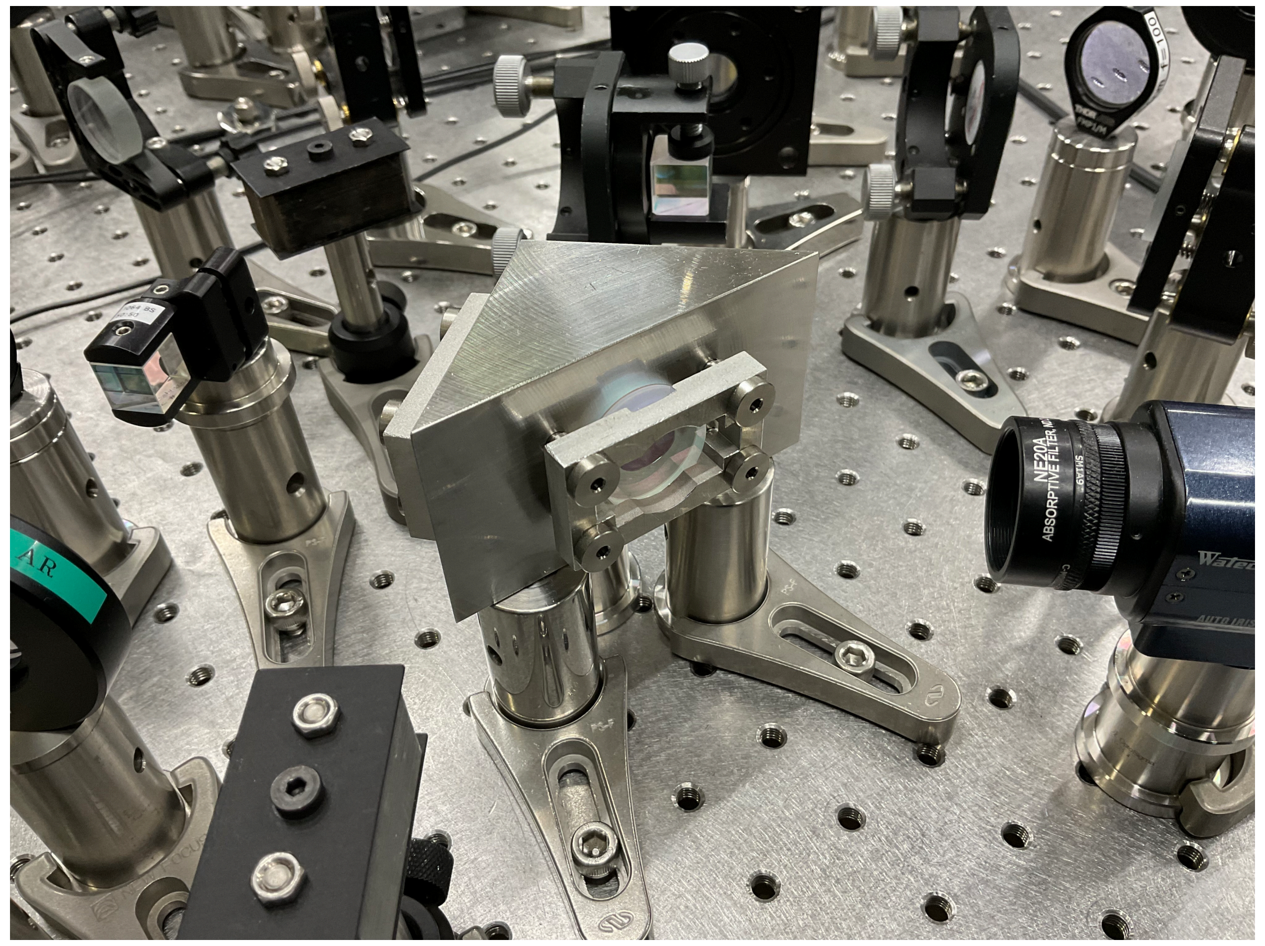
Evaluation of reflection phase difference

Evaluation of reflection phase difference between s- and p-pol. of zero phase shift mirror with a folded cavity

1. Proof of principle for simultaneous resonance
2. Suppress time fluctuations of beat note between s- and p-pol.

→ In order to improve calibration accuracy to the sensitivity, we need to estimate reflection phase difference between s- and p-pol. per mirror accurately





- Fix mirrors with a jig
- Super-invar spacer

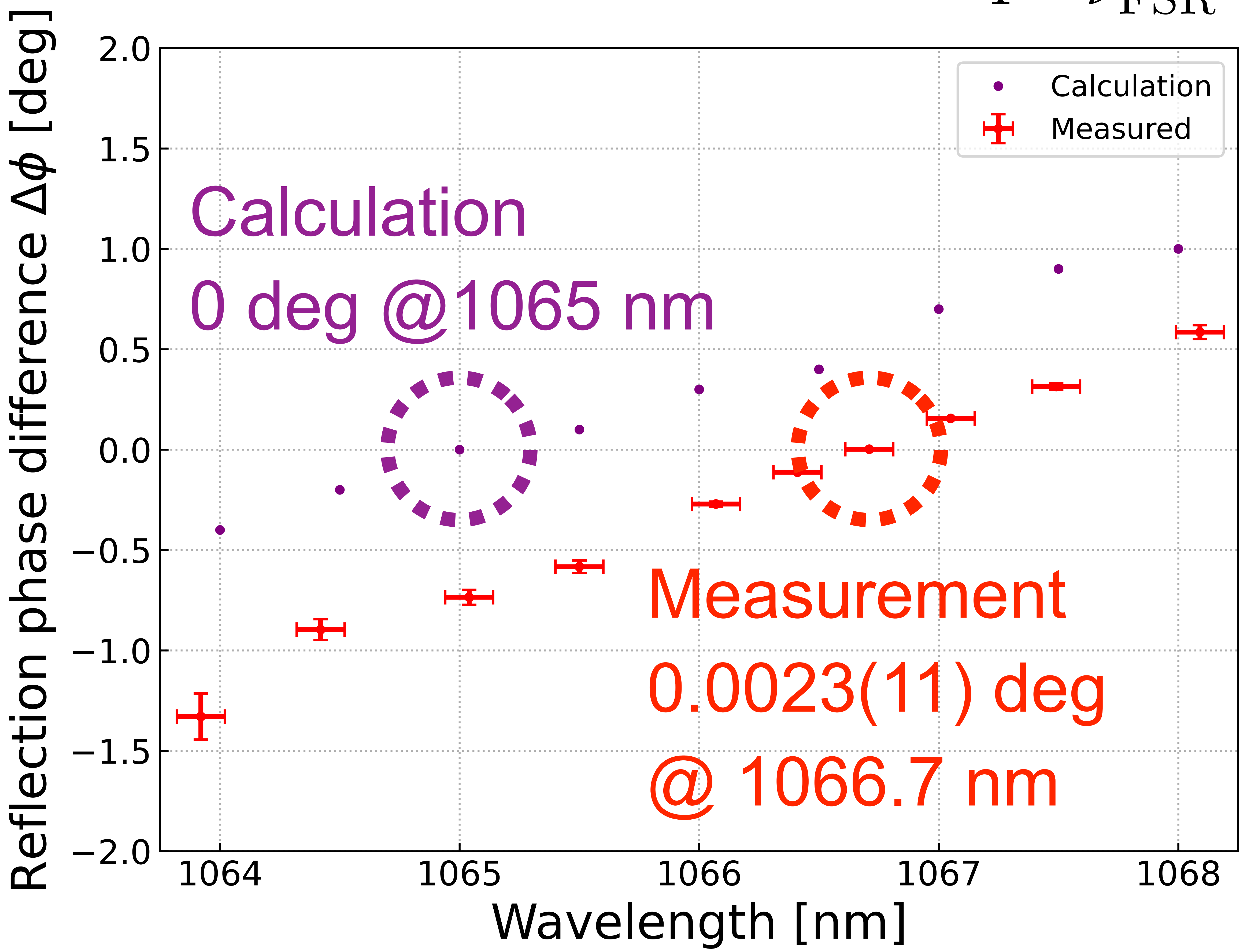
Mirror	Reflectivity	CC [mm]
Input	99%	50
End	99%	50
Test	s-pol.: 99.99%, p-pol.: 99.97%	1000

Evaluation of reflection phase difference

1. Proof of principle for simultaneous resonance

Requirement for reflection phase difference between s- and p-pol. per mirror

$$|\Delta\phi - \Delta\phi_{\mathrm{ave}}| \leq \frac{1}{4}\frac{\nu_{\mathrm{HWHM,p}}}{\nu_{\mathrm{FSR}}} \times 360\,\mathrm{deg} = \underline{8.6 \times 10^{-3}\,\mathrm{deg}}$$



Half width at half maximum (HWHM) of p-pol. with a mirror reflectivity of 99.97%

- Confirmed that simultaneous resonance is achievable at 1066.7 nm

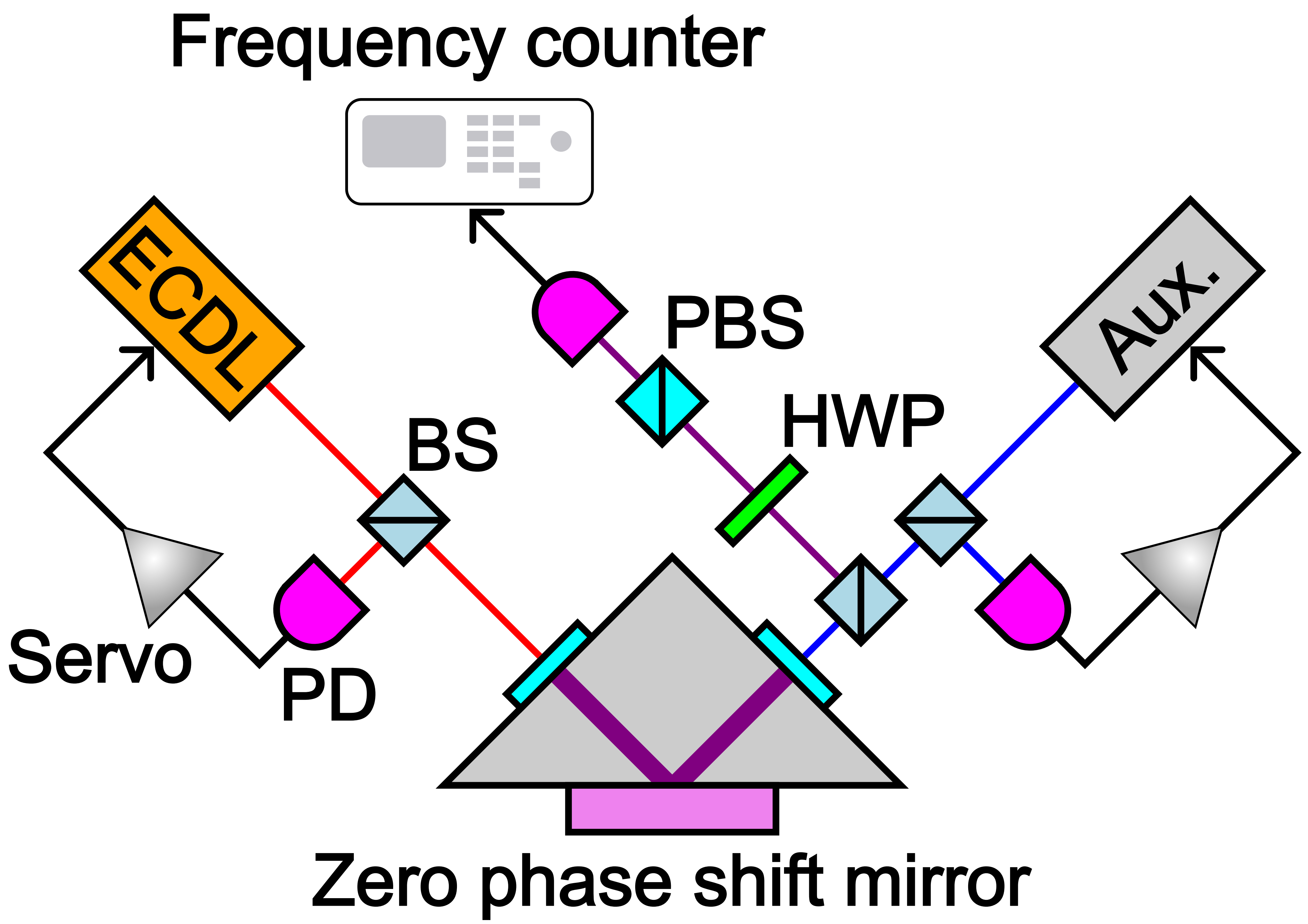
→ Shift from the design specification due to error of mirror coating thickness

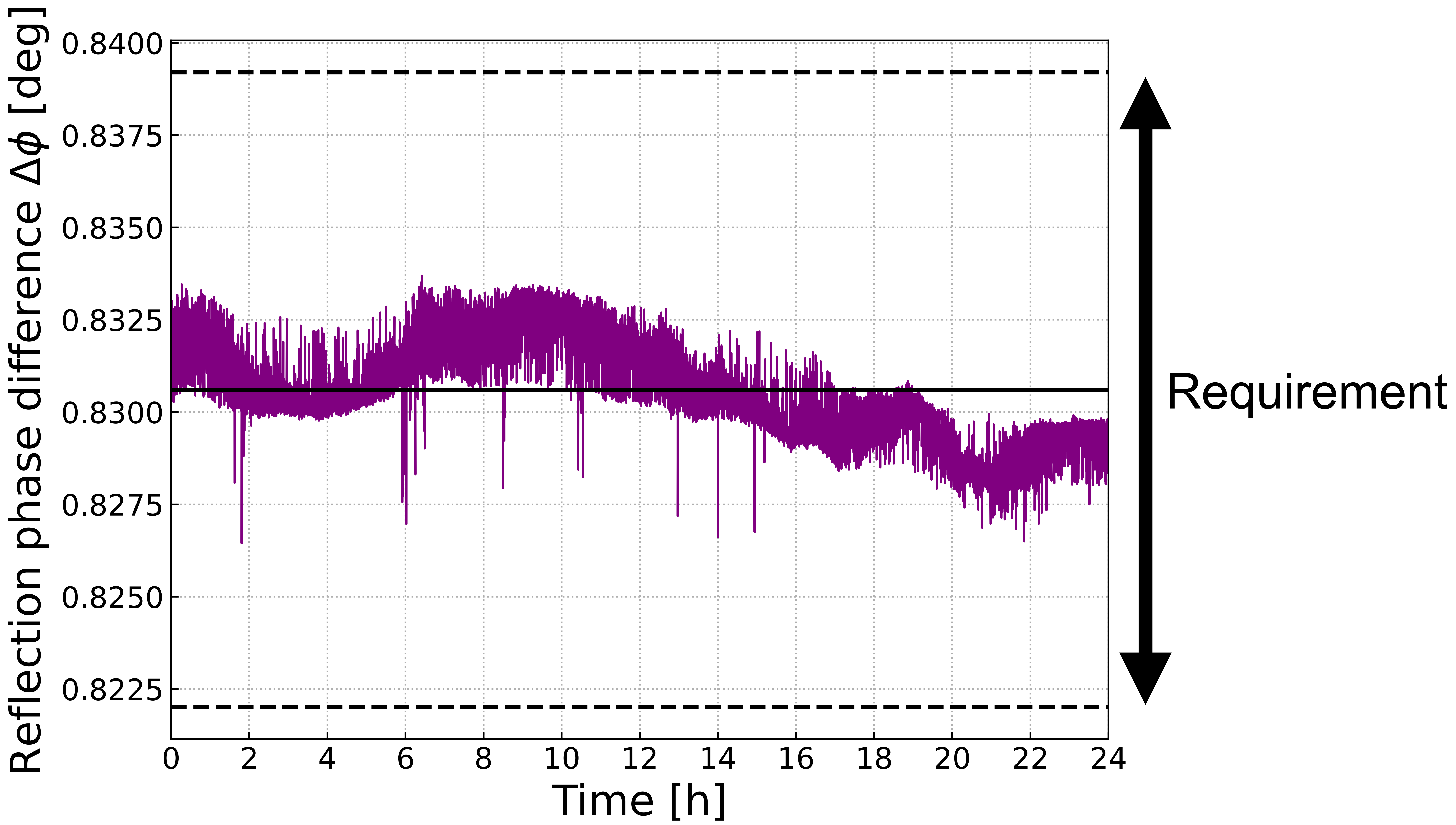
- Satisfied the requirement

Evaluation of reflection phase difference

2. Suppress time fluctuations of beat note between s- and p-pol.

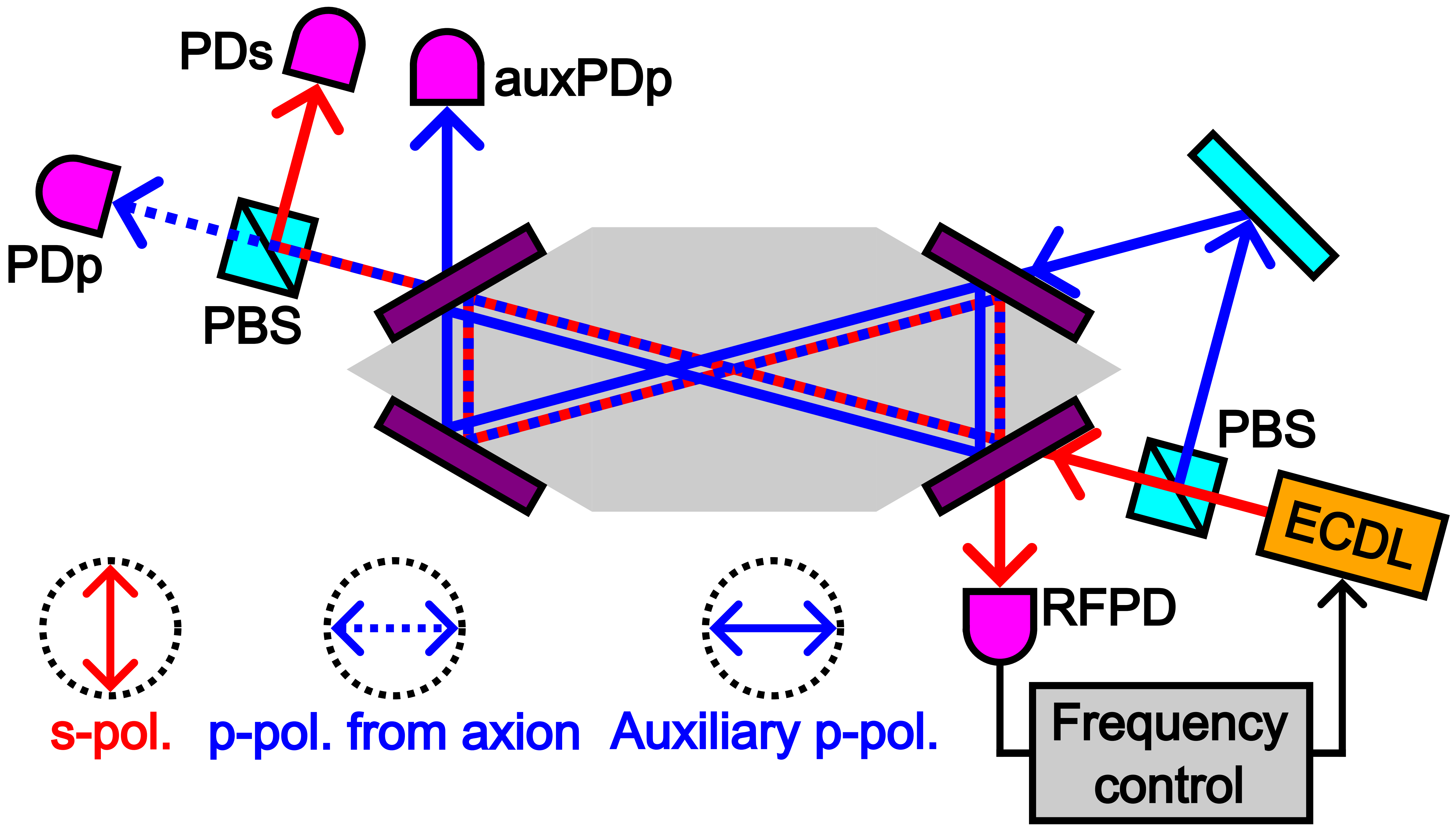
- Satisfied the requirement $|\Delta\phi - \Delta\phi_{\mathrm{ave}}| \leq 8.6 \times 10^{-3}\,\mathrm{deg}$
- Temperature fluctuations are likely to be dominant noise

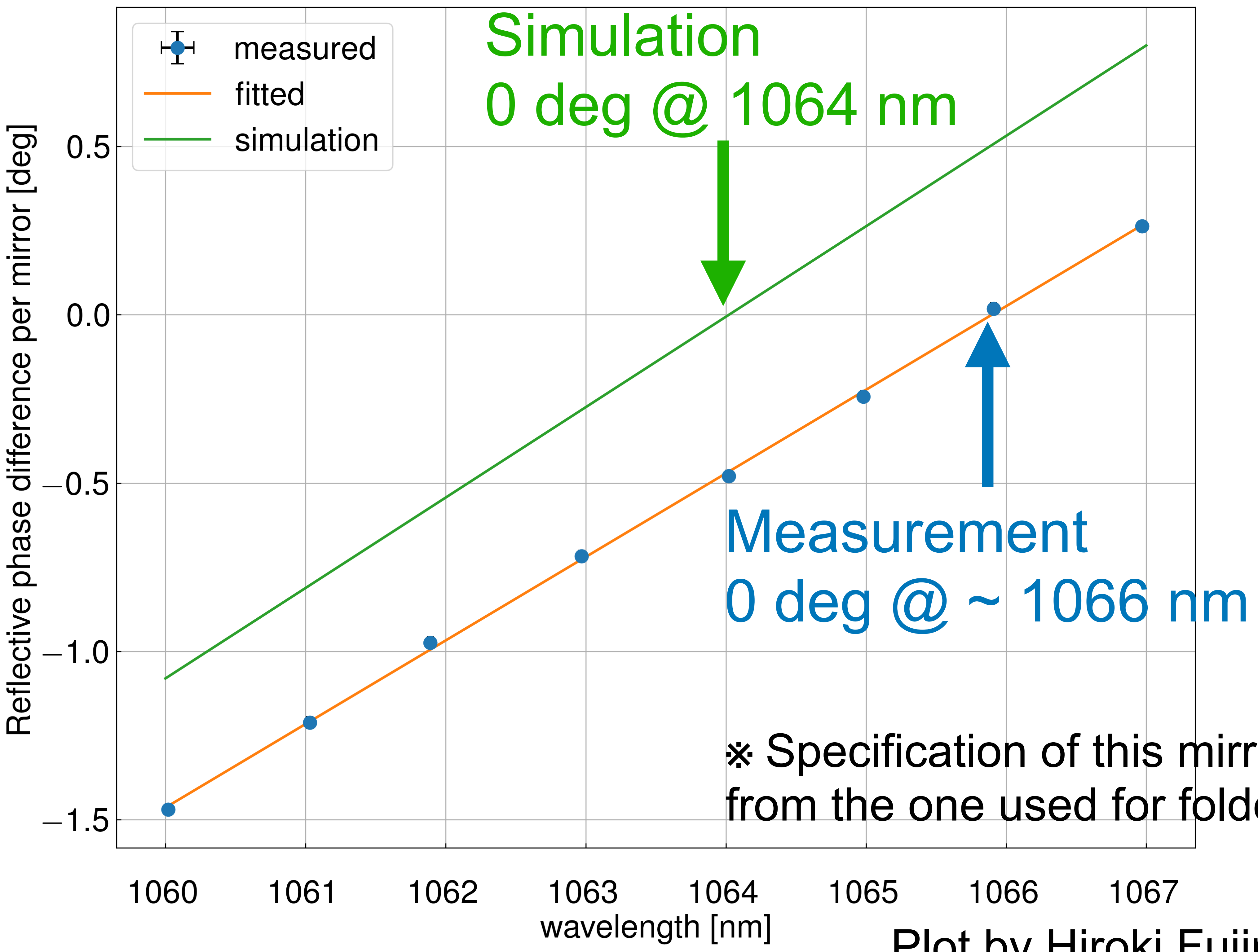




DANCE with zero phase shift mirror and ECDL

- Measured reflection phase difference with a bow-tie ring cavity
- It is possible to achieve simultaneous resonance by tuning at ~ 1066 nm



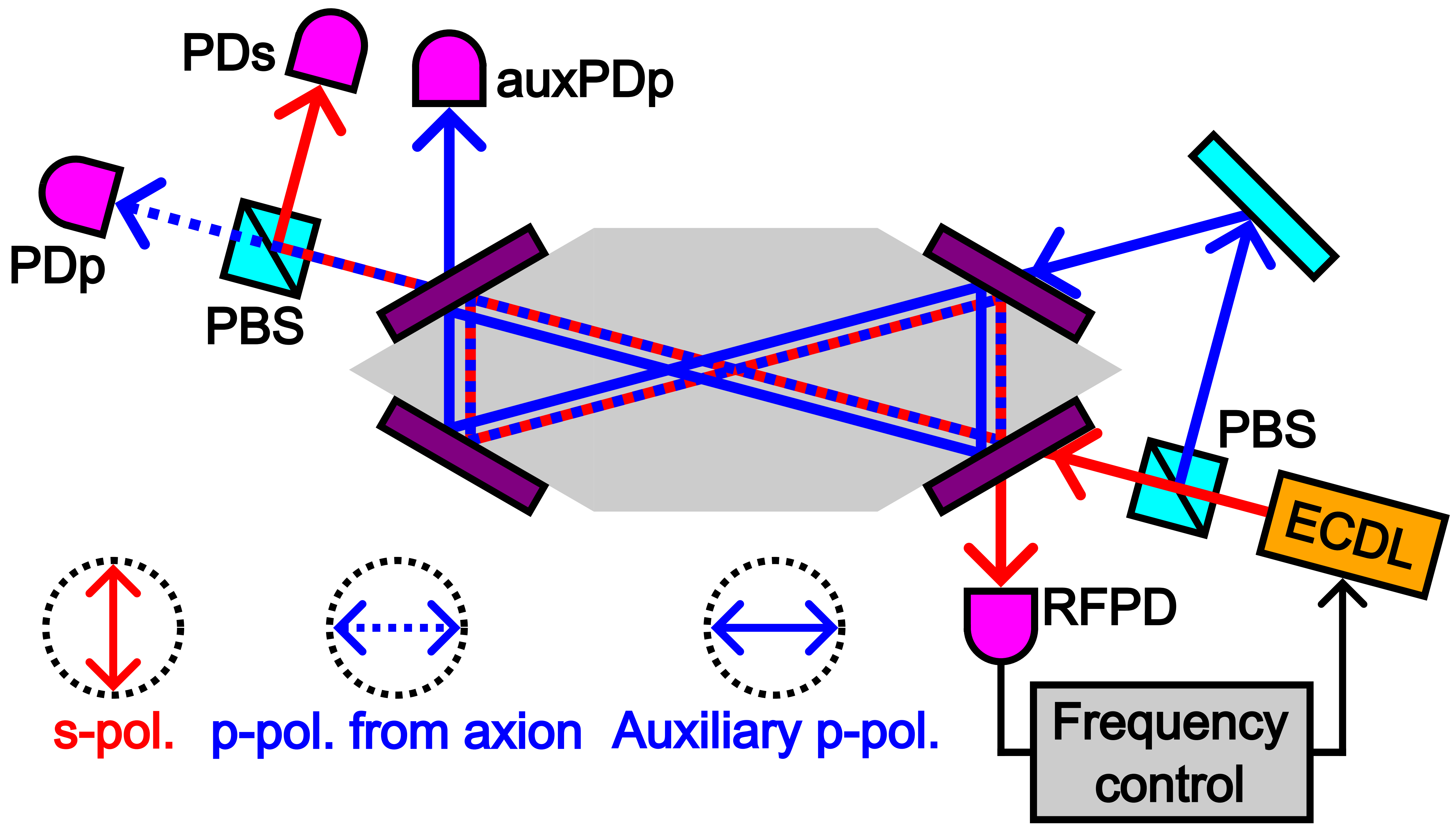


※ Specification of this mirror is different from the one used for folded cavity

Plot by Hiroki Fujimoto

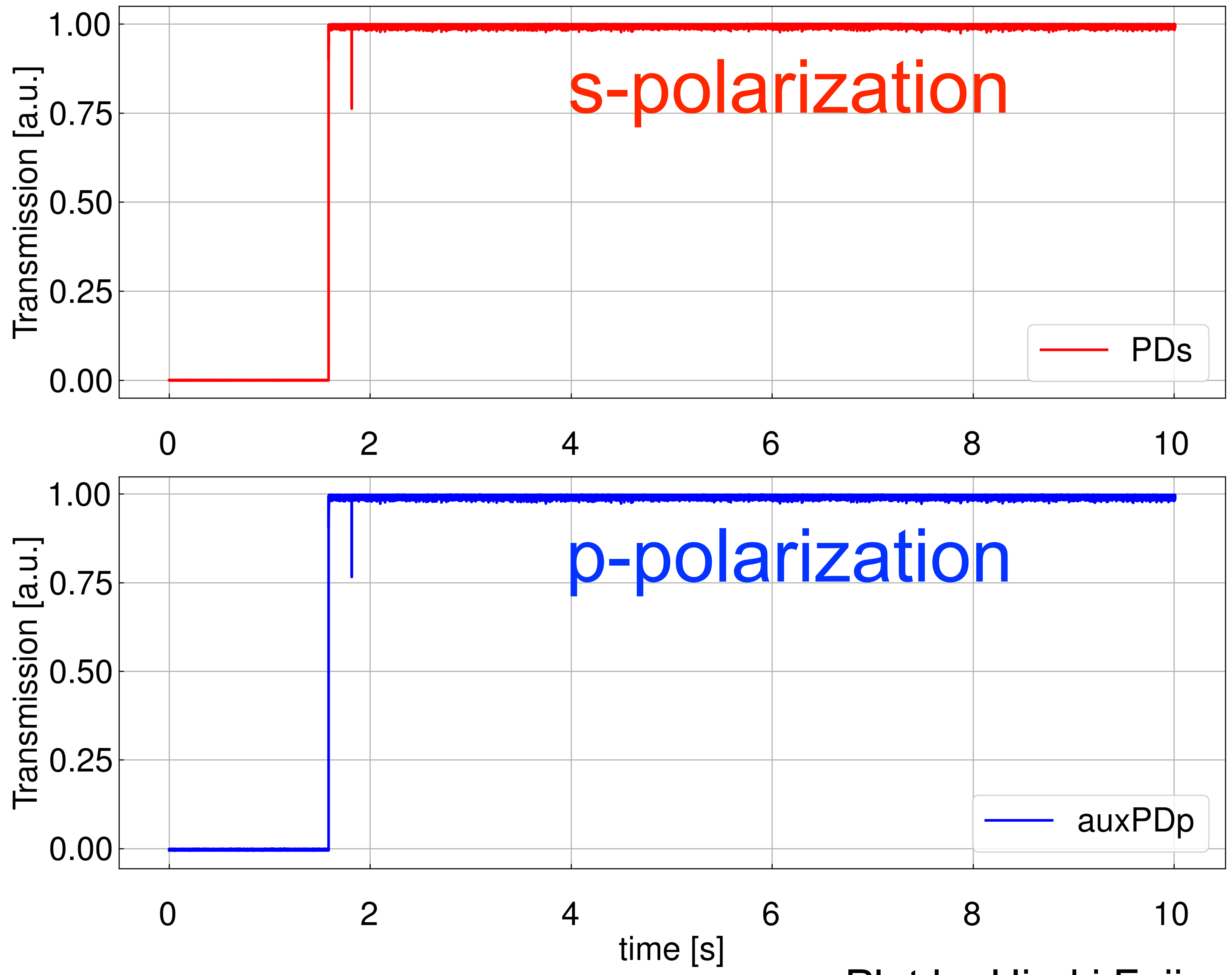
DANCE with zero phase shift mirror and ECDL

- Achieved simultaneous resonance at 1065.84(2) nm
- Satisfied the design value of finesse



Finesse (s-pol.)	$3.82(19) \times 10^3$
Finesse (p-pol.)	$3.82(15) \times 10^3$

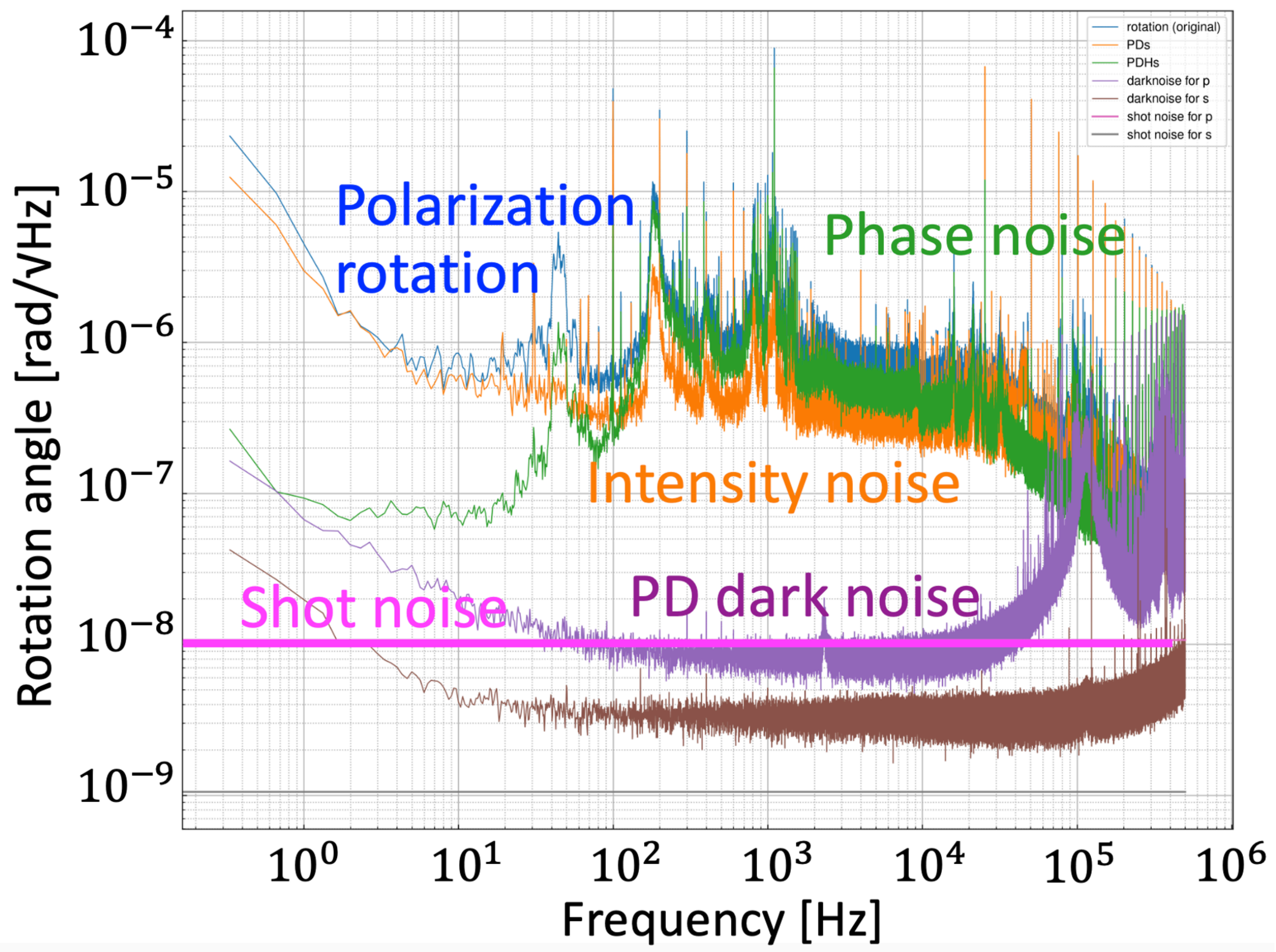
Transmission of s- and p-pol.

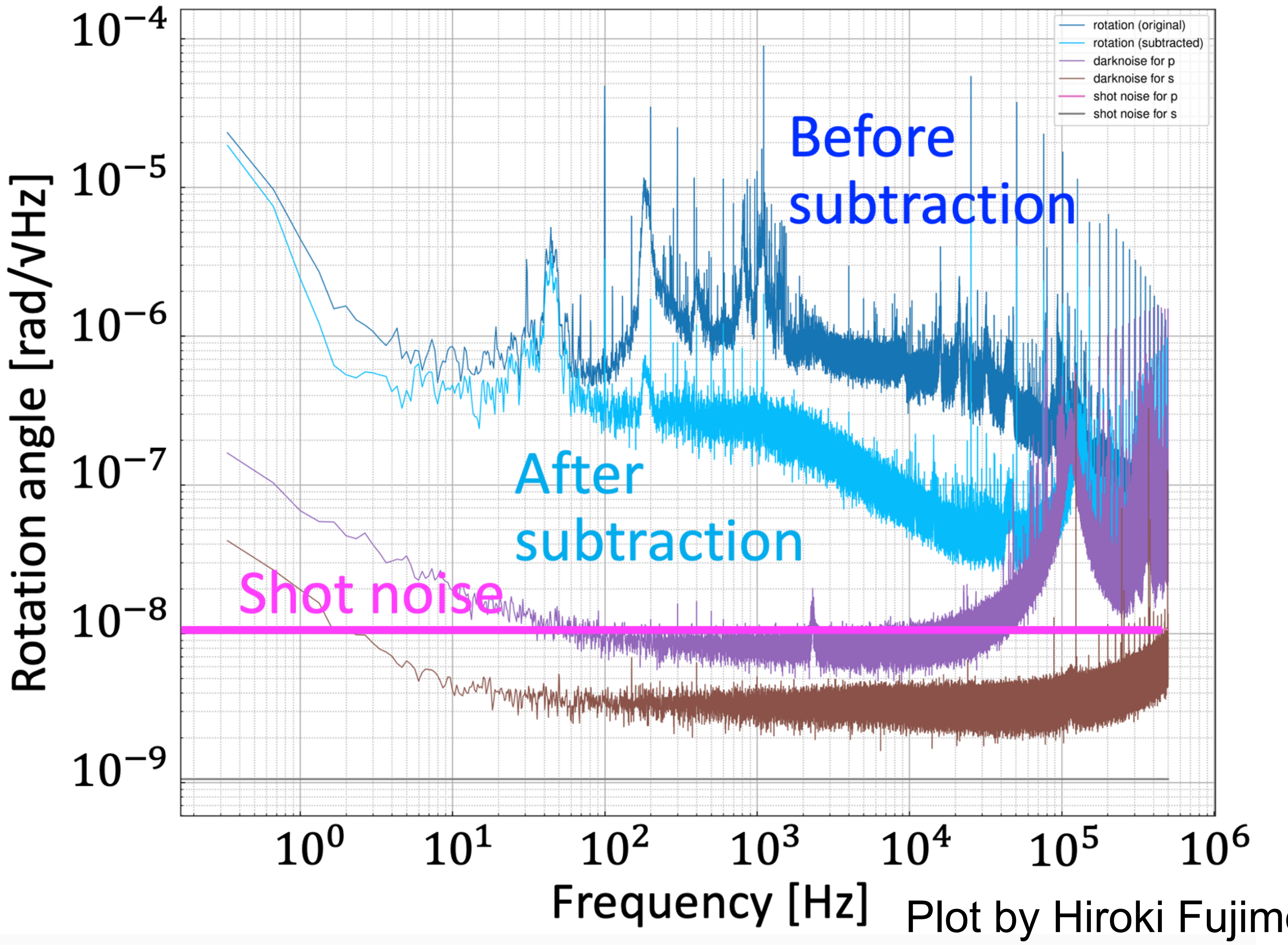


Plot by Hiroki Fujimoto

DANCE with zero phase shift mirror and ECDL

- Phase noise is likely to be couple to birefringence inside the cavity
- Succeeded in subtracting phase noise and intensity noise by offline analysis

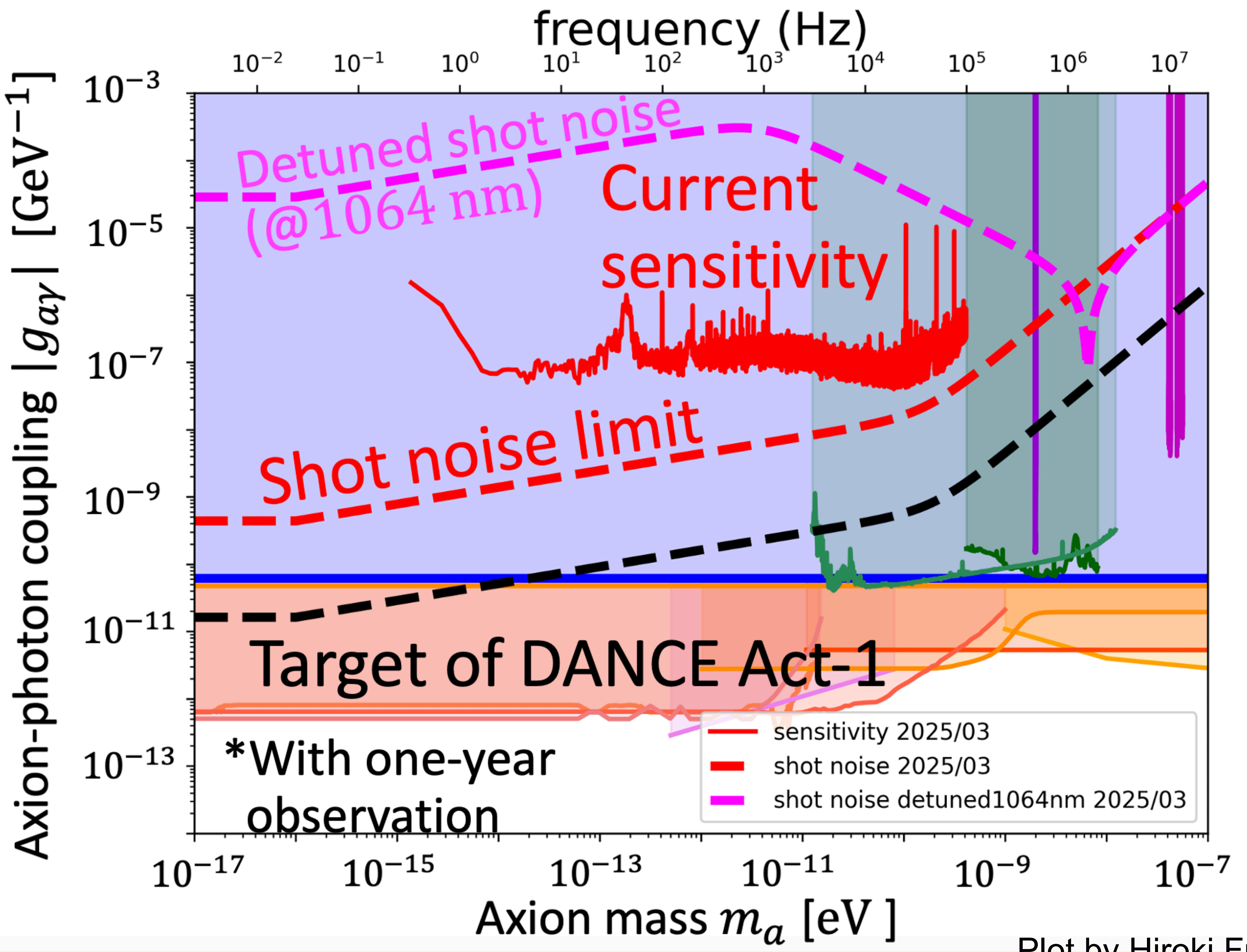




Plot by Hiroki Fujimoto

Axion signal is proportional to the square of the birefringence inside the cavity
→ Its contribution is negligible in offline analysis

DANCE with zero phase shift mirror and ECDL



Plot by Hiroki Fujimoto

- Shot noise limit is better about 4 orders of magnitude than detuned shot noise
- Identify and reduce technical noise to reach shot noise
- Introduce power amp. to reach target of DANCE Act-1

Comparison with other groups

	Round-trip	Finesse	Input power	Observation bandwidth	How to tune resonant frequency difference between s- and p-pol.
DANCE (UTokyo)	~1 m	s-pol.: ~3800 p-pol.: ~3800	6 mW	Broadband 1 feV - 0.4 neV (Possible with narrowband)	• Zero phase shift mirror • Wavelength tunable laser
ADBC (MIT)	~4.7 m	s-pol.: ~7260 p-pol.: ~212	0.8 W	Narrowband 40.9 - 56.7 neV	Tuning incident angle by rotating the mirrors
LIDA (Birmingham)	~10 m	s-pol.: ~74220 p-pol.: ~2220	12 W	Narrowband 1.97 - 2.01 neV	Plan to tune angle of the mirrors

Summary

DANCE: Dark matter Axion search with riNg Cavity Experiment

- Dark matter axion search with a bow-tie ring cavity by detecting a rotation angle of linearly polarized light
- Achieved simultaneous resonance with zero-phase-shift mirror and ECDL
- Reduce technical noise and introduce power amp. to improve the sensitivity