Sensitivity improvement of DANCE for my Ph.D. thesis

Hinata Takidera (D3)
Department of Physics, The University of Tokyo

Midterm report meeting, April 27th, 2026

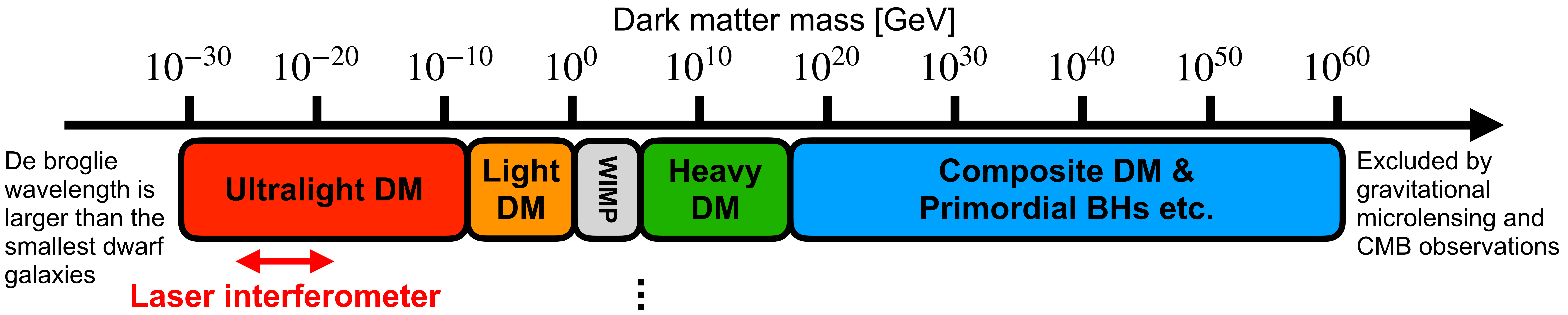
Contents

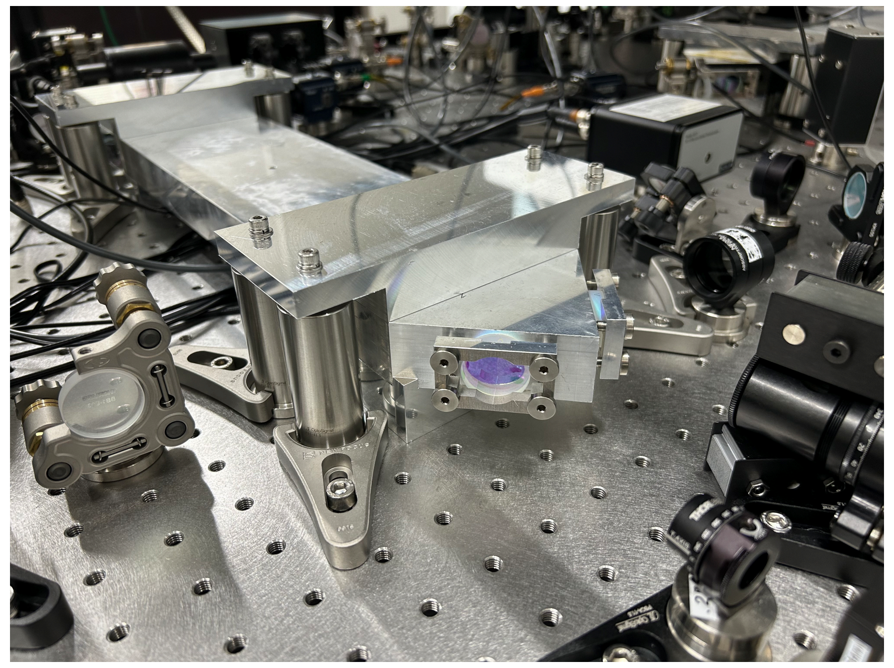
- Introduction of dark matter search
- Principle of DANCE
- DANCE Act-1
  - Previous research
  - Sensitivity improvement strategies
- Summary

Contents

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

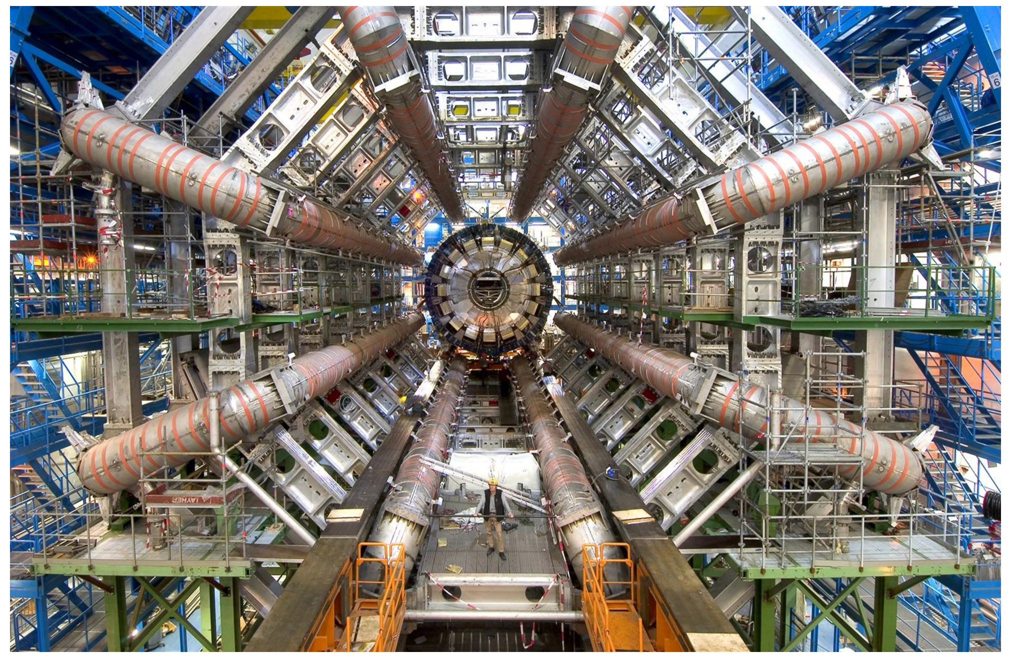




DANCE

KAGRA

XENON

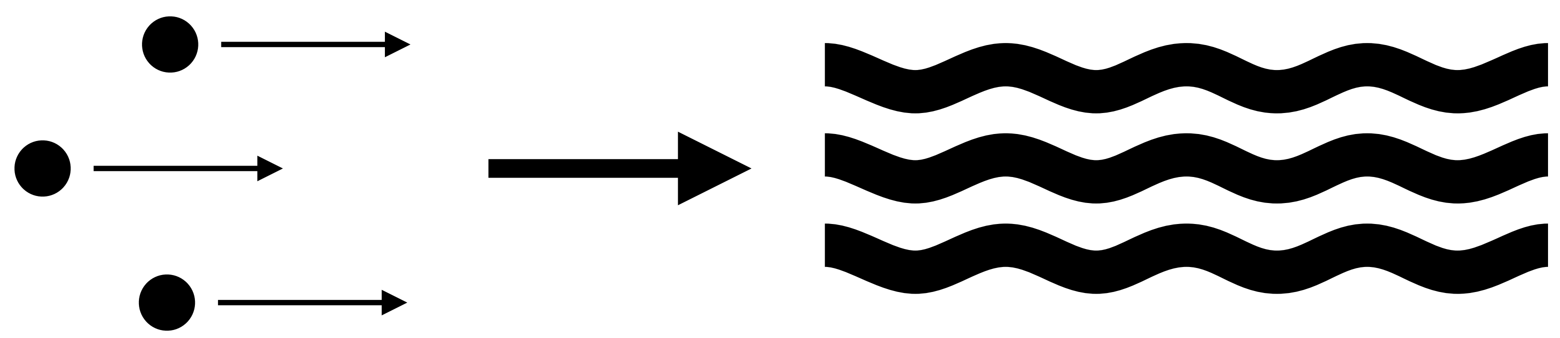


LHC

Subaru telescope

QCD axion and Axion-like particles (ALPs)

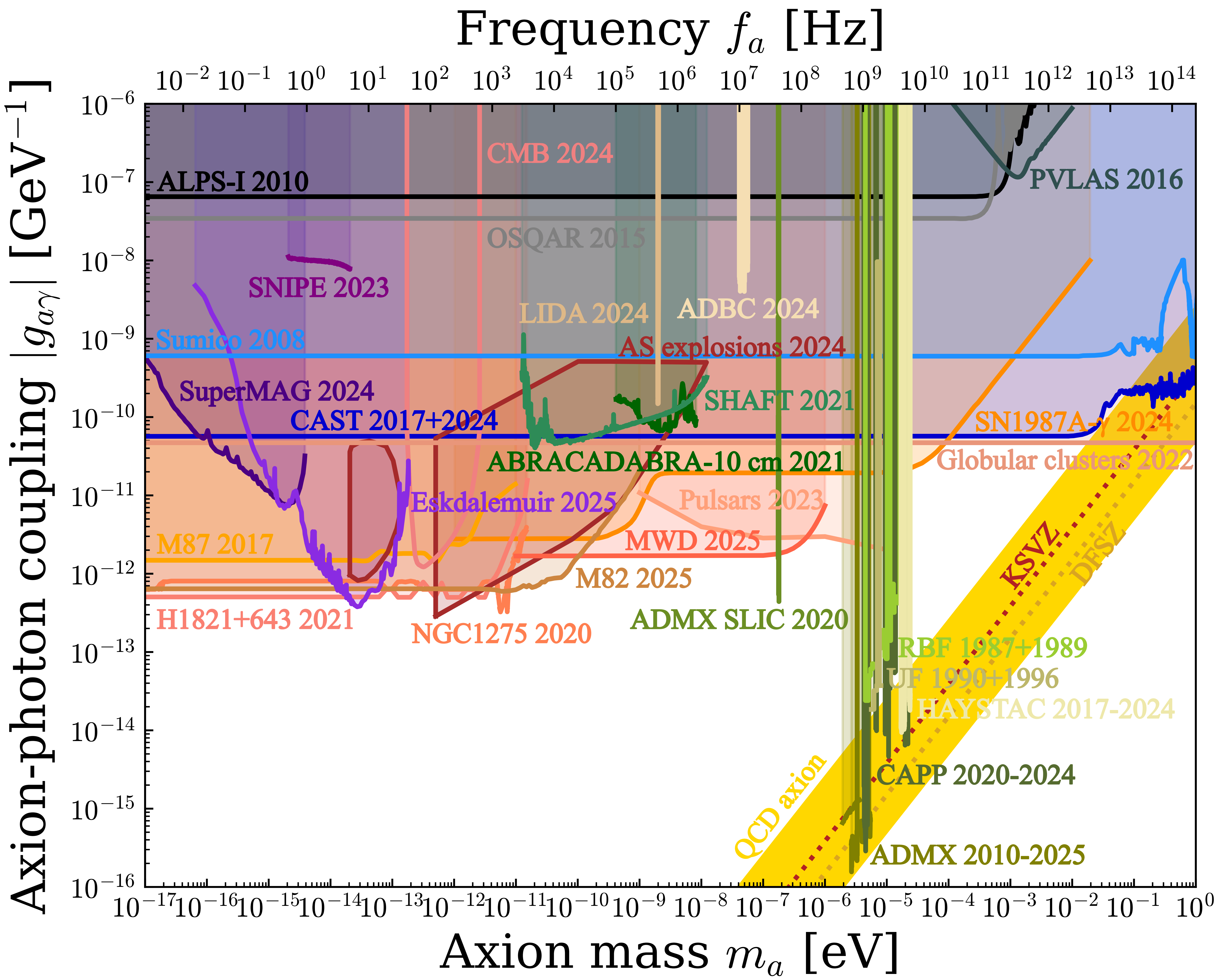
- QCD axion was originally proposed to solve the strong CP problem in quantum chromodynamics (QCD)
- Axion-like particles (ALPs) are predicted by string theory and supergravity



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

- Ultralight particles → Behave like waves
- Axion can weakly interact with photons, electrons, protons, and neutrons
- Many experiments have utilized the axion-photon conversion under magnetic field (Primakoff effect), but axion has not been observed yet

Current upper limit



Contents

Axion-photon interaction

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

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

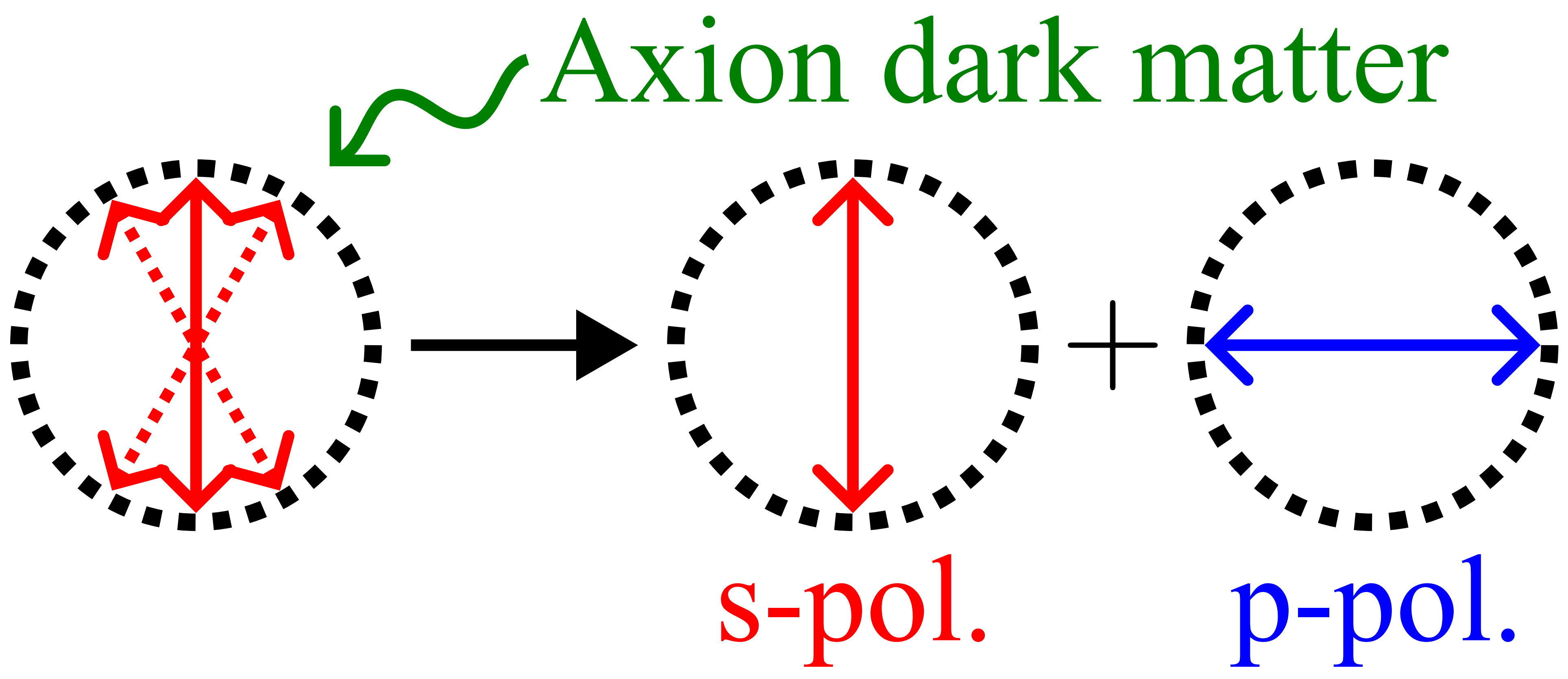
Phase velocity

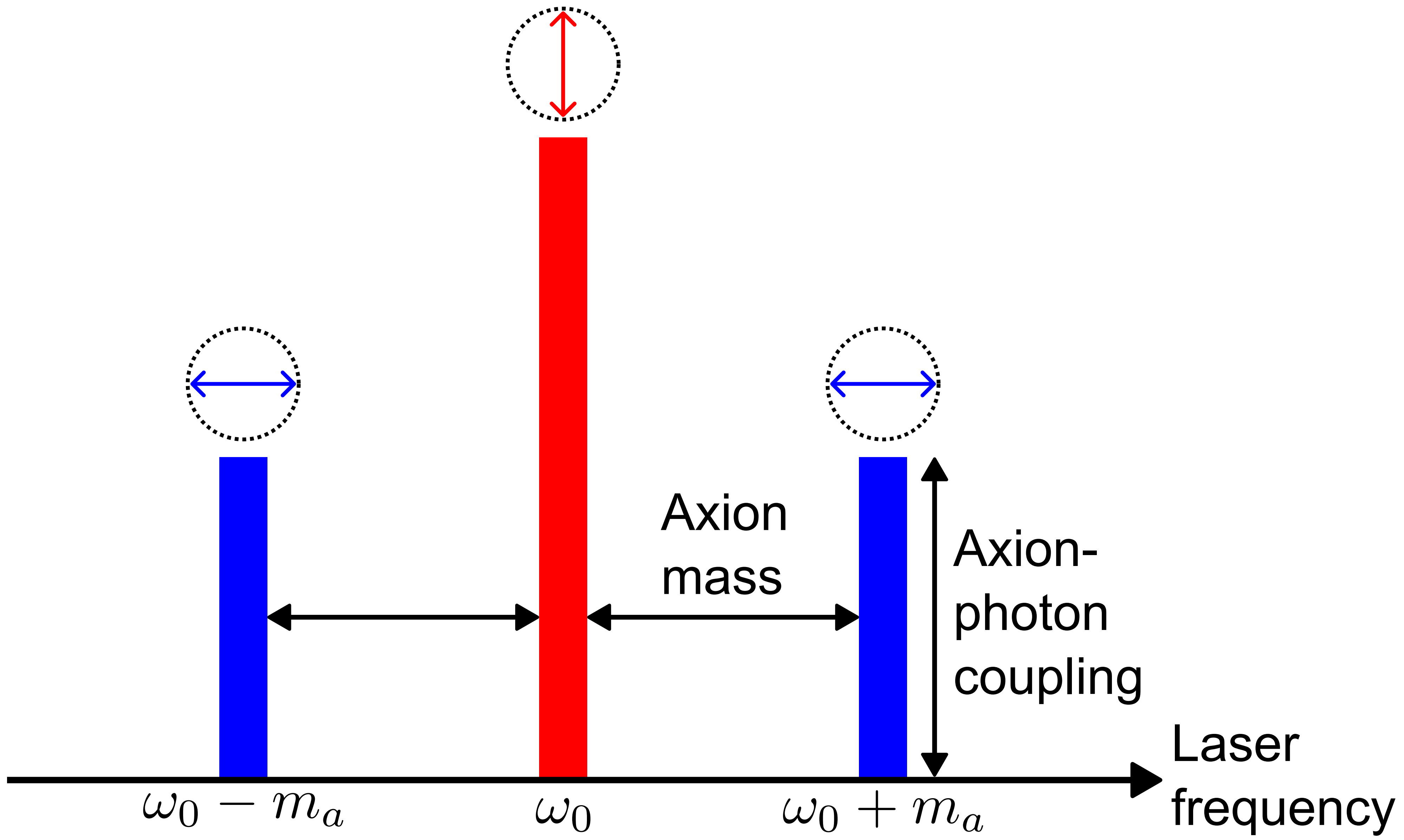
Axion-photon coupling

Axion field

Axion mass

→ Rotation of linearly polarized light

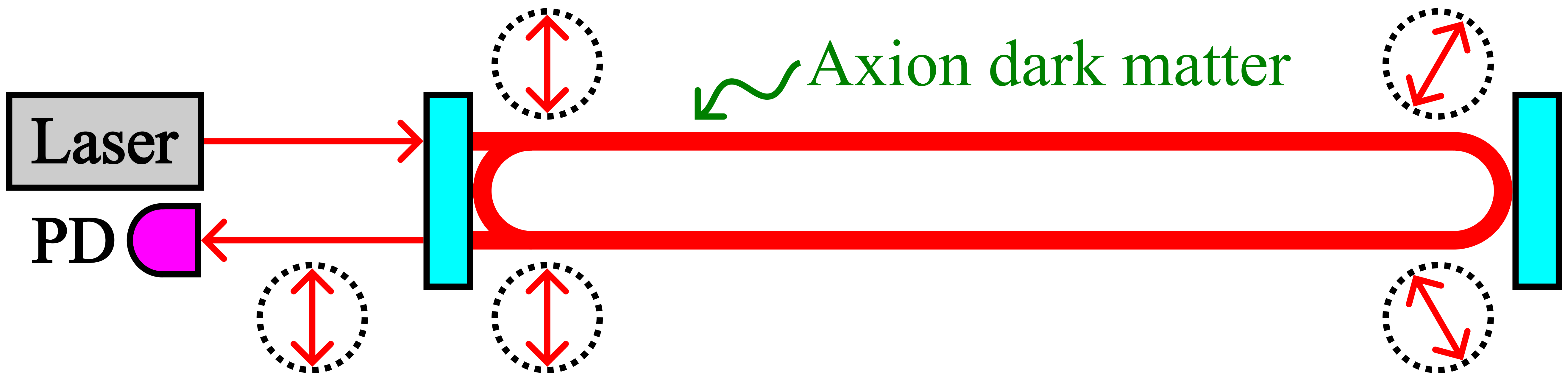




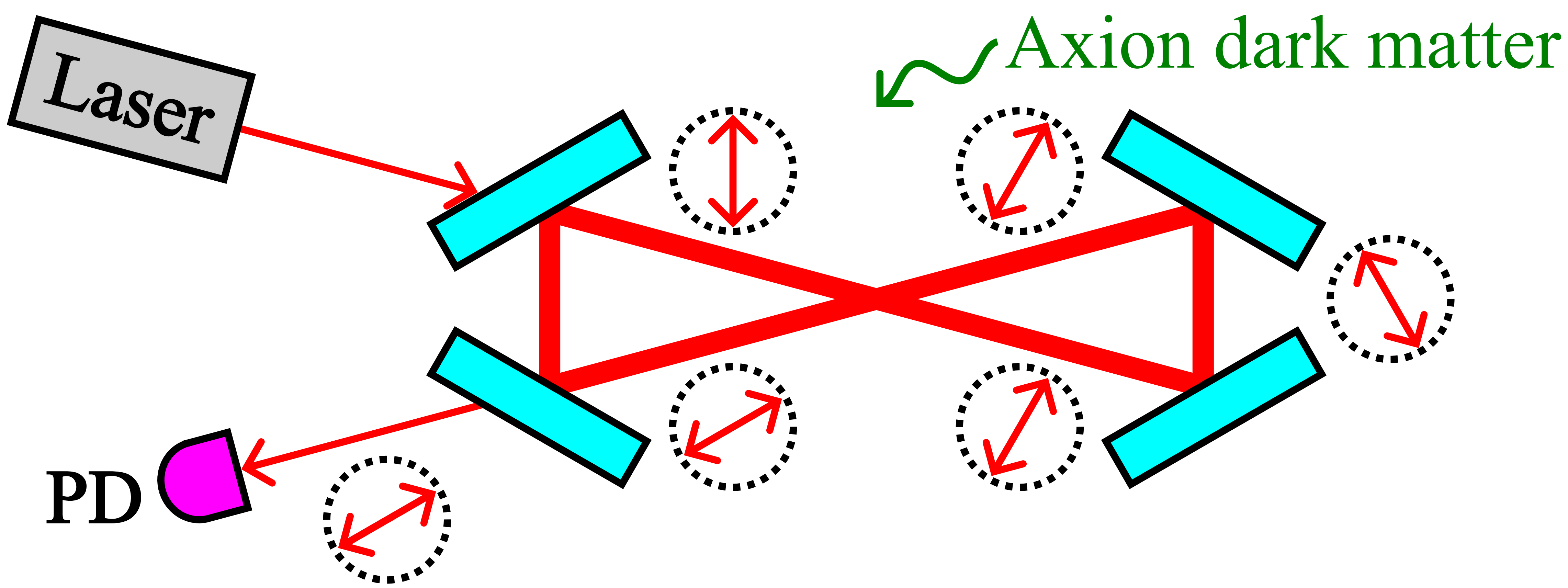
How to amplify the axion signal

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

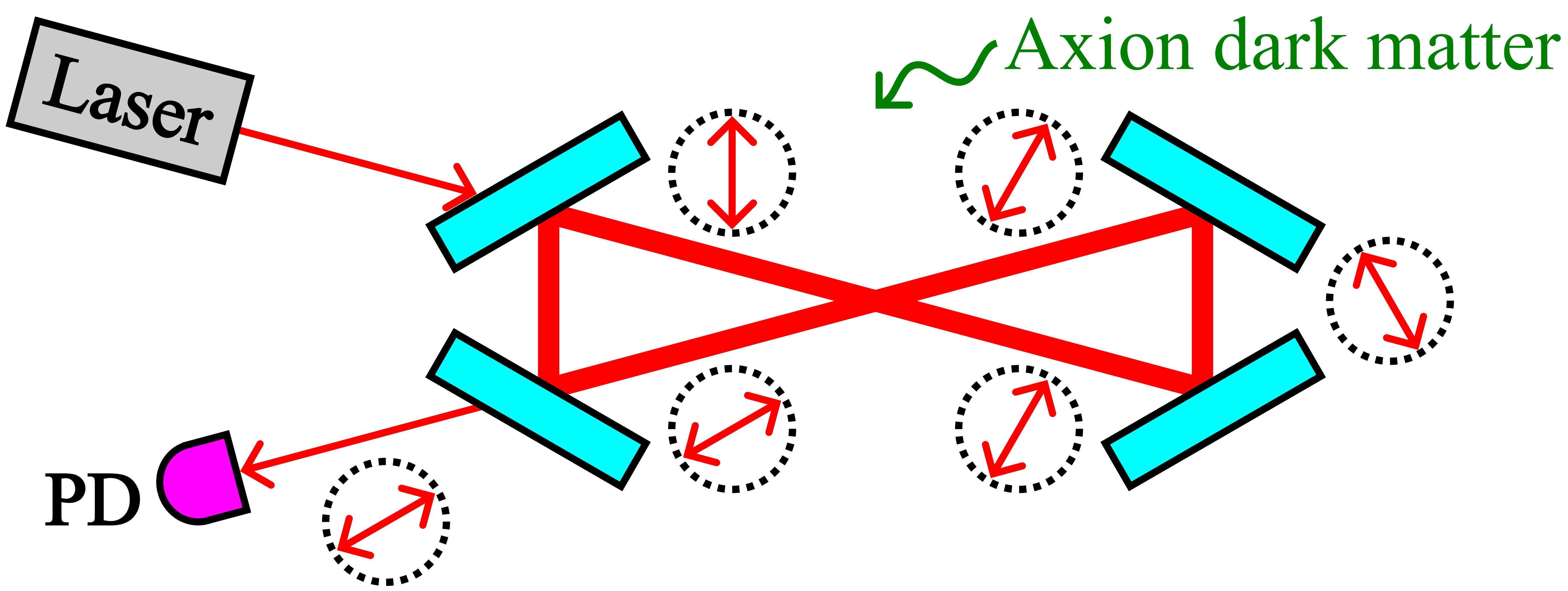


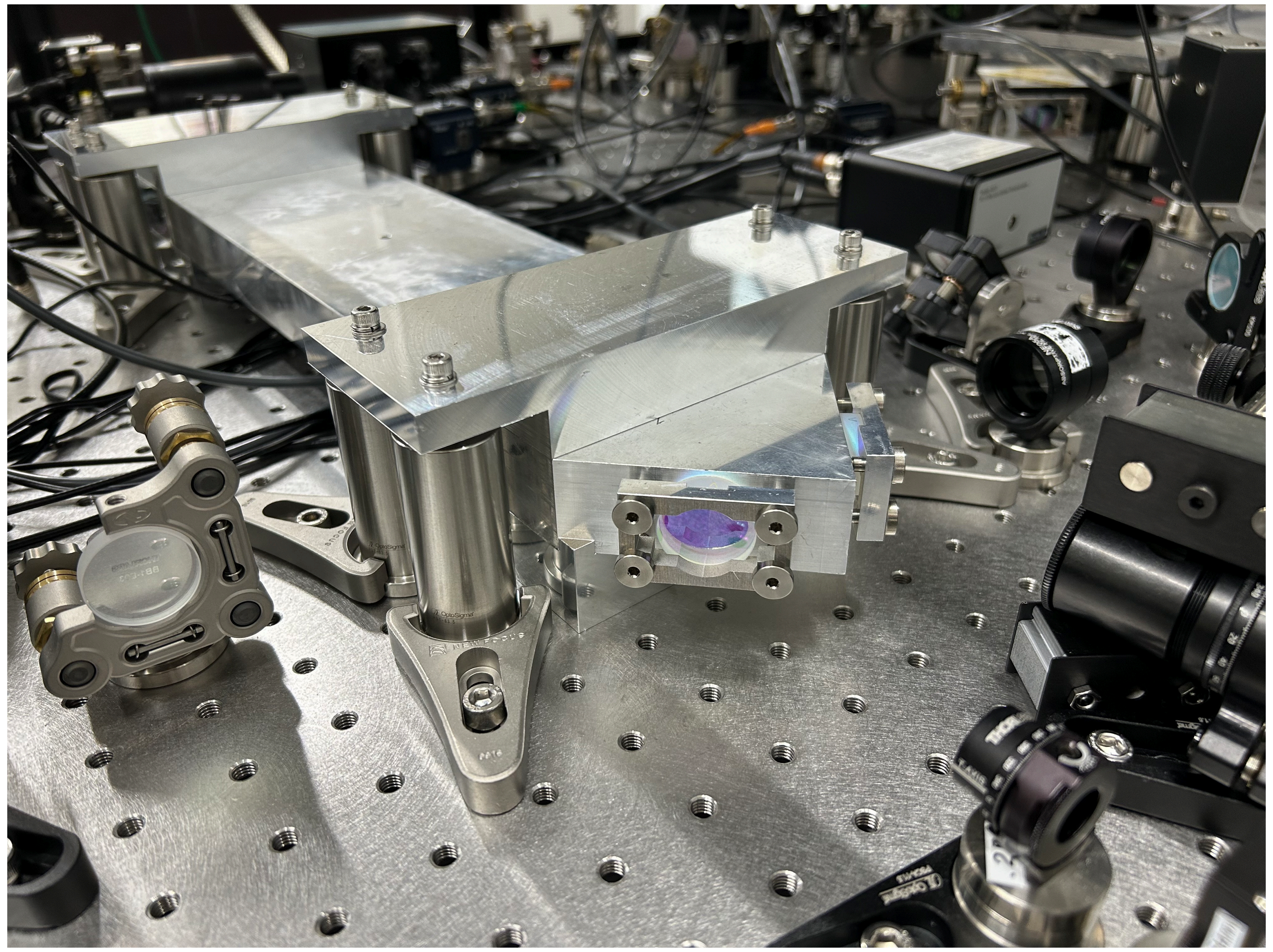
I. Obata *et al.*, Phys. Rev. Lett. **121**, 161301 (2018).

DANCE

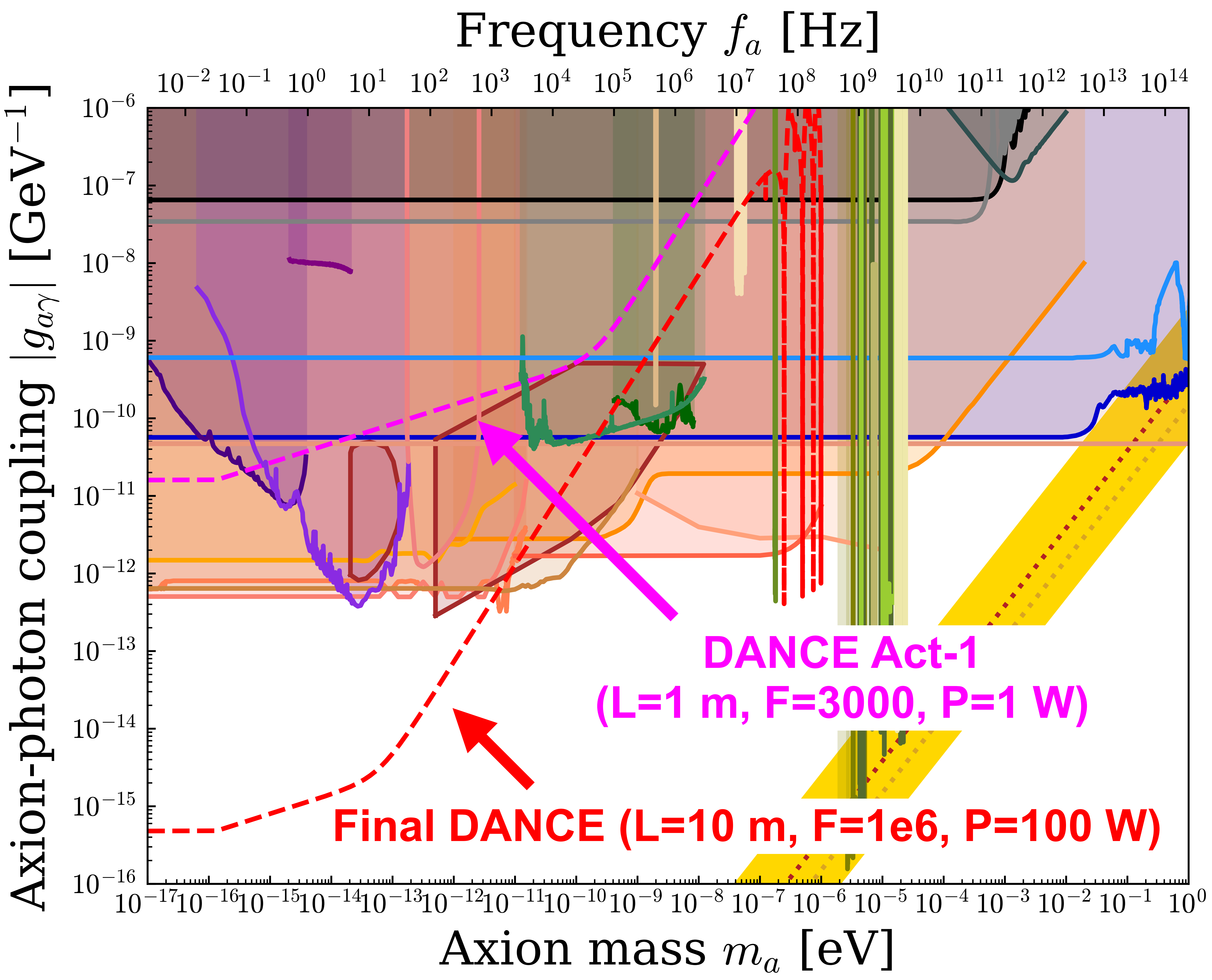
DANCE: Dark matter Axion search with riNg Cavity Experiment

- Amplify p-polarization (Axion signal) generated by the axion-photon coupling
- Polarization flip is canceled upon reflections on both two mirrors
- Prototype experiment: DANCE Act-1 is in progress at B111





Target sensitivity of DANCE



- Assume observation time is 1year
- Shot noise limited

L : Round-trip

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

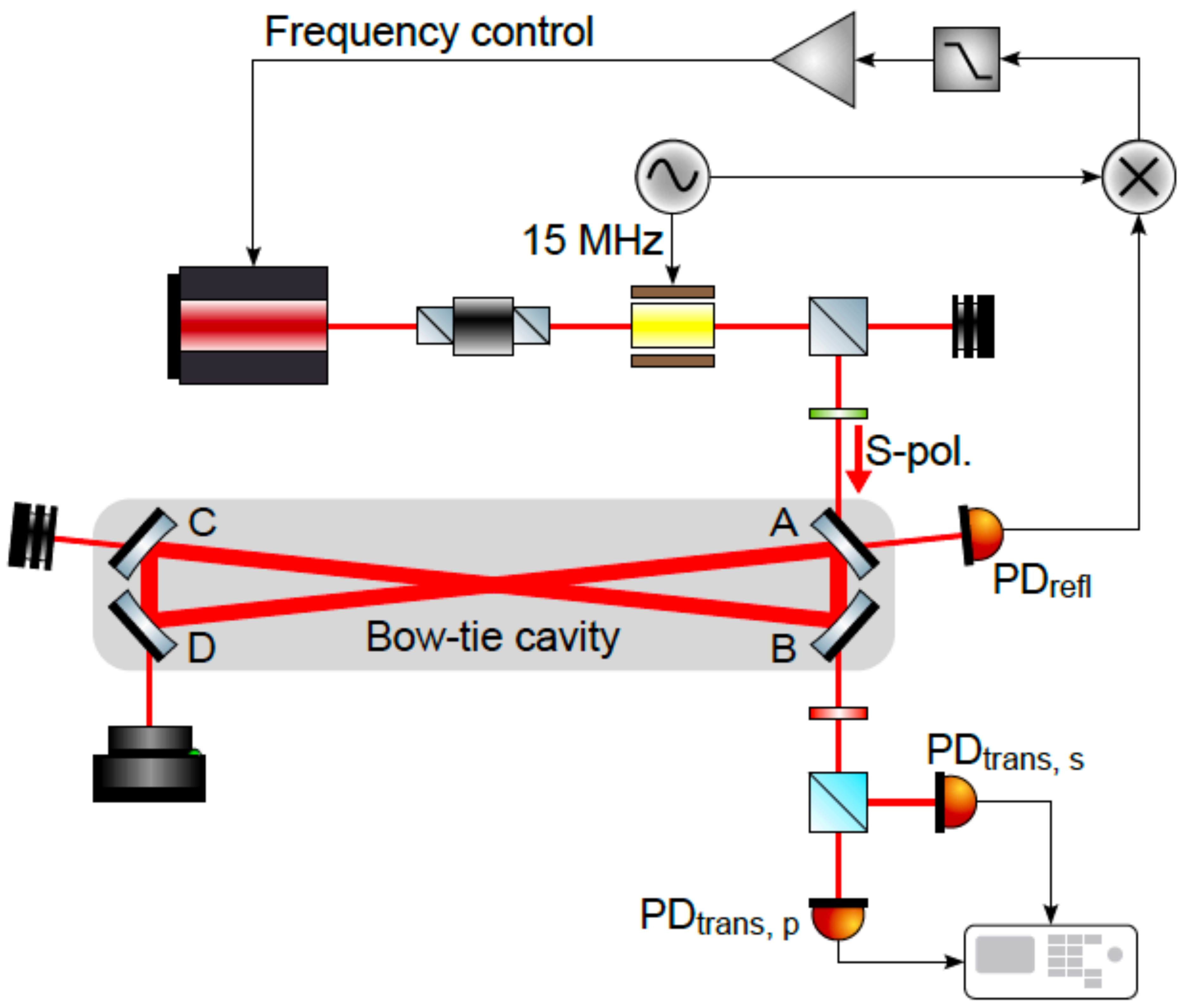
P_{in} : Input power

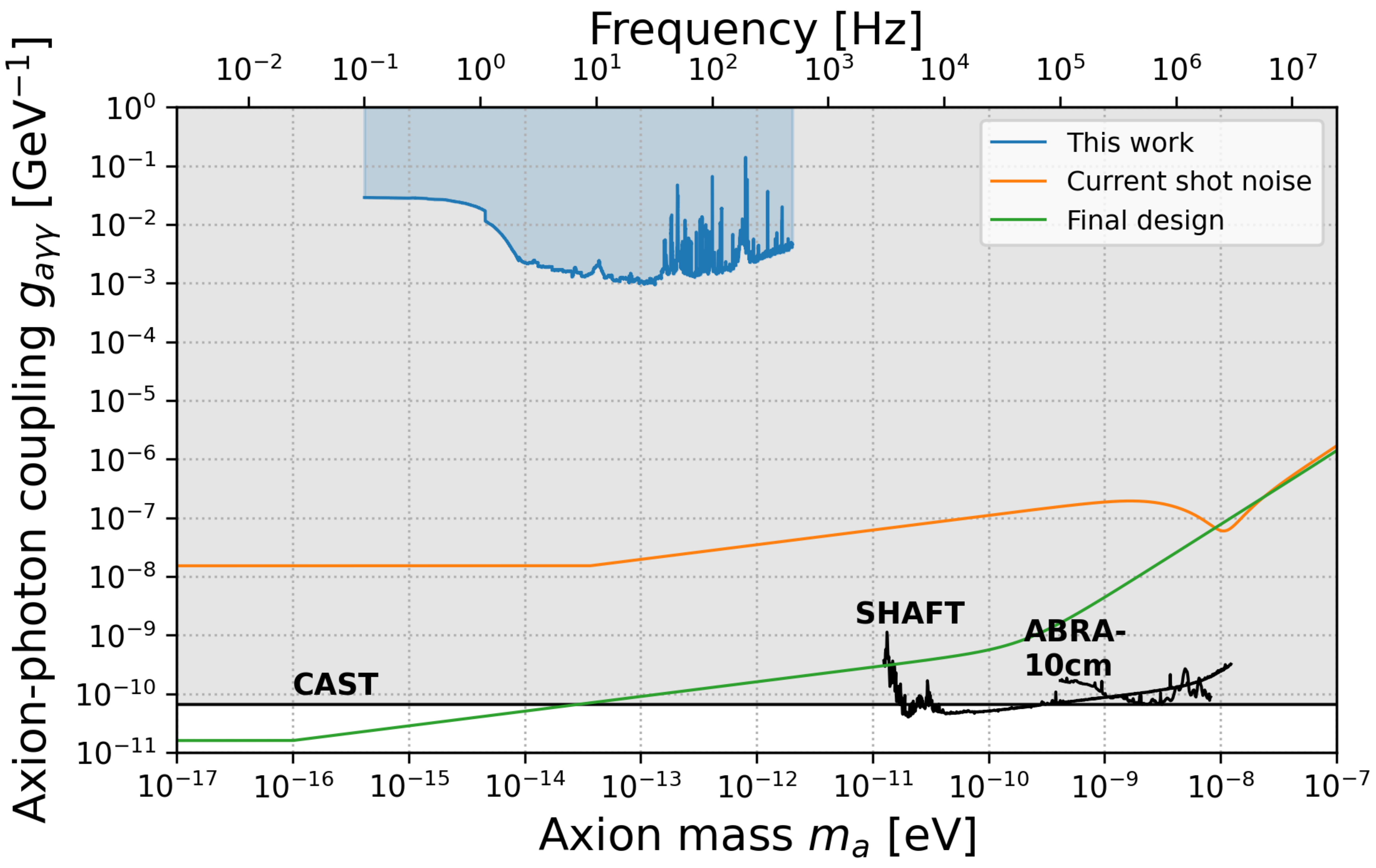
Conduct a sensitive axion search by improving DANCE parameters

Contents

DANCE Act-1

- First demonstration of dark matter axion search with a bow-tie ring cavity
- Upper limit was worse than target sensitivity by 7 orders of magnitude





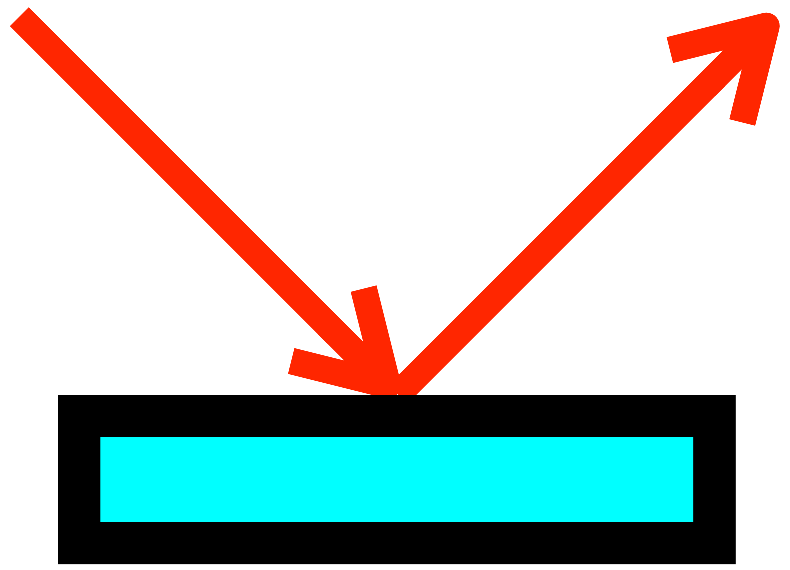
Y. Oshima *et al.*, Phys. Rev. D **108**, 072005 (2023).

Issue: Non-simultaneous resonance

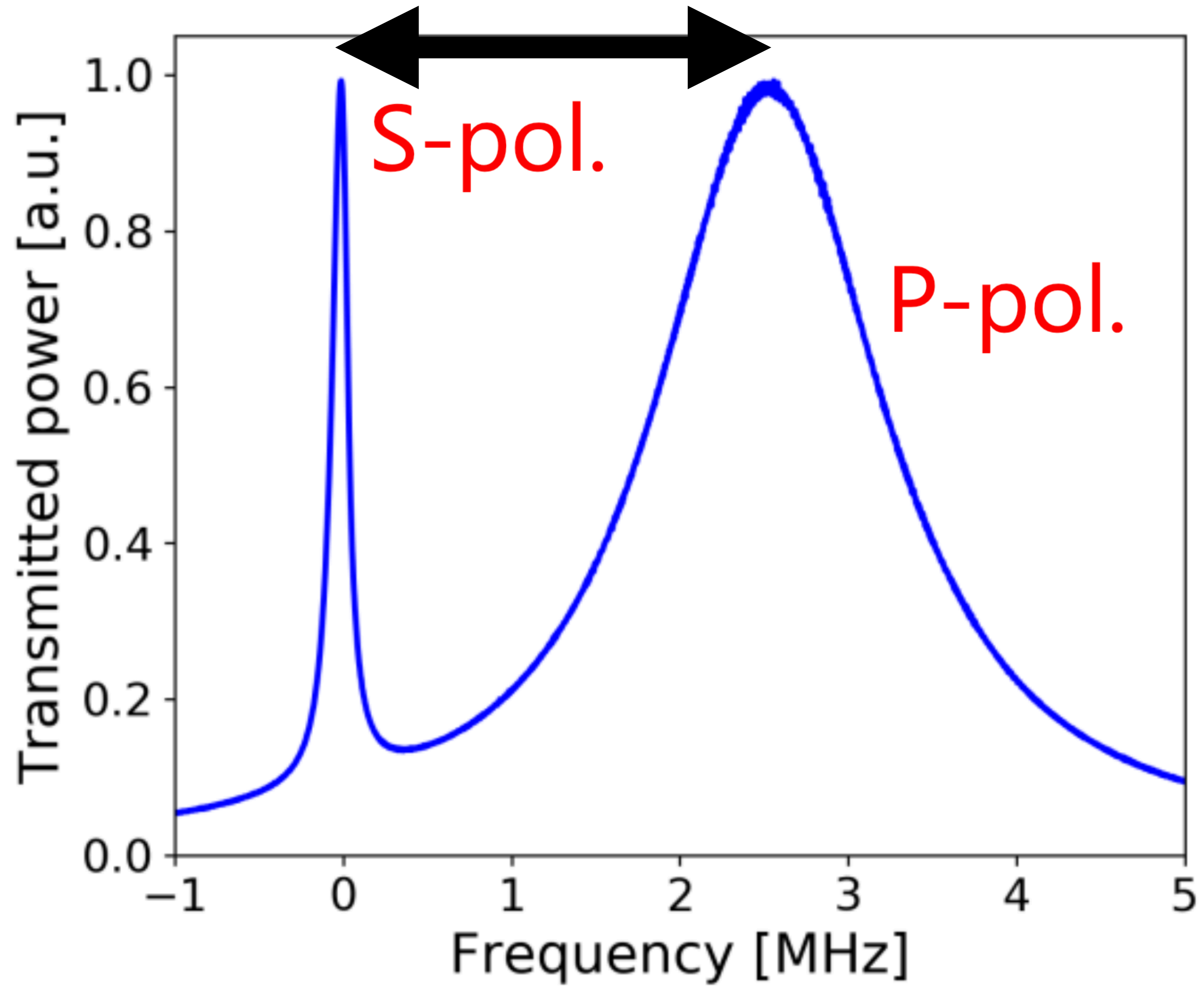
Issue: Degrading the sensitivity due to non-simultaneous resonance

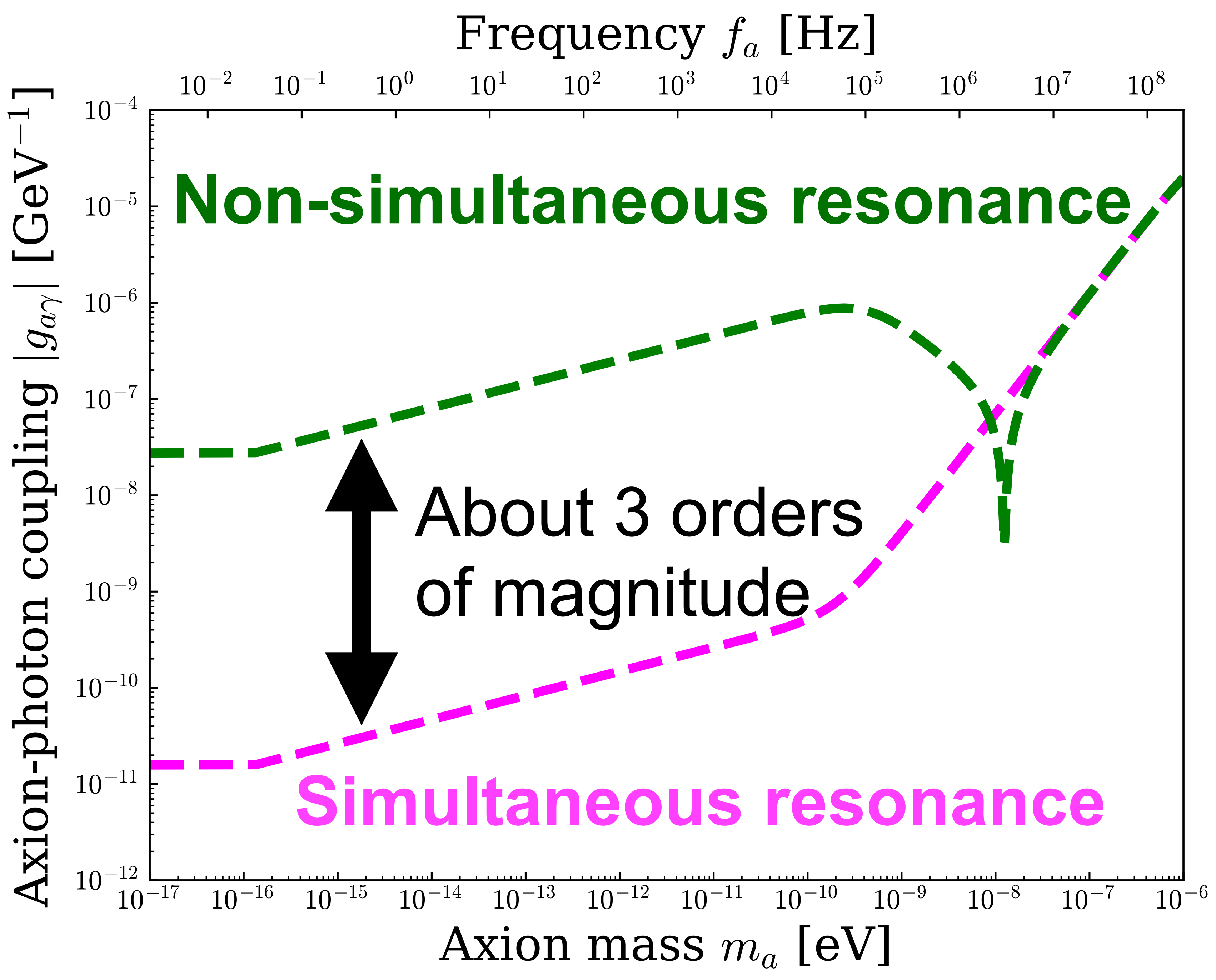
Reflection phase difference between s- and p-pol.

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



Resonant frequency difference between s- and p-pol.





→ Method 1: Auxiliary cavity

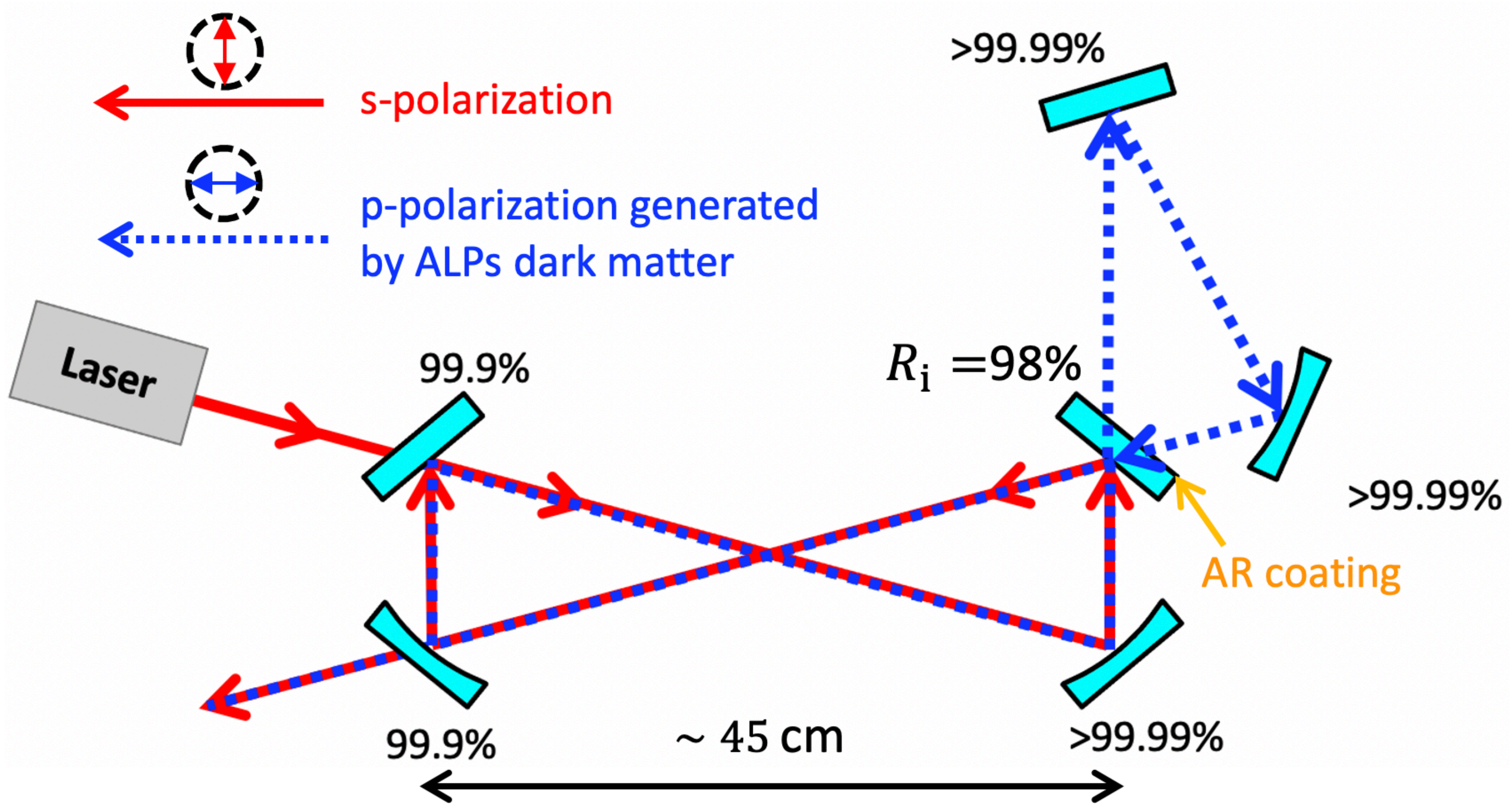
Method 2: Zero phase shift mirror and wavelength tunable laser

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

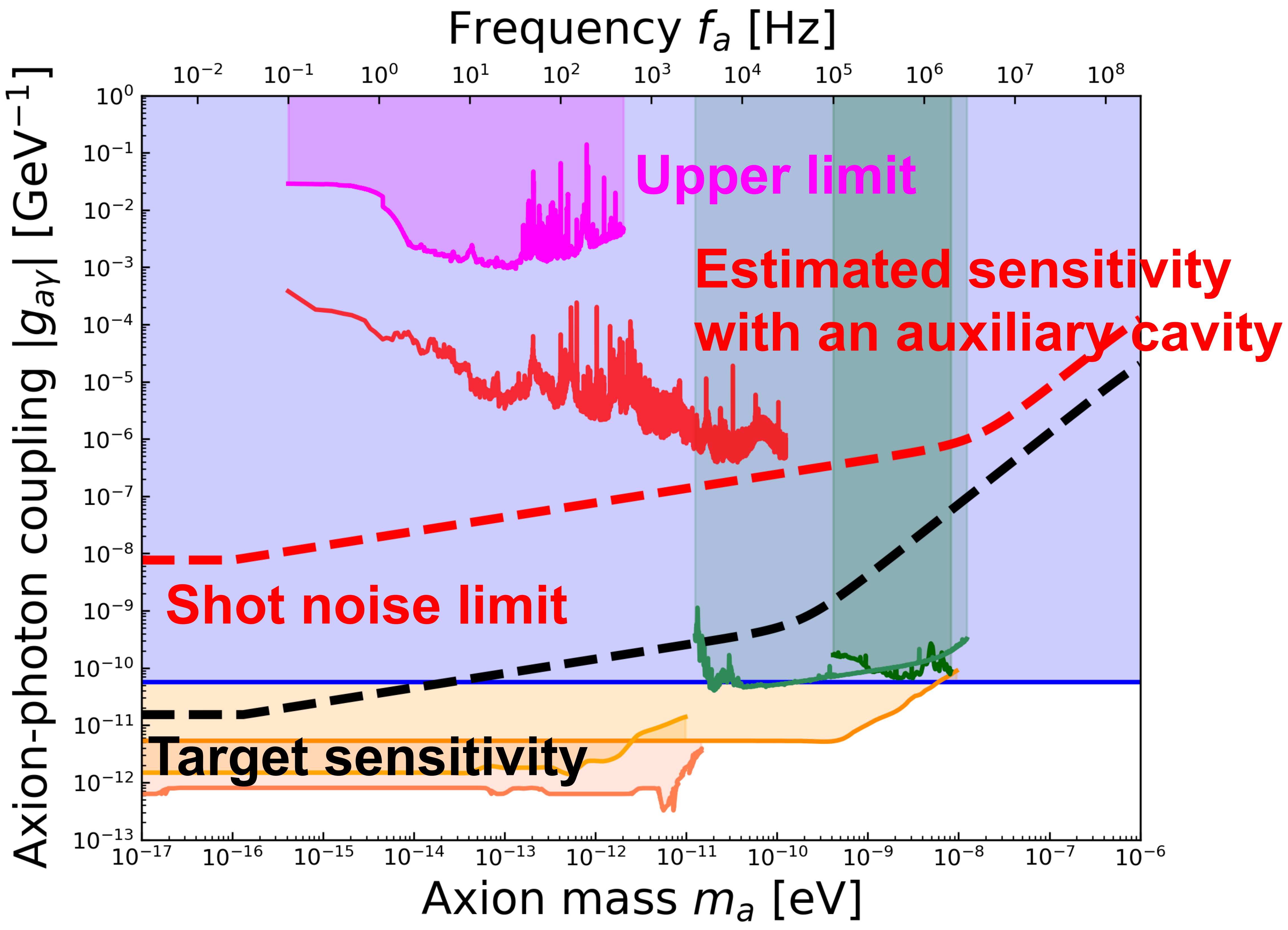
Achievement of simultaneous resonance

Method 1: Auxiliary cavity

- Add an auxiliary cavity to compensate for the resonant frequency difference between s- and p-polarization
- Optical loss generated on PBS between the main and auxiliary cavity degrades the sensitivity



H. Fujimoto *et al*., J. Phys. Conf. Ser. **2156**, 012182 (2021).

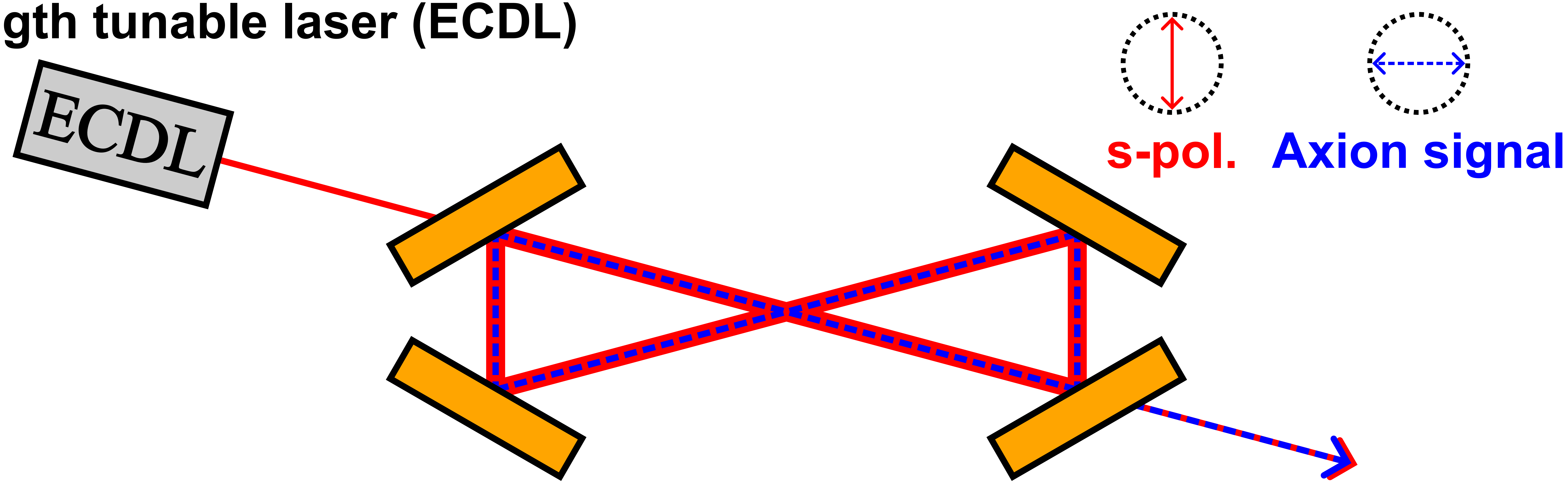


Achievement of simultaneous resonance

Method 2: Zero phase shift mirror and wavelength tunable laser

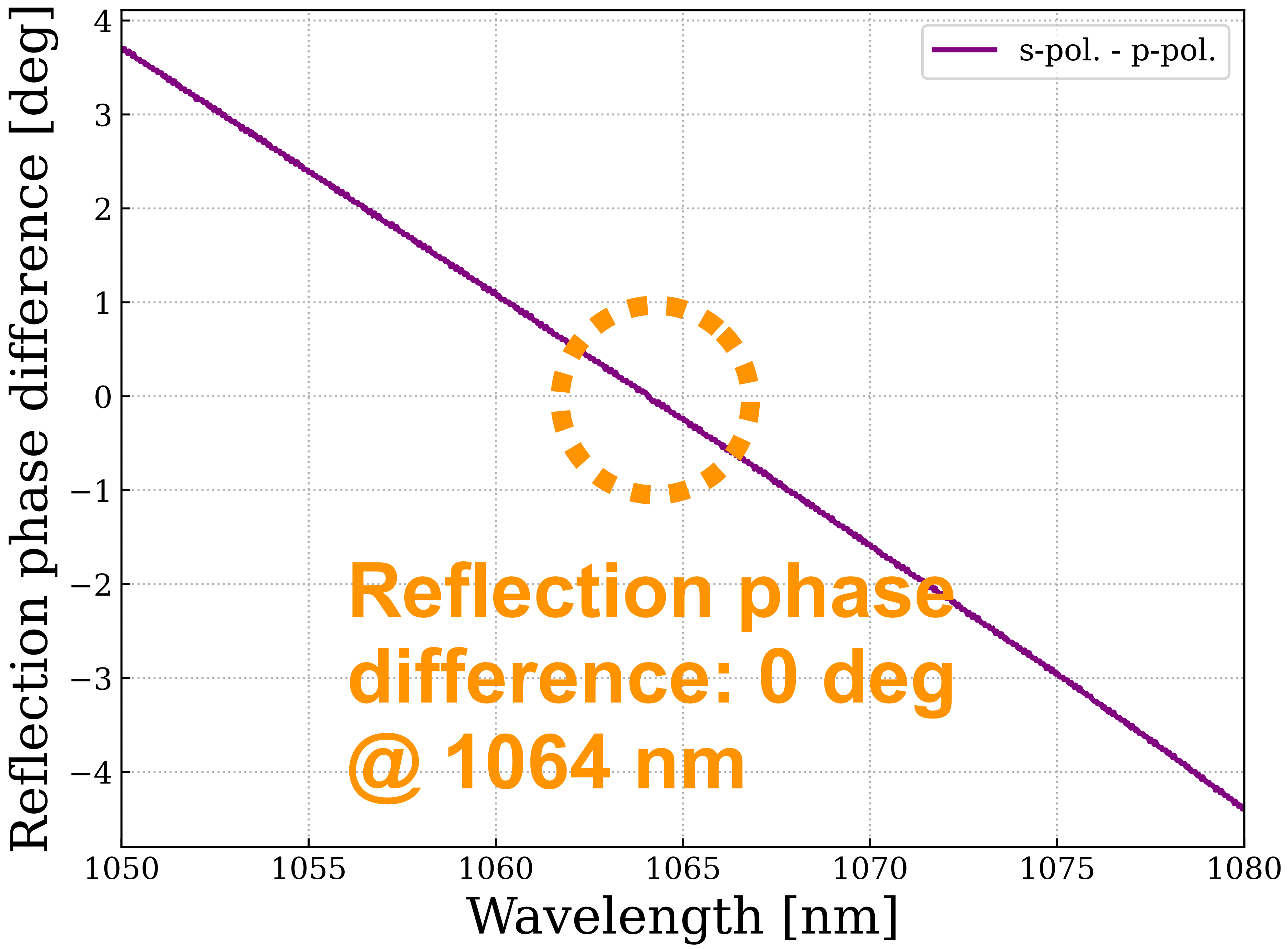
- Tuning the reflection phase difference between s- and p-polarization by tuning the laser wavelength
- Without an auxiliary cavity

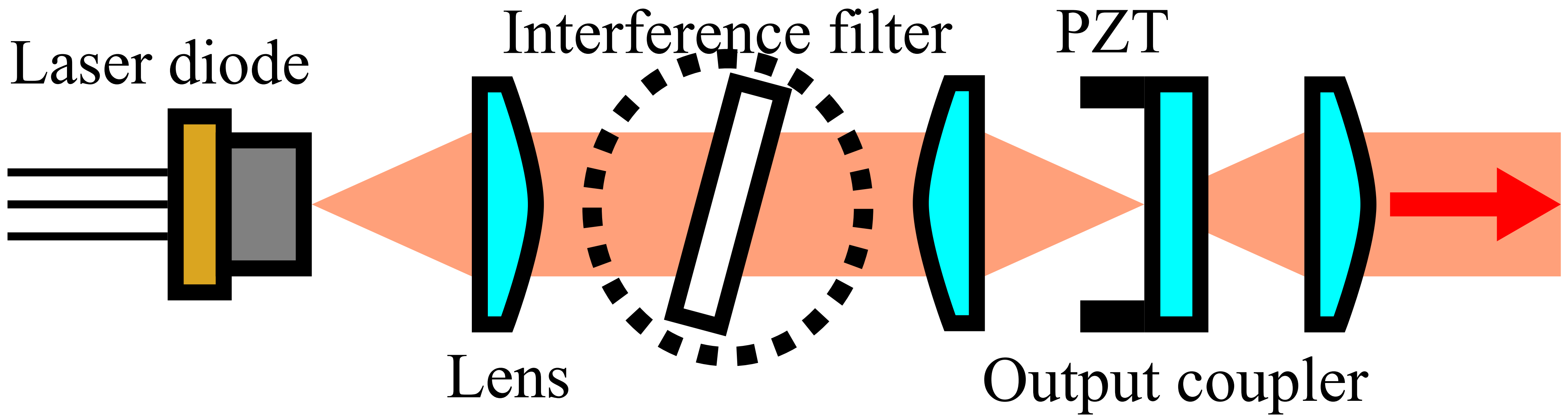
Wavelength tunable laser (ECDL)



Bow-tie cavity with zero phase shift mirrors

Achievement of simultaneous resonance





Select wavelength by rotating interference filter

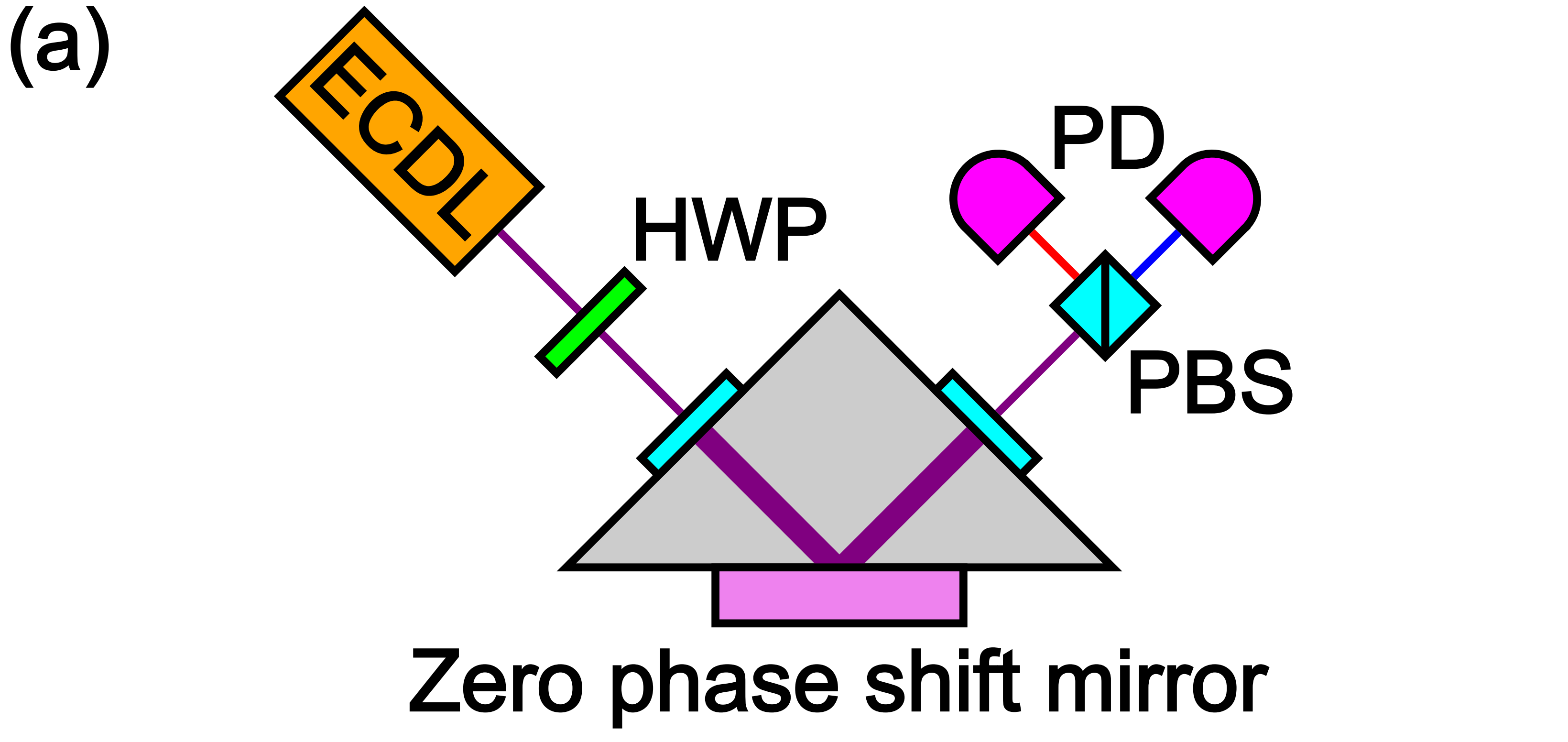
Wavelength tunable laser (ECDL)

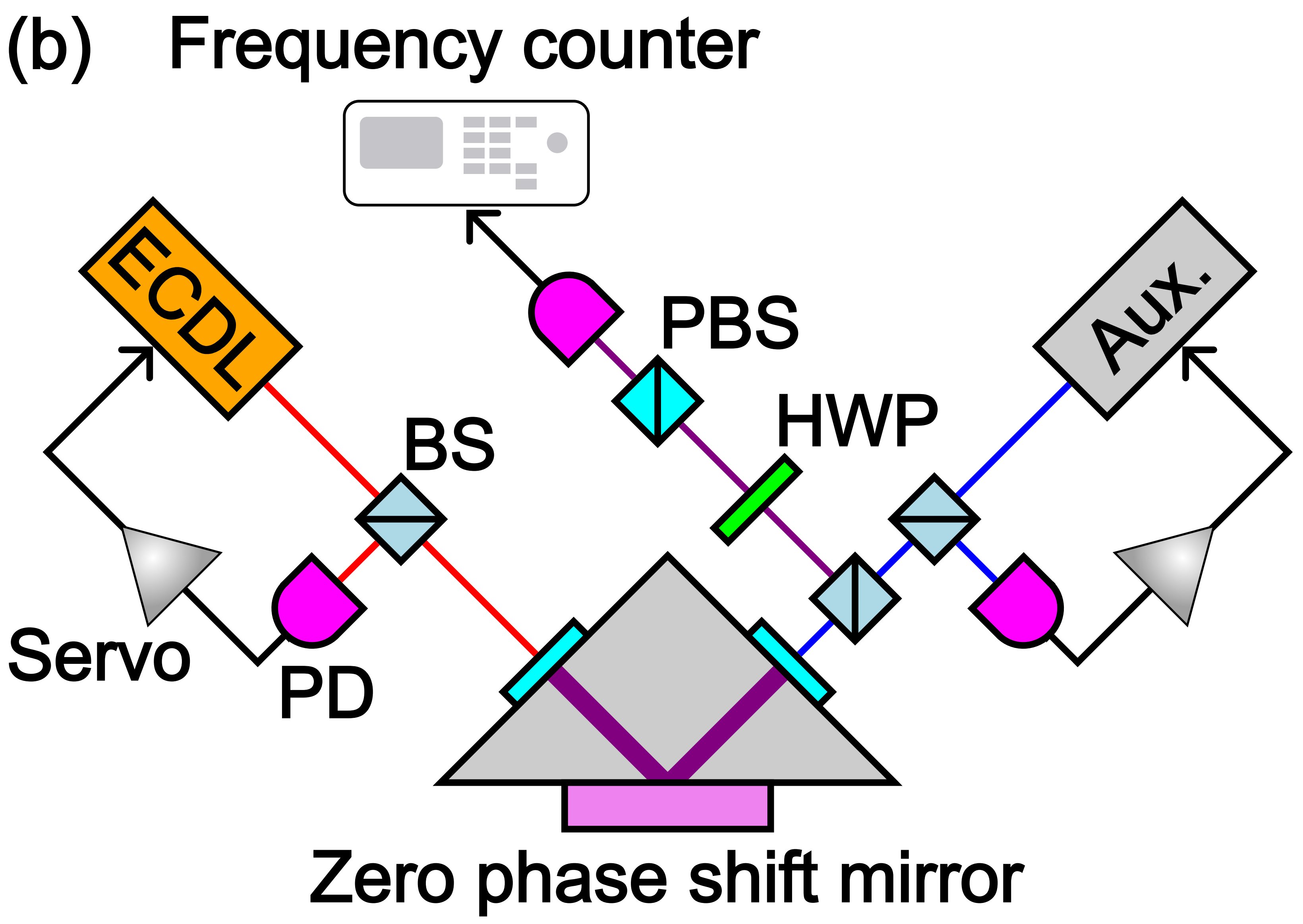
- Wavelength tuning range: 1034 - 1067 nm
- Laser linewidth: 200 kHz
- Output: < 36.5 mW

- Zero phase shift mirror
  - Reflection phase difference is 0 deg at a specific wavelength and angle of incidence
  - Coating thickness error: ± 2 deg >> Requirement: 0.015 deg
- Wavelength tunable laser (ECDL)
  - Coating thickness error can be compensated by tuning laser wavelength

Evaluation of zero phase shift mirror

Measurement of reflection phase difference between s- and p-polarizations per mirror with a folded cavity





(a) Proof of principle for simultaneous resonance

➡Measurement of wavelength that achieves simultaneous resonance

(b) Time fluctuation stability of resonant frequency difference between s- and p-polarizations

➡Measurement of detuning from the simultaneous resonance during long-term observation

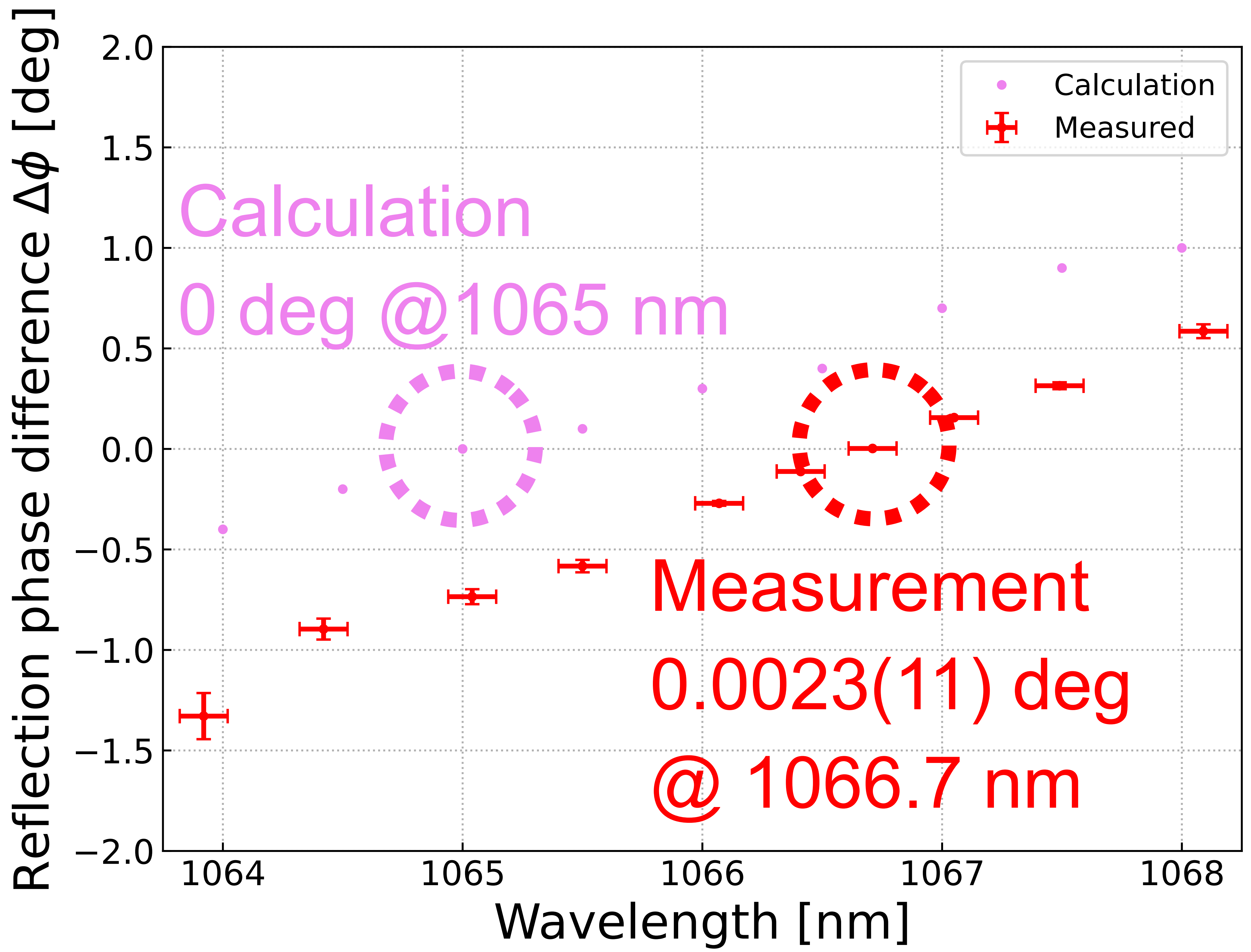
HT *et al.*, Phys. Rev. D **112**, 063048 (2025).

Evaluation of reflection phase difference

(a) Wavelength dependence of reflection phase difference

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

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



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

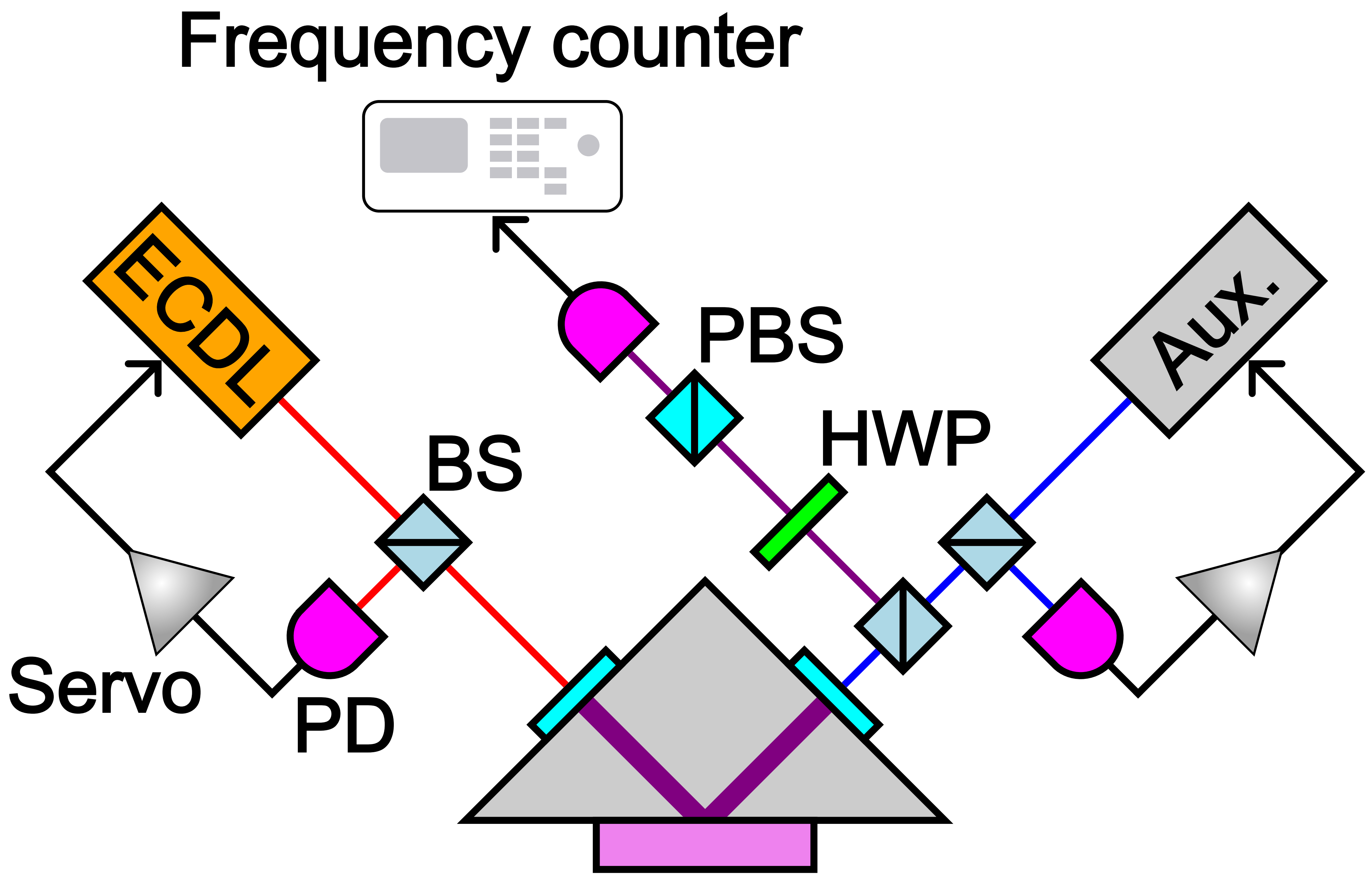
- Satisfied the requirement

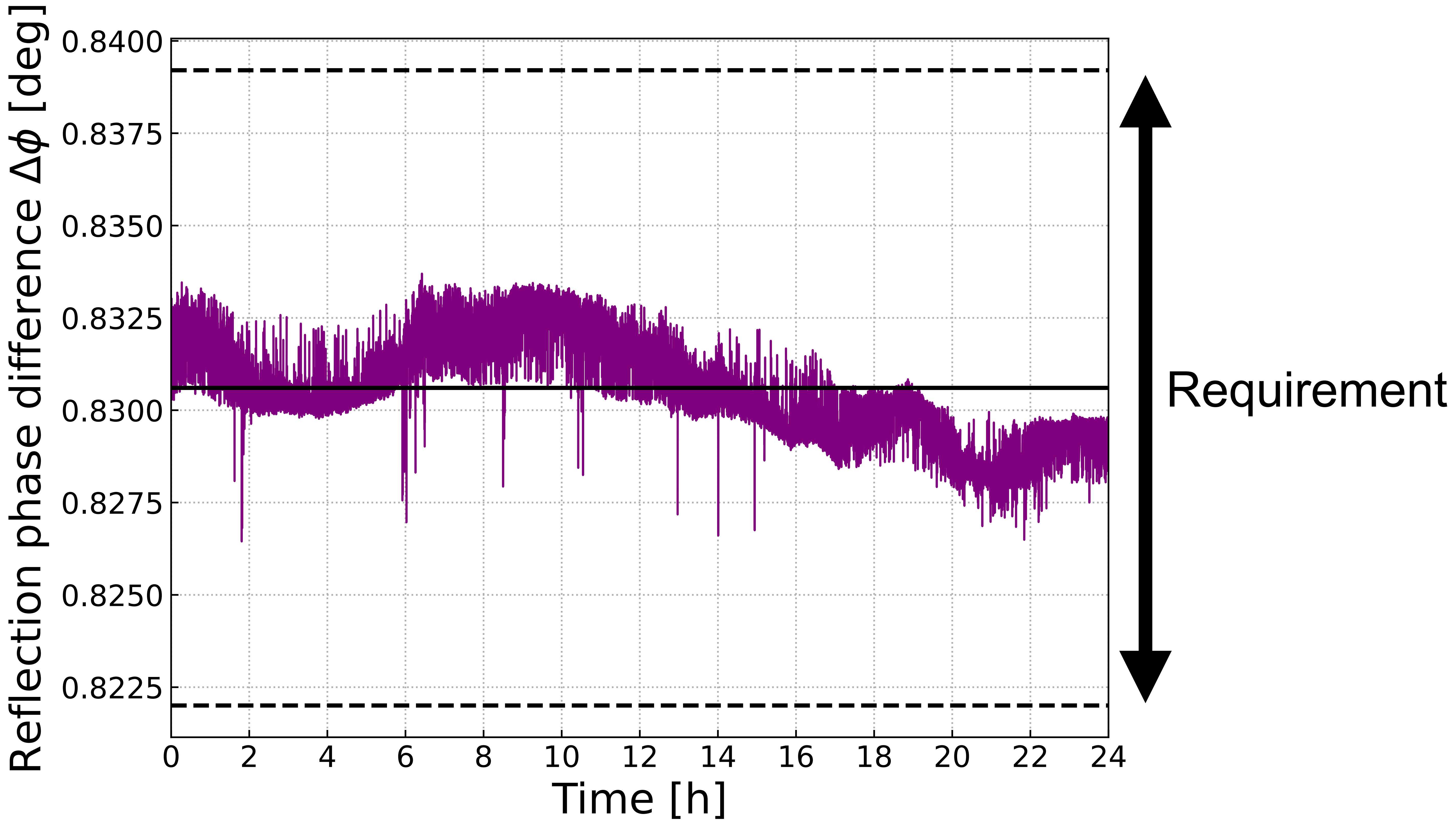
HT *et al.*, Phys. Rev. D **112**, 063048 (2025).

Evaluation of reflection phase difference

(b) Suppress time fluctuations of the beat note between s- and p-pol.

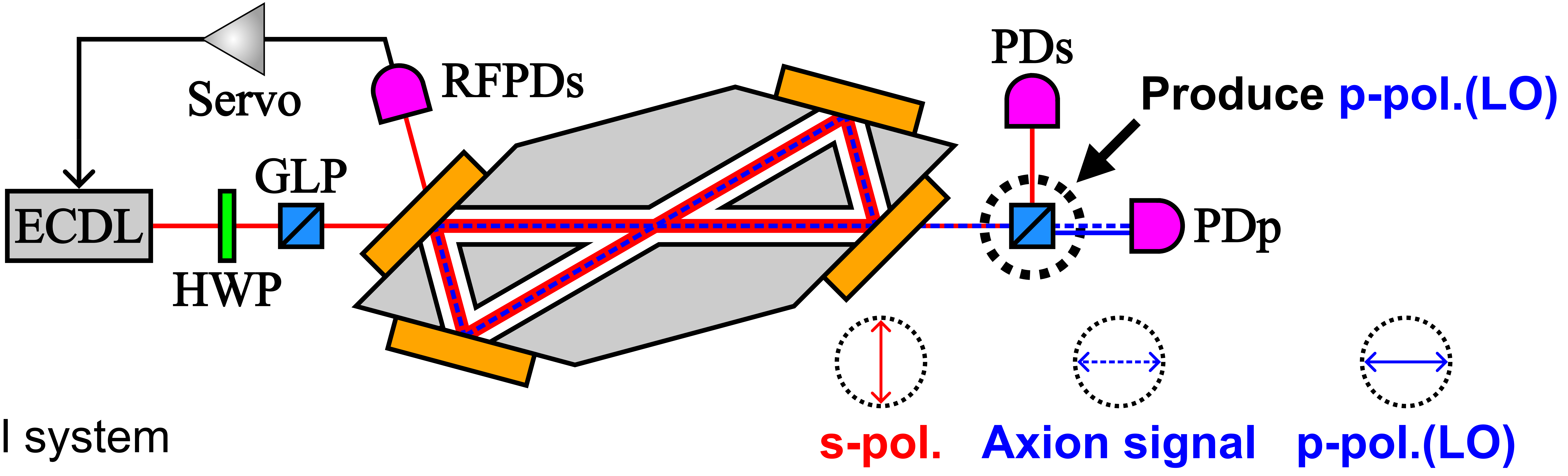
- Satisfied the requirement $|\Delta\phi - \Delta\phi_{\mathrm{ave}}| \leq 8.6 \times 10^{-3}\,\mathrm{deg}$
- Temperature fluctuations are likely to be dominant noise





HT *et al.*, Phys. Rev. D **112**, 063048 (2025).

Experimental setup

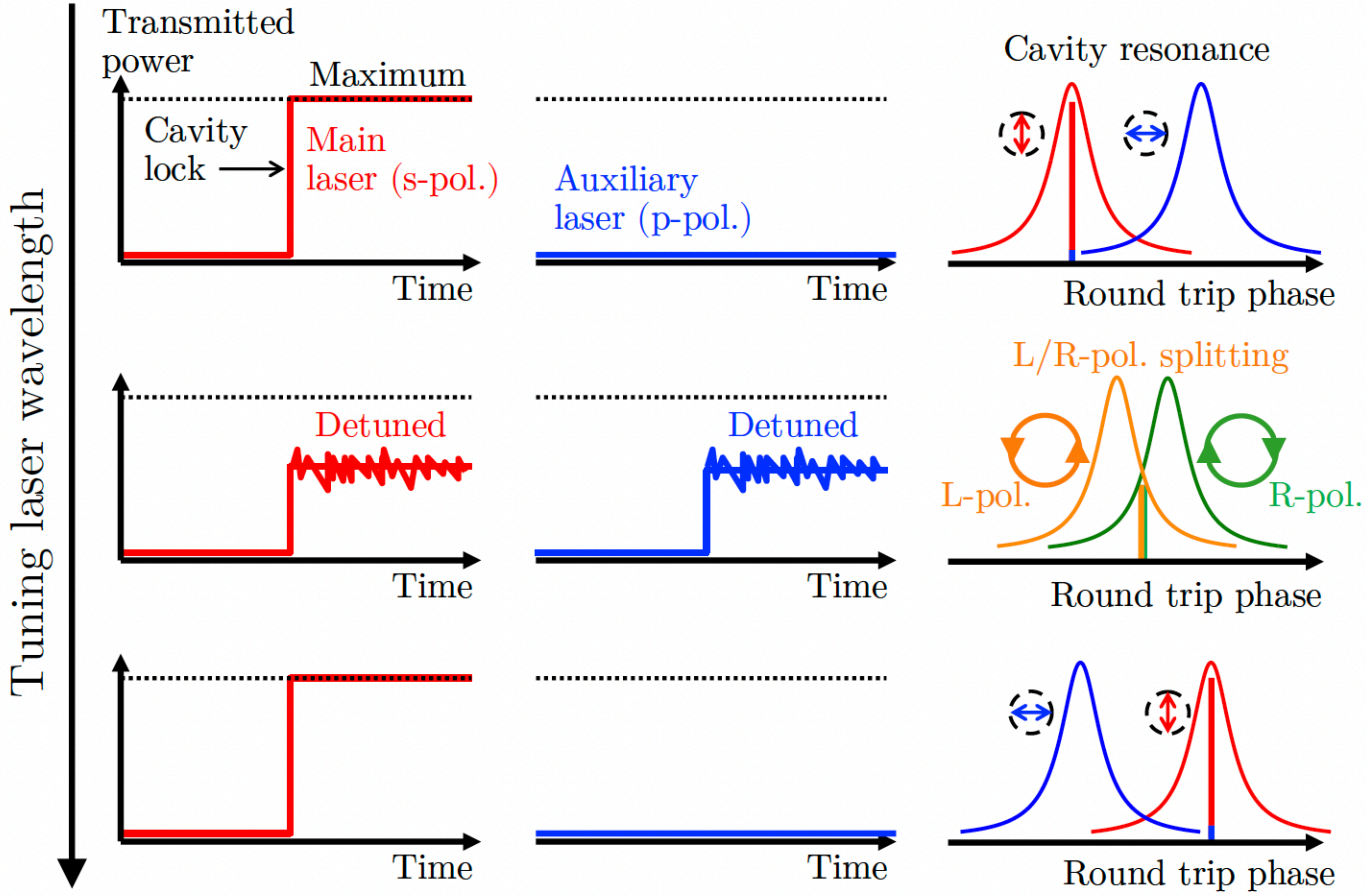


- Control system
  - Low frequency (< 500 Hz): PZT inside ECDL
  - High frequency (> 500 Hz): Current source of LD
  - Control bandwidth: ~ 450 kHz
- Finesse: s-pol.: $2.60(4) \times 10^3$, p-pol.: $2.86(6) \times 10^3$
- Measurement: Rotating output GLP to produce p-pol. (LO) from s-pol.

➡Obtain beat signal between axion signal and the LO

H. Fujimoto, Ph.D. thesis

Issue: L/R-pol. splitting



H. Fujimoto, Ph.D. thesis

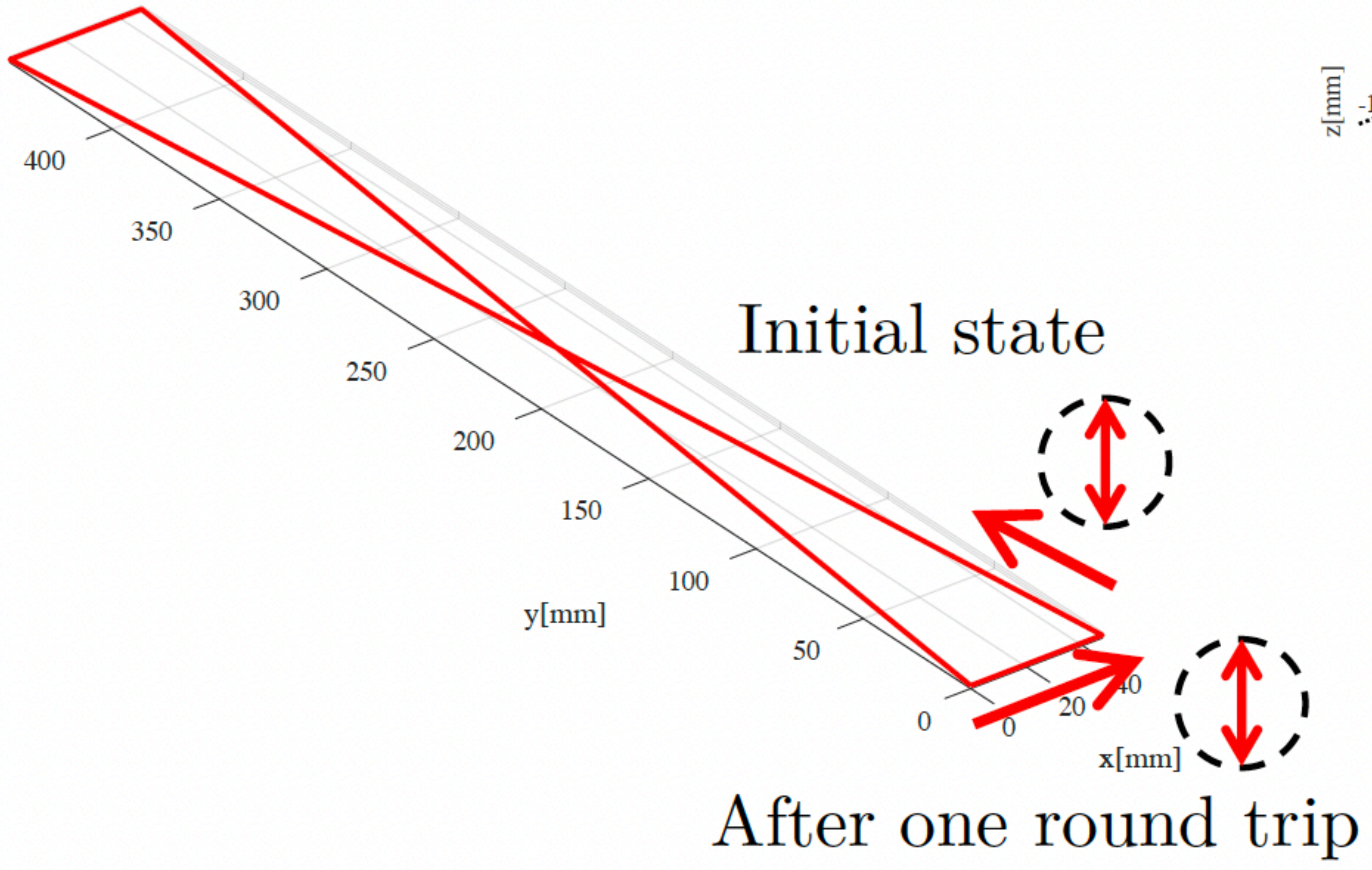
L/R-pol. splitting by cavity non-planarity

In general, when 4 or more mirrors are used, the optical path can be non-planar

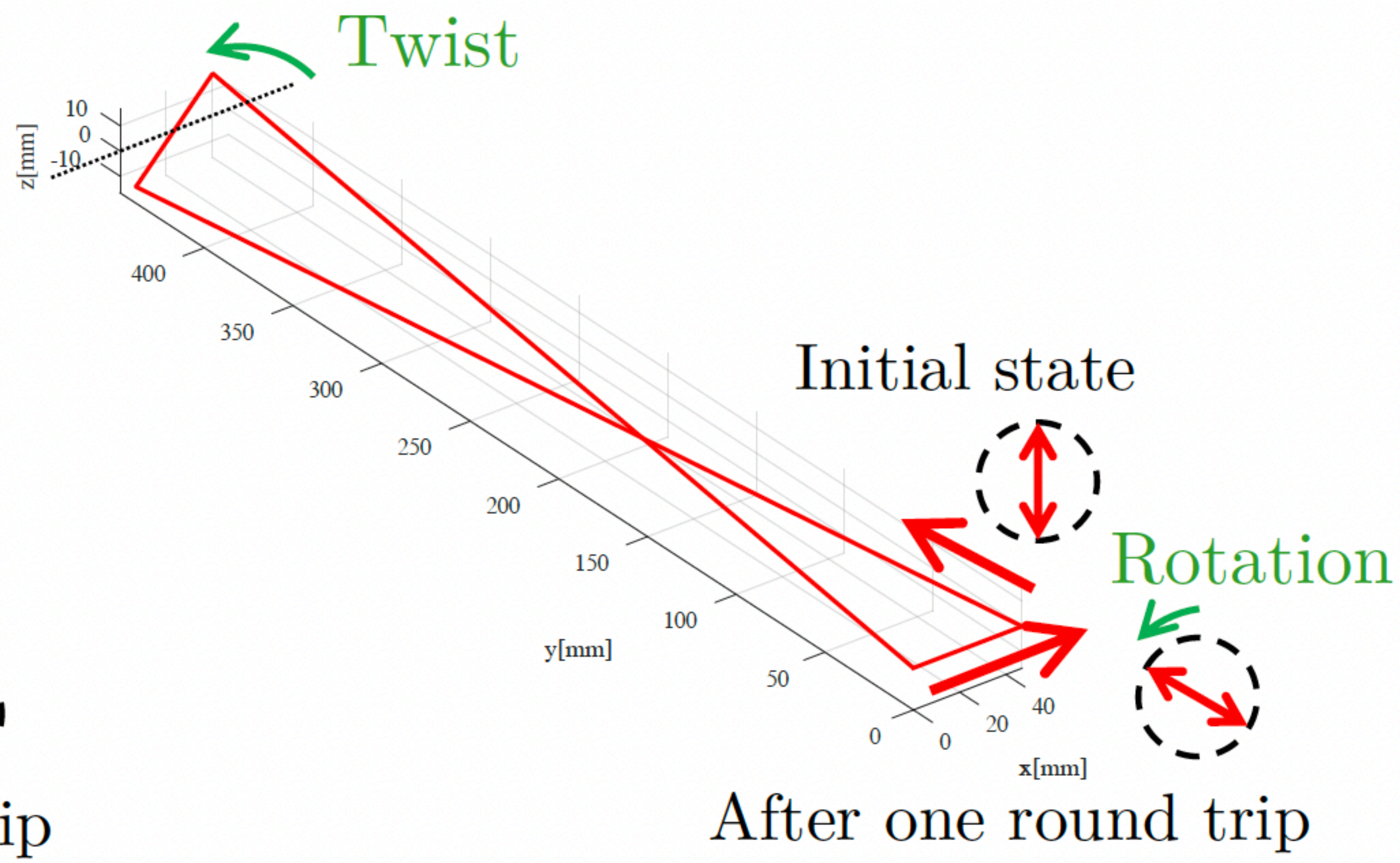
➡DC rotation of linear polarization occurs within the cavity (non-simultaneous resonance of L/R-pol.)

➡Solution: Adjustment of the fastening tightness of the jig that fixes the mirror

➢ Planar cavity



➢ Non-planar cavity



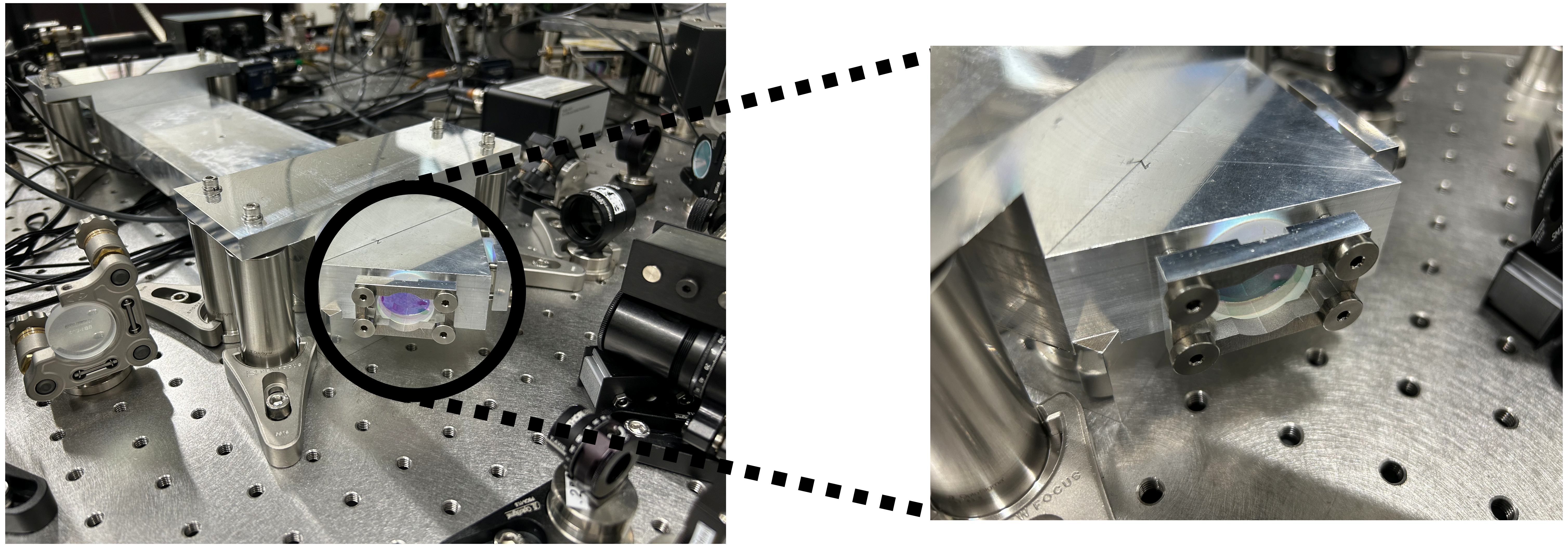
H. Fujimoto, Ph.D. thesis

Adjustment method for cavity non-planarity

① Minimize mixture of p-pol. under non-simultaneous resonance
- Adjust the GLP so that the incident light is s-pol. and the transmitted polarization is p-pol.
- Tune the tightness of the jig

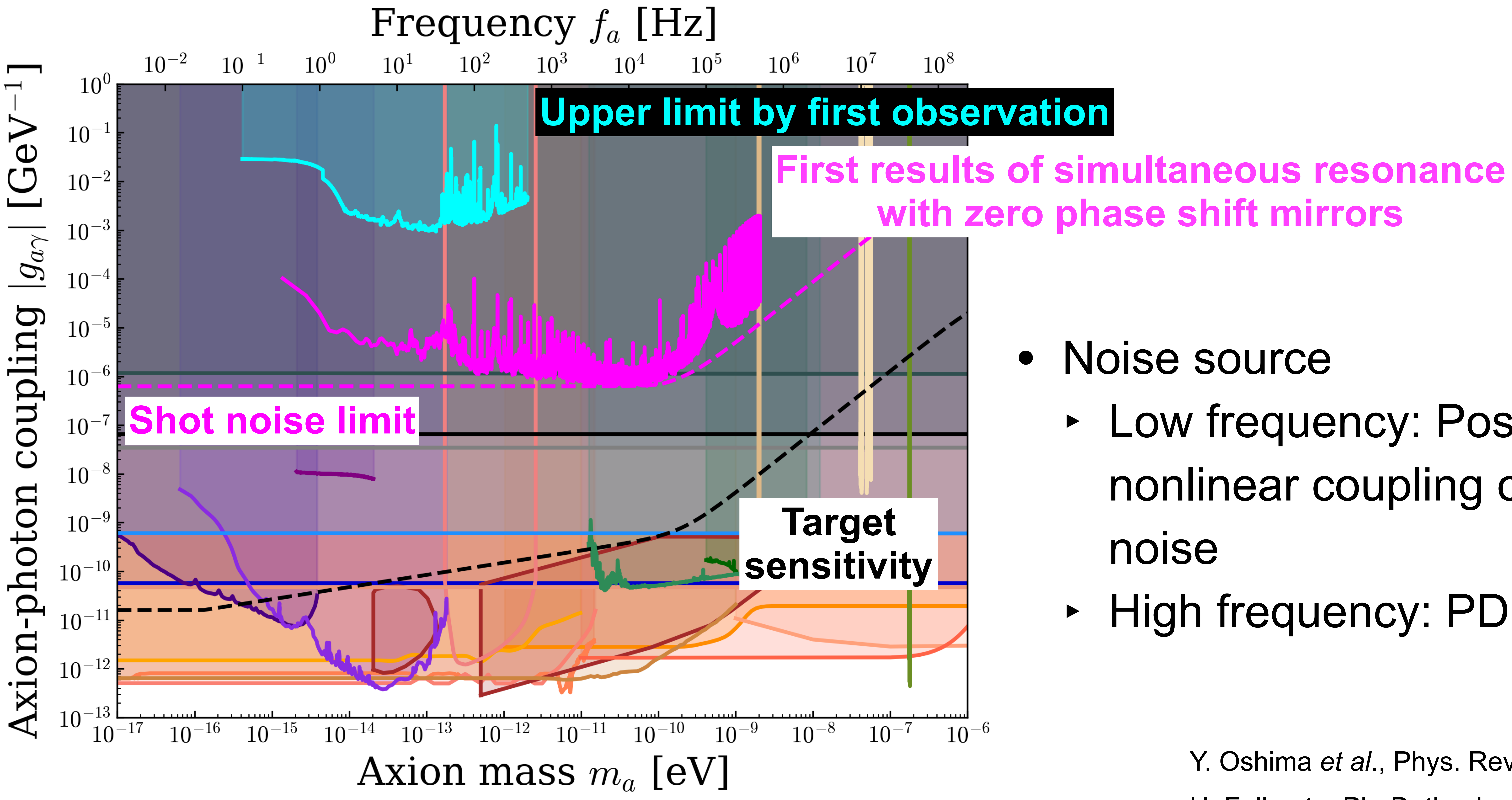
② Change the laser wavelength to a wavelength that achieves simultaneous resonance

③ Readjust the jig fastening to eliminate the residual cavity non-planarity



H. Fujimoto, Ph.D. thesis

Sensitivity in Ph.D. thesis



- Noise source
  - Low frequency: Possibility of nonlinear coupling of frequency noise
  - High frequency: PD dark noise

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

H. Fujimoto, Ph. D. thesis

Contents

- Introduction of dark matter search
- Principle of DANCE
- DANCE Act-1
  - Previous research
  - Sensitivity improvement strategies
- Summary

Research roadmap

DANCE Act-1

- Simultaneous resonance
- Identify noise
- Noise reduction
- Improve shot noise limit

- Long cavity
- High finesse
- High power

→ **Final DANCE**

Necessary to achieve target sensitivity of DANCE Act-1

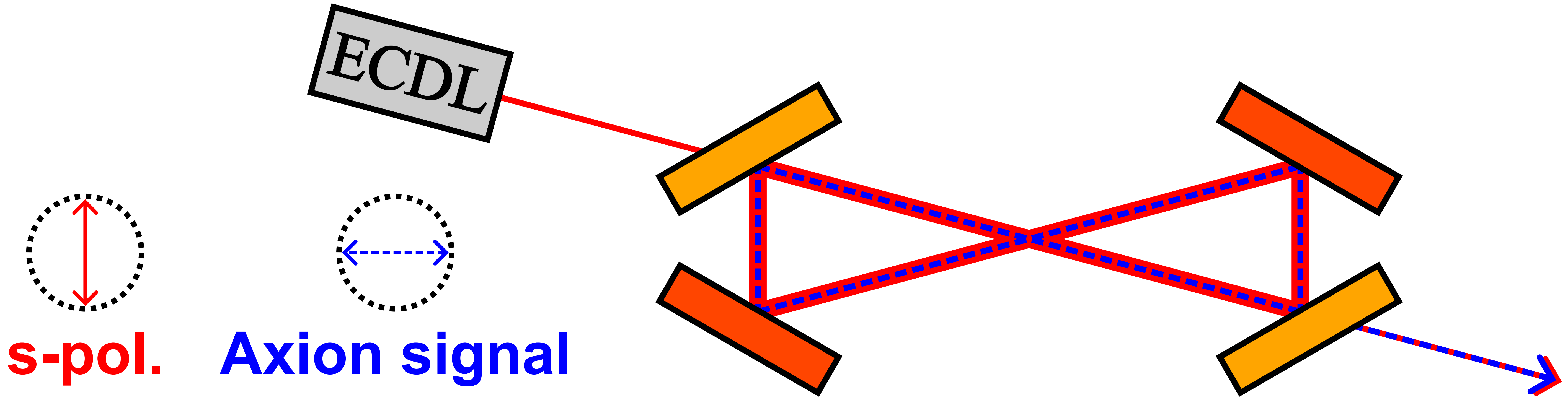
① Critical couple cavity
  - Cavity transmission: ~2.4x better (17% → 99%)
  - Finesse: ~2.2x better (s-pol.: 2600 → 6200, p-pol.: 2860 → 5900)

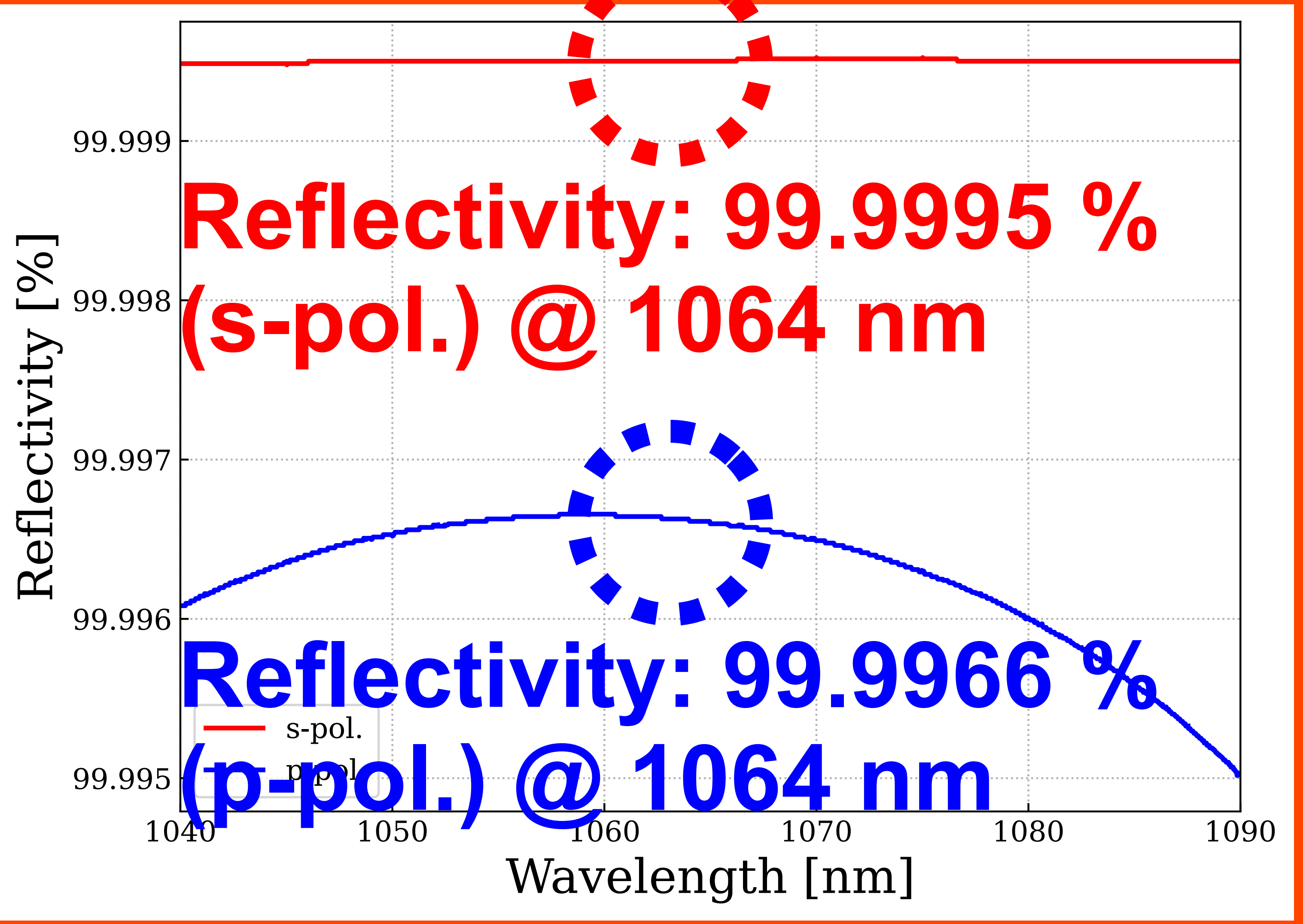
② Input power increase via power amplifier: ~1 order better (6 mW → 1 W)

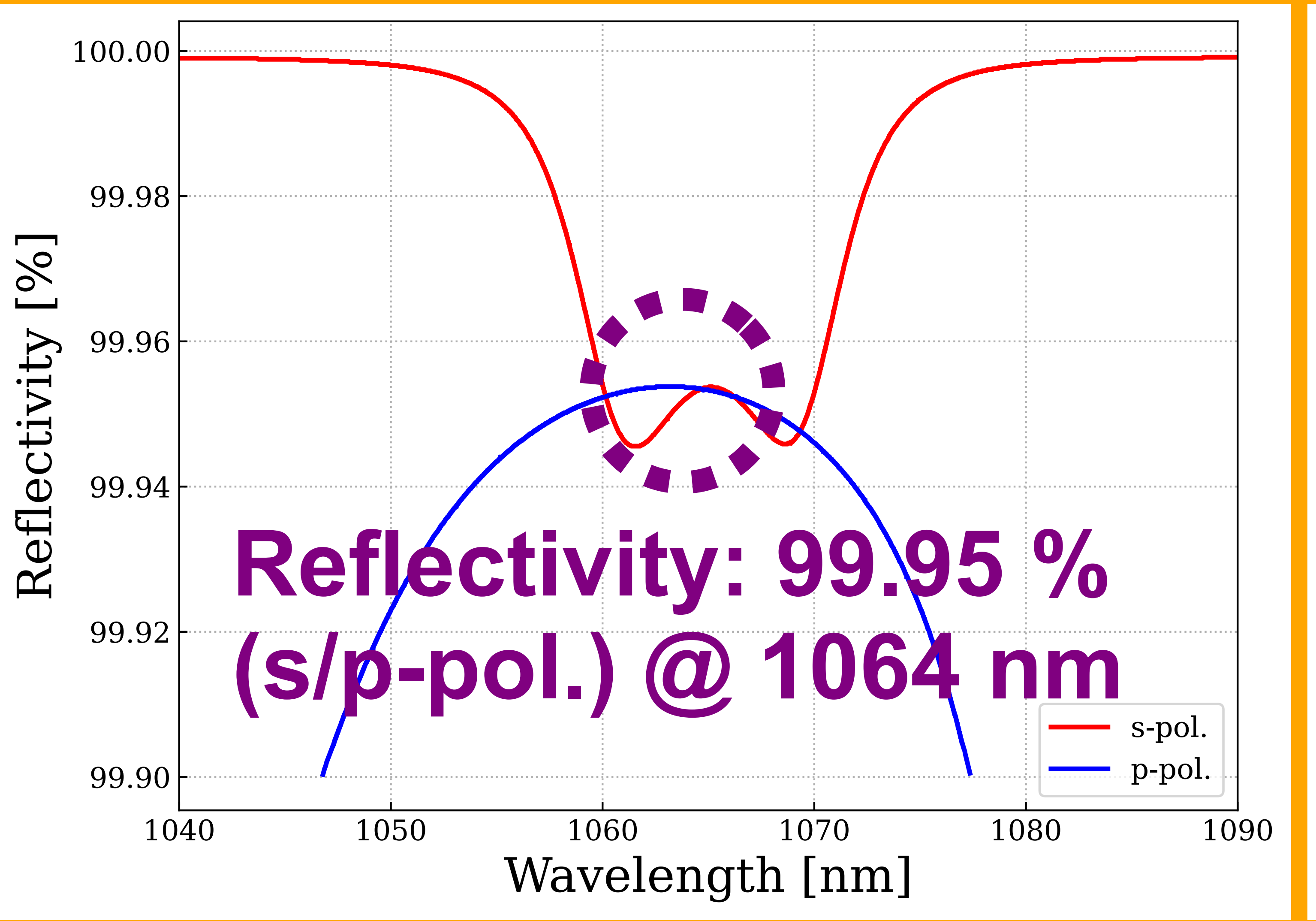
③ Long-term observation: ~2 - 3 orders better (30 s → 1 month)

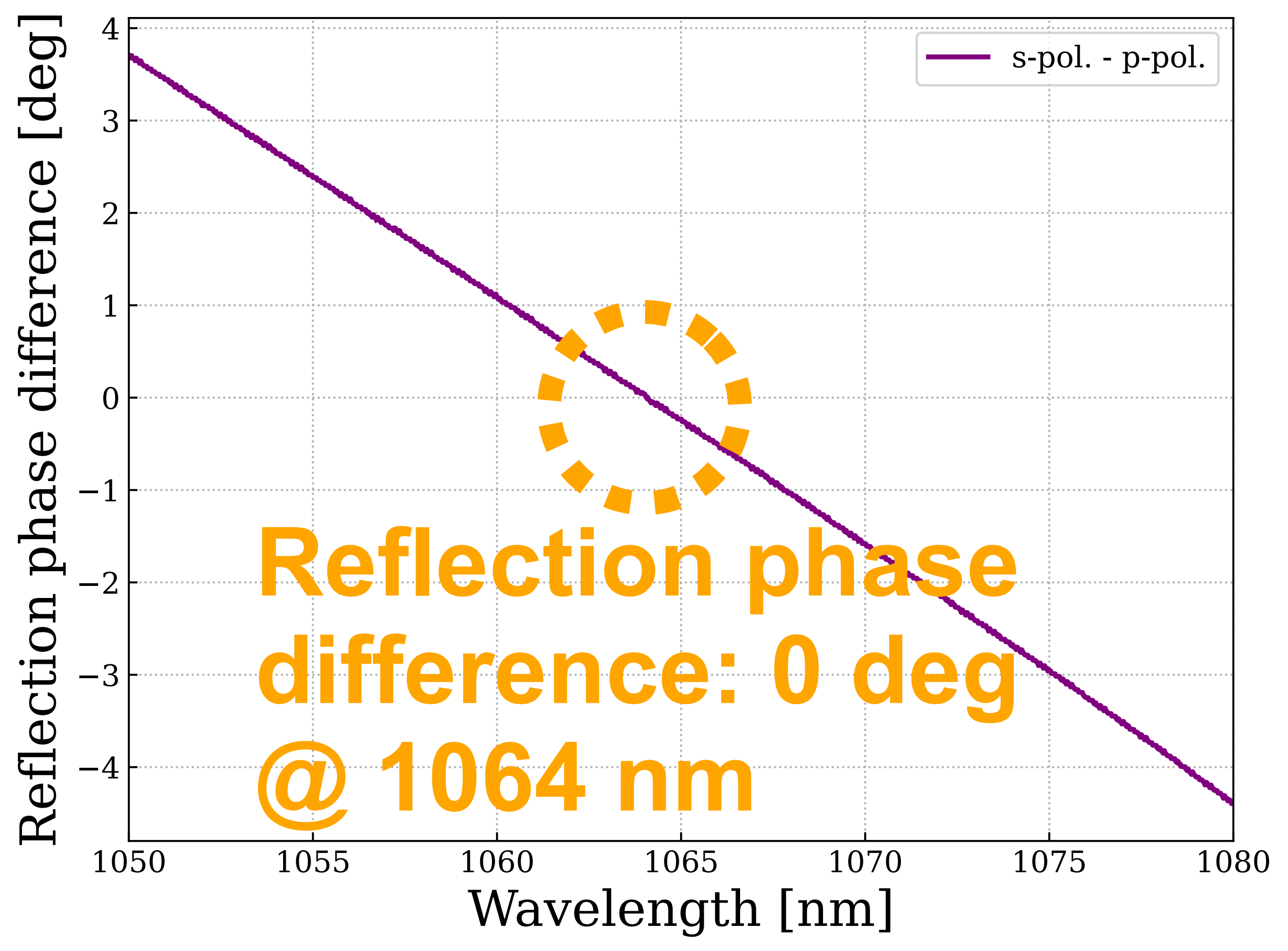
Critical couple cavity

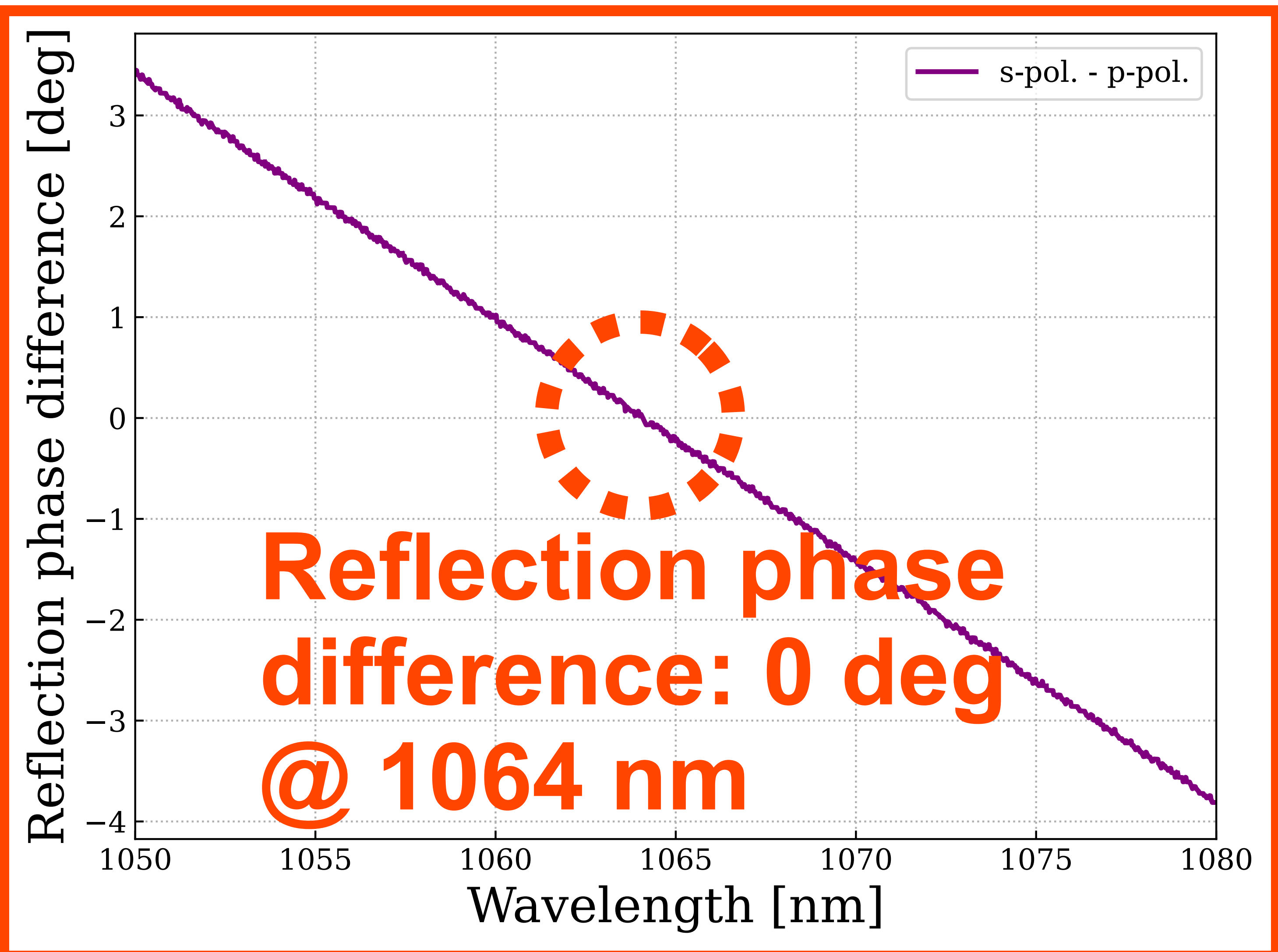
Replaced 2 out of 4 mirrors with high reflectivity zero phase shift mirrors



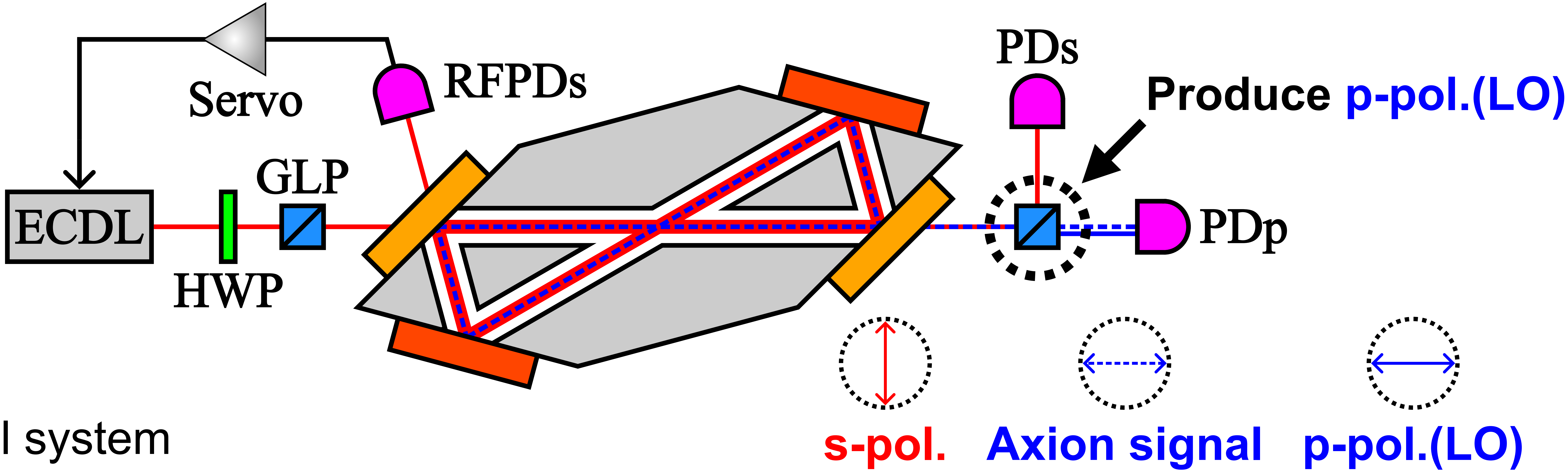








Experimental setup



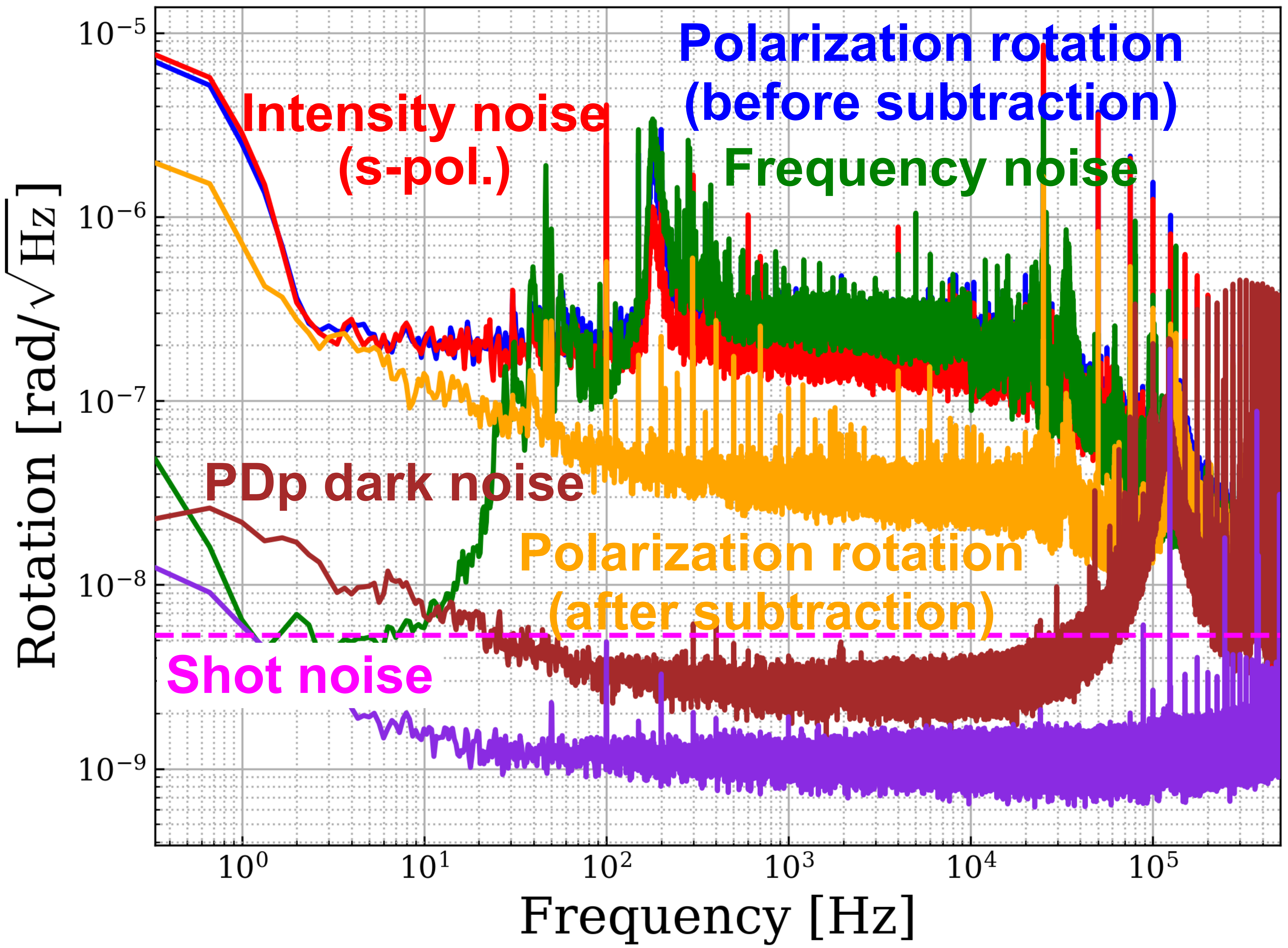
- Control system
  - Low frequency (< 400 Hz): PZT inside ECDL
  - High frequency (> 400 Hz): Current source of LD
  - Control bandwidth: ~ 450 kHz
- Finesse: s-pol.: $4.8(6) \times 10^3$, p-pol.: $4.8(5) \times 10^3$
- Measurement: Rotating output GLP to produce p-pol. (LO) from s-pol.

➡Obtain beat signal between axion signal and the LO

Polarization rotation spectrum

Residual resonant frequency difference: 5.3(5) kHz

➡Satisfy requirement (within HWHM): 25.6 kHz



- Changed from 1065.99(2) nm to 1064.83(2) nm

➡Error of mirror coating thickness

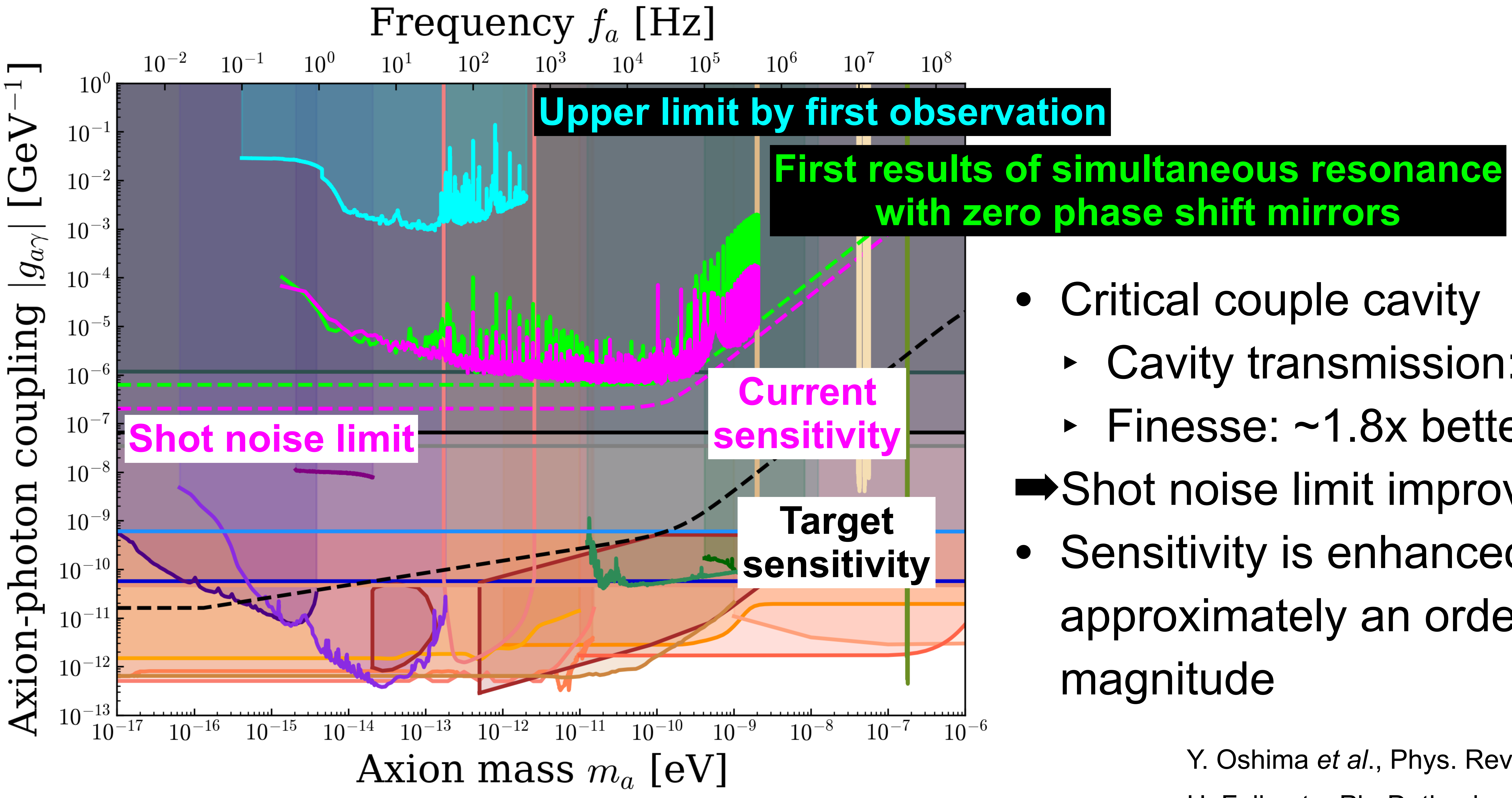
- Subtract noise by offline analysis

➡Successful subtraction by up to ~1 order of magnitude

- < 60 kHz: Possibility of nonlinear coupling of frequency noise
- > 60 kHz: Limited by PDp dark noise

➡Sensitivity did not reach shot noise

Current sensitivity



- Critical couple cavity
  - Cavity transmission: ~1.6x better
  - Finesse: ~1.8x better

➡Shot noise limit improved by ~2.9x

- Sensitivity is enhanced by up to approximately an order of magnitude

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

H. Fujimoto, Ph. D. thesis

Power amplifier for ECDL

CW Ytterbium Fiber Amplifier

- Wavelength range: 1060 - 1075 nm
- Input power range: 1 - 31.6 mW
- Input/output fiber type: PANDA 980
- Maximum output power: 1.995 W

Intensity noise of power amplified ECDL is expected to be worse in low frequency due to electronic noise from current driver in power amp.

➡Intensity noise subtraction may not be sufficient due to common mode rejection ratio (CMRR)

➡Introduce intensity stabilization system (ISS)

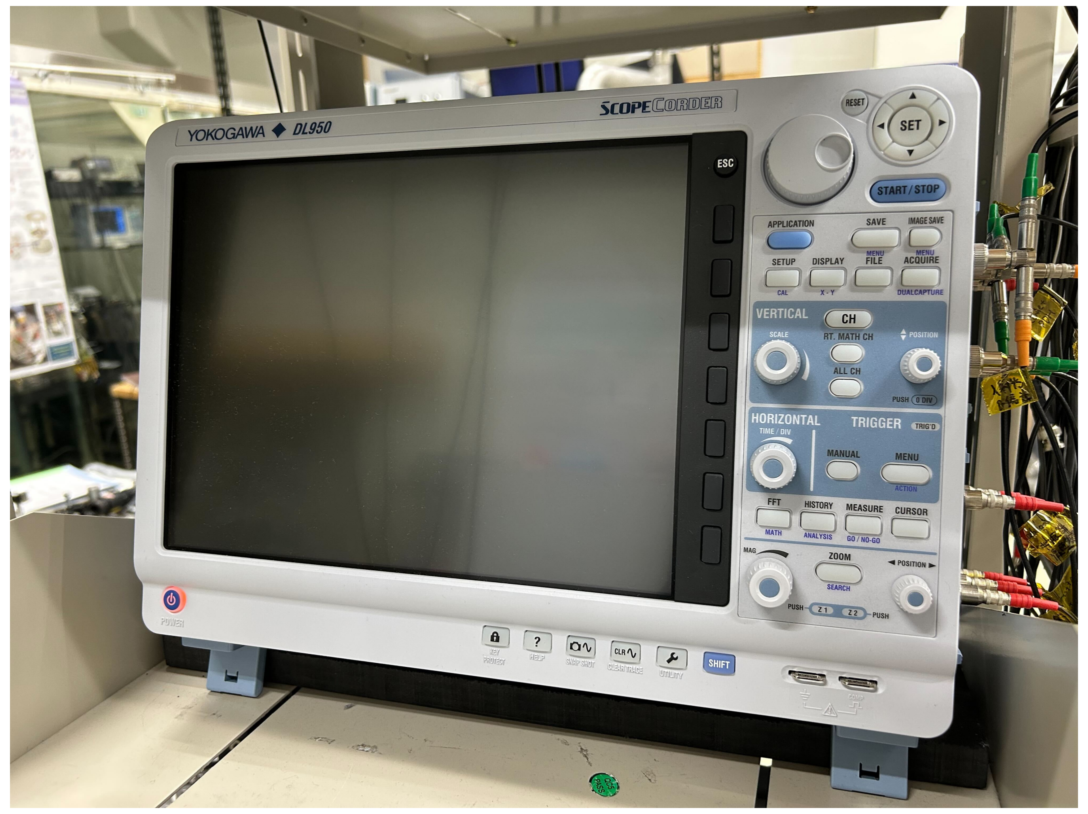
Data logger for long-term observation

Plan to use 5ch during measurements

- PDs (AC/DC coupling)
- PDp (AC/DC coupling)
- Error signal

➡Sampling rate of DL950 is better than that of DL850E

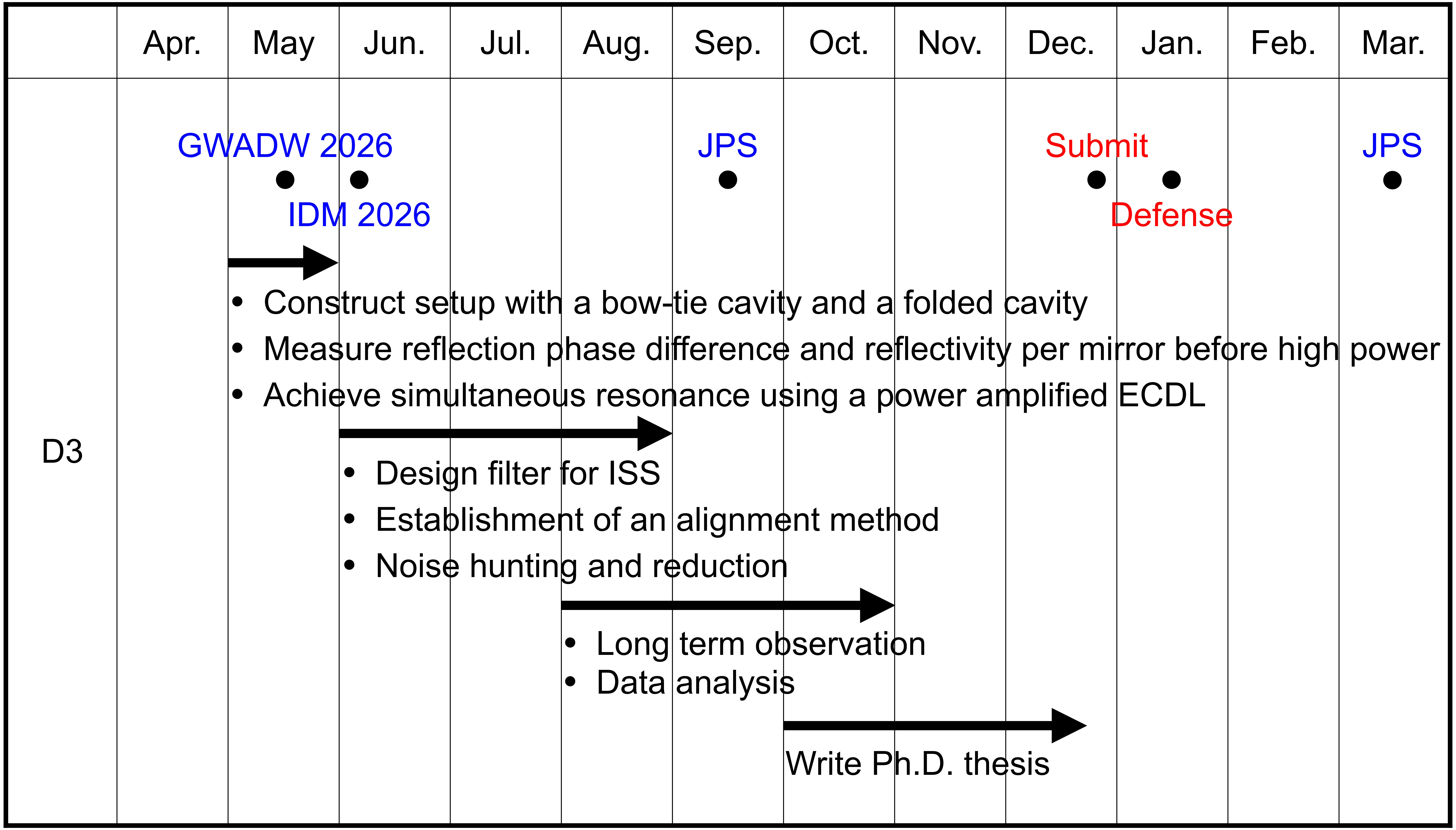
➡Replace DL850E with DL950 and conduct long-term observation



DL950

Measurement time	Sampling rate [Hz] (DL850E)	Sampling rate [Hz] (DL950)
20 h	1k	10k
5 days	200	1k
30 days	20	100

Schedule toward Ph.D.



Contents

- Introduction of dark matter search
- Principle of DANCE
- DANCE Act-1
  - Previous research
  - Sensitivity improvement strategies
- Summary

Summary

DANCE: Dark matter Axion search with riNg Cavity Experiment

- Search for axion dark matter with a bow-tie cavity
- Succeeded in realizing simultaneous resonance with a critical couple cavity
- Currently developing a system to improve shot noise limit
- I would like to amplify the power of ECDL and achieve simultaneous resonance as soon as possible
- I aim to complete DANCE Act-1 and present roadmap toward Final DANCE in my Ph.D. thesis