Recent progress of Dark matter Axion search with riNg Cavity Experiment (DANCE)

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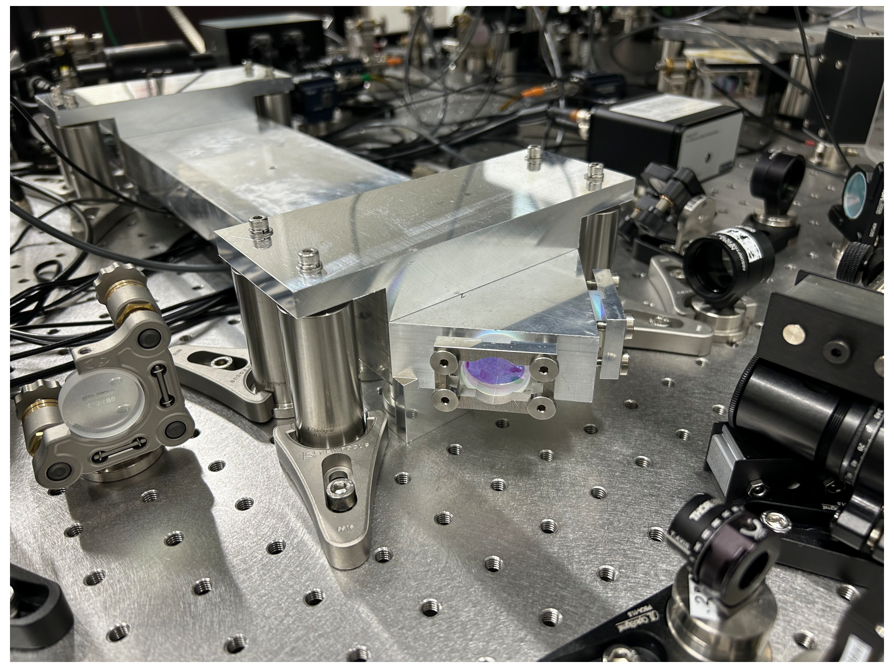
Ultralight dark matter: Axion

- One of the leading candidates of dark matter: Axion
- Axion behaves as classical waves
- Laser interferometer can be sensitive to this oscillation

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

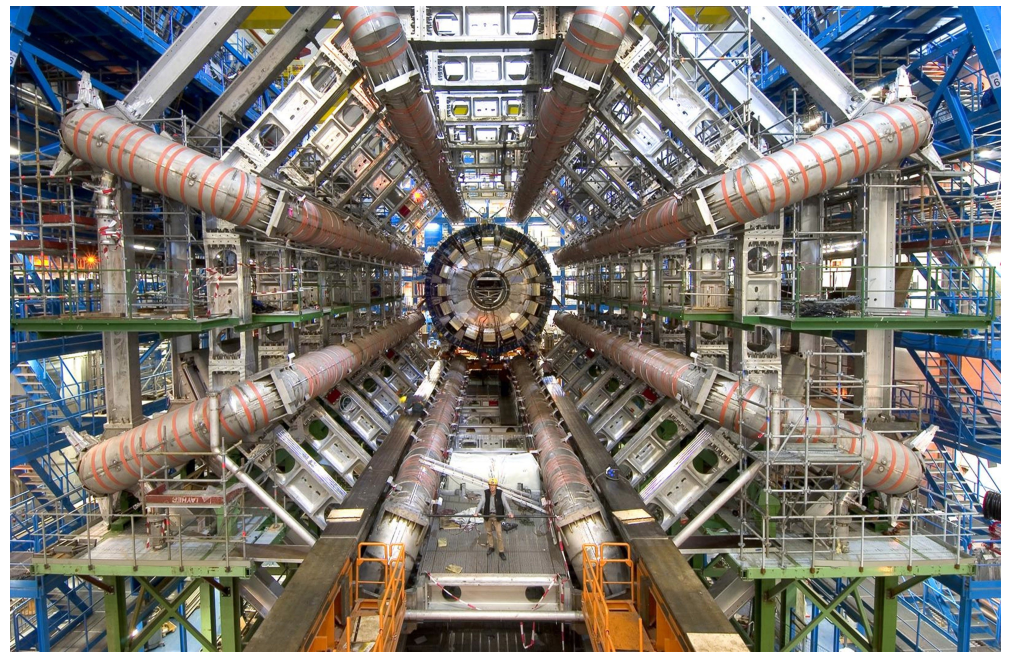
Laser interferometer



DANCE

KAGRA

XENON



LHC

Subaru telescope

Target: Axion-like particles (ALPs)

Axion-photon interaction

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

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

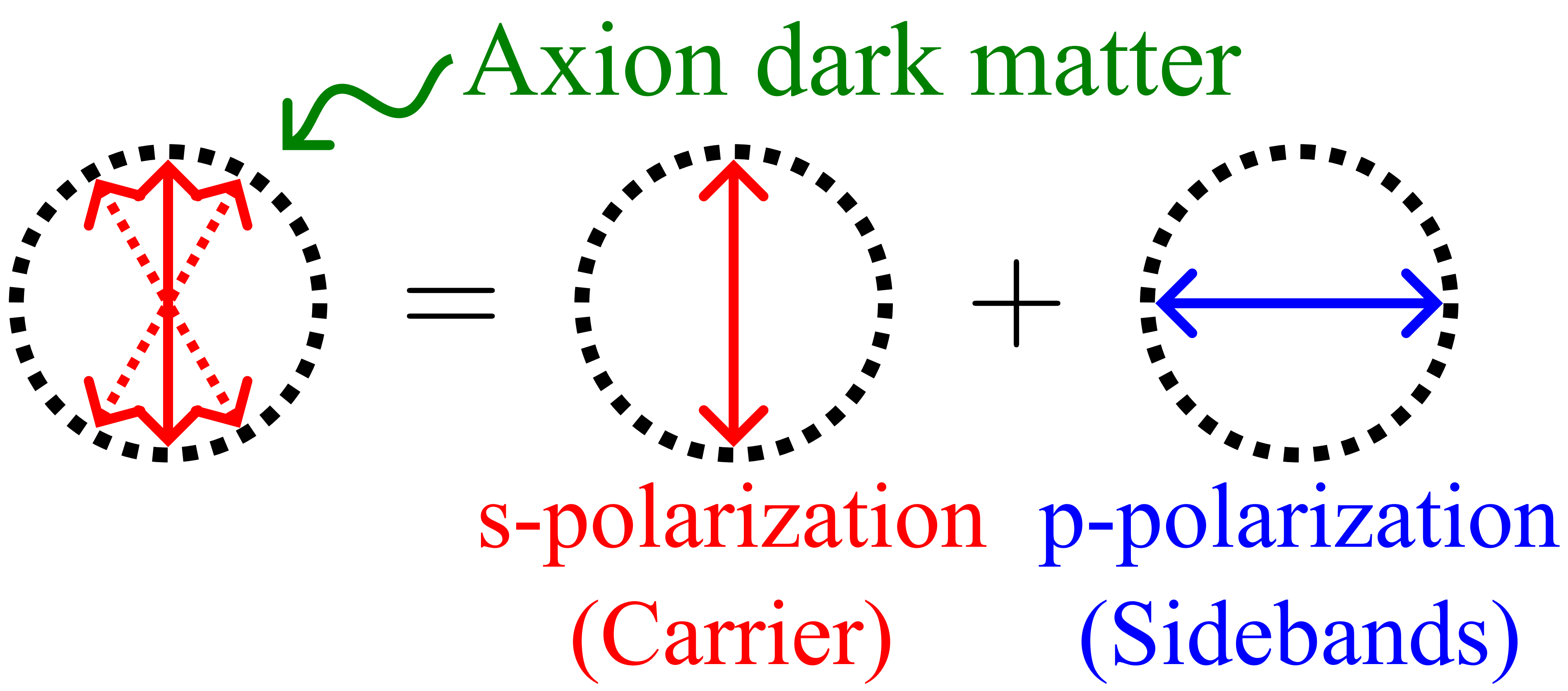
Phase velocity

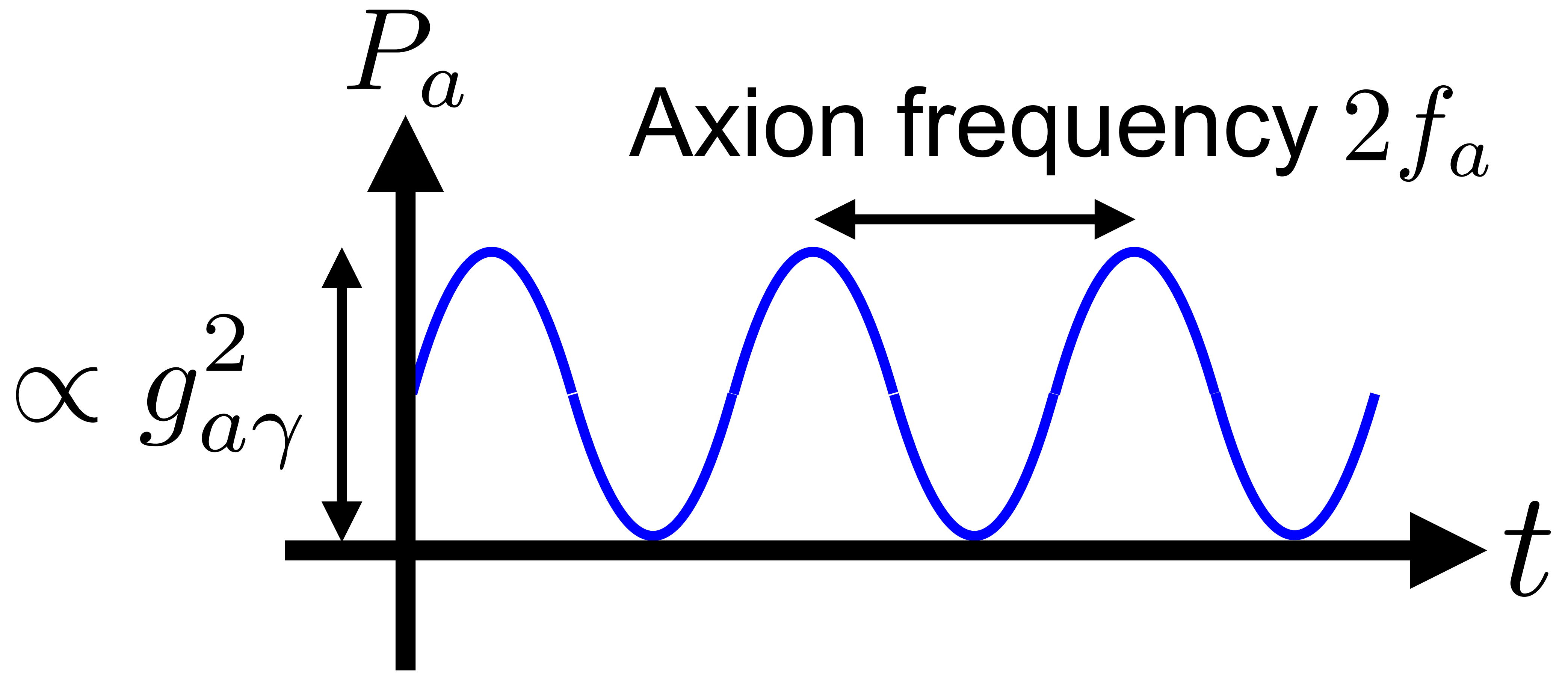
Axion-photon coupling

Axion field

Axion mass

➡Rotation of linearly polarized light

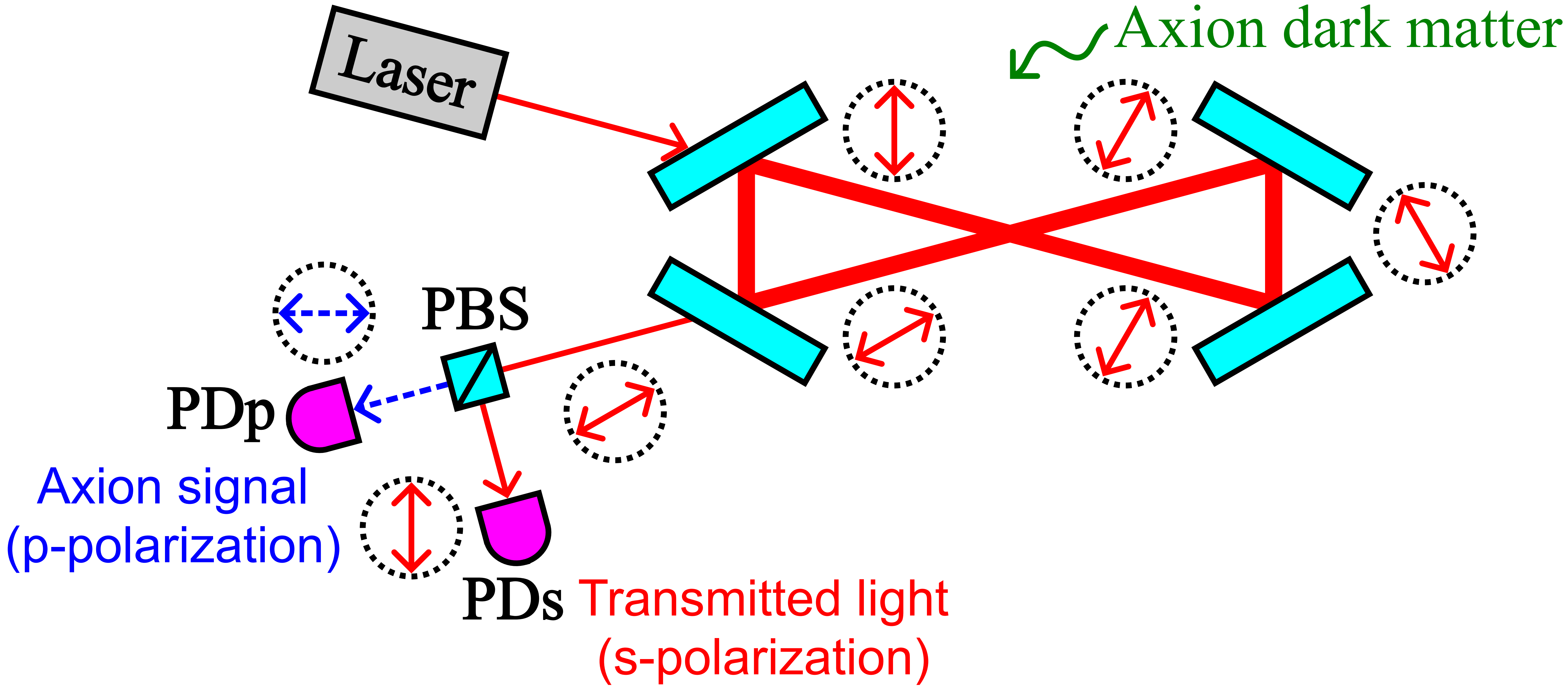


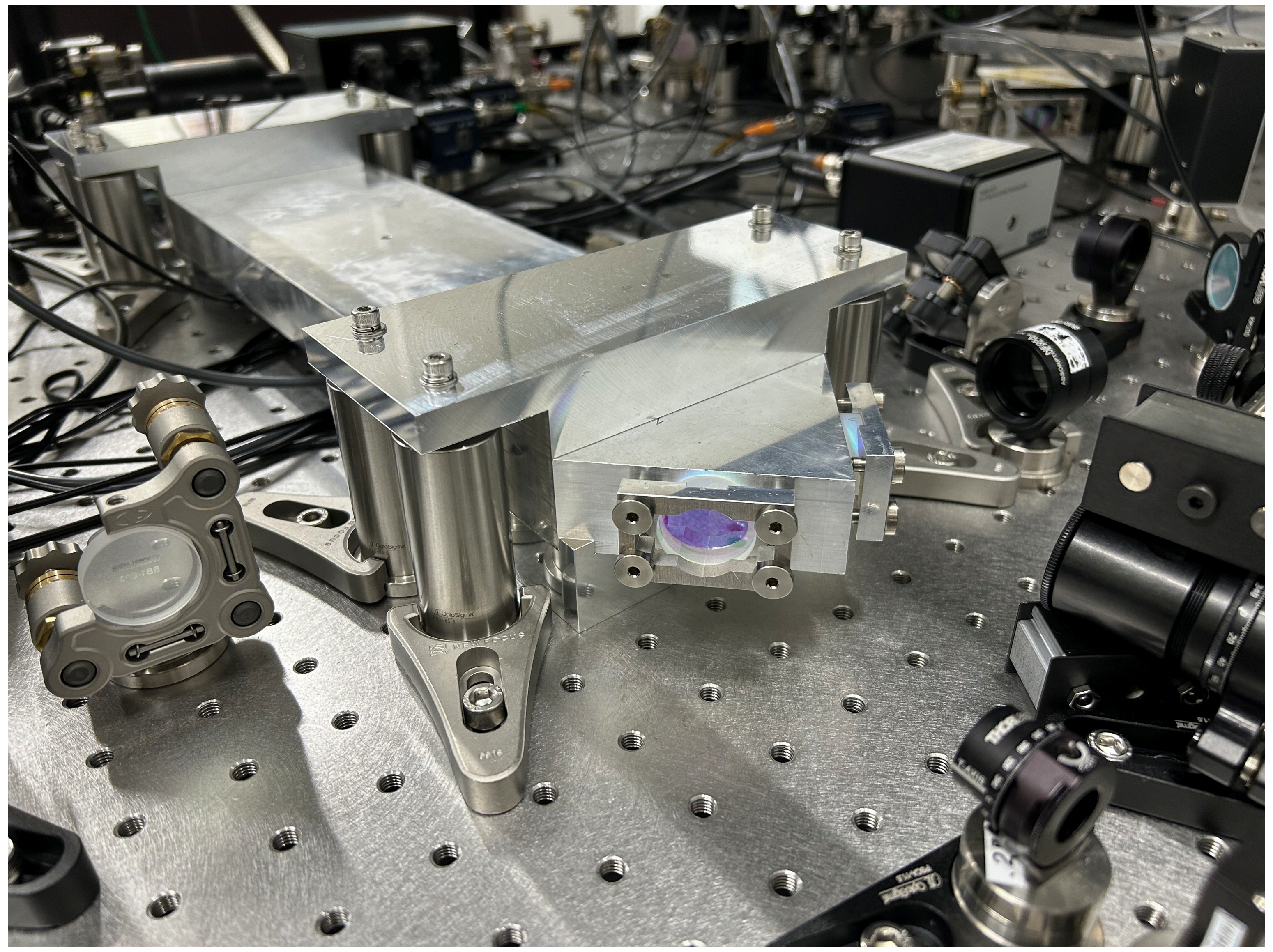


Principle of DANCE

DANCE: Dark matter Axion search with riNg Cavity Experiment

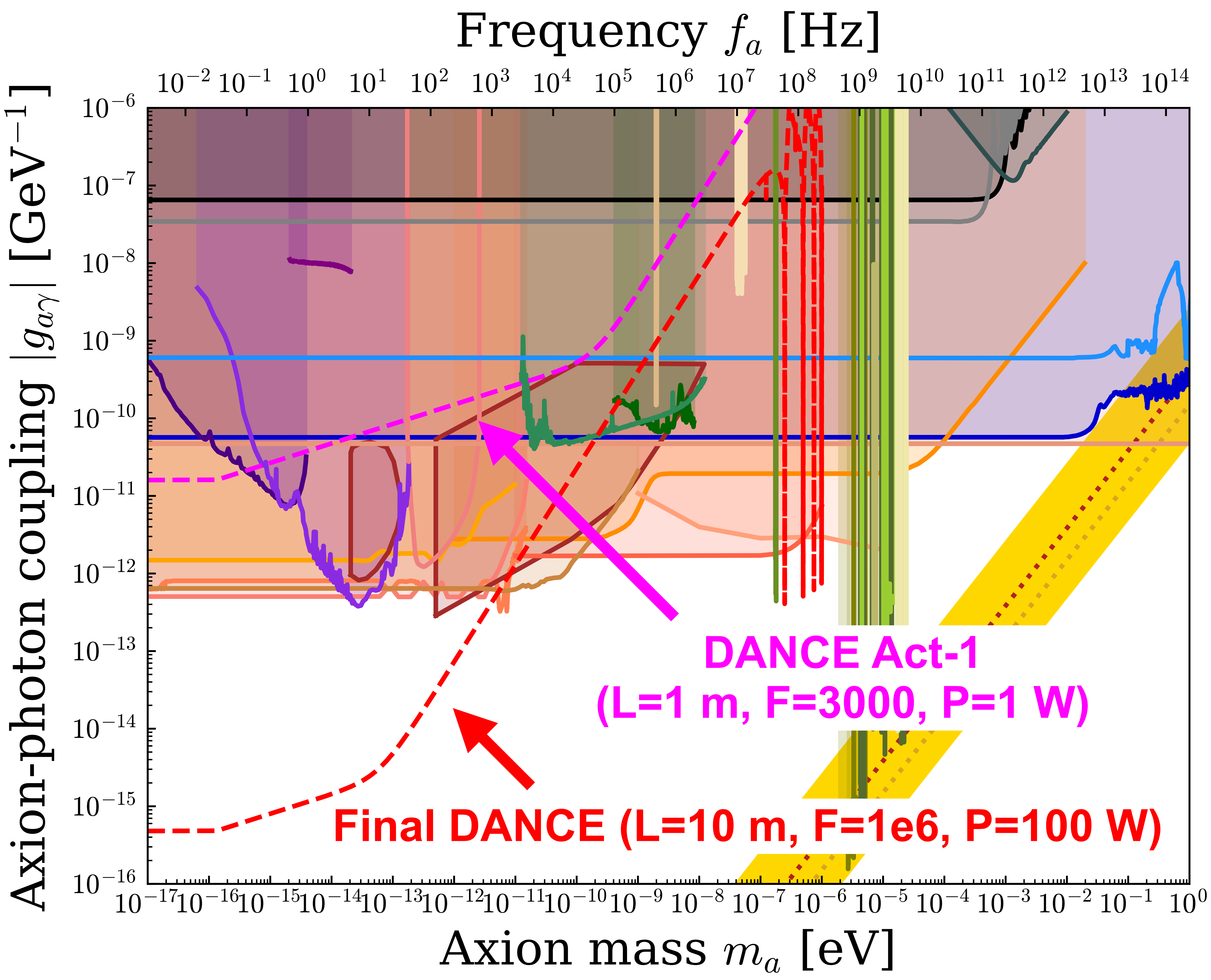
- Amplify polarization rotation with a bow-tie ring cavity
- Measure polarization rotation using a PBS and two PDs
- DANCE Act-1 (prototype experiment), which has round-trip of 1 m, is ongoing





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

Target sensitivity of DANCE



- Assume dark matter consists of ALPs
- Shot noise limited

Parameter of optical cavity

L : Round-trip

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

P_{in} : Input power

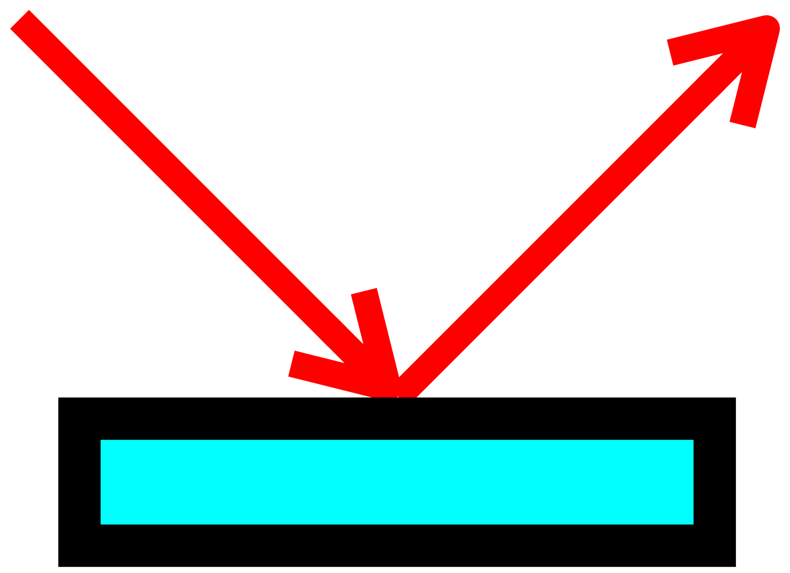
Conduct a sensitive axion search by improving parameters

$T_{\mathrm{obs}} = 1$ year

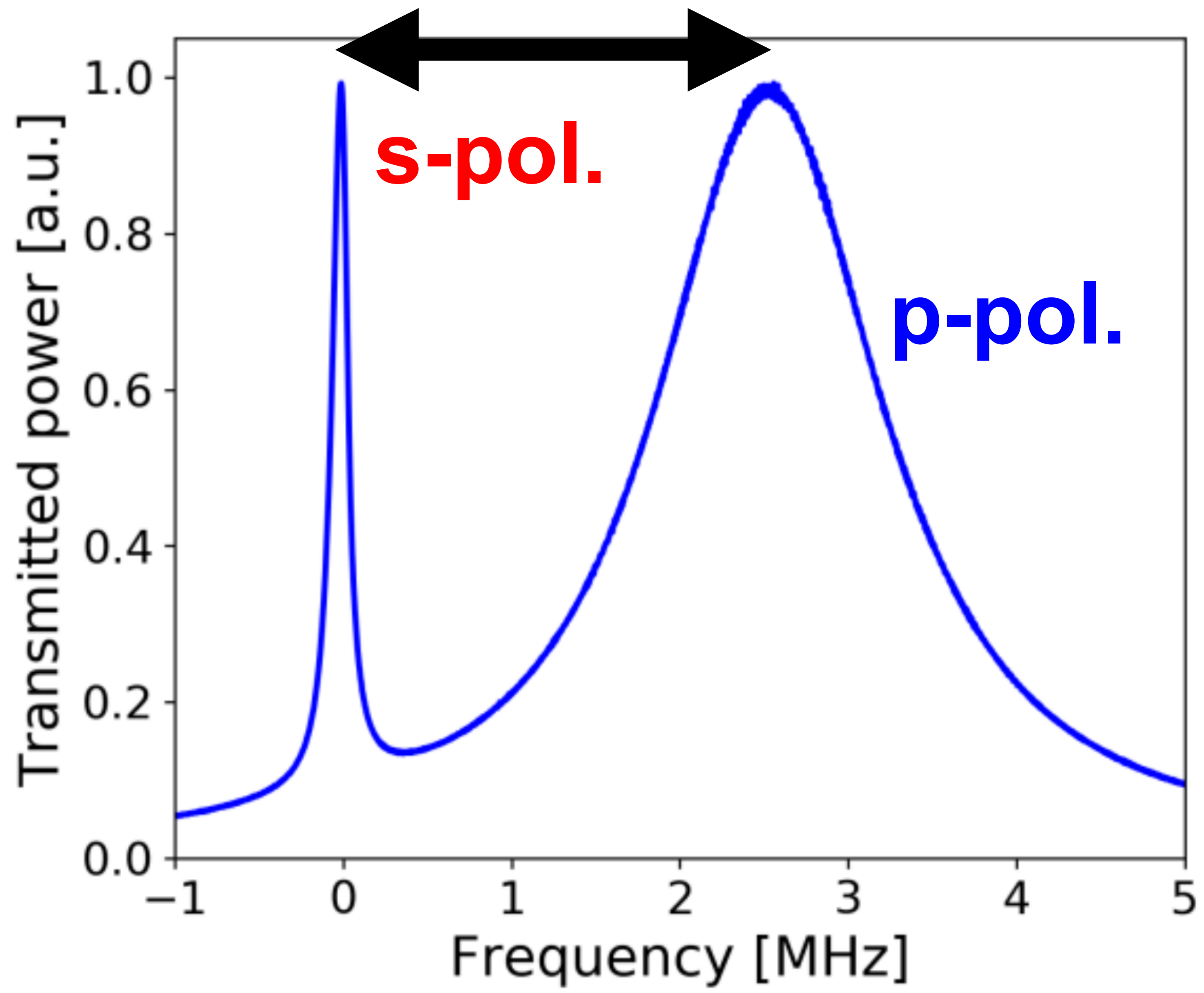
Issue: Non-simultaneous resonance

Reflection phase difference between s- and p-pol.

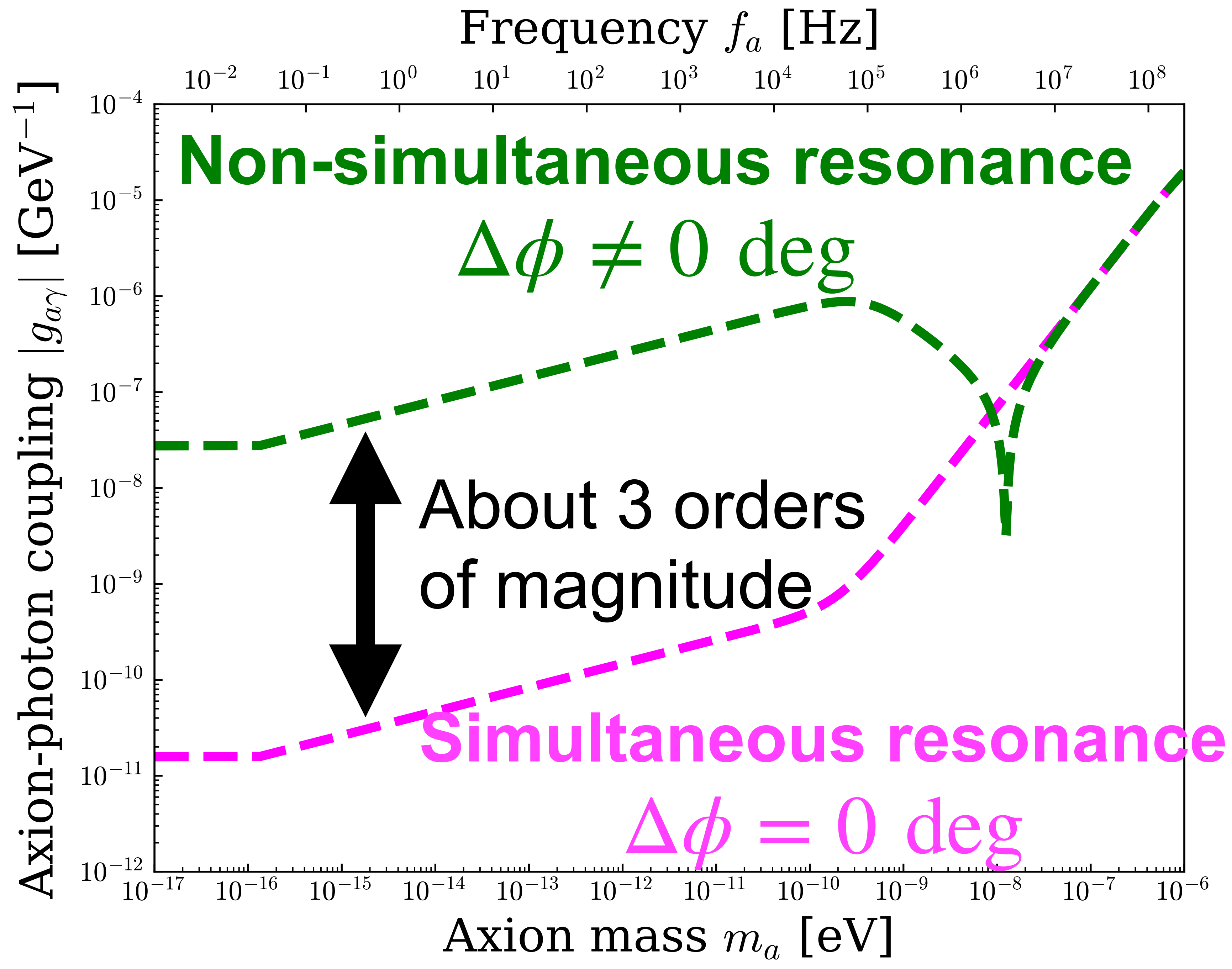
$$\Delta\phi = \phi_\mathrm{s} - \phi_\mathrm{p} \neq 0 \ \mathrm{deg}$$



Resonant frequency difference between s- and p-pol.



Assume resonant frequency difference is 3 MHz

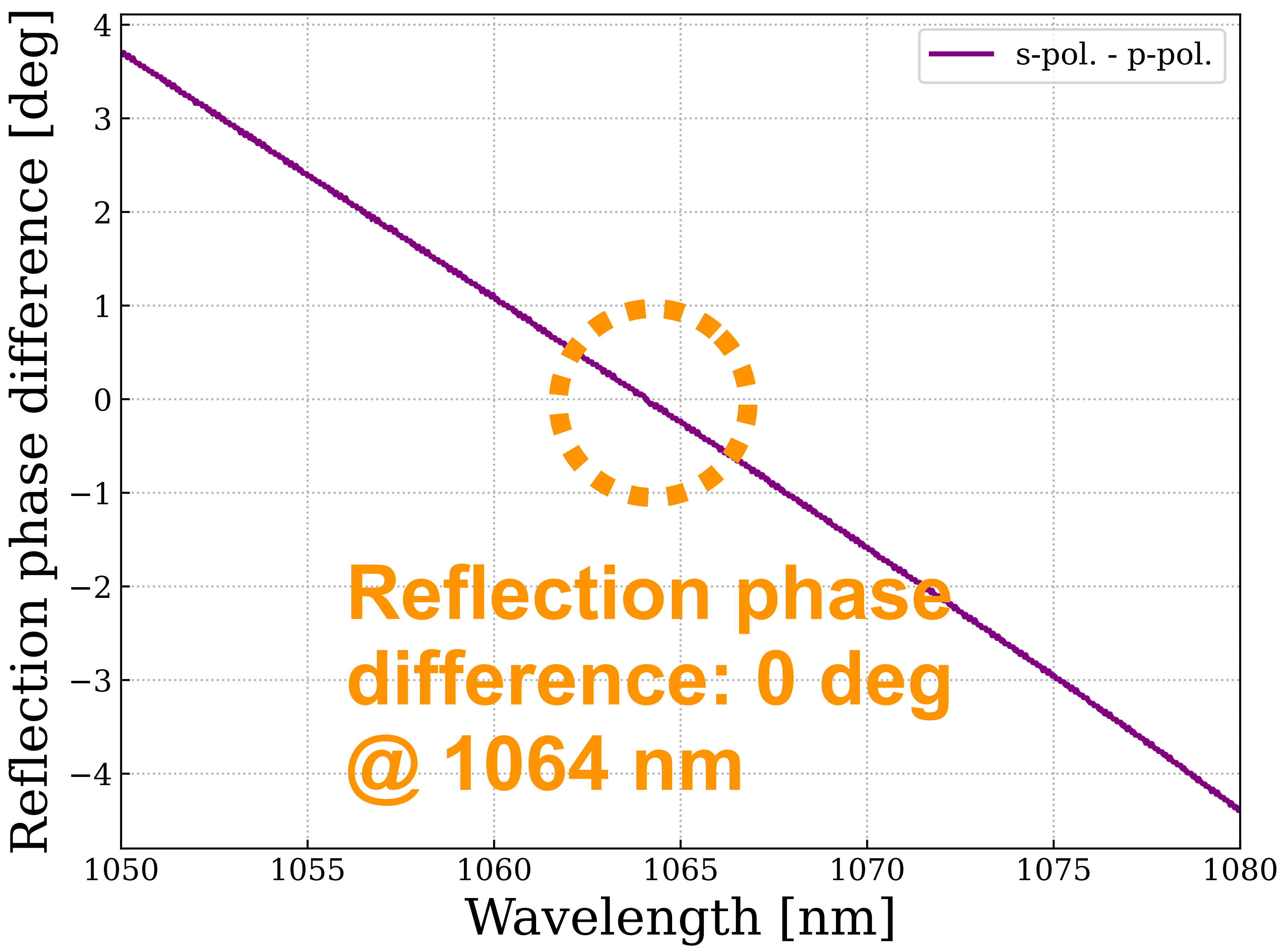


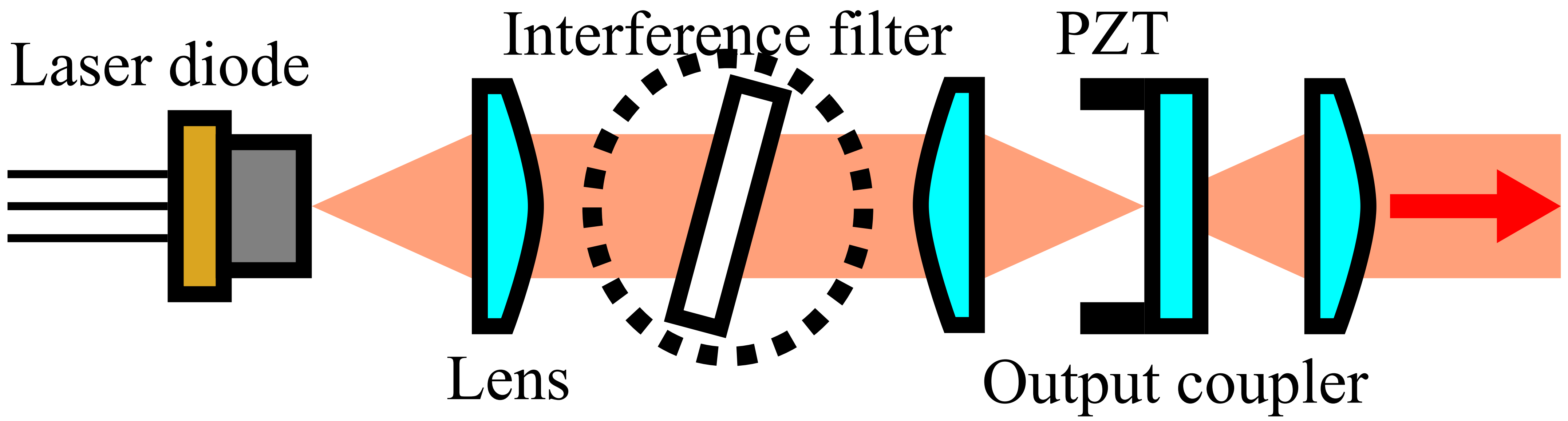
Y. Oshima *et al.*, Phys. Rev. D **108**, 072005 (2023).

Non-simultaneous resonance (s-pol. is resonant in the cavity, while p-pol. is not)

➡p-pol. generated by the axion-photon interaction is not amplified, degrading the sensitivity

Method 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 wavelength and an 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

➡ Achieve simultaneous resonance (s-pol. and p-pol. are resonant in the cavity)

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

Research roadmap

DANCE Act-1

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

- Long cavity: 10x
- High finesse: ~3000x
- High power: 100x

→ **Final DANCE**

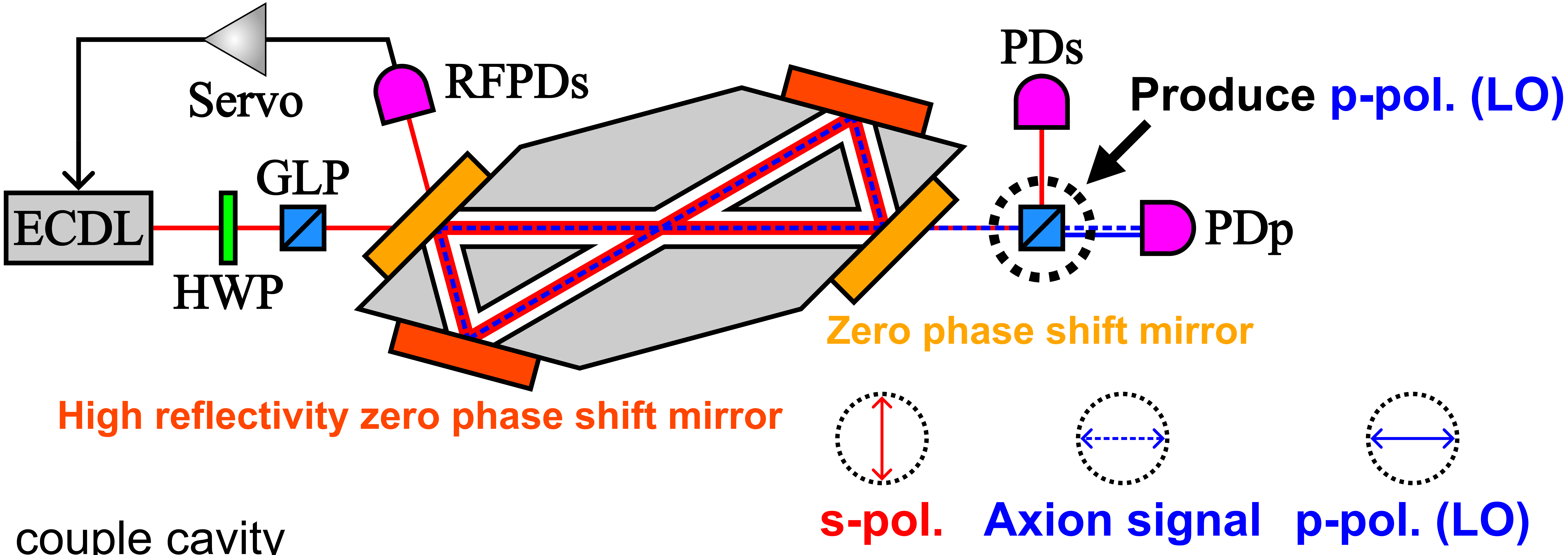
Necessary to achieve target sensitivity of DANCE Act-1

① Critical couple cavity
  - Cavity transmission: ~2.4x better (17% → 99%)
  - Finesse: ~2.2x better (s-pol.: 2600 → 6219, p-pol.: 2860 → 5882)

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)

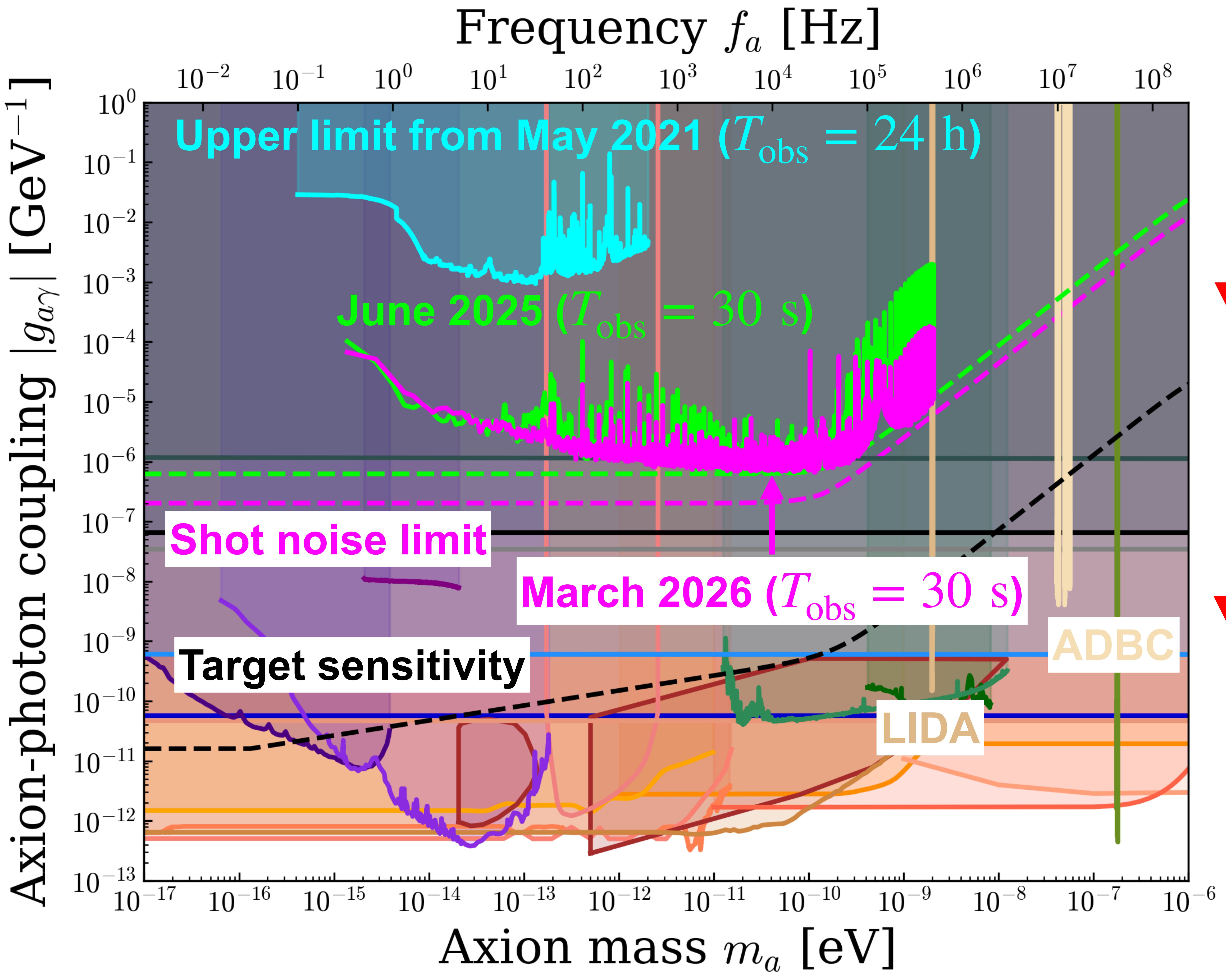
Experimental setup



- Critical couple cavity
- 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 note between axion signal and the LO

Current sensitivity



- Upper limit from May 2021
  - First observation using optical cavities

Simultaneous resonance

- June 2025
  - ~3 orders of magnitude improvement

Critical couple cavity

- March 2026 (current sensitivity)
  - Up to ~1 order of magnitude improvement

Y. Oshima *et al.*, Phys. Rev. D **108**, 072005 (2023).
H. Fujimoto, Ph.D. thesis

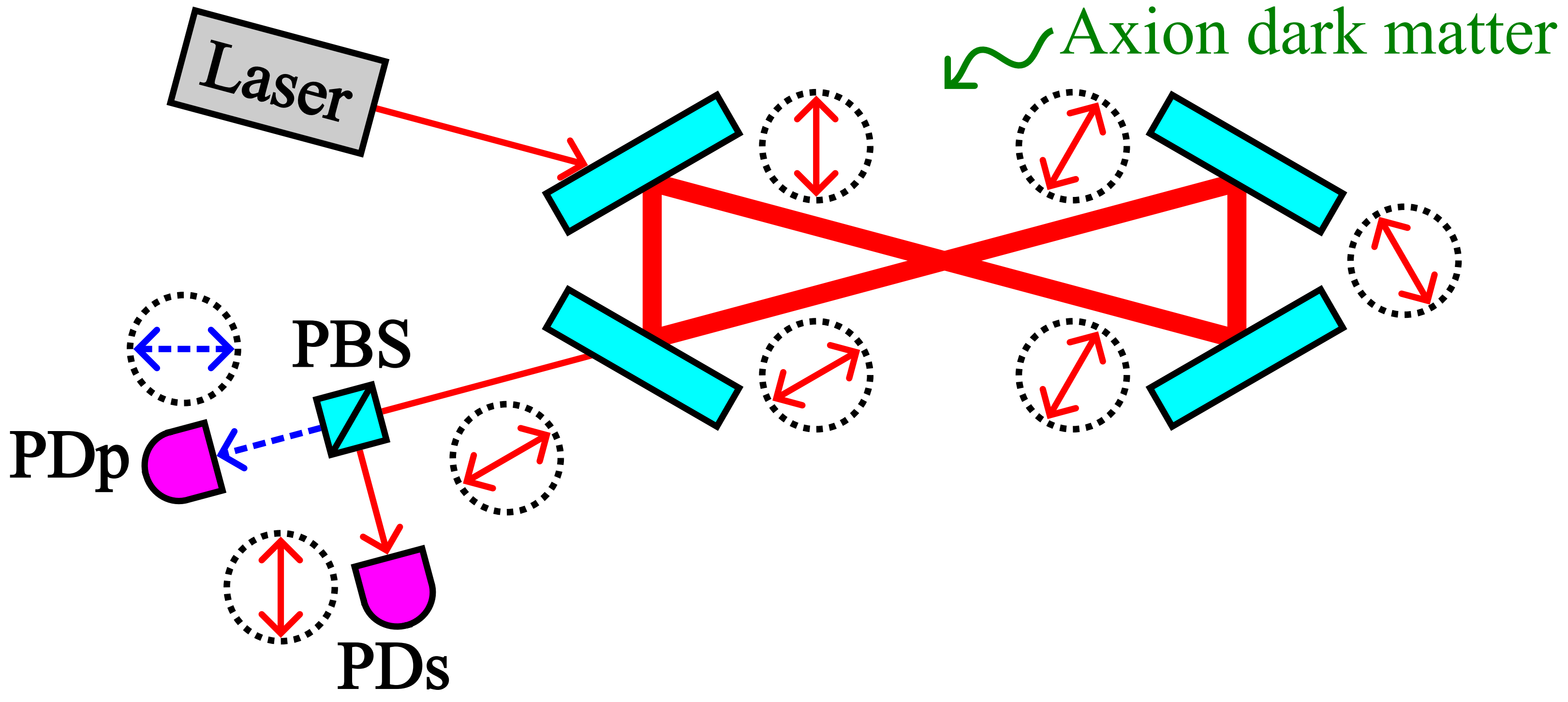
Comparison with other groups

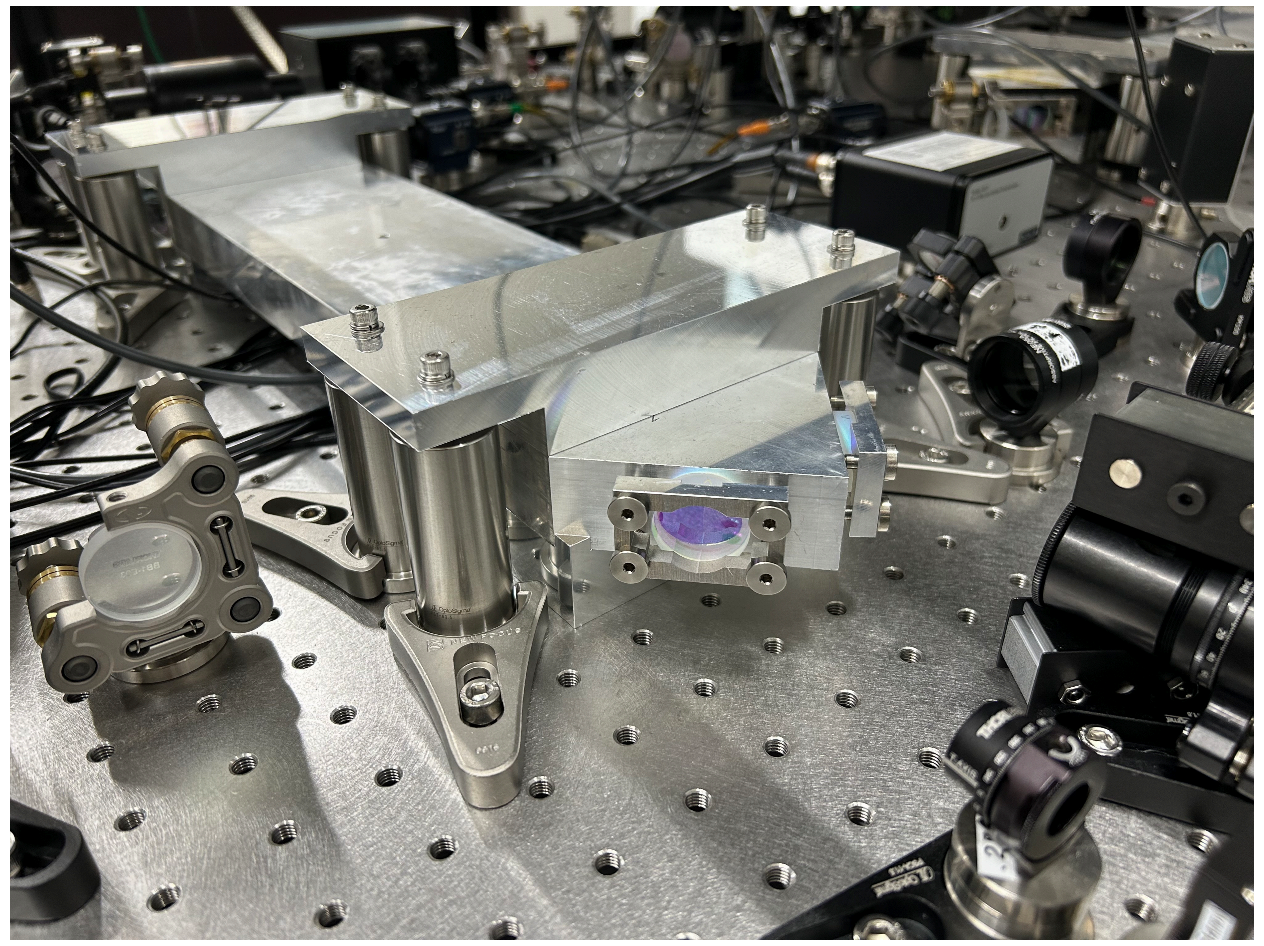
	Round-trip	Finesse	Input power	Observation bandwidth	How to tune resonant frequency difference between s- and p-pol.
DANCE (UTokyo)	~1 m	s-pol.: ~4800 p-pol.: ~4800	6 mW	Broadband 1.4 feV - 2.1 neV (Possible with narrowband)	• Zero phase shift mirror • Wavelength tunable laser
ADBC (MIT)	~4.7 m	s-pol.: ~7260 p-pol.: ~212	0.8 W	Narrowband 40.9 - 56.7 neV	Tuning incident angle by rotating the cavity 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 cavity mirrors

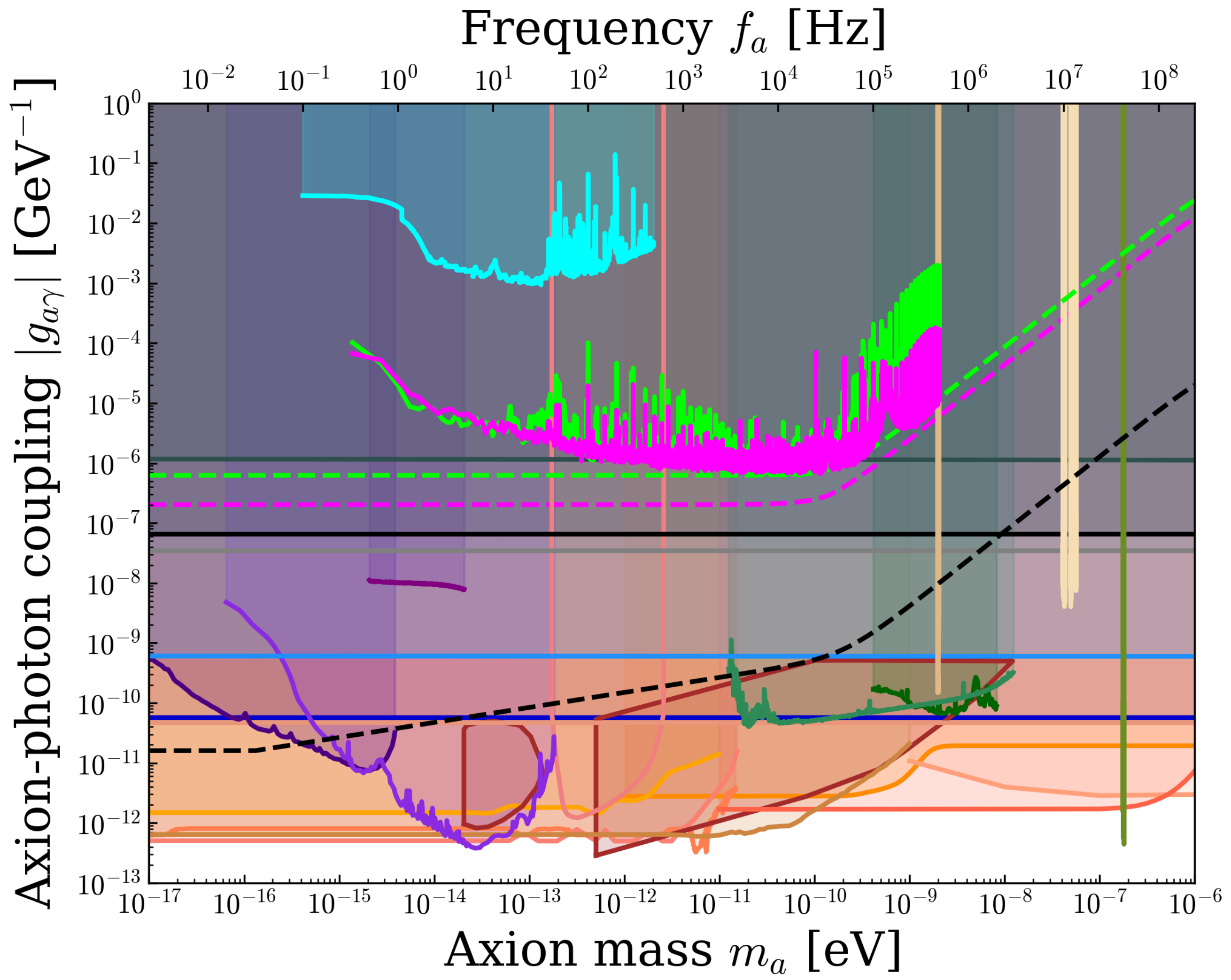
Summary

DANCE: Dark matter Axion search with riNg Cavity Experiment

- Achieved simultaneous resonance using zero phase shift mirrors and a wavelength tunable laser, improving the sensitivity
- Future prospects for DANCE
  - Introduce power amplifier to increase input power into a bow-tie ring cavity
  - Long-term observation
  - Single photon counting





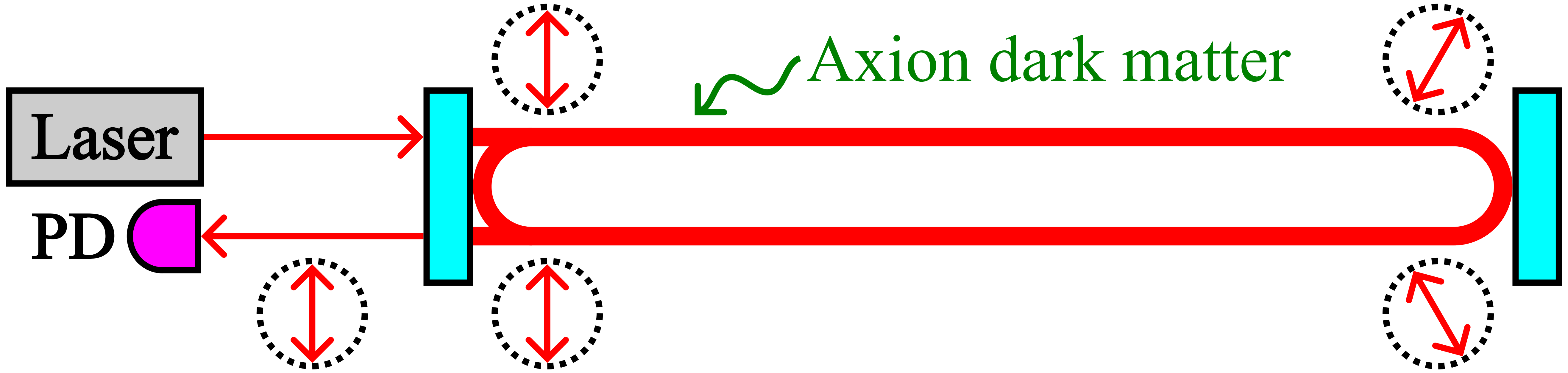


Backup

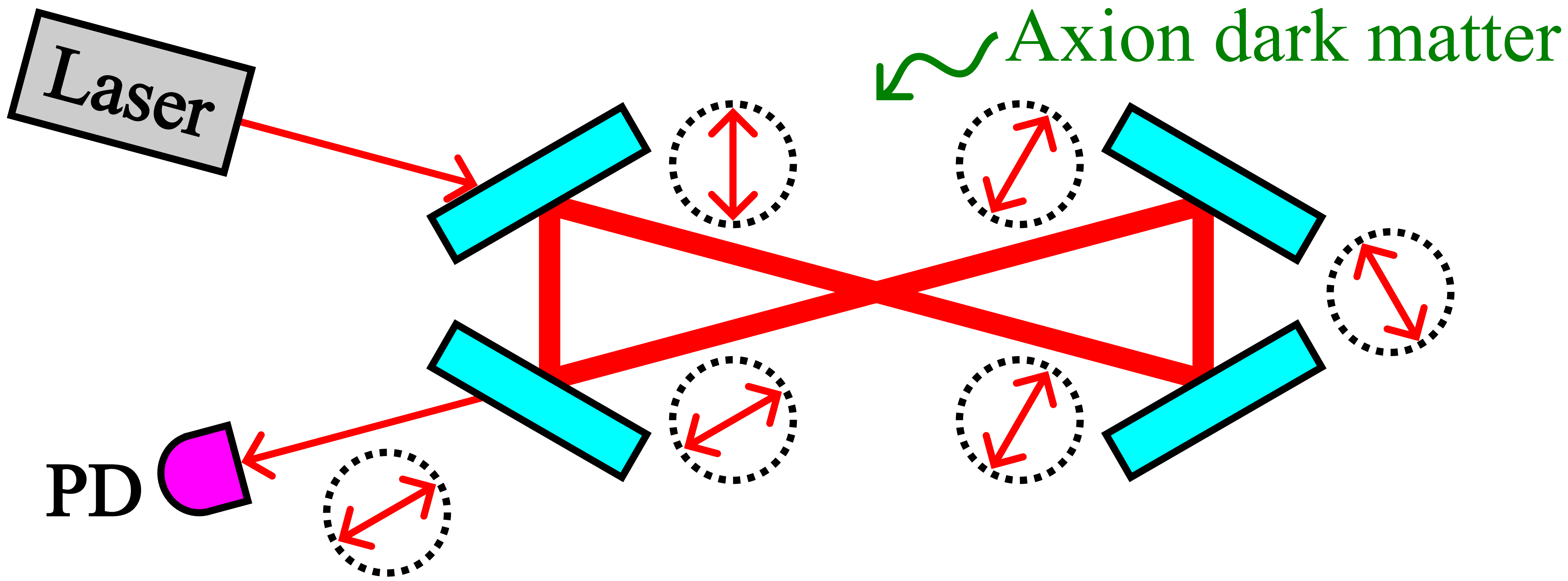
How to amplify the axion signal

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



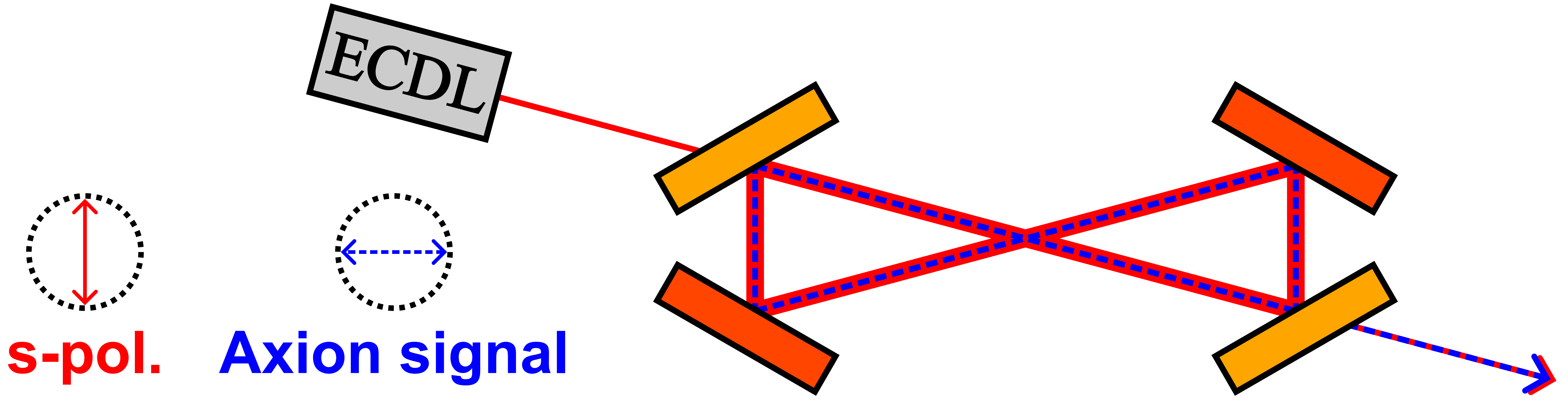
Extend optical path with a bow-tie ring cavity
Rotation of polarization can be amplified because the flip is canceled upon reflections on both two mirrors

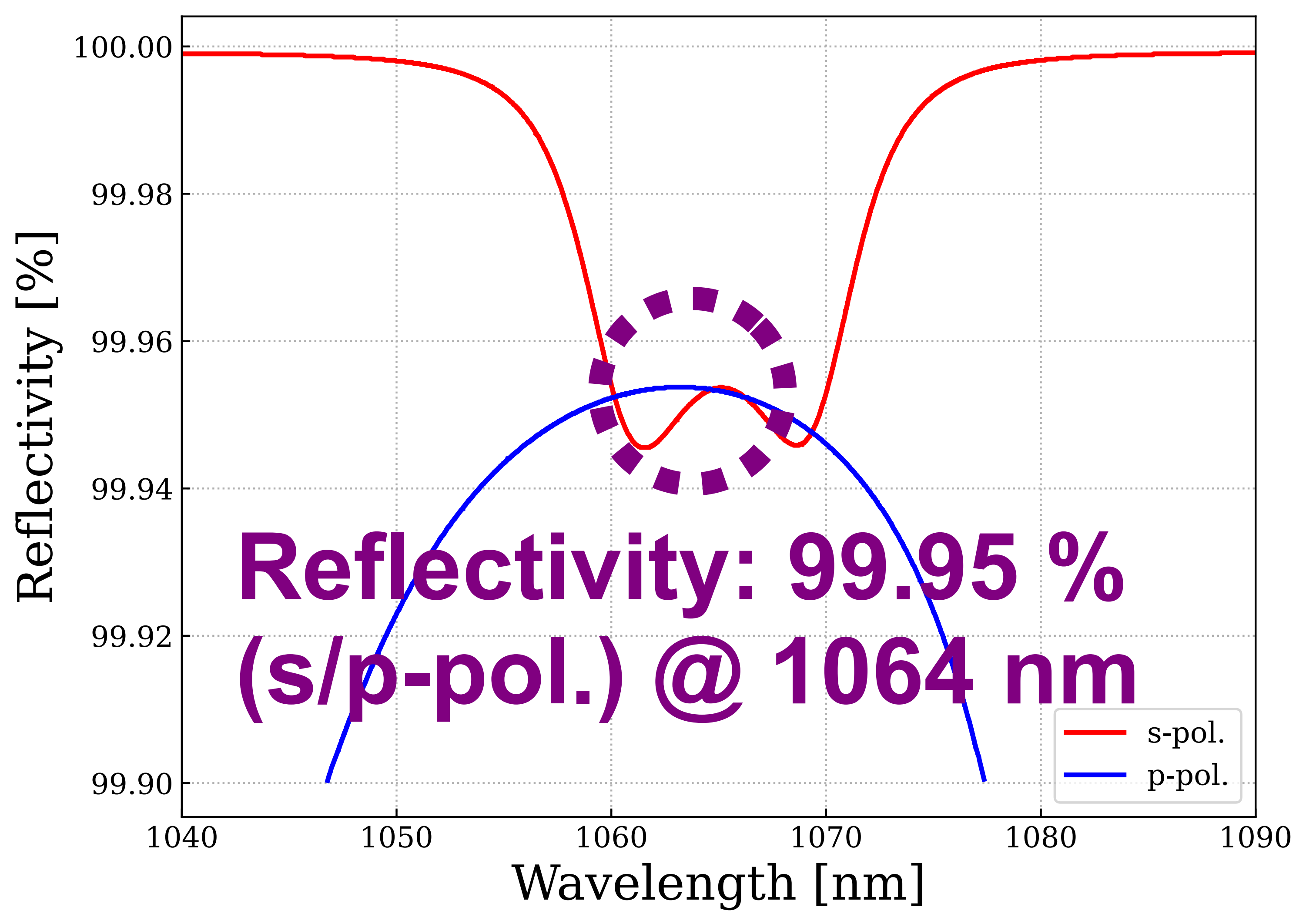


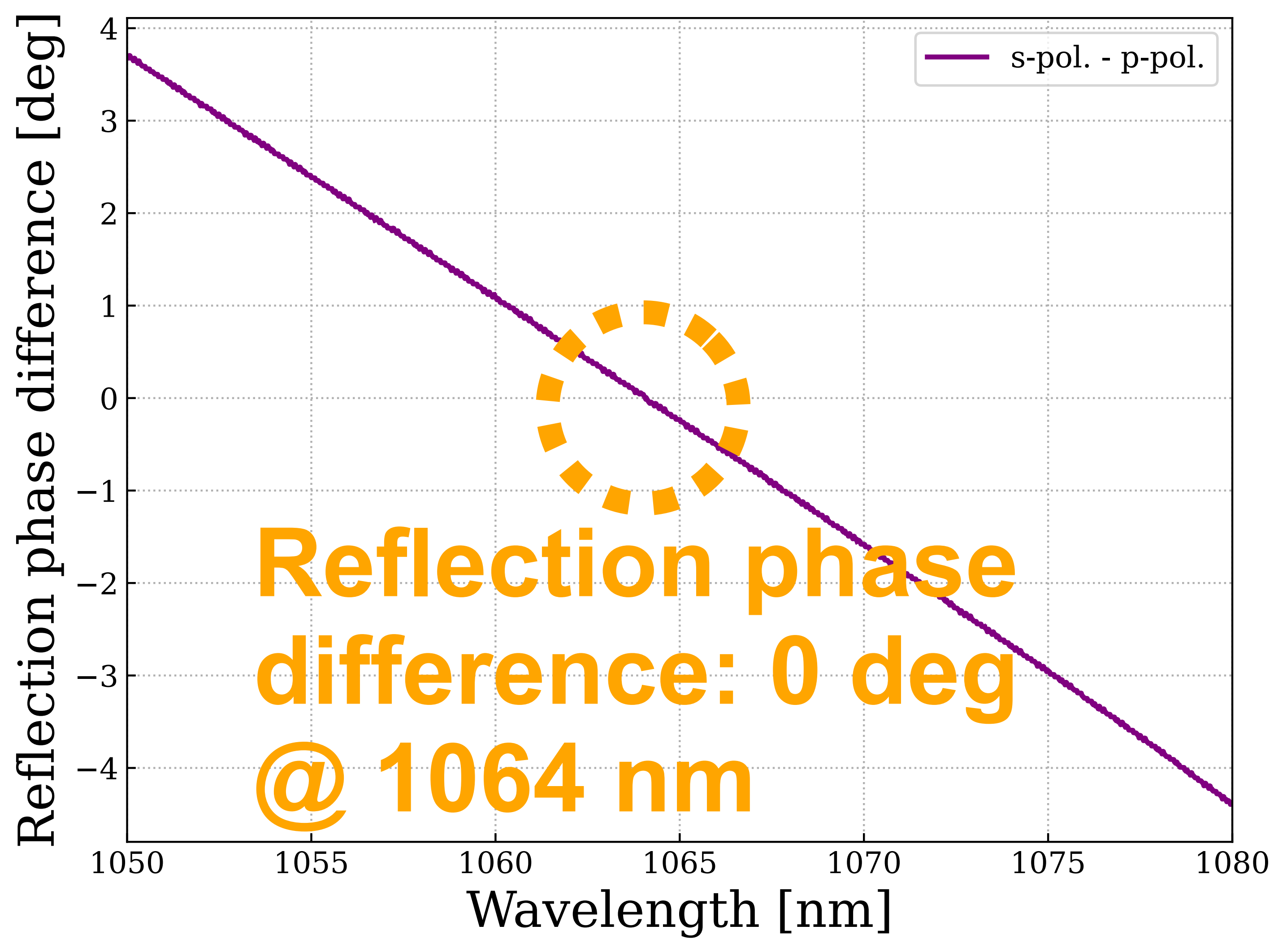
I. Obata *et al.*, Phys. Rev. Lett. **121**, 161301 (2018).

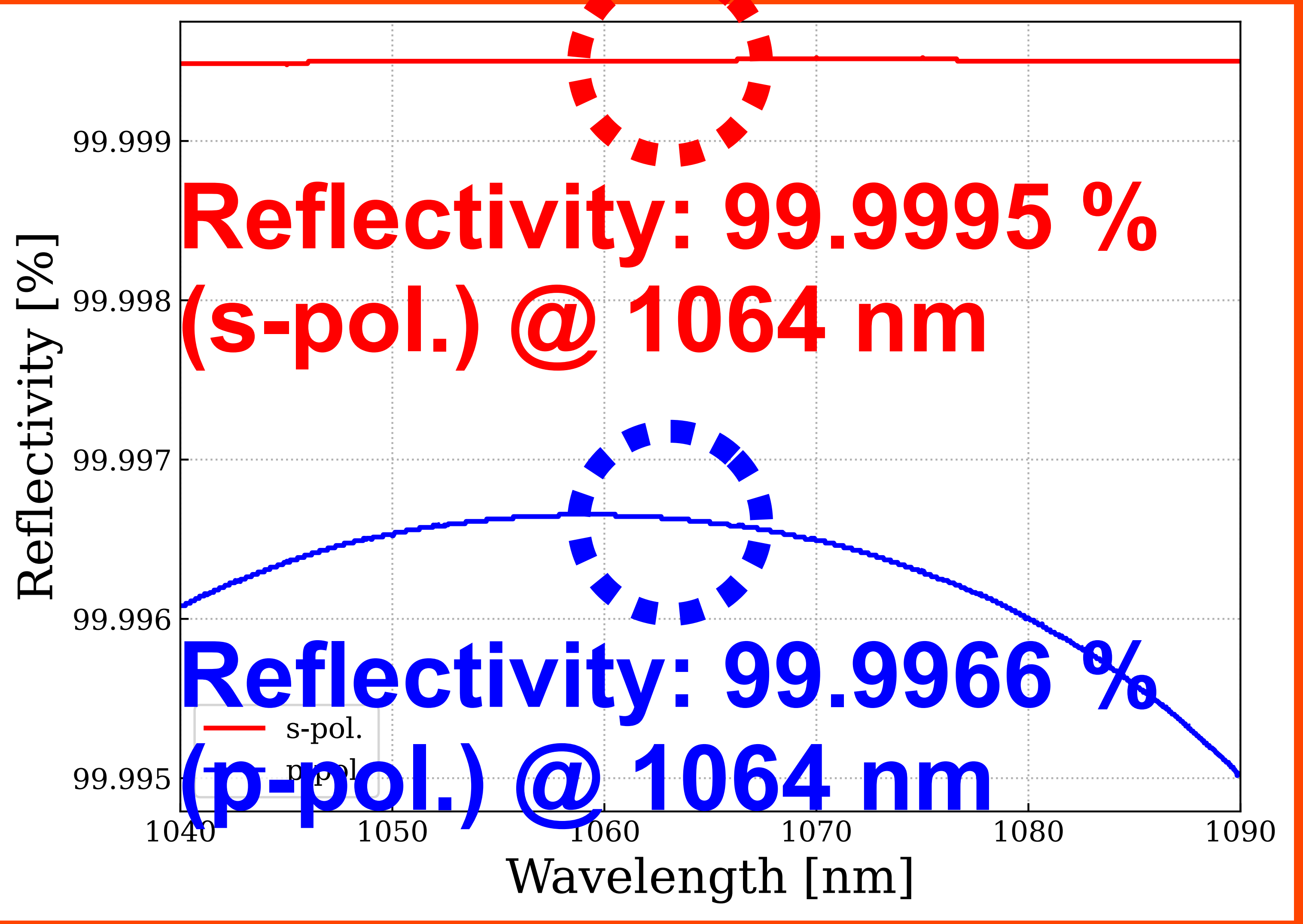
Critical couple cavity

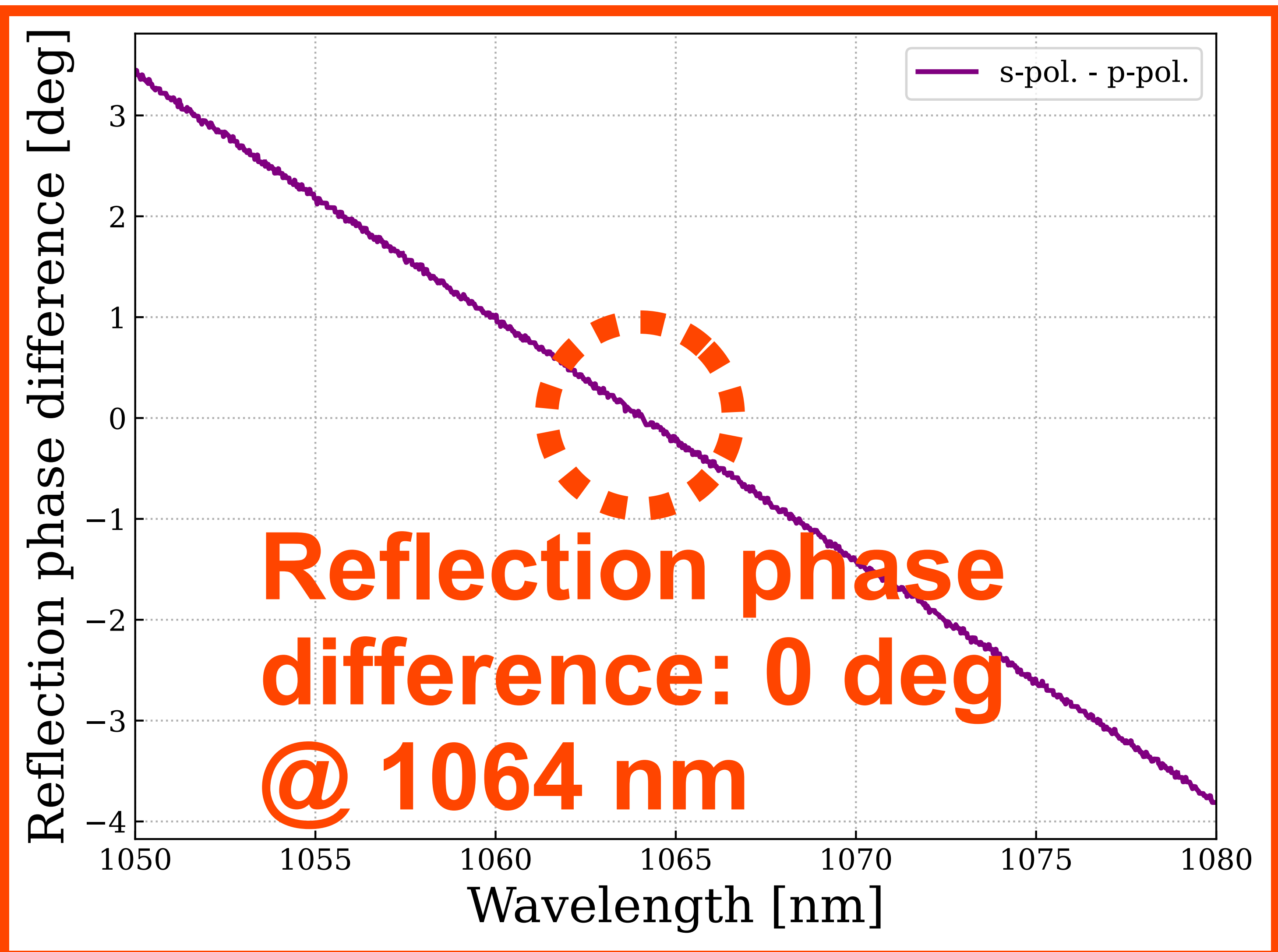
Replaced 2 out of 4 mirrors with high reflectivity zero phase shift mirrors



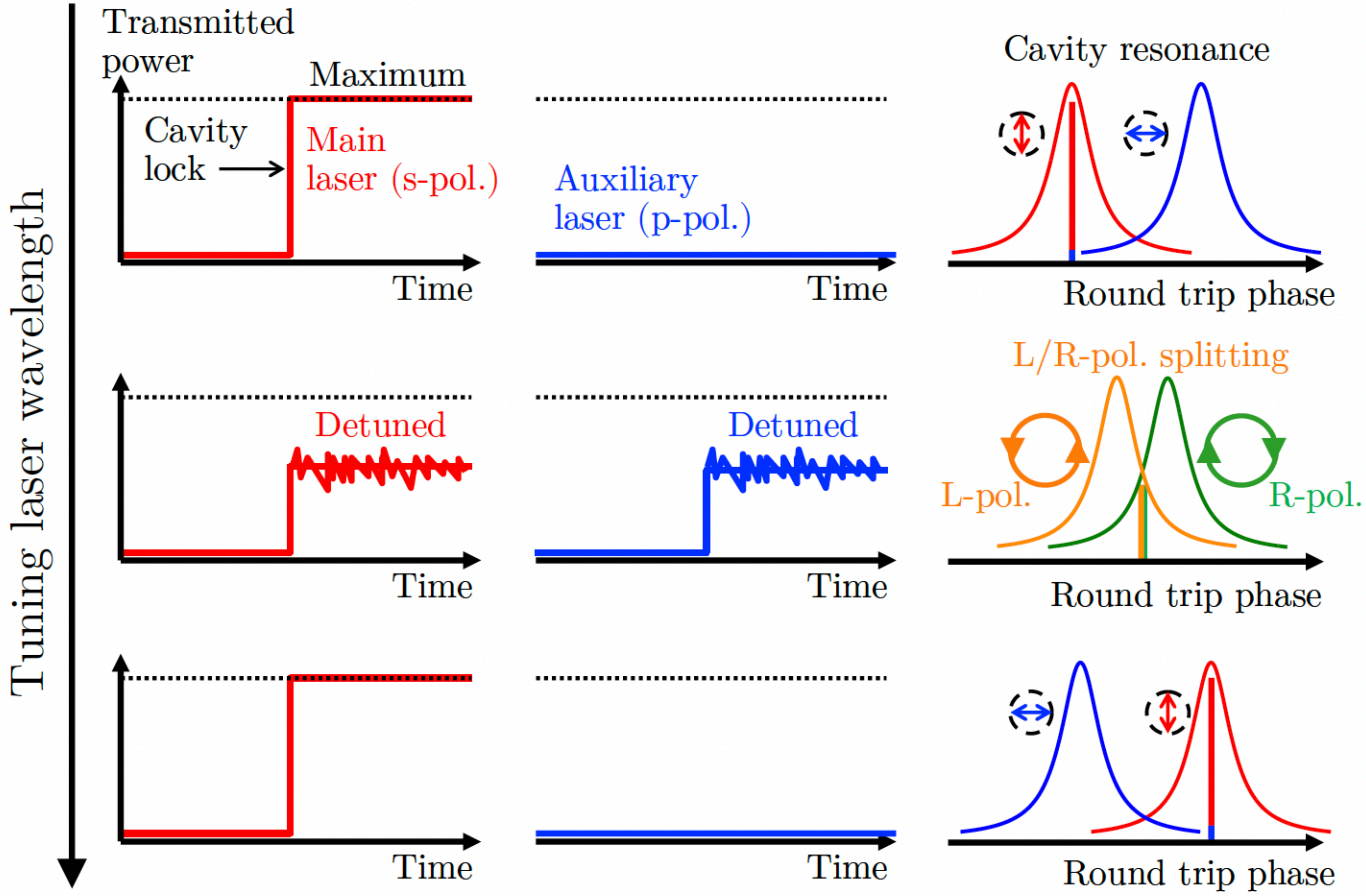








Issue: L/R-polarization splitting



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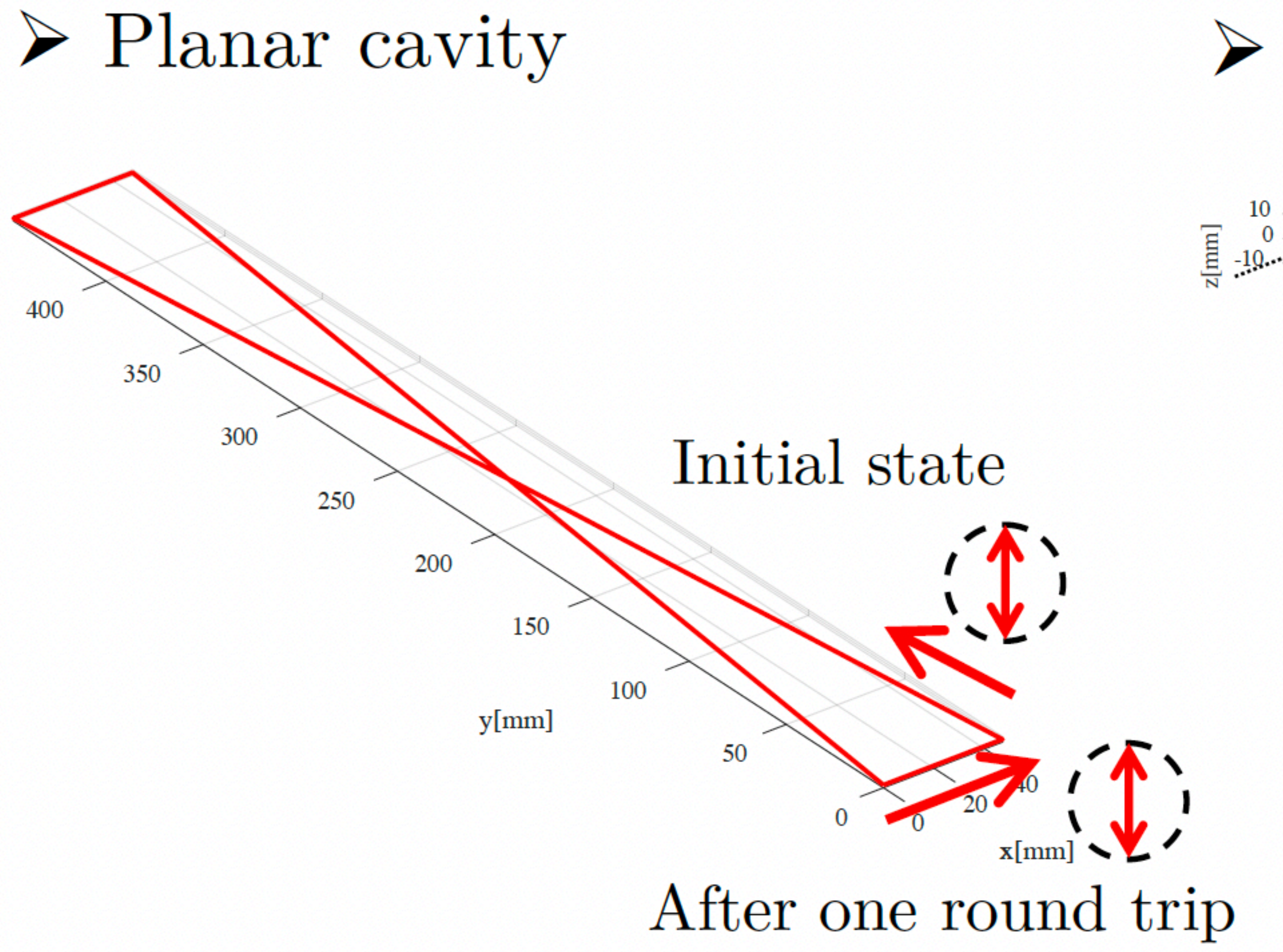
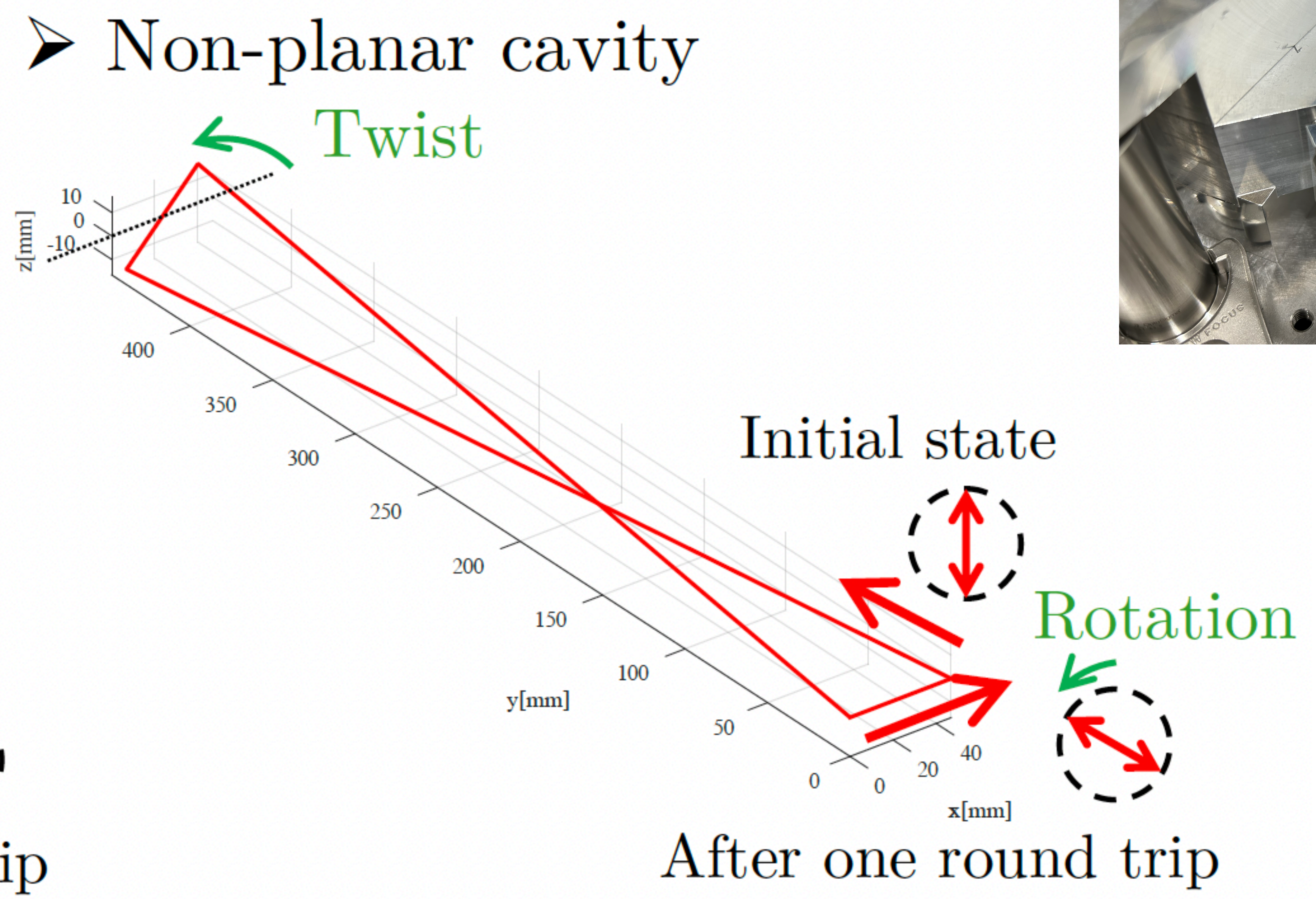
L/R-pol. splitting by cavity non-planarity

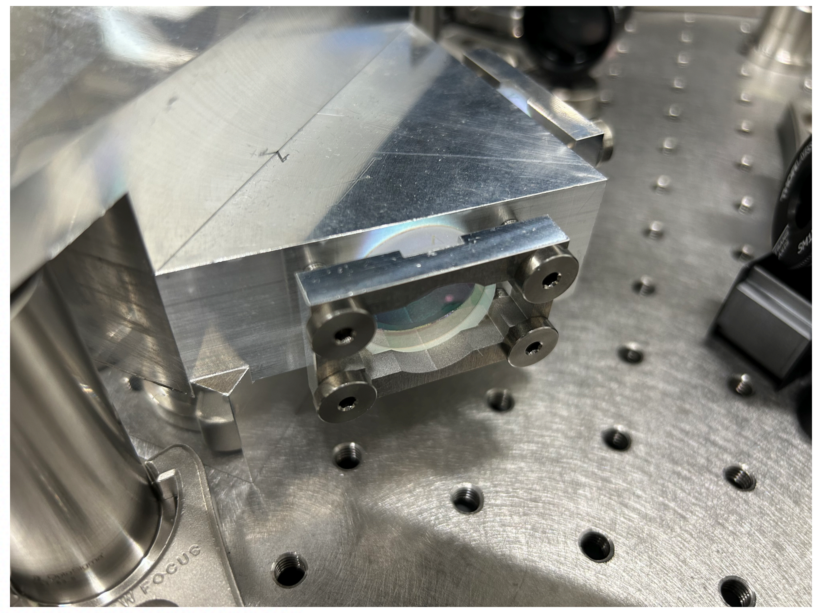
In general, when 4 or more mirrors are used, the optical path can be non-planar

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

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







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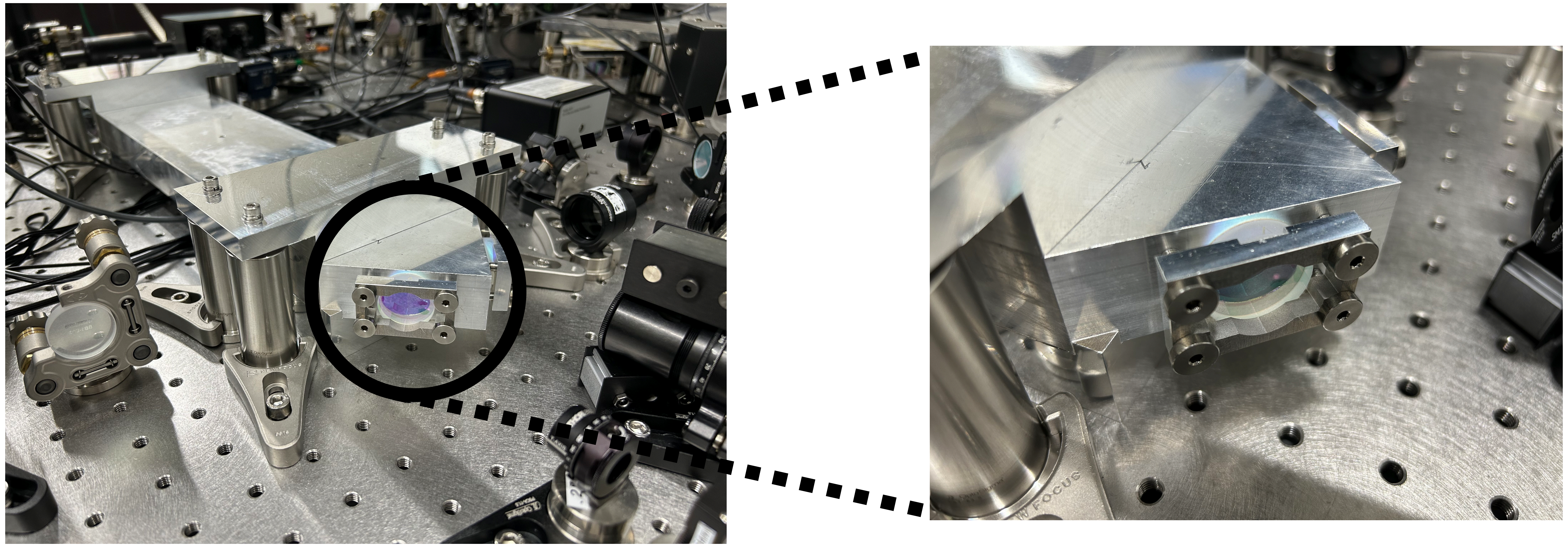
Adjustment method for cavity non-planarity

① Minimize mixture of p-polarization under non-simultaneous resonance
- Adjust the angle of GLP so that the incident light is s-polarization and the transmitted polarization is p-polarization
- 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



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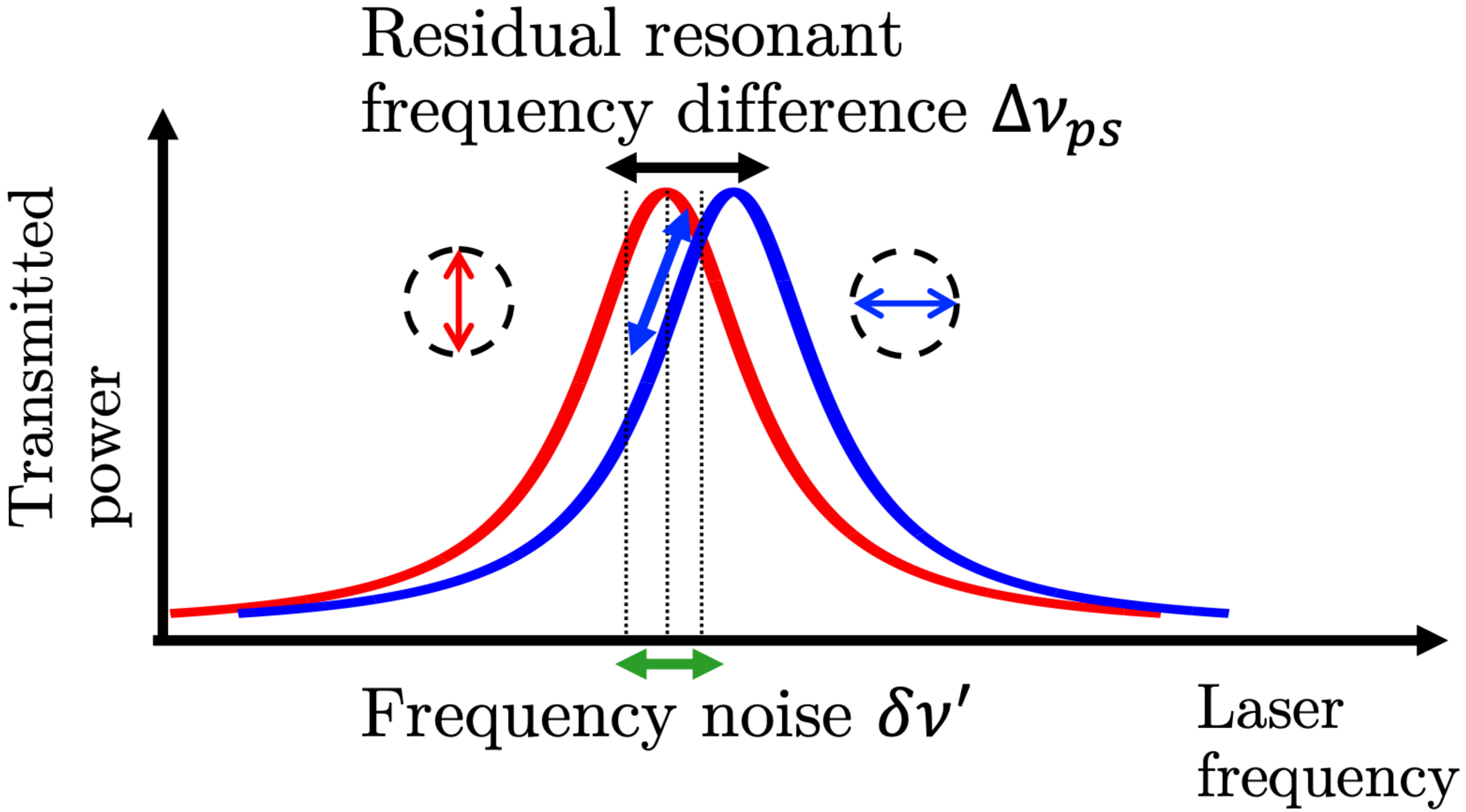
Mechanism of frequency noise coupling



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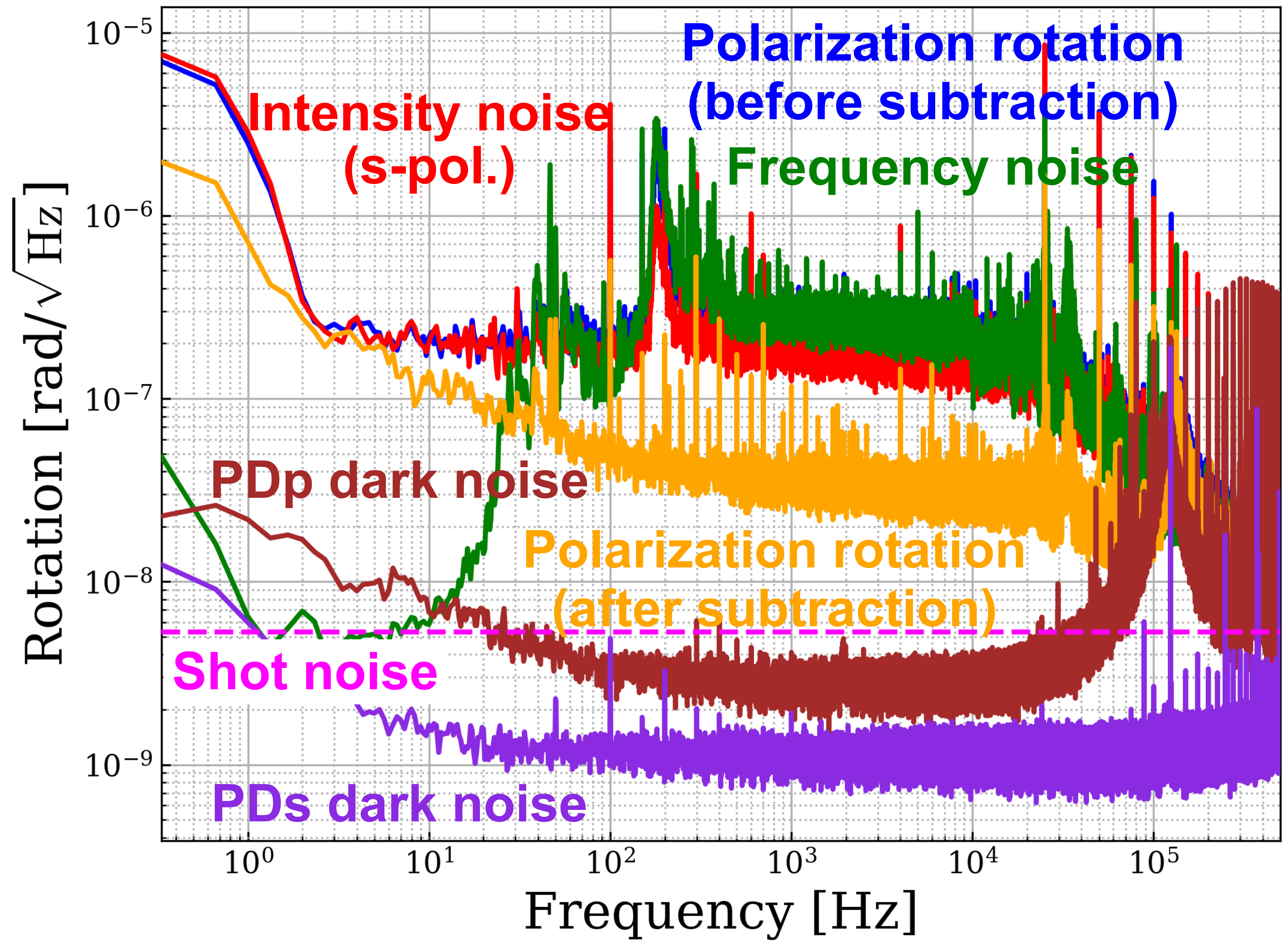
Polarization rotation spectrum

Residual resonant frequency difference: 5.3(5) kHz

➡Satisfy requirement (within HWHM of p-polarization): 25.6 kHz



- Subtract intensity noise (s-pol.) and frequency noise from polarization rotation by offline analysis

➡Successful subtraction by up to ~1 order of magnitude

Noise source

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