

Dark matter Axion search with riNg Cavity Experiment (DANCE): Simultaneous resonance for sensitive broadband axion search

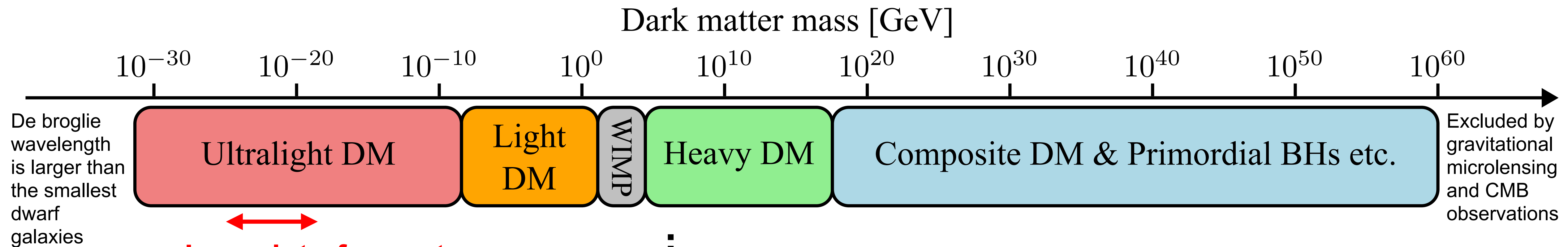
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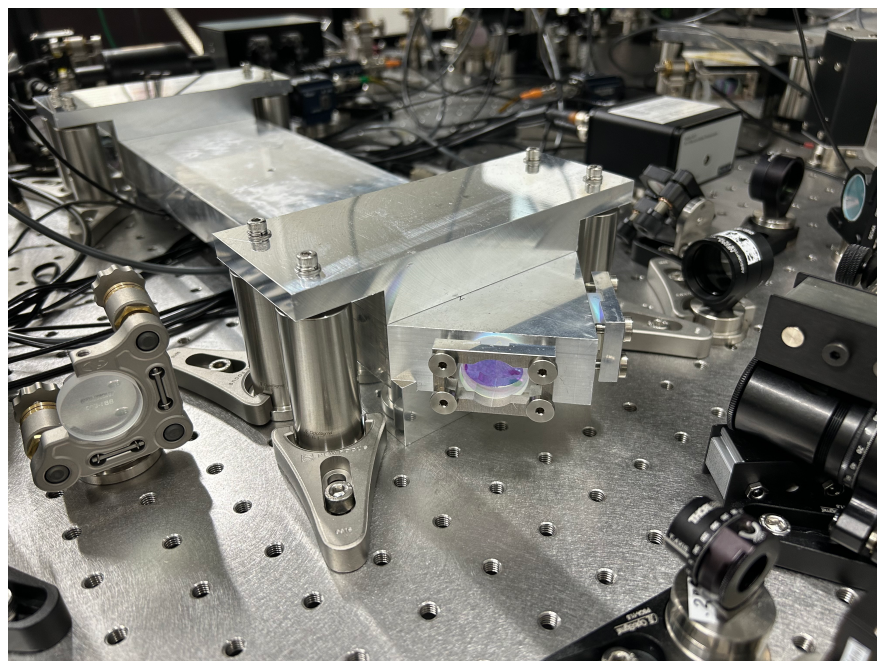
Dark matter

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- 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**



Laser interferometer



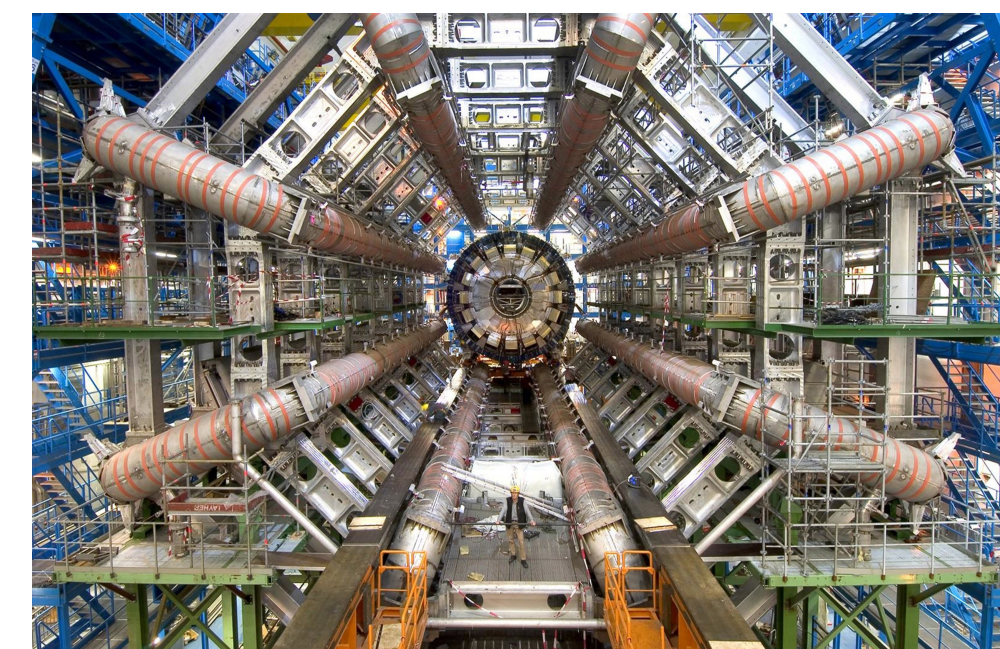
DANCE



KAGRA



XENON



LHC



Subaru telescope

Target: Axion-like particles (ALPs)

Axion-photon interaction

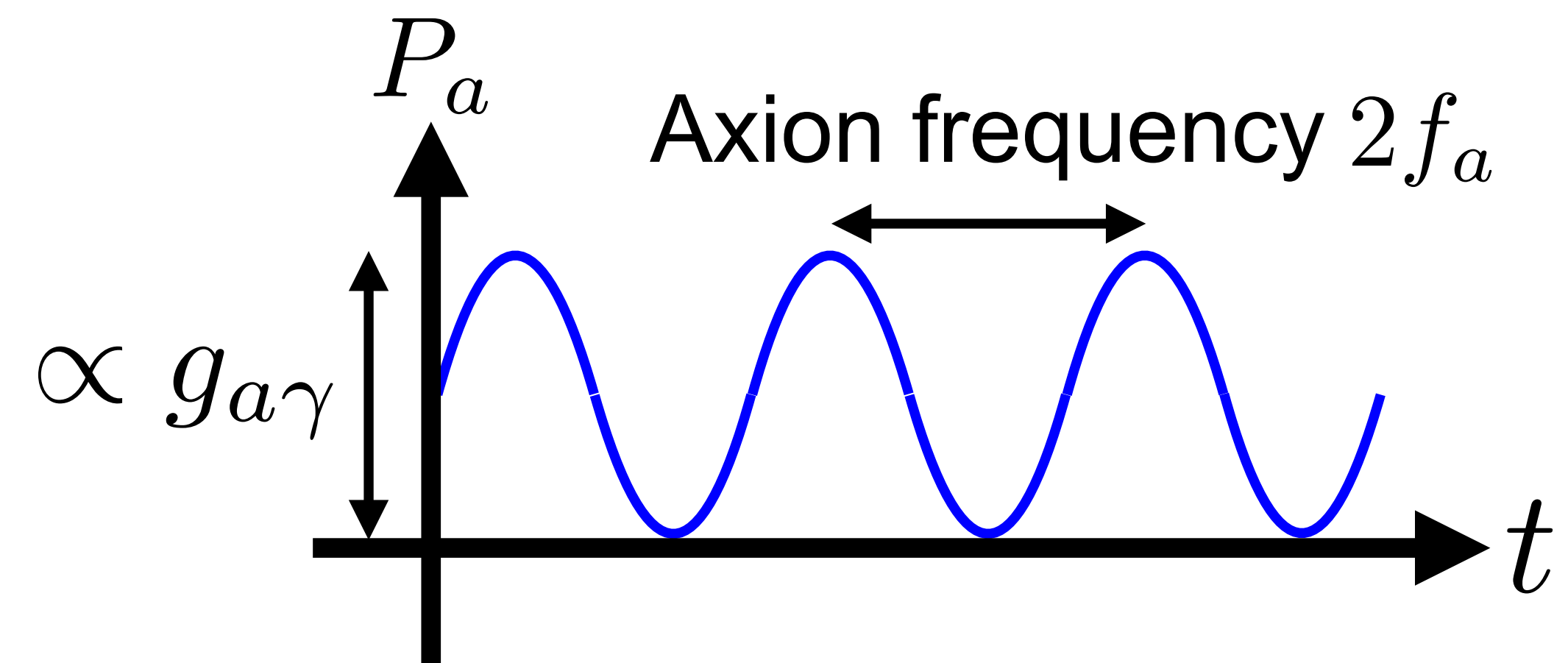
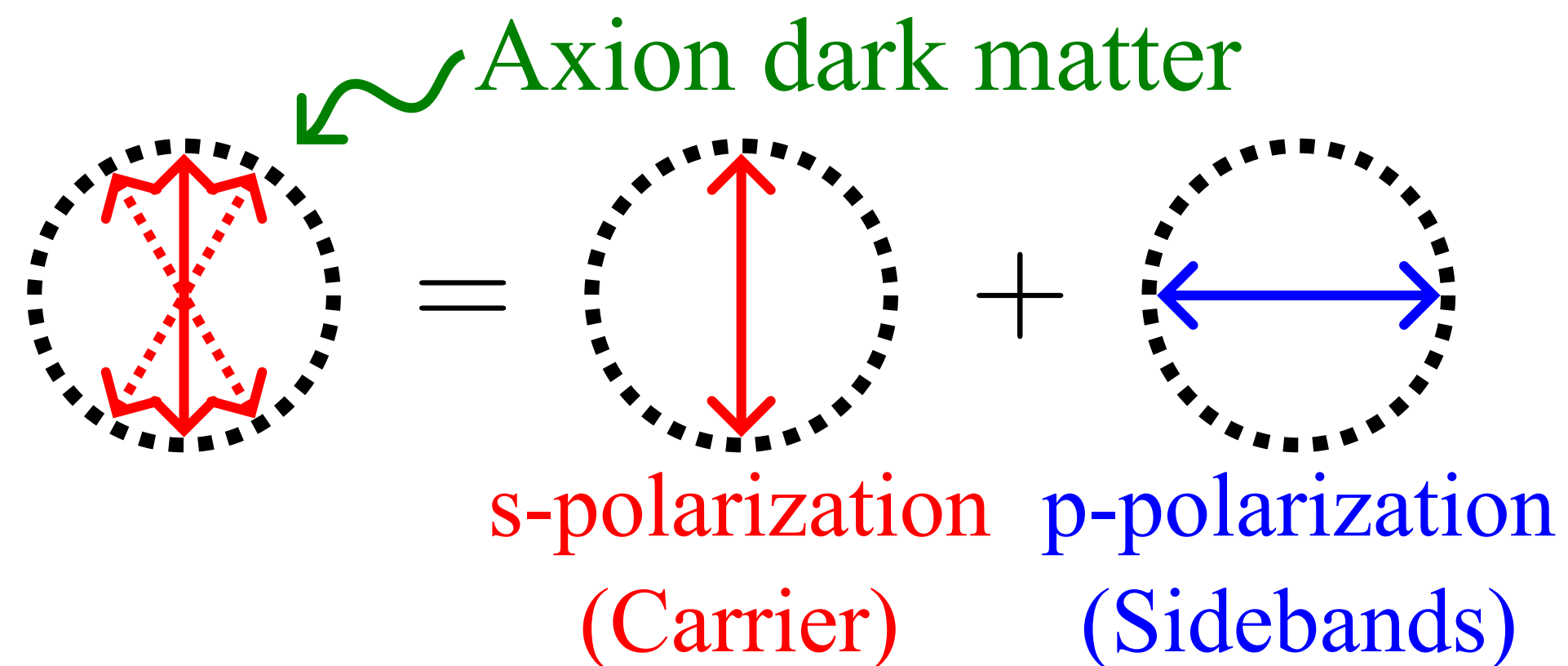
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Axion-photon interaction induces phase velocity difference between left- and right-handed circularly polarized light

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

Phase velocity $\rightarrow c_{L/R}(t)$
 Axion-photon coupling $\rightarrow g_{a\gamma}$
 Axion field $\rightarrow a_0$
 Axion mass $\rightarrow m_a$

➡ Rotation of linearly polarized light

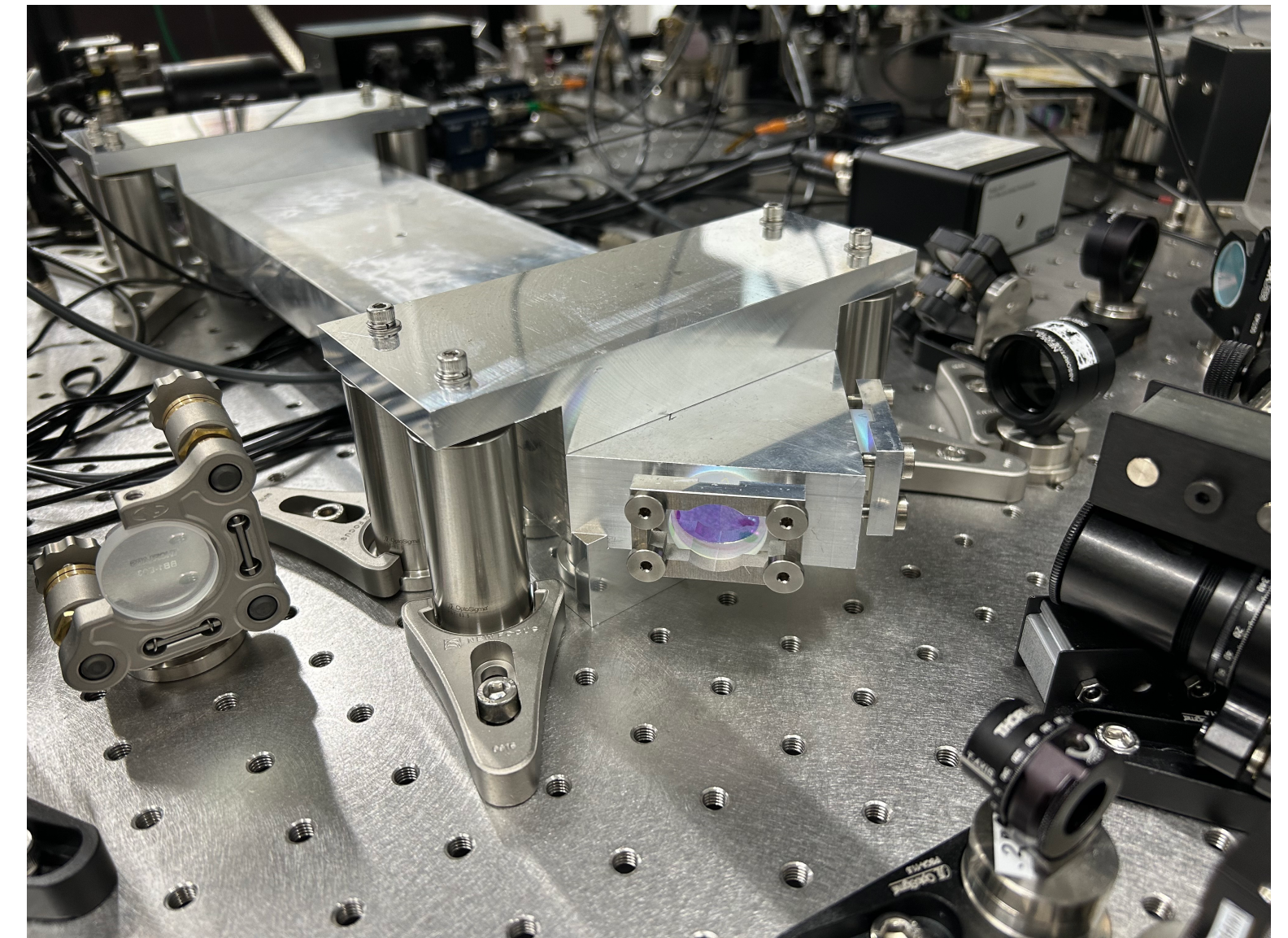
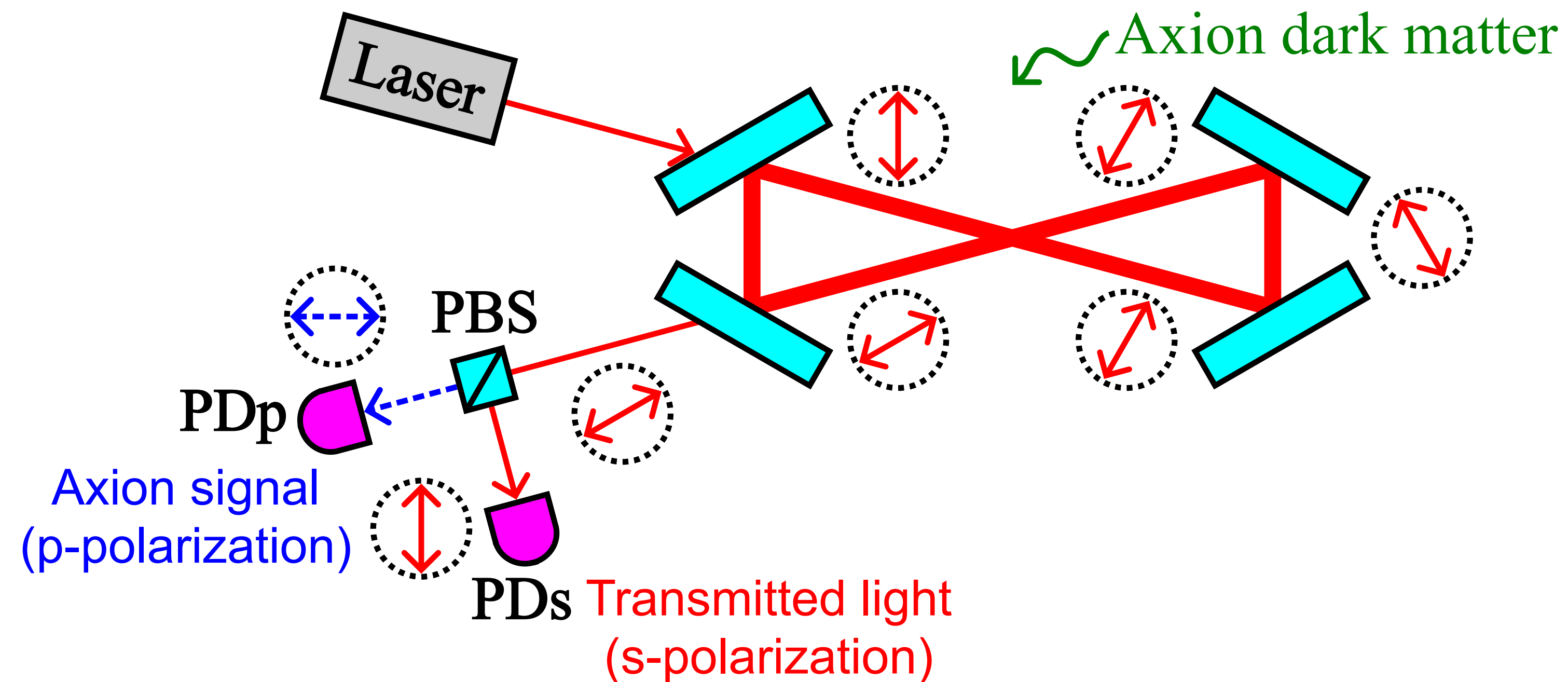


Principle of DANCE

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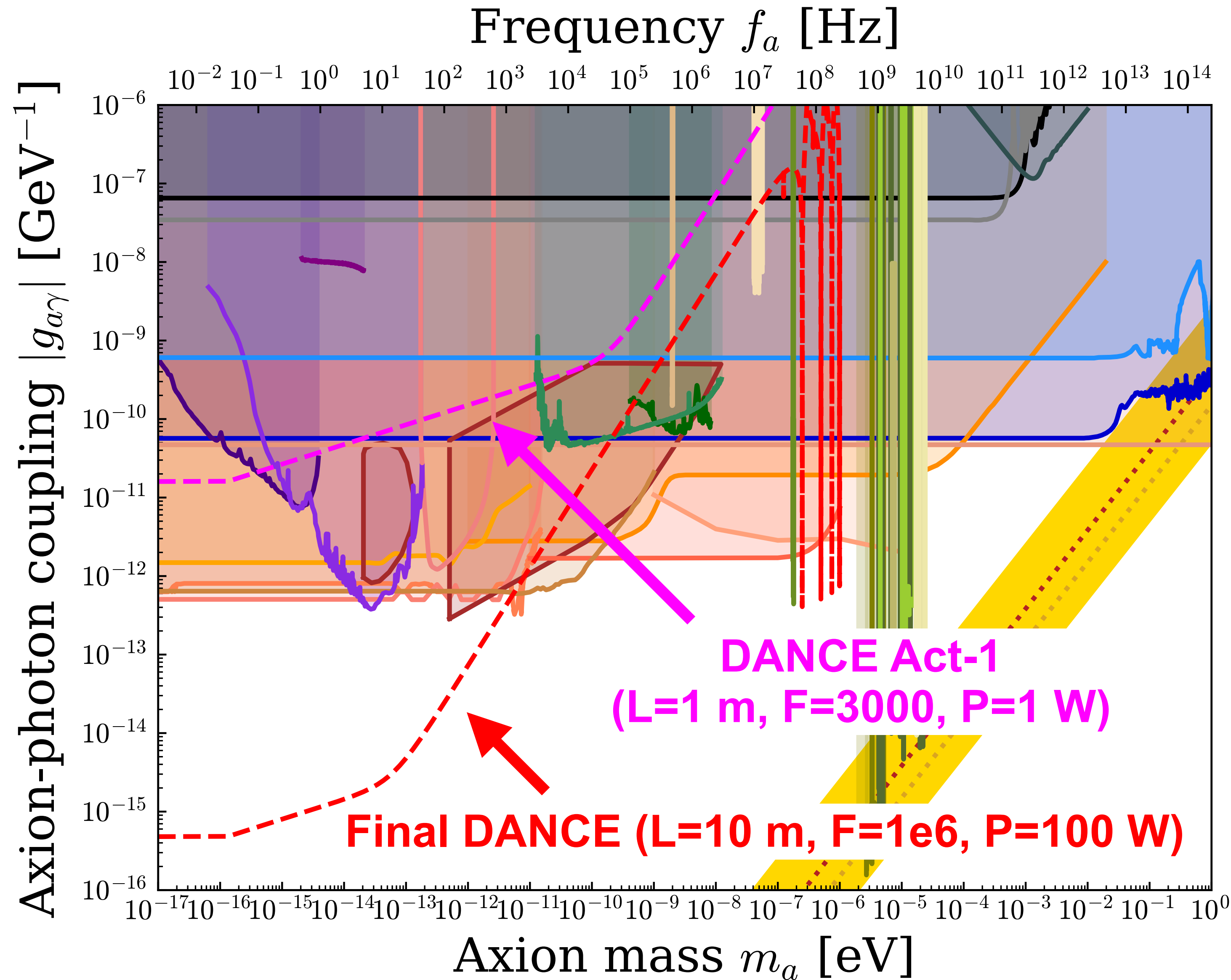
DANCE: Dark matter Axion search with ring Cavity Experiment

- 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



Target sensitivity of DANCE

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- Assume dark matter consists of ALPs
- Shot noise limited

Parameter of optical cavity

L : Round-trip

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

P_{in} : Input power

Conduct a sensitive axion search
by improving parameters

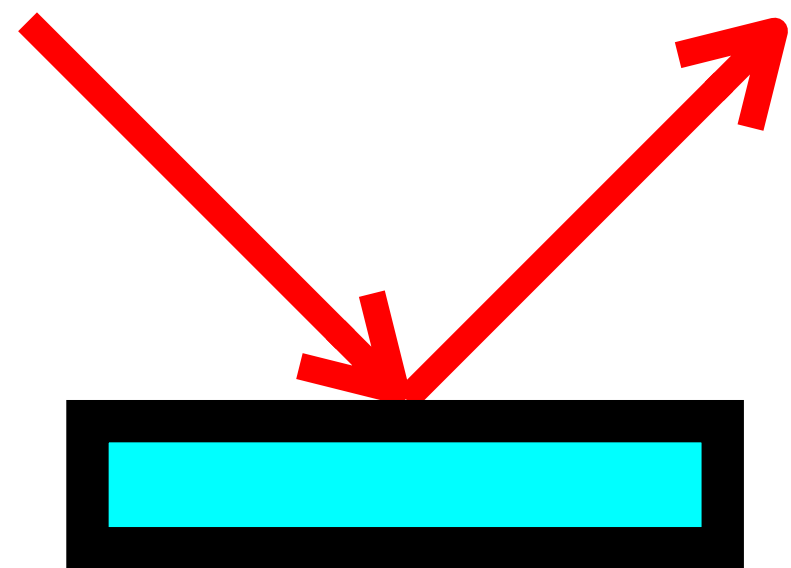
$T_{\text{obs}} = 1 \text{ year}$

Issue: Non-simultaneous resonance

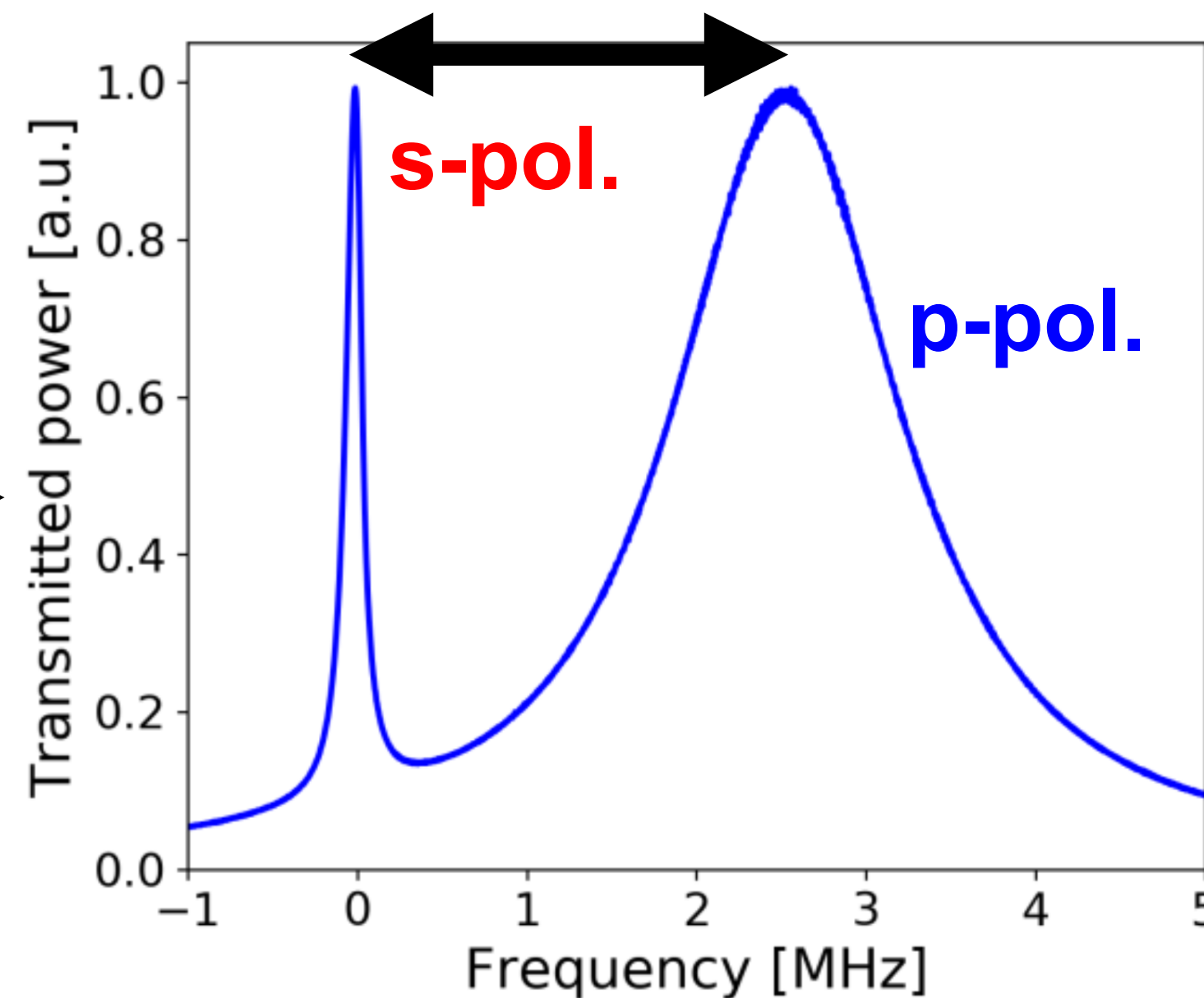
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Reflection phase difference
between s- and p-pol.

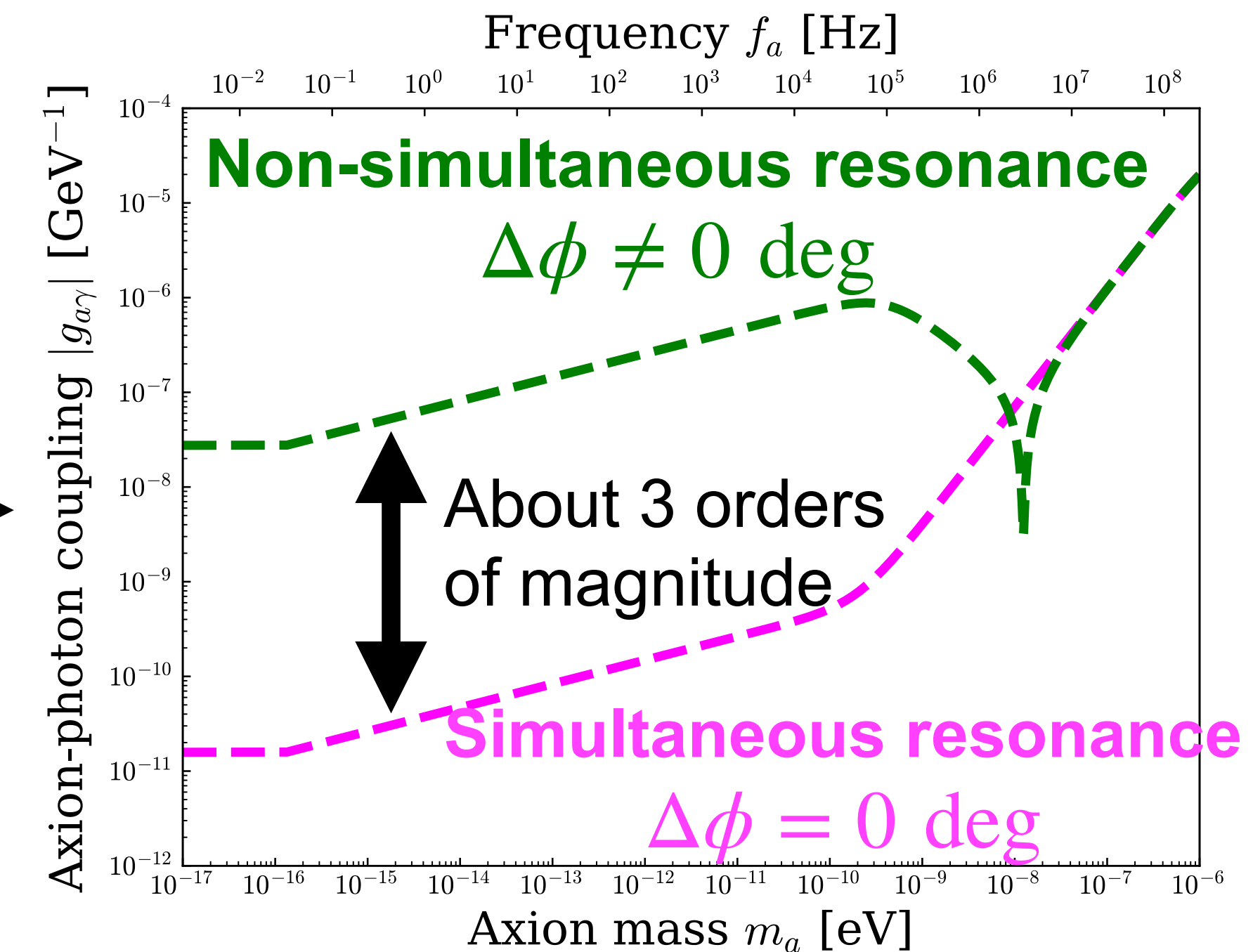
$$\Delta\phi = \phi_s - \phi_p \neq 0 \text{ deg}$$



Resonant frequency difference
between s- and p-pol.



Assume resonant frequency
difference is 3 MHz



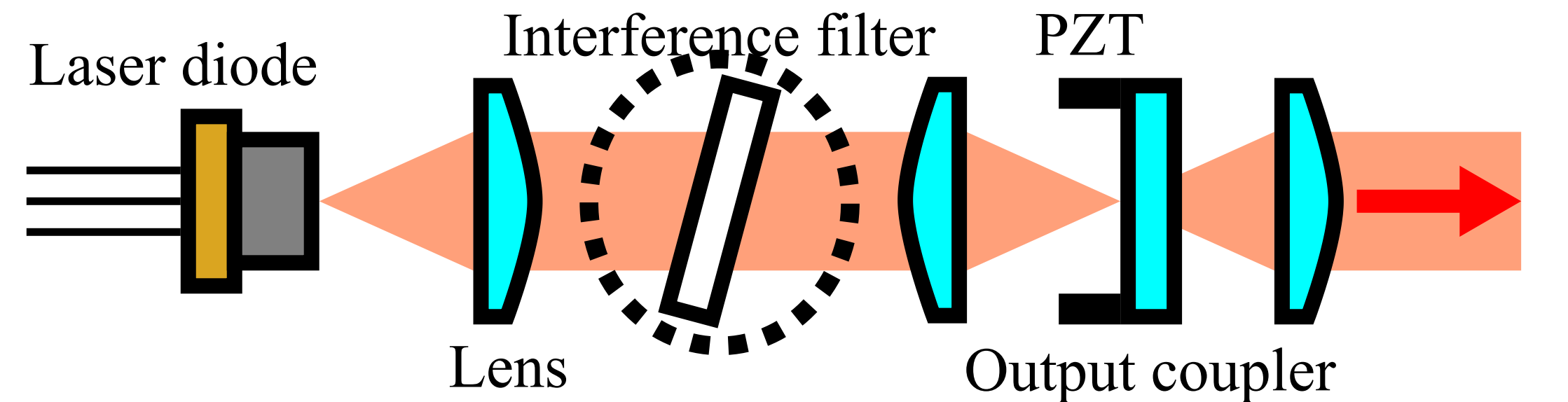
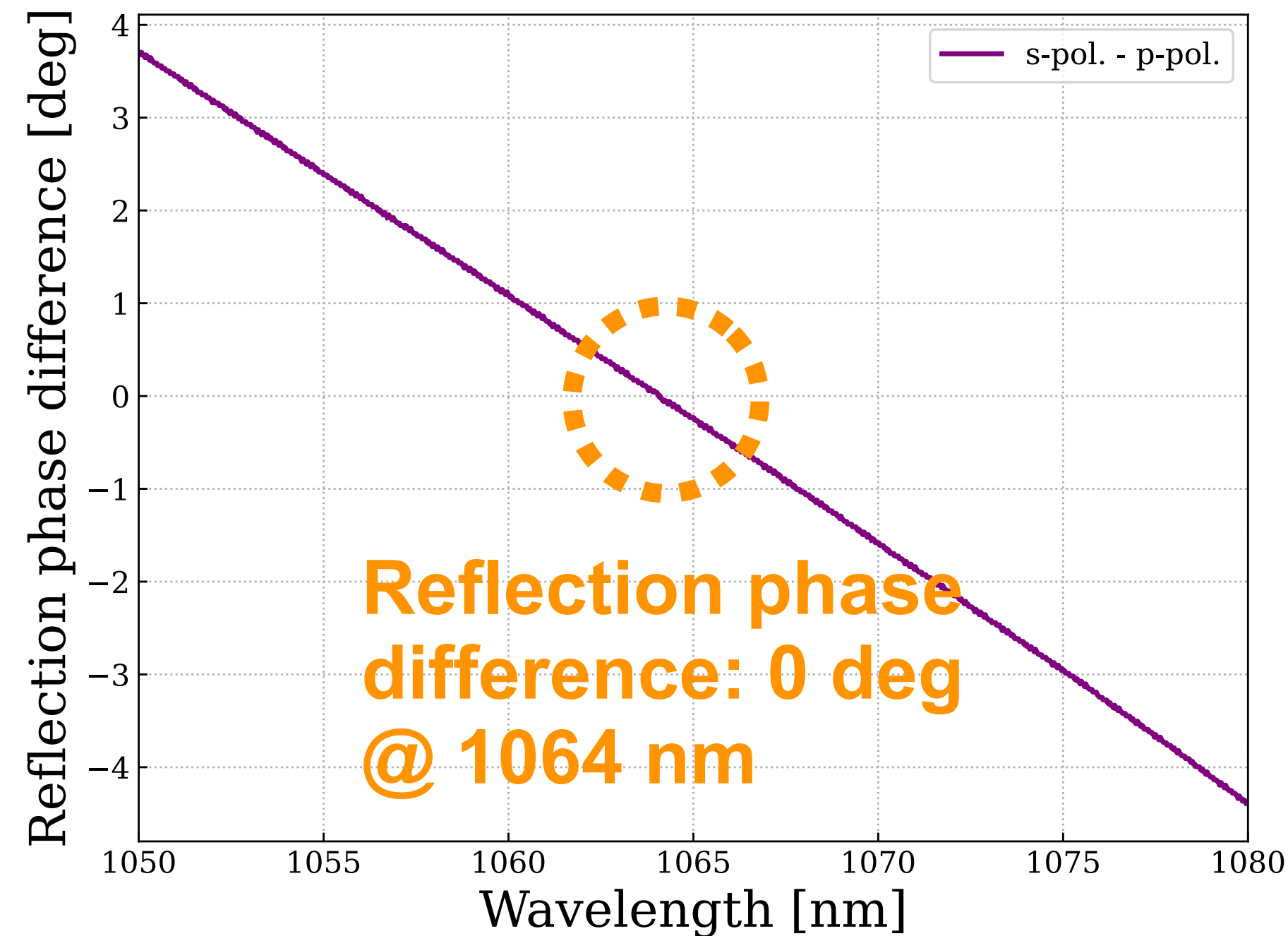
Y. Oshima *et al.*, Phys. Rev. D **108**, 072005 (2023).

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

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Select wavelength by rotating interference filter

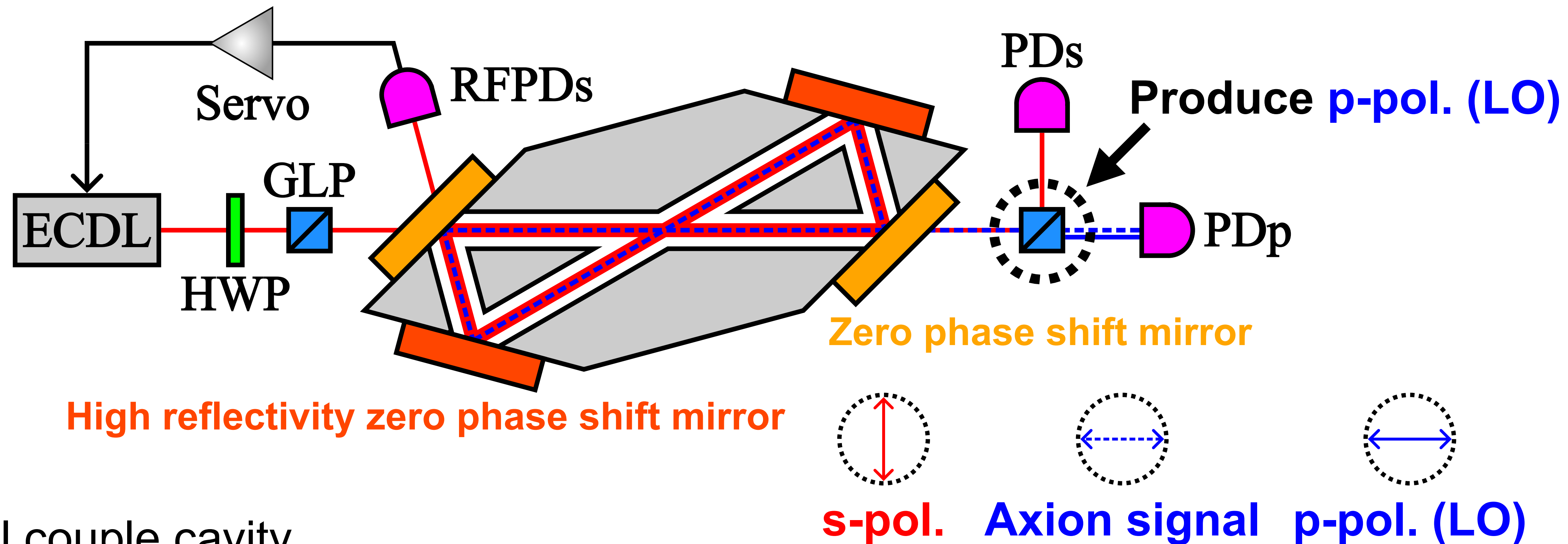
Wavelength tunable laser (ECDL)

- 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 $\gg$ 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)

Experimental setup

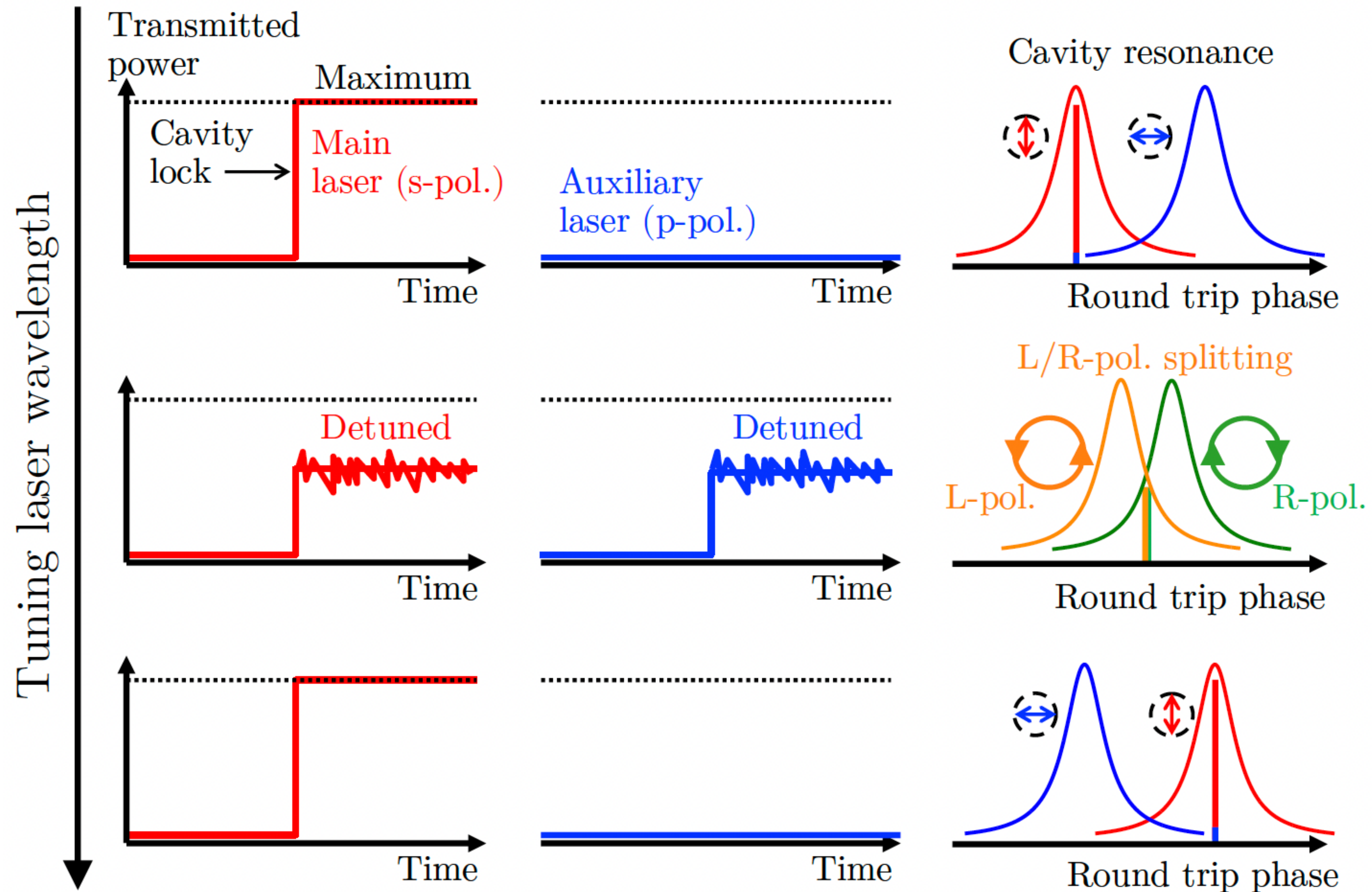
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- Critical couple cavity
 - Control bandwidth: ~ 450 kHz
 - Finesse: **s-pol.**: $4.8(6) \times 10^3$, **p-pol.**: $4.8(5) \times 10^3$
 - Measurement: Rotating output GLP to produce **p-pol. (LO)** from **s-pol.**
- ➡ Obtain beat signal between axion signal and the LO

Issue: L/R-polarization splitting

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

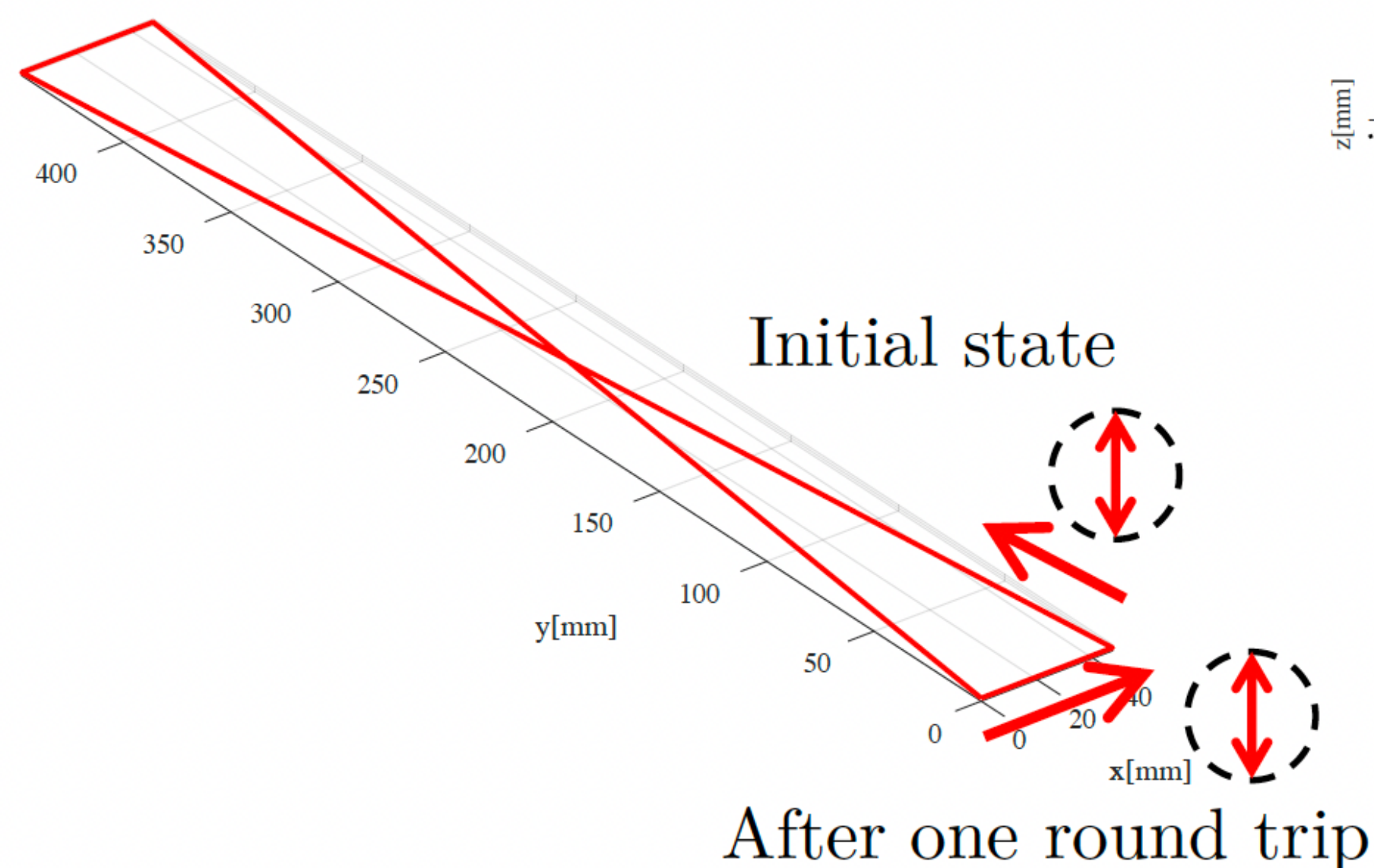
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In general, when 4 or more mirrors are used, the optical path can be non-planar

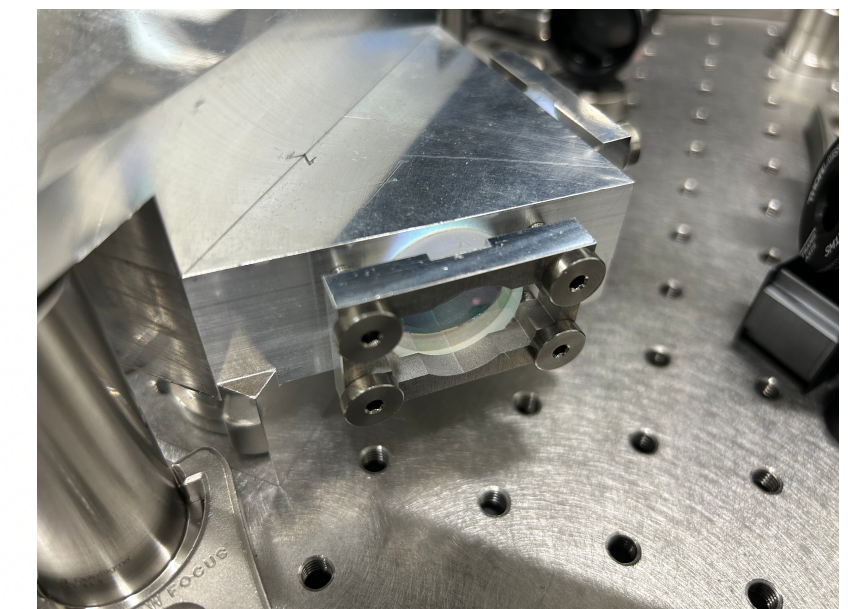
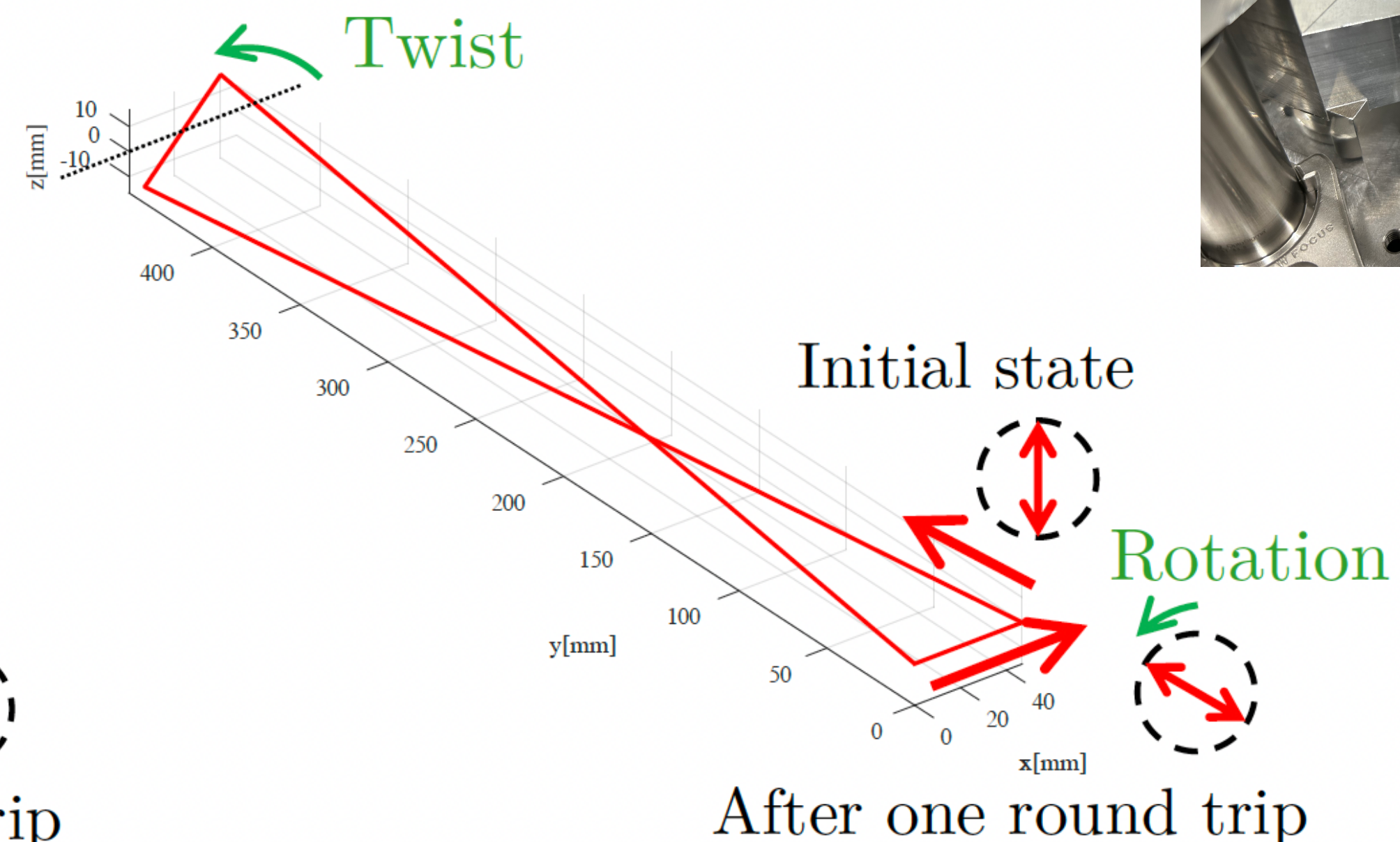
➡ DC rotation of linear polarization occurs within the cavity (non-simultaneous resonance of L/R-polarization)

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

➤ Planar cavity



➤ Non-planar cavity

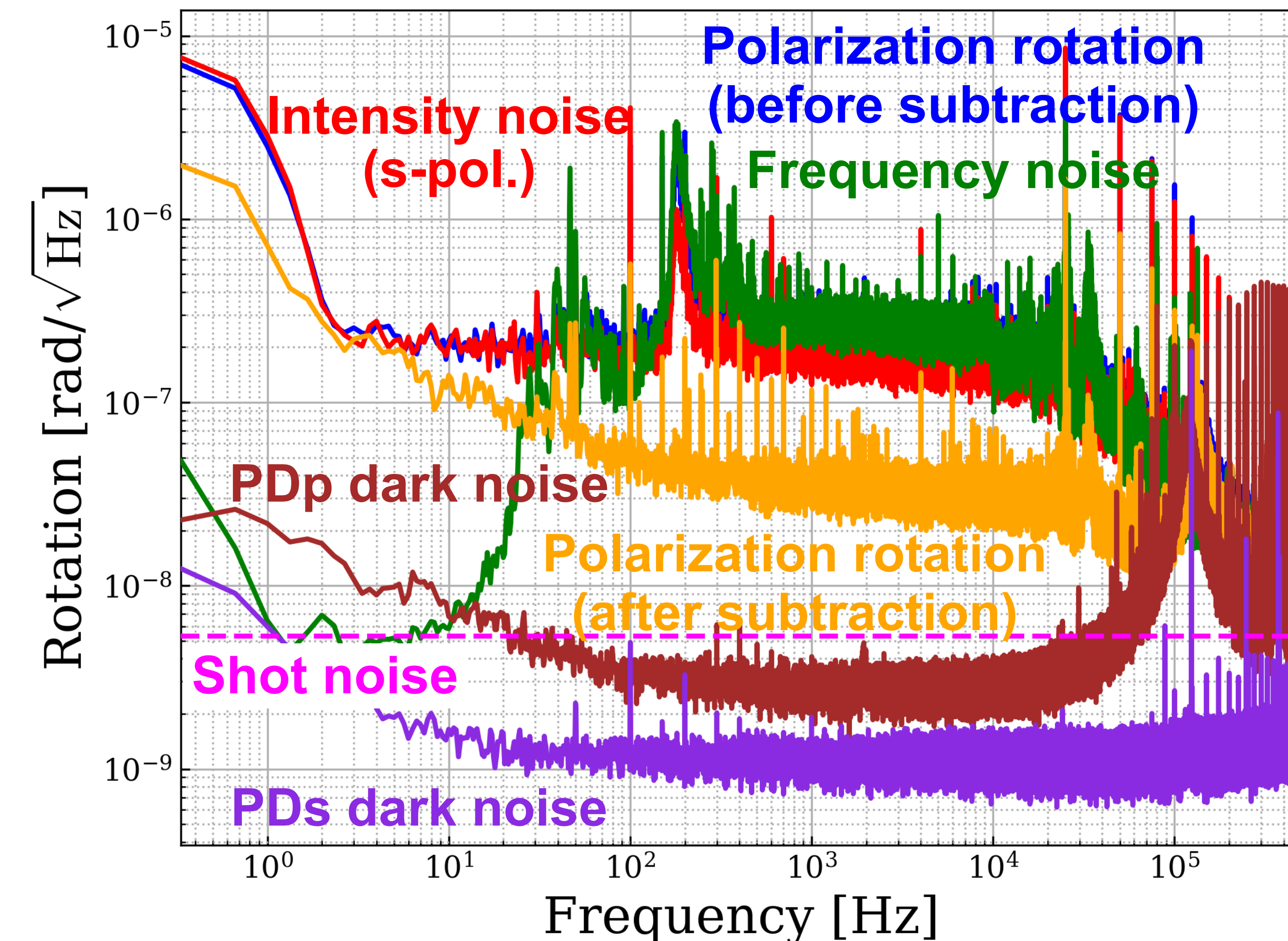


Polarization rotation spectrum

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Residual resonant frequency difference: 5.3(5) kHz

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

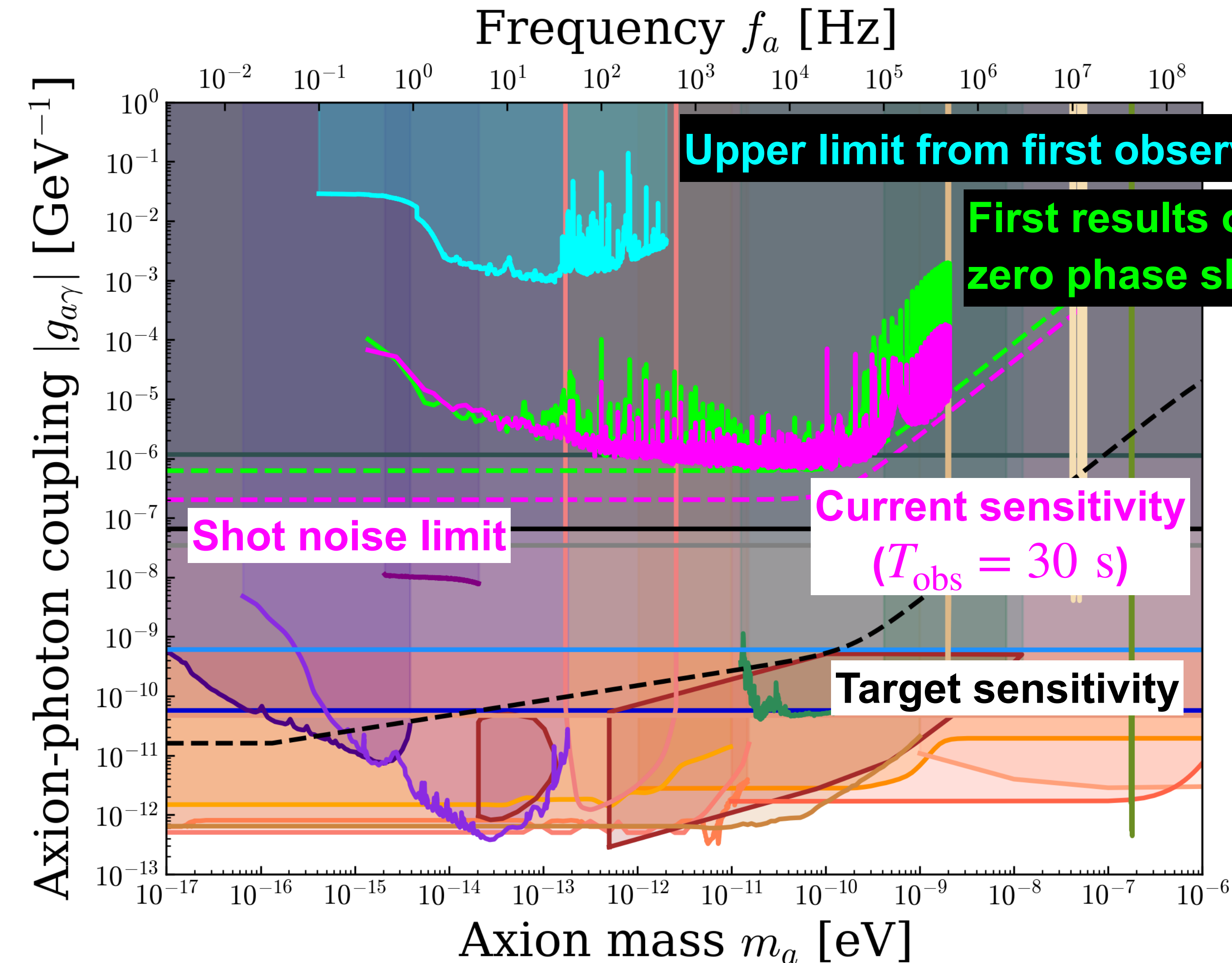


- Subtract **intensity noise (s-pol.)** and **frequency noise** from **polarization rotation** by offline analysis

➡ Successful subtraction by up to ~1 order of magnitude

Noise source

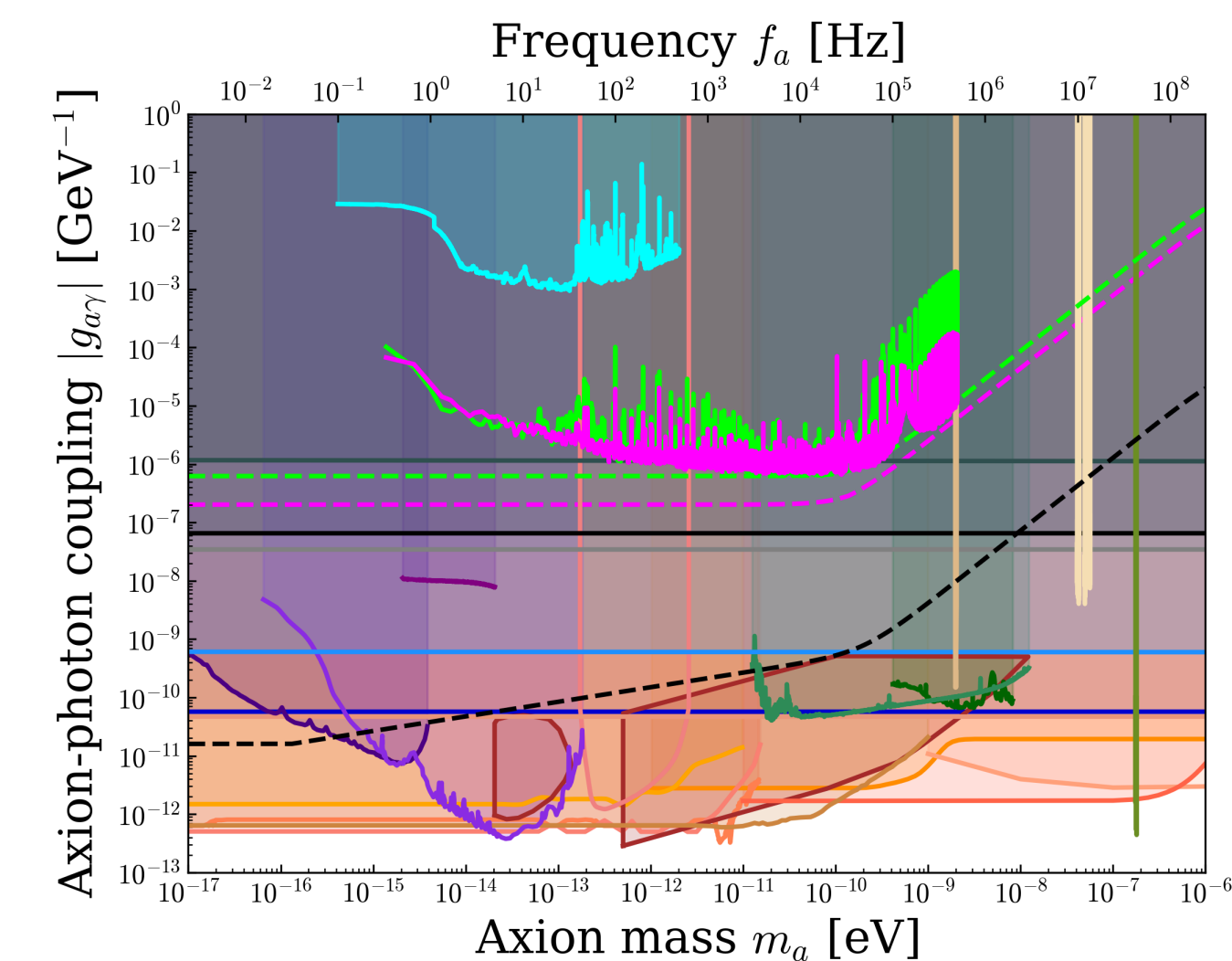
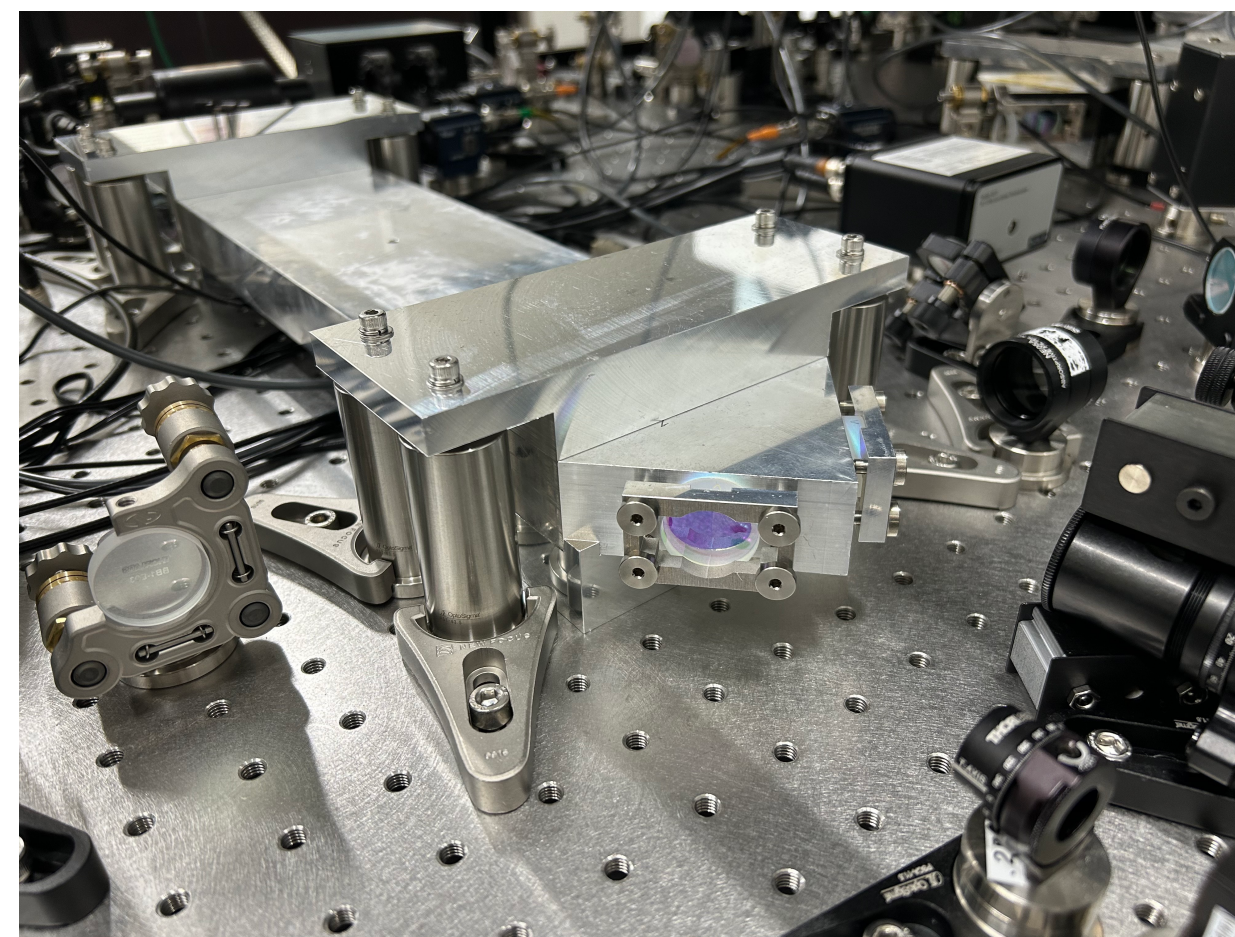
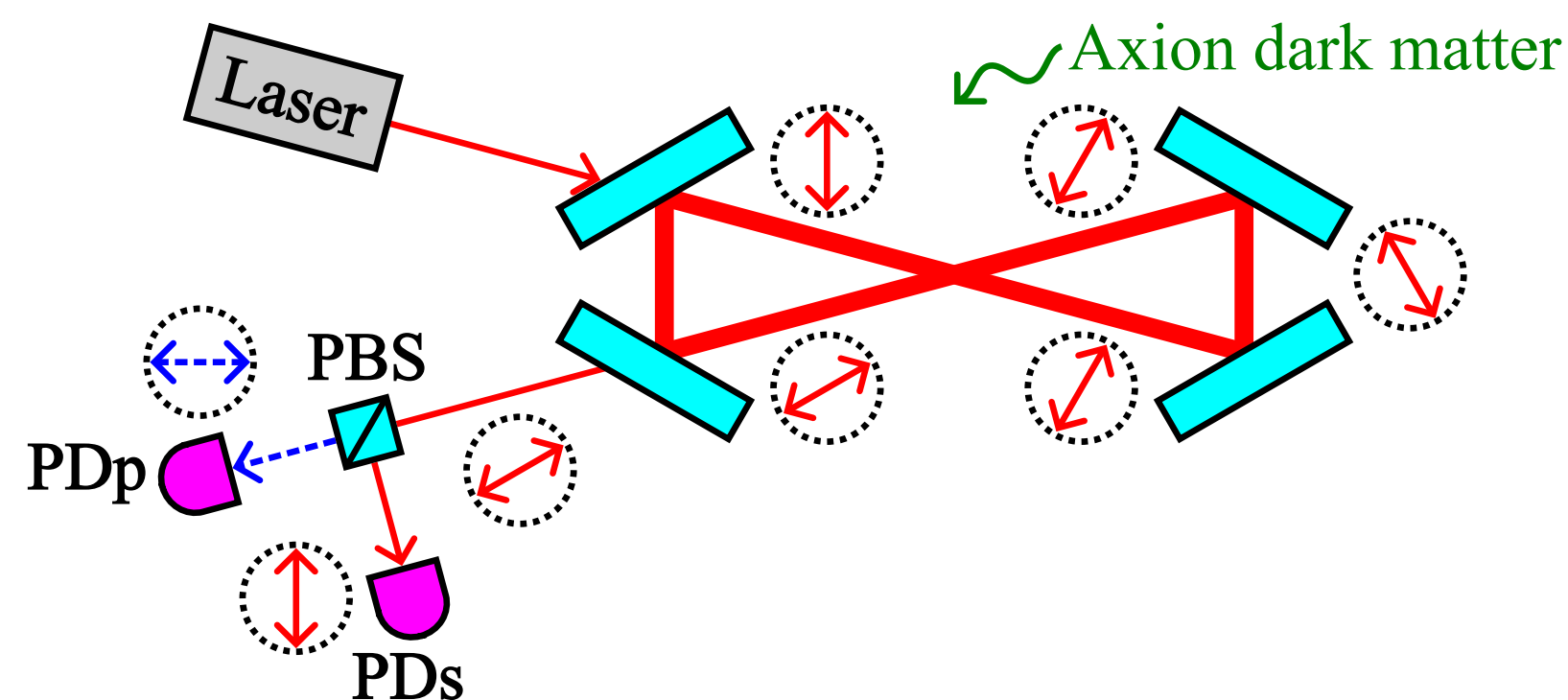
- < 60 kHz: Possibility of nonlinear coupling of frequency noise
- > 60 kHz: Limited by **PDp dark noise**



- Compared to first results of simultaneous resonance with zero phase shift mirrors,
- shot noise limit improved by $\sim 2.86x$
 - sensitivity is enhanced by up to ~ 1 order of magnitude

DANCE: Dark matter Axion search with riNg Cavity Experiment

- Development of simultaneous resonance of s- and p-polarizations using zero phase shift mirrors and a wavelength tunable laser
- Simultaneous resonance using a critical couple cavity improved the sensitivity by ~ 3 orders of magnitude compared to the upper limit from first observation
- Future prospects for DANCE
 - Introduce power amplifier to increase input power into a bow-tie ring cavity
 - Long term observation



Backup

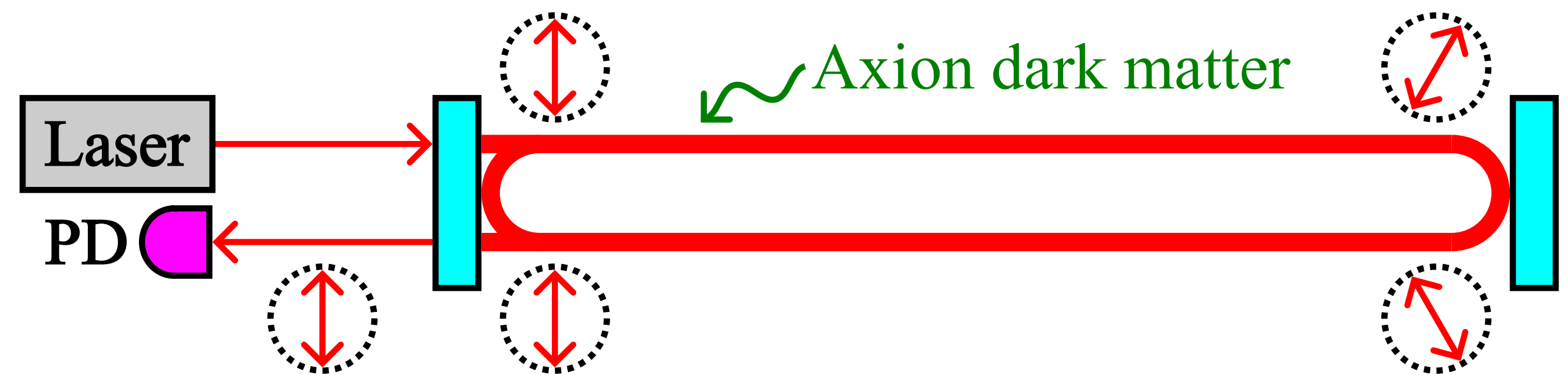
How to amplify the axion signal

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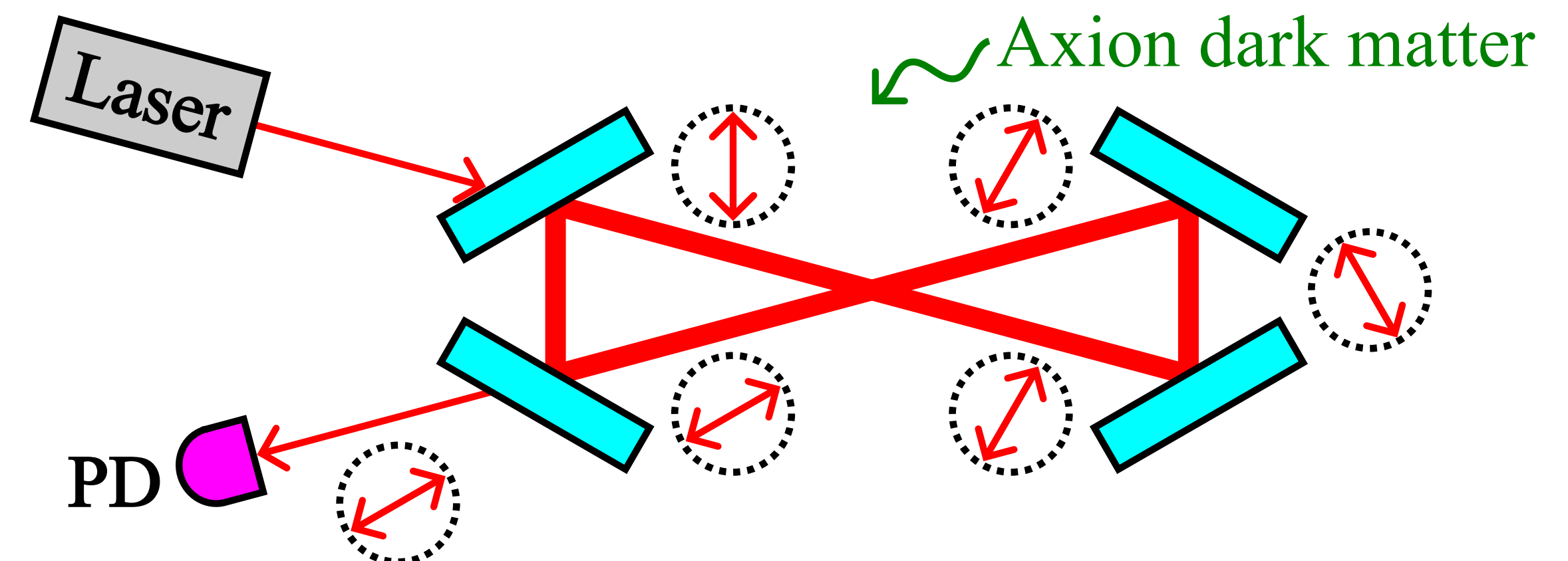
Rotation of polarization is small
for short optical path



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



DANCE Act-1

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

- Long cavity: 10x
- High finesse: $\sim 3000x$
- High power: 100x



Final DANCE

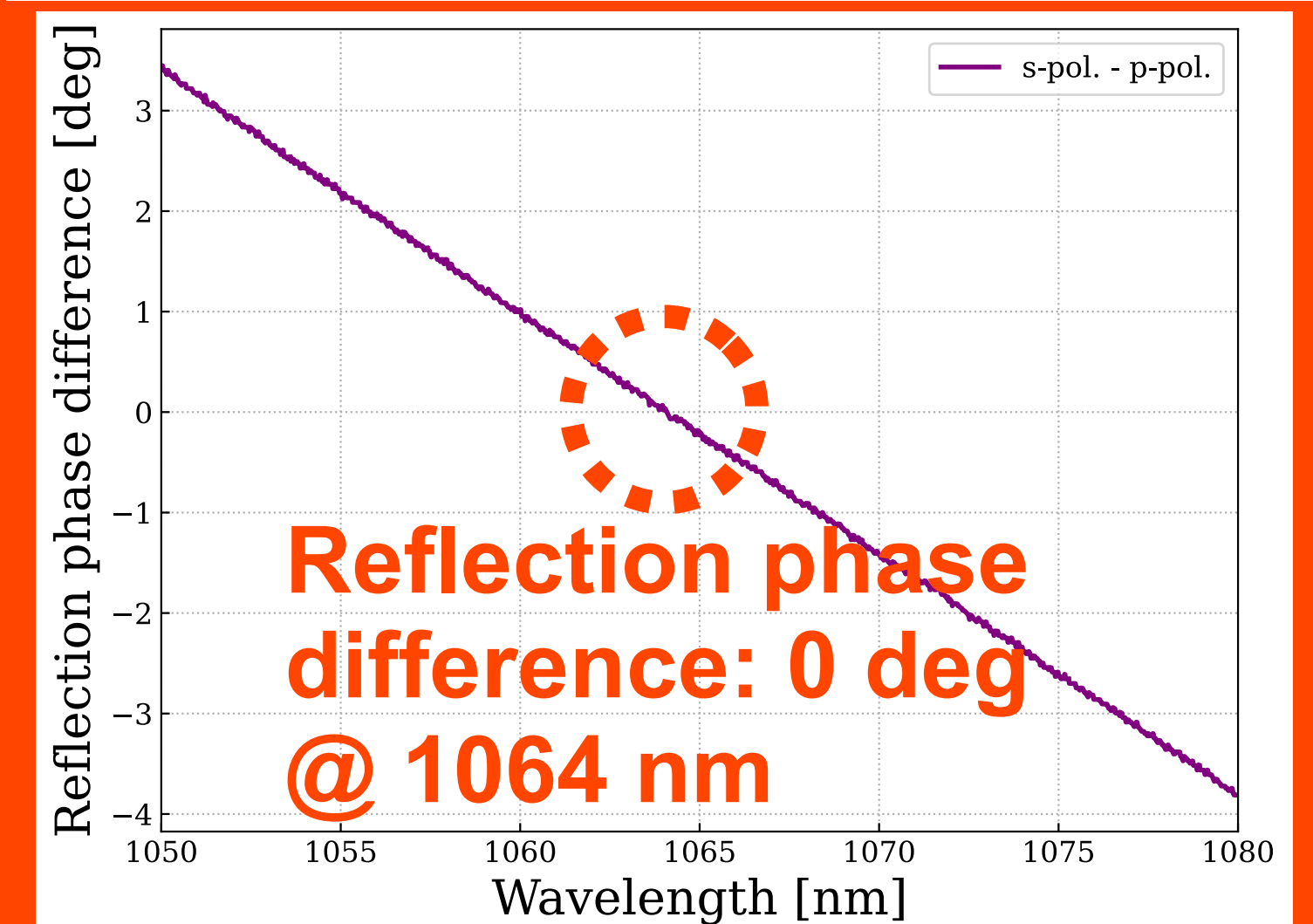
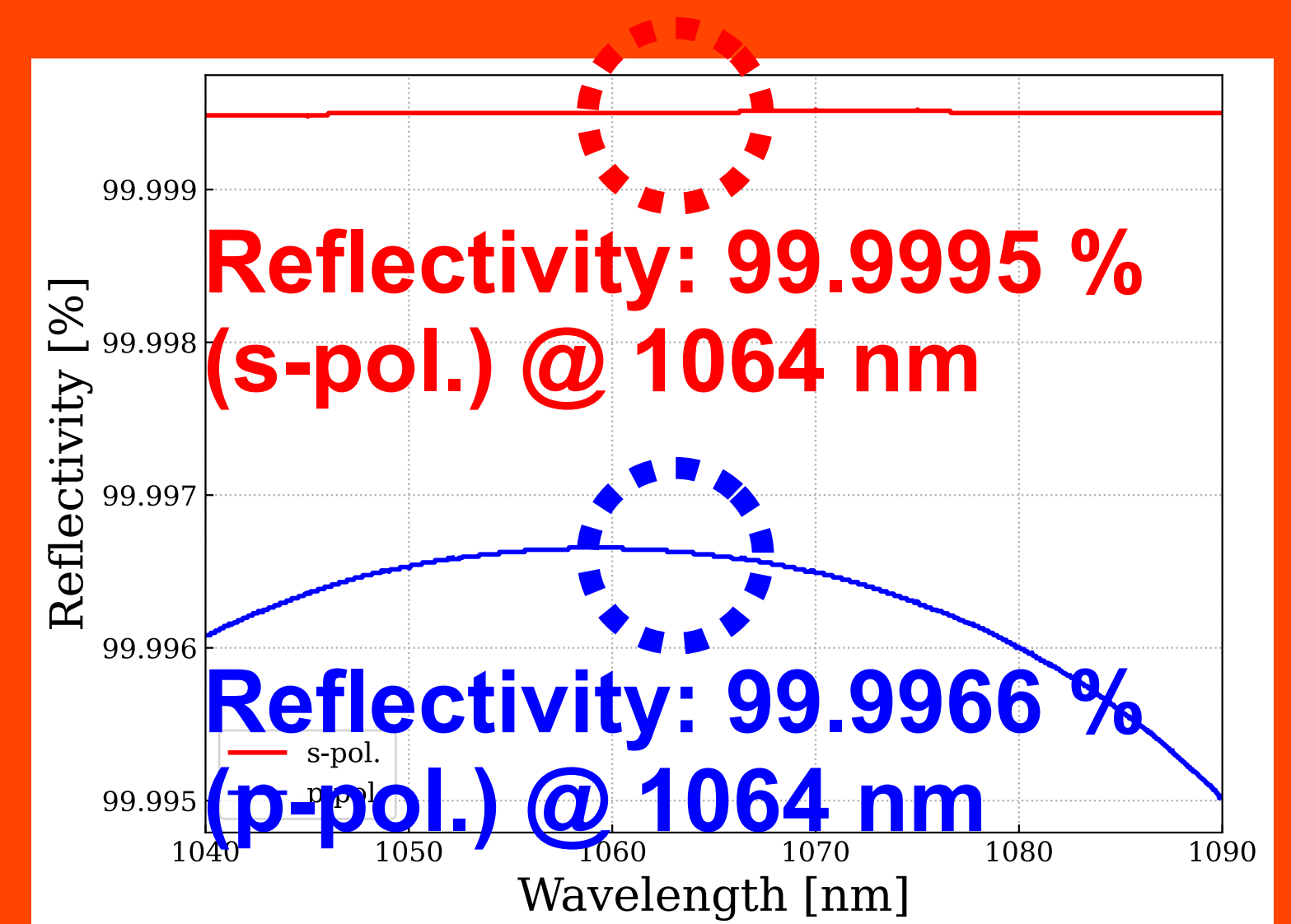
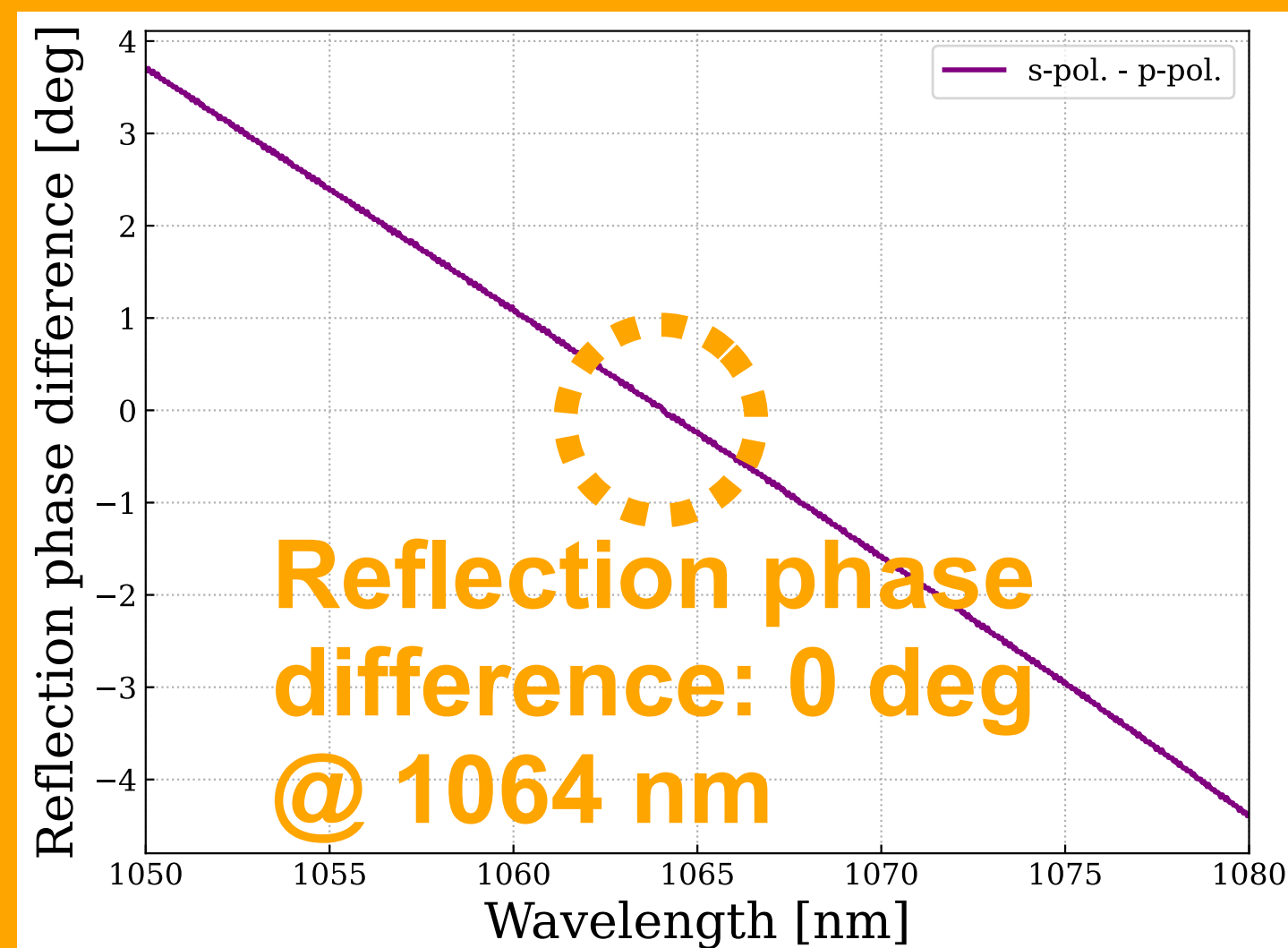
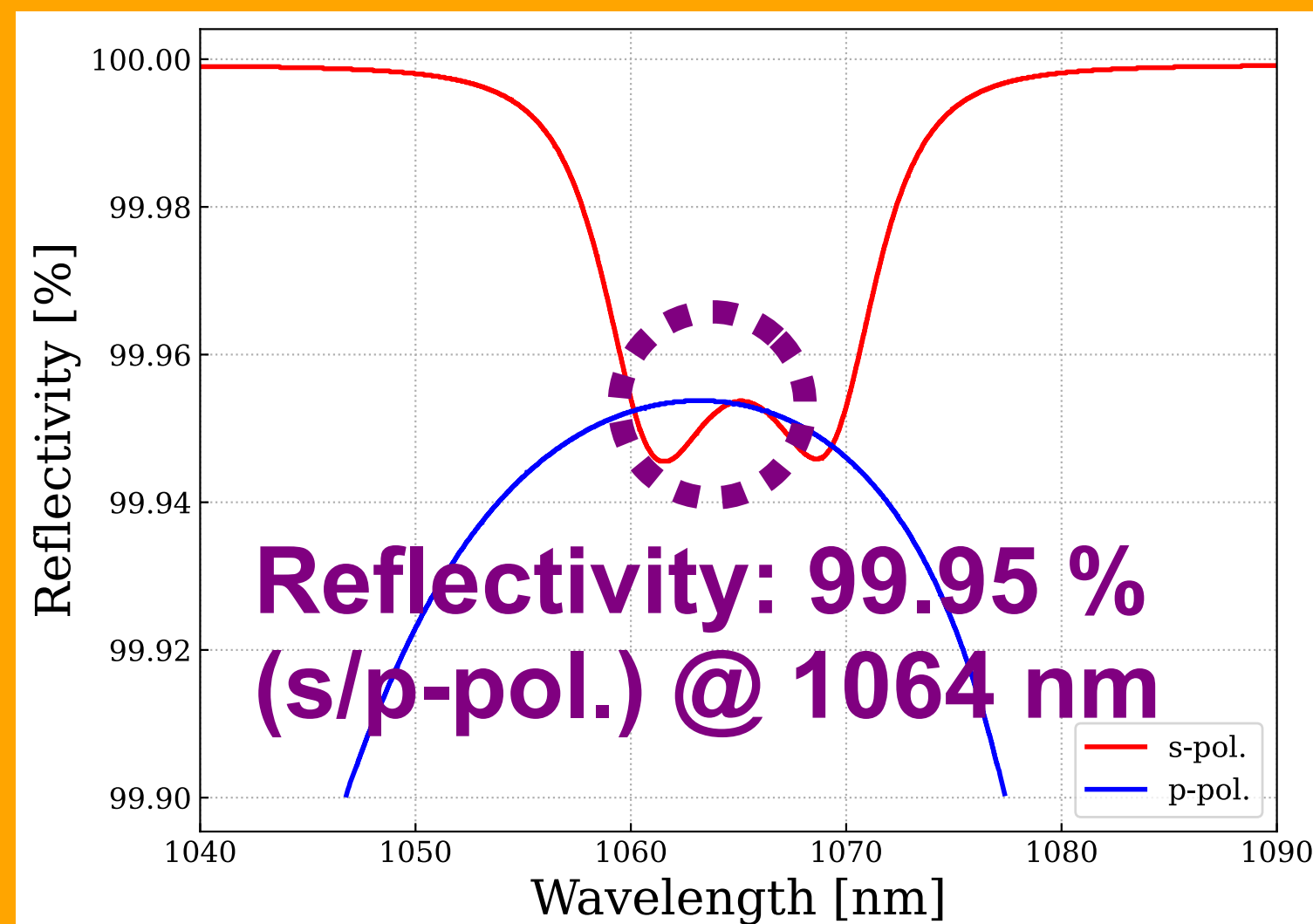
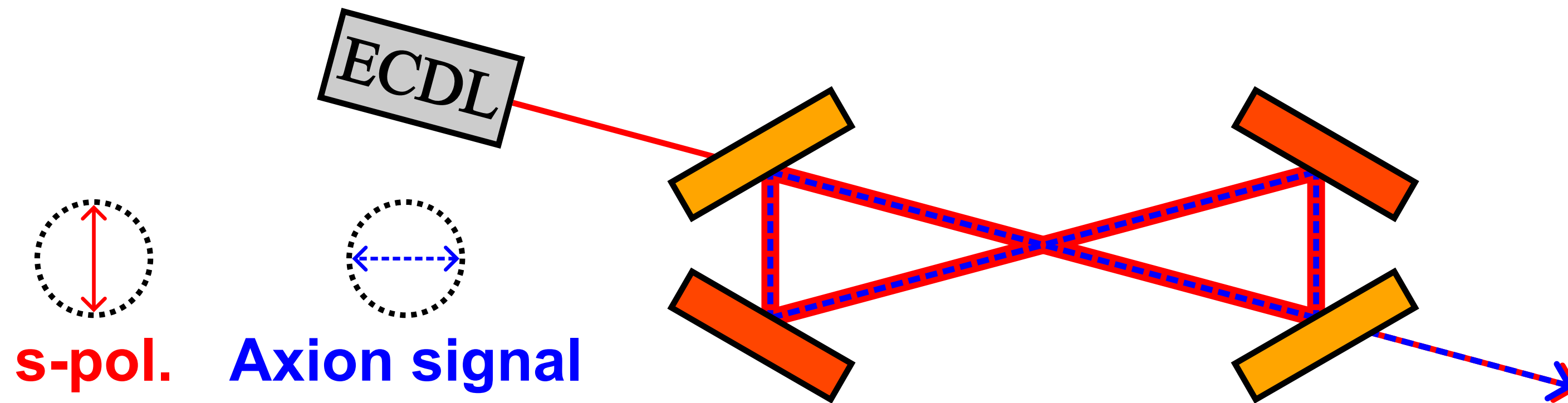
Necessary to achieve target sensitivity of DANCE Act-1

- ① Critical couple cavity
 - Cavity transmission: $\sim 2.4x$ better (17% $\rightarrow$ 99%)
 - Finesse: $\sim 2.2x$ better (s-pol.: 2600 $\rightarrow$ 6219, p-pol.: 2860 $\rightarrow$ 5882)
- ② Input power increase via power amplifier: ~ 1 order better (6 mW $\rightarrow$ 1 W)
- ③ Long-term observation: $\sim 2 - 3$ orders better (30 s $\rightarrow$ 1 month)

Critical couple cavity

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



Adjustment method for cavity non-planarity 18

- 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

