Current status and future plans of Dark matter Axion search with riNg Cavity Experiment (DANCE)

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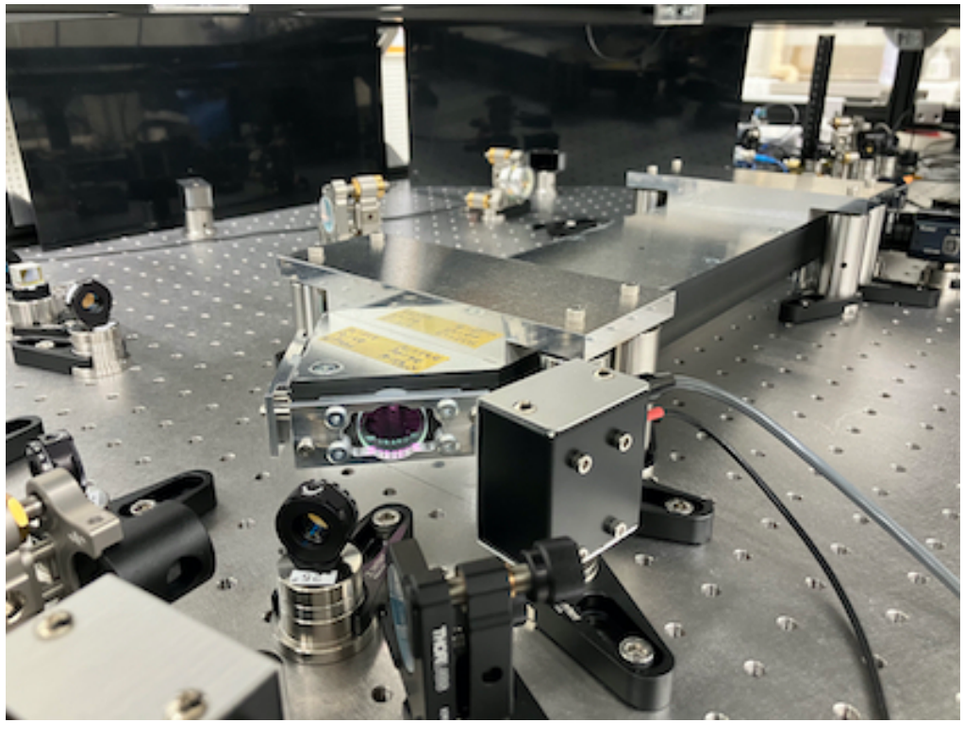
Abstract

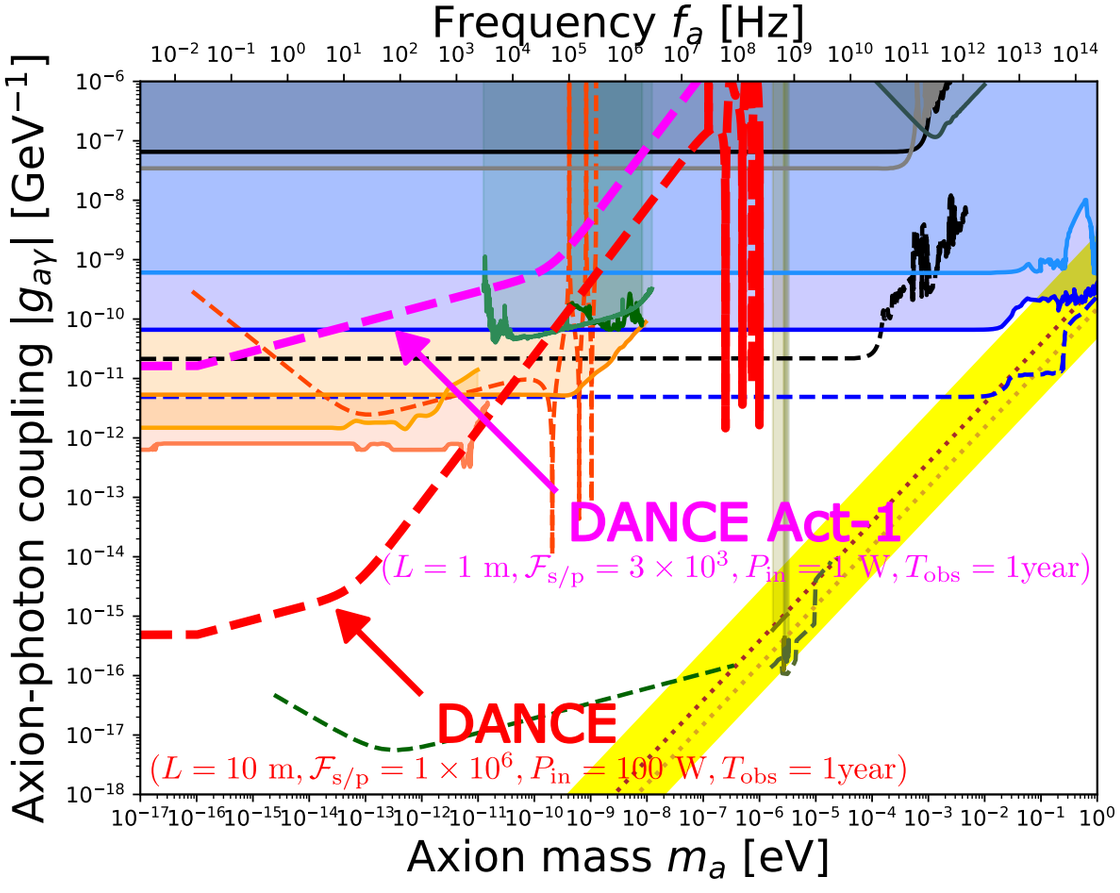
Aim to detect axion with a bow-tie optical ring cavity

- Laser interferometer
- Axion-photon interaction
- Simultaneous resonance

→ Conduct a sensitive broadband axion search



DANCE



Contents

- Introduction
- First results of DANCE Act-1
- Simultaneous resonance
- Current status of DANCE Act-1
- Future plans for DANCE
- Summary

Dark matter

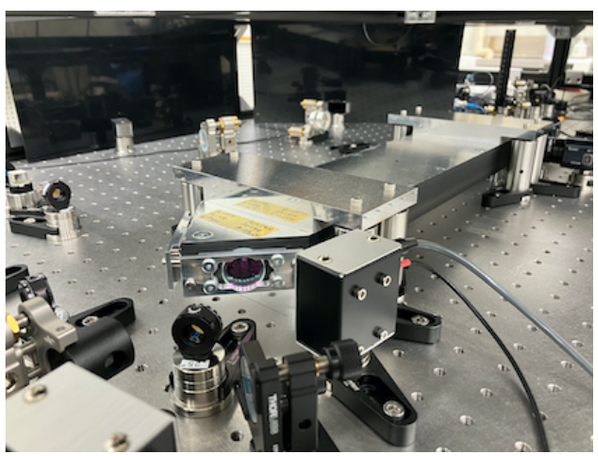
- Account for about 80% of all the matter in the universe
- Extensive research is being conducted
- One of the leading candidates of dark matter: Axion

Dark matter mass [GeV]

10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50} 10^{60}

Excluded | **Ultralight DM** | **Light DM** | **WIMP** | **Heavy DM** | **Composite DM & Primordial BHs etc.** | Excluded

Laser interferometer



DANCE

KAGRA

XENON

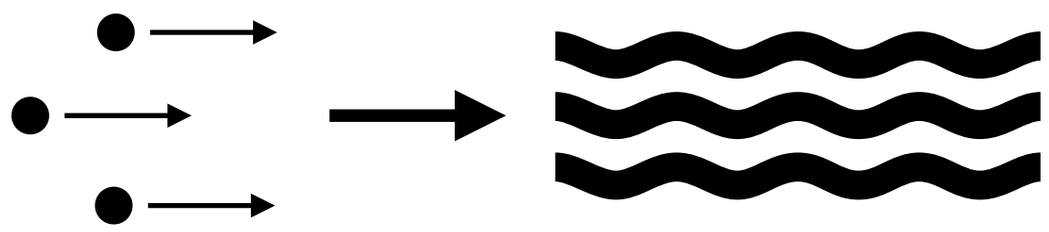
Subaru telescope

Axion and Axion-Like-Particles (ALPs)

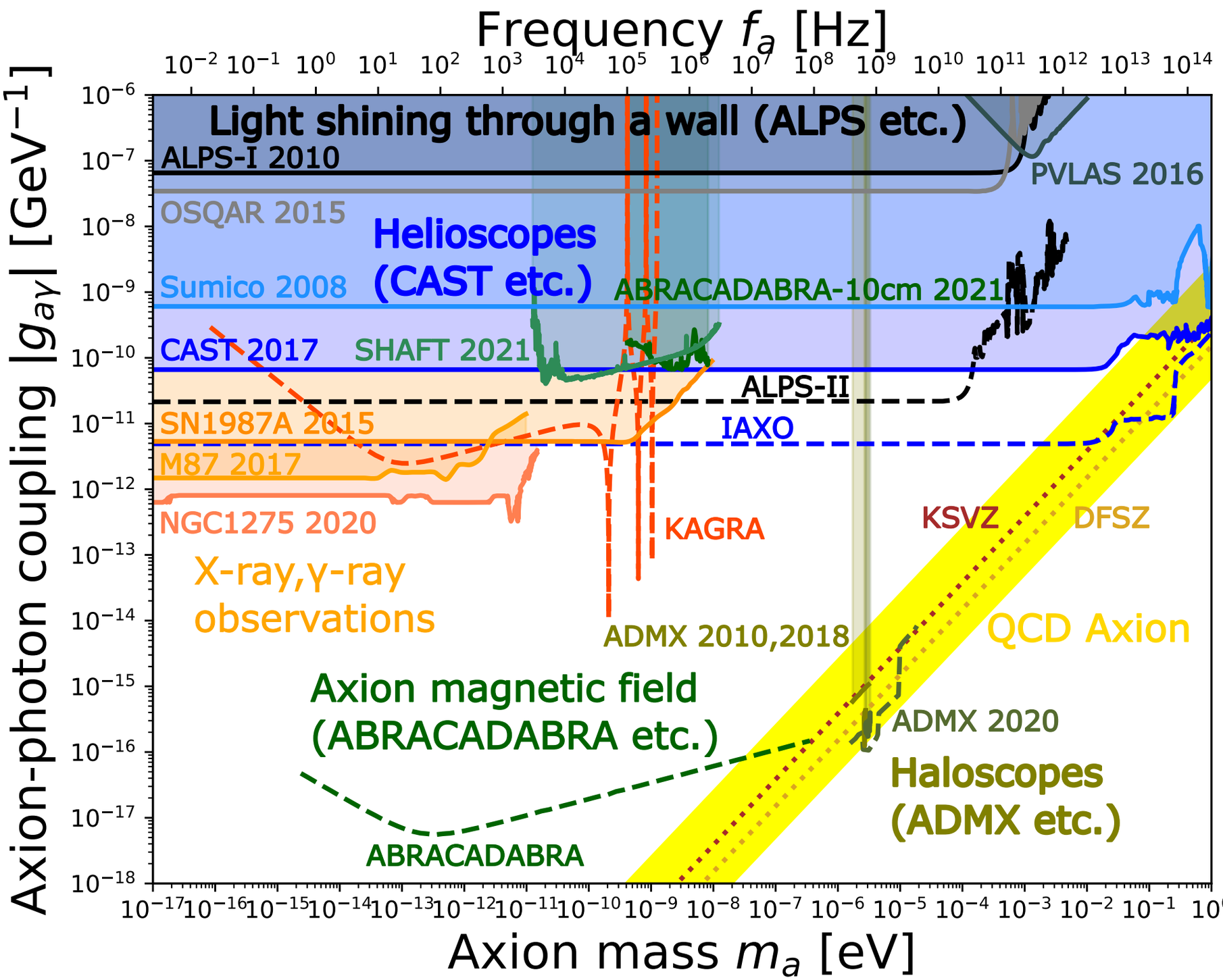
- Pseudo-scalar particle (QCD axion) is suggested to solve strong CP problem on Quantum Chromo Dynamics (QCD)
- Various Axion-Like-Particles (ALPs) is predicted
- Many experiments have utilized the axion-photon conversion under magnetic field (Primakoff effect). However, axion has not been observed yet.

<u>Characteristics (ALPs)</u>

- Very light particles → Behave like waves
- Axion weakly interacts with photon, electron, proton



Previous searches



Relation between axion mass and frequency

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

Axion-photon interaction

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

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

Axion mass

Phase velocity

Axion-photon coupling

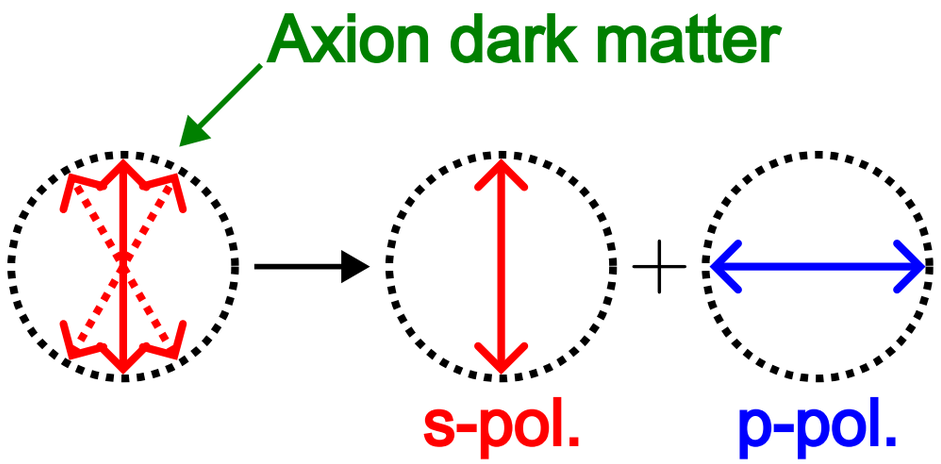
Axion field

Phase factor

⟶ Regard as a rotation of linearly polarized light

Rotation angle of linearly polarized light

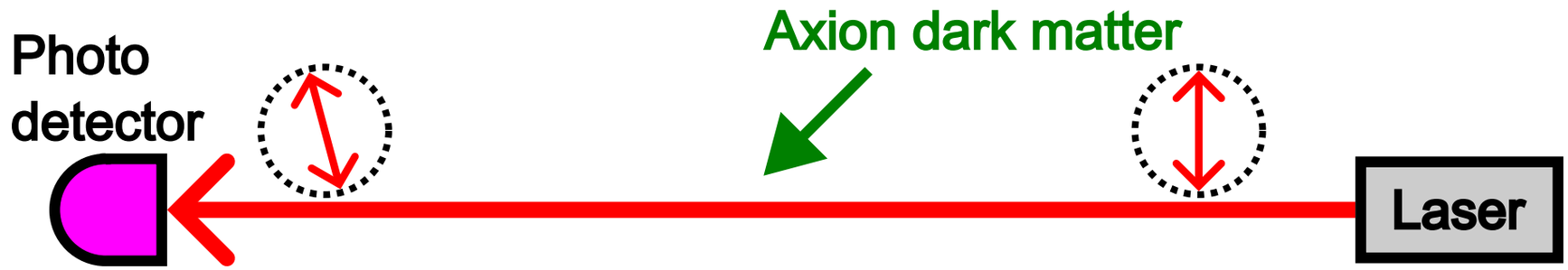
$$\Delta\theta(l,t) = \frac{g_{a\gamma}\sqrt{2\rho_a}}{m_a} \sin\left(m_a \frac{l}{2}\right) \sin\left(m_a\left(t - \frac{l}{2}\right) + \delta_\tau\right)$$



- Detect p-polarized light (Axion signal)
- Amplify it by using longer optical path

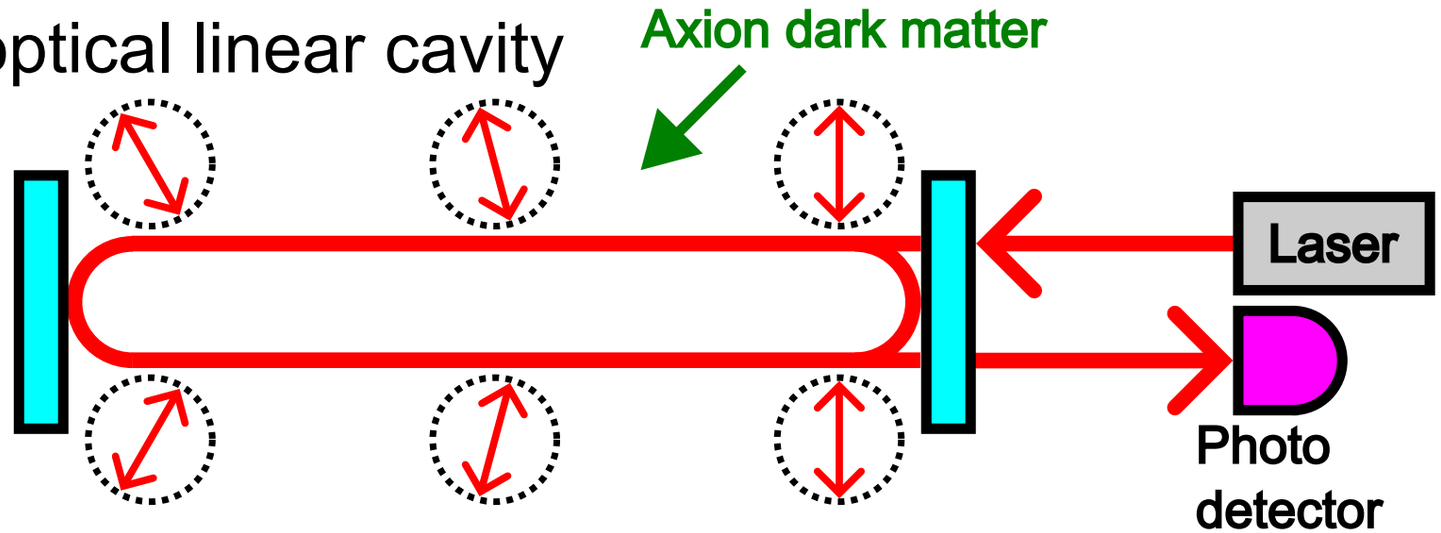
How to amplify the axion signal

Rotation of polarization is small for short optical path



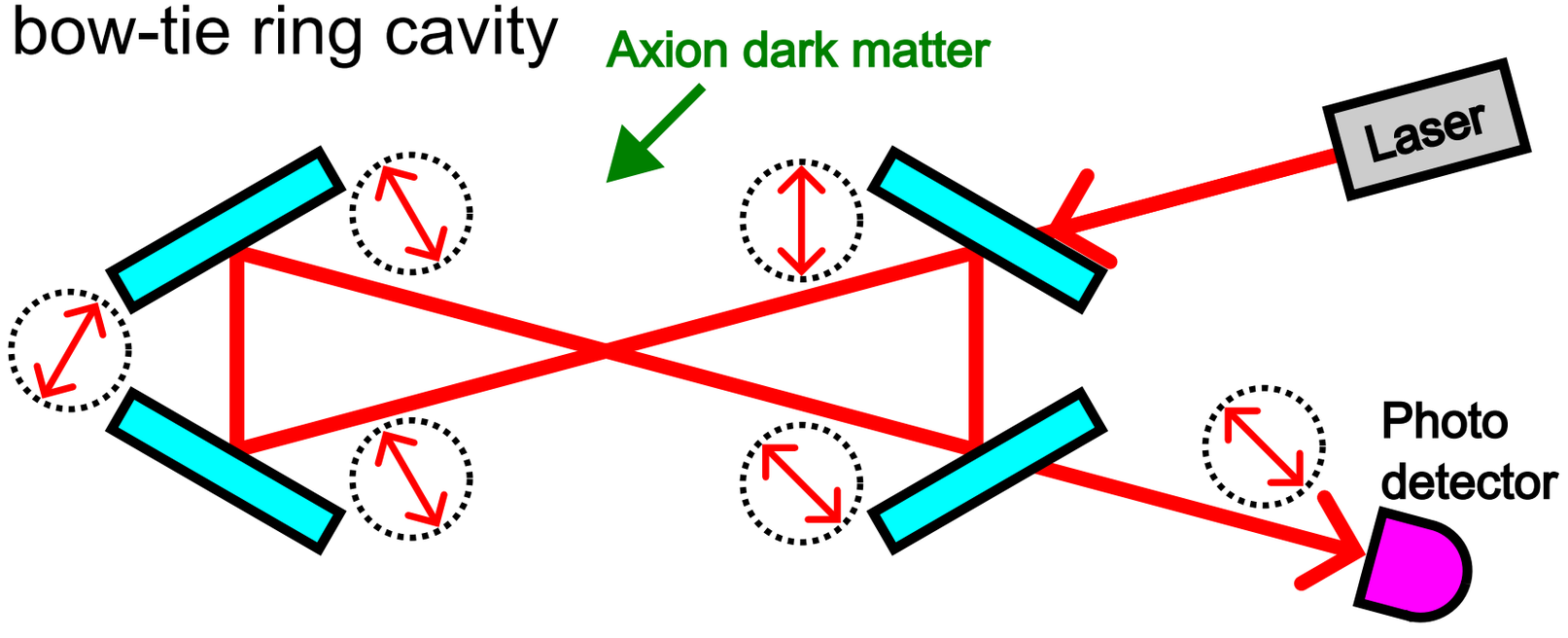
Extend optical path with a optical linear cavity

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



Extend optical path with a bow-tie ring cavity

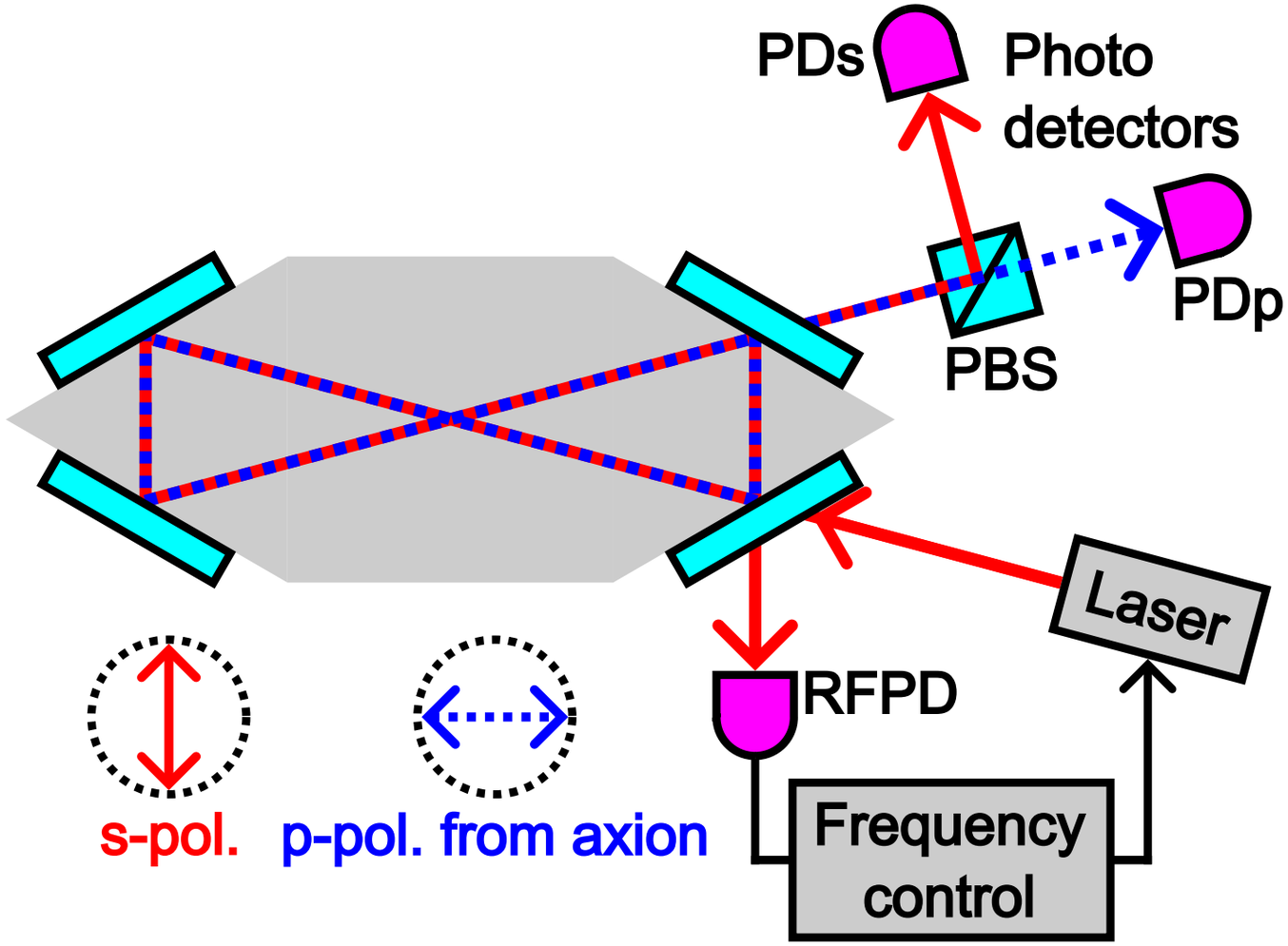
Rotation of polarization can be amplified because the flip is canceled by reflections on both two mirrors

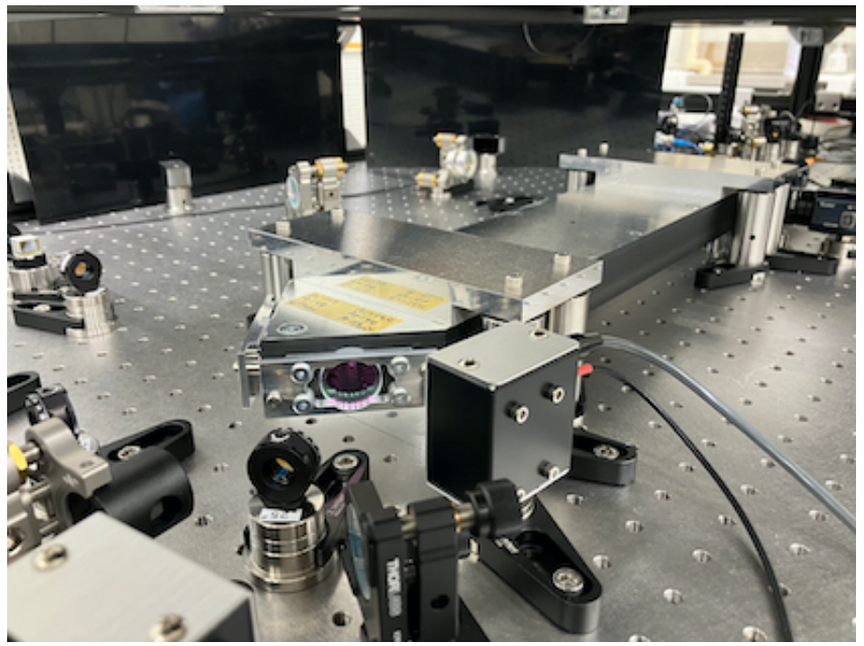


DANCE

DANCE (Dark matter Axion search with riNg Cavity Experiment)

- Dark matter axion search with laser interferometer technique
- Bow-tie optical ring cavity





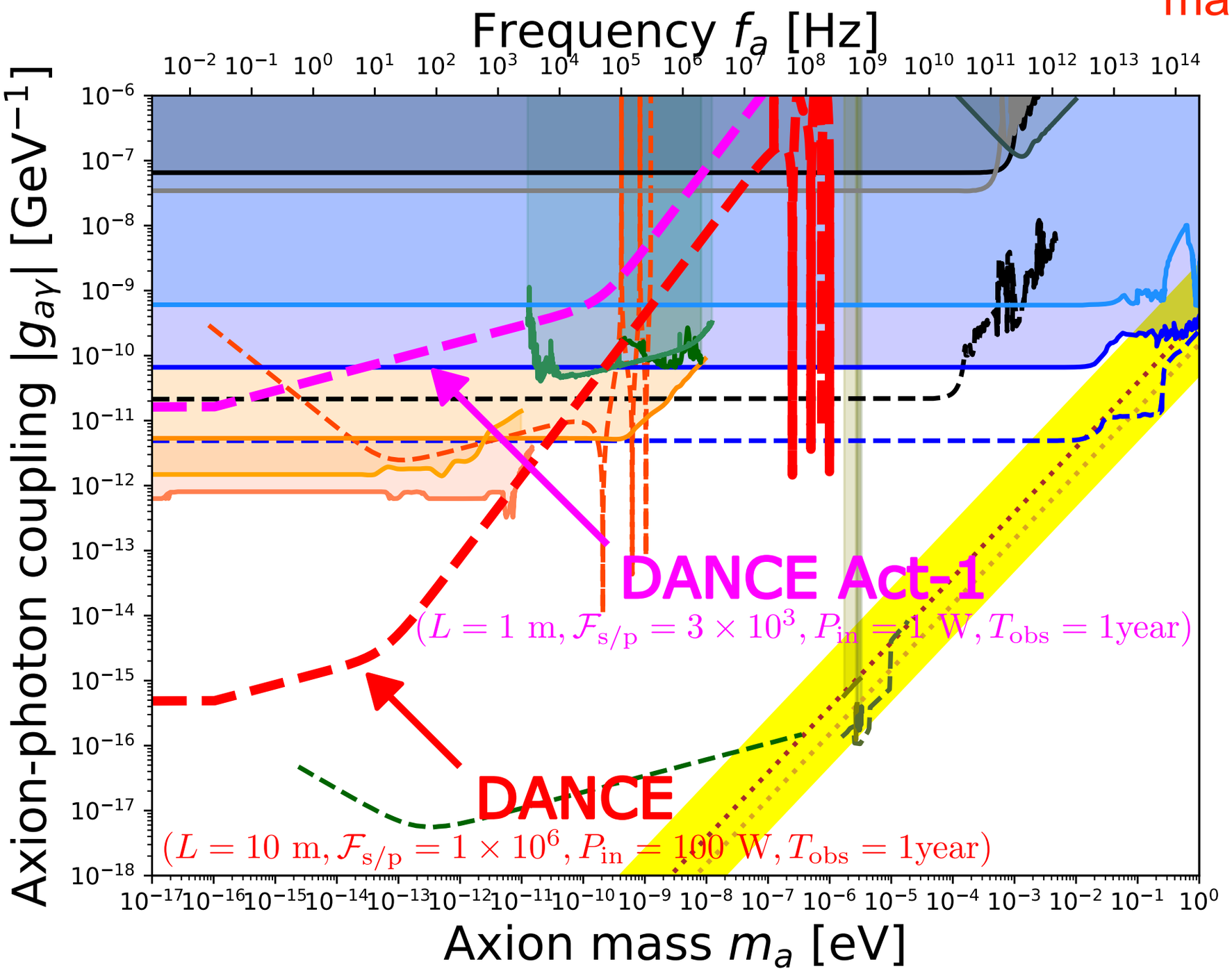
Measure the amount of modulated p-polarized light (Axion signal) by amplifying it with a bow-tie optical ring cavity

Target sensitivity of DANCE

Aim to detect axion dark matter in low mass region

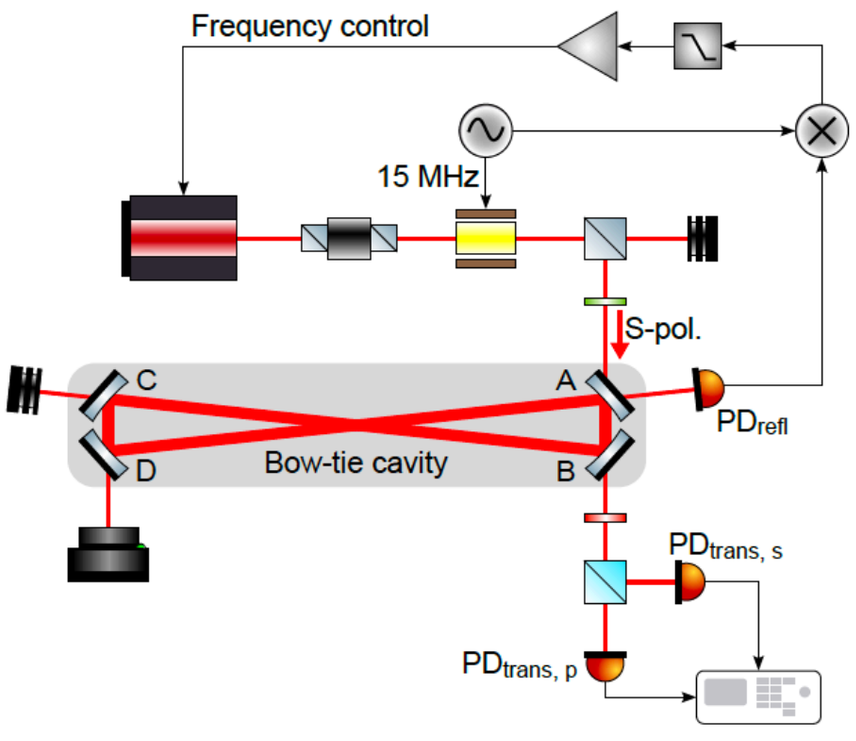
L : Round-trip, $\mathcal{F}_{\mathrm{s/p}}$: Finesse s/p-pol., P_{in} : Input power

- Shot noise limit
- Assume dark matter is Axion



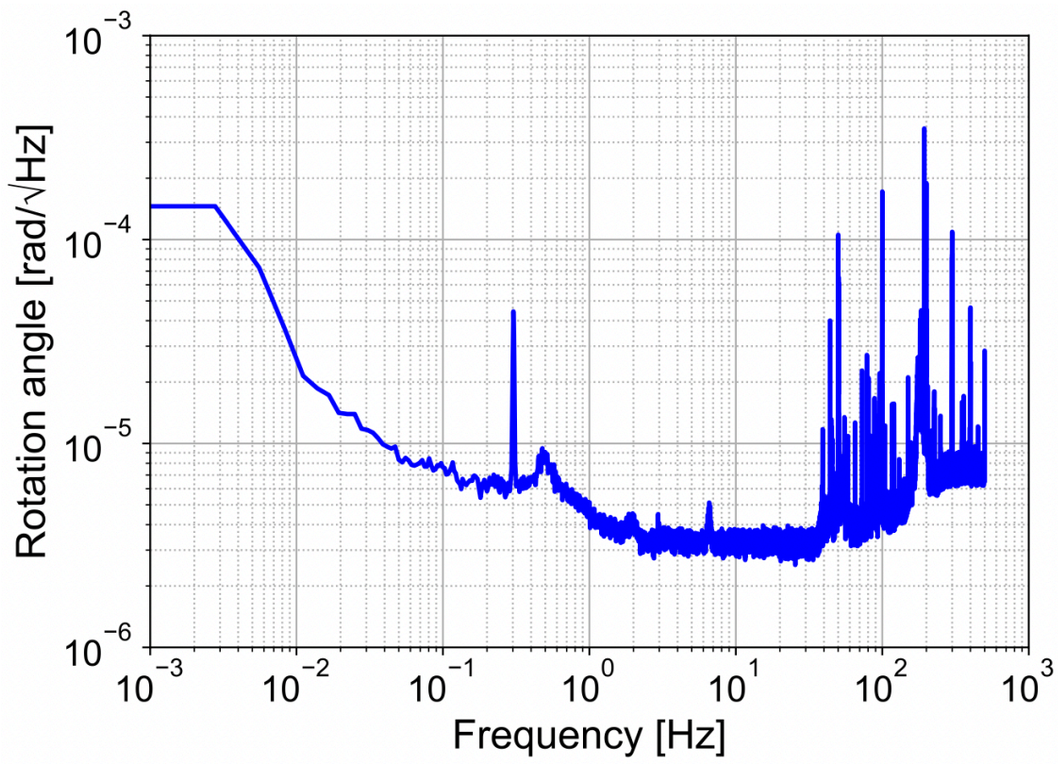
First observation of DANCE Act-1

- DANCE Act-1: the prototype experiment
- Started in 2019
- First observation was conducted in May 18-30, 2021
- Obtained the rotation angle of linear polarization → Data analysis



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

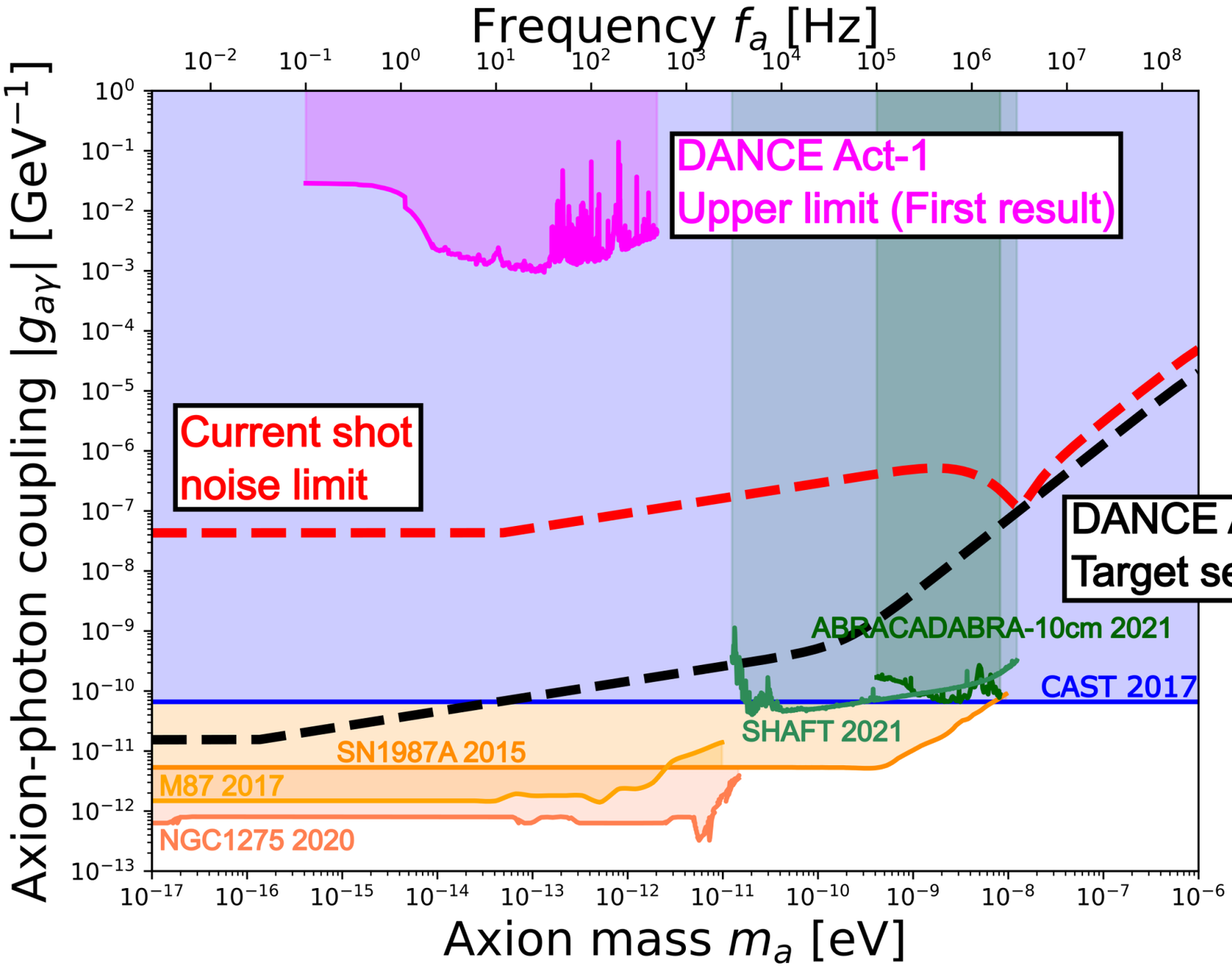
$$\phi(t) = \sqrt{\frac{P_{\mathrm{p}}(t)}{P_{\mathrm{s}}(t) + P_{\mathrm{p}}(t)}} - 2\theta_{\mathrm{HWP}}$$



Y. Oshima *et al.*: arXiv:2110.10607

Result

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



Input power	242(12) mW
Finesse (s-pol.)	$2.85(5) \times 10^3$
Finesse (p-pol.)	195(3)
Phase difference	3.03(2) deg

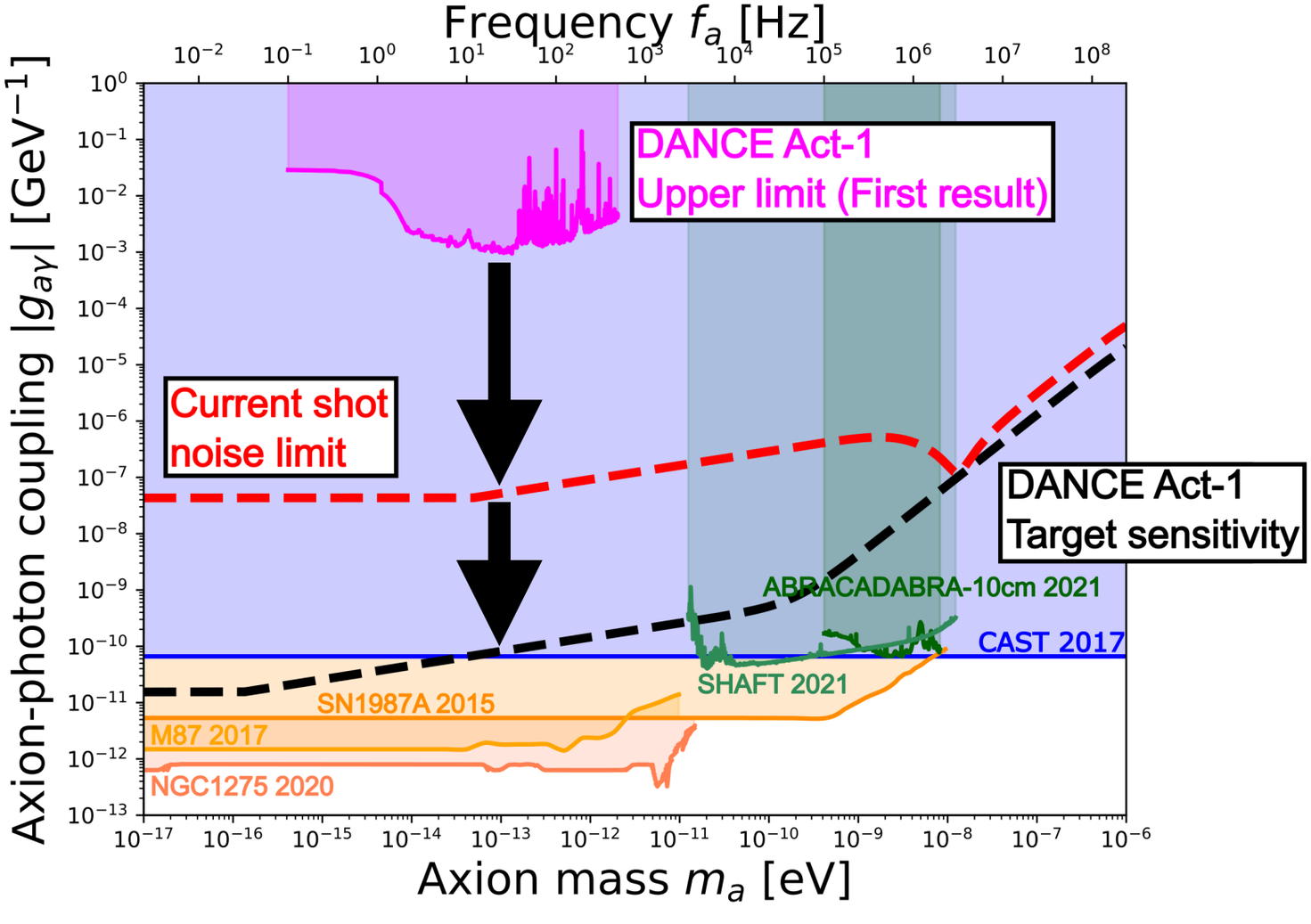
Consideration

- Improve classical noises (laser intensity noise, laser frequency noise, and mechanical vibration)

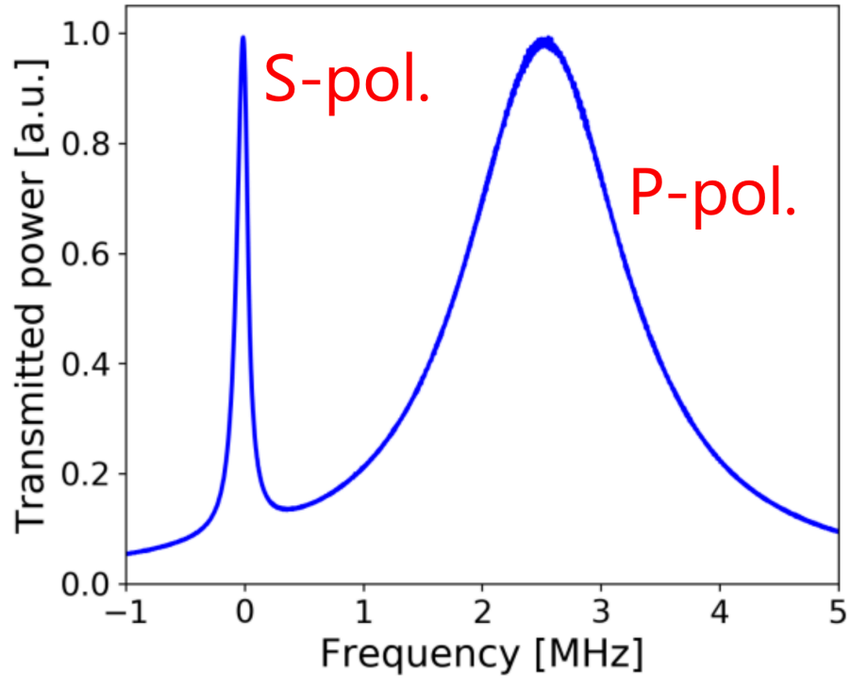
→ Reach current shot noise limit

- Improve observation time, input power, finesse
- Achieve simultaneous resonance between s-pol. and p-pol.

→ Reach target sensitivity



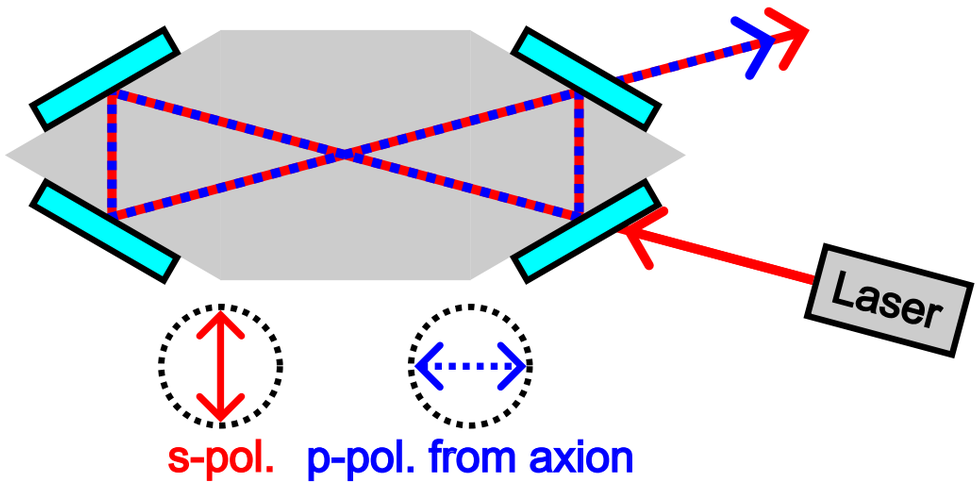
No simultaneous resonance between s-pol. and p-pol.



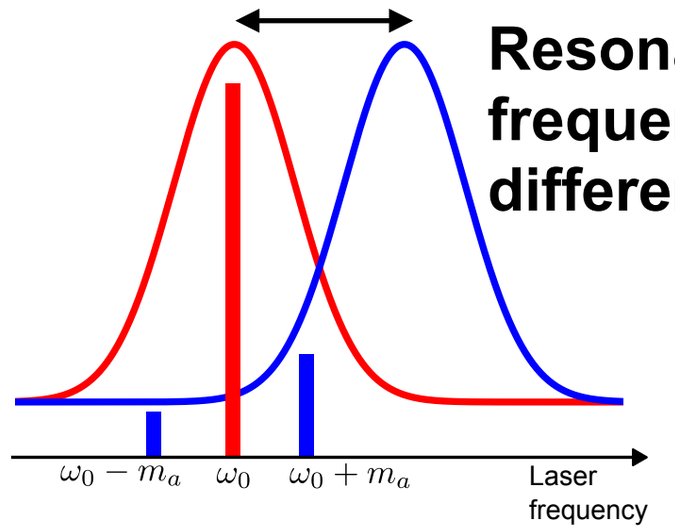
Simultaneous resonance

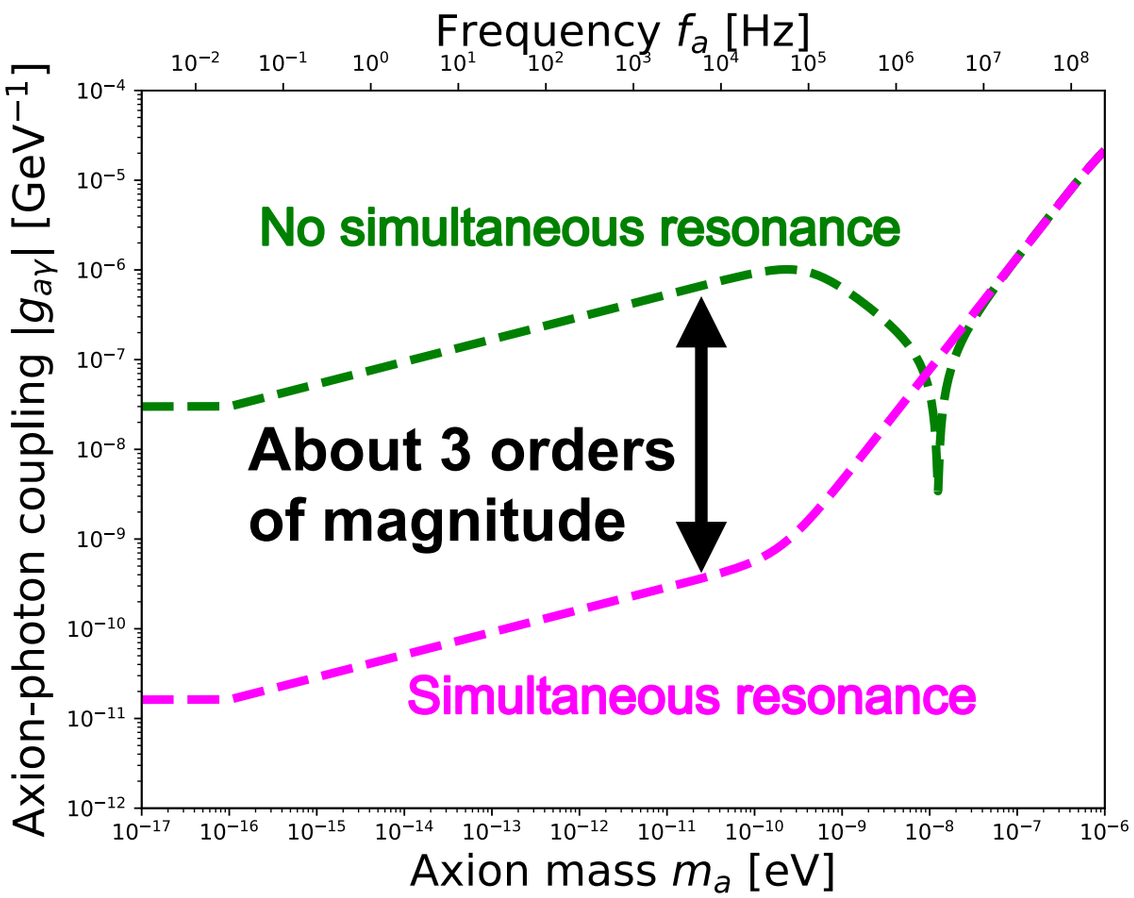
Oblique incidence

→ Reflection phase difference

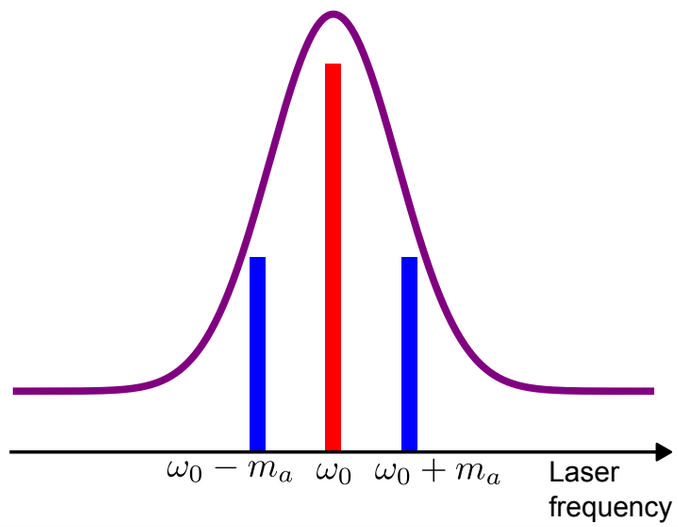


No simultaneous resonance





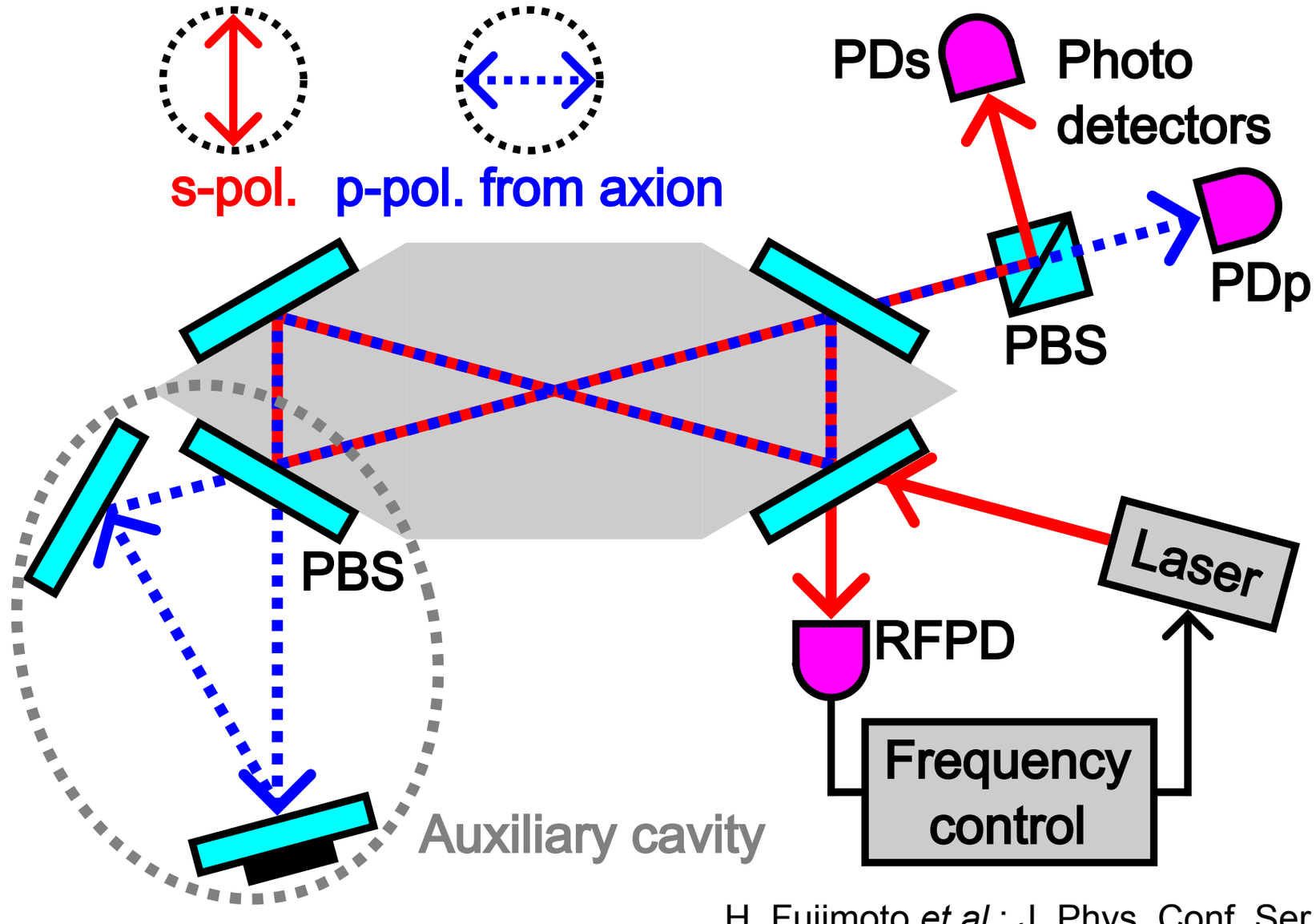
Simultaneous resonance



Simultaneous resonance is necessary to conduct a sensitive broadband axion search

① DANCE with an auxiliary cavity

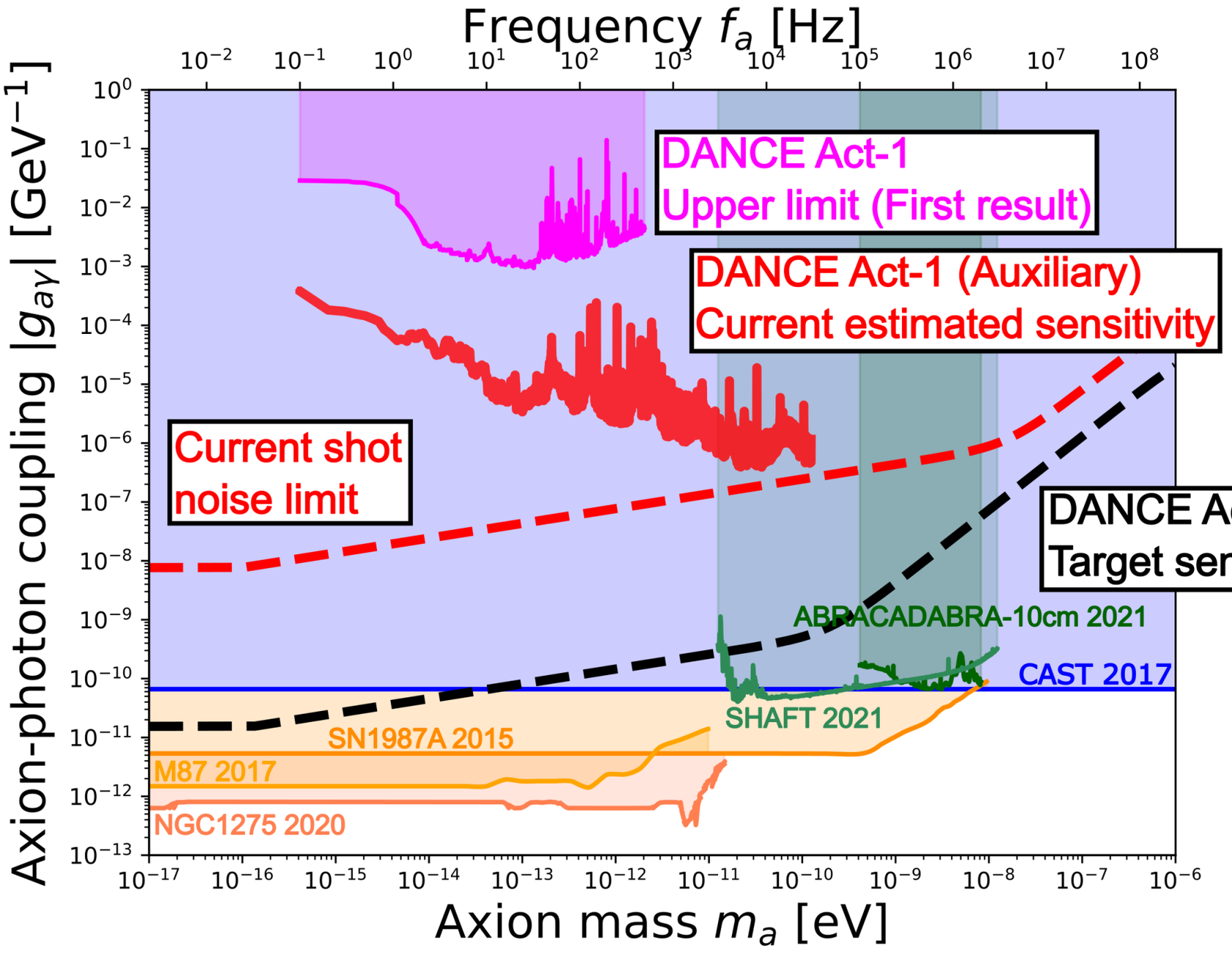
- Achieved simultaneous resonance for the first time in November 2021 by adding an auxiliary cavity to compensate for the reflection phase difference between s-pol. and p-pol.
- p-pol. is resonant in an auxiliary cavity by tuning PZT



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

① DANCE with an auxiliary cavity

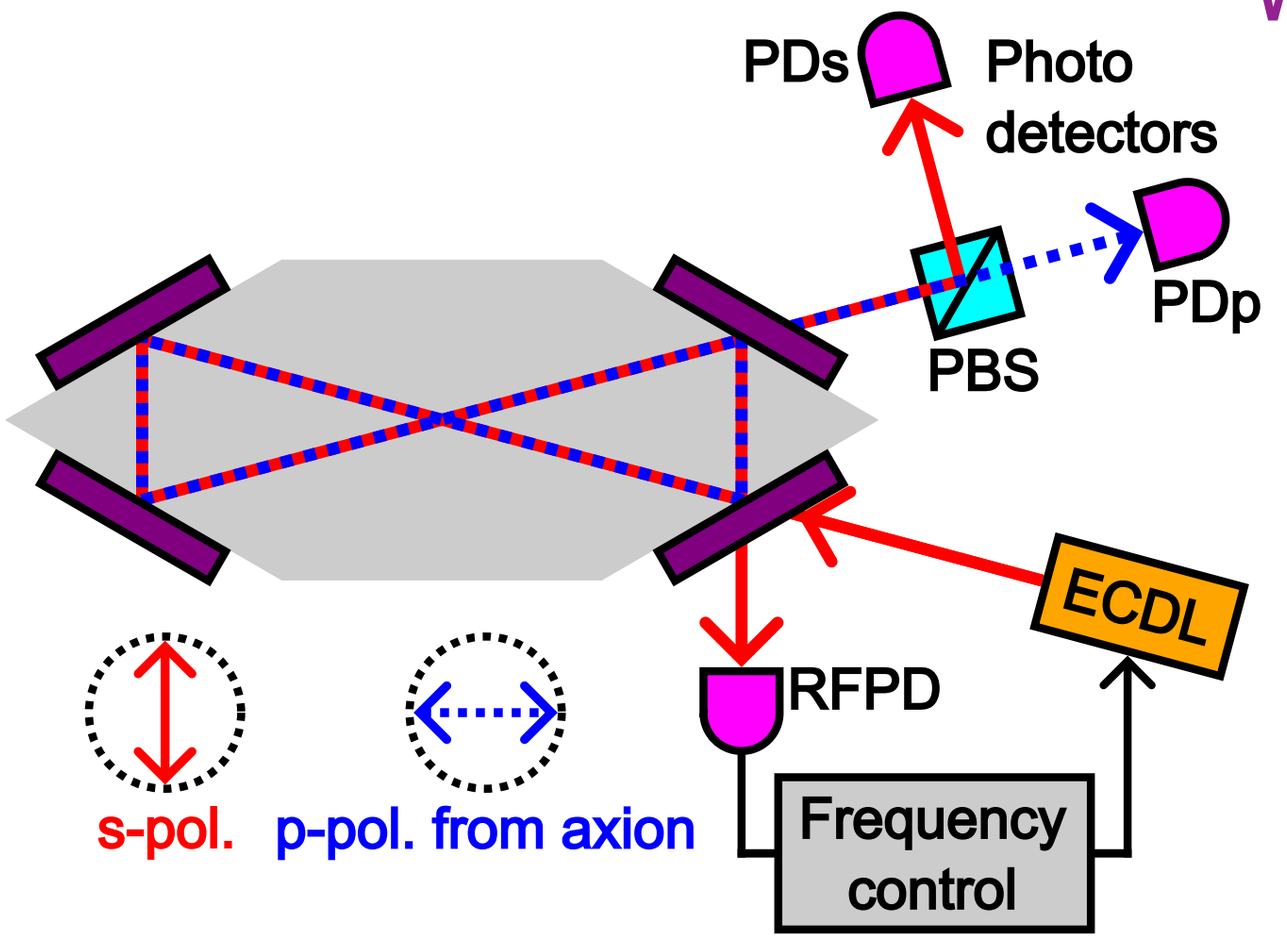
- Improved by more than 2 orders of magnitude than first results of DANCE Act-1
- Need to reduce the optical loss in an auxiliary cavity



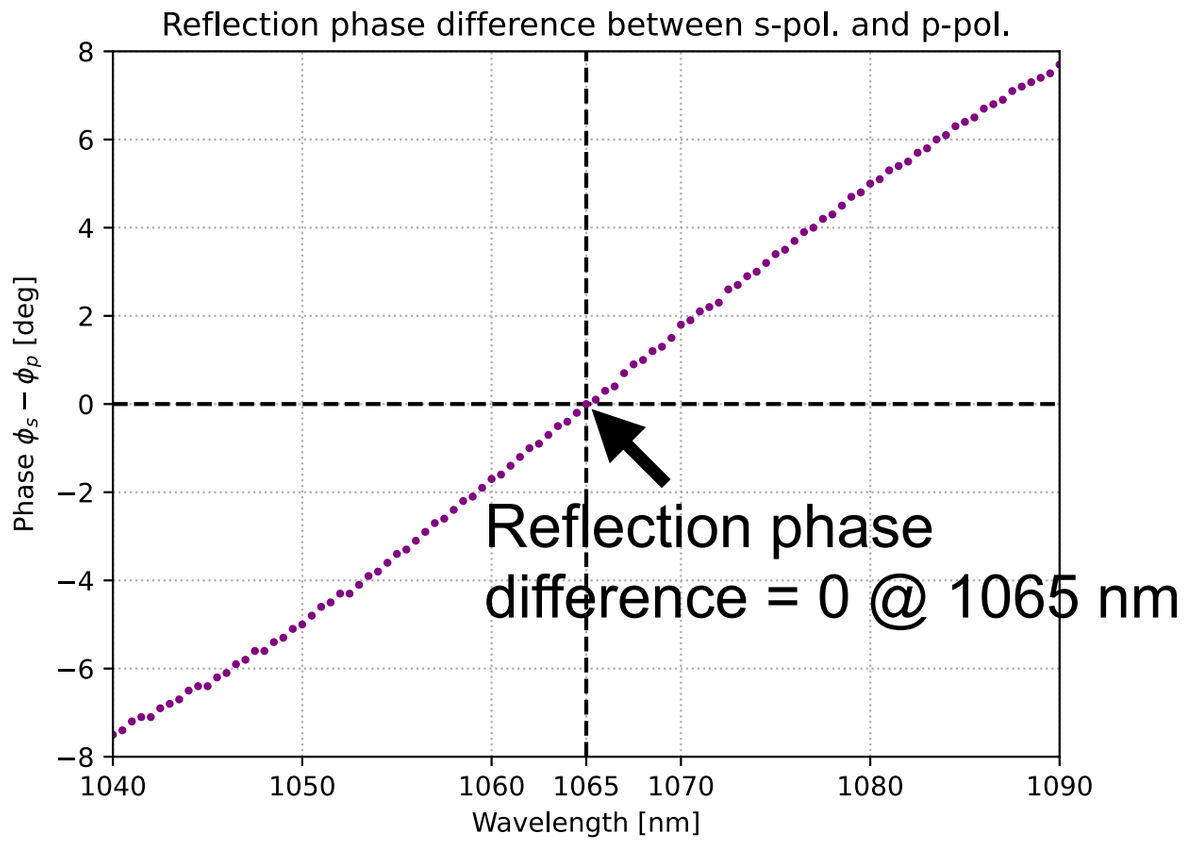
Input power	~20 mW
Finesse (s-pol.)	549(3)
Finesse (p-pol.)	36.8(2)
Phase difference	0 deg

② DANCE with an ECDL

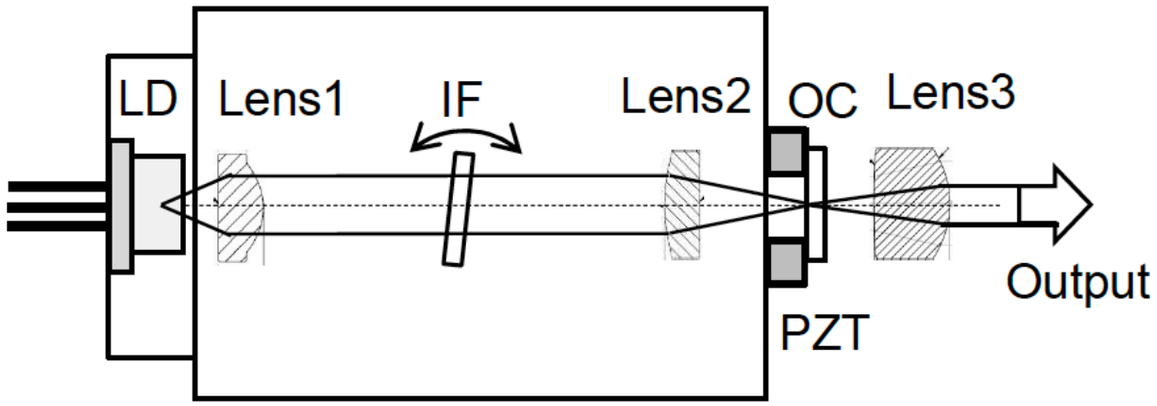
- Mirrors of reflection phase difference between s-pol.and p-pol. depends on laser wavelength
  → **Wavelength sensitive phase-shifting mirror**
- Select the wavelength by wavelength tunable laser: **ECDL (External Cavity Diode Laser)**
- Constructing setup is in progress

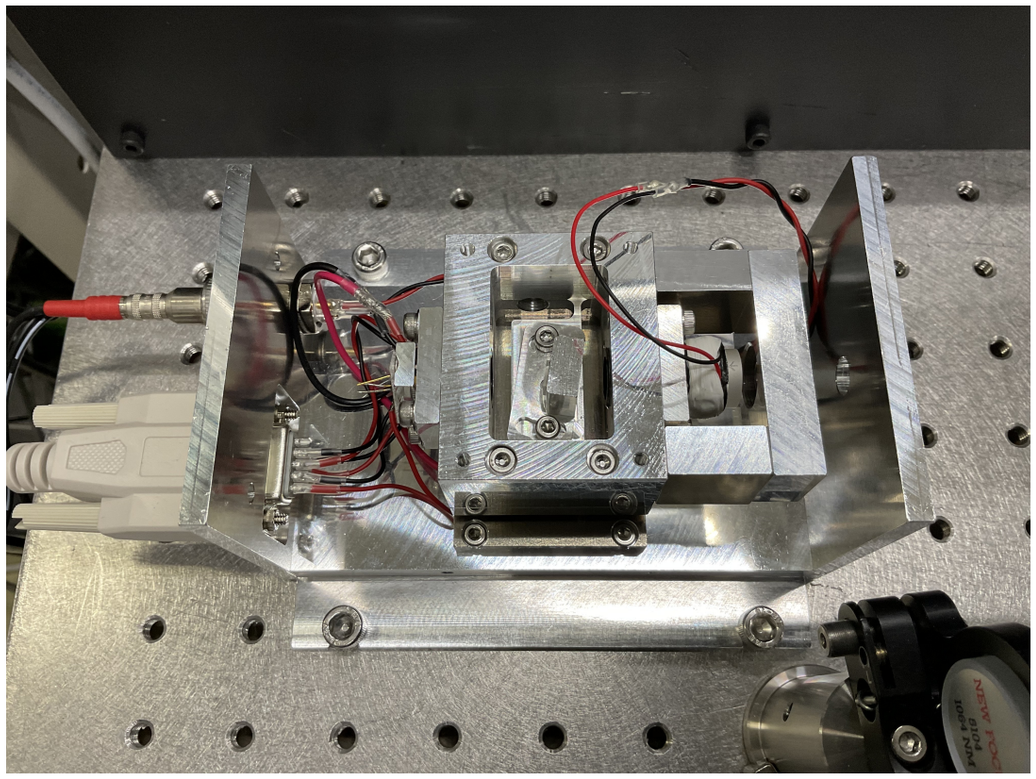


Wavelength sensitive phase-shifting mirror



② DANCE with an ECDL





ECDL (External Cavity Diode Laser)

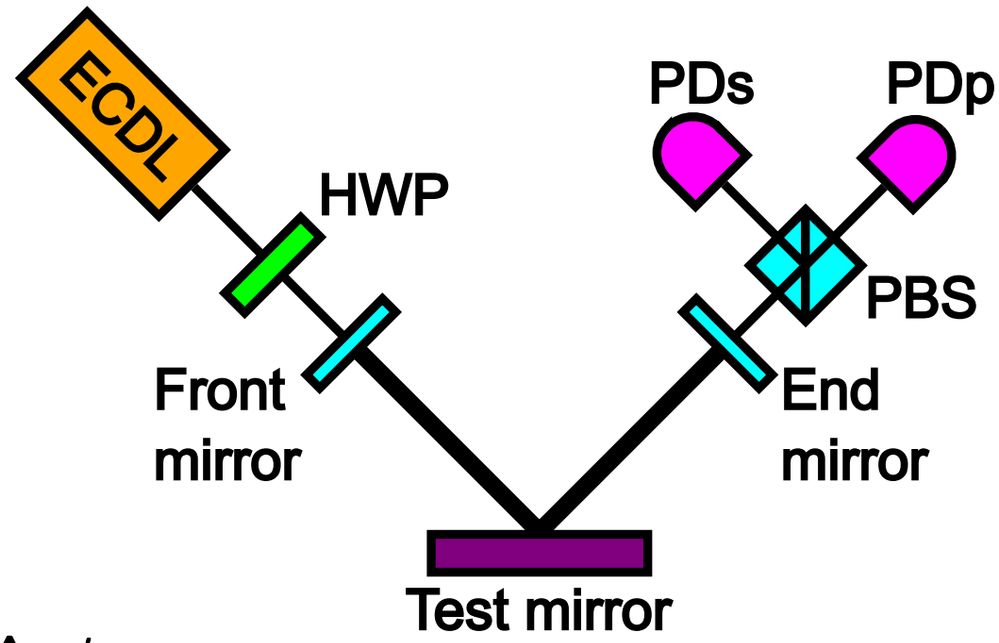
- Wavelength range: 1045 - 1068 nm
- FWHM: 200 kHz
- Output power: 20 - 50 mW

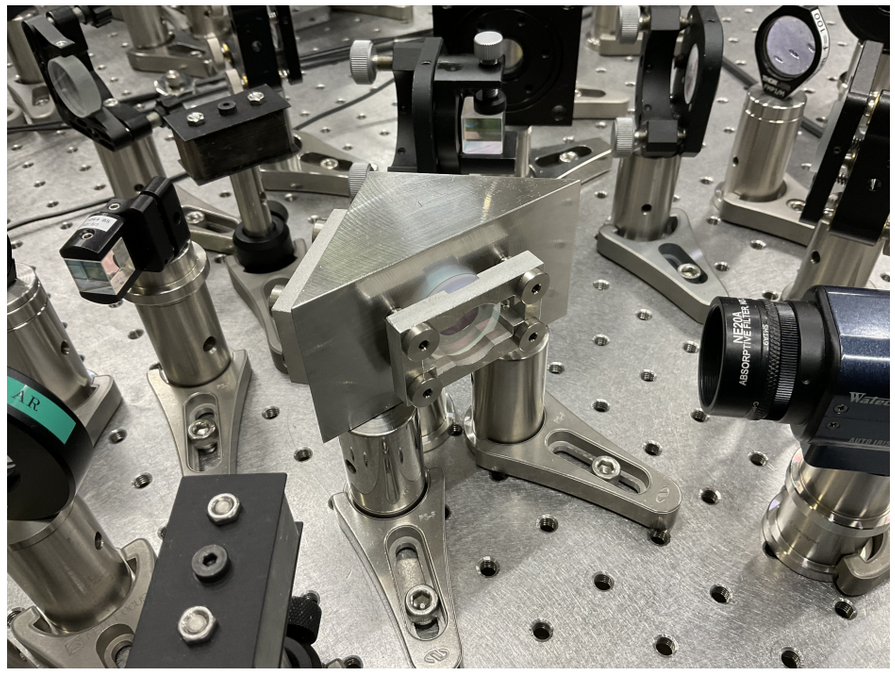
Characteristics

- Select wavelength by finely adjusting the angle of the Interference Filter (IF)
  → The optical axis remains because the structure has a transparent design
- Amplify output power by constructing cavity between LD and OC
- Closed structure → Resistant to acoustic noise and vibrations

② DANCE with an ECDL

- Proof of principle of simultaneous resonance with a folded cavity
- Reflection phase difference between s-pol. and p-pol. depends on wavelength
- Time drift of the reflection phase difference between s-pol. and p-pol.
  → Solve this issue to conduct an accurately sensitive axion search





$\Delta\phi$: reflection phase difference between s-pol. and p-pol. per mirror

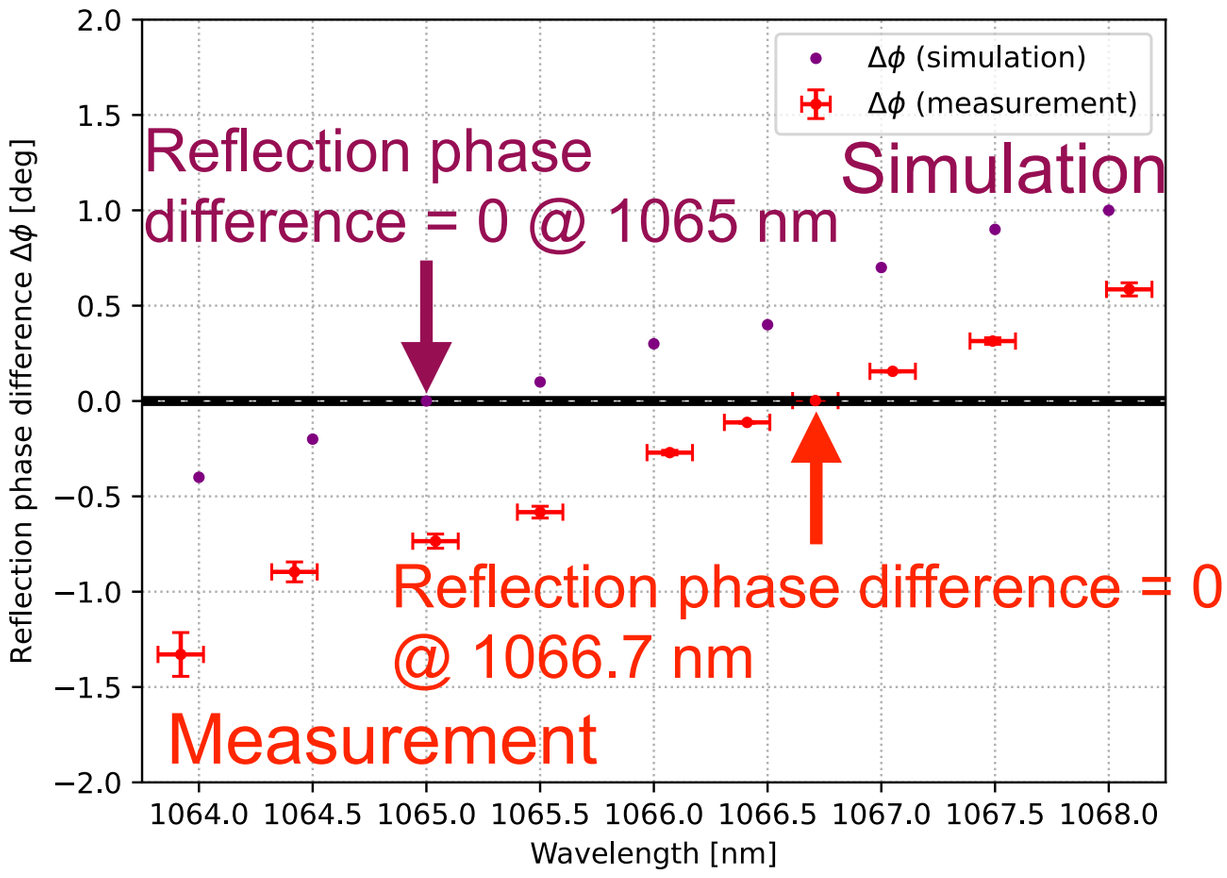
Requirement for simultaneous resonance

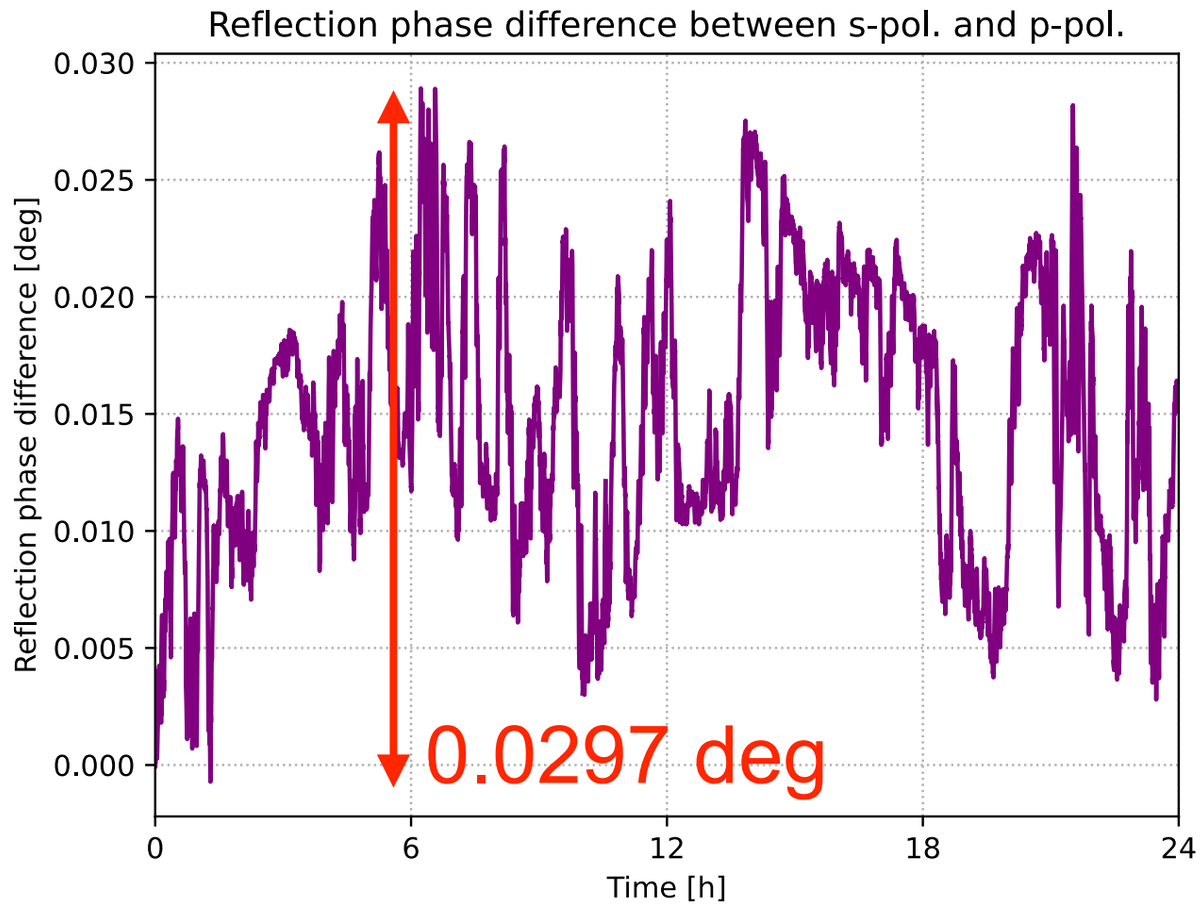
$$\Delta\phi \leq 0.015 \text{ deg}$$

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

② DANCE with an ECDL

- Proof of principle of simultaneous resonance with a folded cavity
- Reflection phase difference between s-pol. and p-pol. depends on wavelength
- Time drift of the reflection phase difference between s-pol. and p-pol.
  → Solve this issue to conduct an accurately sensitive axion search





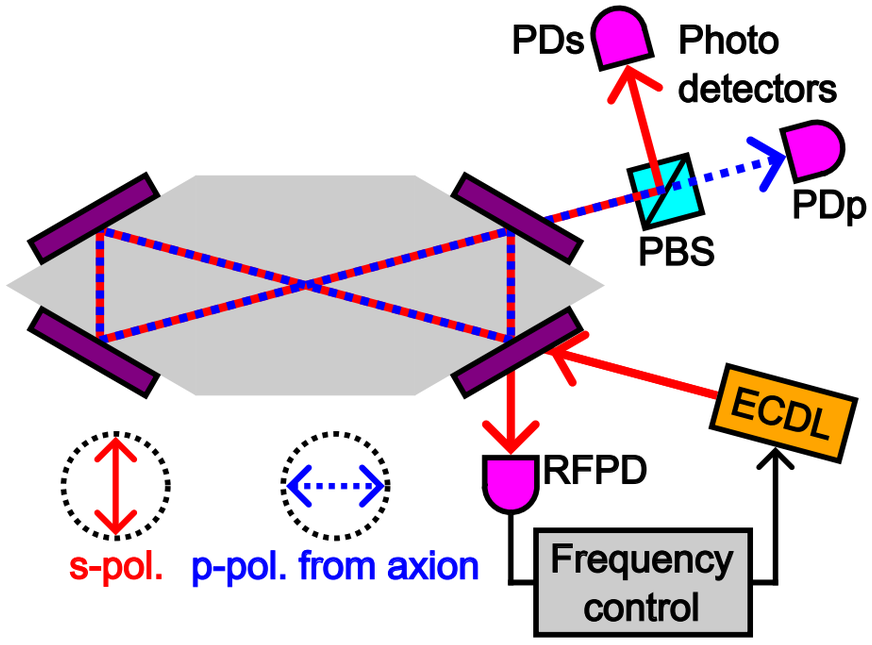
Satisfy requirement for simultaneous resonance

- **Coherence with temperature**
- **Need to reduce time drift**

② DANCE with an ECDL

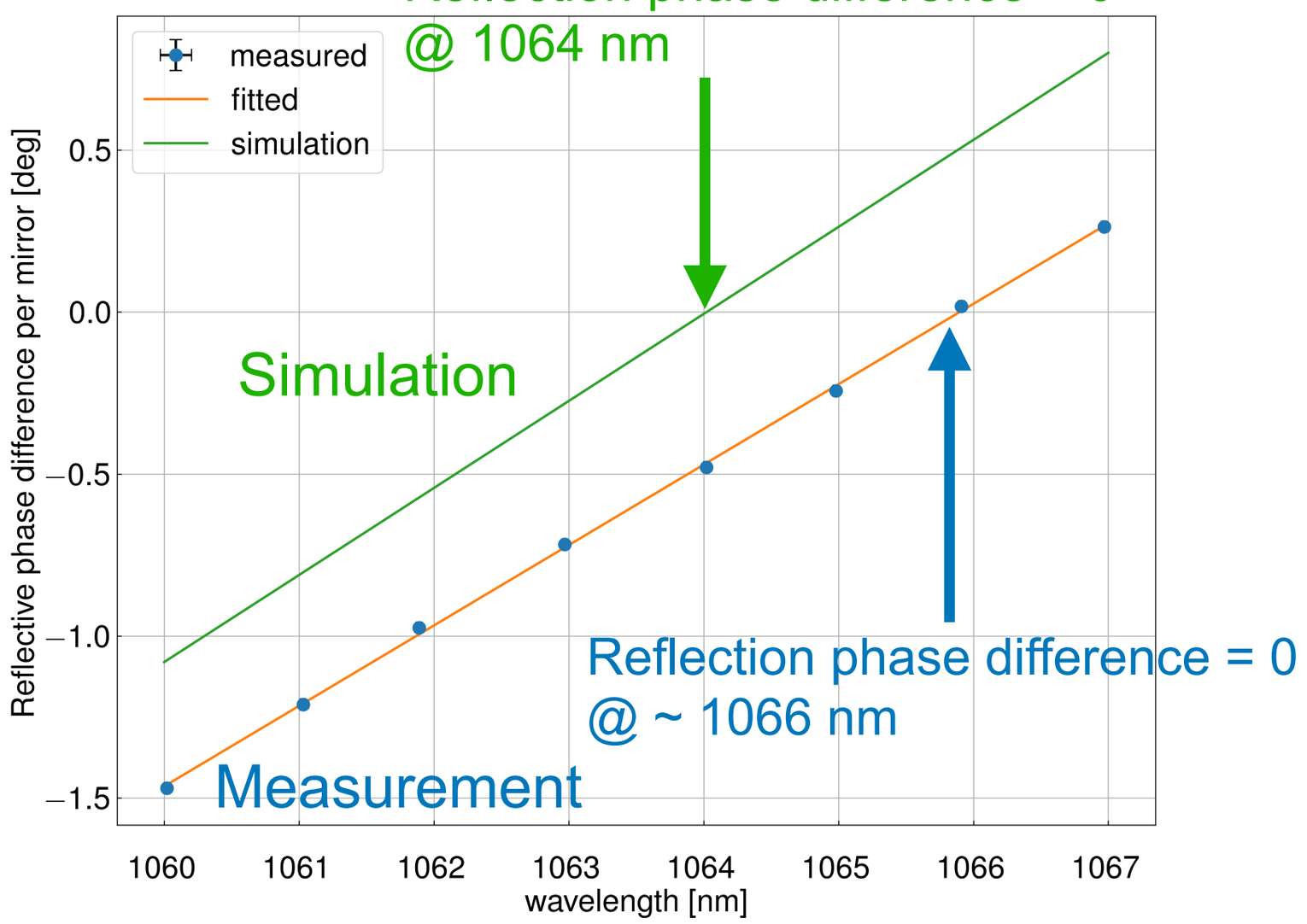
- Current status of DANCE with an ECDL
- Able to achieve simultaneous resonance by tuning at ~ 1066 nm

→ Tune the wavelength precisely to achieve simultaneous resonance



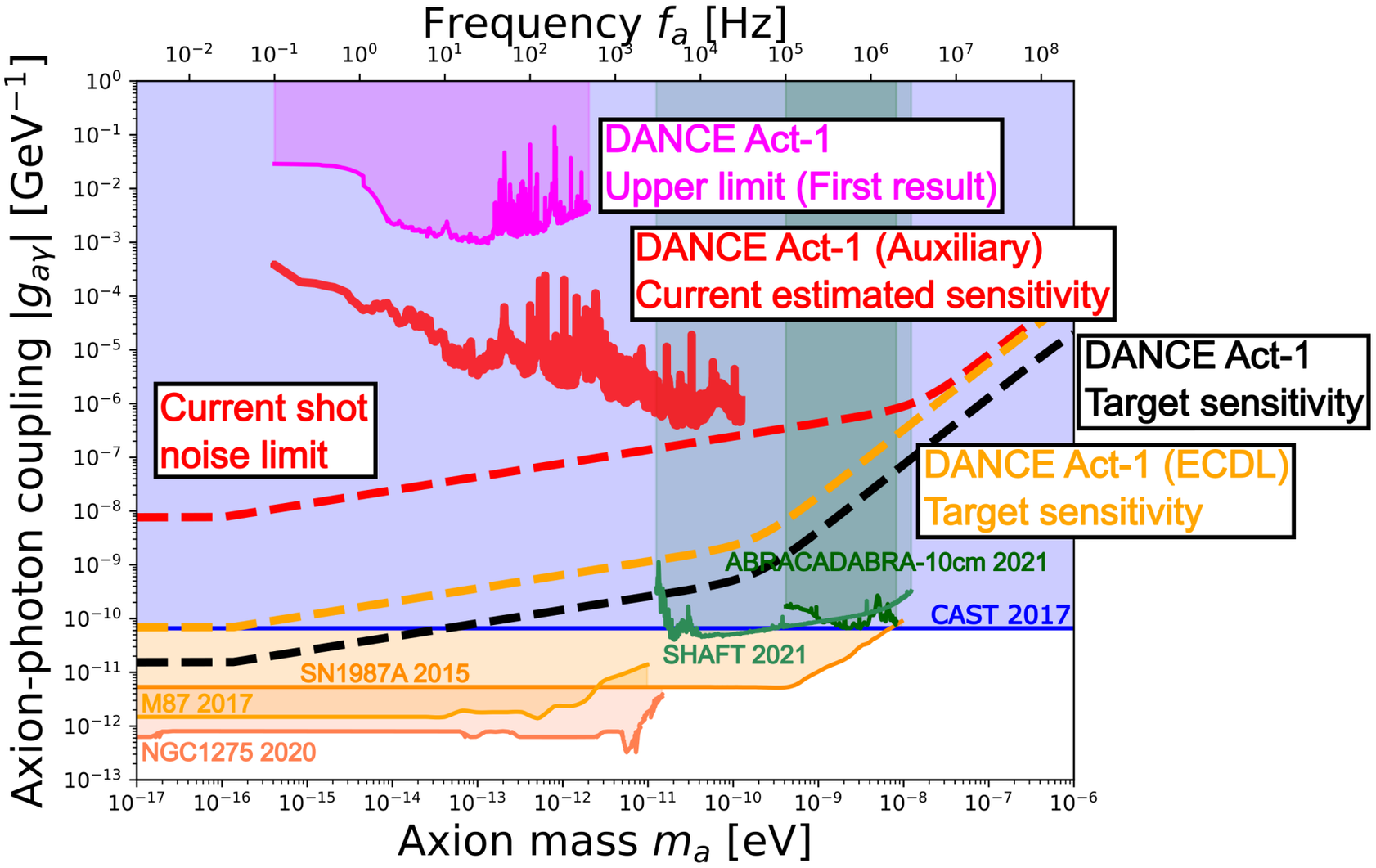
Finesse (s-pol.)	$3.9(2) \times 10^3$
Finesse (p-pol.)	$3.9(2) \times 10^3$

※ Specification of this mirror is different from before one



Future plans for DANCE

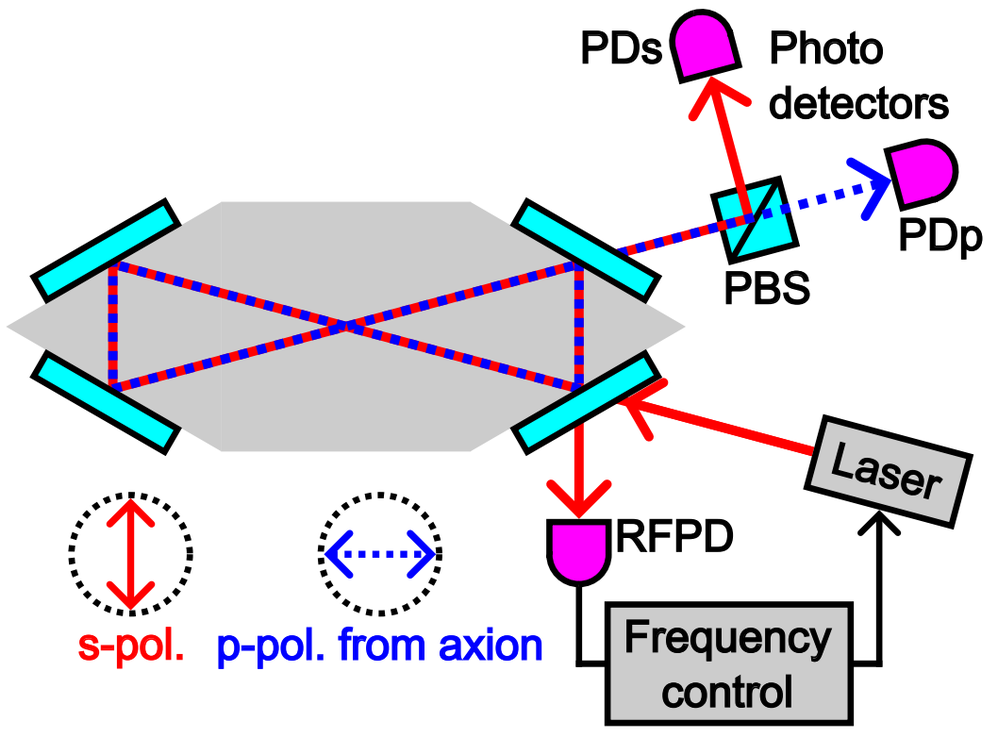
- Long-term observation of DANCE with an auxiliary cavity
  → Determine upper limit
- Investigating the cause of time drift of the reflection phase difference between s-pol. and p-pol. with a folded cavity
- Introduce power amplifier (50 mW → 1 W) for DANCE with an ECDL
  → Achieve target sensitivity

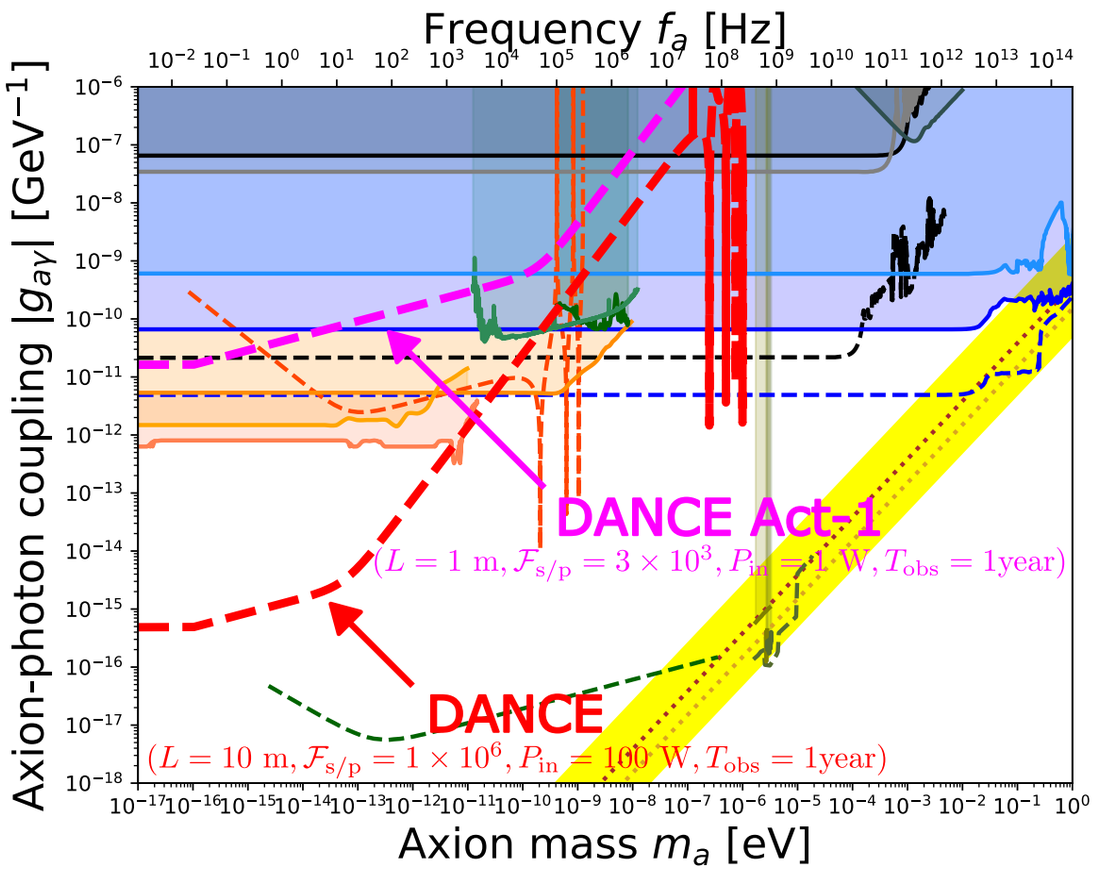


Summary

DANCE (Dark matter Axion search with riNg Cavity Experiment)

- Dark matter axion search with a bow-tie optical ring cavity by detecting a rotation angle of linearly polarized light
- First observation of DANCE Act-1 was conducted in May 18-30, 2021
- Achieved simultaneous resonance in November 2021 by adding an auxiliary cavity
- DANCE with an ECDL is in progress
- Aim to achieve the world's most sensitive dark matter axion search





Backup

Data analysis

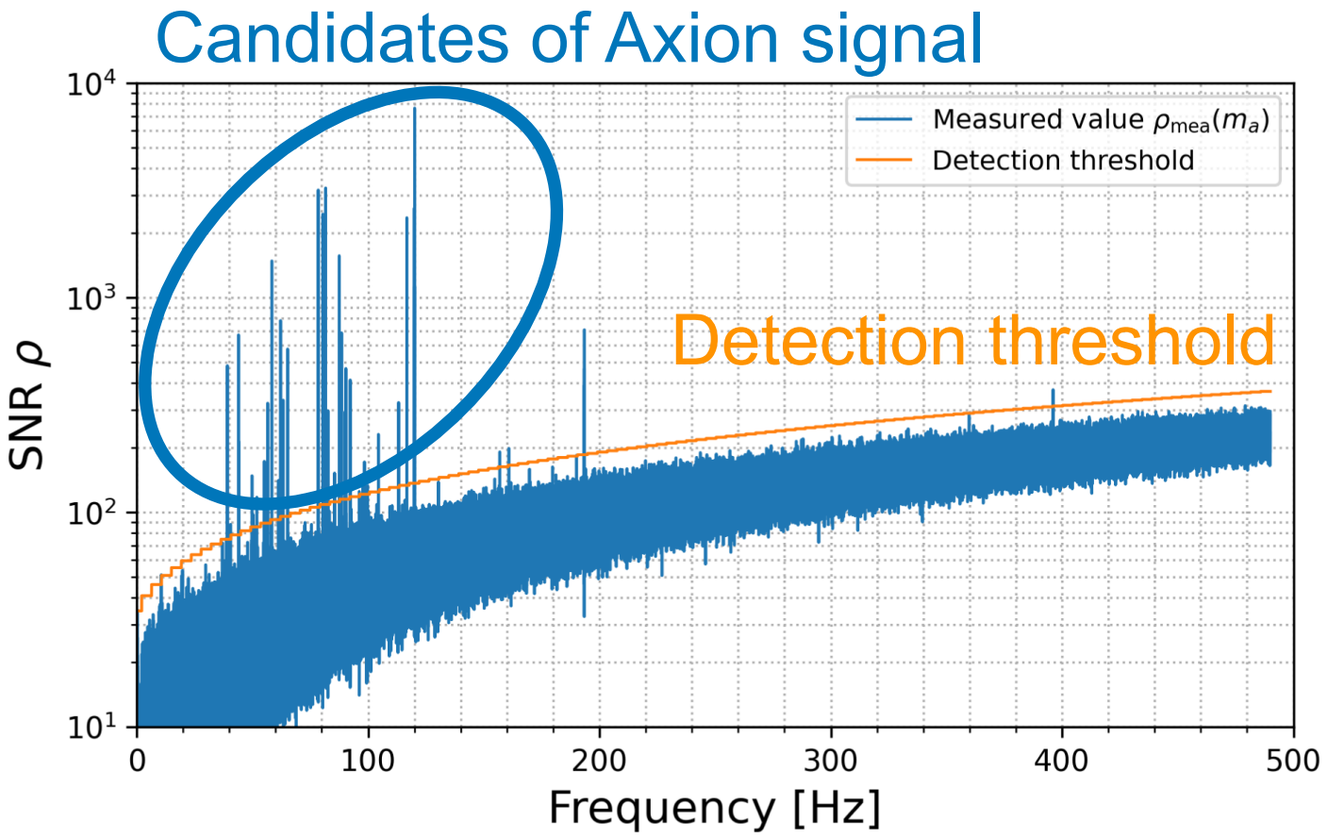
- 556 points exceeded the detection threshold
- Veto candidates of axion signal as follow procedures

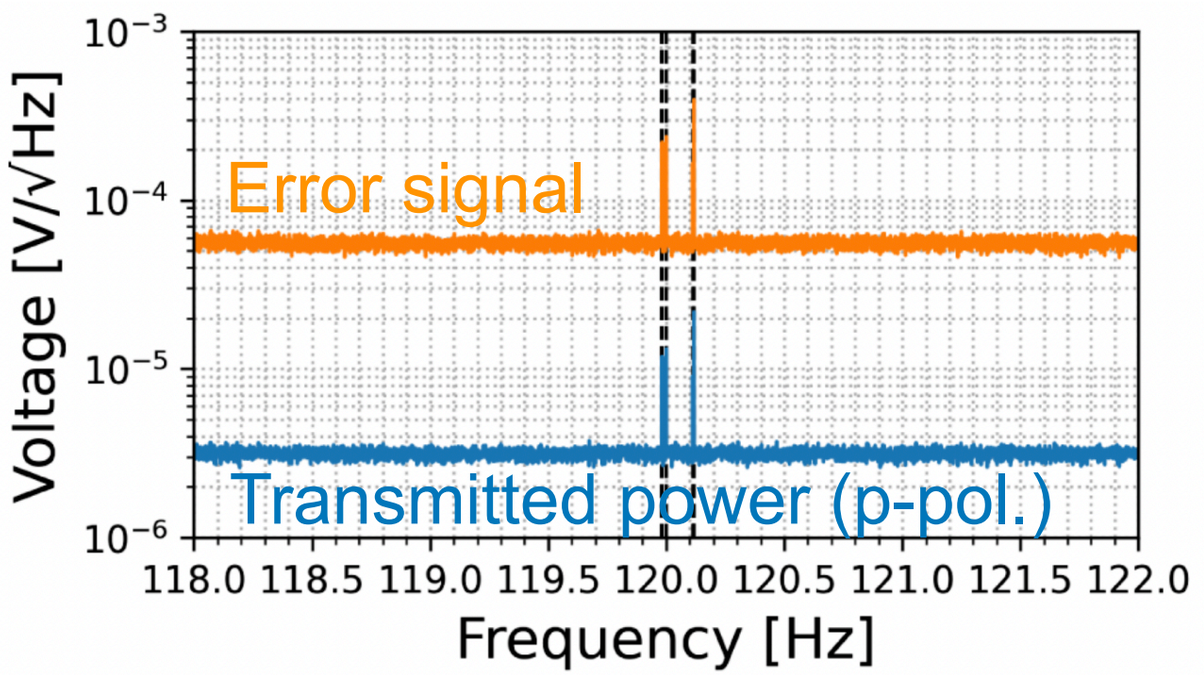
① The persistence veto (Comparison with two set of data): 556 → 257

② The line width veto (Comparison with the expected line width of the galactic dark matter): 257 → 7

③ Comparison with error signal: 7 → 0

→ We succeed to veto all candidates of Axion signal



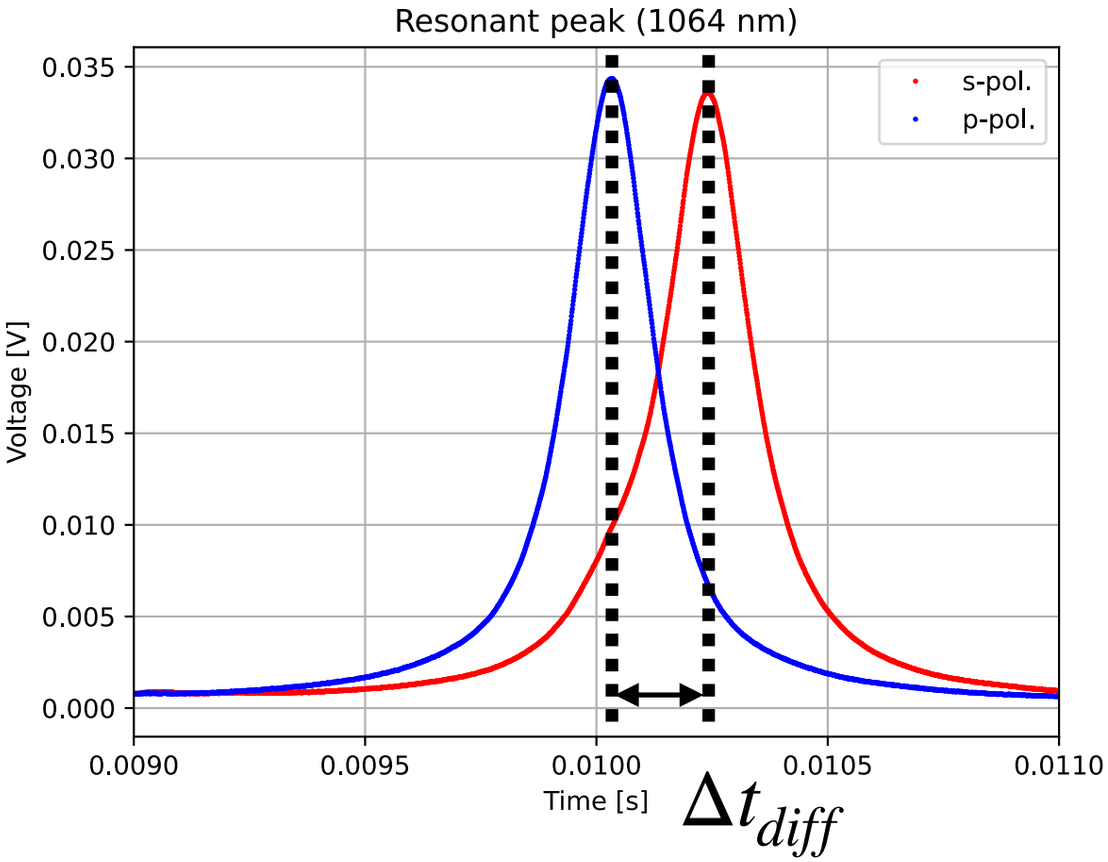


Y. Oshima *et al.*: Phys. Rev. D. **108**, 072005 (2023).

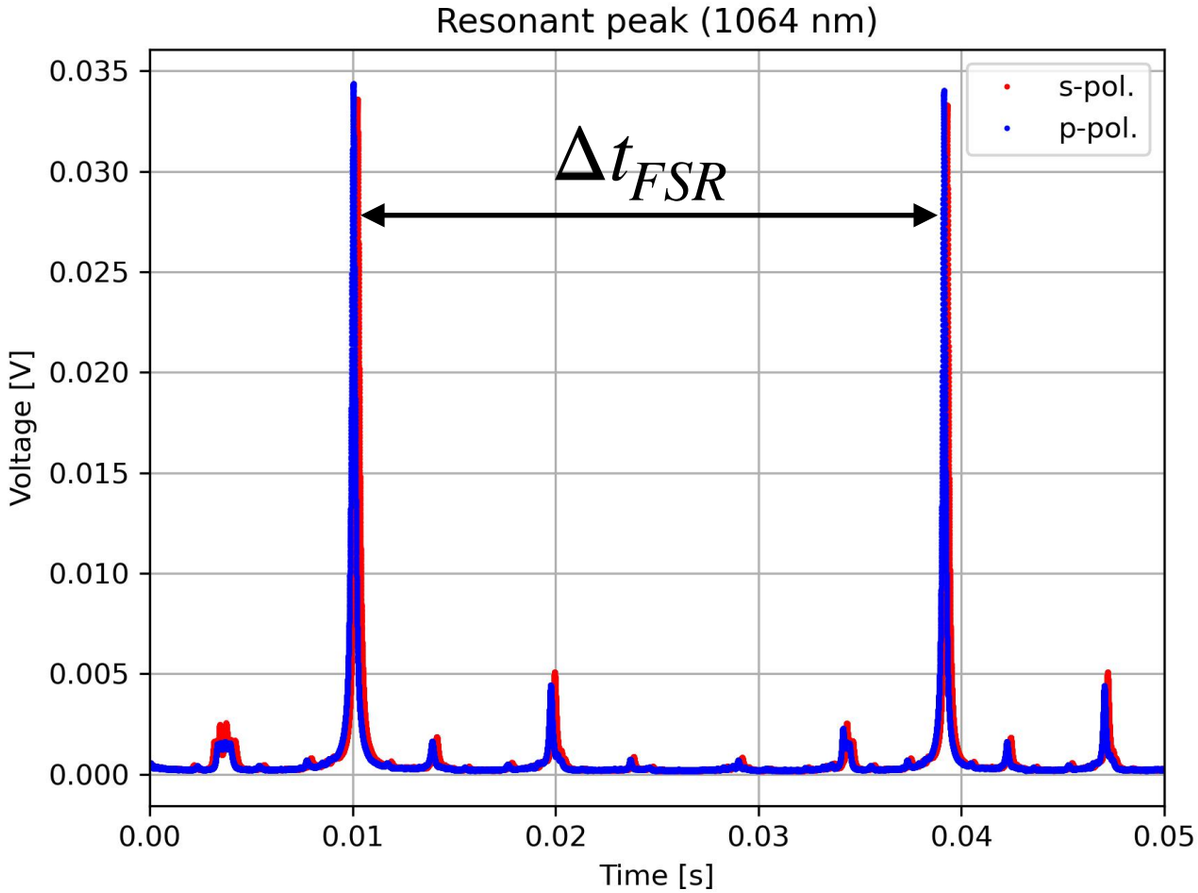
How to calibrate reflection phase difference

Reflection phase difference per mirror

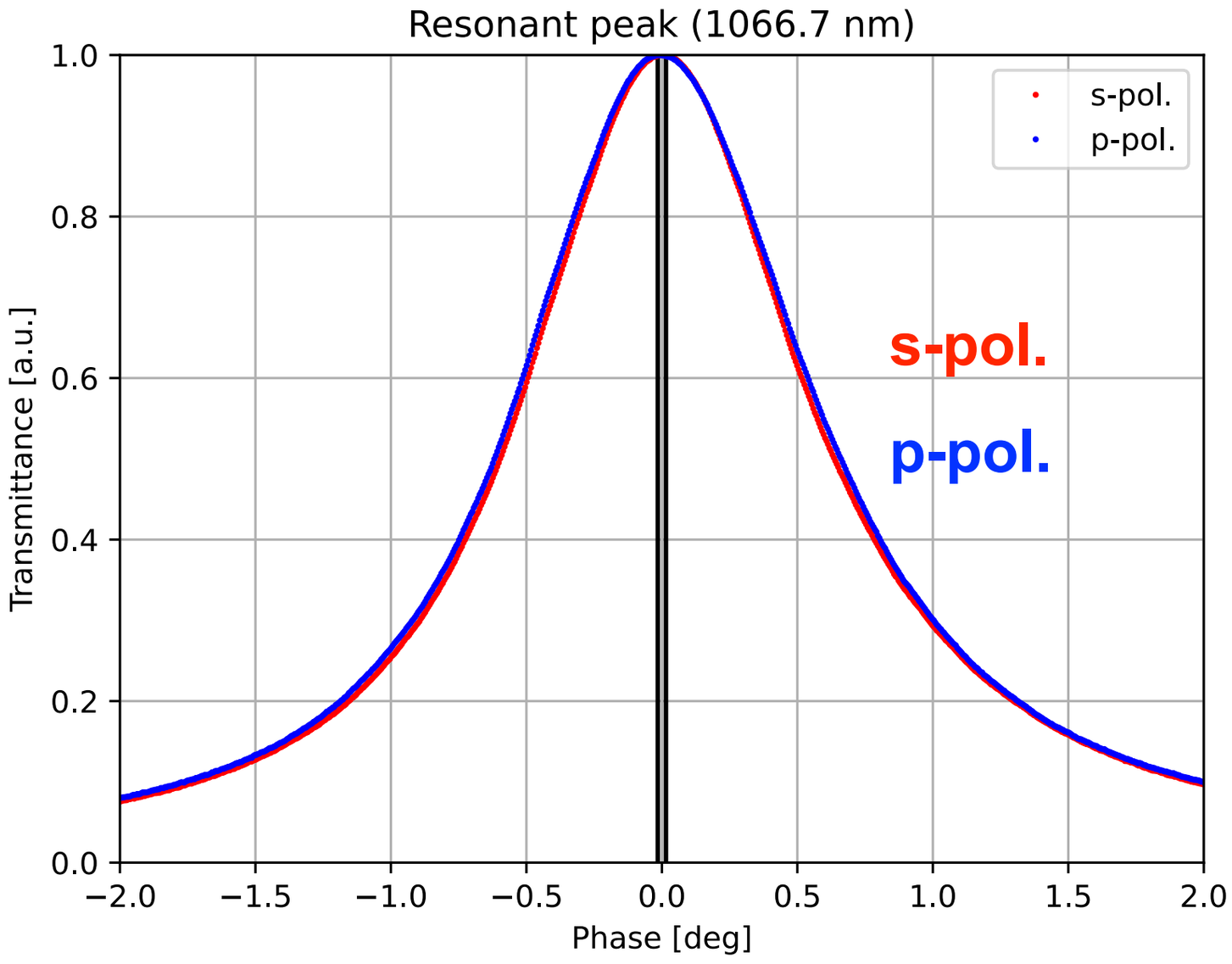
$$\Delta\phi = \frac{\Delta t_{\mathrm{diff}}}{\Delta t_{\mathrm{FSR}}} \times 180\ \mathrm{deg}$$



Resonant frequency difference



Reflection phase difference



Measurement result $\Delta\phi = \phi_{\mathrm{s}} - \phi_{\mathrm{p}} = 0.002(1)\,\mathrm{deg}$ @$1066.7\,\mathrm{nm}$

→ Satisfy requirement for simultaneous resonance: $\Delta\phi \leq 0.015\,\mathrm{deg}$

→ Obtained wavelength which achieves simultaneous resonance