Laser wavelength tuning for sensitivity improvement of DANCE for axion dark matter search

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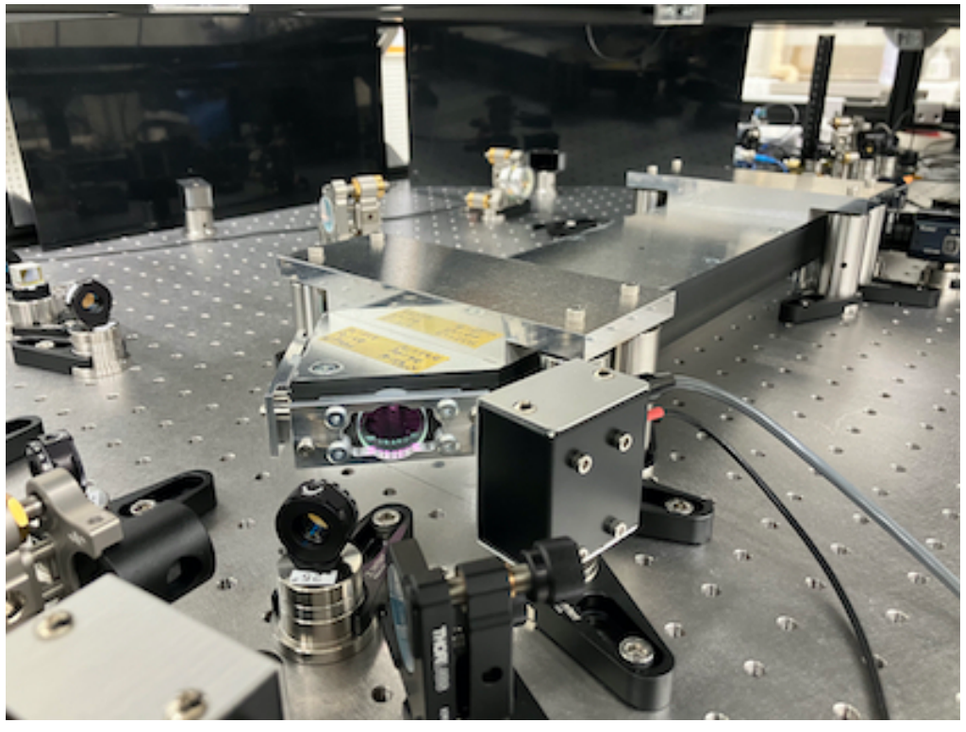
Dark matter symposium, March 8th, 2024

Abstract

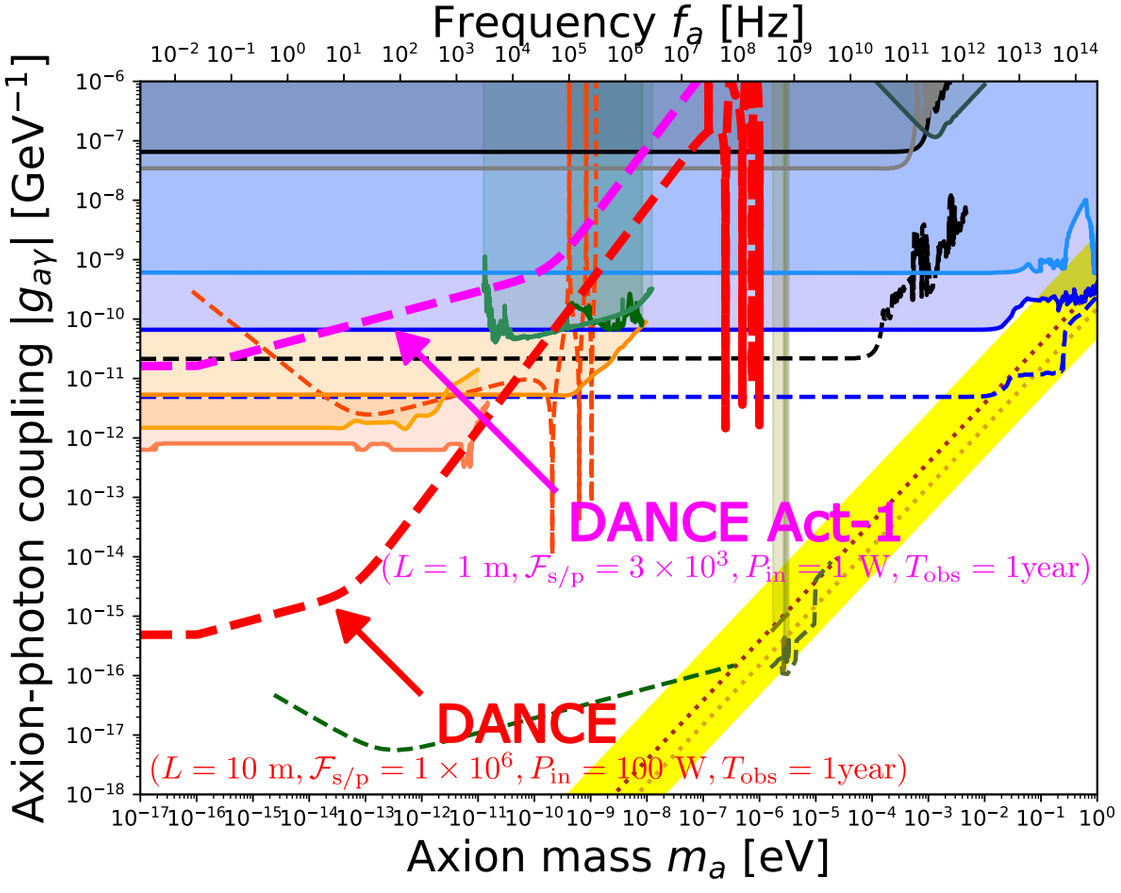
Aim to detect axion with a bow-tie optical ring cavity

- Laser interferometer
- Axion-photon interaction
- Simultaneous resonance

⟹ Conduct a sensitive broadband axion search



DANCE



Dark matter

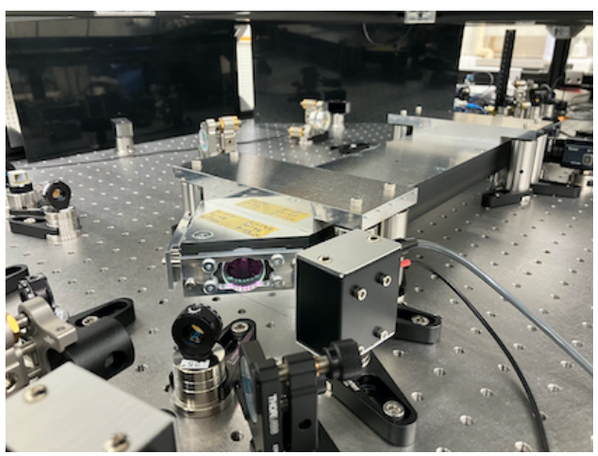
- Account for about 80% of all the matter in the universe
- Extensive research is being conducted
- One of the leading candidates of dark matter: Axion

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

Laser interferometer



DANCE

KAGRA

XENON

Subaru telescope

Axion and Axion-Like-Particles (ALPs)

- Strong CP problem on Quantum ChromoDynamics (QCD)

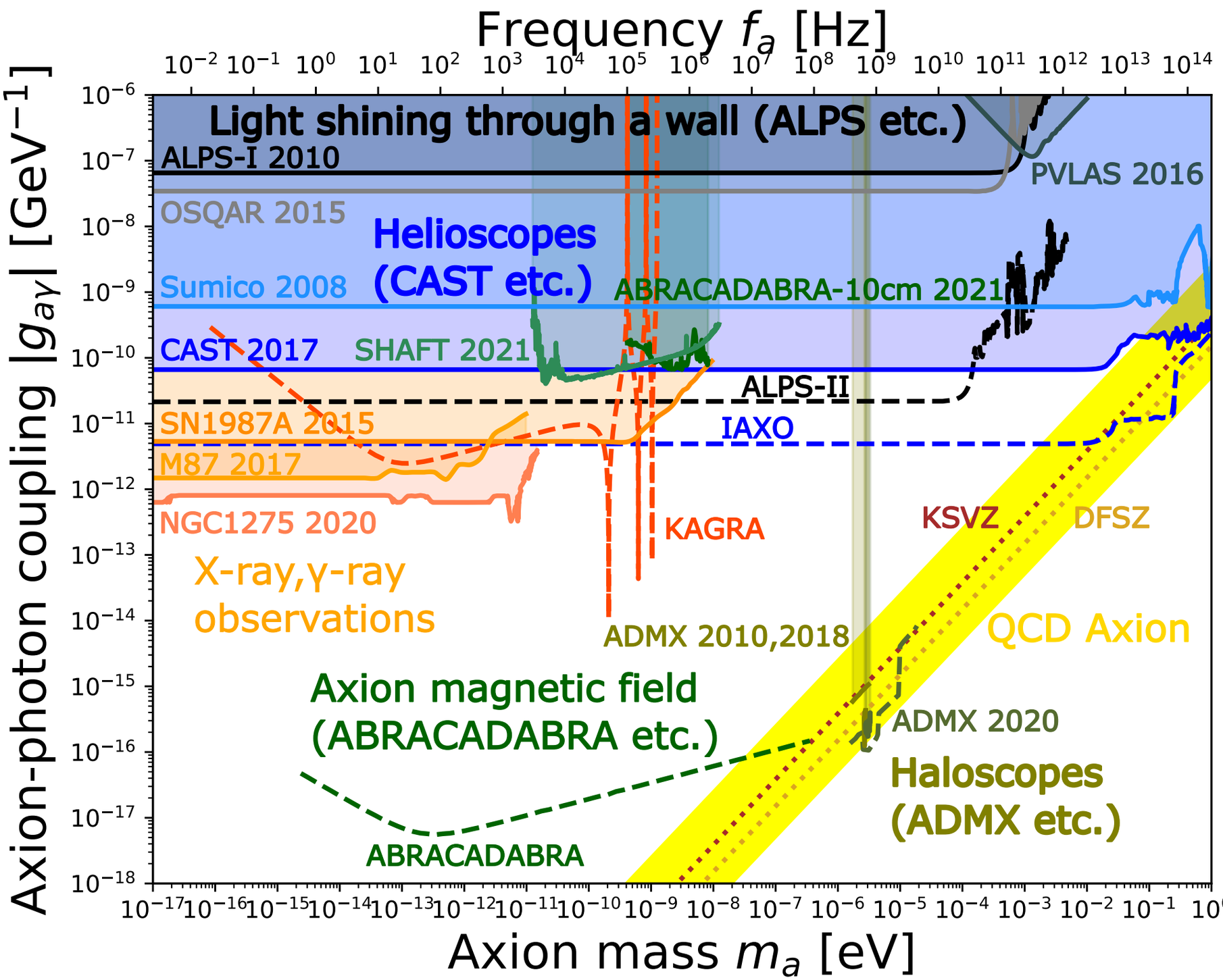
⟹ Pseudo-scalar particle (QCD axion) is suggested to solve this problem

- 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

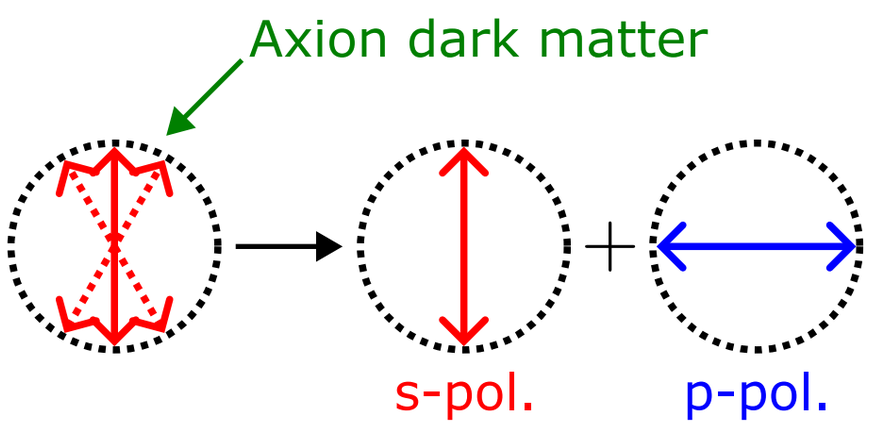
Axion field

Phase factor

→ Regard as a rotation of linearly polarized light

Rotation angle of linearly polarized light

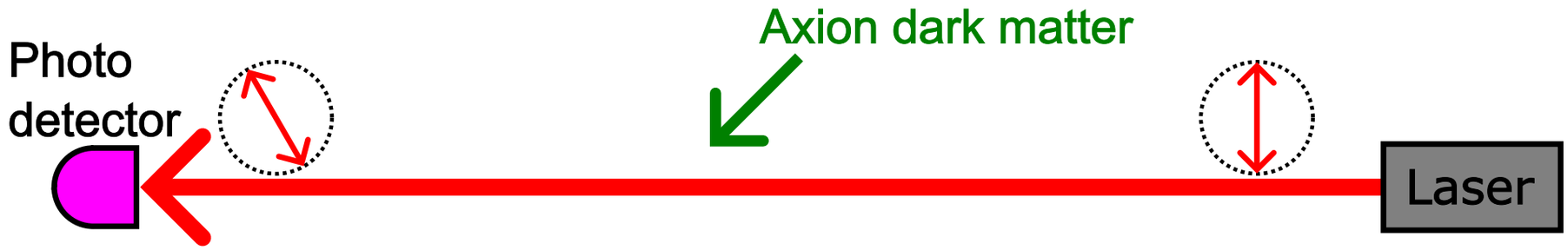
$$\Delta\theta(l,t) = \frac{g_{a\gamma}\sqrt{2\rho_a}}{m_a} \sin\left(m_a \frac{l}{2}\right) \sin\left(m_a\left(t - \frac{l}{2}\right) + \delta_\tau\right)$$



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

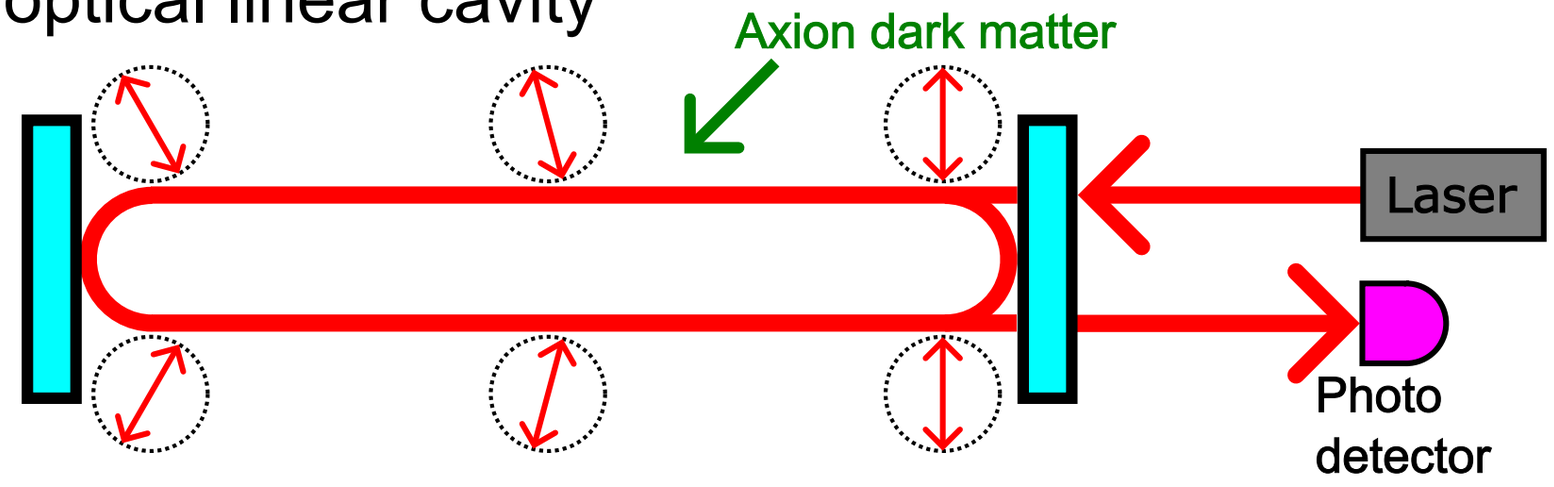
How to amplify the axion signal

Rotation of polarization is small for short optical path



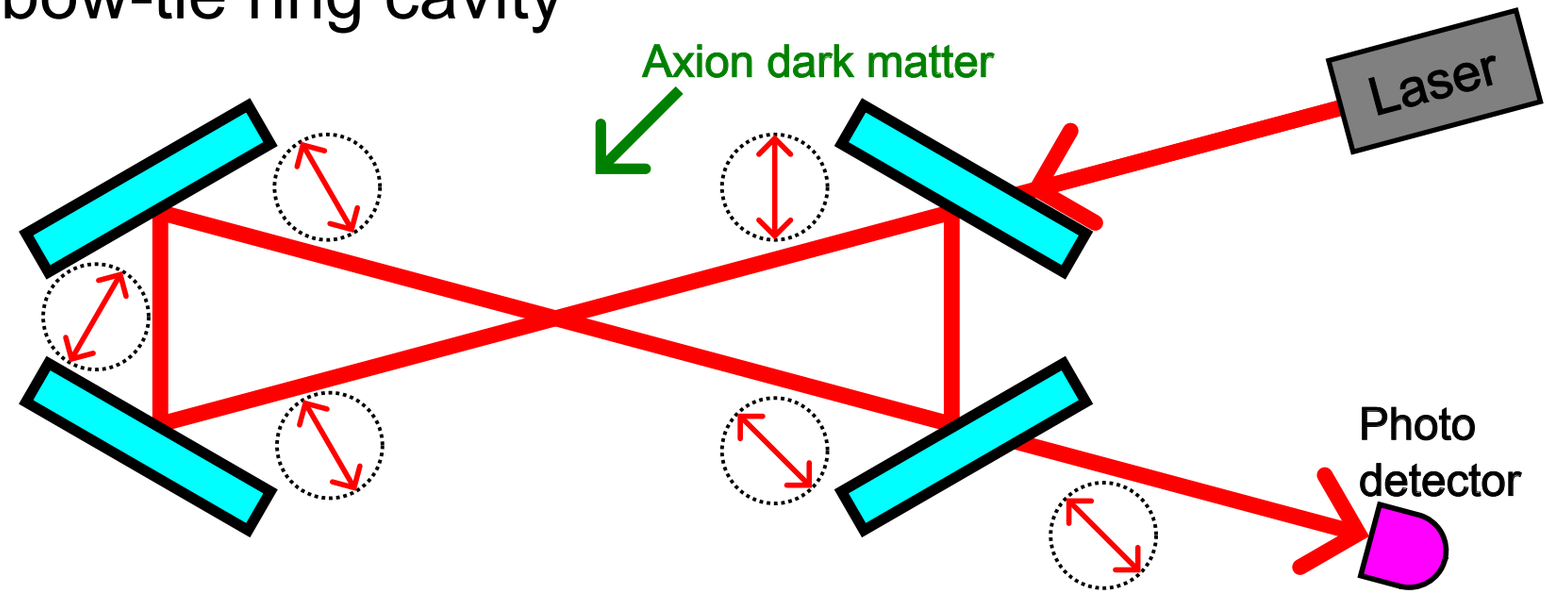
Extend optical path with a optical linear cavity

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



Extend optical path with a bow-tie ring cavity

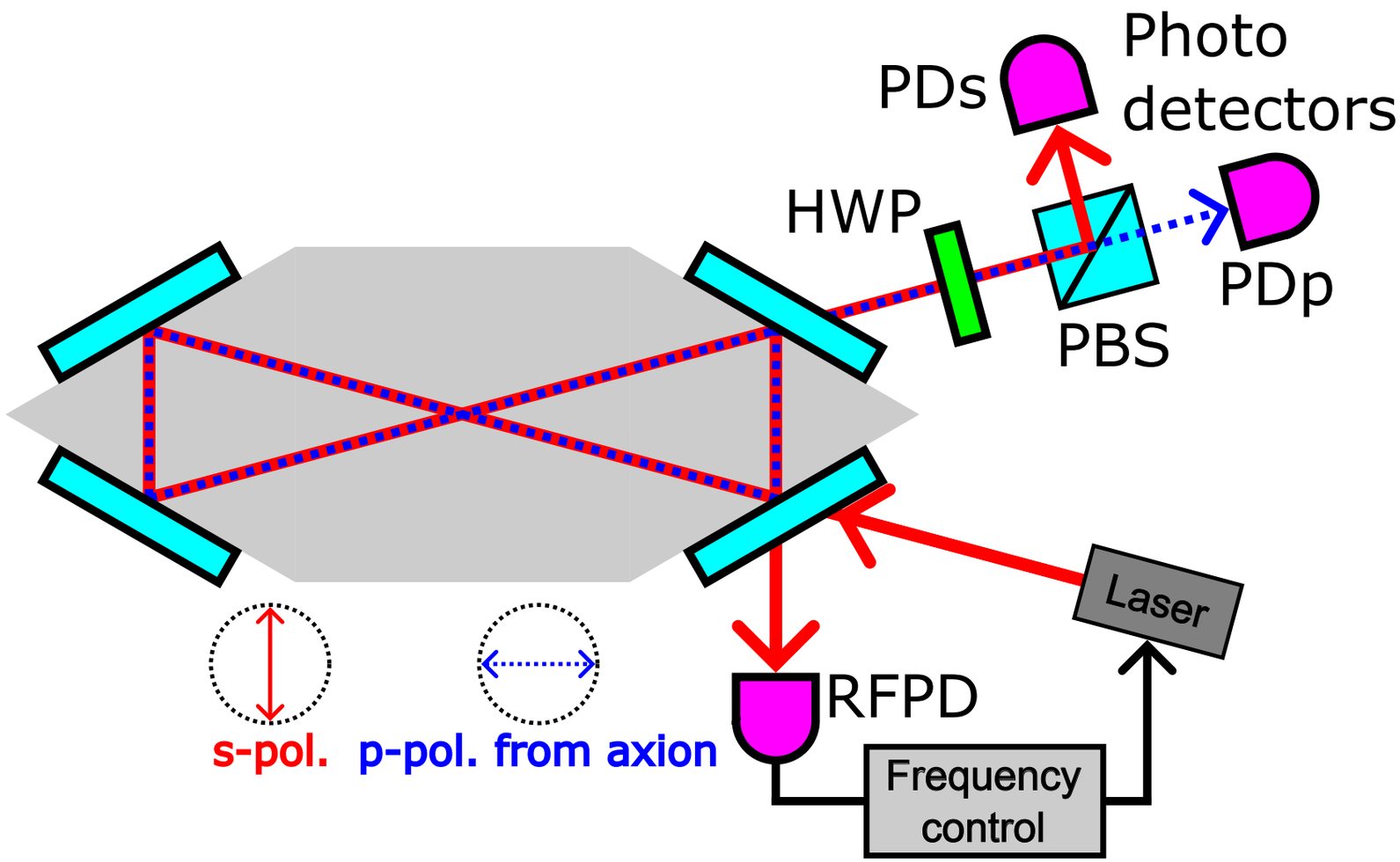
Rotation of polarization can be amplified because the flip is canceled by reflections on both two mirrors



DANCE

DANCE (Dark matter Axion search with riNg Cavity Experiment)

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

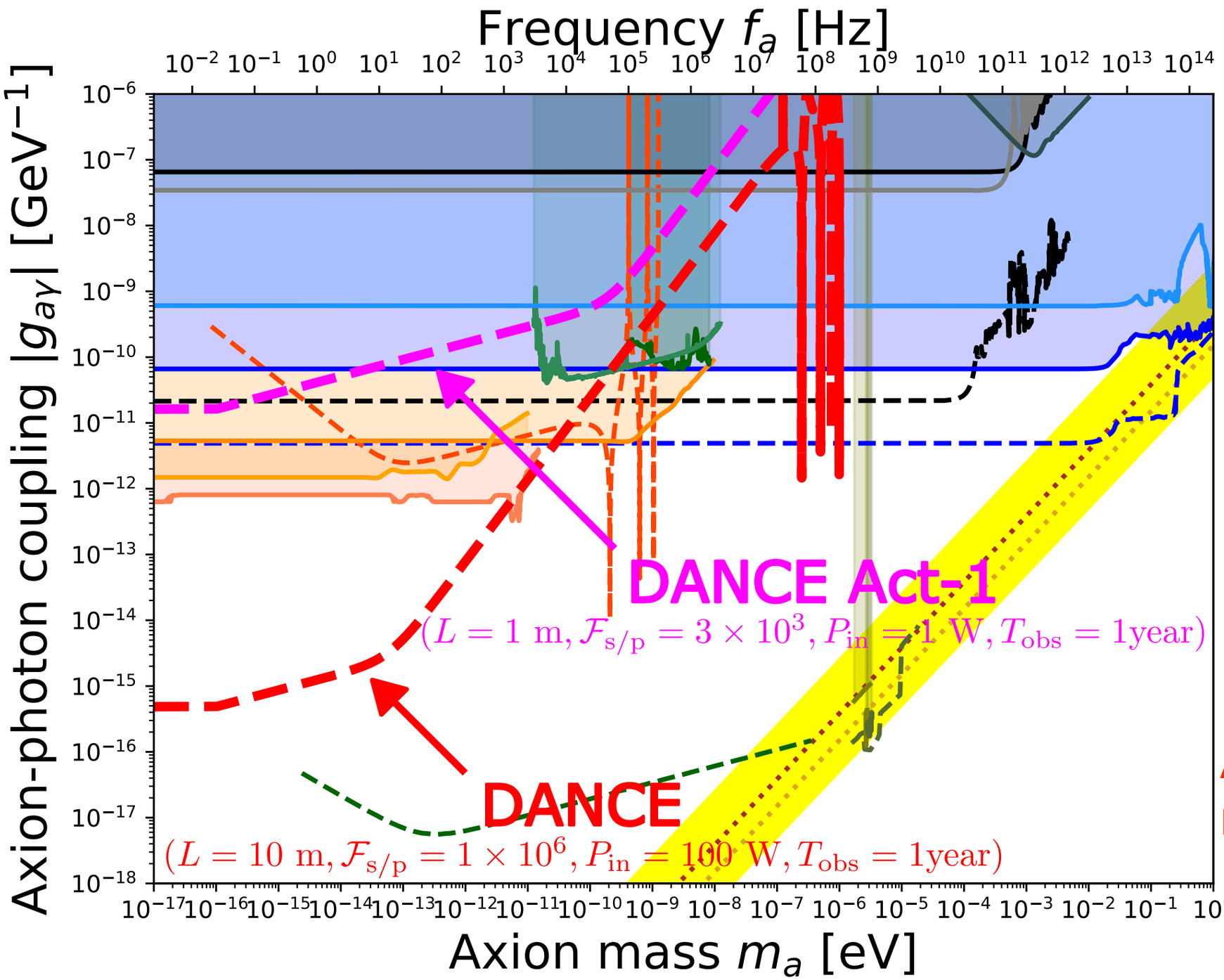


Measure the amount of modulated p-polarized light (Axion signal) by amplifying it with a bow-tie optical ring cavity

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



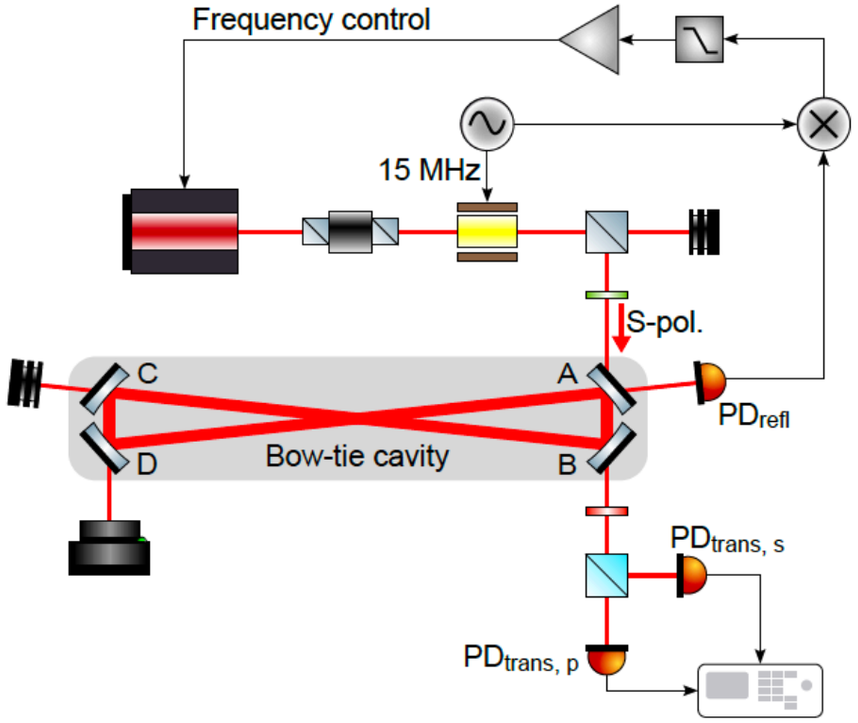
Assume shot noise limit

Current status of DANCE Act-1

- Started in 2019 ⟹ First observation was finished in May 2021
- Issue: s-pol. and p-pol. do not resonate simultaneously

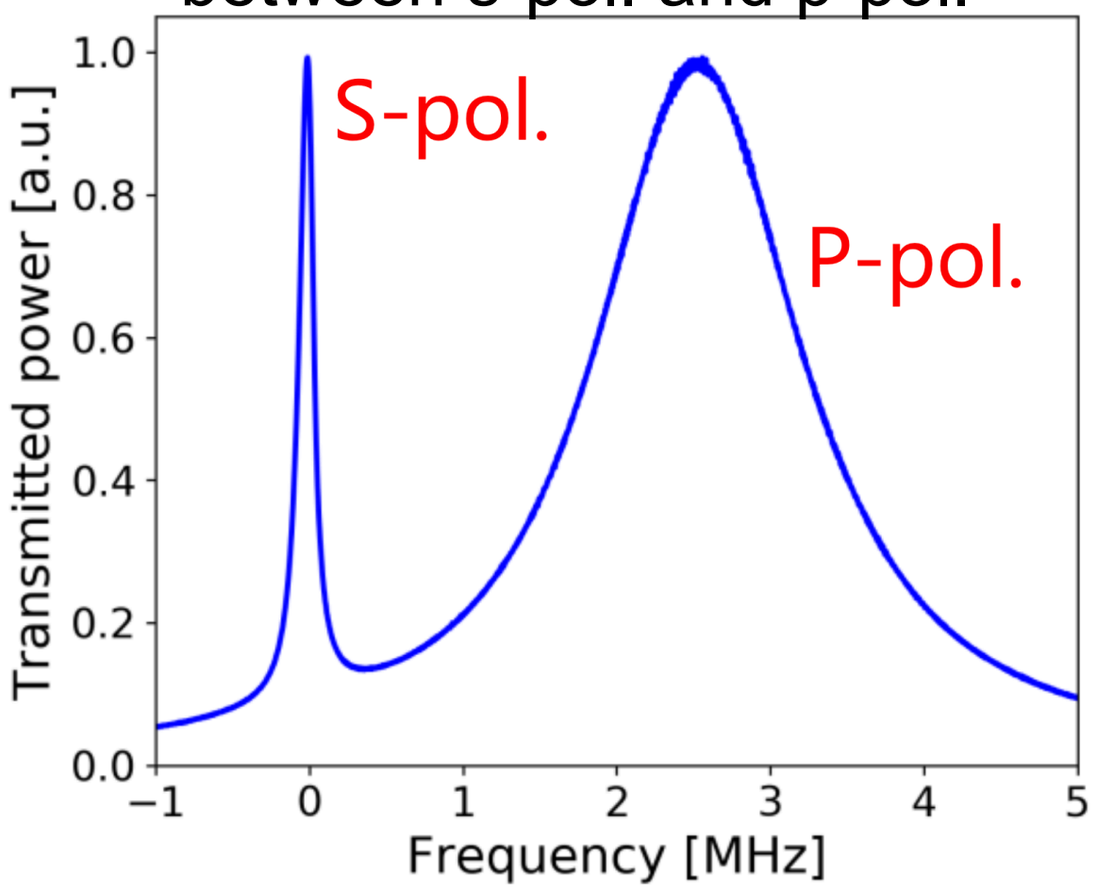
⟹ Degrade the sensitivity to axion in low axion mass region

- Achieved simultaneous resonance for the first time with an auxiliary cavity in November 2021



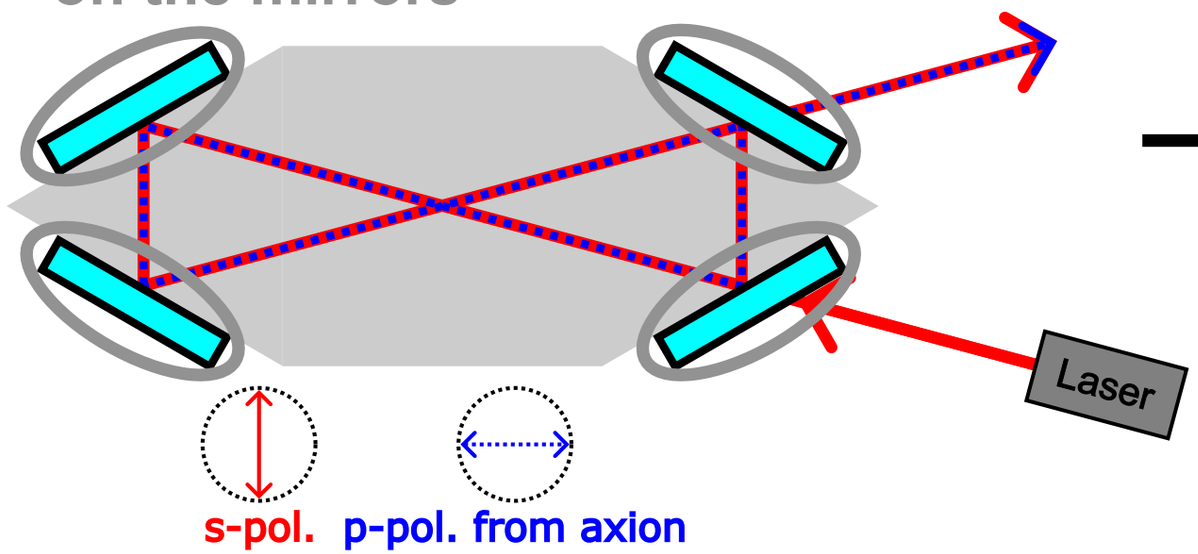
Y. Oshima *et al.*: Phys. Rev. D. **108**, 072005 (2023).

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

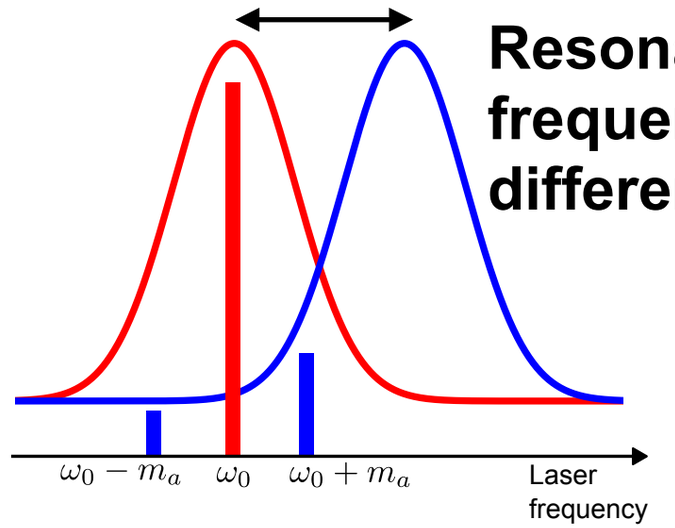


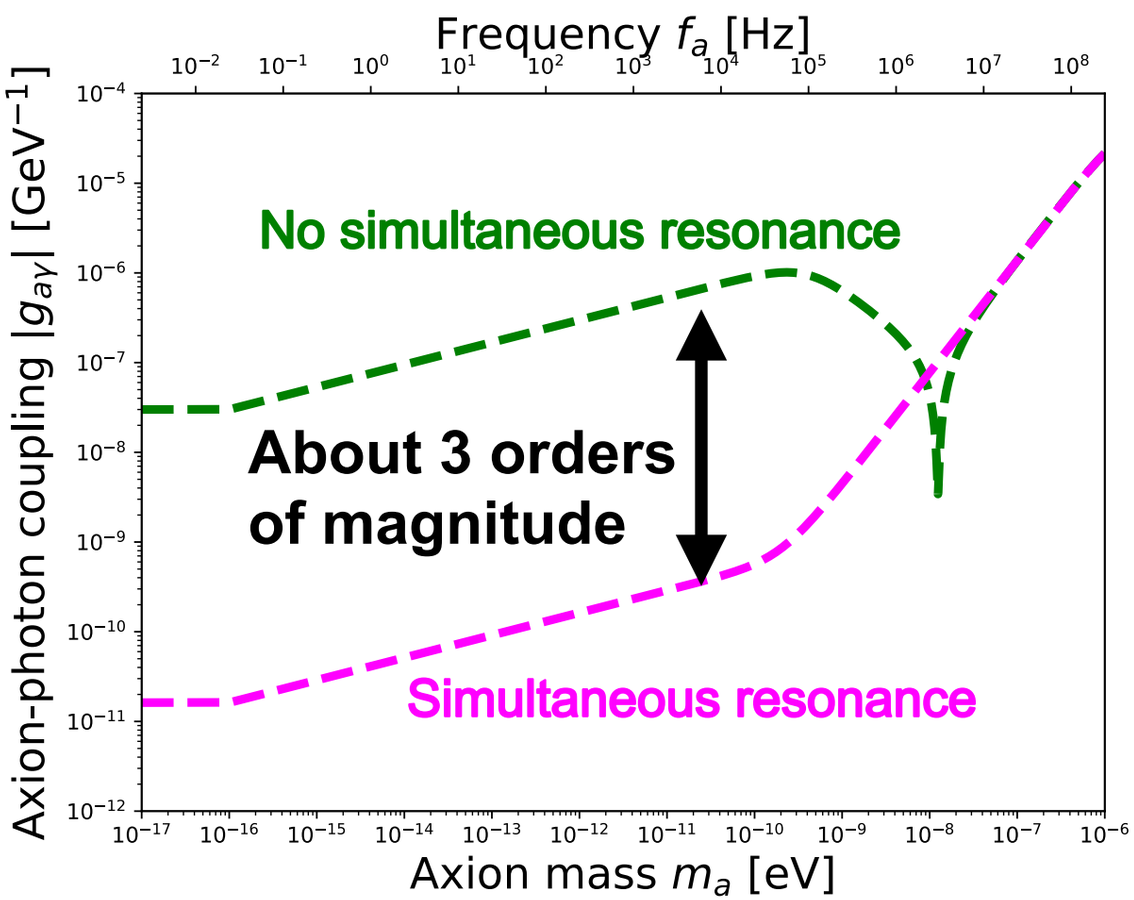
Issue: Simultaneous resonance

Reflection phase difference on the mirrors

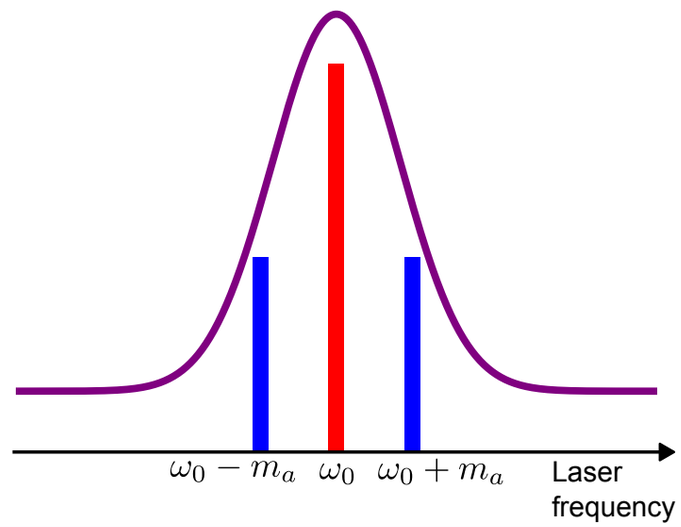


No simultaneous resonance





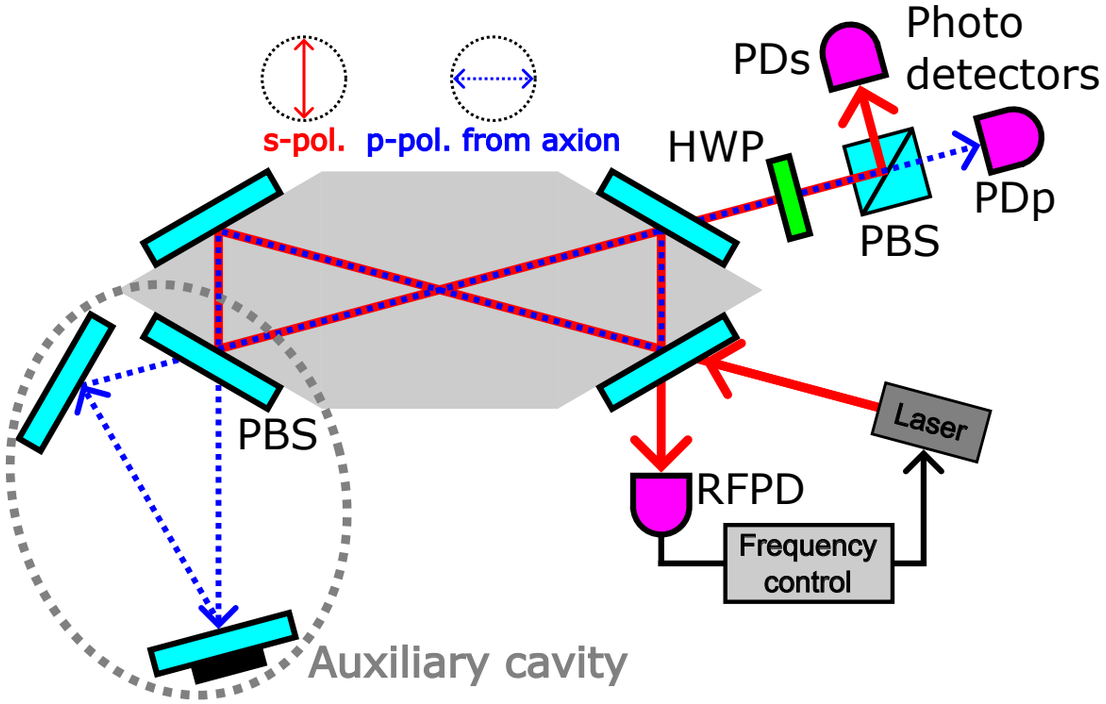
Simultaneous resonance



Simultaneous resonance is necessary to conduct a sensitive broadband axion search

How to achieve simultaneous resonance

DANCE with an auxiliary cavity



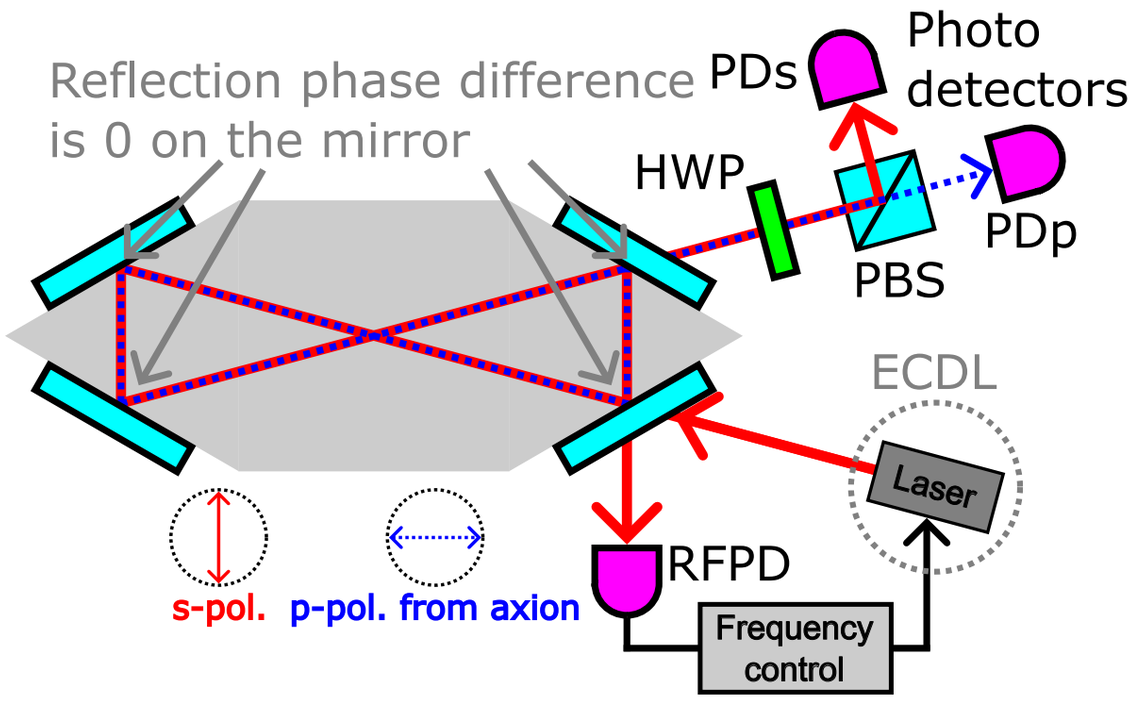
Advantage

Control the reflection phase difference between s-pol. and p-pol. for simultaneous resonance easily

Disadvantage

The optical loss on the polarizing beam splitter (PBS) between a bow-tie ring cavity and an auxiliary cavity degrades the sensitive to axion

DANCE with an ECDL



Advantage

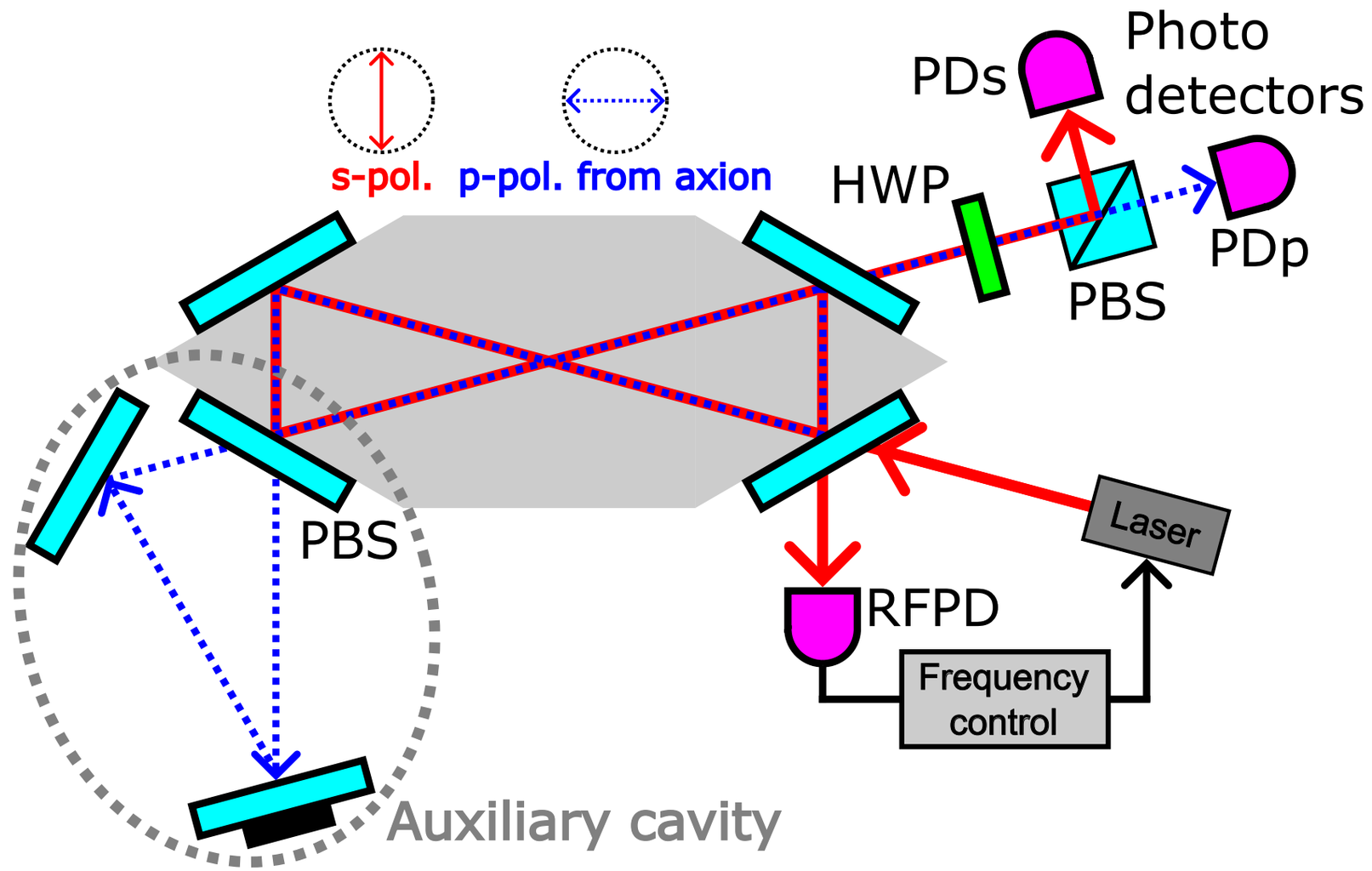
Achieve simultaneous resonance without an auxiliary cavity

Disadvantage

- Difficult to conduct mirror coating to cancel the reflection phase difference between s-pol. and p-pol.
- Need to use stable wavelength tunable laser

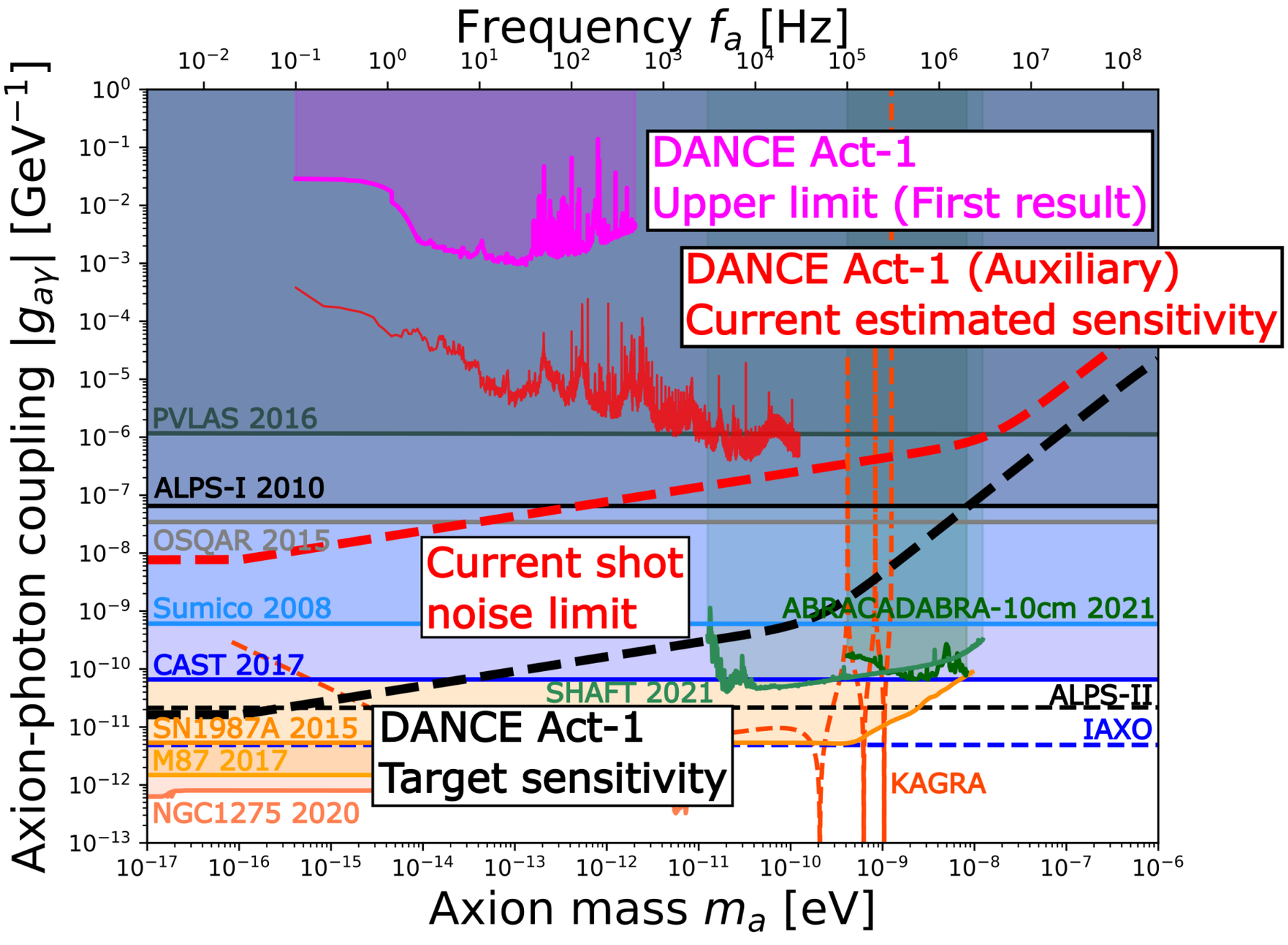
Simultaneous resonance with an auxiliary cavity

- Achieved simultaneous resonance 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



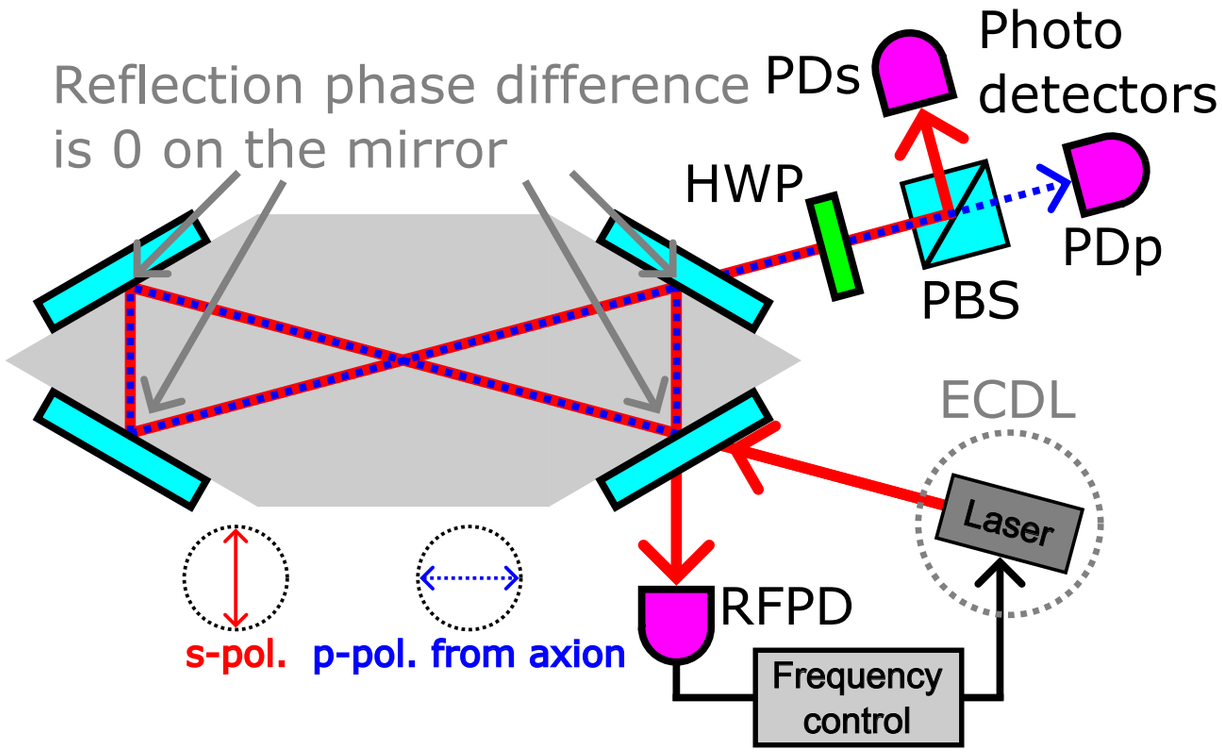
Simultaneous resonance with an auxiliary cavity

- Improved by more than 2 orders of magnitude
- Need to reduce the optical loss between a main cavity and an auxiliary cavity

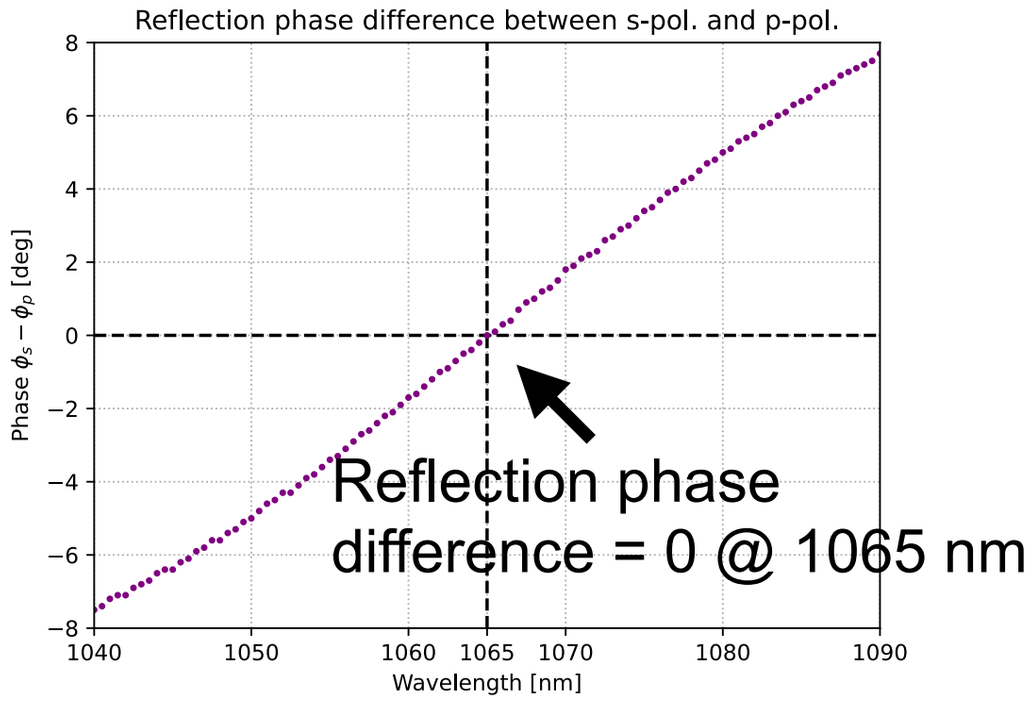


Simultaneous resonance with an ECDL

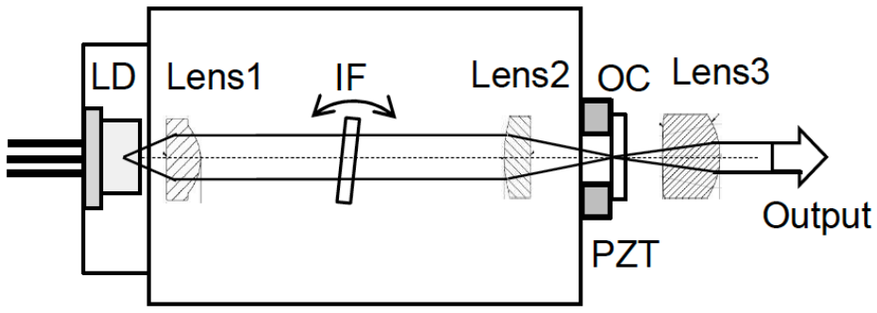
- Mirrors of reflection phase difference between s-pol.and p-pol. depends on laser wavelength
- Select the wavelength by finely adjusting the angle of the interference filter (IF)
- Constructing setup is in progress



Wavelength sensitive phase-shifting mirror



ECDL (wavelength tunable laser)



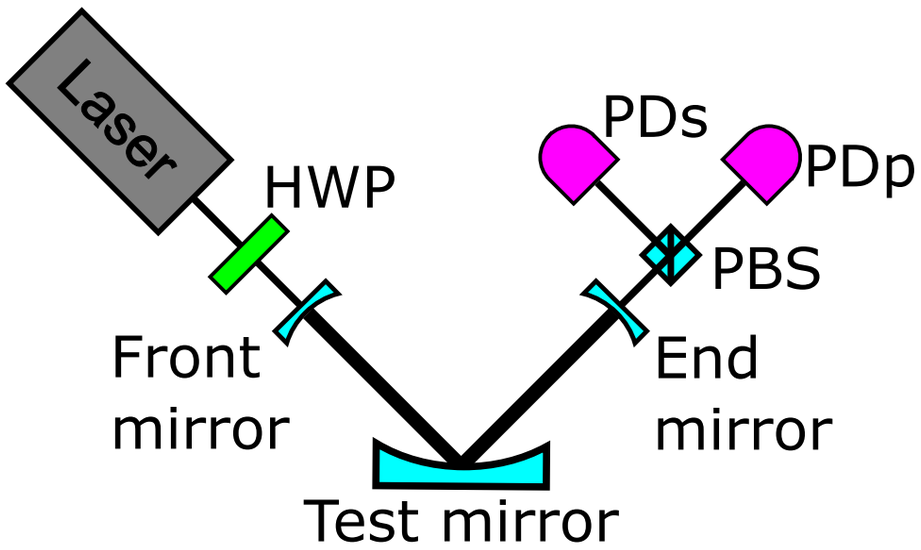
- Wavelength range: 1045 - 1068 nm
- FWHM: 200 kHz
- Output power: 20 - 50 mW

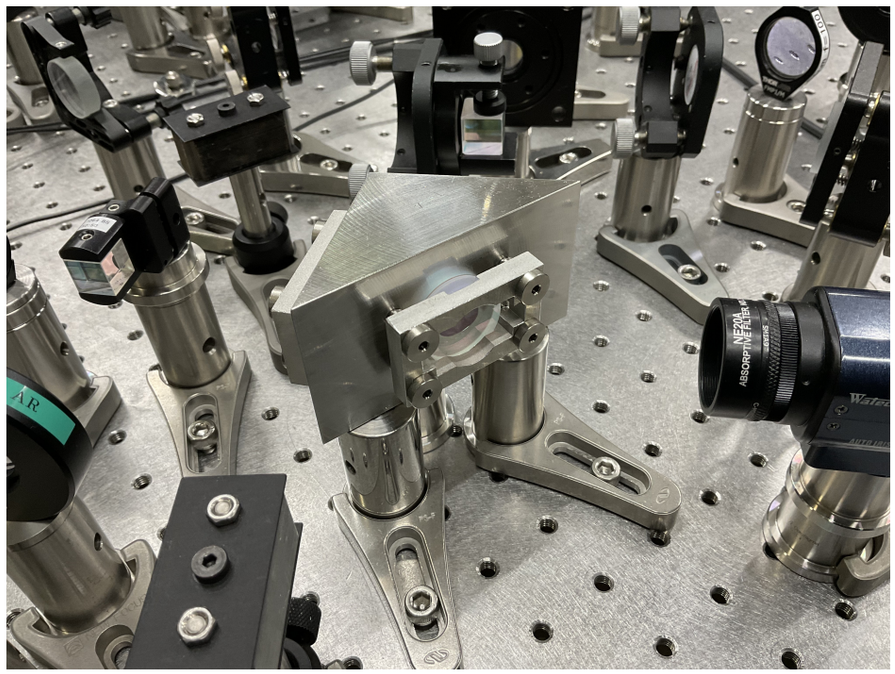
Measurement of reflection phase difference

Establishment 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.

⟹ Difficult to conduct an accurately sensitive axion search





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

Requirement for simultaneous resonance

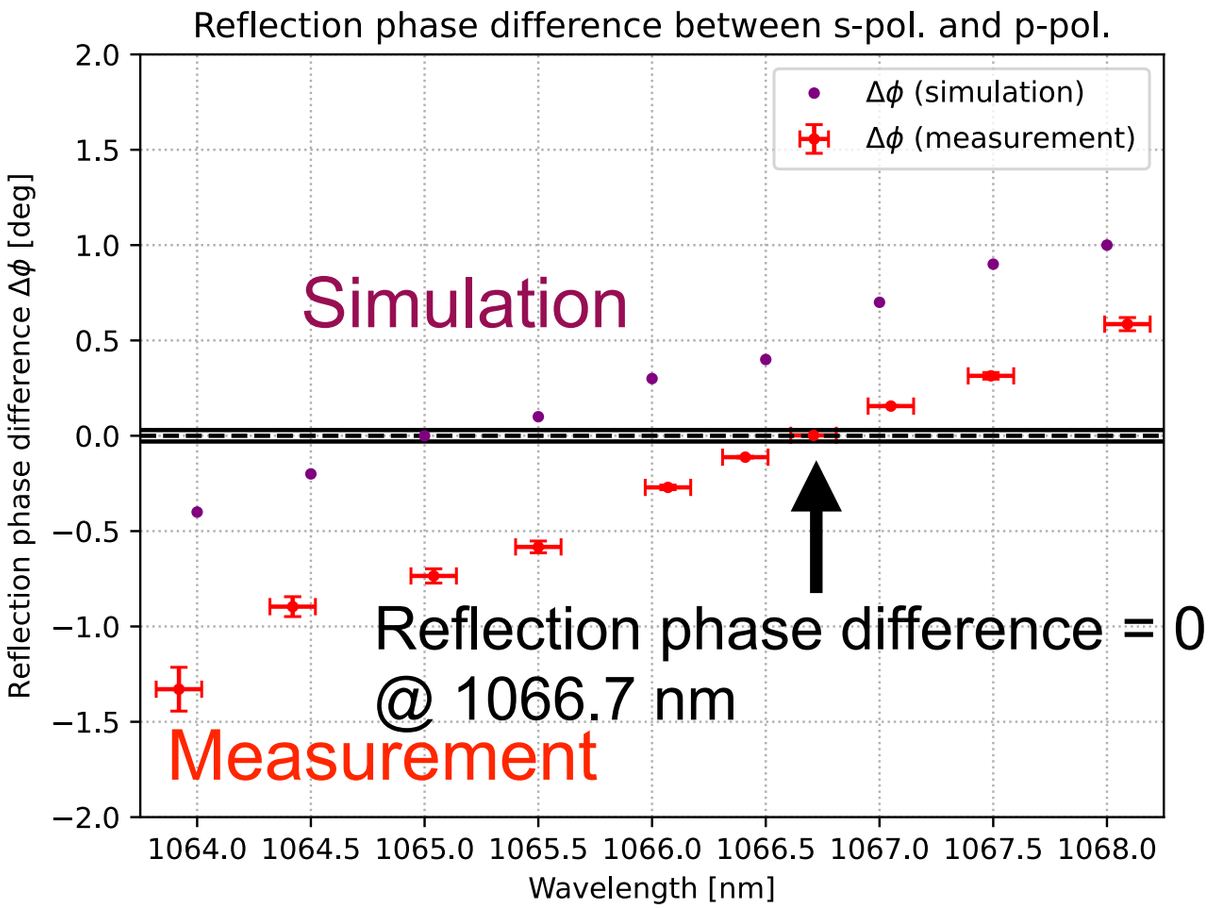
$$\Delta\phi \leq 0.015 \text{ deg}$$

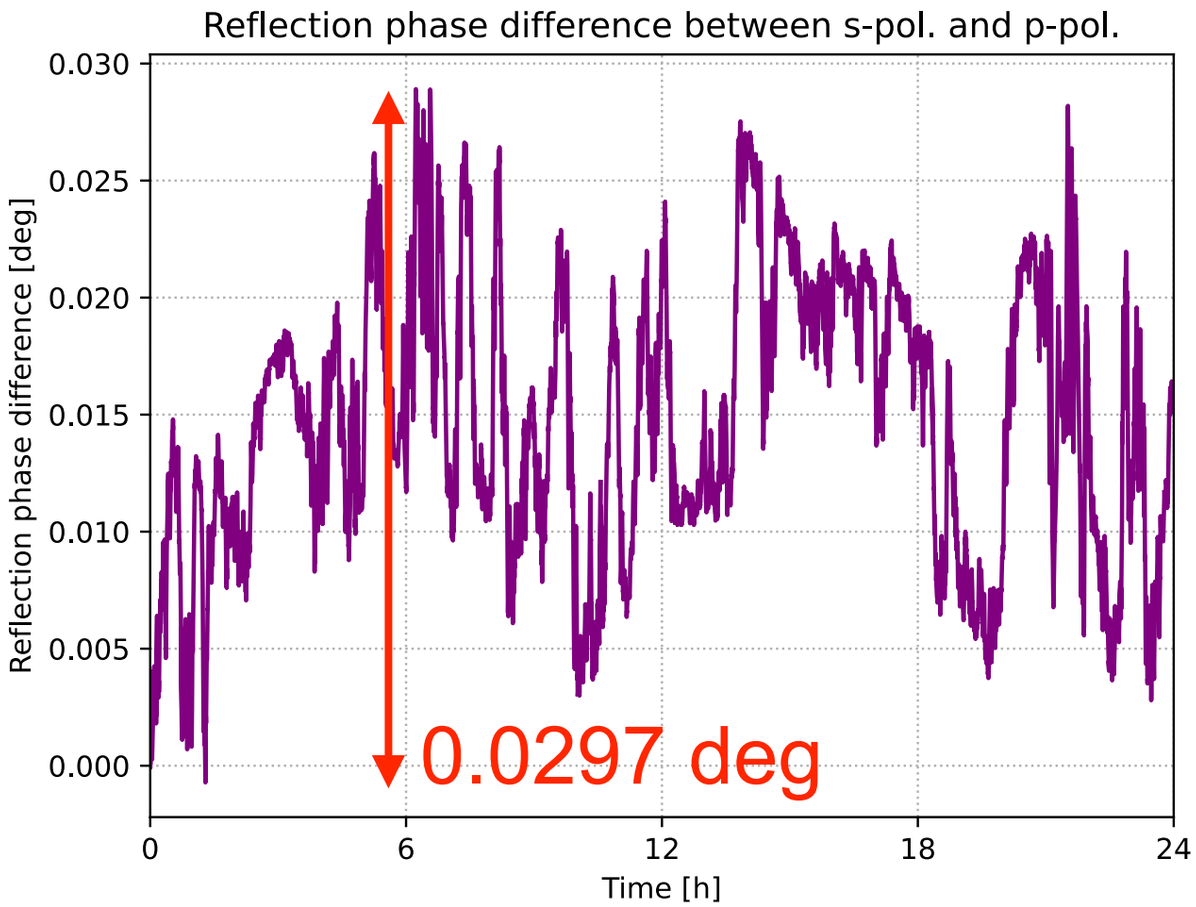
Mirror	Reflectivity	CC[mm]
Front	99%	50
End	99%	50
Test	s-pol.: 99.99%, p-pol.: 99.97%	1000

Measurement of reflection phase difference

Establishment of simultaneous resonance with a folded cavity

- Reflection phase difference between s-pol. and p-pol. depends on wavelength (left figure)
- Time drift of the reflection phase difference between s-pol. and p-pol. (right figure)





Satisfy requirement for simultaneous resonance

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

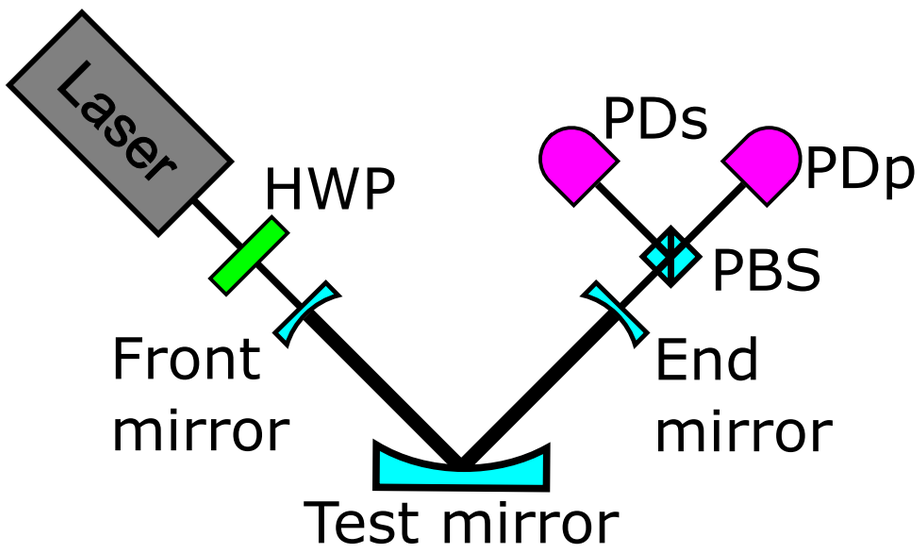
Future plans for DANCE

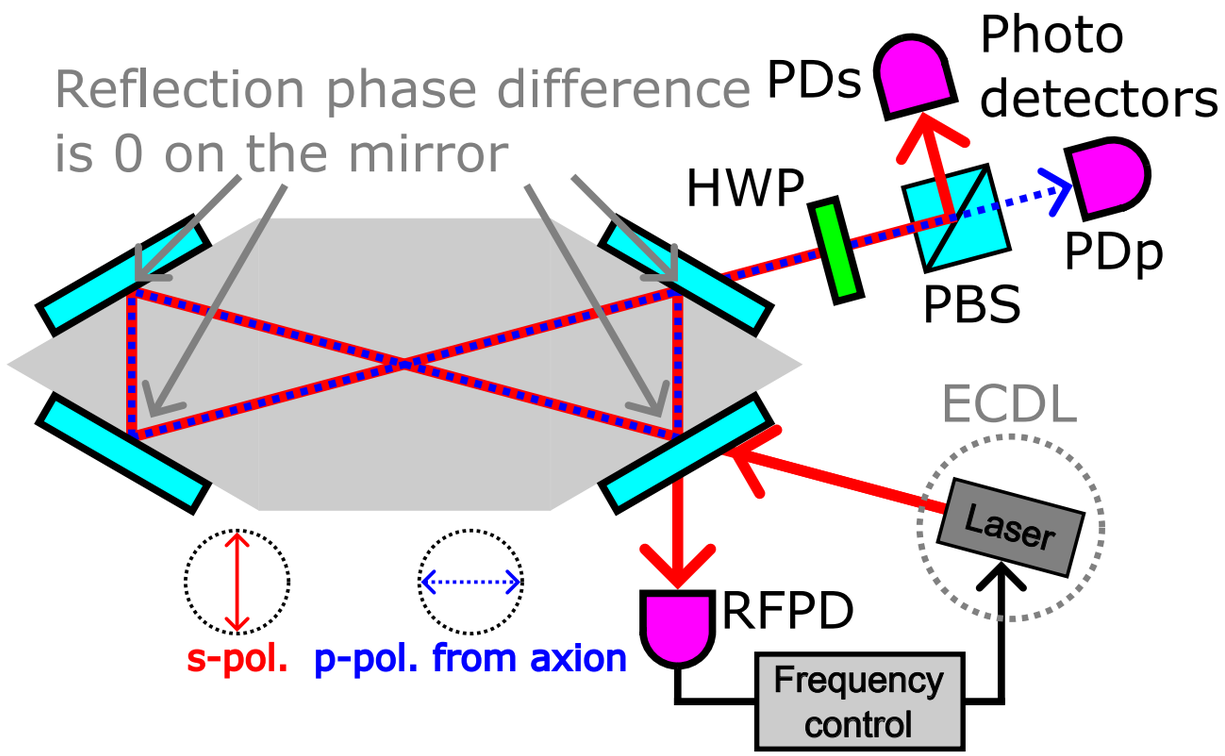
- Investigating the cause of time drift of the reflection phase difference s-pol. and p-pol. with a folded cavity
- Some various wavelength sensitive phase-shifting mirrors we ordered will arrive in the end of March

⟹ Evaluate wavelength dependence of these mirrors

- Constructing DANCE with an ECDL for simultaneous resonance is in progress

⟹ Aim to achieve simultaneous resonance in March





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 finished in May 2021
- Achieved simultaneous resonance in November 2021 by adding an auxiliary cavity
- Achieve the world's most sensitive dark matter axion search