Current status of sensitivity improvement of Dark matter Axion search with riNg Cavity Experiment (DANCE)

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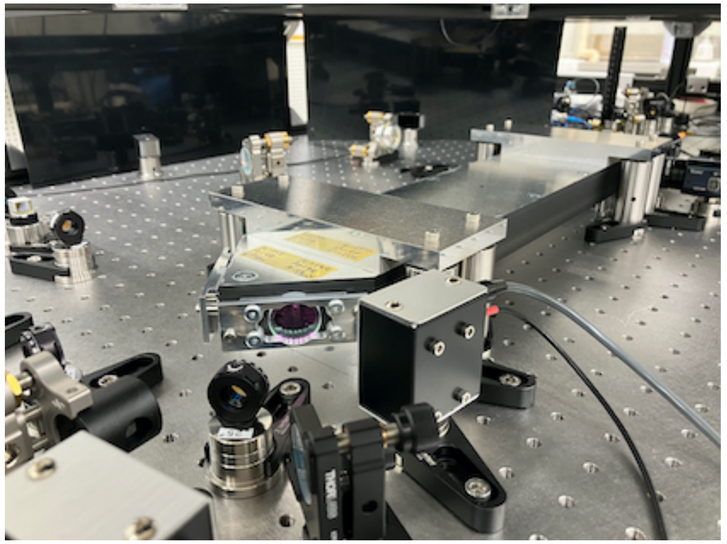
Abstract

DANCE: sensitive broadband axion search with a bow-tie optical ring cavity

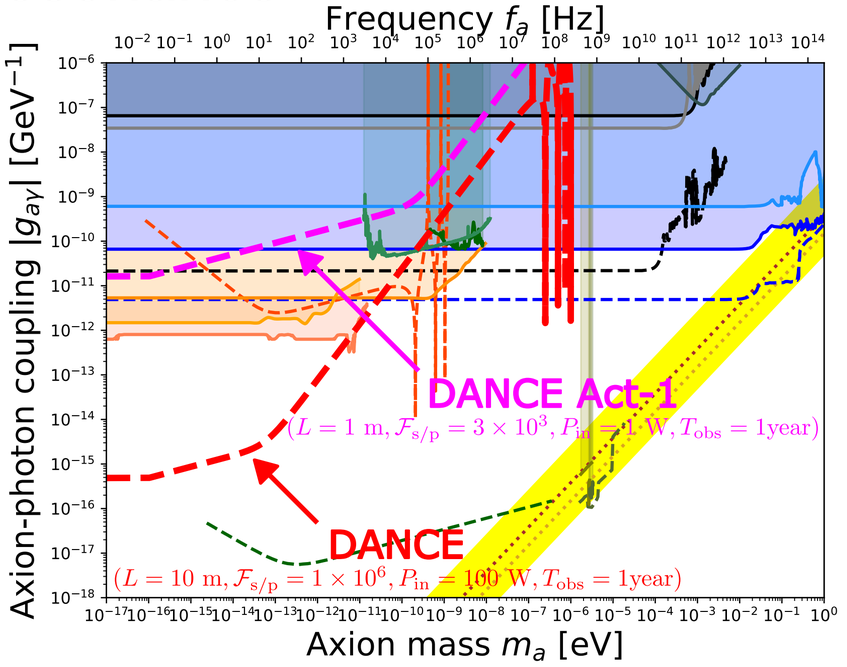
- Laser interferometer
- Axion-photon interaction

DANCE Act-1: prototype experiment started in 2019

- Non-simultaneous resonance degrades sensitivity
- Currently operating for simultaneous resonance

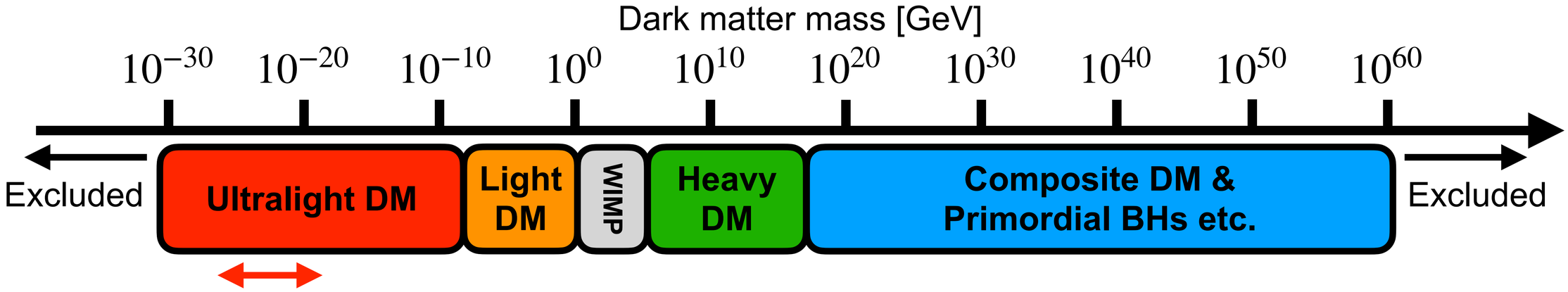


DANCE

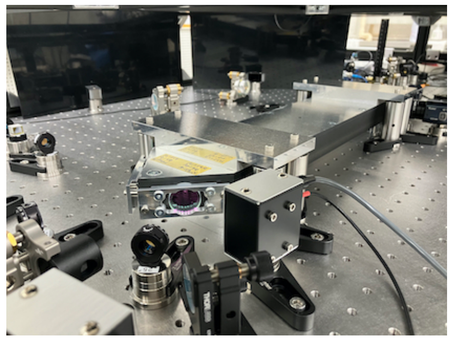


Dark matter

- 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



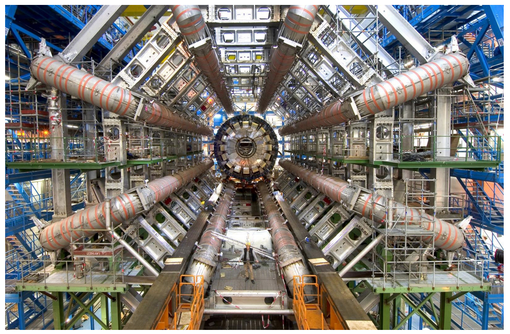
Laser interferometer



DANCE

KAGRA

XENON



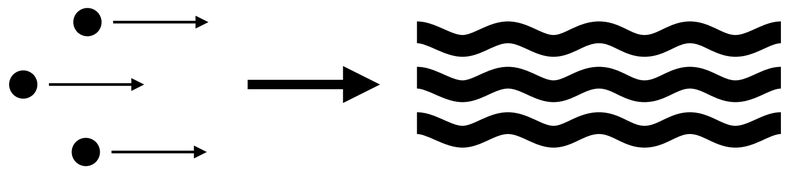
LHC

Subaru telescope

Axion and Axion-Like-Particles (ALPs)

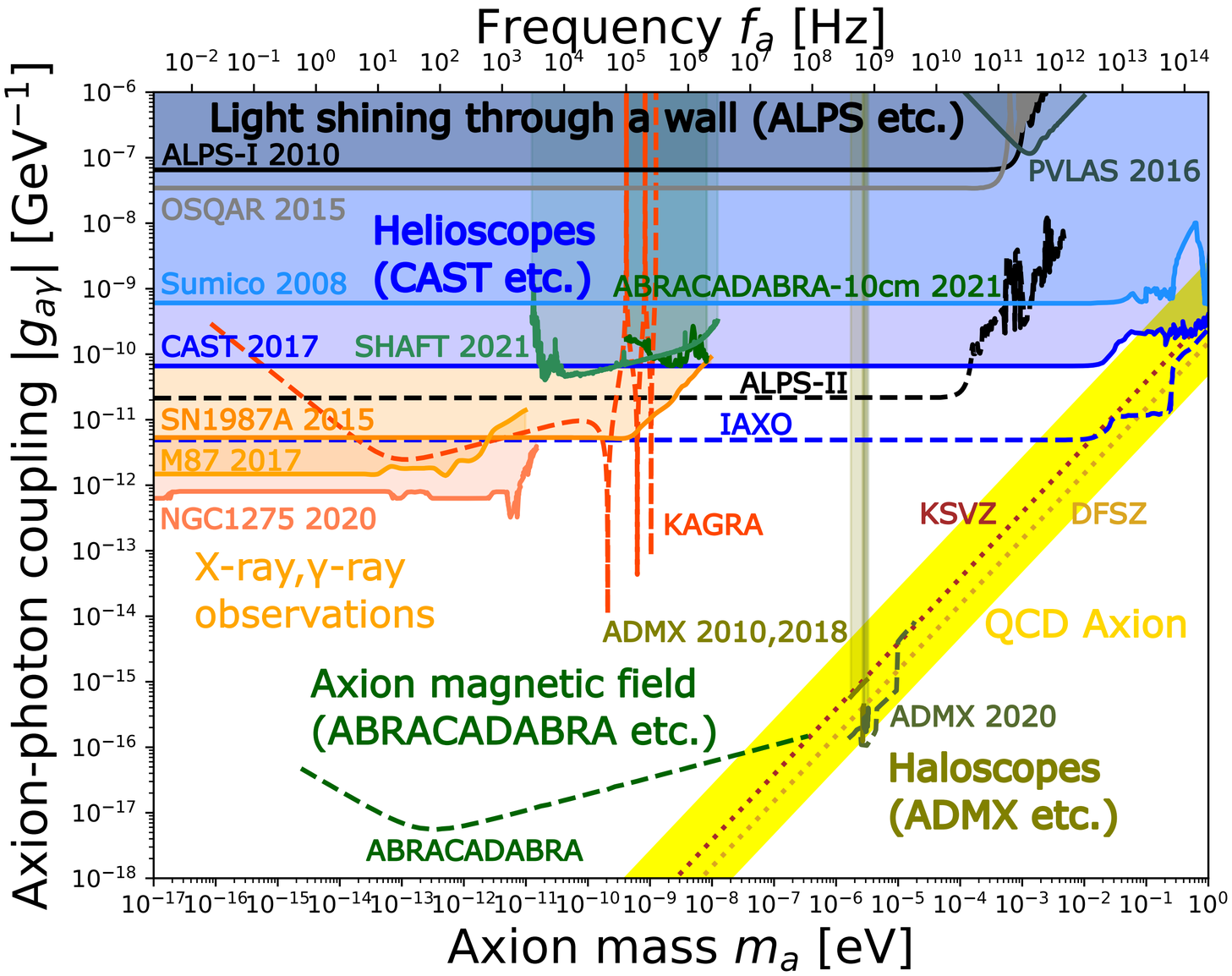
- Axion is suggested to solve strong CP problem on Quantum Chromo Dynamics (QCD)
- Various Axion-Like-Particles (ALPs) is predicted
- Axion weakly interacts with photon, electron, proton, neutron
- Very light particles → Behave like waves

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



- Many experiments have utilized the axion-photon conversion under magnetic field (Primakoff effect). However, axion has not been observed yet.

Previous searches



Relation between axion mass and frequency

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

- Solid line is upper limit
- Dotted line is target sensitivity
- White region is unexplored

Axion-photon interaction

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

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

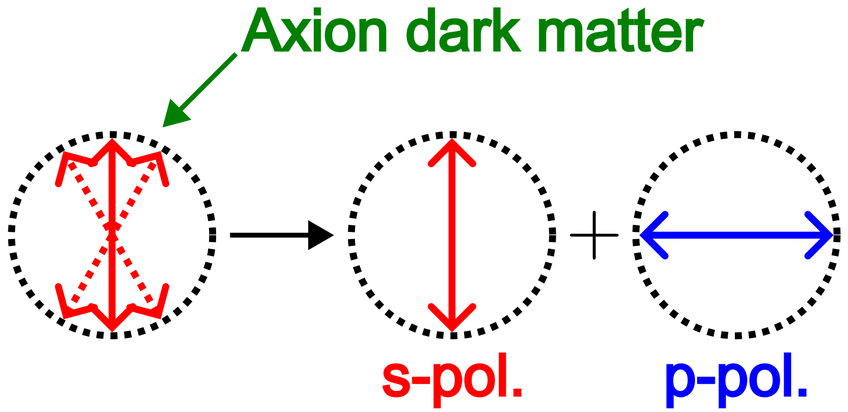
Phase velocity

Axion-photon coupling

Axion field

Axion mass

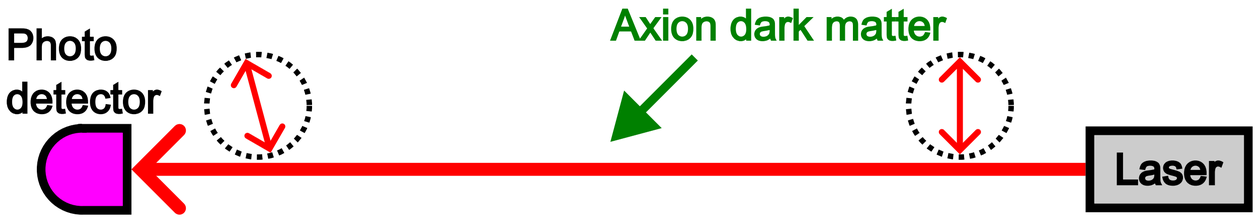
→ A rotation of linearly polarized light



- Axion produce p-polarization (Axion signal)
- Period of rotational oscillation → Axion mass
- Amplitude of rotational oscillation → Axion-photon coupling

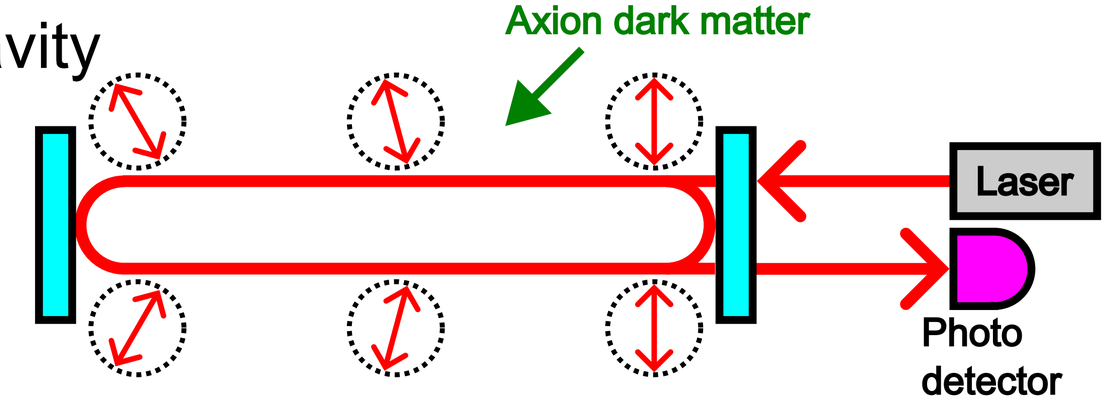
How to amplify the axion signal

Rotation of polarization is small
for short optical path



Extend optical path with a optical linear cavity

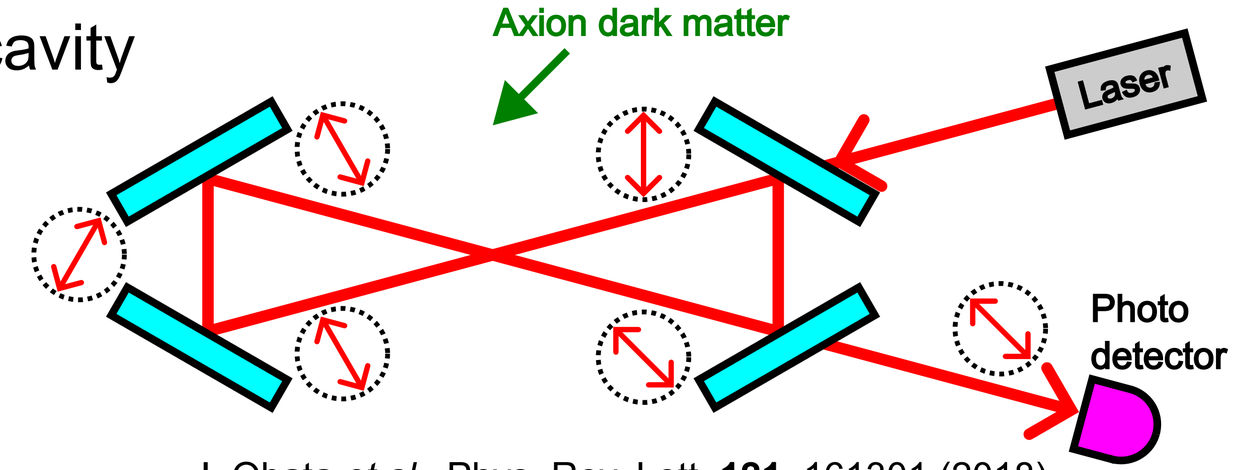
However, rotation of polarization
can not be amplified because it is
flipped by reflections



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

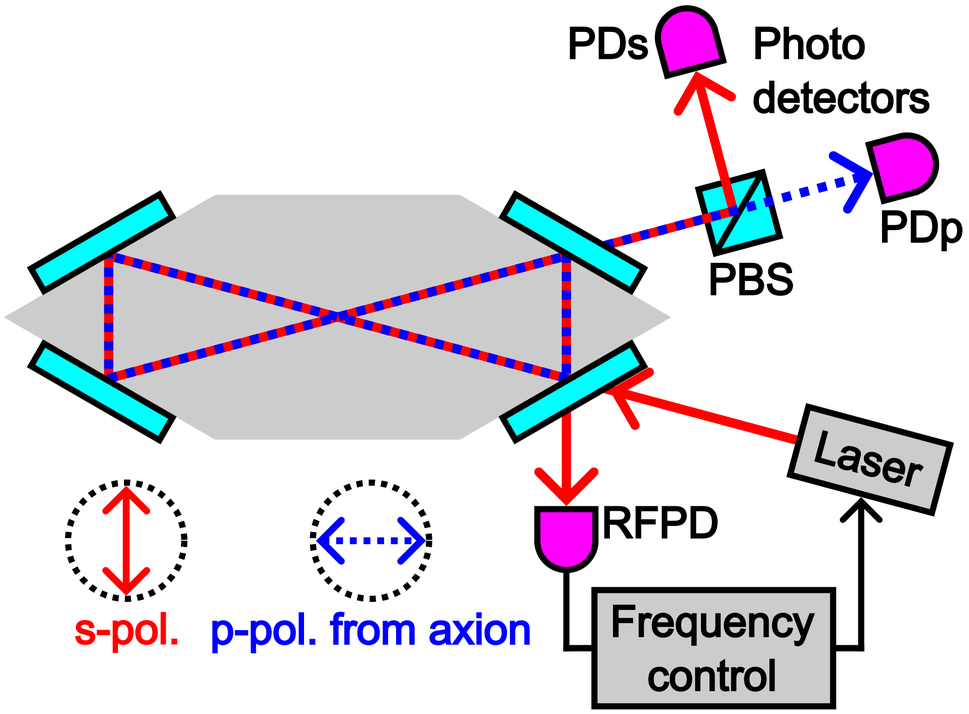
※ Without magnetic field

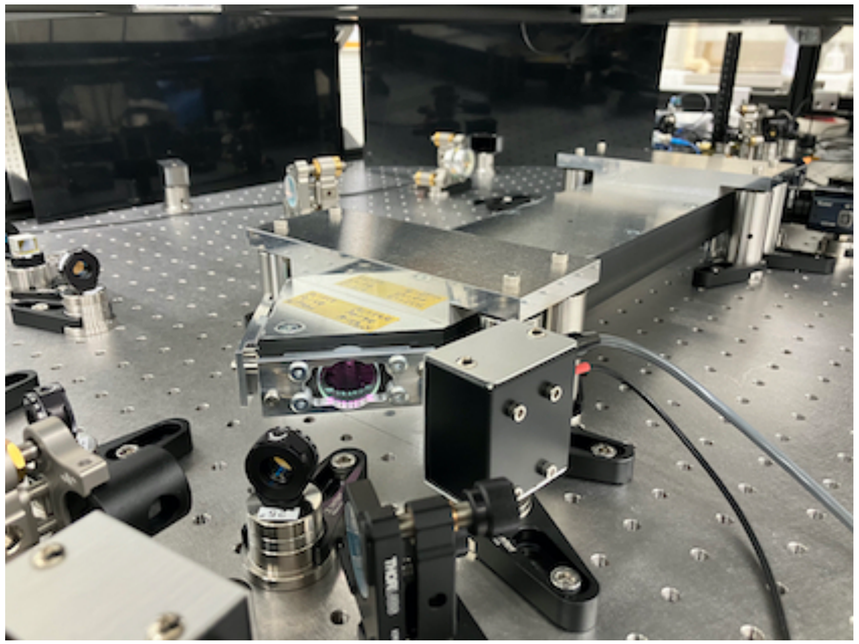


I. Obata *et al.,* Phys. Rev. Lett. **121**, 161301 (2018).

DANCE (Dark matter Axion search with riNg Cavity Experiment)

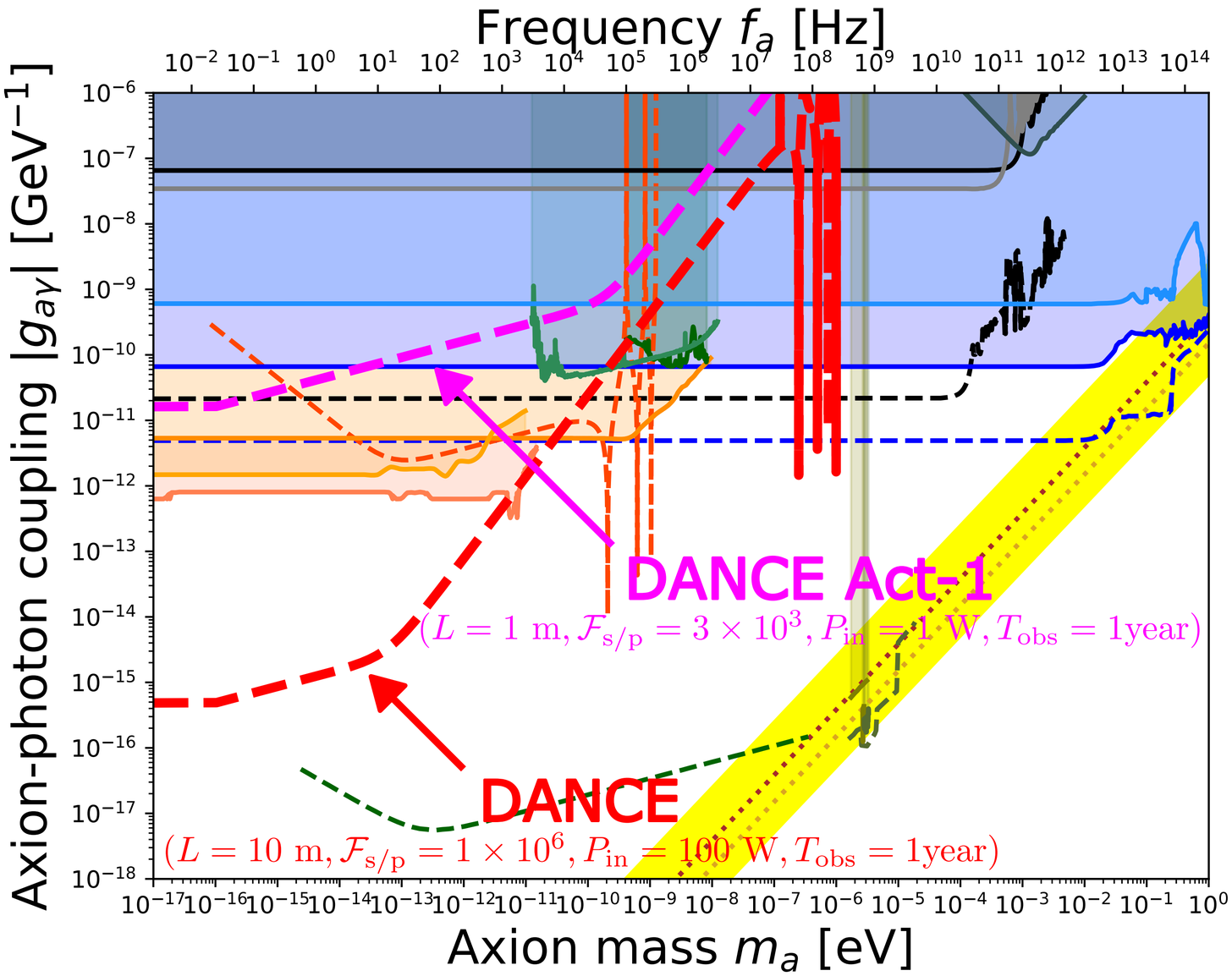
- Dark matter axion search with laser interferometer
- Bow-tie optical ring cavity





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

Target sensitivity of DANCE



- Shot noise limited
- Assume all dark matter is axion

L : Round-trip

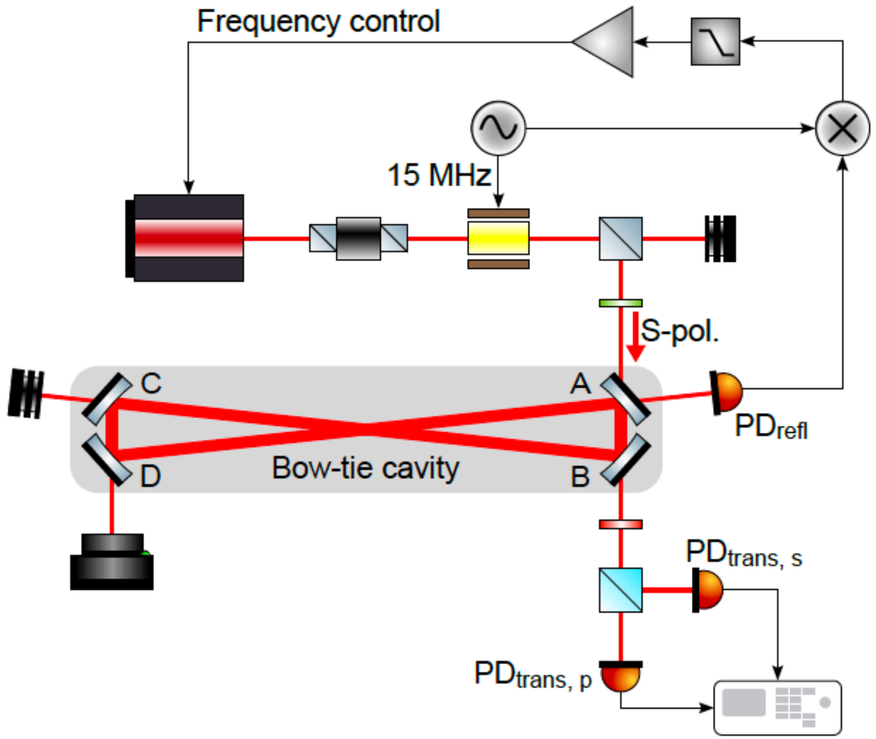
$\mathcal{F}_{\mathrm{s/p}}$: Finesse (s/p-pol.)

P_{in} : Input power

Able to conduct a sensitive axion search by improving parameters

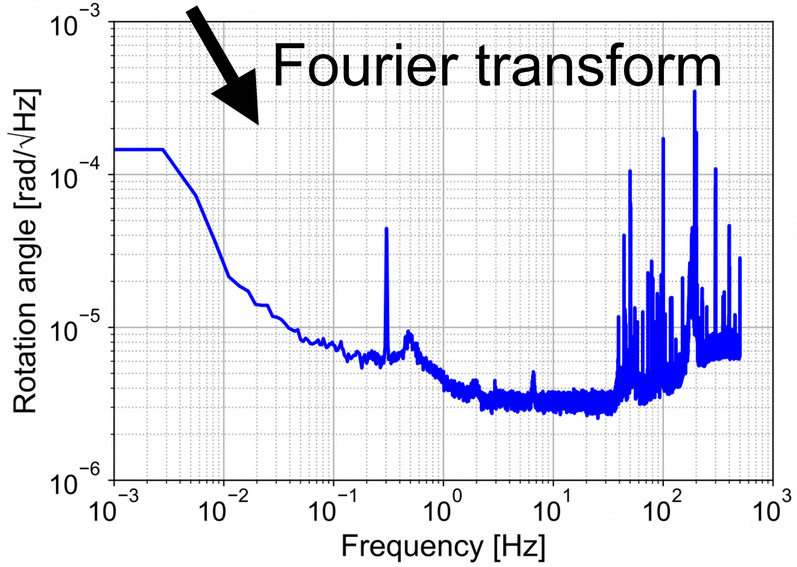
First observation of DANCE Act-1

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



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

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

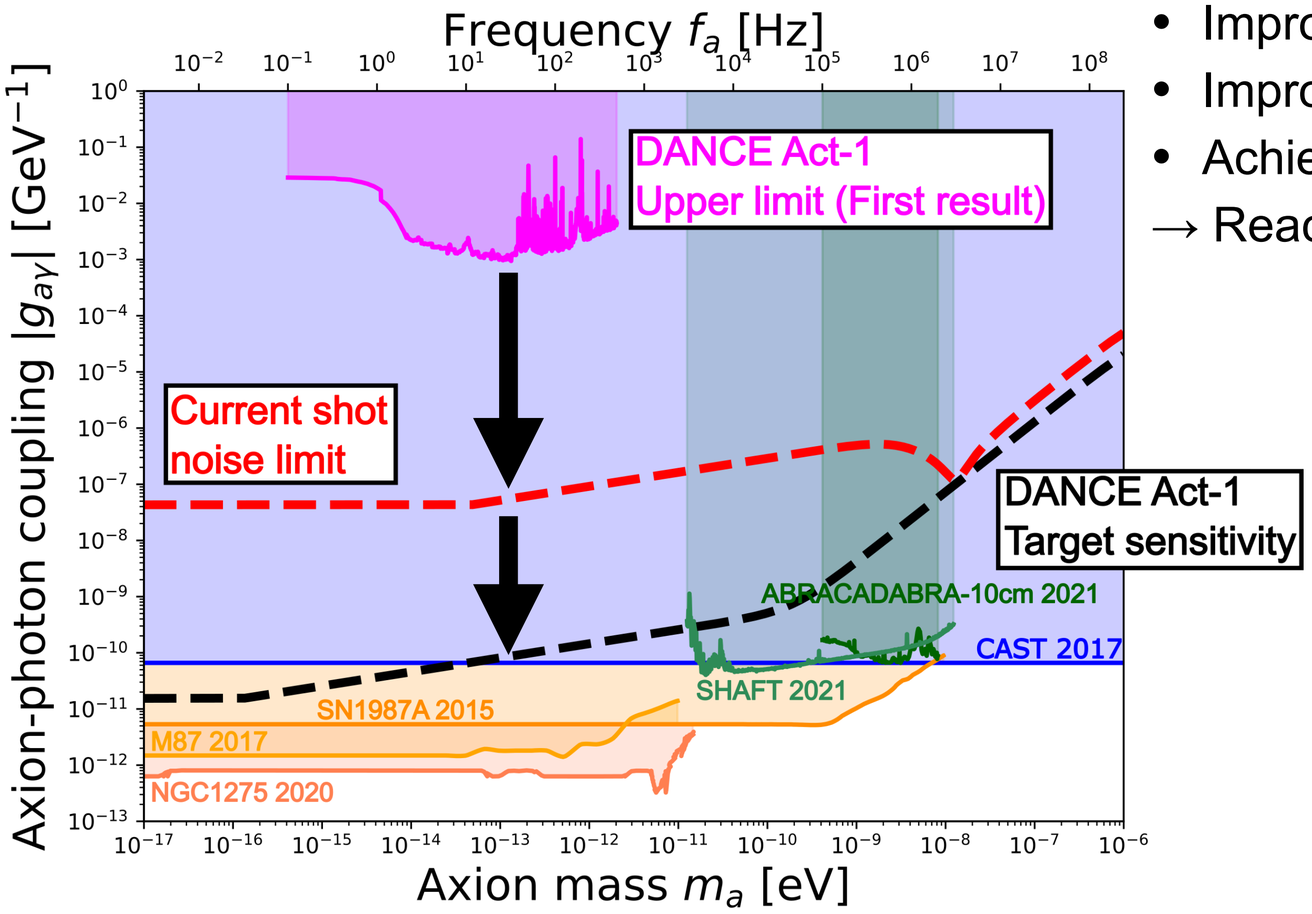


Y. Oshima *et al.,* Phys. Rev. D **108**, 072005 (2023).

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

Result and consideration

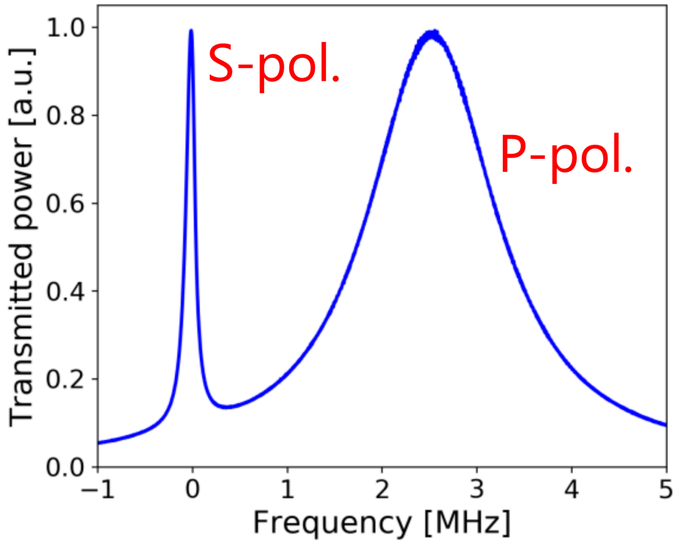
- First demonstration of dark matter axion search with a bow-tie optical ring cavity
- Upper limit was worse than target sensitivity by 7 orders of magnitude



- Improve classical noises → Reach current shot noise limit
- Improve observation time, input power, finesse
- Achieve simultaneous resonance between s-pol. and p-pol.

→ Reach target sensitivity

Resonant frequency difference
between s-pol. and p-pol.

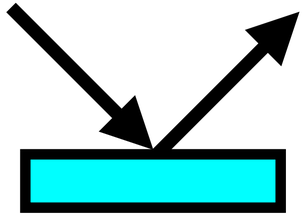


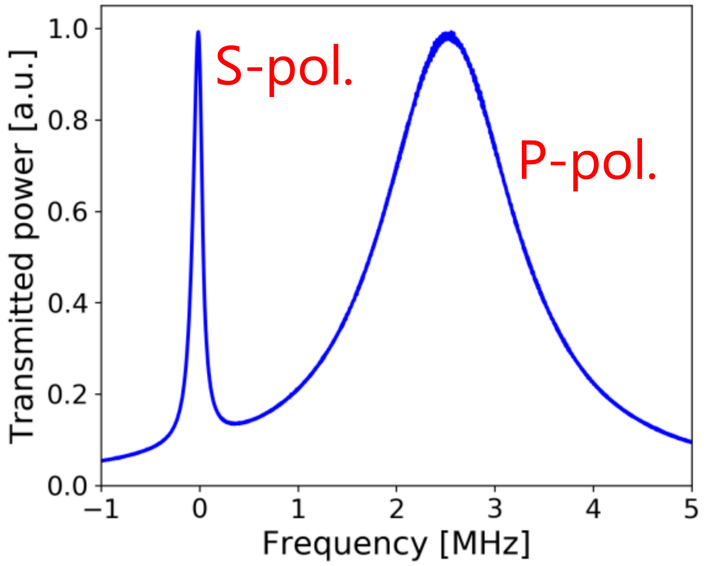
Simultaneous resonance

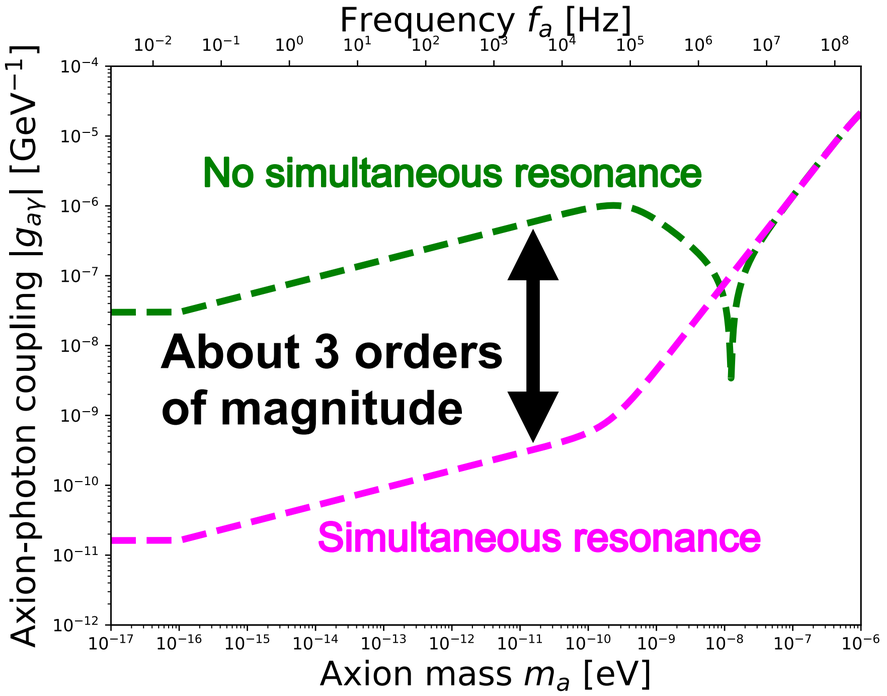
Oblique incidence → Resonant frequency difference → Degrades sensitivity

Reflection phase difference between s-pol. and p-pol.

$$\Delta\phi \neq 180 \text{ deg}$$







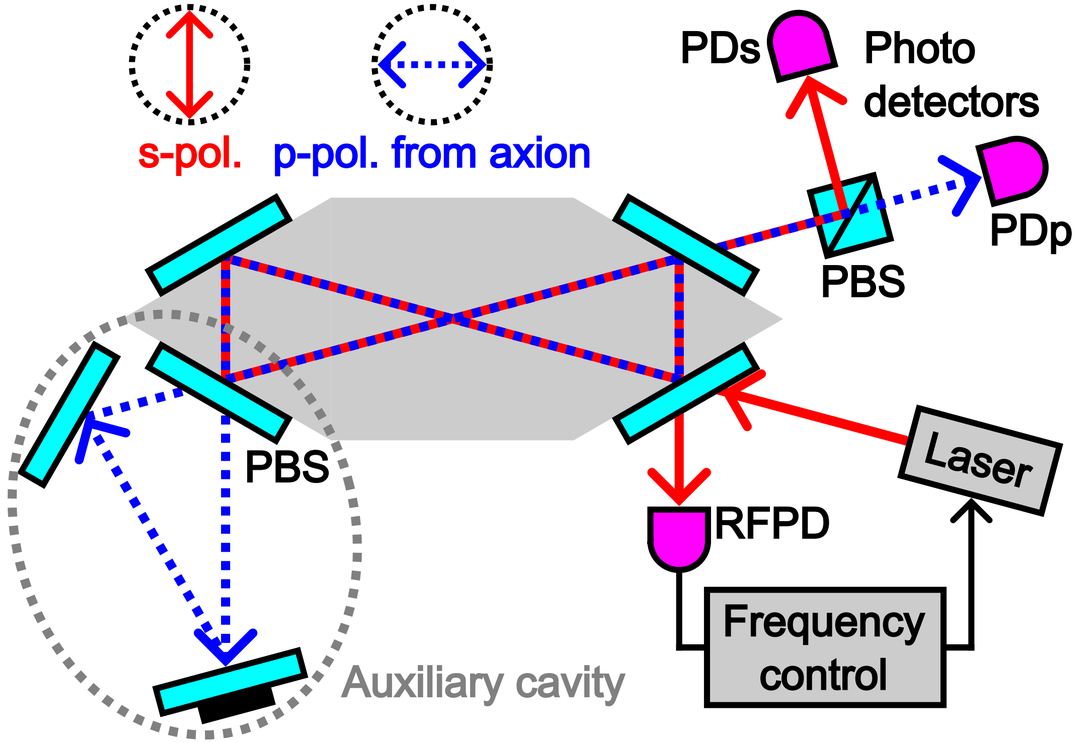
Simultaneous resonance is necessary to conduct a sensitive broadband axion search

① DANCE with an auxiliary cavity

② DANCE with zero-phase-shift mirror and ECDL

① DANCE with an auxiliary cavity

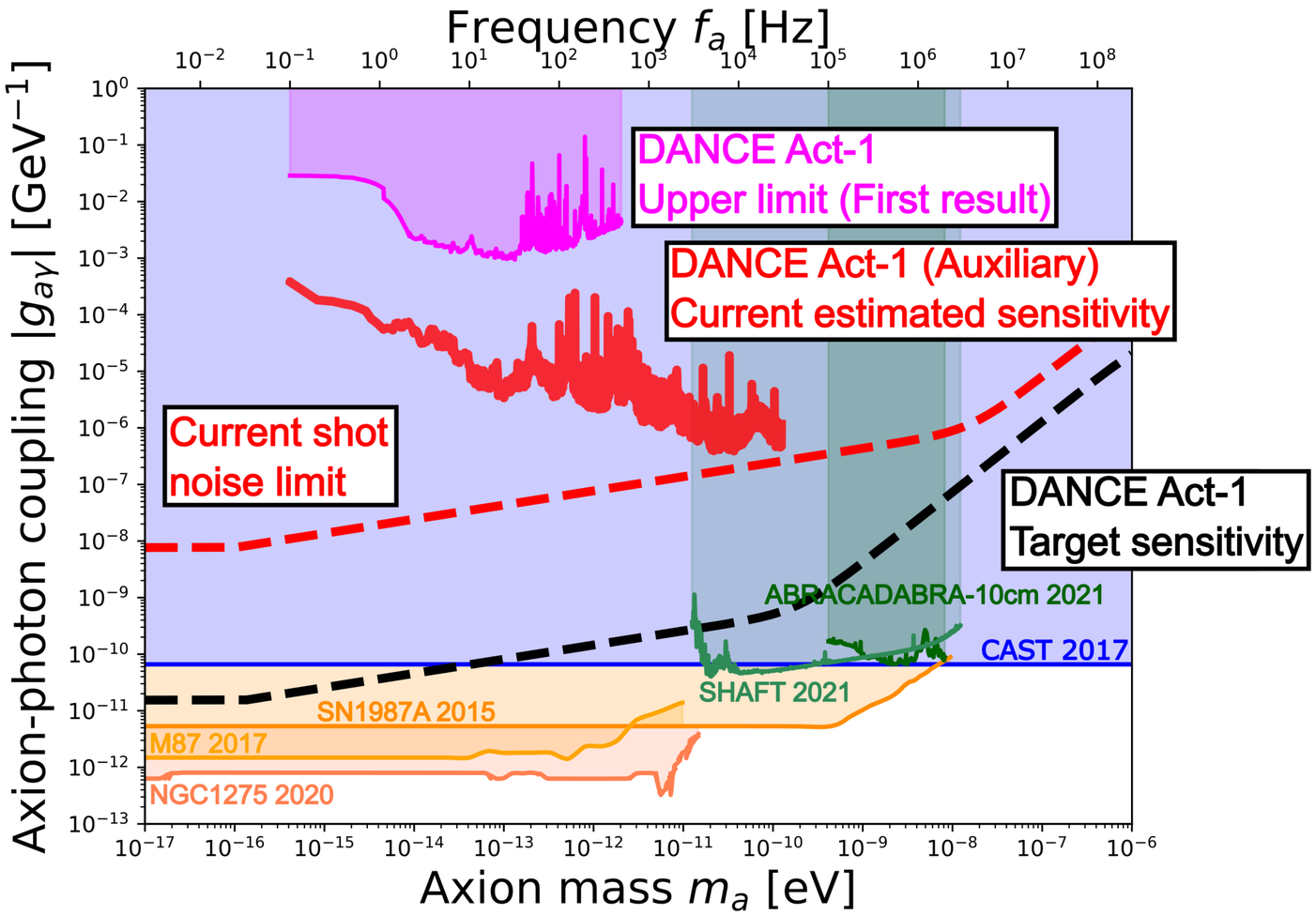
- Achieved simultaneous resonance for the first time in November 2021 by adding an auxiliary cavity to compensate for the reflection phase difference between s-pol. and p-pol.
- p-pol. is resonant in an auxiliary cavity by tuning PZT



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

① DANCE with an auxiliary cavity

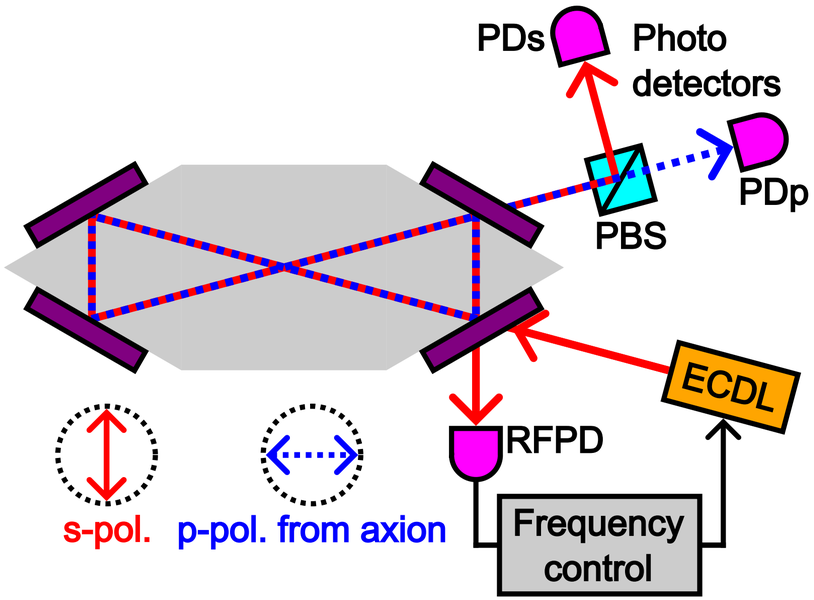
- Improved by more than 2 orders of magnitude than first results of DANCE Act-1
- Need to reduce the optical loss in an auxiliary cavity

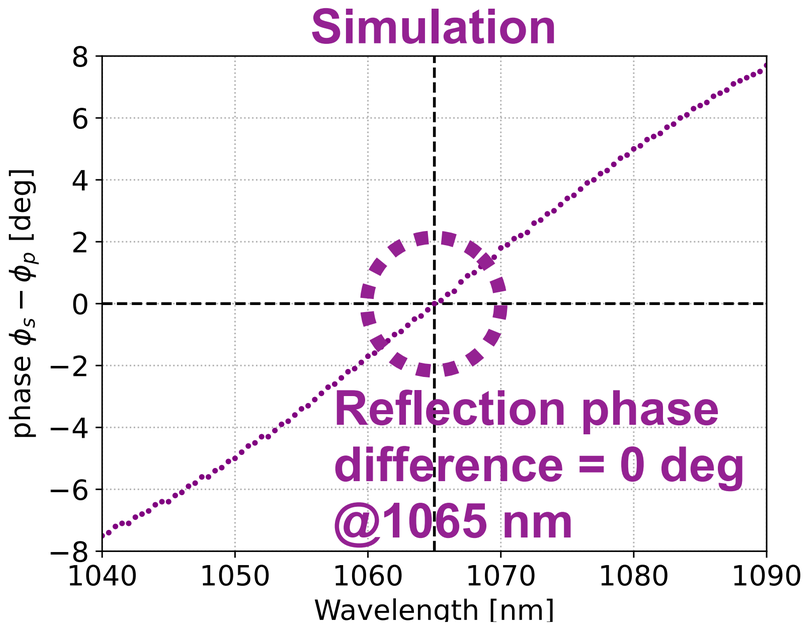


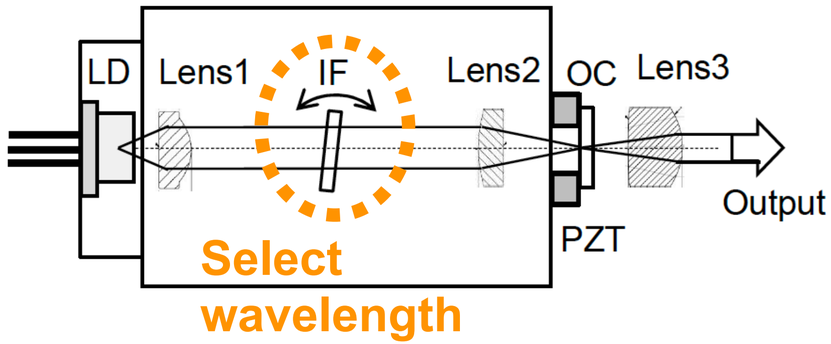
Input power	20 mW
Finesse (s-pol.)	549(3)
Finesse (p-pol.)	36.8(2)
Phase difference	0 deg

② DANCE with zero-phase-shift mirror and ECDL

New method of simultaneous resonance







ECDL (External Cavity Diode Laser)

- Wavelength range: 1037.5 - 1068 nm
- FWHM: 200 kHz
- Output: 20 - 50 mW

Zero-phase-shift mirror: Reflection phase difference between s-pol. and p-pol. is 0 deg at specific wavelength

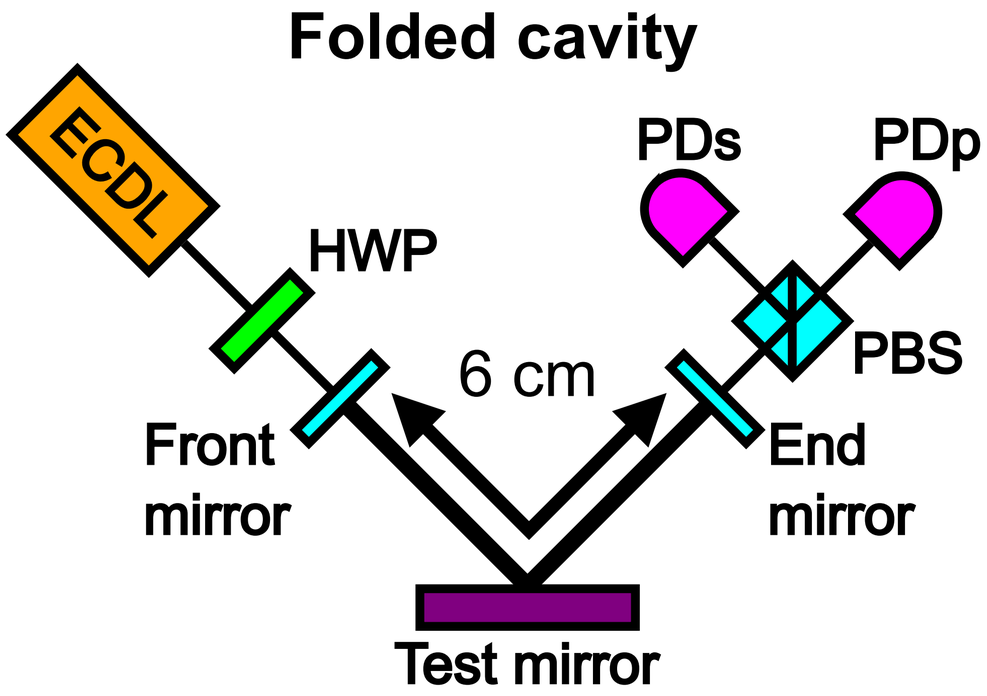
ECDL: Select wavelength by changing angle of IF

→ Tuning wavelength to cross point of zero-phase-shift mirror with an ECDL

② DANCE with zero-phase-shift mirror and ECDL

Evaluation of reflection phase difference between s-pol. and p-pol. of zero-phase-shift mirror with a folded cavity

1. Proof of principle of simultaneous resonance
2. Suppress time fluctuation of reflection phase difference which needs to conduct long term axion dark matter search



Measure reflection phase difference on a **zero-phase-shift mirror**

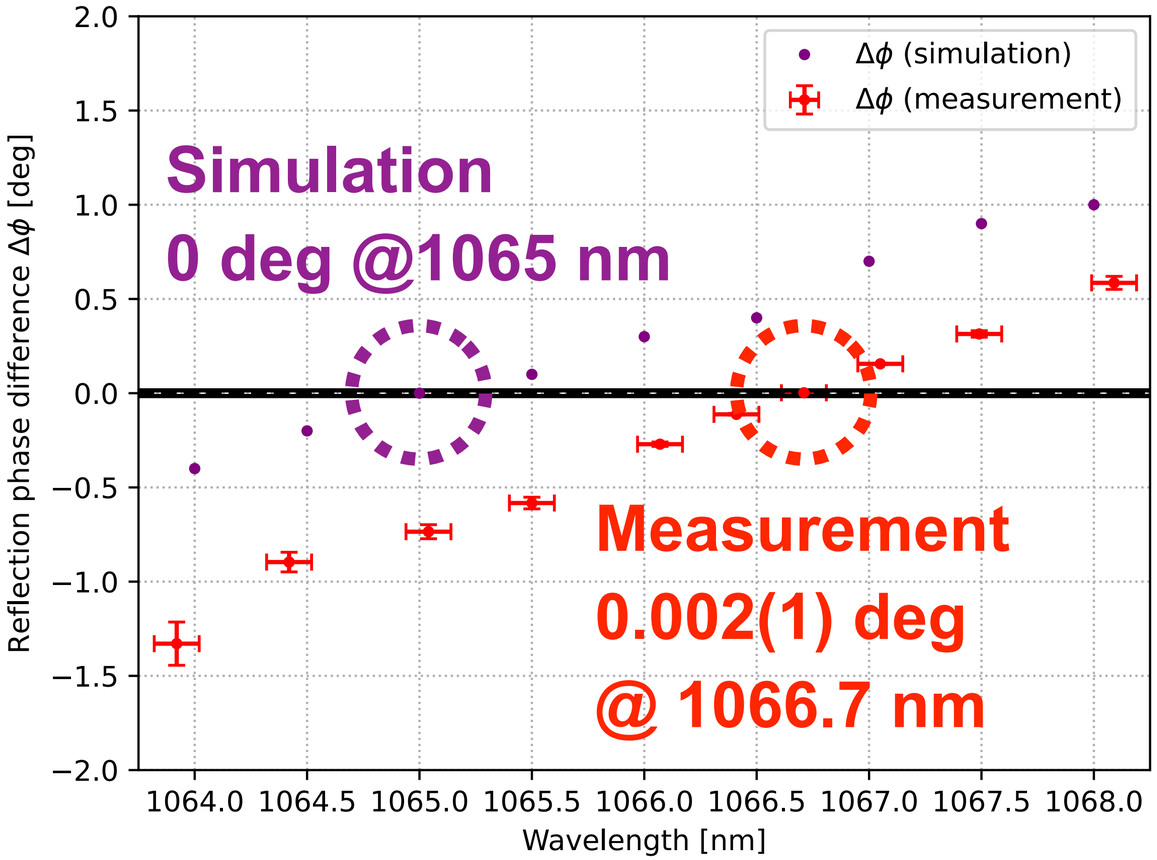
Mirror	Reflectivity	CC mm
Front	99%	50
End	99%	50
Test	s-pol.: 99.99%, p-pol.: 99.97%	1000

② DANCE with zero-phase-shift mirror and ECDL

1. Proof of principle of simultaneous resonance

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

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

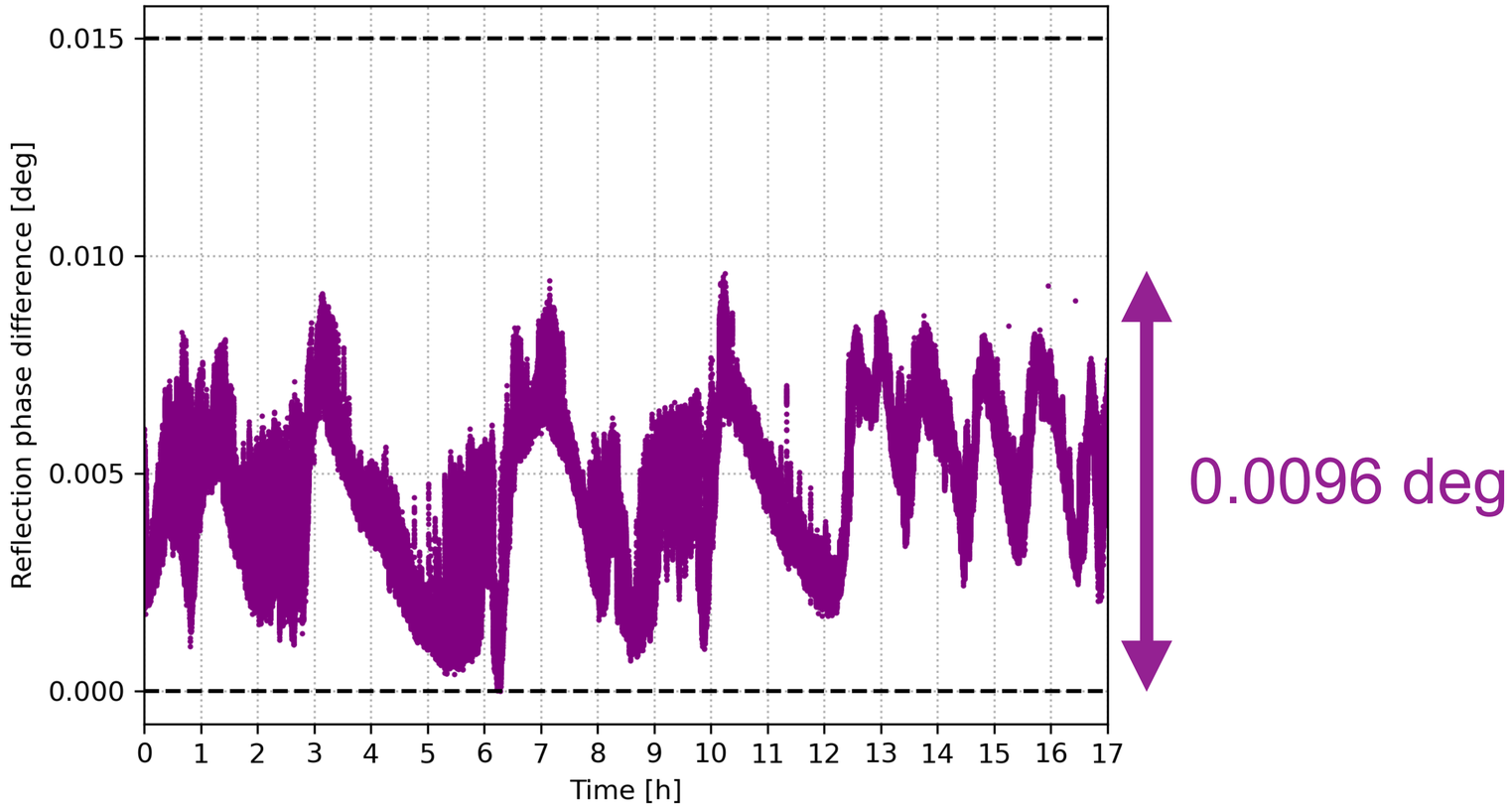


- Confirmed being able to achieve simultaneous resonance @ 1066.7 nm
- Satisfied requirement for simultaneous resonance

② DANCE with zero-phase-shift mirror and ECDL

2. Suppress time fluctuation of reflection phase difference which needs to conduct long term axion dark matter search

- Satisfied requirement $\Delta\phi \leq 0.015\ \mathrm{deg}$
- Investigating the cause of the fluctuation

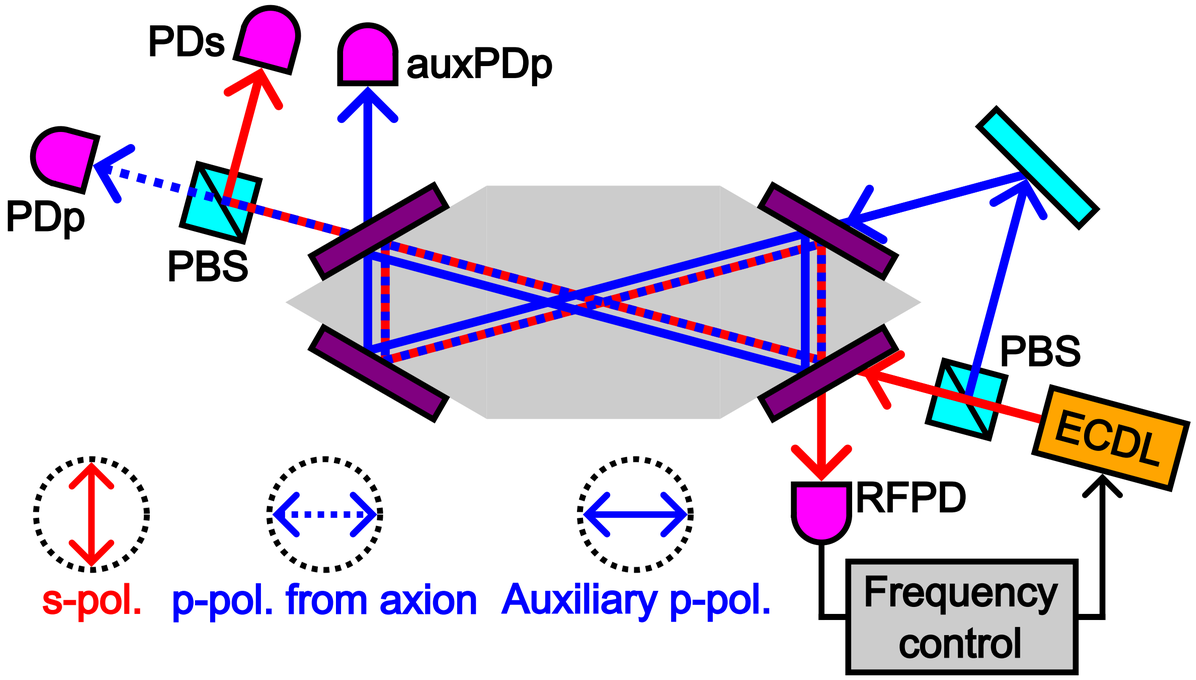


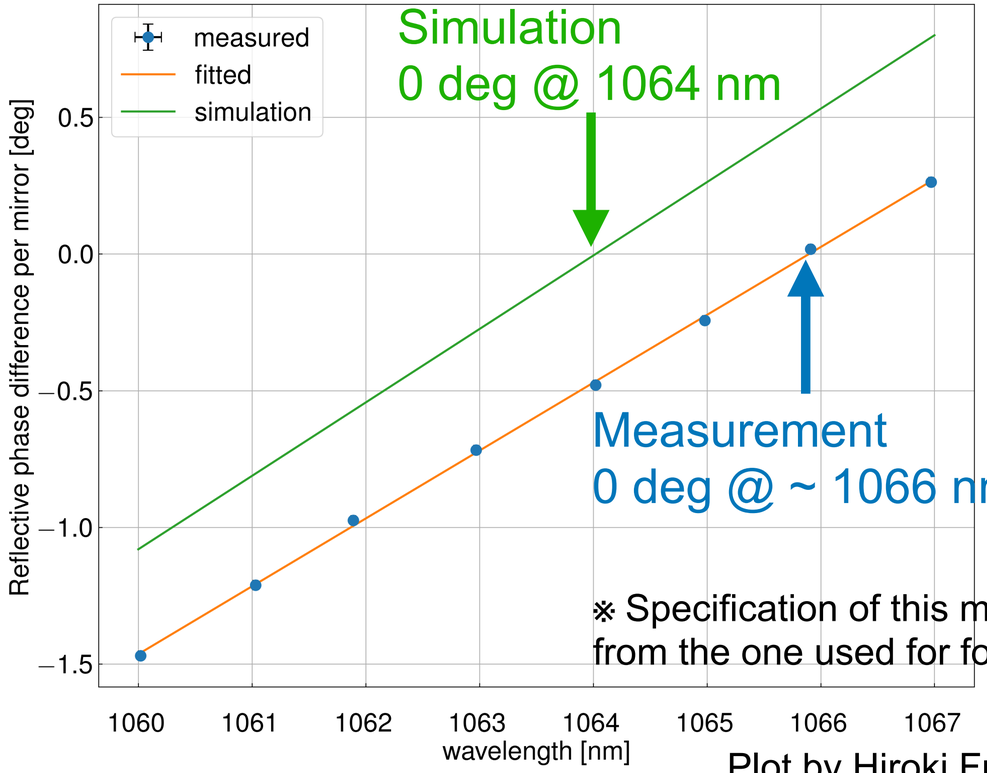
② DANCE with zero-phase-shift mirror and ECDL

Current status of DANCE with zero-phase-shift mirror and ECDL

- Measured reflection phase difference with a bow-tie optical ring cavity
- Able to achieve simultaneous resonance by tuning @ ~ 1066 nm

→ Tune the wavelength precisely to achieve simultaneous resonance





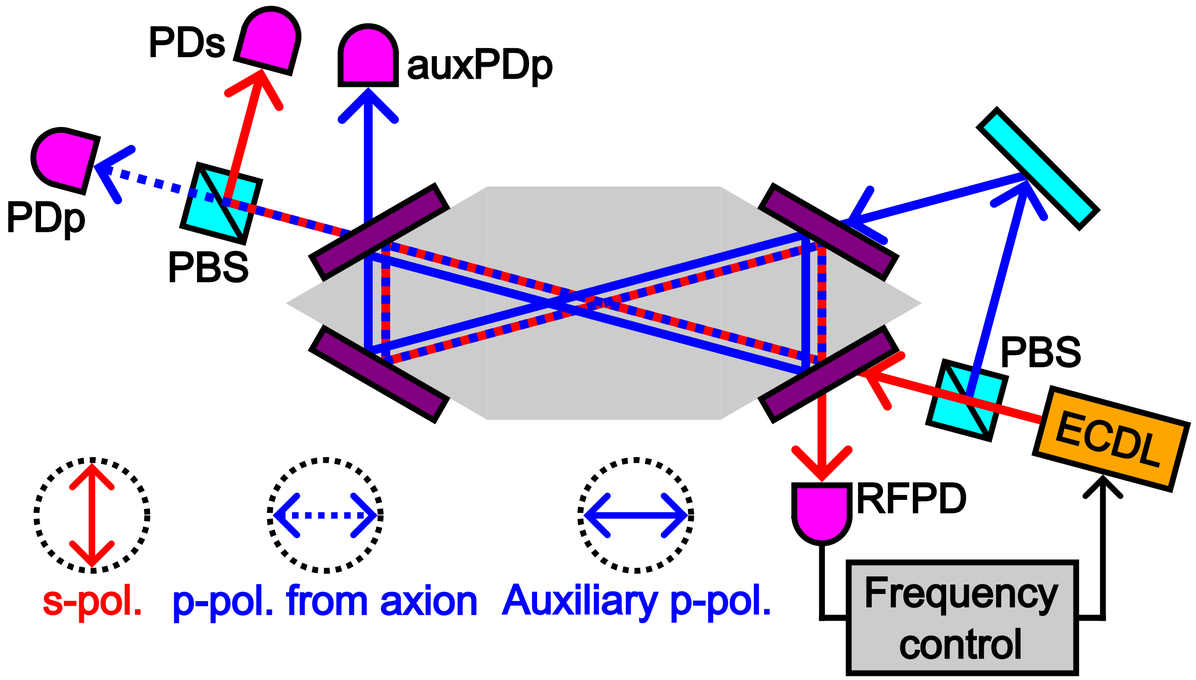
※ Specification of this mirror is different from the one used for folded cavity

Plot by Hiroki Fujimoto

② DANCE with zero-phase-shift mirror and ECDL

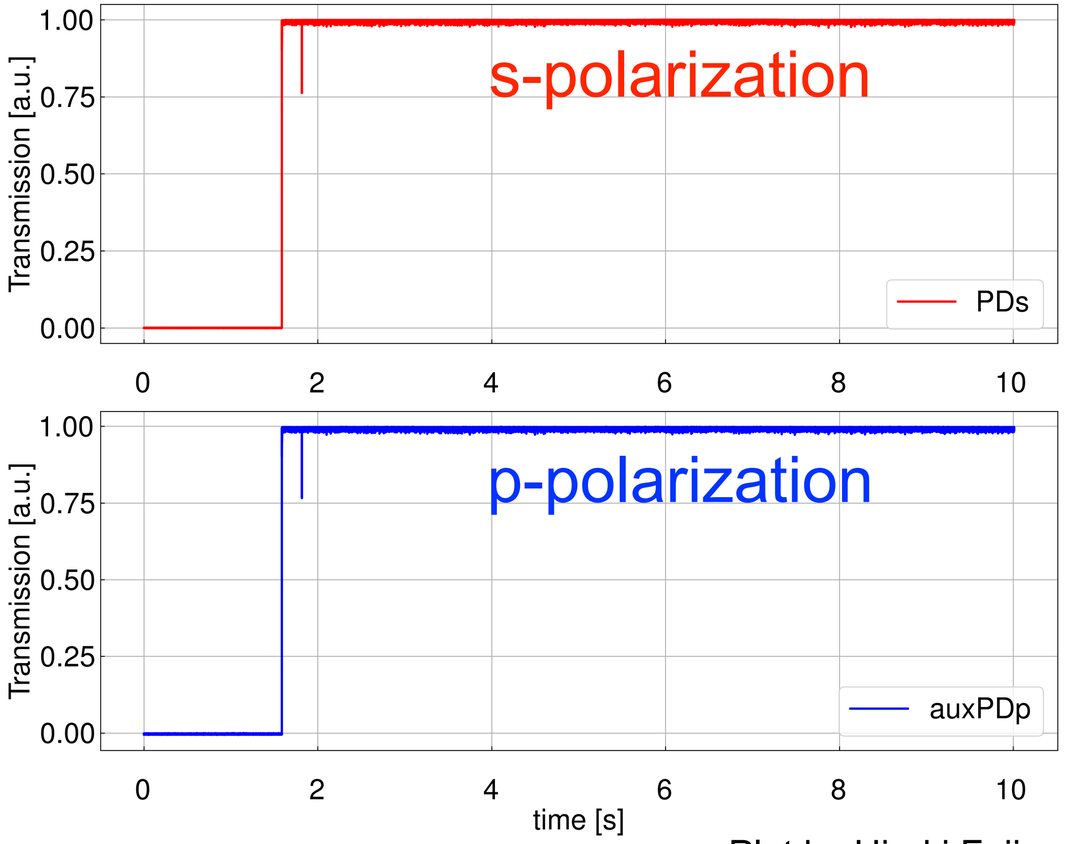
Current status of DANCE with zero-phase-shift mirror and ECDL

- Achieved simultaneous resonance @ 1065.84(2) nm
- Satisfied the design value of finesse



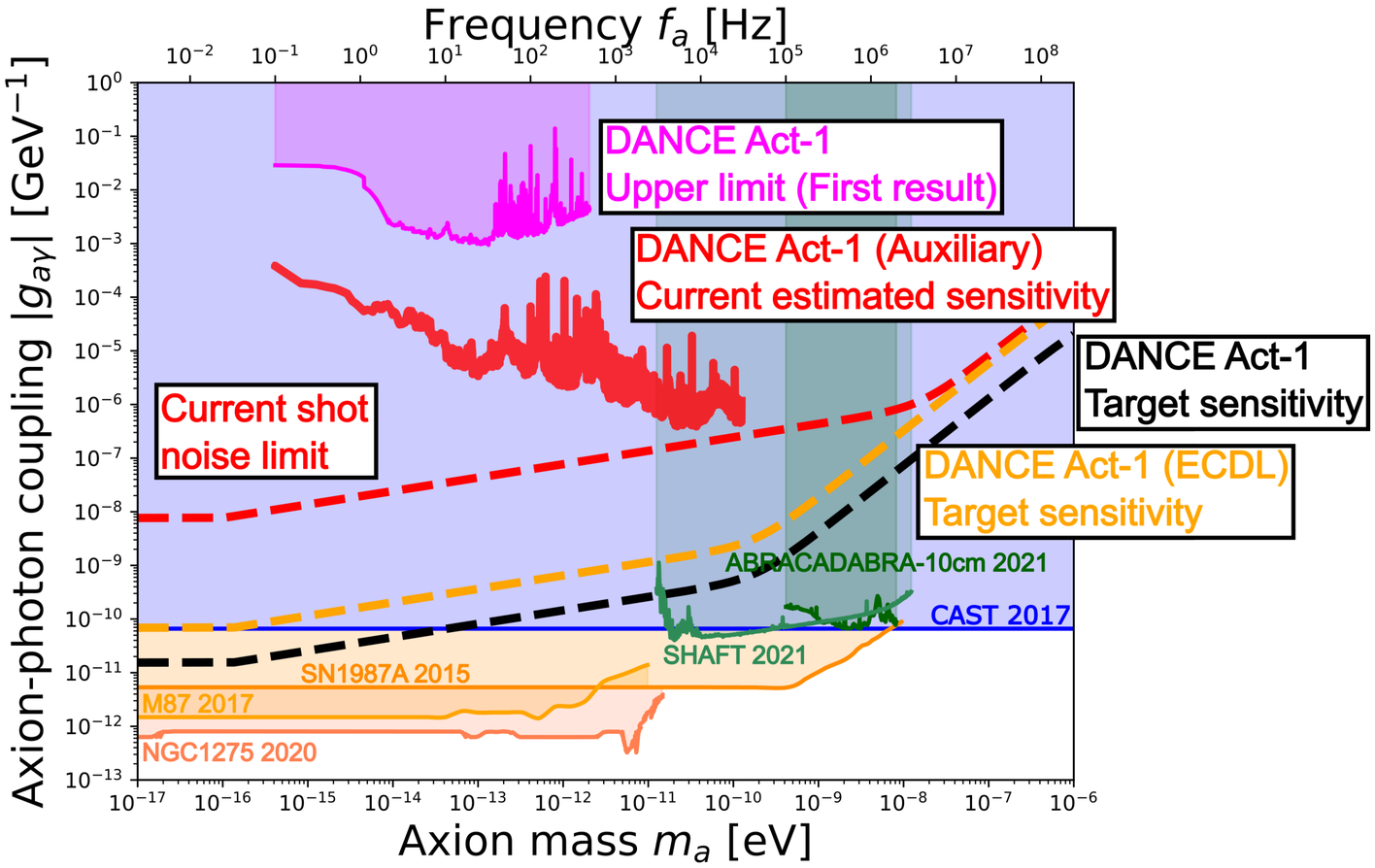
Finesse (s-pol.)	$3.82(19) \times 10^3$
Finesse (p-pol.)	$3.82(15) \times 10^3$

Transmission of s-pol. and p-pol.



Plot by Hiroki Fujimoto

Future plans for DANCE



- Investigating the cause of time fluctuation of reflection phase difference between s-pol. and p-pol. with a folded cavity
- Long term observation of DANCE with zero-phase-shift mirror and ECDL
- Introduce high power laser for DANCE (50 mW → 1 W)
  → 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
- Achieved simultaneous resonance with zero-phase-shift mirror and ECDL
- Aim to achieve the world's most sensitive dark matter axion search