Future plans for DANCE Act-1 / Automated alignment and mode-matching with machine learning

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Contents

◆Future plans for DANCE Act-1

- Dark matter search and DANCE
- Principle and target sensitivity of DANCE
- Current status of DANCE Act-1
- Future plans / Research topics
  ① Improvement of shot noise limit
  ② Reduction of noise
  ③ Automated cavity locking system
  ④ Investigation of the resonant frequency difference
  ⑤ Simultaneous resonance with wavelength tunable laser

◆Automated alignment and mode-matching with machine learning

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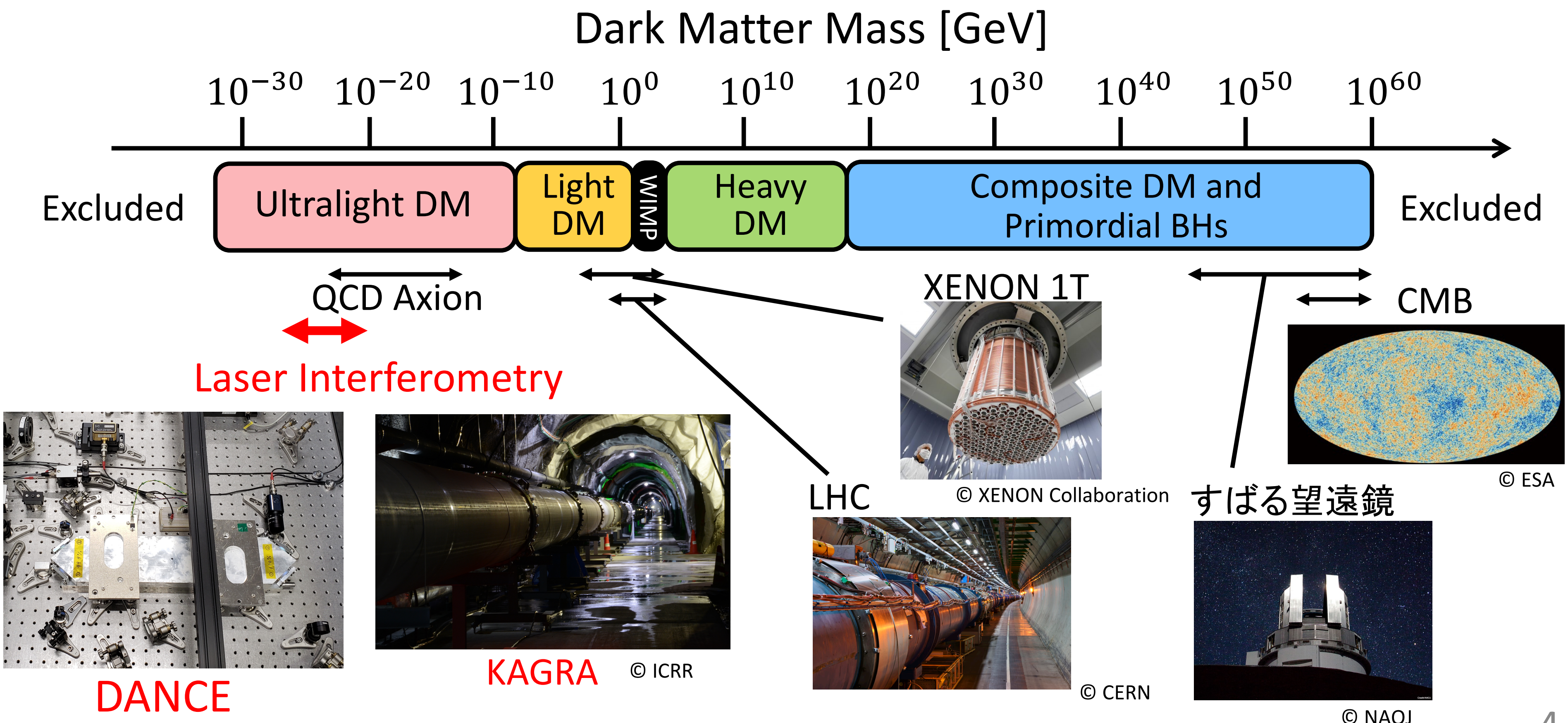
Dark matter search and DANCE

- More than 80% of the universe's matter is unknown
  ⇒Dark matter
- Dark matter search experiment by interferometer
- DANCE searches for axion-like particle (ALP) dark matter



Axion-like particles (ALPs)

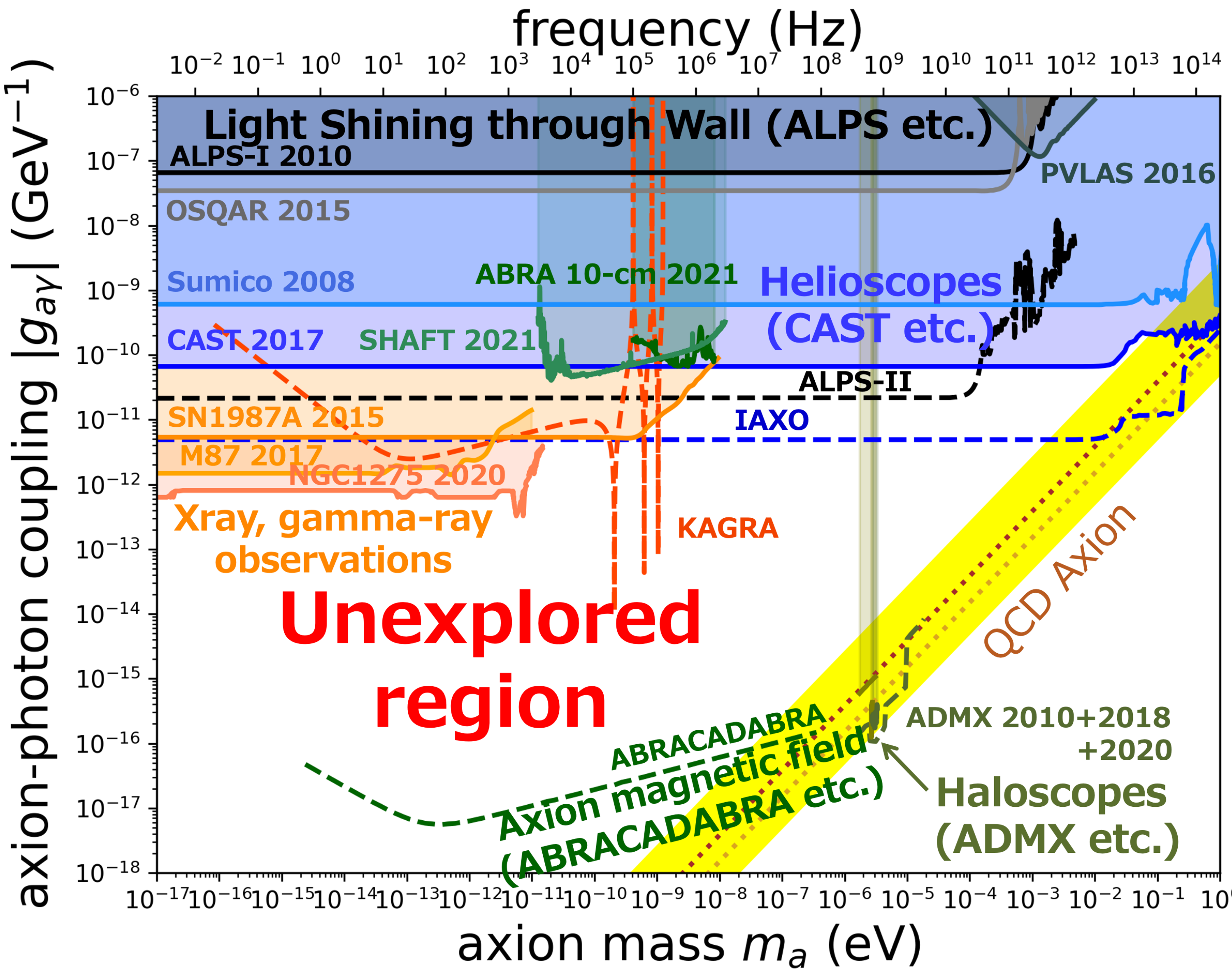
- Undiscovered particles predicted from string theory (originally predicted from QCD as QCD axion)

- One of the dark matter candidates

- Slightly interact with photon

DANCE aims to detect this interaction with laser

Previous researches



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Axion-photon interaction

Axion-photon interaction causes phase velocity difference

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

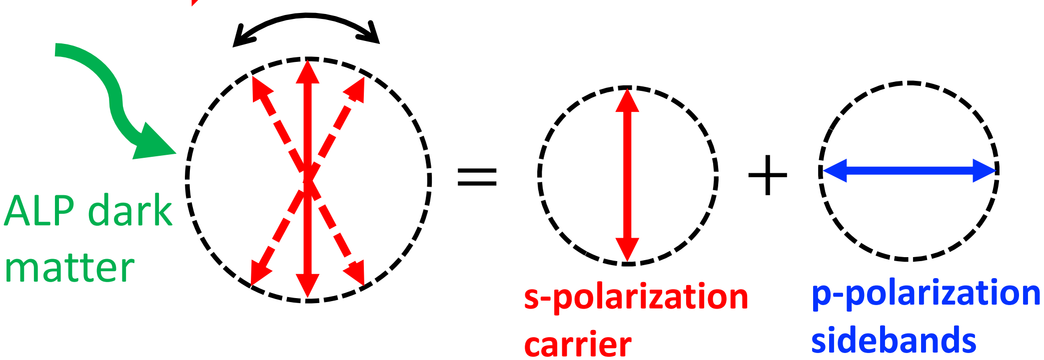
Left-/Right-handed polarization

Axion-photon coupling constant

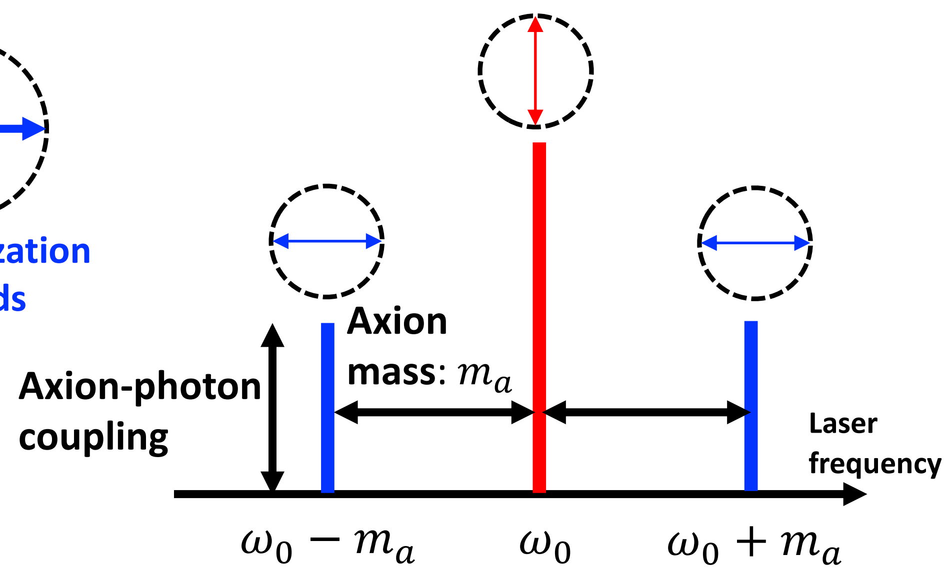
Axion field

Axion mass

Rotational oscillation of linearly polarized light

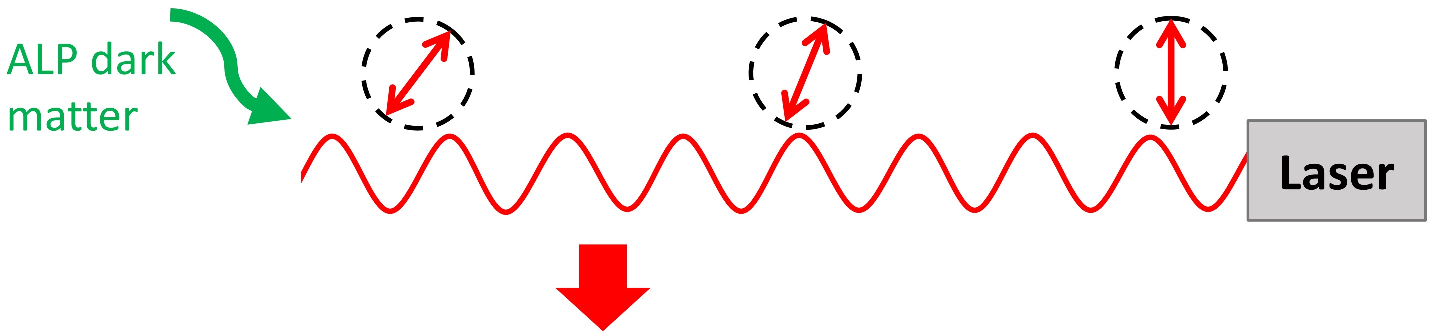


Axion signal is produced as p-polarization



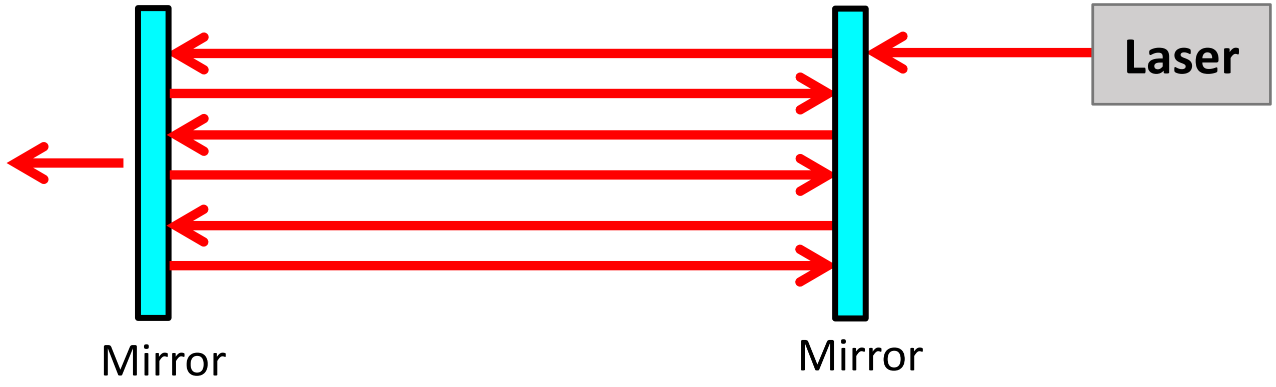
Principle of DANCE

- Rotational amplitude becomes large as light path increases



Need to enhance the light path for sensitive search

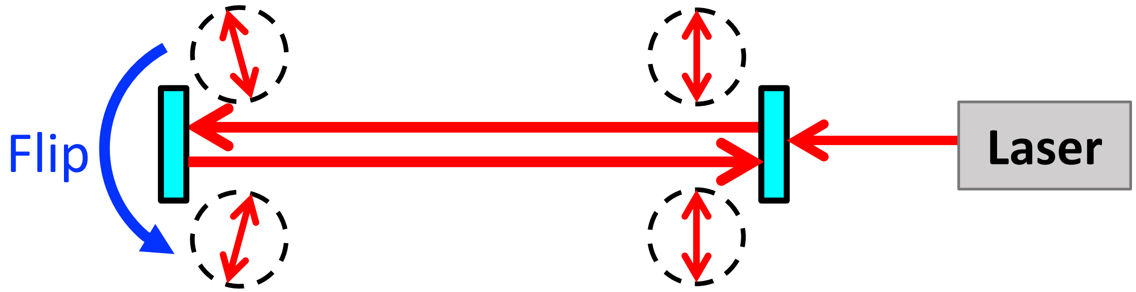
- Optical cavity can enhance the light path



Principle of DANCE

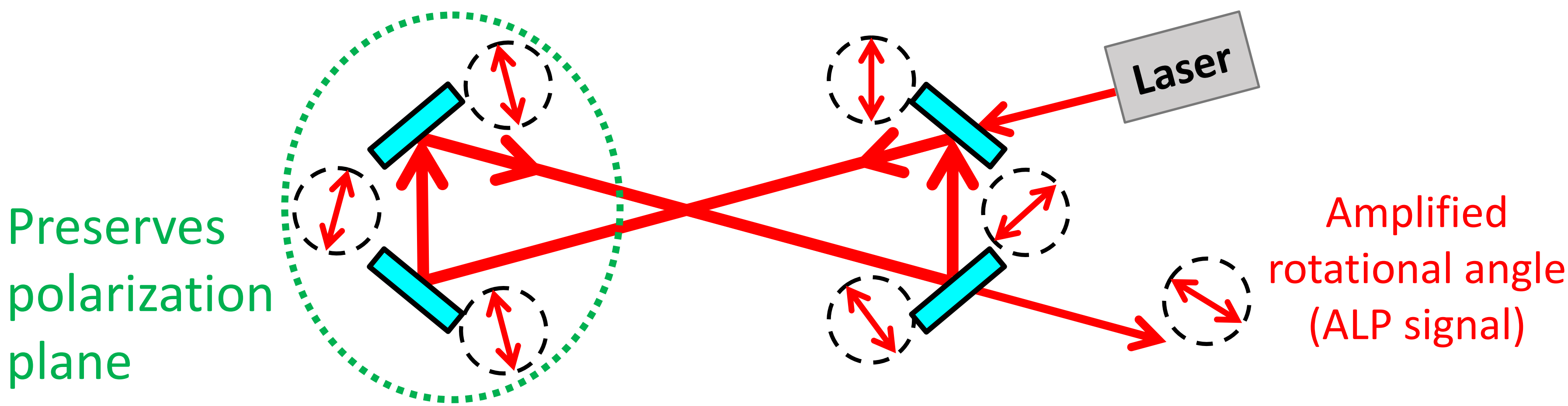
- Linear cavity

Plane of polarization flips by reflection ⇒ cancels rotation



- Bow-tie ring cavity [1]

Two reflections prevent polarization flip ⇒ enhances rotational angle



[1] I. Obata, T. Fujita, and Y. Michimura: Phys. Rev. Lett. 121, 161301 (2018).

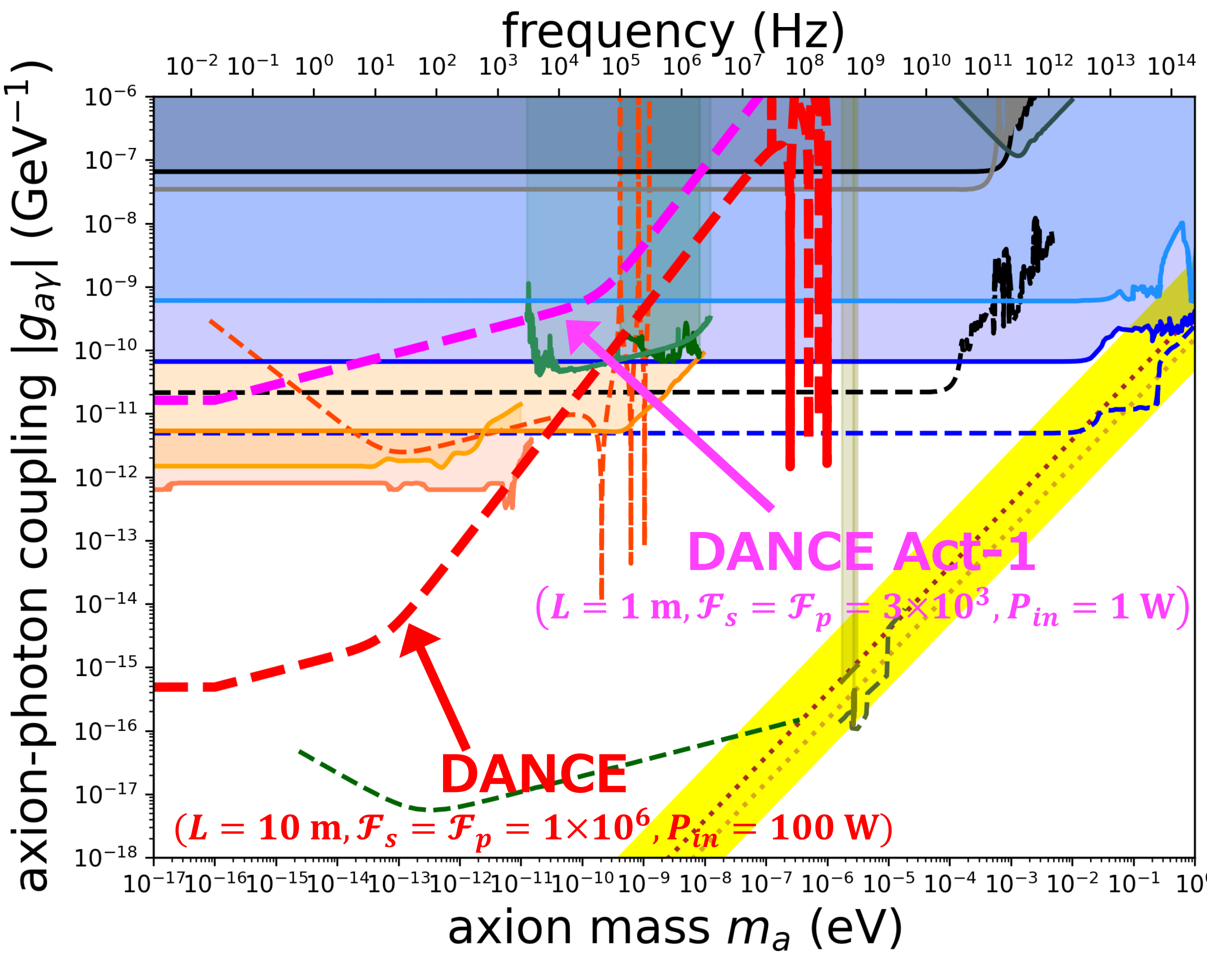
Target sensitivity of DANCE

Parameters of DANCE

- L: Round-trip length
- F: Finesse (number of round trips)
- P_{in}: Input laser power

lengthen light path

improve shot noise



Shot noise limit in one-year observation

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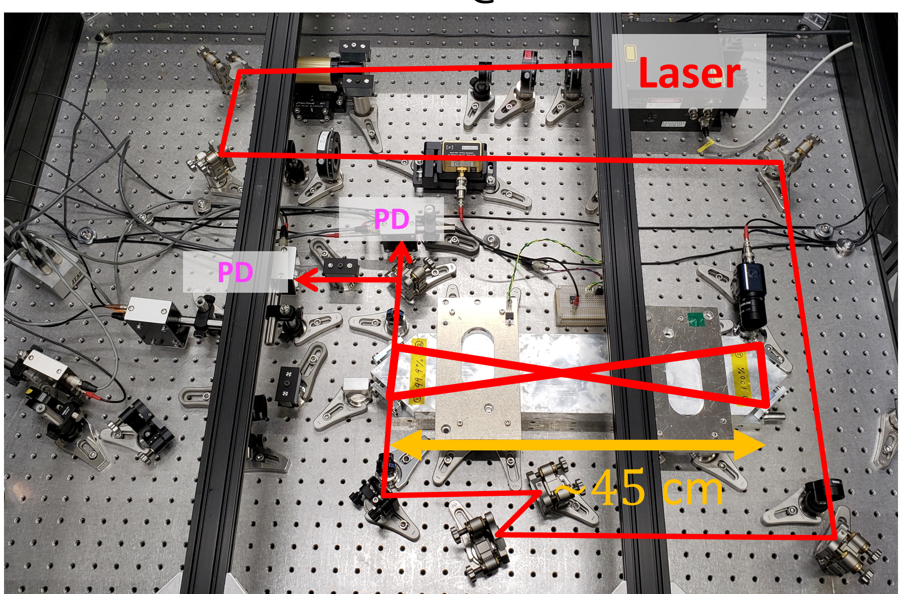
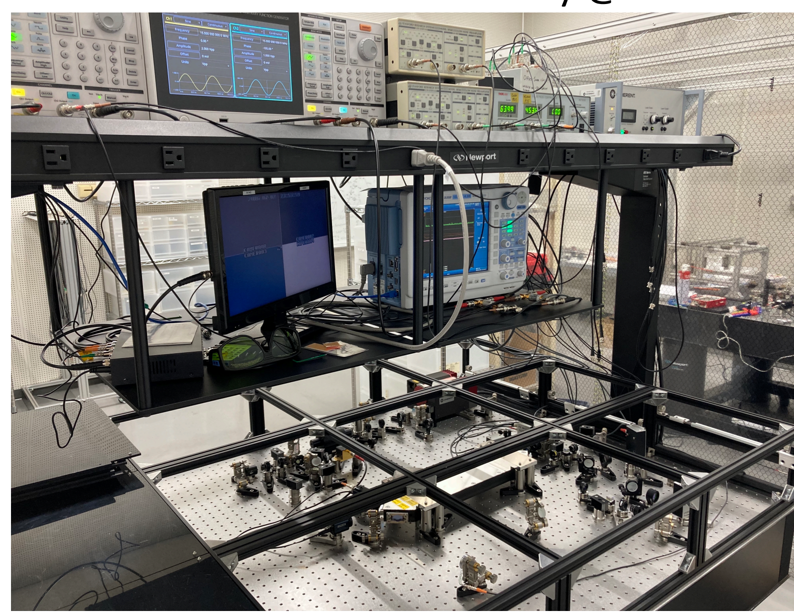
DANCE Act-1

- Prototype experiment for
  - ➢identifying technical issues ⇒ resonant frequency difference
  - ➢proof of principle
- Feasible parameters (Round-trip length = 1 m,
  Designed finesse = 3000, Input laser power = 1 W)
- DANCE Act-1 with auxiliary cavity ⇒ my master thesis

DANCE Act-1 @ B207

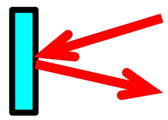


DANCE Act-1 with aux. cavity @ B111



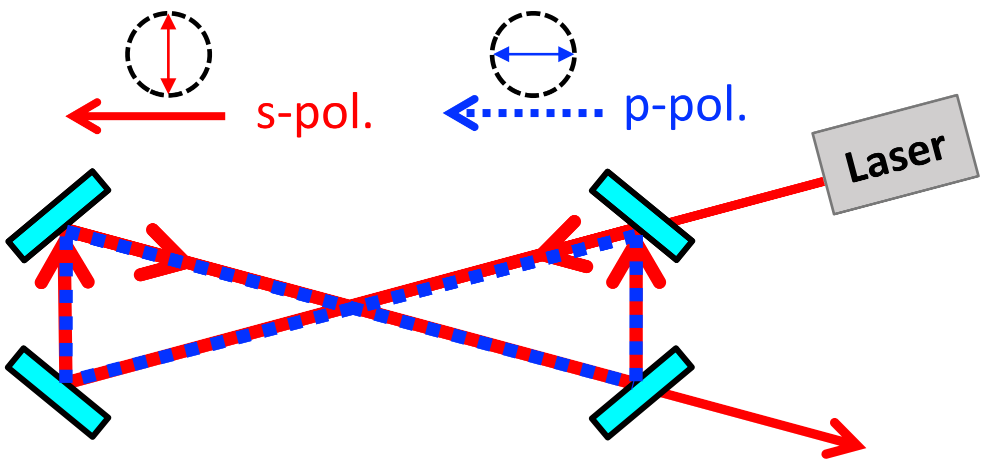
Issue –Resonant frequency difference–

- There is resonant frequency difference between s-pol. and p-pol. (3 MHz in DANCE Act-1)

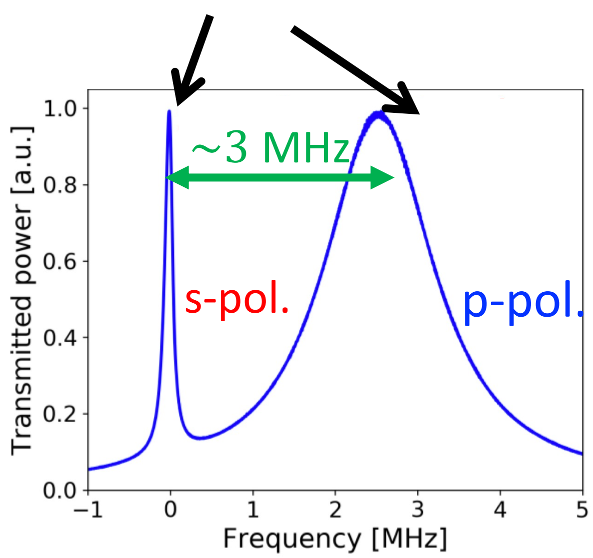


Reflective phase difference in oblique incidence seems the cause.

s-pol. and p-pol. can not resonate simultaneously

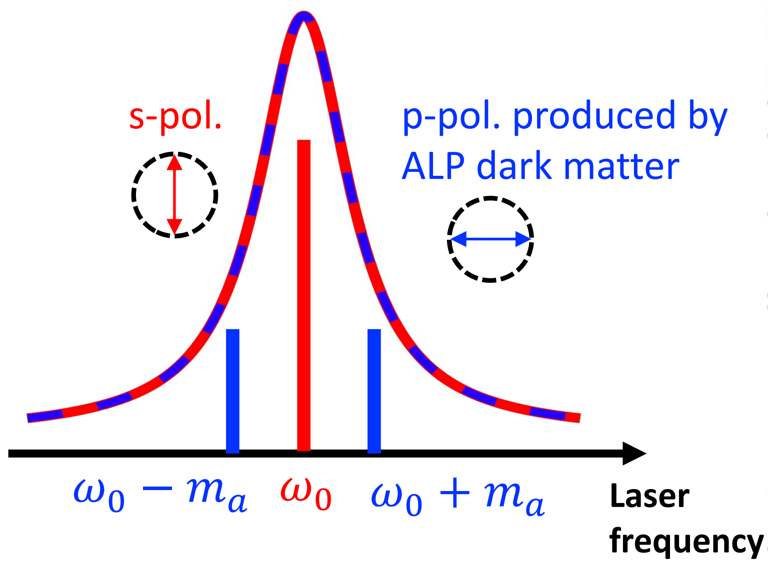


Resonant peaks

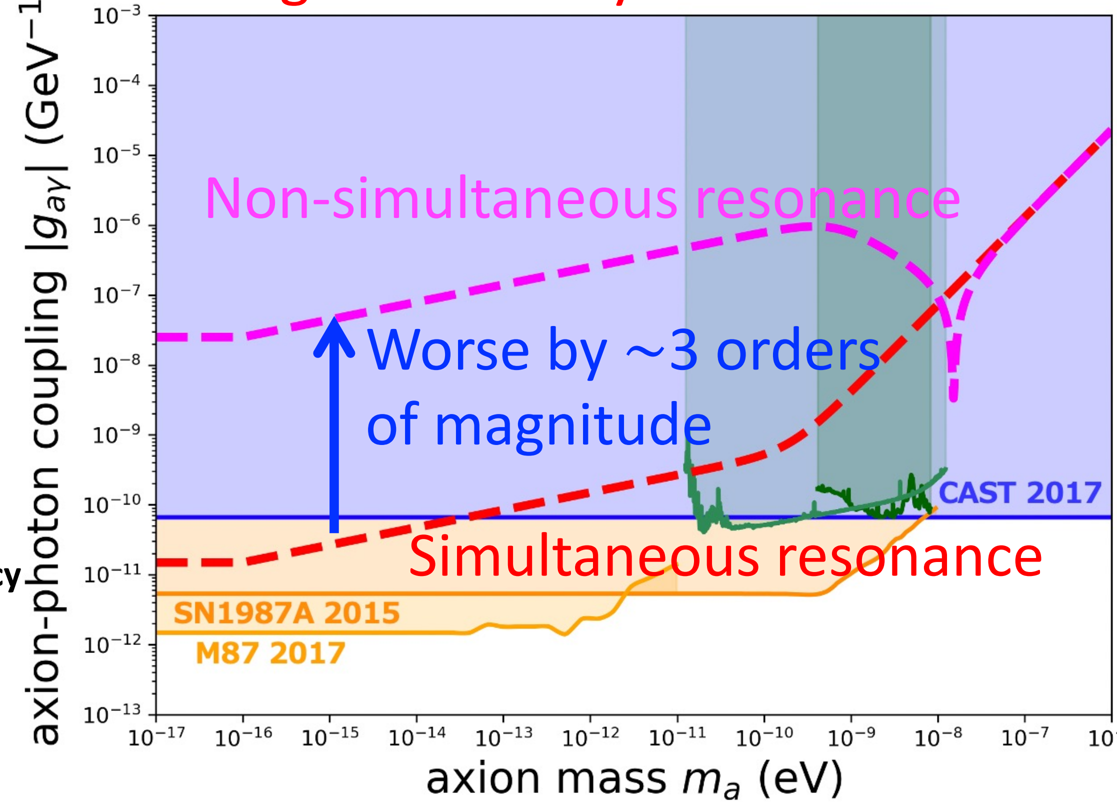


Degradation of sensitivity

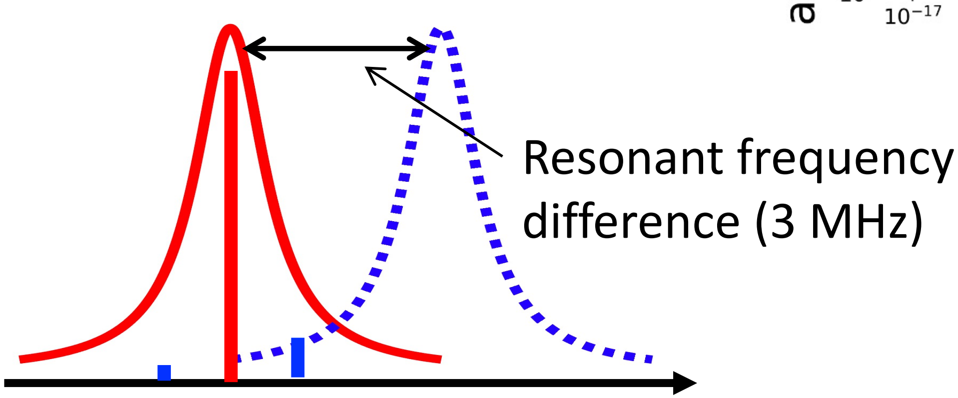
Simultaneous resonance



Target sensitivity of DANCE Act-1



Non-simultaneous resonance



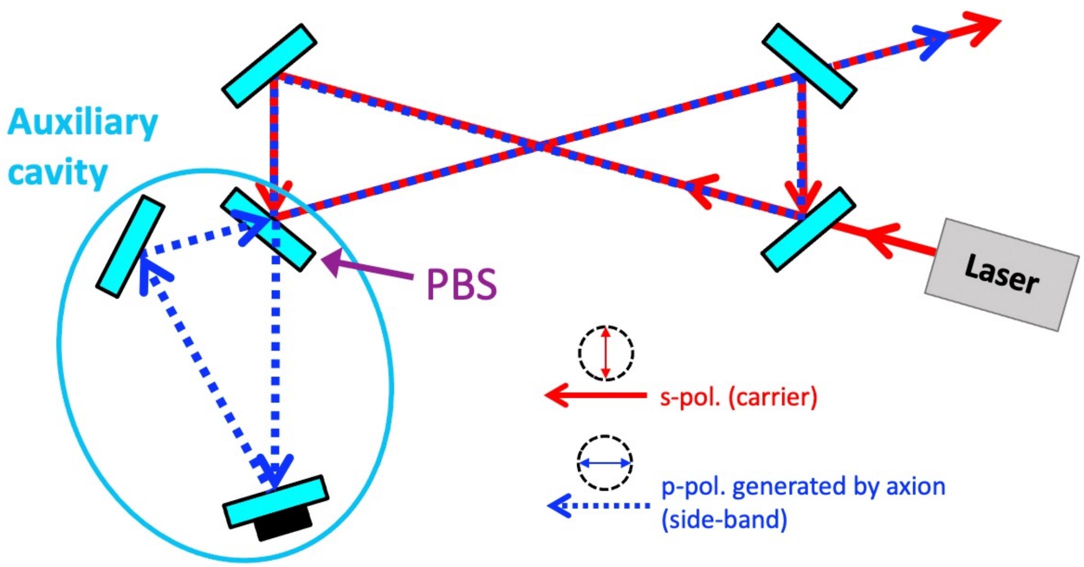
Simultaneous resonance is necessary for high sensitivity

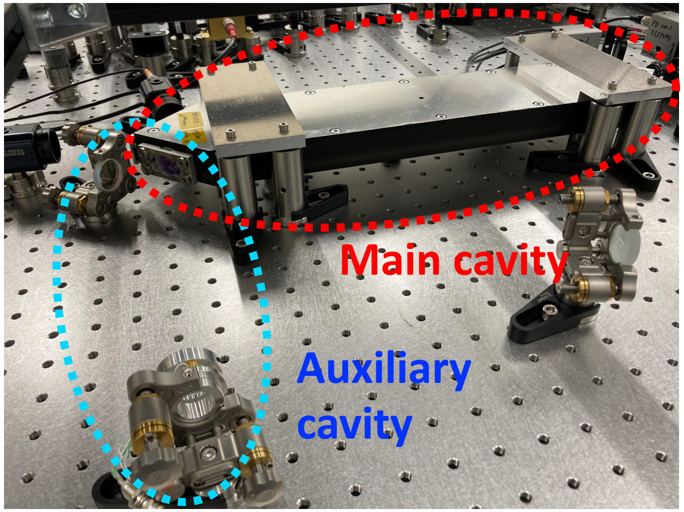
Auxiliary cavity for simultaneous resonance

- Auxiliary cavity can control the phase difference between s- and p-pol. [2, 3]

Resonant frequency difference can be cancelled out

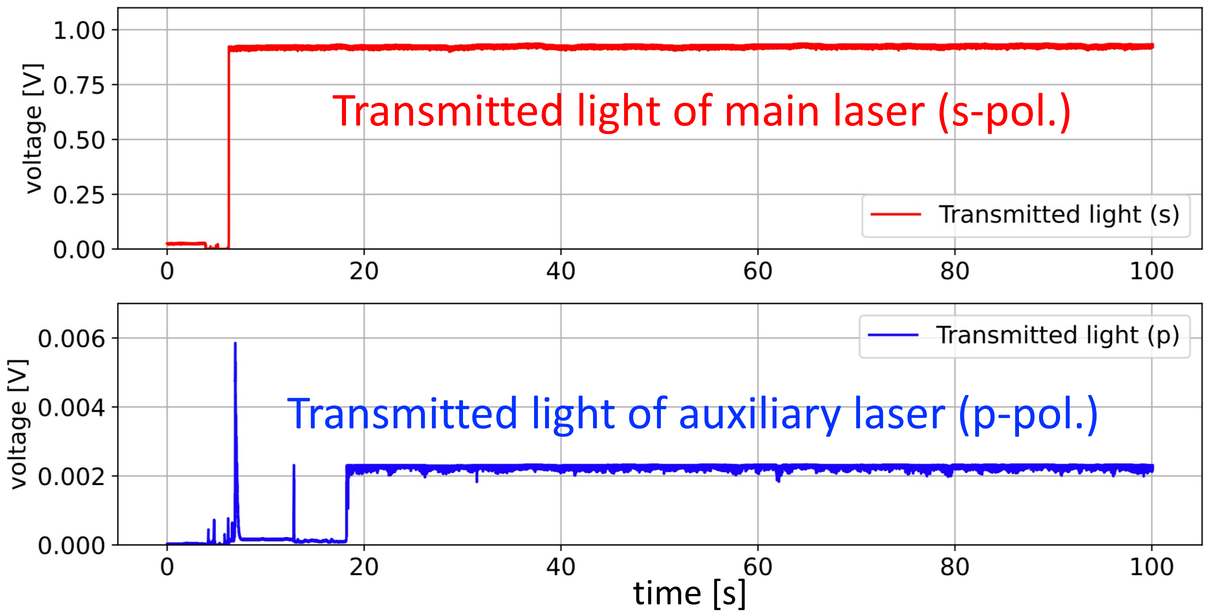
- Realized auxiliary cavity with PBS method for my master thesis
- Finesse : $\mathcal{F}_s = 1204 \pm 12$, $\mathcal{F}_p = 91 \pm 2$



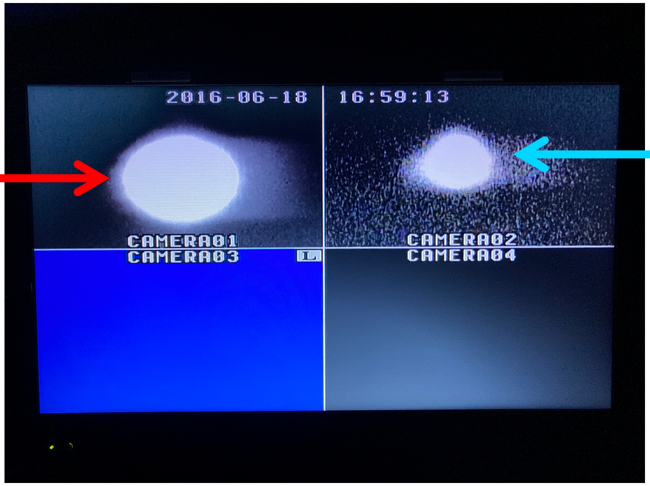


[2] D. Martynov and H. Miao: *Phys. Rev. D* **101**, 095034 (2020) [3] H. Fujimoto *et al.*: arXiv:2110.12023

Simultaneous resonance of s- and p-pol.



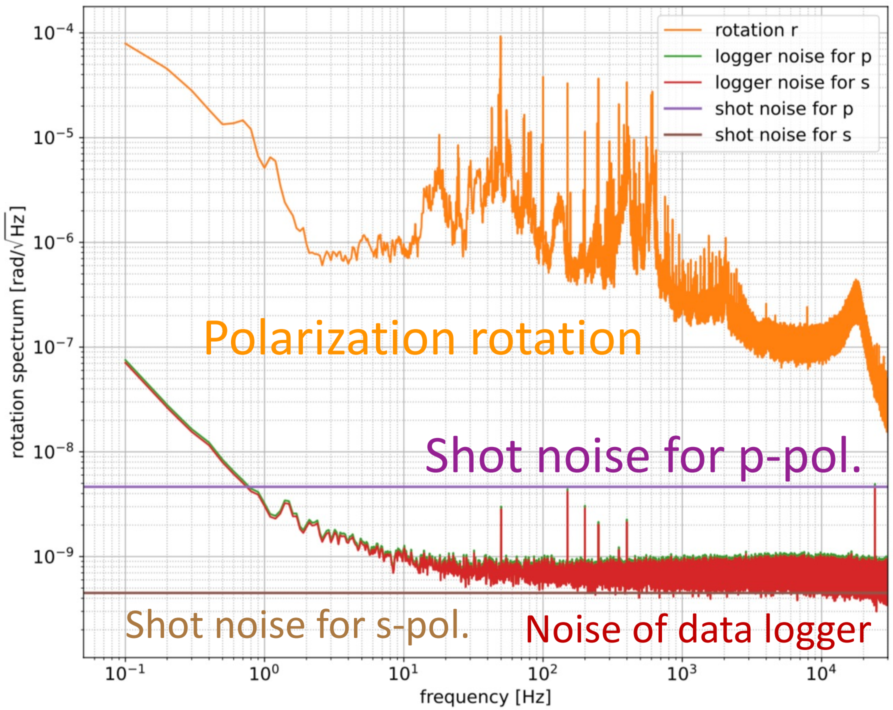
Transmitted light of main laser (s-pol.)

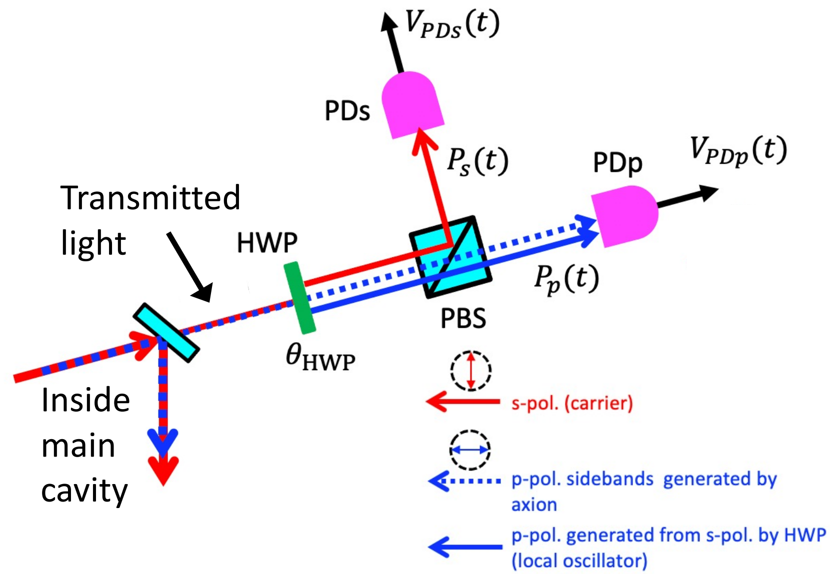


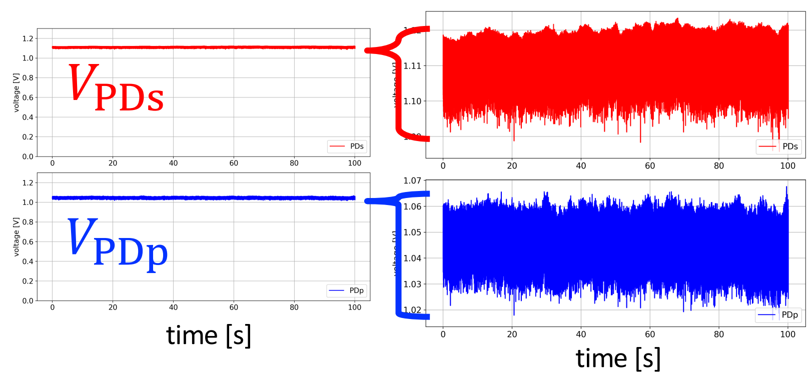
Transmitted light of auxiliary laser (p-pol.)

Power spectrum of polarization rotation

- Measured the rotational angle of the transmitted light

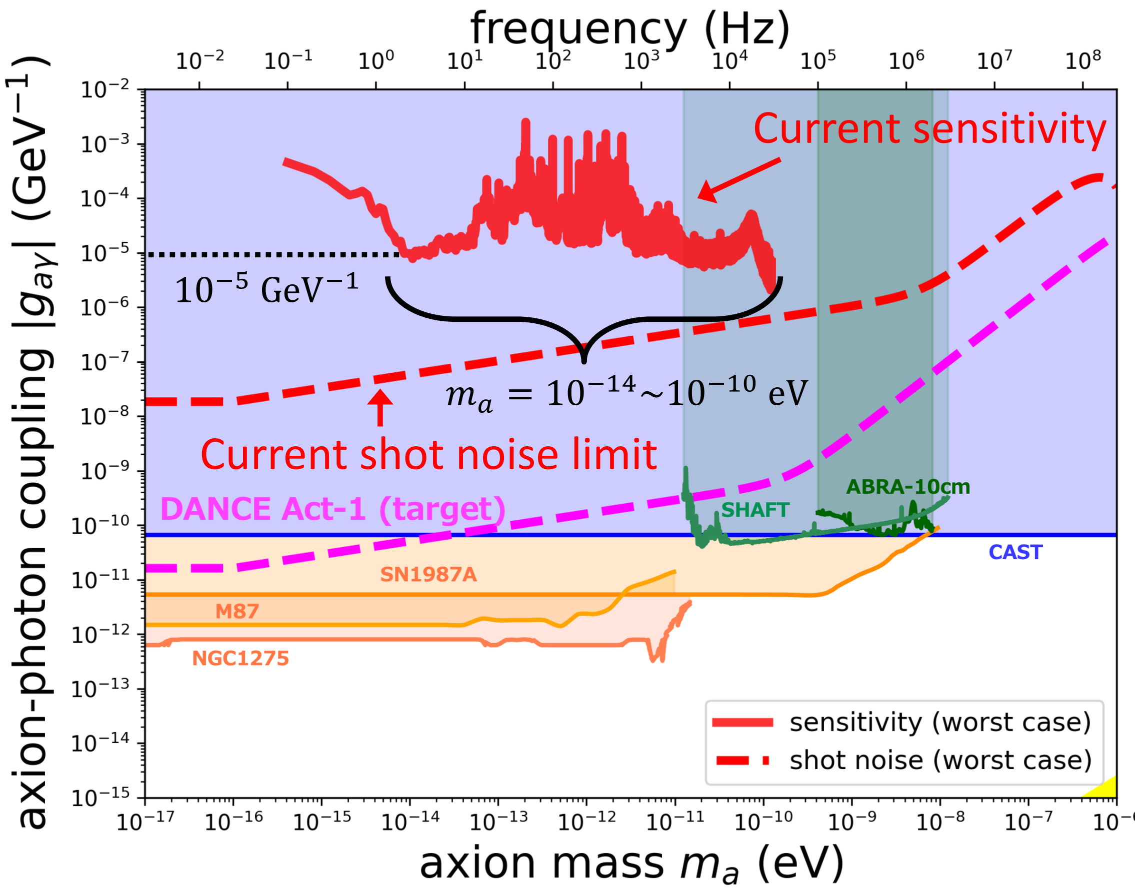






- Current noise is larger than shot noise by 1~3 orders of magnitude

Estimated sensitivity



- Axion dark matter with $m_a = 10^{-14}\sim10^{-10}$ eV, $g_{a\gamma} >\sim 10^{-5}$ GeV^{-1} can be detectable
- $\sim$5 orders of magnitude larger than CAST limit

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① Improvement of shot noise limit
- ➢Replacement of PBS for higher finesse
- ➢High power laser

② Reduction of noise
- ➢Removal of p-pol. from input laser
- ➢Removal of parasitic resonance of actuator

③ Automated cavity locking system

④ Investigation of the resonant frequency difference

⑤ Simultaneous resonance with wavelength tunable laser

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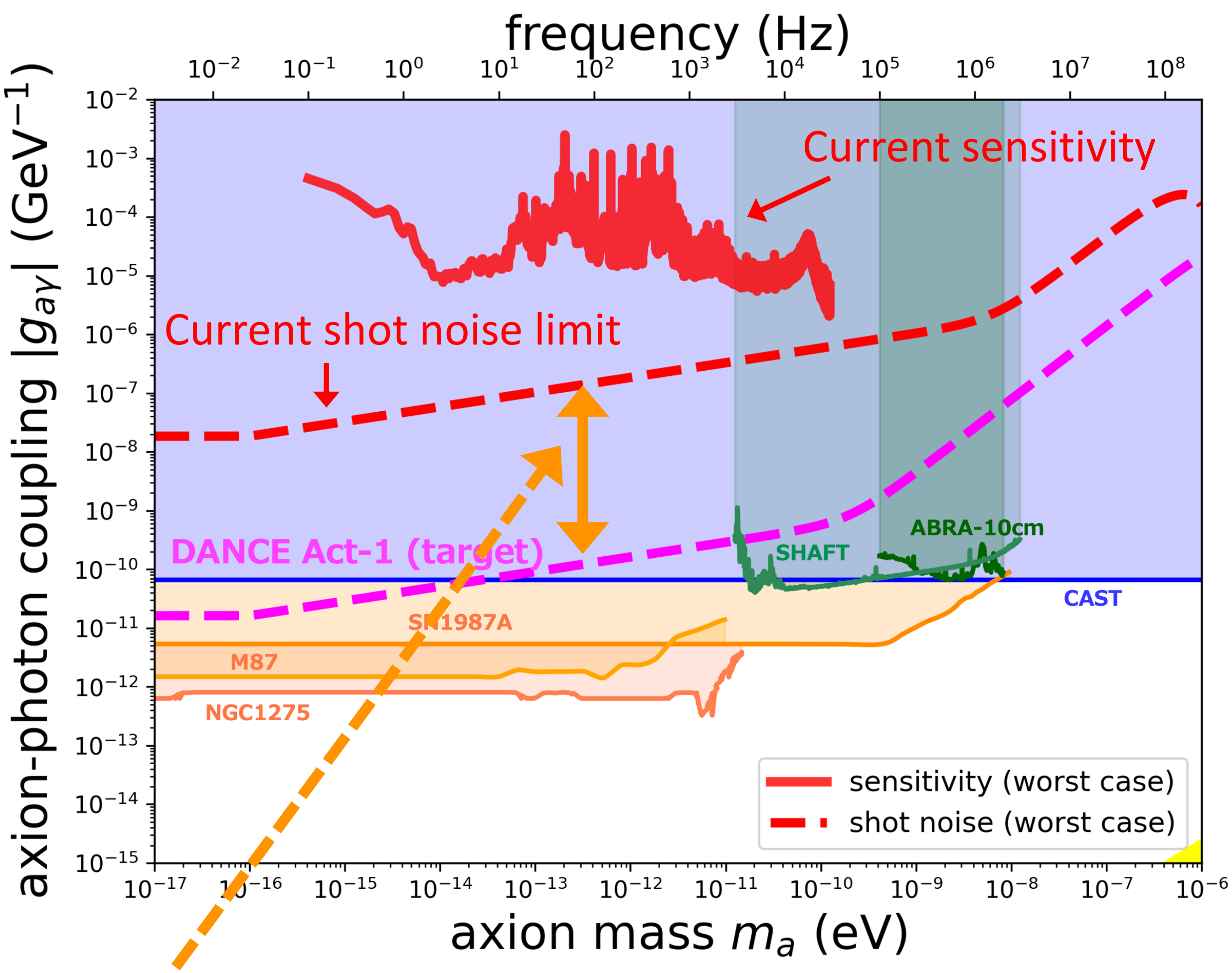
① Improvement of shot noise limit



Current shot noise is ~3 orders of magnitude larger than target sensitivity

① Improvement of shot noise limit

	$\mathcal{F}_s$	$\mathcal{F}_P$	P_{in}
Target value	3000	3000	$1\ \mathrm{W}$
Design value	2985 ± 6	551 ± 137	$21.4 \pm 0.9\ \mathrm{mW}$
Measured value	1204 ± 12	91 ± 2	$21.4 \pm 0.9\ \mathrm{mW}$

Loss at auxiliary cavity degraded reflectivity of aux. cavity: $R_{\text{aux},s} = 99.7 \pm 0.1\%$, $R_{\text{aux},p} = 93.5 \pm 0.2\%$ (degrade sensitivity by ~2 orders of magnitude)

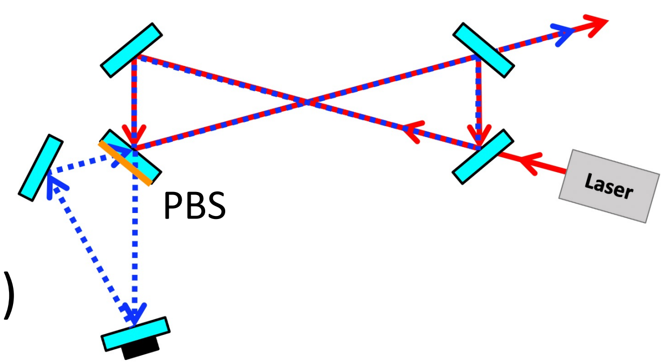
- Incorrect incident angle for PBS
- No AR coating on PBS

Input power was limited for ease (degrade sensitivity by ~1 order of magnitude)

Future improvements

- Input high power (2 W)
- Replace PBS (for 42° incidence with AR coating)

$\Rightarrow \mathcal{F}_s : 1204 \Rightarrow \sim 3000?$, $\mathcal{F}_p : 91 \Rightarrow \sim 600?$



Future plans / Research topics

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- Replacement of PBS for higher finesse
- High power laser

② Reduction of noise
- Removal of p-pol. from input laser
- Removal of parasitic resonance of actuator

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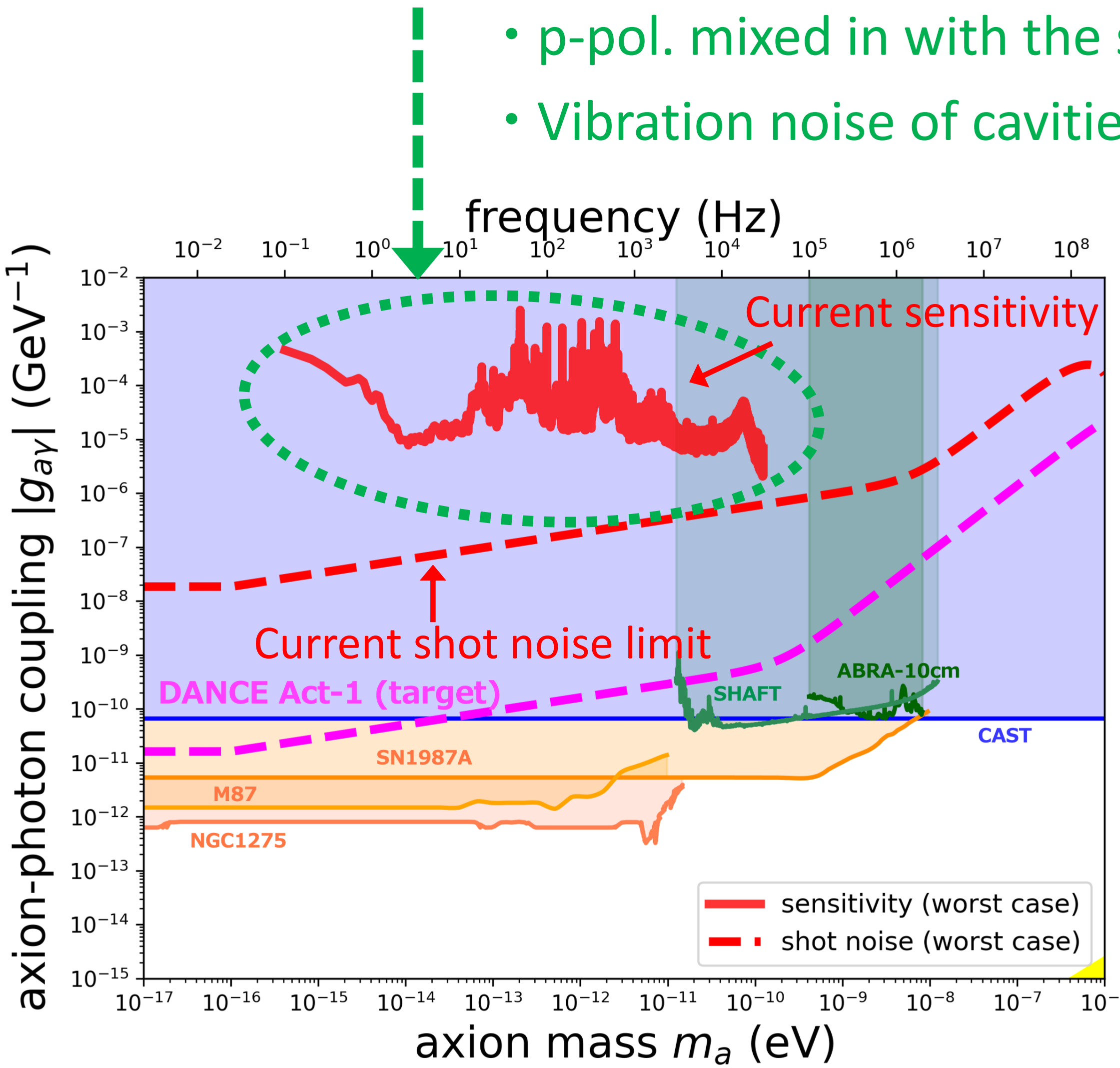
② Reduction of noise

Current noise sources:

- p-pol. mixed in with the s-pol. input
- Vibration noise of cavities



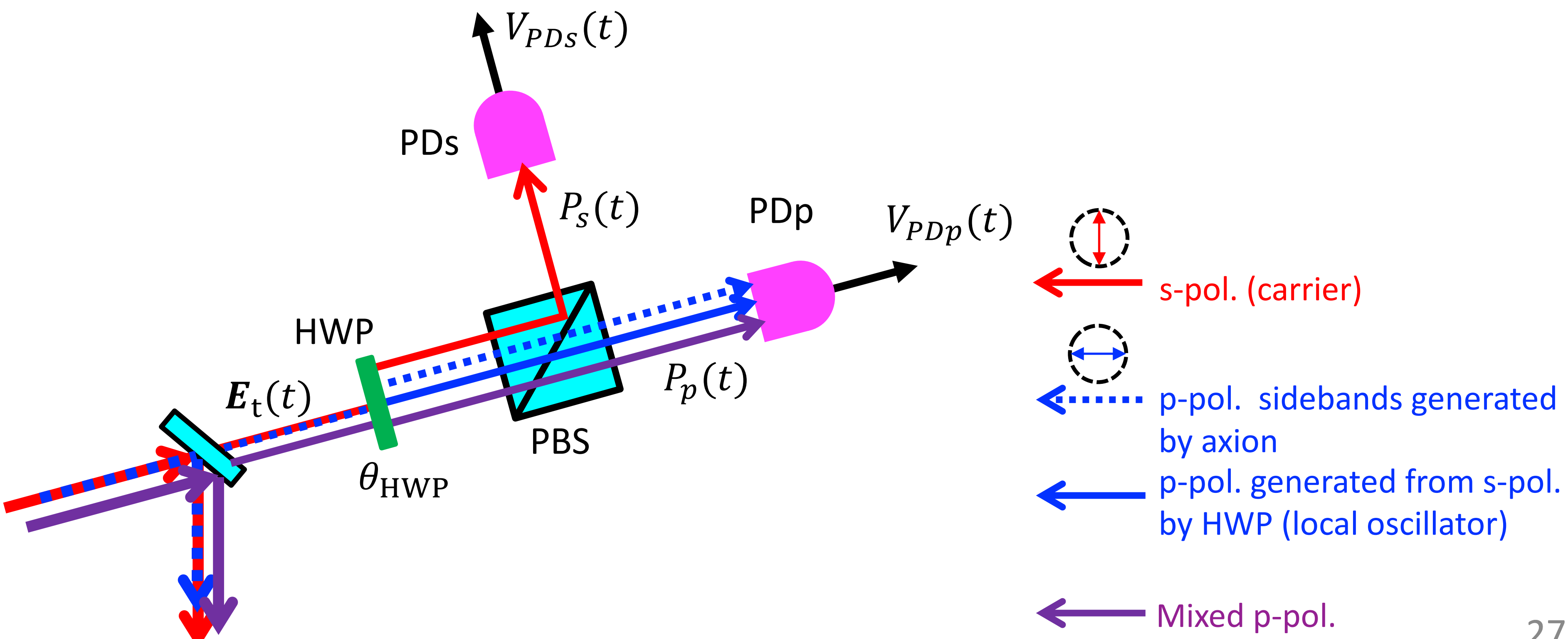
② Reduction of noise

Mixed p-pol. interferes with local oscillator at detection port

$$P_s(t) = P_{t,s}(t)$$

$$P_p(t) = P_{t,s}(t)(4\theta_{\mathrm{HWP}}^2 + 4\theta_{\mathrm{HWP}}\mathrm{Re}\left[\delta\phi(t)\right]) + 4\theta_{\mathrm{HWP}}\mathrm{Re}[E_{t,s}^* E_{t,p}]$$

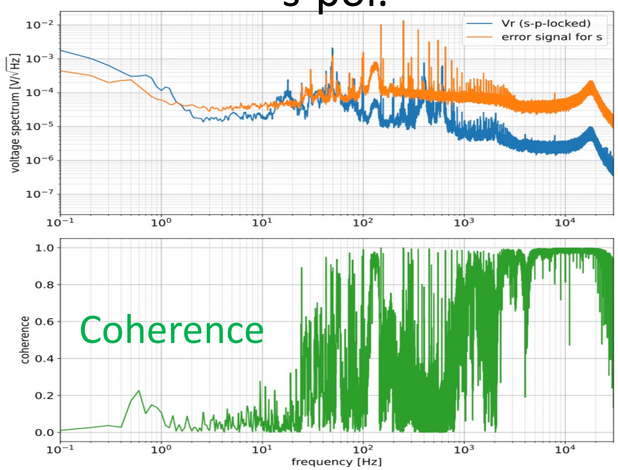
⇒Vibration of cavities couple to the mixed p-pol.



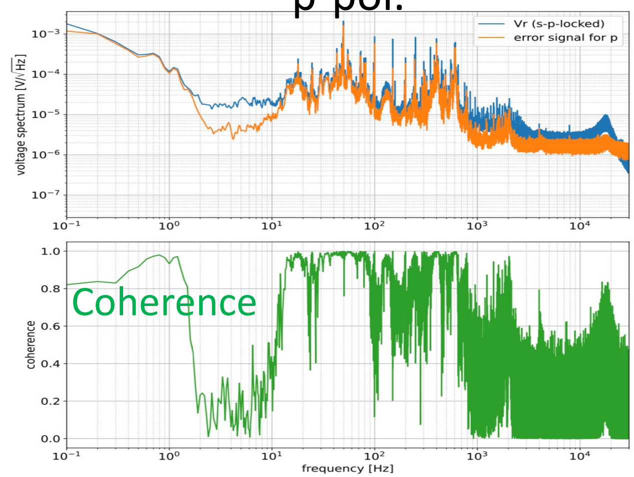
② Reduction of noise

Coherence between error signal and polarization rotation

s-pol.



p-pol.

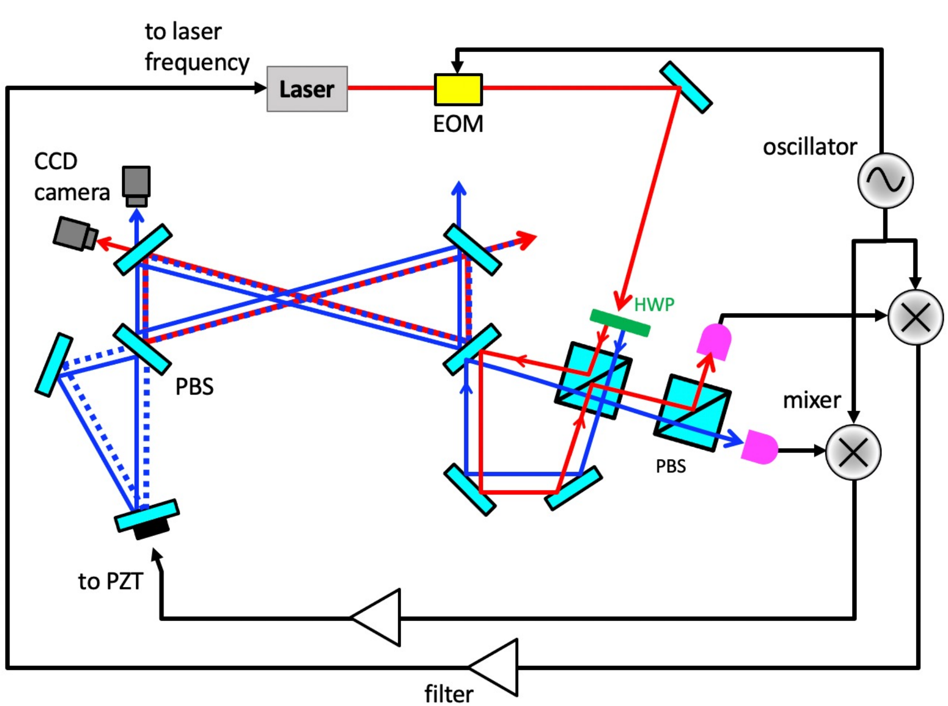


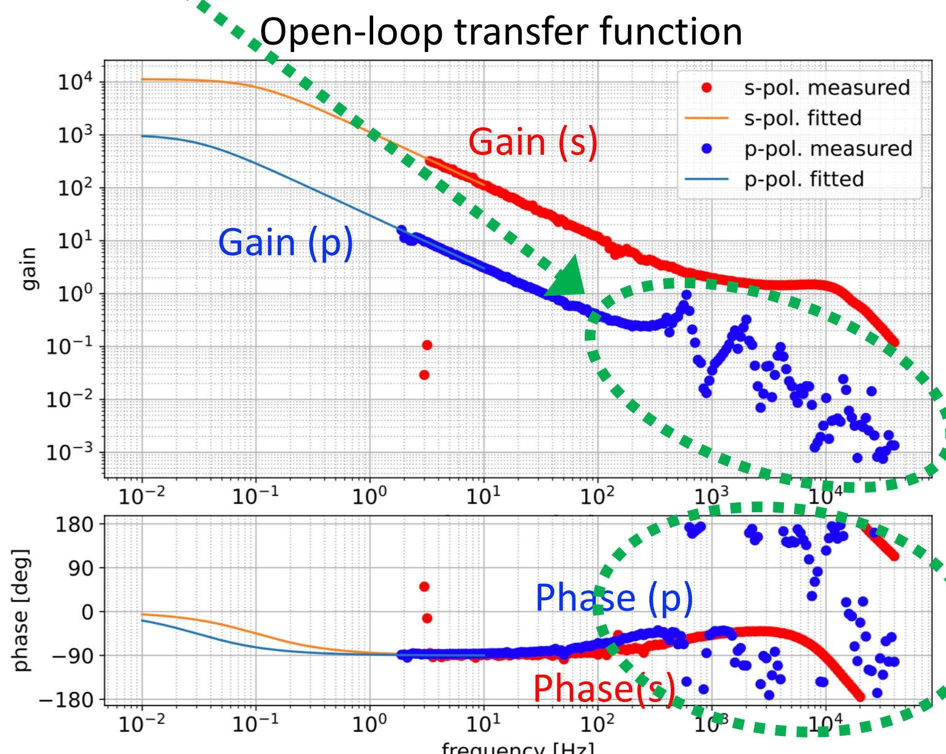
Future improvements

- Removal of mixed p-pol.
  - ➢Install high extinction ratio polarizer before the cavity
  - ➢ Align polarization plane of input s-pol. to that of cavity's eigenmode
  - ➢Need to deal with birefringence? or back scattering?
- Reduction of vibration noise
  - ➢Develop unified spacer including main and aux. cavity
  - ➢Suppress vibration noise with feedback control

② Reduction of noise –parasitic resonance–

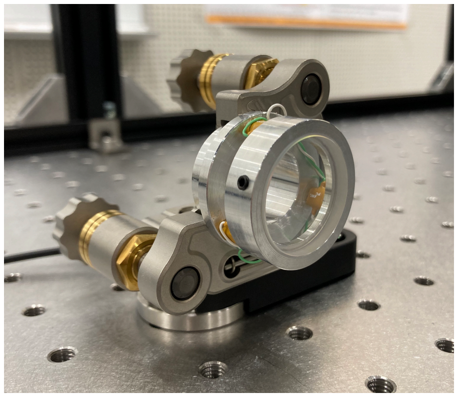
- Bandwidth of feedback control for p-pol. is narrow (UGF ≃ 30 Hz)
  ⇒ can not suppress vibration noise of aux. cavity
- Parasitic resonance of the actuator is limiting the bandwidth



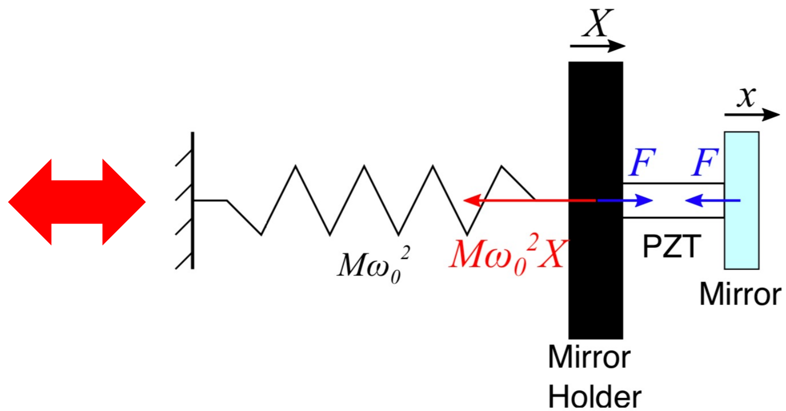


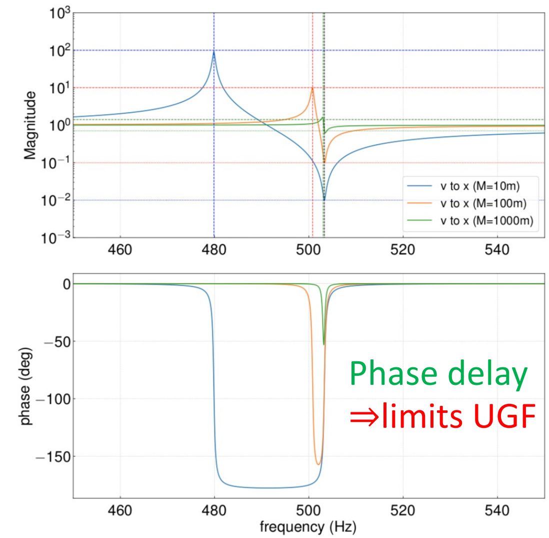
② Reduction of noise –parasitic resonance–

- Piezo-actuated mirror can cause parasitic resonance



Piezo-actuated mirror for p-pol. of DANCE Act-1





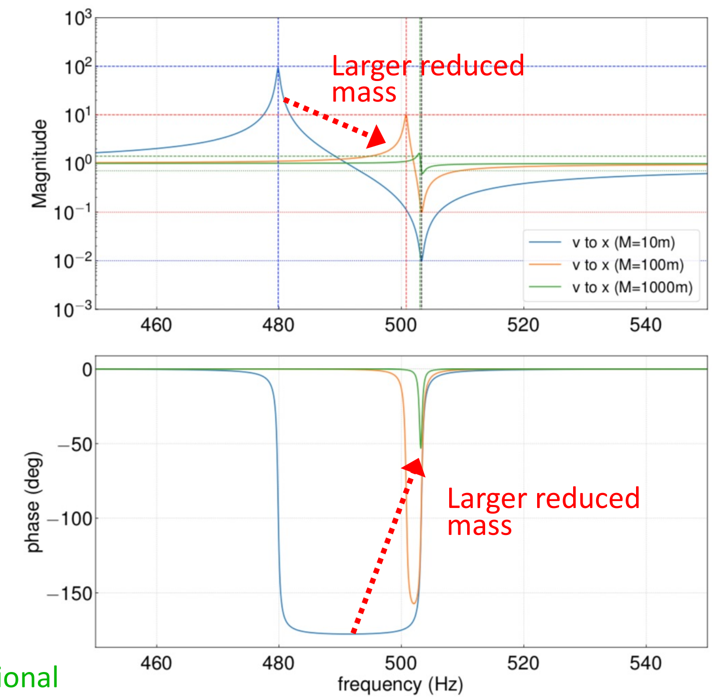
(cited from Takano-san's awesome note on parasitic resonance: https://granite.phys.s.u-tokyo.ac.jp/takano/documents/ParasticResonance.pdf)

- 4 plans to remove parasitic resonance:
  - Plan A: Piezo-actuated mirror attached on heavy rigid mass
  - Plan B: Piezo-actuated mirror mounted in soft materials
  - Plan C: Inverse transfer function implemented by digital filter
  - Plan D: Robust control (Modern control)

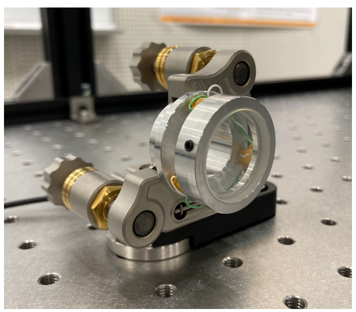
② Reduction of noise –parasitic resonance–

➢Plan A: Piezo-actuated mirror attached on heavy rigid mass

- Larger reduced mass (換算質量) of the holder
  ⇒ Smaller peak, dip and phase delay

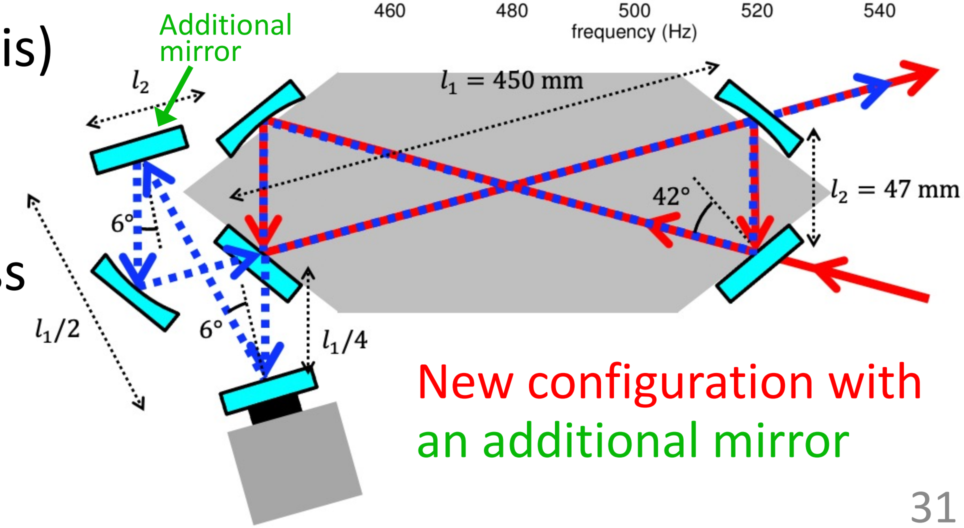


Use heavy rigid mass as a holder



(Used in Ohmae-san's doctoral thesis)

- We can't align piezo-mirror on a mass
  ⇒ Need an additional mirror
  for alignment



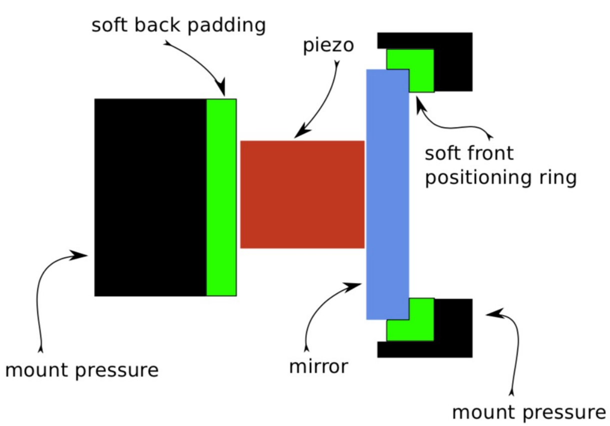
New configuration with an additional mirror

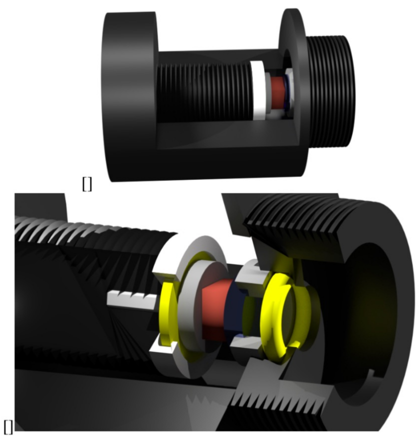
② Reduction of noise –parasitic resonance–

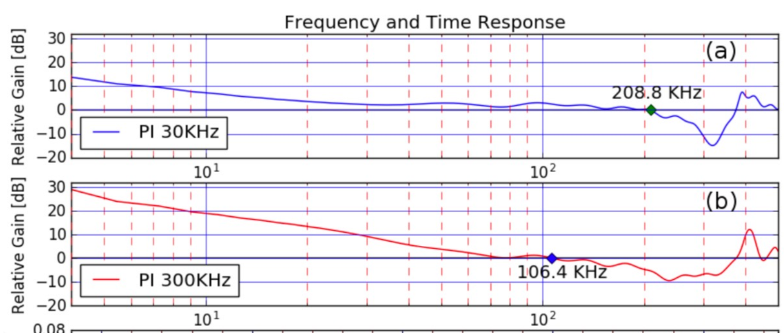
- Plan B: Piezo-actuated mirror mounted in soft materials

  - [D. Goldovsky, V. Jouravsky, and A. Pe’er, Opt. Express 24, 28239-28246 (2016)]()

    - Soft materials (rubber or soft silicone gel pads) can isolate mechanical resonance
    - Able to use knobs of the mount for alignment
    - Locked a cavity with UGF ≃ 200 kHz





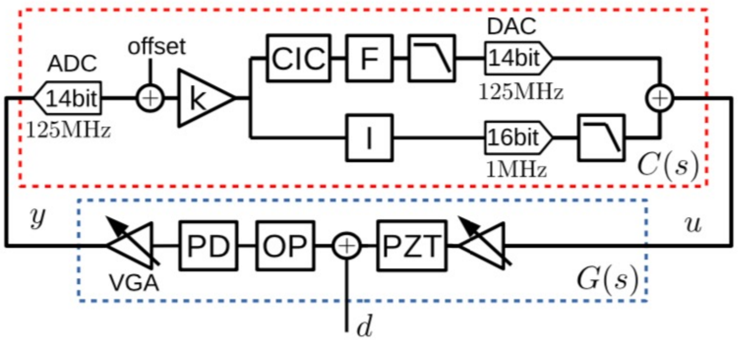


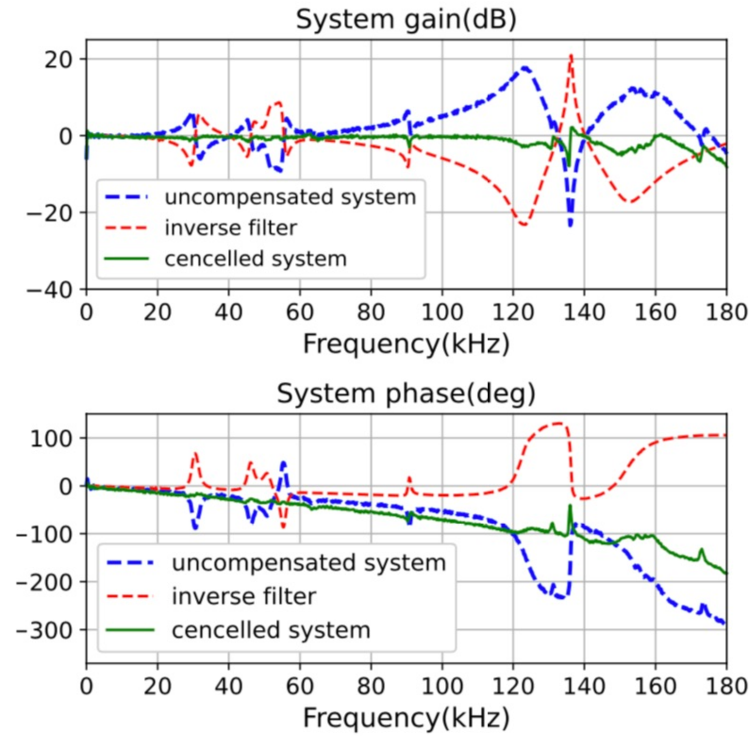
Research topics

- Understand this mechanism with a theoretical model

② Reduction of noise –parasitic resonance–

- Plan C: Inverse transfer function implemented by digital filter
  - [M. Okada *et al.*, Review of Scientific Instruments 91, 055102 (2020)]
    - Implement the inverse transfer function of parasitic resonance with IIR filter
    - FPGA is used (Moku:Lab or SEAGULL are also available for us)





- This is a feedforward method

⇒ unable to deal with temperature dependency of parasitic resonance

② Reduction of noise –parasitic resonance–

- Plan D: Robust control (Modern control)
  - Parasitic resonance appear in engineering field (e.g. robotics)
  - known as “resonance of 2-inertia system (2慣性系)”
  - Application of robust control has been researched

able to deal with the change of the characteristics of the control target (e.g. temperature dependency)

- [K. Salkata, K. Saiki, and H. Fujimoto, Proc. IEE of Japan Technical Meeting Record, IIC-11- 065, 83–88, (2010)]

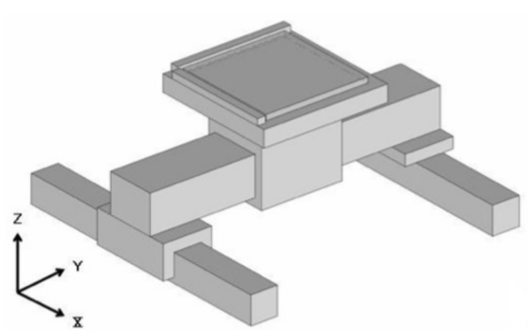
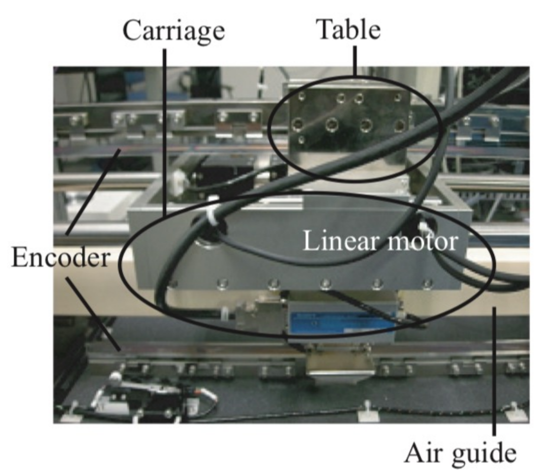


Fig. 1 Structure of XY gantry stage.



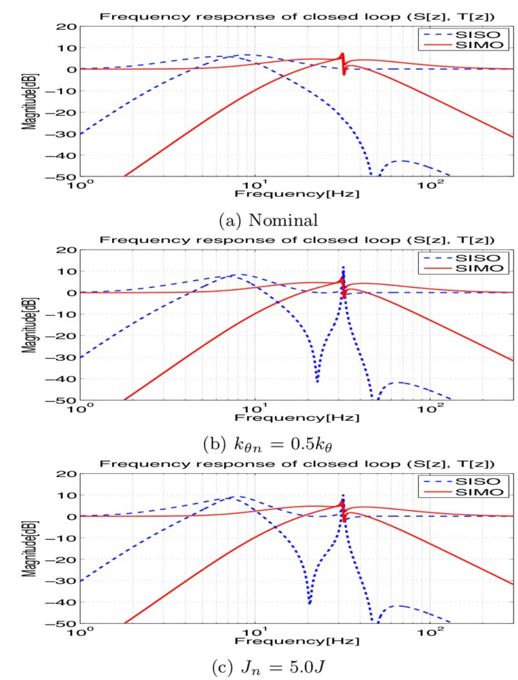


Fig. 7 Frequency responses of closed loop (Model).

Future plans / Research topics

① Improvement of shot noise limit
- Replacement of PBS for higher finesse
- High power laser

② Reduction of noise
- Removal of p-pol. from input laser
- Removal of parasitic resonance of actuator

③ Automated cavity locking system

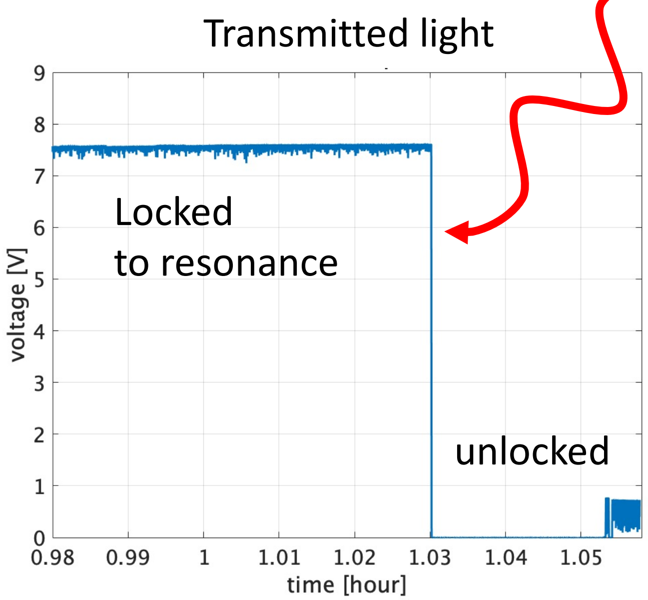
④ Investigation of the resonant frequency difference

⑤ Simultaneous resonance with wavelength tunable laser

③ Automated cavity locking system

- SNR can be improved with observation time T_{obs}
  ⇒need to lock the cavity for a long time
- Cavity can be inevitably unlocked by sudden shock or vibration

shock or vibration
(earthquake, human walking, etc.)



③ Automated cavity locking system

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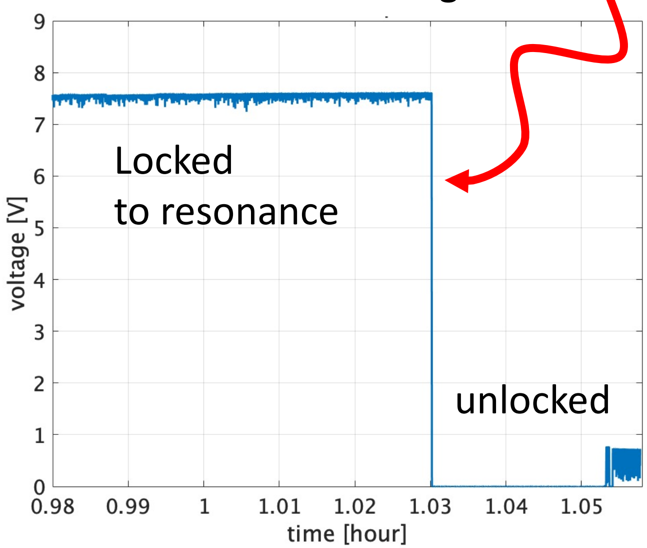
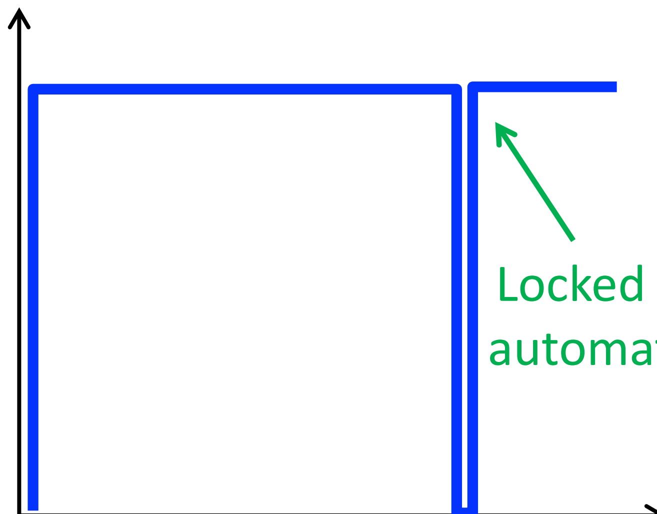


Automated cavity locking system

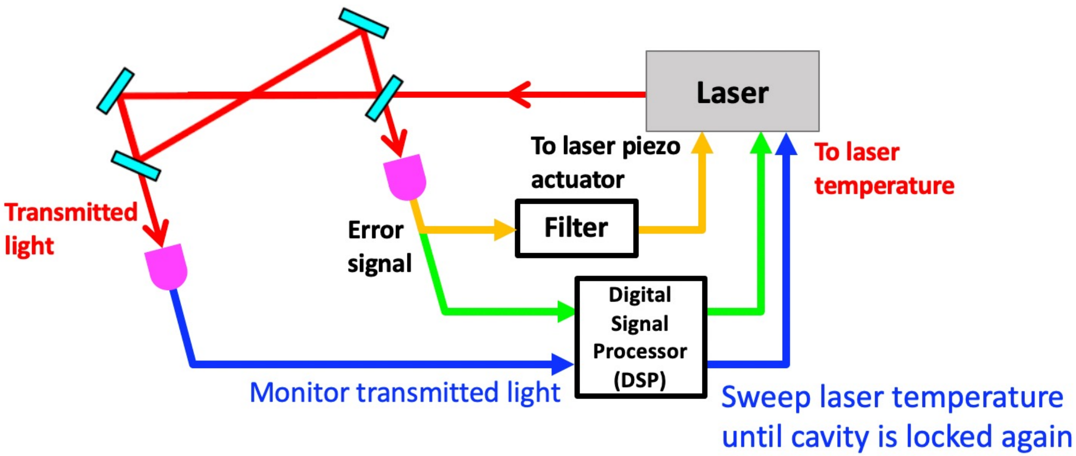


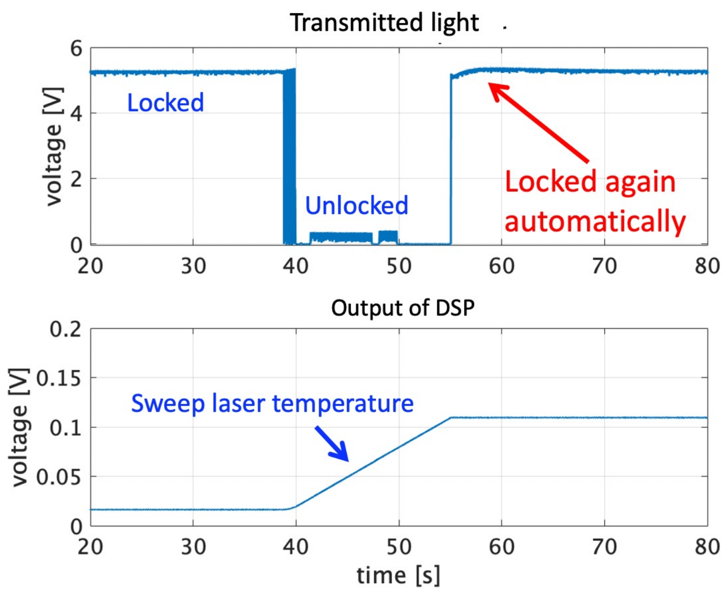
Locked again automatically

Cavity can be relocked automatically during long-term observation.

③ Automated cavity locking system

- Automated cavity locking for s-polarization has already developed (H. Fujimoto et al., arXiv:2105.08347)





Research topics

- Automated cavity locking system for simultaneous resonance of s- and p-pol.

Future plans / Research topics

① Improvement of shot noise limit
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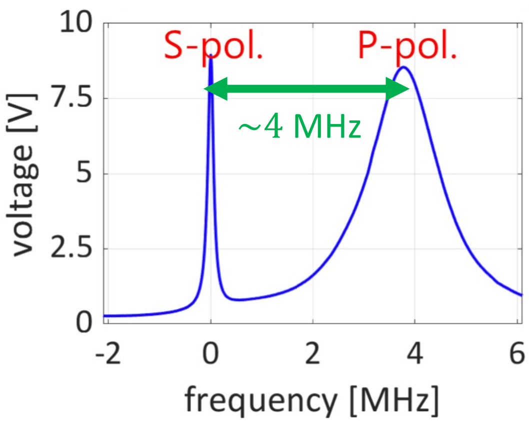
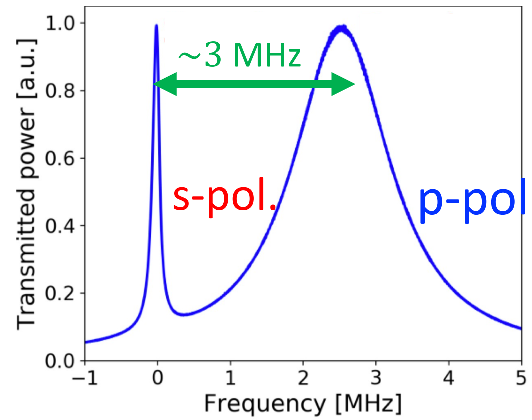
④ Investigation of the resonant frequency difference

- Resonant frequency difference can drift for some reason…





Observed resonant frequency differences in DANCE Act-1 @ B207 are listed here by Oshima-san

Research topics

- Investigation of the cause of the drift:
  - ➢Property change of the mirror coating by high power?
  - ➢Temperature dependency?
  - ➢Tilt of the attached mirrors?

- Development of a new actuator of resonant frequency difference

⇒Able to realize simultaneous resonance with only one cavity and reduce noise!

Future plans / Research topics

① Improvement of shot noise limit
- ➢Replacement of PBS for higher finesse
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- ➢Removal of p-pol. from input laser
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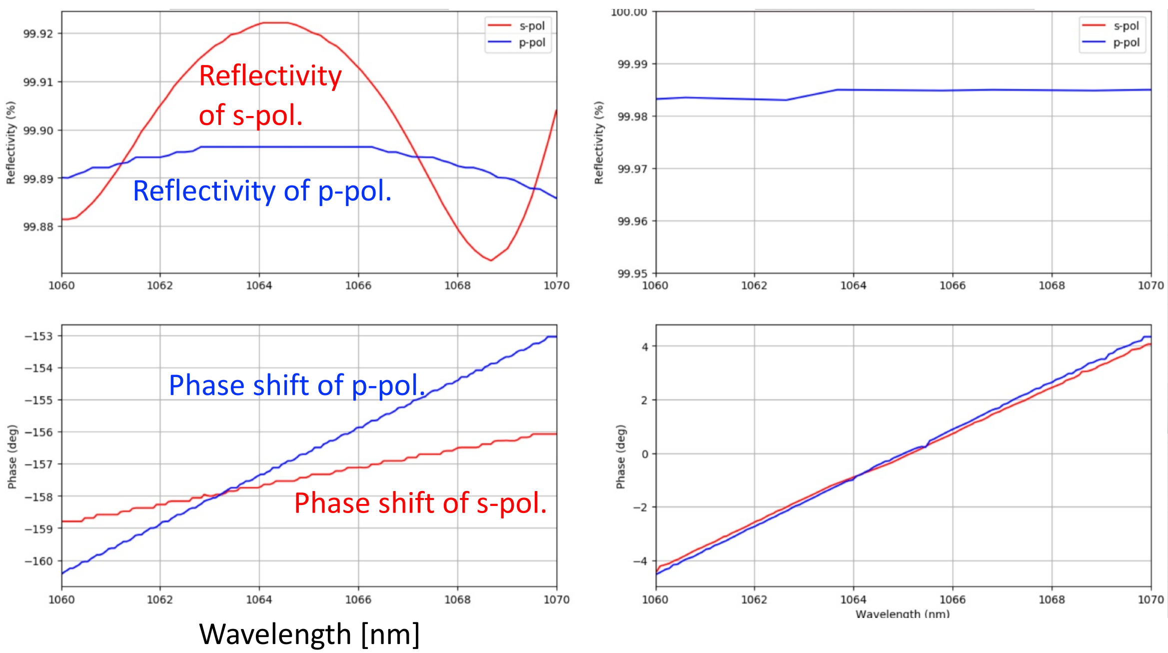
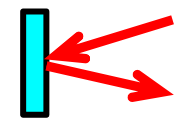
⑤ Simultaneous resonance with wavelength tunable laser

⑤ Simultaneous resonance with wavelength tunable laser

- Reflective phase shift varies with wavelength





Reflective phase difference occurs in oblique incidence

Research topics

- Simultaneous resonance with wavelength tunable laser
  - ➢Investigation of the property of mirror coating and wavelength tunable laser

⇒Able to realize simultaneous resonance with only one cavity and reduce noise!

Future plans / Research topics

① Improvement of shot noise limit ← Fujimoto
- Replacement of PBS for higher finesse
- High power laser

② Reduction of noise
- Removal of p-pol. from input laser
- Removal of parasitic resonance of actuator ← B4

③ Automated cavity locking system

④ Investigation of the resonant frequency difference

⑤ Simultaneous resonance with wavelength tunable laser

If you are interested in these topics, please let me know!

Contents

◆Future plans for DANCE Act-1

- Dark matter search and DANCE
- Principle and target sensitivity of DANCE
- Current status of DANCE Act-1
- Future plans / Research topics
  ① Improvement of shot noise limit
  ② Reduction of noise
  ③ Automated cavity locking system
  ④ Investigation of the resonant frequency difference
  ⑤ Simultaneous resonance with wavelength tunable laser

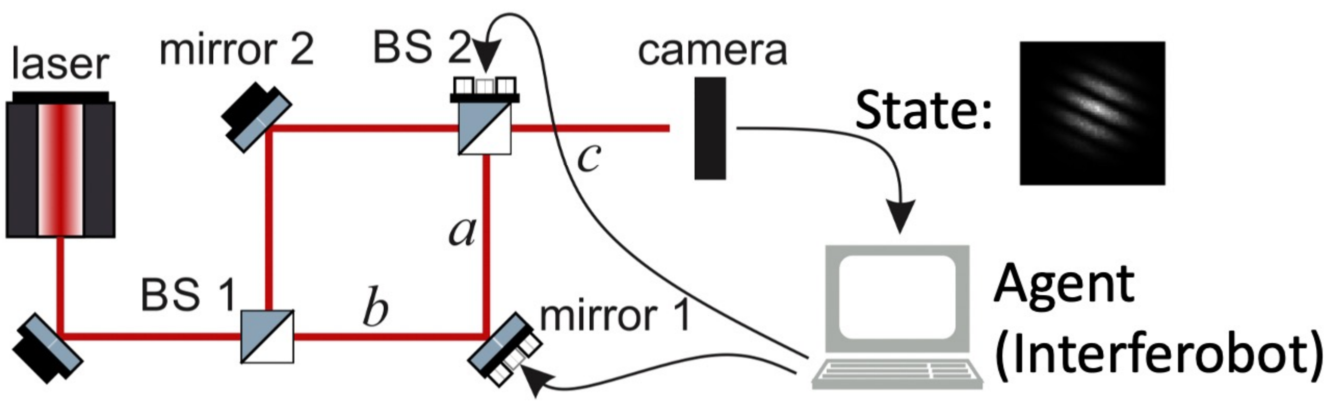
◆Automated alignment and mode-matching with Machine Learning

Experiments for B4 students

- B4 students chose two topics:

➢ Removal of parasitic resonance of piezo-actuated mirror

➢ Automated alignment with Machine Learning (ML)

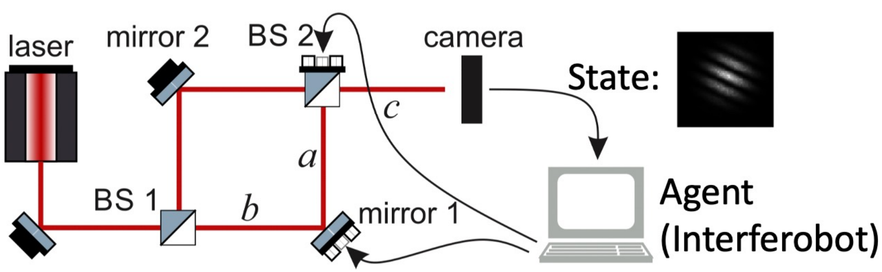


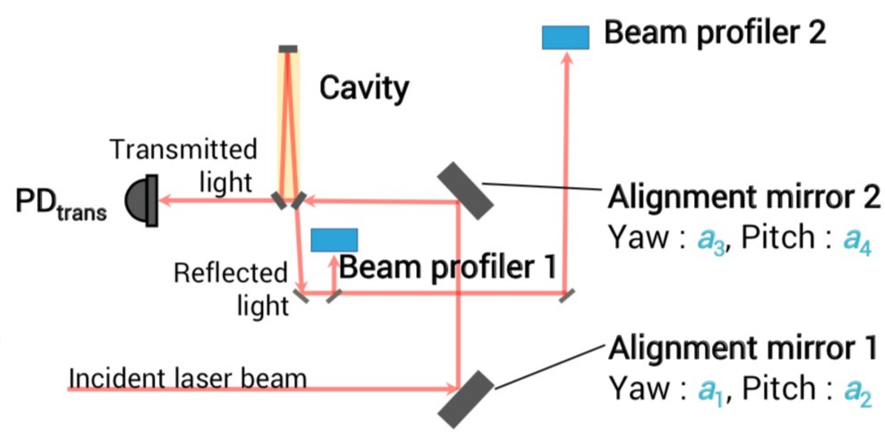
D. Sorokin et al., arXiv:2006.02252

Automated alignment with Machine Learning

- Application of ML to alignment of interferometer:
  - Alignment of a Mach-Zehnder interferometer (D. Sorokin et al., arXiv:2006.02252)
  - Alignment of a ring cavity (Tahara-san's master thesis @ Mio Lab.)
  - Combination of ML and Wave Front Sensor (Tachihara-san's master thesis @ Somiya Lab.)
  - etc.

Ando Lab. Seminar given by me

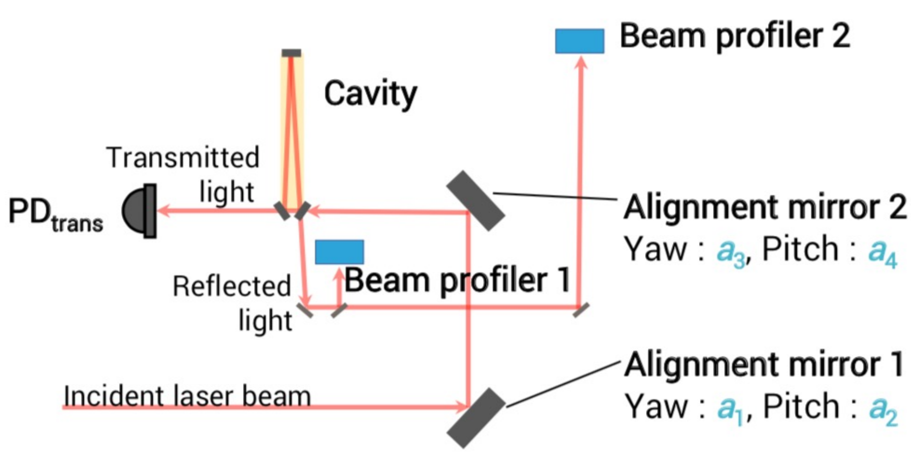


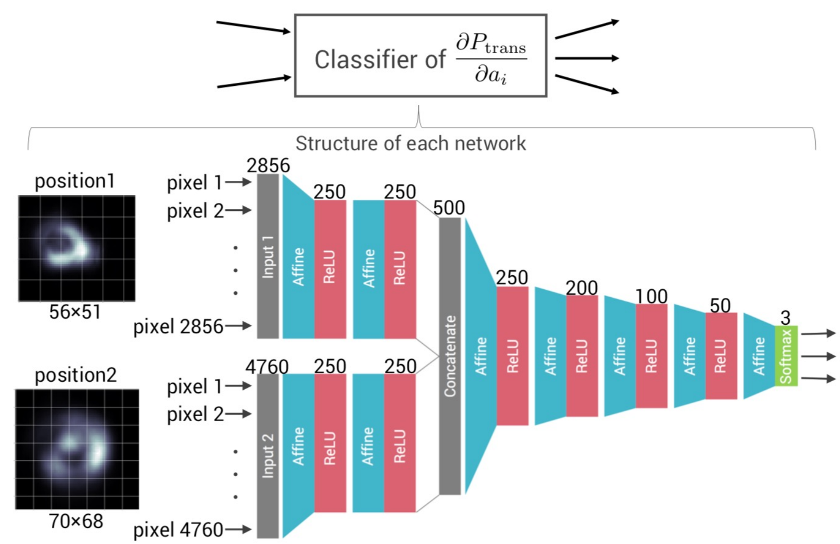


(Cited from Tahara-san's master thesis)

Automated alignment with Machine Learning

- These auto alignments for interferometer might be difficult for beginners…
  - ➢Need to capture image data from CCD camera or profiler to PC
  - ➢Convolutional Neural Network (CNN) is required
  - ➢Reinforcement learning is needed in some cases

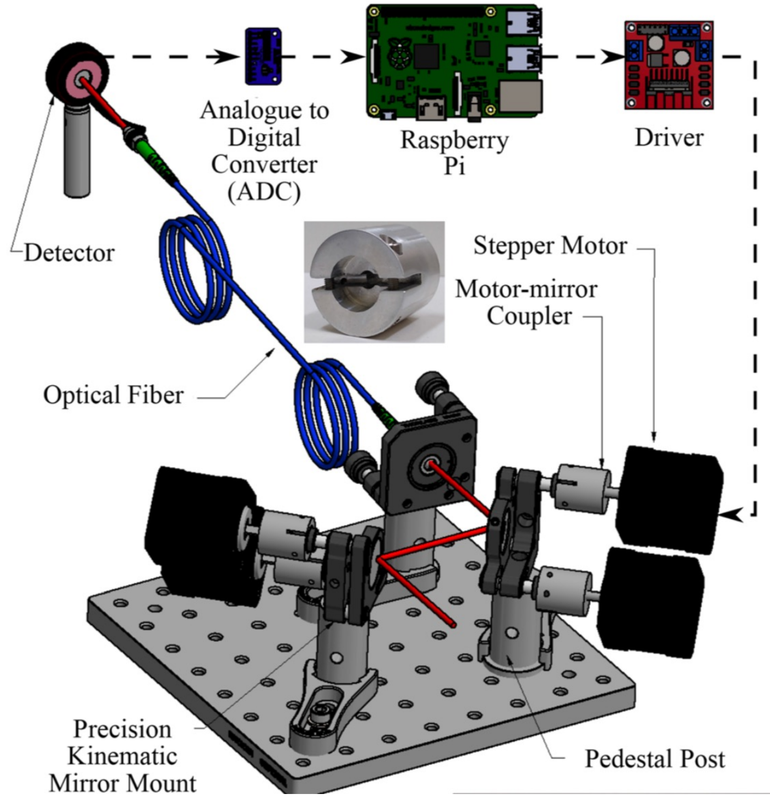




(Cited from Tahara-san's master thesis)

Automated alignment into optical fiber

- Automated alignment into fiber seems better for beginners
  - ◆[R. S. Mathew *et al.*, Review of Scientific Instruments 92, 015117 (2021)]
    - ➢Use only laser power (1D data)
    - ➢No need for CNN
    - ➢M-LOOP (ML Package for controlling real devices) is effective
    - ➢(This might be too easy…)



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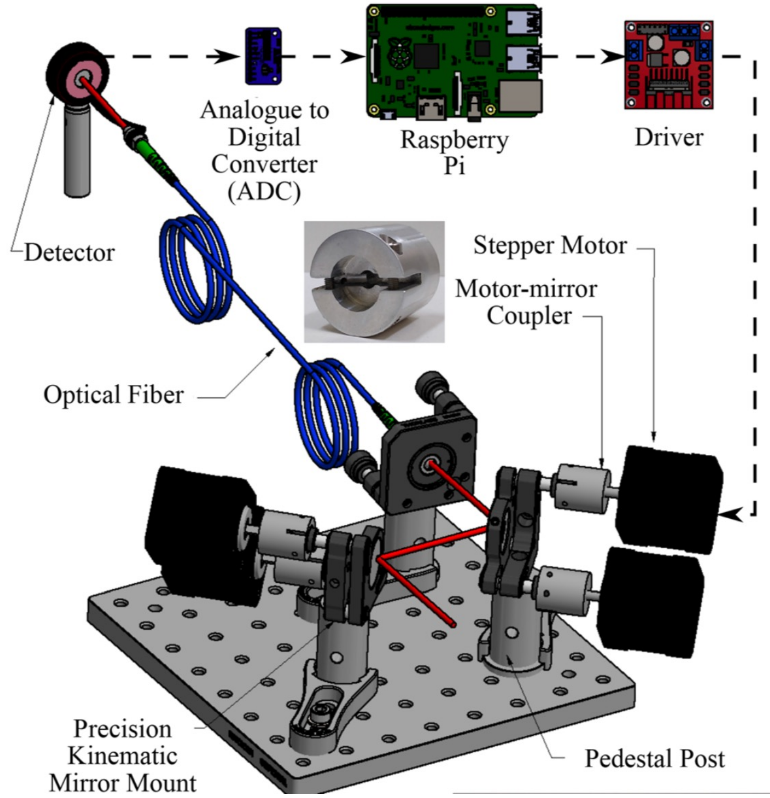
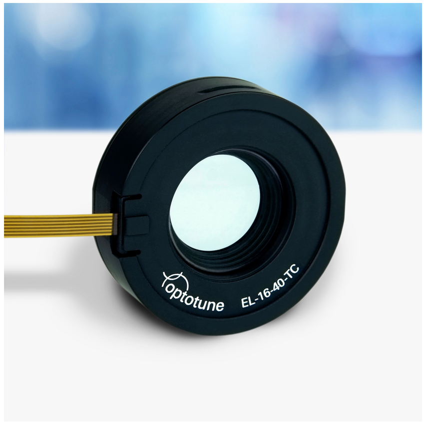


Automated mode-matching machine

- ➢Study above did not consider mode-matching
- ➢If completed, we'll be free from the very stressful work!!

Automated mode-matching machine

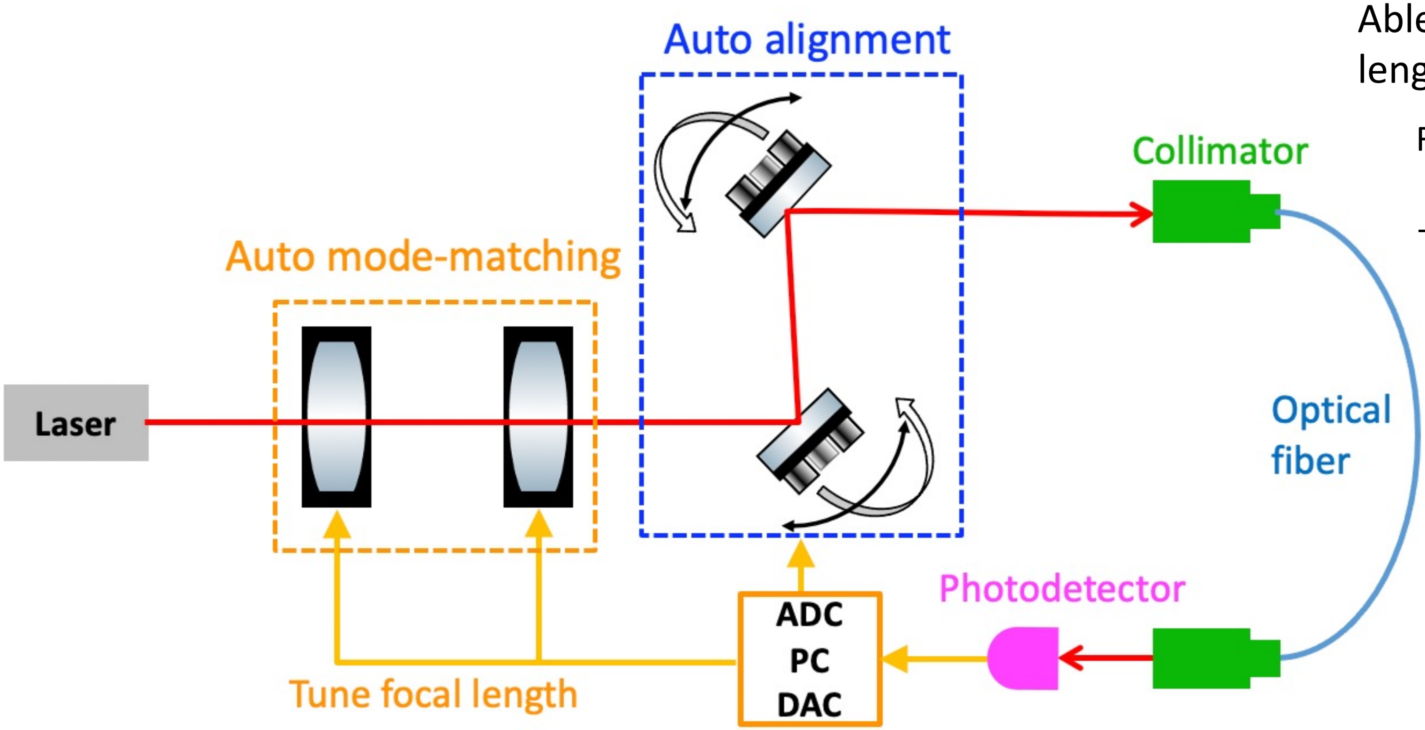
- Idea: Use focus tunable lenses
  - ➢ Tune two focus tunable lenses
  - ➢ Optimize the beam waist and the waist position



(https://www.optotune.com/focus-tunable-lenses)

Able to change the focal length by electric signal

Focal length:
-77 mm $\sim$ 77 mm,
-667 mm $\sim$ 286 mm, etc.



Summary

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