arXiv:2303.03594 submitted on March 7

First Results of Axion Dark Matter Search with DANCE

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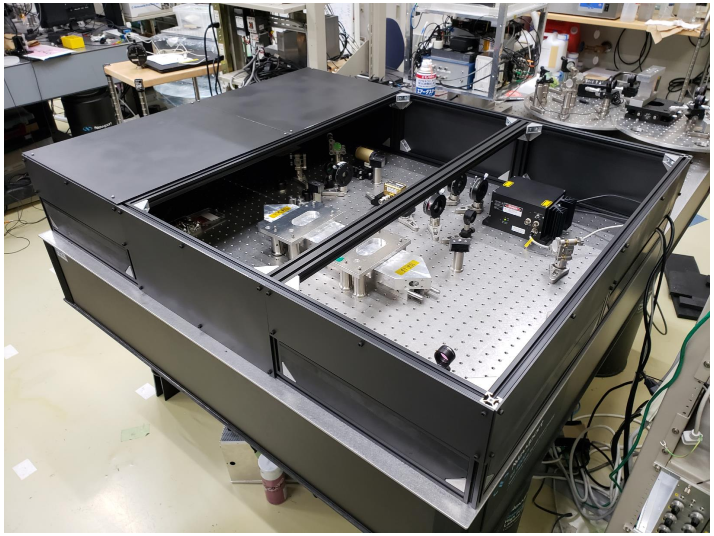
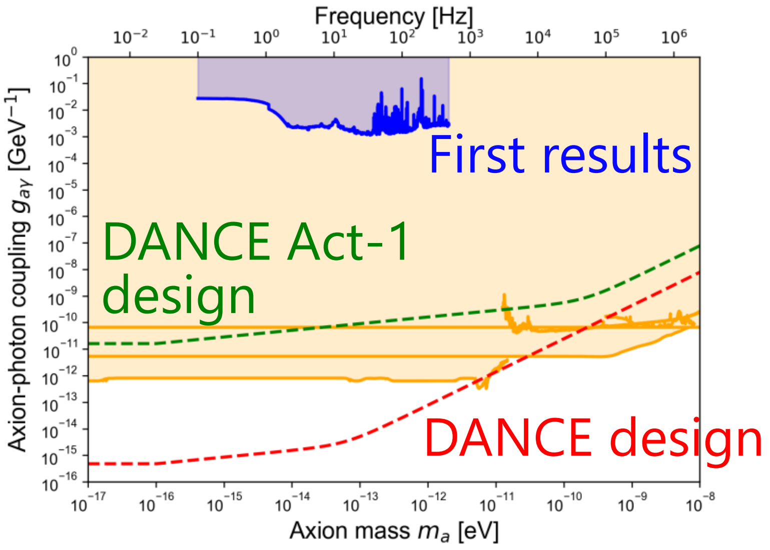
Overview

- New experimental project to search for axion DM with an optical cavity
  I. Obata, T. Fujita, Y. Michimura
  [PRL 121, 161301 (2018)]
  DANCE: Dark matter Axion search
  with riNg Cavity Experiment

- First results of prototype experiment DANCE Act-1 from long-term observation
  YO, H. Fujimoto+, [arXiv:2303.03594]

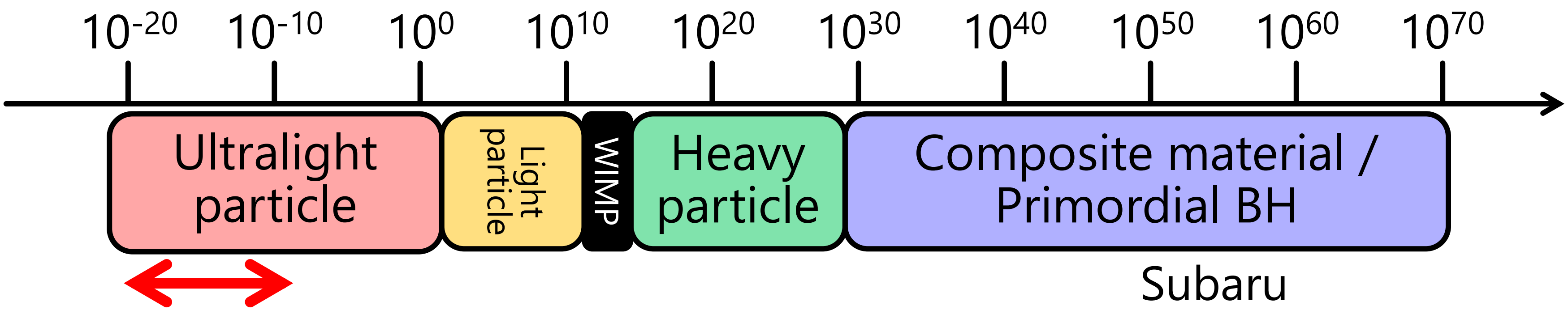




Axion search with laser interferometers

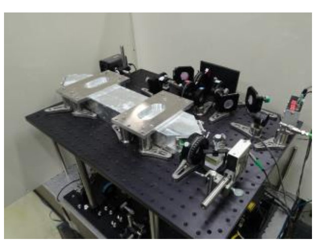
- We need to search for DM in a wider mass range
- Laser interferometers are useful to search for ultralight DM
- DANCE focuses on axion DM

Dark matter mass [eV]



Laser interferometers

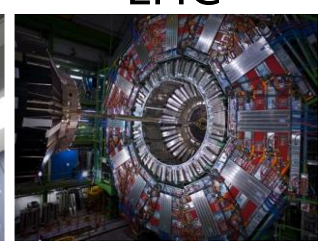
DANCE



KAGRA

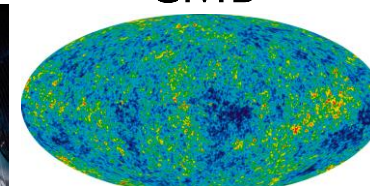
XENON1T

LHC



Subaru Telescope

CMB



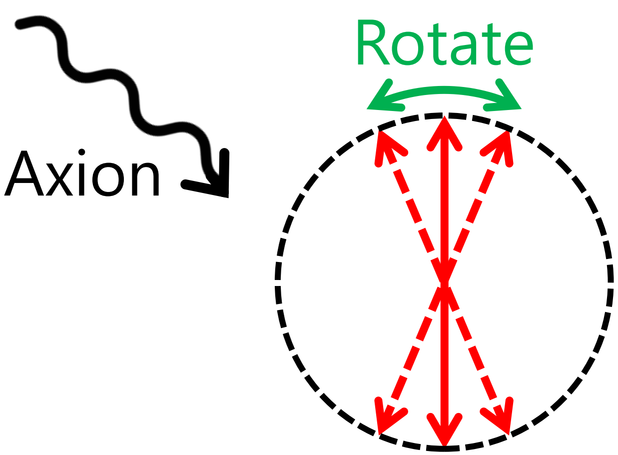
Polarization rotation from axions

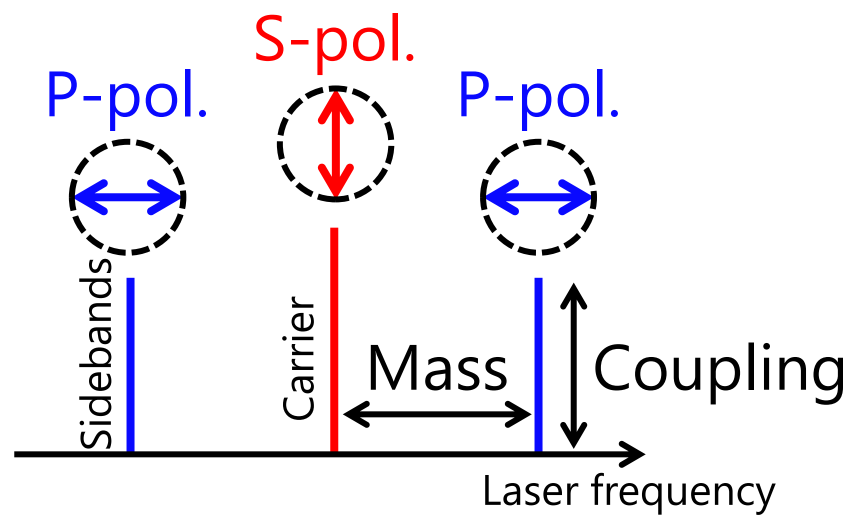
- Axion-photon coupling causes phase velocity difference between left- and right-handed photons

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

Coupling constant　　Axion field　　Axion mass

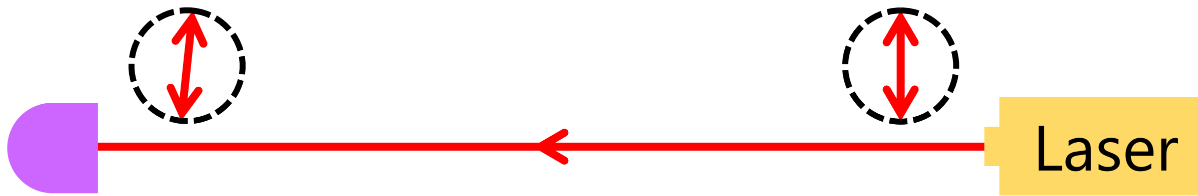
- Phase velocity difference of circular polarizations makes linear polarization rotate and oscillate



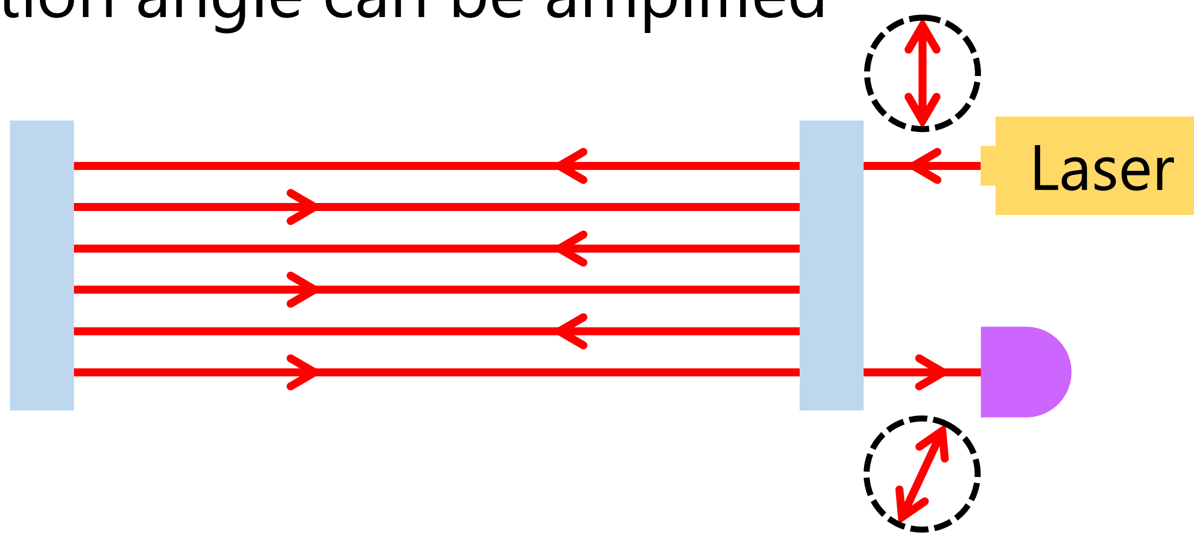


Signal amplification with cavities

- Rotation angle is too small to be observed without a cavity

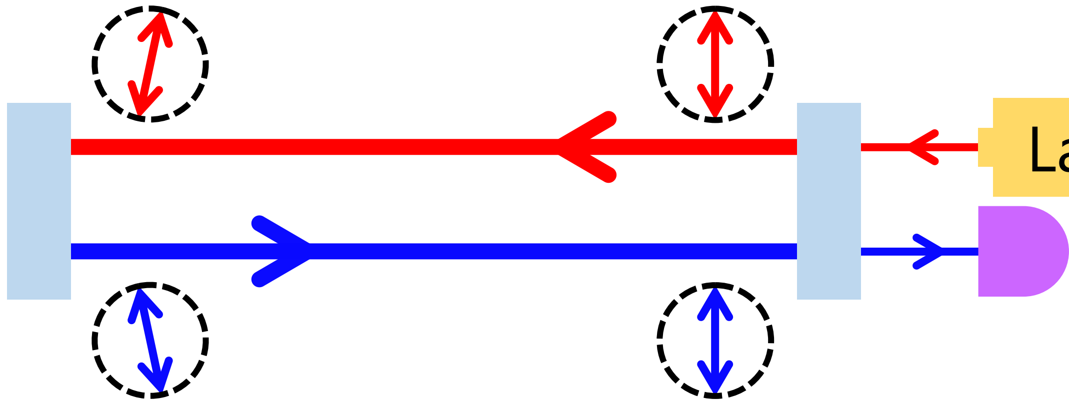


- Laser light runs many times between mirrors in an optical cavity
  → Rotation angle can be amplified

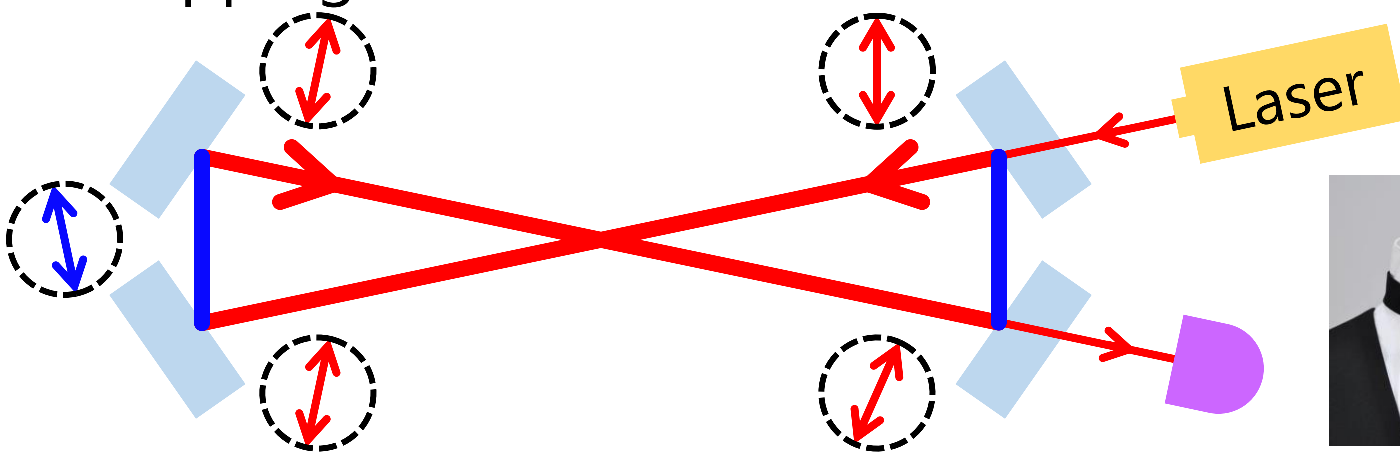


Bow-tie ring cavity

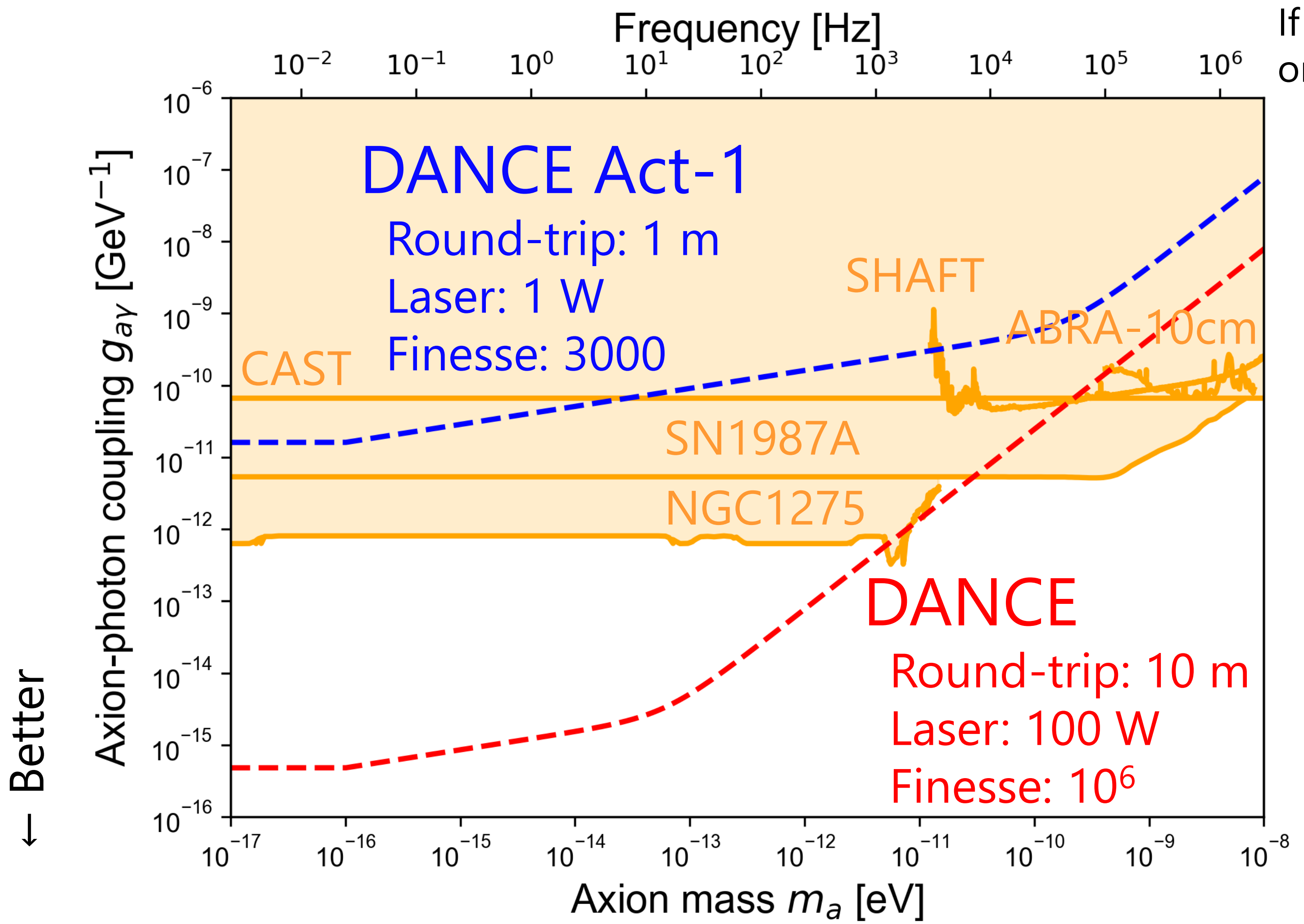
- Rotated direction is inverted by reflection on mirrors
  → Rotation effect is canceled out



- A bow-tie ring cavity prevents linear polarization from flipping



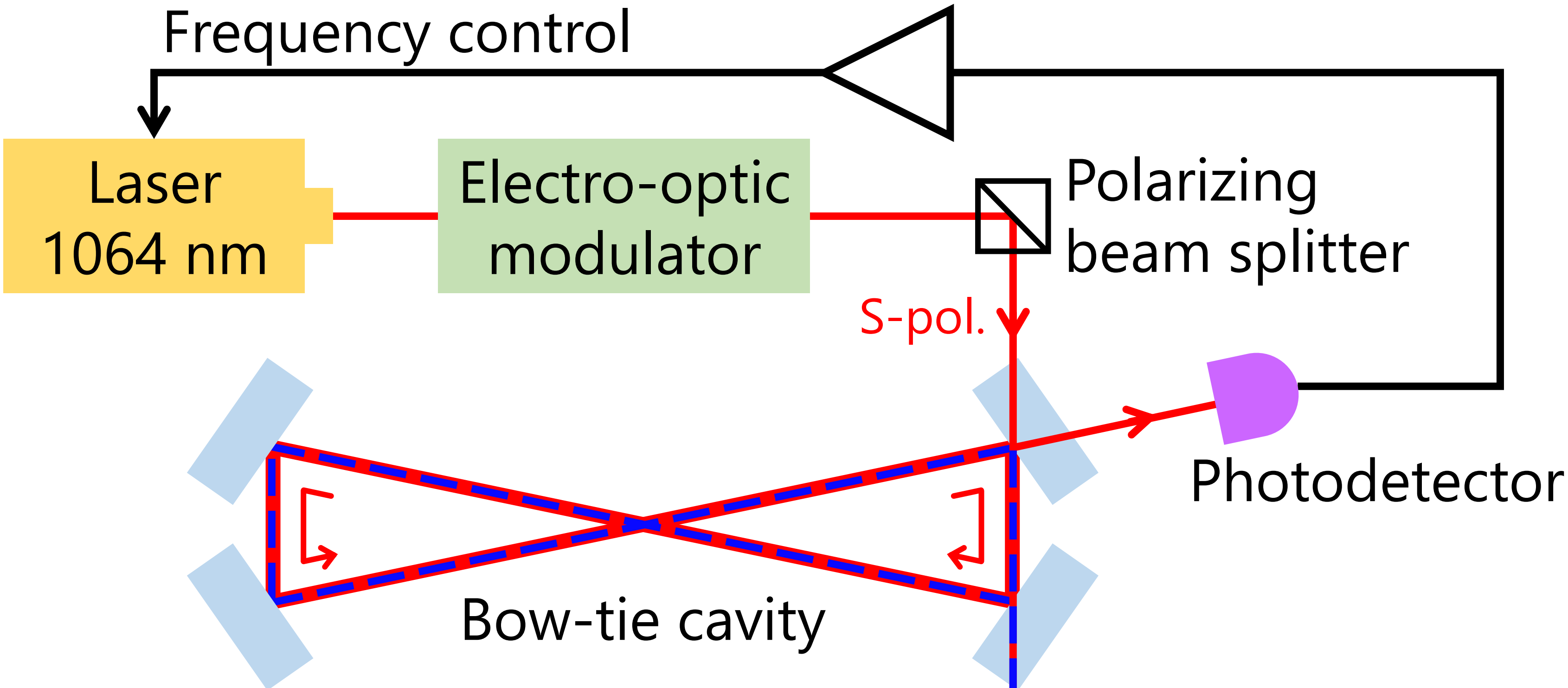
Design sensitivity of DANCE

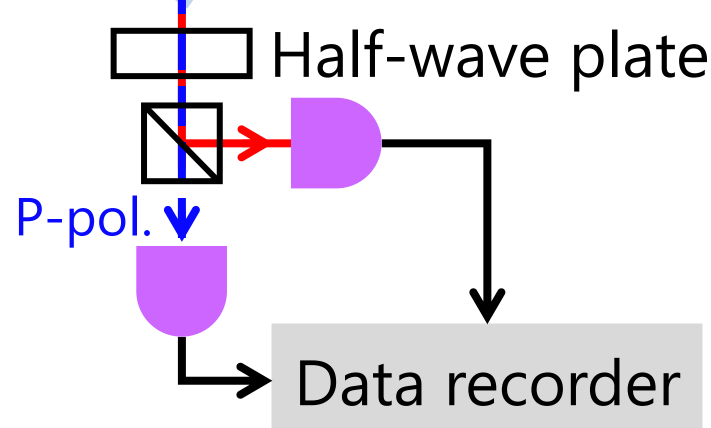


If only shot noise and one-year observation

- Shot noise is caused by fluctuations in photons' number
- Need to minimize the other noise sources

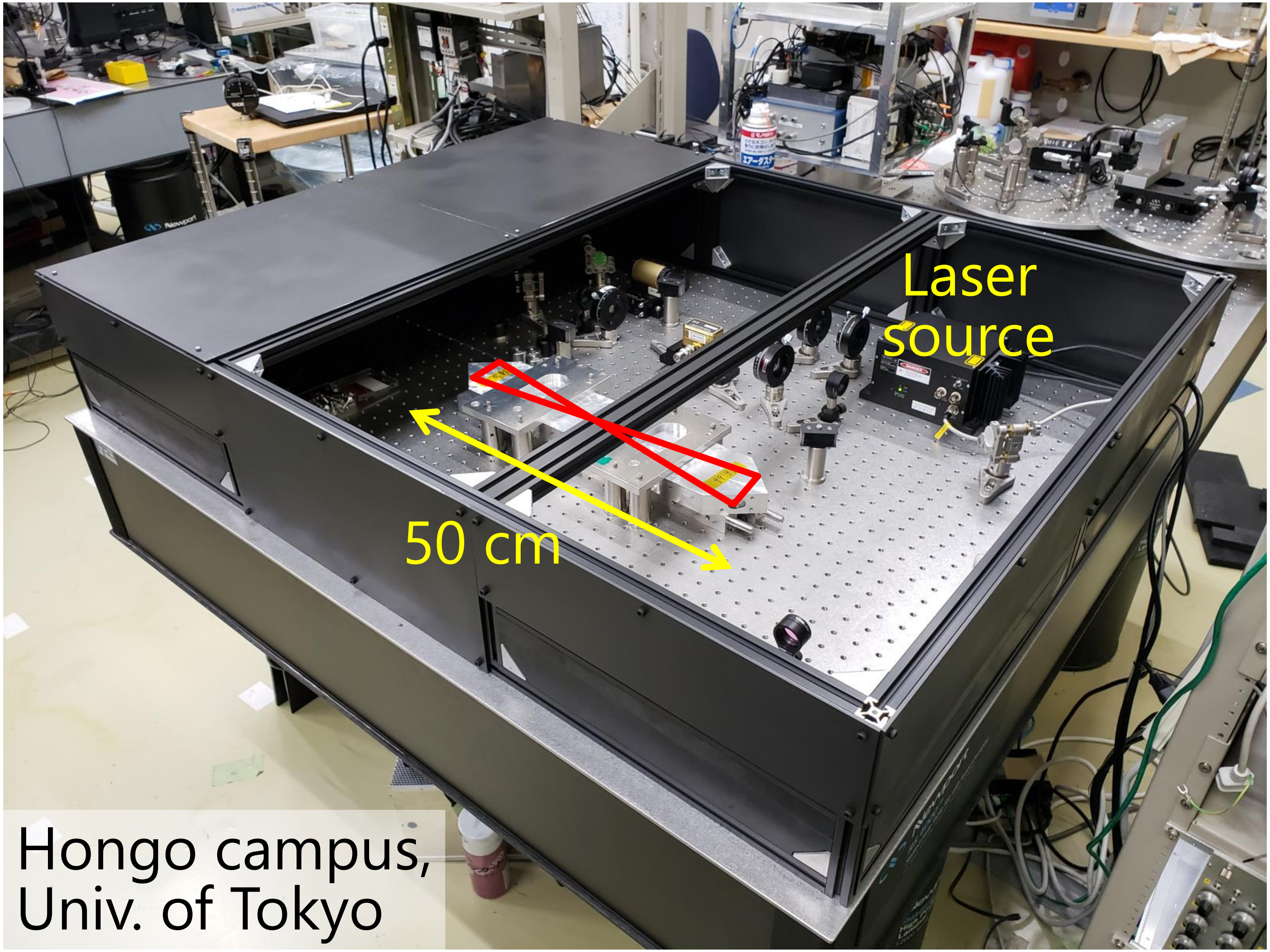
Setup of DANCE Act-1





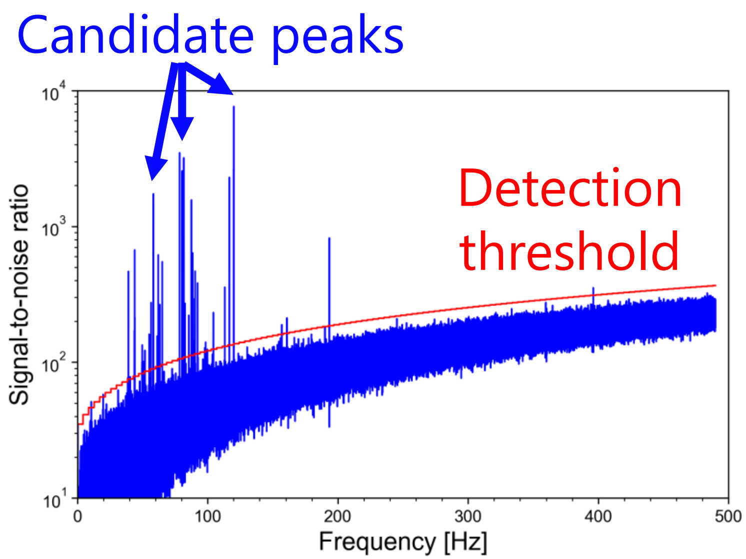
- Input laser power: 242(12) mW
- Finesse of s-pol.: 2.85(5)$\times 10^3$
- Finesse of p-pol.: 195(3)
- Resonant freq. difference between s- and p-pol.: 2.52(2) MHz

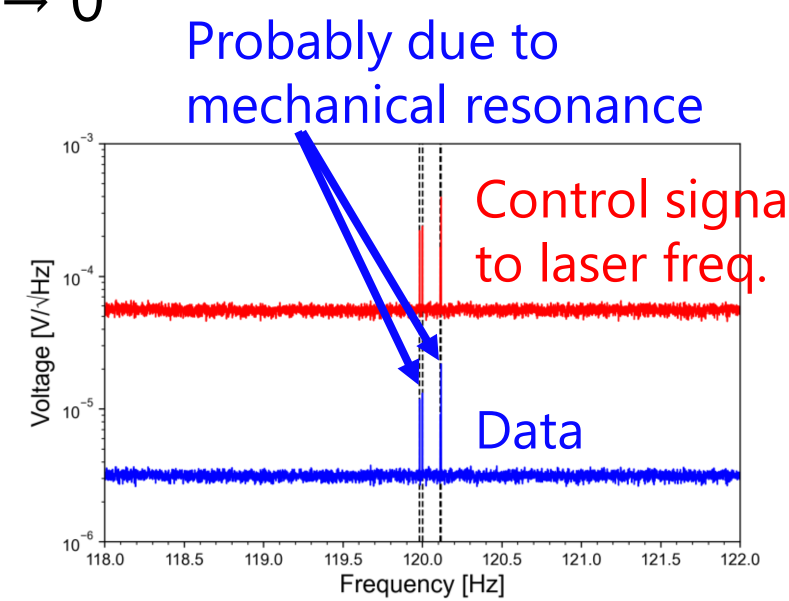
Picture of DANCE Act-1



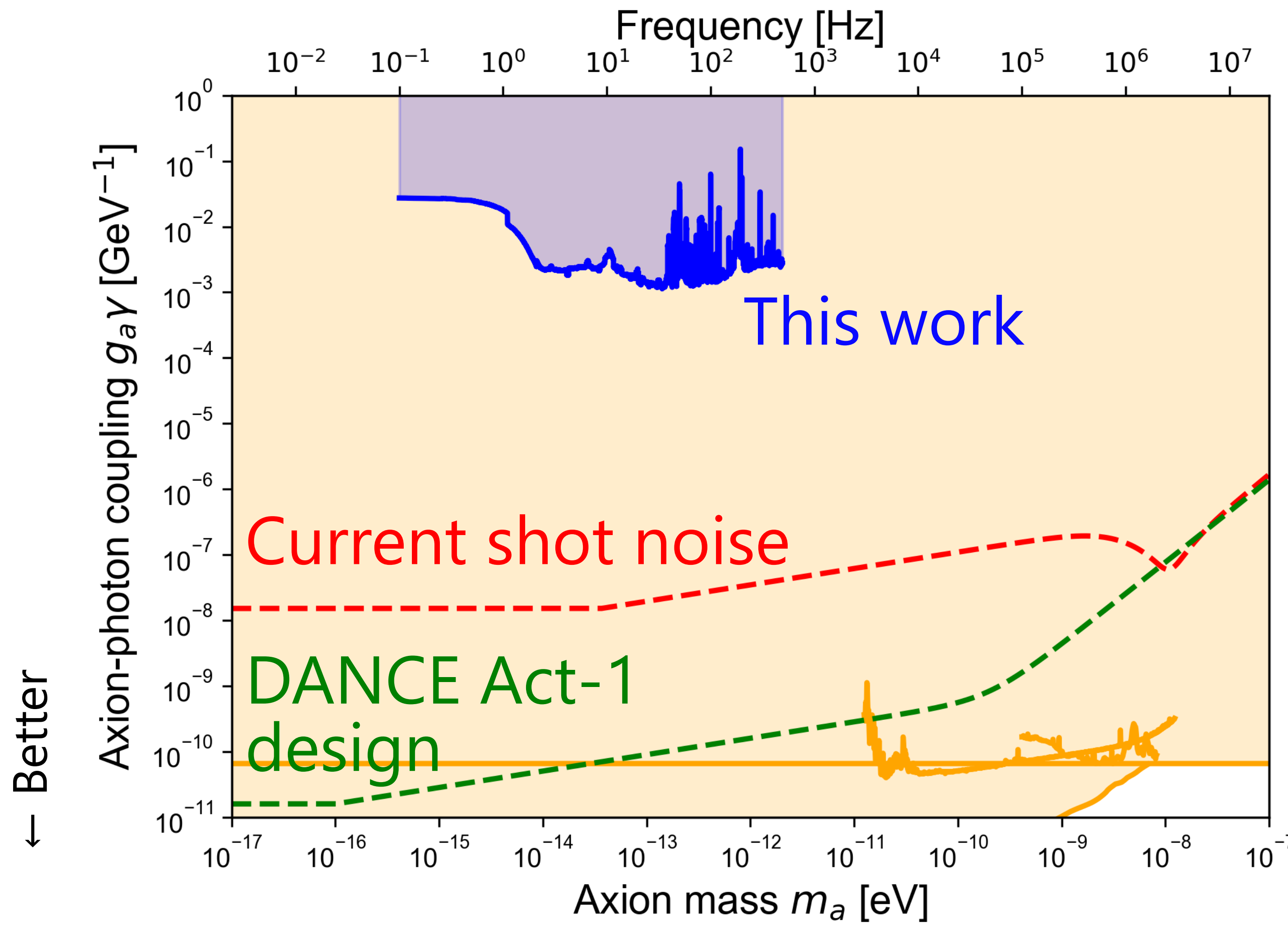
Data acquisition and analysis

- Recorded the data in May 18-30, 2021
- The first 86,400-second (24-hour) data was selected
- After passing the data through the analysis pipeline, 551 points exceeded the threshold
- All candidate peaks were rejected by 3 veto procedures
  - Consistency veto: 551 → 271
  - Linewidth veto: 271 → 7
  - Control signal veto: 7 → 0



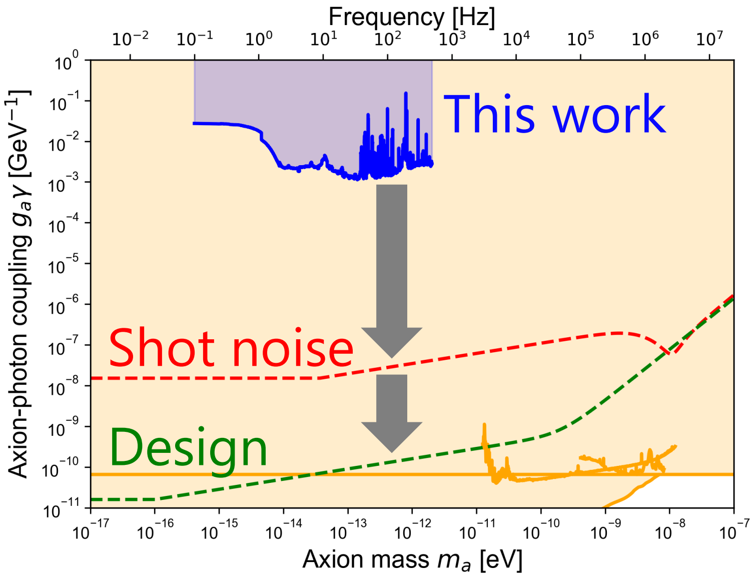


Results



- Worse than design sensitivity by 7 orders of magnitude
- First results of axion DM search with an optical cavity

Discussion to improve the sensitivity



1. This work to shot noise

- We need to reduce classical noises
  - Laser intensity noise
  - Laser frequency noise
  - Mechanical vibration

2. Shot noise to design sensitivity

- We need to improve the parameters
  - Input laser power: 0.2 W → 1 W
  - Observation time: 24 hours → 1 year
  - Resonant freq. difference between s- and p-pol.: 3 MHz → 0 Hz (simultaneous resonance)

We are installing an auxiliary cavity (Hiroki's talk)

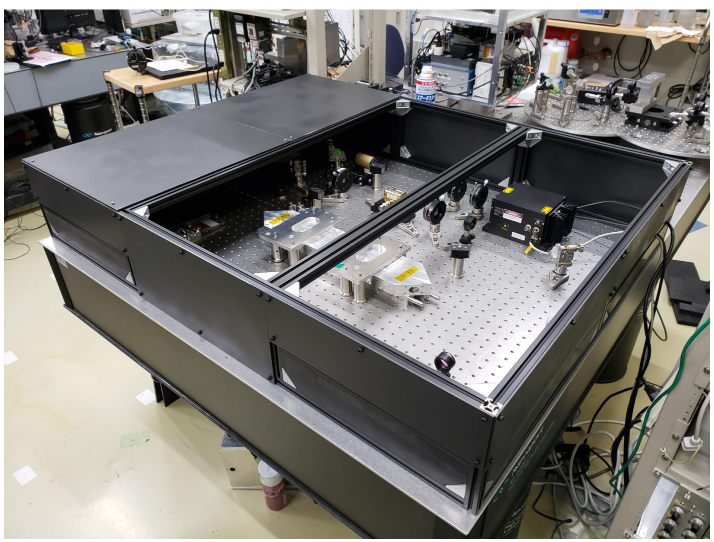
Summary

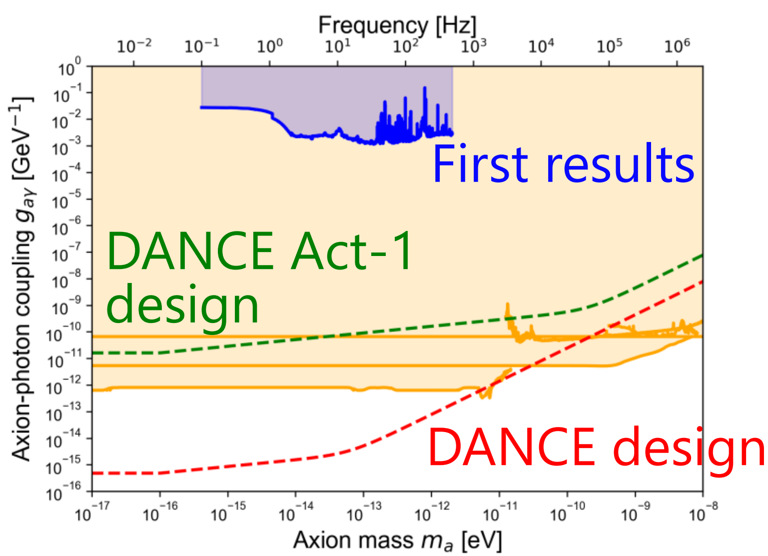
- New experimental project to search for axion DM with a bow-tie cavity: DANCE

I. Obata, T. Fujita, Y. Michimura
PRL 121, 161301 (2018)

- Prototype experiment DANCE Act-1 is ongoing
  - Long-term observation in May 2021
  - The first upper bounds on $g_{a\gamma}$ with an optical cavity
  - We continue to improve the sensitivity

YO, H. Fujimoto+, arXiv:2303.03594
H. Fujimoto, YO+, JPCS 2156, 012182 (2021)

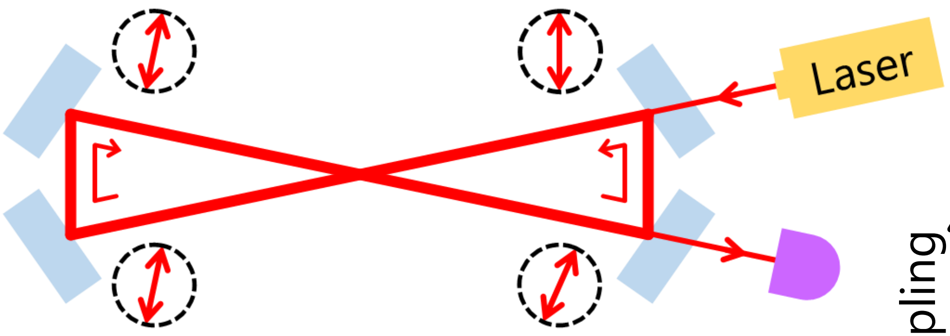


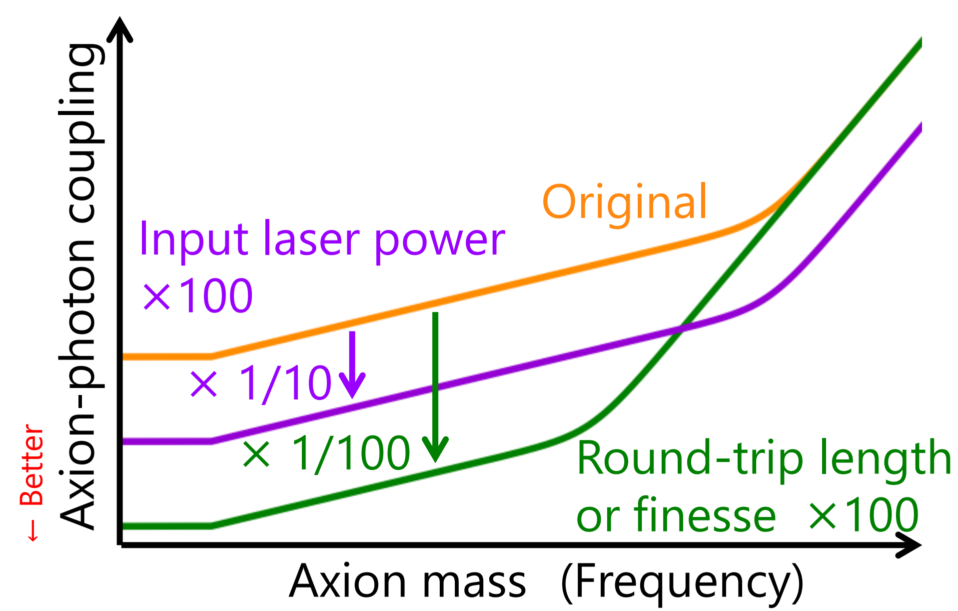


Extra Slides

Important parameters (1)

- Input laser power ・・・ Shot noise
- Round-trip length ・・・ Optical length
- Finesse ・・・ Number of round trip

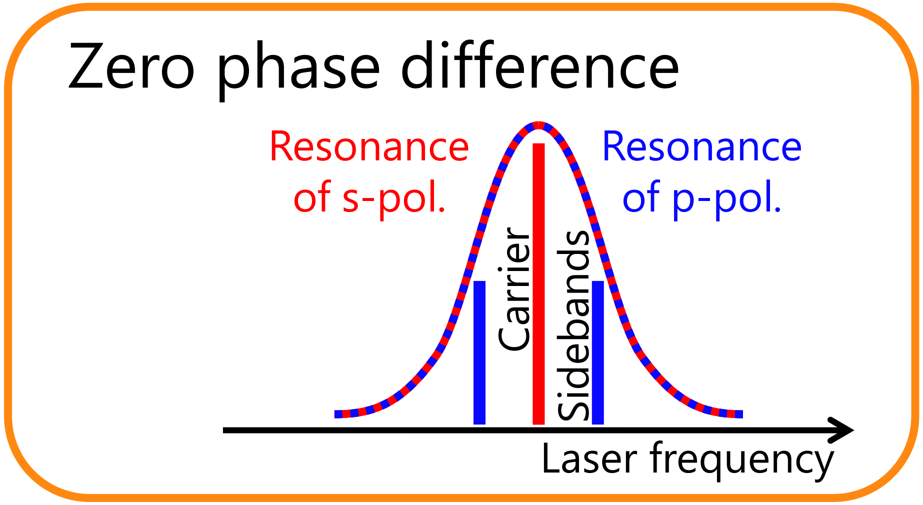


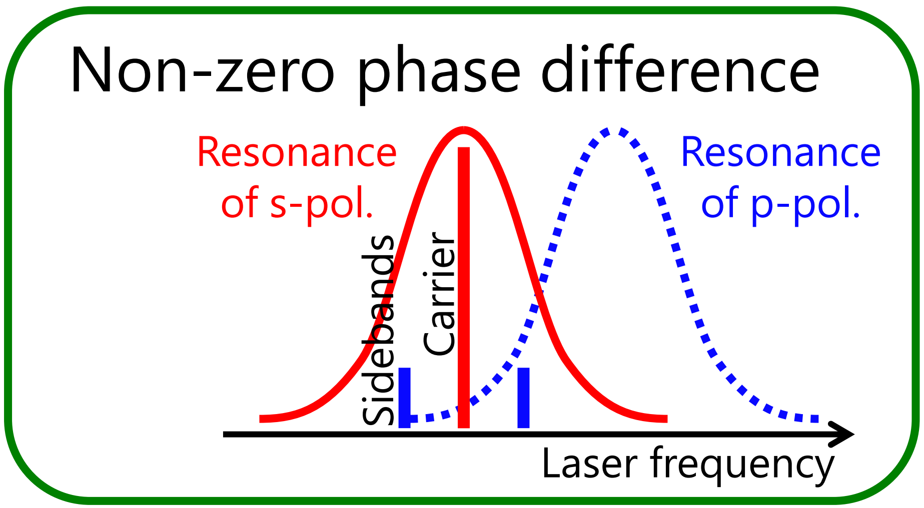


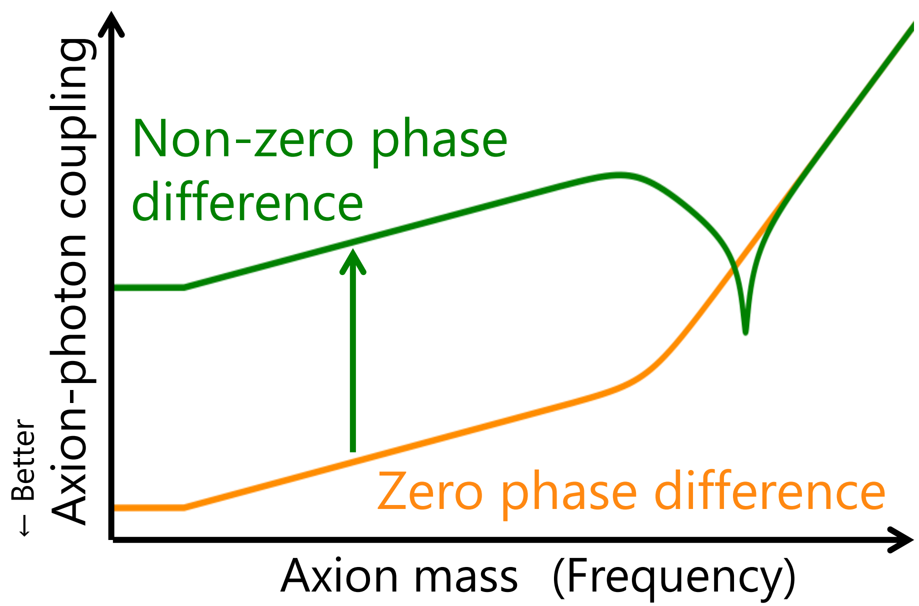
Important parameters (2)

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

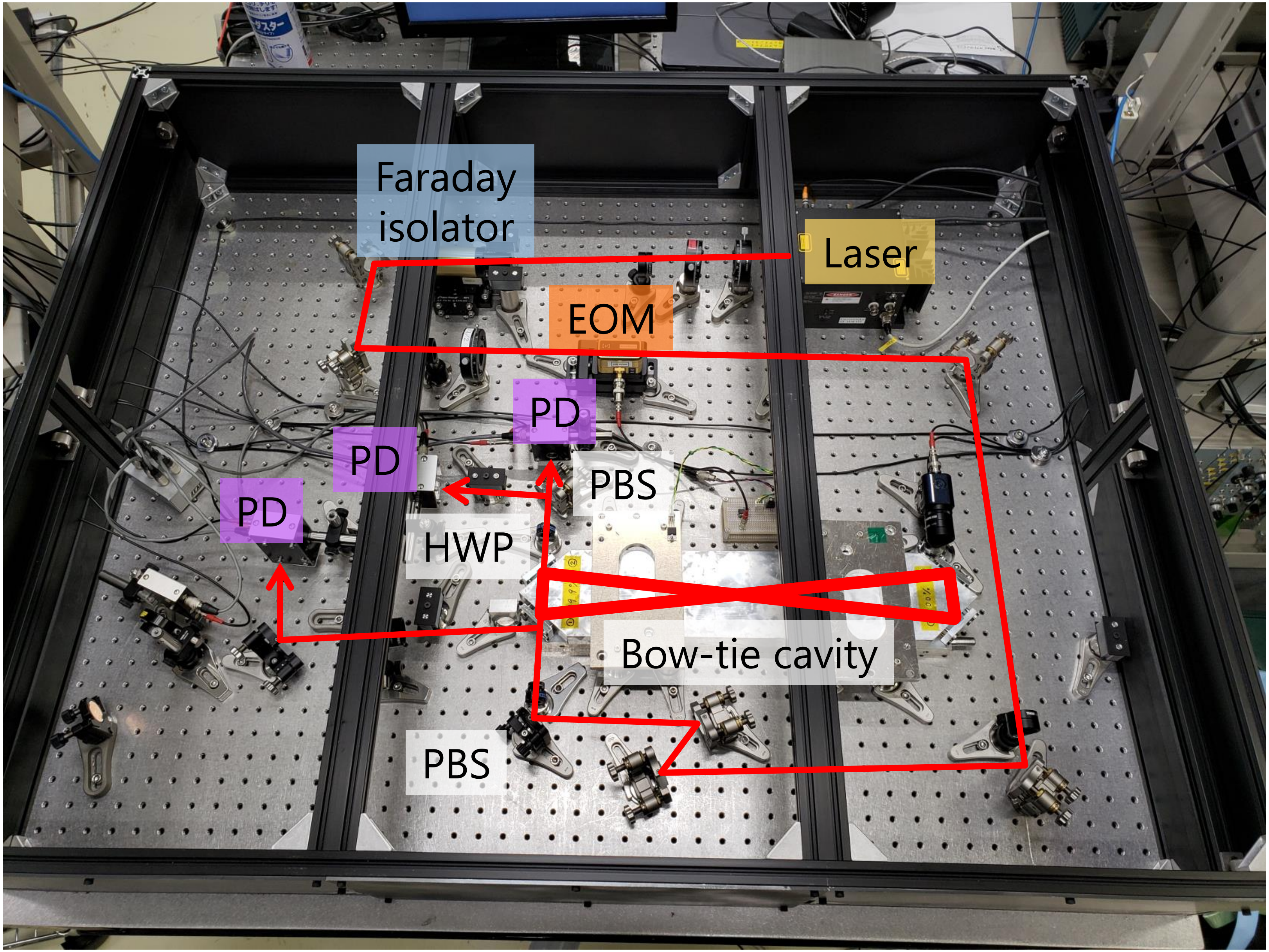
  ・・・ From different phase shifts by reflections on mirrors





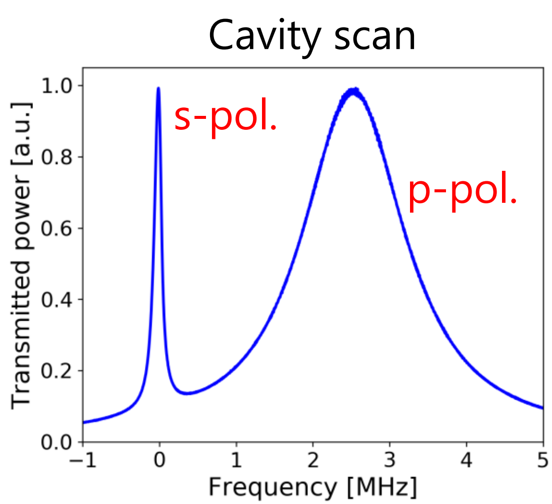


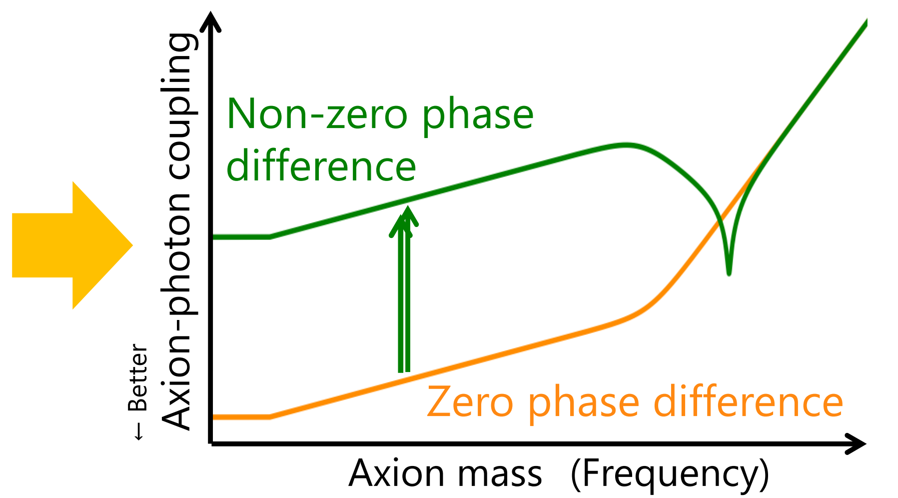
Picture of experimental setups



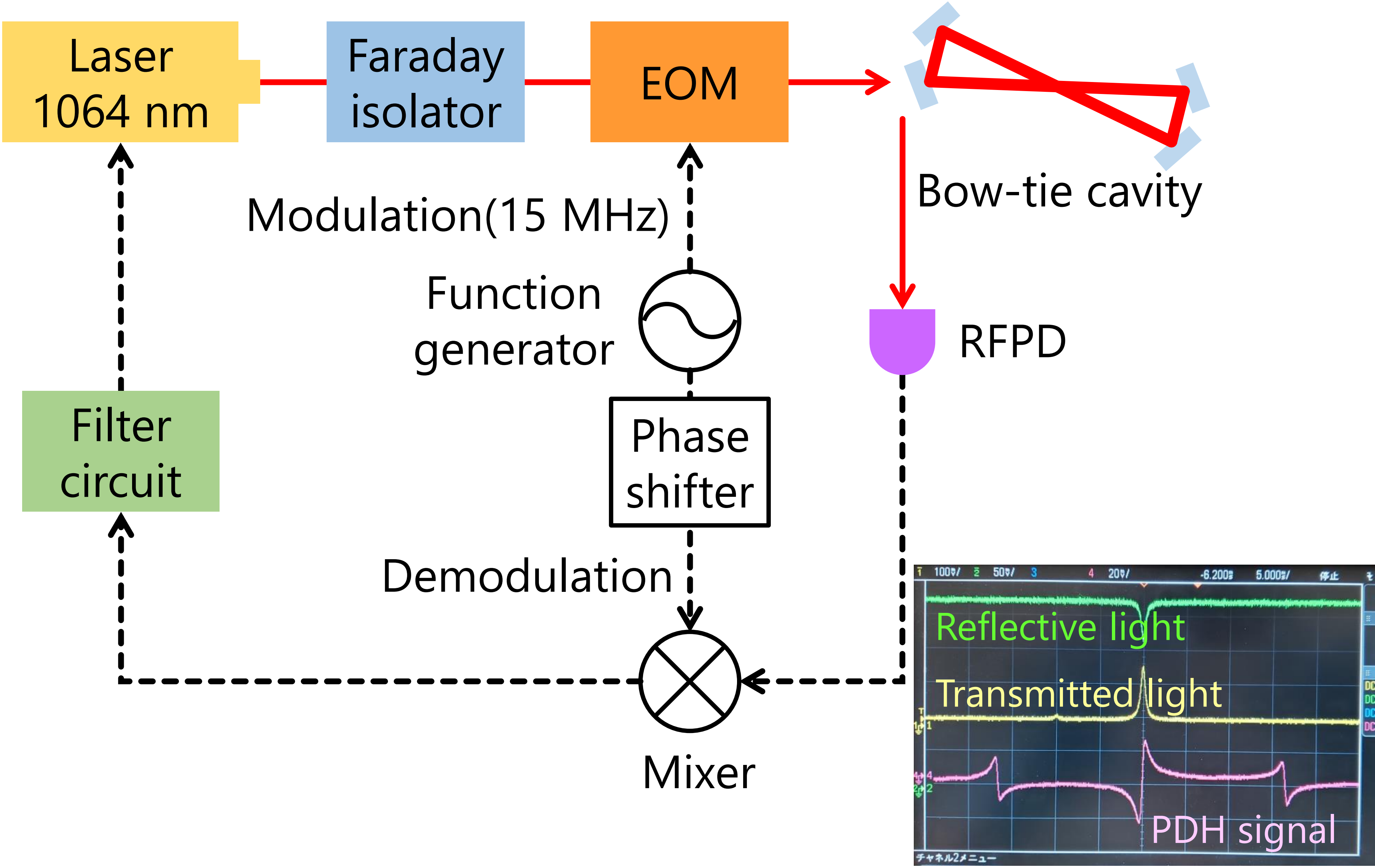
Performance of the cavity

	Designed values	Measured values
Input laser power	1 W	242(12) mW
Transmitted laser power	1 W	153(8) mW
Finesse of s-pol.	3×10^3	$2.85(5)\times10^3$
Finesse for p-pol.	3×10^3	195(3)
Reflective phase difference between s- and p-pol.	<1 mrad	52.4(4) mrad



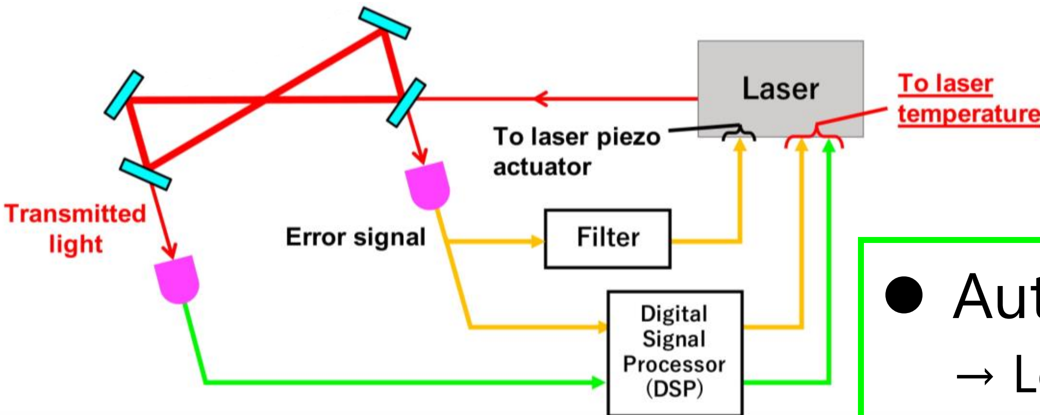


Frequency servo by PDH technique



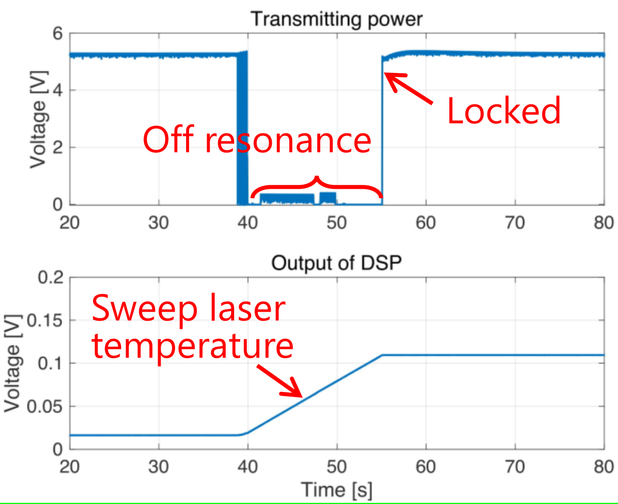
Long-term frequency control

- SNR can be improved with observation time
  → Need to observe for a long time
  (e.g. First test operation: 12 days, Final goal: 1 year)

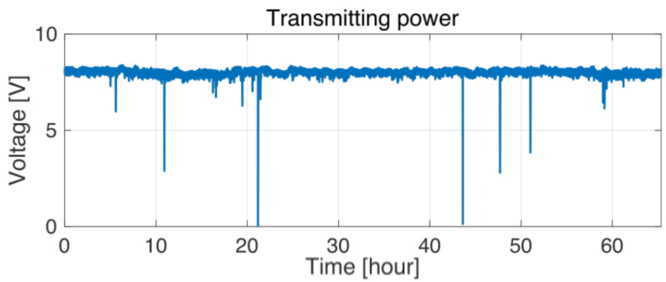


Experiment by H. Fujimoto
arXiv:2105.08347 (2021)

- Automated cavity locking system
  → Locked automatically by identifying whether on or off resonance

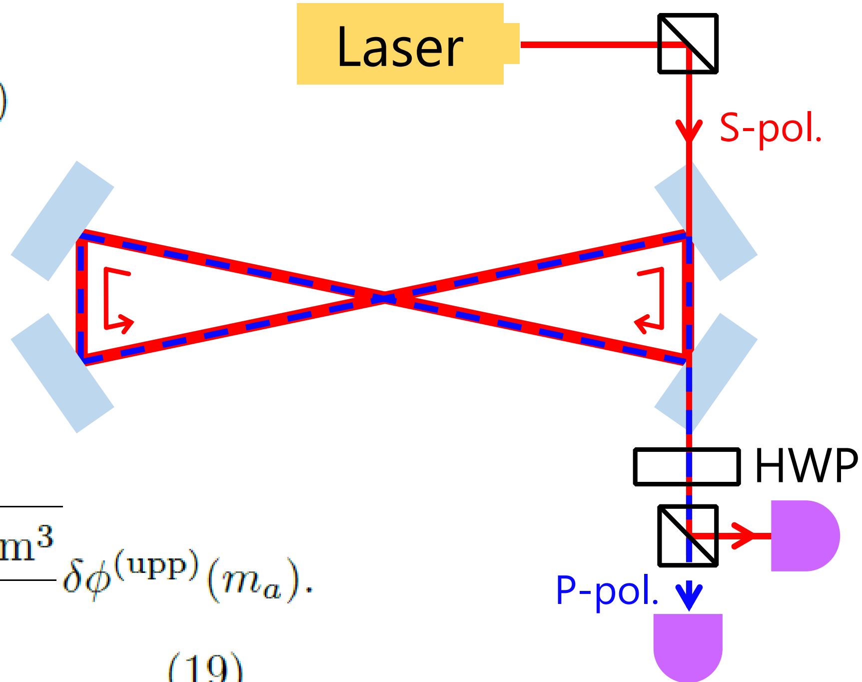


- Double-loop control
  → Kept resonance longer than 60 hours



Signal calibration

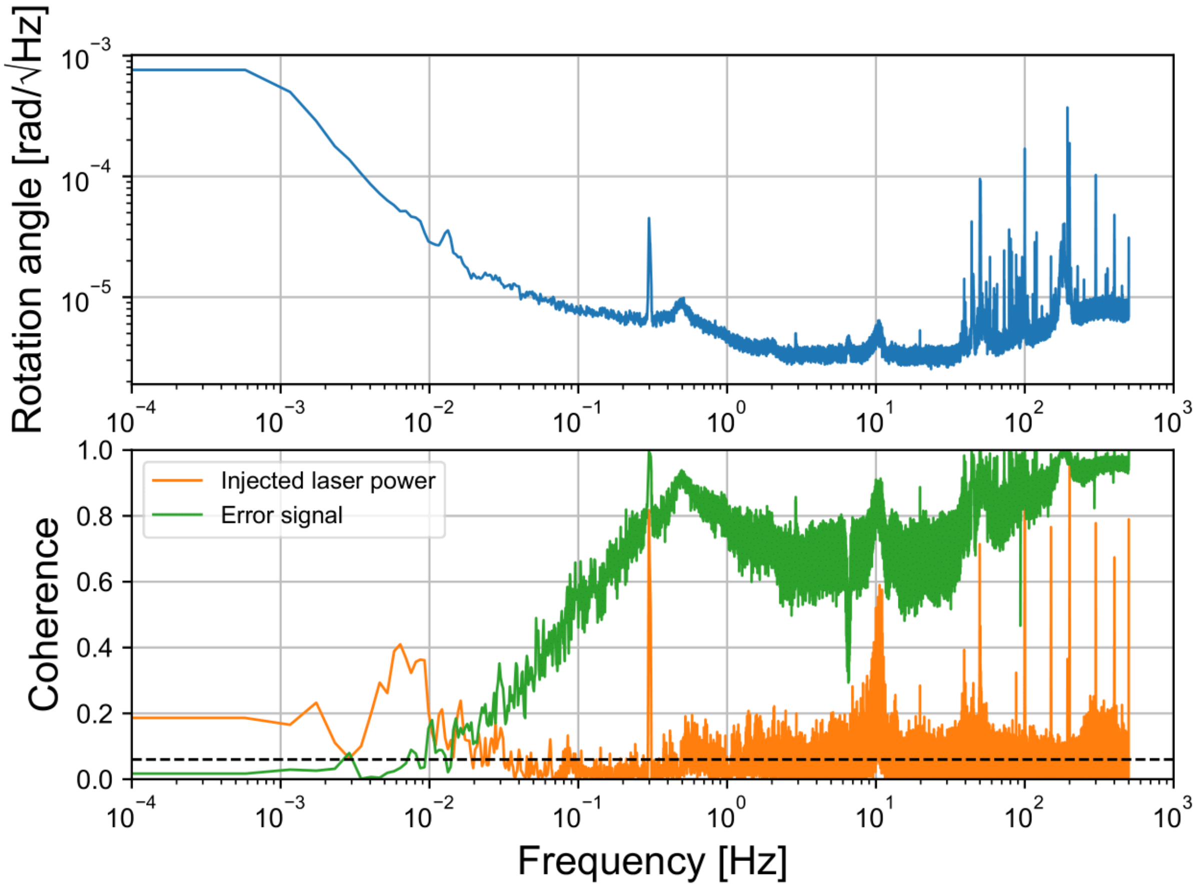
$$\phi(t) = \sqrt{\frac{P_{\rm p}(t)}{P_{\rm s}(t) + P_{\rm p}(t)}} - 2\theta_{\rm HWP}, \qquad (16)$$



$$g_{a\gamma}(m_a) = \frac{2k_0 \delta\phi^{(\rm upp)}(m_a)}{\sqrt{2\rho_a}|H'_a(m_a)|}$$
$$= 5.10 \times 10^{11}\,{\rm GeV}^{-1} \frac{{\rm eV}^{-1}}{|H'_a(m_a)|/k_0} \sqrt{\frac{{\rm GeV/cm^3}}{\rho_a}} \delta\phi^{(\rm upp)}(m_a). \qquad (19)$$

$$H_a(\omega) \equiv k_0 \sqrt{\frac{1-r_{\rm 1p}^2}{1-r_{\rm 1s}^2}} \frac{1}{i\omega(1-r_{\rm 1p}^2 r_{\rm 2p}^2) e^{-i\omega(2l_1+2l_2)}}$$
$$\times \left[(1-e^{-i\omega l_2}) \left(r_{\rm 1s} r_{\rm 2s} r_{\rm 1p} r_{\rm 2p} e^{-i\omega l_1} + r_{\rm 1p}^2 r_{\rm 2p}^2 e^{-i\omega(2l_1+l_2)} \right) \right.$$
$$\left. -(1-e^{-i\omega l_1}) \left(r_{\rm 1s} r_{\rm 2s}^2 r_{\rm 1p} + r_{\rm 1s} r_{\rm 1p} r_{\rm 2p}^2 e^{-i\omega(l_1+l_2)} \right) \right]. \qquad (13)$$

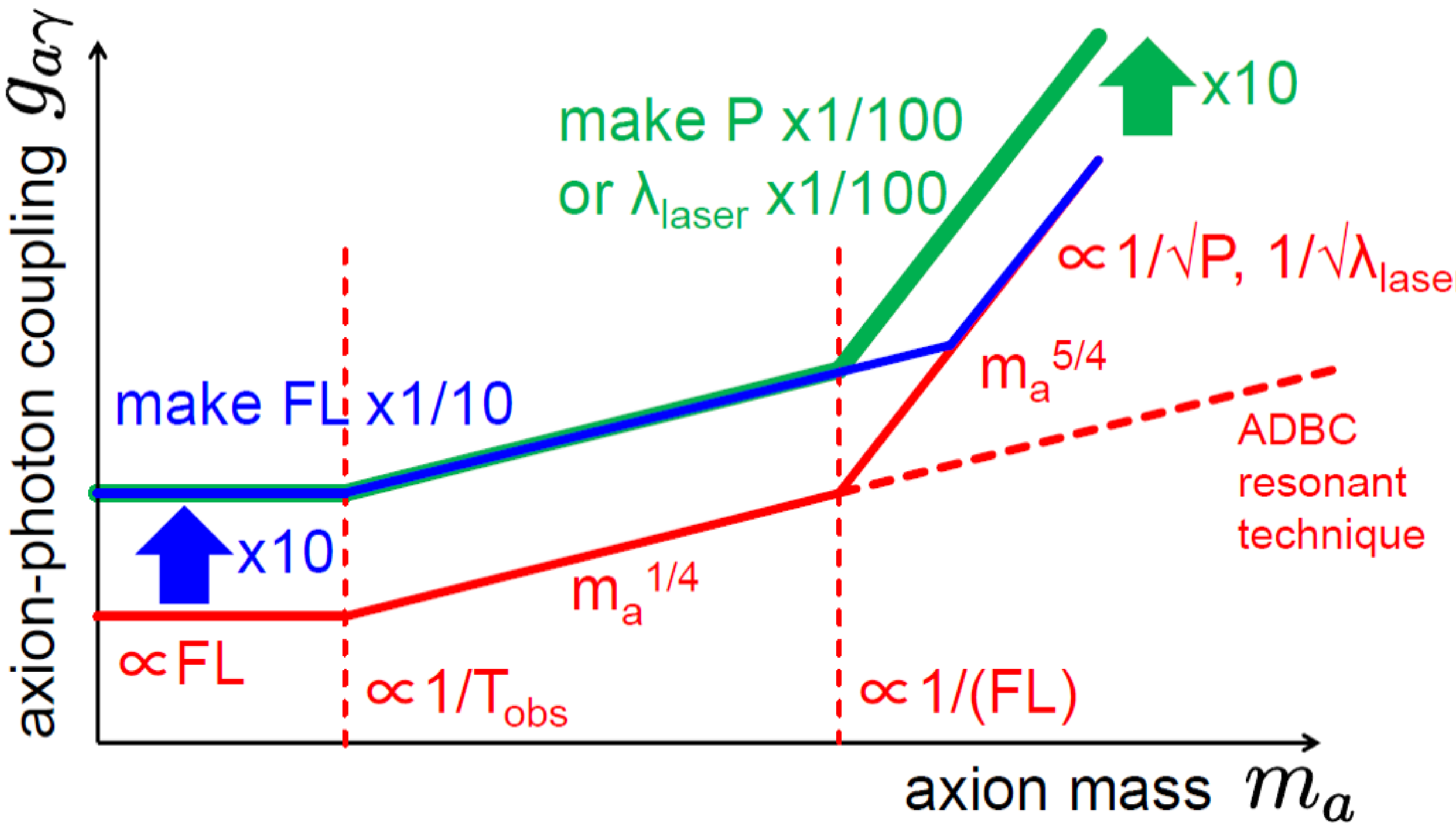
Discussion for noise sources



- -0.01 Hz: Suggested to be limited by laser intensity noise
- 0.01 Hz-: Suggested to be limited by
  mechanical vibration and laser freq. noise

Sensitivity Design

- Brute force necessary, you cannot win for free



Coherent Time Scale

- SNR grows with √Tobs if integration time is shorter than coherent time scale
- SNR grows with $(\mathrm{Tobs})^{1/4}$ if integration time is longer

$$\mathrm{SNR} = \begin{cases} \dfrac{\sqrt{T_{\rm obs}}}{2\sqrt{S_{\rm noise}(f)}}\dfrac{\delta c}{c} & (T_{\rm obs} \lesssim \tau) \\ \dfrac{(T_{\rm obs}\tau)^{1/4}}{2\sqrt{S_{\rm noise}(f)}}\dfrac{\delta c}{c} & (T_{\rm obs} \gtrsim \tau) \end{cases}$$

$$\tau \simeq 1\ \mathrm{year}\left(\frac{10^{-16}\ \mathrm{eV}}{m_a}\right)$$