First test operation of DANCE: Dark matter Axion search with riNg Cavity Experiment

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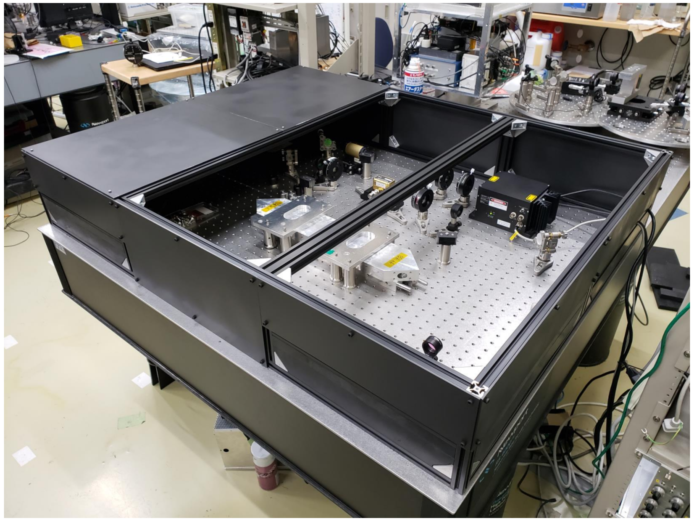
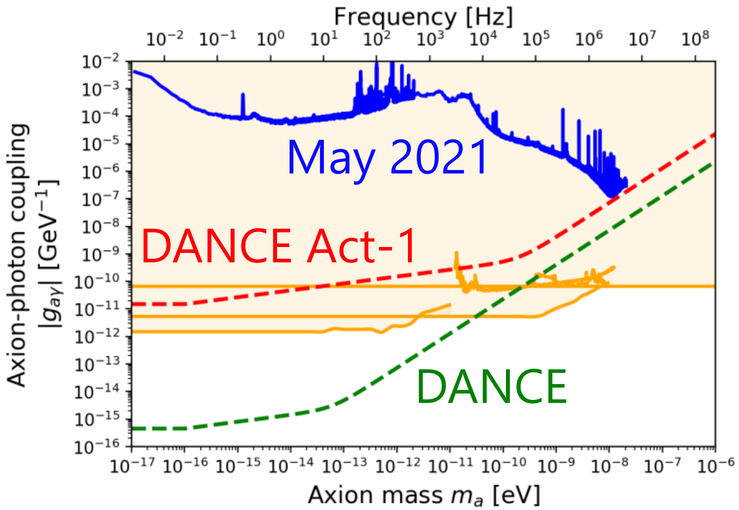
Overview

- We proposed a new experiment to search for axion dark matter with a ring cavity
  DANCE: Dark matter Axion search with riNg Cavity Experiment

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

- Prototype experiment DANCE Act-1 is ongoing
  - Assembled and evaluated the optics
  - Obtained the first data for 12 days

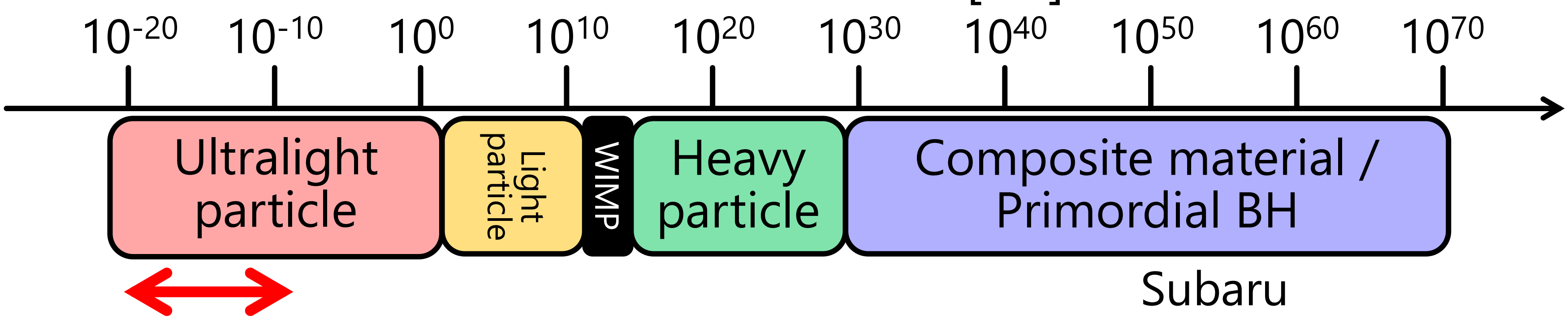




Axion search with laser interferometers

- Need to search for dark matter in wider mass range
- Ultralight dark matter can be searched with laser interferometers
- DANCE focuses on axion dark matter

Dark matter mass [eV]



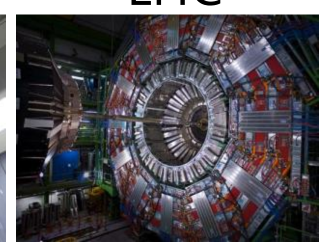
Laser interferometers

DANCE

KAGRA

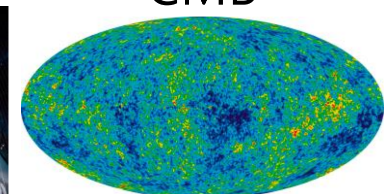
XENON1T

LHC



Subaru Telescope

CMB



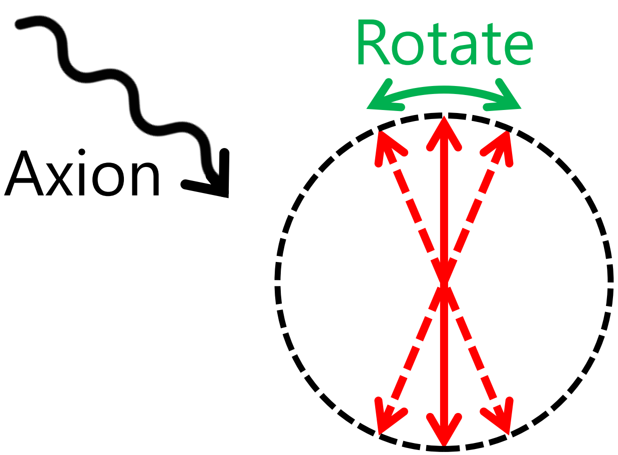
Polarization rotation from axions

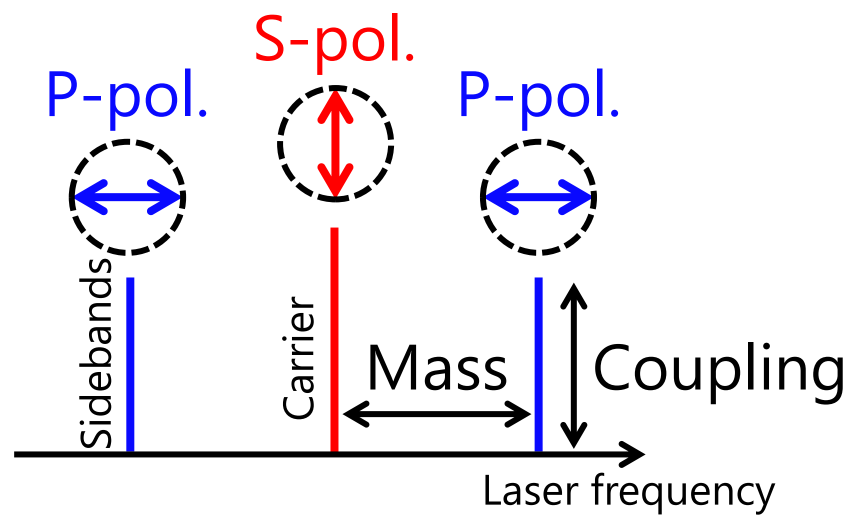
- Axion-photon coupling causes phase velocity difference between left- and right-handed photons

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

Coupling constant　　Axion field　　Axion mass

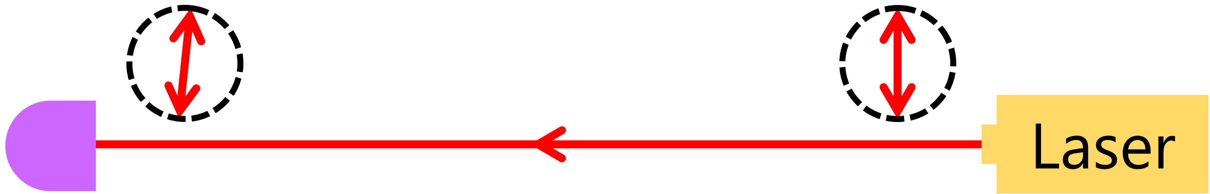
- Phase velocity difference of circular polarizations makes linear polarization rotate



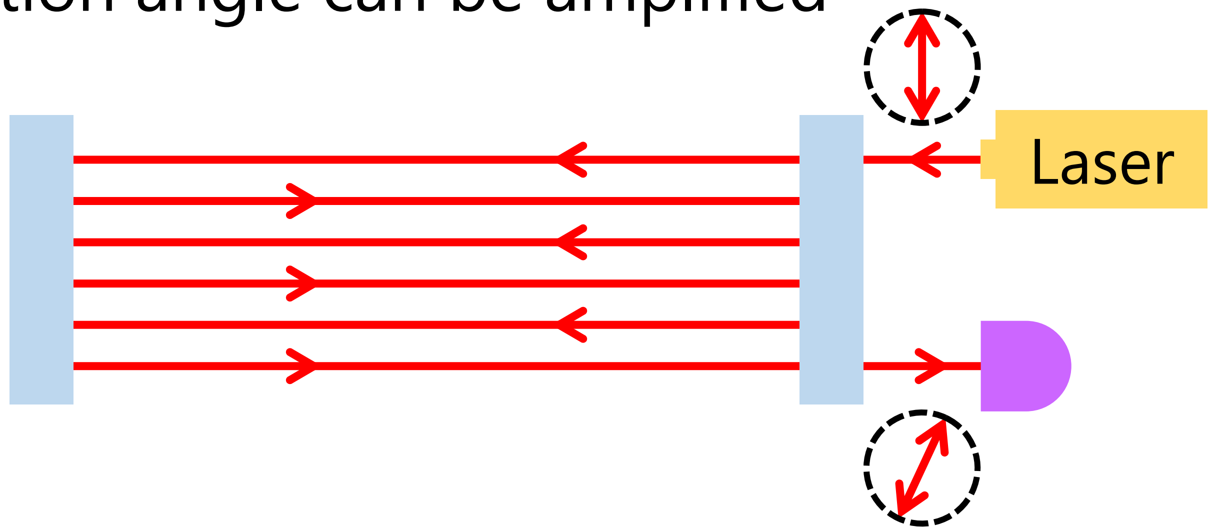


Signal amplification with cavities

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

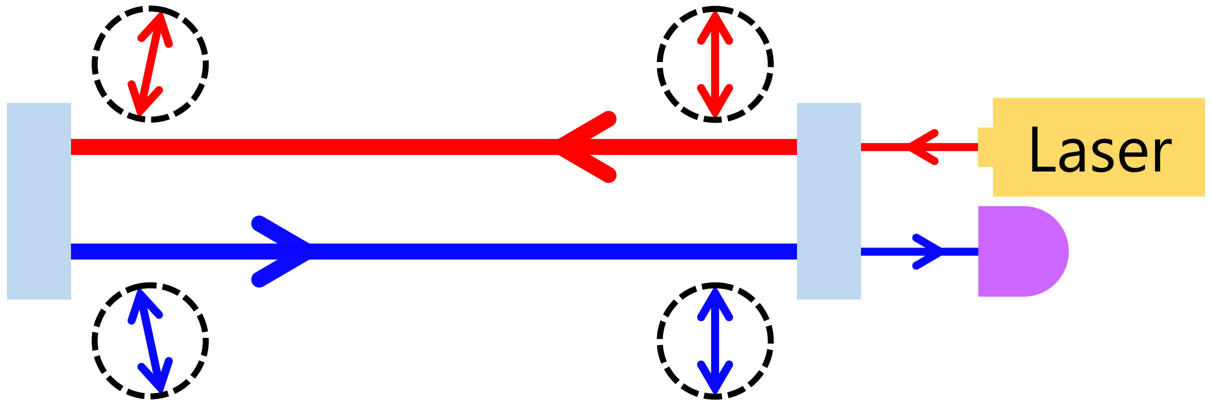


- Laser light runs between mirrors many times in a cavity
  → Rotation angle can be amplified

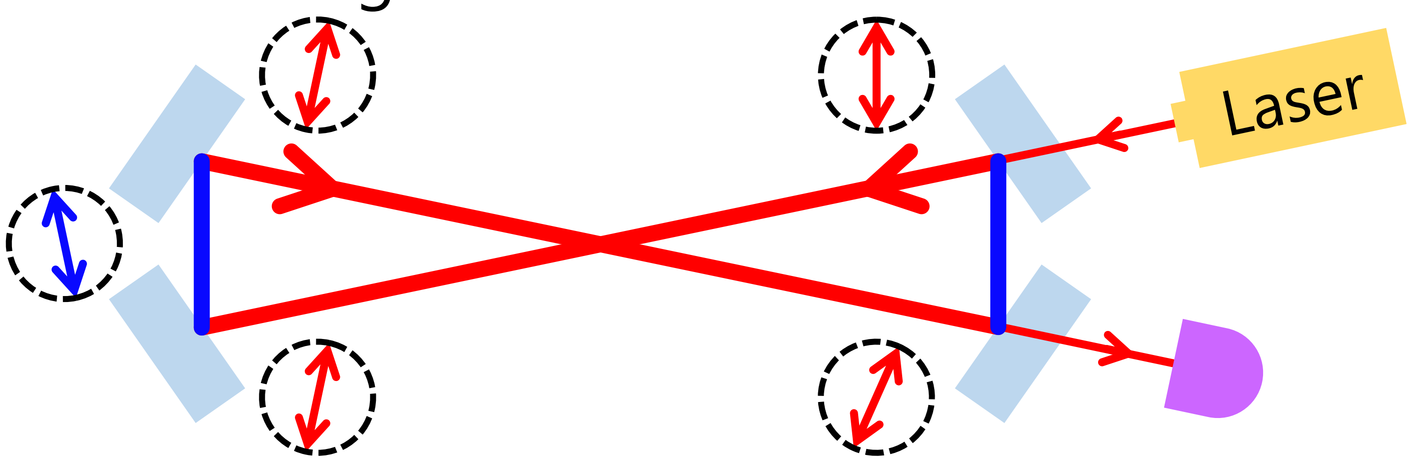


Bow-tie ring cavity

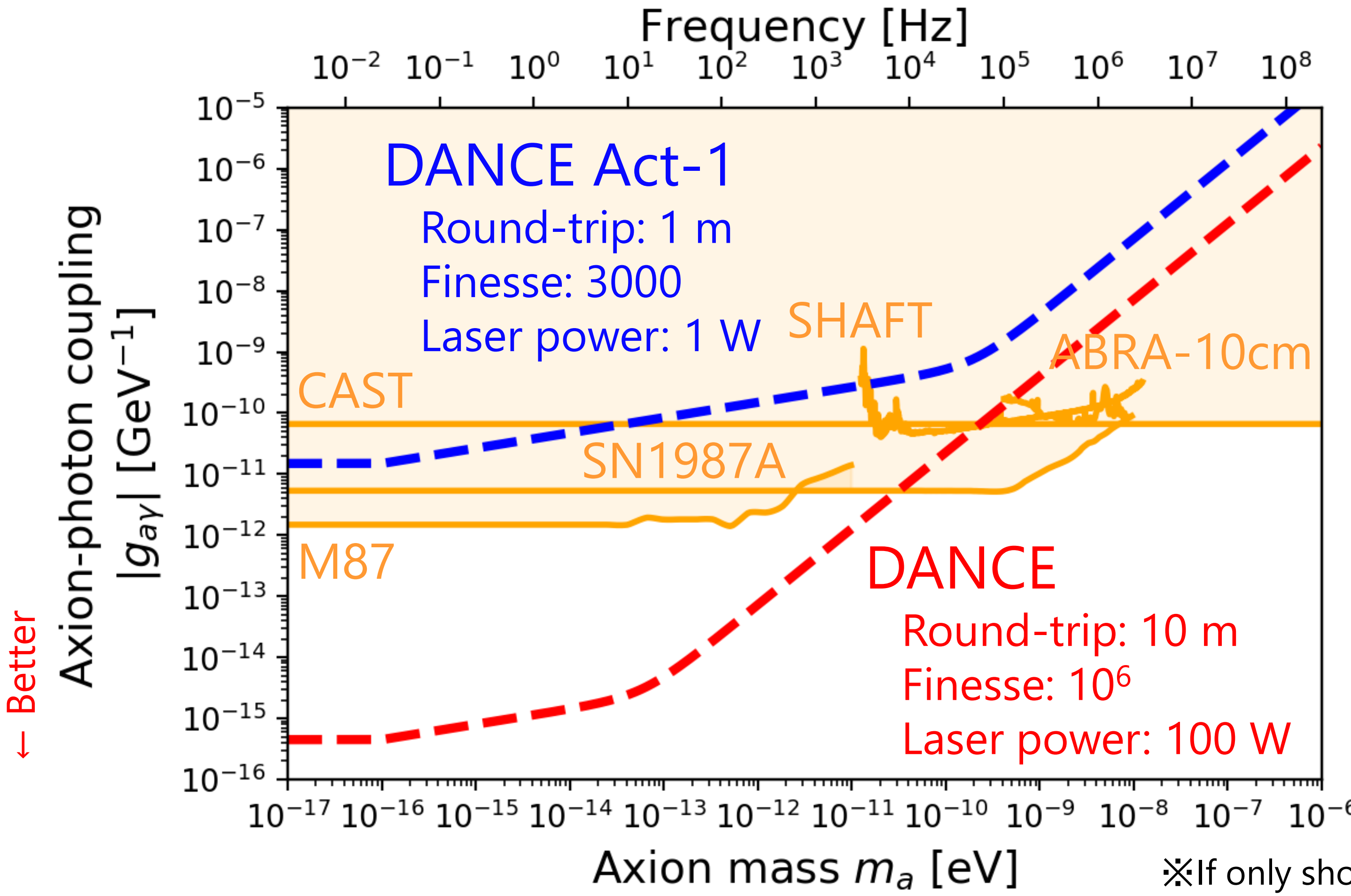
- Rotated direction is inverted in a linear cavity
  → Rotation effect is cancelled out



- A bow-tie ring cavity prevents linear polarization from inverting rotated direction



Design sensitivity of DANCE



Anastassopoulos+ (2017)
Payez+ (2015)
Marsh+ (2017)
Gramolin+ (2021)
Salemi+ (2021)

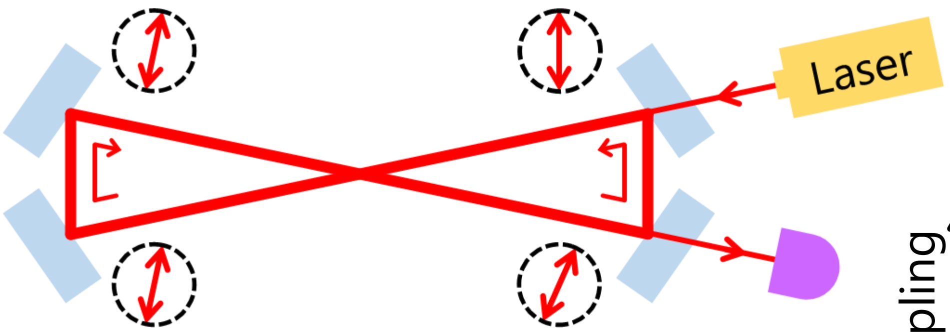
※If only shot noise
If one-year observation
If DM is all composed of axion

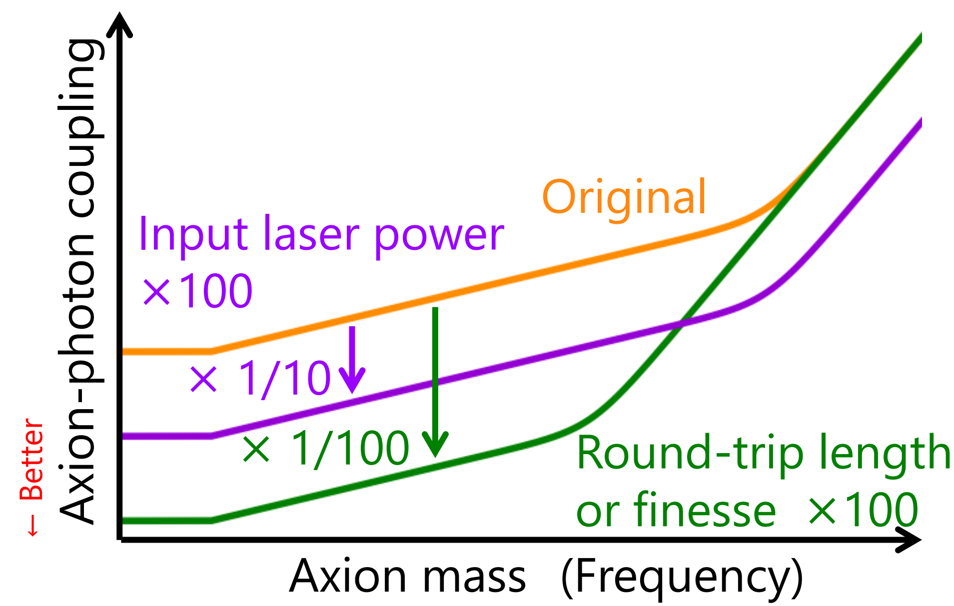
- Shot noise is caused by fluctuations of number of photons
- Need to minimize the other noises

Important parameters (1)

- Input laser power ・・・ Shot noise

- Round-trip length ・・・ Optical length
- Finesse ・・・ Number of round trip

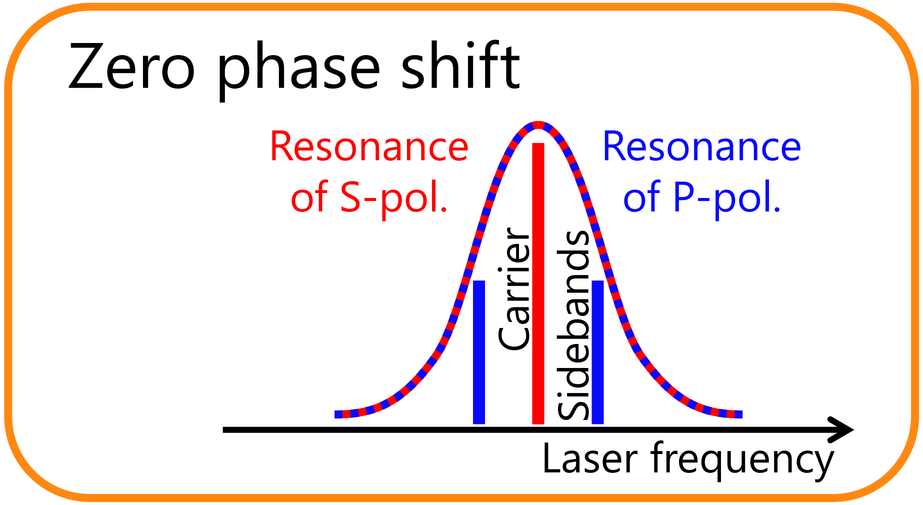


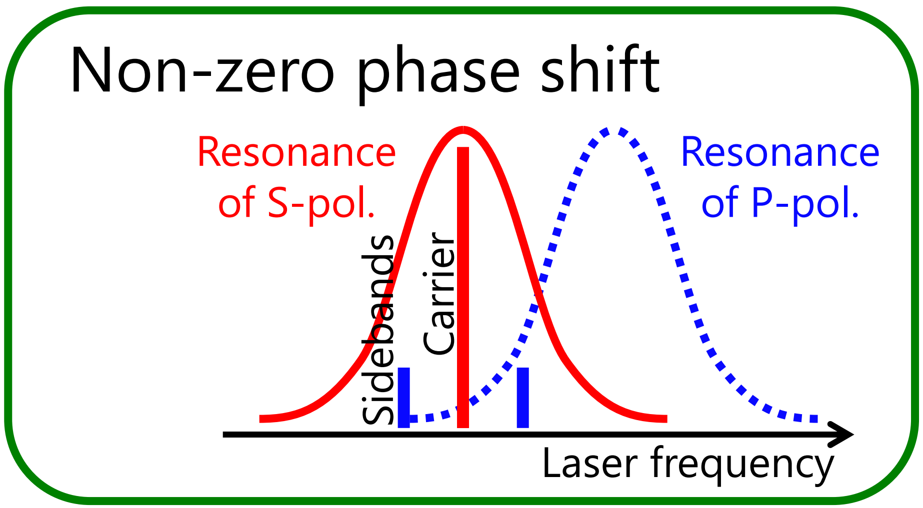


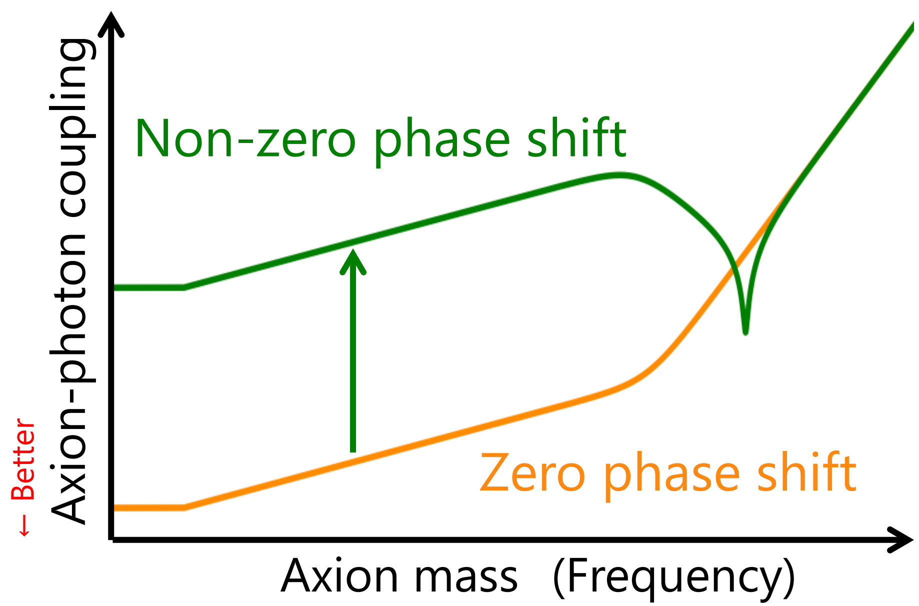
Important parameters (2)

- Resonant frequency difference between S- and P-pol.

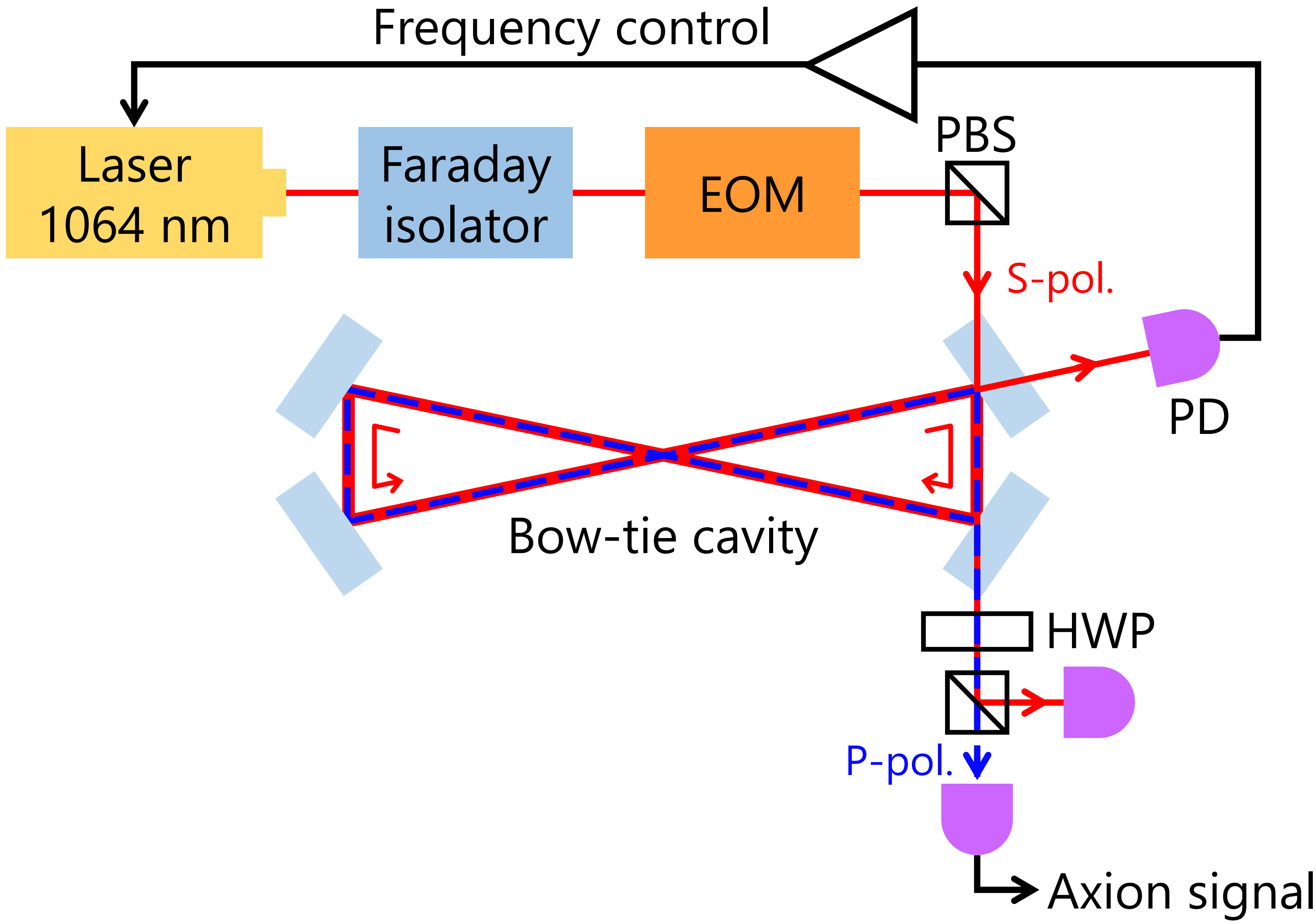
  ・・・From non-zero phase shift by mirror coating at reflections



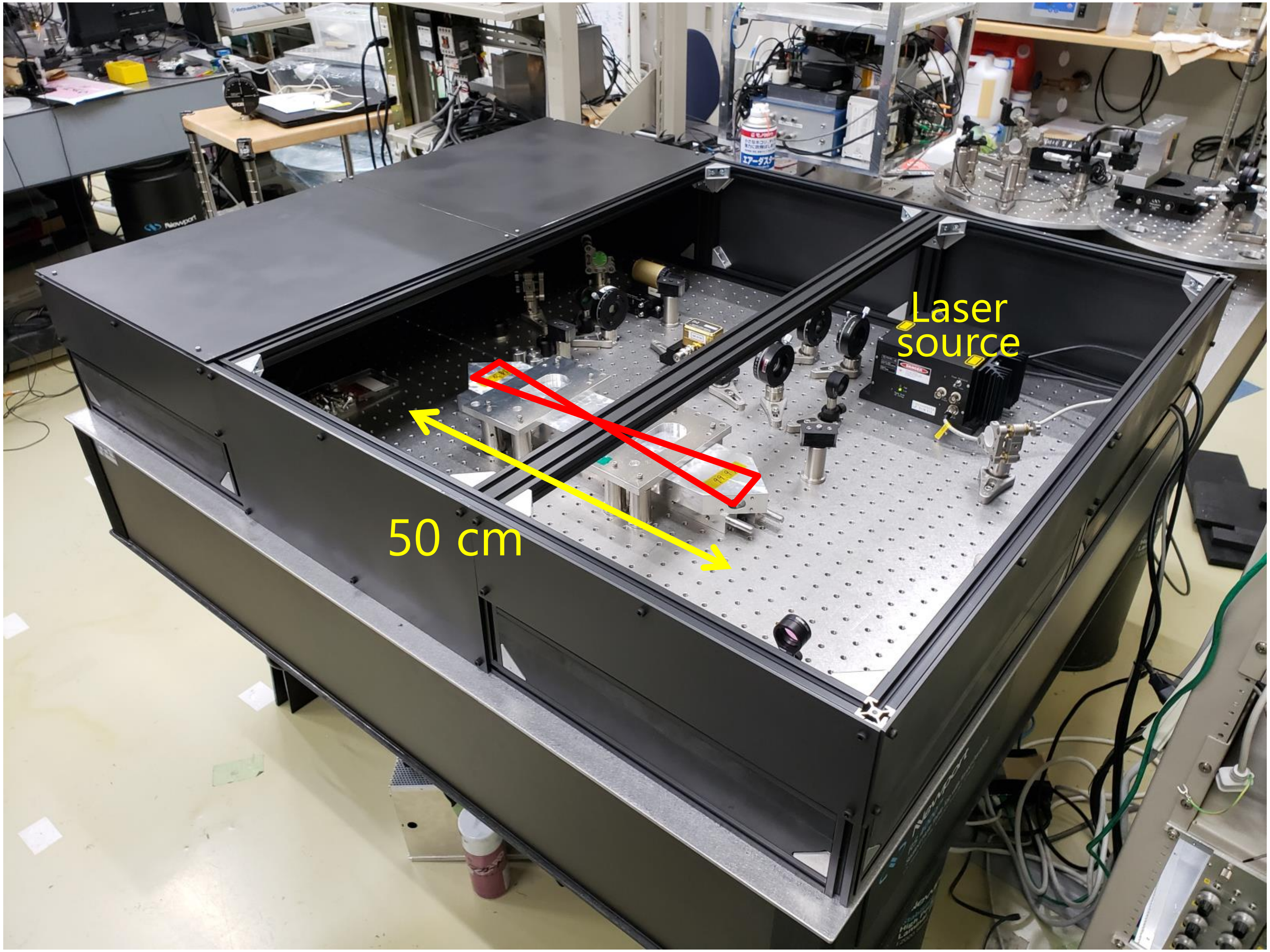




Experimental setup of DANCE

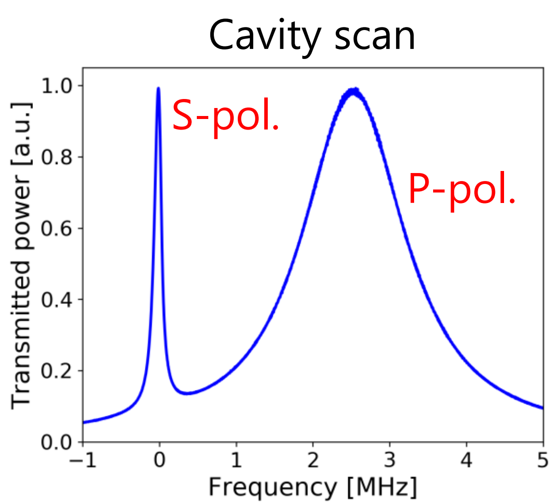


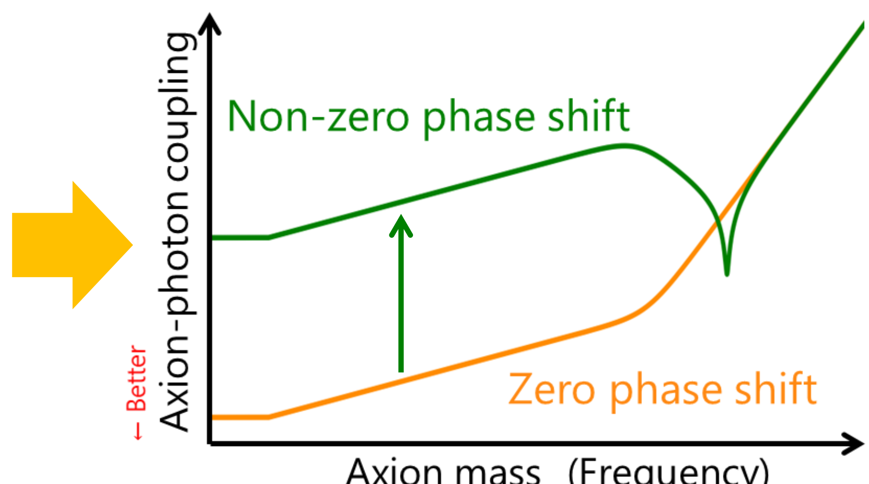
Picture of DANCE Act-1



Performance evaluation of the cavity

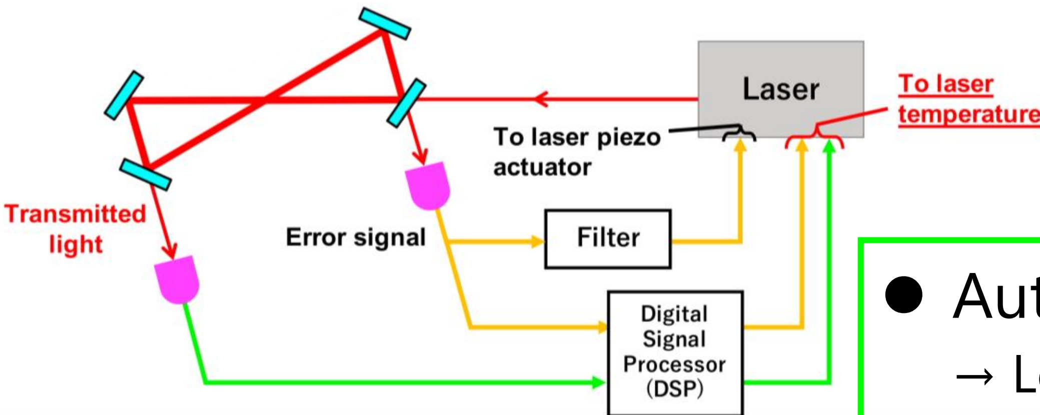
	Designed values	Measured values
Input laser power	1 W	242(12) mW
Transmitted laser power	1 W	153(8) mW
Finesse for carrier	3×10^3	$2.85(5)\times10^3$ (S-pol.)
Finesse for sidebands	3×10^3	195(3) (P-pol.)
Resonant frequency difference between S- and P-pol.	0 Hz	2.52(2) MHz





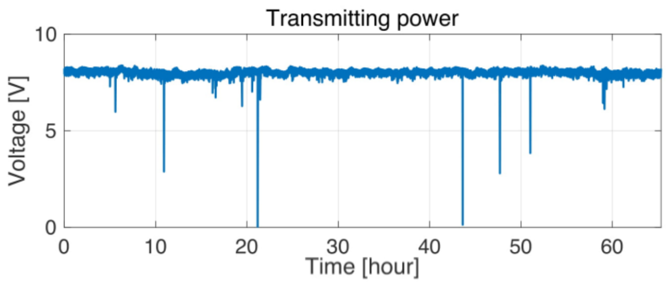
Long-term frequency control

- 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)

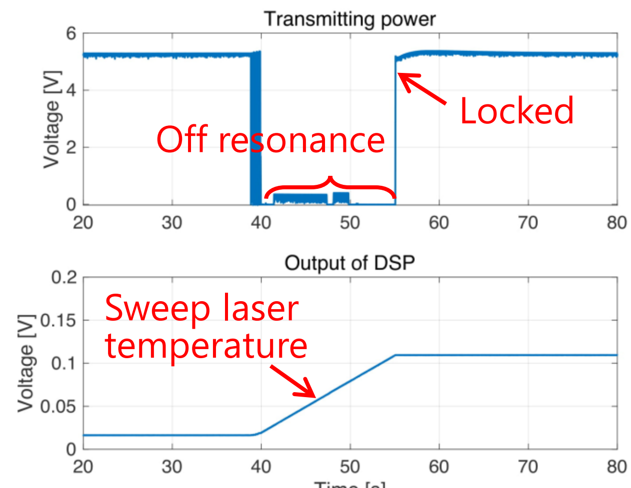


Experiment by H. Fujimoto
arXiv:2105.08347 (2021)

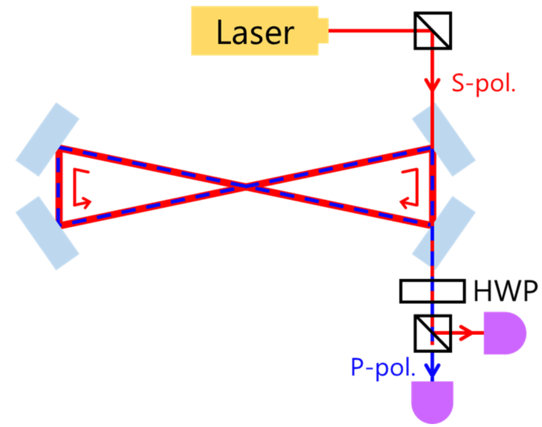
- Double-loop control
  → Kept resonance longer than 60 hours



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



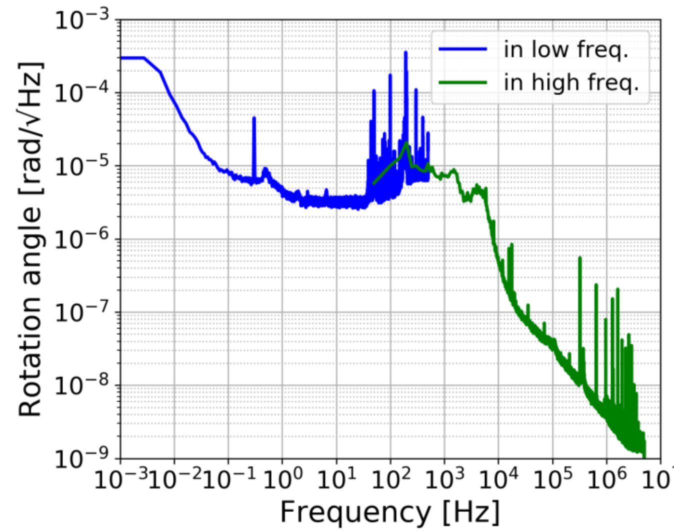
Data acquisition and calibration



- Recorded amount of P-pol. $P_\mathrm{P}(t)$ and total transmitted light $P_\mathrm{tot}(t)$
  - Data in low freq.: for 12 days (May 18-30, 2021) with 1 kHz sampling
  - Data in high freq.: with 10 MHz sampling

- Calibrated to rotation angle of pol.

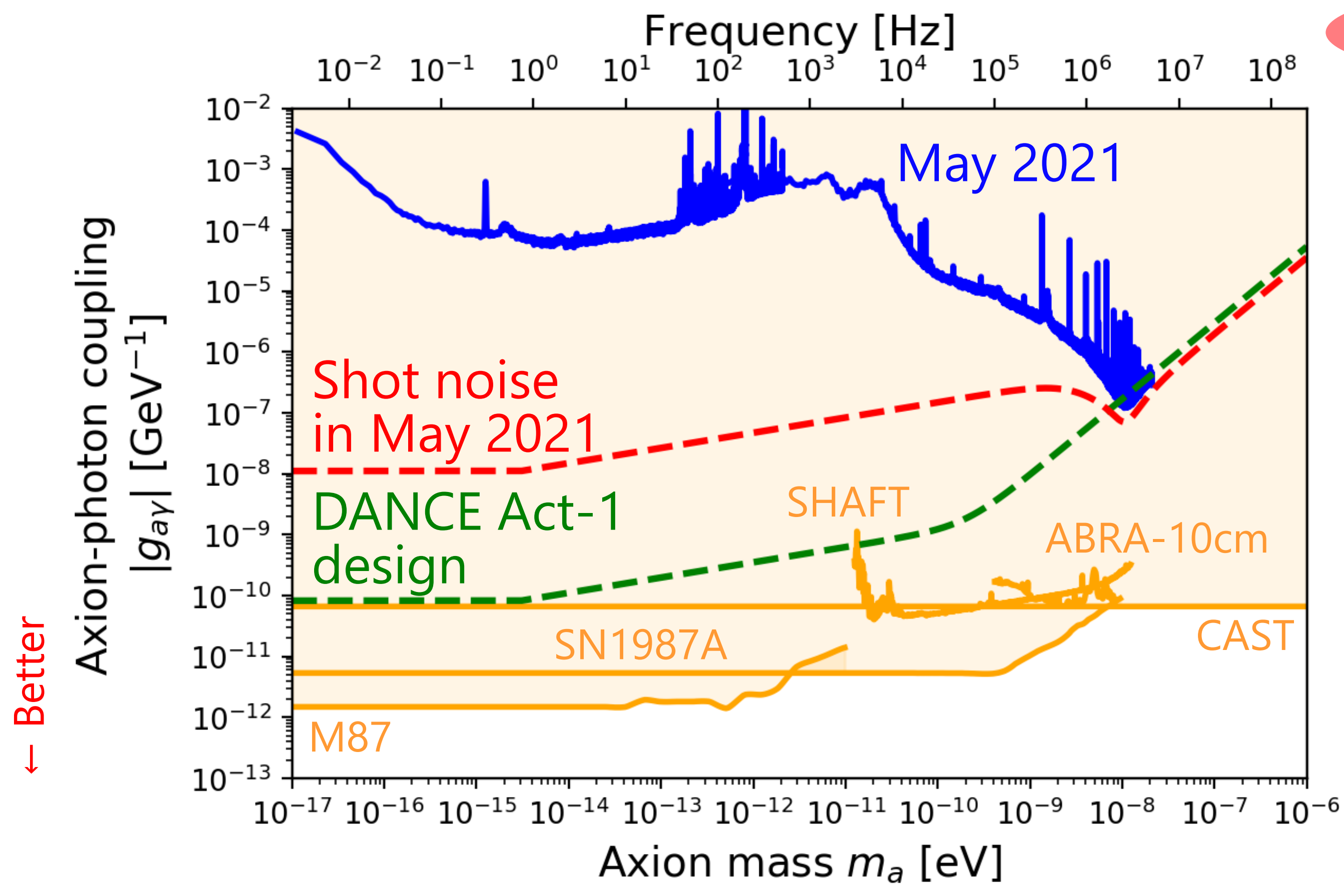
$$\phi(t) = \sqrt{P_\mathrm{P}(t)/P_\mathrm{tot}}$$



Estimated sensitivity

Assuming 12-day observation

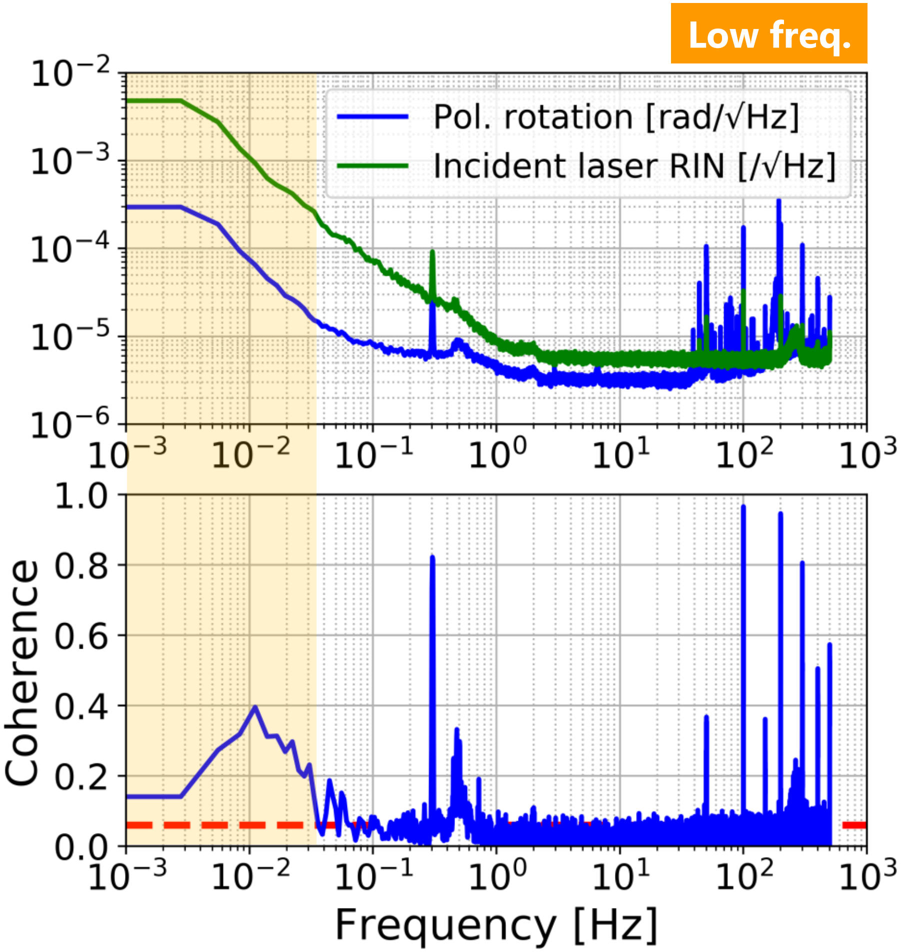
Preliminary



- Need to reduce noises to reach shot noise
- Need to reduce resonant frequency difference between pol. and inject higher laser power to achieve DANCE Act-1 design

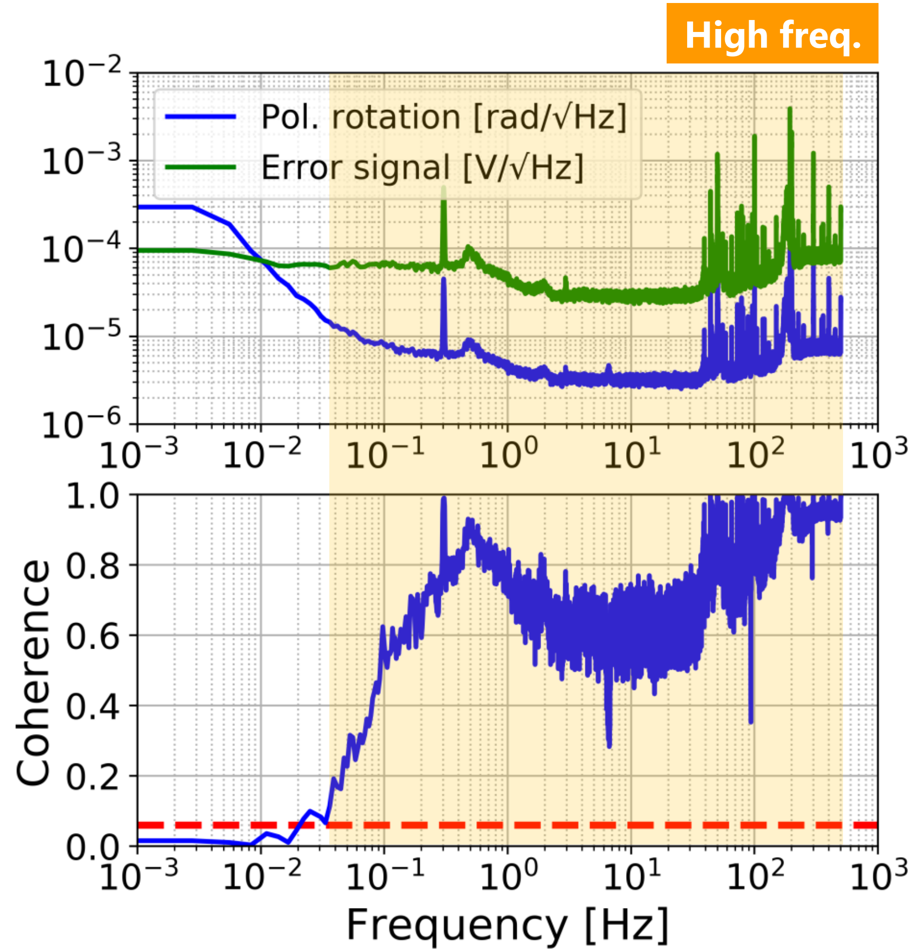
Discussion for noises

Correlation with incident light



Suggested to be limited by laser intensity noise below 0.03 Hz

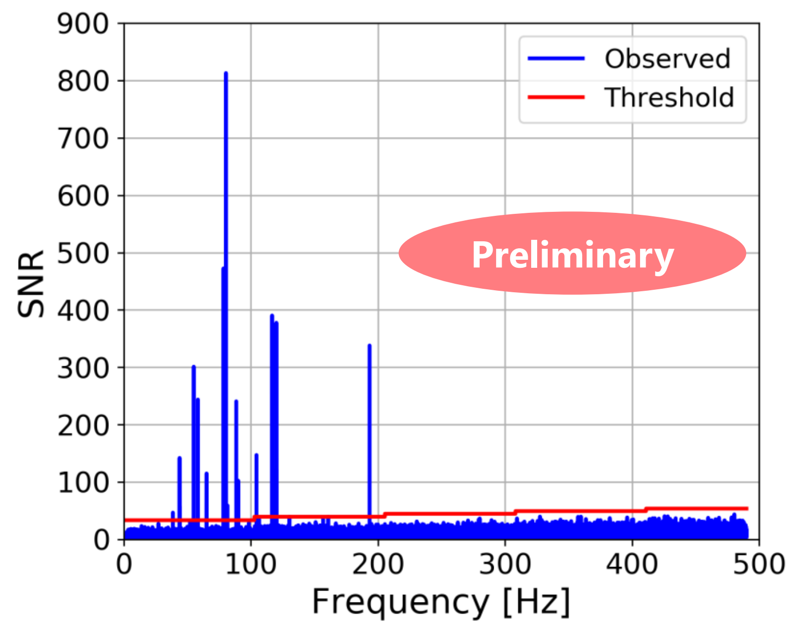
Correlation with error signal



Suggested to be limited by external noises such as mechanical vibration above 0.03 Hz

Data analysis

- Applied the ultralight dark matter data analysis pipeline developed by S. Morisaki and J. Kume
- We have 12-day data, but started with one-hour data due to high computational cost
  → Found 82 candidate peaks

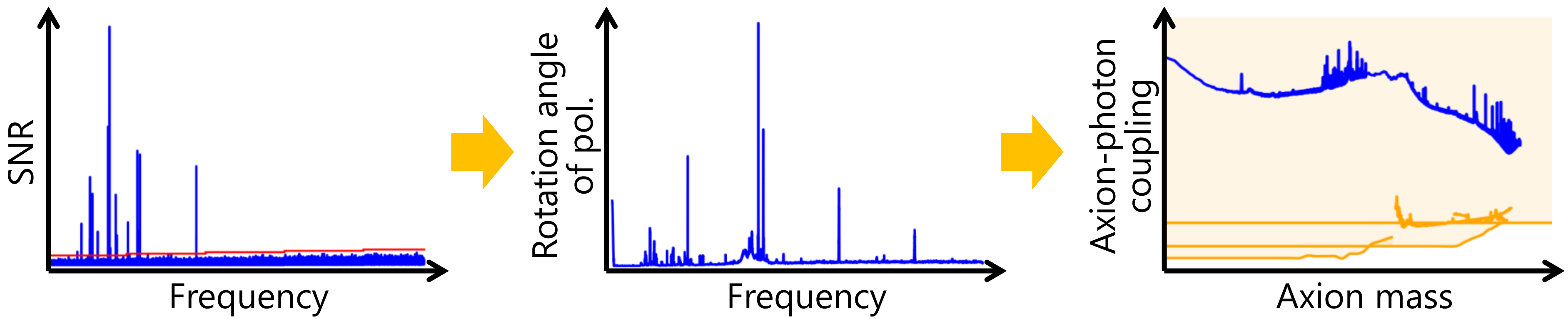


- Next step: veto noise peaks
  - Sharpness of peaks
  - Coincidence between several segments of data

Future plans

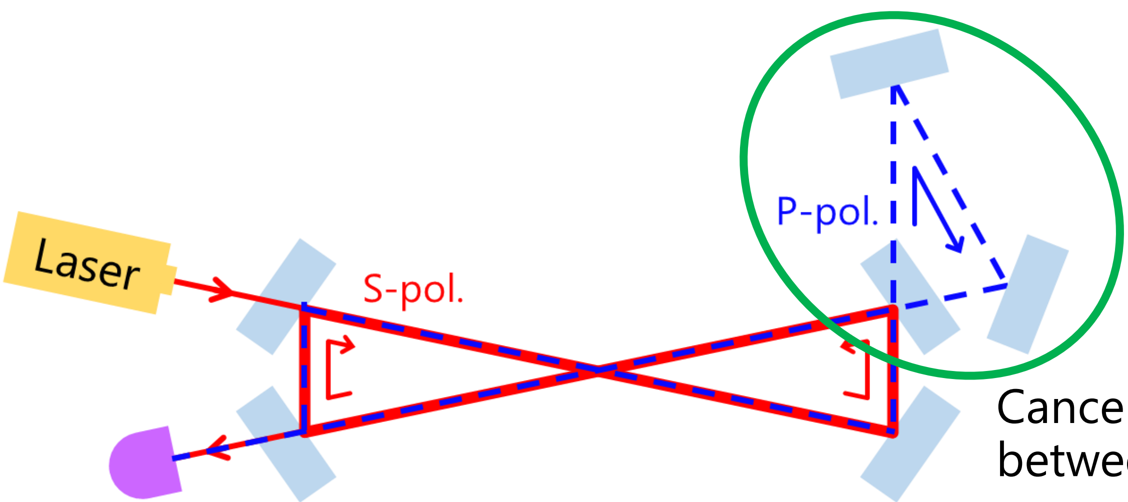
- Data analysis to set the upper limit

1. Find candidates
2. Veto noise peaks
3. Set the upper limit to rotation angle of pol.
4. Convert to coupling constant



- New setup of DANCE Act-1 to improve the sensitivity

D. Martynov, H. Miao
PRD 101, 095034 (2020)



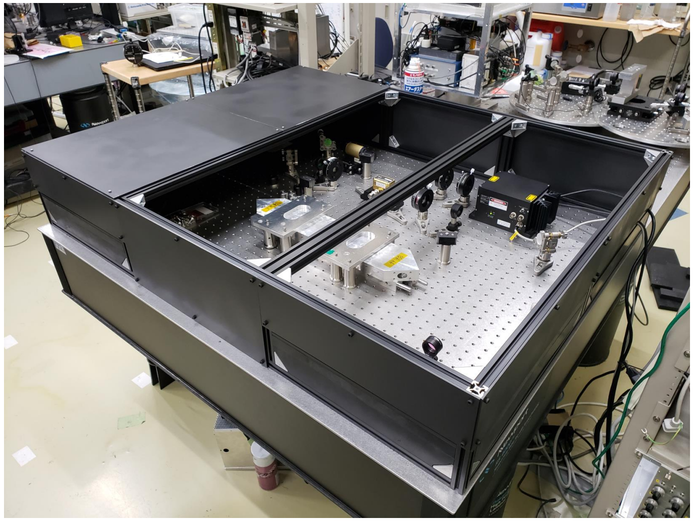
Cancel out resonant frequency difference between S- and P-pol.

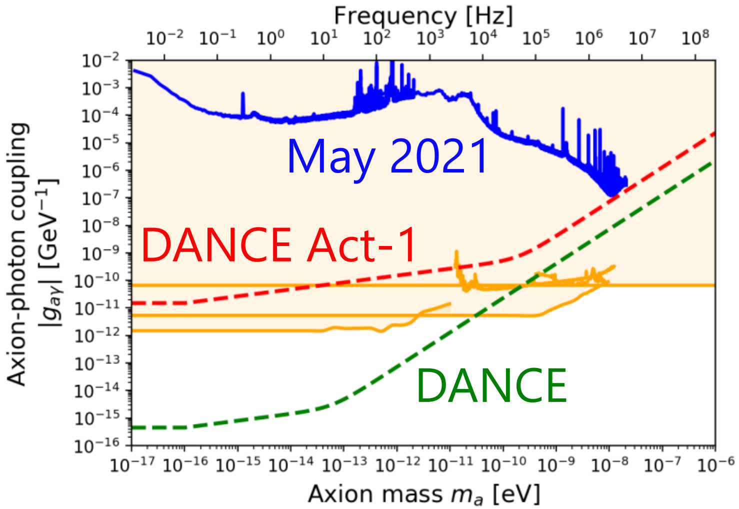
Summary

- A new experiment to search for axion dark matter with a ring cavity (DANCE)

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

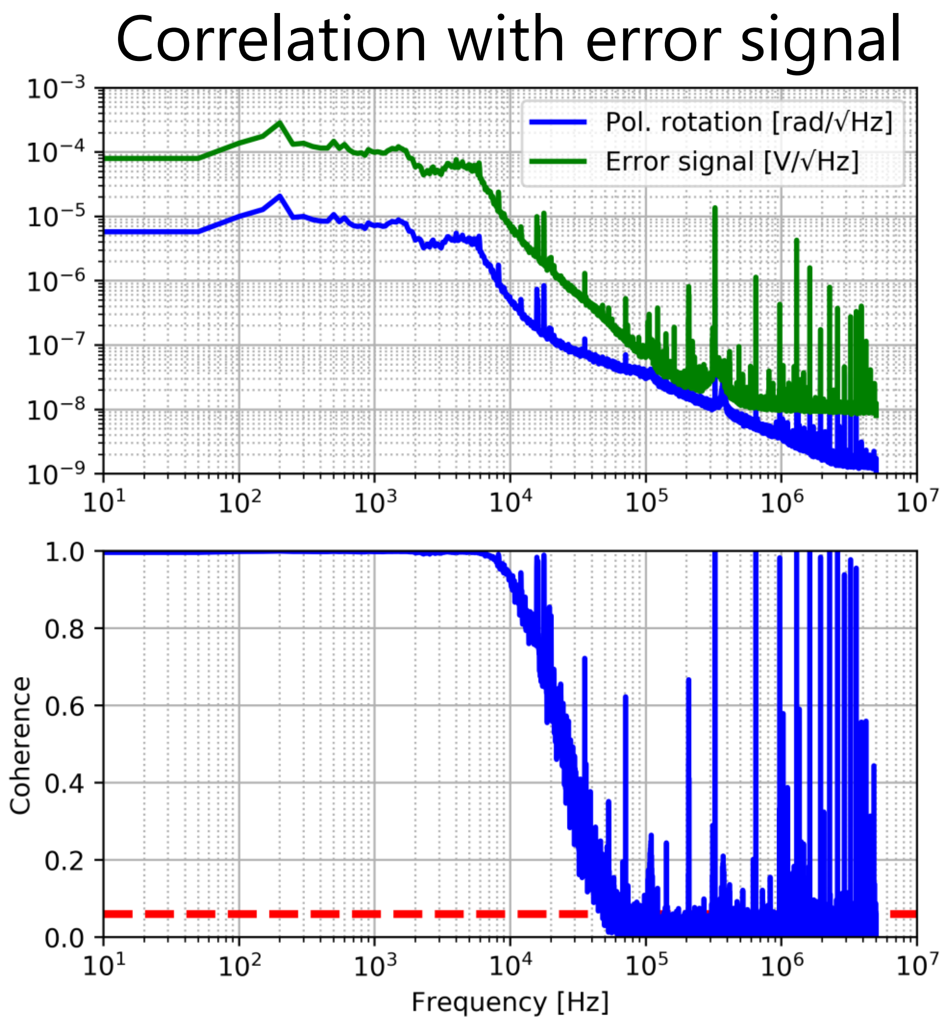
- Prototype experiment DANCE Act-1 is ongoing
  - Assembled and evaluated the optics
    - Found resonant frequency difference between pol.
  - Obtained the first data for 12 days
    - Estimated the sensitivity and analyzing the data





Extra Slides

Discussion for noises in MHz band



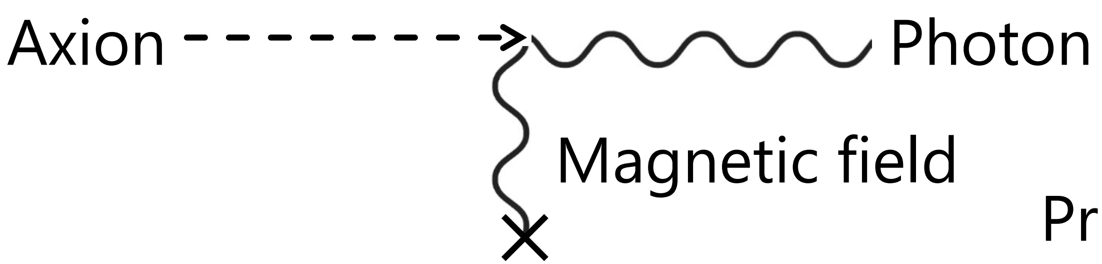
- Suggested to be limited by external noises below 100 kHz
- Could not identify noise source above 100 kHz

Axion

- Hypothetical particles to solve the strong CP problem in QCD

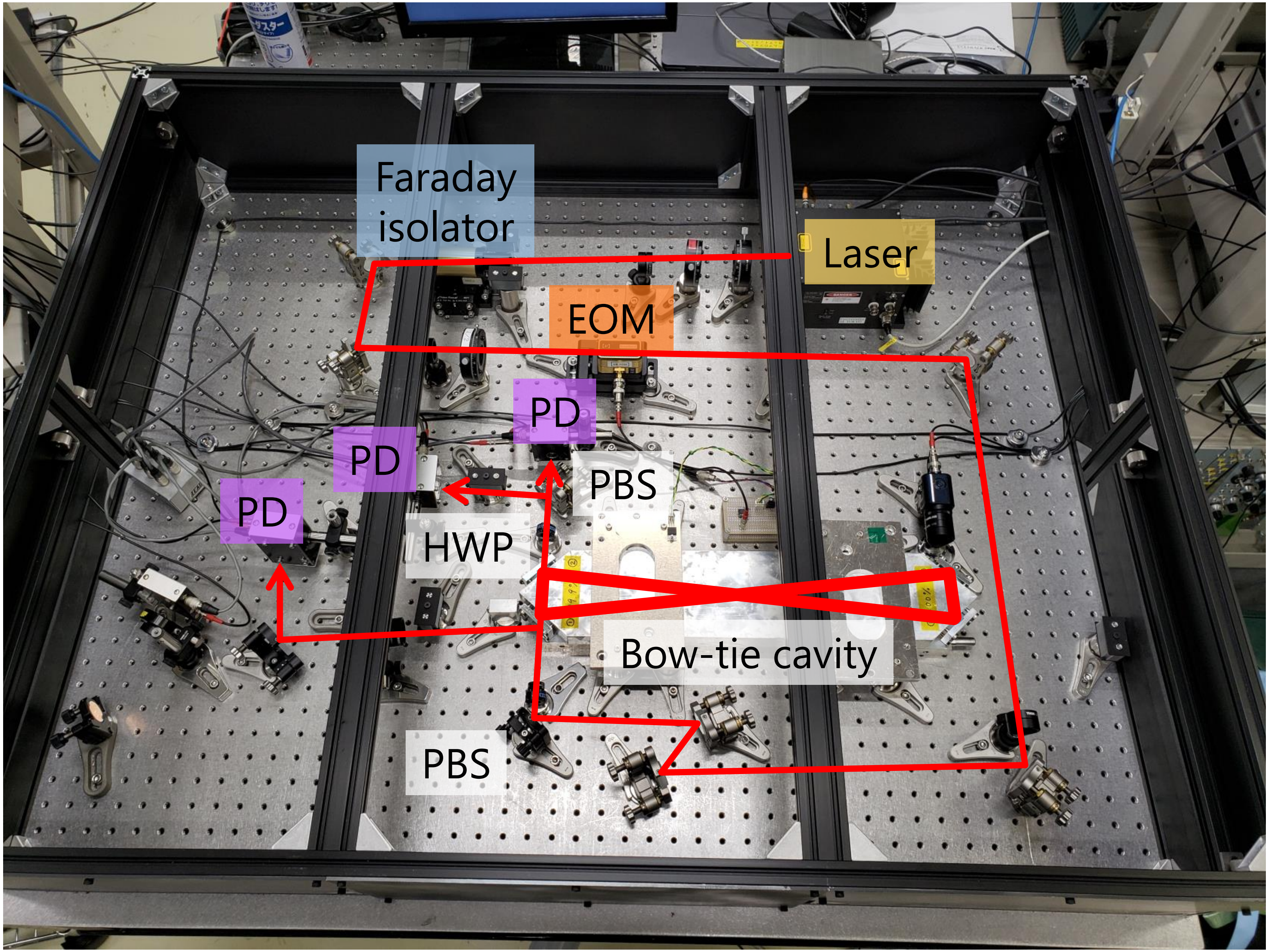
- Many kinds of axion-like particles (ALPs) are predicted by superstring theory
  - One of the candidates for dark matter

- Various methods of measuring axion-photon coupling, especially by using magnetic field, are proposed in many treatise

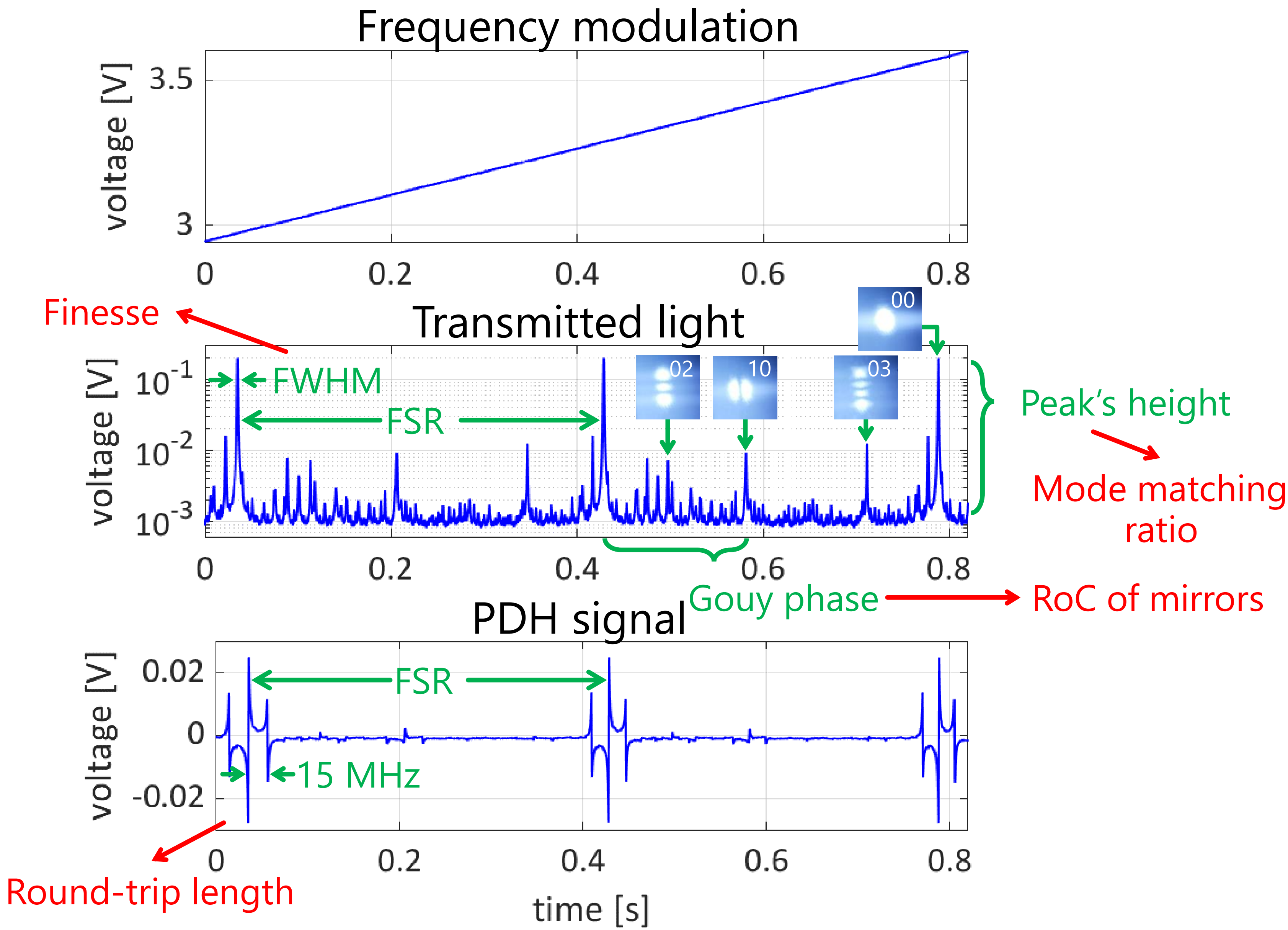


Primakoff effect

Picture of experimental setups



Cavity scan



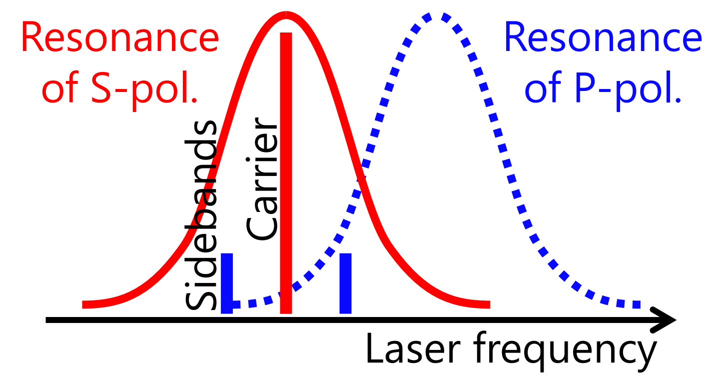
Frequency modulation
voltage [V]
3.5
3
0
0.2
0.4
0.6
0.8
Finesse
Transmitted light
00
02
10
03
10^{-1}
10^{-2}
10^{-3}
FWHM
FSR
Peak's height
Mode matching ratio
Gouy phase
RoC of mirrors
PDH signal
0.02
0
-0.02
FSR
15 MHz
Round-trip length
time [s]

Performance evaluation of the cavity

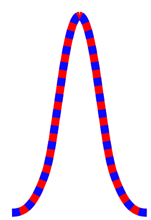
	Design values	Ver. Nov. 2020	Ver. Mar. 2021
Reflectivity of mirrors	Low: 99.9 % High: 100 %	Low: 99.9 % High: 99.95 % (Measured with P-pol.)	Low: 99.90(2) % High: <99.99 % (Designed for S-pol. by Layertec)
Finesse for carrier	3140	525(19) (P-pol.)	$2.85(5)\times10^3$ (S-pol.)
Finesse for sidebands	3140	~300 (S-pol.)	195(3) (P-pol.)
Resonant frequency difference between polarizations	0 Hz	~28 MHz	2.52(2) MHz
Round-trip length	99.4 cm	102(4) cm	97.1(4.5) cm
RoC of mirrors	all 100 cm	95.6(3.7) cm	98.3(2.2) cm
Incident angle	42 deg	40.9(2.4) deg	42.3(1.4) deg
Mode matching ratio	<99 %	83.03(9) %	82.3(1.6) %
Input laser power	1 W	~40 mW	242(12) mW
Transmitted laser power	1 W	~1.2 mW	153(8) mW

Important parameters (3)

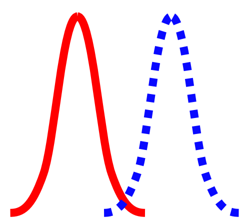
- Finesse difference between polarizations
  ・・・ From mirrors' reflectivity difference
- Resonant frequency difference between polarizations
  ・・・ From non-zero phase shift by mirror reflections



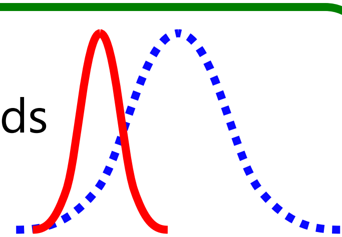
- Finesse for carrier
  = Finesse for sidebands
- Zero phase shift

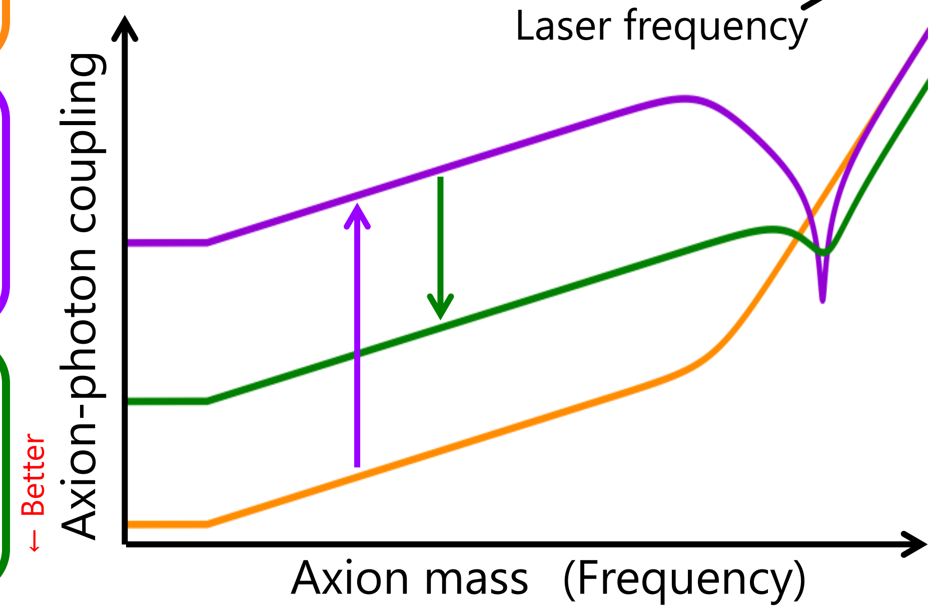


- Finesse for carrier
  = Finesse for sidebands
- Non-zero phase shift



- Finesse for carrier
  > Finesse for sidebands
- Non-zero phase shift





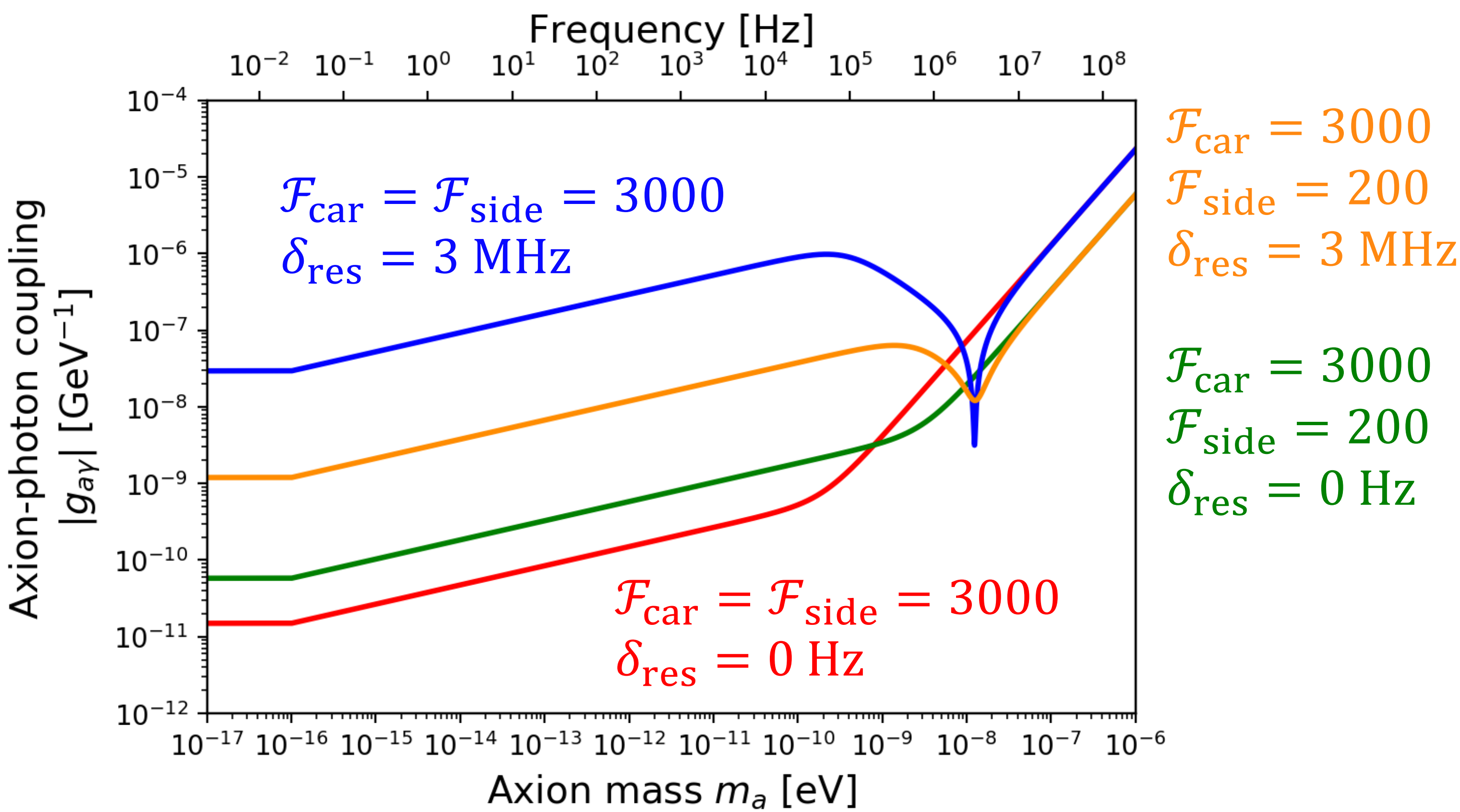
Sensitivity with various parameters

Fixed parameters

- Wavelength of laser: 1064 nm
- Round-trip length: 1 m
- Input laser power: 1 W
- Observation time: 1 year

Variable parameters

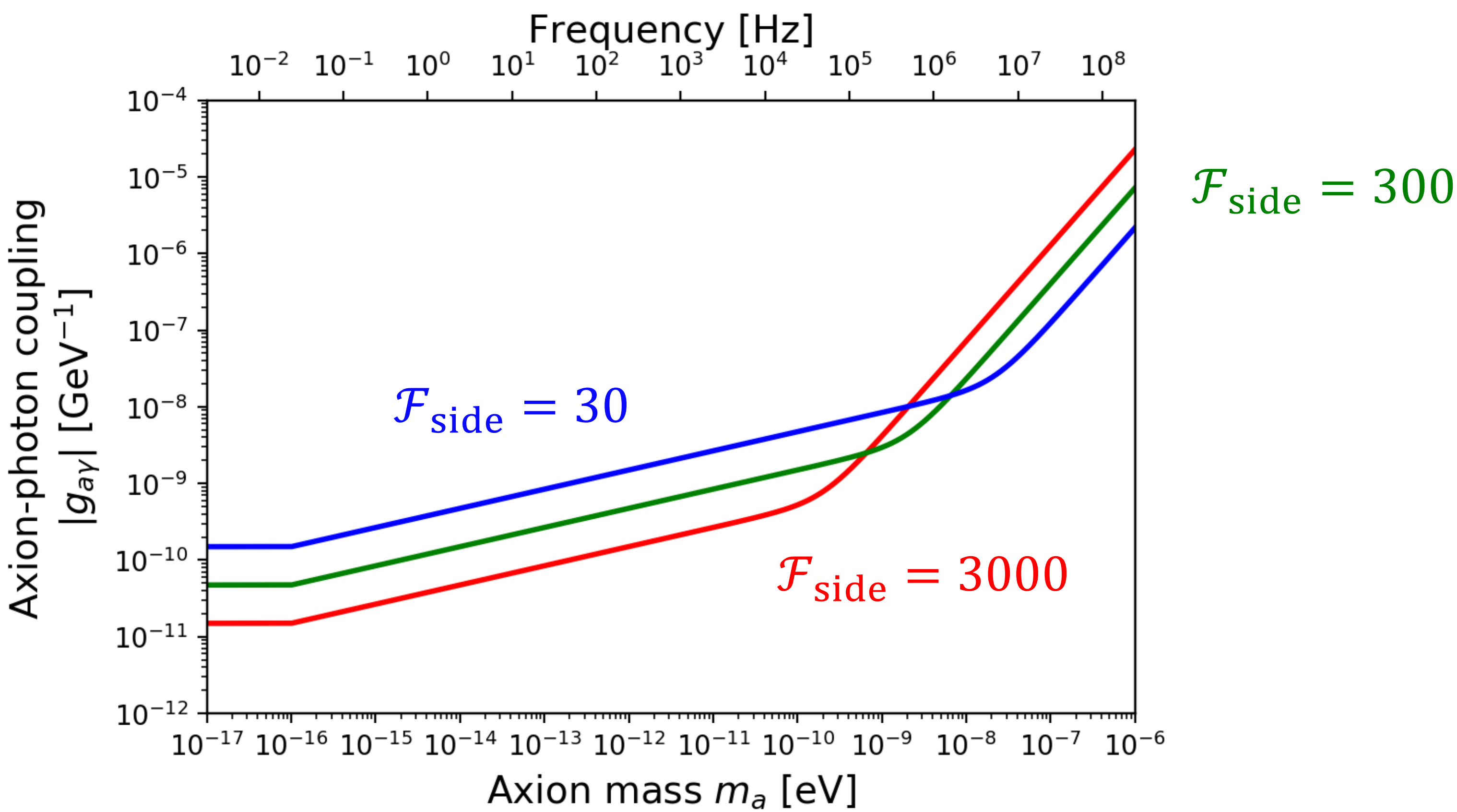
- Finesse for carrier $\mathcal{F}_{\mathrm{car}}$
- Finesse for sidebands $\mathcal{F}_{\mathrm{side}}$
- Resonant frequency difference between polarizations δ_{res}



Sensitivity with various parameters

Fixed parameters

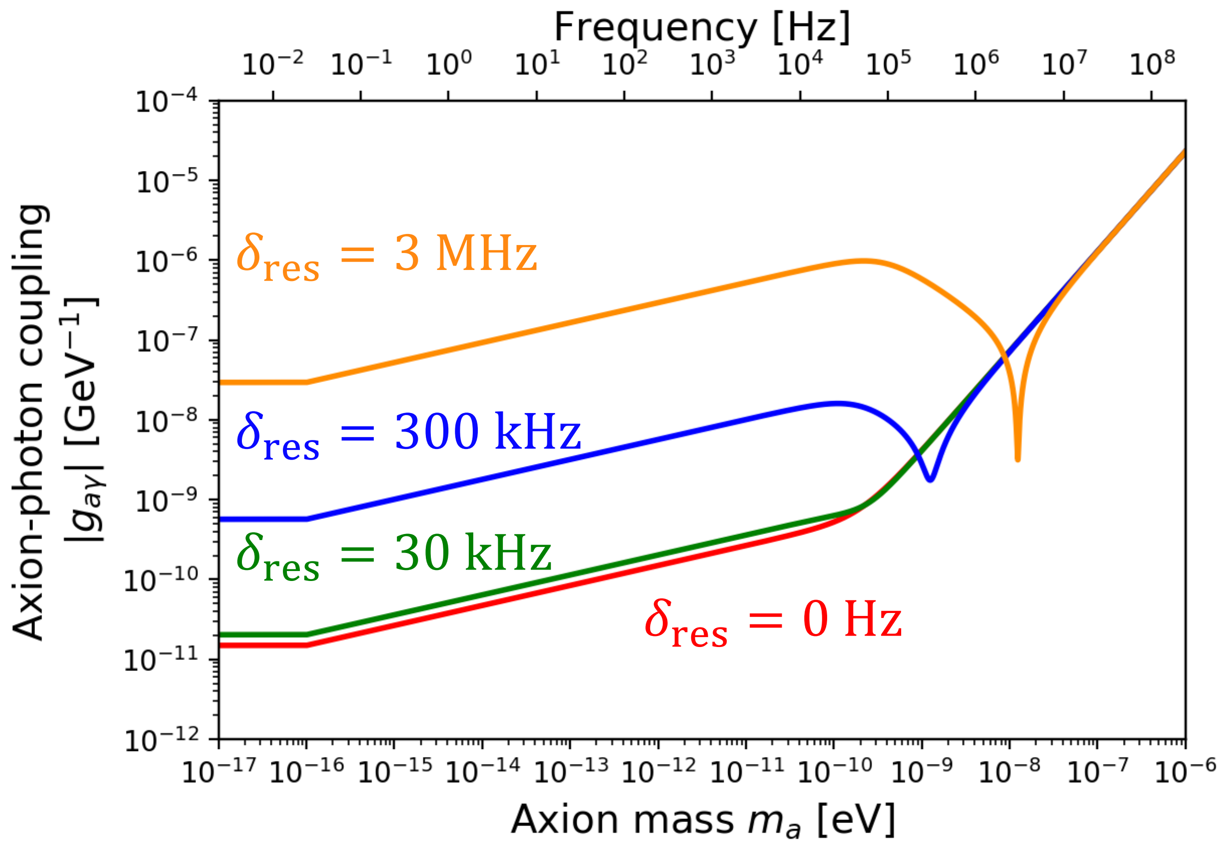
- Wavelength of laser: 1064 nm
- Round-trip length: 1 m
- Input laser power: 1 W
- Observation time: 1 year
- Finesse for carrier: 3000
- Resonant frequency difference between polarizations: 0 Hz



Sensitivity with various parameters

Fixed parameters

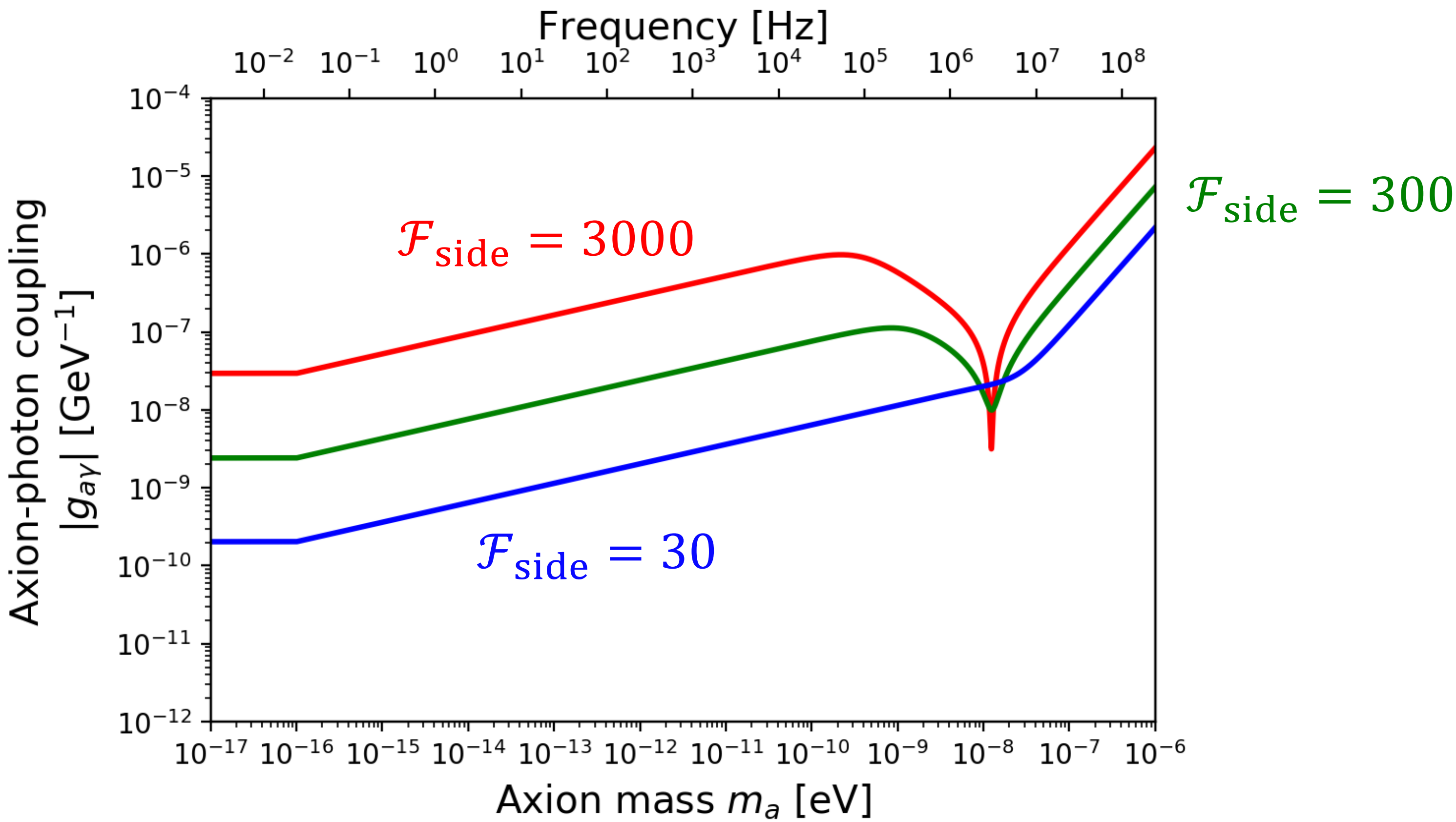
- Wavelength of laser: 1064 nm
- Round-trip length: 1 m
- Input laser power: 1 W
- Observation time: 1 year
- Finesse for carrier: 3000
- Finesse for sidebands: 3000



Sensitivity with various parameters

Fixed parameters

- Wavelength of laser: 1064 nm
- Round-trip length: 1 m
- Input laser power: 1 W
- Observation time: 1 year
- Finesse for carrier: 3000 $\mathcal{F}_{\mathrm{car}}$
- Resonant frequency difference between polarizations: 3 MHz



Signal calibration

$$\begin{pmatrix} E_S \\ E_P \end{pmatrix} = \begin{pmatrix} E_0 \cos\phi(t) \\ E_0 \sin\phi(t) \end{pmatrix}$$

HWP $\begin{pmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{pmatrix}$

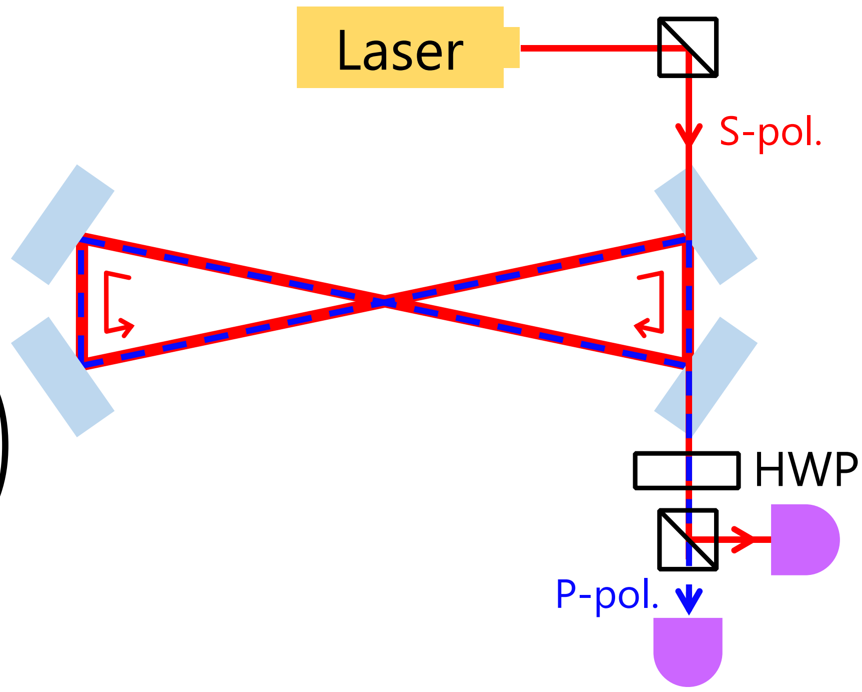
$$\rightarrow \begin{pmatrix} E_S{'} \\ E_P{'} \end{pmatrix} = \begin{pmatrix} E_0 \cos(2\theta + \phi(t)) \\ E_0 \sin(2\theta + \phi(t)) \end{pmatrix}$$

$$P_S = {E_S'}^2 = E_0^2 \cos^2(2\theta + \phi(t))$$
$$P_P = {E_P'}^2 = E_0^2 \sin^2(2\theta + \phi(t))$$

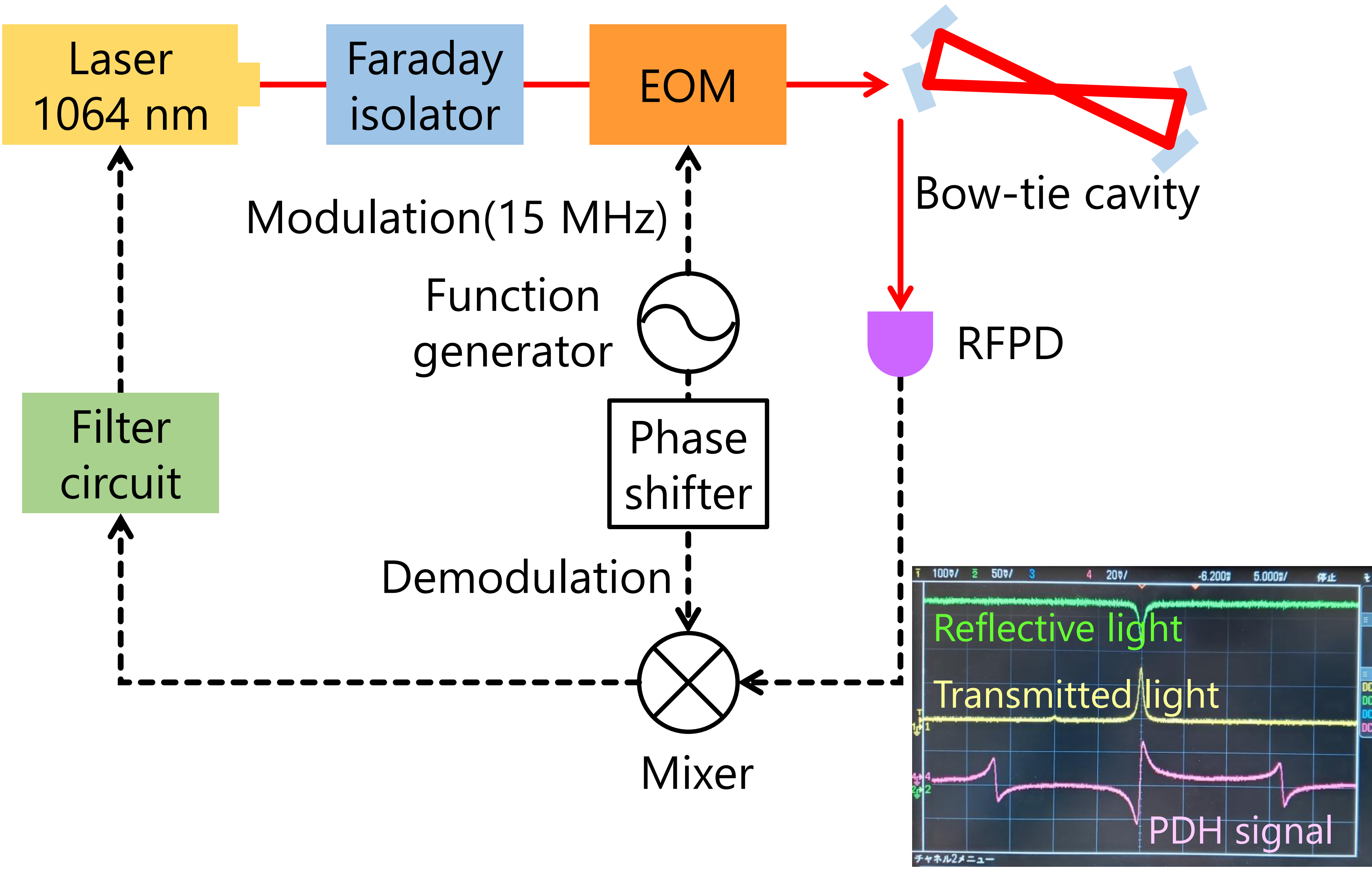
When $2\theta + \phi \ll 1$, $\sin\big(2\theta + \phi(t)\big) \approx 2\theta + \phi(t)$

Pol. rotation angle $2\theta + \phi(t) = \frac{E_P'}{E_0}$

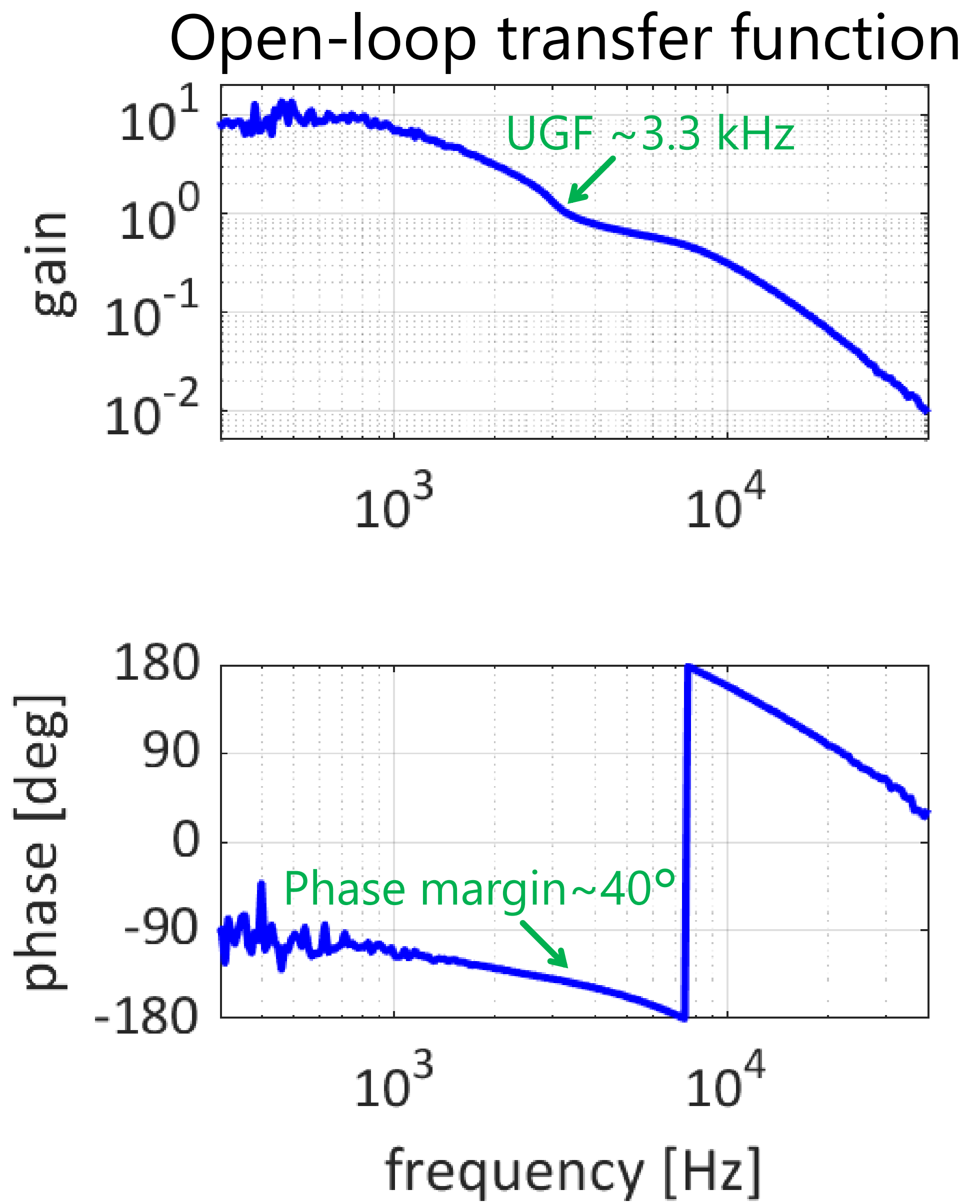
Spectrum is independent of $2\theta = \mathrm{const.}$



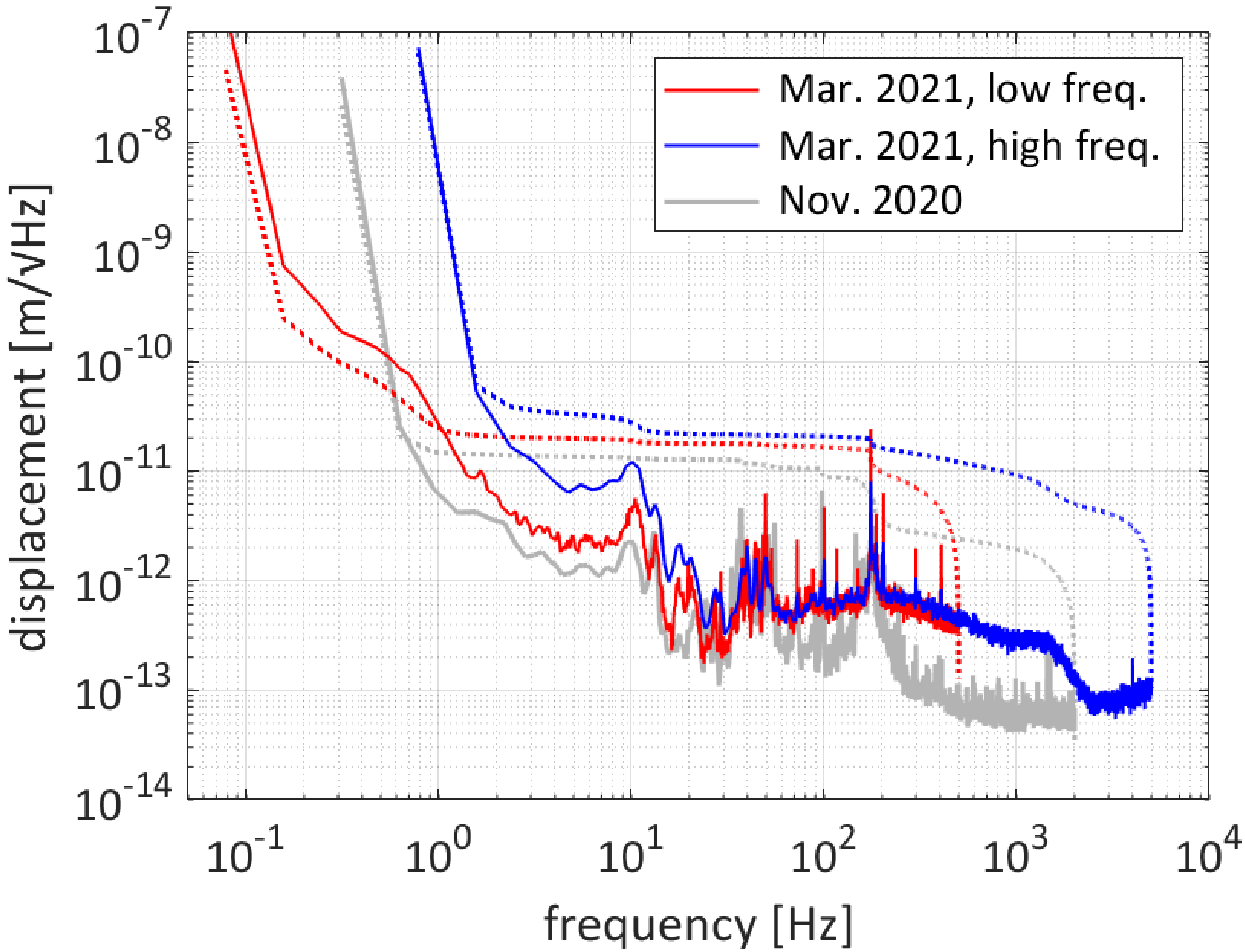
Frequency servo by PDH technique



Stability of frequency servo



Spectrum of external noises

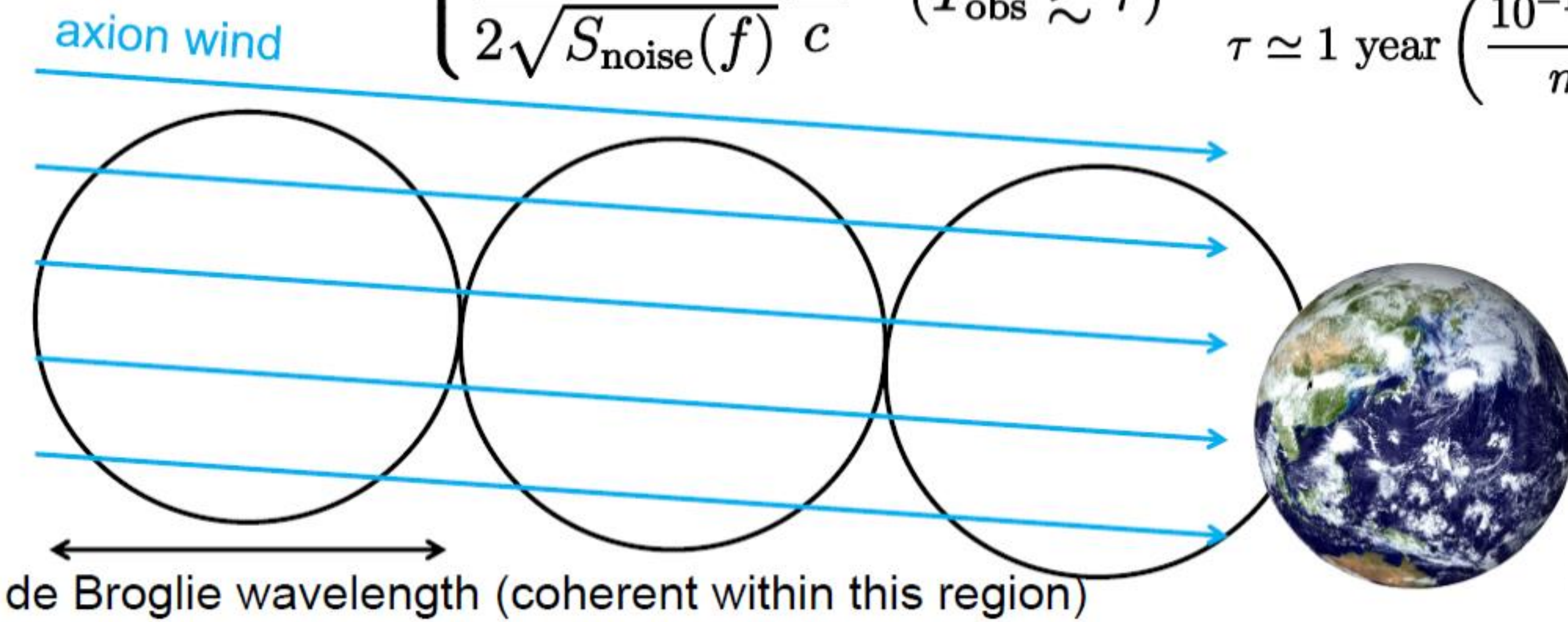


Coherent Time Scale

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

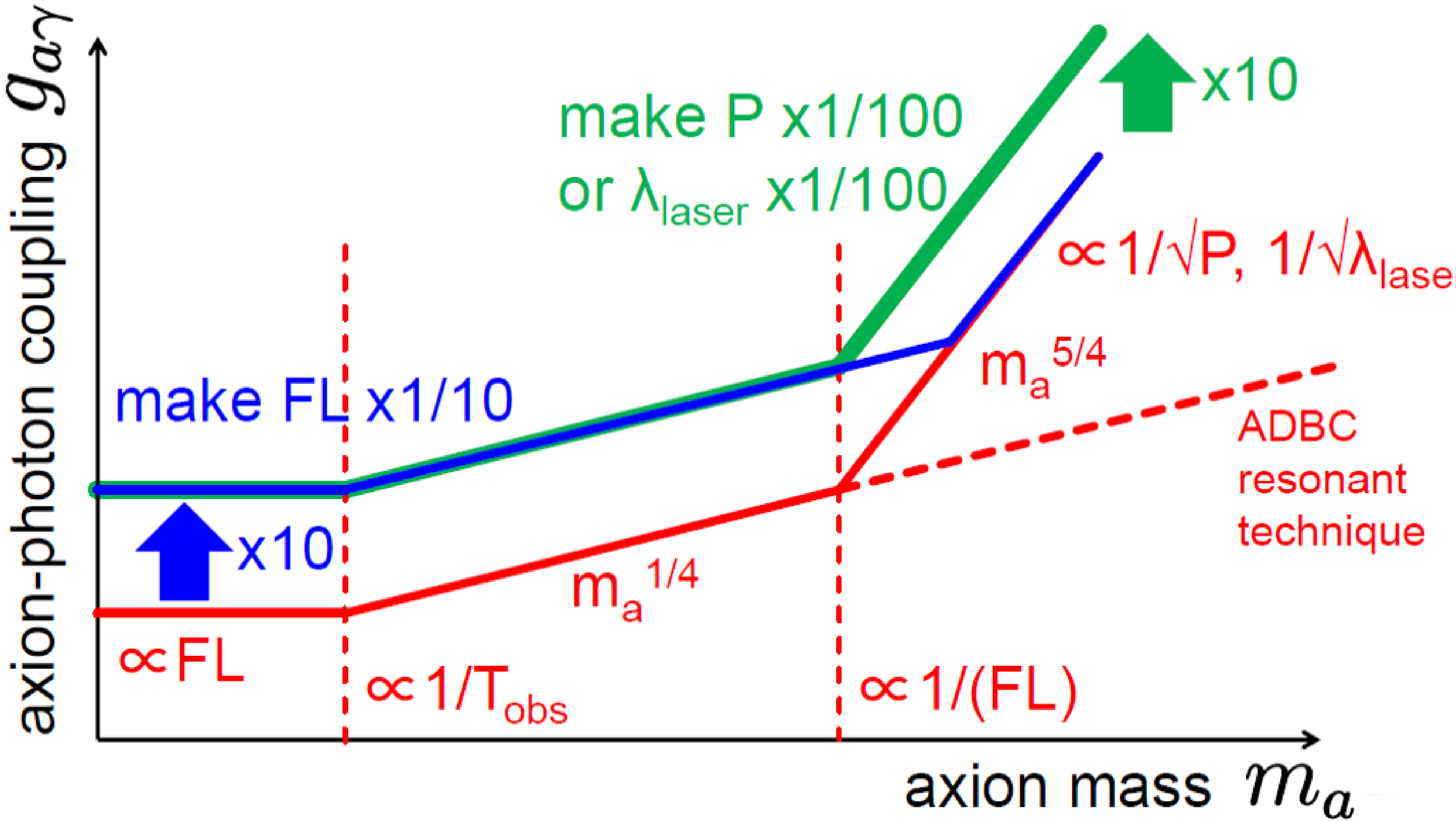
$$\text{SNR} = \begin{cases} \dfrac{\sqrt{T_{\text{obs}}}}{2\sqrt{S_{\text{noise}}(f)}}\dfrac{\delta c}{c} & (T_{\text{obs}} \lesssim \tau) \\ \dfrac{(T_{\text{obs}}\tau)^{1/4}}{2\sqrt{S_{\text{noise}}(f)}}\dfrac{\delta c}{c} & (T_{\text{obs}} \gtrsim \tau) \end{cases}$$

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



Sensitivity Design

- Brute force necessary, you cannot win for free

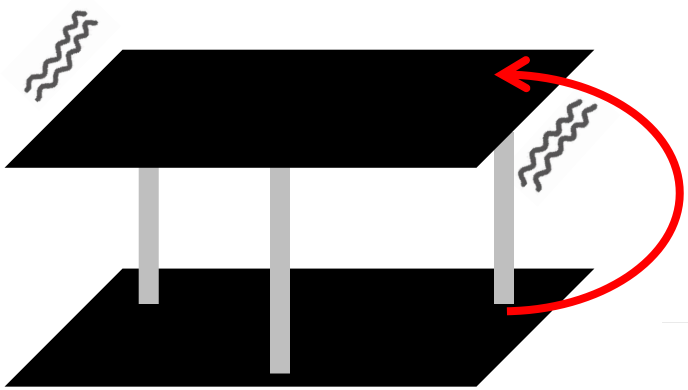


Optical table and optical fiber

Issues of ver. Nov. 2020

- Built a two-story optical table
- Lifted laser light with an optical fiber

Unstable setup

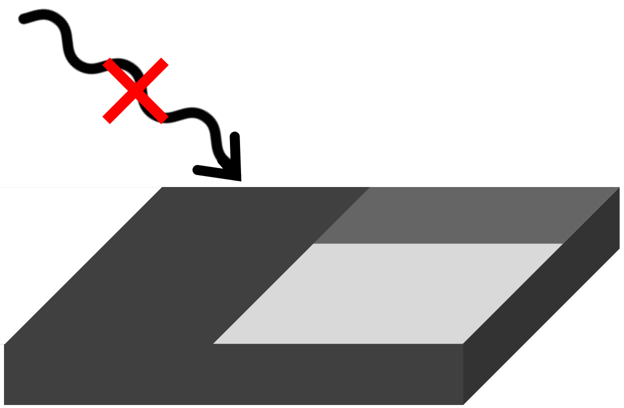


Loss of 50 %
Large intensity noise

Improvement of ver. Mar. 2021

- Assembled the optics on the first floor without the fiber
- Surrounded the optical table by aluminum plates

Wind
Light



More stable frequency servo
Easier to avoid natural light

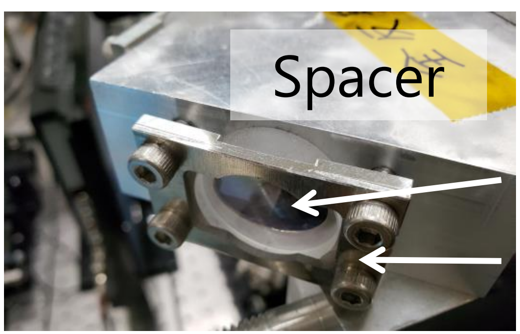
Mirrors and alignment

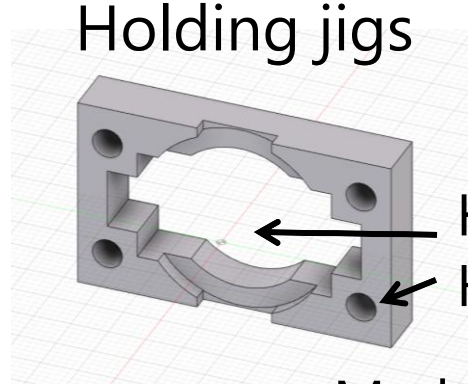
Issues of ver. Nov. 2020

- Mirrors had low reflectivity and large loss
- Mirror alignment was not accurate due to holding jigs
  → Small finesse

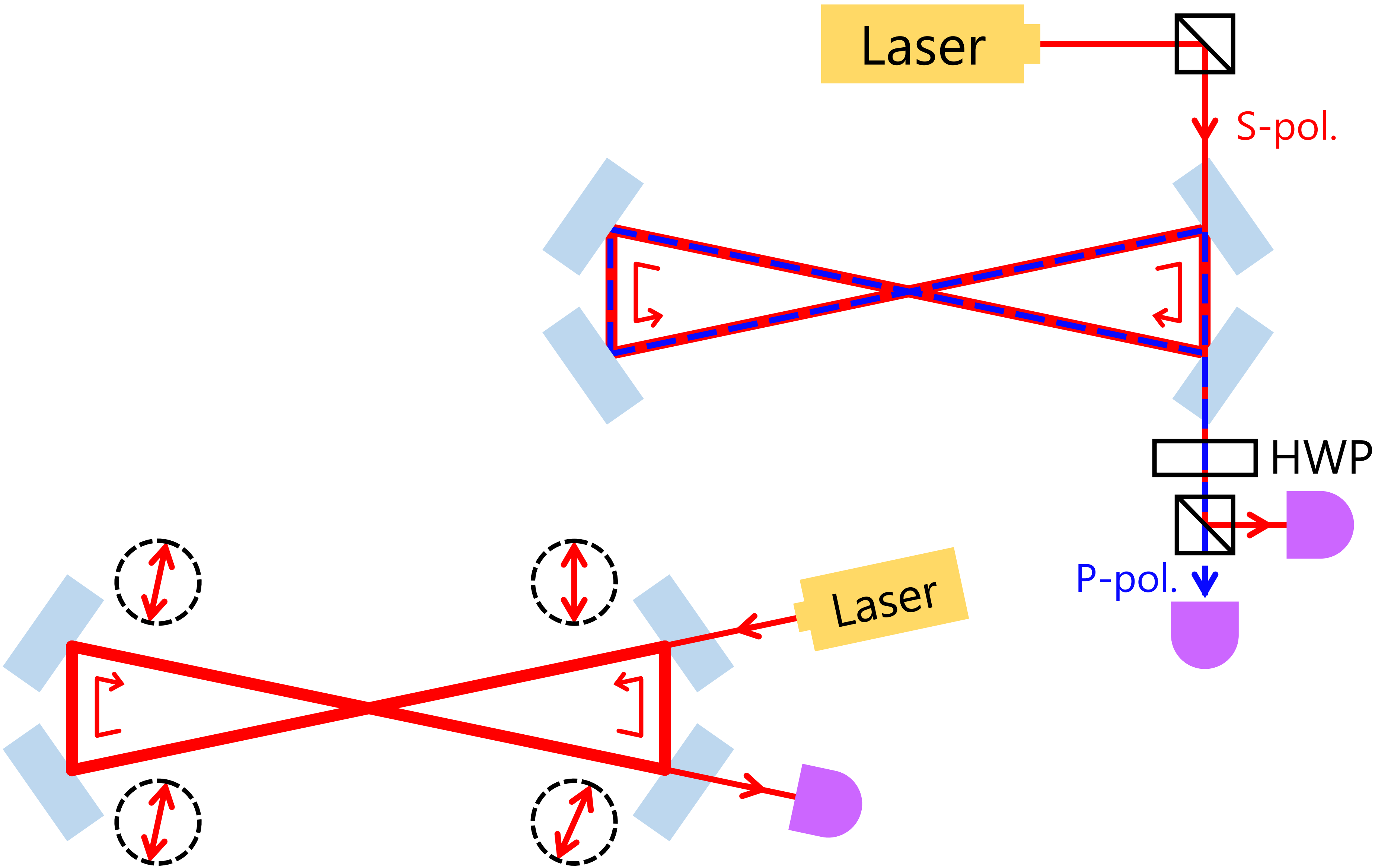
Improvement of ver. Mar. 2021

- Changed to mirrors with high reflectivity and small loss
- Improved alignment by changing mirror holding jigs
  → Improved finesse





Figure



Figure