Dark matter Axion search with riNg Cavity Experiment DANCE: Signal calibration and sensitivity evaluation

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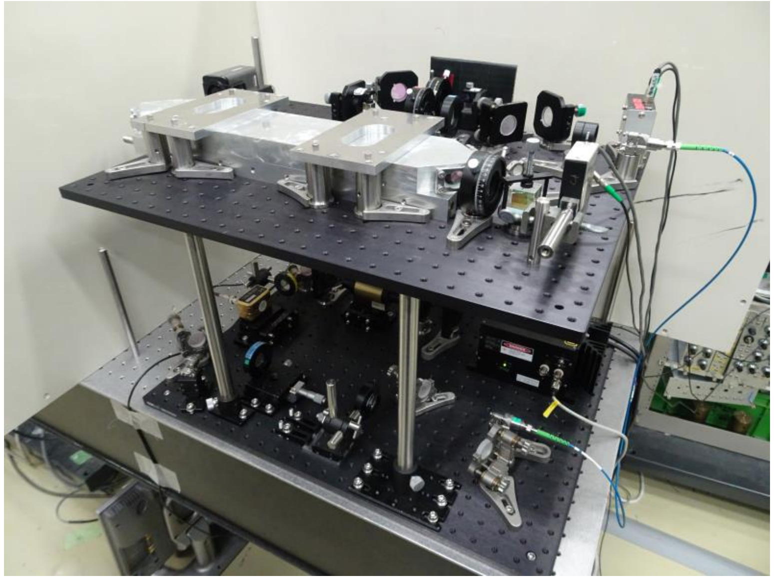
Overview

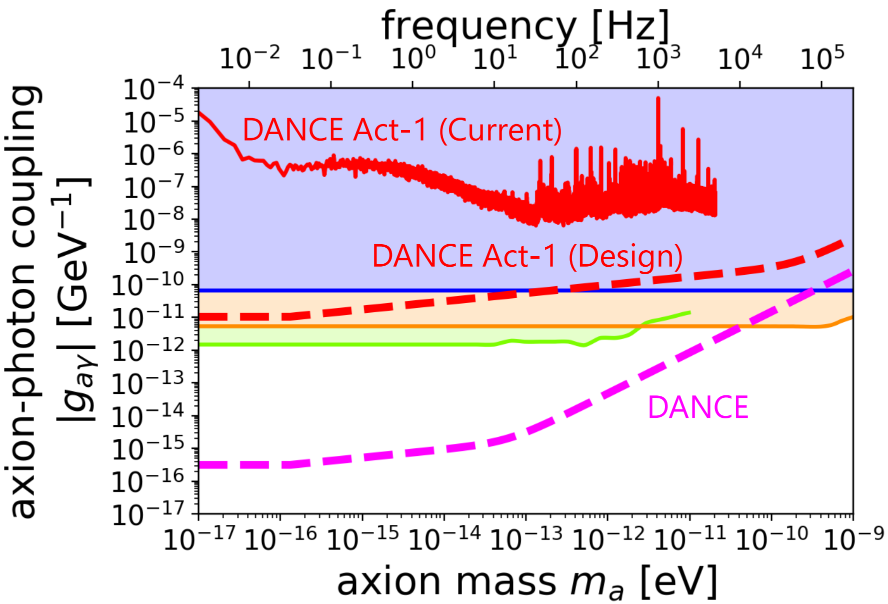
- A new method to search for axion-like particles with a table-top experiment

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

- DANCE: Dark matter Axion search with riNg Cavity Experiment

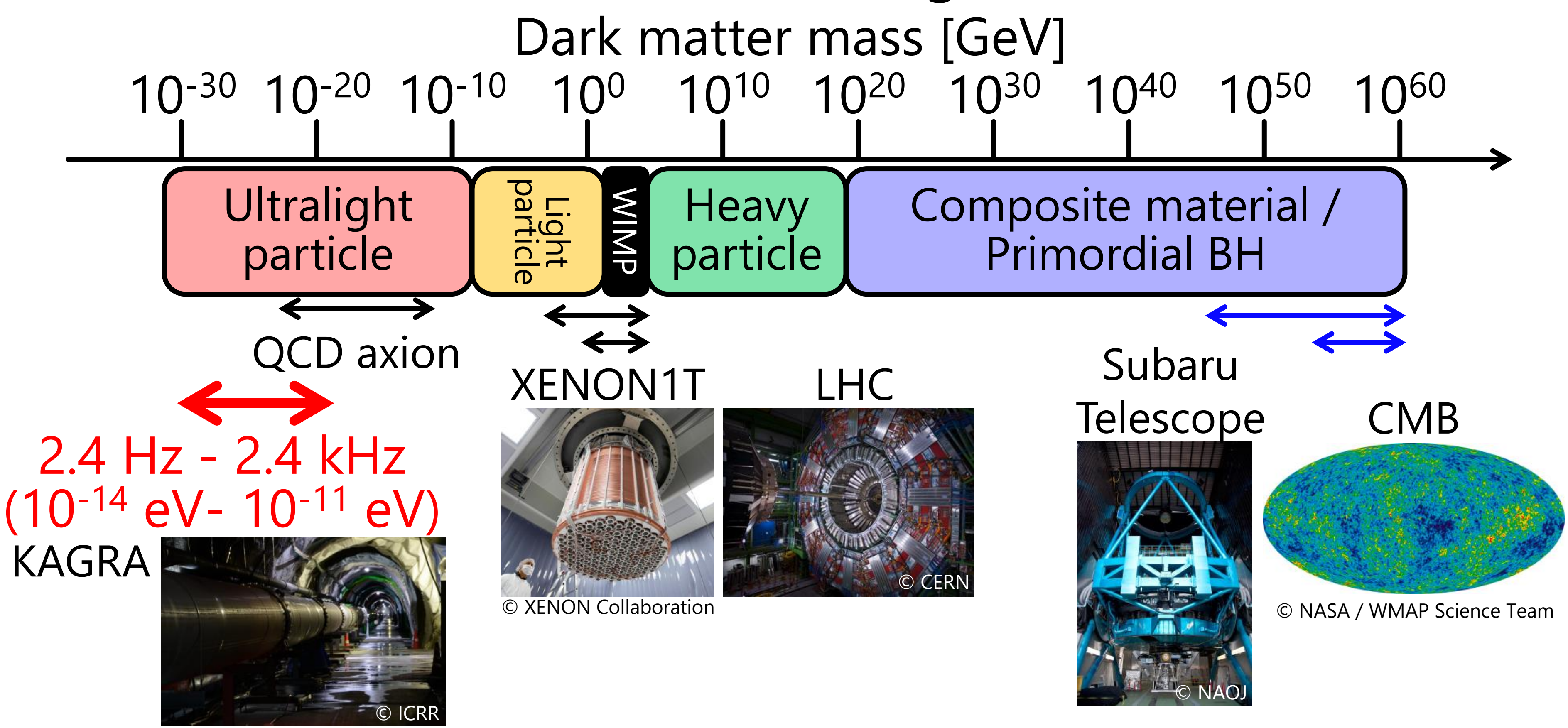
- Prototype experiment DANCE Act-1 is ongoing



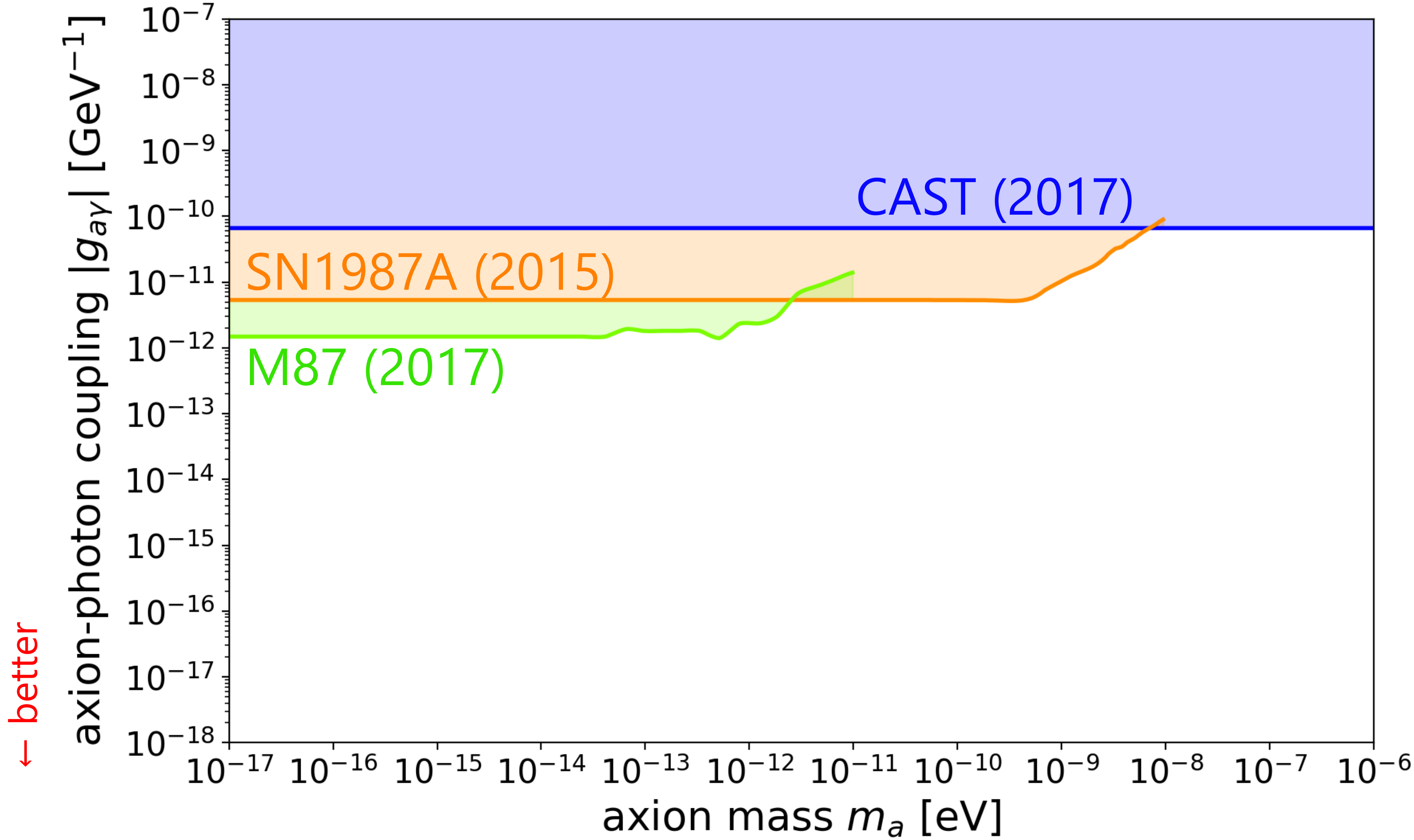


DM search with laser interferometers

- Dark matter has not been detected yet
- Need to search in wider mass range
- Ultralight dark matter search with laser interferometers is attracting attention

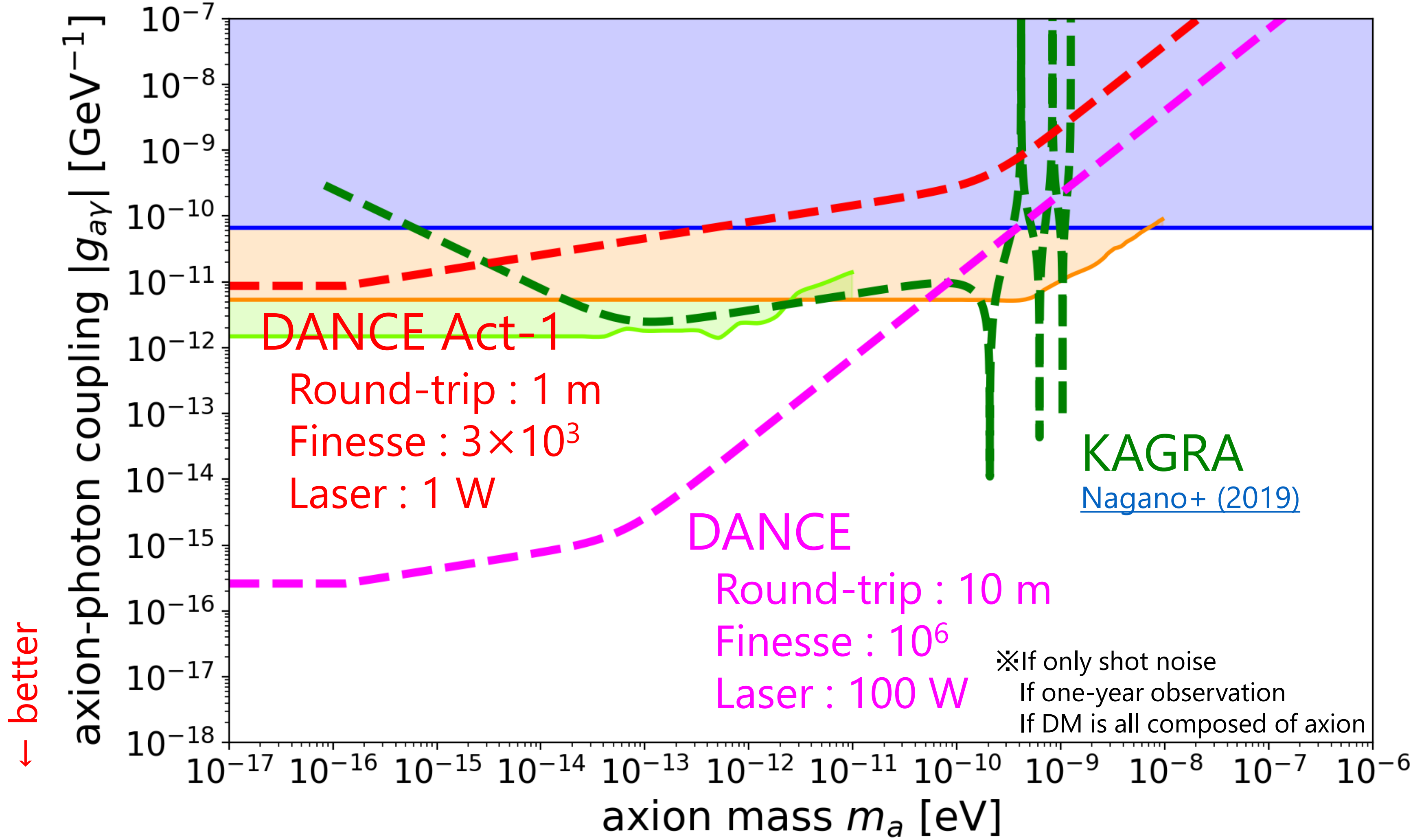


Upper limits from previous researches



Anastassopoulos+ (2017)
Payez+ (2015)
Marsh+ (2017)

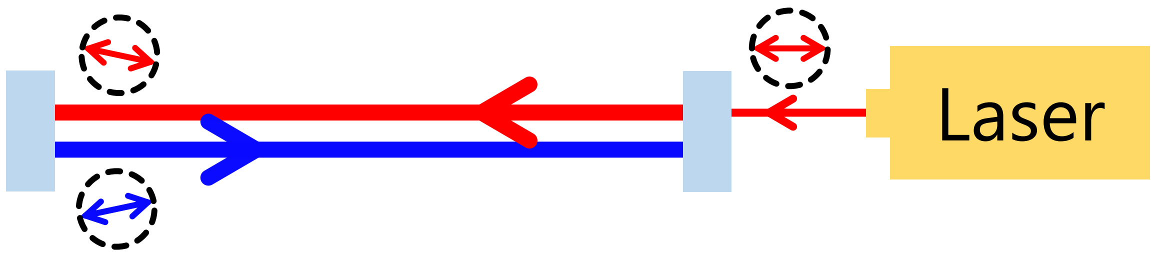
Sensitivity of DANCE



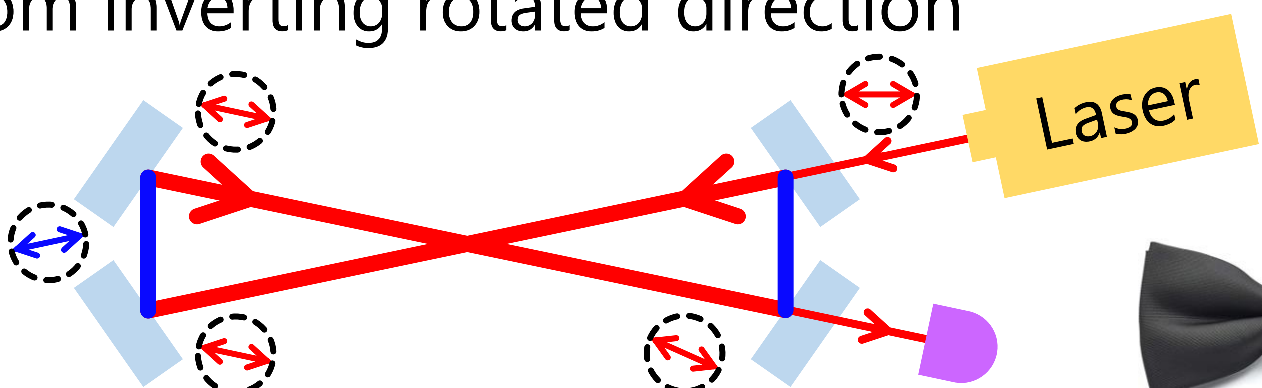
- DANCE will improve limits by several orders of magnitude
- Mass band of DANCE is complementary to that of KAGRA

Bow-tie ring cavity

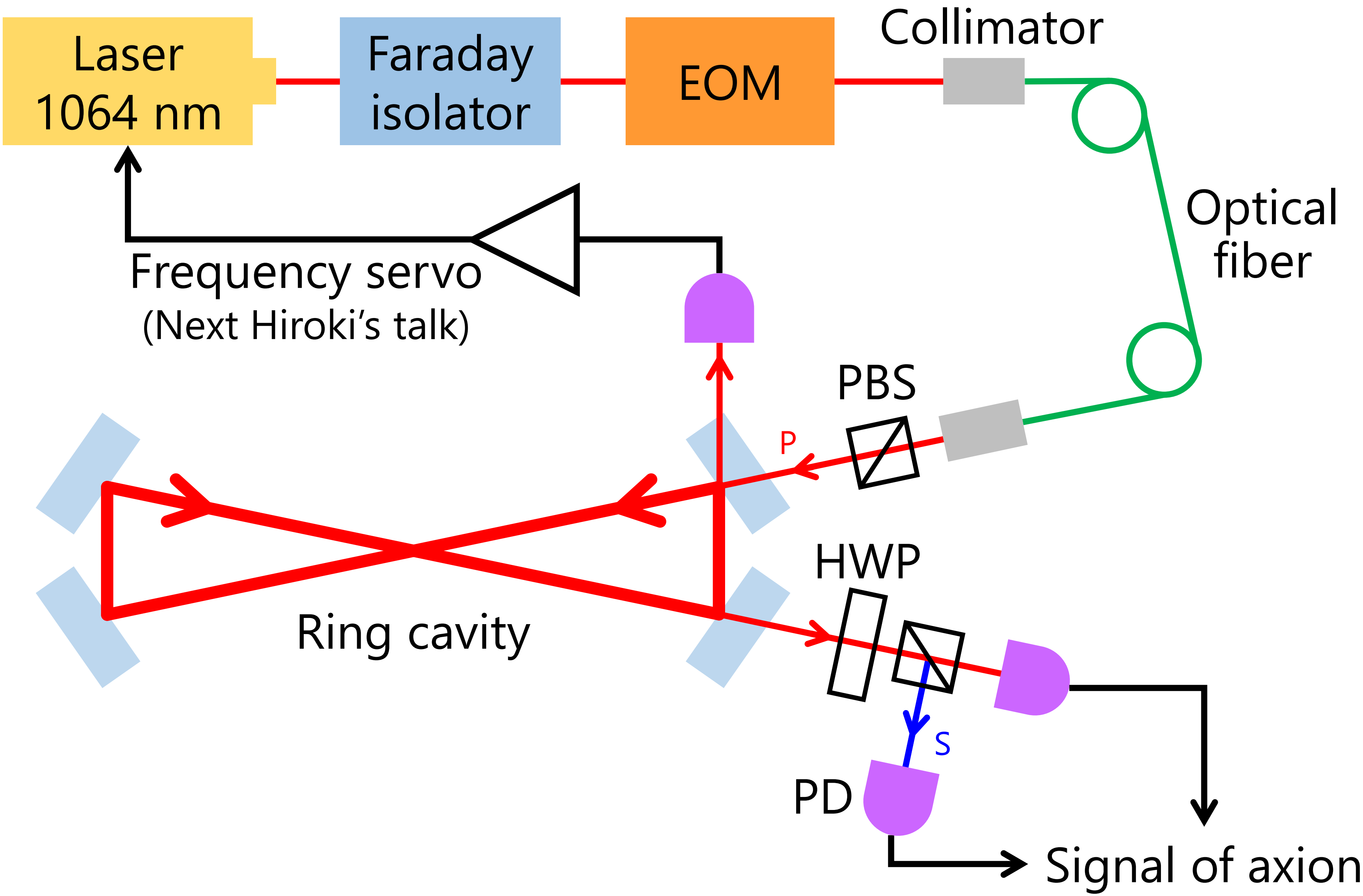
- DANCE observes rotation angle of linear polarization caused by axion (if axion is DM)
- Rotated direction is inverted in a linear cavity
  → Rotation effect is cancelled out



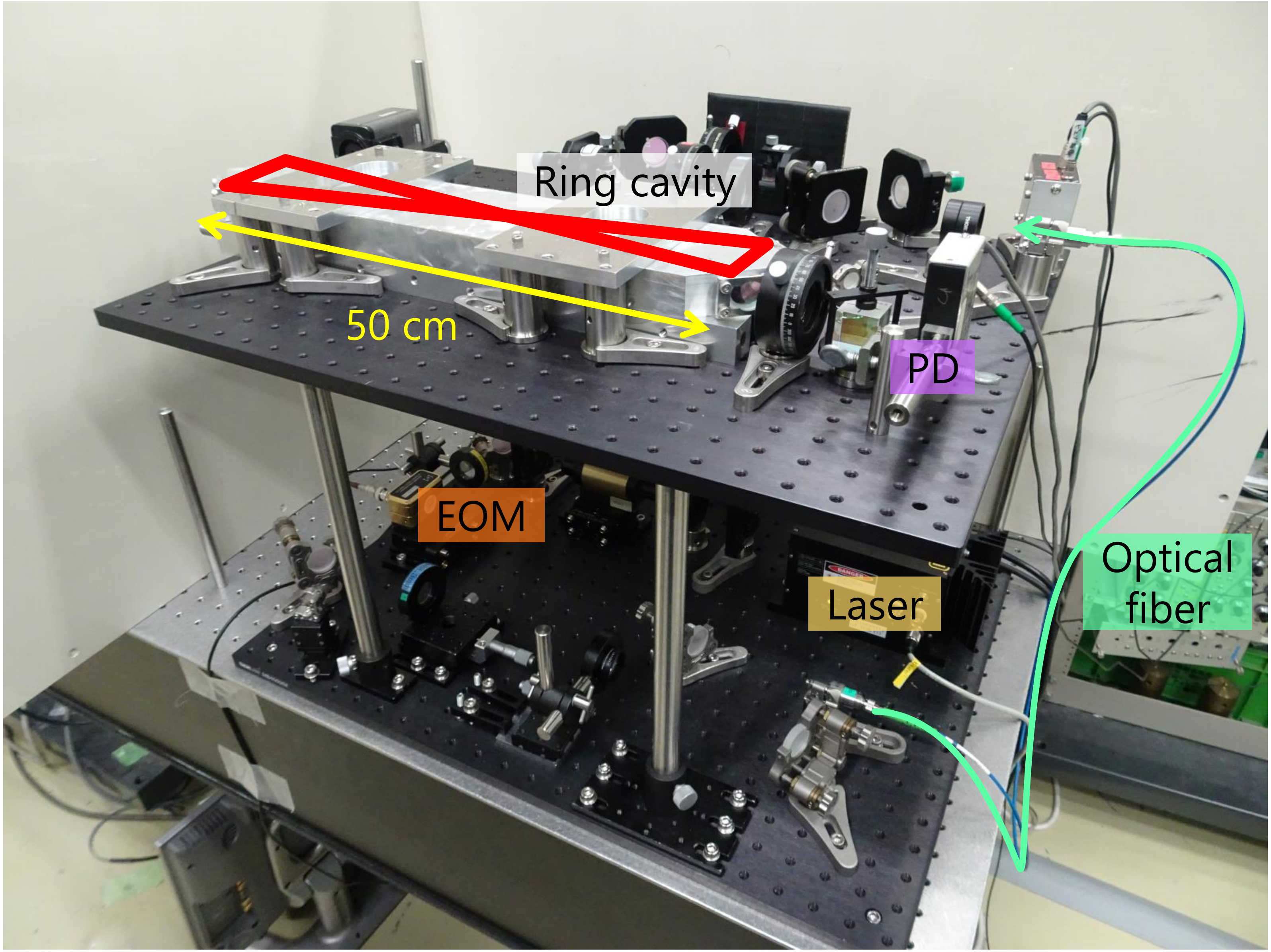
- A bow-tie ring cavity prevents linear polarization from inverting rotated direction



Experimental setups of DANCE



Picture of the setups



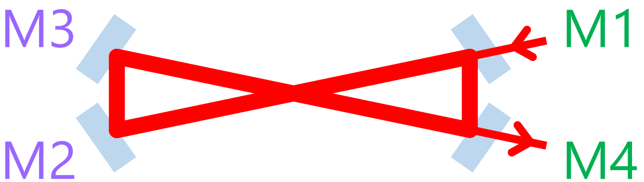
Performance evaluation of a cavity

	Design value	Measured value (P polarization)
Reflectance of mirrors	M1, M4: 99.9 % M2, M3: 100 %	M1, M4: 99.9 % M2, M3: 99.95 %
Finesse	3140	525 ± 19 (S pol. : 527 ± 29)
Round-trip length	99.4 cm	102 ± 4 cm
Radius of curvature of mirrors	100 cm (all)	102 ± 2 cm
Incident angle	42 deg	41.9 ± 1.7 deg
Mode matching ratio	99.9987 %	83.03 ± 0.09 %
Input power	~1 W	~40 mW

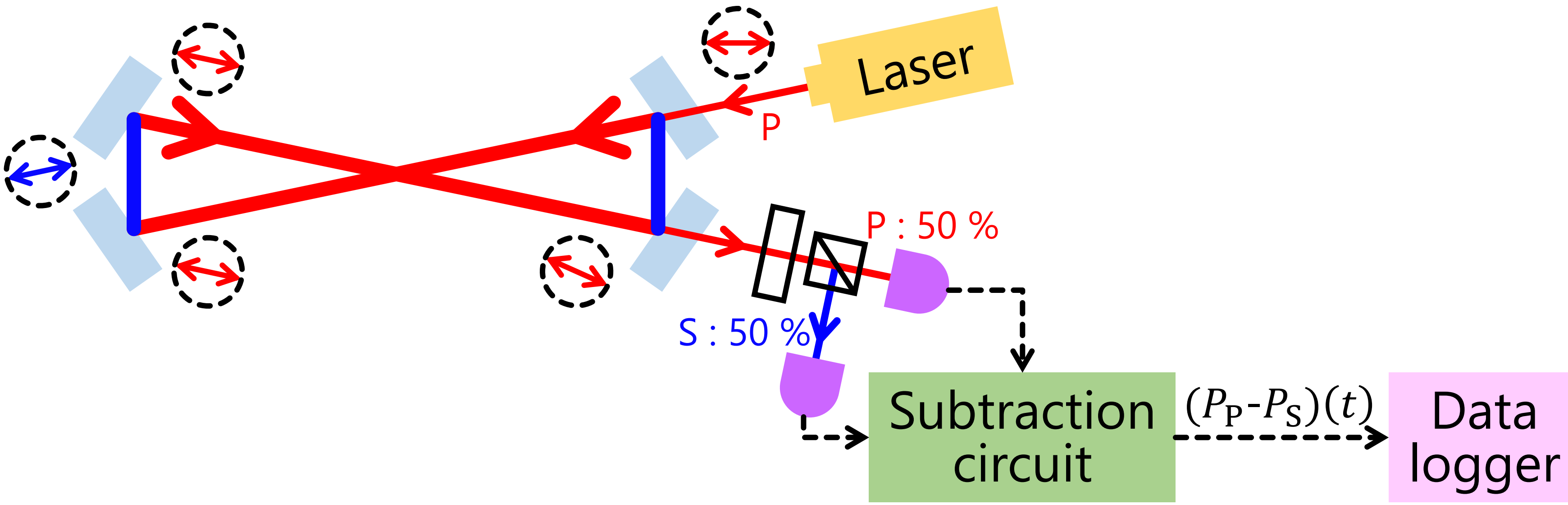
→ Finesse 2100

→ Loss of light 0.91 %

→ Misalignment 0.9 deg

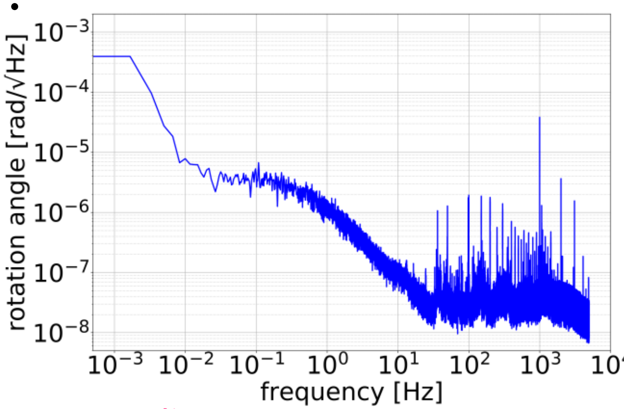


Data acquisition & Data analysis

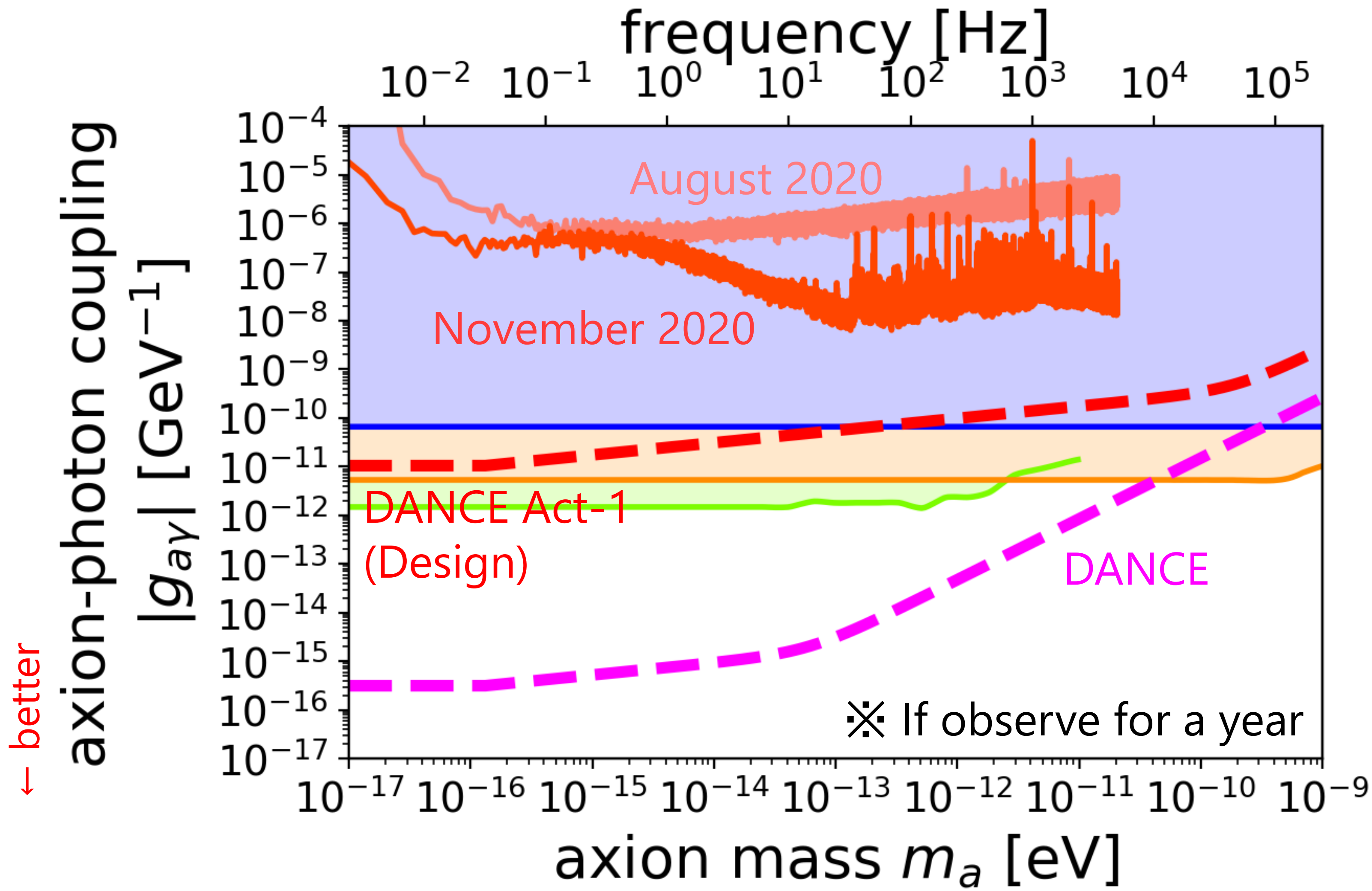


- HWP is fixed to make equal amount of P and S polarization
- Record a differential power $(P_P\text{-}P_S)(t)$, P_P and P_S
- Rotation angle of linear polarization :

$$\phi(t) = \frac{(P_P - P_S)(t)}{2(P_P + P_S)}$$

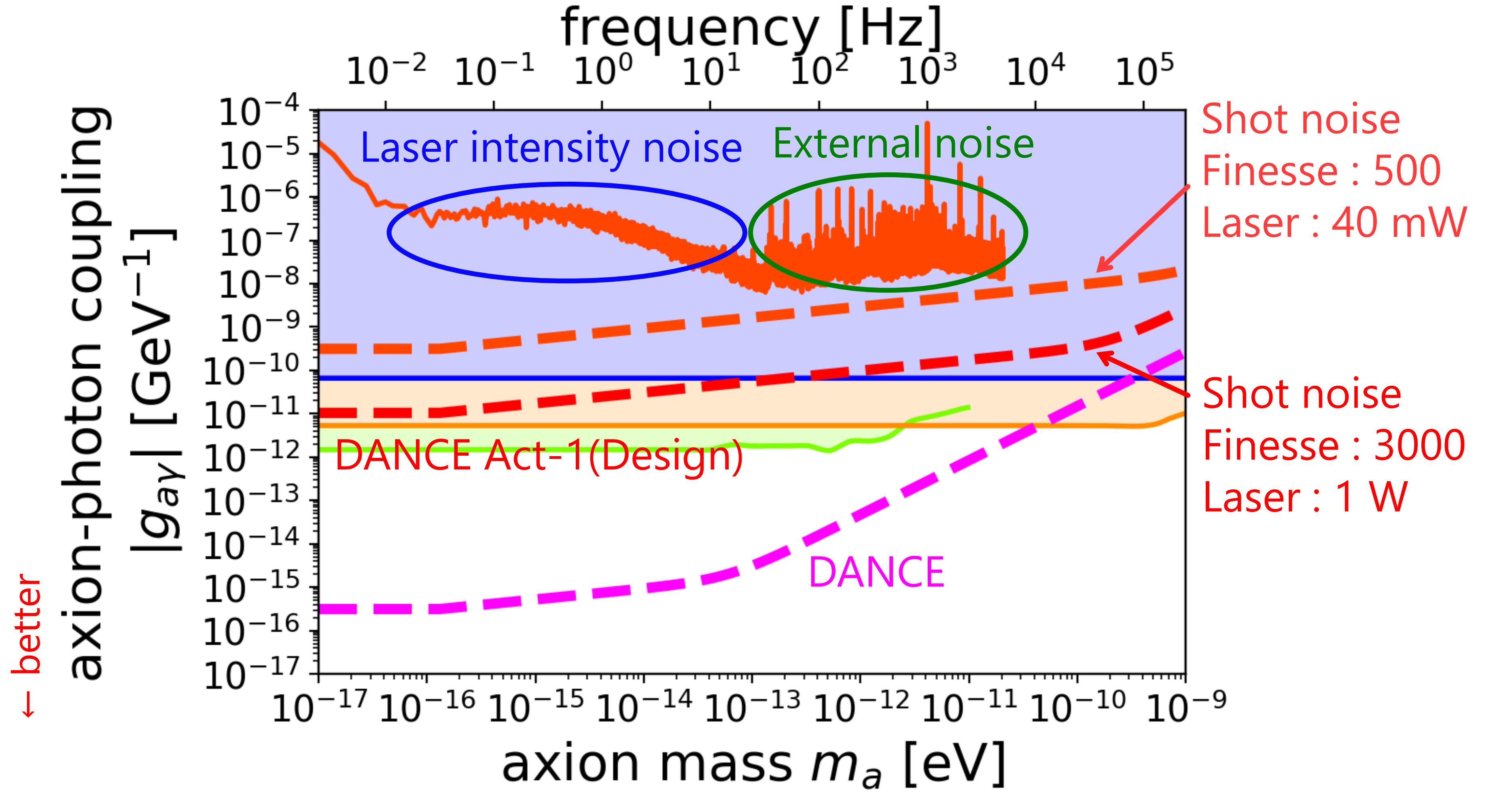


Current estimated sensitivity



- We have to improve the current sensitivity by 10^3-10^5 times to reach the design sensitivity

Estimation of sensitivity improvement



- Shot noise limited : +10^1-10^3 times
- Finesse (500 → 3000) : +10 times
- Laser (40 mW → 1 W) : +10 times

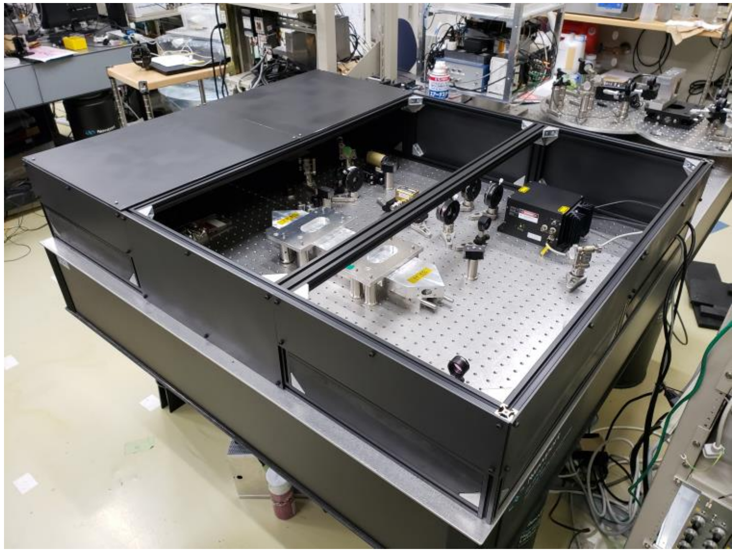
New setups & Future plans

- Improve finesse → ~2300
  - Change to high quality mirrors
  - Improve alignment of mirrors

- Reduce noises → one order of magnitude
  - Construct setups only on the 1st floor
  - Surround an optical table with plates

- Higher laser input power
  → ~500 mW

- Plan to take data for a week
  during New Year holidays



Summary

- A new table-top experiment searches for ALPs with a ring cavity
  DANCE: Dark matter Axion search with riNg Cavity Experiment
- DANCE observes rotation of linear polarization in a bow-tie cavity
- Prototype experiment DANCE Act-1 is ongoing
  - Now improving finesse and reducing noises to achieve the design sensitivity

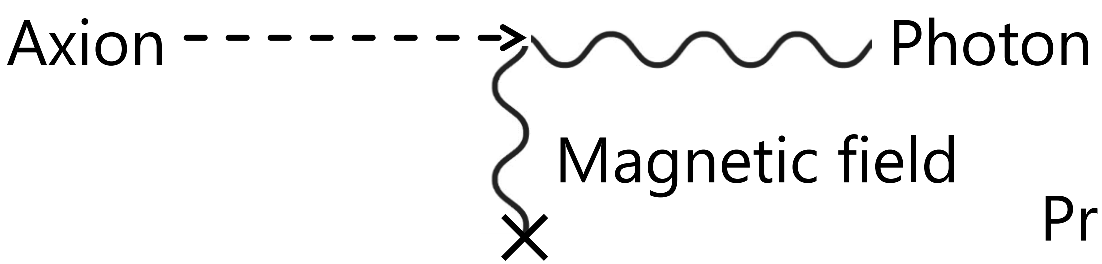
Extra Slides

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

Rotation of linear polarization

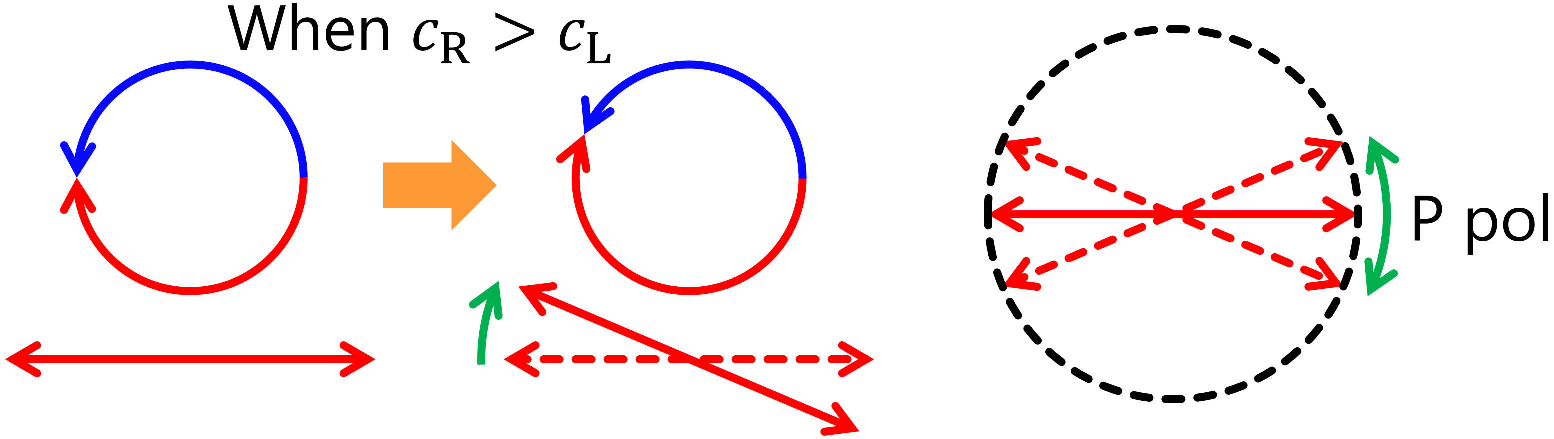
- Axion-photon coupling causes phase velocity difference between left- and right-handed photons

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

Coupling constant　Axion field　Axion mass

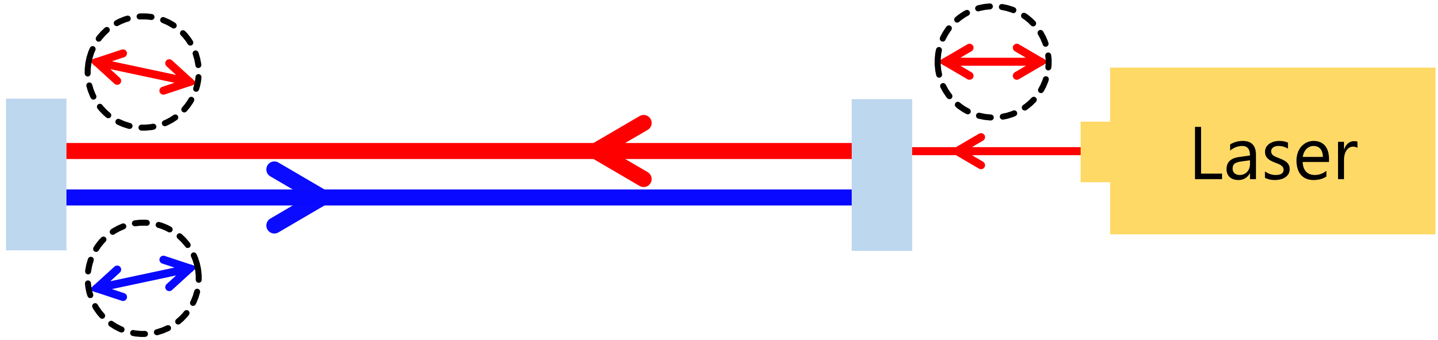
- Phase velocity difference of circular polarizations makes linear polarization rotate

When $c_{\mathrm{R}} > c_{\mathrm{L}}$

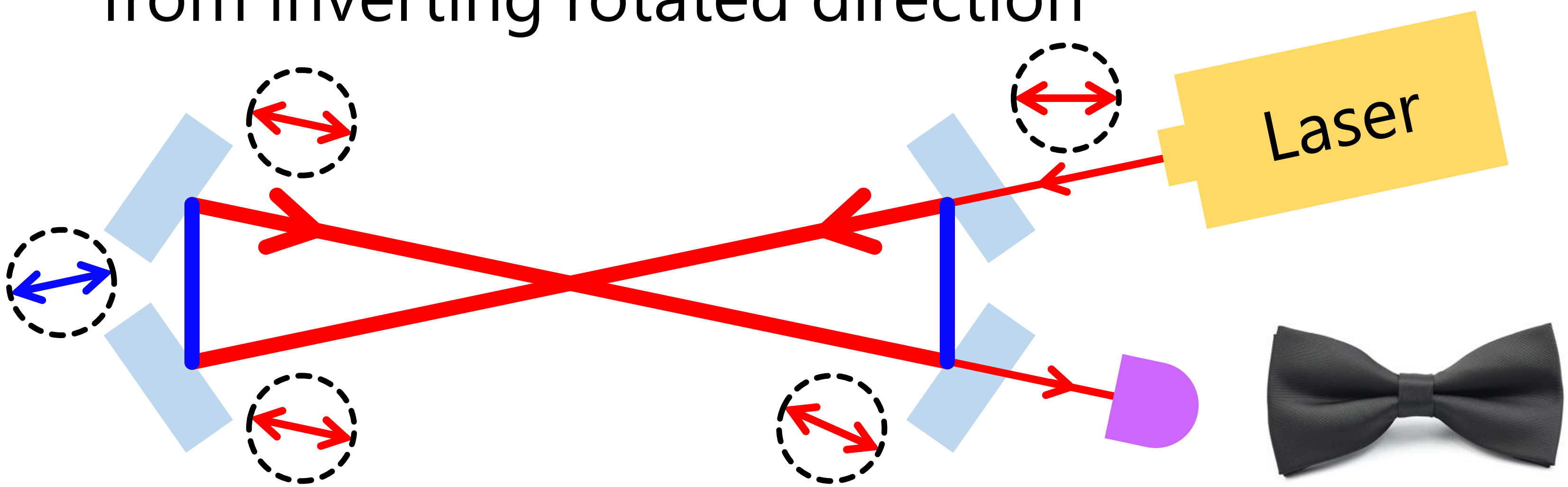


Bow-tie ring cavity

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

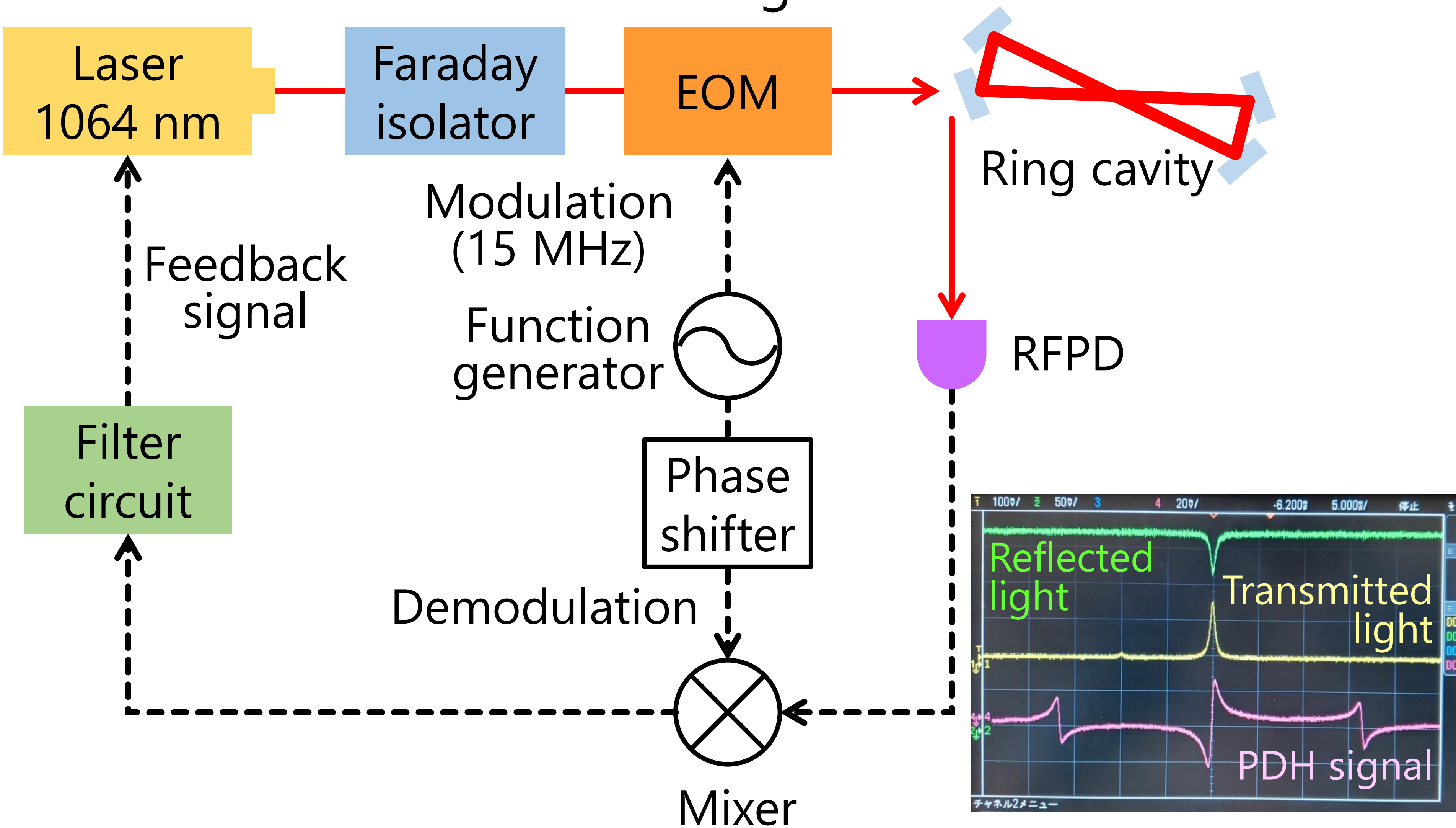


- A bow-tie ring cavity prevents linear polarization from inverting rotated direction

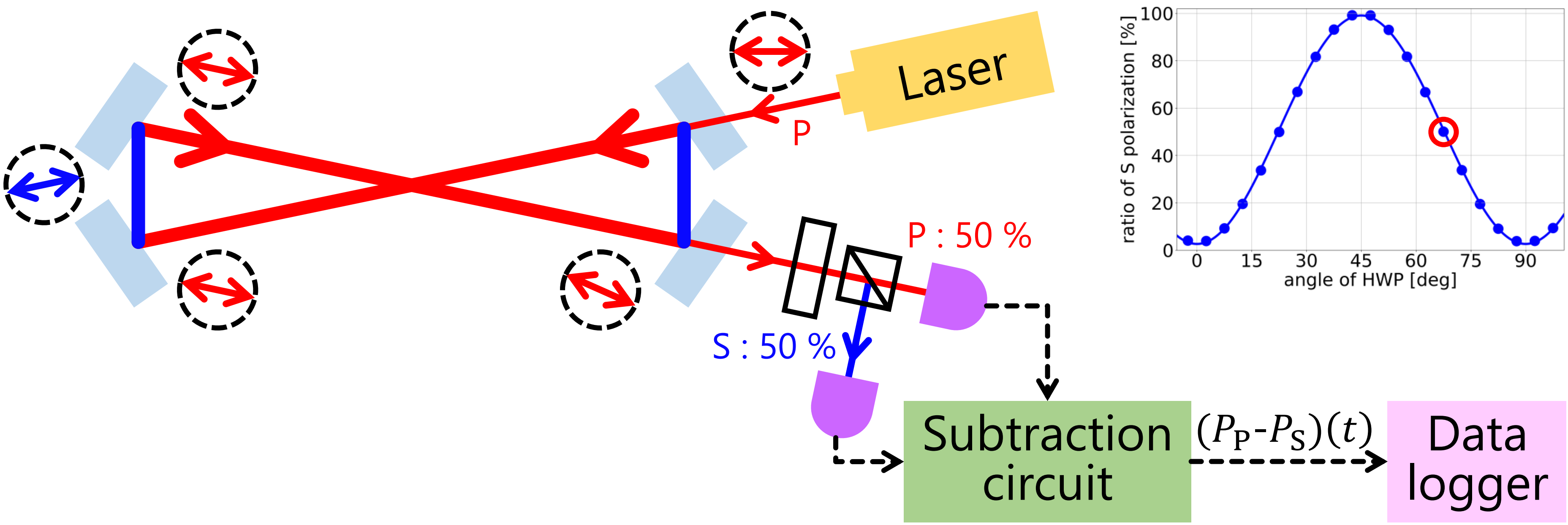


Frequency servo by PDH technique

- Lock laser frequency to resonance of a cavity to obtain data for a long time



Data acquisition

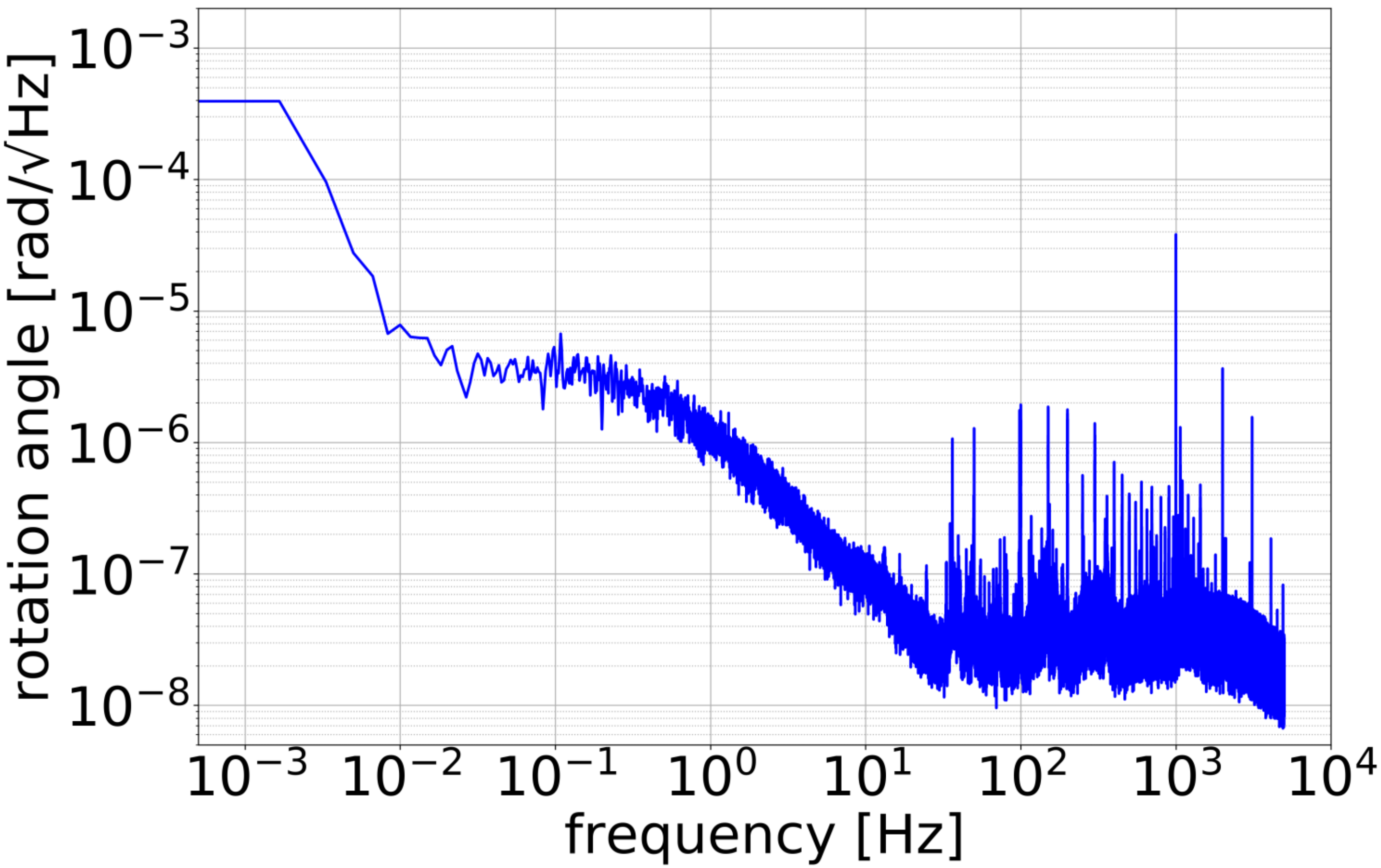


- HWP is fixed to make equal amount of P and S polarization
- Record a differential power $(P_\mathrm{P}\text{-}P_\mathrm{S})(t)$
- Use a subtraction circuit to remove common noise of P and S polarization and to reduce quantization noise of a data logger

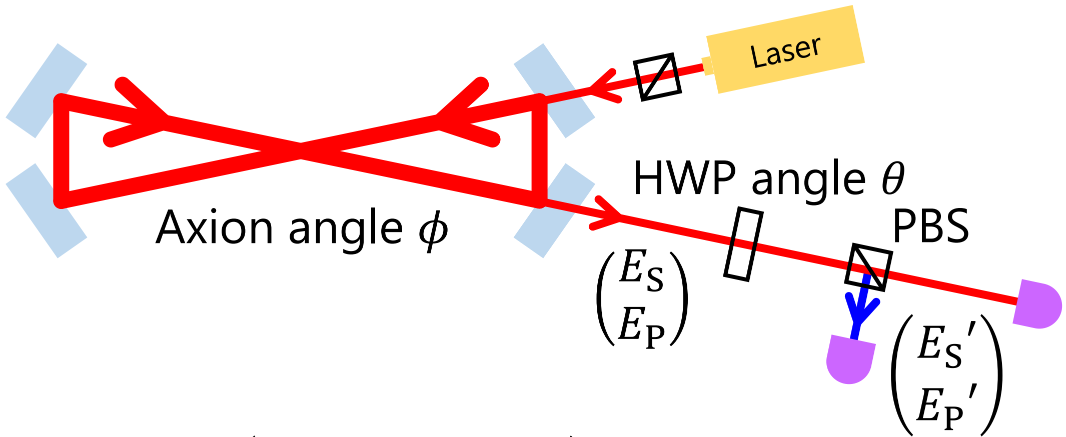
Data analysis

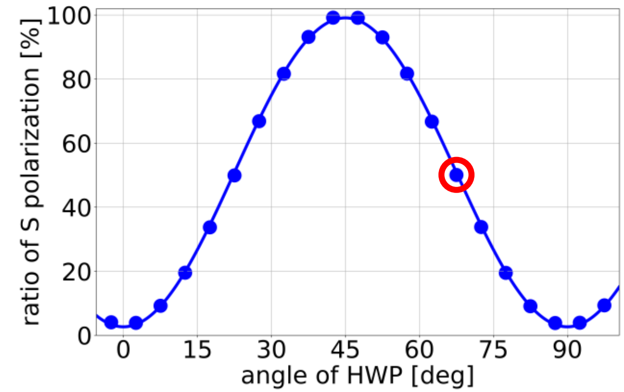
Rotation angle of linear polarization

$$\phi(t) = \frac{(P_{\mathrm{P}} - P_{\mathrm{S}})(t)}{2(P_{\mathrm{P}} + P_{\mathrm{S}})}$$



Data analysis





$$\begin{pmatrix} E_S \\ E_P \end{pmatrix} = \begin{pmatrix} E_0 \sin \phi(t) \\ E_0 \cos \phi(t) \end{pmatrix}, \text{ HWP } \begin{pmatrix} \cos 2\theta & \sin 2\theta \\ -\sin 2\theta & \cos 2\theta \end{pmatrix}$$

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

$$P_S = {E_S'}^2 = E_0^2 \sin^2\left(2\theta + \phi(t)\right)$$

$$P_P = {E_P'}^2 = E_0^2 \cos^2\left(2\theta + \phi(t)\right)$$

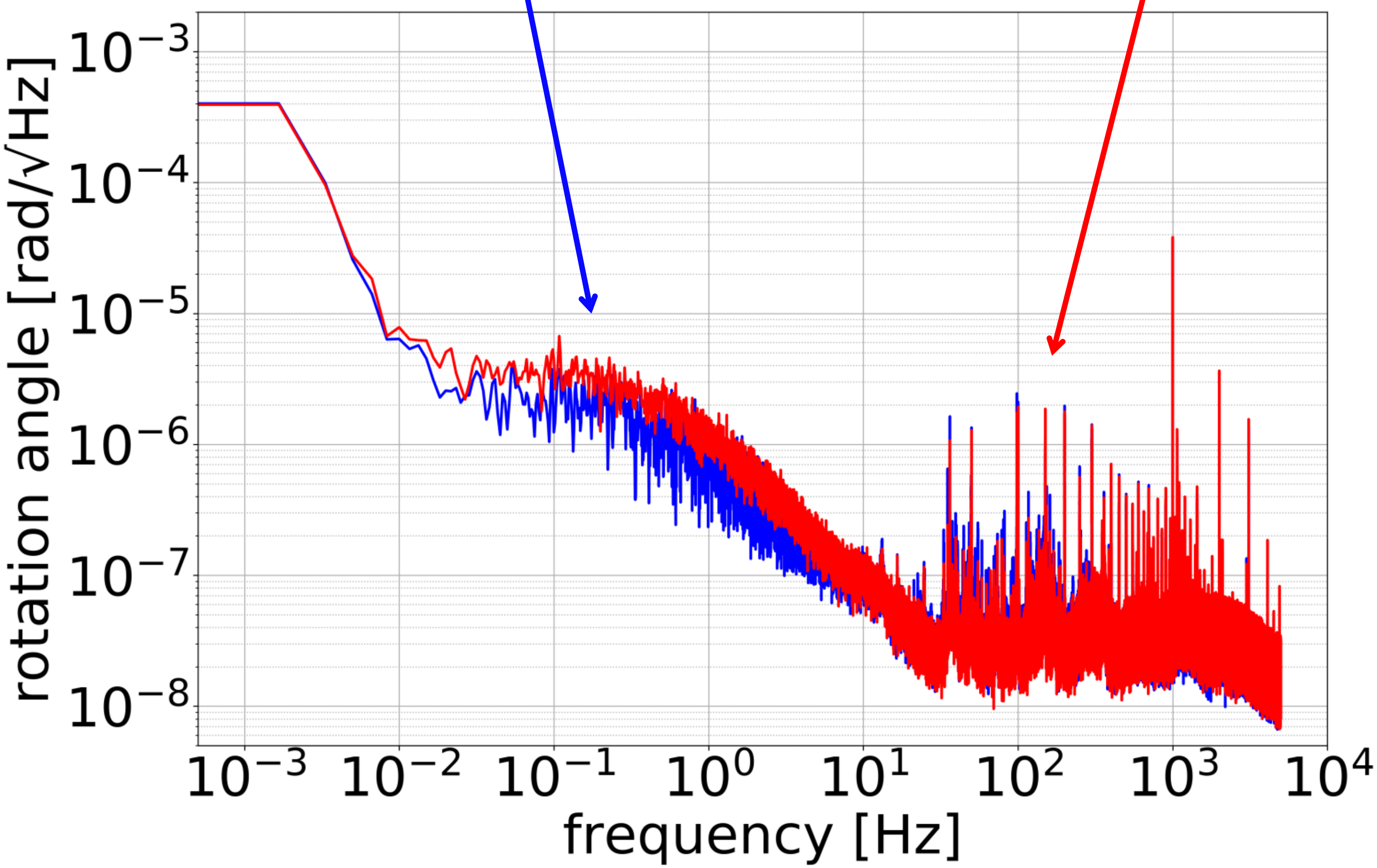
Differential : $P_P - P_S = E_0^2 \cos(2(2\theta + \phi(t)))$

When HWP angle $2\theta = 45$ deg, $P_P - P_S = 2E_0^2 \phi(t)$

Comparison for data analysis

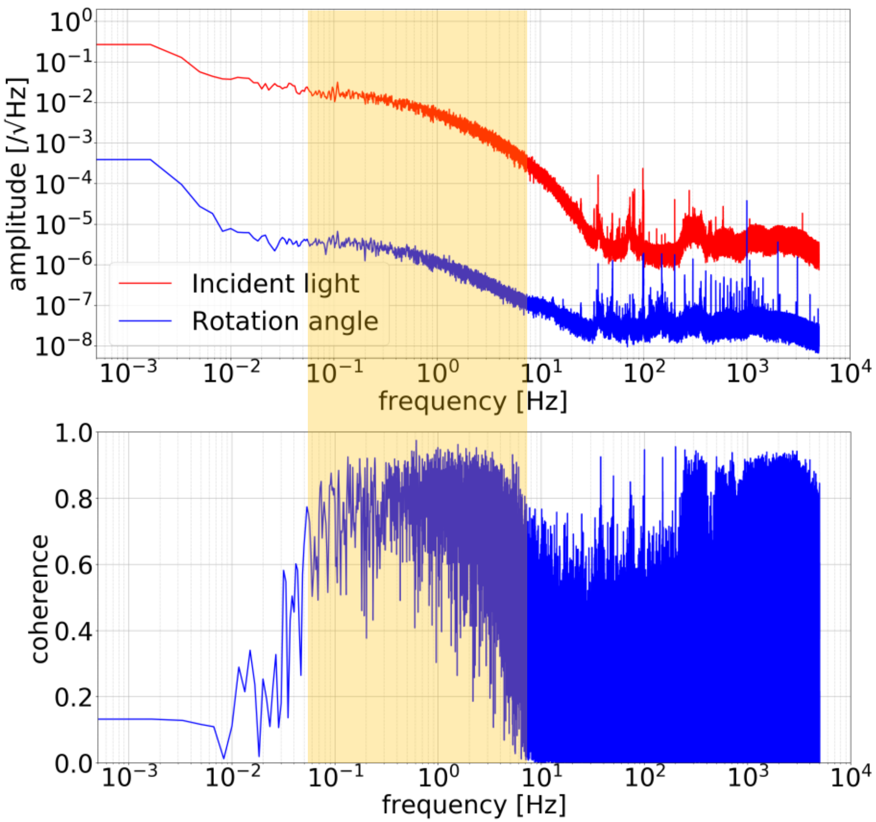
$$\phi(t) = \frac{(P_\mathrm{P} - P_\mathrm{S})(t)}{2(P_\mathrm{P}(t) + P_\mathrm{S}(t))}$$

$$\phi(t) = \frac{(P_\mathrm{P} - P_\mathrm{S})(t)}{2(\overline{P_\mathrm{P} + P_\mathrm{S}})}$$



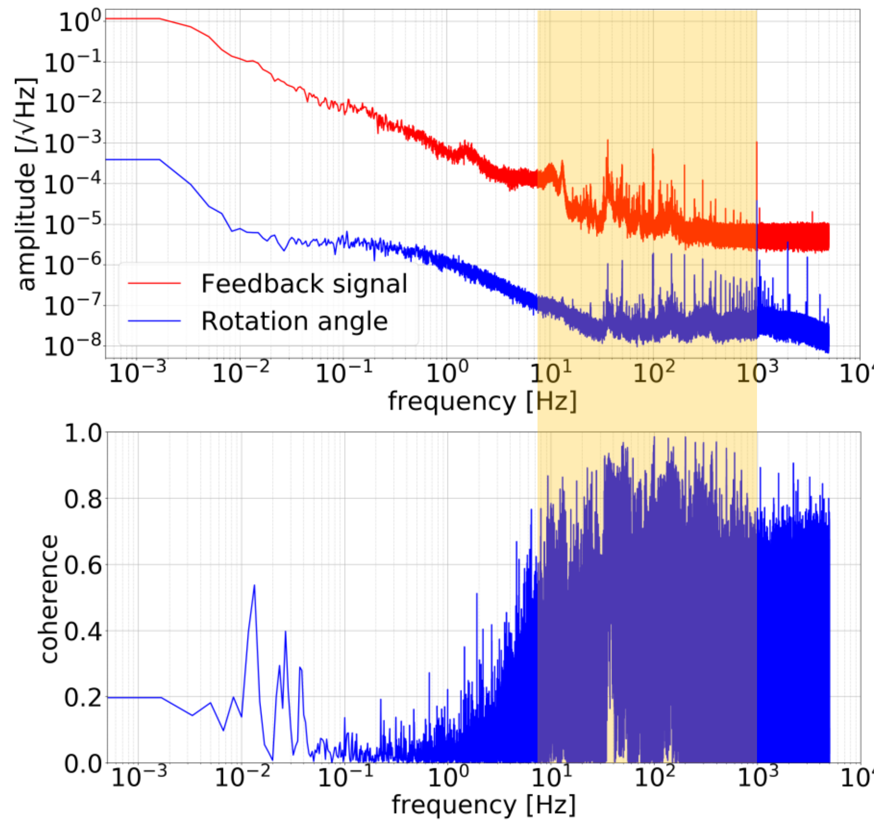
Discussion for noise

Correlation with incident light



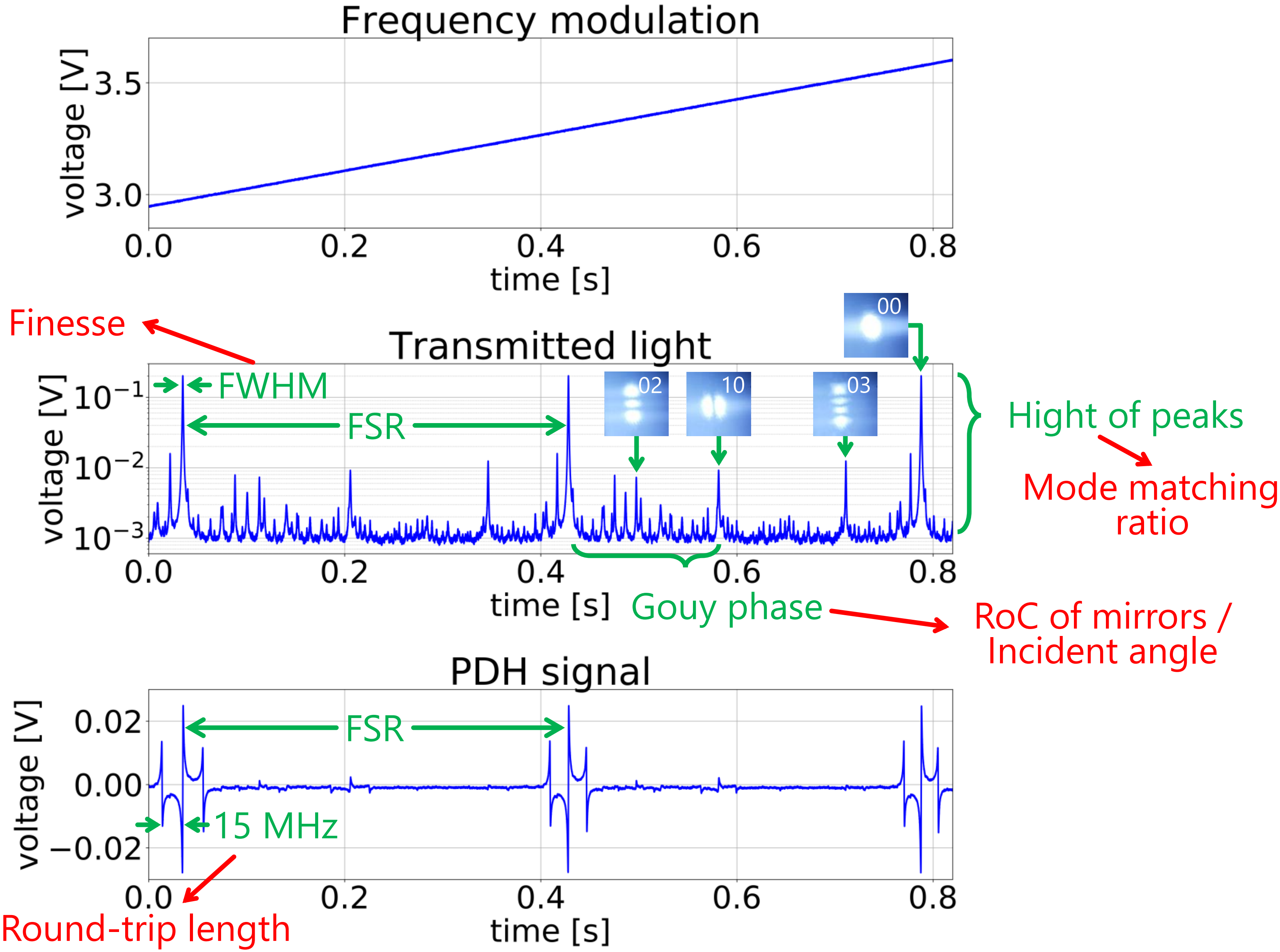
- Sensitivity is limited by laser intensity noise in 0.1 Hz-10 Hz
  - An optical fiber

Correlation with feedback signal



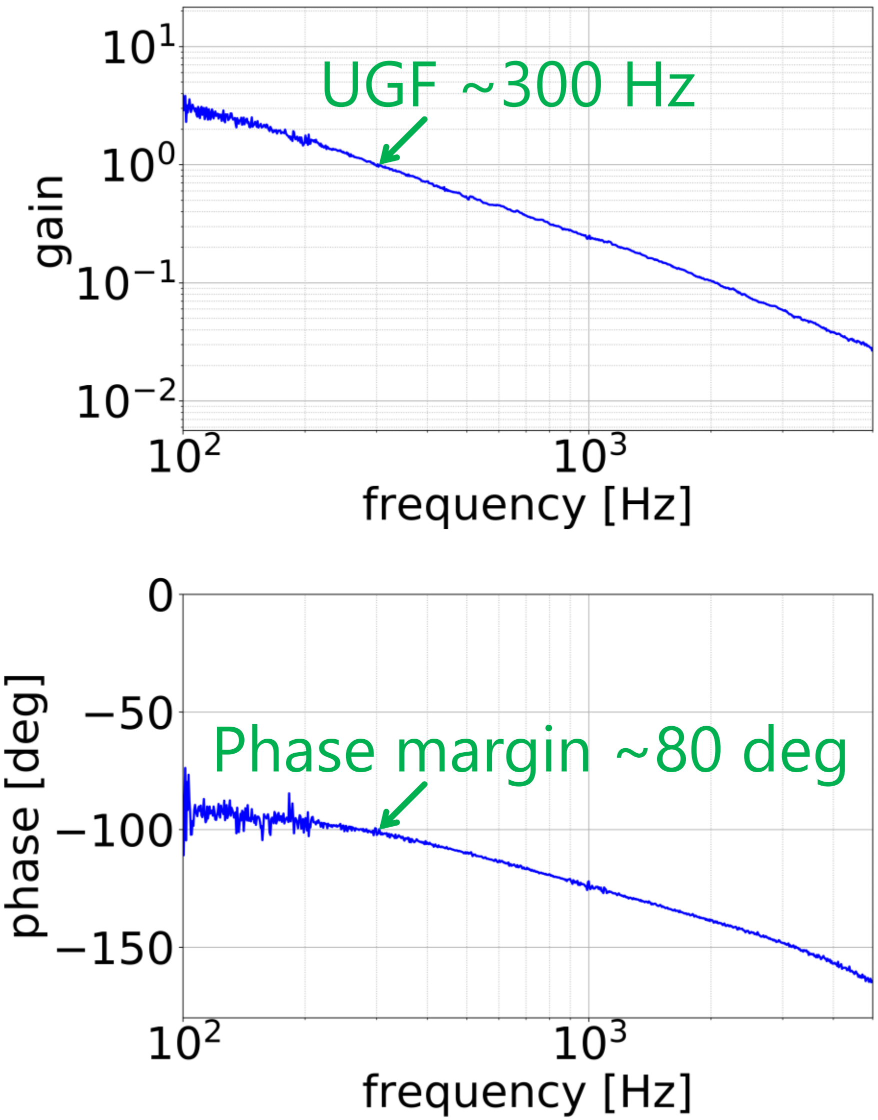
- Sensitivity is limited by external noise in 10 Hz-1 kHz
  - Vibration (seismic, sounds, mechanical)

Cavity scan

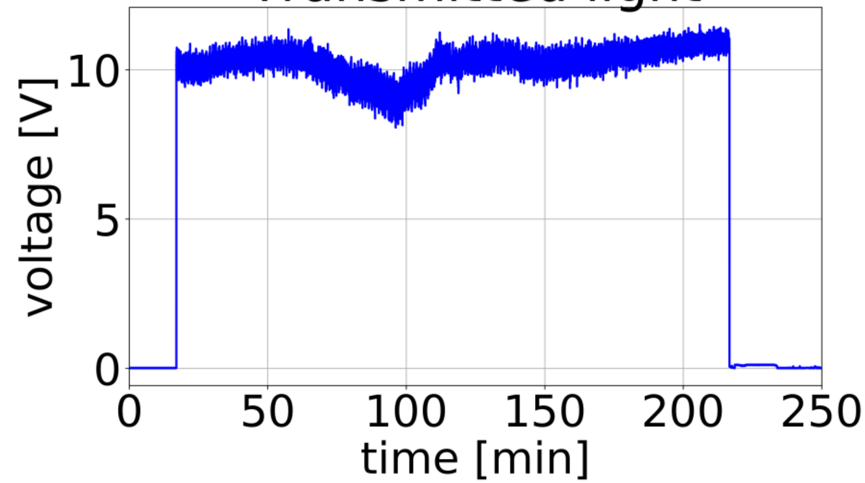

Frequency modulation
voltage [V]
3.5
3.0
0.0
0.2
0.4
0.6
0.8
time [s]
Finesse
Transmitted light
00
02
10
03
FWHM
FSR
10^{-1}
10^{-2}
10^{-3}
Hight of peaks
Mode matching ratio
Gouy phase
RoC of mirrors / Incident angle
PDH signal
0.02
0.00
−0.02
FSR
15 MHz
Round-trip length

Stability of feedback control

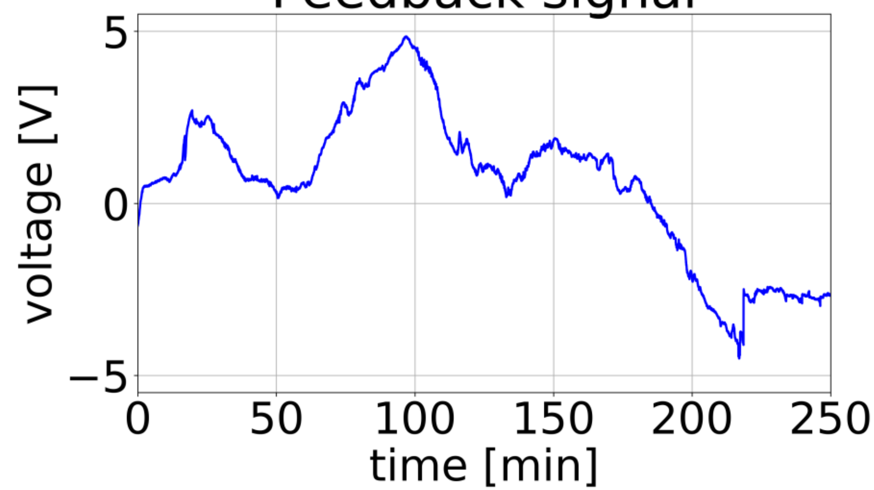
Open-loop transfer function



Transmitted light



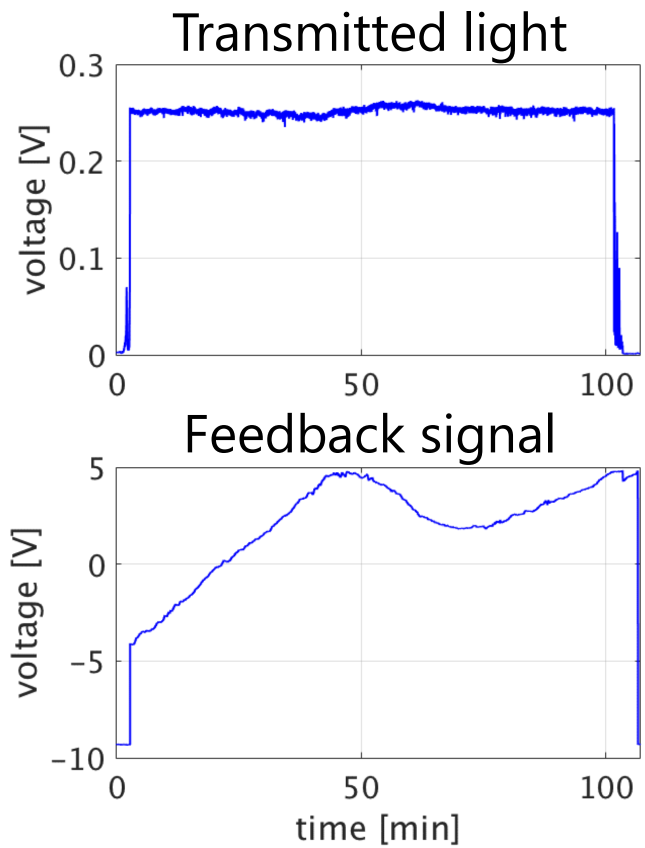
Feedback signal



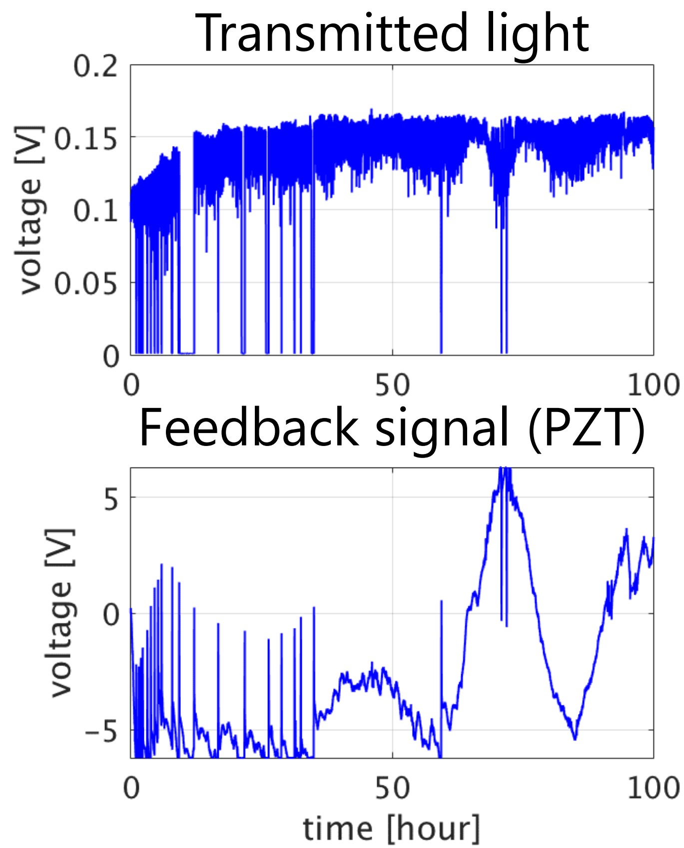
- Control continued in a few hours

Double-loop control

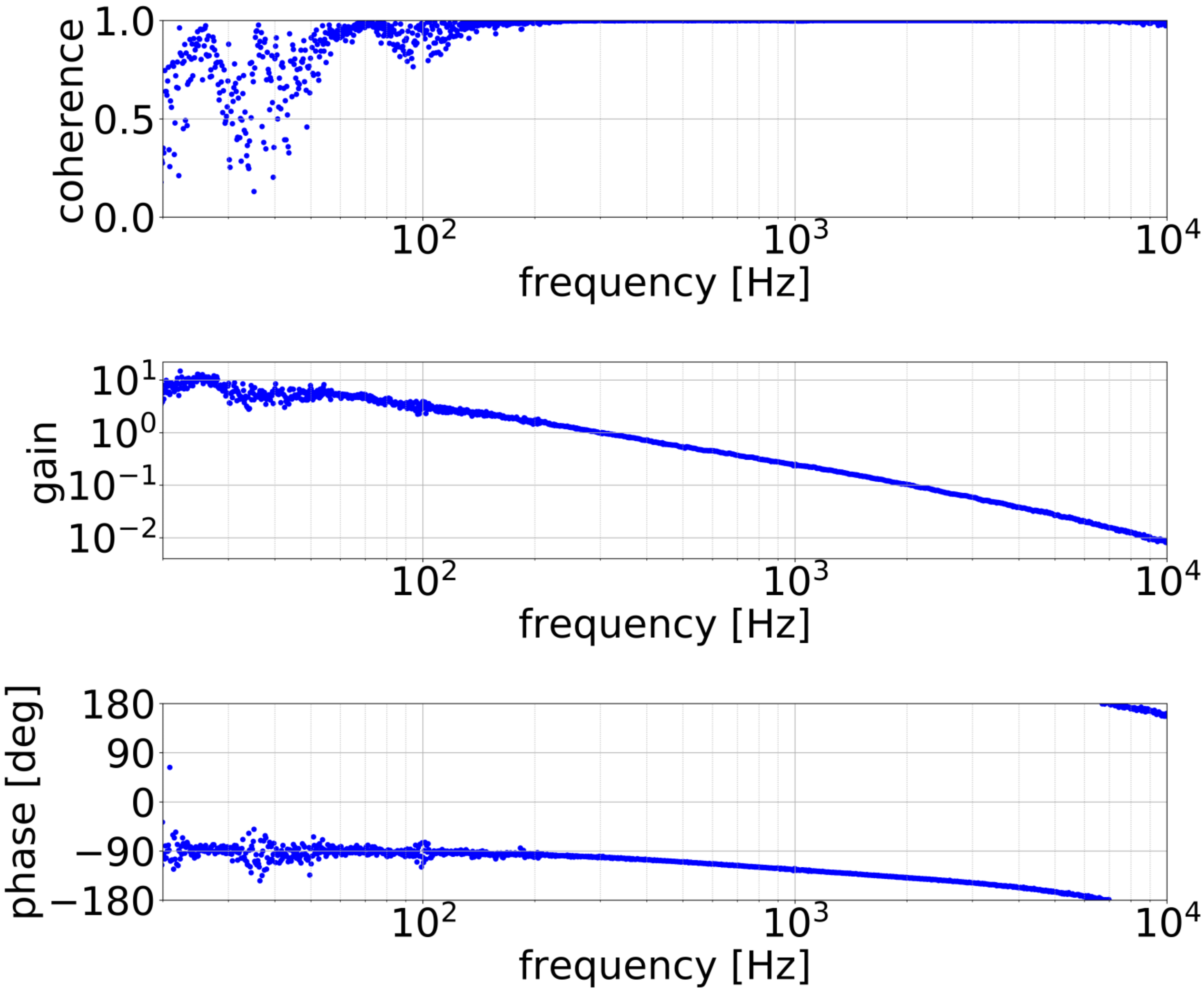
Only with laser PZT actuator
: in a few hours



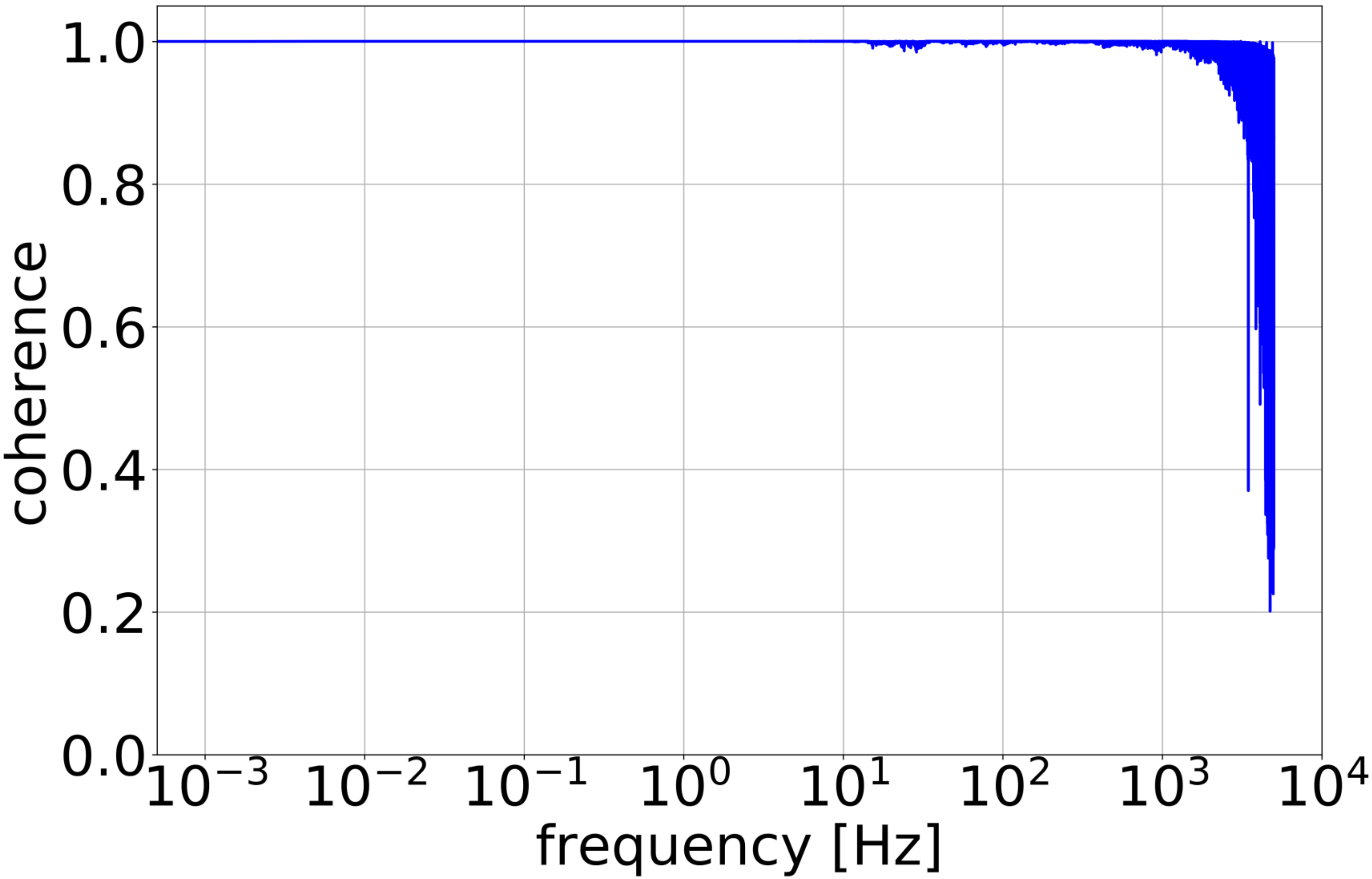
With laser PZT actuator
and temperature actuator
: in a few days



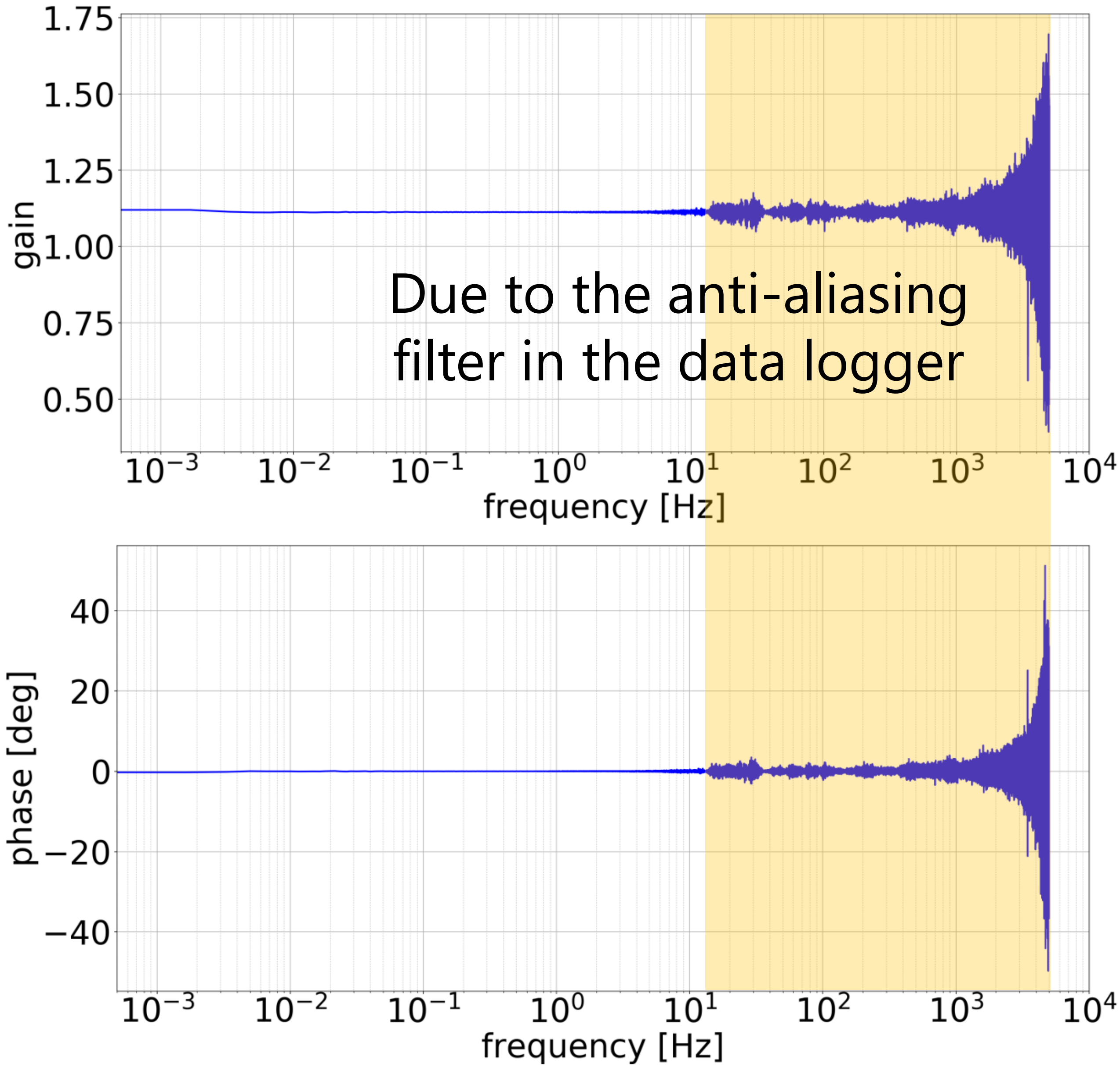
Open-loop transfer function (raw data)



Coherence between polarizations



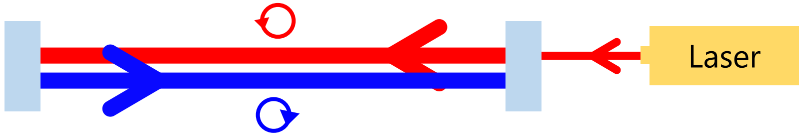
Transfer function between polarizations



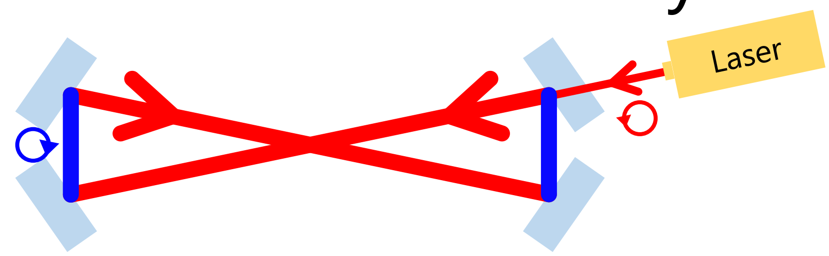
Bow-tie cavity & Double-pass configuration

- Bow-tie ring cavity

The effect is canceled in a linear cavity



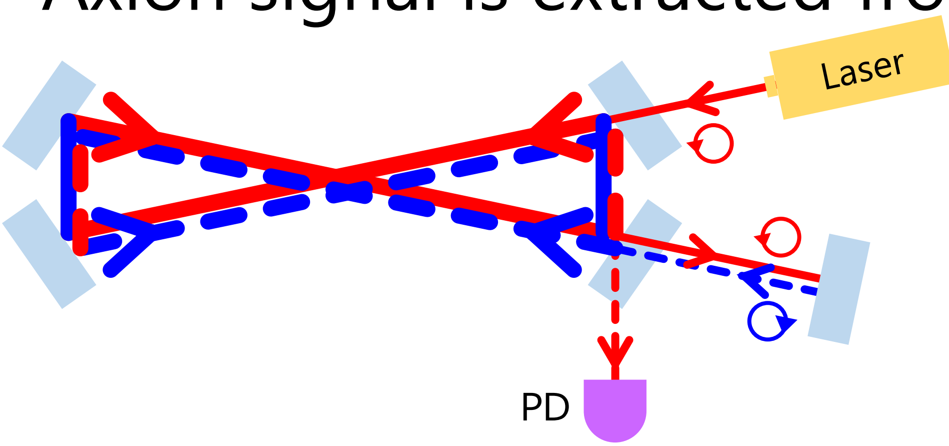
Not canceled in a bow-tie cavity



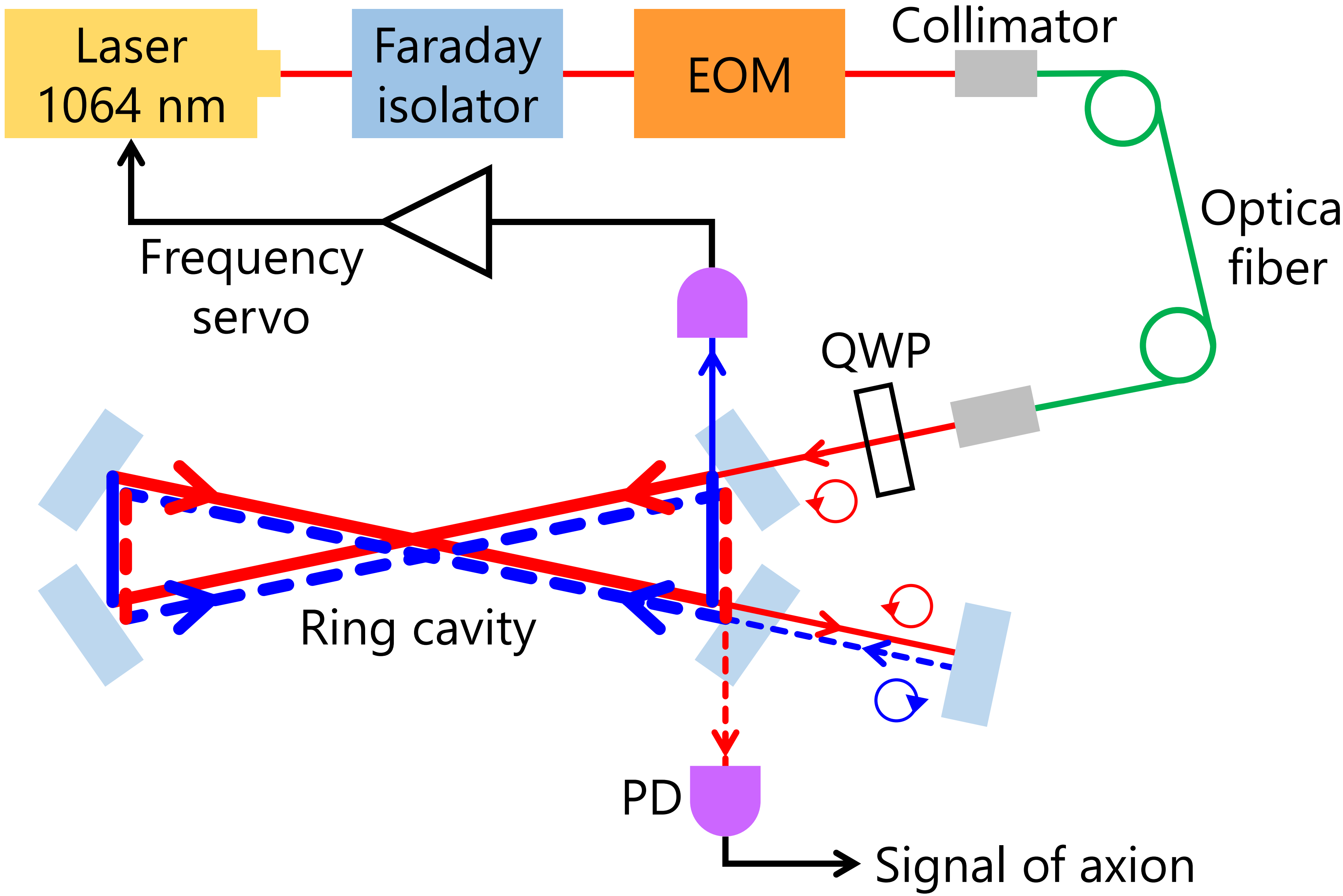
- Double-pass configuration

Transmitted beam is reflected back into a cavity
Axion signal is extracted from the reflection

(null measurement)

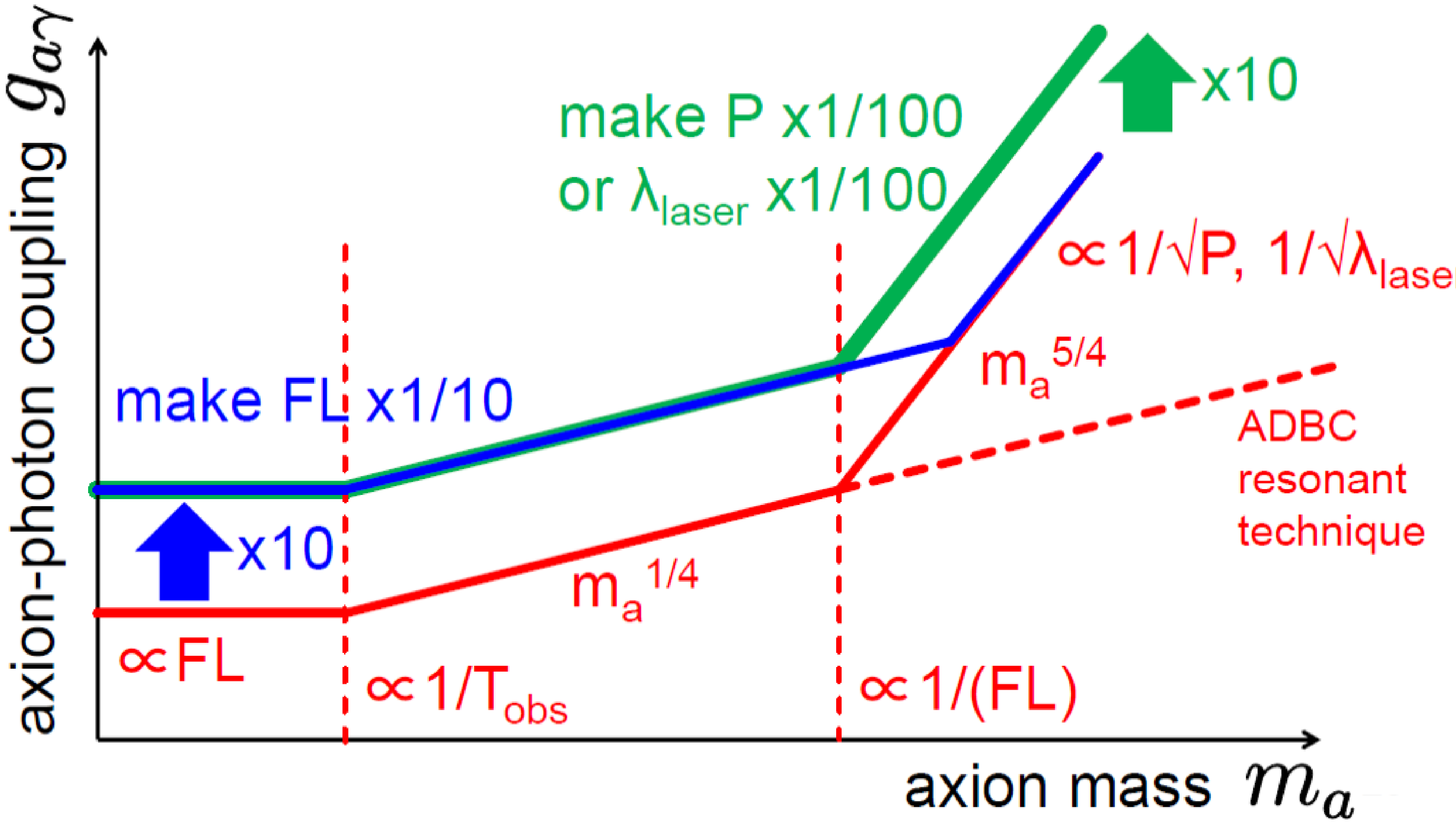


Setups (Circular pol. & Double-pass)



Sensitivity Design

- Brute force necessary, you cannot win for free



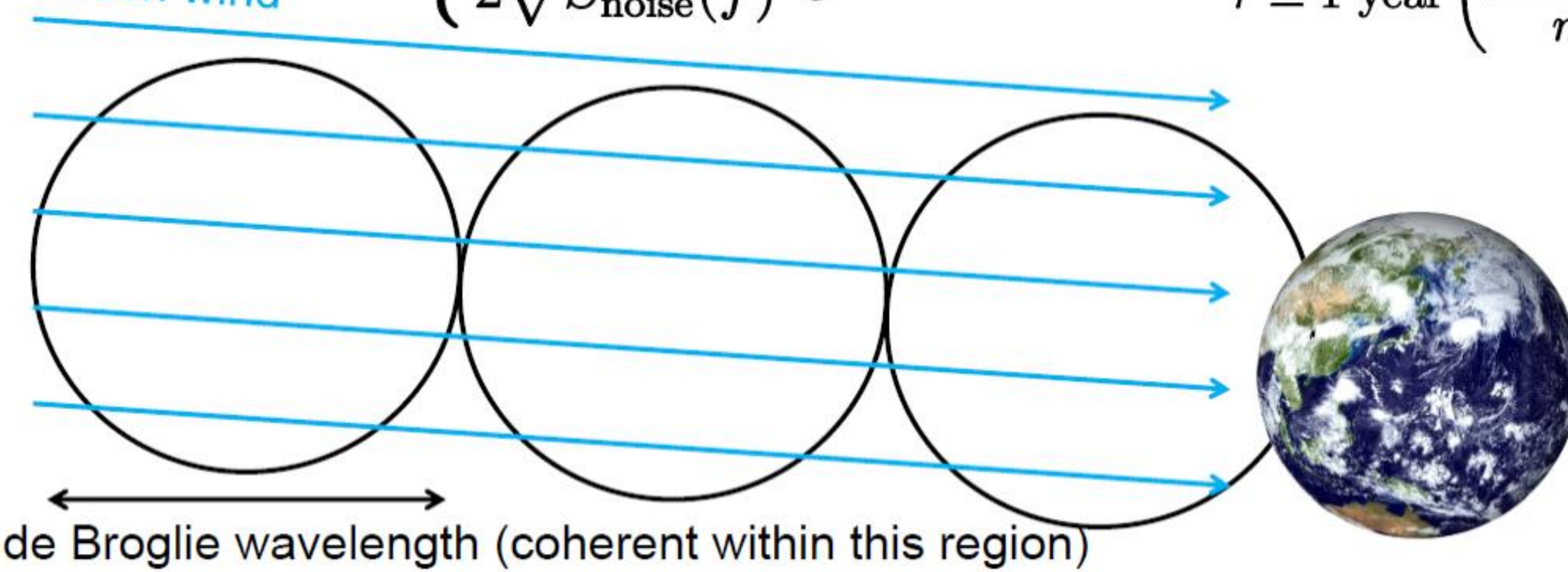
Made by Yuta Michimura

Coherent Time Scale

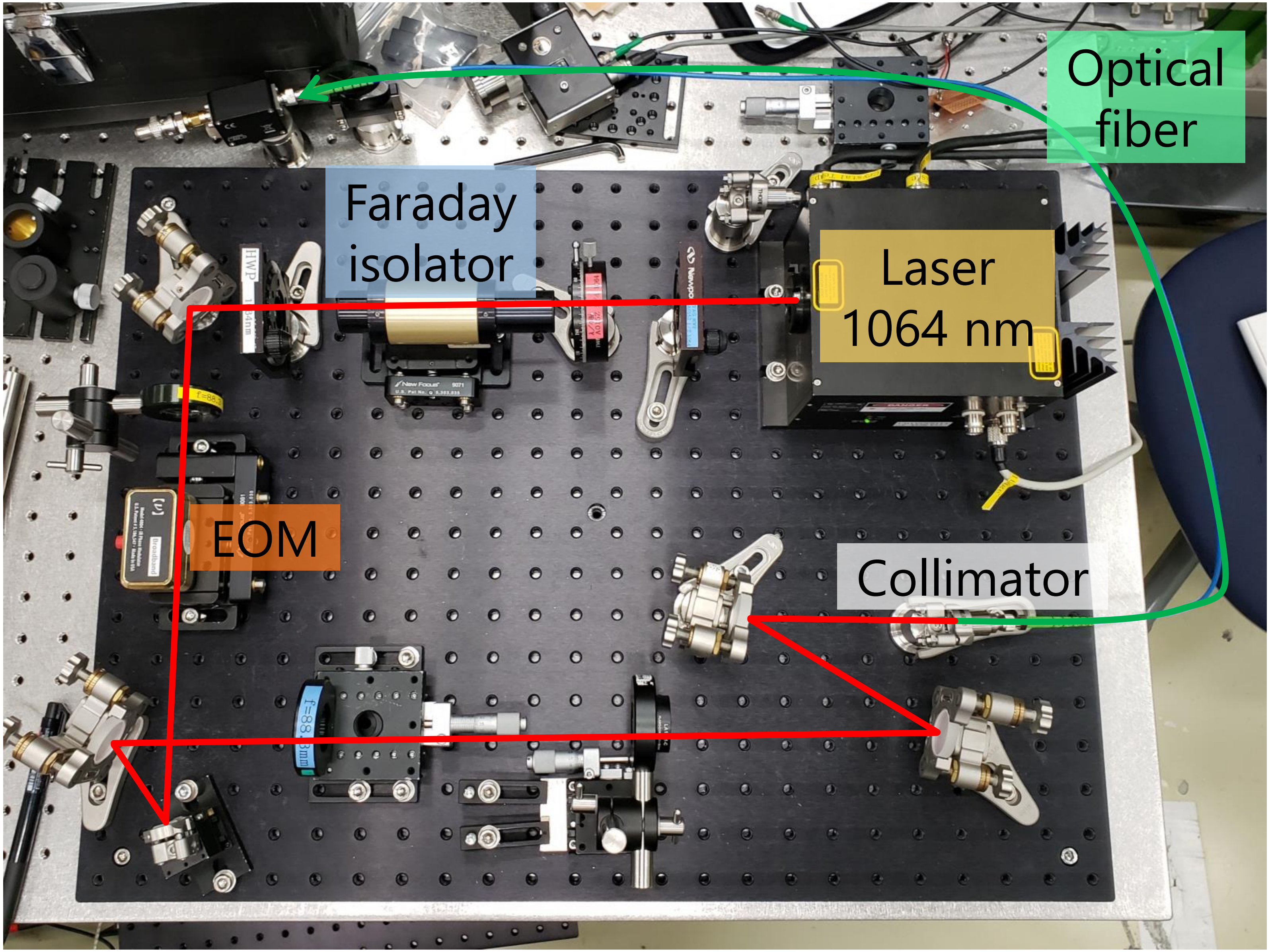
- SNR grows with $\sqrt{T_{obs}}$ if integration time is shorter than coherent time scale
- SNR grows with $(T_{obs})^{1/4}$ if integration time is longer

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

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



Picture of the setups (1st floor)



Picture of the setups (2nd floor)