The current sensitivity of DANCE Act-1

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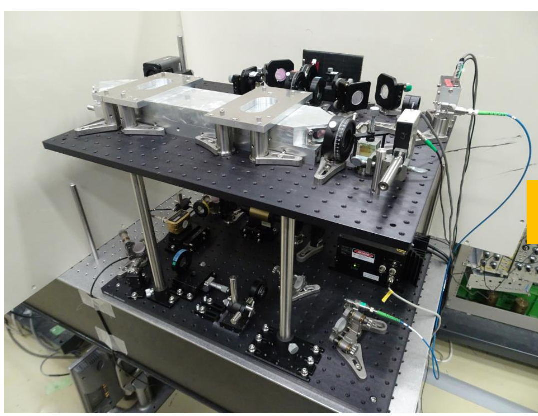
Overview

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

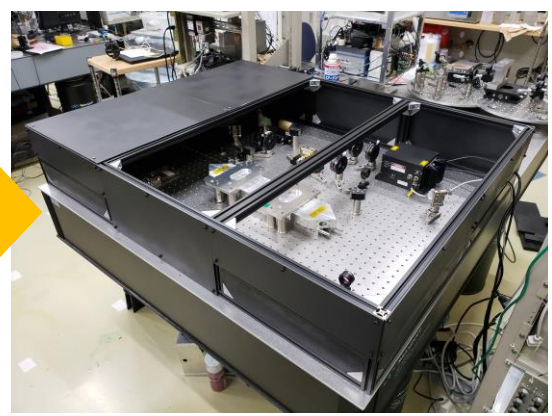
I. Obata, T. Fujita, Y. Michimura
PRL 121, 161301 (2018)

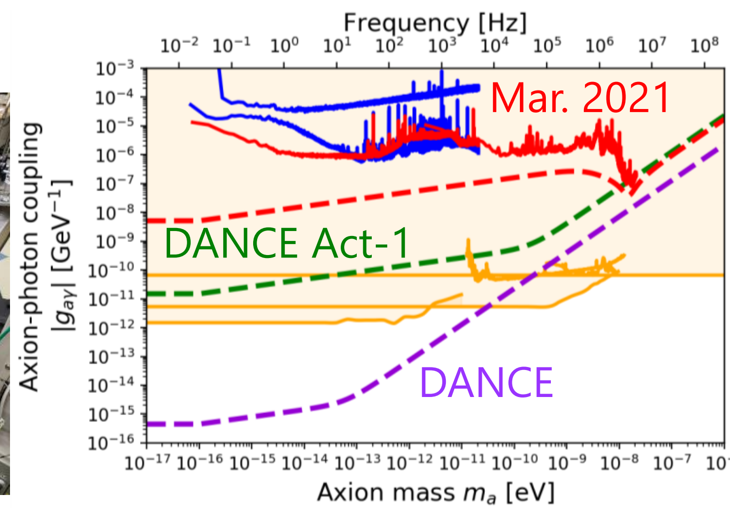
- Prototype experiment DANCE Act-1 is ongoing
  - Improved and evaluated the optics
  - Obtained the data and estimated the sensitivity

Ver. Nov. 2020



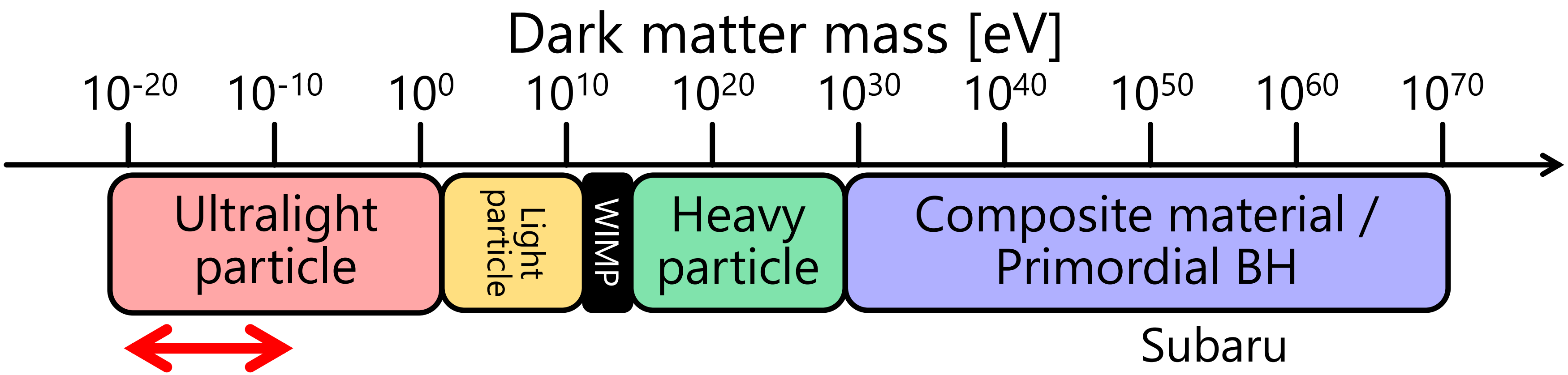
Ver. Mar. 2021





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



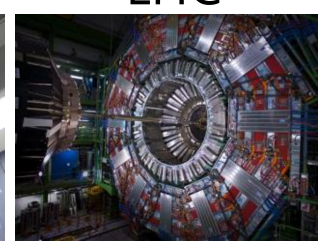
Laser interferometers

DANCE

KAGRA

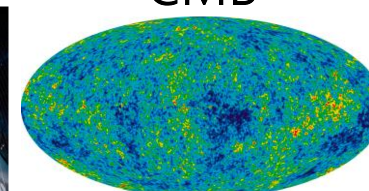
XENON1T

LHC



Subaru Telescope

CMB



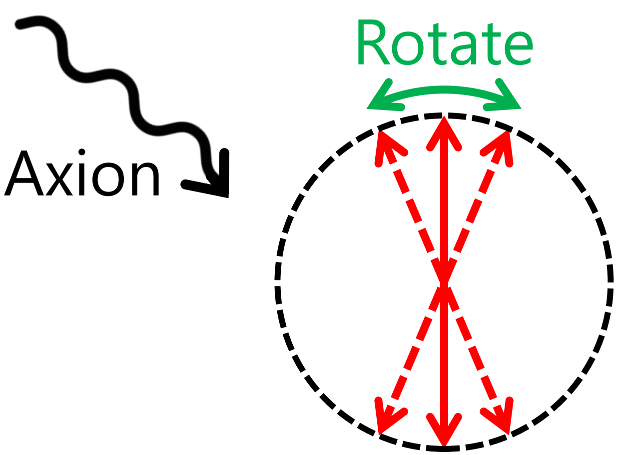
Rotation of linear polarization

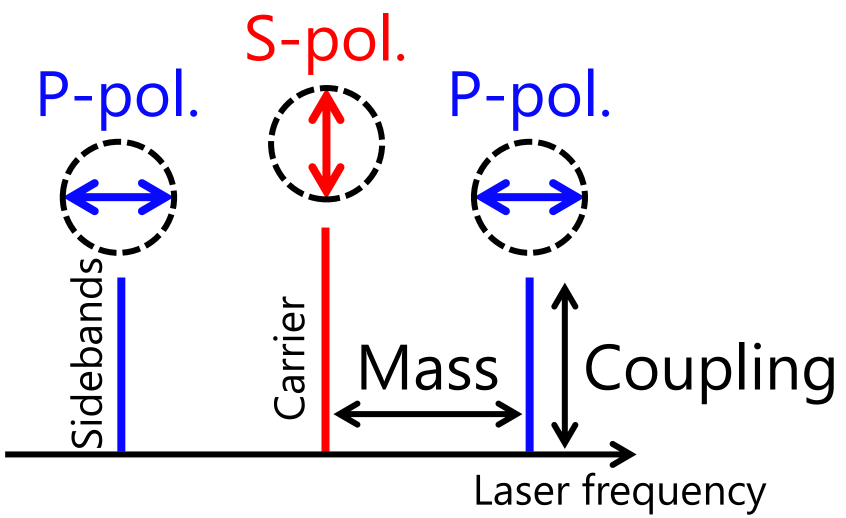
- Axion-photon coupling causes phase velocity difference between left- and right-handed photons

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

Coupling constant   Axion field   Axion mass

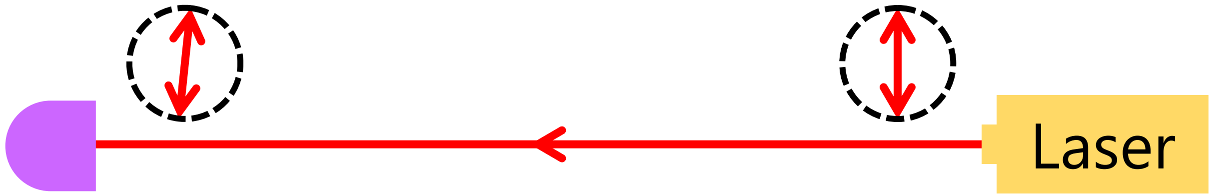
- Phase velocity difference of circular polarizations makes linear polarization rotate



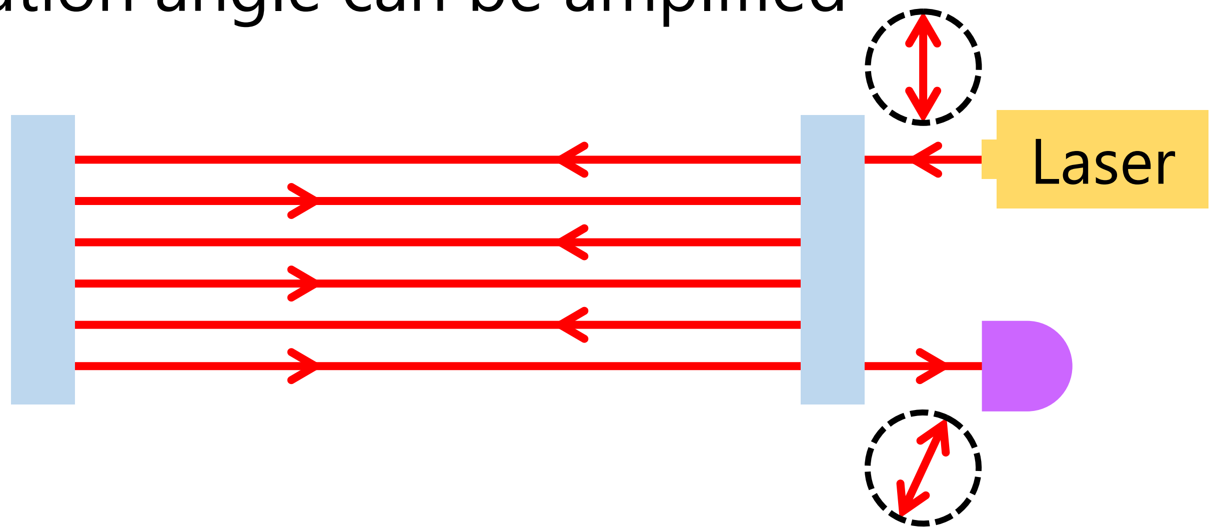


Amplification of rotation angle

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

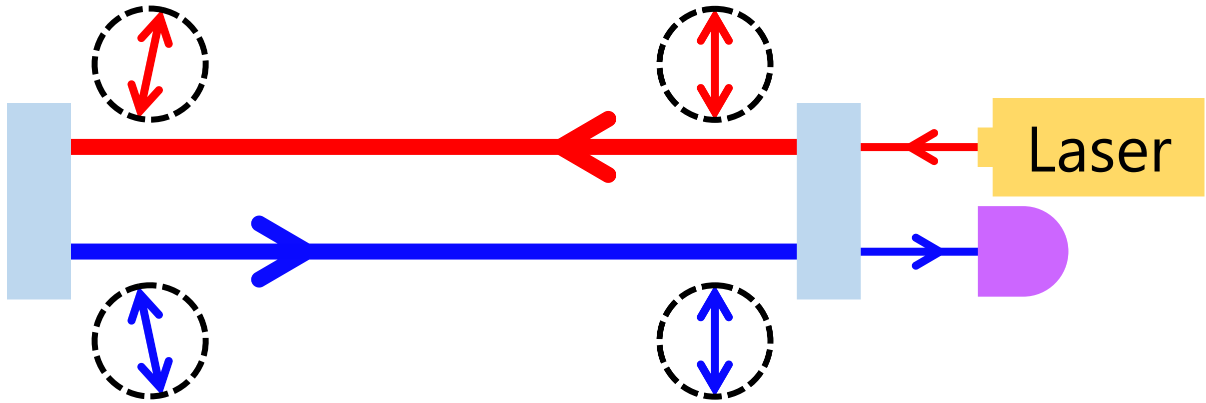


- Laser light runs between mirrors many times in a cavity
  → Rotation angle can be amplified

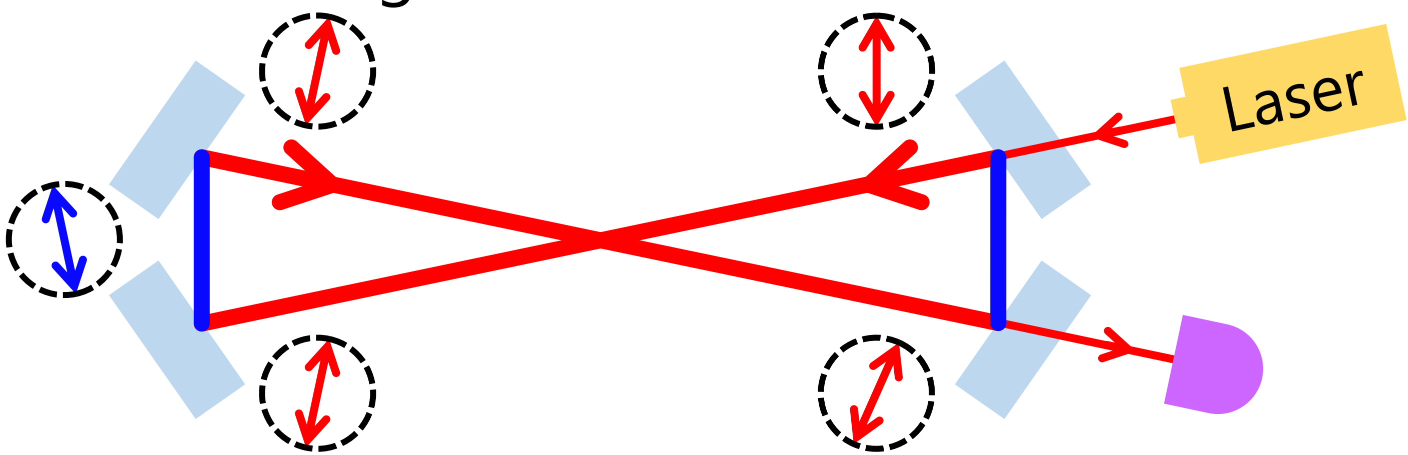


Bow-tie ring cavity

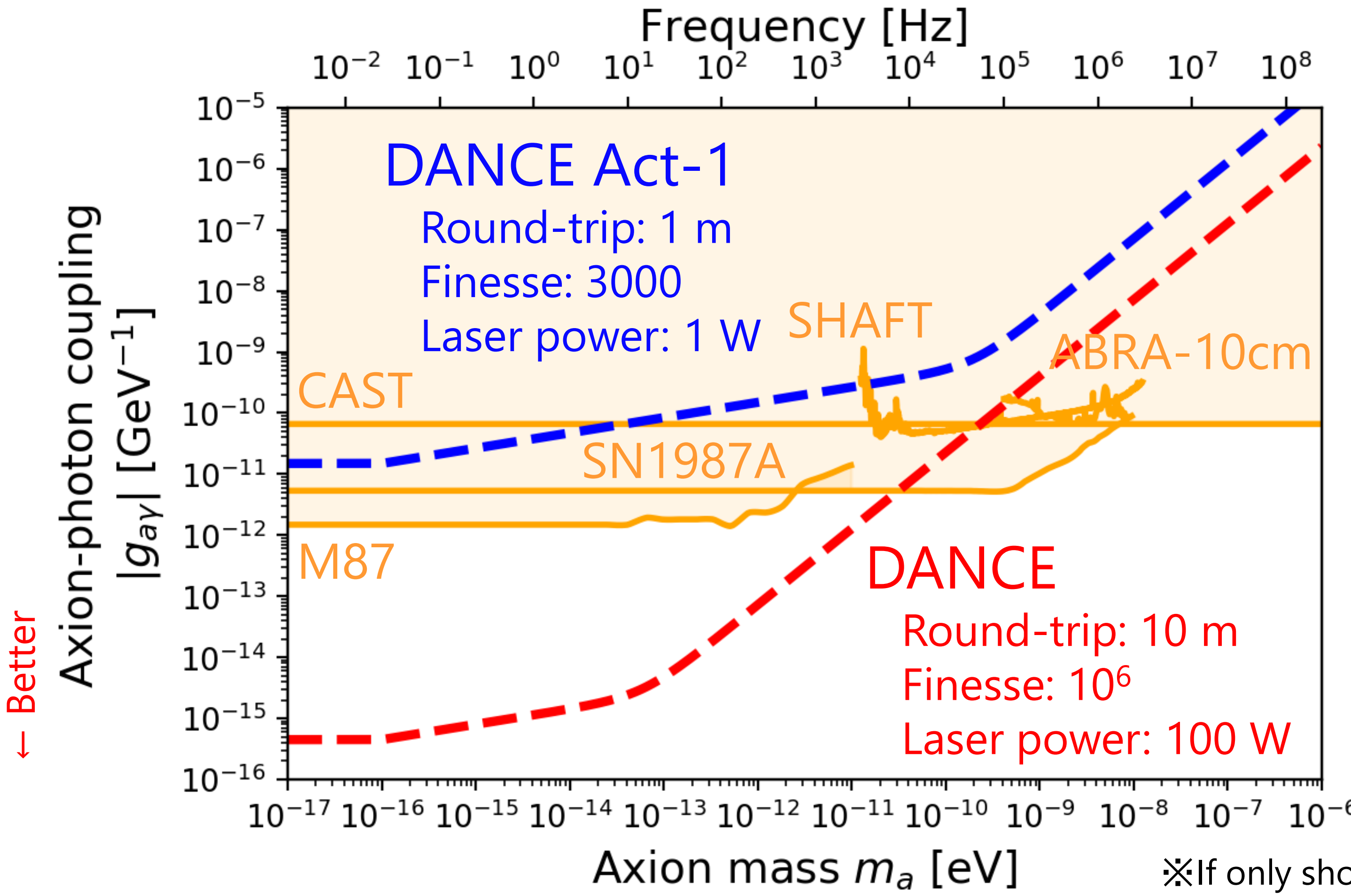
- Rotated direction is inverted in a linear cavity
  → Rotation effect is cancelled out



- 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)

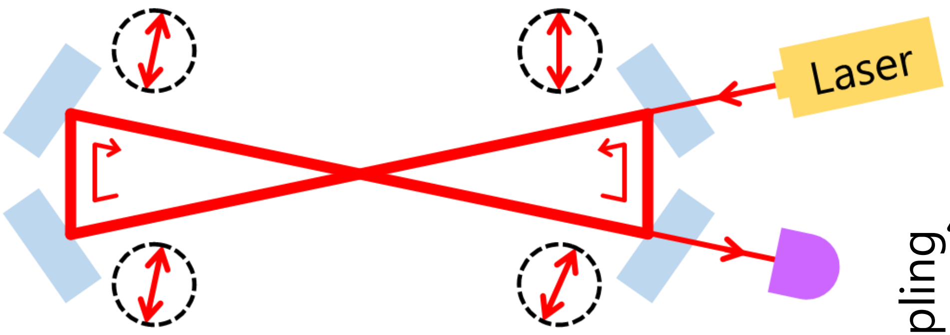
※If only shot noise
If one-year observation
If DM is all composed of axion

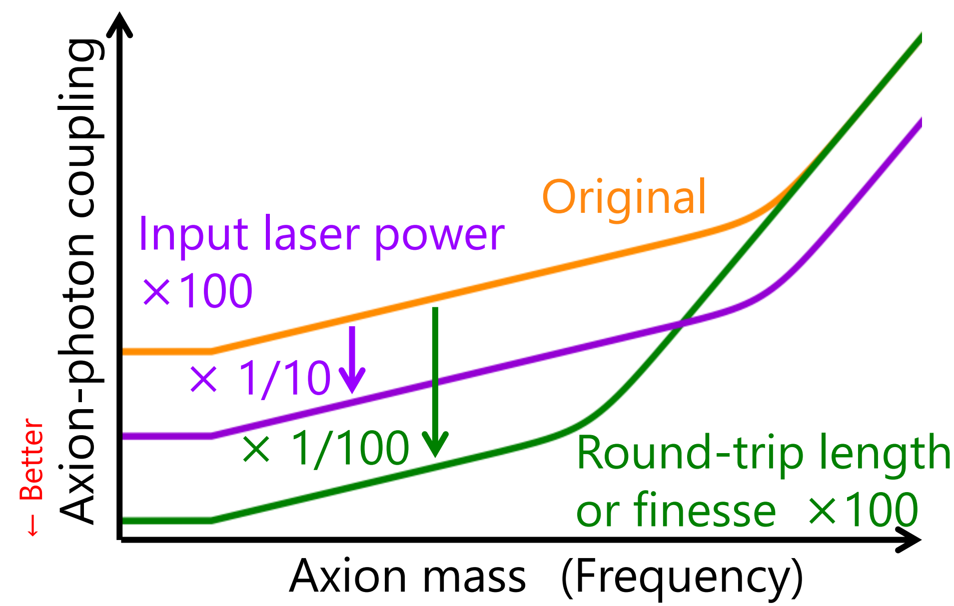
- Shot noise is caused by fluctuations of number of photons
- Need to minimize the other noises

Important parameters (1)

- Input laser power ・・・ Shot noise

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

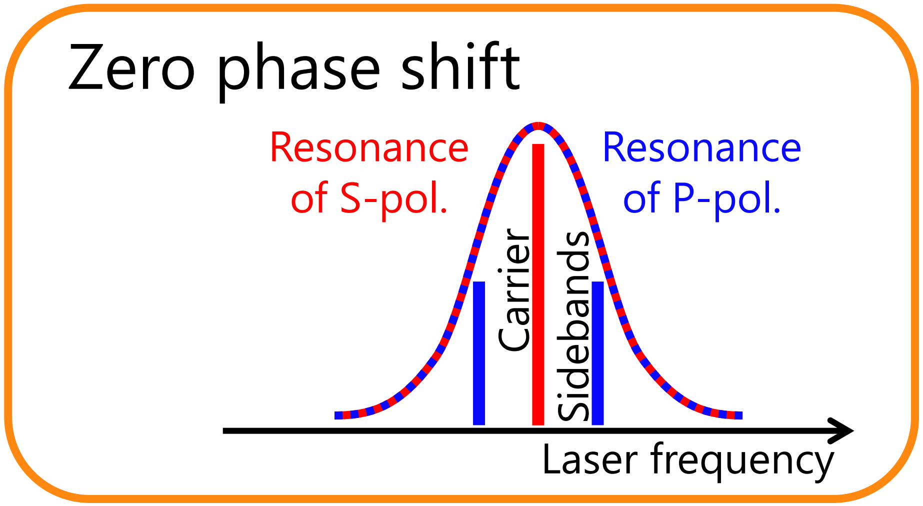


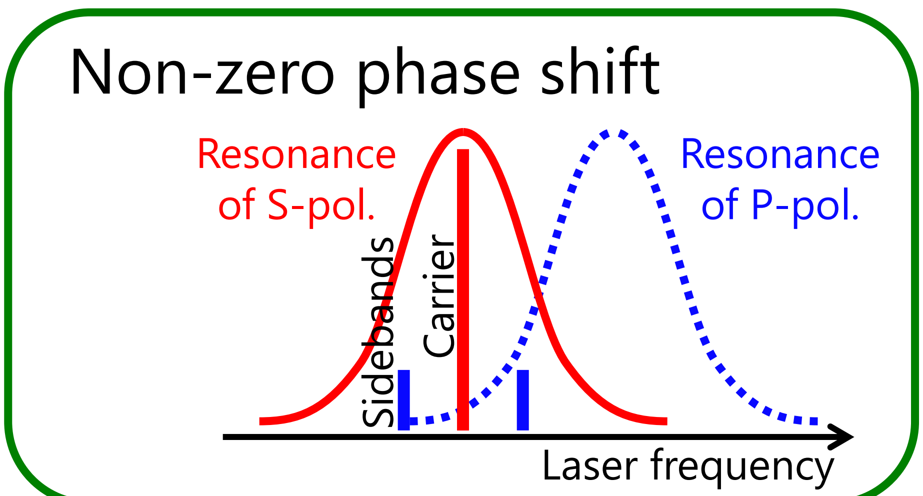


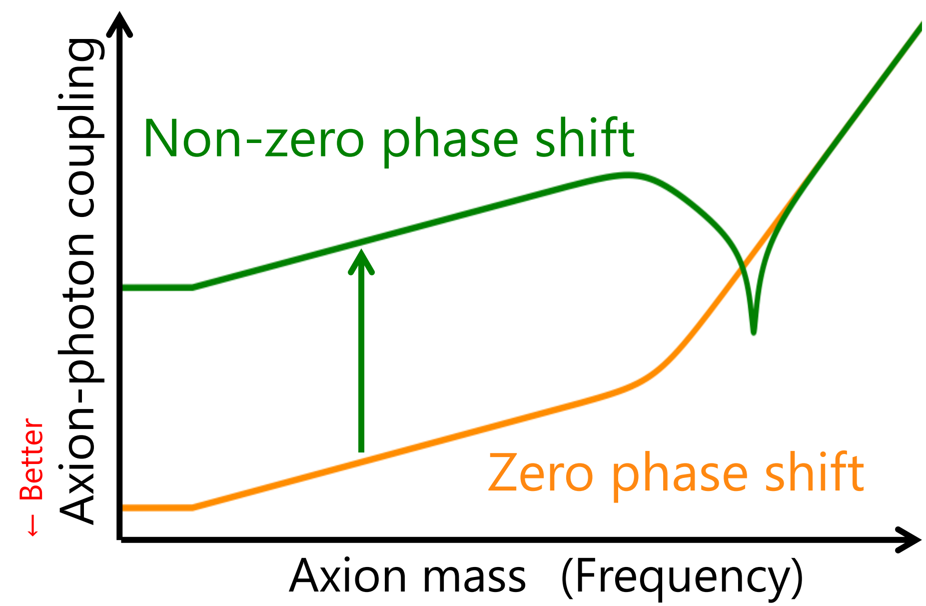
Important parameters (2)

- Resonant frequency difference between polarizations

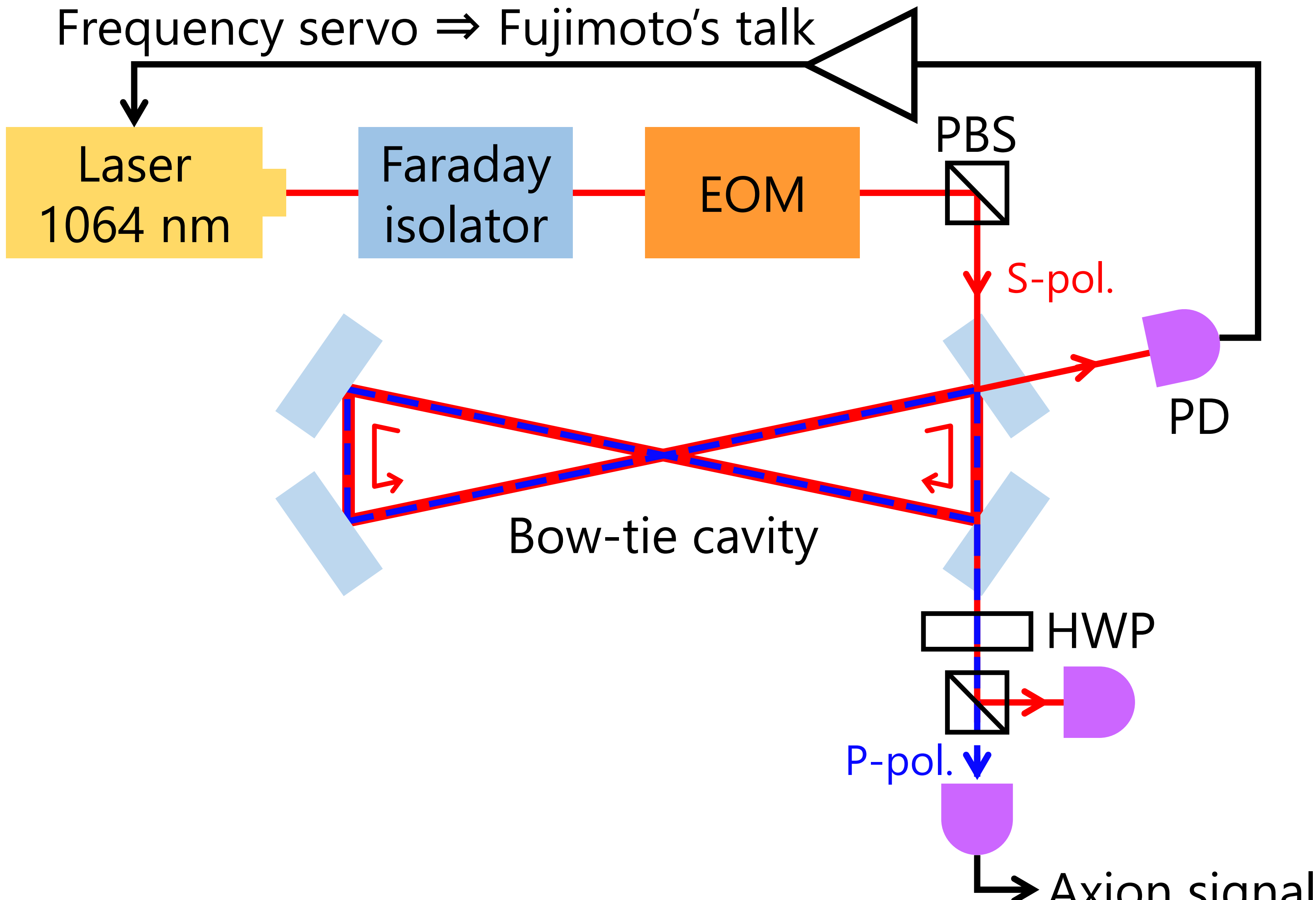
  ･･･ From non-zero phase shift by mirror coating at reflections





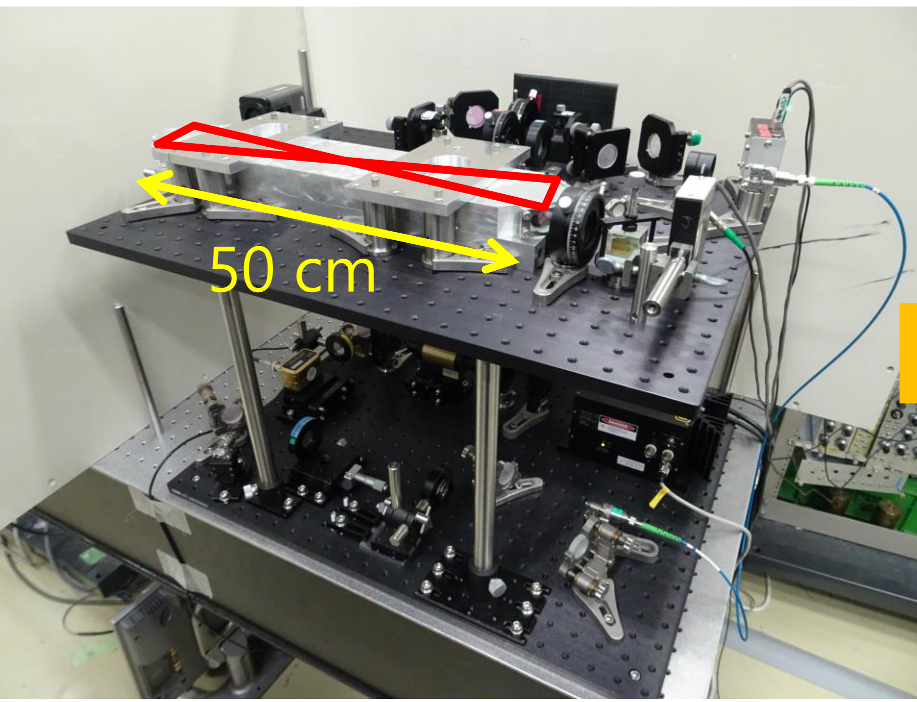


Experimental setups of DANCE

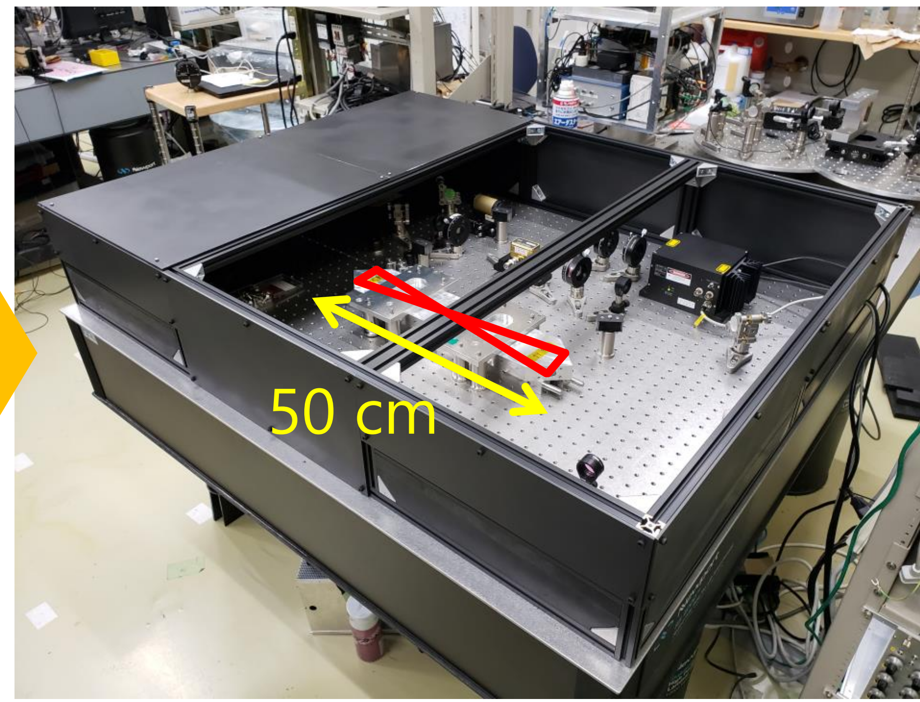


Progress of the experiment

DANCE Act-1
ver. Nov. 2020
(Apr. 2019 – Nov. 2020)



DANCE Act-1
ver. Mar. 2021
(Dec. 2020 – Now)

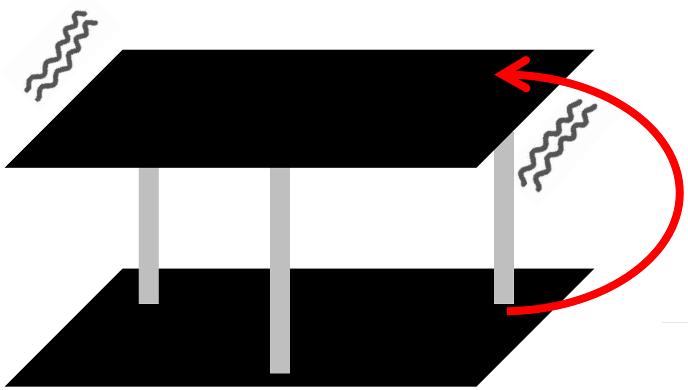


Optical table and optical fiber

Issues of ver. Nov. 2020

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

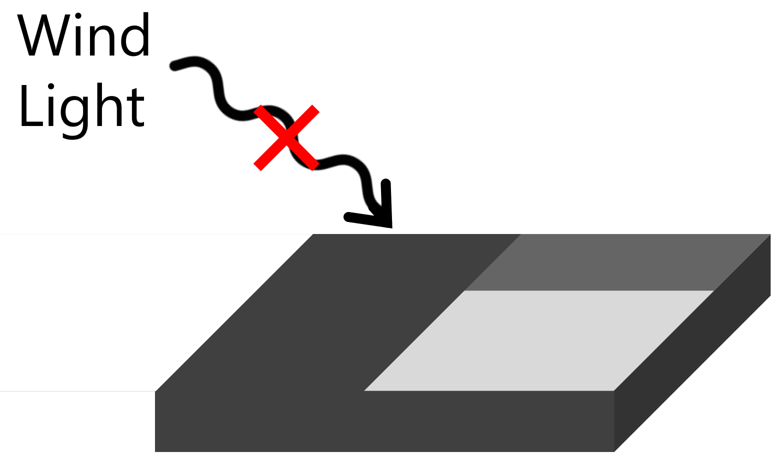
Unstable setup



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



More stable frequency servo
Easier to avoid natural light

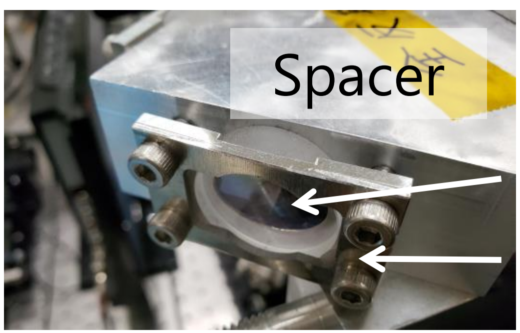
Mirrors and alignment

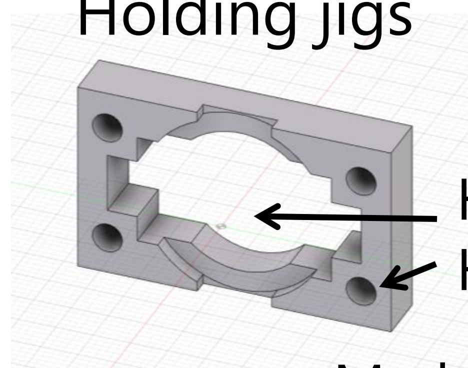
Issues of ver. Nov. 2020

- 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

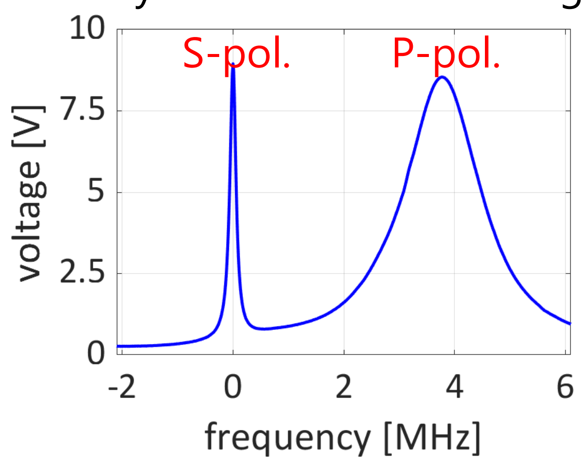


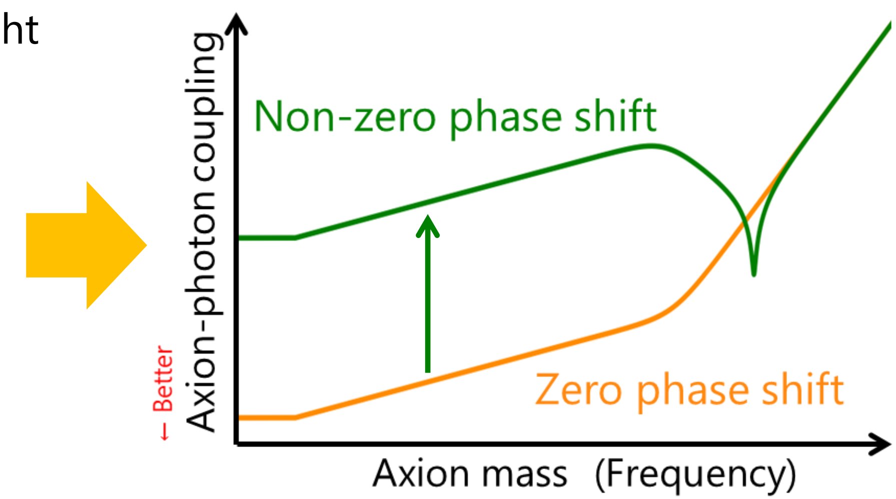


Performance evaluation of the cavity

	Design values	Ver. Nov. 2020	Ver. Mar. 2021
Input laser power	1 W	~40 mW	274(14) mW
Transmitted laser power	1 W	~1.2 mW	158(8) mW
Finesse for carrier	3×10^3	525(19) (P-pol.)	$2.80(34)\times10^3$ (S-pol.)
Finesse for sidebands	3×10^3	~300 (S-pol.)	193(10) (P-pol.)
Resonant frequency difference between polarizations	0 Hz	~28 MHz	3.92(16) MHz

Cavity scan of transmitted light

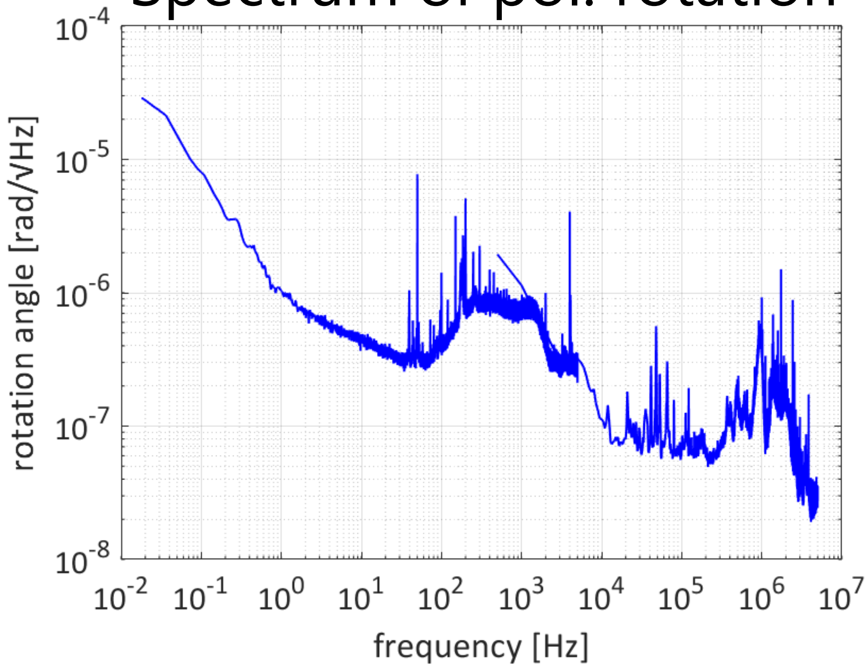


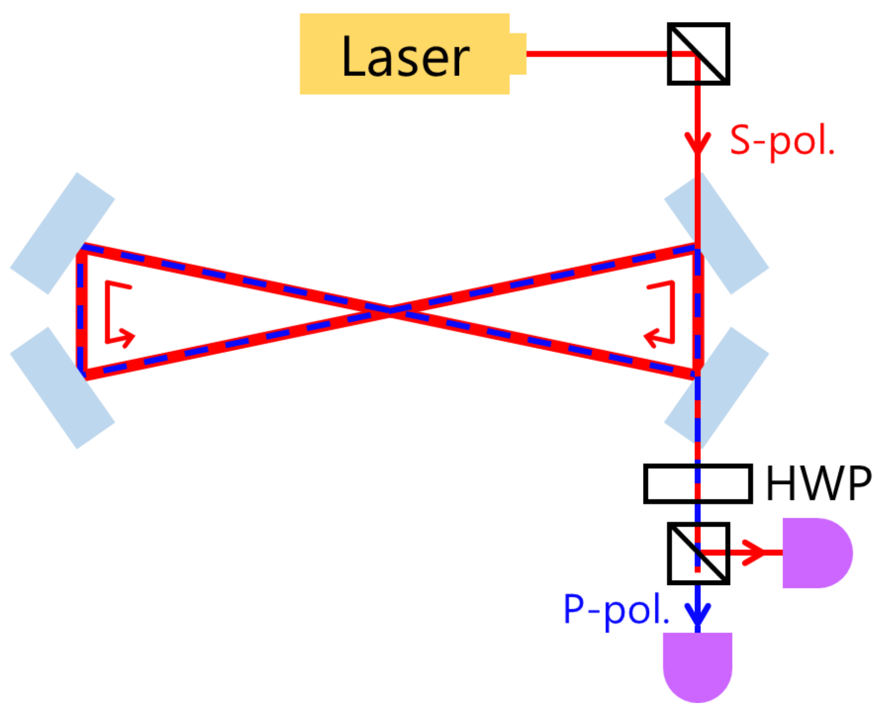


Signal calibration

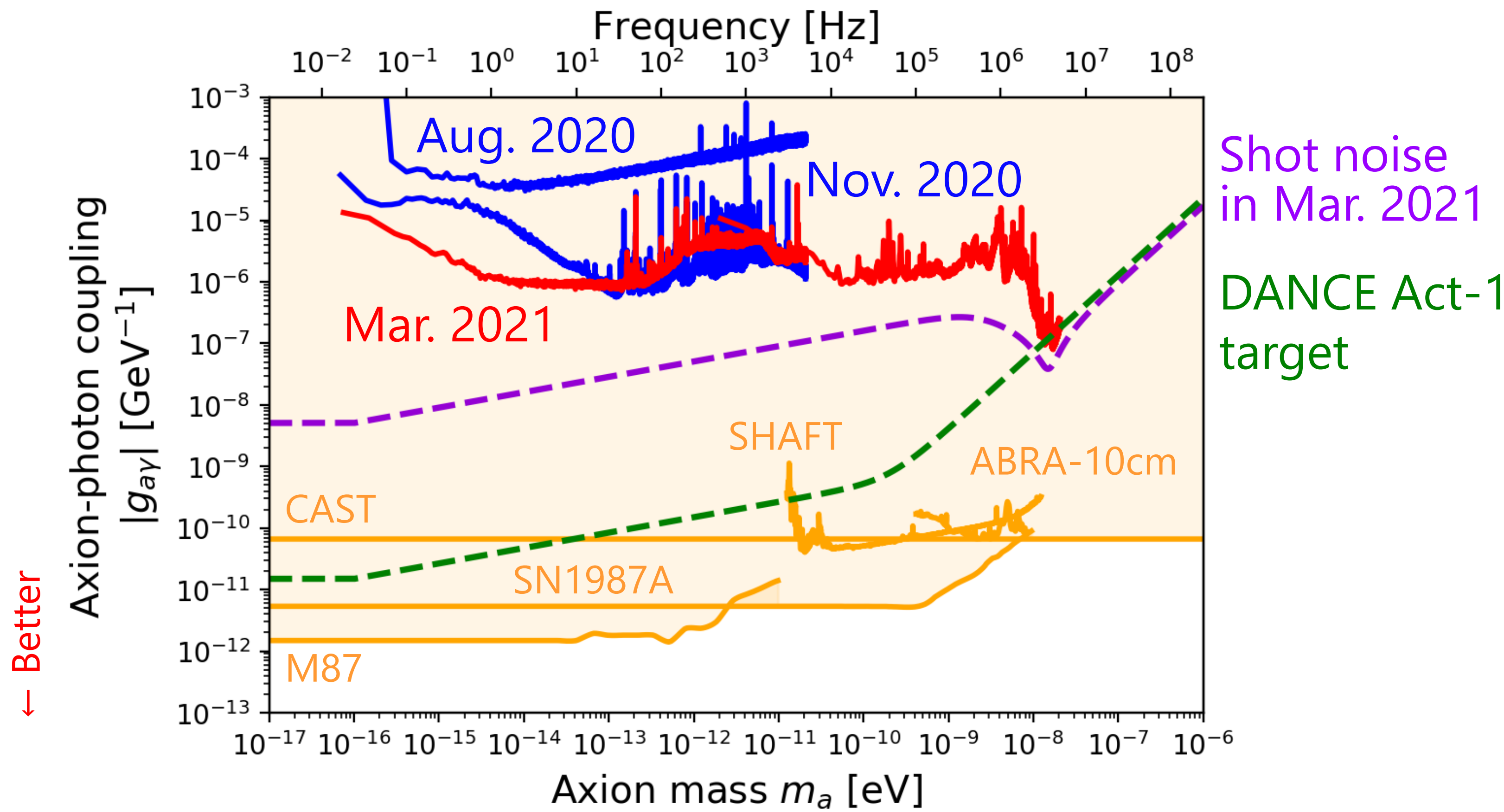
- Fixed HWP to make a little amount of P-pol.
- Recorded amount of P-pol. $P_\mathrm{P}(t)$ and total amount of transmitted light $P_\mathrm{tot}(t)$ for 50 min
- Electric field amplitude of them $E_\mathrm{P,tot}(t) = \sqrt{P_\mathrm{P,tot}(t)}$
- Rotation angle of linear polarization $\phi(t) = \frac{E_\mathrm{P}(t)}{E_\mathrm{tot}}$

Spectrum of pol. rotation





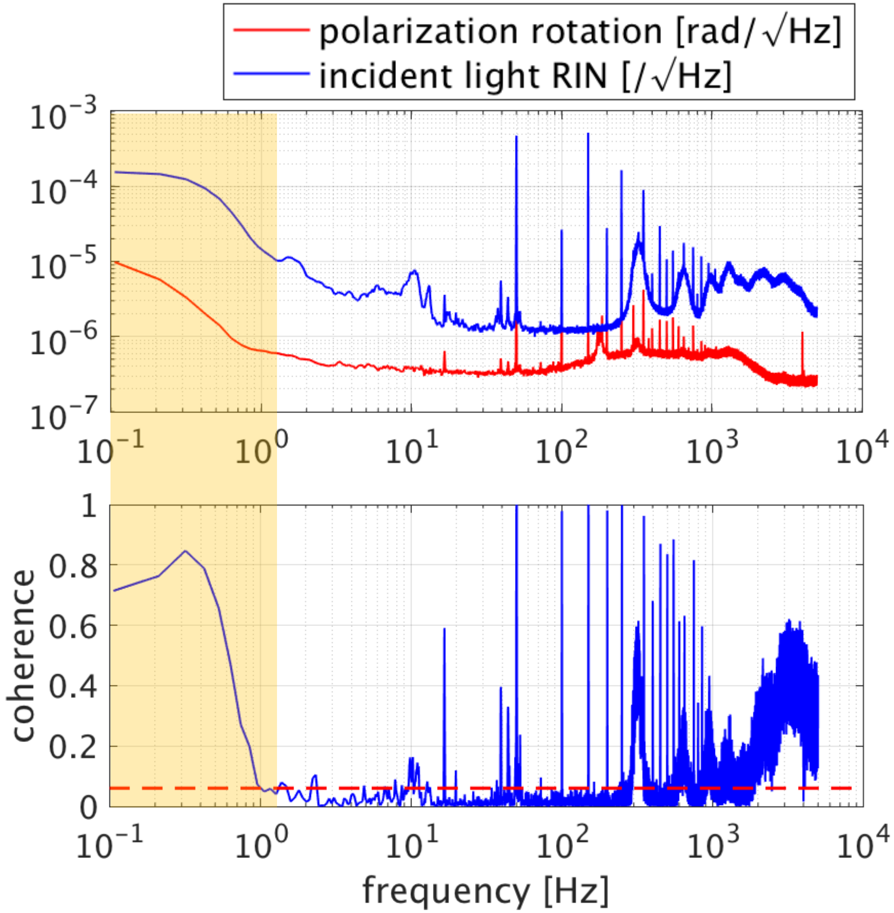
The estimated sensitivity (if one-year observation)



- The sensitivity was gradually improved
- Need to reduce noises to reach shot noise in Mar. 2021
- Need to lessen resonant frequency difference between pol. and inject higher laser power to achieve DANCE Act-1 target

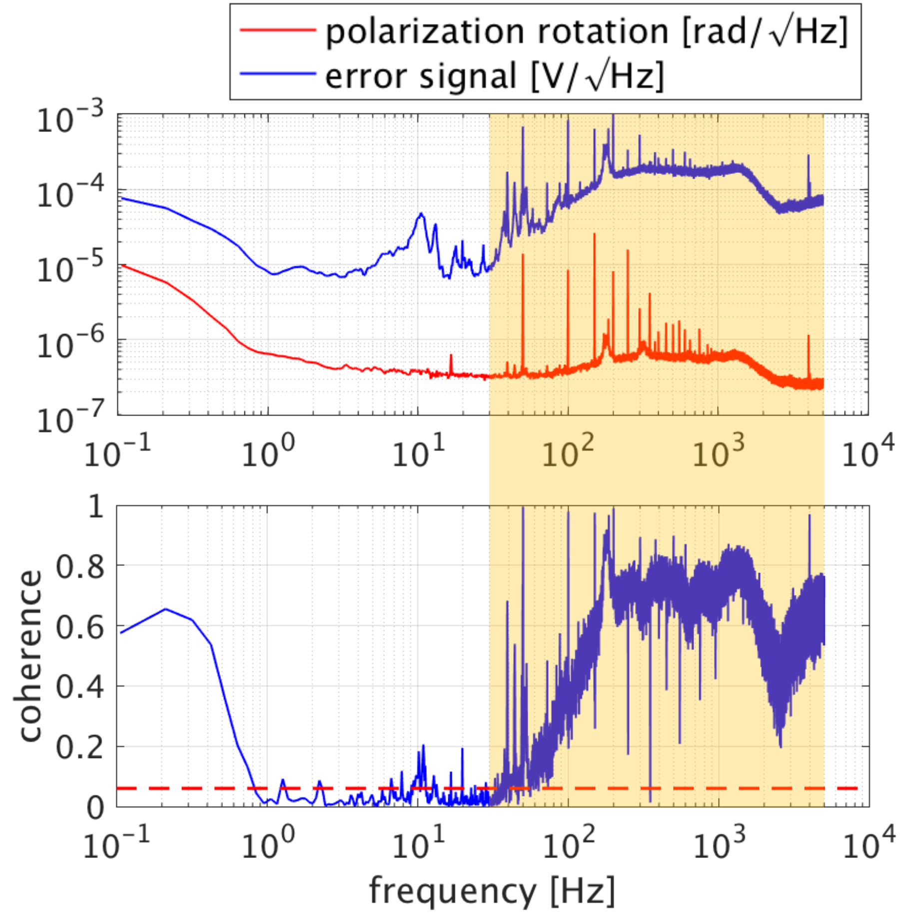
Discussion for current noises

Correlation with incident light



Suggested to be limited by laser intensity noise in 0.1 Hz-1 Hz

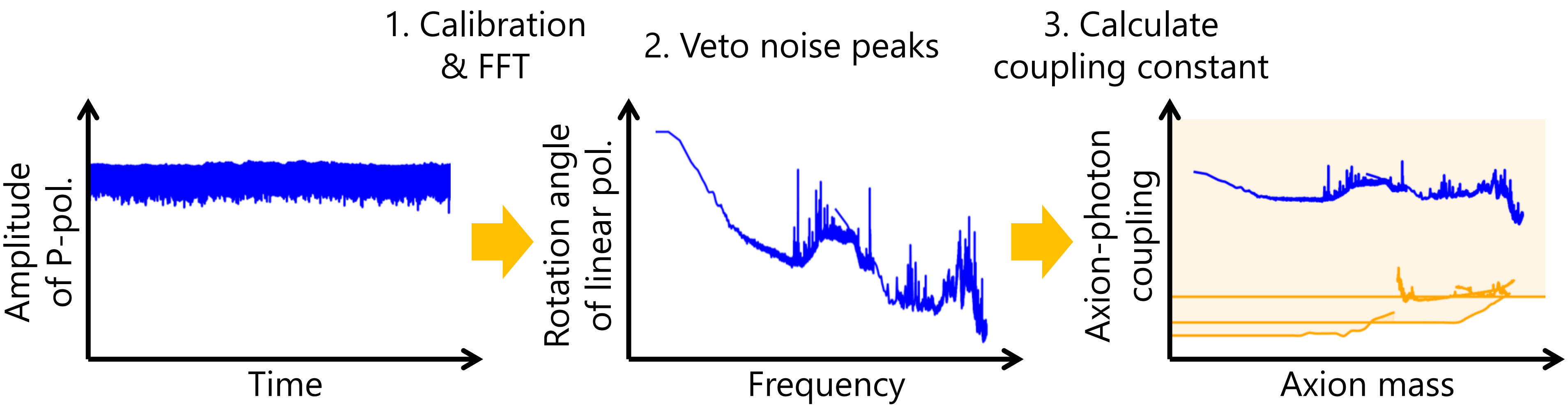
Correlation with error signal



Suggested to be limited by external noises such as mechanical vibration in 30 Hz-5 kHz

Future plans

- Plan to observe for a week and analyze the data
  - Final preparations underway for data acquisition
  - Data analysis environment is under construction



- Plan to build a new setup of DANCE Act-1 in order to improve the sensitivity ⇒ Fujimoto's talk

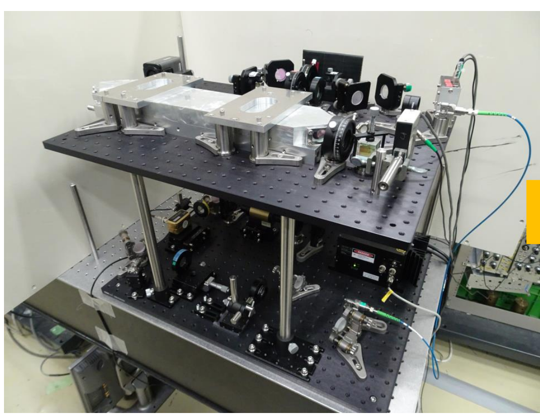
Summary

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

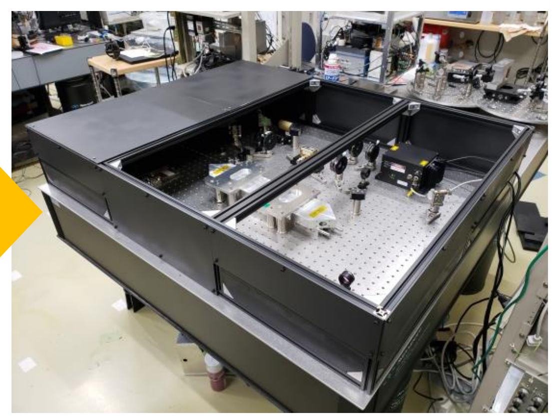
  I. Obata, T. Fujita, Y. Michimura
  PRL 121, 161301 (2018)

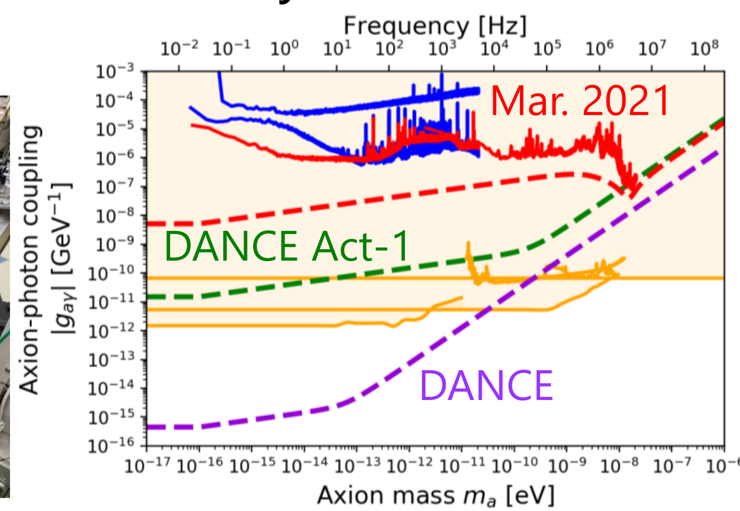
- Prototype experiment DANCE Act-1 is ongoing
  - Improved and evaluated the optics
    - Improved finesse and laser power
    - Found resonant frequency difference between pol.
  - Obtained the data and estimated the sensitivity
    - 9×10^{-7} GeV^{-1} at 10^{-13} eV if observe for a year

Ver. Nov. 2020



Ver. Mar. 2021





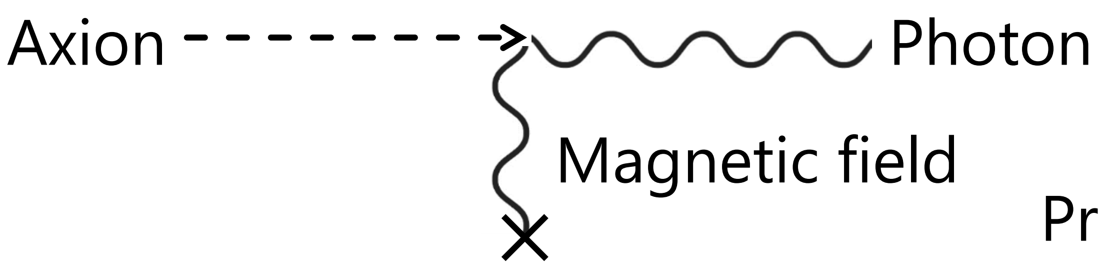
Extra Slides

Axion

- Hypothetical particles to solve the strong CP problem in QCD

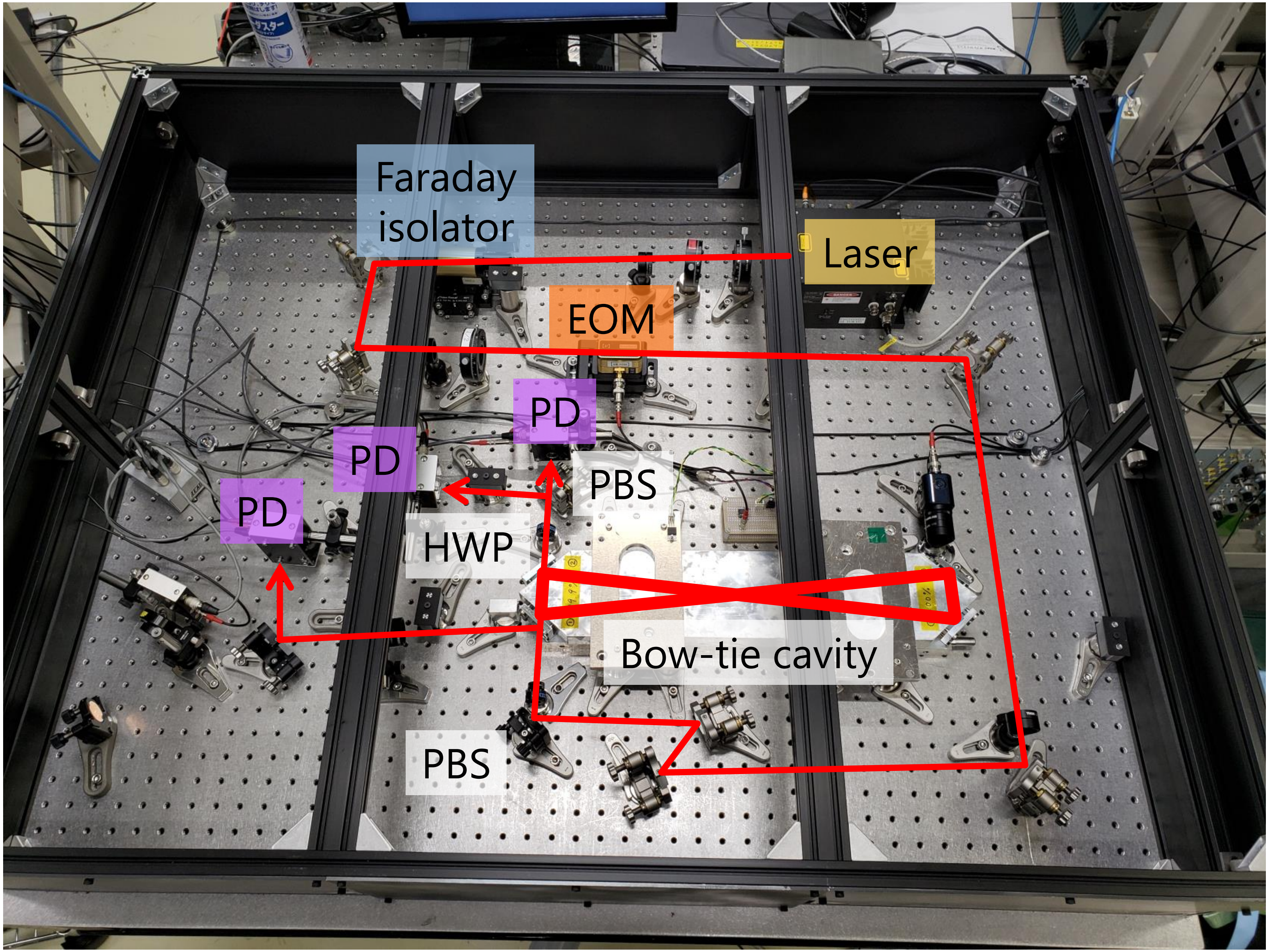
- Many kinds of axion-like particles (ALPs) are predicted by superstring theory
  - One of the candidates for dark matter

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

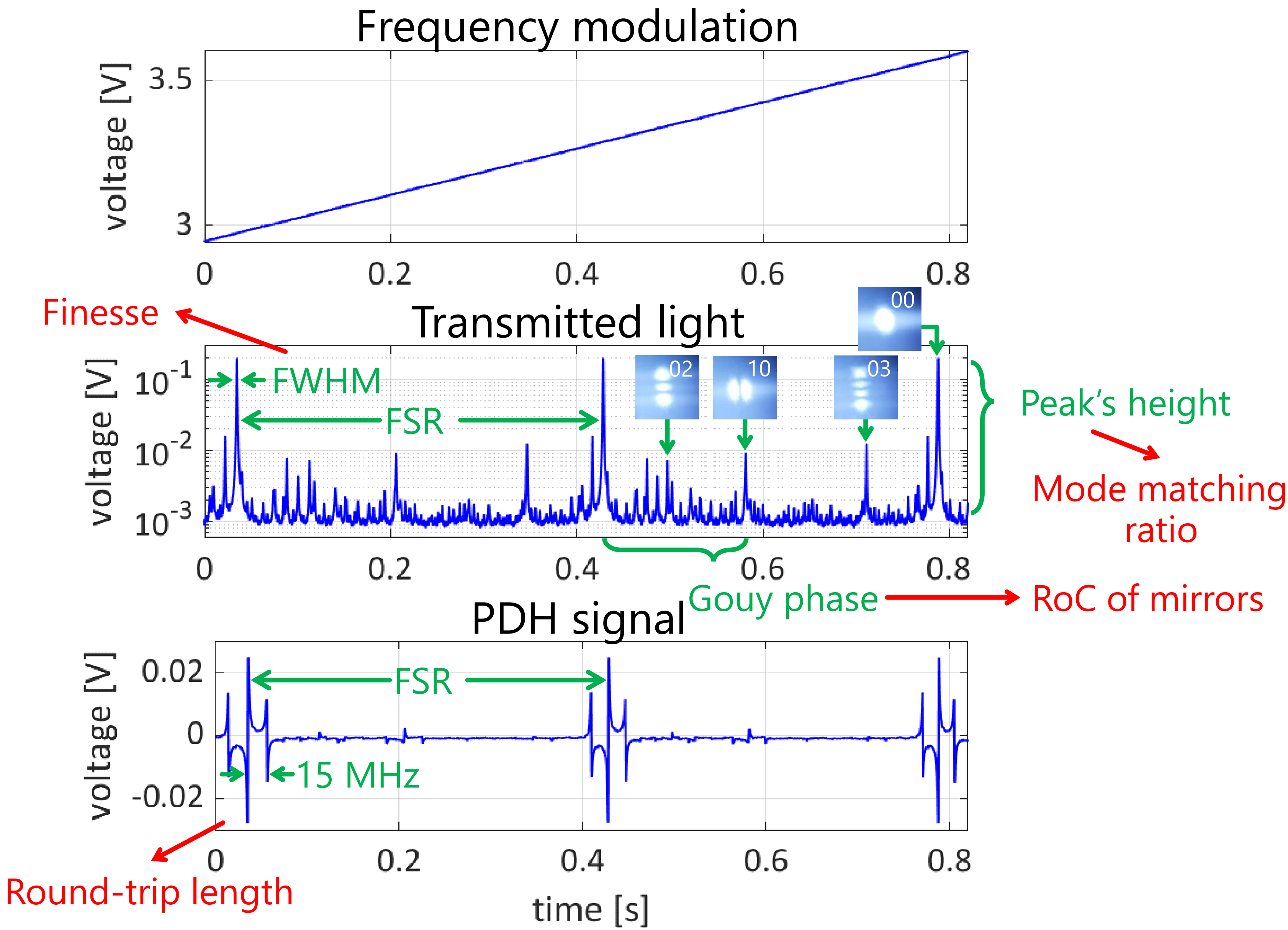


Primakoff effect

Picture of experimental setups



Cavity scan

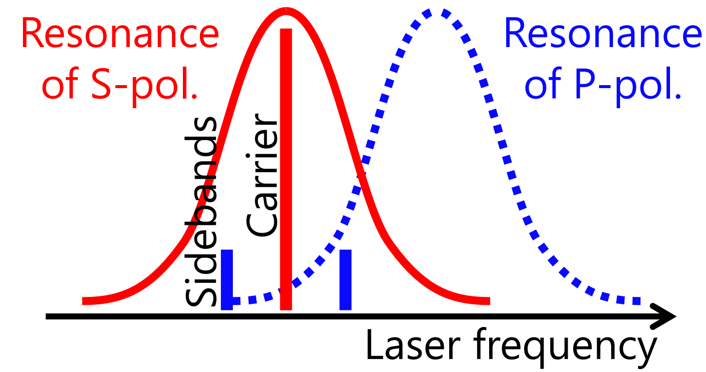

Frequency modulation
voltage [V]
3.5
3
0
0.2
0.4
0.6
0.8
Transmitted light
Finesse
FWHM
FSR
00
02
10
03
Peak's height
Mode matching ratio
10-1
10-2
10-3
Gouy phase
RoC of mirrors
PDH signal
0.02
-0.02
15 MHz
Round-trip length
time [s]

Performance evaluation of the cavity

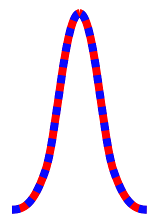
	Design values	Ver. Nov. 2020	Ver. Mar. 2021
Reflectivity of mirrors	Low: 99.9 % High: 100 %	Low: 99.9 % High: 99.95 % (Measured with P-pol.)	Low: 99.90(2) % High: <99.99 % (Designed for S-pol. by Layertec)
Finesse for carrier	3140	525(19) (P-pol.)	$2.80(34)\times10^3$ (S-pol.)
Finesse for sidebands	3140	~300 (S-pol.)	193(10) (P-pol.)
Resonant frequency difference between polarizations	0 Hz	~28 MHz	3.92(16) 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	274(14) mW
Transmitted laser power	1 W	~1.2 mW	158(8) mW

Important parameters (3)

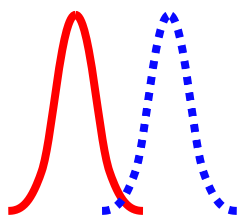
- Finesse difference between polarizations
  ・・・ From mirrors' reflectivity difference
- Resonant frequency difference between polarizations
  ・・・ From non-zero phase shift by mirror reflections



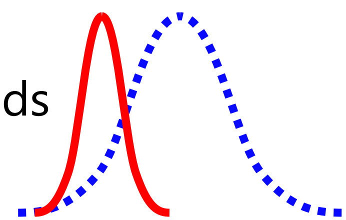
- Finesse for carrier
  = Finesse for sidebands
- Zero phase shift

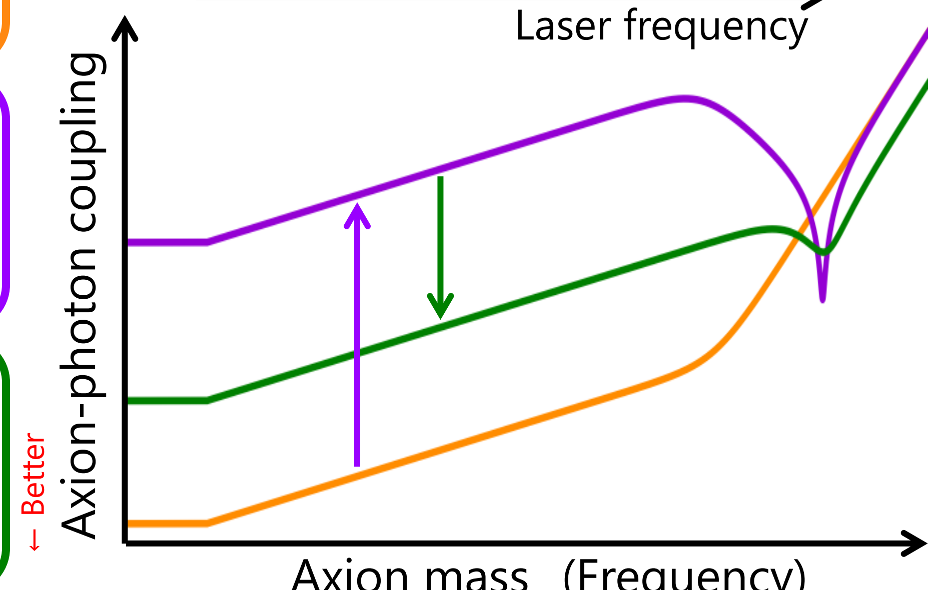


- Finesse for carrier
  = Finesse for sidebands
- Non-zero phase shift



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





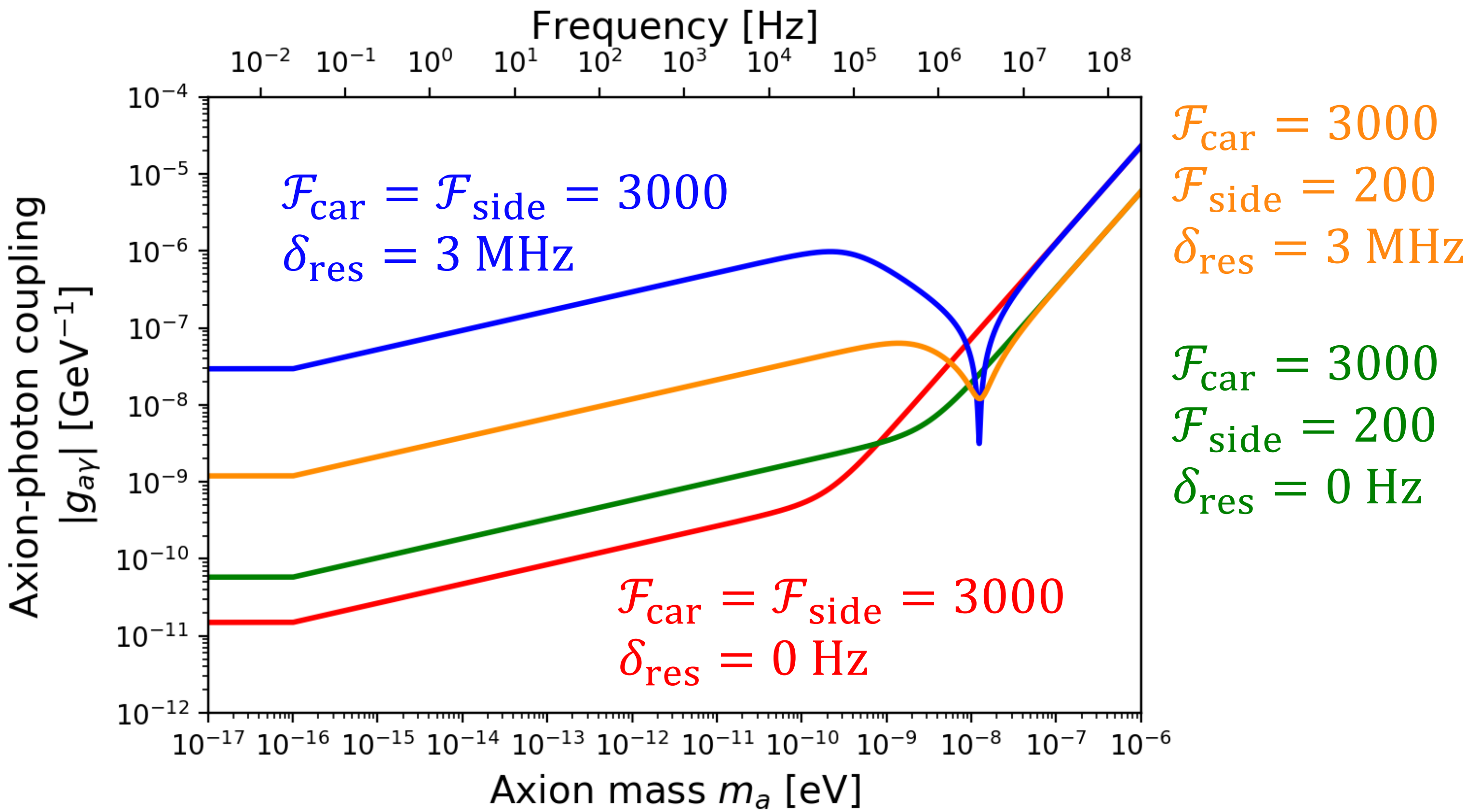
Sensitivity with various parameters

Fixed parameters

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

Variable parameters

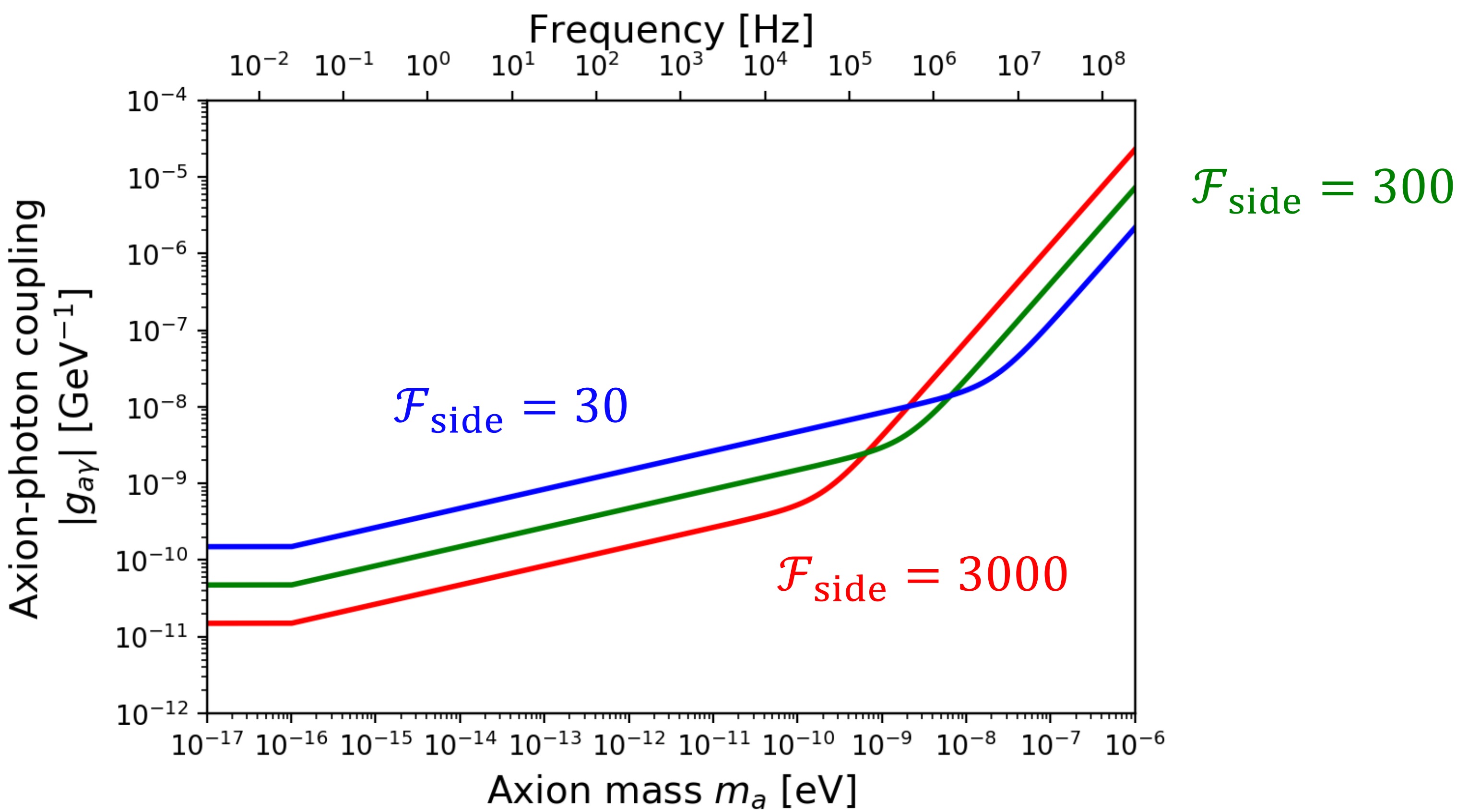
- Finesse for carrier $\mathcal{F}_{\rm car}$
- Finesse for sidebands $\mathcal{F}_{\rm side}$
- Resonant frequency difference between polarizations $\delta_{\rm res}$



Sensitivity with various parameters

Fixed parameters

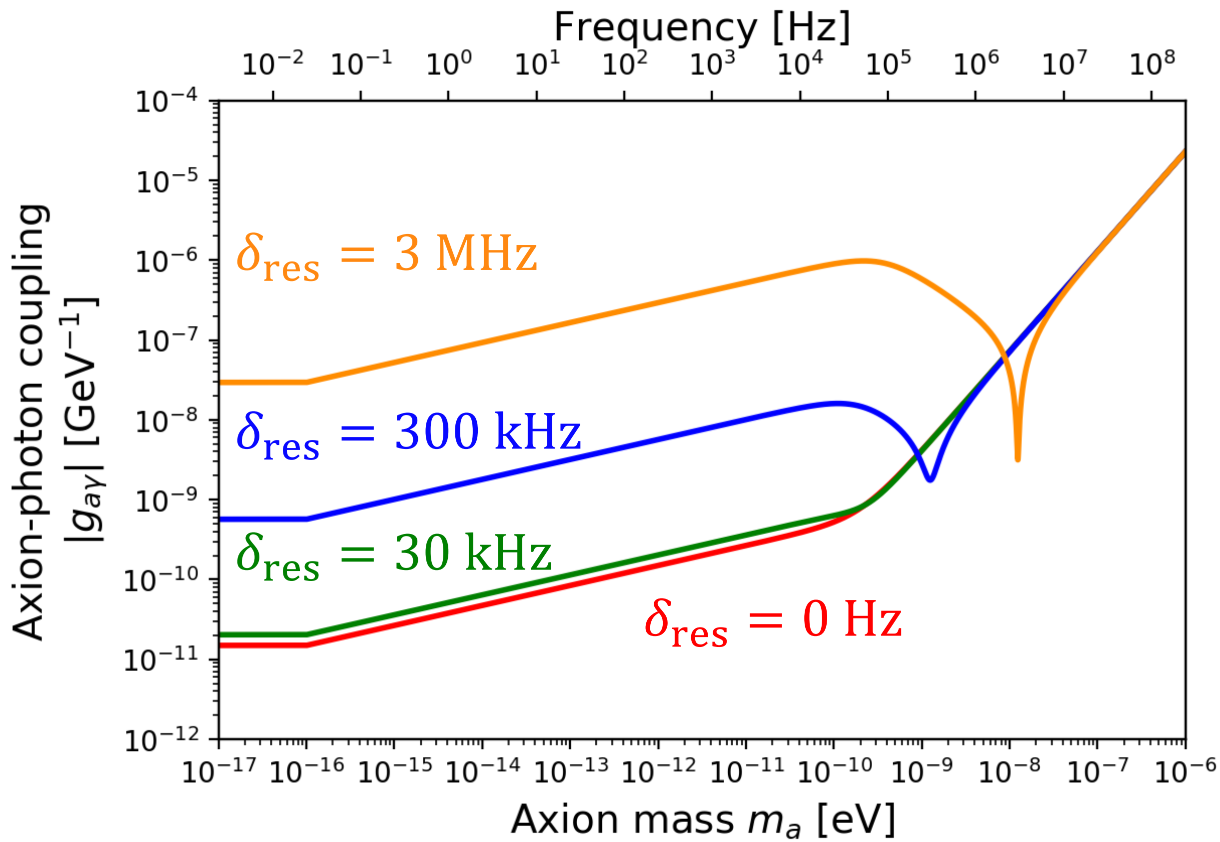
- Wavelength of laser: 1064 nm
- Round-trip length: 1 m
- Input laser power: 1 W
- Observation time: 1 year
- Finesse for carrier: 3000
- Resonant frequency difference between polarizations: 0 Hz



Sensitivity with various parameters

Fixed parameters

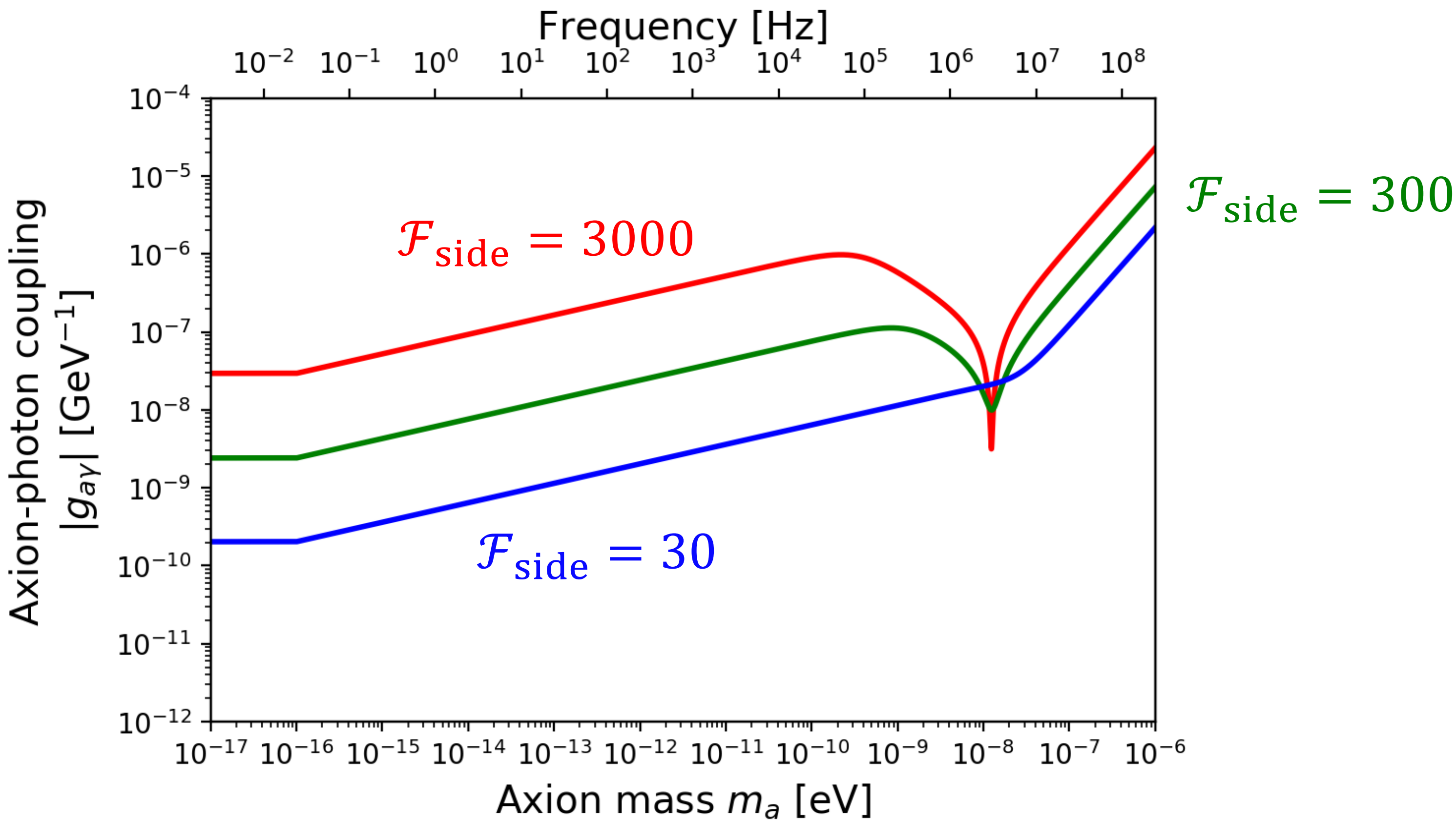
- Wavelength of laser: 1064 nm
- Round-trip length: 1 m
- Input laser power: 1 W
- Observation time: 1 year
- Finesse for carrier: 3000
- Finesse for sidebands: 3000



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

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

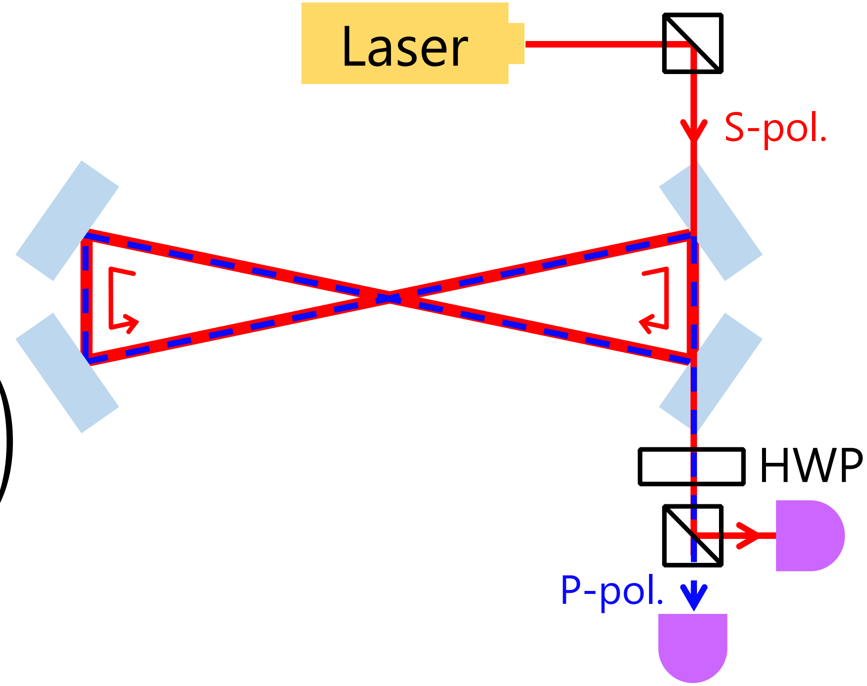
$$P_S = {E_S'}^2 = E_0^2 \cos^2(2\theta + \phi(t))$$

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

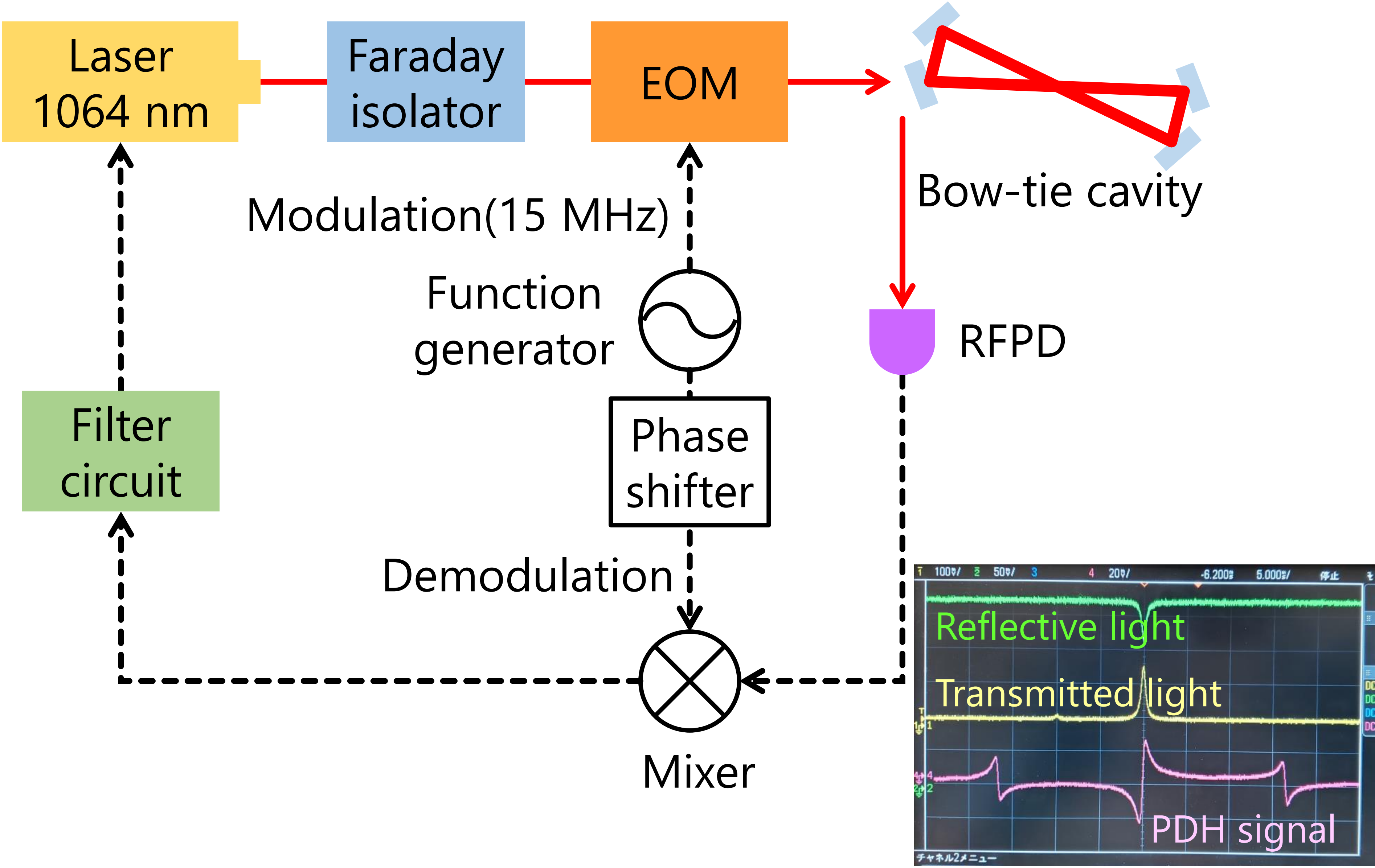
When $2\theta + \phi \ll 1$, $\sin\big(2\theta + \phi(t)\big) \approx 2\theta + \phi(t)$

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

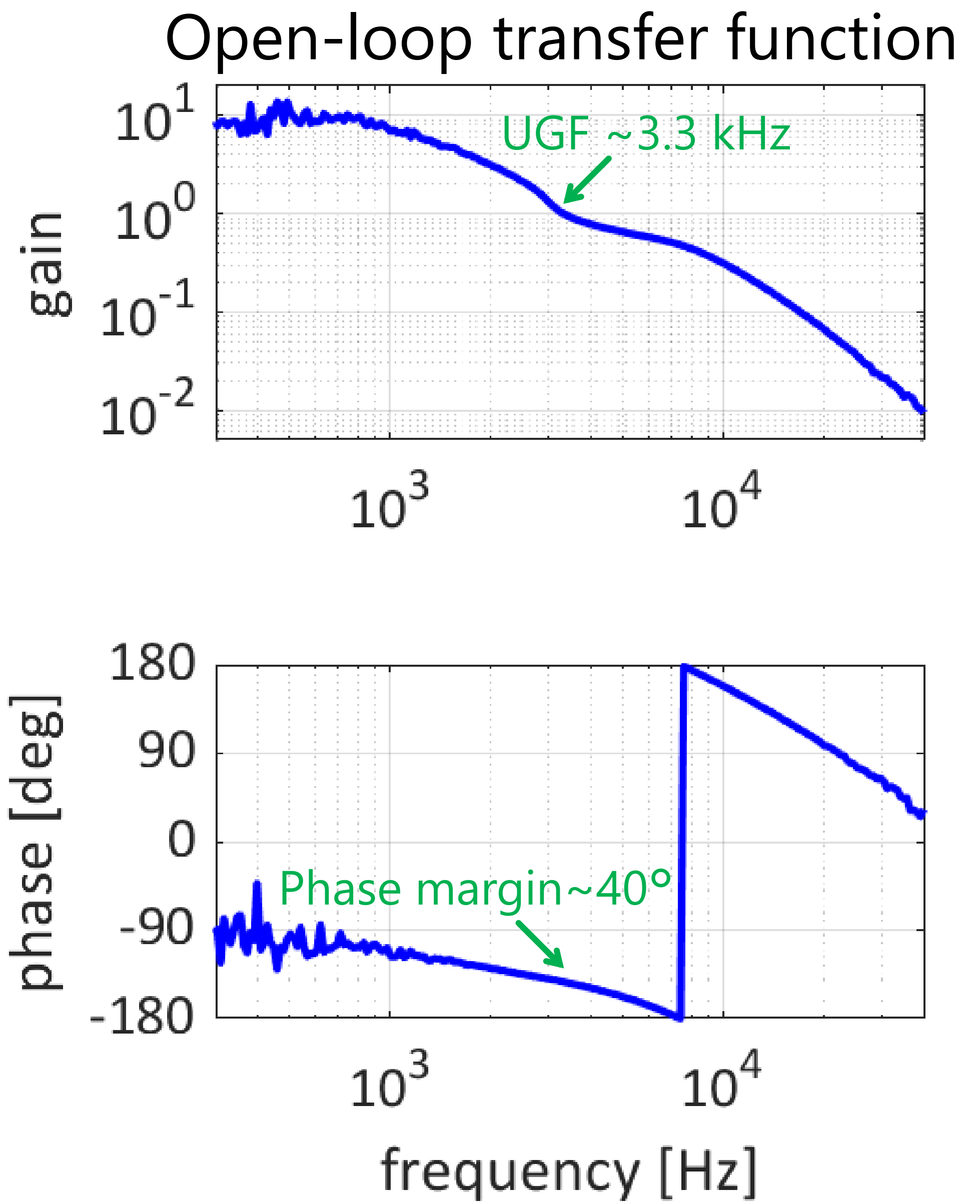
Spectrum is independent of $2\theta = \mathrm{const.}$



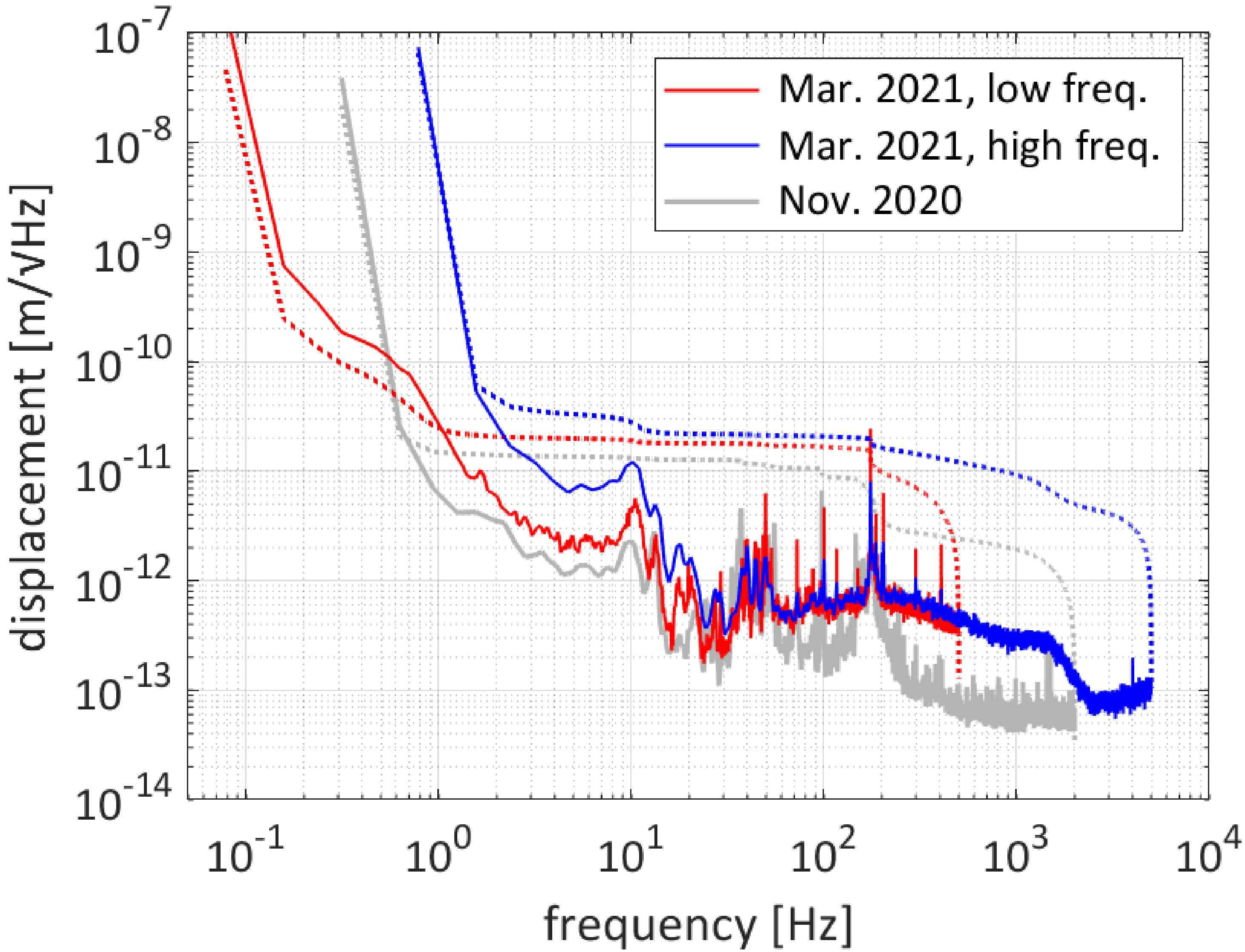
Frequency servo by PDH technique



Stability of frequency servo



Spectrum of external noises

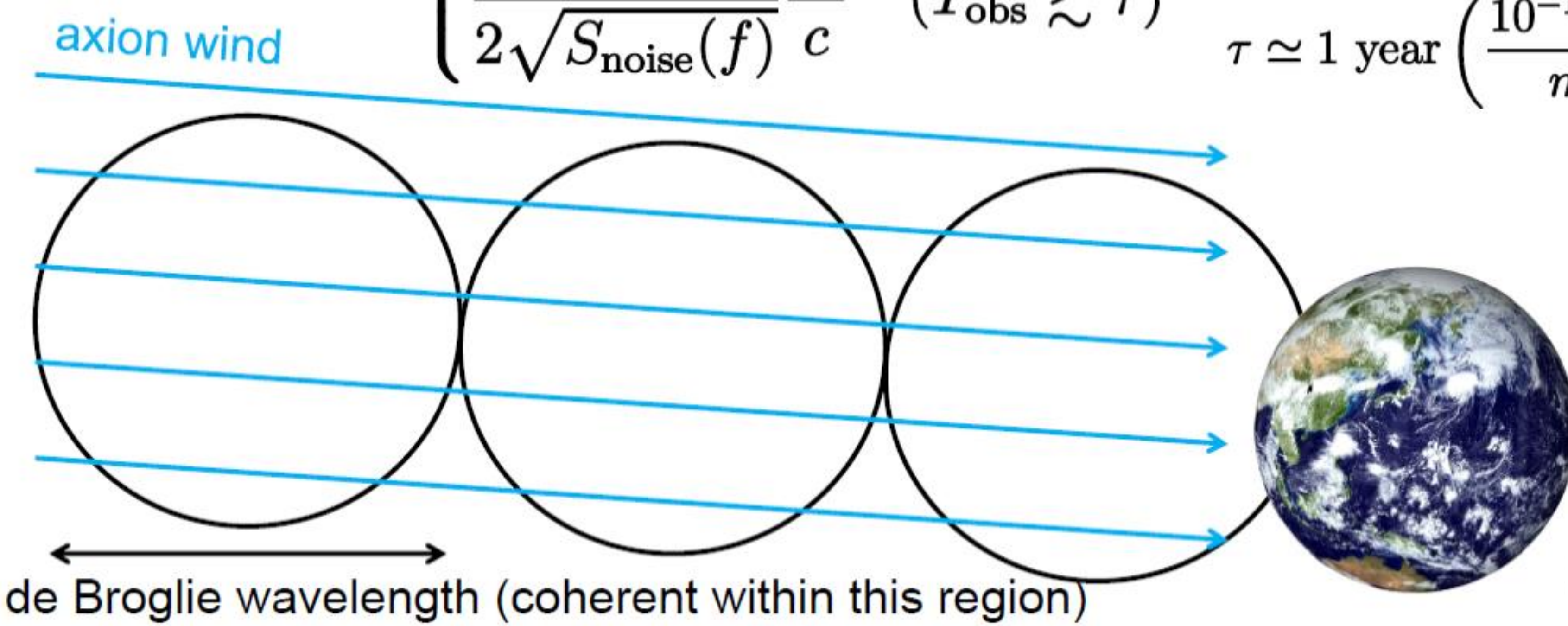


Coherent Time Scale

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

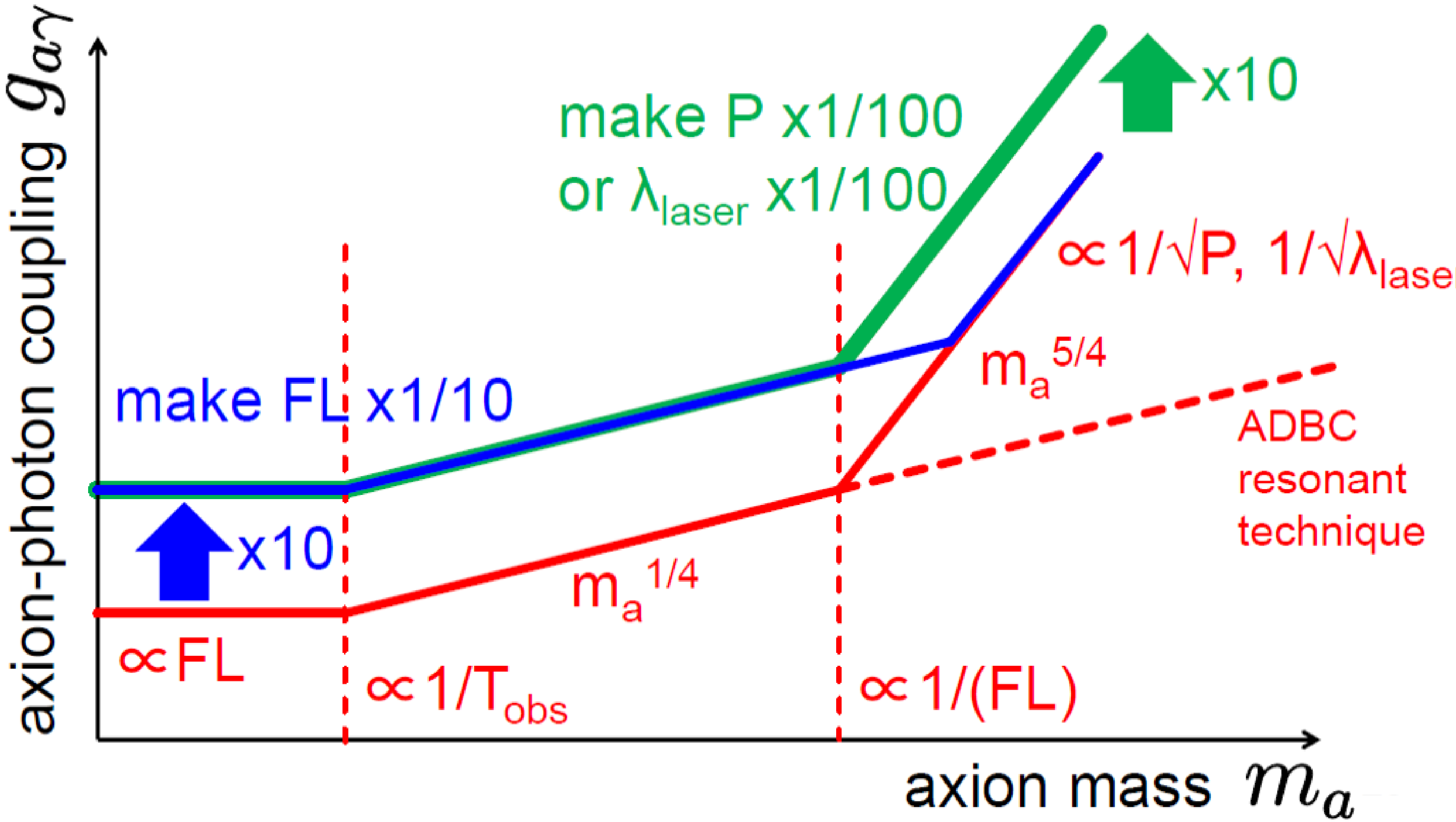
$$\mathrm{SNR} = \begin{cases} \dfrac{\sqrt{T_{\rm obs}}}{2\sqrt{S_{\rm noise}(f)}}\dfrac{\delta c}{c} & (T_{\rm obs} \lesssim \tau) \\ \dfrac{(T_{\rm obs}\tau)^{1/4}}{2\sqrt{S_{\rm noise}(f)}}\dfrac{\delta c}{c} & (T_{\rm obs} \gtrsim \tau) \end{cases}$$

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

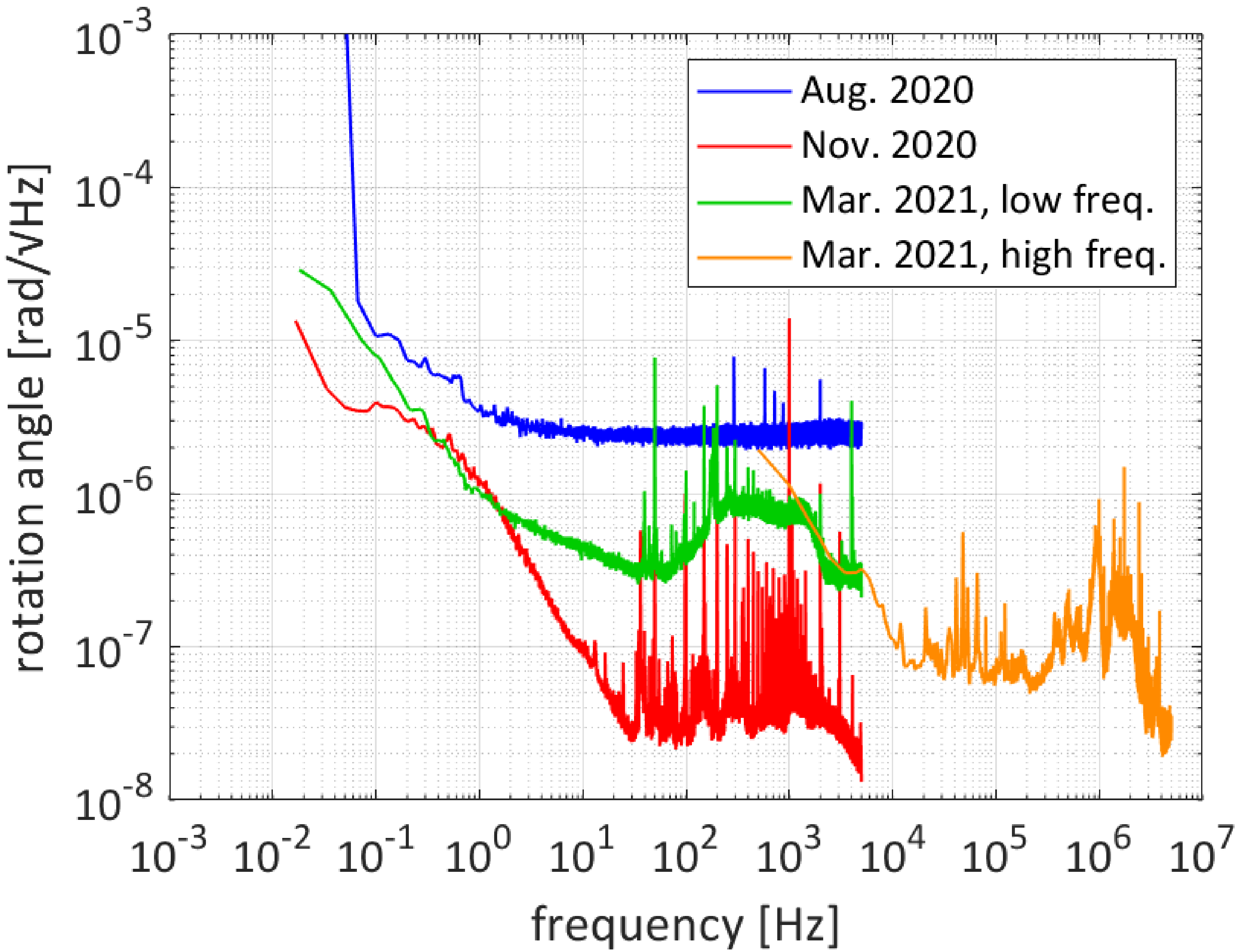


Sensitivity Design

- Brute force necessary, you cannot win for free

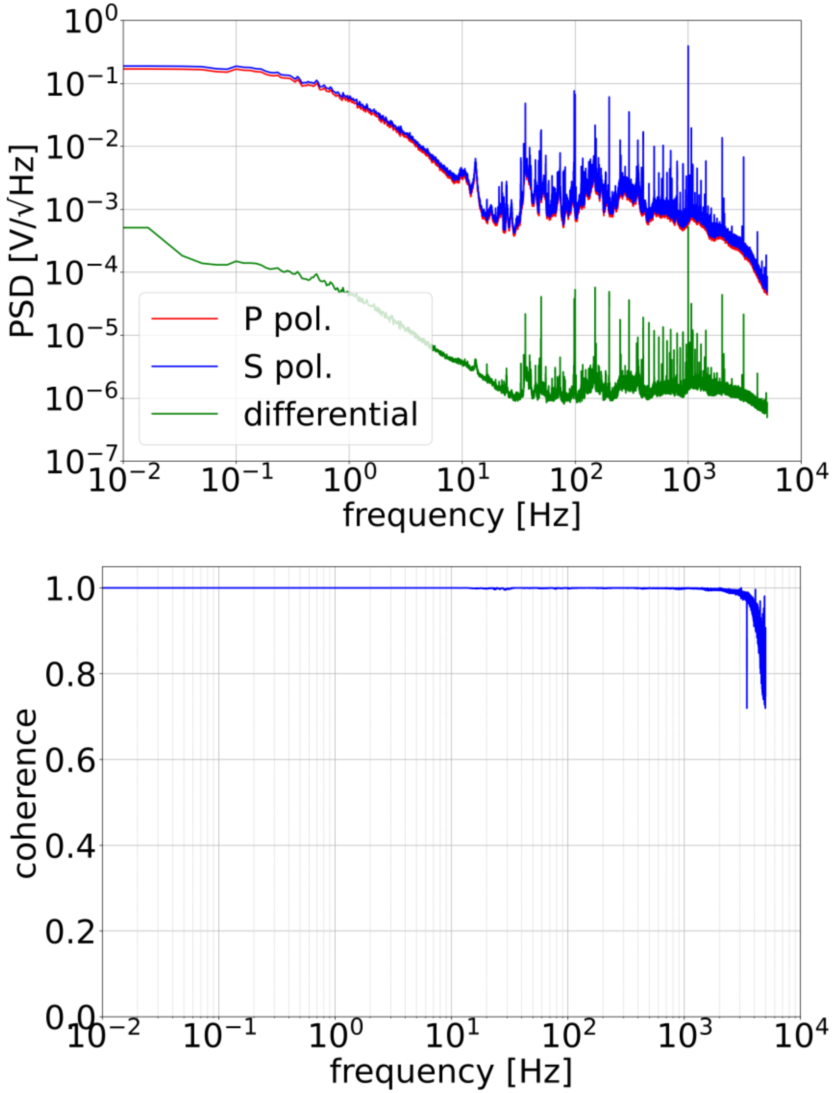


Sensitivity comparison with pol. rotation

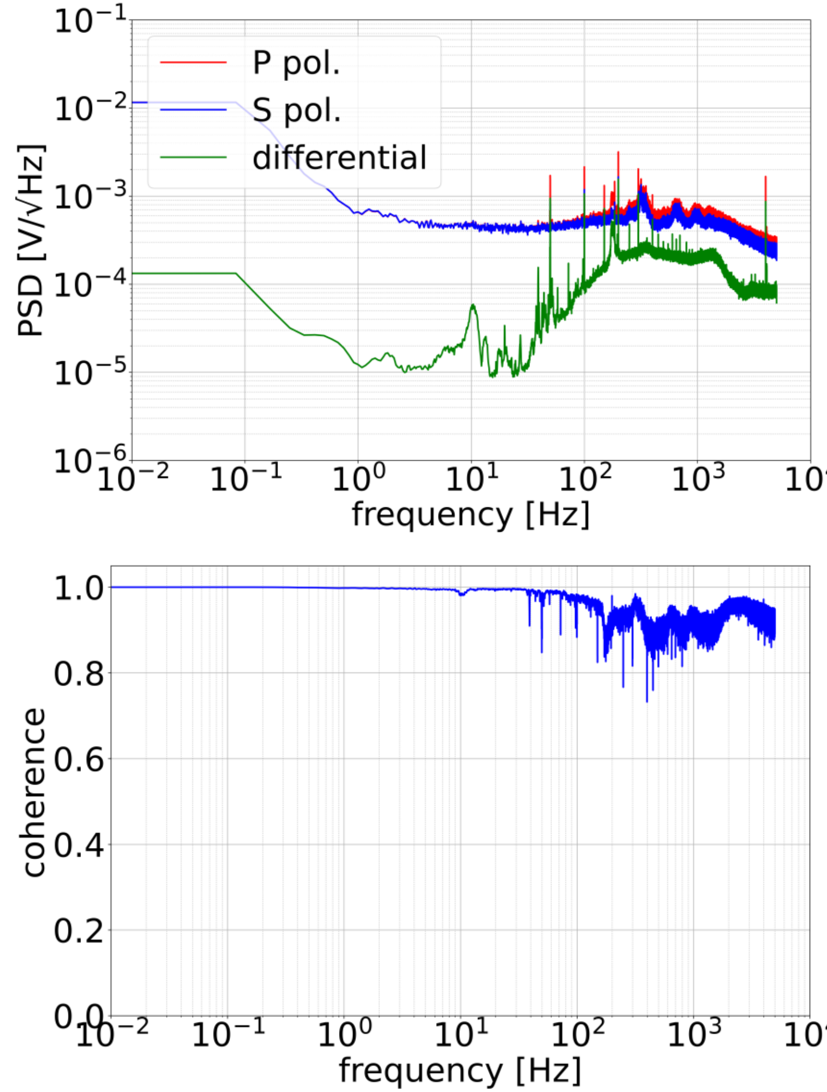


Couldn‘t subtract in Mar. 2021

Nov. 2020

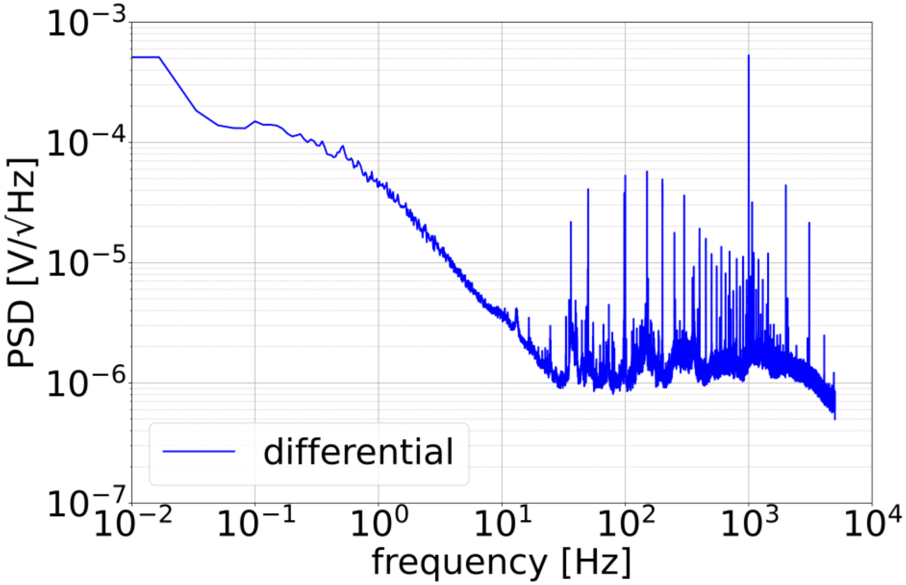


Mar. 2021

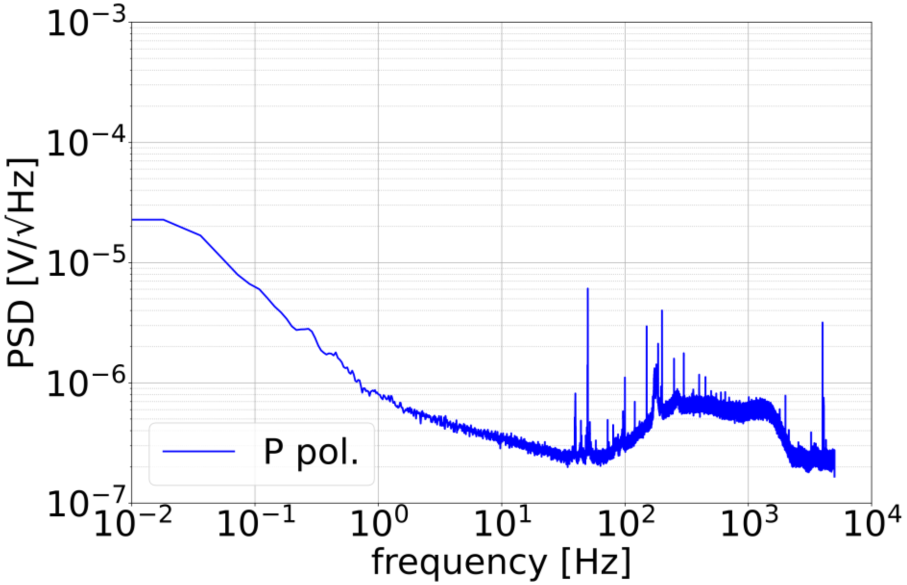


Sensitivity comparison with V/√Hz

Nov. 2020



Mar. 2021



Figure