# DANCE Act-1 and Coupled WFS for TOBA

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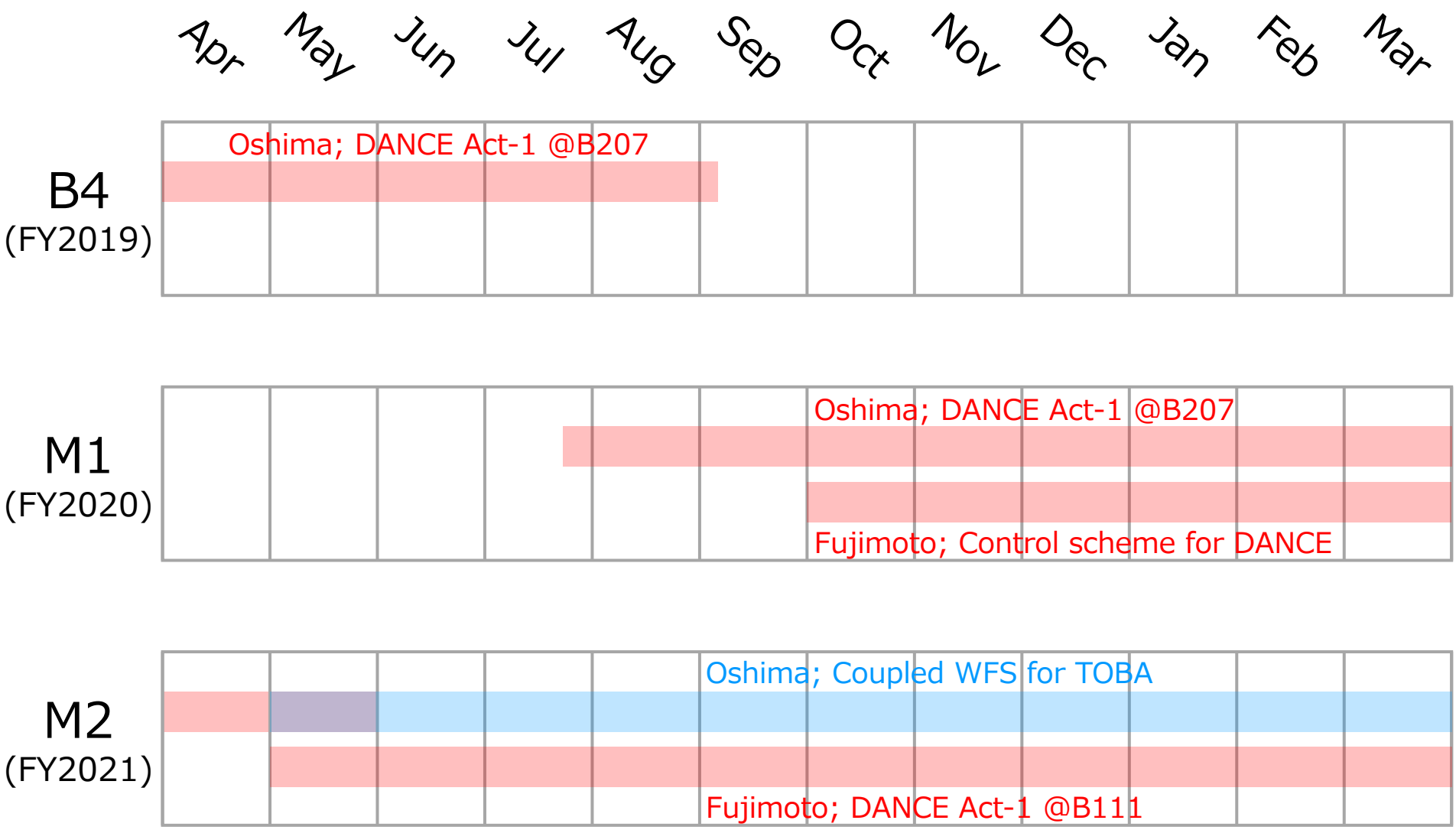
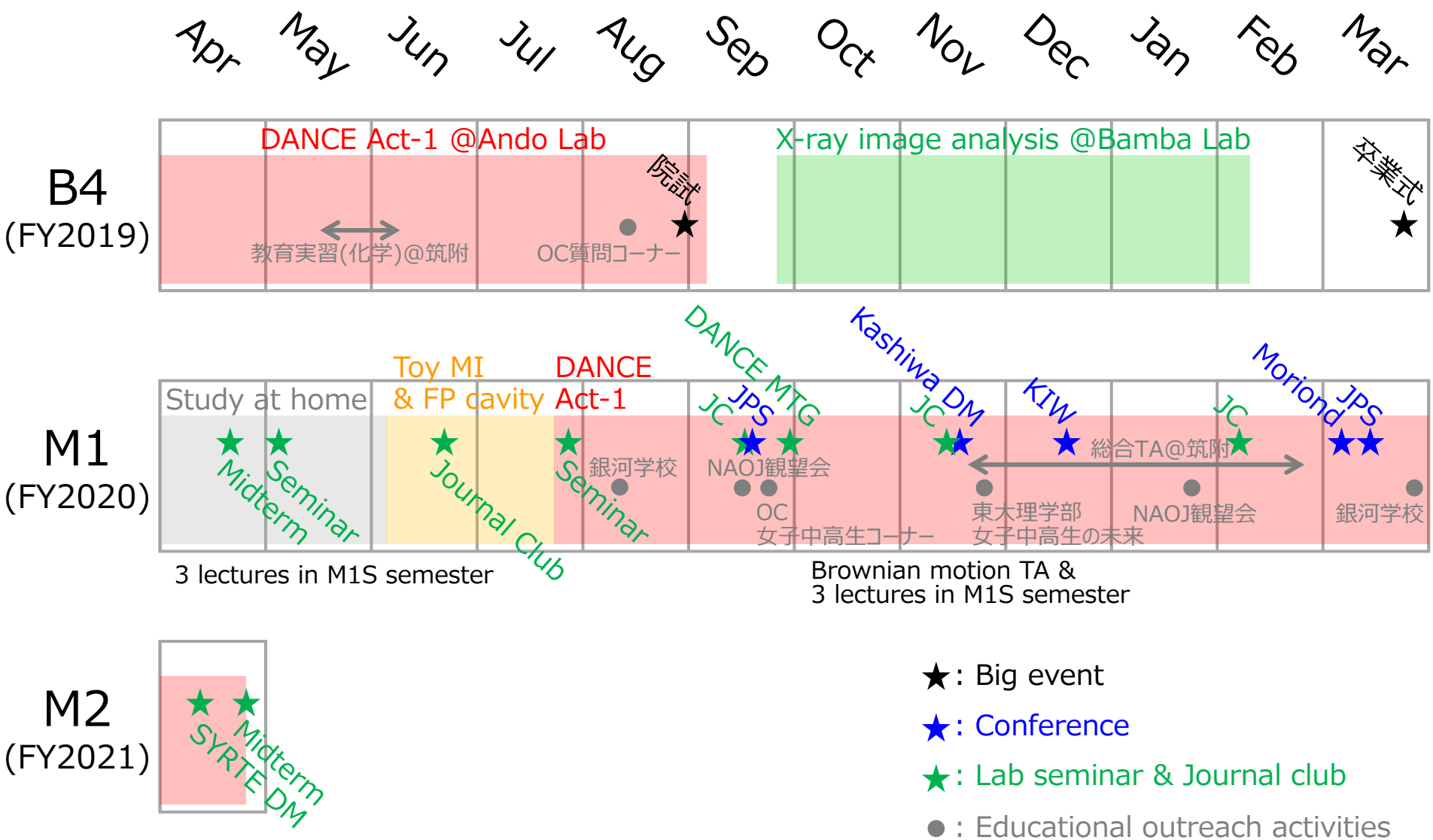
Department of Physics, University of Tokyo

# Contents

# Timeline of Fujimoto-kun & me



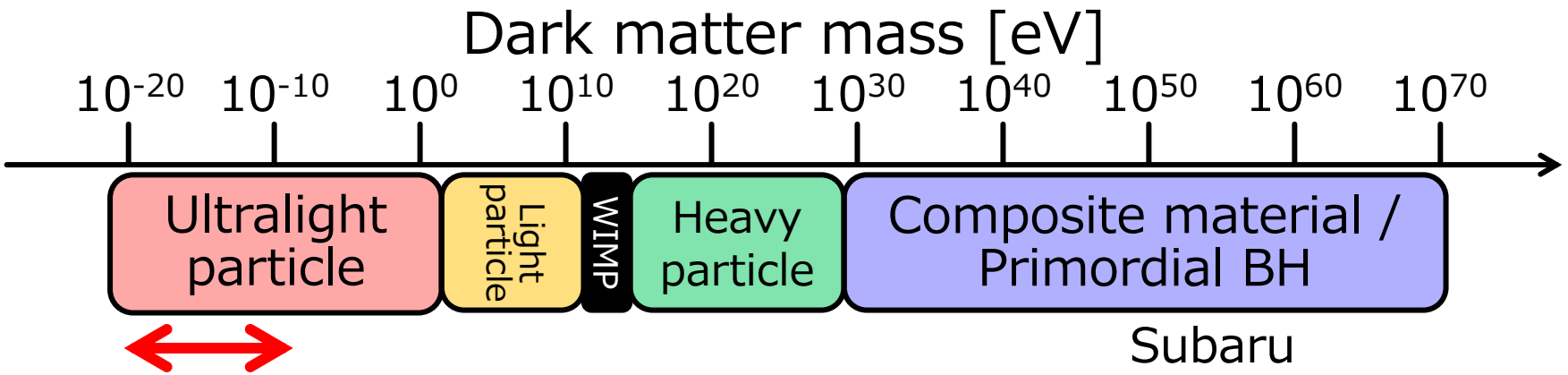
# What I did so far



# Contents

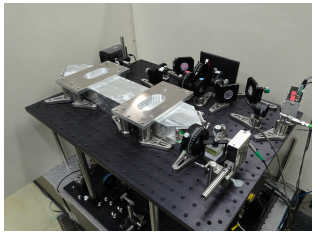
# Axion search with laser interferometers

- Need to search for dark matter in wider mass range
- Ultralight dark matter can be searched with laser interferometers
- DANCE (Dark matter Axion search with riNg Cavity Experiment) focuses on axion dark matter



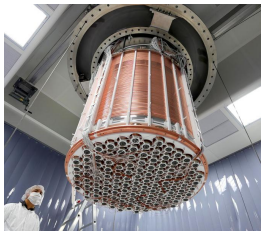

Laser interferometers

DANCE

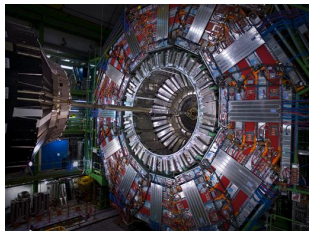


KAGRA

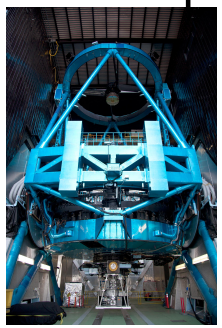
XENON1T



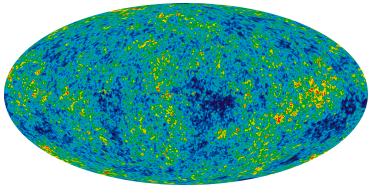
LHC



Subaru Telescope



CMB



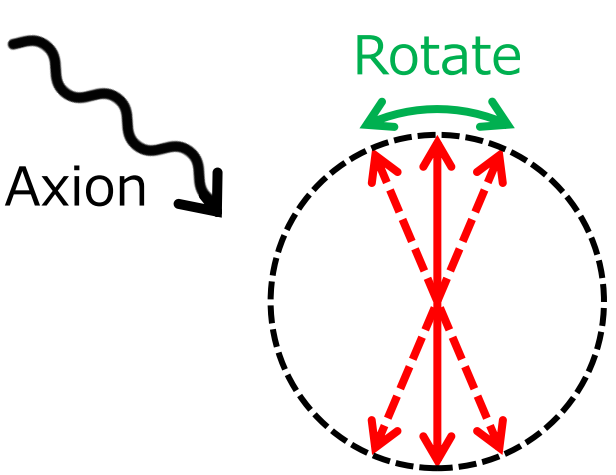
# Rotation of linear polarization

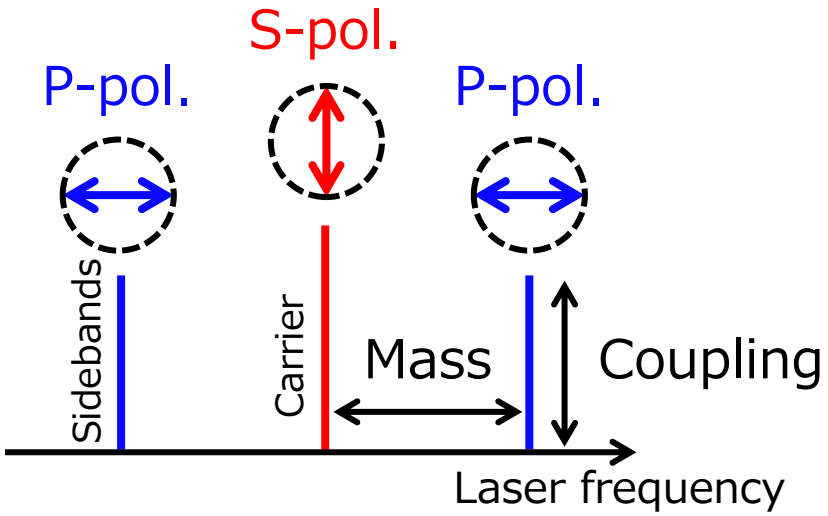
- Axion-photon coupling causes phase velocity difference between left- and right-handed photons

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

Coupling constant　Axion field　Axion mass

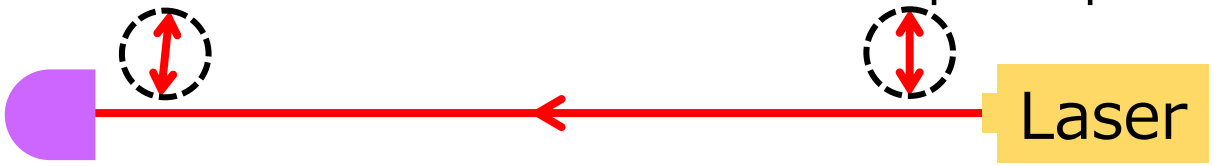
- Phase velocity difference of circular polarizations makes linear polarization rotate



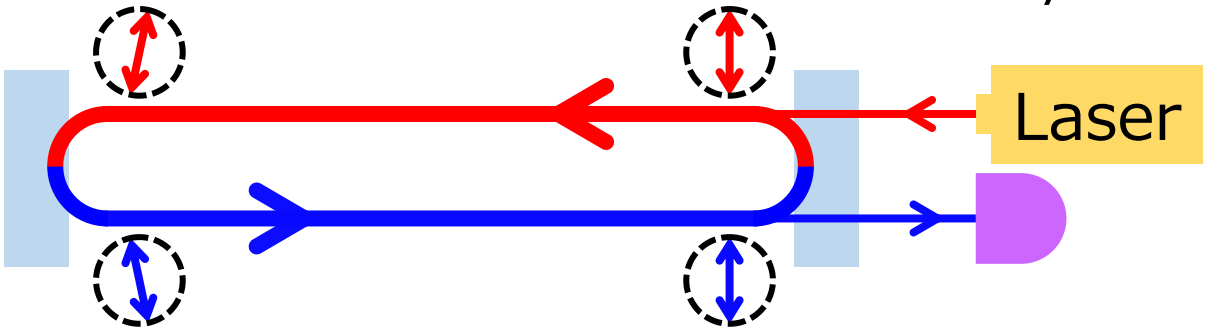



# Bow-tie cavity to amplify the signal

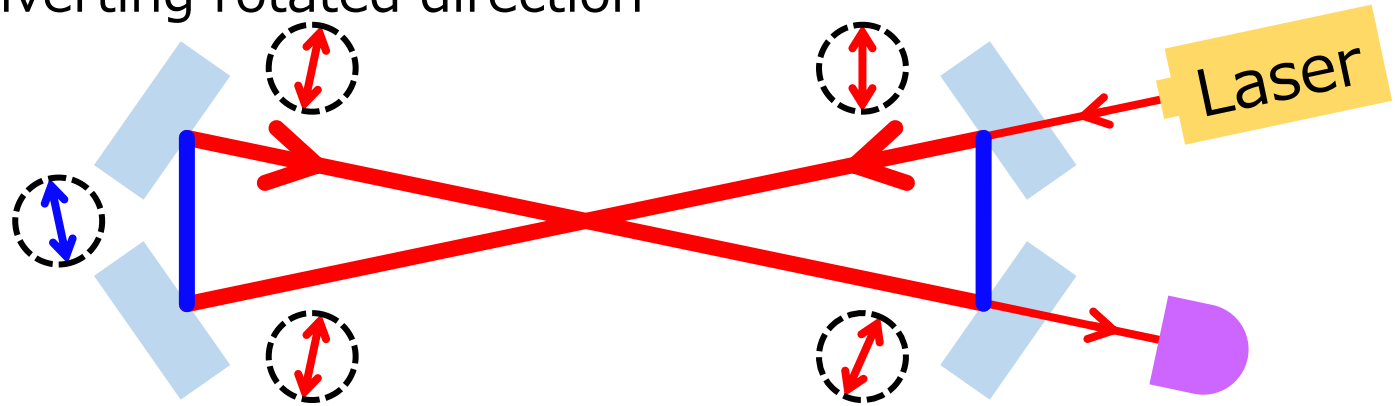
- Polarization rotation is too small for short optical path



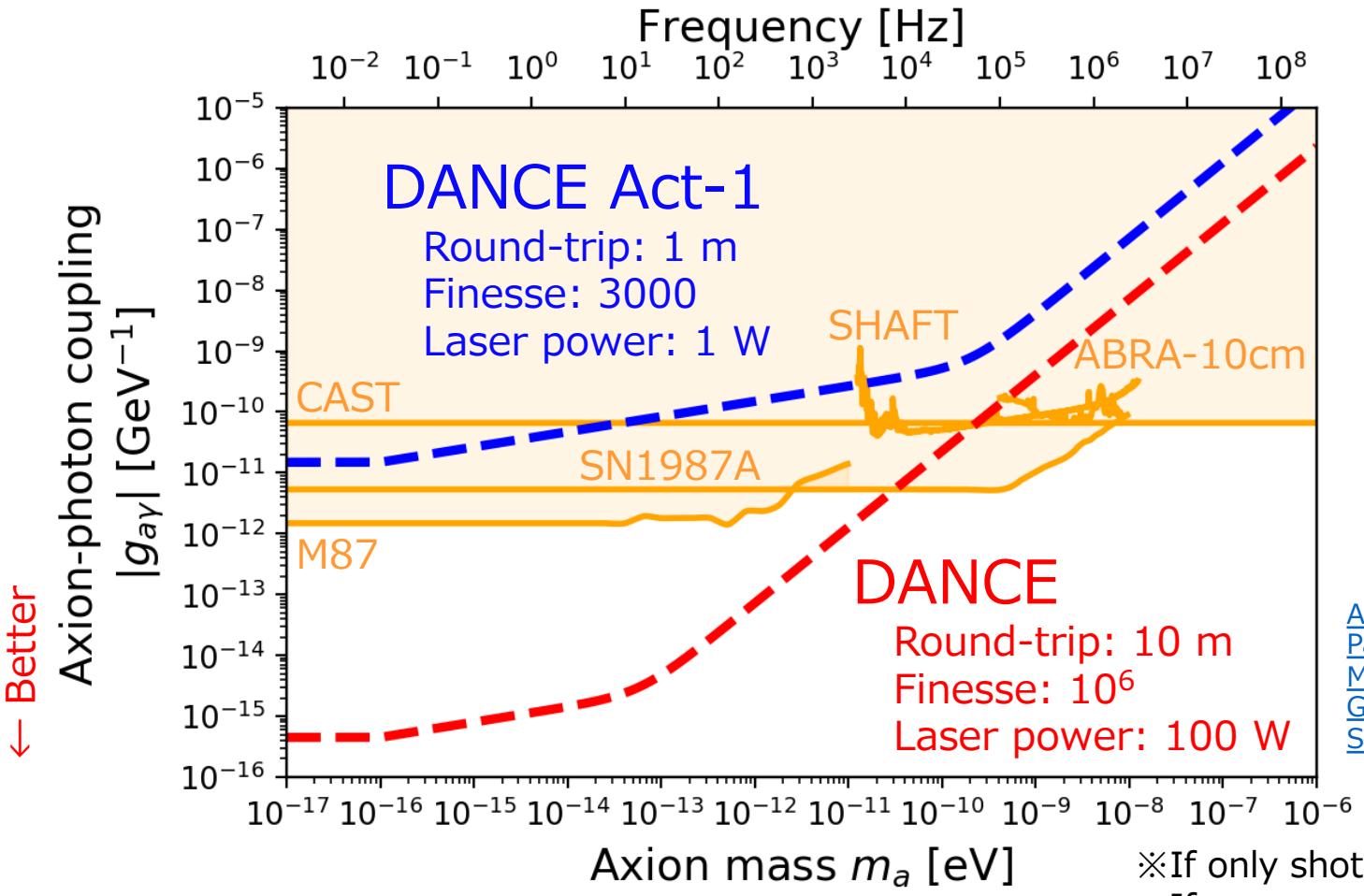

- A linear cavity can amplify polarization rotation
- But rotated direction is inverted in a linear cavity




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



# Design sensitivity of DANCE




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

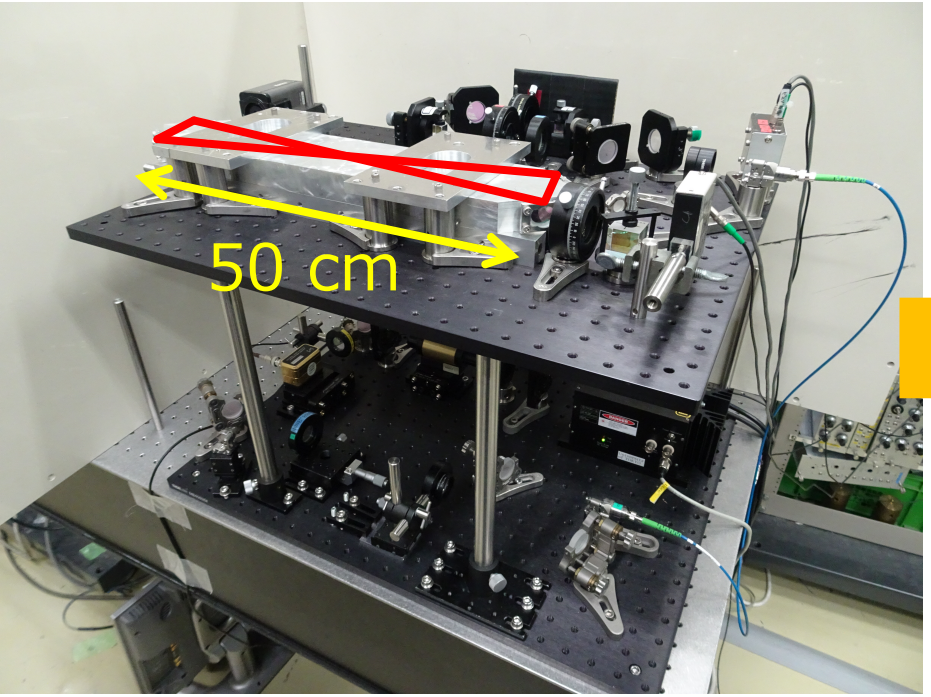
※If only shot noise
If one-year observation
If DM is all composed of axion

- DANCE will improve the current limits by several orders of magnitude without magnet field
- I started DANCE Act-1 from Apr. 2019

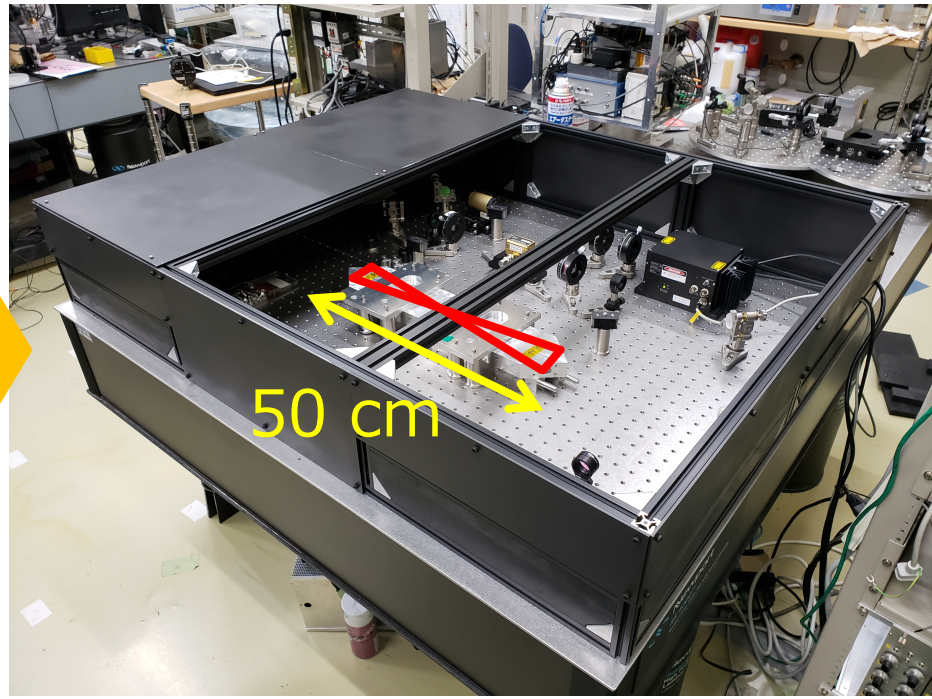
# Contents

# Progress of experiment

## Ver. Nov. 2020
(Apr. 2019 – Nov. 2020)

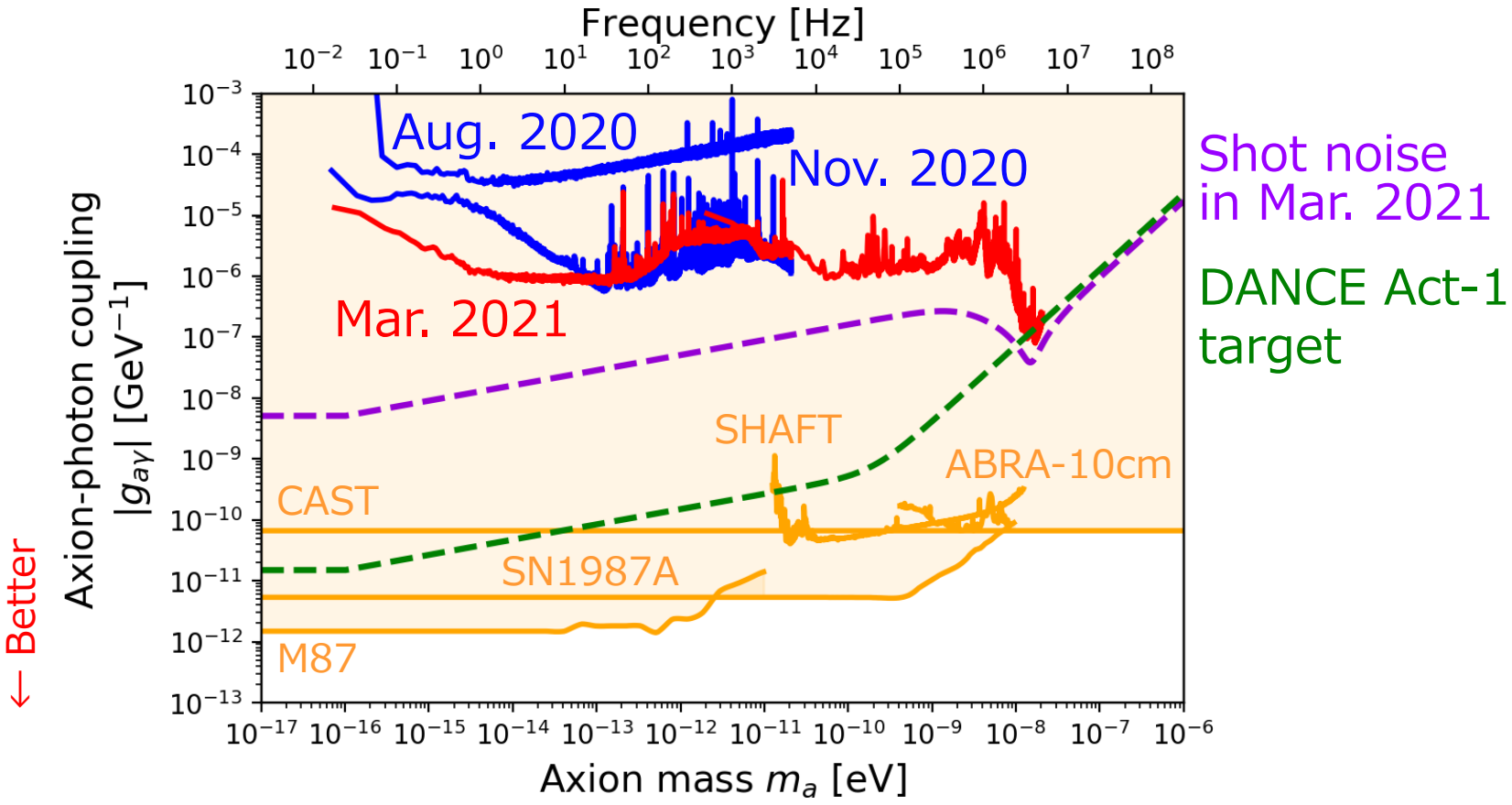



## Ver. Mar. 2021
(Dec. 2020 – Now)




- Improved some points
  - Finesse
  - Resonant frequency difference between polarizations
  - Input laser power
  - Laser intensity noise

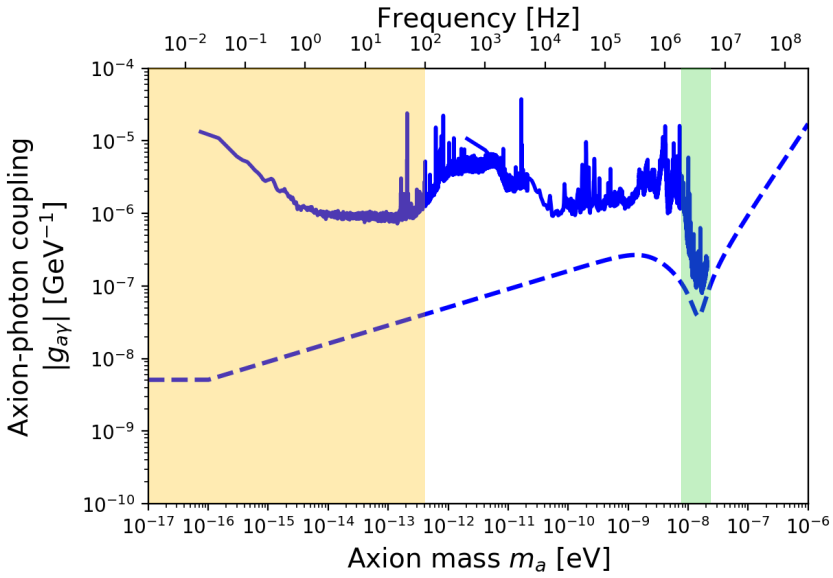
# Current estimated sensitivity




- Sensitivity was gradually improved
- Current main issue is resonant frequency difference between polarizations
  → Fujimoto-kun will deal with this issue

# Contents

# Future plans (1): Data acquisition




Broad band in low frequencies

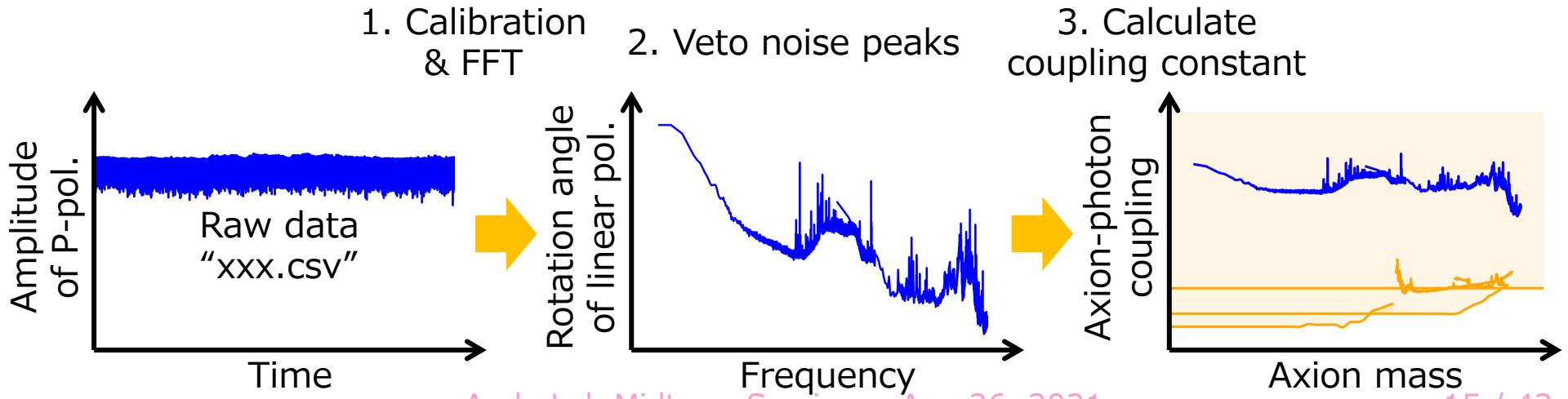
- Observe for a week
  with sampling rate of 100 Hz

Narrow band in high frequencies

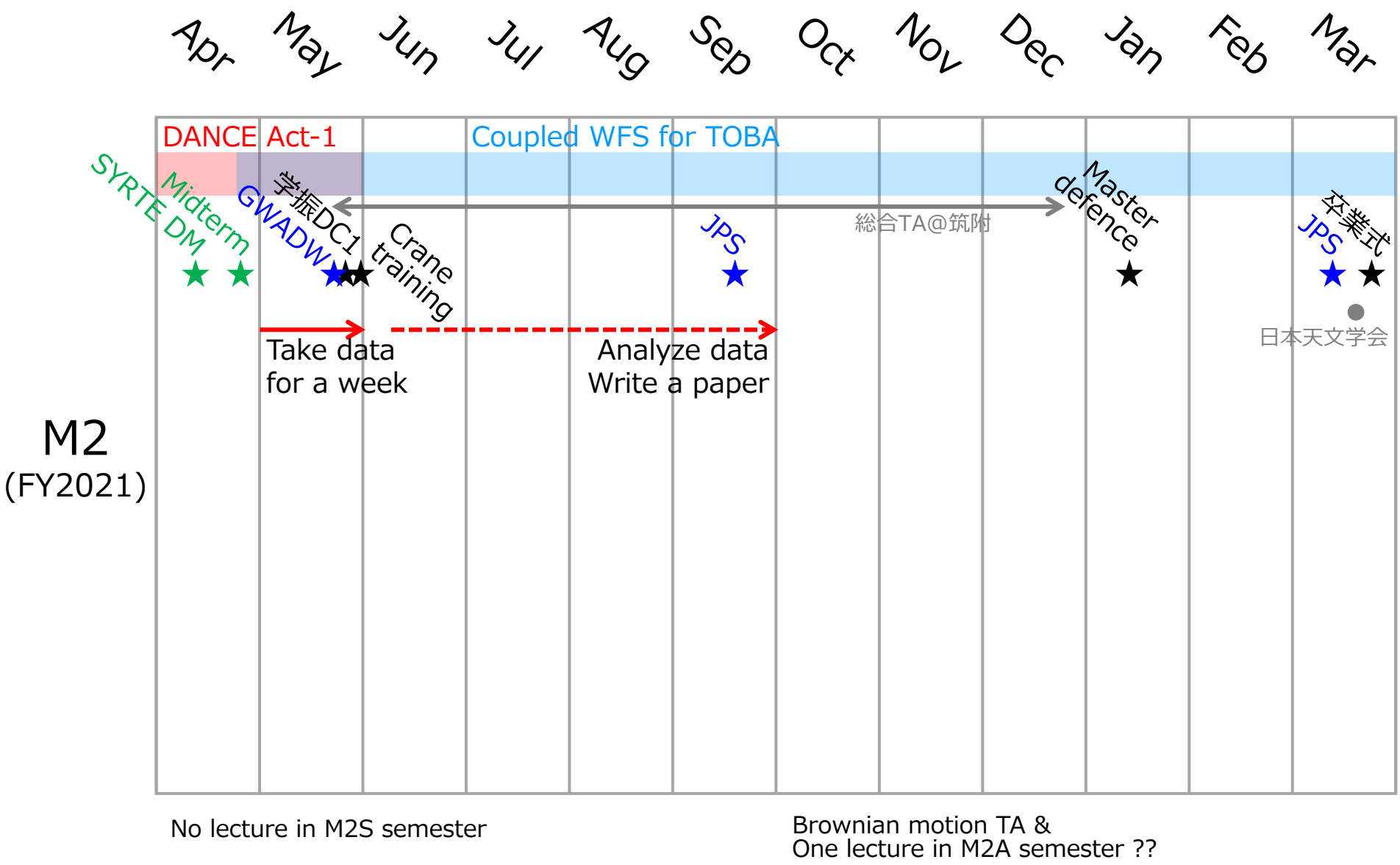
- Measure resonant frequency difference between pol. accurately
  - Current smallest error: 1 % (= sampling rate 30 kHz)
  - Target error: 0.01 % (= sampling rate 300 Hz)
- Make dual phase lock-in amp. with Red Pitaya
- Observe for a few days (with sampling rate of 300 Hz ?)

# Future plans (2): Data analysis

- Plan to use Morisaki-san's code as a reference
- Finished constructing analysis environment
- Source code written by Morisaki-san is for data format "xxx.gwf", but our raw data is "xxx.csv"
- We have to convert csv format to gwf format
  or write source code by myself imitating Morisaki-san's code
  → Ask Morisaki-san which way is easier



# What I will do in this year



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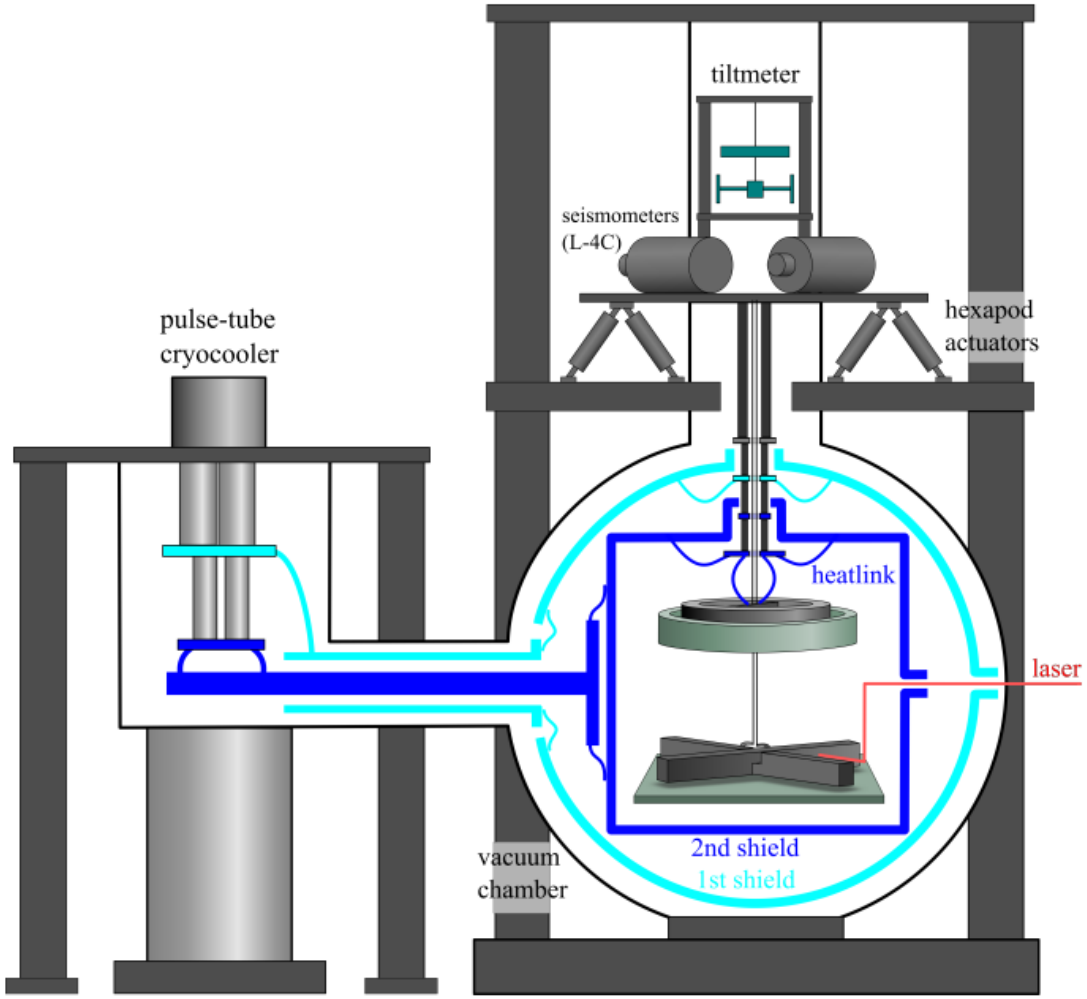
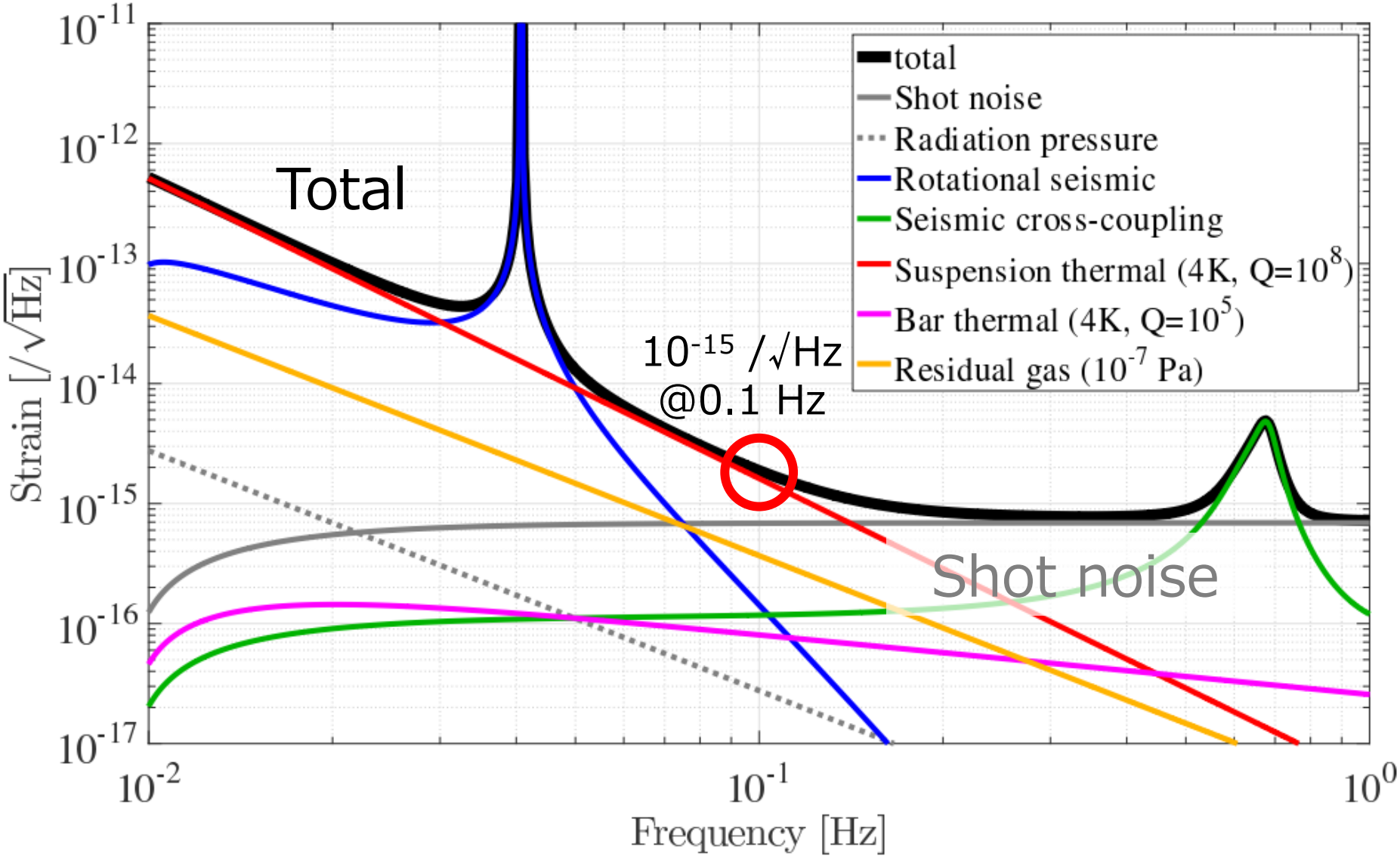
# Setup of Phase-III TOBA




- Cooling to 4 K
- Active vibration isolation
- 35 cm Si test mass
- High Q value wire
- Sensitive readout optics

# Design sensitivity of Phase-III TOBA




→ Sensitive angular sensor is needed: coupled WFS

# WFS is used in many experiments

- Alignment of cavities can be controlled with WFS
  - KAGRA
  - ALPS II

arXiv:2010.02334
I reviewed in Journal Club on Feb. 4

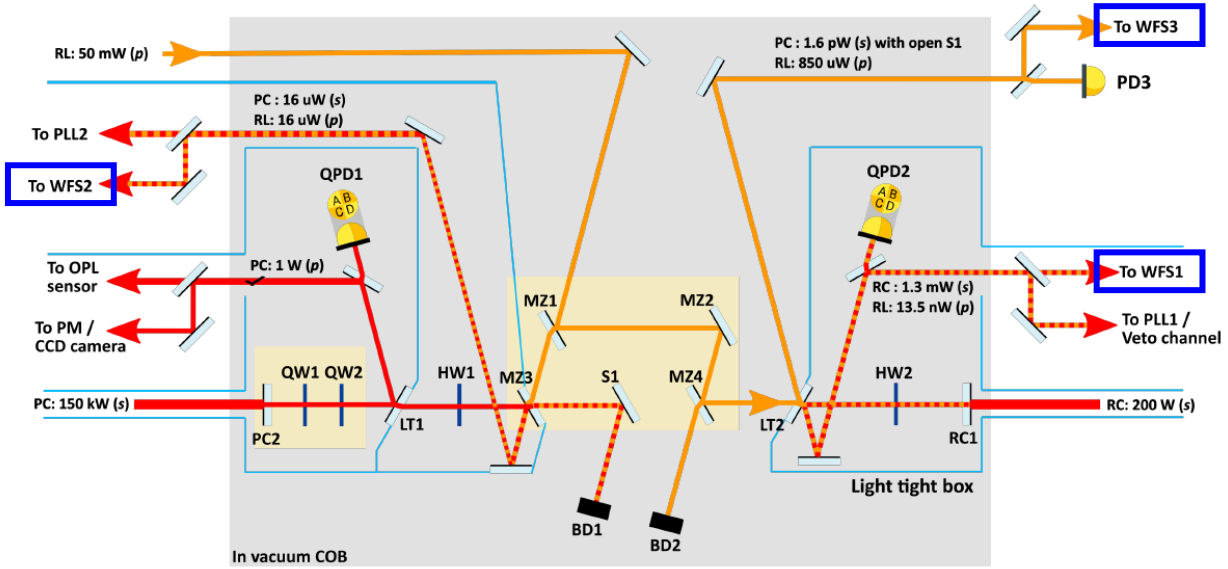
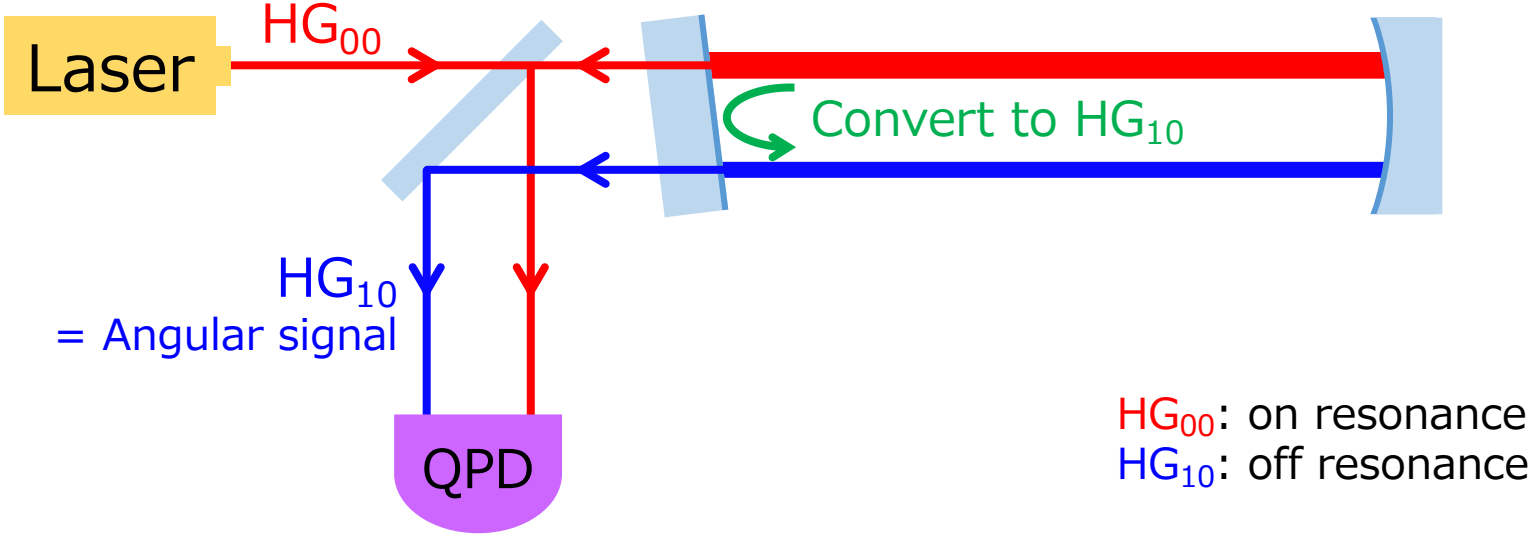



FIG. 2. Optical layout of the central optical bench (COB). HW: Half-Wave plate, MZ: partially transmissive mirror of the Mach-Zehnder-like interferometer, LT: partially transmissive mirror of the Light-Tight box, PC: Production Cavity, OPL: Optical Path Length, CCD camera: monitors spatial mode, PD: Photodetector, PLL: Phase-Locked Loop, QW: Quarter-Wave plate, QPD: Quadrant Photodetector, RL: Reference Laser, RC: Regeneration Cavity, S1: Shutter, WFS: Wavefront Sensor, BD: Beam Dump, $s$: vertical polarization direction, $p$: horizontal polarization direction. The power levels of the three laser fields are estimated based on known mirror reflectivities and transmissivities.

# Principle of simple WFS


- Tilted mirror converts $HG_{00}$ to $HG_{10}$
- $HG_{10}$ mode from cavity is detected as angular signal

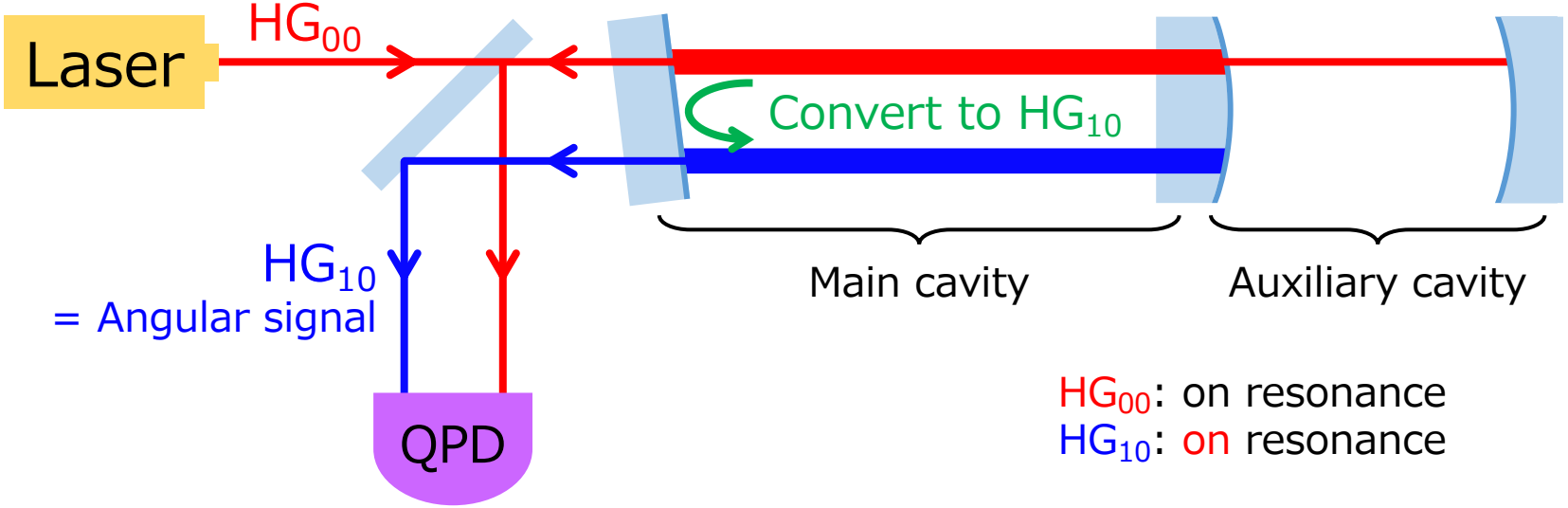



- $HG_{00}$ and $HG_{10}$ cannot be resonant simultaneously since $HG_{10}$ mode gets different phase from $HG_{00}$ mode by Gouy phase ($\varphi_{10} = \varphi_{00} + \Phi_{\mathrm{Gouy}}$)

  → $HG_{10}$ mode signal cannot be amplified in simple WFS

# Principle of coupled WFS

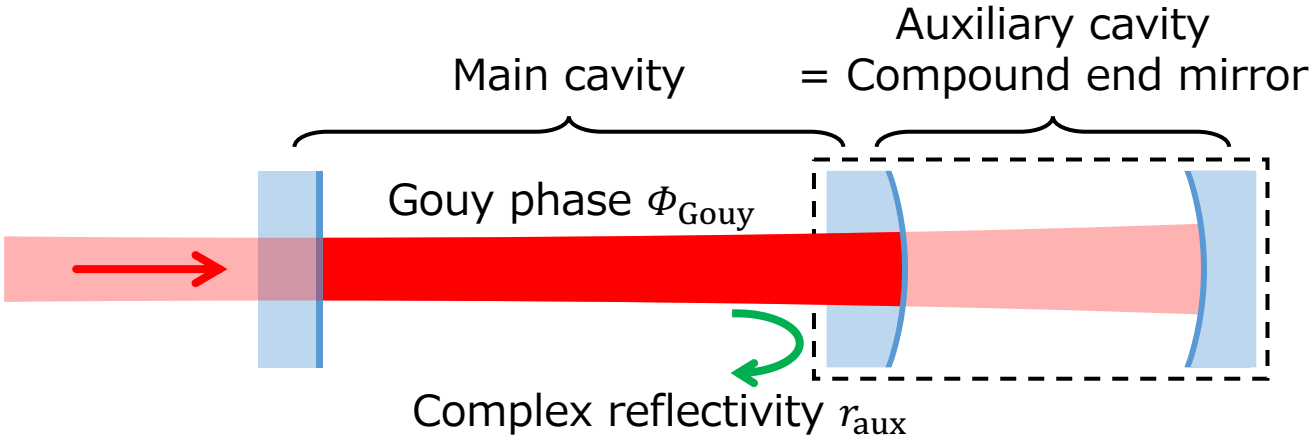

- Tilted mirror converts $HG_{00}$ to $HG_{10}$
- $HG_{10}$ mode from cavity is detected as angular signal

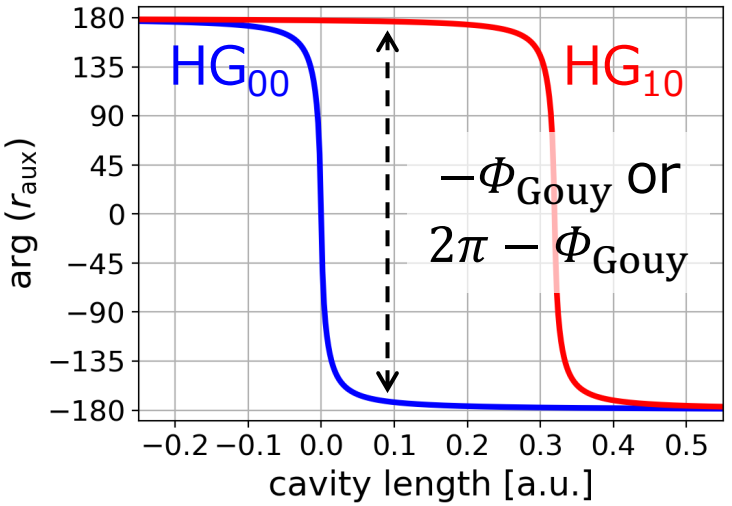



- $HG_{00}$ and $HG_{10}$ can be resonant simultaneously since reflection phase of auxiliary cavity can compensate Gouy phase in main cavity ($\varphi_{10} = \varphi_{00} + 2n\pi$)

  → $HG_{10}$ mode signal can be amplified in coupled WFS

# Phase compensation with auxiliary cavity



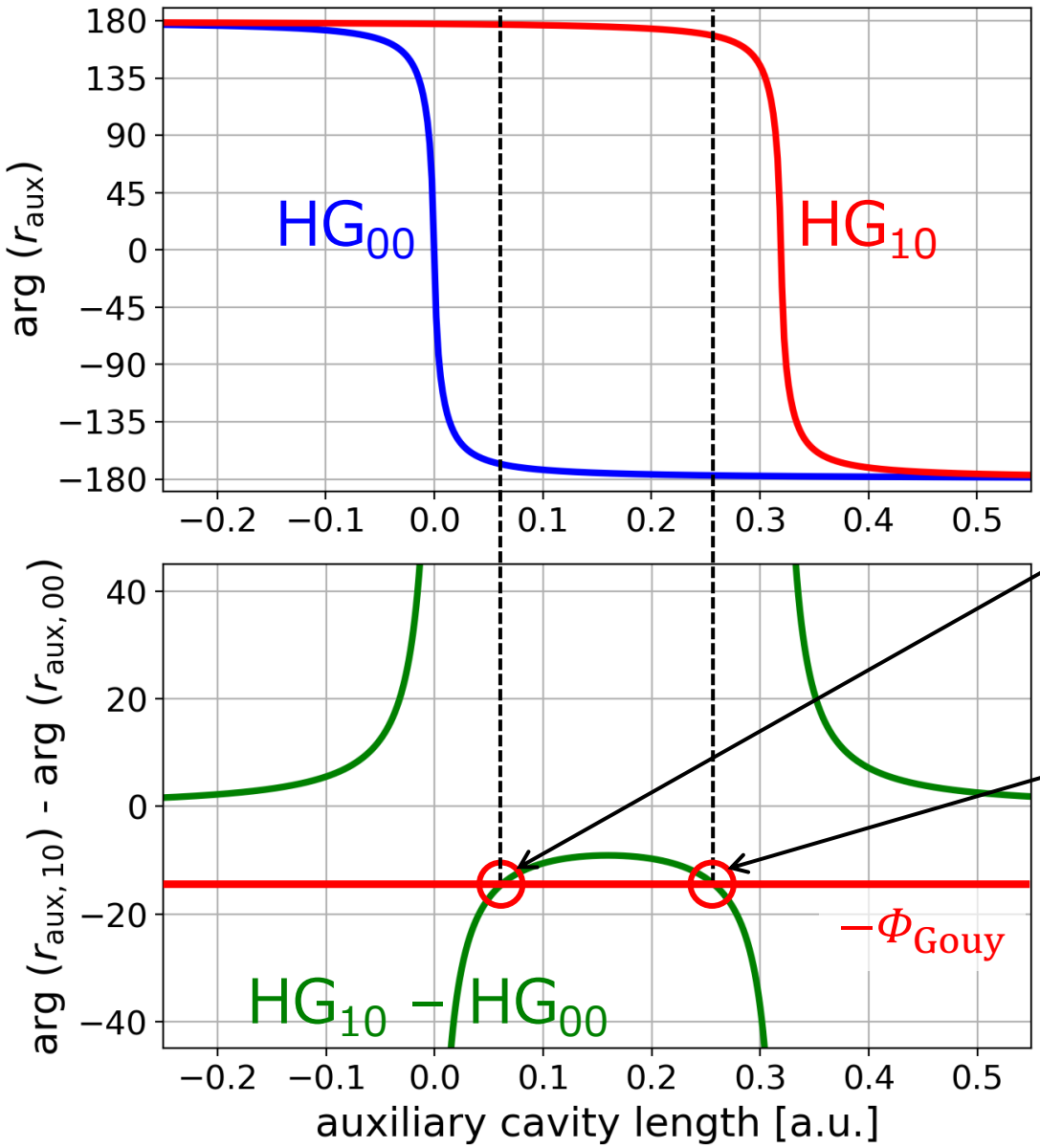




- Round-trip phase in main cavity

$$\varphi_{10} = \varphi_{00} + \Phi_{\mathrm{Gouy}} + \arg\left(r_{\mathrm{aux},10}\right) - \arg\left(r_{\mathrm{aux},00}\right)$$
$$= \varphi_{00} + 2n\pi$$

→ $HG_{00}$ and $HG_{10}$ can be resonant simultaneously

# Lock points of auxiliary cavity

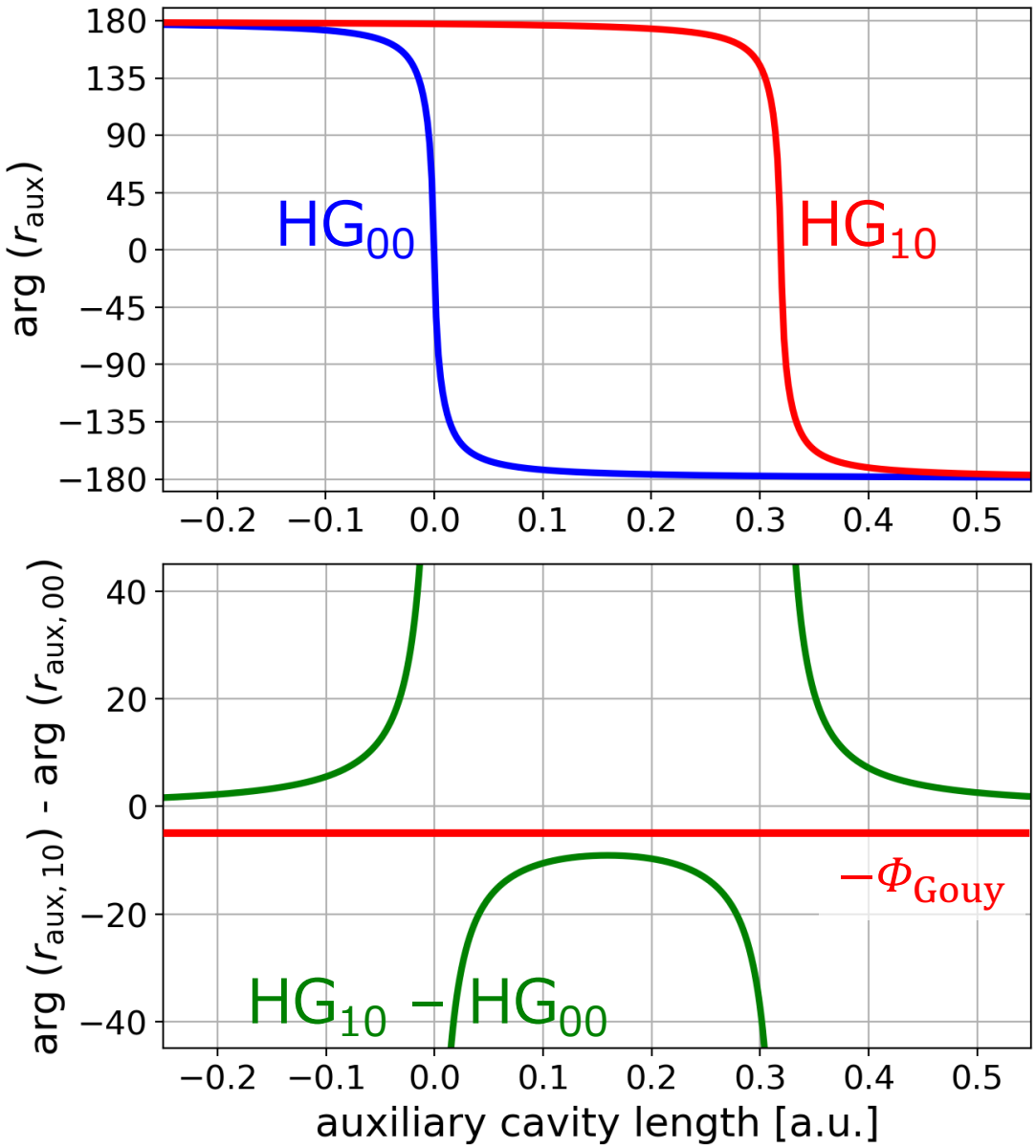



- Detune auxiliary cavity from resonance
- Some solutions exist

Change HG$_{00}$ phase
HG$_{10}$ off resonance

HG$_{00}$ off resonance
Change HG$_{10}$ phase

# Solutions do not always exist




Requirement:

enough large $\Phi_{\mathrm{Gouy}}$

- Long cavity
  ↔ Chamber size
- Small beam
  (= Small RoC of mirrors)
  ↔ Thermal noise

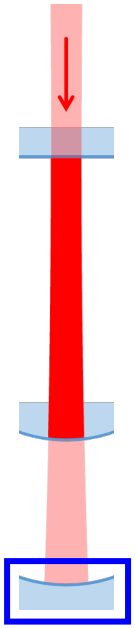
We have to design proper

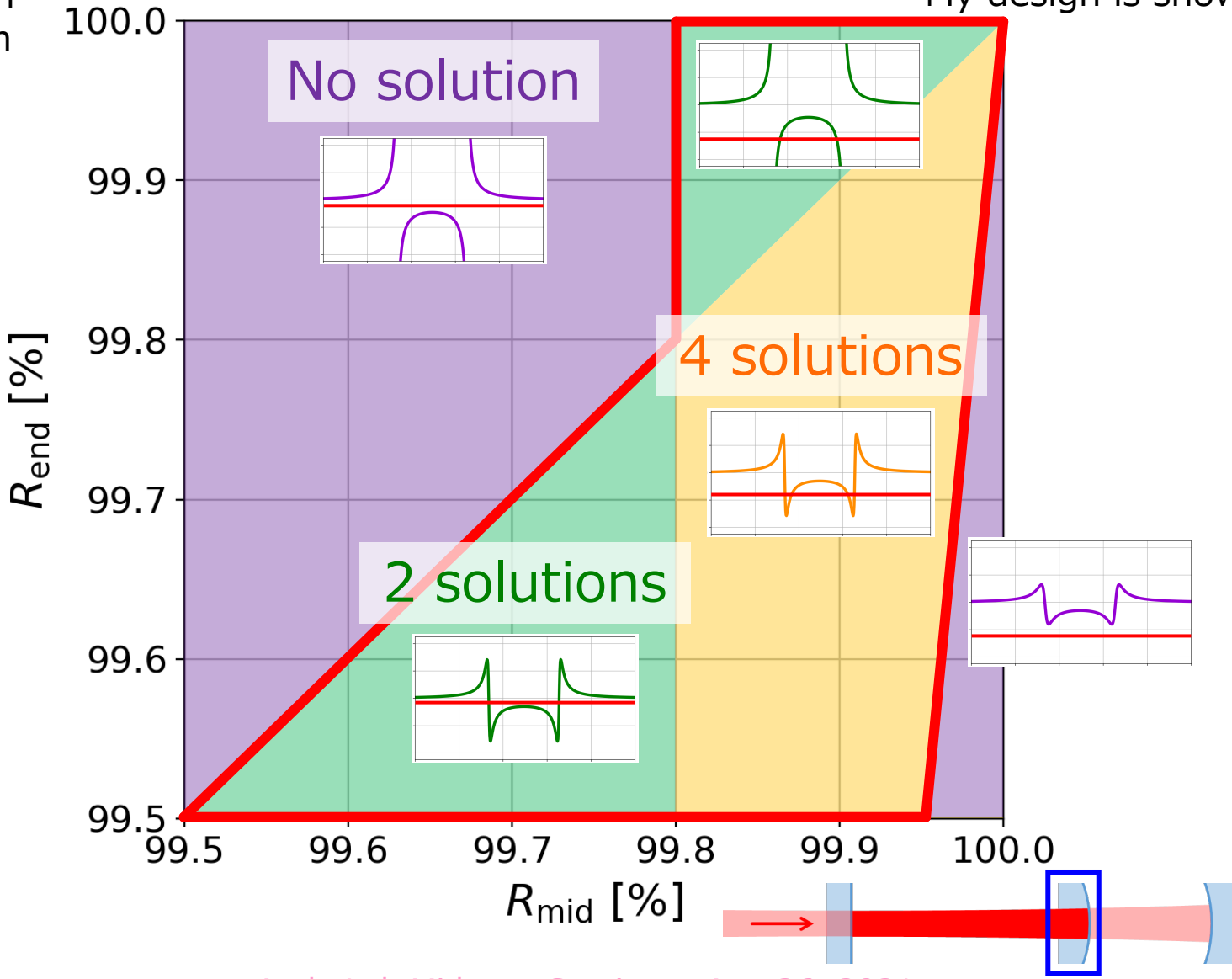
- Length of cavities
- Reflectivity of mirrors
- RoC of mirrors

# Allowed reflectivity

Beam: 800 μm
Main: 10 cm
Aux: 7.5 cm

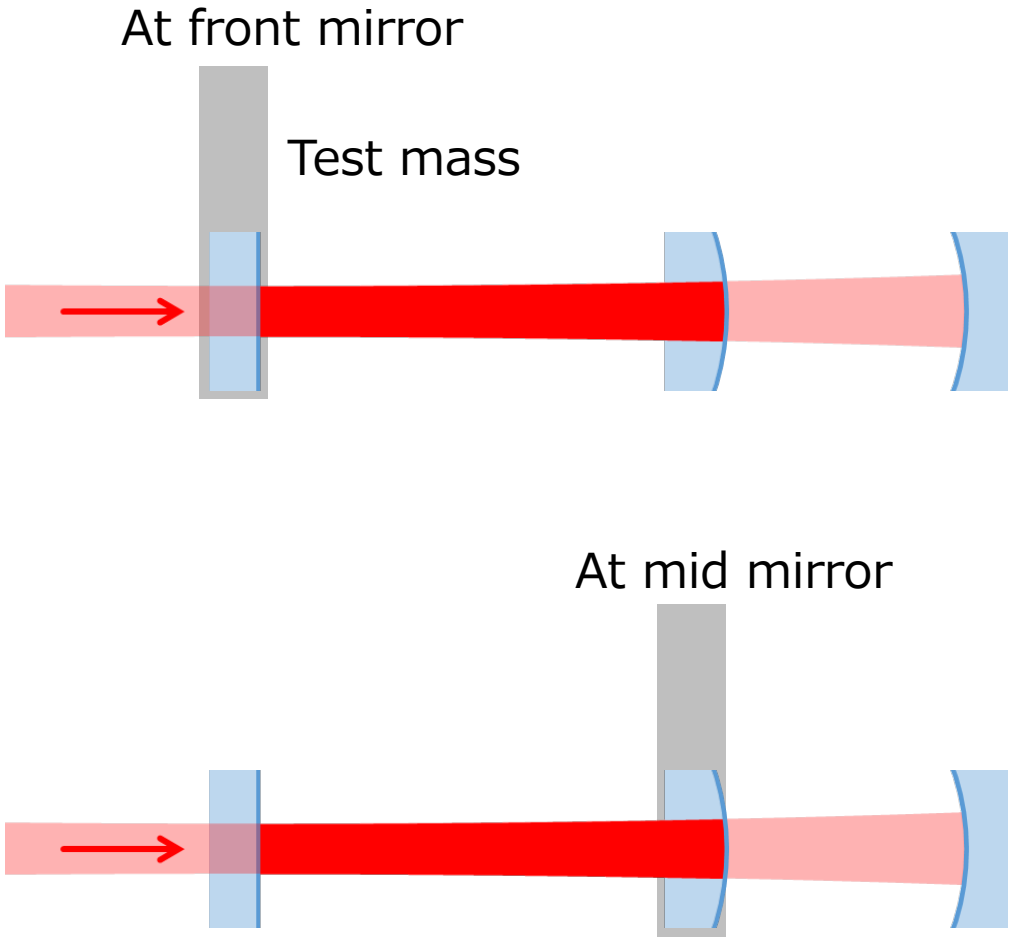
Designed by Shimoda-san
My design is shown later

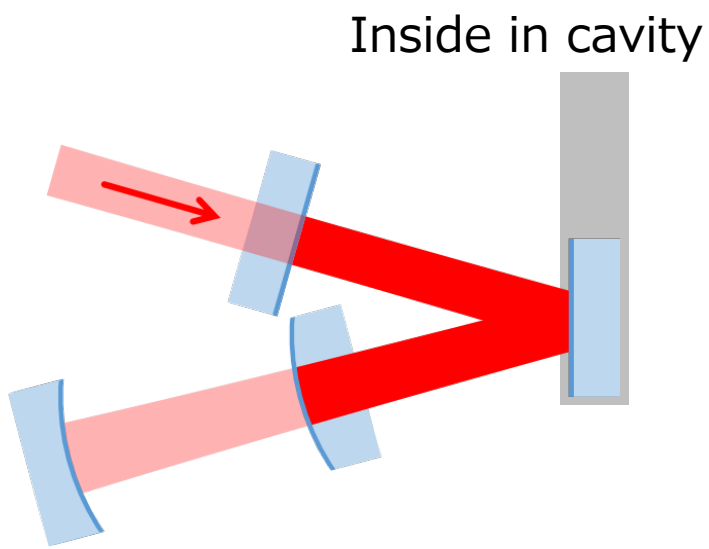




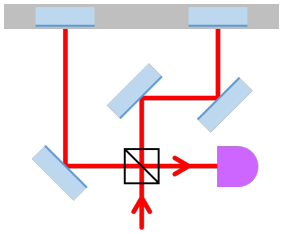
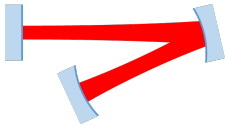
# Possible configurations

- Test mass can be put anywhere

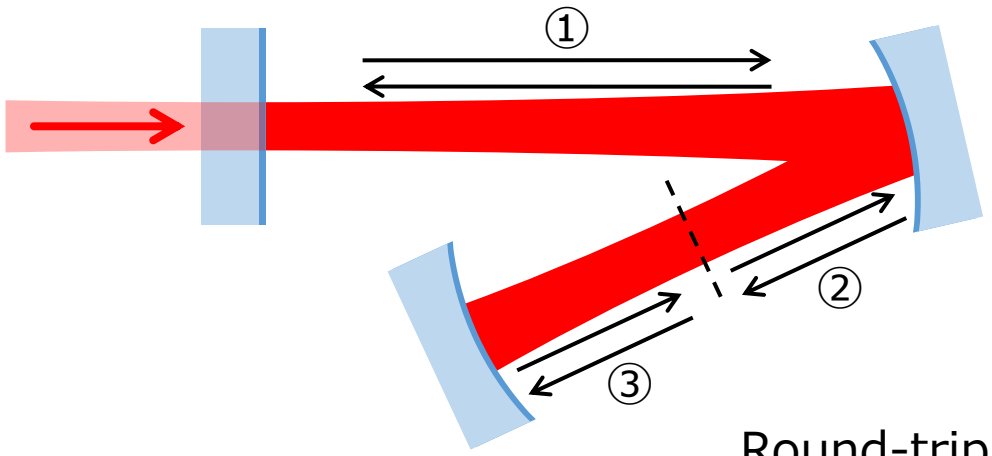


# Comparison of angular sensors

| From Miyazaki-san & Shimoda-san's thesis | MI | Optical lever | Simple WFS | Folded WFS | Coupled WFS |
|---|---|---|---|---|---|
| |  |  |  |  |  |
| Shot noise (Phase-III TOBA requirement: $5\times10^{-16}$ rad/√Hz) | ○ | × | × | ○ | ○ |
| Beam jitter | △ | × | × | ○ | ○ |
| Frequency noise | × | ○ | ○ | ○ | ○ |
| Trans coupling | × | ○ | ○ | ○ | ○ |
| Other demerits | | | | Weak to shrink in cryostat | Difficult to control with two DoF |

# Folded WFS




Round-trip Gouy phase in cavity

(①+②+③)×2 = 2 $\pi$

- $HG_{00}$ and $HG_{10}$ can be resonant simultaneously by changing cavity length

  → $HG_{10}$ mode signal can be amplified in folded WFS

# Contents

DANCE Act-1

- Principle
- Experiment & Sensitivity
- Future plans

Coupled WFS for TOBA

- Principle
- Plans of experimental setups

# Miyazaki-san's master thesis

○ Confirmed $HG_{10}$ signal amplification
and principle of coupled WFS successfully

△ Control of two DoF: auxiliary cavity was 肩 locked

△ Large RoC of mirrors and beam radius:
severe requirement to alignment

△ Large loss of mirrors: difficult to compensate phase

△ Instable lock by resonance of mirror mounts

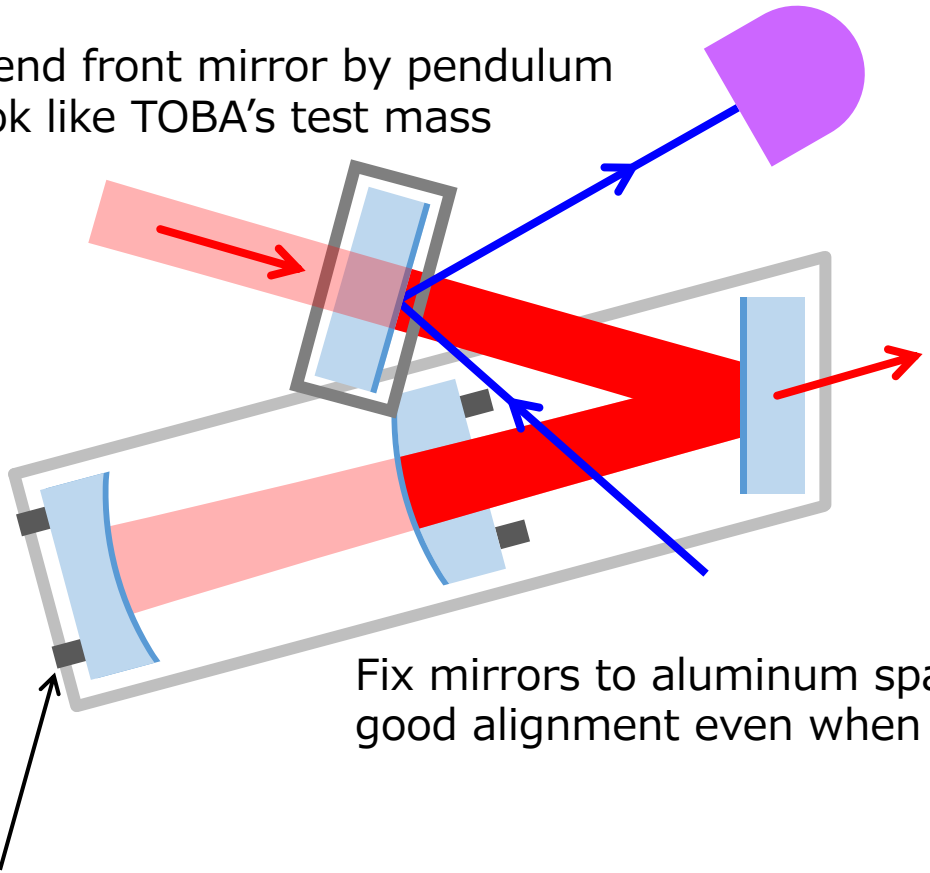
△ Could not extract signal inside main cavity

Plan to improve these issues
in my experiment

# Setup of cavities

Build optical lever to control alignment and compare to sensitivity

Suspend front mirror by pendulum to look like TOBA's test mass

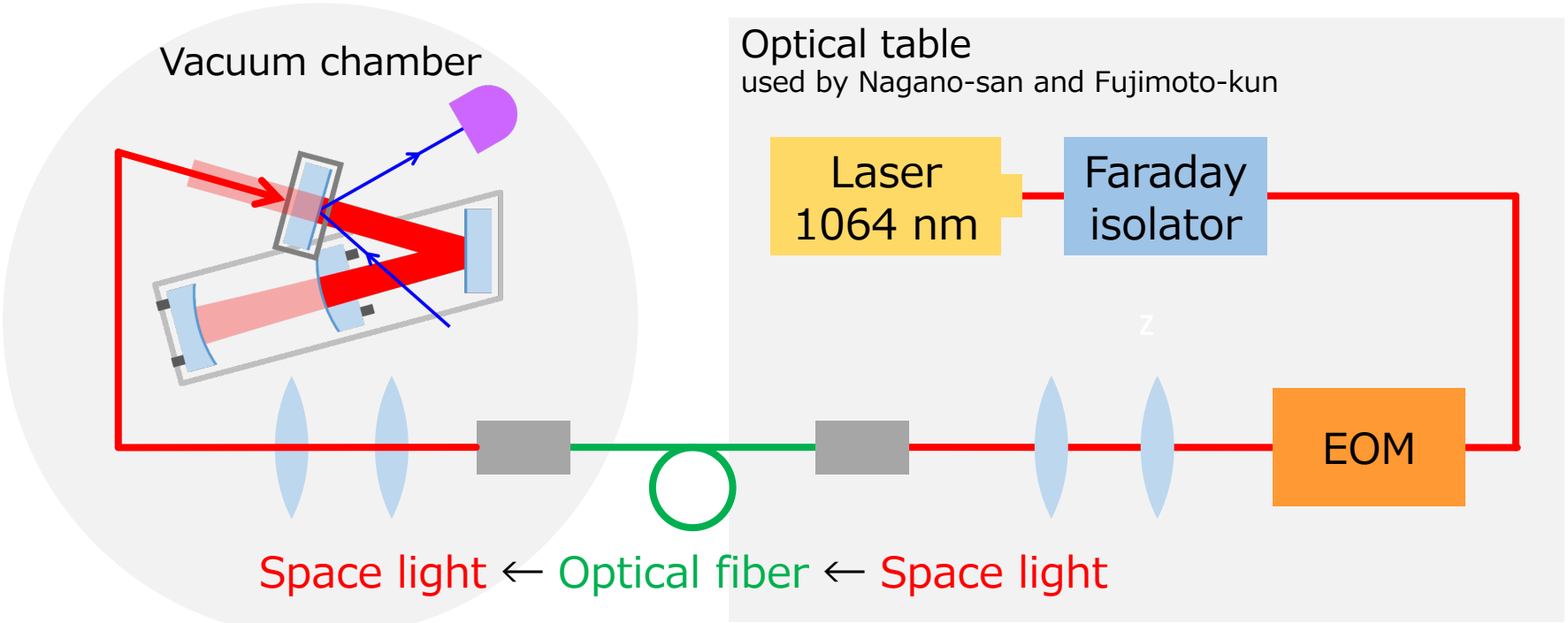


Fold main cavity to extract signal inside main cavity

Fix mirrors to aluminum spacer in order to keep good alignment even when mirrors are changed

Put PZT actuators for length and alignment control (Achieve at the same time as spacer ?)

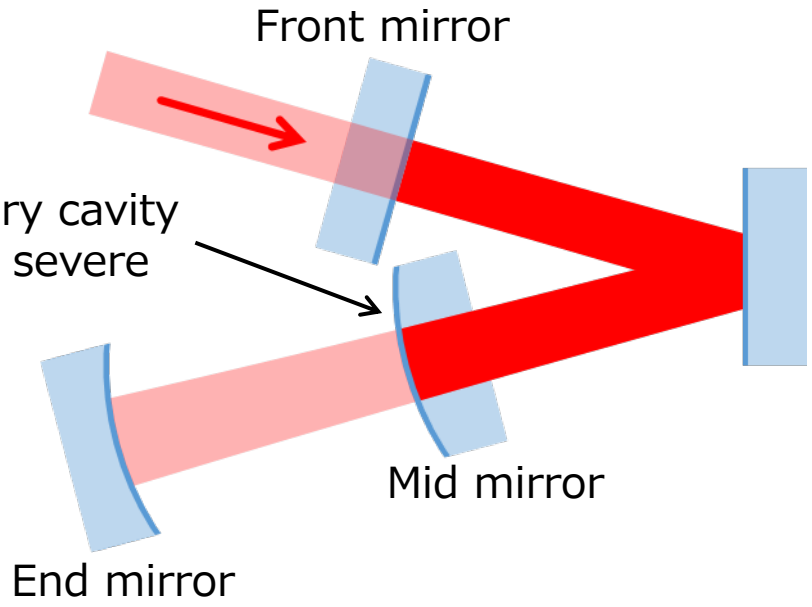
# Setup of whole optics




- Cavities
- Optical lever
- Pendulum
- QPD・PD

- Incident optics

# Mirrors I purchased from Layertec




Large RoC is better for thermal noise
Small RoC is better for alignment

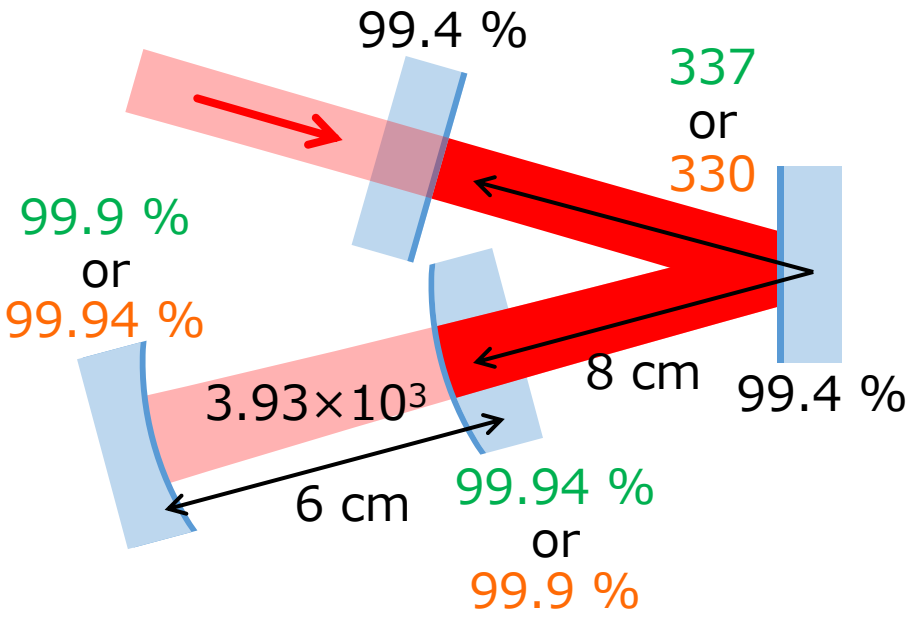
| | Front & Folded | Mid | End |
|---|---|---|---|
| Radius of curvature | ∞ (flat) | 7 m convex | 4 m concave |
| Reflectivity (1) | 99.4 % | 99.94 % | 99.9 % |
| Reflectivity (2) | | 99.9 % | 99.94 % |

Auxiliary cavity is

under-coupled
(better to control)

over-coupled
(better to compensate phase)

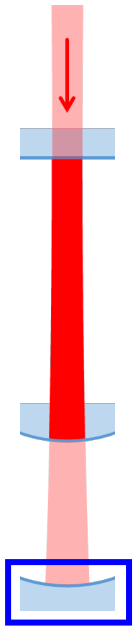
# Cavity parameters

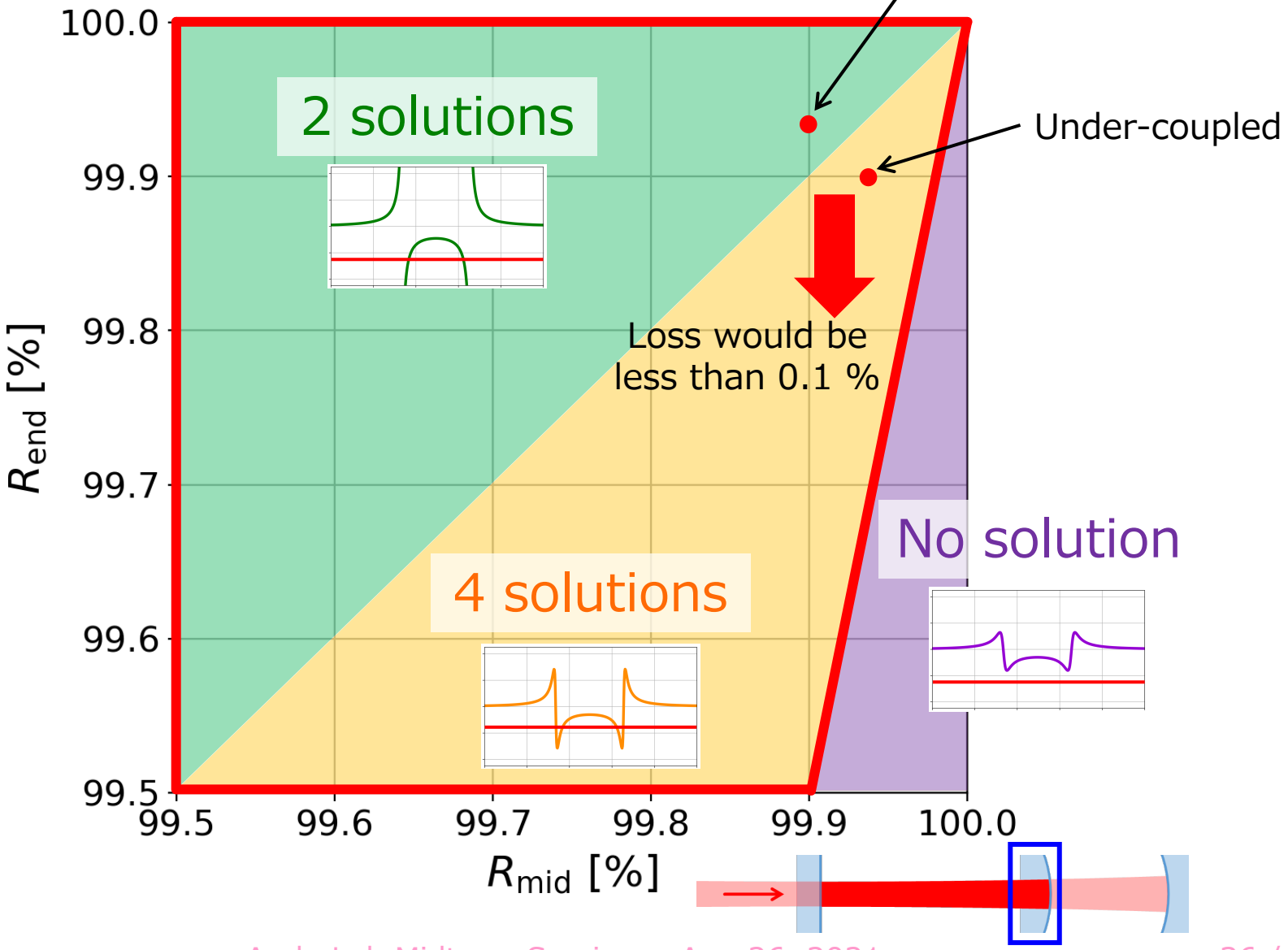



- Cavity length
  - 8 cm (total of main)
  - 6 cm (auxiliary)
- Beam radius
  - 500 μm at front mirror (waist)
  - 508 μm at end mirror
- Finesse
  - 337 (main when auxiliary is under-coupled)
  - 330 (main when auxiliary is over-coupled)
  - $3.93\times10^3$ (auxiliary)

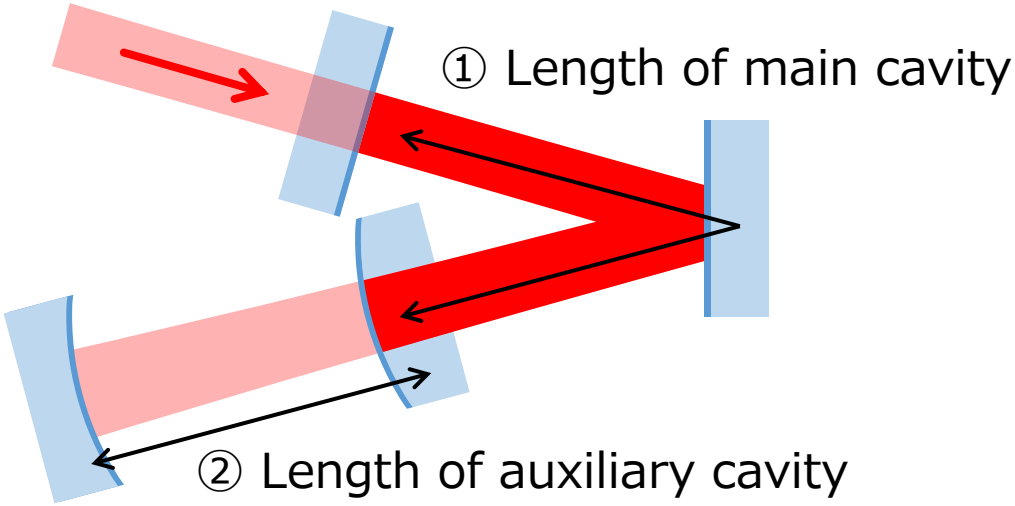
# My designs are strong to loss

Beam: 500 μm
Main: 8 cm
Aux: 6 cm





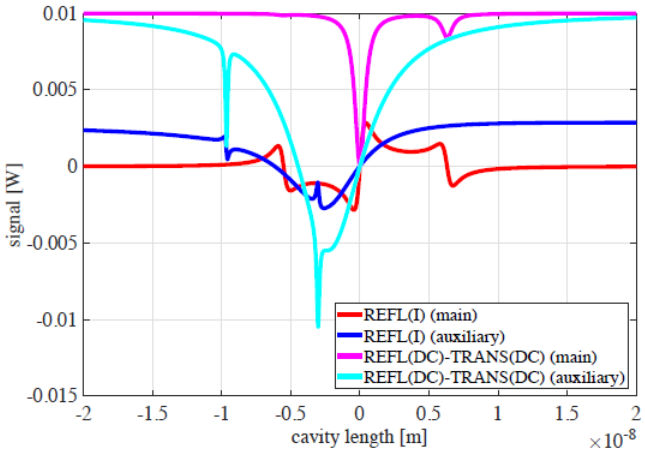
# Control of two DoF




- Plan to control with PDH technique for both cavities
- Signal separation (main-auxiliary) is important
- Under-coupled cavity gives better signal separation

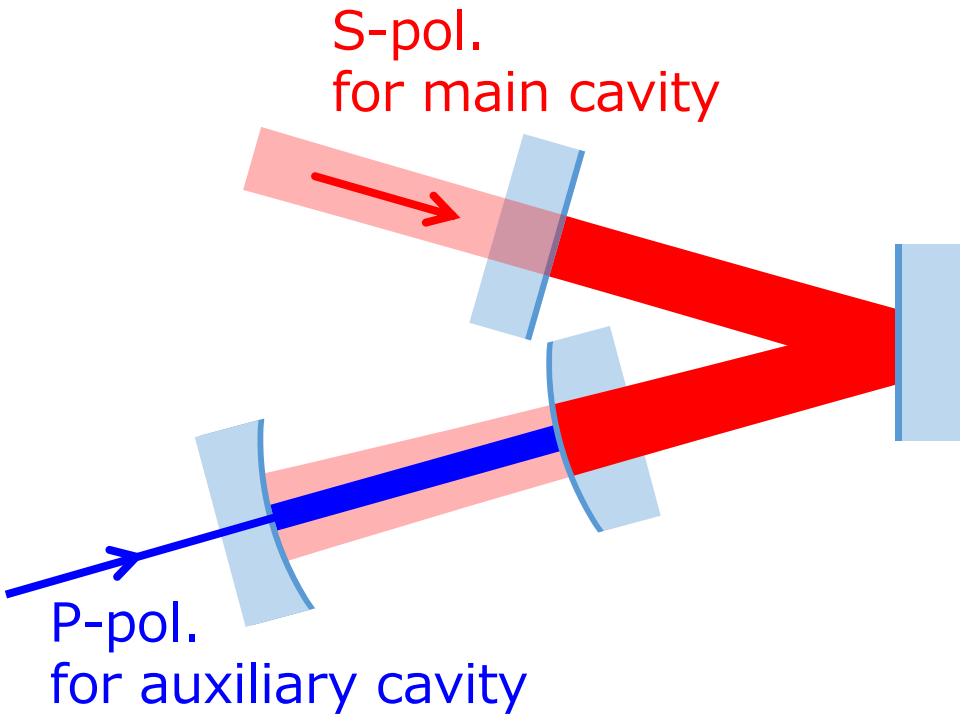
Shimoda-san calculated it
I want to calculate with Opticle

| sensing matrix | main cavity | auxiliary cavity |
|---|---|---|
| PDH signal (refl) | 1 | 0.09 |
| DC signal (refl-trans) | 0 | 1 |



# Idea of control (1)

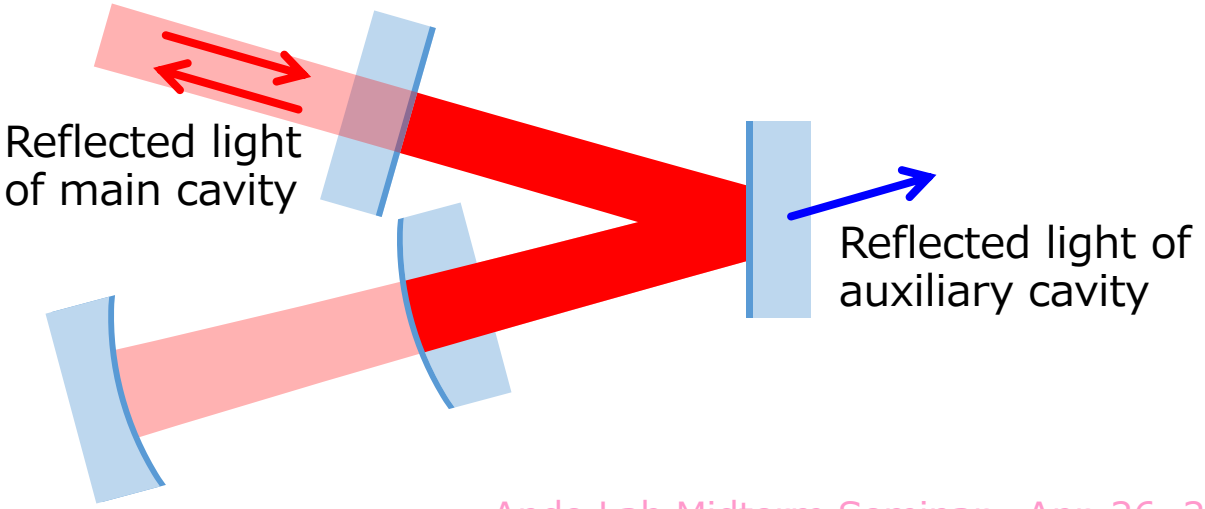
- Inject different polarizations into auxiliary cavity from behind
- Reflected light of main and auxiliary cavity is detected independently

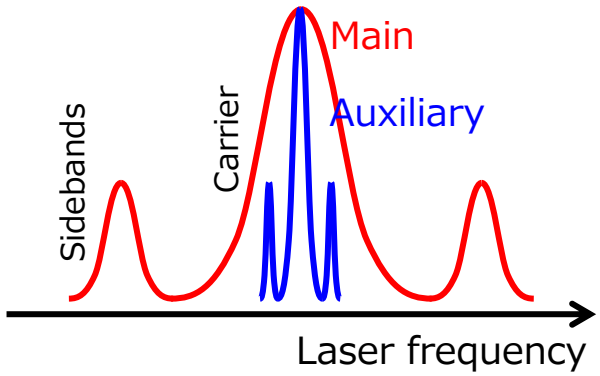


# Idea of control (2)

- Use two different modulation frequencies for main and auxiliary cavity
- Reflected light of auxiliary cavity is detected from folded mirror

| | Length | FSR | Finesse | FWHM | Possible modulation freq. |
|---|---|---|---|---|---|
| Main | 8 cm | 3.8 GHz | 300 | 13 MHz | 40 MHz |
| Auxiliary | 6 cm | 5 GHz | 4000 | 1.3 MHz | 4 MHz |



# What is new for me

Same technique as DANCE Act-1

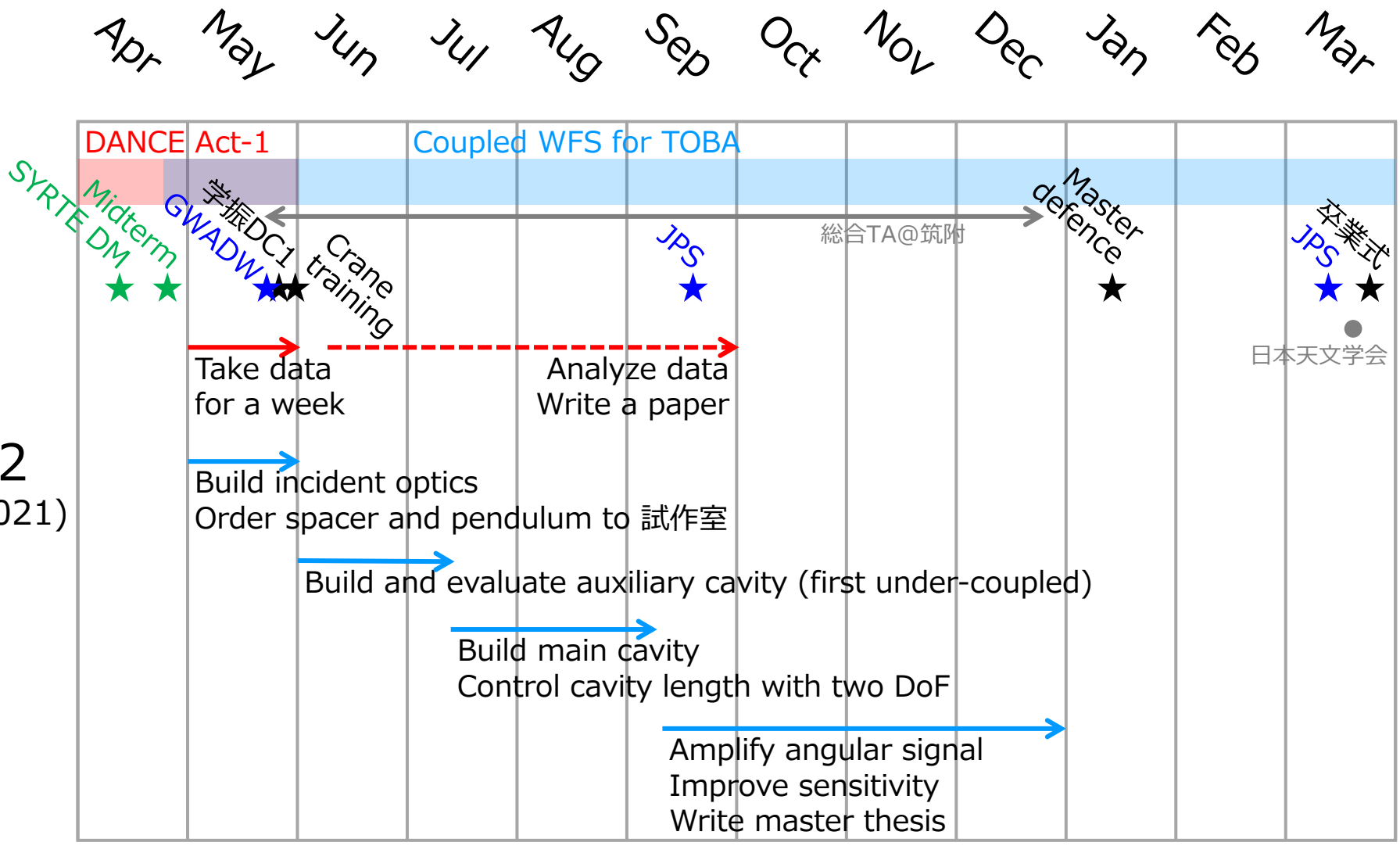
- Optical cavity
- Mode matching
- Optical fiber
- PDH technique
- Polarizations

New technique for me

- Vacuum chamber
- Pendulum
- Control with two DoF
- QPD
- Alignment control

I want to finish the same thing as DANCE Act-1 as soon as possible and focus on something new

# What I will do in this year



# Summary

## DANCE Act-1

- I started DANCE Act-1 in 2019 and ongoing
- First result in 2020 successfully
- Plan for data acquisition and analysis in 2021

## Coupled WFS for TOBA

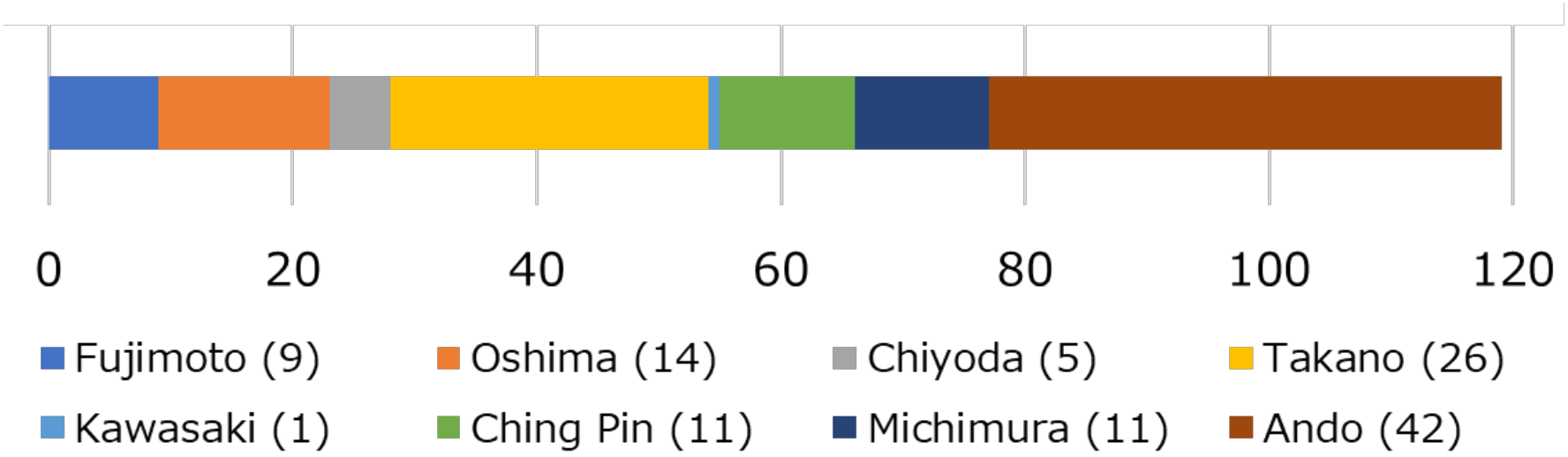
- Coupled WFS is a sensitive angular sensor
- Plan to build coupled WFS in order to achieve two DoF control and good sensitivity

また1年間よろしくお願いします

# Bonus Slides

# Lab e-log analysis

- 119 e-log were posted in Apr. 1, 2020 – Mar. 31, 2021
- 40 meetings were held




Names listed without honorifics

- Aritomi-san posted to NAOJ e-log
- Takeda-san wrote comments for meeting log

# List of e-log I posted

This page is just a memo for myself

- 2020/6/16 #4292 Toy Michelson Interferometer
- 2020/7/15 #4498 Performance of Piezo Amplifier E-610
- 2020/7/16 #4504 Toy Fabry–Pérot Cavity
- 2020/10/2 #4858 Mirror Holding Jig Design
- 2020/10/2 #4867 New power meter S132C is delivered
- 2020/10/13 #4898 New data logger DL850E is available
- 2020/10/16 #4951 Power Spectrum of Transmitted Light

# List of e-log I posted

This page is just a memo for myself

- 2020/10/29 #5002
  Survey of the Seismic Noise on Faculty of Science Bldg.1
- 2020/11/5 #5059

Aluminum frames and plates surrounding optical table

- 2020/12/24 #5320 Status report of DANCE
- 2021/1/11 #5353 Performance evaluation of a cavity
- 2021/1/12 #5375
  Mirror Design for Coupled Wave Front Sensor
- 2021/1/28 #5446
  P and S polarizations do not resonate simultaneously
- 2021/2/5 #5551 Lattice mirrors again

# List of movies I watched

I watched many movies with my family due to COVID-19

My father rented many foreign movies

Please let me know your favorites !

- Back to the Future series
- Jurassic Park series
- Night at the Museum series
- Star Wars series ← Takano-san's favorite. I like so-so
- Columbo series
- Agatha Christie's Poirot series ← My favorite. I'm also reading novels
- Sherlock Holmes series
- Mission:Impossible series
- Roman Holiday
- Wait Until Dark
- Outbreak
- Interstellar ← Fujimoto-kun's favorite. I don't like

⋮

# Extra Slides

# データ解析

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

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

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

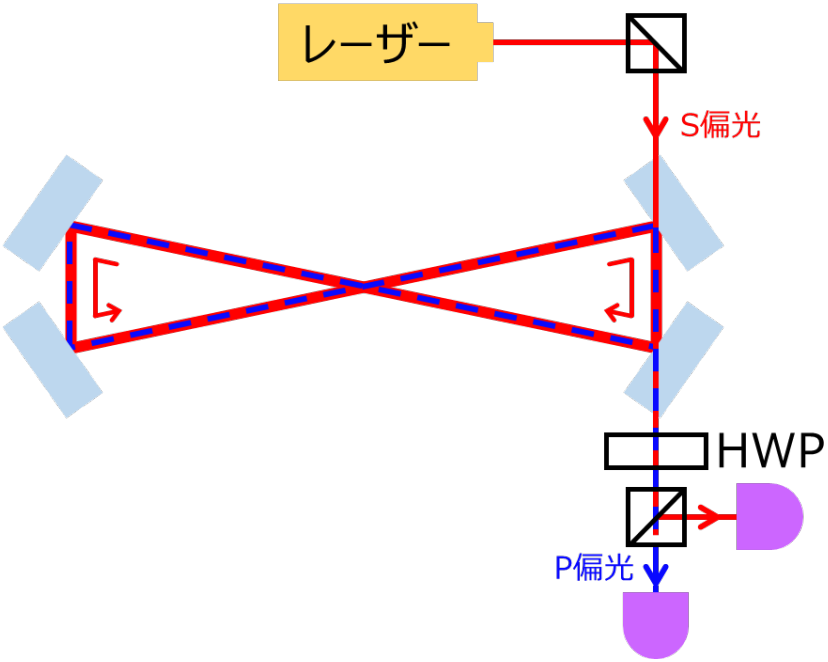
$$P_S = E_S'^2 = E_0^2 \cos^2(2\theta + \phi(t))$$

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

$2\theta + \phi \ll 1$ のとき $\sin(2\theta + \phi(t)) \approx 2\theta + \phi(t)$

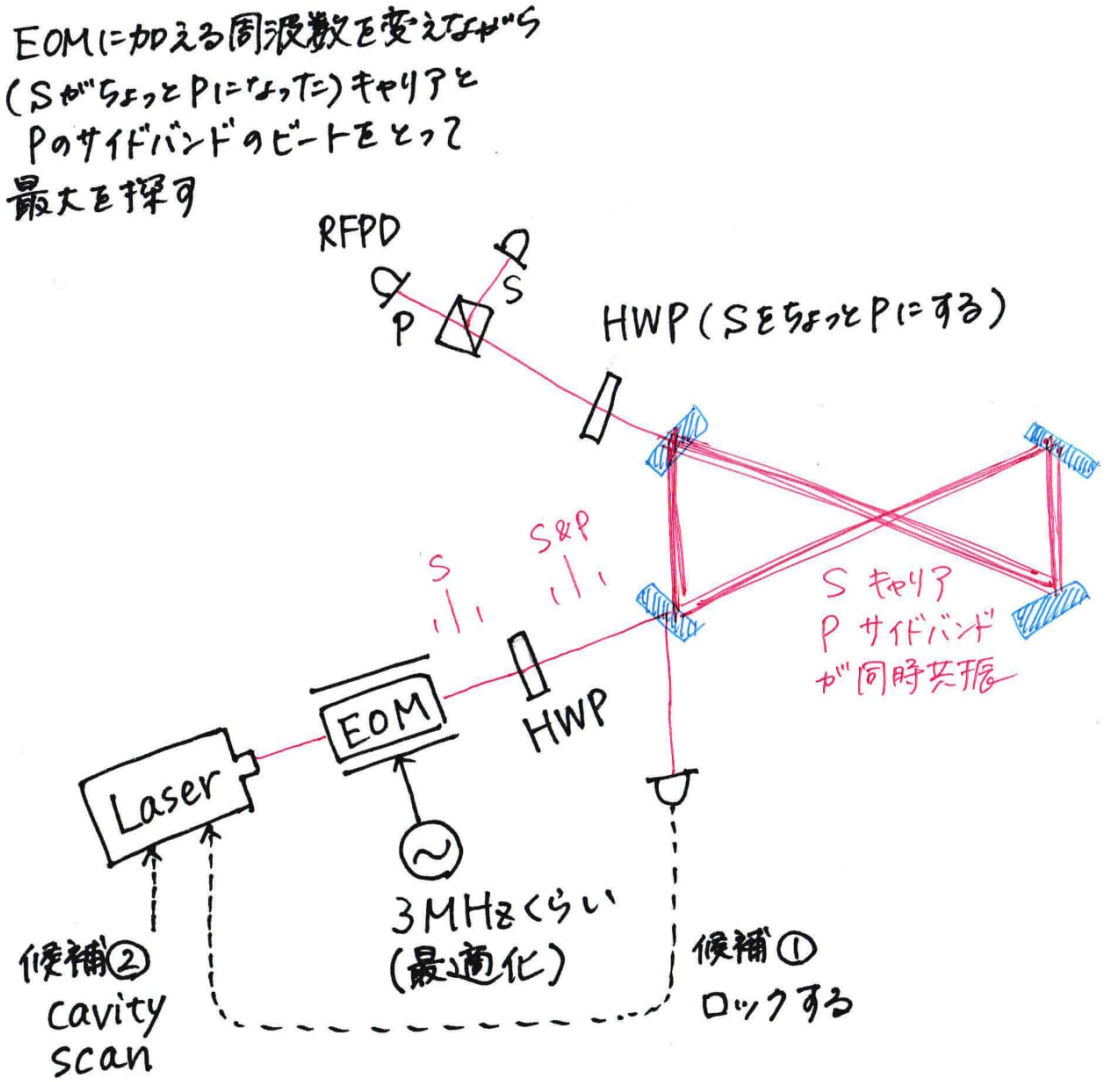
偏光の回転角 $2\theta + \phi(t) = \frac{E_P'}{E_0}$

$2\theta$は定数だからスペクトルに寄与しない



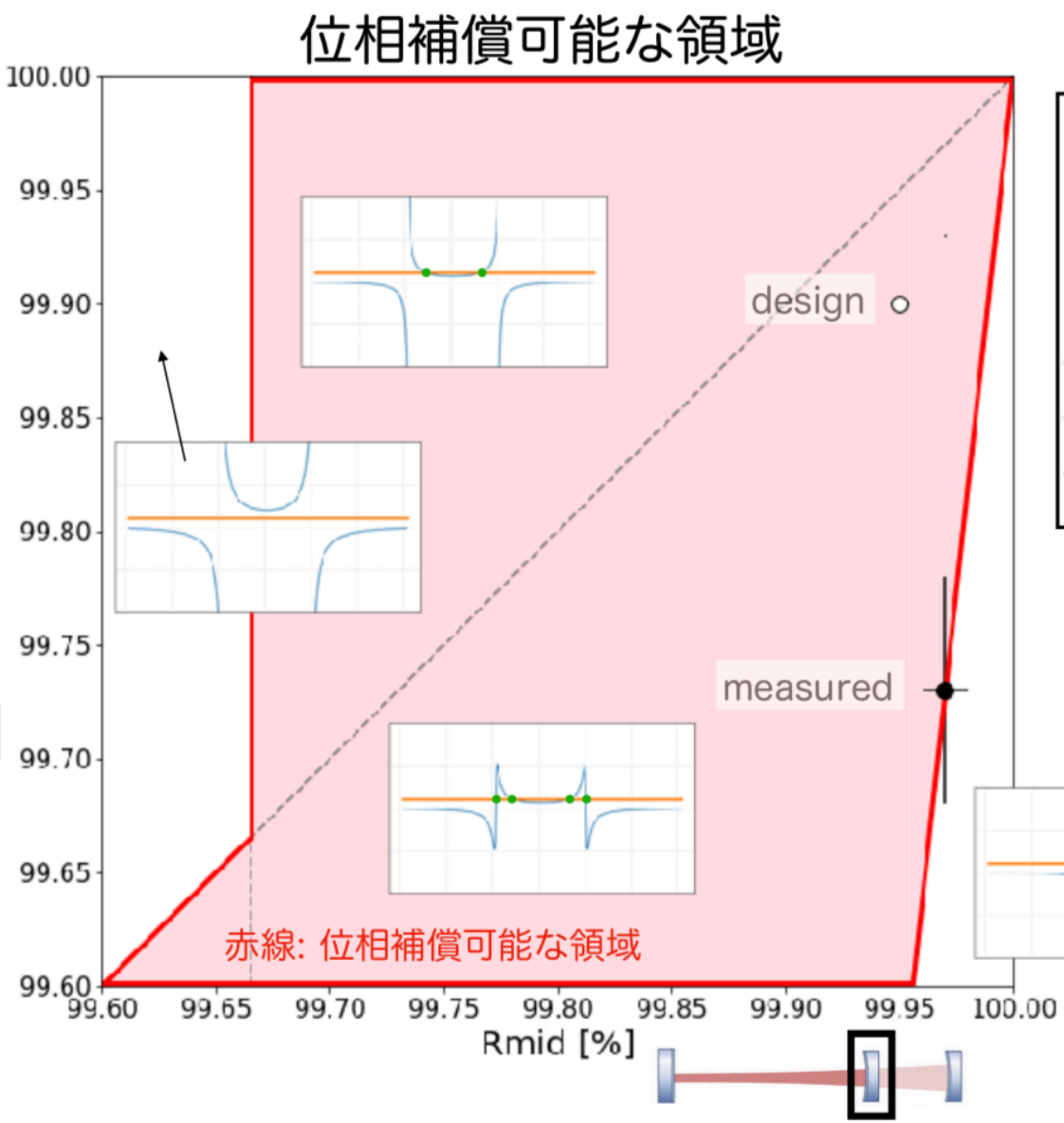
# How to measure resonant freq. dif.

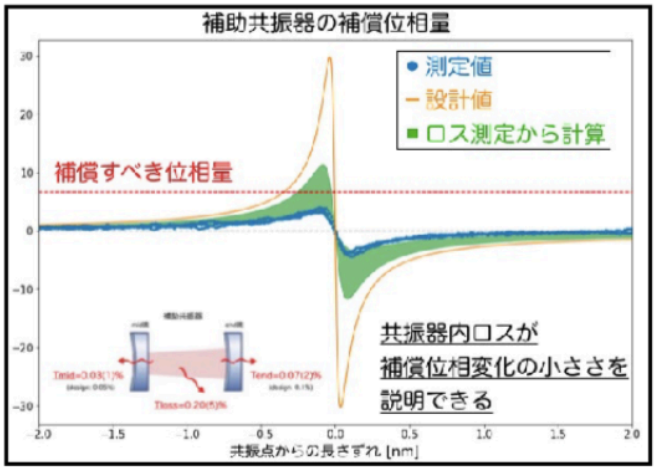
From e-log #5655



# Miyazaki-san's design

From Miyazaki-san's slides




w0 = 0.8mm
Rfront = 99%
$\lambda$ = 1064nm
RoCfront = inf
RoCmid = 30m
RoCend = 15m
LenMain = 10cm
LenAux = 10cm
GouyMain = 6.7deg
GouyAux = 6.7deg

# Design of mirrors and finesse

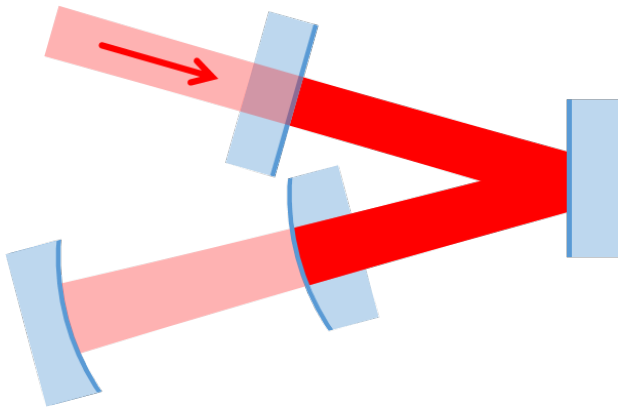
| | Front & Folded | Mid | End |
|---|---|---|---|
| Radius of curvature | ∞ (flat) | 7 m (±2 %) convex | 4 m (±1 %) concave |
| Reflectivity (1) | 99.4(3) % | 99.94(2) % | 99.90(2) % |
| Reflectivity (2) | | 99.90(2) % | 99.94(2) % |

Auxiliary cavity is

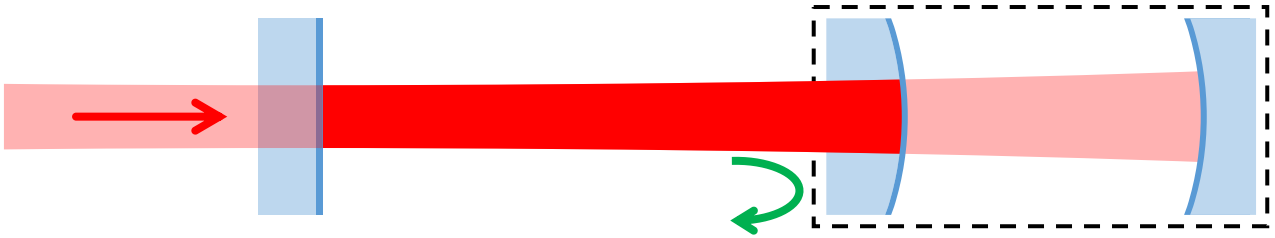
under-coupled

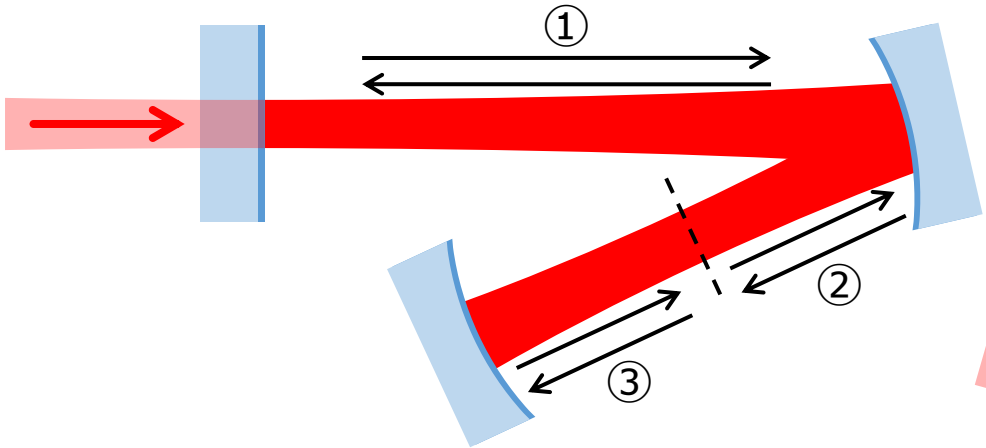
over-coupled

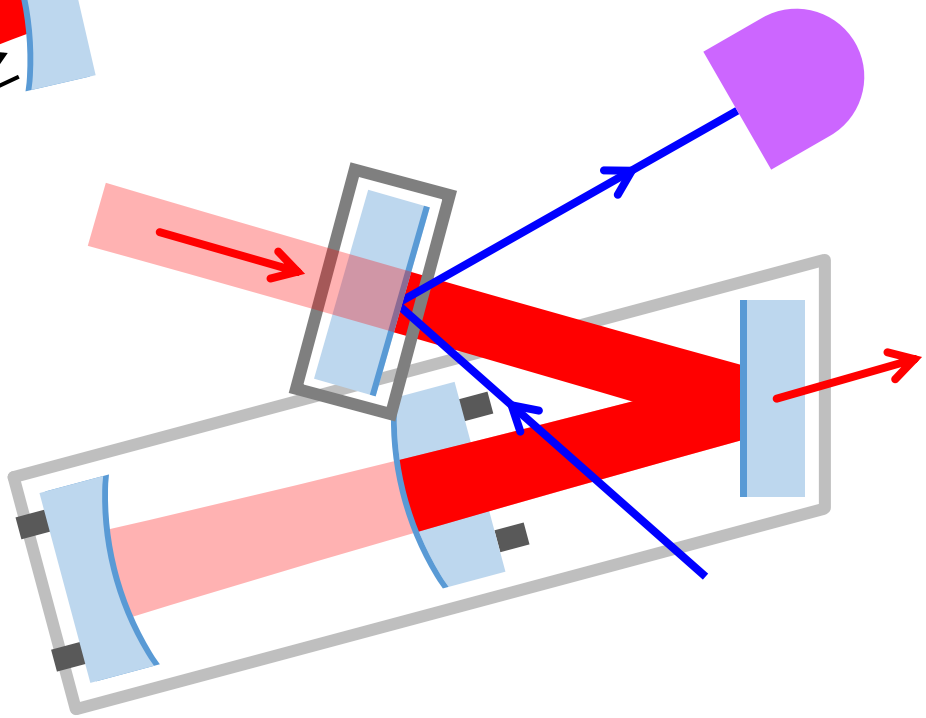
- Finesse
  - 337 (225-667) (main when auxiliary is under-coupled)
  - 330 (222-640) (main when auxiliary is over-coupled)
  - 3.93 (3.14-5.23) $\times 10^3$ (auxiliary)



# Figures





# Figures