Future plans of DANCE Act-1 toward the Ph.D.

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Contents

- Review of DANCE Act-1
- Current status of DANCE Act-1 / What to do for Ph.D.?
- Future plans
  - Improvement of shot noise limit
  - Reduction of noises
    ① Reduce coupling coefficient
      - Additional injection of p-pol. for cancelling birefringence

    ② Reduce cavity vibration and air turbulence
      - Stack isolation system
      - Vacuum chamber

    ③ Suppress phase noises by feedback control
      - 4-mirror auxiliary cavity to reduce parasitic resonance
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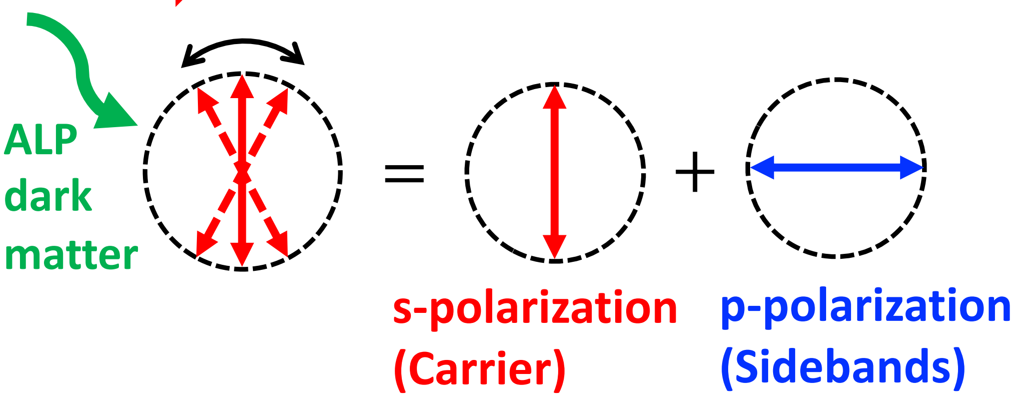
Axion-photon interaction

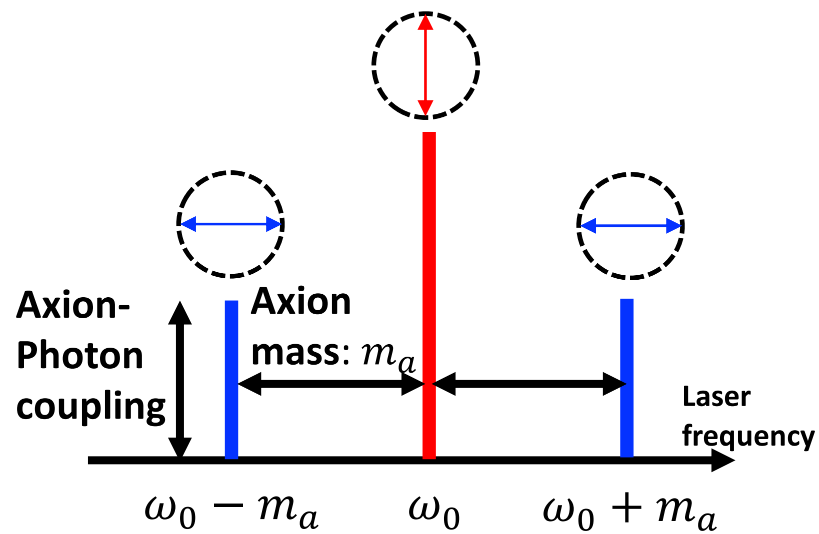
Axion-photon interaction causes phase velocity difference

$$c_{L/R} = 1 \pm \frac{g_{a\gamma} a_0 m_a}{2k} \sin(m_a t + \delta_\tau)$$

Left-/Right-handed polarization — **Axion-photon coupling constant** — **Axion field** — **Axion mass**

⇒ Rotational oscillation of linearly polarized light

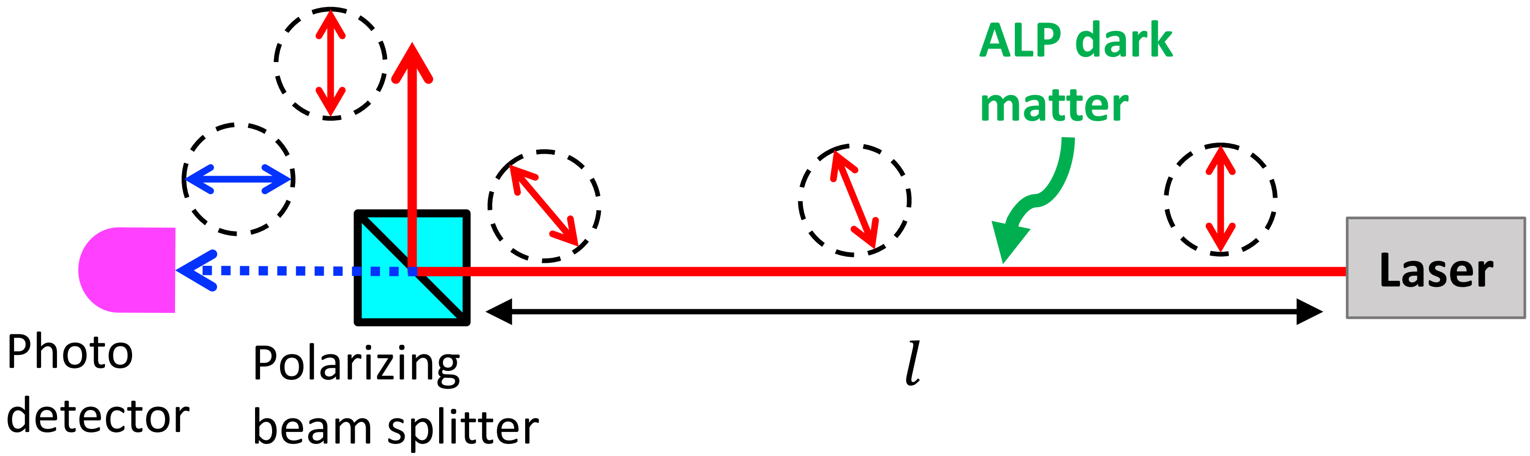




- Axion signal appears as p-pol. sidebands in amplitude quadrature
- No need for strong magnetic fields

Light path dependency of polarization rotation

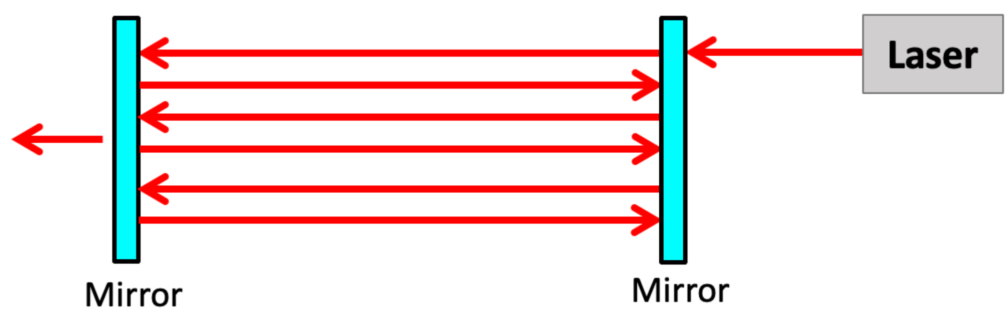
- Polarization rotation can be measured with a PBS and PDs



Rotation : $\Delta\theta(t,l) = \underbrace{\frac{g_{a\gamma}\sqrt{2\rho_a}}{m_a}\sin(m_a l)}_{\text{Amplitude}}\ \underbrace{\sin(m_a t + \delta_\tau)}_{\text{Oscillation}}$

Rotational amplitude becomes large as light path increases

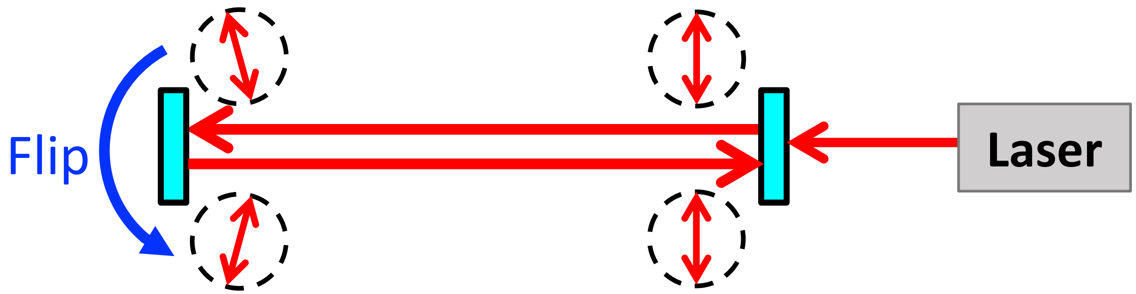
Use an optical cavity to enhance the light path



Principle of DANCE

- Linear cavity

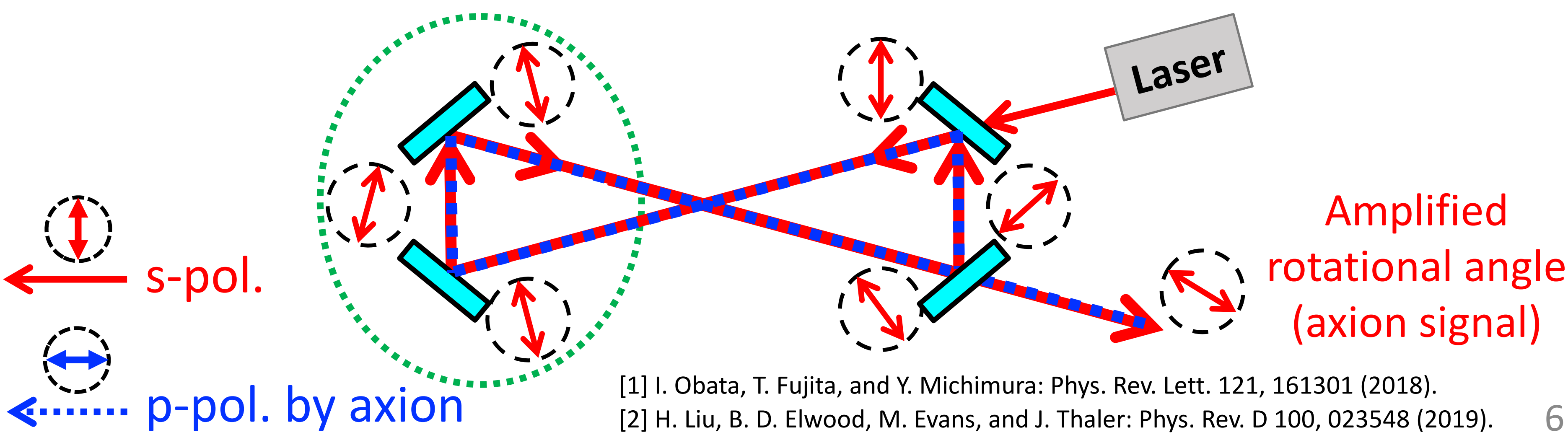
Polarization plane flips by reflection ⇒ cancels rotation in a round trip



- Bow-tie ring cavity [1,2]

Two reflections prevent polarization flip ⇒ enhances rotational angle

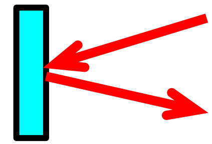
Both s-pol. and p-pol. need to be resonant



[1] I. Obata, T. Fujita, and Y. Michimura: Phys. Rev. Lett. 121, 161301 (2018).
[2] H. Liu, B. D. Elwood, M. Evans, and J. Thaler: Phys. Rev. D 100, 023548 (2019).

Issue –Resonant frequency difference–

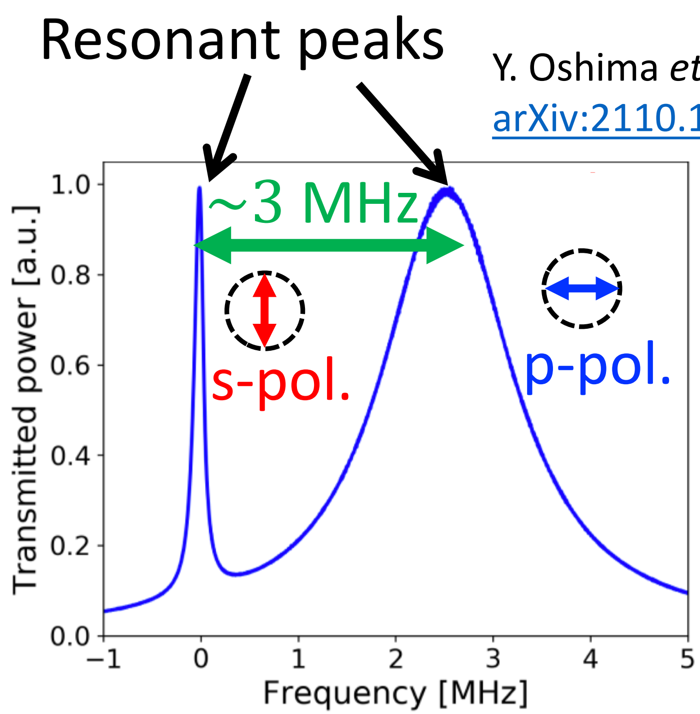
- There is resonant frequency difference between s-pol. and p-pol. (~3 MHz in DANCE Act-1)



by phase shift $\Delta\phi$ on cavity mirrors

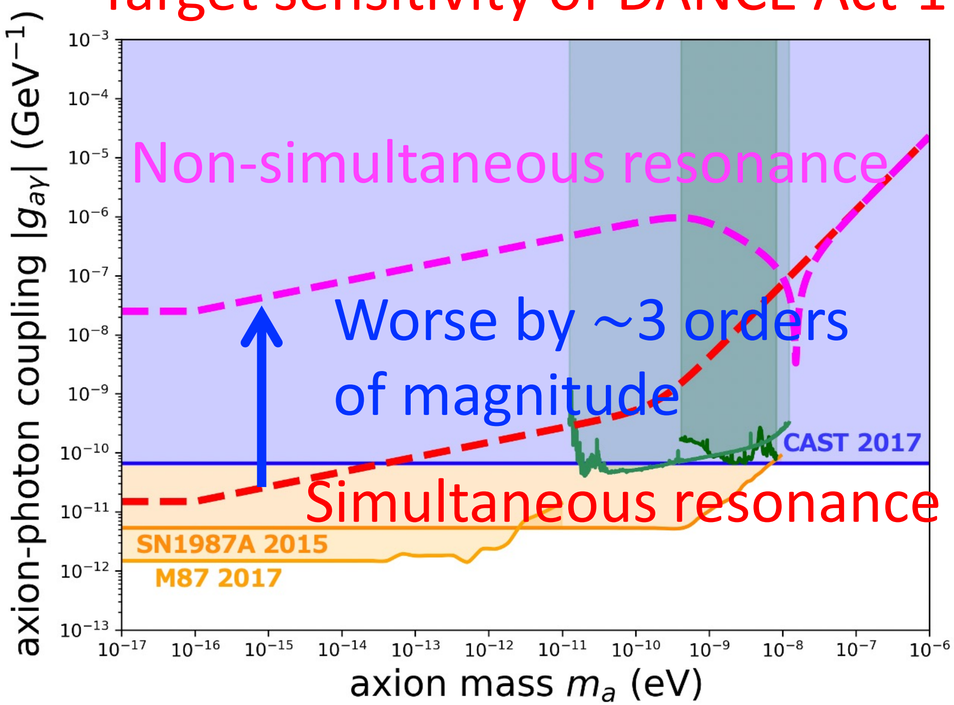
➢ s-pol. and p-pol. can not resonate simultaneously

➢ Sensitivity is degraded



Y. Oshima *et al.*: arXiv:2110.10607

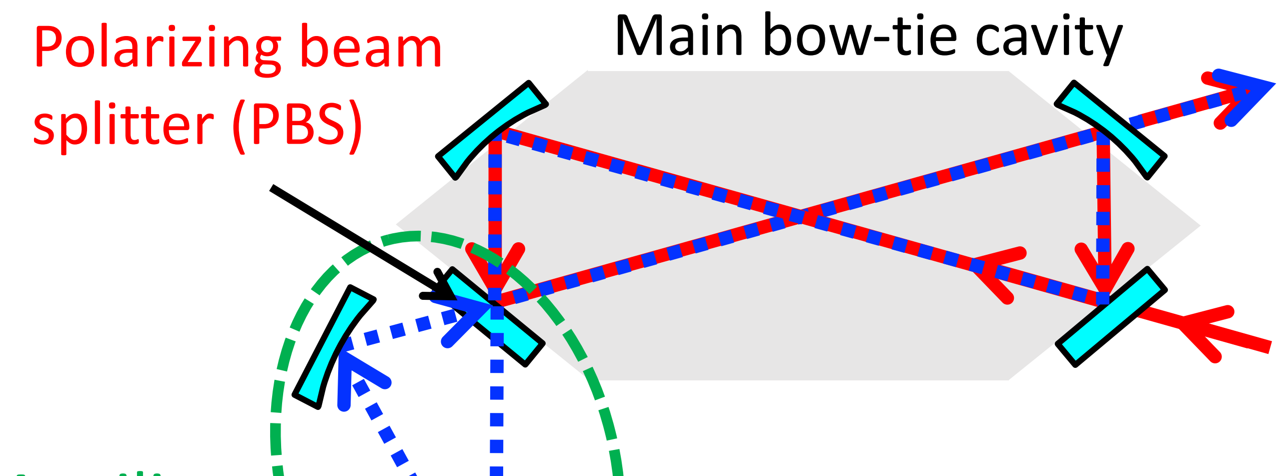
Target sensitivity of DANCE Act-1

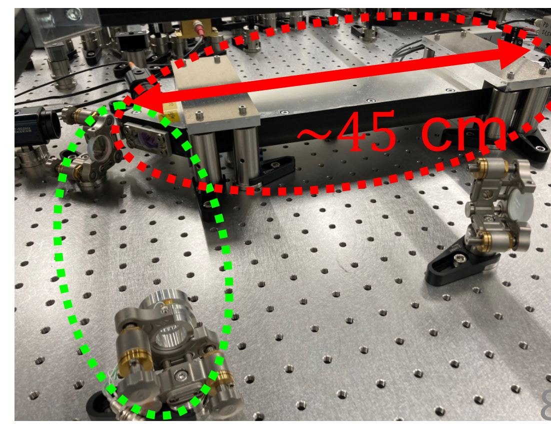


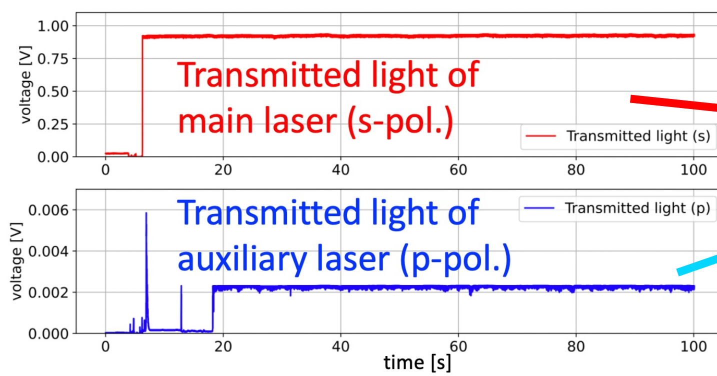
Auxiliary cavity for simultaneous resonance

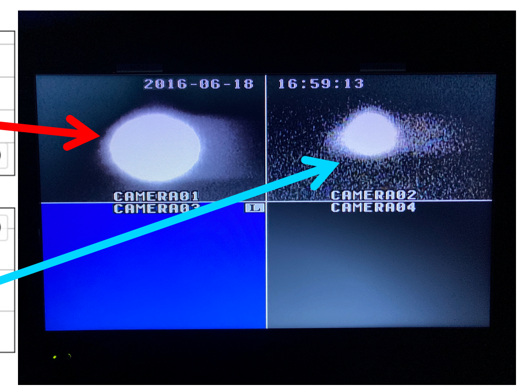
- Auxiliary cavity can control the length of light path for p-pol.

➡ able to compensate resonant frequency difference and realize simultaneous resonance









D. Martynov and H. Miao: PRD **101**, 095034 (2020). H. Fujimoto *et al.*: arXiv:2110.12023.

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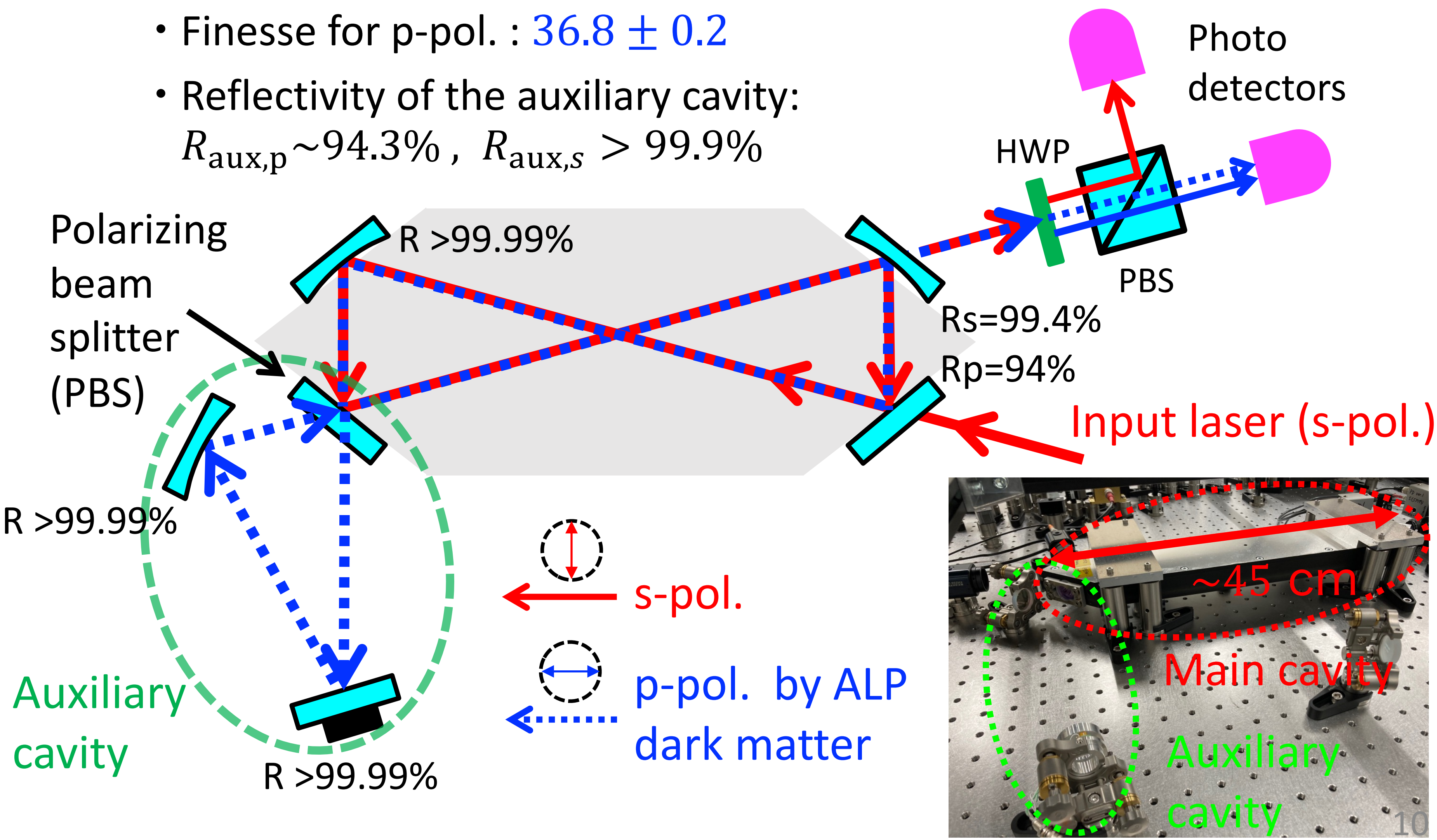
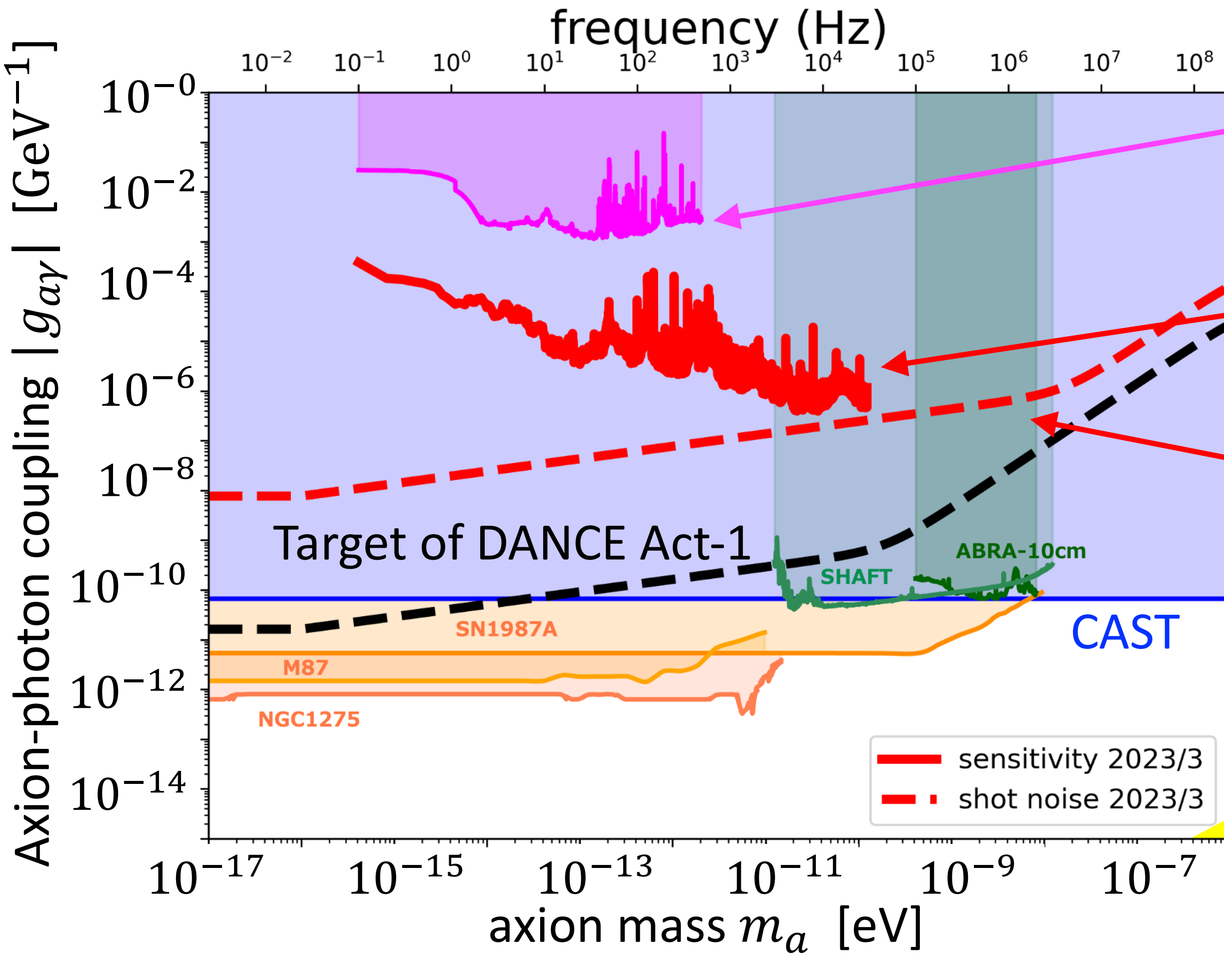
Performance of optical cavities

- Input power: $\sim$20 mW
- Finesse for s-pol. : 549 ± 3
- Finesse for p-pol. : 36.8 ± 0.2
- Reflectivity of the auxiliary cavity:
  $R_{\mathrm{aux,p}} \sim 94.3\%$, $R_{\mathrm{aux},s} > 99.9\%$



Estimated sensitivity



*With one-year observation

- $>$ 2 orders of magnitude better than the first result of DANCE Act-1
- $1-4$ orders of magnitude worse than shot noise limit
- $\sim$4 orders of magnitude worse than CAST limit

What to do for Ph.D.?

- Can I set upper bound better than CAST limit?

⇒ Extremely difficult due the issue of the auxiliary cavity…
Even for improved shot noise.

Goal: Finish DANCE Act-1 with an auxiliary cavity toward DANCE Act-2

- Identify technical noises that appear in interferometric axion search
- Maximize the sensitivity: ← Main content of this talk
  - Vacuum
  - Vibration isolation
  - High power laser
  - Optimized cavity mirrors
  - Optimized feedback control
- Long-term observation and Data analysis
- Accumulate knowledge for next DANCE Act-2 (with wavelength tunable laser?)

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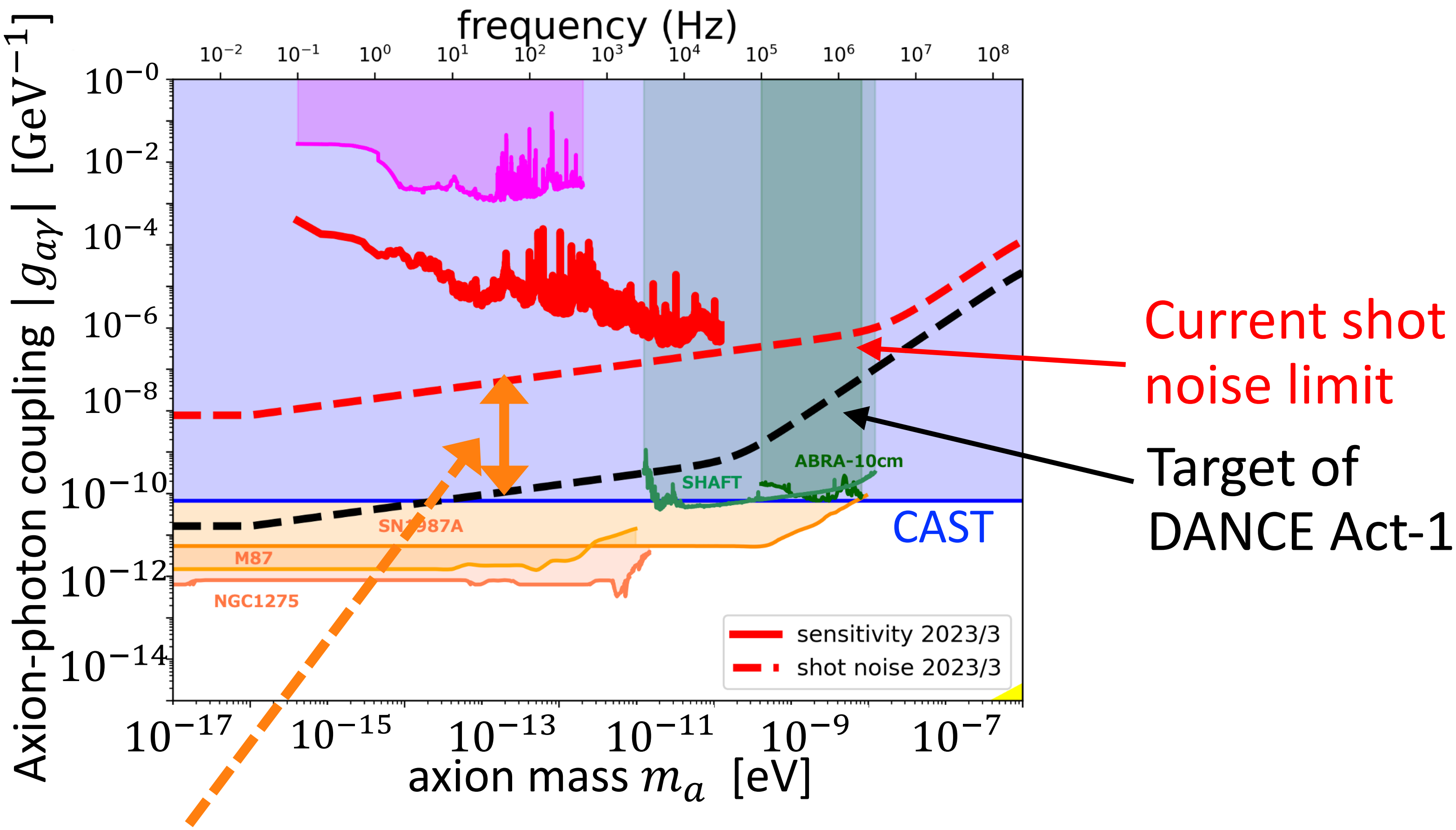
Improvement of shot noise limit



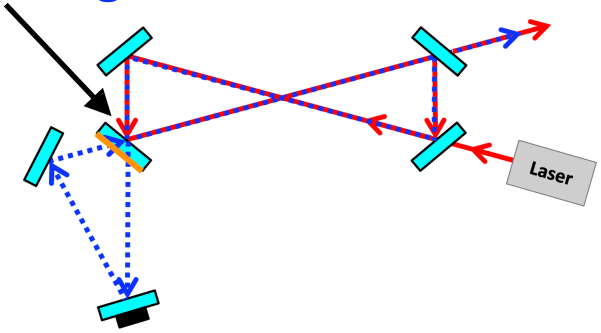
➢Current shot noise is ~3 orders of magnitude larger than target sensitivity

- Low finesses: $\mathcal{F}_s \sim 550, \mathcal{F}_p \sim 37$ and signal loss by non-criticality ⇒ ~2 orders
- Limited input power : $P_{\rm in} \sim 20$ mW ⇒ ~1 order

Improvement of shot noise limit

	$\mathcal{F}_S$	$\mathcal{F}_P$
Target value	3000	3000
Measured value	549 ± 3	36.8 ± 0.2

- s-pol.: Due to low R at input/output mirrors: $R_\mathrm{s} = 99.4\%$ (Target: 99.9%)
- p-pol.: Due to low R at input/output mirrors: $R_\mathrm{p} = 94\%$ (Target: 99.9%)
  and loss at aux. cavity: $R_\mathrm{aux,p} = 94\%$ (Target: >99.99%)
  Limited by $R_\mathrm{PBS,p}$ and AR coating of PBS



➢ We need high performance PBS
- $R_\mathrm{s} > 99.9\%$
- $R_\mathrm{p} < 0.1\%$
- R of AR coating $< 0.1\%$

Impossible to make (Wavelength tuning method for simultaneous resonance can avoid this issue)

➢ Toward my Ph.D. thesis, I stopped seeking for better PBS, but optimize the R of input/output mirrors for a little improvement

Improvement of shot noise limit

R of input/output mirrors:

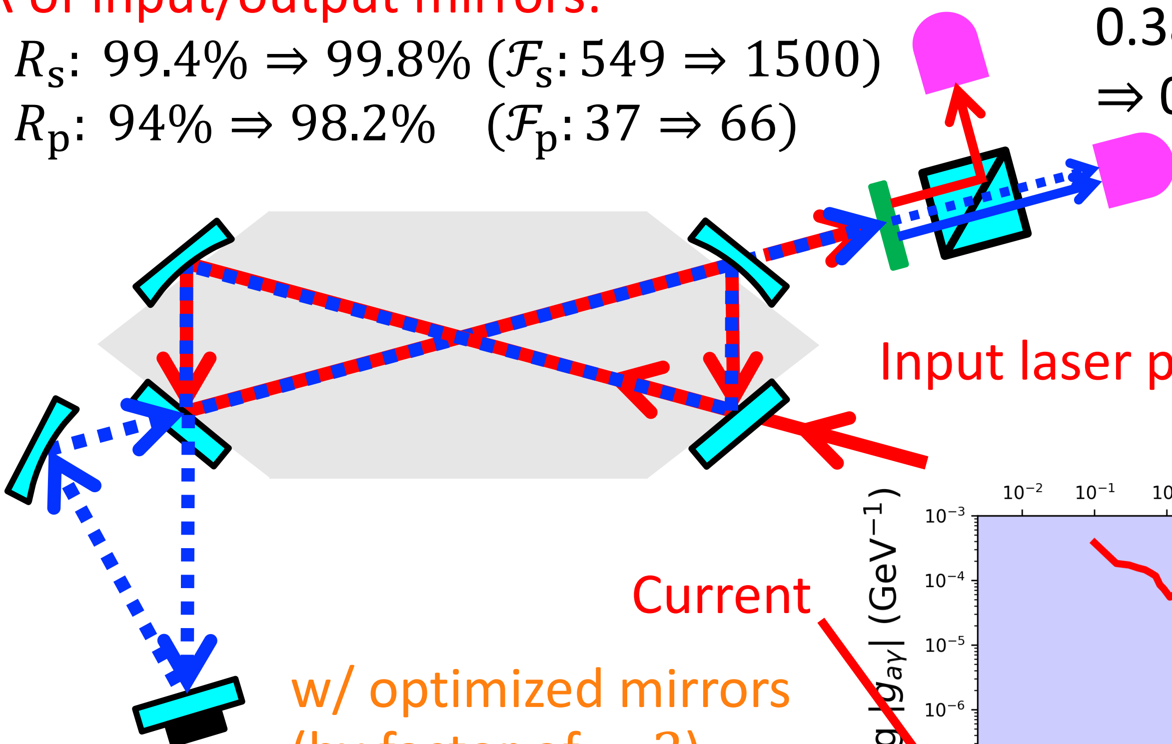
R_s: 99.4% ⇒ 99.8% ($\mathcal{F}_s$: 549 ⇒ 1500)

R_p: 94% ⇒ 98.2% ($\mathcal{F}_p$: 37 ⇒ 66)

PD quantum efficiency:

0.38 A/W (Si, S3759)

⇒ 0.73 A/W (InGaAs, G10899)

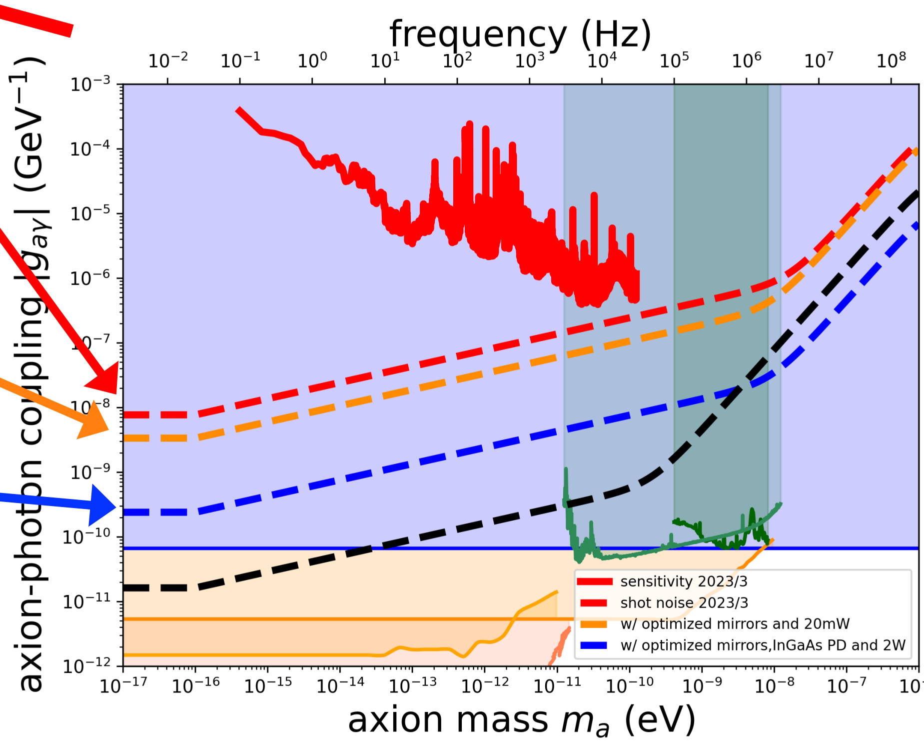


Input laser power: 20 mW ⇒ 2 W

Current

w/ optimized mirrors
(by factor of ~ 2)

w/ optimized mirrors,
InGaAs PD and 2 W input
(by factor of ~ 30)



- Close to CAST limit by factor of ~ 3

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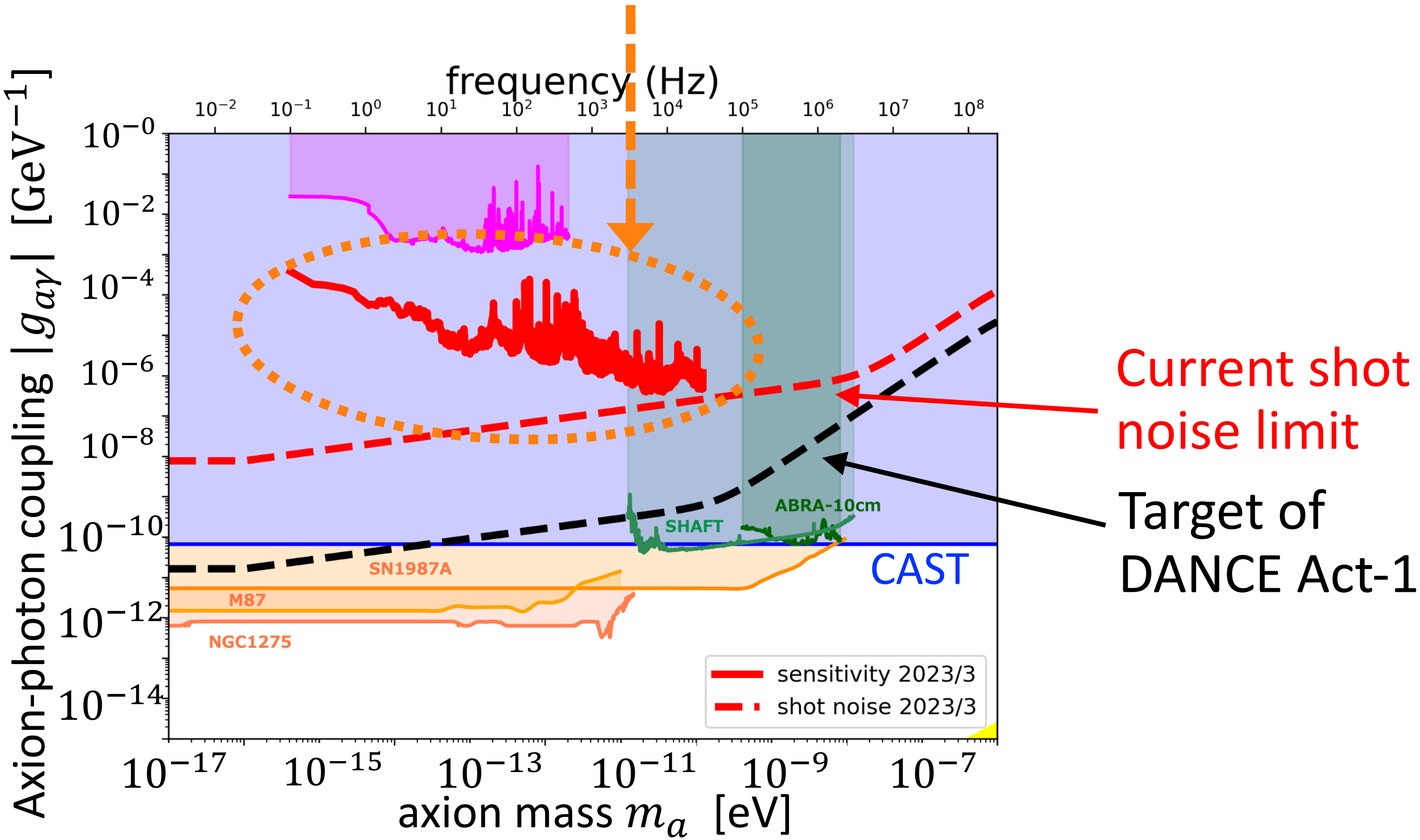
Reduction of noises

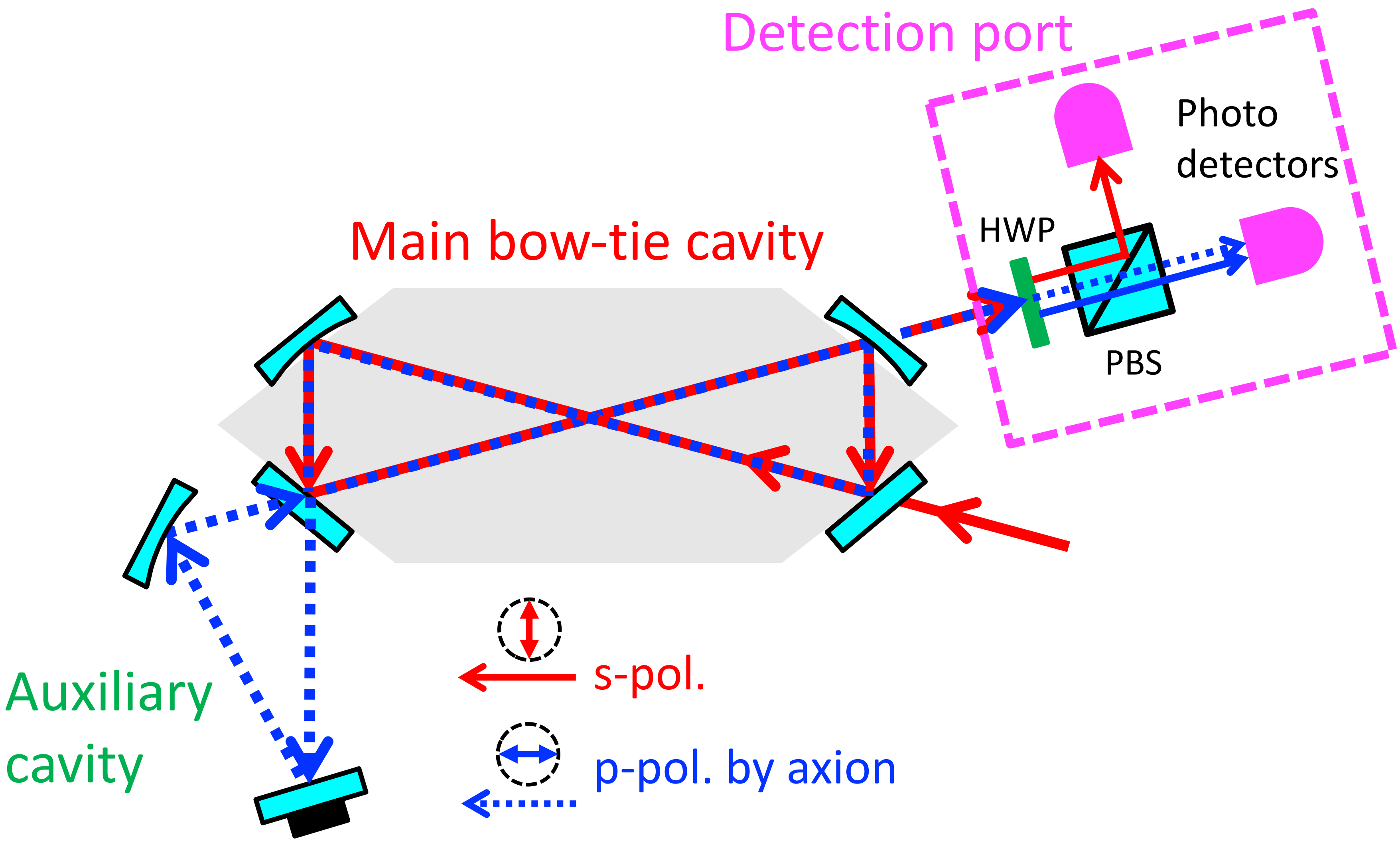
- Current sensitivity is 1-4 orders of magnitude worse than shot noise



➤ We need further reduction of technical noises

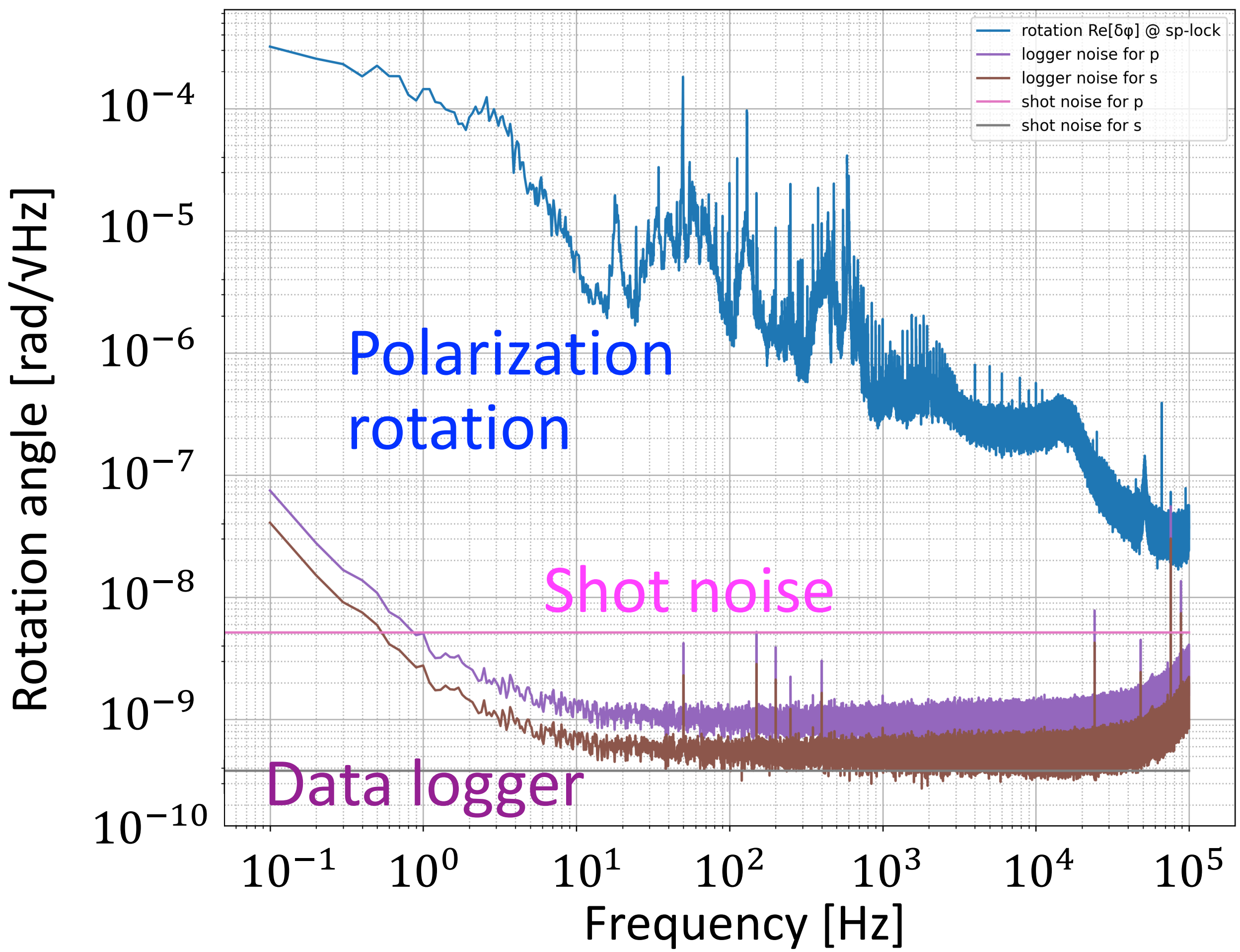
Measurement of polarization rotation

- Axion signal: rotational oscillation of polarization plane (p-pol.)
- Can be measured with HWP, PBS and PDs



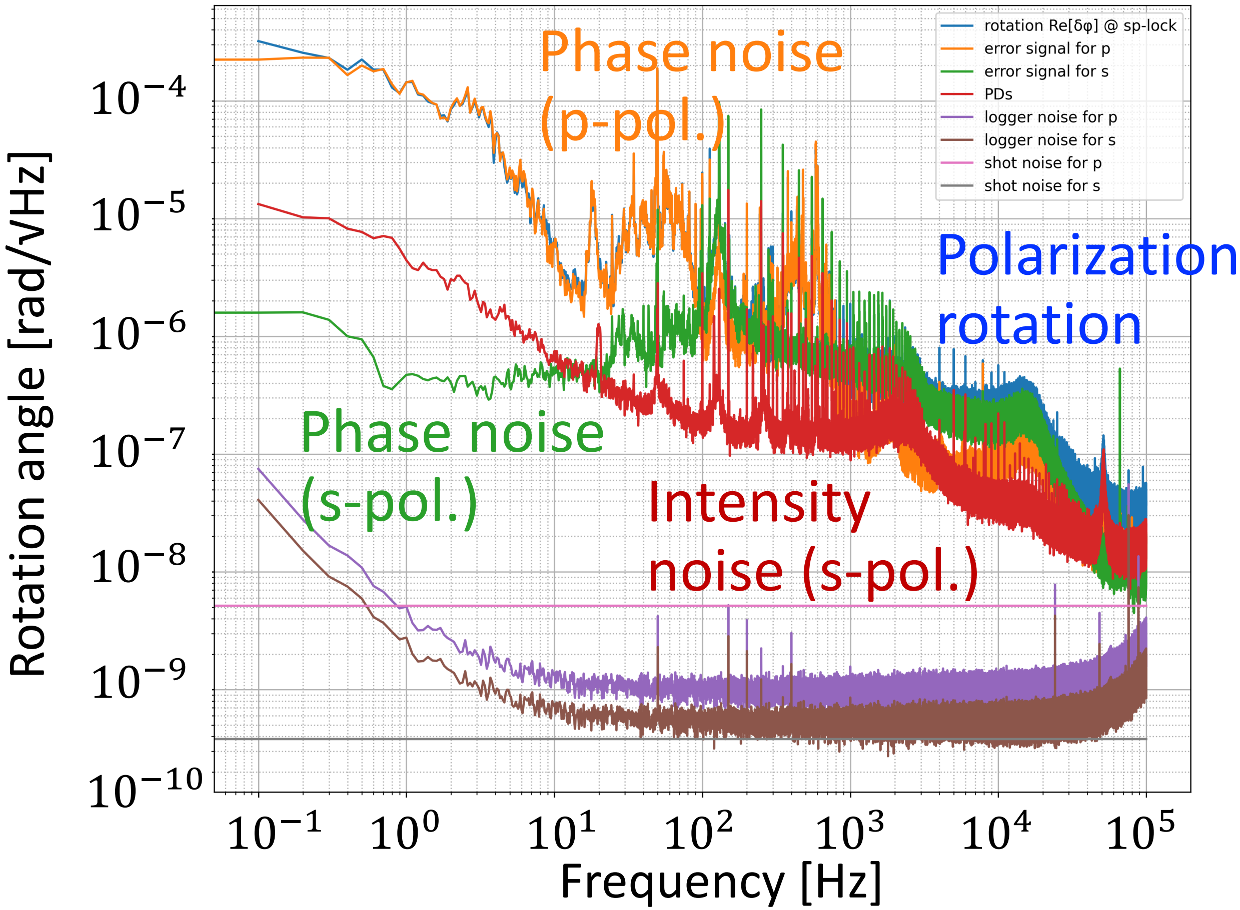
Raw power spectrum of polarization rotation

- Measured the rotational angle of the transmitted light



- Measured noise is larger than shot noise by 1~4 orders of magnitude

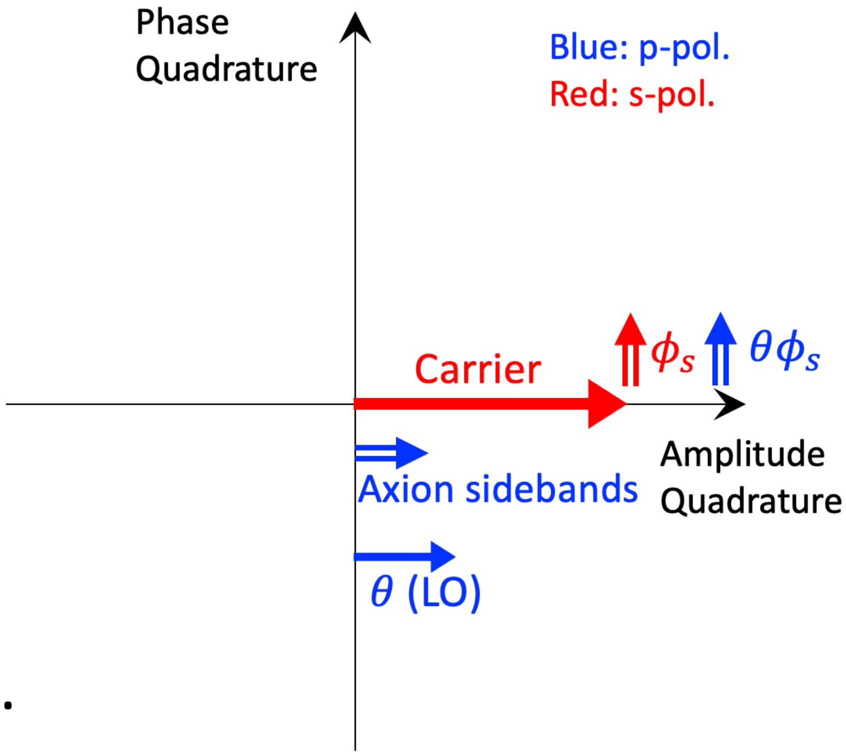
Noise hunting



- Phase noise (cavity vibration, laser frequency noise) is limiting
- In principle, phase noise is negligible in DANCE…
- Phase noise couples to the p-pol. generated by birefringence of cavity mirrors or polarization mismatch at injection port

Phasor diagram of DANCE

- θ: HWP coupling for LO generation
- ϕ_p: phase noise of p-pol.
- ϕ_s: phase noise of s-pol.



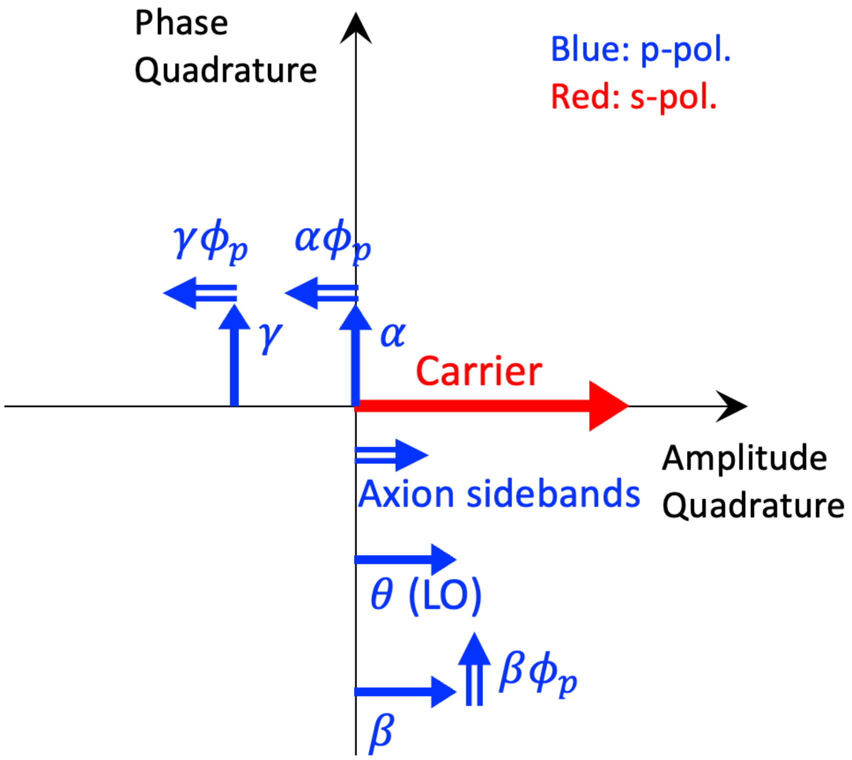
- PD measures the power of p-pol.

➡ PD output at detection ∝ $\theta\times$(Axion sidebands)

- Axion signal appears in amplitude quadrature
- Phase noises (cavity vibration, laser frequency noise, thermal noise) are negligible in DANCE principally

Cross-coupling of p-pol. phase noise

- α: birefringence coupling in cavity
- β: unwanted amplitude-p-pol. (polarization mismatch at injection)
- γ: unwanted phase-p-pol. (polarization mismatch at injection)
- θ: HWP coupling for LO generation
- ϕ_p: phase noise of p-pol.

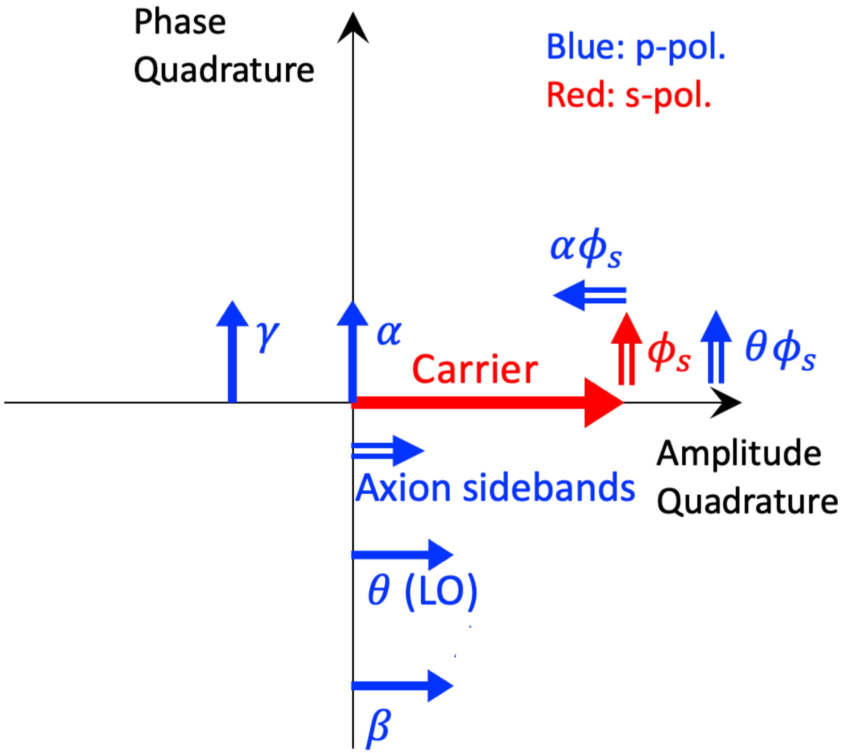


PD output at detection $\propto -\theta(\alpha+\gamma)\phi_p$

Coherence with phase noise of p-pol.

Cross-coupling of s-pol. phase noise

- α: birefringence coupling in cavity
- β: unwanted amplitude-p-pol. (polarization mismatch at injection)
- γ: unwanted phase-p-pol. (polarization mismatch at injection)
- θ: HWP coupling for LO generation
- ϕ_s: phase noise of s-pol.



PD output at detection $\propto (-\beta\alpha + \gamma\theta)\phi_s$

Coherence with phase noise of s-pol.

How to reduce the current noises

- 3 plans to reduce the current noises:
  - ① Reduce the coupling coefficient
    - Additional injection of p-pol. to cancel the cavity birefringence (no so effective?)
  - ② Reduce the cavity vibration and air turbulence
    - Stack isolation system
    - Vacuum chamber
  - ③ Suppress the phase noises by feedback control
    - 4-mirror auxiliary cavity to deal with the parasitic resonance

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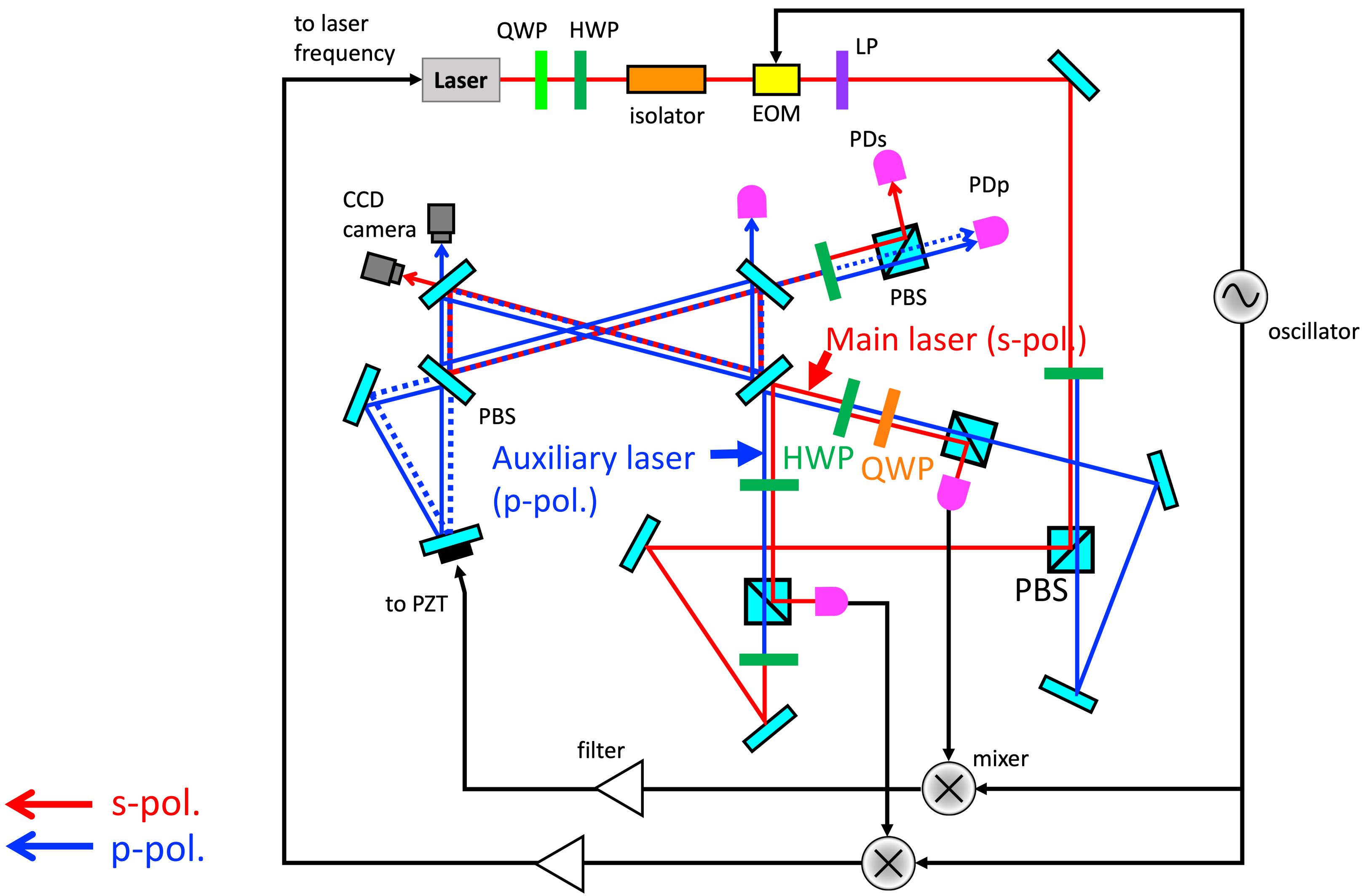
① Reduction of coupling coefficient

- To cancel the cavity birefringence, inject additional p-pol.
- Adjust the HWP and the QWP at the injection port



① Reduction of coupling coefficient

- Inject p-pol. so that cavity birefringence can be cancelled $(\gamma = -\alpha)$

➡ PD output at detection ∝ $-\theta(\alpha+\gamma)\phi_p = 0\times\phi_p$

- However, for dependency of ϕ_s,

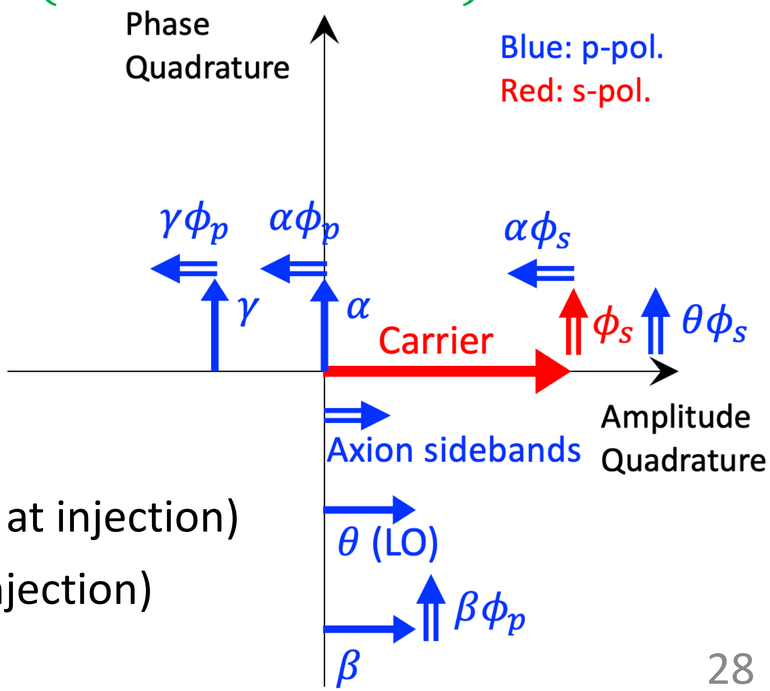
PD output at detection ∝ $(-\beta\alpha+\gamma\theta)\phi_s = -\alpha(\theta+\beta)\,\phi_s$

- For axion signal,

PD output at detection ∝ $(\theta+\beta)\times(\text{axion sidebands})$

- Ratio of coefficients:

$$\text{Axion} : \phi_s : \phi_p = 1 : \alpha : 0$$



- ϕ_p: phase noise of p-pol.
- ϕ_s: phase noise of s-pol.
- α: birefringence coupling in cavity
- β: unwanted amplitude-p-pol. (polarization mismatch at injection)
- γ: unwanted phase-p-pol. (polarization mismatch at injection)
- θ: HWP coupling for LO generation

① Reduction of coupling coefficient

- Inject p-pol. so that ϕ_s can be cancelled $(\gamma = \alpha\beta/\theta)$

➡ PD output at detection $\propto (-\beta\alpha + \gamma\theta)\phi_s = 0 \times \phi_s$

- However, for dependency of ϕ_p,

  PD output at detection $\propto -\theta(\alpha + \gamma)\phi_p = -\alpha(\theta + \beta)\phi_p$

- For axion signal,

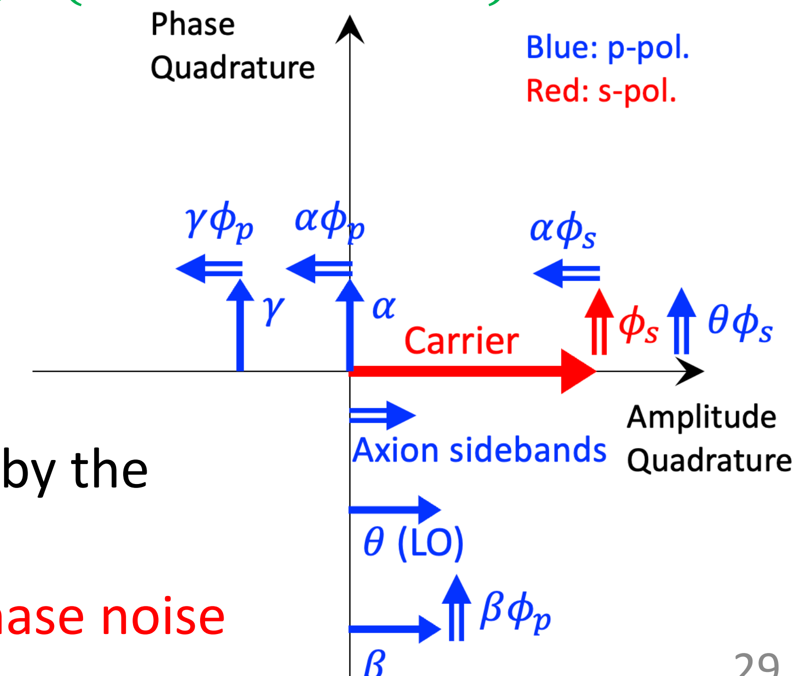
  PD output at detection $\propto (\theta + \beta) \times (\text{axion sidebands})$

- Ratio of coefficients:

$$\text{Axion} : \phi_s : \phi_p = 1 : 0 : \alpha$$

- In the case of $(\gamma = -\alpha)$ (previous slide) :

$$\text{Axion} : \phi_s : \phi_p = 1 : \alpha : 0$$



➢ We can't cancel the effect of birefringence by the injection method

➢ We can switch the dependency to lower phase noise

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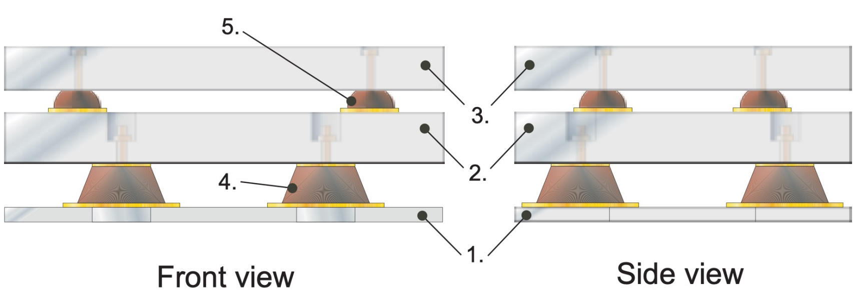
② Reduce cavity vibration and air turbulence

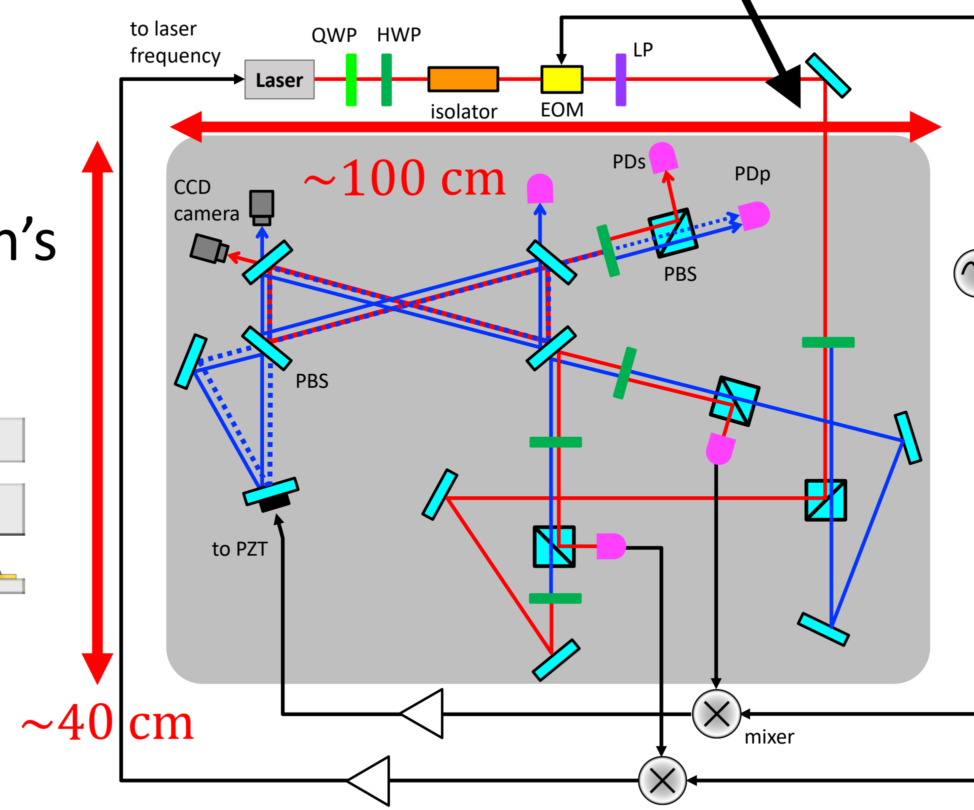
To reduce the cavity vibration and air turbulence, install followings:

- Vacuum chamber
  - 40 cm × 100 cm, rectangular shape like Michimura-san's chamber for B-L DM
  - Going to order to Ono Denki
- Stack isolation system
  - Going to refer to Numata-san's stack isolation system

Inject laser from a view port



(from Numata-san's Ph.D. thesis)



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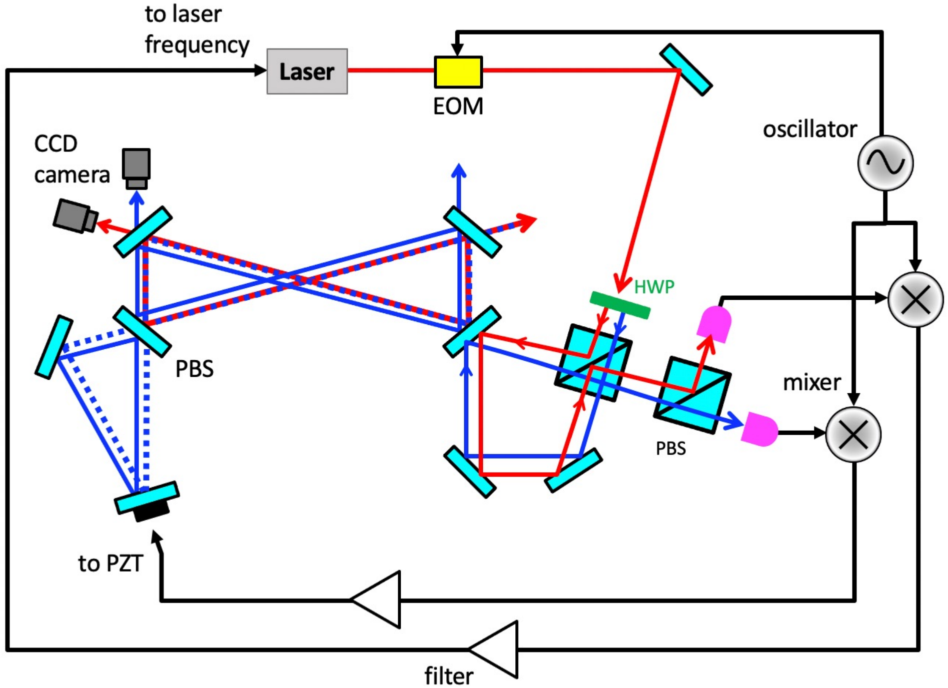
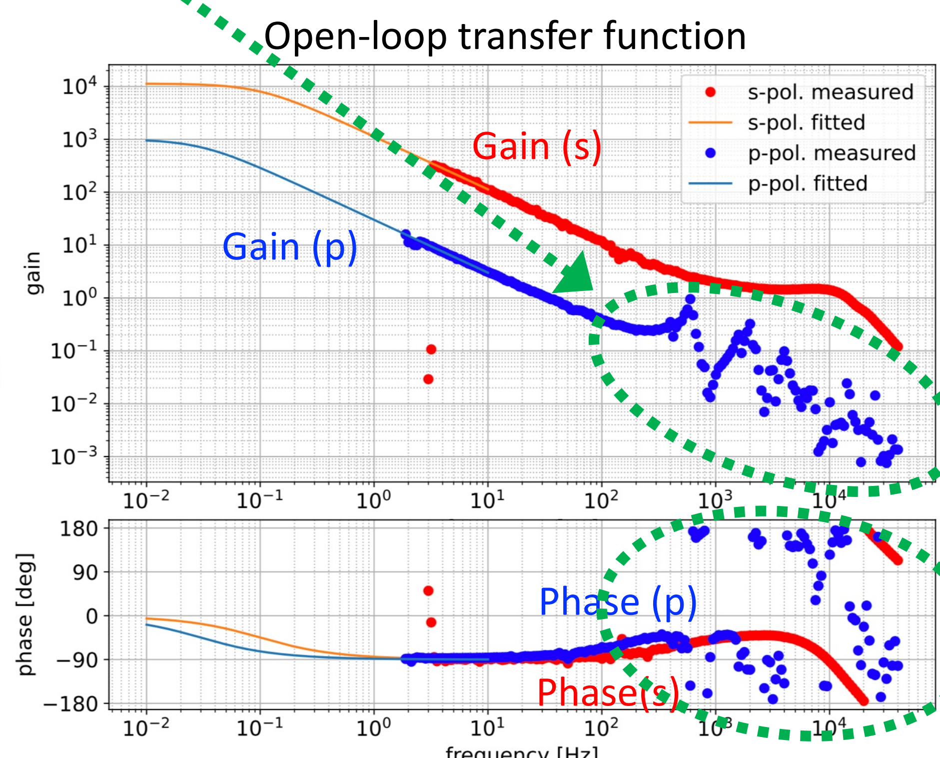
③ Suppress phase noises by feedback control

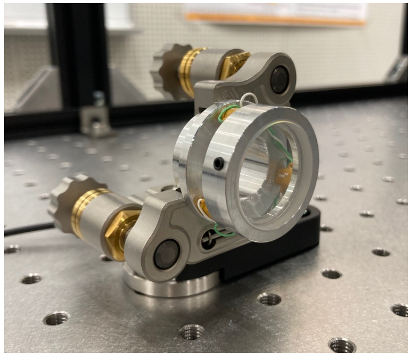
- Phase noise can be suppressed by feedback control
- Bandwidth of feedback control for p-pol. is narrow (UGF ≃ 30 Hz)
  ⇒ can not suppress vibration noise of aux. cavity
- Parasitic resonance of the actuator is limiting the bandwidth



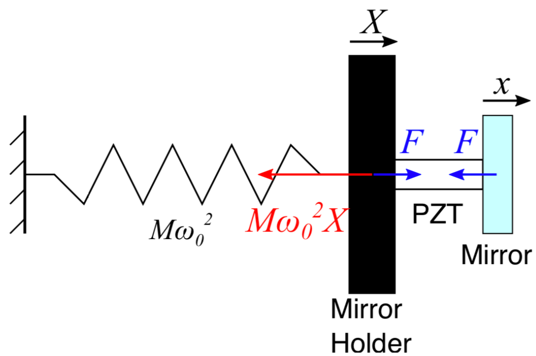


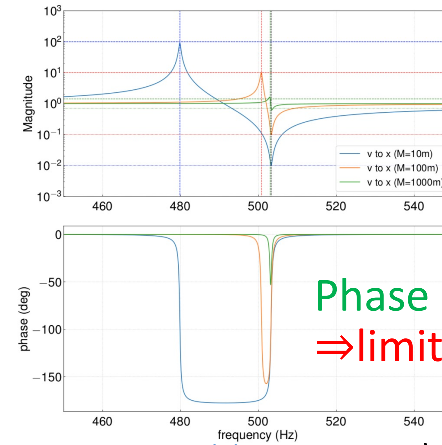
③ Suppress phase noises by feedback control

- Piezo-actuated mirror can cause parasitic resonance



Piezo-actuated mirror for p-pol. of DANCE Act-1





(cited from Takano-san's awesome note on parasitic resonance)

- 4 plans to remove parasitic resonance:
  - ➢Plan A: Piezo-actuated mirror attached on heavy rigid mass
  - ➢Plan B: Piezo-actuated mirror mounted in soft materials
    - B4 experiment in 2022 S Semester by Okuma-kun and Sugawara-kun
    - Great improvement but for the drift by temperature
  - ➢Plan C: Inverse transfer function implemented by digital filter
  - ➢Plan D: Robust control (Modern control)

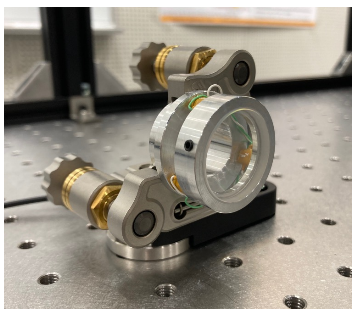
Introduced in the Midterm report 2022

③ Suppress phase noises by feedback control

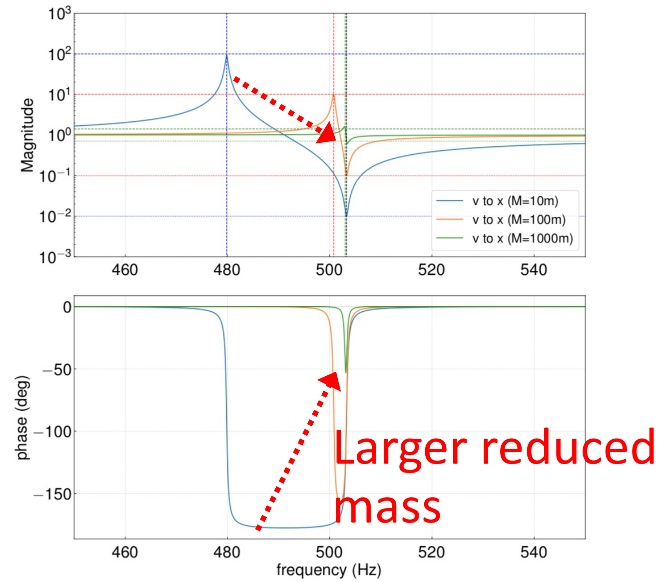
➢Plan A: Piezo-actuated mirror attached on heavy rigid mass

- Larger reduced mass (換算質量) of the holder
  ⇒ Smaller peak, dip and phase delay

Use heavy rigid mass as a holder



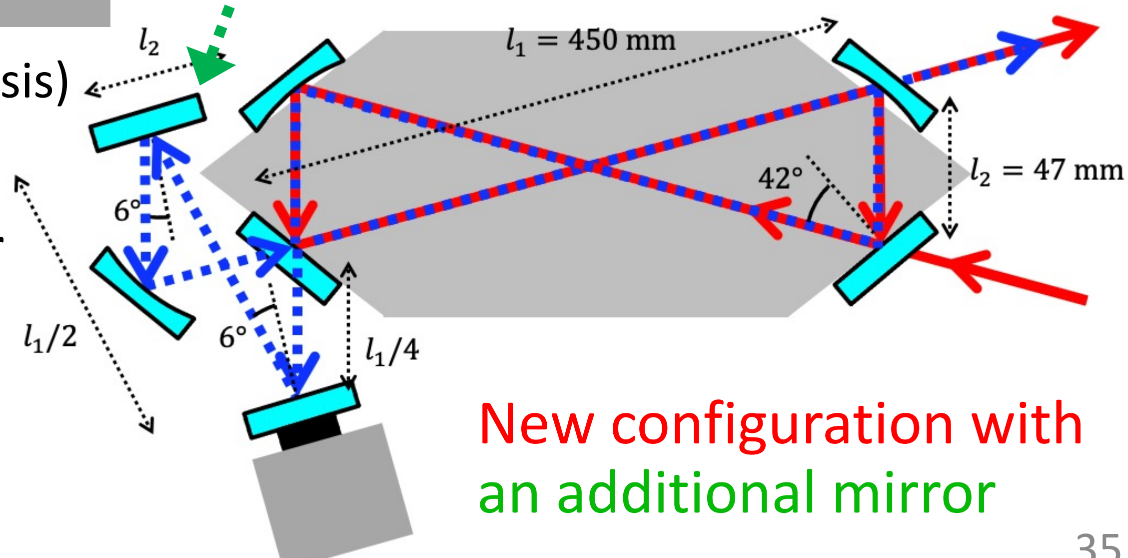
(Used in Ohmae-san's doctoral thesis)



Additional mirror

- We can't align piezo-mirror on a mass

Need an additional mirror for alignment

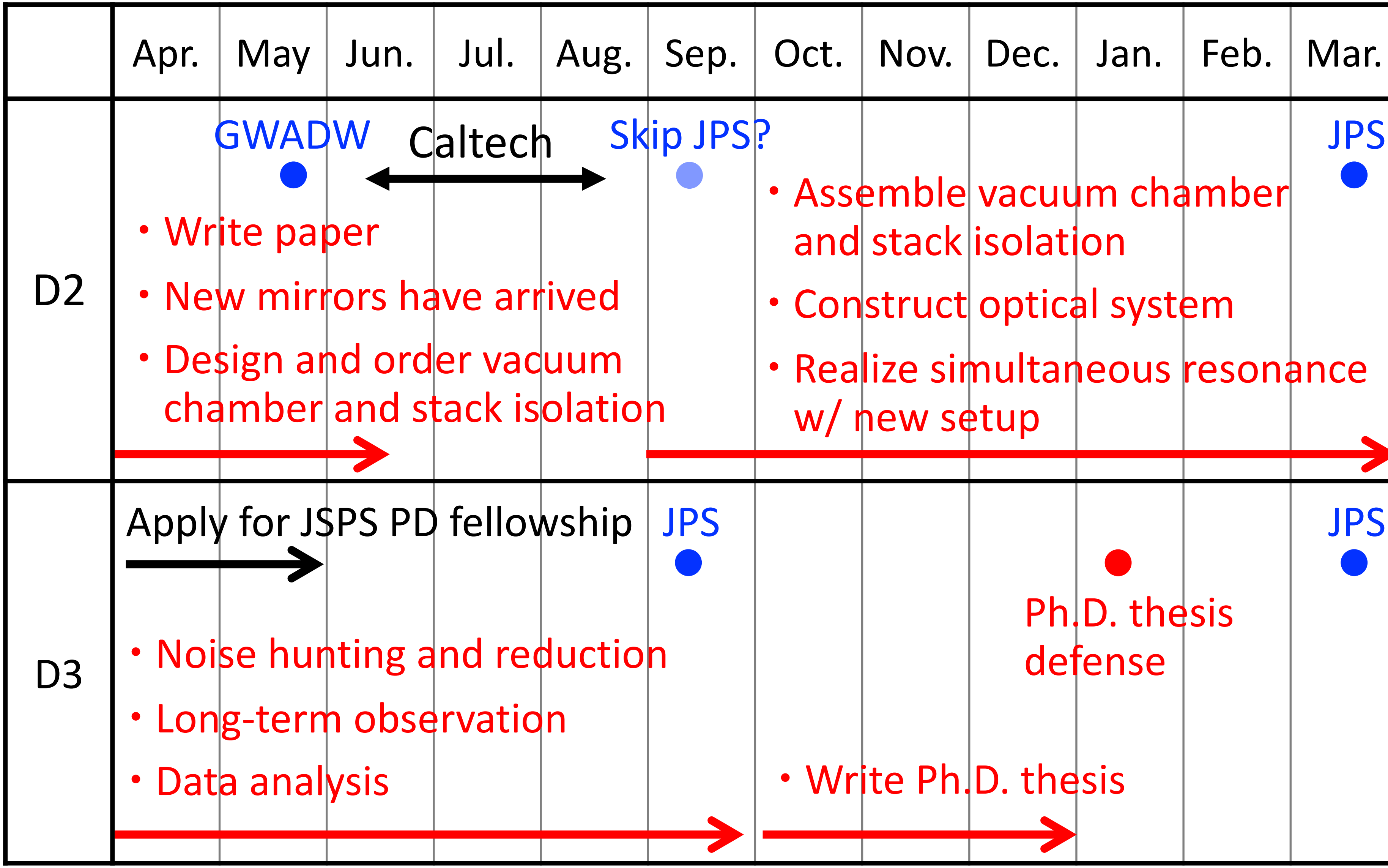


New configuration with an additional mirror

Contents

- Review of DANCE Act-1
- Current status of DANCE Act-1 / What to do for Ph.D.?
- Future plans
  - Improvement of shot noise limit
  - Reduction of noises
    1. Reduce coupling coefficient
       - Additional injection of p-pol. for cancelling birefringence
    2. Reduce cavity vibration and air turbulence
       - Stack isolation system
       - Vacuum chamber
    3. Suppress phase noises by feedback control
       - 4-mirror auxiliary cavity to reduce parasitic resonance
- Rough schedule for Ph.D. / Summary

Rough schedule toward Ph.D.



Summary

- Future plans of DANCE Act-1 toward Ph.D.
  - Improvement of shot noise limit
  - Reduction of noises
    - ① Reduce coupling coefficient
      - Additional injection of p-pol. for cancelling birefringence
    - ② Reduce cavity vibration and air turbulence
      - Stack isolation system
      - Vacuum chamber
    - ③ Suppress phase noises by feedback control
      - 4-mirror auxiliary cavity to reduce parasitic resonance
- Schedule for the next two years