Recent Upgrades of Optical System and Data Analysis in DANCE

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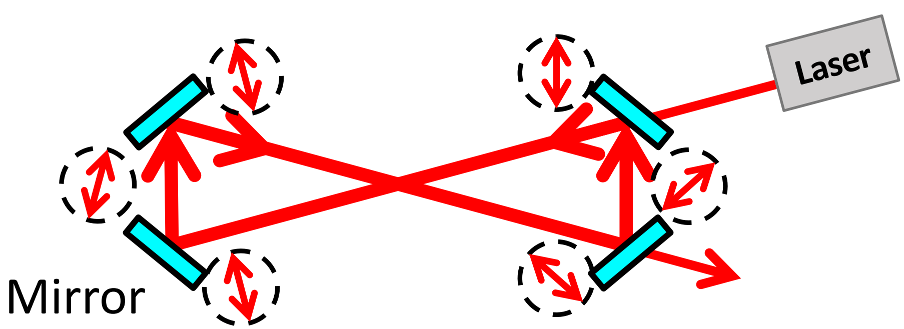
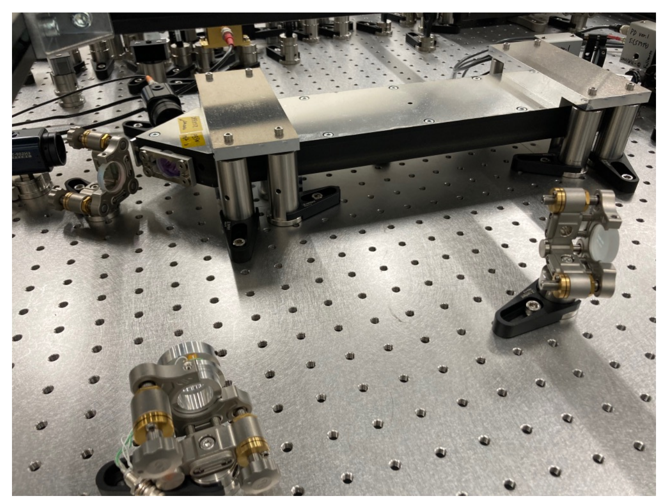
Overview

- DANCE: Dark matter Axion search with riNg Cavity Experiment
  - ➢Search for axion dark matter with optical bow-tie ring cavity
  - ➢Prototype experiment: DANCE Act-1 is underway
- First results from DANCE Act-1 (Y. Oshima's talk)
- Recent upgrades of DANCE Act-1 (this talk)
  - ➢Development of auxiliary cavity for simultaneous resonance
  - ➢Noise hunting and offline noise reduction
  - ➢Latest sensitivity and Future plans





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Axion-photon interaction

Axion-photon interaction causes phase velocity difference

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

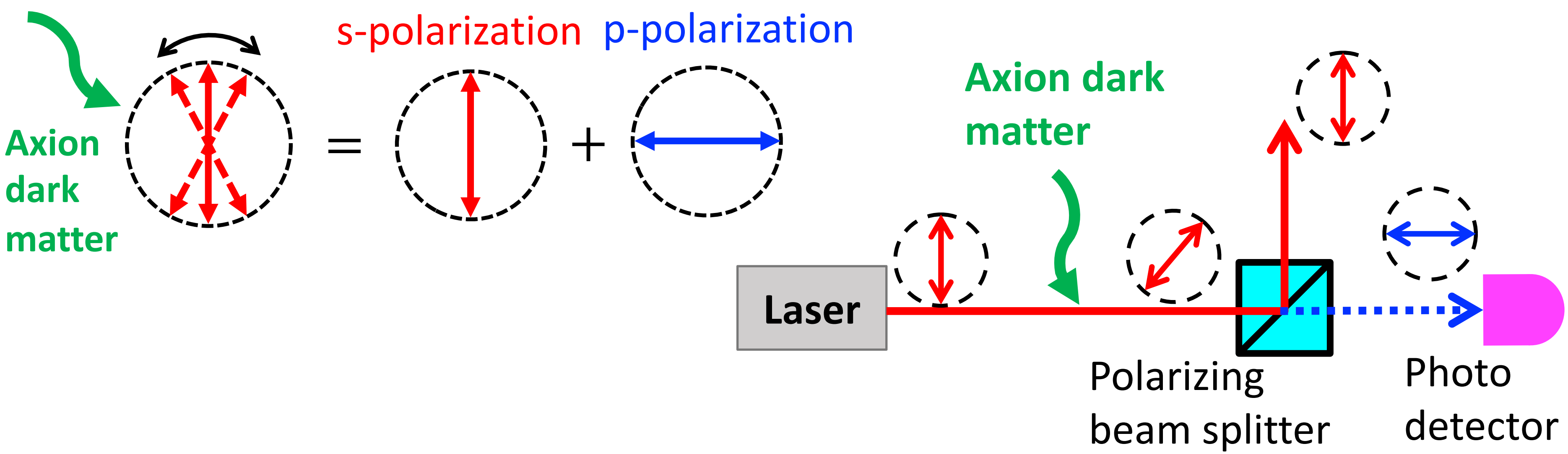
Left-/Right-handed polarization

Axion-photon coupling constant

Axion field

Axion mass

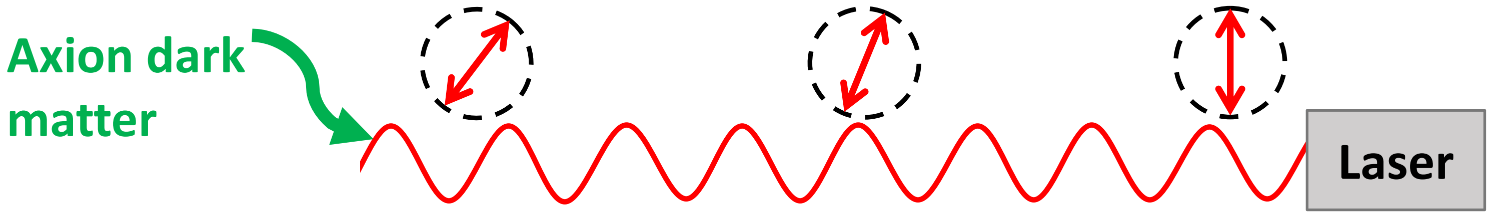
Rotational oscillation of linearly polarized light



- Axion signal is produced as p-polarization

Principle of DANCE

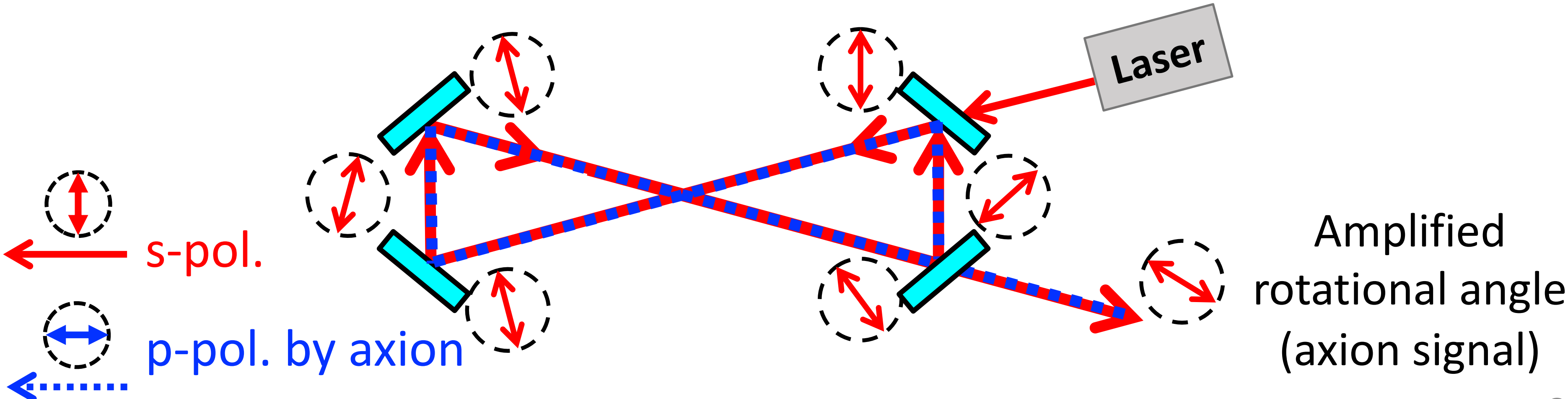
- Rotational amplitude becomes larger as light path increases



➡ Enhance light path and rotation with bow-tie ring cavity

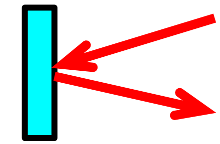
- Resonant condition: Roundtrip length $= n\lambda$
  ⇒Light circulates between 4 mirrors
- Both s-pol. and p-pol. need to be resonant

I. Obata, T. Fujita, and Y. Michimura: [PRL 121, 161301 (2018)](). H. Liu *et al.*: [PRD 100, 023548 (2019)]().



Issue –Resonant frequency difference–

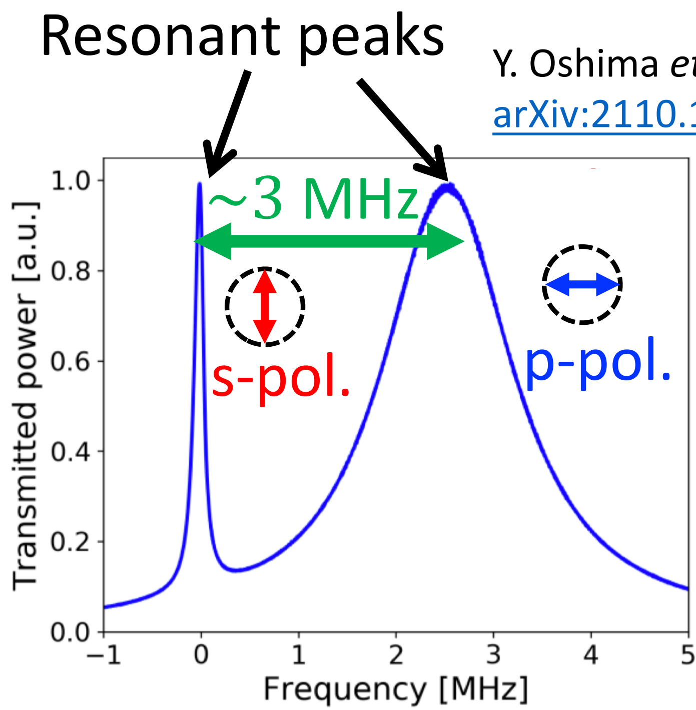
- There is resonant frequency difference between s-pol. and p-pol. (~3 MHz in DANCE Act-1)



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

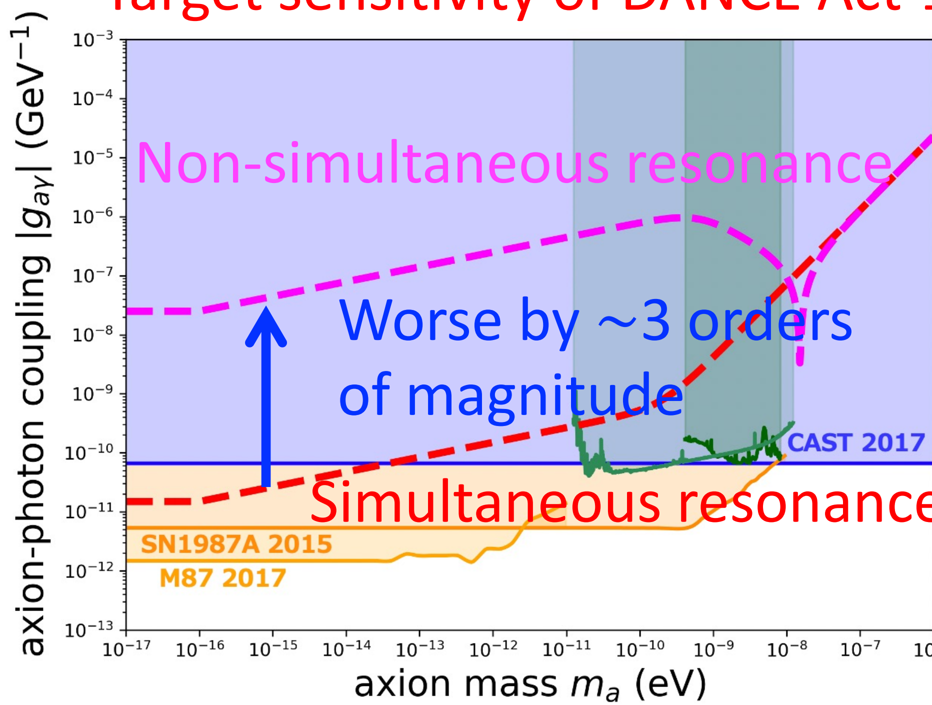
➢ s-pol. and p-pol. can not resonate simultaneously

➢ Sensitivity is degraded



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

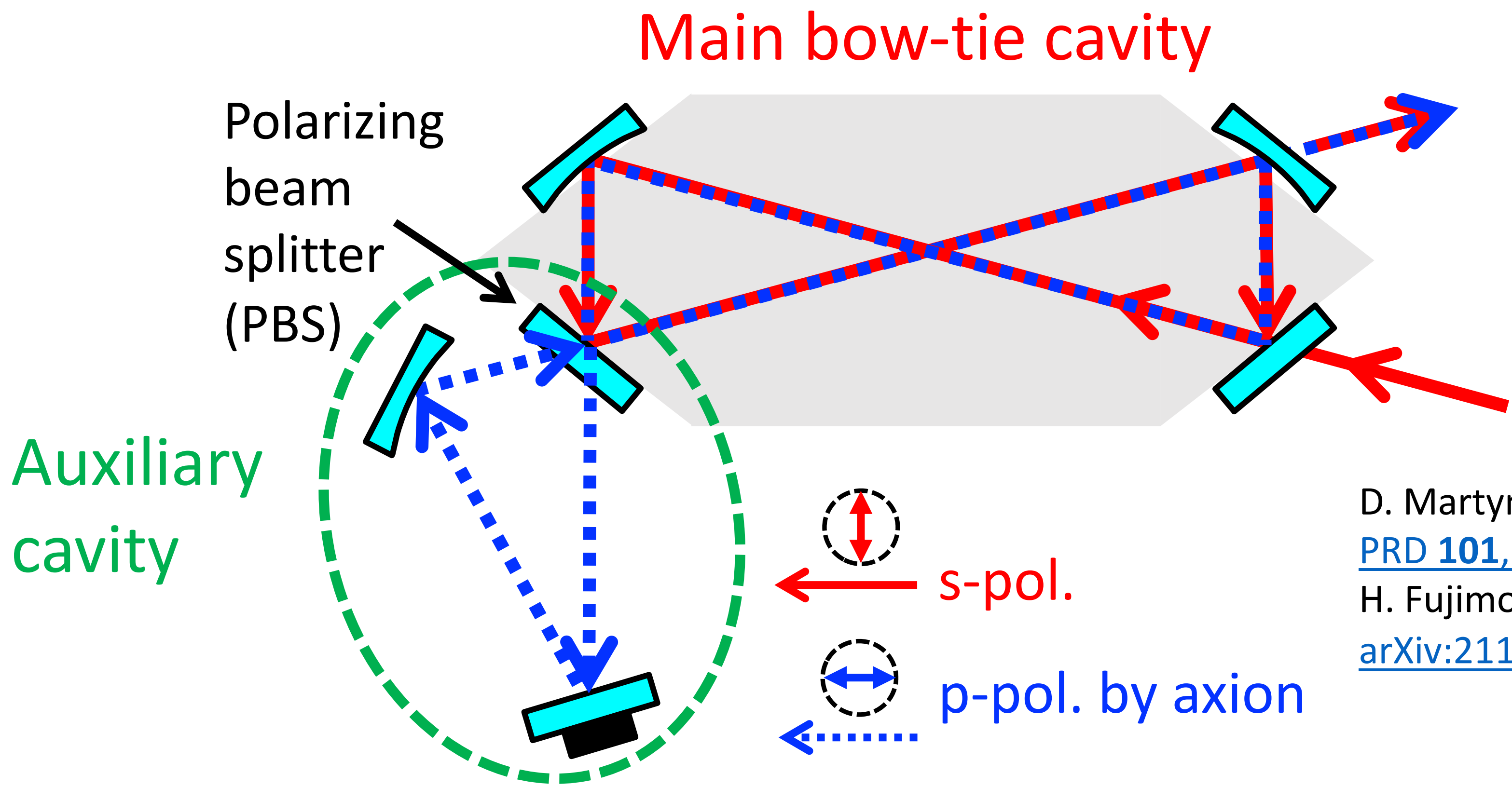
Target sensitivity of DANCE Act-1



Auxiliary cavity for simultaneous resonance

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

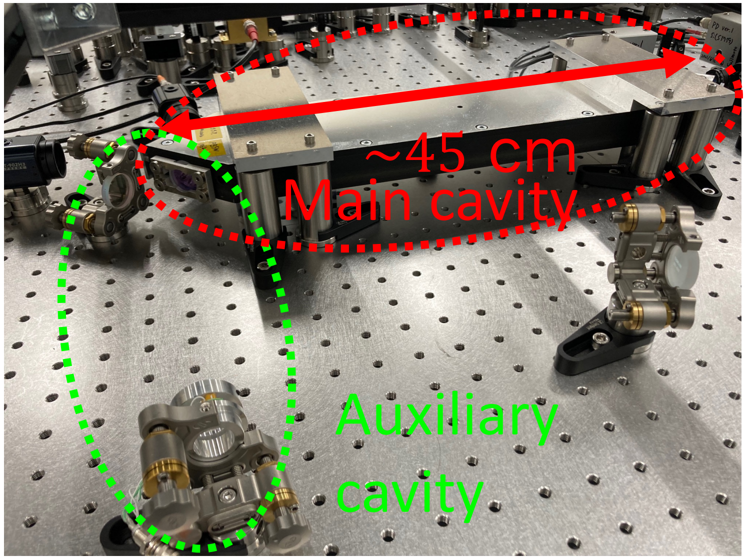
➡ able to compensate resonant frequency difference and realize simultaneous resonance

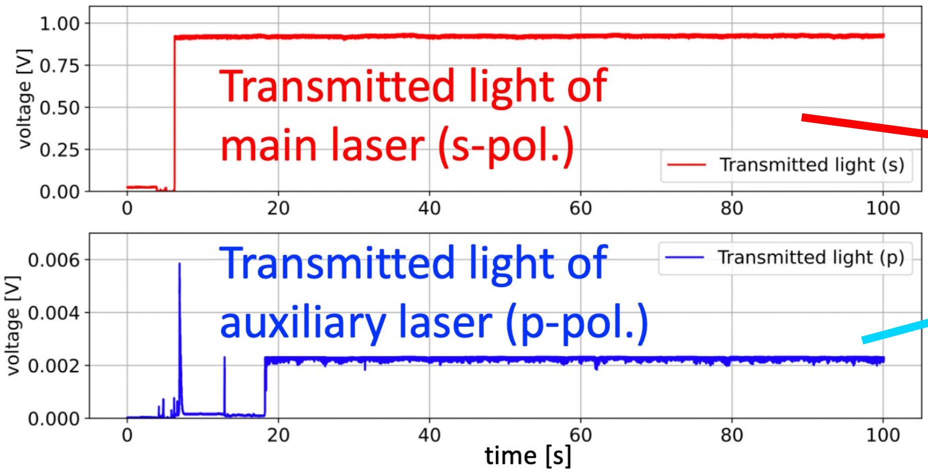


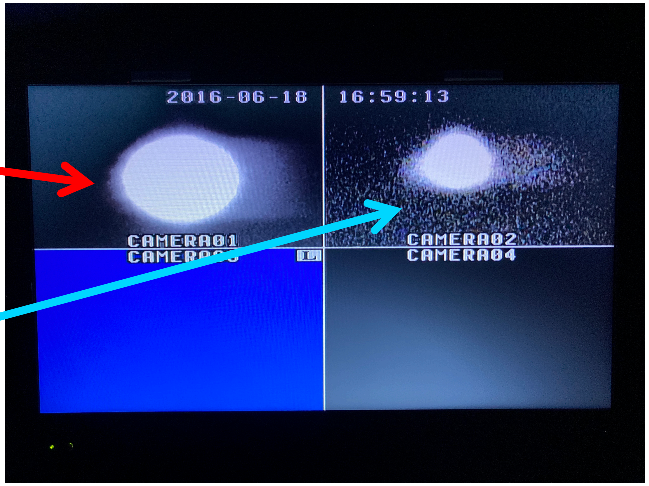
D. Martynov and H. Miao: PRD **101**, 095034 (2020).
H. Fujimoto *et al.*: arXiv:2110.12023.

Development of auxiliary cavity

- Auxiliary cavity is now installed
- Succeeded in simultaneous resonance
- Performance of the cavities:
  - Finesse for s-pol. : 549 ± 3
  - Finesse for p-pol. : 36.8 ± 0.2







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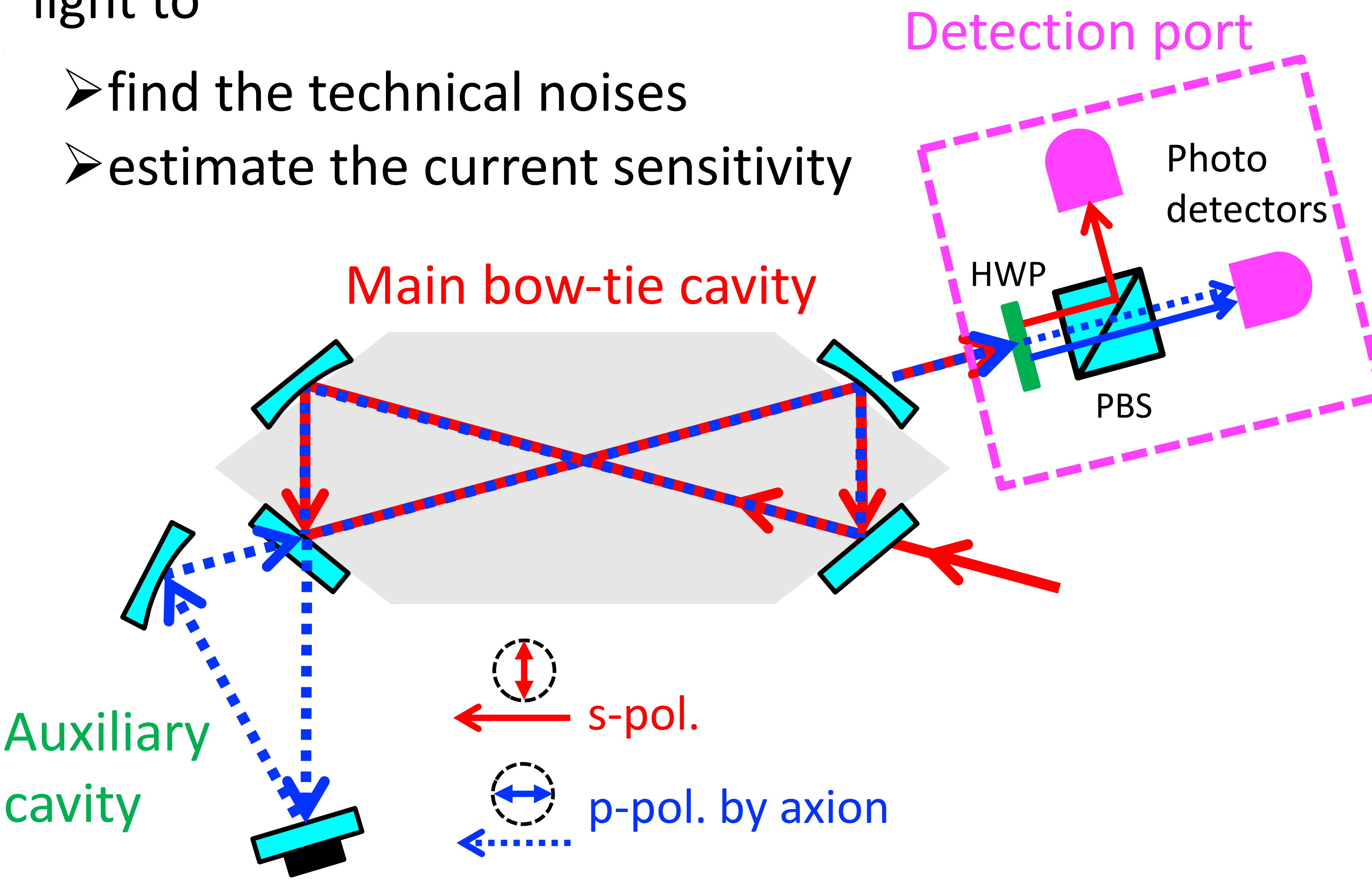
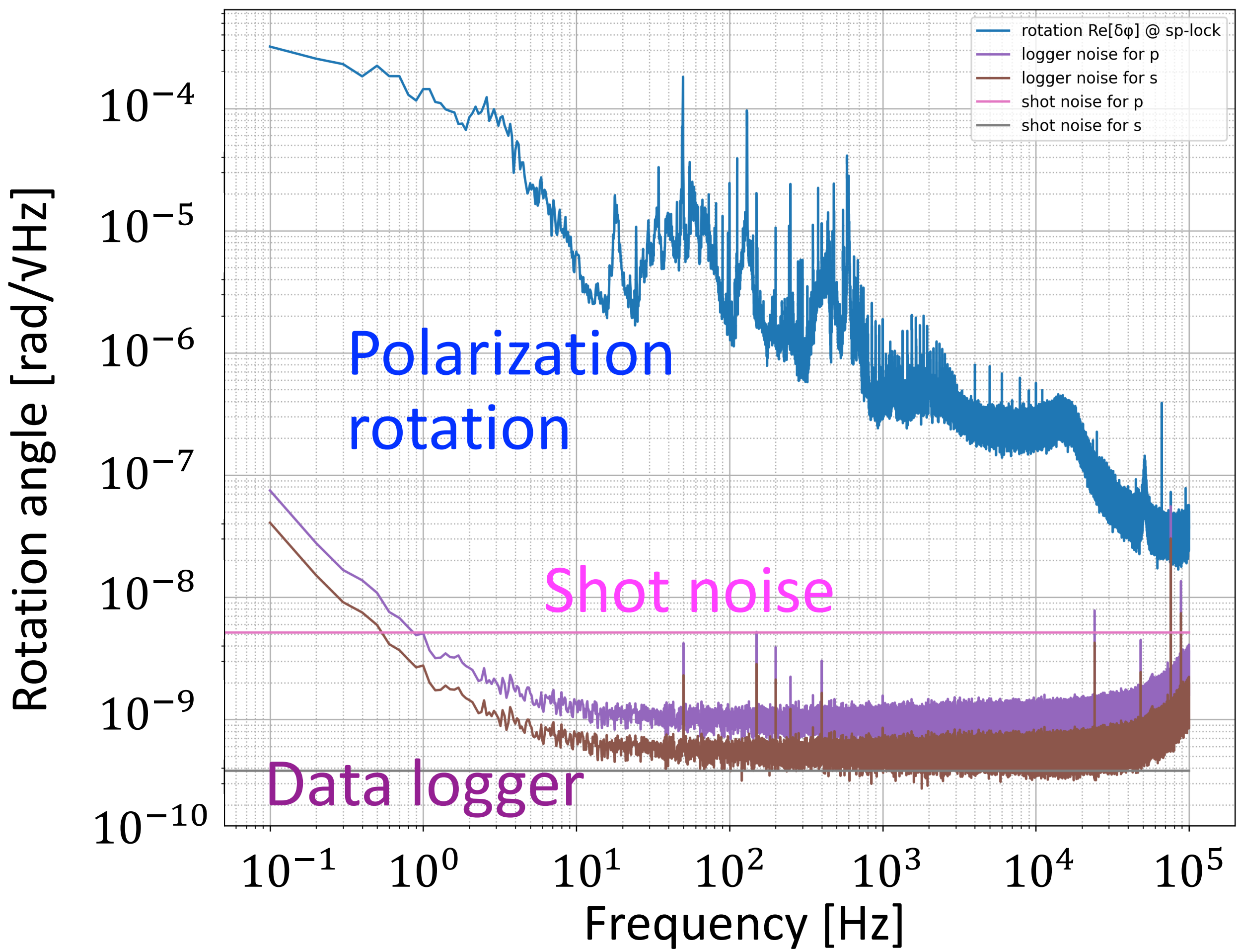
Measurement of polarization rotation

- Measured the polarization rotation of transmitted light to
  - ➢find the technical noises
  - ➢estimate the current sensitivity



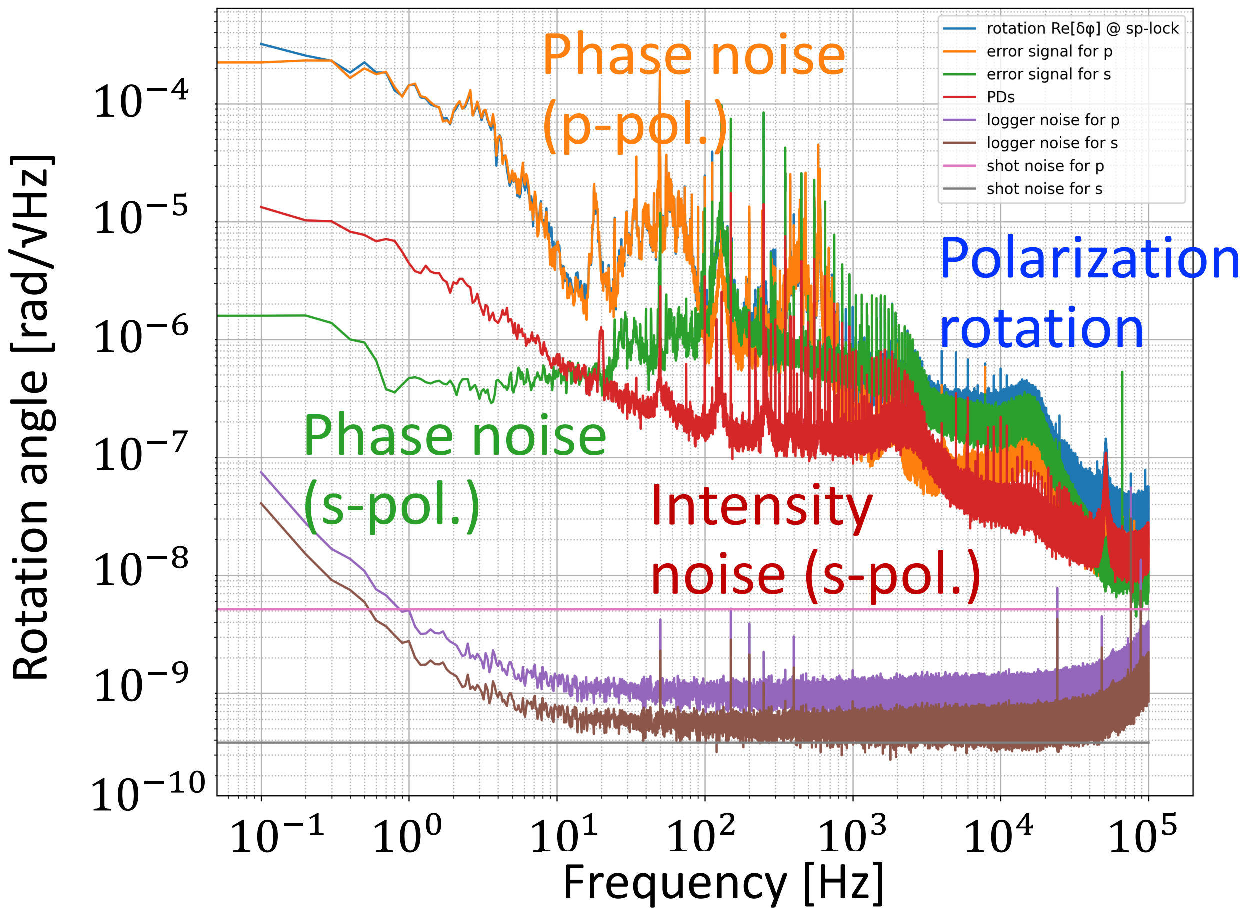
Power spectrum of polarization rotation

- 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

Offline noise reduction

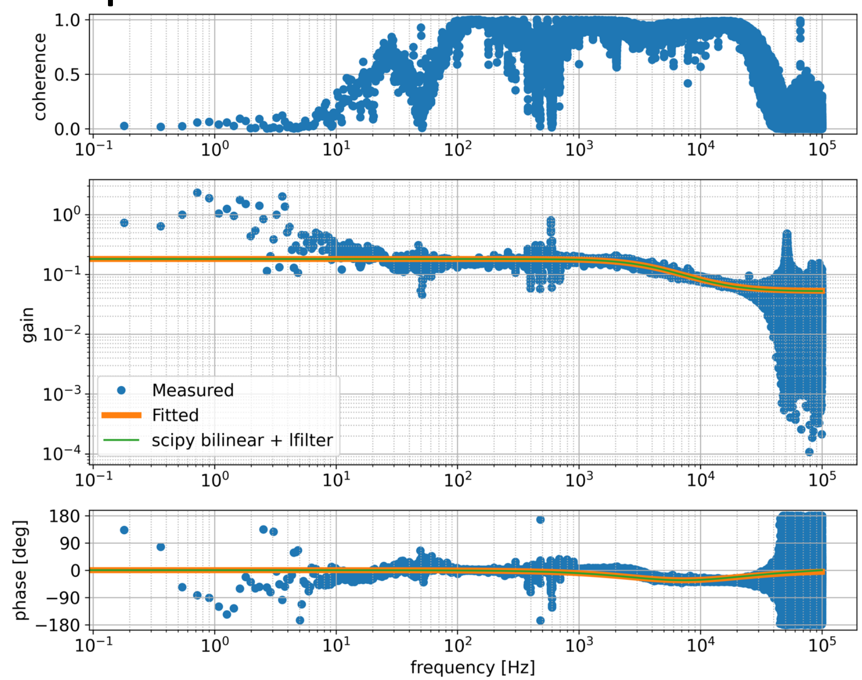
- Subtract noise using obtained noise data:
  - ➢Error signals for simultaneous resonance control (phase noise)
  - ➢Intensity signal of transmitted light (intensity noise)

①Estimate transfer functions (TFs) from each noise data to pol. rotation

②Apply IIR filters generated from obtained transfer functions to noise data (SciPy bilinear function)

③Subtract filtered noise data from the data of pol. rotation

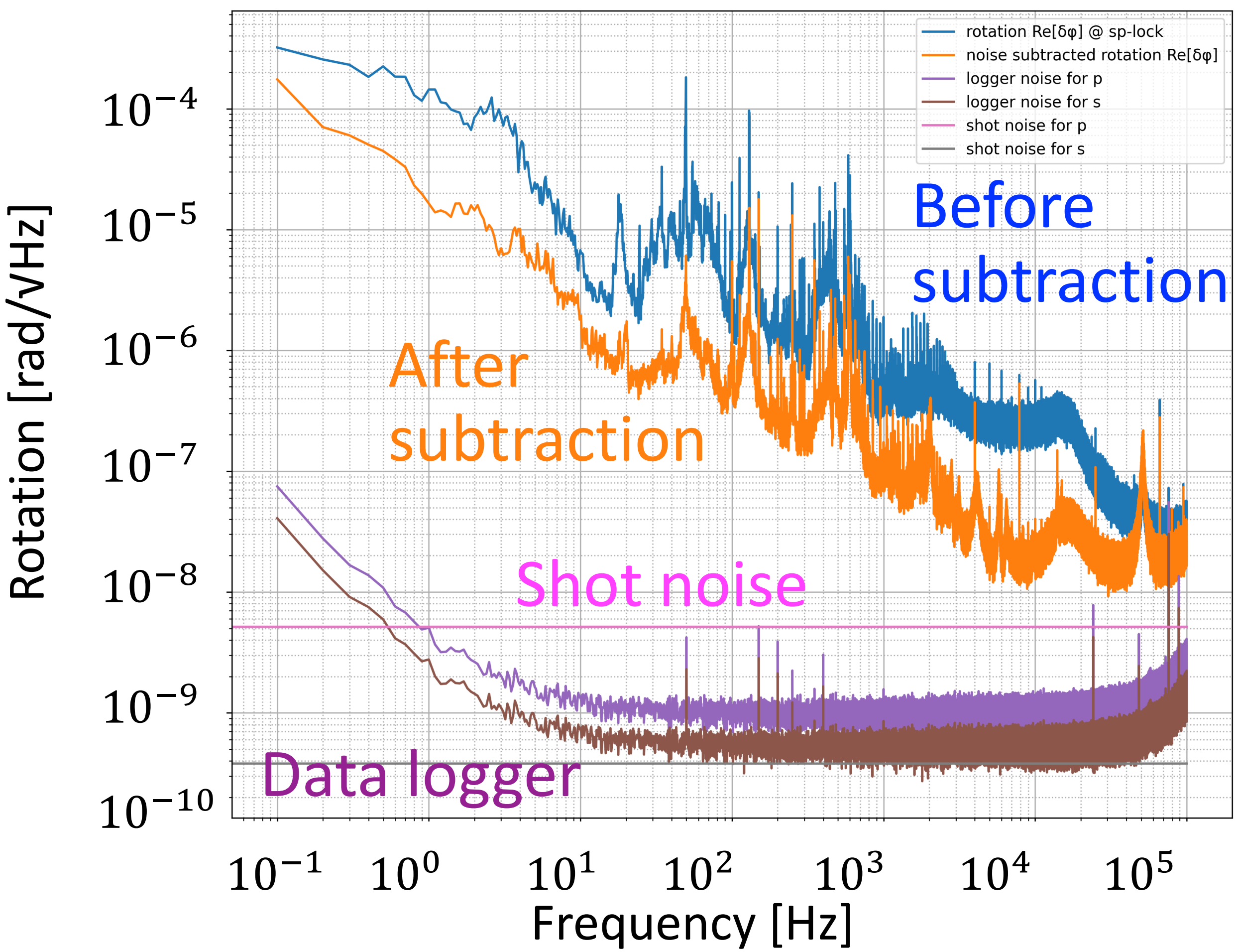
TF from error signal (s-pol.) to polarization rotations



＊Subtracted axion signal∝(amount of cavity birefringence)^2

Negligibly small

Offline noise reduction



- Succeeded in reducing noise by ~1 order of magnitude in broad range

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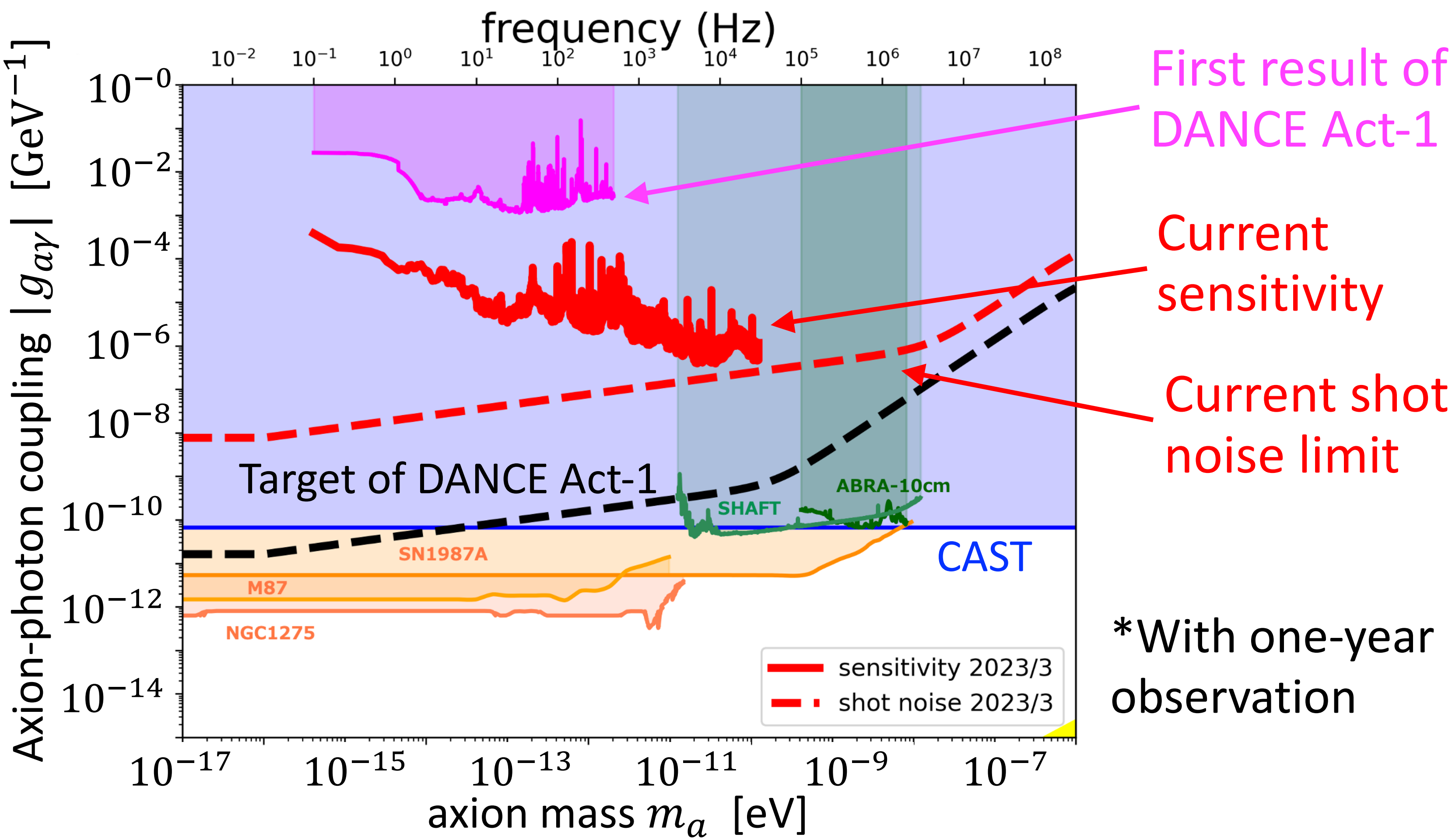
Estimated sensitivity

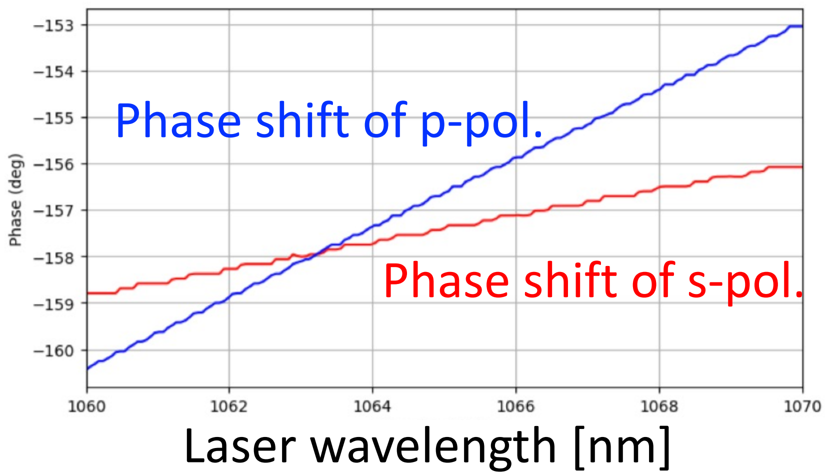


- Current sensitivity: $g_{a\gamma} \gtrsim 10^{-6}\ \mathrm{GeV}^{-1}$ at $m_a = 10^{-15} \sim 10^{-10}\ \mathrm{eV}$
- > 2 orders of magnitude better than the first result of DANCE Act-1
- ~ 4 orders of magnitude worse than CAST limit

Future plans of DANCE Act-1

- Reduction of various noises
  - ➢ Optimize cavity resonance control to reduce phase noise
  - ➢ Replace cavity mirrors for higher finesse
  - ➢ High power laser for better shot noise

- Simultaneous resonance without using auxiliary cavity
  - ➢ Auxiliary cavity introduces optical losses and phase noise
  - ➢ Frequency-tunable laser may change the reflective phase shift and realize simultaneous resonance



Summary

- DANCE searches for axion dark matter with ring cavity by enhancing the rotation of linear polarization.
- Prototype experiment: DANCE Act-1 is underway:
  - ➢ Development of auxiliary cavity for simultaneous resonance between s- and p-pol.
  - ➢ Noise hunting and offline noise reduction
- Further commissioning and development of advanced simultaneous resonance are needed for better sensitivity