2023 Fall meeting of APS DNP and JPS
DBD23
(Hilton Waikoloa Village, Hawaii)

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Ultralight axion dark matter search with DANCE

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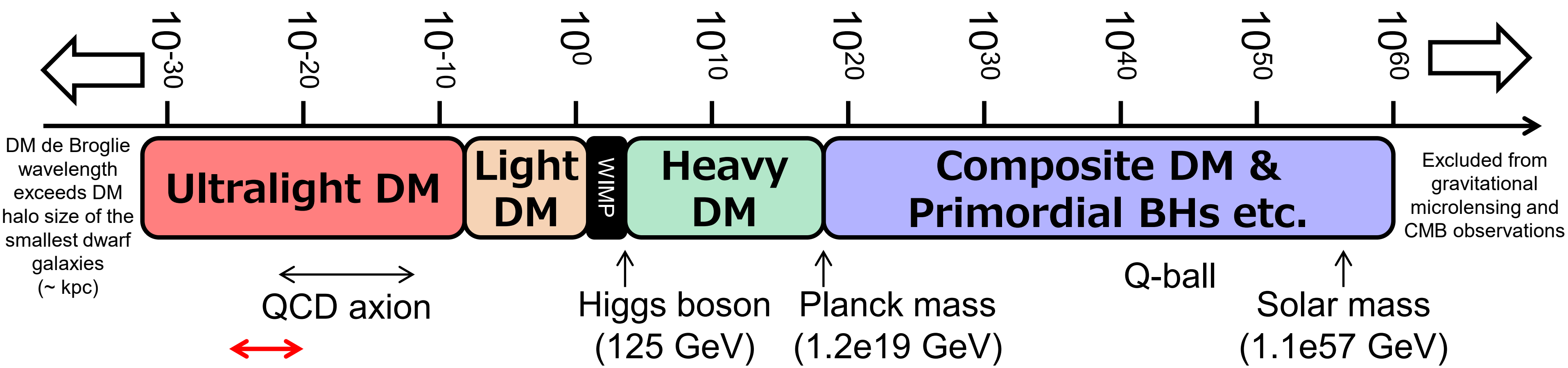
Dark Matter Models

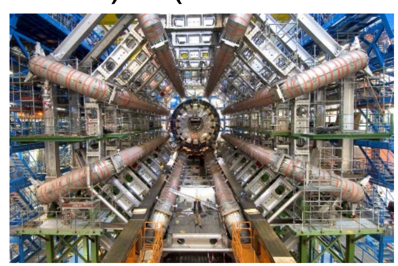
- ~90 orders of magnitude in mass
- Searches focused on WIMPs, but not detected yet
- Motivates new searches for other candidates



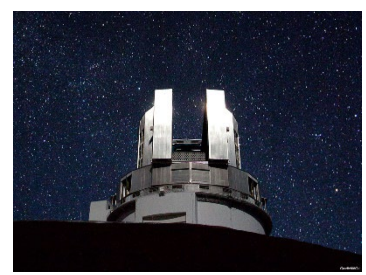
2.4 Hz ~ 2.4 kHz
(1e-14 ~ 1e-11 eV)

Laser Interferometry

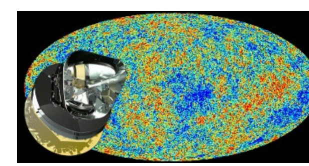
Underground experiments (XENONnT etc.)



LHC



Subaru telescope etc.



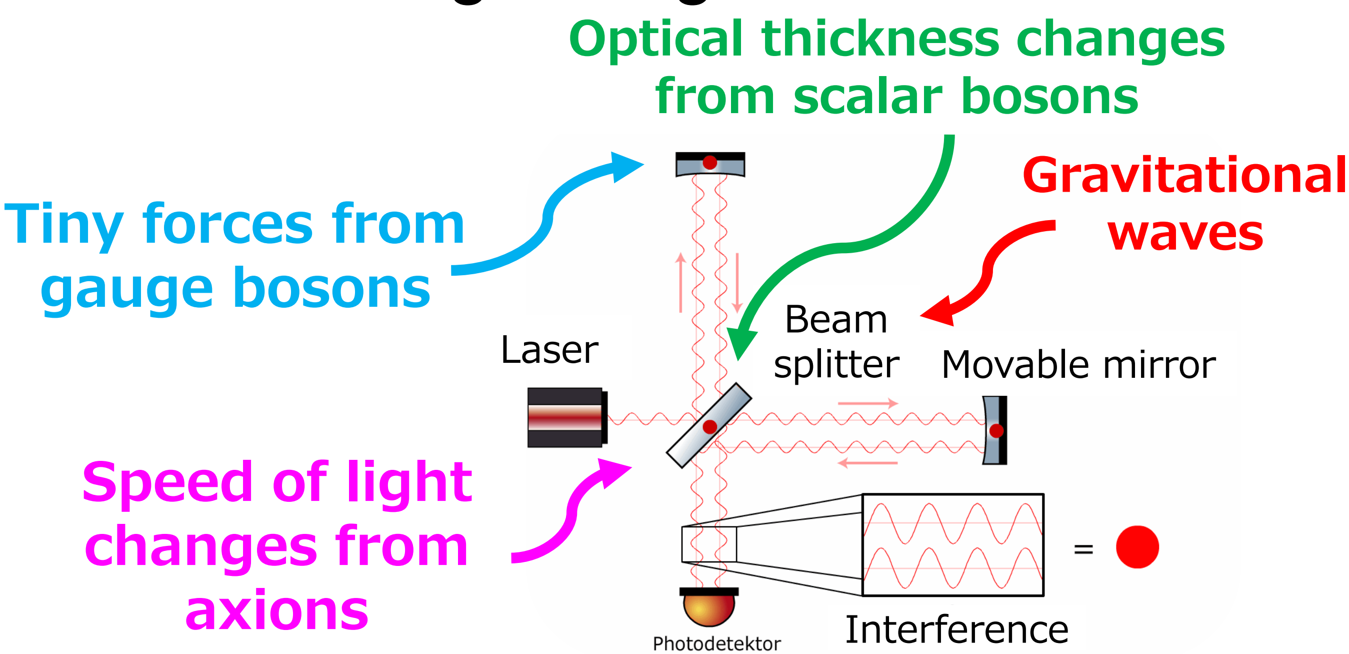
Cosmic microwave background

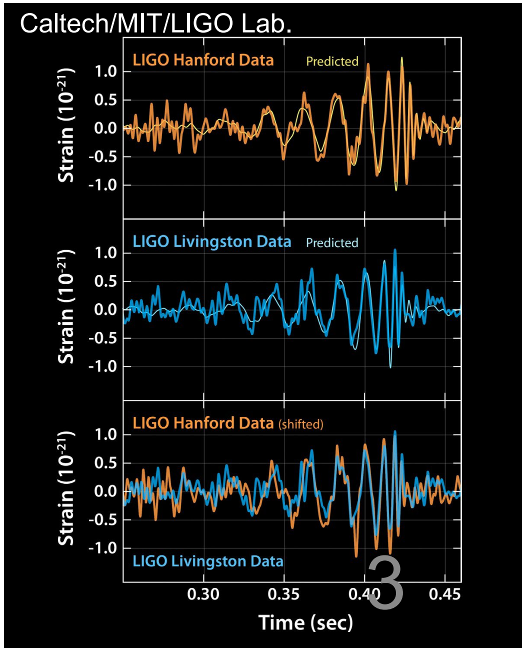
Ultralight DM with Interferometers

- Bosonic ultralight field (<~1 eV) are well-motivated from cosmology
- Behaves as classical waves

$$f = 242\ \mathrm{Hz} \left(\frac{m_{\mathrm{DM}}}{10^{-12}\ \mathrm{eV}} \right)$$

- Laser interferometers are sensitive to such oscillating changes





Recent Proposals and Searches

- **$U(1)_B$ or $U(1)_{B-L}$ gauge bosons(vector field)**
  - P. W. Graham+, PRD **93**, 075029 (2016)
  - A. Pierce+, PRL **121**, 061102 (2018)
  - H-K Guo+, Commun. Phys. **2**, 155 (2019) LIGO O1 data analysis
  - Y. Michimura, T. Fujita, S. Morisaki, H. Nakatsuka, I. Obata, PRD **102**, 102001 (2020)
  - D. Carmey+, New J. Phys. **23**, 023041 (2021)
  - J. Manley+, PRL **126**, 061301 (2021)
  - S. Morisaki, T. Fujita, Y. Michimura, H. Nakatsuka, I. Obata, PRD **103**, L051702 (2021)
  - LIGO-Virgo-KAGRA Collaboration, PRD **105**, 063030 (2022) LIGO/Virgo O3 data analysis

- **Scalar bosons**
  - Y. V. Stadnik & V. V. Flambaum, PRL **114**, 161301 (2015)
  - Y. V. Stadnik & V. V. Flambaum, PRA **93**, 063630 (2016)
  - A. A. Geraci+, PRL **123**, 031304 (2019)
  - H. Grote & Y. V. Stadnik, PRR **1**, 033187 (2019)
  - S. Morisaki & T. Suyama, PRD **100**, 123512 (2019)
  - C. Kennedy+, PRL **125**, 201302 (2020)
  - E. Savalle+, PRL **126**, 051301 (2021)
  - S. M. Vermeulen+, Nature **600**, 424 (2021) GEO600 data analysis

Many recent proposals

First searches with real data from GW detectors already done for gauge bosons and scalar bosons.

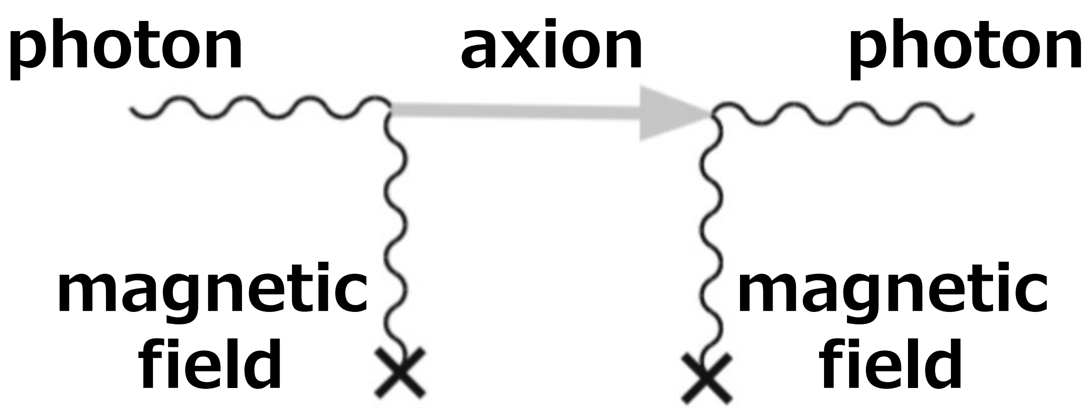
- **Axion & axion-like particles (ALPs)**
  - W. DeRocco & A. Hook, PRD **98**, 035021 (2018)
  - I. Obata, T. Fujita, Y. Michimura, PRL **121**, 161301 (2018) ⇐ This talk
  - H. Liu+, PRD **100**, 023548 (2019)
  - K. Nagano, T. Fujita, Y. Michimura, I. Obata, PRL **123**, 111301 (2019)
  - D. Martynov & H. Miao, PRD **101**, 095034 (2020)
  - K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita, Y. Michimura, I. Obata, PRD **104**, 062008 (2021)
  - Y. Oshima+, PRD 108, 072005 (2023) DANCE first results ⇐ This talk
  - J. Heinze+, arXiv:2307.01365 LIDA first results

Not exhaustive. The ones which require magnetic fields are not listed.

Axion and Axion-Like Particles

- Pseudo-scalar particle originally introduced to solve strong CP problem (QCD axion)
- Various axion-like particles (ALPs) predicted by string theory and supergravity
- Many experiments to search for ALPs through axion-photon coupling

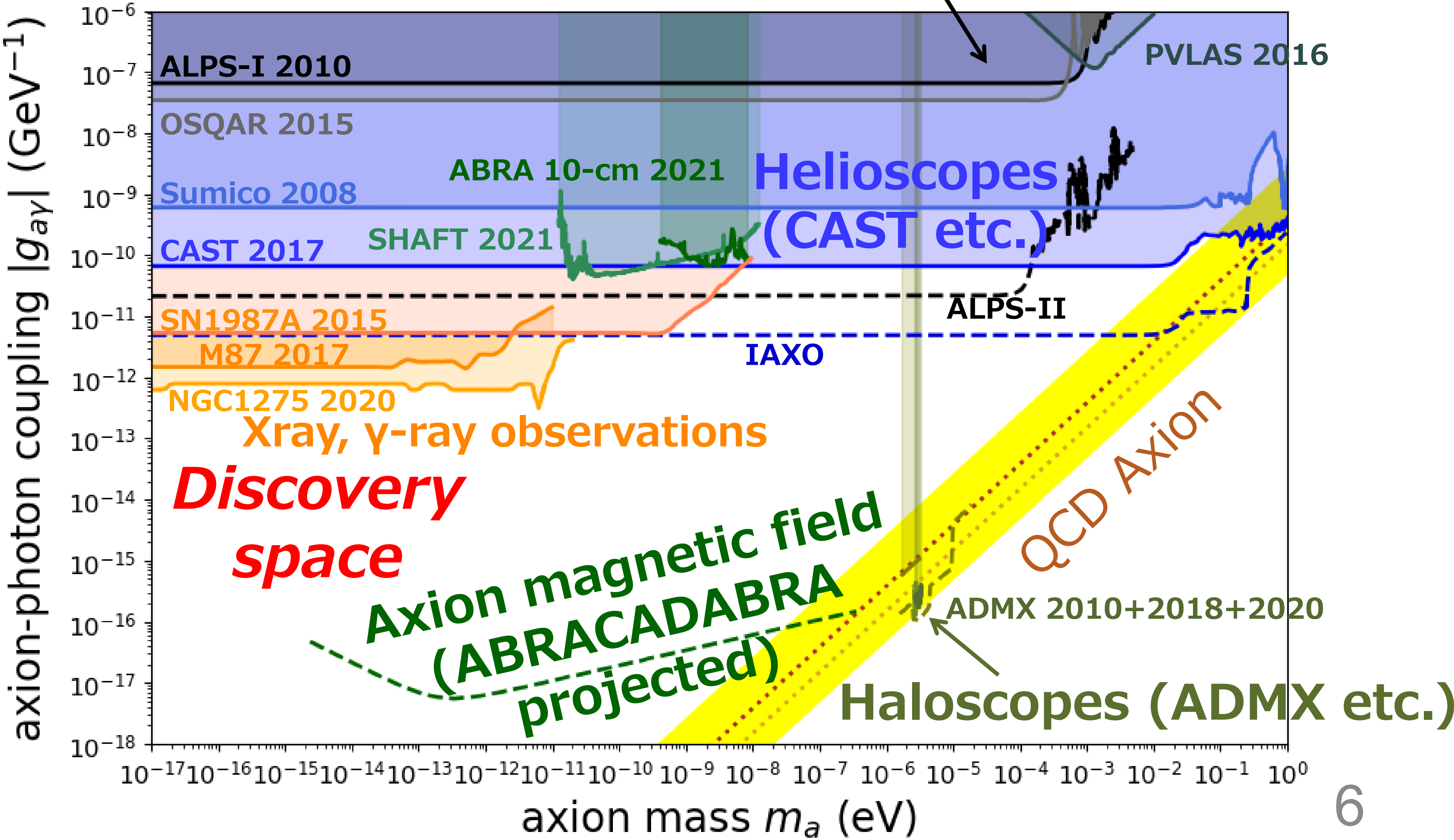
  Especially by using magnetic fields



Primakoff effect

Current Upper Limits


CERN CAST



Polarization Modulation from Axions

- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

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

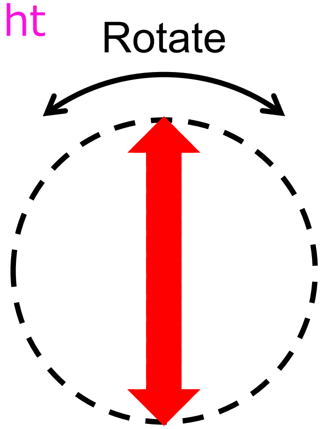
coupling constant

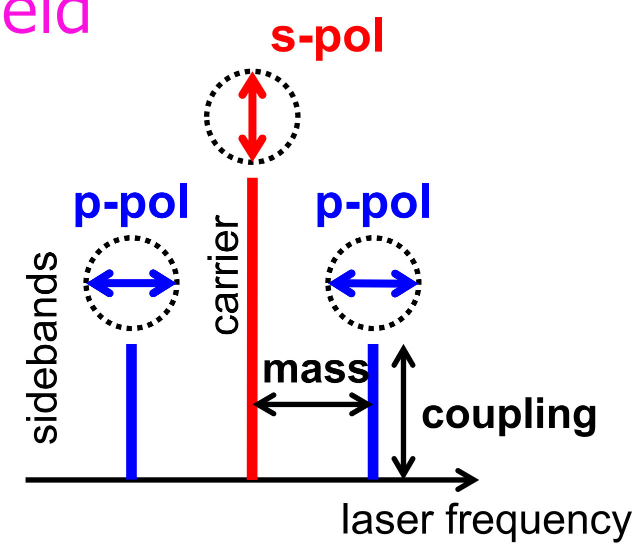
Wave number of light

axion field

axion mass

- Linear polarization will be modulated
  - p-pol sidebands will be generated from s-pol
- Search can be done without magnetic field





Enhancing the Signal with Cavities

- Polarization rotation is small for short optical path

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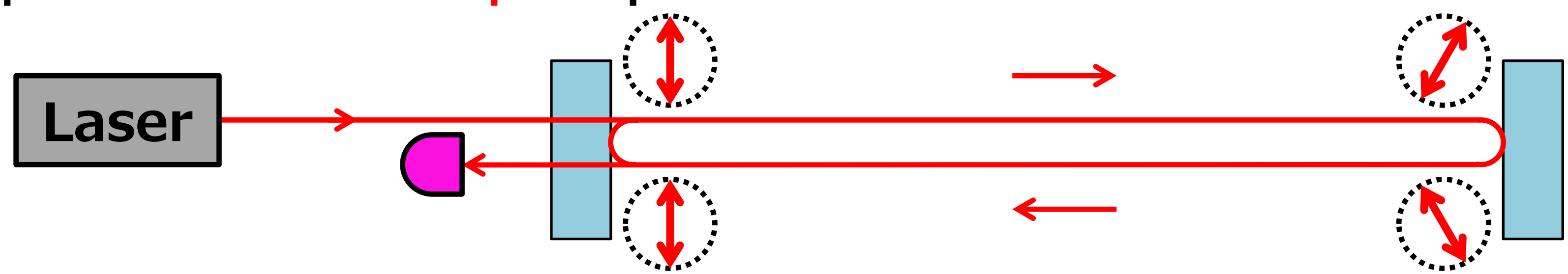
- Optical cavities can enhance the path, but polarizations flips upon mirror reflections



Enhancing the Signal with Cavities

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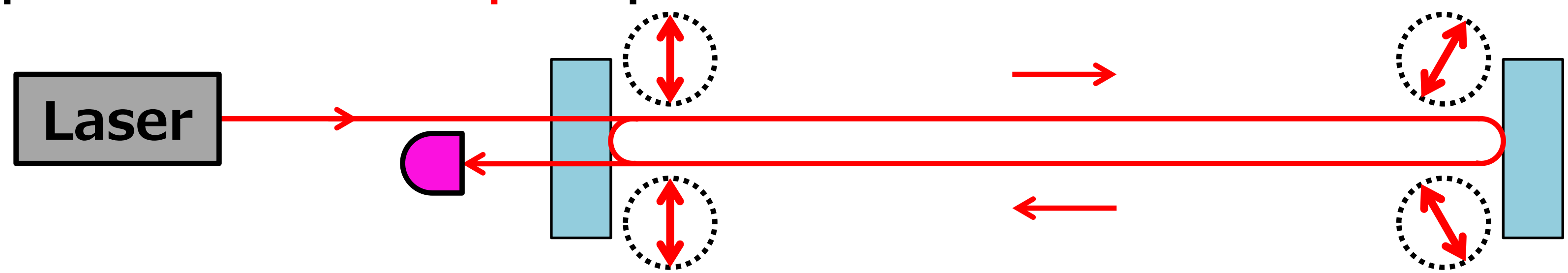
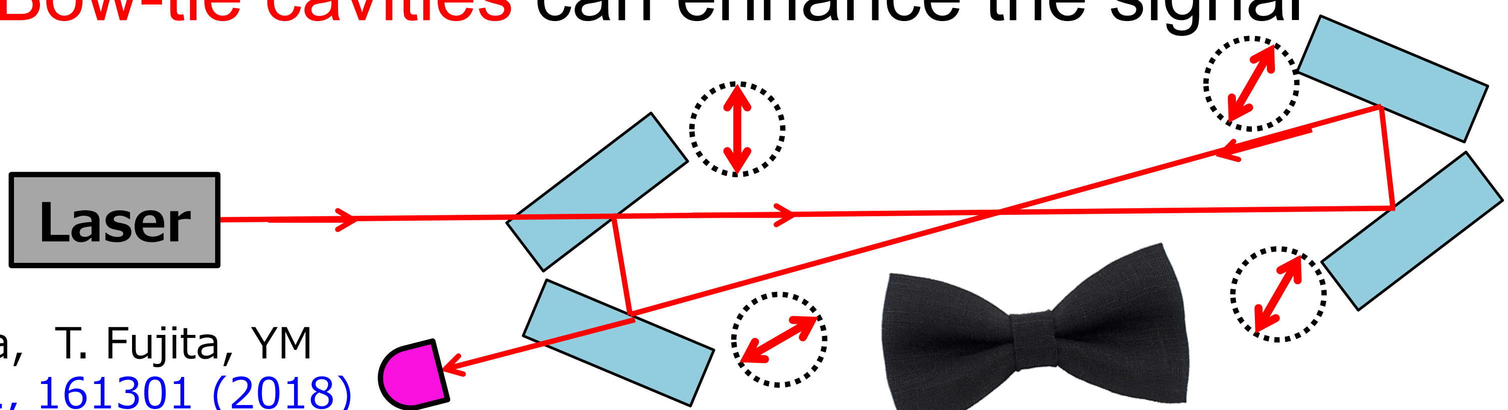
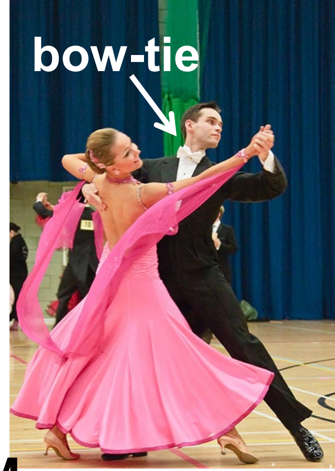


- Bow-tie cavities can enhance the signal



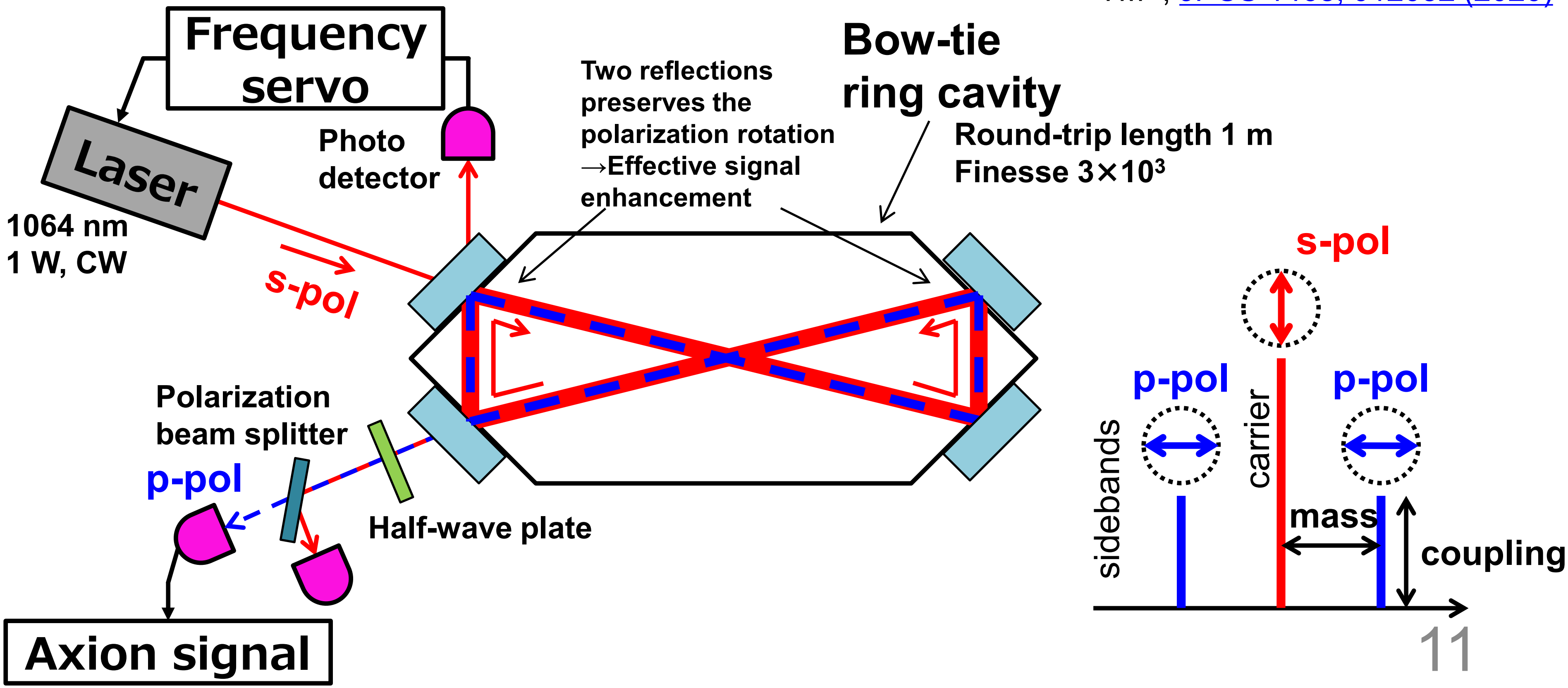
I. Obata, T. Fujita, YM
PRL **121**, 161301 (2018)

Setup of DANCE



- Dark matter Axion search with riNg Cavity Experiment
- Aim for most sensitive search for axion DM

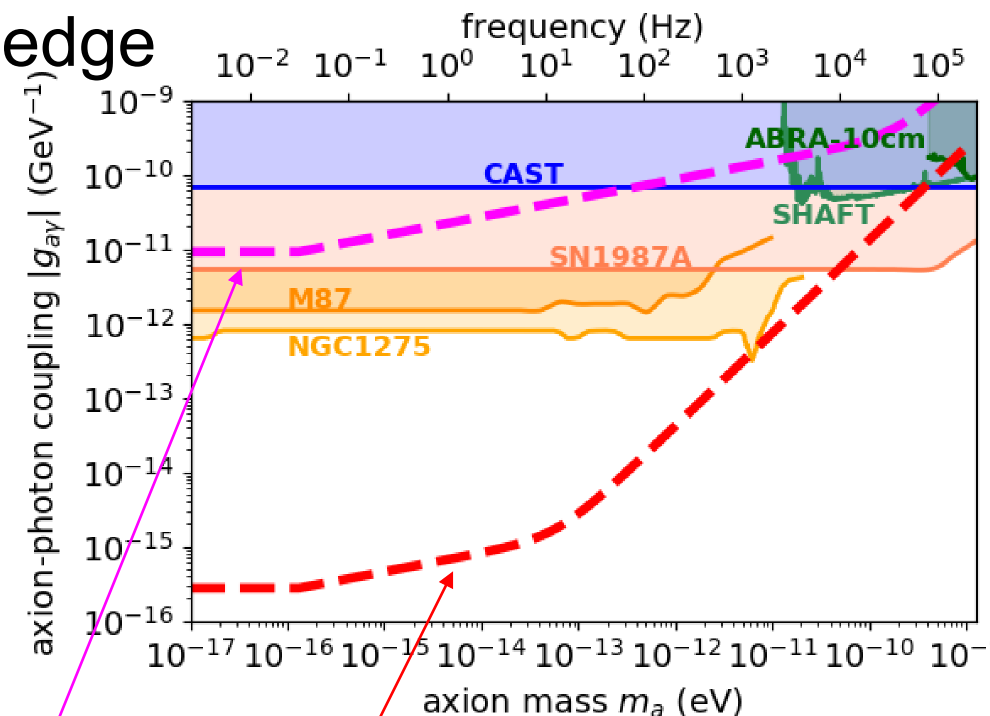
YM+, JPCS 1468, 012032 (2020)



DANCE and DANCE Act-1

- Reach beyond CAST limit by several orders of magnitude with cutting-edge technologies and 1-year run
- CAST level reach even with moderate parameters

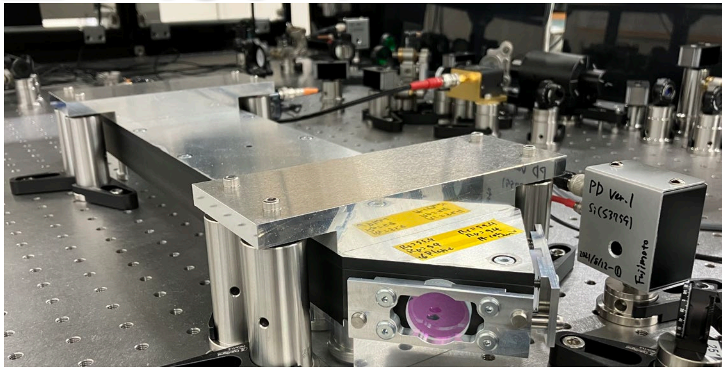
  * Shot noise limited sensitivity assumed

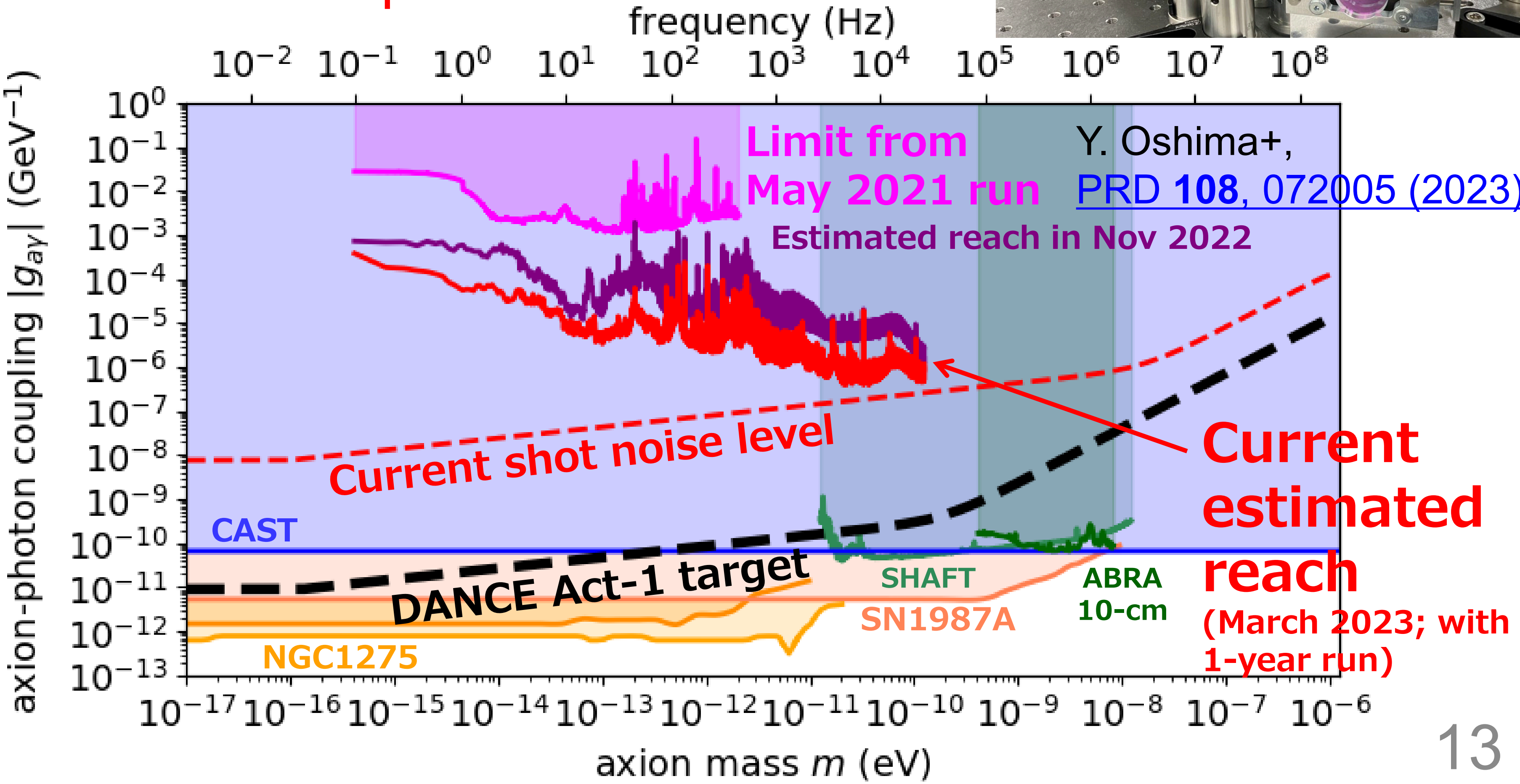


	DANCE Act-1 target	DANCE
Round-trip length	1 m	10 m
Input laser power	1 W	100 W
Finesse (how many times light travels inside the cavity)	3×10^{3}	1×10^{6}

Status of DANCE Act-1

- Started in 2019
- First observing run in May 2021
- ~x100 improvement since then

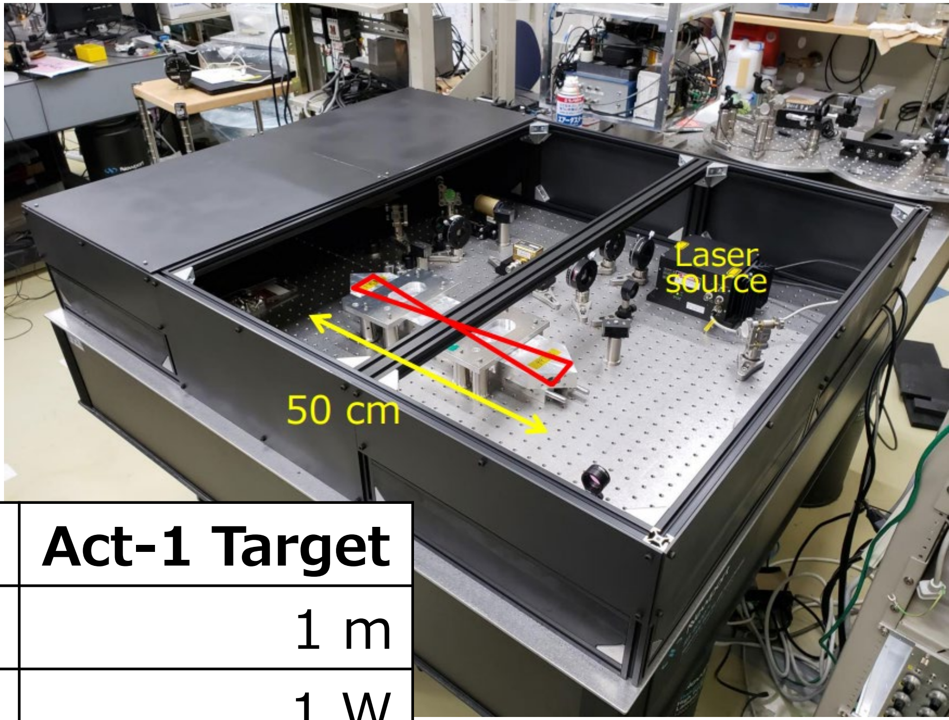




First Observing Run in May 2021

- Same scale as Act-1 target
- 12-day test run from May 8th to 30th

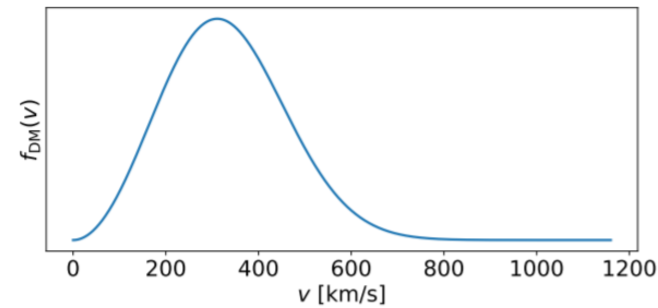
Y. Oshima+, JPCS 2156, 012042 (2021)

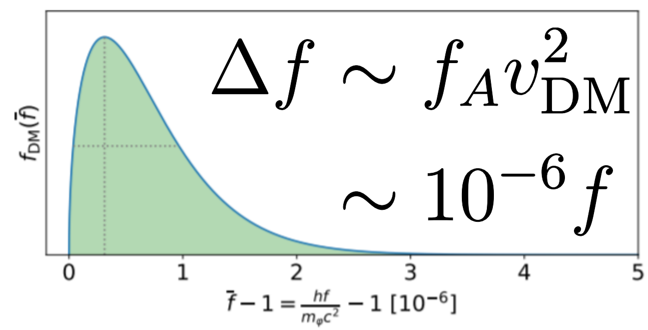


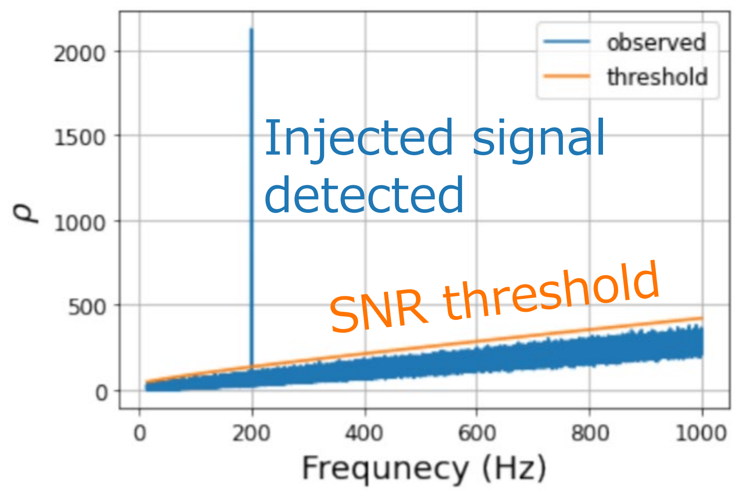
	May 2021	Act-1 Target
Round-trip length	1 m	1 m
Input power	242(12) mW (Source: 0.5 W)	1 W
Finesse (for carrier)	$2.85(5)\times10^3$ s-pol	3×10^3
Finesse (for sidebands)	195(3) p-pol	3×10^3
s/p-pol resonant freq. difference	2.52(2) MHz	0 Hz

Data Analysis Pipeline

E. Savalle+,
PRL 126, 051301 (2021)







- Nearly monochromatic signal

$$\omega_i = m_A \left(1 + \frac{v_i^2}{2}\right)$$

- Stack the spectra in this frequency region to calculate SNR

$$\rho = \sum \frac{4|\tilde{d}(f_k)|^2}{T_{\mathrm{obs}} S_n(f_k)}$$

Data

PSD

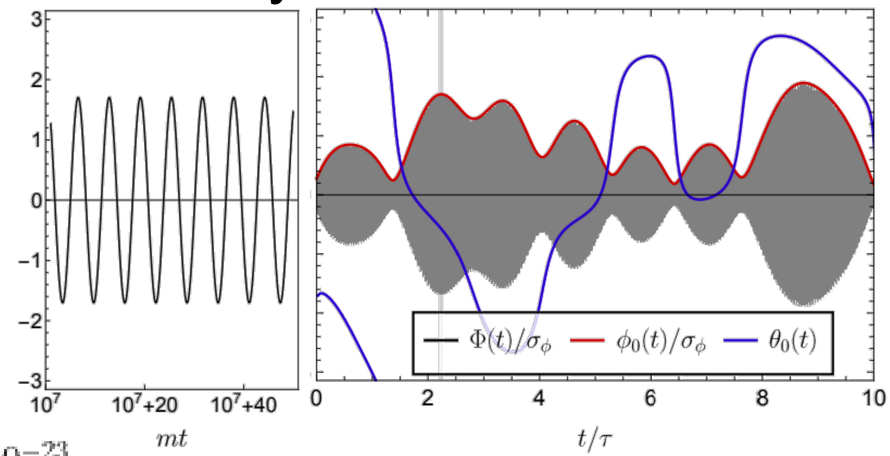
Obs. time

$m_A \leq 2\pi f_k \leq m_A(1 + \kappa v_{\mathrm{DM}}^2)$

- Detection threshold determined assuming ρ follows χ^2 distribution (=assuming Gaussian noise)
- From ρ , calculate 95% upper limit on coupling constant
- Applied the pipeline to mock data for verification

Stochastic Nature of DM Signal

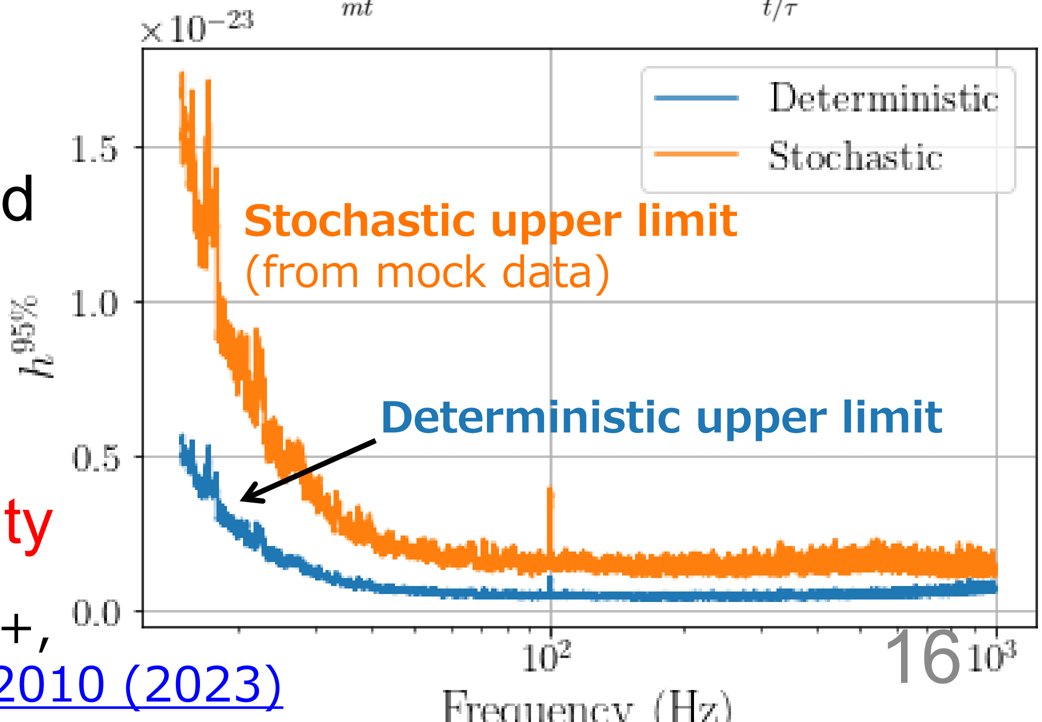
- DM signal is from superposition of many waves with various momentum, phase and polarization



- The amplitude fluctuates at the time scale of

$$\tau = 2\pi/(m_A v_{\rm DM}^2)$$

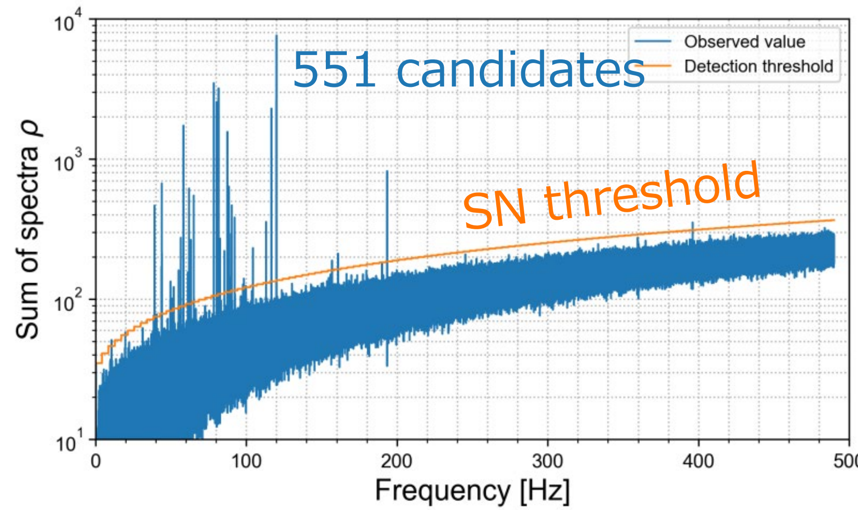
- At low frequencies, DM signal could be too small by chance and elude detection
- Method to calculate upper limit taking into account this stochasticity developed

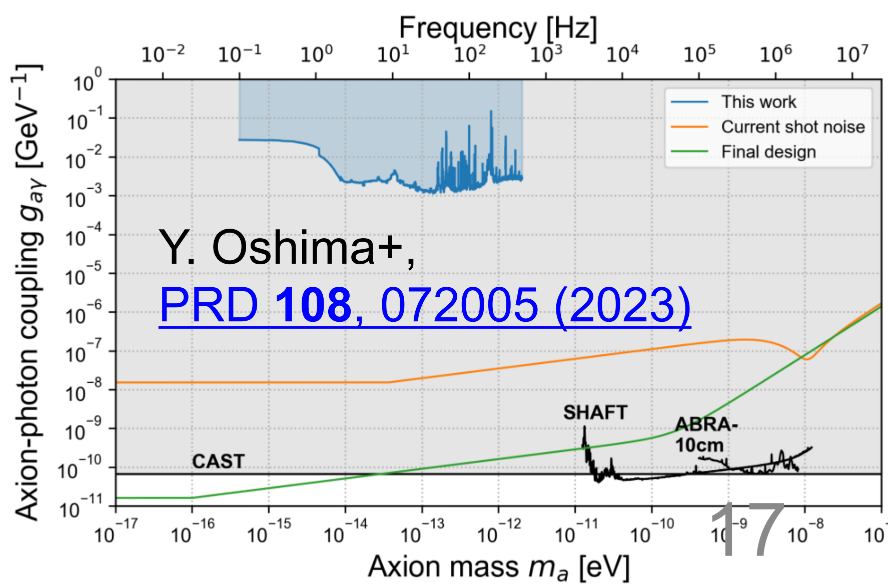


H. Nakatsuka+, PRD **108**, 092010 (2023)

First Results

- Used 24 hour data from 12-day run
- 551 candidates found
- Veto analysis
  - Persistence veto
    (If dark matter, two data sets should give the same frequency → 257 candidates)
  - Linewidth veto
    (If dark matter, Q~10^6 → 7 candidates)
  - All remaining 7 candidates were also found in the frequency servo data, and found to me mechanical origin
    (all harmonics of ~40 Hz)
- First end-to-end test
- First limit with no magnets

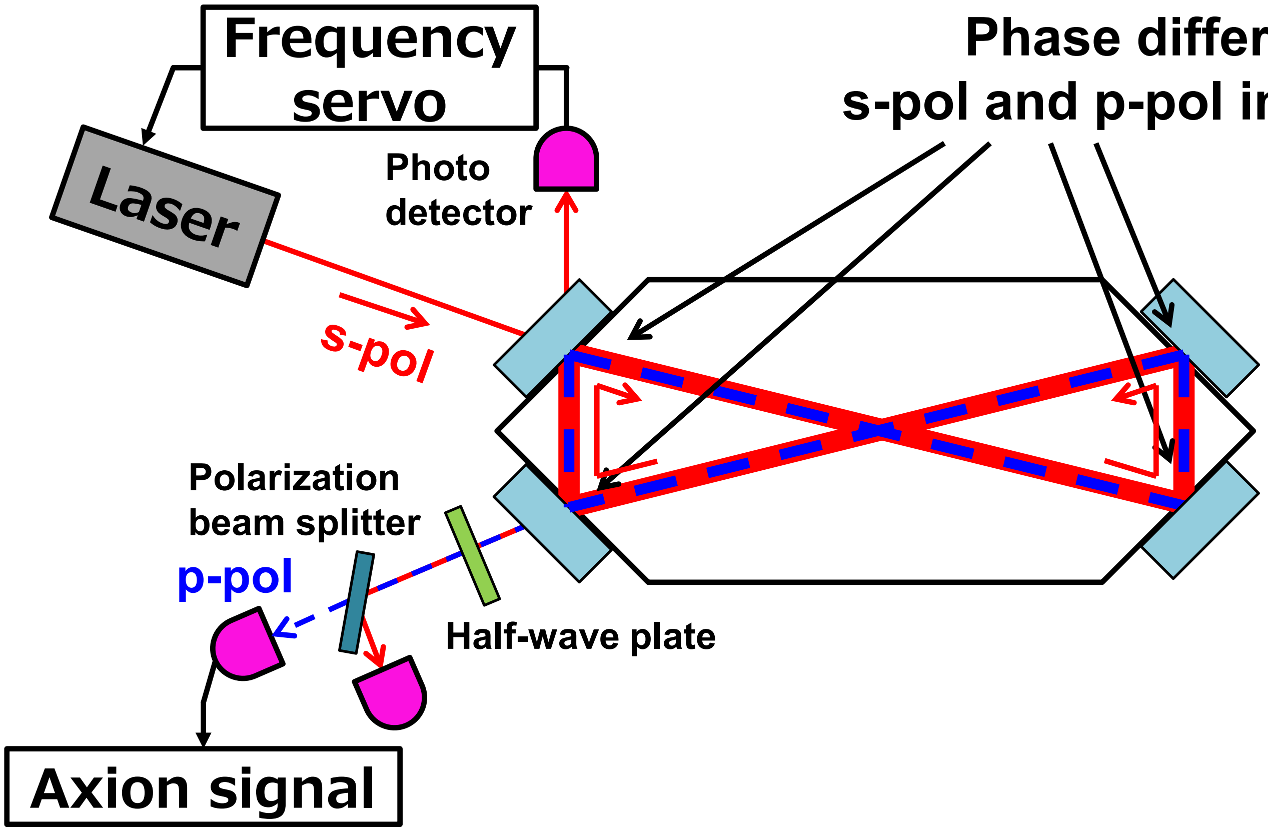


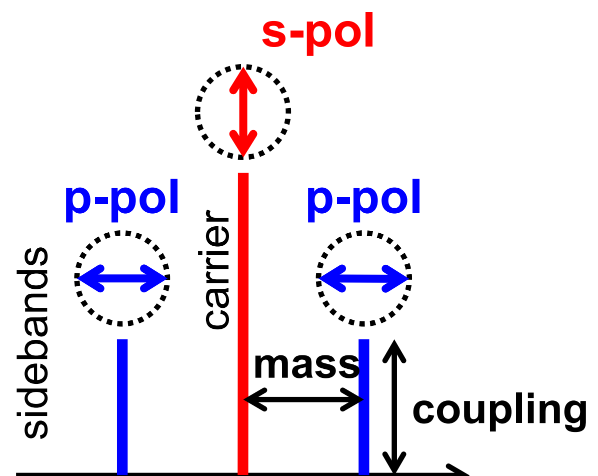


Y. Oshima+, [PRD **108**, 072005 (2023)]

Resonant Frequency Split

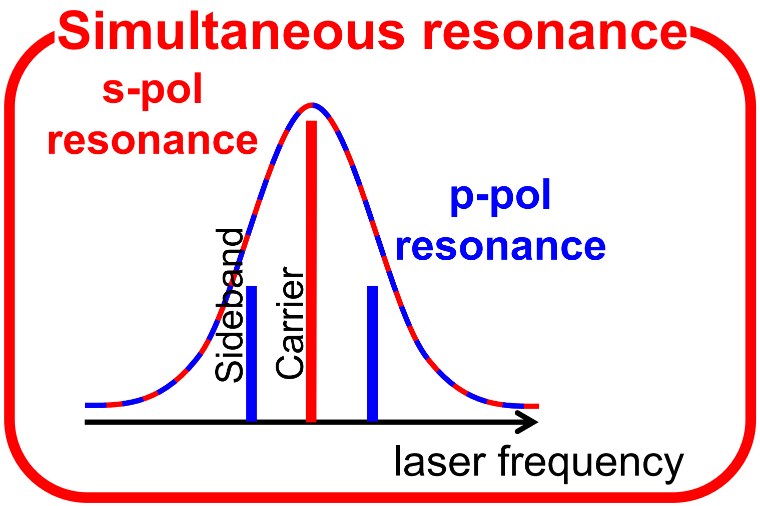
- During the first run, s-pol and p-pol did not resonate simultaneously
- Due to phase difference in mirror reflections from non-zero incident angle

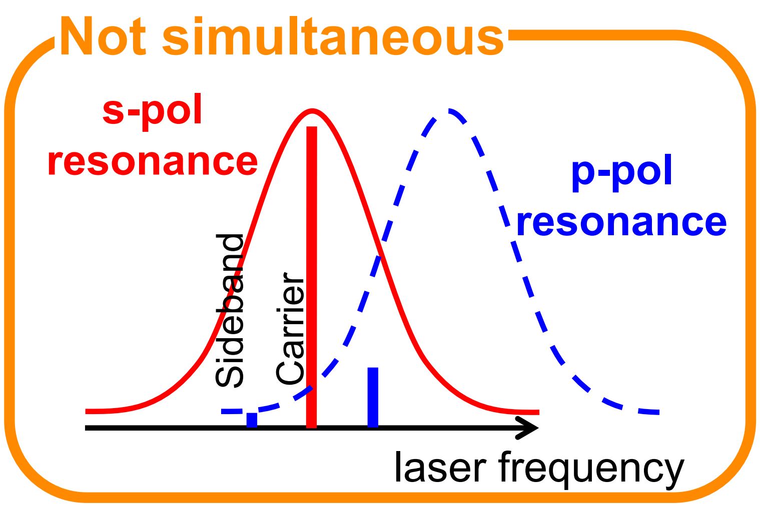


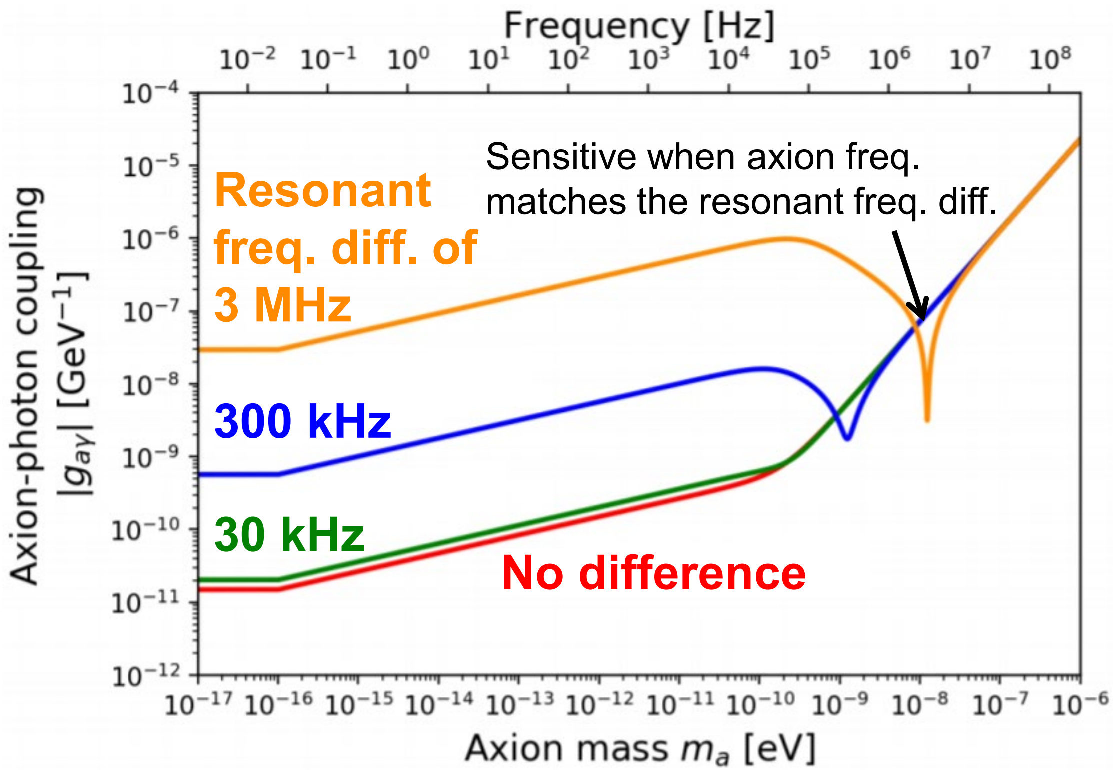


Simultaneous Resonance

- Carrier pol and sideband pol needs to be enhanced simultaneously for improving the sensitivity



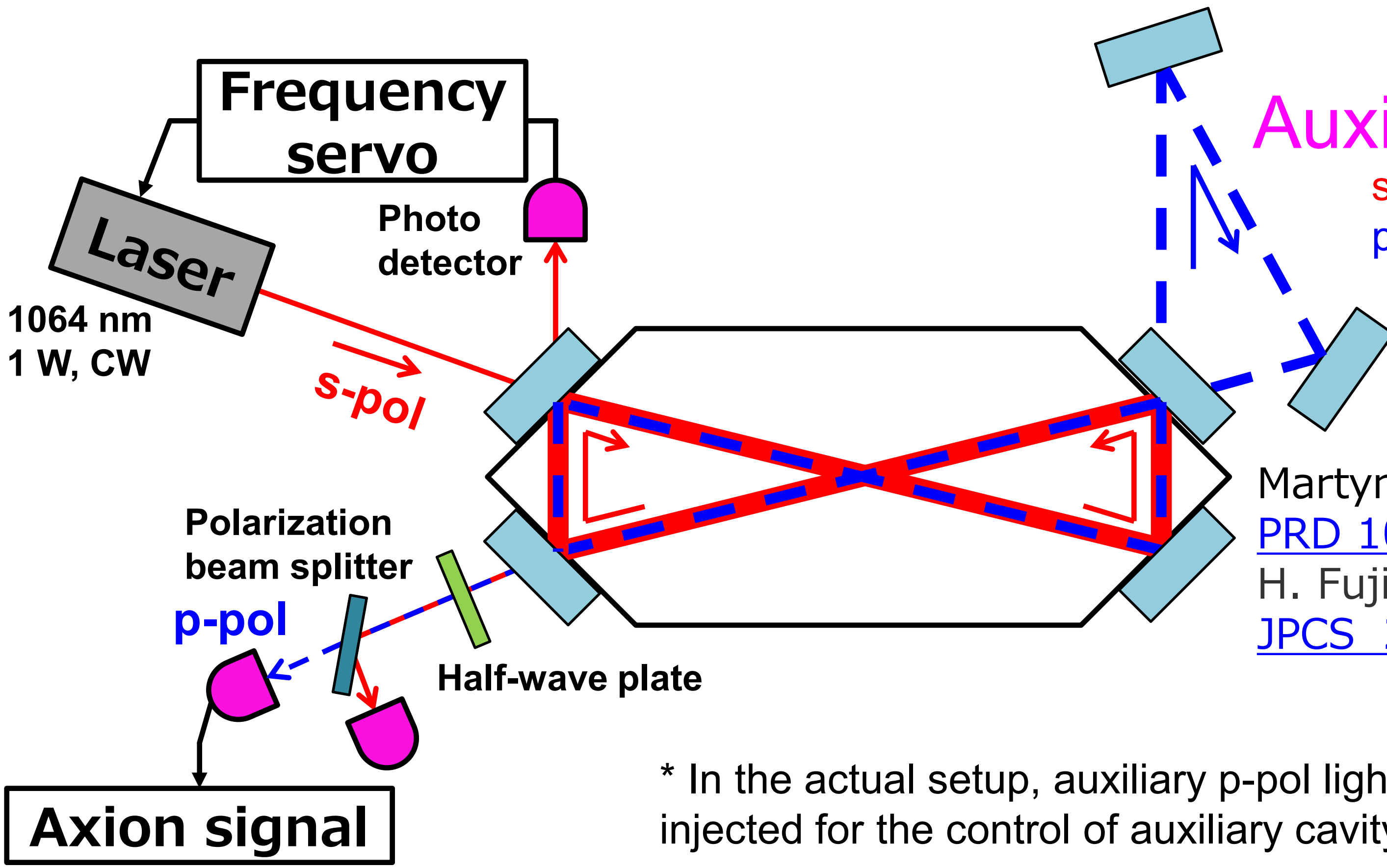




Plot by Y. Oshima & H. Fujimoto

Auxiliary Cavity as Solution

- Make resonant condition for auxiliary cavity different between s/p-pol to make reflected phase different
- This compensates phase difference in the main cavity

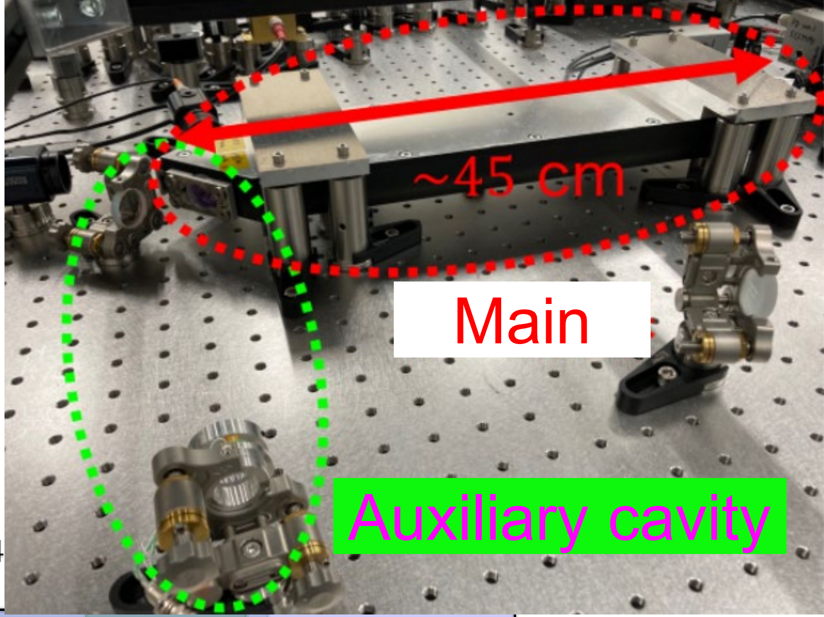


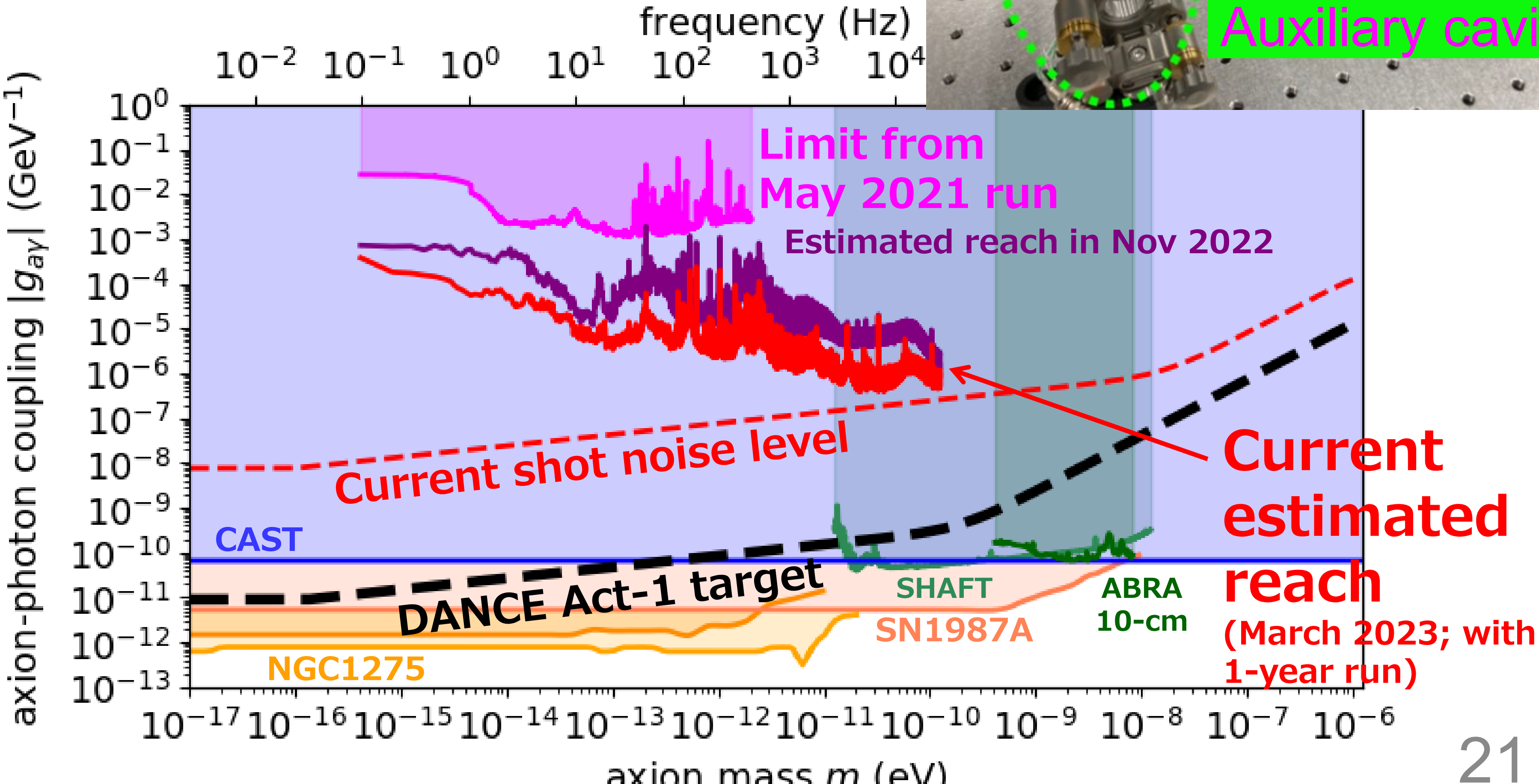
Martynov & Miao
PRD 101, 095034 (2020)
H. Fujimoto+,
JPCS 2156, 012182 (2021)

* In the actual setup, auxiliary p-pol light is also injected for the control of auxiliary cavity length

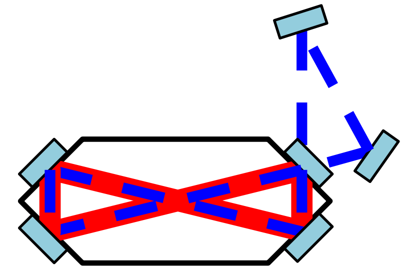
Updated Setup

- ~x100 improvement with auxiliary cavity





Optical Losses and Vibrations

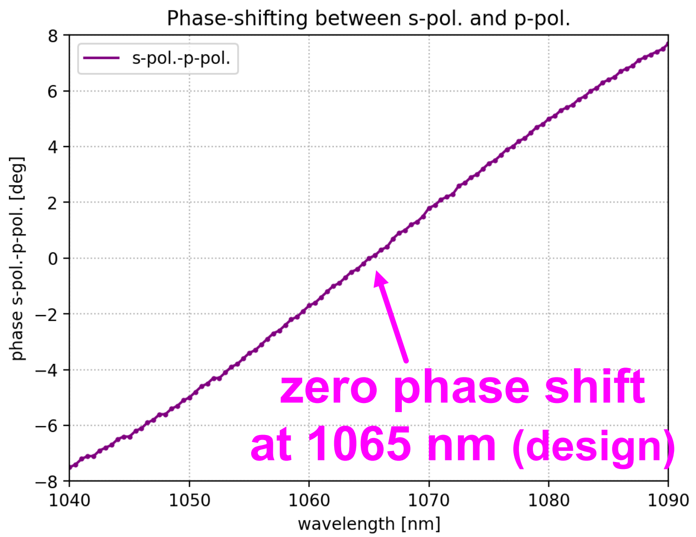


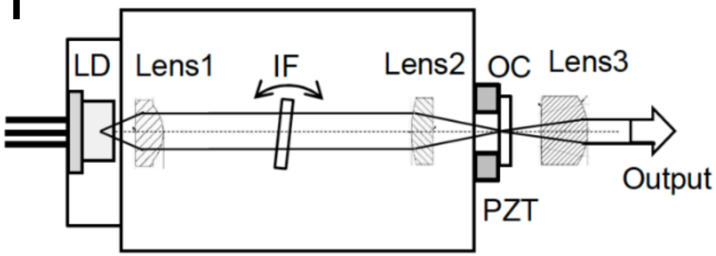
- Finesse was limited due to optical losses in auxiliary cavity
- Noise from vibrations were worse due to reduced common mode rejection

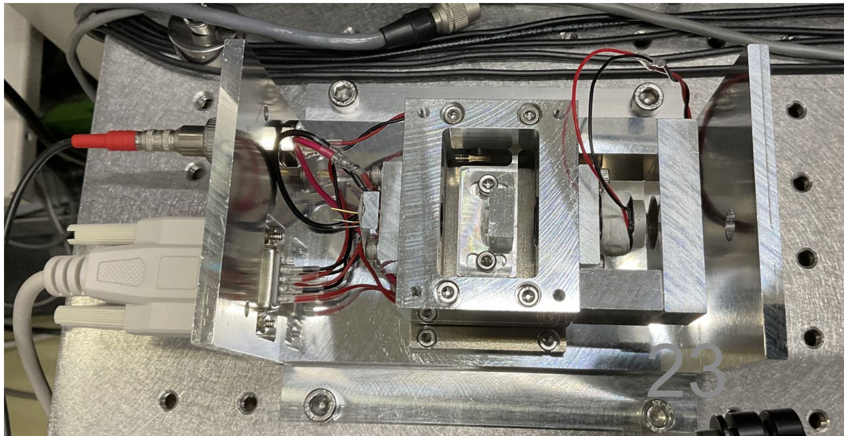
	May 2021	Best (March 2023)	Act-1 Target
Round-trip length	1 m	1 m (+0.5 m aux. cavity)	1 m
Input power	242(12) mW (Source: 0.5 W)	21.4(9) mW (Source: 2 W)	1 W
Finesse (for carrier)	$2.85(5)\times10^3$ s-pol	549(3) s-pol, with cavity lock	3×10^3
Finesse (for sidebands)	195(3) p-pol	36.8(2) p-pol, with cavity lock	3×10^3
s/p-pol resonant freq. difference	2.52(2) MHz	~0 Hz with lock (Originally ~92 MHz)	0 Hz

Next Idea: Wavelength Tuning

- Phase difference between polarization is wavelength dependent
- Simultaneous resonance can be obtained by tuning the laser wavelength
- Developed wavelength tunable laser (External Cavity Diode Laser)
  wavelength: 1045-1068 nm
  linewidth: 200 kHz
  output: 50 mW

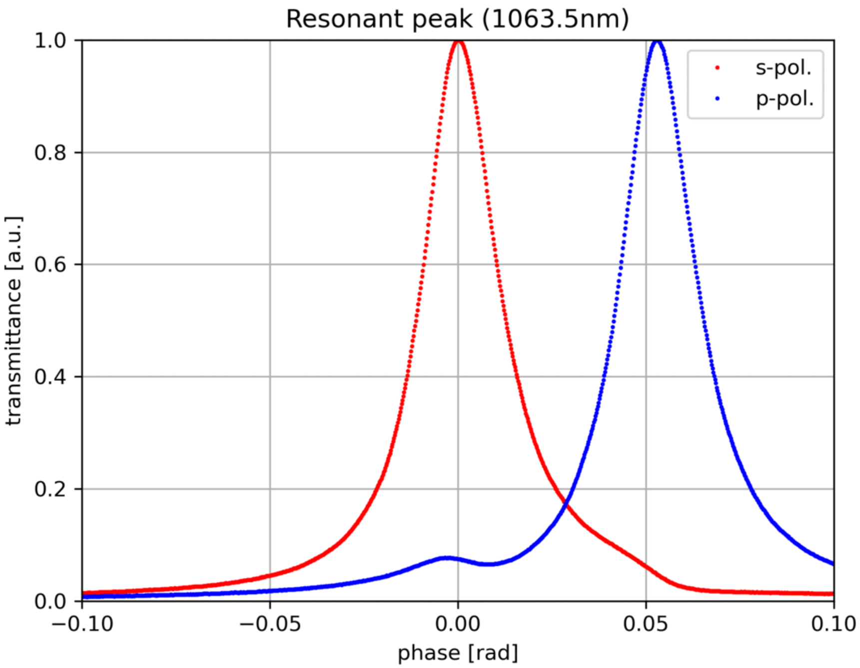


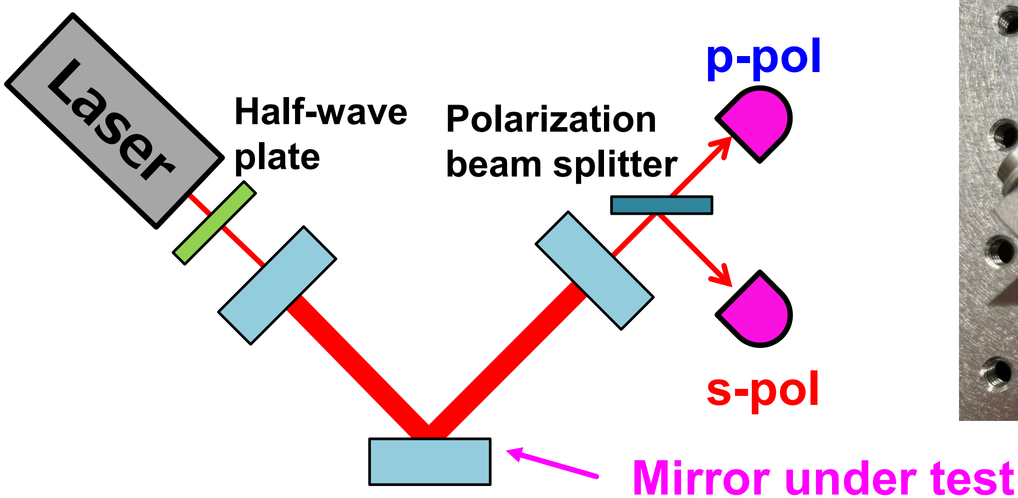


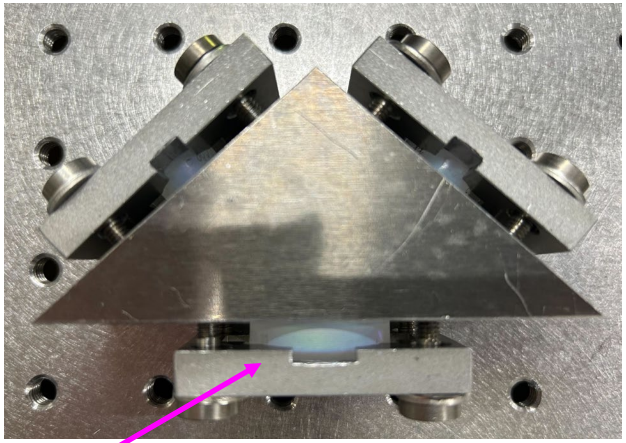


Measuring Phase Anisotropy

- Phase difference of a mirror measured with V-shaped cavity
- Zero-phase shift achieved at ~1067 nm (designed at 1065 nm)



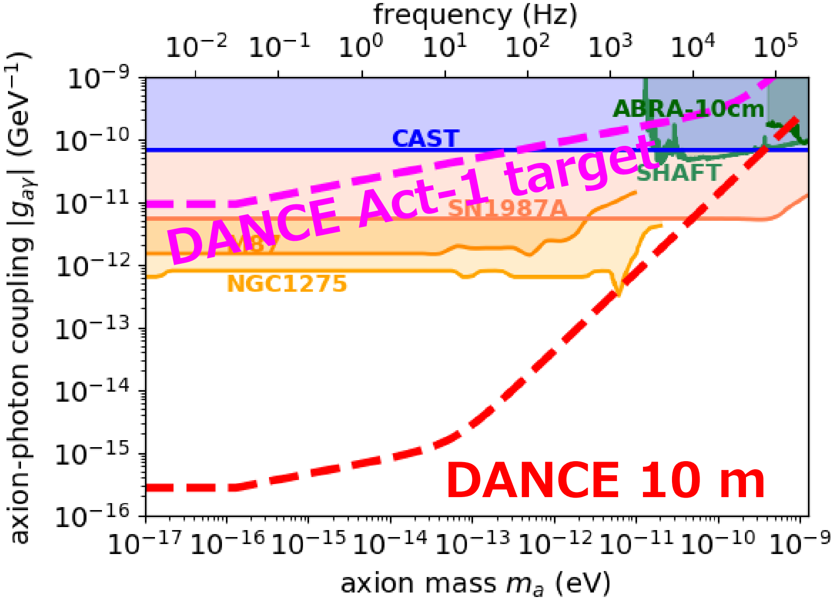




Plot by H. Takidera

Future Plans

- Demonstrate simultaneous resonance with a bow-tie cavity by tuning laser wavelength
  - Can be done within the range of tuning
  - Finesse of ~10^4 can be achieved
  - High common-mode rejection ratio
- First data taking by Spring 2024
- x10 larger cavity & higher laser power
  - vibration isolation
  - In-vacuum

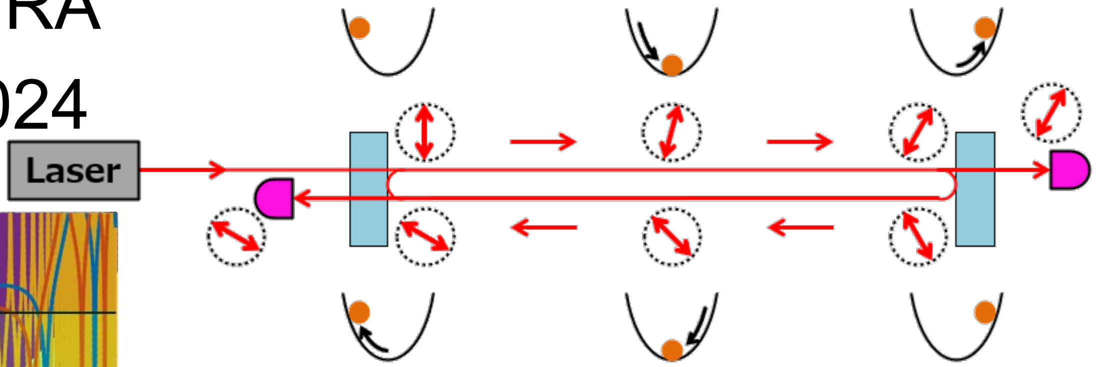


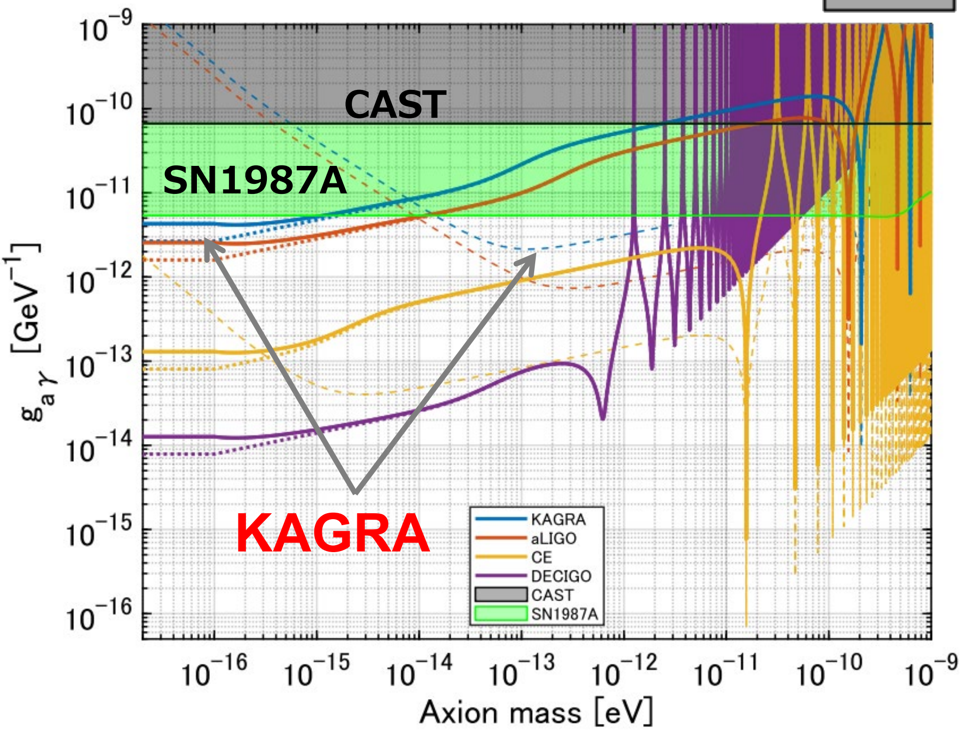
- Use phonon to improve higher mass sensitivity

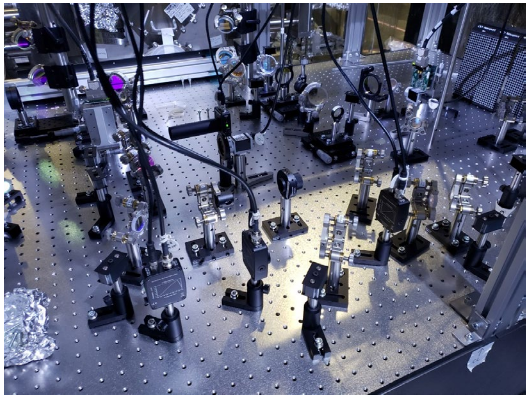
C. Murgui, Y. Wang, K. M. Zurek, arXiv:2211.08432

Search with KAGRA and LIGO

- Linear cavities can be sensitive when the round-trip time equals odd-multiples of axion oscillation period
- Polarization optics installed at 3-km arm cavity transmission of KAGRA
- O4b run in Spring 2024







K. Nagano, T. Fujita, Y. Michimura, I. Obata, PRL **123**, 111301 (2019)
K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita, Y. Michimura, I. Obata, PRD **104**, 062008 (2021)

Summary

- DANCE searches for ultralight axion dark matter by polarization measurements with optical cavity
- Data analysis and veto pipeline developed, first results released

Y. Oshima+, PRD **108**, 072005 (2023)
H. Nakatsuka+, PRD **108**, 092010 (2023)

- Stay tuned for new results from the upgrade

公益財団法人 住友財団
The Sumitomo Foundation

科研費 KAKENHI

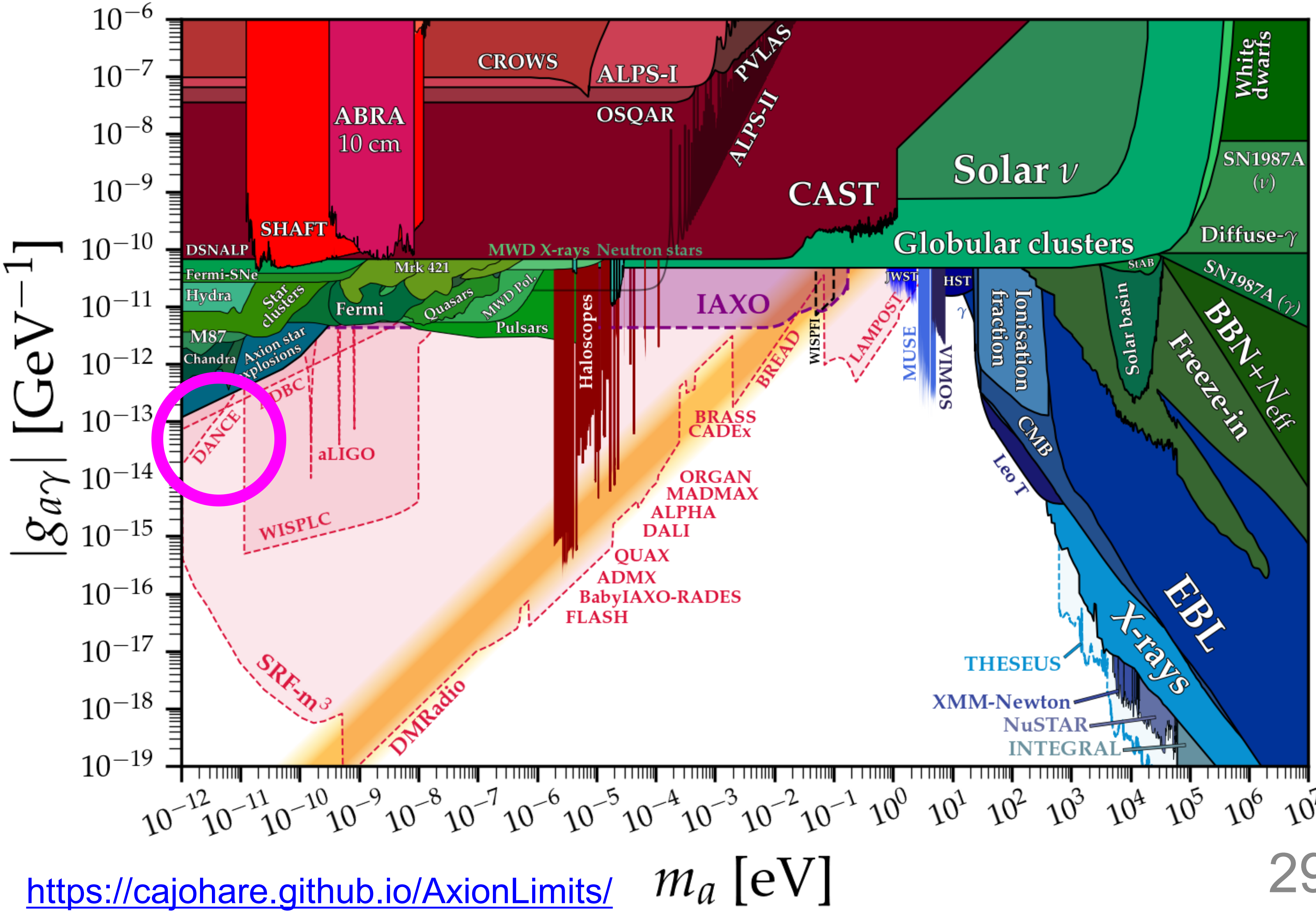
ダークマターの正体は何か？
広大なディスカバリースペースの網羅的研究
What is dark matter? - Comprehensive study of the huge discovery space in dark matter
文部科学省 科学研究費助成事業 学術変革領域研究（2020–2024）

JST Japan Science and Technology Agency

PRESTO SAKIGAKE

Supplemental Slides

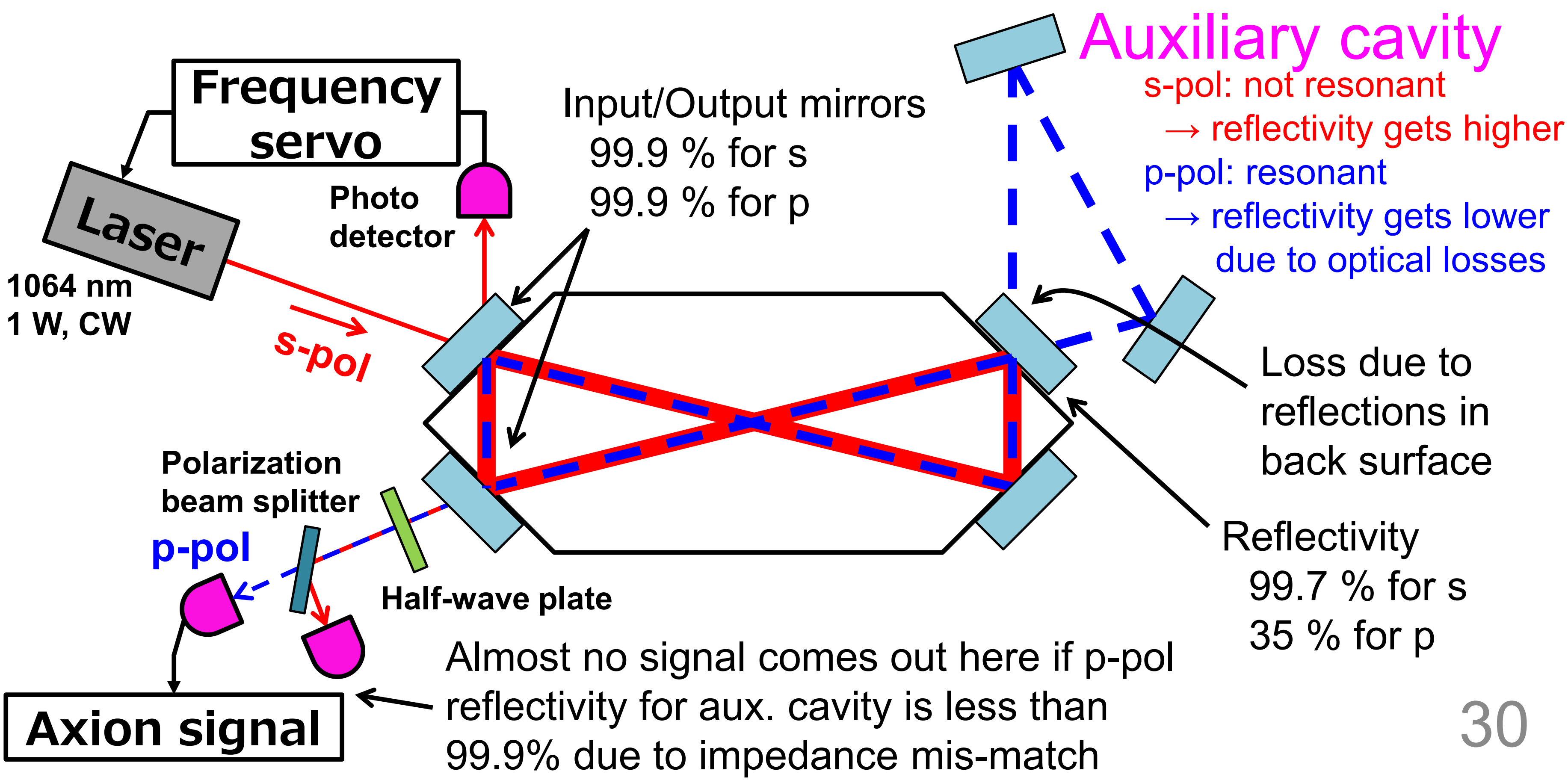
AxionLimits



https://cajohare.github.io/AxionLimits/

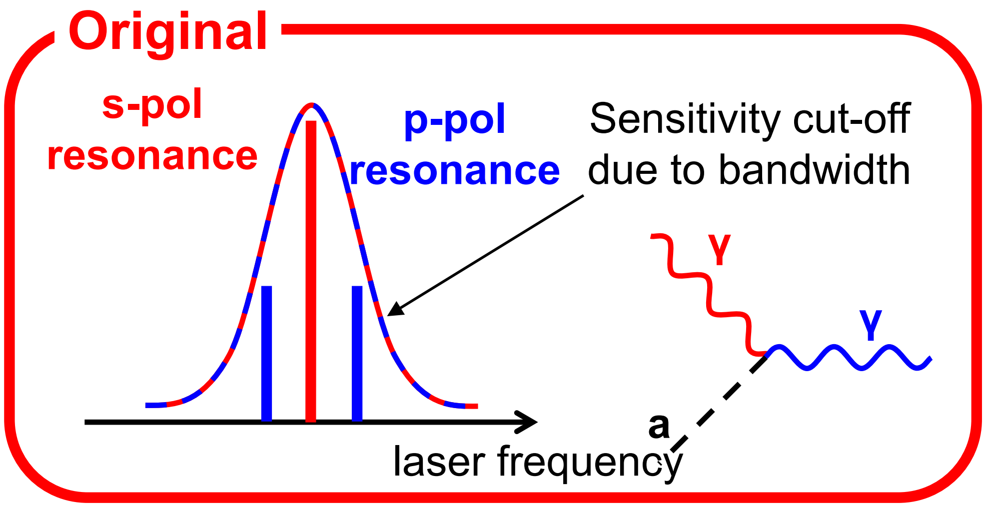
Losses in Auxiliary Cavity

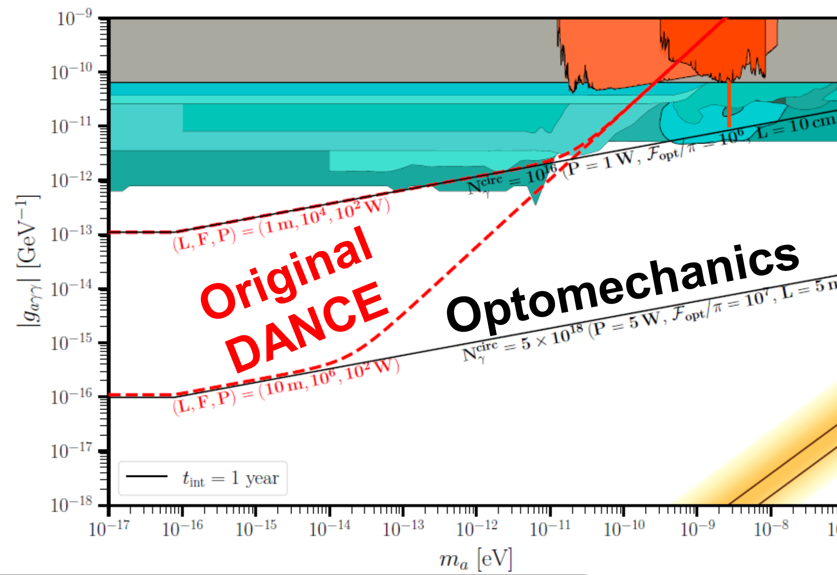
- Amount of p-pol is affected by optical losses at back reflections and mode mis-match
- Signal is largely lost due to this optical losses

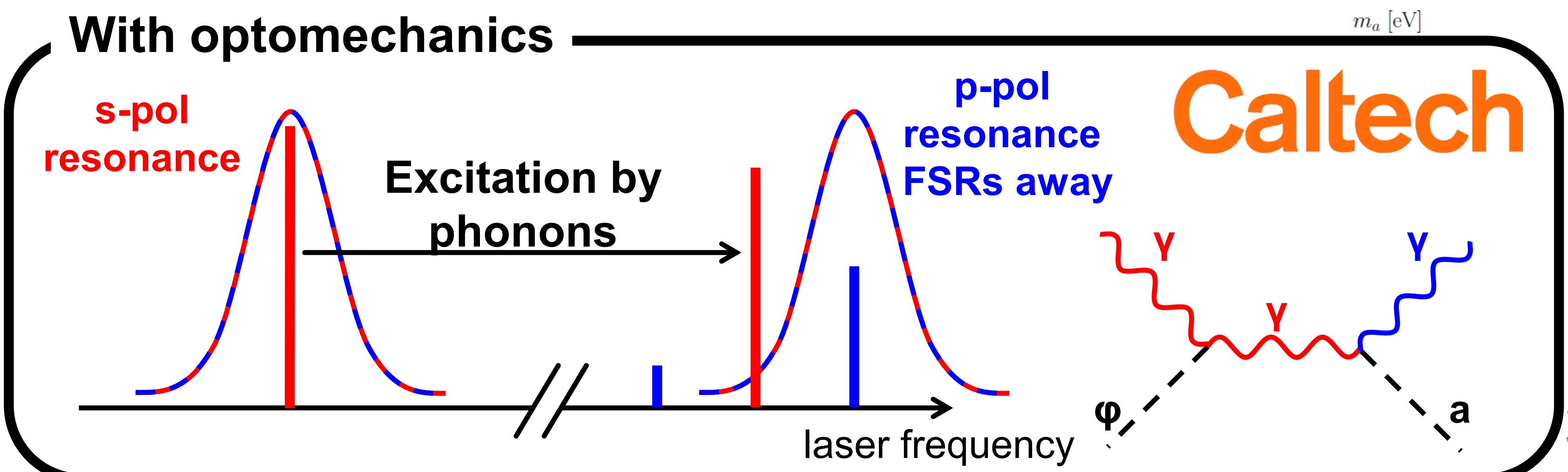


Axion + Optomechanics

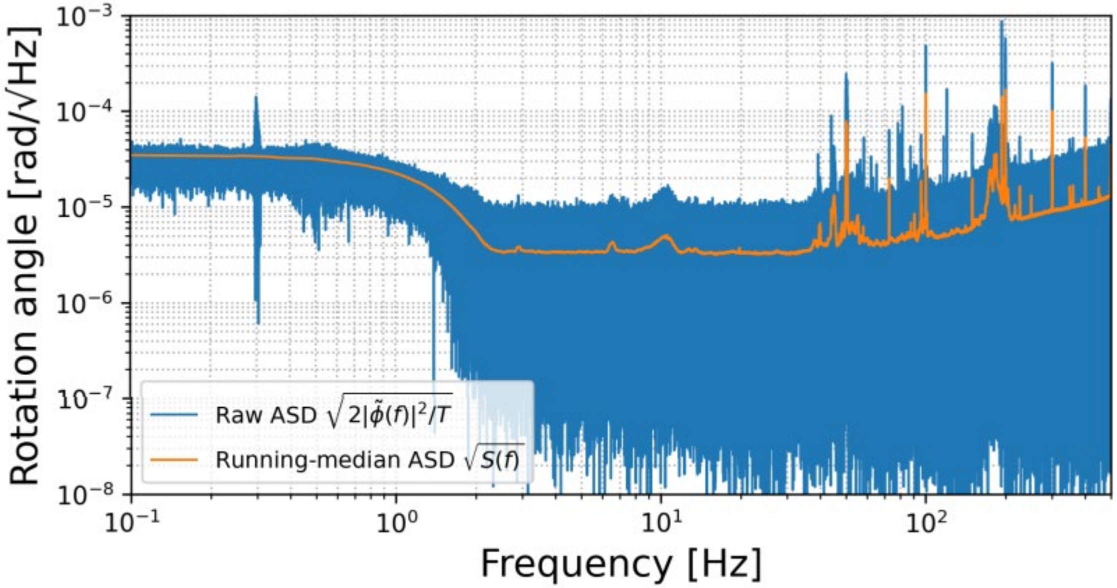
- Optomechanics to improve higher mass sensitivity
  C. Murgui, Y. Wang, K. M. Zurek, arXiv:2211.08432







Sensitivity to Pol. Rotation Angle



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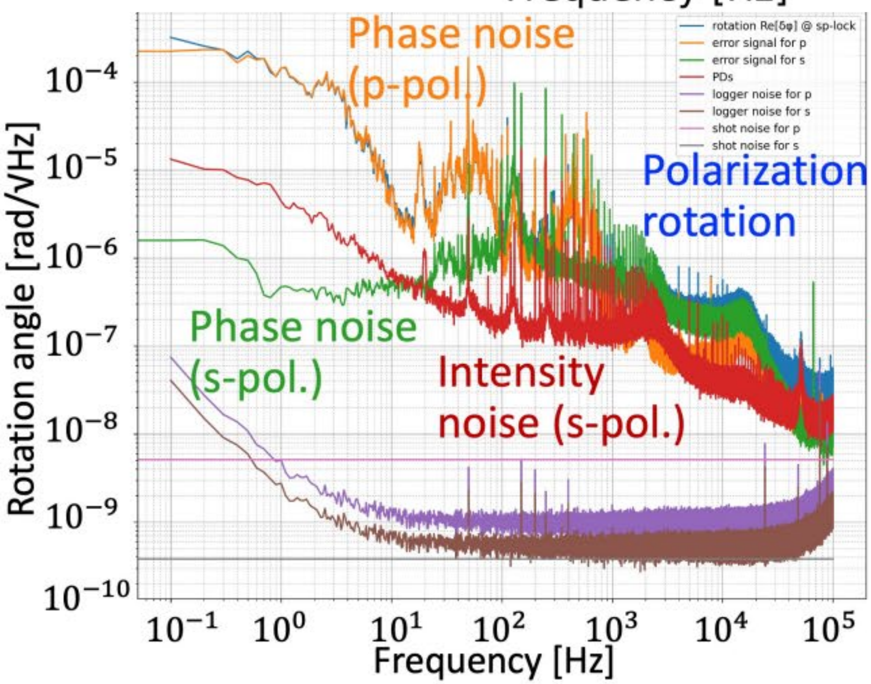
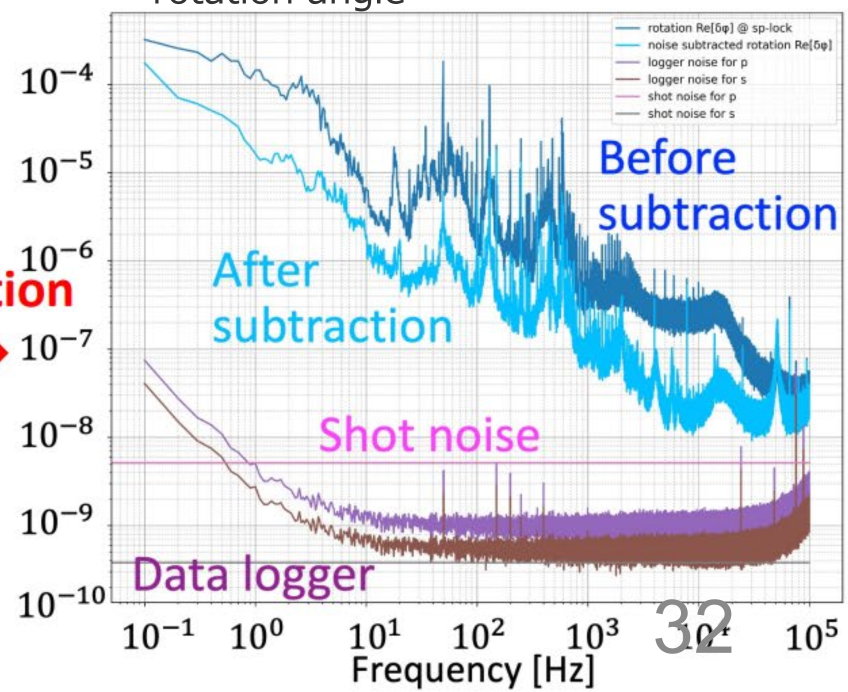


Offline noise subtraction

Latest sensitivity to polarization rotation angle



Veto Analysis

TABLE II. Summary of remaining peaks after the veto procedures.

Frequency (Hz)	SNR ρ (Measured value)	SNR ρ (Detection threshold)
81.6712	3243	109
119.983	2073	137
120.001	2616	137
120.113	1125	137
120.117	159	137
120.118	7637	137
396.142	373	313

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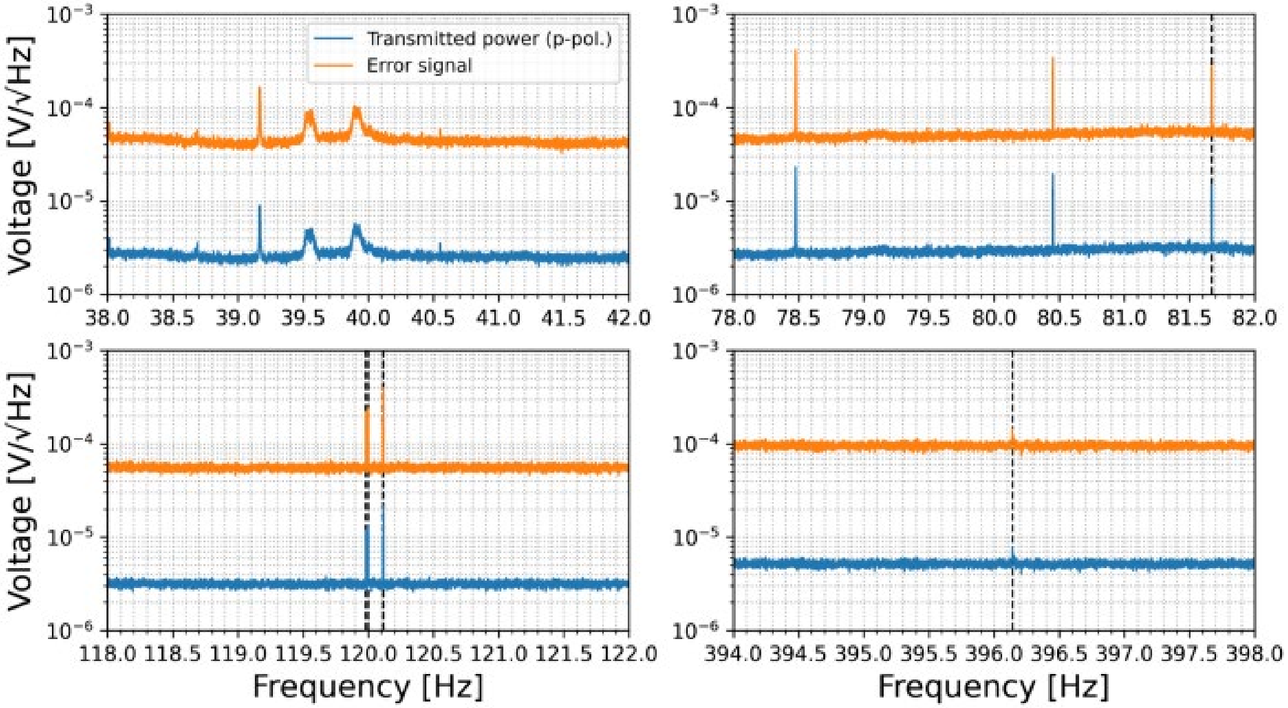
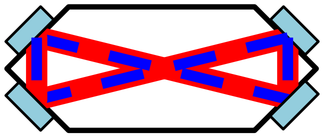


Methods Comparison



	Auxiliary cavity	**Wavelength tunable laser**	**Incident angle tuning**
Proposal	Birmingham PRD 101, 095034 (2020)	**This work**	MIT PRD 100, 023548 (2019)
Demostration	**DONE (This work)**	**On-going**	Not yet
High finesse	Limited	Possible	Possible
High laser power	Easy	Wide-band amp might be needed	Easy
Cavity lock	Complicated	Easy	Easy
Sweeping for search	Easy	Need to re-lock	Need to change mechanically
Coating dependence	Not much	Depend on luck	Depend on luck
Vibration CMRR	Different path beteeen s/p	Same path between s/p	Same path (but complicated mount)