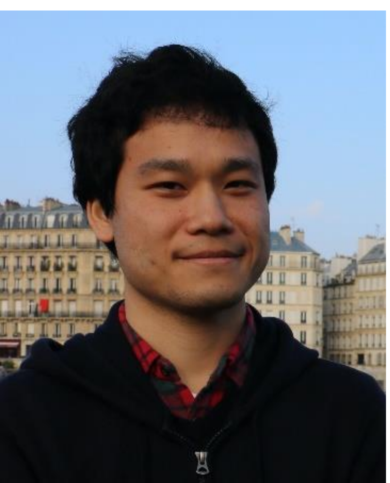
ASU Cosmology Seminar @ Online

March 16, 2022

DANCE

Dark matter Axion search with riNg Cavity Experiment



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PRESTO, JST

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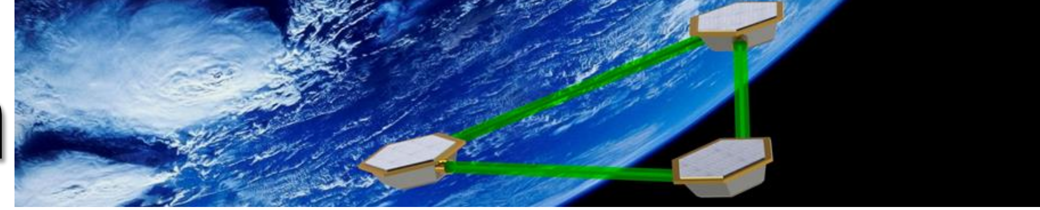
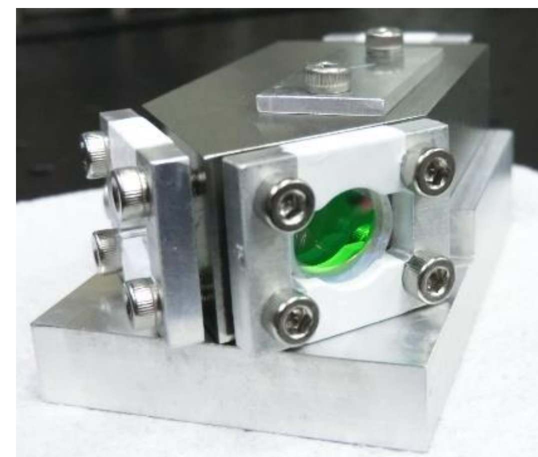
Slides are available at https://tinyurl.com/YM20220316

Self Introduction

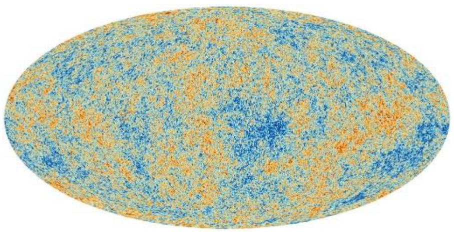


- Yuta Michimura (道村唯太)
  Assistant Professor
  at Department of Physics, University of Tokyo
- Laser interferometric gravitational wave detectors
  - KAGRA
  - DECIGO (SILVIA)
- Searches for new physics with laser interferometry
  - Lorentz invariance test
  - Gravity/quantum experiments with milligram-scale optomechanics
  - Dark matter searches etc…



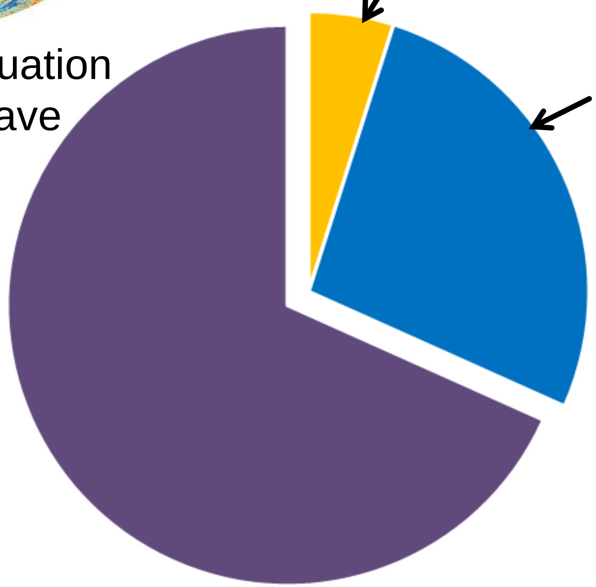
Dark Matter Mystery

- Suggested in 1930s from galaxy rotation curves
- Accounts for ~80% of all the matter of the universe
- The nature remains mystery



Temperature fluctuation of cosmic microwave background

Derive energy



Ordinary matter (~5%)
can be explained by the standard model of particle physics

Dark matter (~27%)
not included in the standard model of particle physics

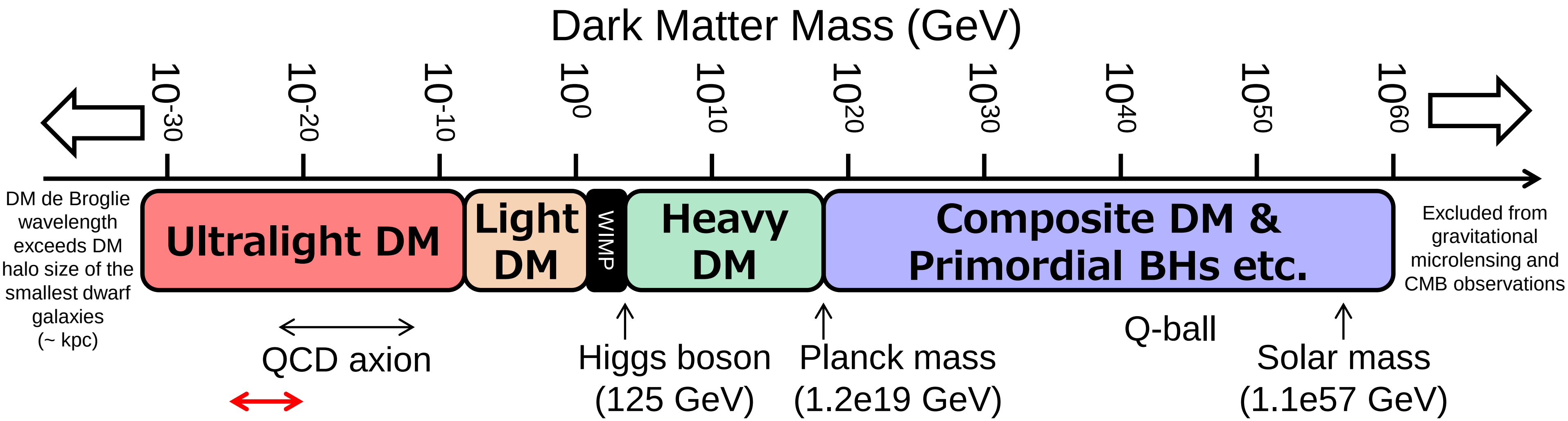
All the matter

Dark energy (~68%)
drives an acceleration of the expansion of the universe

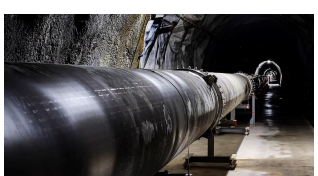
This standard model of cosmology is amazingly consistent with various observations

Dark Matter Models

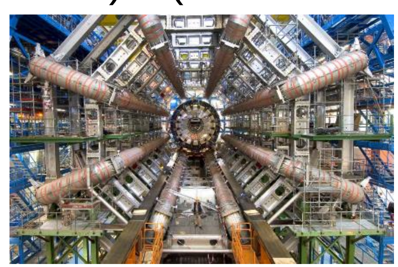
- ~90 orders of magnitude
- Searches focused on WIMPs, but not detected yet
- Motivates new searches for other candidates



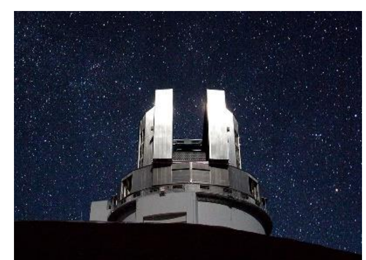
2.4 Hz ~ 2.4 kHz
(1e-14 ~ 1e-11 eV)
Laser Interferometry



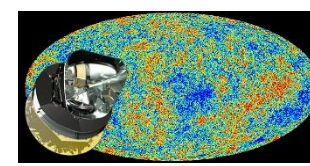
Underground experiments (XENON1T etc.)



LHC



Subaru telescope etc.



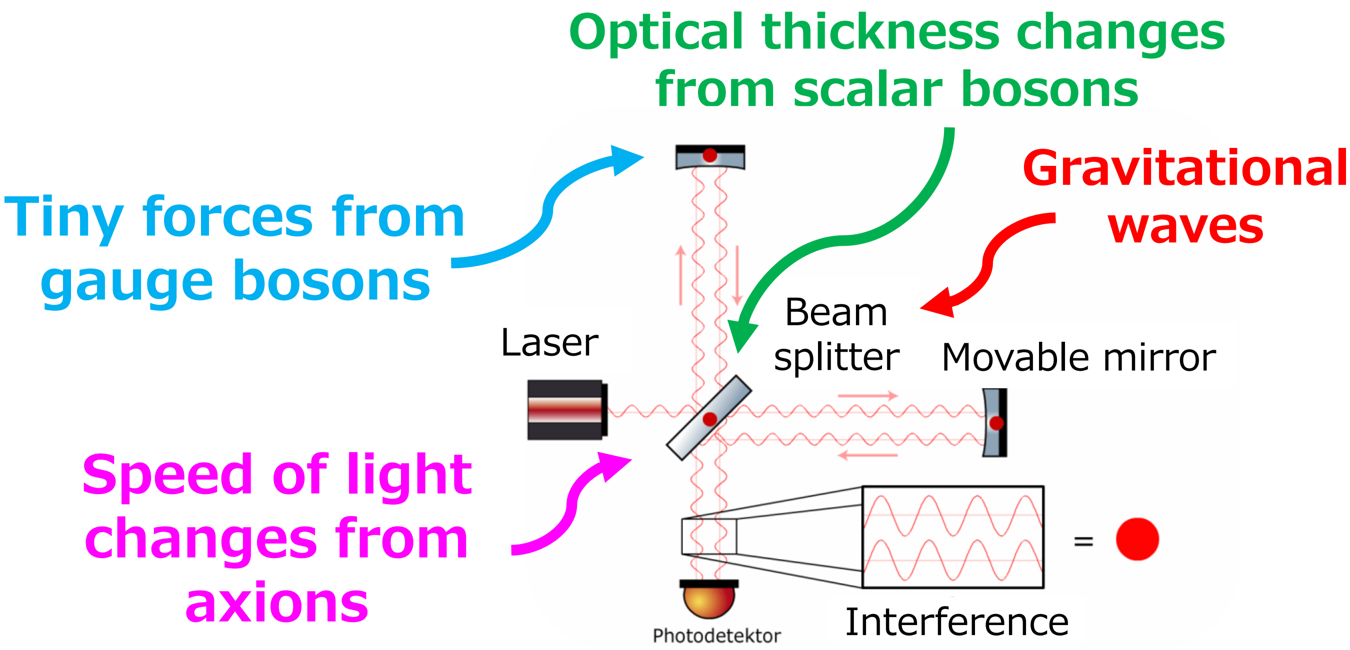
Cosmic microwave background

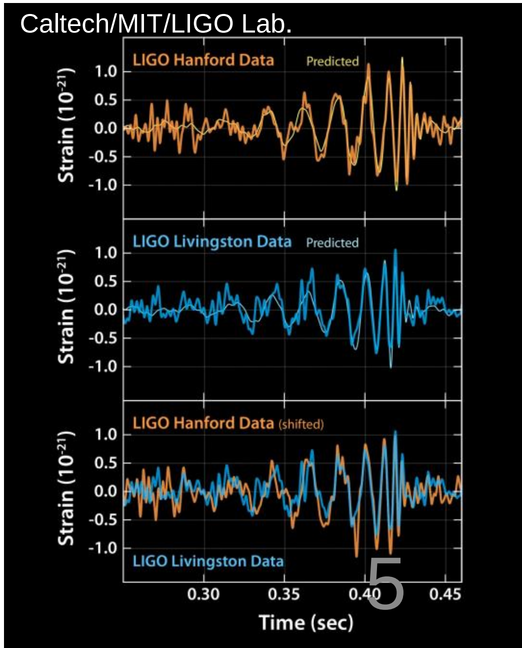
Ultralight DM with Interferometers

- 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, arXiv:2105.13085   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.

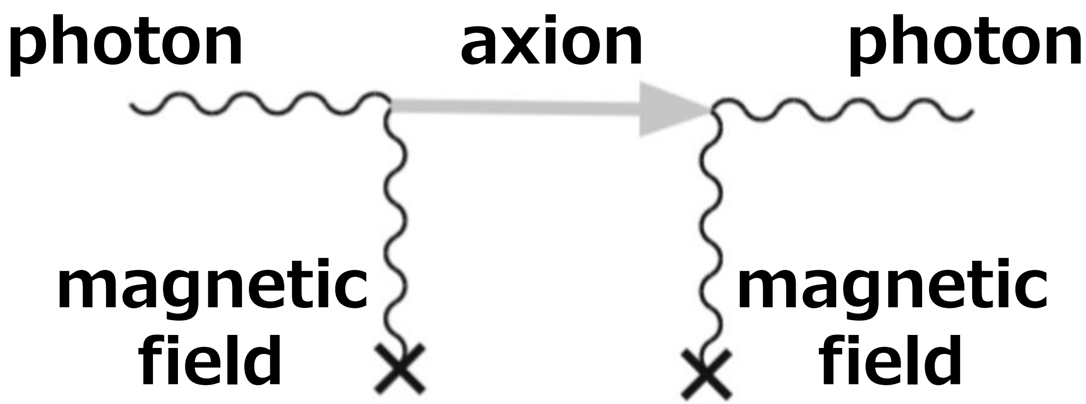
- **Axion & axion-like particles (ALPs)**
  - W. DeRocco & A. Hook, PRD **98**, 035021 (2018)
  - I. Obata, T. Fujita, Y. Michimura, PRL **121**, 161301 (2018) ⟸ This talk
  - H. Liu+, PRD **100**, 023548 (2019)
  - K. Nagano, T. Fujita, Y. Michimura, I. Obata, PRL **123**, 111301 (2019)
  - D. Martynov & H. Miao, PRD **101**, 095034 (2020)
  - K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita, Y. Michimura, I. Obata, PRD **104**, 062008 (2021)

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

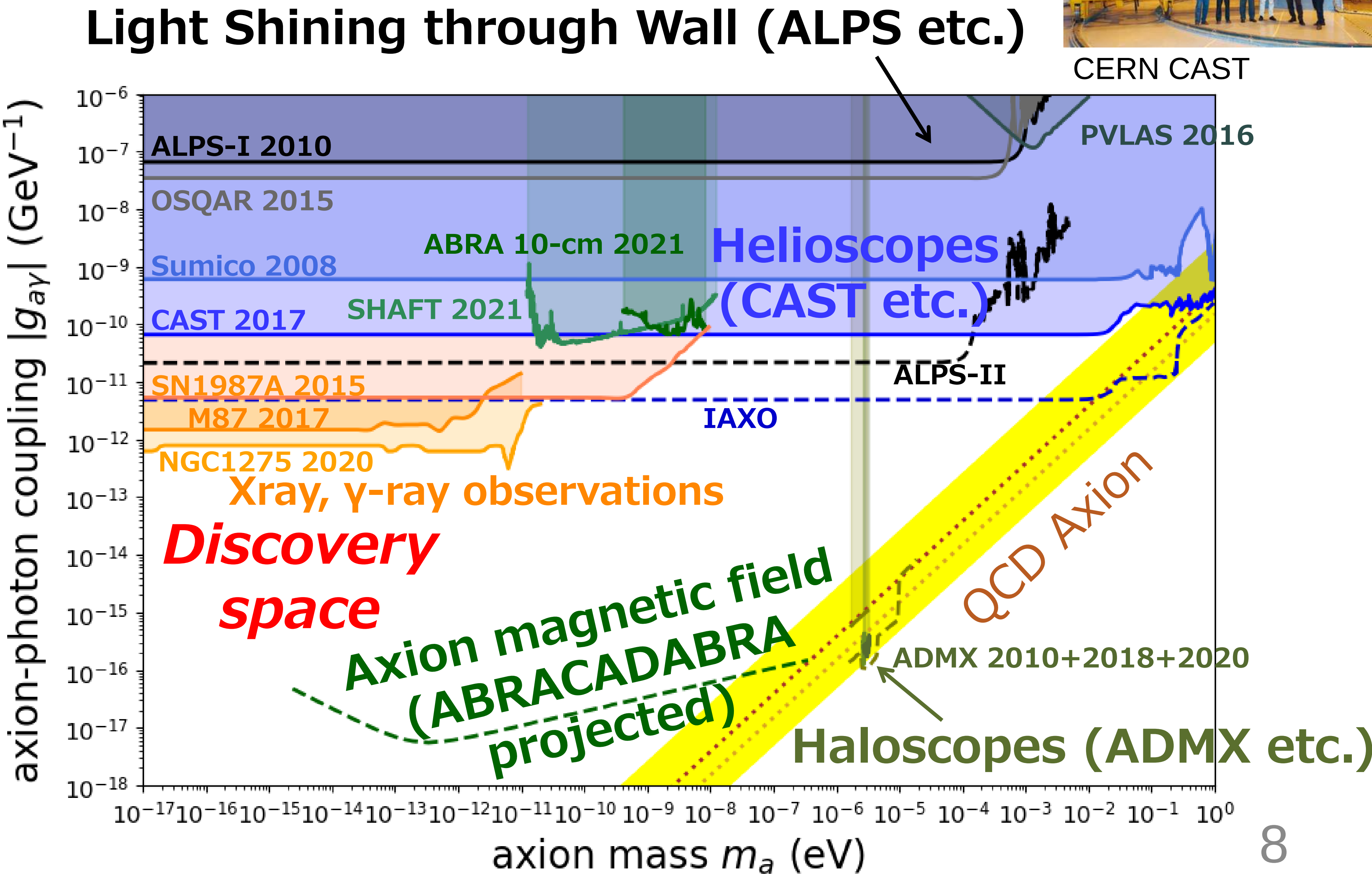
  Especially by using magnetic fields



Primakoff effect

Current Upper Limits

CERN CAST



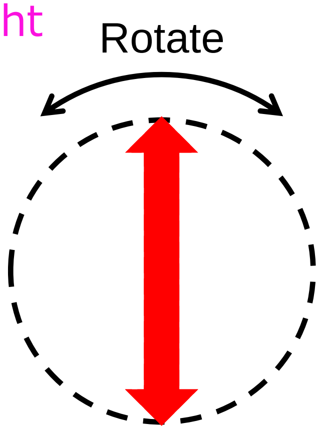
Polarization Modulation from Axions

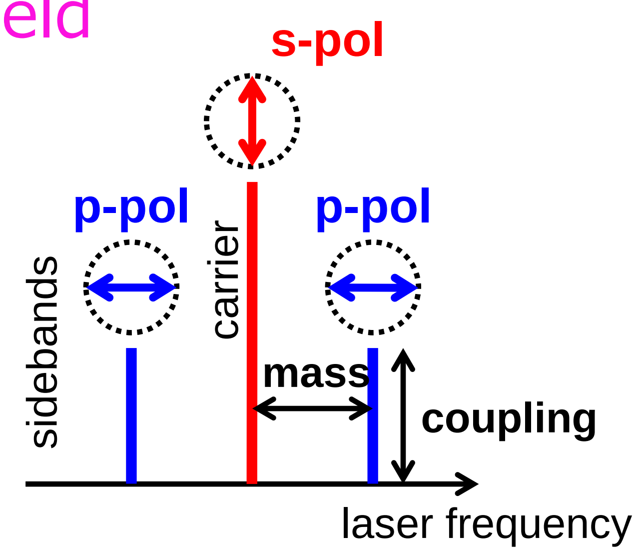
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

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

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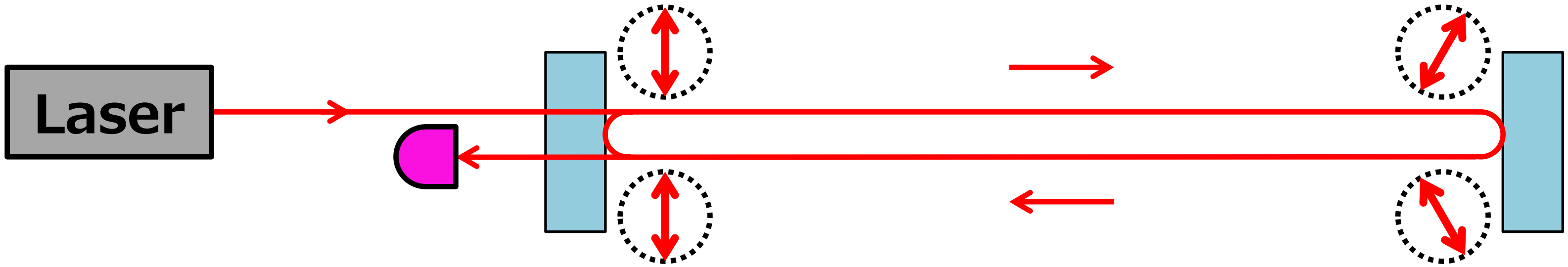
- Optical cavities can enhance the path, but polarizations flips upon mirror reflections



Enhancing the Signal with Cavities

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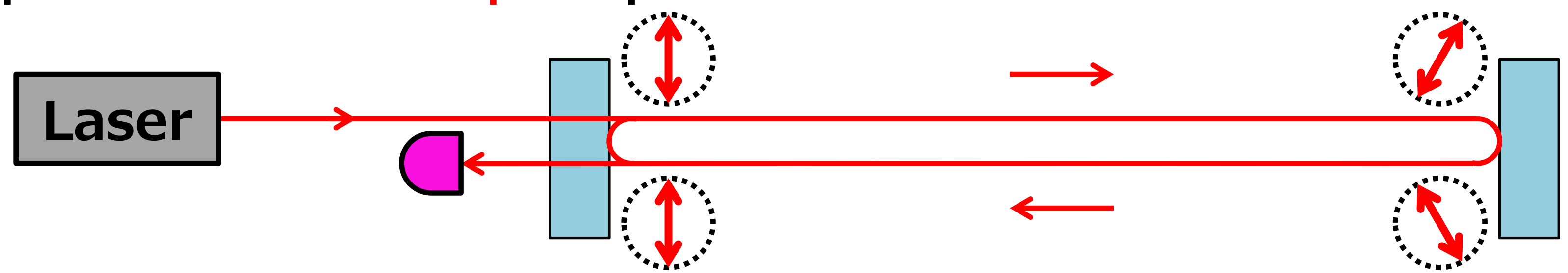
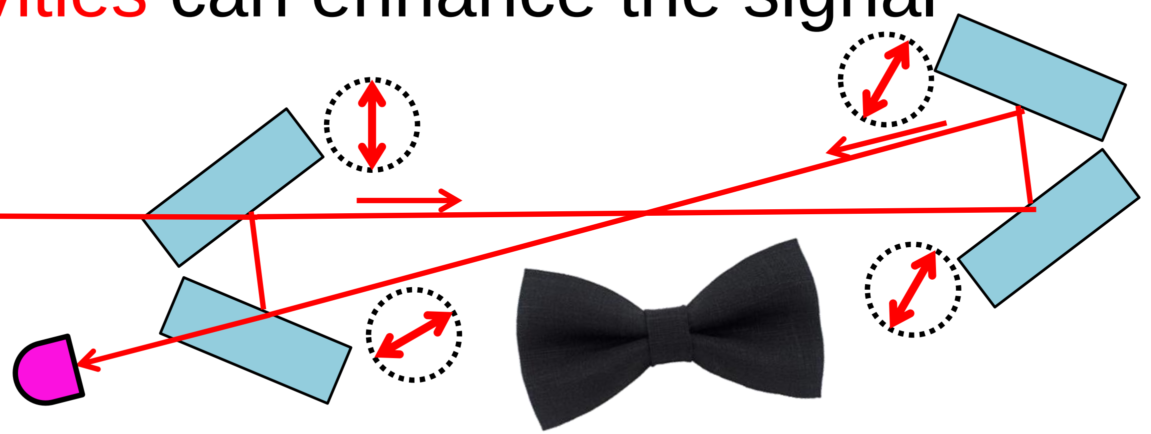
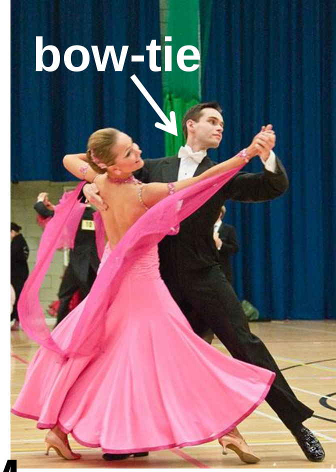


- Bow-tie cavities can enhance the signal



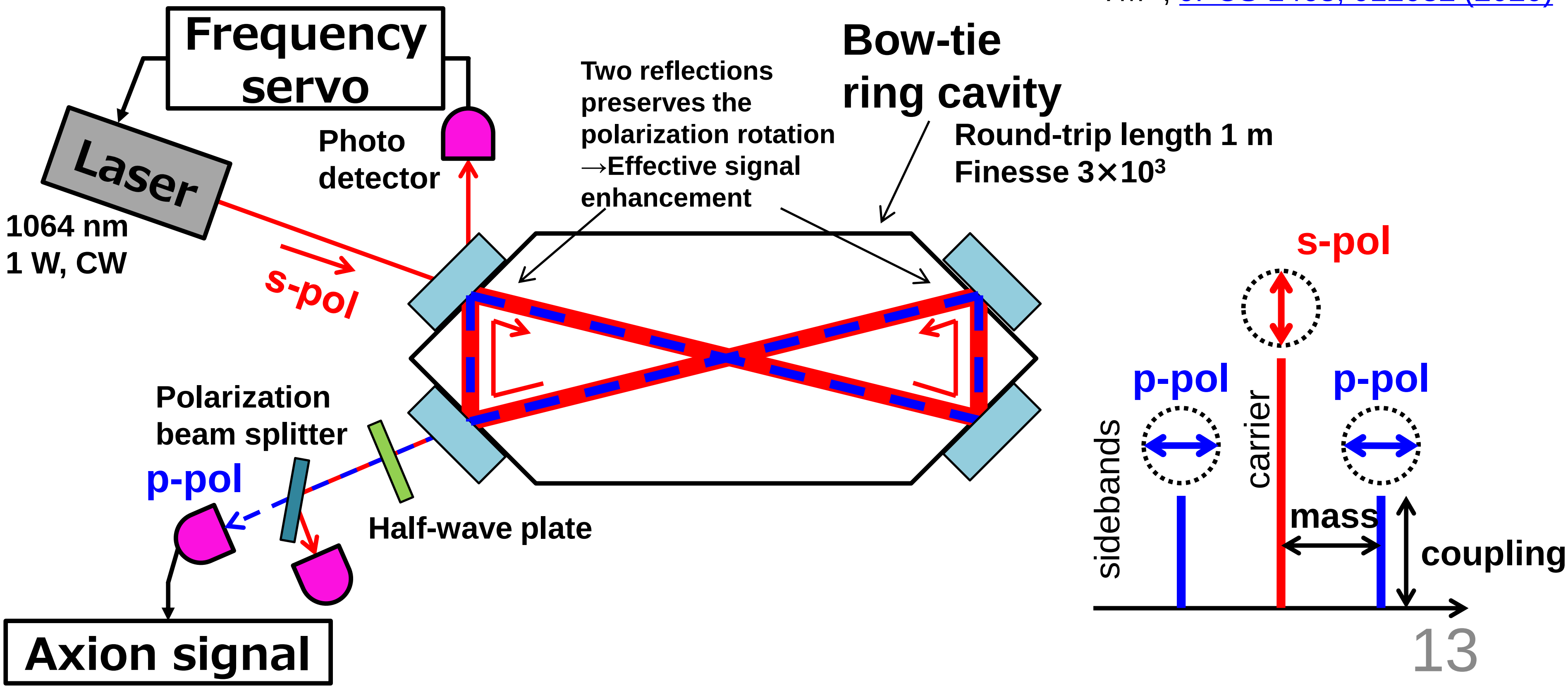
I. Obata, T. Fujita, YM
PRL **121**, 161301 (2018)

Setup of DANCE



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

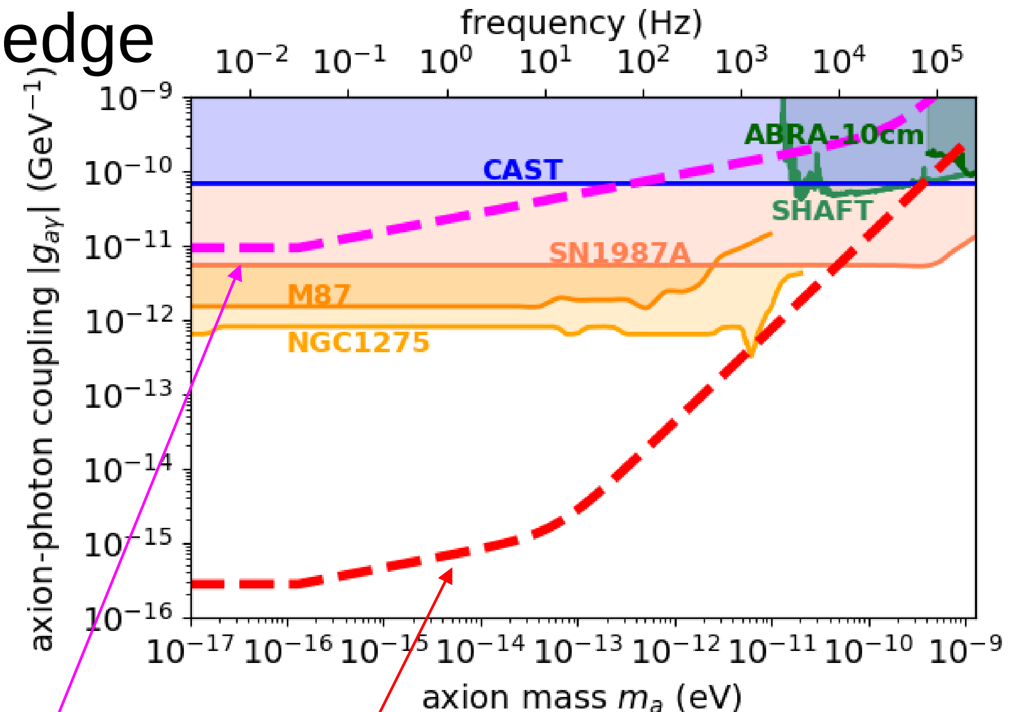
YM+, JPCS 1468, 012032 (2020)



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

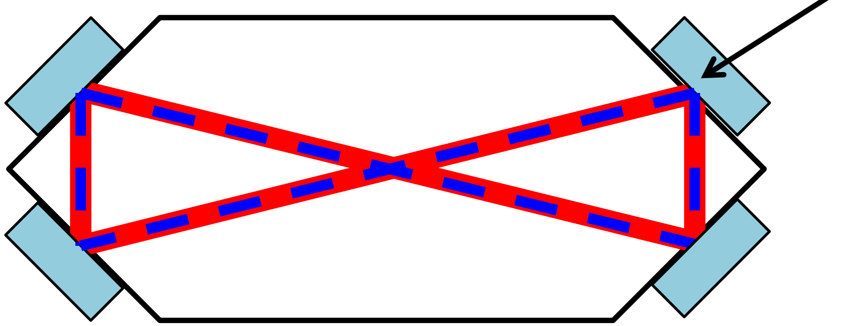
  * Shot noise limited sensitivity assumed



	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
- After reassembly of the optics by several times and installation of digital servo system for long runs, first 12-day observation was achieved in May 2021
  - Issue: s-pol and p-pol do not resonate simultaneously
    Due to phase difference in mirror reflections
- Designed an auxiliary cavity, and achieved simultaneous resonance for the first time in November 2021

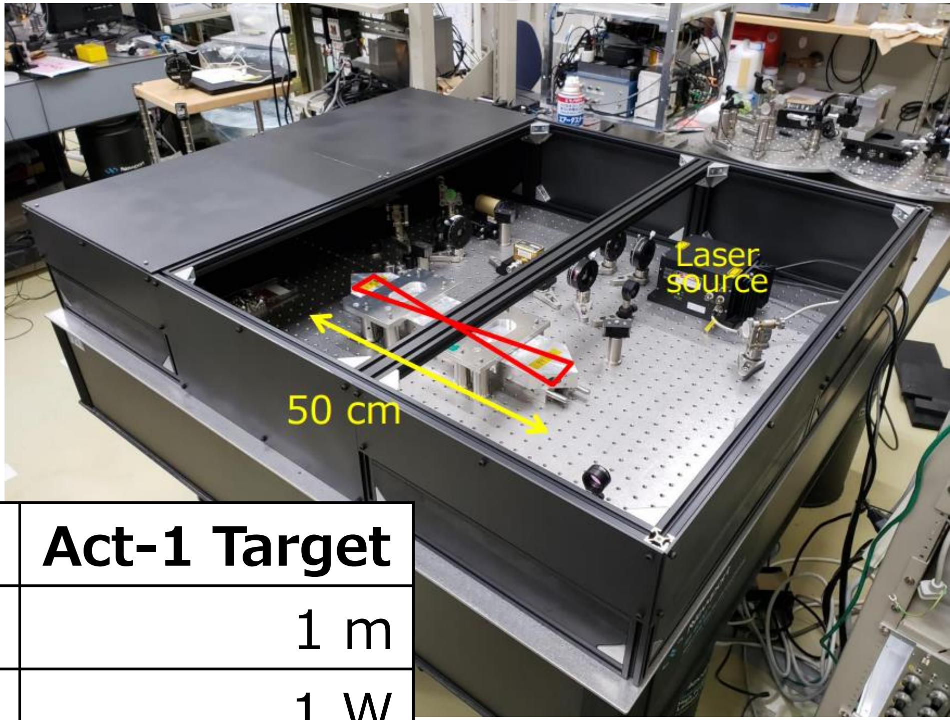


s-pol and p-pol obtain different phase on mirror reflections at non-zero incident angle
→ results in resonant frequency difference

Y. Oshima+, arXiv:2105.06252
H. Fujimoto+, arXiv:2105.08347
Y. Oshima+, arXiv:2110.10607
H. Fujimoto+, arXiv:2110.12023

First Observing Run in May 2021

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

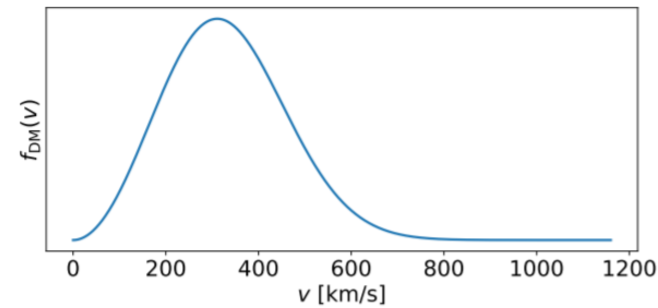


Y. Oshima+, arXiv:2110.10607

	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

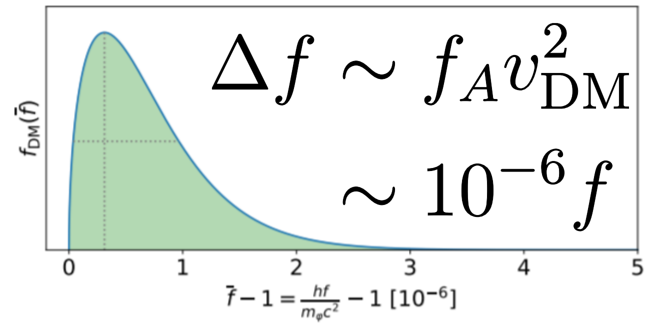
Data Analysis Pipeline

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

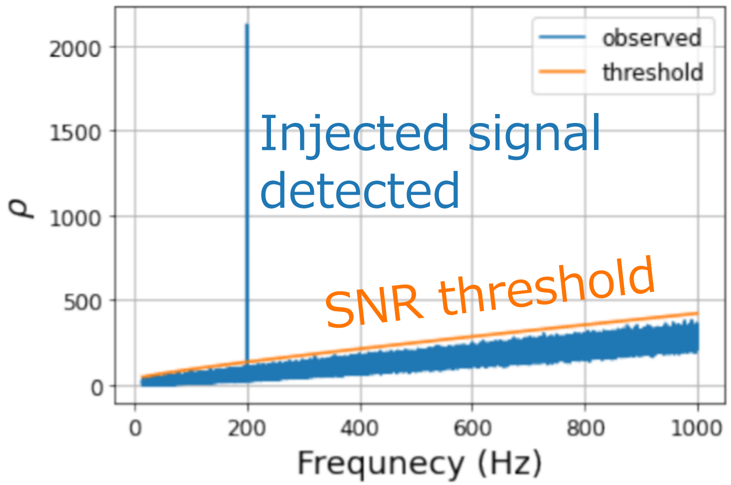
$$\rho = \sum \frac{4|\tilde{d}(f_k)|^2}{T_{\rm obs} S_n(f_k)}$$

Data

PSD

Obs. time

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



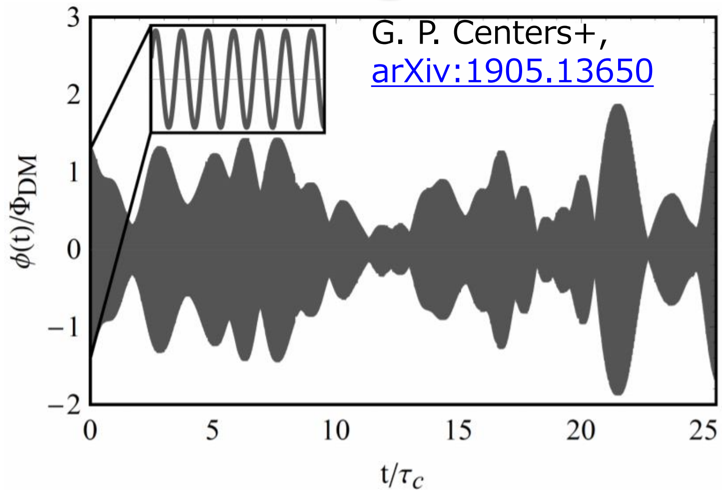
- Detection threshold determined assuming ρ follows χ^2 distribution (=assuming Gaussian noise)
- From ρ, calculate 95% upper limit on coupling constant
- Applied the pipeline to mock data for verification

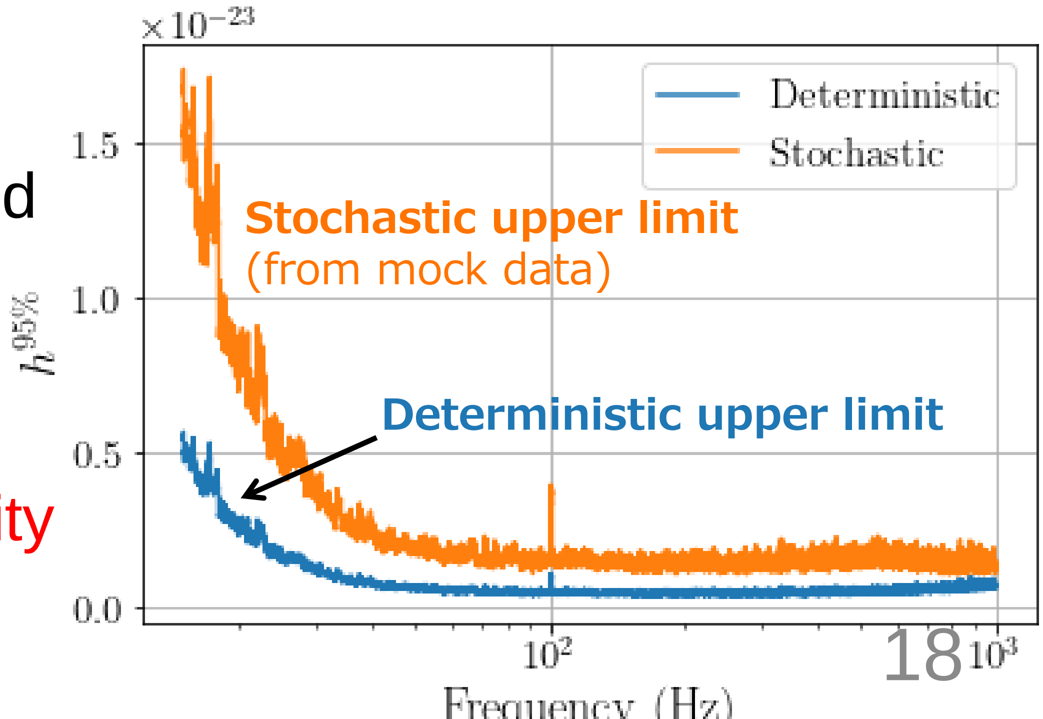
Stochastic Nature of DM Signal

- 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

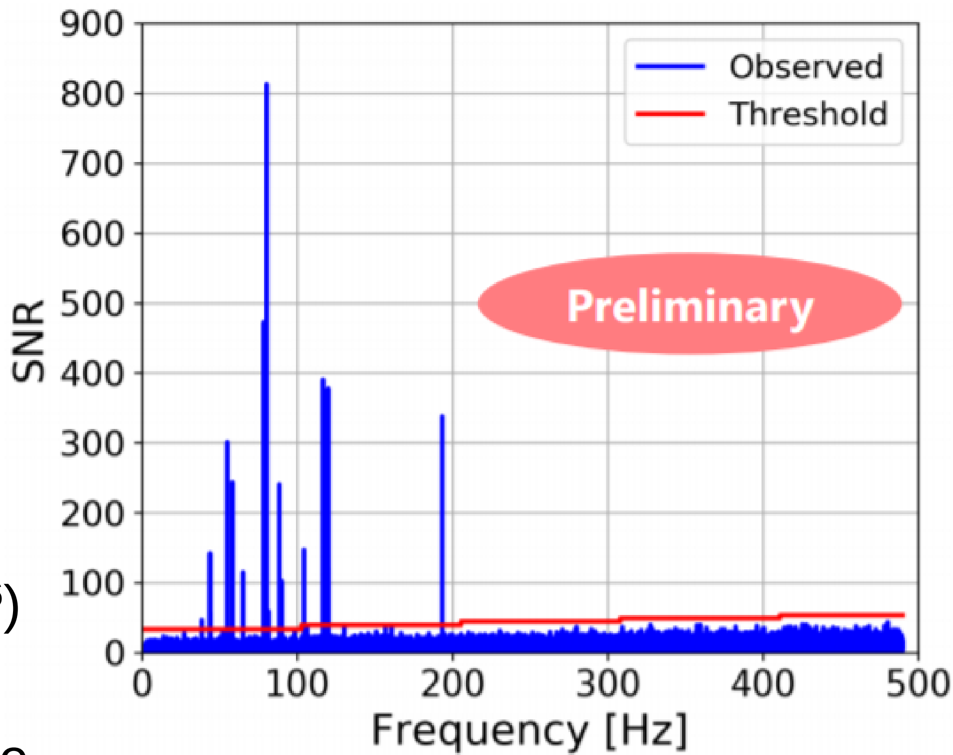




H. Nakatsuka+, *in preparation*

Preliminary Analysis Results

- Used 10-hour data from 12-day run
- 82 candidates found from initial analysis
- Veto analysis
  - Q-factor veto
    (DM signal must have Q of 10^6)
  - Consistency veto
    (Frequency should be the same for different set of 10-hour data)



→ Currently, 8 candidates left (under investigation)

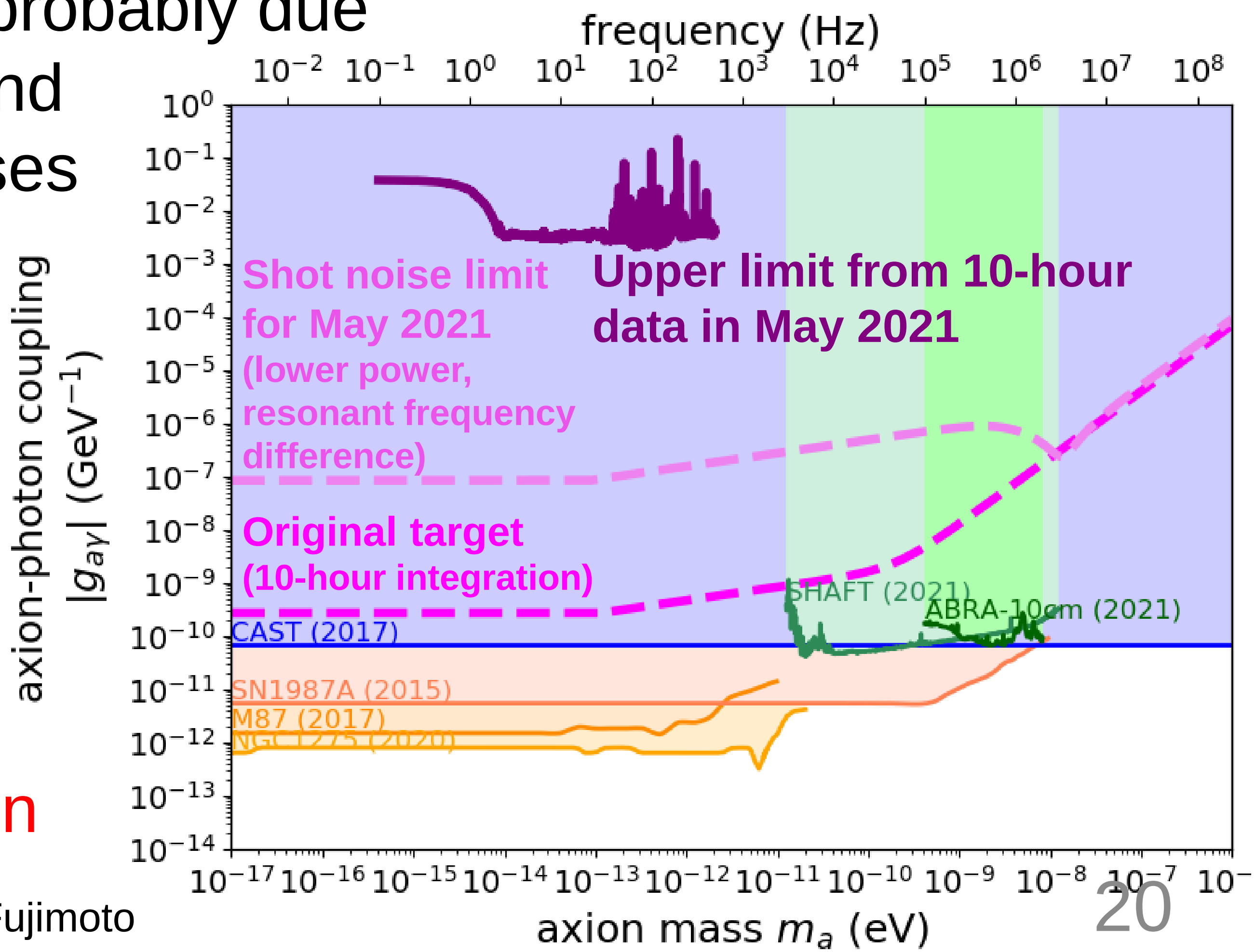
They are all ~40 Hz harmonics

Probably from some mechanical resonances

Analysis by Y. Oshima
Pipeline developed by
J. Kume, S. Morisaki *et al.*

Preliminary Upper Limit

- Shot noise limit worse by 3 orders of magnitude due to resonant frequency difference between s/p-pol
- Even worse probably due to intensity and vibration noises

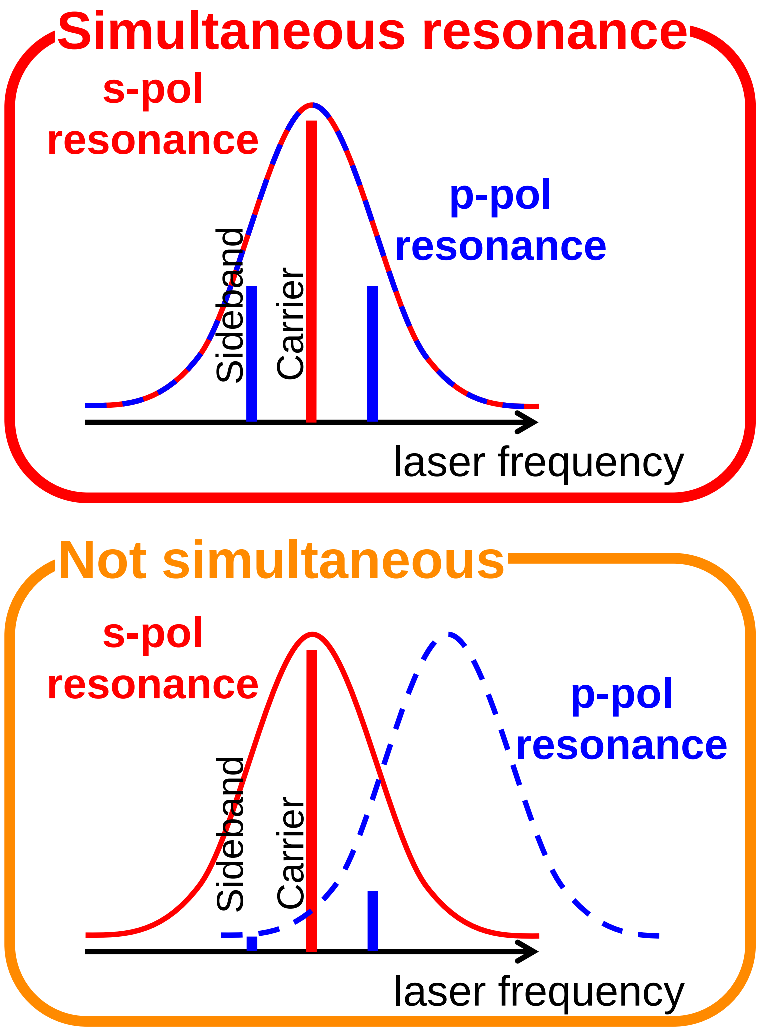


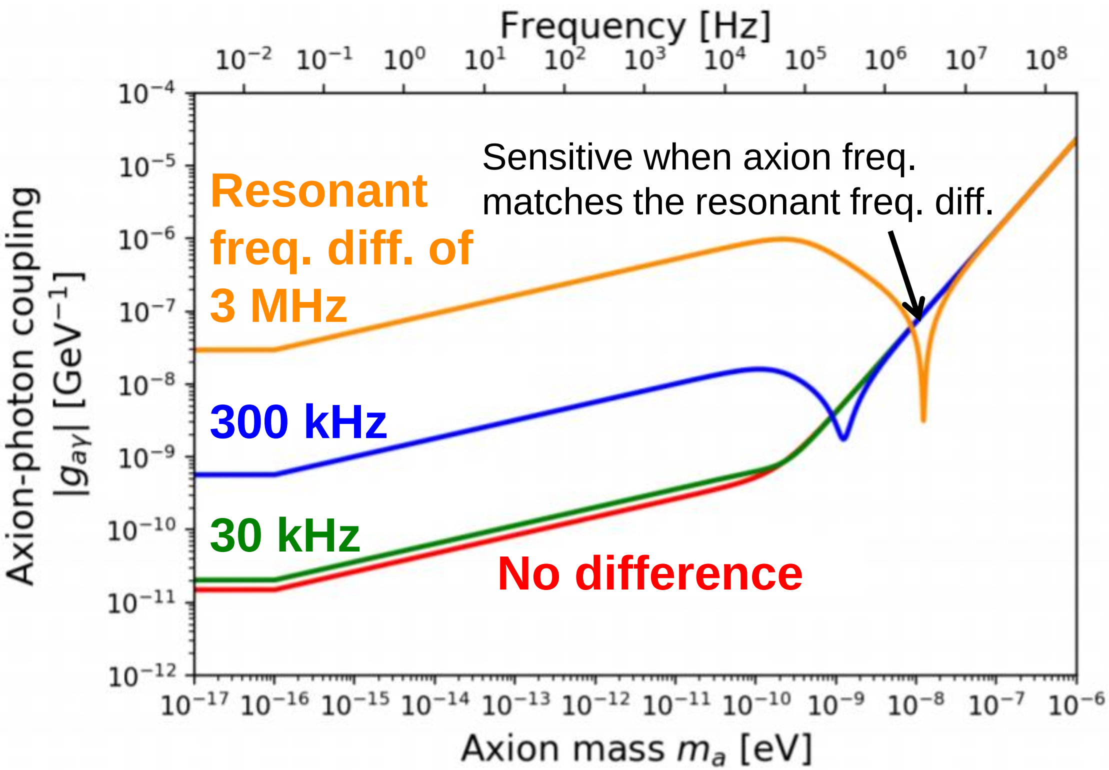
- First end-to-end demonstration

Analysis by Y. Oshima & H. Fujimoto

Simultaneous Resonance

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

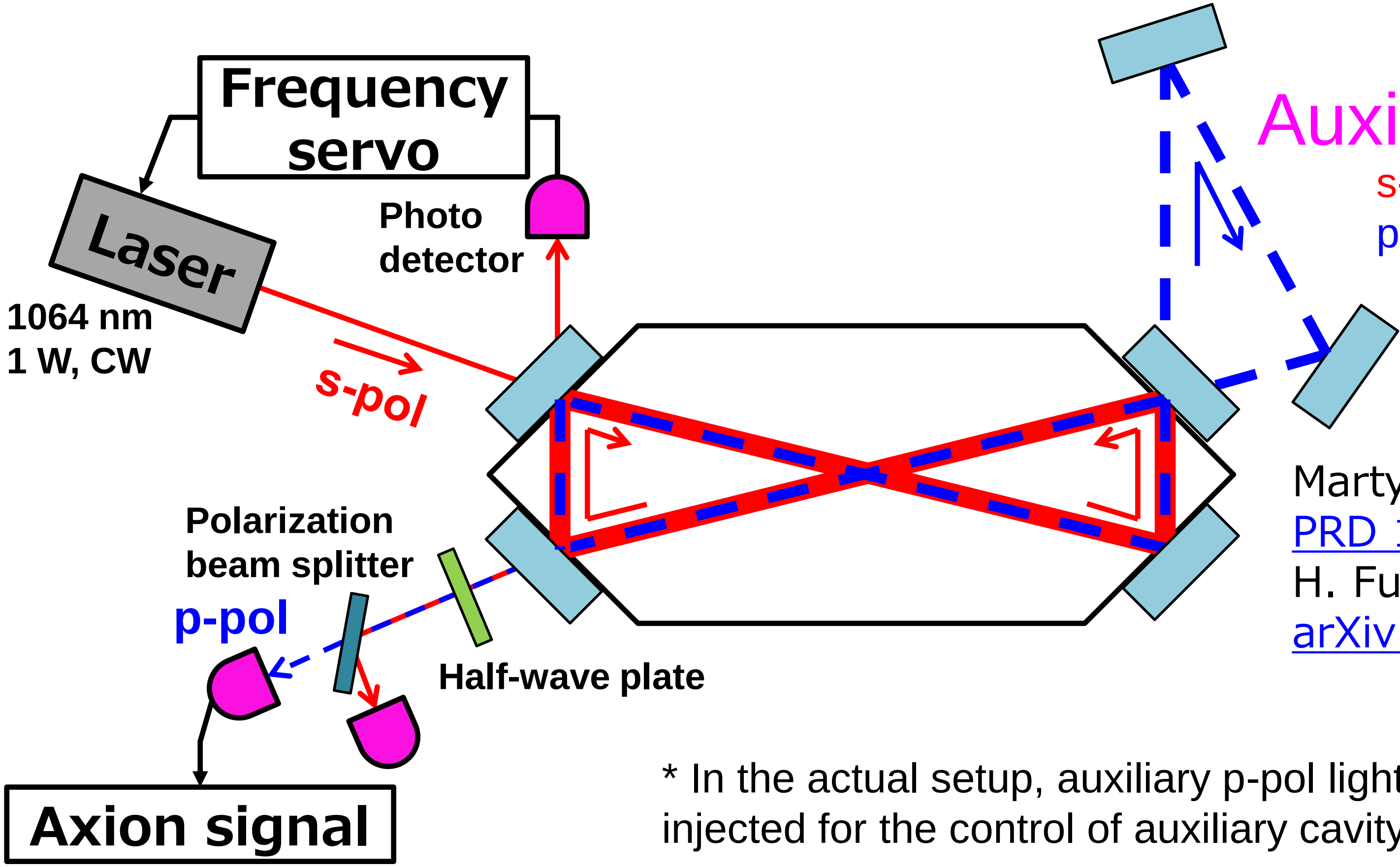




Plot by Y. Oshima & H. Fujimoto

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+,
arXiv:2110.12023

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

Updated Setup

- New lab prepared
- New 2W laser source obtained
  (previously, 0.5W laser source)
- Installed an auxiliary cavity

Auxiliary cavity

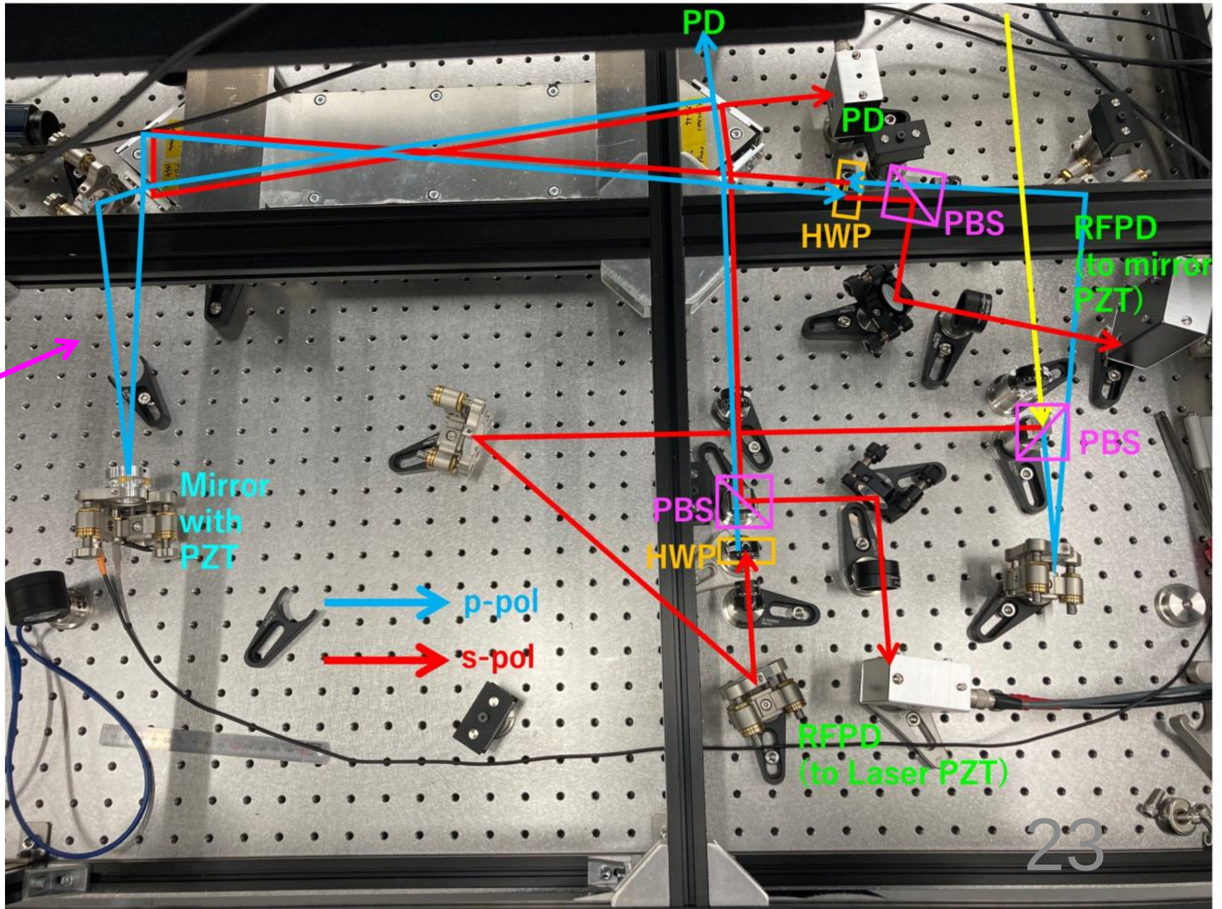
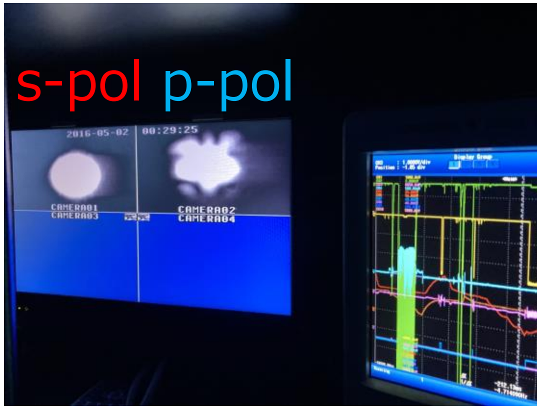


Photo by H. Fujimoto

Simultaneous Resonance Achieved

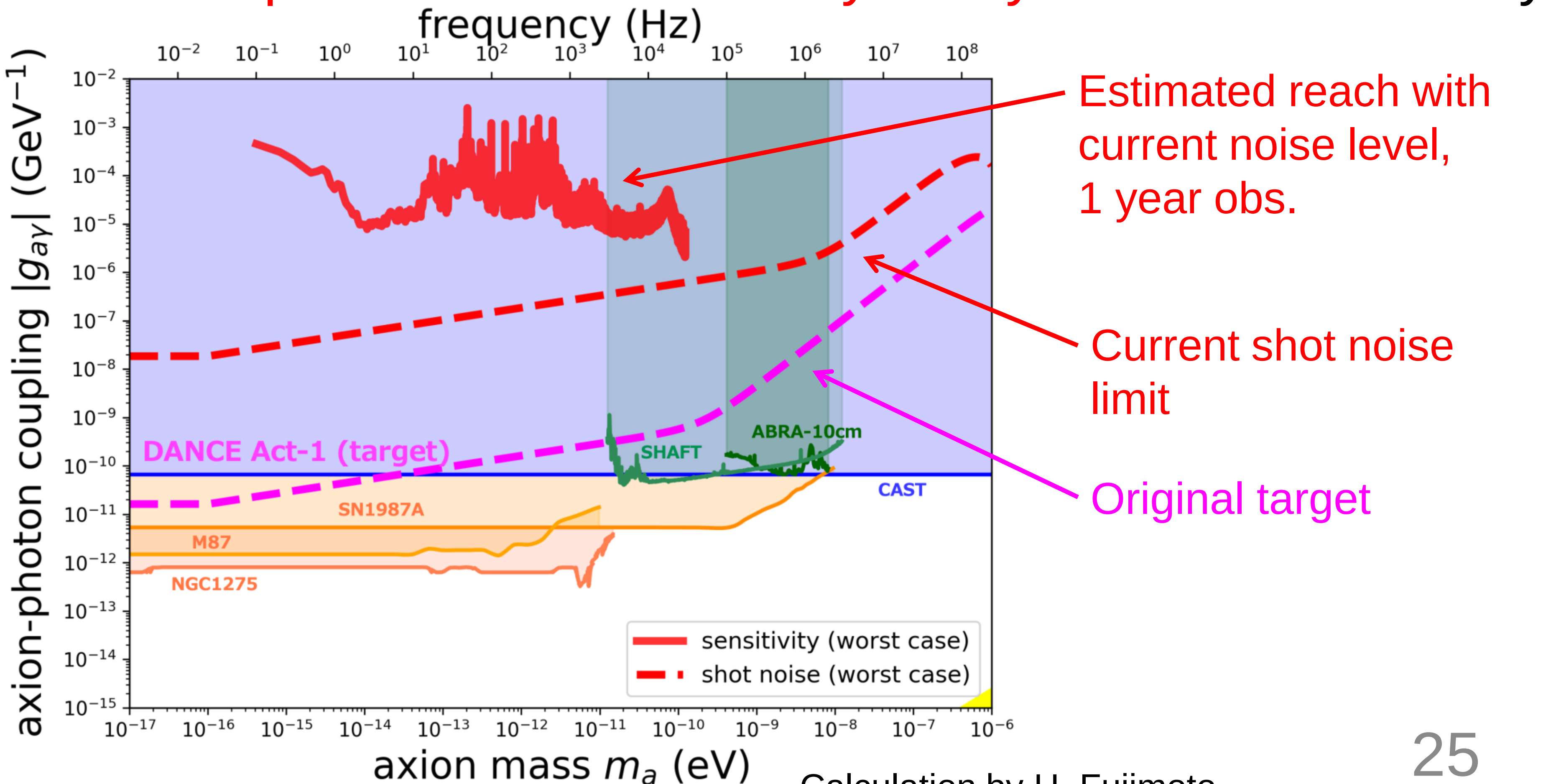
- First demonstration in November 2021 (with a PBS we already had)
- Ordered better mirrors optimized for this setup



	May 2021	Now (Jan 2021)	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	1204(12) s-pol, with cavity lock	3×10^3
Finesse (for sidebands)	195(3) p-pol	91(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

Sensitivity with Auxiliary Cavity

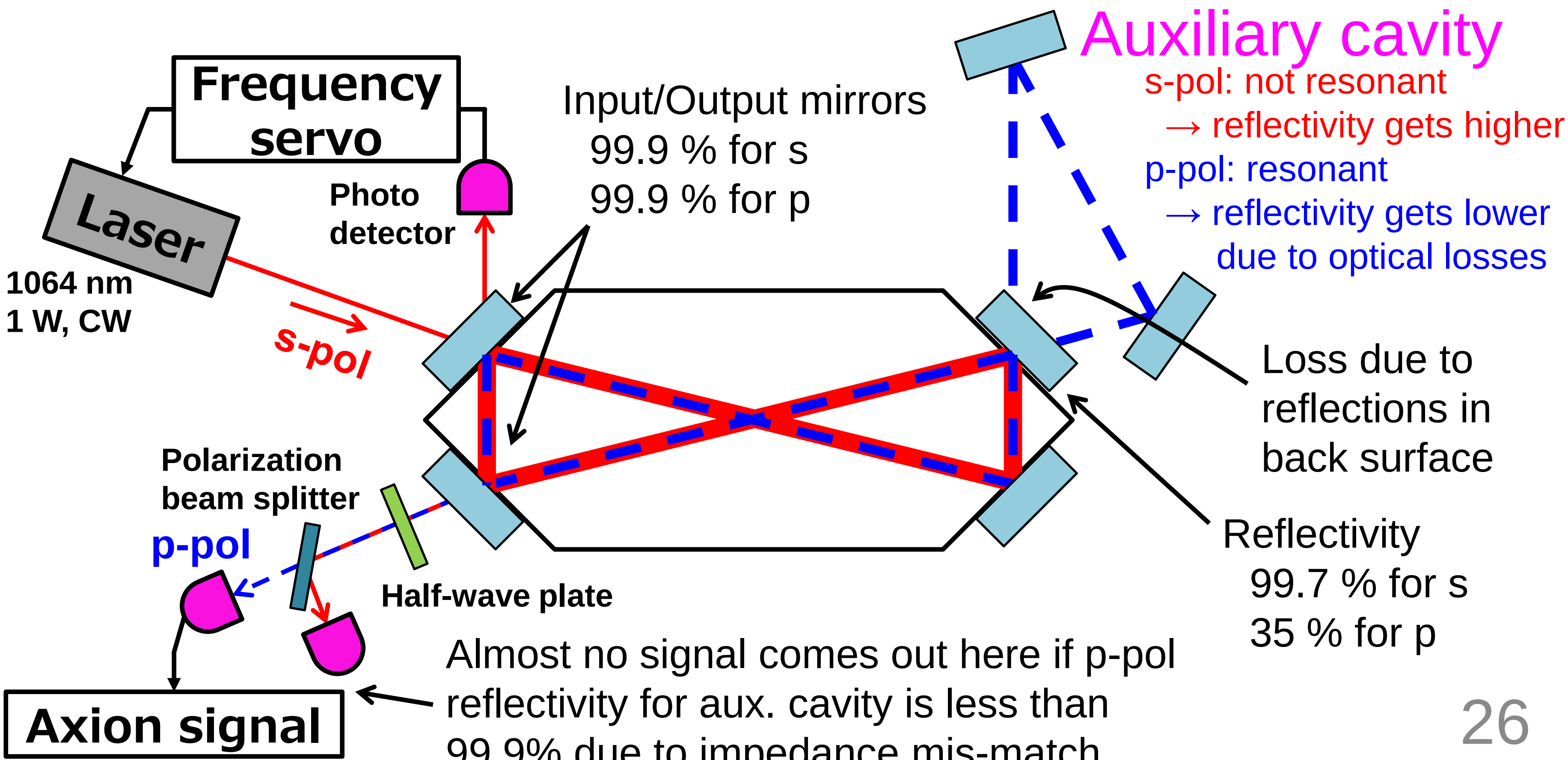
- Sensitivity improved in broad mass ranges with simultaneous resonance
- But optical losses in auxiliary cavity limits the sensitivity



Calculation by H. Fujimoto

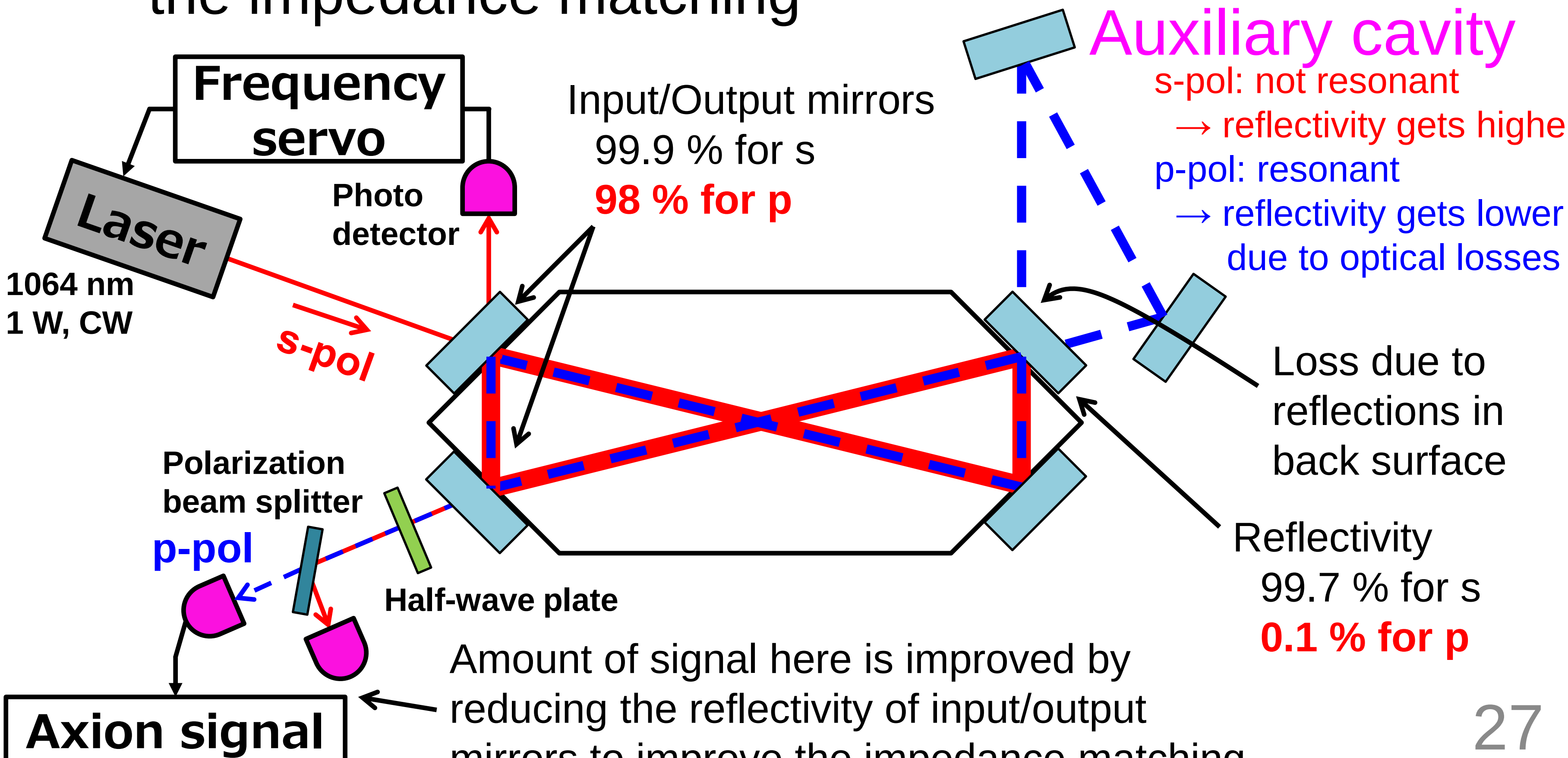
Losses in Auxiliary Cavity

- 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



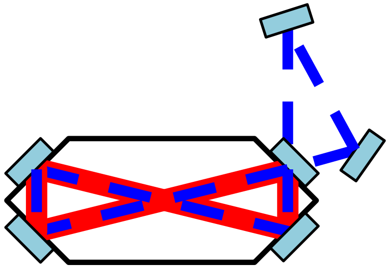
Avoiding the Signal Loss

- Lower finesse for p-pol in aux. cavity so that losses in back reflections are not enhances
- Lower reflectivity for input/output mirrors for improving the impedance matching



Future Plans

- Realize simultaneous resonance with further optimized mirrors
- Reduce various noises to achieve shot noise limited sensitivity
  - laser intensity stabilization
  - optimization of cavity length control
  - use PBS with better extinction ratio
  - environmental monitors (e.g., accelerometers) etc…
- Make two cavities for correlation analysis



Our Team

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Hiromasa Nakatsuka
WIAS, Waseda U.
Tomohiro Fujita
ISAS, JAXA
Koji Nagano
Max-Planck-Institut für Astrophysik
Ippei Obata
U. of Wisconsin-Milwaukee
Soichiro Morisaki

… and more to come!

We also work on axion DM and vector DM searches with KAGRA

公益財団法人 住友財団
The Sumitomo Foundation

科研費
KAKENHI

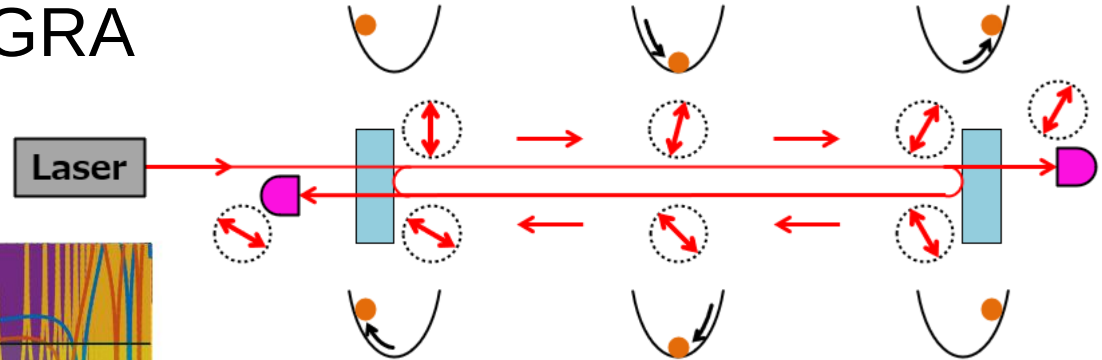
ダークマターの正体は何か？
広大なディスカバリースペースの網羅的研究
What is dark matter? - Comprehensive study of the huge discovery space in dark matter
文部科学省
科学研究費助成事業
学術変革領域研究
(2020–2024)

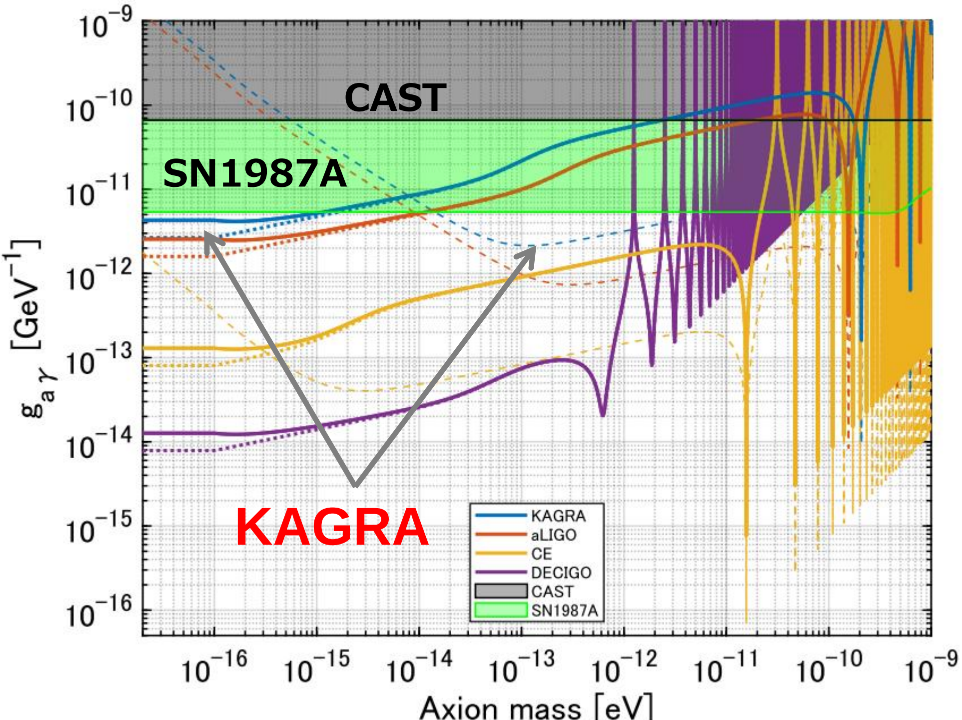
JST Japan Science and Technology Agency

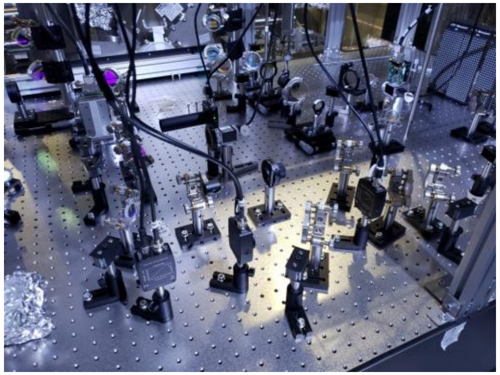
PRESTO
SAKIGAKE

Axion DM Search with KAGRA

- 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
- O4 run in 2022







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Summary

- New searches for ultralight dark matter can be done with laser interferometers
- Axion-like particles can be searched with DANCE to search for polarization modulation of light with optical ring cavity (without magnets!)
- Prototype experiment DANCE Act-1 is underway
- 12-day test run completed in May 2021
- Data analysis pipeline was developed, and first upper limit was set from the analysis of real data
- Working on further sensitivity improvement with s/p-pol simultaneous resonance etc.