KEK Theory Seminar @ KEK Theory Center

June 18, 2023

Ultralight dark matter searches with laser interferometry

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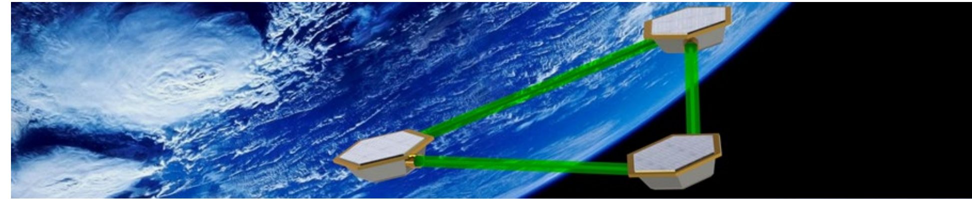
THE UNIVERSITY OF TOKYO

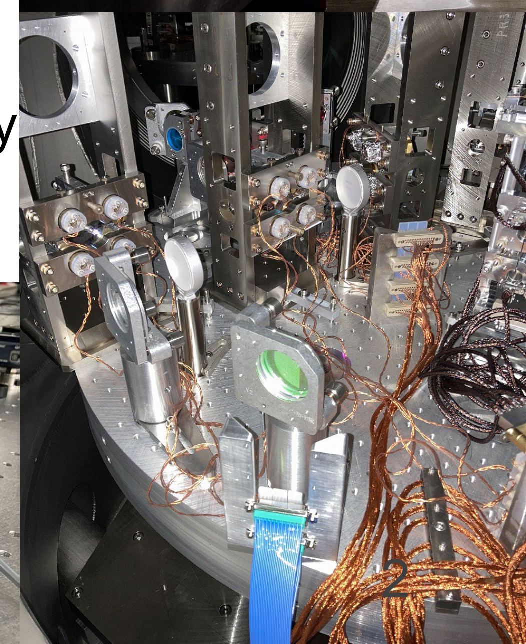
RESEARCH CENTER FOR THE EARLY UNIVERSE

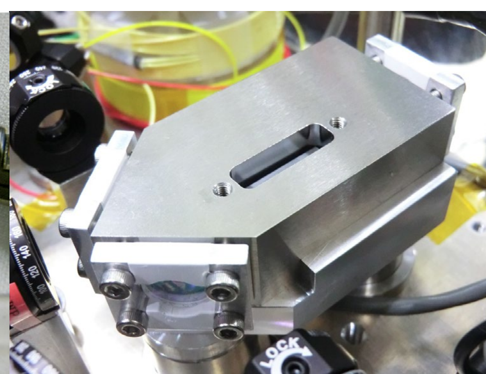
RESCEU

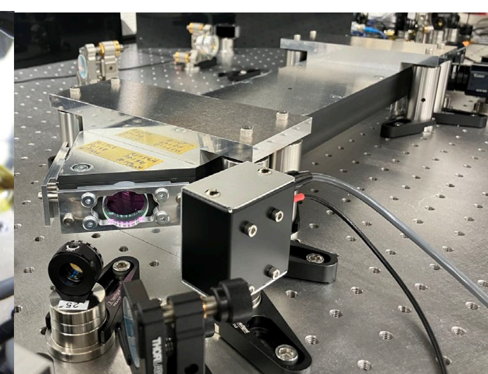
Self Introduction



- Yuta Michimura (道村 唯太)
  - Associate Prof. at RESCEU, UTokyo
- Laser interferometric gravitational wave detectors
  - Ground based: KAGRA, LIGO
  - Space based: DECIGO (SILVIA)
- Gravitational physics with laser interferometry
  - Lorentz invariance test
  - Optomechanical test of quantum nature of gravity
  - Dark matter searches …



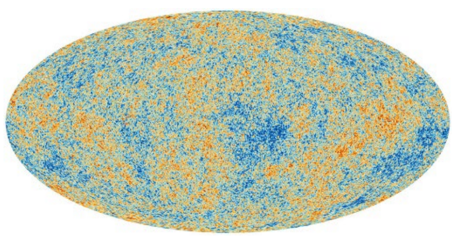




KEK Summer Challenge 2008

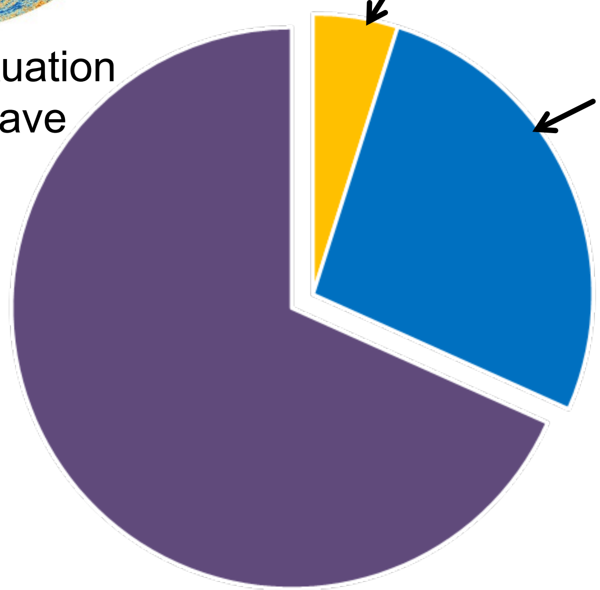
Dark Matter Mystery

- 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

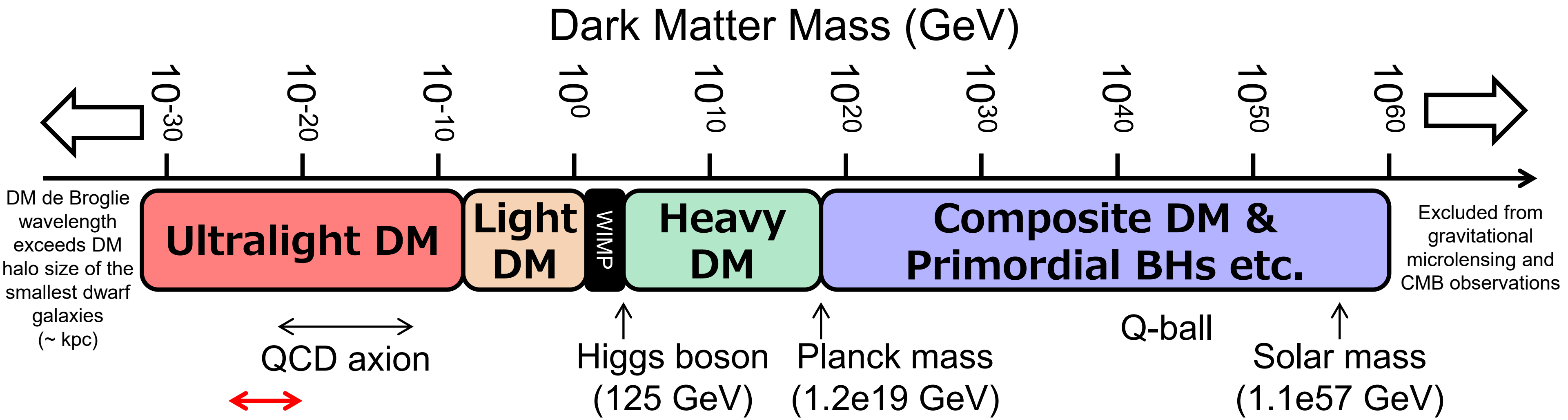
All the matter

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

This standard model of cosmology is amazingly consistent with various observations

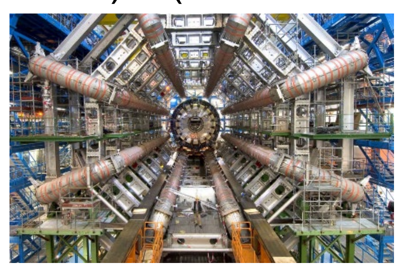
Dark Matter Models

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

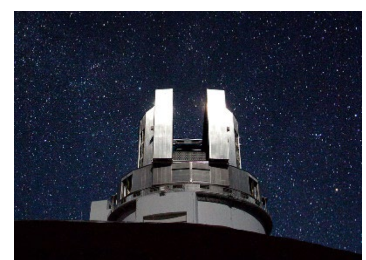


2.4 Hz ~ 2.4 kHz
(1e-14 ~ 1e-11 eV)
Laser Interferometry

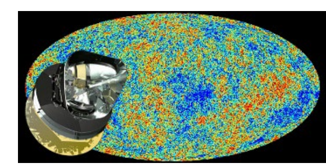
Underground experiments (XENON etc.)



LHC



Subaru telescope etc.



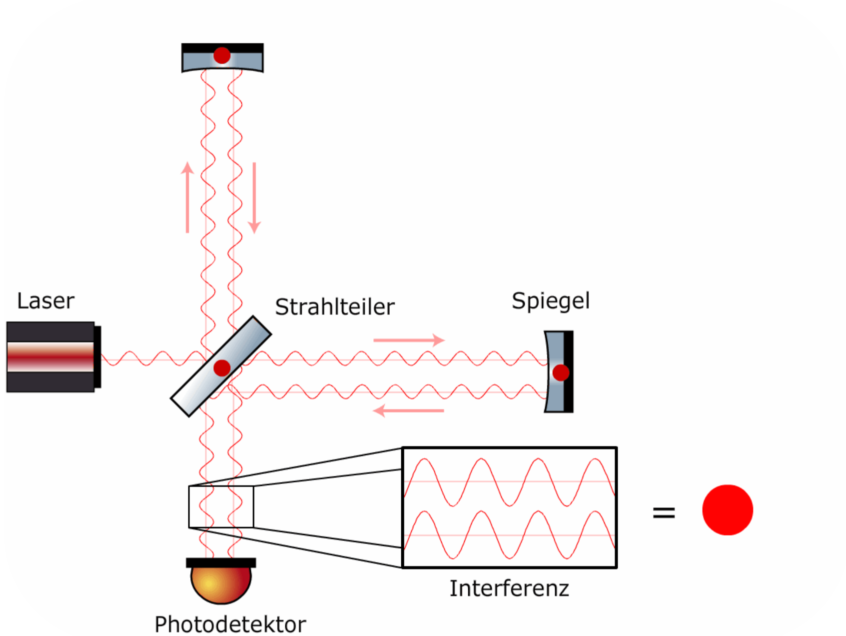
Cosmic microwave background

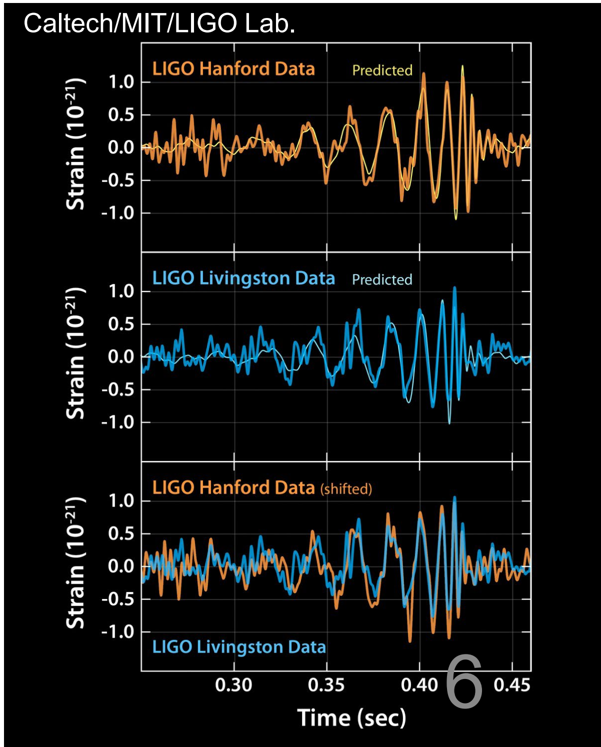
Ultralight DM with Interferometers

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

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

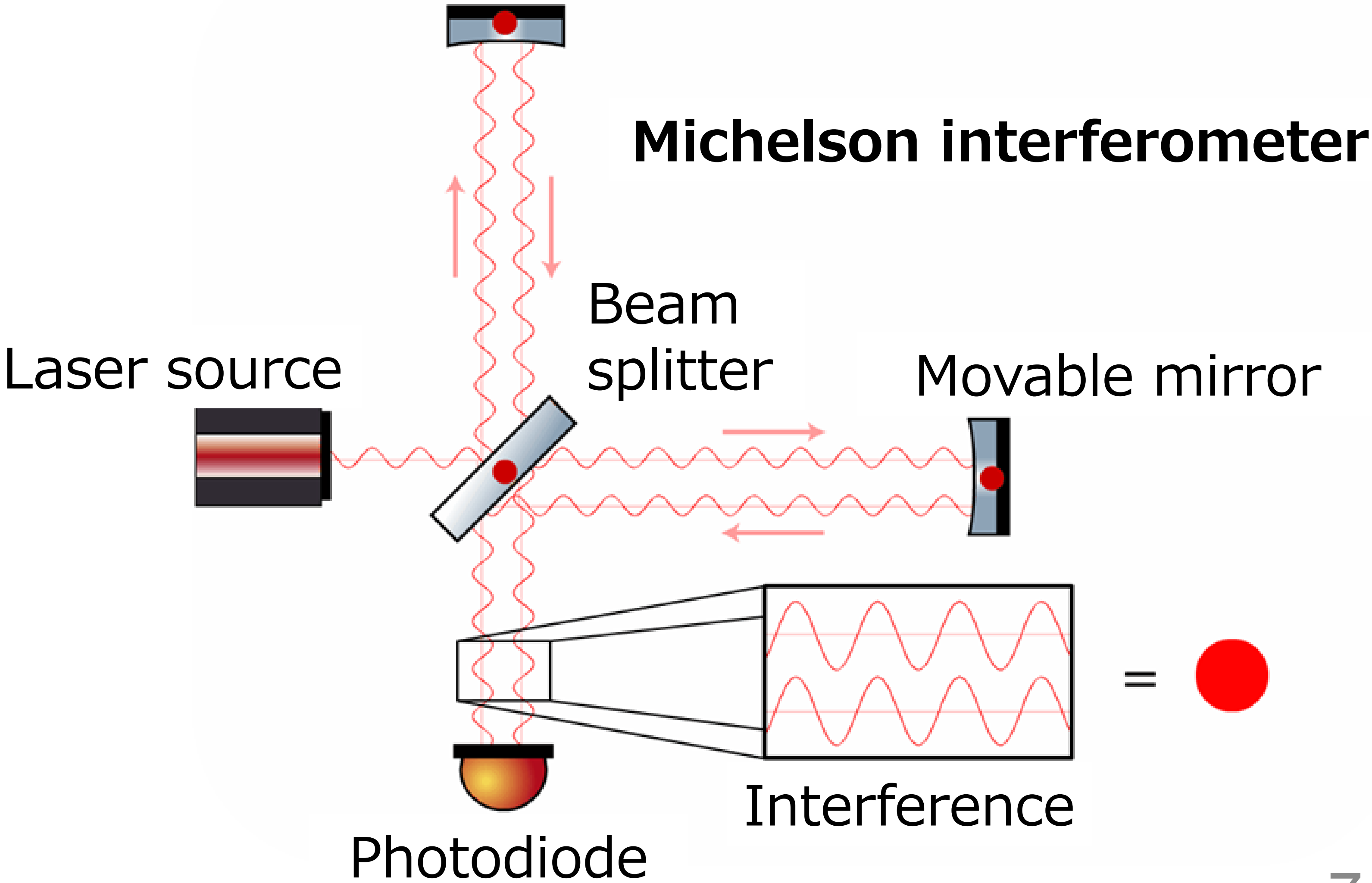
- Laser interferometers are sensitive to such oscillating changes





Laser Interferometry

- measures differential arm length change



Laser Interferometry

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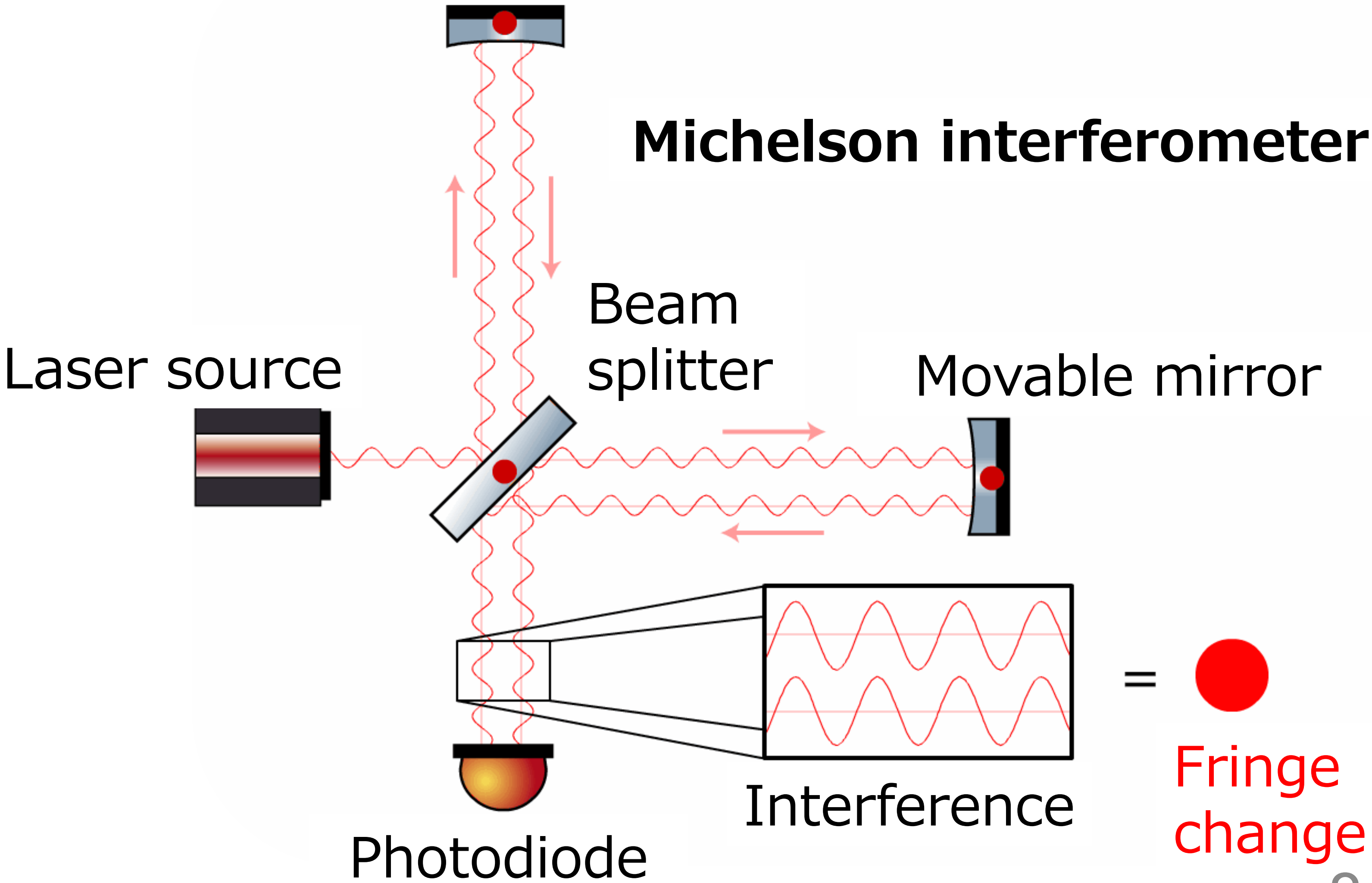

Laser Interferometry

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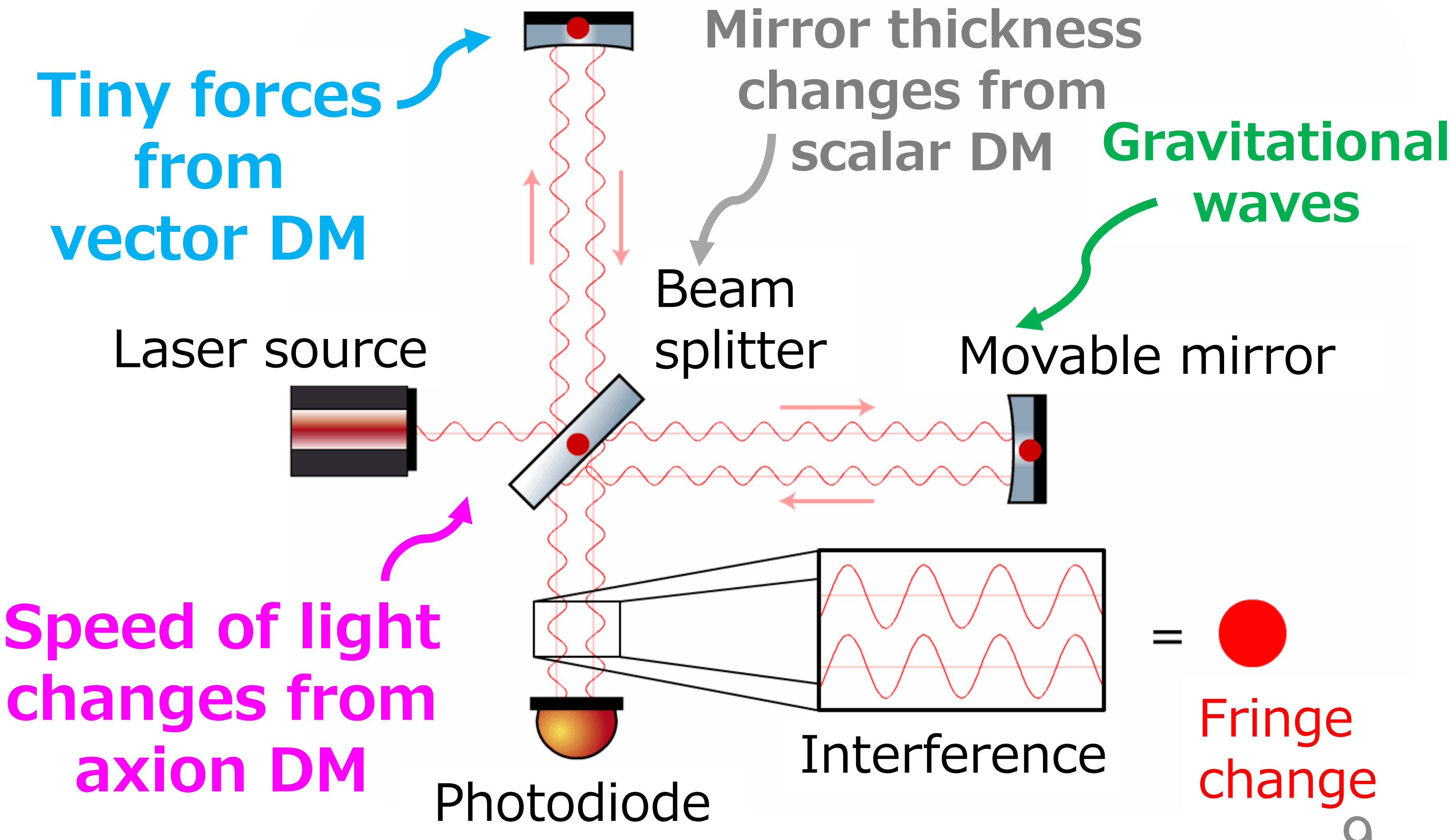


Recent Proposals and Searches

- **Scalar bosons**
  - Y. V. Stadnik & V. V. Flambaum, PRL **114**, 161301 (2015), 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**
  - K. Fukusumi, S. Morisaki, T. Suyama, arXiv:2303.13088 **LIGO/Virgo O3 data analysis**

- **Axion & axion-like particles (ALPs)**
  - W. DeRocco & A. Hook, PRD **98**, 035021 (2018)
  - I. Obata, T. Fujita, Y. Michimura, PRL **121**, 161301 (2018)
  - 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 result**

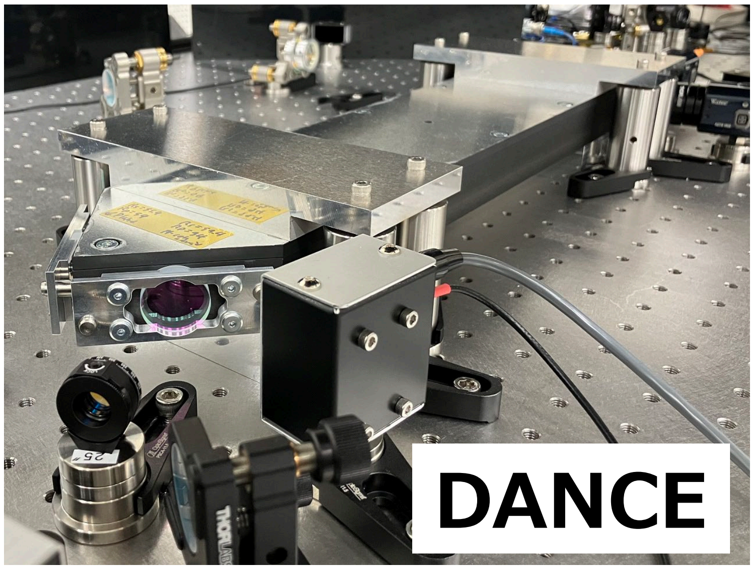
Not exhaustive.
The ones which require magnetic fields are not listed.

- **$U(1)_B$ 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**
  - LIGO-Virgo-KAGRA Collaboration, arXiv:2403.03004 **KAGRA O3GK data analysis**

- **Spin-2 bosons (tensor field)**
  - Y. Manita, K. Aoki, T. Fujita, S. Mukohyama, PRD 107, 104007 (2023)
  - Y. Manita, H. Takeda, K. Aoki, T. Fujita, S. Mukohyama, arXiv:2310.10646

Our Projects

- Use both table-top optical cavities and large-scale laser interferometric gravitational wave detectors



Ultralight DM

Broad band → **Axion like particles**

PRL **121**, 161301 (2018)

Narrow band → **Axion like particles**

PRL **123**, 111301 (2019)

PRD **104**, 062008 (2021)

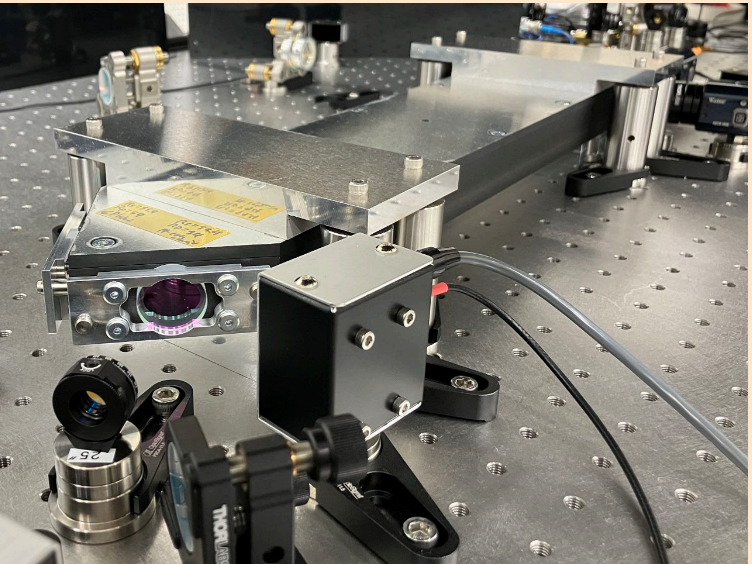
+ Polarization measurement → **Vector bosons**

PRD **102**, 102001 (2020)

PRD **103**, L051702 (2021)

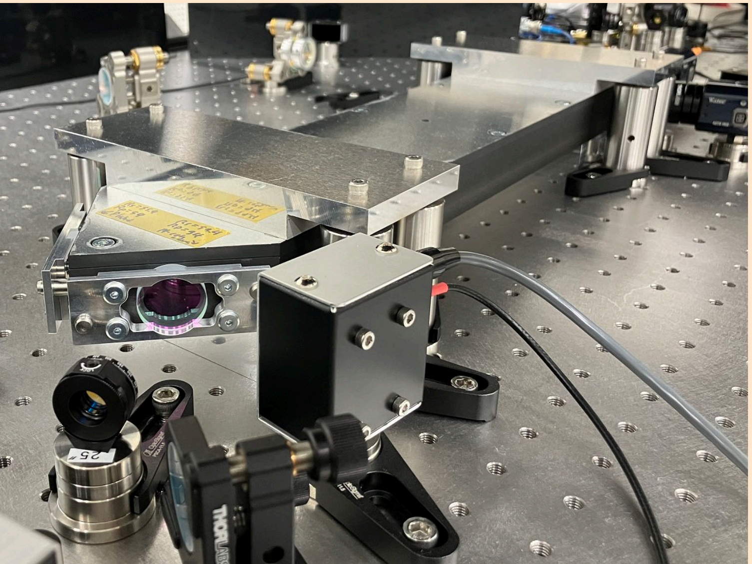
Contents

- Axion dark matter search
  with table-top optical ring cavity
- Axion dark matter search
  with gravitational wave detectors
- Vector dark matter search
  with gravitational wave detectors



Contents

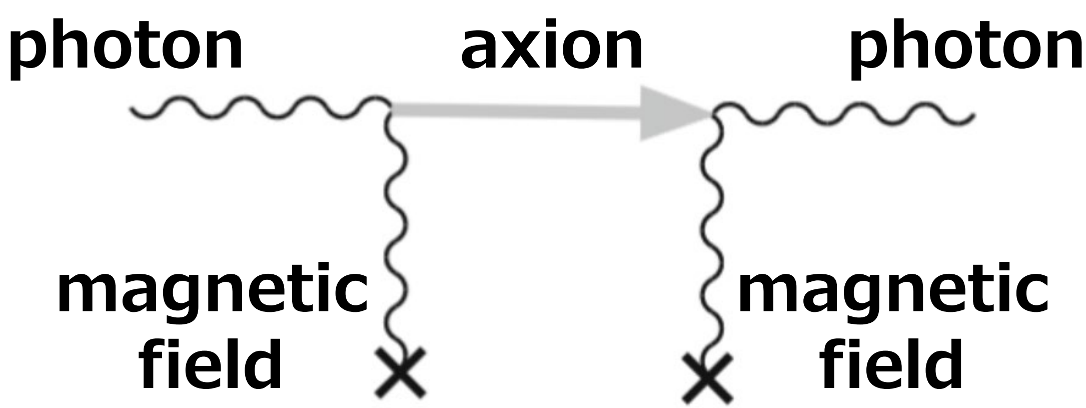
- **Axion dark matter search with table-top optical ring cavity**
- Axion dark matter search with gravitational wave detectors
- Vector dark matter search with gravitational wave detectors



Axion and Axion-Like Particles

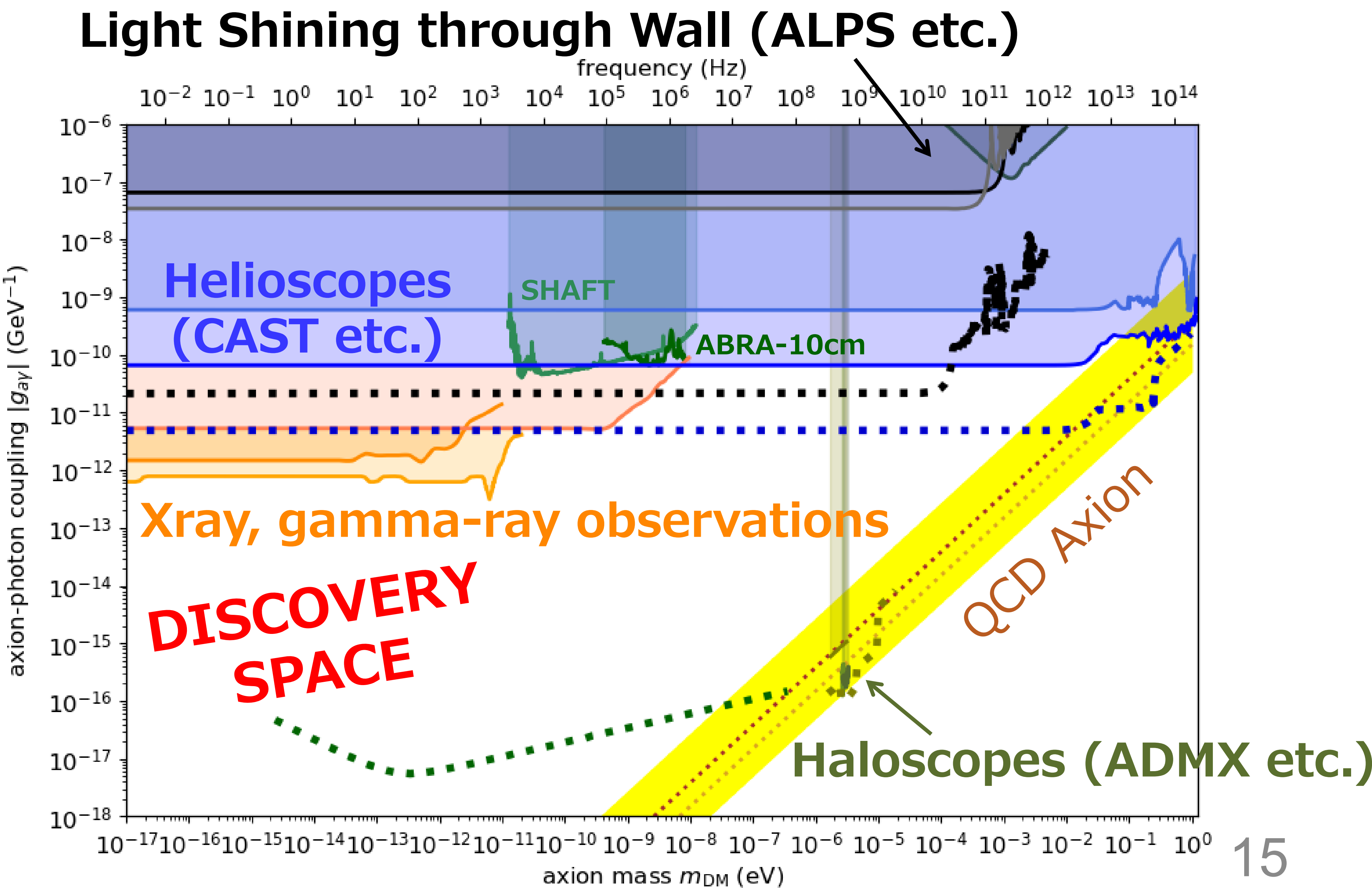
- Pseudo-scalar particle originally introduced to solve strong CP problem (QCD axion)
- Various axion-like particles (ALPs) predicted by string theory and supergravity
- Many experiments to search for ALPs through axion-photon coupling

  Especially by using magnetic fields



Primakoff effect

Previous Searches



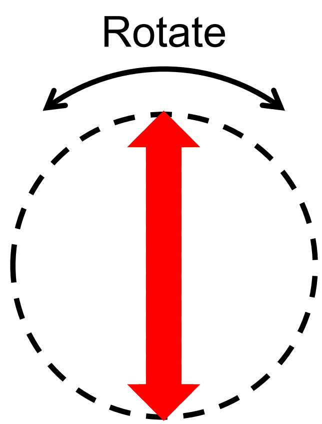
Polarization Modulation from Axions

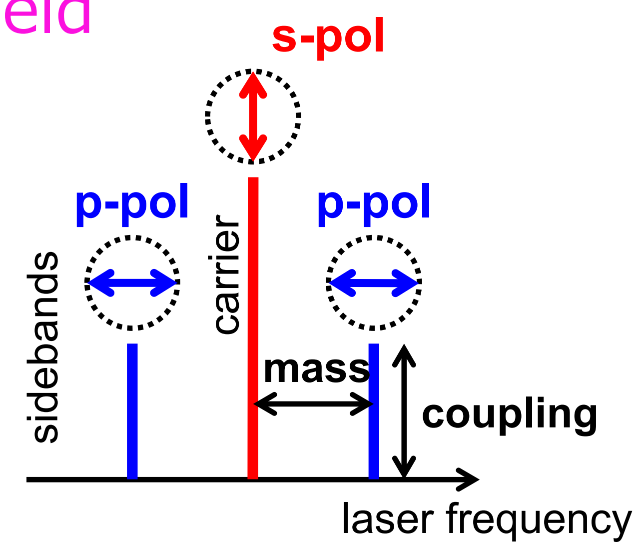
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

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

coupling constant ($g_{a\gamma}$), axion field (a_0), axion mass (m_a)

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





Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

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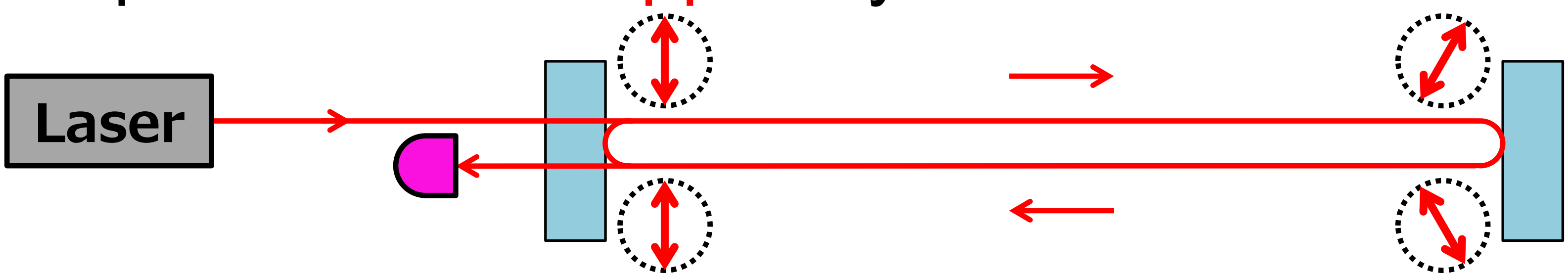
- Optical cavities can increase the optical path, but the polarization is flipped by mirror reflections



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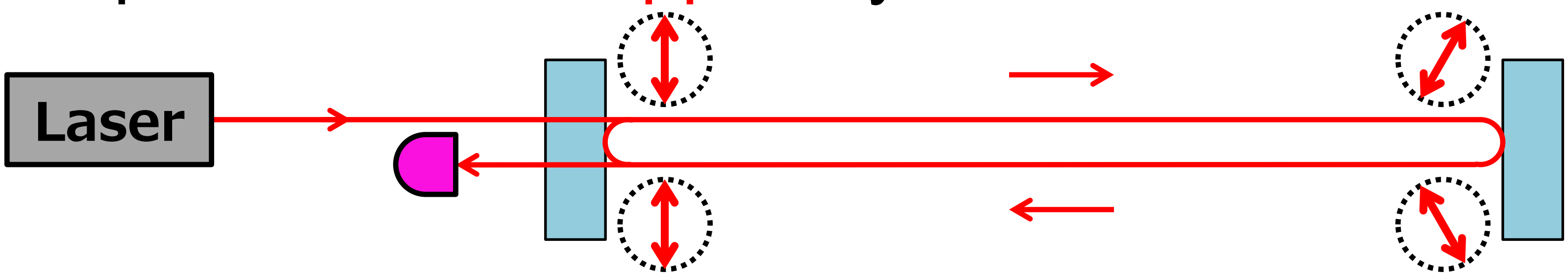
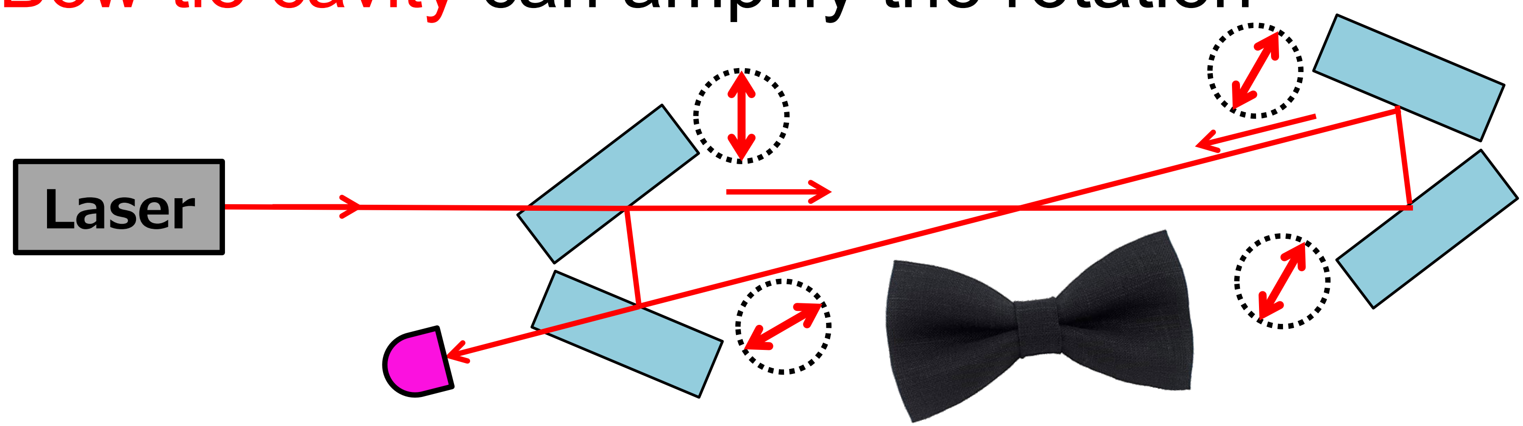


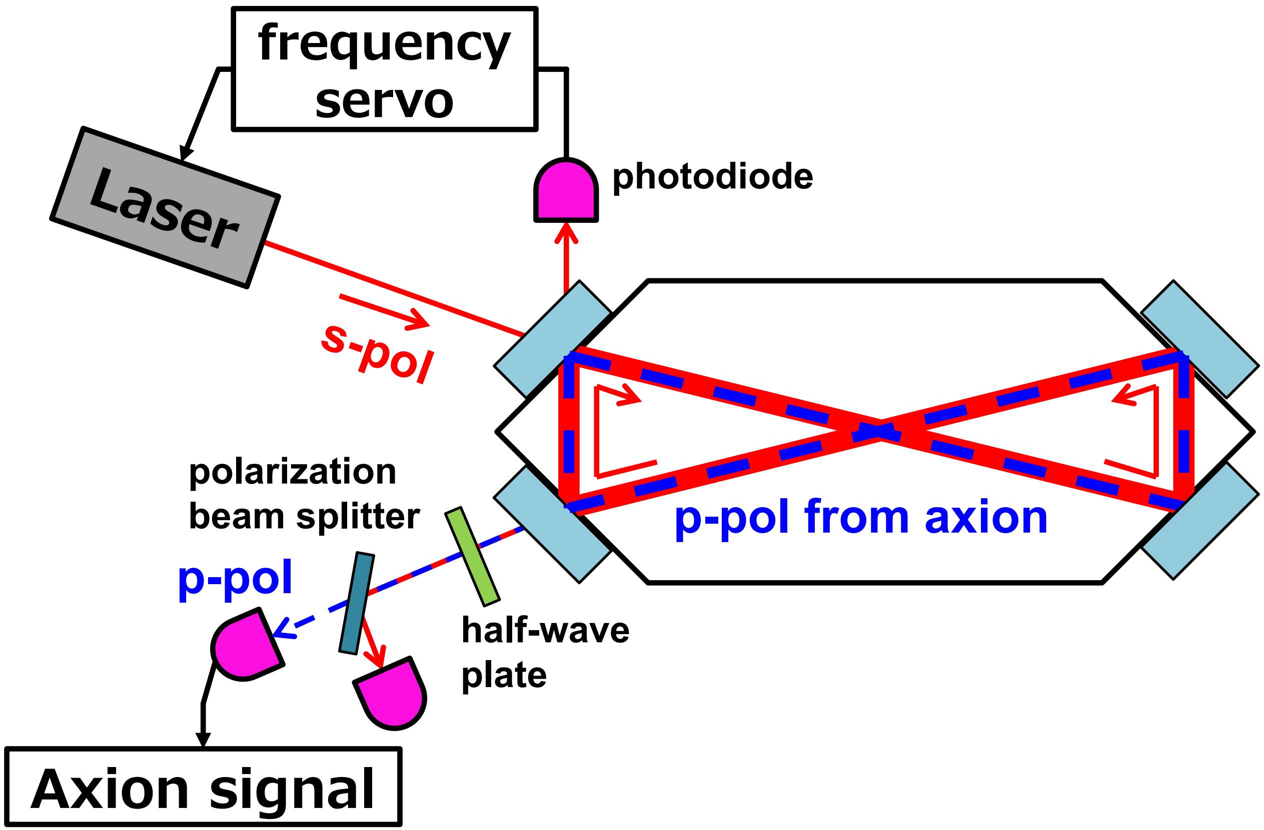
- Bow-tie cavity can amplify the rotation

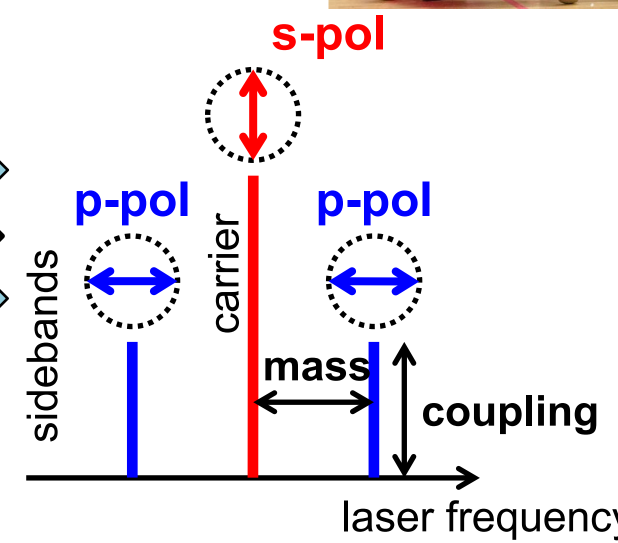


DANCE Setup

Dark matter Axion search with riNg Cavity Experiment

- Look for amount of modulated p-pol generation in each frequency

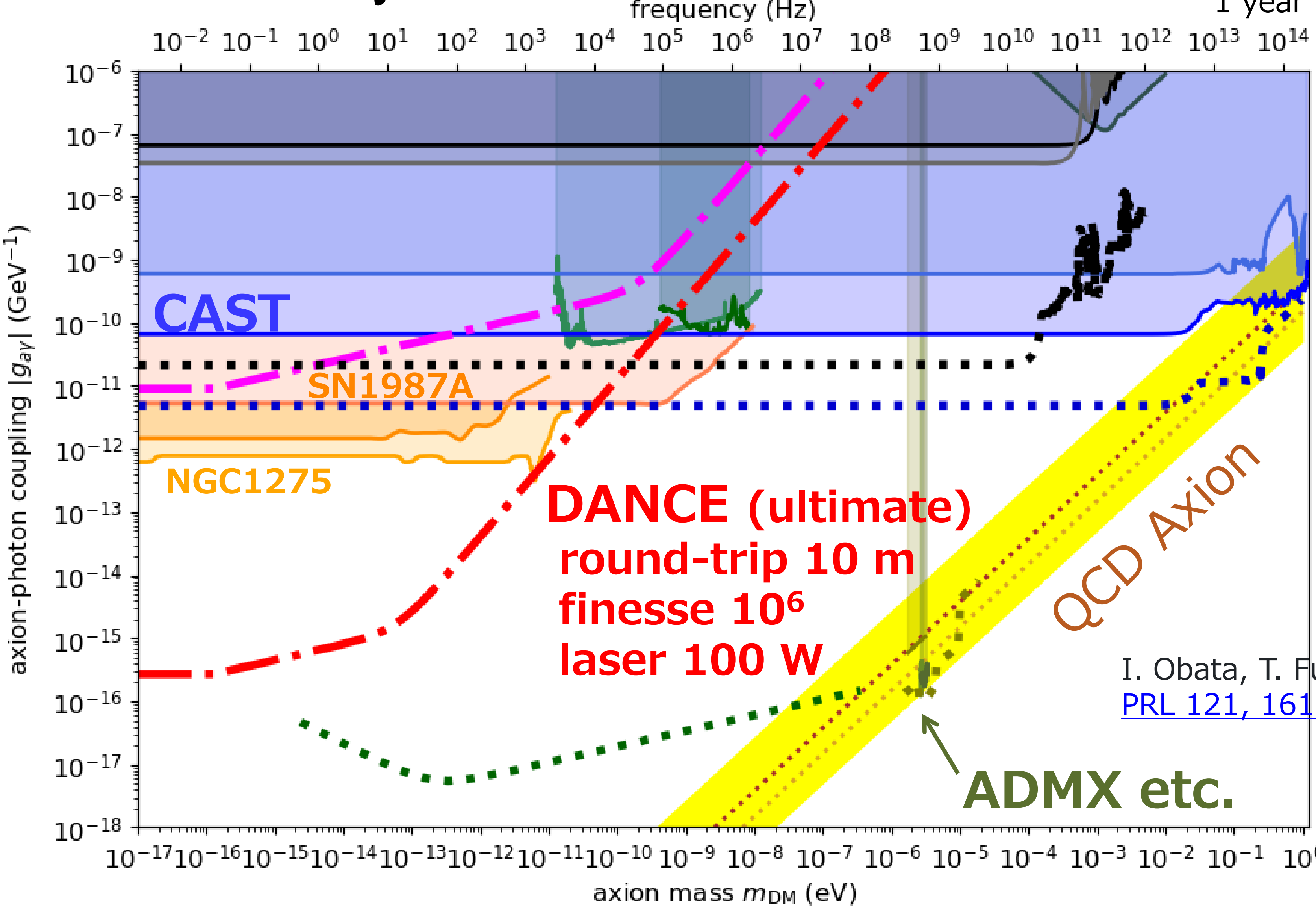




Sensitivity of DANCE

- Sensitivity better than CAST limit

* Shot noise limited
1 year observation



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

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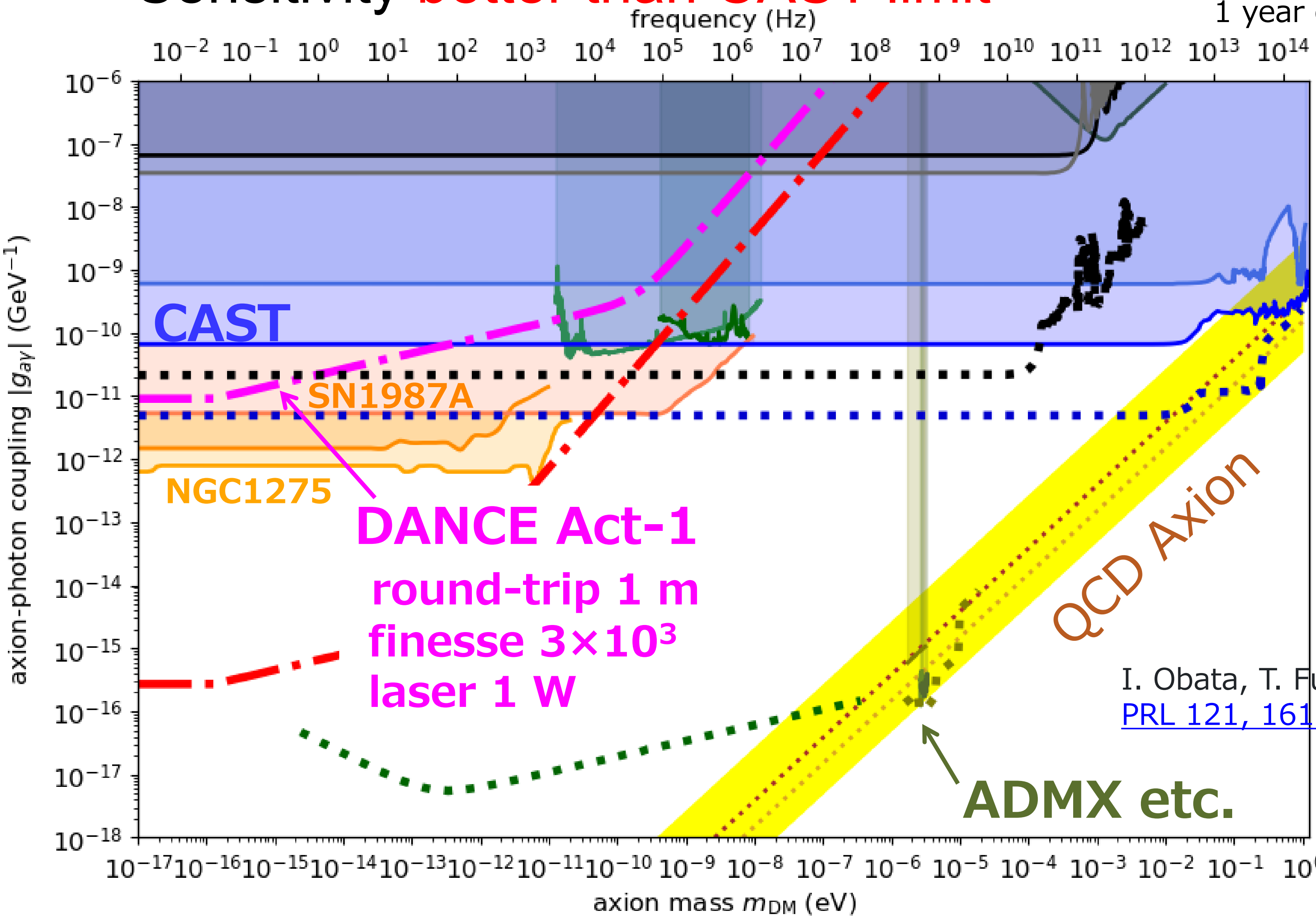
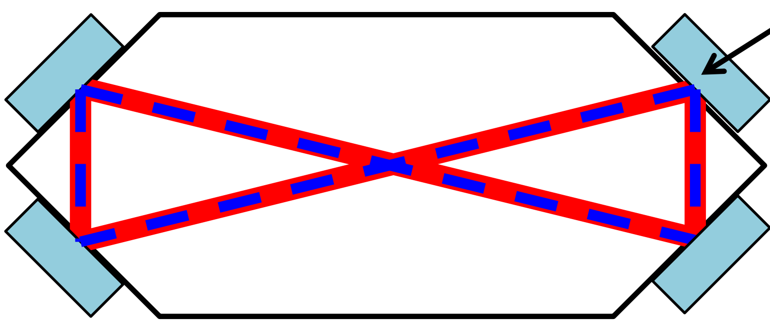


I. Obata, T. Fujita, YM, PRL 121, 161301 (2018)

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

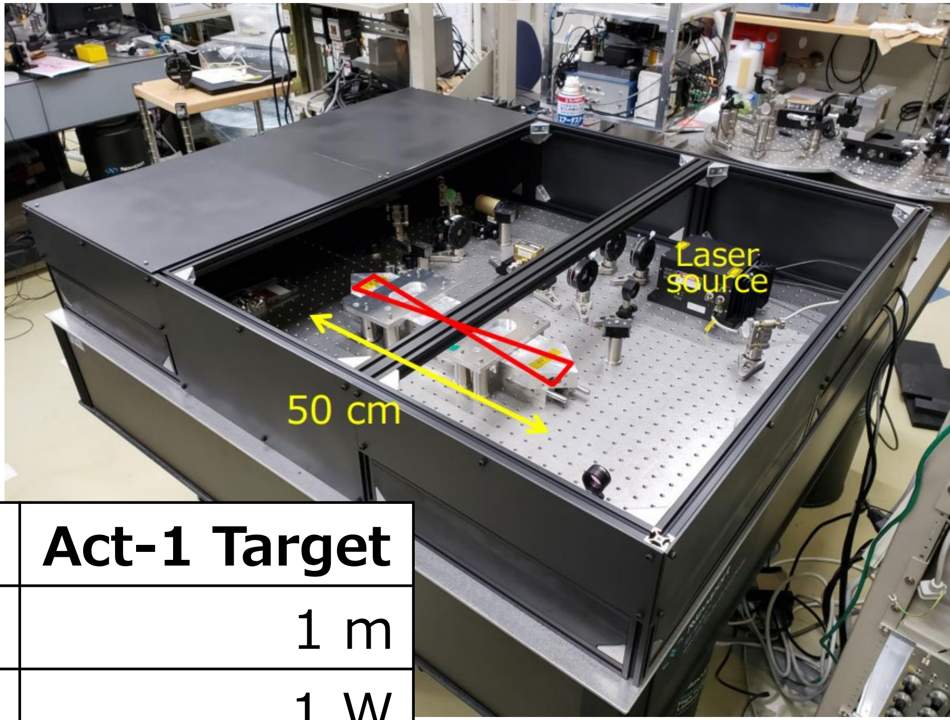


s-pol and p-pol obtain different phase on mirror reflections at non-zero incident angle
→ results in resonant frequency difference

Y. Oshima+, arXiv:2105.06252
H. Fujimoto+, arXiv:2105.08347
Y. Oshima+, JPCS **2156**, 012042 (2021)
H. Fujimoto+, JPCS **2156**, 012182 (2021)

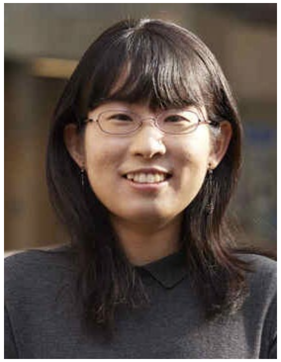
First Observing Run in May 2021

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



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

	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

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

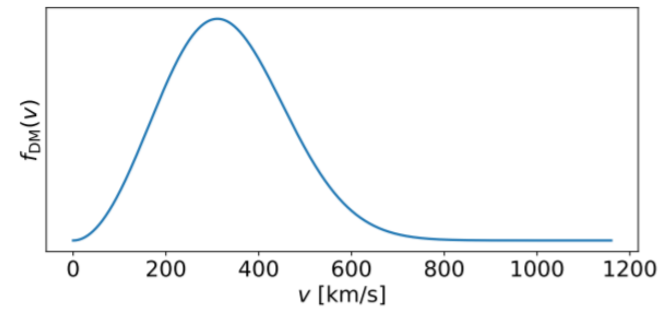
Data

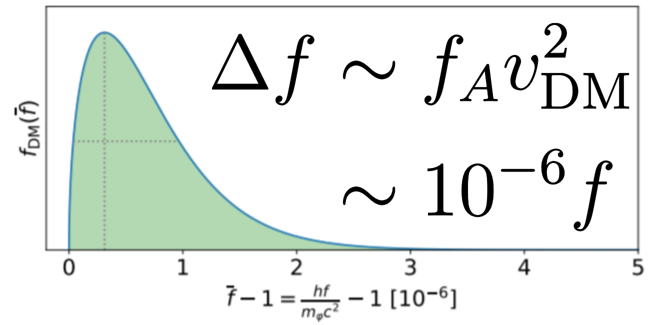
PSD

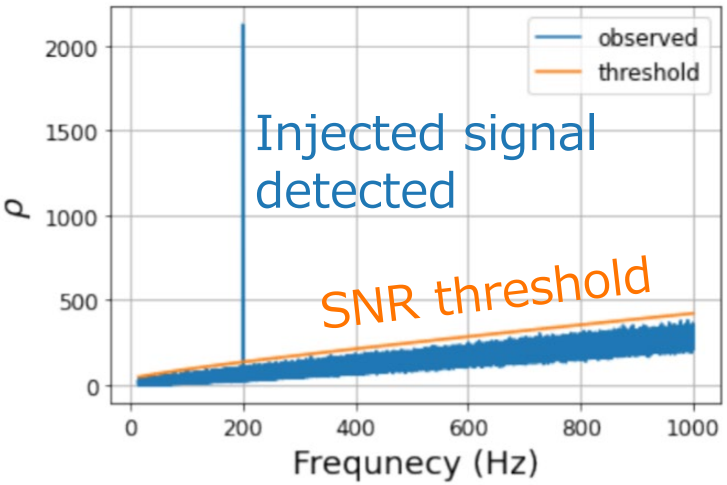
Obs. time

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

- Detection threshold determined assuming ρ follows χ^2 distribution (=assuming Gaussian noise)





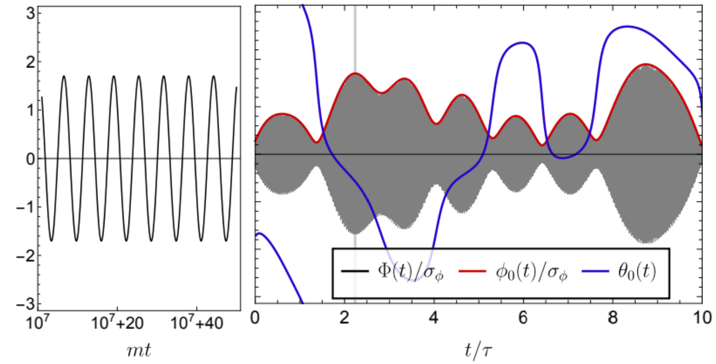


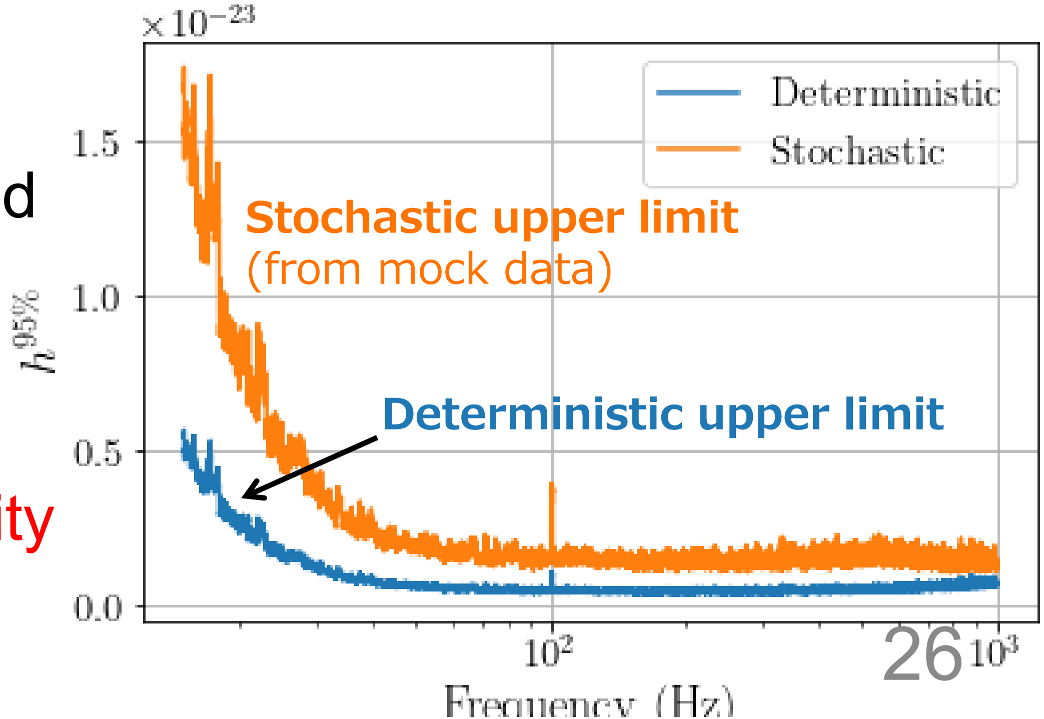
- From ρ , calculate 95% upper limit on coupling constant
- Applied the pipeline to mock data for verification

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

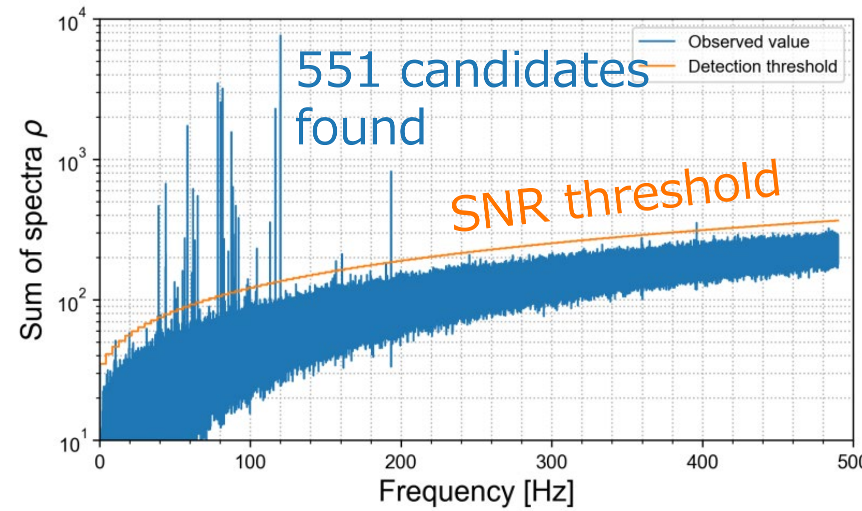
H. Nakatsuka+,
PRD **108**, 092010 (2023)

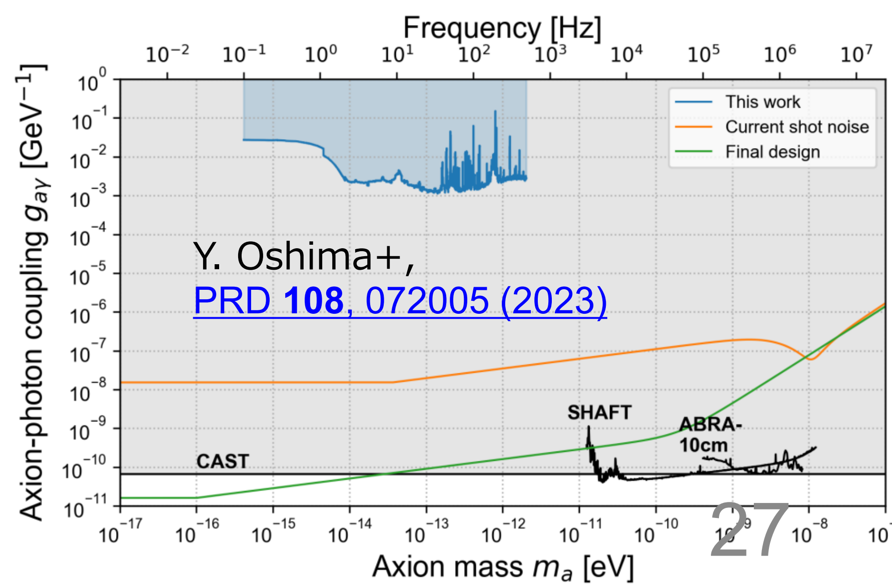




First Data Analysis Results

- Used 24-hour data from 12-day run
- 551 candidates found from initial analysis
- Veto analysis
  - Consistency veto
    (Frequency should be the same for different set of 24-hour data)
  - Q-factor veto
    (DM signal must have Q of 10^6)
  - Remaining 7 candidates (all multiples of ~40 Hz) are also found in laser frequency control, and thus rejected
- Placed upper limits

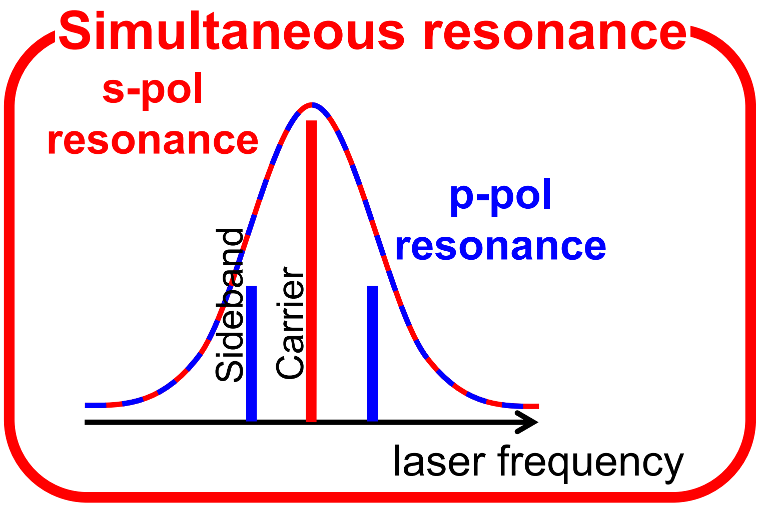


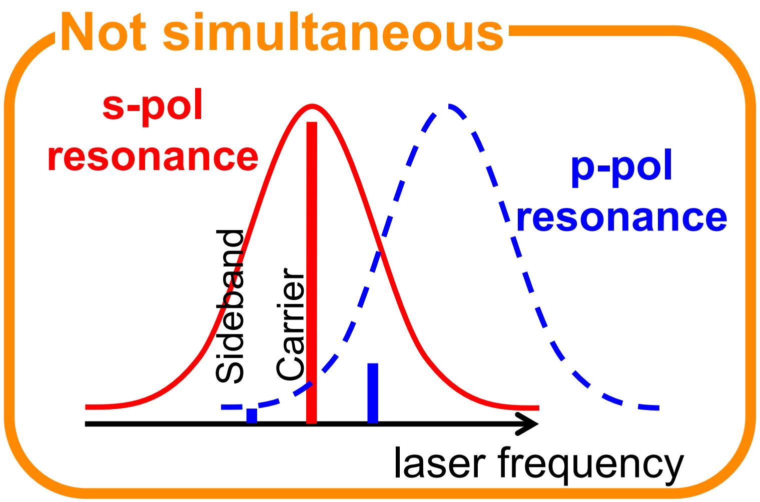


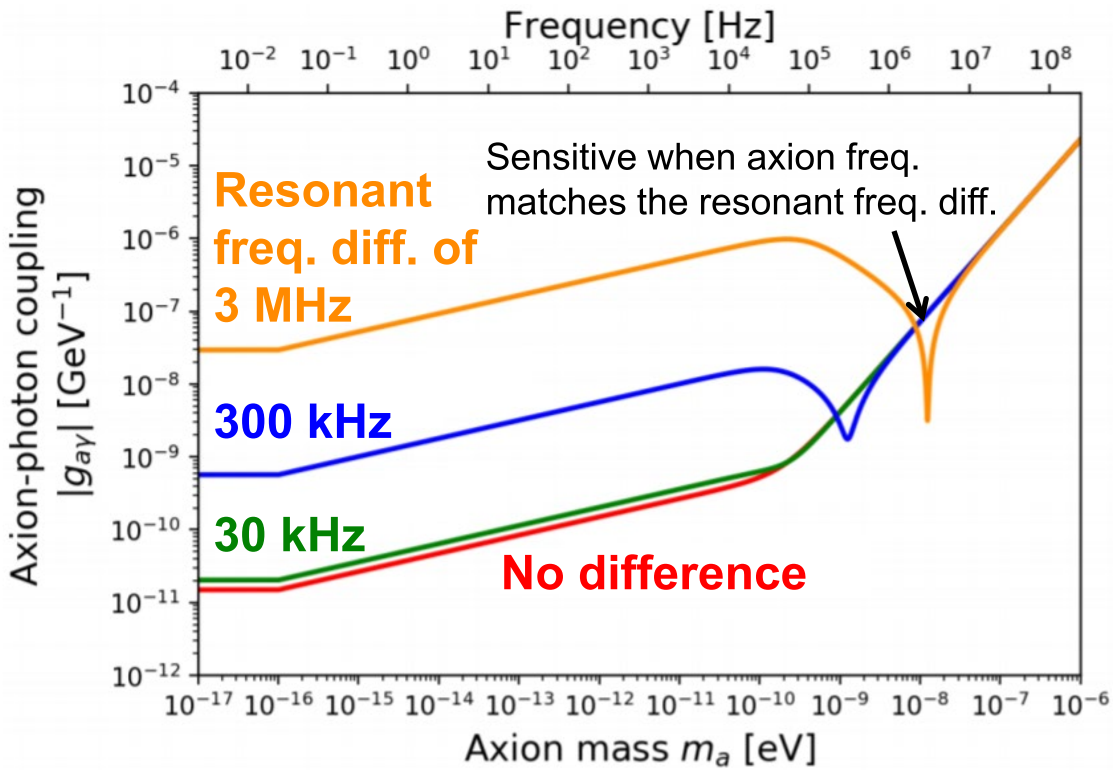
Y. Oshima+, PRD **108**, 072005 (2023)

Simultaneous Resonance

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



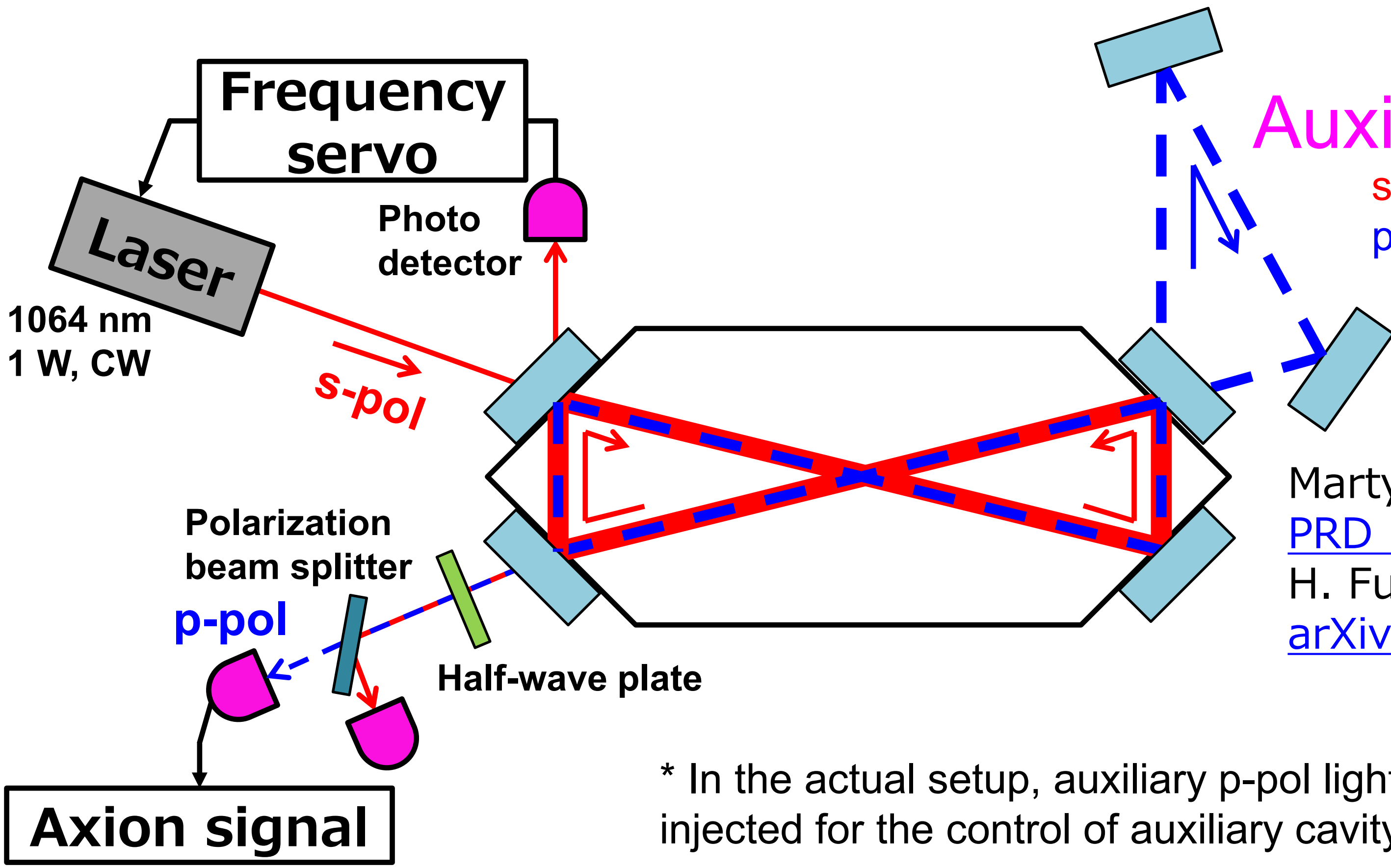




Plot by Y. Oshima & H. Fujimoto

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



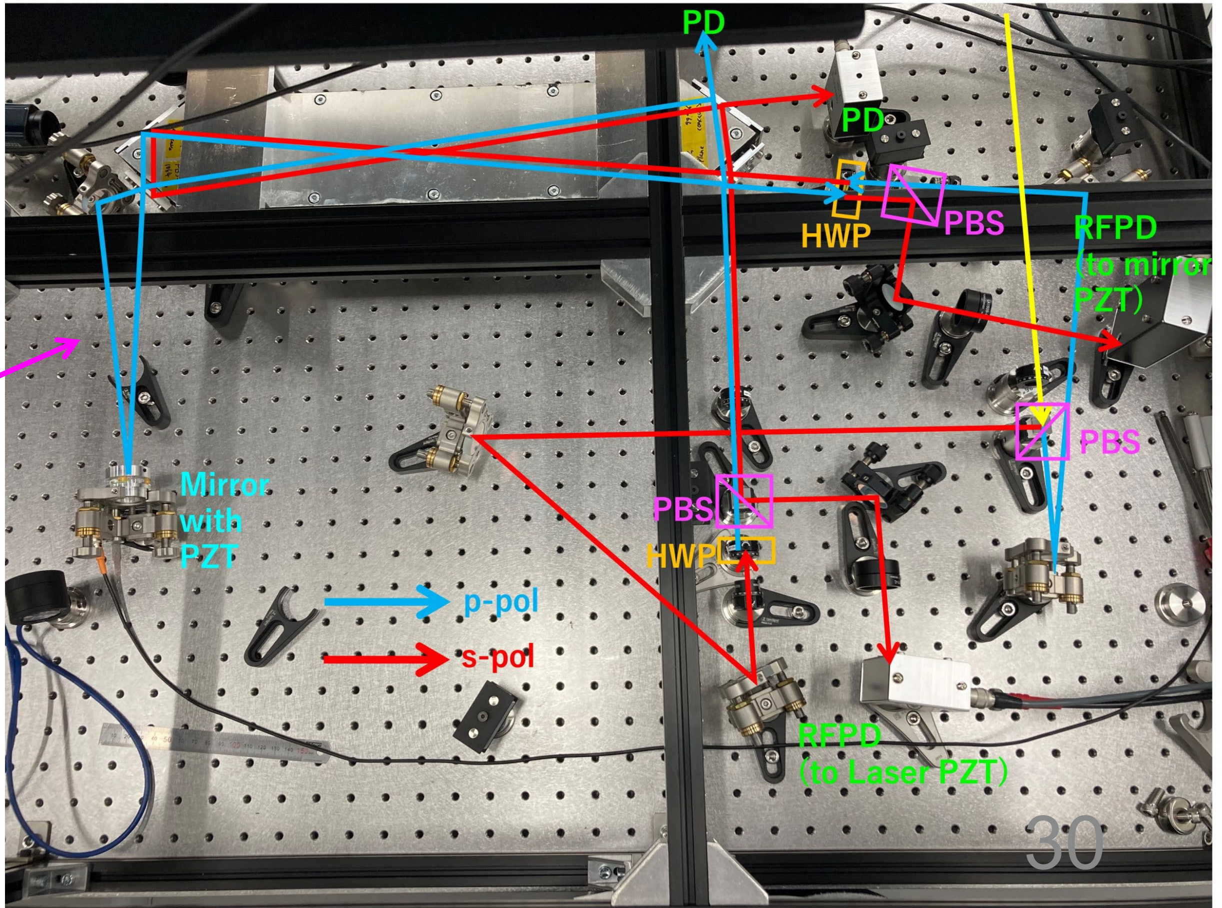
Martynov & Miao
PRD 101, 095034 (2020)
H. Fujimoto+,
arXiv:2110.12023

* 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



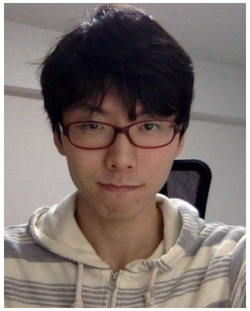
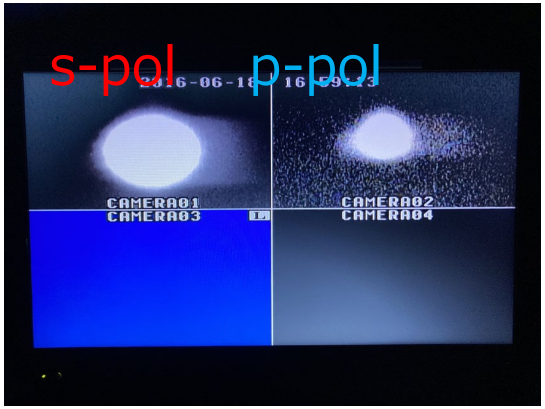


Photo by H. Fujimoto

Simultaneous Resonance Achieved

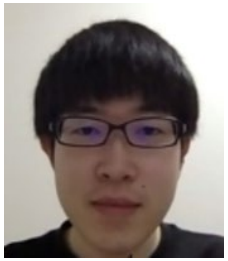
- First demonstration in November 2021
- Finesse reduced due to optical losses in auxiliary cavity

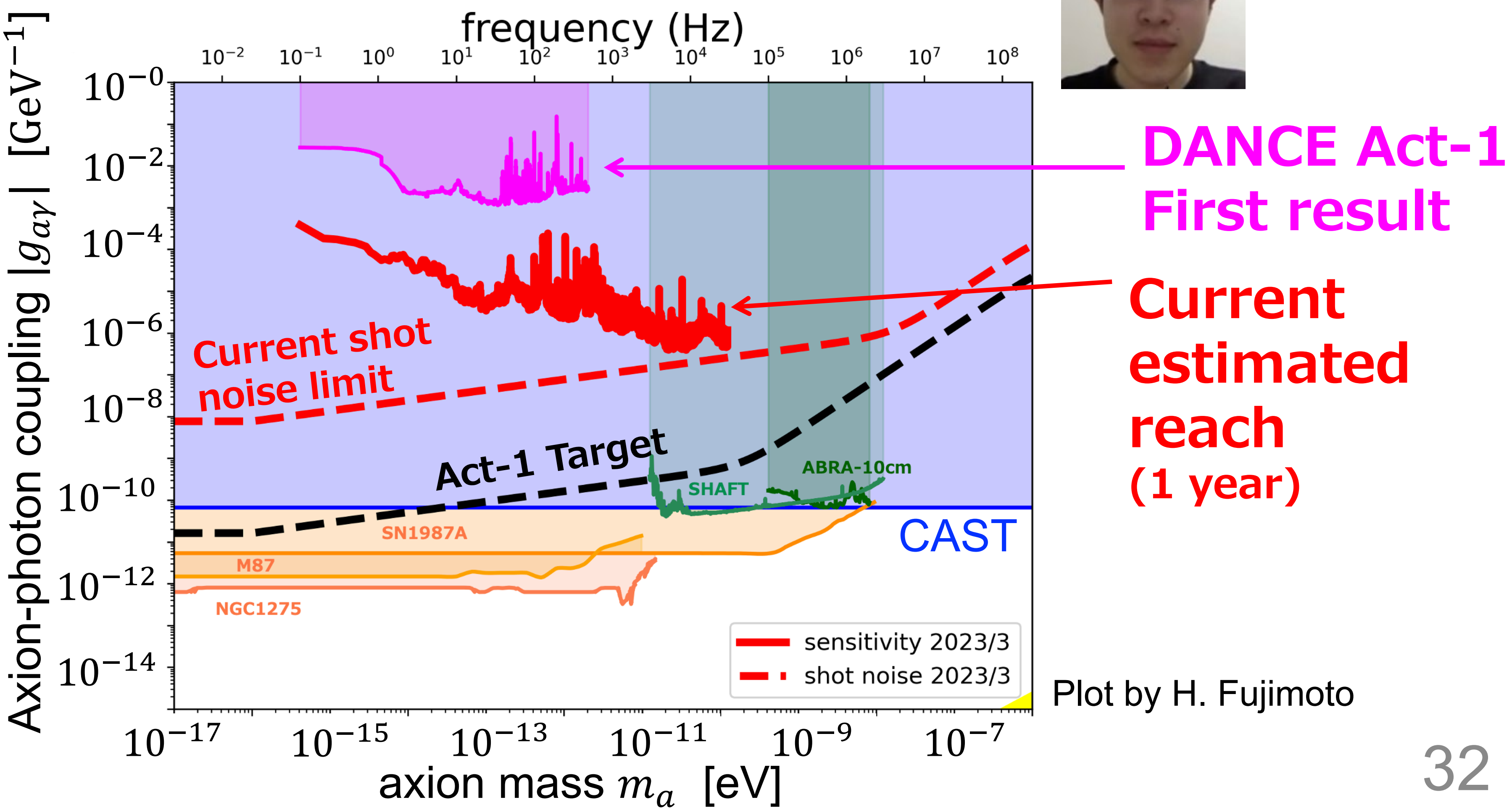


	May 2021	Now (Mar 2023)	Act-1 Target
Round-trip length	1 m	1 m (+0.5 m aux. cavity)	1 m
Input power	242(12) mW (Source: 0.5 W)	21.4(9) mW (Source: 2 W)	1 W
Finesse (for carrier)	$2.85(5)\times10^3$ s-pol	549(3) s-pol, with cavity lock	3×10^3
Finesse (for sidebands)	195(3) p-pol	36.8(2) p-pol, with cavity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

Current Estimated Sensitivity

- Improved by more than two orders of magnitude
- Next: new ideas! (ask me later)

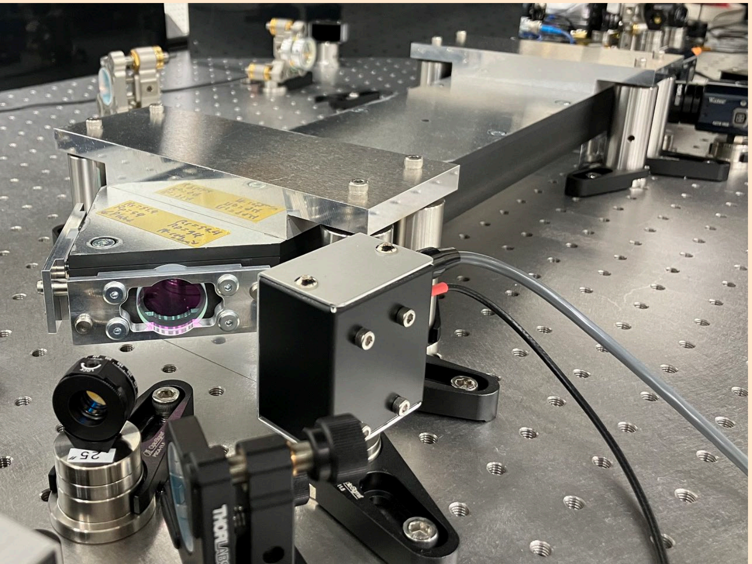




Plot by H. Fujimoto

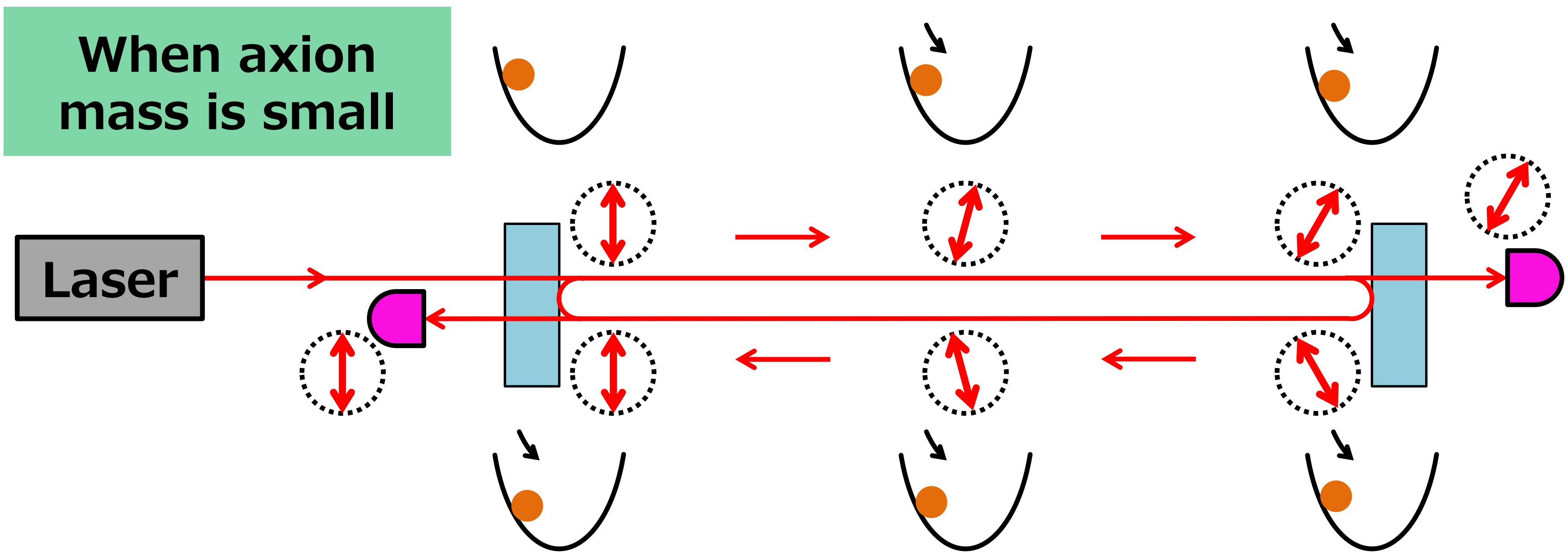
Contents

- Axion dark matter search with table-top optical ring cavity
- **Axion dark matter search with gravitational wave detectors**
- Vector dark matter search with gravitational wave detectors



Linear Cavities for Axion Search

- Polarization flip at mirror reflection can be used to enhance the signal when the round-trip time equals odd-multiples of axion oscillation period
- Long baseline linear cavities in gravitational wave detectors are suitable



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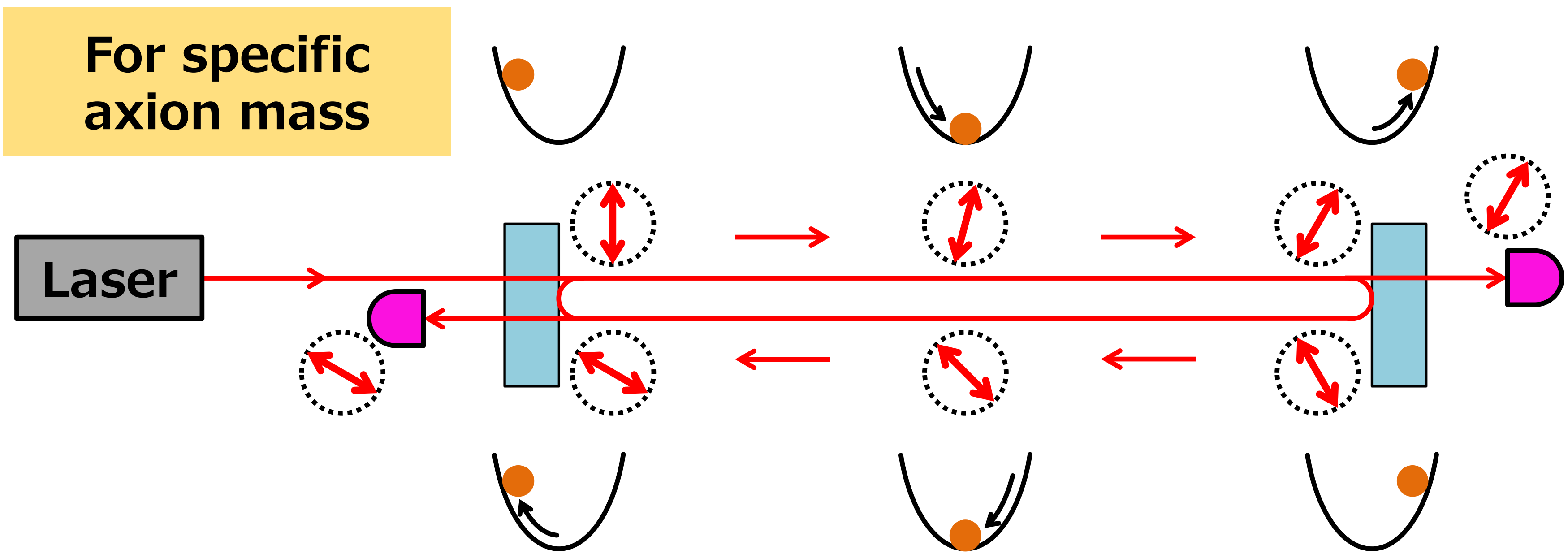
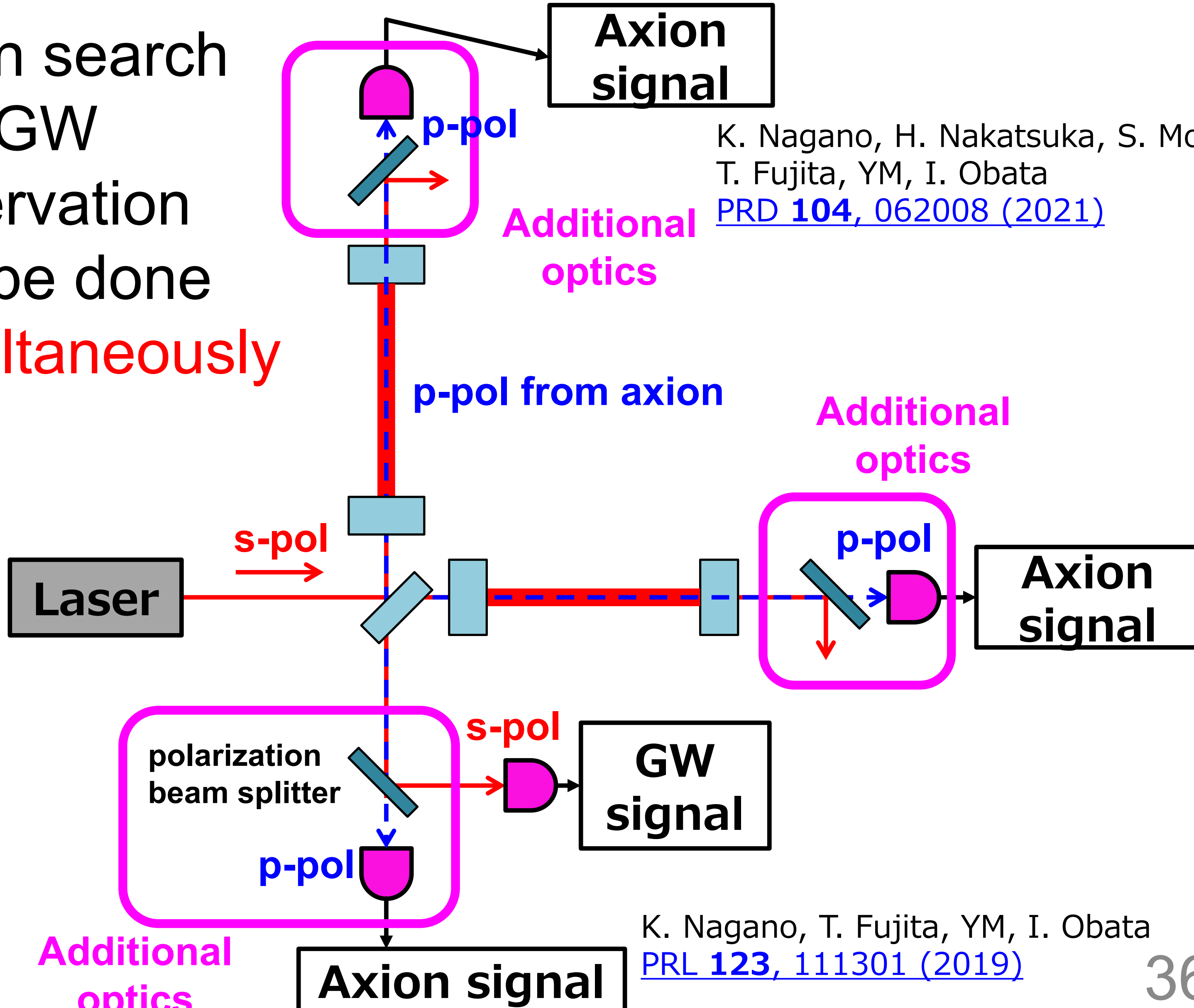


Axion Search with GW Detectors

- Axion search and GW observation can be done simultaneously

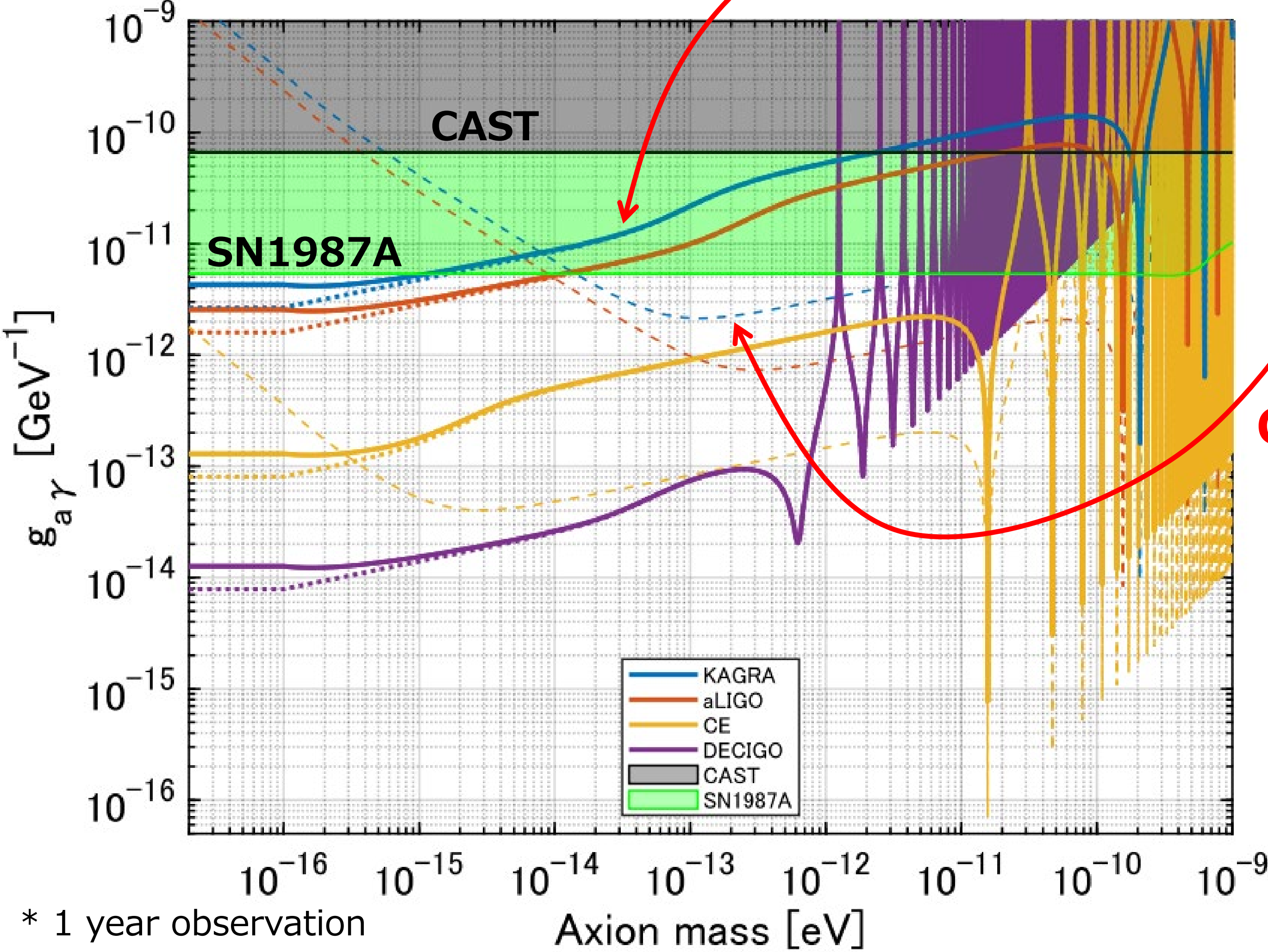


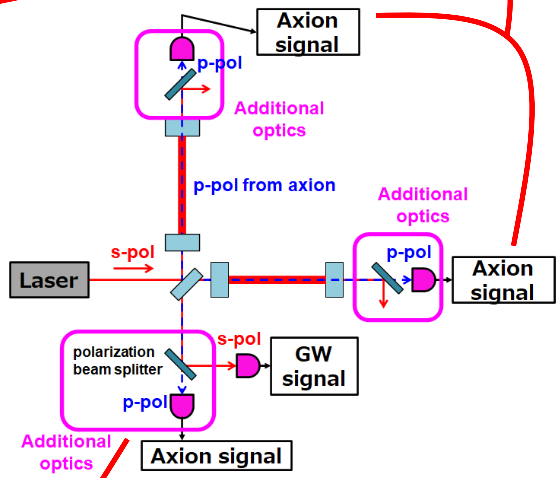
K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita, YM, I. Obata
PRD **104**, 062008 (2021)

K. Nagano, T. Fujita, YM, I. Obata
PRL **123**, 111301 (2019)

Axion Sensitivity

Arm cavity transmission ports





GW detection port

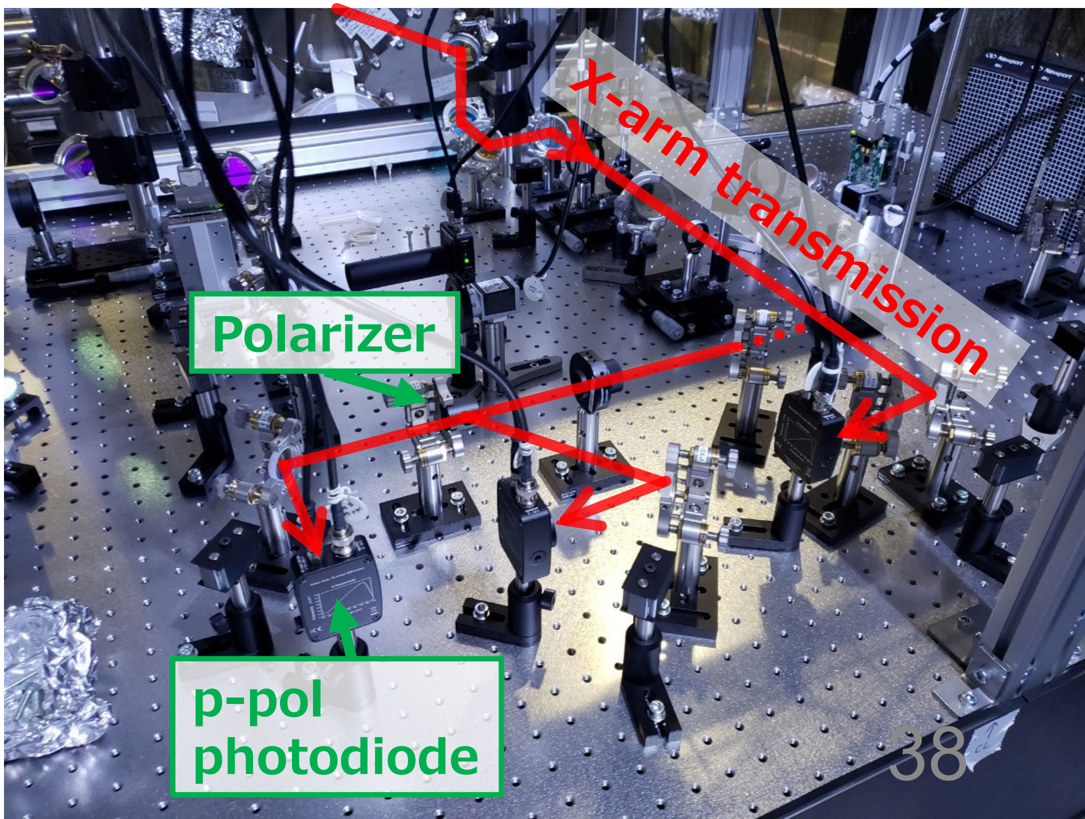
Complemental search using different ports

* 1 year observation

arXiv:2106.06800

Optics for Axion Search Installed

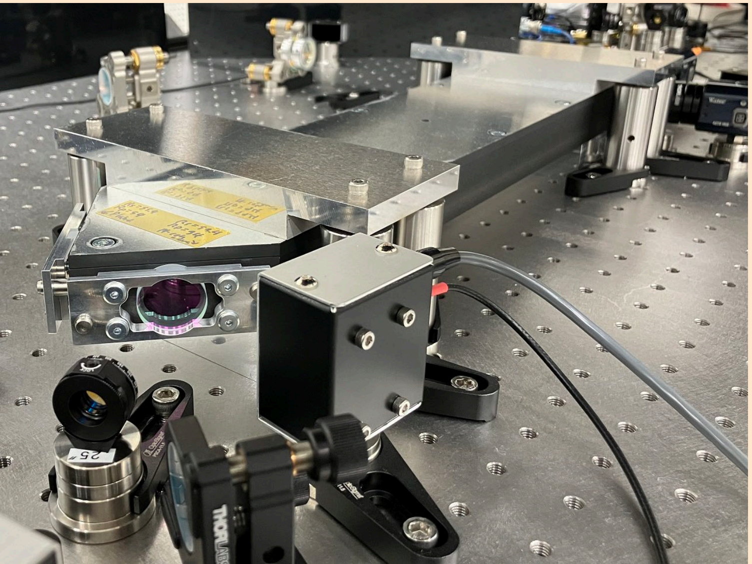
- For KAGRA, polarization optics were installed at transmission ports in 2021
  - Ready to take data in O4b (by June 2025!)
  - Currently recovering from Noto earthquake
- For LIGO, auxiliary port of output Faraday isolator can be used (calibration method needs to be developed)



klog #17692

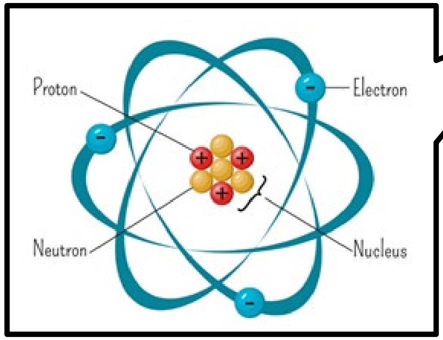
Contents

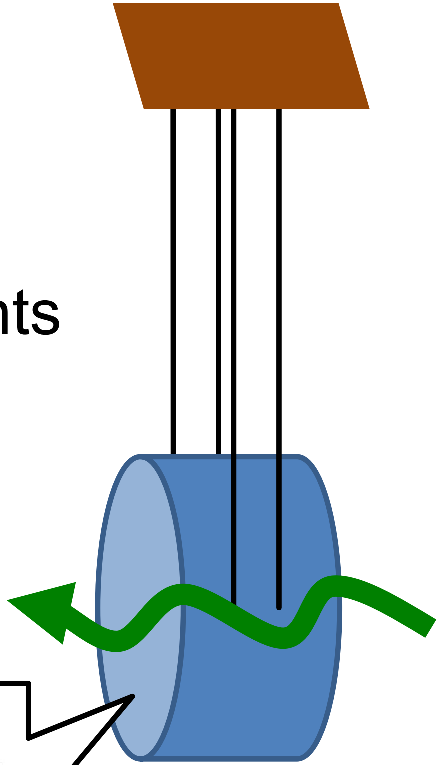
- Axion dark matter search
  with table-top optical ring cavity
- Axion dark matter search
  with gravitational wave detectors
- **Vector dark matter search
  with gravitational wave detectors**



Gauge Boson

- Possible new physics beyond the standard model:
  New gauge symmetry and gauge boson
- New gauge boson can be dark matter
- B-L (baryon minus lepton number)
  - Conserved in the standard model
  - Can be gauged without additional ingredients
  - Equals to the number of neutrons
  - Roughly 0.5 per neutron mass,
    but slightly different between materials
    Fused silica: 0.501
    Sapphire: 0.510
- Gauge boson DM
  gives oscillating force





Oscillating Force from Gauge Field

- Acceleration of mirrors

$$\vec{a}(t,\vec{x}) = \epsilon_D e \frac{q_D}{M} \sqrt{2\rho_{DM}}\, \vec{e}_A \sin\left(m_A t - \vec{k}\cdot\vec{x}\right)$$

charge

gauge boson mass

polarization

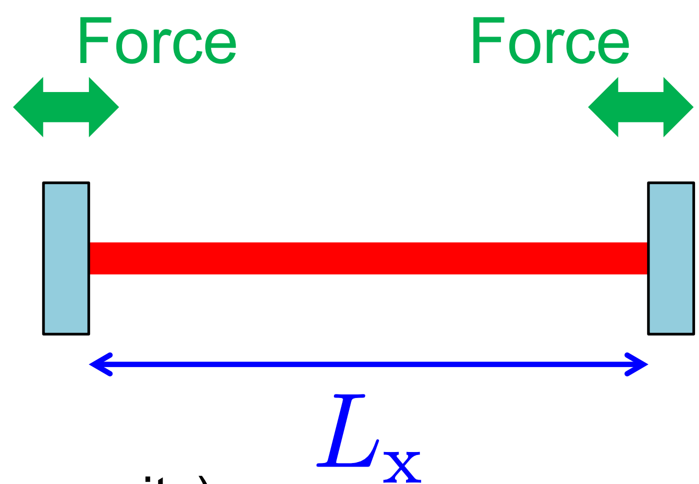
coupling
(normalized by e)

mirror mass

DM density

different phase at
different position

- Gauge boson mass and coupling can be measured by measuring the oscillating mirror displacement

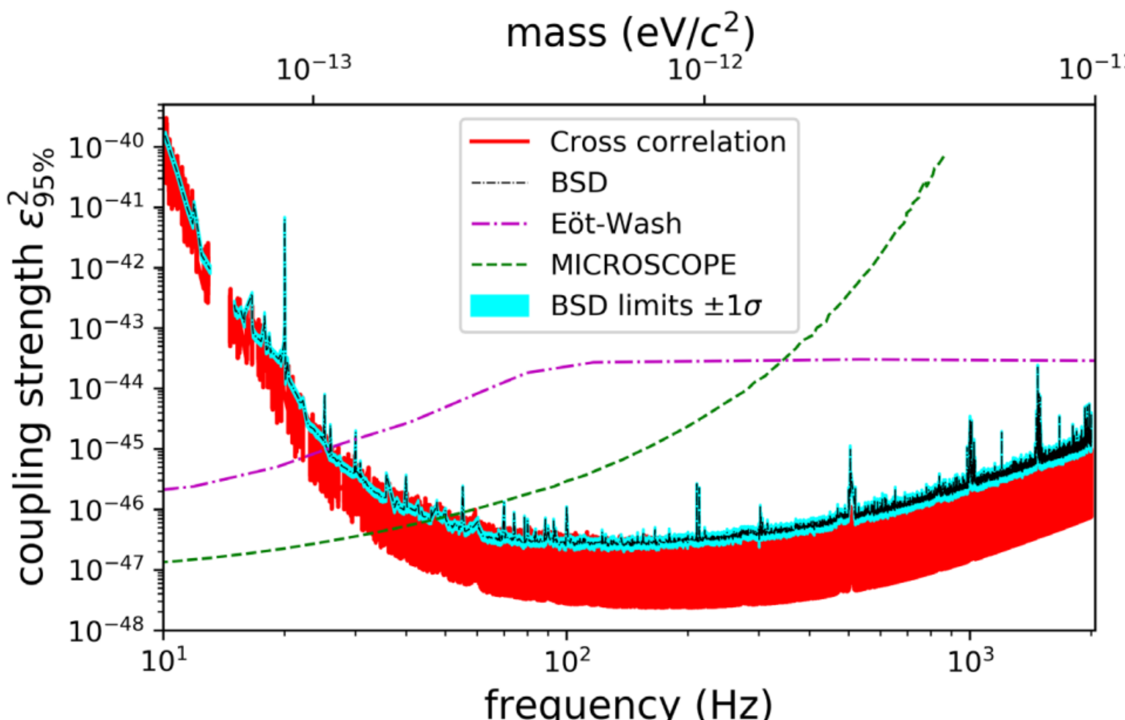


- Almost no signal for symmetric cavity if cavity length is short
(phase difference is 10^{-5} rad @ 100 Hz for km cavity)
- How about using interferometric GW detectors?

A. Pierce+, PRL **121**, 061102 (2018)

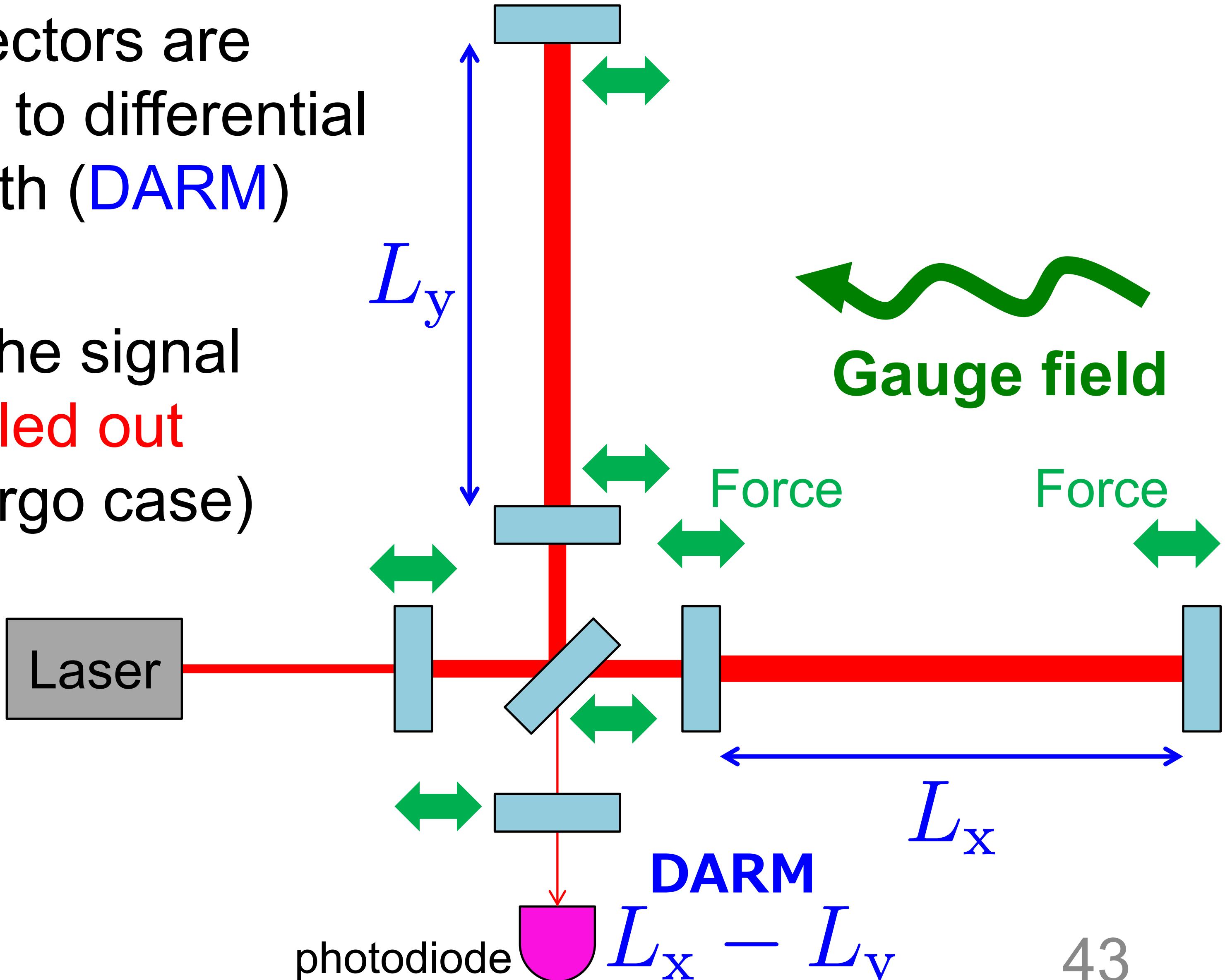
Previous Searches with LIGO/Virgo

- Gauge boson dark matter search with LIGO O1 data and LIGO/Virgo O3 data have been done
  H-K Guo+, Communications Physics **2**, 155 (2019)
  LIGO, Virgo, KAGRA Collaboration, PRD **105**, 063030 (2022)
- Better constraint than equivalence principle tests
- Even better constraint could be obtained from KAGRA



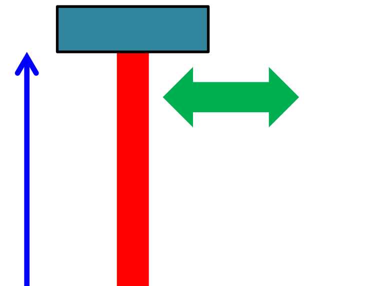
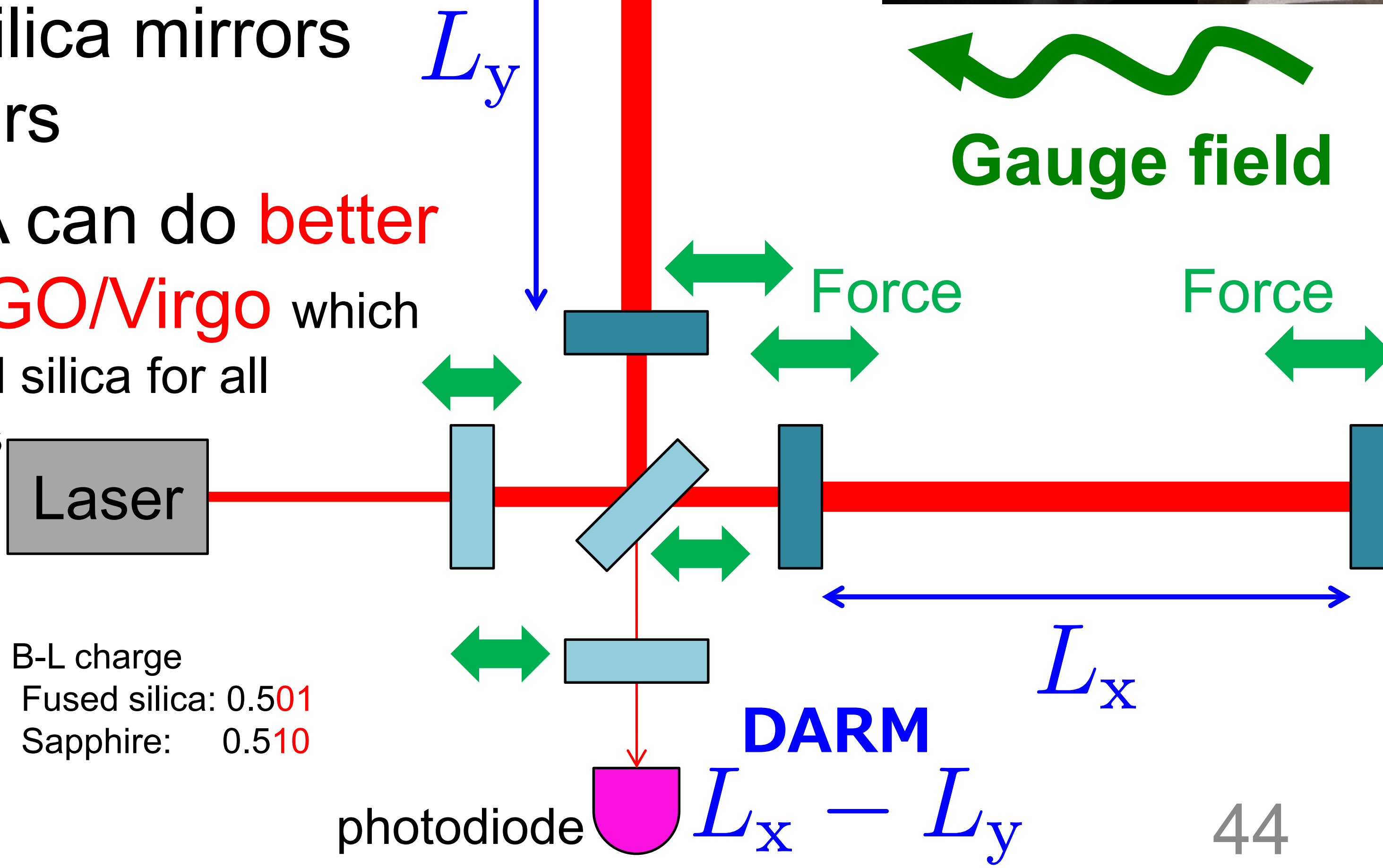
Search with GW Detectors

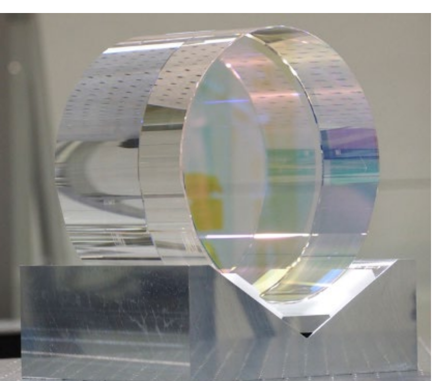
- GW Detectors are sensitive to differential arm length (DARM) change
- Most of the signal is cancelled out (LIGO/Virgo case)



Search with KAGRA

- KAGRA uses cryogenic sapphire mirrors for arm cavities, and fused silica mirrors for others
- KAGRA can do better than LIGO/Virgo which uses fused silica for all the mirrors

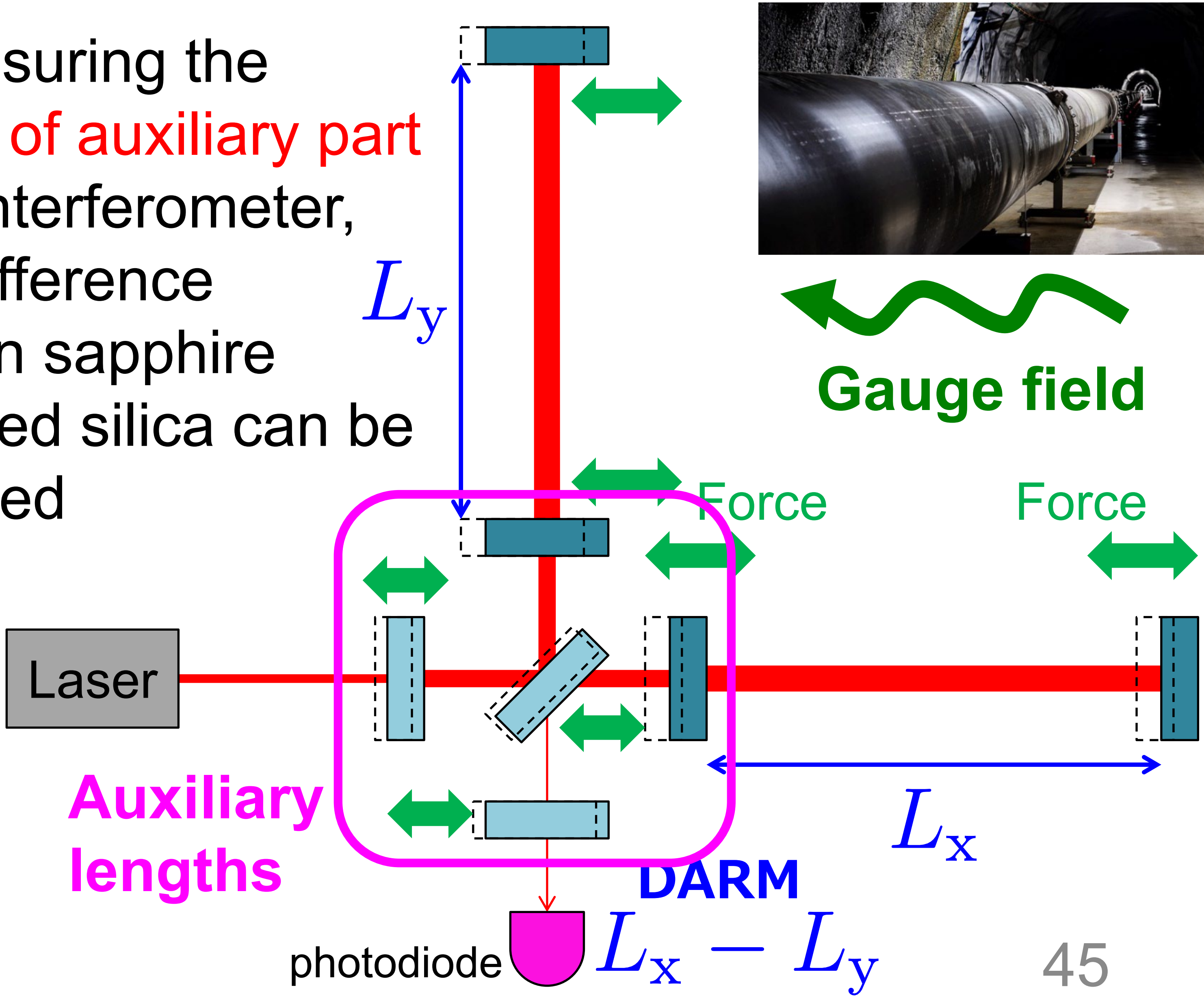





B-L charge
Fused silica: 0.501
Sapphire: 0.510

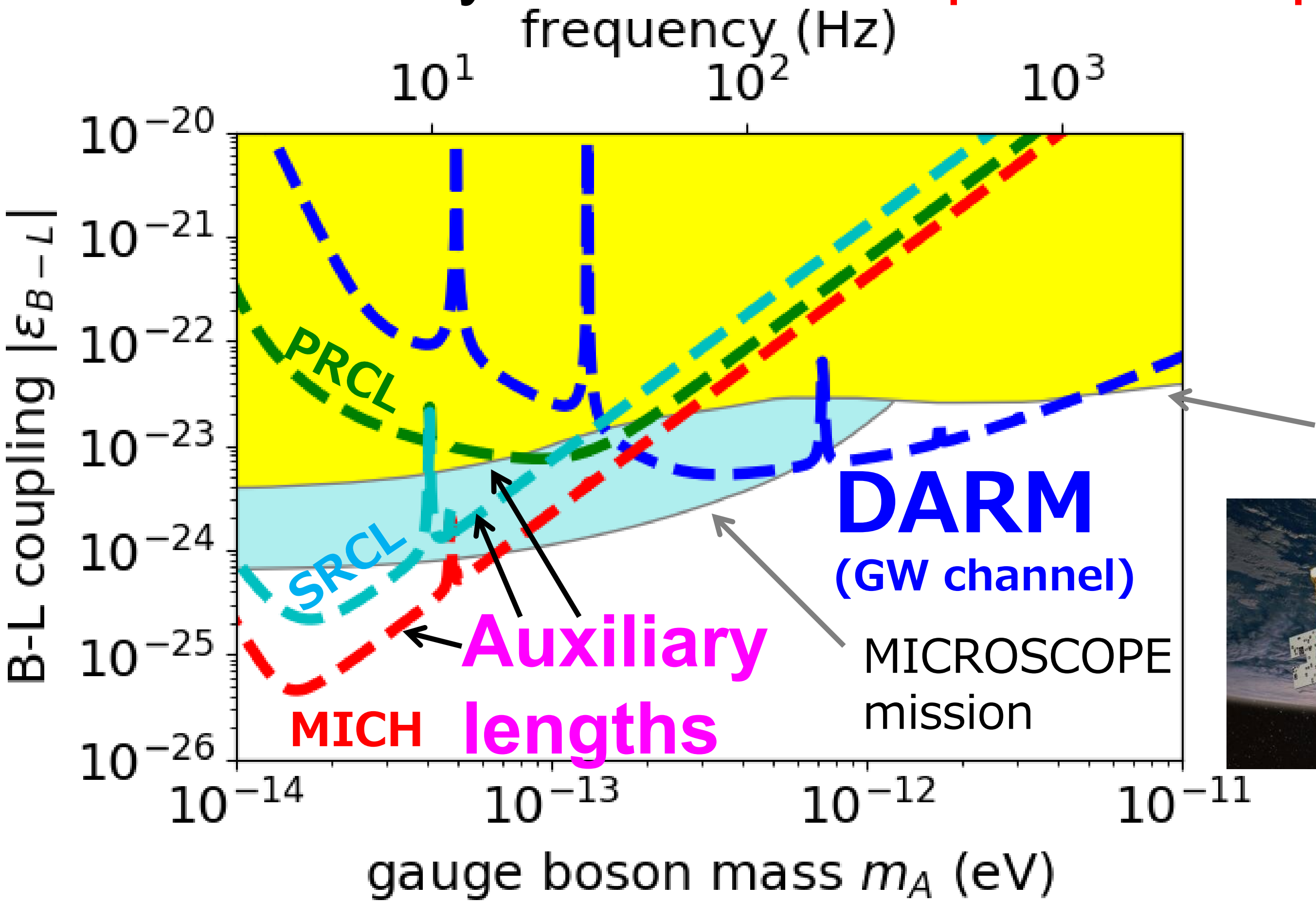
Search with KAGRA

- By measuring the lengths of auxiliary part of the interferometer, force difference between sapphire and fused silica can be measured



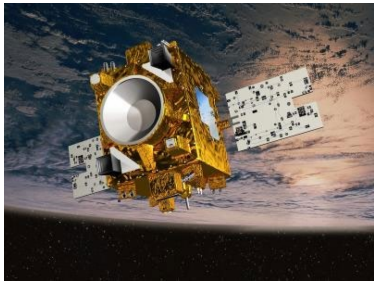
KAGRA Gauge Boson Sensitivity

- Auxiliary length channels have better design sensitivity than DARM (GW channel) at low mass range
- Sensitivity better than equivalence principle tests



YM, T. Fujita, S. Morisaki, H. Nakatsuka, I. Obata, PRD 102, 102001 (2020)

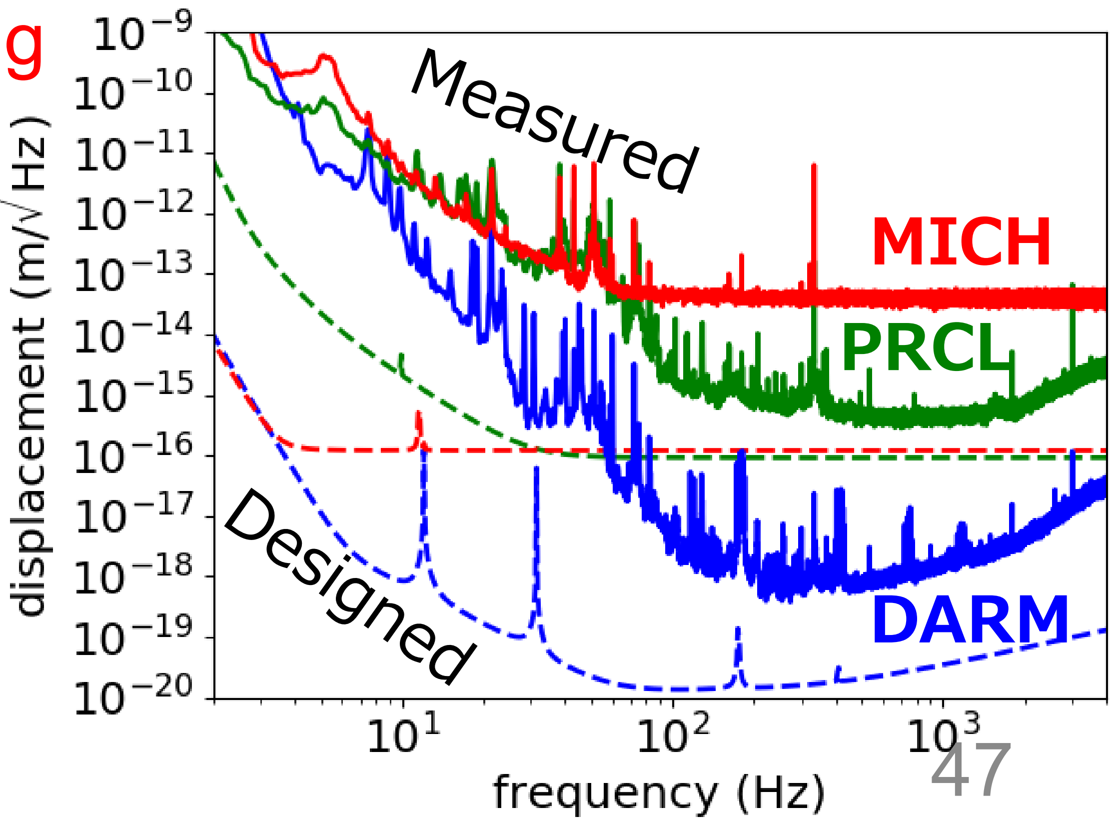
S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata, PRD 103, L051702 (2021)



KAGRA 2020 Data Analysis

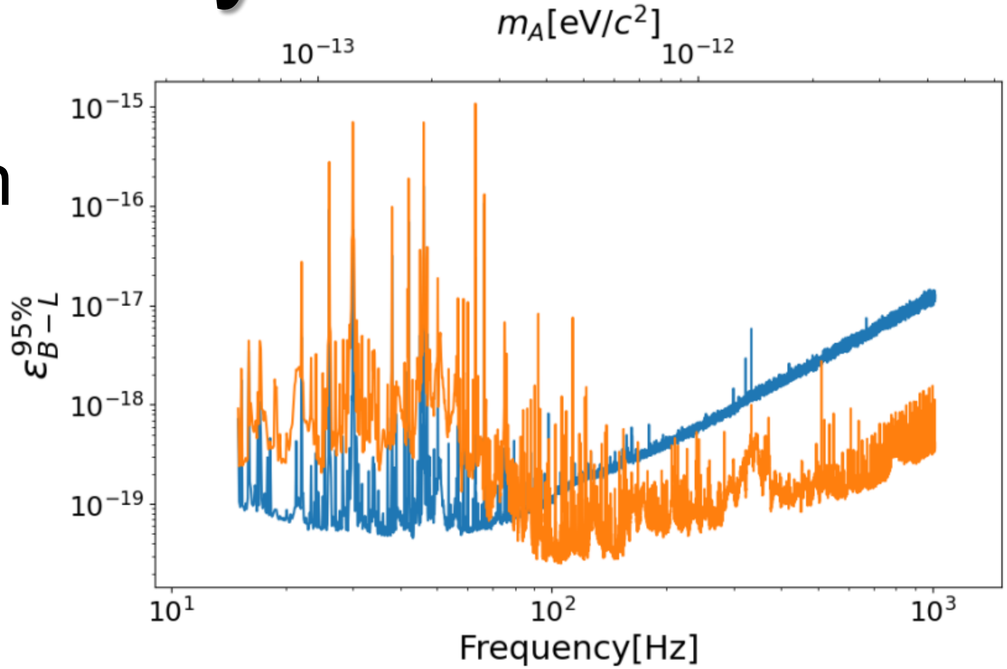
- KAGRA performed joint observing run in April 2020 with GEO600 (O3GK)
- Displacement sensitivity still not good
  ~ 6 orders of magnitude to go at 10 Hz
- Data analysis using the same pipeline used for DANCE

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



KAGRA Data Analysis Results

- Still ~5 orders of magnitude worse than equivalence principle tests
- Demonstrated the feasibility of using auxiliary channels for astrophysics
- New data will be available from O4b and beyond



Ultralight vector dark matter search using data from the KAGRA O3GK run

arXiv:2403.03004v1 [astro-ph.CO] 5 Mar 2024

LIGO-Virgo-KAGRA, arXiv:2403.03004
(Paper written by J. Kume with 1800+ authors!)

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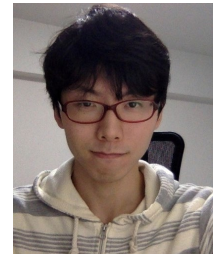
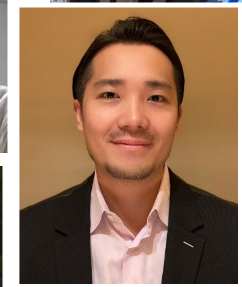
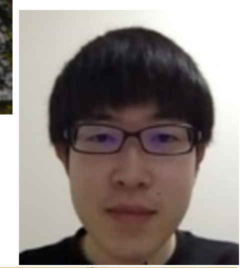
UTokyo

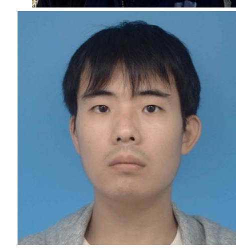
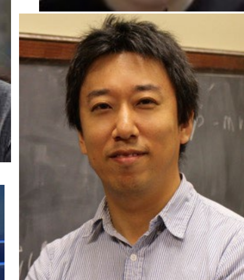
UNITRENTO



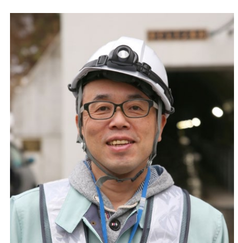








Summary

- Laser interferometers open up new possibilities for dark matter search
- **Axion DM search with DANCE**
  - First result from 24-hour data reported
  - Upgrade underway   Y. Oshima+, PRD **108**, 072005 (2023)
- **Axion DM search with LIGO-Virgo-KAGRA**
  - Polarization optics installed in KAGRA and LIGO
  - First search to be done in O4b (by June 2025!)
- **Vector DM search with LIGO-Virgo-KAGRA**
  - Most stringent bound obtained from LIGO-Virgo
  - New search using sapphire mirrors of KAGRA

科研費 KAKENHI
Japan Science and Technology Agency
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 文部科学省 科学研究費助成事業 学術変革領域研究（2020–2024）
What is dark matter? - Comprehensive study of the huge discovery space in dark matter
PRESTO SAKIGAKE
公益財団法人 住友財団 The Sumitomo Foundation

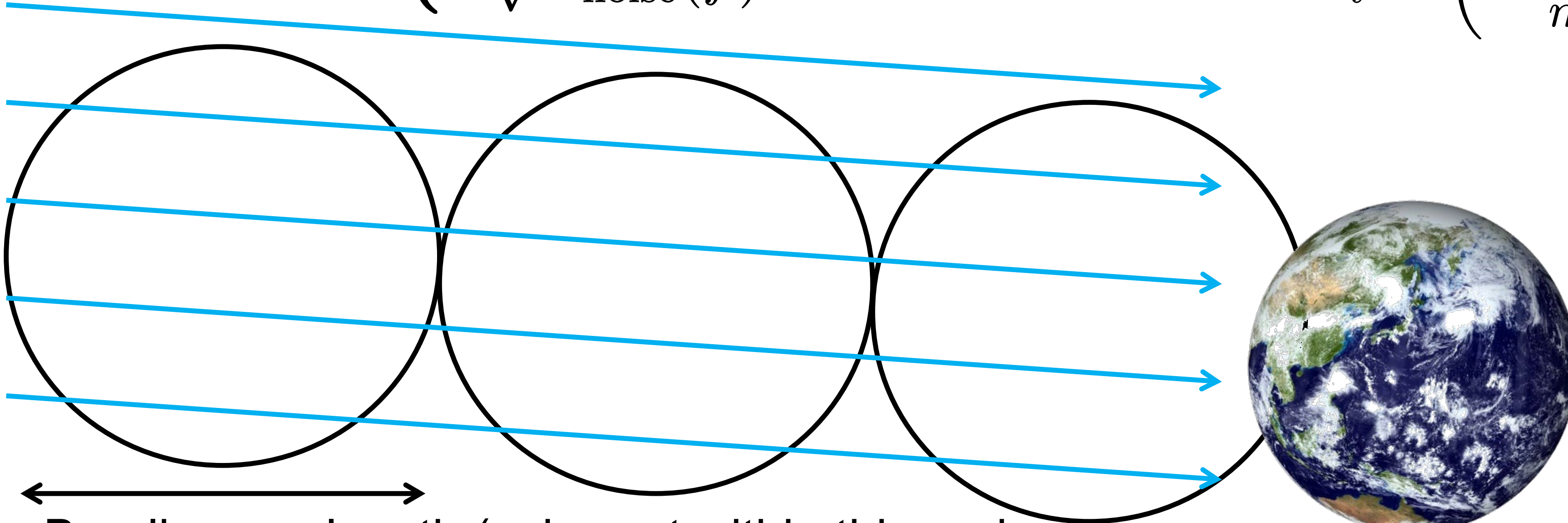
Additional Slides

Coherence Time

- SNR grows with √Tobs if integration time is shorter than coherence time
- SNR grows with (Tobs)$^{1/4}$ if integration time is longer

$$\mathrm{SNR} = \begin{cases} \dfrac{\sqrt{T_{\rm obs}}}{2\sqrt{S_{\rm noise}(f)}}\dfrac{\delta c}{c} & (T_{\rm obs} \lesssim \tau) \\ \dfrac{(T_{\rm obs}\tau)^{1/4}}{2\sqrt{S_{\rm noise}(f)}}\dfrac{\delta c}{c} & (T_{\rm obs} \gtrsim \tau) \end{cases}$$

$$\tau \simeq 1\ \mathrm{year}\left(\frac{10^{-16}\ \mathrm{eV}}{m_a}\right)$$



Freq-Mass-Coherence Time

Frequency	Mass	Coherent Time	Coherent Length
0.1 Hz	4.1e-16 eV	0.32 year	3e12 m
1 Hz	4.1e-15 eV	1e6 sec 12 days	3e11 m
10 Hz	4.1e-14 eV	1.2 days	3e10 m
100 Hz	4.1e-13 eV	2.8 hours	3e9 m
1000 Hz	4.1e-12 eV	17 minutes	3e8 m
10000 Hz	4.1e-11 eV	1.7 minutes	3e7 m