# Ultralight dark matter searches with laser interferometry



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# 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**



http://ksc.kek.jp/



#### **Dark Matter Mystery**

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



drives an acceleration of the expansion of the universe

#### **Dark Matter Models**

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



# 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

• measures differential arm length change



#### Laser Interferometry measures differential arm length change Mirror thickness **Tiny forces** changes from scalar DM Gravitational from waves vector DM Beam splitter Laser source Movable mirror Speed of light changes from Fringe Interference axion DM change Photodiode

#### **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

#### U(1)<sub>B</sub> or U(1)<sub>B-L</sub> 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

Not exhaustive. The ones which require

magnetic fields are not listed.

### **Our Projects**

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

![](_page_10_Figure_2.jpeg)

#### 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

![](_page_11_Picture_4.jpeg)

![](_page_11_Picture_5.jpeg)

#### Contents

- Axion dark matter search with table-top optical ring cavity
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   with gravitational wave detectors
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![](_page_12_Picture_4.jpeg)

![](_page_12_Picture_5.jpeg)

#### **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

![](_page_13_Figure_5.jpeg)

![](_page_14_Figure_0.jpeg)

# **Polarization Modulation from Axions**

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

![](_page_15_Figure_2.jpeg)

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

![](_page_15_Figure_5.jpeg)

# Optical Cavity to Amplify the Signal

• Polarization rotation is small for short optical path

![](_page_16_Picture_2.jpeg)

# Optical Cavity to Amplify the Signal

Polarization rotation is small for short optical path

Laser

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

![](_page_17_Figure_3.jpeg)

# Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

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

![](_page_18_Figure_3.jpeg)

• Bow-tie cavity can amplify the rotation

![](_page_18_Picture_5.jpeg)

### **DANCE** Setup

Dark matter Axion search with riNg Cavity Experiment

bow-tie

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

![](_page_19_Figure_3.jpeg)

![](_page_20_Figure_0.jpeg)

![](_page_21_Figure_0.jpeg)

### 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

![](_page_22_Picture_5.jpeg)

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

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

# First Observing Run in May 2021

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

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

![](_page_23_Picture_4.jpeg)

|                                      | May 2021                      | Act-1 Target      |
|--------------------------------------|-------------------------------|-------------------|
| Round-trip length                    | 1 m                           | 1 m               |
| Input power                          | 242(12) mW<br>(Source: 0.5 W) | 1 W               |
| Finesse<br>(for carrier)             | 2.85(5)×10³<br>s-pol          | 3×10 <sup>3</sup> |
| Finesse<br>(for sidebands)           | 195(3)<br>p-pol               | 3×10 <sup>3</sup> |
| s/p-pol resonant<br>freq. difference | 2.52(2) MHz                   | 0 Hz              |

![](_page_23_Picture_6.jpeg)

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# Data Analysis Pipeline

- 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

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

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

- Obs. time **Detection threshold** determined assuming  $\rho$  follows  $\chi^2$  distribution (=assuming Gaussian noise)
- From  $\rho$ , calculate 95% upper limit on coupling constant

PSD

- Applied the pipeline to mock data for verification
- E. Savalle+, PRL 126, 051301 (2021)  $f_{DM}(V)$ Ó 200 400 600 800 1000 1200 v [km/s]  $\Delta f \sim f_A v_{\rm DM}^2$  $\sim 10^{-6} f$  $f_{\mathsf{DM}}(\bar{f})$ i  $\bar{f} - 1 = \frac{hf}{m_{e}c^{2}} - 1 \ [10^{-6}]$ observed 2000 threshold Injected signal 1500 detected σ 1000 SNR threshold 500 0 200 400 600 800 1000 Frequnecy (Hz)

25

# 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
   1.5
- Method to calculate upper limit taking into account this stochasticity developed

![](_page_25_Figure_6.jpeg)

#### **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<sup>6</sup>)
  - Remaining 7 candidates (all multiples of ~40 Hz) are also found in laser frequency control, and thus rejected
- Placed upper limits

![](_page_26_Figure_8.jpeg)

#### Simultaneous Resonance

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

![](_page_27_Figure_2.jpeg)

# 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

![](_page_28_Figure_3.jpeg)

# **Updated Setup**

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

Auxiliary cavity

![](_page_29_Picture_5.jpeg)

Photo by H. Fujimoto

![](_page_29_Picture_7.jpeg)

![](_page_29_Picture_8.jpeg)

### Simultaneous Resonance Achieved

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

![](_page_30_Picture_3.jpeg)

|                                      | May 2021                         | <b>NOW</b> (Mar 2023)                   | Act-1 Target      |
|--------------------------------------|----------------------------------|---|-------------------|
| Round-trip length                    | 1 m                              | 1 m<br>(+0.5 m aux. cavity)             | 1 m               |
| Input power                          | 242(12) mW<br>(Source: 0.5 W)    | 21.4(9) mW<br>(Source: 2 W)             | 1 W               |
| Finesse<br>(for carrier)             | 2.85(5)×10 <sup>3</sup><br>s-pol | 549(3) s-pol, with cavity lock          | 3×10 <sup>3</sup> |
| Finesse<br>(for sidebands)           | 195(3)<br>p-pol                  | 36.8(2) p-pol, with cavity lock         | 3×10 <sup>3</sup> |
| s/p-pol resonant<br>freq. difference | 2.52(2) MHz                      | ~0 Hz with lock<br>(Originally ~92 MHz) | 0 Hz<br>31        |

#### **Current Estimated Sensitivity**

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

![](_page_31_Figure_3.jpeg)

![](_page_31_Figure_4.jpeg)

#### 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

![](_page_32_Picture_4.jpeg)

![](_page_32_Picture_5.jpeg)

#### 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

![](_page_33_Figure_3.jpeg)

#### 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
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![](_page_34_Figure_3.jpeg)

#### Axion Search with GW Detectors

![](_page_35_Figure_1.jpeg)

![](_page_36_Figure_0.jpeg)

### **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)

![](_page_37_Picture_5.jpeg)

<u>klog #17692</u>

#### Contents

- Axion dark matter search with table-top optical ring cavity
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   with gravitational wave detectors
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![](_page_38_Picture_4.jpeg)

![](_page_38_Picture_5.jpeg)

### Gauge Boson

 Possible new physics beyond the standard model: New gauge symmetry and gauge boson

Proton

Neutron

Electron

Nucleus

gauge

field

- 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

![](_page_40_Figure_2.jpeg)

- Almost no signal for symmetric cavity if cavity length is short (phase difference is 10<sup>-5</sup> 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+, <u>Communications Physics 2, 155 (2019)</u> LIGO, Virgo, KAGRA Collaboration, <u>PRD 105, 063030 (2022)</u>
- Better constraint than equivalence principle tests
- Even better constraint could be obtained from KAGRA

![](_page_41_Figure_4.jpeg)

#### Search with GW Detectors

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

![](_page_42_Figure_3.jpeg)

#### Search with KAGRA 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<sub>r</sub>

![](_page_43_Picture_3.jpeg)

![](_page_43_Figure_4.jpeg)

# Search with KAGRA KAGRA

![](_page_44_Figure_1.jpeg)

# 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 frequency\_(Hz) YM, T. Fujita, S. Morisaki, 10<sup>1</sup> 10<sup>3</sup> H. Nakatsuka, I. Obata,  $10^{-20}$ PRD 102, 102001 (2020)  $10^{-21}$ S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata,  $\mathcal{E}_B$ PRD 103, L051702 (2021) 10-22 coupling Eöt-Wash  $10^{-23}$ torsion pendulum DARM  $10^{-24}$ (GW channel)  $10^{-25}$ MICROSCOPE mission aths MICH  $10^{-26}$  $10^{-12}$  $10^{-11}$ 10 gauge boson mass  $m_A$  (eV)

#### **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)

![](_page_46_Figure_5.jpeg)

# **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

![](_page_47_Picture_4.jpeg)

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

![](_page_47_Figure_6.jpeg)

Team **Tomohiro Fujita** Hiroki Fujimoto Takumi Fujimori **Kentaro Komori** Jun'ya Kume Matteo Leonardi **Yuta Michimura** Shinji Miyoki **Yusuke Manita** Soichiro Morisaki **Atsushi Nishizawa Ippei Obata** Yuka Oshima Hinata Takidera Haoyu Wang

![](_page_48_Picture_1.jpeg)

お茶の水女子大学 Ochanomizu University

![](_page_48_Picture_2.jpeg)

![](_page_48_Picture_3.jpeg)

![](_page_48_Picture_4.jpeg)

![](_page_48_Picture_5.jpeg)

![](_page_48_Picture_6.jpeg)

![](_page_48_Picture_7.jpeg)

![](_page_48_Picture_8.jpeg)

![](_page_48_Picture_9.jpeg)

<sup>49</sup> 

# 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

![](_page_49_Picture_11.jpeg)

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.

![](_page_49_Picture_12.jpeg)

![](_page_49_Picture_13.jpeg)

![](_page_49_Picture_14.jpeg)

![](_page_49_Picture_15.jpeg)

#### **Additional Slides**

### LIGO-Virgo-KAGRA Obs. Plans

| Updated 2024-06-14 |      | 01        |              | 02          |                | 3         |      |        |            | 04           |      |      |            | 05            | 5    |
|--------------------|------|-----------|--------------|-------------|----------------|-----------|------|--------|------------|--------------|------|------|------------|---------------|------|
| LIGO               |      | 80<br>Мрс | 100<br>Мрс   |             | 100-140<br>Мрс |           |      |        | 150 -<br>M | 160+<br>pc   |      |      | 2          | 240-32<br>Mpc | 5    |
| Virgo              |      |           | 30<br>Мро    | C           | 40-50<br>Мрс   |           |      |        |            | 40-80<br>Мрс |      |      | s<br>///// | See te>       | ct   |
| KAGRA              |      |           |              |             | 0.7<br>Мрс     | C         |      |        | 1-3<br>Mpc | ≃10<br>Mpc   |      |      |            | 25-128<br>Mpc | 3    |
| G2002127-v25       | 2015 | 2016      | l<br>2017 20 | 1<br>018 20 | 19 2020        | l<br>2021 | 2022 | 1 2023 | 2024       | 2025         | 2026 | 2027 | l<br>2028  | l<br>2029     | 2030 |

### **Coherence Time**

- SNR grows with √Tobs if integration time is shorter than coherence time
- SNR grows with (Tobs)<sup>1/4</sup> if integration time is longer

![](_page_52_Figure_3.jpeg)

#### **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<br>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           |