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

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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)_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

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



Contents

- Axion dark matter search with table-top optical ring cavity
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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





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



- 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



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



Optical Cavity to Amplify the Signal

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



• Bow-tie cavity can amplify the rotation



DANCE Setup

Dark matter Axion search with riNg Cavity Experiment

bow-tie

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







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+, <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 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)×10³ 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



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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 ρ follows χ^2 distribution (=assuming Gaussian noise)
- From ρ , 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] $\Delta f \sim f_A v_{\rm DM}^2$ $\sim 10^{-6} f$ $f_{\mathsf{DM}}(\bar{f})$ 1 $\bar{f} - 1 = \frac{hf}{m_{e}c^{2}} - 1 \ [10^{-6}]$ observed 2000 threshold Injected signal 1500 detected σ 1000 SNR threshold 500 0 200 400 600 800 1000 Frequnecy (Hz)

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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



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 10⁶)
 - Remaining 7 candidates (all multiples of ~40 Hz) are also found in laser frequency control, and thus rejected
- Placed upper limits



Simultaneous Resonance

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



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



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)×10 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 31

Current Estimated Sensitivity

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





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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





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)



<u>klog #17692</u>

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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



- 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+, <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



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

- 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_r





Search with KAGRA KAGRA



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, 10¹ 10³ 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)



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



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



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



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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



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.









Additional Slides

LIGO-Virgo-KAGRA Obs. Plans

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

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



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