学術変革領域A Transformative Research Area (A)

CosmoGenesis: 宇宙創生の物理法則は何か？

Kick-off Workshop

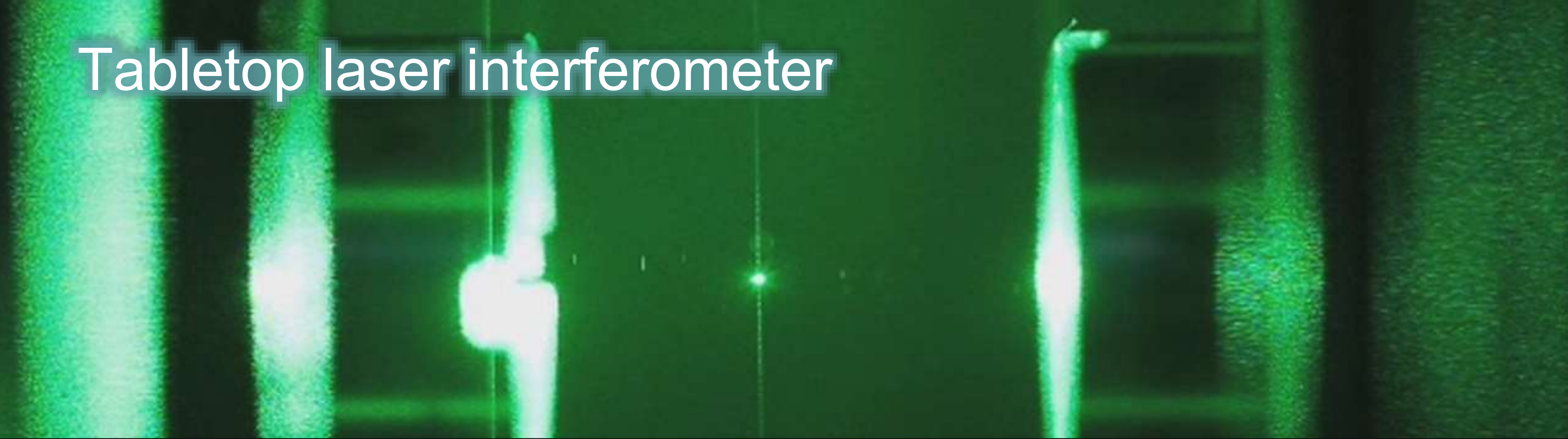
C02: Exploring the origin of the Universe w/ tabletop laser interferometers & gravitational-wave observatories

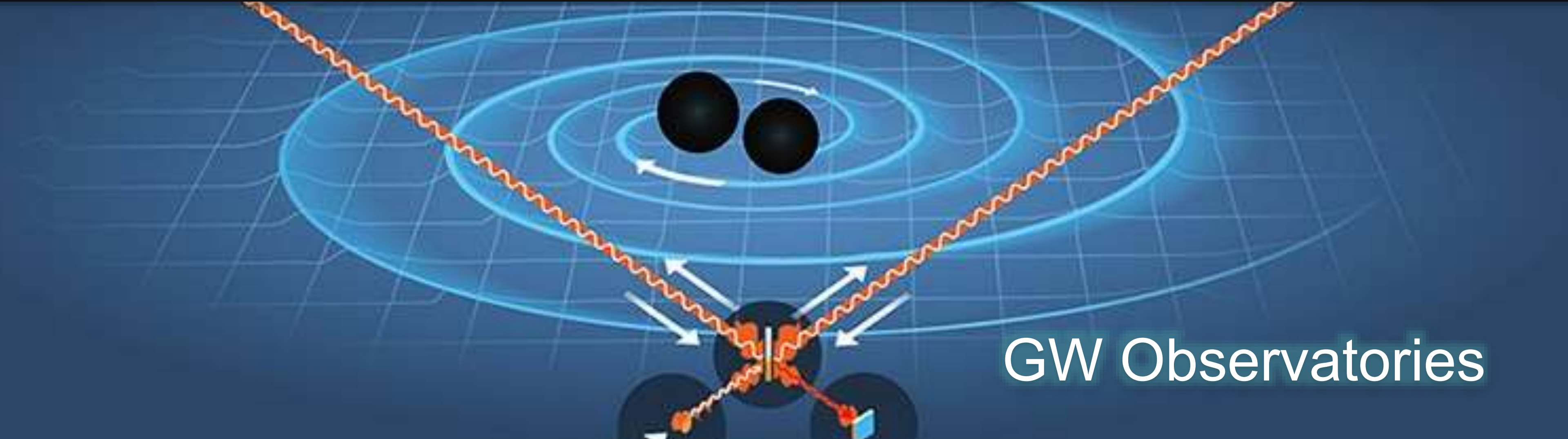
Tomohiro Fujita (Ochanomizu U.)

C02 Group Members: Yuta Michimura (RESCEU),
Kentaro Somiya (Science Tokyo),
Takafumi Ushiba (ICRR)

Based on Obata, TF& Michimura PRL121, 161301 (2018)
Nagano, TF, Obata & Michimura PRL123,111301(2019)
Michimura, TF, Morisaki et al., PRD102, 102001 (2020)
Morisaki, TF, Michimura et al., PRD103, L051702 (2021)

@ U. Tokyo. Koshiba Hall 2026. Jul. 7


Tabletop laser interferometer

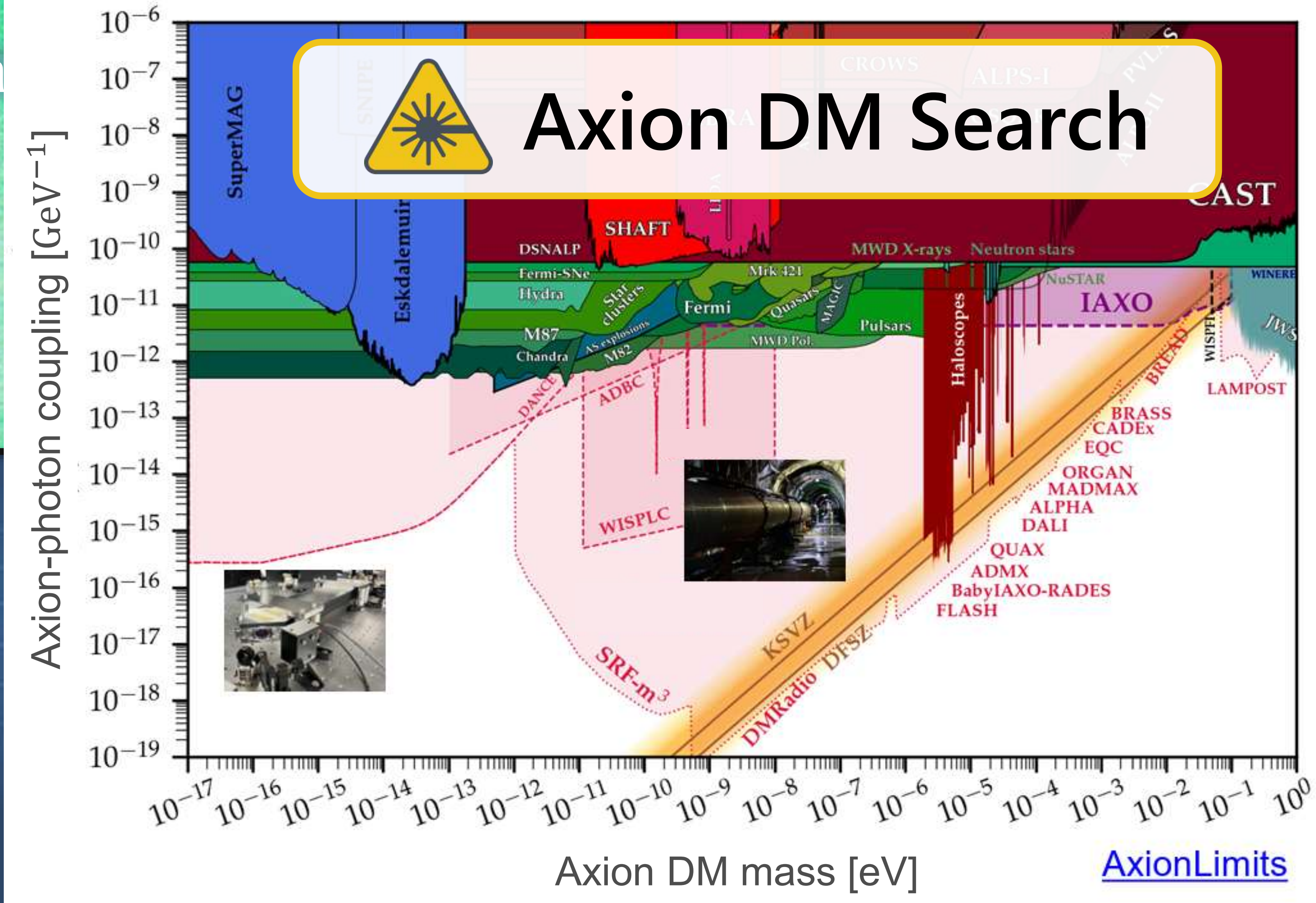

GW Observatories

We hunt Ultralight Dark Matter

with laser technologies

Ta

Axion DM Search



es

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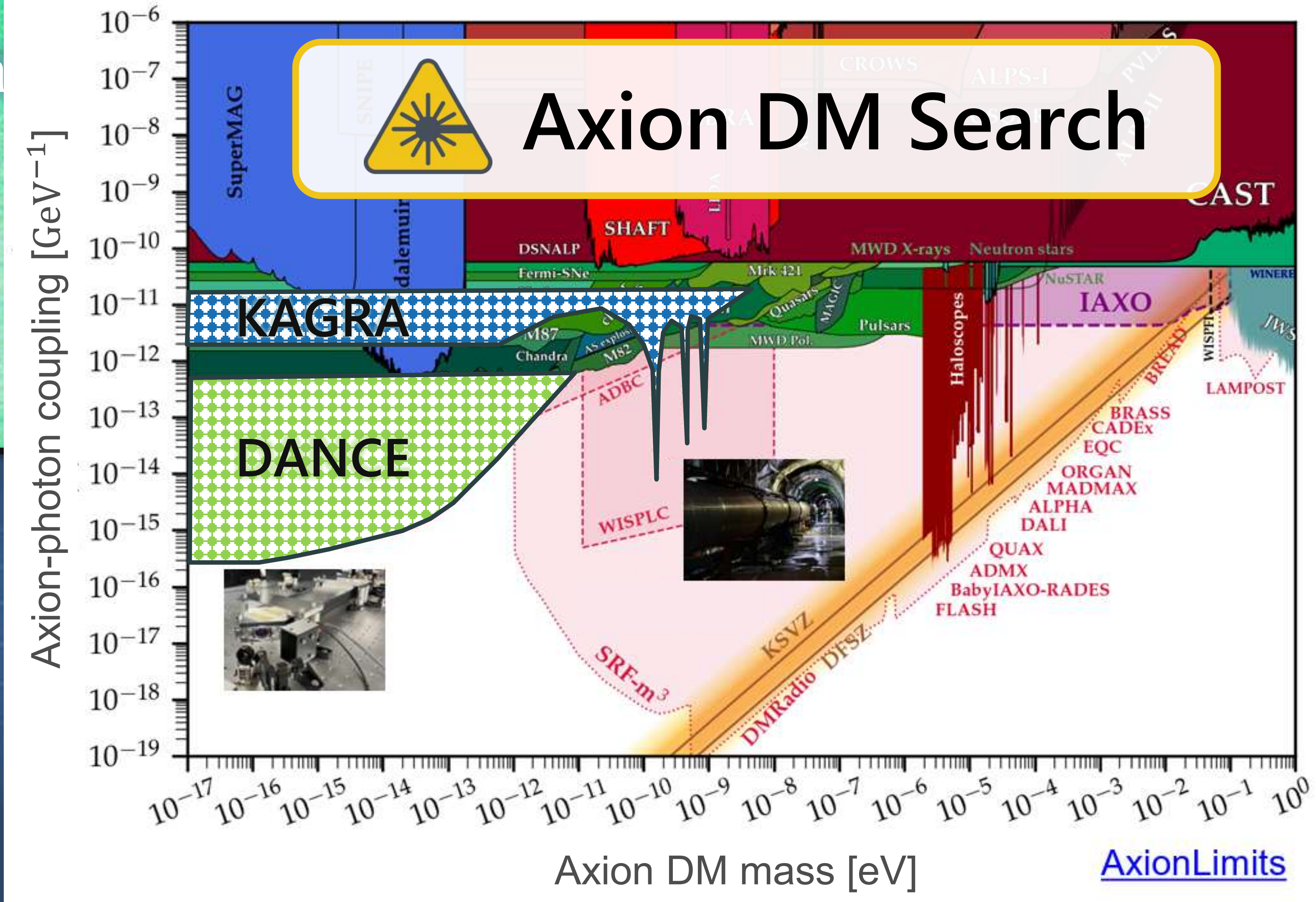

Axion DM Search
KAGRA
DANCE
SuperMAG
SHAFT
DSNALP
Fermi-SNe
M87
Chandra
M82
Mrk 421
Quasars
MAGIC
Pulsars
MWD Pol.
MWD X-rays
Neutron stars
NuSTAR
IAXO
WINERED
JWST
CAST
Haloscopes
ADBC
WISPLC
SRF-m^3
KSVZ
DMRadio
DFSZ
BREAD
WISPFI
LAMPOST
BRASS
CADEx
EQC
ORGAN
MADMAX
ALPHA
DALI
QUAX
ADMX
BabyIAXO-RADES
FLASH
Axion-photon coupling [GeV^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0}
Axion DM mass [eV]
AxionLimits

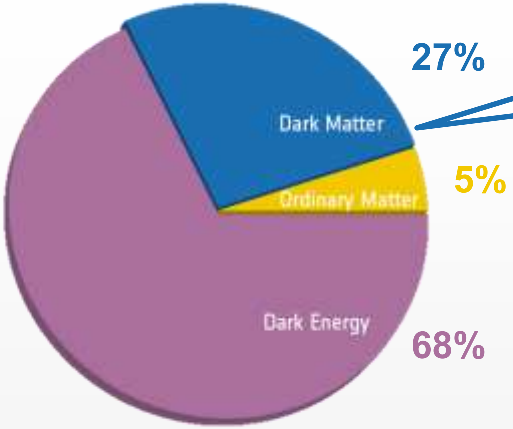
es

Outline

1. Introduction to DM search
2. Axion (coll. w/ C03)
3. Vector DM (coll. w/ A01,02)
4. Summary

Dark Matter

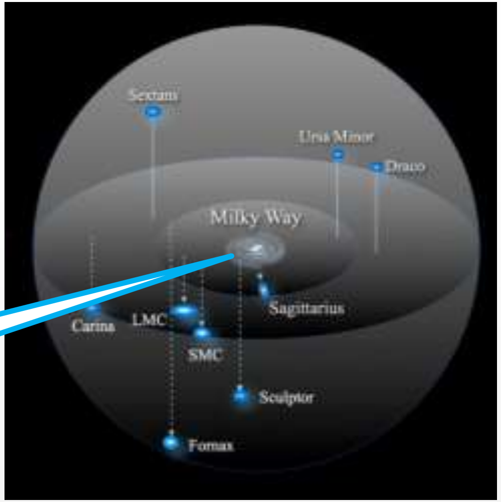
Cosmic pie chart



$\bar{\rho}_{\rm DM} \approx 10^{-6} {\rm GeV/cm^3}$

$\rho_{\rm DM}^{\rm local} = 0.3 {\rm GeV/cm^3}$

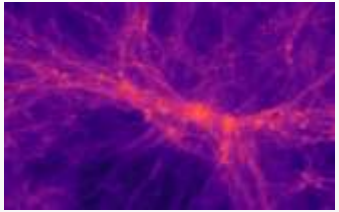
Local DM Halo



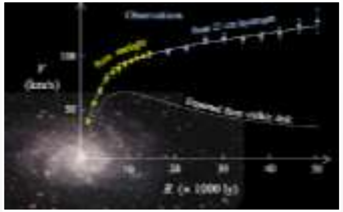
We live inside a high density DM halo!

DM Search I

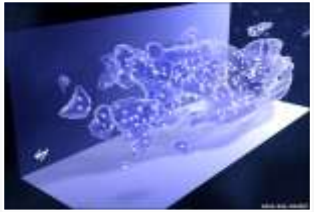
Existence of DM is confirmed
only through its gravitational interaction



Structure formation



Galaxy rotation curve



Gravitational lensing

Bullet cluster

→ **DM is something gravitating**

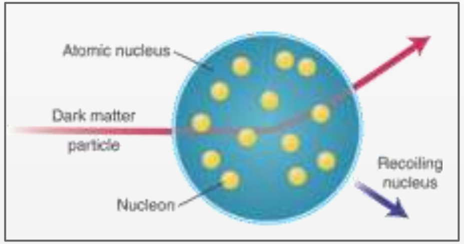
DM Search II

Unsatisfied… ☹ → **We want to identify DM!**

1 Assume a DM model with **additional interaction**

2 Search for its signal

WIMP case



WIMP scatters with nuclei

Underground experiment
(Xenon 1T)

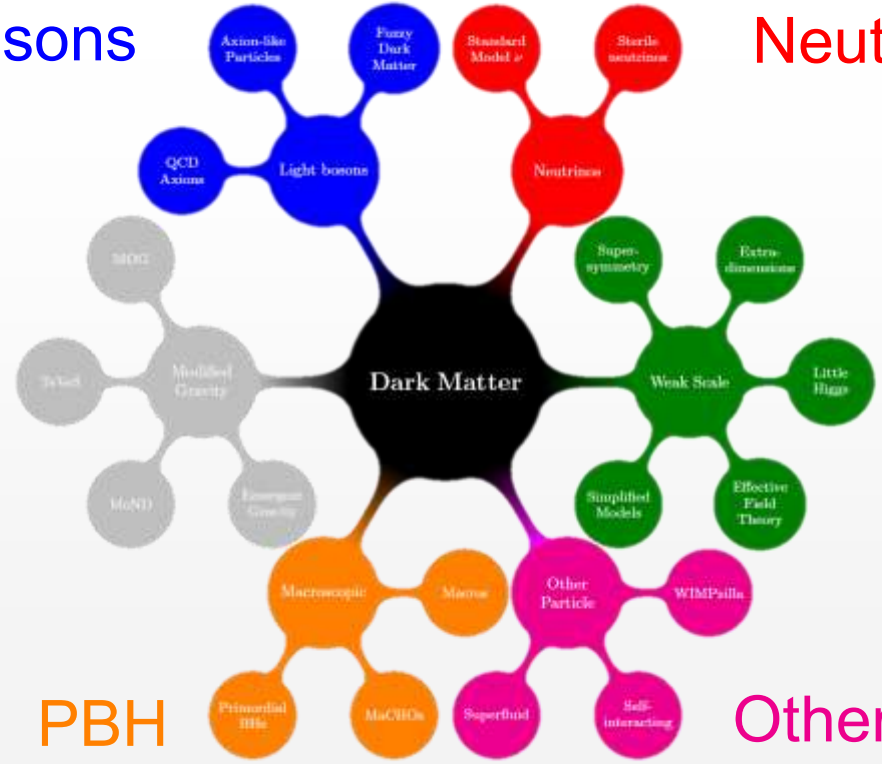
DM Candidates

Bosons

Neutrino

Modified gravity

WIMP



PBH

Other

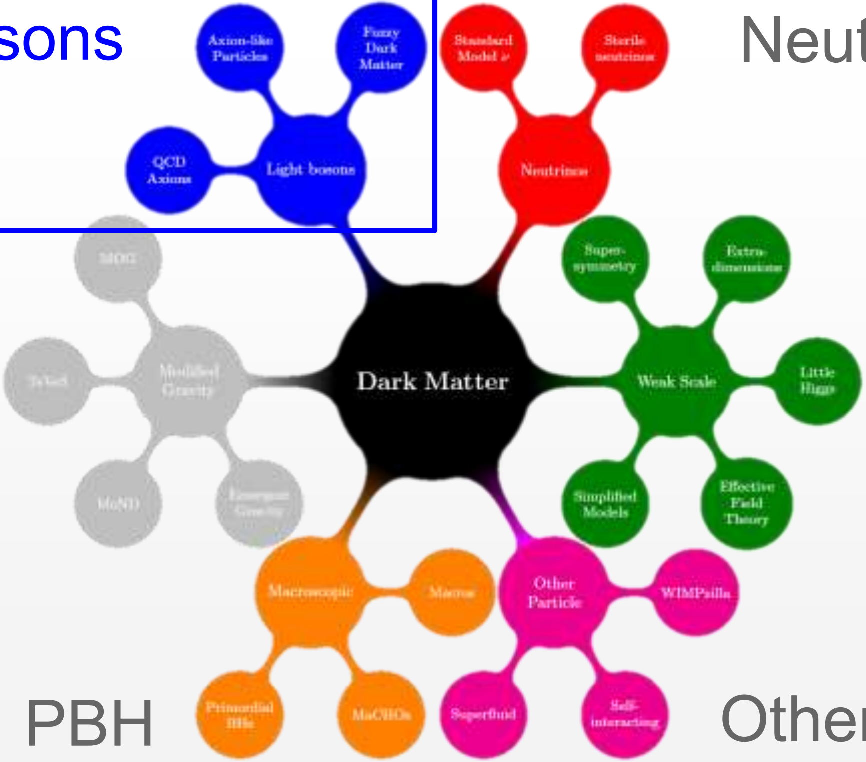
DM Candidates

Bosons

Neutrino

Modified gravity

WIMP

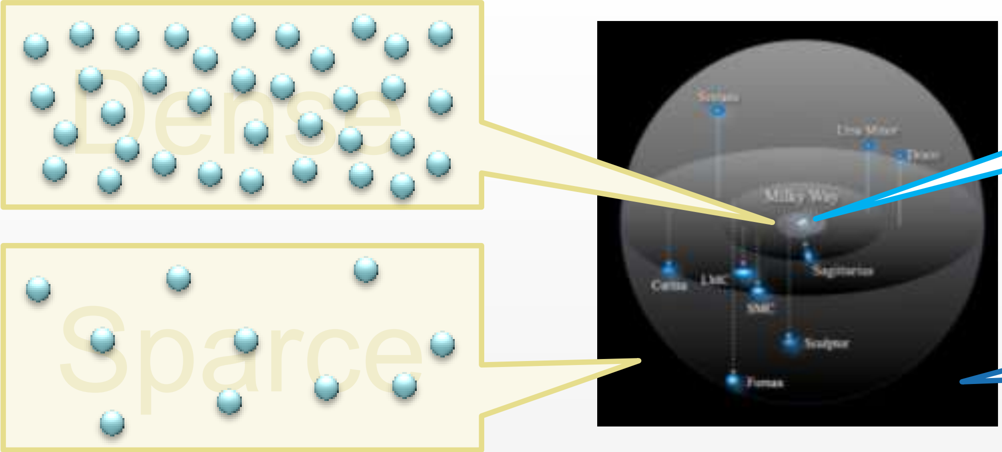


PBH

Other

DM density

WIMP

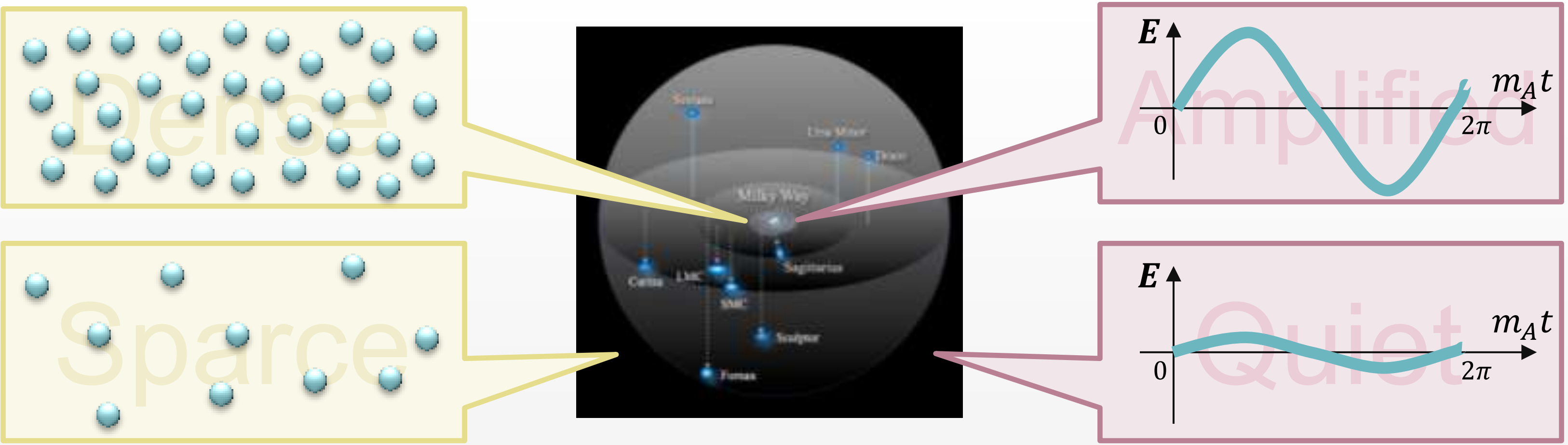


$\rho_{\mathrm{DM}}^{\mathrm{local}} = 0.3\mathrm{GeV/cm^3}$

$\bar{\rho}_{\mathrm{DM}} \approx 10^{-6}\mathrm{GeV/cm^3}$

DM density

WIMP | **“Wave” DM**



Wave-like DM is also a good candidate!

DM search

	Axion	Vector	WIMP
Image	Birefringent media	Electric wave with a mass	**Massive Particle**
Interaction	Photon	B or B-L	**Nuclei**
Search	**DANCE (Table-top)** **KAGRA+PD**	**KAGRA Aux.** **Small Table-top**	**Particle collider** **Undergrond exp.**

DM search

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Axion DM (a.k.a. ALP DM)

Ultralight wave-like DM oscillates: $\phi = \phi_0 \cos(m_\phi t)$

3 propeties. ADM is

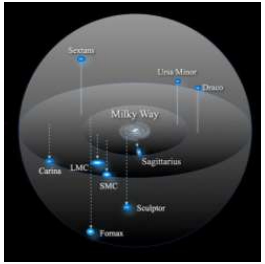
1. Scalar : no direction
2. Parity violating : Left & right become asymmetric
3. Coupled to photons : $\mathcal{L}_{\text{int}} = \frac{1}{4} g \phi F^{\mu\nu} \tilde{F}_{\mu\nu}$ (Chern-Simons coupling)

Photon in ADM

EoM for photon with ADM ϕ is

$$[\partial_t^2 - \nabla^2]\boldsymbol{A} = \underline{-g\dot{\phi}\boldsymbol{\nabla} \times \boldsymbol{A}} \quad \Leftarrow \quad \phi = \phi_0 \cos(m_\phi t)$$

Additional Interaction



live in ADM

Dispersion relations of left/right polarization are modified as

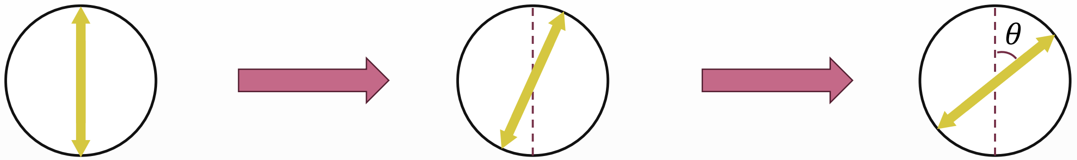
$$\omega_{L,R}^2 = c^2 k^2 \left[1 \pm g\phi_0 \frac{m}{k} \sin(mt)\right] \qquad (i\hat{\boldsymbol{k}} \times \boldsymbol{e}_{L,R} = \pm\, \boldsymbol{e}_{L,R})$$

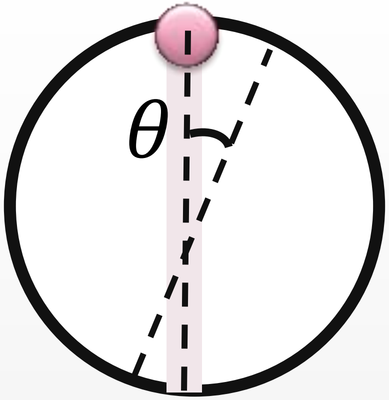
Speed of light changes depending on circular polarization!

ADM = Birefringent media

Optical Rotation by ADM

Linearly polarized photons traveling in ADM rotates its pol. plane





Rotation angle θ for light path L is $\quad (\rho_{\rm DM}^{\rm local} = m_\phi^2 \phi_0^2/2 \approx 0.3{\rm GeV/cm^3})$

$$\theta \simeq g\phi_0 \sin(mL/2) \xrightarrow{mL \ll 1} 10^{-14} \left(\frac{g}{10^{-12}{\rm GeV^{-1}}}\right)\left(\frac{L}{3{\rm km}}\right)$$

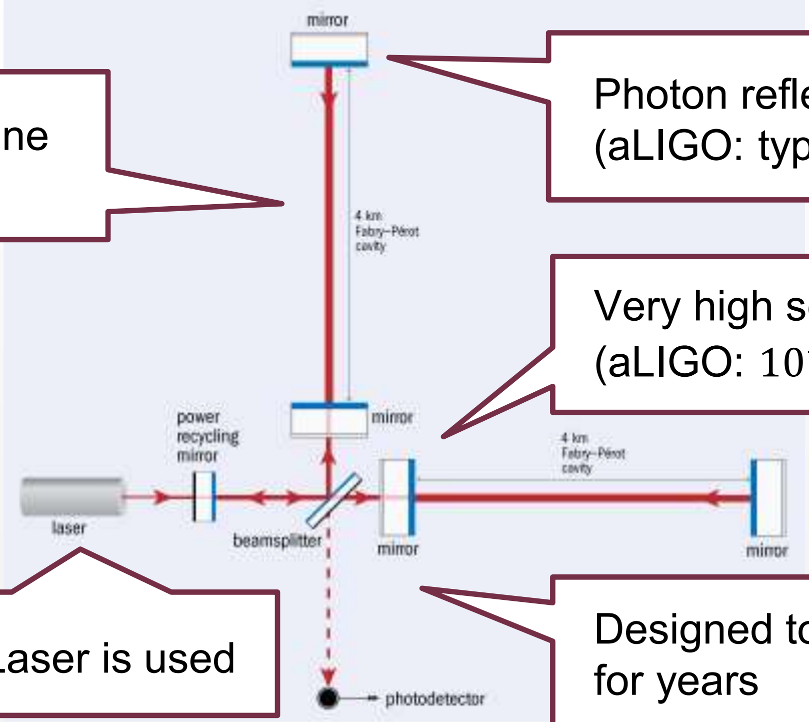
Signal is small! So we need

1. **Long light path**
2. **High sensitivity**
3. **Long runtime**

DM search

	Axion	Vector	WIMP
Image	Birefringent media	Electric wave with a mass	**Massive Particle**
Interaction	Photon	B or B-L	**Nuclei**
Search	**DANCE (Table-top)** **KAGRA+PD**	**KAGRA Aux.** **Small Table-top**	**Particle collider** **Undergrond exp.**

GW interferometer is ideal!!



Very Long Baseline
(aLIGO: 4km)

Photon reflects many times
(aLIGO: typically 500 times)

Very high sensitivity
(aLIGO: $10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$)

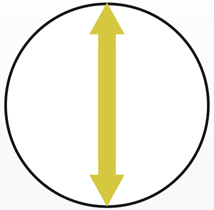
Linear Polarized Laser is used

Designed to run
for years

Measure ADM signal

Nagano, TF, Obata & Michimura
PRL123,111301(2019)

Measure the **s-polarized light** induced by ADM birefringence

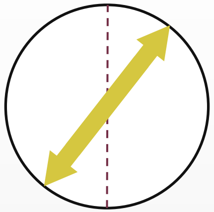


Originally
P-polarized

Measure ADM signal

Nagano, TF, Obata & Michimura
PRL123,111301(2019)

Measure the **s-polarized light** induced by ADM birefringence

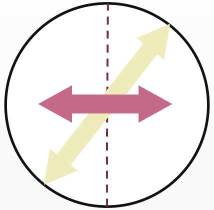


Optical
rotation

Measure ADM signal

Nagano, TF, Obata & Michimura
PRL123,111301(2019)

Measure the **s-polarized light** induced by ADM birefringence

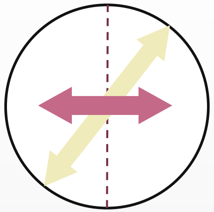


S-polarization
produced by
ADM

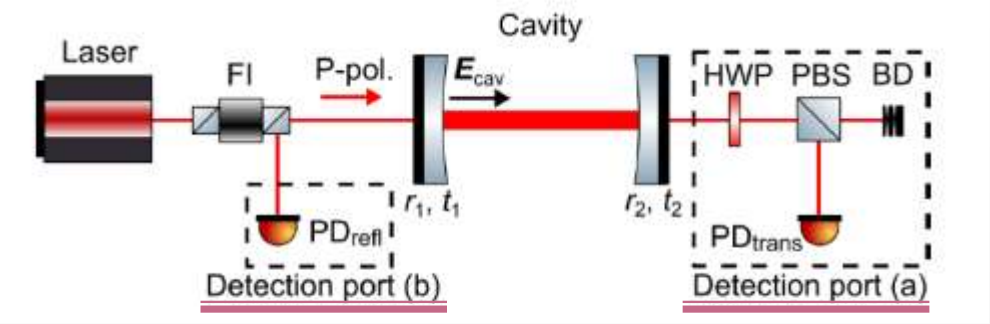
Measure ADM signal

Nagano, TF, Obata & Michimura
PRL123,111301(2019)

Measure the **s-polarized light** induced by ADM birefringence



S-polarization produced by ADM

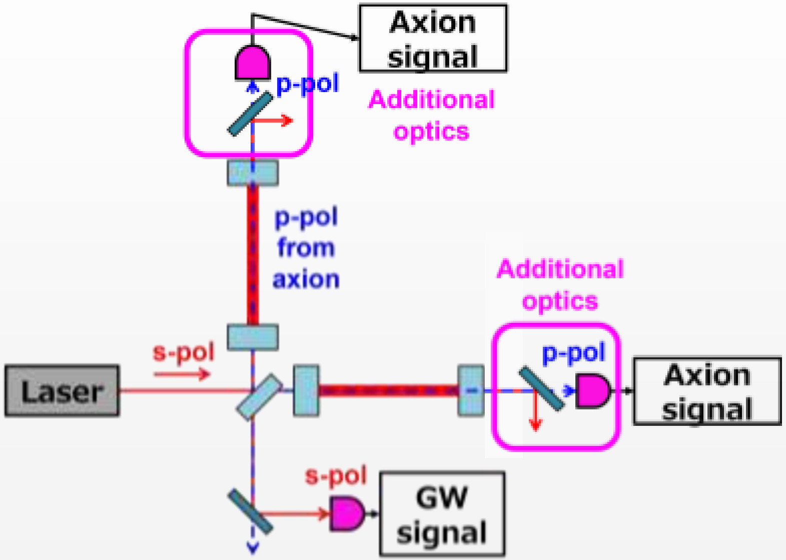


Adding a photodetector at port (a) or (b) makes KAGRA an ADM detector.

This ADM search is compatible with GW observation

Status: KAGRA Axion Search

- Proposed in **2019**
- Polarization optics installed in **2021**



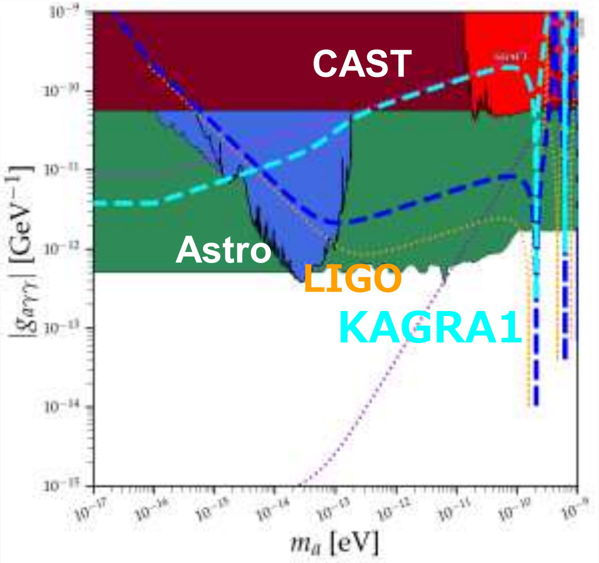
KAGRA in Kamioka, Gifu, Japan

Nagano, TF, Obata & Michimura PRL123,111301(2019)

Status: KAGRA Axion Search

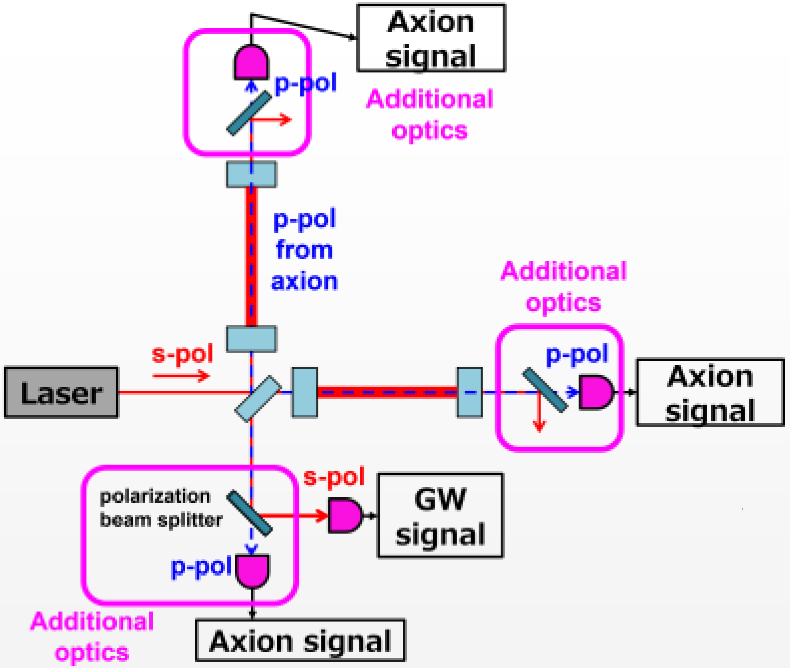
- Proposed in **2019**
- Polarization optics installed in **2021**
- First data taken in June-Aug **2025**
  - Fujimori-kun is analyzing
- High frequency data in Feb **2026**
  - 1 MHz sampling, 10 minutes
  - Kawaguchi-kun is checking data and doing calibration

Please check their posters for details!



Nagano, TF, Obata & Michimura PRL123,111301(2019)

Status: KAGRA Axion Search



Nagano, TF, Obata & Michimura PRL123,111301(2019)

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- Proposed in **2019**
- Polarization optics installed in **2021**
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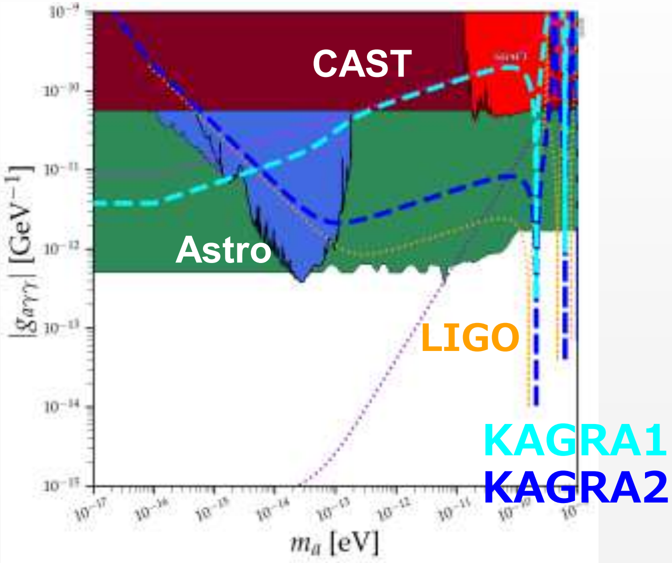
  - Fujimori-kun is analyzing
- High frequency data in Feb **2026**
  - 1 MHz sampling, 10 minutes
  - Kawaguchi-kun is checking data and doing calibration
- Plan to improve the optics this year before IR1
  - x8 more power JGW-G2617250



Nagano, TF, Obata & Michimura PRL123,111301(2019)

DM search

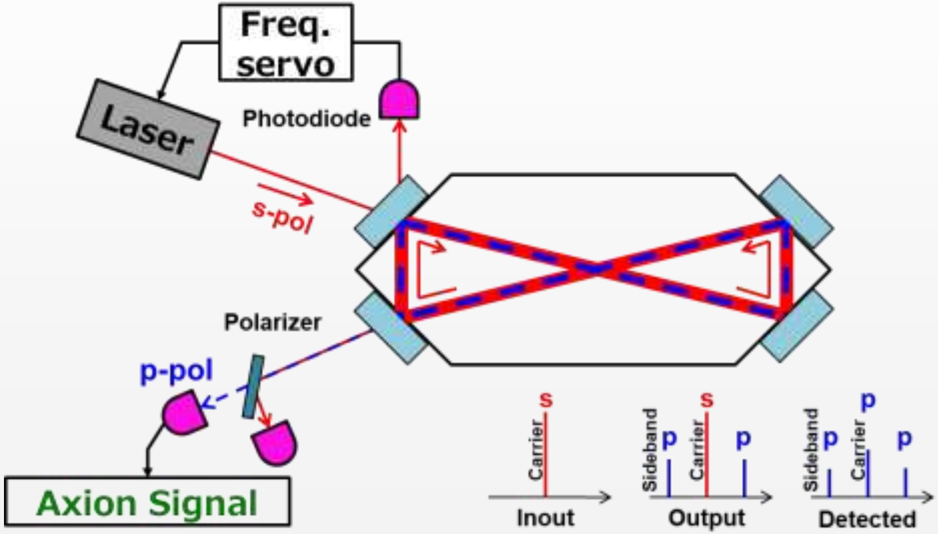
	Axion	Vector	WIMP
Image	**Birefringent media**	**Electric wave with a mass**	**Massive Particle**
Interaction	**Photon**	**B** or **B-L**	**Nuclei**
Search	**DANCE** (Table-top) **KAGRA+PD**	**KAGRA Aux.** **Small Table-top**	**Particle collider** **Undergrond exp.**

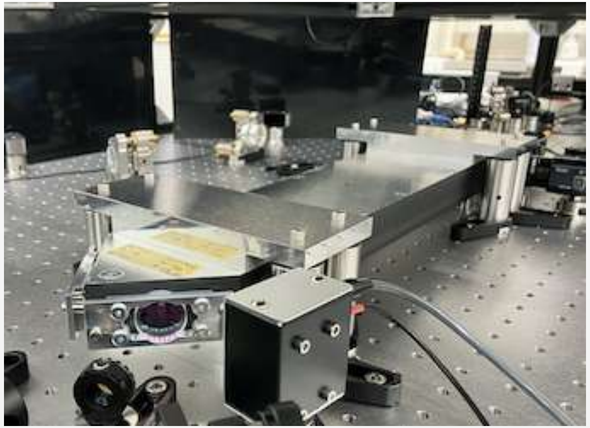
DANCE

Dark matter Axion search
with riNg Cavity Experiment



Obata, TF& Michimura PRL121, 161301 (2018)



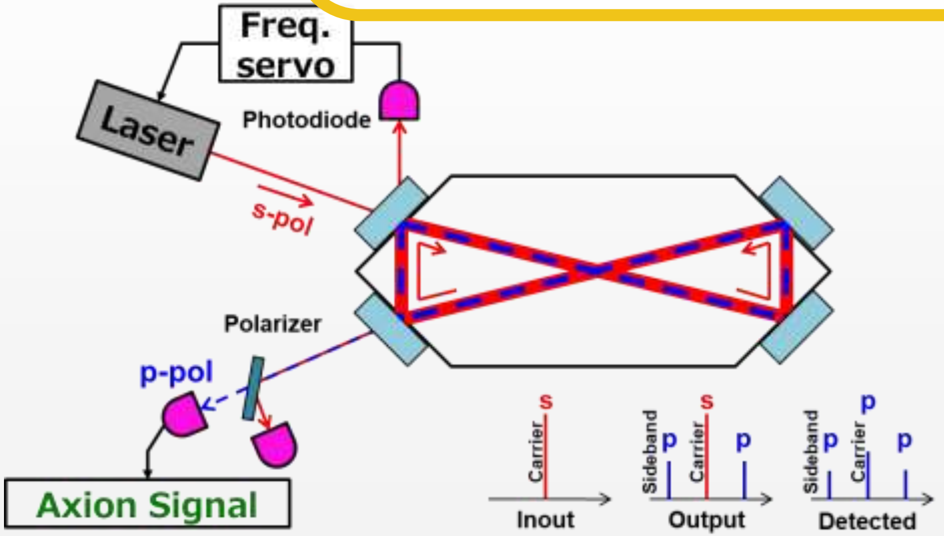


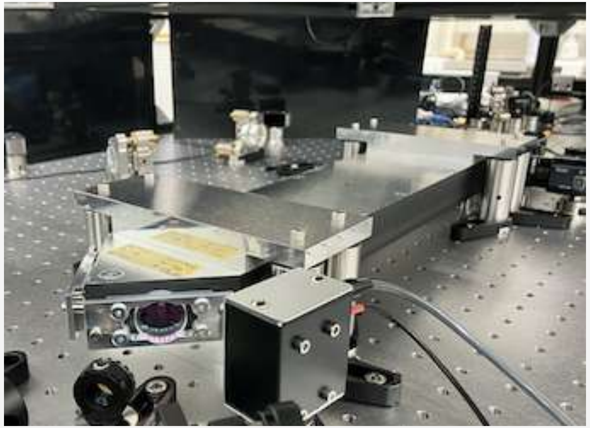
DANCE

Dark matter **A**xion search
with ri**N**g **C**avity **E**xperiment

DANCE is running
right here on the B1 floor!

Obata, TF& Michimura PRL121, 161301 (2018)



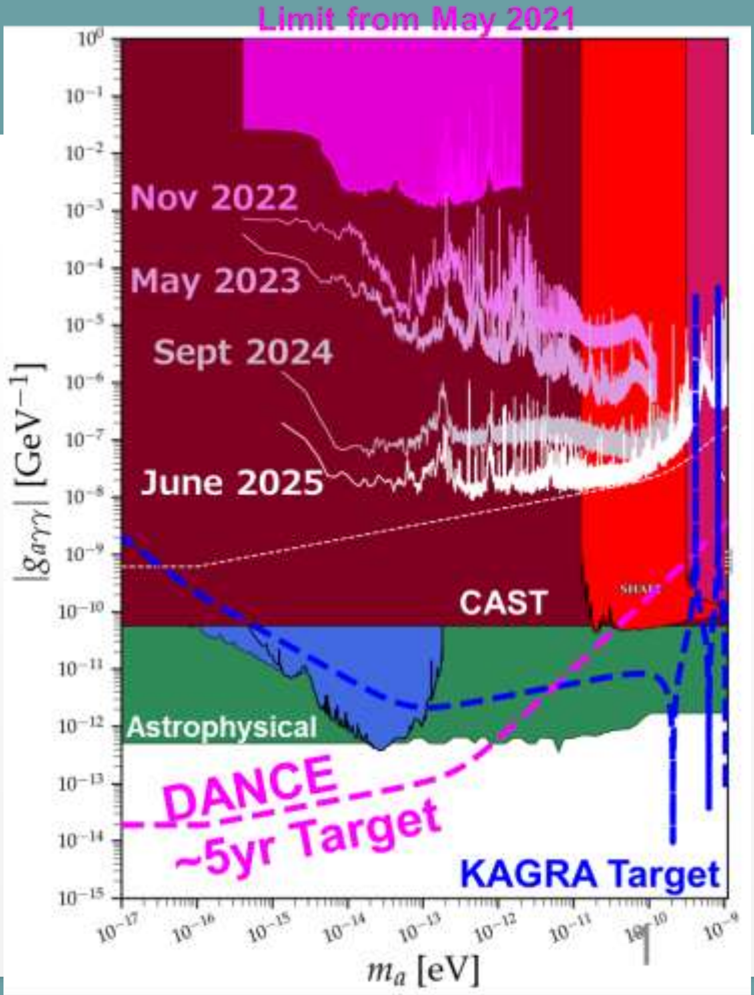


Status: DANCE

- Proposed in 2018
  I. Obata, TF, Y. Michimura, PRL **121**, 161301 (2018)
- First demonstration in 2021
  ~5 orders of magnitude
  improvement since then
  Y. Oshima+, PRD **108**, 072005 (2023)
- Upgrade with higher power
  (6 mW → 1 W) underway,
  lead by Takidera-kun

H. Takidera+, PRD **112**, 063048 (2025)
H. Fujimoto, PhD thesis (UTokyo 2025)

Stay tuned for
Taki's talk next!

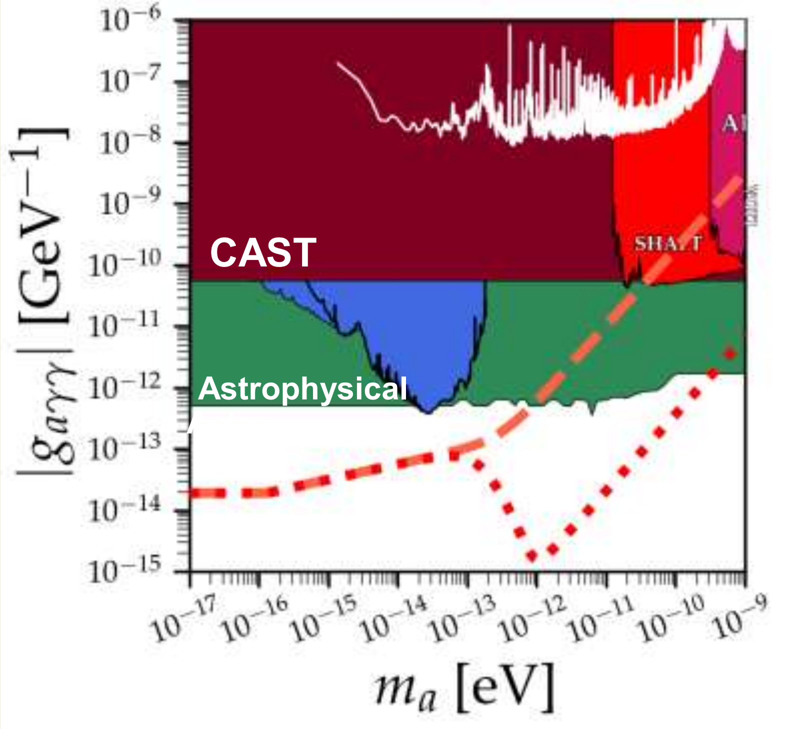


Collaboration with C03-group

DANCE and Photon Counting

- Sensitivity ultimately limited by quantum shot noise
- This can be avoided with single photon detection

H. Ysu+, PRD **109**, 095042 (2024)
S. M. Vermeulen+, PRX 15, 011034 (2025)

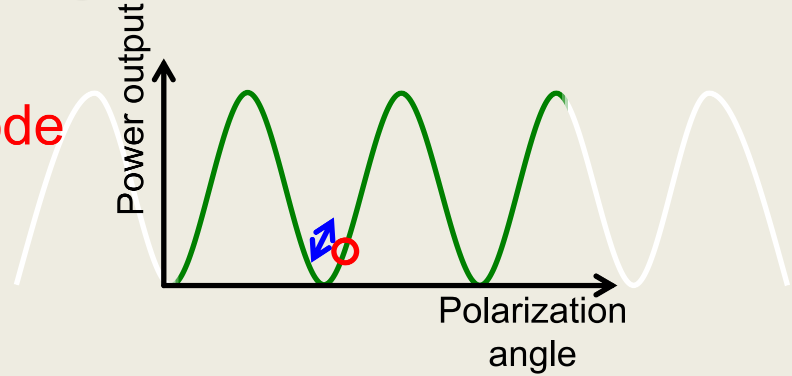


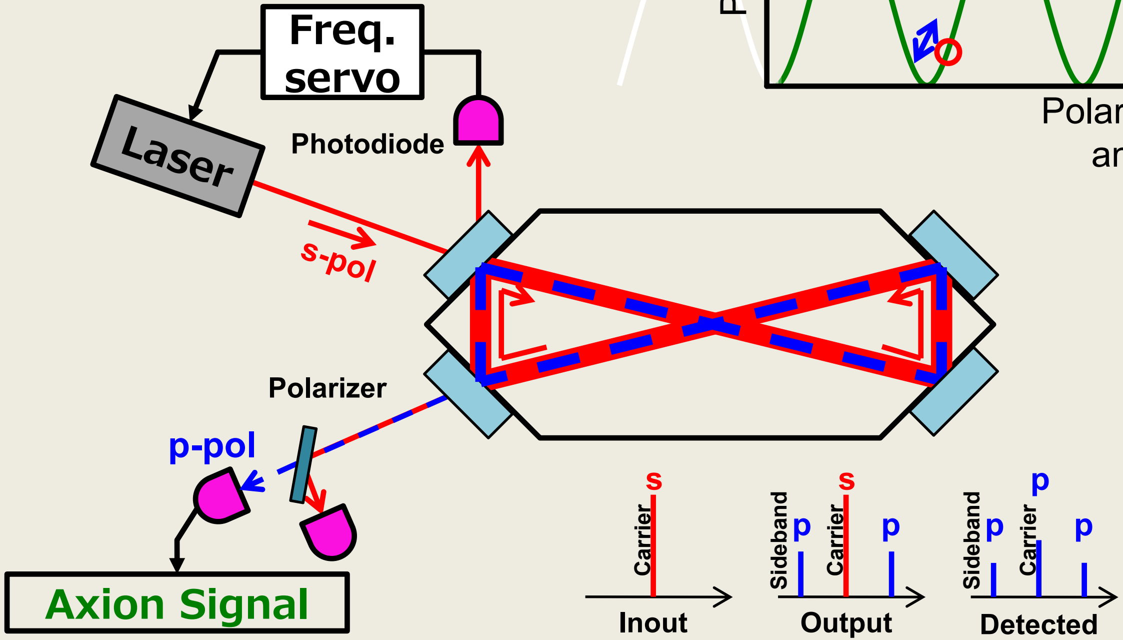
Example sensitivity improvement
Dark count rate: 10^{-6} Hz
Bandwidth: 1 Hz

Caveat: Envelope of narrowband search is shown

DANCE Setup Now

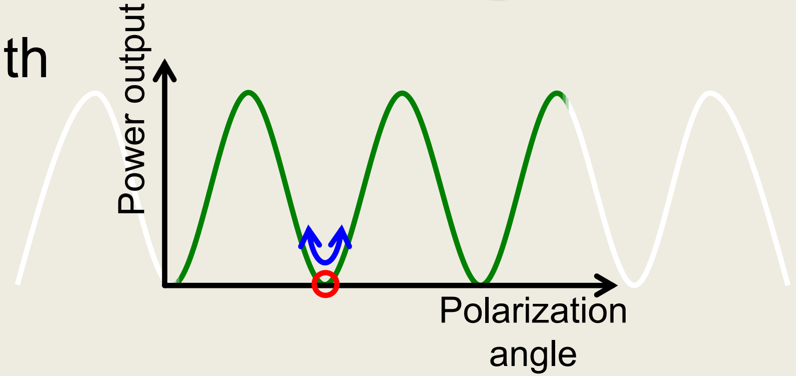
- P-pol power change monitored with a photodiode

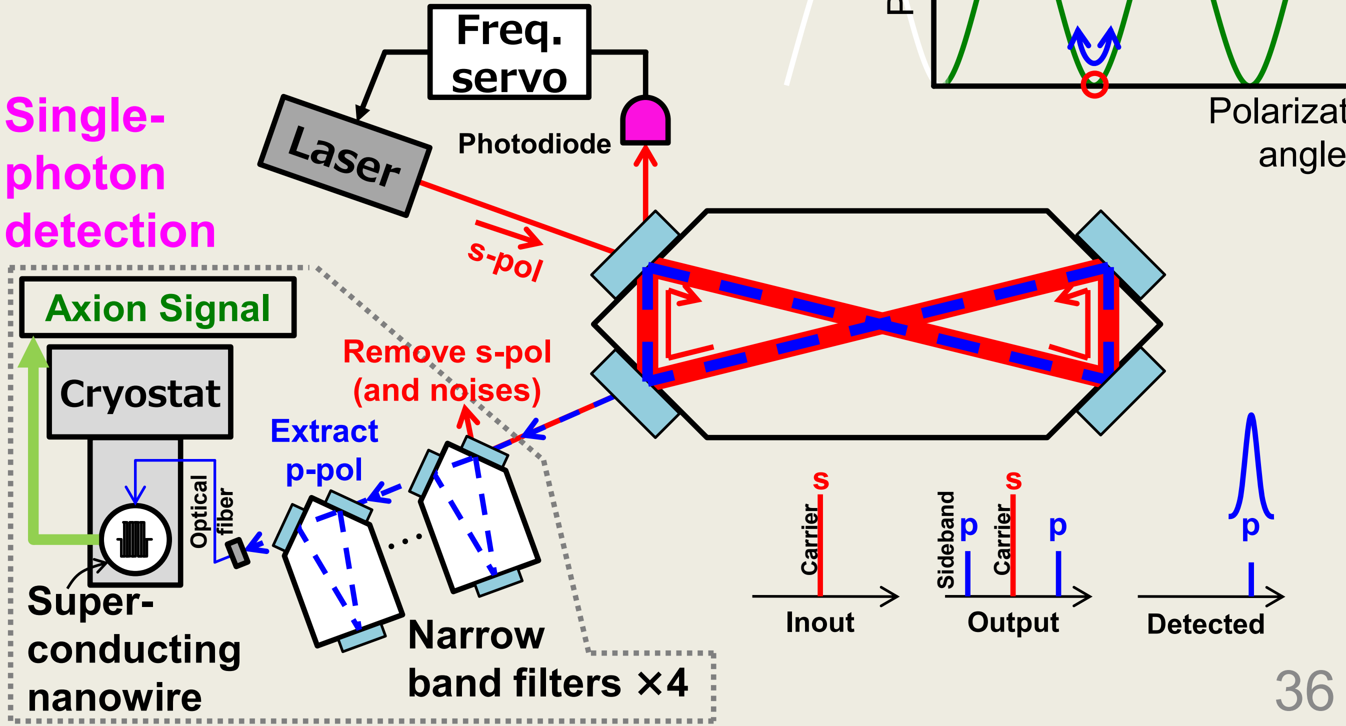




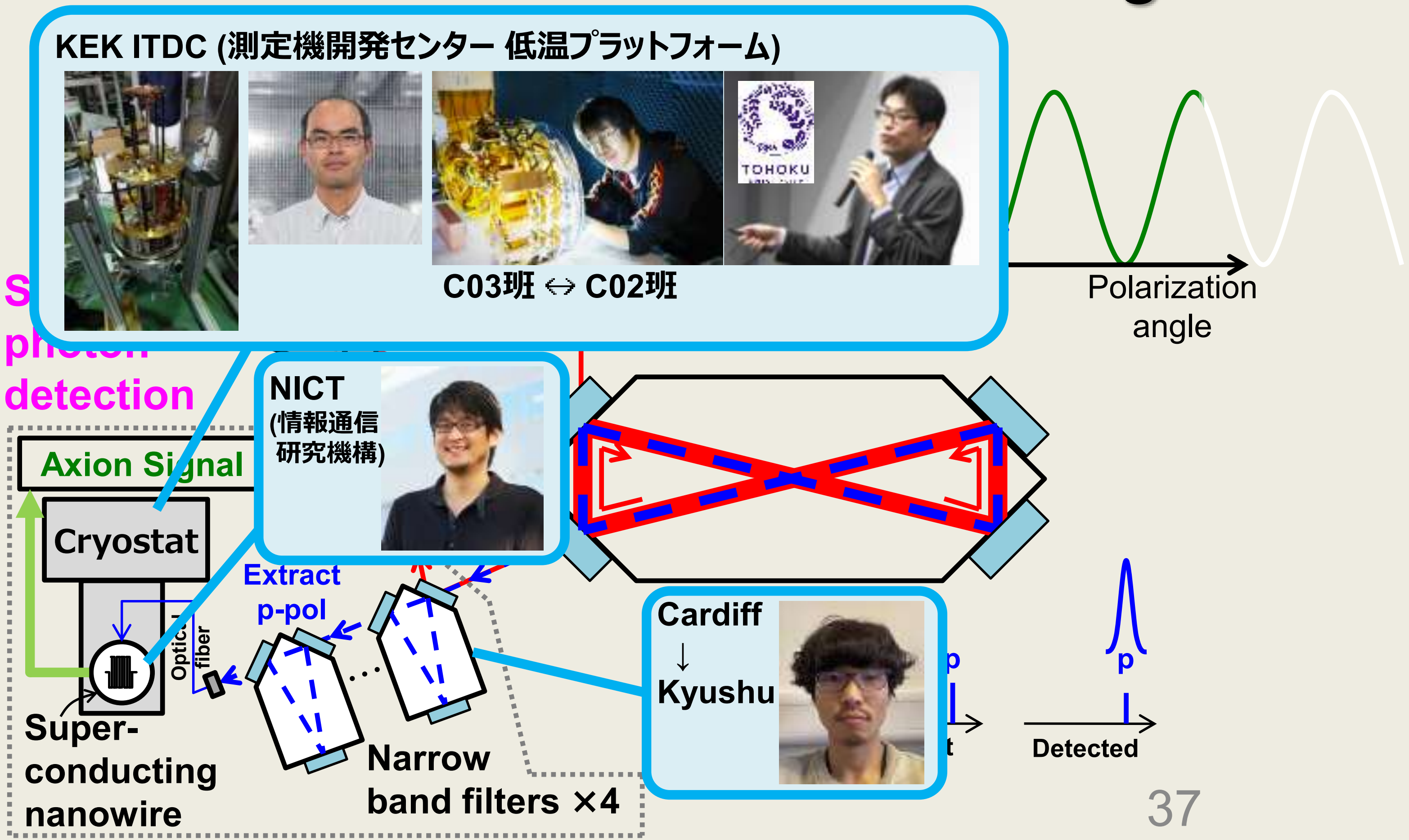
DANCE with Photon Counting

- Signal photon detected with a single-photon detector





DANCE with Photon Counting



DM search

	Axion	Vector	WIMP
Image	Birefringent media	Electric wave with a mass	**Massive Particle**
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Search	**DANCE (Table-top)** **KAGRA+PD**	**KAGRA Aux.** **Small Table-top**	**Particle collider** **Undergrond exp.**

Vector DM (a.k.a. Dark photon DM)

VDM = Electric wave with a mass

Theory : $\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \epsilon_D e J_D^\mu A_\mu$

Electromagnetism with a mass

Electric part : $\boldsymbol{E} = -\dot{\boldsymbol{A}} \sim \omega \boldsymbol{A},$ Magnetic part : $\boldsymbol{B} = \nabla \times \boldsymbol{A} \sim k\boldsymbol{A},$

Dispersion relation : $\omega^2 = k^2 + m_A^2 \simeq m_A^2 \gg k^2,$ $\left(k = m_A v, \quad v_{\rm DM}^{\rm local} \approx 10^{-3} c\right)$

$\Rightarrow$ $\boldsymbol{E} \simeq \boldsymbol{E}_0 \cos(m_A t) \gg \boldsymbol{B}$

Electr~~omagnet~~ic wave!

VDM Coupling

VDM = Electric wave with a mass

Theory : $\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\mu A_\mu - \underline{\underline{\epsilon_D e J_D^\mu A_\mu}}$ $(D = B \text{ or } B - L)$

Additional Interaction

Charge for VDM = B (baryon #) or B-L (baryon # - Lepton #)

[Note: B(proton)=B(neutron)=L(electron)=1, otherwise=0]

Coupling strength relative to electromagnetism : $\boxed{\epsilon_B, \epsilon_{B-L} \lesssim 10^{-23}}$

→ **Need to be extremely sensitive!**

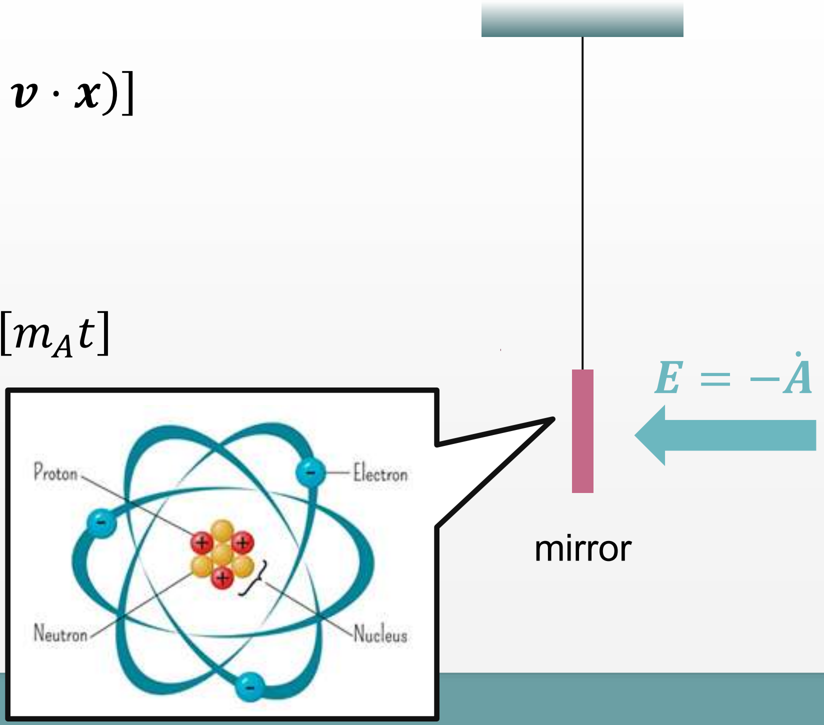
VDM acts on Mirrors

VDM (≈ electric wave) pushes mirrors, just as $\vec{E}$ does electrons.

VDM : $\boldsymbol{A} = \boldsymbol{A_0} \sin[m_A(t - \boldsymbol{v} \cdot \boldsymbol{x})]$

Force : $\boldsymbol{F} = -\epsilon_D e Q_D \dot{\boldsymbol{A}}$

Mirror : $\delta \boldsymbol{x} = \dfrac{\epsilon_D e Q_D}{m_A M} \boldsymbol{A_0} \sin[m_A t]$



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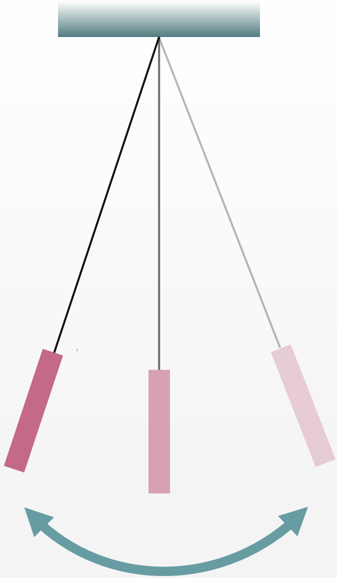
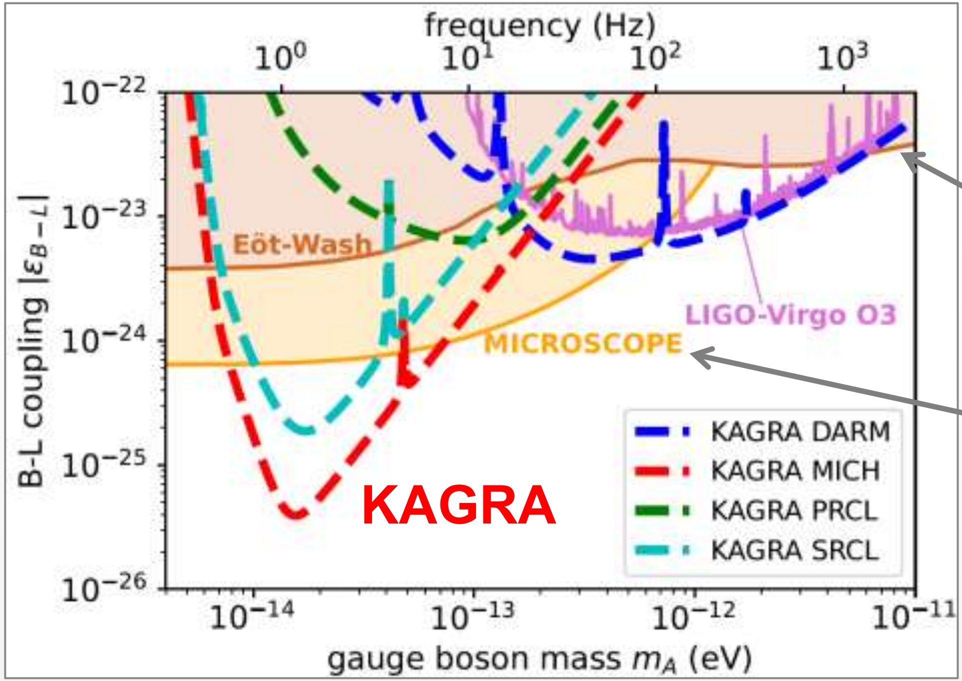


VDM oscillates mirrors

DM search

	Axion	Vector	WIMP
Image	Birefringent media	Electric wave with a mass	**Massive Particle**
Interaction	Photon	B or B-L	**Nuclei**
Search	**DANCE** **(Table-top)** **KAGRA+PD**	$\boxed{\textbf{KAGRA Aux.}}$ **Small Table-top**	**Particle collider** **Undergrond exp.**

KAGRA will be the best



For B-L coupling, KAGRA goes beyond aLIGO

Michimura, TF, Morisaki, Nakatsuka and Obata PRD102, 102001(2020)

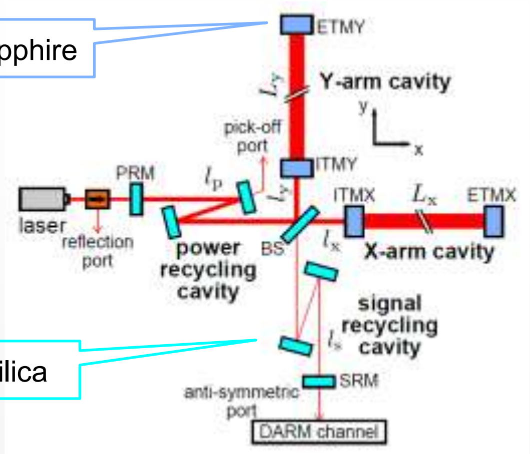
Auxiliary channels

Michimura, TF, Morisaki,
Nakatsuka and Obata
PRD102, 102001(2020)

All mirrors in aLIGO are fused silica, but KAGRA uses **sapphire** mirrors.

Sapphire

fused silica

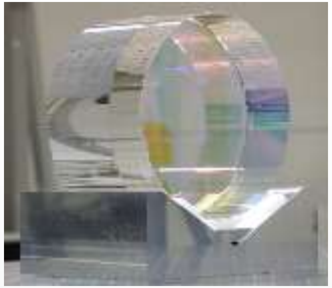


KAGRA measures

DARM : $\delta(L_x - L_y)$

MICH : $\delta(l_x - l_y)$

SRCL : $\delta[(l_x + l_y)/2 + l_s]$



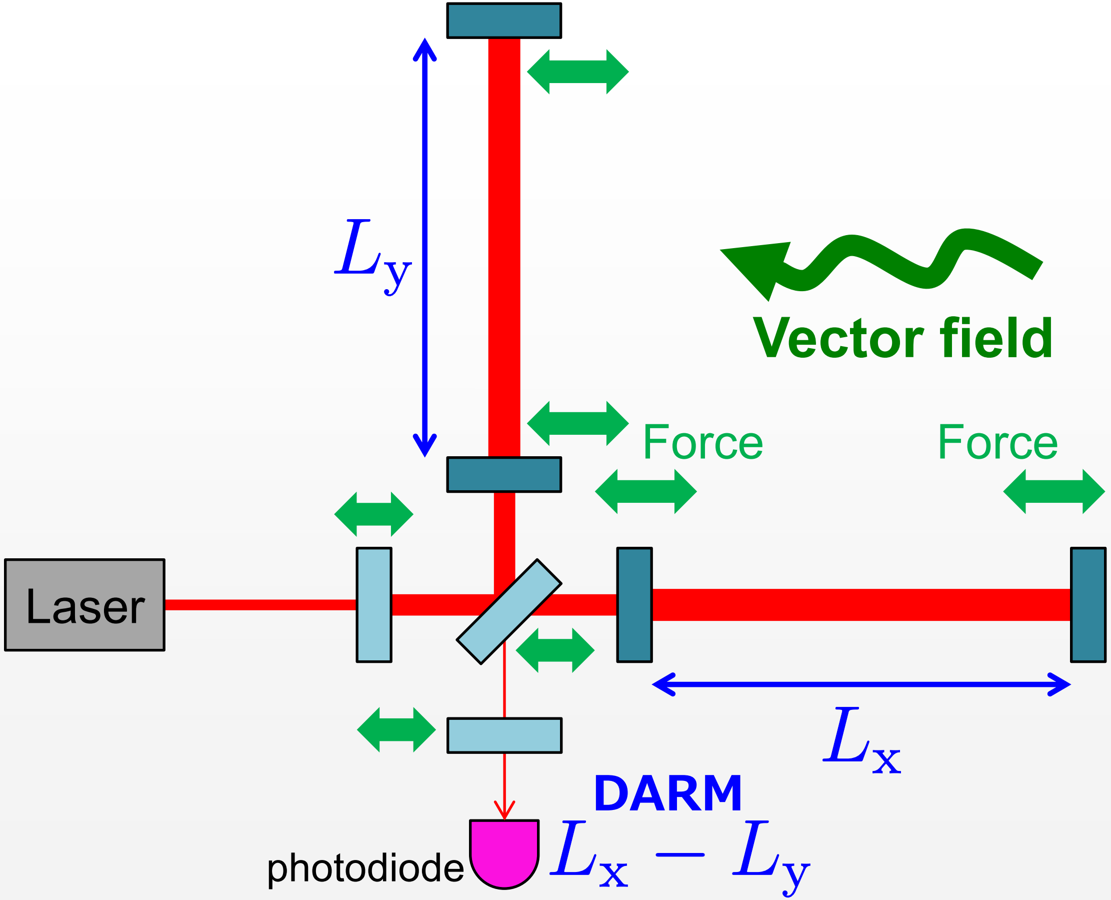
MICH & SRCL observe distance btw mirrors made of different material

→ **VDM acts differently**

This effect can be seen
only in KAGRA
that uses different
mirror materials.

B-L charge
Fused silica: 0.501
Sapphire: 0.510

VDM with B-L coupling differentiates mirror motion by 2%



Status: KAGRA

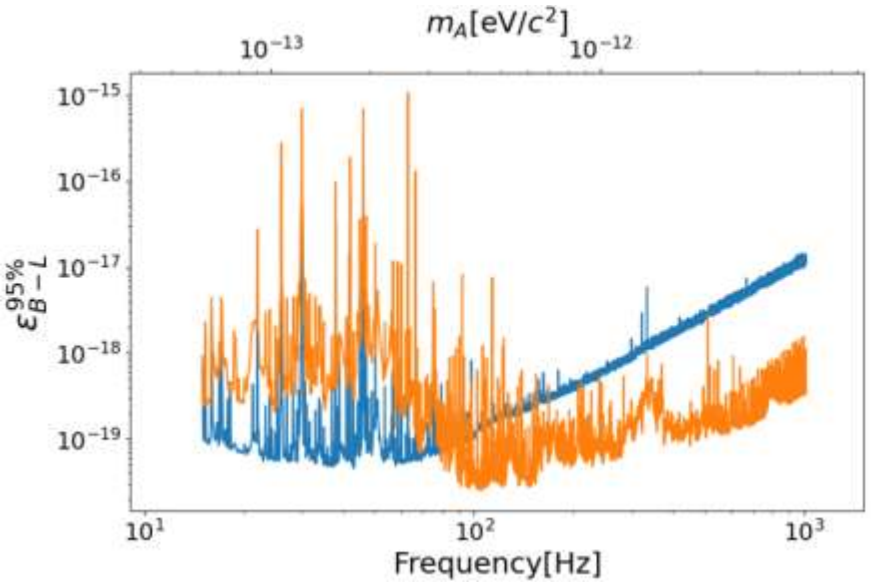
- **First Result**! Using data from KAGRA O3GK run in 2020

  LIGO-Virgo-KAGRA, PRD **110**, 042001 (2024)
  (Paper written by J. Kume with 1800 authors!)

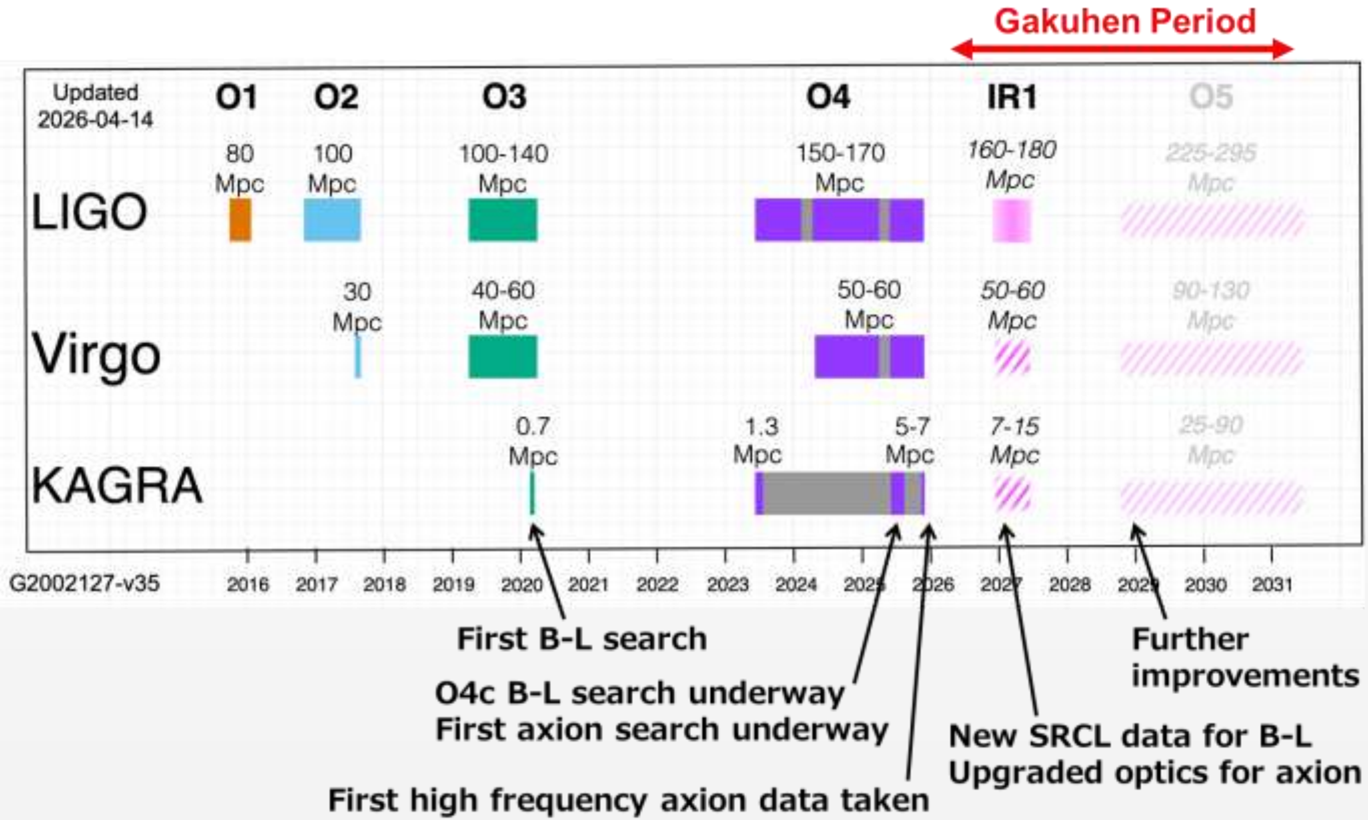
- Still ~5 orders of magnitude worse than equivalence principle tests

- O4c data analysis ongoing
  (LVK working group circulation of the paper started)

- New data from SRCL will be available from IR1
  (KAGRA interferometer configuration will be new)



Plan: LVK observation



Collaboration with A-groups

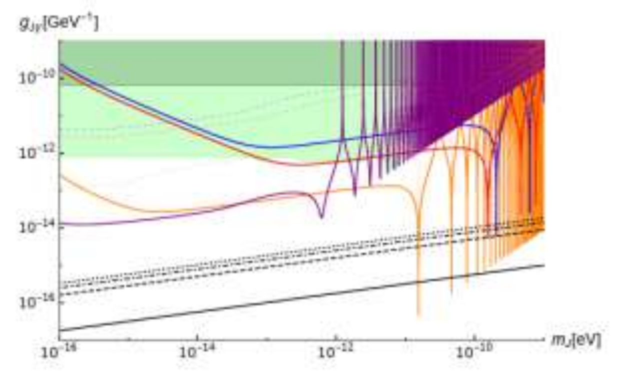
Other targets?

Ippei Obata

Majoron DM with QED anomaly

$$\mathcal{L} \supset \frac{1}{4} g_{J\gamma} J F \tilde{F}$$

can also be searched by GWD!



Probing Majoron Dark Matter with Gravitational Wave Detectors

Ippei Obata[a,b] and Tsutomu T. Yanagida[b,c]

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[b] *Kavli IPMU (WPI), UTIAS, The University of Tokyo, Kashiwa 277-8583, Japan*

[c] *Tsung-Dao Lee Institute & School of Physics and Astronomy, Shanghai Jiao Tong University, Pudong New Area, Shanghai 201210, China*

Abstract

The Majoron is a hypothetical (pseudo) Nambu-Goldstone boson arising from the spontaneous breaking of a global lepton number symmetry, and is known as a candidate for dark matter in our Universe. In this paper, we investigate the possibility of probing the Majoron dark matter with a linear optical cavity used in the interferometric gravitational wave detectors. We consider a scenario in which the Majoron dark matter couples to photons through a QED anomaly, leading to an oscillatory photon birefringence induced by the coherent dark matter background. The anomaly coefficient is fixed by requiring the model to simultaneously reproduce the electroweak Higgs scale and a typical right-handed Majorana neutrino mass scale, and the resulting dark matter-photon coupling naturally falls within the sensitivity range of optical interferometers. By incorporating additional optics to extract the birefringence signal, we find that ground-based laser interferometers such as Advanced LIGO, KAGRA, as well as future detectors, can probe a region of the parameter space of Majoron dark matter.

arXiv:2604.08193v1 [hep-ph] 9 Apr 2026

DM search

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We are Hiring!

- **One postdoc** will come to U. Tokyo this winter
- Will work on DANCE&KAGRA and data analysis
- We want one more Assistant prof. or postdoc next year !

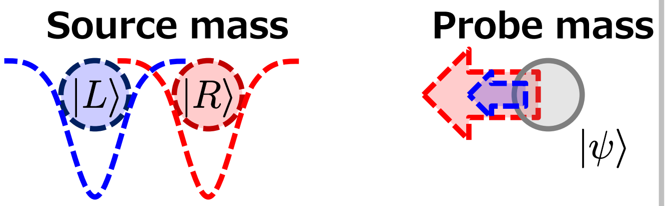
Thank You!

Search for (low-energy) Quantum Gravity

Key Idea of BMV Proposals

- If gravity is quantum

$$\Phi(\hat{x}, \hat{X}) = -\frac{GM}{|\hat{x} - \hat{X}|}$$



Newtonian potential act as an operator

$$e^{\frac{i}{\hbar}m\Phi(\hat{X})t}\frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right) \otimes |\psi\rangle$$

$$= \frac{1}{\sqrt{2}}\left(|L\rangle \otimes e^{i\phi_L}|\psi\rangle + |R\rangle \otimes e^{i\phi_R}|\psi\rangle\right)$$

Gravity induced entanglement

Key Idea of BMV Proposals

- If gravity is quantum

$$\Phi(\hat{x},\hat{X}) = -\frac{GM}{|\hat{x}-\hat{X}|}$$

Source mass **Probe mass**

Newtonian potential act as an operator

$$e^{\frac{i}{\hbar}m\Phi(\hat{X})t}\frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)\otimes|\psi\rangle$$

$$= \frac{1}{\sqrt{2}}\left(|L\rangle\otimes e^{i\phi_L}|\psi\rangle + |R\rangle\otimes e^{i\phi_R}|\psi\rangle\right)$$

Gravity induced entanglement

- If gravity is classical

$$\Phi(\hat{x}) = -\left\langle \frac{GM}{|\hat{x}-\hat{X}|}\right\rangle$$

Source mass **Probe mass**

Newtonian potential act as a c-number

$$e^{\frac{i}{\hbar}m\Phi t}\frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)\otimes|\psi\rangle$$

$$= \frac{1}{\sqrt{2}}\left(|L\rangle + |R\rangle\right)\otimes e^{\frac{i}{\hbar}m\Phi t}|\psi\rangle$$

Remains separable

What is the Best Oscillator?

- We computed the amount of entanglement for arbitrary quadratic potential
- Hamiltonian

$$H = \sum_{i=1,2} \left(\frac{p_i^2}{2m} + \frac{1}{2} k_i x_i^2 \right) + \frac{Gm^2}{d^3} (x_1 - x_2)^2$$

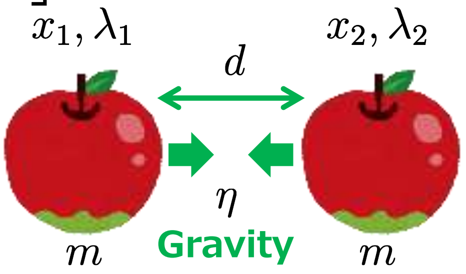
$$= \frac{\omega}{2} \left[\sum_{i=1,2} (P_i^2 + \lambda_i X_i^2) + \eta (X_1 - X_2)^2 \right]$$

Distance between masses

Sign of potential
+1 for harmonic
0 for free-falling
-1 for inverted

Strength of gravitational coupling

$$\eta = \frac{2Gm}{\omega^2 d^3}$$



TF, Y. Kaku, A. Matsumura, Y.Michimura
CQG **42**, 165003 (2025)

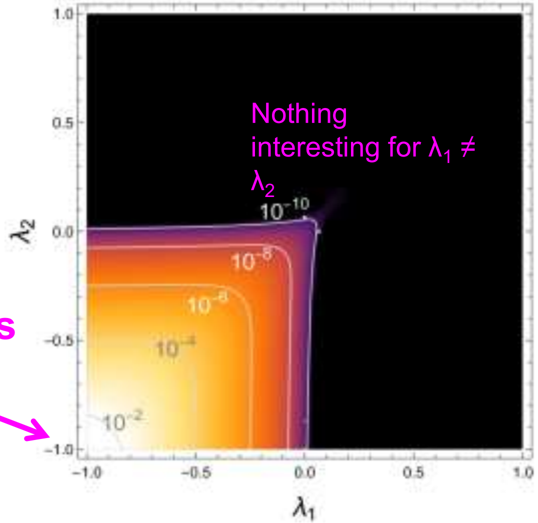
Inverted Oscillators are the Best

- Logarithmic negativity when $\lambda \equiv \lambda_1 = \lambda_2$

$$E_N \simeq 3[\eta f_{\rm gra}(t) - \mu f_{\rm dec}(t)]$$

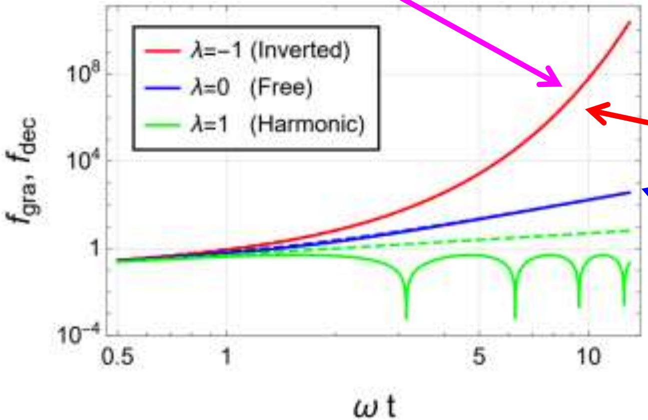
Strength of gravitational coupling

Amount of decoherenc
e



Exponential growth of entanglement

Inverted oscillators are the best



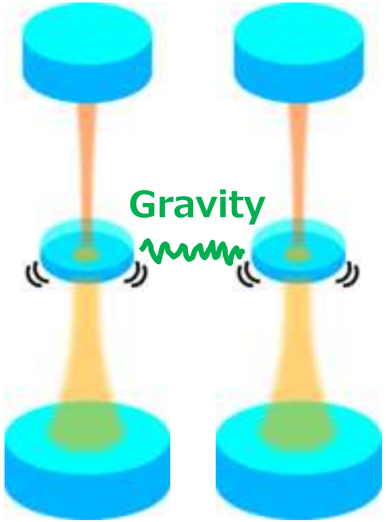
$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8}e^{2\omega t}$$

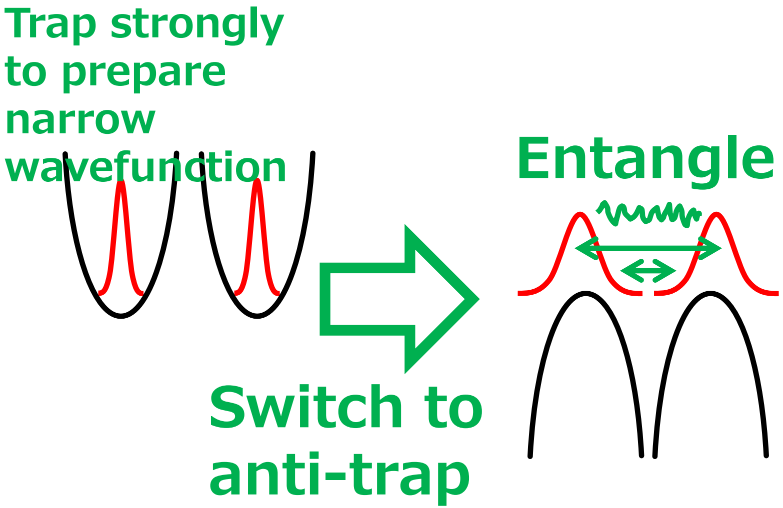
$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8}(\omega t)^3$$

$$f_{\rm gra}(t) \simeq \frac{1}{2}|\sin(\omega t)|, \; f_{\rm dec}(t) \simeq \frac{1}{2}\omega t$$

Realization with Levitated Mirrors

- Switching between trap and anti-trap is easy with optically levitated mirrors
- Entanglement can be tested in horizontal motion
- Can be done similar with other systems





YM, Y. Kuwahara+, [Optics Express 25, 13799 (2017)]

Example Setup

- To prepare 1 kHz anti-spring for 0.1 mg mirror

$$\mu << \eta = 2.7 \times 10^{-13} \omega_{\mathrm{kHz}} \left(\frac{m/d^3}{2\,\mathrm{g/cm^3}} \right)$$

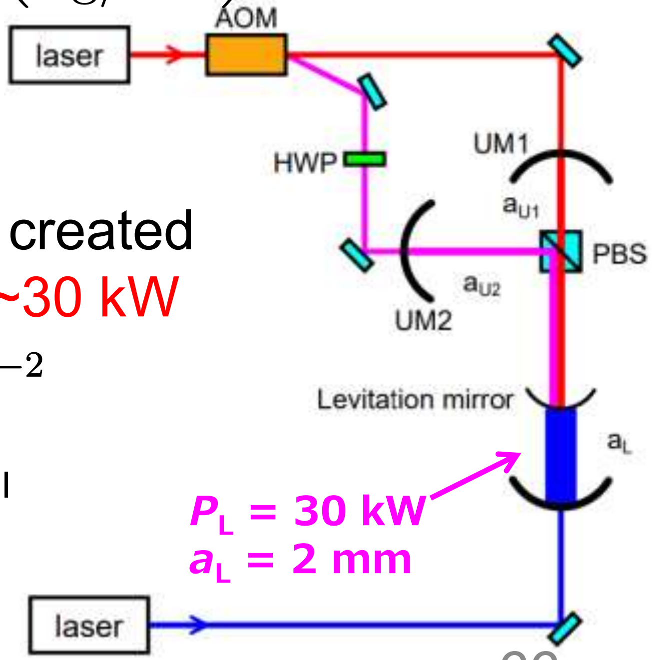
- Requires T < ~1 K and P < ~10^{-17} Pa (as usual)
- ~1 kHz anti-spring can be created with intra-cavity power of ~30 kW
- Time to generate $E_N = 10^{-2}$

$$\tau_{\mathrm{ent}} = 4.2 \omega_{\mathrm{kHz}}^{-1/3}\ \mathrm{sec}$$ for free-fall

300 times faster

$$\tau_{\mathrm{ent}} = 1.3 \times 10^{-2} \omega_{\mathrm{kHz}}^{-1/3}\ \mathrm{sec}$$

for



Fabricating Mirrors for Levitation

- To support the mass:

$$mg = \frac{2P_{\mathrm{circ}}}{c}$$

Roughly 1.5 kW of power is required to levitate 1 mg mirror

- Mirror needs to be curved, high reflectivity and low absorption. Our target now is:

φ 3 mm, 0.1 mm thick (~1.6 mg for fused silica)
Curvature RoC = ~30 mm convex
Reflectivity R > 99.95 %
Absorption A < ~0.5 ppm (LIGO, Virgo, KAGRA level)

- Experiment in ANU suggest higher absorption makes the system unstable (photothermal effects)

C. Gu+, New J. Phys. **25**, 123051 (2023)

How to Make Tiny Mirrors

2014 Approach (Company in Japan)

(1) Make 3 mm dia. lens

(2) Coat

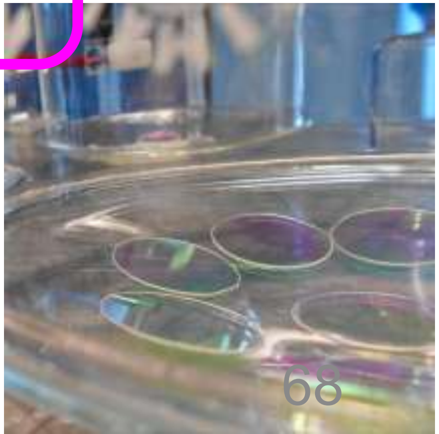
2020- Approach

**(2018-2024 ANR-JST CREST、
2025-2027 France- Japan JSPS Bilateral program)**

(1) Make 1 inch dia.
0.1 mm thick disk

(2) Coat (bend due to stress)

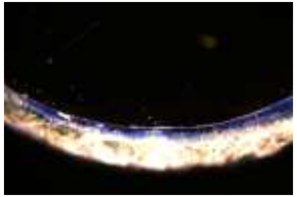
(3) Cut into 3 mm dia.



Fabrication Status in LMA

- HR coating with amplitude transmittance T=10 ppm (6.2 um thick)
- Cut into φ3 mm is tough
- Curvature was not enough O(10 cm)
- Now trying thinner substrate (25 um) with laser cutting

1/4 thick, 1/16 curvature



M. Croquette+, [AVS Quantum Science 5, 014403 (2023)]