Probing ultralight dark matter and the quantum nature of gravity with laser interferometry

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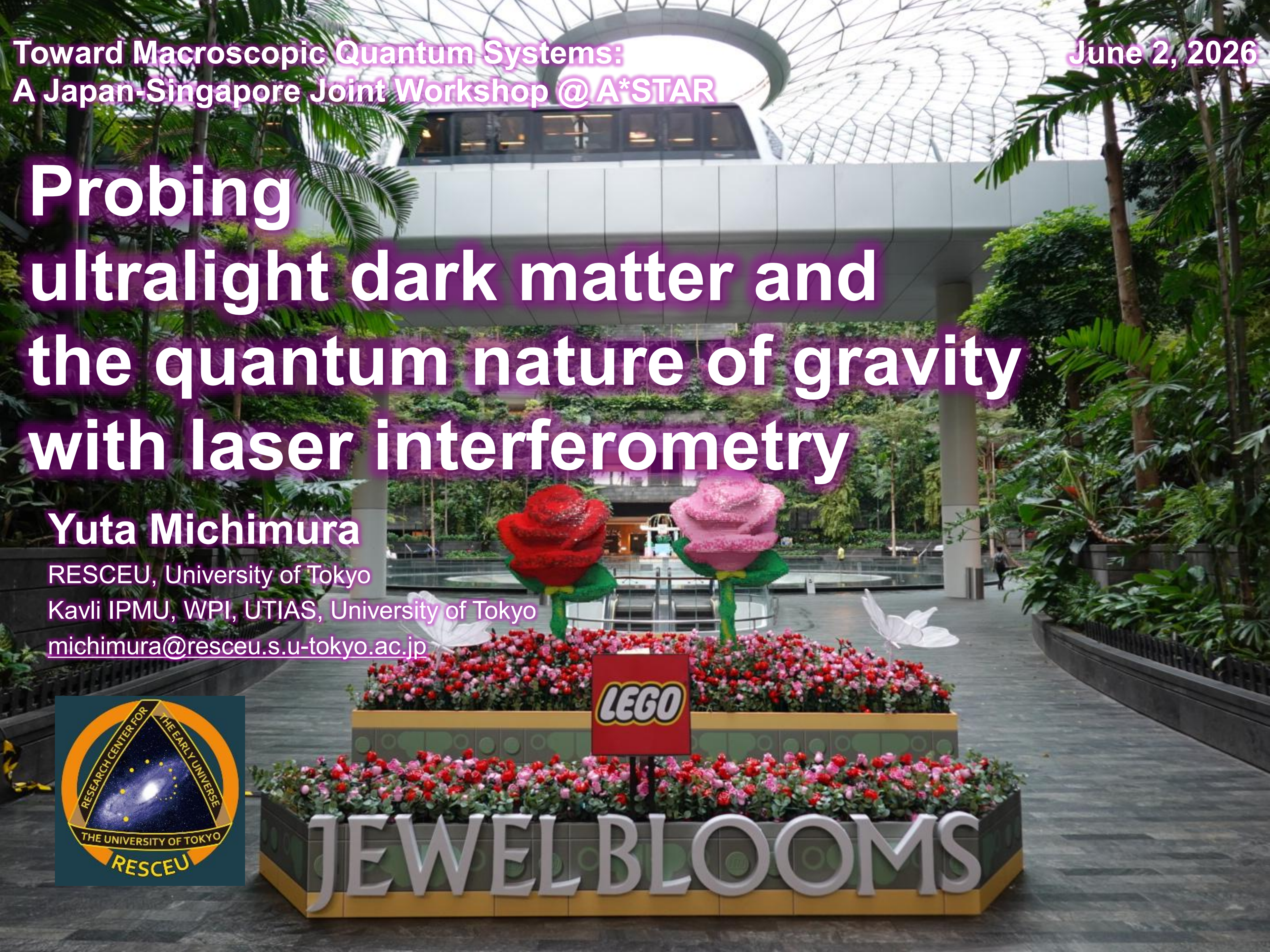
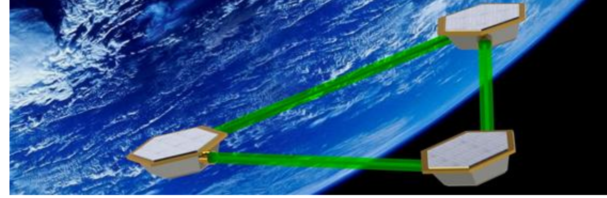
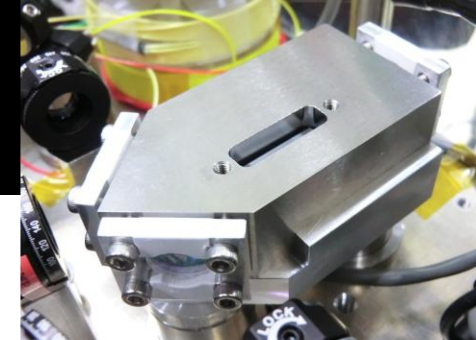


MICHIMURA, Yuta

道村 唯太





1987 — Yokohama, Kanagawa

2014

2015 — ← PhD in Physics

KAGRA

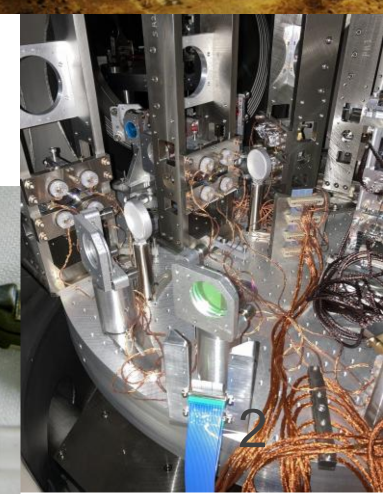
Assistant Professor at
Department of Physics, UTokyo

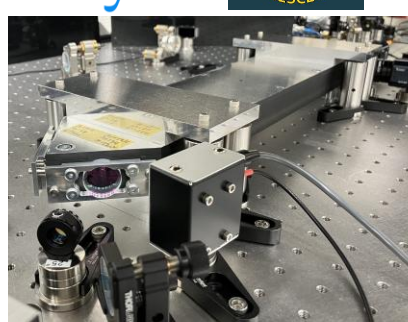
LIGO

2022 — Research Scientist at
LIGO Lab, Caltech

2024 — Associate Professor at
RESCEU, UTokyo

Today





NEXUS Japan-Singapore

Quantum Innovation Centre
A*STAR Q.InC

- Joint call from JST and A*STAR
- Period: April 2026 – March 2029
- 先進的な防振技術による巨視的量子系の実現
  Enabling Macroscopic Quantum Systems through Advanced Vibration Damping Technology

Japan side

Yuta Michimura
(PI)

Kentaro Komori
(Co-I)

Masaki Ando
(Collaborator)

Singapore side

Tao Wang
(PI)

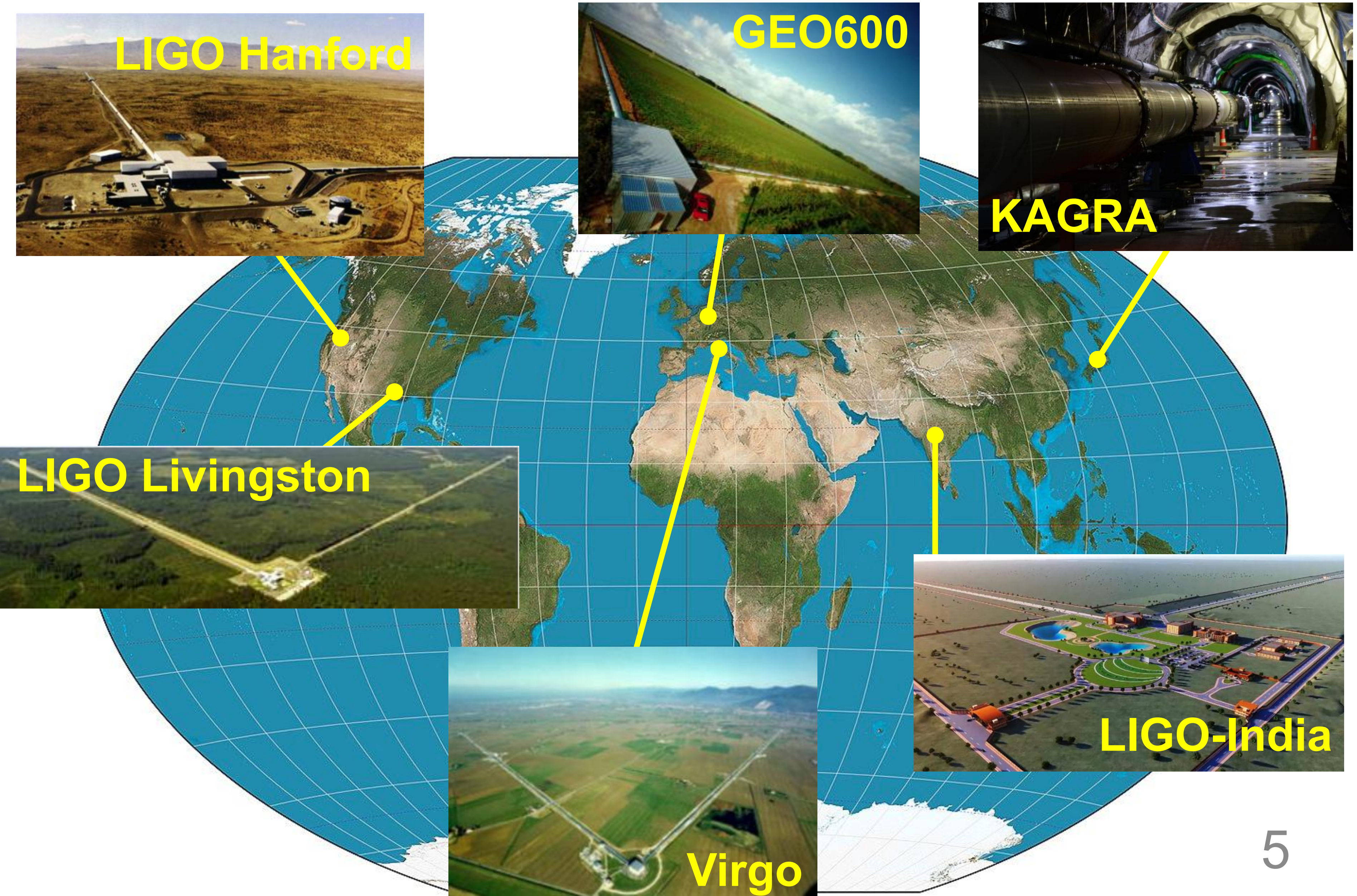
Syed Muhamad Assad
(Co-I)

Ping Koy Lam
(Collaborator)

NEXUS 日ASEAN科学技術・イノベーション協働連携事業
Networked Exchange, United Strength for Stronger Partnerships between Japan and ASEAN

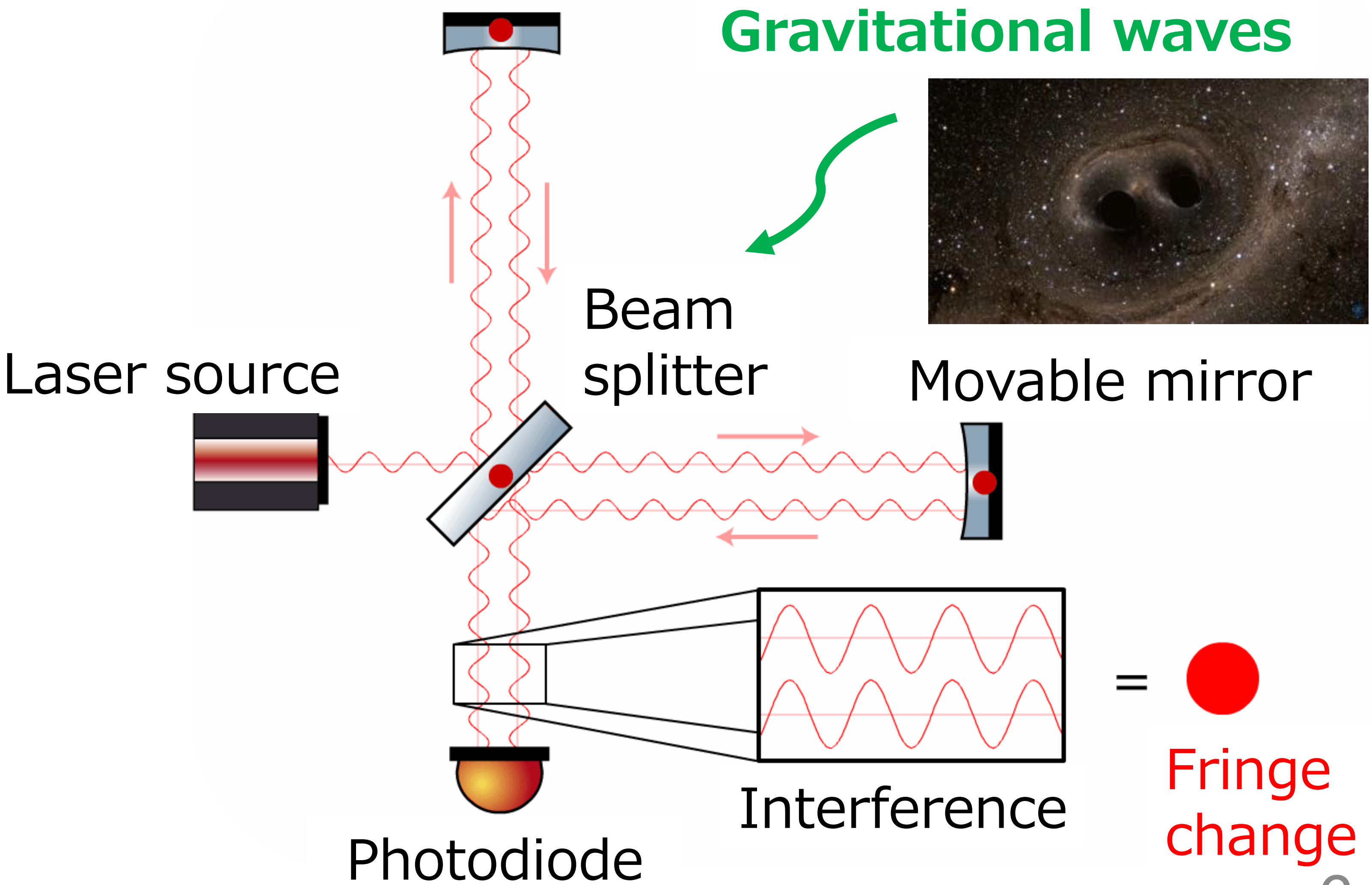
NEXUS Japan-Singapore

Laser Interferometric GW Detectors



Laser Interferometric GW Detectors

- measures differential arm length change

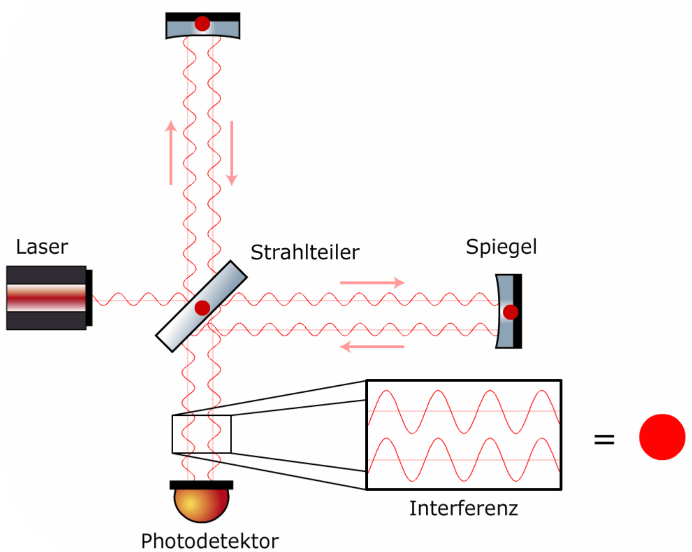


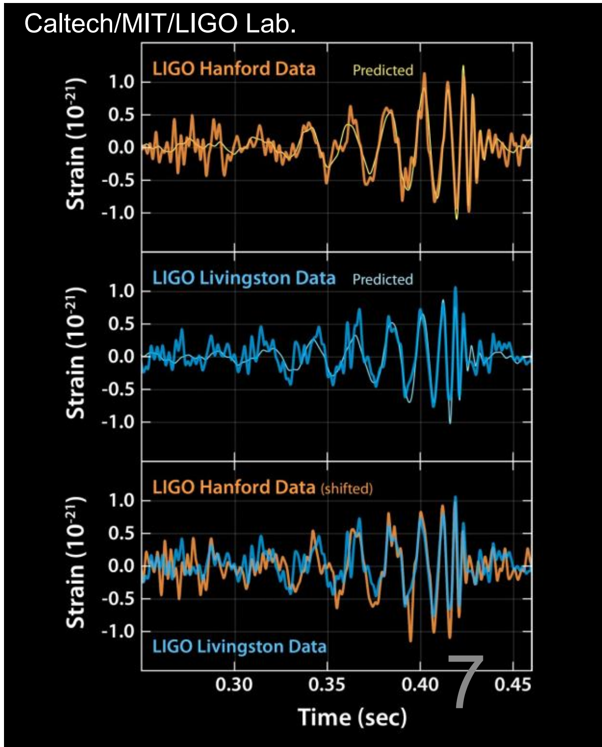
Also Sensitive to Ultralight DM

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

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

- Laser interferometers are sensitive to such oscillating changes (rather than "pulse" signals from particles)





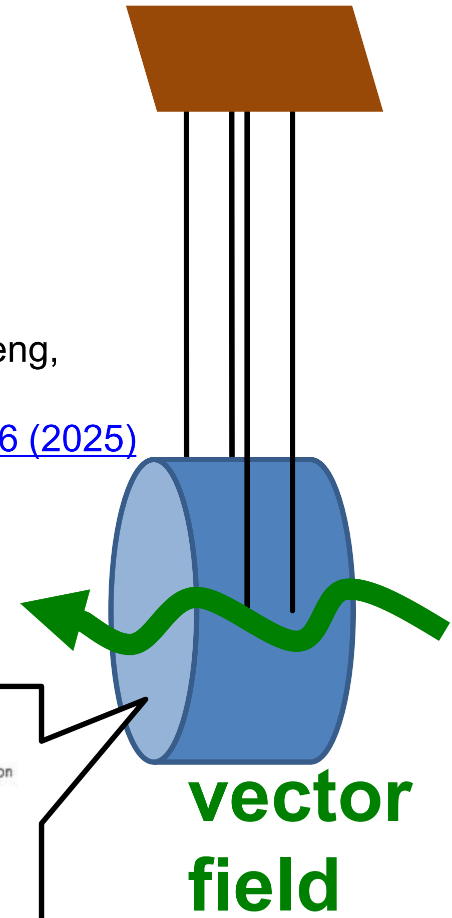
Gauge Boson Dark Matter

- 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
  - Motivations from neutrino mass, matter-antimatter asymmetry
  - Roughly 0.5 per neutron mass, but slightly different between materials

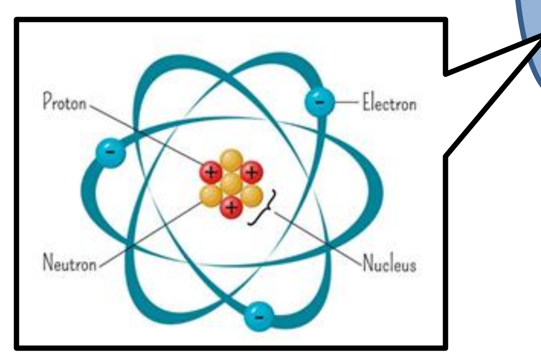
    Fused silica: 0.501

    Sapphire: 0.510

Y. Cheng, J. Sheng, T. T. Yanagida, [PLB 860, 139156 (2025)]



- Gauge boson DM gives oscillating force



Oscillating Force from Gauge Field

- Acceleration of mirrors

charge

gauge boson mass

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

polarization

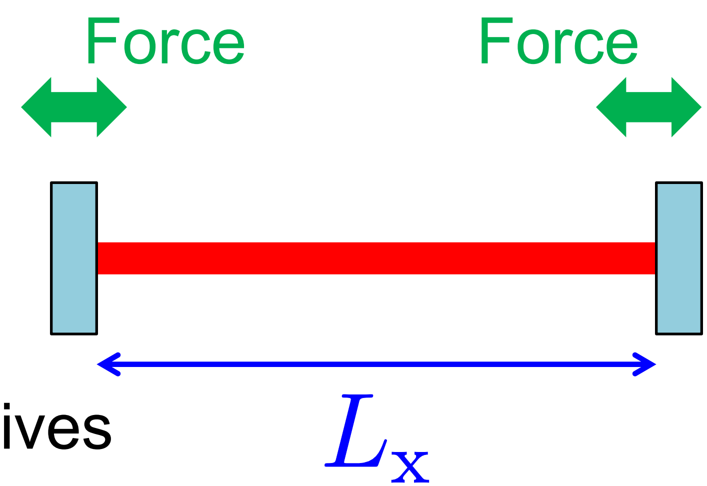
coupling
(normalized by e)

mirror mass

DM density

different phase at
different position

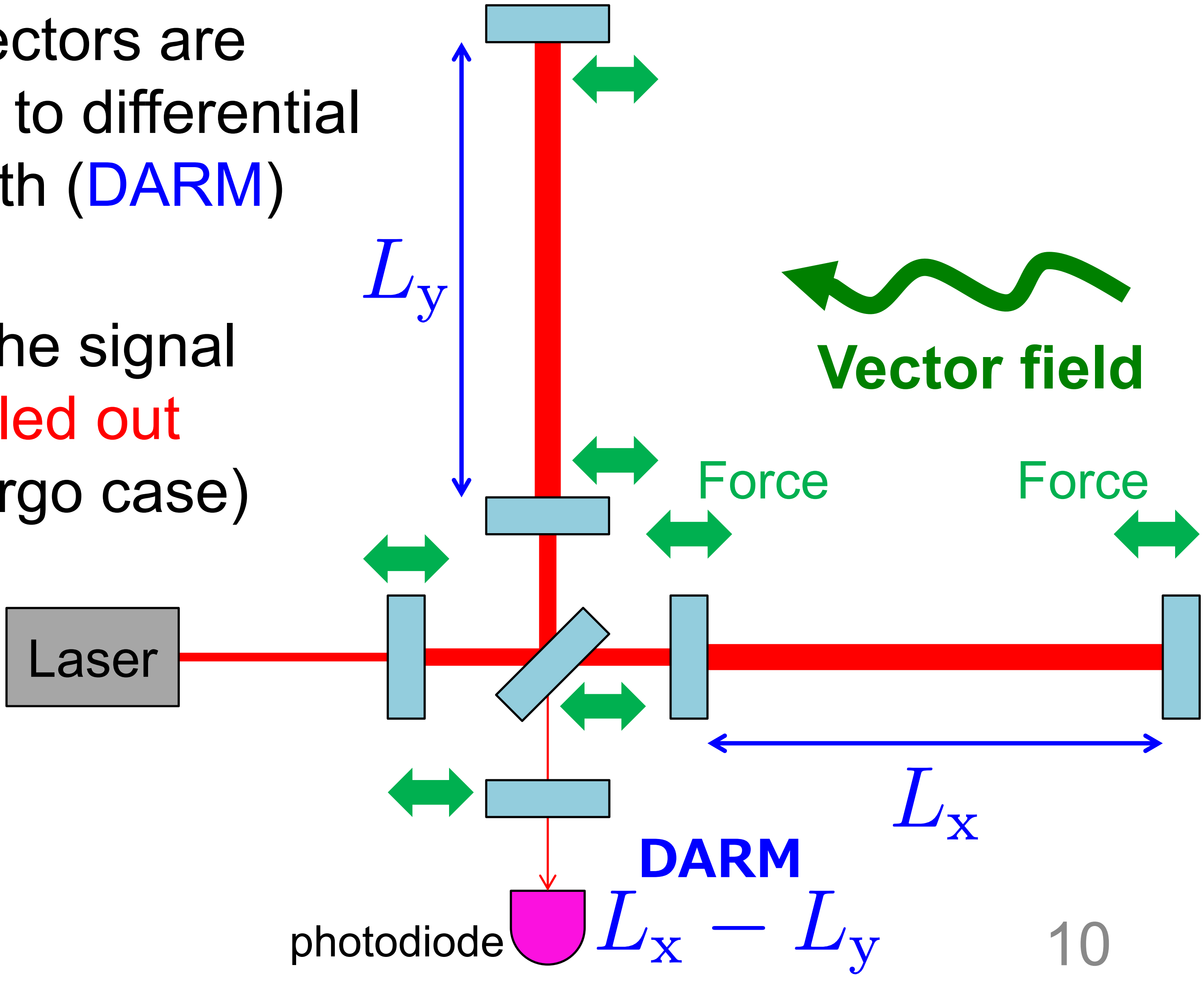
- Gauge boson mass and coupling can be measured by measuring the oscillating mirror displacement



- Almost no signal for symmetric cavity, but finite light traveling time gives some signal
(phase difference is 10^{-5} rad @ 100 Hz for km cavity)

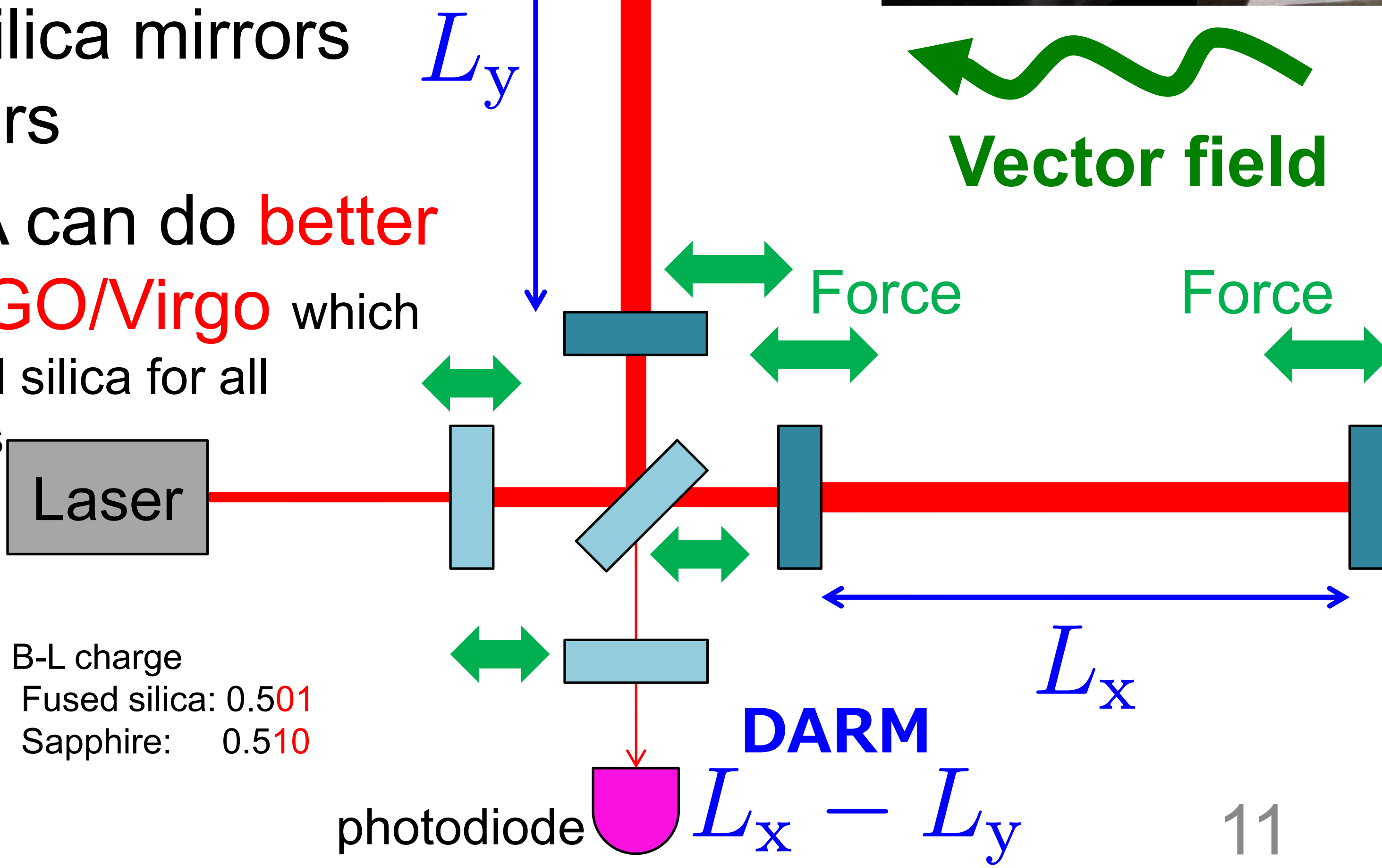
Search with GW Detectors

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

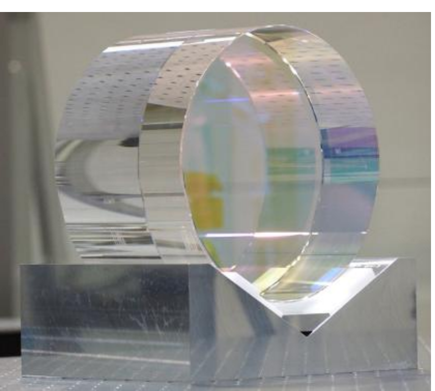


Search with KAGRA

- 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

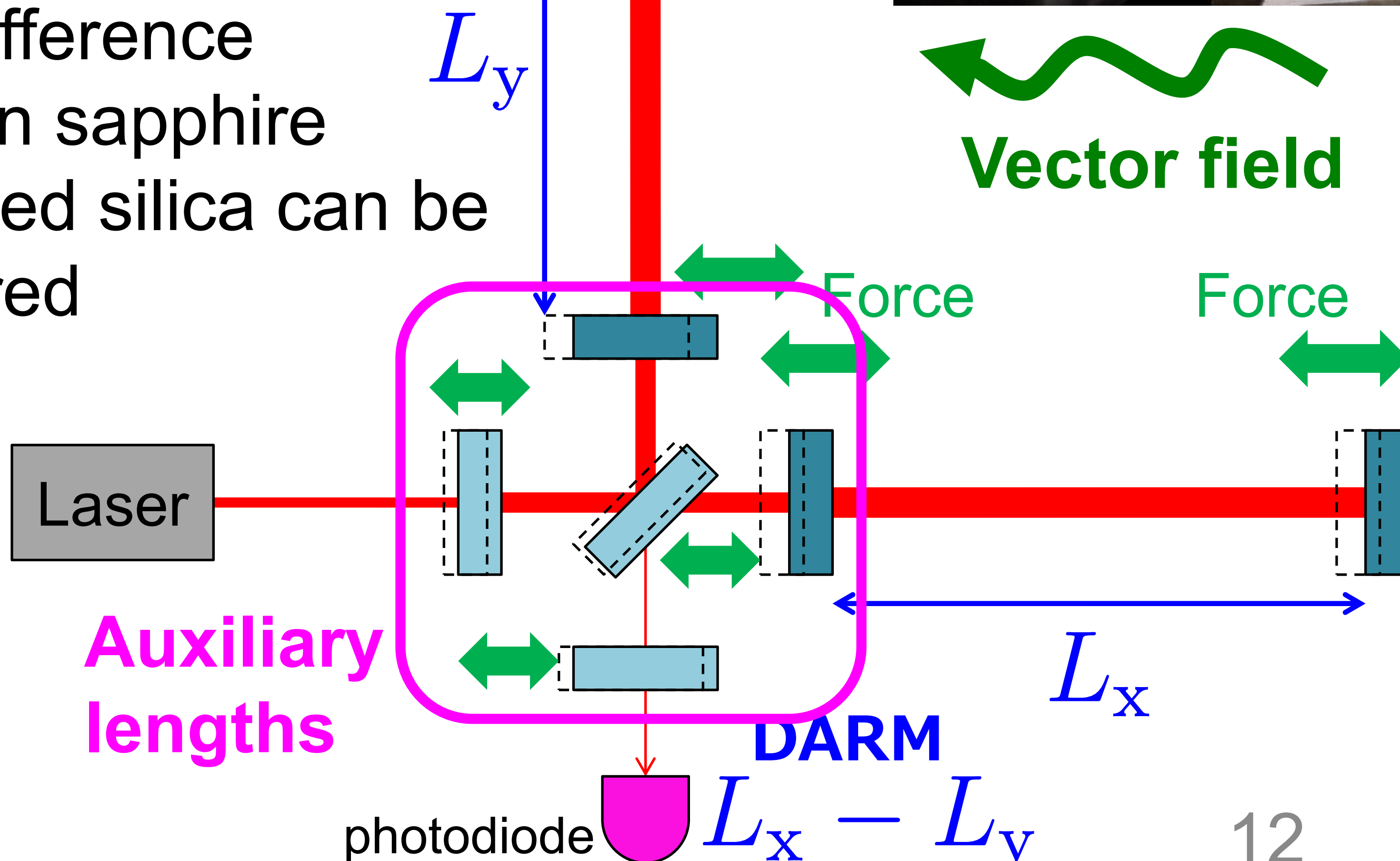


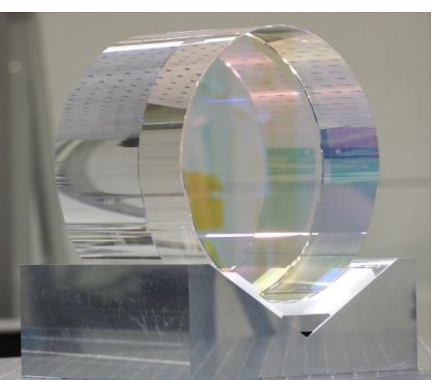
B-L charge
Fused silica: 0.501
Sapphire: 0.510



Search with KAGRA

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

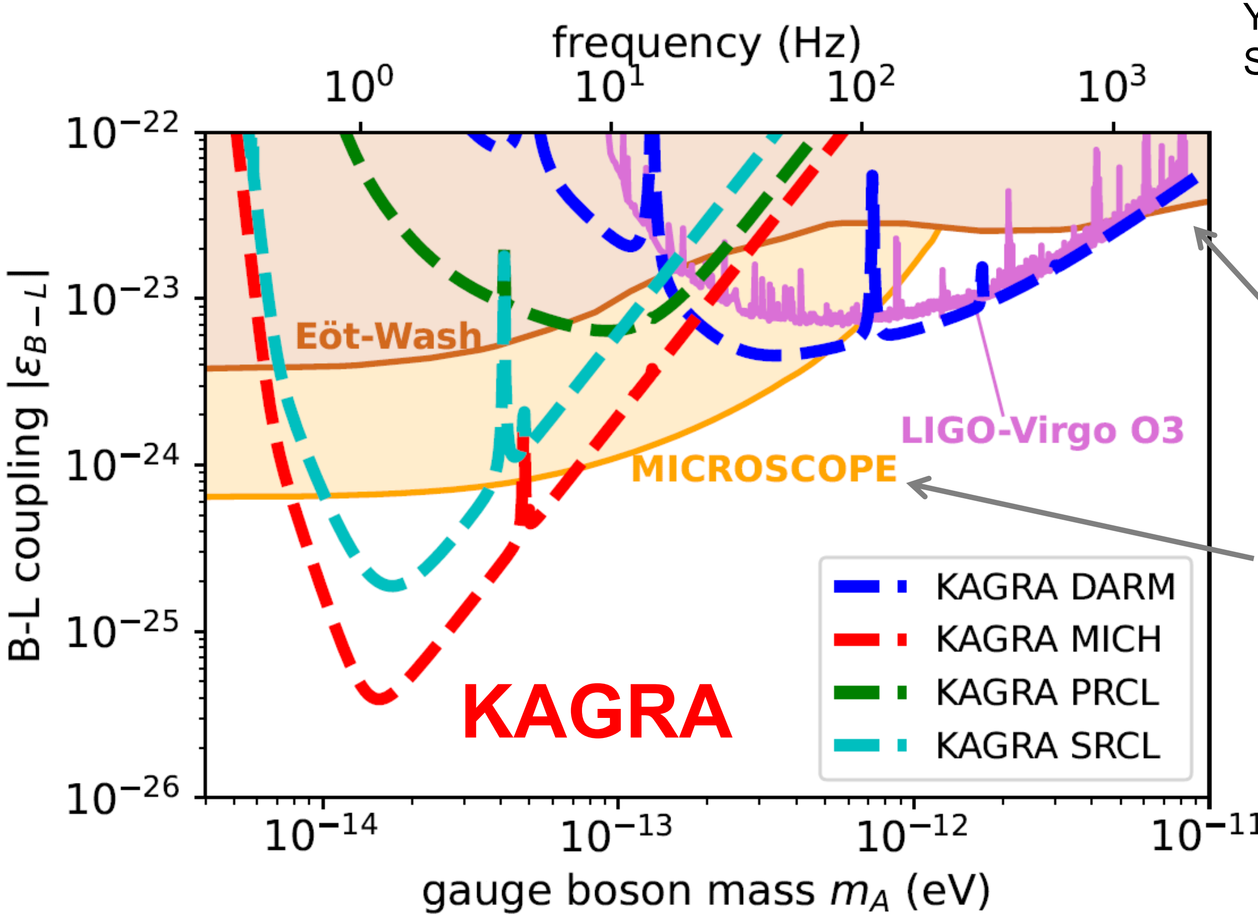




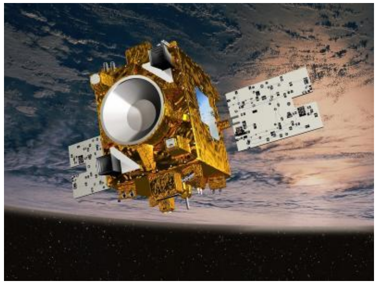
Sensitivity to Gauge Boson DM

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

YM+, PRD **102**, 102001 (2020)
S. Morisaki+, PRD **103**, L051702 (2021)

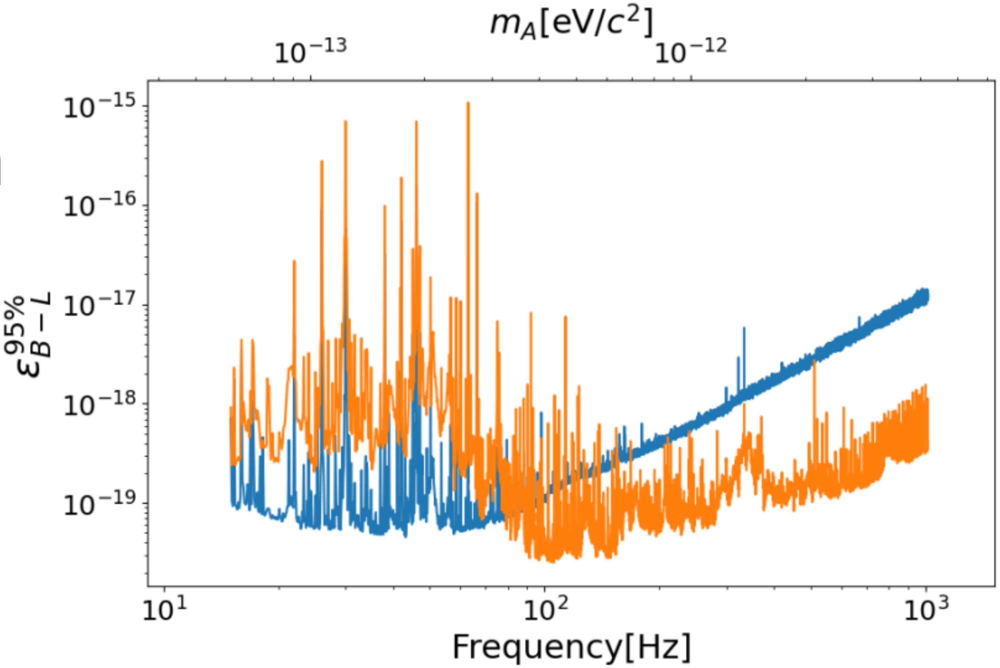


Eöt-Wash
torsion pendulum

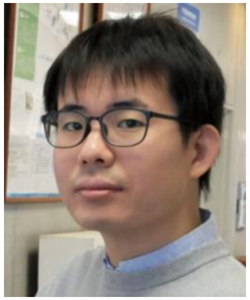


First Results from KAGRA

- Using data from KAGRA O3GK run in 2020
- Still ~5 orders of magnitude worse than equivalence principle tests
- Demonstrated the feasibility of using auxiliary channels for astrophysics
- Search with latest observing run (O4c) on going

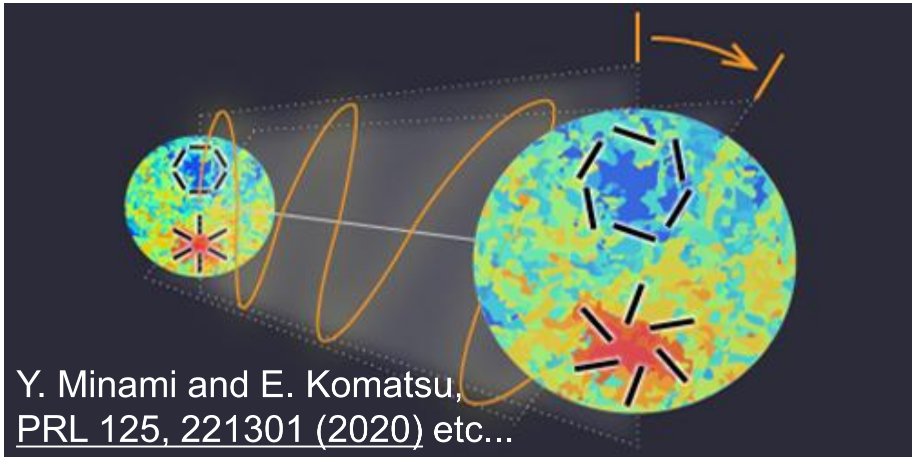


LIGO-Virgo-KAGRA, PRD **110**, 042001 (2024)
(Paper written by J. Kume with 1800 authors!)

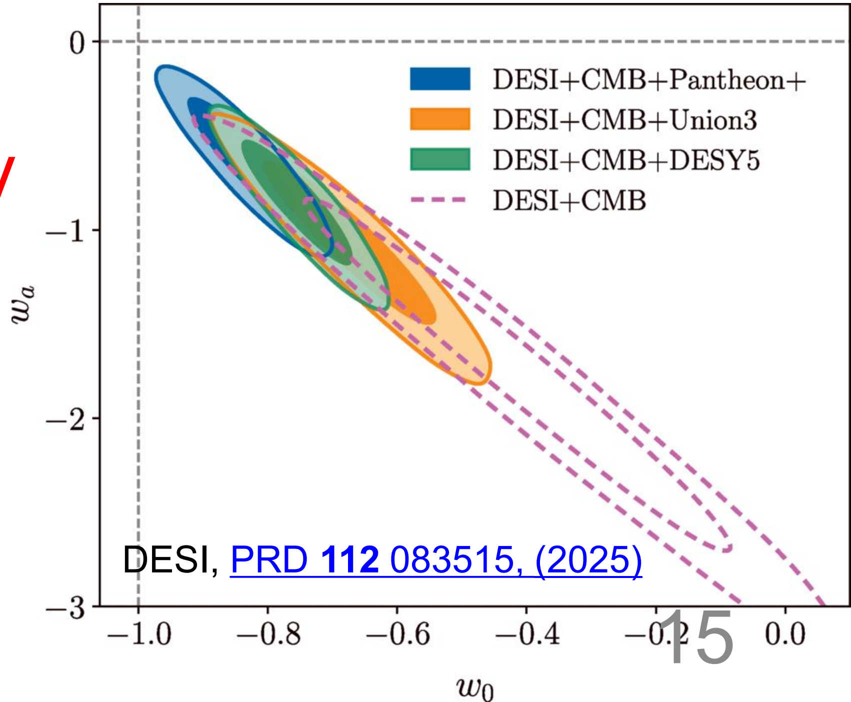


Axion (ALP) Dark Matter

- Various axion-like particles predicted by string theory and supergravity
- Possible explanation to recent measurements of cosmic birefringence and dynamical dark energy
- Many experiments to search for ALPs through axion-photon coupling, using magnetic fields



Y. Minami and E. Komatsu, PRL 125, 221301 (2020) etc...



DESI, PRD **112** 083515, (2025)

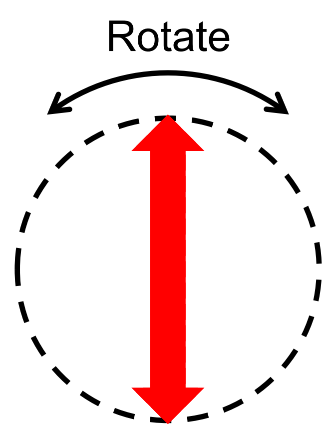
Polarization Modulation from Axions

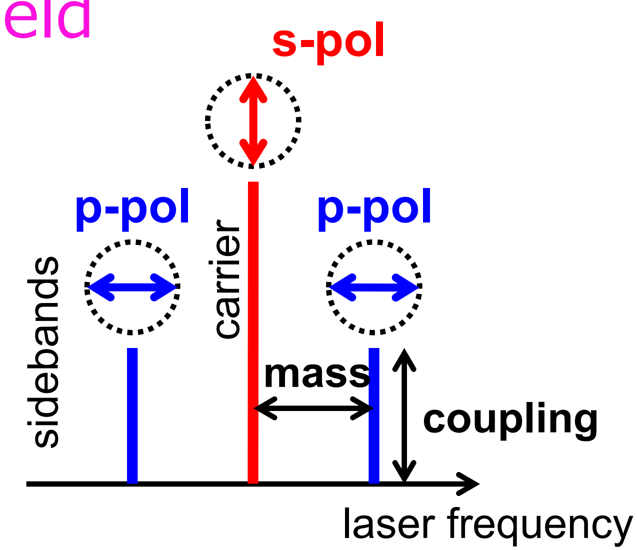
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

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

coupling constant — axion field — axion mass

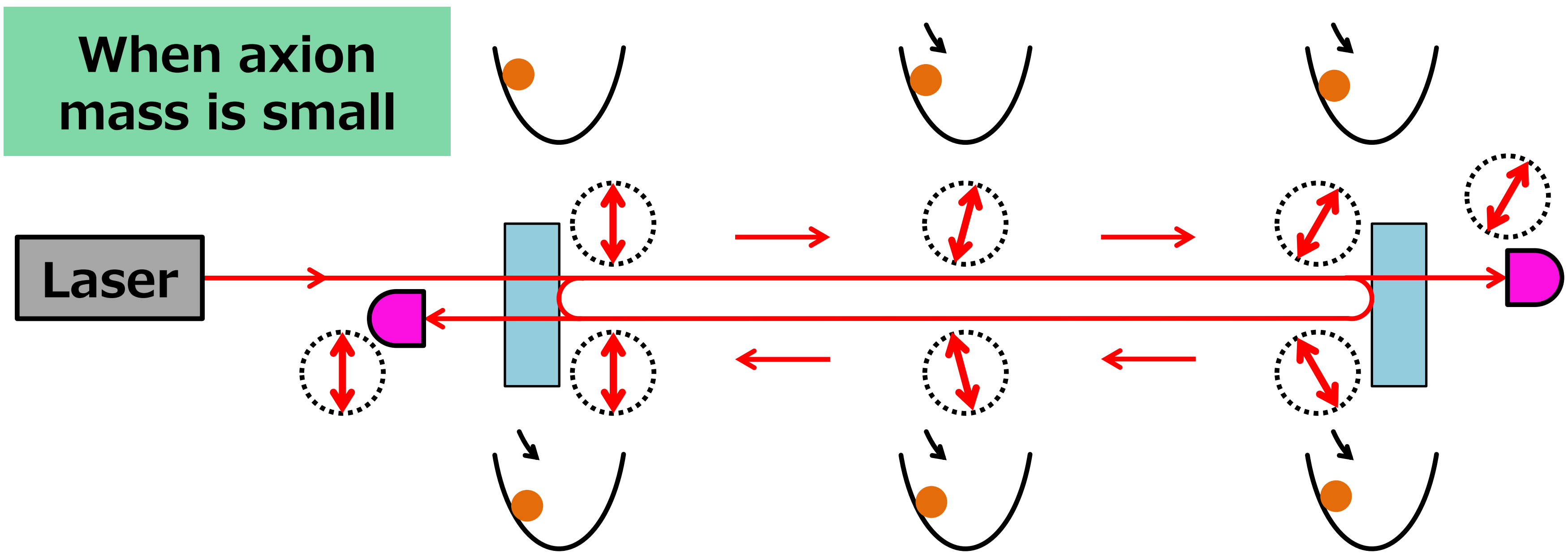
- Linear polarization will be modulated
  - p-pol sidebands will be generated from s-pol
- Search can be done without magnetic field





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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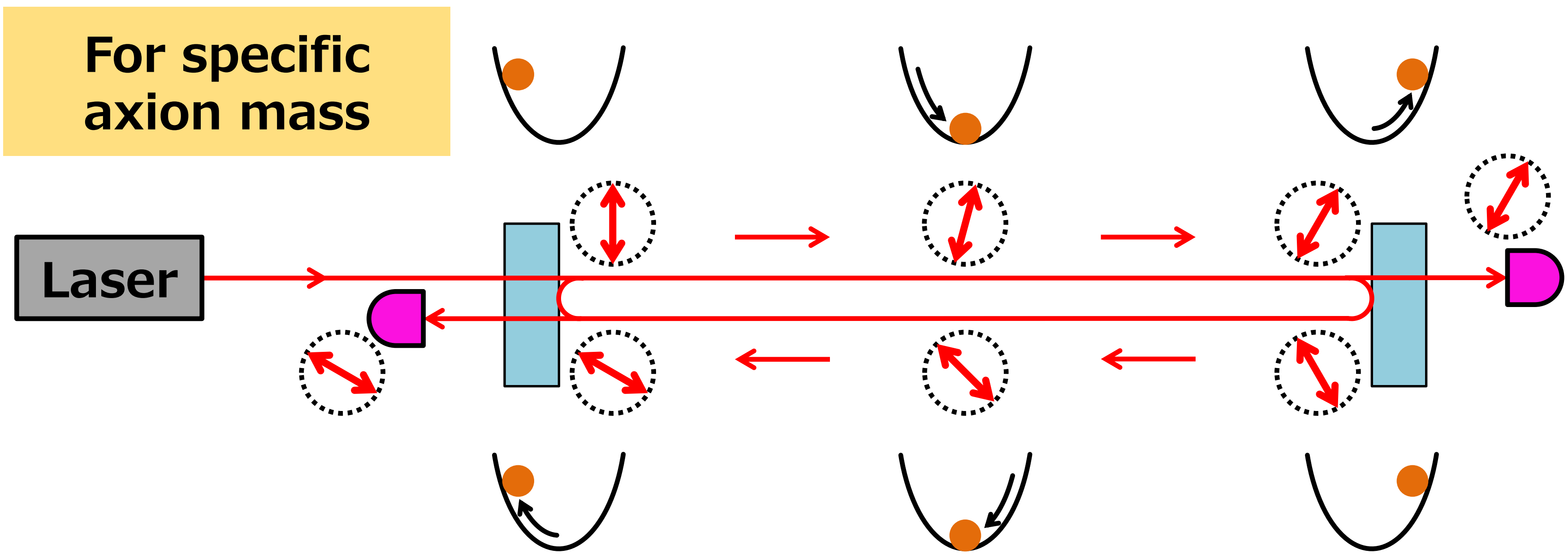
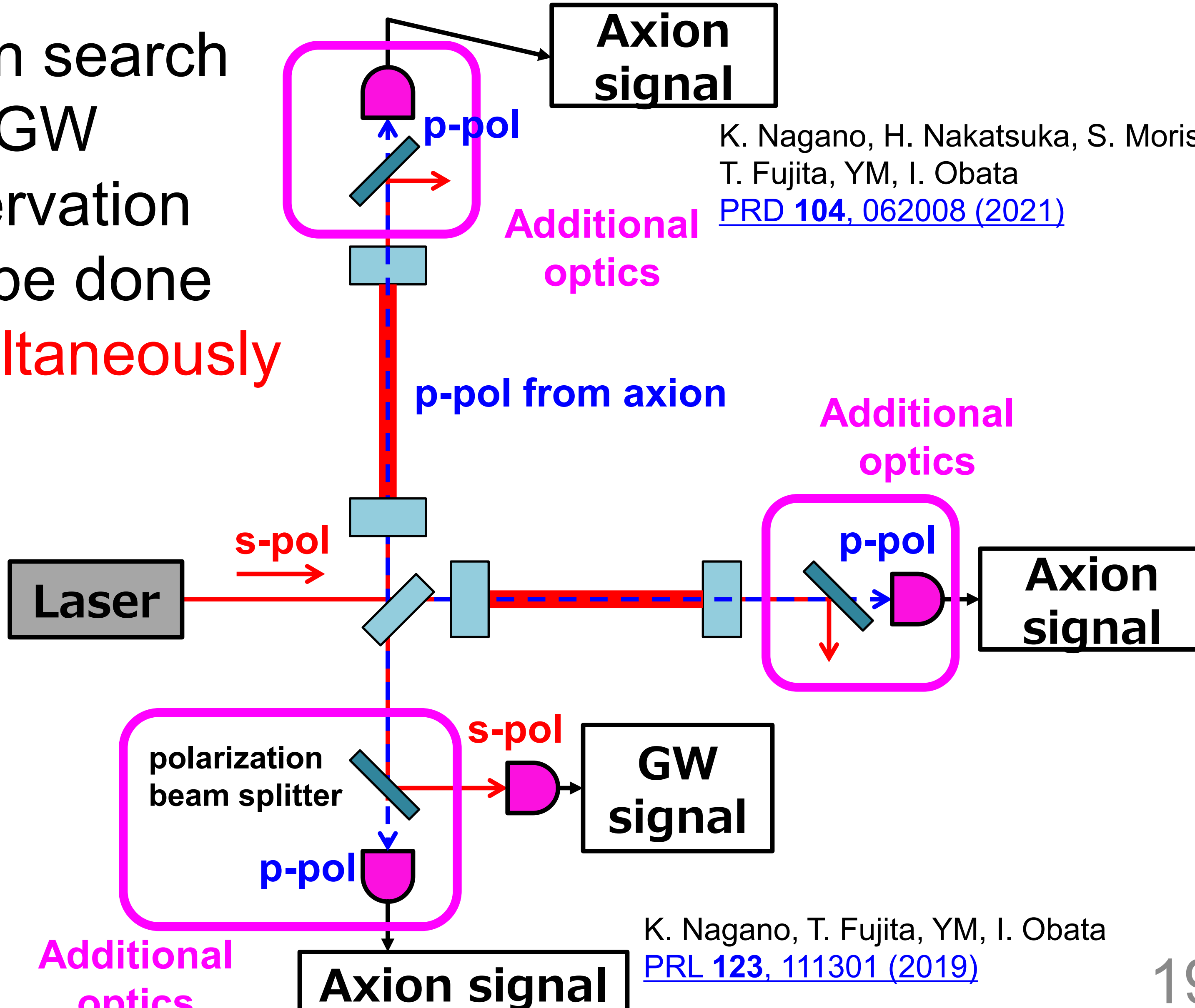


Axion Search with GW Detectors

- Axion search and GW observation can be done simultaneously

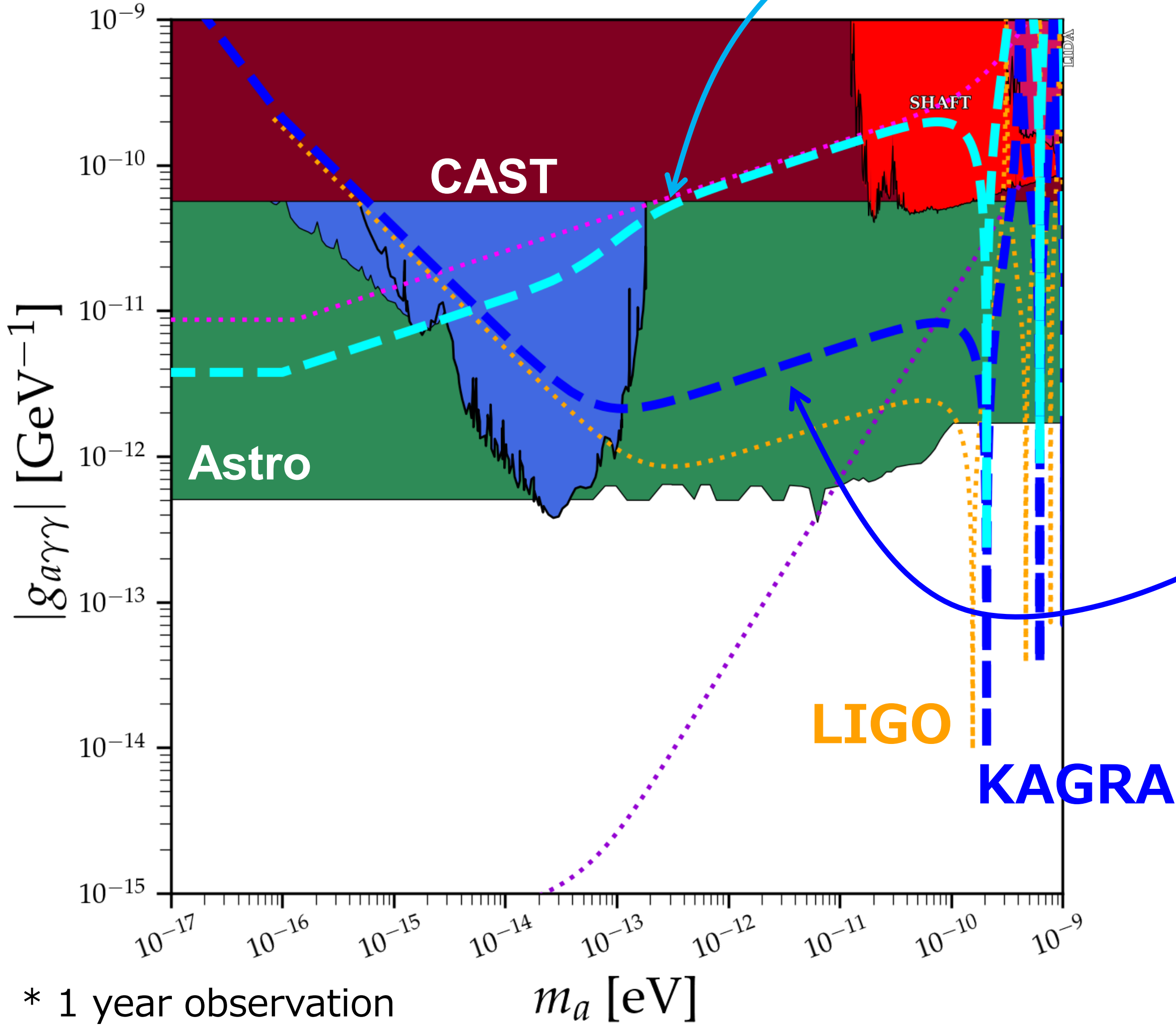


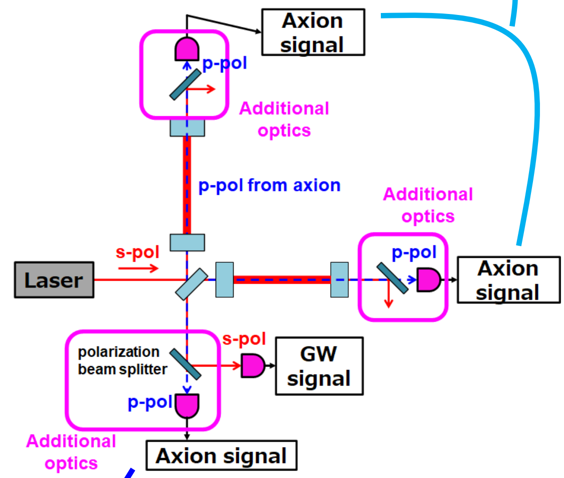
K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita, YM, I. Obata
PRD **104**, 062008 (2021)

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

Axion Sensitivity

Arm cavity transmission ports





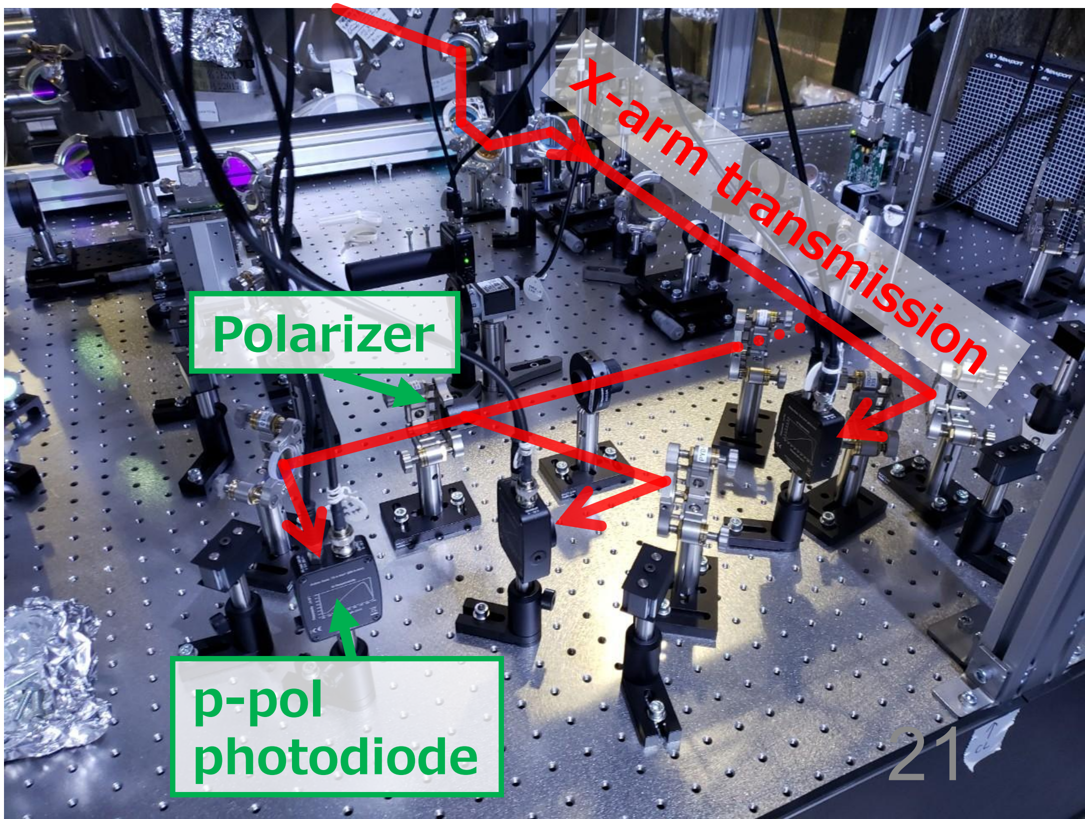
GW detection port

Complemental search using different ports

* 1 year observation

Axion Search with KAGRA Started

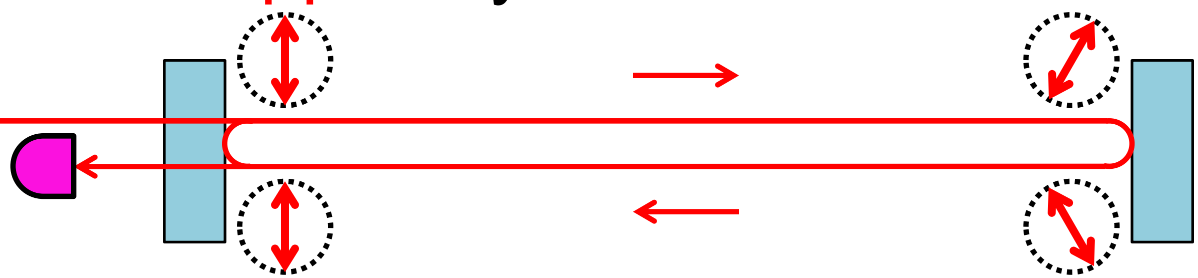
- Polarization optics were installed at transmission ports of KAGRA in 2021
- First simultaneous observation of gravitational waves and axions during O4 (June-August 2025)
- Data analysis underway
- KAGRA is now the only detector which can also search for axions



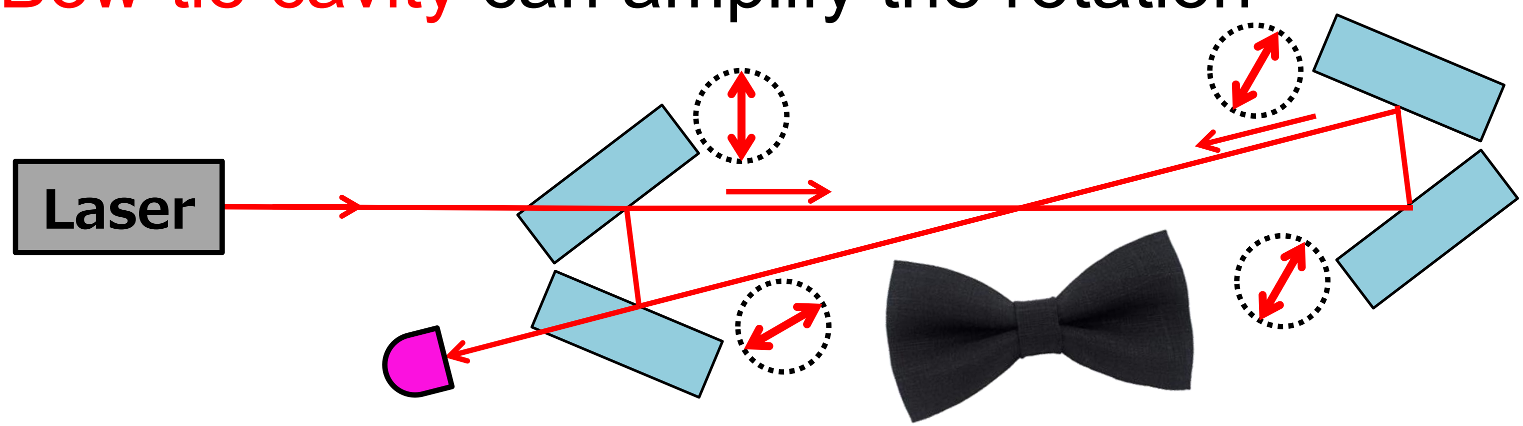
Bow-tie Cavity for Broadband

- Polarization rotation is small for short optical path

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



- Bow-tie cavity can amplify the rotation

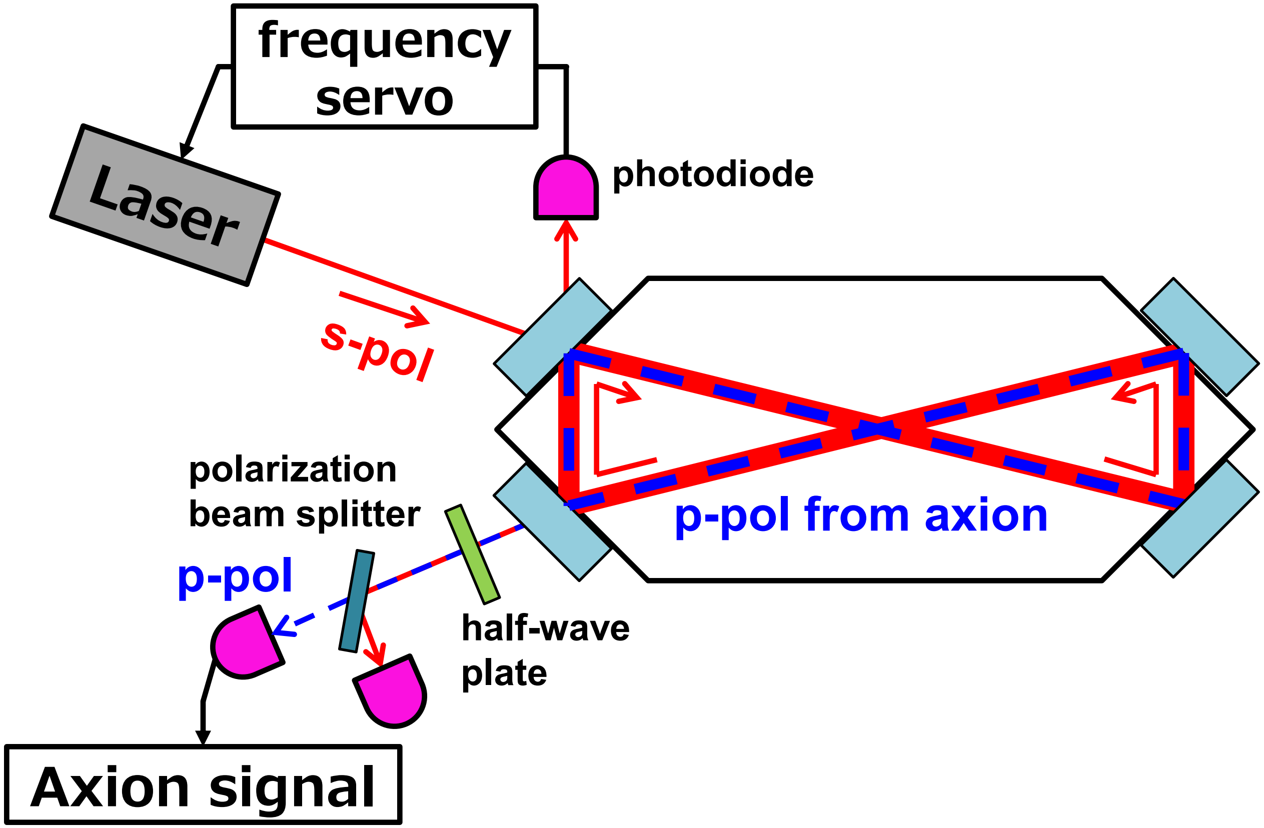


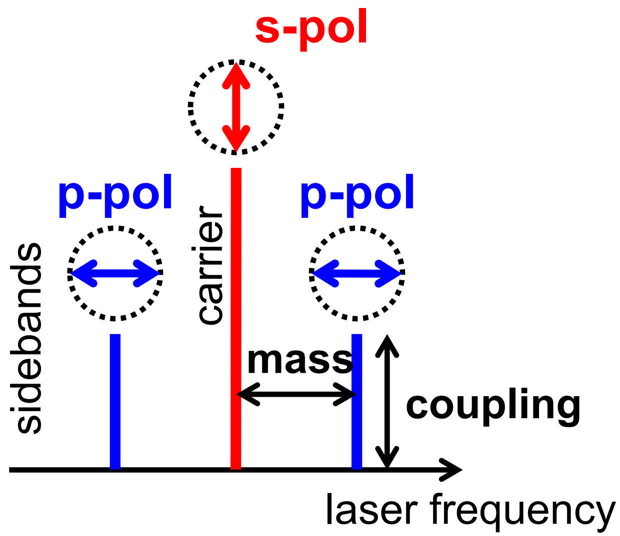
DANCE Setup

Dark matter Axion search with riNg Cavity Experiment

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

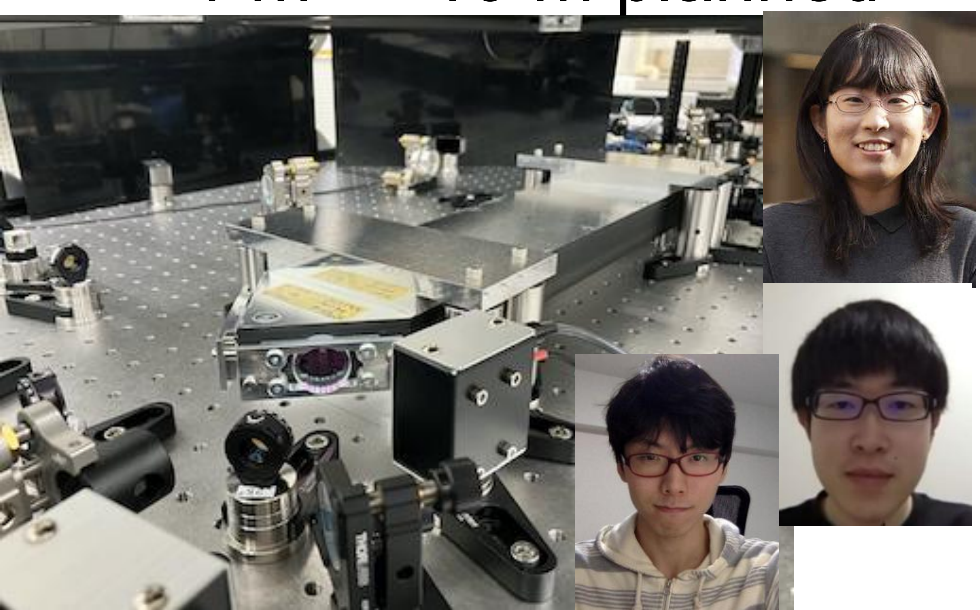
I. Obata, T. Fujita, YM,
PRL **121**, 161301 (2018)

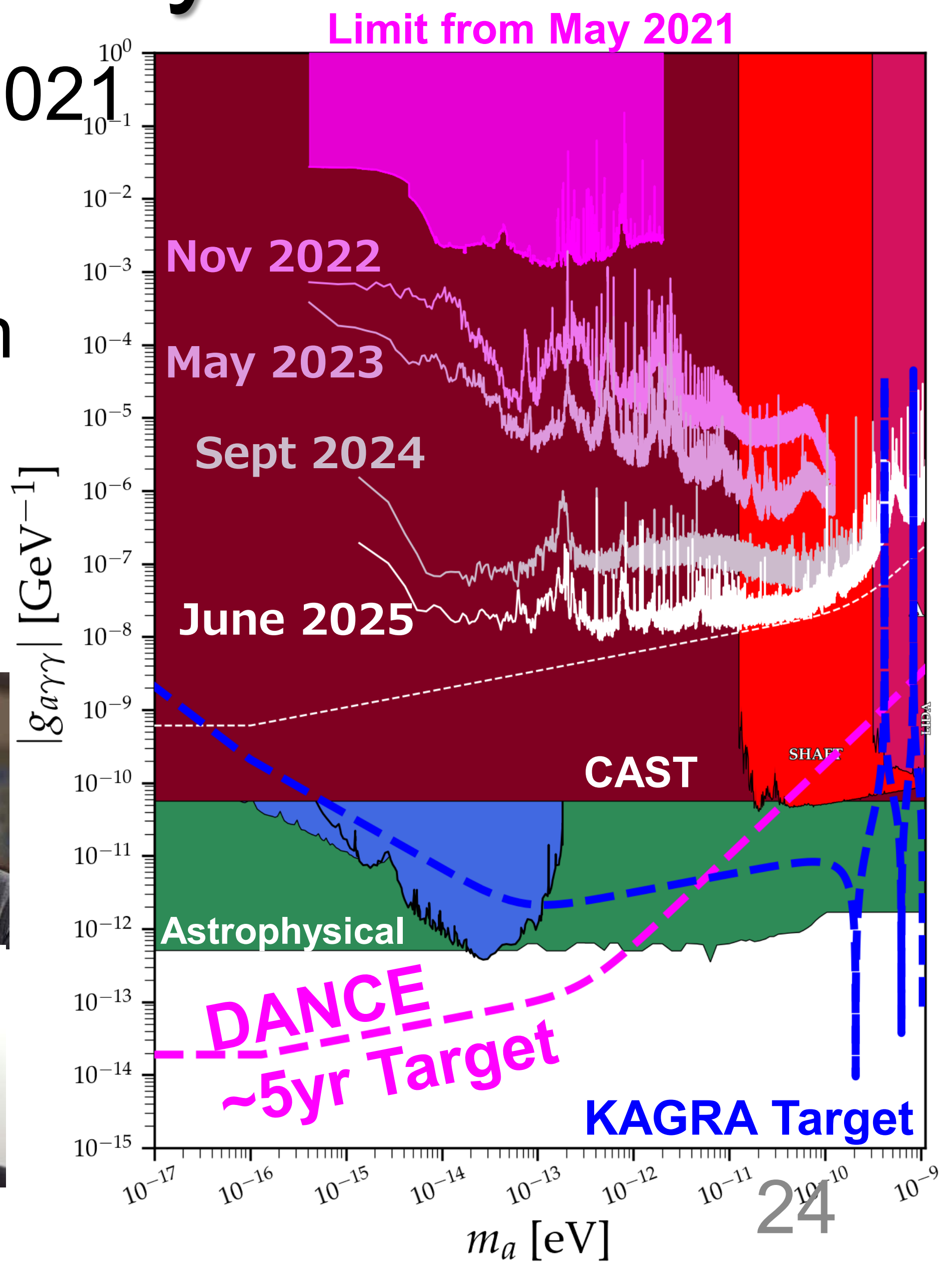




DANCE Sensitivity Evolution

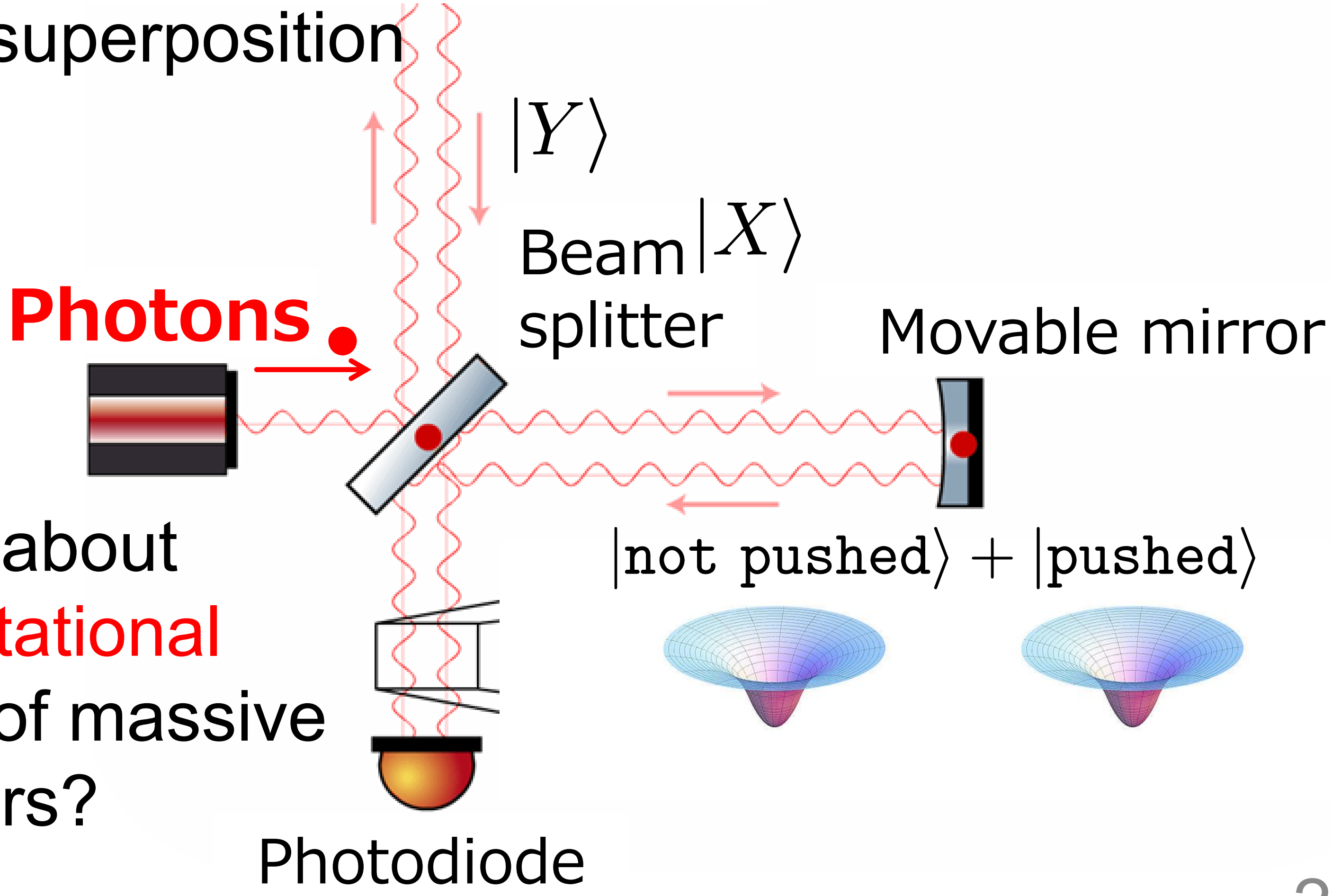
- First demonstration in 2021
  Y. Oshima+, PRD **108**, 072005 (2023)
- ~5 orders of magnitude improvement since then
  H. Takidera+, PRD **112**, 063048 (2025)
  H. Fujimoto, PhD thesis (UTokyo 2025)
- 6 mW → 1 W,
  1 m → 10 m planned





Interferometers as Quantum Probe

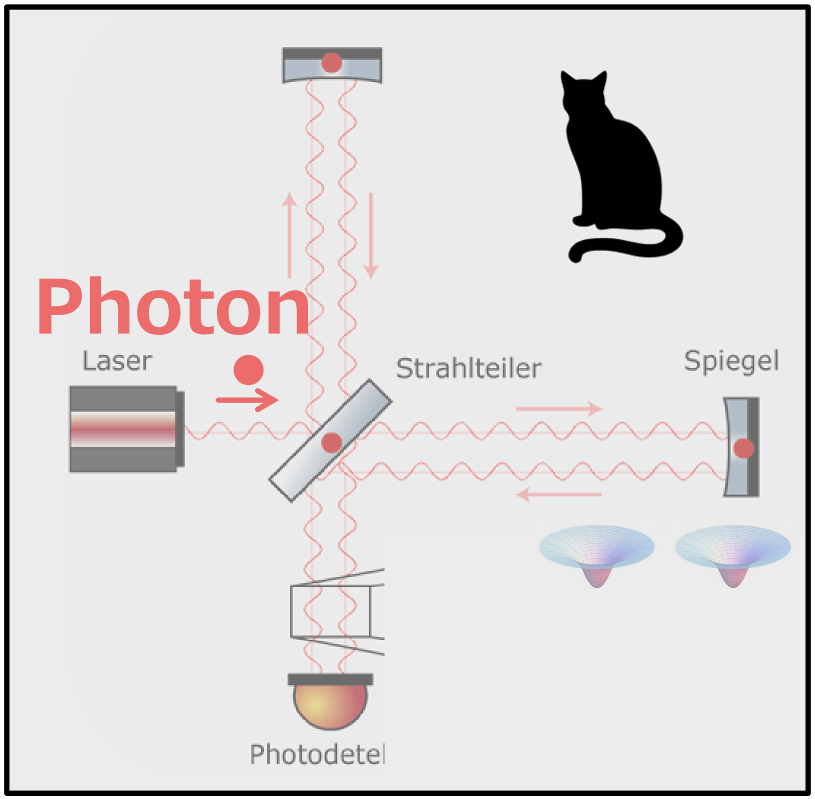
- Photon going to X or Y arm is in superposition
- Mirrors pushed or not pushed by radiation pressure is in superposition

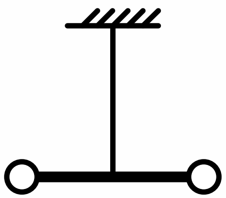


- How about gravitational field of massive mirrors?

Schrödinger’s KAGRA

- If you put KAGRA in a box and bring a torsion pendulum close to one of its mirrors, will the torsion pendulum oscillate due to the mirror’s gravity, not oscillate at all, or oscillate half???





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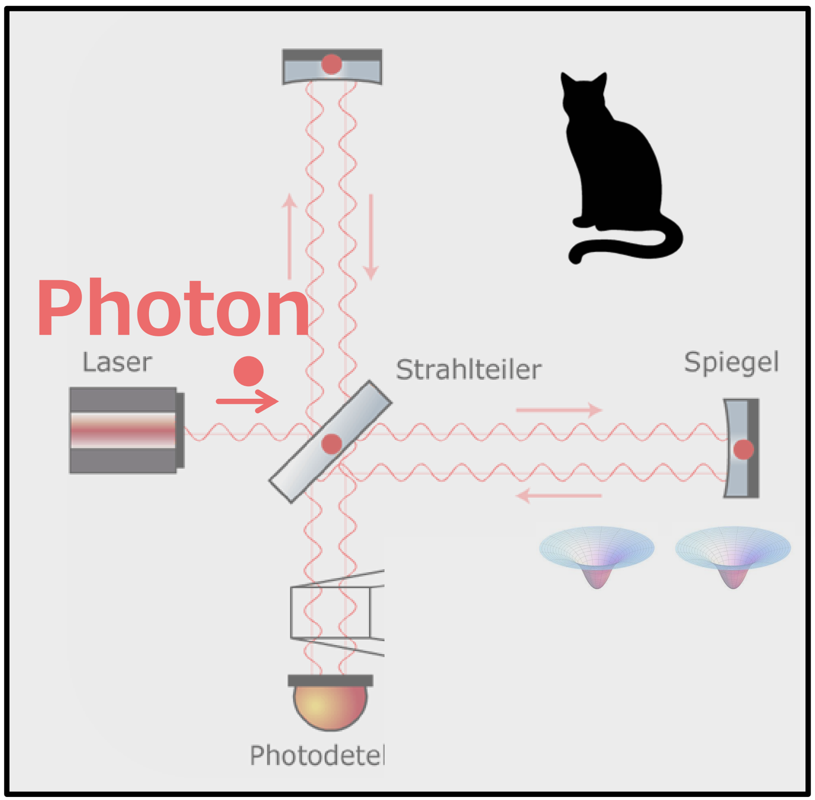
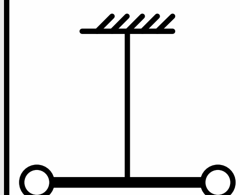


$$\nabla^2\Phi = 4\pi G\langle \text{Mass distribution} \rangle$$

Expectation value



Semiclassical Gravity
(e.g. Schrödinger-Newton model)

Very strange model, but not experimentally falsified completely.

Various Gravity Models

TABLE I. Summary of collapse, Schrödinger-Newton, and classical gravity models that rely on auxiliary observers. We propose a unified model in which classical gravity depends on the outcomes of auxiliary observers as well as the results of experiments performed by the experimentalist.

Class	Model	Auxiliary observers introduced?	Auxiliary outcomes used to generate ϕ?	Experimental measurement outcomes used to generate ϕ?	Features
Collapse models	Diosi-Penrose [18,43]	Measure **g** everywhere	No	No	Gravity not implemented
	CSL [20,44]	Measure smeared matter distribution	No	No	
Schrödincer-Newton	Preselection [4,7] S-N	No	No	No	Violates Page-Geilker
	Postselection S-N [7]	No	No	Yes	Future measurement choices influence past.
	Causal-conditional S-N [8,9,11,12]	No	No	Obtain conditional expectation of positions then generate gravity via classical feedback	Preserves causality
Classical grmvity with auxiliary observers	N-H extension of S-N [45]	Measure **g** everywhere	Yes	No	Classical gravity via Diosi-Penrose measurements
	KTM Model [21,22]	Measure position of each mass	Uses instant outputs of position channels	No	Instant outputs are very noisy
	Oppenheim's model [23]	Yes	Yes	No	More general and includes NH and KTM
	Unified model	Measure position of each mass	Yes	Yes	Can incorporate all above models

This model is falsified by D. N. Page, C. D. Geilker, PRL 47, 979 (1981)

Violates causality

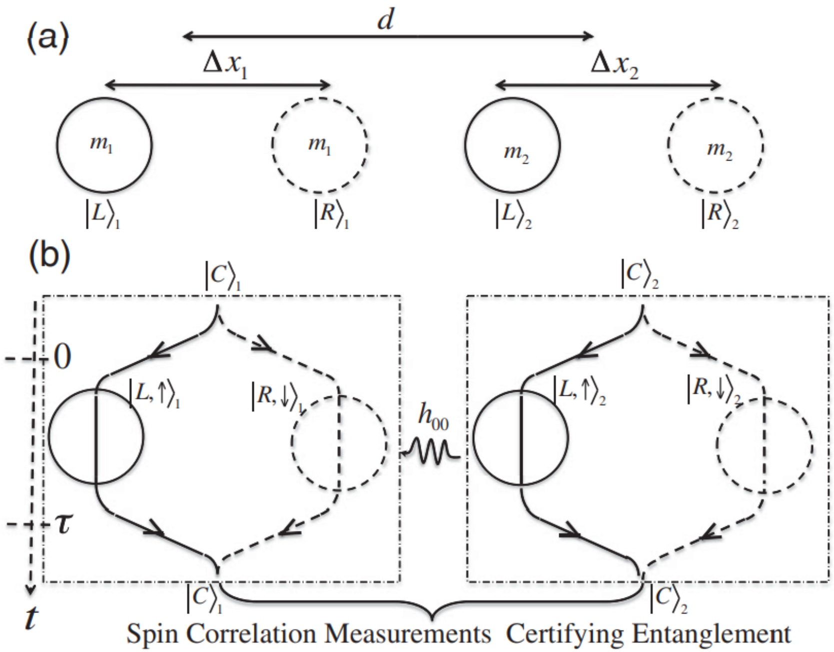
Preserves causality

D. Miki, Y. Kaku, Y. Liu, Y. Ma, Y. Chen, PRD 111, 104084 (2025)

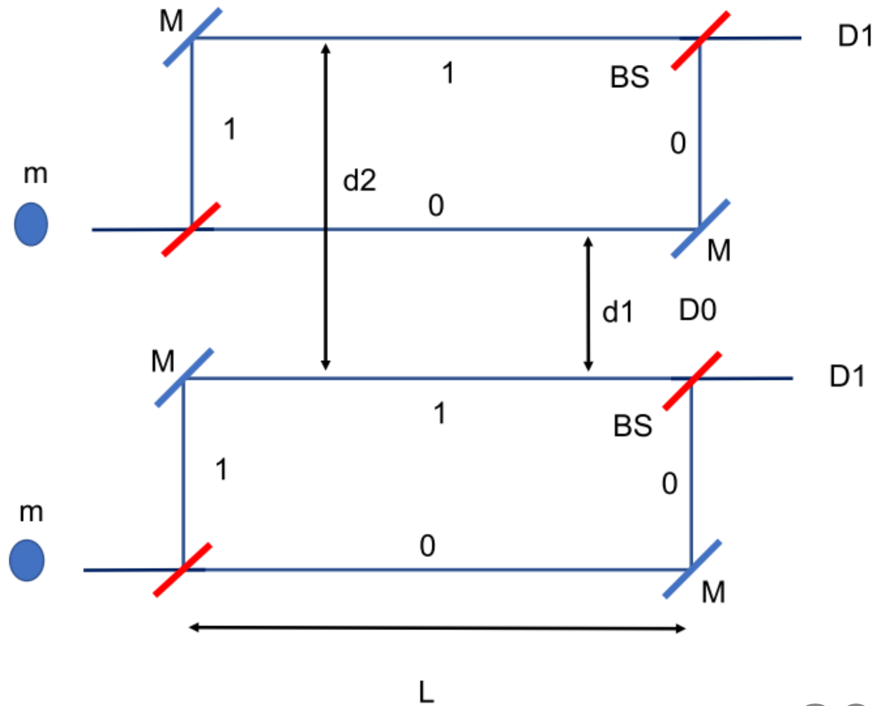
BMV Proposals

- Quantum nature of gravity can be tested by testing gravity-induced entanglement with adjacent matter interferometers

S. Bose+,
[Phys. Rev. Lett. 119, 240401 (2017)](https://doi.org/10.1103/PhysRevLett.119.240401)



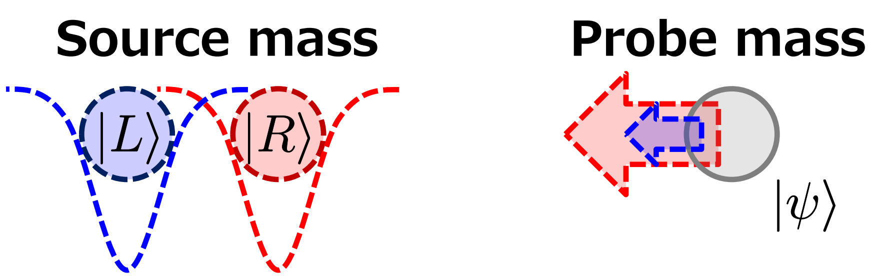
C. Marletto & V. Vedral,
[Phys. Rev. Lett. 119, 240402 (2017)](https://doi.org/10.1103/PhysRevLett.119.240402)



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

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

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

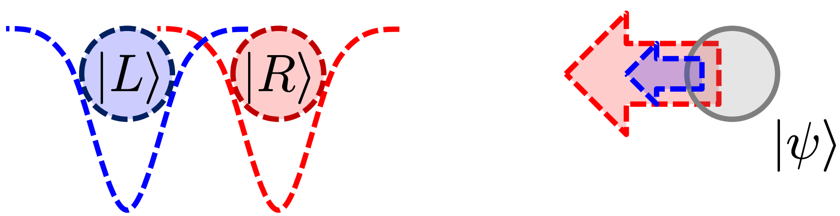
Gravity induced entanglement

Key Idea of BMV Proposals

- If gravity is quantum

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

Source mass **Probe mass**



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

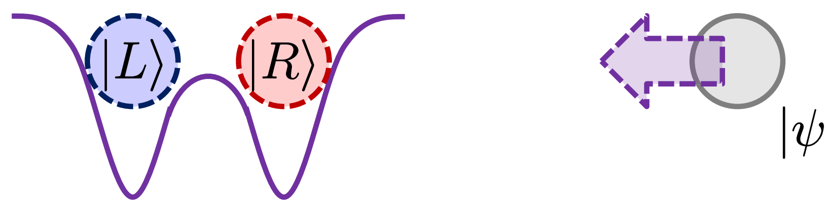
$$= \frac{1}{\sqrt{2}}\left(|L\rangle\otimes e^{i\phi_L}|\psi\rangle + |R\rangle\otimes e^{i\phi_R}|\psi\rangle\right)$$

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

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

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

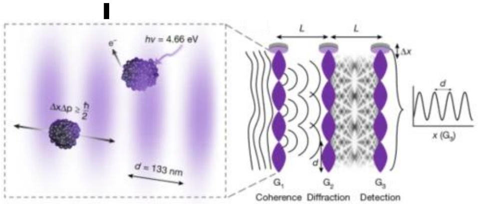
Remains separable

Quantum and Gravity Experiments

Quantum → ← **Gravity**

Mass

Planck mass
22 ug

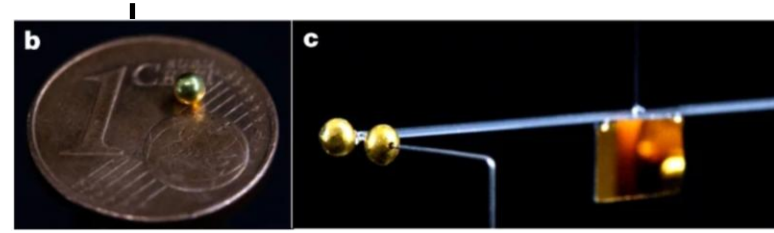


sodium nanoparticles,
3e-19 g
Pedalino+ (2026)

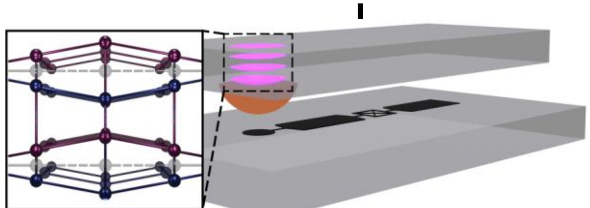
Interference

cantilever, 50 ng
Cripe+ (2019)

Backaction



torsion pendulum, 90 mg
Westphal+ (2021)



Cat state

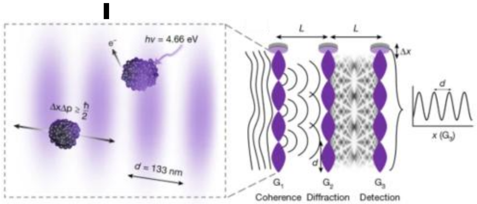
acoustic wave, 16 ug
Bild+ (2023)

Quantum and Gravity Experiments

Quantum → **Quantum regime of gravity** ← **Gravity**

Mass

Planck mass
22 ug

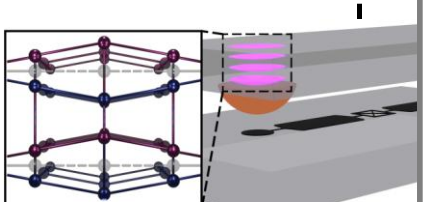


sodium nanoparticles,
3e-19 g
Pedalino+ (2026)

Interference

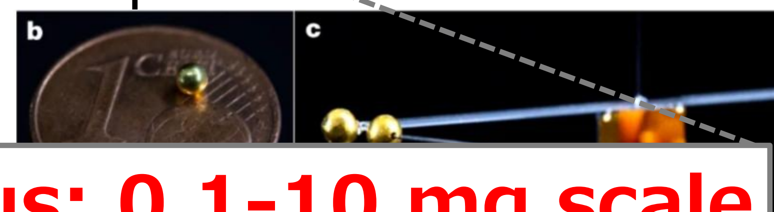
cantilever, 50 ng
Cripe+ (2019)

Backaction



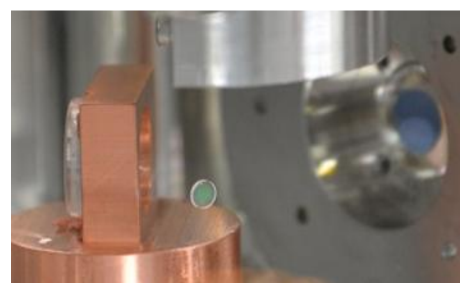
Cat state

acoustic wave,
Bild+ (2023)



Our focus: 0.1-10 mg scale

optical levitation,
~0.2 mg



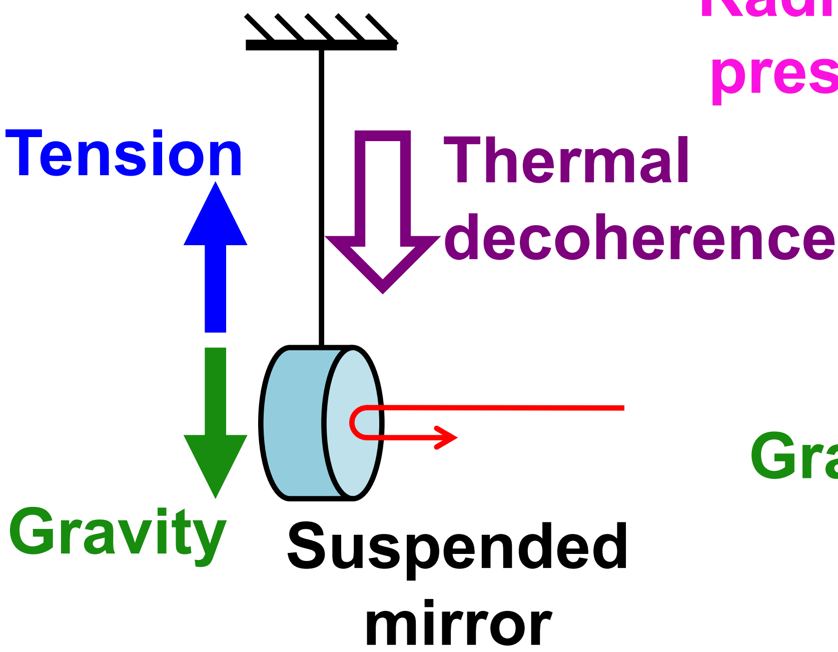
suspended disk, 7 mg
Matsumoto+ (2019)

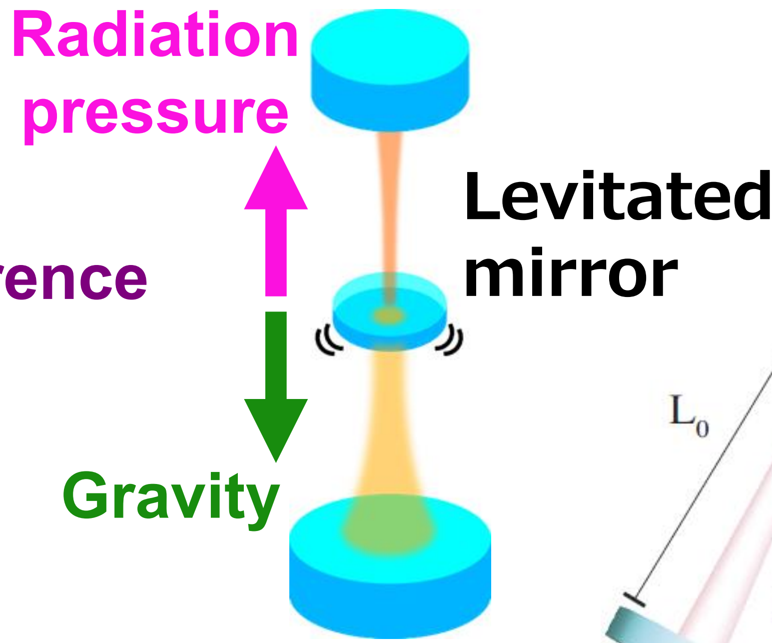
suspended bar, 10 mg
Komori+ (2019)

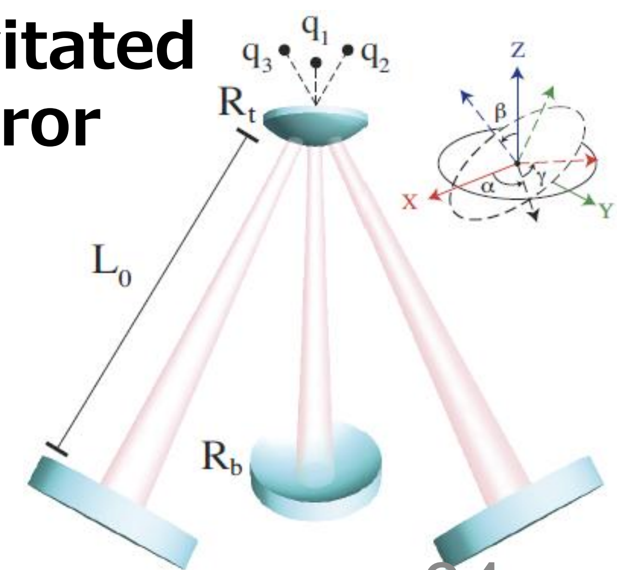
Optical Levitation of Mirrors

- Support a mirror with radiation pressure alone
- Free from thermal decoherence from mechanical support

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







G. Guccione+: [PRL 111, 183001 (2013)]

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 at ANU suggest higher absorption makes the system unstable (photothermal effects)

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

How to Make Tiny Mirrors

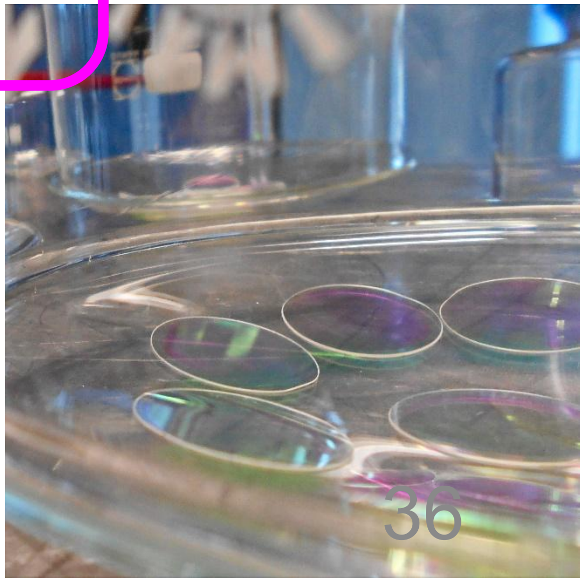
2014 Approach (Company in Japan)

(1) Make 3 mm dia. lens → (2) Coat →

2020- Approach

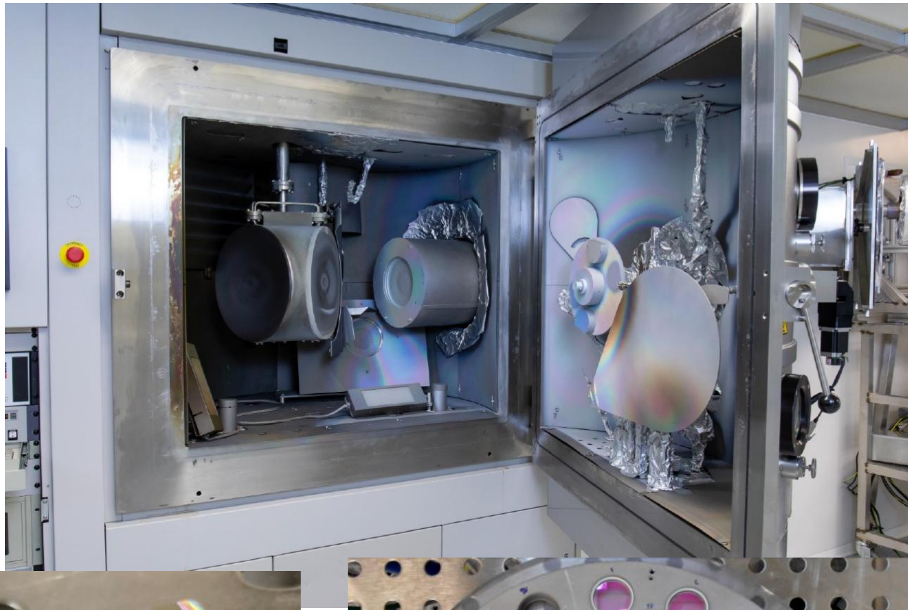
(2018-2024 ANR-JST CREST、
2025-2027 France- Japan JSPS Bilateral program)

(1) Make 1 inch dia. 0.1 mm thick disk → (2) Coat (bend due to stress) → (3) Cut into 3 mm dia.

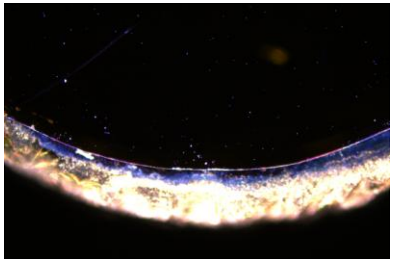


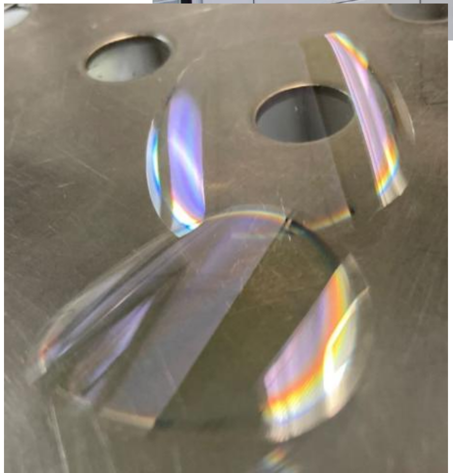
Fabrication Status in LMA

- 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)]

Summary

- KAGRA can also search for
  - axion dark matter
  - vector dark matter
- DANCE project to search for axions underway at the University of Tokyo
- Aiming to levitate a mirror to ultimately probe the quantum nature of gravity
- Fabrication of levitation mirrors underway in collaboration with LMA
- Let's collaborate more on these topics!

NEXUS 日ASEAN科学技術・イノベーション協働連携事業

Networked Exchange, United Strength for Stronger Partnerships between Japan and ASEAN