QUPosium2024 @ Tsukuba International Congress Center

December 11, 2024

Laser interferometric searches for signatures of dark matter and quantum gravity

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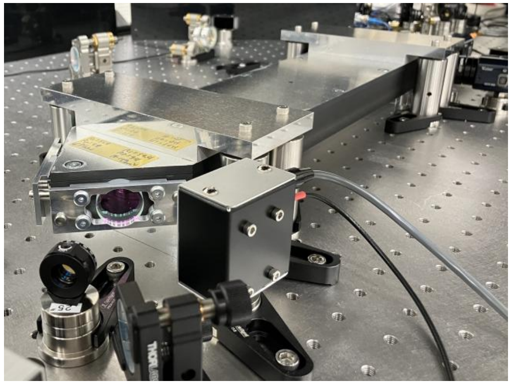
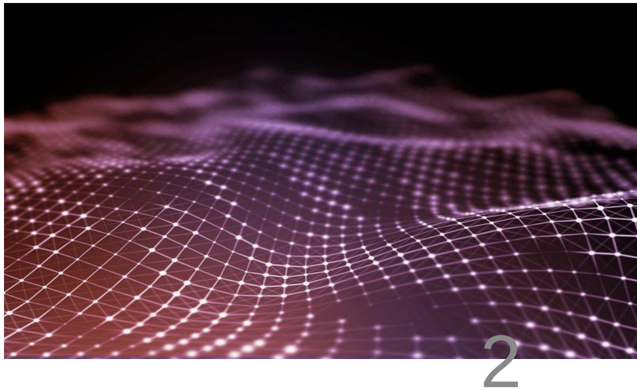
Plan of the Talk

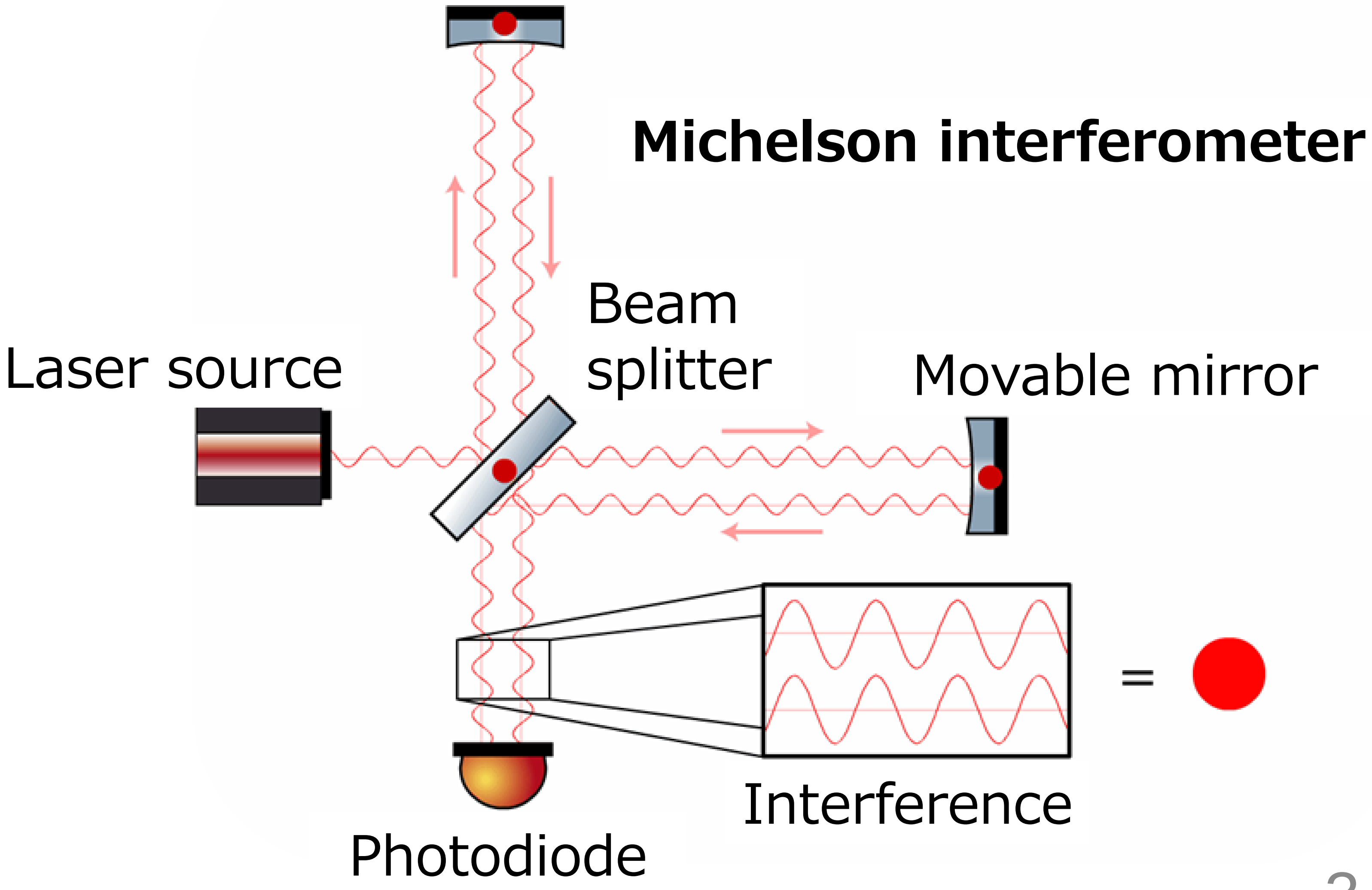
- **Basics of laser interferometry**
- **Search for ultralight vector dark matter**
  - LIGO-Virgo-KAGRA, PRD **110**, 042001 (2024)
- **Search for ultralight axion dark matter**
  - K. Nagano, T. Fujita, YM, I. Obata, PRL **123**, 111301 (2019)
  - Y. Oshima+, PRD **108**, 072005 (2023)
- **Testing quantum nature of gravity**
  - T. Fujita, Y. Kaku, A. Matsumura, YM, arXiv:2308.14552
- **Search for quantum fluctuations of space-time**





Laser Interferometry

- measures differential arm length change



Laser Interferometry

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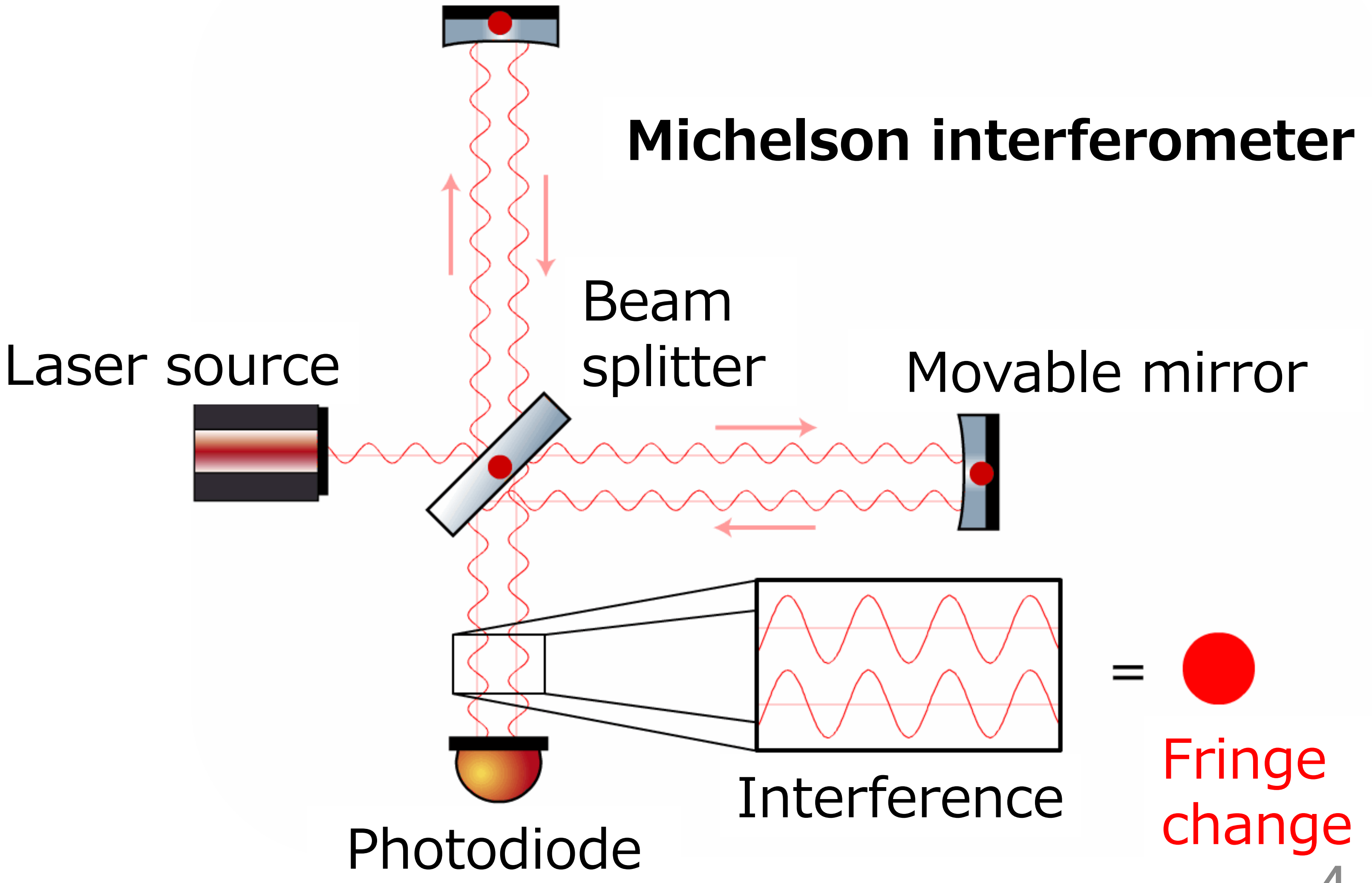


Michelson interferometer

Beam splitter

Laser source

Movable mirror

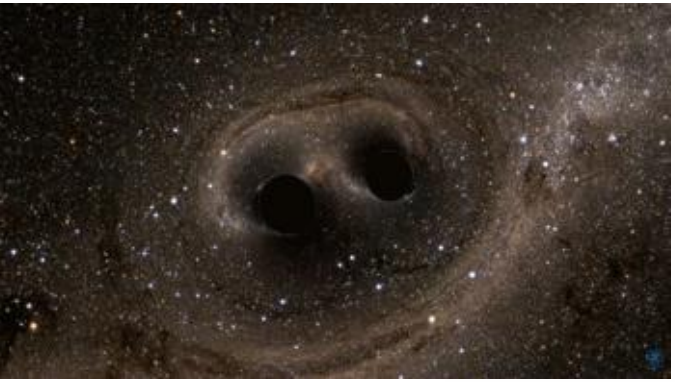
Photodiode

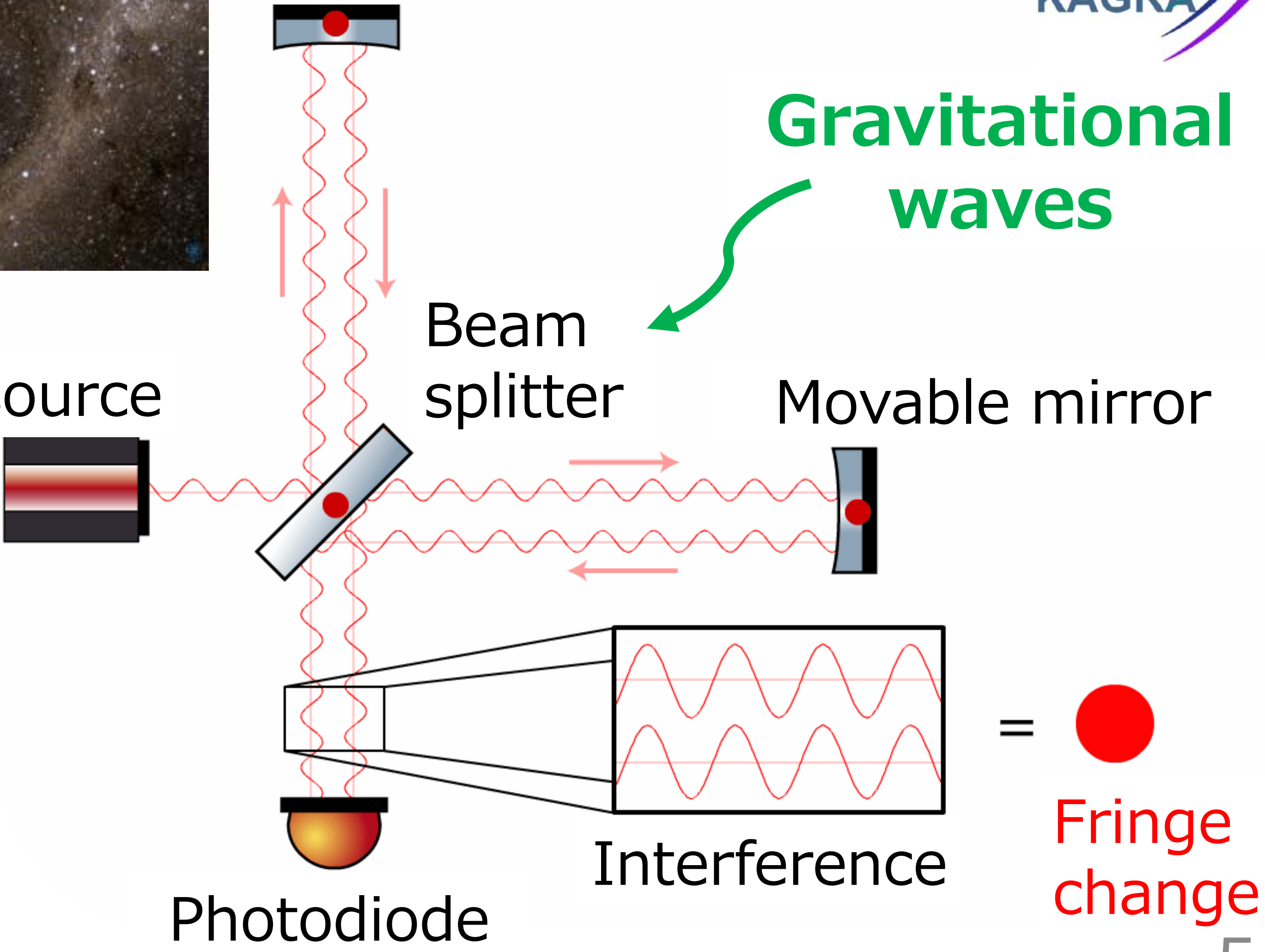
Interference

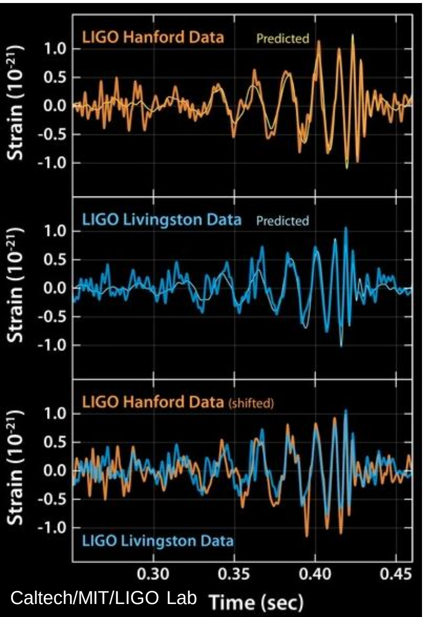
=

Fringe change

For Gravitational Waves

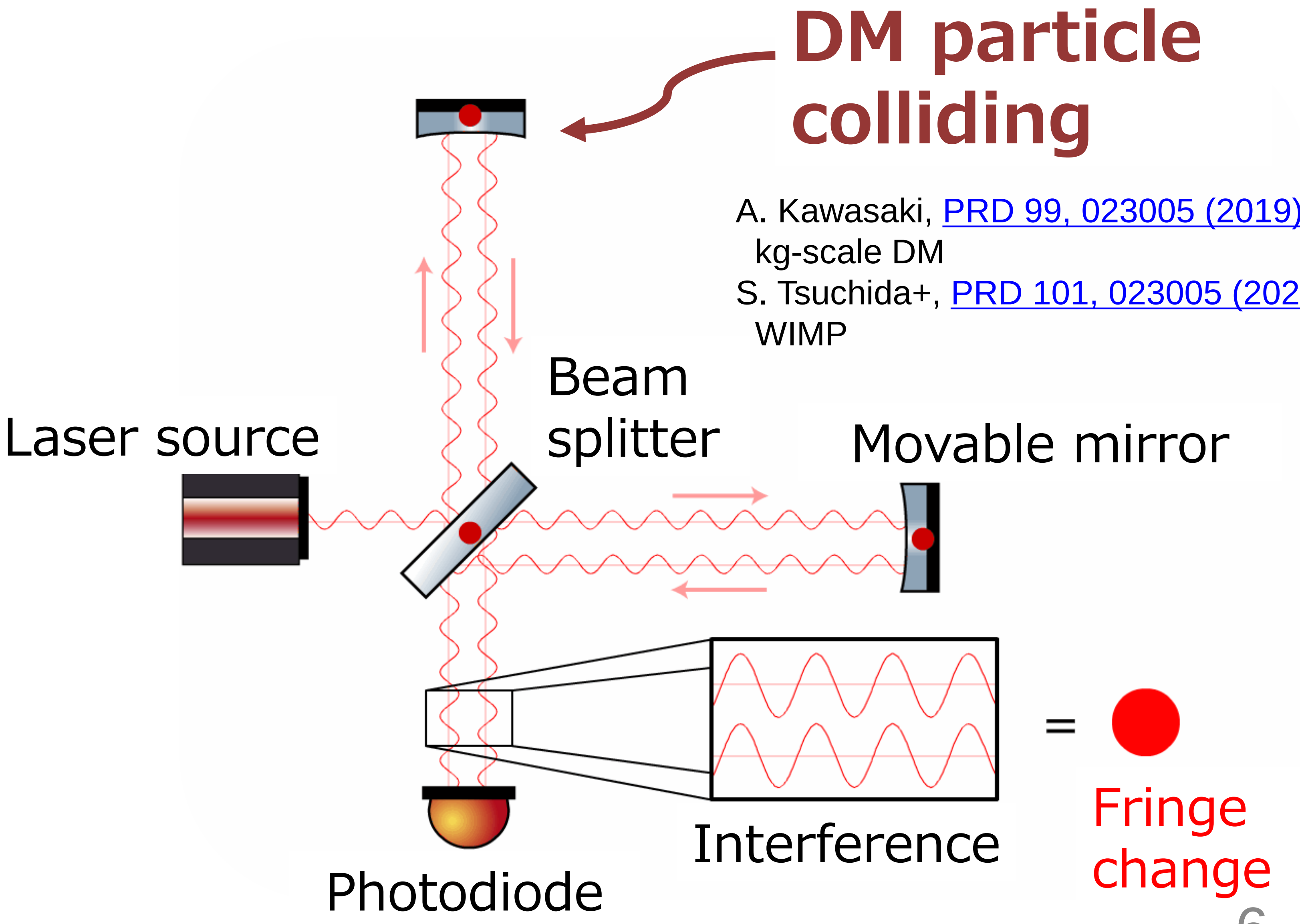






Caltech/MIT/LIGO Lab

For Particle Dark Matter



A. Kawasaki, PRD 99, 023005 (2019)
kg-scale DM
S. Tsuchida+, PRD 101, 023005 (2020)
WIMP

For Ultralight Dark Matter

Tiny forces from vector DM

LIGO-Virgo-KAGRA,
PRD **105**, 063030 (2022)
LIGO/Virgo O3 analysis
LIGO-Virgo-KAGRA,
PRD 110, 042001 (2024)
KAGRA O3GK analysis

Mirror thickness changes from scalar DM

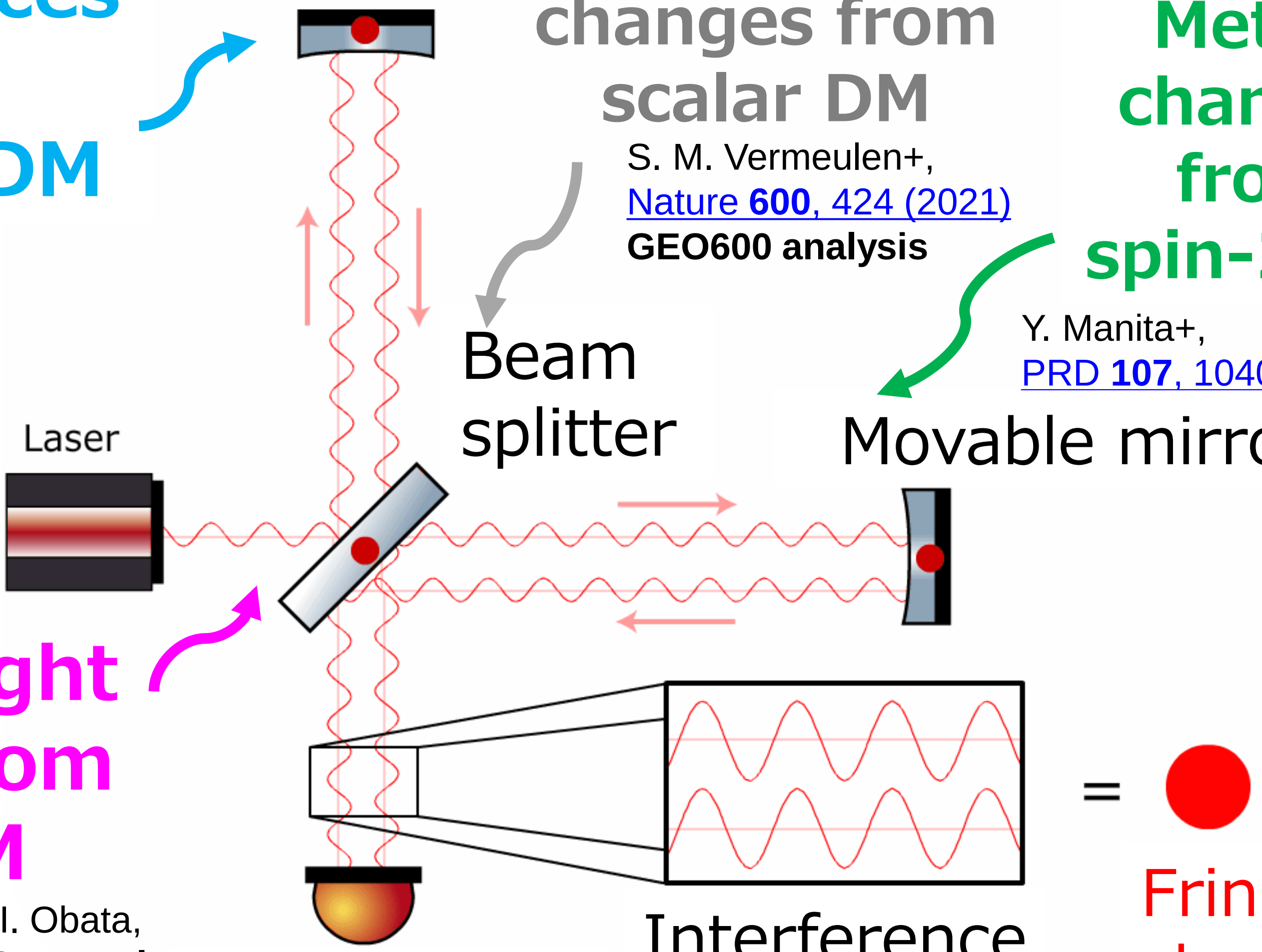
S. M. Vermeulen+,
Nature **600**, 424 (2021)
GEO600 analysis

Metric changes from spin-2 DM

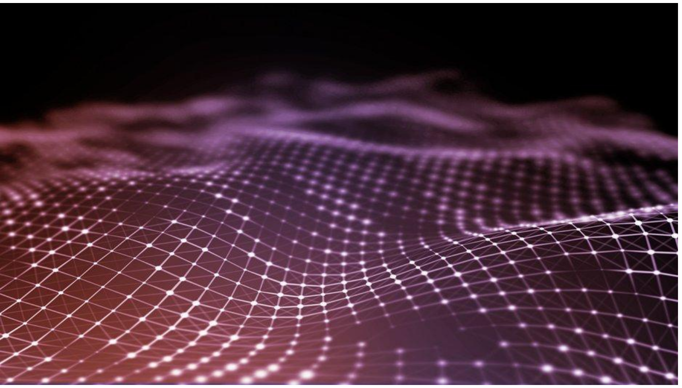
Y. Manita+,
PRD **107**, 104007 (2023)

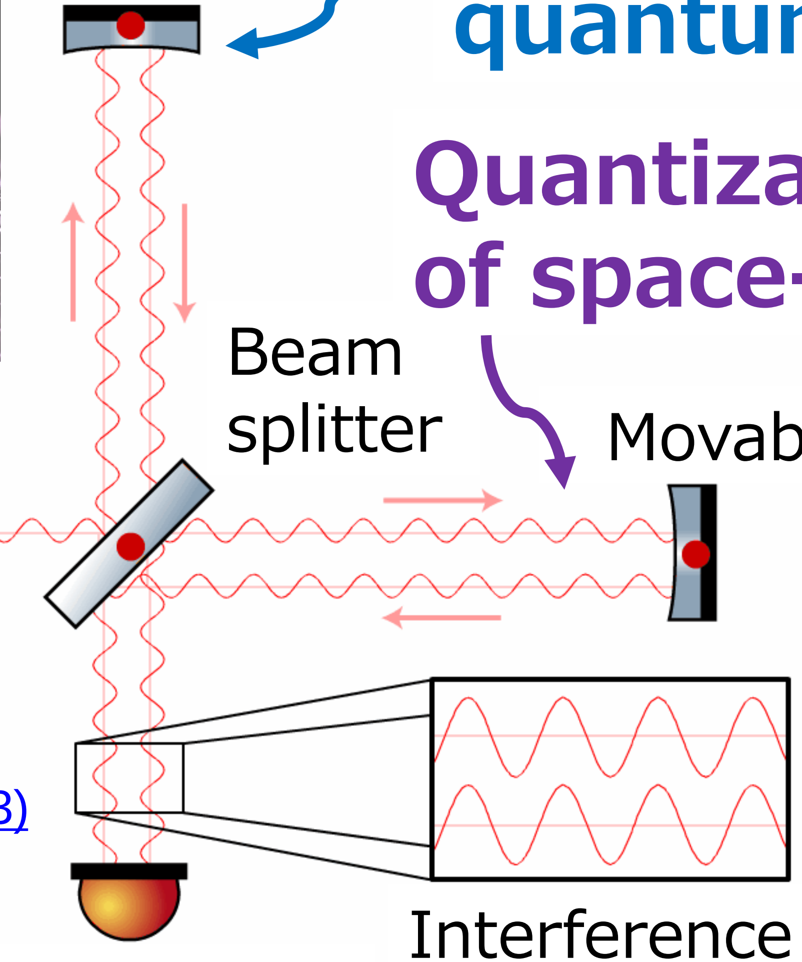
Speed of light changes from axion DM

K. Nagano, T. Fujita, YM, I. Obata,
PRL **123**, 111301 (2019) **Proposal**
Y. Oshima+, PRD **108**, 072005 (2023)
Table-top experiment DANCE analysis



For Quantum Gravity





Gravity from quantum mass

Quantization of space-time

K. M. Zurek, [arXiv:2205.01799]

D. Li+, [PRD 107, 024002 (2023)]

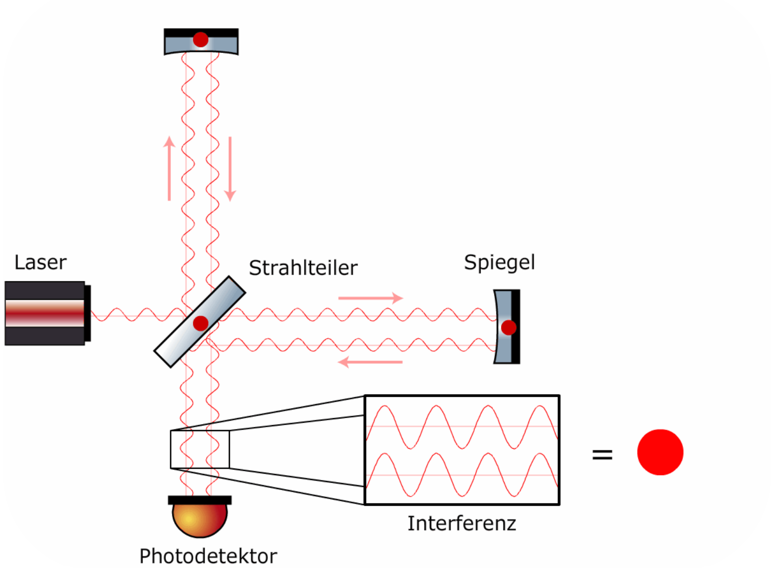
Ultralight Dark Matter Searches

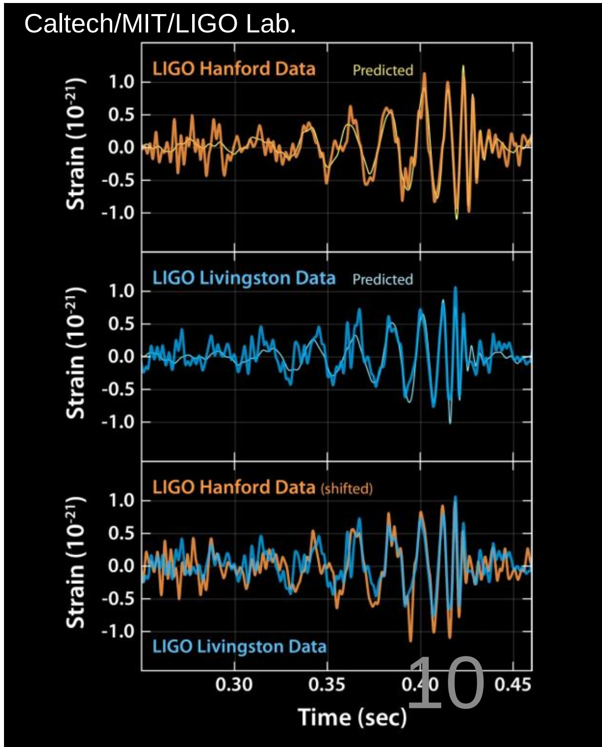
Ultralight Dark Matter

- 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)




Caltech/MIT/LIGO Lab.

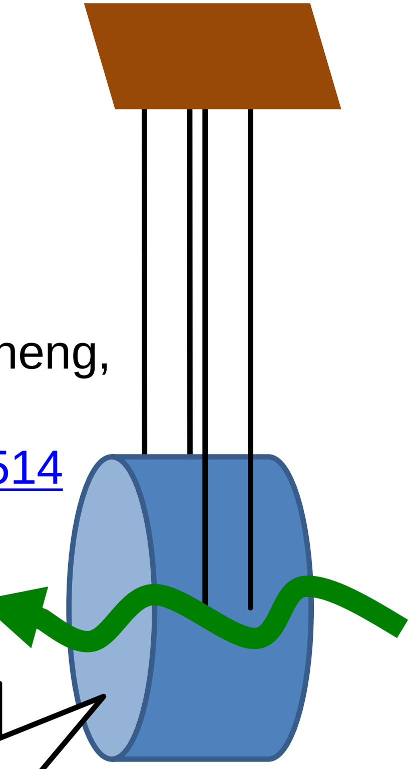
Vector Boson Dark Matter

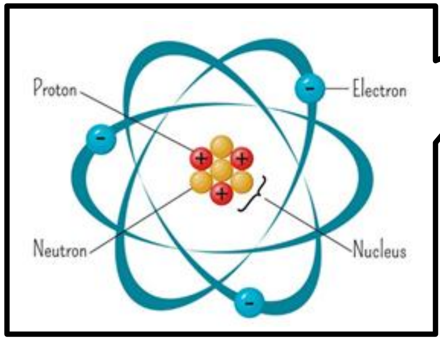
- Possible new physics beyond the standard model: New gauge symmetry and gauge boson
- New gauge boson can be dark matter
- B-L (baryon minus lepton number)
  - Conserved in the standard model
  - Motivations from neutrino mass, matter-antimatter asymmetry
  - Roughly 0.5 per neutron mass, but slightly different between materials

    Fused silica: 0.501

    Sapphire: 0.510
- Gauge boson DM gives oscillating force

Y. Cheng, J. Sheng, T. T. Yanagida, arXiv:2402.14514





Oscillating Force from Gauge Field

- Acceleration of mirrors

charge

gauge boson mass

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

coupling
(normalized by e)

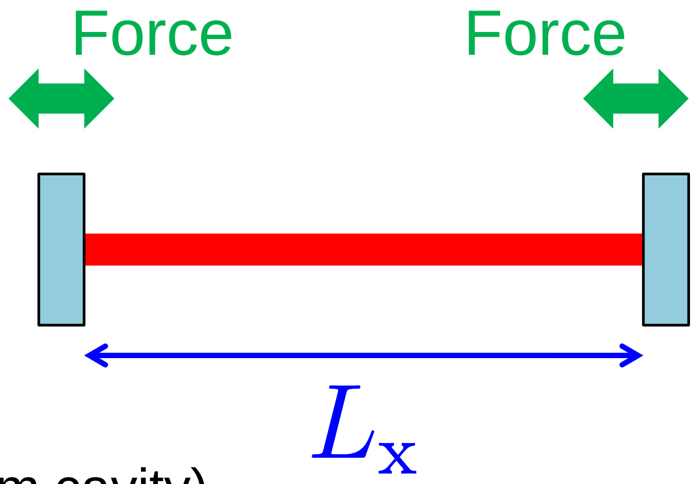
mirror mass

DM density

polarization

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?

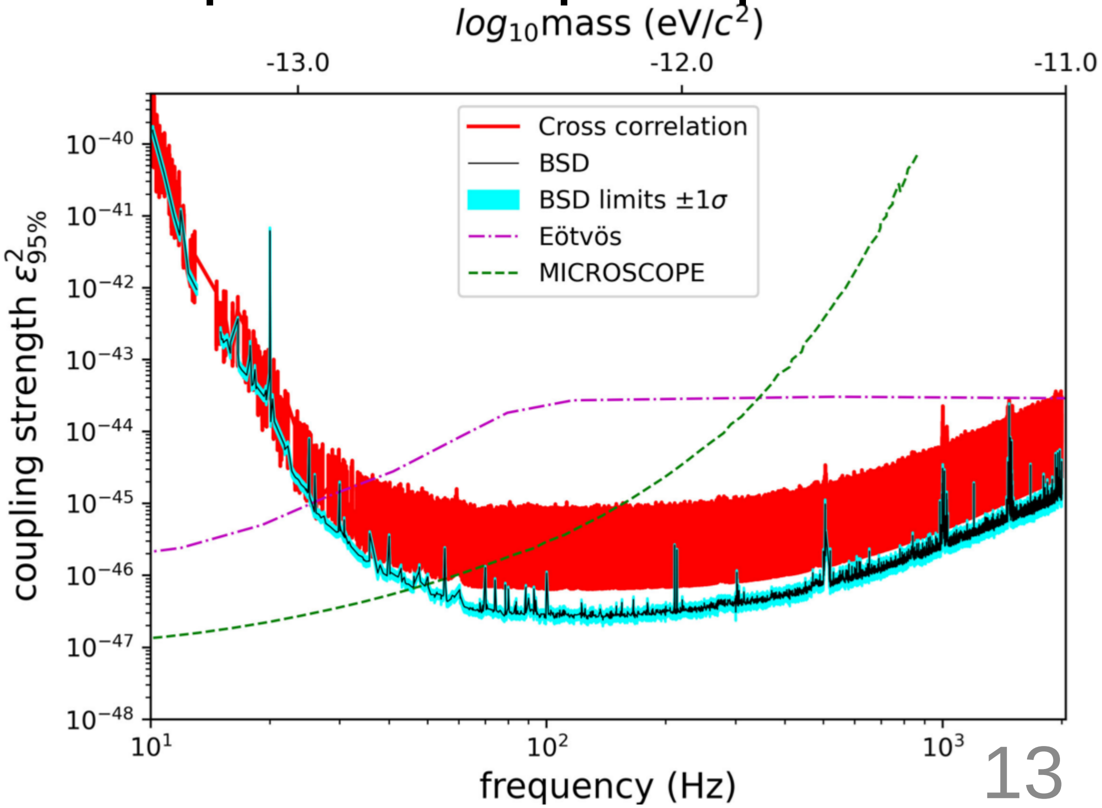
A. Pierce+, PRL **121**, 061102 (2018)

Previous Searches with LIGO/Virgo

- Gauge boson dark matter search with LIGO O1 data and LIGO/Virgo O3 data have been done

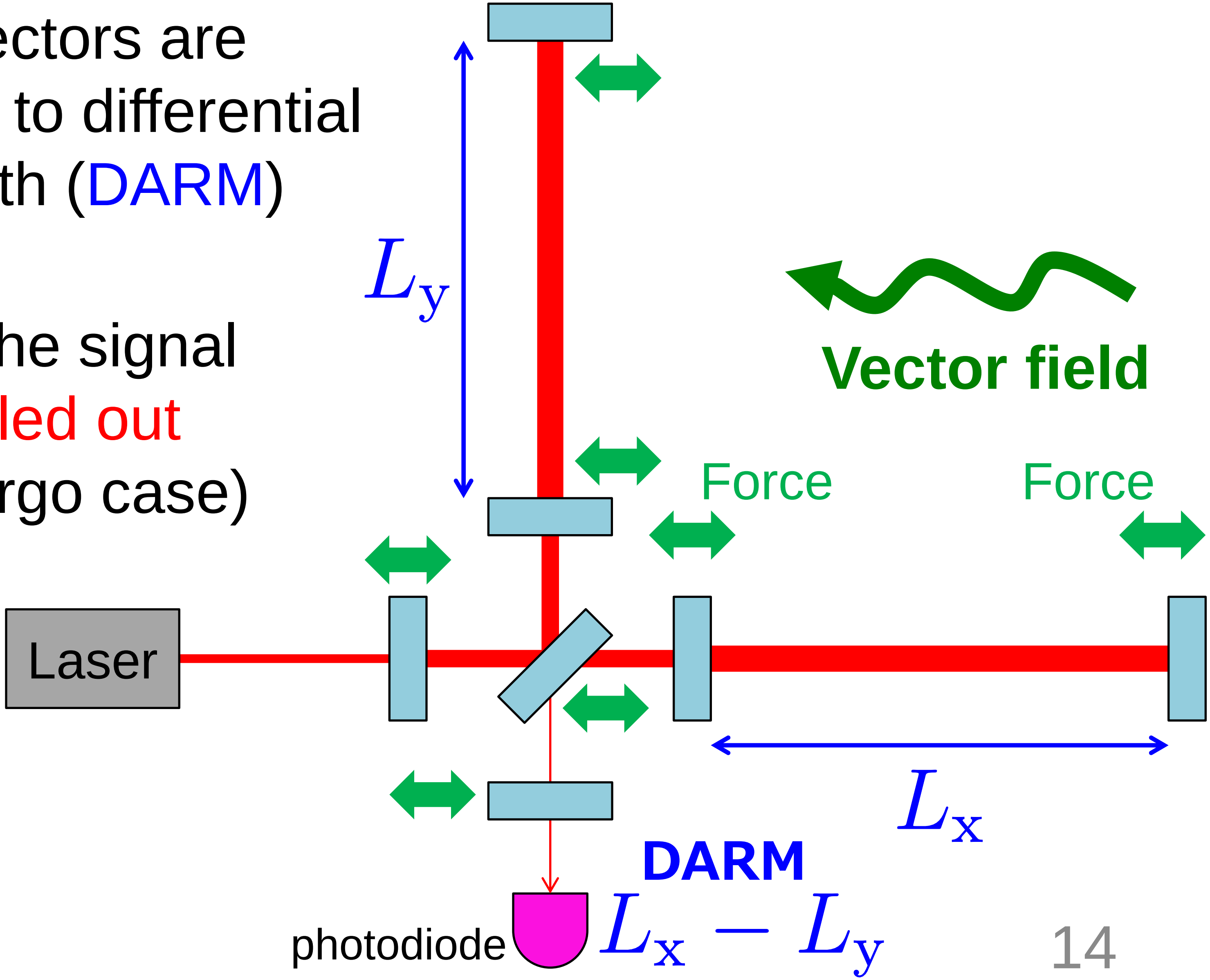
  H-K Guo+, Communications Physics **2**, 155 (2019)
  LIGO, Virgo, KAGRA Collaboration, PRD **105**, 063030 (2022)

- Better constraint than equivalence principle tests
- Even better constraint could be obtained from KAGRA



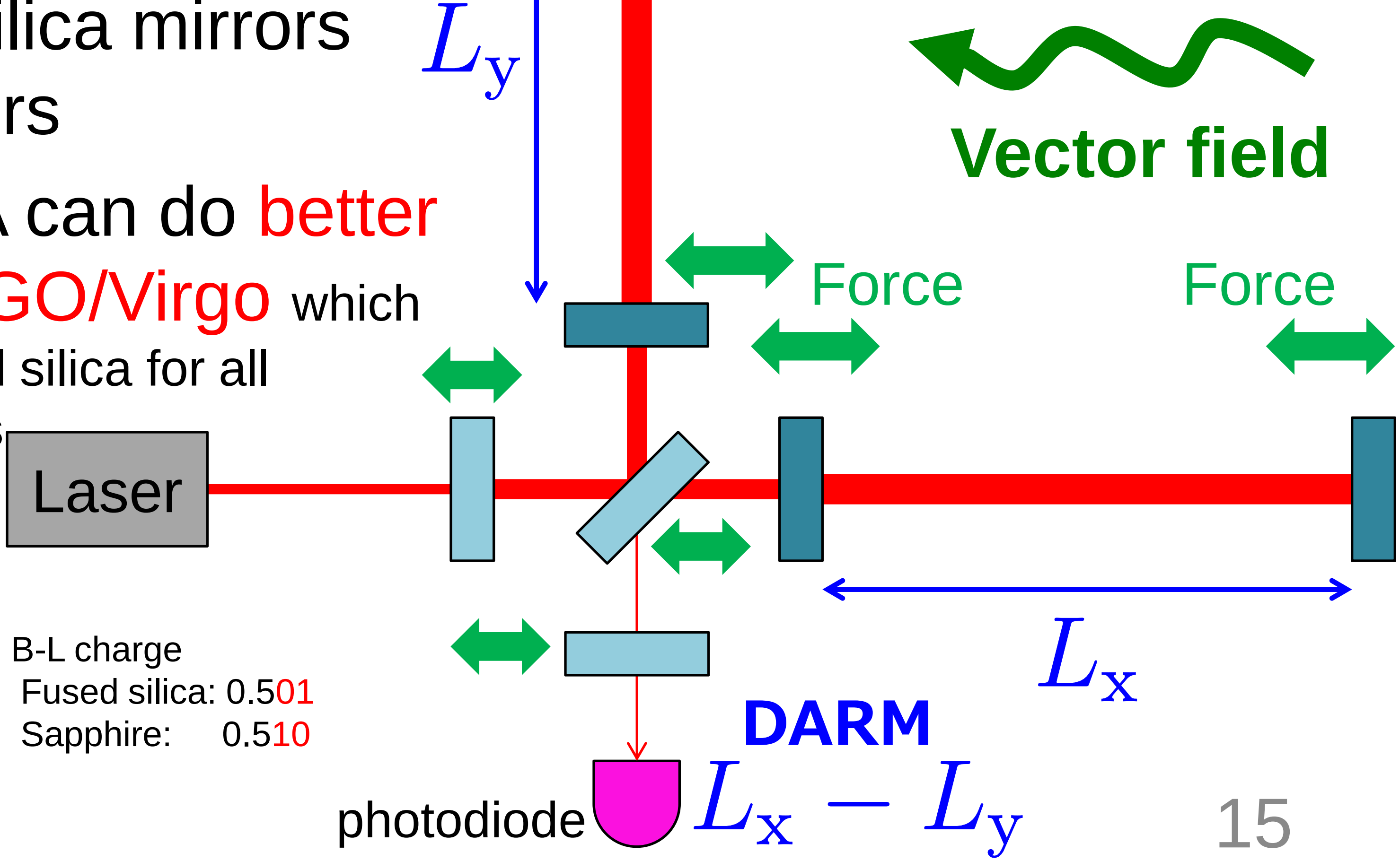
Search with GW Detectors

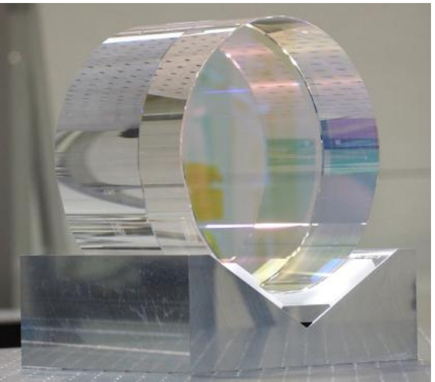
- GW Detectors are sensitive to differential arm length (DARM) change
- Most of the signal is cancelled out (LIGO/Virgo case)



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

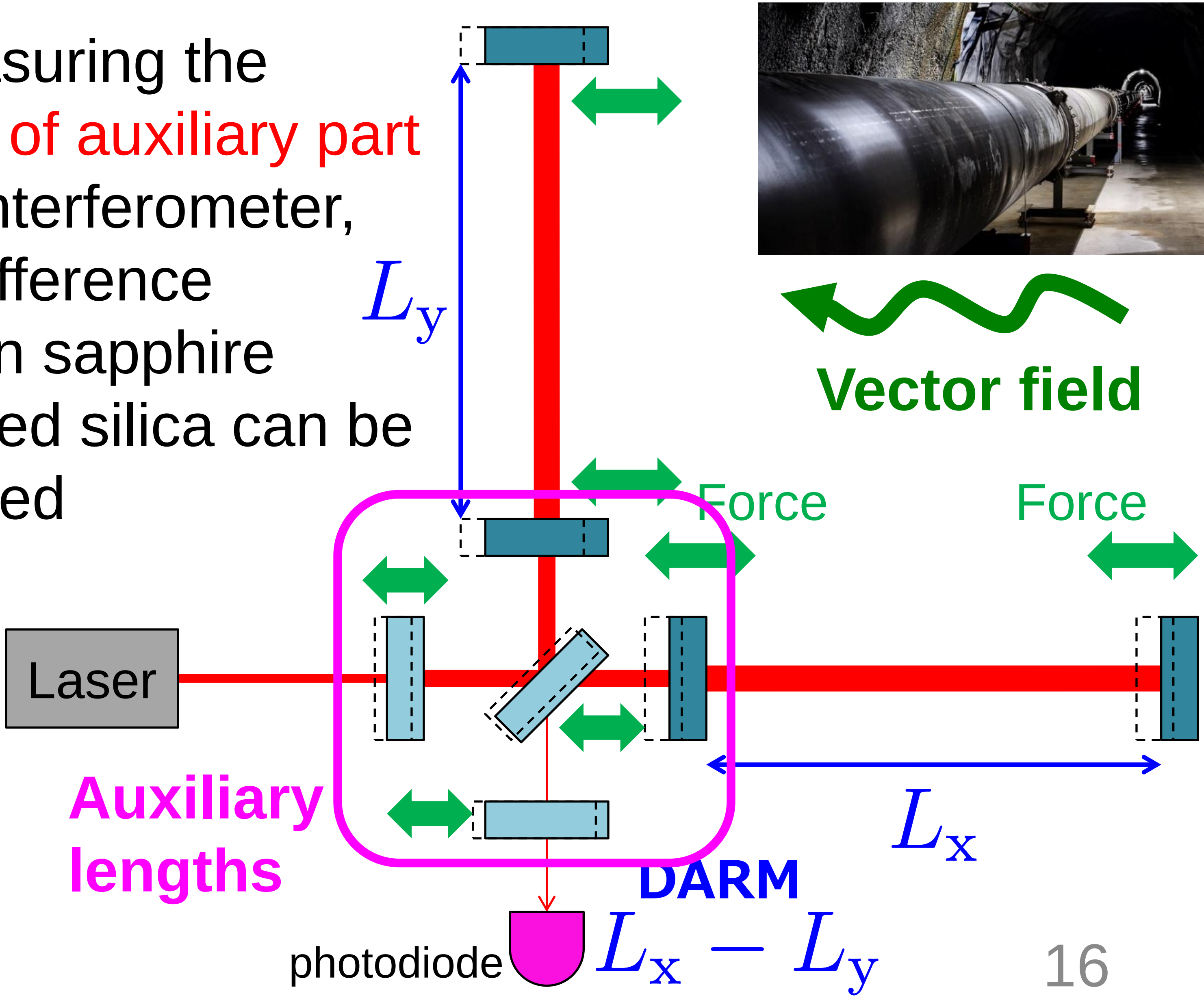


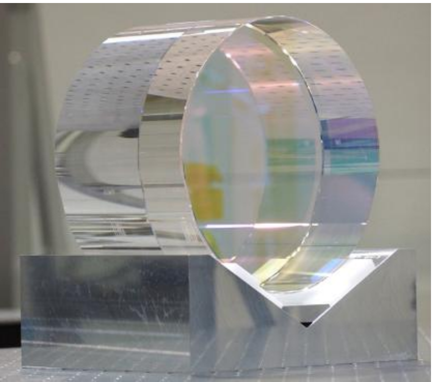


B-L charge
Fused silica: 0.501
Sapphire: 0.510

Search with KAGRA

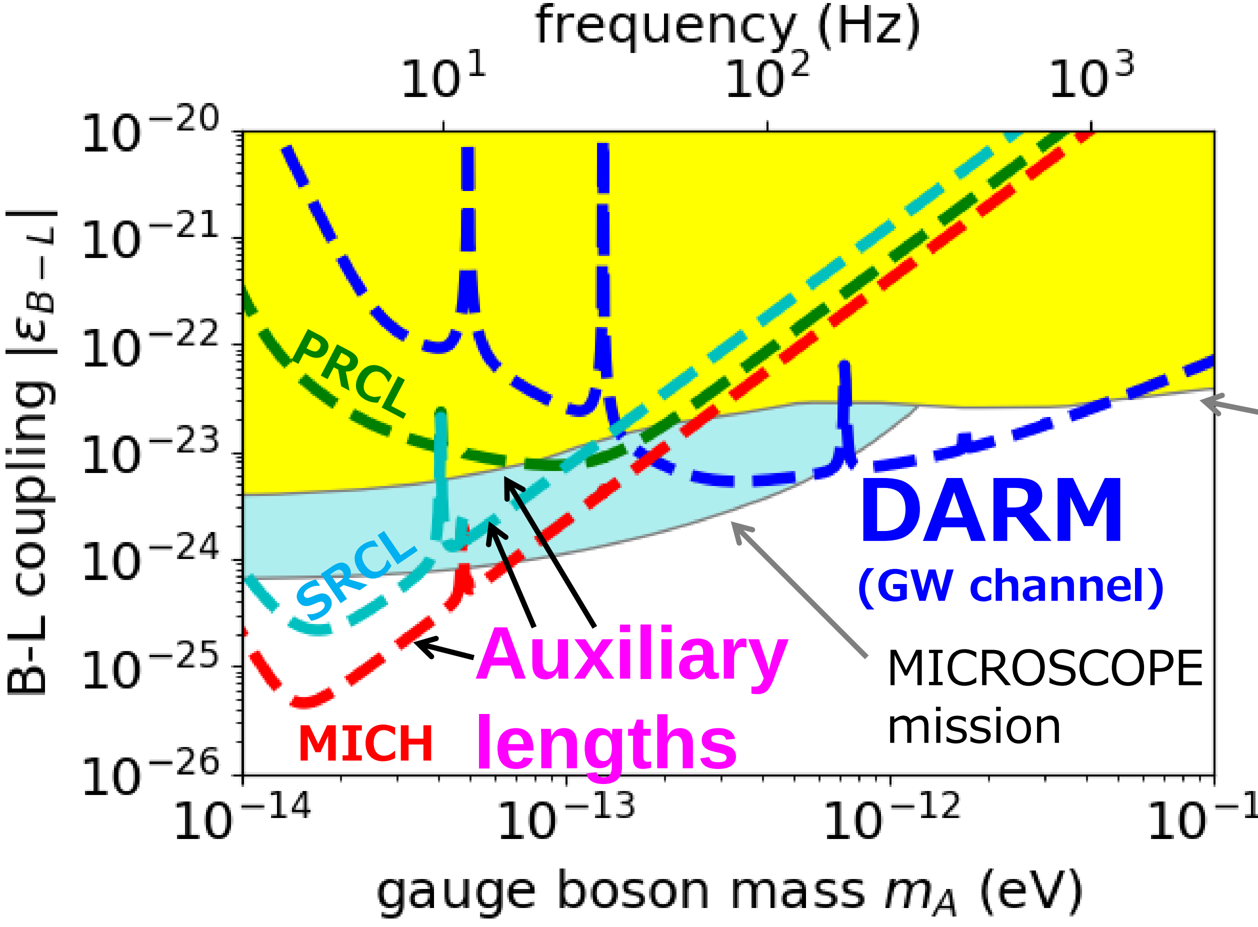
- By measuring the lengths of auxiliary part of the interferometer, force difference between sapphire and fused silica can be measured





KAGRA Vector DM Sensitivity

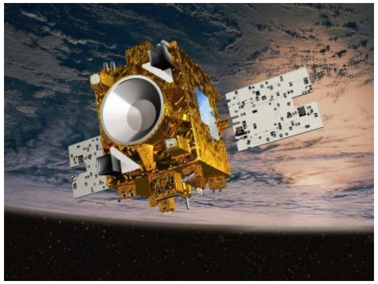
- Auxiliary length channels have better design sensitivity than DARM (GW channel) at low mass range
- Sensitivity better than equivalence principle tests



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

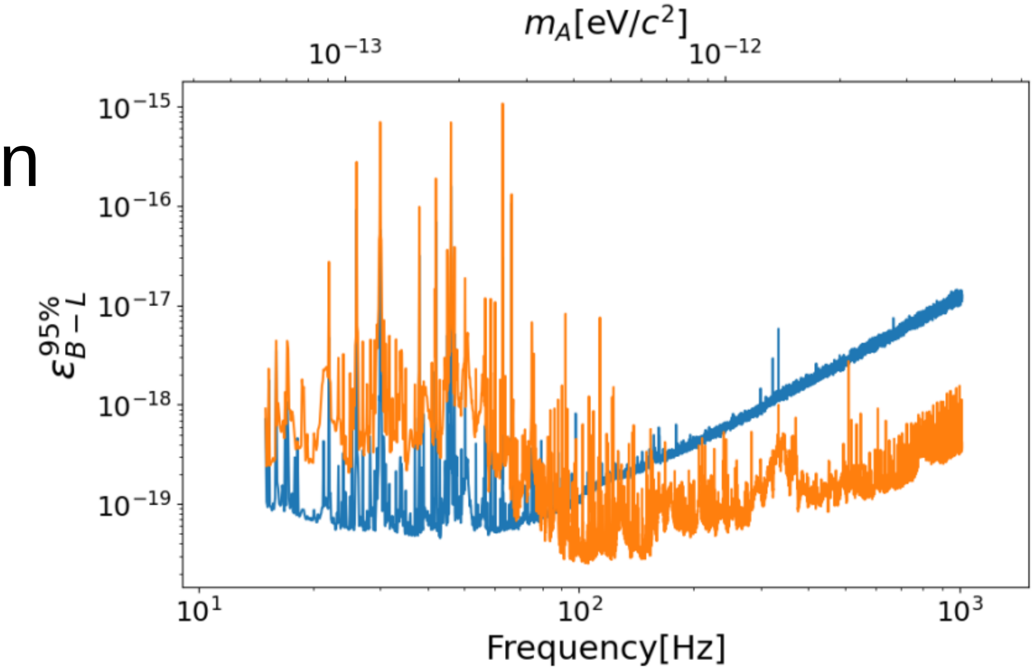
S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata, PRD 103, L051702 (2021)

Eöt-Wash torsion pendulum



KAGRA First Results from KAGRA

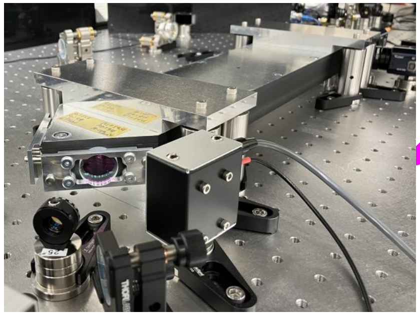
- Using data from KAGRA O3GK run in 2020
- Still ~5 orders of magnitude worse than equivalence principle tests
- Demonstrated the feasibility of using auxiliary channels for astrophysics
- New data will be available from O4b (~June 2025) and beyond



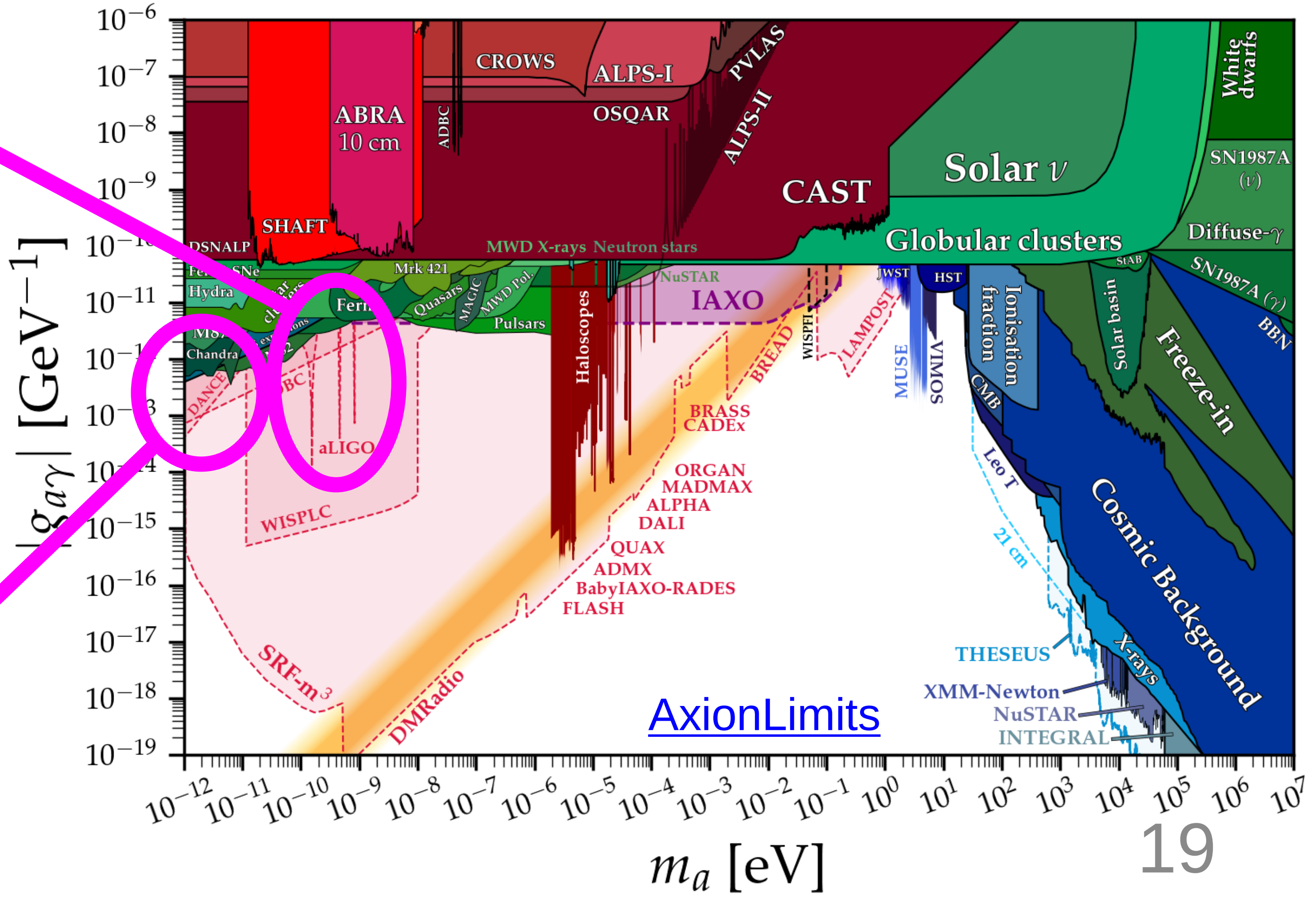
LIGO-Virgo-KAGRA, PRD **110**, 042001 (2024)
(Paper written by J. Kume with 1800 authors!)

Axion Dark Matter

- Many experiments to search for ALPs through axion-photon coupling, especially by using magnetic fields (but **ours don't**)



DANCE



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

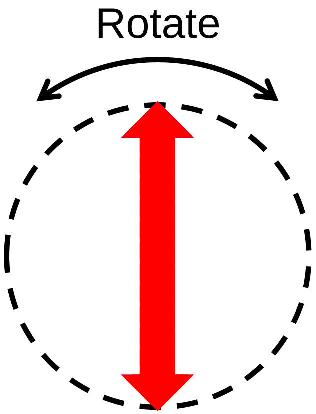
$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

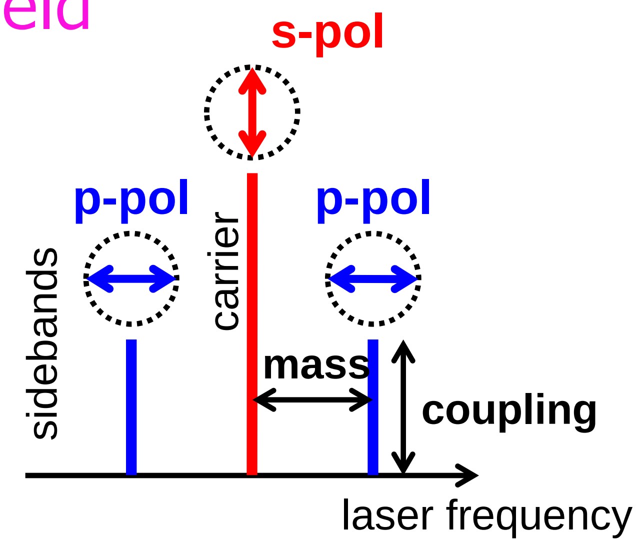
coupling constant

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

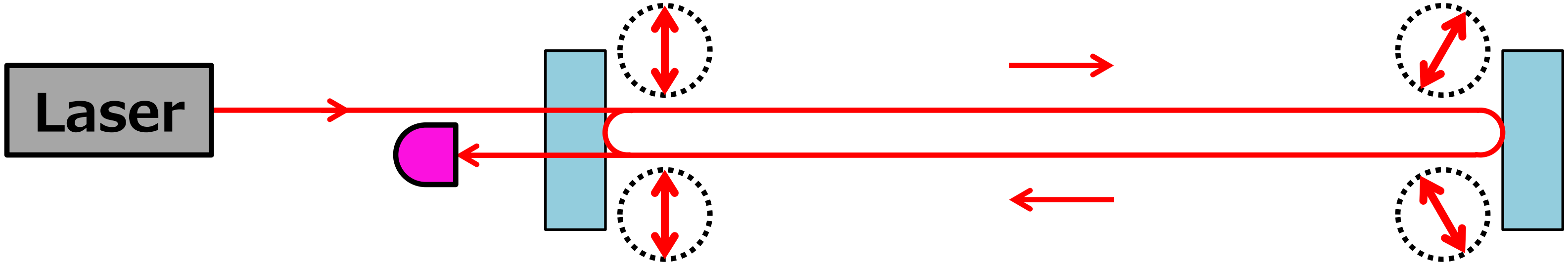




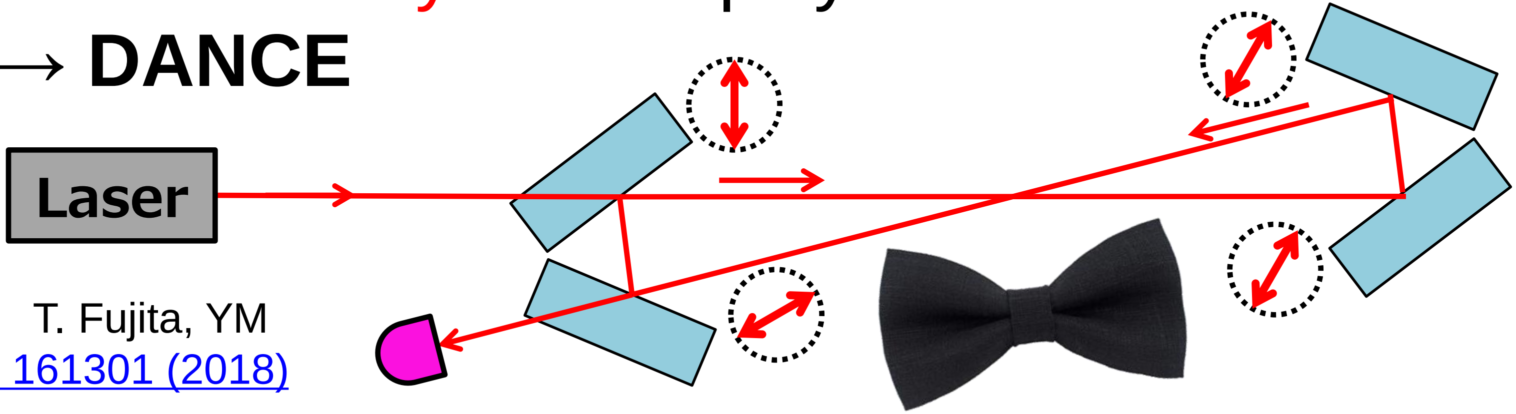
Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

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



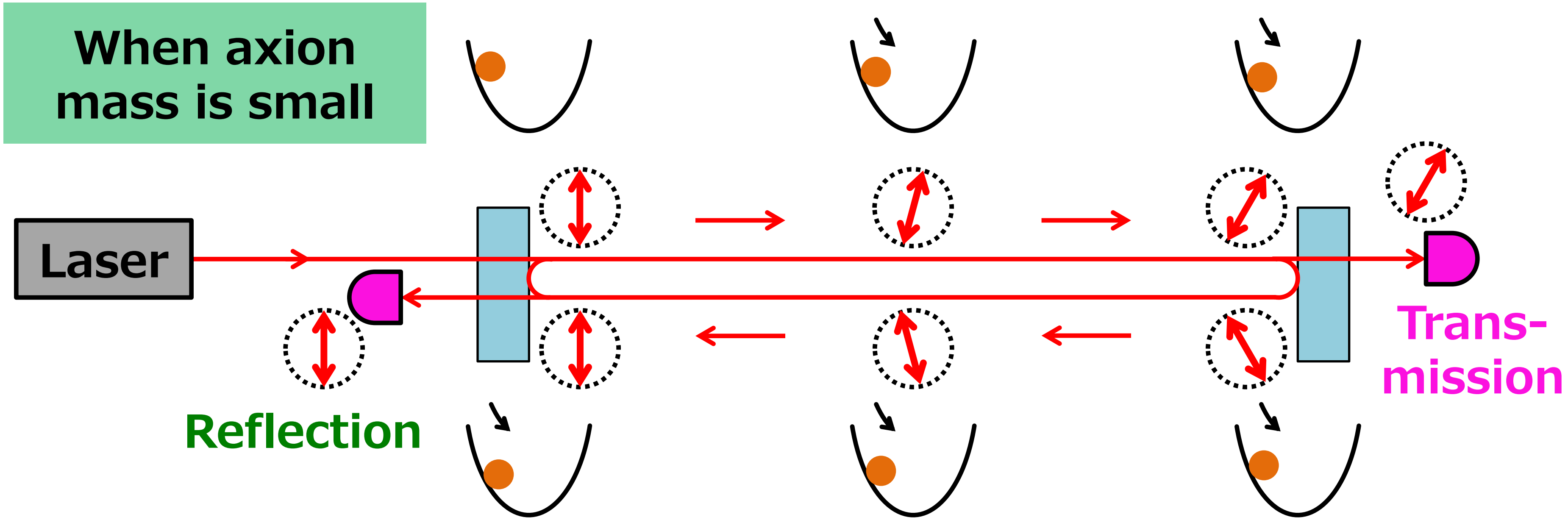
- Bow-tie cavity can amplify the rotation
  → **DANCE**



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

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



Linear Cavities for Axion Search

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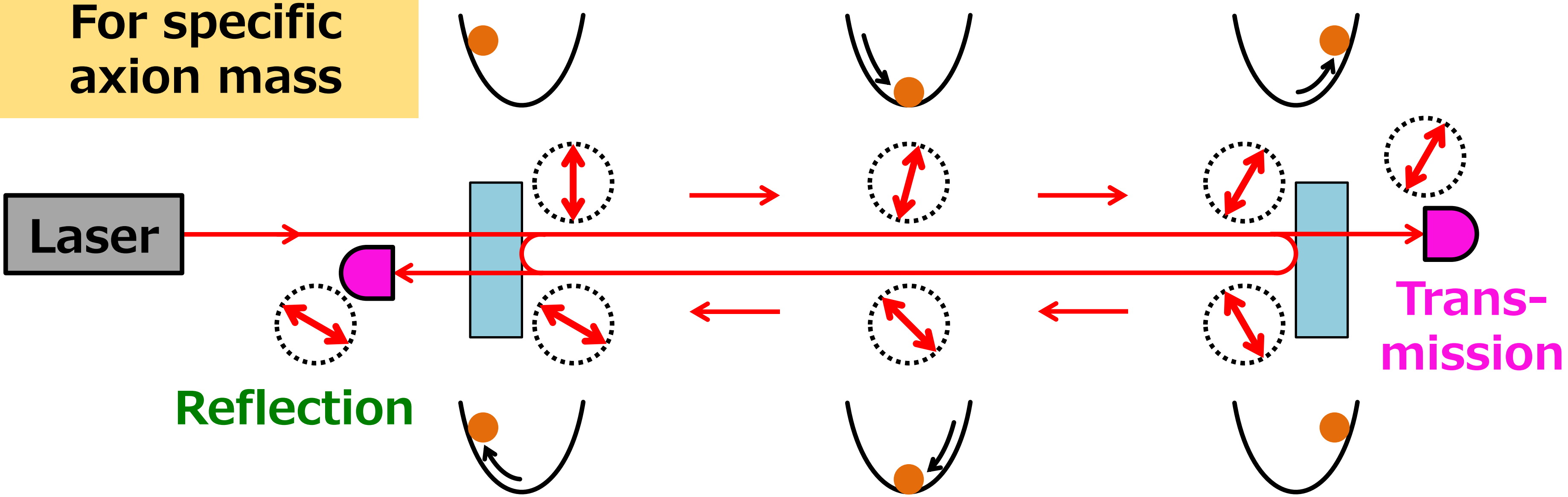
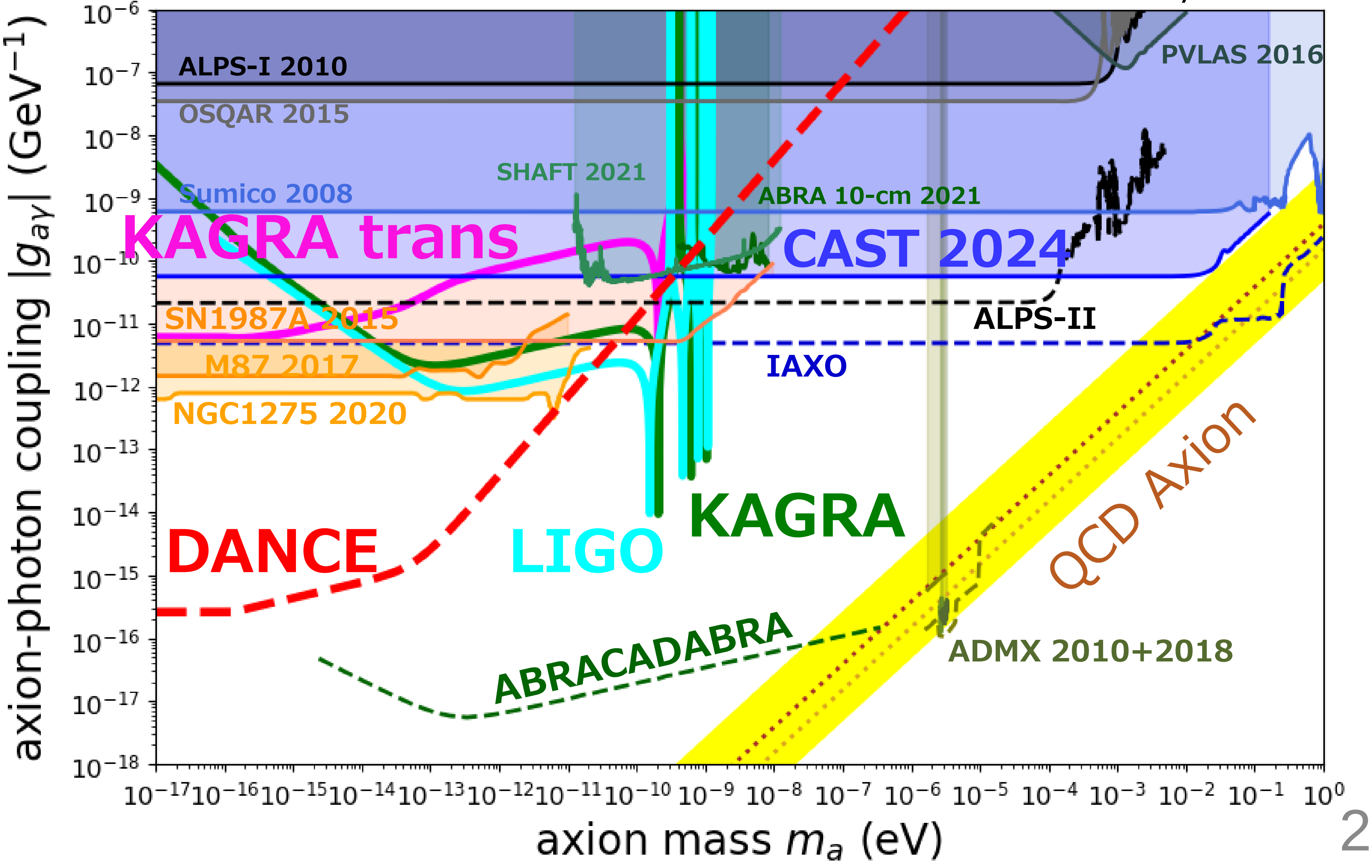
For specific axion mass



Estimated Reach

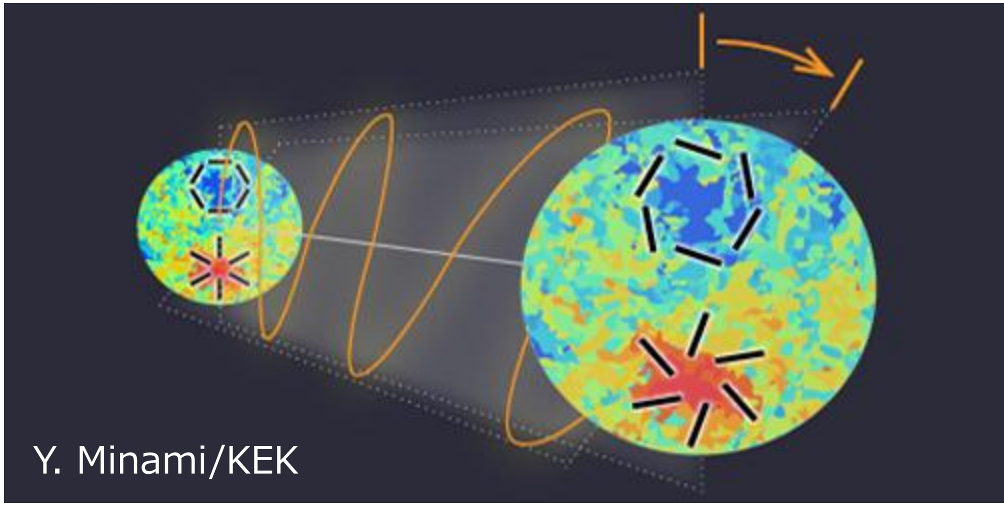
- Better than CAST below 10^{-10} eV

* Shot noise limited,
1-year observation

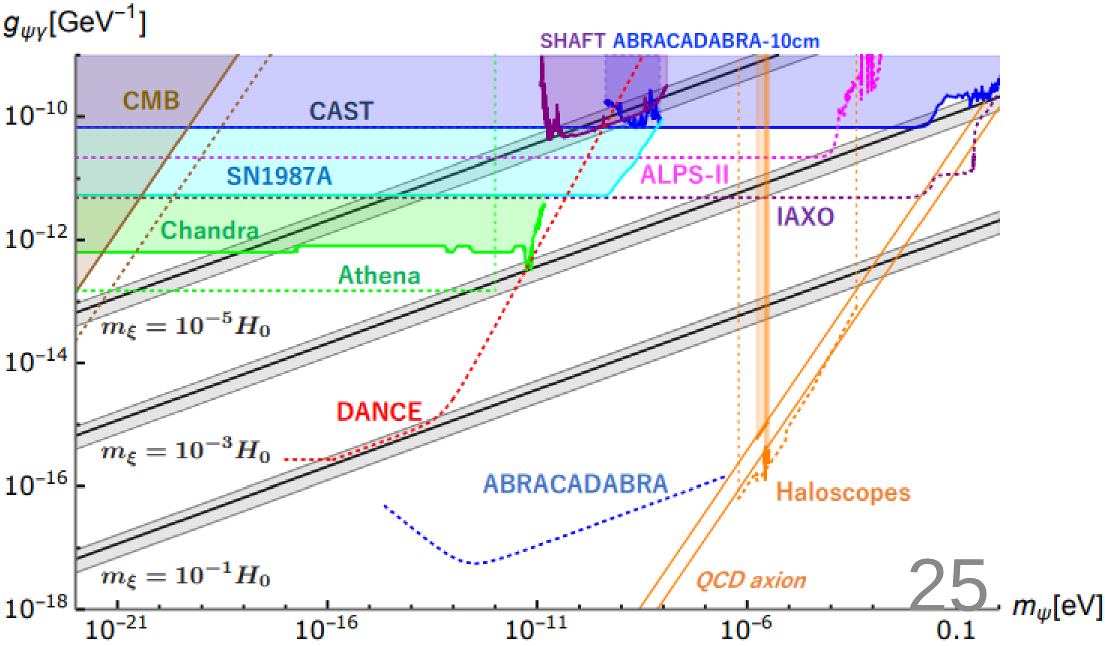


Relationship with Cosmic Birefringence

- Same principle
- Two-axion model can explain both cosmic birefringence and dark matter in the mass range of DANCE and GW detectors

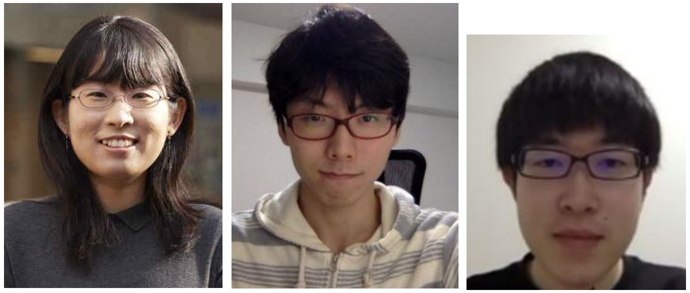


Y. Minami/KEK



I. Obata,
[JCAP **09**, 062 (2022)]

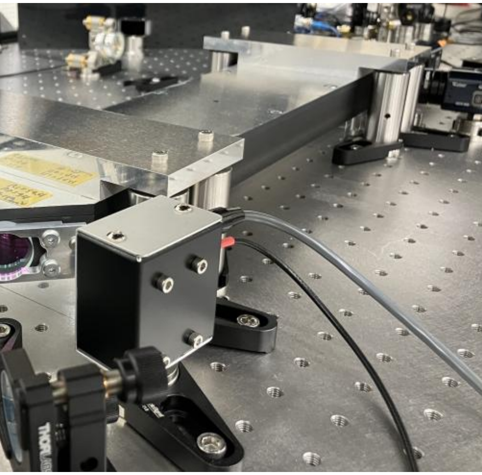
Status of DANCE

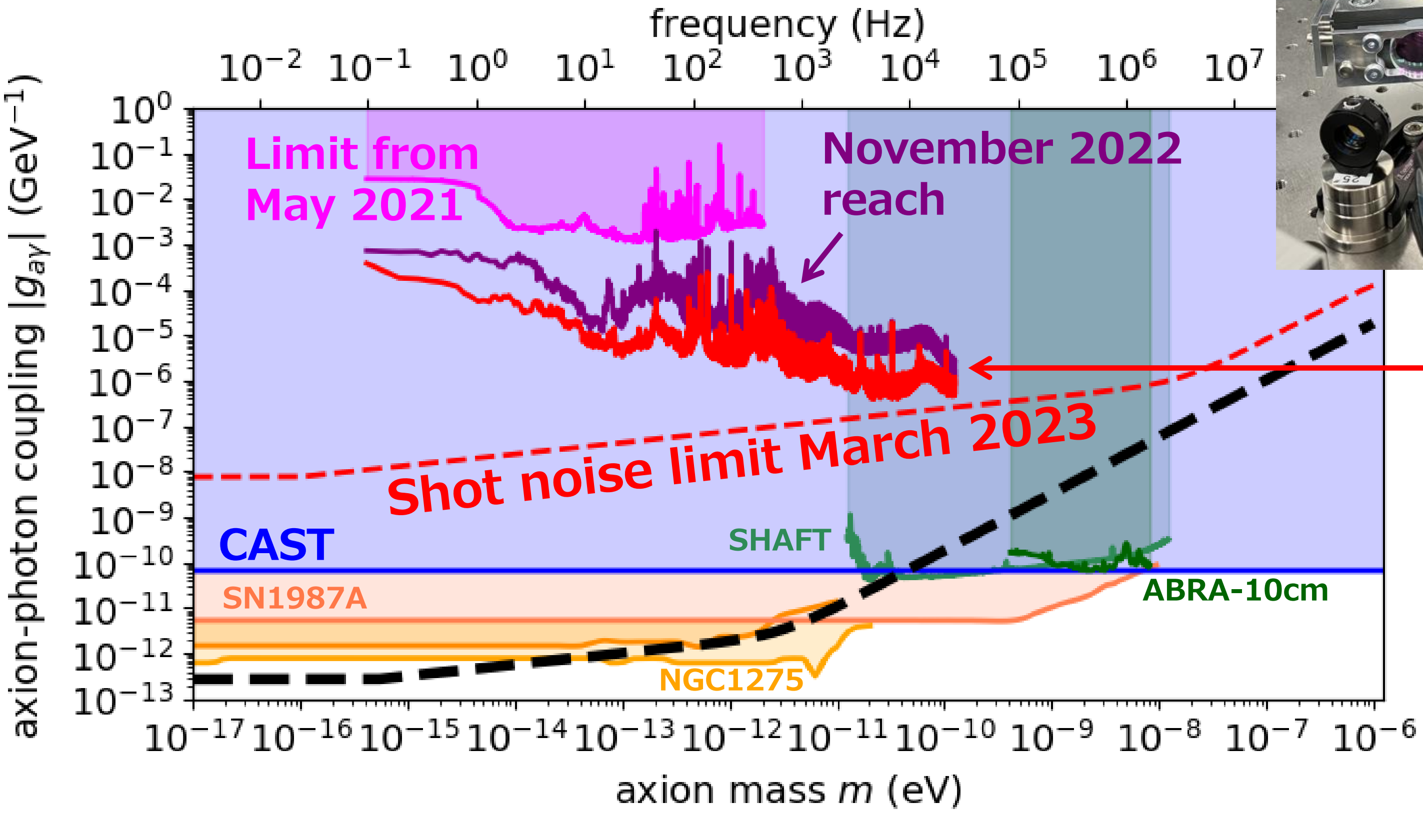


- First result from May 2021 run

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

- Major upgrade using wavelength tunable laser ongoing

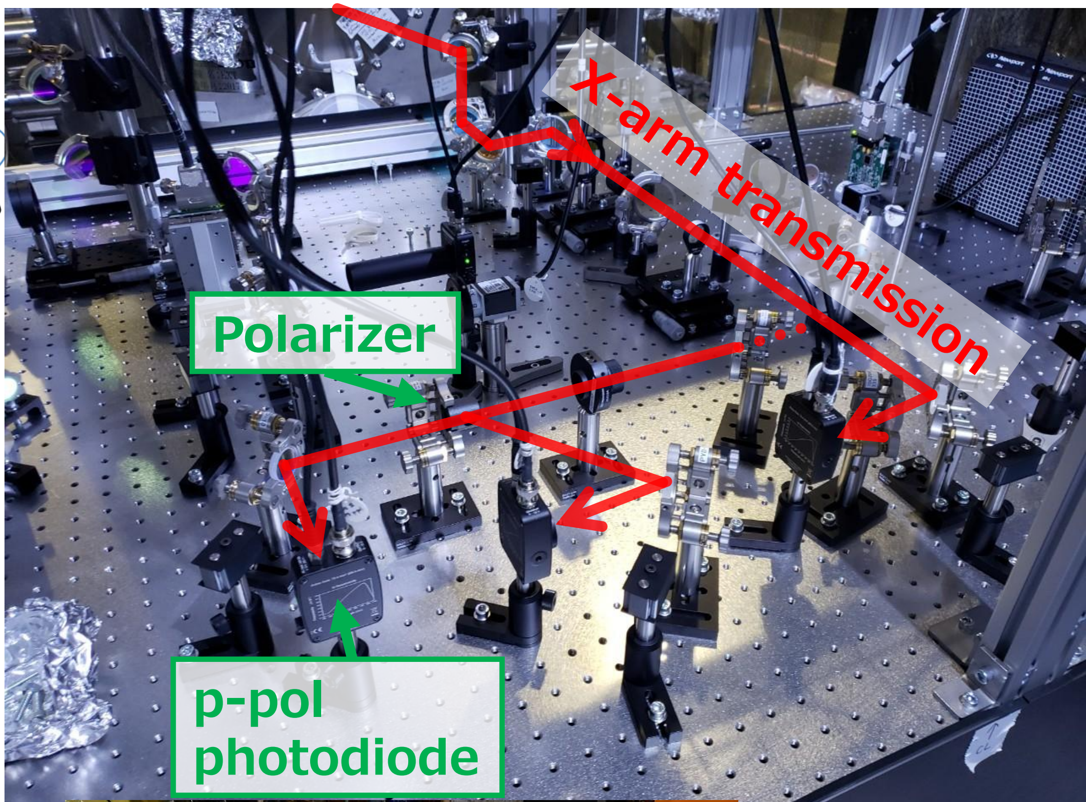


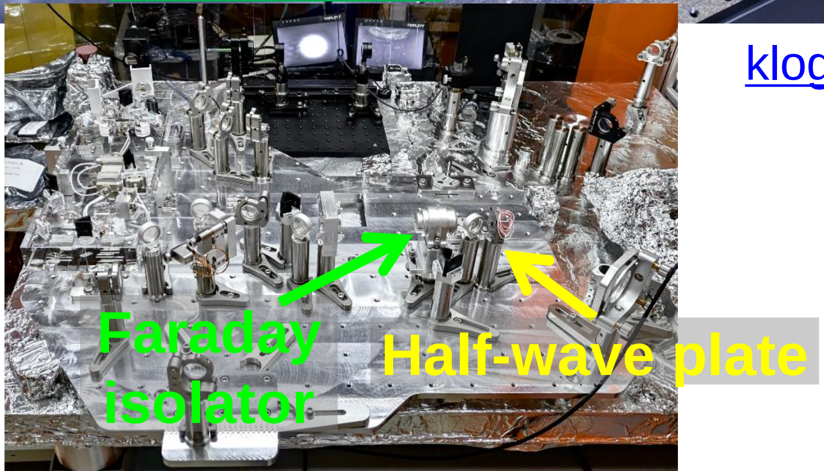


Estimated reach with sensitivity in March 2023
(assuming 1-year observation)

Axion Search with GW Detectors

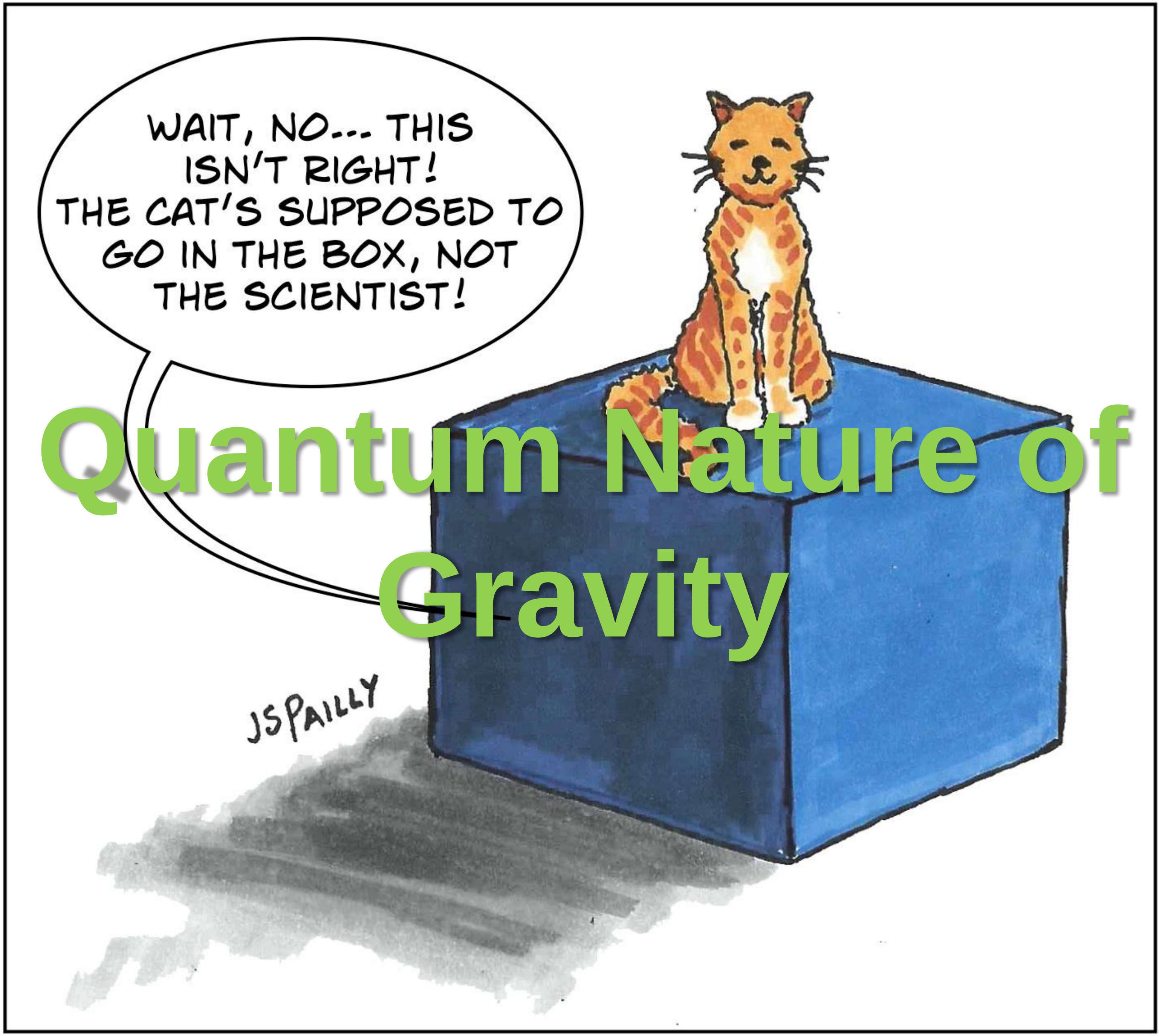
- Polarization optics installed in KAGRA transmission in 2021
  - First data taking from June 2025
- Prototype experiment using **Caltech 40m interferometer** also ongoing to test calibration methods





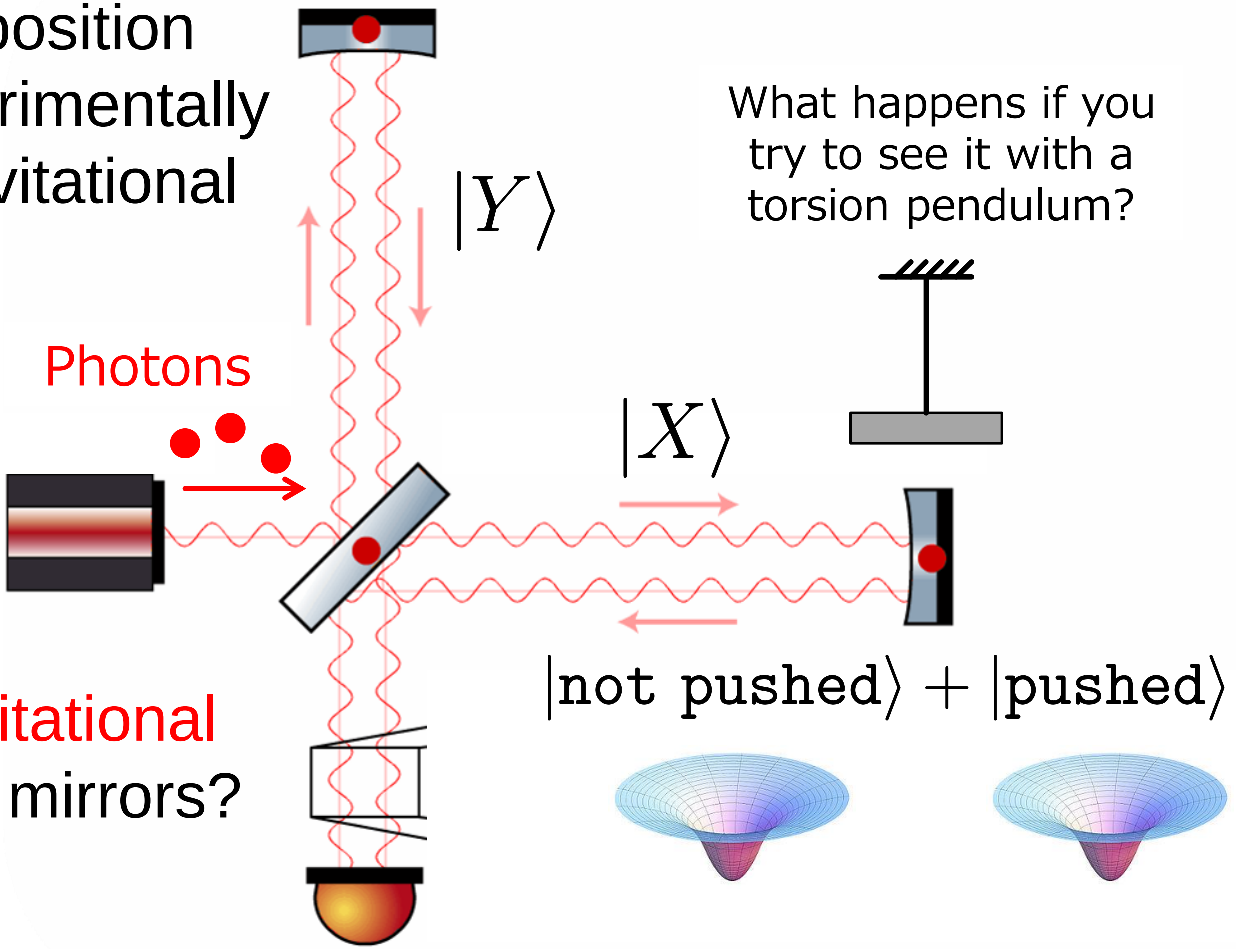
klog #17692

Quantum Nature of Gravity



Testing Quantum Nature of Gravity

- Photon going to X arm or Y arm is in quantum superposition
- Mirrors pushed or not pushed by radiation pressure is in quantum superposition (this is not experimentally verified yet; gravitational decoherence?)



Photons

$|Y\rangle$

$|X\rangle$

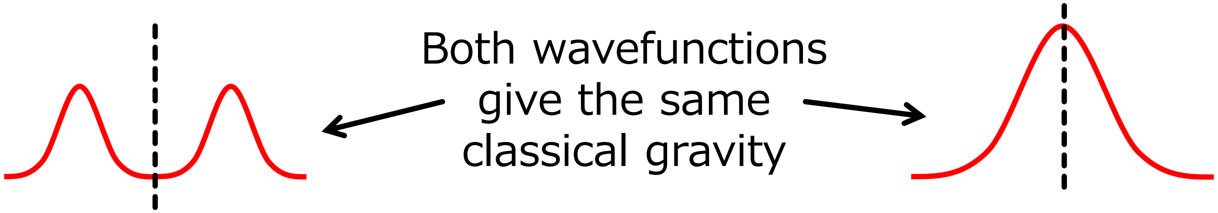
What happens if you try to see it with a torsion pendulum?

$|\texttt{not pushed}\rangle + |\texttt{pushed}\rangle$

- How about gravitational field of massive mirrors?

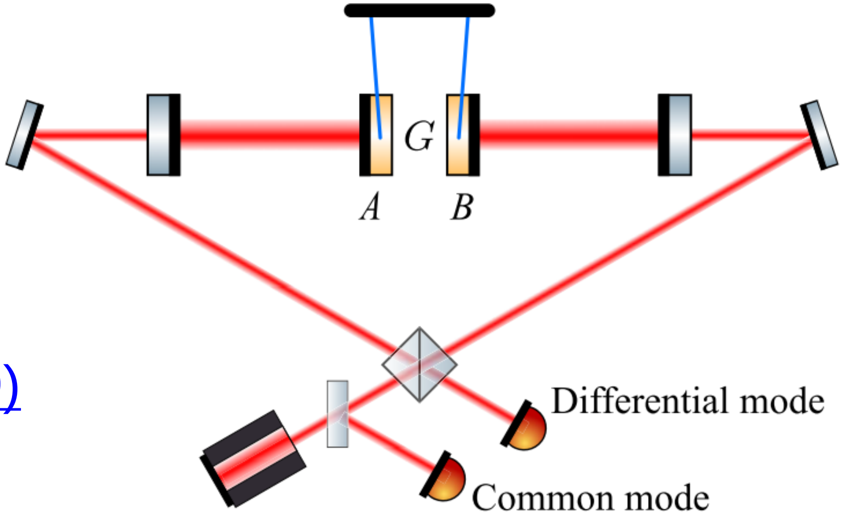
Semiclassical Gravity

- In semiclassical gravity (Schrödinger-Newton model), quantum matter is coupled to a classical gravitational field through expectation values



Both wavefunctions give the same classical gravity

- People have been proposing experiments to falsify this
- For example, through gravity-induced entanglement

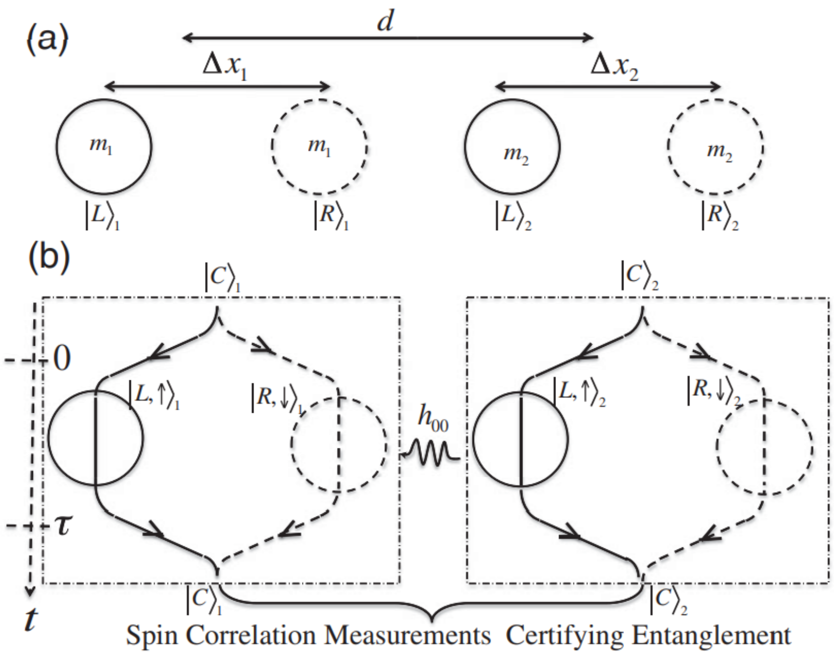


- For review, see
  D. Carney+, CQG **36**, 034001 (2019)
- Also, see
  H. Miao+, PRA **101**, 063804 (2020)
  A. Datta & H. Miao, Quantum Science and Technology 6, 045014 (2021)

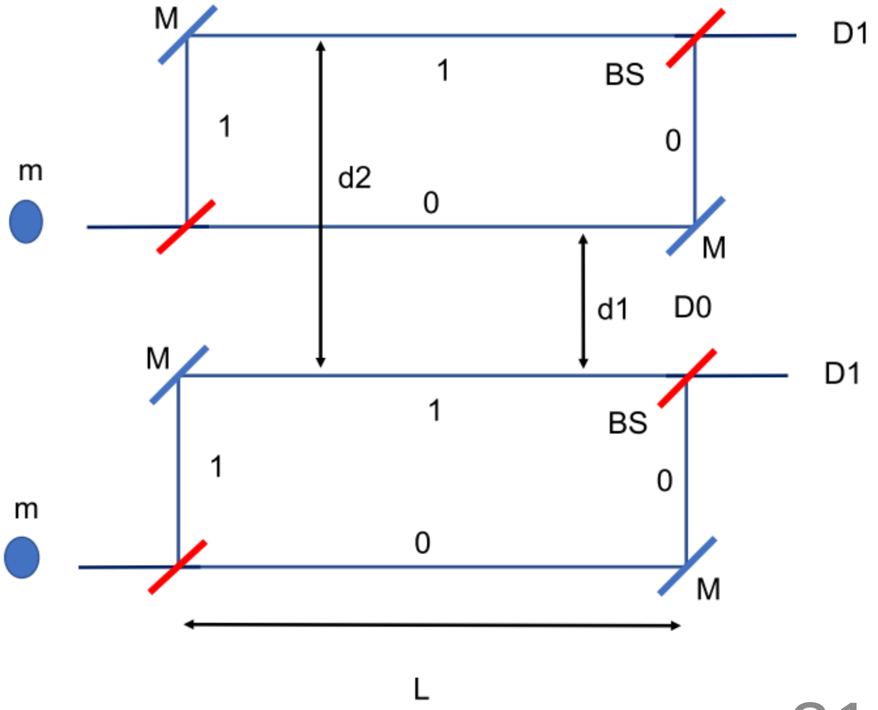
BMV Experiment Proposals

- Gravity-induced entanglement can be tested with adjacent matter interferometers

S. Bose+,
Phys. Rev. Lett. 119, 240401 (2017)

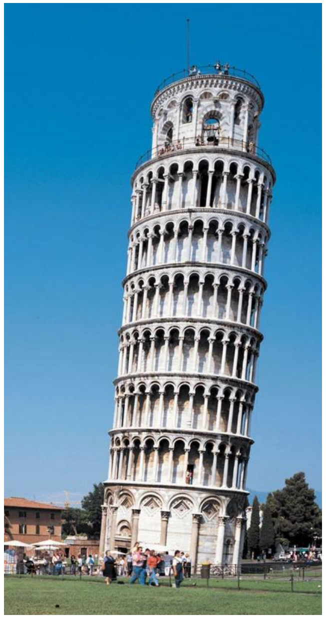


C. Marletto & V. Vedral,
Phys. Rev. Lett. 119, 240402 (2017)



Decoherence and Free-Fall Time

- Decoherence estimates suggest
  T < 1 K and P < 10^{-16} Pa are required
- Also, free-fall time and height are in the orders of ~1 sec and ~10 m
- Sounds tough…



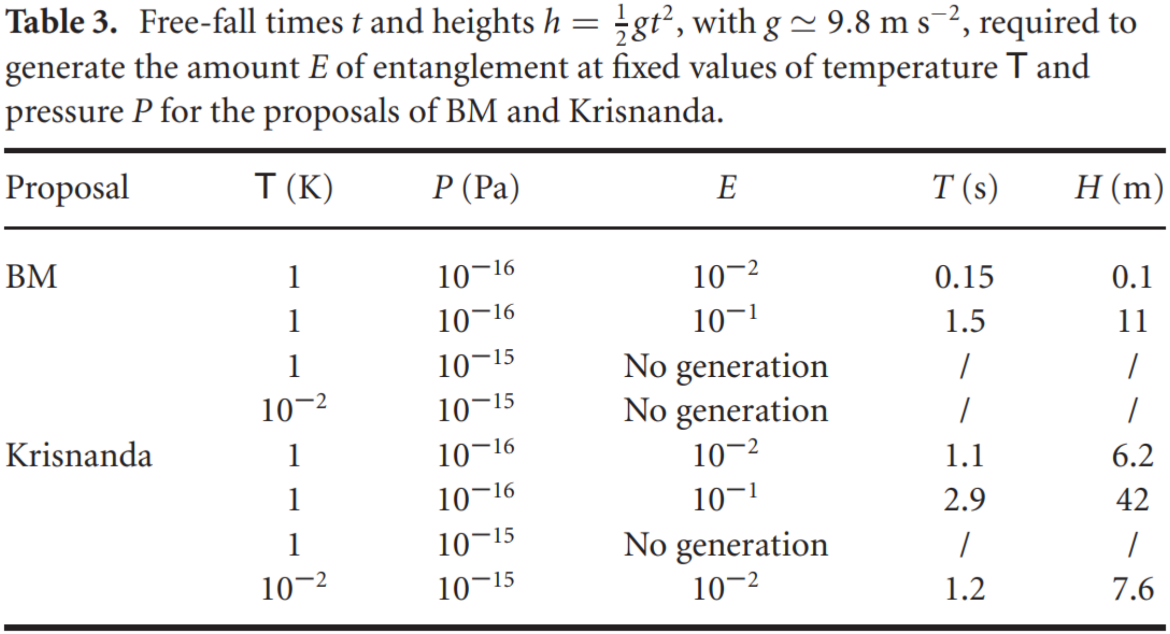


Table 3. Free-fall times t and heights $h = \frac{1}{2}gt^2$, with $g \simeq 9.8$ m s^{-2}, required to generate the amount E of entanglement at fixed values of temperature T and pressure P for the proposals of BM and Krisnanda.

Proposal	T (K)	P (Pa)	E	T (s)	H (m)
BM	1	10^{-16}	10^{-2}	0.15	0.1
	1	10^{-16}	10^{-1}	1.5	11
	1	10^{-15}	No generation	/	/
	10^{-2}	10^{-15}	No generation	/	/
Krisnanda	1	10^{-16}	10^{-2}	1.1	6.2
	1	10^{-16}	10^{-1}	2.9	42
	1	10^{-15}	No generation	/	/
	10^{-2}	10^{-15}	10^{-2}	1.2	7.6

S. Rijavec+, New J. Phys. **23**, 043040 (2021)

What is the Best Oscillator?

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

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

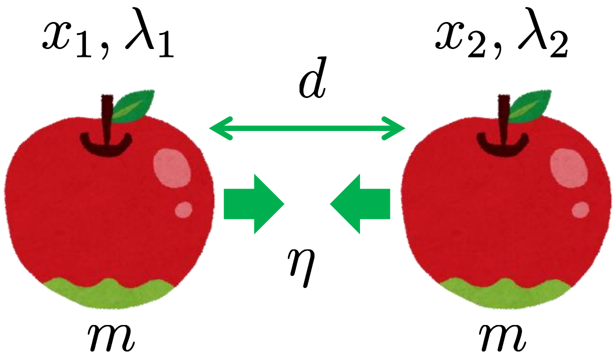
Distance between masses

$$= \frac{\omega}{2} \left[\sum_{i=1,2} (P_i + \lambda_i X_i^2) + \eta (x_1 - x_2)^2 \right]$$

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

Strength of gravitational coupling

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



T. Fujita, Y. Kaku, A. Matsumura, YM, arXiv:2308.14552

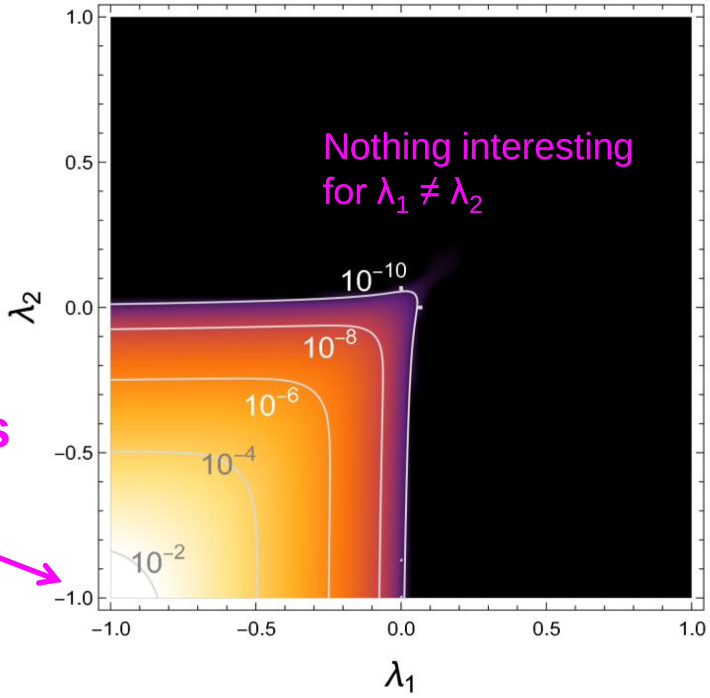
Inverted Oscillators are the Best

- 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

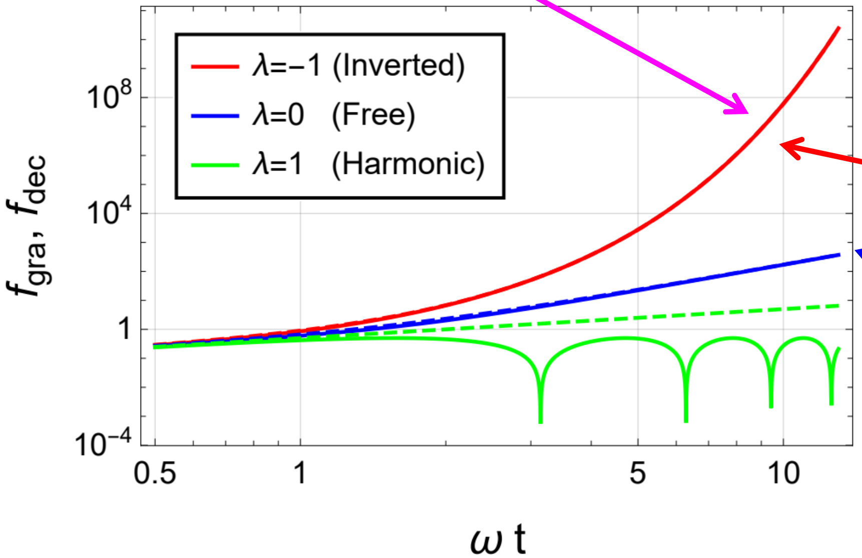
Amount of decoherence



Nothing interesting for $\lambda_1 \neq \lambda_2$

Exponential growth of entanglement

Inverted oscillators are the best



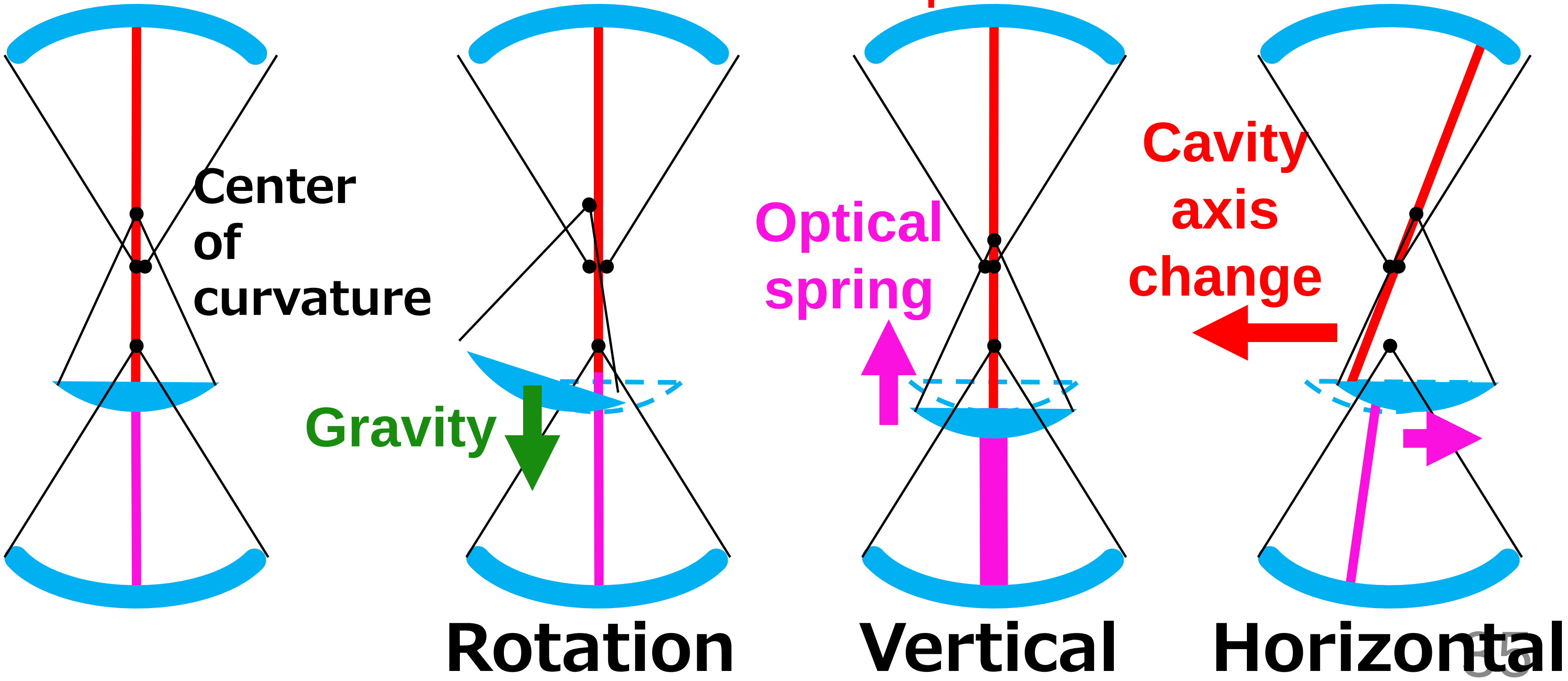
$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8}e^{2\omega t}$$

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

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

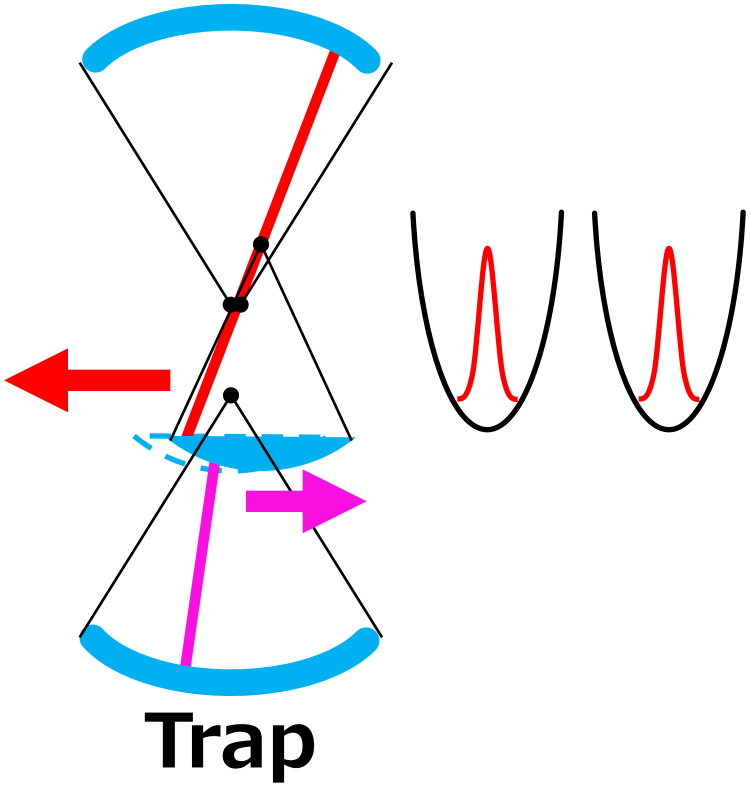
Preparing Inverted Oscillators

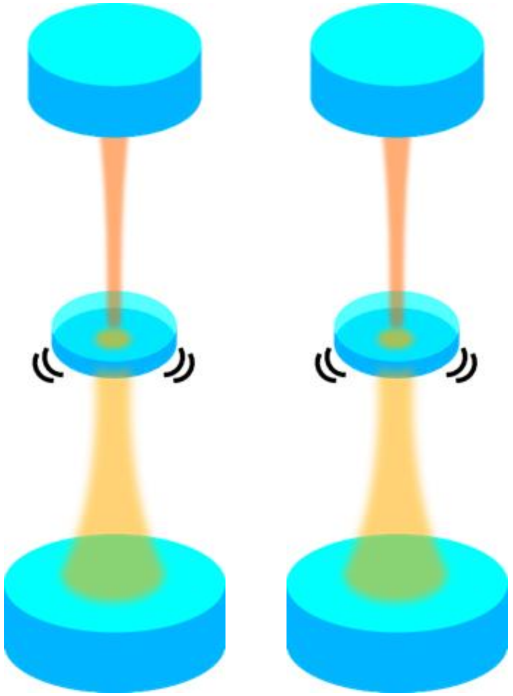
- Sandwich configuration for trapping a mirror all optically
  YM, Y. Kuwahara+, [Optics Express 25, 13799 (2017)]()
- Trap in horizontal motion demonstrated
  T. Kawasaki+, [PRA 102, 053520 (2020)]()
- Can also be used to anti-trap



Procedure to Switch the Trap

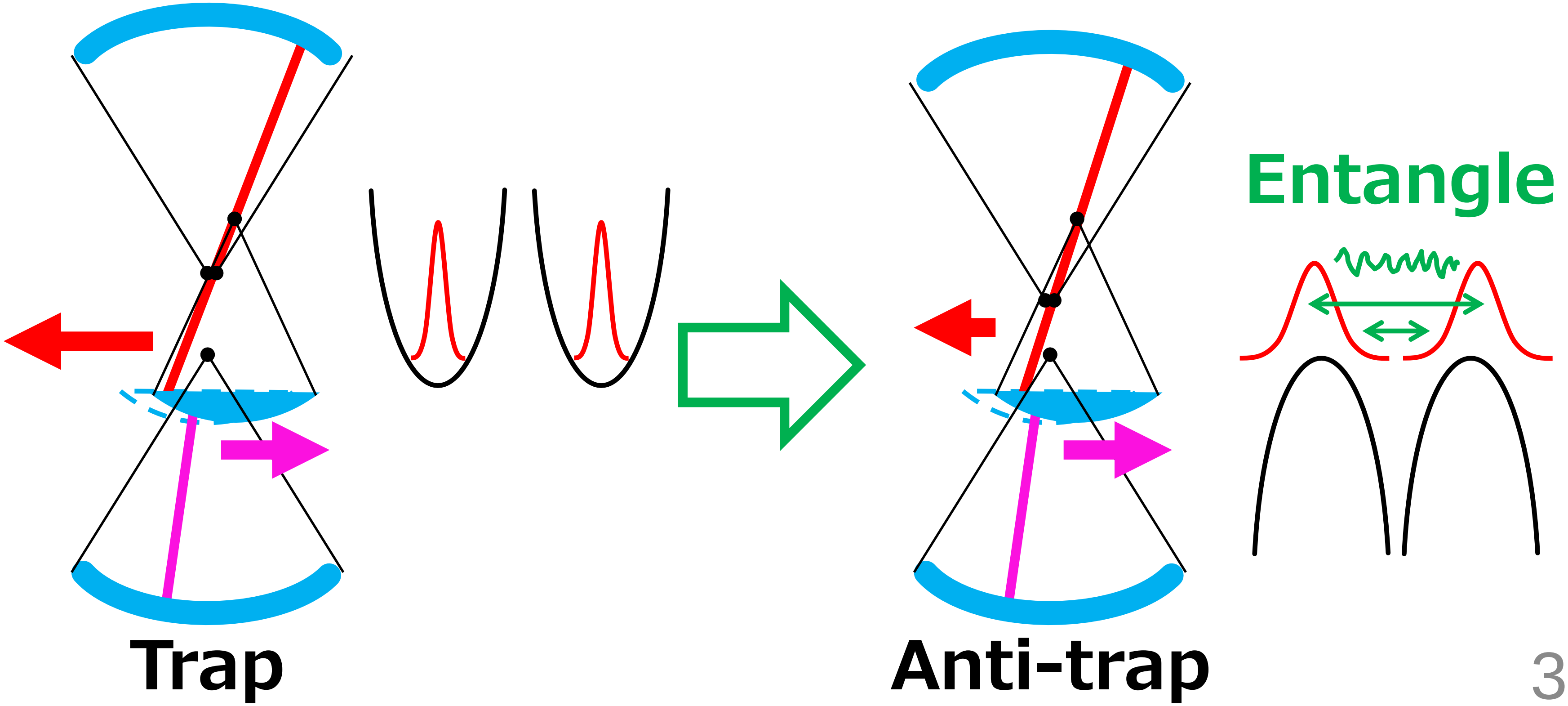
- First, trap strongly to prepare narrow wavefunctions





Procedure to Switch the Trap

- First, trap strongly to prepare narrow wavefunctions
- And then switch to anti-trap to broaden the wavefunction fast (this can be done by effectively switching the cavity geometry)



Example Setup

- ~1 kHz anti-spring for 0.1 mg mirror can be created with intra-cavity power of ~30 kW
- Time to generate $E_N = 10^{-2}$

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

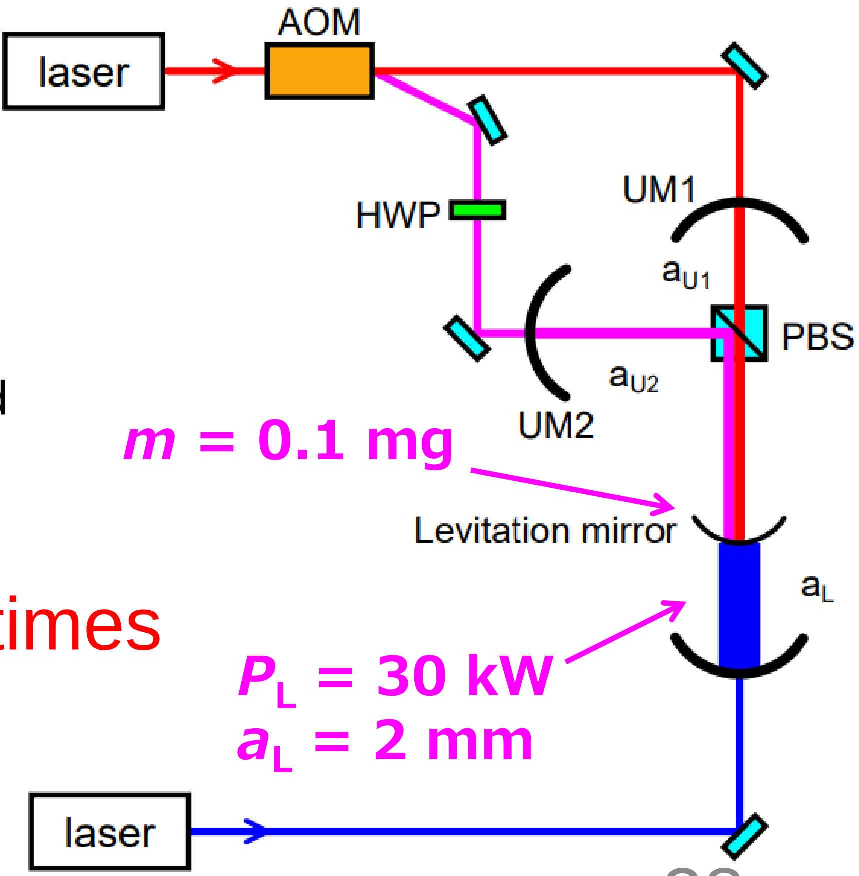
for free-fall

300 times faster

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

for inverted

- No free-fall necessary
- Can be repeated multiple times to improve statistics



***m* = 0.1 mg**

***P*$_L$ = 30 kW**

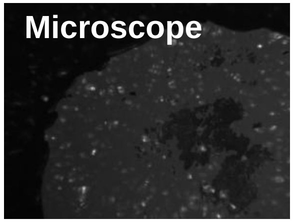
***a*$_L$ = 2 mm**

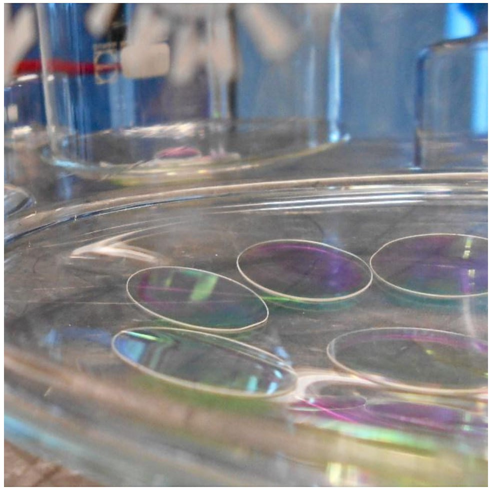
Status of the Levitation Experiment

- Fabrication of 0.1-1 mg scale mirror with a curvature is a challenge, and we are collaborating with LMA and ANU for mirror fabrication and characterization

LABORATOIRE MATÉRIAUX AVANCÉS

Australian National University

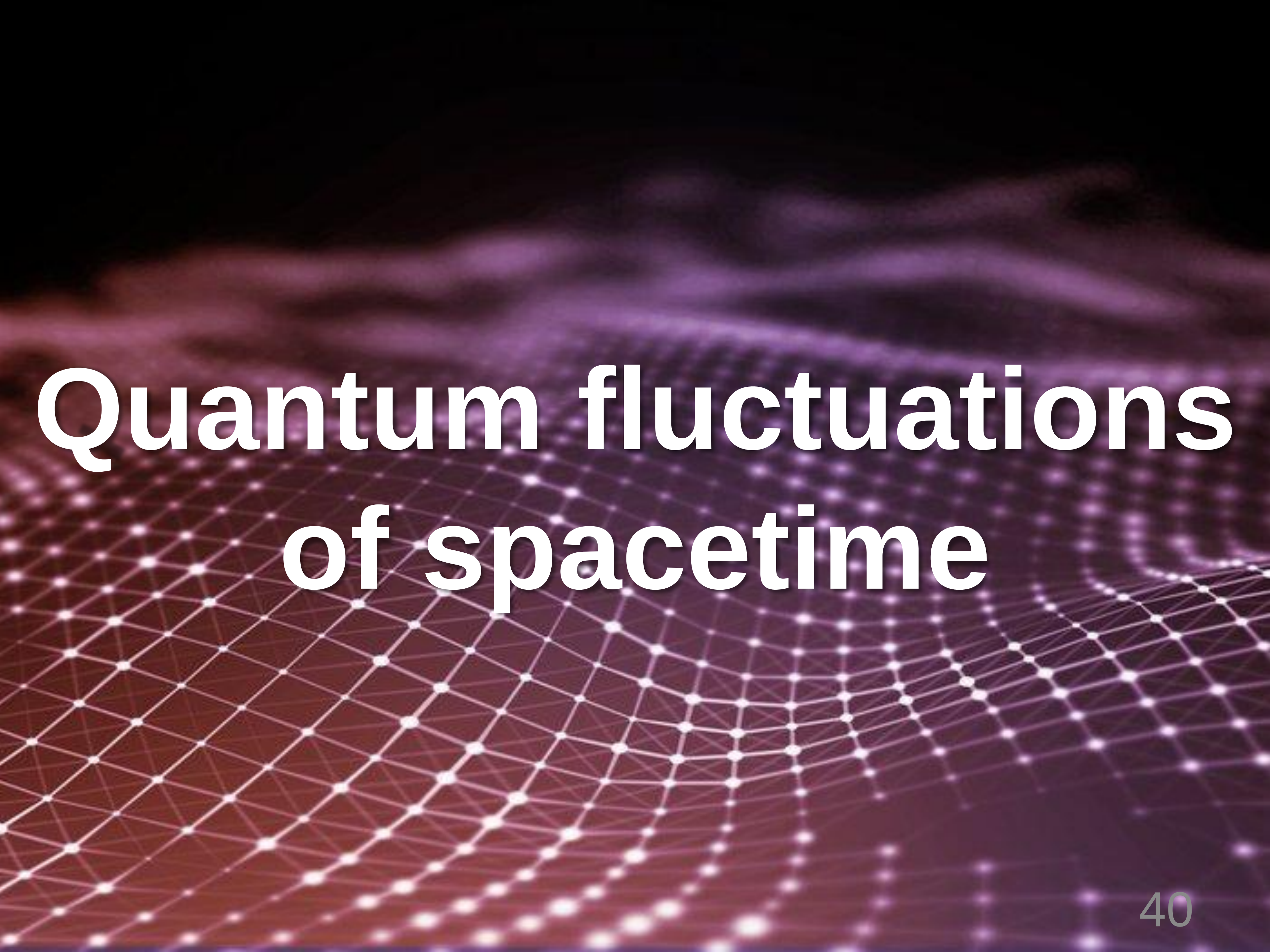




Coated 1-inch dia. 0.1 mm thick mirrors

Cut into 3 mm dia.

Characterization at UTokyo/ANU



Quantum fluctuations of spacetime

Quantum Fluctuations of Spacetime

- According to pixellon model (quantum gravity with a scalar field), length fluctuates with

$$\delta L^2 \sim \alpha l_{\rm p} L/(4\pi)$$

Planck length

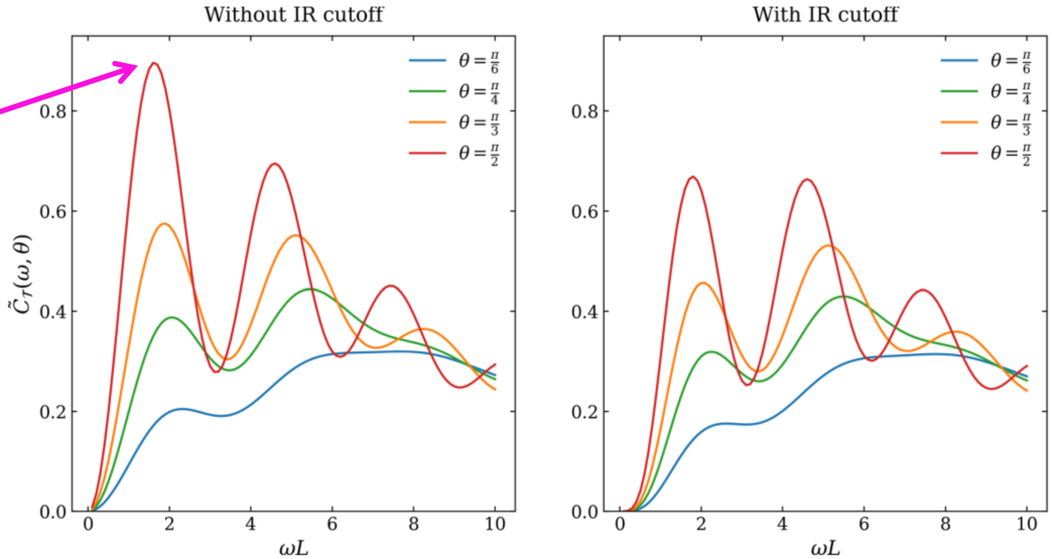
Arm length

not $\delta L \sim l_{\rm p}$

Verlinde & Zurek,
[PLB **822**, 136663 (2021)]
K. M. Zurek,
[arXiv:2205.01799]

- Parametrized by the power of noise α
(Natural benchmark $\alpha \sim 1$)

Displacement noise peaks at odd x c/(4L)
(~18.8 kHz for LIGO)

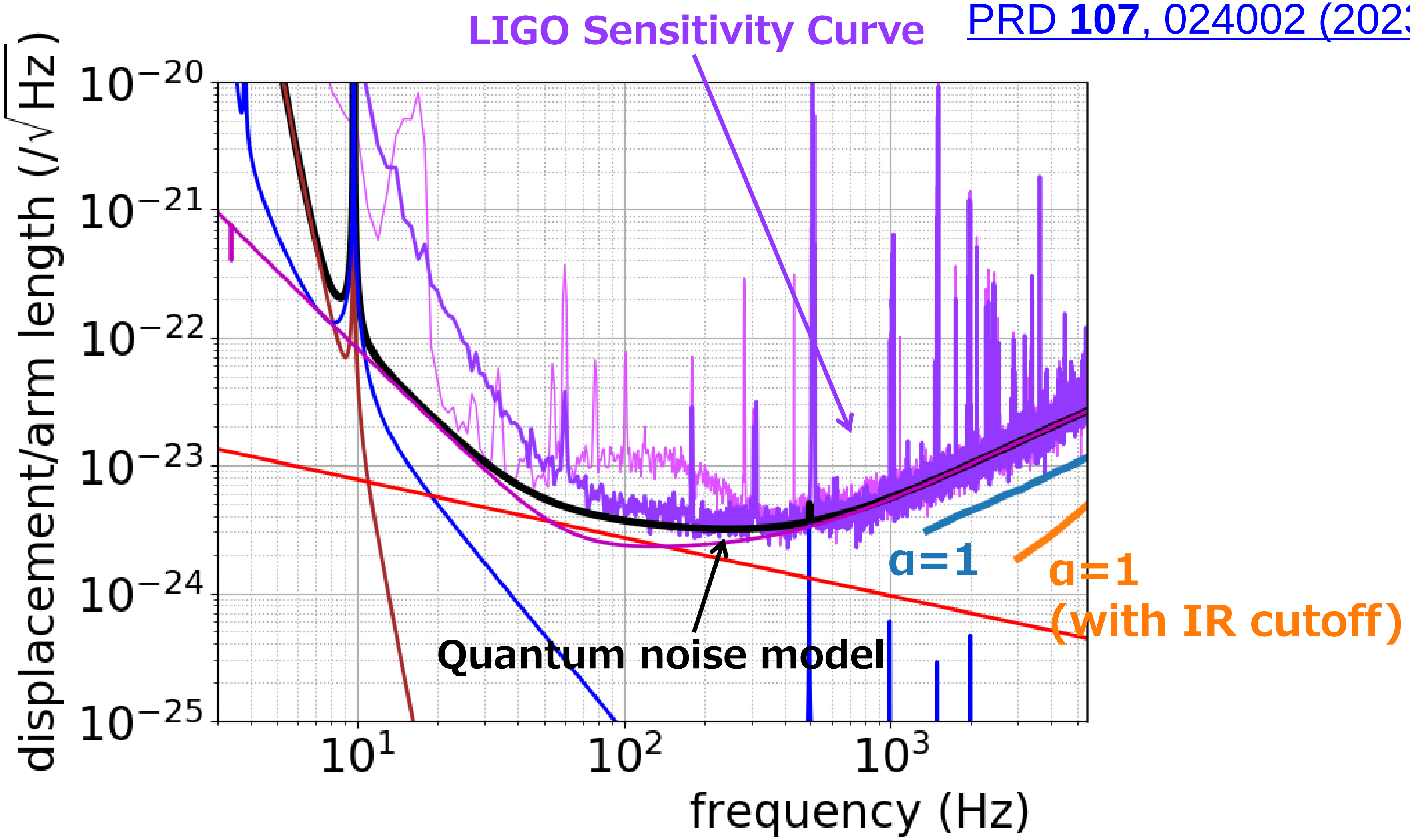


D. Li+,
[PRD **107**, 024002 (2023)]

Search with LIGO Detector

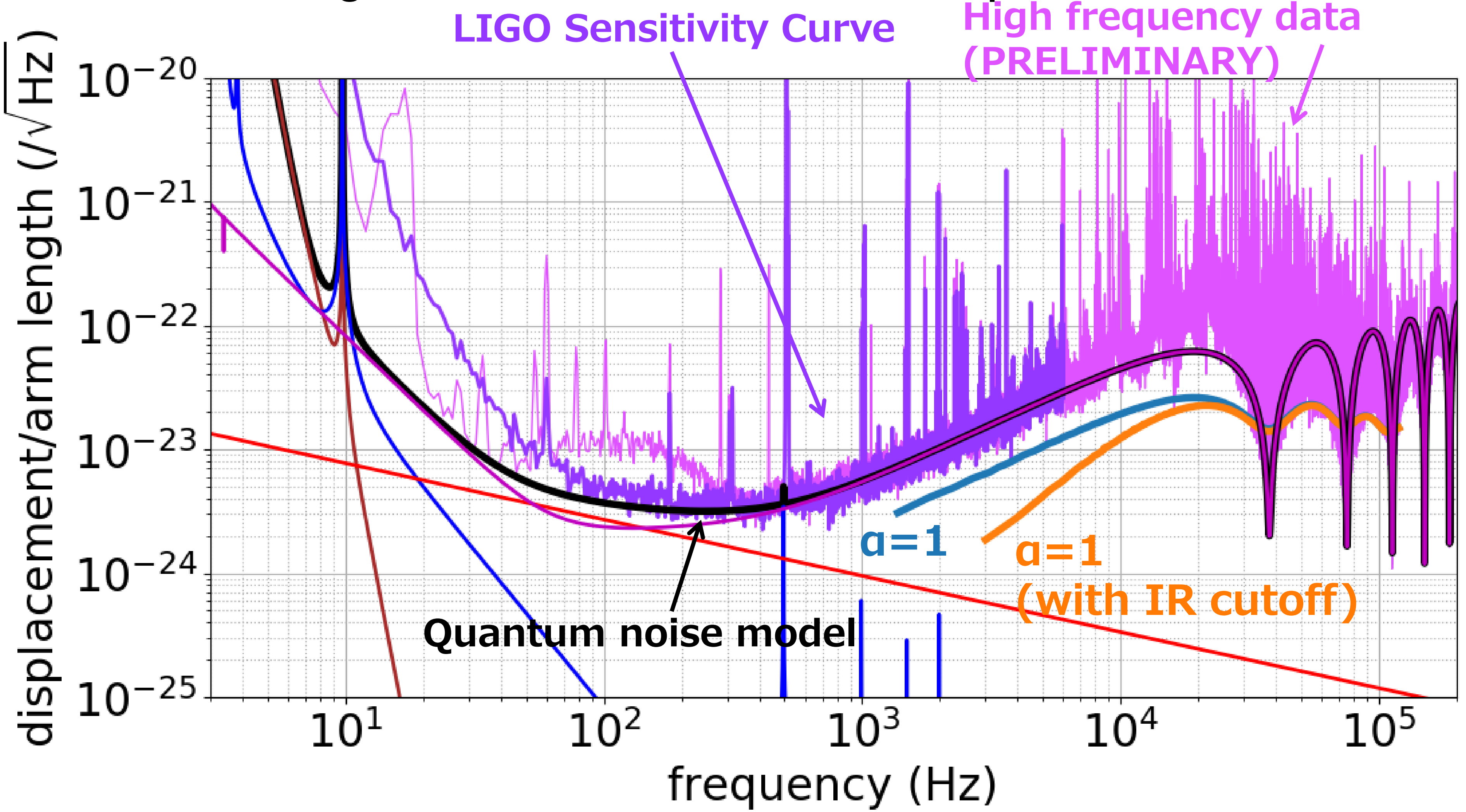
- Search below signal peak done with 2019-2020 data

D. Li+,
PRD **107**, 024002 (2023)



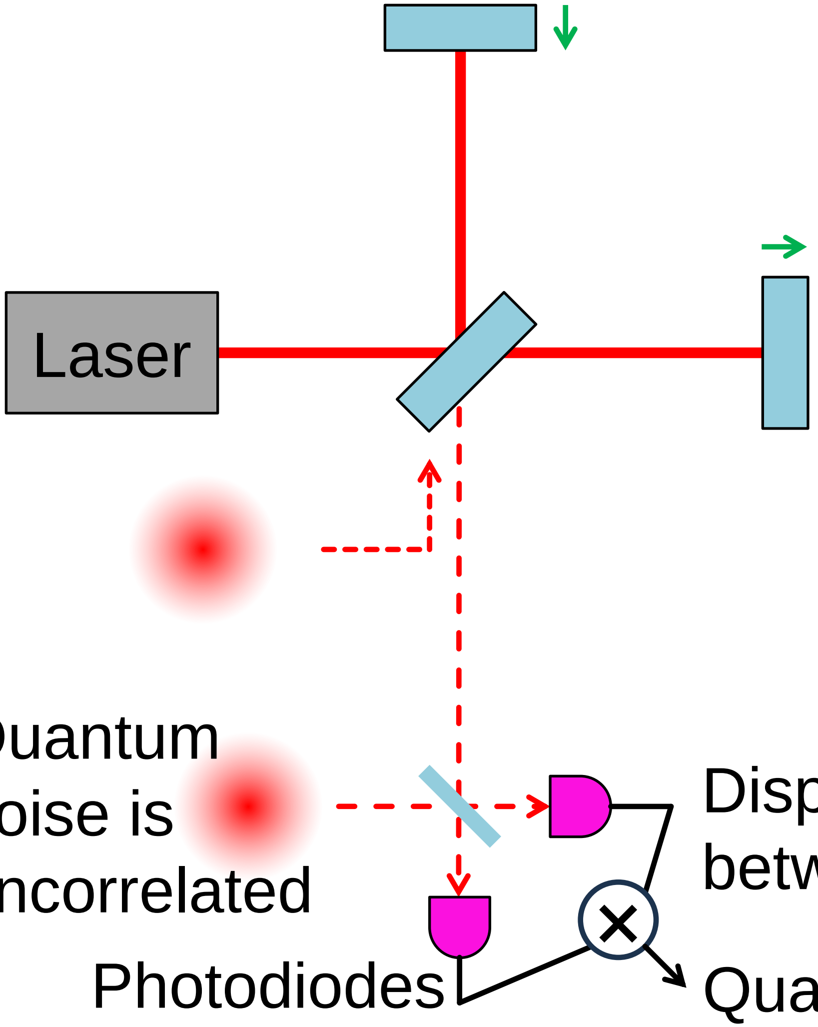
Search with High Frequency Data

- Data acquisition at 524 kHz installed for current observing run $\rightarrow \alpha \sim 10^{-2}$ search possible



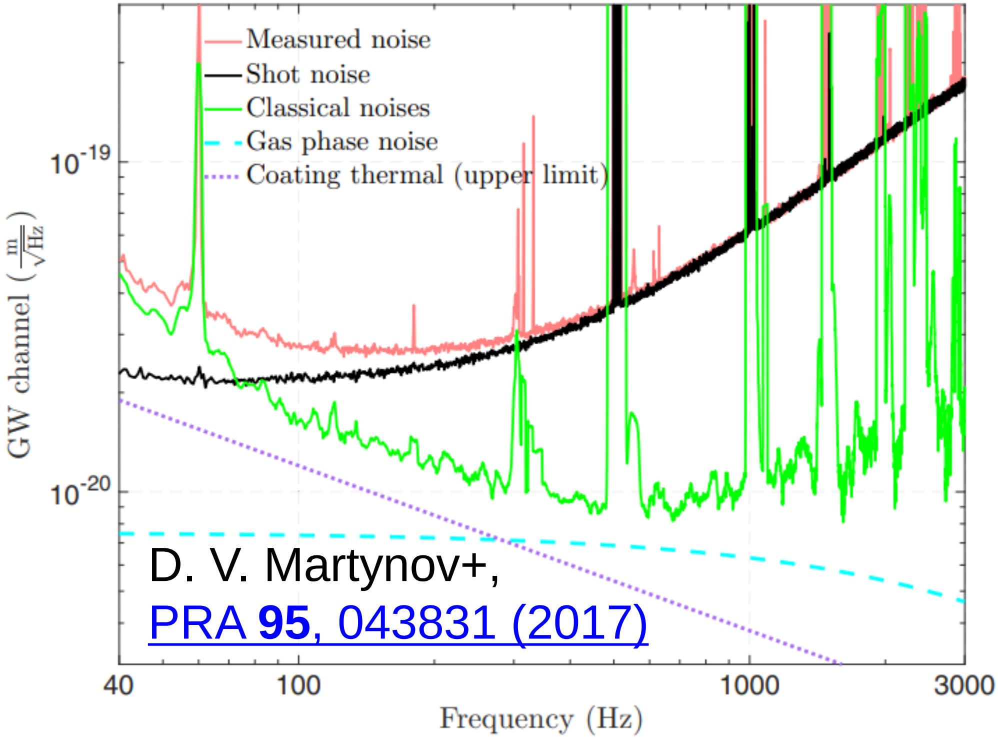
Quantum Correlation Enhancement

- Quantum correlation will enhance the sensitivity beyond shot noise limit



Quantum noise is uncorrelated

Photodiodes



D. V. Martynov+, PRA **95**, 043831 (2017)

Displacement signal is correlated between photodiodes

Quantum correlation

Summary

- You can do many things with laser interferometers
  - Ultralight dark matter
  - Quantum nature of gravity
  - Quantum fluctuations of space-time

Acknowledgements

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 matter

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