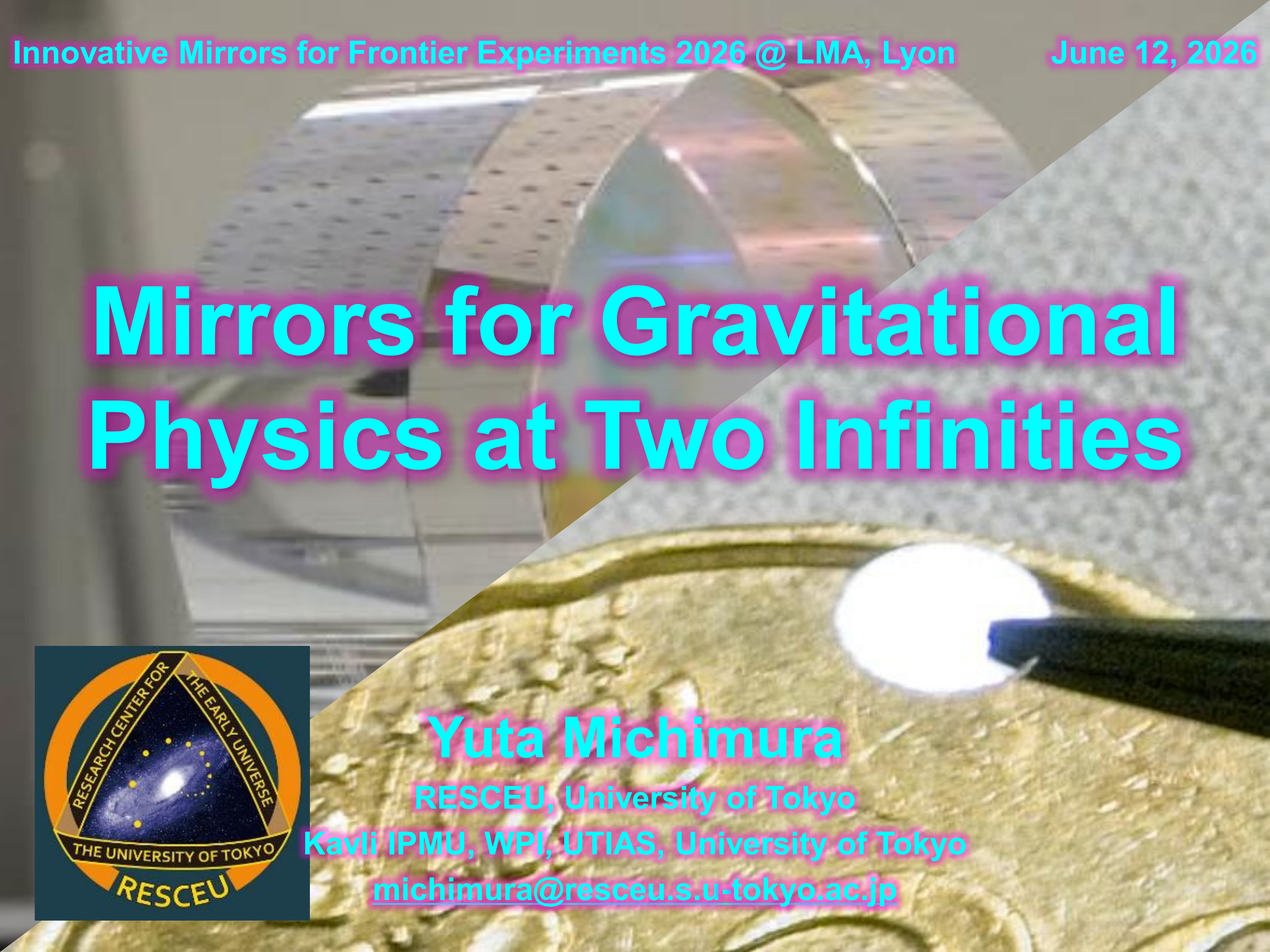
Innovative Mirrors for Frontier Experiments 2026 @ LMA, Lyon June 12, 2026

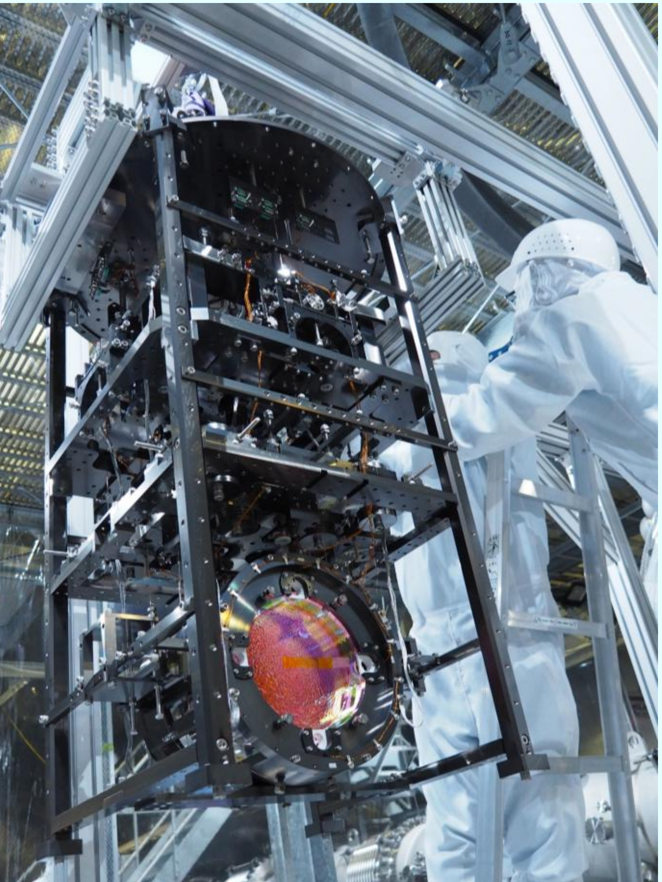


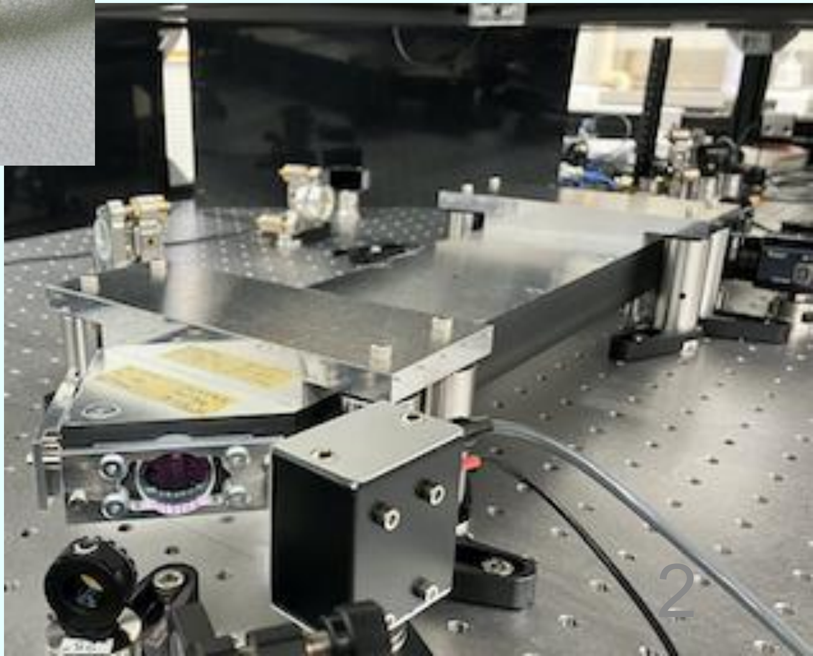
Mirrors for Gravitational Physics at Two Infinities

Yuta Michimura
RESCEU, University of Tokyo
Kavli IPMU, WPI, UTIAS, University of Tokyo
michimura@resceu.s.u-tokyo.ac.jp

Menu

- Update on KAGRA sapphire suspension
- Tiny mirrors for optical levitation
- Zero phase shift mirrors for axion searches



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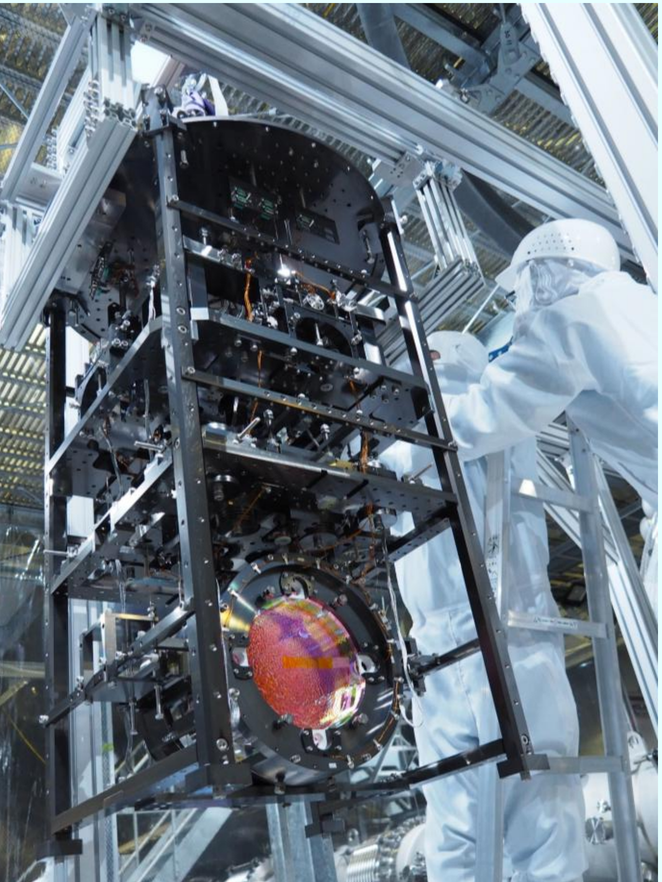
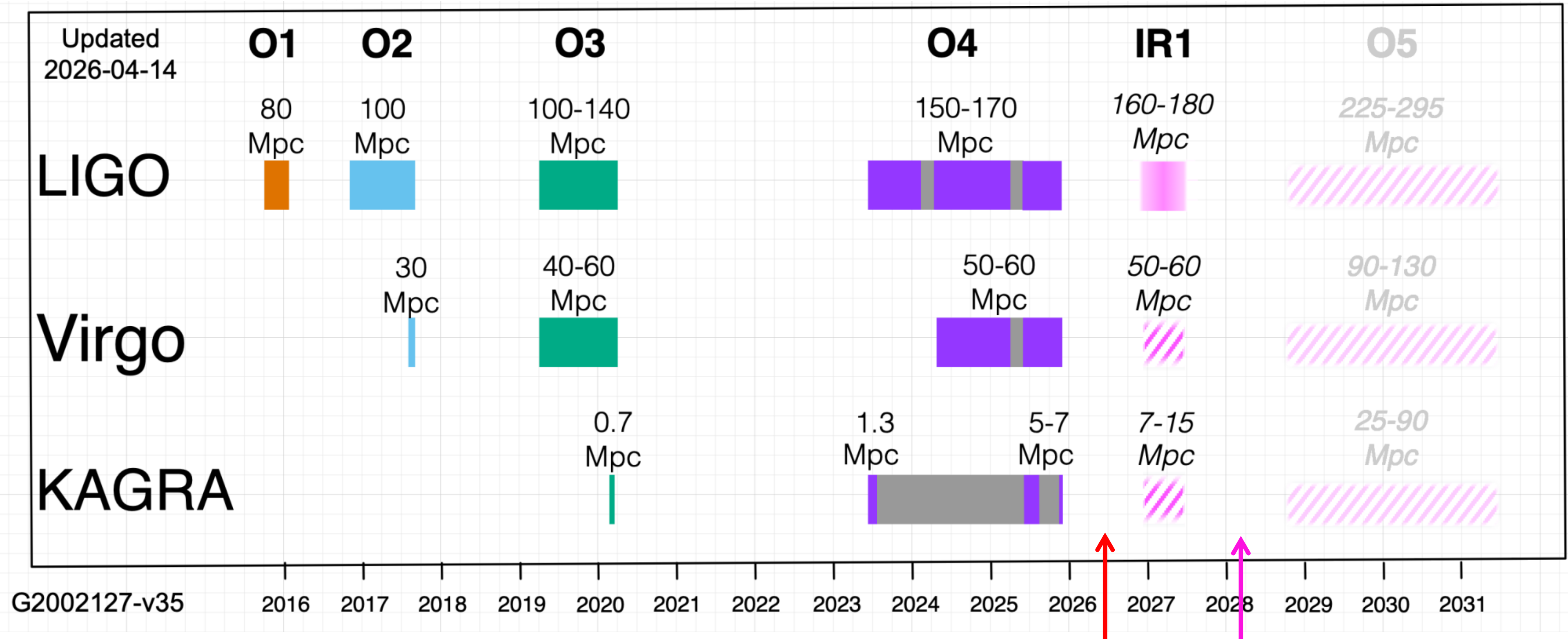


KAGRA Schedule

- ~7 Mpc at maximum with PRFPMI configuration
- Now trying RSE for IR1



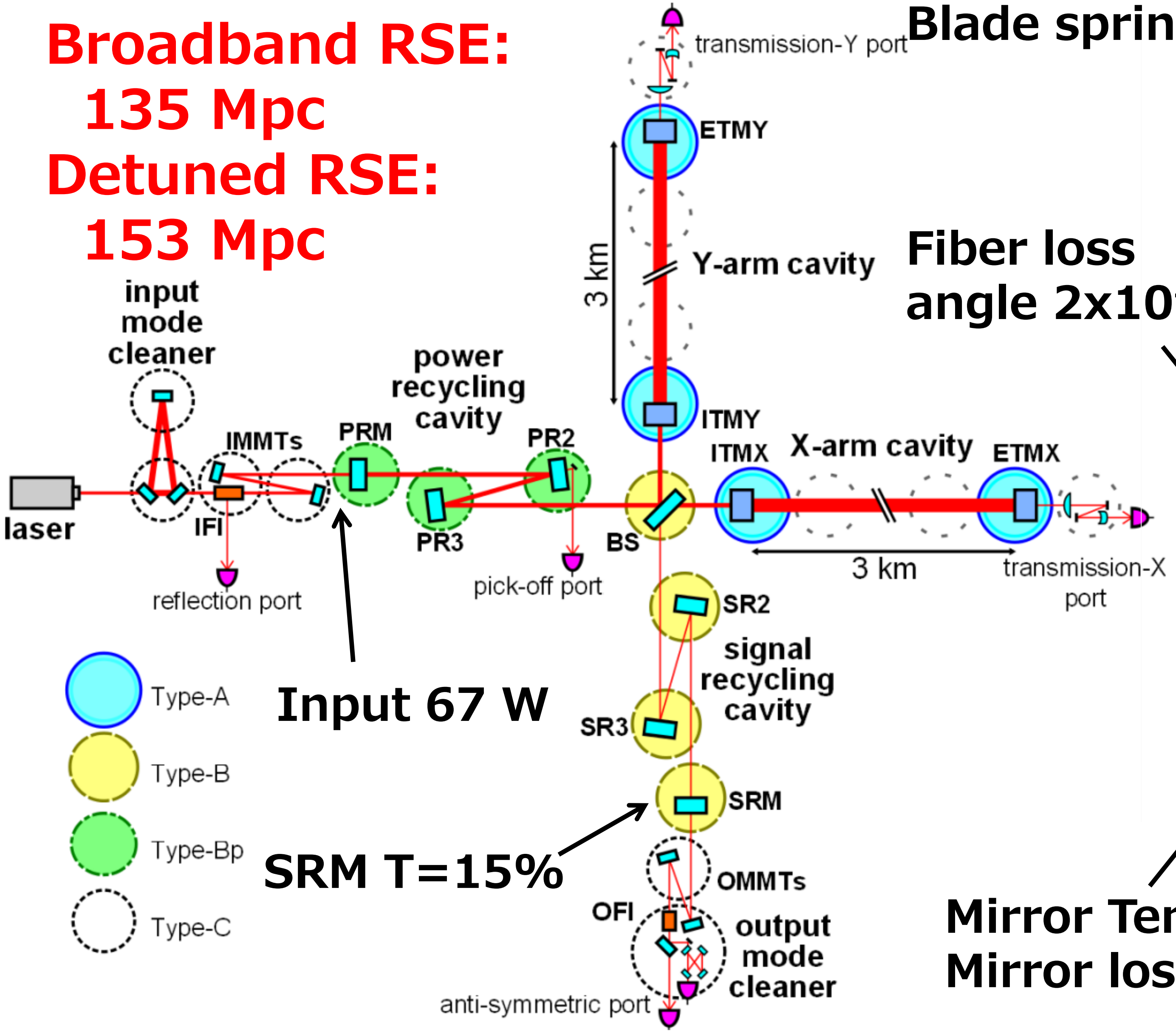
https://observing.docs.ligo.org/plan/

Today: T=15% SRM installed
RSE commissioning

ITMs to be replaced before O5

KAGRA Designed Configuration

Broadband RSE:
135 Mpc
Detuned RSE:
153 Mpc

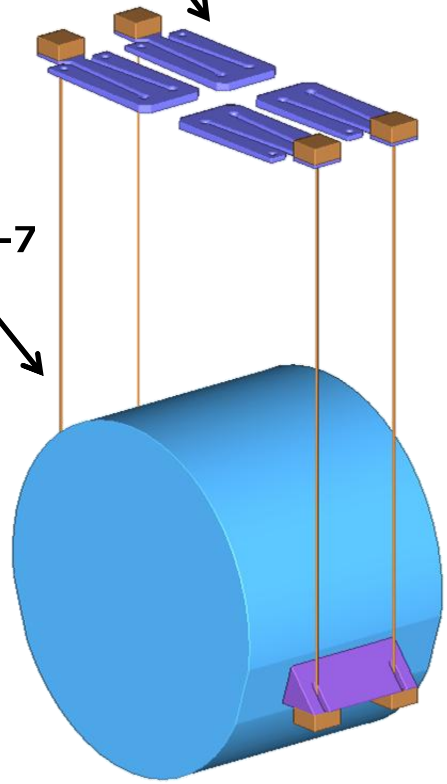


Input 67 W

SRM T=15%

Blade spring loss angle 7×10^{-7}

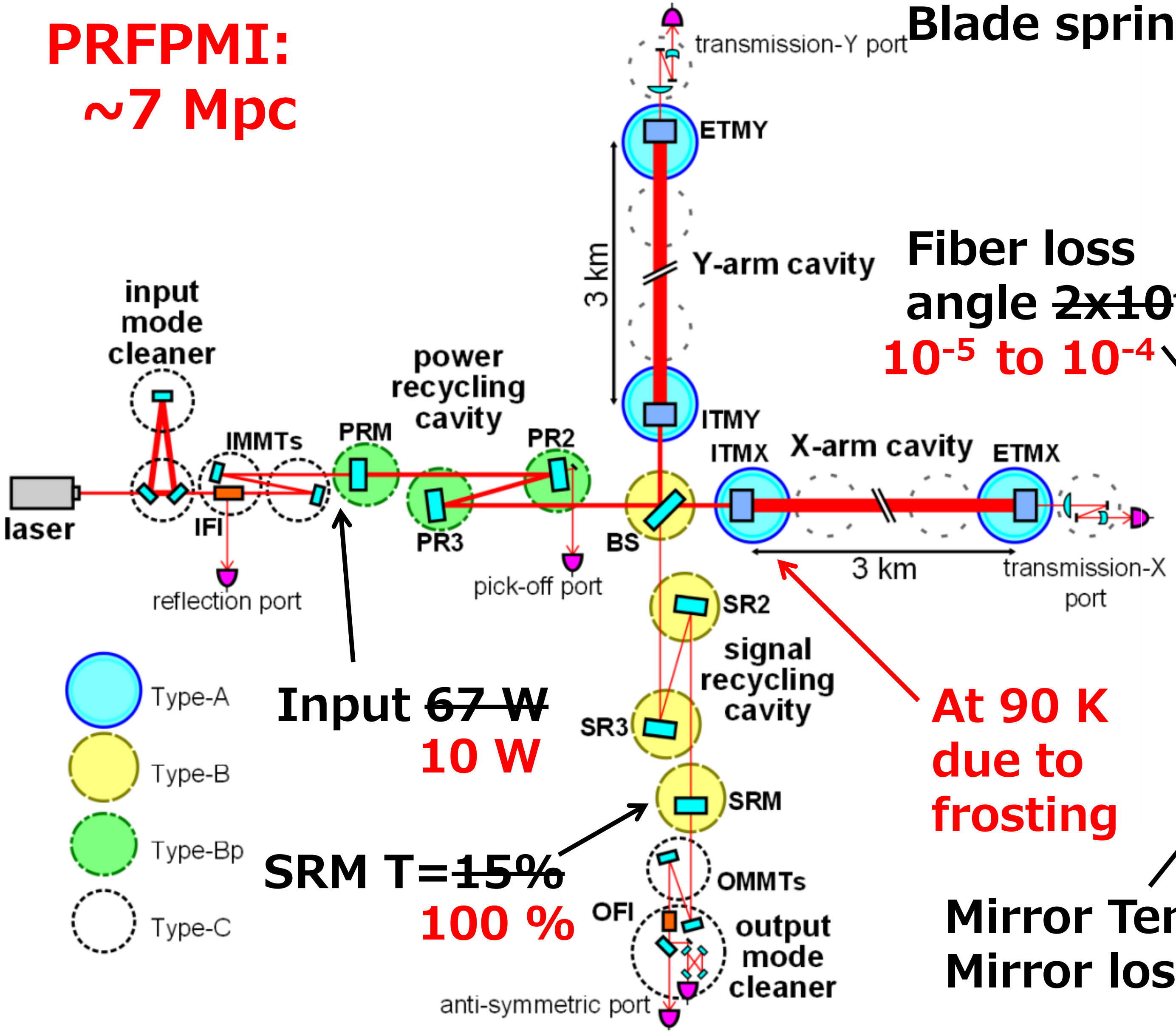
Fiber loss angle 2×10^{-7}



Mirror Temp. 22 K
Mirror loss angle 10^{-8}

KAGRA O4c Result

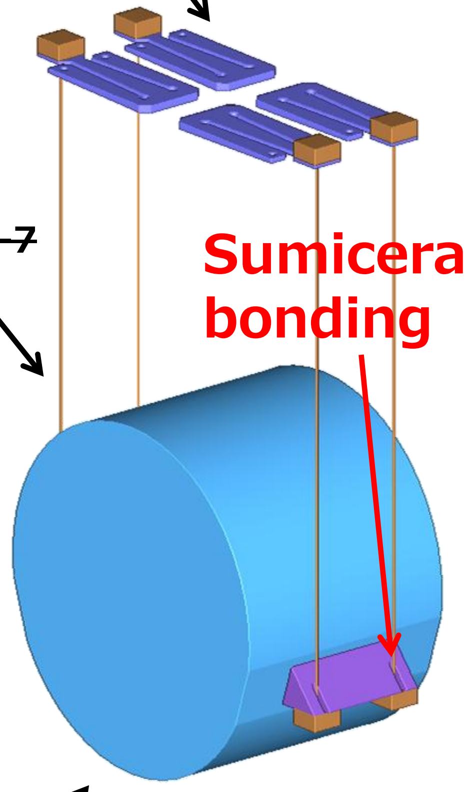
PRFPMI:
~7 Mpc



Input ~~67 W~~
10 W

SRM T=~~15%~~
100 %

At 90 K due to frosting



Blade spring loss angle ~~7×10^{-7}~~
1×10^{-4}

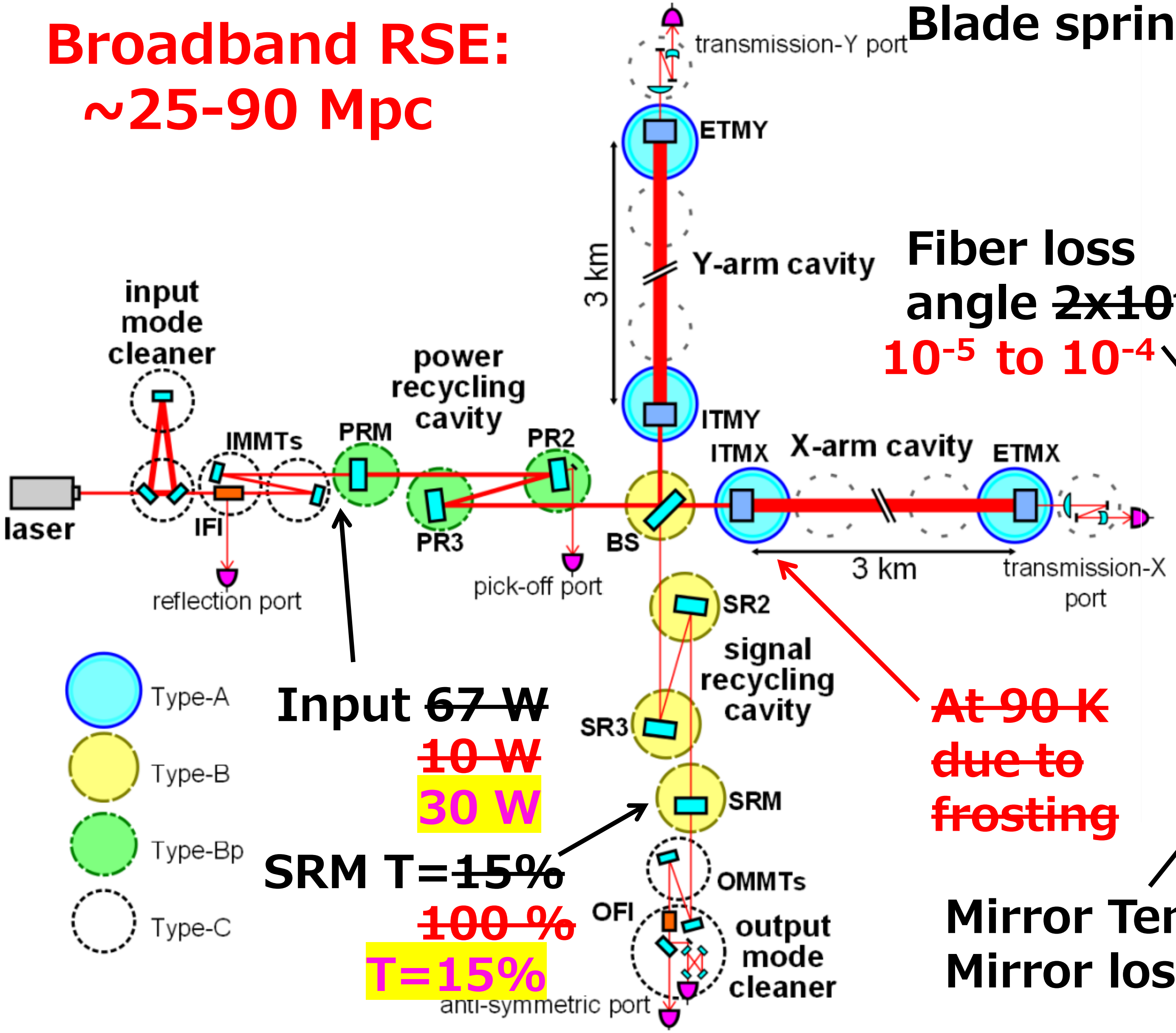
Fiber loss angle ~~2×10^{-7}~~
10^{-5} to 10^{-4}

Sumiceram bonding

30-90 K
Mirror Temp. ~~22 K~~
Mirror loss angle ~~10^{-8}~~
10^{-6}

KAGRA O5 Target

Broadband RSE:
~25-90 Mpc



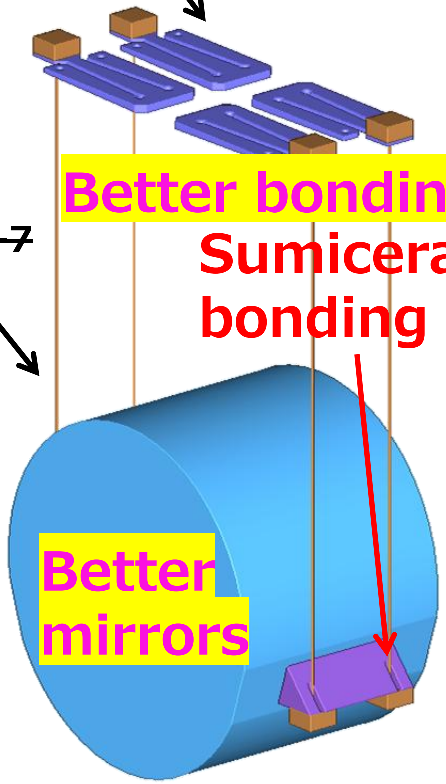
Input ~~67 W~~
~~10 W~~
30 W

SRM T=~~15%~~
~~100 %~~
T=15%

~~At 90 K due to frosting~~

Blade spring loss angle ~~7x10^{-7}~~
1x10^{-4}

Fiber loss angle ~~2x10^{-7}~~
10^{-5} to 10^{-4}



Better bonding?

Sumiceram bonding

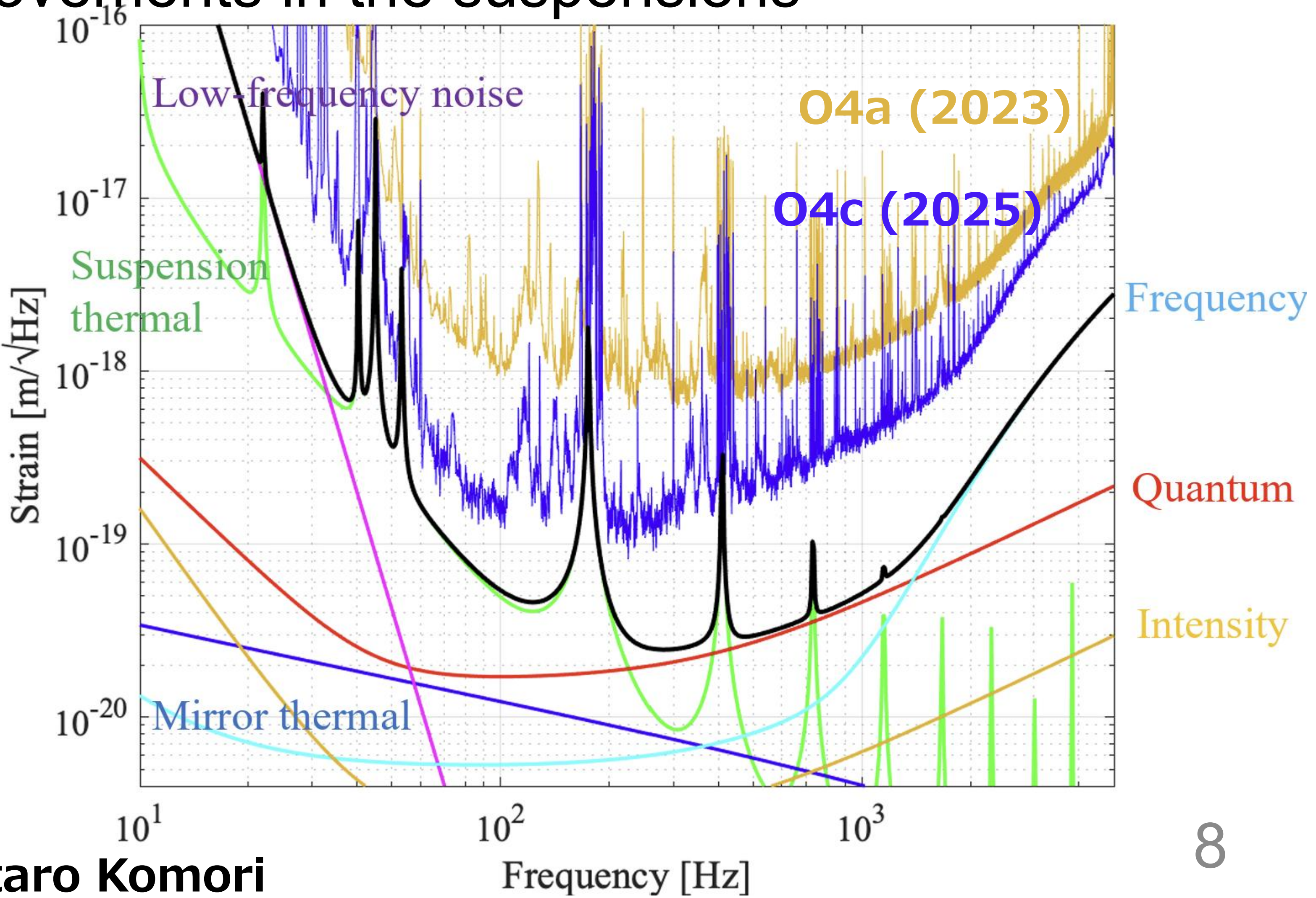
Better mirrors

30 K
~~30-90 K~~

Mirror Temp. ~~22 K~~
Mirror loss angle ~~10^{-8}~~
10^{-6}

KAGRA O5a Range

- 33 Mpc with RSE, all mirrors 30 K, no improvements in the suspensions

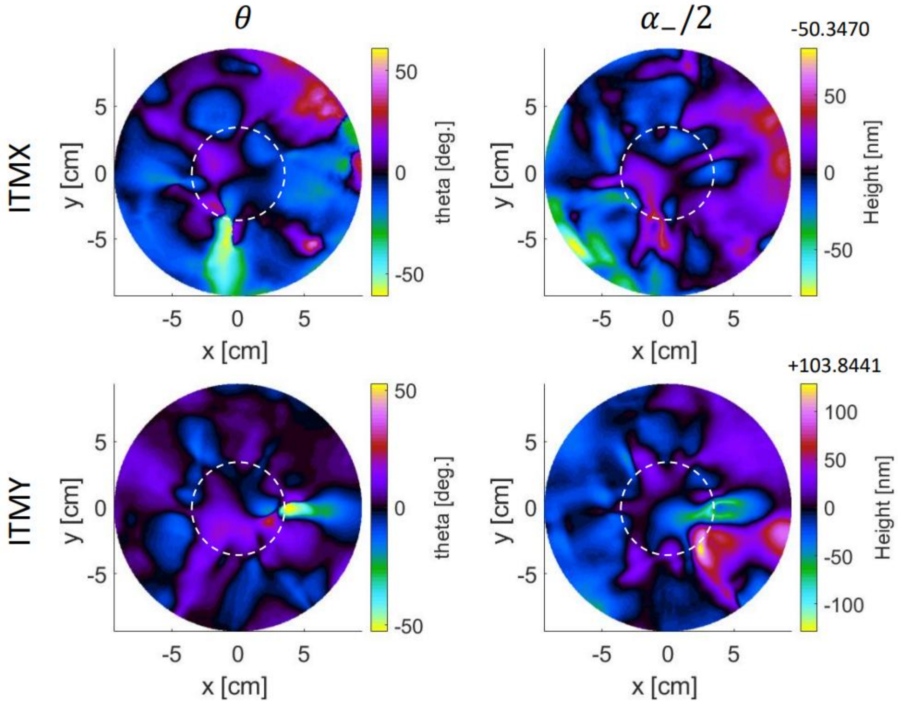


Plot by Kentaro Komori

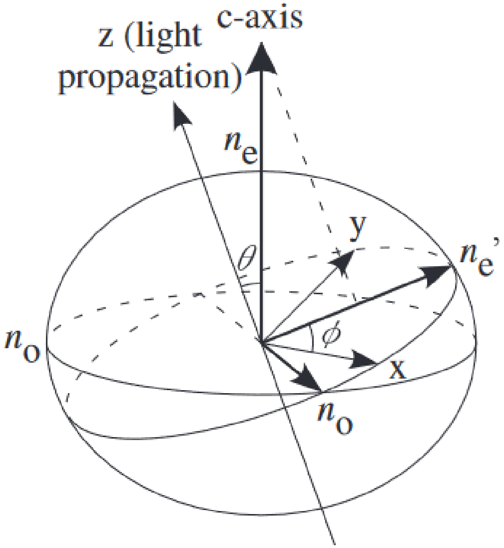
Current Sapphire Mirrors

- Current ones have inhomogeneous mirror thickness differences between polarizations in the order of O(10) nm, resulting in the power loss of
  ITMX: ~4% (~0.3% if arm locked)
  ITMY: ~8% (~4% if arm locked)

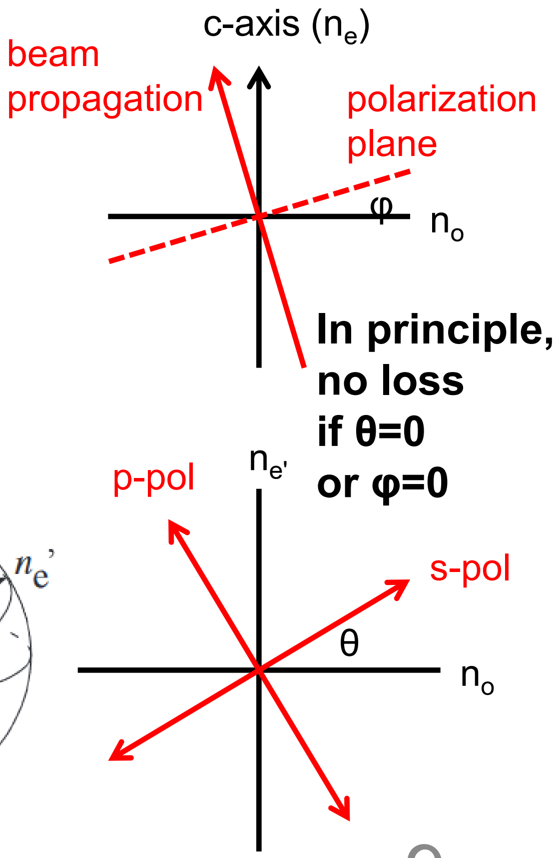
H. Wang+, PRD **110**, 082007 (2024)



H. Wang, YM+, LIGO-P2600052



Tokunari+, JPCS 32, 432 (2006)

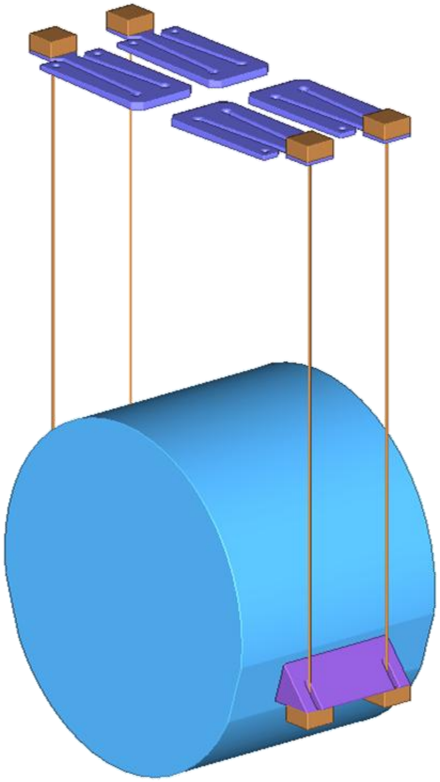


In principle, no loss if θ=0 or φ=0

New Sapphire Mirrors for O5

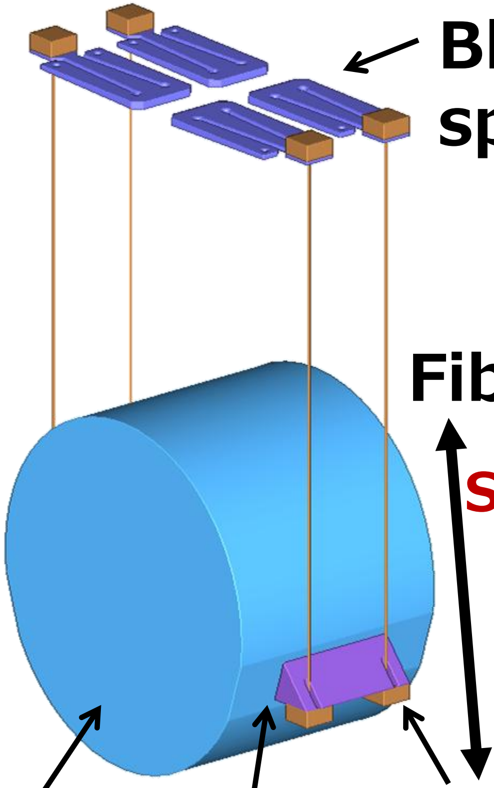
- Side-cut substrate currently at NAOJ under characterization before coating
- Less and more uniform birefringence (α_- in the order of O(1) nm) but θ could be ~40 deg
- To be confirmed …
- Possible countermeasures
  - Birefringence compensation plates
  - Rotate and cut again
  - Rotate input polarization

    (BS needs to be replaced to have 50:50 for both polarizations with a zero phase shift)



Sapphire Suspension Plans

- Currently Sumiceram bonding is used since welding didn’t have enough strength
- Work in progress in collaboration with University of Glasgow



Blade spring

Fiber(φ1.6 mm)

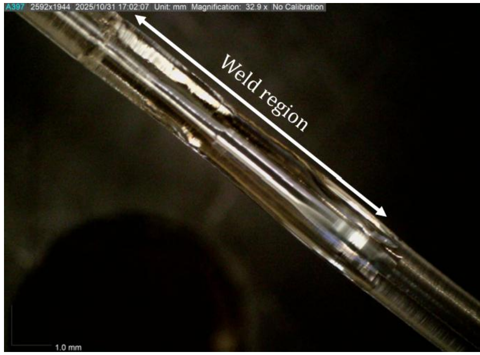
Sumiceram bonding
→ Plasma welding or Laser welding

Nailhead

Mirror ↔ **Ear** ↔ **Nailhead**

HCB

Galium bonding



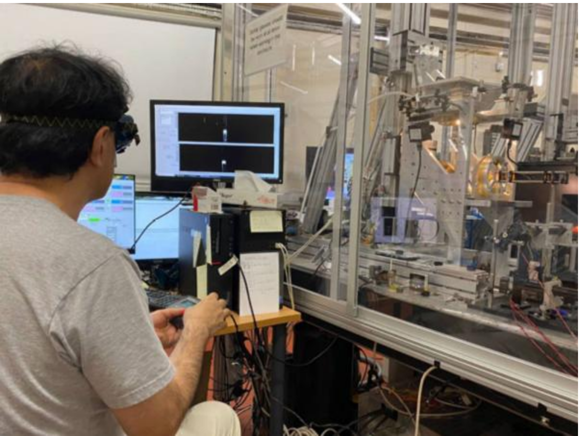


Photo: Munetake Ohtsuka

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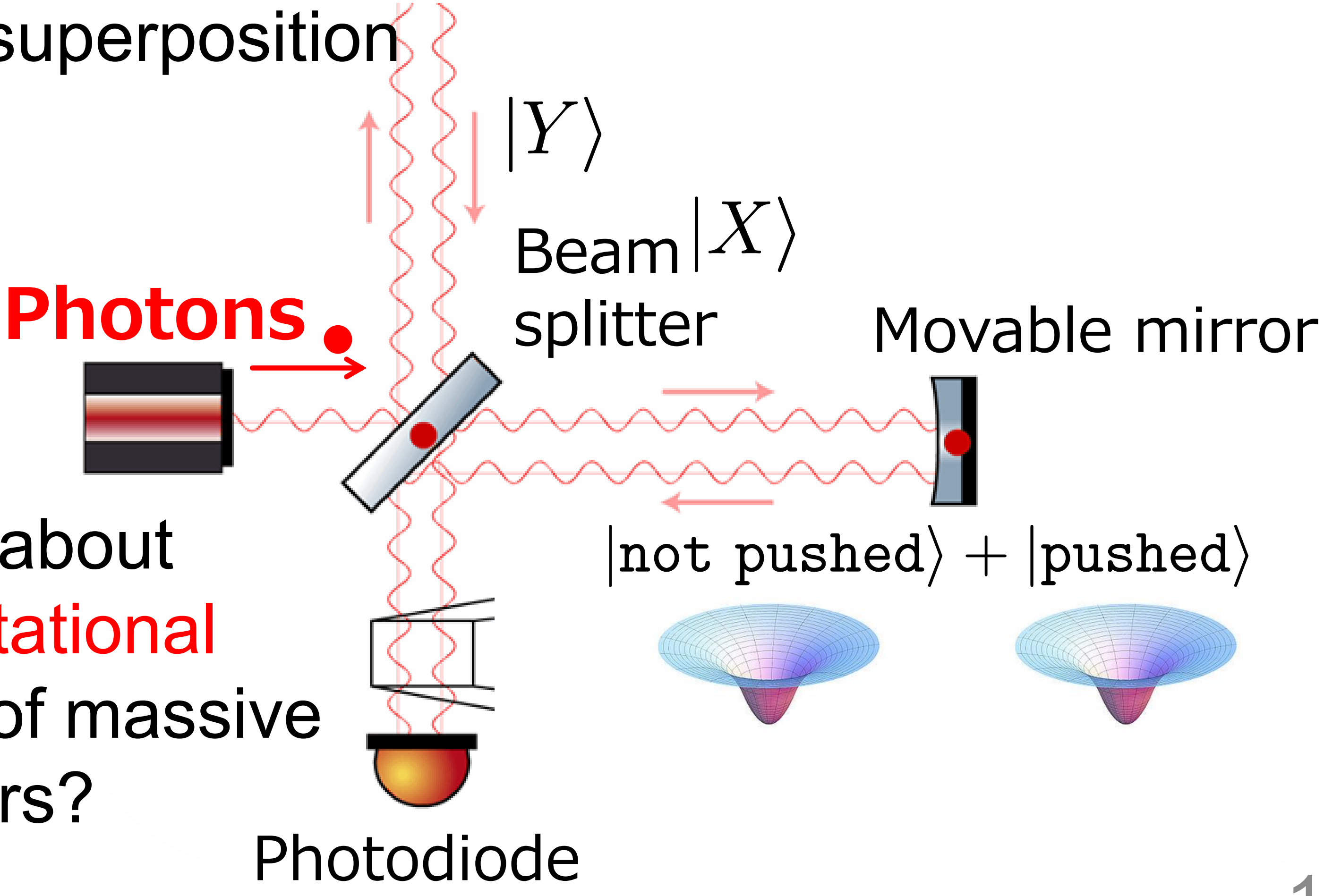
- Update on KAGRA sapphire suspension
- **Tiny mirrors for optical levitation**
- Zero phase shift mirrors for axion searches

Quantum Nature of Gravity

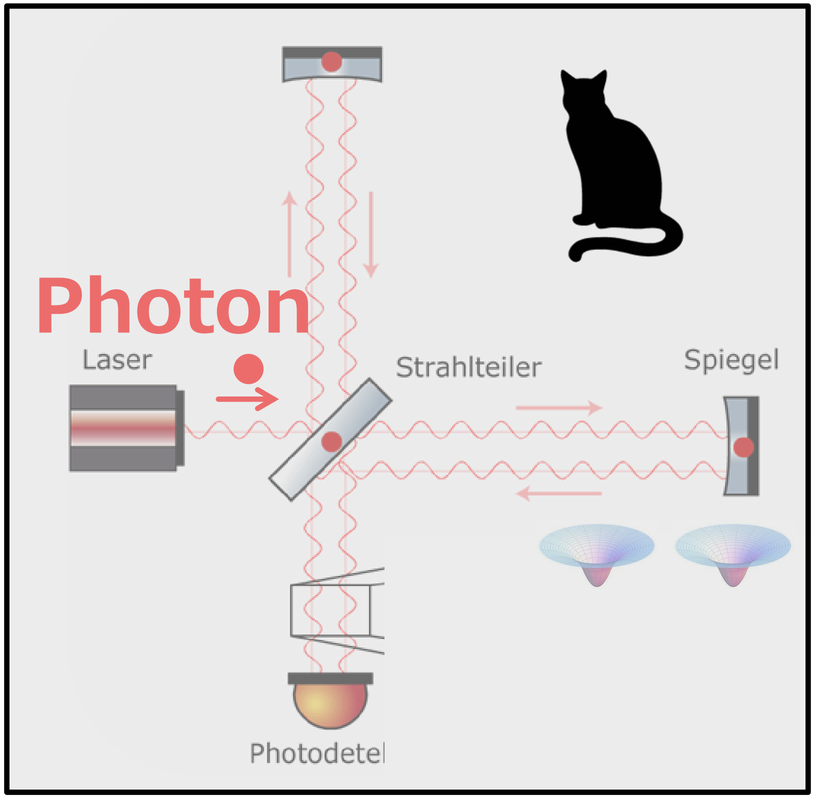
- Photon going to X or Y arm is in superposition
- Mirrors pushed or not pushed by radiation pressure is in superposition

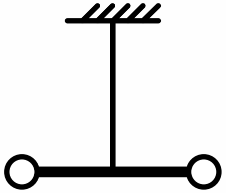


- How about gravitational field of massive mirrors?

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???



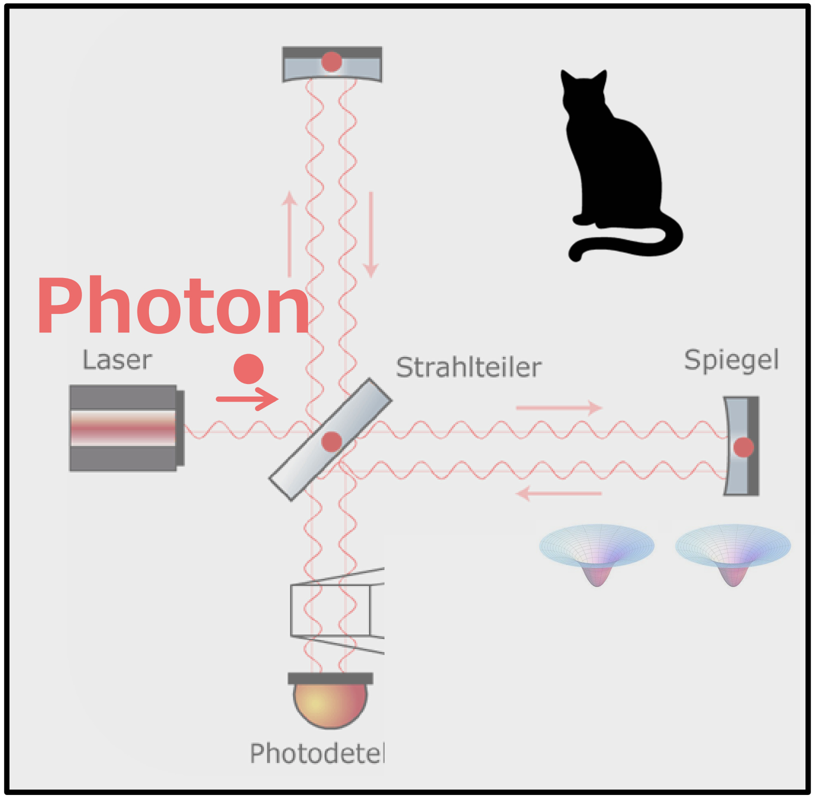


If gravity is quantum, torsion pendulum orientation will be entangled with mirror motion

Gravity induced entanglement

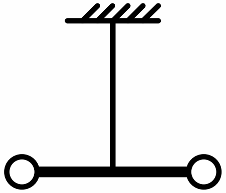
Schrödinger's KAGRA

- 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???



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

Expectation value



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

Very strange model, but not experimentally falsified completely.

Realization with Levitated Mirrors

- By levitating the mirrors, thermal decoherence from mechanical support can be avoided

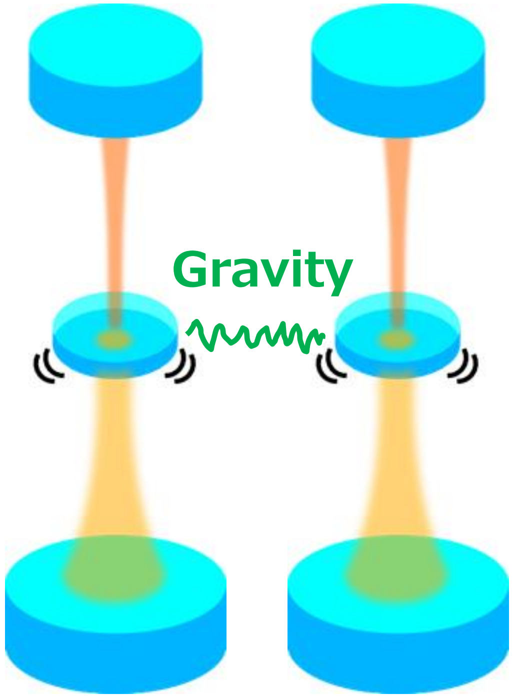
YM, Y. Kuwahara+,
Optics Express 25, 13799 (2017)

- Gravity induced entanglement generation can be accelerated with unstable trap, and this can be done with optically levitated mirrors

T. Fujita, Y. Kaku, A. Matsumura, YM,
CQG **42**, 165003 (2025)

(Should also be possible with diamagnetic levitation)

- Scattering-free optical levitation has not been realized yet



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

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

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

Making Tiny Mirrors

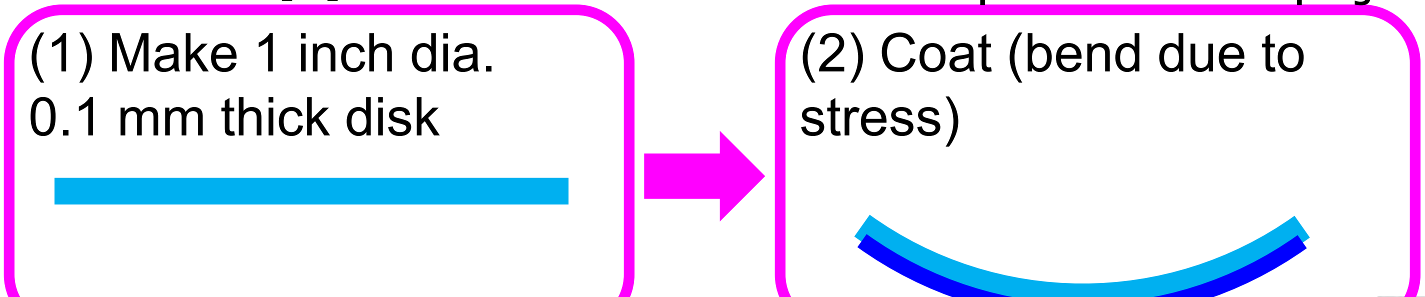
2014 Approach (Company in Japan)

(1) Make 3 mm dia. lens

(2) Coat

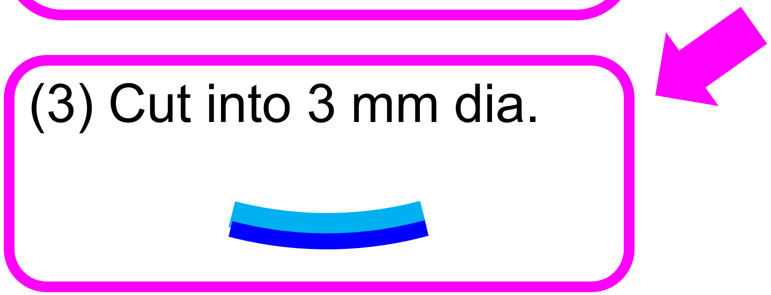
2020- Approach

**(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.

**Now trying thinner substrate (25 um)
with laser cutting
to have more curvature**

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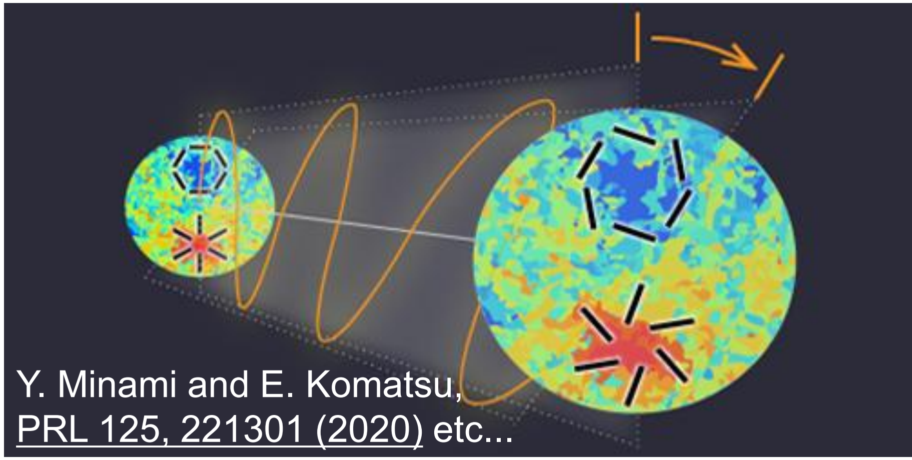
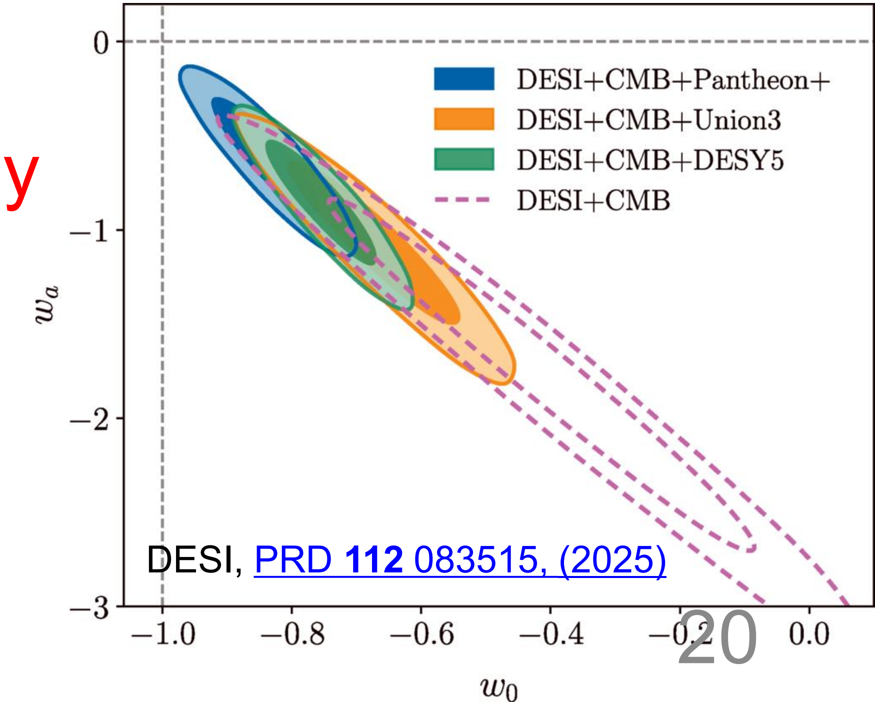
Axion (ALP) Dark Matter

- 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

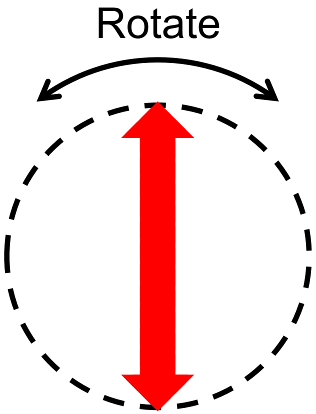
$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

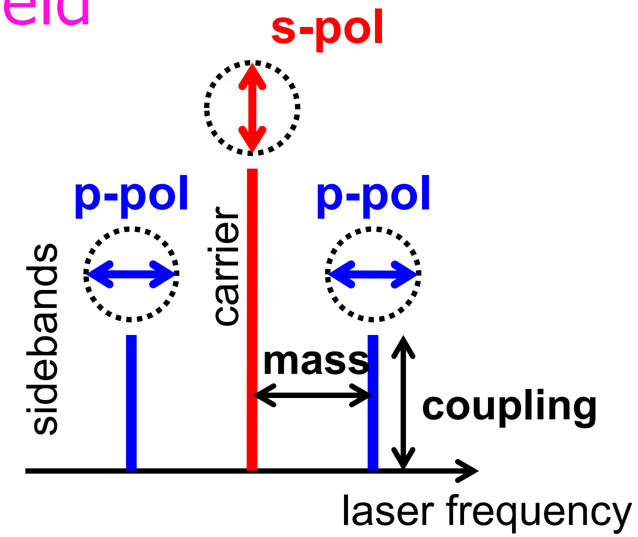
coupling constant

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

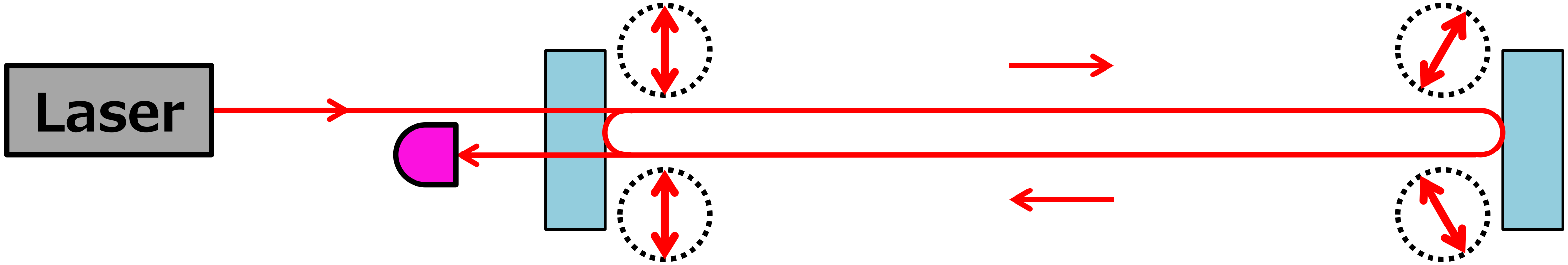




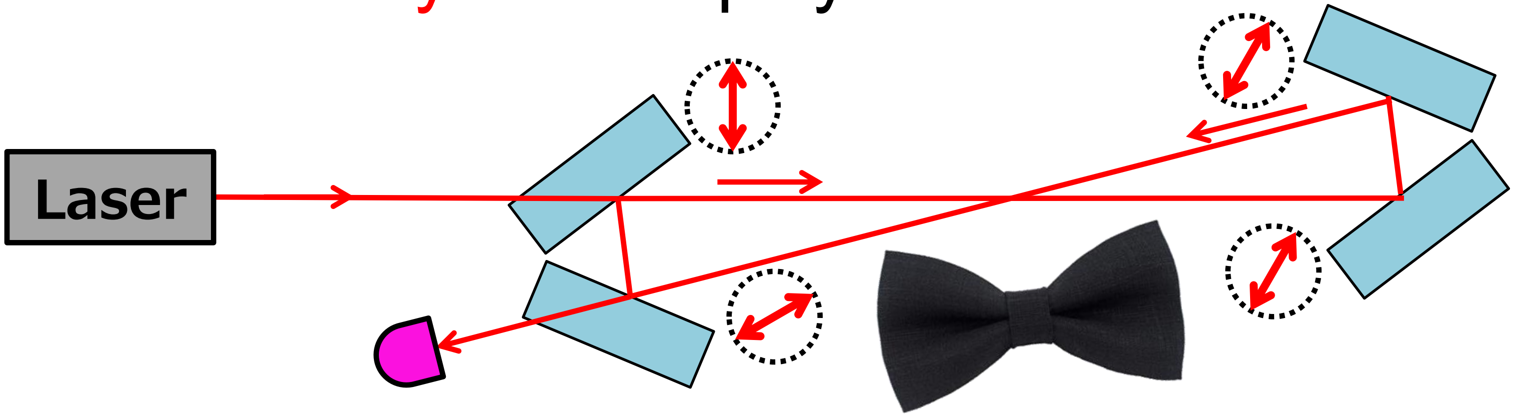
Bow-tie Cavity for Broadband

- 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

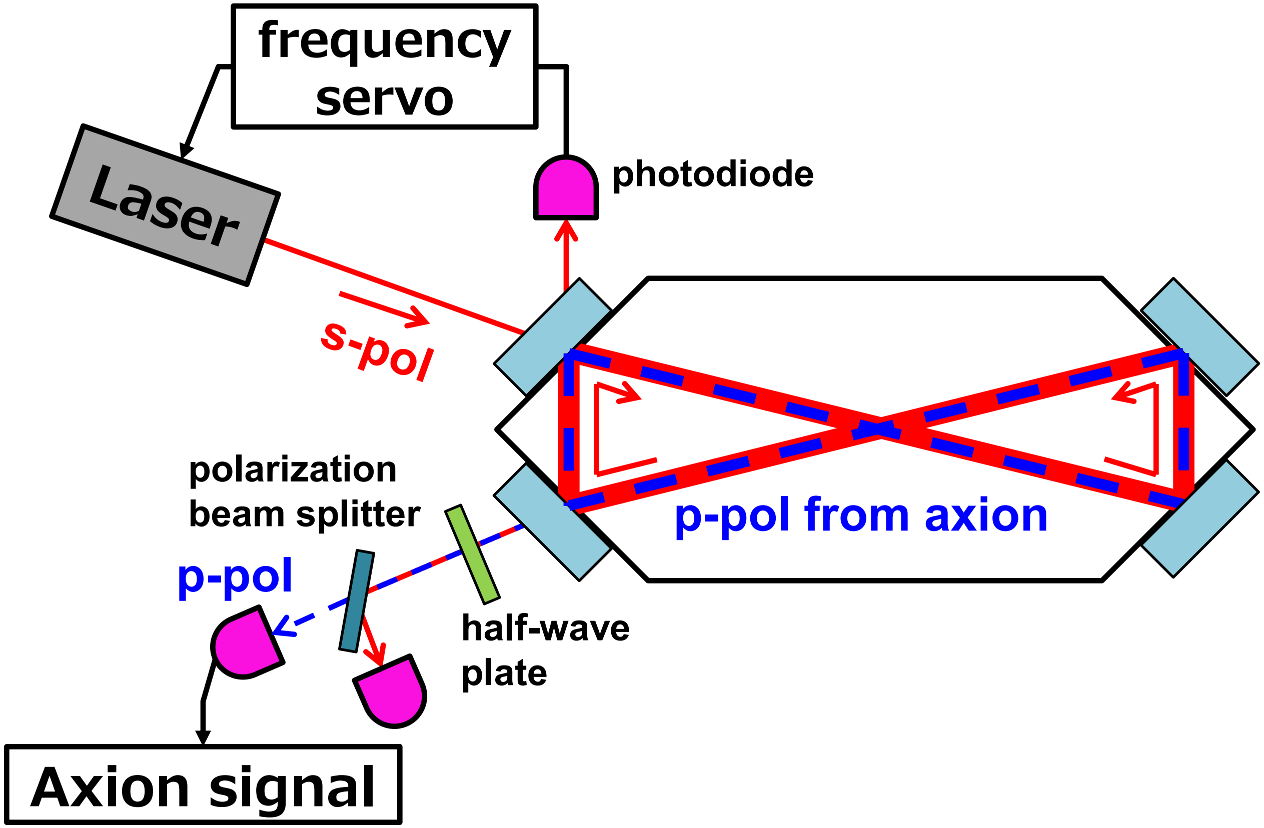


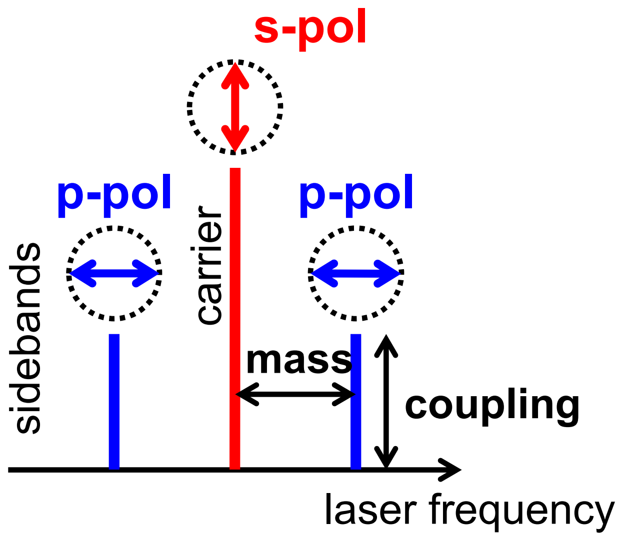
DANCE Setup

Dark matter Axion search with riNg Cavity Experiment

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

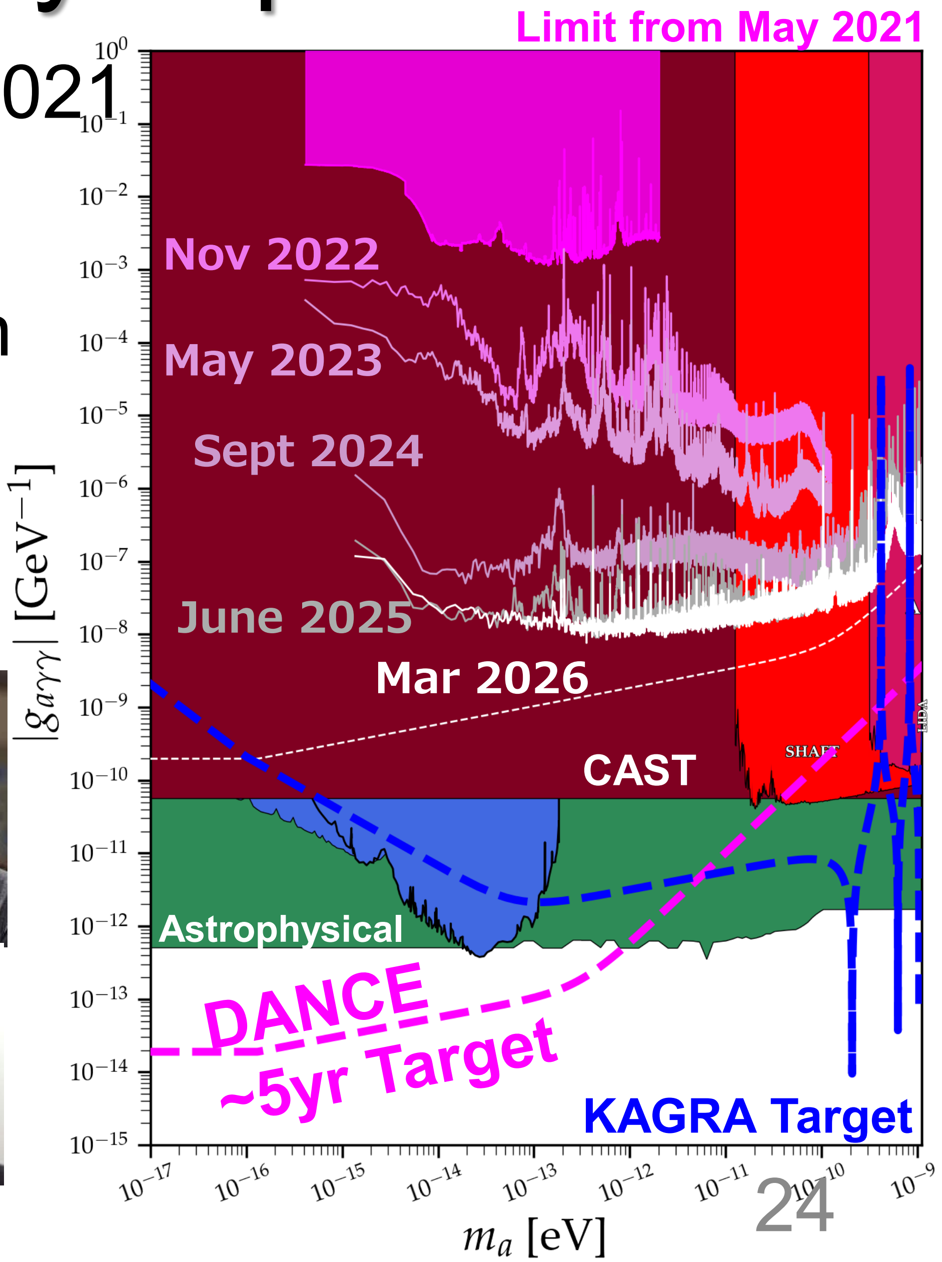
I. Obata, T. Fujita, YM, PRL **121**, 161301 (2018)

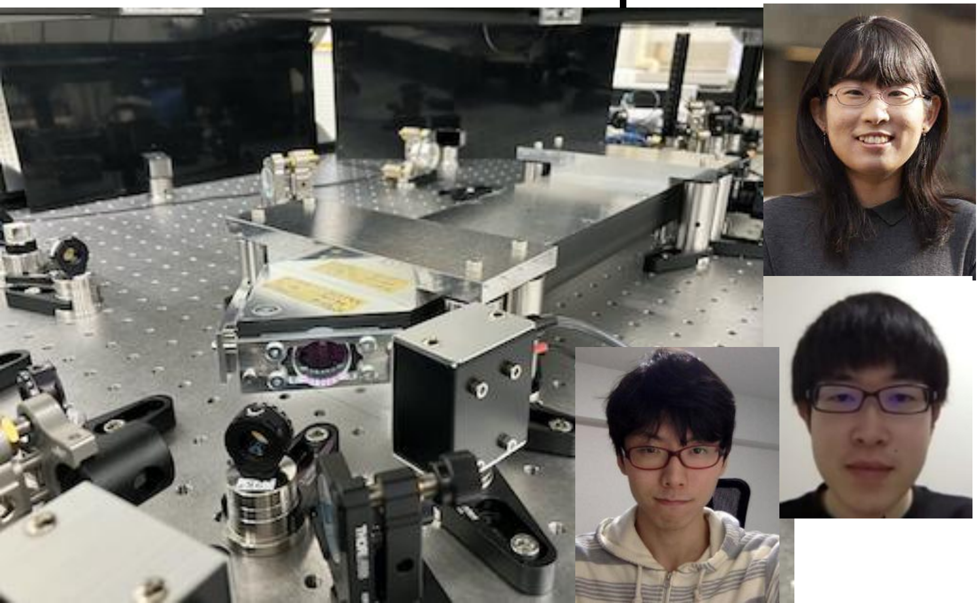




DANCE Sensitivity Improvements

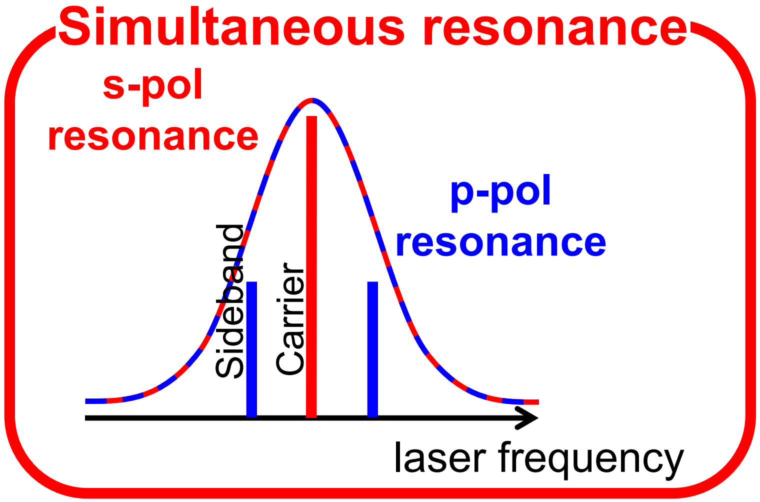
- First demonstration in 2021
  Y. Oshima+, PRD **108**, 072005 (2023)
- ~5 orders of magnitude improvement since then
  H. Takidera+, PRD **112**, 063048 (2025)
  H. Fujimoto, PhD thesis (UTokyo 2025)
- 6 mW → 1 W,
  1 m → 10 m planned

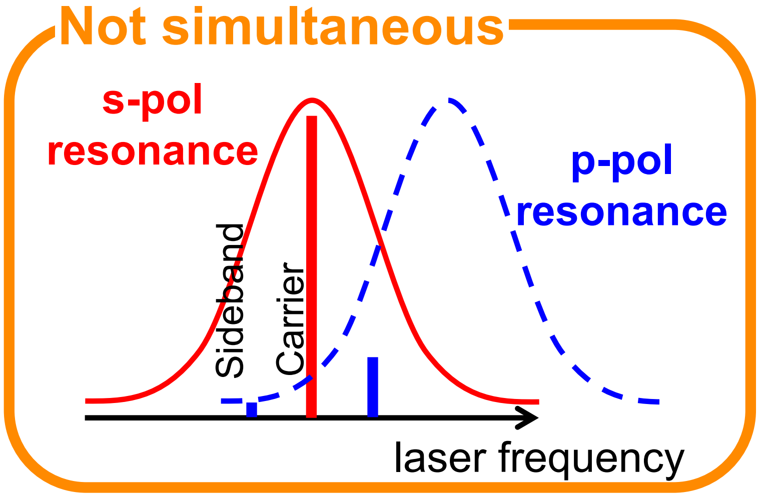


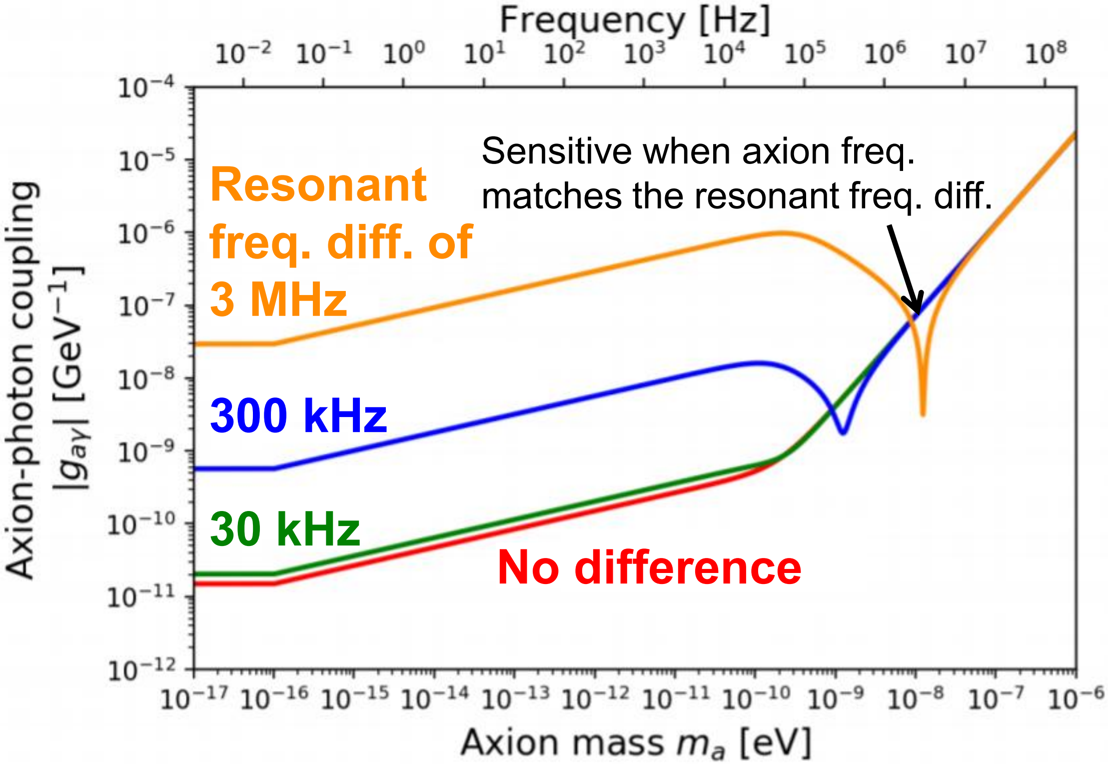


Simultaneous Resonance

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





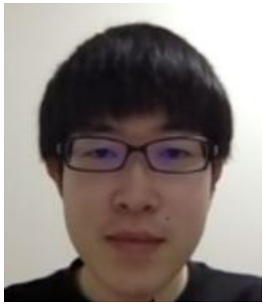


Sensitive when axion freq. matches the resonant freq. diff.

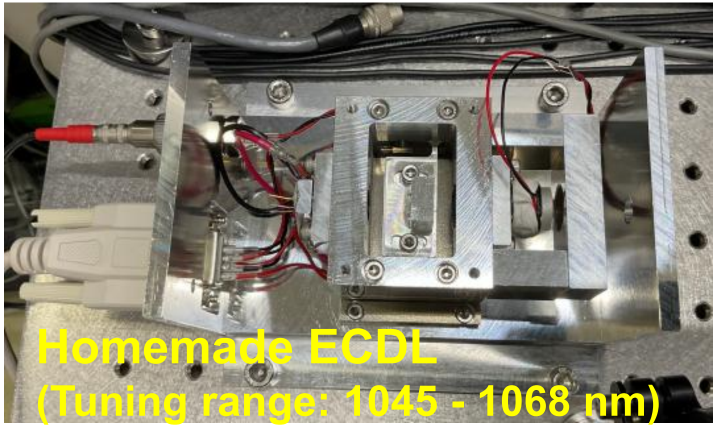
Plot by Y. Oshima & H. Fujimoto

Cavity Birefringence Tuning

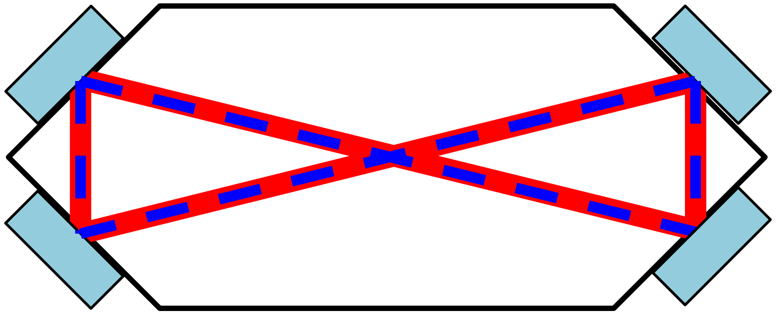
- Near 45 deg incidence on cavity mirrors create reflection phase difference, which leads to non-simultaneous resonance
- Reflection phase can be tuned by tuning laser wavelength

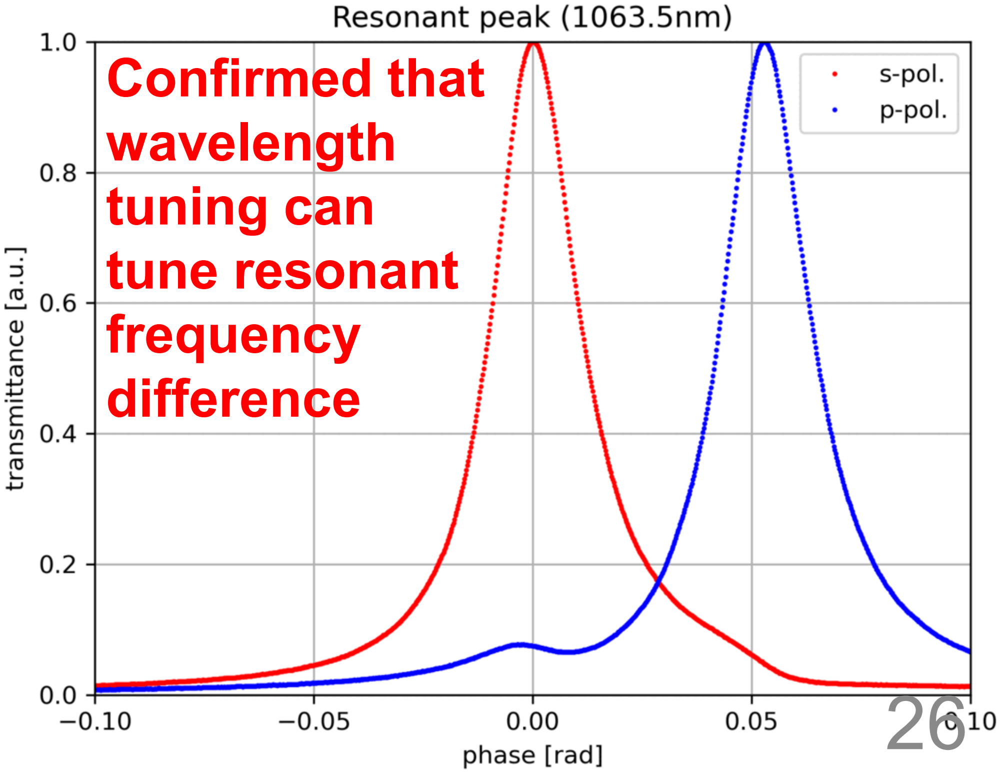


H. Takidera+, PRD **112**, 063048 (2025)



Homemade ECDL
(Tuning range: 1045 - 1068 nm)



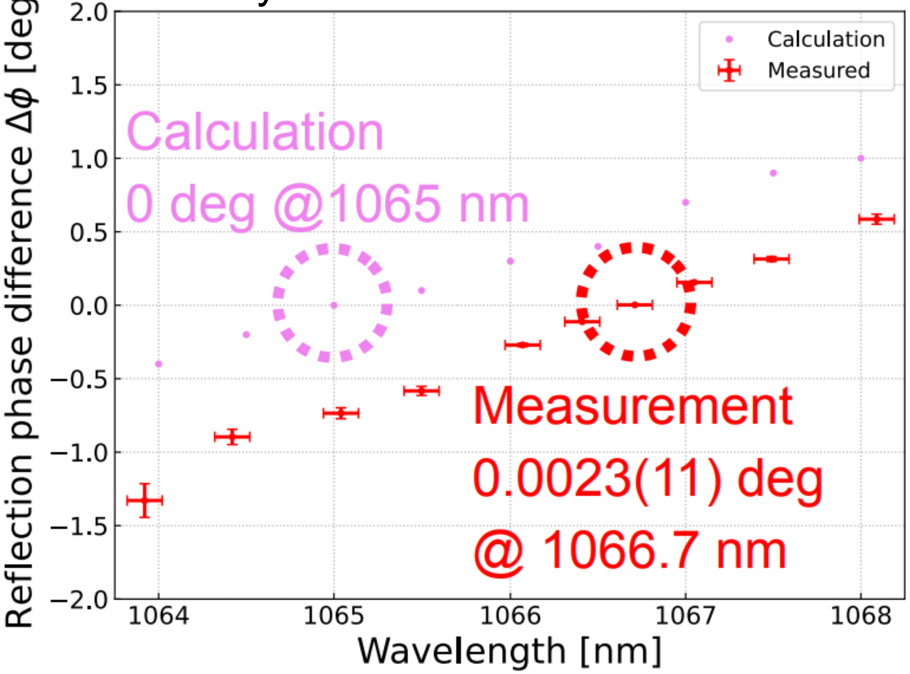


Confirmed that wavelength tuning can tune resonant frequency difference

Zero Phase Shift Mirrors

- Phase difference between polarizations should be zero at some wavelength
  (within tunable range: 1034-1067 nm)
- Should also be useful for polarization balanced BS and polarization speedmeters

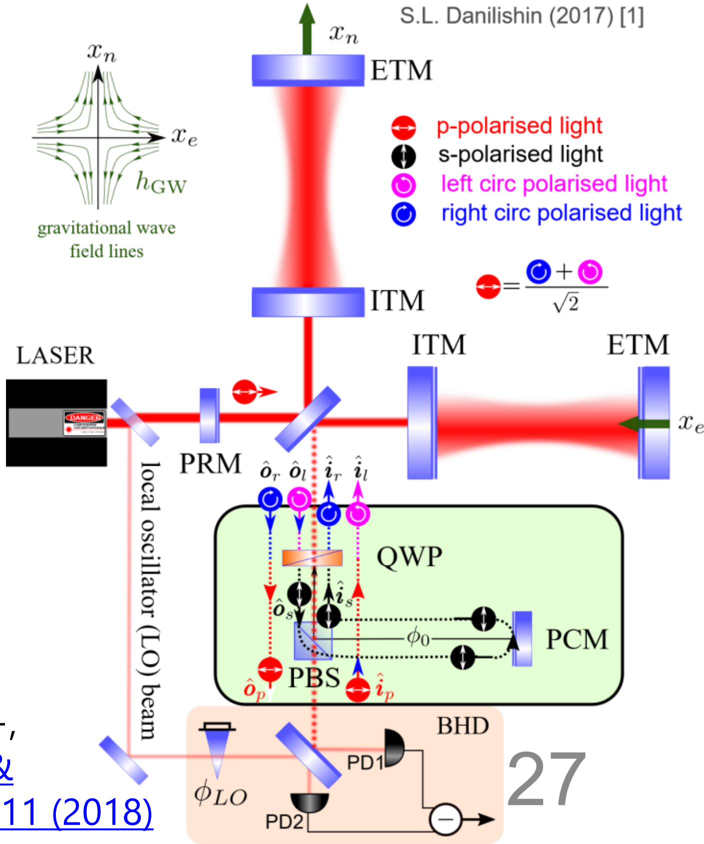
Plot by H. Takidera



Calculation
0 deg @1065 nm

Measurement
0.0023(11) deg
@ 1066.7 nm

S.L. Danilishin (2017) [1]



S. L. Danilishin+,
Light: Science & Applications 7, 11 (2018)

Summary

We welcome

- Good sapphire mirrors and suspensions
- Tiny mirrors for levitation
- Zero phase shift mirrors for axion searches