観測天文学特別講義I @ 理1-1043
Observational Astronomy Advanced Course I

November 28, 2025

レーザー干渉計型重力波検出器
Laser interferometric gravitational wave detectors
6. Applications

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

https://yutamich.gitlab.io/lectures.html#lectures

Assignment for Nov 28

- Give one example of a research topic that can be done using the technologies of laser interferometric gravitational wave detectors, other than those mentioned in the lecture.
- You may also answer from the Google Form below https://forms.gle/6AwJ48XcpWQXqMon9

Don't forget to put your name and student#

You may answer in any language

FORM

Plan of the Lecture Today

- My research history
  - Tests of Lorentz invariance
  - Tests of quantum nature of gravity
  - Dark matter searches

- **Goal**: Understand how techniques used for laser interferometric gravitational wave detection can be applied to other fields

Dark Matter Detected!?

PRESS RELEASES

After nearly 100 years, scientists may have detected dark matter

Research news

Public Relations Office | Graduate School of Science / Faculty of Science

November 26, 2025

In the early 1930s, Swiss astronomer Fritz Zwicky observed galaxies in space moving faster than their mass should allow, prompting him to infer the presence of some invisible scaffolding — dark matter — holding the galaxies together. Nearly 100 years later, NASA's Fermi Gamma-ray Space Telescope may have provided direct evidence of dark matter, allowing the invisible matter to be "seen" for the very first time.

Dark matter has remained largely a mystery since it was proposed so many years ago. Up to this point, scientists have only been able to indirectly observe dark matter through its effects on observable matter, such as its ability to generate enough gravitational force to hold galaxies together. The reason dark matter can't be observed directly is because the particles that make up dark matter don't interact with electromagnetic force — meaning dark matter doesn't absorb, reflect or emit light.

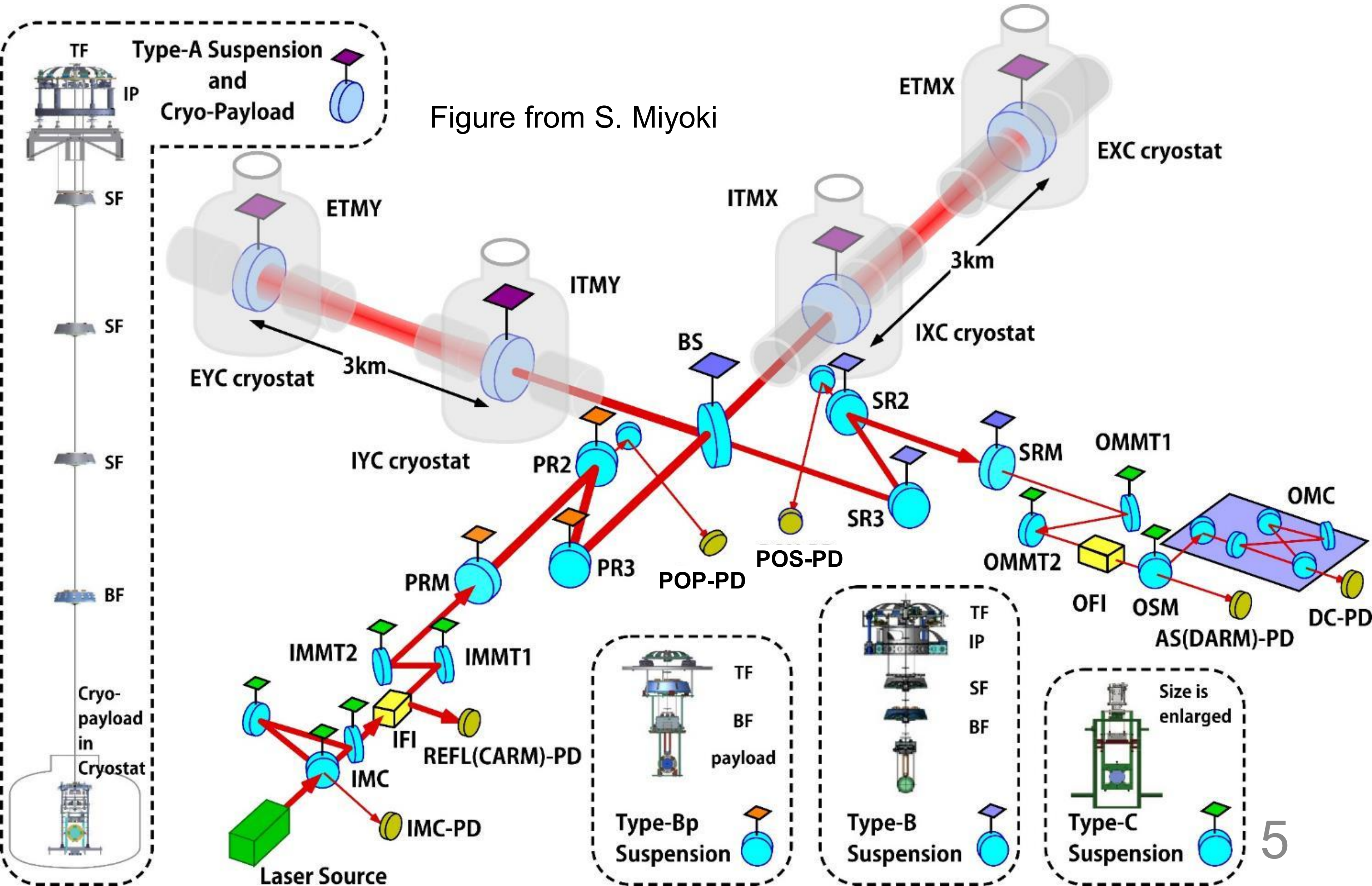
Theories abound, but many researchers hypothesize that dark matter is made up of something called weakly interacting massive particles, or WIMPs, which are heavier than protons but interact very little with other matter. Despite this lack of interaction, when two WIMPs collide, it is predicted that the two particles will annihilate one another and release other particles, including gamma ray photons.

Researchers have targeted regions where dark matter is concentrated, such as the center of the Milky Way, through astronomical observations for years in search of these specific gamma rays. Using the latest data from the Fermi Gamma-ray Space Telescope, Professor Tomonori Totani from the Department of Astronomy at the University of Tokyo believes he has finally detected the specific gamma rays predicted by the annihilation of theoretical dark matter particles.

Gamma-ray image of the Milky Way halo. Gamma-ray intensity map excluding components other than the halo, spanning approximately 100 degrees in the direction of the Galactic center. The horizontal gray bar in the central region corresponds to the Galactic plane area, which was excluded

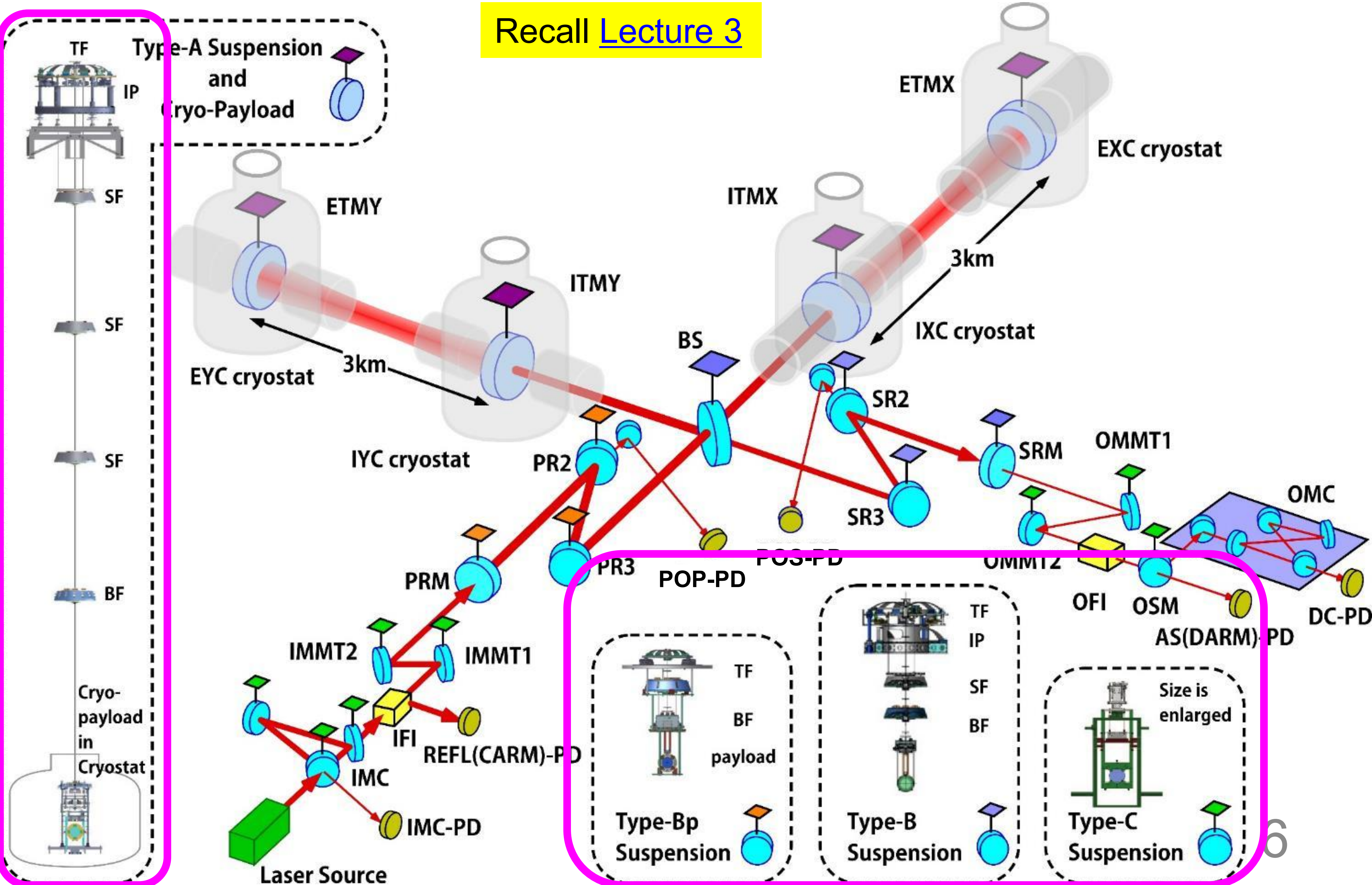
T. Totani,
[JCAP **11**, 080 (2025)]

Techniques for GW



Tech. for GW: Vibration Isolation

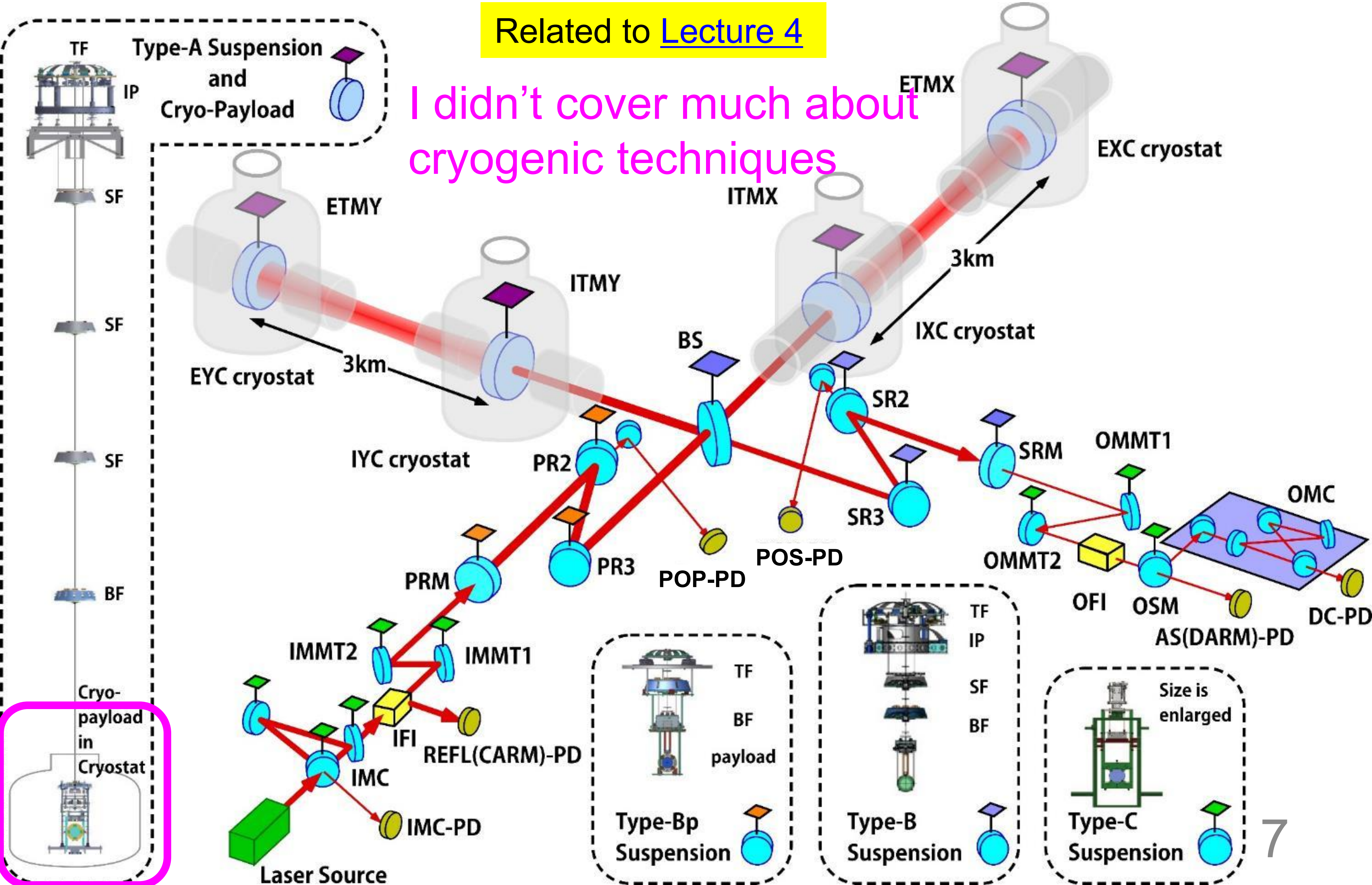
Recall Lecture 3



Tech. for GW: Cryogenics

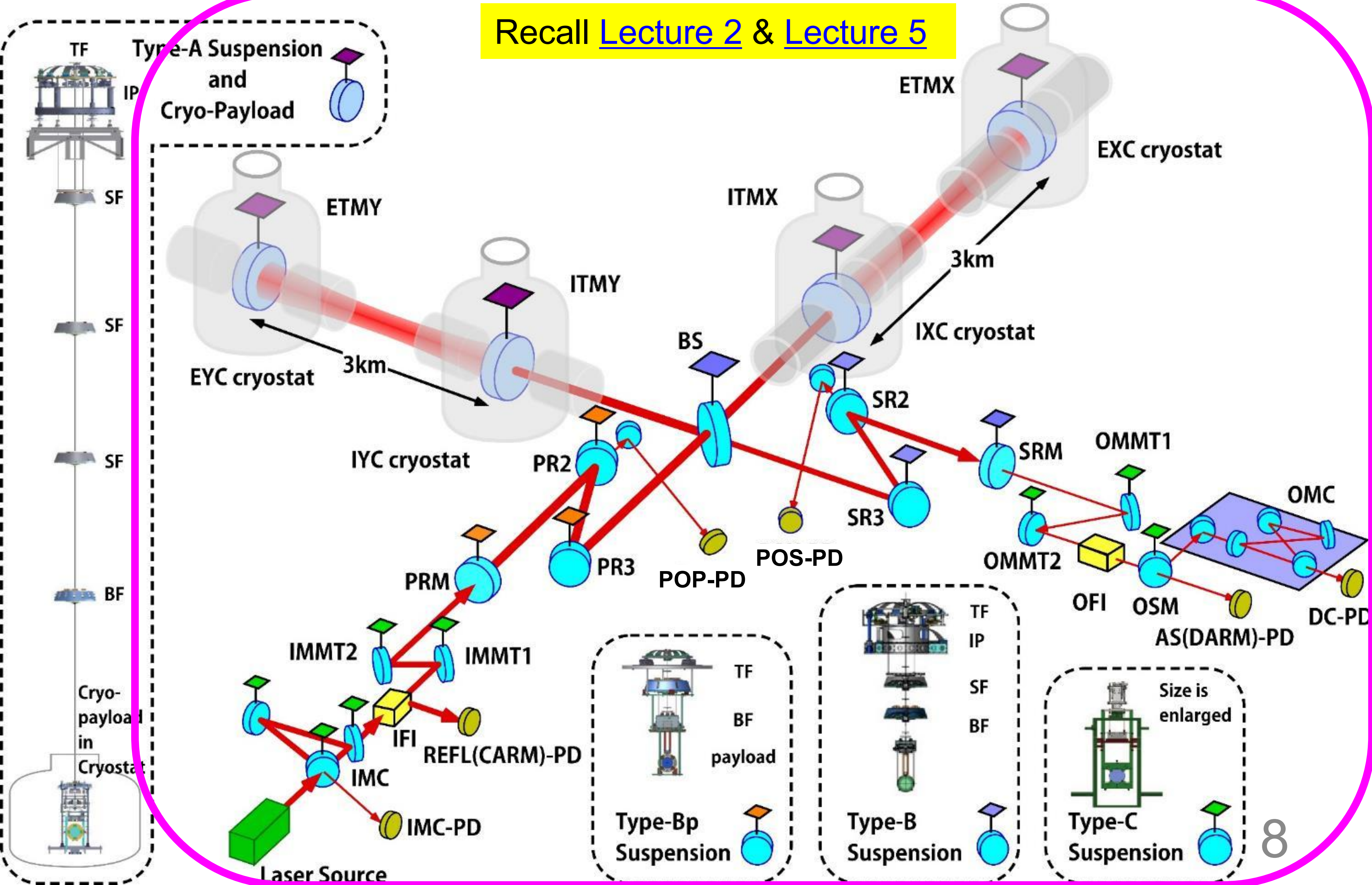
Related to Lecture 4

I didn't cover much about cryogenic techniques



Tech. for GW: Interferometry

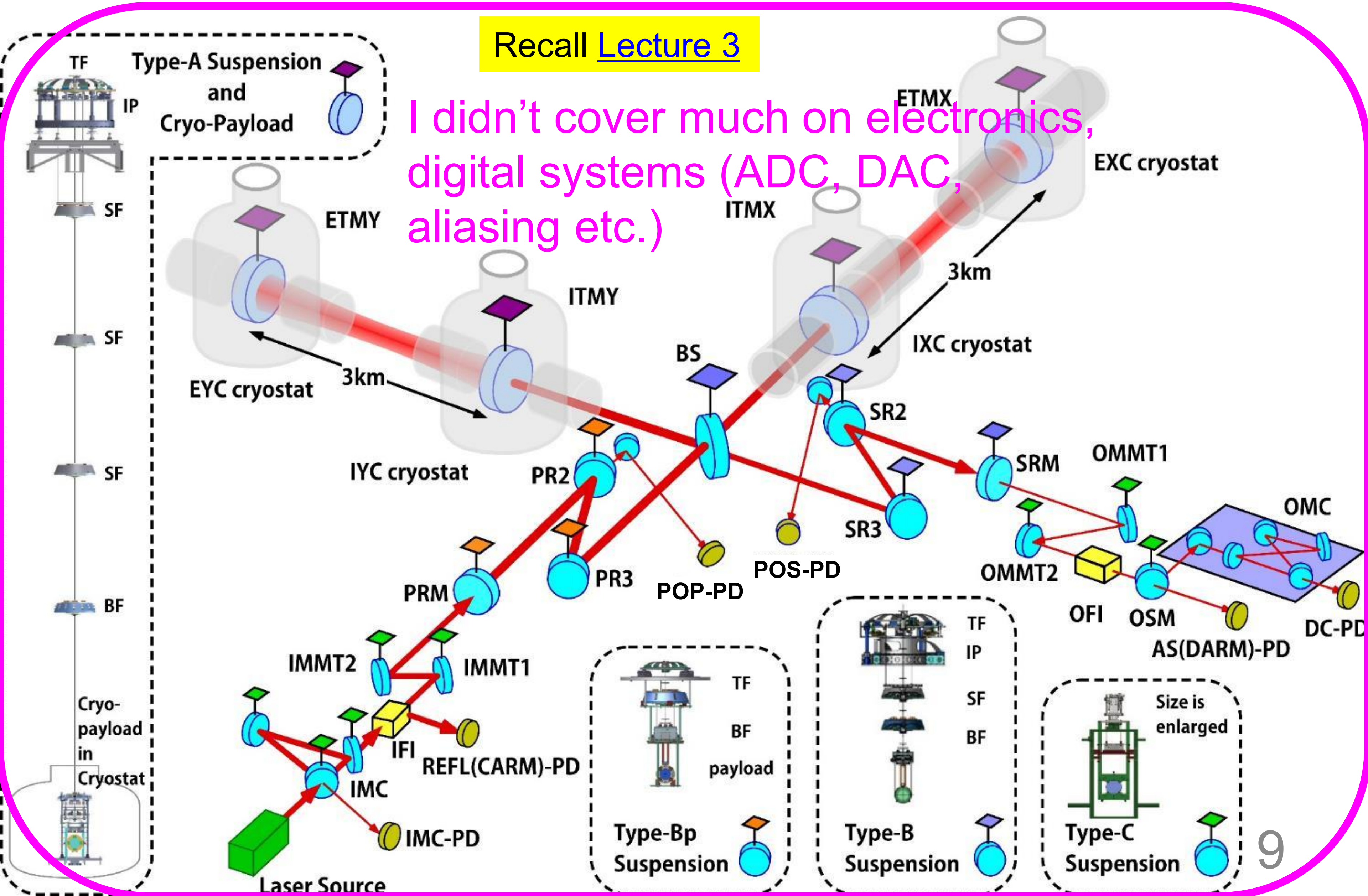
Recall Lecture 2 & Lecture 5



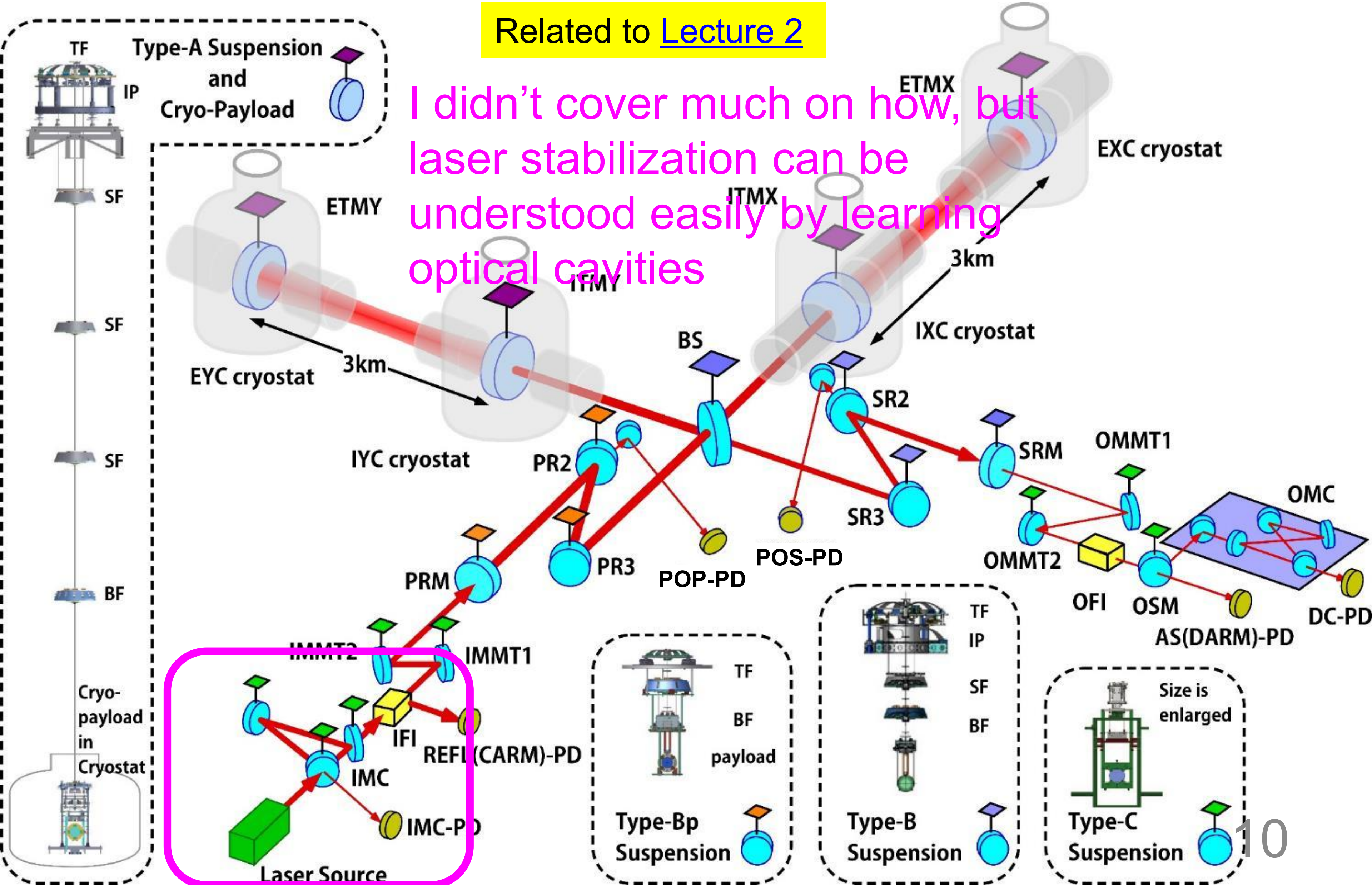
Tech. for GW: Feedback Controls

Recall Lecture 3

I didn't cover much on electronics, digital systems (ADC, DAC, aliasing etc.)



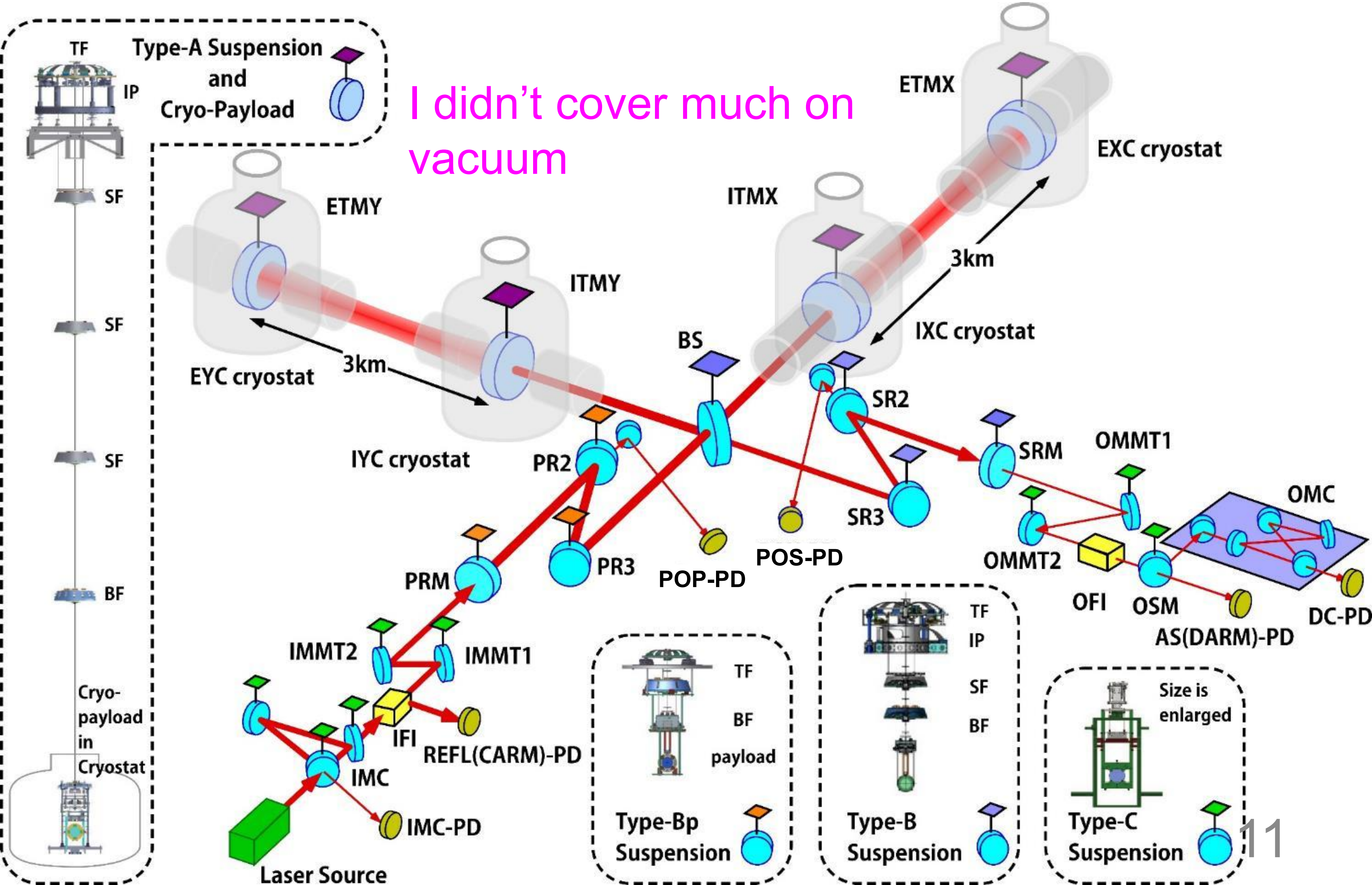
Tech. for GW: Laser Stabilization



Related to Lecture 2

I didn’t cover much on how, but laser stabilization can be understood easily by learning optical cavities

Tech. for GW: Vacuum

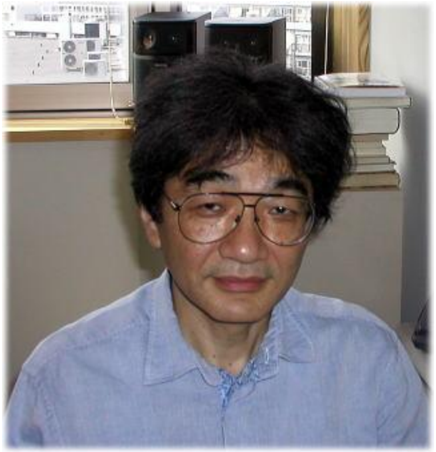


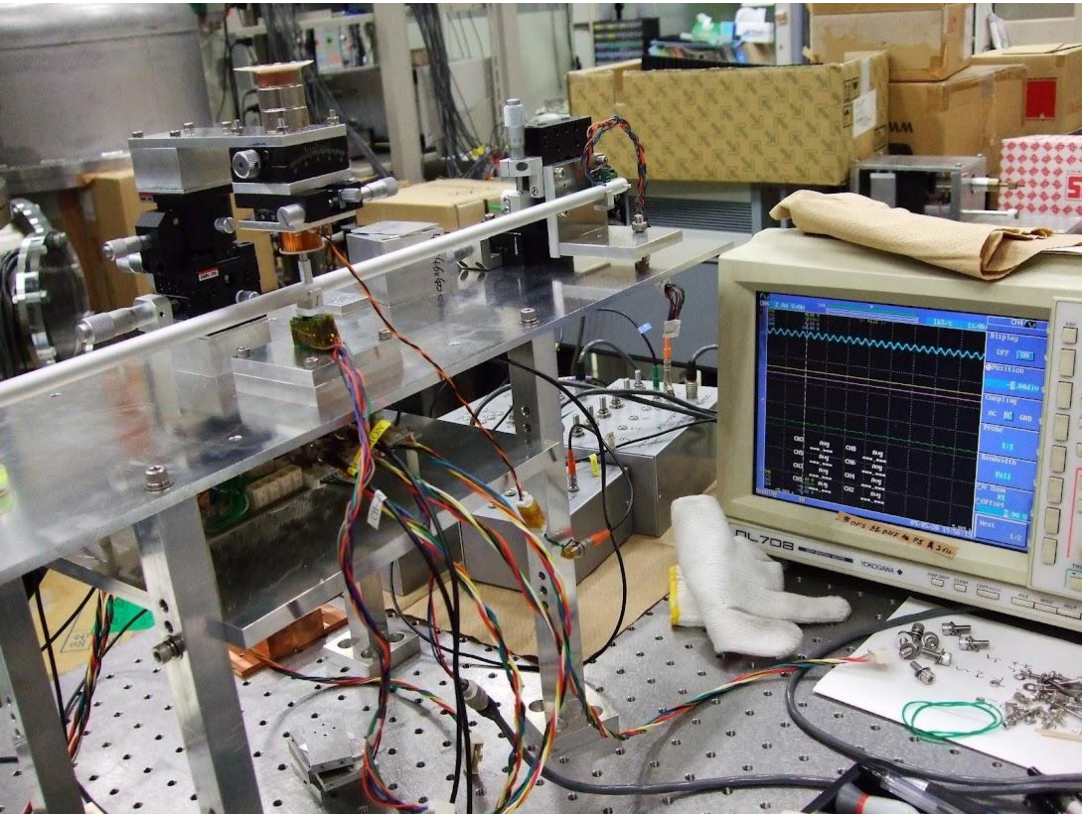
I didn't cover much on vacuum

2009- (B4)

Magnetic Levitation

- Joined Tsubono Group for 特別実験
- Magnetic levitation of a torsion pendulum
  - Just for a start

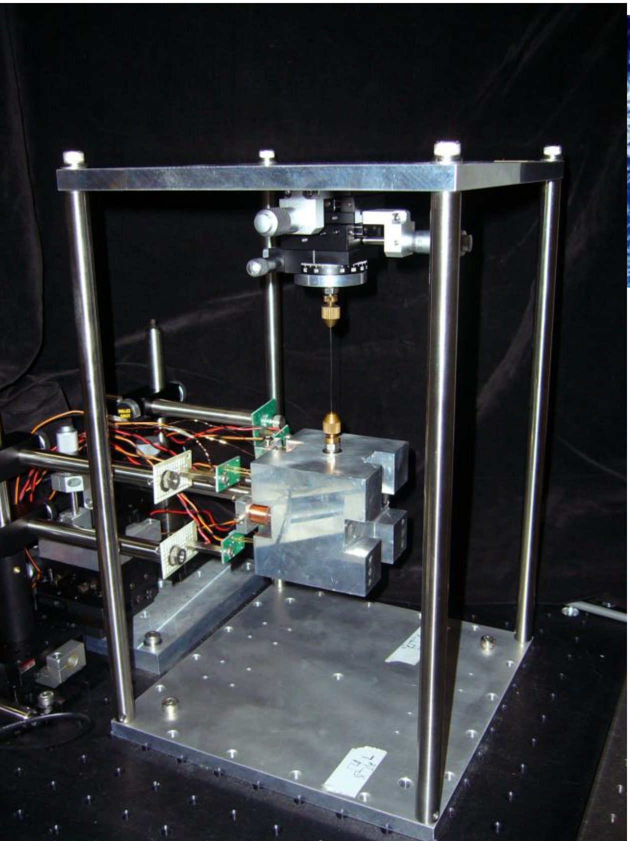


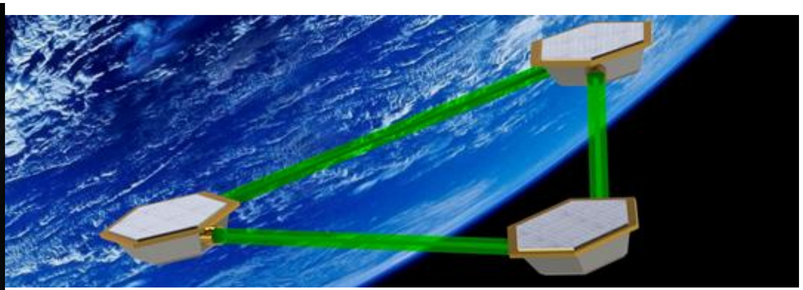


2009- (B4)

Test Mass for DPF

- Digital control of suspended test mass for DECIGO Pathfinder
  - Just because Shoda-san wanted to do something with satellite

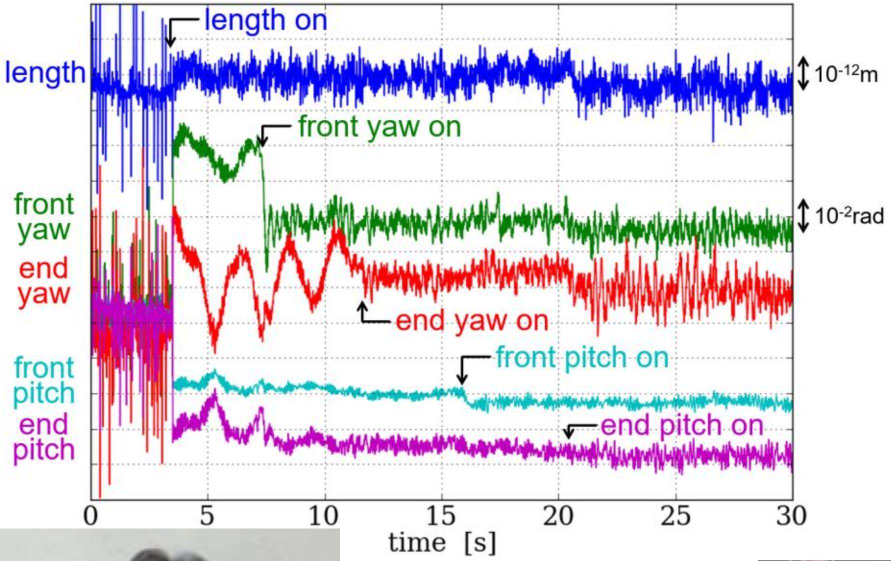


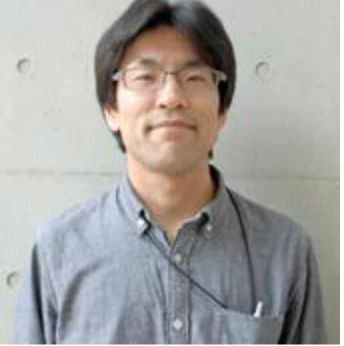


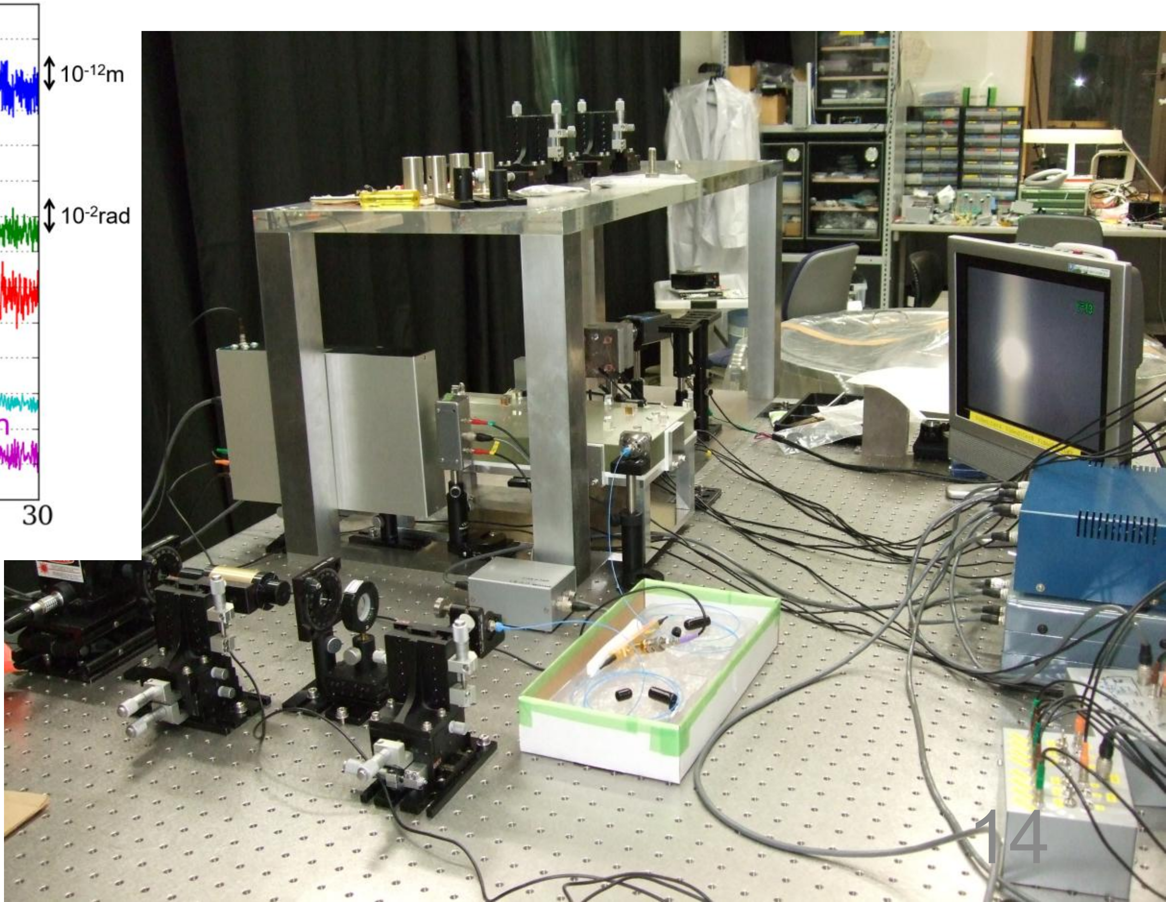
2009- (B4/M1)

FP for DPF

- Digital control of suspended Fabry-Perot cavity for DECIGO Pathfinder (DPF)
  - First demonstration of locking full degrees of freedom using FPGAs and monolithic optical bench





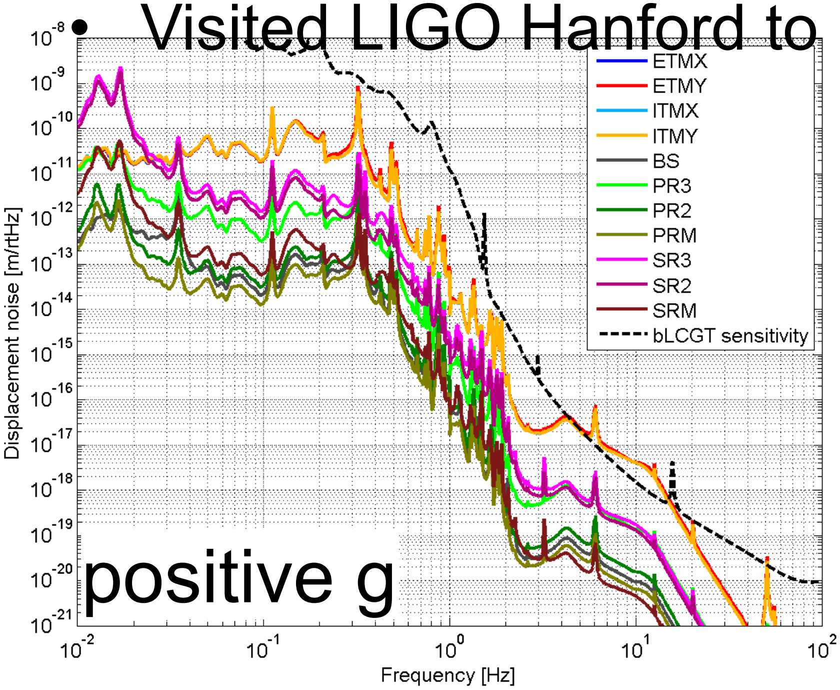


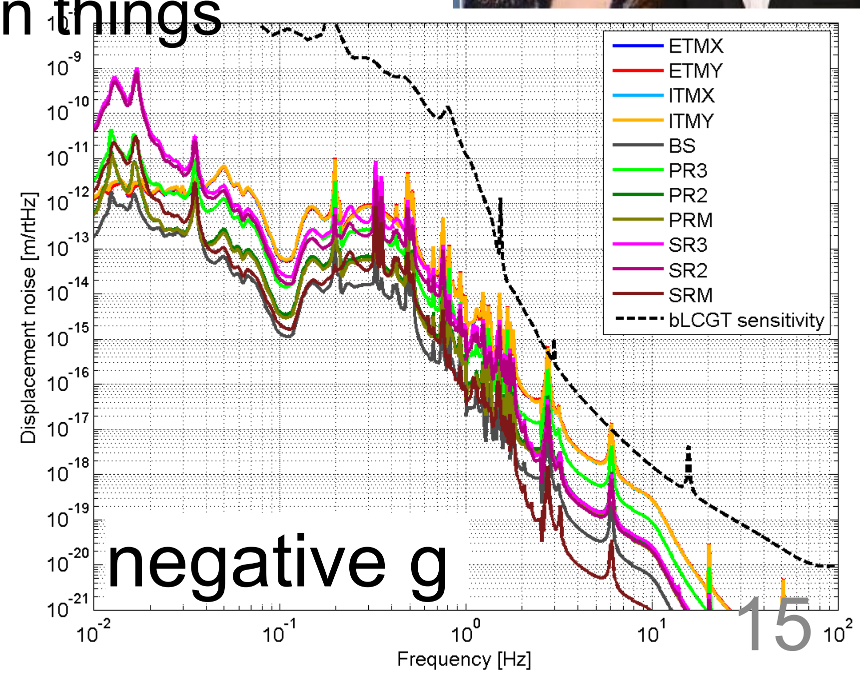
2010- (M1/M2)

ASC for LCGT

- LCGT (now called KAGRA) was funded
- Aso-san asked me to work on alignment sensing and controls (ASC) simulation for LCGT
  - Just because I had an experience in ASC for DECIGO Pathfinder

- Learned more on interferometer
- Visited LIGO Hanford to learn things

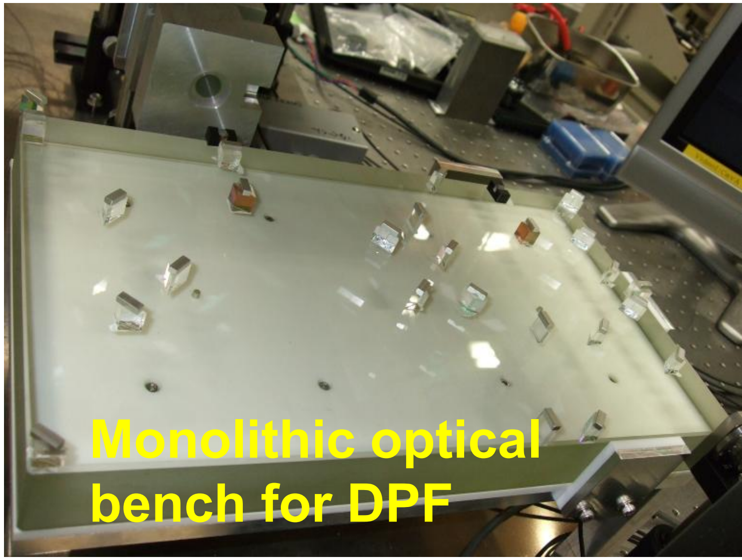


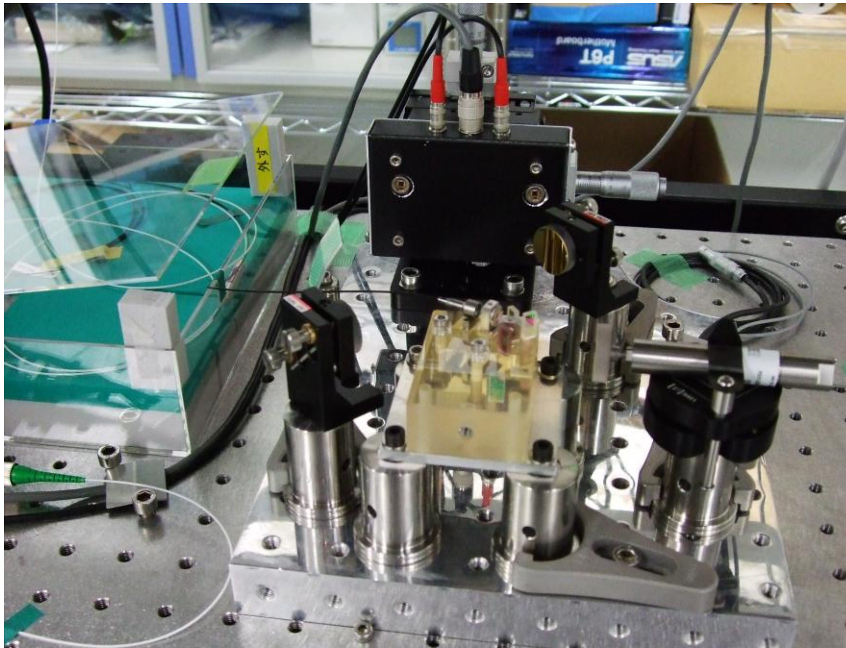


2011- (M1/M2)

Monolithic Michelson

- Characterization of monolithic Michelson interferometer at Kyoto University
  - Just because of Tohoku Earthquake


Monolithic optical bench for DPF



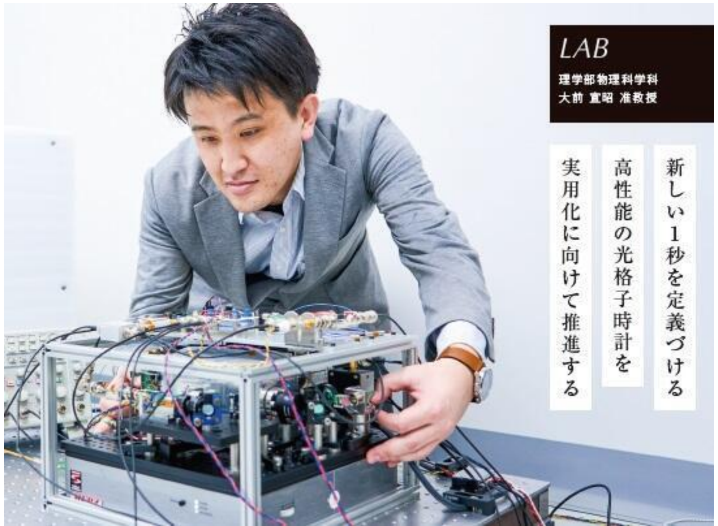
2011- (M2)

Lorentz Invariance

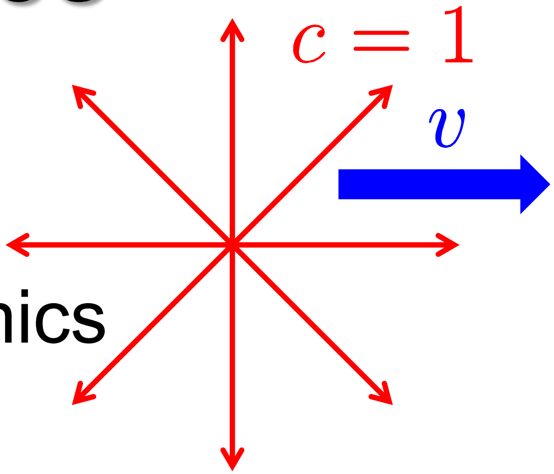
- Ando-san suggested to work on Lorentz invariance test using a monolithic Michelson interferometer
- But Michelson Morley-type of tests seemed too hard, and found that odd-parity tests could be easier
- Kokuyama-san found this groundbreaking paper

  Qasem Exirifard, arXiv:1010.2057

- Ohmae-san who is an expert on double-pass configuration was also in Tsubono Group
- Decided to work on odd-parity test for my Masters in July of M2

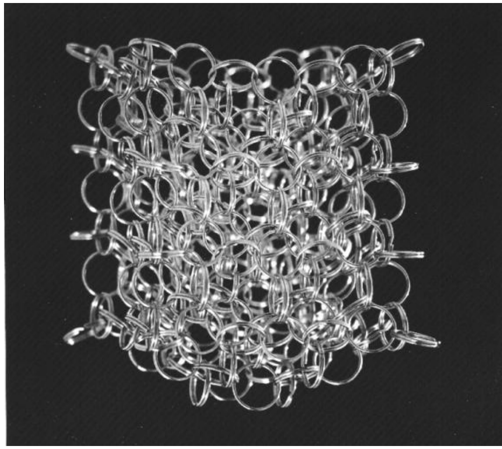


Lorentz Invariance



- Special Relativity (1905)
  speed of light is constant
- Lorentz invariance in electrodynamics
- no one could find any violation
- but…
  - quantum gravity suggests
    violation at some level
    e.g. $\delta c/c \sim 10^{-17}$

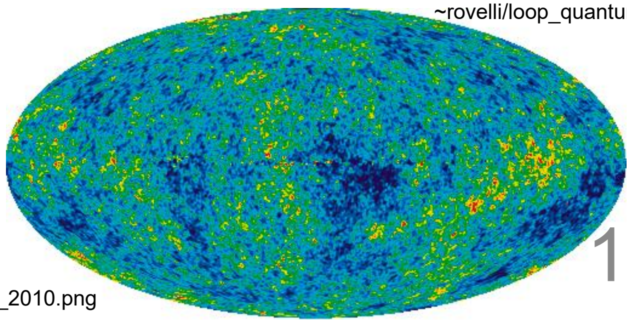
D. Colladay and V. Alan Kostelecký:PRD 58 (1998) 116002



http://www.cpt.univ-mrs.fr/~rovelli/loop_quantum_gravity.jpg

  - anisotropy in CMB
    possible preferred frame?

$\longrightarrow$ motivation for testing SR

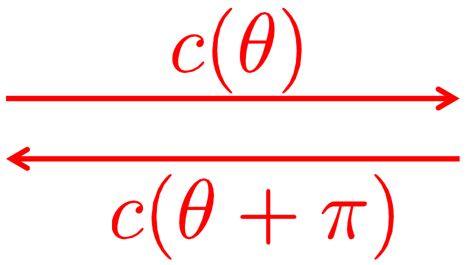


http://en.wikipedia.org/wiki/File:WMAP_2010.png

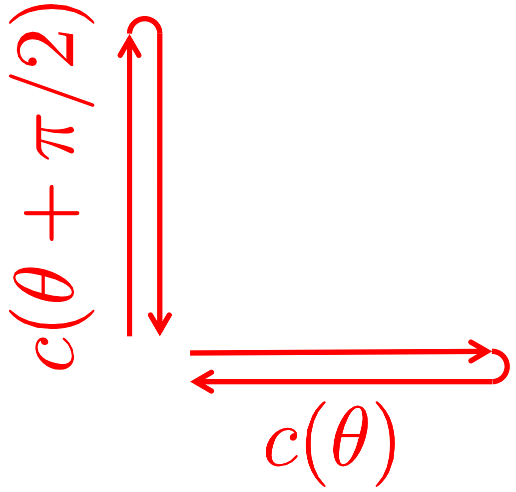
Test of Lorentz Invariance

- We focus especially on the isotropy of the speed of light (Lorentz invariance in photons)
- two types of test: even-parity and odd-parity

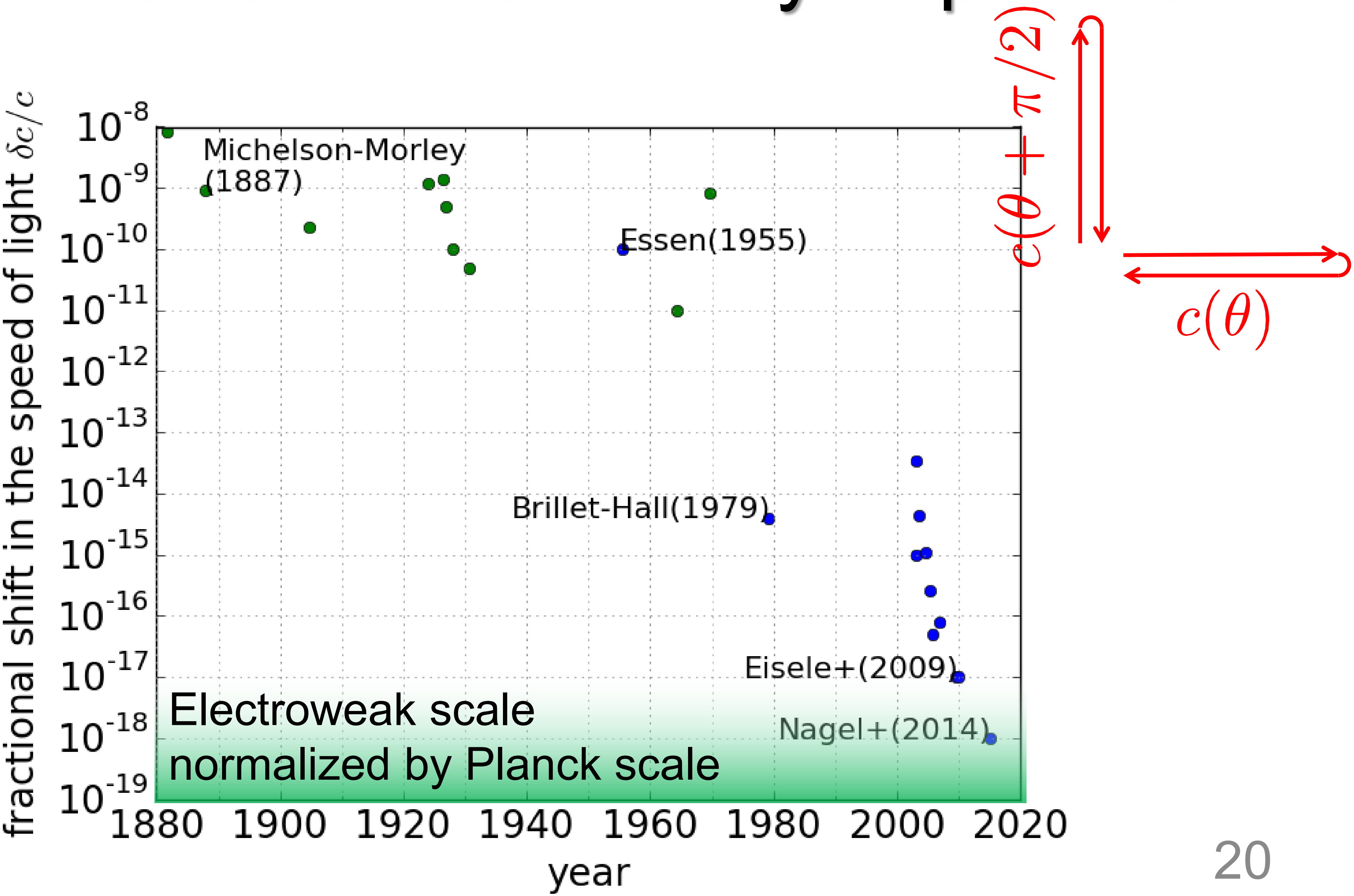
odd-parity test
(Ives-Stilwell type test)



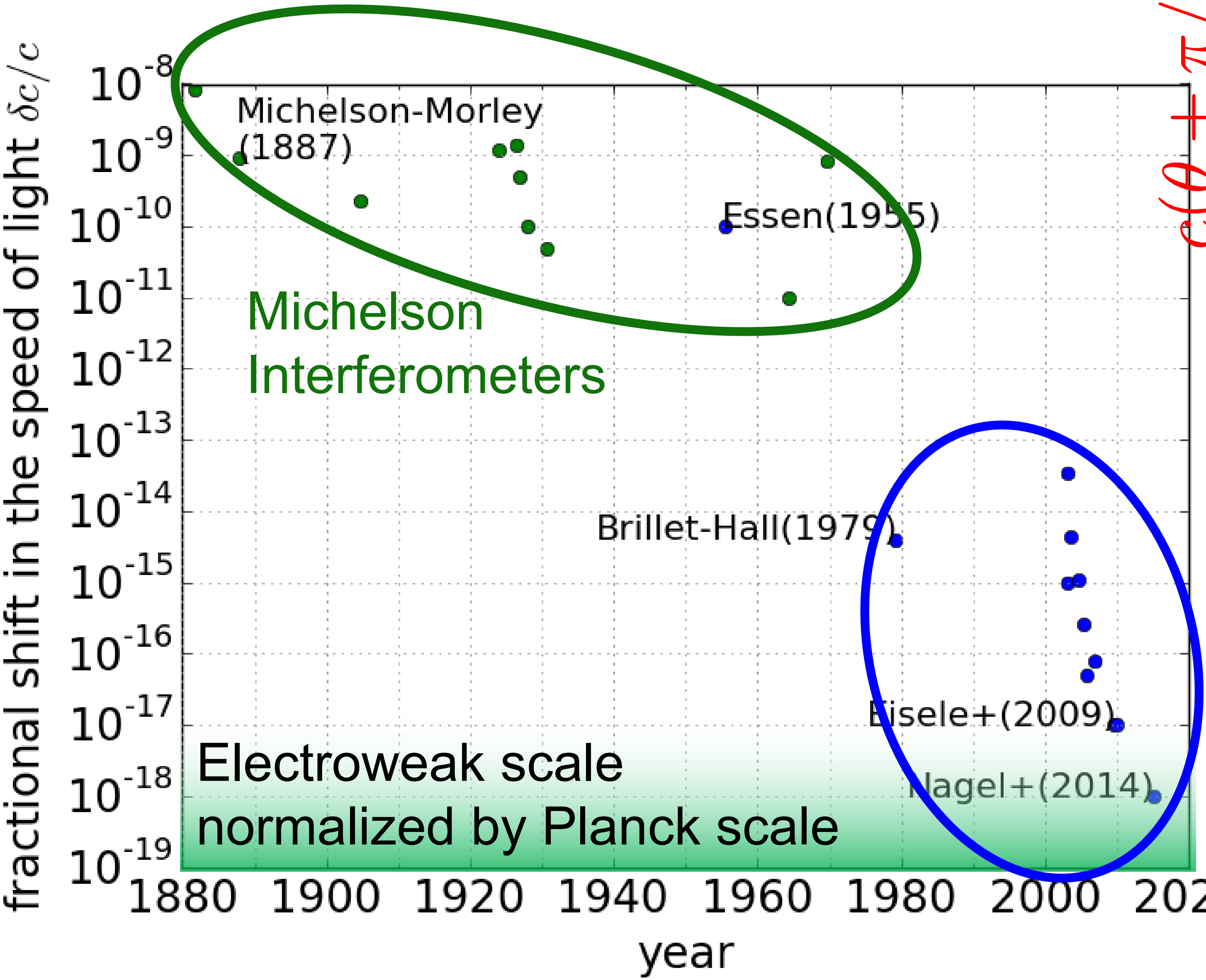
even-parity test
(Michelson-Morley type test)



Previous Even-Parity Experiments



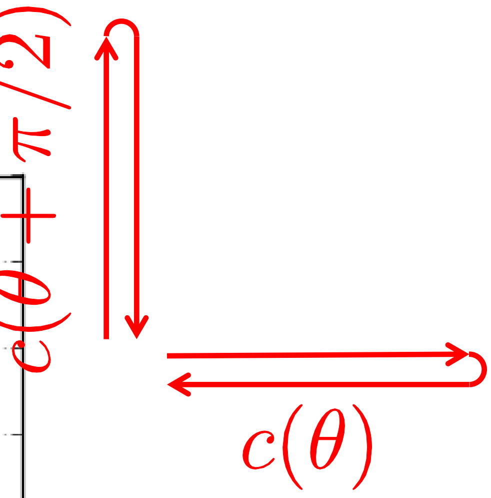
Previous Even-Parity Experiments



Michelson Interferometers

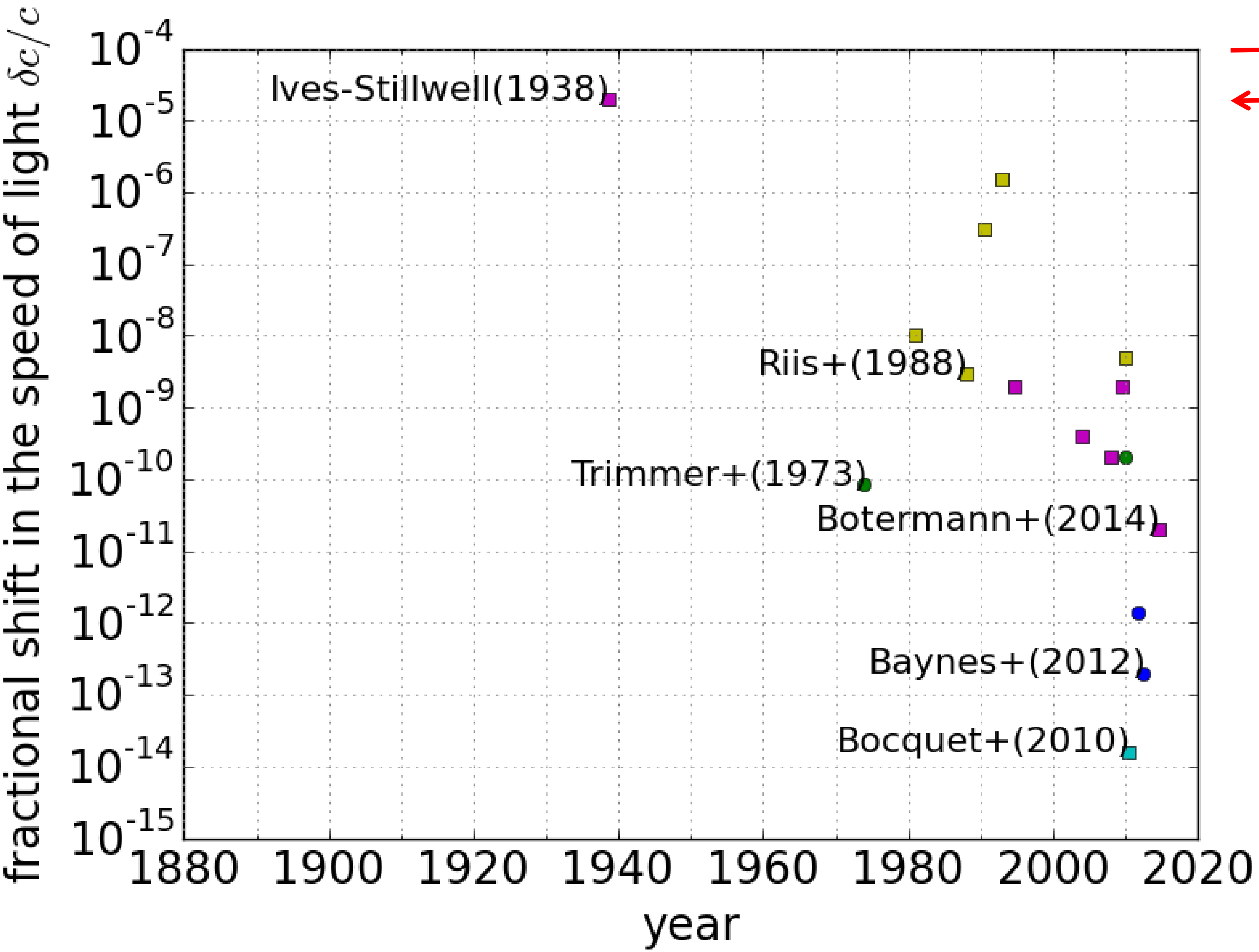
Electroweak scale normalized by Planck scale

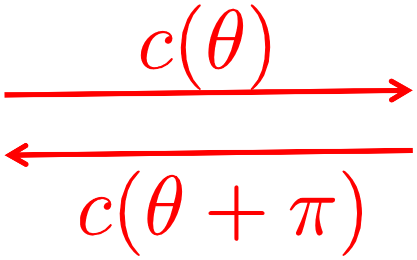
Optical and microwave cavities



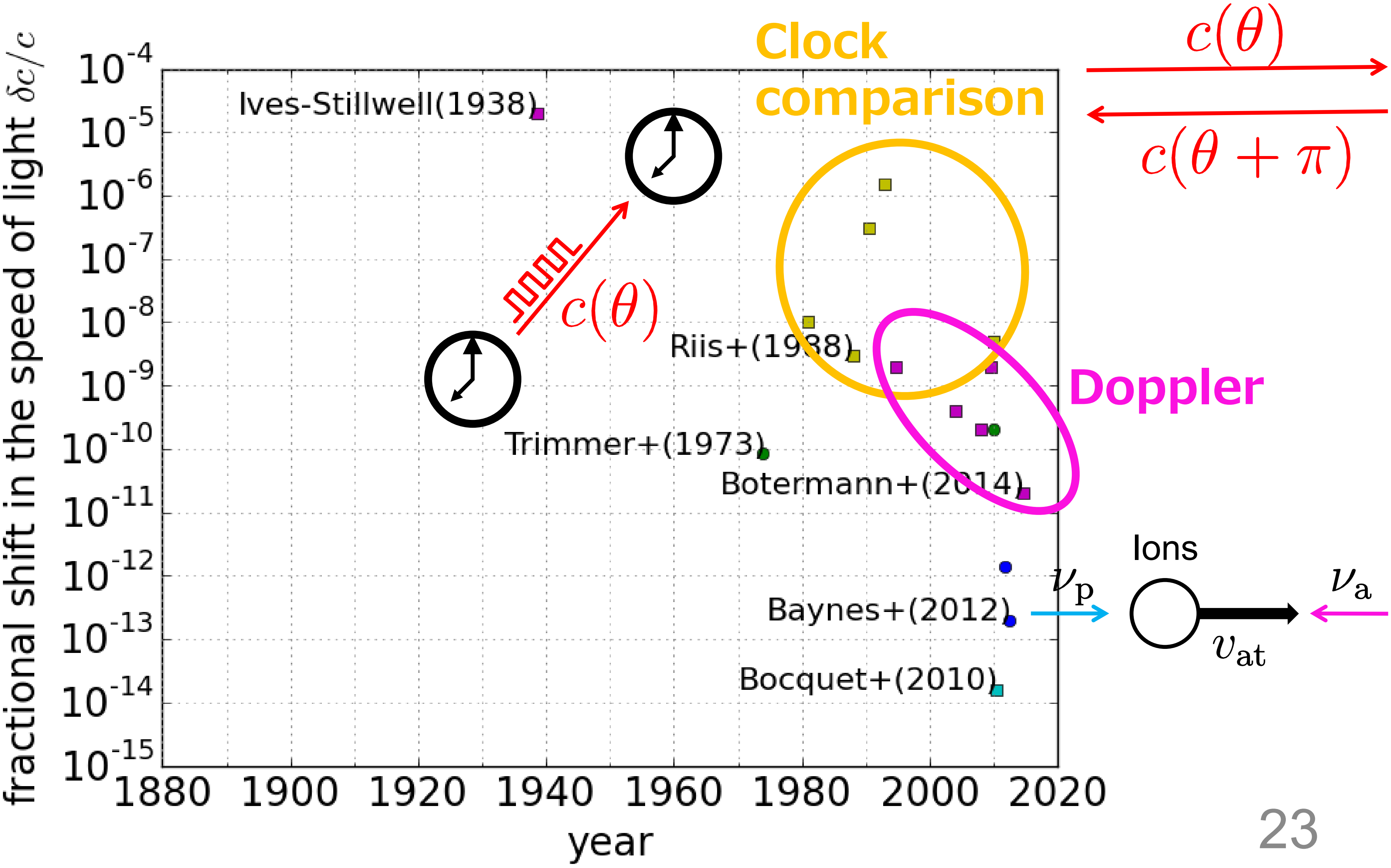
$$\left|\frac{\delta c}{c}\right| \lesssim 10^{-18}$$

Previous Odd-Parity Experiments



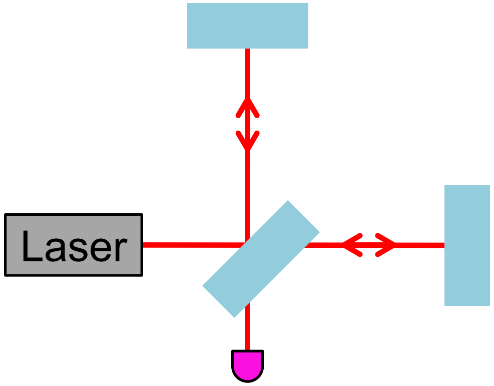


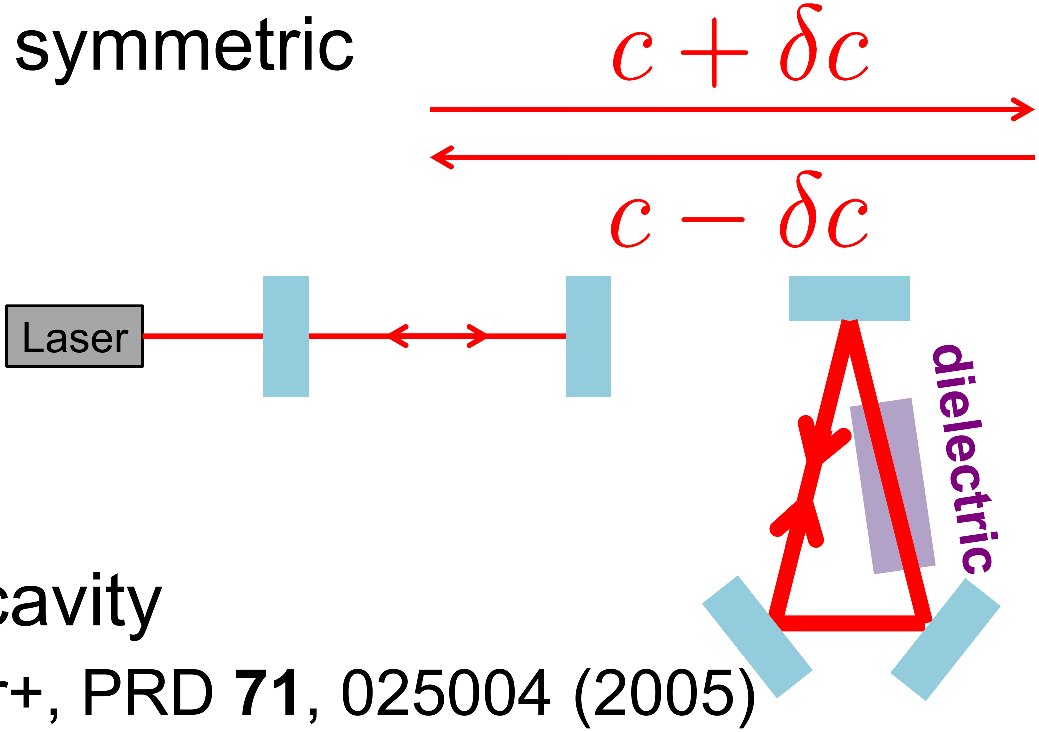
Previous Odd-Parity Experiments



Odd-Parity with Interferometers?

- Not easy with ordinary interferometers or cavities since they are parity symmetric





- Asymmetric optical cavity

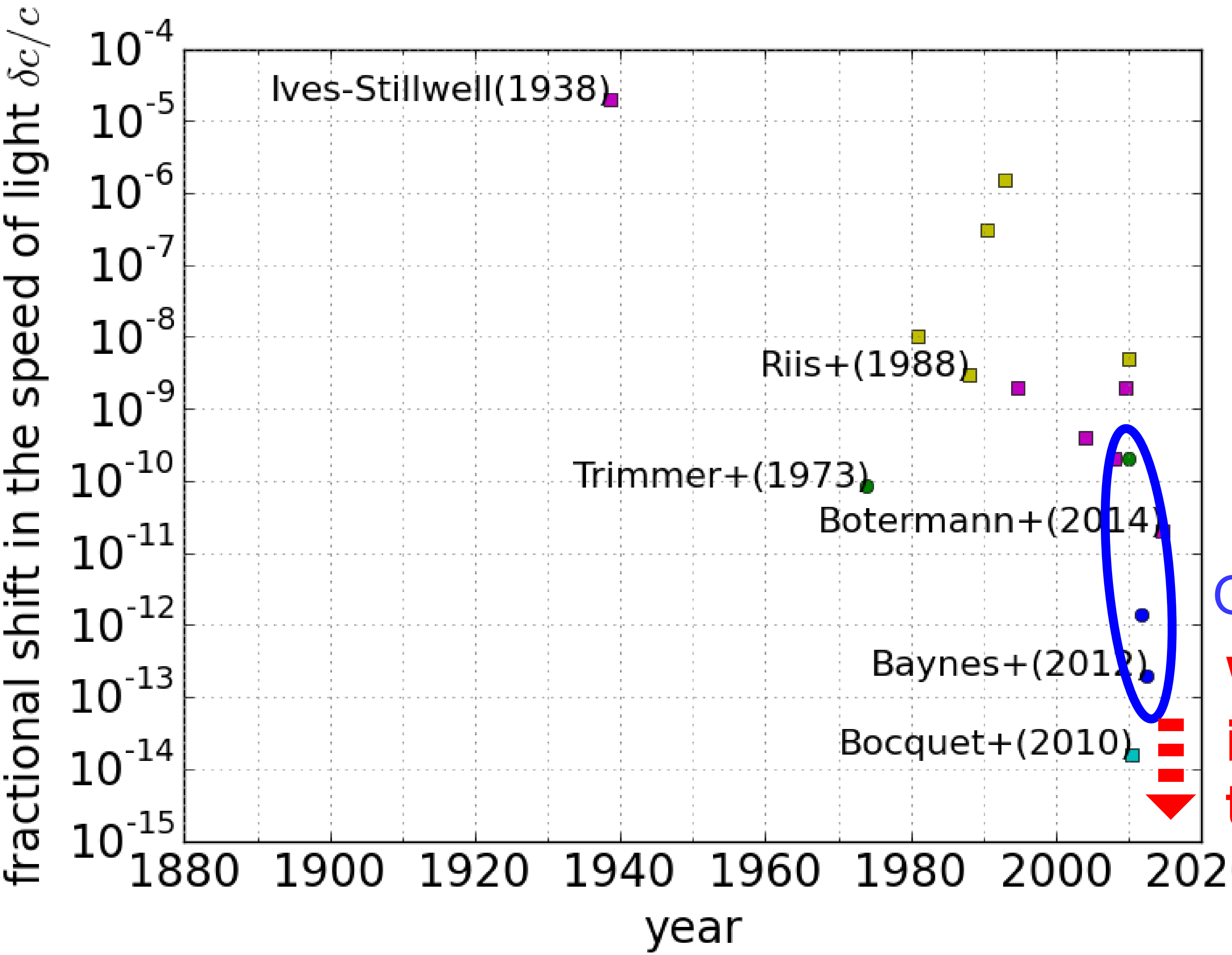
  Proposal: M. E. Tobar+, PRD **71**, 025004 (2005)

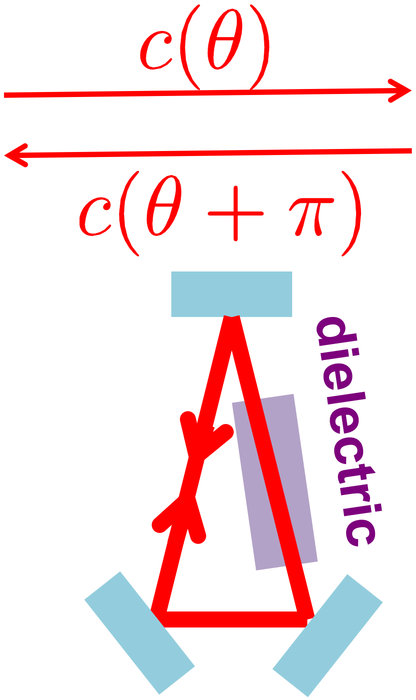
  Demonstration: F. Baynes+, PRL **108**, 260801 (2012)

$$\left| \frac{\delta c}{c} \right| \lesssim 10^{-13}$$

→ We have improved the sensitivity in this kind of experiments

Previous Odd-Parity Experiments

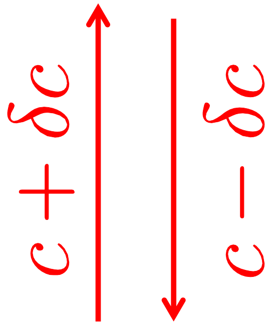
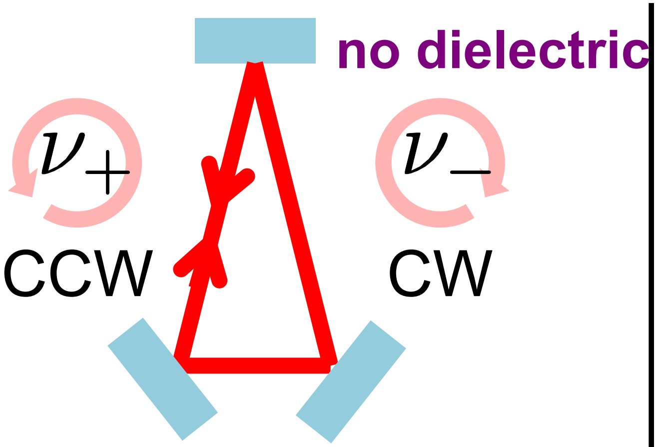
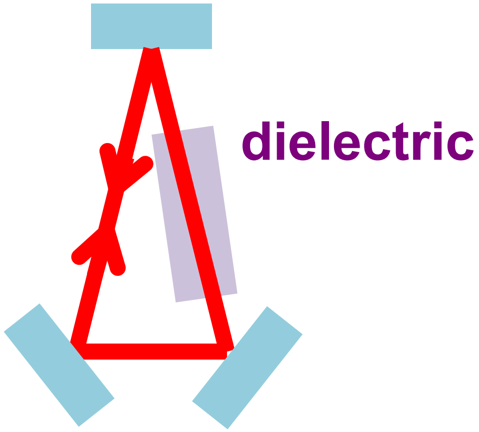




We improved the limit

Optical Ring Cavity

- sensitive to LV when a dielectric is contained

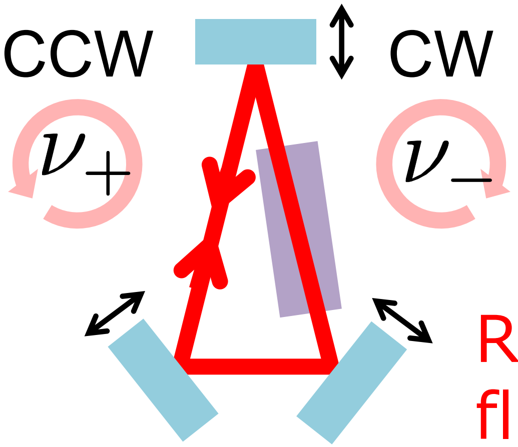
		
no LV	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu$ $\nu_- = \nu$
LV	$\nu_+ = \nu_0$ $\nu_- = \nu_0$	$\nu_+ = \nu - \delta\nu$ $\nu_- = \nu + \delta\nu$

freq. shift ∝ LV

- $\nu_+ - \nu_-$ gives LV signal (null measurement)

Differential Measurement

- Cavity length change gives common resonant frequency change, and can be rejected by differential measurement
- Highly insensitive to environmental disturbances
- Differential measurement done by double-pass configuration



$$\nu_+ = \nu + \delta\nu_{\mathrm{noise}} - \delta\nu_{\mathrm{LV}}$$
$$\nu_- = \nu + \delta\nu_{\mathrm{noise}} + \delta\nu_{\mathrm{LV}}$$

Resonant frequency fluctuation from cavity length change is common

Resonant frequency shift from LV is differential

Techniques for GW Applied

- Silicon for large asymmetry (high refractive index)
  - Considered for next gen. detectors
- Hänsch-Couillaud method (偏光解析法)
- Double-pass configuration
  - Considered for laser stabilization

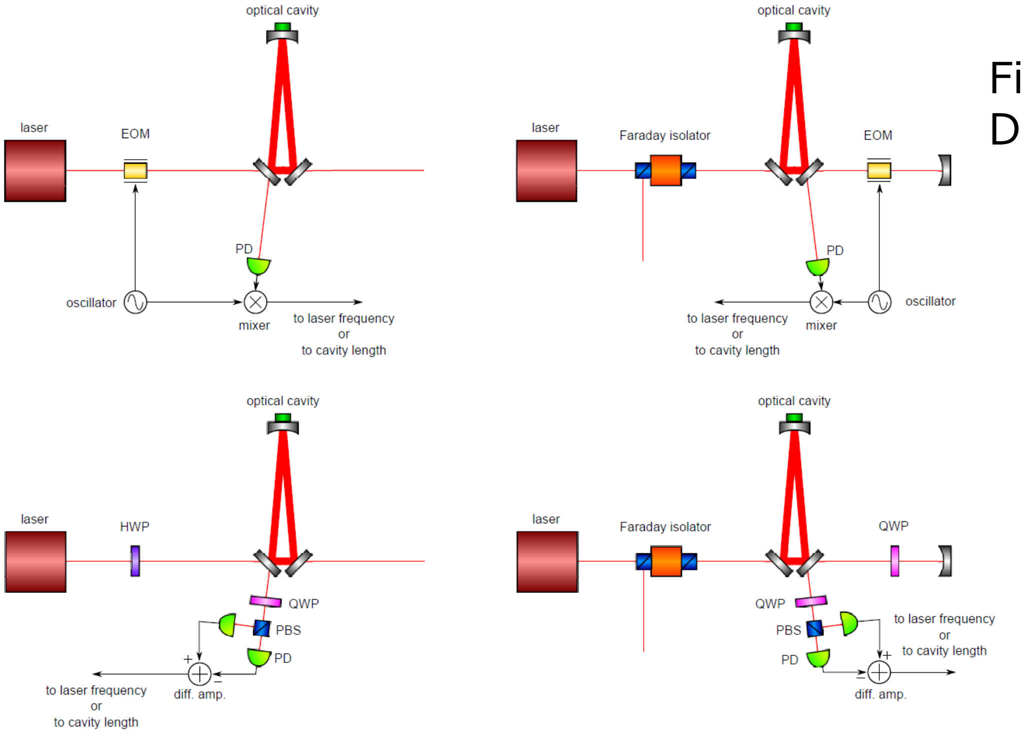
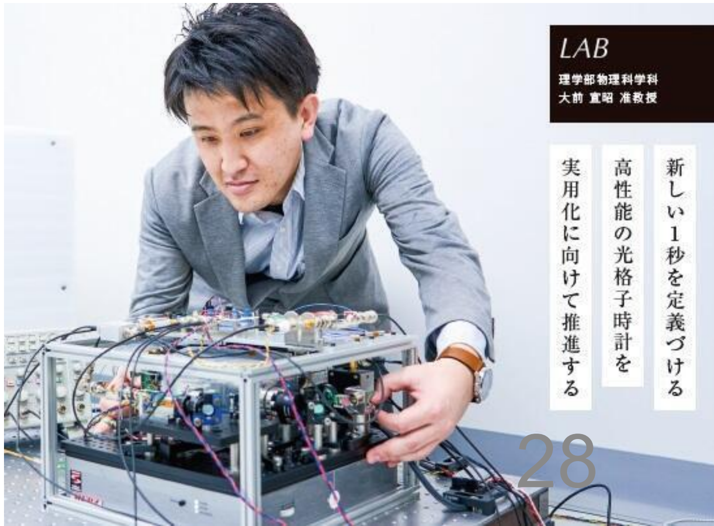
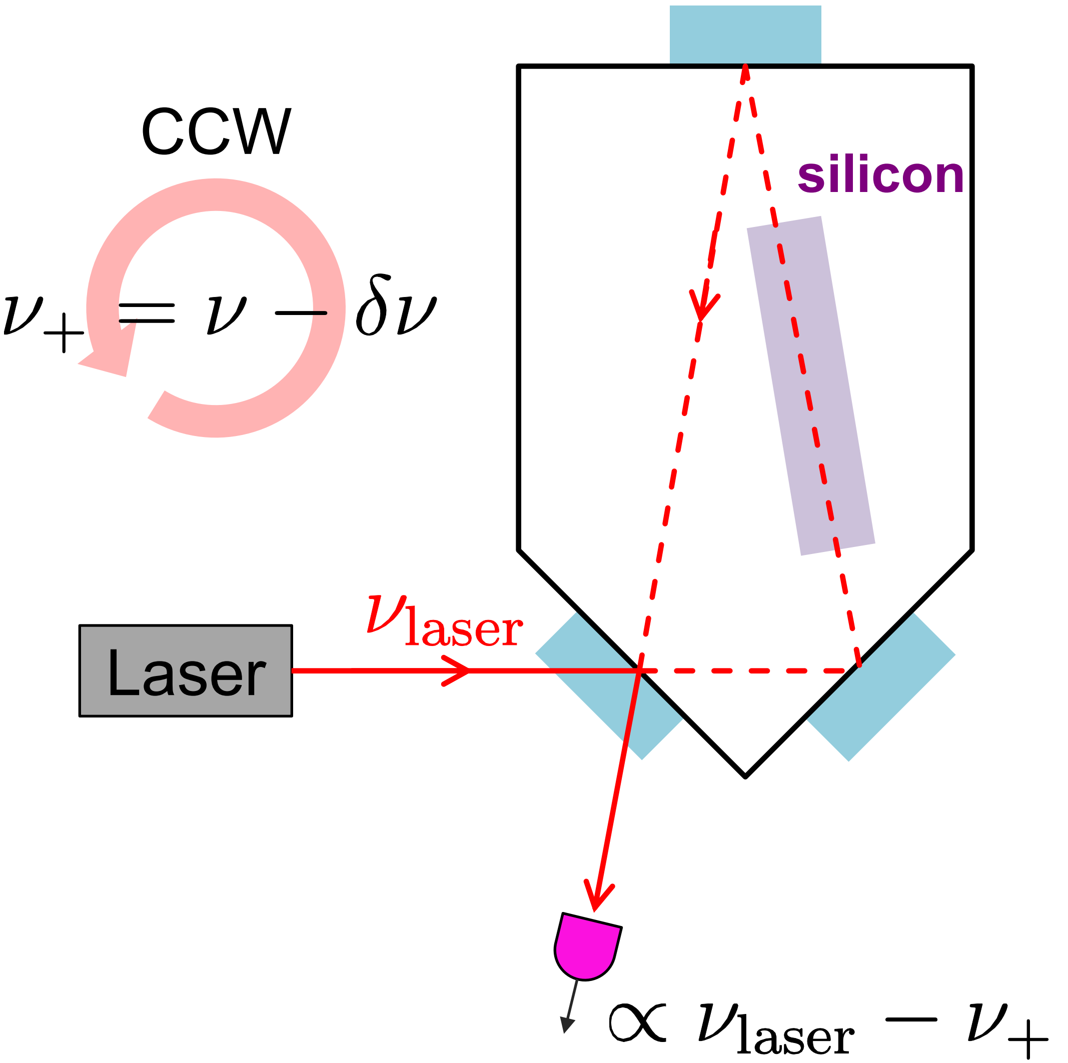


Figure from N. Ohmae,
Doctoral Thesis (UTokyo 2011)



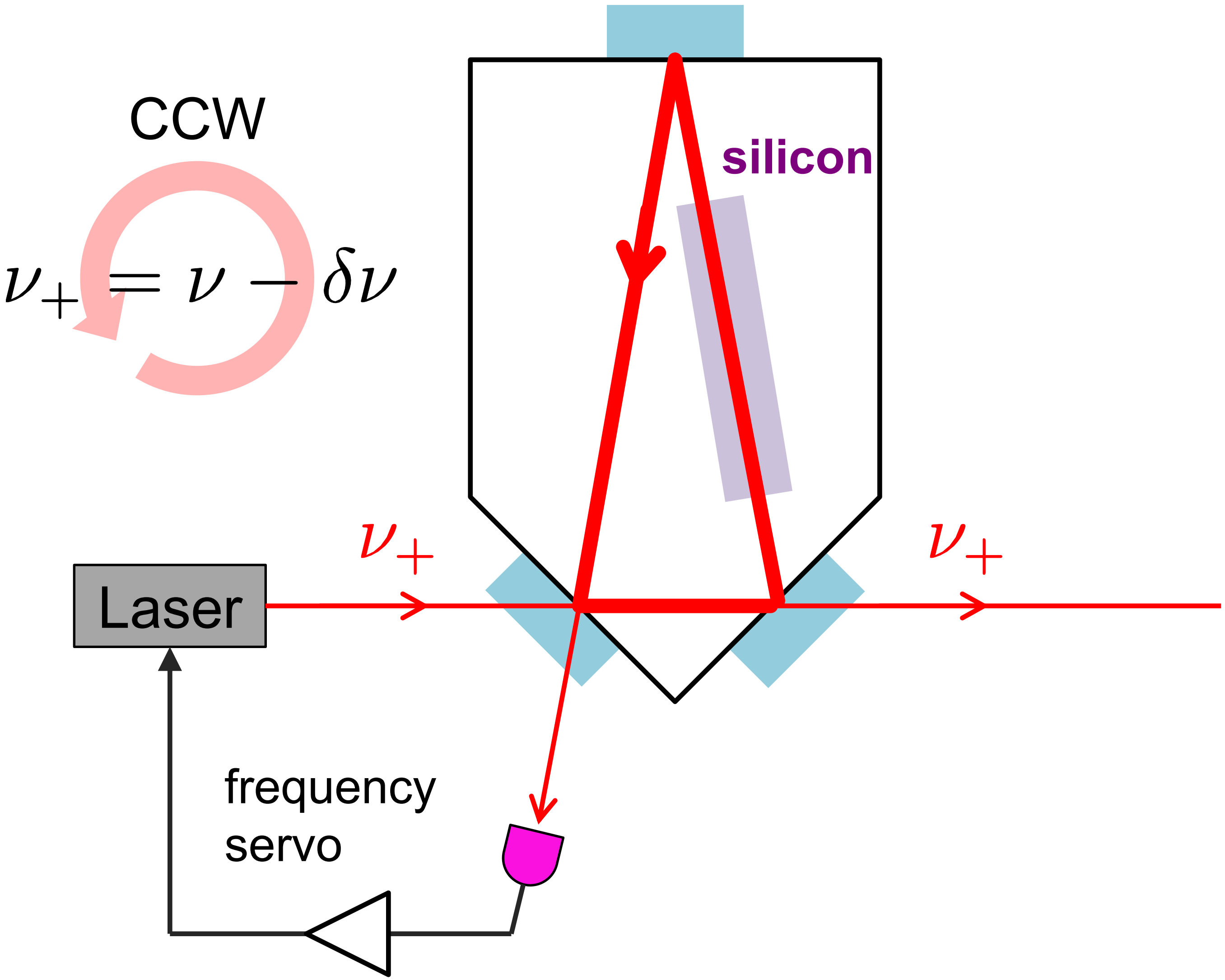
Double-Pass Configuration 1/4

- inject laser beam in CCW



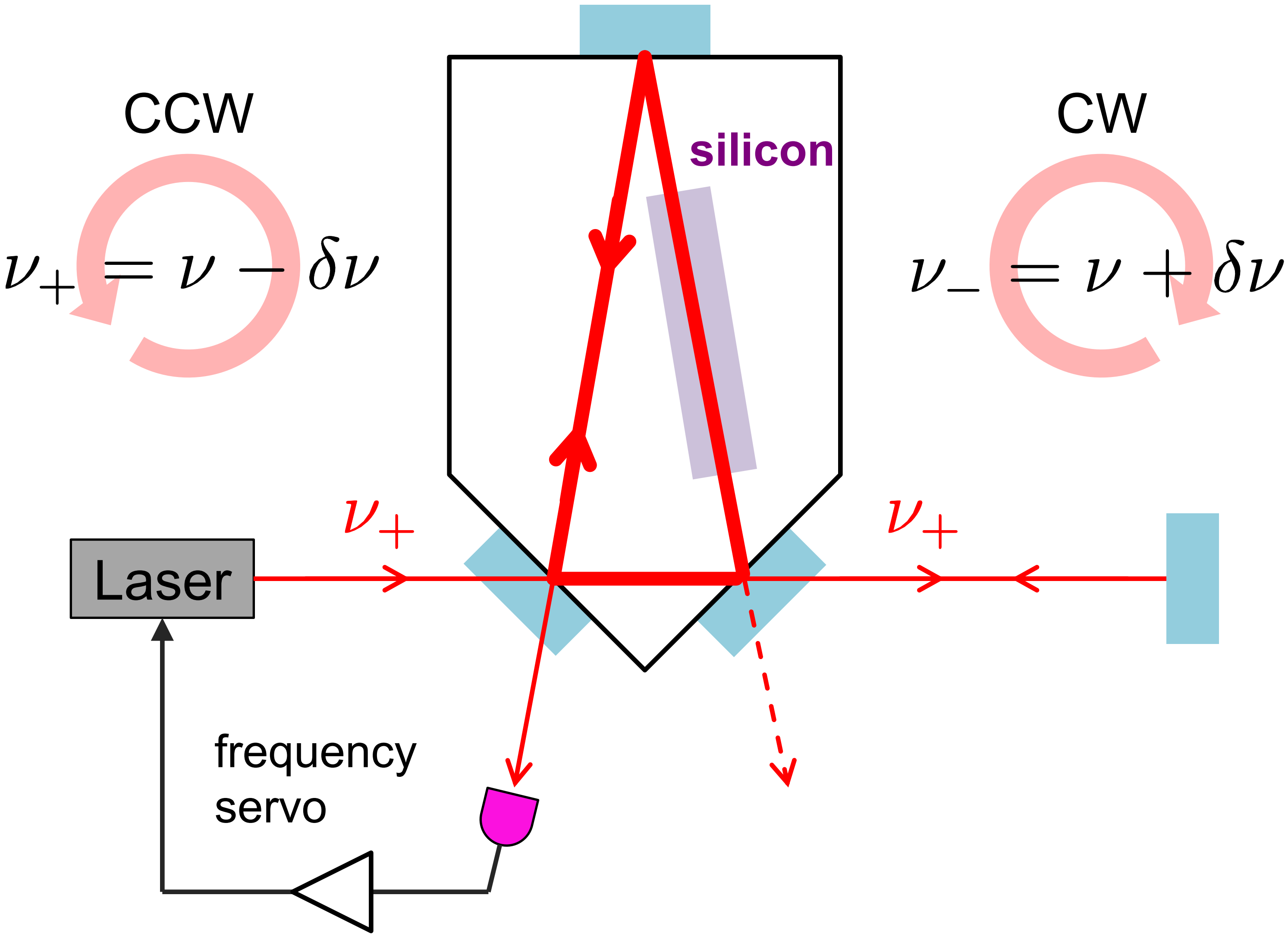
Double-Pass Configuration 2/4

- lock laser frequency to CCW resonance (ν_+)



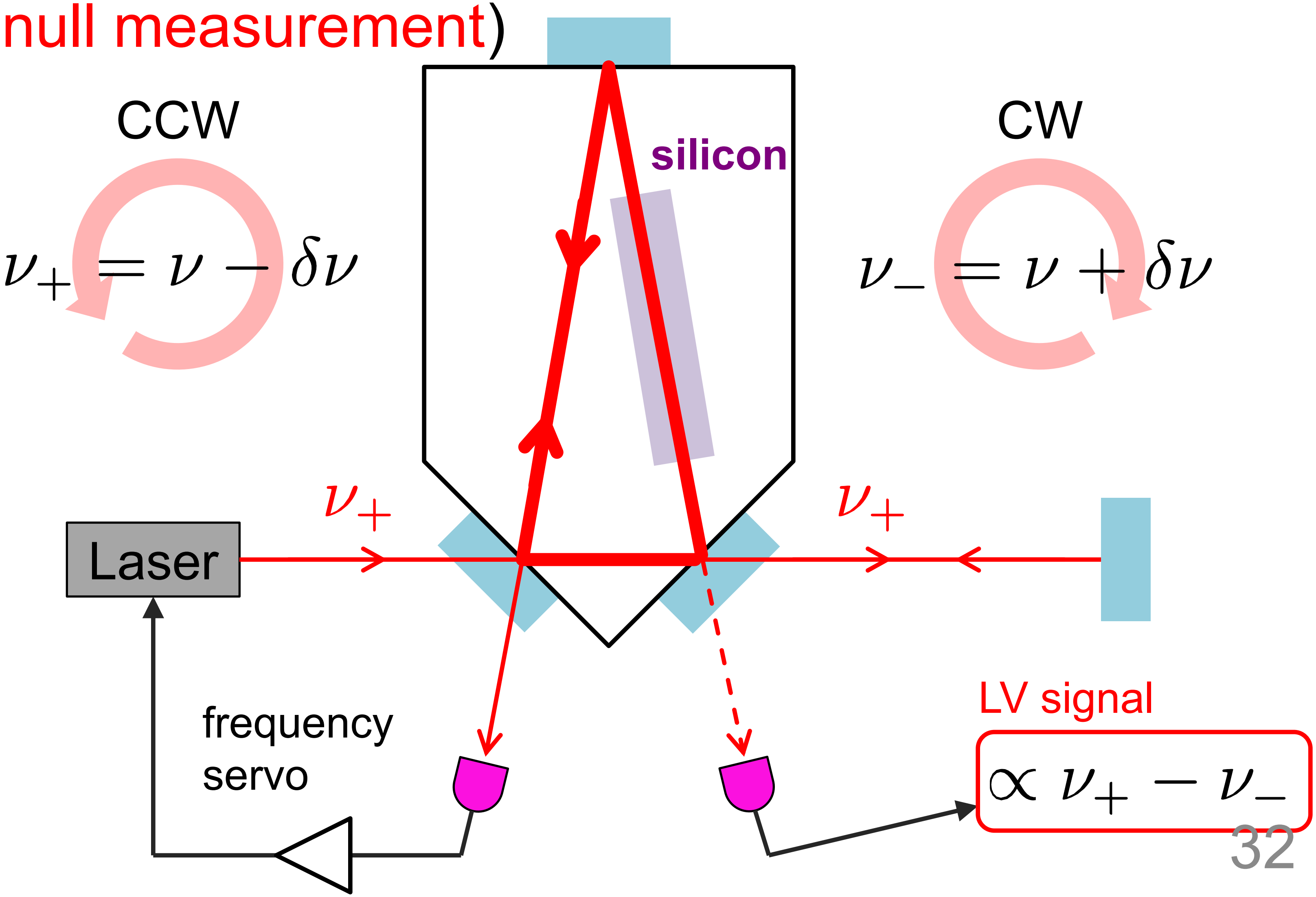
Double-Pass Configuration 3/4

- reflect the beam back into the cavity in CW



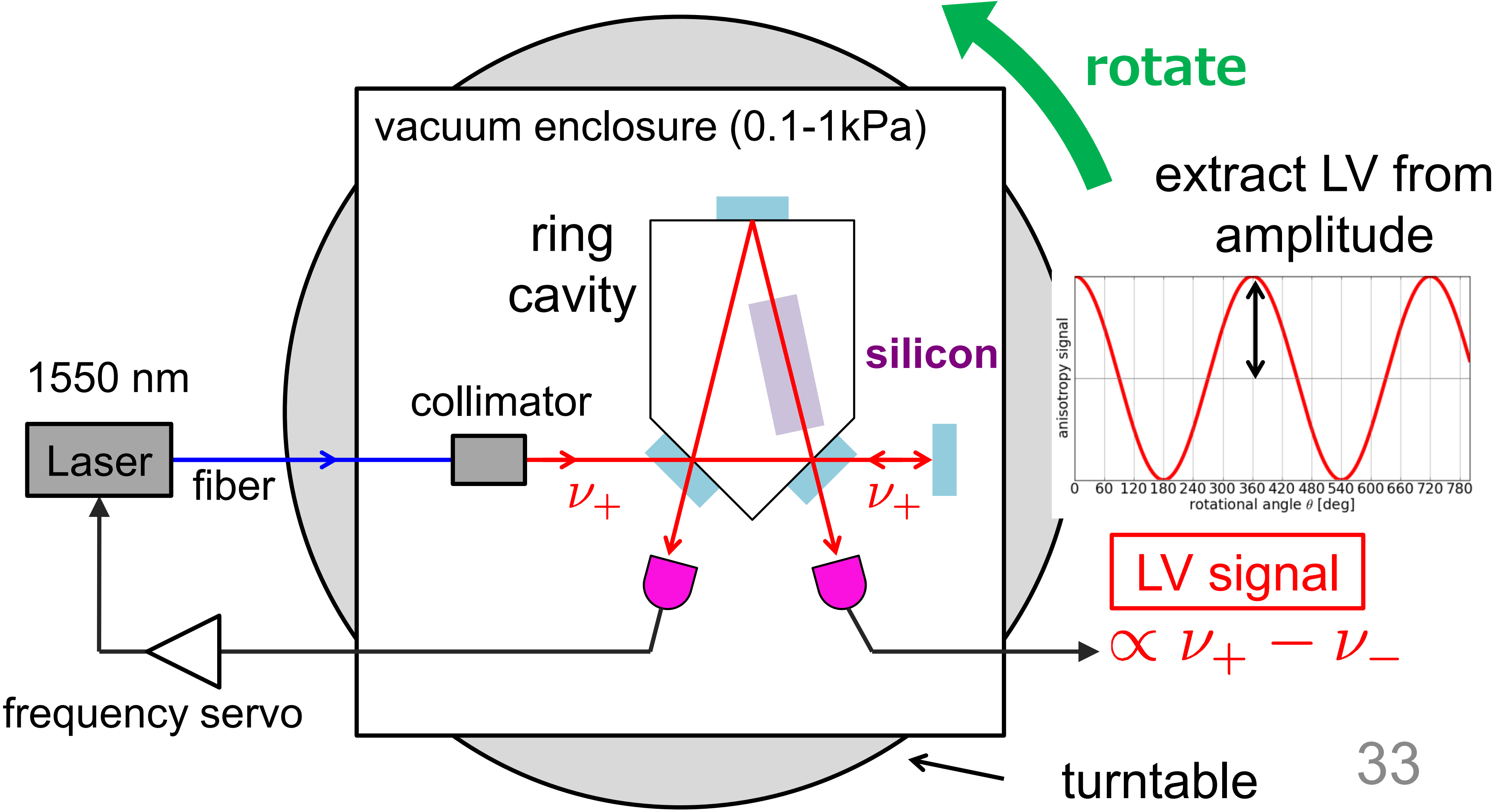
Double-Pass Configuration 4/4

- LV signal obtained from cavity reflection (null measurement)



Experimental Setup

- frequency comparison using double-pass setup
- rotate and modulate LV signal



rotate

extract LV from amplitude

vacuum enclosure (0.1-1kPa)

ring cavity

silicon

1550 nm

collimator

Laser

fiber

ν_+

ν_+

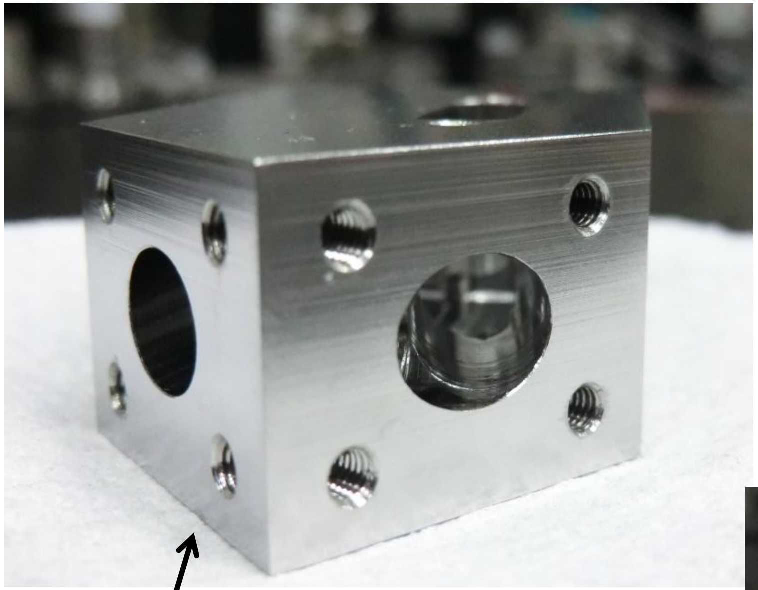
LV signal

$\propto \nu_+ - \nu_-$

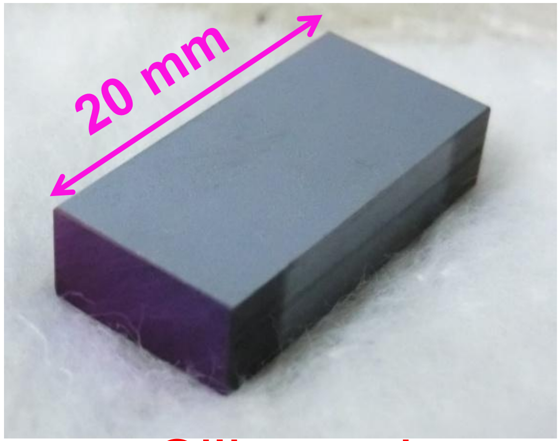
frequency servo

turntable

Photo of the Ring Cavity

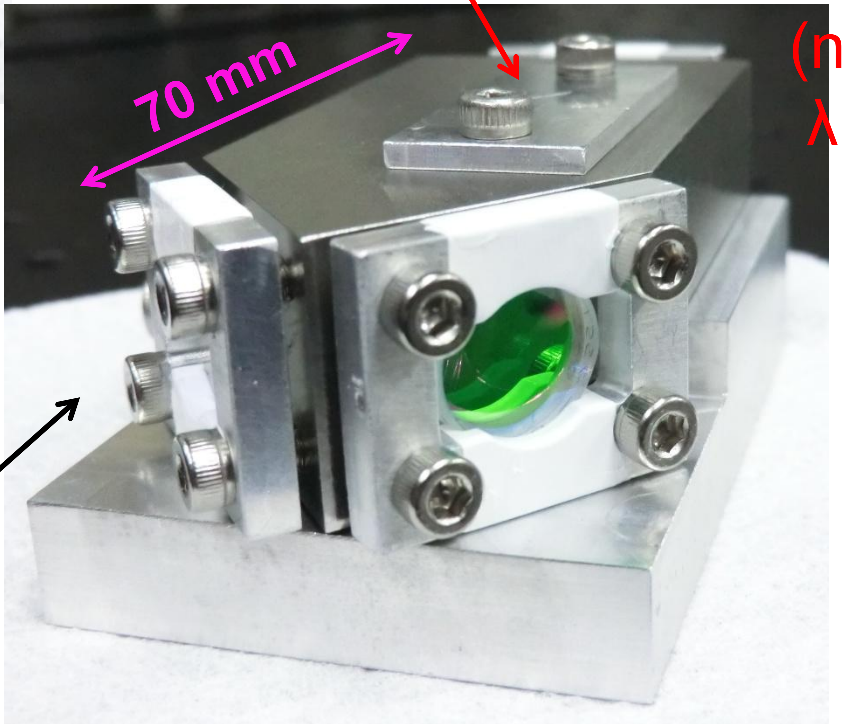


Spacer made of
Super Invar
(low thermal
expansion 10^{-7}/K)



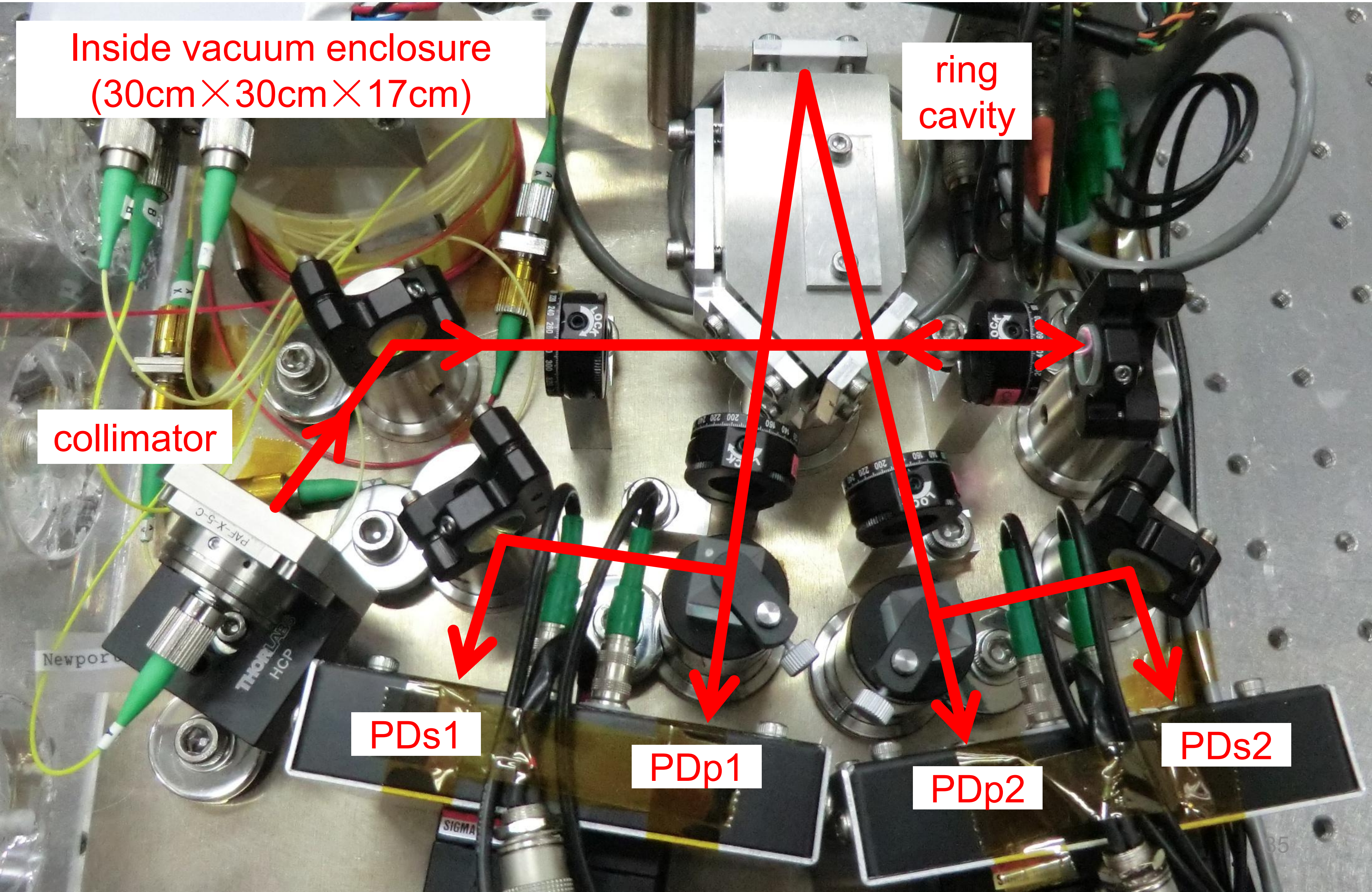
Silicon piece
(n=3.69 at
λ=1550 nm)

Silicon piece inside



With mirrors

Photo of the Optics



Inside vacuum enclosure
(30cm×30cm×17cm)

ring
cavity

collimator

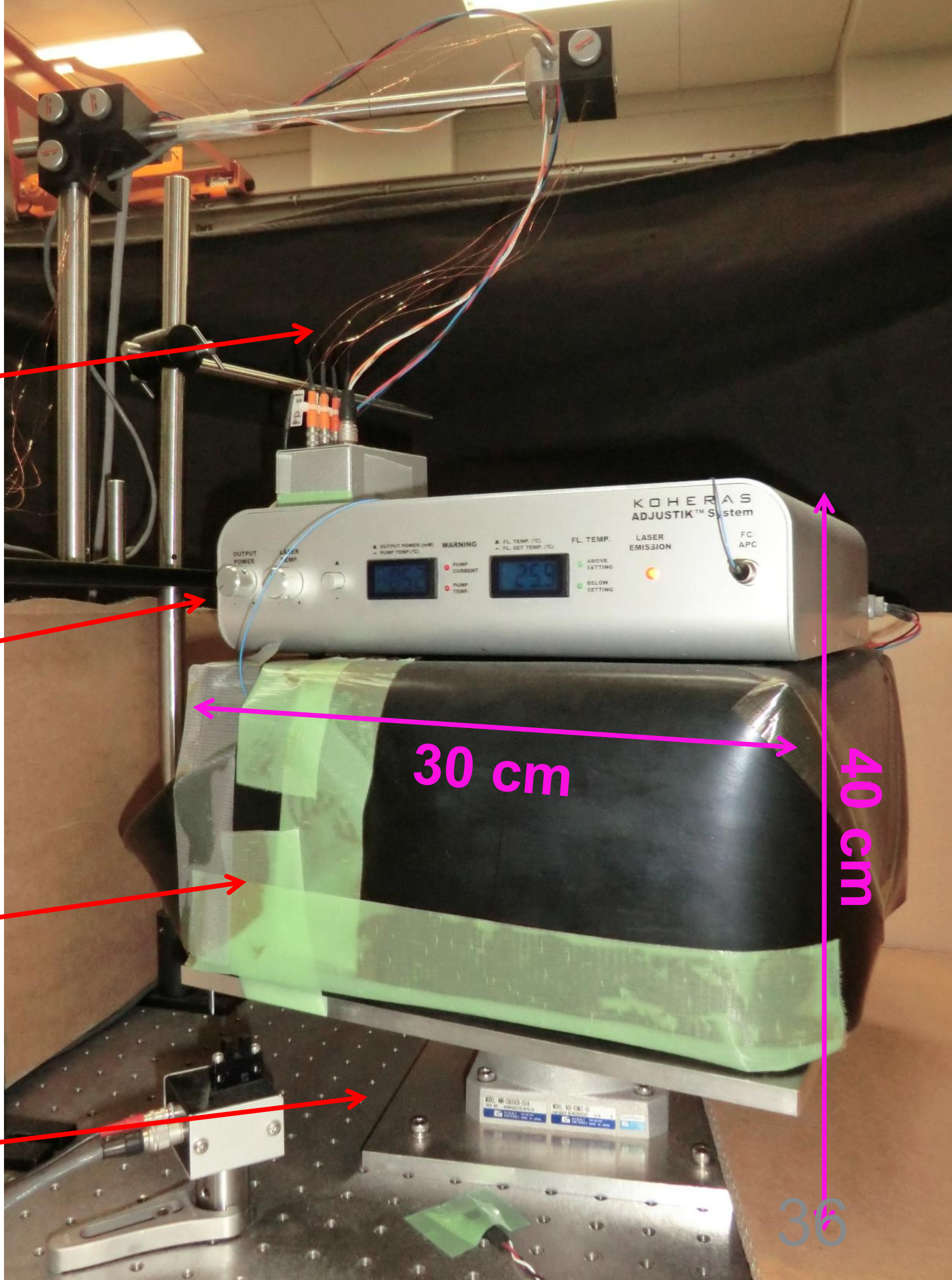
PDs1

PDp1

PDp2

PDs2

Photo of the Whole Setup



electrical cables

laser source

vacuum enclosure
+ shielding
(optics inside)

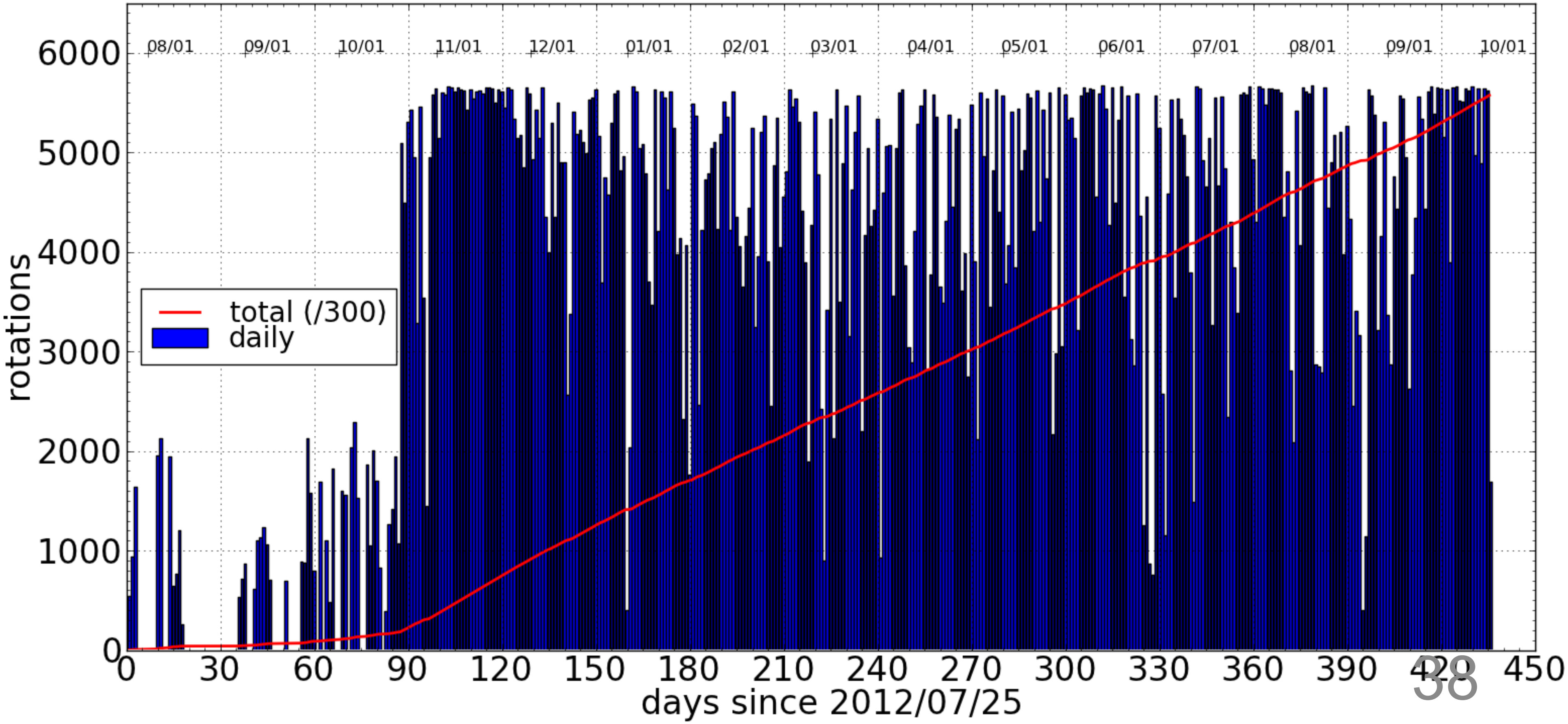
turntable

Rotation

- 12 sec / rotation, alternately

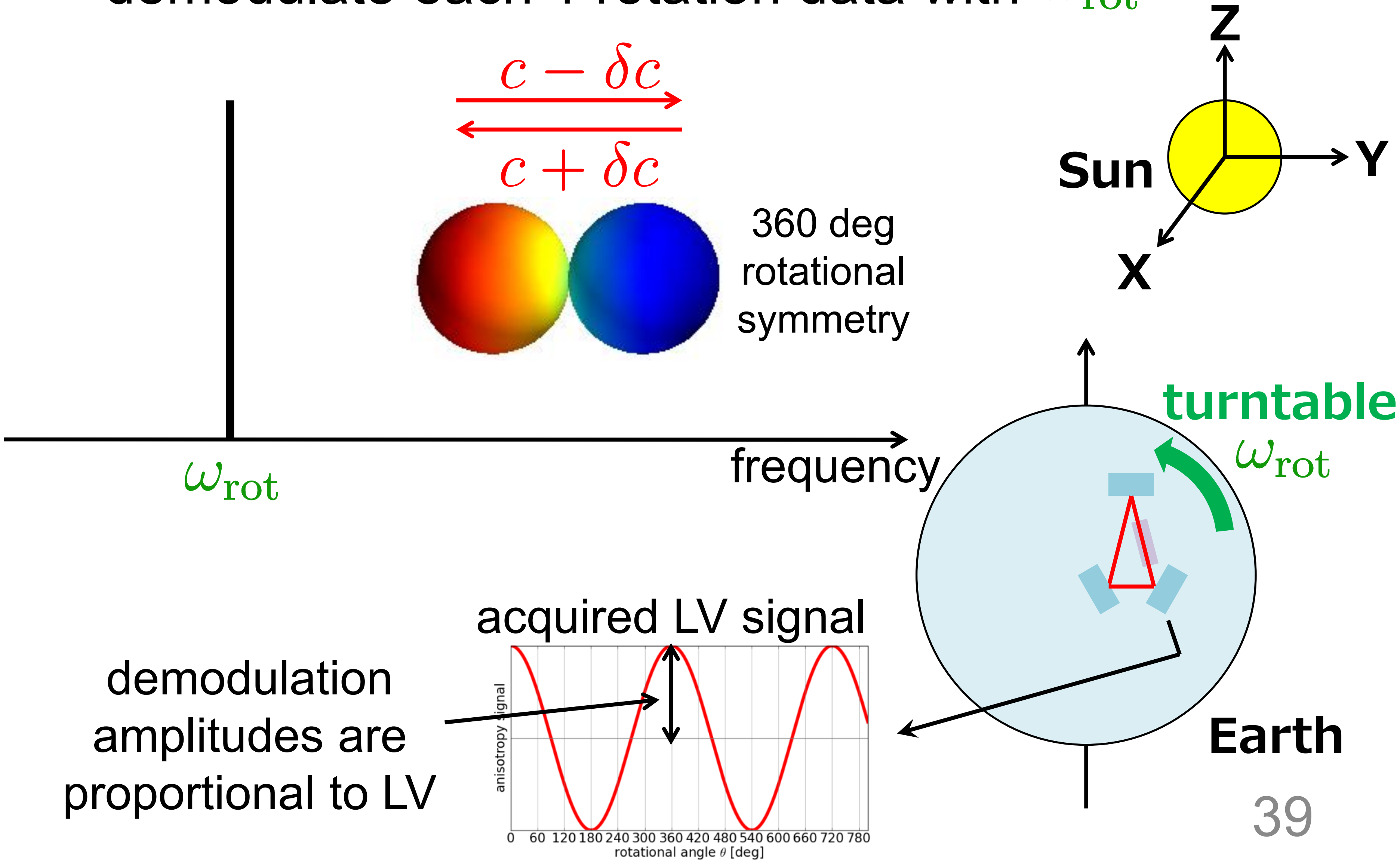
Observation Data

- from July 2012 to October 2013 at Tokyo
- 393 days, 1.67 million rotations
- duty cycle: 53% (64% after Oct 2012)



Data Analysis 1/3

- demodulate each 1 rotation data with ω_{rot}

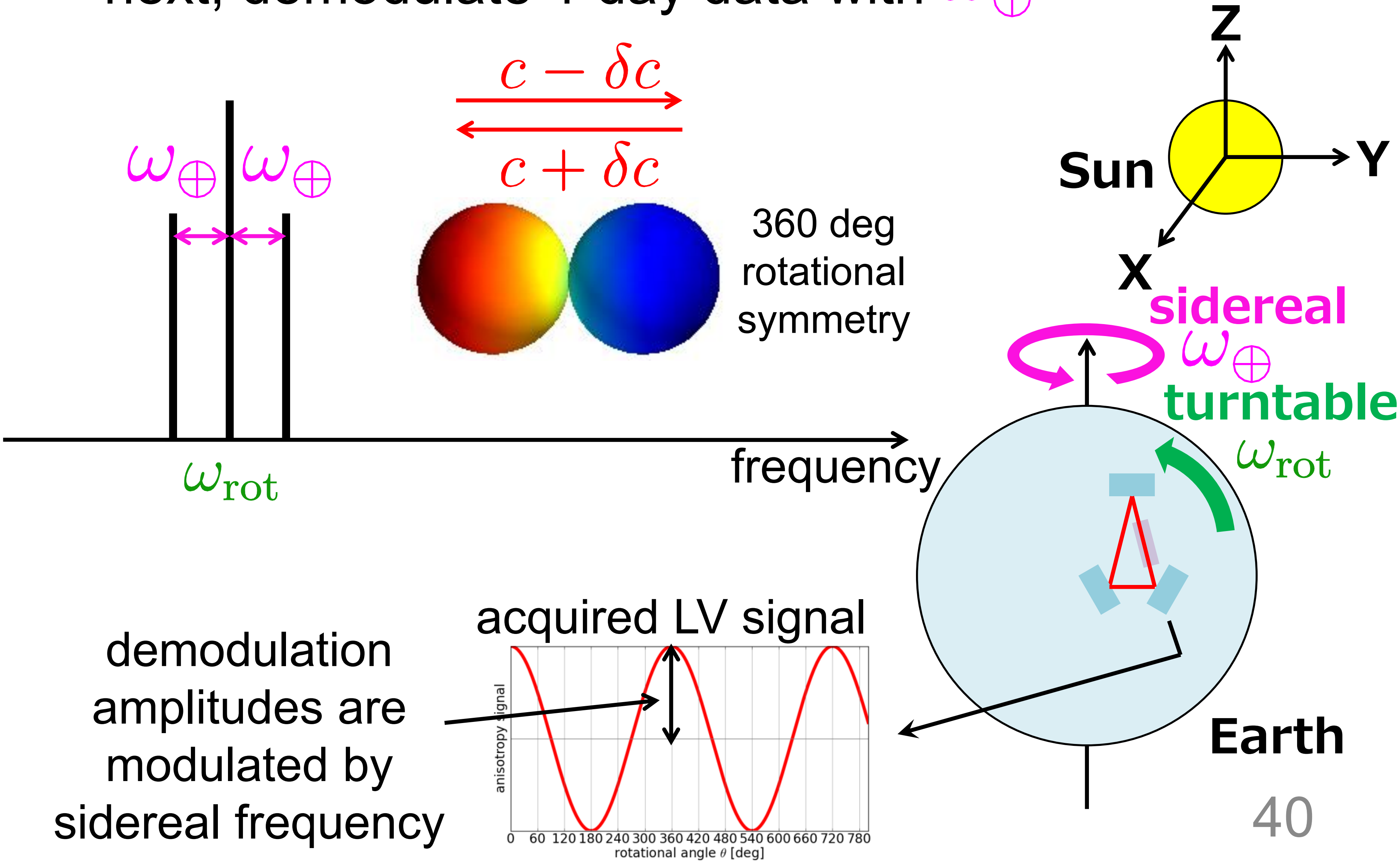


360 deg rotational symmetry

demodulation amplitudes are proportional to LV

Data Analysis 2/3

- next, demodulate 1 day data with $\omega_\oplus$



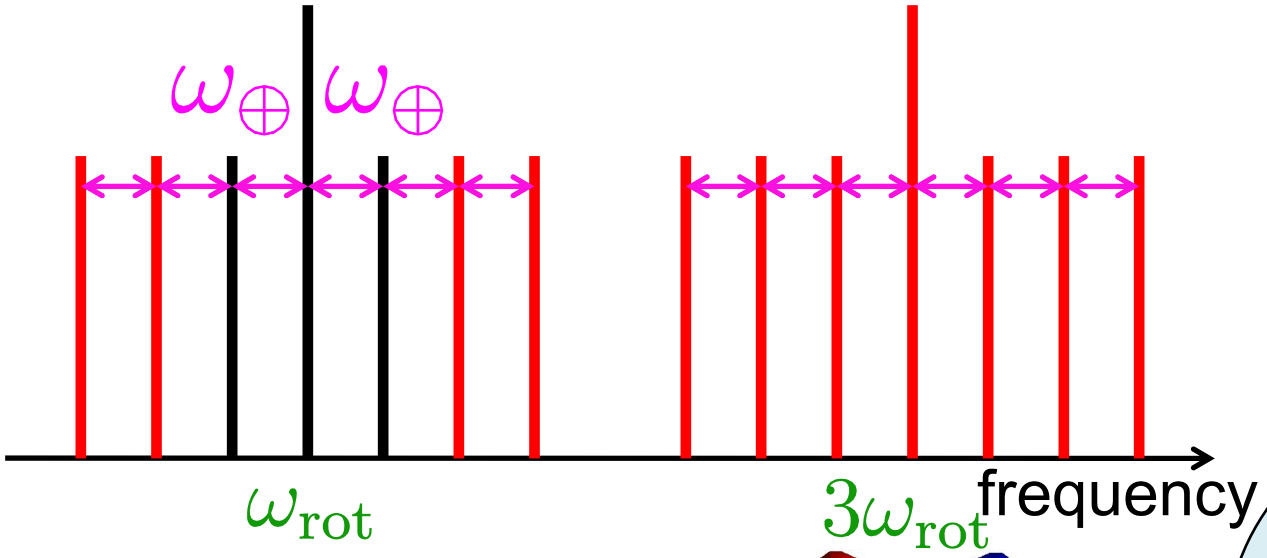
360 deg rotational symmetry

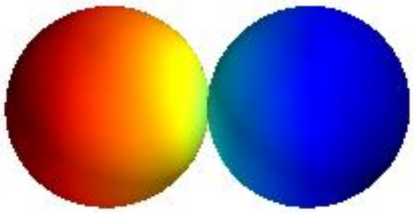
acquired LV signal

demodulation amplitudes are modulated by sidereal frequency

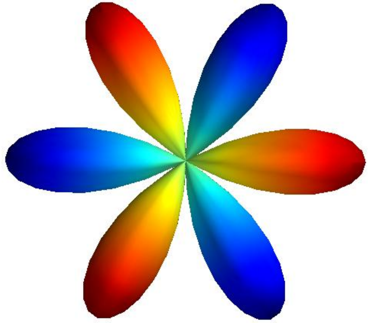
Data Analysis 3/3

- higher order LV appear at higher harmonics

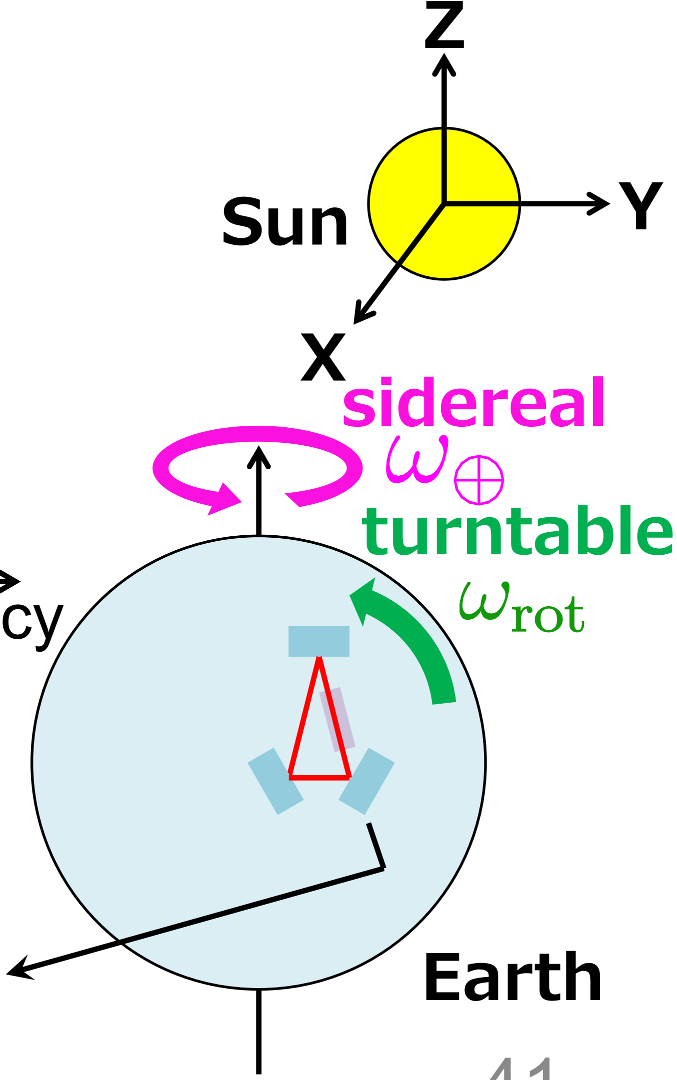




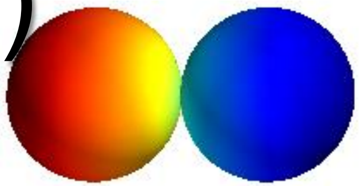
360 deg
rotational symmetry



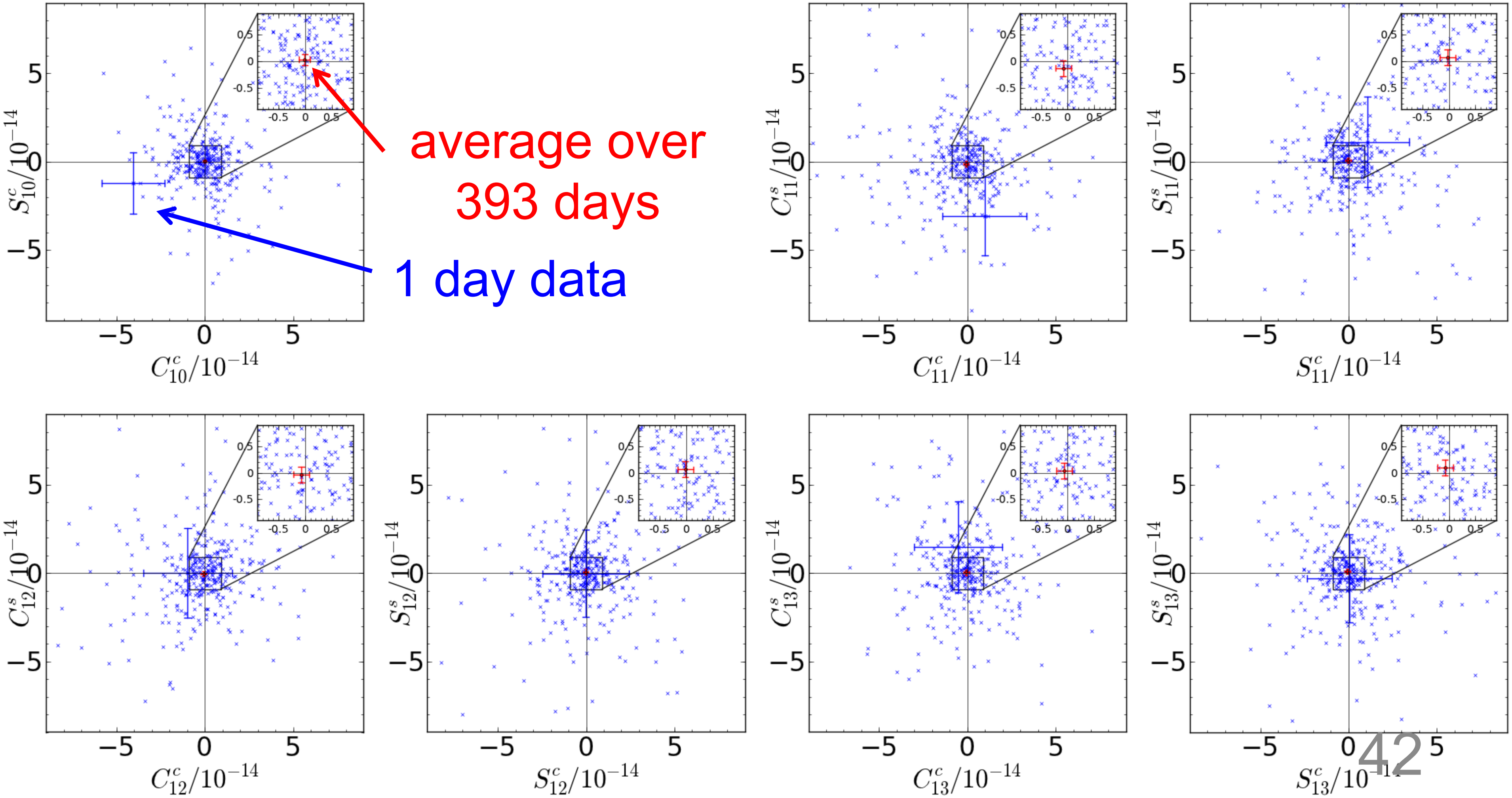
120 deg
rotational symmetry



Demodulation Amps($\omega_{\rm rot}$)



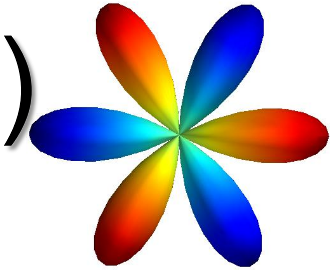
- zero consistent at 2σ
  $\longrightarrow$ no significant LV can be claimed



average over 393 days

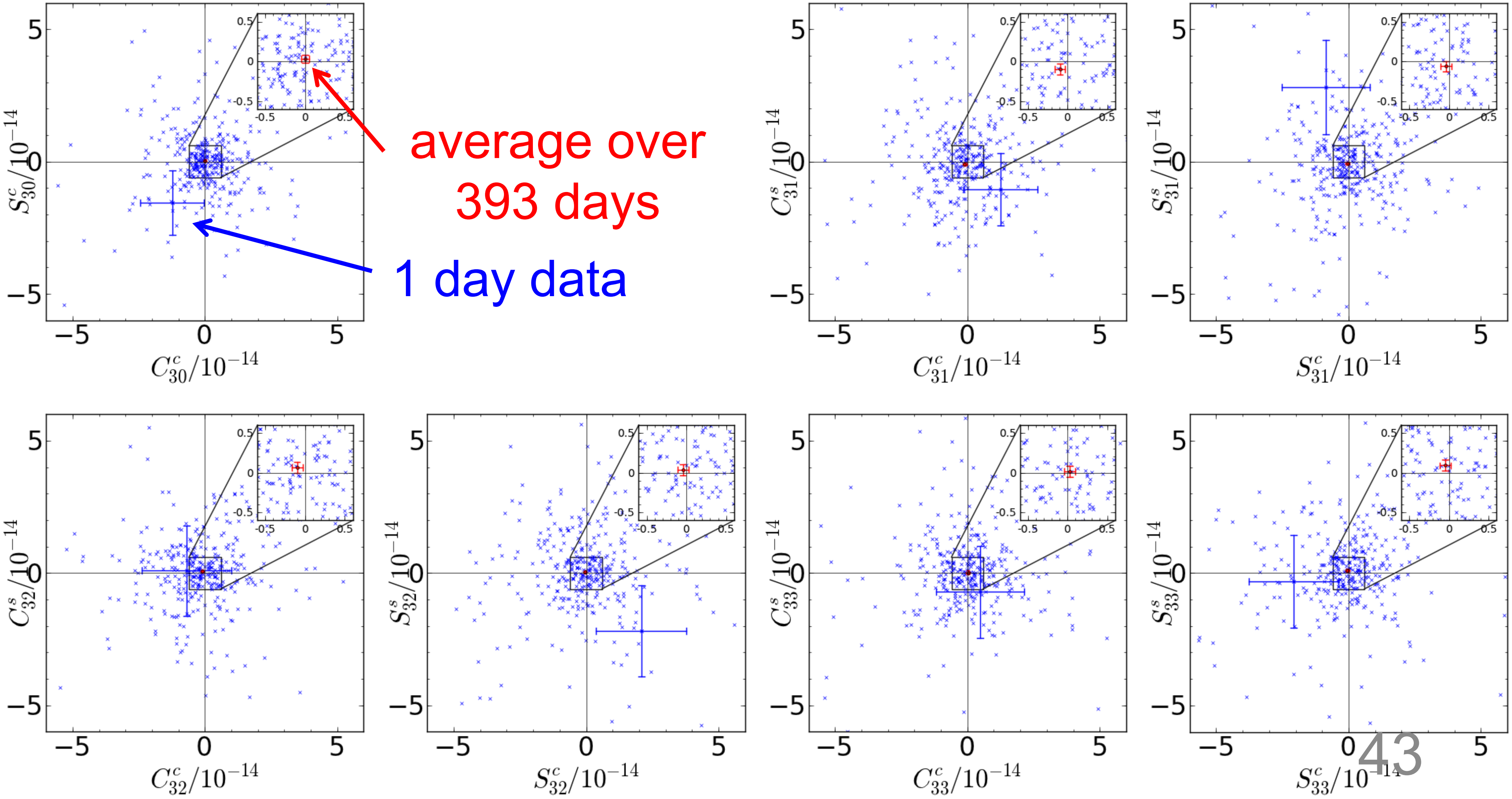
1 day data

Demodulation Amps($3\omega_{\mathrm{rot}}$)



- zero consistent at 2σ

  ⟶ no significant LV can be claimed



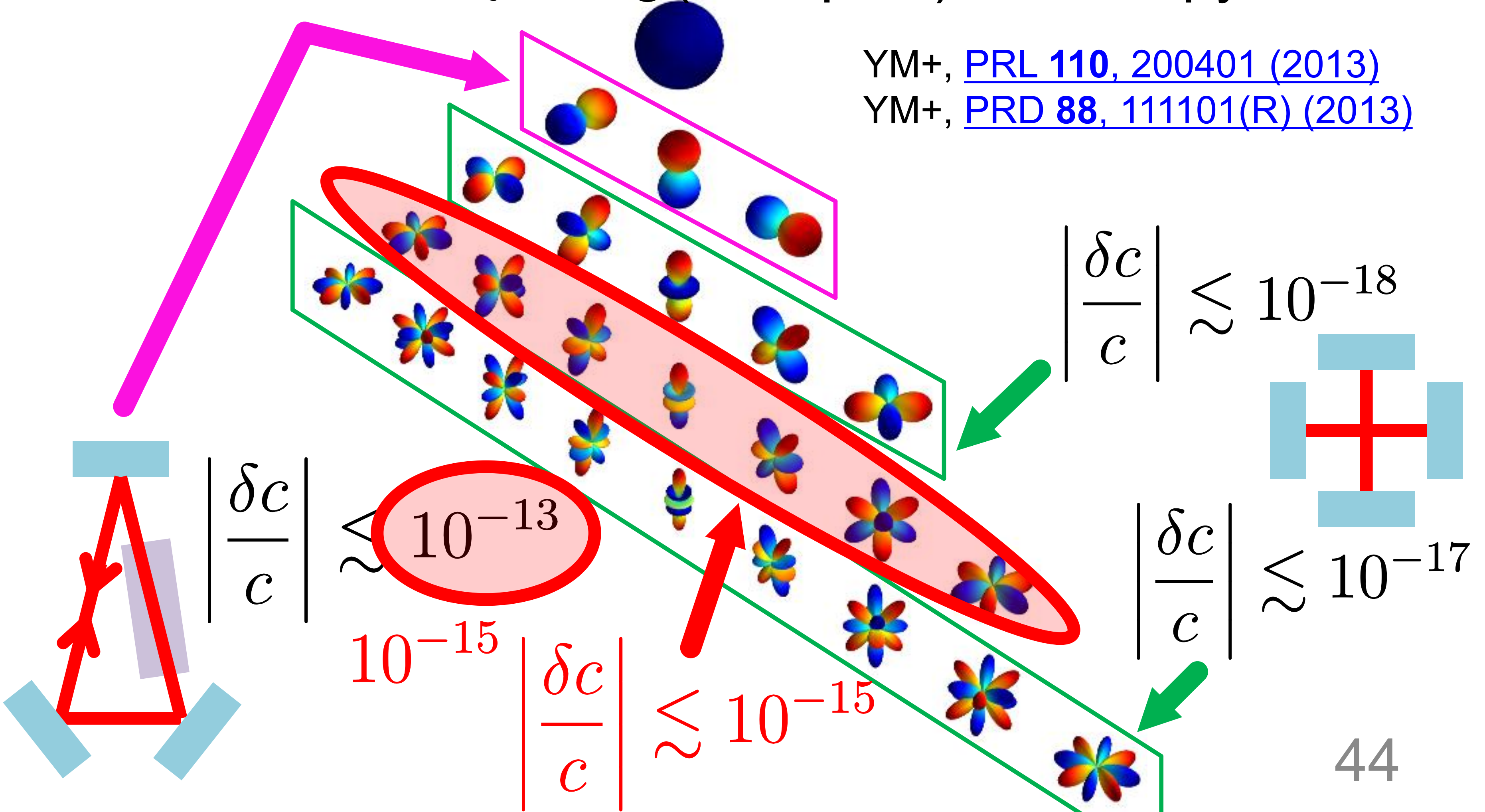
average over 393 days

1 day data

Our Limits

- improved limits on $l = 1$(dipole) anisotropy
- new limits on $l = 3$(hexapole) anisotropy

YM+, PRL **110**, 200401 (2013)
YM+, PRD **88**, 111101(R) (2013)



$\left|\frac{\delta c}{c}\right| \lesssim 10^{-18}$

$\left|\frac{\delta c}{c}\right| \lesssim 10^{-17}$

$\left|\frac{\delta c}{c}\right| \lesssim 10^{-13}$

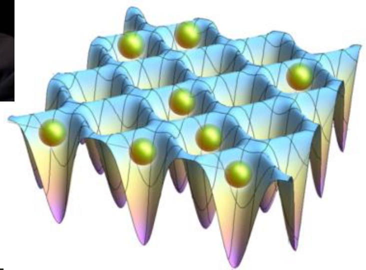
10^{-15}

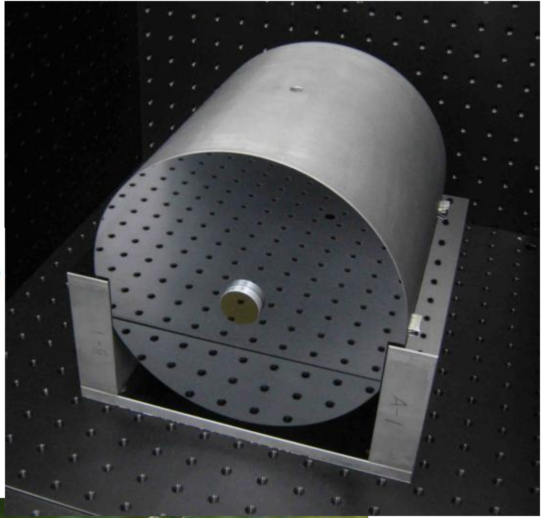
$\left|\frac{\delta c}{c}\right| \lesssim 10^{-15}$

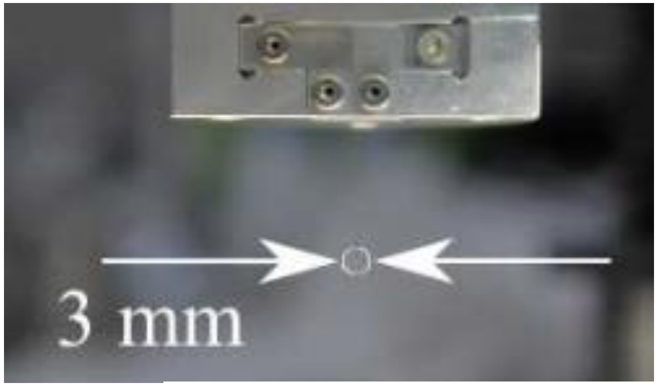
2013- (D1)

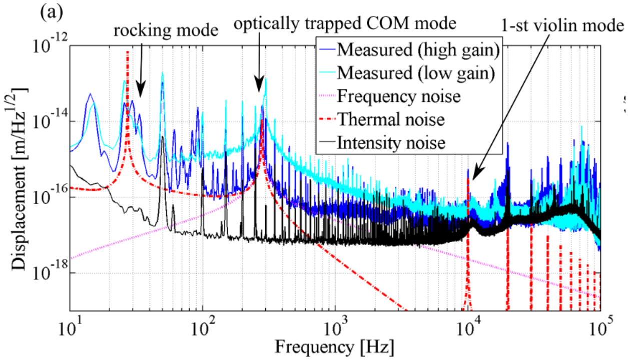
Related Experiments in the Group

- Laser frequency stabilization using cryogenic silicon cavity for optical lattice clocks
- Optomechanical experiments using milligram scale suspended mirrors for testing macroscopic quantum mechanics





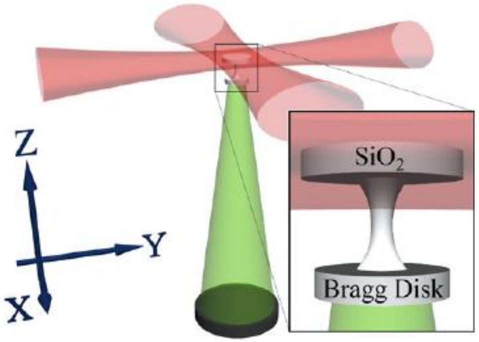




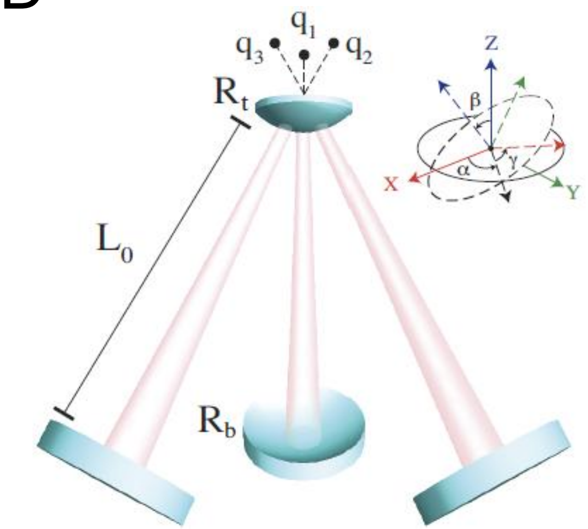
2013- (D2)

Optical Levitation

- I was looking for something new for my PhD theme
- Found G. Guccione+: PRL 111, 183001 (2013)
- Did some calculations and found a new way to levitate a mirror
- I continued to do KAGRA and Lorentz violation search as well. In the end, I ended up doing Lorentz violation for PhD

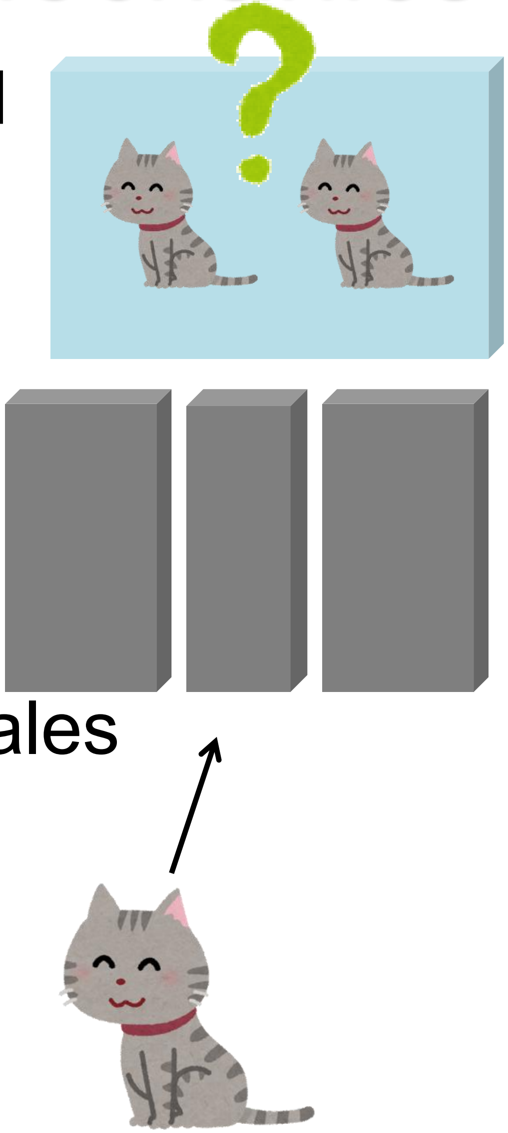


S. Singh+: PRL 105, 213602 (2010)



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

Macroscopic Quantum Mechanics

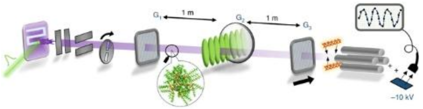


- Quantum mechanics do not depend on scales
- But macroscopic quantum superposition has never been observed (double-slit experiment upto 25 kDa (4e-23 kg)) [Nature Physics **15**, 1242 (2019)]
- Two possibilities at macroscopic scales
  - Quantum mechanics is valid, but too much classical decoherence
  - Quantum mechanics should be modified
    (e.g. non-linear Schrödinger Eq.,
    Gravitational decoherence …)

Optomechanical Systems

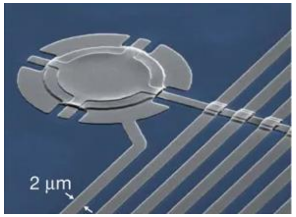
- SQL not yet reached above Planck mass scale

Double-slit



molecules, 40 zg
Fein+ (2019)

Ground state cooling

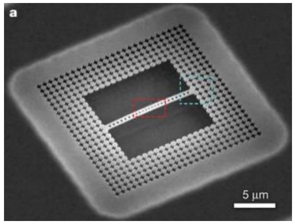


membrane, 48 pg
Taufel+ (2011)

Quantum radiation pressure

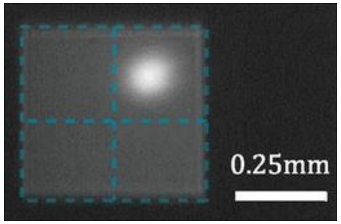
cantilever, 50 ng
Cripe+ (2019)

Ground state cooling



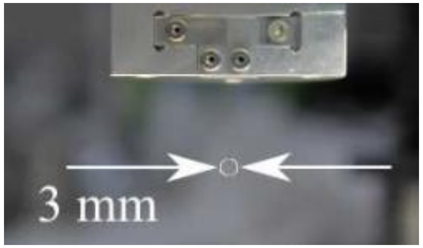
nanobeam, 331 fg
Chan+ (2011)

Ground state cooling



membrane, 7 ng
Peterson+ (2016)

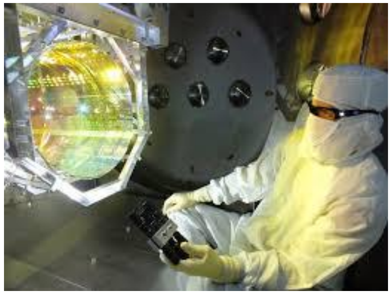
Planck mass (22 ug)



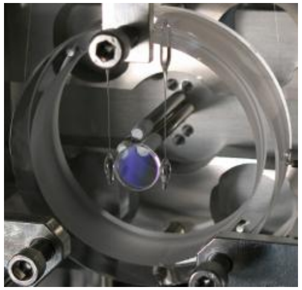
suspended disk, 7 mg
Matsumoto+ (2019)

suspended bar, 10 mg
Komori+ (2019)

Factor of ~3 to SQL



suspended disk, 40 kg
Advanced LIGO



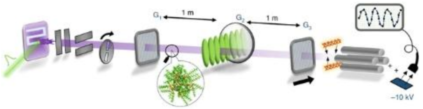
suspended disk, 1 g
Neben+ (2012)

fg pg ng ug mg g kg

Optomechanical Systems

- SQL not yet reached above Planck mass scale

Double-slit



molecules, 40 zg
Fein+ (2019)

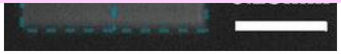
Planck mass (22 ug)

Quantum radiation pressure

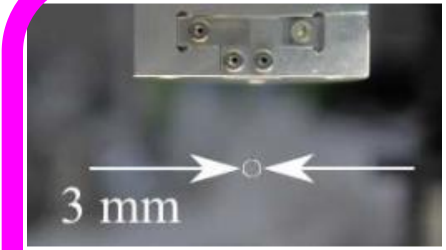
Ground state cooling

We are focusing on mg-scale experiments to probe boundary between quantum world and gravitational world

nanobeam, 331 fg
Chan+ (2011)



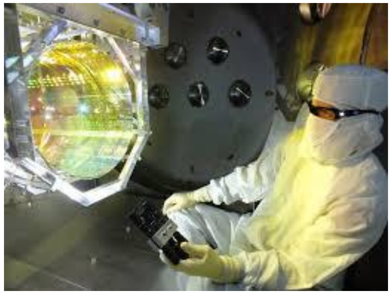
membrane, 7 ng
Peterson+ (2016)



suspended disk, 7 mg
Matsumoto+ (2019)

suspended bar, 10 mg
Komori+ (2019)

Factor of ~3 to SQL



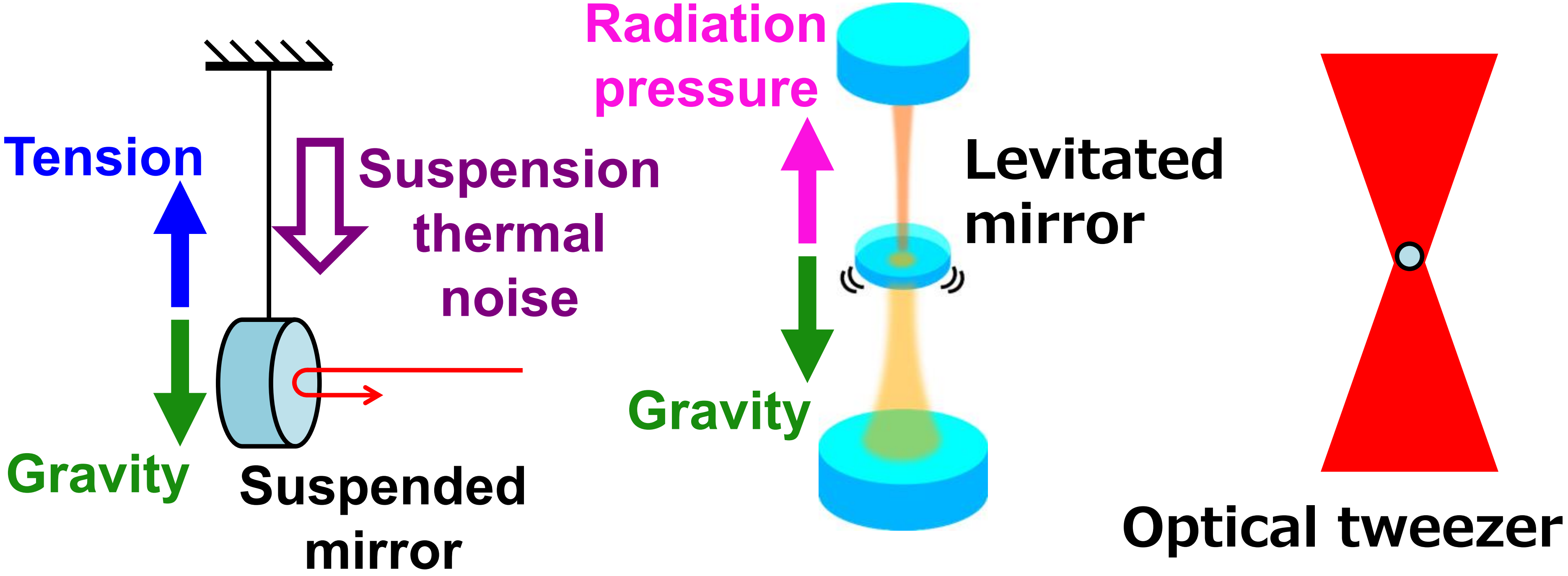
suspended disk, 40 kg
Advanced LIGO

suspended disk, 1 g
Neben+ (2012)

fg pg ng ug mg g kg

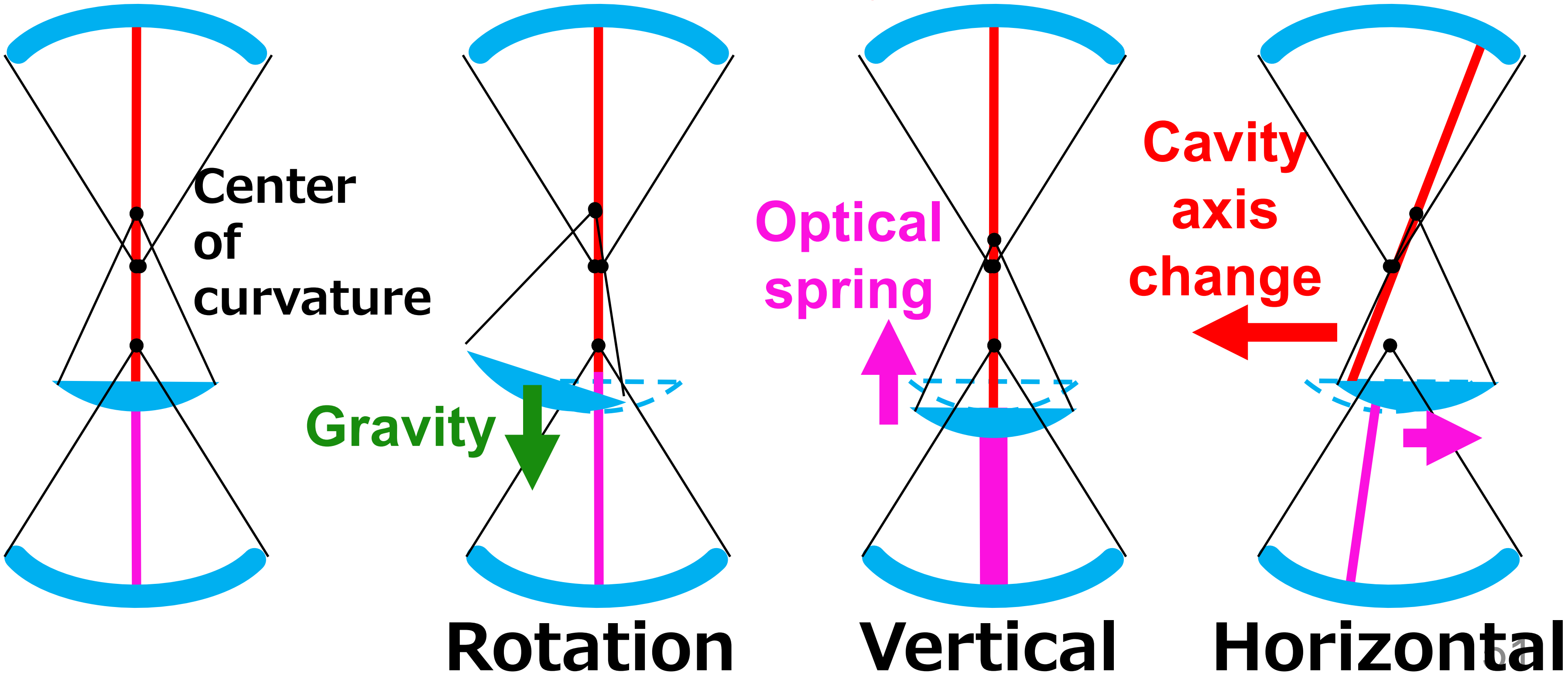
Optical Levitation of Mirror

- Support a mirror with radiation pressure alone
- Free from suspension thermal noise
- Large coupling compared with optical tweezers



Stability of Levitation

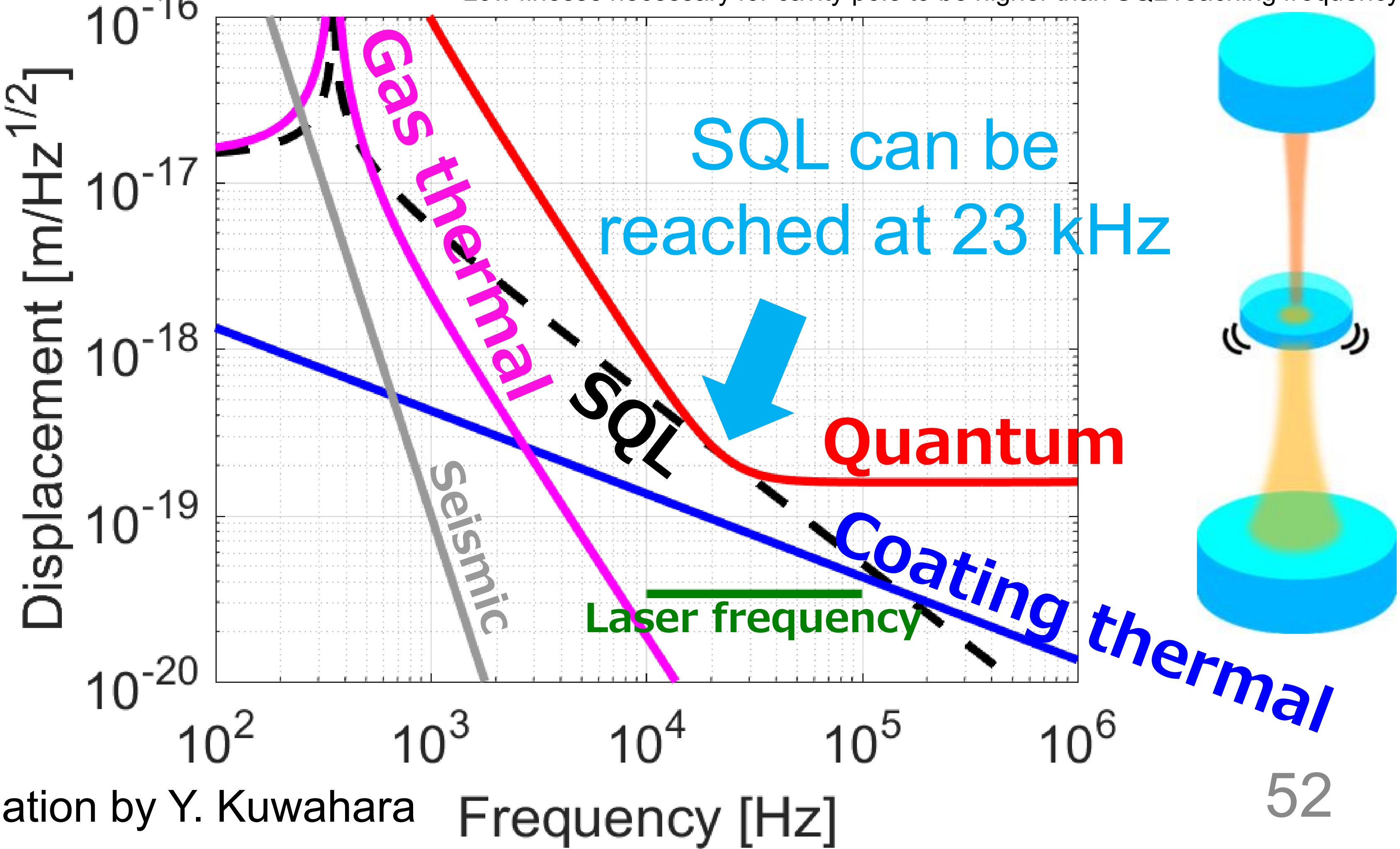
- Rotational motion is stable with gravity
- Vertical motion is stable with optical spring
- Horizontal motion is stable with cavity axis change
- *Curved mirror is necessary!*



Reaching SQL

- Constraint on design: intra-cavity power to support the mass
- 0.2 mg fused silica mirror, Finesse of 100, 13 W + 4 W input

Low finesse necessary for cavity pole to be higher than SQL reaching frequency



SQL can be reached at 23 kHz

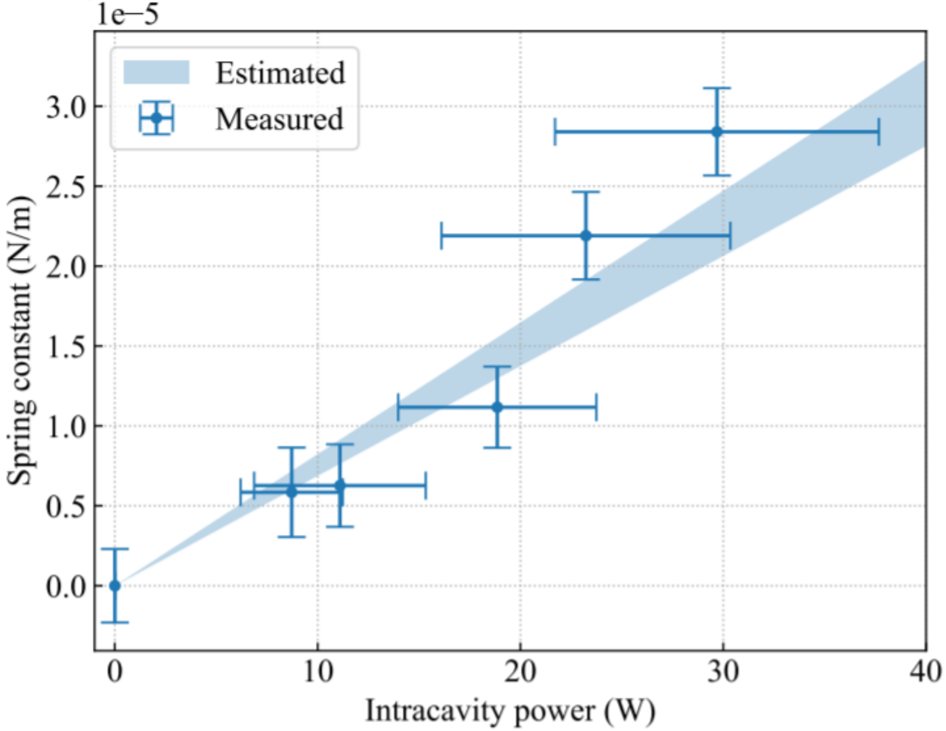
Calculation by Y. Kuwahara

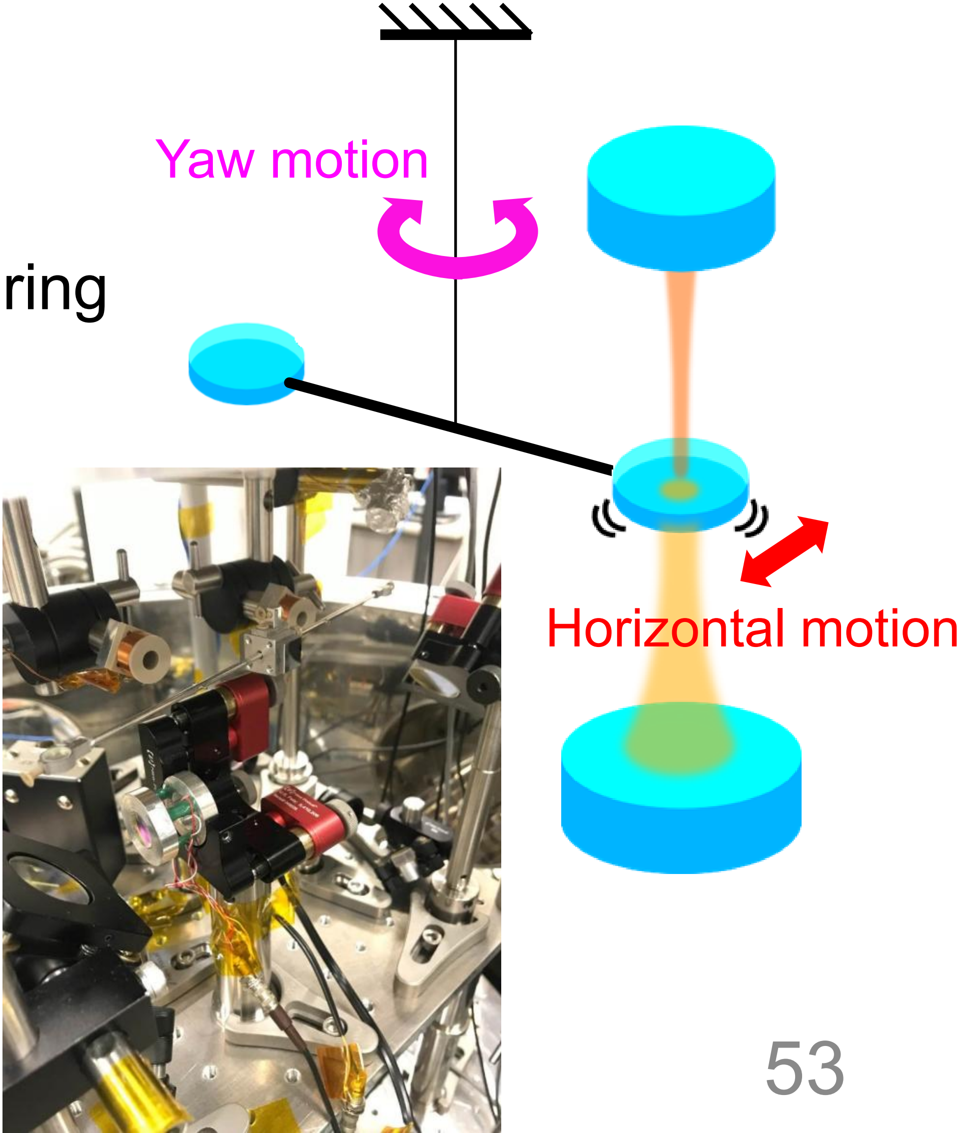
Experiment to Verify the Stability

- Verified the stability with a torsion pendulum and a dummy mirror

T. Kawasaki, …, YM,
PRA 102, 053520 (2020)

Measured optical geometrical spring agreed with expectation



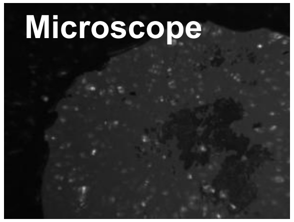


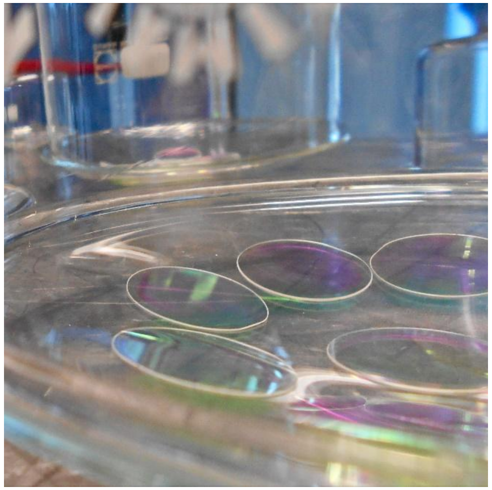
Fabrication of Levitation Mirrors

- 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

LMA
LABORATOIRE MATÉRIAUX AVANCÉS

Australian National University





Coated 1-inch dia. 0.1 mm thick mirrors

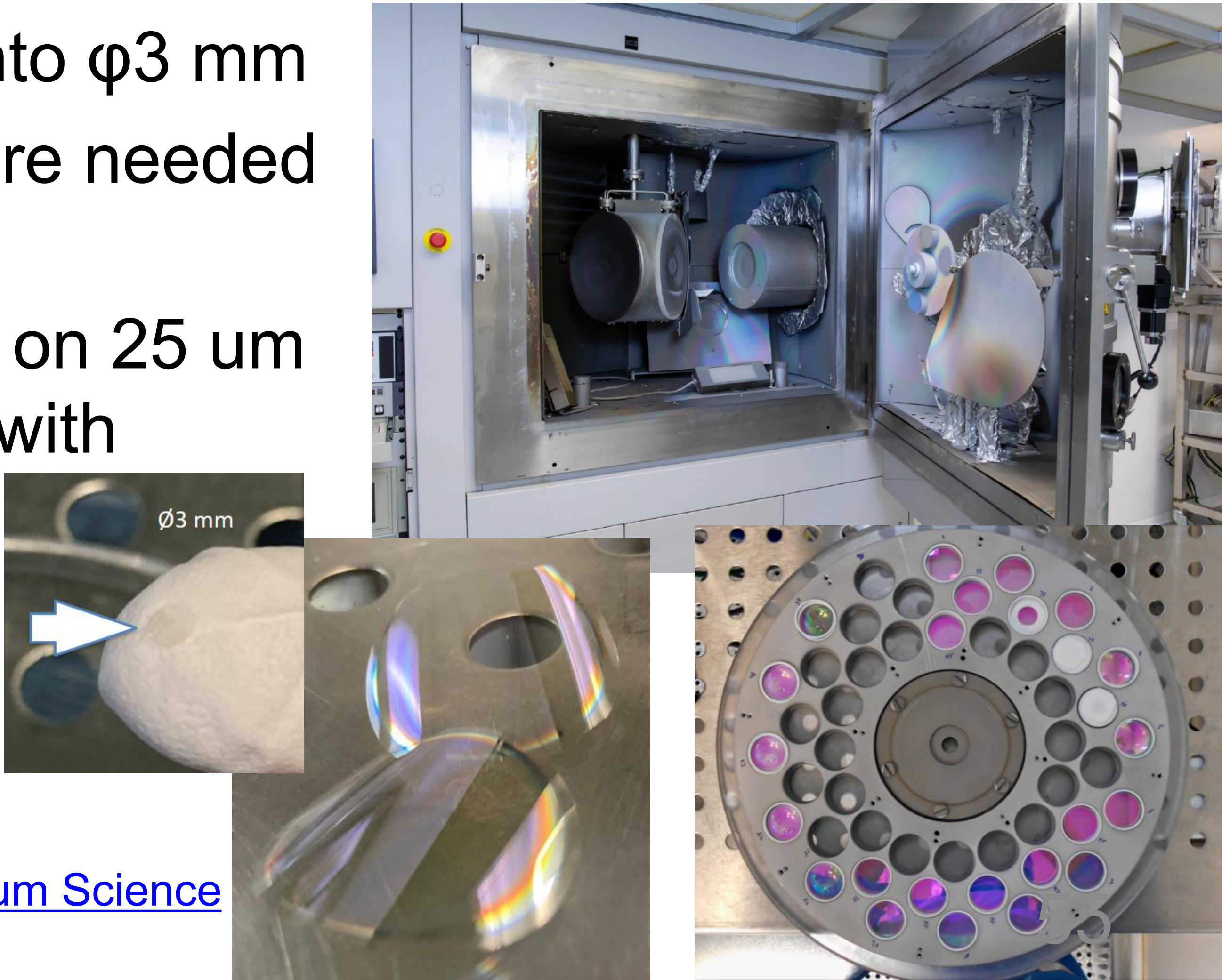
Cut into 3 mm dia.

Characterization at UTokyo/ANU

Collaboration with LMA

- Same as LIGO/Virgo high quality coating (T=10 ppm, 6.2 um thick)
- Hard to cut into φ3 mm
- More curvature needed *O*(10 cm)
- Now working on 25 um thick mirrors with laser cutting

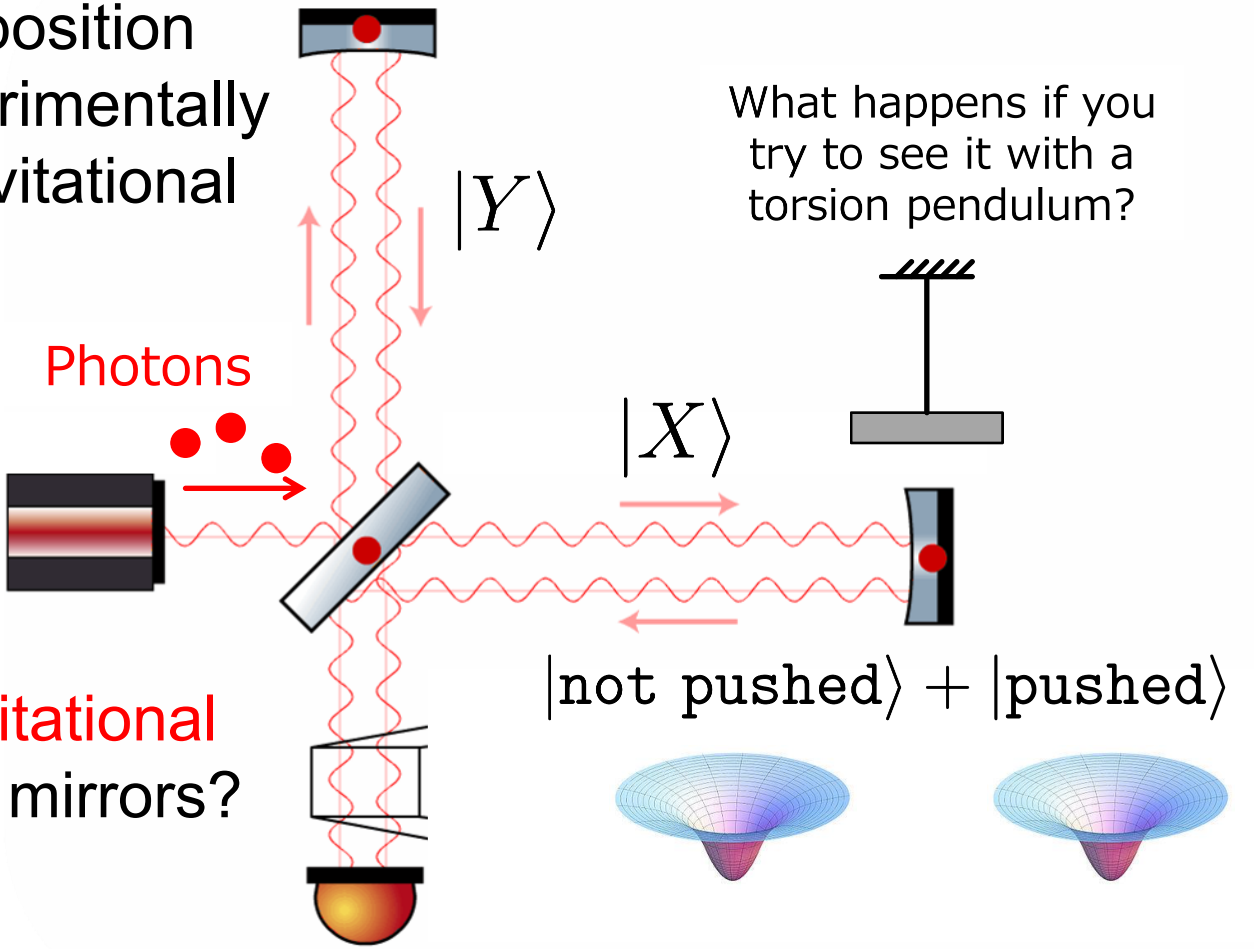
  1/4 thickness gives 1/16 curvature



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

Testing Quantum Nature of Gravity

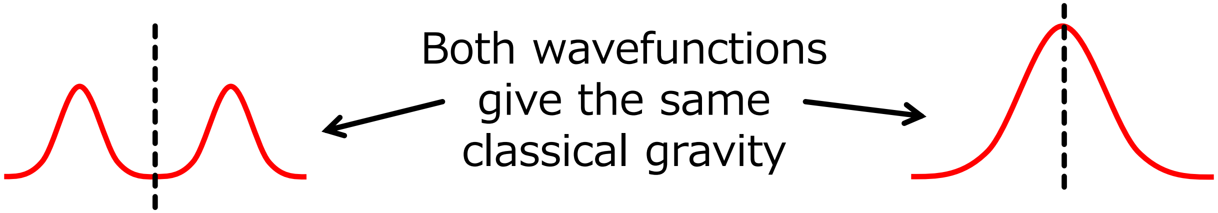
- Photon going to X arm or Y arm is in quantum superposition
- Mirrors pushed or not pushed by radiation pressure is in quantum superposition (this is not experimentally verified yet; gravitational decoherence?)



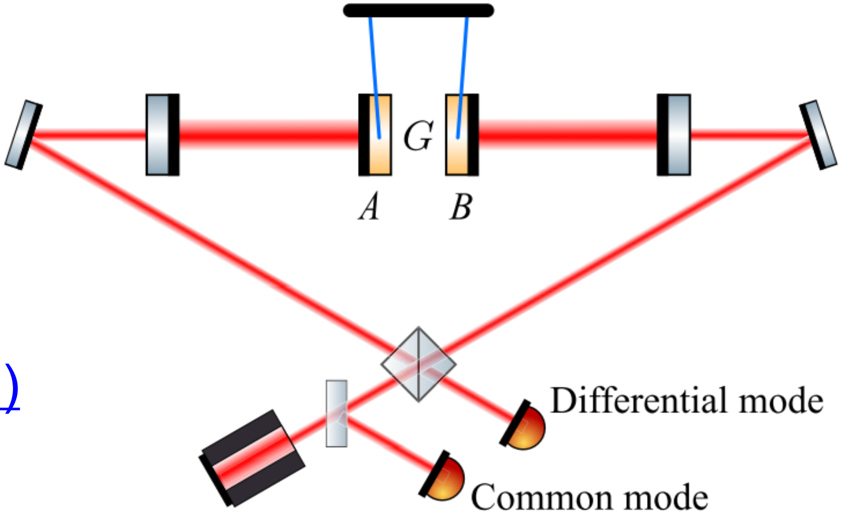
- How about gravitational field of massive mirrors?

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

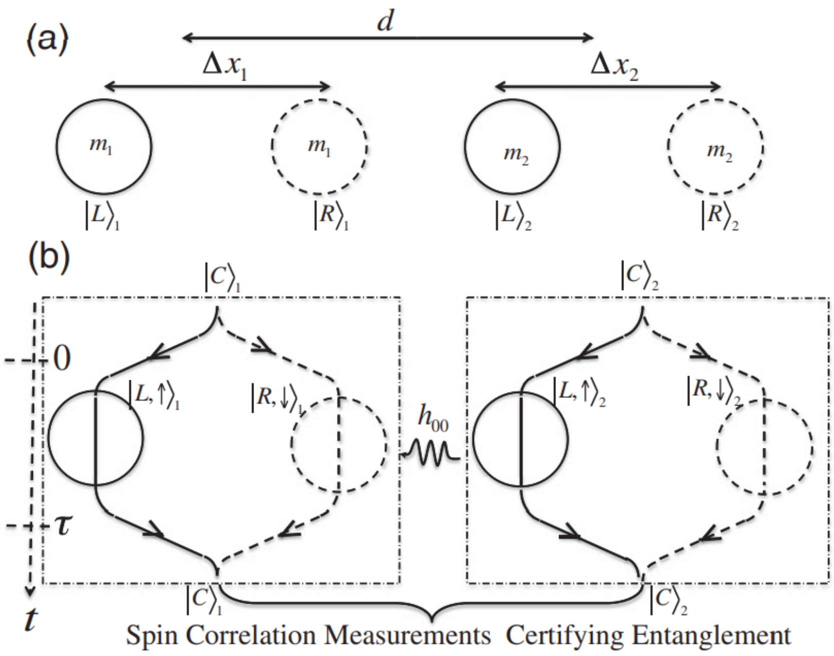


- For review, see
  D. Carney+, [CQG **36**, 034001 (2019)]
- Also, see
  H. Miao+, [PRA **101**, 063804 (2020)]
  A. Datta & H. Miao, [Quantum Science and Technology 6, 045014 (2021)]

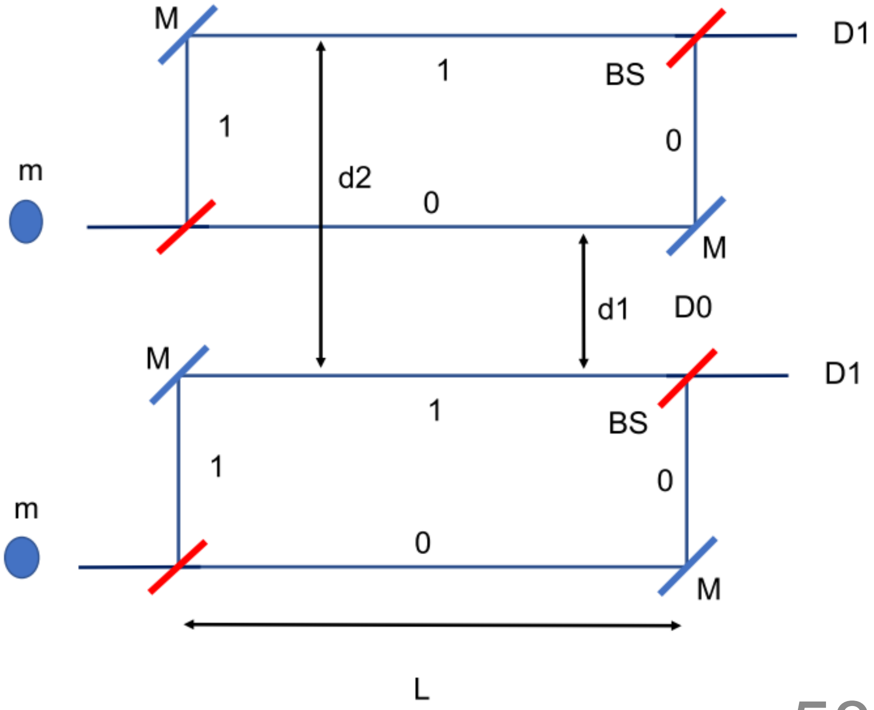
BMV Experiment Proposals

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

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

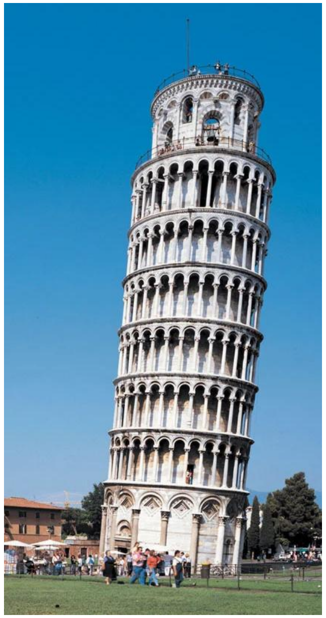


C. Marletto & V. Vedral,
Phys. Rev. Lett. 119, 240402 (2017)



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…



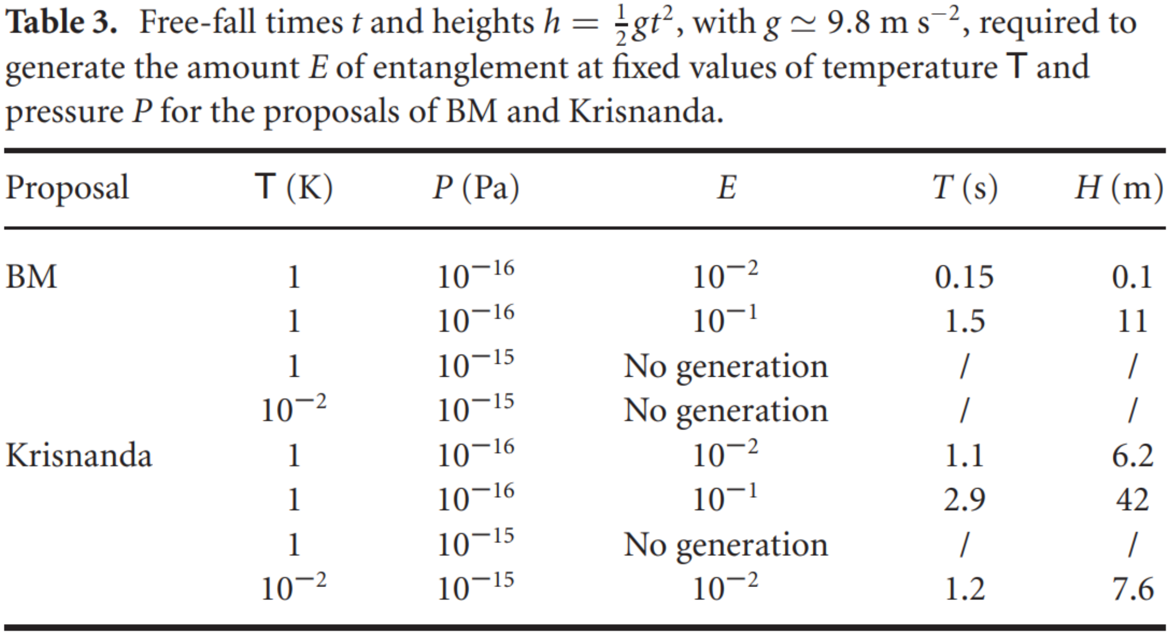


Table 3. Free-fall times t and heights $h = \frac{1}{2}gt^2$, with $g \simeq 9.8$ m s^{-2}, required to generate the amount E of entanglement at fixed values of temperature T and pressure P for the proposals of BM and Krisnanda.

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)

FKMM Proposal

Tomo visited Caltech in Feb 2023
All visited Caltech in Feb 2024

- Entanglement generation can be made faster if we use anti-trap

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

- Measurably big entanglement generation time (logarithmic negativity of more than 10^{-2}) will be:

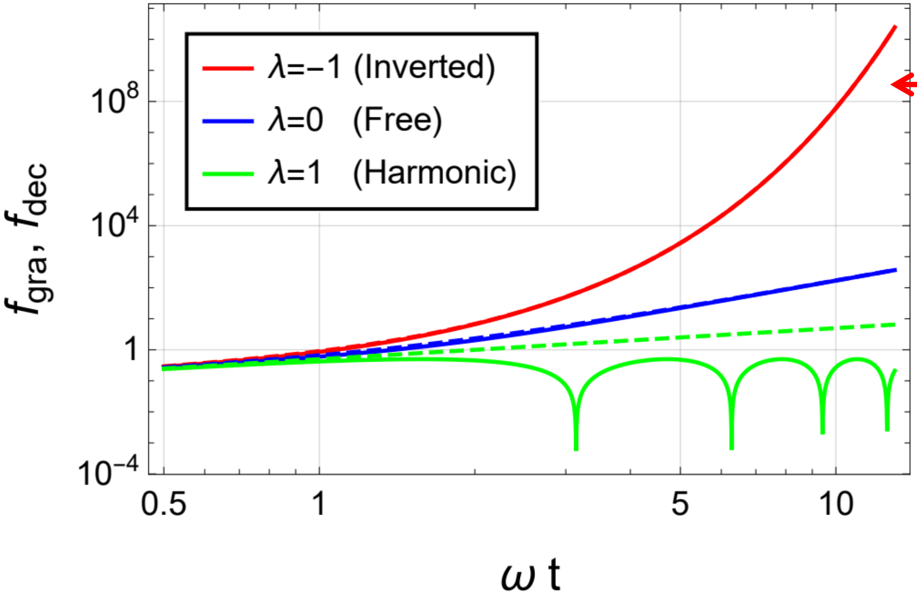
Free-fall

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

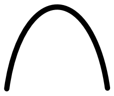
Inverted

$$\tau_{\rm ent} = 1.3\times10^{-2}\omega_{\rm kHz}^{-1/3}\,{\rm sec}$$

Negligible fall, can be repeated many times



Exponential for inverted case

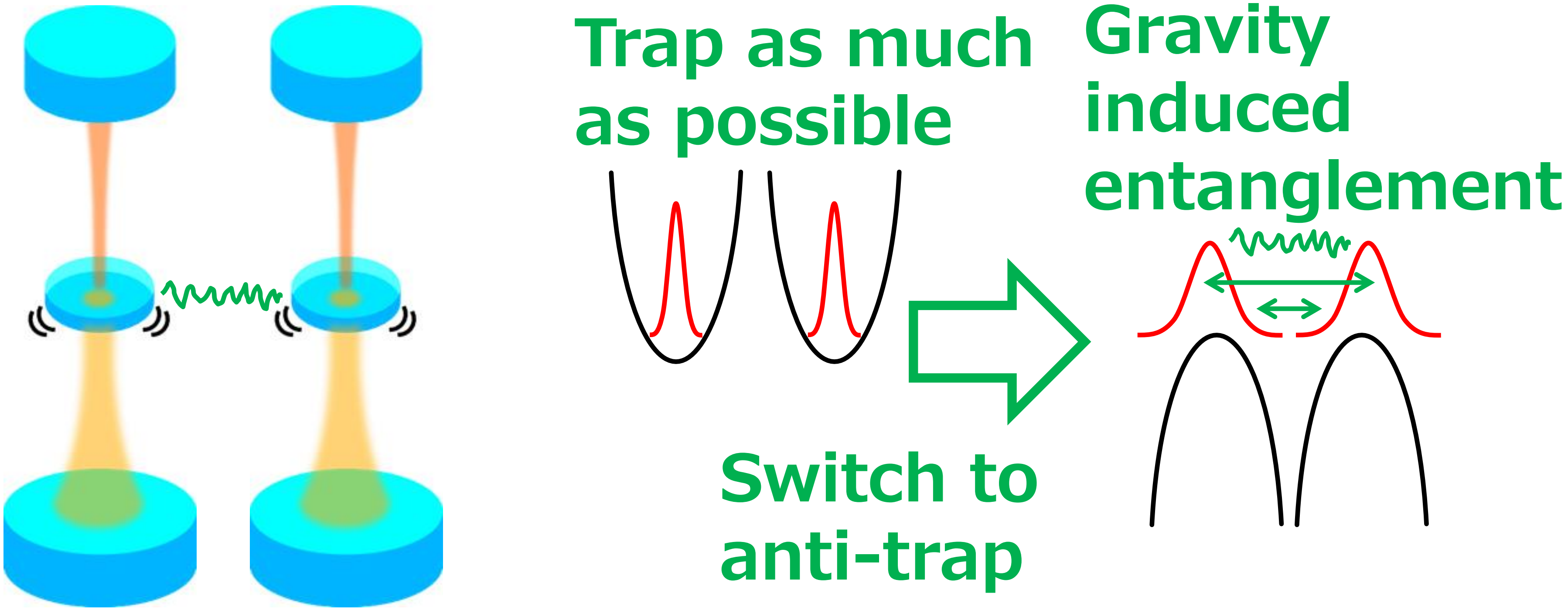


Free-fall case

Harmonic oscillator case

Anti-trap with Levitation

- Switching between trap and anti-trap can be done using optically levitated mirrors
- Entanglement in horizontal motion



Trap as much as possible

Switch to anti-trap

Gravity induced entanglement

2018- (助教)

Dark Matter Searches

- All started from a sudden email in Feb 2018 from I. Obata
- Optical ring cavity I made to search for the difference in the speed of light from Lorentz violation could be used to search for the difference in the phase velocity of light from axion-photon coupling

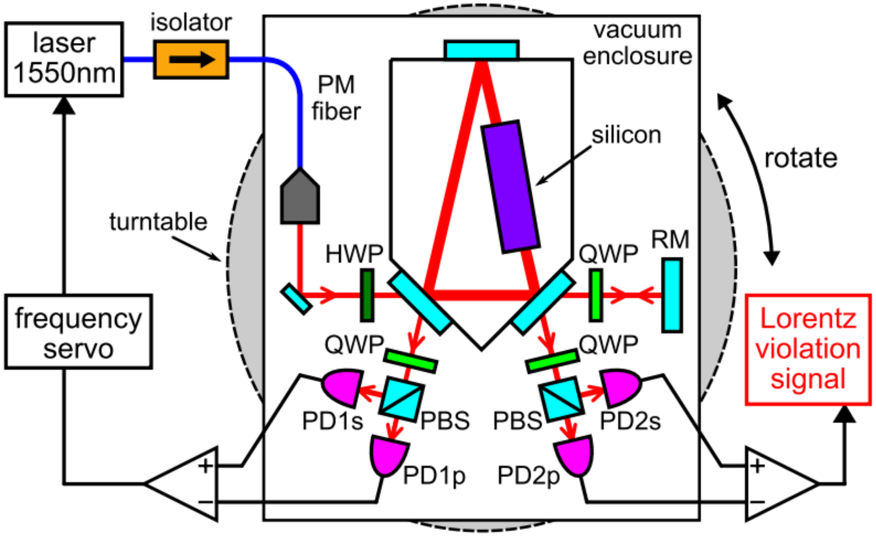


Figure from
YM+, PRL **110**, 200401 (2013)

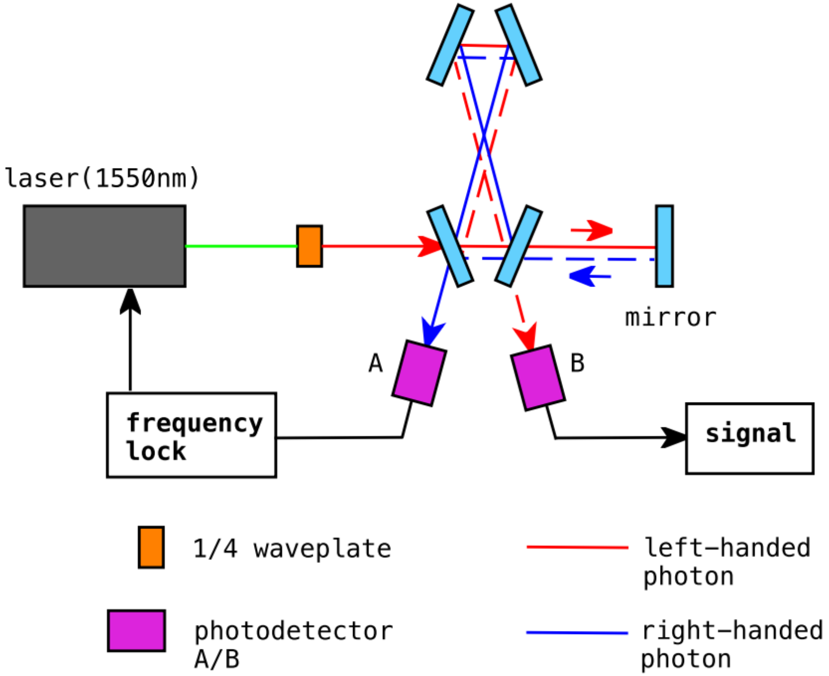


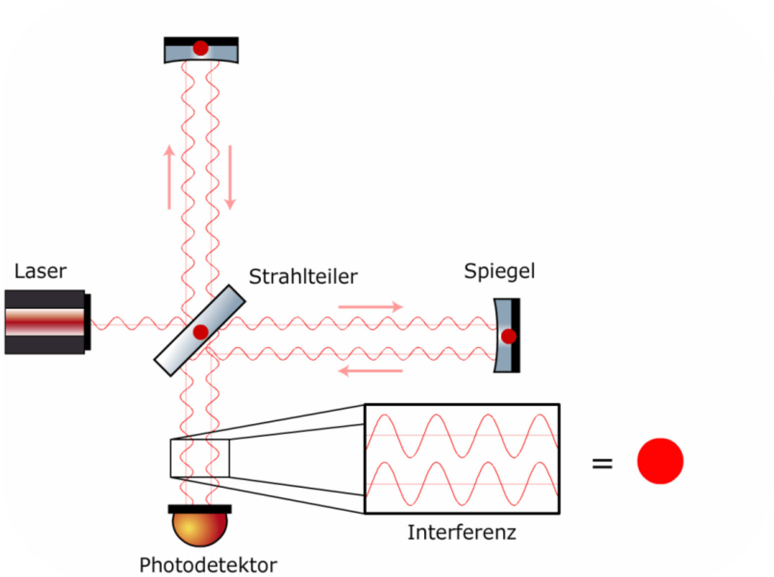
Figure from
I. Obata, T. Fujita, YM,
PRL **121**, 161301 (2018)

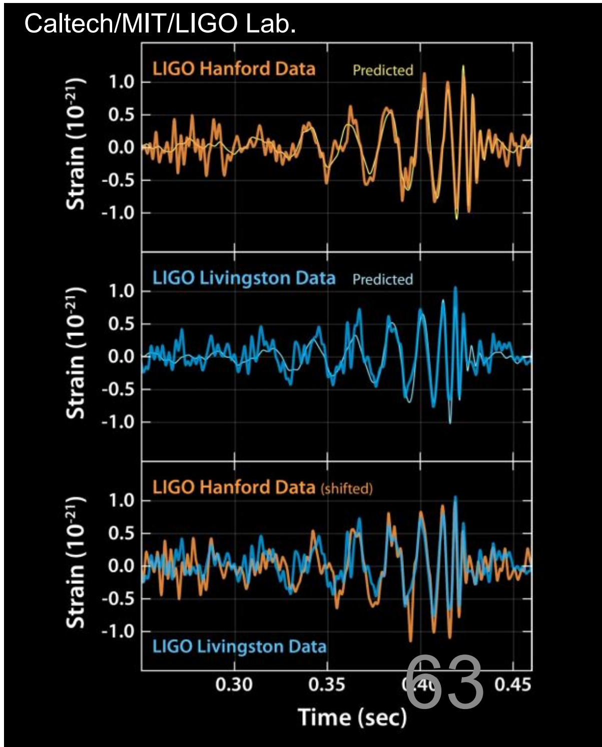
Ultralight Dark Matter

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

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

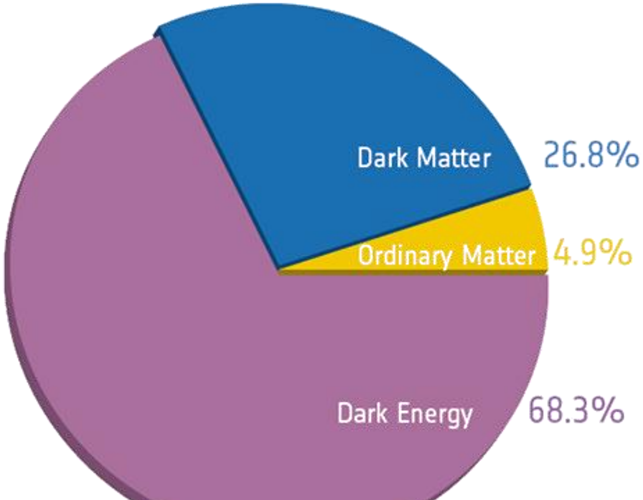
- Laser interferometers are sensitive to such oscillating changes (rather than “pulse” signals from particles)



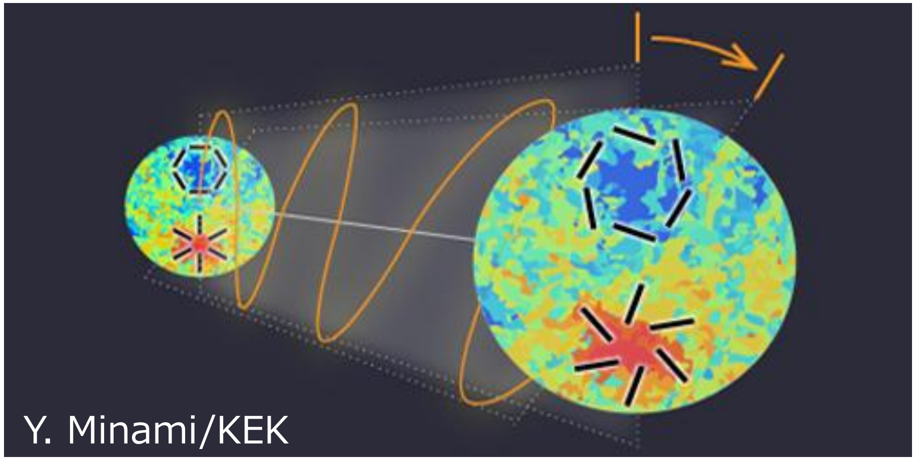

Caltech/MIT/LIGO Lab.

Motivations for Axions (ALPs)

Dark Matter and Dark Energy

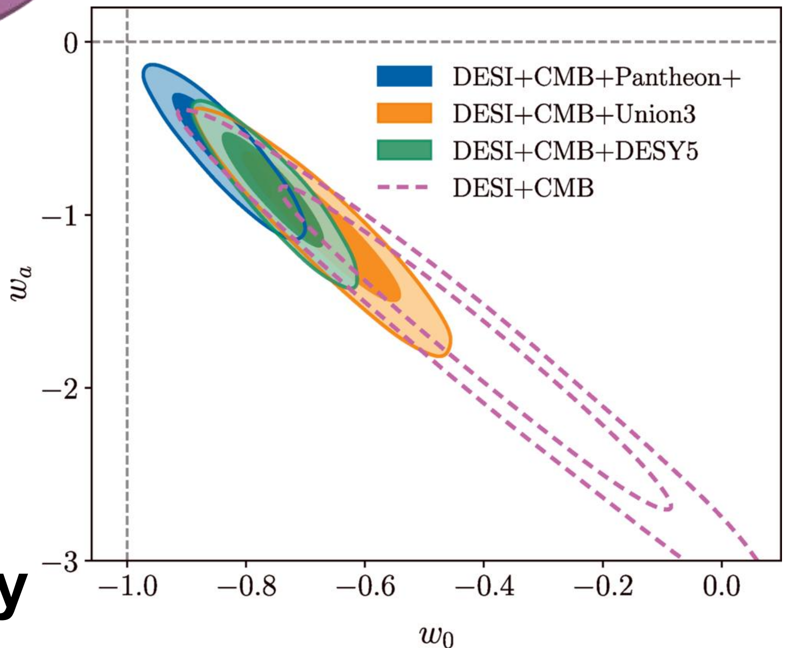


Cosmic Birefringence


Y. Minami/KEK

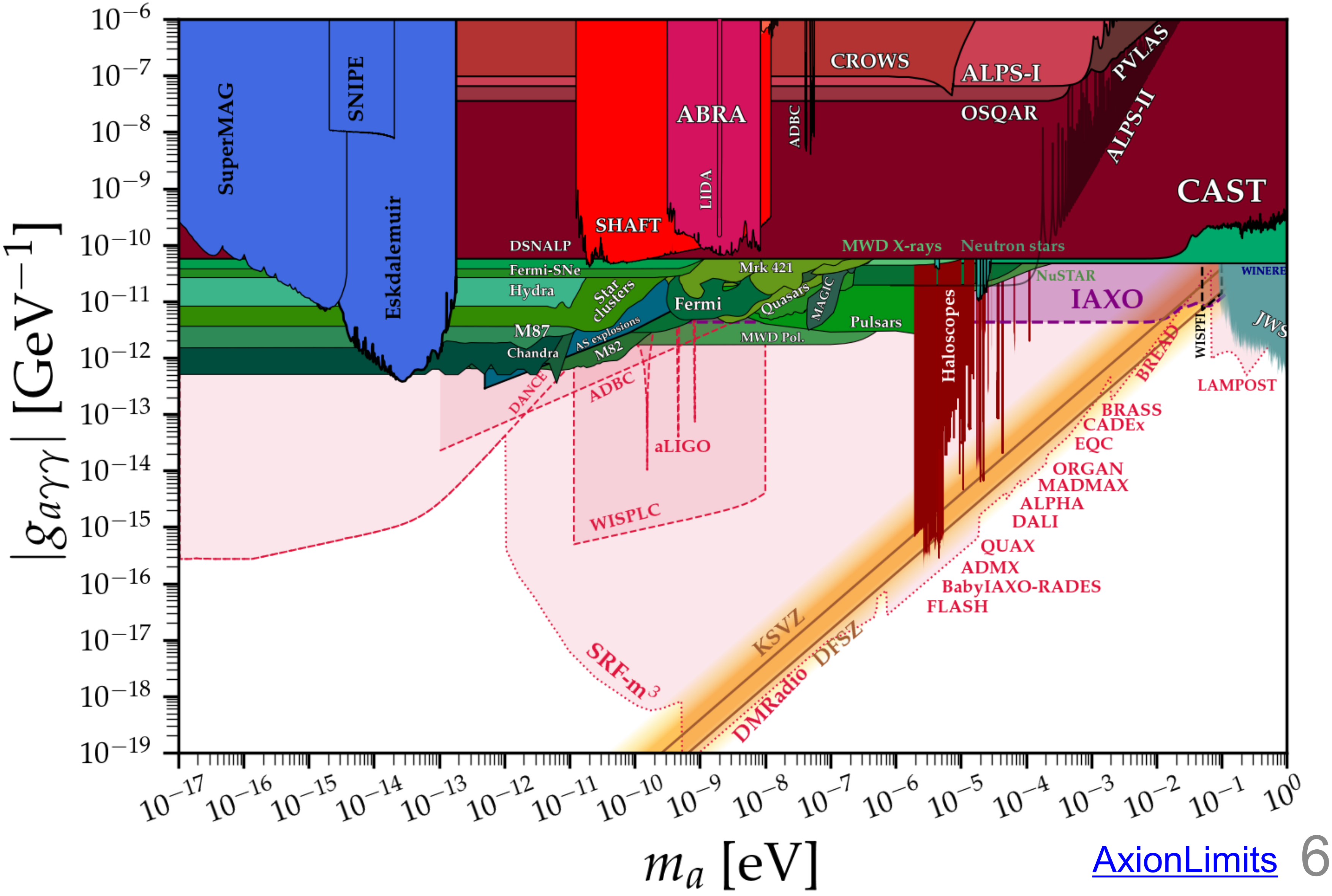
Y. Minami and E. Komatsu, PRL 125, 221301 (2020) etc...

Dynamical Dark Energy



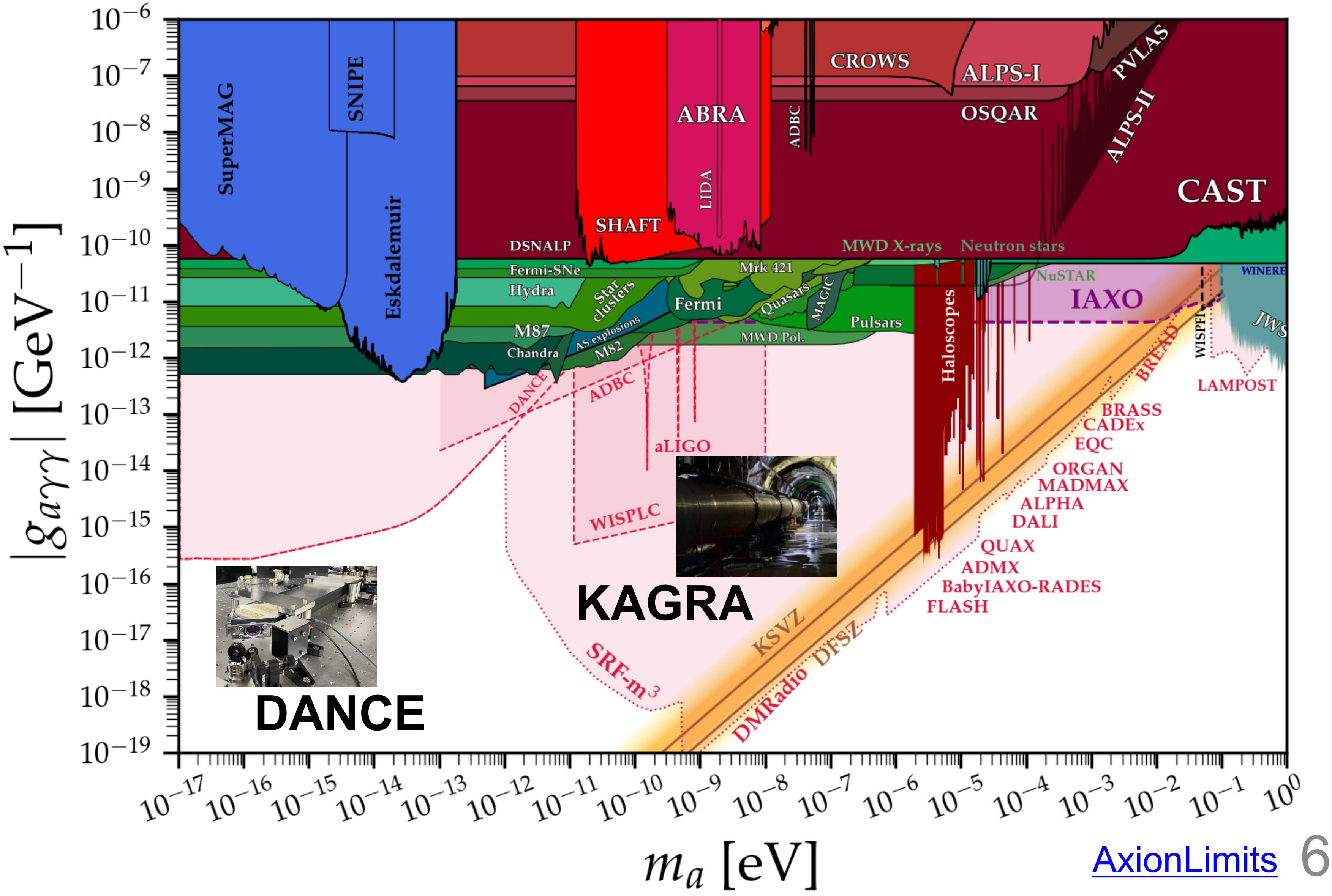
DESI, PRD **112** 083515, (2025)

Axion-Photon Coupling



AxionLimits

Searches with DANCE and KAGRA



AxionLimits

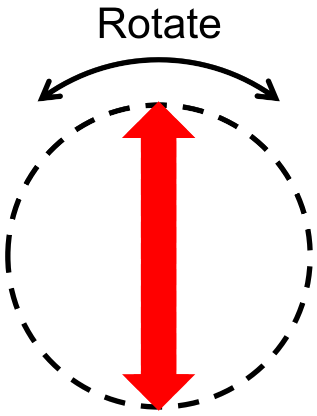
Polarization Modulation from Axions

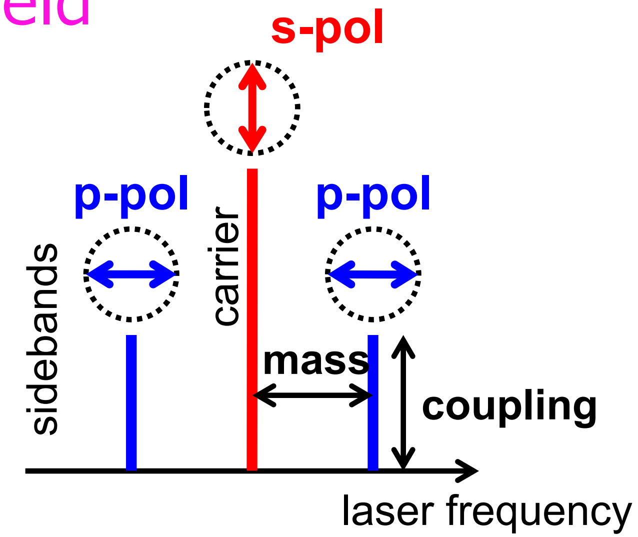
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

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

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





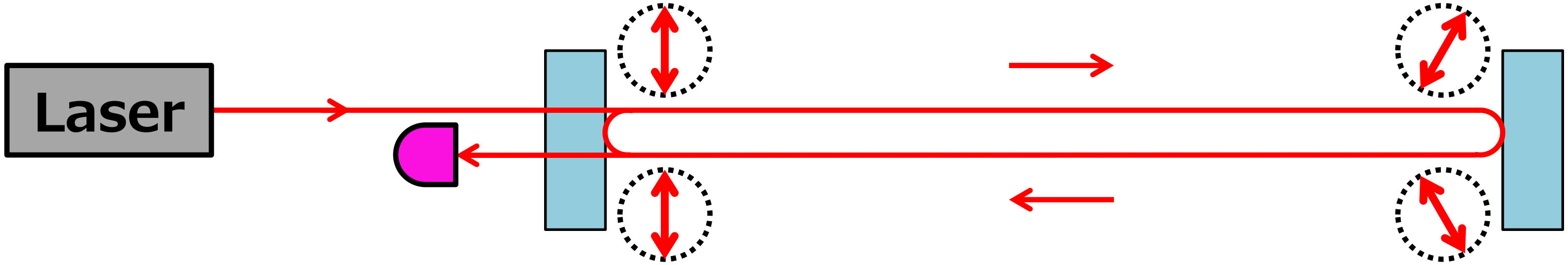
Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

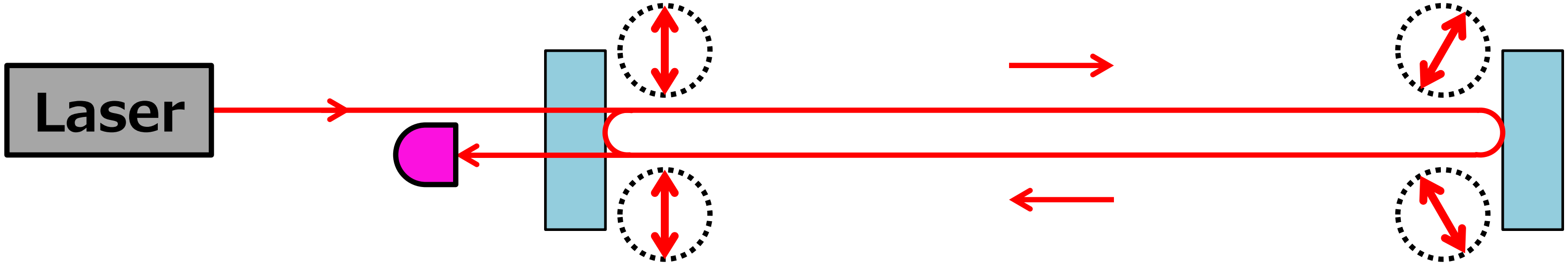
- Optical cavities can increase the optical path, but the polarization is flipped by mirror reflections



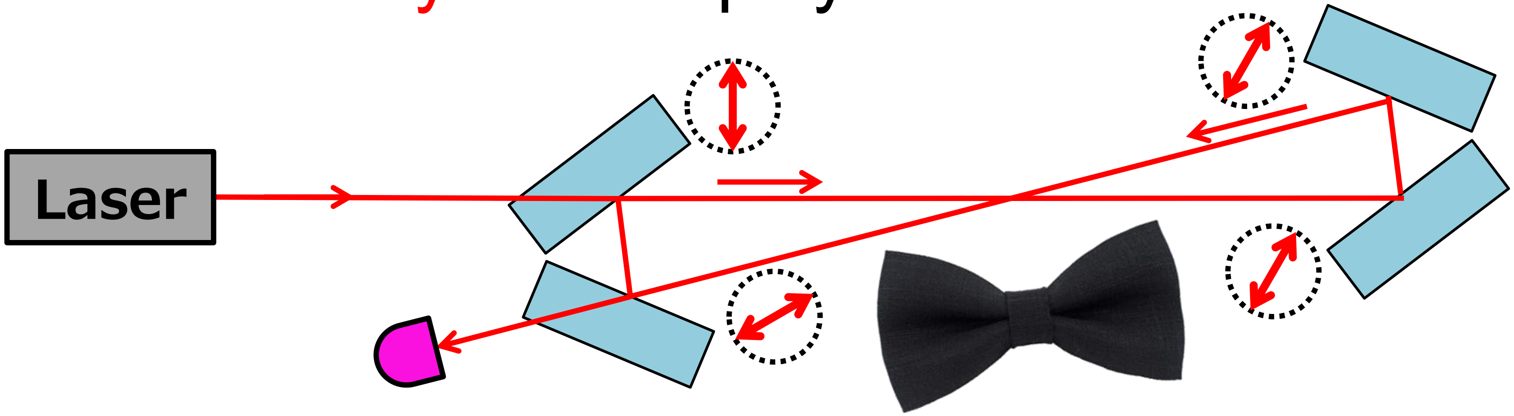
Optical Cavity to Amplify the Signal

- 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

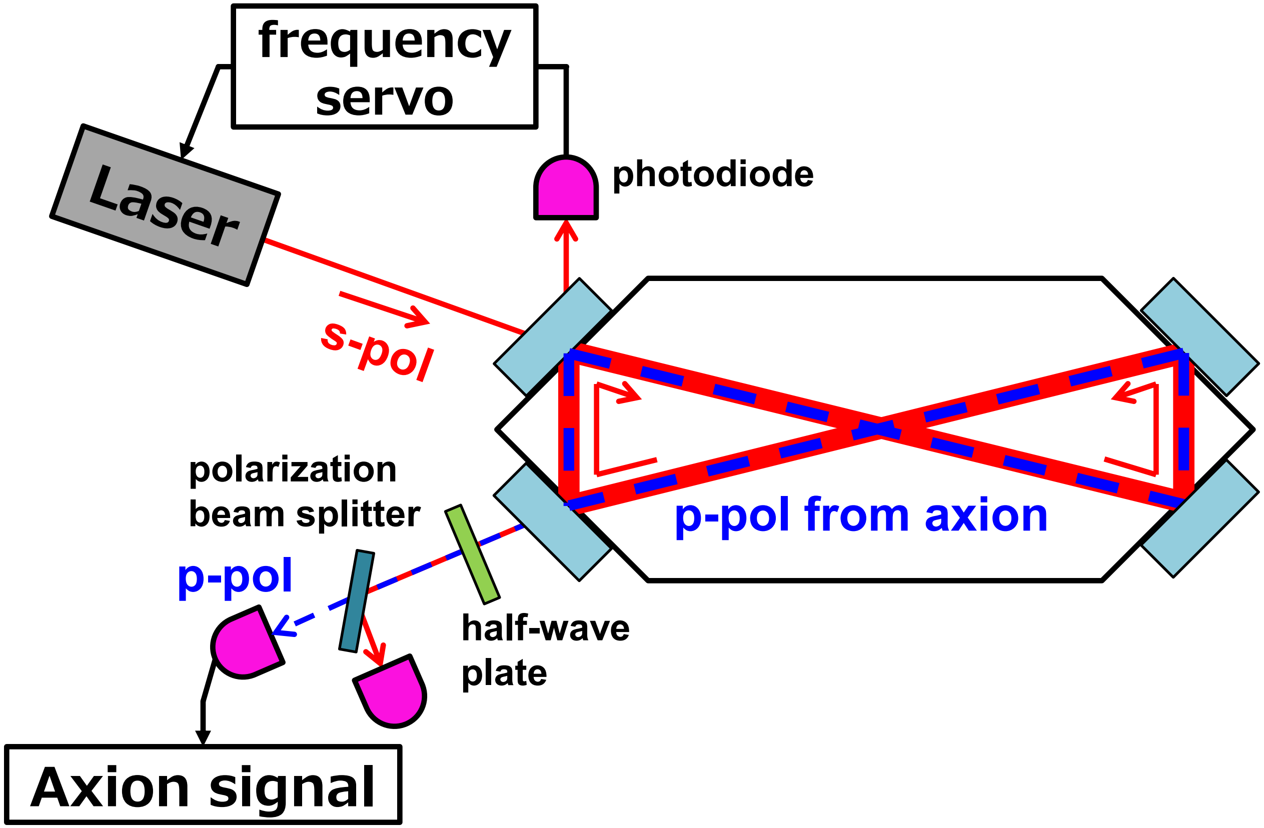


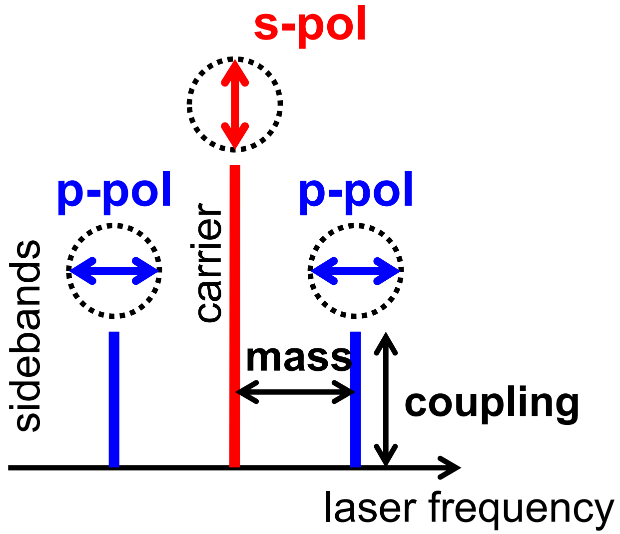
DANCE Setup

Dark matter Axion search with riNg Cavity Experiment

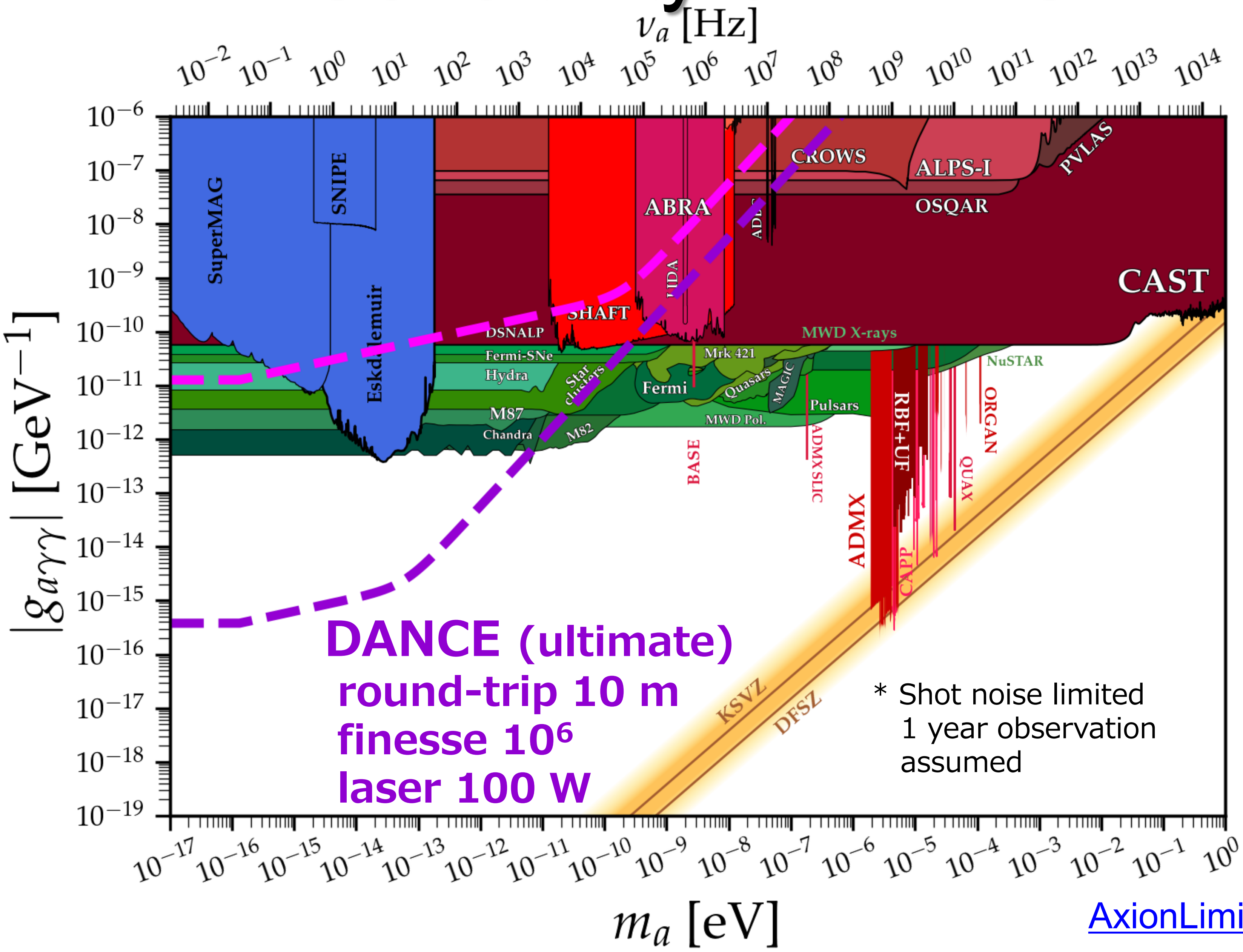
- Look for amount of modulated p-pol generation in each frequency

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





Sensitivity of DANCE

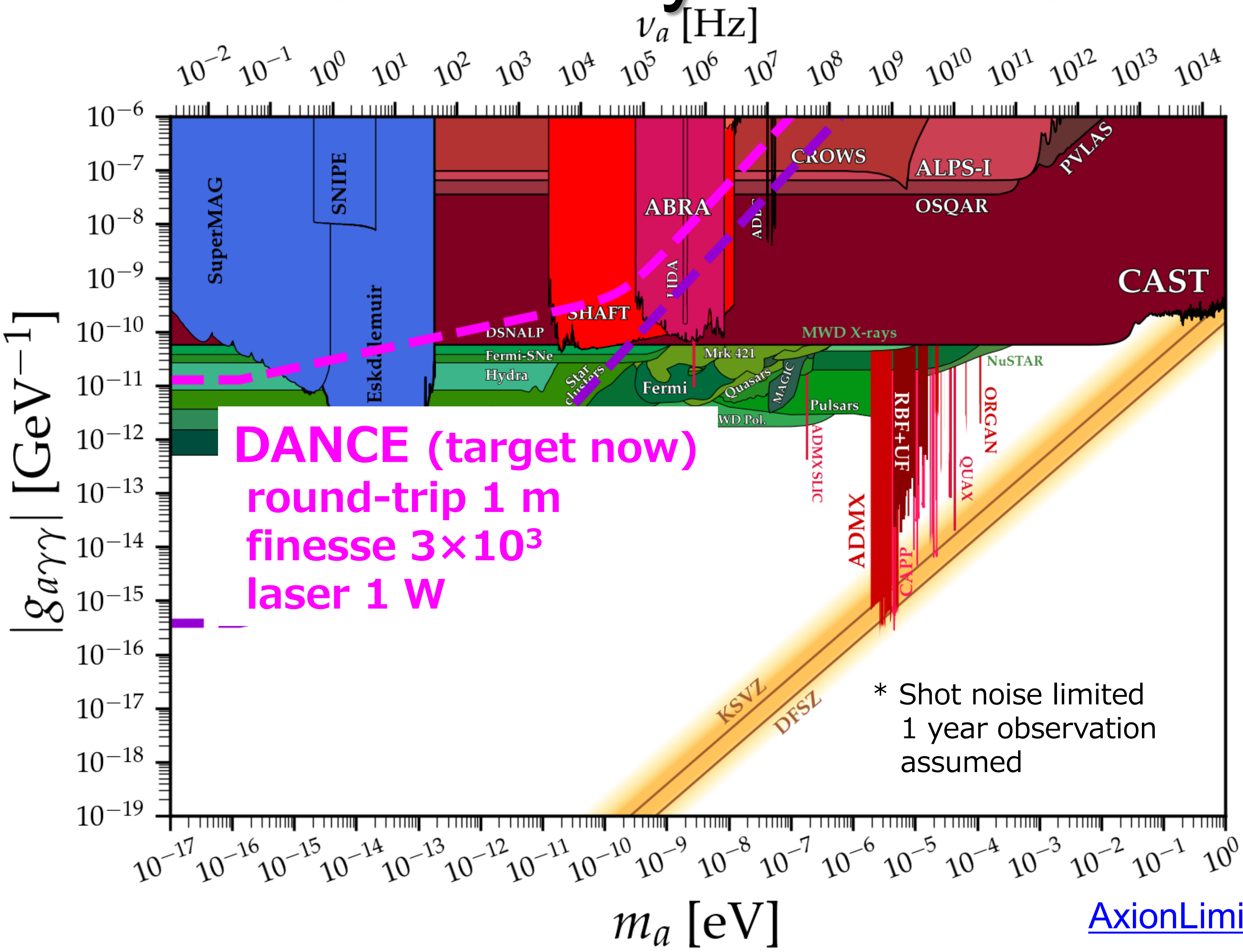


DANCE (ultimate)
round-trip 10 m
finesse 10^6
laser 100 W

* Shot noise limited
1 year observation
assumed

AxionLimits

Sensitivity of DANCE



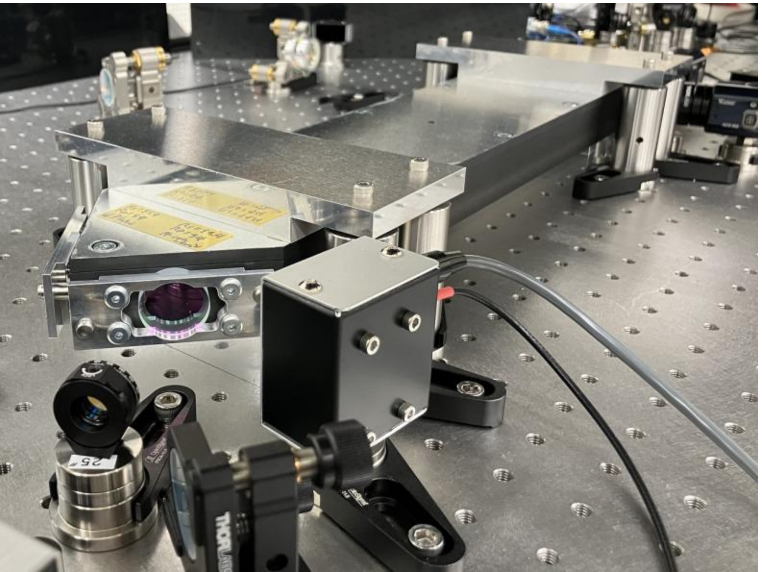
DANCE (target now)
round-trip 1 m
finesse 3×10³
laser 1 W

* Shot noise limited
1 year observation
assumed

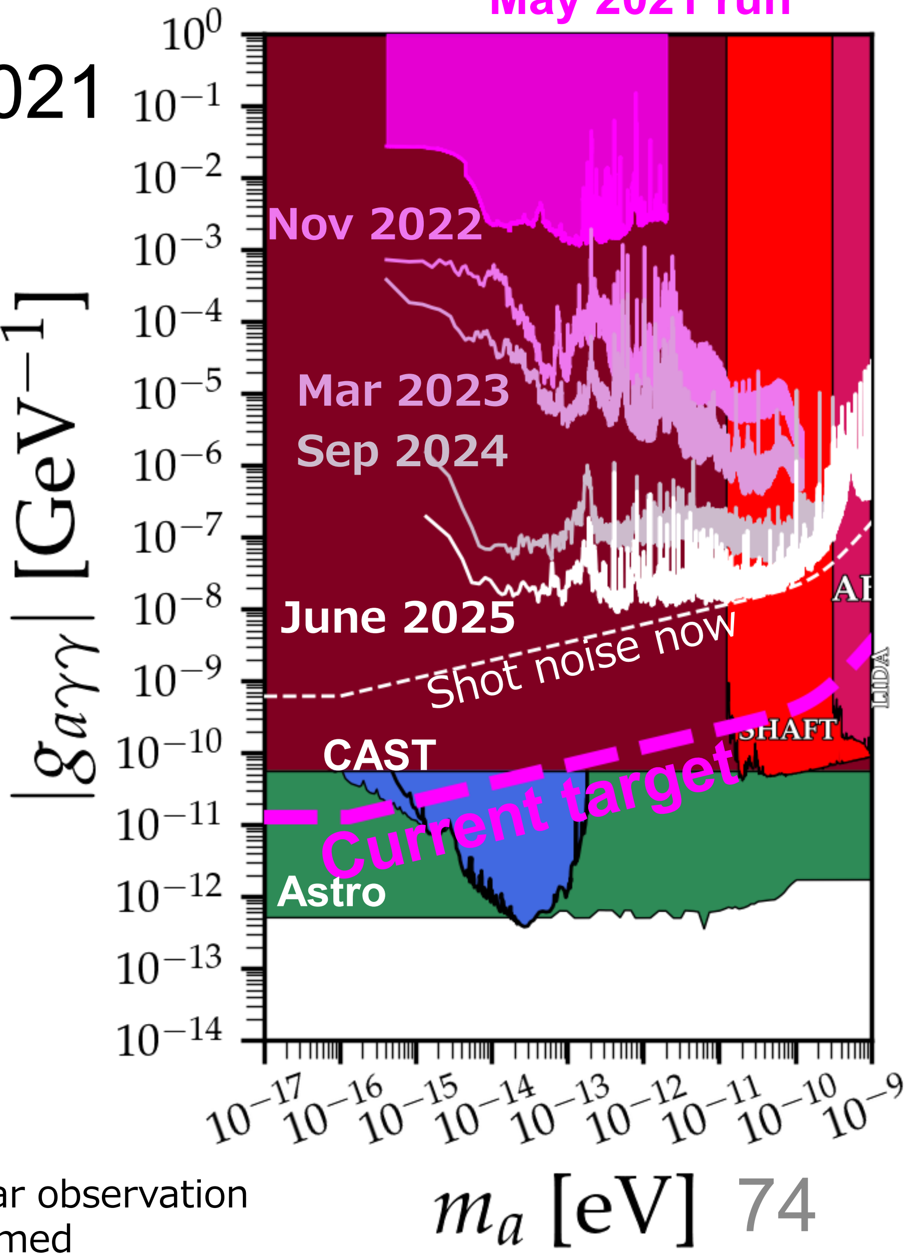
AxionLimits

Status of DANCE

- 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)



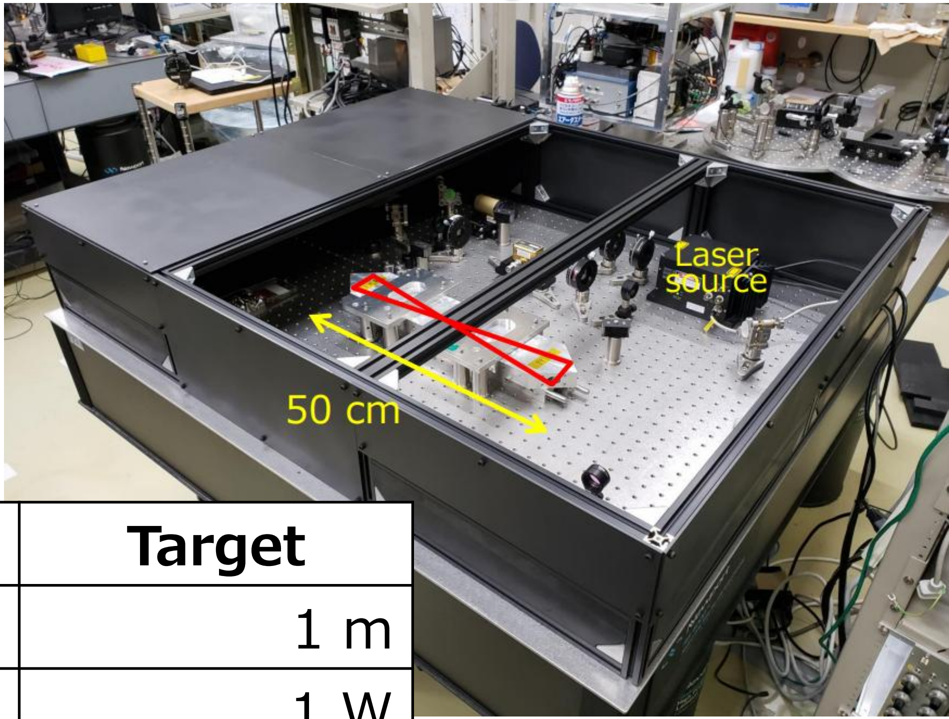
Limit from May 2021 run



* 1 year observation assumed

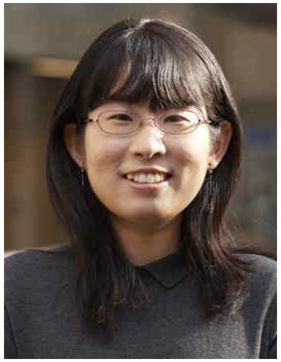
First Observing Run in May 2021

- 1 m prototype
- 12-day test run from May 8th to 30th



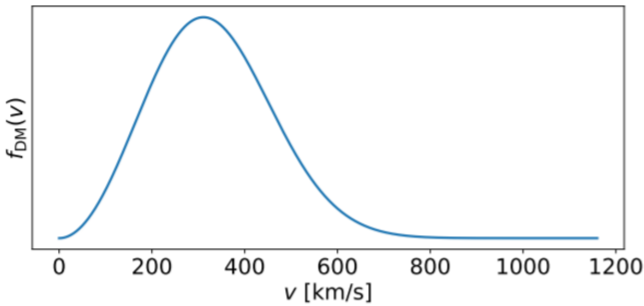
Y. Oshima+, PRD **108**, 072005 (2023)

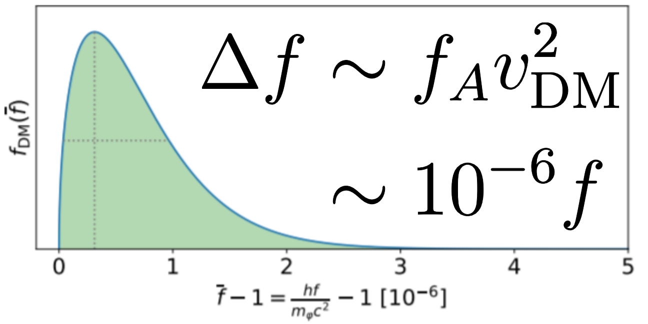
	May 2021	**Target**
Round-trip length	1 m	1 m
Input power	242(12) mW (Source: 0.5 W)	1 W
Finesse (for carrier)	$2.85(5)\times10^3$ s-pol	3×10^3
Finesse (for sidebands)	195(3) p-pol	3×10^3
s/p-pol resonant freq. difference	2.52(2) MHz	0 Hz

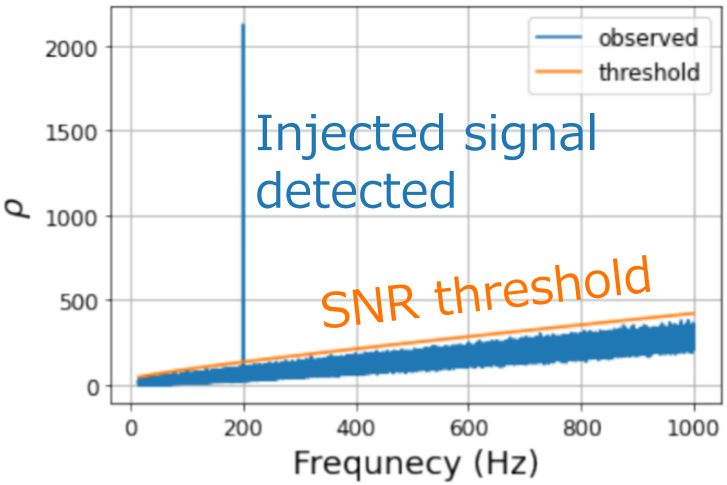


Data Analysis Pipeline

E. Savalle+, PRL 126, 051301 (2021)







- Nearly monochromatic signal

$$\omega_i = m_a \left(1 + \frac{v_i^2}{2}\right)$$

- Stack the spectra in this frequency region to calculate SNR

$$\rho = \sum \frac{4|\tilde{d}(f_k)|^2}{T_{\rm obs} S_n(f_k)}$$

Data

PSD

Obs. time

$m_A \leq 2\pi f_k \leq m_A(1 + \kappa v_{\rm DM}^2)$

- Detection threshold determined assuming ρ follows χ^2 distribution (=assuming Gaussian noise)
- From ρ , calculate 95% upper limit on coupling constant
- Applied the pipeline to mock data for verification

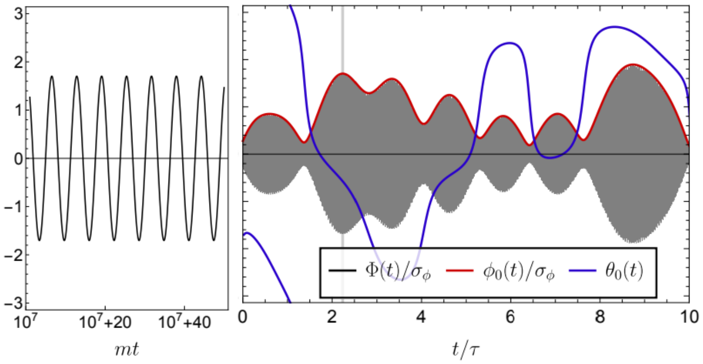
Stochastic Nature of DM Signal

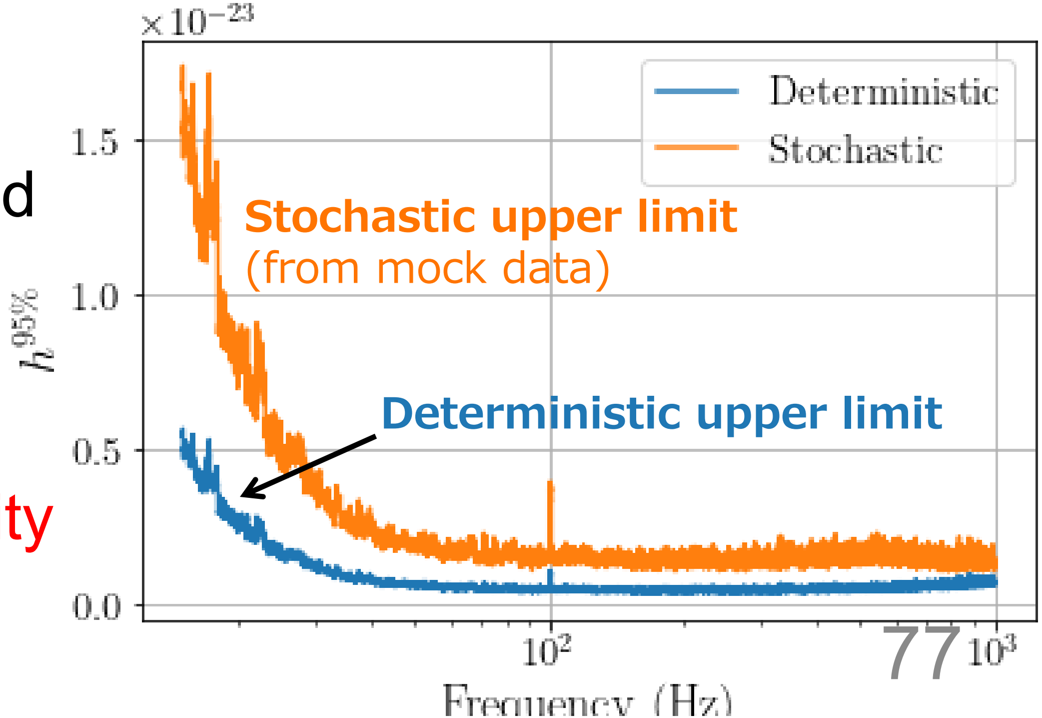
- DM signal is from superposition of many waves with various momentum, phase and polarization
- The amplitude fluctuates at the time scale of

$$\tau = 2\pi/(m_a v_{\rm DM}^2)$$

- At low frequencies, DM signal could be too small by chance and elude detection
- Method to calculate upper limit taking into account this stochasticity developed

H. Nakatsuka+,
PRD **108**, 092010 (2023)





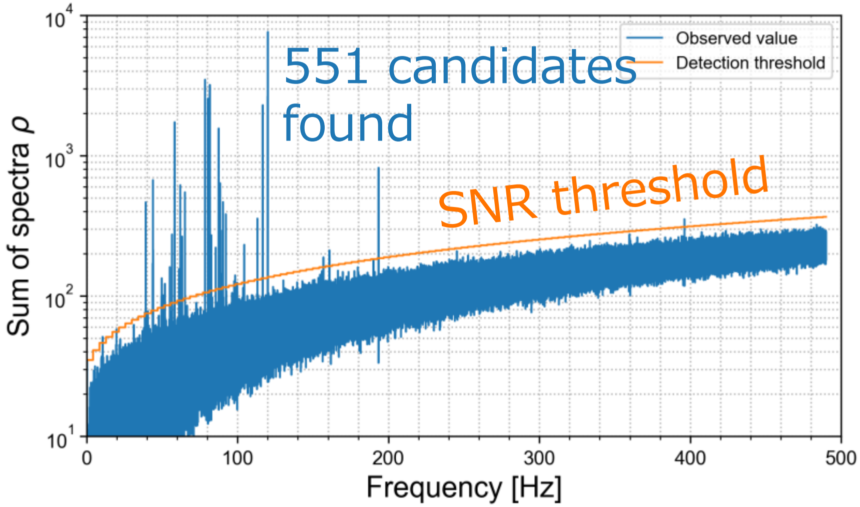
Stochastic upper limit
(from mock data)

Deterministic upper limit

First Data Analysis Results

- Used 24-hour data from 12-day run in May 2021
- 551 candidates found from initial analysis

  H. Nakatsuka+,
  [PRD **108**, 092010 (2023)]



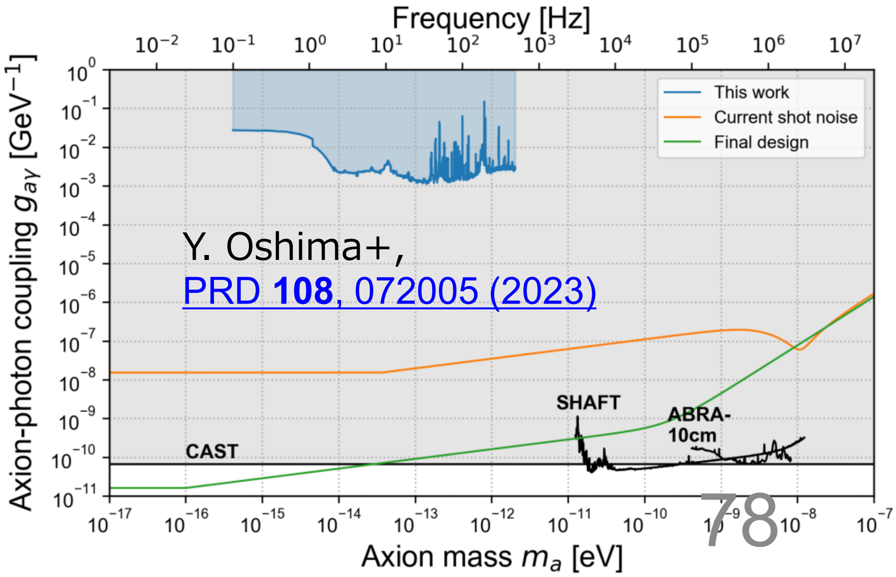
551 candidates found

SNR threshold

- Veto analysis
  - Consistency veto

    (Frequency should be the same for different set of 24-hour data)
  - Q-factor veto

    (DM signal must have Q of 10^6)
  - Remaining 7 candidates (all multiples of ~40 Hz) are also found in laser frequency control, and thus rejected
- First end-to-end test

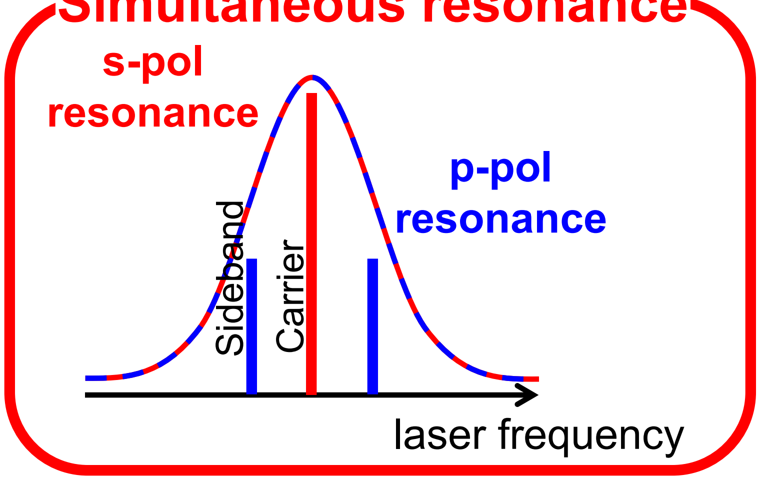


Y. Oshima+,
[PRD **108**, 072005 (2023)]

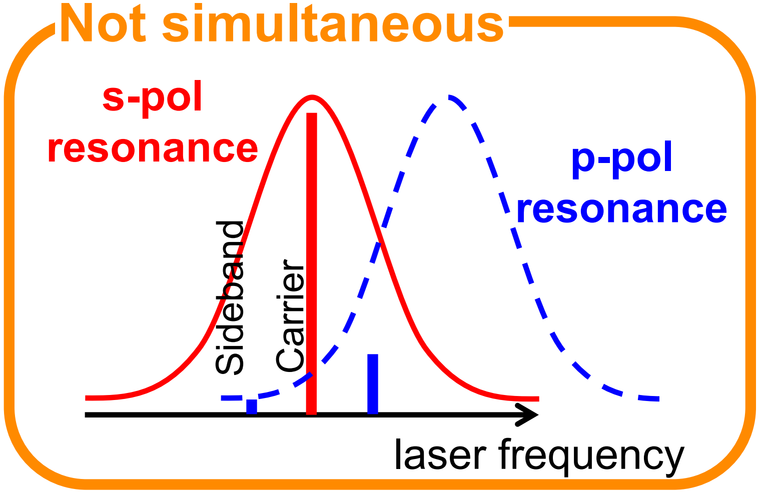
Simultaneous Resonance

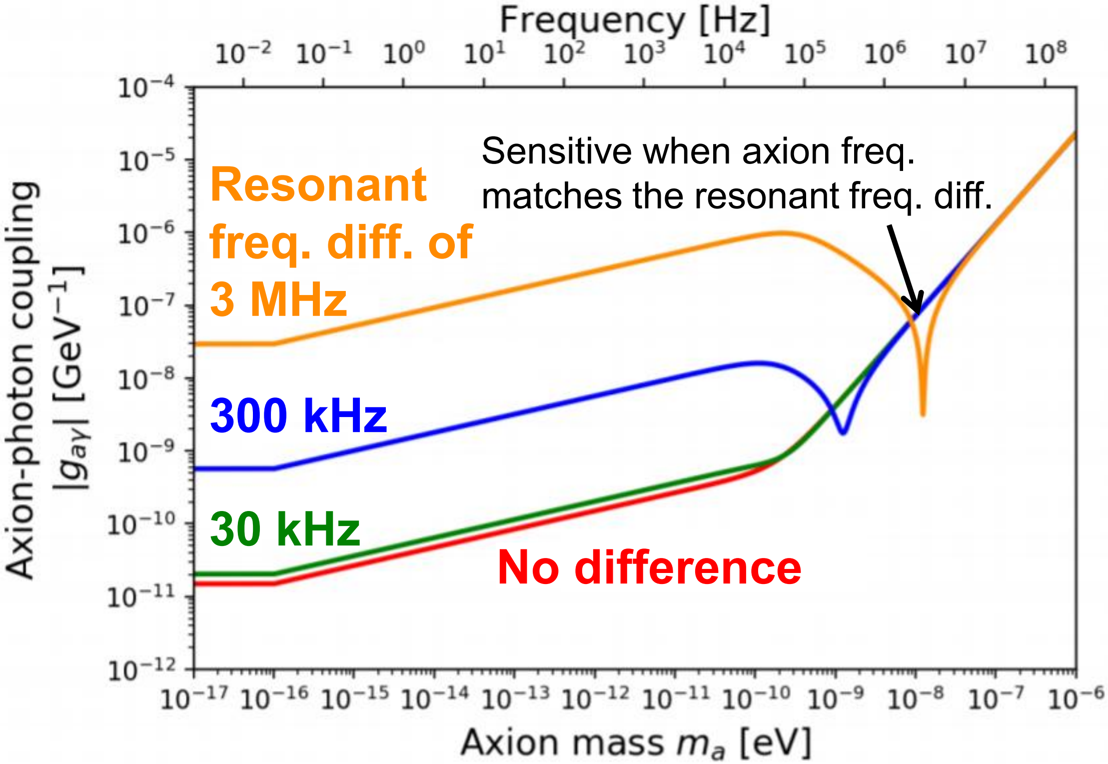
- Carrier pol and sideband pol needs to be enhanced simultaneously for improving the sensitivity

Simultaneous resonance



Not simultaneous

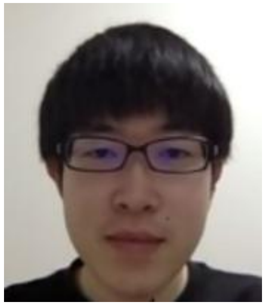




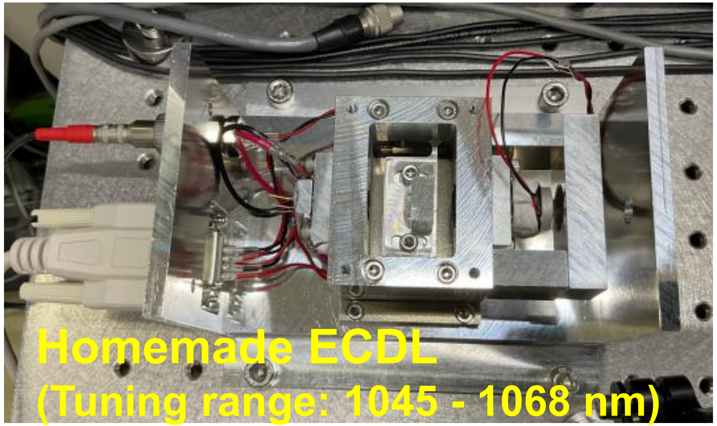
Plot by Y. Oshima & H. Fujimoto

Cavity Birefringence Tuning

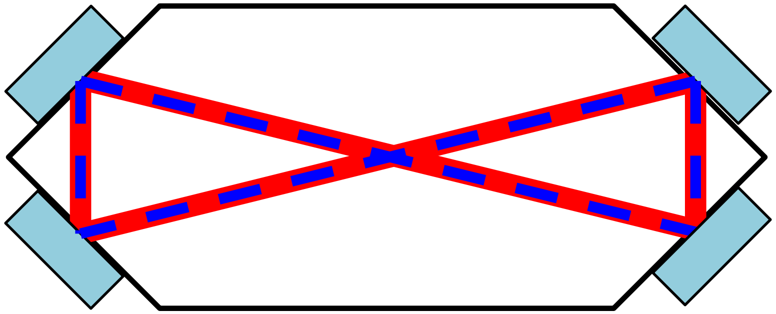
- Near 45 deg incidence on cavity mirrors create reflection phase difference, which leads to non-simultaneous resonance
- Reflection phase can be tuned by tuning laser wavelength

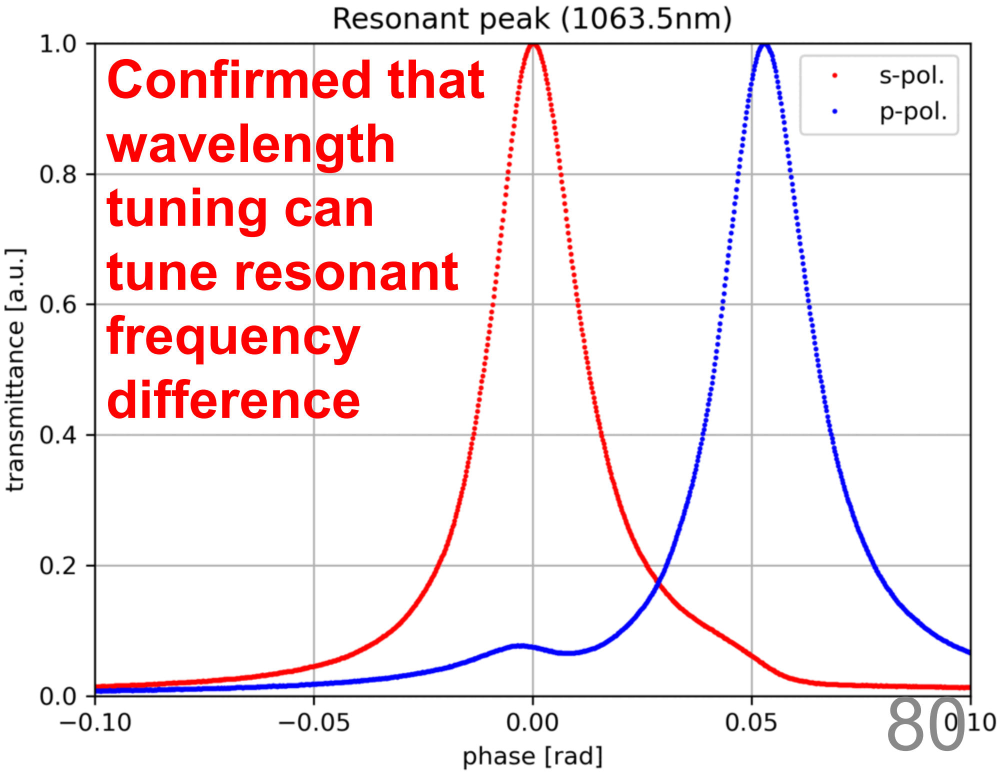


H. Takidera+, PRD **112**, 063048 (2025)



Homemade ECDL
(Tuning range: 1045 - 1068 nm)





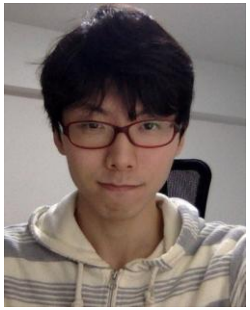
Resonant peak (1063.5nm)

Confirmed that wavelength tuning can tune resonant frequency difference

Current DANCE Parameters

- Resonance tuning demonstrated
- Finesse (almost) reached the target
- Now developing laser power amplifier (1 W)

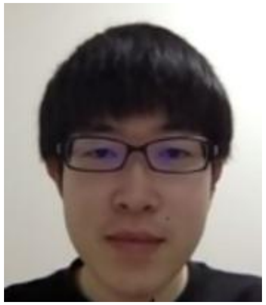
H. Fujimoto, PhD thesis (UTokyo 2025)

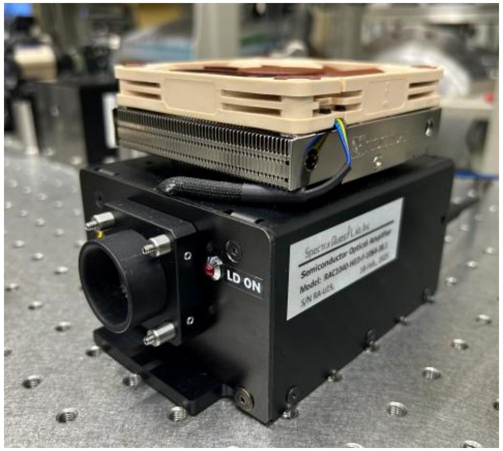


	May 2021	**Now (July 2025)**	**Target**
Round-trip length	1 m	1 m	1 m
Input power	242(12) mW (Source: 0.5 W)	6 mW (Source: 36.5 mW)	1 W
Finesse (for carrier)	$2.85(5)\times10^3$ s-pol	$2.60(4)\times10^3$ s-pol	3×10^3
Finesse (for sidebands)	195(3) p-pol	$2.86(6)\times10^3$ p-pol	3×10^3
s/p-pol resonant freq. difference	2.52(2) MHz	<~8.11 kHz @ 1066 nm (~1.57(2) MHz @ 1064 nm)	0 Hz

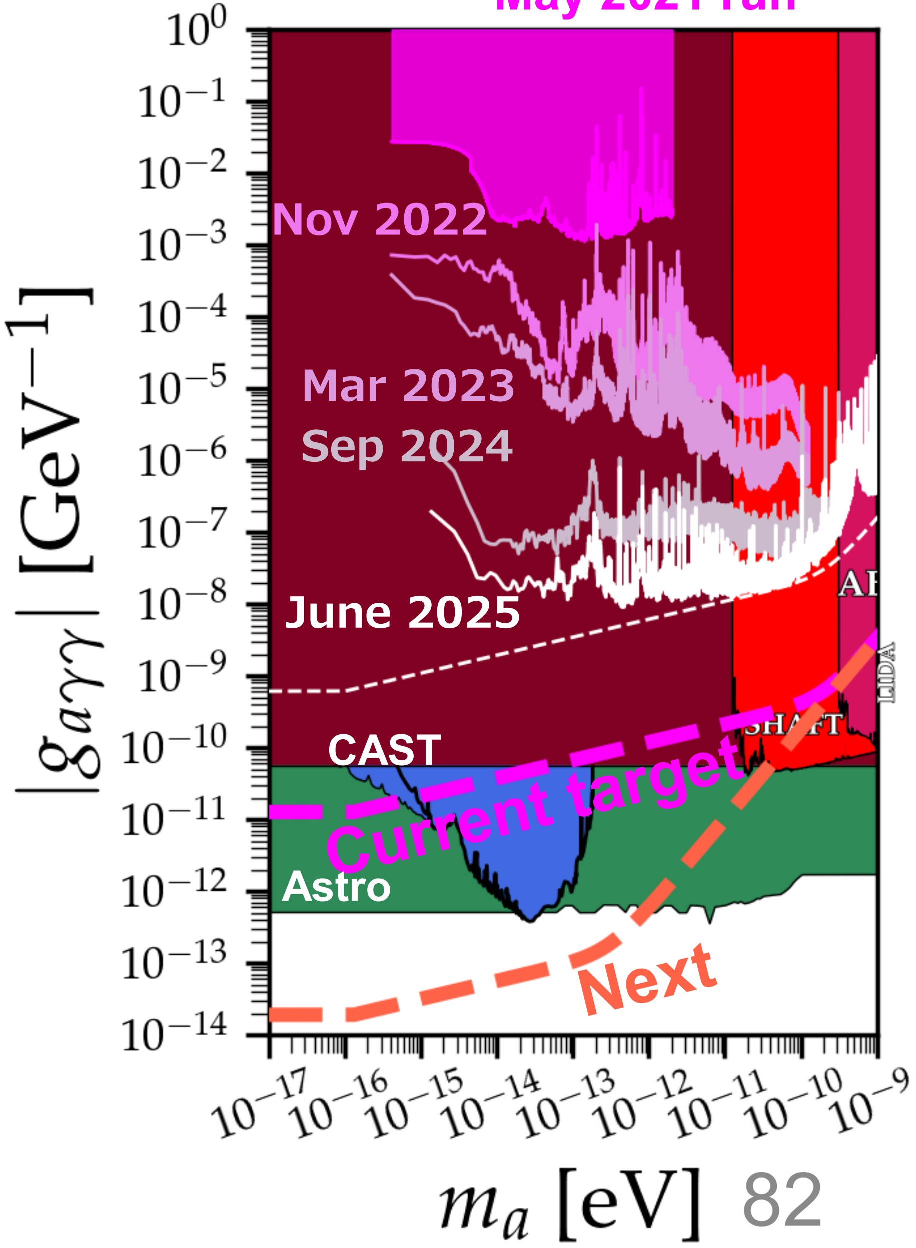
Plans for DANCE

- Achieve ~CAST limit with 1 W laser power
- Put the cavity in-vacuum for reducing vibrations

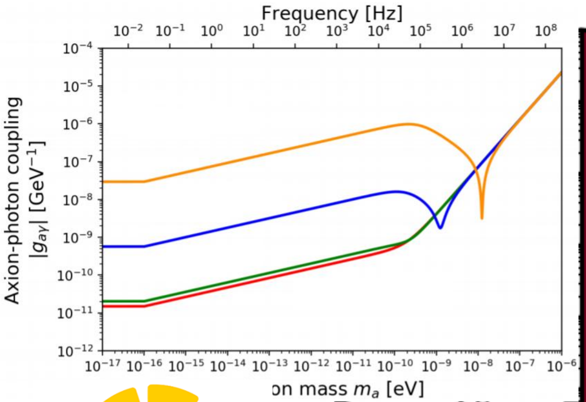


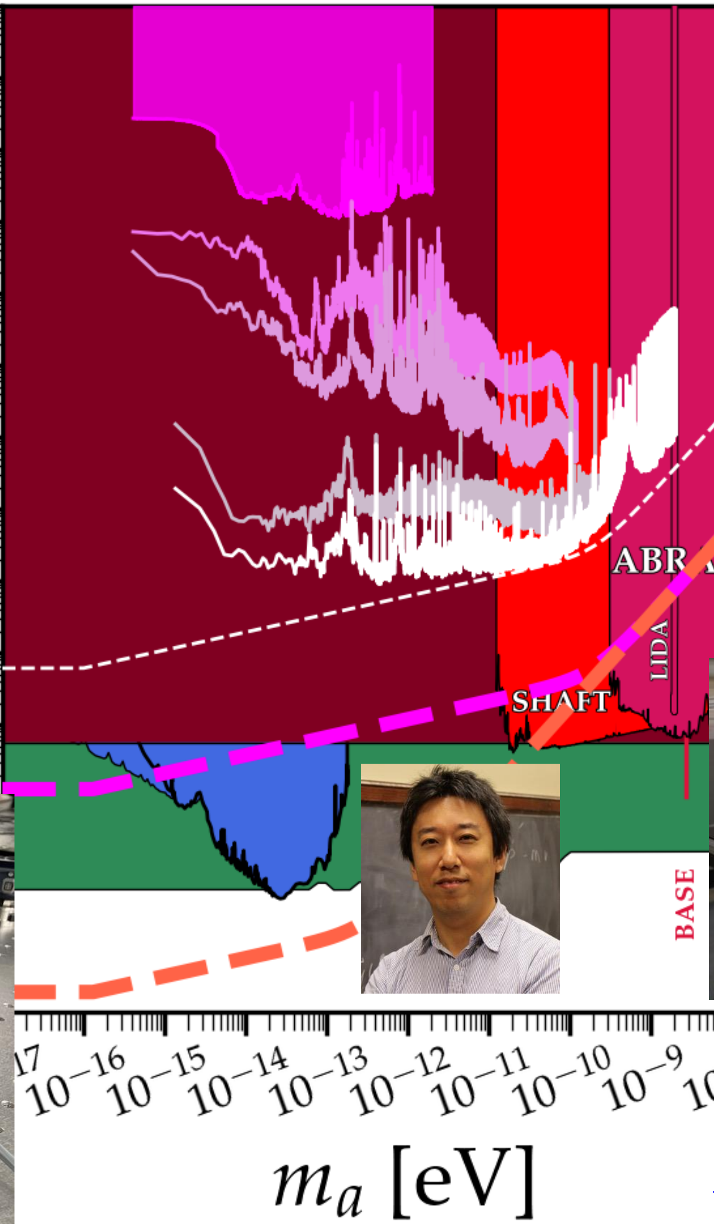


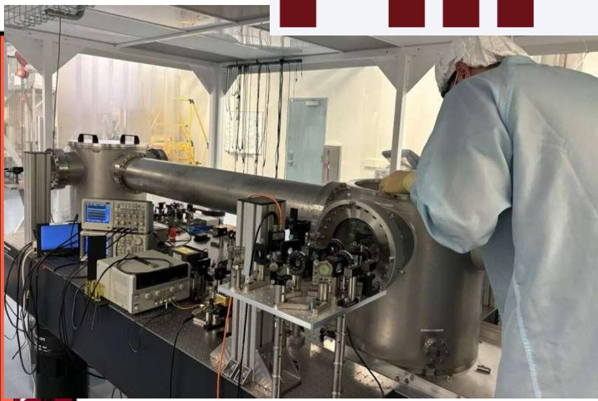
- Make cavity length x10 larger (10 m round-trip)



DANCE vs LIDA vs ADBC





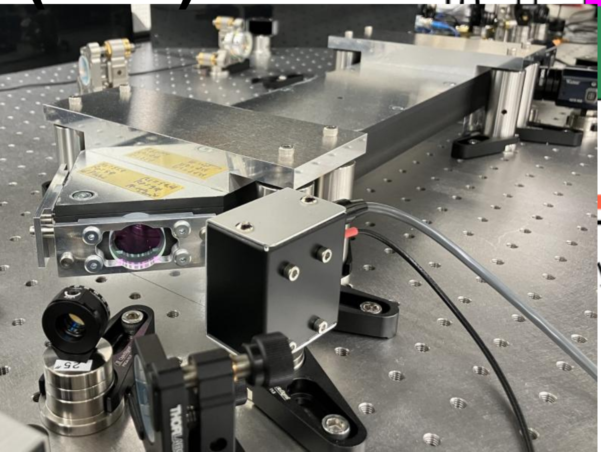


ADBC (4.7 m)

S. Pandey+,
PRL 133, 111003 (2024)

UTokyo

DANCE (1 m)



UNIVERSITY OF BIRMINGHAM

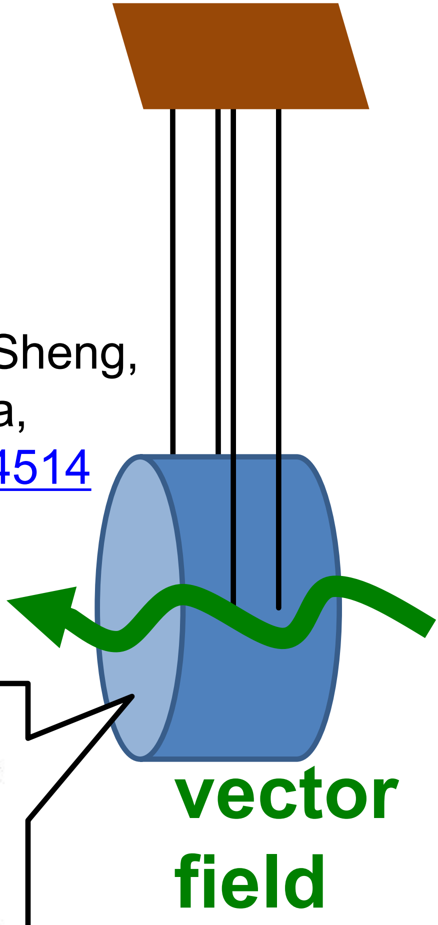
LIDA (10 m)

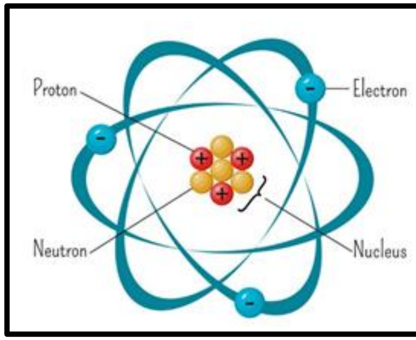
J. Heinze+,
PRL **132**, 191002 (2024)

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)

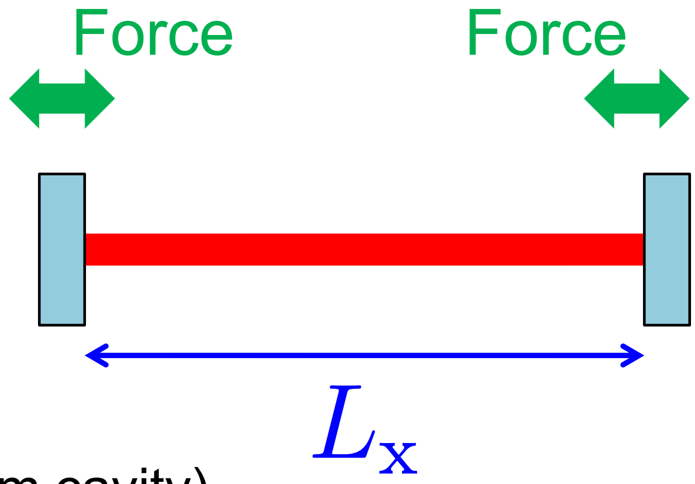
mirror mass

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?

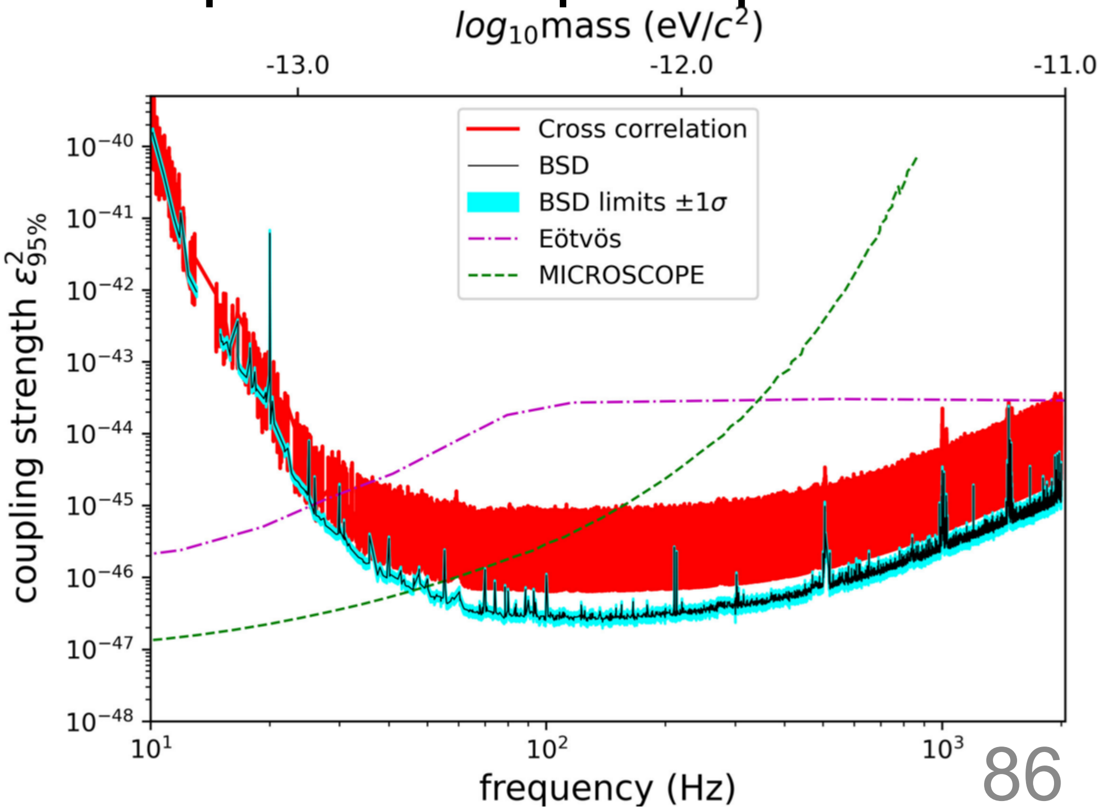
A. Pierce+, PRL **121**, 061102 (2018)

Previous Searches with LIGO/Virgo

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

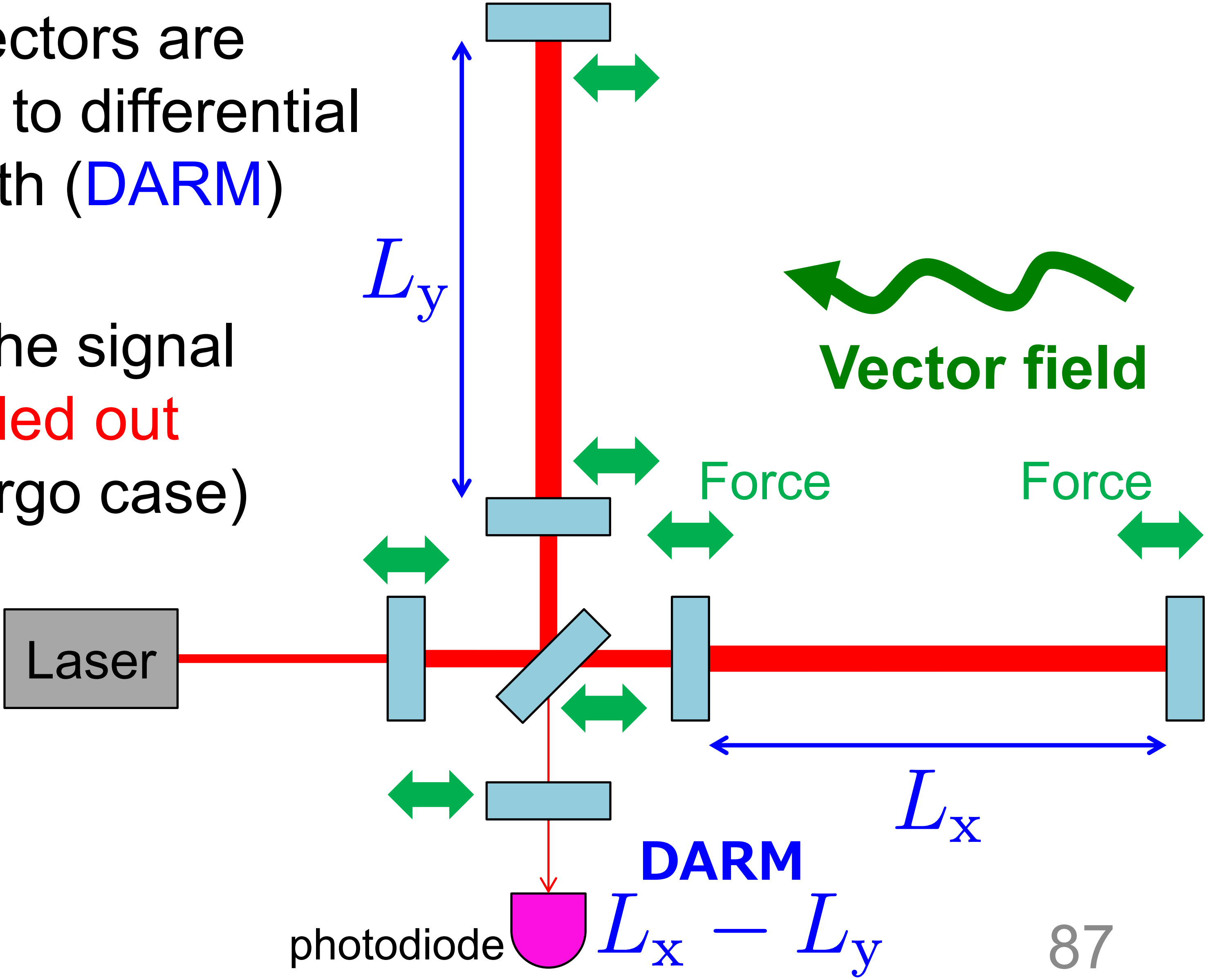
  H-K Guo+, Communications Physics **2**, 155 (2019)
  LIGO, Virgo, KAGRA Collaboration, PRD **105**, 063030 (2022)

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



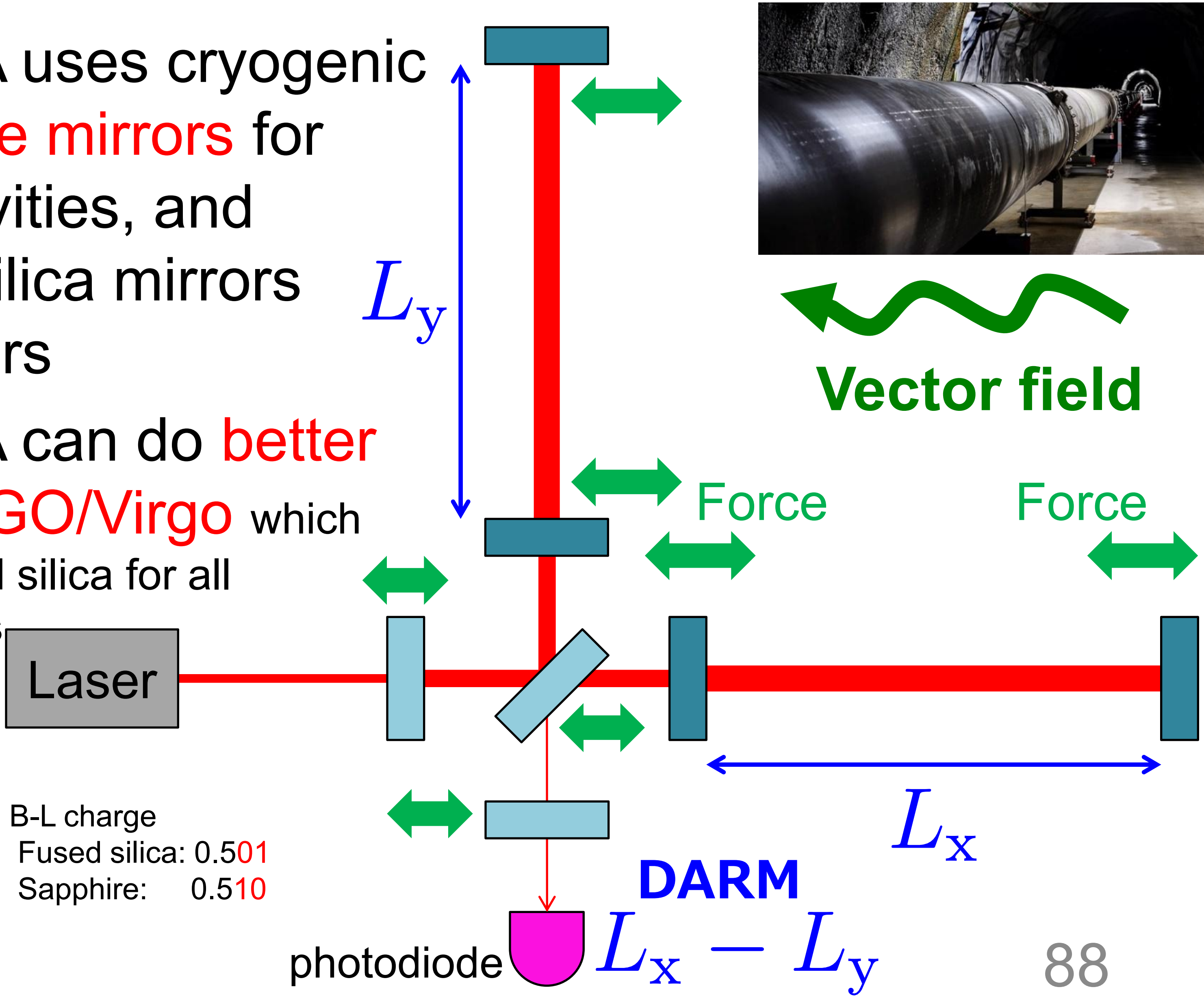
Search with GW Detectors

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

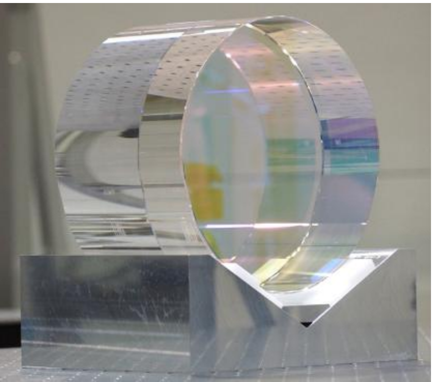


Search with KAGRA

- 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

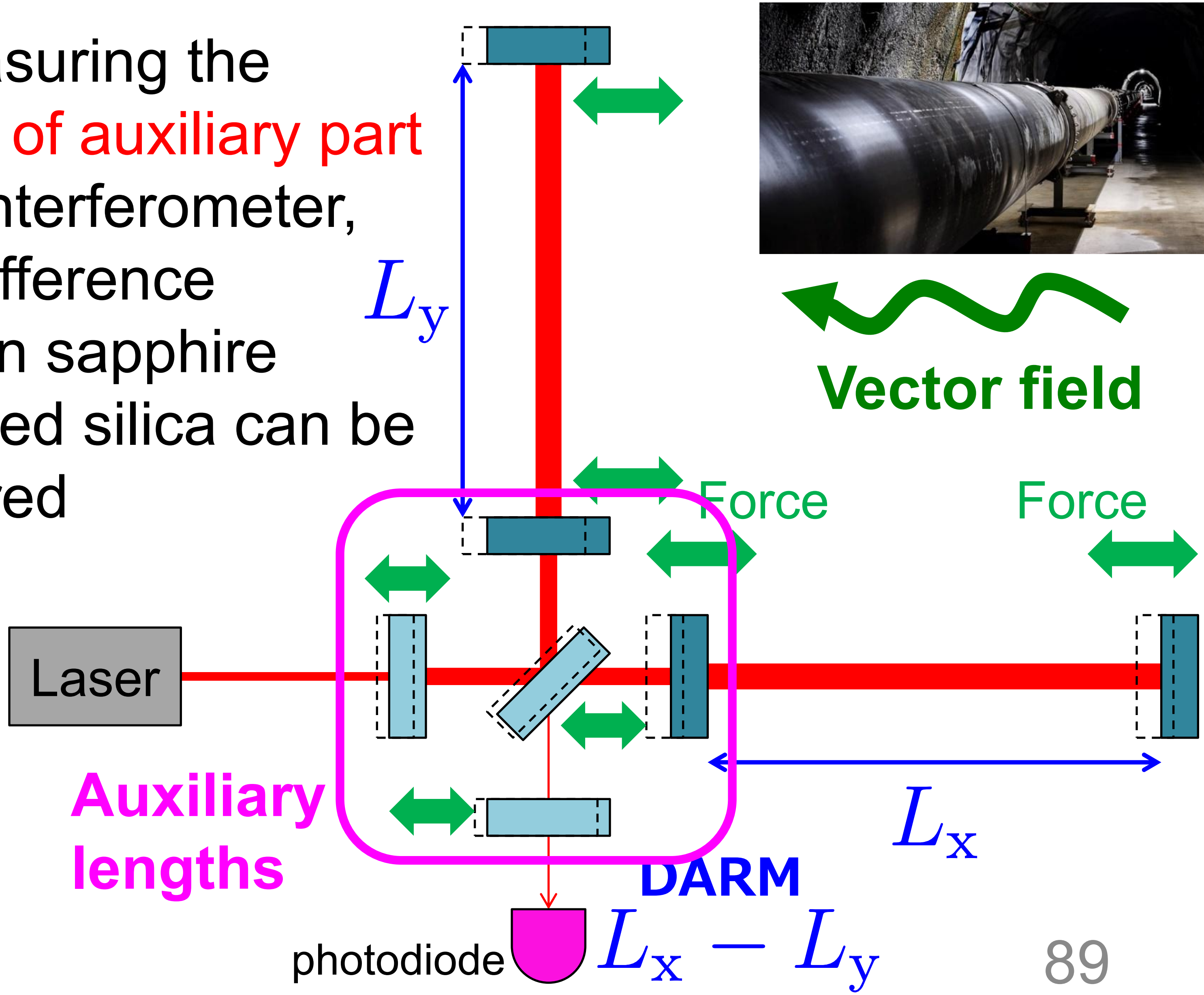


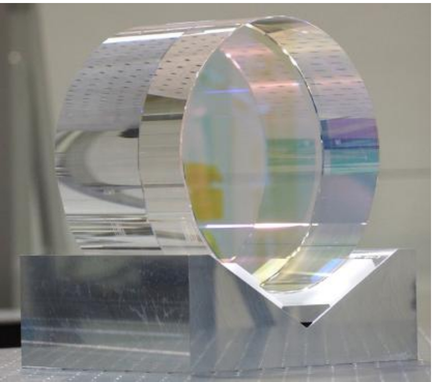
B-L charge
Fused silica: 0.501
Sapphire: 0.510



Search with KAGRA

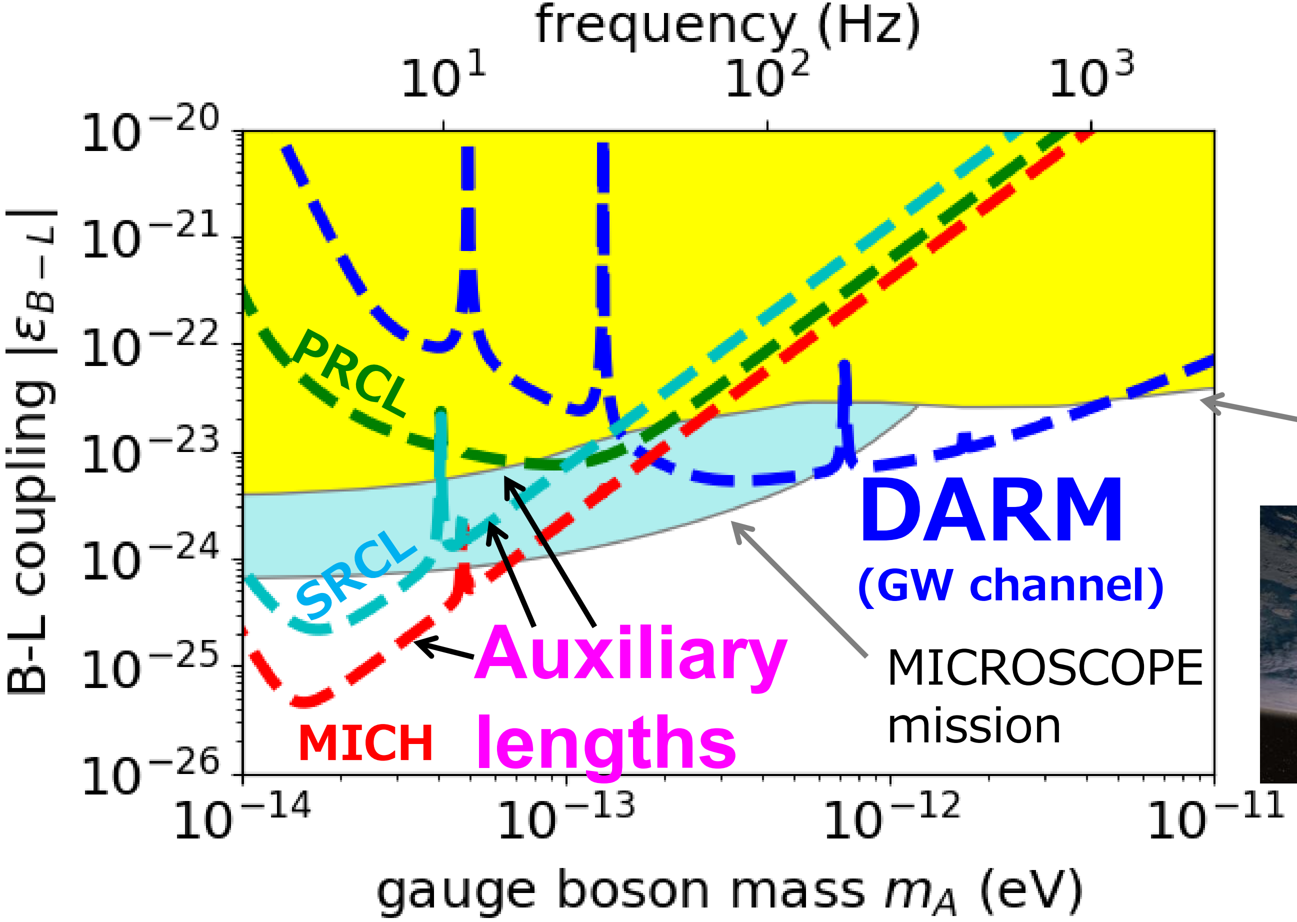
- By measuring the lengths of auxiliary part of the interferometer, force difference between sapphire and fused silica can be measured





KAGRA Vector DM Sensitivity

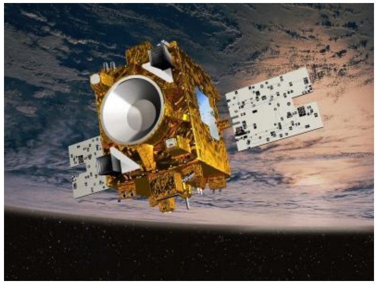
- Auxiliary length channels have better design sensitivity than DARM (GW channel) at low mass range
- Sensitivity better than equivalence principle tests



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

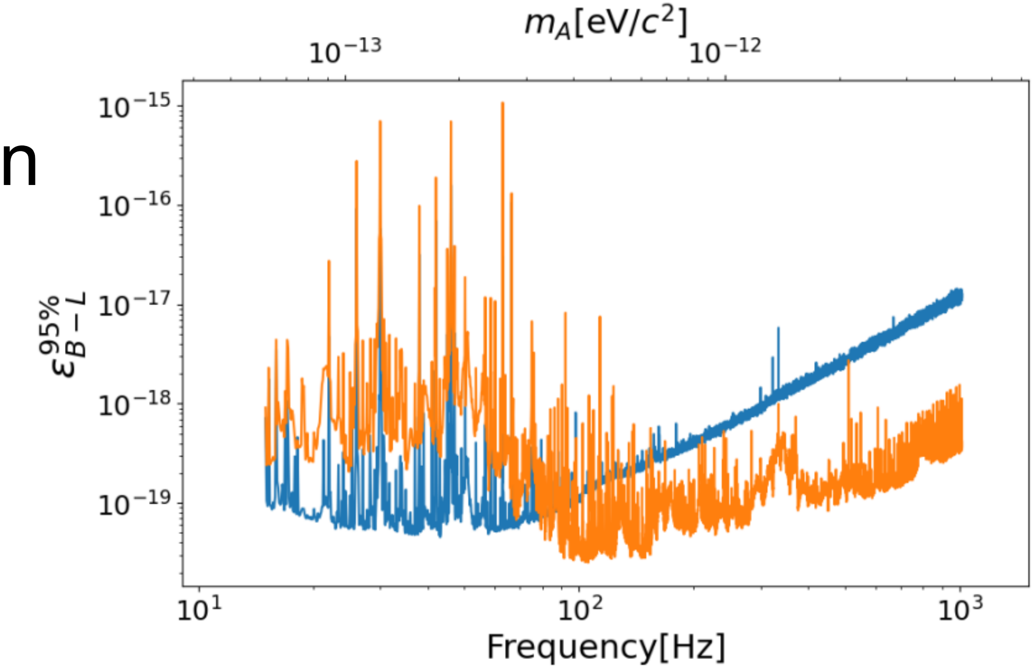
S. Morisaki, T. Fujita, YM,
H. Nakatsuka, I. Obata,
PRD 103, L051702 (2021)

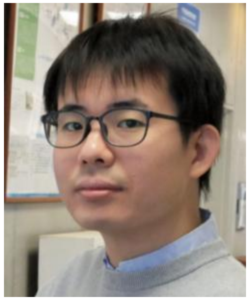
Eöt-Wash
torsion pendulum



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!)

Summary

- You can do a lot of things with laser interferometers
- See, also
  高エネルギーニュース 第41巻3号
  研究紹介
  　「レーザー干渉計で探るダークマター」

  東京大学 理学部ニュース 2024年7月号
  1+1から∞の理学 第25回
  　「一石十鳥の重力波望遠鏡」

Assignment for Nov 28

- Give one example of a research topic that can be done using the technologies of laser interferometric gravitational wave detectors, other than those mentioned in the lecture.
- You may also answer from the Google Form below https://forms.gle/6AwJ48XcpWQXqMon9

Don't forget to put your name and student#

You may answer in any language