Gakuhen Dark Matter Kick-off Symposium @ Online

February 6, 2021

B01
Laser interferometric searches for ultralight dark matter

Yuta Michimura

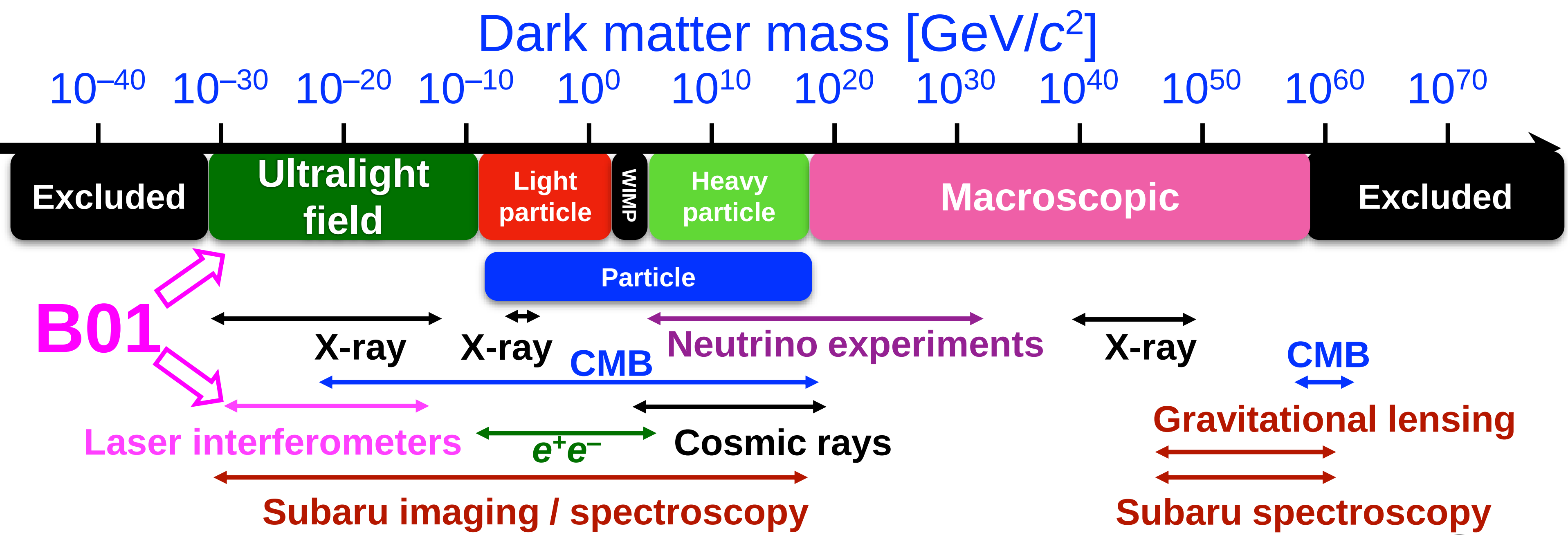
Department of Physics, University of Tokyo

michimura@phys.s.u-tokyo.ac.jp

Slides are available at https://tinyurl.com/YM20210206

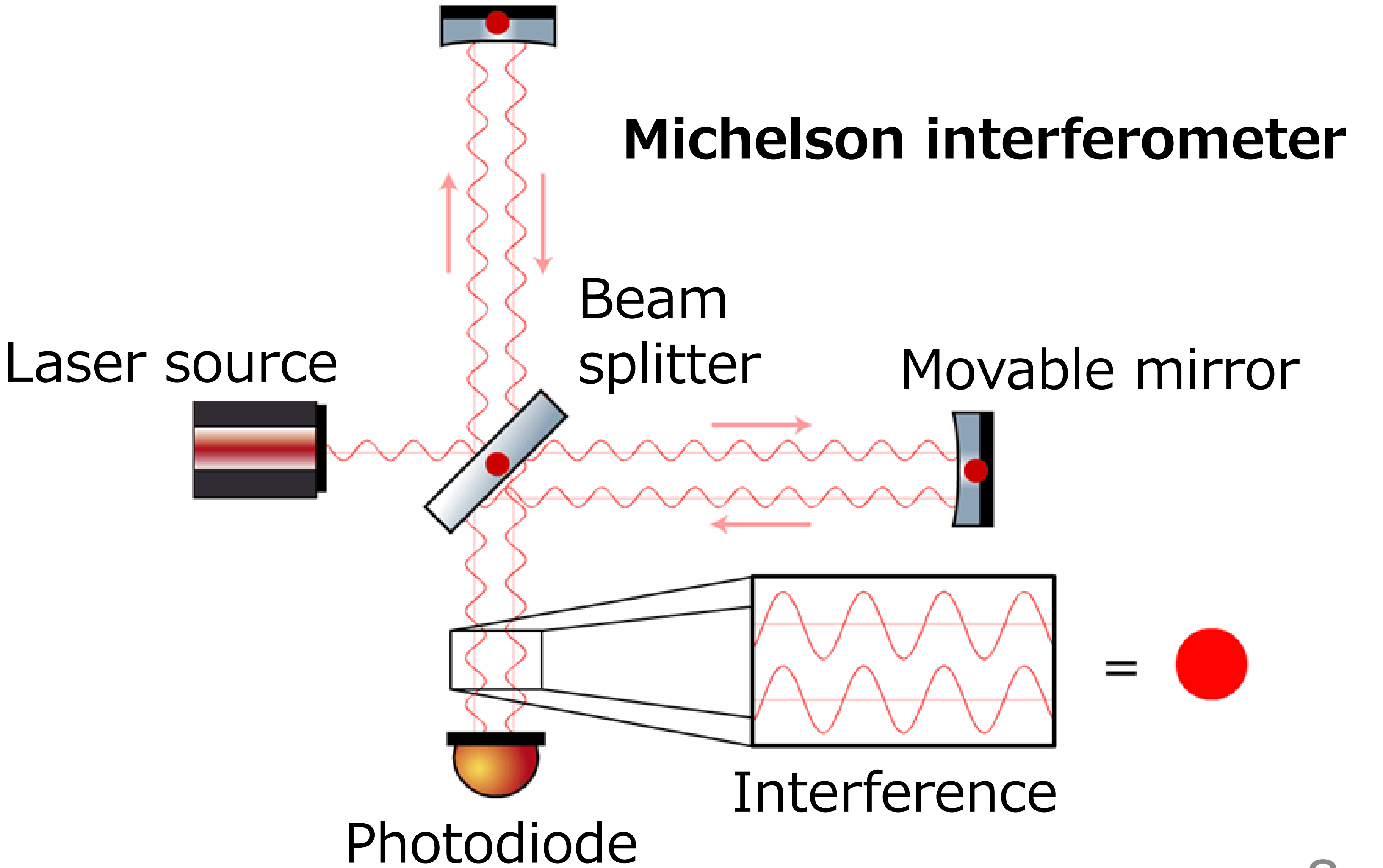
Ultralight Dark Matter

- Ultralight DM (<~1 eV) behaves as classical wave fields
$$f = 2.4\ \mathrm{Hz}\left(\frac{m_{\mathrm{DM}}}{10^{-14}\ \mathrm{eV}}\right)$$
- Laser interferometers are sensitive to tiny length changes from such oscillations



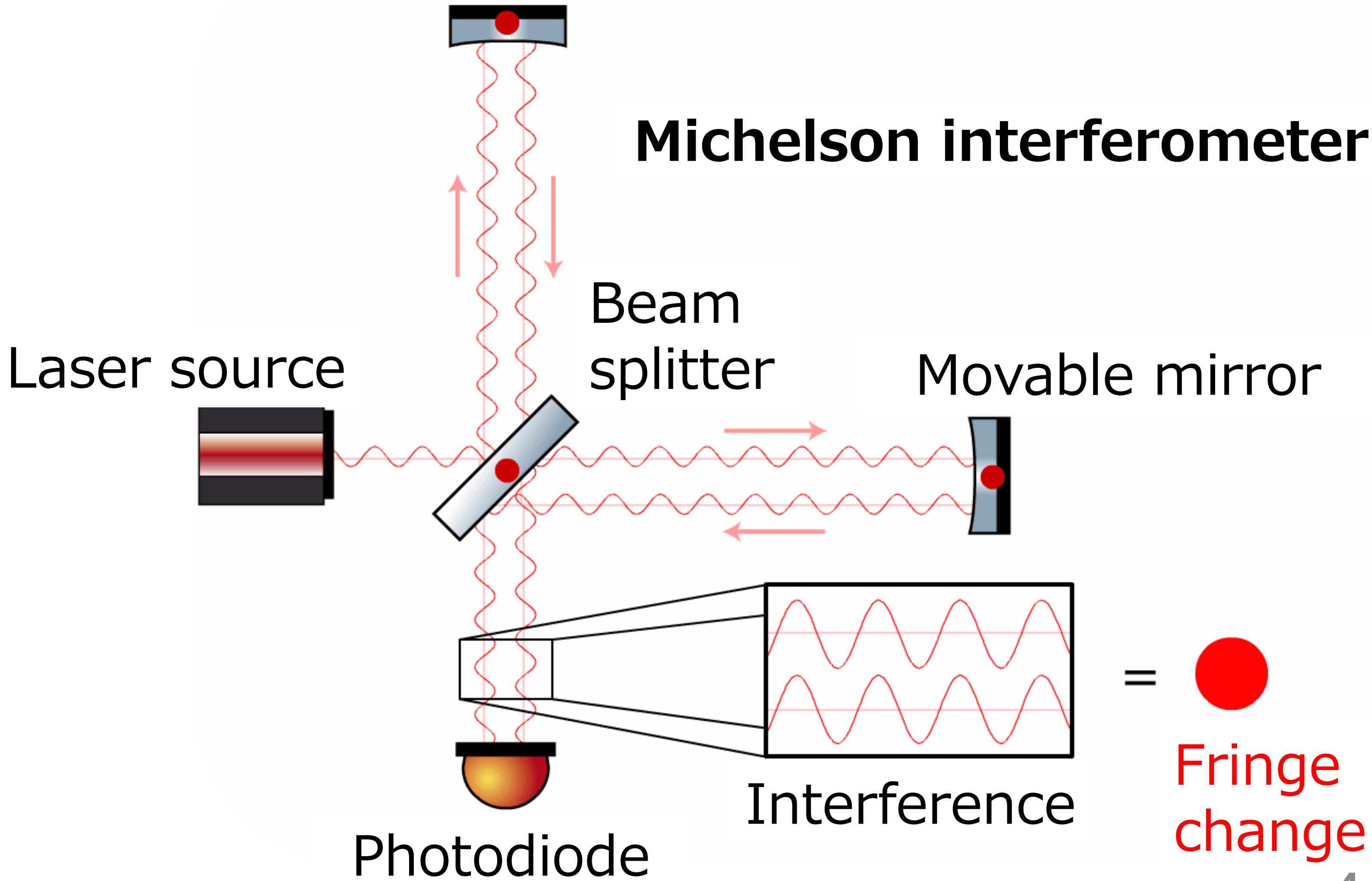
Laser Interferometry

- measures differential arm length change



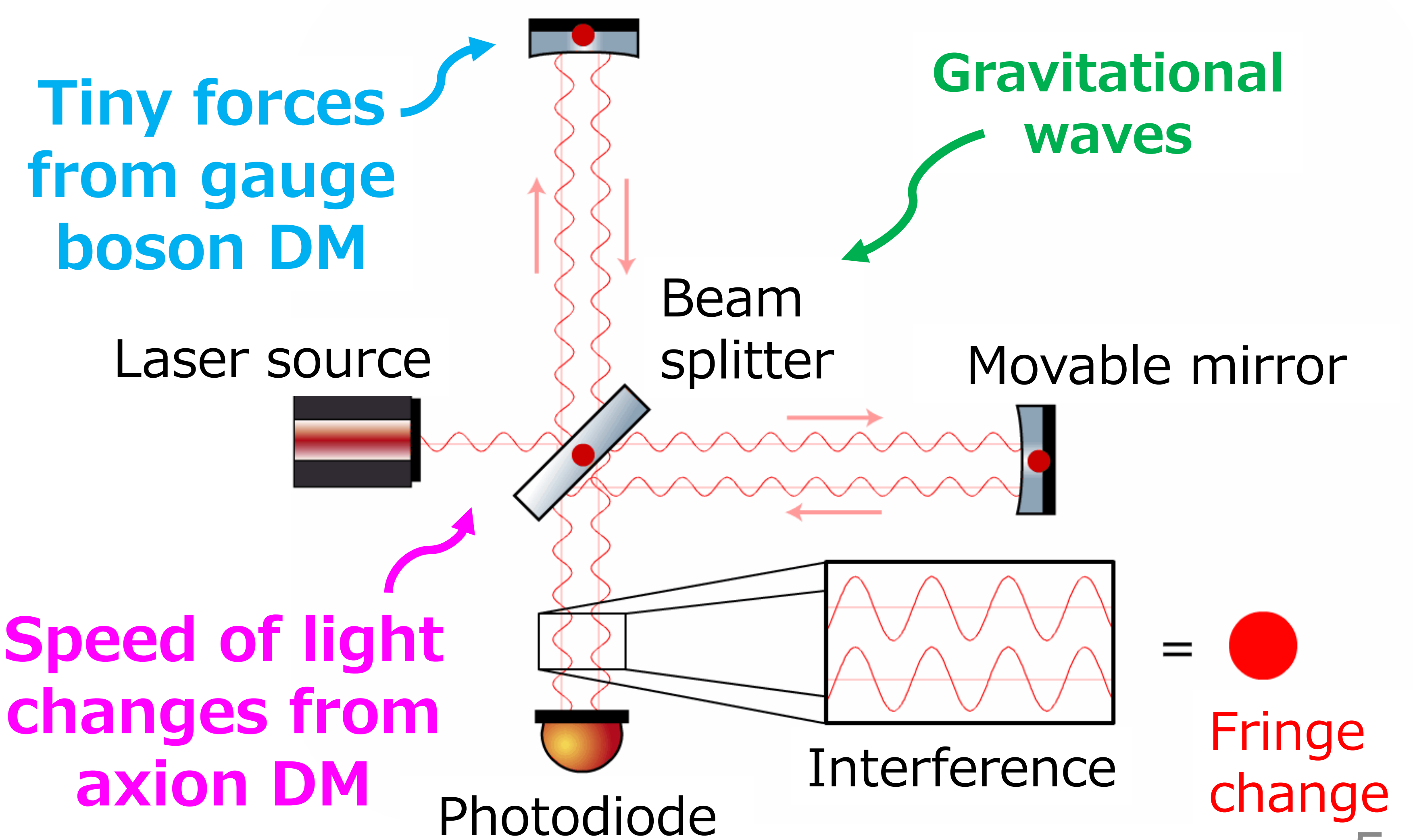
Laser Interferometry

- measures differential arm length change



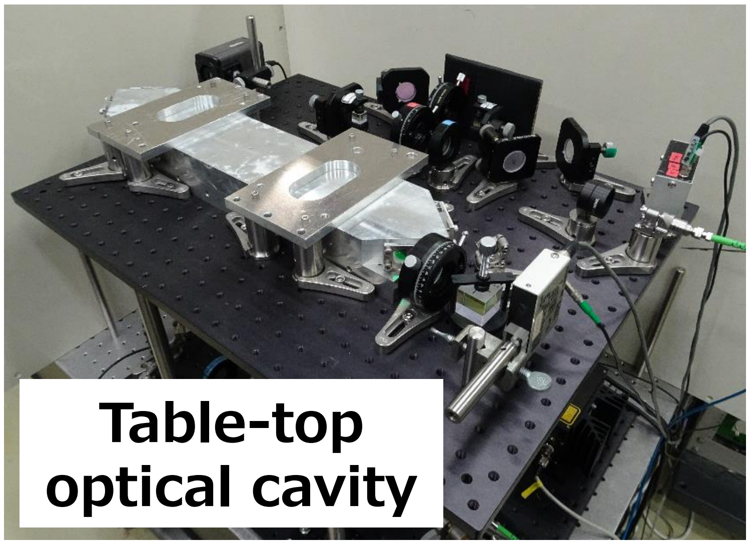
Laser Interferometry

- measures differential arm length change



Our Strategy

- Use both table-top optical cavities and large-scale laser interferometric gravitational wave detectors



Ultralight DM

Broad band

PRL 121, 161301 (2018)

Axion like particles

Narrow band

PRL 123, 111301 (2019)

\+ Polarization measurement

PRD 102, 102001 (2020)

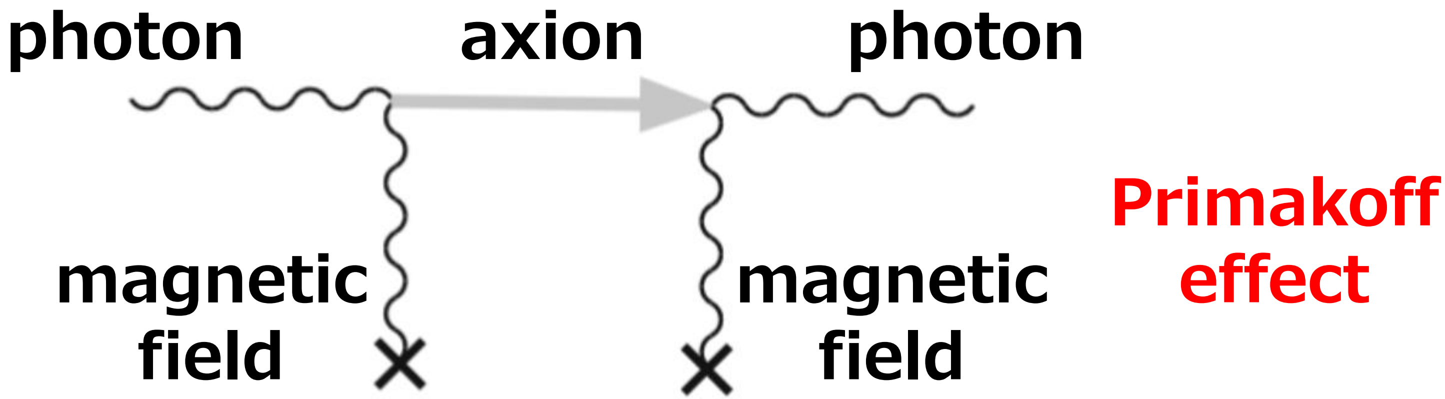
arXiv:2011.03589

Gauge bosons

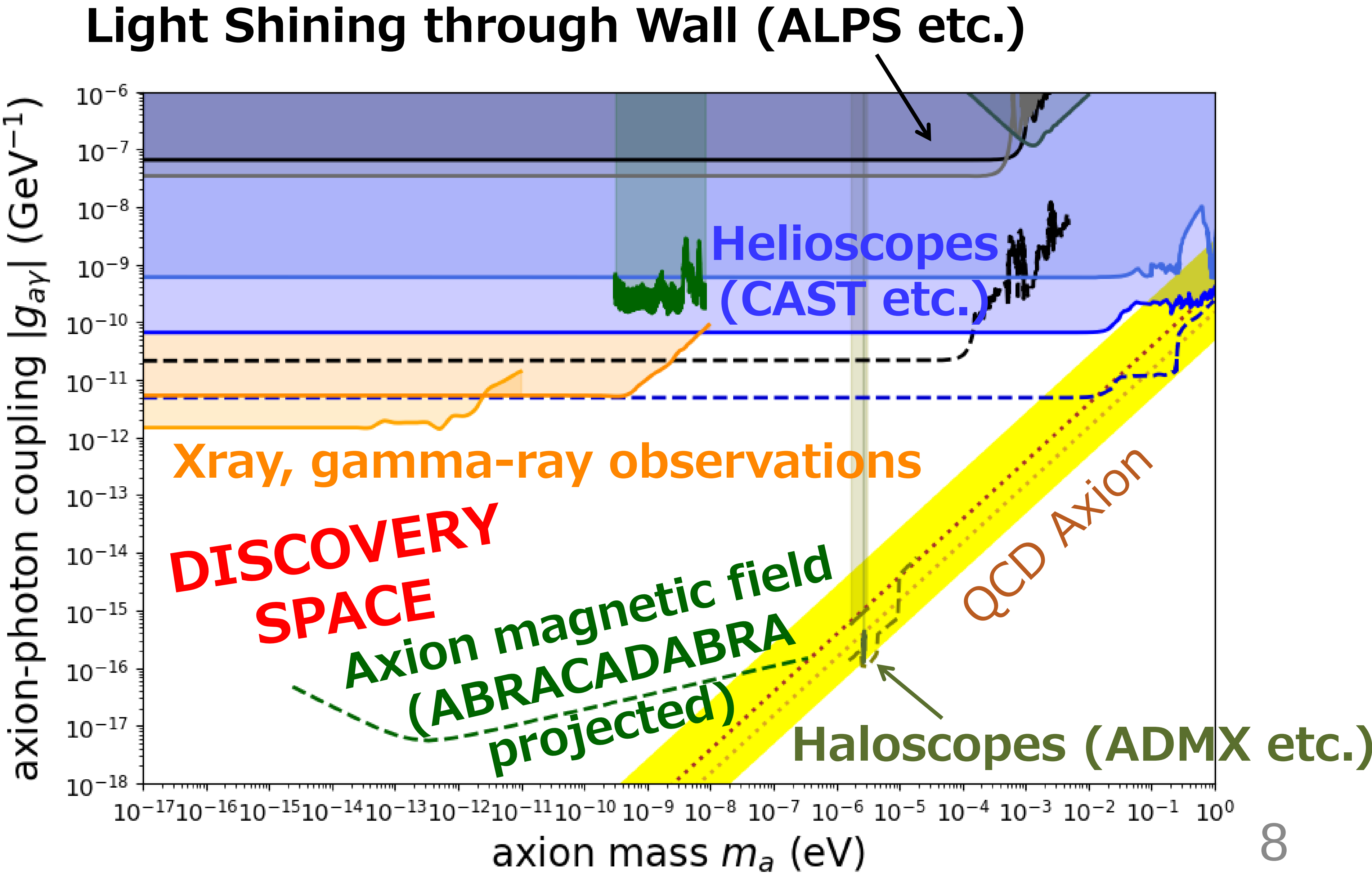
Axion and Axion-Like Particles

- Pseudo-scalar particle originally introduced to solve strong CP problem (QCD axion)
- Various axion-like particles (ALPs) predicted by string theory and supergravity
- Many experiments to search for ALPs through axion-photon coupling

    Especially by using magnetic fields



Previous Searches



Polarization Modulation from Axions

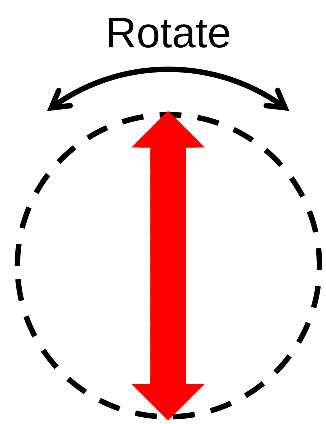
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

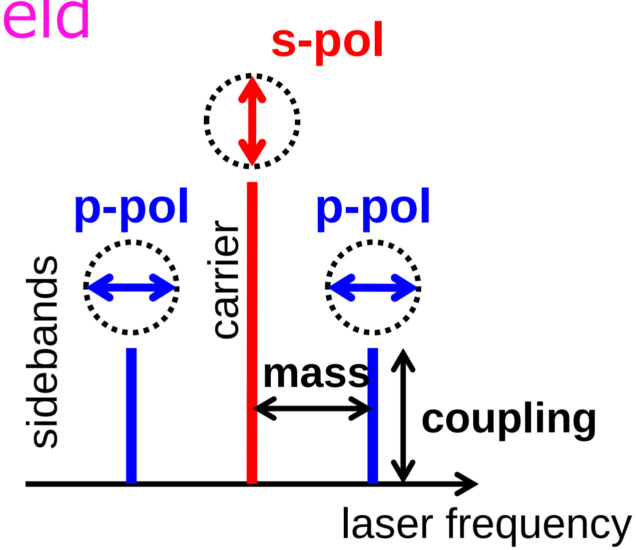
$$c_{\mathrm{L/R}} = \sqrt{1 \pm \frac{g_{a\gamma} a_0 m_a}{k} \sin(m_a t + \delta_\tau)}$$

axion mass

coupling constant axion field

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





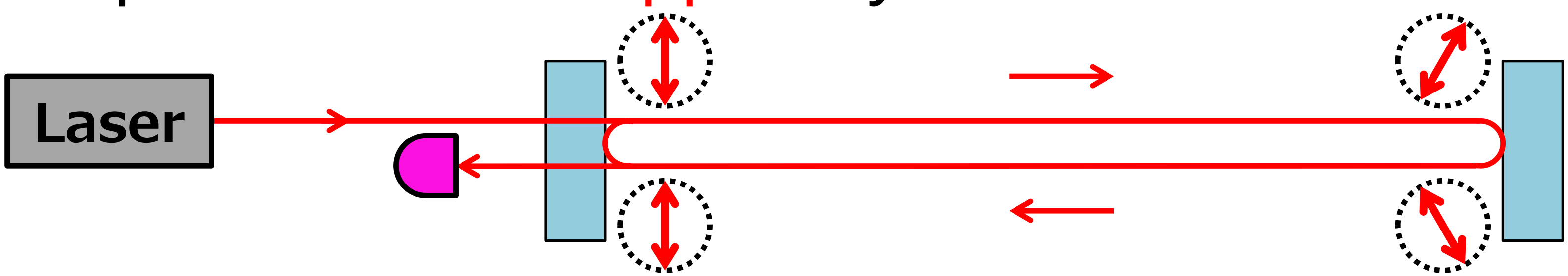
Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

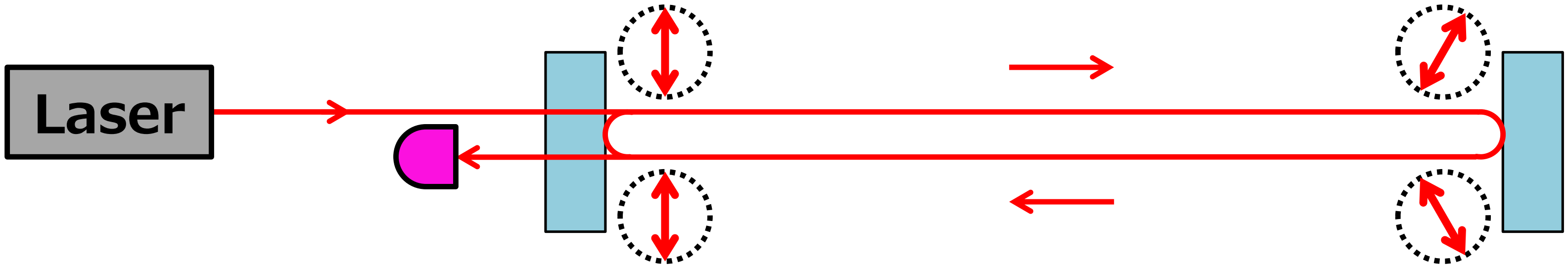
- Optical cavities can increase the optical path, but the polarization is flipped by mirror reflections



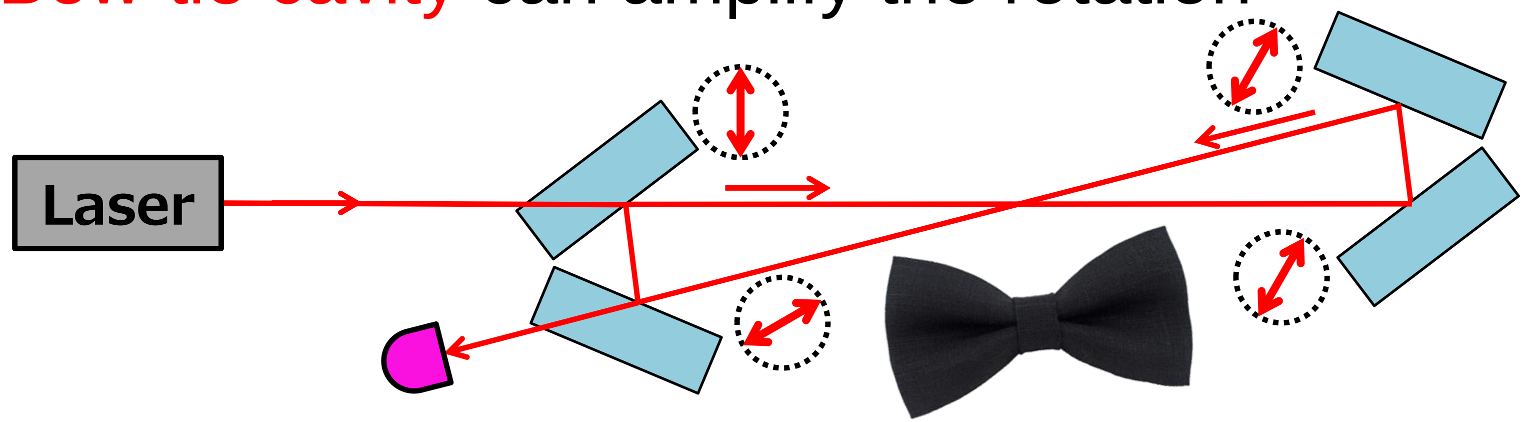
Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

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



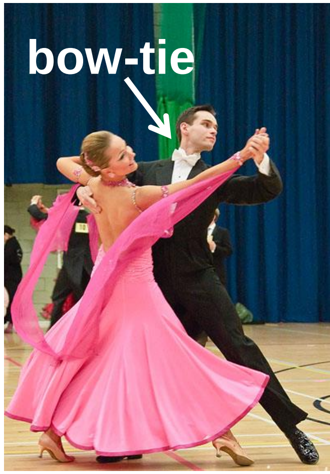
- Bow-tie cavity can amplify the rotation

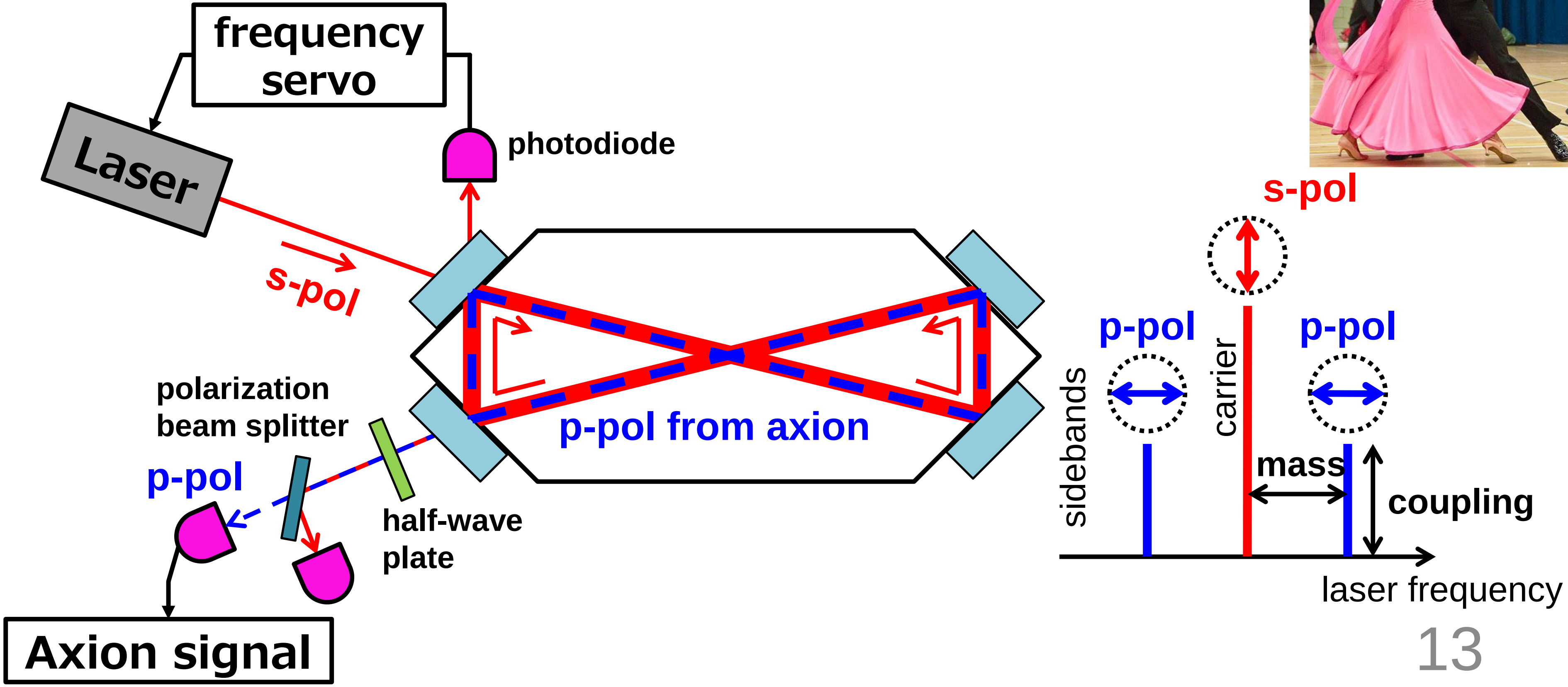


DANCE Setup

Dark matter Axion search with riNg Cavity Experiment

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

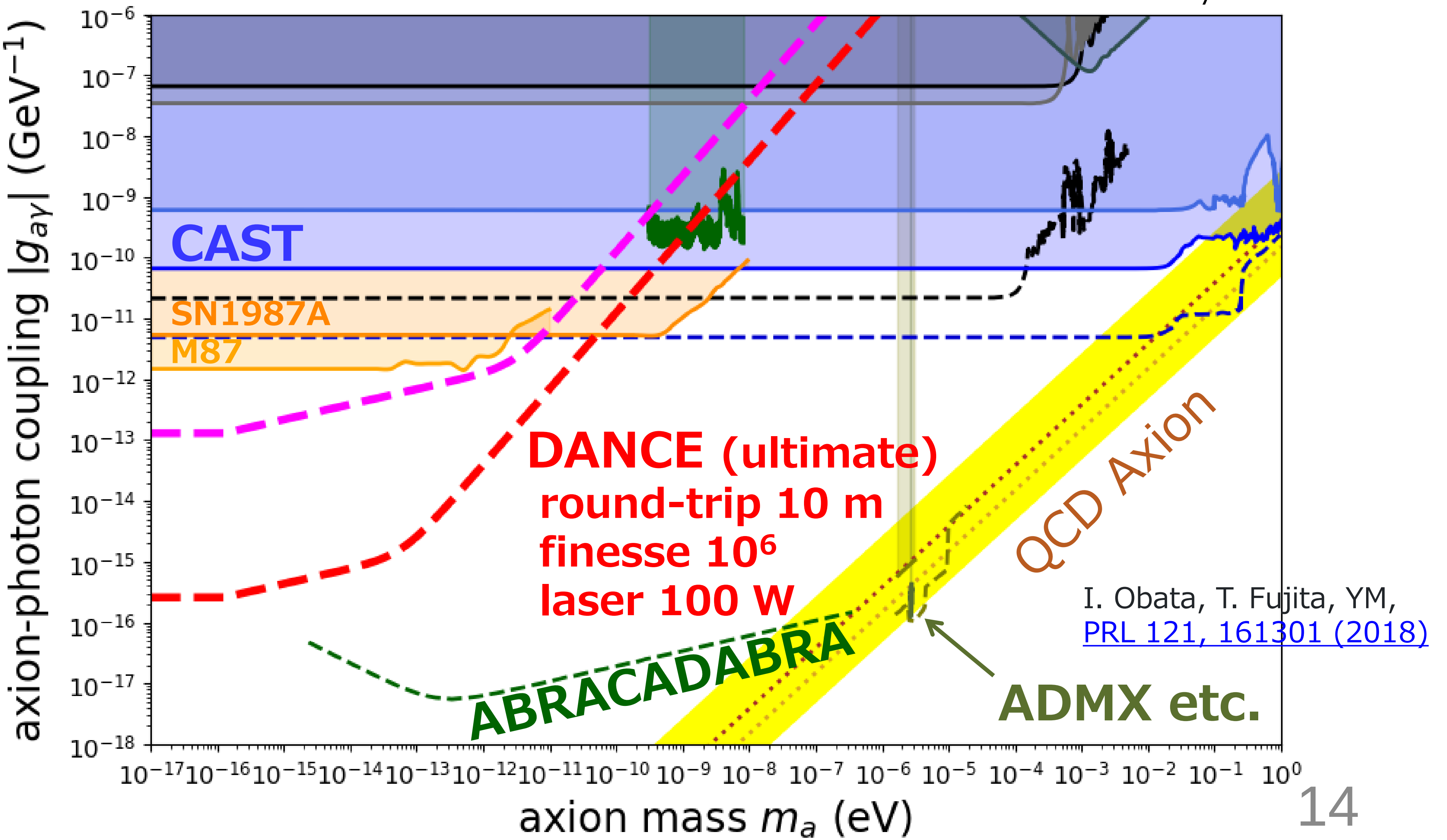




Sensitivity of DANCE

- Sensitivity better than CAST limit

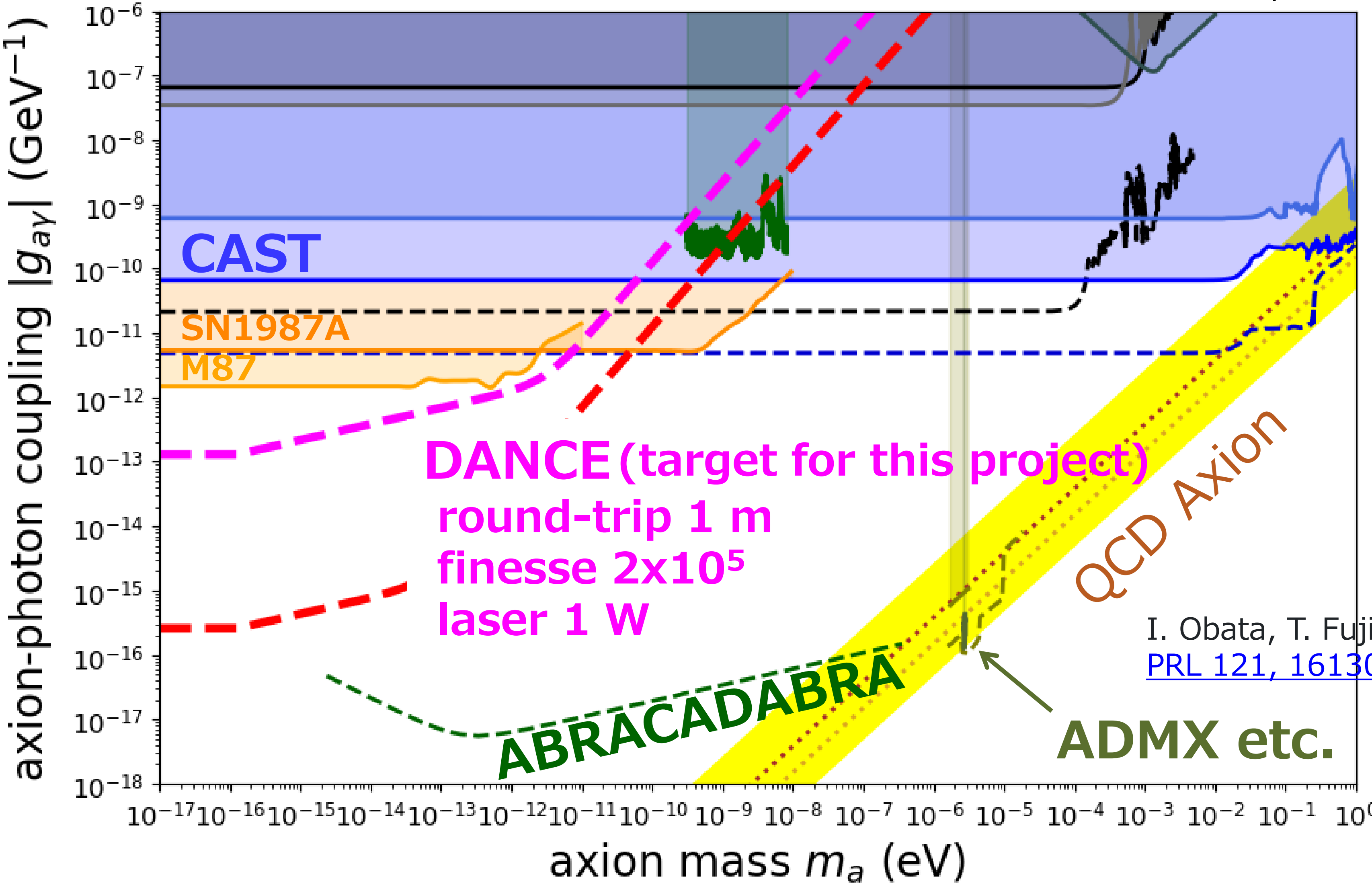
* Shot noise limited
1 year observation



Sensitivity of DANCE

- Sensitivity better than CAST limit

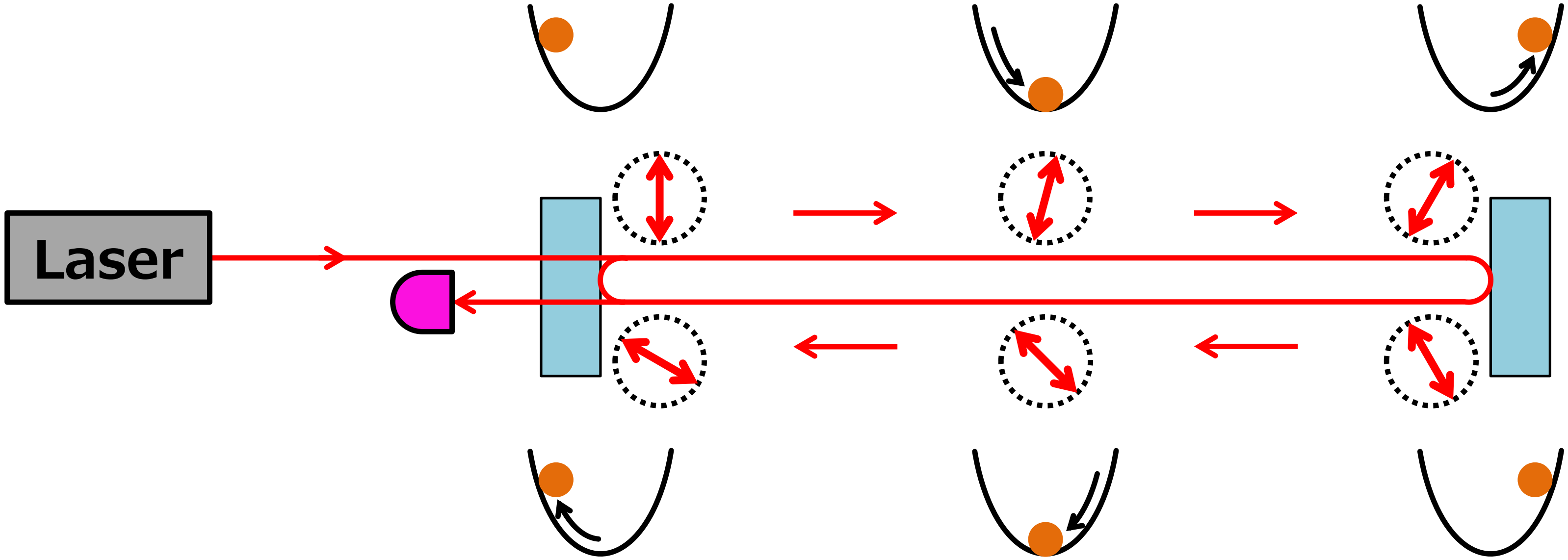
* Shot noise limited
1 year observation



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

Linear Cavities for Axion Search

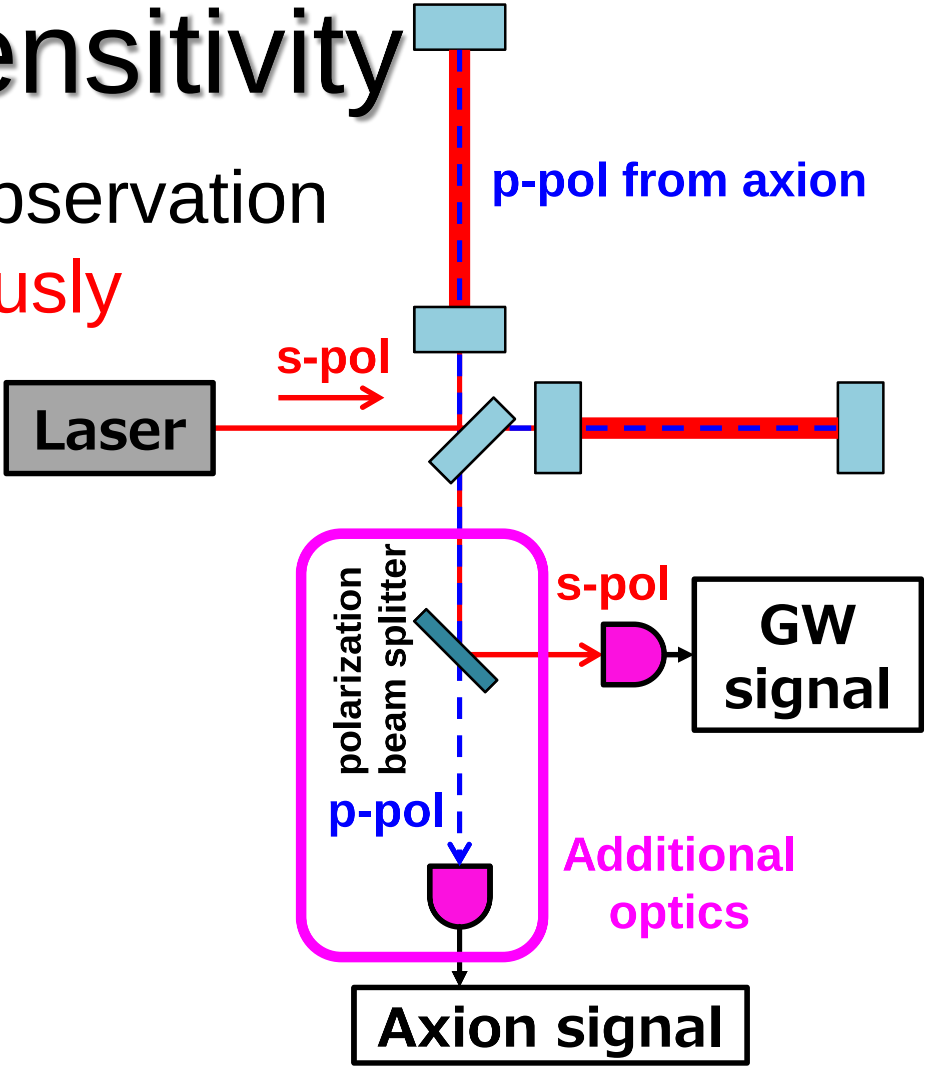
- When finite light traveling time is considered, linear cavities can also be used



- Can be sensitive when the round-trip time equals odd-multiples of axion oscillation period
- Long baseline linear cavities in gravitational wave detectors are suitable

KAGRA Axion Sensitivity

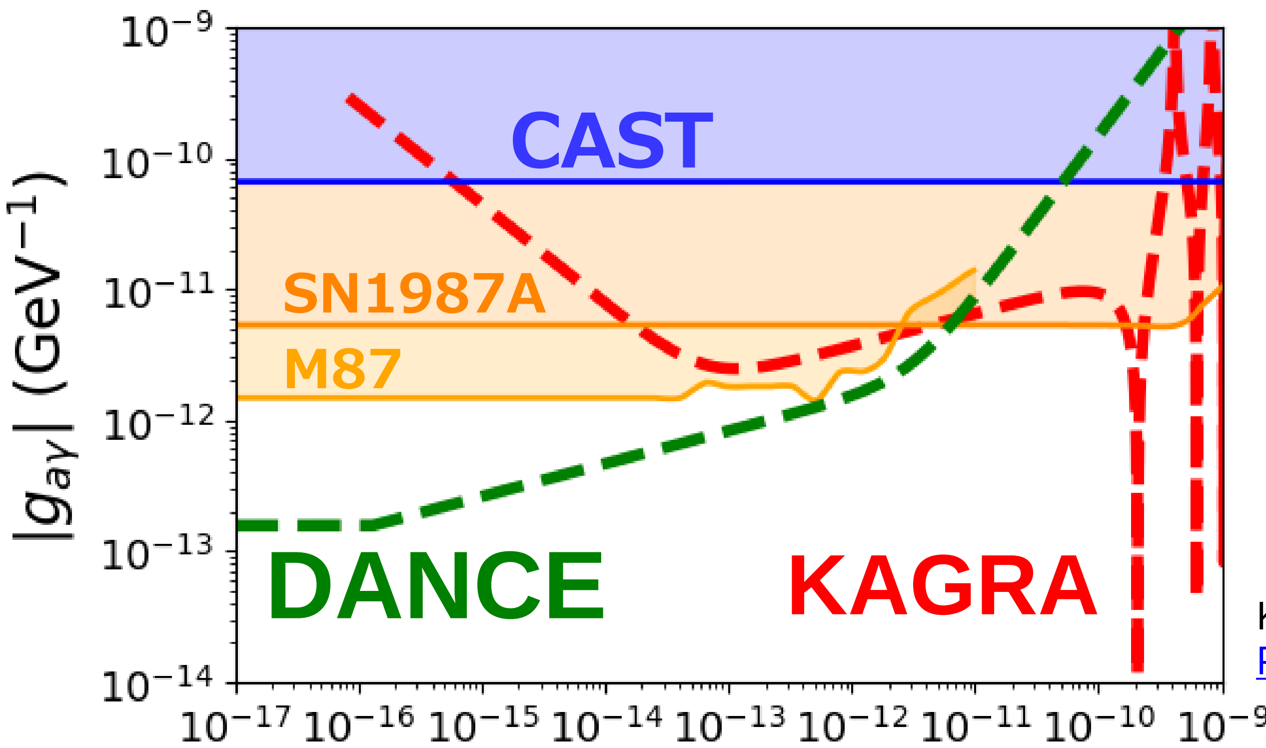
- Axion search and GW observation can be done simultaneously

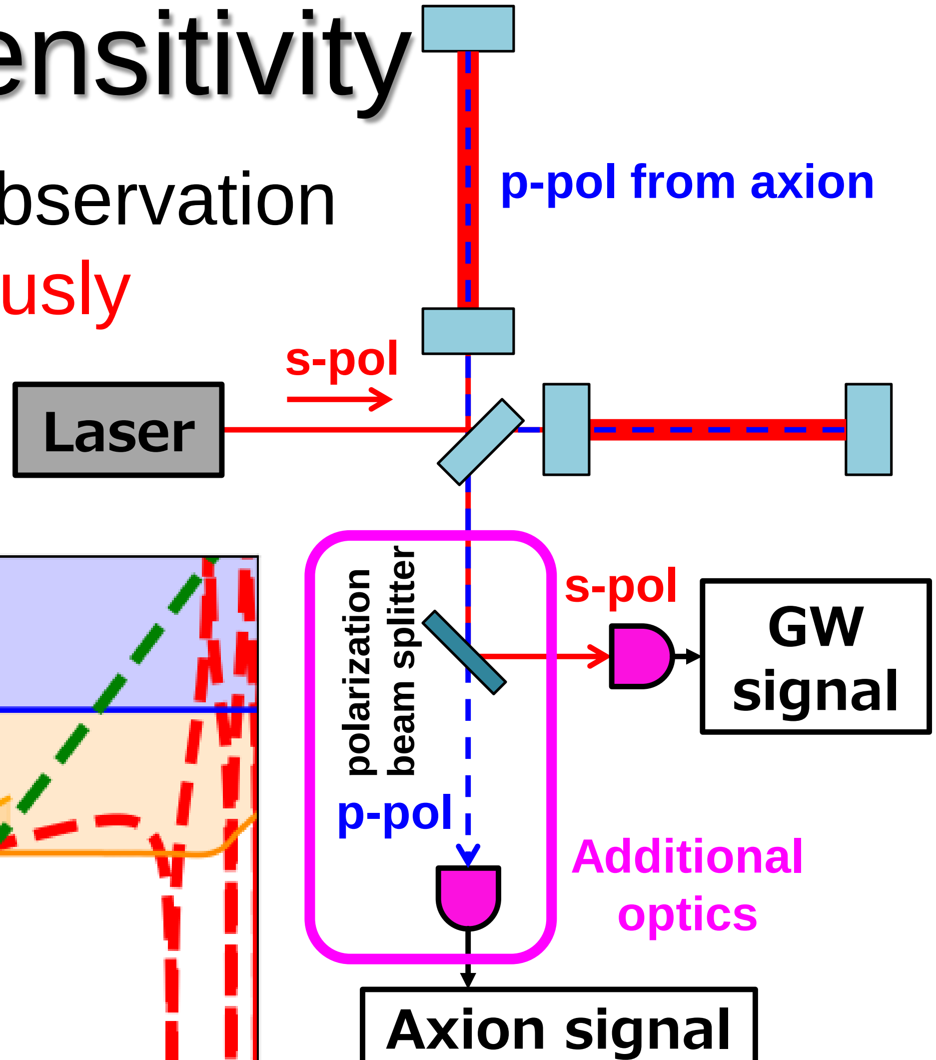


K. Nagano, T. Fujita, YM, I. Obata
[PRL 123, 111301 (2019)]

KAGRA Axion Sensitivity

- Axion search and GW observation can be done simultaneously
- KAGRA and DANCE are complementary



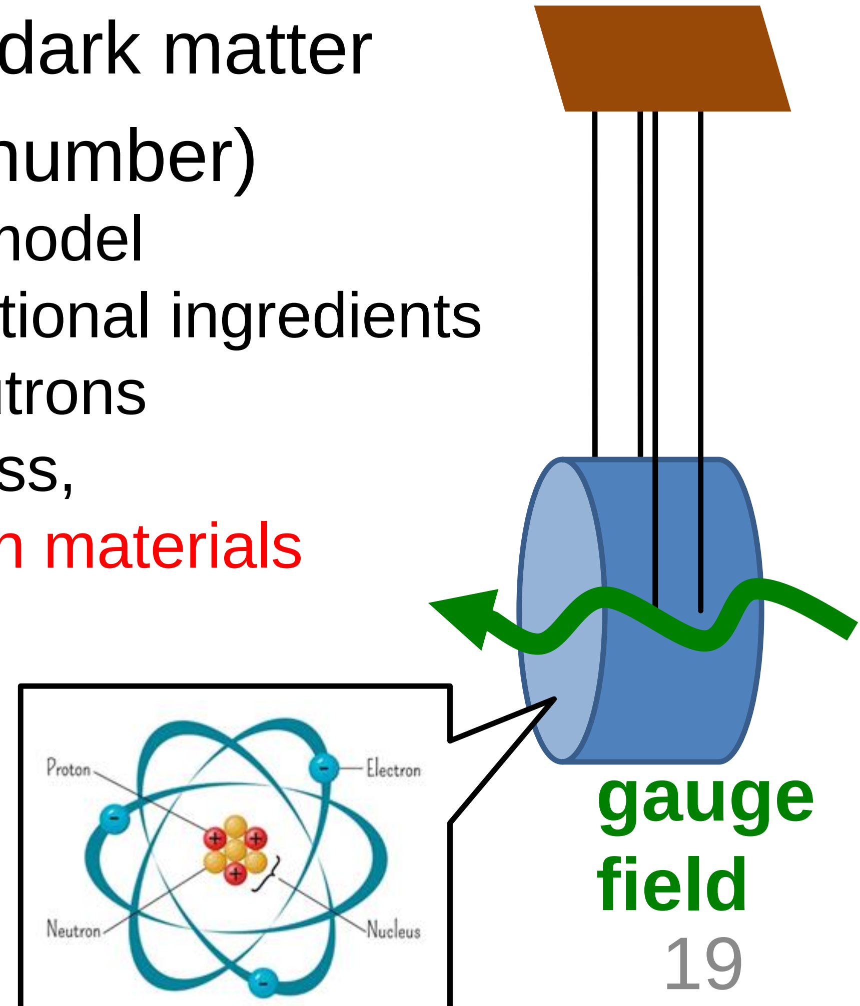


K. Nagano, T. Fujita, YM, I. Obata
[PRL 123, 111301 (2019)]

* 1 year observation

Gauge Bosons

- 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
  - Can be gauged without additional ingredients
  - Equals to the number of neutrons
  - Roughly 0.5 per neutron mass,
    but slightly different between materials
    Fused silica: 0.501
    Sapphire: 0.510
- Gauge boson DM
  gives oscillating force



Oscillating Force from Gauge Field

- Acceleration of mirrors

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

charge

gauge boson mass

coupling
(normalized by e)

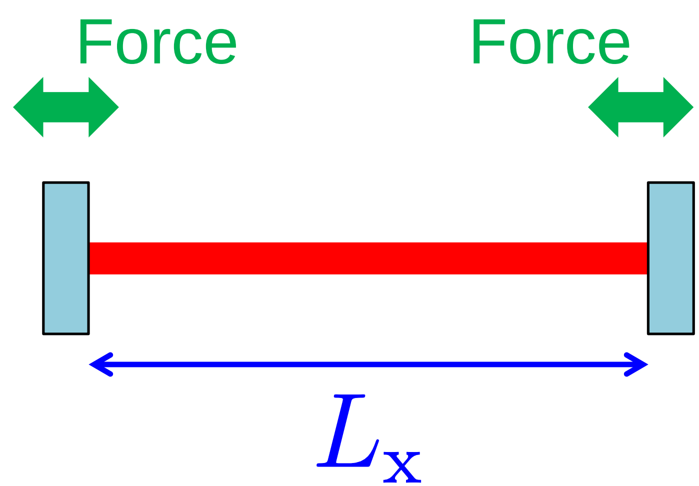
mirror mass

DM density

polarization

different phase at
different position

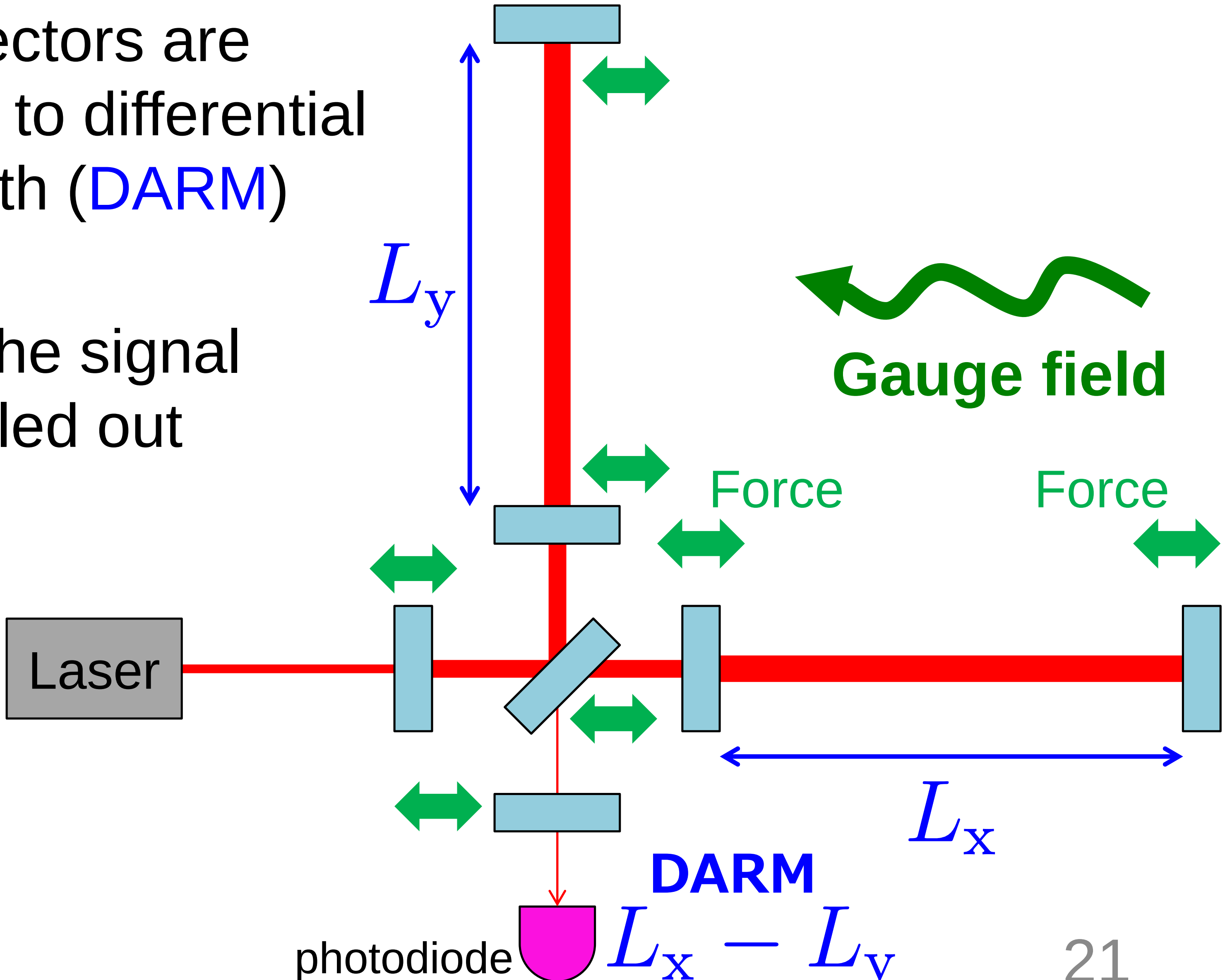
- Gauge boson mass and coupling can be measured by measuring the oscillating mirror displacement



- Almost no signal for symmetric cavity if cavity length is short
(phase difference is 10^{-5} rad @ 100 Hz for km cavity)

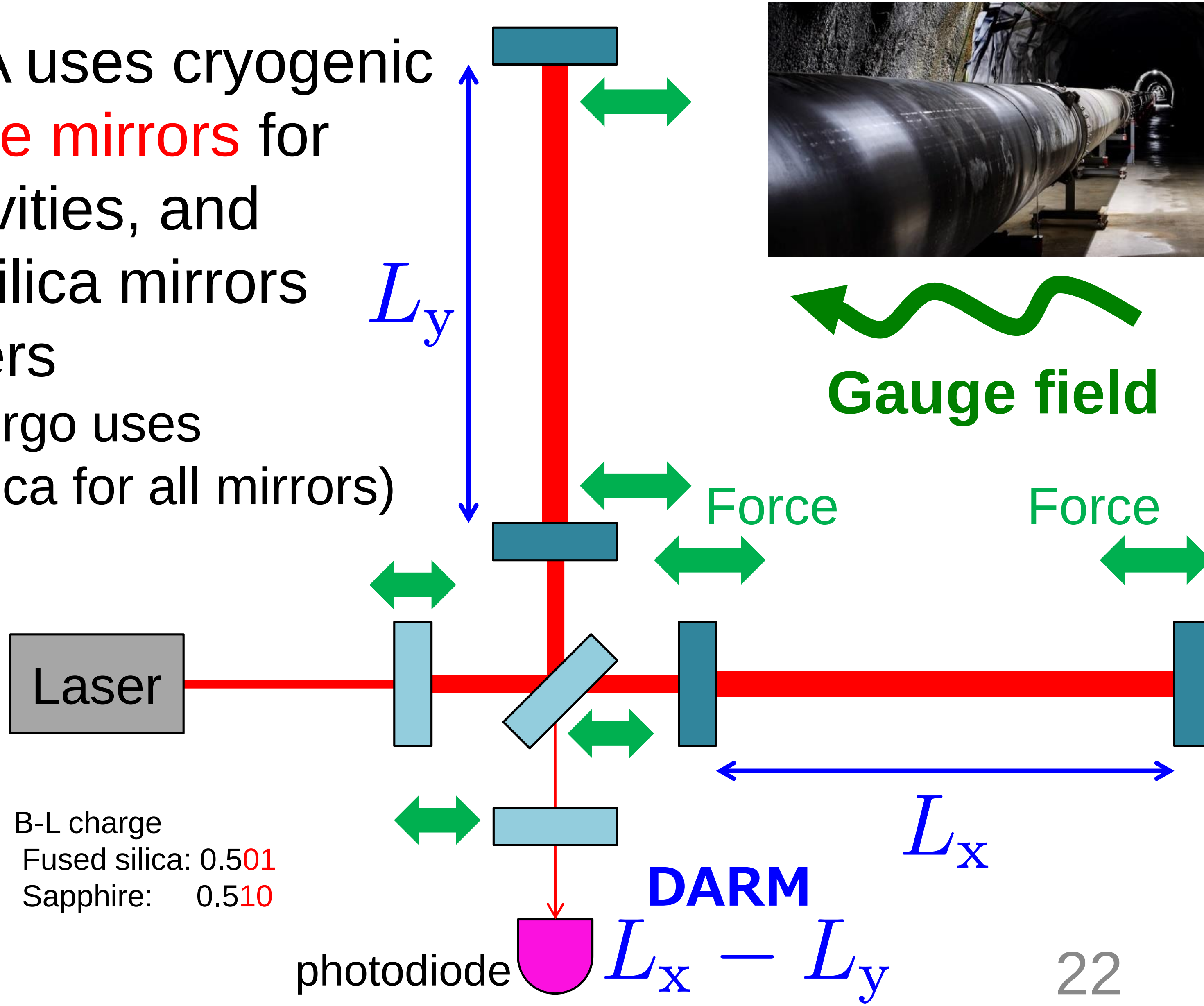
Search with GW Detectors

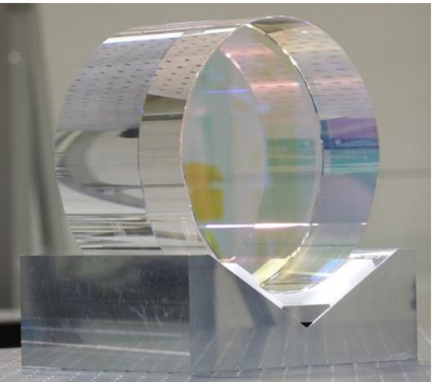
- GW Detectors are sensitive to differential arm length (DARM) change
- Most of the signal is cancelled out



Search with KAGRA

- KAGRA uses cryogenic sapphire mirrors for arm cavities, and fused silica mirrors for others
  (LIGO/Virgo uses fused silica for all mirrors)

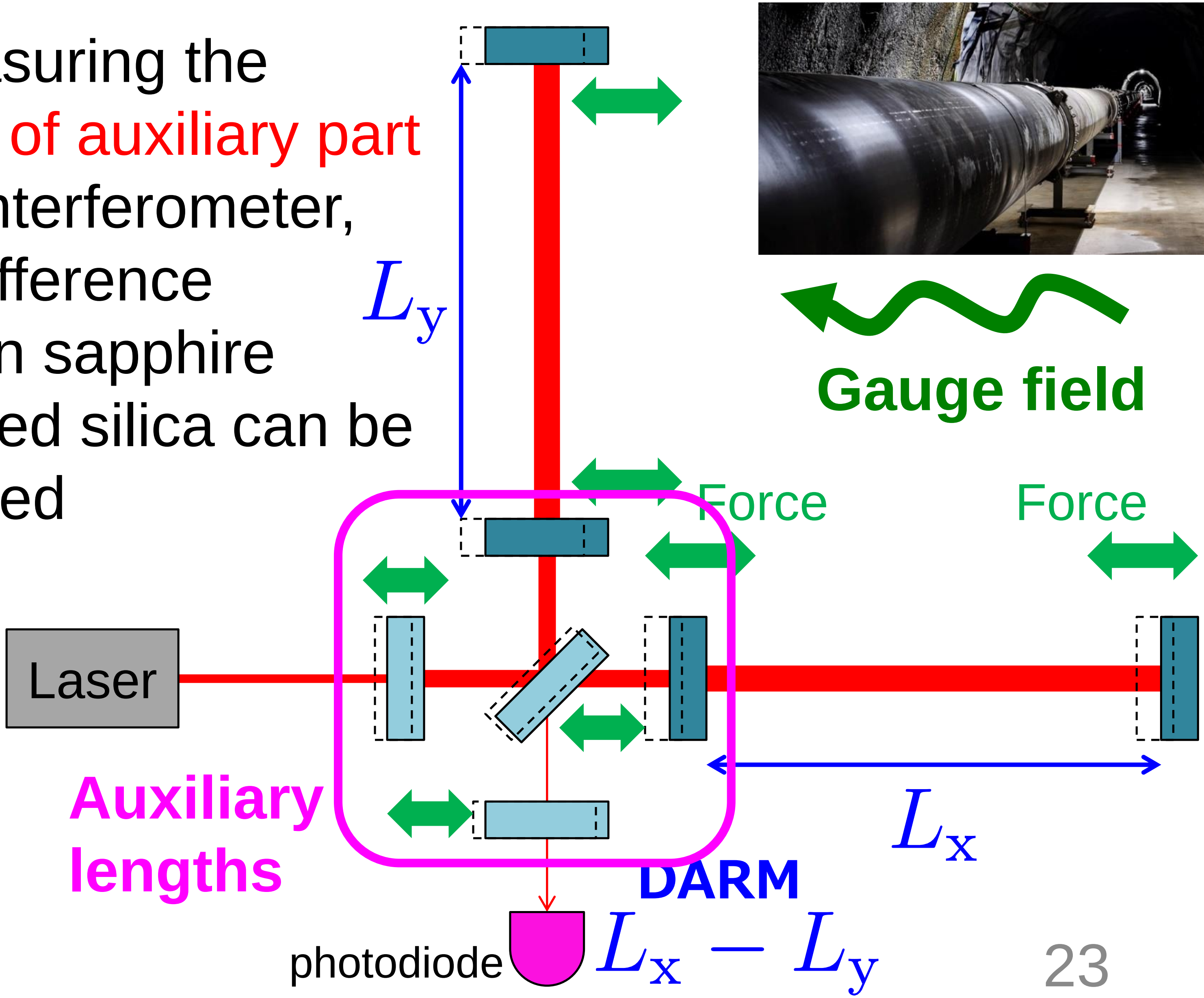




B-L charge
Fused silica: 0.501
Sapphire: 0.510

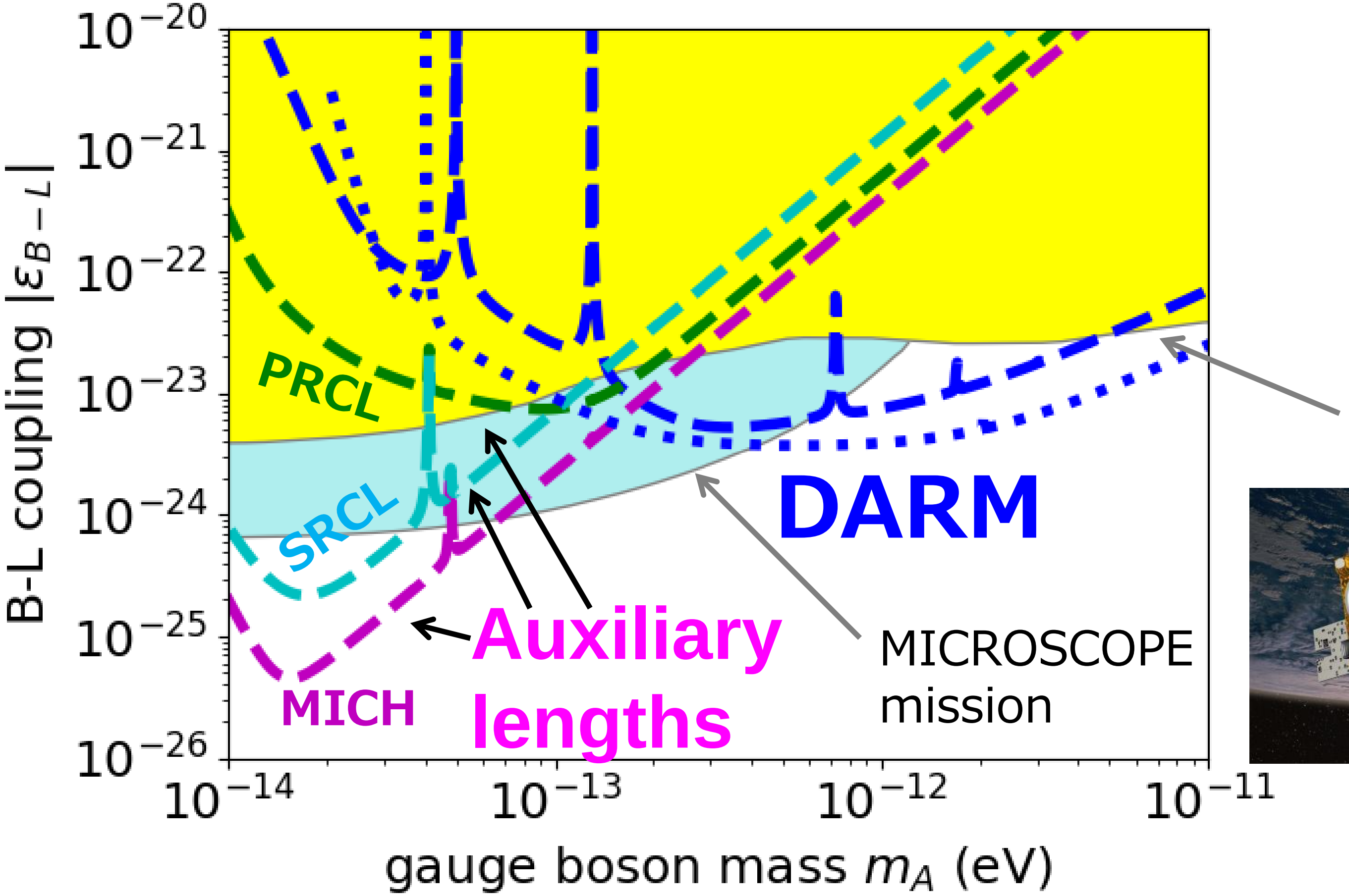
Search with KAGRA

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



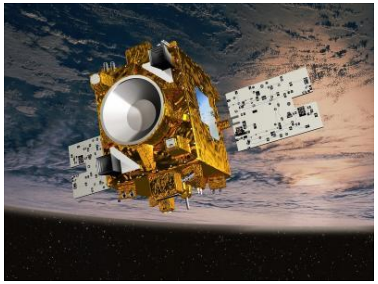
KAGRA Gauge Boson Sensitivity

- Auxiliary length channels have better sensitivity than DARM at low mass range
- Sensitivity better than equivalence principle tests



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

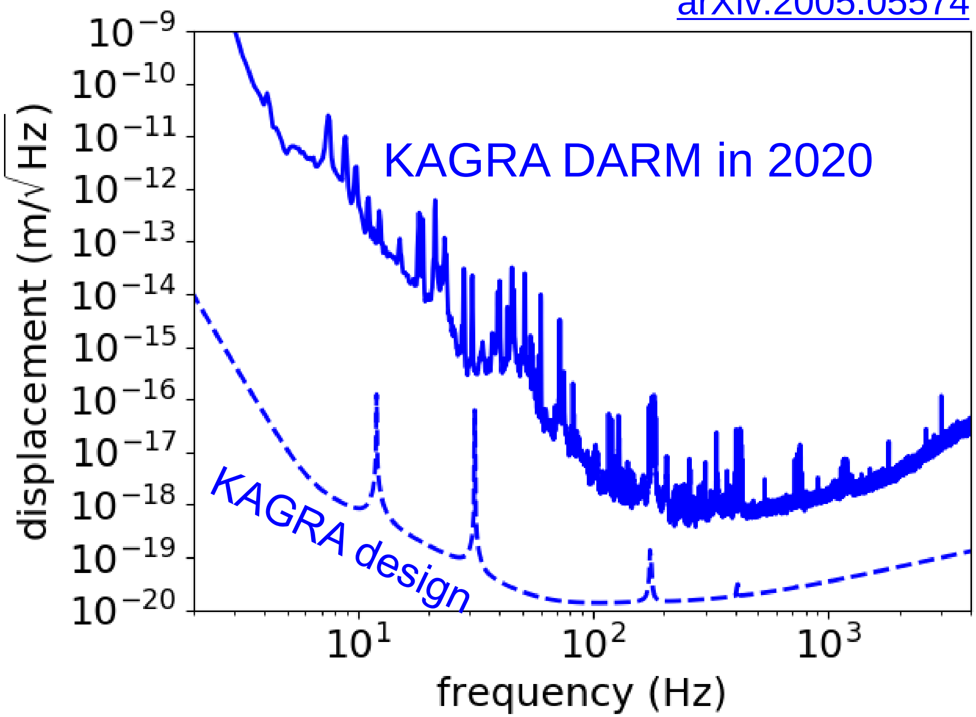
S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata, [arXiv:2011.03589]

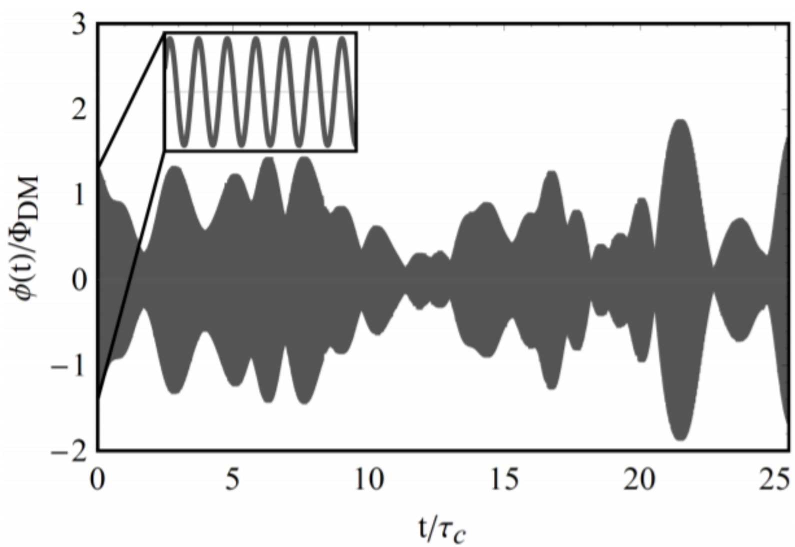


Recent Progresses: KAGRA

- First (gravitational-wave) observing run in Feb-Apr 2020
- Ultralight DM data analysis pipeline developed
- Found many peaks above threshold
  - Developing veto procedure to remove detector artifacts
- Statistical studies on stochastic fluctuation

KAGRA Collab.
arXiv:2005.05574

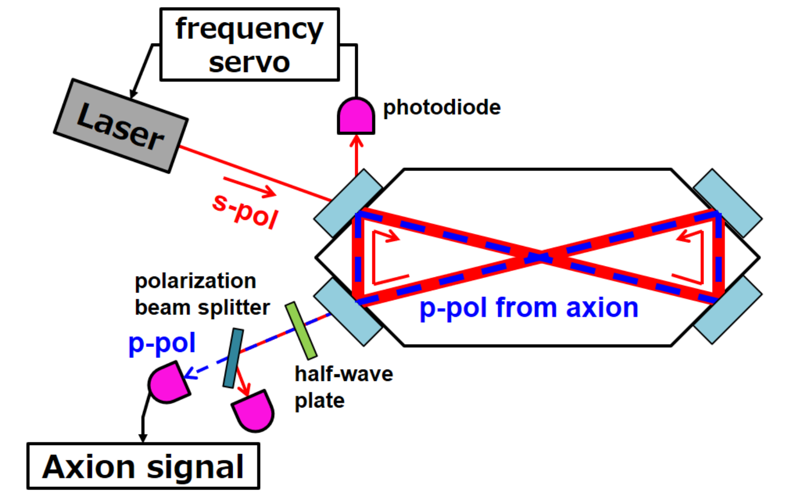


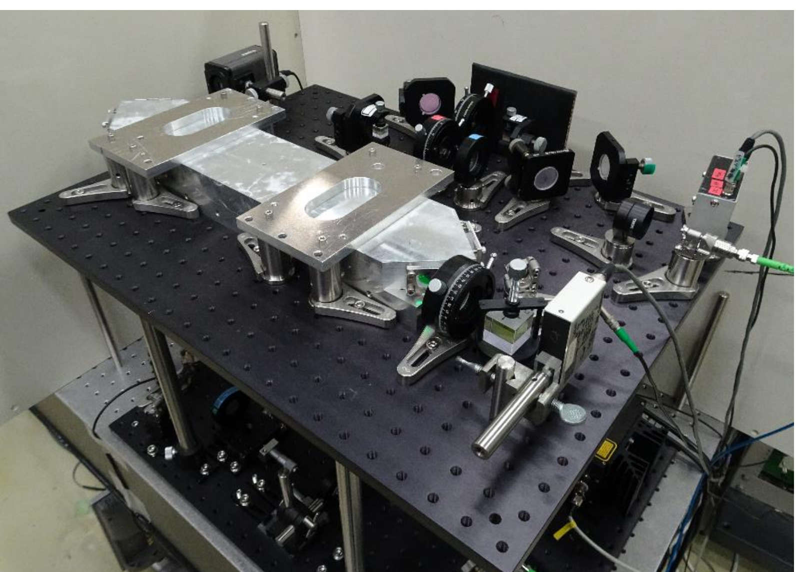


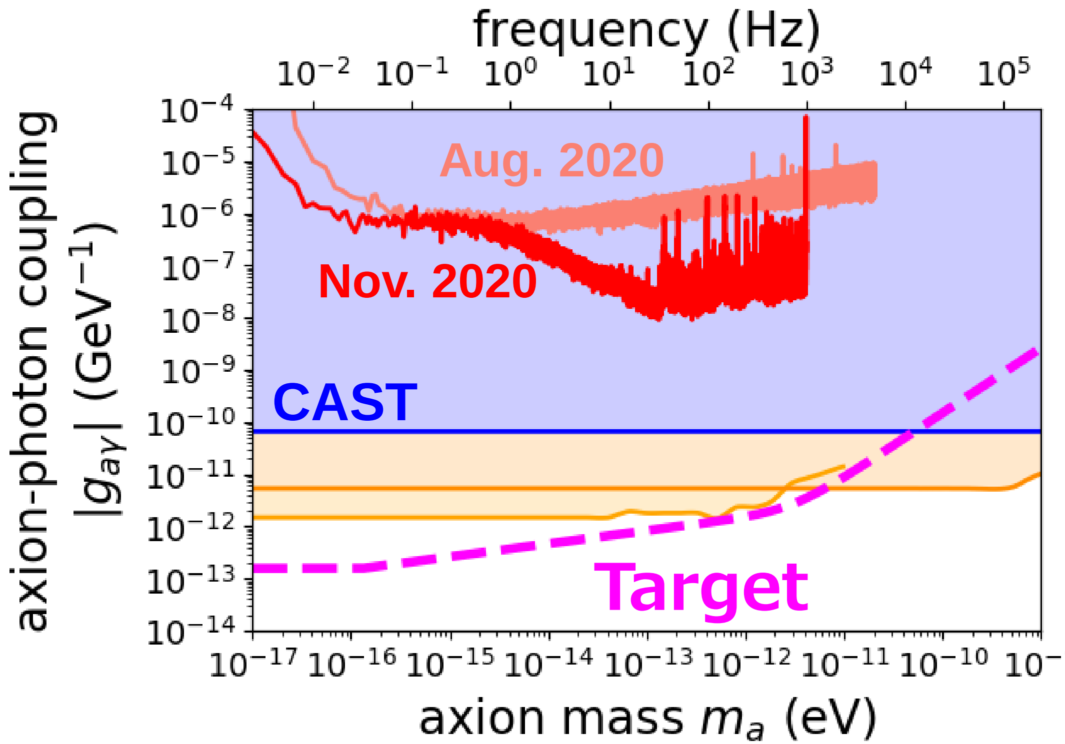
G. P. Centers+
arXiv:1905.13650

Recent Progresses: DANCE

- Successfully demonstrated the operation in 2020





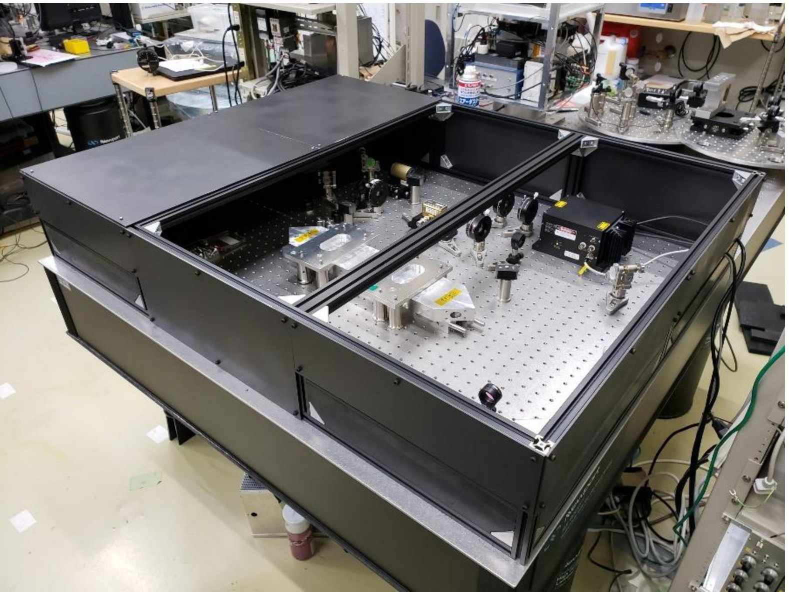


Estimated reach if we observe for 1 year with current noise level

Recent Progresses: DANCE

- Now working on
  - Reducing excess noises
  - Increasing the finesse and input laser power

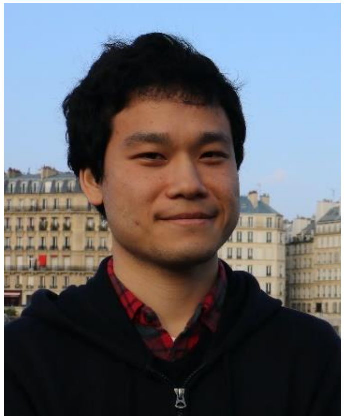
	Nov. 2020	**Now**	**Target**
Round-trip length	1 m	1 m	1 m
Finesse	525(19)	$2.56(8)\times10^3$	2×10^5
Laser power	40 mW	260 mW	1 W



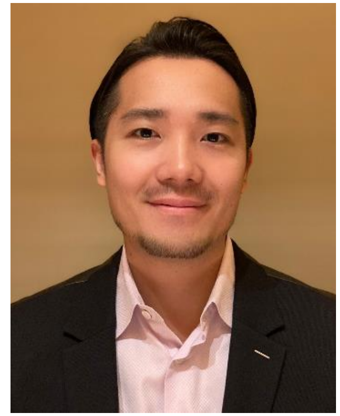
Shielding to reduce air turbulence


A Whole New Room (63 m^2)
Two optical tables and a laser source
for DANCE will be delivered in March
@ UTokyo Hongo Campus

B01 Team



PI: Yuta Michimura
(道村唯太, UTokyo)
Experiment
Yuka Oshima
Hiroki Fujimoto
Koji Nagano



Co-I: Tomohiro Fujita
(藤田智弘, ICRR)
Theory
& Data analysis
Ippei Obata
Hiromasa Nakatsuka
Soichiro Morisaki
Jun’ya Kume
Atsushi Nishizawa

東京大学
THE UNIVERSITY OF TOKYO

MAX-PLANCK-GESELLSCHAFT

... and more to come!

国立天文台
NAOJ
National Astronomical Observatory of Japan

Co-I: Matteo Leonardi
(マテオ·レオナルディ, NAOJ)
Optical characterization

ICRR
Institute for Cosmic Ray Research
University of Tokyo

Co-I: Shinji Miyoki
(三代木伸二, ICRR)
KAGRA

Summary

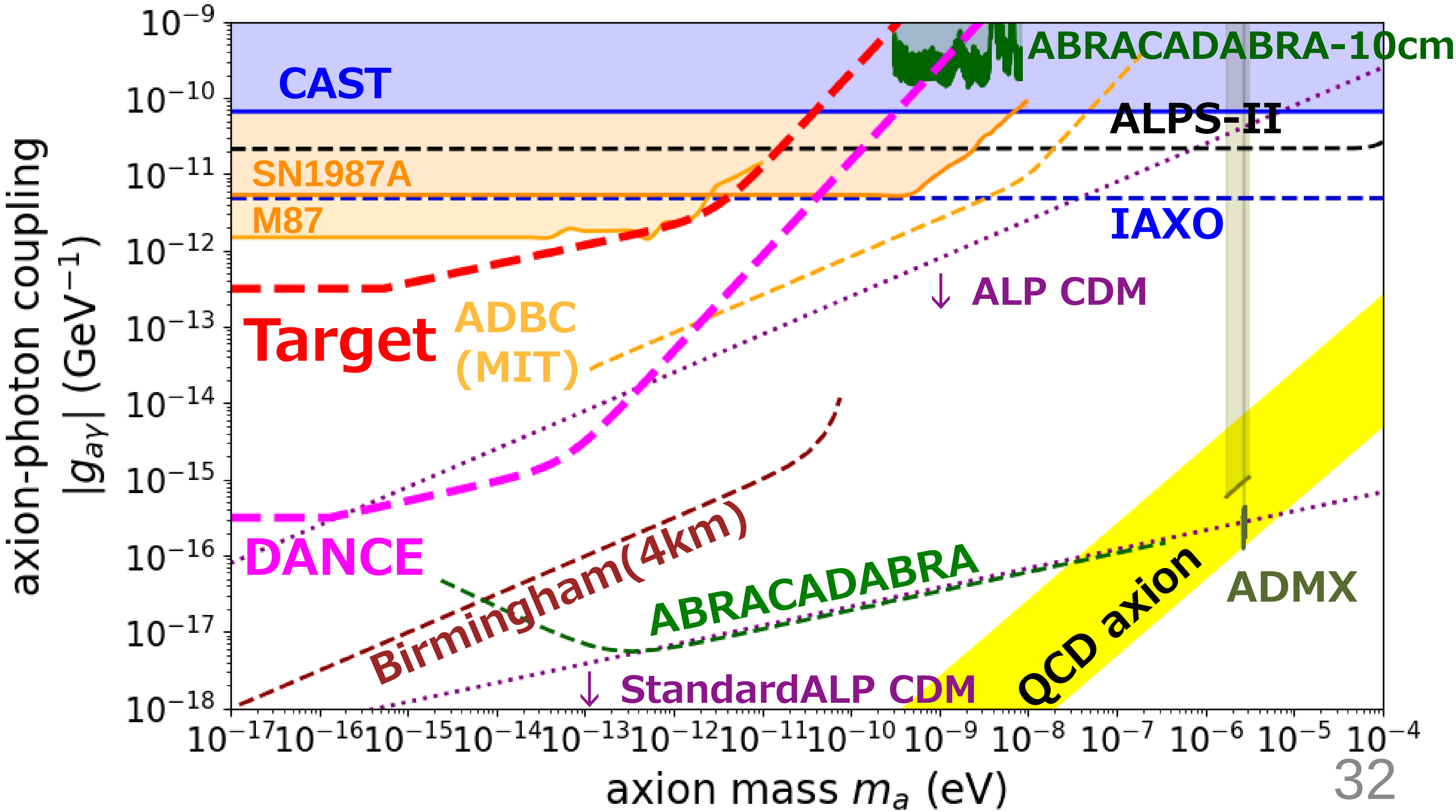
- Laser interferometers open up new possibilities for dark matter search
- **Our goal**: search for axion DM and gauge boson DM with unprecedented sensitivity
  - DANCE for broad band axion
  - KAGRA +polarimetry for narrow band axion
  - KAGRA for gauge boson
- Analysis of KAGRA data in 2020 on going
- Prototype experiments of DANCE on going

- We expect a lot of new ideas from our Transformative Research Area

Additional Slides

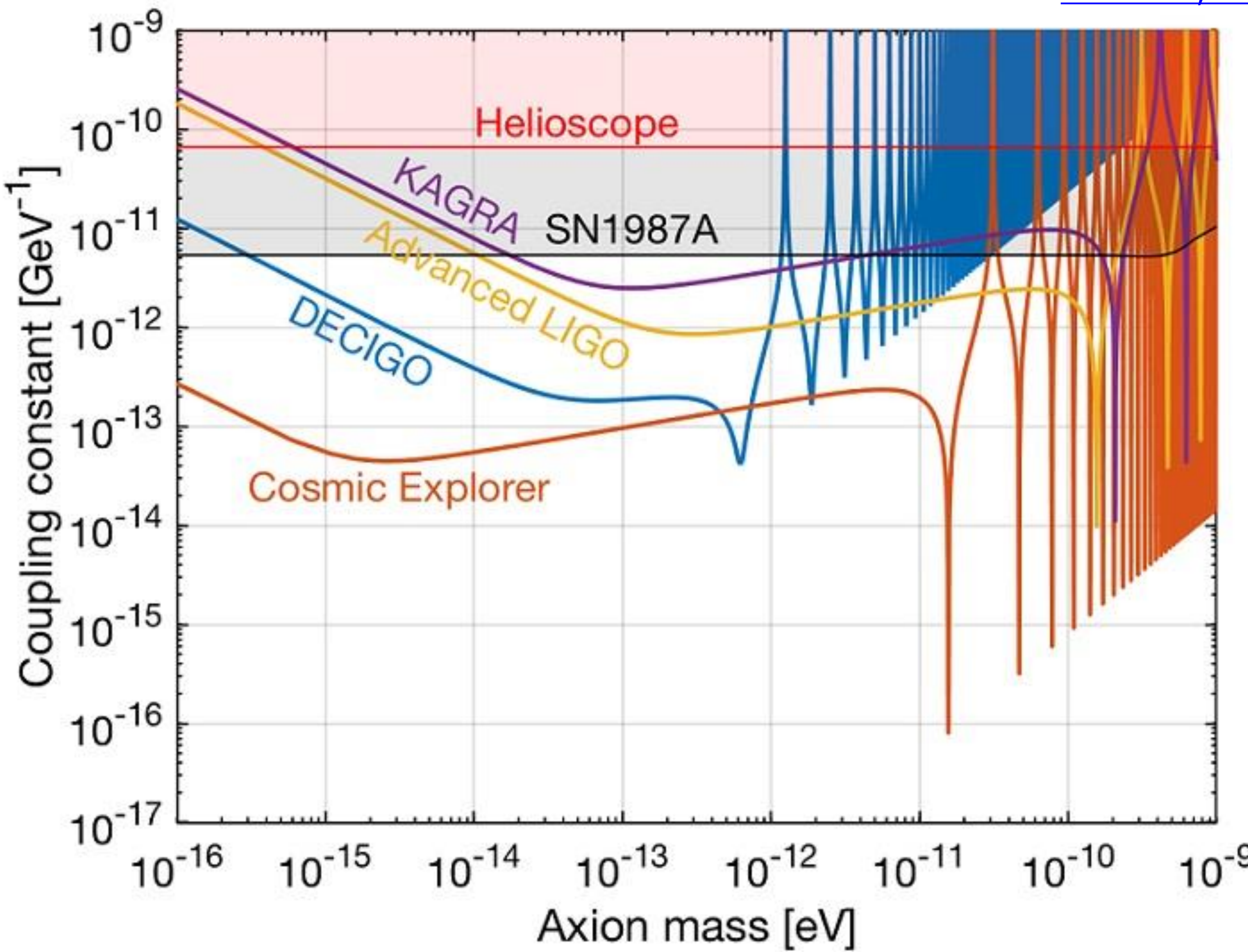
Comparison with Other Groups

Purple dotted lines from
P. Arias+ JCAP 06, 013 (2012)

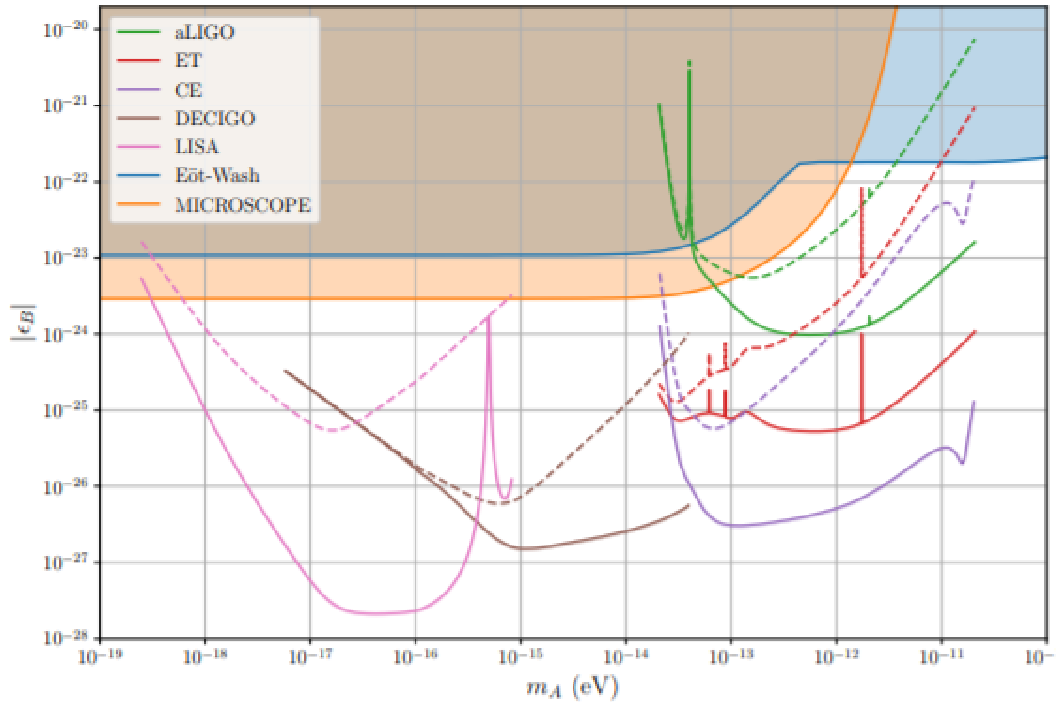


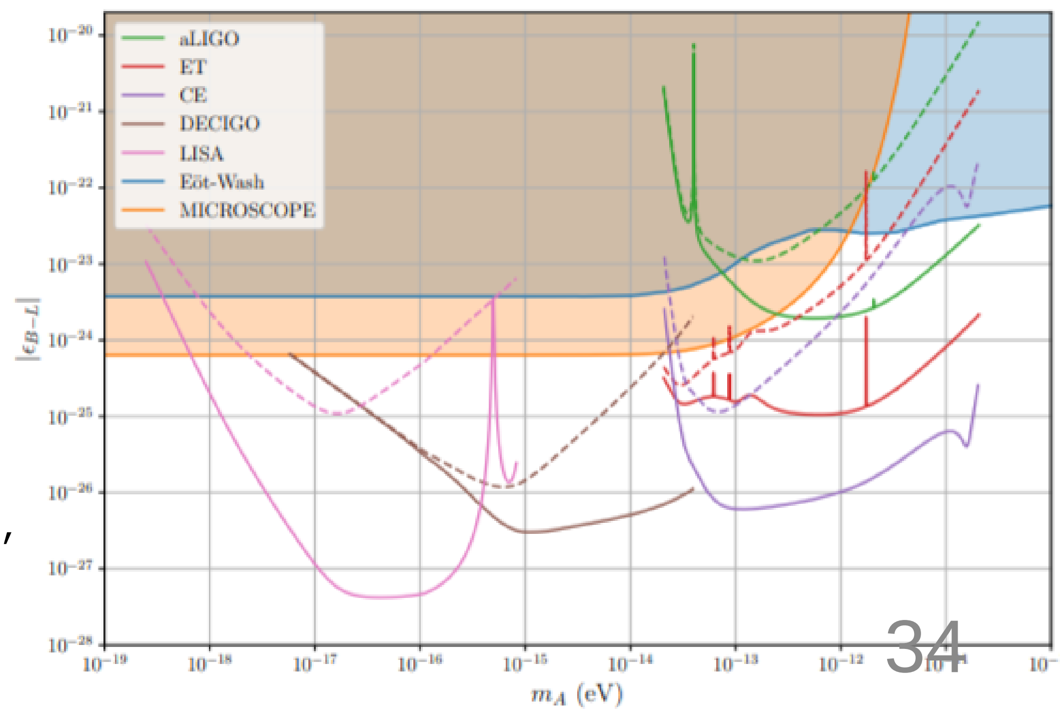
Axion Search with GW Detectors

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



Gauge Boson Search





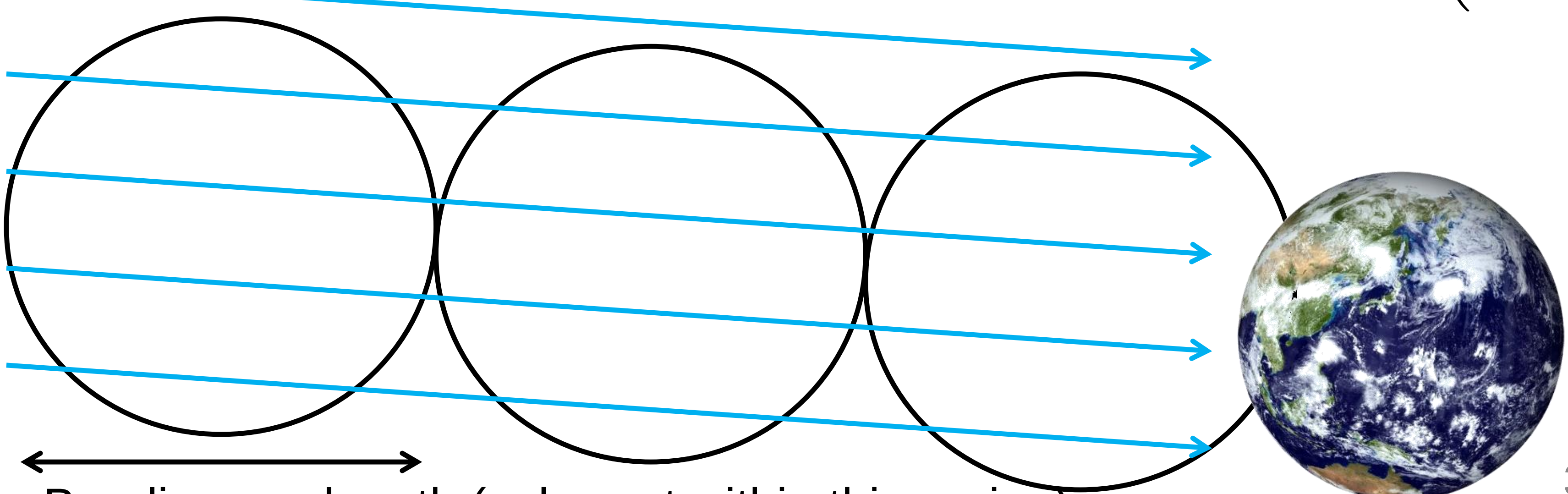
S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata, arXiv:2011.03589

Coherence Time

- SNR grows with √Tobs if integration time is shorter than coherence time
- SNR grows with (Tobs)$^{1/4}$ if integration time is longer

$$\mathrm{SNR} = \begin{cases} \dfrac{\sqrt{T_{\mathrm{obs}}}}{2\sqrt{S_{\mathrm{noise}}(f)}}\dfrac{\delta c}{c} & (T_{\mathrm{obs}} \lesssim \tau) \\ \dfrac{(T_{\mathrm{obs}}\tau)^{1/4}}{2\sqrt{S_{\mathrm{noise}}(f)}}\dfrac{\delta c}{c} & (T_{\mathrm{obs}} \gtrsim \tau) \end{cases}$$

$$\tau \simeq 1\ \mathrm{year}\left(\frac{10^{-16}\ \mathrm{eV}}{m_a}\right)$$



Freq-Mass-Coherence Time

Frequency	Mass	Coherent Time	Coherent Length
0.1 Hz	4.1e-16 eV	0.32 year	3e12 m
1 Hz	4.1e-15 eV	1e6 sec 12 days	3e11 m
10 Hz	4.1e-14 eV	1.2 days	3e10 m
100 Hz	4.1e-13 eV	2.8 hours	3e9 m
1000 Hz	4.1e-12 eV	17 minutes	3e8 m
10000 Hz	4.1e-11 eV	1.7 minutes	3e7 m