SYRTE-UTokyo DM Seminar @ Online

March 5, 2021

Laser interferometric searches for ultralight dark matter

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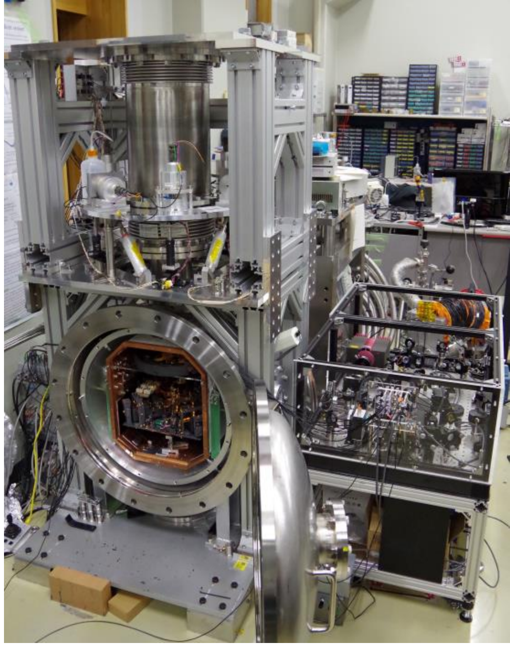
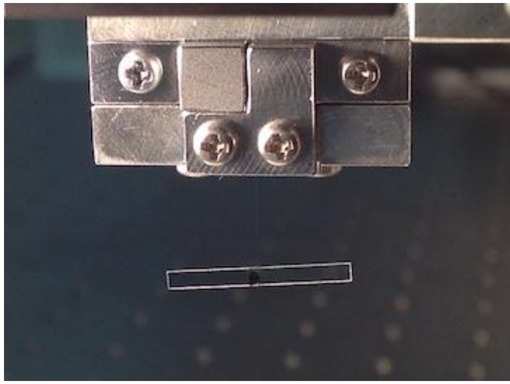
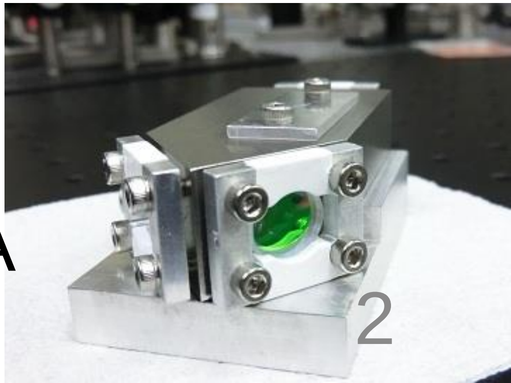
Slides are available at https://tinyurl.com/YM20210305

Ando Group

- Gravitational wave detectors
  - Ground-based detector KAGRA
  - Space detector DECIGO
  - Torsion bar antenna TOBA
- Optomechanics
  - mg-scale torsion pendulum
  - Optical levitation of mg-scale disk
- Tests of Lorentz invariance
  - Isotropy of speed of light
- Dark matter search
  - Axion search DANCE
  - Dark matter searches with KAGRA



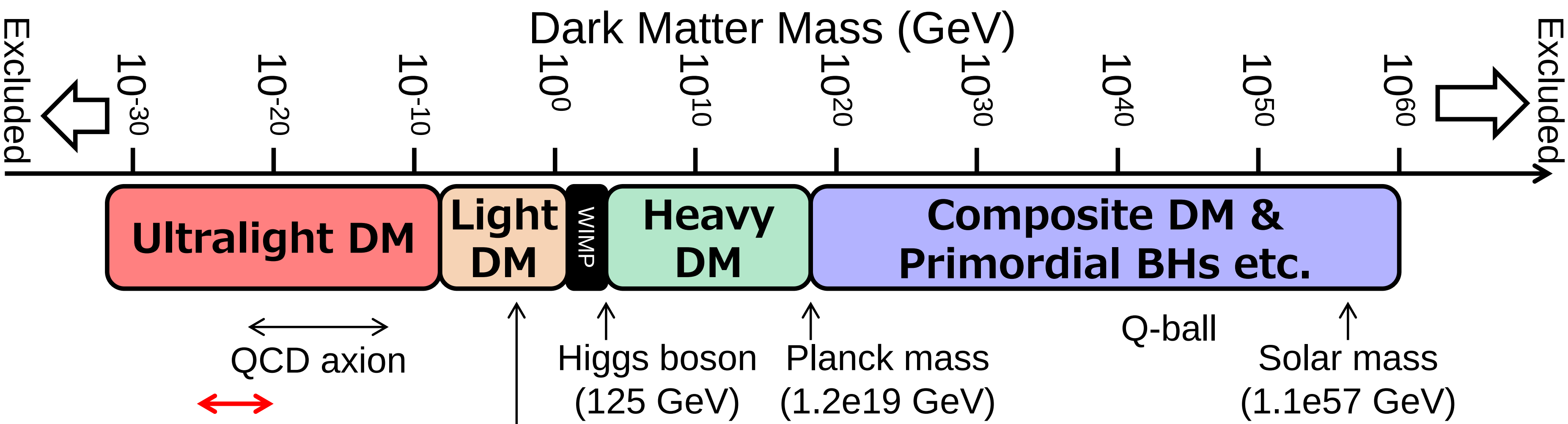




Ultralight Dark Matter

- Ultralight DM (<~1 eV) behaves as classical wave fields

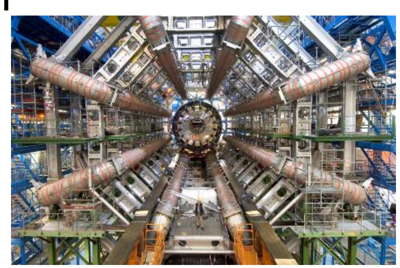
$$f = 242\ \mathrm{Hz}\left(\frac{m_{\mathrm{DM}}}{10^{-12}\ \mathrm{eV}}\right)$$

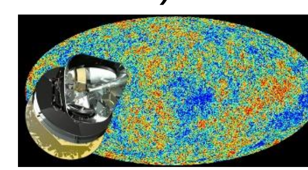


2.4 Hz ~ 2.4 kHz
(1e-14 ~ 1e-11 eV)

XENON1T limits on ALP
(1-210 keV)
arXiv:2006.09721

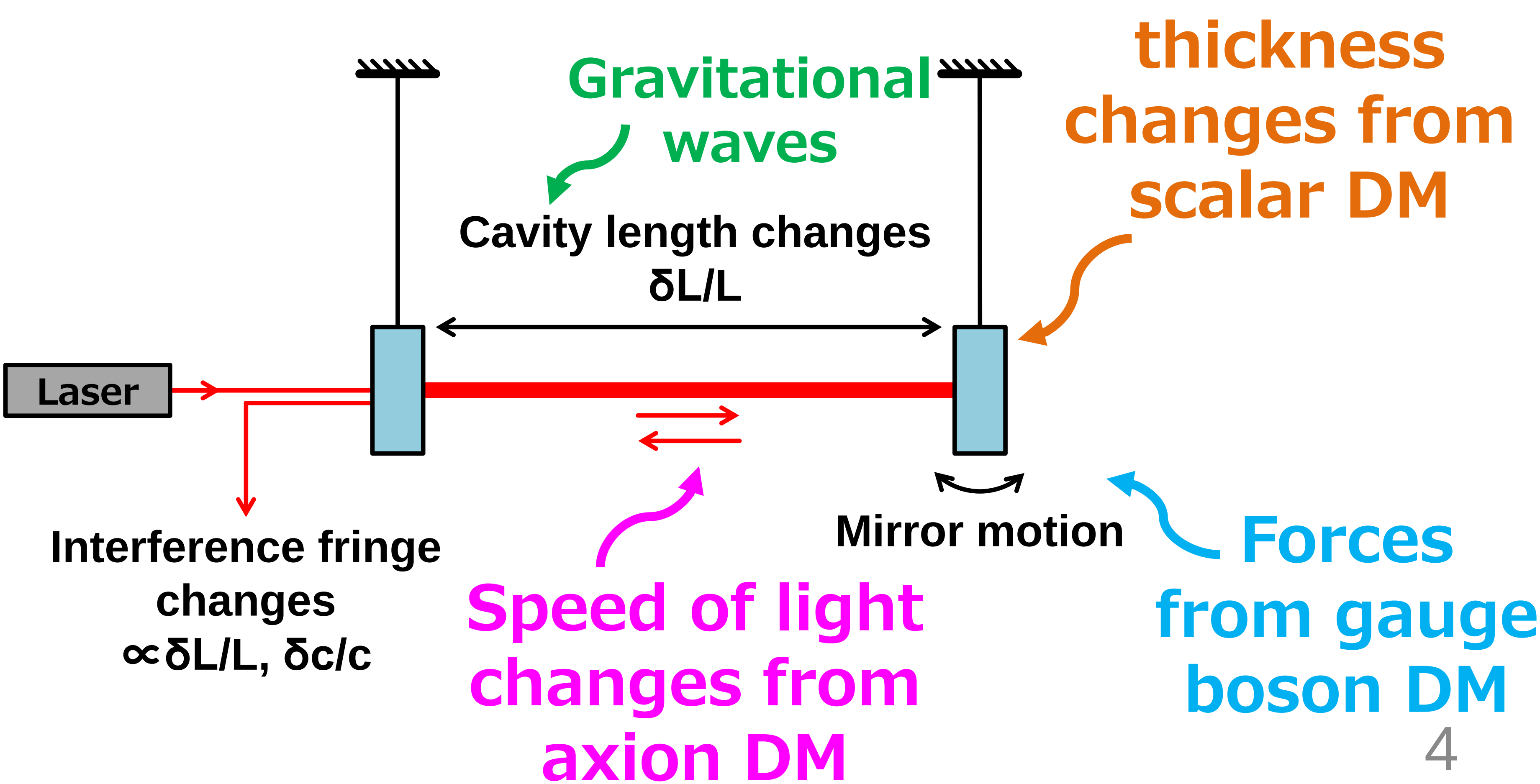
Laser Interferometry





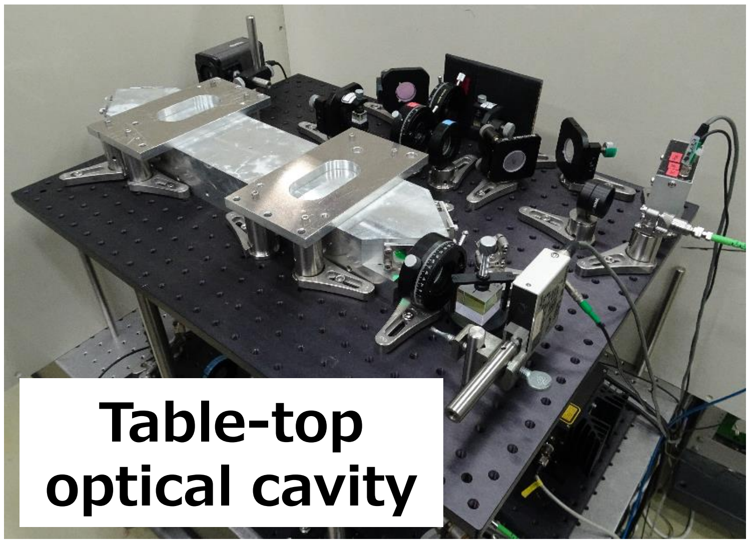
Laser Interferometry for DM Search

- Laser interferometers and optical cavities are sensitive to tiny oscillations from gravitational waves and also dark matter



Our Strategy

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



Broad band

PRL 121, 161301 (2018)

Narrow band

PRL 123, 111301 (2019)

+ Polarization measurement

PRD 102, 102001 (2020)
arXiv:2011.03589

Ultralight DM

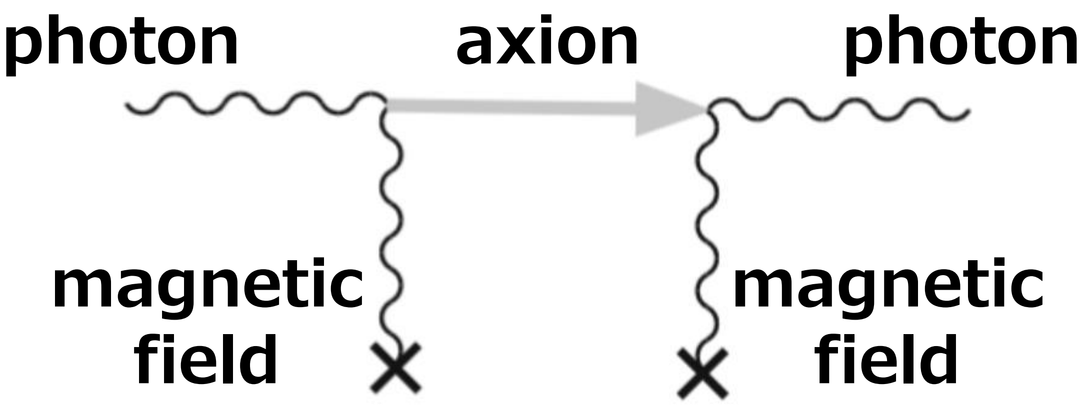
Axion like particles

Gauge bosons

Axion and Axion-Like Particles

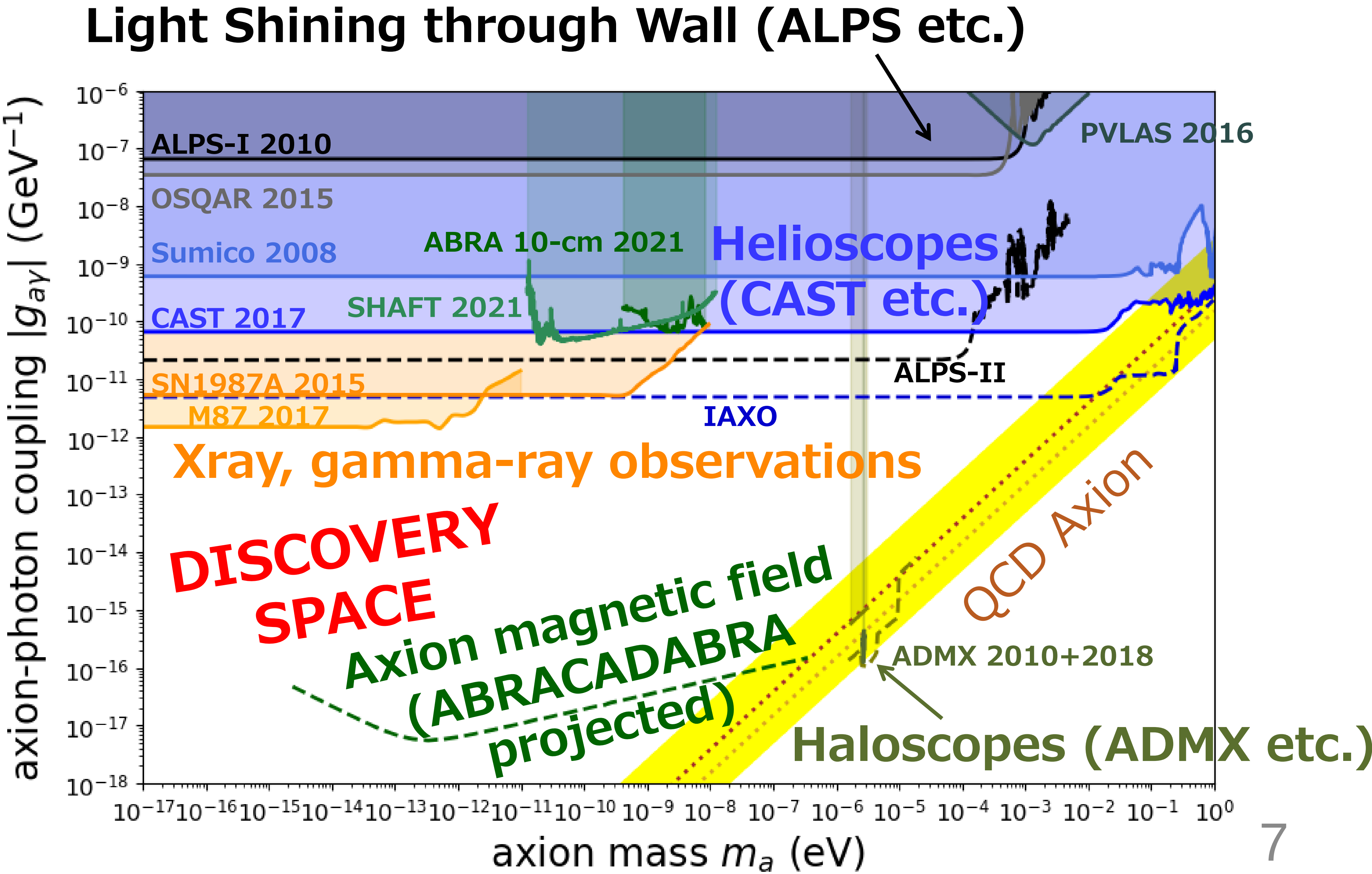
- Pseudo-scalar particle originally introduced to solve strong CP problem (QCD axion)
- Various axion-like particles (ALPs) predicted by string theory and supergravity
- Many experiments to search for ALPs through axion-photon coupling

    Especially by using magnetic fields



Primakoff effect

Previous Searches



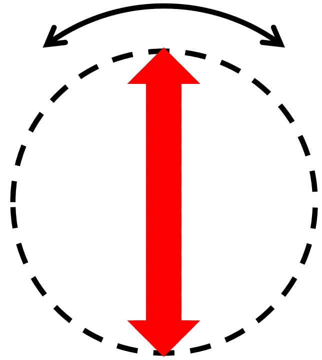
Polarization Modulation from Axions

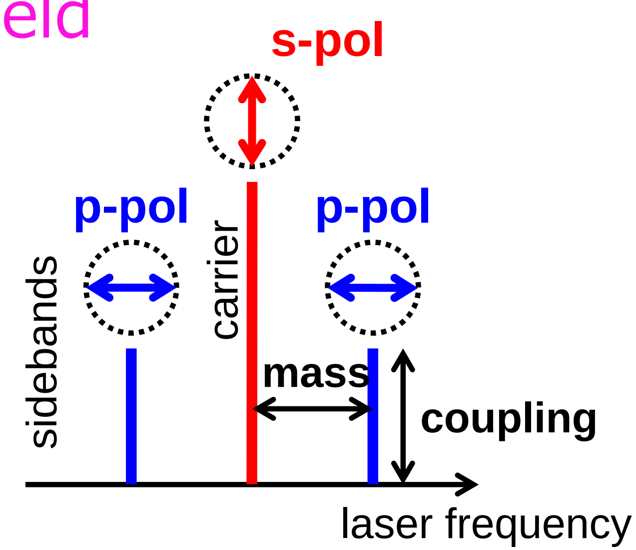
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

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

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

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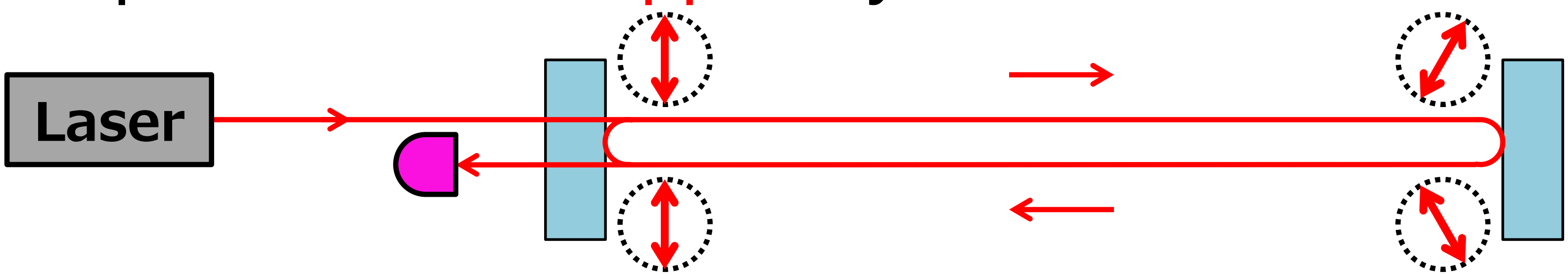
- Optical cavities can increase the optical path, but the polarization is flipped by mirror reflections



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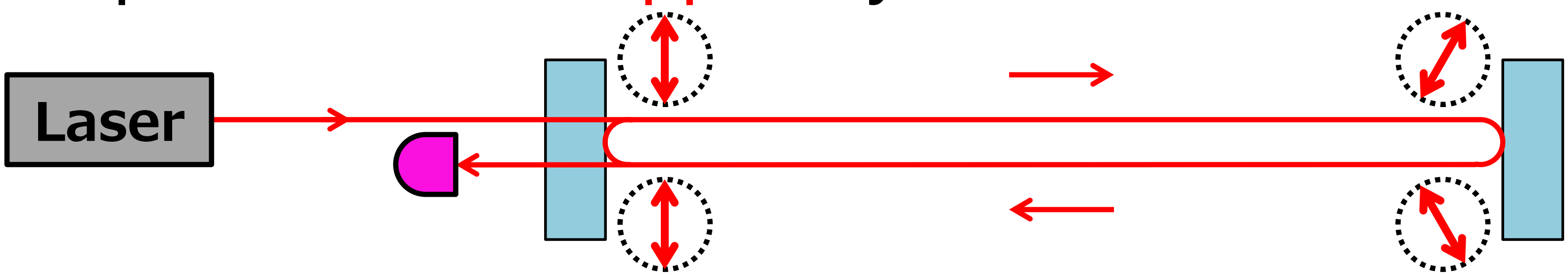
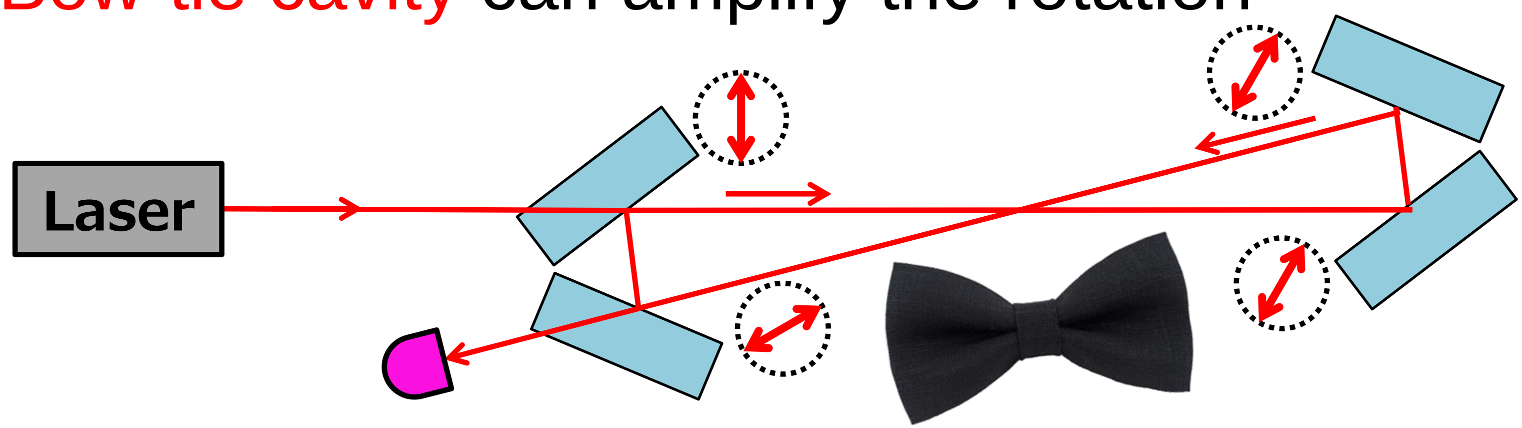


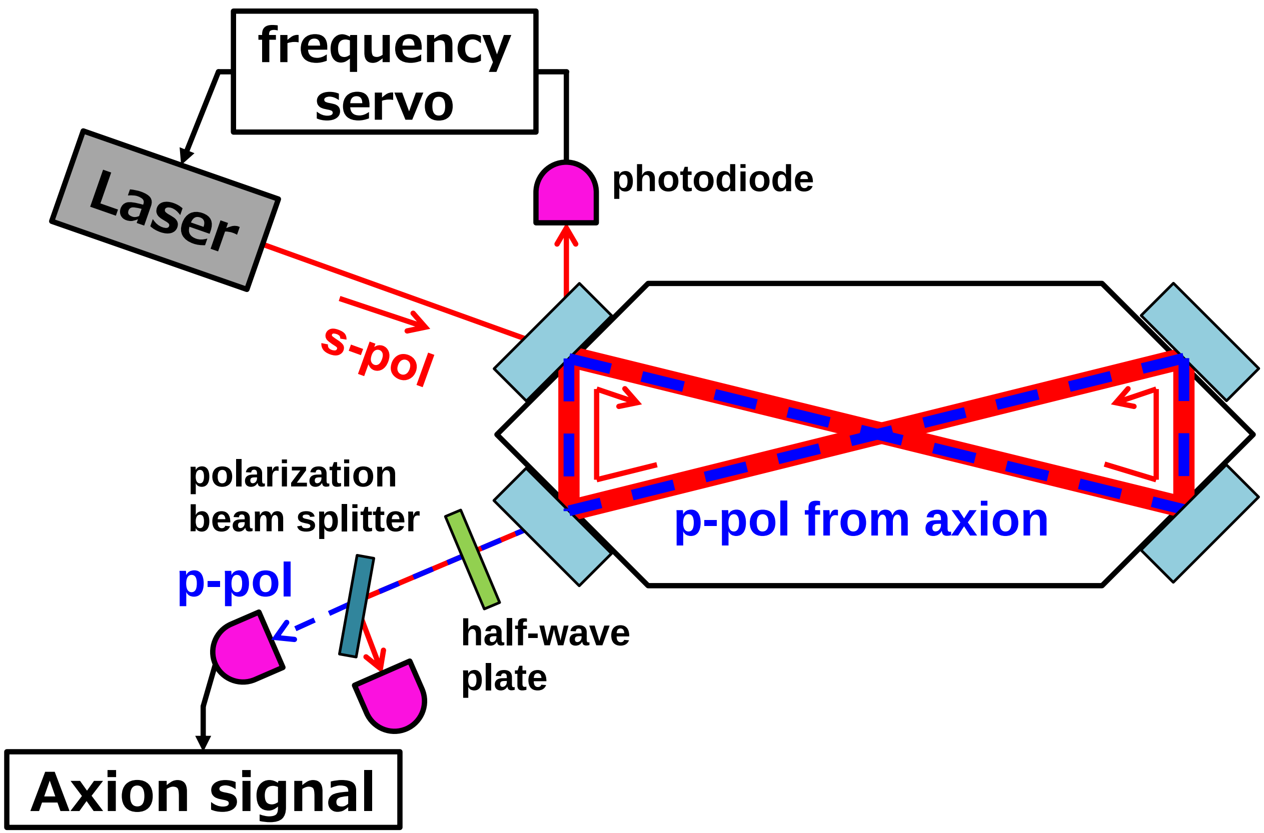
- Bow-tie cavity can amplify the rotation

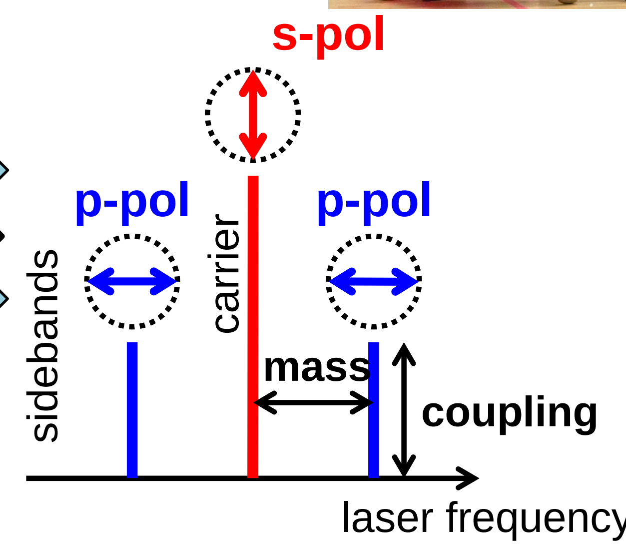


DANCE Setup

Dark matter **A**xion search with ri**N**g **C**avity **E**xperiment

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

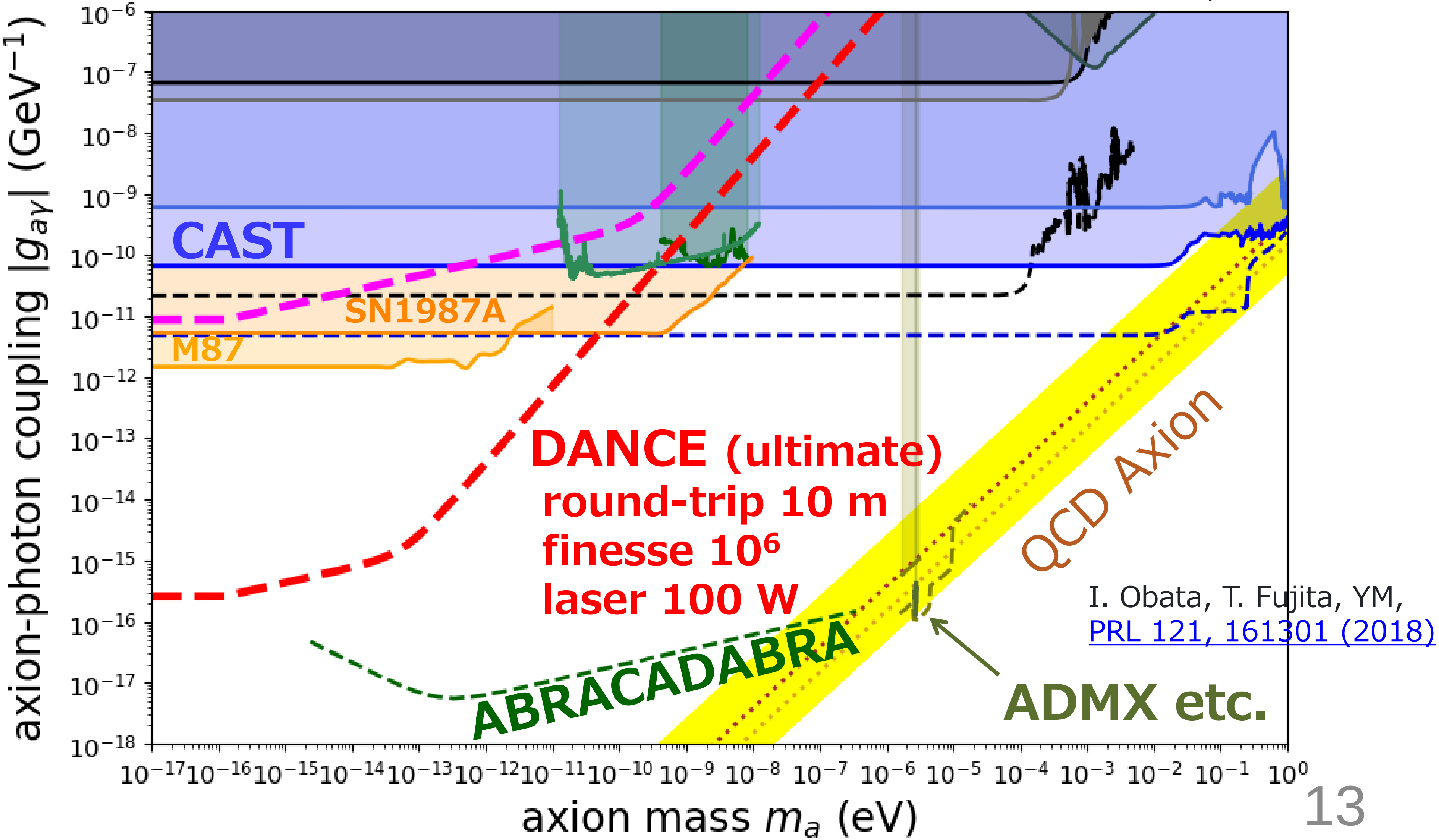




Sensitivity of DANCE

- Sensitivity better than CAST limit

* Shot noise limited
1 year observation



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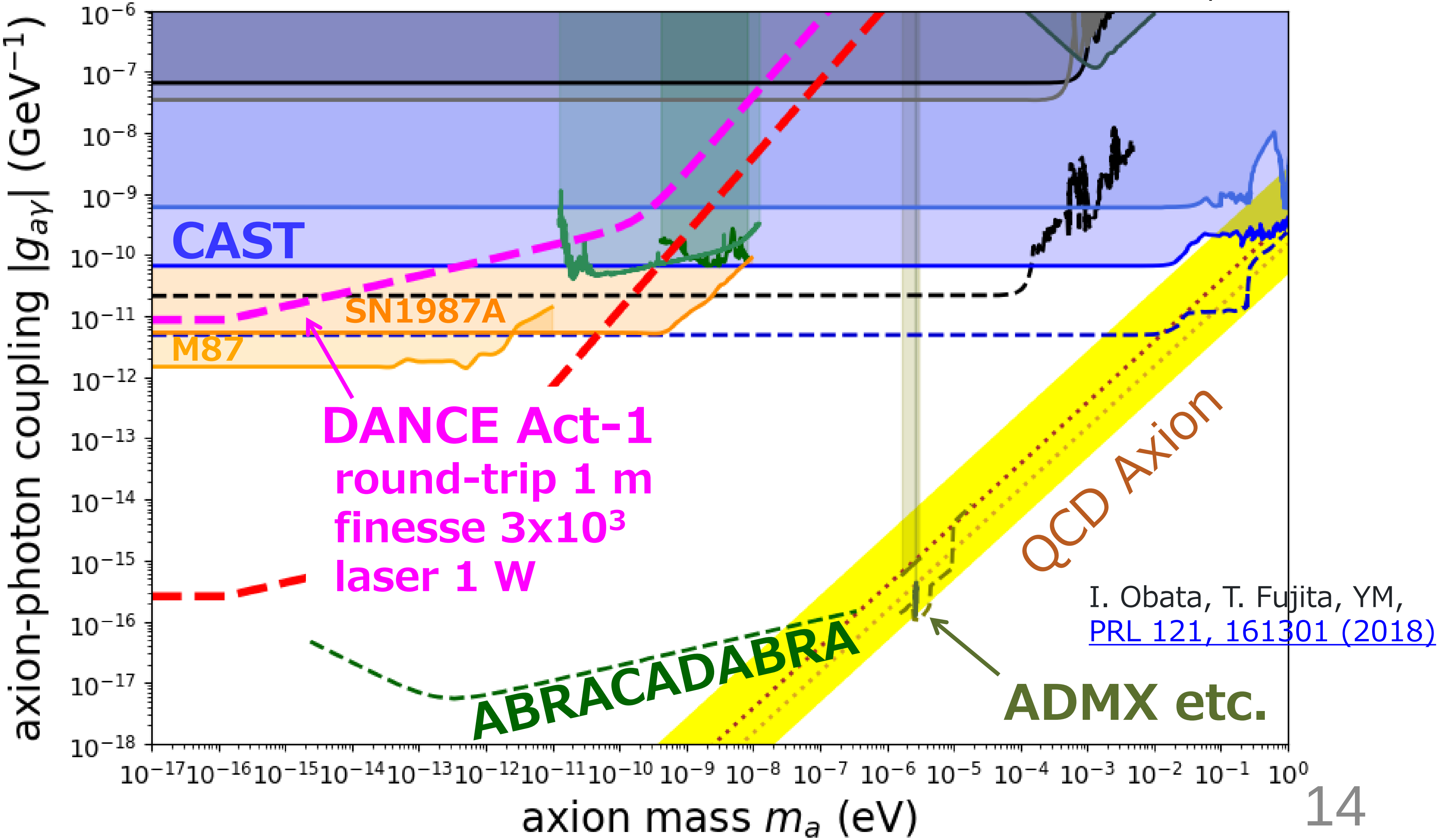
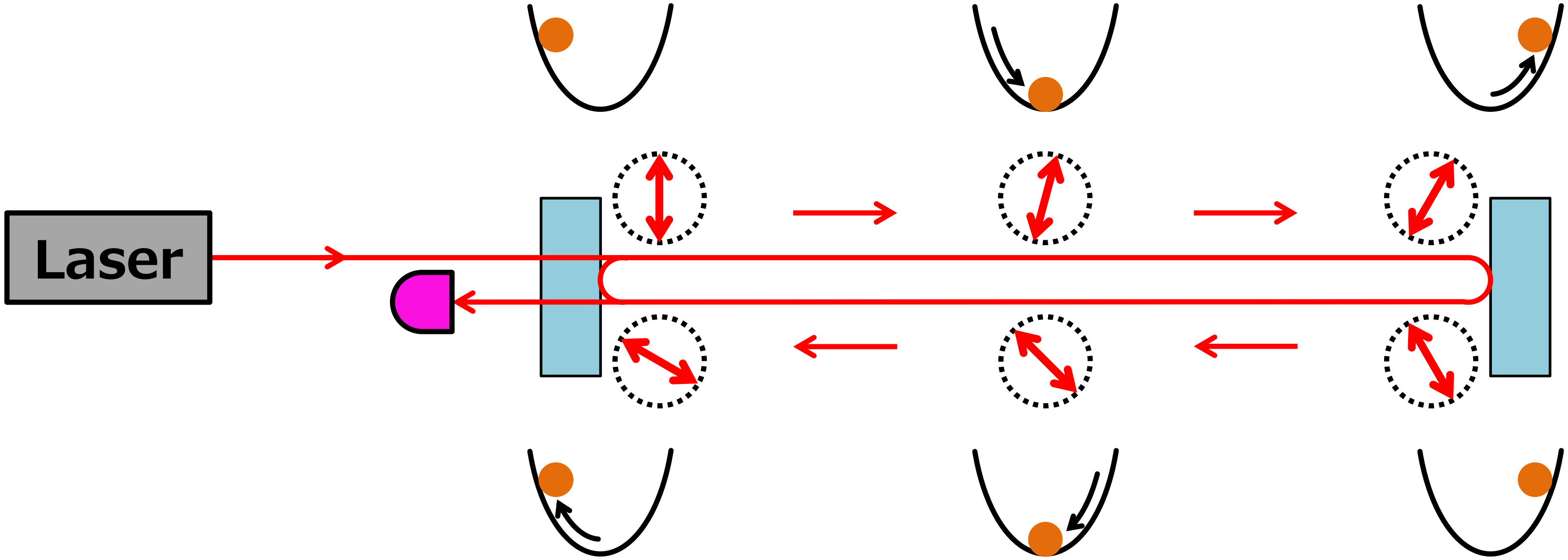


Linear Cavities for Axion Search

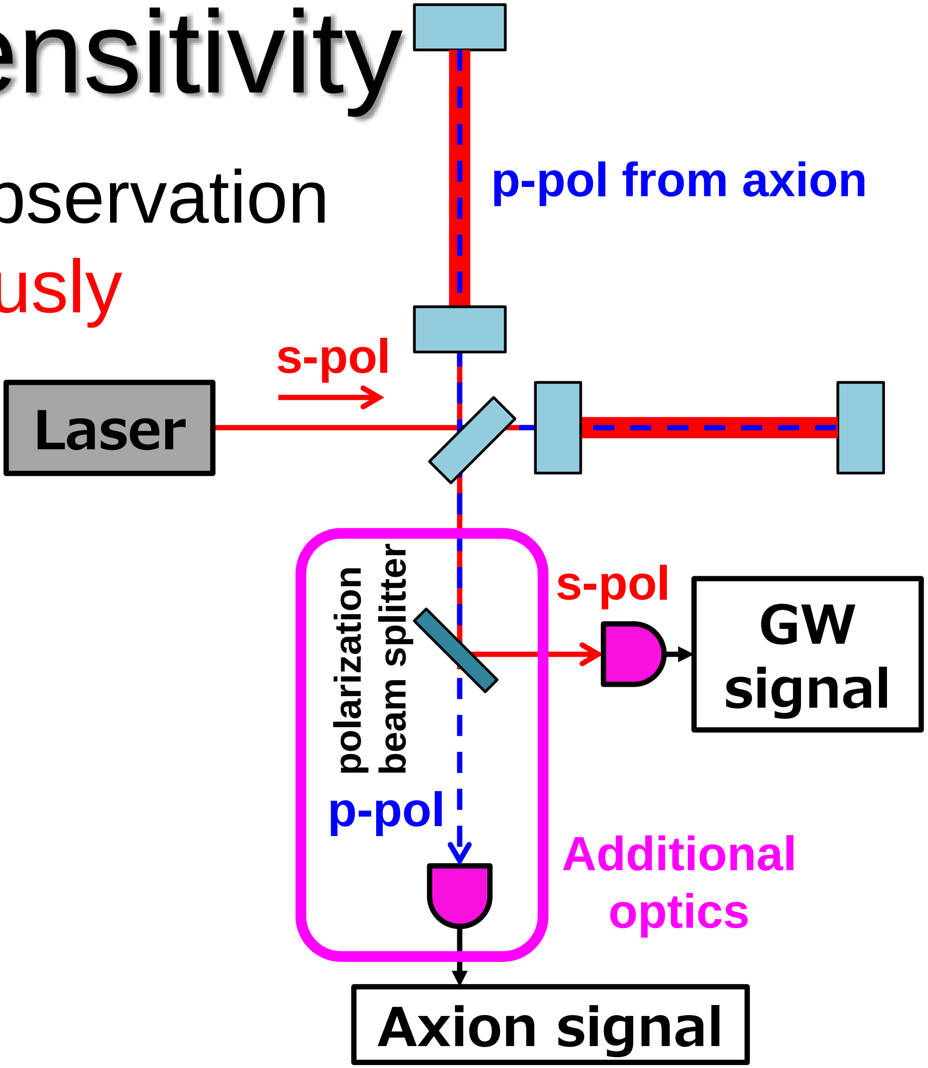
- When finite light traveling time is considered, linear cavities can also be used



- 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

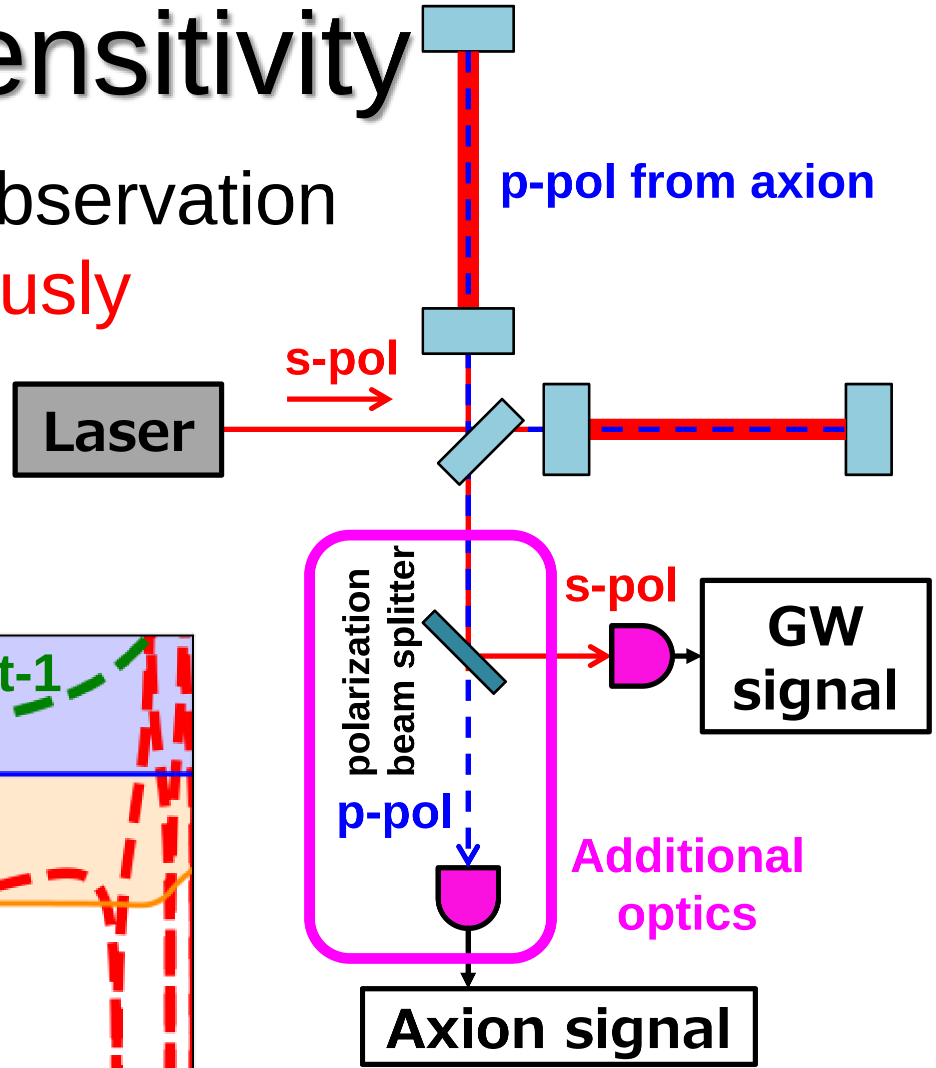
- Axion search and GW observation can be done simultaneously

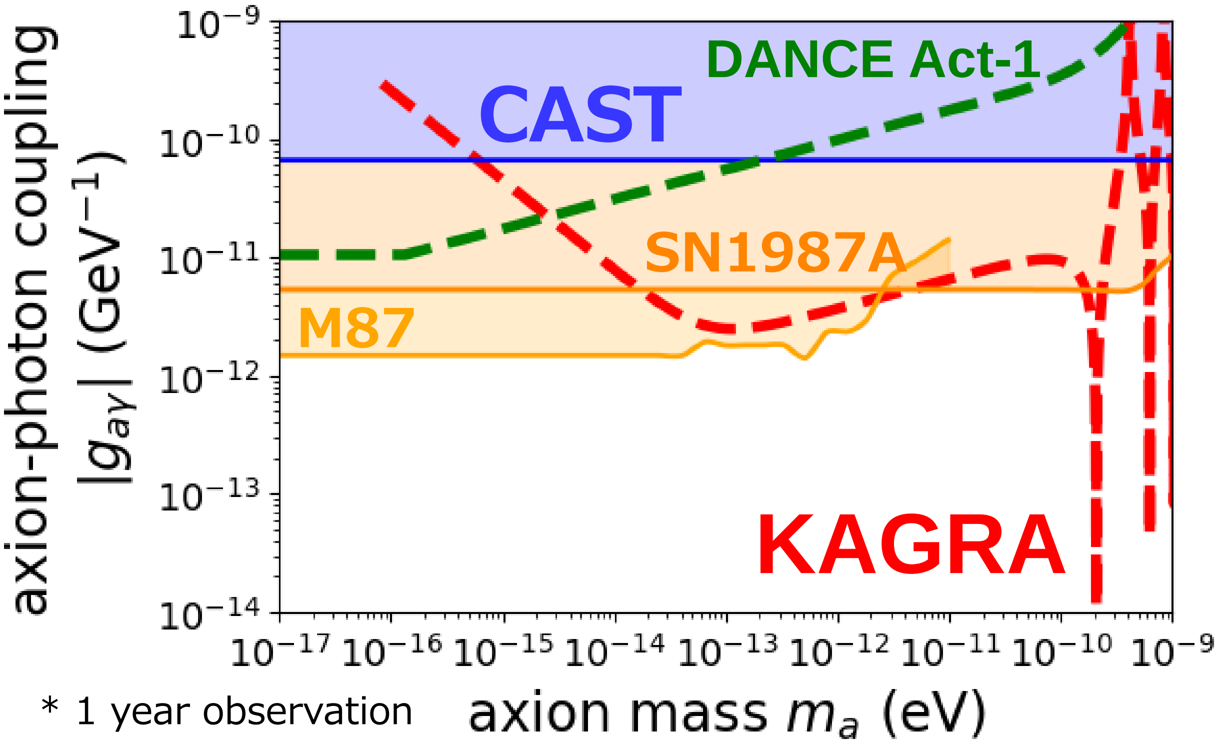


K. Nagano, T. Fujita, YM, I. Obata
PRL 123, 111301 (2019)

KAGRA Axion Sensitivity

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



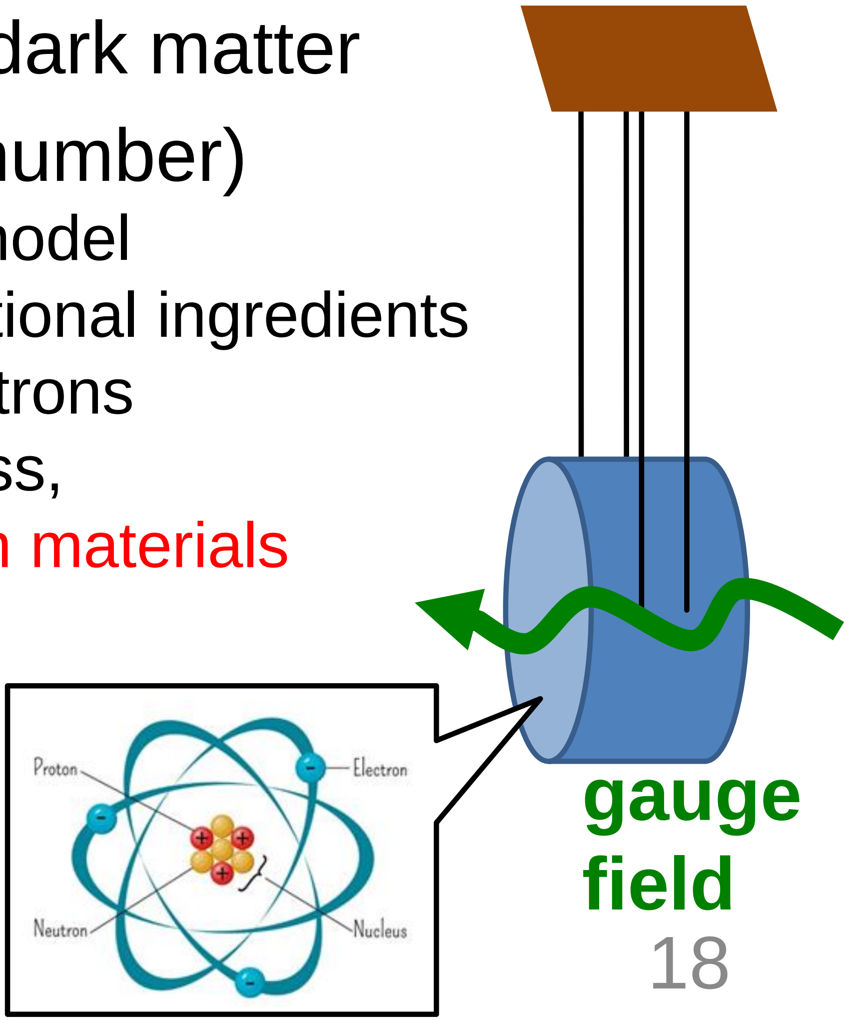


* 1 year observation

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

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

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)

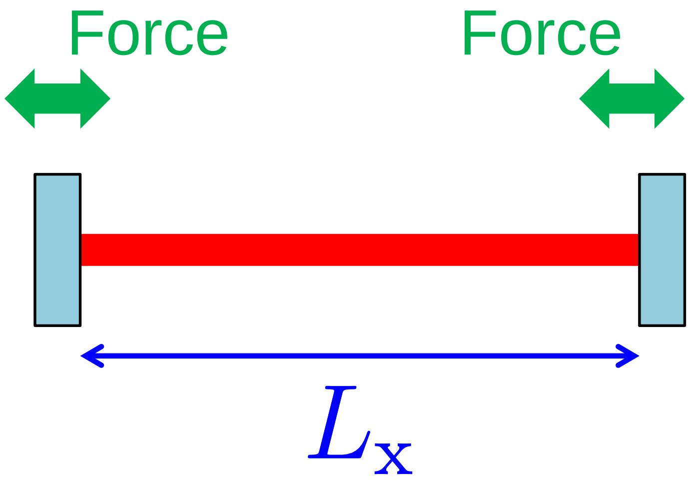
mirror mass

DM density

polarization

different phase at different position

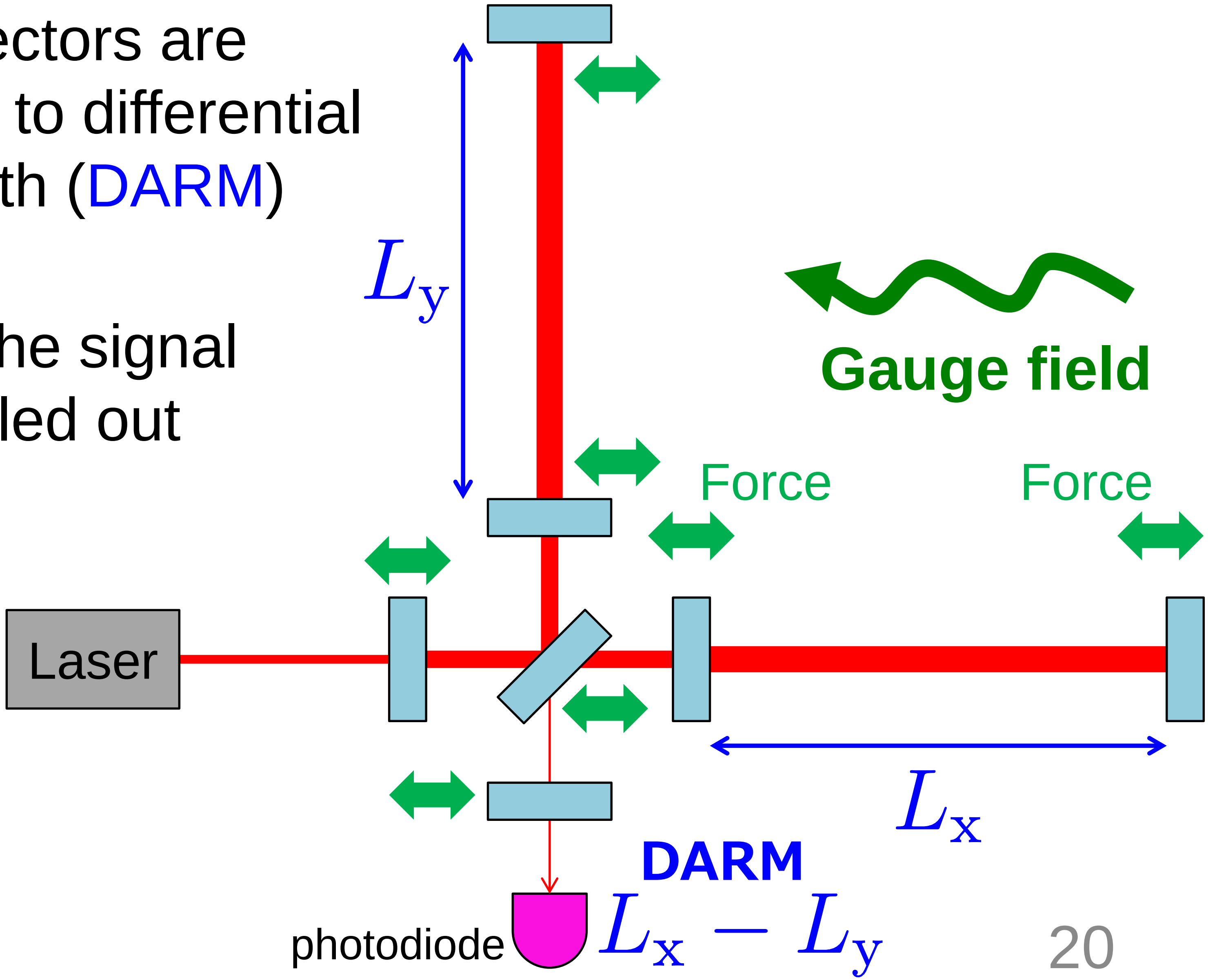
- Gauge boson mass and coupling can be measured by measuring the oscillating mirror displacement



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

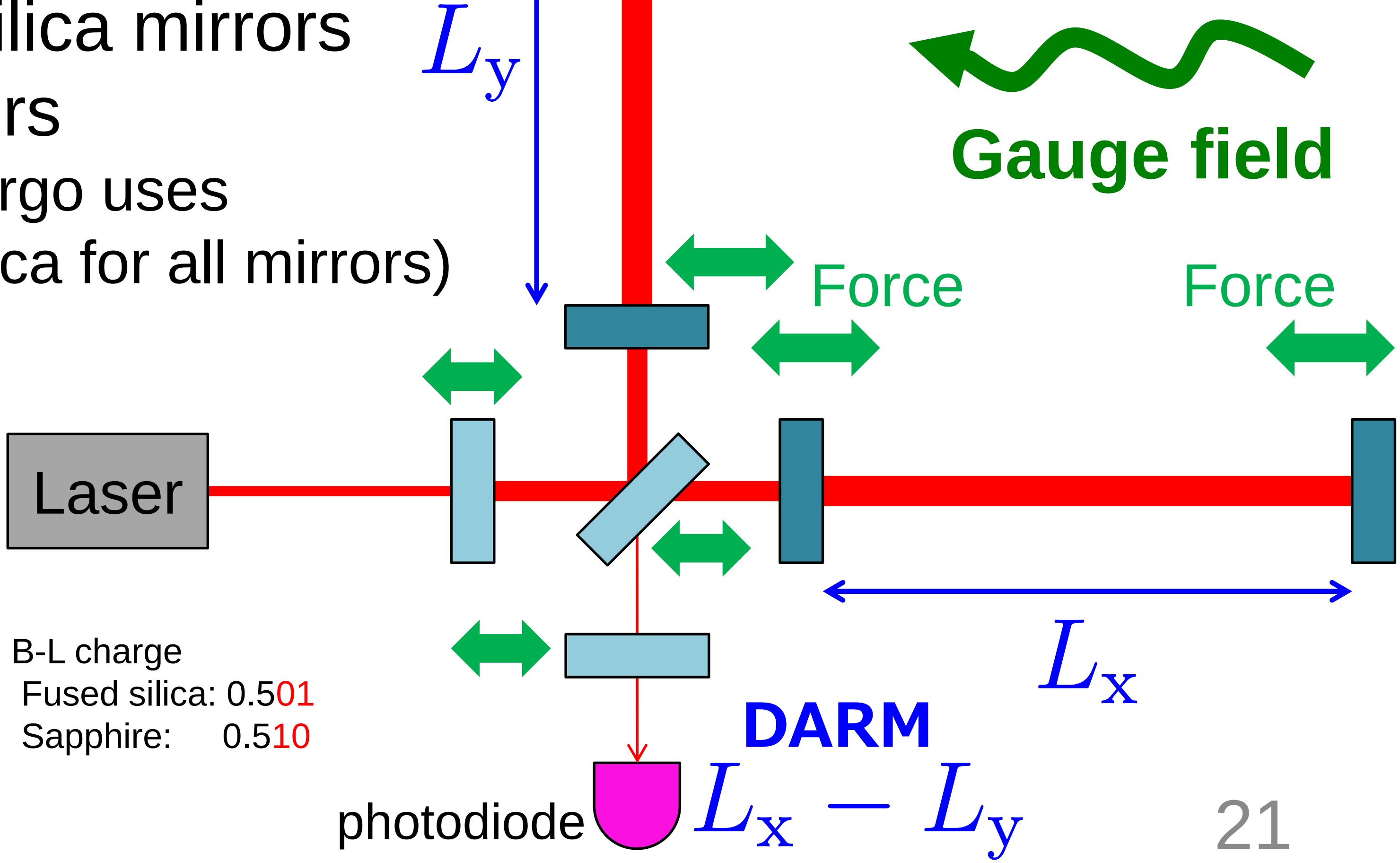
Search with GW Detectors

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

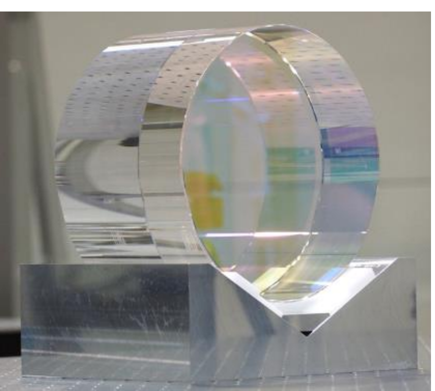


Search with KAGRA

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

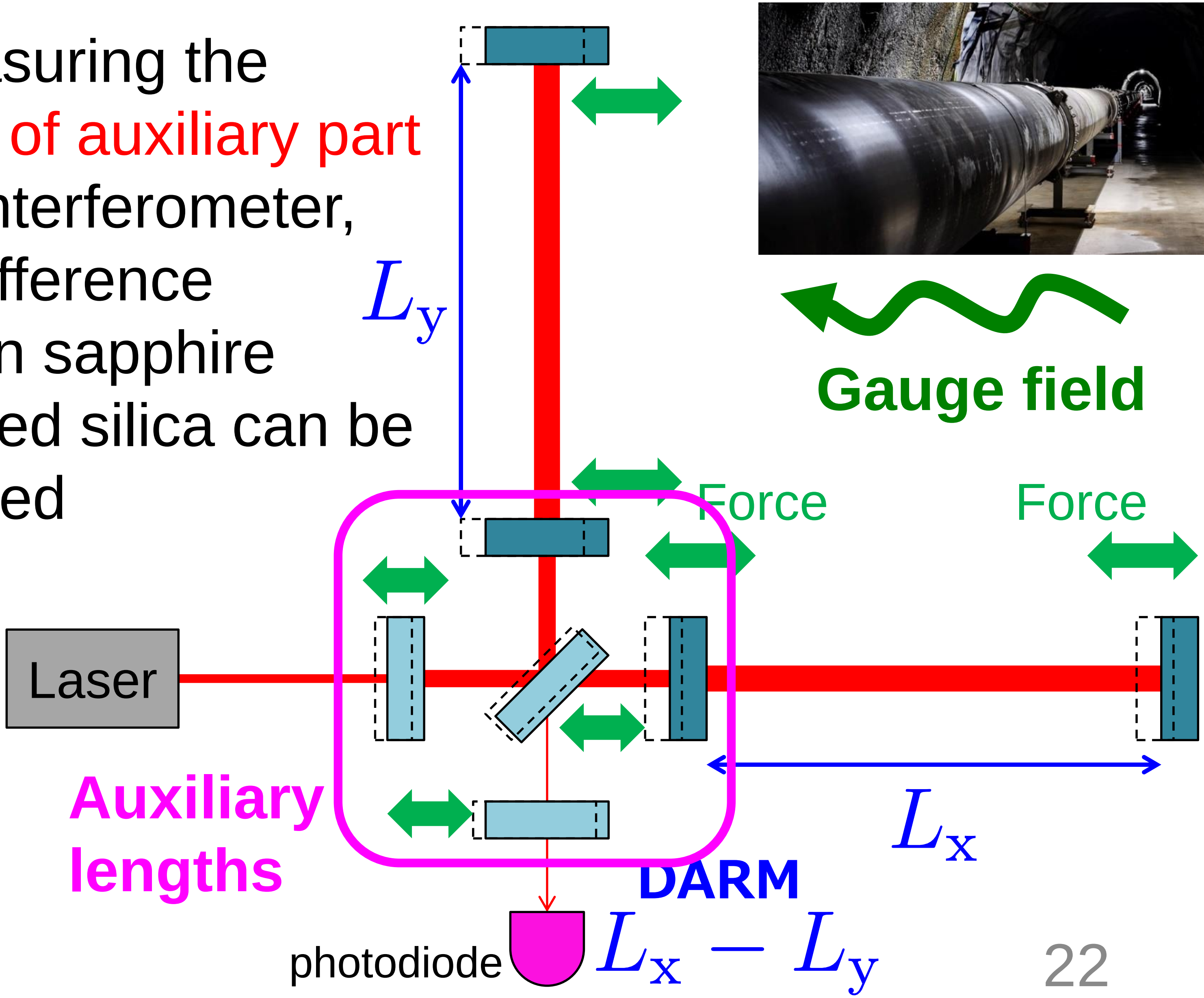


B-L charge
Fused silica: 0.501
Sapphire: 0.510



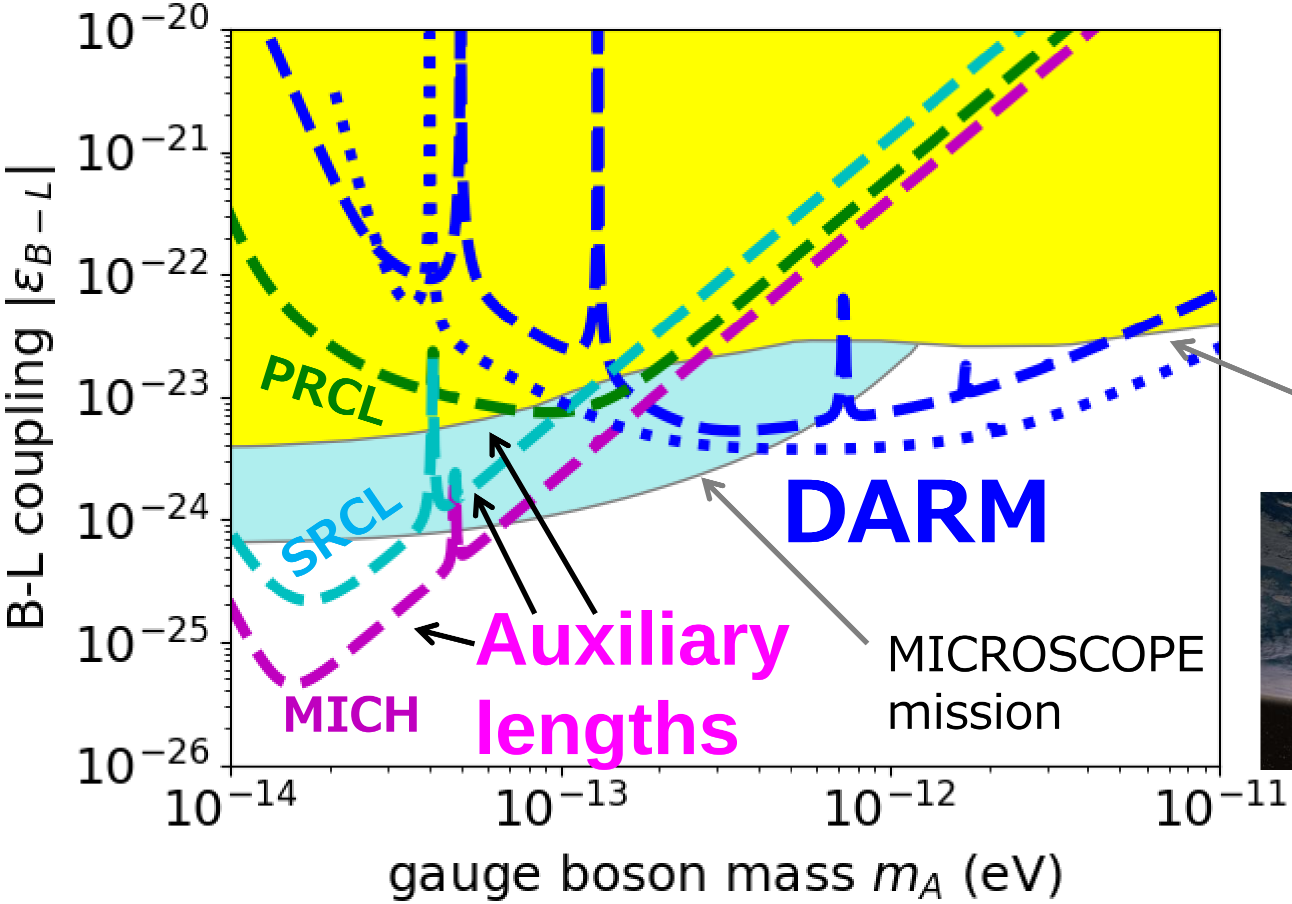
Search with KAGRA

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



KAGRA Gauge Boson Sensitivity

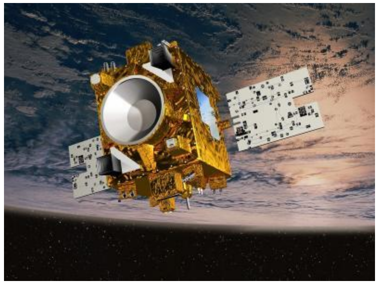
- Auxiliary length channels have better sensitivity than DARM at low mass range
- Sensitivity better than equivalence principle tests



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

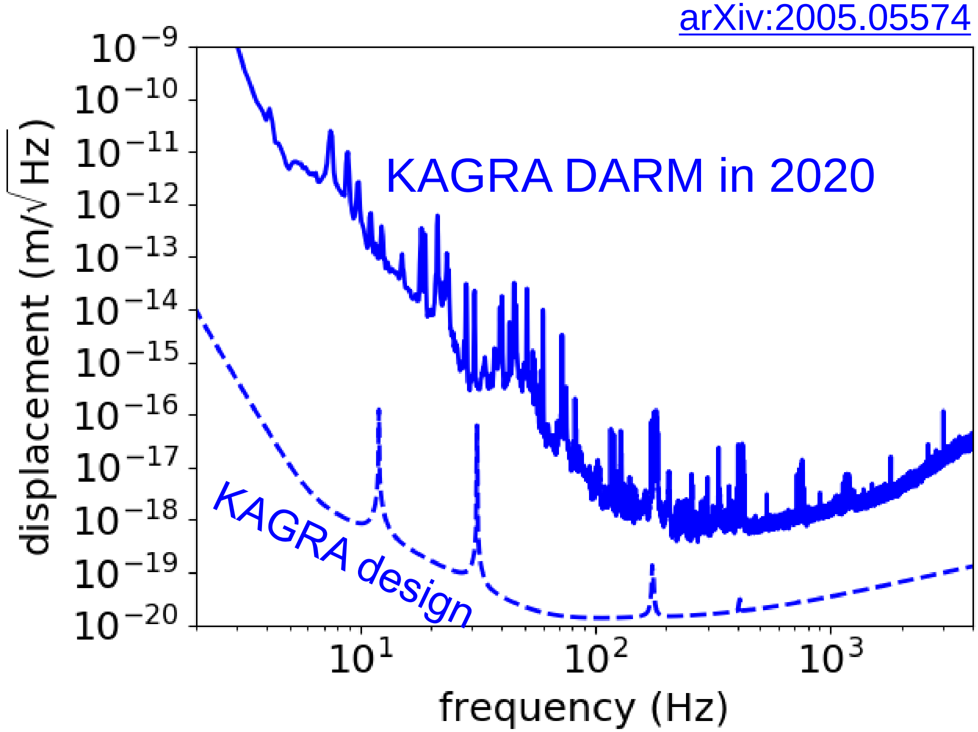
Eöt-Wash torsion pendulum

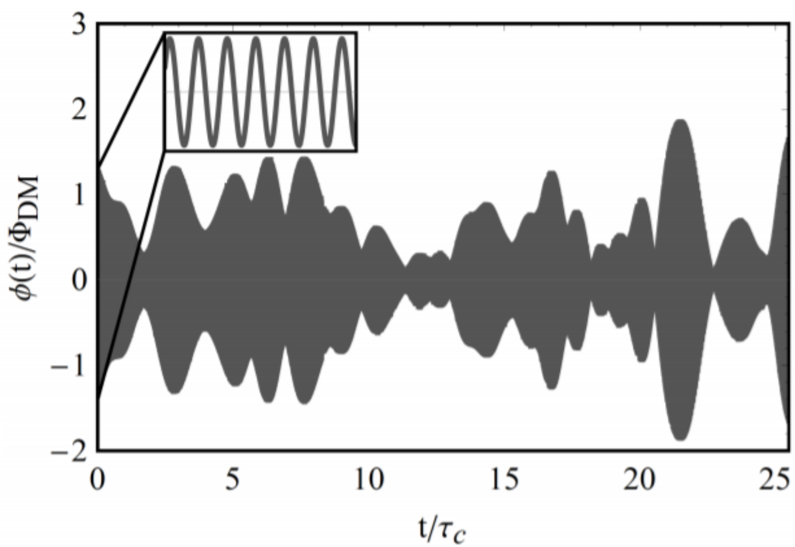


Recent Progresses: KAGRA

- 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

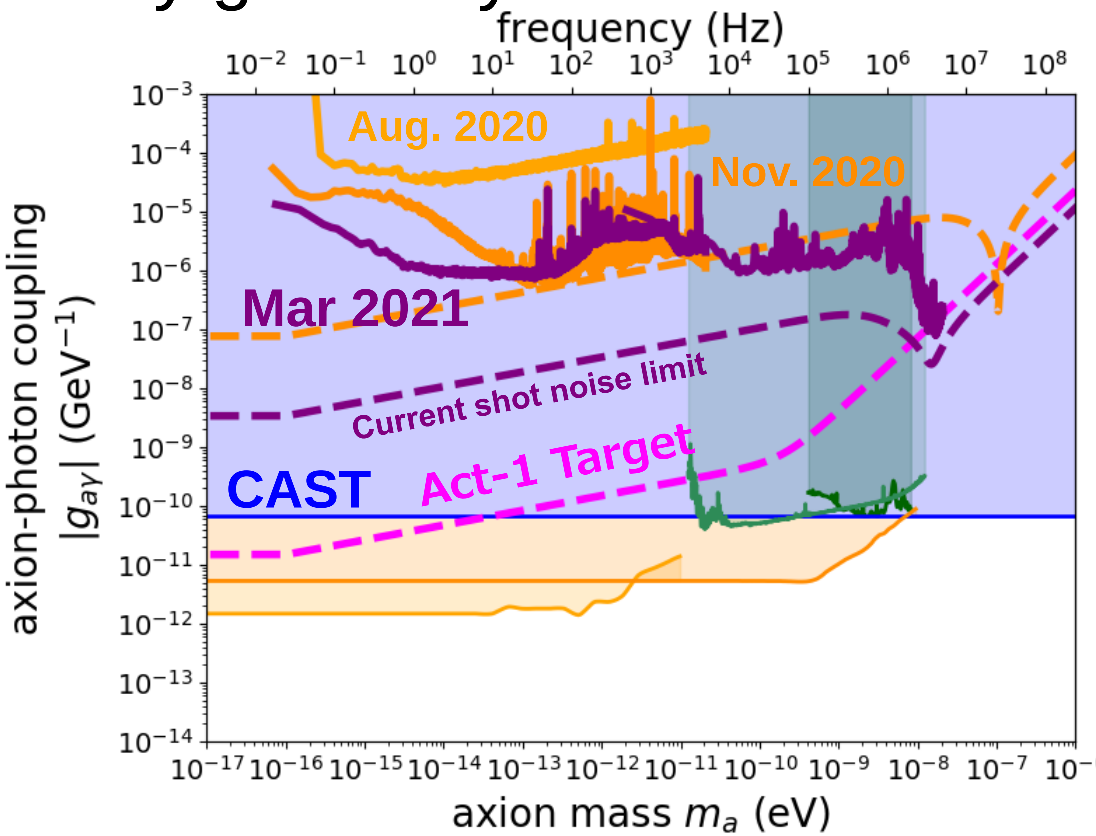
- Successfully demonstrated the operation in 2020
- Recent upgrades
  - Shielding for reducing external disturbances
  - Increasing the finesse and input laser power

	Nov. 2020	**Now**	**Act-1 Target**
Round-trip length	1 m	1 m	1 m
Input laser power	~40 mW	274(1) mW	1 W
Output laser power	~1.2 mW	158(1) mW	1 W
Finesse for carrier	525(19) p-pol	$2.80(34)\times10^3$ s-pol	3×10^3
Finesse for sidebands	~300 s-pol	193(10) p-pol	3×10^3
Resonant frequency difference between polarizations	~28 MHz	3.92(16) MHz	0 Hz

From non-zero phase shift difference in cavity mirror reflections

Recent Progresses: DANCE

- Improving the sensitivity gradually
- Stable lock lasted ~60 hours
- First test run expected this year



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

(Degraded sensitivity at low frequencies due to resonant frequency difference between polarizations)

Summary and Outlook

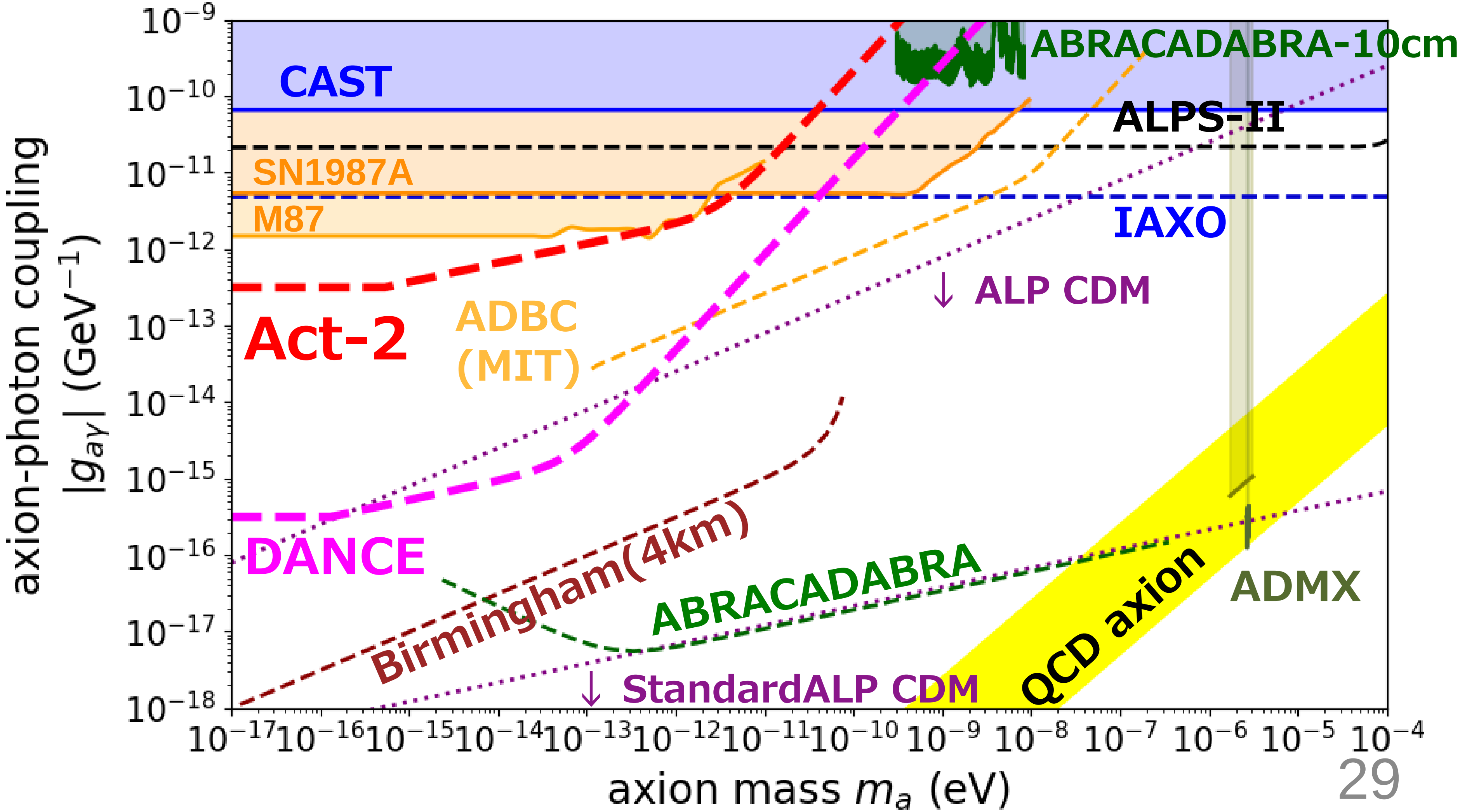
- Laser interferometers open up new possibilities for dark matter search
- We have recently started a table-top experiment and analysis of KAGRA data
  - DANCE — for broad band axion
  - KAGRA +polarimetry — for narrow band axion
  - KAGRA — for gauge boson
- Expecting first results this year

- We are also interested in scalar DM search
- We look forward to further discussions and collaboration!

Additional Slides

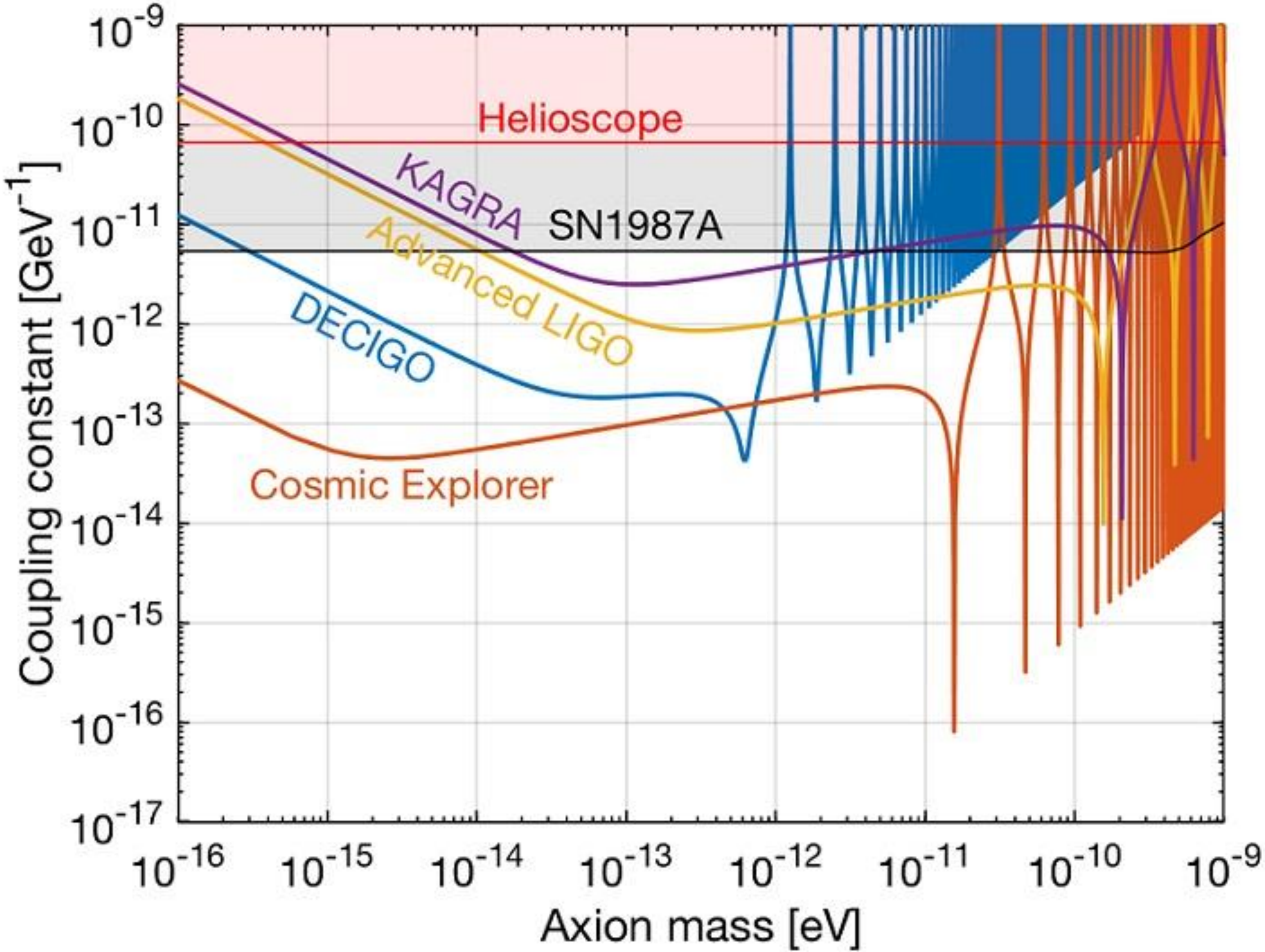
Comparison with Other Groups

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

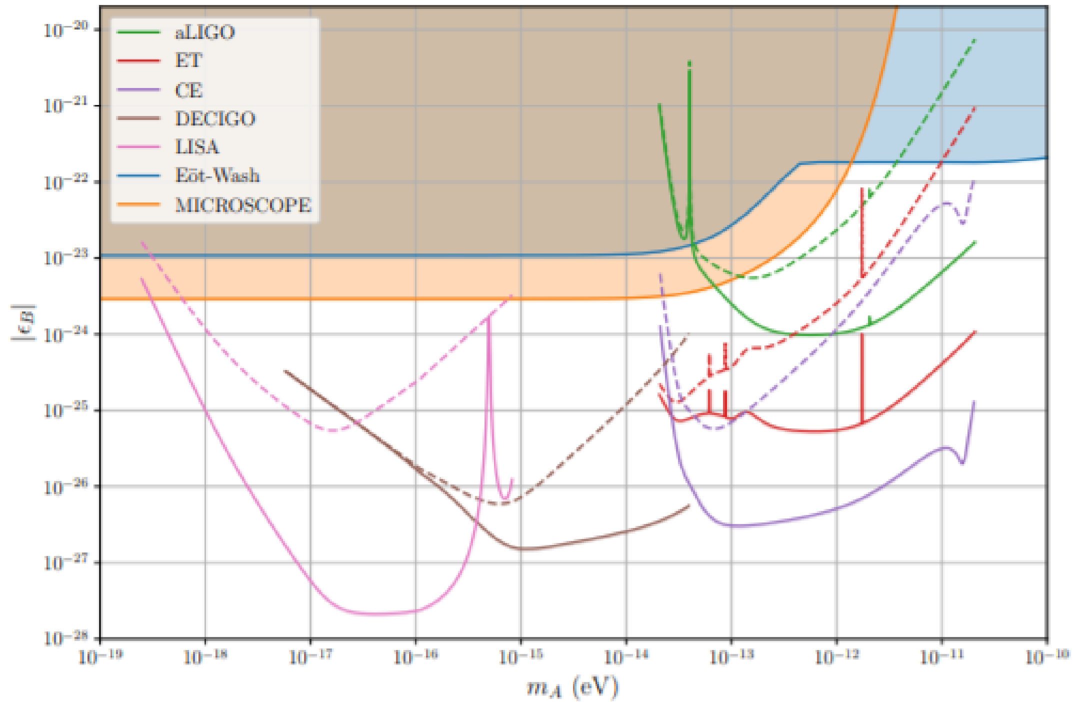


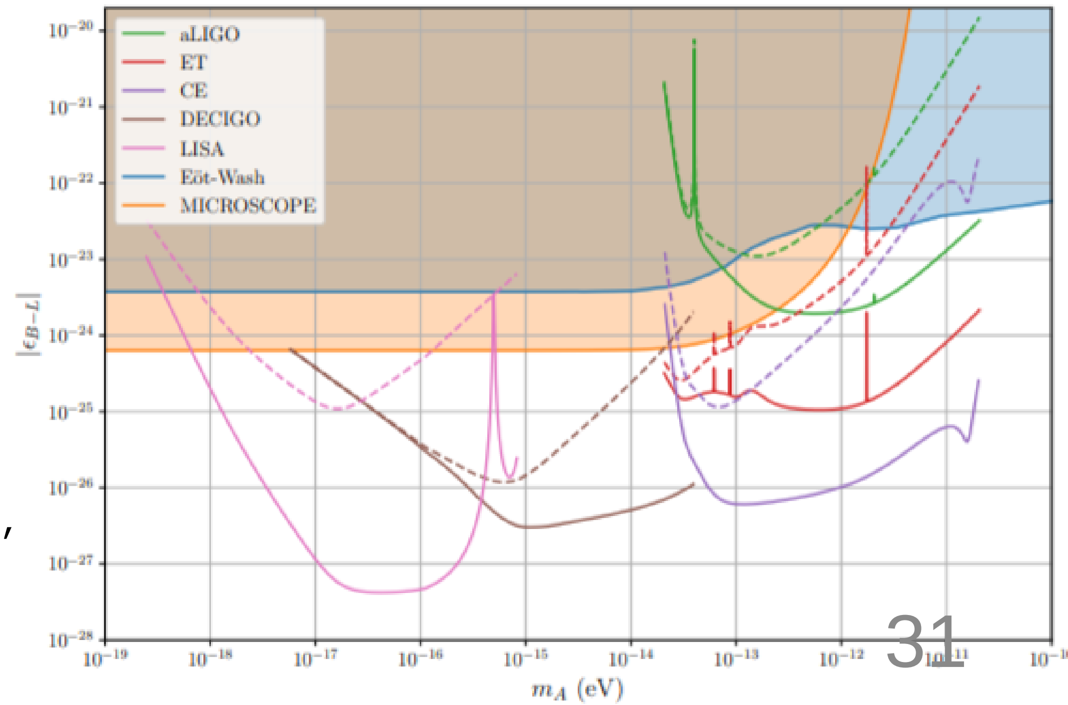
Axion Search with GW Detectors

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



Gauge Boson Search





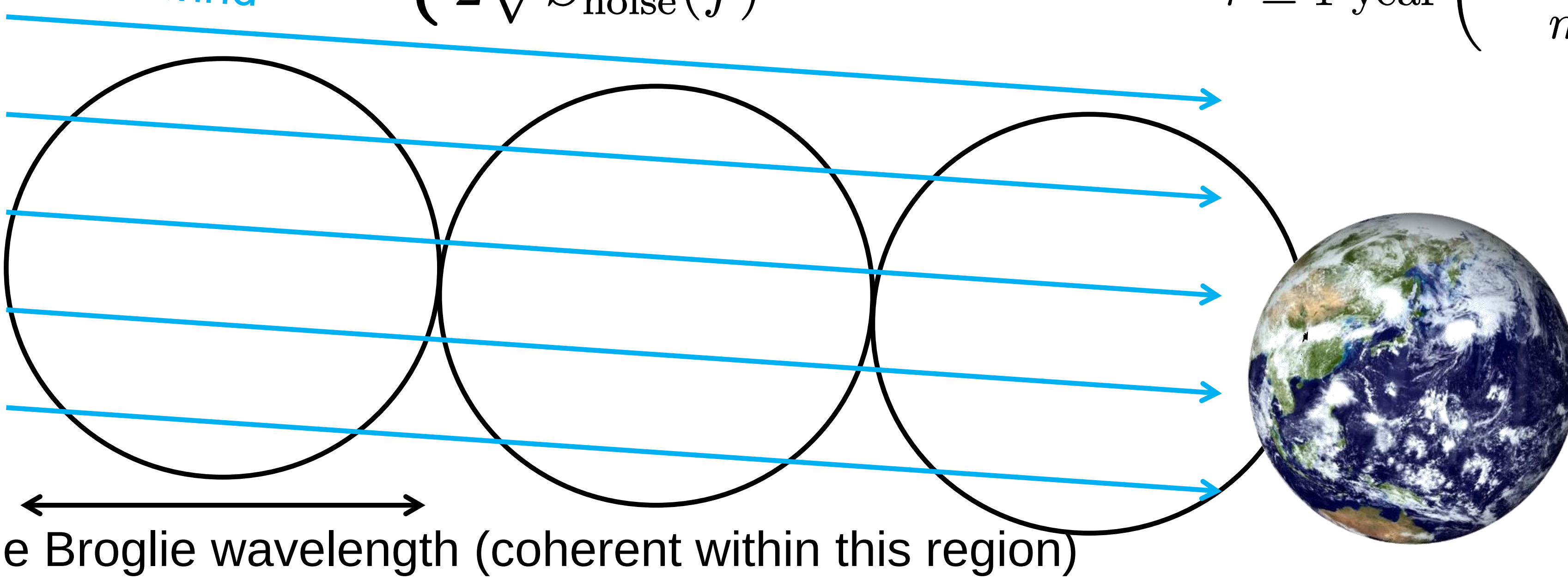
S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata, arXiv:2011.03589

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