Amaldi 15 @ Online

July 19, 2023

Ultralight dark matter searches with laser interferometry

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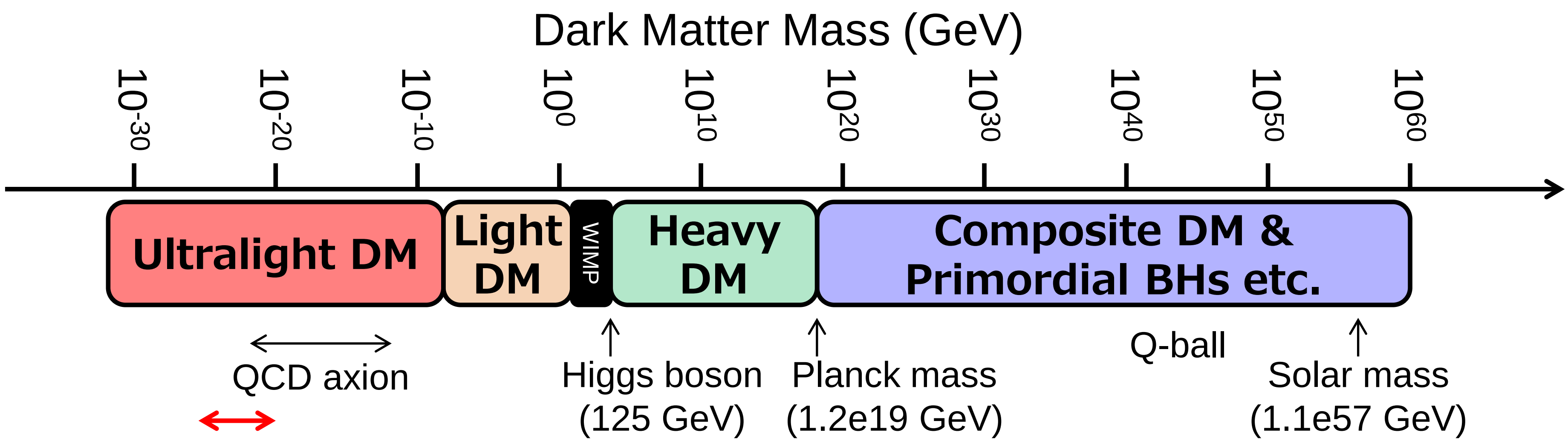
Dark Matter Mystery

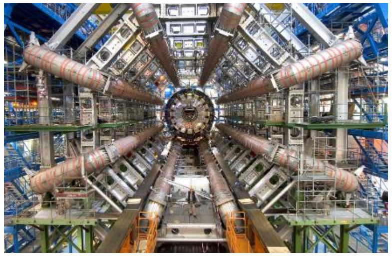
- Accounts for ~80% of all the matter of the universe
- Searches focused on WIMPs, but not detected yet
- Motivates new searches for other candidates



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

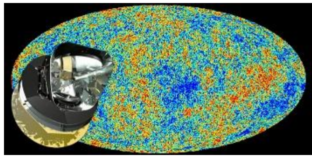
Laser Interferometry

Underground experiments (XENON1T etc.)



LHC

Subaru telescope etc.



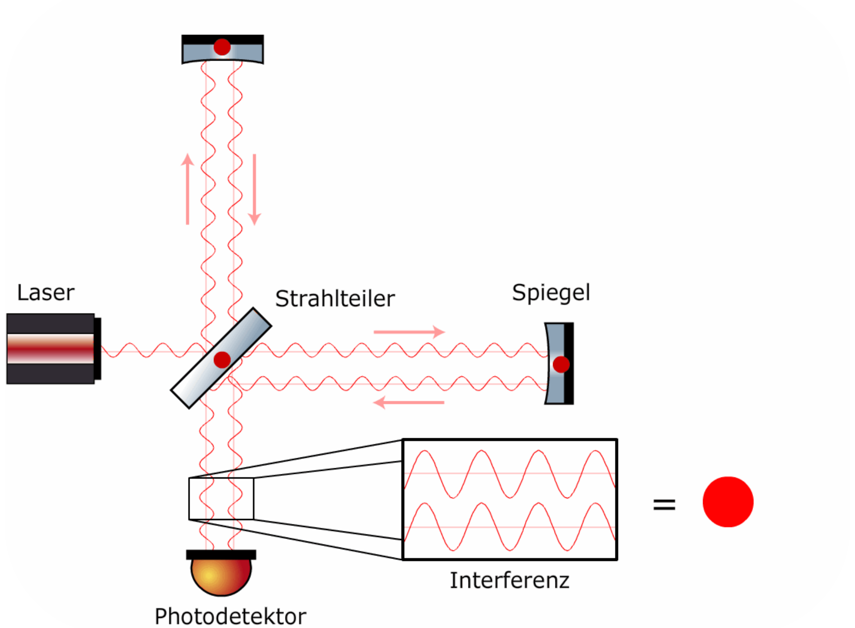
Cosmic microwave background

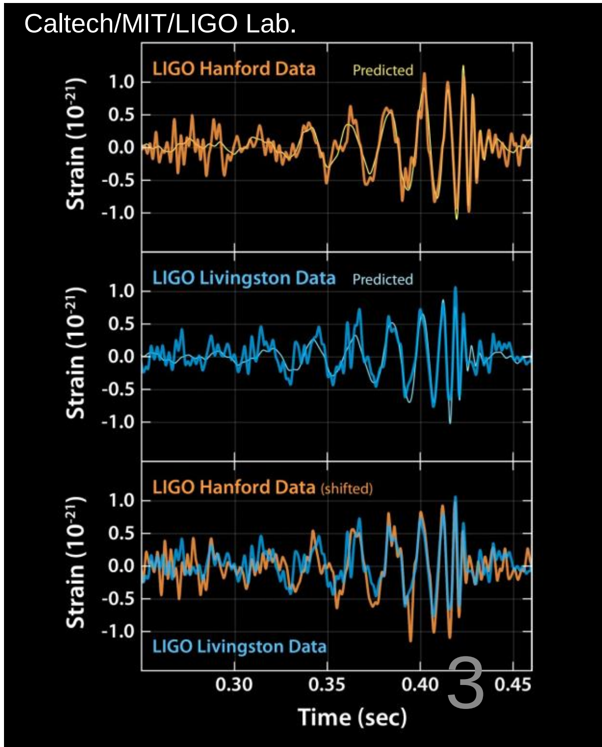
Ultralight DM with Interferometers

- 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





Sensitive to Various DM Models

Tiny forces from vector DM

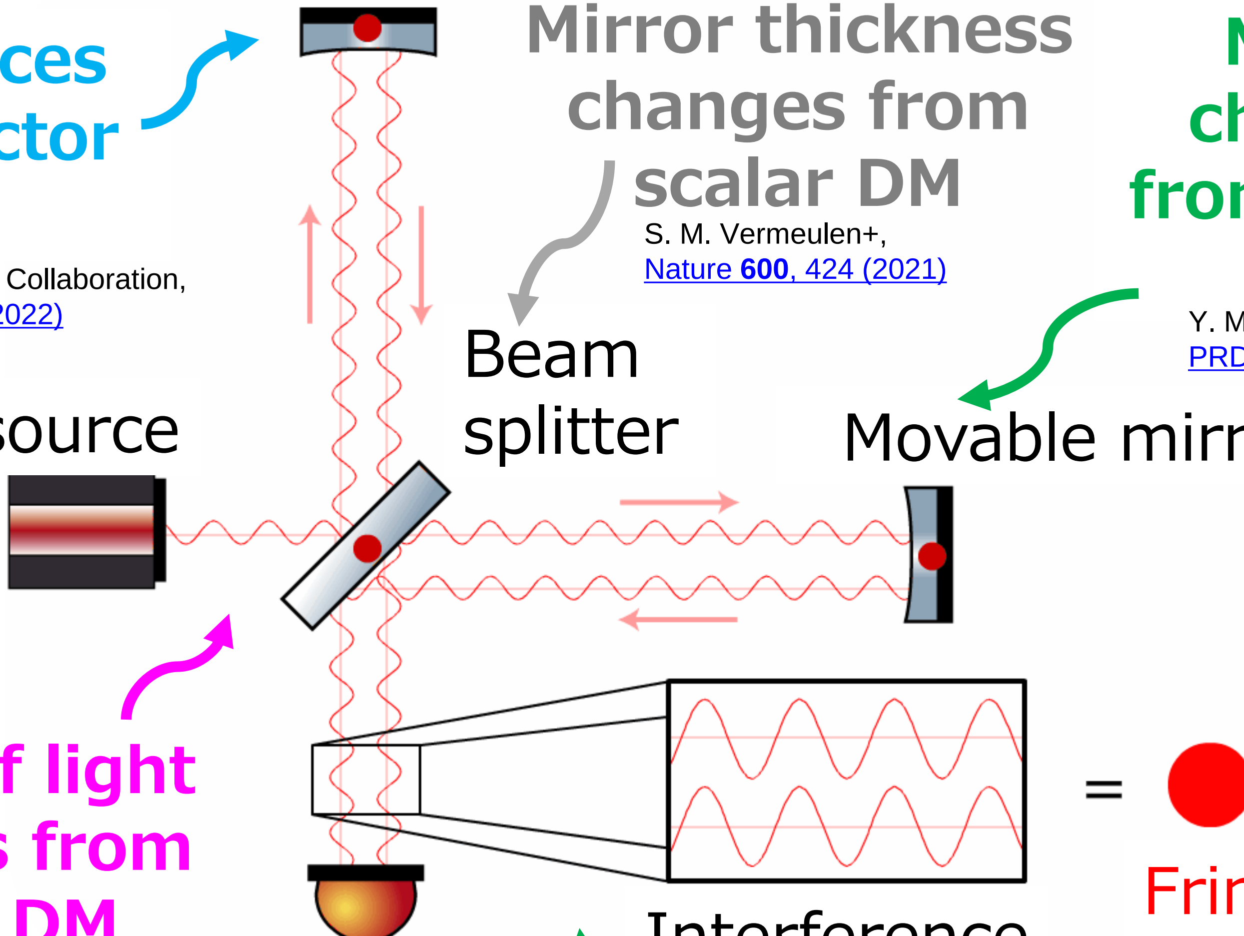
LIGO-Virgo-KAGRA Collaboration, PRD **105**, 063030 (2022)

Mirror thickness changes from scalar DM

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

Metric changes from spin-2 DM

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



Speed of light changes from axion DM

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

Gravitational waves

Sensitive to Various DM Models

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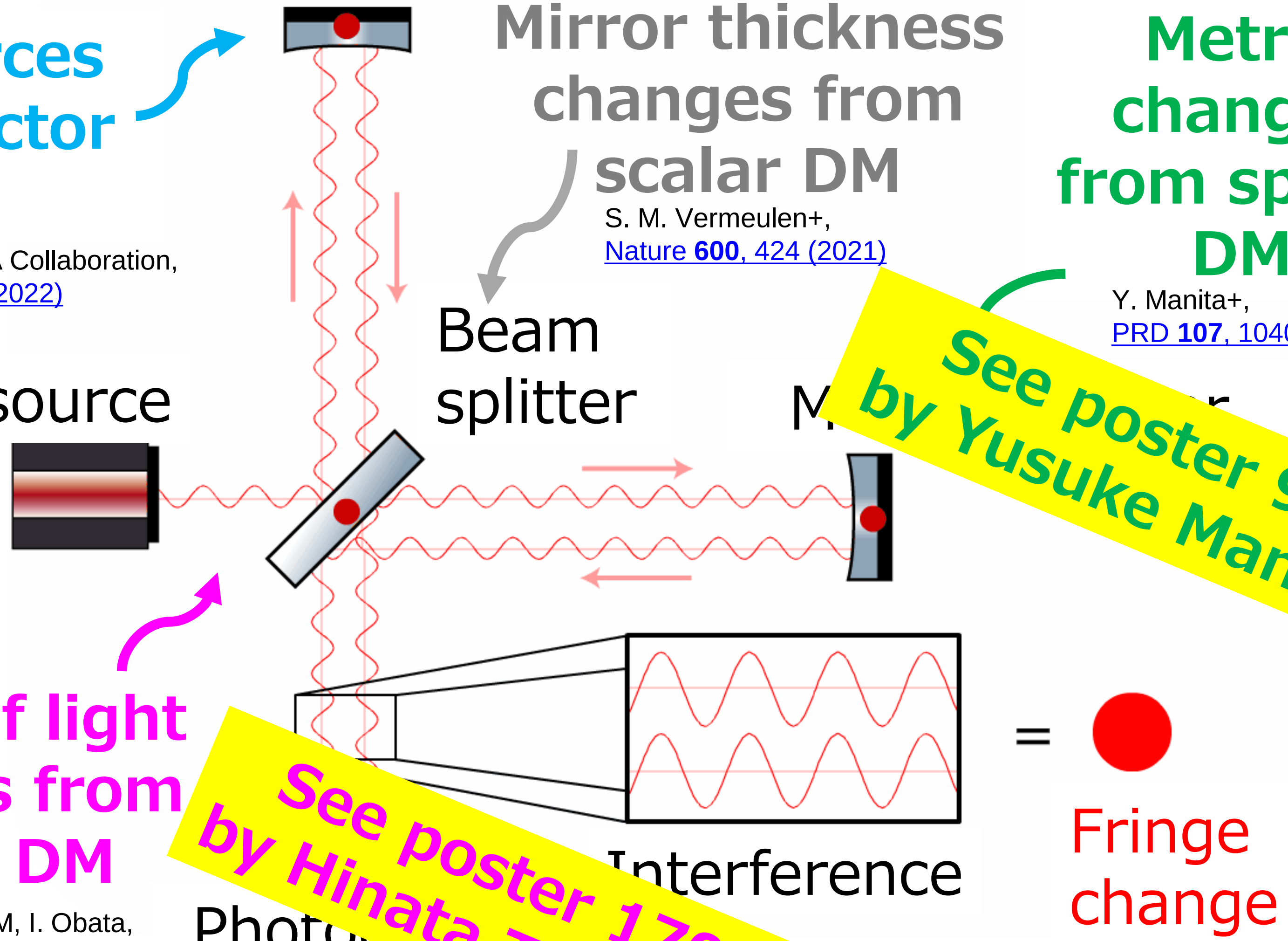
See poster 98 by Yusuke Manita



Speed of light changes from axion DM

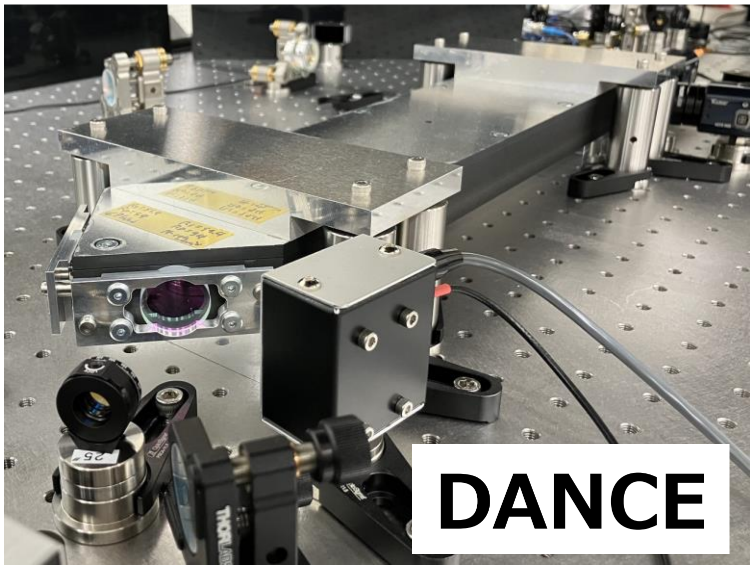
K. Nagano, T. Fujita, YM, I. Obata, PRL **123**, 111301 (2019)

See poster 170 by Hinata Takidera

Gravitational waves

Our DM Search Projects

- 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)

PRD **104**, 062008 (2021)

\+ **Polarization measurement**

PRD **102**, 102001 (2020)

PRD **103**, L051702 (2021)

Ultralight DM

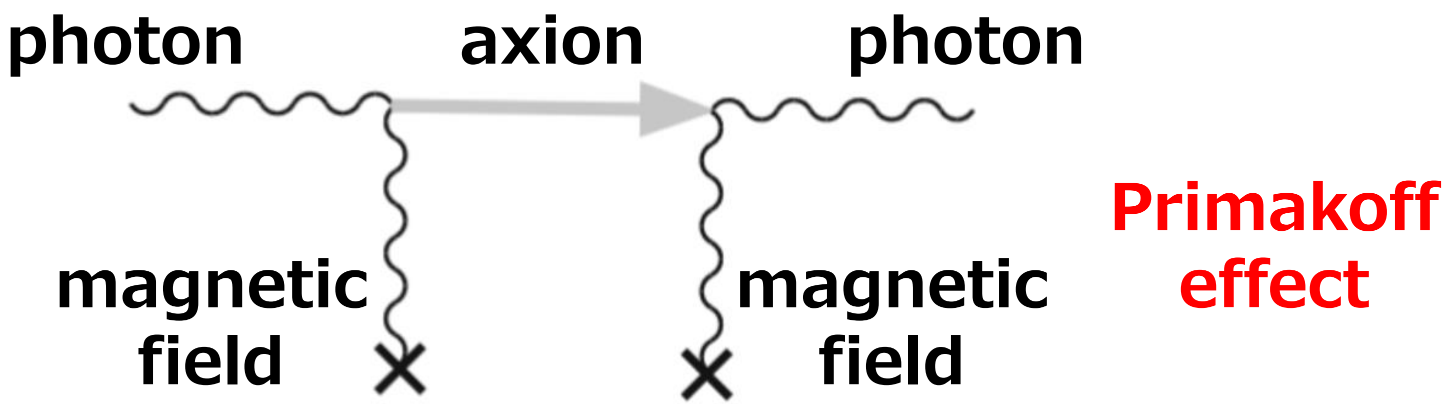
Axion like particles

Vector 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



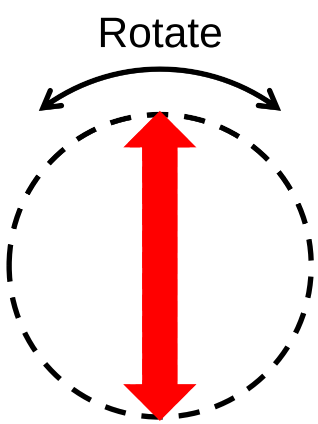
Polarization Modulation from Axions

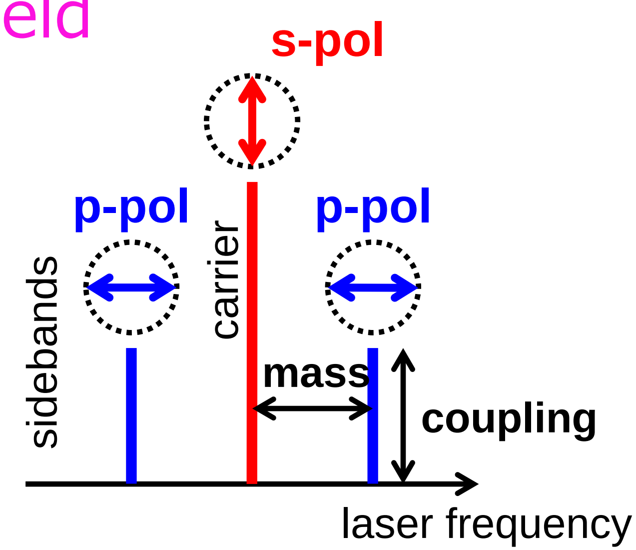
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

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

coupling constant axion field axion mass

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

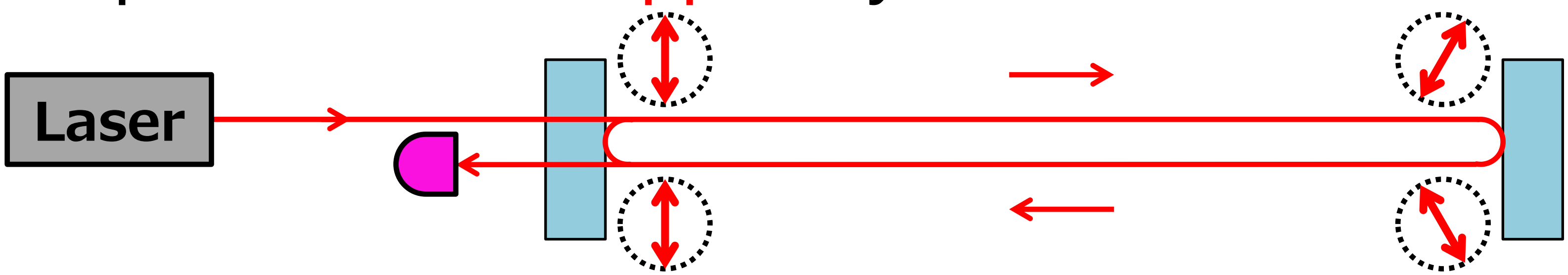




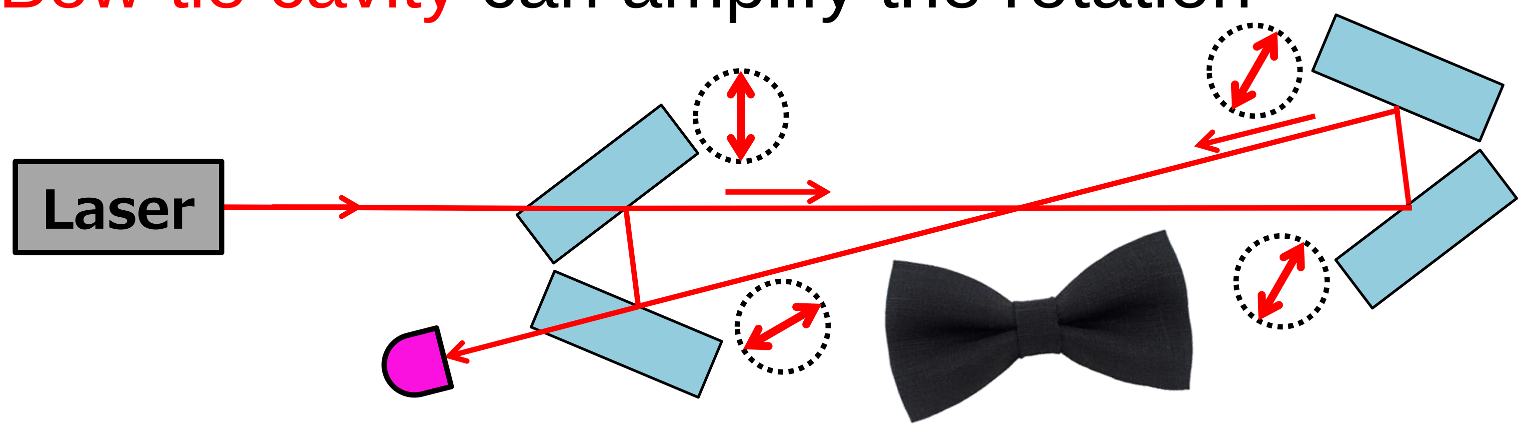
Optical Cavity to Amplify the Signal

- Polarization rotation is small for short optical path

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



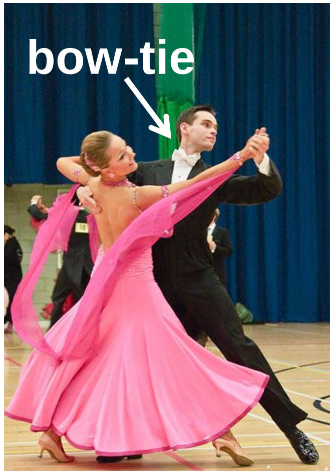
- Bow-tie cavity can amplify the rotation

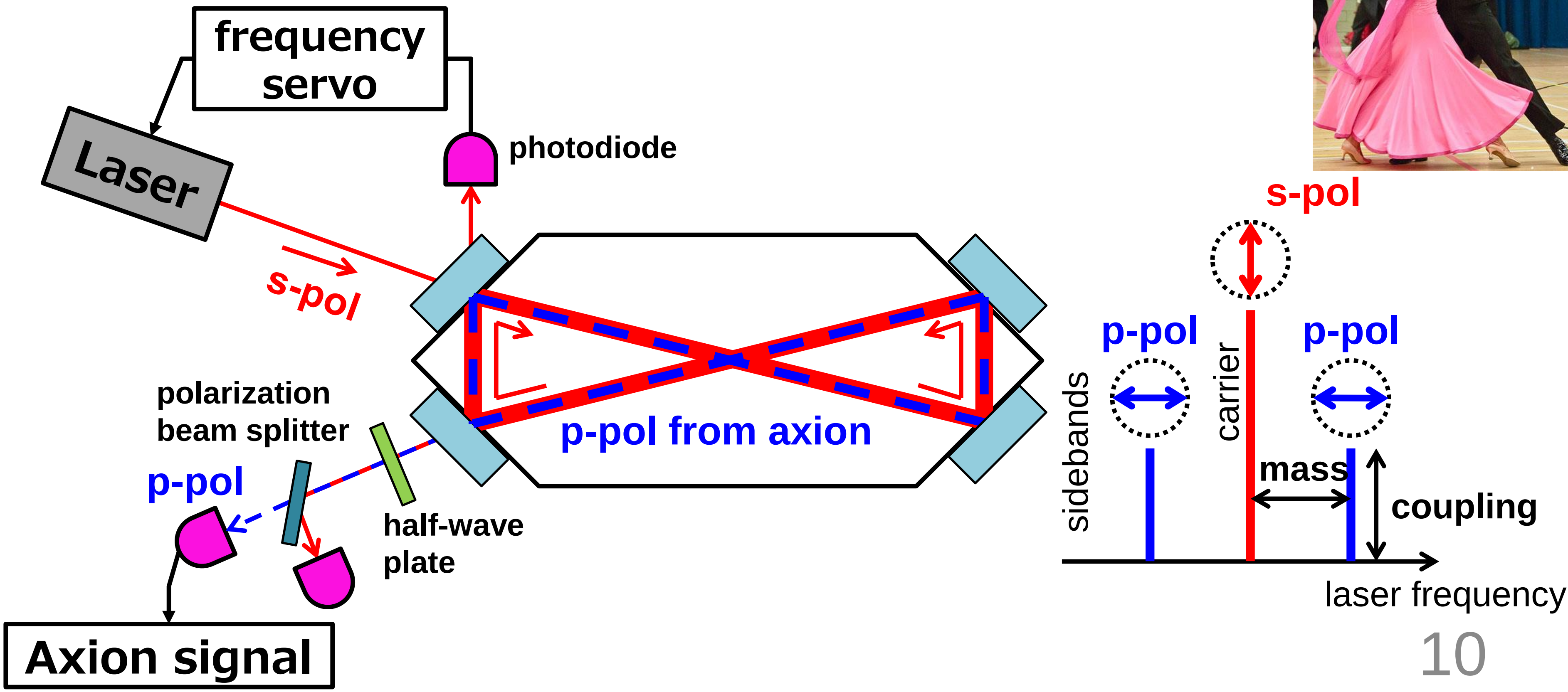


DANCE Setup

Dark matter Axion search with riNg Cavity Experiment

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

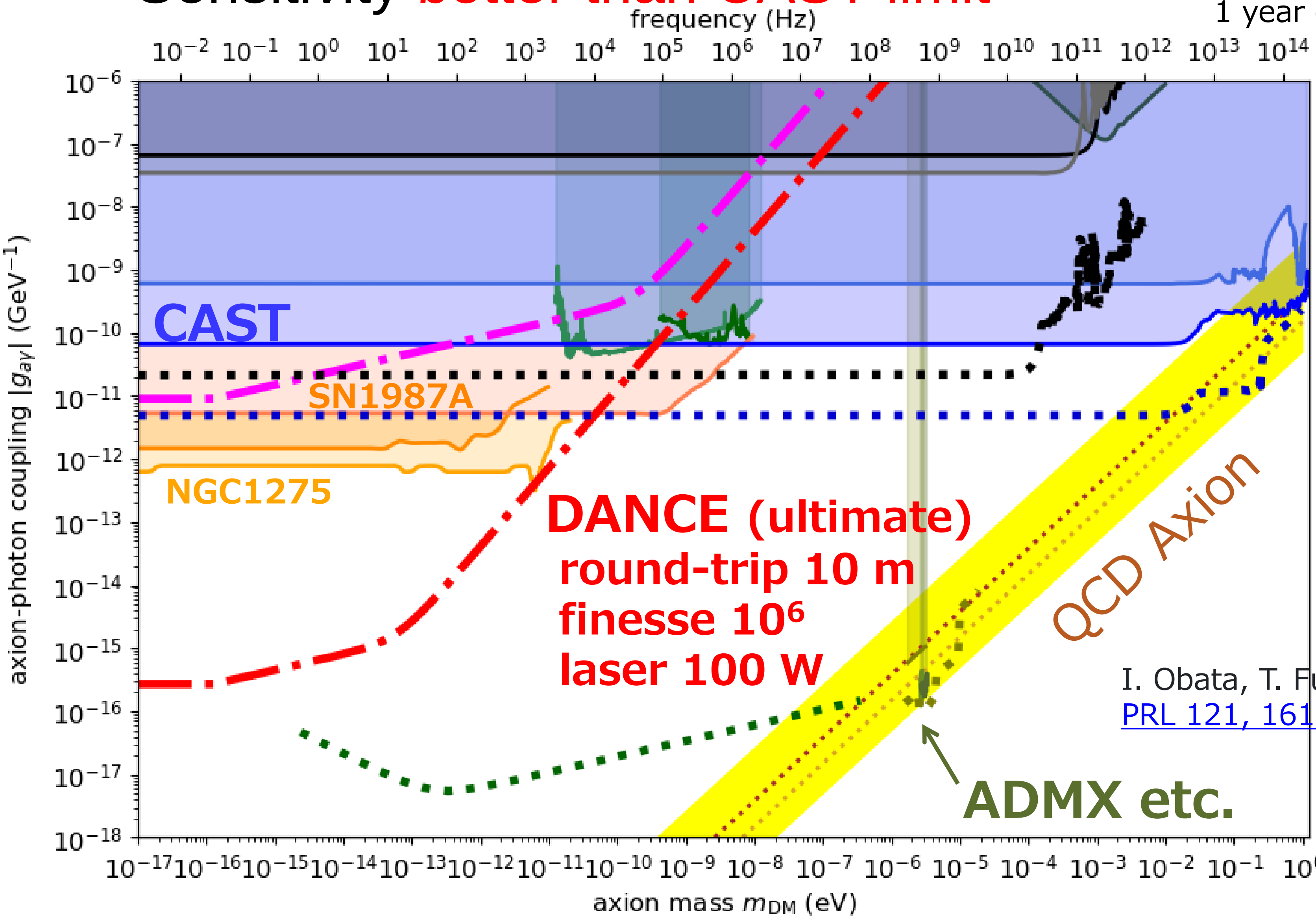




Sensitivity of DANCE

- Sensitivity better than CAST limit

* Shot noise limited
1 year observation



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

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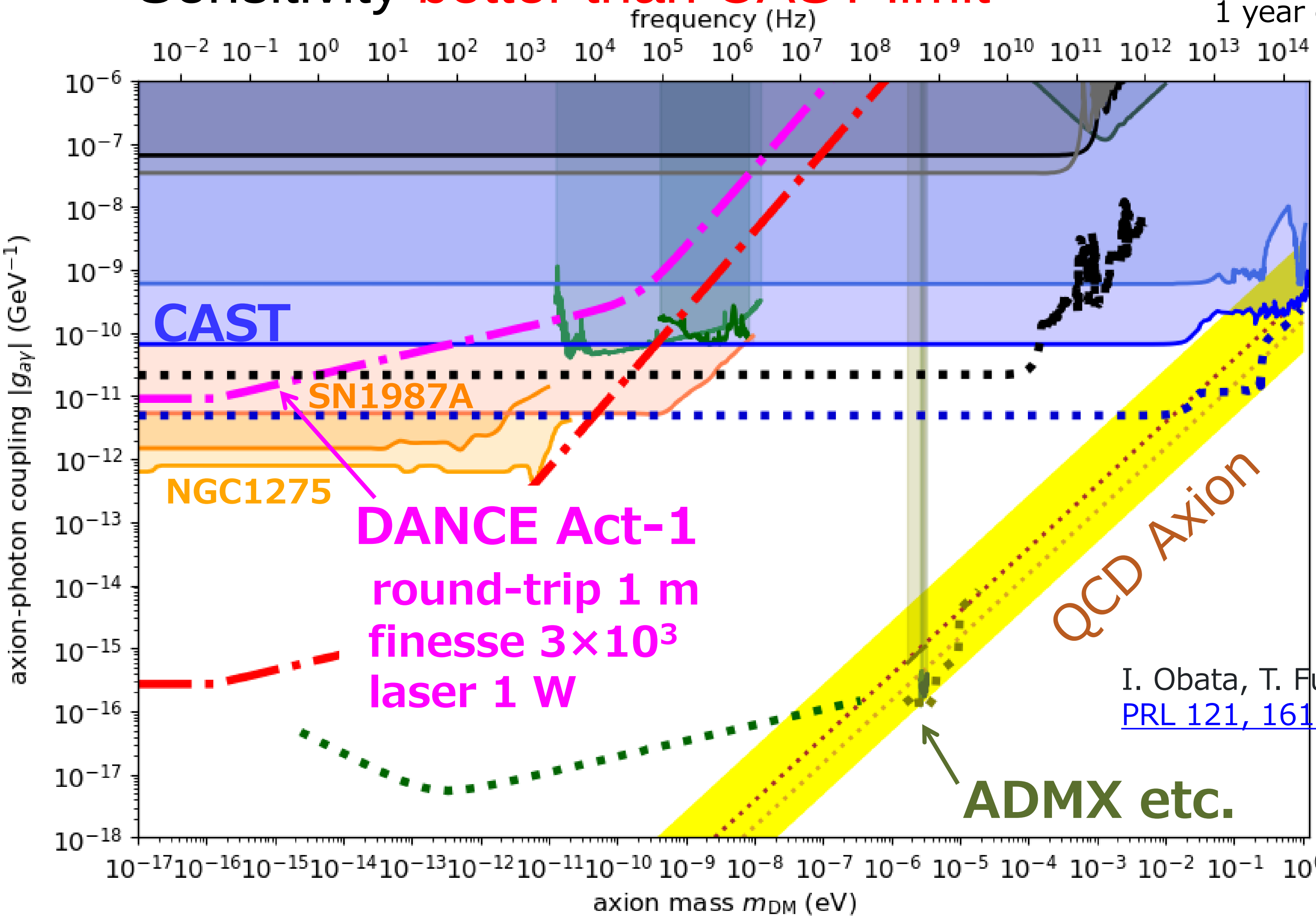
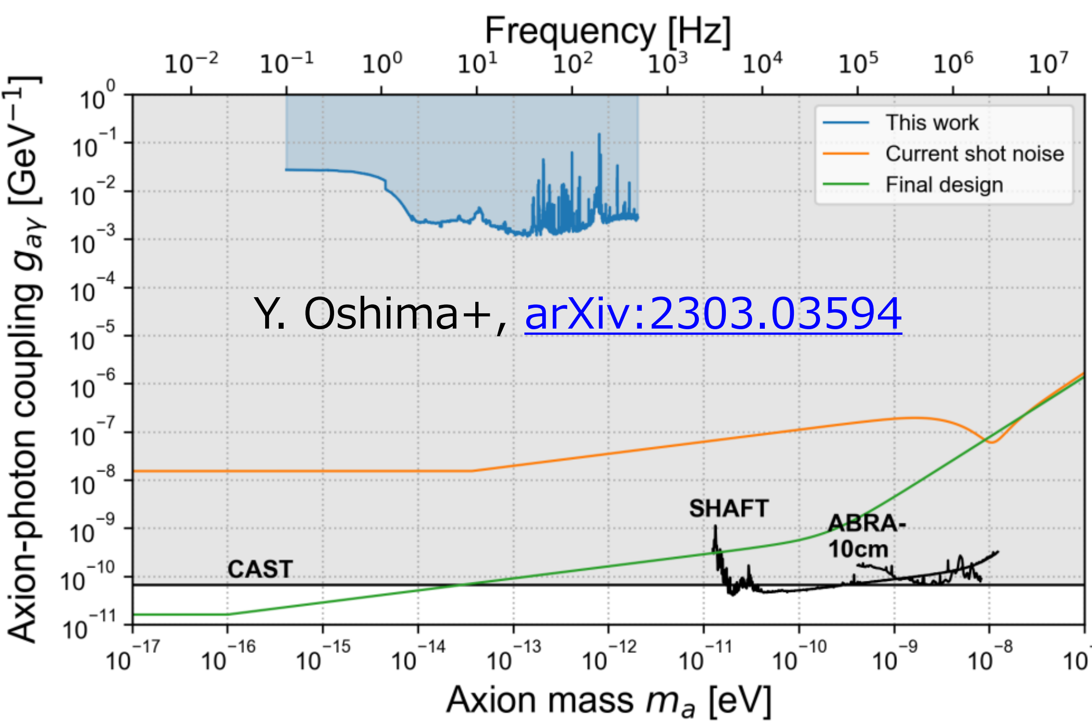
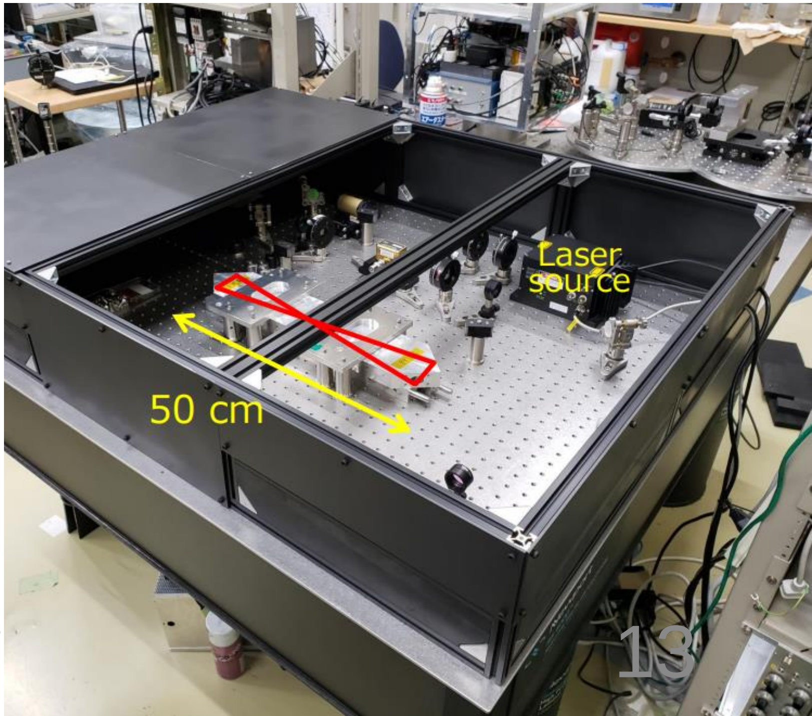


I. Obata, T. Fujita, YM, PRL 121, 161301 (2018)

First Observing Run in May 2021

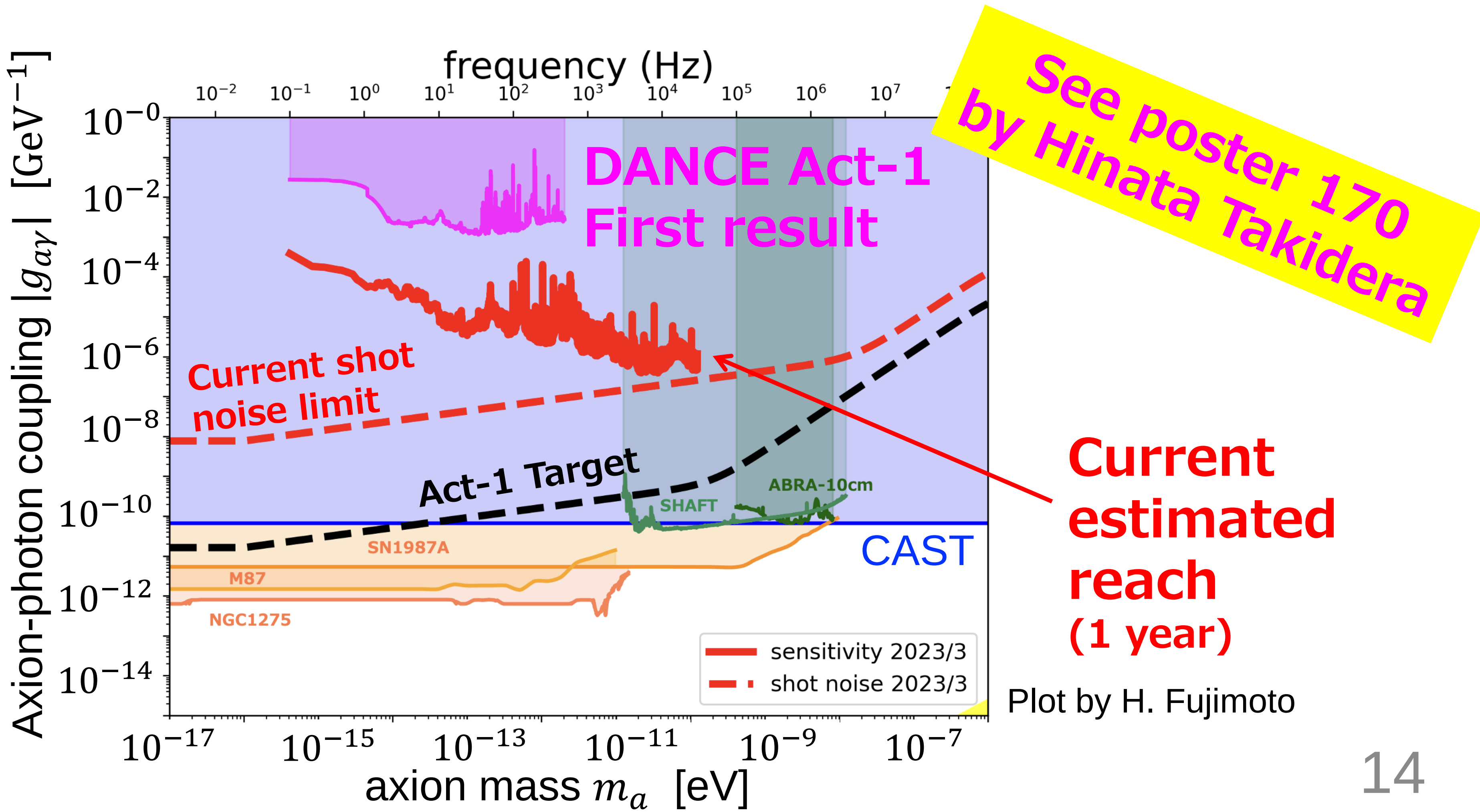
- First 12-day run was performed
- Used 24-hour data to put an upper limit
- Demonstrated the principle and the data analysis methods (Analysis methods presented in H. Nakatsuka+, arXiv:2205.02960)





Upgrade Underway

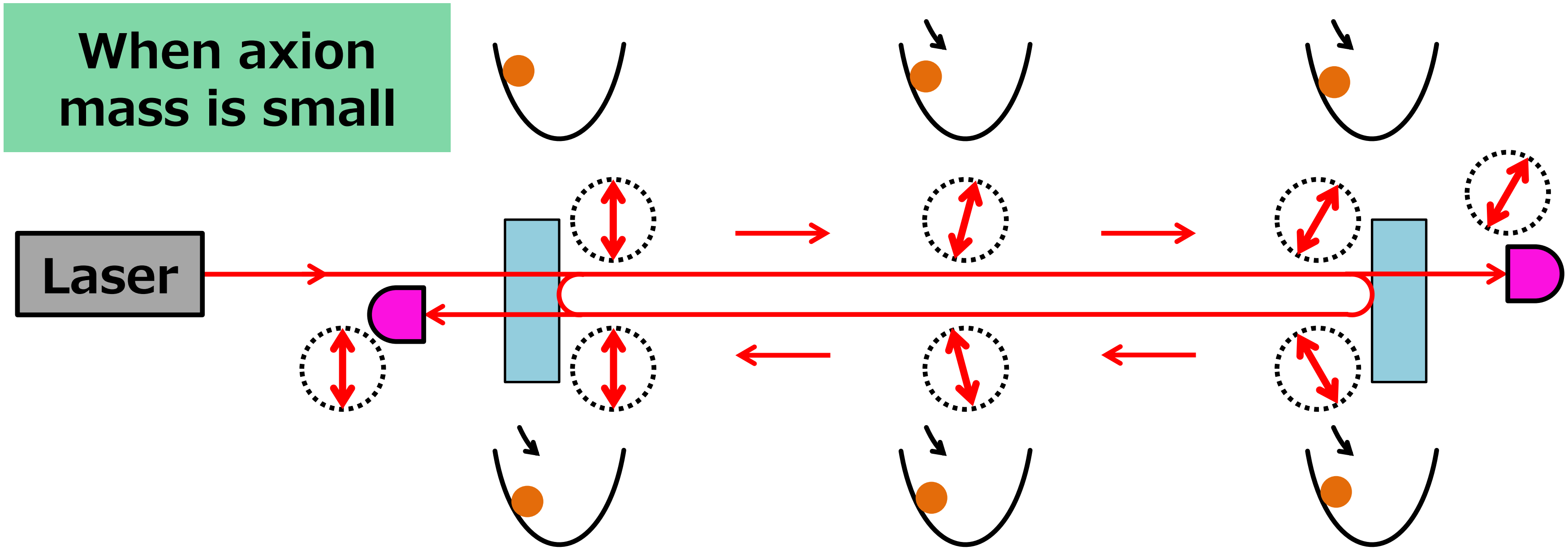
- Aiming for broadband sensitivity improvement by co-resonating both polarizations



Plot by H. Fujimoto

Linear Cavities for Axion Search

- Polarization flip at mirror reflection can be used to enhance the signal when the round-trip time equals odd-multiples of axion oscillation period
- Long baseline linear cavities in gravitational wave detectors are suitable



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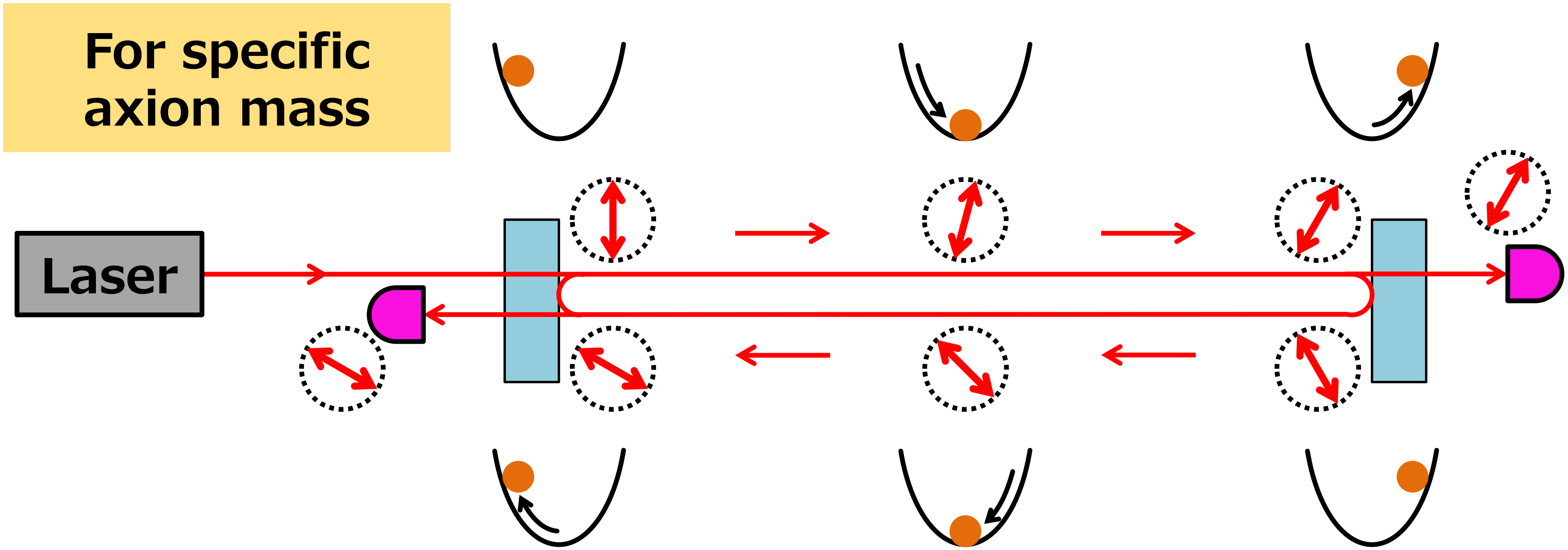
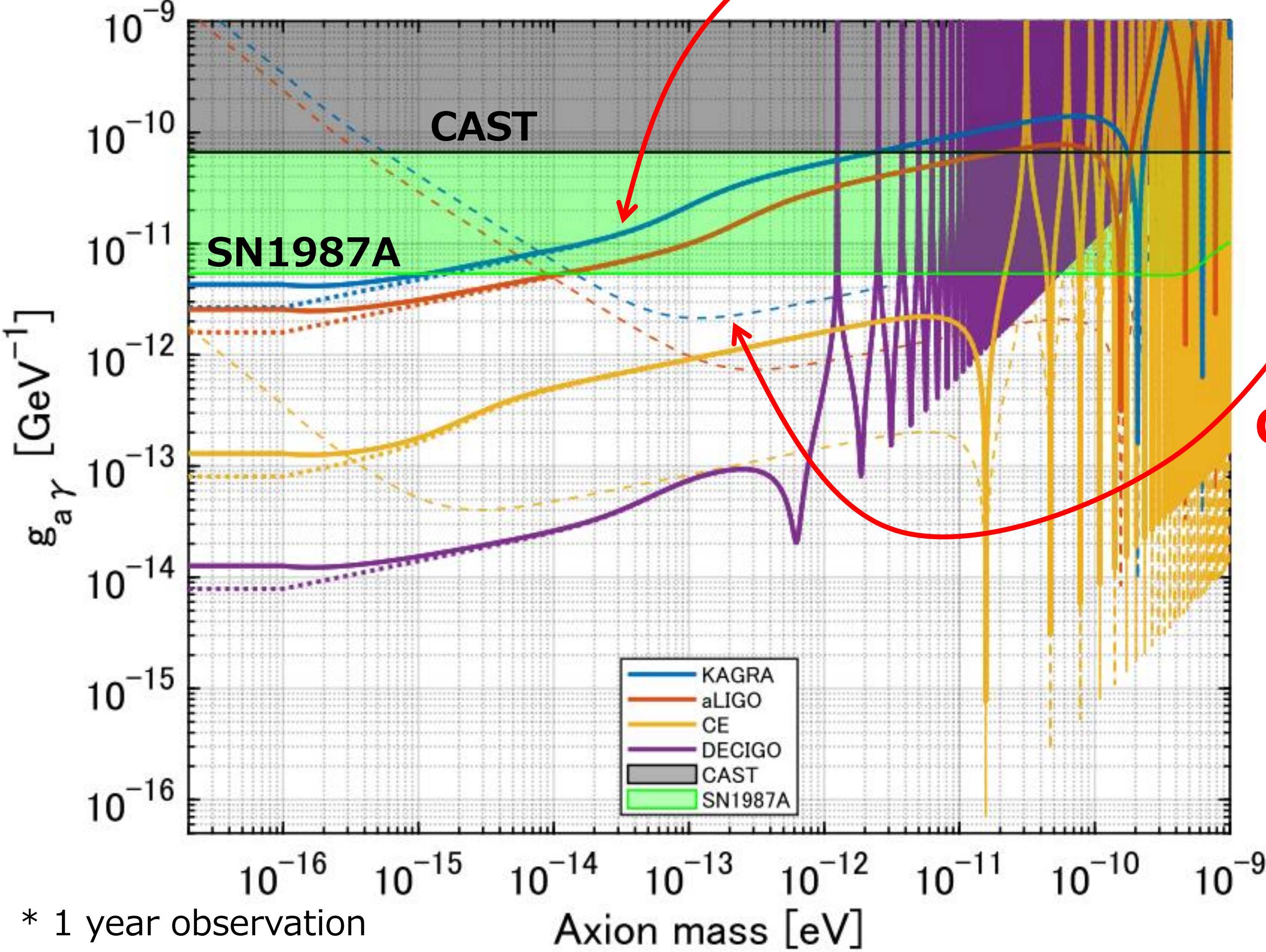
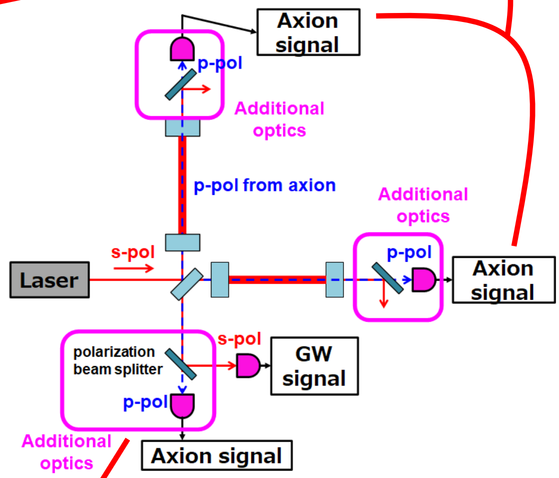


Axion Sensitivity

Arm cavity transmission ports





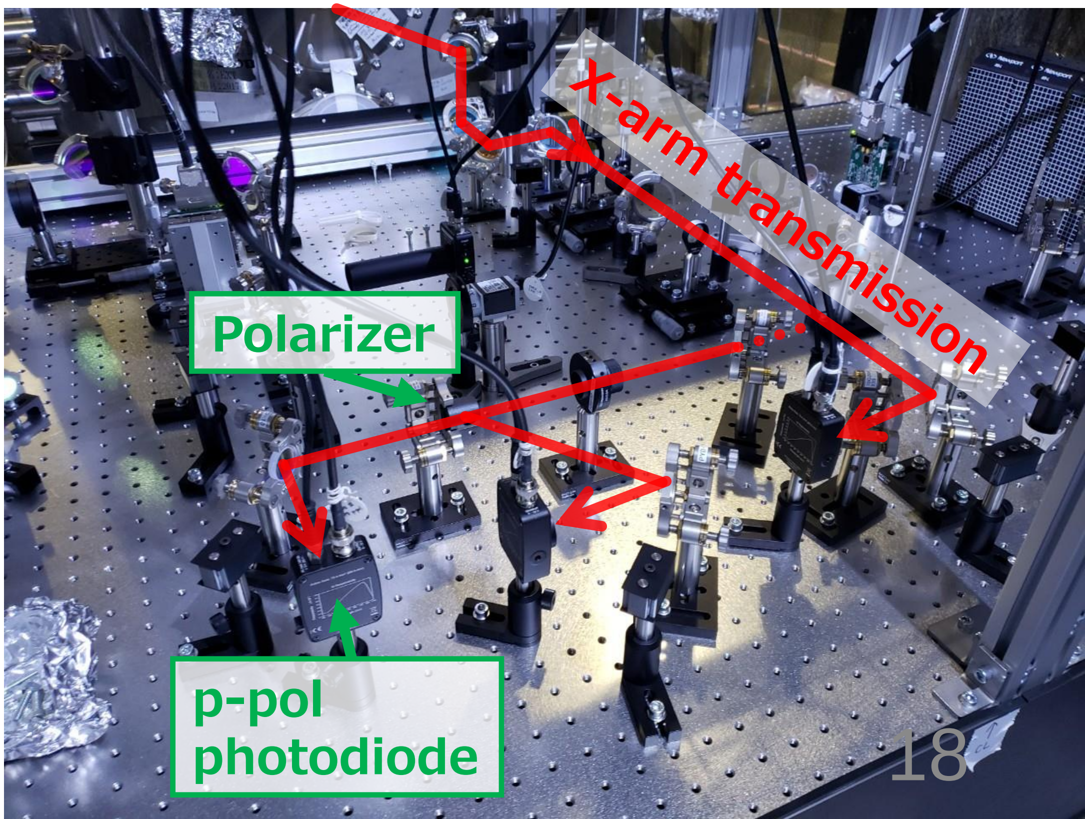
GW detection port

K. Nagano, T. Fujita, YM, I. Obata
PRL **123**, 111301 (2019)
K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita, YM, I. Obata
PRD **104**, 062008 (2021)

* 1 year observation

Optics for Axion Search Installed

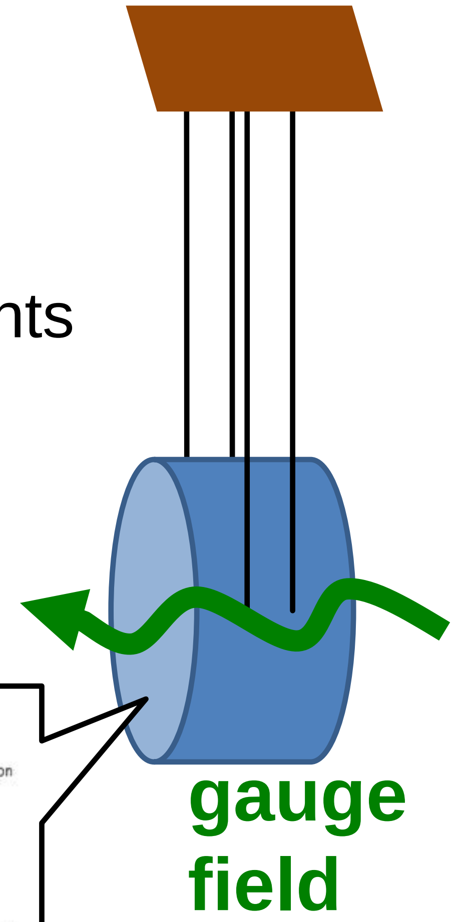
- For KAGRA, polarization optics were installed for X-arm transmission in July 2021 and Y-arm transmission in December 2021
  - Data to be taken during O4
- For LIGO, auxiliary port of output Faraday isolator can be used (calibration method needs to be developed)

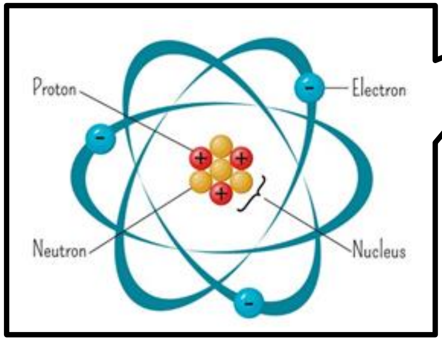


klog #17692

Gauge Boson

- 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)

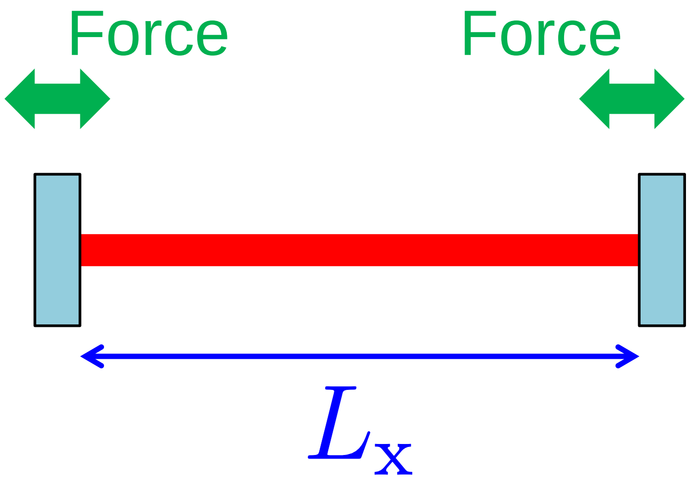
mirror mass

DM density

polarization

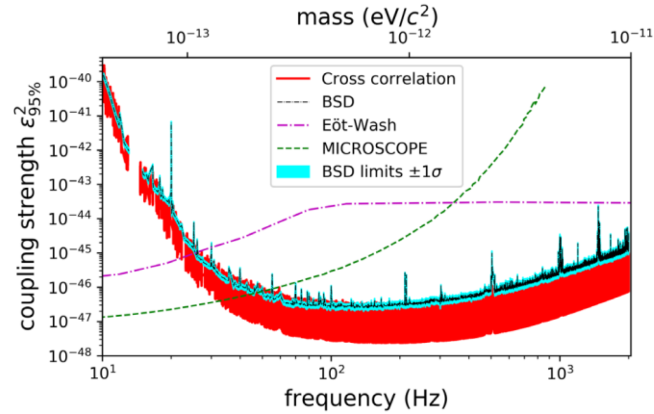
different phase at different position

- 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

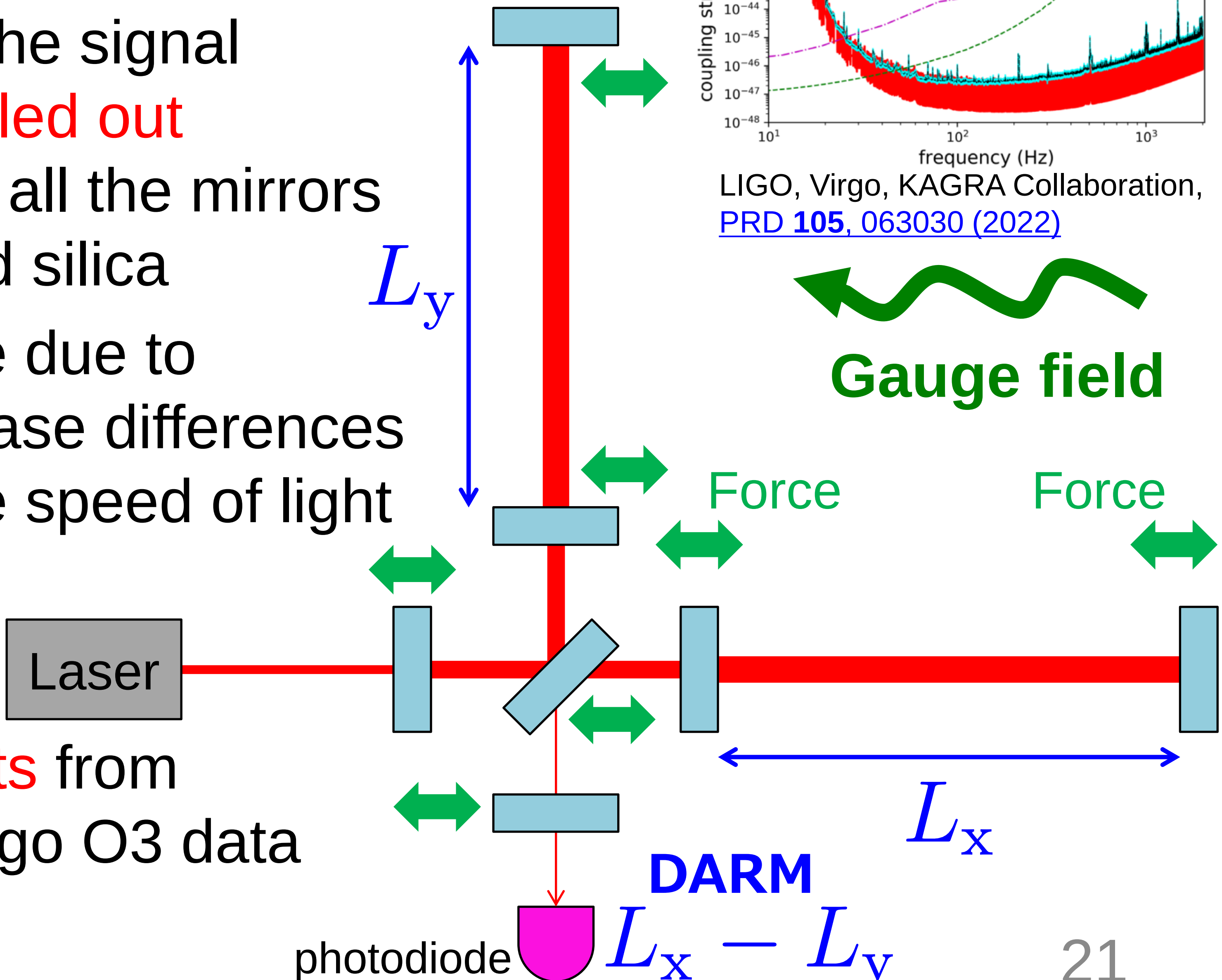


Search with LIGO/Virgo

- Most of the signal is cancelled out because all the mirrors are fused silica
- Sensitive due to slight phase differences and finite speed of light



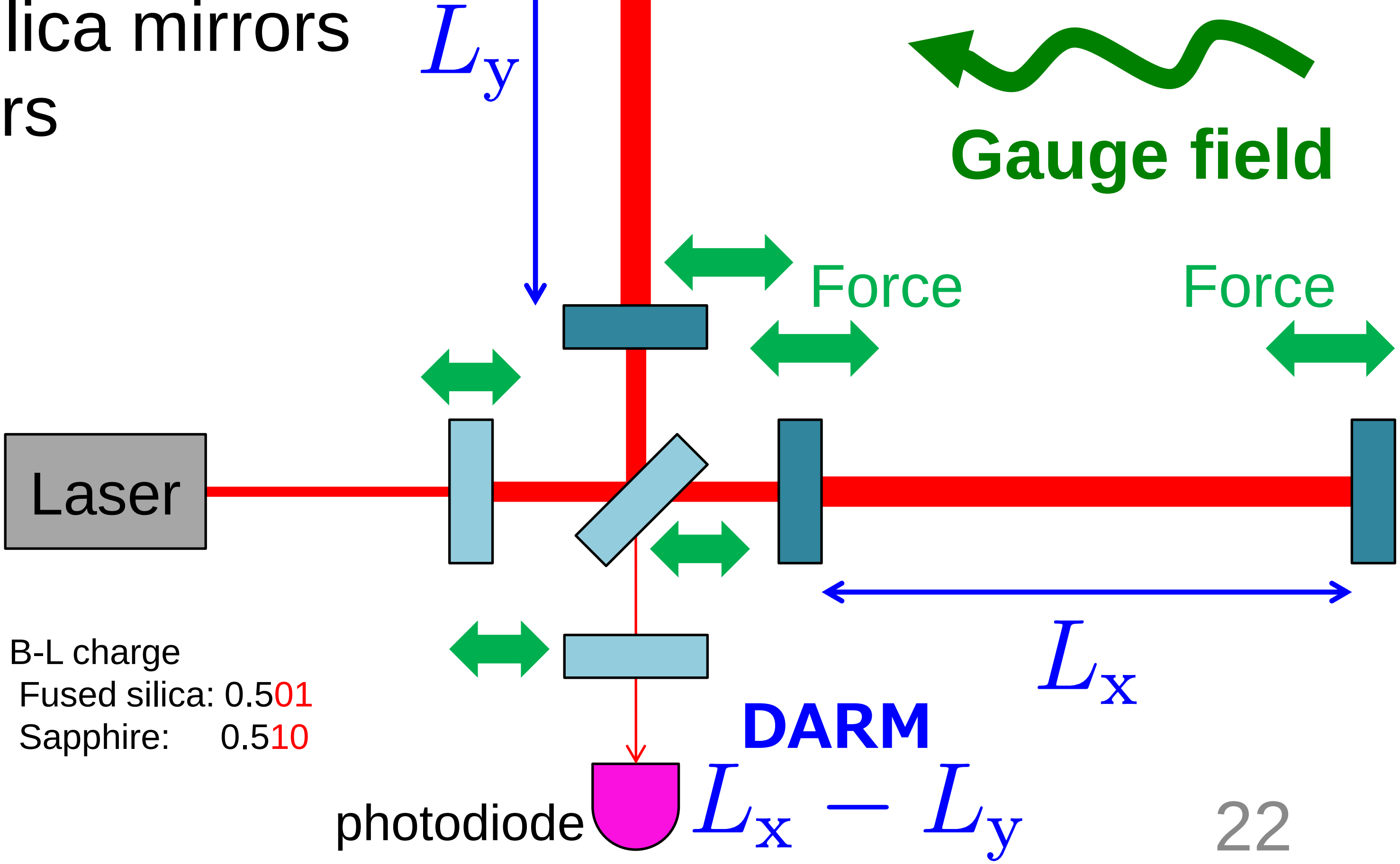
LIGO, Virgo, KAGRA Collaboration, [PRD **105**, 063030 (2022)]

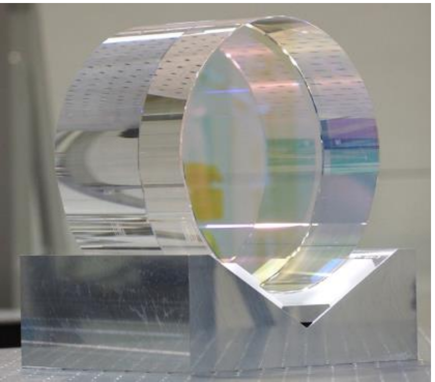


- Best limits from LIGO/Virgo O3 data

Search with KAGRA

- KAGRA uses cryogenic sapphire mirrors for arm cavities, and fused silica mirrors for others

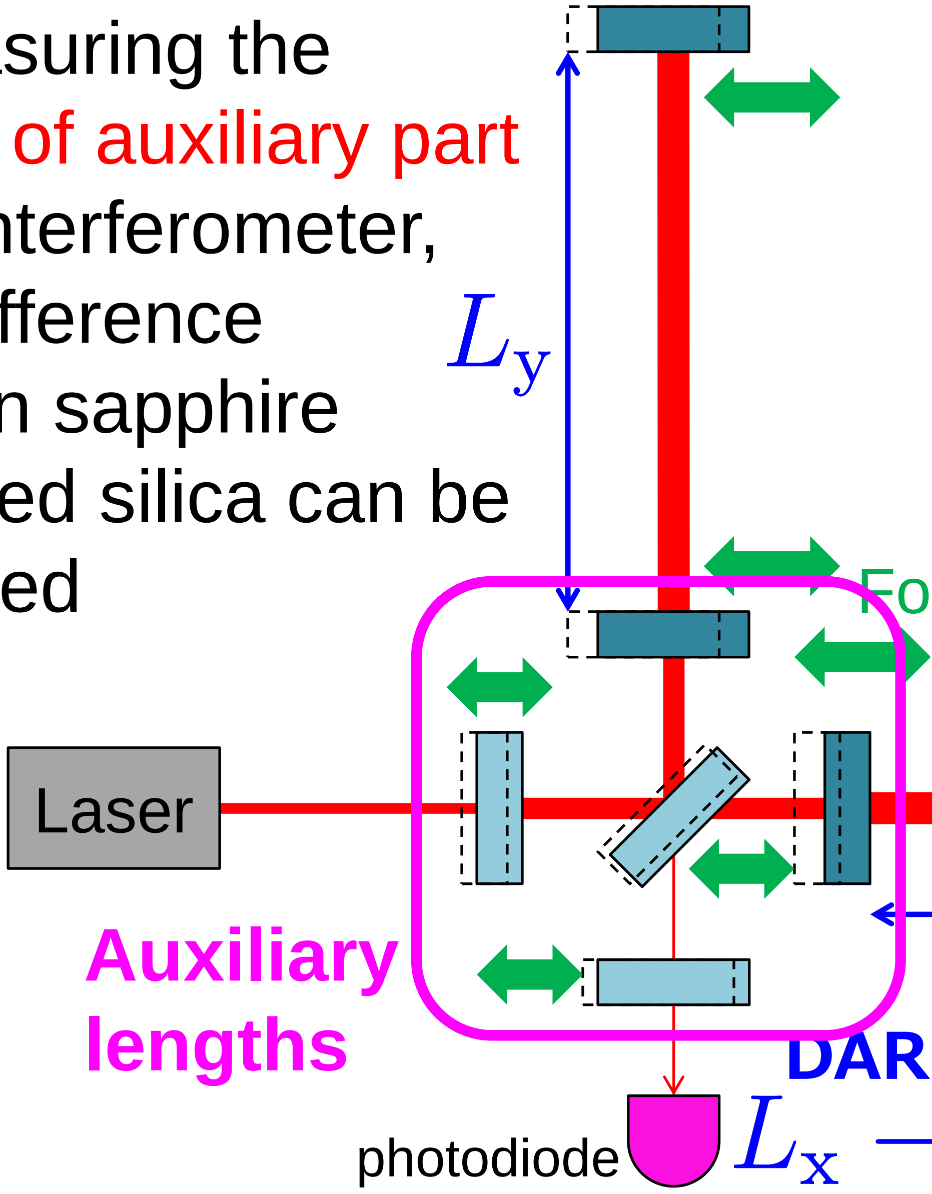




B-L charge
Fused silica: 0.501
Sapphire: 0.510

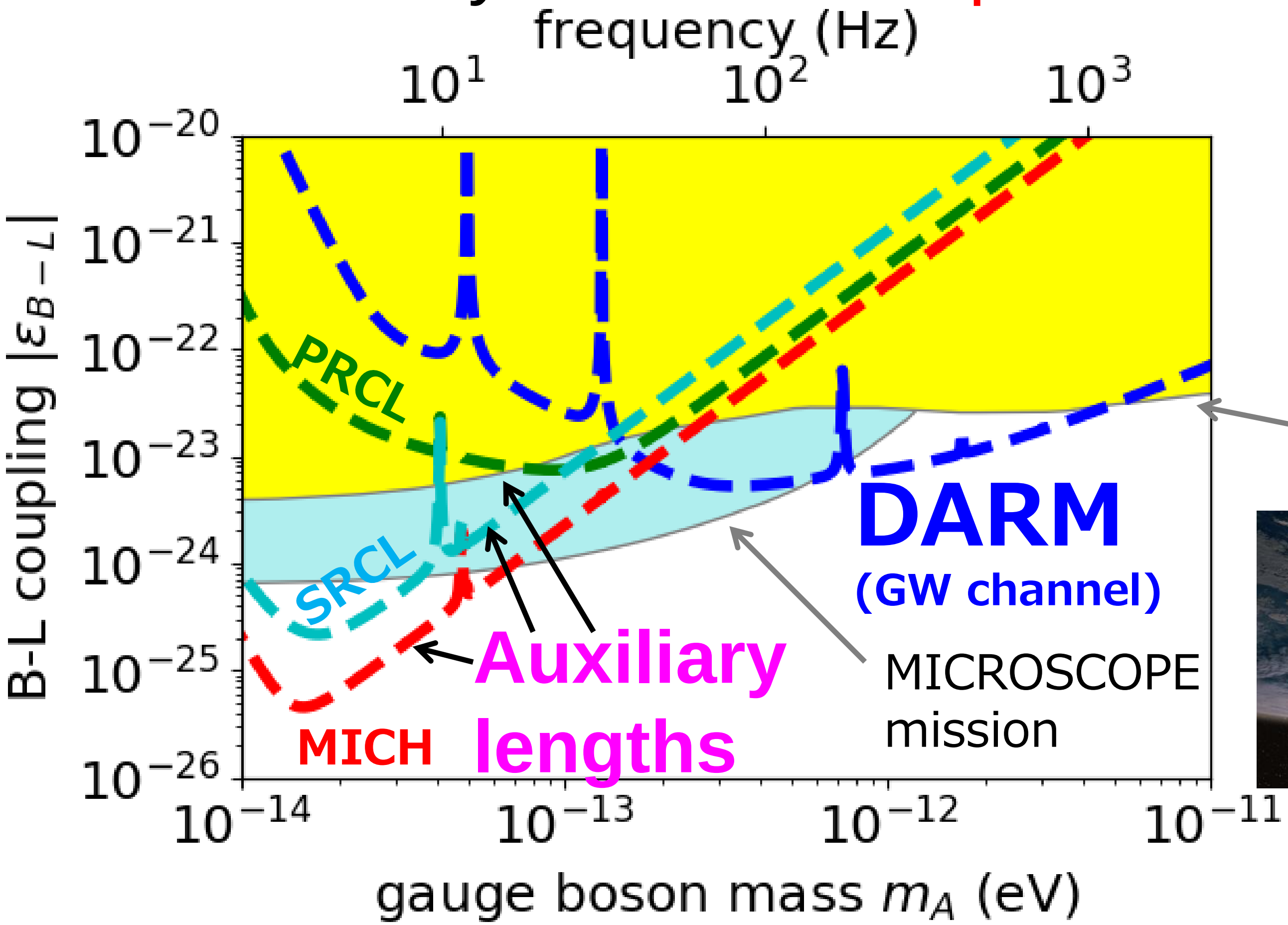
Search with KAGRA

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



KAGRA Gauge Boson Sensitivity

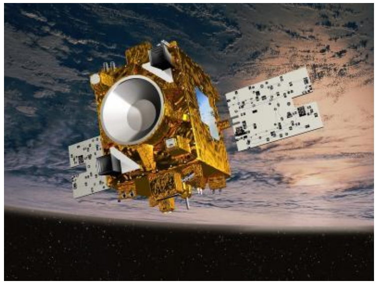
- Auxiliary length channels have better design sensitivity than DARM (GW channel) at low mass range
- Sensitivity better than equivalence principle tests



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

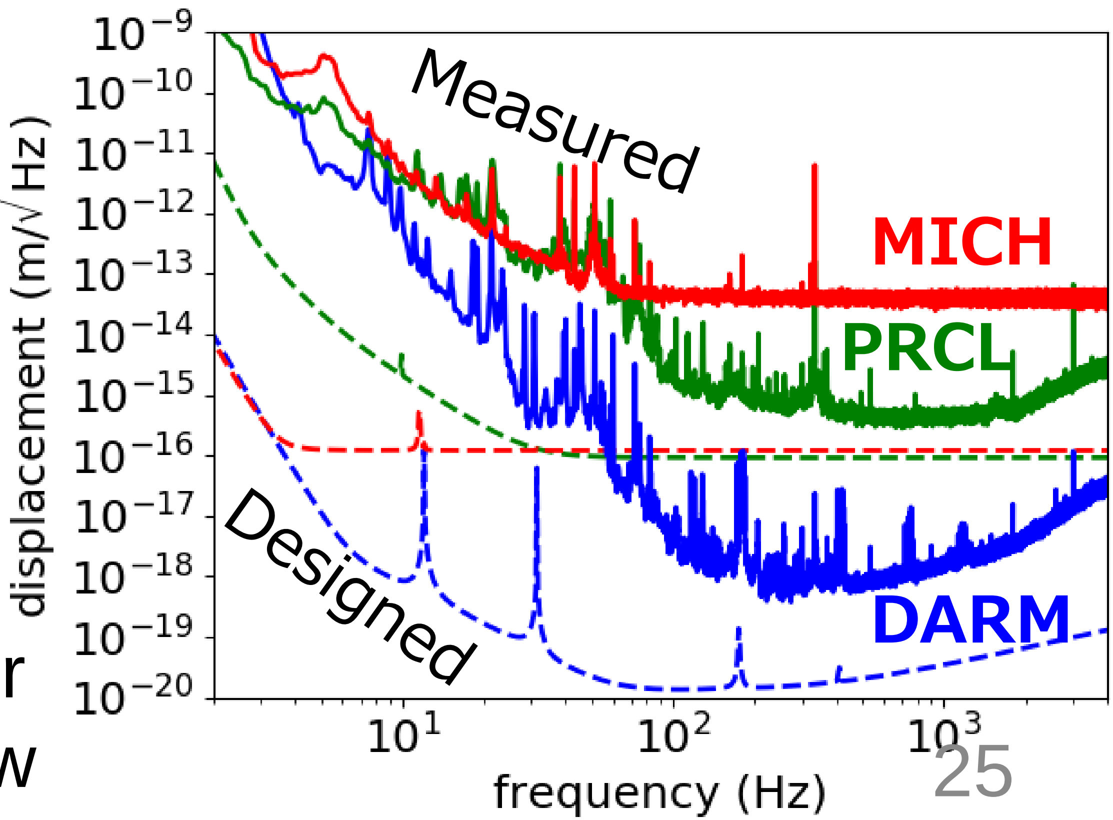
S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata, PRD 103, L051702 (2021)

Eöt-Wash torsion pendulum



KAGRA 2020 Data Analysis

- KAGRA performed joint observing run in April 2020 with GEO600 (O3GK)
- Displacement sensitivity still not good
  ~ 6 orders of magnitude to go at 10 Hz
- Data analysis underway using the same pipeline used for DANCE
  H. Nakatsuka+, [arXiv:2205.02960]
- Results will be available summer 2023 after LVK internal review



Summary

- Laser interferometers open up new possibilities for dark matter search
- **Axion DM search with DANCE**
  - First result from 24-hour data reported
  - Upgrade underway
- **Axion DM search with LIGO-Virgo-KAGRA**
  - Polarization optics installed in KAGRA and LIGO
  - First search to be done with O4 data
- **Vector DM search with LIGO-Virgo-KAGRA**
  - Most stringent bound obtained from LIGO-Virgo
  - New search using sapphire mirrors of KAGRA underway

科研費 KAKENHI

Japan Science and Technology Agency

ダークマターの正体は何か？
広大なディスカバリースペースの網羅的研究
文部科学省 科学研究費助成事業 学術変革領域研究 (2020–2024)
What is dark matter? - Comprehensive study of the huge discovery space in dark matter

PRESTO SAKIGAKE

公益財団法人 住友財団
The Sumitomo Foundation

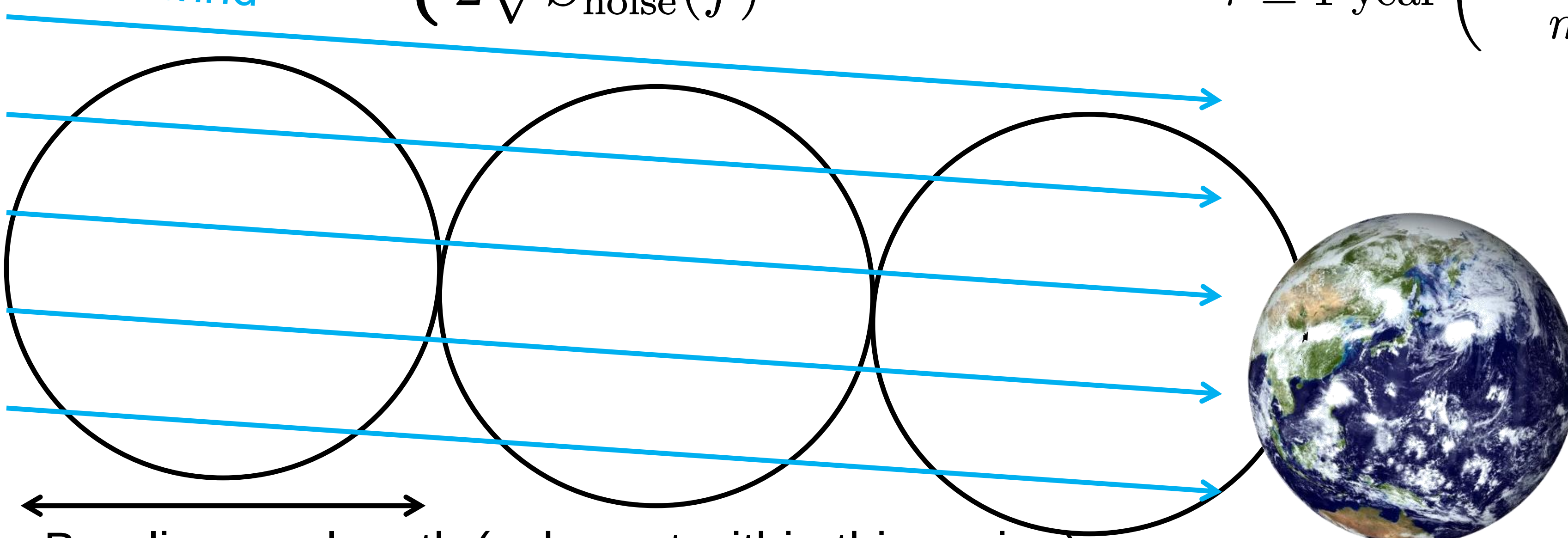
Additional Slides

Coherence Time

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

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

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



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