Ultralight dark matter searches with KAGRA gravitational wave telescope

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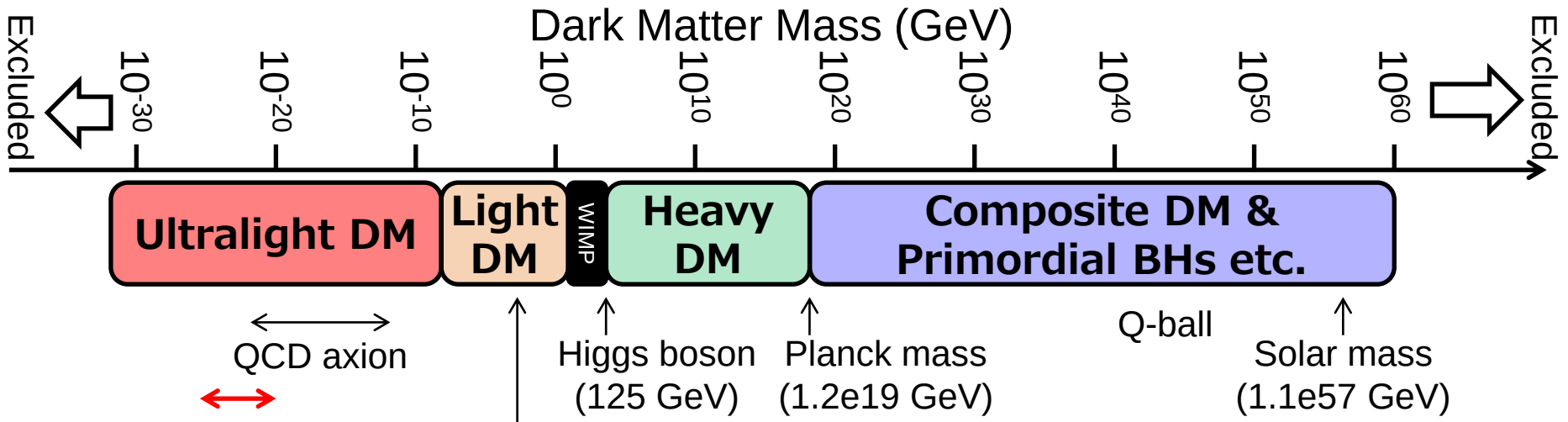
Slides are available at https://tinyurl.com/YM20210823

Ultralight Dark Matter

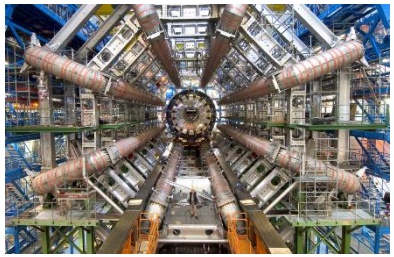
- Ultralight DM (<~1 eV) behaves as classical wave fields $f = 242\ \mathrm{Hz} \left(\frac{m_{\mathrm{DM}}}{10^{-12}\ \mathrm{eV}} \right)$

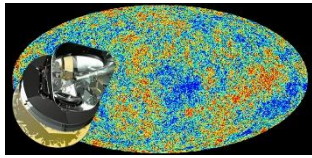


2.4 Hz ~ 2.4 kHz
(1e-14 ~ 1e-11 eV)

Laser Interferometry

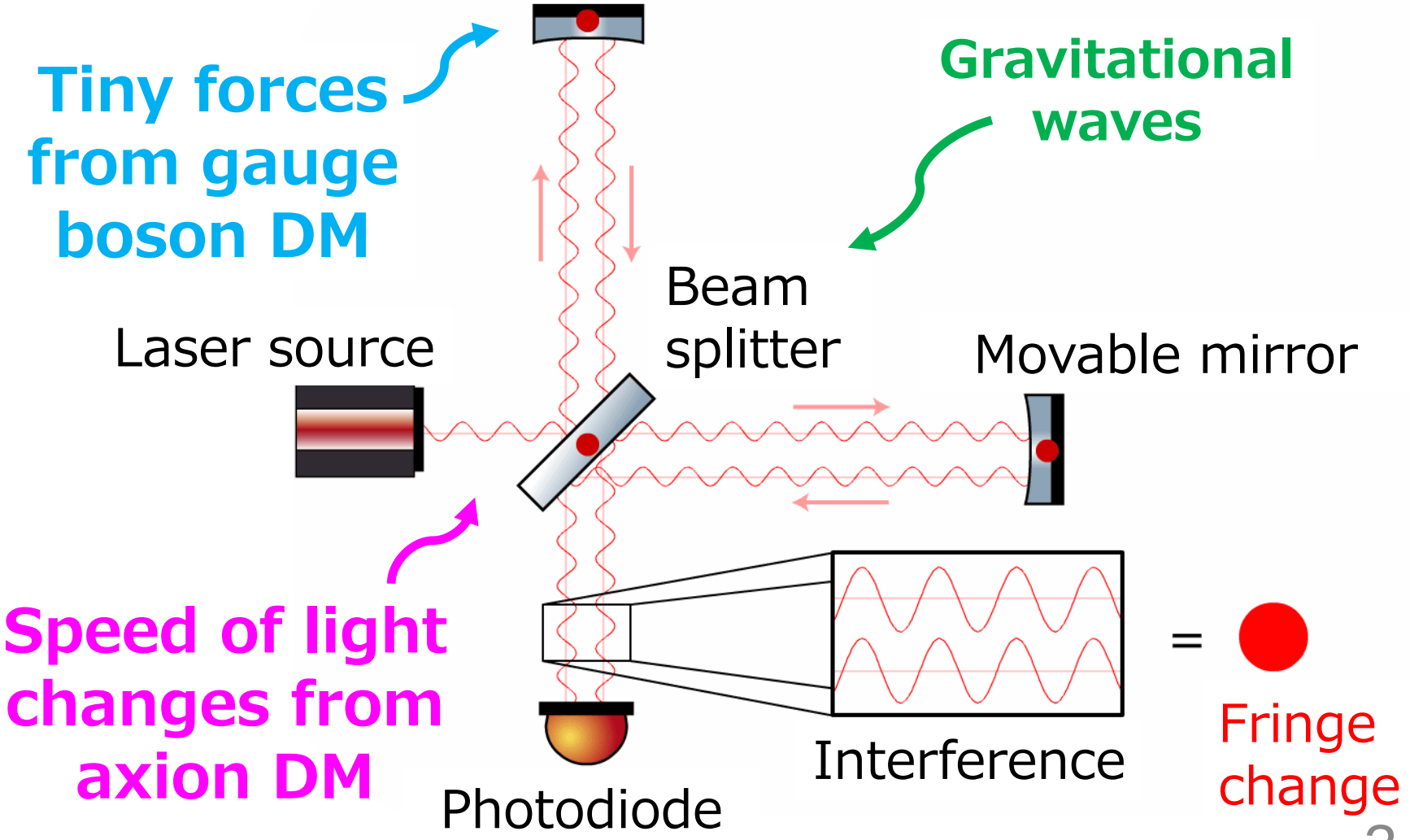
XENON1T limits on ALP
(1-210 keV)
arXiv:2006.09721





Laser Interferometry

- Sensitive to length / speed of light changes



Dark Matter Search with KAGRA

- Use underground, cryogenic gravitational wave detector KAGRA in Japan to search for ultralight dark matter

+ **Polarization measurement**

PRL 123, 111301 (2019)
arXiv:2106.06800
(PRD accepted)

PRD 102, 102001 (2020)
PRD 103, L051702 (2021)

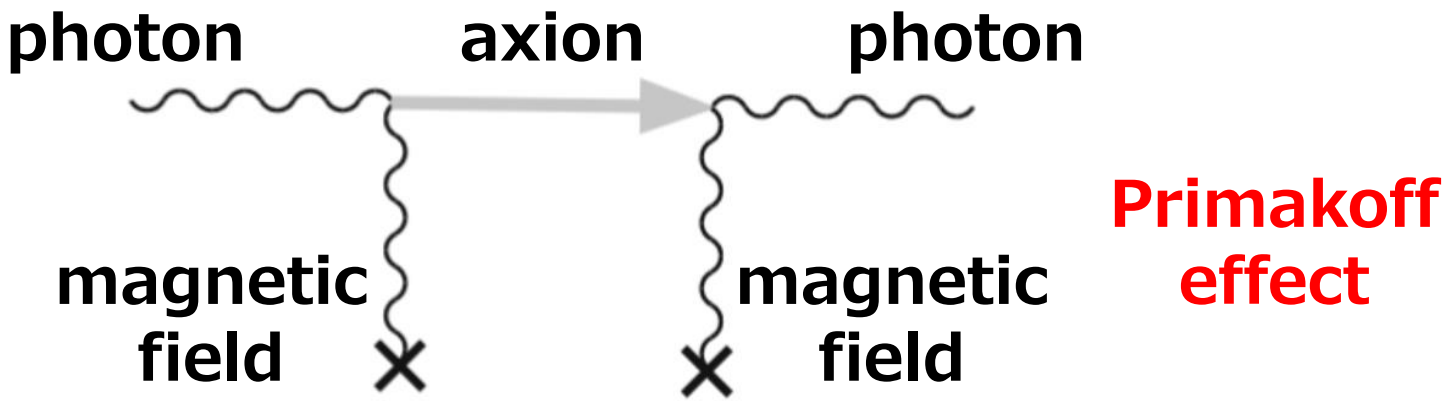
Ultralight DM

- **Axion like particles**
- **Gauge bosons**

Axion and Axion-Like Particles

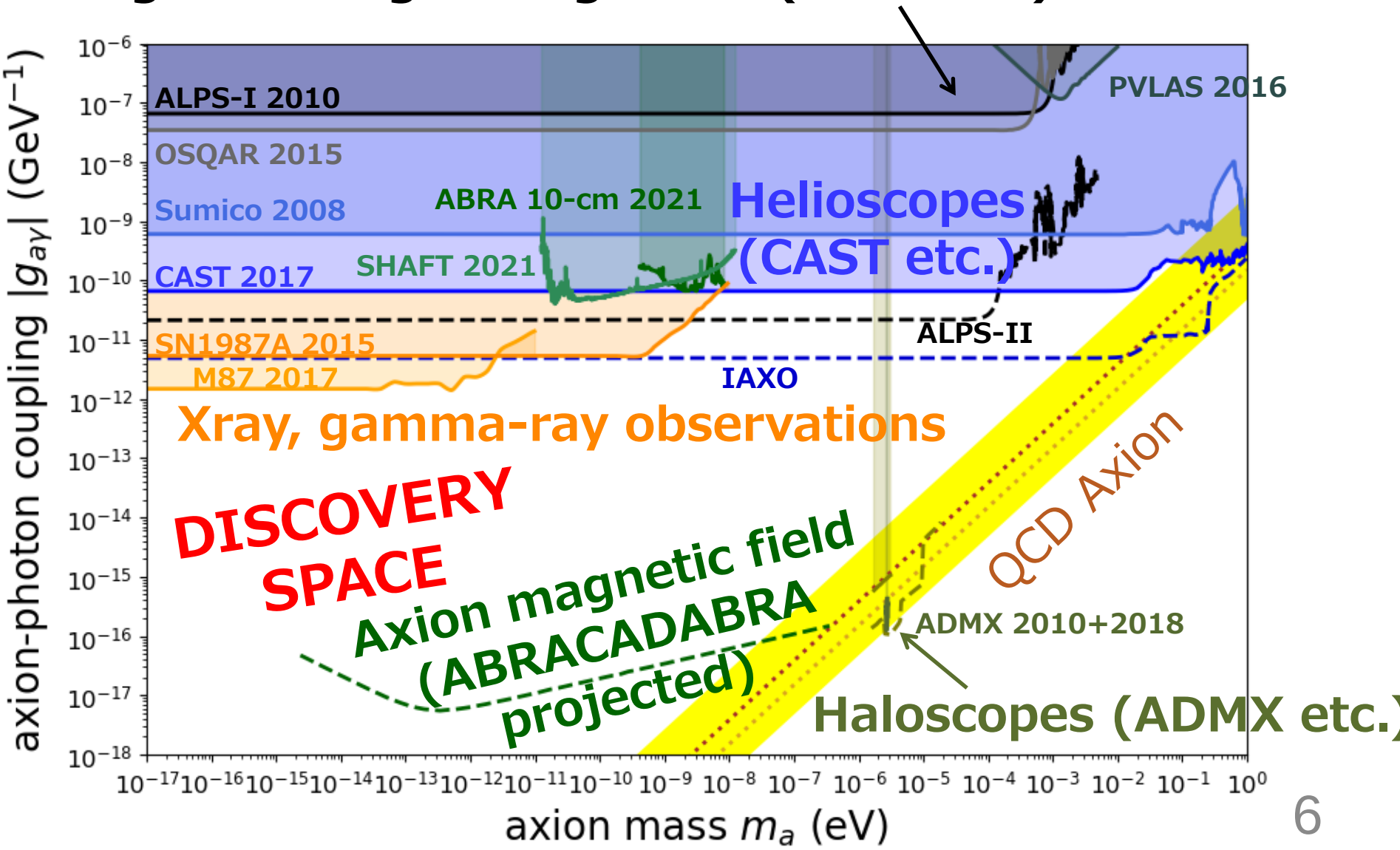
- Pseudo-scalar particle originally introduced to solve strong CP problem (QCD axion)
- Various axion-like particles (ALPs) predicted by string theory and supergravity
- Many experiments to search for ALPs through axion-photon coupling

  Especially by using magnetic fields



Previous Searches

Light Shining through Wall (ALPS etc.)



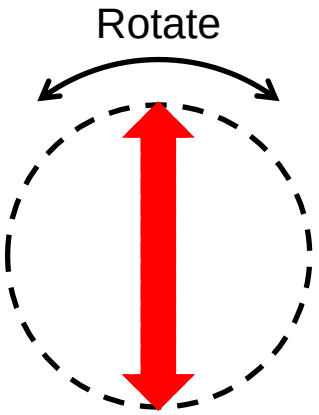
Polarization Modulation from Axions

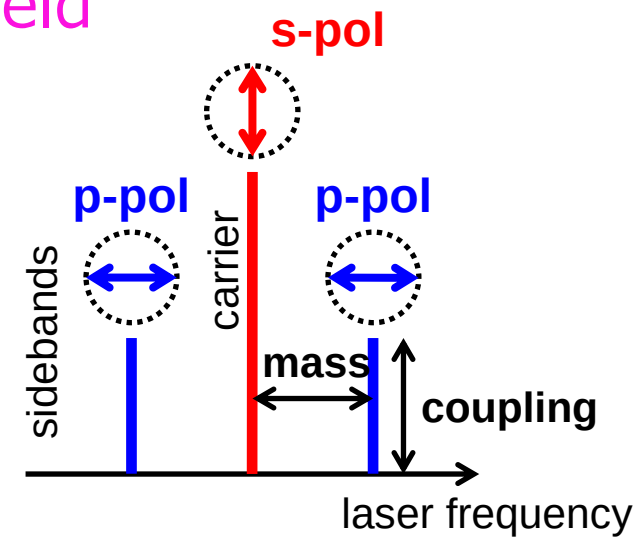
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

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

coupling constant　axion field　axion mass

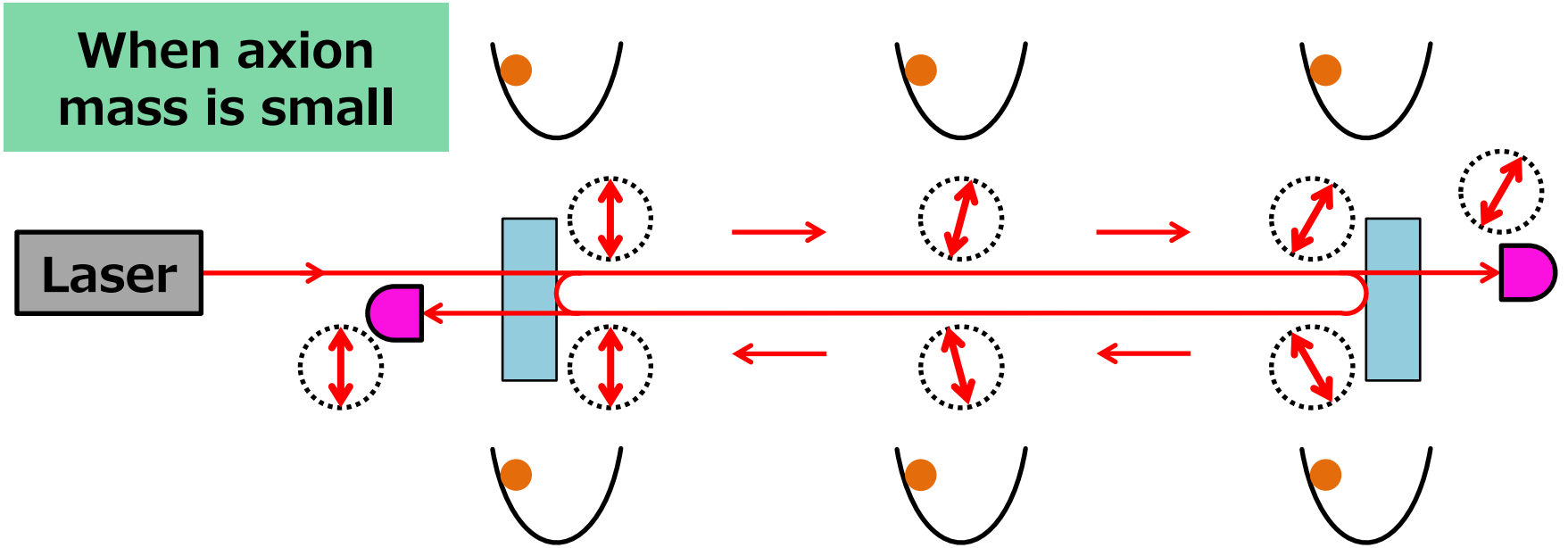
- Linear polarization will be modulated
  - p-pol sidebands will be generated from s-pol
- Search can be done without magnetic field





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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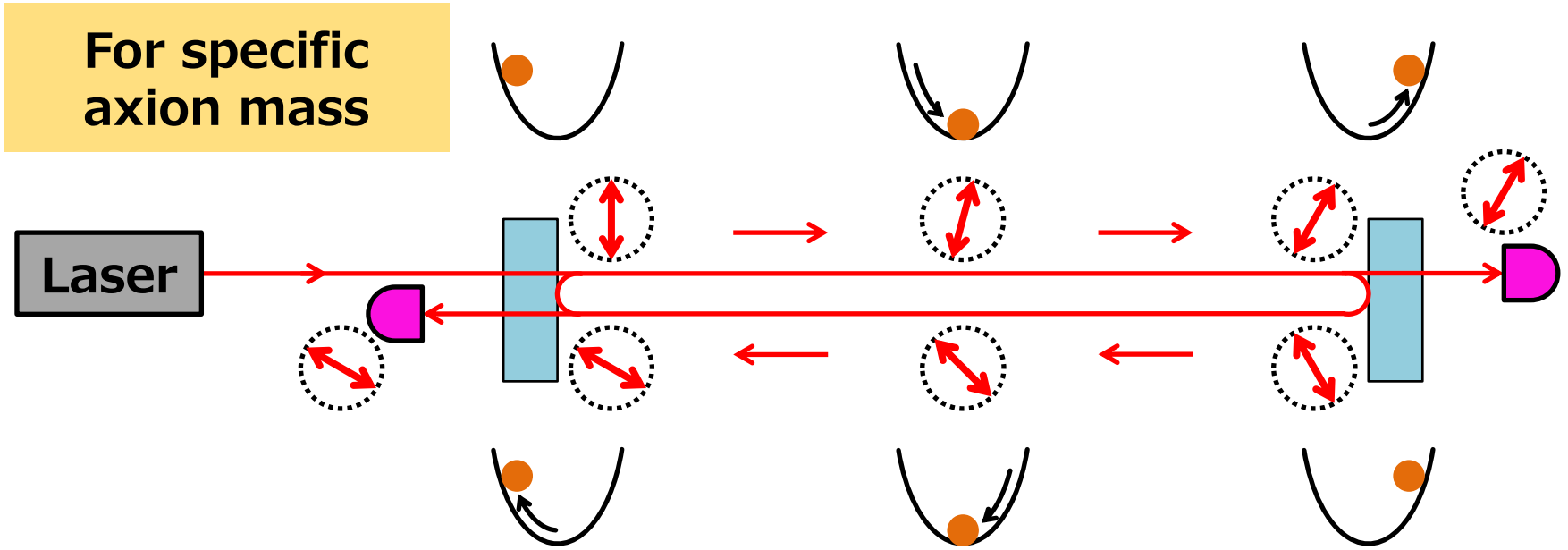
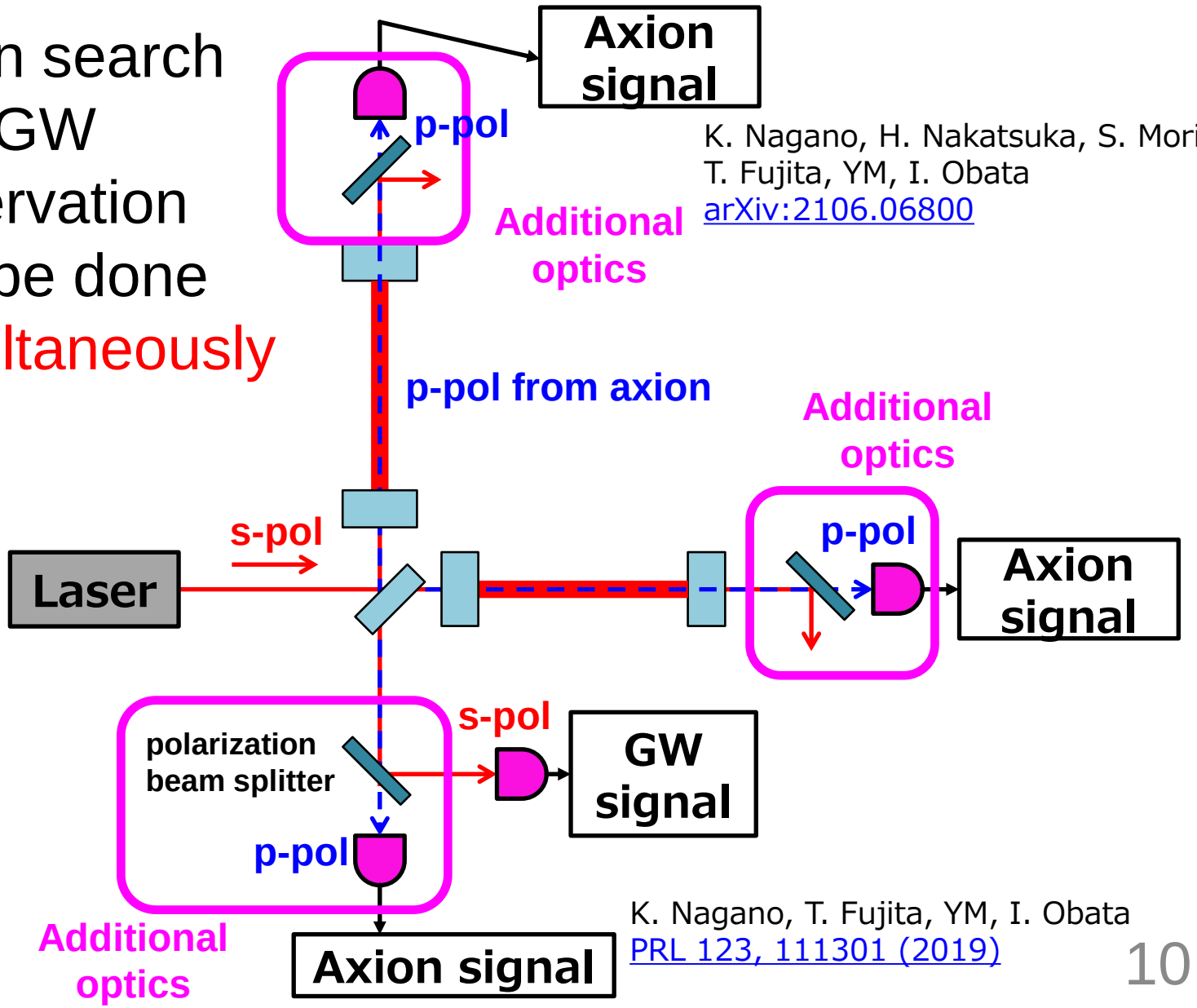


Axion Search with KAGRA

- Axion search and GW observation can be done simultaneously

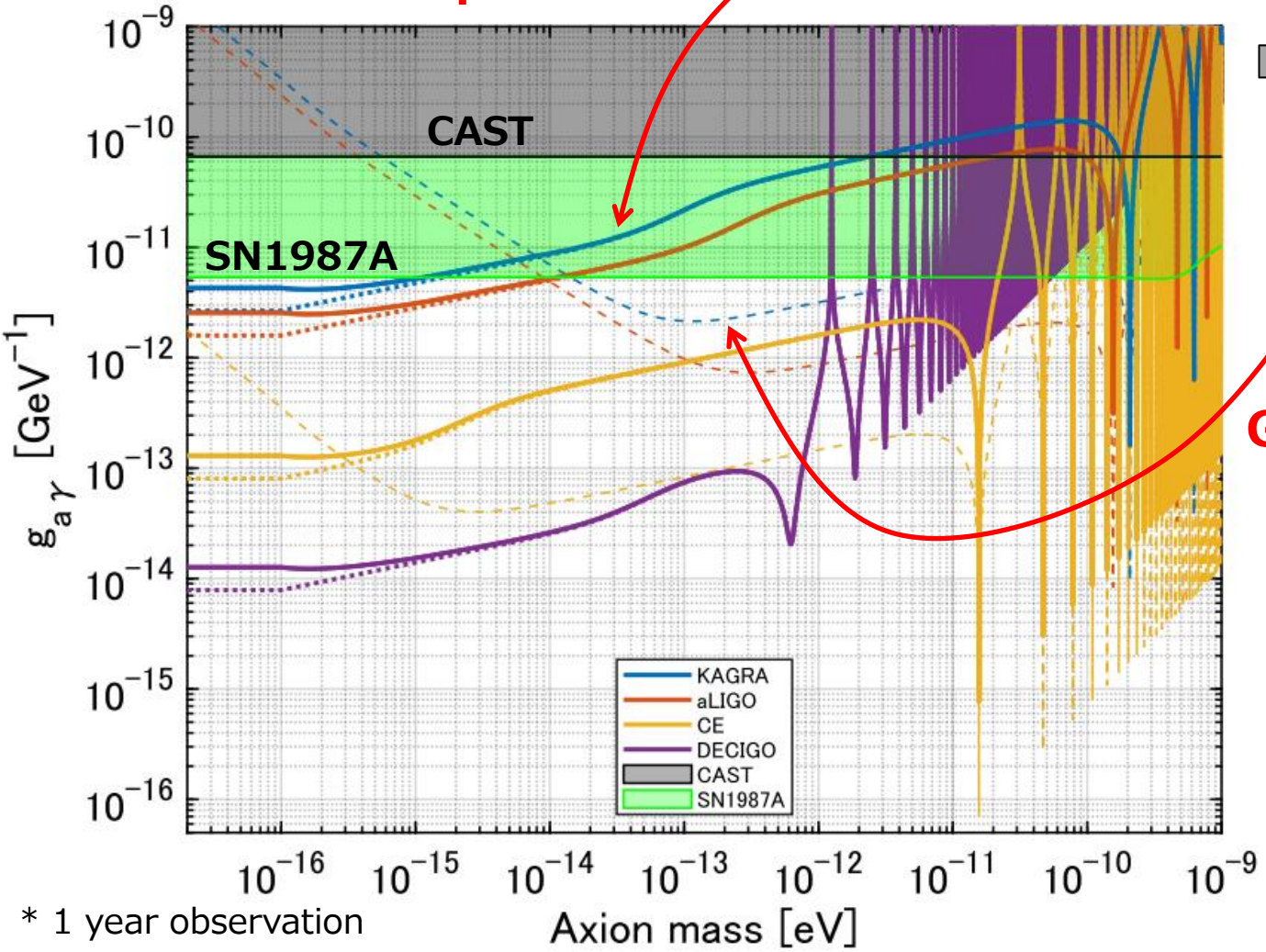


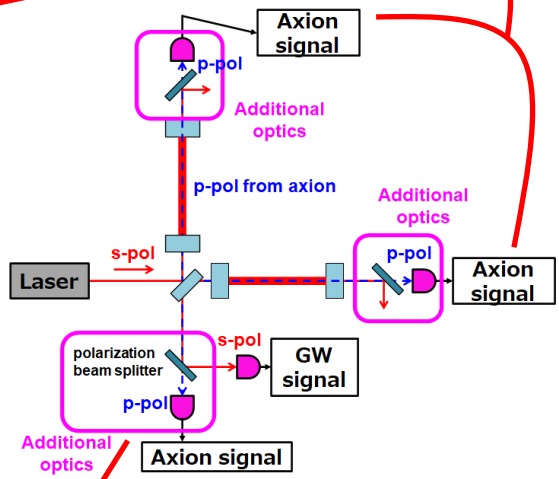
K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita, YM, I. Obata
arXiv:2106.06800

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

KAGRA Axion Sensitivity

Arm cavity transmission ports





GW detection port

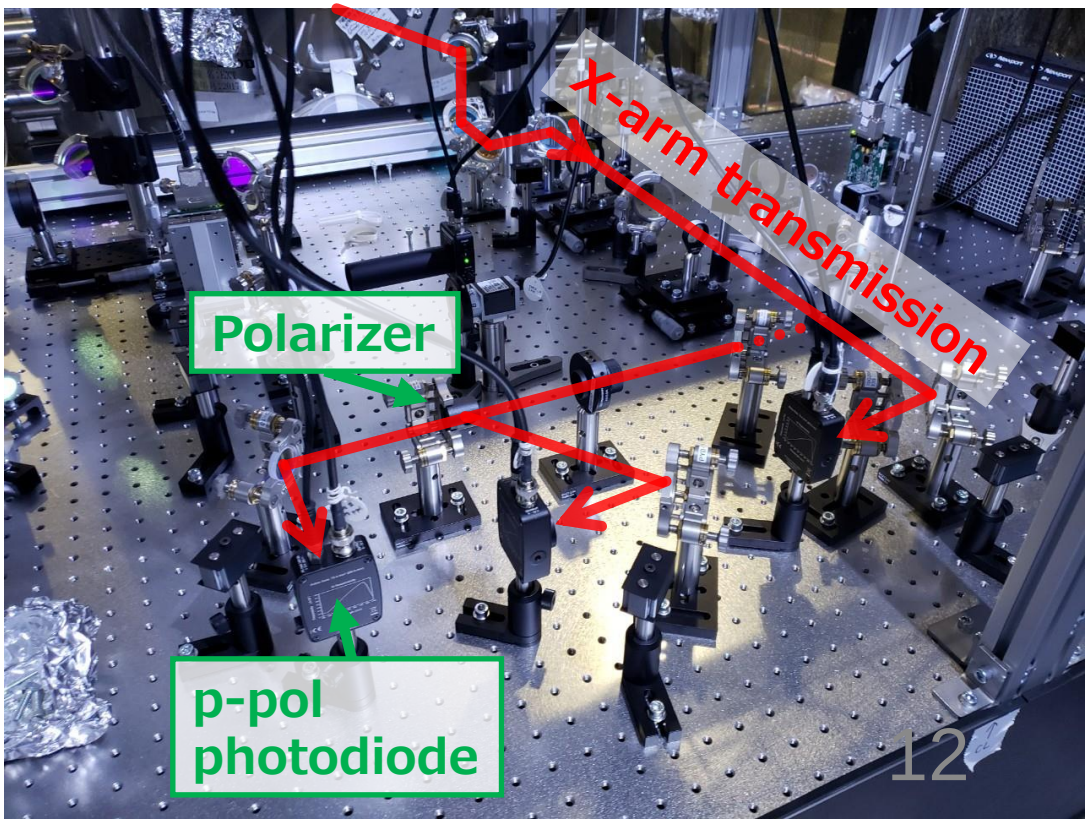
Complemental search using different ports

* 1 year observation

arXiv:2106.06800

Optics for Axion Search Installed

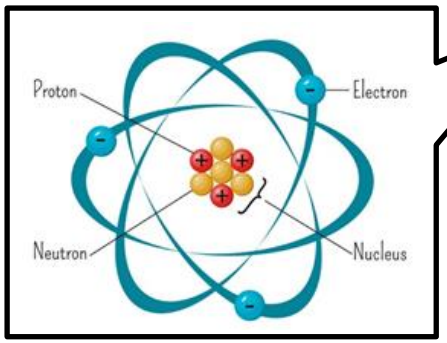
- Polarization optics mostly installed at X-arm transmission port
- Connected to the data acquisition system
- Axion search to be done in the next observing run O4 in 2022-2023

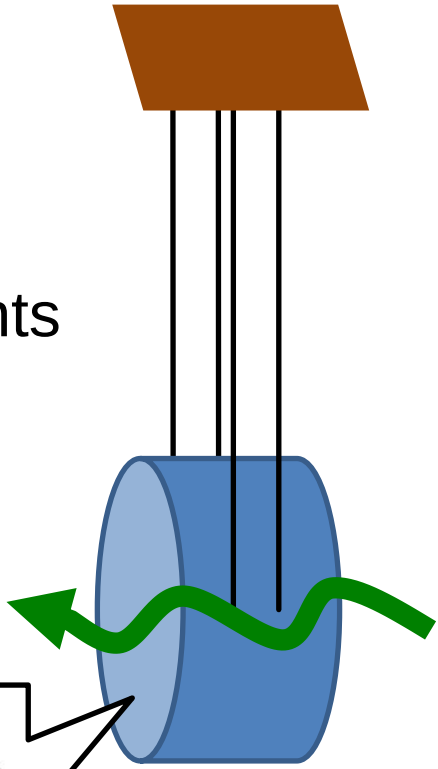


klog #17692

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





gauge field

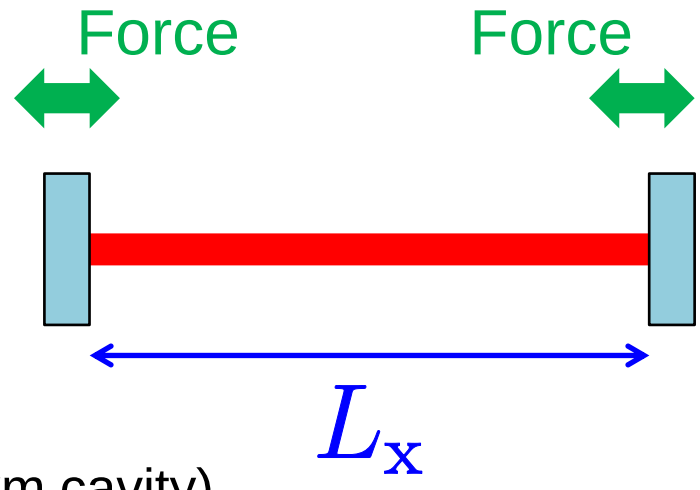
Oscillating Force from Gauge Field

- 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

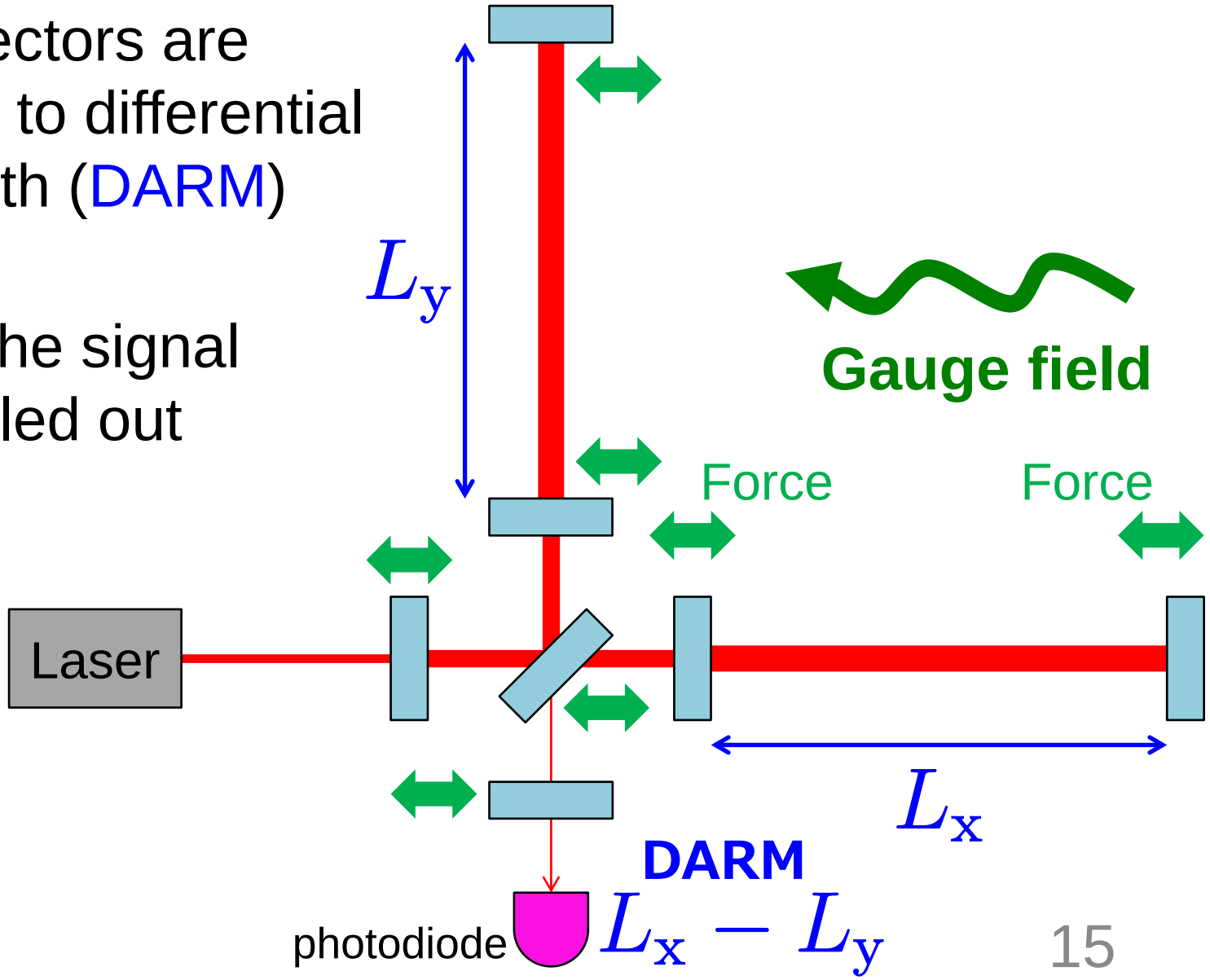
- Gauge boson mass and coupling can be measured by measuring the oscillating mirror displacement
- Almost no signal for symmetric cavity if cavity length is short
  (phase difference is 10^{-5} rad @ 100 Hz for km cavity)
- How about using interferometric GW detectors?



A. Pierce+, Phys. Rev. Lett. **121**, 061102 (2018)

Search with GW Detectors

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



Previous Search with LIGO/Virgo

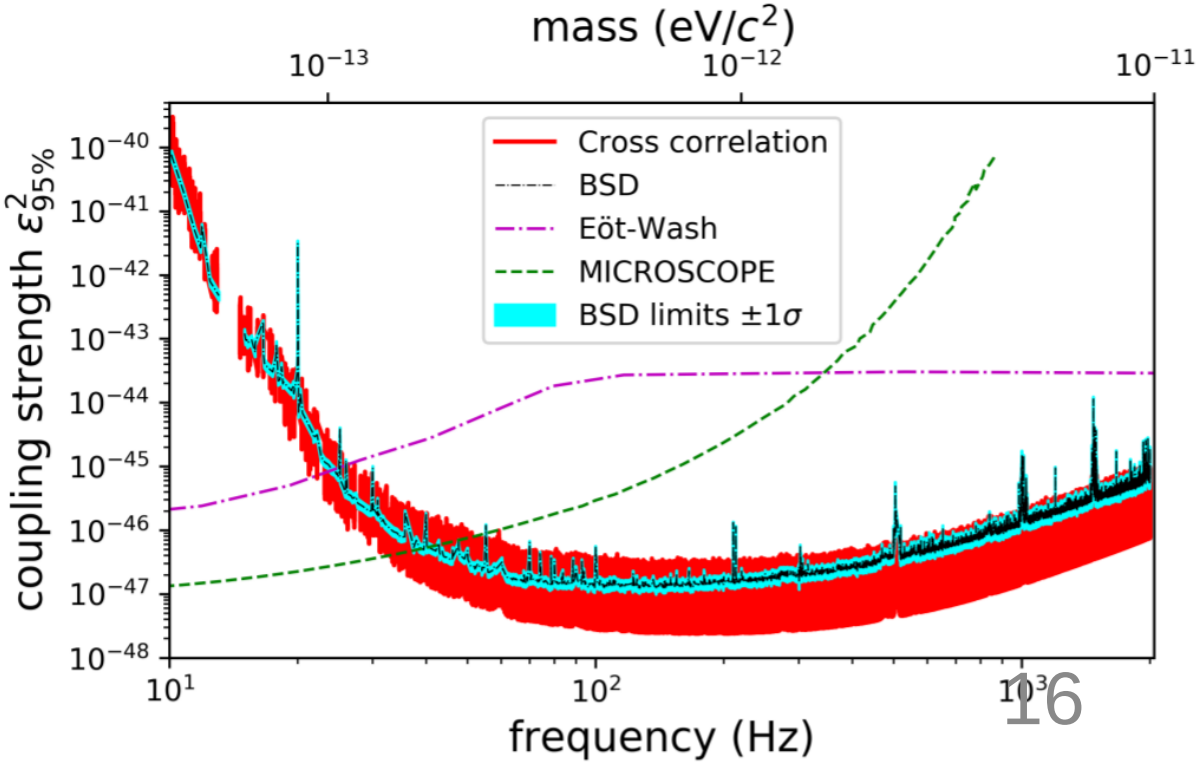
- Gauge boson dark matter search with LIGO O1 data and LIGO/Virgo O3 data have been done

  H-K Guo+, Communications Physics **2**, 155 (2019)
  LIGO, Virgo, KAGRA Collaboration, arXiv:2105.13085

- Better constraint than equivalence principle tests

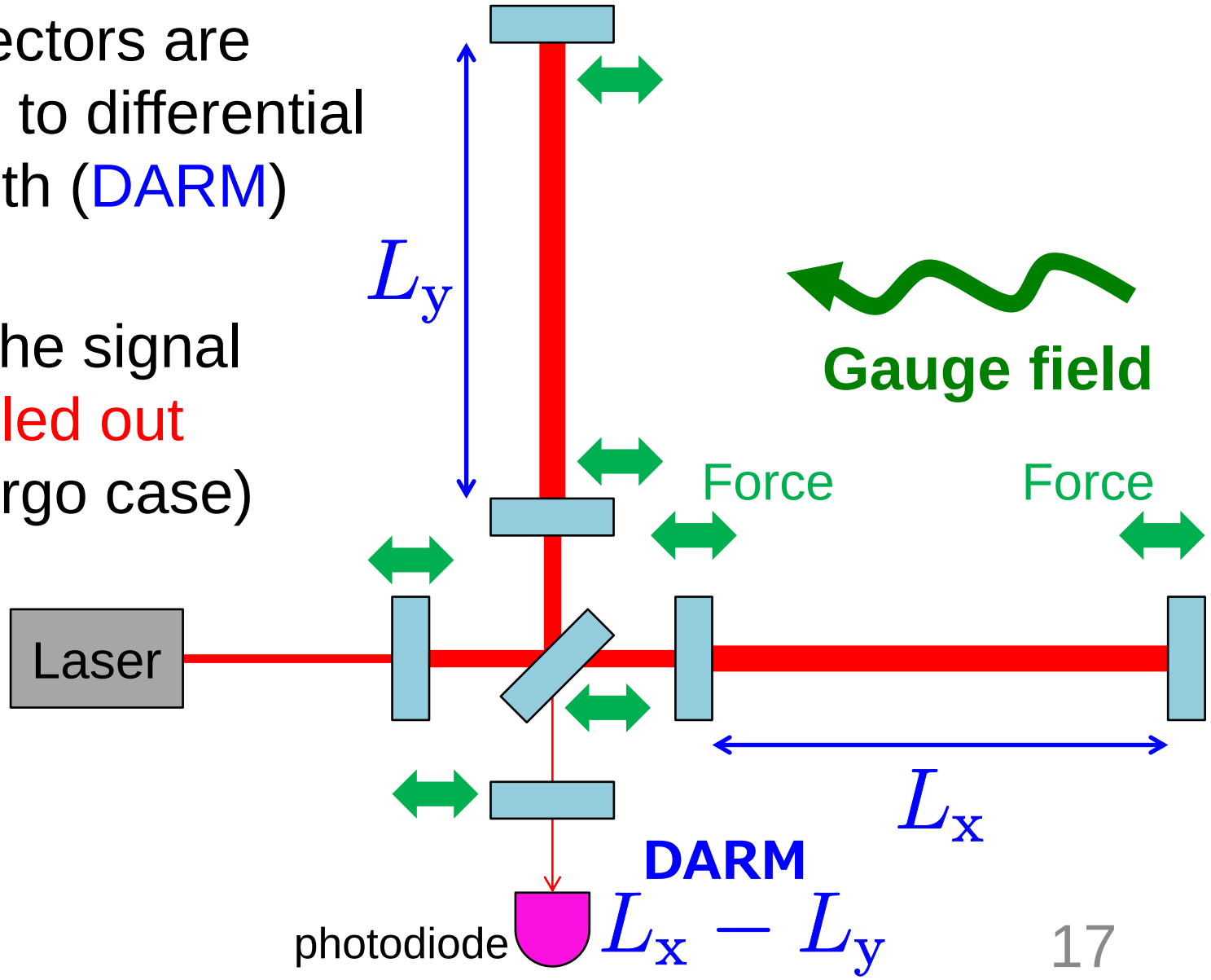
  So far searches focus on $U(1)_B$ baryon number coupling

- Why repeat the search with KAGRA?



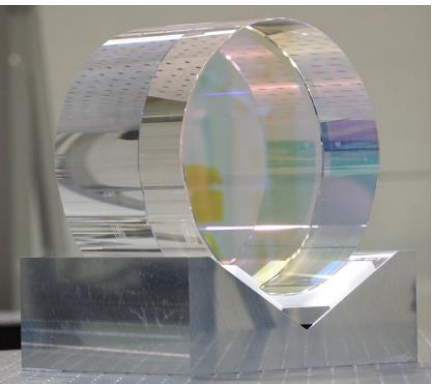
Search with GW Detectors

- 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



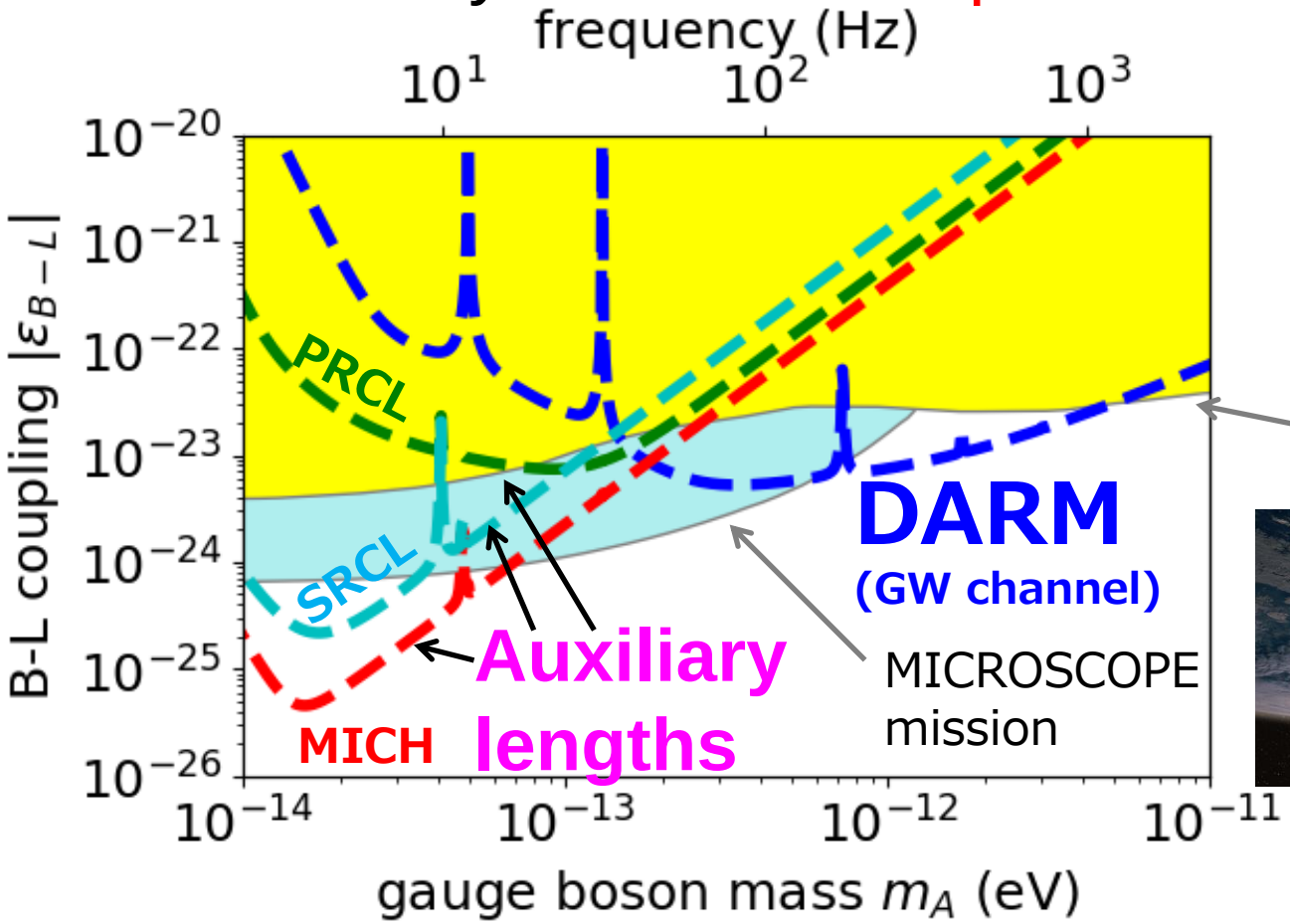
B-L charge
Fused silica: 0.501
Sapphire: 0.510

Search with KAGRA

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

KAGRA Gauge Boson Sensitivity

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

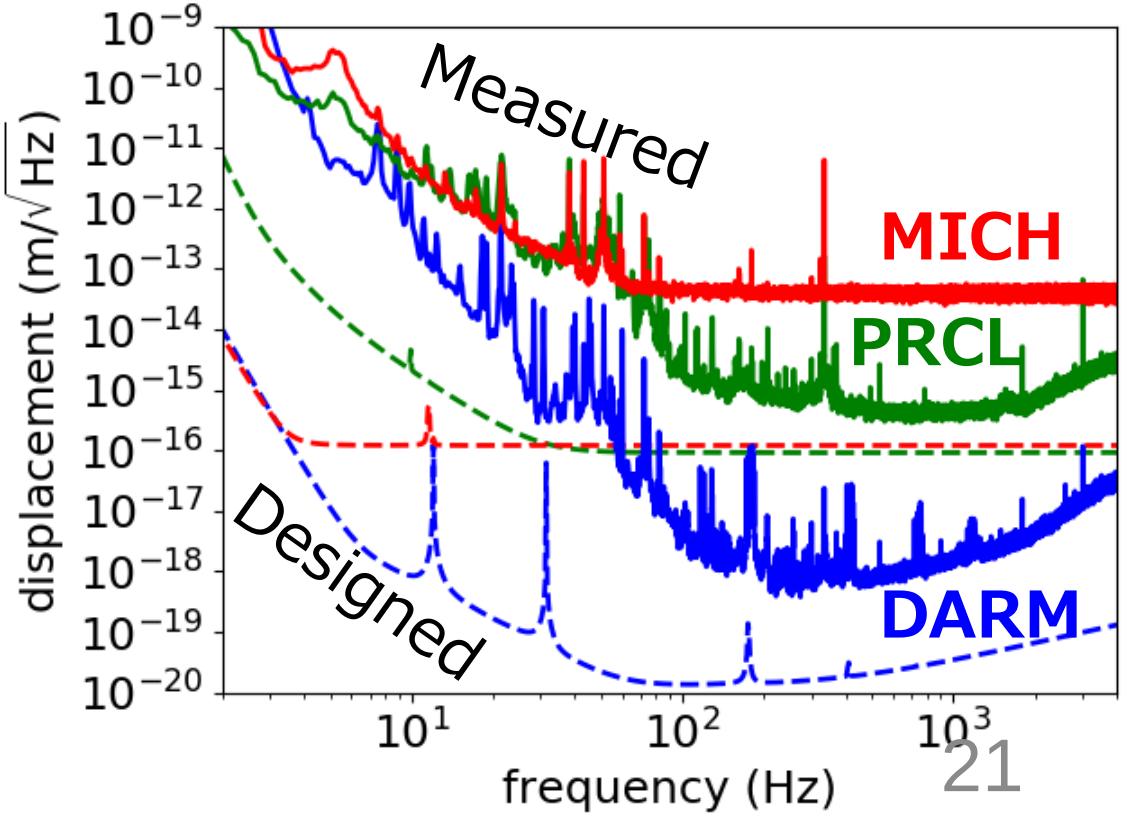


YM, T. Fujita, S. Morisaki, H. Nakatsuka, I. Obata, PRD 102, 102001 (2020)

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

KAGRA's Observing Run in 2020

- 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
- We have developed a data analysis pipeline to search for gauge boson DM
- Applying the pipeline for two sets of 10^4 sec data



Summary

- Laser interferometers open up new possibilities for dark matter search
- Two ultralight DM search activities in KAGRA
  - **Axion DM search**
    Polarization optics installed
    Ready to search in the next observing run
    O4 in 2022-2023
  - **Gauge boson DM search**
    First data analysis using O3GK 2020 data
    on going
- Both can be done simultaneously with gravitational wave observation
- Stay tuned for future observing runs!