Search for ultralight dark matter with laser interferometric gravitational wave detectors

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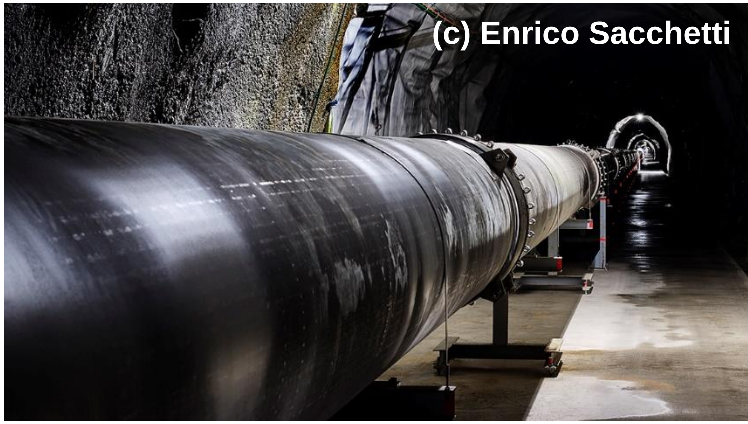
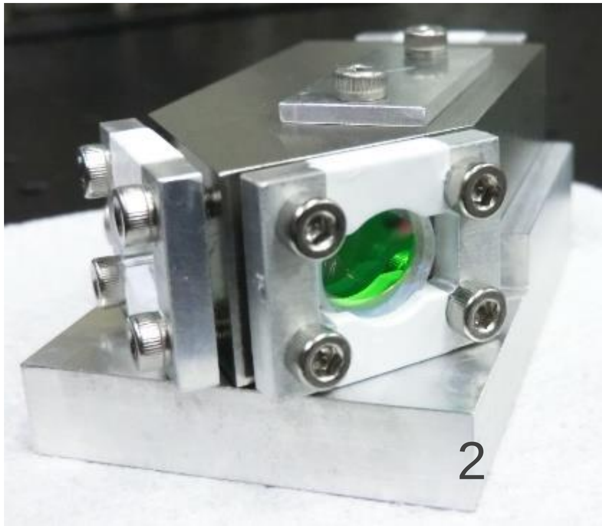
Slides are available at https://tinyurl.com/YM20200713

Self Introduction

- Yuta Michimura (道村唯太)
  Department of Physics, University of Tokyo
- Laser interferometric gravitational wave detectors
  - KAGRA
  - DECIGO
- Search for new physics with laser interferometry
  - Lorentz violation
  - Macroscopic quantum mechanics
  - Dark matter searches

  etc …





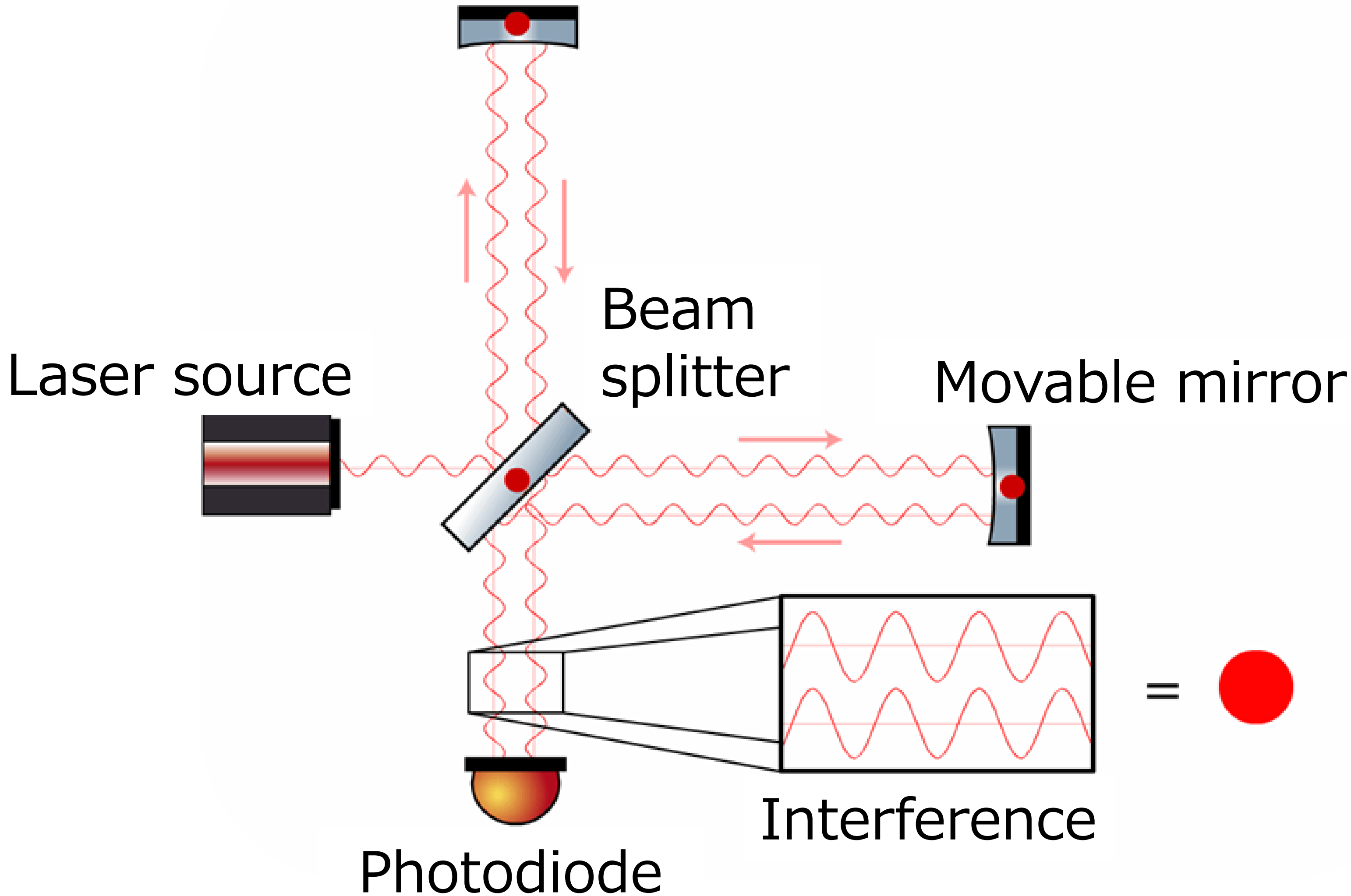
Plan of the Talk

- Basics of laser interferometry
  - Michelson interferometer and optical cavity
  - Laser interferometric gravitational wave detectors
  - Key aspects
- Ultralight dark matter searches
  - Axion like particles (pseudoscalar)
  - Scalar fields
  - $U(1)_B$ and $U(1)_{B-L}$ gauge bosons (vector)
- Dark matter search with KAGRA
  - Current status of KAGRA
  - Prospected sensitivity for KAGRA
- Summary

Basics of laser interferometry

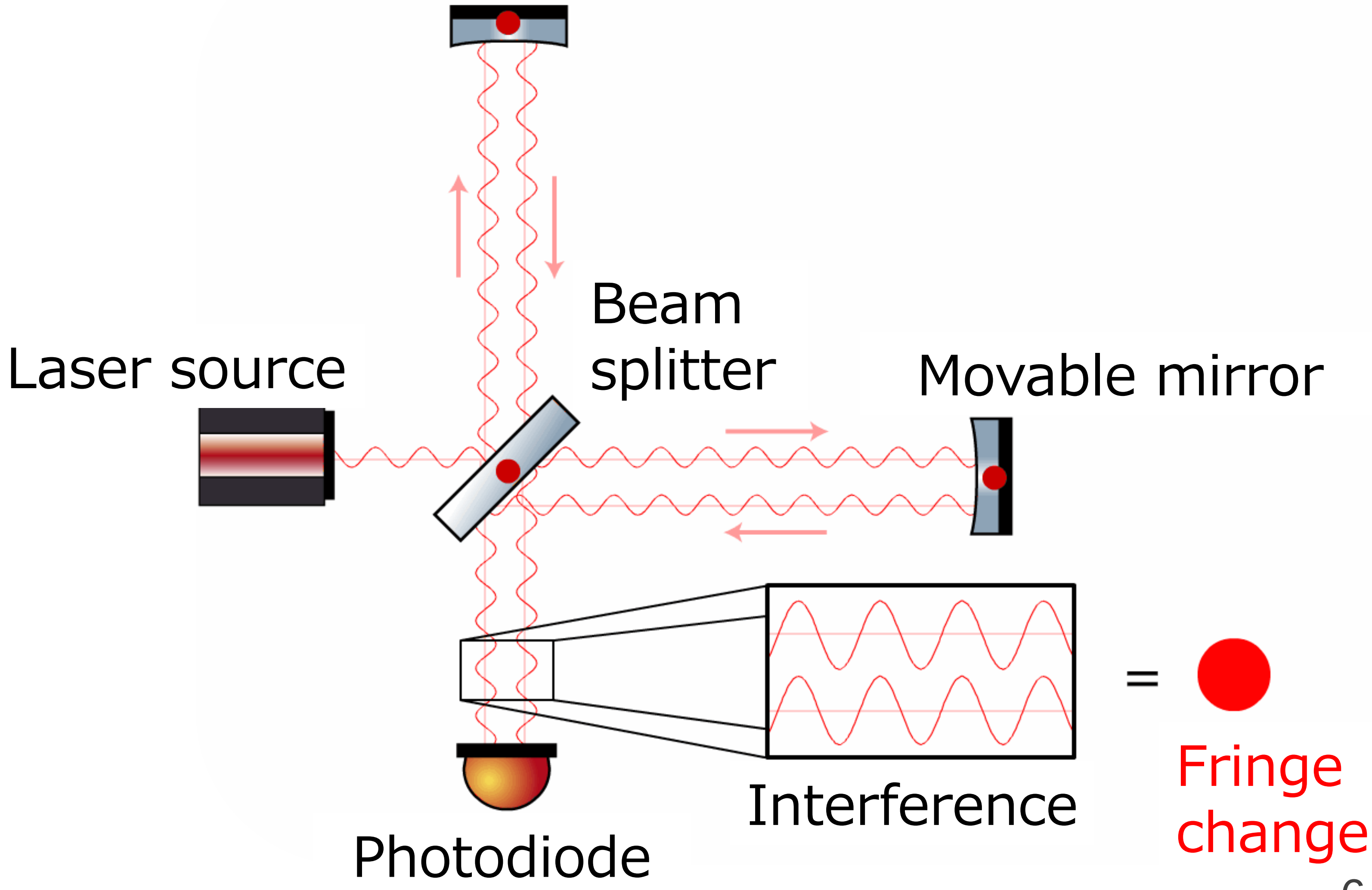
Michelson Interferometer

- measures differential arm length change



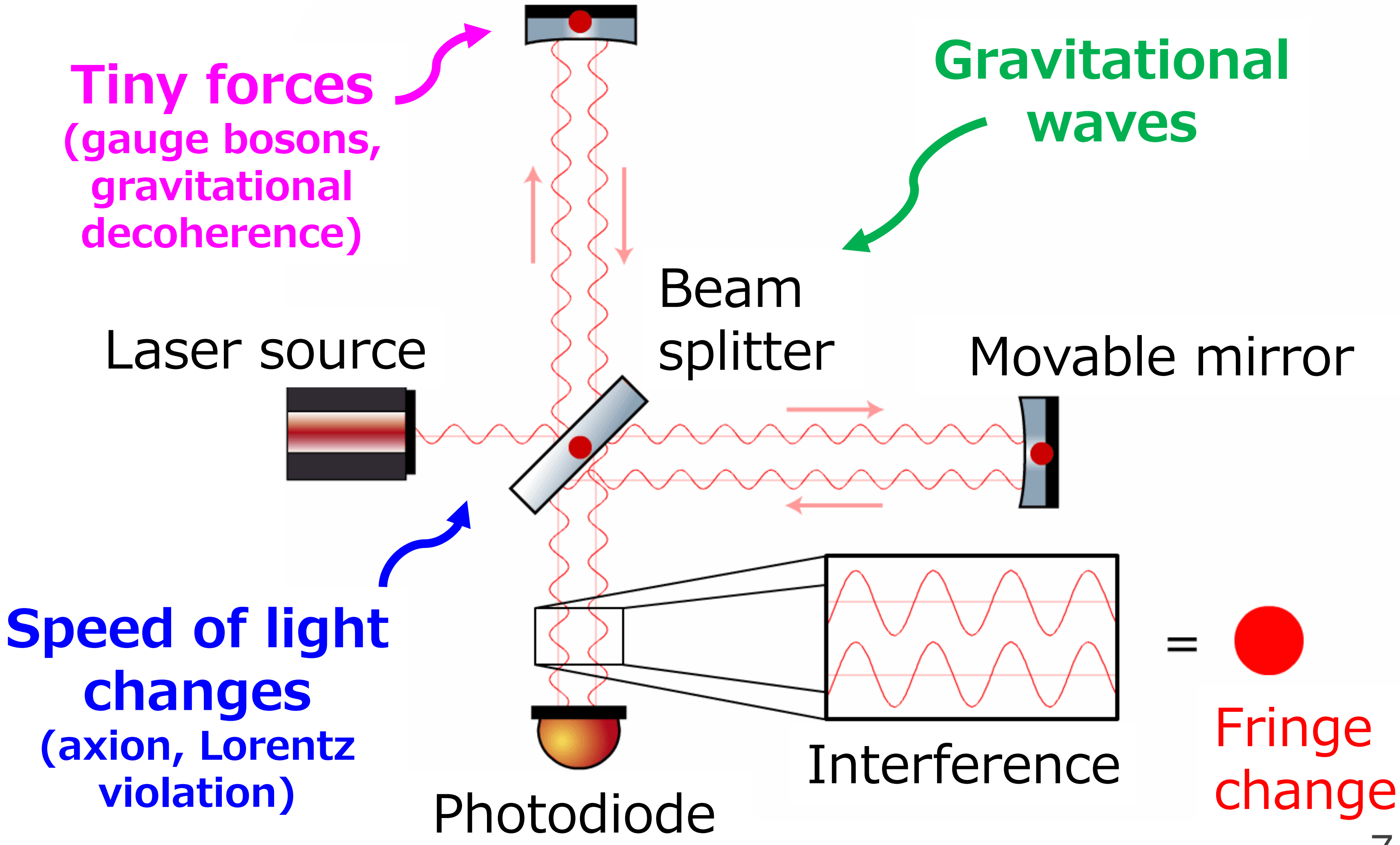
Michelson Interferometer

- measures differential arm length change



Michelson Interferometer

- measures differential arm length change



Fabry-Perot Cavity

- Two highly reflective mirrors
- Sense mirror displacement multiple times
- Displacement sensitivity is enhanced by

$$N_{\mathrm{eff}} = \frac{2\mathcal{F}}{\pi}$$

Finesse $\mathcal{F} = \dfrac{2\pi}{t_1^2 + t_2^2}$

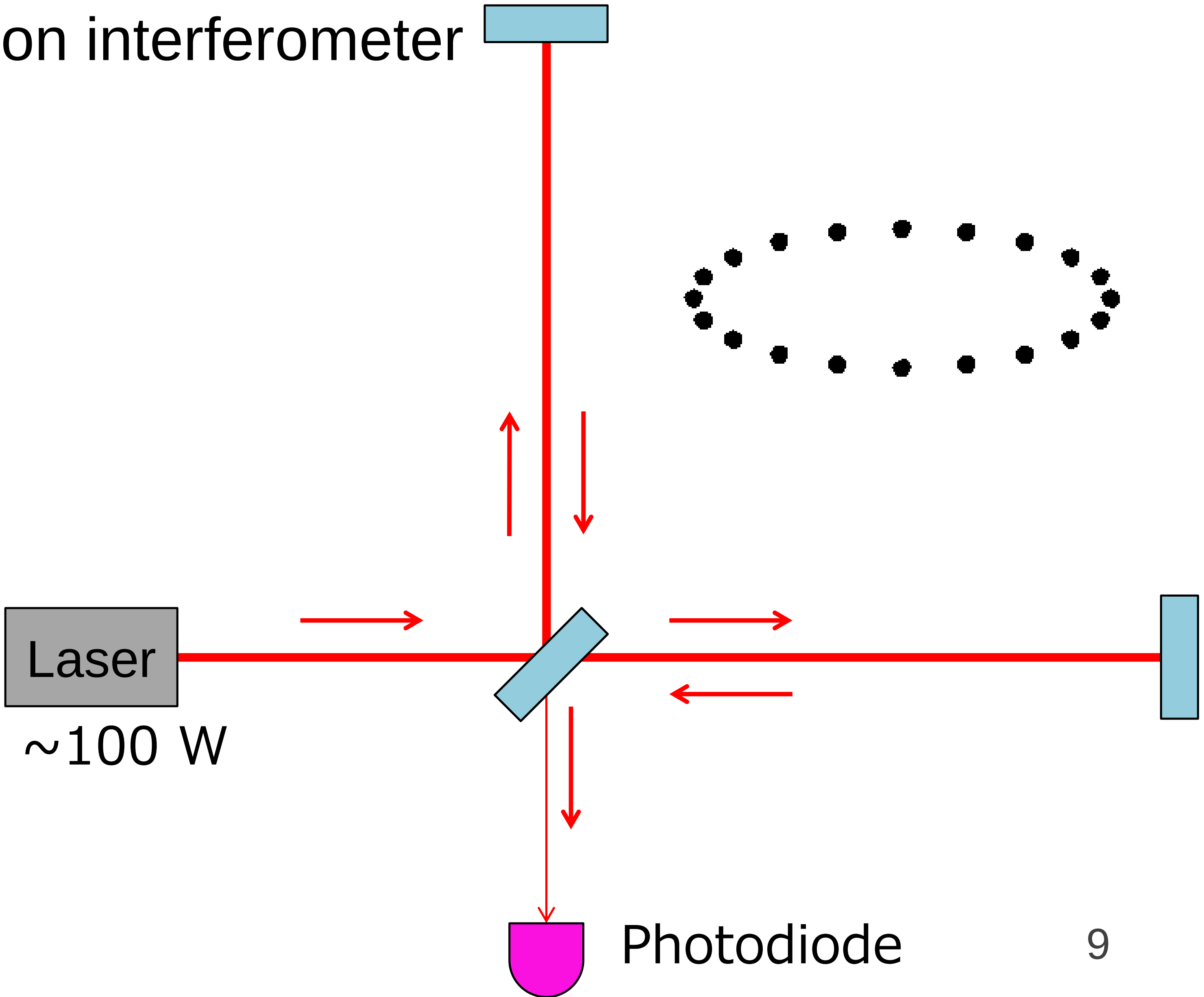
$r_1,\ t_1$
input mirror

$r_2,\ t_2$
end mirror

$$r_i^2 + t_i^2 = 1$$

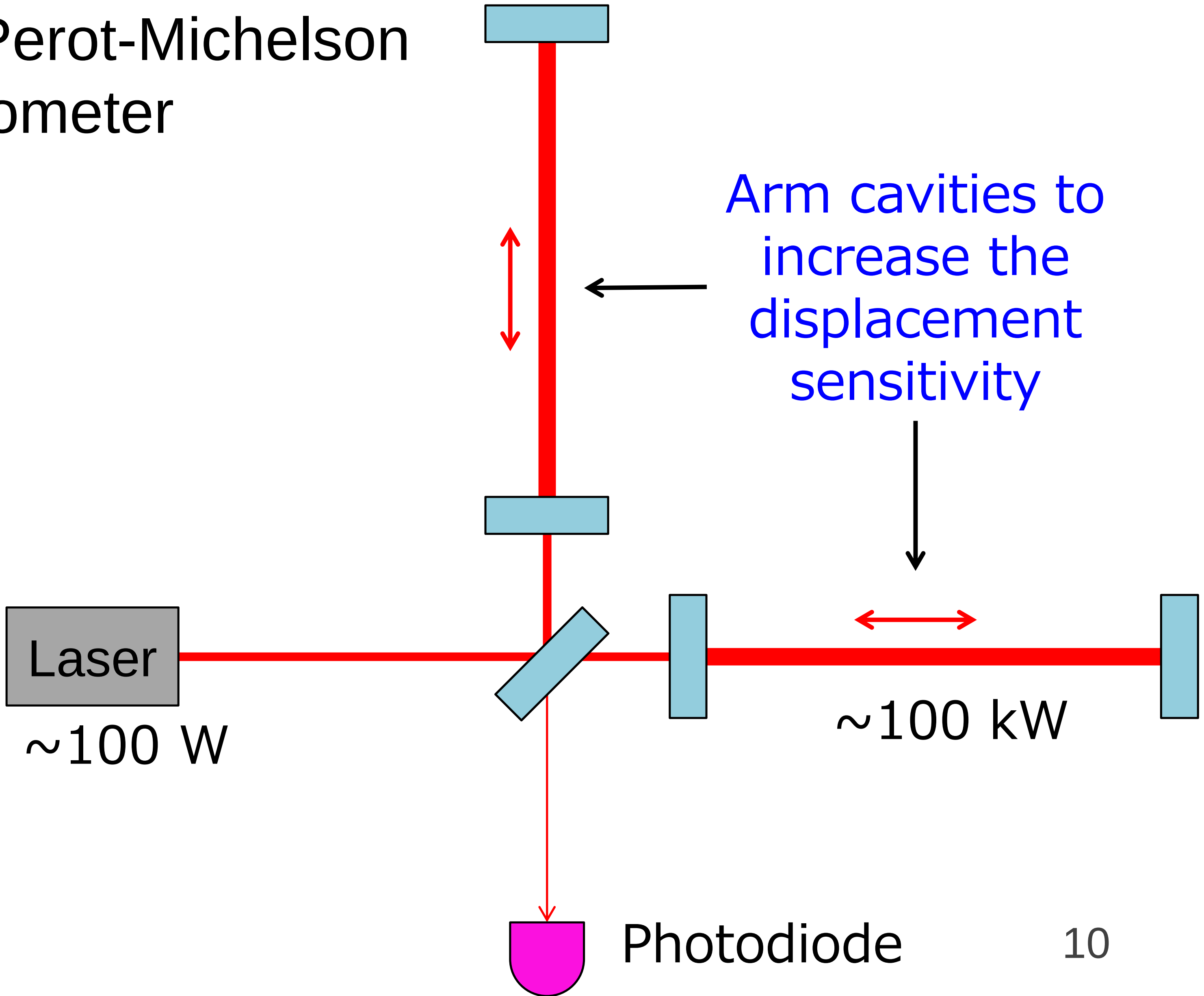
Gravitational Wave Detector

- Michelson interferometer



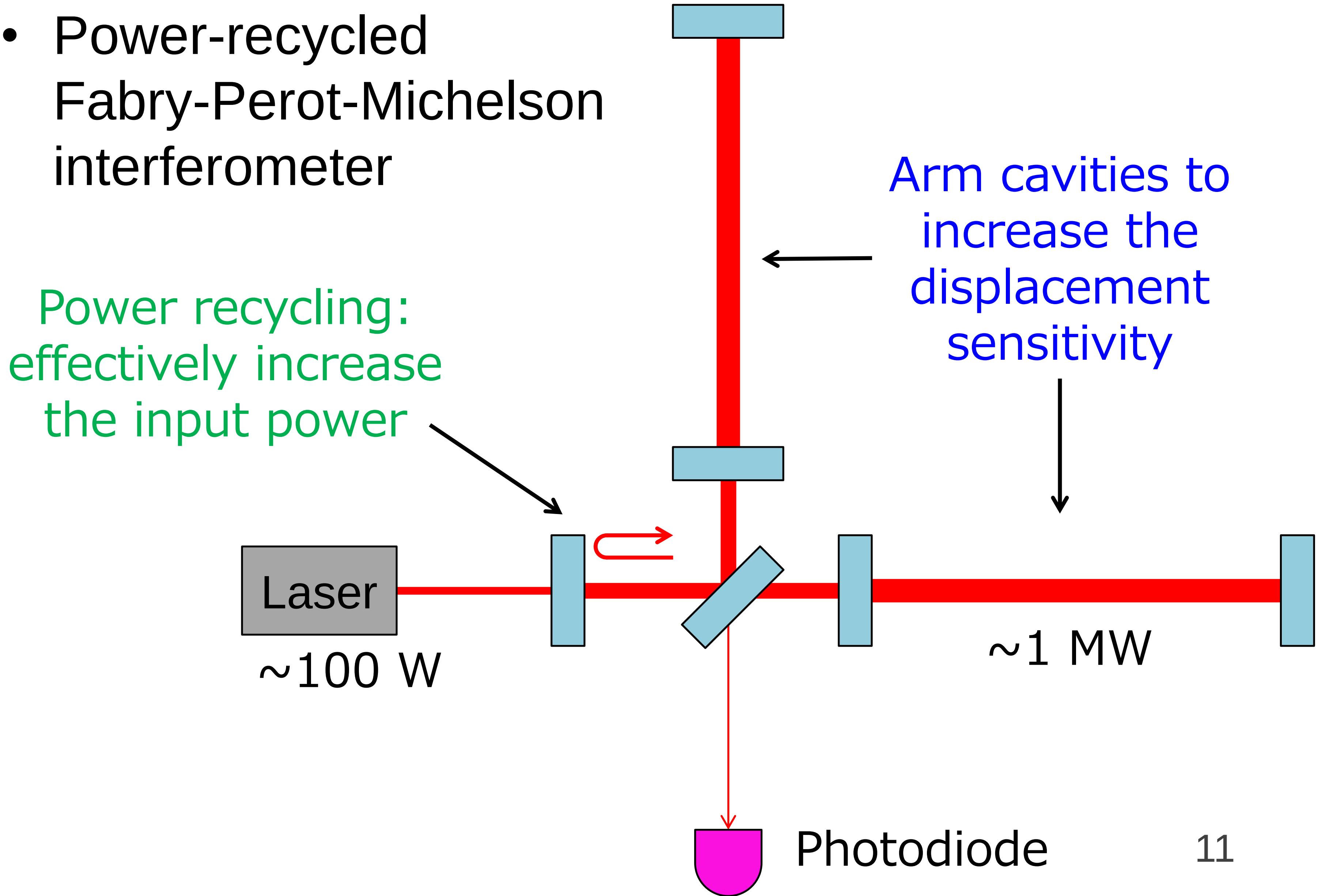
Gravitational Wave Detector

- Fabry-Perot-Michelson interferometer



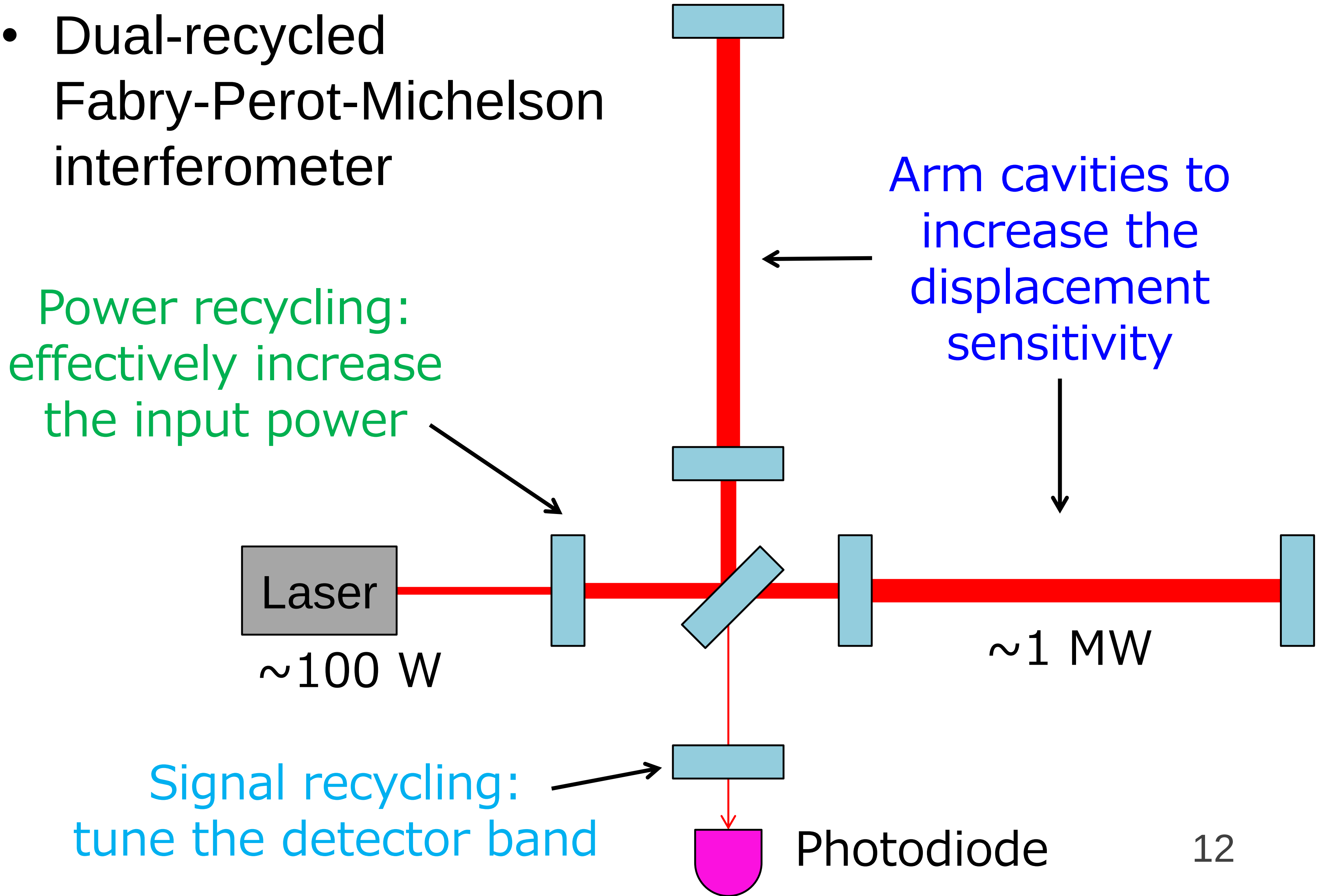
Gravitational Wave Detector

- Power-recycled Fabry-Perot-Michelson interferometer



Gravitational Wave Detector

- Dual-recycled Fabry-Perot-Michelson interferometer

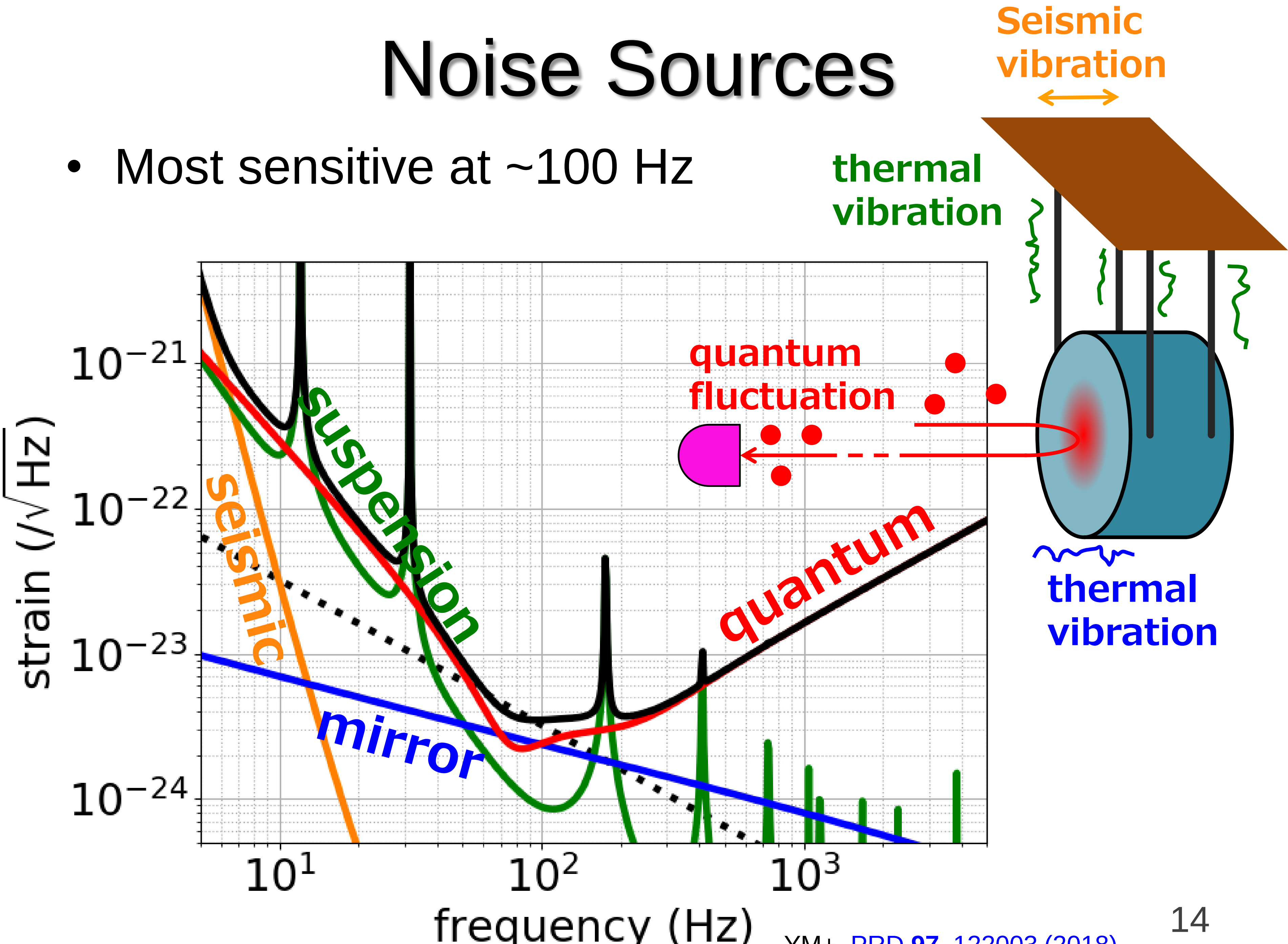


Global Network of GW Detectors

- All are laser interferometric GW detectors

Noise Sources

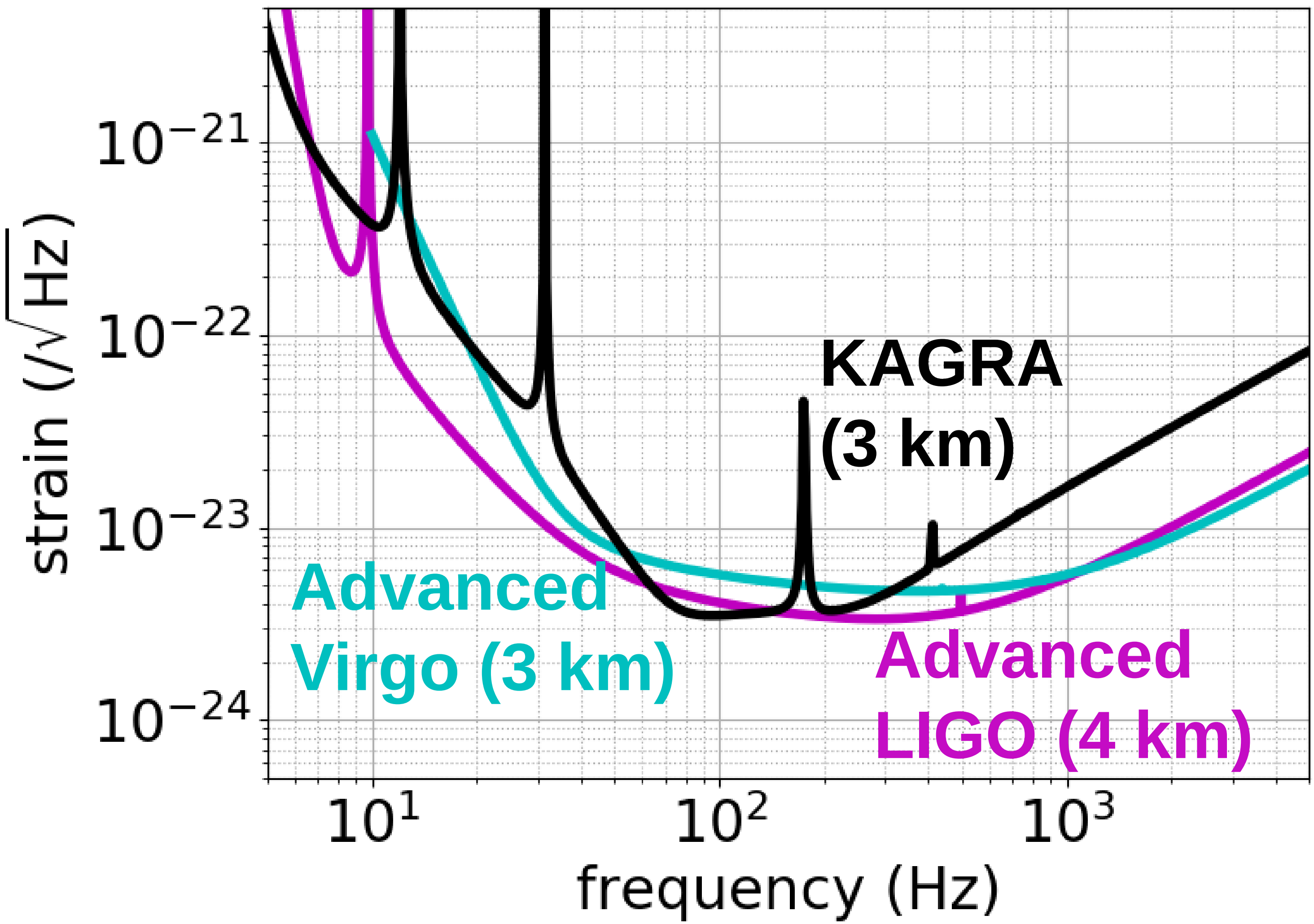
- Most sensitive at ~100 Hz



YM+, PRD **97**, 122003 (2018)

Sensitivity of LIGO/Virgo/KAGRA

- Similar strain sensitivity (displacement sensitivity divided by arm length)



$$h = \frac{\delta L}{L}$$

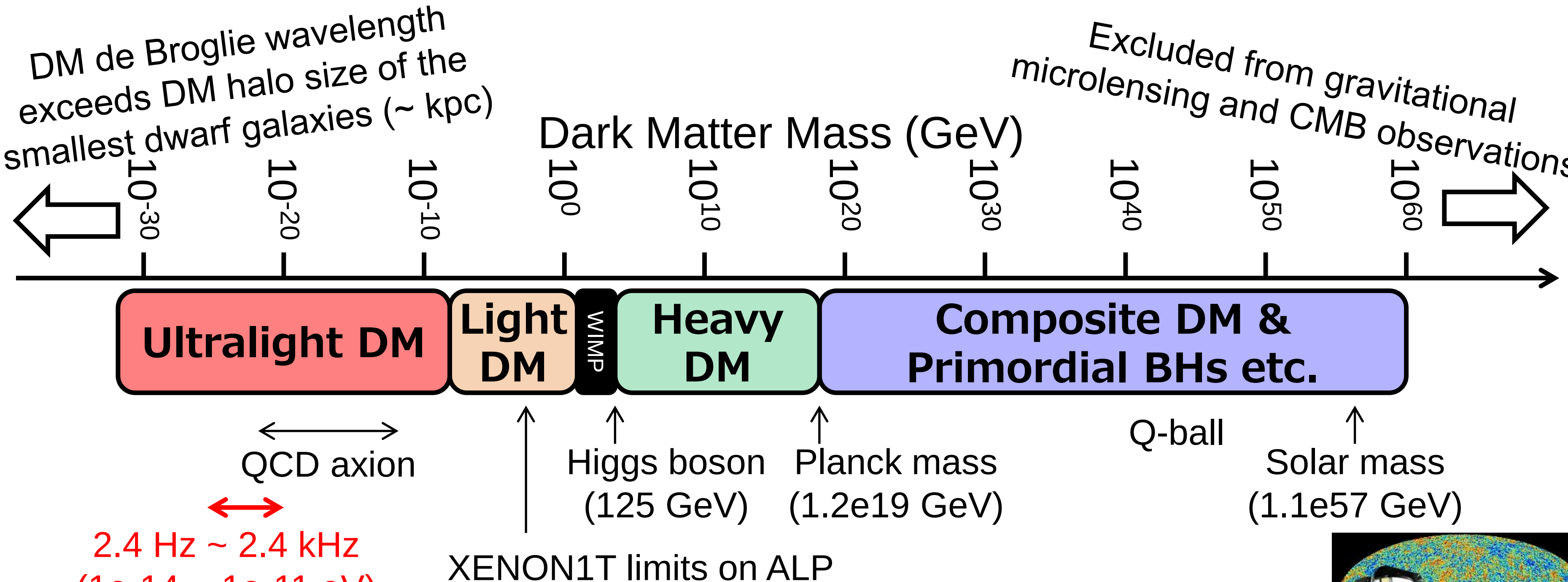
Key Aspects to Remember

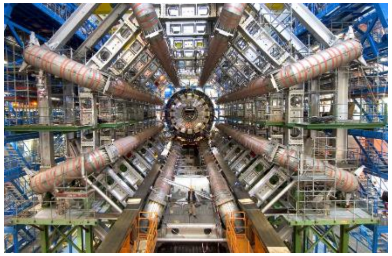
- Michelson interferometer measure the differential length between two arms
  - insensitive to common length changes
- Optical cavities measure the distance (optical path length) between mirrors
  - insensitive to common displacements
- They are also sensitive to the changes in the speed of light $\frac{\delta L}{L} = \frac{\delta c}{c}$
- They are not sensitive to translational motion of mirrors (to the first order)

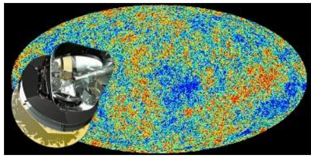
Ultralight dark matter searches

Dark Matter Models

- ~90 orders of magnitude
- Ultralight DMs behave as classical wave fields





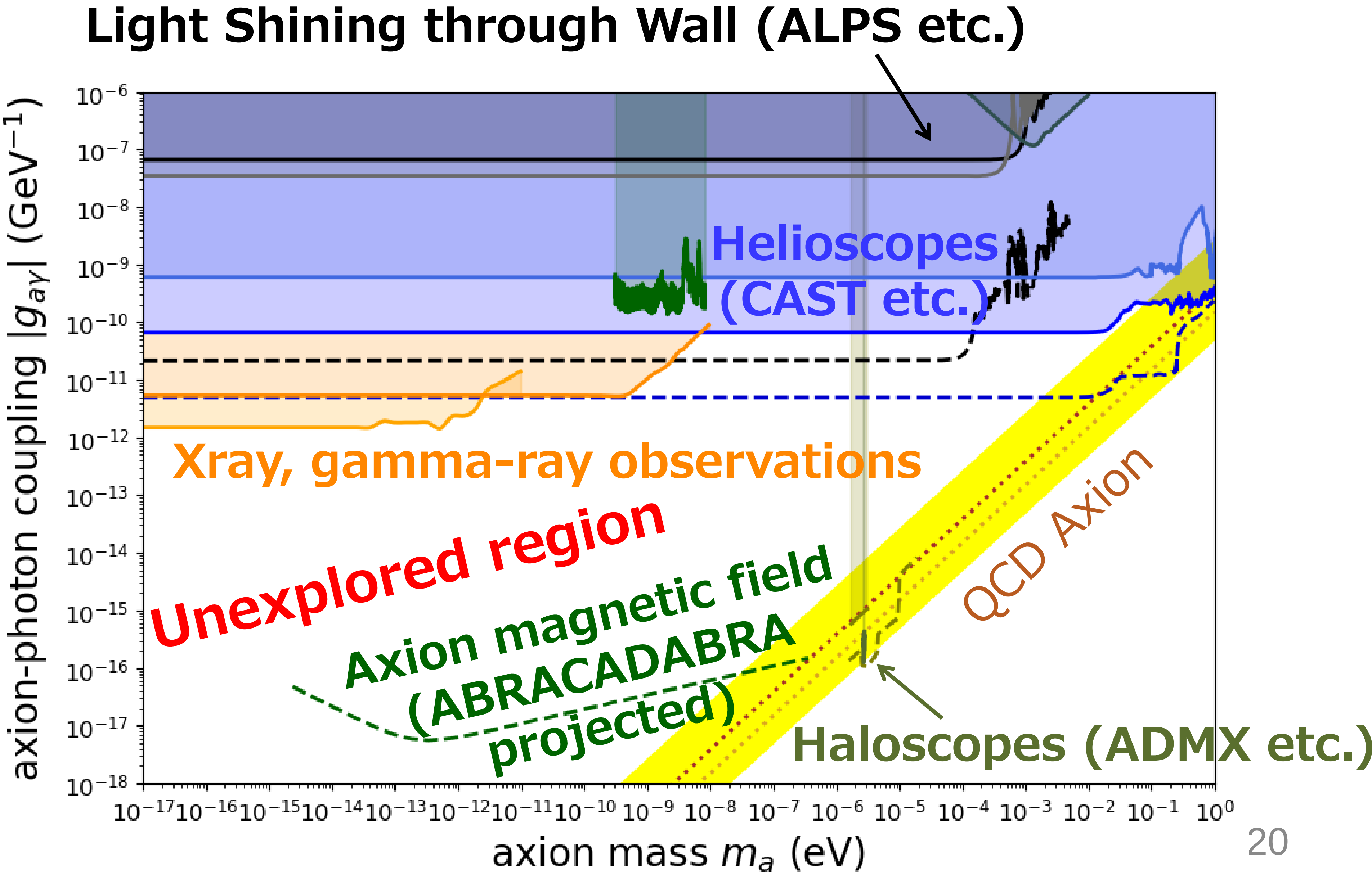


Various Proposals

- **Axion-like particles**
  - W. DeRocco & A. Hook, PRD **98**, 035021 (2018)
  - I. Obata, T. Fujita, YM, PRL **121**, 161301 (2018)
  - H. Liu+, PRD **100**, 023548 (2019)
  - K. Nagano, T. Fujita, YM, I. Obata, PRL **123**, 111301 (2019)
  - D. Martynov & H. Miao, PRD **101**, 095034 (2020)
- **Scalar fields**
  - Y. V. Stadnik & V. V. Flambaum, PRL **114**, 161301 (2015)
  - Y. V. Stadnik & V. V. Flambaum, PRA **93**, 063630 (2016)
  - A. A. Geraci+, PRL **123**, 031304 (2019)
  - H. Grote & Y. V. Stadnik, PRR **1**, 033187 (2019)
  - S. Morisaki & T. Suyama, PRD **100**, 123512 (2019)
- **$U(1)_B$ or $U(1)_{B-L}$ gauge bosons**
  - P. W. Graham+, PRD **93**, 075029 (2016)
  - A. Pierce+, PRL **121**, 061102 (2018)
  - D. Carney+, arXiv:1908.04797

Not exhaustive. There are also proposals for heavier DM (I think they are not promising).
The ones which require magnetic fields are not listed.

Search for Axion-Photon Coupling



Velocity of Circular Polarizations

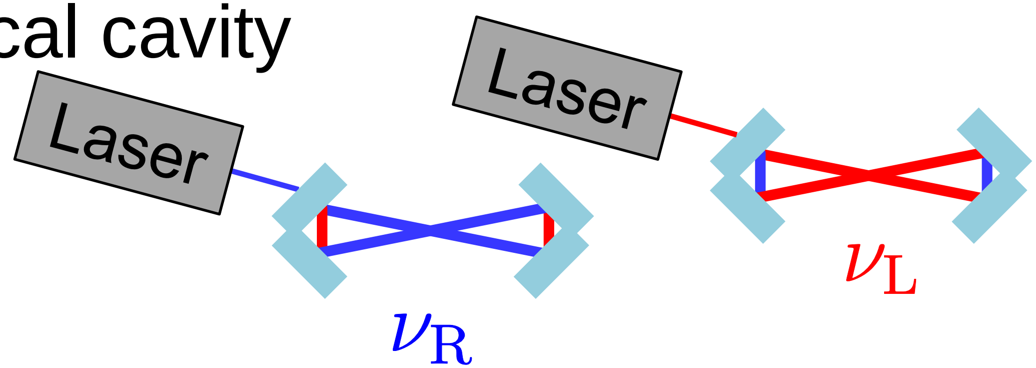
- Axion-photon coupling ($\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$) gives different phase velocity between left-handed and right-handed circular polarizations

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

coupling constant ($g_{a\gamma}$), axion field (a_0), axion mass (m_a)

- Measure the difference as resonant frequency difference in an optical cavity

$$\frac{\delta c}{c} = \frac{\nu_L - \nu_R}{\nu}$$

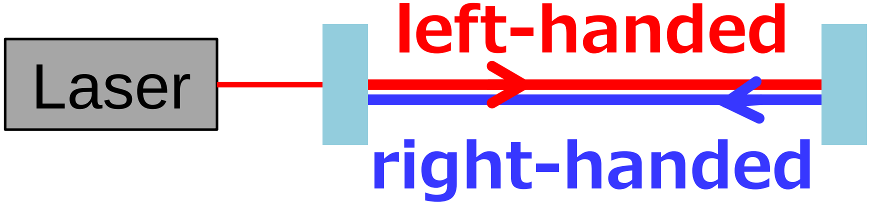


- Search can be done without magnetic field

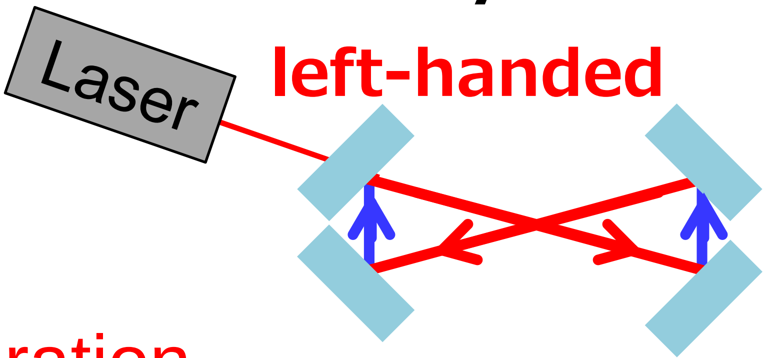
Our Ideas

- Use of bow-tie cavity

The effect is canceled in a linear cavity



Not canceled in a bow-tie cavity



- Use of double-pass configuration

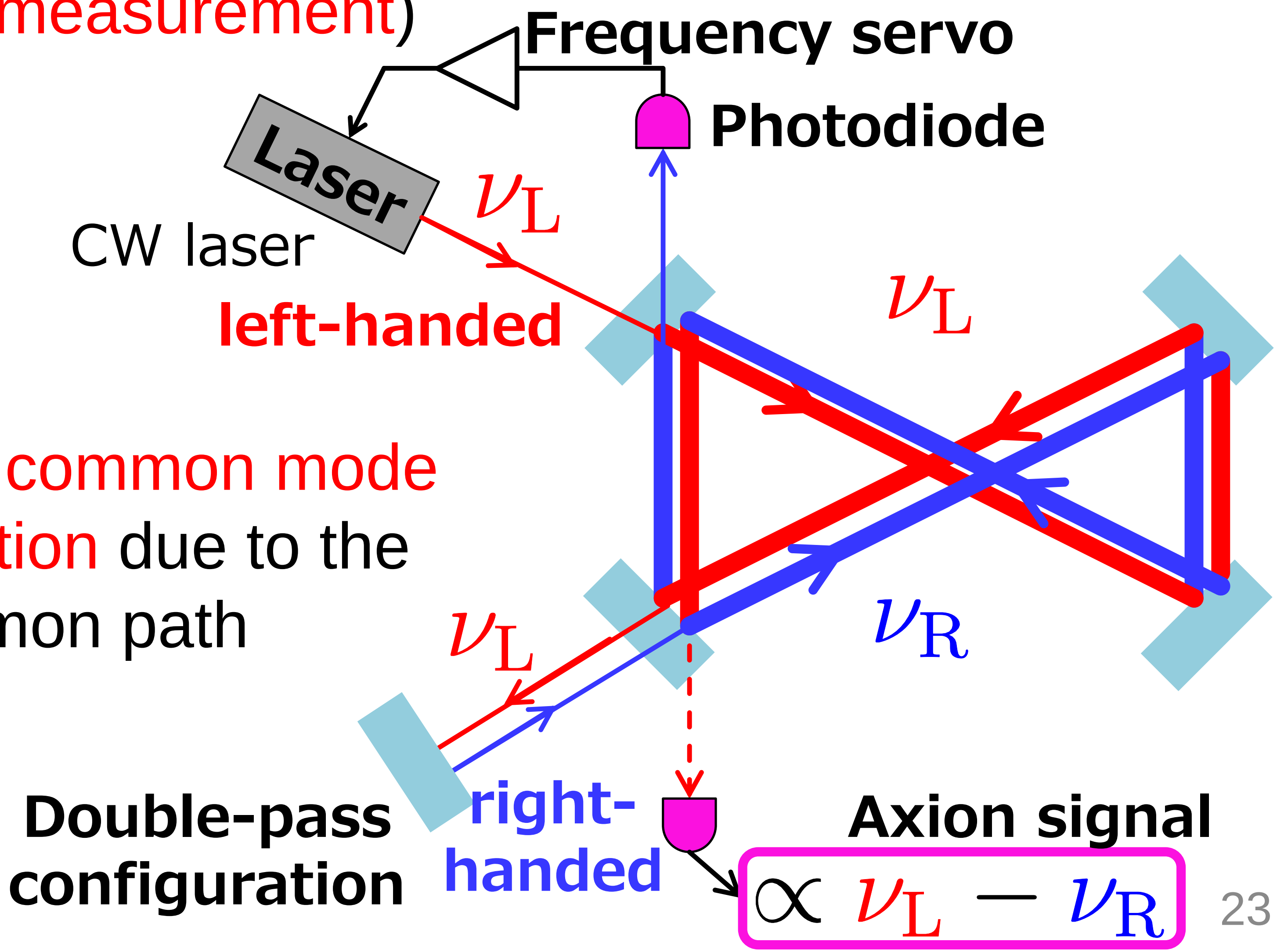
  Transmitted beam is reflected back into the same cavity as different polarization to realize a null measurement of the resonant frequency difference

Y.M+, PRL 110, 200401 (2013)

Double-Pass Configuration

- Axion signal is extracted from the cavity reflection (null measurement)

- High common mode rejection due to the common path



Sensitivity Calculation

- Cavity length changes (displacement noises) will not be a fundamental noise due to common mode rejection
- Ultimately limited by quantum shot noise

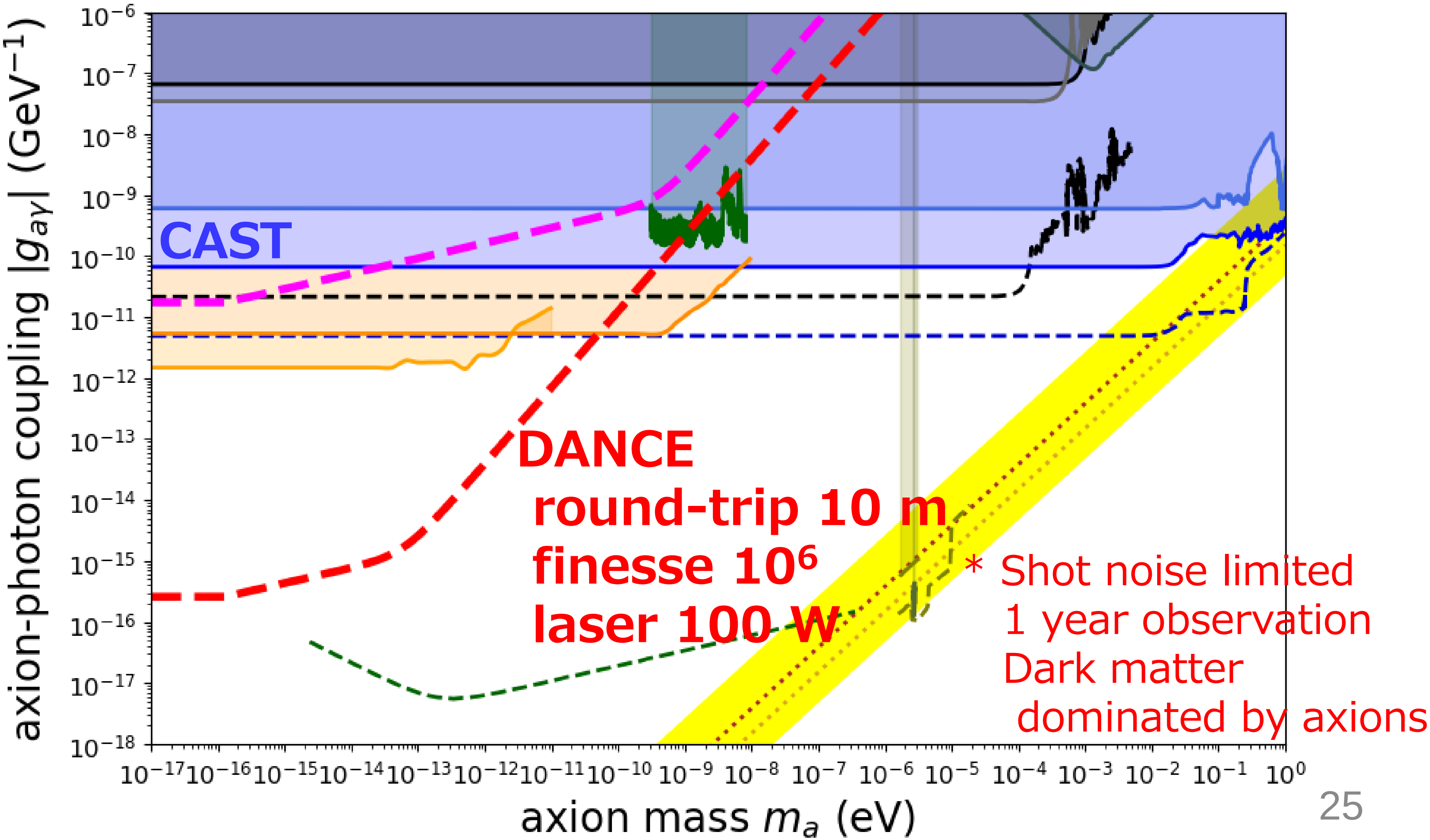
$$\sqrt{S_{\rm shot}} = \sqrt{\frac{\lambda}{4\pi P}\left(\frac{\pi^2}{L^2\mathcal{F}^2} + m_a^2\right)}$$

input laser power (P)
cavity length (L)
finesse ($\mathcal{F}$)
axion mass (m_a)

- Sensitivity to axion-photon coupling can be calculated by assuming
  axion density = dark matter density

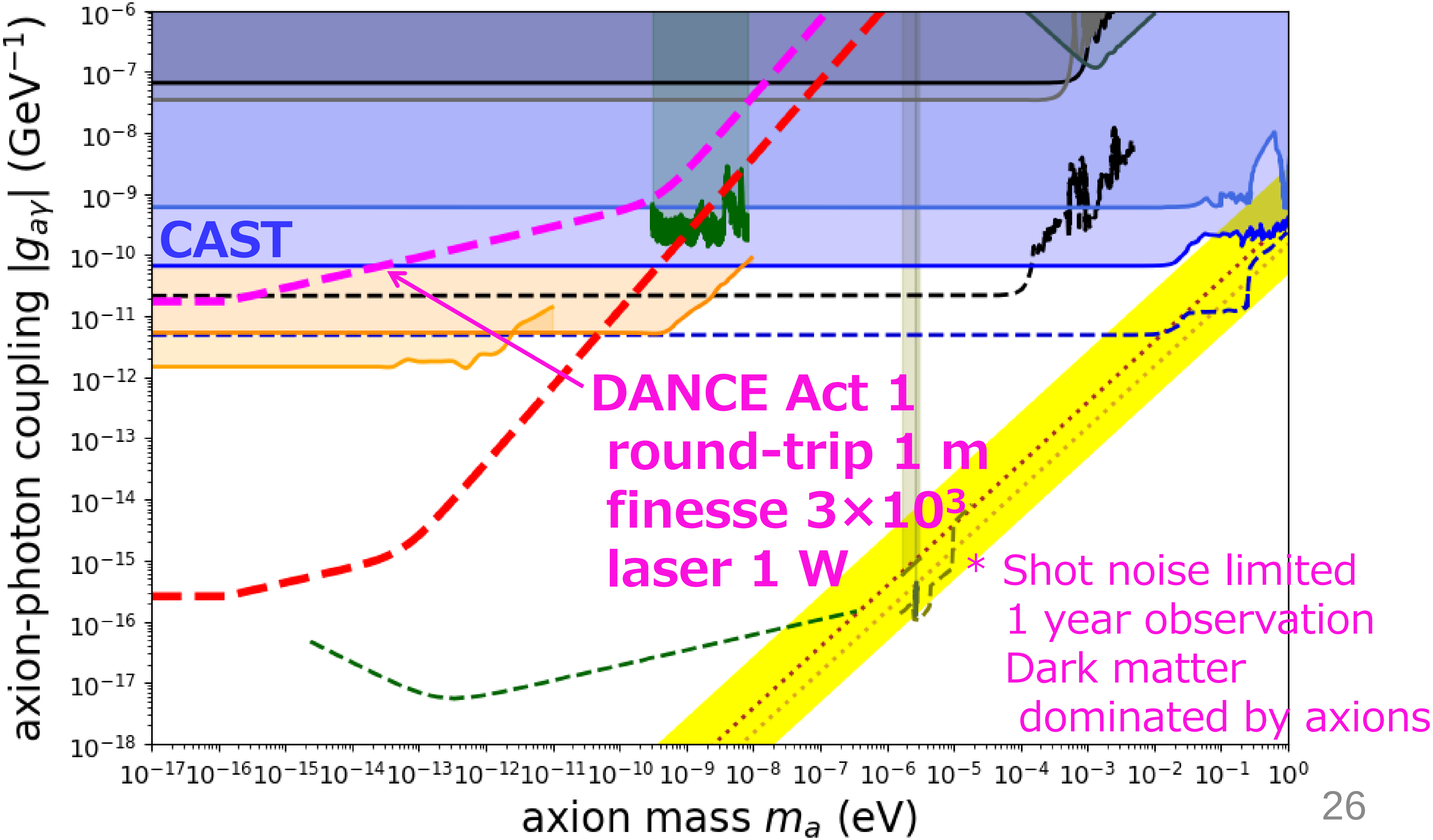
Search for Unexplored Region

Dark matter Axion search with riNg Cavity Experiment



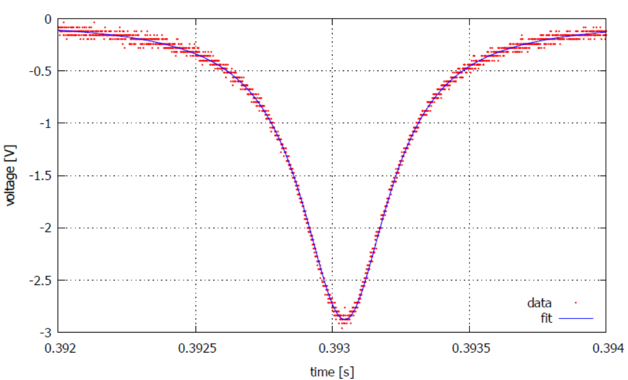
Prototype Experiment

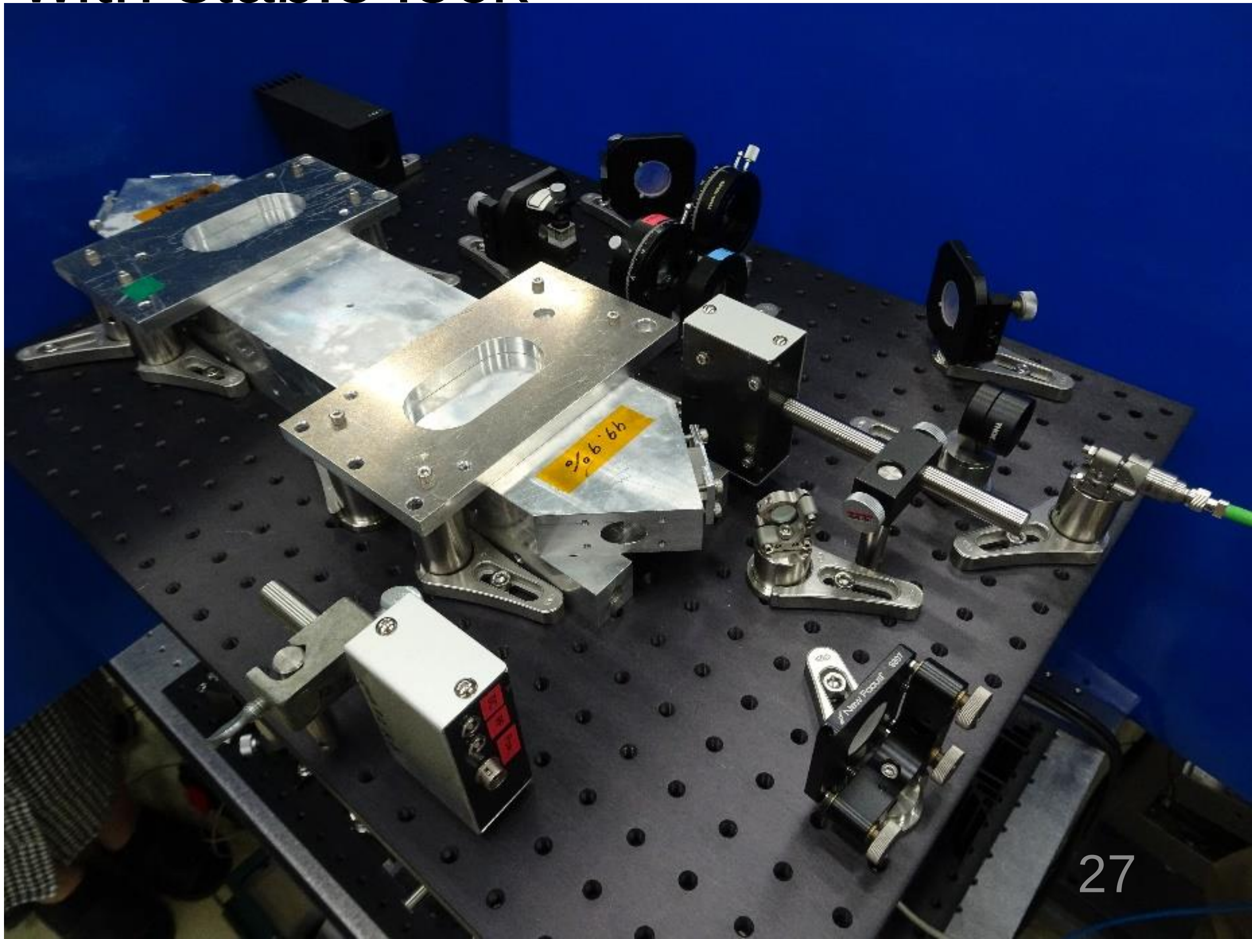
Dark matter Axion search with riNg Cavity Experiment



DANCE Act 1

- Completed the assembly of optics
- Finesse measured to be 515 +/- 6 (design: 3×10^3)
- Having trouble with stable lock
- Aiming for first run in 2020





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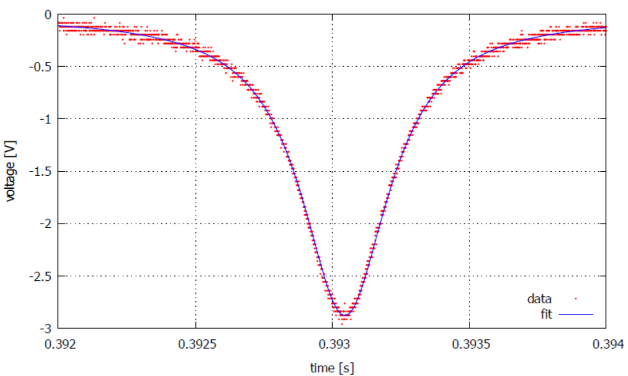
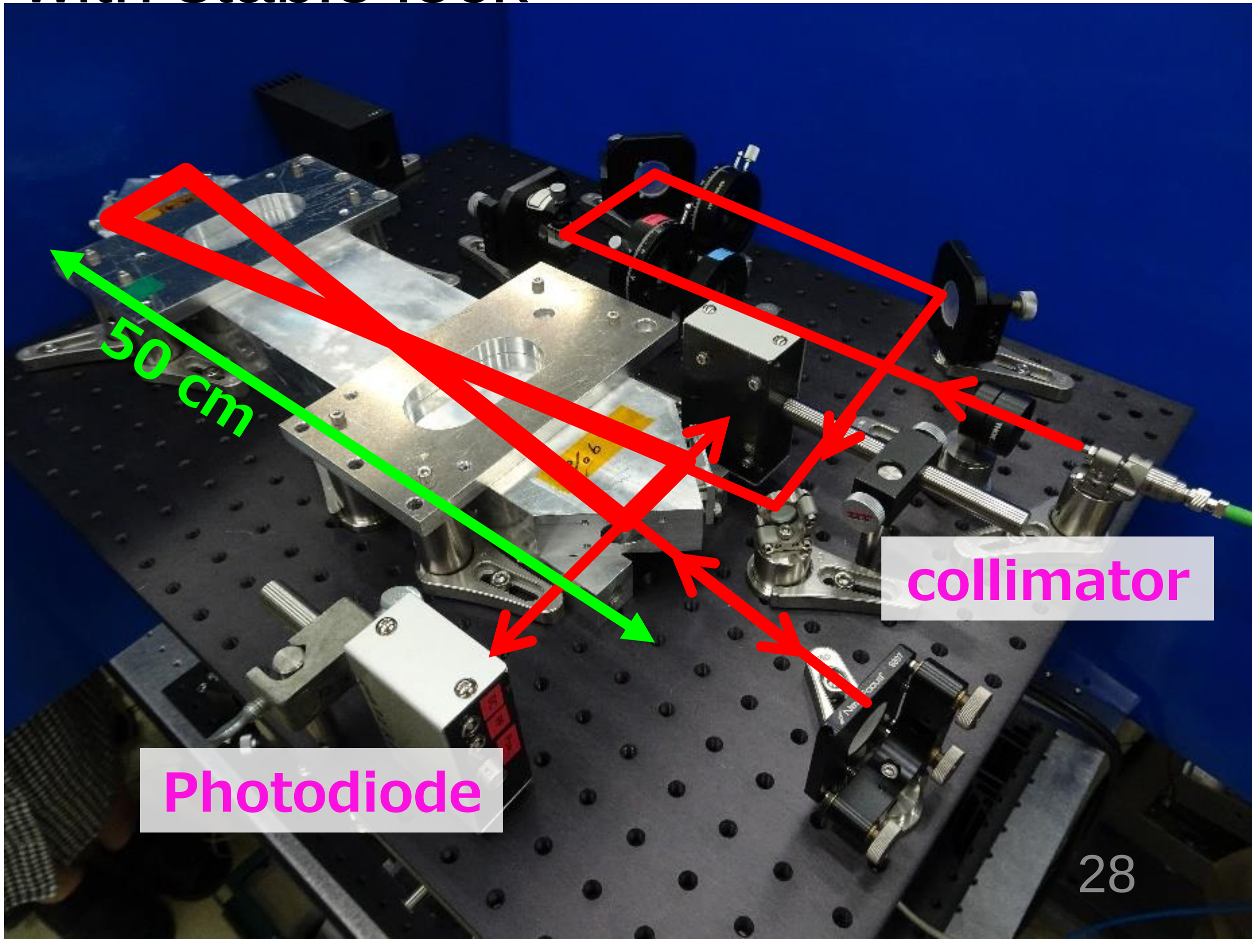
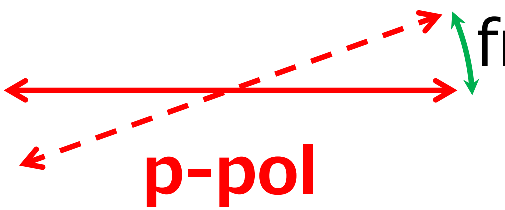
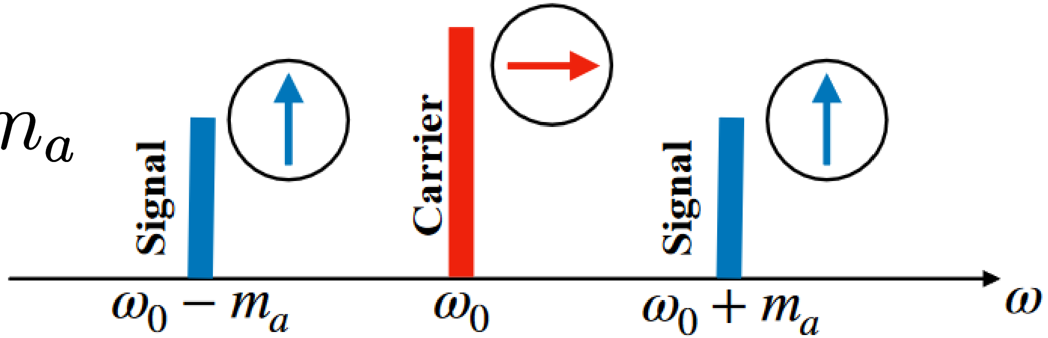




Search with Linear Cavity

- Linear polarization rotates at axion frequency



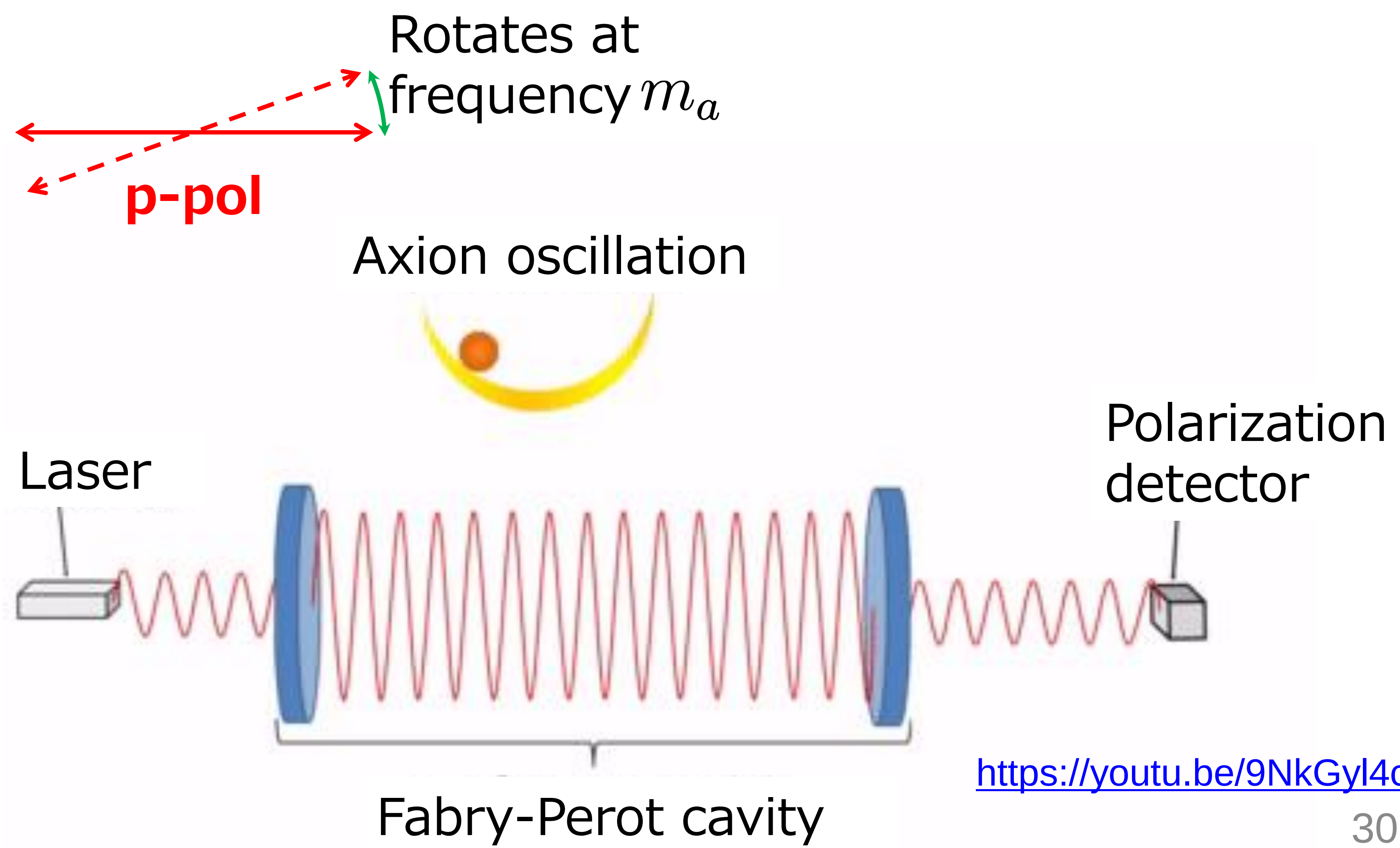


Liu+, PRD **100**, 023548 (2019)

- Sensitive when axion oscillation period and round-trip time of optical cavity is the same

Search with Linear Cavity

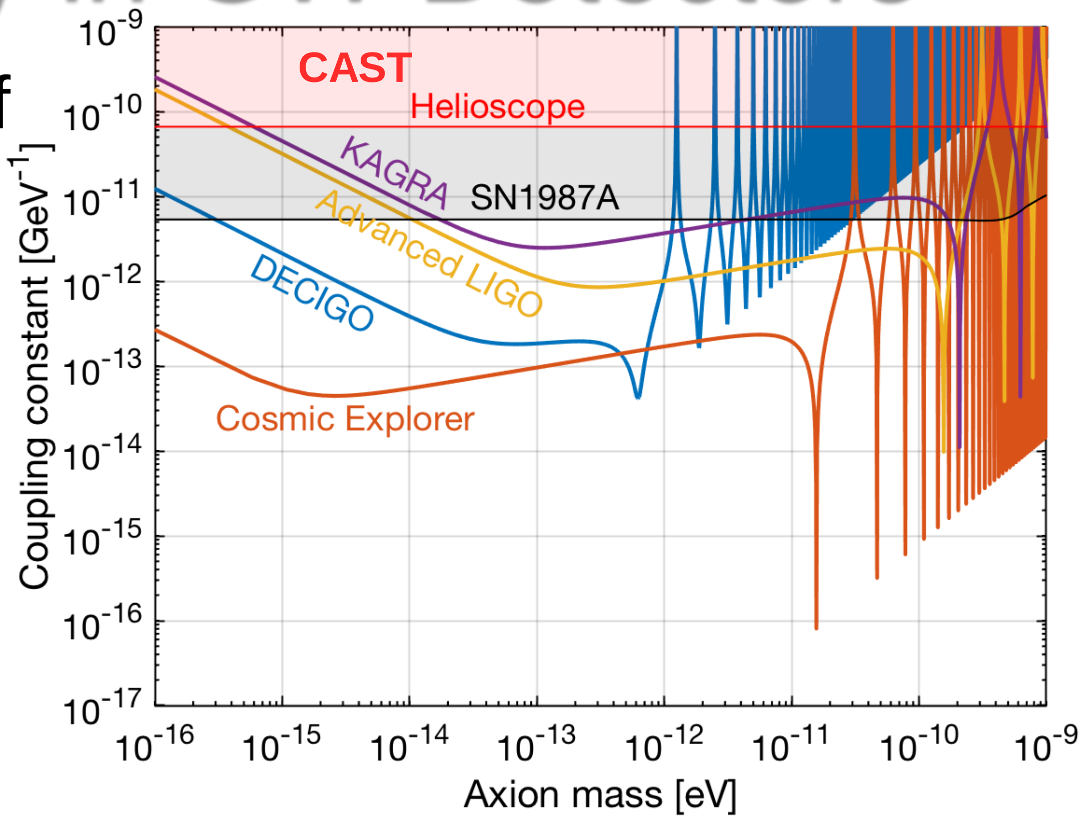
- Linear polarization rotates at axion frequency

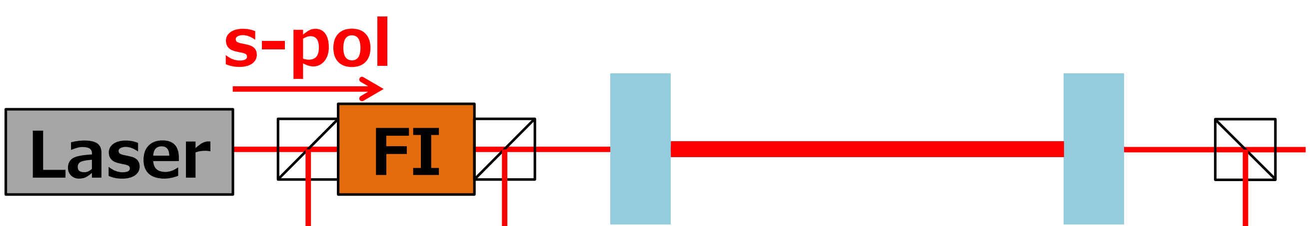


https://youtu.be/9NkGyl4cEks

Linear Cavity in GW Detectors

- Suitable because of long arms and high power
- Can be done simultaneously with GW observation
- Considering of applying to KAGRA





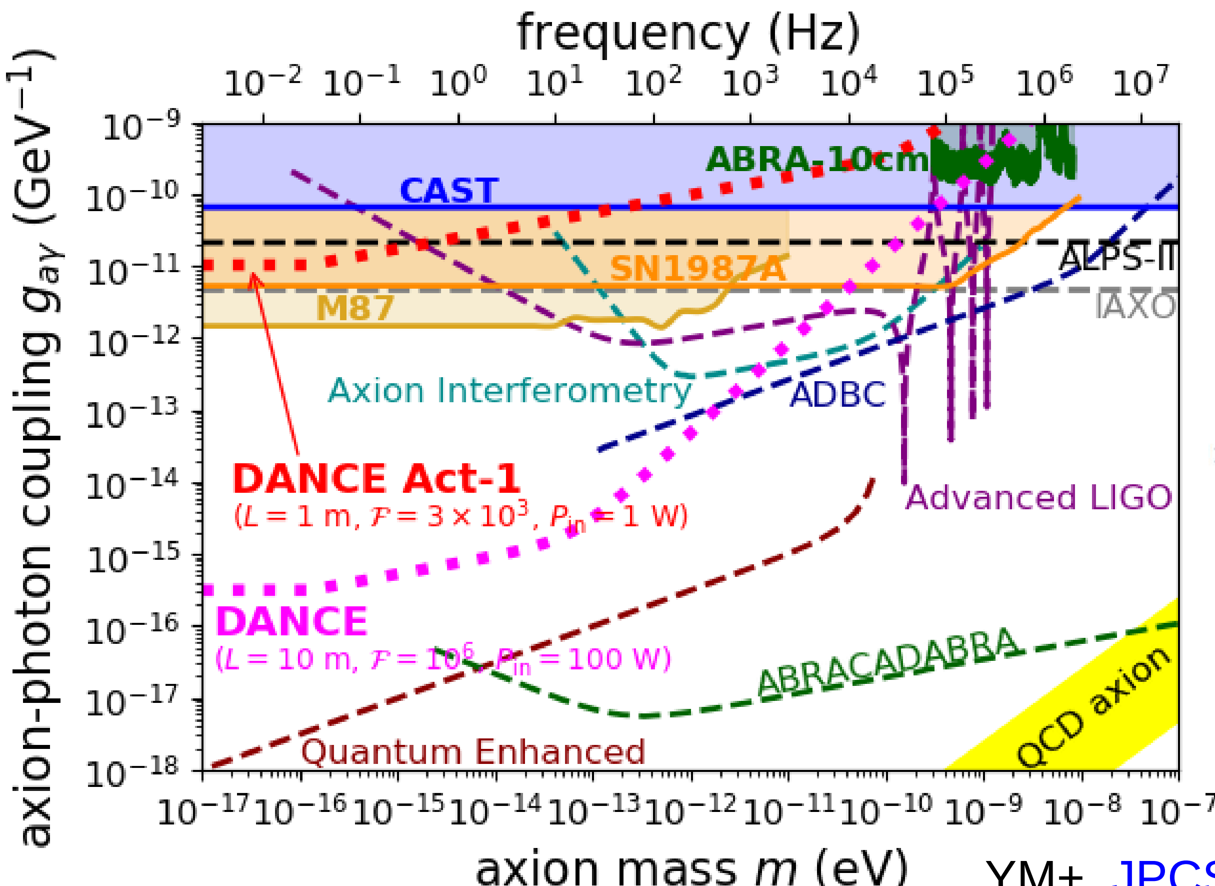
Nagano+, [PRL **123**, 111301 (2019)]

s-pol (GW signal) p-pol (Axion signal) p-pol (Axion signal)

Other Recent Proposals

- There are also different proposals for axion dark matter search with laser interferometers

  DeRocco & Hook, PRD **98**, 035021 (2018); Liu+, PRD **100**, 023548 (2019) ; Martynov & Miao, PRD **101**, 095034 (2020)



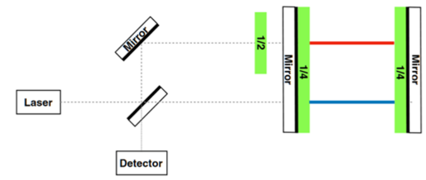


FIG. 3. A diagram of our proposed axion interferometer where

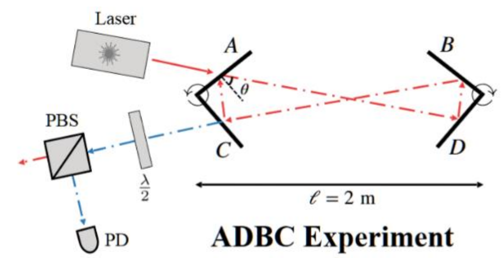
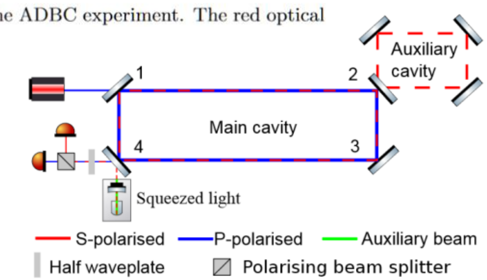


FIG. 2: Schematic of the ADBC experiment. The red optical



YM+, JPCS **1468**, 012032 (2020)

Search for Scalar Dark Matter

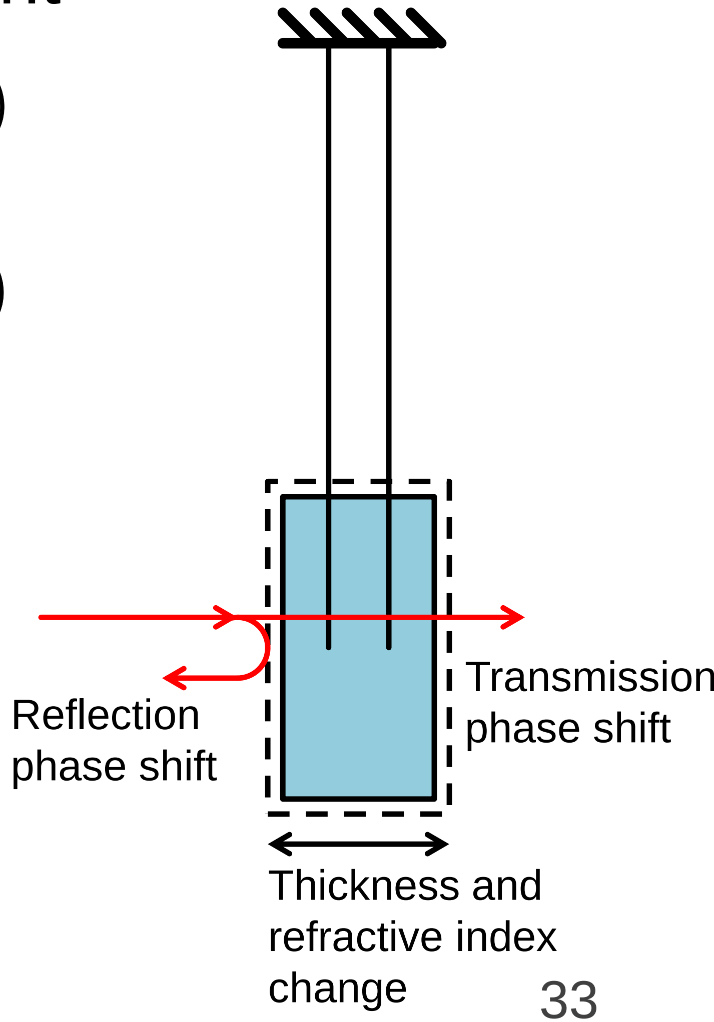
- Dilaton-like scalar DM drives oscillations in electron mass and fine structure constant

$$\frac{\delta m_{\mathrm{e}}}{m_{\mathrm{e}}} = \frac{1}{\Lambda_f}\phi_0 \cos\left(m_\phi t - \vec{k}\cdot\vec{r}\right)$$

$$\frac{\delta \alpha}{\alpha} = \frac{1}{\Lambda_\gamma}\phi_0 \cos\left(m_\phi t - \vec{k}\cdot\vec{r}\right)$$

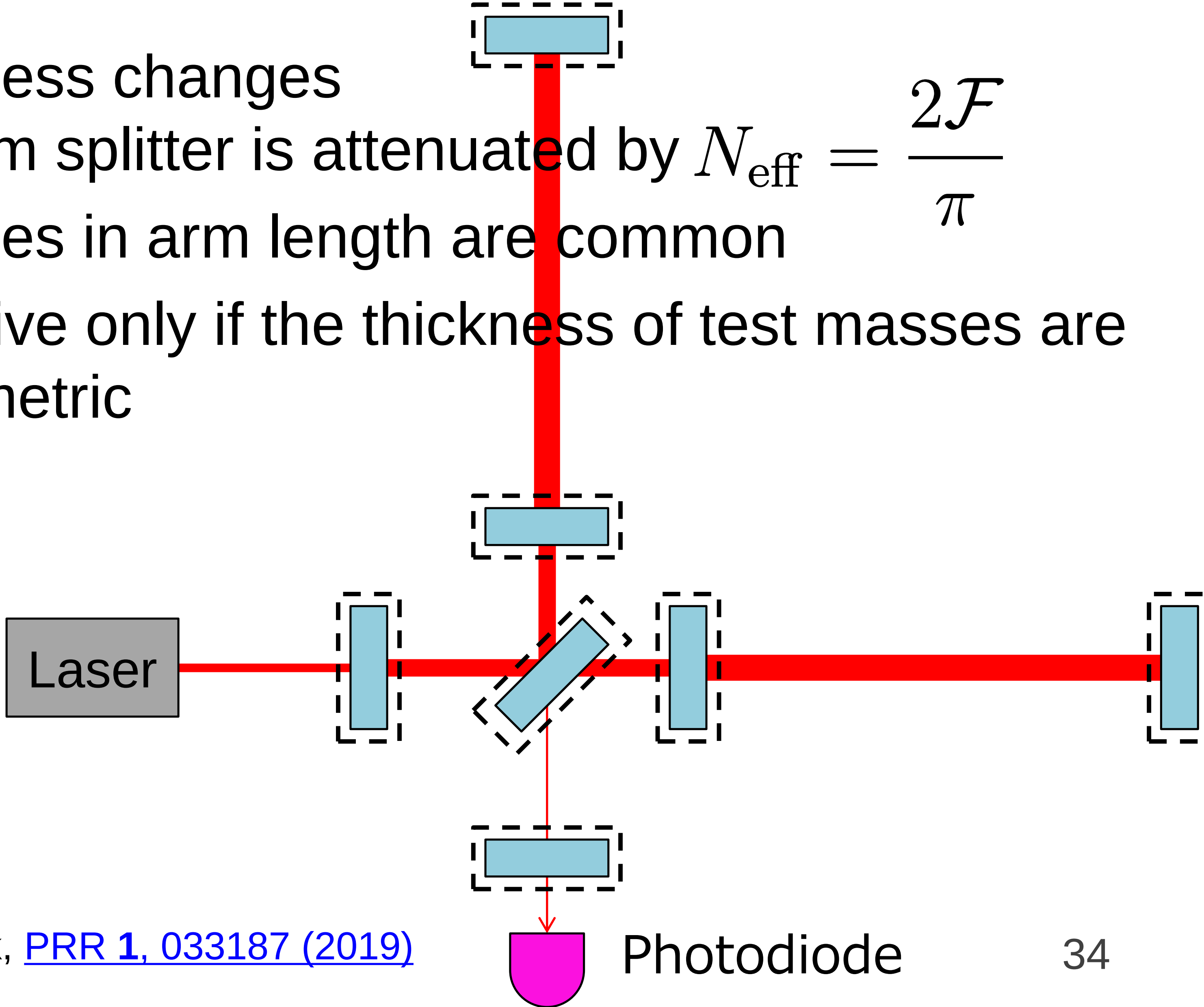
- This drives oscillations in the Bohr radius $a_0 = \frac{\hbar}{\alpha m_{\mathrm{e}} c}$
- The size and refractive index of mirrors changes

$$\frac{\delta l}{l} = \left(-\frac{\delta\alpha}{\alpha} - \frac{\delta m_{\mathrm{e}}}{m_{\mathrm{e}}}\right)$$



Search with GW Detectors

- Thickness changes in beam splitter is attenuated by $N_{\mathrm{eff}} = \frac{2\mathcal{F}}{\pi}$
- Changes in arm length are common
- Sensitive only if the thickness of test masses are asymmetric



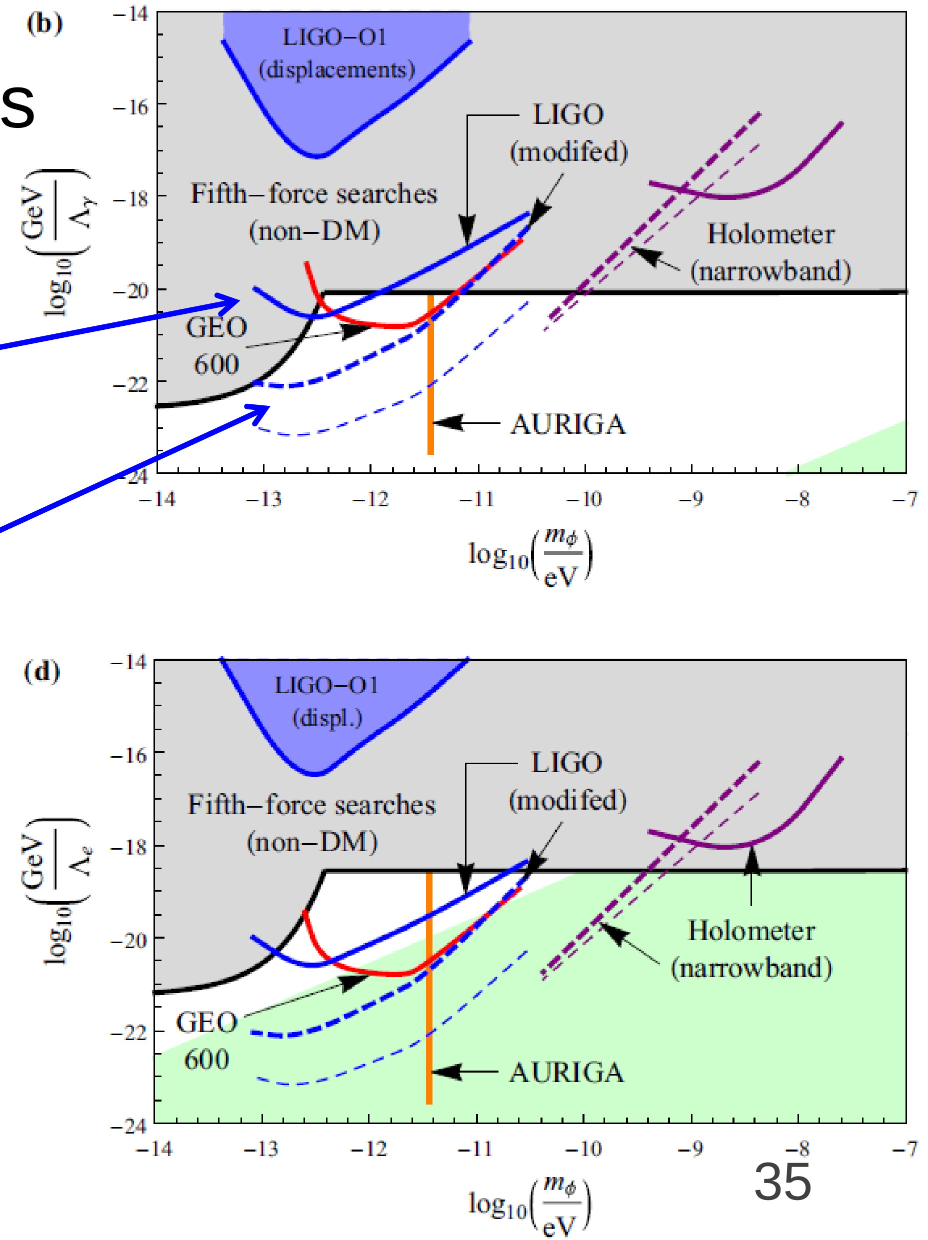
Grote & Stadnik, PRR **1**, 033187 (2019)

Sensitivity to Scalar DM

- Promising if test masses are asymmetric

Advanced LIGO design
(ΔI_{TM} = 80 um; BS effect dominates)

Advanced LIGO modified
($\Delta I_{TM} / I_{TM}$ = 10%; TM effect dominates)



* 10^8 sec observation assumed

Grote & Stadnik, PRR **1**, 033187 (2019)

Search for Vector Dark Matter

- Dark gauge bosons (e.g. dark photon)
- New gauge symmetry: B-L (baryon number minus lepton number)
  - B-L is conserved in standard model
  - B-L could be the charge for dark gauge boson
- Gauge bosons give acceleration to mirrors

Dimensionless coupling strength

Dark charge
q/M ~ 1/2 /GeV for B-L

$$\vec{a}(t,\vec{r}_i) = \epsilon_{\mathrm{B-L}} e \frac{q_{\mathrm{B-L},i}}{M_i} m_{\mathrm{A}} \vec{A}_0 \cos\left(m_{\mathrm{A}} t - \vec{k}_{\mathrm{A}} \cdot \vec{r}_i\right)$$

- Arm cavity differential length change

If q/M is the same for all the mirrors

$$\sqrt{\langle \delta L^2 \rangle} = \frac{\sqrt{2}}{3} \frac{|a| kL}{m_{\mathrm{A}}^2}$$

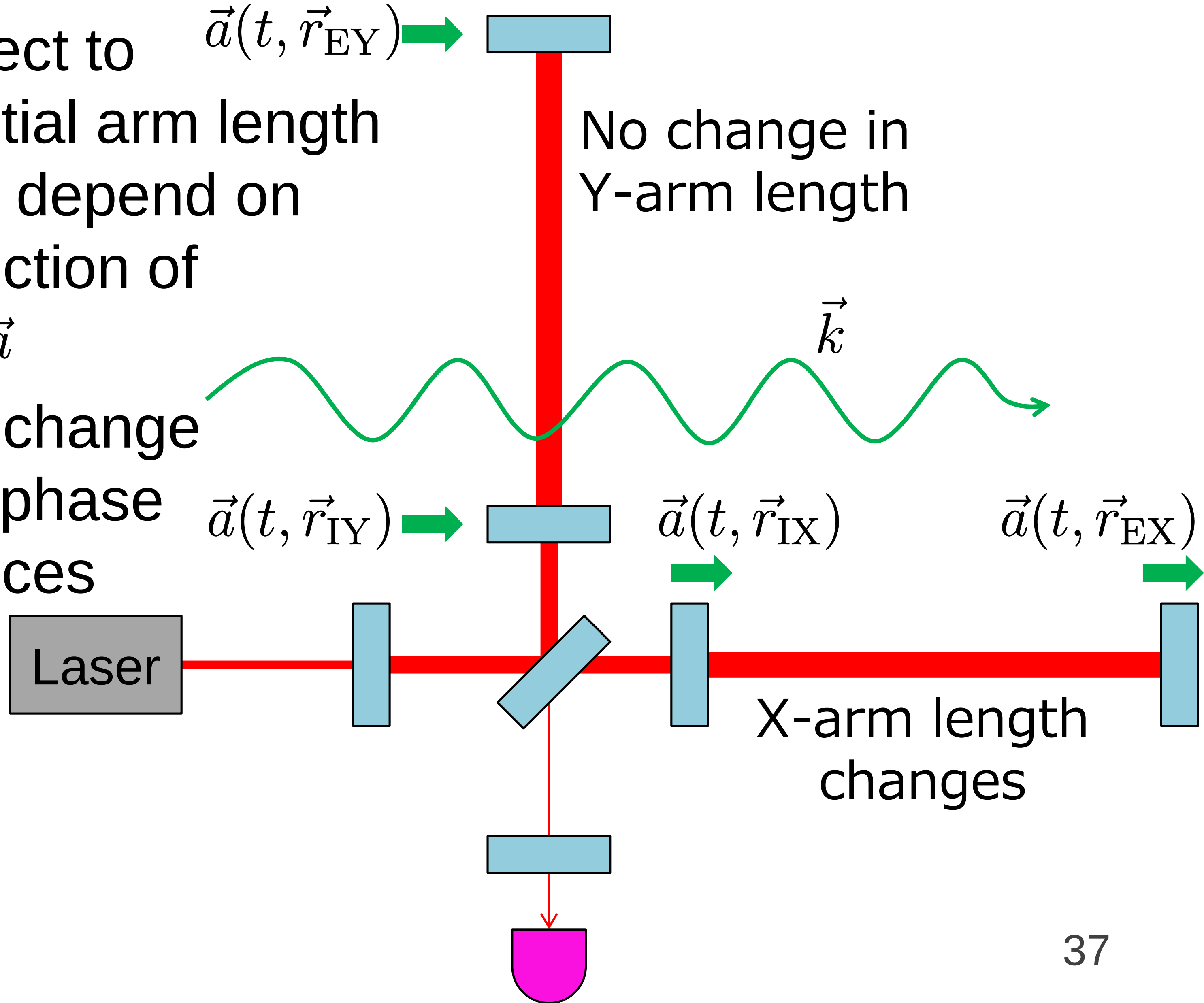
~10^{-6}
for mA = 100 Hz = 4e-13 eV
and L=4 km (Advanced LIGO)

Averaged over all directions of a and k

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

Sensitivity to $U(1)_{B-L}$ Gauge Boson

- The effect to differential arm length change depend on the direction of $\vec{k}$ and $\vec{a}$
- Length change rely on phase differences

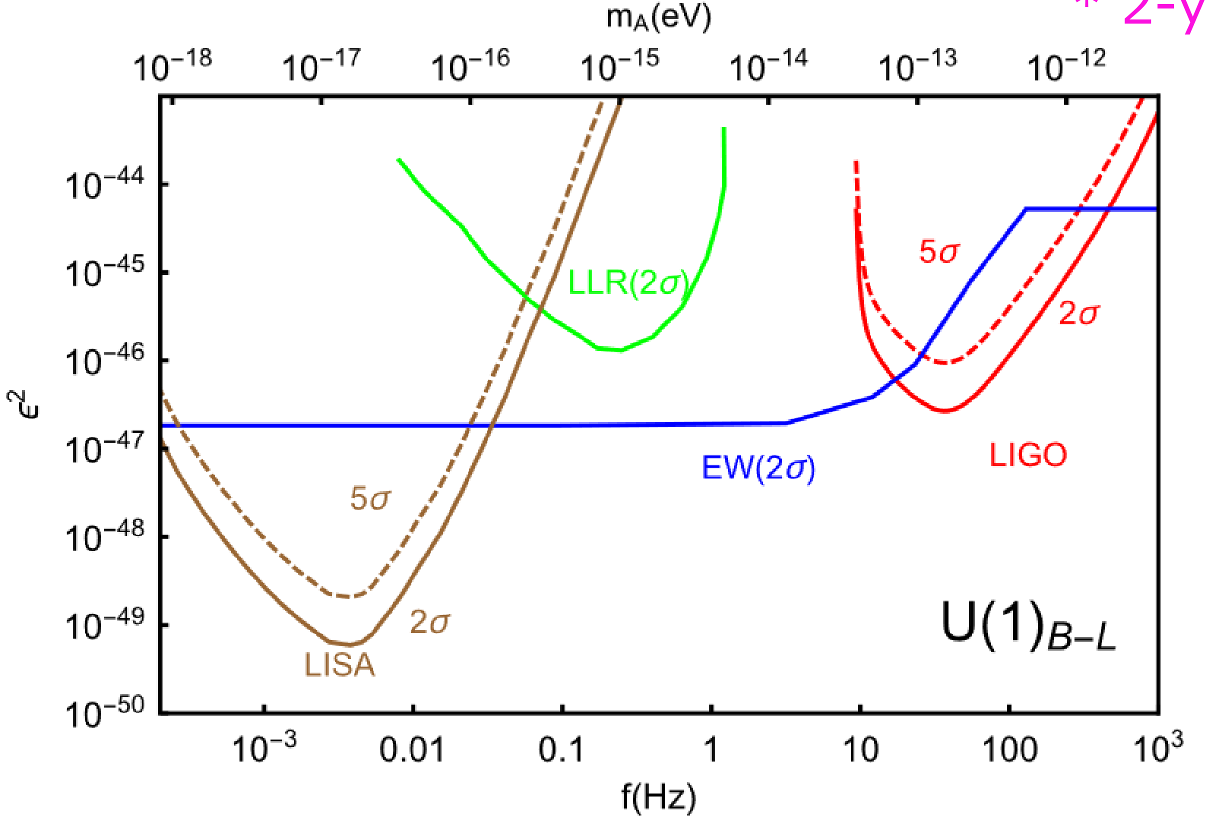


Sensitivity to $U(1)_{B\text{-}L}$ Gauge Boson

- Sensitivity can be better than equivalence principle tests with torsion pendulum

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

* 2-year observation assumed



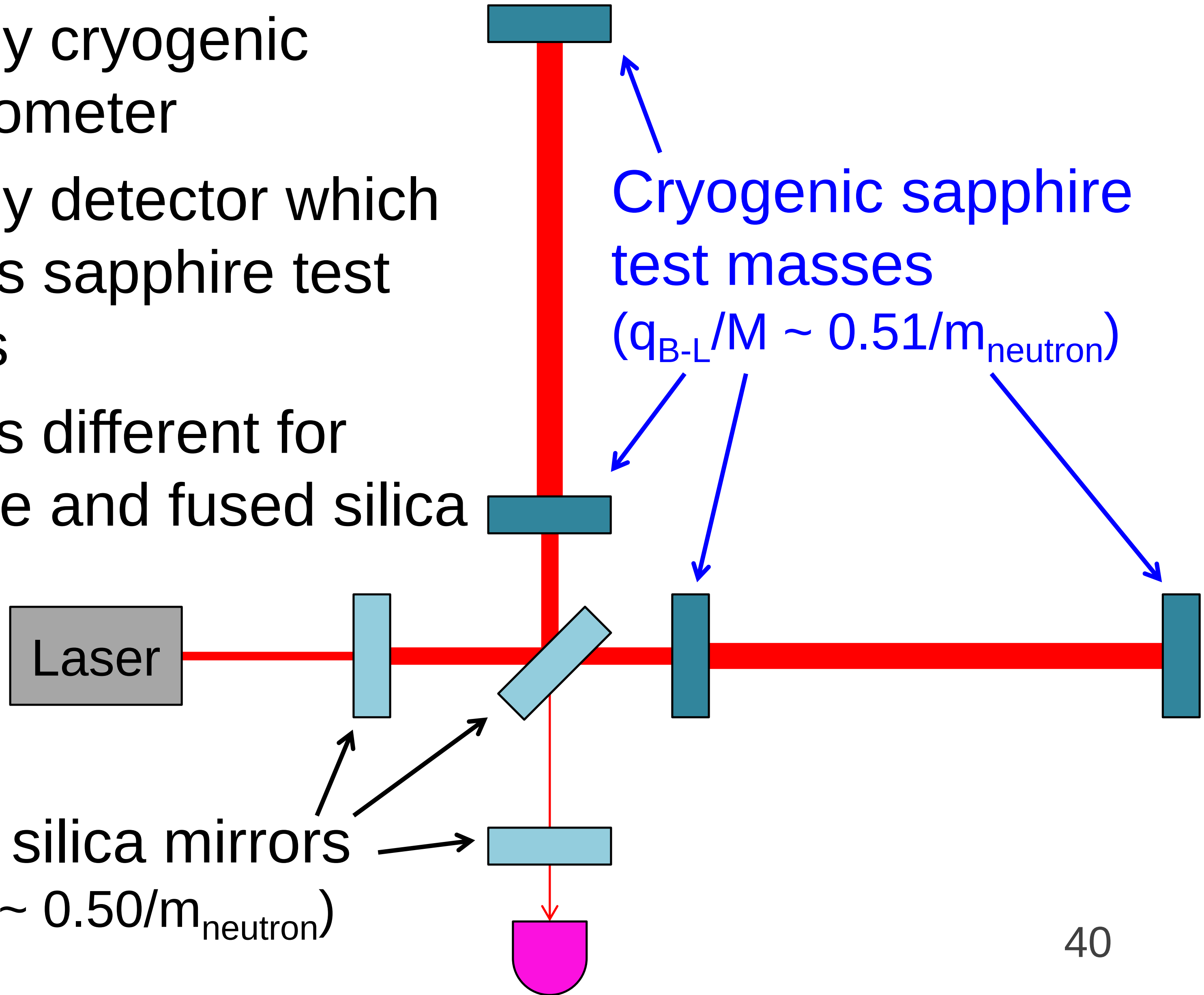
Our New Idea

- Issues with previous proposals for scalar and vector dark matter search
  - the effect is common to test masses
  - the effect is common to both arm cavities
- The sensitivity rely on slight asymmetry in the arm cavities or small phase differences in distant test masses

- How about using auxiliary length signals to enhance the sensitivity?
  - power/signal recycling cavity
  - Michelson interferometer

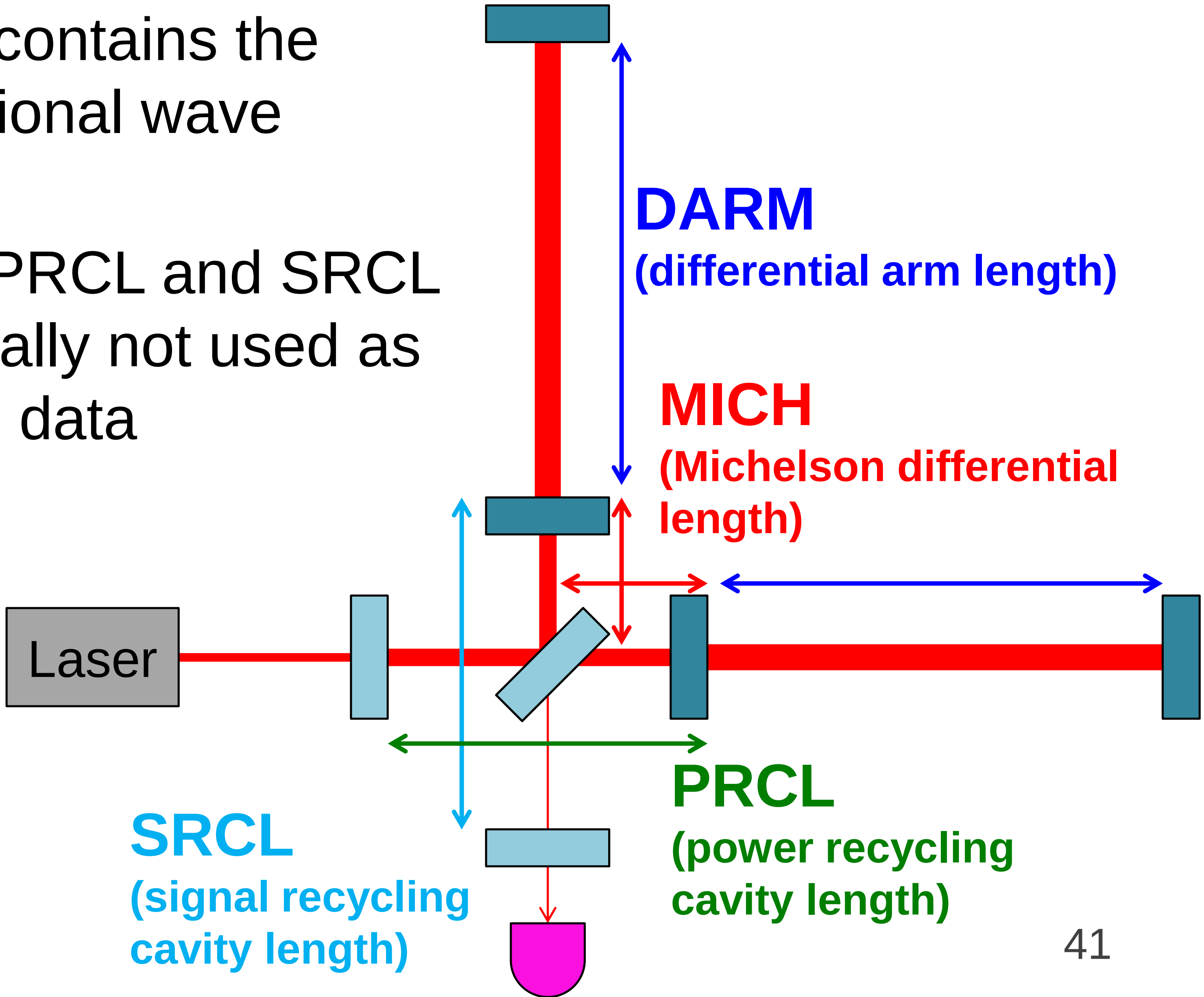
KAGRA Interferometer

- The only cryogenic interferometer
- The only detector which employs sapphire test masses
- q_{B-L}/M is different for sapphire and fused silica



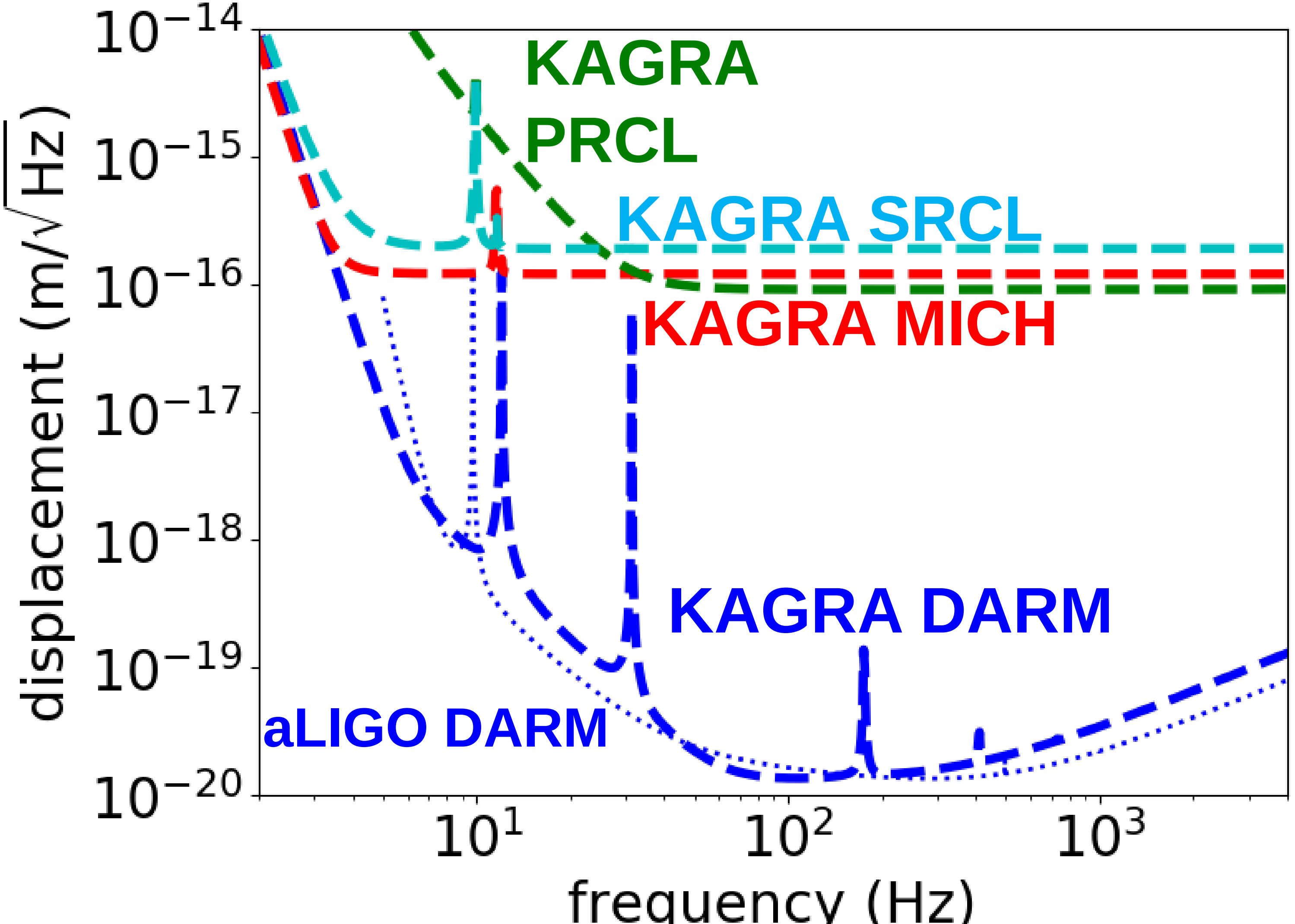
Auxiliary Length Signals

- DARM contains the gravitational wave signal
- MICH, PRCL and SRCL are usually not used as science data



Displacement Sensitivity

- Auxiliary signals are not so sensitive at high freq.



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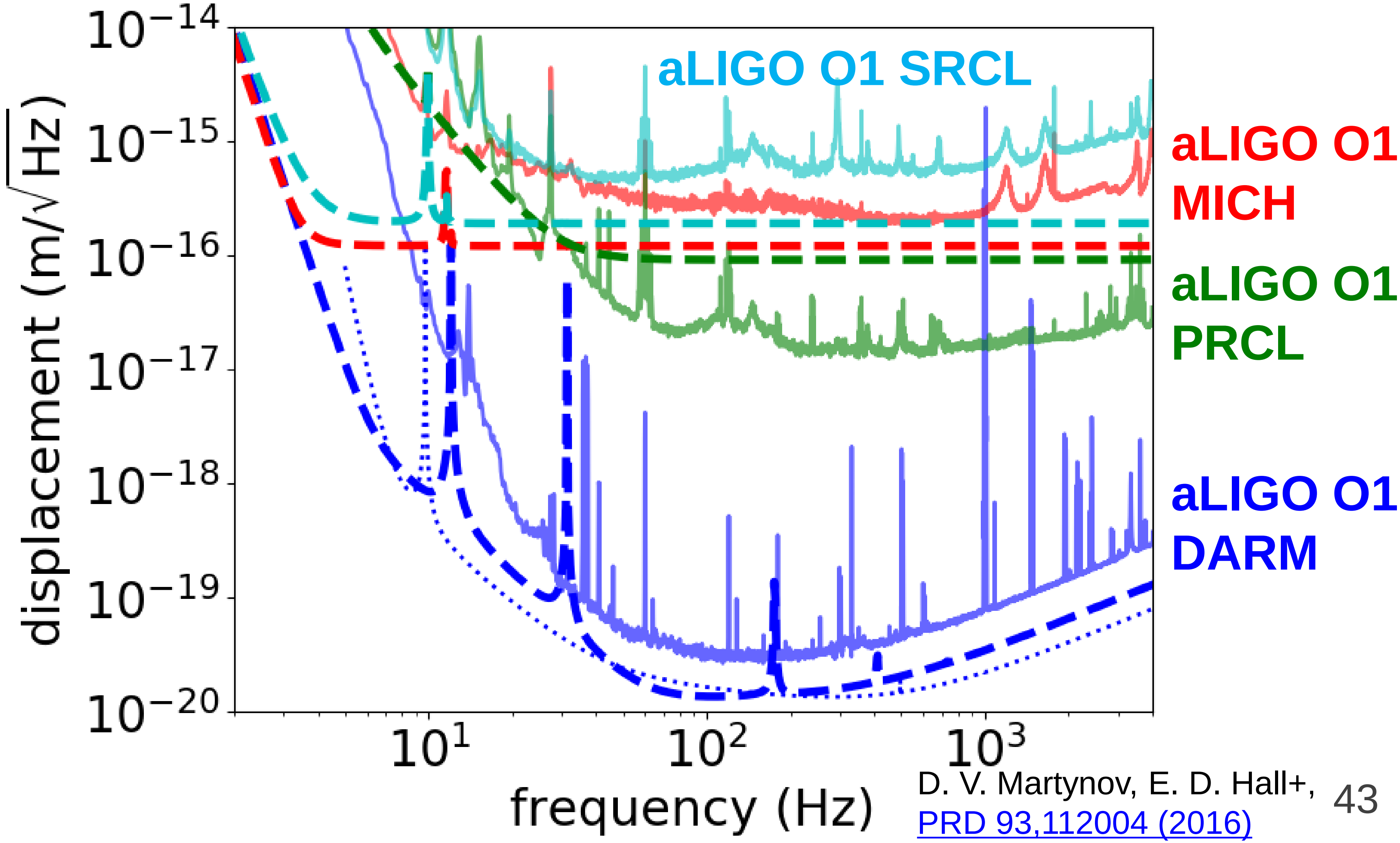
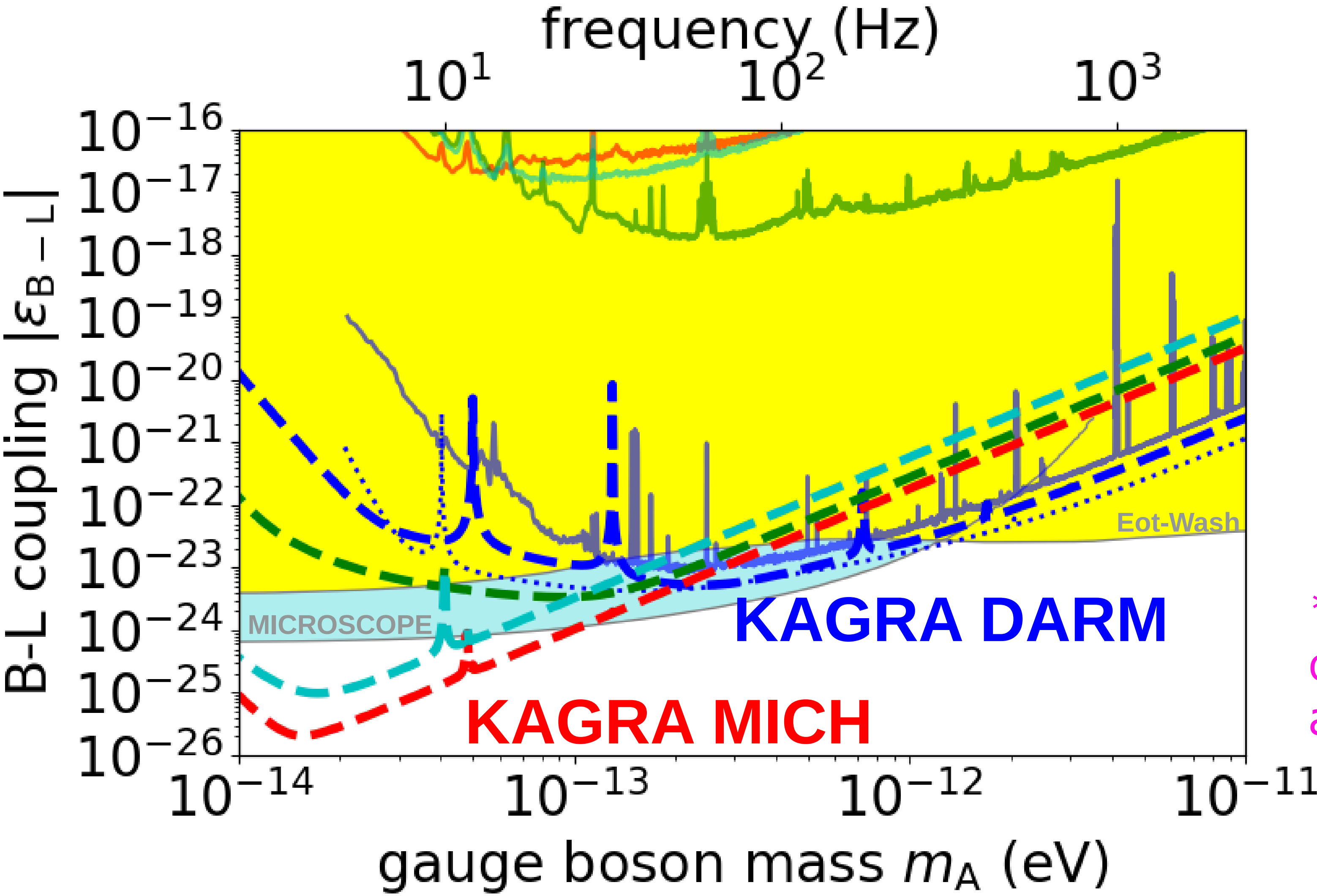


D. V. Martynov, E. D. Hall+, PRD 93,112004 (2016)

Sensitivity to $U(1)_{B\text{-}L}$ Gauge Boson

- Auxiliary signals can have better sensitivity



* 1-year observation assumed

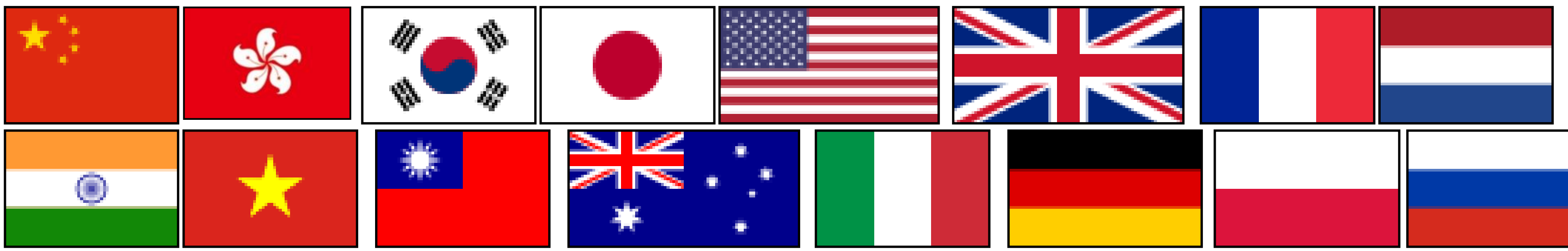
Dark matter search with KAGRA

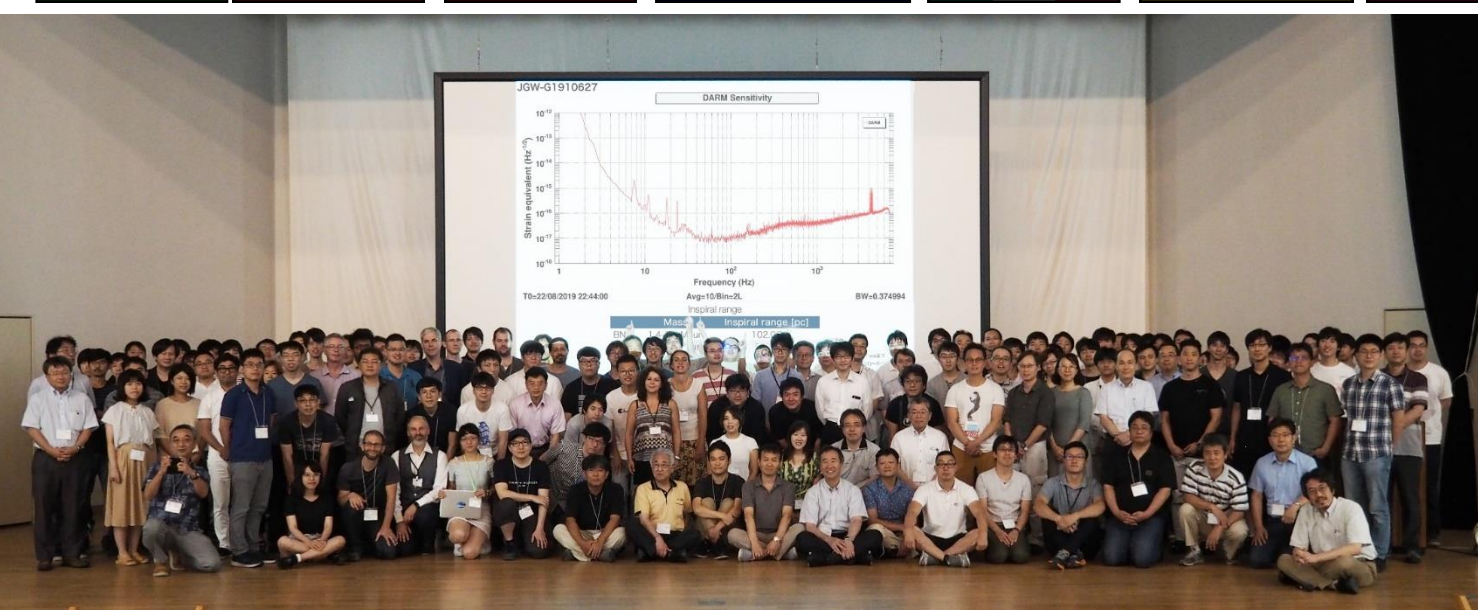
KAGRA Project

KAGRA

- Budget approved in 2010
- 110 institutes, 450+ collaborators (200 authors)
- Cryogenic and underground

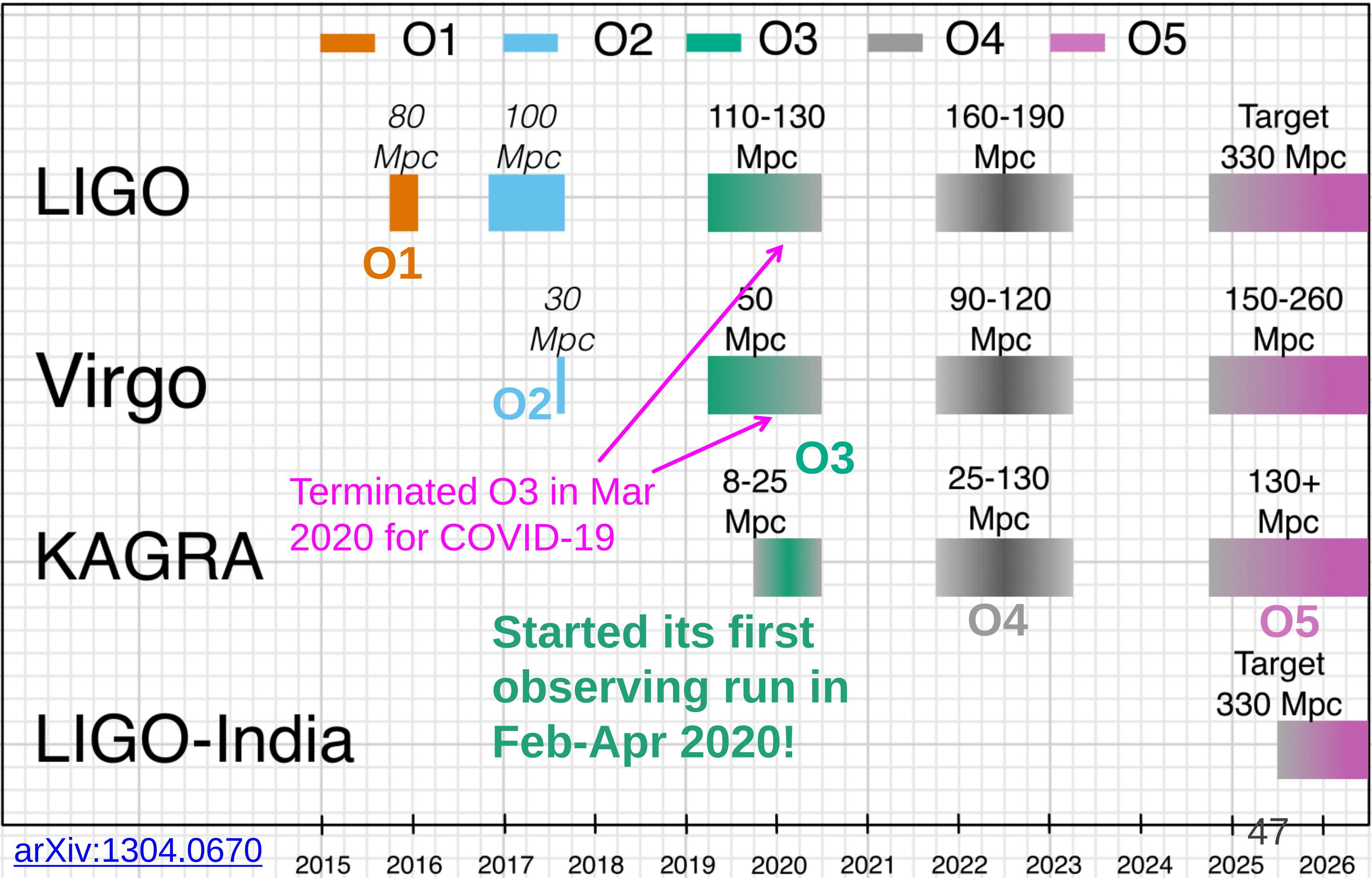
Join us!





Aug 2019
F2F meeting
@ Toyama

Observing Plans



arXiv:1304.0670

First KAGRA Observing Run

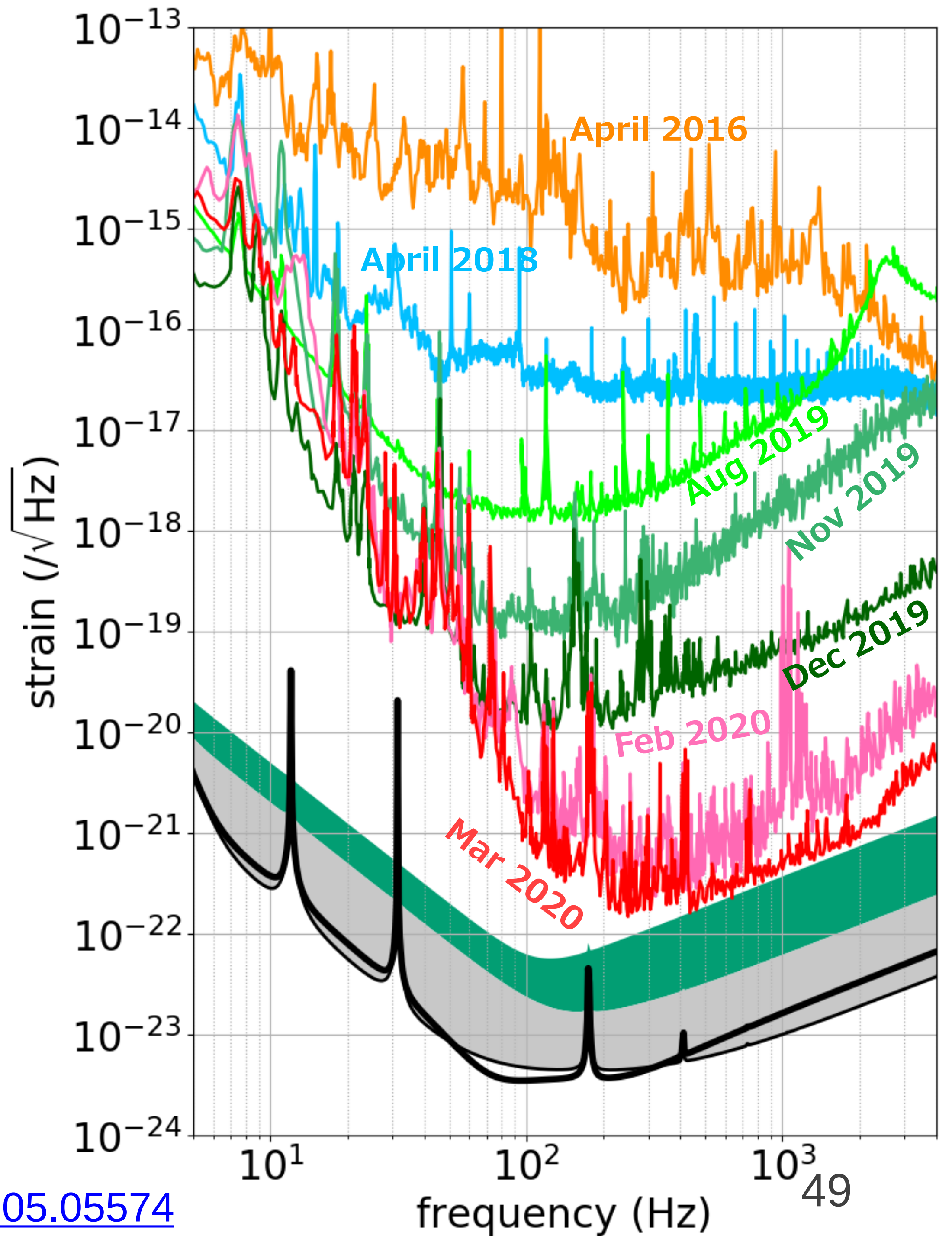
- Officially started on February 25, 2020
- But soon stopped to resume interferometer tuning
- Observing run restarted on April 7 to April 21
  - with ~0.6 Mpc in binary neutron star range
  - ~170 hours of science data

arXiv:2005.05574

- Joint observation with LIGO and Virgo was not possible

Sensitivity Improvements

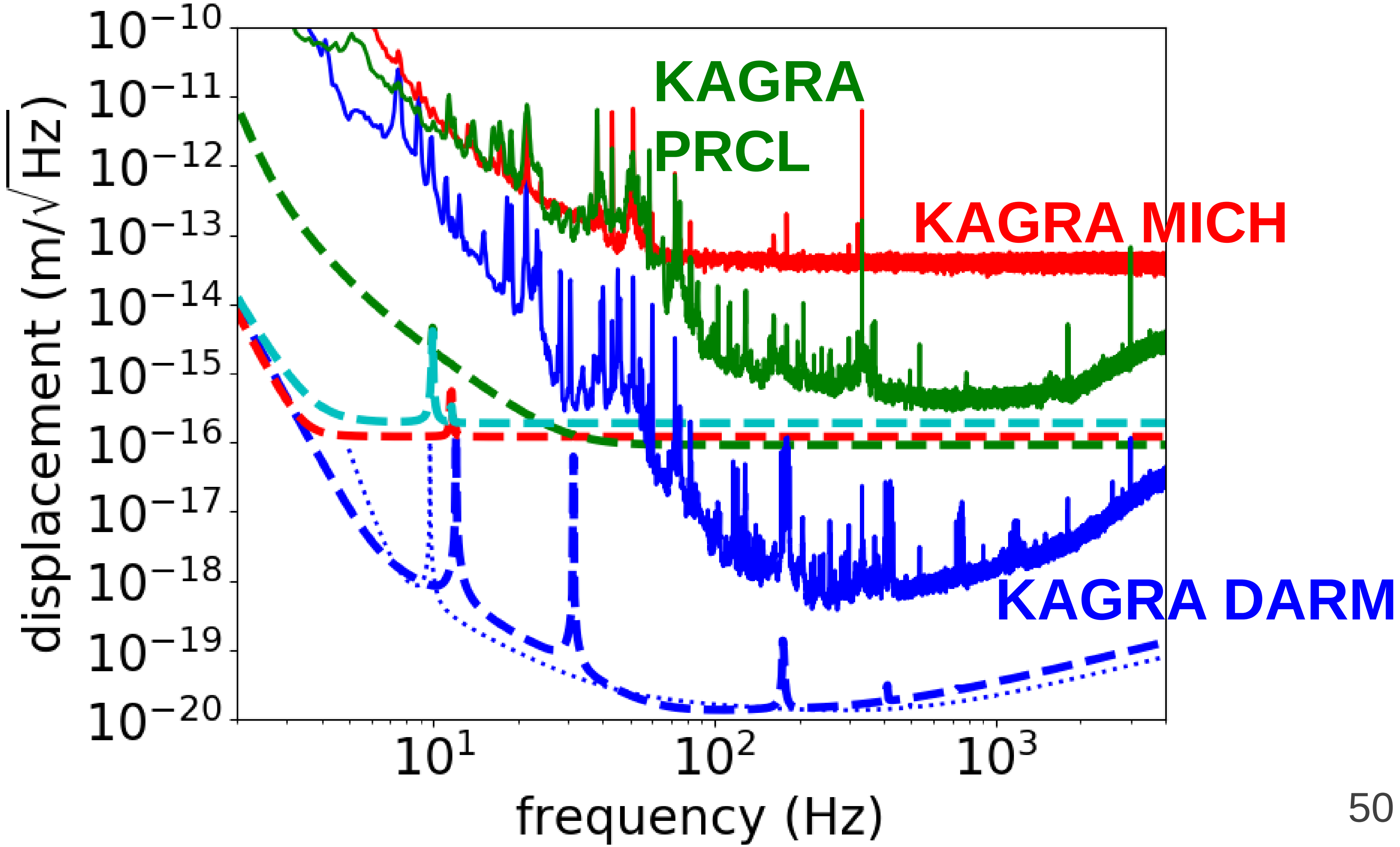
- Dramatic sensitivity improvement in the last 7 months



[arXiv:2005.05574](https://arxiv.org/abs/2005.05574)

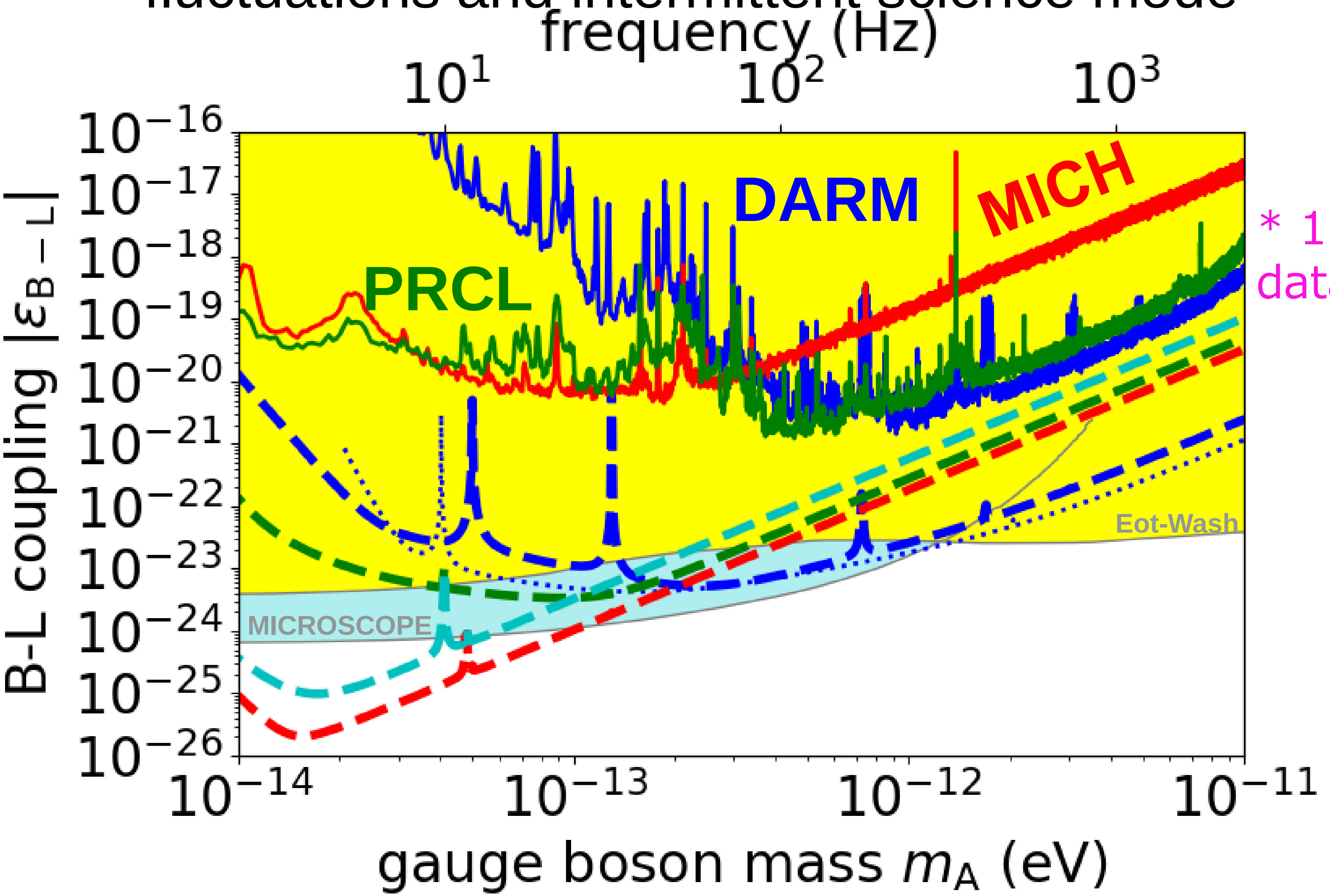
Best Sensitivity on March 20, 2020

- ~2 orders of magnitude worse than the designed



Prospected Sensitivity for $U(1)_{B-L}$

- Actual limit would be worse due to sensitivity fluctuations and intermittent science mode



* 170 hours of data assumed

Plans for Dark Matter Search

- Development of data analysis code underway
- First try with O3 data
  - this will be the first search for $U(1)_{B-L}$ gauge boson with laser interferometer
- Planning to install polarization optics to search for axion-like particles by O4 (~2021)
- Stay tuned for dark matter signals from gravitational wave detectors!

Summary

- Laser interferometers are attractive tools to search for ultralight dark matter
- Axion-like particles can be searched with polarization measurements
- Scalar fields can be searched through variations in the optical thickness of mirrors
- Gauge bosons can be searched through measuring forces acting on mirrors
- KAGRA can do unique searches because of the use of sapphire mirrors