16th Marcel Grossmann Meeting @ Online

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Searching for ultralight vector dark matter with the cryogenic gravitational wave telescope KAGRA

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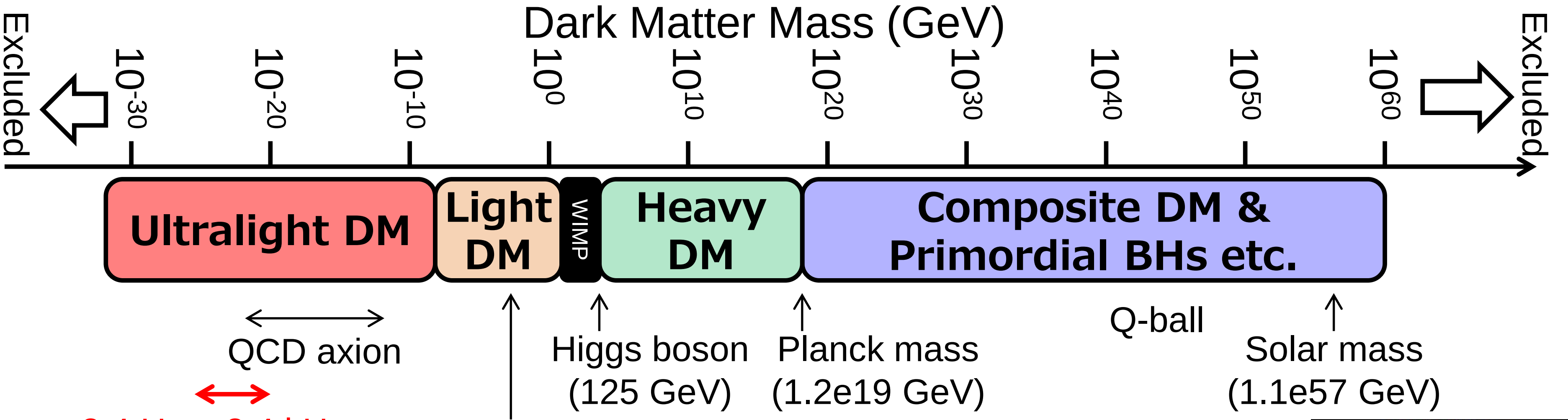
Dark Matter Searches

- Previous searches focused mainly on WIMPs
- Need for new ideas to search for huge variety of other candidates



Dark Matter Mass (GeV)

Excluded ← 10^{-30} 10^{-20} 10^{-10} 10^{0} 10^{10} 10^{20} 10^{30} 10^{40} 10^{50} 10^{60} → Excluded

Ultralight DM | **Light DM** | WIMP | **Heavy DM** | **Composite DM & Primordial BHs etc.**

QCD axion

Higgs boson (125 GeV)

Planck mass (1.2e19 GeV)

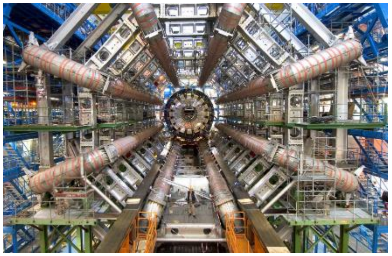
Q-ball

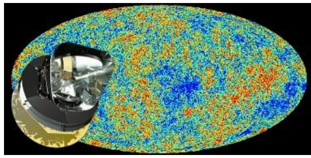
Solar mass (1.1e57 GeV)

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

XENON1T limits on ALP
(1-210 keV)

Laser Interferometry



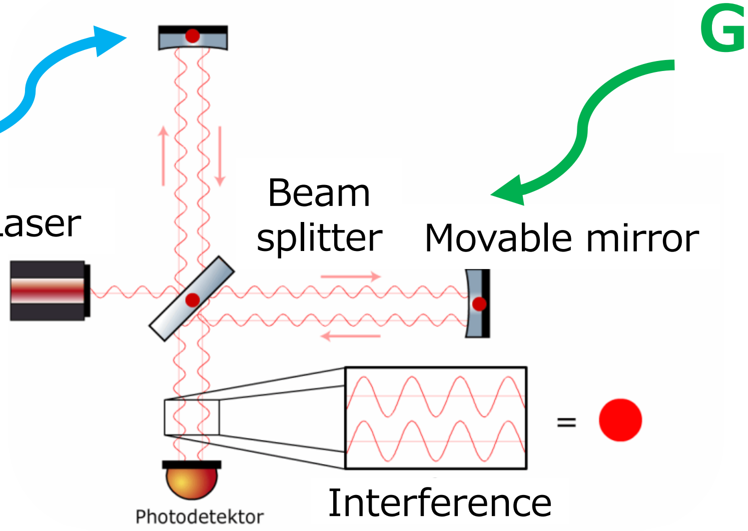


Ultralight DM with Interferometry

- Bosonic ultralight fields (<~1 eV) are well motivated by cosmology
- Behaves as classical wave fields

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

- Laser interferometers are sensitive to tiny length changes from such oscillations



Tiny forces from gauge boson DM

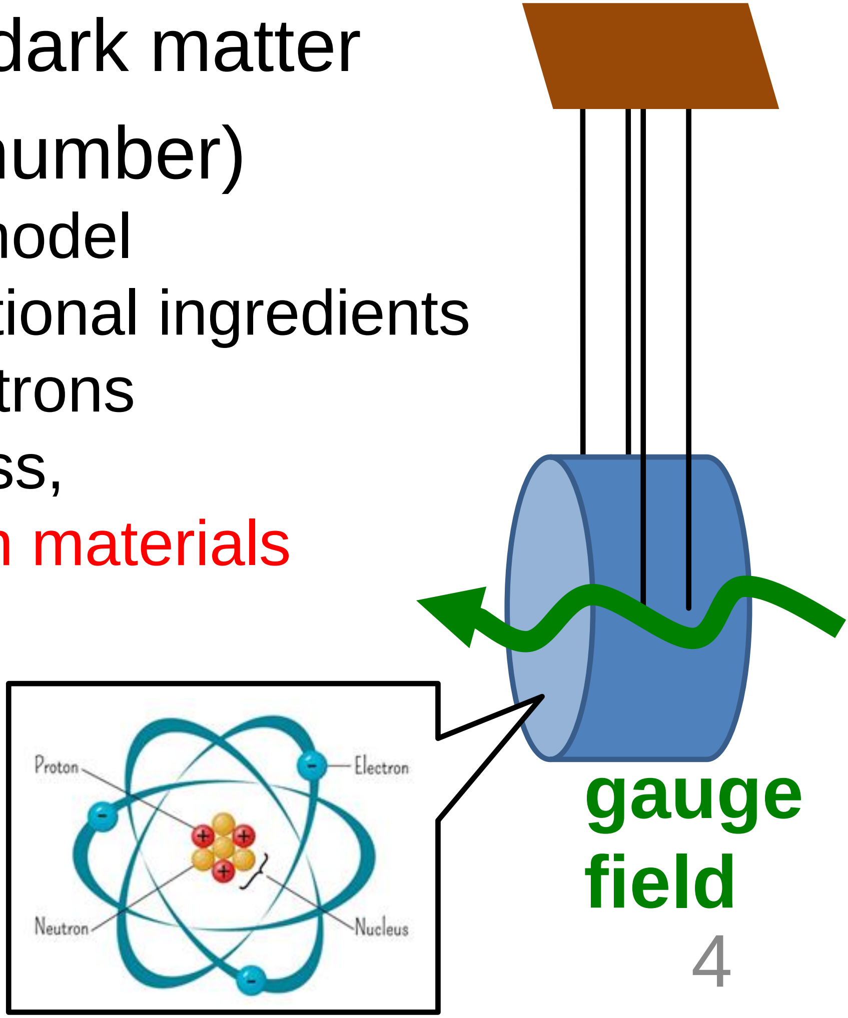
Gravitational waves

Our Target: 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

charge

gauge boson mass

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

polarization

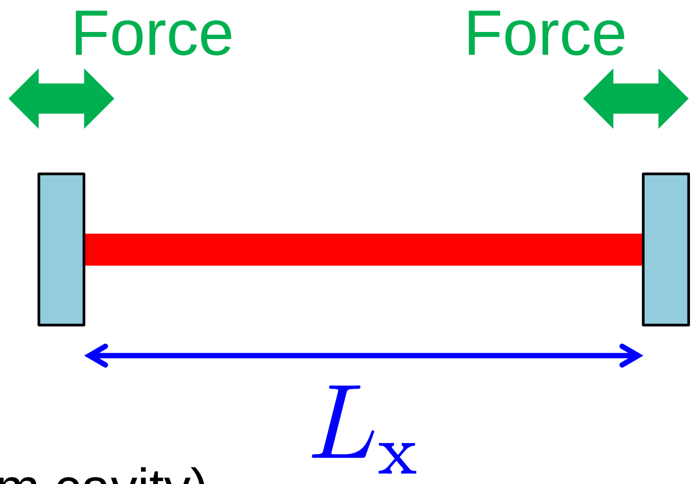
coupling
(normalized by e)

mirror mass

DM density

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)

Previous Search with LIGO/Virgo

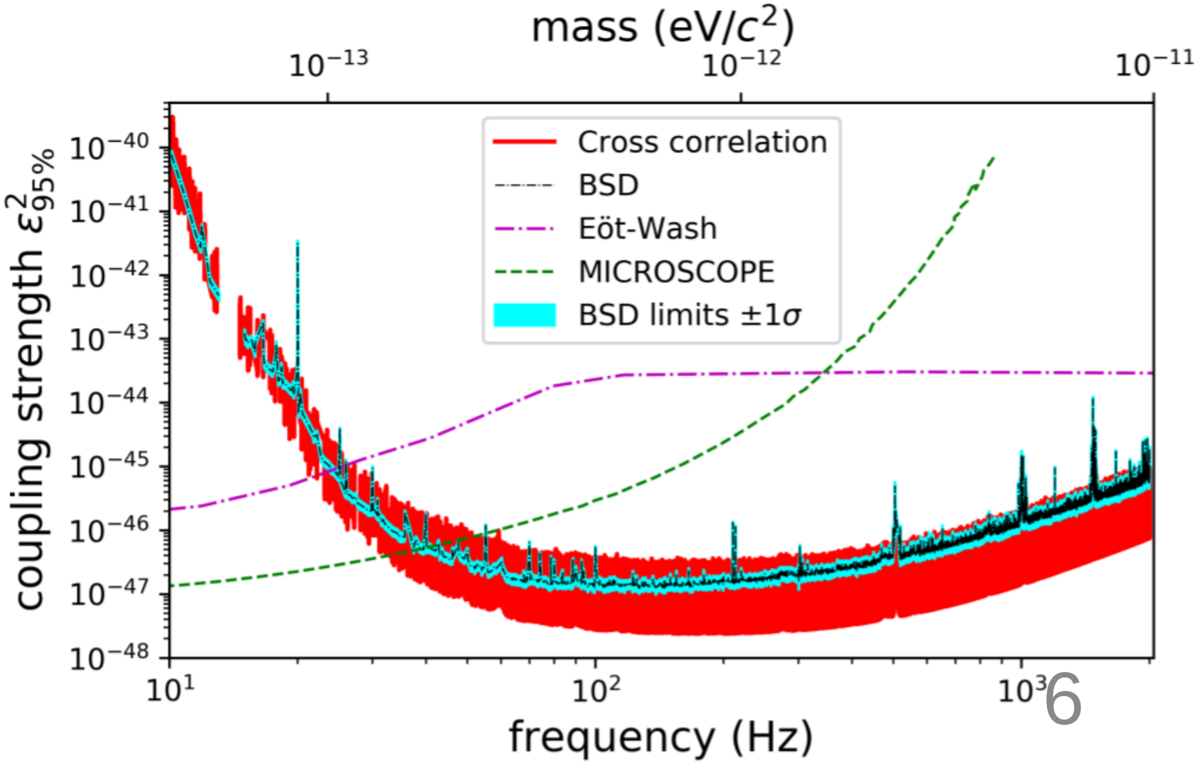
- Gauge boson dark matter search with LIGO O1 data and LIGO/Virgo O3 data have been done

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

- Better constraint than equivalence principle tests

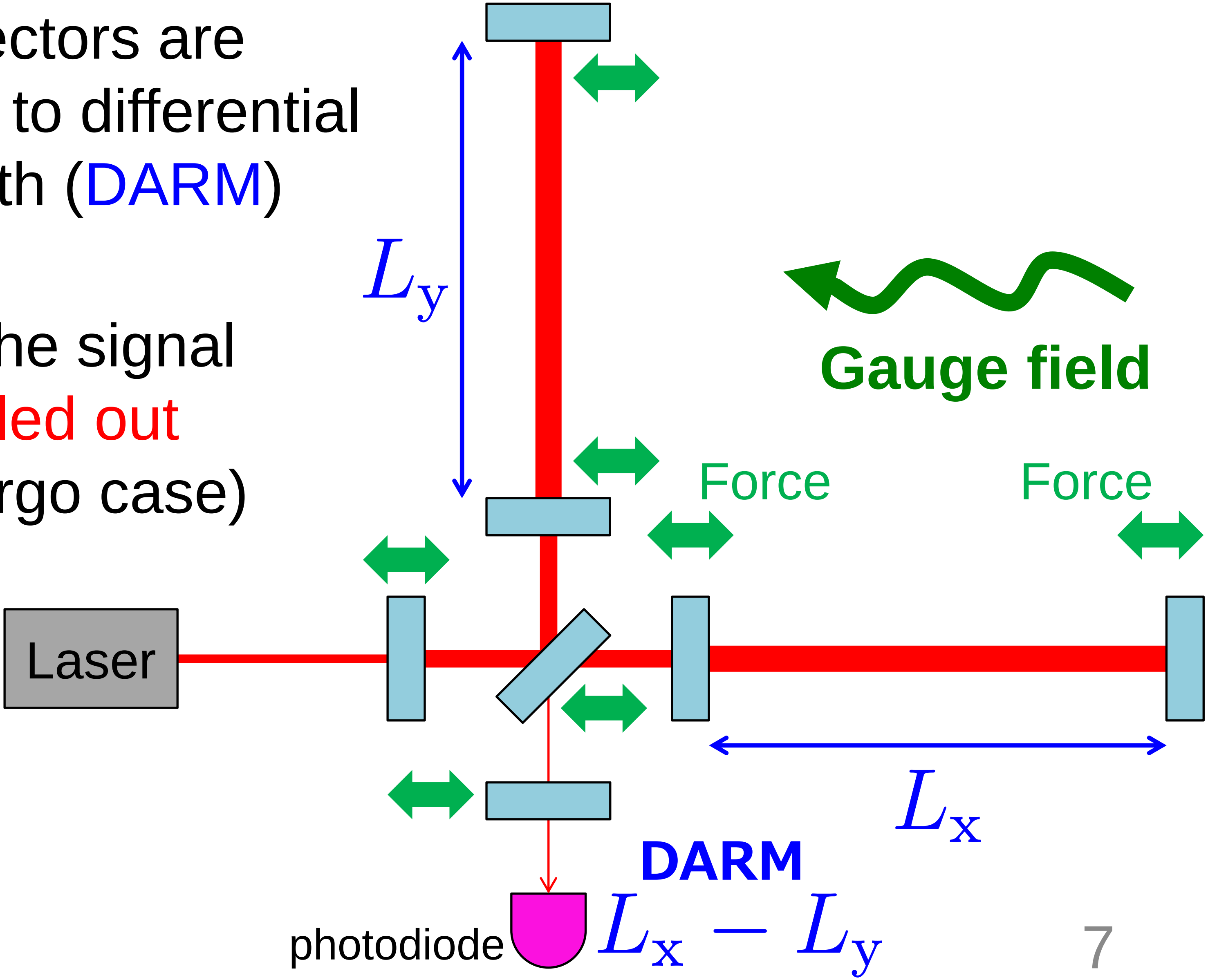
  So far searches focus on $U(1)_B$ baryon number coupling

- Why repeat the search with KAGRA?



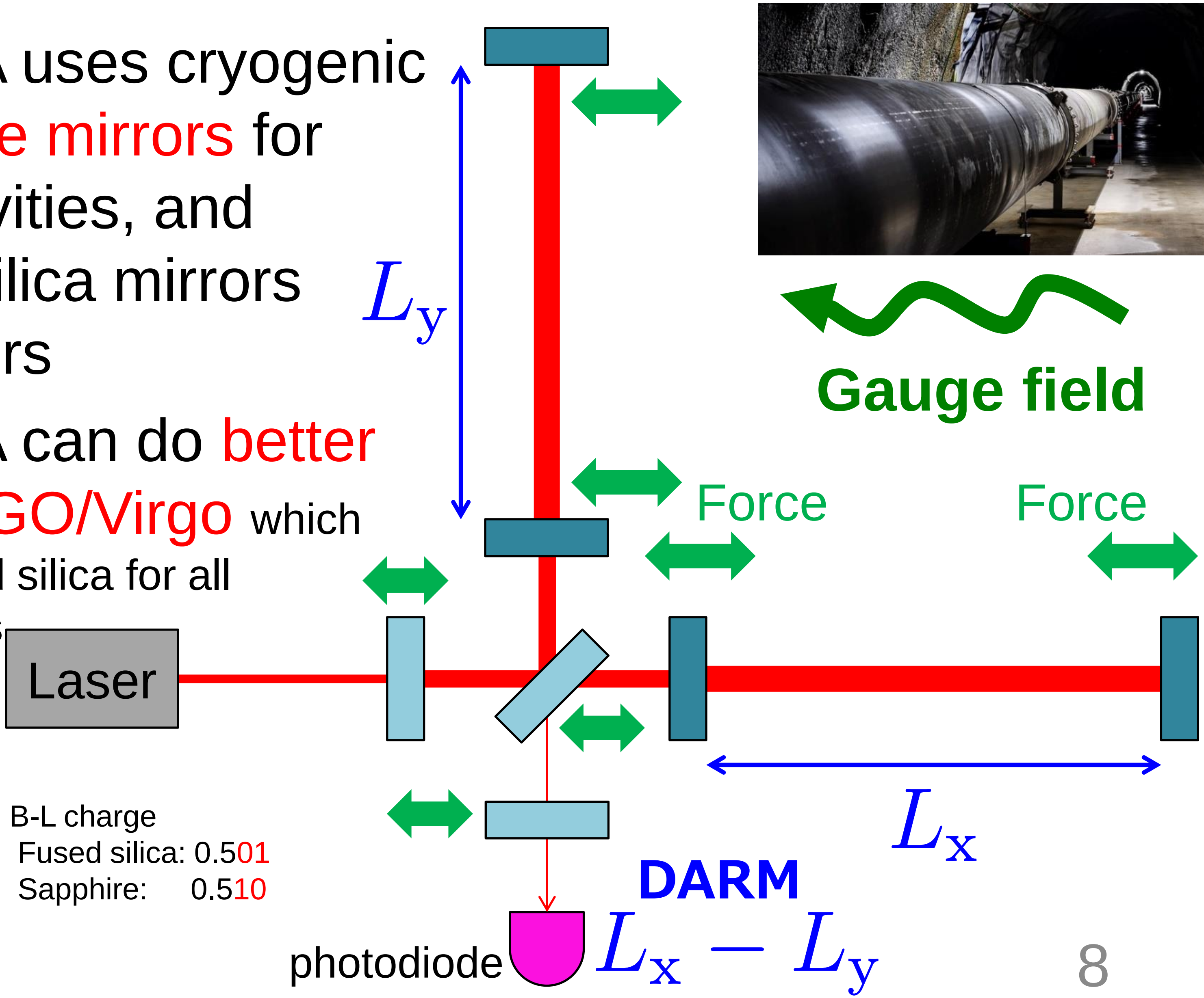
Search with GW Detectors

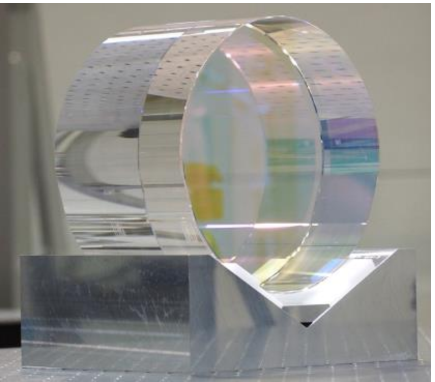
- GW Detectors are sensitive to differential arm length (DARM) change
- Most of the signal is cancelled out (LIGO/Virgo case)



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

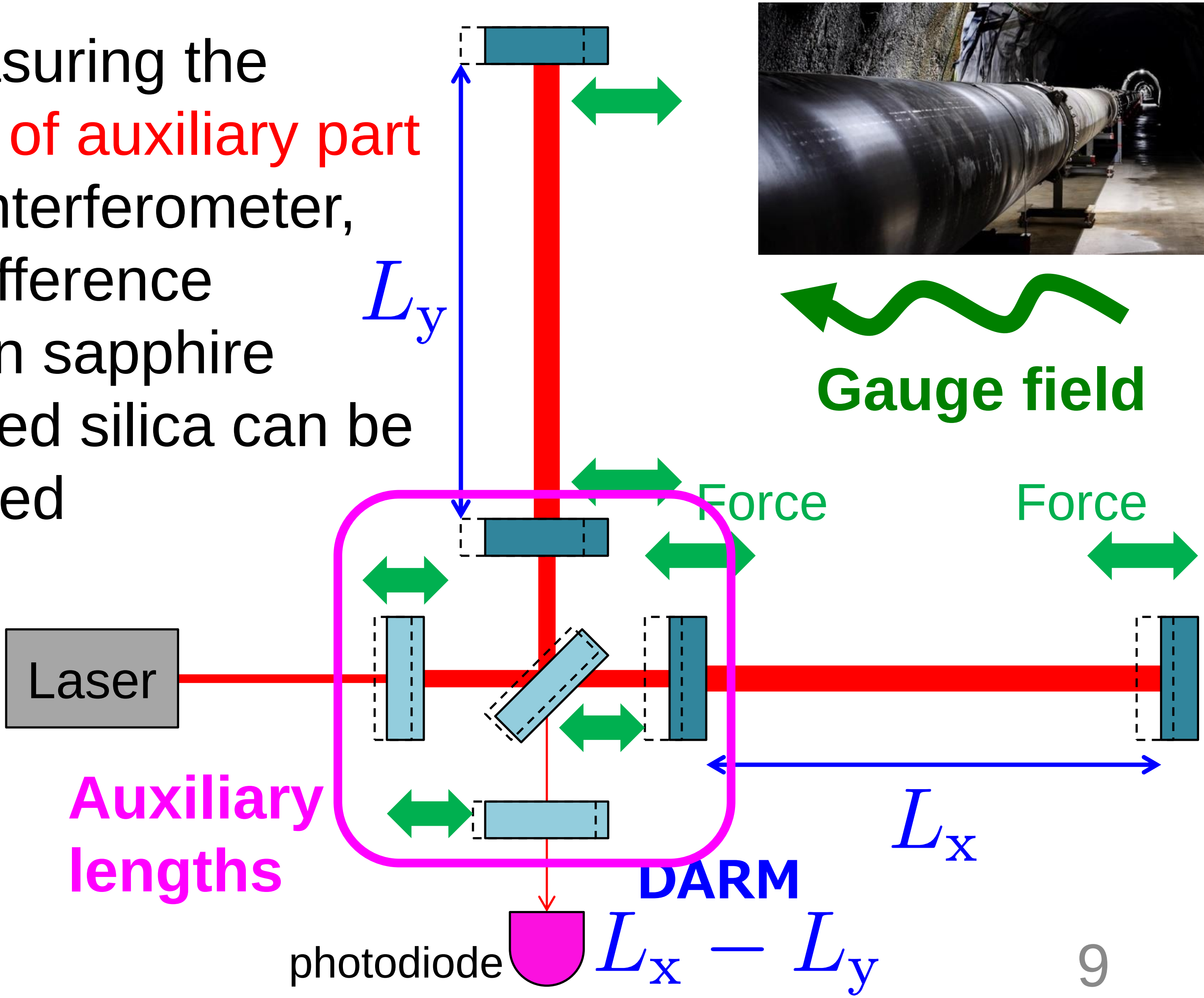




B-L charge
Fused silica: 0.501
Sapphire: 0.510

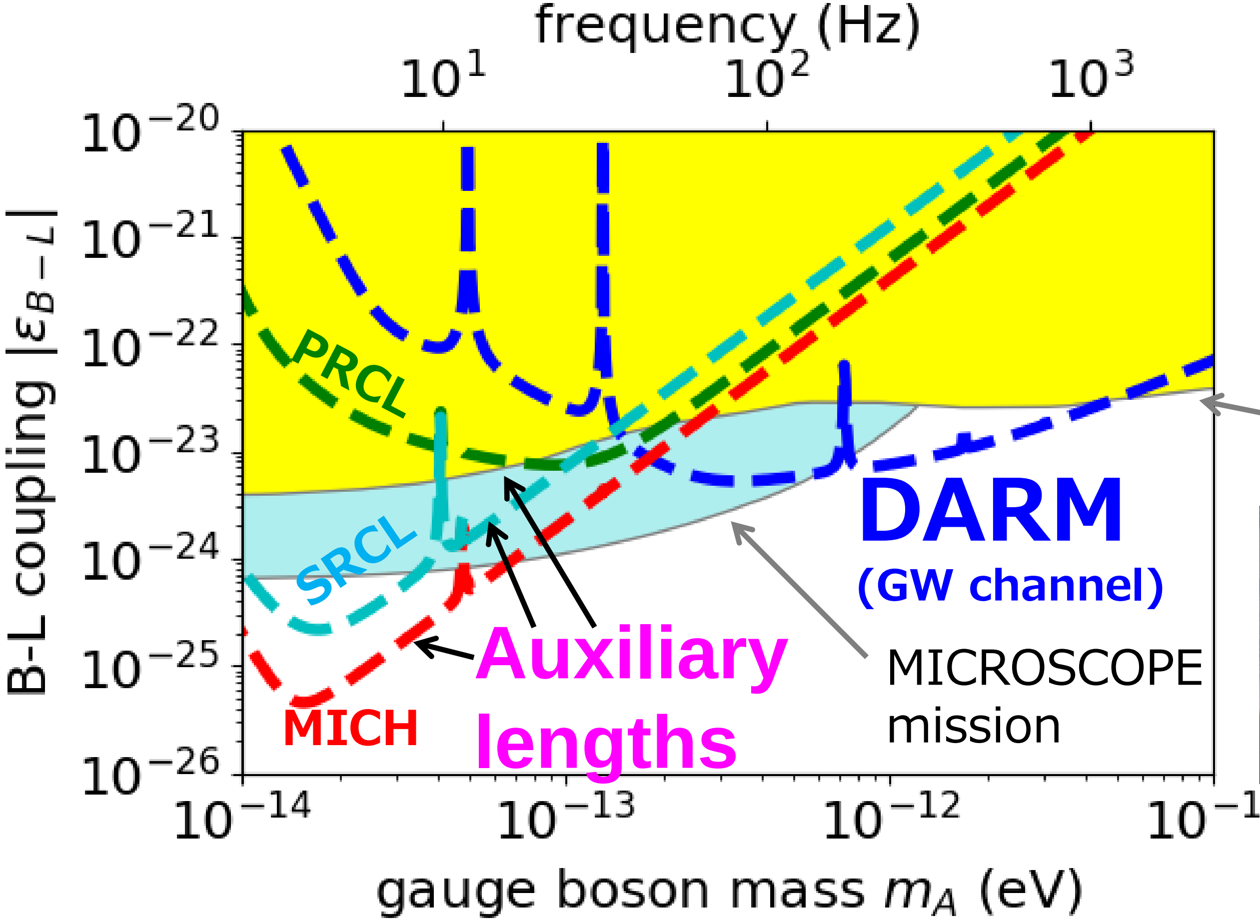
Search with KAGRA

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



KAGRA Gauge Boson Sensitivity

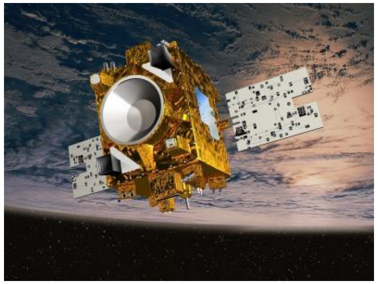
- Auxiliary length channels have better design sensitivity than DARM (GW channel) at low mass range
- Sensitivity better than equivalence principle tests



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

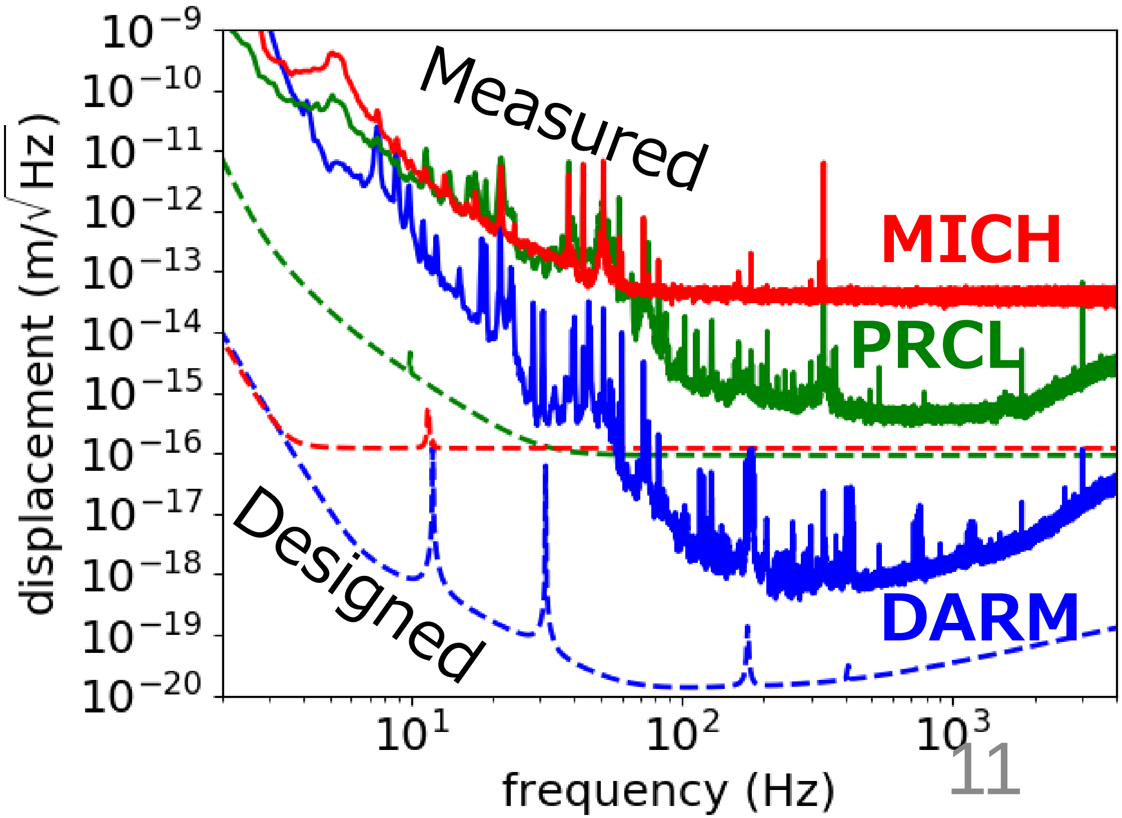
S. Morisaki, T. Fujita, YM, H. Nakatsuka, I. Obata, PRD 103, L051702 (2021)

Eöt-Wash torsion pendulum



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



Data Analysis Pipeline

E. Savalle+,
PRL 126, 051301 (2021)

- Nearly monochromatic signal

$$\omega_i = m_A \left(1 + \frac{v_i^2}{2}\right)$$

- Stack the spectra in this frequency region to calculate SNR

$$\rho = \sum \frac{4|\tilde{d}(f_k)|^2}{T_{\mathrm{obs}} S_n(f_k)}$$

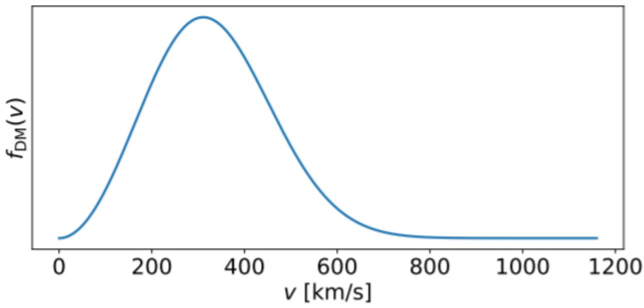
Data

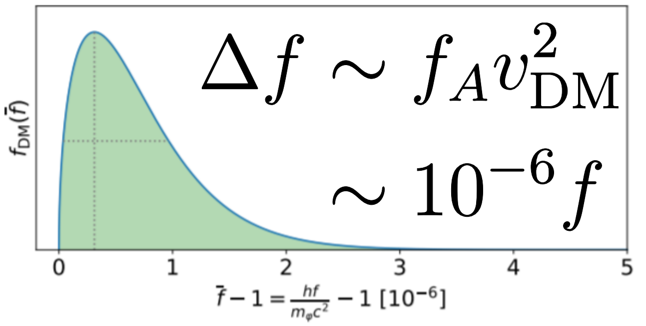
PSD

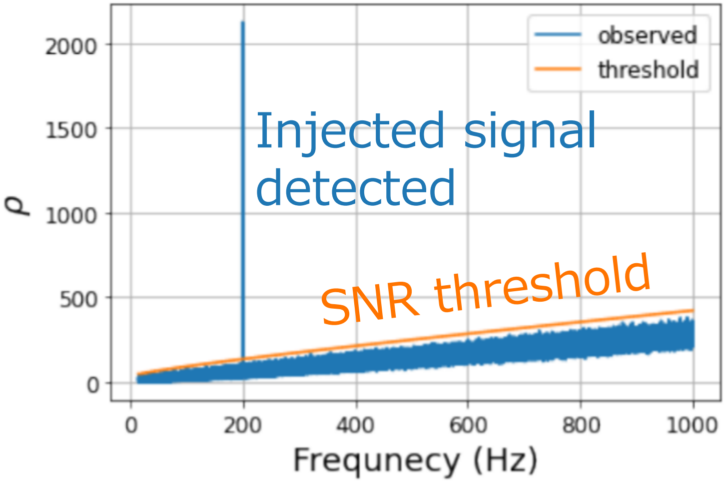
Obs. time

$m_A \leq 2\pi f_k \leq m_A(1 + \kappa v_{\mathrm{DM}}^2)$

- Detection threshold determined assuming ρ follows χ^2 distribution (=assuming Gaussian noise)
- From ρ , 95% upper limit on coupling constant calculated
- Applied the pipeline to mock data for verification





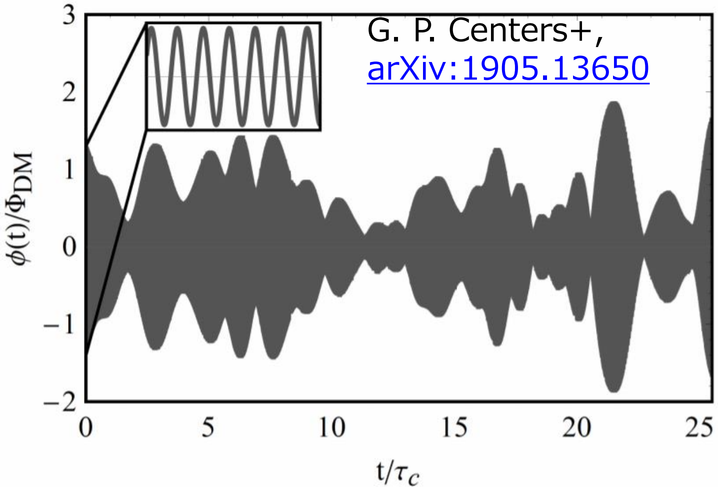


Stochastic Nature of DM Signal

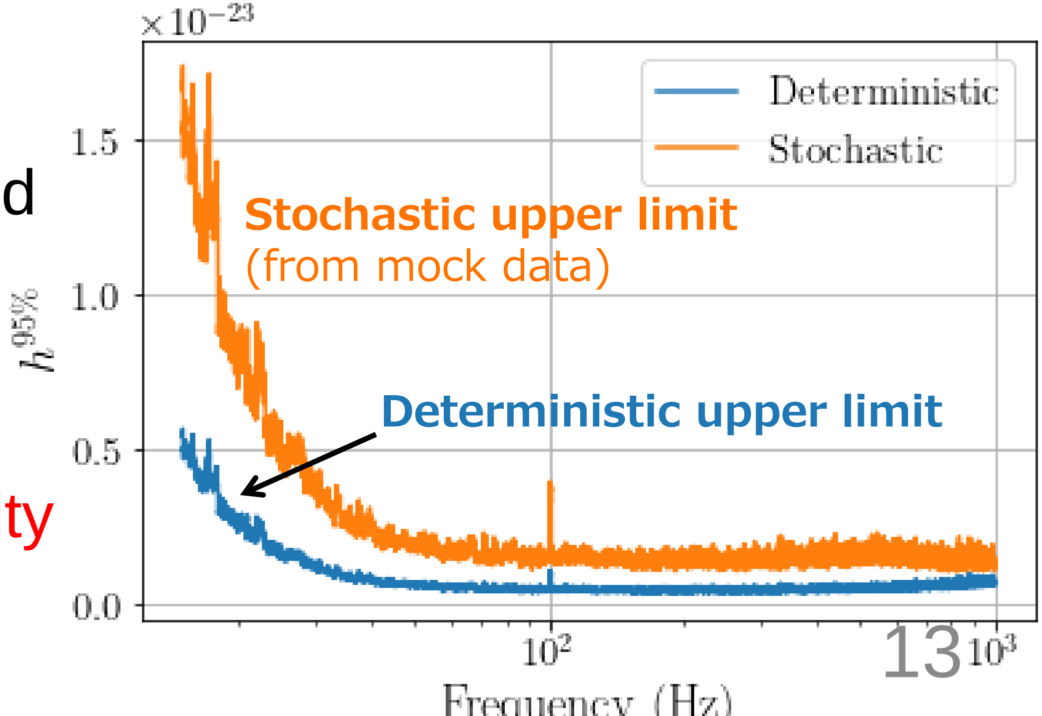
- DM signal is from superposition of many waves with various momentum, phase and polarization
- The amplitude fluctuates at the time scale of

$$\tau = 2\pi/(m_A v_{\mathrm{DM}}^2)$$

- At low frequencies, DM signal could be too small by chance and elude detection
- Method to calculate upper limit taking into account this stochasticity developed



G. P. Centers+, arXiv:1905.13650



Stochastic upper limit
(from mock data)

Deterministic upper limit

H. Nakatsuka+, *in preparation*

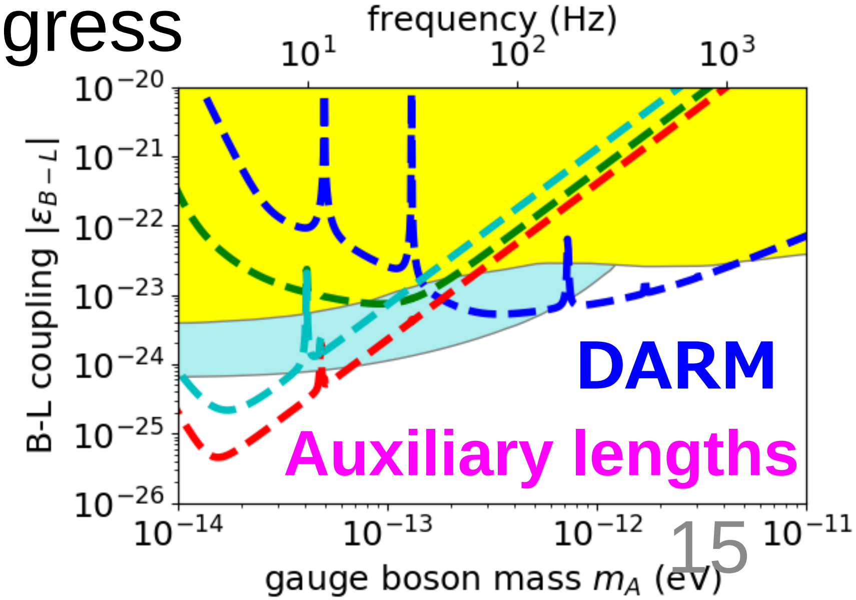
Testing Method on O3GK Data

- Applying the pipeline for two sets of 10^4 sec data
- Veto using
  - sharpness of the peak ($\Delta f / f \sim 10^{-6}$ for DM)
  - consistency between segments
- Some candidates found (mostly in noise contaminated region)
- Working on further veto by
  - shape of the peaks
  - line noise investigations
  - consistency between channels etc.
- Obtained proof-of-principle results from O3GK data
  - internal review to be done

Summary and Outlook

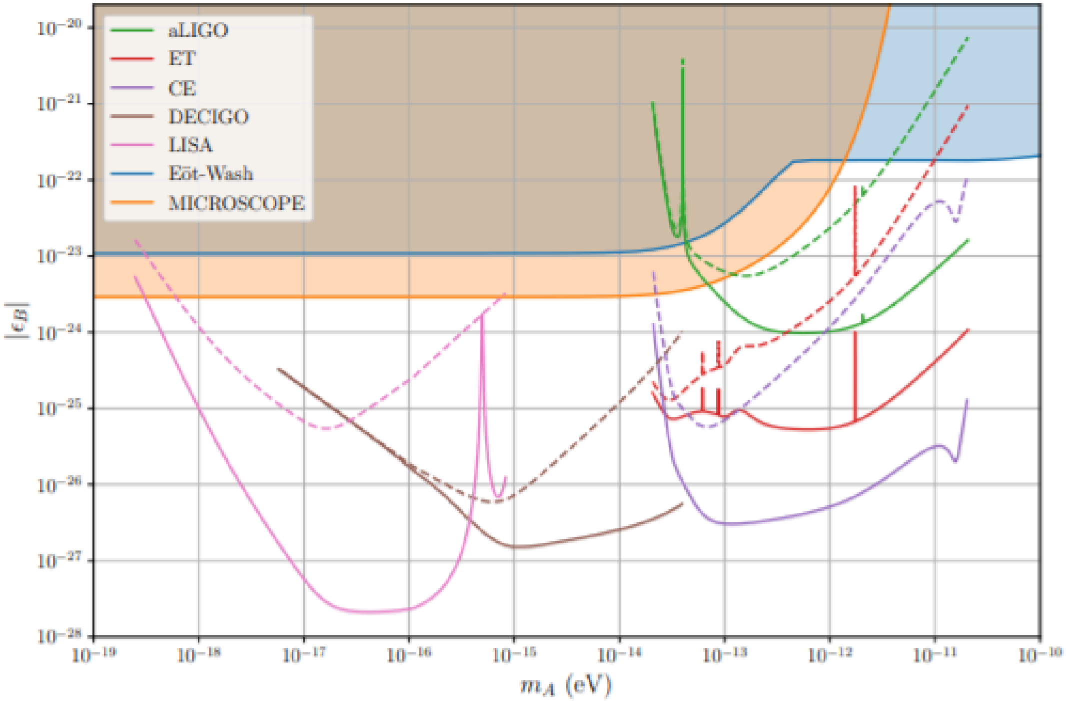
- KAGRA can do unique gauge boson dark matter search since the interferometer consist of sapphire and fused silica mirrors
- Data analysis pipeline developed
- Applied the pipeline to real KAGRA data in 2020 and got proof of principle results
- Further veto studies in progress

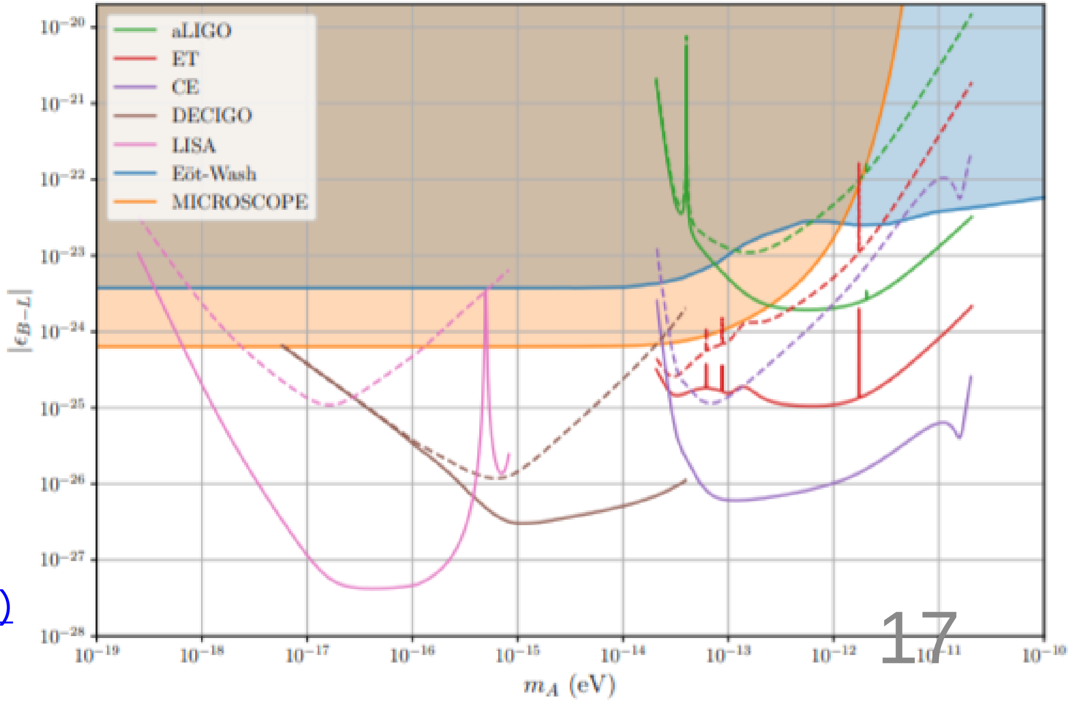
- Observing run in 2022 planned with better sensitivity (O4)
- Stay tuned!



Additional Slides

With Space and 3G Detectors





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

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