PASCOS 2024 @ Quy Nhon, Vietnam

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First results from ultralight vector dark matter search with KAGRA

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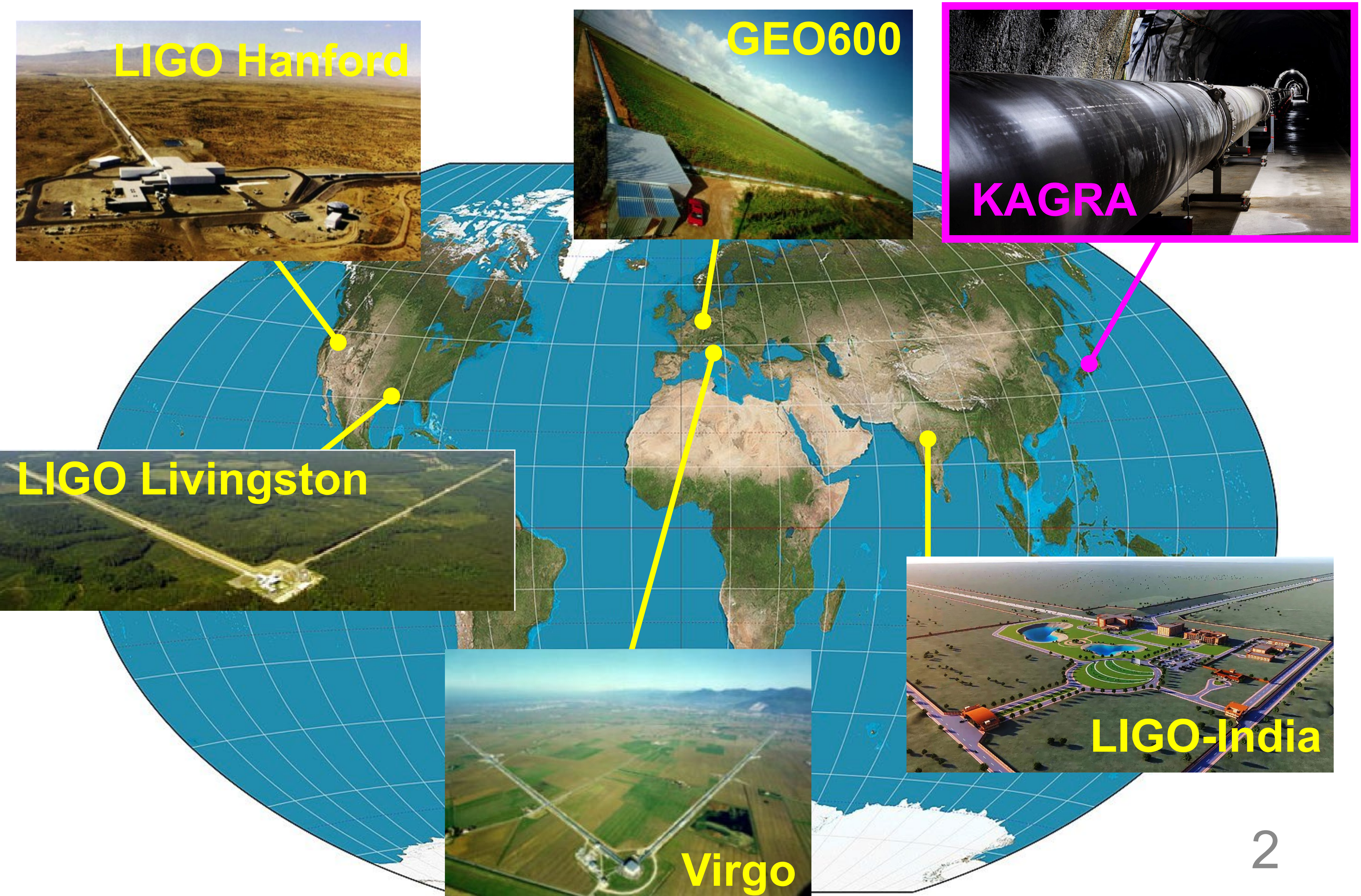
on behalf of the LIGO-Virgo-KAGRA Collaboration

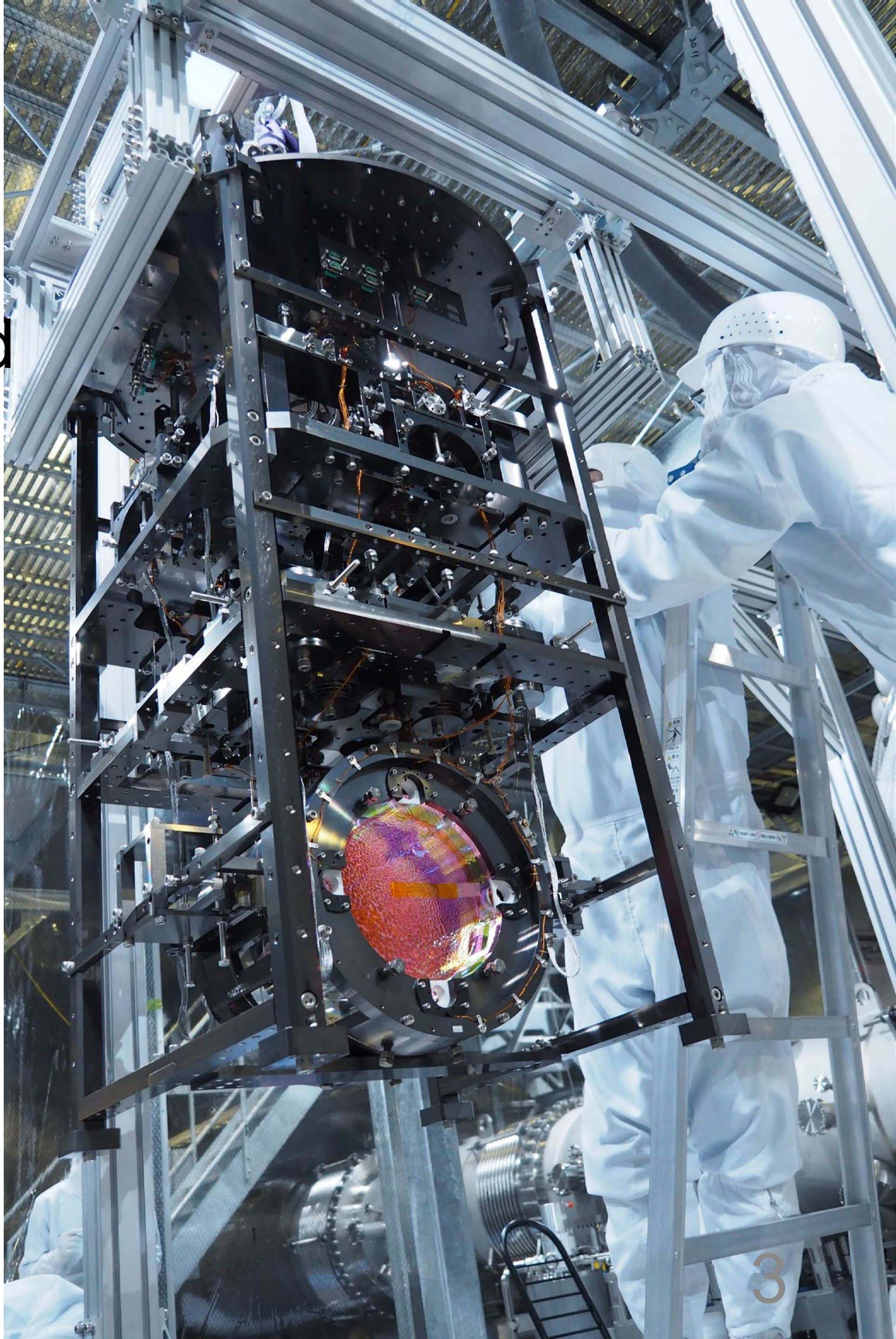
Global Network of GW Detectors



KAGRA Project

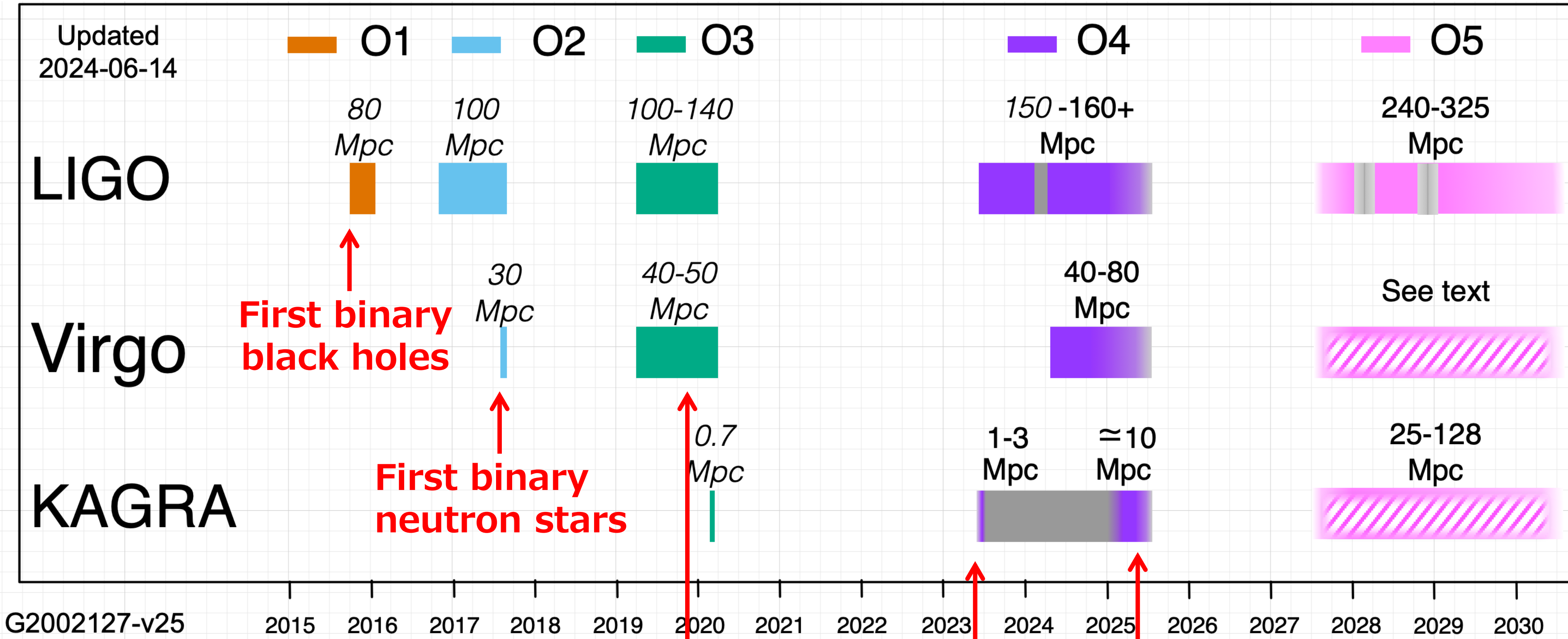
- Project started in 2010
- Construction completed and signed MoA with LIGO/Virgo in 2019
- 13 countries
- 400+ collaborators
- First (and so far only) underground and cryogenic detector

KAGRA



LIGO-Virgo-KAGRA Observing Plan

- Coordinated runs to detect GW signals by multiple detectors



https://observing.docs.ligo.org/plan/

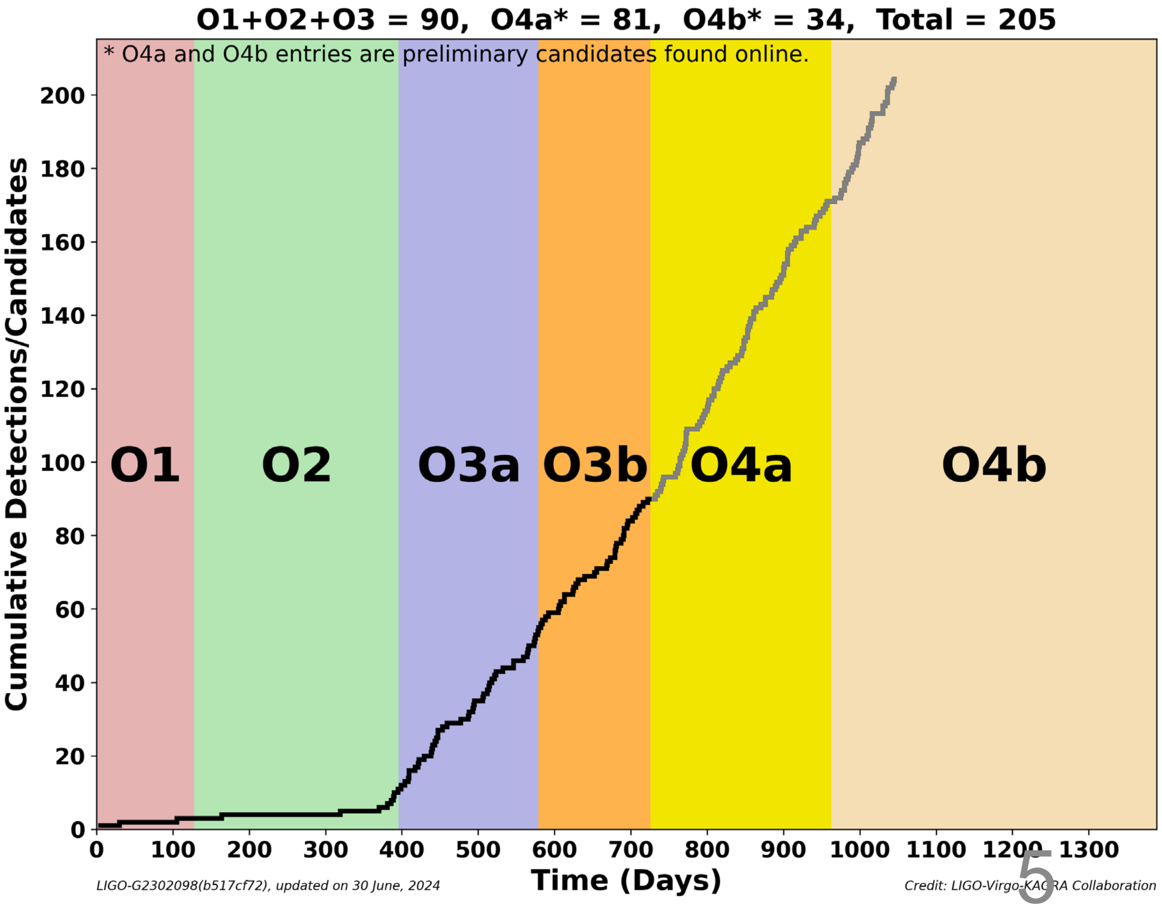
First neutron star-black hole binary

Planning to restart by June 2024

O4 started on May 24, 2023

LIGO-Virgo-KAGRA O4 Run Status

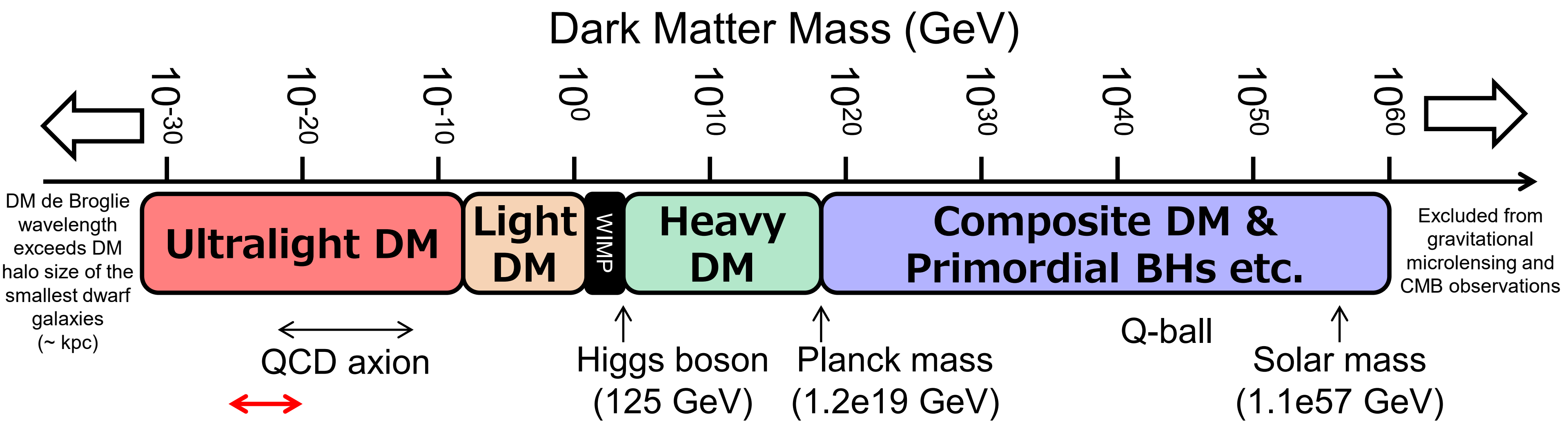
- More than 100 events reported from LIGO-Virgo
- Will continue until June 9, 2024
- KAGRA plans to join by the end of O4
- Currently recovering from 7.6 magnitude earthquake on January 1, 2024 (vacuum work completed)



LIGO-G2302098

Various Dark Matter Models

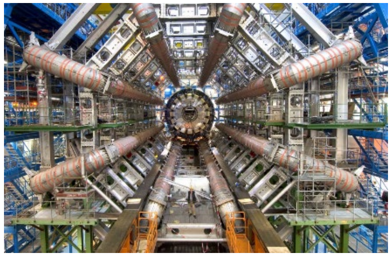
- ~90 orders of magnitude
- Searches focused on WIMPs, but not detected yet
- Motivates new searches for other candidates



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

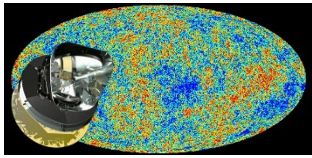
Laser Interferometry

Underground experiments (XENON etc.)



LHC

Subaru telescope etc.



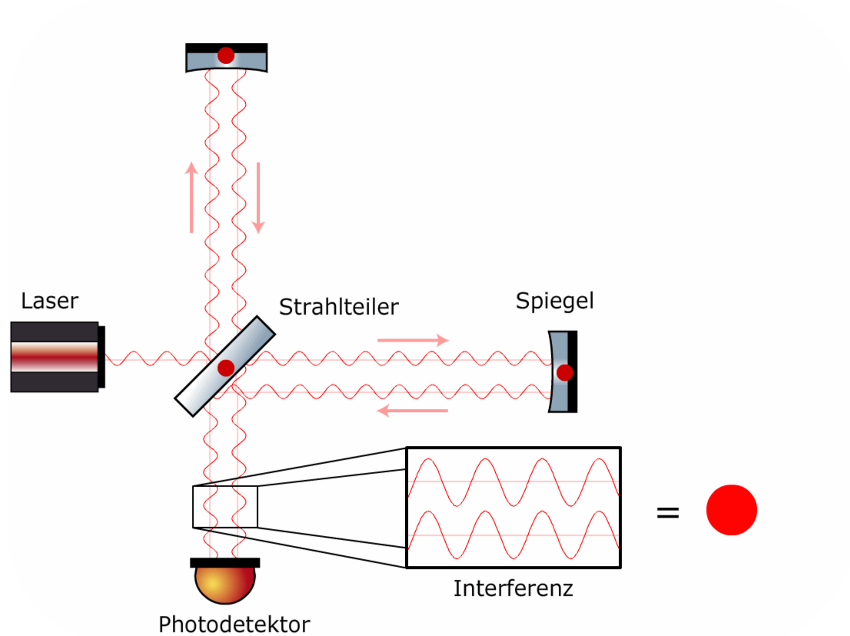
Cosmic microwave background

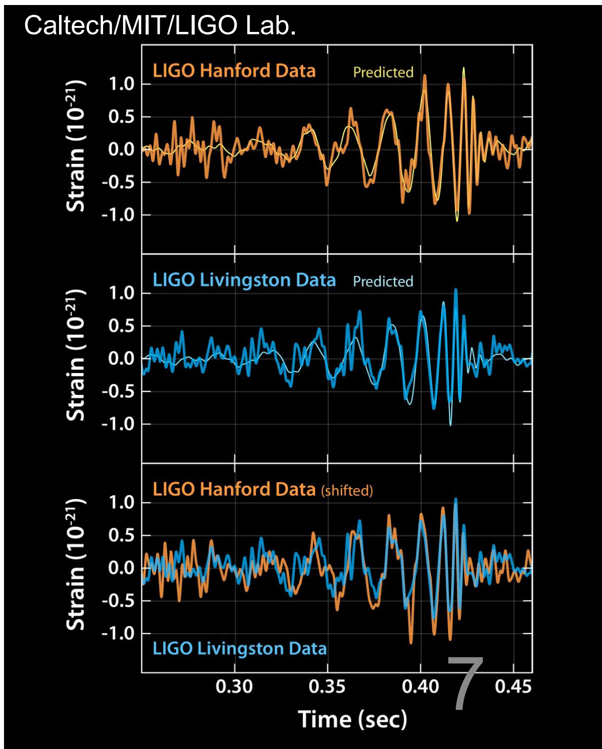
Ultralight DM with Interferometers

- Bosonic ultralight field (<~1 eV) are well-motivated from cosmology
- Behaves as classical waves

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

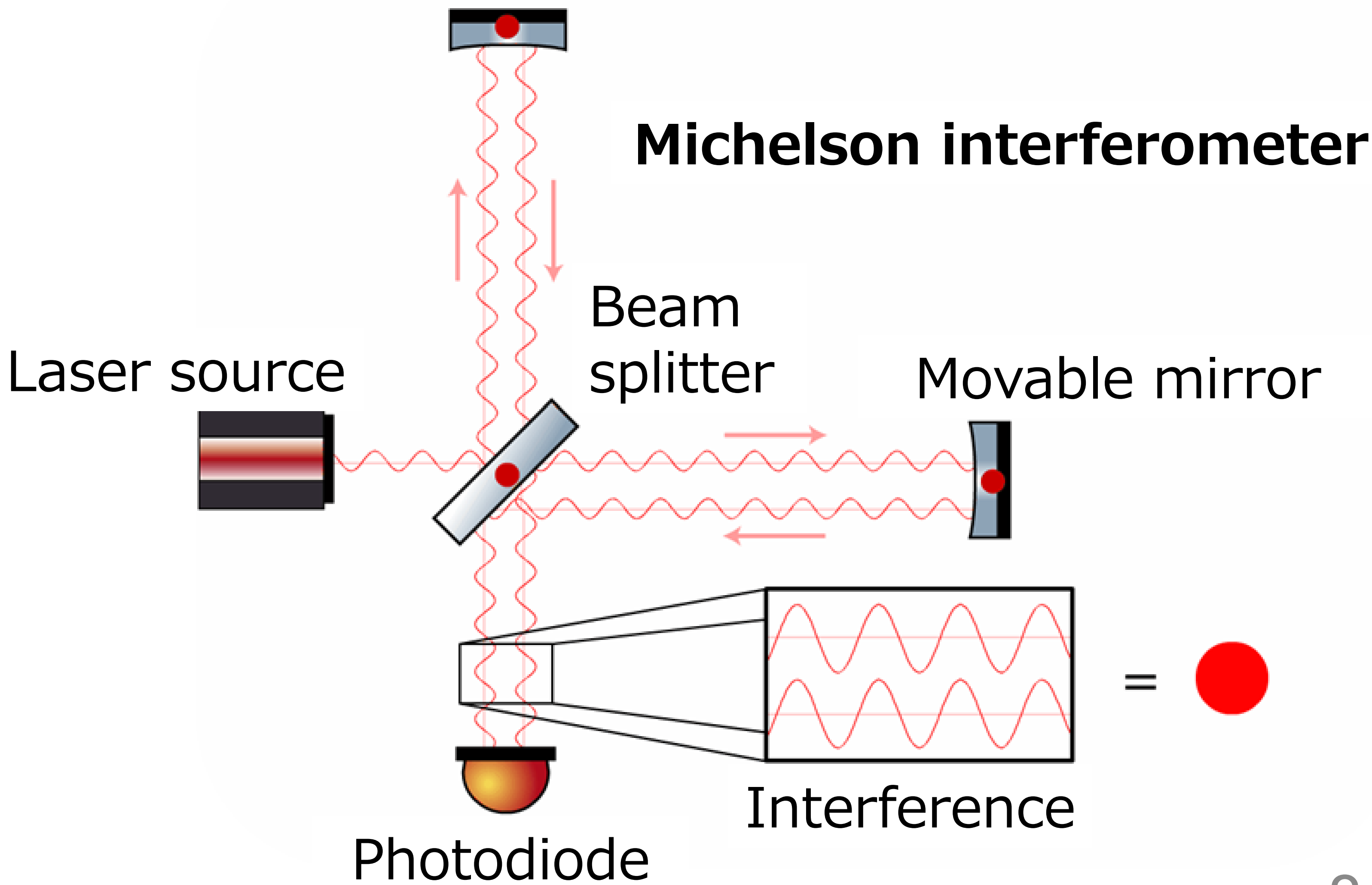
- Laser interferometers are sensitive to such oscillating changes





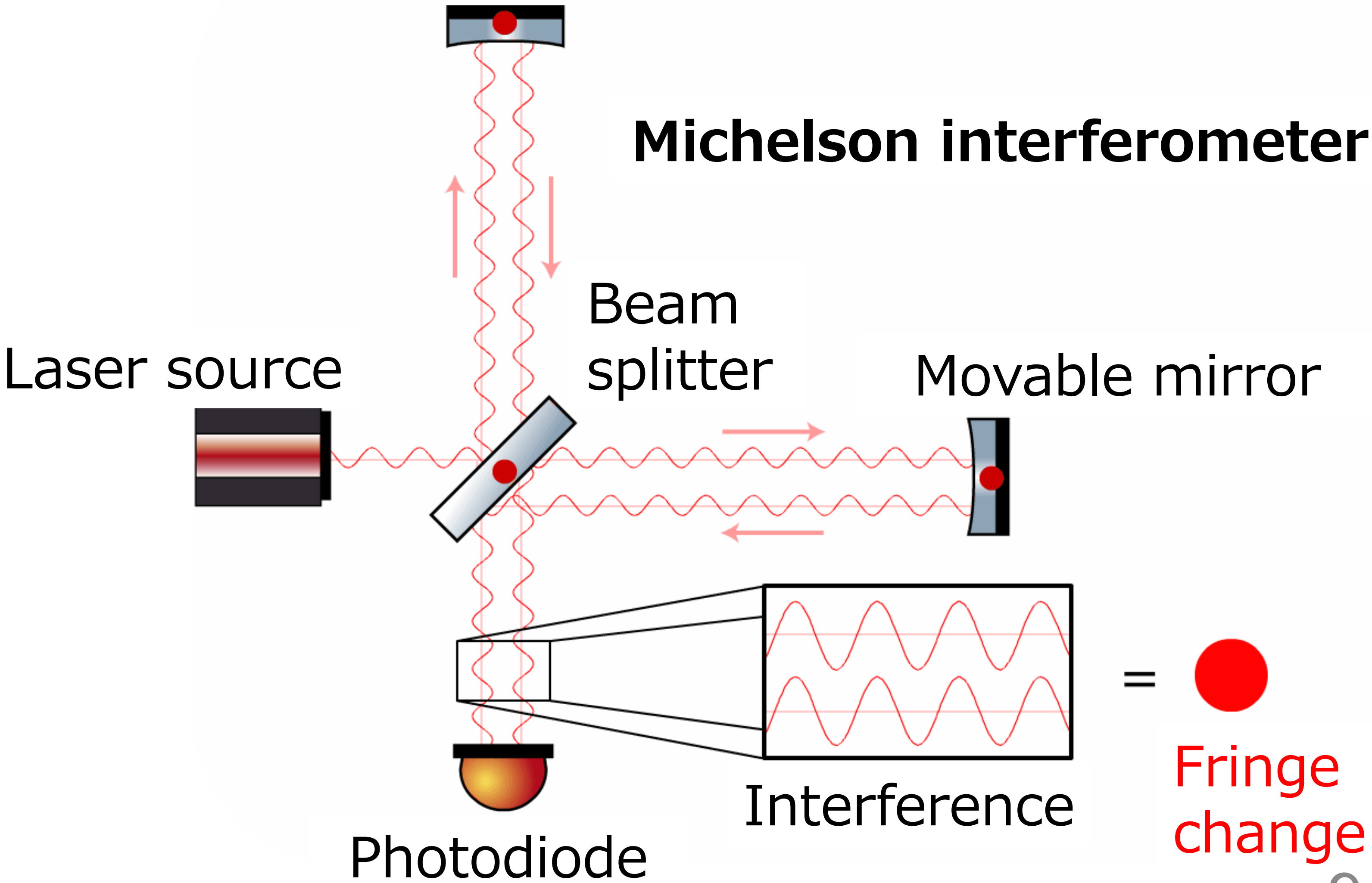
Laser Interferometry

- measures differential arm length change



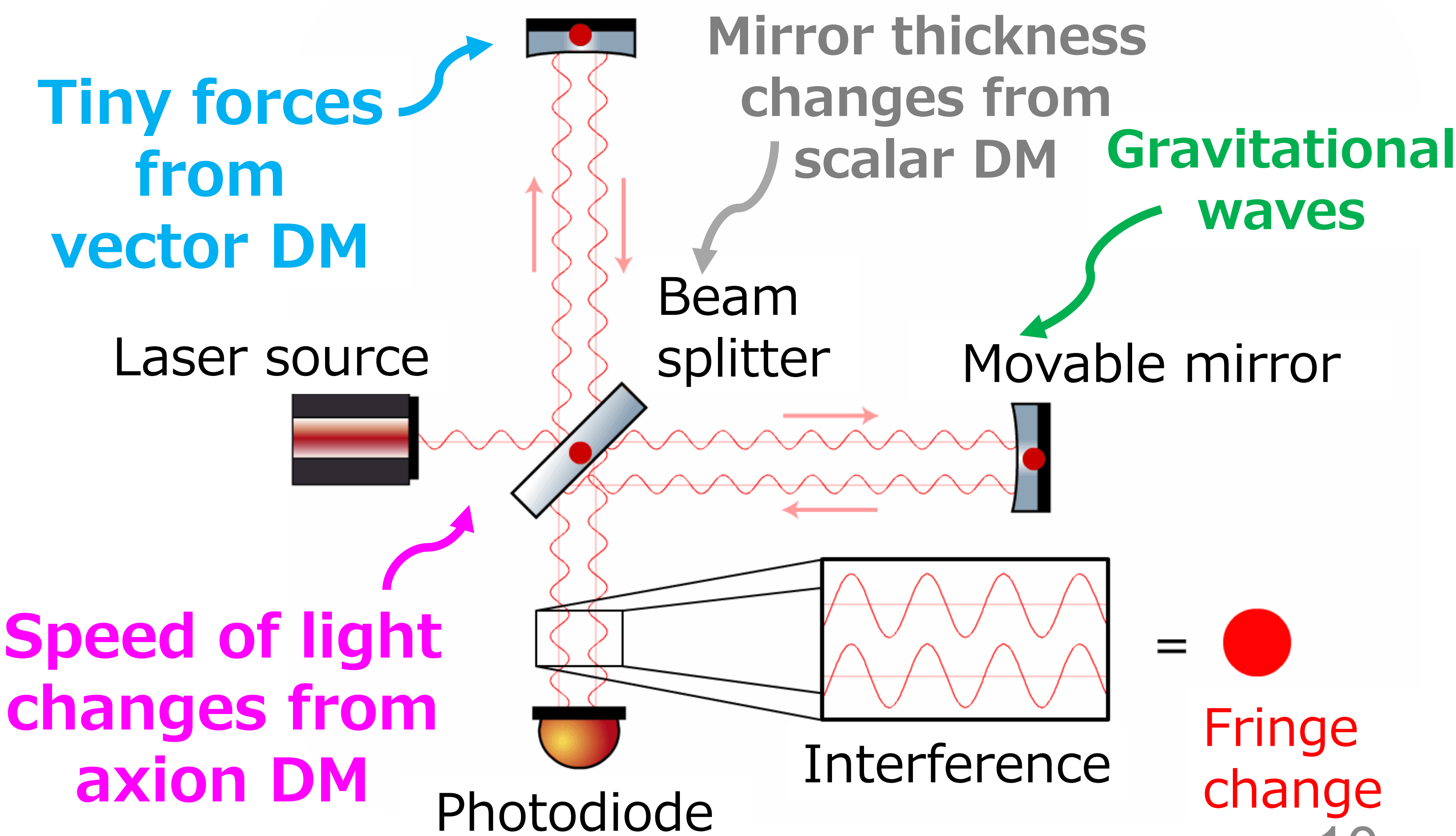
Laser Interferometry

- measures differential arm length change



Laser Interferometry

- measures differential arm length change



Recent Proposals and Searches

- **Scalar bosons**
  - Y. V. Stadnik & V. V. Flambaum, PRL **114**, 161301 (2015), 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)
  - C. Kennedy+, PRL **125**, 201302 (2020)
  - E. Savalle+, PRL 126, 051301 (2021)
  - S. M. Vermeulen+, Nature **600**, 424 (2021) **GEO600 data analysis**
  - K. Fukusumi, S. Morisaki, T. Suyama, arXiv:2303.13088 **LIGO/Virgo O3 data analysis**

- **Axion & axion-like particles (ALPs)**
  - W. DeRocco & A. Hook, PRD **98**, 035021 (2018)
  - I. Obata, T. Fujita, Y. Michimura, PRL **121**, 161301 (2018)
  - H. Liu+, PRD **100**, 023548 (2019)
  - K. Nagano, T. Fujita, Y. Michimura, I. Obata, PRL **123**, 111301 (2019)
  - D. Martynov & H. Miao, PRD **101**, 095034 (2020)
  - K. Nagano, H. Nakatsuka, S. Morisaki, T. Fujita, Y. Michimura, I. Obata, PRD **104**, 062008 (2021)
  - Y. Oshima+, PRD **108**, 072005 (2023) **DANCE first result**

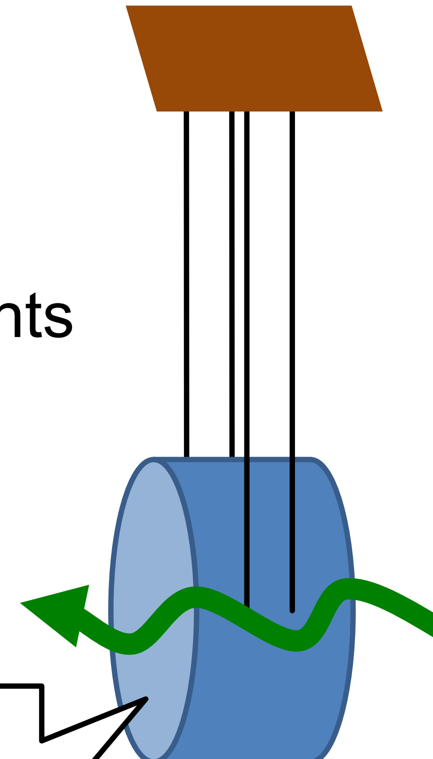
Not exhaustive.
The ones which require magnetic fields are not listed.

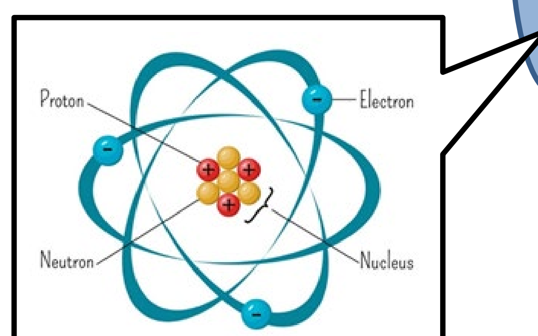
- **$U(1)_B$ or $U(1)_{B-L}$ gauge bosons (vector field)**
  - P. W. Graham+, PRD **93**, 075029 (2016)
  - A. Pierce+, PRL **121**, 061102 (2018)
  - H-K Guo+, Commun. Phys. **2**, 155 (2019) **LIGO O1 data analysis**
  - Y. Michimura, T. Fujita, S. Morisaki, H. Nakatsuka, I. Obata, PRD **102**, 102001 (2020)
  - D. Carmey+, New J. Phys. **23**, 023041 (2021)
  - J. Manley+, PRL **126**, 061301 (2021)
  - S. Morisaki, T. Fujita, Y. Michimura, H. Nakatsuka, I. Obata, PRD **103**, L051702 (2021)
  - LIGO-Virgo-KAGRA Collaboration, PRD **105**, 063030 (2022) **LIGO/Virgo O3 data analysis**
  - LIGO-Virgo-KAGRA Collaboration, arXiv:2403.03004 **KAGRA O3GK data analysis** THIS TALK

- **Spin-2 bosons (tensor field)**
  - Y. Manita, K. Aoki, T. Fujita, S. Mukohyama, PRD 107, 104007 (2023)
  - Y. Manita, H. Takeda, K. Aoki, T. Fujita, S. Mukohyama, arXiv:2310.10646

Vector Boson

- Possible new physics beyond the standard model:
  New gauge symmetry and vector boson
- New vector 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
- Vector boson DM
  gives oscillating force





Oscillating Force from Vector 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)

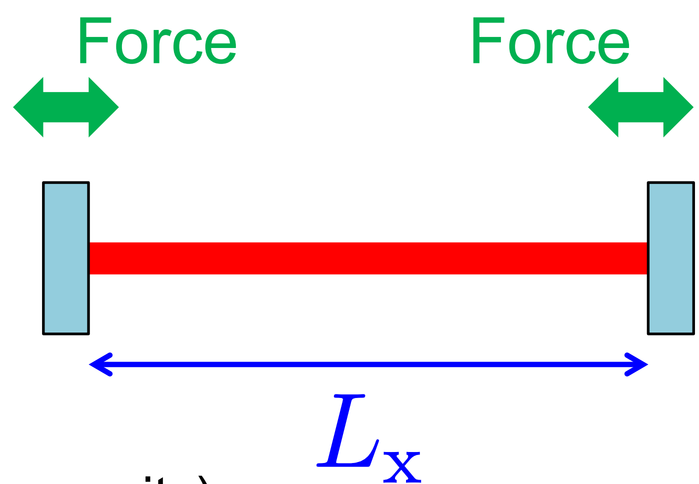
mirror mass

DM density

polarization

different phase at
different position

- Vector 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?

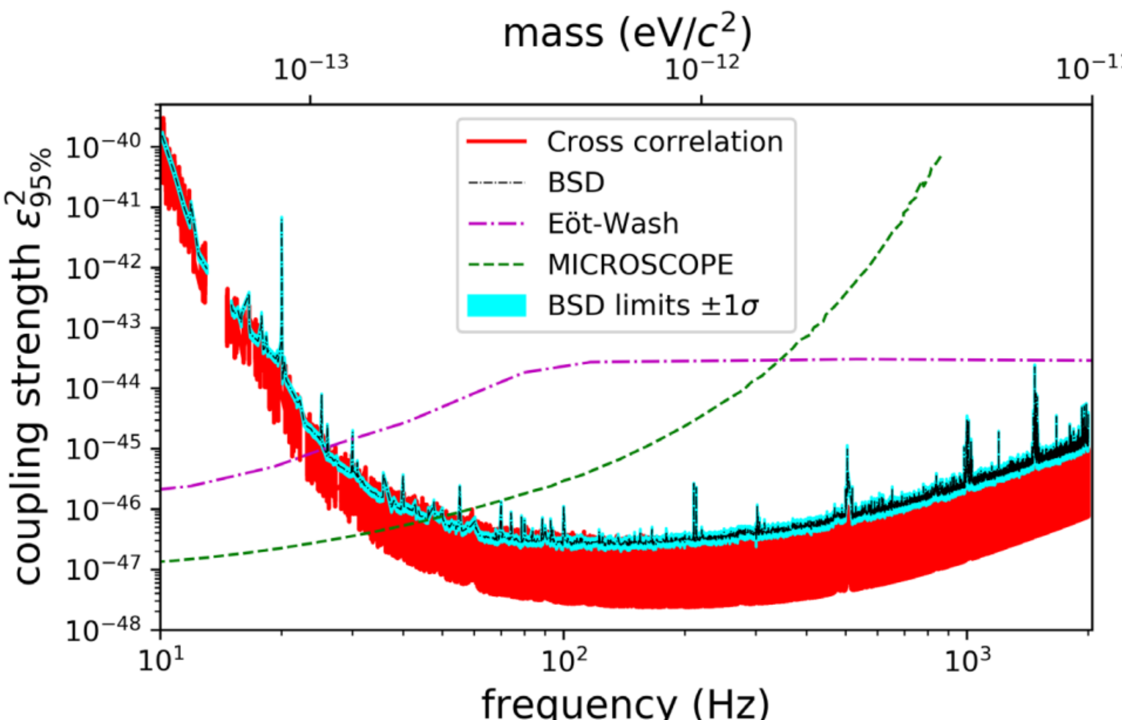
A. Pierce+, PRL **121**, 061102 (2018)

Previous Searches with LIGO/Virgo

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

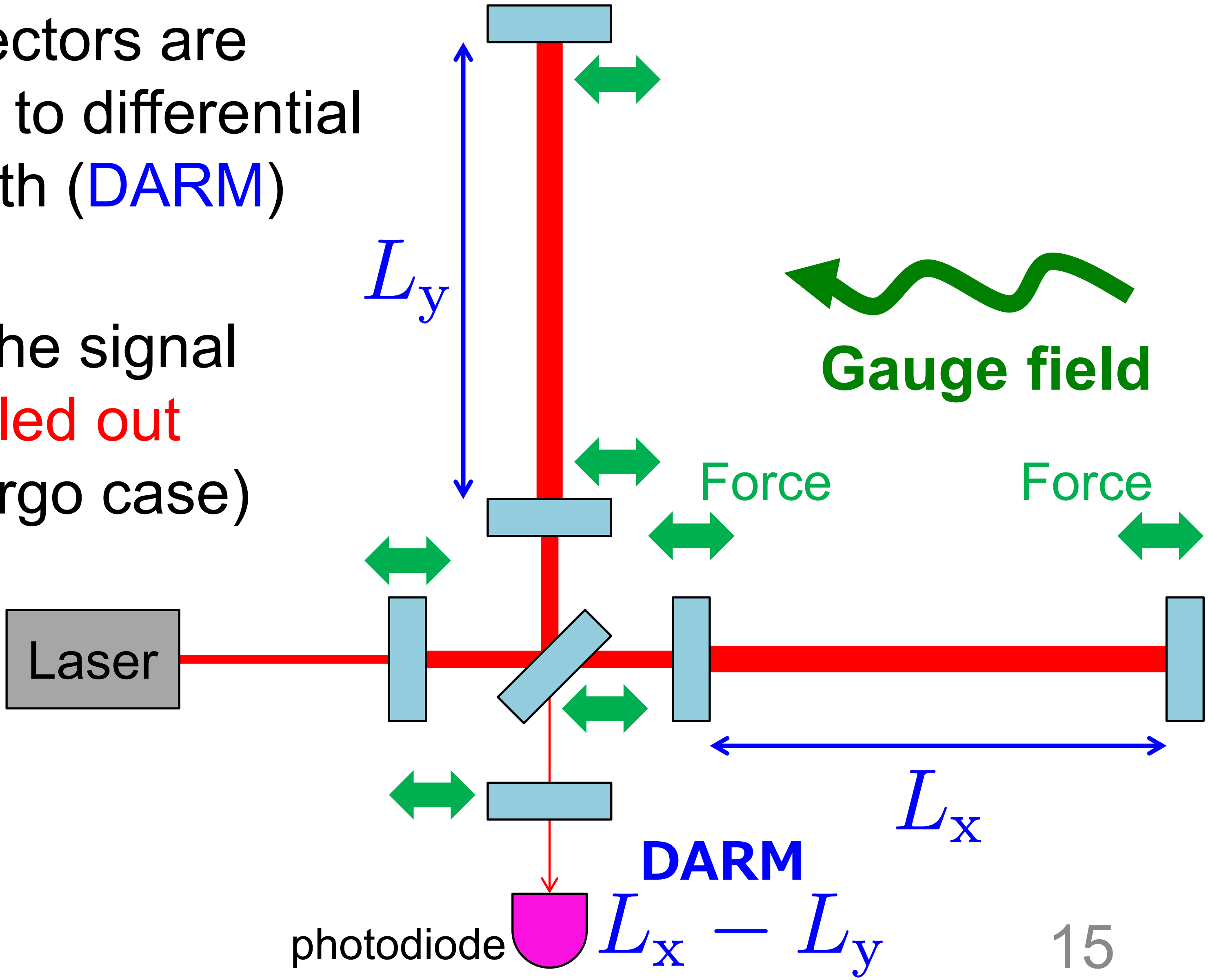
  H-K Guo+, [Communications Physics **2**, 155 (2019)]()
  LIGO, Virgo, KAGRA Collaboration, [PRD **105**, 063030 (2022)]()

- Better constraint than equivalence principle tests
- Even better constraint could be obtained from KAGRA

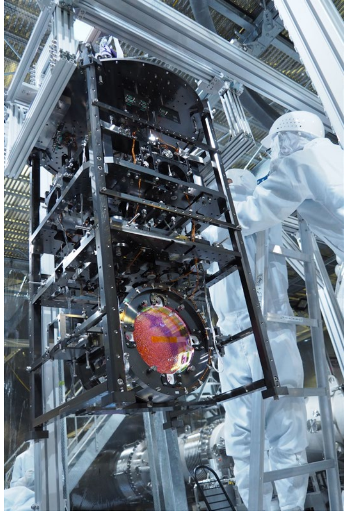


Search with GW Detectors

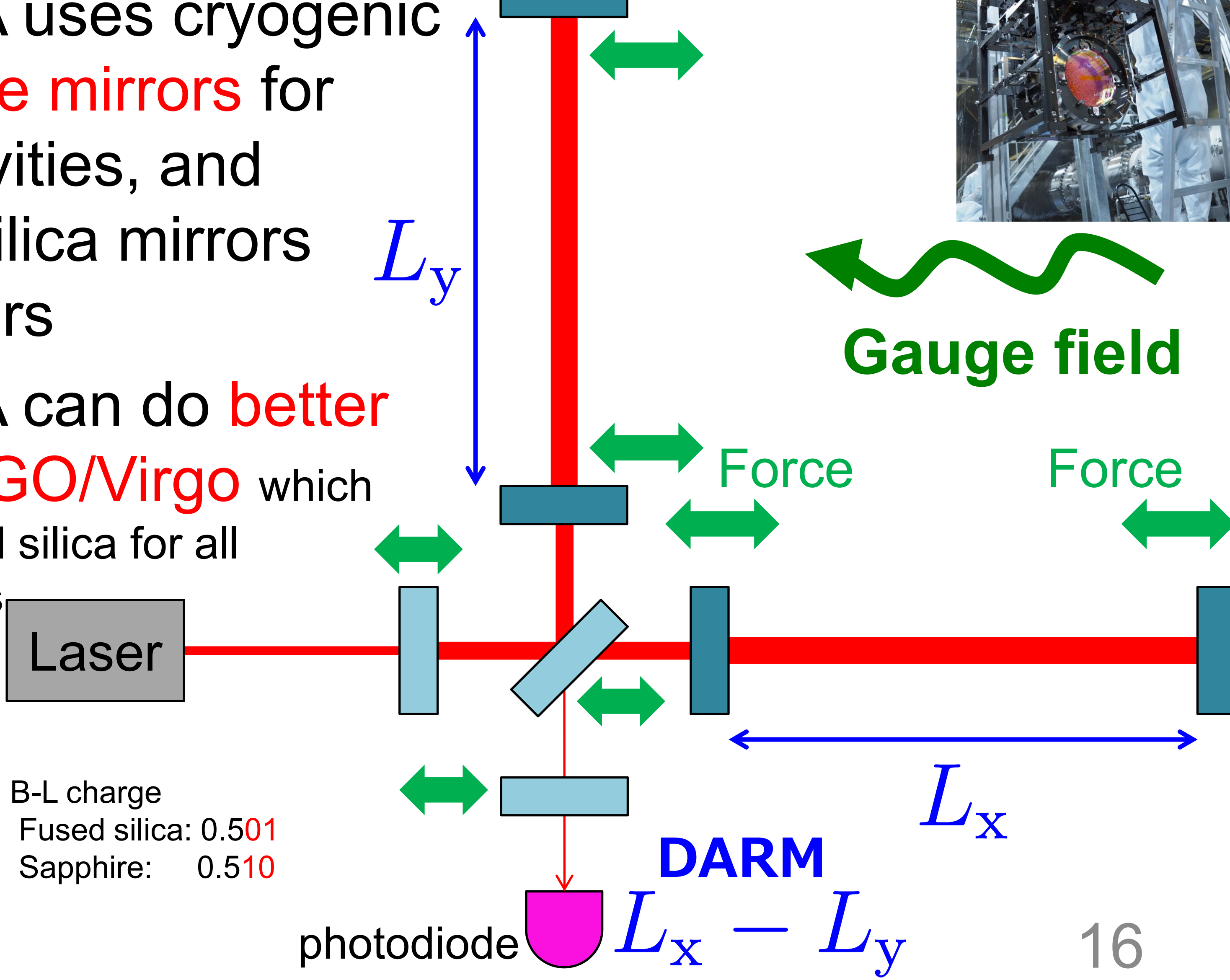
- GW Detectors are sensitive to differential arm length (DARM) change
- Most of the signal is cancelled out (LIGO/Virgo case)

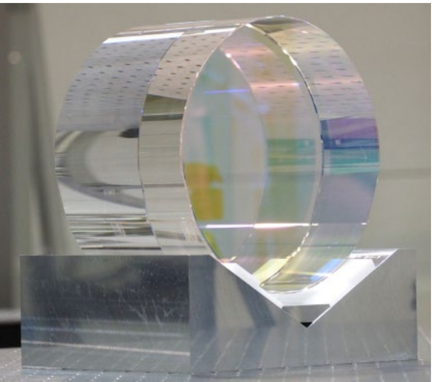


Search with KAGRA



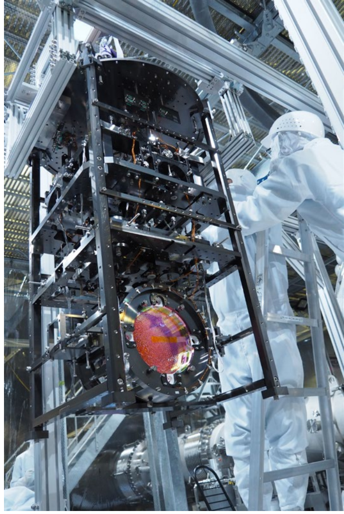
- KAGRA uses cryogenic sapphire mirrors for arm cavities, and fused silica mirrors for others
- KAGRA can do better than LIGO/Virgo which uses fused silica for all the mirrors



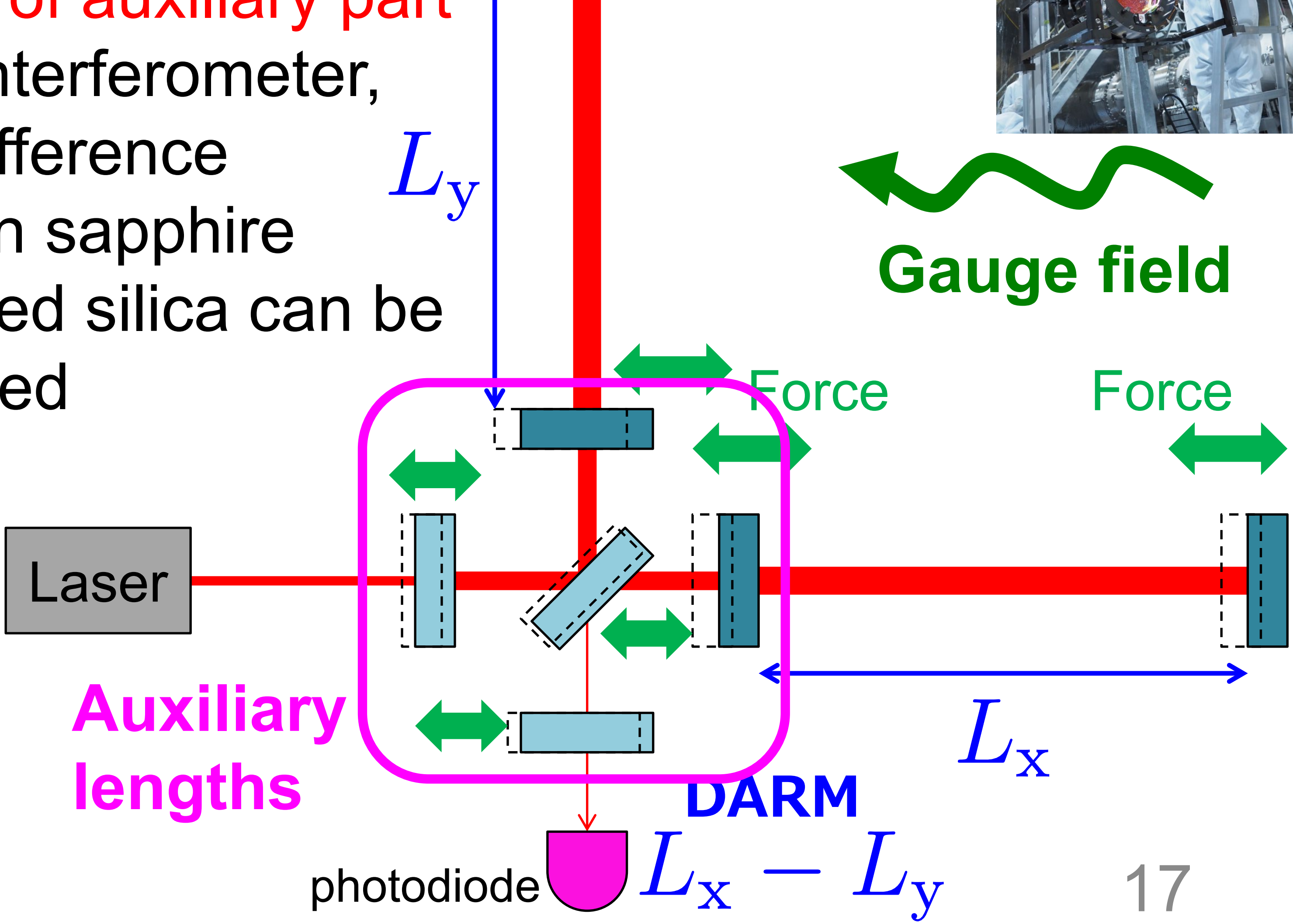


B-L charge
Fused silica: 0.501
Sapphire: 0.510

Search with KAGRA

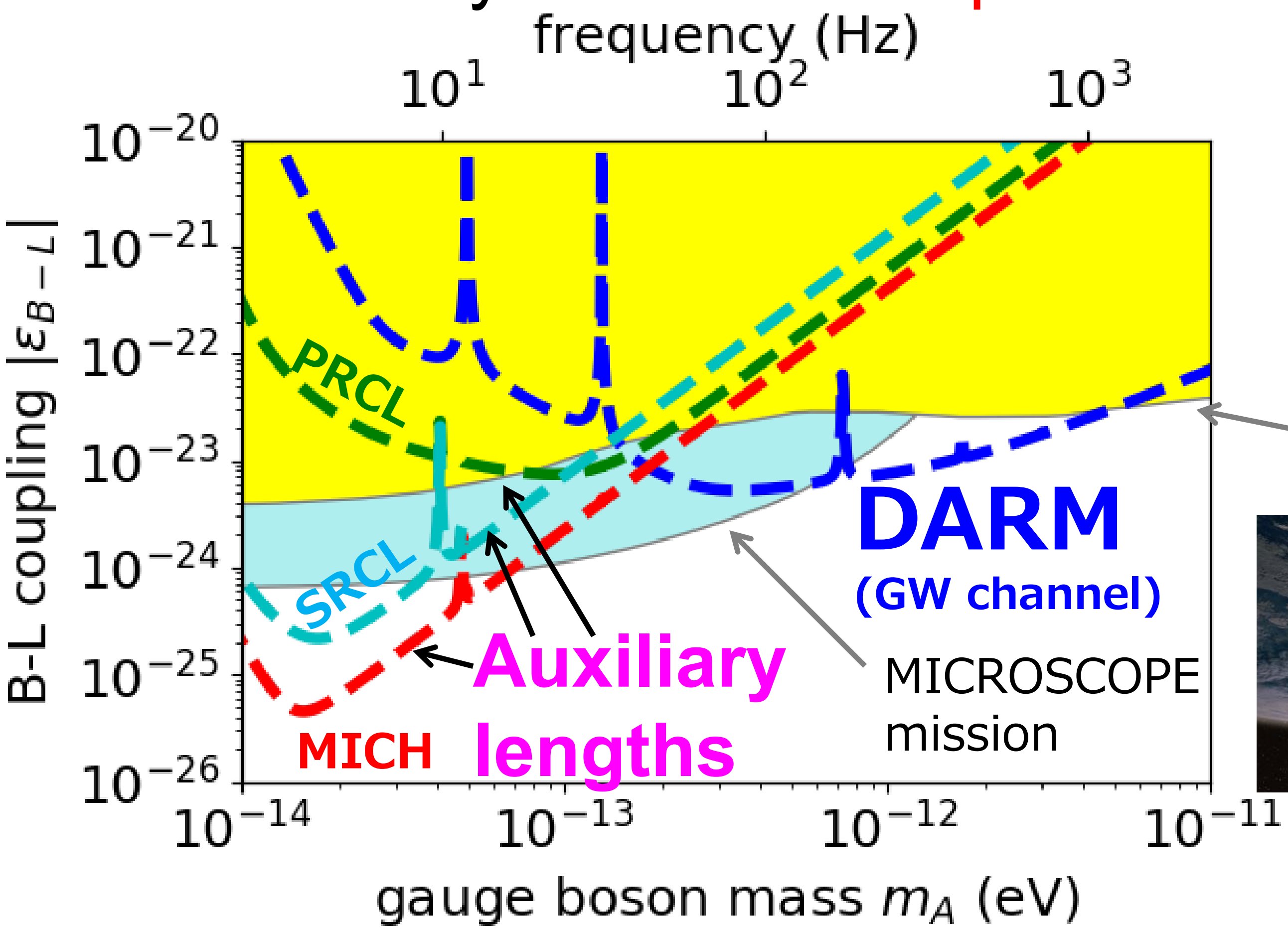


- By measuring the lengths of auxiliary part of the interferometer, force difference between sapphire and fused silica can be measured



KAGRA Gauge Boson Sensitivity

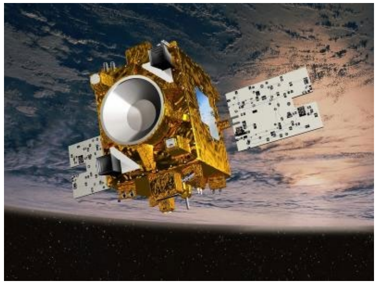
- Auxiliary length channels have better design sensitivity than DARM (GW channel) at low mass range
- Sensitivity better than equivalence principle tests



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)

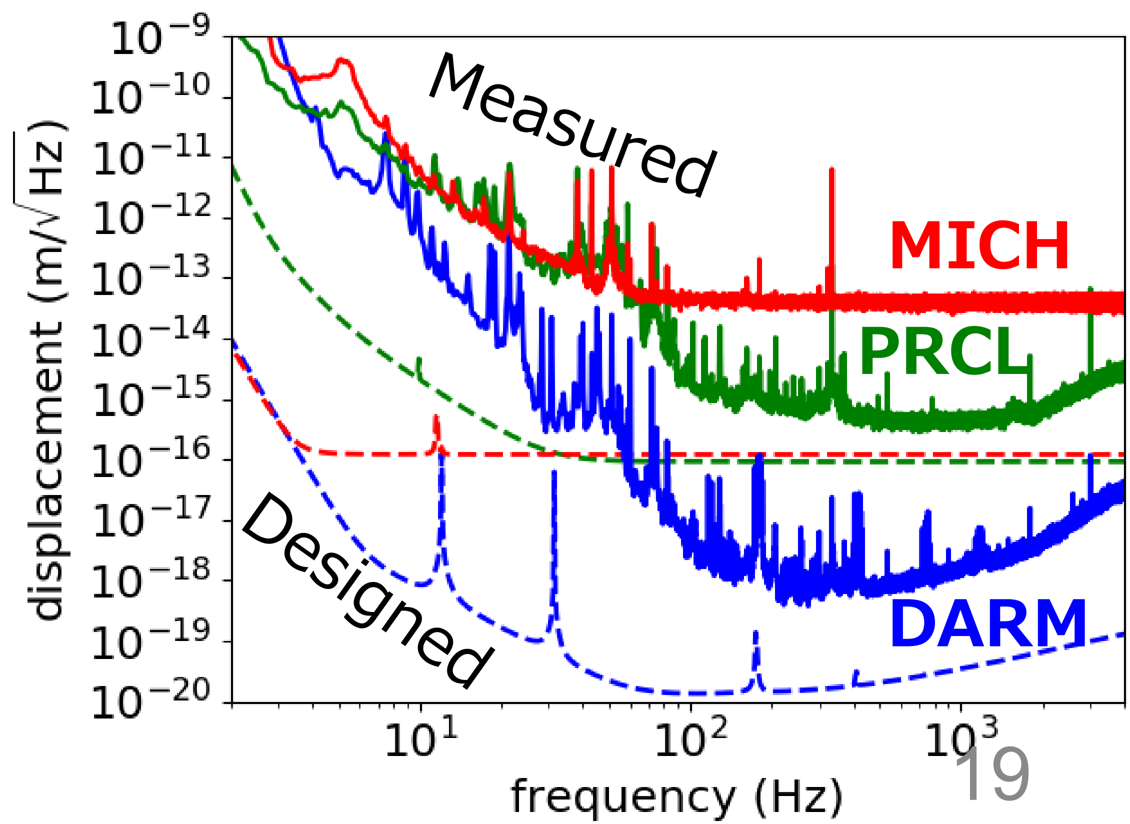
Eöt-Wash torsion pendulum



KAGRA 2020 Data Analysis

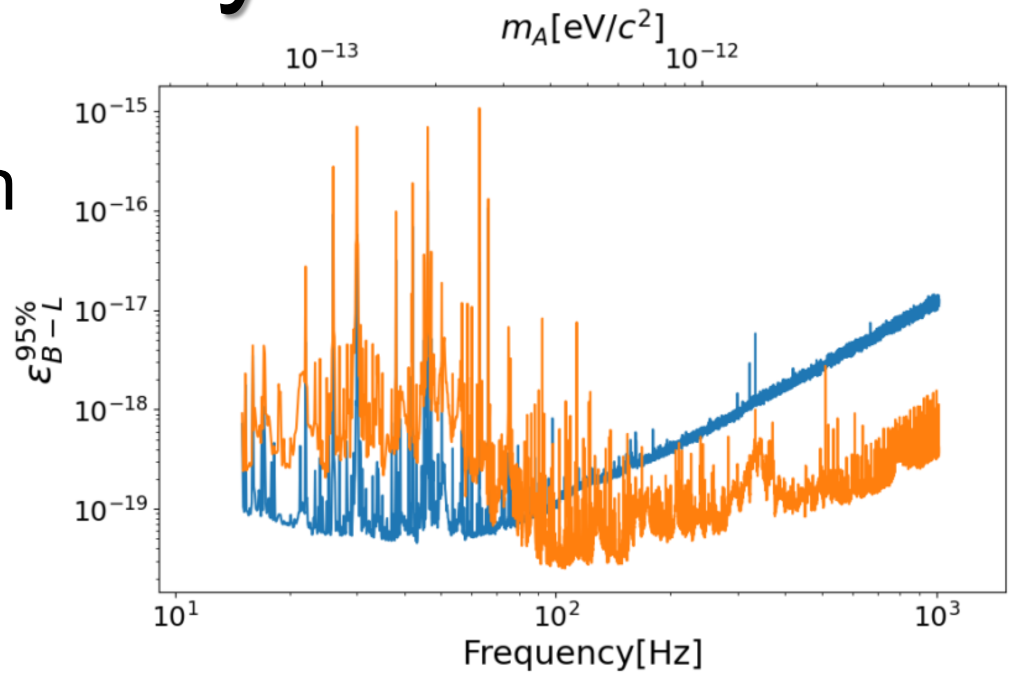
- KAGRA performed joint observing run in April 2020 with GEO600 (O3GK)
- Displacement sensitivity still not good
  ~ 6 orders of magnitude to go at 10 Hz
- Data analysis done using a new pipeline

H. Nakatsuka+,
PRD **108**, 092010 (2023)



KAGRA Data Analysis Results

- Still ~5 orders of magnitude worse than equivalence principle tests
- Demonstrated the feasibility of using auxiliary channels for astrophysics
- New data will be available from O4b and beyond



Ultralight vector dark matter search using data from the KAGRA O3GK run

arXiv:2403.03004v1 [astro-ph.CO] 5 Mar 2024

LIGO-Virgo-KAGRA, arXiv:2403.03004
(Paper written by J. Kume with 1800+ authors!)

Summary

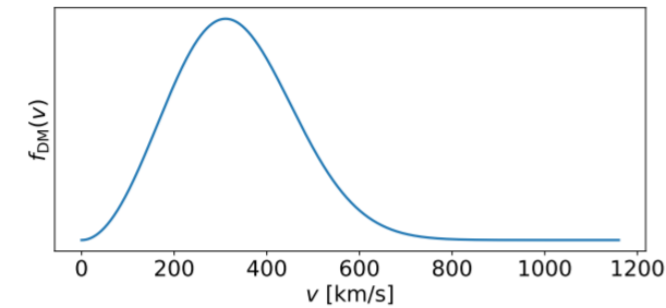
- Laser interferometers open up new possibilities for dark matter search
- First ultralight vector dark matter search using KAGRA 2020 data was performed
  - Sapphire mirrors allowed a new search
  - LIGO-Virgo-KAGRA, arXiv:2403.03004
- New data will be available by June 2024

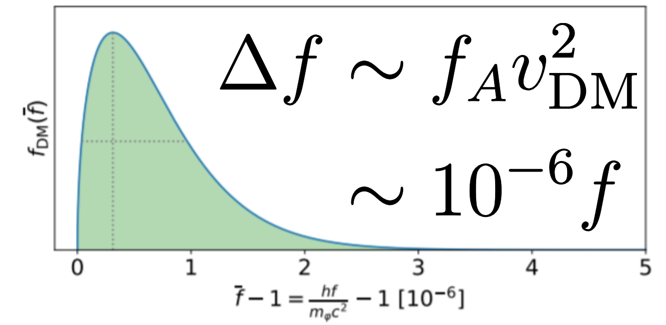
- Also… first ultralight axion dark matter data will be available by June 2024 (ask me later!)

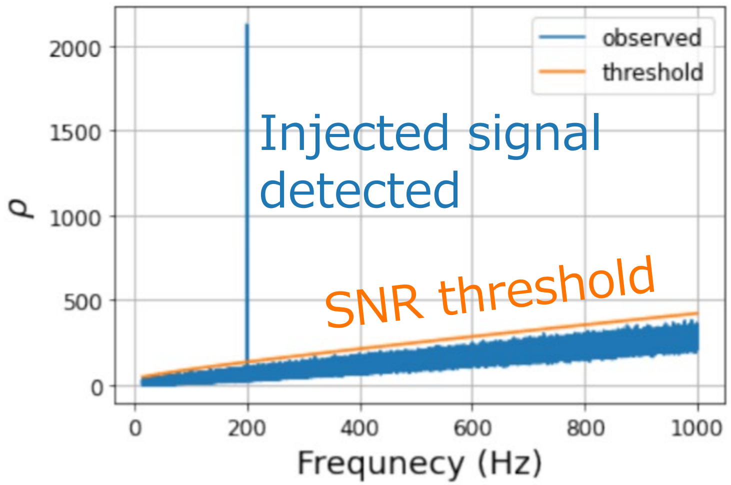
Additional Slides

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

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

Data

PSD

Obs. time

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

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

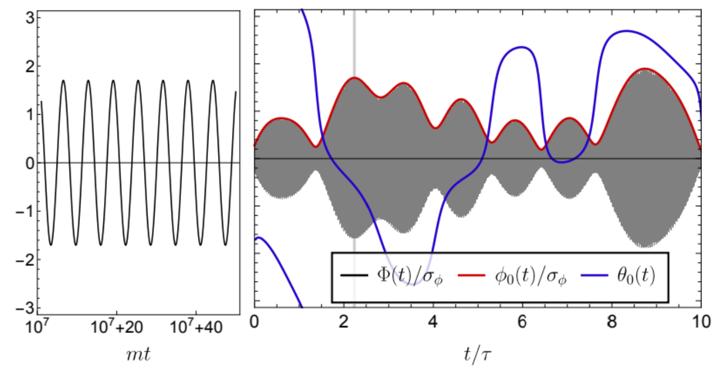
Stochastic Nature of DM Signal

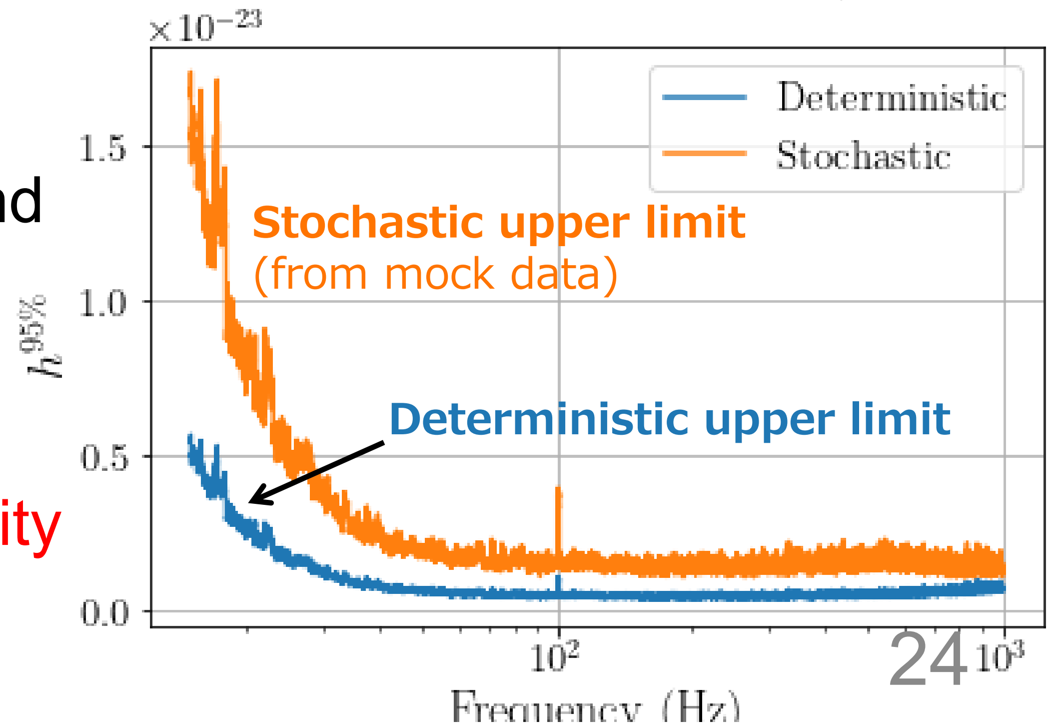
- DM signal is from superposition of many waves with various momentum, phase and polarization
- The amplitude fluctuates at the time scale of

$$\tau = 2\pi/(m_a v_{\rm DM}^2)$$

- 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

H. Nakatsuka+,
PRD **108**, 092010 (2023)



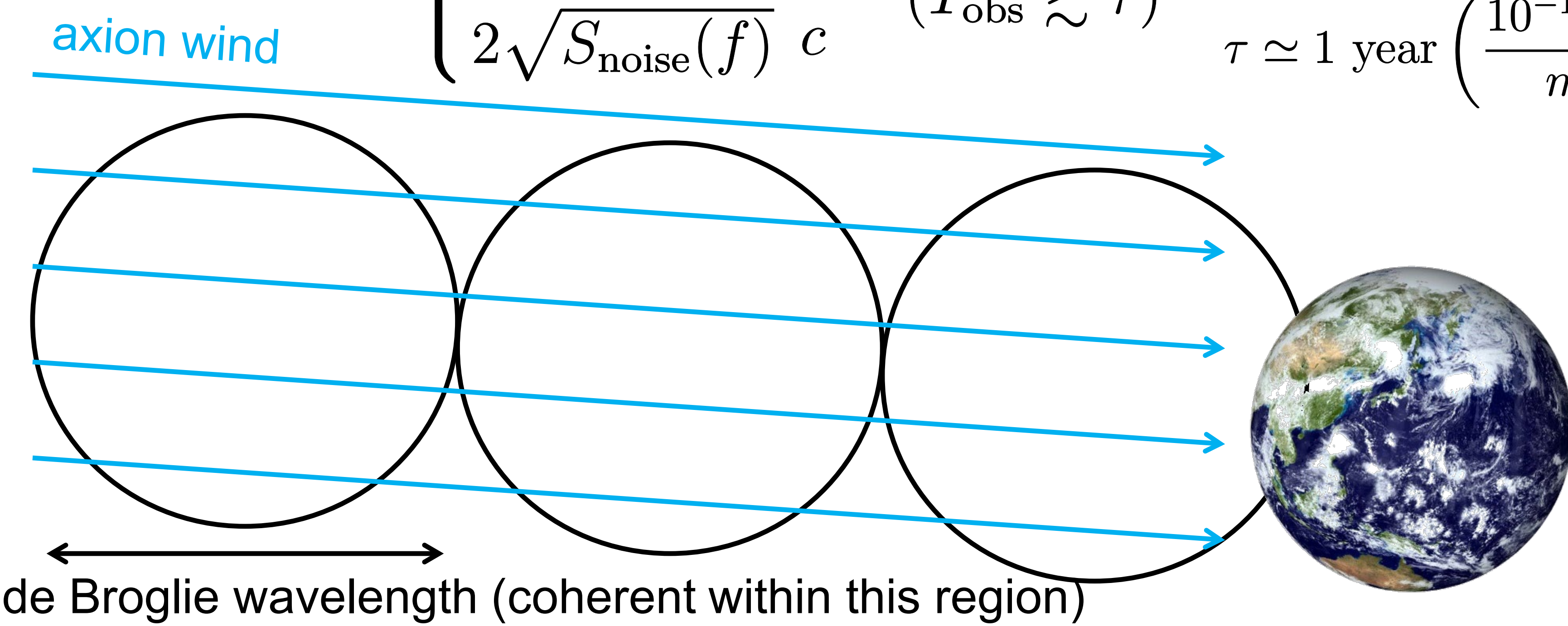


Coherence Time

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

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

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



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