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First results from ultralight vector dark matter search with KAGRA

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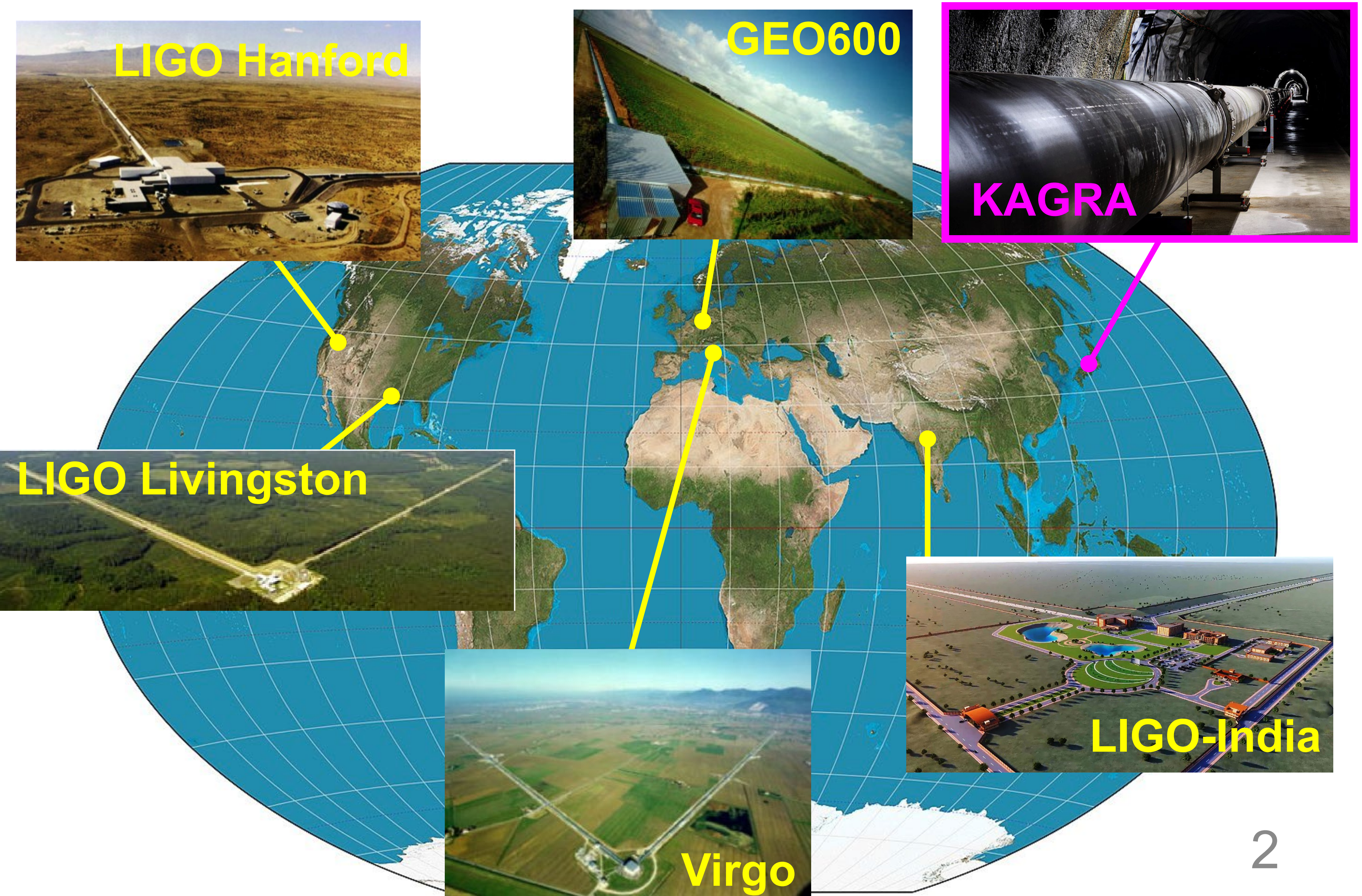
on behalf of the LIGO-Virgo-KAGRA Collaboration

Based on arXiv:2403.03004

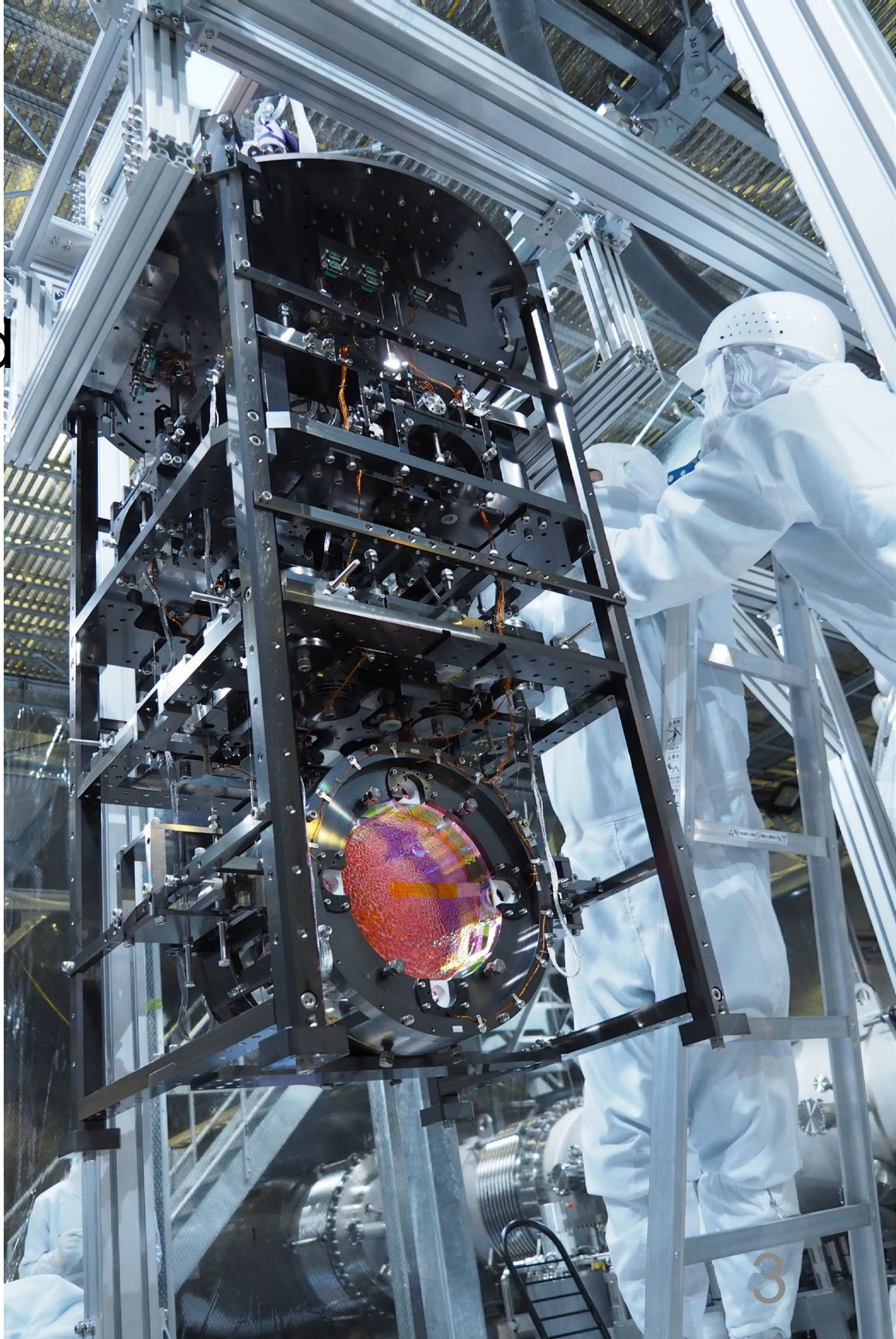
Global Network of GW Detectors



KAGRA Project

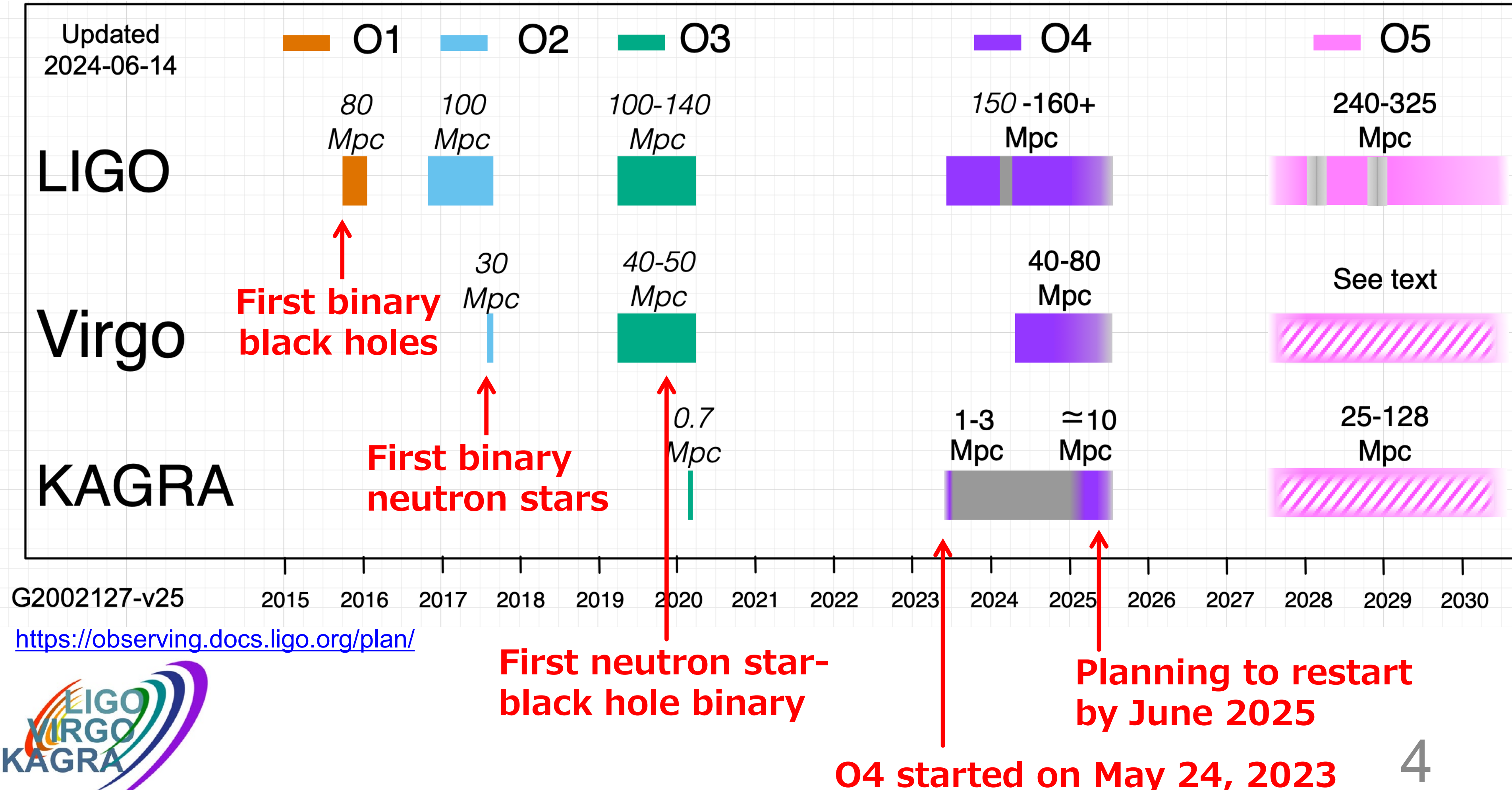
- Project started in 2010
- Construction completed and signed MoA with LIGO/Virgo in 2019
- 400+ collaborators
- 13 countries
- First (and so far, only) underground and cryogenic detector

KAGRA



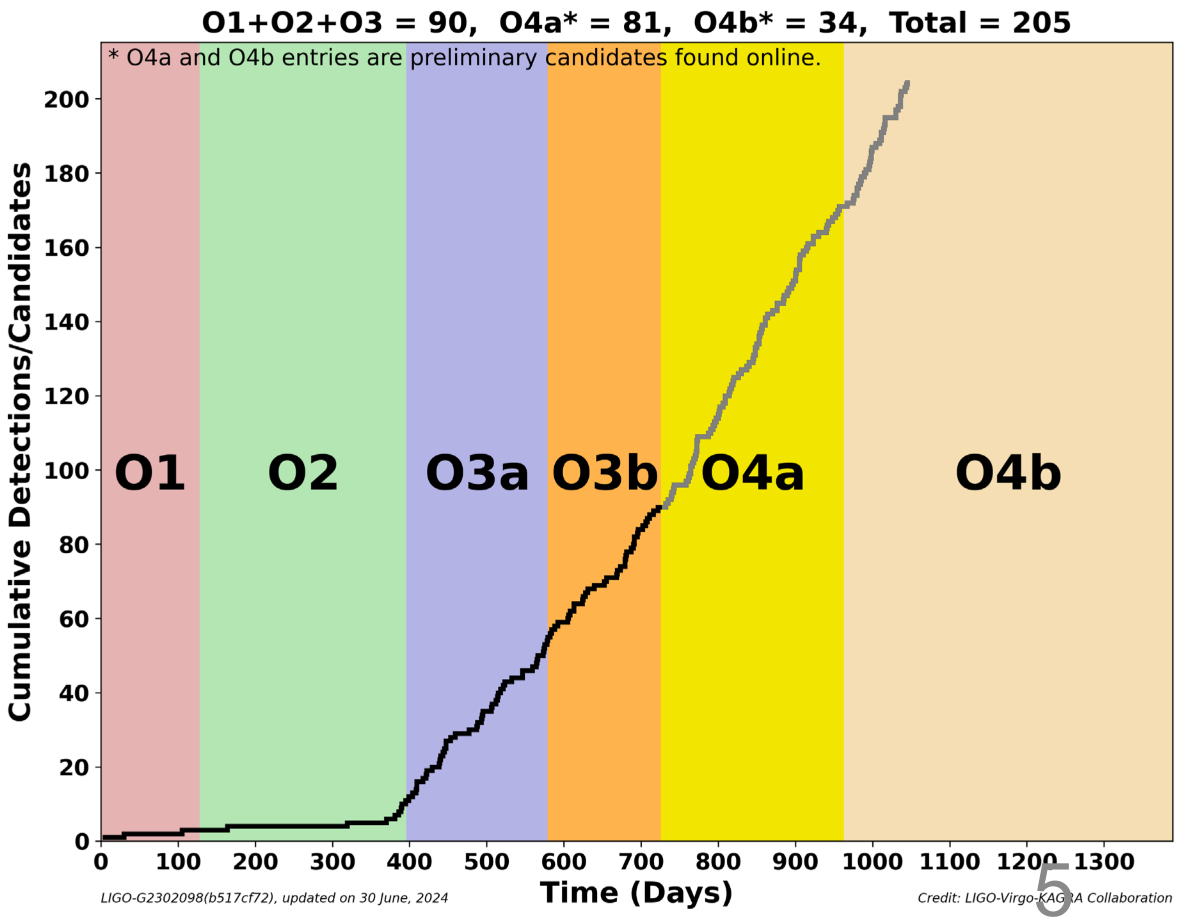
LIGO-Virgo-KAGRA Observing Plan

- Coordinated runs to detect GW signals by multiple detectors



LIGO-Virgo-KAGRA O4 Run Status

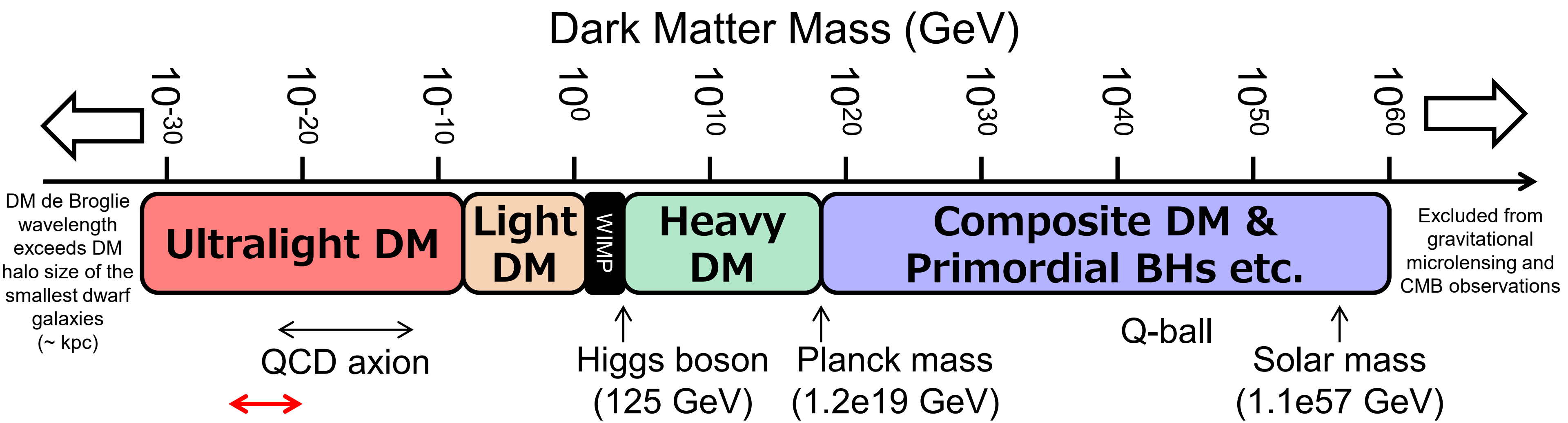
- More than 100 events reported from LIGO-Virgo
- Will continue until June 9, 2025
- KAGRA plans to join by the end of O4
- Currently recovering from 7.6 magnitude earthquake on January 1, 2024 (hardware work completed)



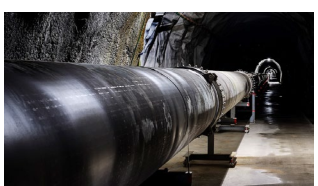
LIGO-G2302098

Various Dark Matter Models

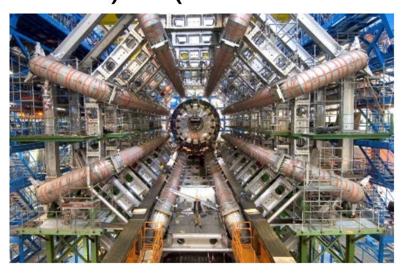
- ~90 orders of magnitude in mass
- Searches focused on WIMPs, but not detected yet
- Motivates new searches for other candidates



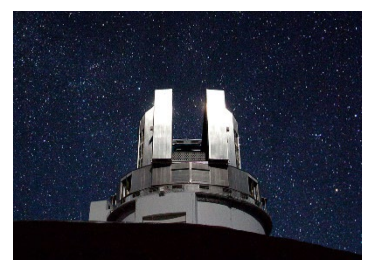
2.4 Hz ~ 2.4 kHz
(1e-14 ~ 1e-11 eV)
Laser Interferometry



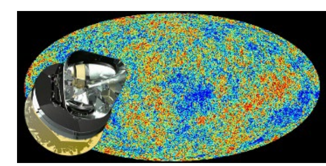
Underground experiments (XENON etc.)



LHC



Subaru telescope etc.



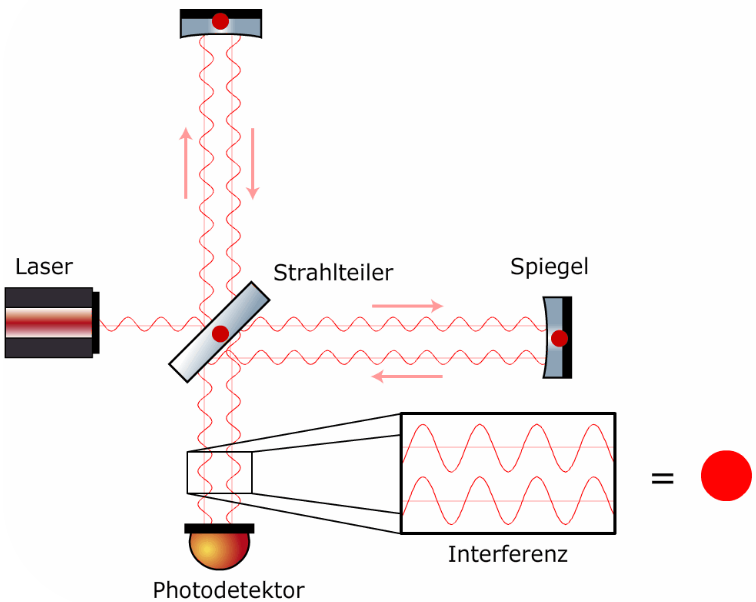
Cosmic microwave background

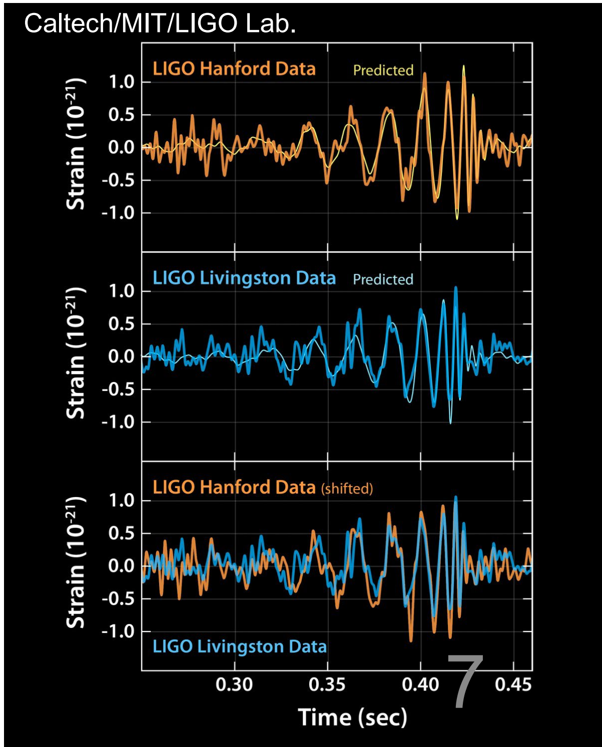
Ultralight DM with Interferometers

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

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

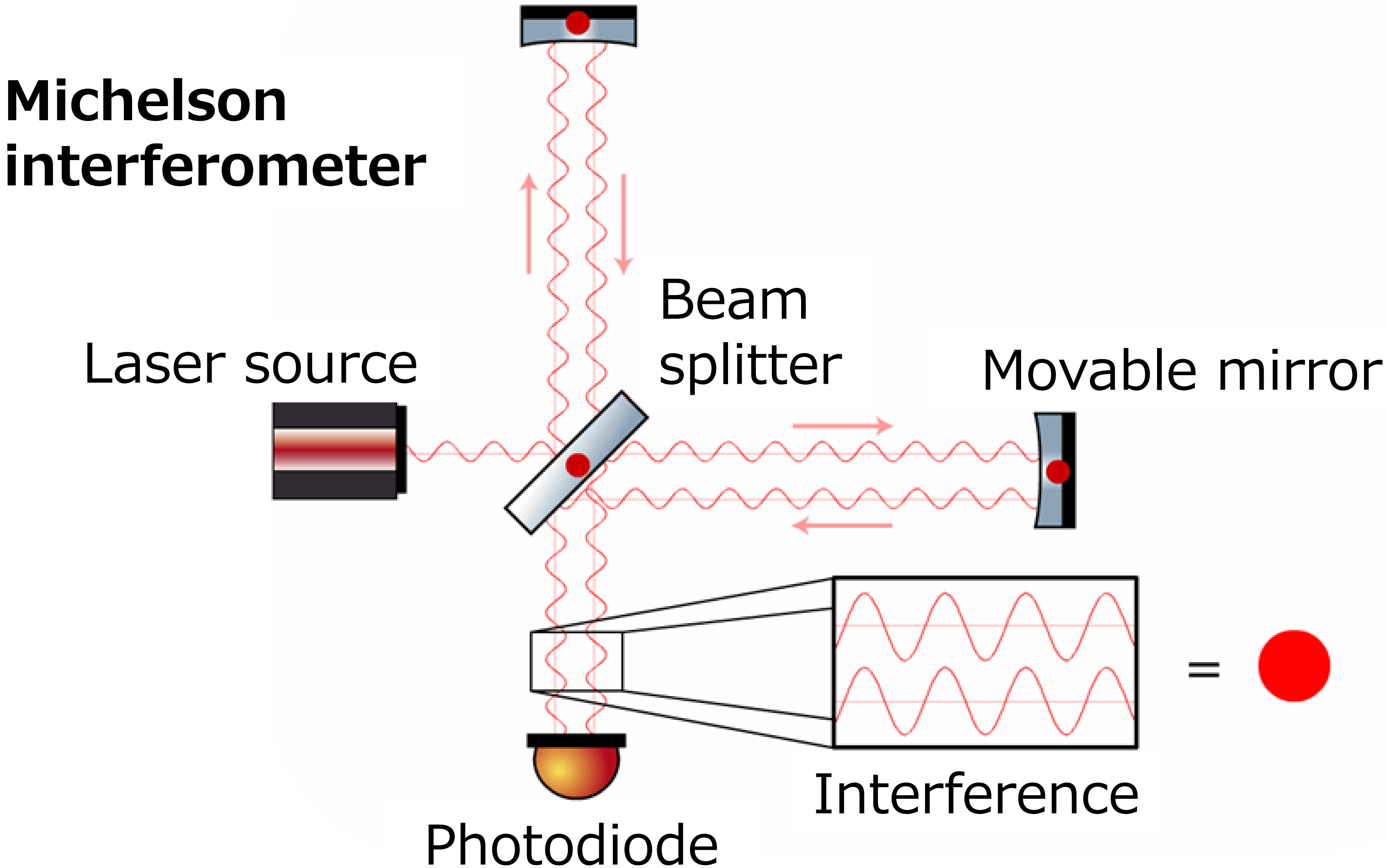
- Laser interferometers are sensitive to such oscillating changes





Laser Interferometry

- measures differential arm length change



Laser Interferometry

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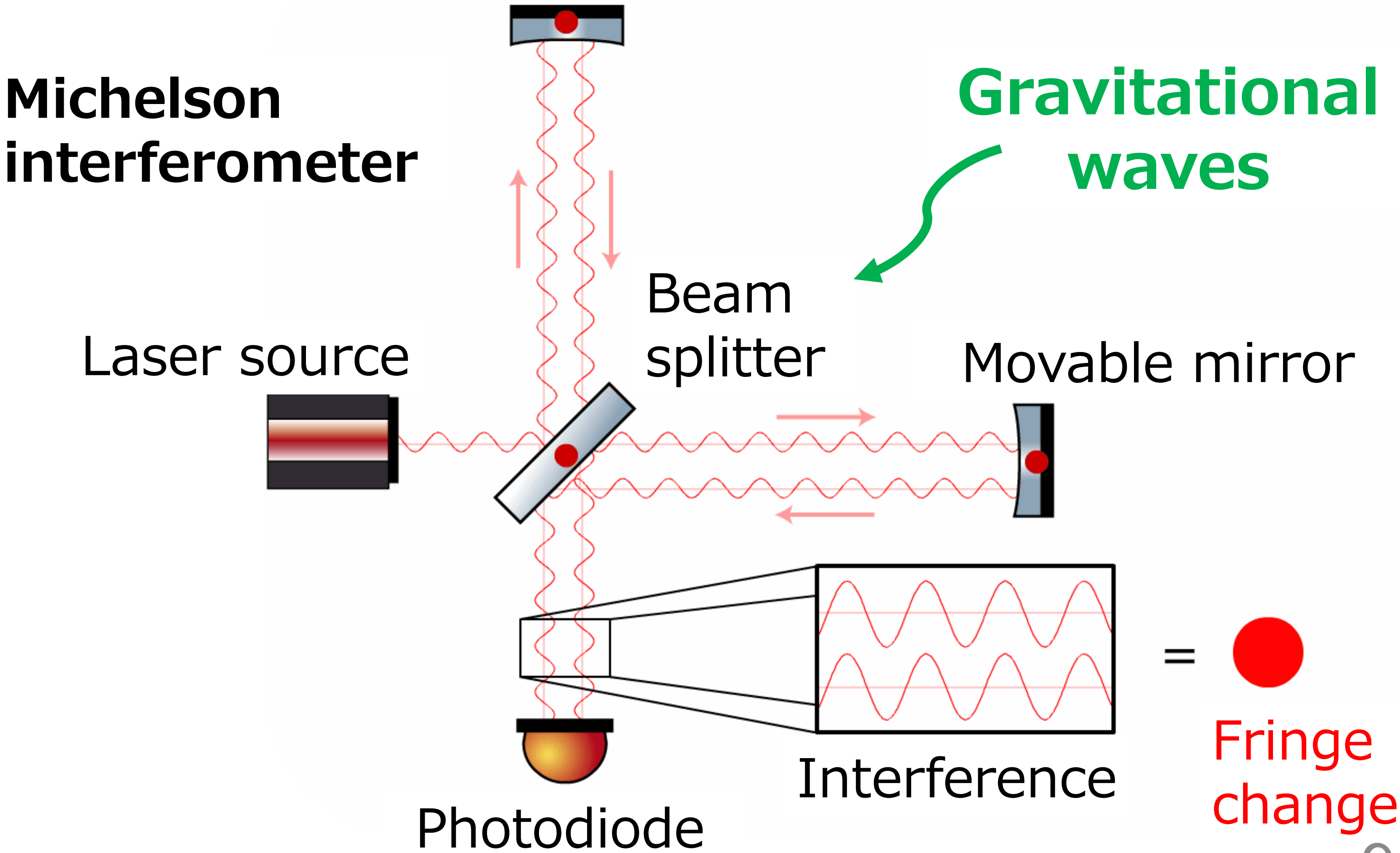
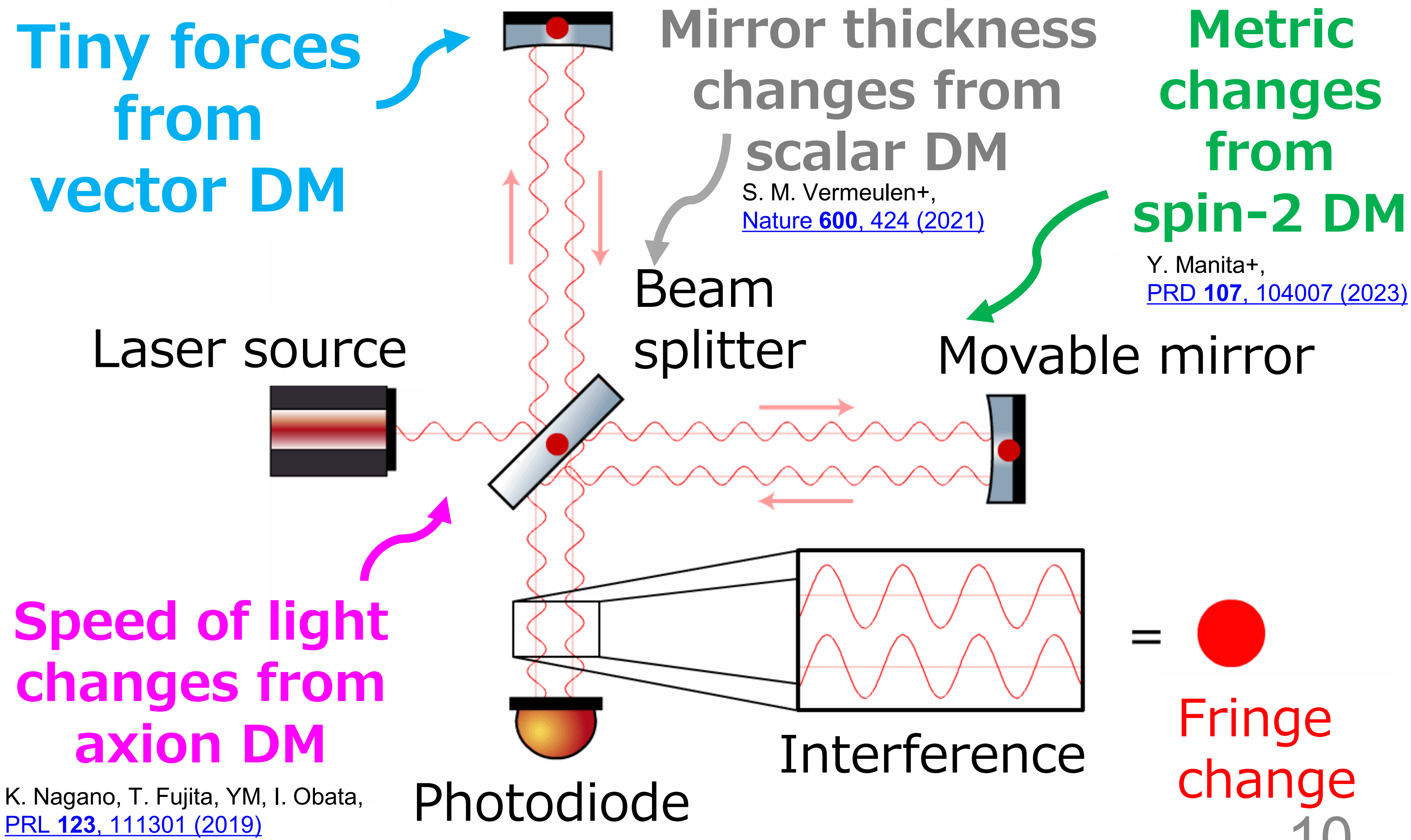


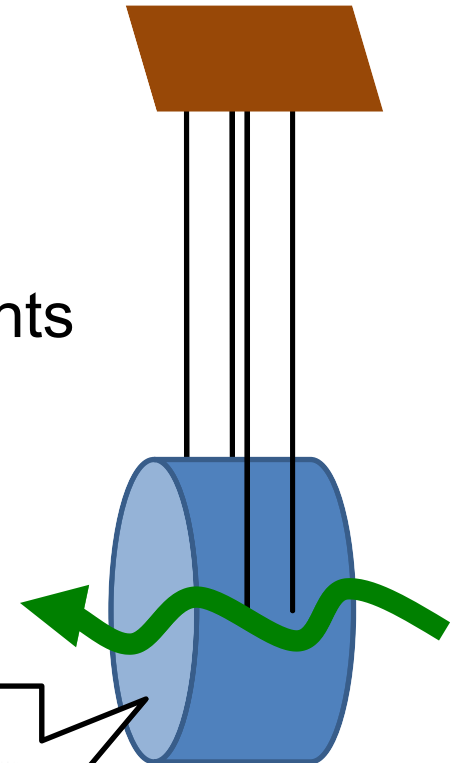
Laser Interferometry

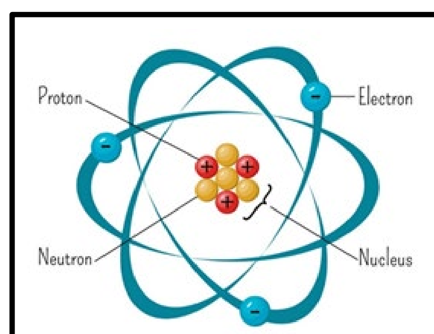
- measures differential arm length change



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

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

charge

vector boson mass

coupling
(normalized by e)

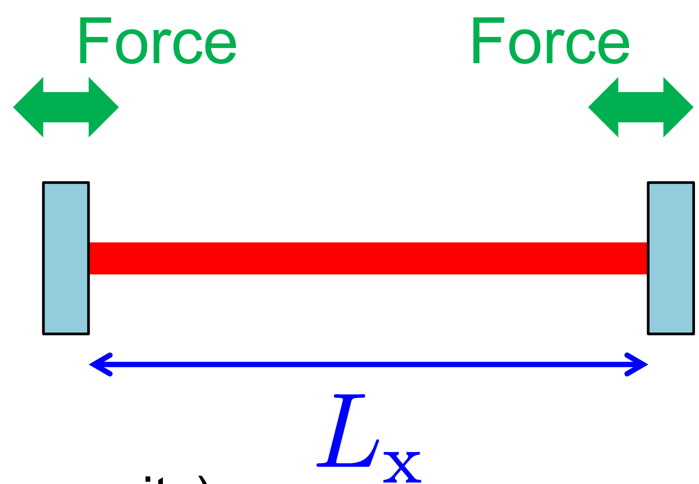
mirror mass

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?

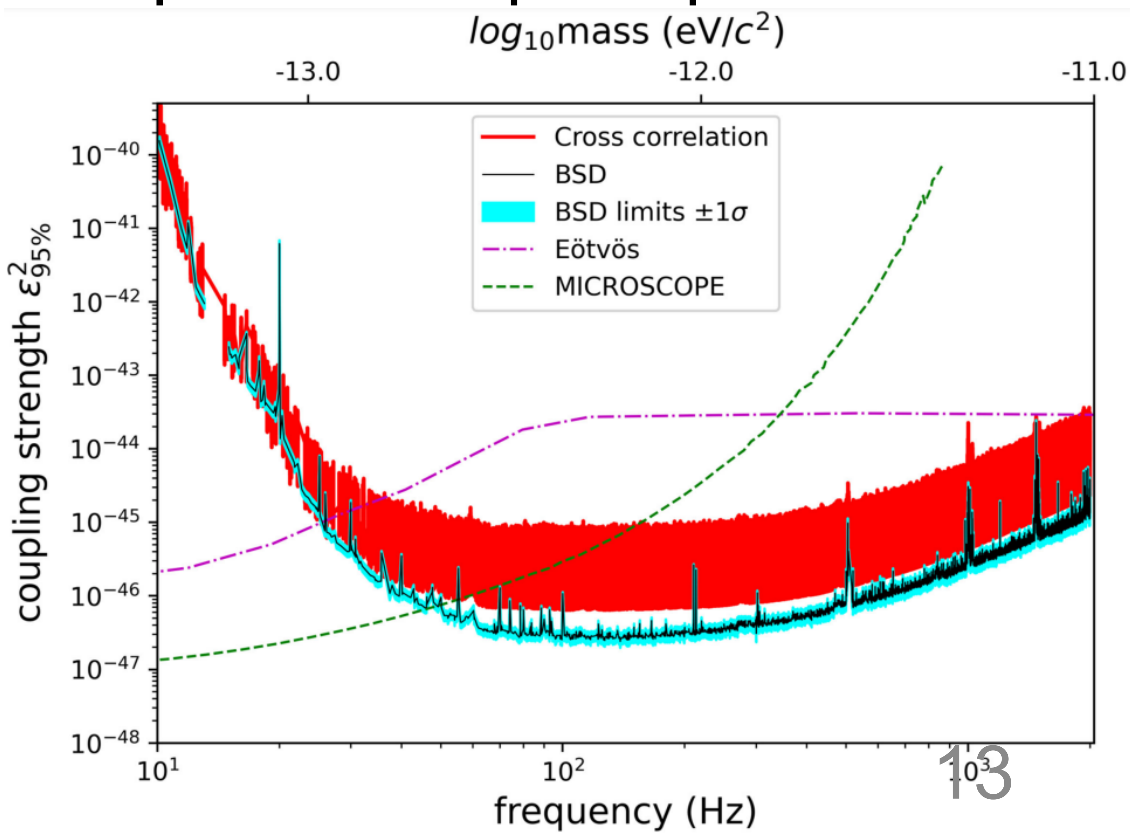
A. Pierce+, PRL **121**, 061102 (2018)

Previous Searches with LIGO/Virgo

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

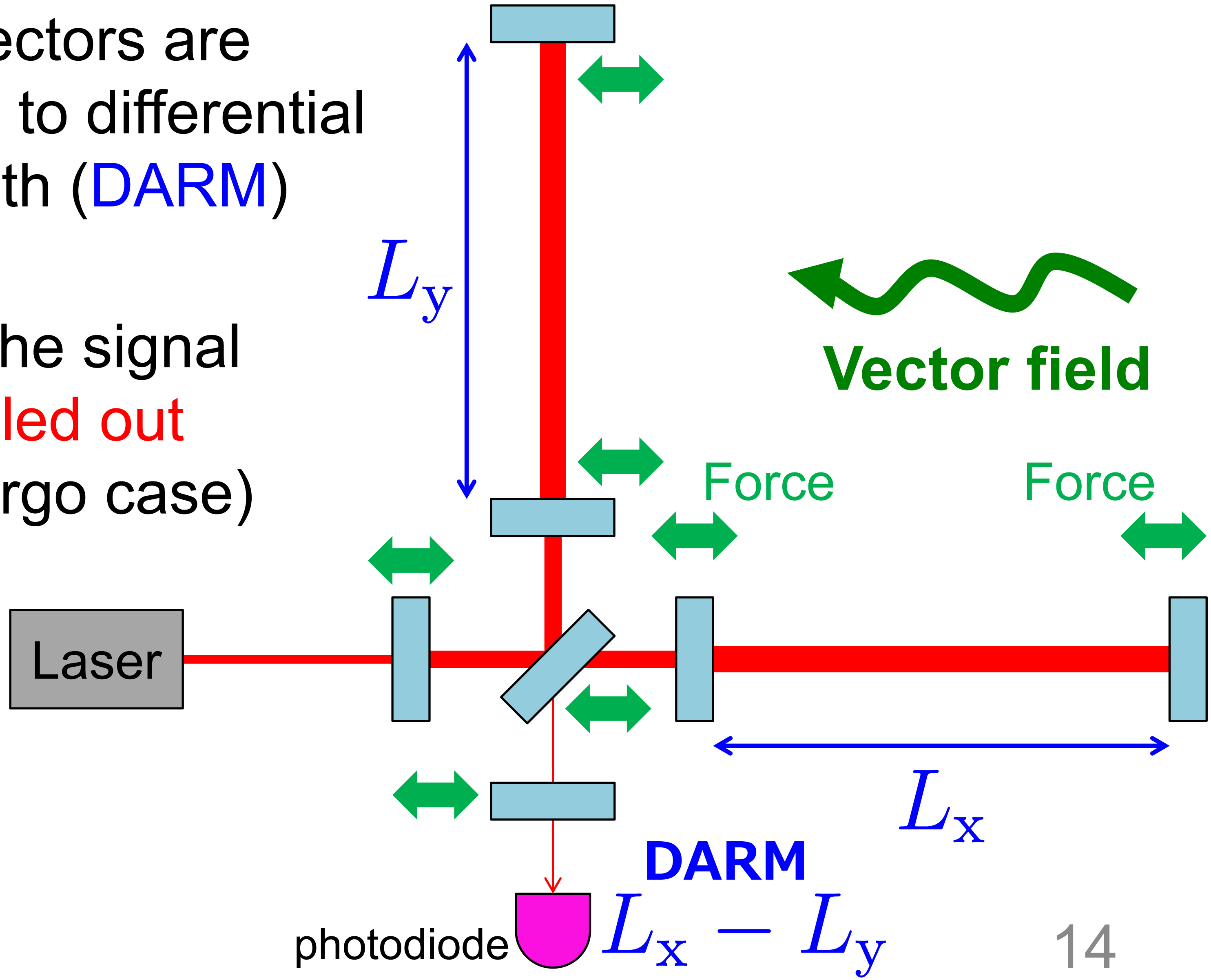
  H-K Guo+, [Communications Physics **2**, 155 (2019)]
  LIGO-Virgo-KAGRA Collaboration, [PRD **105**, 063030 (2022)]

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

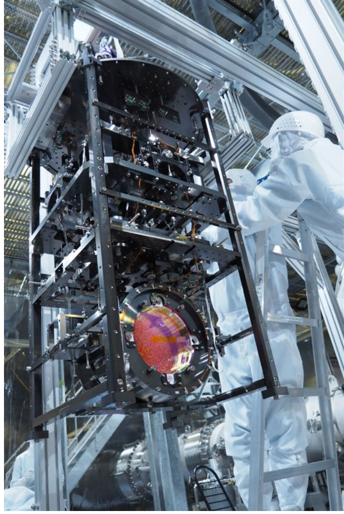


Search with GW Detectors

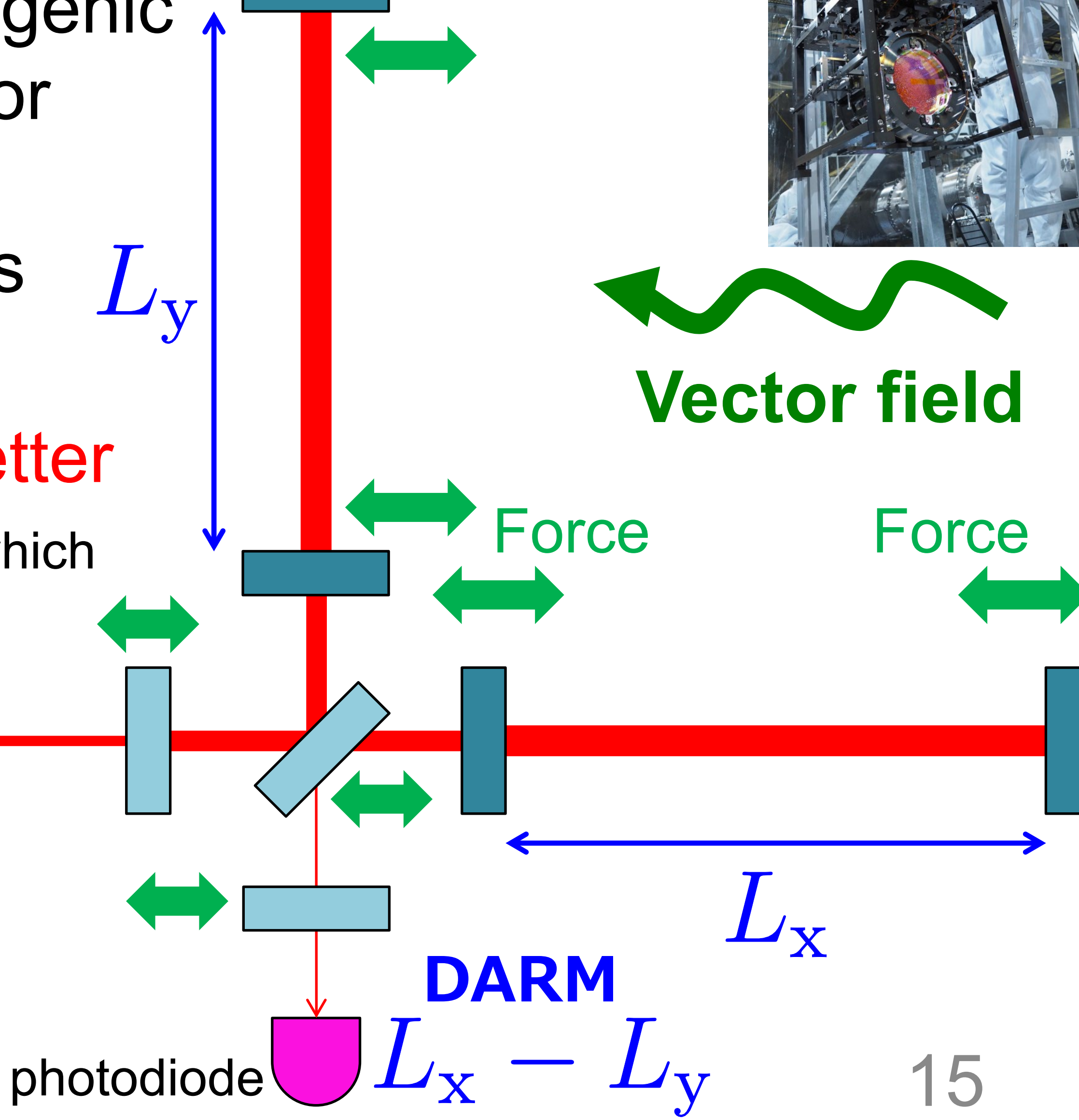
- GW Detectors are sensitive to differential arm length (DARM) change
- Most of the signal is cancelled out (LIGO/Virgo case)



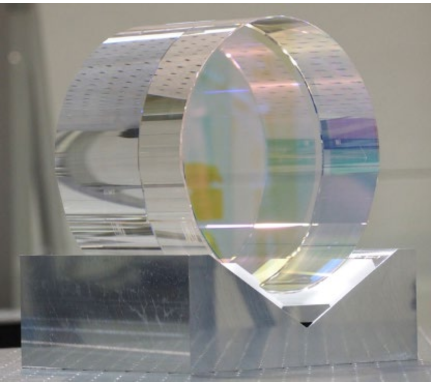
Search with KAGRA



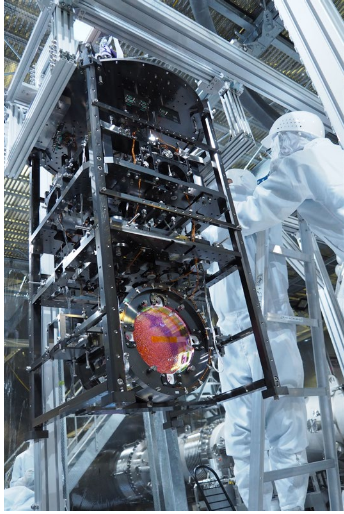
- KAGRA uses cryogenic sapphire mirrors for arm cavities, and fused silica mirrors for others
- KAGRA can do better than LIGO/Virgo which uses fused silica for all the mirrors



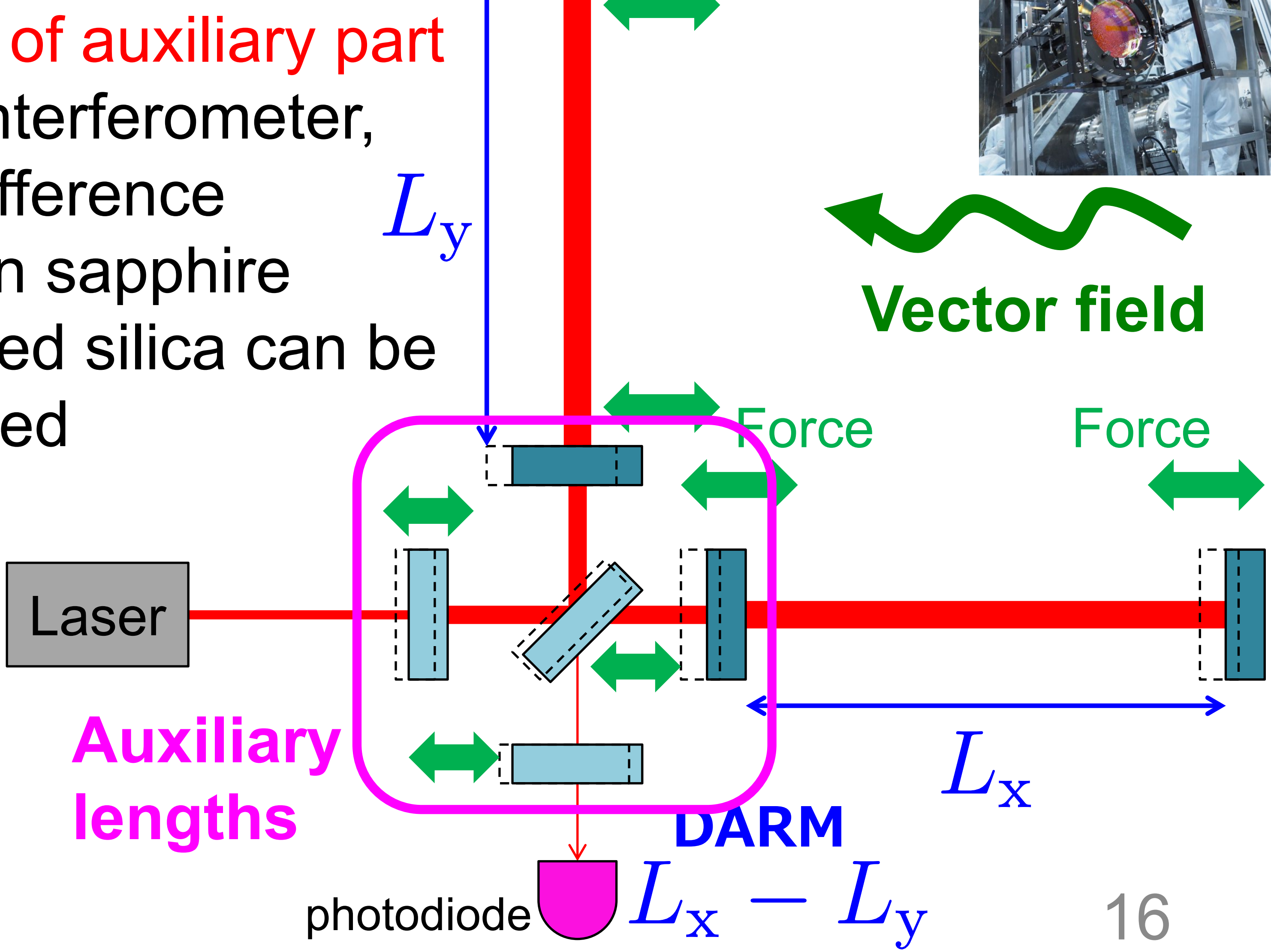
B-L charge
Fused silica: 0.501
Sapphire: 0.510



Search with KAGRA

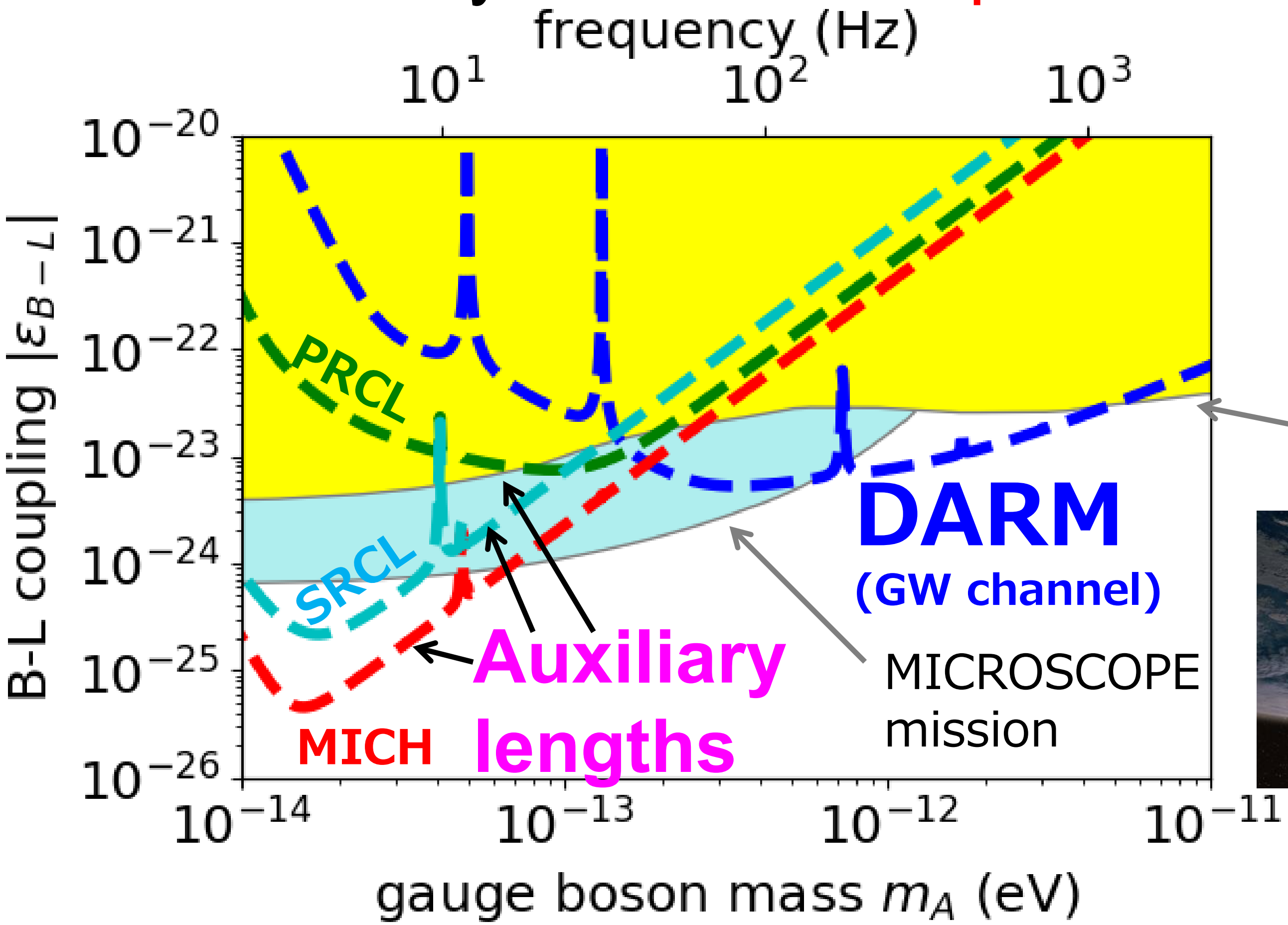


- By measuring the lengths of auxiliary part of the interferometer, force difference between sapphire and fused silica can be measured



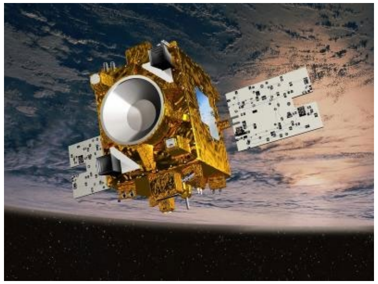
KAGRA Vector Boson Sensitivity

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



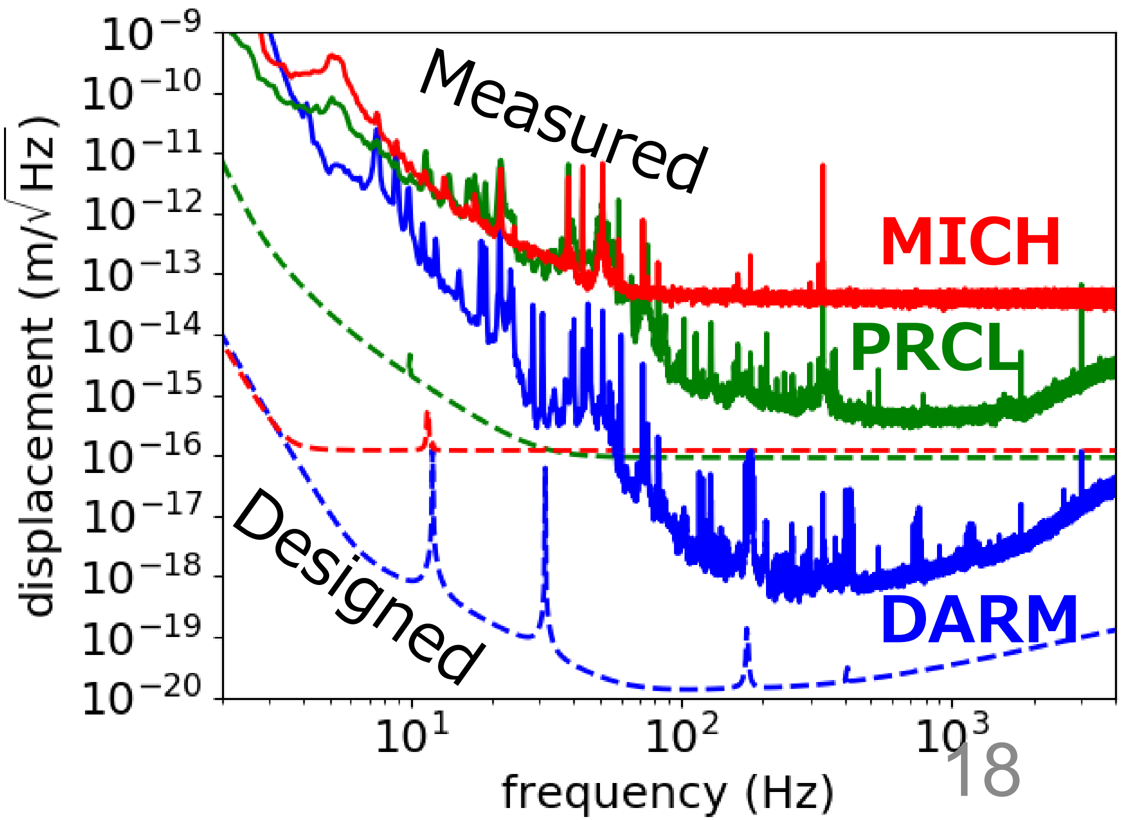
YM, T. Fujita, S. Morisaki, H. Nakatsuka, I. Obata, PRD 102, 102001 (2020)

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



KAGRA 2020 Data Analysis

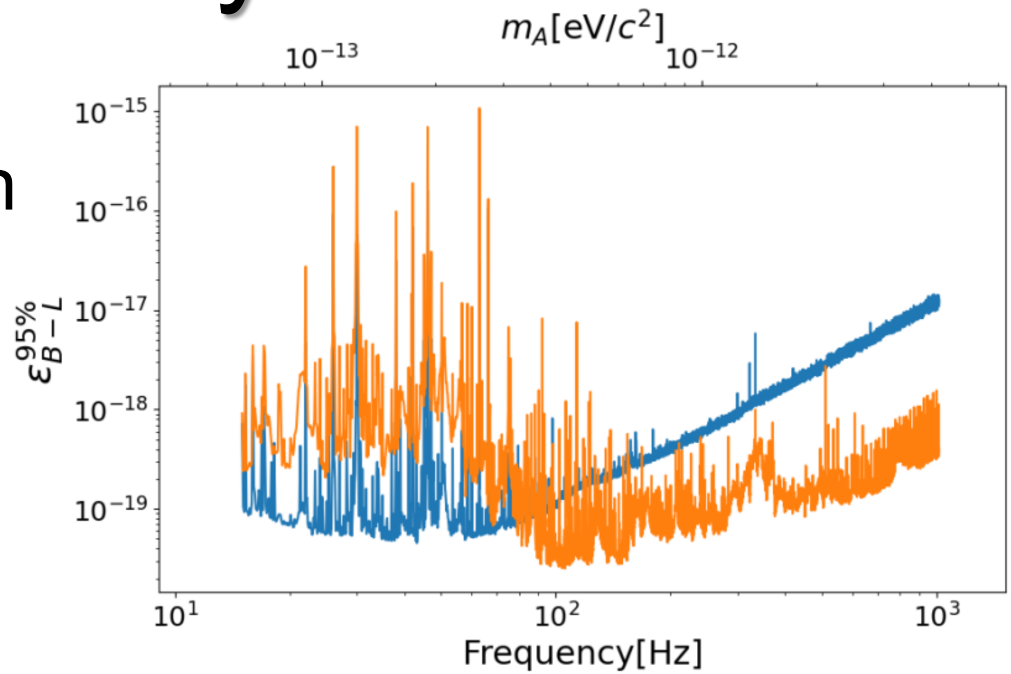
- KAGRA performed joint observing run in April 2020 with GEO600 (O3GK)
- Displacement sensitivity still not good
  ~ 6 orders of magnitude to go at 10 Hz
- Auxiliary data not even considered as useful science data
- Data analysis done using a new pipeline



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!)

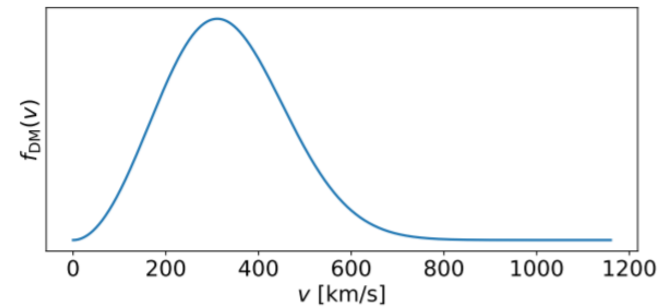
Summary

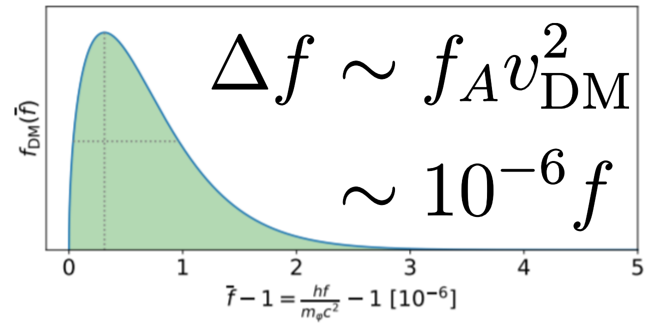
- Laser interferometers open up new possibilities for dark matter search
- First ultralight vector dark matter search using KAGRA 2020 data was performed
  - Sapphire mirrors allowed a new search
  - LIGO-Virgo-KAGRA collab., arXiv:2403.03004 (to be appeared in PRD)
- New data will be available by June 2025
- Also… first ultralight axion dark matter data will be available by June 2025 (ask me later!)

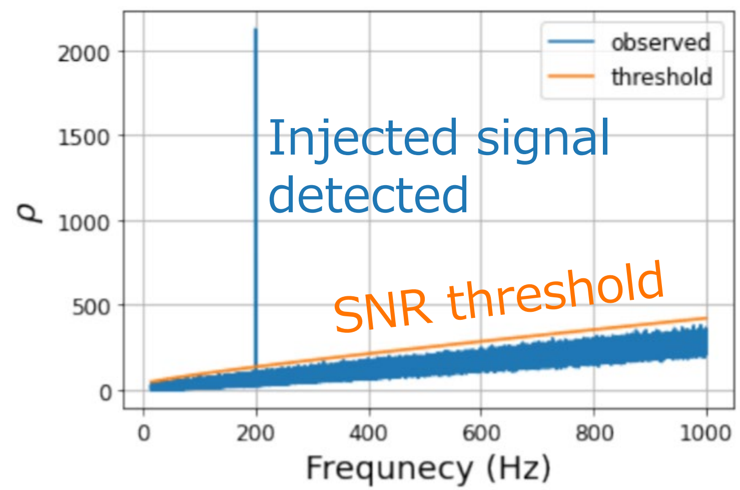
Additional Slides

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

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

Data

PSD

Obs. time

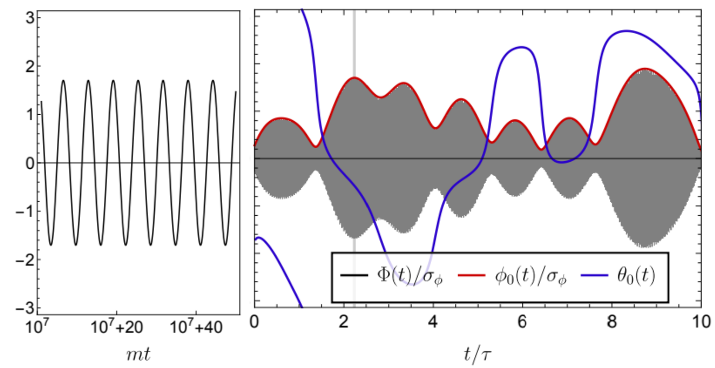
$m_A \leq 2\pi f_k \leq m_A(1 + \kappa v_{\mathrm{DM}}^2)$

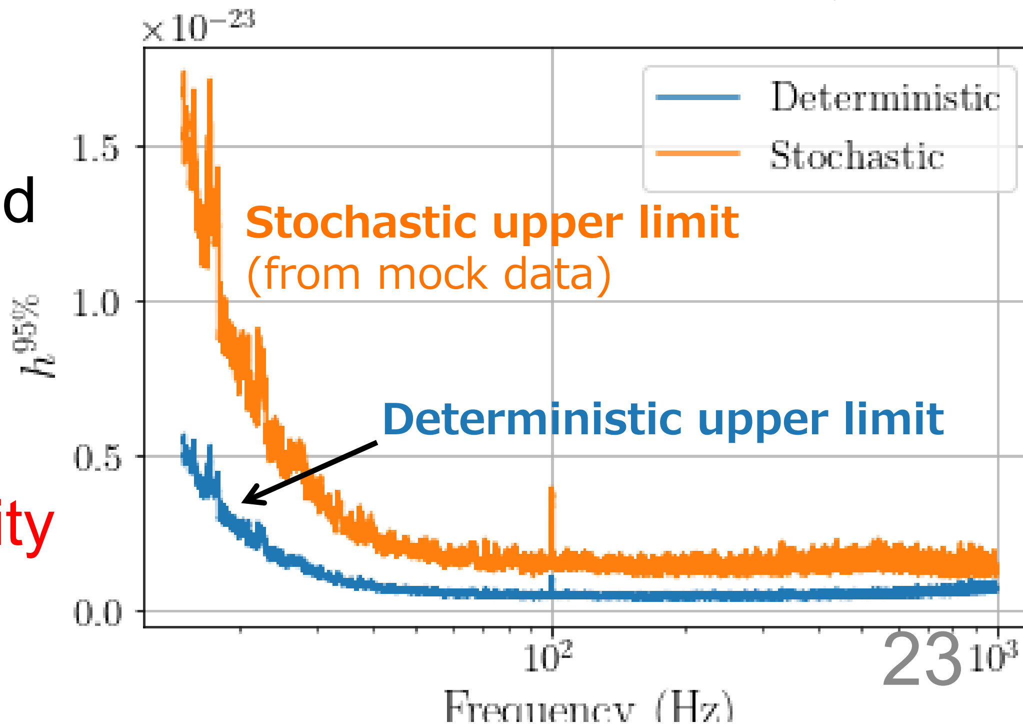
- Detection threshold determined assuming ρ follows χ^2 distribution (=assuming Gaussian noise)
- From ρ , calculate 95% upper limit on coupling constant
- Applied the pipeline to mock data for verification

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)



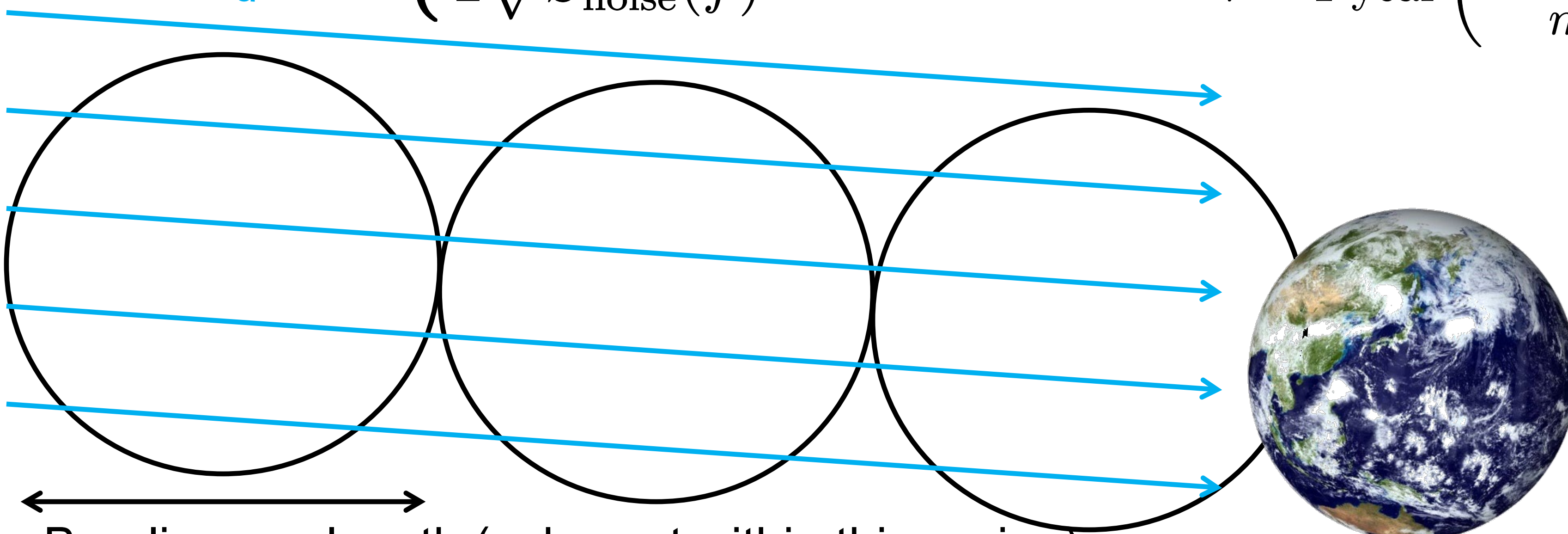


Coherence Time

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

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

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

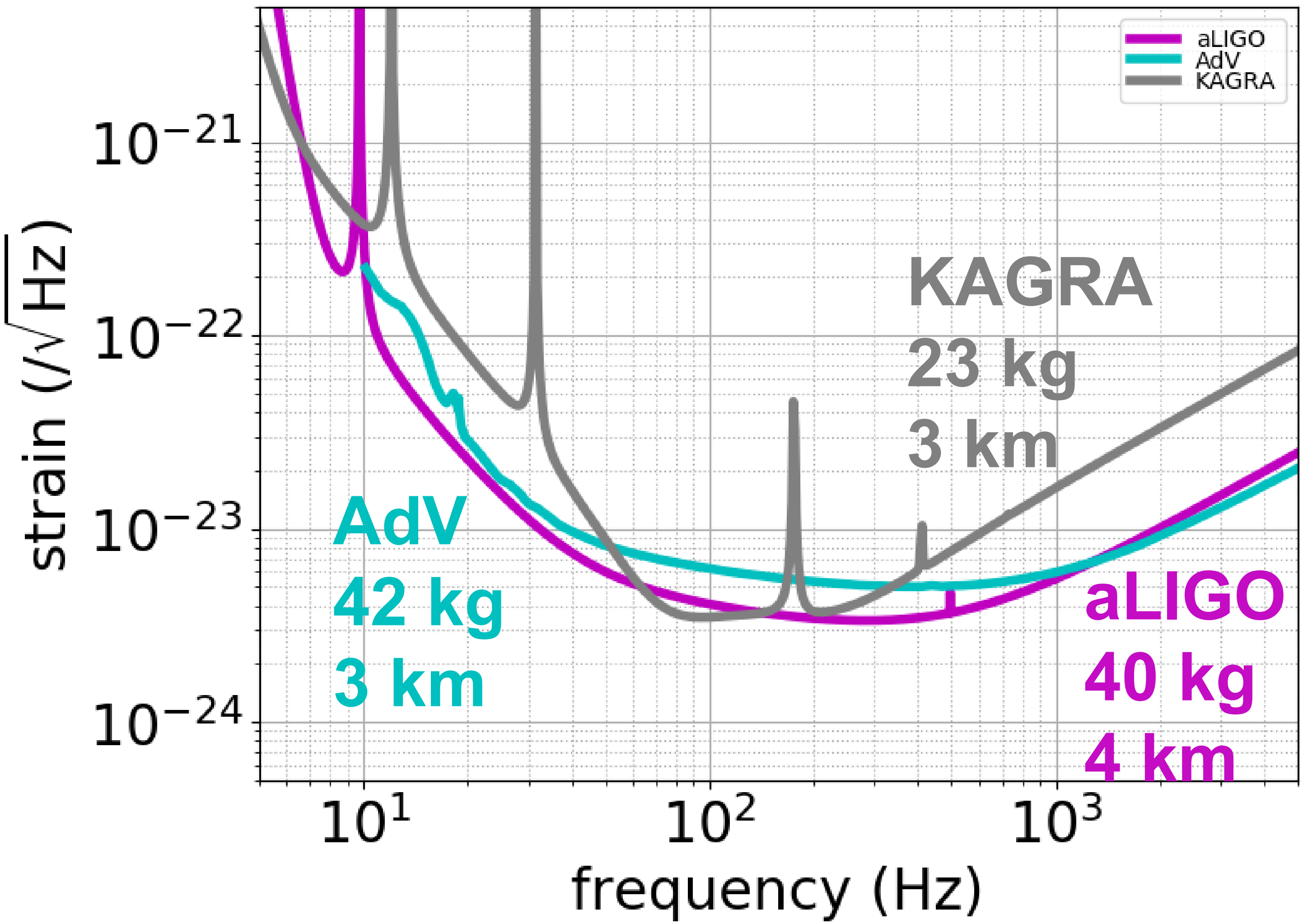


Freq-Mass-Coherence Time

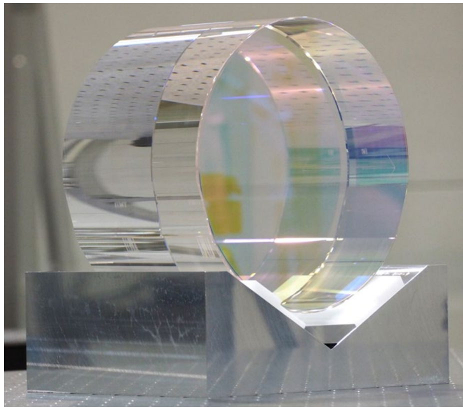
Frequency	Mass	Coherent Time	Coherent Length
0.1 Hz	4.1e-16 eV	0.32 year	3e12 m
1 Hz	4.1e-15 eV	1e6 sec 12 days	3e11 m
10 Hz	4.1e-14 eV	1.2 days	3e10 m
100 Hz	4.1e-13 eV	2.8 hours	3e9 m
1000 Hz	4.1e-12 eV	17 minutes	3e8 m
10000 Hz	4.1e-11 eV	1.7 minutes	3e7 m

KAGRA Design Sensitivity

- Not good at low freq. because of thick and short fiber (35 cm, φ1.6 mm) to extract heat, and lower mass

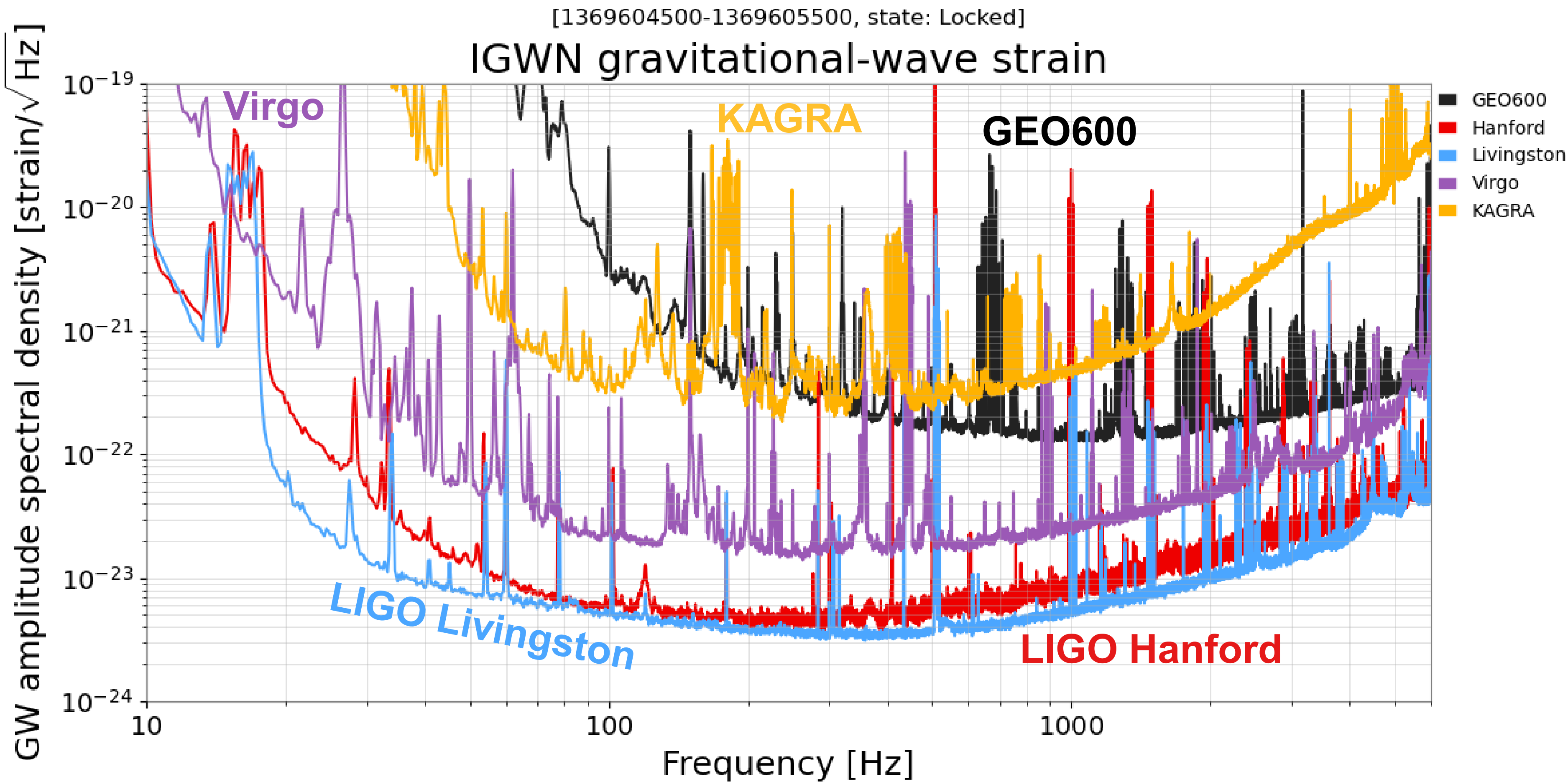


23 kg was the largest available sapphire mirror



(Roughly) Current Sensitivity

- Smaller the better in y-axis

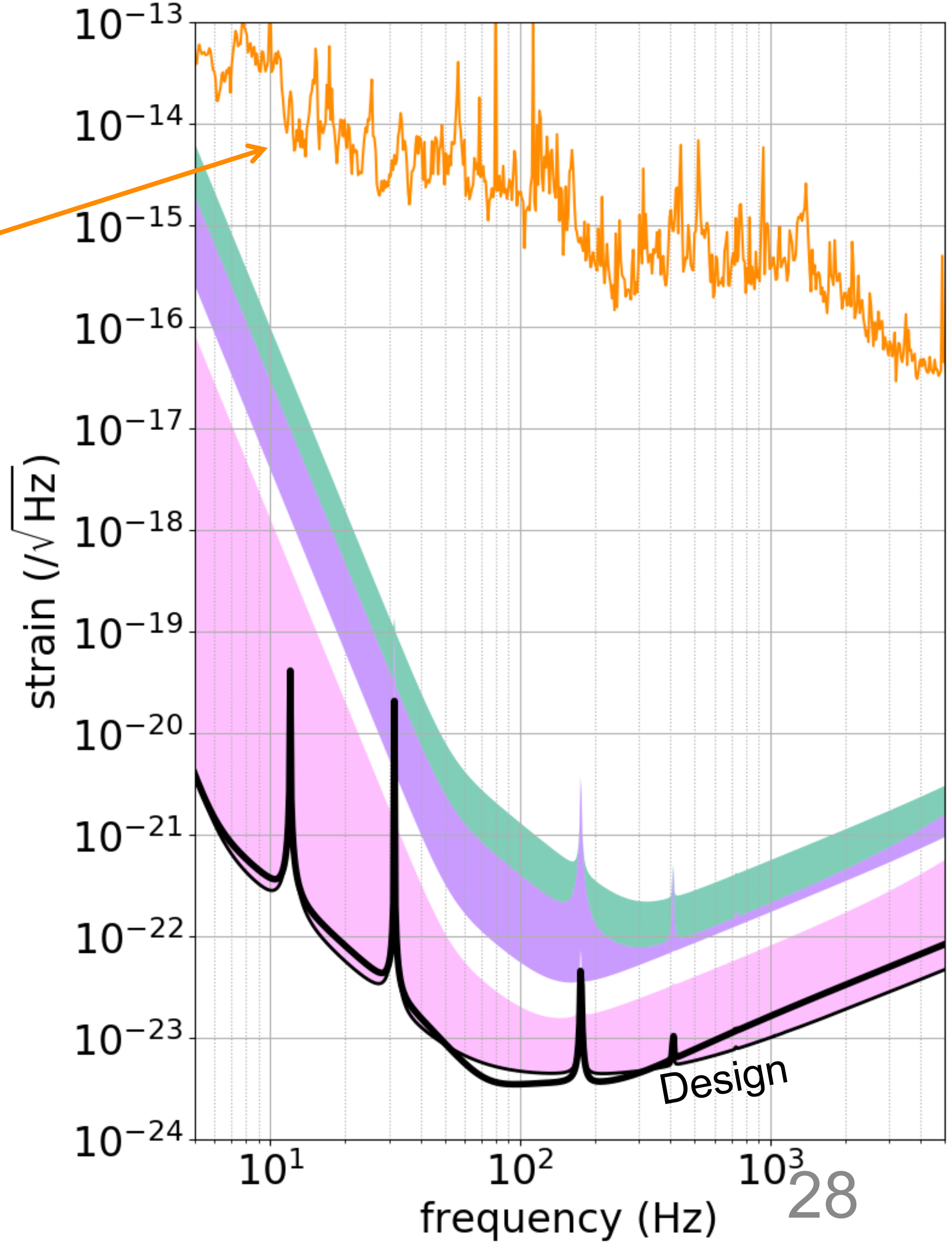


NOTE: Not the latest. Taken when 5 detectors are locked simultaneously on June 1, 2023

KAGRA Sensitivity

iKAGRA (2016)
- First test run
- 1+2 weeks
- Room temperature
- Michelson interferometer

[PTEP **2018**, 013F01 (2018)]

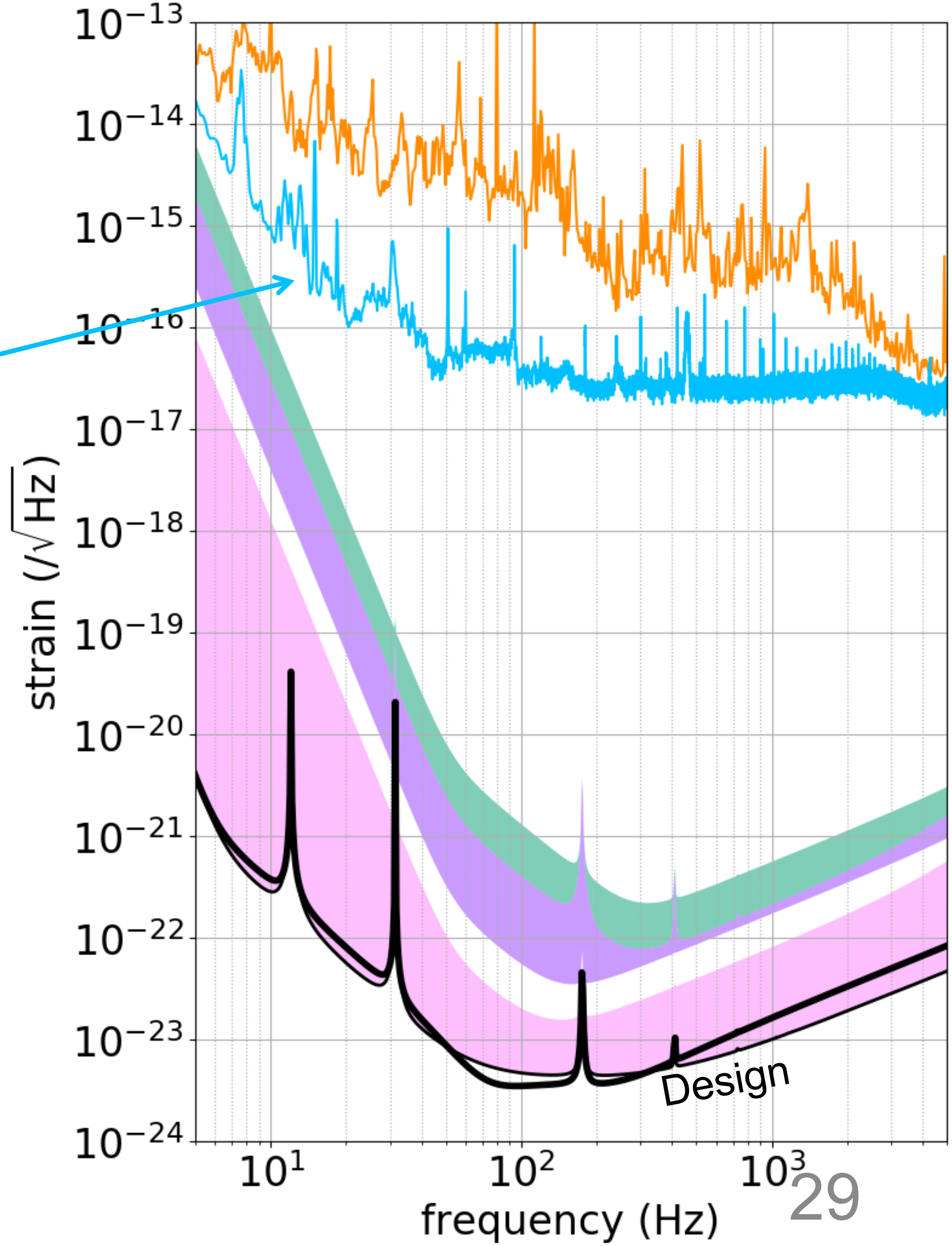


KAGRA Sensitivity

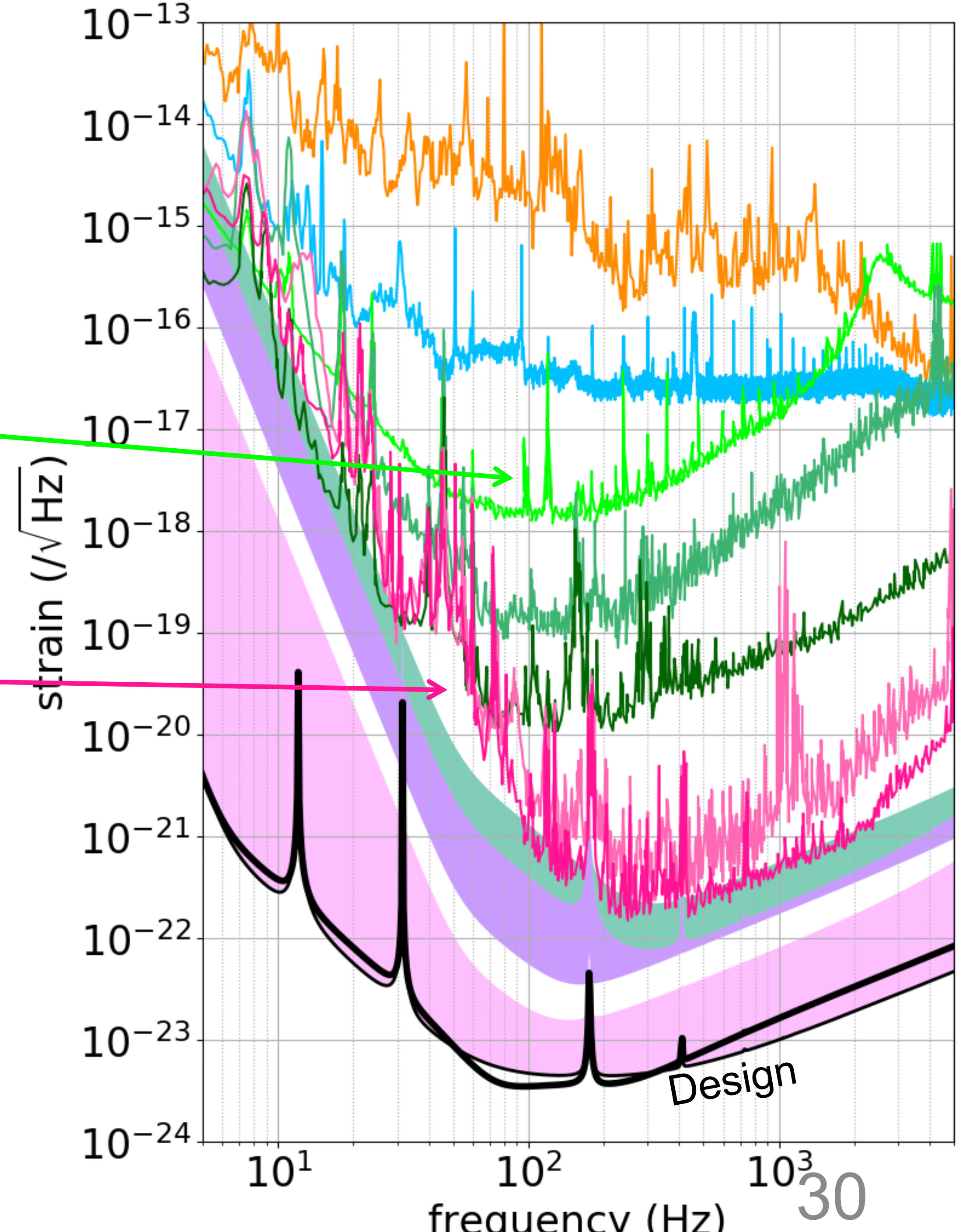
bKAGRA Phase 1 (2018)

- First test run with < 20 K test mass
- 10 days
- Michelson interferometer

CQG **36**, 165008 (2019)



KAGRA Sensitivity



First FPMI lock (Aug 2019)

O3GK (2020)

- First observing run with GEO600
- Feb-Apr 2020
- ~250 K
- Power-recycled Fabry-Perot Michelson interferometer

PTEP **2021**, 05A101 (2021)

KAGRA Sensitivity

O4a target (1-3 Mpc)

O4b target (3-10 Mpc)

O4a (May 2023)
- Started with LIGO
- May-Jun 2020
- ~250 K
- Power-recycled Fabry-Perot Michelson interferometer