

# Opportunities around gravitational wave detectors

Yuta Michimura

道村 唯太

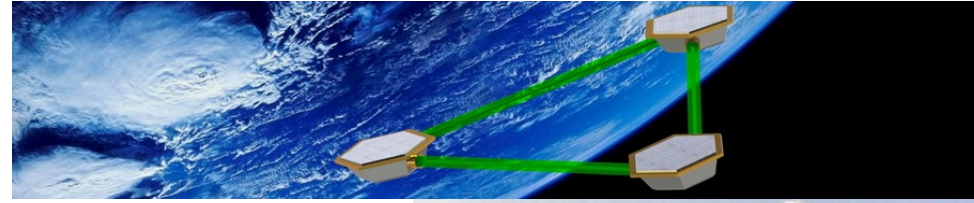
RESCEU, University of Tokyo

[michimura@resceu.s.u-tokyo.ac.jp](mailto:michimura@resceu.s.u-tokyo.ac.jp)

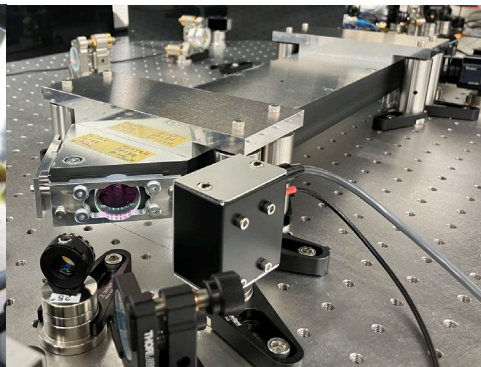
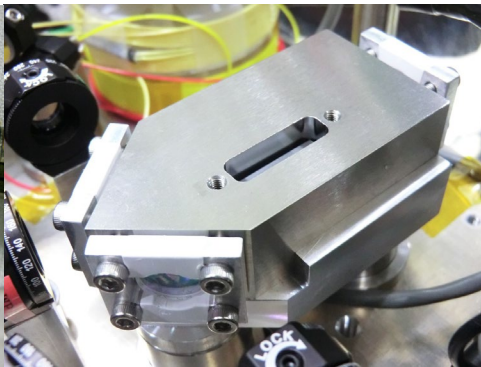
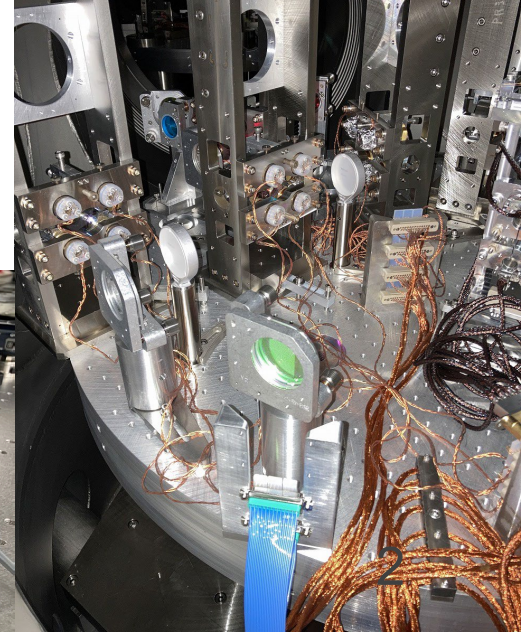
Slides are available at <https://tinyurl.com/YM20240523>



# Self Introduction



- **PhD in 2015** from Tsubono→Ando Group
  - Most precise **Lorentz invariance test**
- **2014-2022** 助教 at Ando Group
  - Chaired **KAGRA Main Interferometer** group
- (**2020-2024** JSTさきがけ研究者)
  - **Axion dark matter** search
- **2022-2024** Research Scientist at Caltech
  - R&D for **LIGO upgrades**
- **2024-present** 准教授 at RESCEU
- Interested in experiments related to **gravity**







# Group Photo 2024





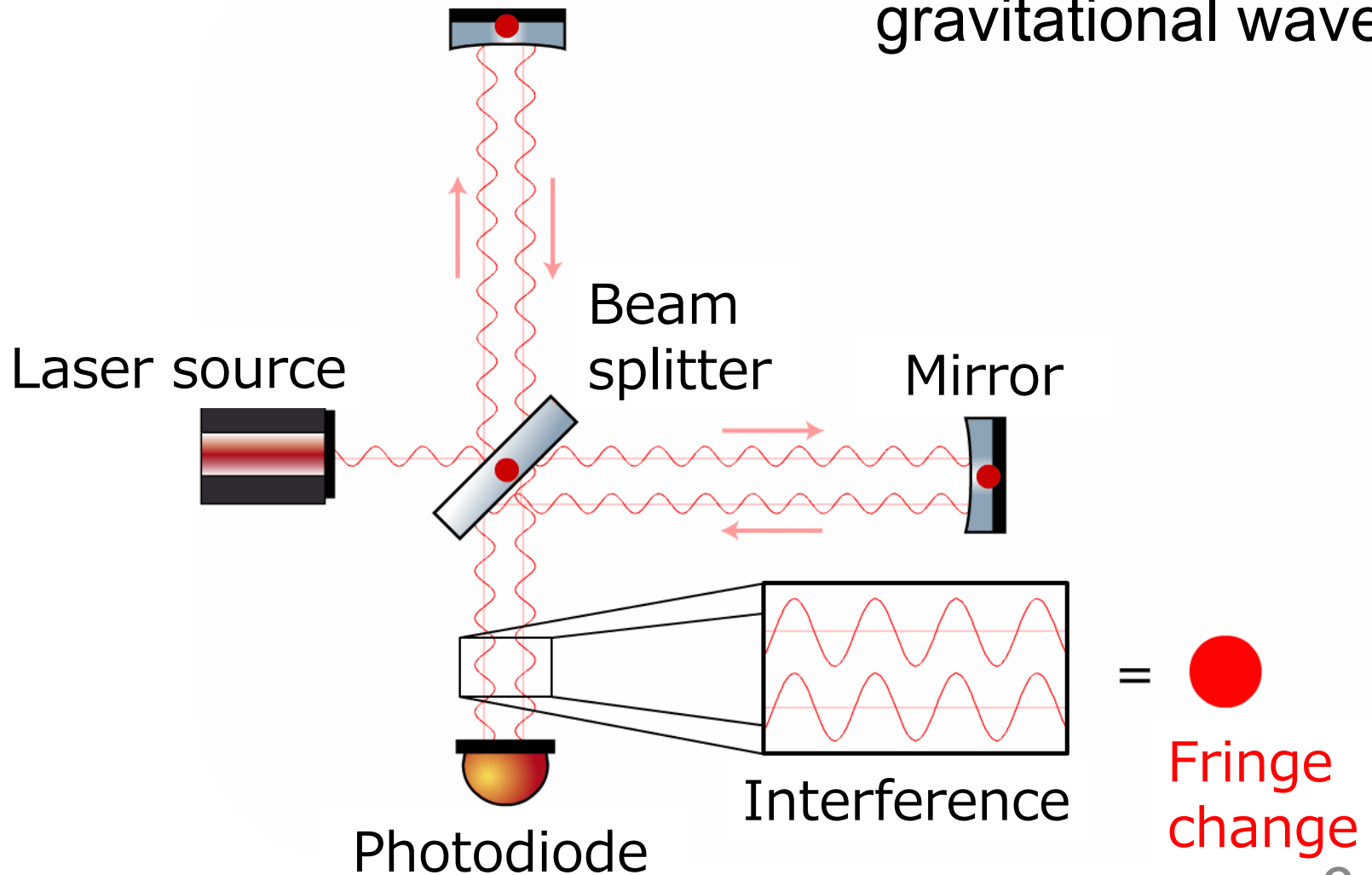
# Plan of the Talk



- **Goal of the talk today**
  - Recruit people to join my work
- **Very brief introduction to GW detectors**
- **Searches for quantum fluctuations of spacetime**
- **Searches for ultralight dark matter**
- **Tests of quantum nature of gravity**
- **Data cleaning**
- **Upgrading calibration**

# Laser Interferometric Detector

- Measures **differential** length change from gravitational waves





# Global Network of GW Detectors

- Network of **ground-based** Advanced **interferometric** gravitational wave detectors

**GEO-HF**



**Advanced LIGO**



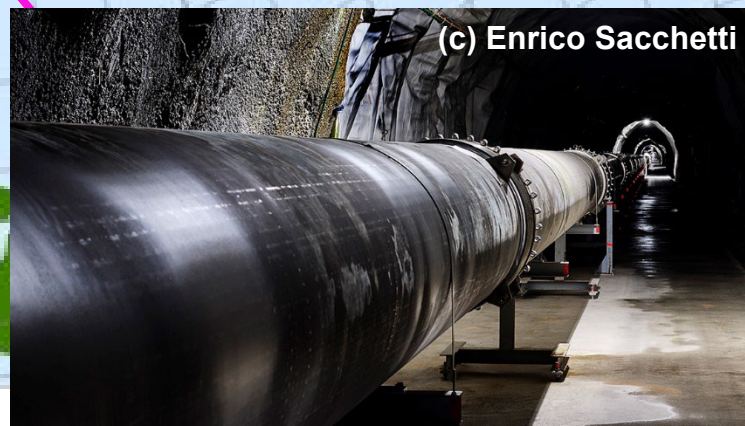
**Advanced Virgo**



**Advanced LIGO**



**KAGRA**



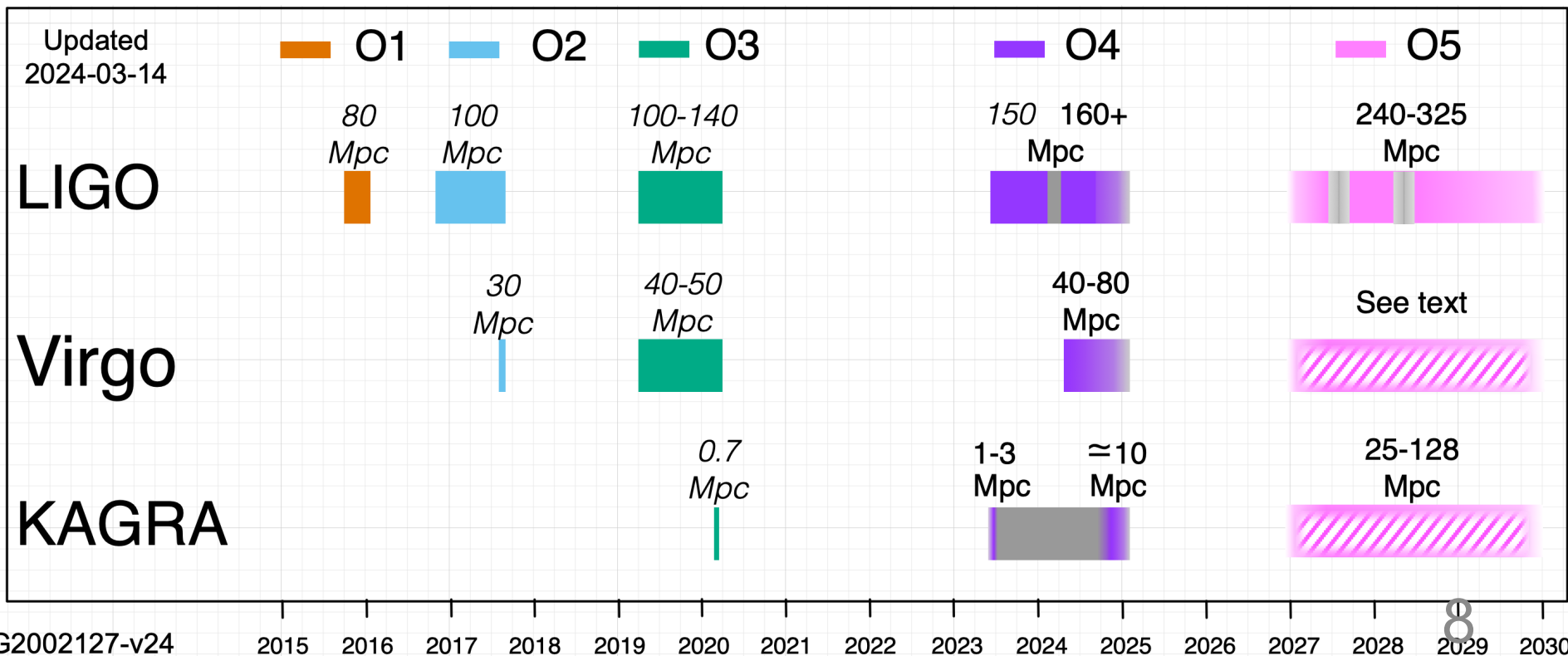
**LIGO-India (approved)**



# LVK Observing Plans

- Second half of **O4** (called O4b) is running
- LIGO: 155-175 Mpc, Virgo: 55-60 Mpc
- KAGRA: Aiming to achieve 10 Mpc by Feb 2025 (end of O4b)
- Upgrades and next generation detectors planned after O5

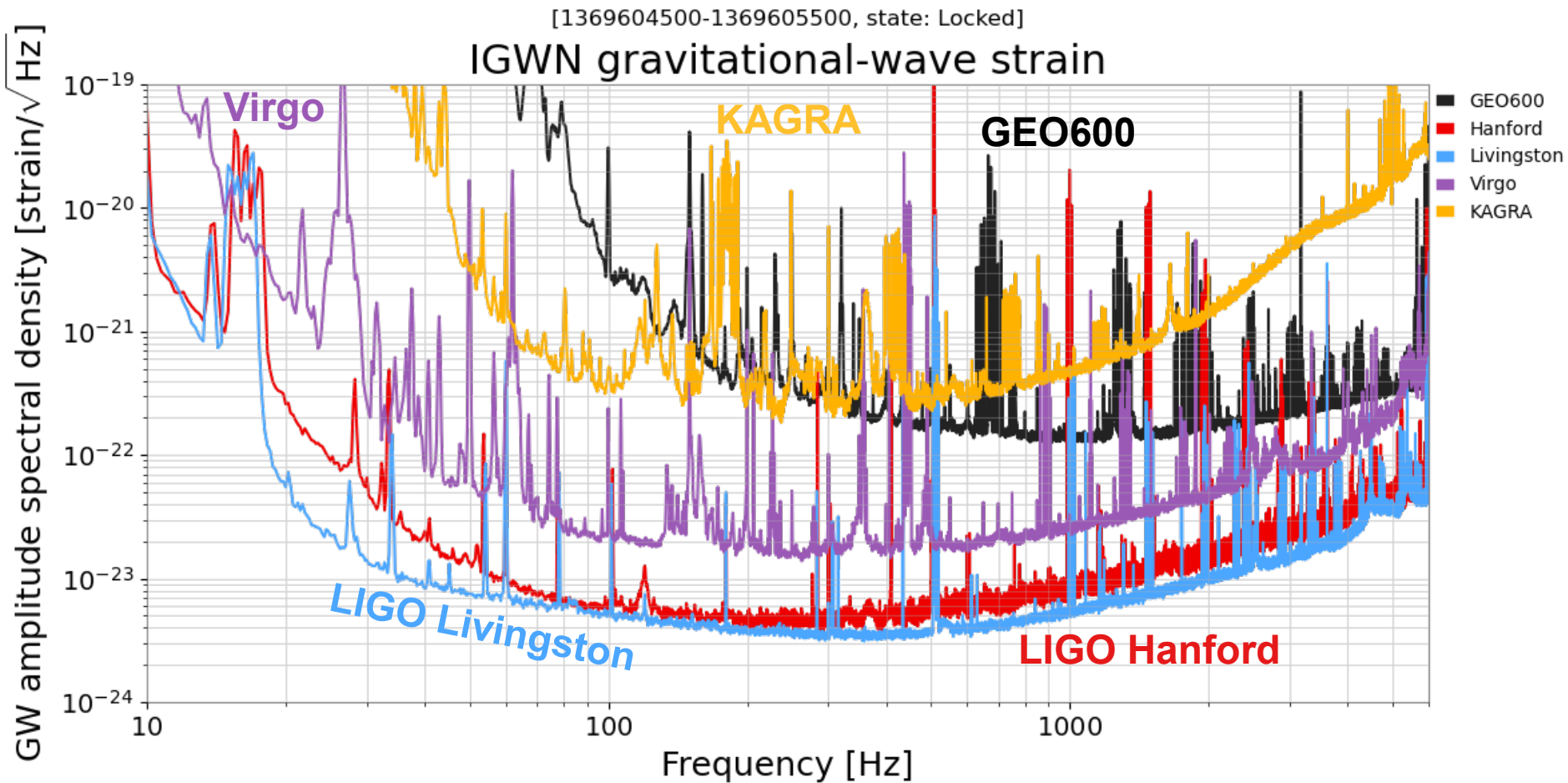
<https://observing.docs.ligo.org/plan/>





# Sensitivity Curves

- Smaller the better in y-axis



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



# Quantum fluctuations of spacetime



# Quantum Fluctuations of Spacetime

- Spacetime vacuum fluctuations in quantum gravity

with a scalar field

Planck length

K. M. Zurek,  
[arXiv:2205.01799](https://arxiv.org/abs/2205.01799)

- Observable

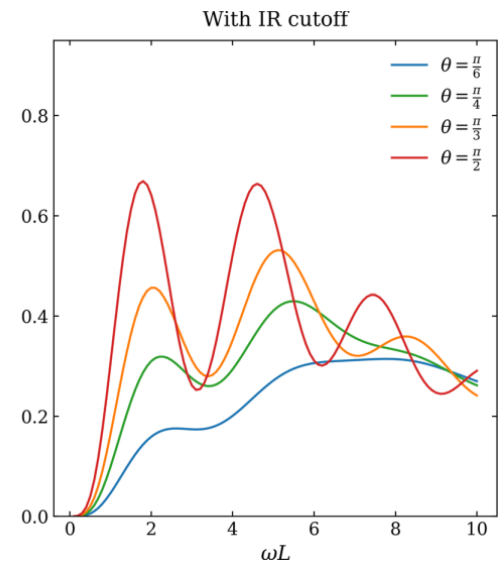
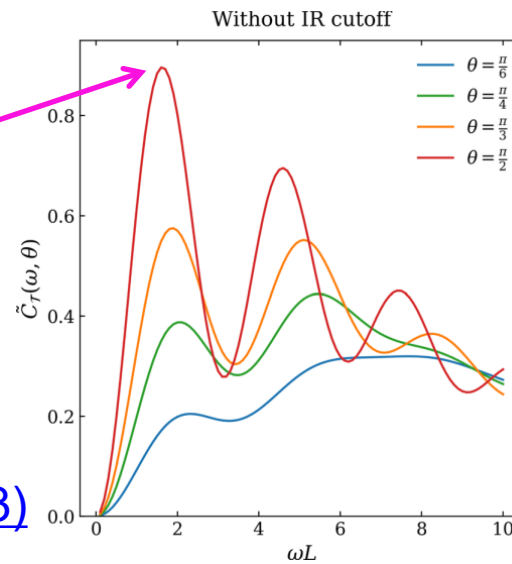
$$\delta L^2 \sim l_p L / (4\pi)$$

↙ ↘  
Planck length      Arm length

not  $\delta L \sim l_p$

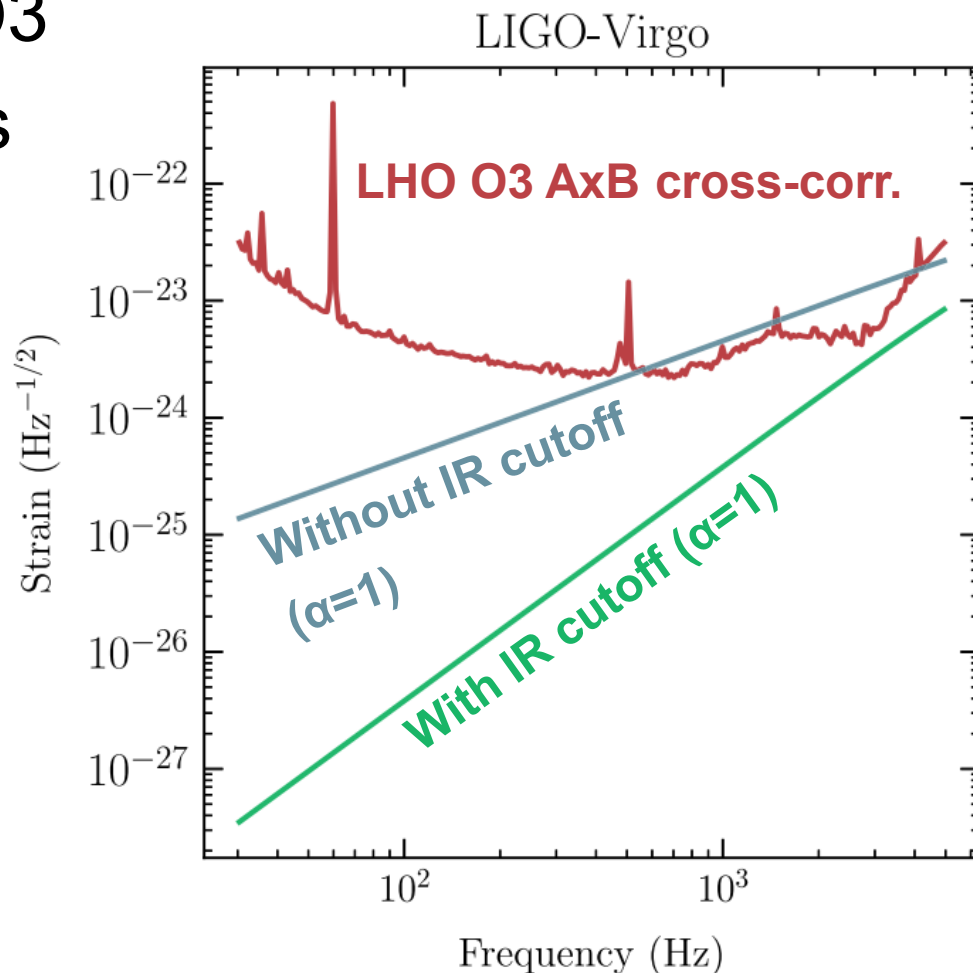
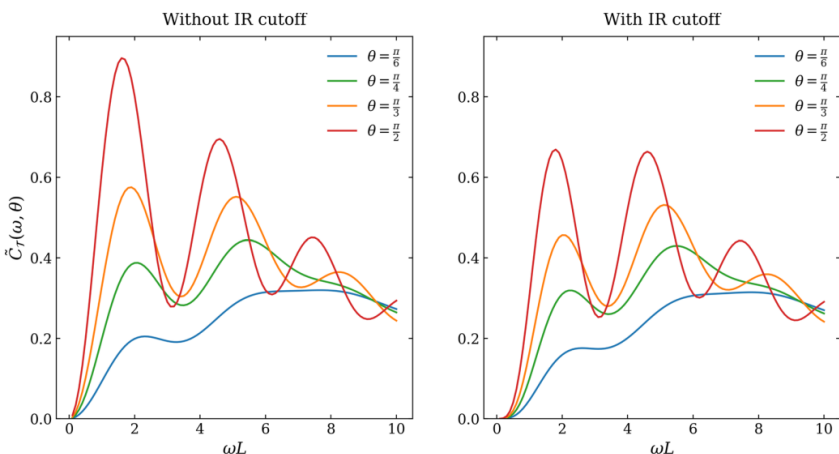
- Parametrized by the power of noise  $\alpha$   
(Natural benchmark  $\alpha \sim 1$ )

Displacement noise peaks at odd  $\times c/(4L)$



# Limit from O3

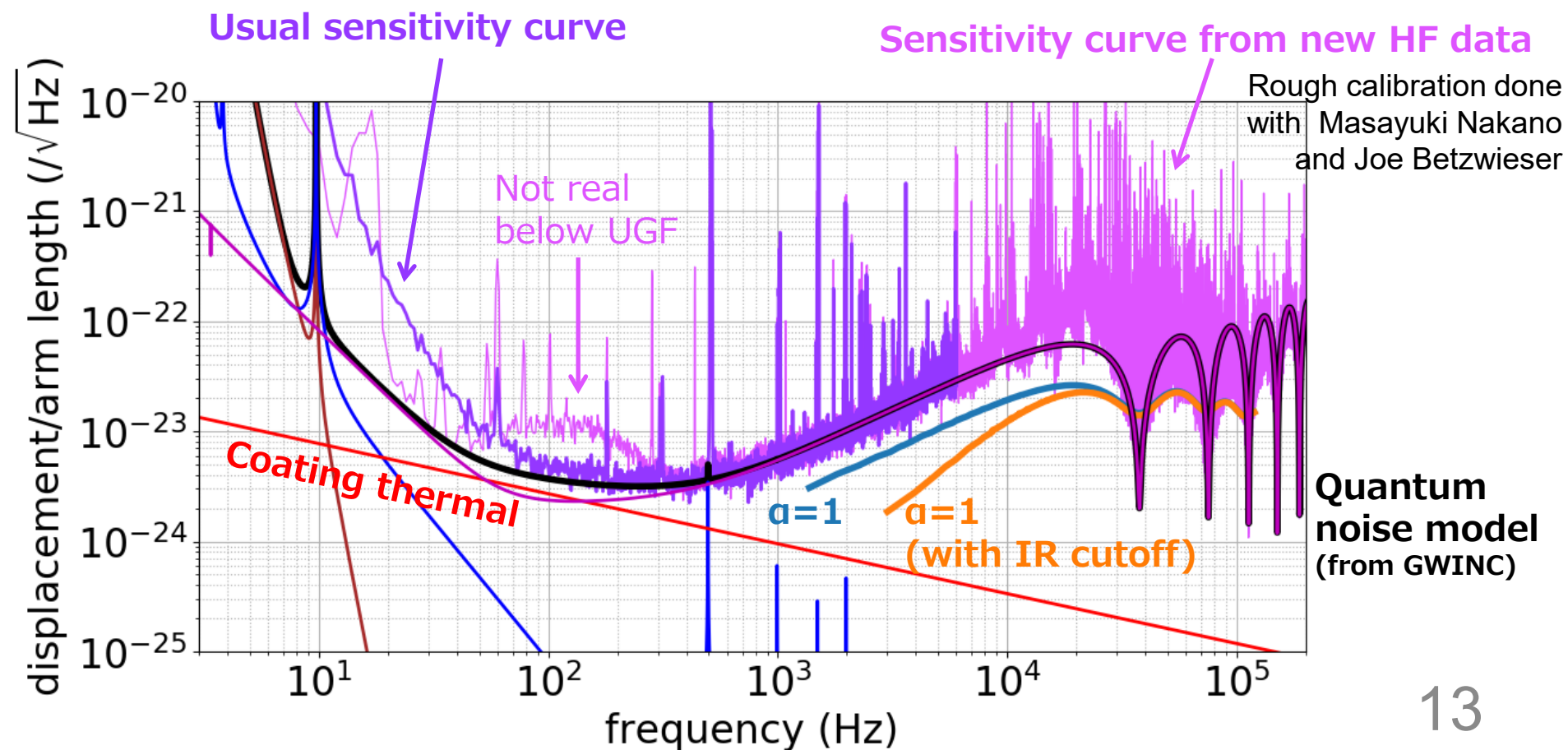
- Roughly  $\alpha \lesssim 0.1$  and  $\alpha \lesssim 3$  (with IR cutoff) at  $3\sigma$  achieved with LIGO O3
- Limit from frequencies below the peak



# High Frequency Data From O4

- LIGO installed 512 KHz ADC from O4 (usually 64 KHz)
- Search at the peaks or at the dips of sensitivity curve can be done

KHz = 1024 kHz





# kHz GW Searches Also Possible

- Primordial black holes, BH superradiance, cosmic strings etc.

N. Aggarwal+,  
[PRL 128, 111101 \(2022\)](#)

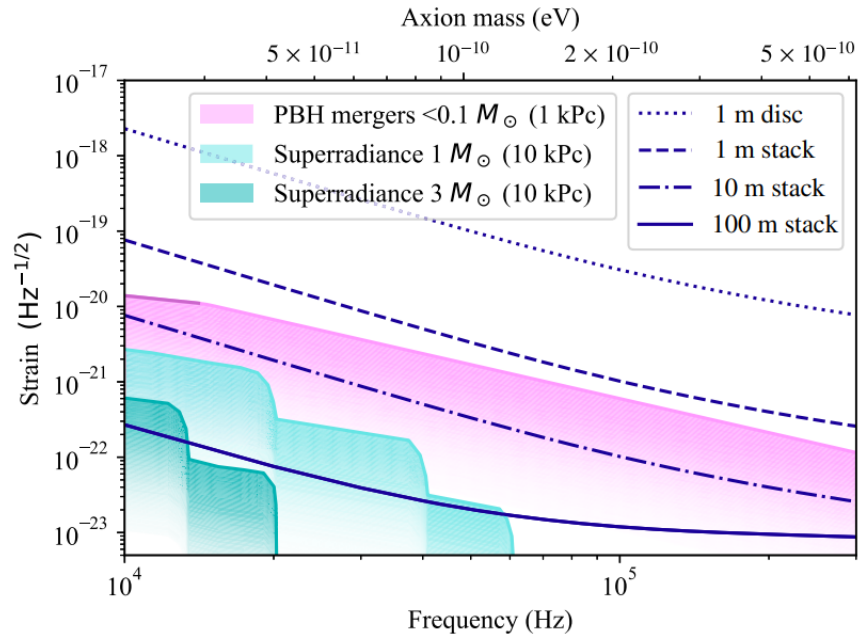
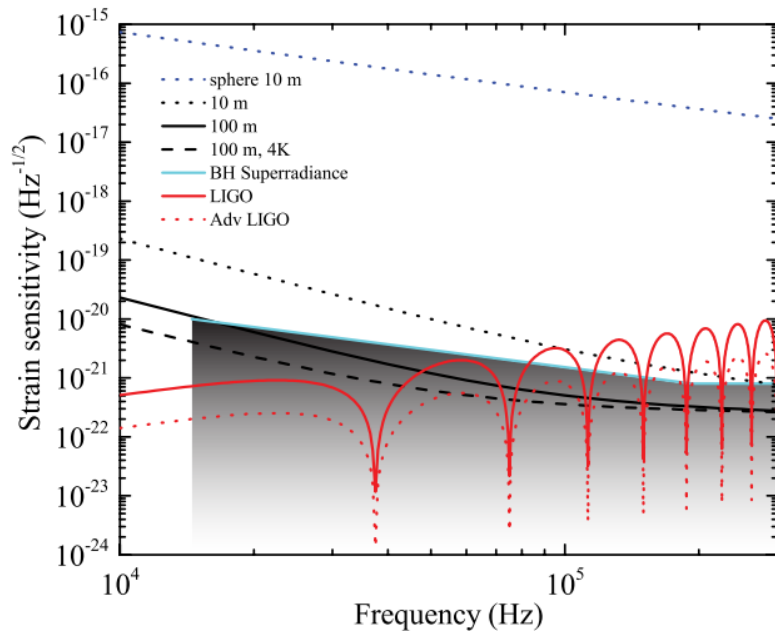


FIG. 2 (color online). Strain sensitivity for optically levitated microdisks (black dashed line) or spheres (blue dashed line) for experimental parameters described in the text. For comparison, also shown are the LIGO and predicted Advanced LIGO sensitivity in the frequency range of 10–300 kHz [25,28]. The shaded region denotes predicted signals due to black hole superradiance.

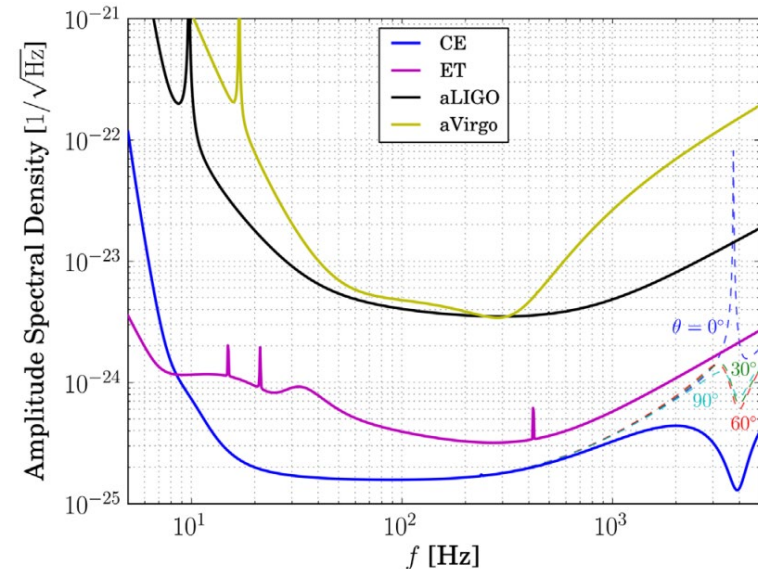
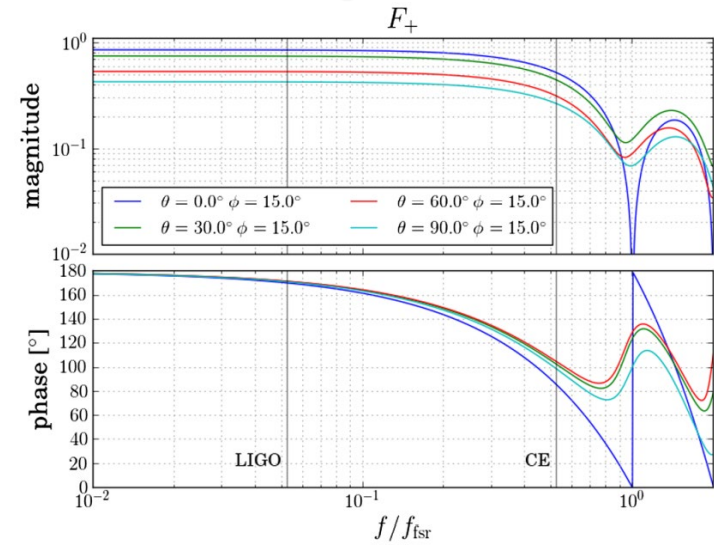
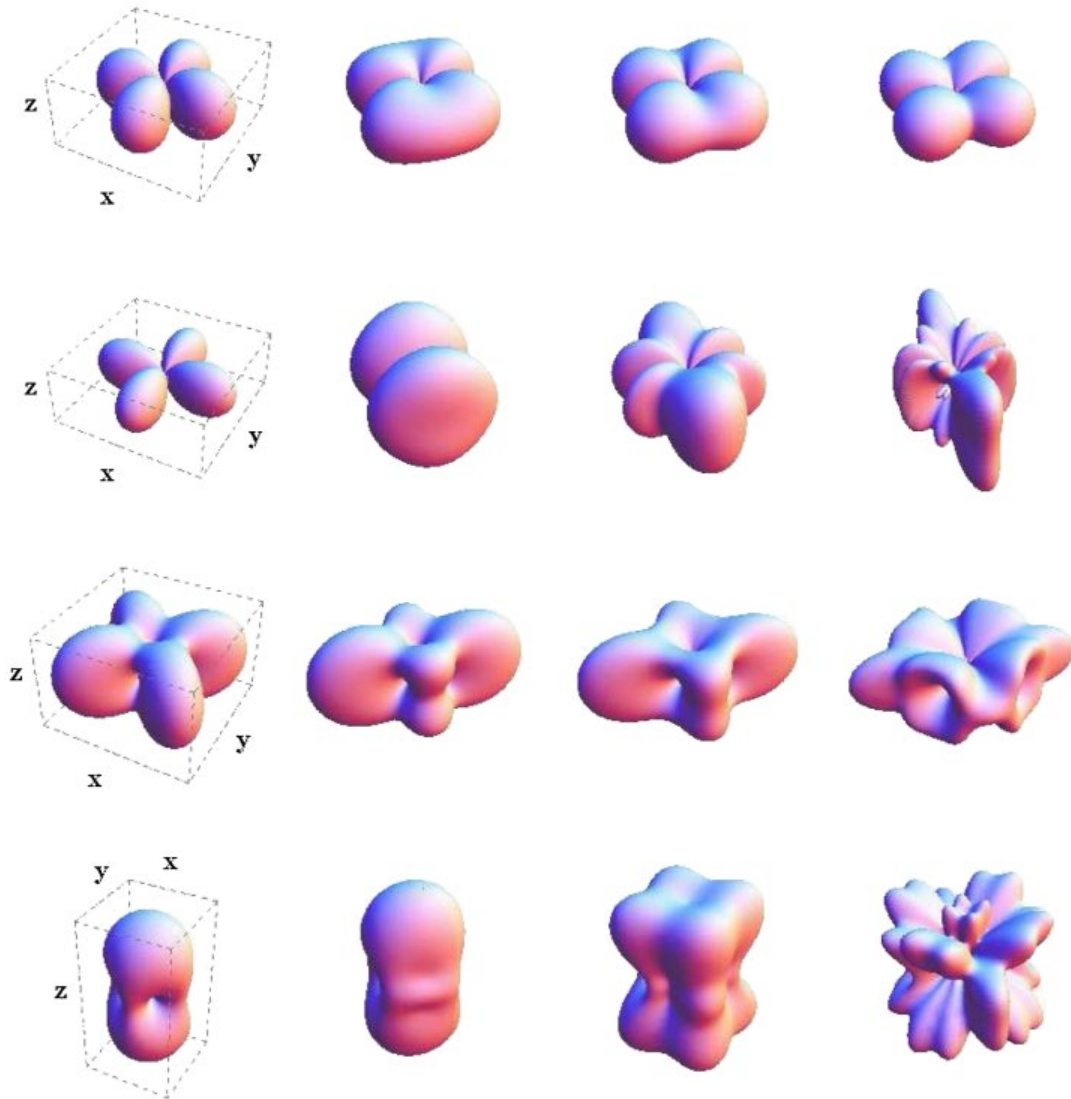
For review, see  
 N. Aggarwal+, [Living Reviews in Relativity 24, 4 \(2021\)](#)

A. Arvanitaki & A. A. Geraci,  
[PRL 110, 071105 \(2013\)](#)

# Why You Should Join

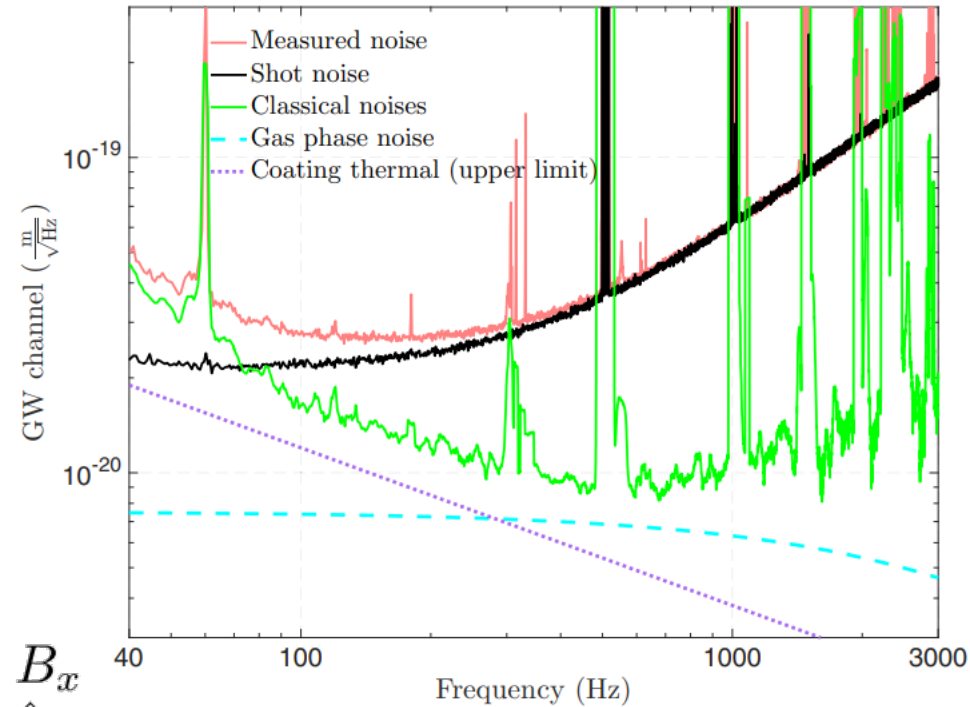
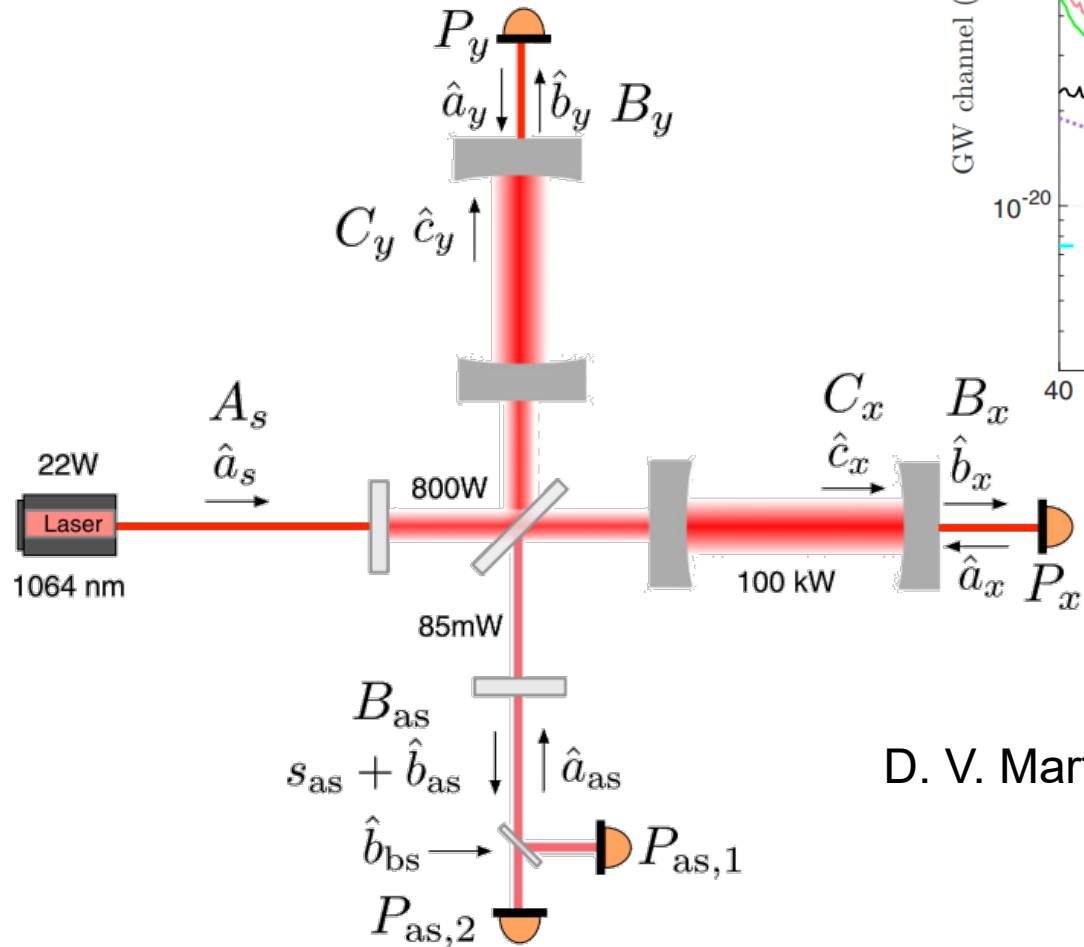
- **Almost no one knows** the data exists from O4
- The **best data in O(10) kHz region**, various science cases
  - No known astrophysical GW sources above  $\sim 10$  kHz
  - Any discovery would indicate **new physics**
- The data is not saved, and not calibrated
  - Still works to be done
  - **Frequency dependent response** need to be considered to develop GW search pipelines (Also useful for 3G detectors) [A. Blaut, [PRD 85, 043005 \(2012\)](#); R. Essick+, [PRD 96, 084004 \(2017\)](#)]
  - Squeezing at high frequencies? Laser noise coupling?
- Further sensitivity improvement possible with **quantum correlation** [D. V. Martynov+, [PRA 95, 043831 \(2017\)](#); H. Yu+, [PRD 106, 063017 \(2022\)](#)]
- Also can be done with KAGRA; just install fast ADC

# Frequency Dependent Response





# Quantum Correlation

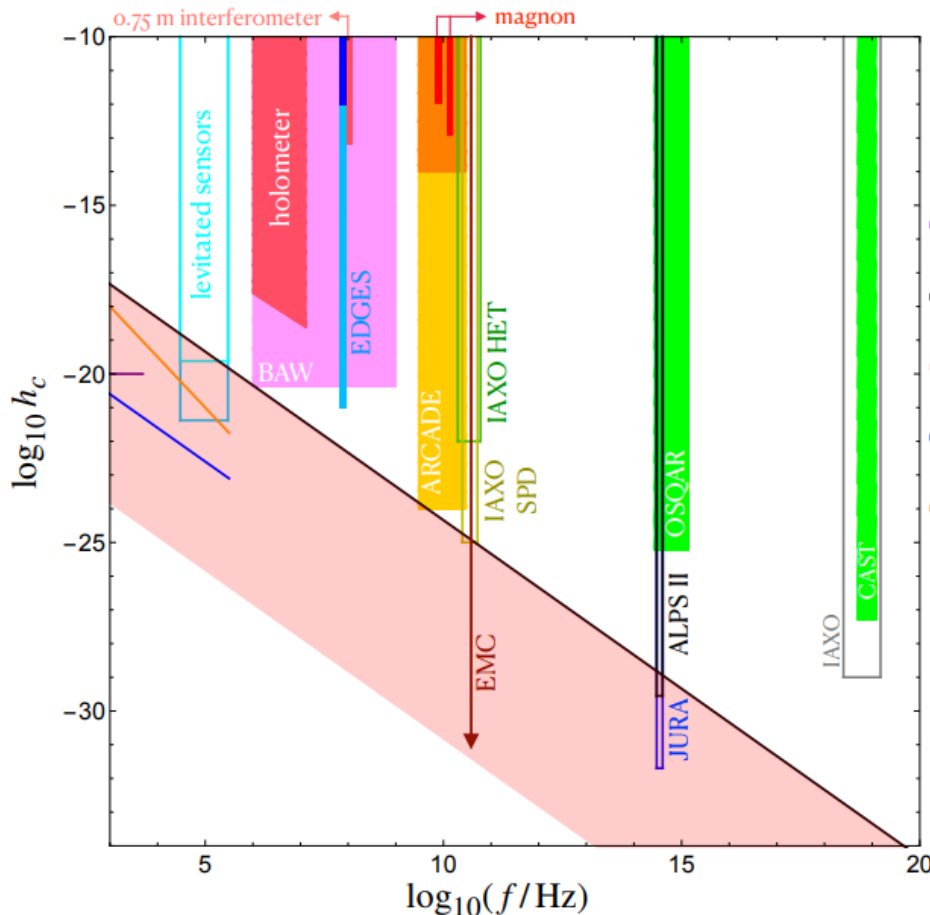


D. V. Martynov+, [PRA 95, 043831 \(2017\)](#)

# Even Higher Frequencies?

## Table-top IFO (~MHz)

T. Akutsu+, [PRL 101, 101101 \(2008\)](#)



## Magnon (~GHz)

T. Ikeda+, [PRD 105, 102004 \(2022\)](#)

More recently from Kusaka Group

### SOURCES LEGEND

- Neutron stars
- Primordial BHs
- Exotic compact objects
- Superradiance (annihilation)
- Superradiance (decay)

**Axion** detectors can also turn into high frequency **GW** detectors  
e.g. V. Domcke+, [PRL 129, 041101 \(2022\)](#)

For review, see

N. Aggarwal+, [Living Reviews in Relativity 24, 4 \(2021\)](#)

# Ultralight Dark Matter

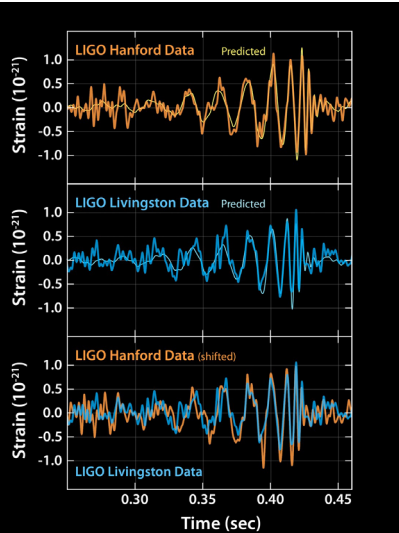
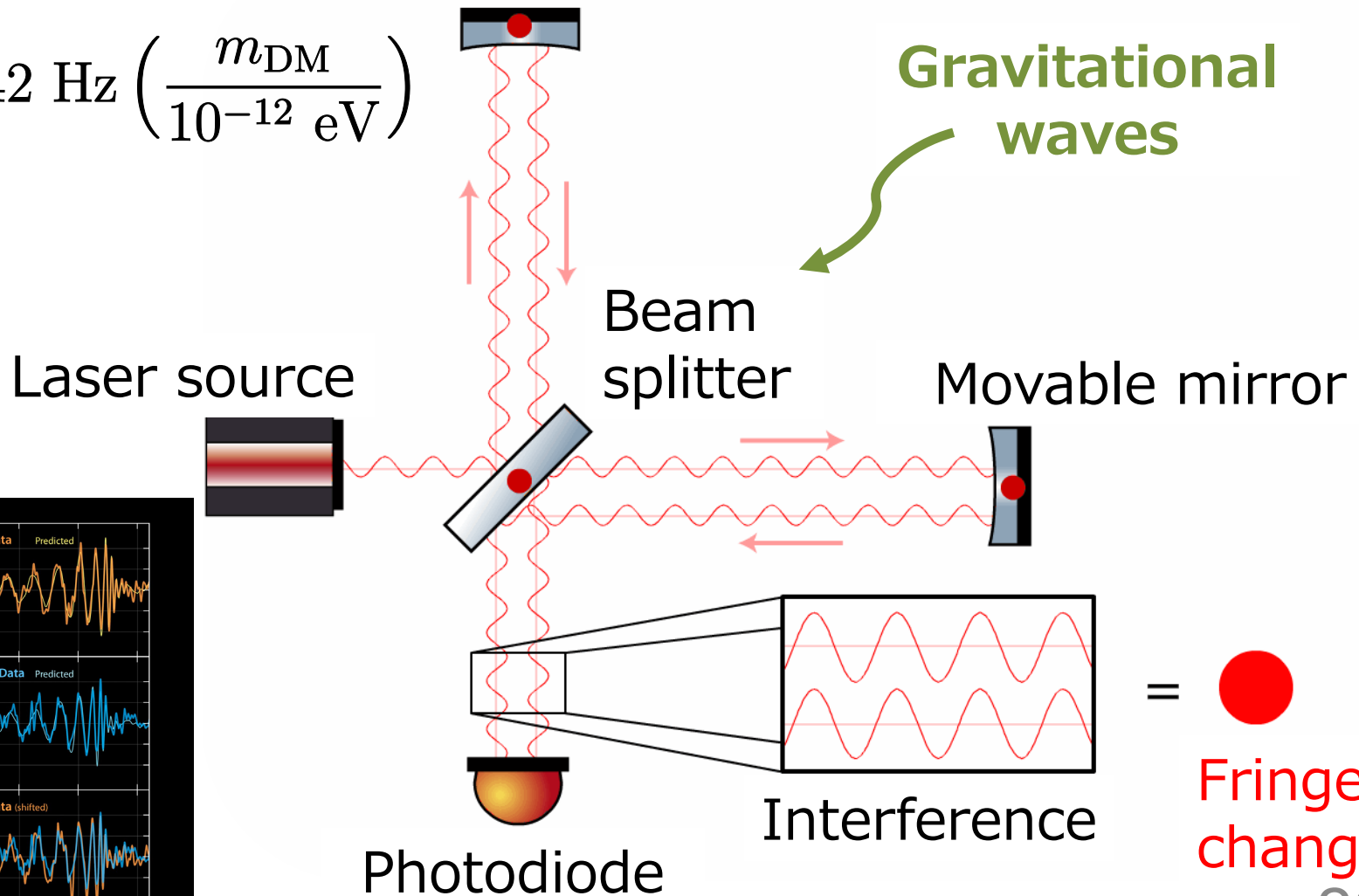




# Interferometers are Sensitive to...

- Gravitational waves, and **wave-like (ultralight) dark matter**

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



# Gauge Boson (Vector) Dark Matter

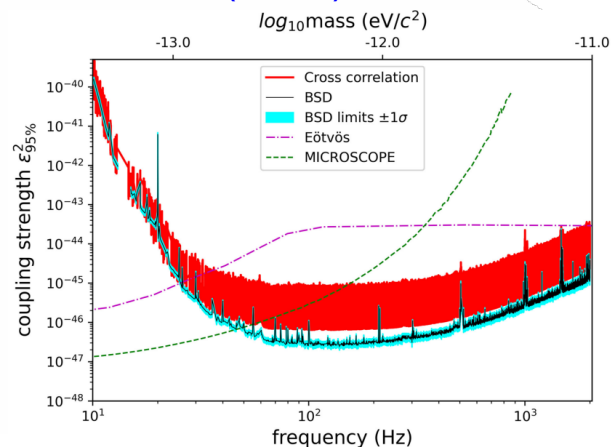
LVK, [PRD 105, 063030 \(2022\)](#)

Erratum: [PRD 109, 089902 \(2024\)](#)

**Tiny forces  
from gauge  
boson DM**

P. W. Graham+,  
[PRD 93, 075029 \(2016\)](#)

Y. Michimura+,  
[PRD 102, 102001 \(2020\)](#)



Laser source

Beam splitter

Movable mirror

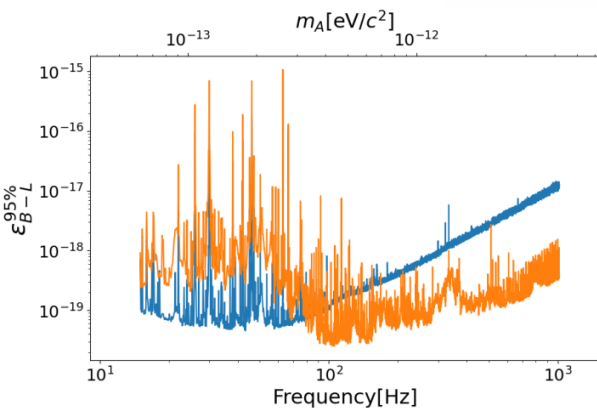
Photodiode

Interference

= ●  
Fringe  
change

21

LVK, [arXiv:2403.03004](#)

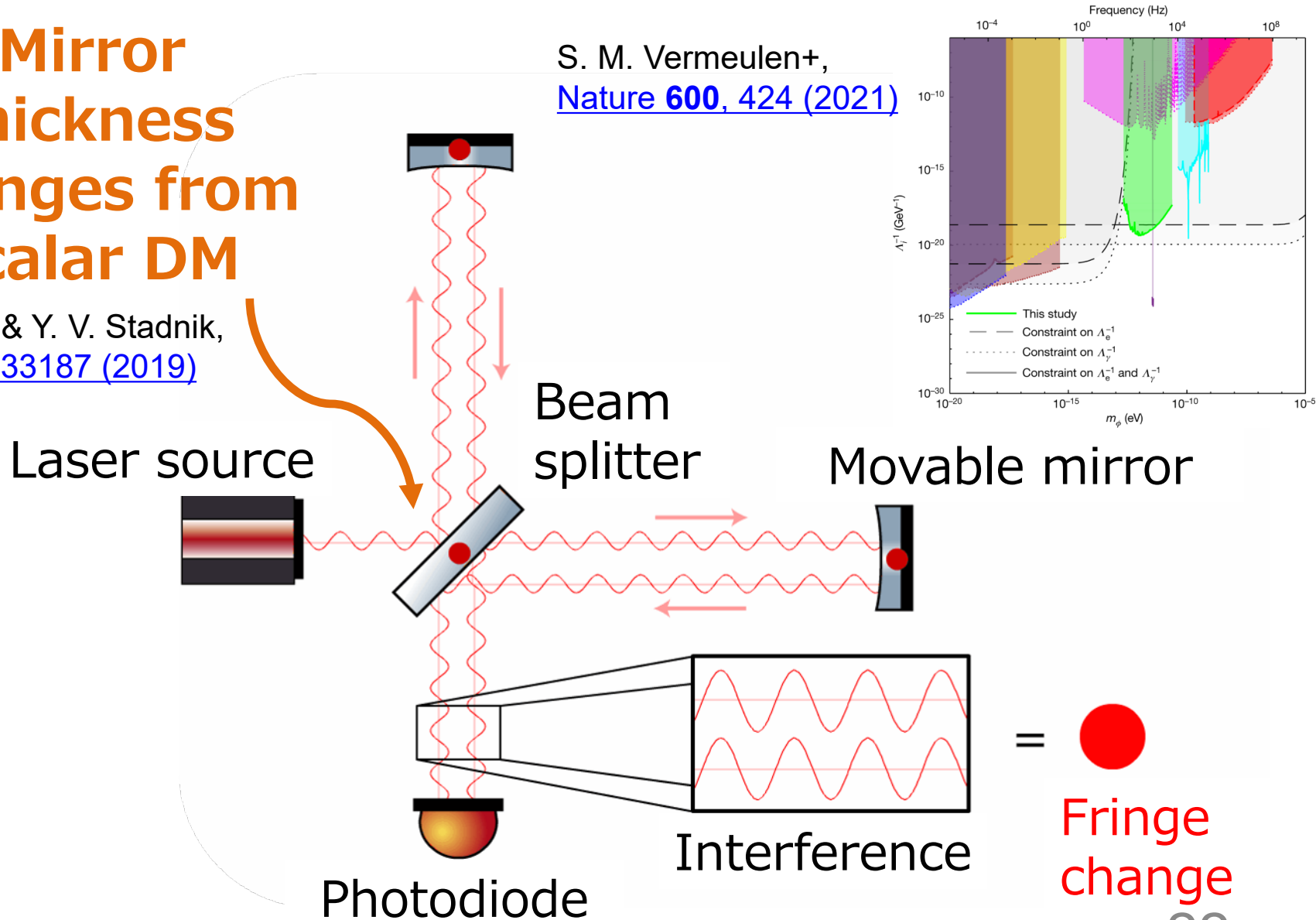


# Scalar Boson Dark Matter

Mirror thickness changes from scalar DM

H. Grote & Y. V. Stadnik, [PRR 1, 033187 \(2019\)](#)

S. M. Vermeulen+, [Nature 600, 424 \(2021\)](#)



= ●  
Fringe change  
22



# Axion-like Dark Matter

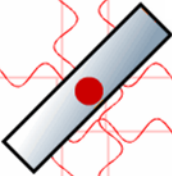
Photon  
phase velocity  
changes from  
axion DM

I. Obata+,  
[PRL 121, 161301 \(2018\)](#)  
K. Nagano+,  
[PRL 123, 111301 \(2019\)](#)

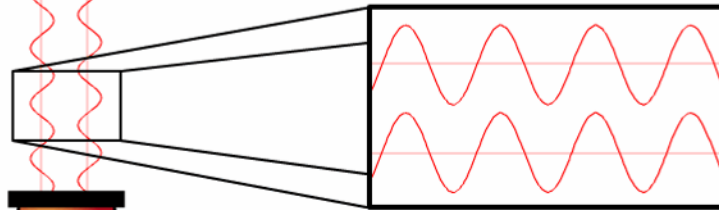
Laser source



Beam  
splitter



Movable mirror



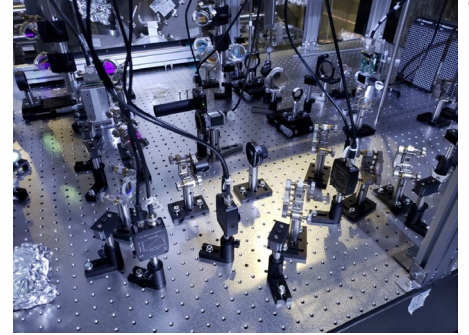
Interference

Photodiode

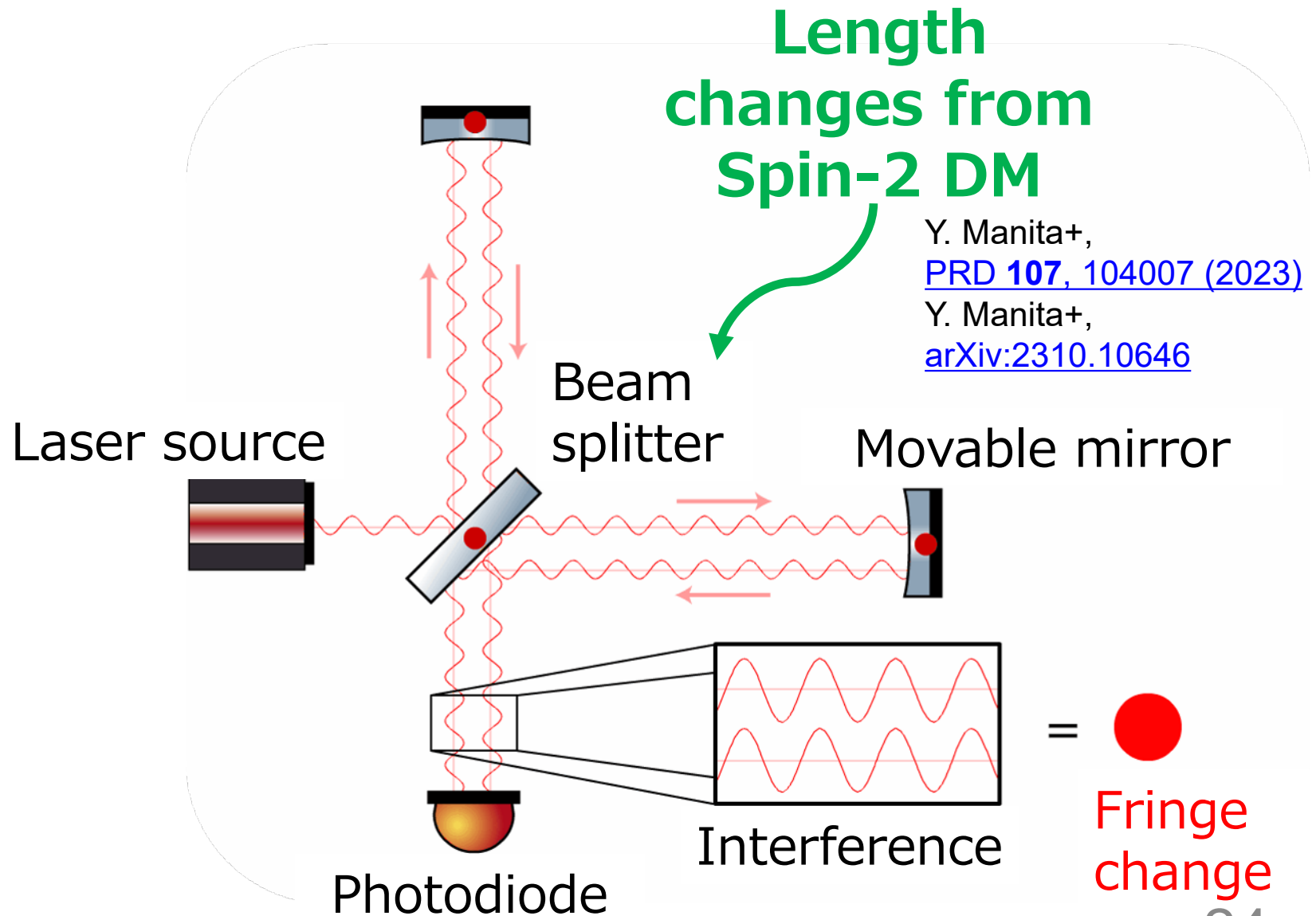


= ●  
Fringe  
change

Polarization optics installed to KAGRA  
to search for birefringence effects from  
axion DM



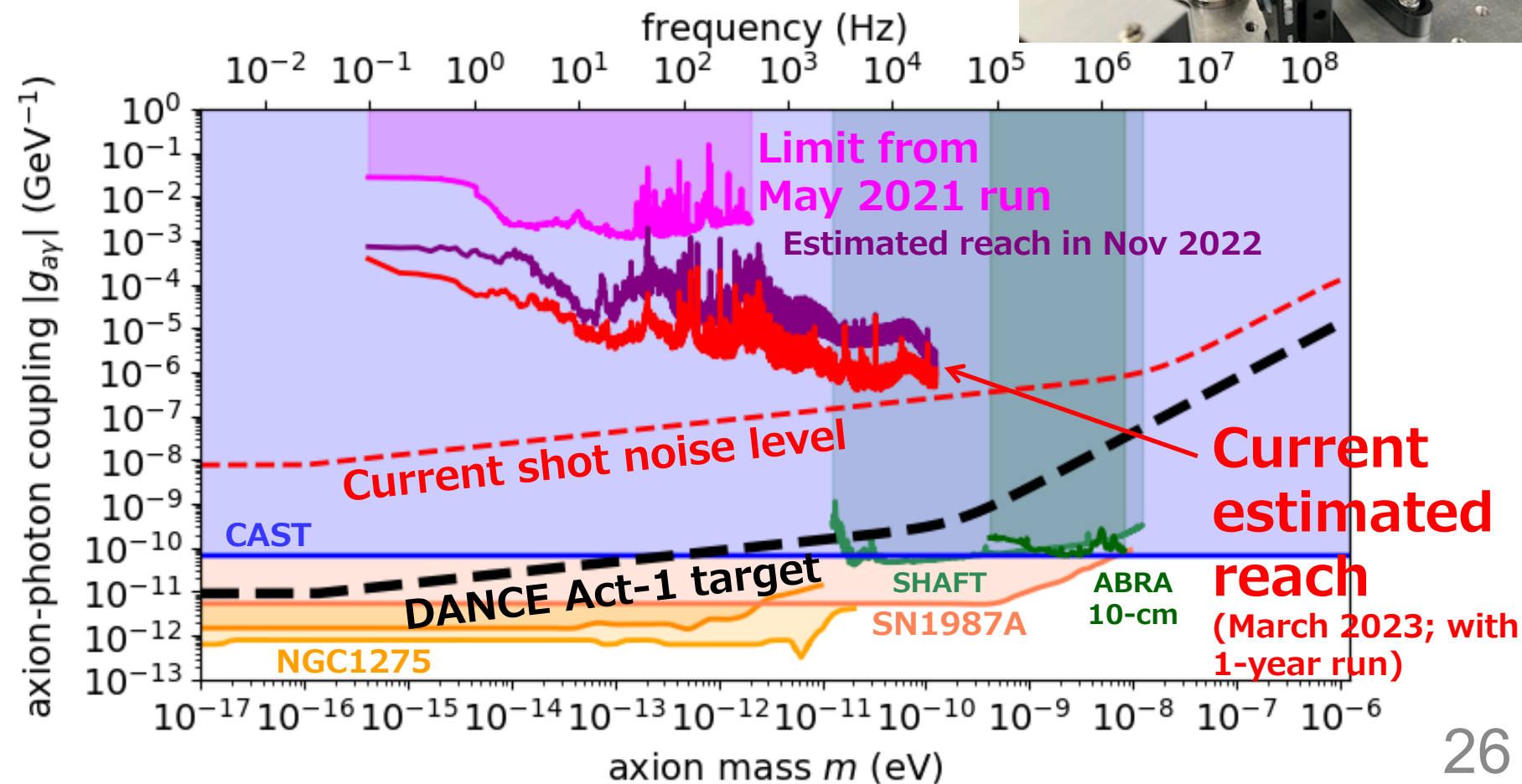
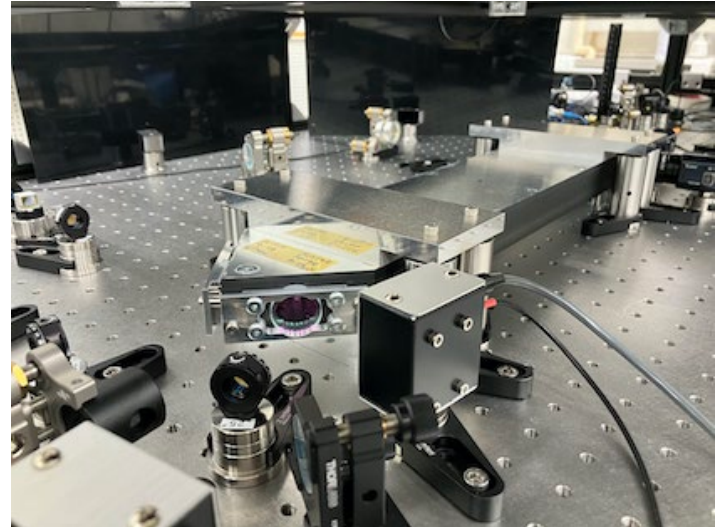
# Spin-2 Dark Matter



# Why You Should Join

- Unique vector dark matter search using **sapphire mirrors** of KAGRA
- Polarization optics were installed to KAGRA, and we will be collecting the **first axion DM data** from gravitational-wave detectors within FY2024
- New searches for **spin-2 DM**, searches with **high frequency data** etc.
- Further **optimization** of data analysis pipelines, **veto** analysis using multiple channels etc.
- Studies are also useful to identify **spectral line noise** sources
- Data analysis pipeline also used for **table-top experiments** [Y. Oshima+, [PRD 108, 072005 \(2023\)](#); H. Nakatsuka+, [PRD 108, 092010 \(2023\)](#)]

# DANCE @理学部1号館





WAIT, NO... THIS  
ISN'T RIGHT!  
THE CAT'S SUPPOSED TO  
GO IN THE BOX, NOT  
THE SCIENTIST!

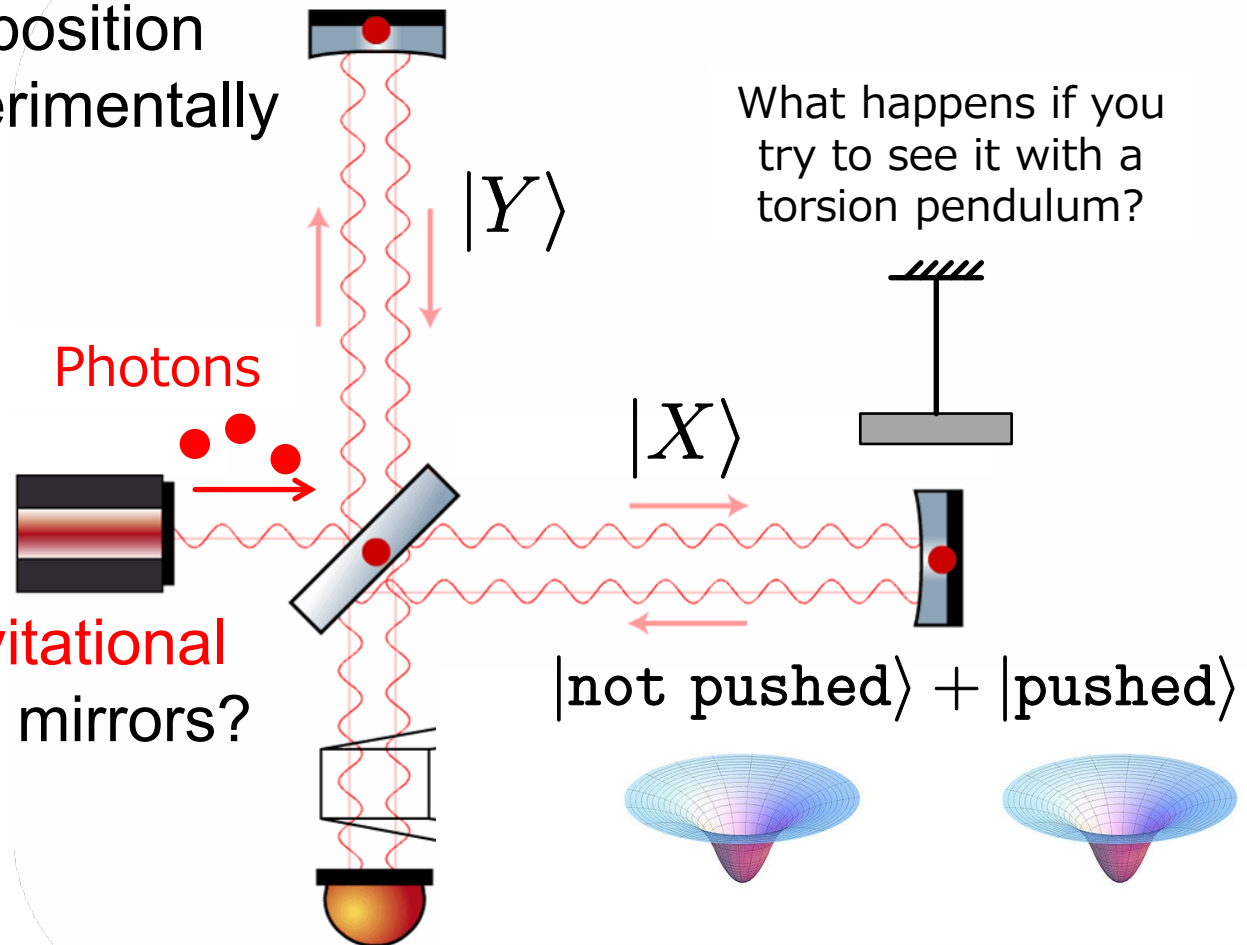


# Quantum Nature of Gravity

JSPAILLY

# Interferometers to Test Quantum

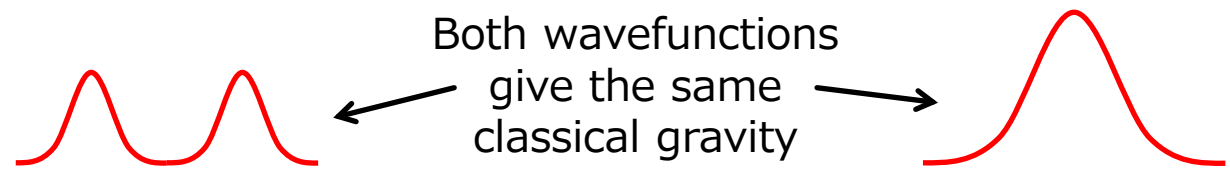
- Photon going to X arm or Y arm is in quantum superposition
- Mirrors pushed or not pushed by radiation pressure is in quantum superposition (this is not experimentally verified yet)



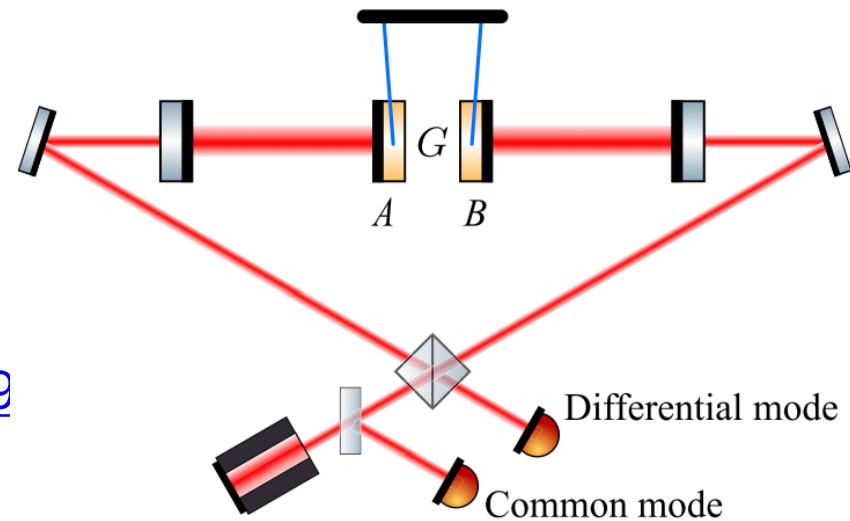
- How about **gravitational field** of massive mirrors?

# Semiclassical Gravity

- In semiclassical gravity (Schrödinger-Newton model), quantum matter is coupled to a classical gravitational field through **expectation values**



- People have been proposing experiments to falsify this
- For example, through **gravity-induced entanglement**



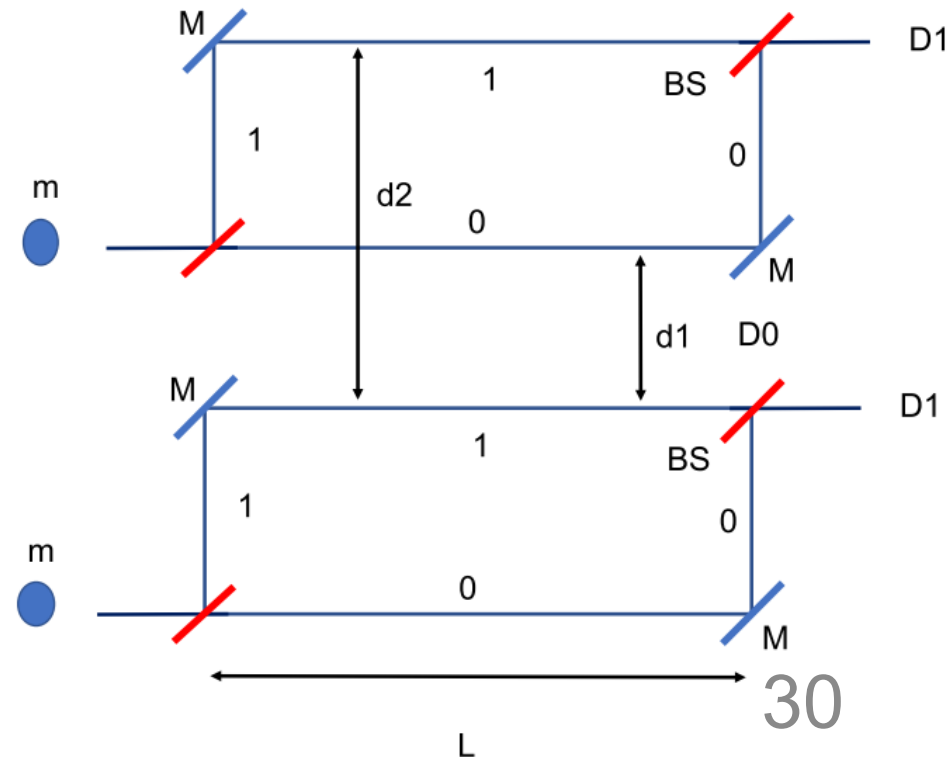
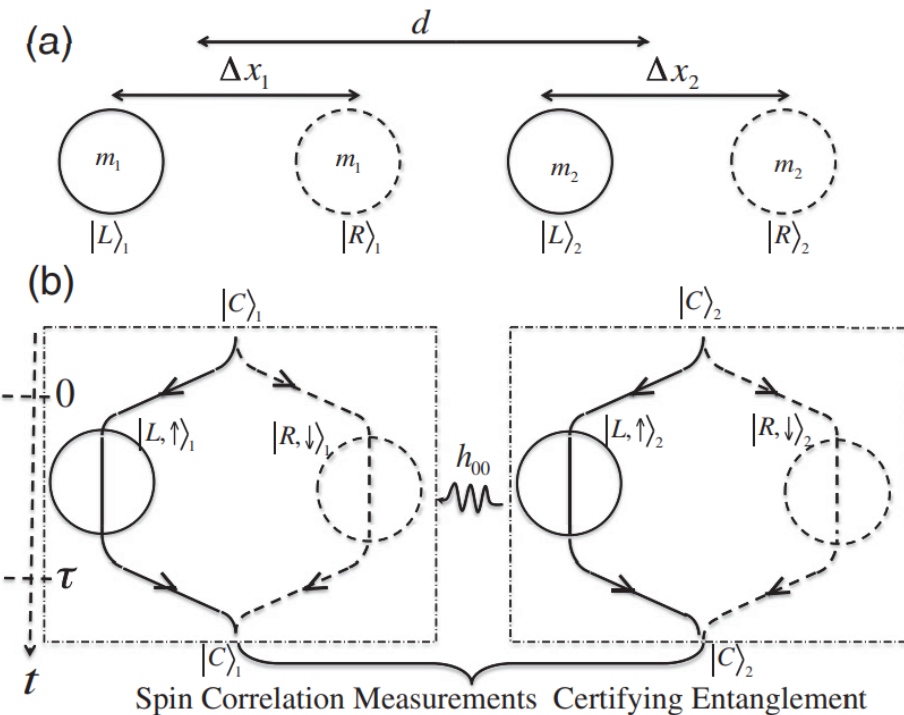
- For review, see  
D. Carney+, [CQG 36, 034001 \(2019\)](#)
- Also, see  
H. Miao+, [PRA 101, 063804 \(2020\)](#)  
A. Datta & H. Miao, [Quantum Science and Technology 6, 045014 \(2021\)](#)

# BMV Proposal

- Gravity-induced entanglement can be tested with **adjacent matter interferometers**

S. Bose+,  
[Phys. Rev. Lett. 119, 240401 \(2017\)](#)

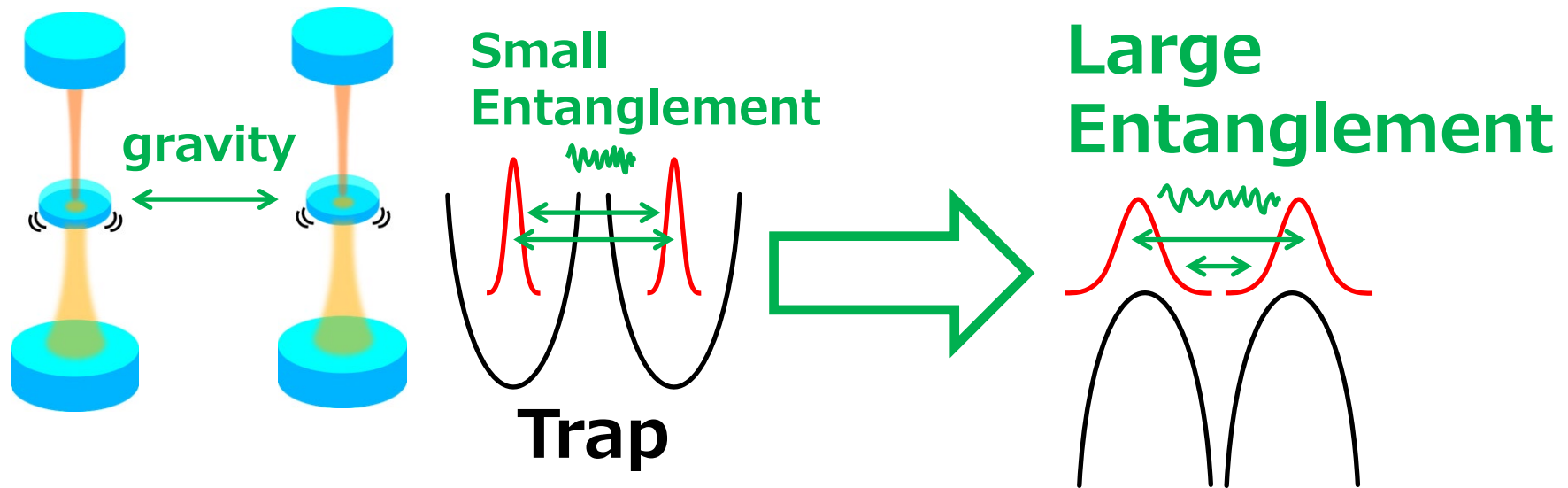
C. Marletto & V. Vedral,  
[Phys. Rev. Lett. 119, 240402 \(2017\)](#)





# Inverted Oscillator Proposal

- Inverted oscillators create gravity-induced entanglement **exponentially**
  - T. Fujita, Y. Kaku, A. Matsumura, YM, [arXiv:2308.14552](https://arxiv.org/abs/2308.14552)
  - With optically levitated mirrors proposed in YM+, [Optics Express 25, 13799 \(2017\)](https://doi.org/10.1364/OE.25.13799), we can repeat the measurements without free-fall



- But still need to satisfy

$$\text{Damping rate (Decoherence)} \rightarrow \gamma k_B T < \frac{\hbar G m}{d^3} \leftarrow \text{Distance}$$

# Test Near Measurement Event

A. Kent,  
[PRD 103, 064038 \(2021\)](#)

QG and Semiclassical gives different result even S1 is held

- Casimir effect will not limit us anymore
- S1 and S2 can be much closer



Hold or Release      Left or Right

Indeterministic quantum measurement



S<sub>1</sub> mass  $m_1$  radius  $r_1$



S<sub>2</sub> mass  $m_2$  radius  $r_2$



$h$

$x_1$

$x_2$

$\Delta t$

$t$

$\Delta t$

$T$

	S1 held	S1 released
Quantized gravity	$ \psi(t)\rangle \approx \frac{1}{\sqrt{2}} ( L\rangle +  R\rangle)$	$ \psi(t)\rangle \approx \frac{1}{\sqrt{2}} \exp(i\phi_L t) ( L\rangle + \exp(i(\phi_R - \phi_L)t)  R\rangle)$
Semiclassical gravity	$ \psi(t)\rangle \approx \frac{1}{\sqrt{2}} \exp(i\phi_L t/2) ( L\rangle + \exp(i(\phi_R - \phi_L)t/2)  R\rangle)$	

# Why You Should Join

- No one have come up with a scheme which is **honestly truly experimentally feasible**
- Could be related to improving the sensitivity of gravitational wave detectors (everyone wants to avoid decoherence)



Eric Carle

Il piccolissimo  
Bruco  
Maisazio

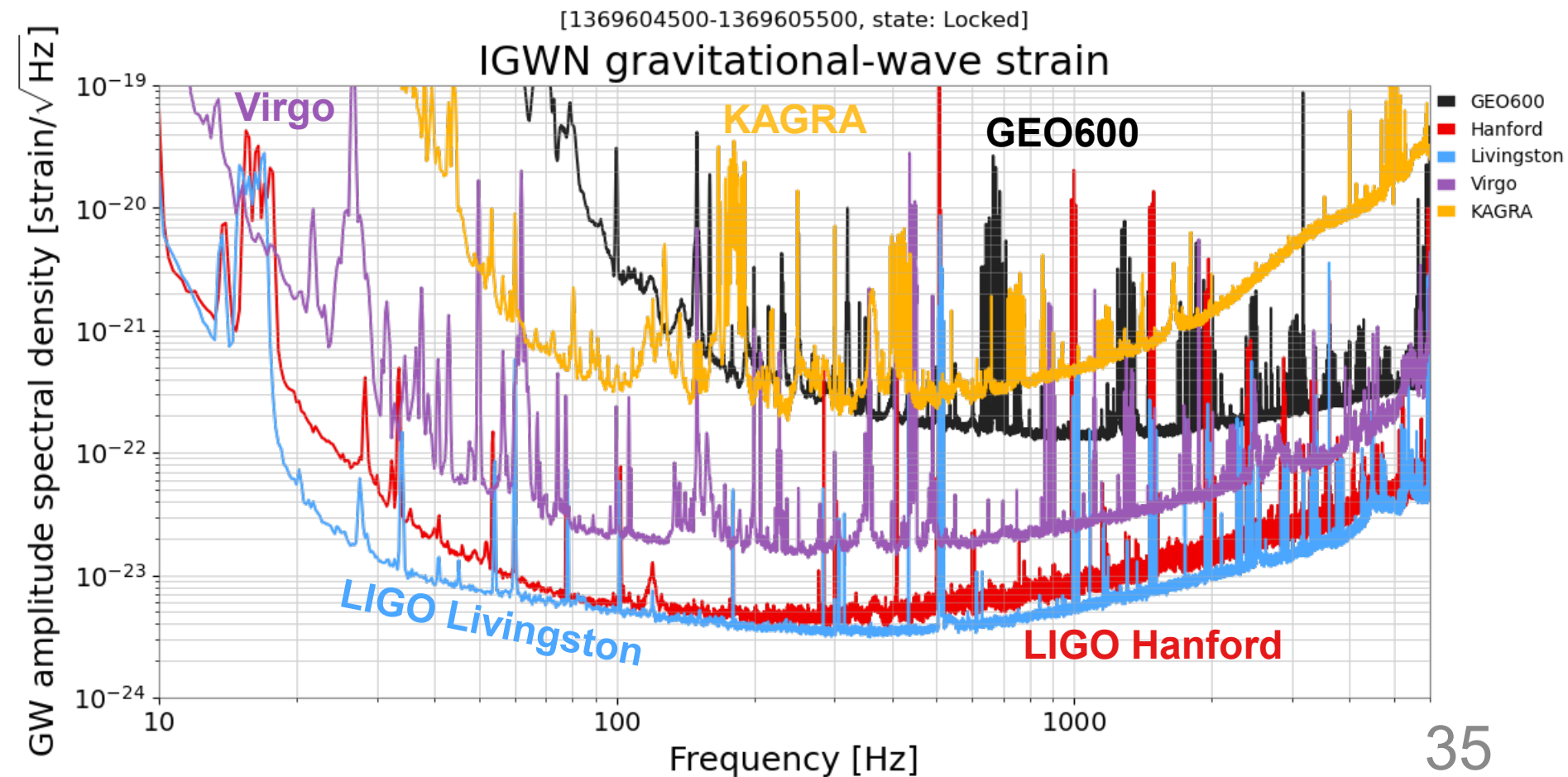
# Data Cleaning





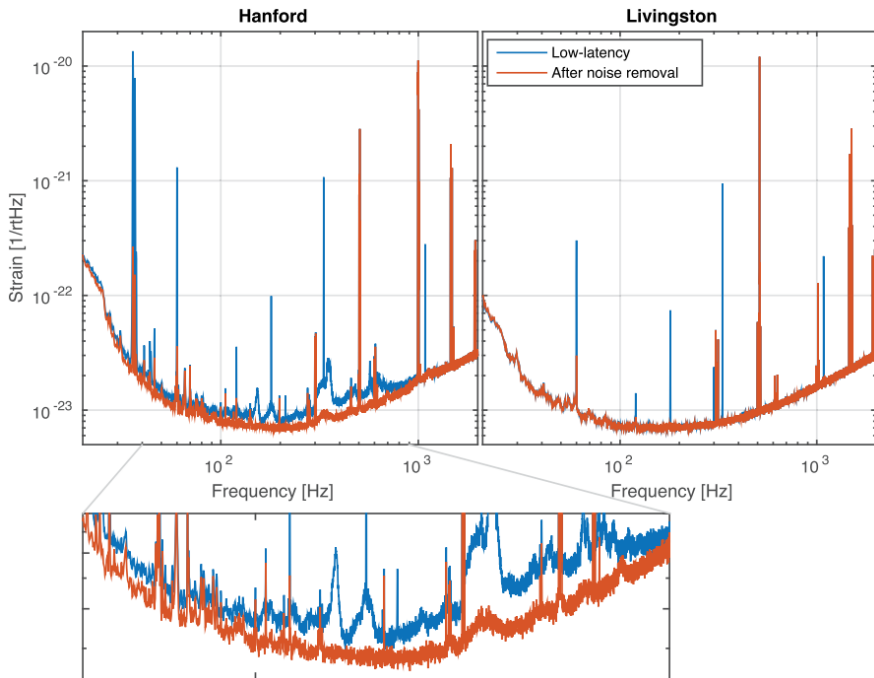
# Data is not Clean

- But you can clean up by **subtracting noises** witnessed with different sensors (e.g. seismometer)

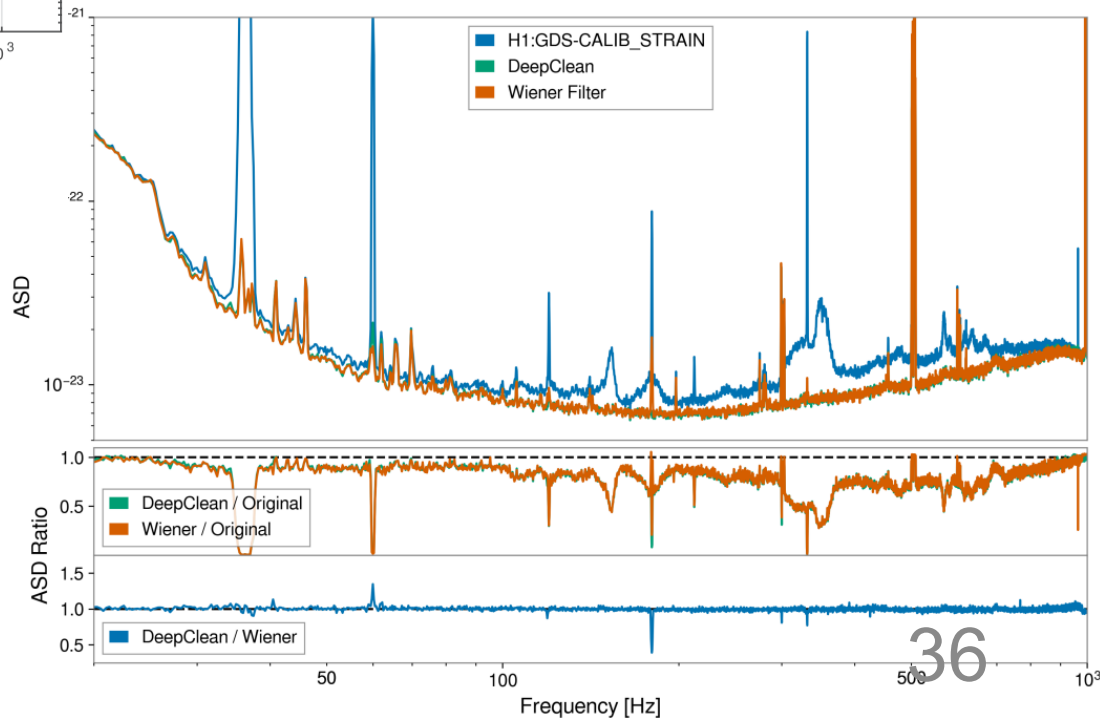


# Wiener Filtering and Deep Learning

- Both works nicely for LIGO (especially Hanford)



DeepClean: linear, non-linear, non-stationary  
R. Ormiston+, [PRR 2, 033066 \(2020\)](#)

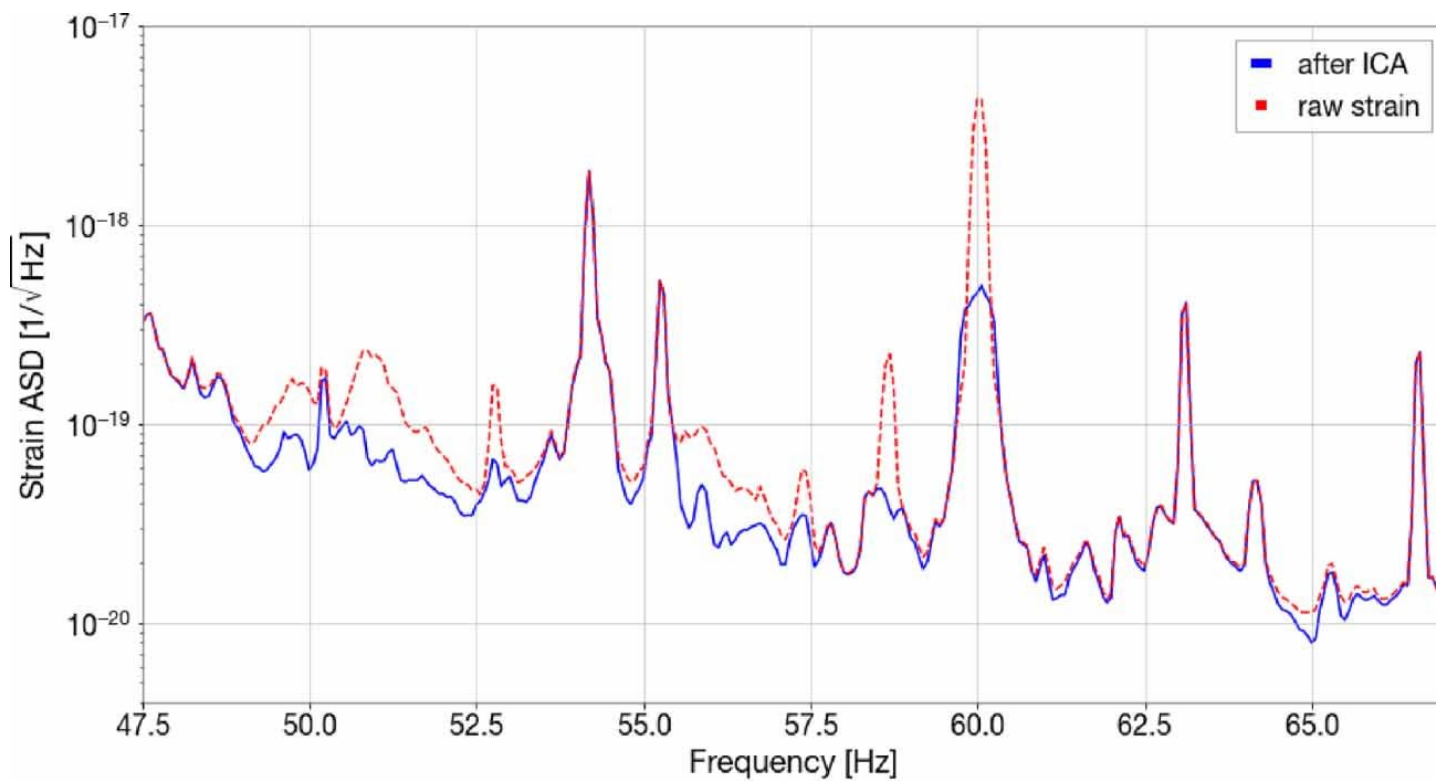


Beam jitter noise subtraction  
with Wiener Filtering

J. C. Driggers+,  
[PRD 99, 042001 \(2019\)](#)

# Independent Component Analysis

- Jun'ya Kume et al. applied to KAGRA data successfully
  - KAGRA Collab., [PTEP 2020, 053F01 \(2020\)](#)
  - KAGRA Collab., [CQG 40, 085015 \(2023\)](#)
- Non-linear ICA on going

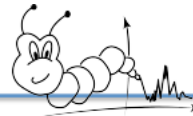


# Which Witness Data to Use?

- BruCo: Brute force coherence
- Automated noise budget? Non-linear?

<https://github.com/gw-pem/bruco>

What do I get?

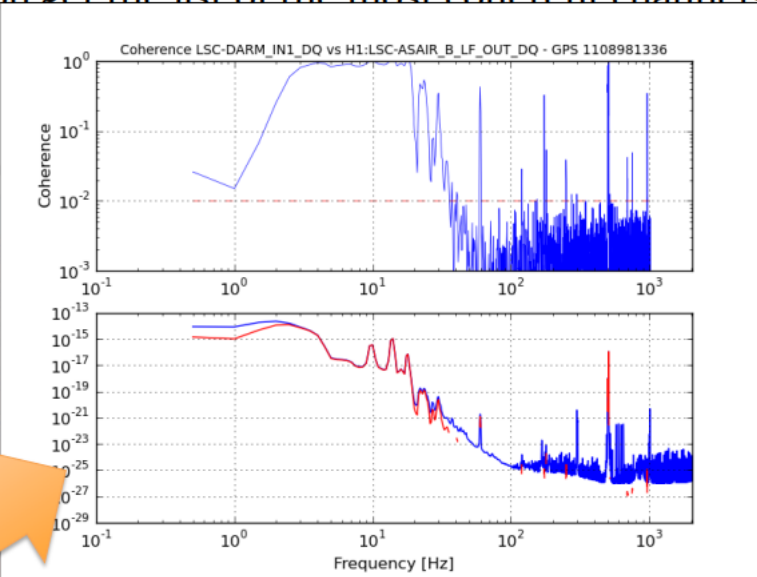


- A web page (index.html) containing a summary table: for each frequency bin, you get the list of the most coherent channels

Top 20 coherences at all frequencies

GPS 1108981336 (Thu Feb 26 10:22:01 2015 UTC) + 60

Frequency [Hz]	Top channels
0.00	ASC_X_TR_B_PIT_OUT_DQ (0.44), ASC_X_TR_A_PIT_OUT_DQ (0.43), ALS-C_TRX_A_LF_OUT_DQ (0.43), SUS_ETM_WIT_P_1 (0.40)
0.50	ASC_X_TR_B_PIT_OUT_DQ (0.33), ASC_AS_B_REH5_L_O_PIT_OUT_DQ (0.32), SUS_ETMX_L3_OPLEV_PIT_OUT_DQ (0.32), ASC_X_TR_A_PIT_OUT_DQ (0.31)
1.00	SUS_OMC_M1_NOISEMON_LF_DQ (0.34), SUS_OMC_M1_NOISEMON_SD_DQ (0.32), SUS_OMC_M1_MASTER_OUT_LF_DQ (0.25), SUS_OMC_M1_MASTER_OUT_SD_DQ (0.25)
1.50	SUS_OMC_M1_MASTER_OUT_SD_DQ (0.48), SUS_OMC_M1_NOISEMON_SD_DQ (0.44), SUS_OMC_M1_NOISEMON_SD_DQ (0.44), SUS_OMC_M1_MASTER_OUT_LF_DQ (0.42)
2.00	LSC-ASAIR_B_LF_OUT_DQ (0.25), LSC-ASAIR_A_LF_OUT_DQ (0.25), ASC-AS_B_DC_SUM_OUT_DQ (0.23), ASC-AS_A_SUM_OUT_DQ (0.23)
2.50	LSC-ASAIR_A_F15_I_ERR_DQ (0.77), LSC-ASAIR_A_F15_I_ERR_DQ (0.77), LSC-ASAIR_B_F15_I_ERR_DQ (0.60), LSC-AS_A_F15_I_ERR_DQ (0.57)
3.00	LSC-ASAIR_B_F15_I_ERR_DQ (0.85), LSC-ASAIR_A_F15_I_ERR_DQ (0.85), LSC-ASAIR_B_F15_I_ERR_DQ (0.81), LSC-AS_A_F15_I_ERR_DQ (0.77)
3.50	LSC-ASAIR_B_F15_I_ERR_DQ (0.89), LSC-ASAIR_A_F15_I_ERR_DQ (0.89), LSC-ASAIR_B_F15_I_ERR_DQ (0.88), LSC-AS_A_F15_I_ERR_DQ (0.80)
4.00	LSC-ASAIR_B_F15_I_ERR_DQ (0.85), LSC-AS_B_DC_SUM_OUT_DQ (0.66), ASC-AS_B_DC_SUM_OUT_DQ (0.66), SUS-ASAIR_A_F15_I_ERR_DQ (0.64), LSC-ASAIR_A_F15_I_ERR_DQ (0.64), LSC-ASAIR_B_F15_I_ERR_DQ (0.64), SUS-ASAIR_A_F15_I_ERR_DQ (0.64), SUS-ASAIR_B_F15_I_ERR_DQ (0.64), SUS-AS_A_F15_I_ERR_DQ (0.64), SUS-AS_B_F15_I_ERR_DQ (0.64), SUS-AS_C_F15_I_ERR_DQ (0.64), SUS-AS_D_F15_I_ERR_DQ (0.64), SUS-AS_E_F15_I_ERR_DQ (0.64), SUS-AS_F_F15_I_ERR_DQ (0.64), SUS-AS_G_F15_I_ERR_DQ (0.64), SUS-AS_H_F15_I_ERR_DQ (0.64), SUS-AS_I_F15_I_ERR_DQ (0.64), SUS-AS_J_F15_I_ERR_DQ (0.64), SUS-AS_K_F15_I_ERR_DQ (0.64), SUS-AS_L_F15_I_ERR_DQ (0.64), SUS-AS_M_F15_I_ERR_DQ (0.64), SUS-AS_N_F15_I_ERR_DQ (0.64), SUS-AS_O_F15_I_ERR_DQ (0.64), SUS-AS_P_F15_I_ERR_DQ (0.64), SUS-AS_Q_F15_I_ERR_DQ (0.64), SUS-AS_R_F15_I_ERR_DQ (0.64), SUS-AS_S_F15_I_ERR_DQ (0.64), SUS-AS_T_F15_I_ERR_DQ (0.64), SUS-AS_U_F15_I_ERR_DQ (0.64), SUS-AS_V_F15_I_ERR_DQ (0.64), SUS-AS_W_F15_I_ERR_DQ (0.64), SUS-AS_X_F15_I_ERR_DQ (0.64), SUS-AS_Y_F15_I_ERR_DQ (0.64), SUS-AS_Z_F15_I_ERR_DQ (0.64)
4.50	LSC-ASAIR_B_F15_I_ERR_DQ (0.92), LSC-AS_A_DC_SUM_OUT_DQ (0.92), ASC-AS_B_DC_SUM_OUT_DQ (0.92), SUS-ASAIR_A_F15_I_ERR_DQ (0.87), LSC-ASAIR_B_F15_I_ERR_DQ (0.87), LSC-AS_A_F15_I_ERR_DQ (0.87), LSC-AS_B_F15_I_ERR_DQ (0.87), LSC-AS_C_F15_I_ERR_DQ (0.87), LSC-AS_D_F15_I_ERR_DQ (0.87), LSC-AS_E_F15_I_ERR_DQ (0.87), LSC-AS_F_F15_I_ERR_DQ (0.87), LSC-AS_G_F15_I_ERR_DQ (0.87), LSC-AS_H_F15_I_ERR_DQ (0.87), LSC-AS_I_F15_I_ERR_DQ (0.87), LSC-AS_J_F15_I_ERR_DQ (0.87), LSC-AS_K_F15_I_ERR_DQ (0.87), LSC-AS_L_F15_I_ERR_DQ (0.87), LSC-AS_M_F15_I_ERR_DQ (0.87), LSC-AS_N_F15_I_ERR_DQ (0.87), LSC-AS_O_F15_I_ERR_DQ (0.87), LSC-AS_P_F15_I_ERR_DQ (0.87), LSC-AS_Q_F15_I_ERR_DQ (0.87), LSC-AS_R_F15_I_ERR_DQ (0.87), LSC-AS_S_F15_I_ERR_DQ (0.87), LSC-AS_T_F15_I_ERR_DQ (0.87), LSC-AS_U_F15_I_ERR_DQ (0.87), LSC-AS_V_F15_I_ERR_DQ (0.87), LSC-AS_W_F15_I_ERR_DQ (0.87), LSC-AS_X_F15_I_ERR_DQ (0.87), LSC-AS_Y_F15_I_ERR_DQ (0.87), LSC-AS_Z_F15_I_ERR_DQ (0.87)
5.00	SUS-AS_A_F15_I_ERR_DQ (0.85), SUS-AS_B_F15_I_ERR_DQ (0.85), SUS-AS_C_F15_I_ERR_DQ (0.85), SUS-AS_D_F15_I_ERR_DQ (0.85), SUS-AS_E_F15_I_ERR_DQ (0.85), SUS-AS_F15_I_ERR_DQ (0.85), SUS-AS_G15_I_ERR_DQ (0.85), SUS-AS_H15_I_ERR_DQ (0.85), SUS-AS_I15_I_ERR_DQ (0.85), SUS-AS_J15_I_ERR_DQ (0.85), SUS-AS_K15_I_ERR_DQ (0.85), SUS-AS_L15_I_ERR_DQ (0.85), SUS-AS_M15_I_ERR_DQ (0.85), SUS-AS_N15_I_ERR_DQ (0.85), SUS-AS_O15_I_ERR_DQ (0.85), SUS-AS_P15_I_ERR_DQ (0.85), SUS-AS_Q15_I_ERR_DQ (0.85), SUS-AS_R15_I_ERR_DQ (0.85), SUS-AS_S15_I_ERR_DQ (0.85), SUS-AS_T15_I_ERR_DQ (0.85), SUS-AS_U15_I_ERR_DQ (0.85), SUS-AS_V15_I_ERR_DQ (0.85), SUS-AS_W15_I_ERR_DQ (0.85), SUS-AS_X15_I_ERR_DQ (0.85), SUS-AS_Y15_I_ERR_DQ (0.85), SUS-AS_Z15_I_ERR_DQ (0.85)
5.50	SUS-AS_A_F15_I_ERR_DQ (0.85), SUS-AS_B_F15_I_ERR_DQ (0.85), SUS-AS_C_F15_I_ERR_DQ (0.85), SUS-AS_D_F15_I_ERR_DQ (0.85), SUS-AS_E_F15_I_ERR_DQ (0.85), SUS-AS_F15_I_ERR_DQ (0.85), SUS-AS_G15_I_ERR_DQ (0.85), SUS-AS_H15_I_ERR_DQ (0.85), SUS-AS_I15_I_ERR_DQ (0.85), SUS-AS_J15_I_ERR_DQ (0.85), SUS-AS_K15_I_ERR_DQ (0.85), SUS-AS_L15_I_ERR_DQ (0.85), SUS-AS_M15_I_ERR_DQ (0.85), SUS-AS_N15_I_ERR_DQ (0.85), SUS-AS_O15_I_ERR_DQ (0.85), SUS-AS_P15_I_ERR_DQ (0.85), SUS-AS_Q15_I_ERR_DQ (0.85), SUS-AS_R15_I_ERR_DQ (0.85), SUS-AS_S15_I_ERR_DQ (0.85), SUS-AS_T15_I_ERR_DQ (0.85), SUS-AS_U15_I_ERR_DQ (0.85), SUS-AS_V15_I_ERR_DQ (0.85), SUS-AS_W15_I_ERR_DQ (0.85), SUS-AS_X15_I_ERR_DQ (0.85), SUS-AS_Y15_I_ERR_DQ (0.85), SUS-AS_Z15_I_ERR_DQ (0.85)



ASC-REFL_A_ERR_OUT_DQ (0.30)
ASC-REFL_B_ERR_OUT_DQ (0.22)
SUS-OMI_M1_DAMP_L_IN1_DQ (0.14)
SUS-OMC_M1_VOLTMON_RT_DQ (0.39)
LSC-ASAIR_A_ERR_I_ERR_DQ (0.09)
ASC-Y_TR_B_NSUM_OUT_DQ (0.17)
ASC-X_TR_B_NSUM_OUT_DQ (0.14)
ASC-Y_TR_A_NSUM_OUT_DQ (0.17)



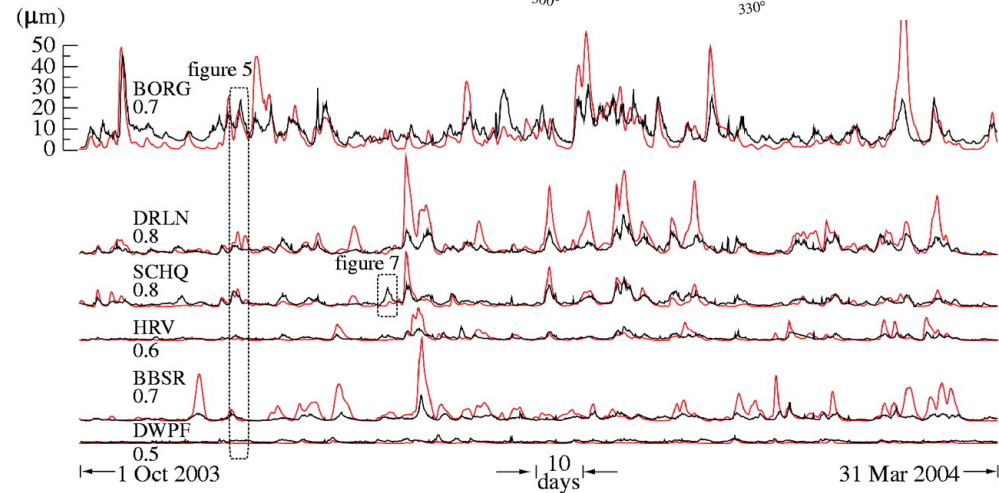
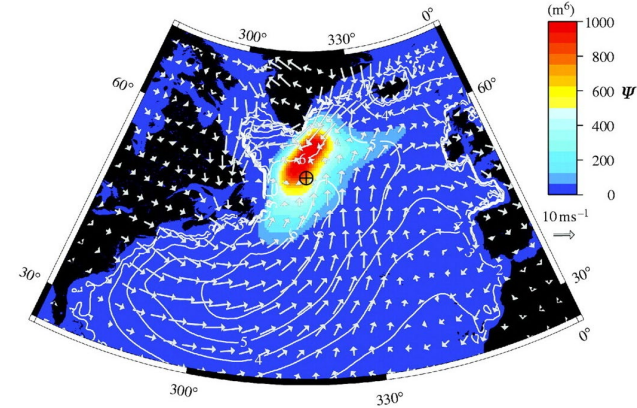
# Seismic Disturbances

- Microseism at Livingston is affected by weather in Greenland

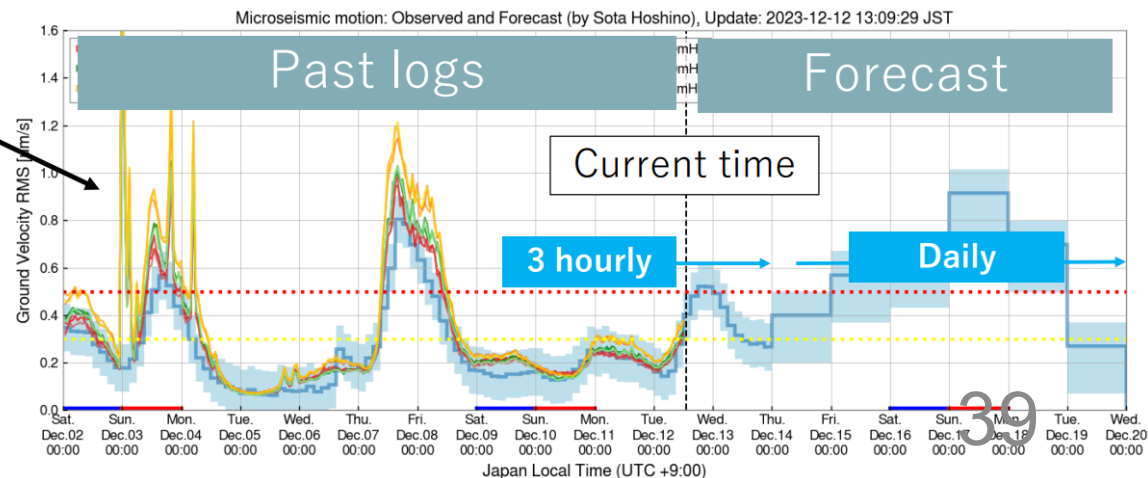
S. Kedar+,  
[Proc. R. Soc. A. 464, 777 \(2008\)](#)

- Microseism level at KAGRA can be predicted from ocean wave data forecast

Principal Component Analysis  
 S. Hoshino+,  
[arXiv:2306.12437](#)  
[JGW-G2315480](#)

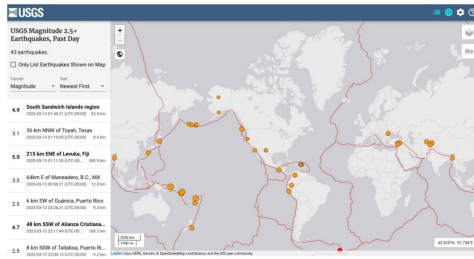


Earthquake



# Protection from Seismic

- LIGO: SEISMON + Picket Fense
  - Switch suspension control modes based on seismic data around the detector (low noise mode or robust mode)



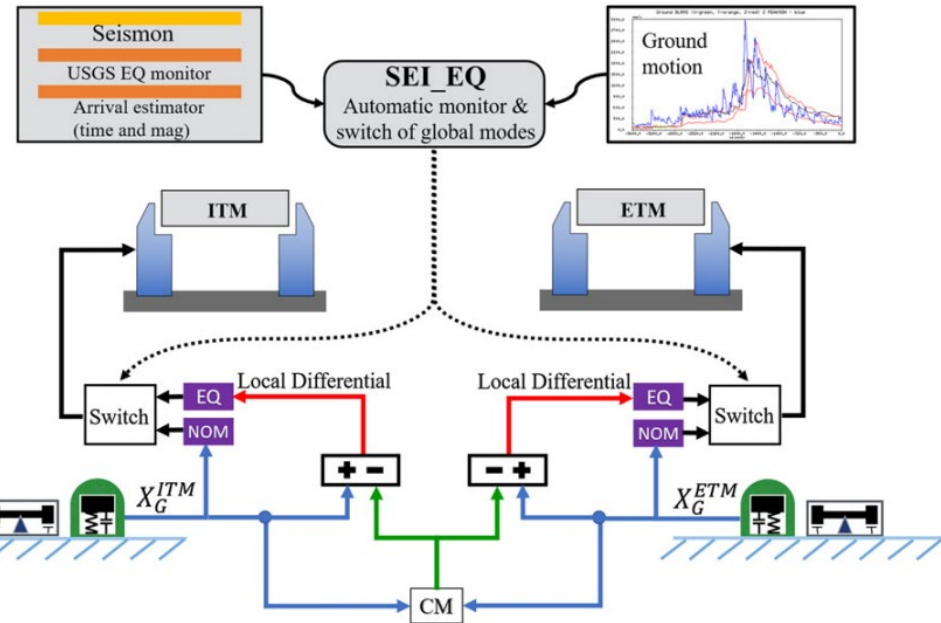
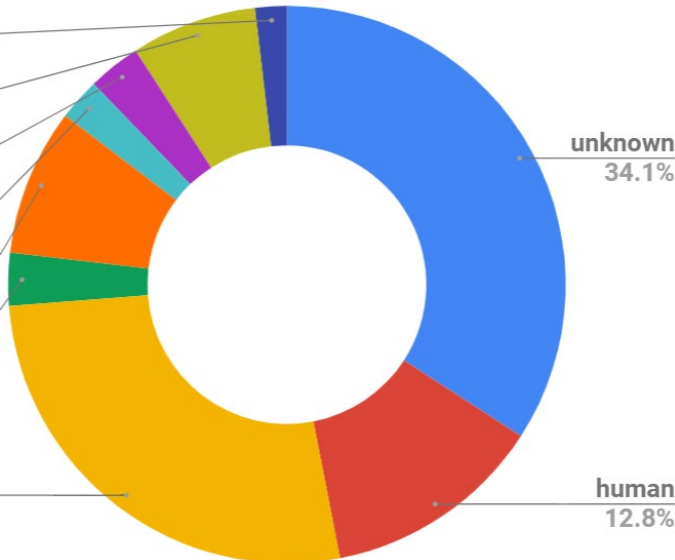
E. Bonilla+, [LIGO-G2300553](#)

E Schwartz+, [CQG 37, 235007 \(2020\)](#)

## Count of classification

### Facilities

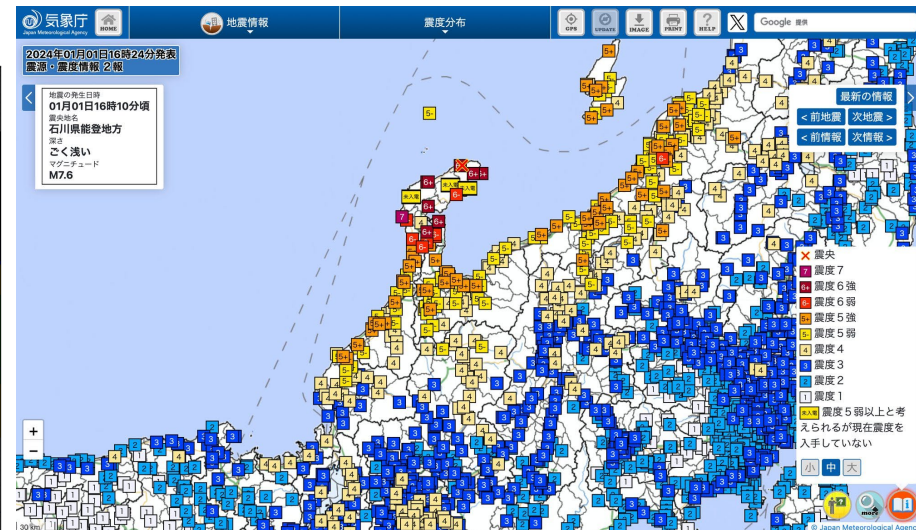
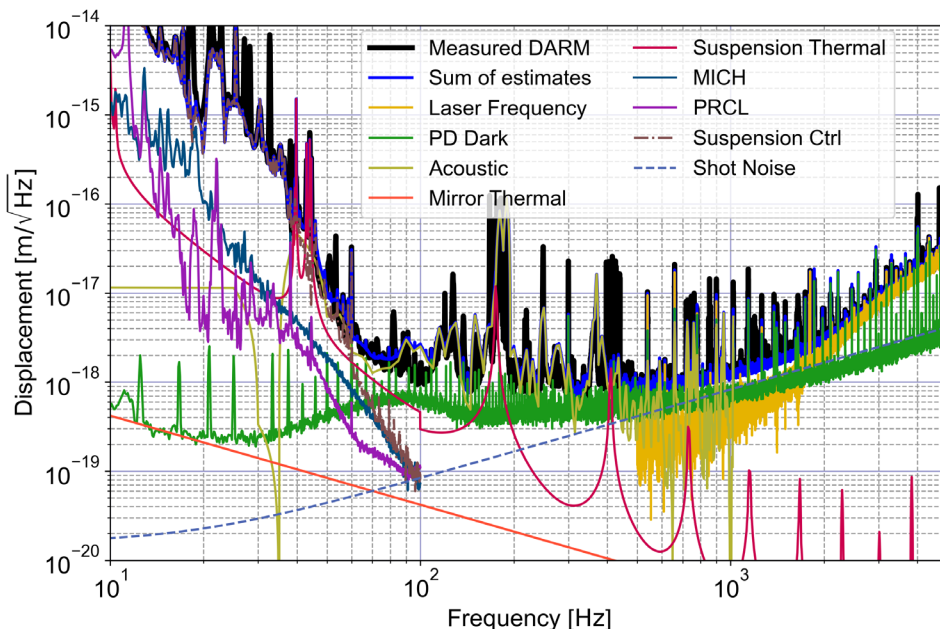
- 1.8% CDS - electronics
- 7.3% SEI - wind
- 3.0% CDS - power outage
- 2.4% SEI - anthro
- 8.5% SEI - useism
- 3.0%
- 26.8% SEI - eq



- Useful to improve duty factor

# Why You Should Join

- Big data! Machine learning!
- KAGRA is still limited a lot by noises that are **subtractable**
- If we can subtract and we can **identify the mechanism**, we can improve the detector to reduce the noise or the coupling
- You could save KAGRA from **earthquakes**

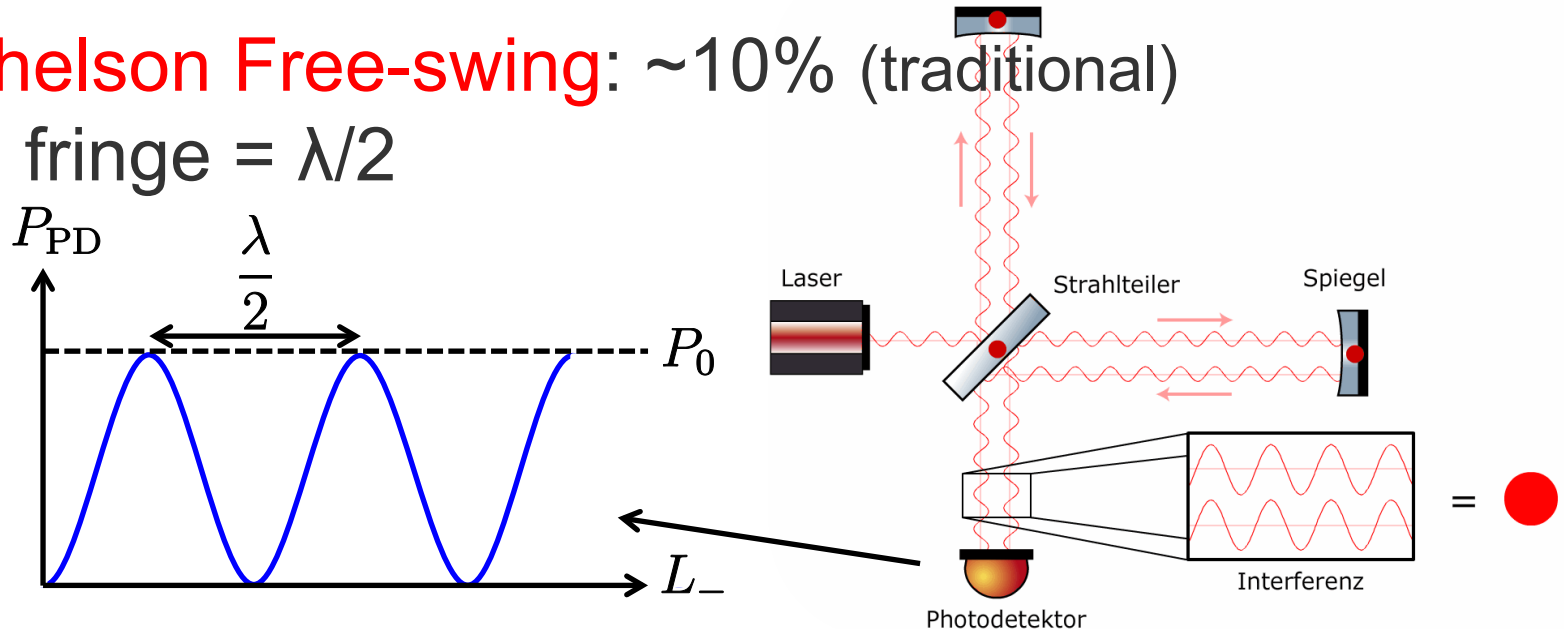


# Upgrading Calibration



# Brief History of Calibration

- Calibration is crucial for **parameter estimation**
  - luminosity distance, polarization, localization, NS tidal deformability ...
- **Michelson Free-swing**:  $\sim 10\%$  (traditional)
  - 1 fringe =  $\lambda/2$

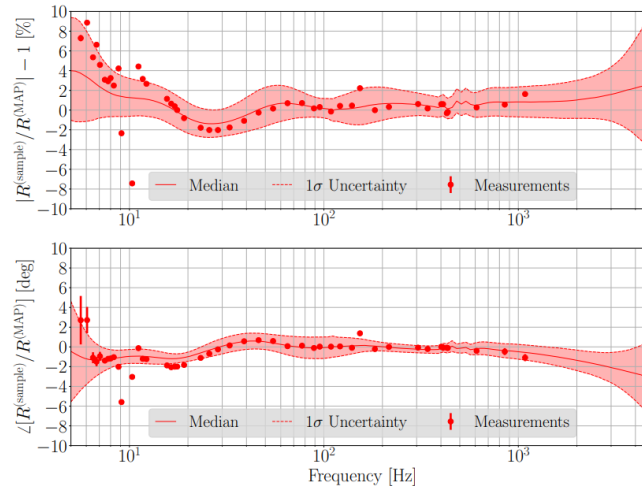
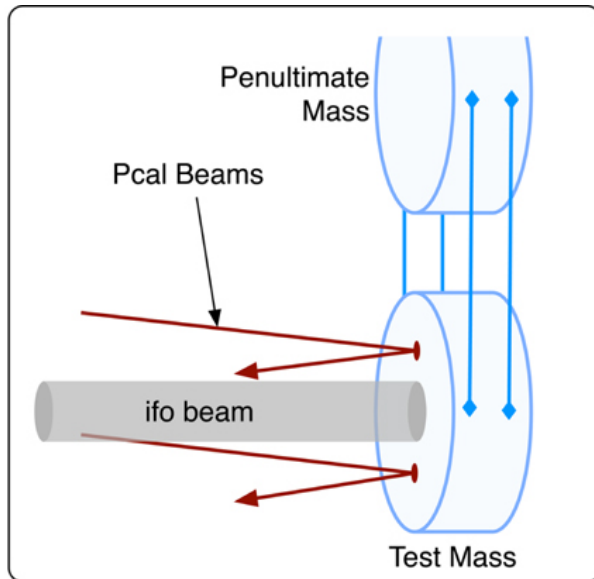


- Photon Calibrator(PCal): 2-5%, 2-5 deg (current)
- Newtonian Calibrator(NCal): 3-5%? (R&D at sites)
- Multicolor Calibrator(SoCal): 0.05-0.4%? (R&D at 40m)
- What's next?

# Photon Calibrator (Pcal)

- Shake mirror by **radiation pressure** from “known” amount of light (current standard)

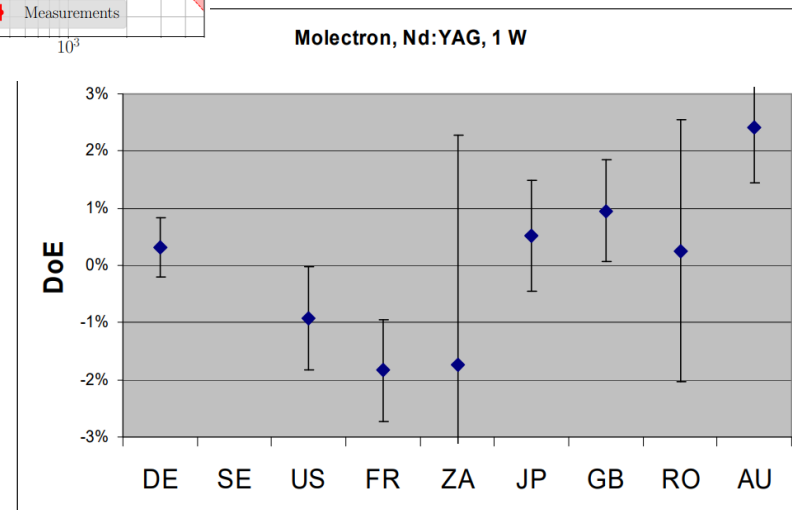
$$F = \frac{2P}{c}$$



L. Sun+,  
[CQG 37, 225008 \(2020\)](#)

S. Karki+, [RSI 87, 114503 \(2016\)](#)

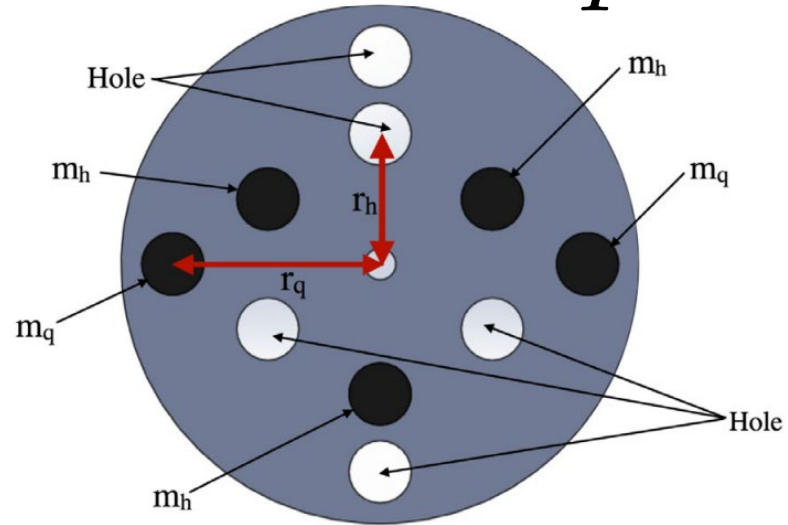
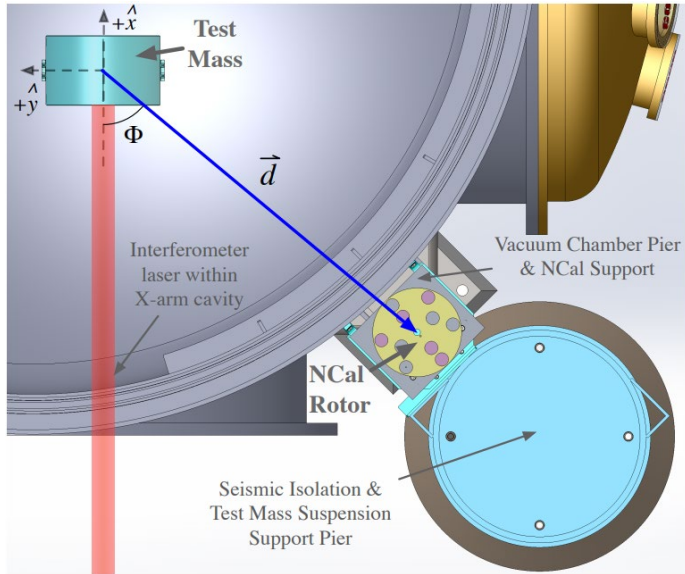
- But light power measurement **do not agree between countries** (by a few %)



Stefan Kück, [Metrologia 47, 02003 \(2010\)](#) 44

# Newtonian Calibrator (NCal or GCal)

- Shake mirror by “known” amount of **gravity**  $F = \frac{GmM}{r^2}$

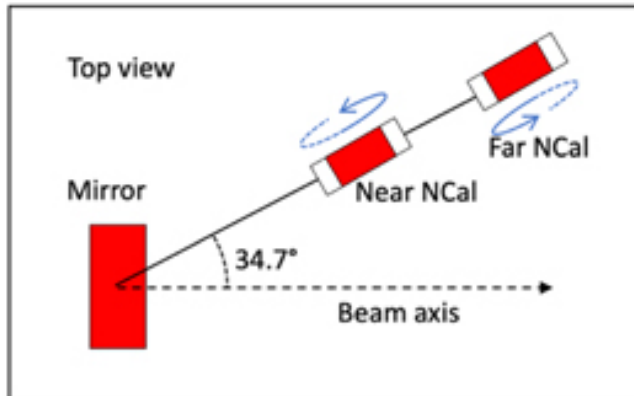


LIGO: ~5% below ~30 Hz

M. P. Ross+, [arXiv:2107.00141](https://arxiv.org/abs/2107.00141)

KAGRA: 0.17% (proposal to combine Pcal and GCal)

Y. Inoue+, [PRD 98, 022005 \(2018\)](https://arxiv.org/abs/1802.02205)



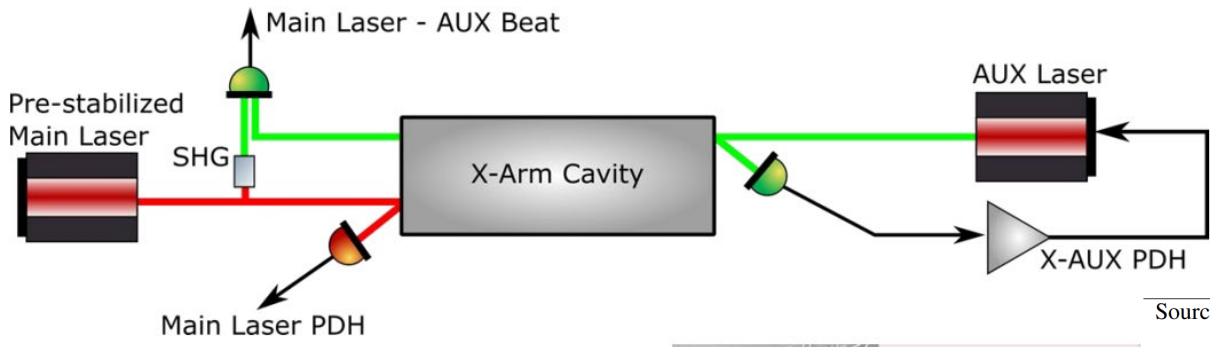
Virgo: ~3% below 120 Hz

D. Estevez+, [CQG 38, 075012 \(2021\)](https://arxiv.org/abs/2107.075012)

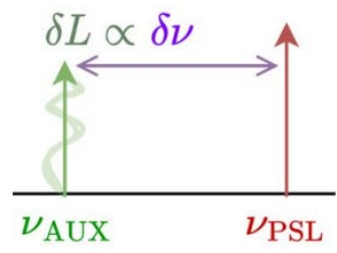
# Multi-color Calibrator (McCal)

- Based on frequency metrology (which is known to be precise)

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



Statistical uncertainty limited (at 40m prototype)

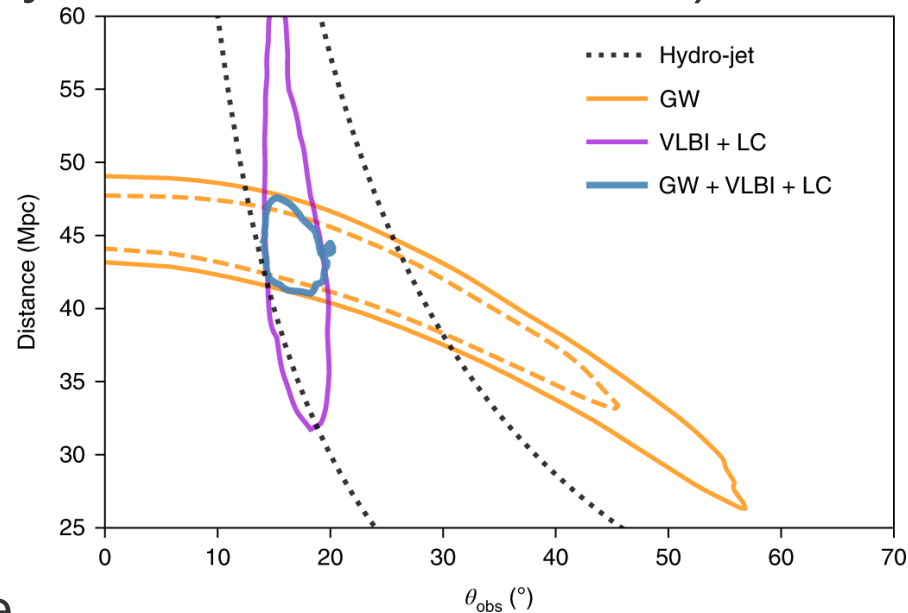


... "never measure anything but frequency"  
A. L. Schawlow

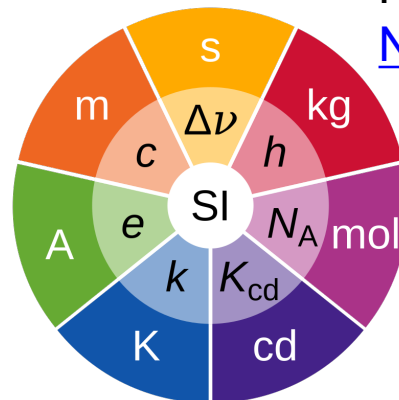
Source	Symbol in Eq. 9.9	Estimated effect on calibration [ppm]				
		33.921 Hz	211.110 Hz	313.31 Hz	575.17 Hz	1418.93 Hz
Laser WaveLength	$\lambda_{main}$	100	100	100	100	100
CARM OLF Drift	$H_{OL}$	0.071	135.5	0.044	0.051	0.022
AUX OLF Drift	$G_{OL}$	12.3	14.9	65.1	224	1043
Beatnote Measurement	$\delta \nu_{beat,i}$	300	300	300	300	300
Arm Lengths	-	665	18	18	18	18
Statistical Uncertainty	-	4200	310	450	900	1590
Total	-	4264	464	554	980	1928

# Why You Should Join

- It will be **more important if KAGRA joins** (luminosity distance & inclination angle degeneracy will be resolved better)
- Even more in **3G**
- Directly connected to GW science, including  $H_0$ , tests of GR, NS EoS ...
- In-between theoretical work and instrument work
  - a lot of papers on the effect of calibration uncertainty to science
- More ideas, better understanding of systematics



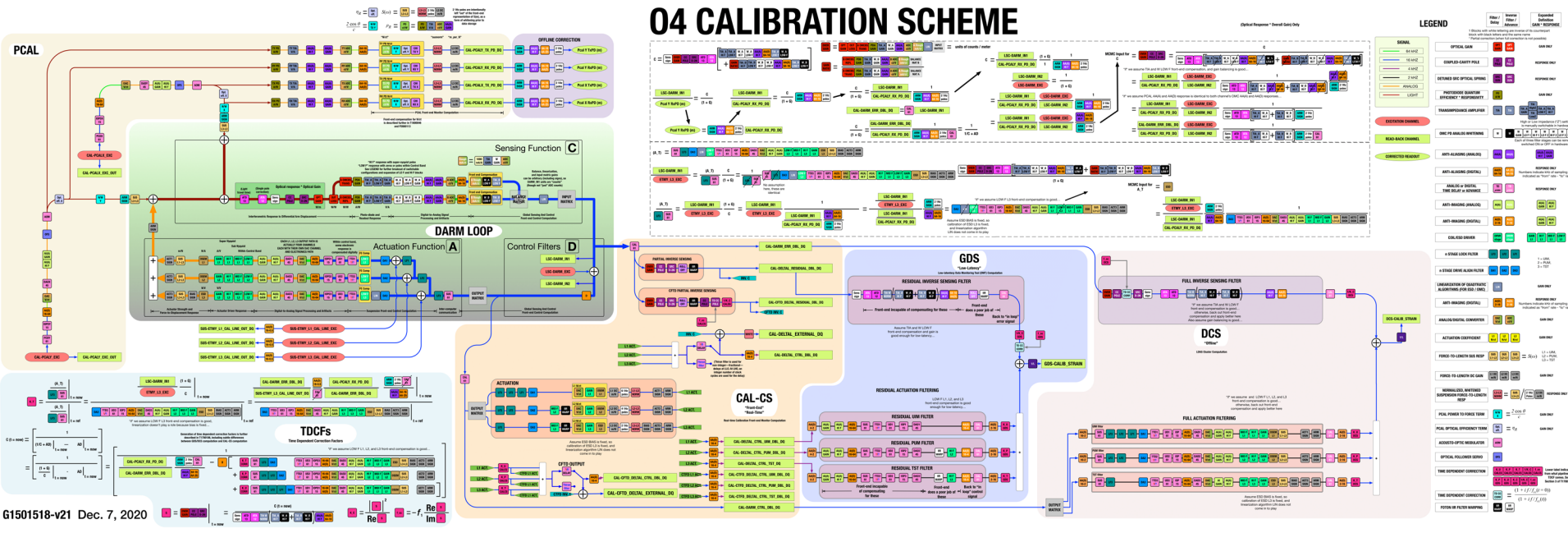
K. Hotokezaka+,  
[Nature Astronomy 3, 940 \(2019\)](#)



... but it is a lot of work



# LIGO O4 Calibration Subway Map



G1501518-v21 Dec. 7, 2020

# Summary

- Let me know if you are interested in any of these topics!
- I live in Room 1615 in Science Building #4 (理学部4号館1615号室)
- You can visit KAGRA anytime (either with me or without me)

