RESCEU Thursday Seminar @ RESCEU

May 23, 2024

Opportunities around gravitational wave detectors

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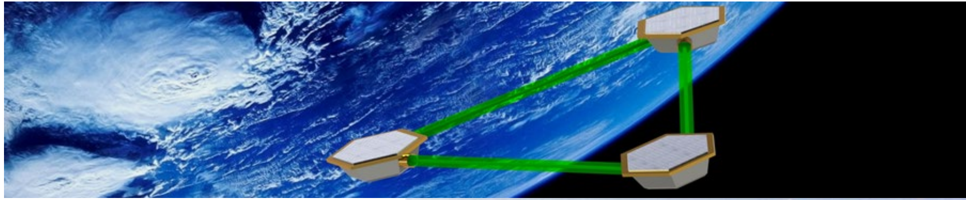
SLIDES

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

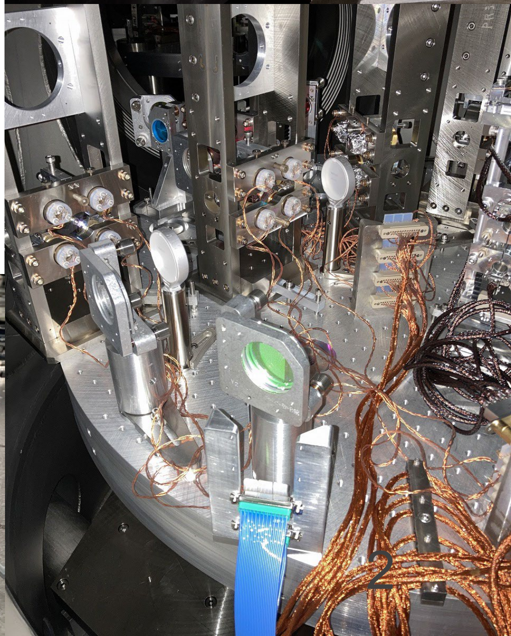
Self Introduction

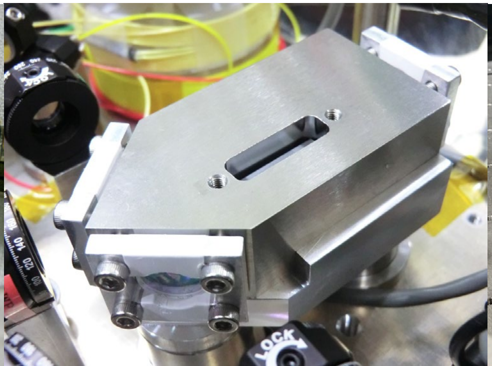
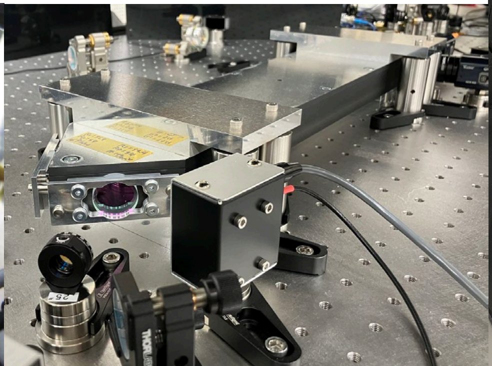


- **PhD in 2015** from Tsubono→Ando Group
  - Most precise Lorentz invariance test
- **2014-2022** 助教 at Ando Group
  - Chaired KAGRA Main Interferometer group

  (**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





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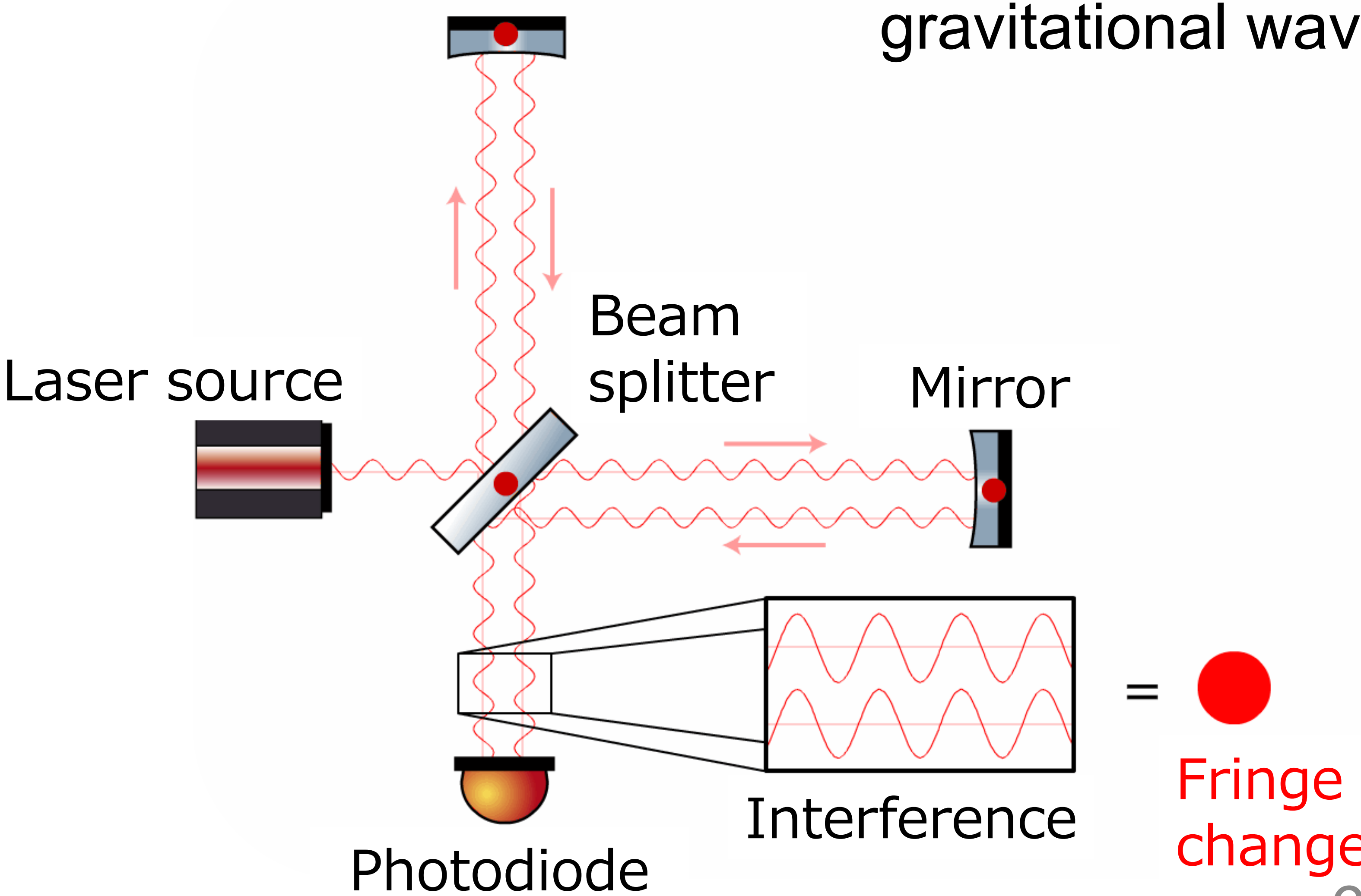
Group Photo 2024

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



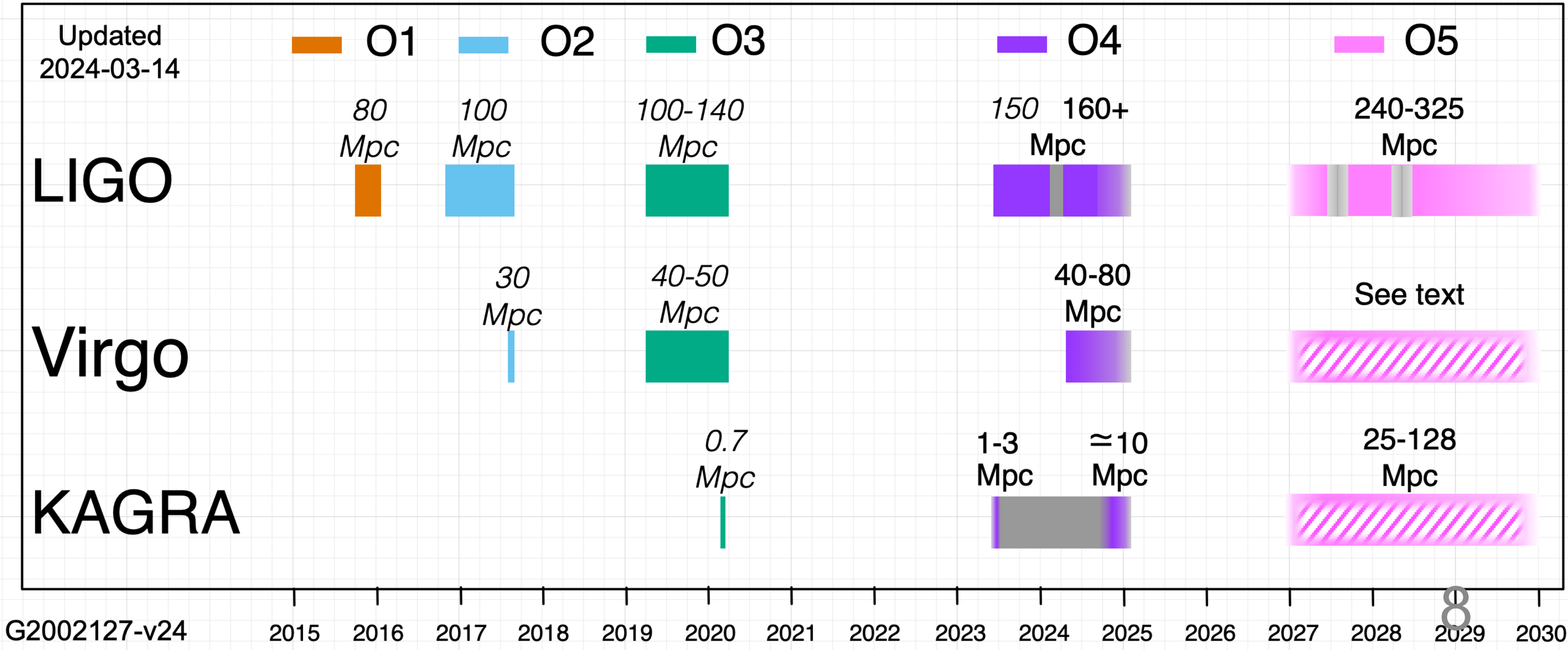
Global Network of GW Detectors

- Network of ground-based Advanced interferometric gravitational wave detectors

LVK Observing Plans

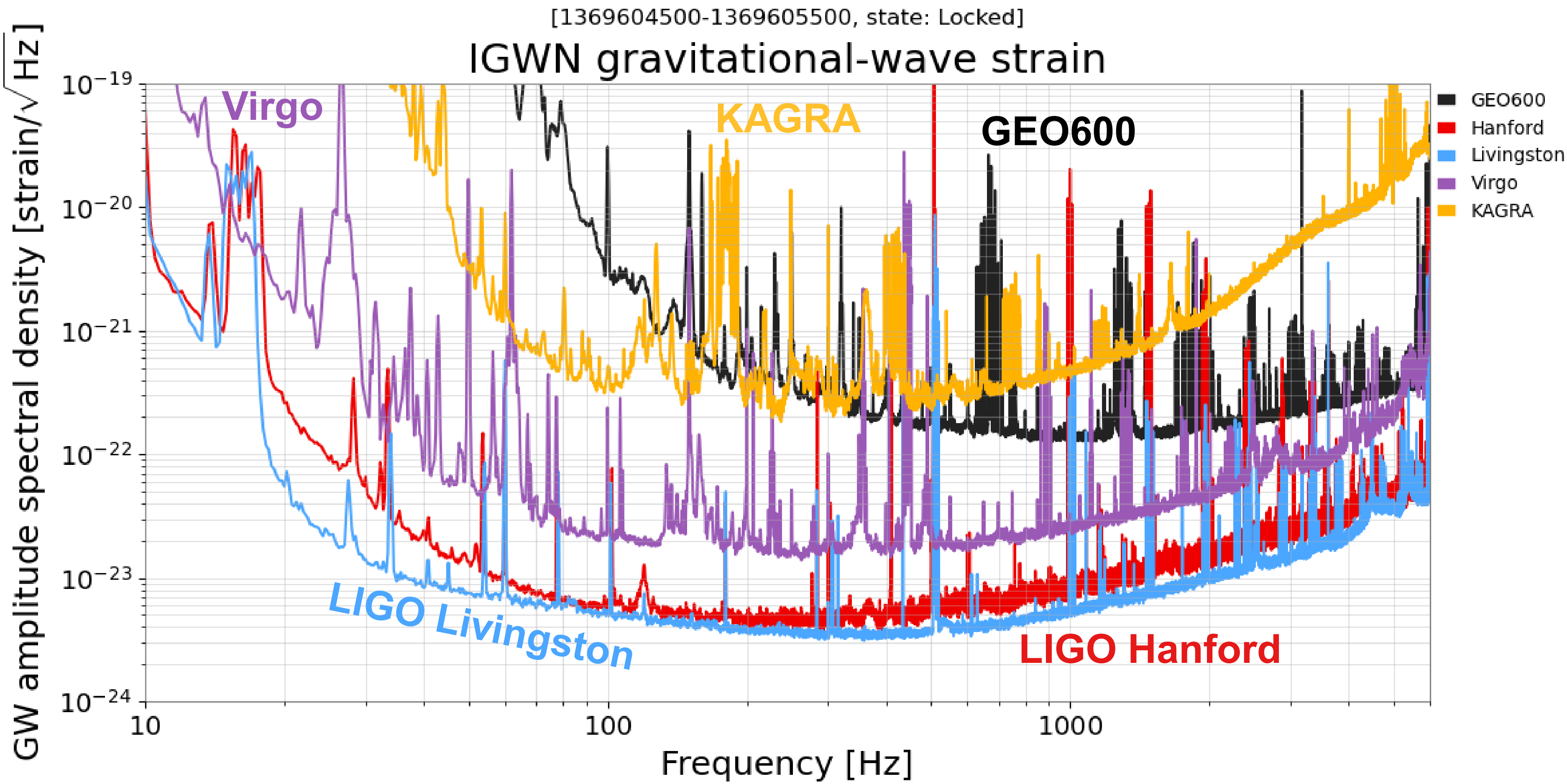
- Second half of O4 (called O4b) is running
- LIGO: 155-175 Mpc, Virgo: 55-60 Mpc
- KAGRA: Aiming to achieve 10 Mpc by Feb 2025 (end of O4b)
- Upgrades and next generation detectors planned after O5

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
- Observable

Planck length

$$\delta L^2 \sim l_{\mathrm{p}} L/(4\pi)$$

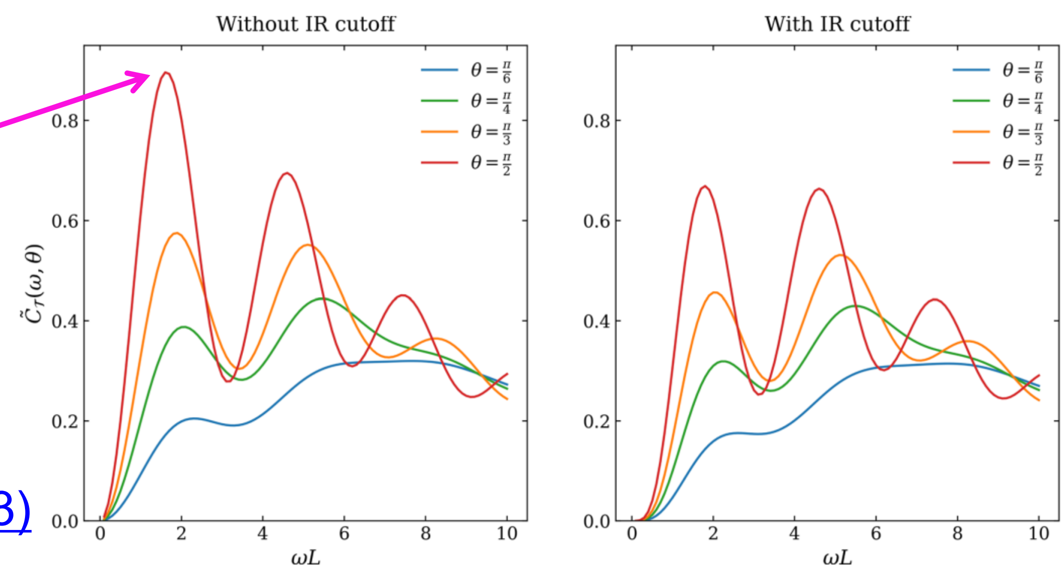
Arm length

not $\delta L \sim l_{\mathrm{p}}$

K. M. Zurek, arXiv:2205.01799

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

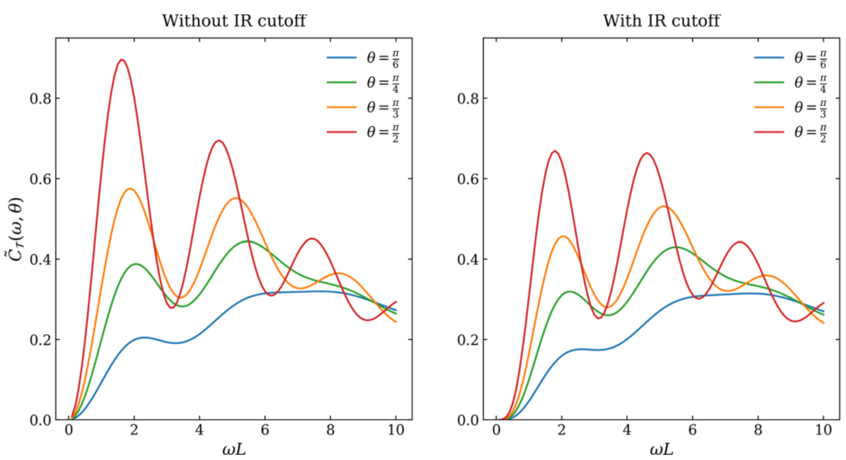
Displacement noise peaks at odd x c/(4L)

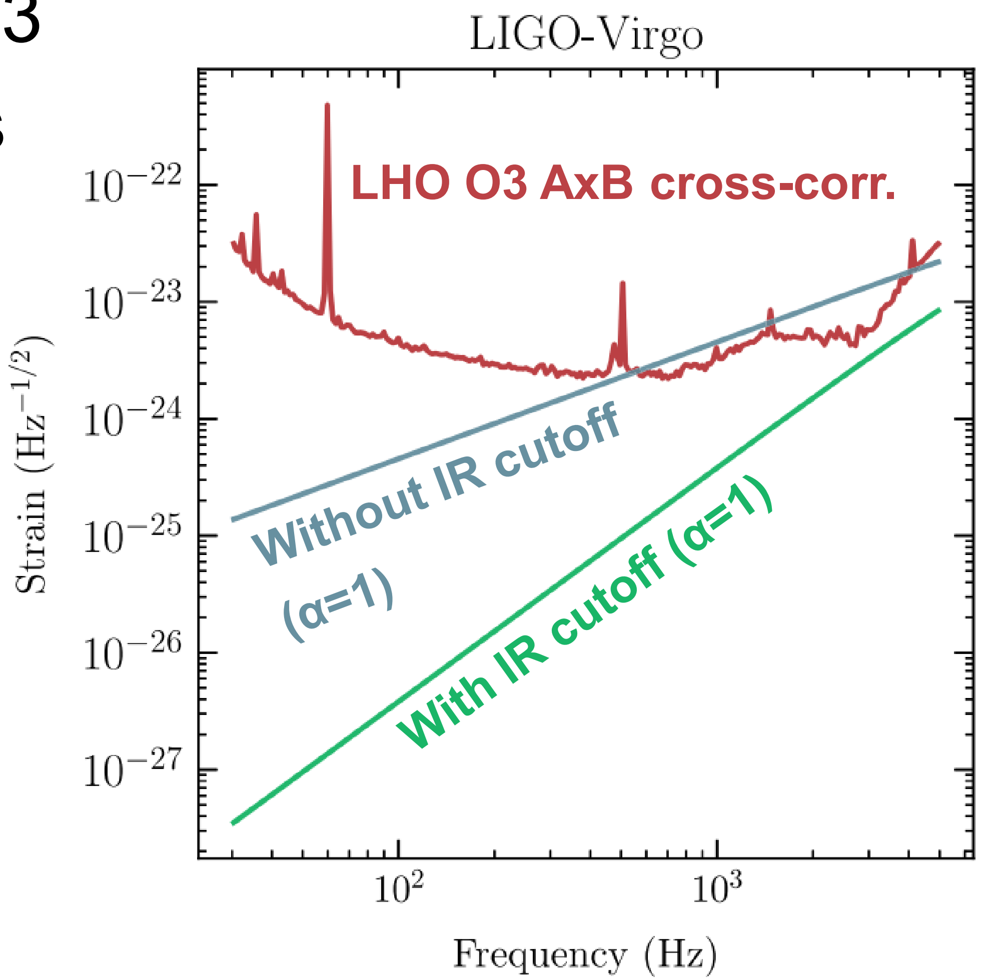


D. Li+, PRD 107, 024002 (2023)

Limit from O3

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



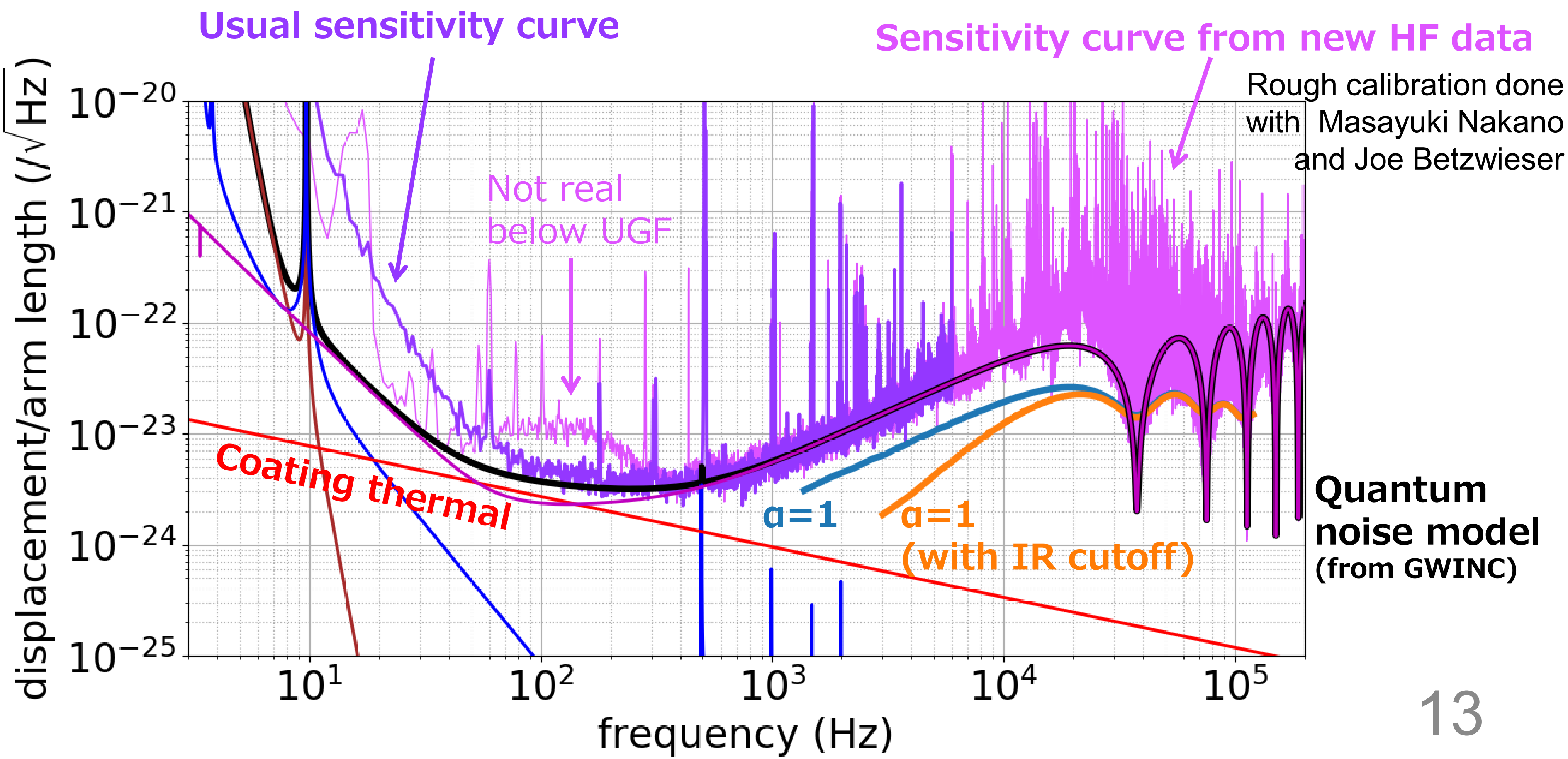


D. Li+, PRD 107, 024002 (2023)

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

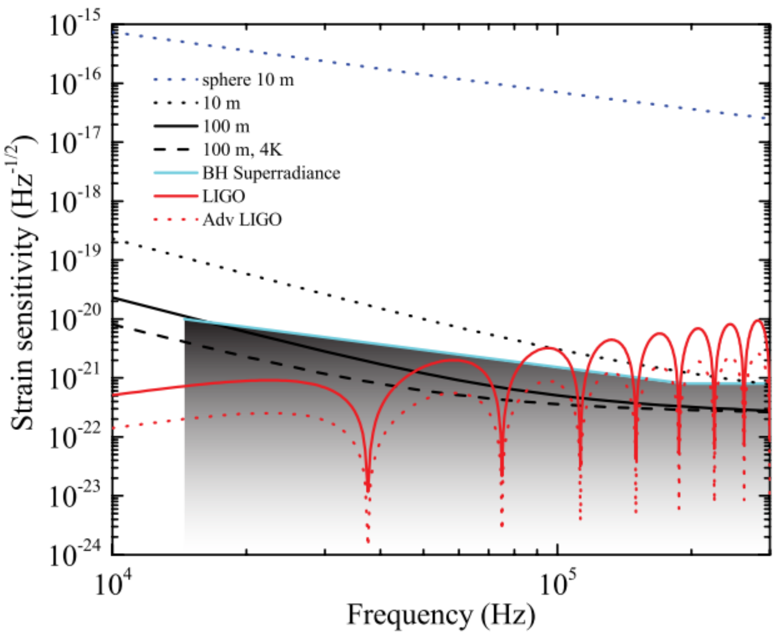
KHz = 1024 kHz



kHz GW Searches Also Possible

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

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



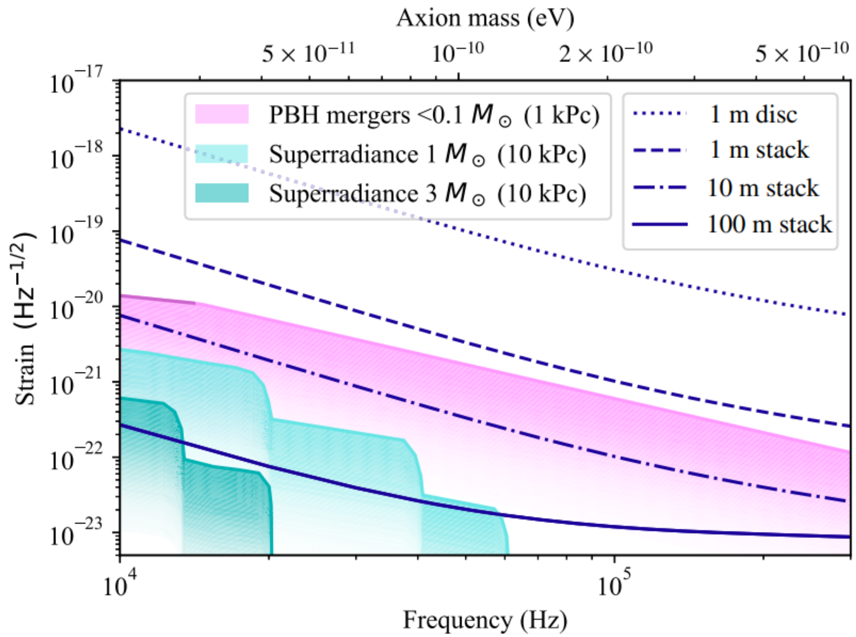


FIG. 2 (color online). Strain sensitivity for optically levitated microdisks (black dashed line) or spheres (blue dashed line) for experimental parameters described in the text. For comparison, also shown are the LIGO and predicted Advanced LIGO sensitivity in the frequency range of 10–300 kHz [25,28].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

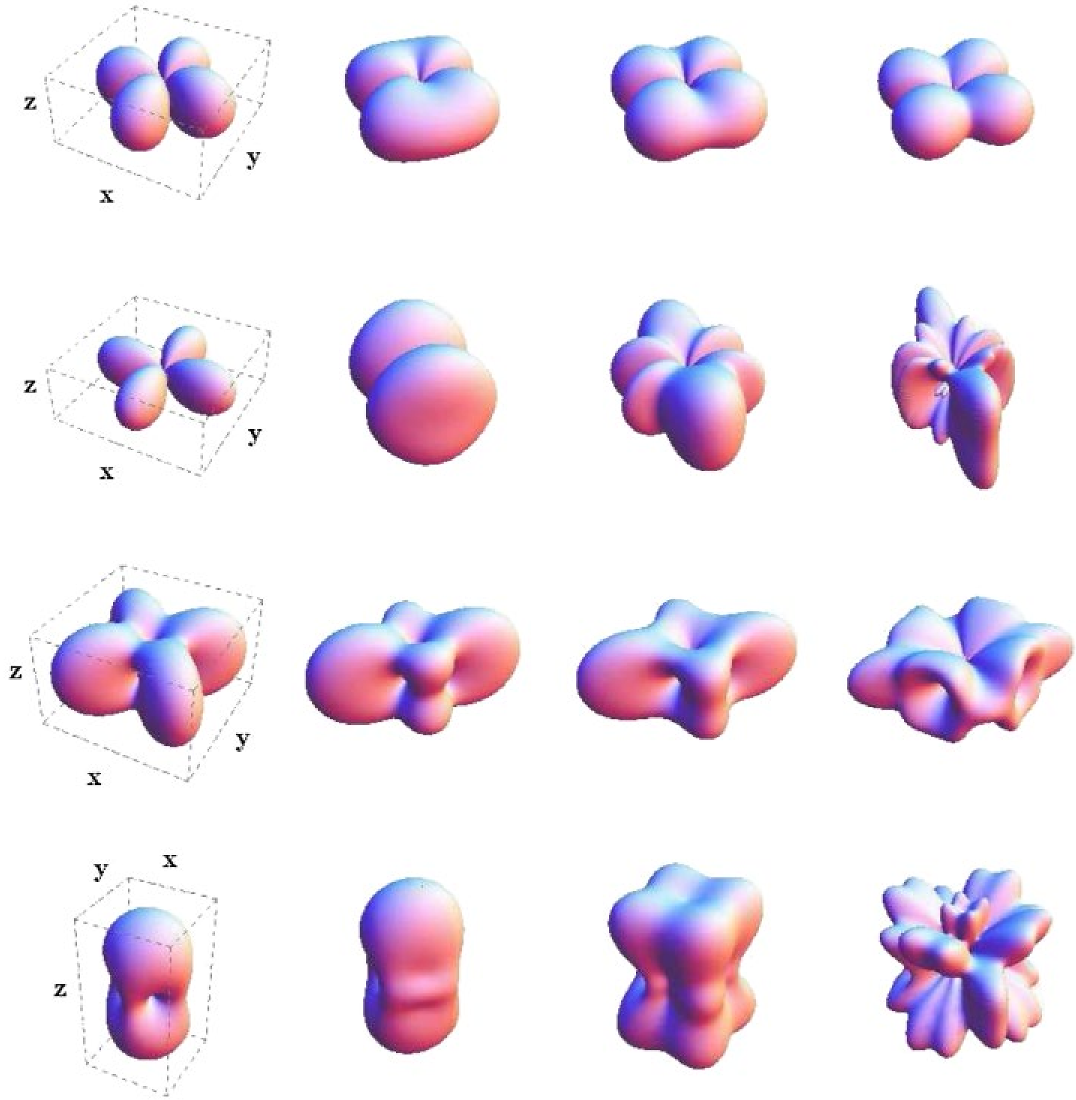
A. Arvanitaki & A. A. Geraci,
[PRL **110**, 071105 (2013)]

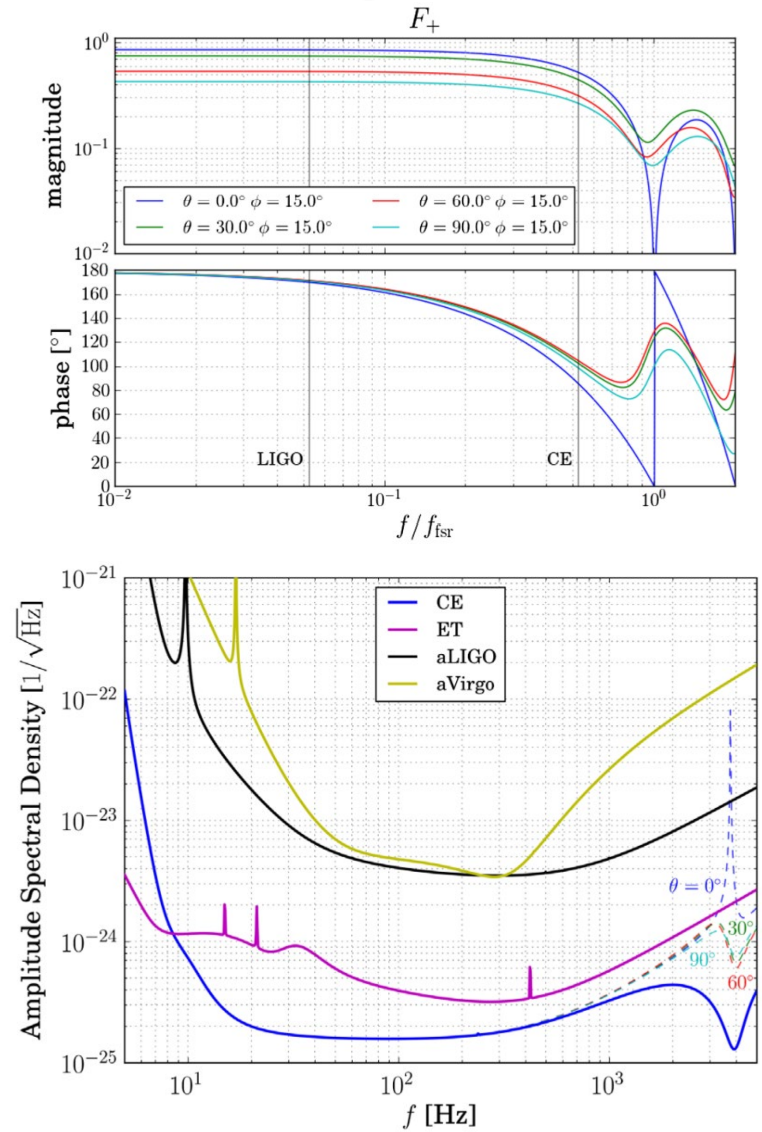
For review, see
N. Aggarwal+, [Living Reviews in Relativity **24**, 4 (2021)]

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 ~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. Błaut, 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

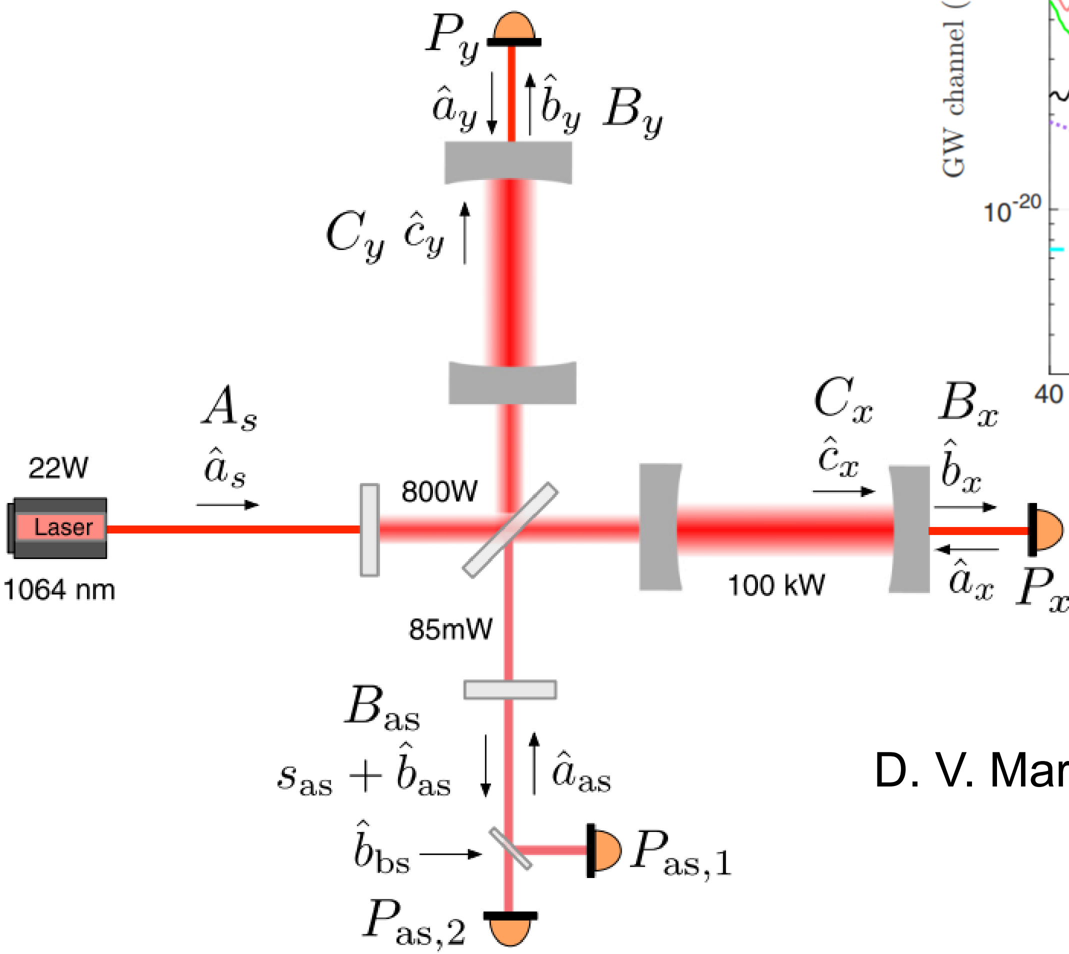
Frequency Dependent Response

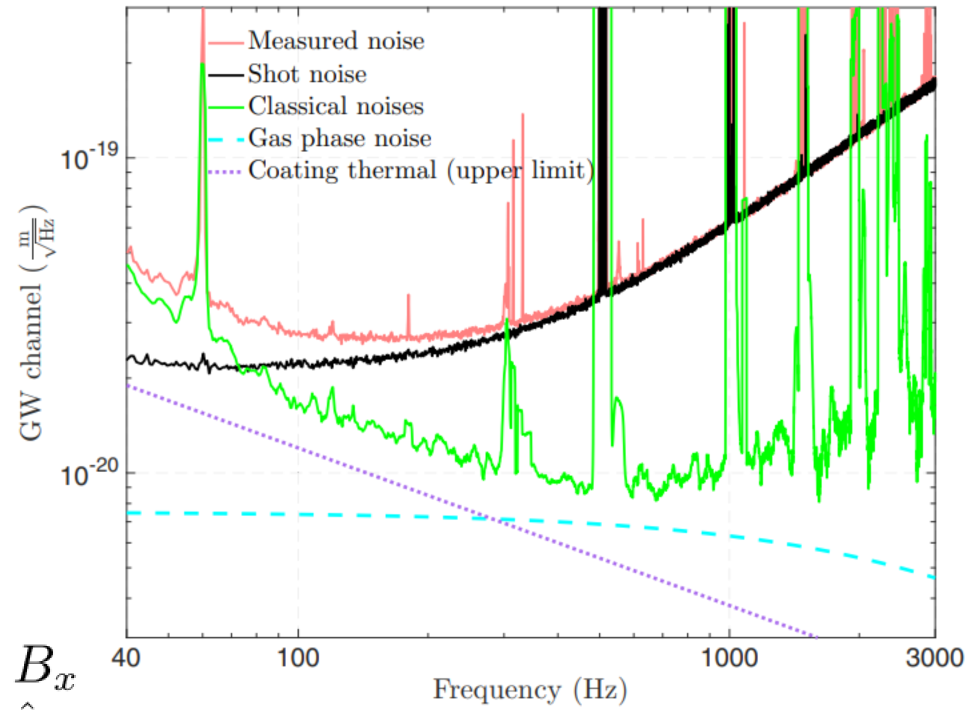




A. Błaut, [PRD **85**, 043005 (2012)] R. Essick+, [PRD **96**, 084004 (2017)]

Quantum Correlation



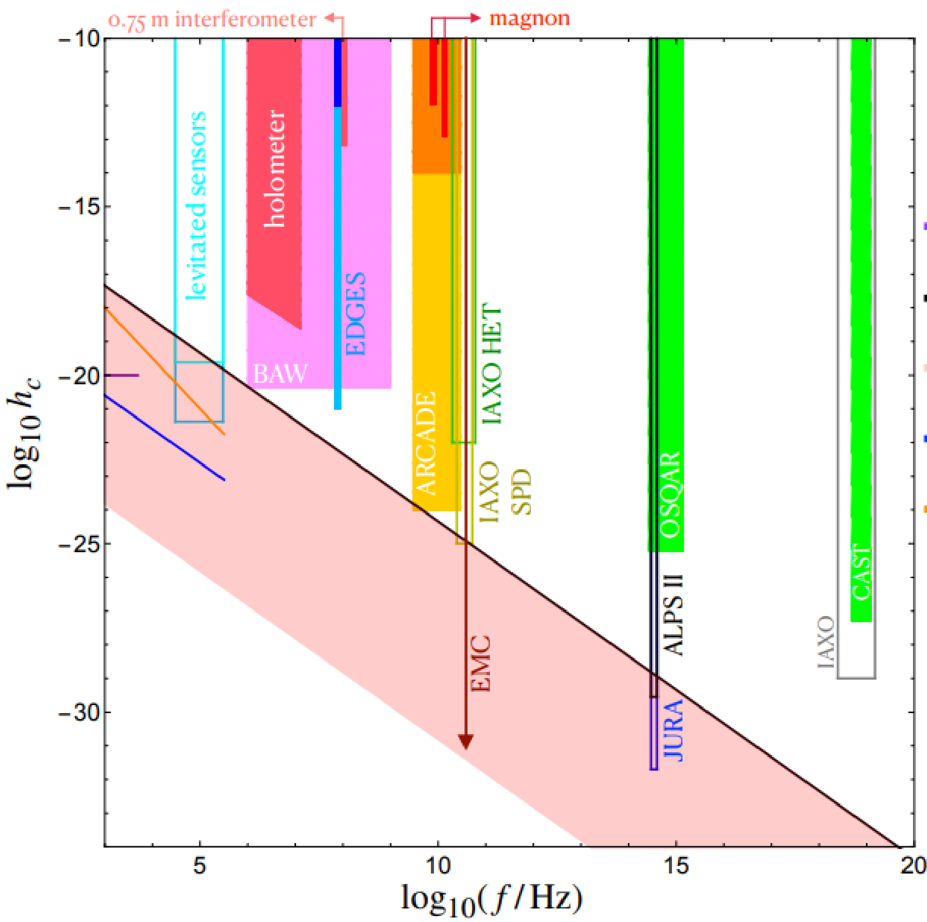


D. V. Martynov+, [PRA **95**, 043831 (2017)]

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)

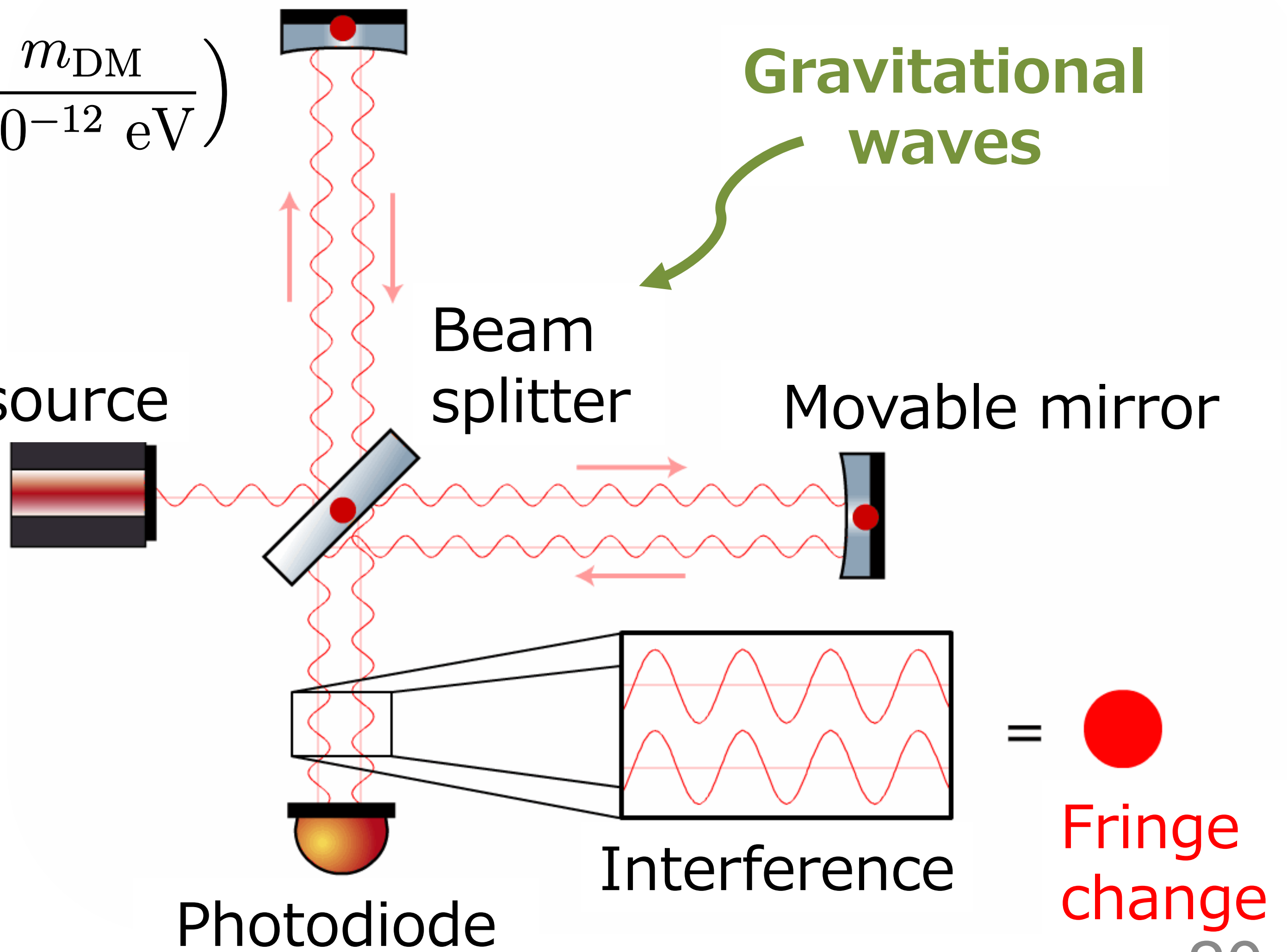
For review, see
N. Aggarwal+, Living Reviews in Relativity **24**, 4 (2021)

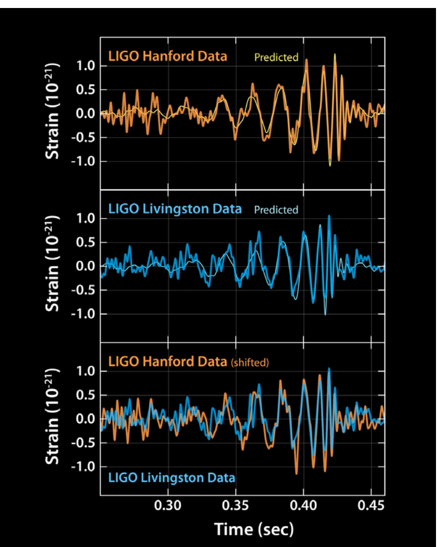
Ultralight Dark Matter

Interferometers are Sensitive to…

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

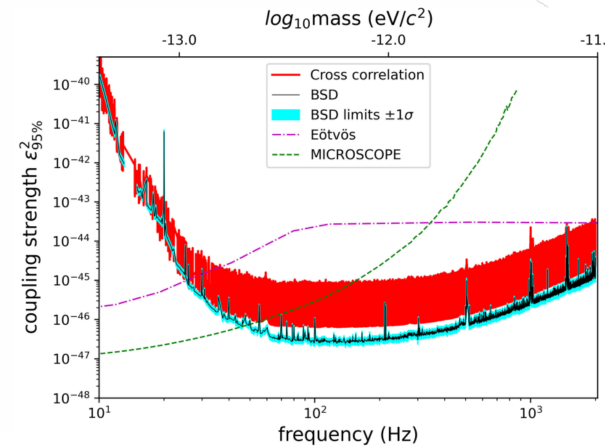
$$f = 242\ \mathrm{Hz}\left(\frac{m_{\mathrm{DM}}}{10^{-12}\ \mathrm{eV}}\right)$$





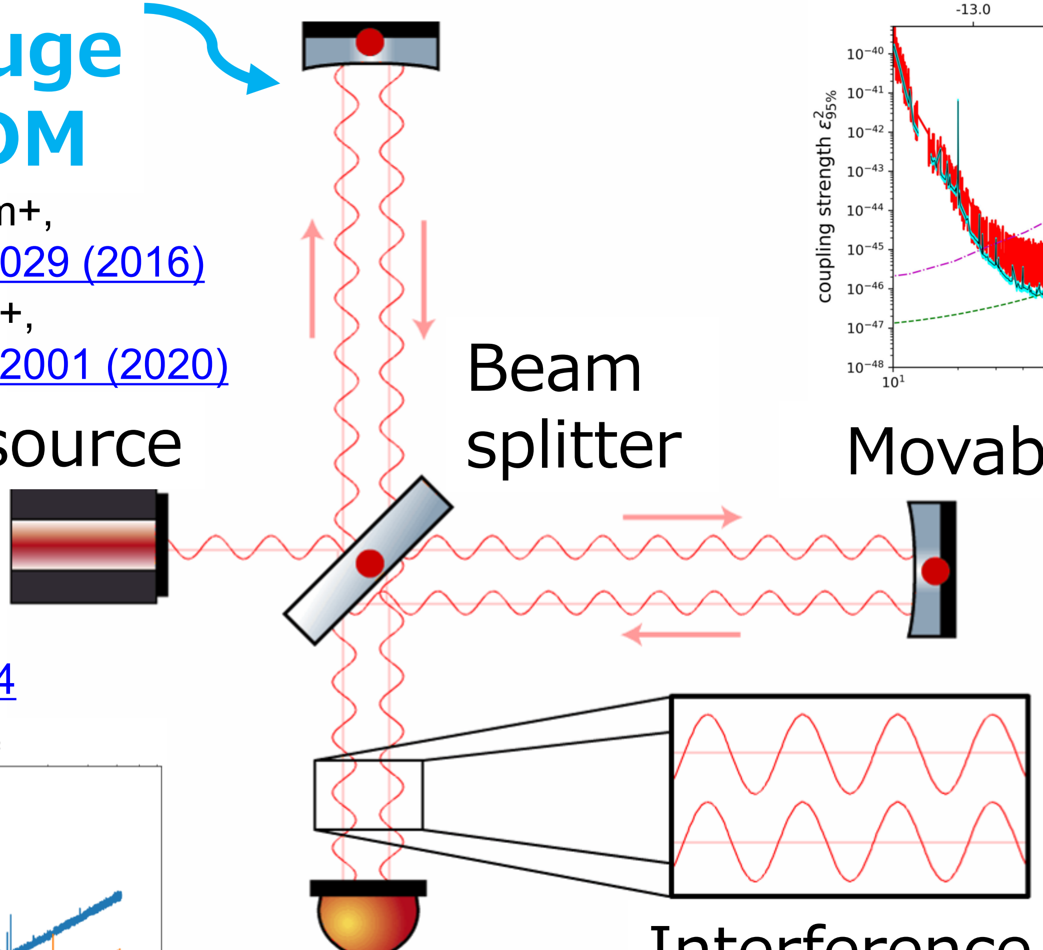
Gauge Boson (Vector) Dark Matter

LVK, PRD 105, 063030 (2022)
Erratum: PRD 109, 089902 (2024)

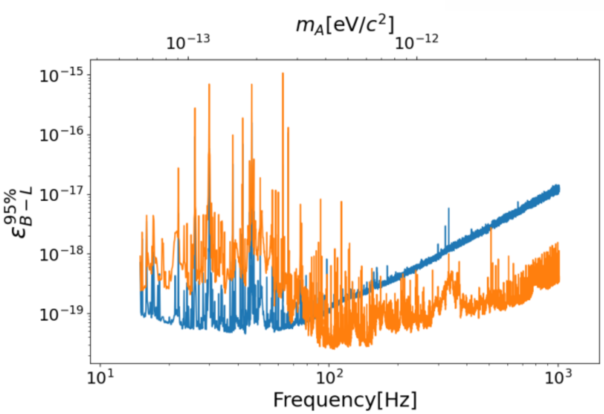


Tiny forces from gauge boson DM

P. W. Graham+,
PRD **93**, 075029 (2016)
Y. Michimura+,
PRD **102**, 102001 (2020)



LVK, arXiv:2403.03004

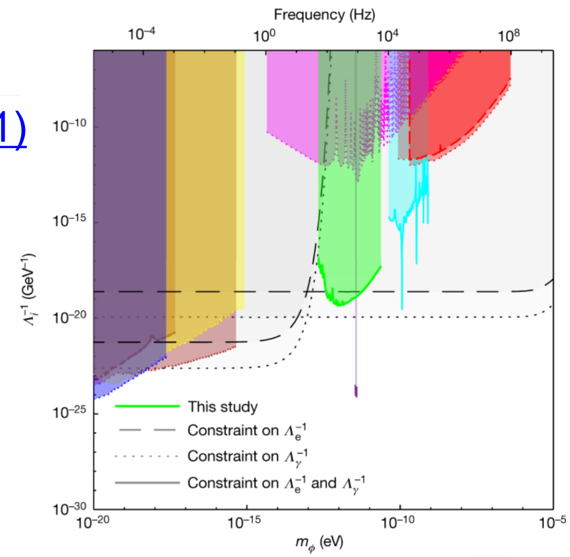


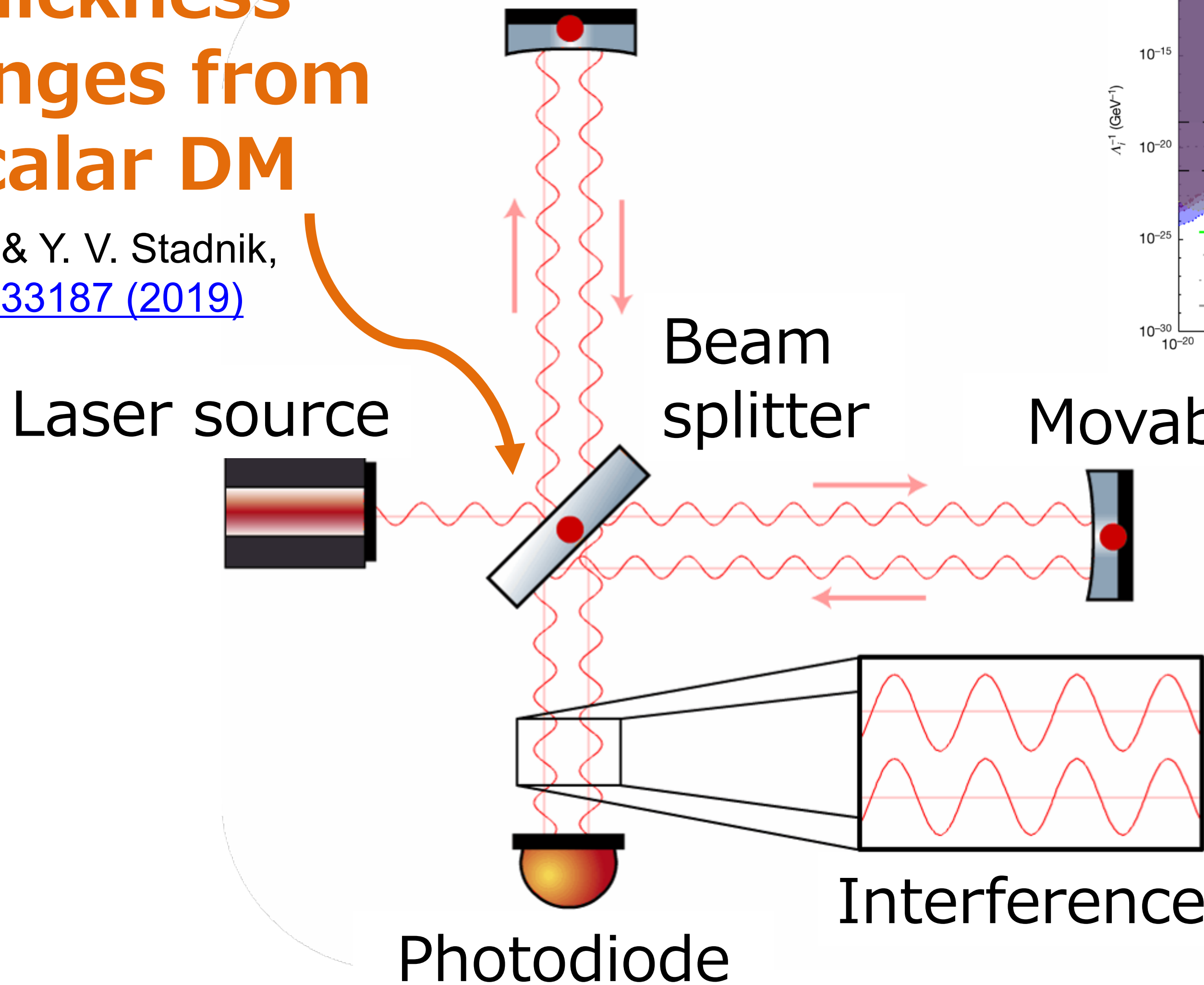
Scalar Boson Dark Matter

Mirror thickness changes from scalar DM

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

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



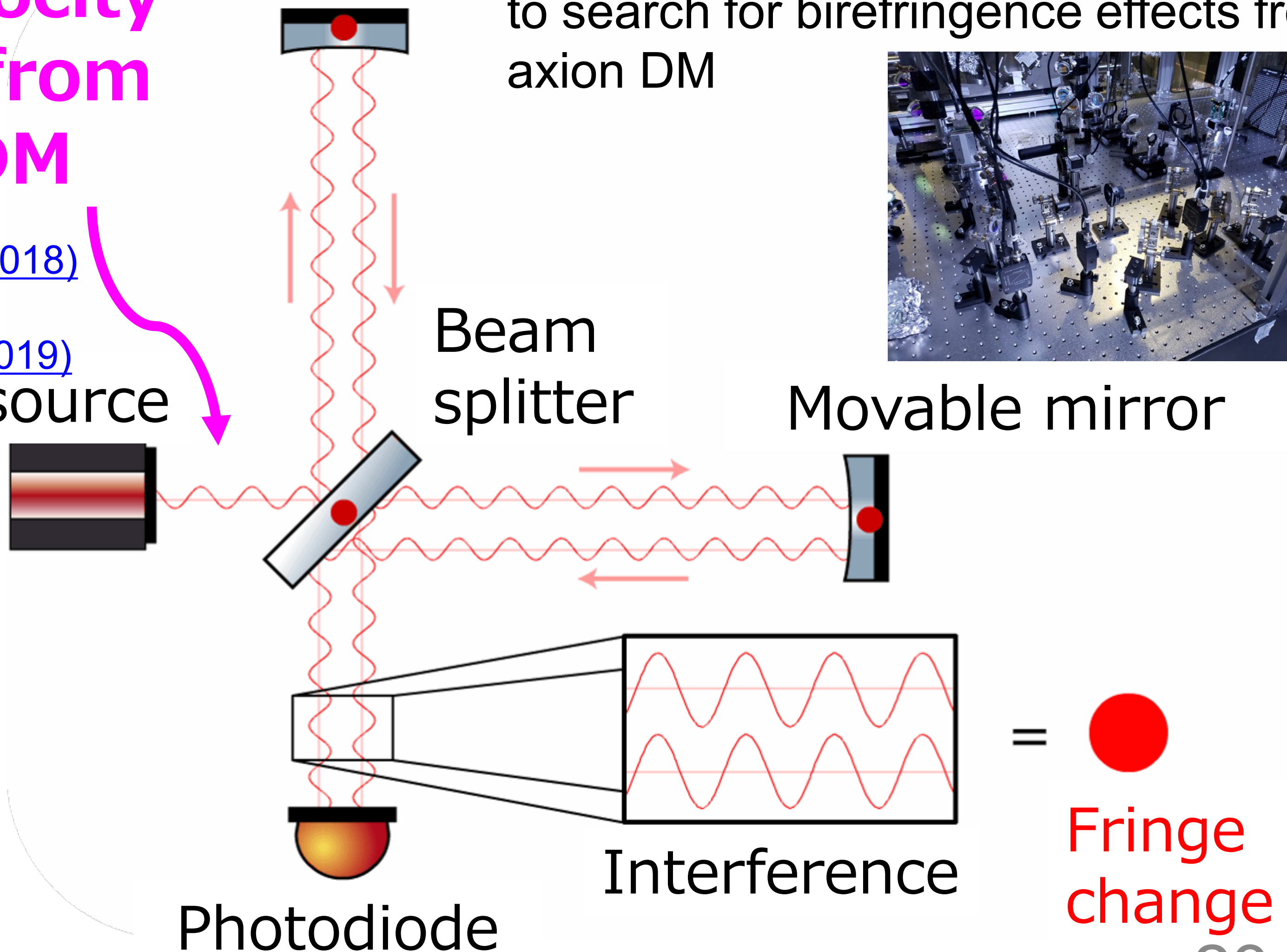


Axion-like Dark Matter

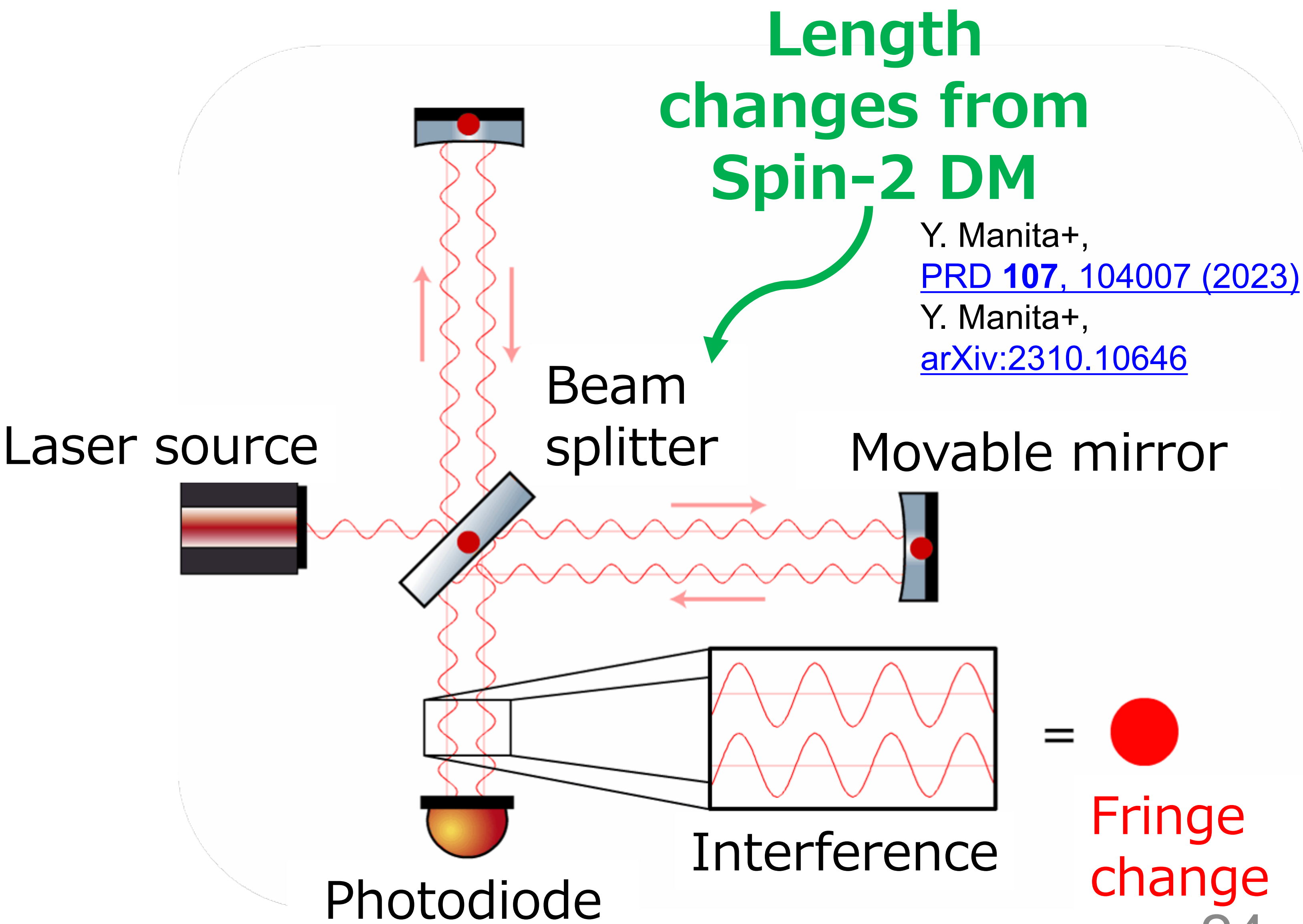
Photon phase velocity changes from axion DM

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

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



Spin-2 Dark Matter

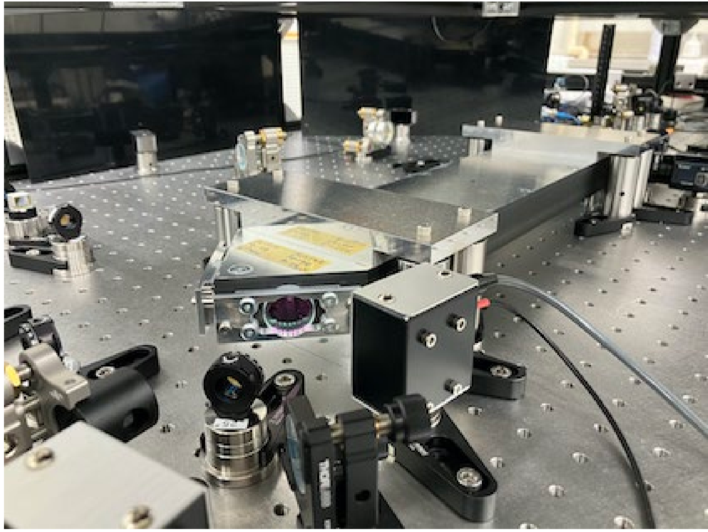


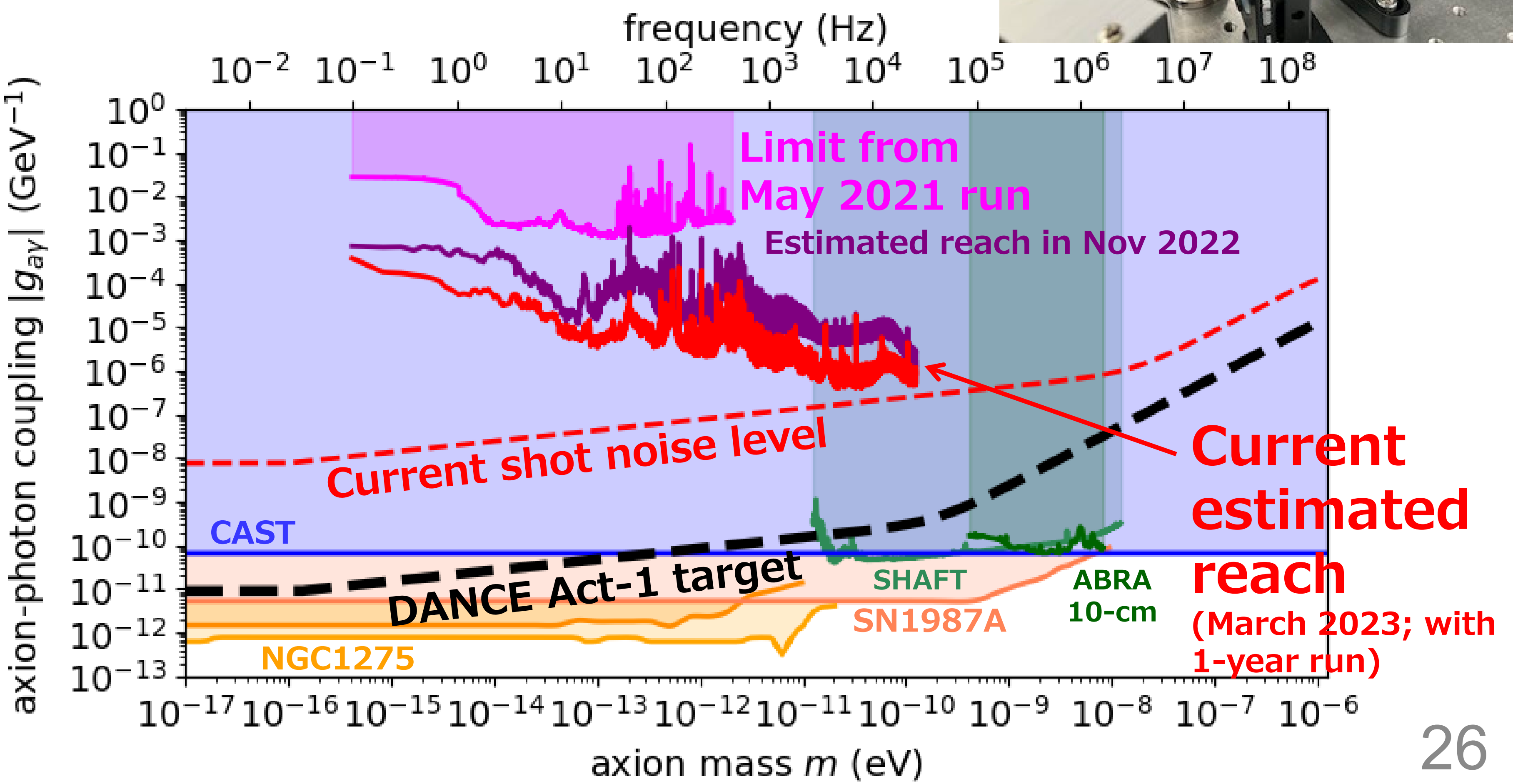
Y. Manita+, PRD **107**, 104007 (2023)
Y. Manita+, arXiv:2310.10646

Why You Should Join

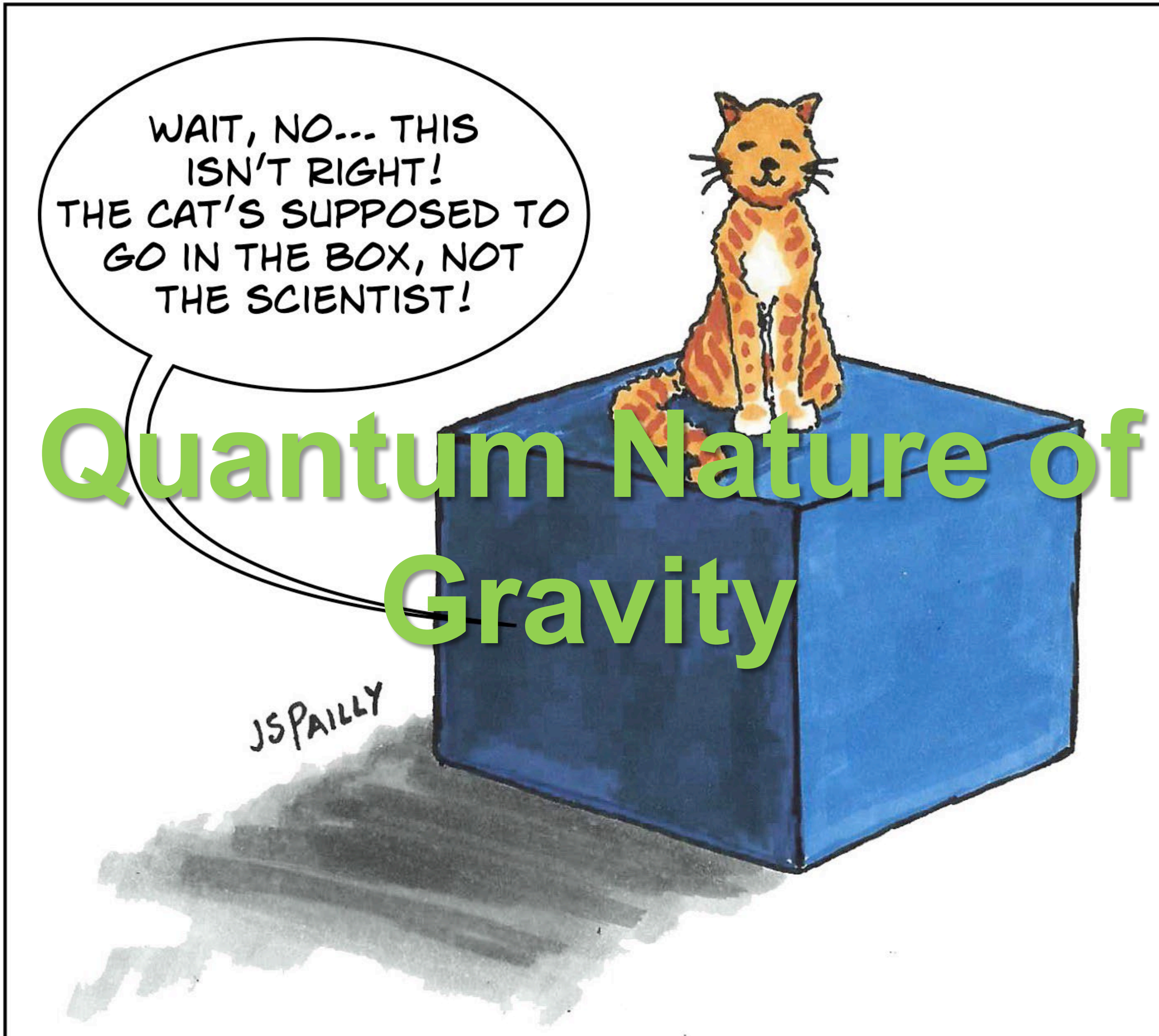
- Unique vector dark matter search using sapphire mirrors of KAGRA
- Polarization optics were installed to KAGRA, and we will be collecting the first axion DM data from gravitational-wave detectors within FY2024
- New searches for spin-2 DM, searches with high frequency data etc.
- Further optimization 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



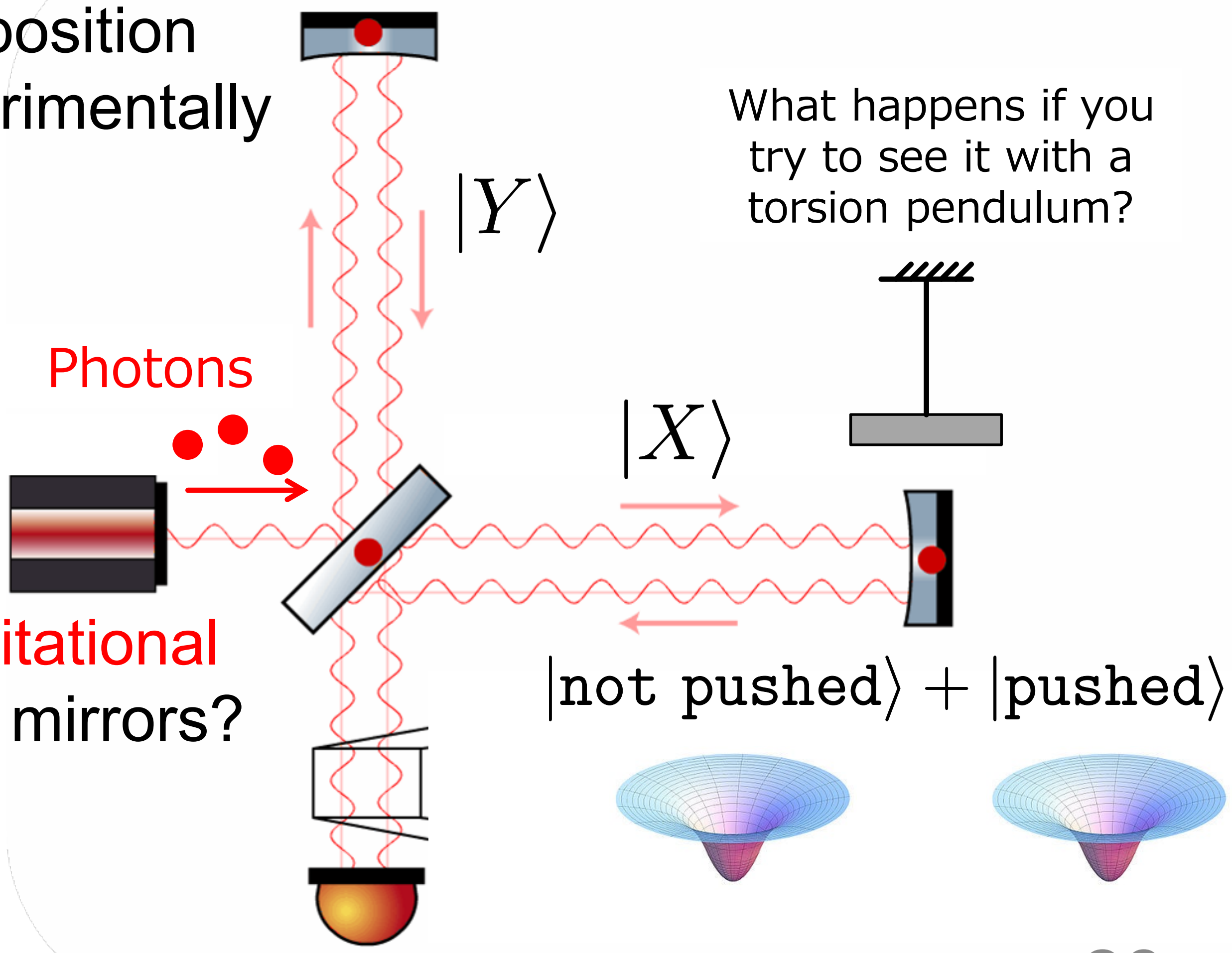


Quantum Nature of Gravity



Interferometers to Test Quantum

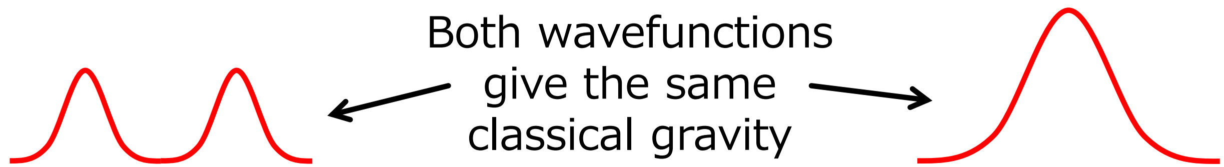
- Photon going to X arm or Y arm is in quantum superposition
- Mirrors pushed or not pushed by radiation pressure is in quantum superposition (this is not experimentally verified yet)



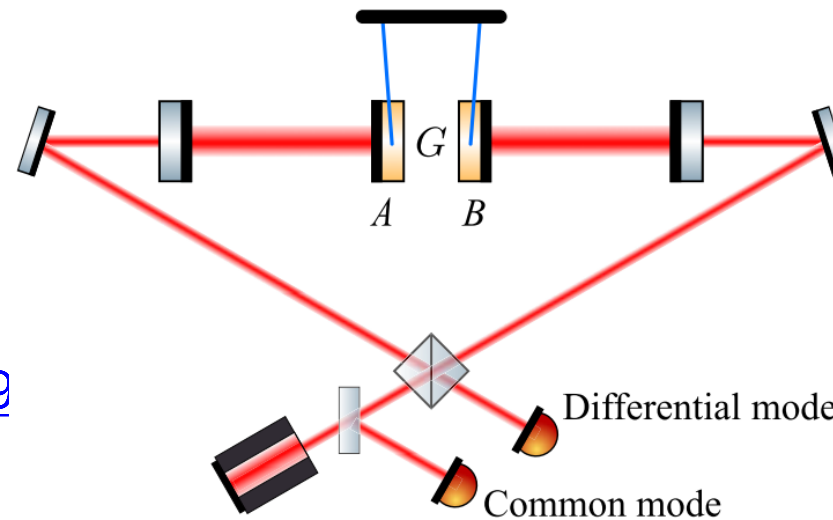
- How about gravitational field of massive mirrors?

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

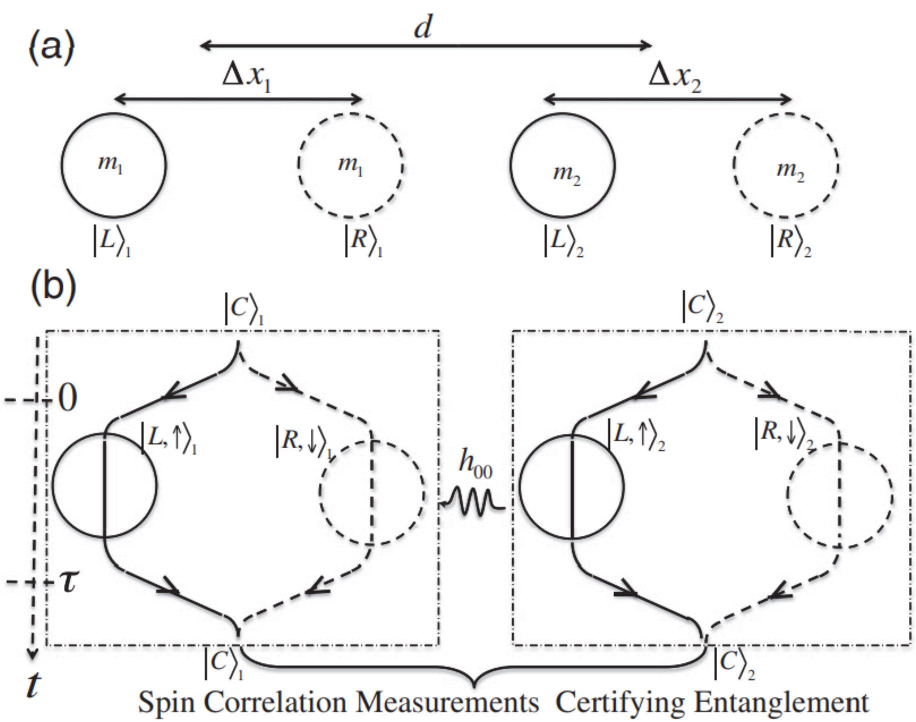


- For review, see
  D. Carney+, [CQG **36**, 034001 (2019]
- Also, see
  H. Miao+, [PRA **101**, 063804 (2020)]
  A. Datta & H. Miao, [Quantum Science and Technology 6, 045014 (2021)]

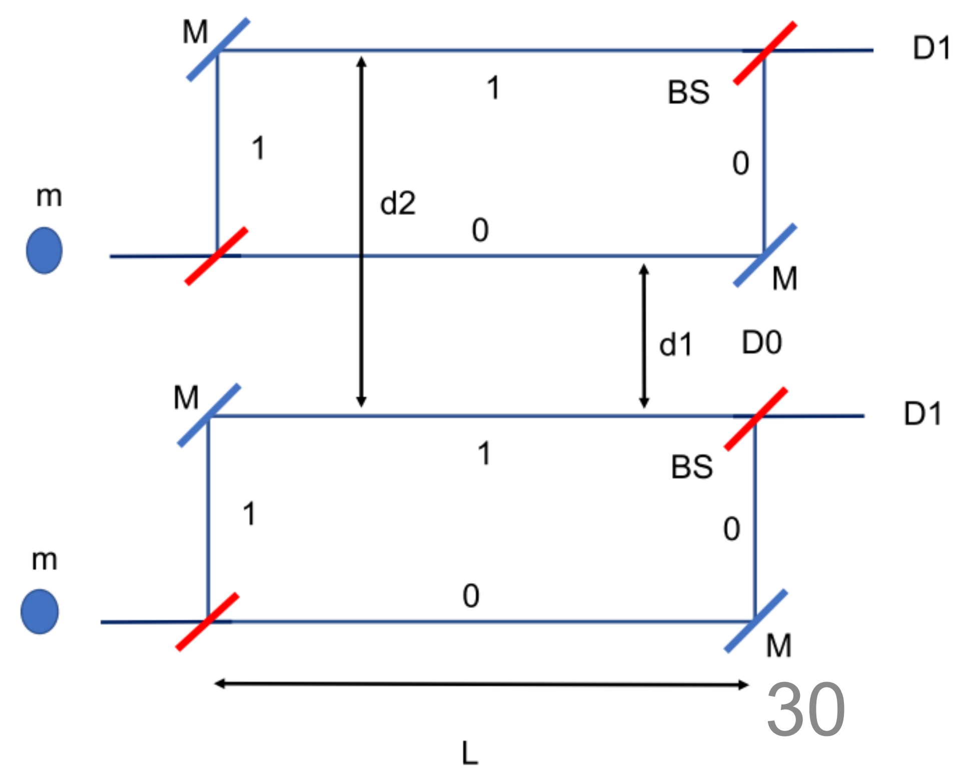
BMV Proposal

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

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

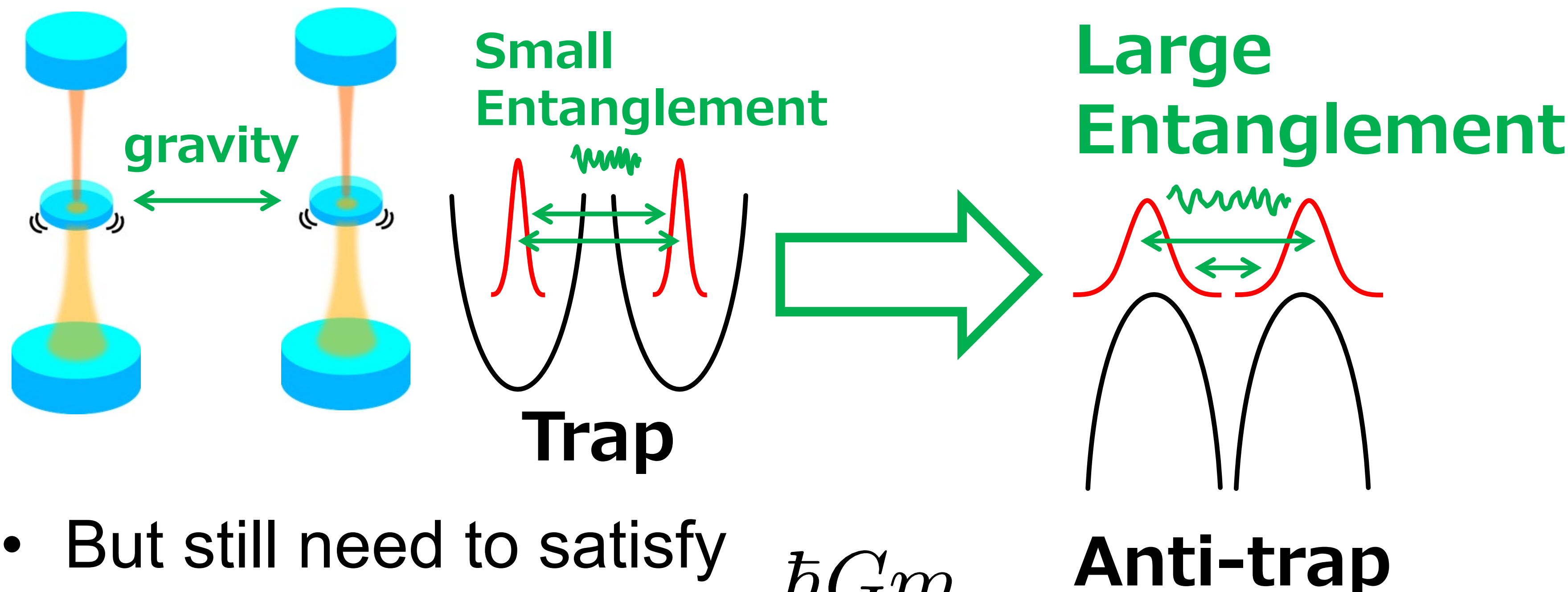


C. Marletto & V. Vedral,
[Phys. Rev. Lett. 119, 240402 (2017)]



Inverted Oscillator Proposal

- Inverted oscillators create gravity-induced entanglement exponentially
  - T. Fujita, Y. Kaku, A. Matsumura, YM, arXiv:2308.14552
  - With optically levitated mirrors proposed in YM+, Optics Express 25, 13799 (2017), we can repeat the measurements without free-fall



- But still need to satisfy

$$\gamma k_{\mathrm{B}} T < \frac{\hbar G m}{d^3}$$

Damping rate (Decoherence) → γ

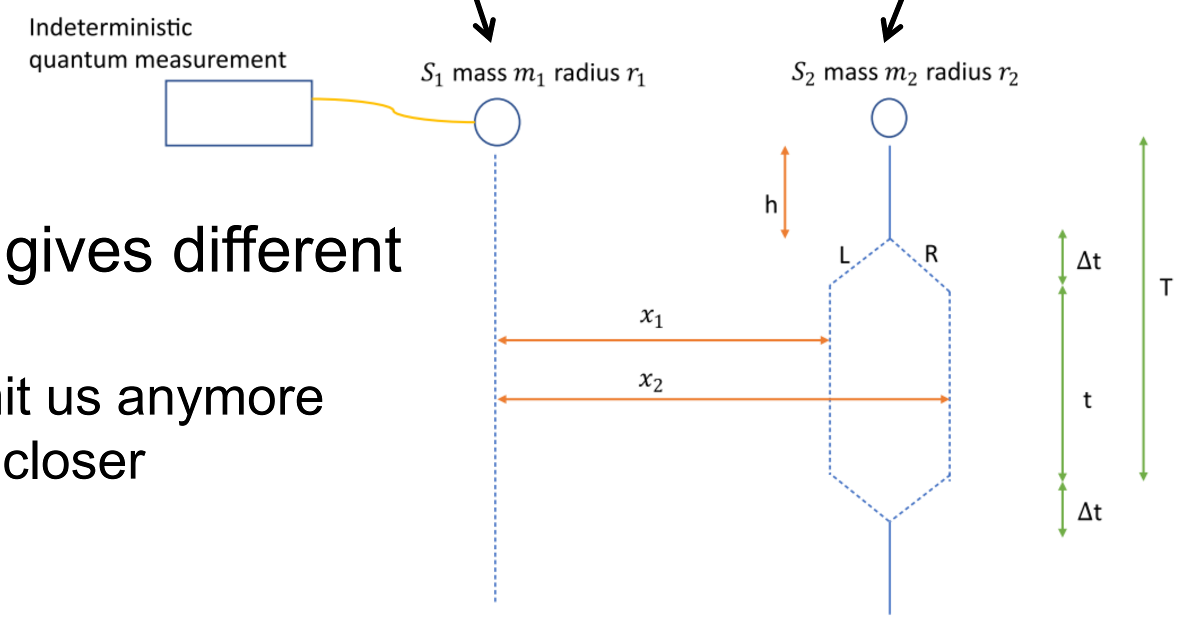
Distance → d

Test Near Measurement Event

A. Kent,
PRD **103**, 064038 (2021)

Hold or Release

Left or Right



QG and Semiclassical gives different result even S1 is held

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

	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	$\|\psi(t)\rangle \approx \frac{1}{\sqrt{2}}\exp(i\phi_L t/2)(\|L\rangle + \exp(i(\phi_R - \phi_L)t/2)\|R\rangle)$	

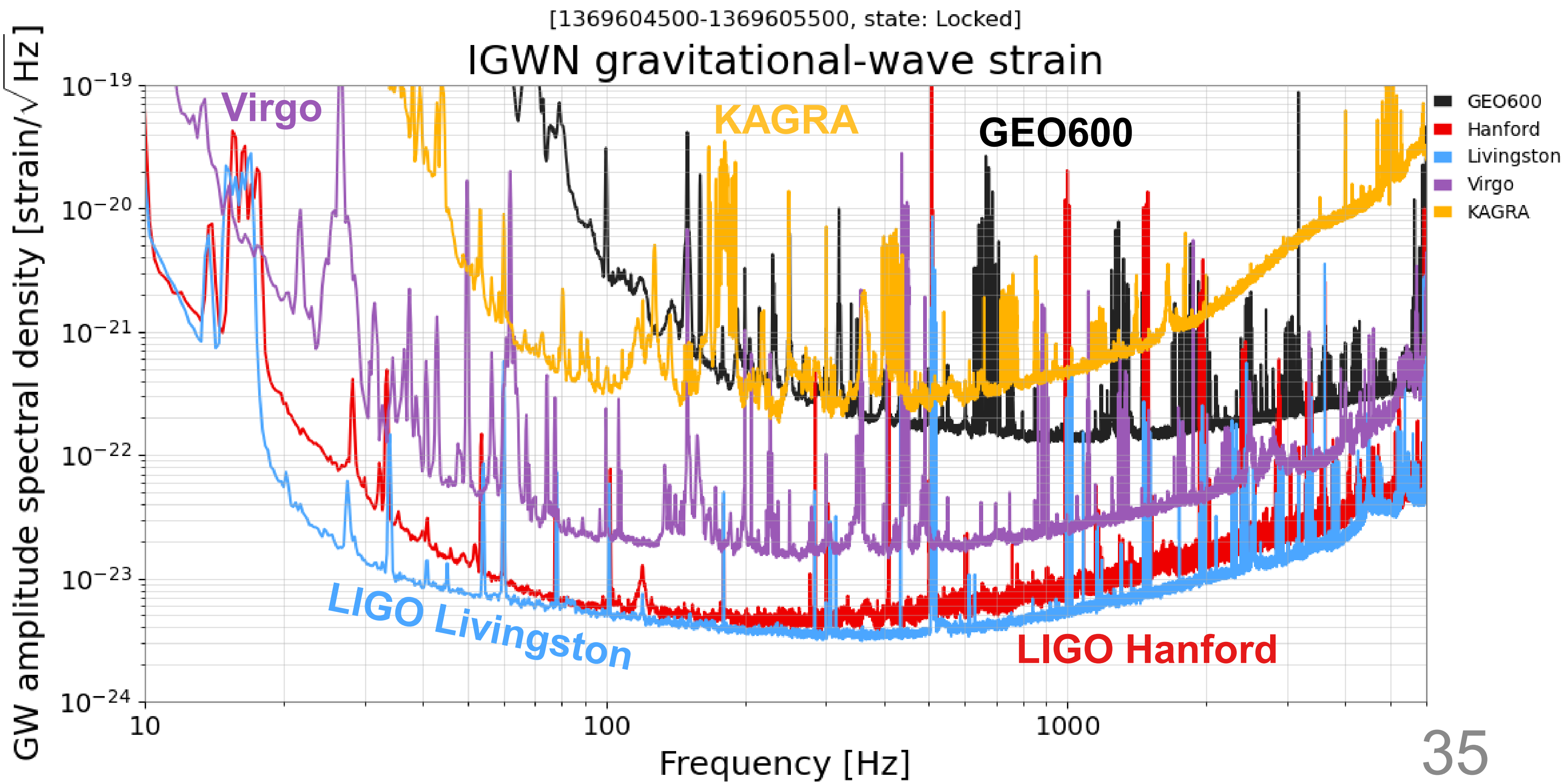
Why You Should Join

- 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)

Data Cleaning

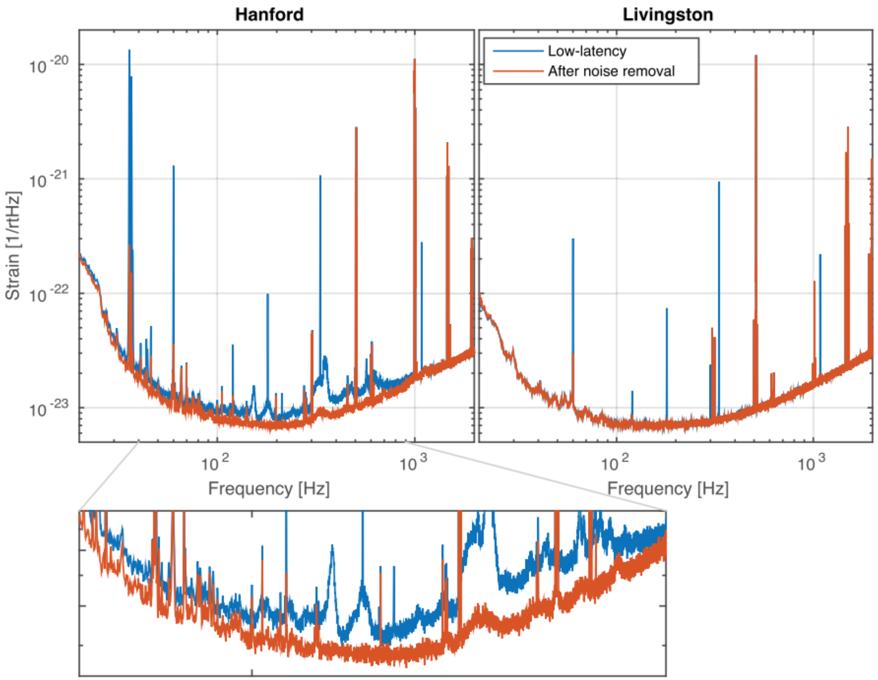
Data is not Clean

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



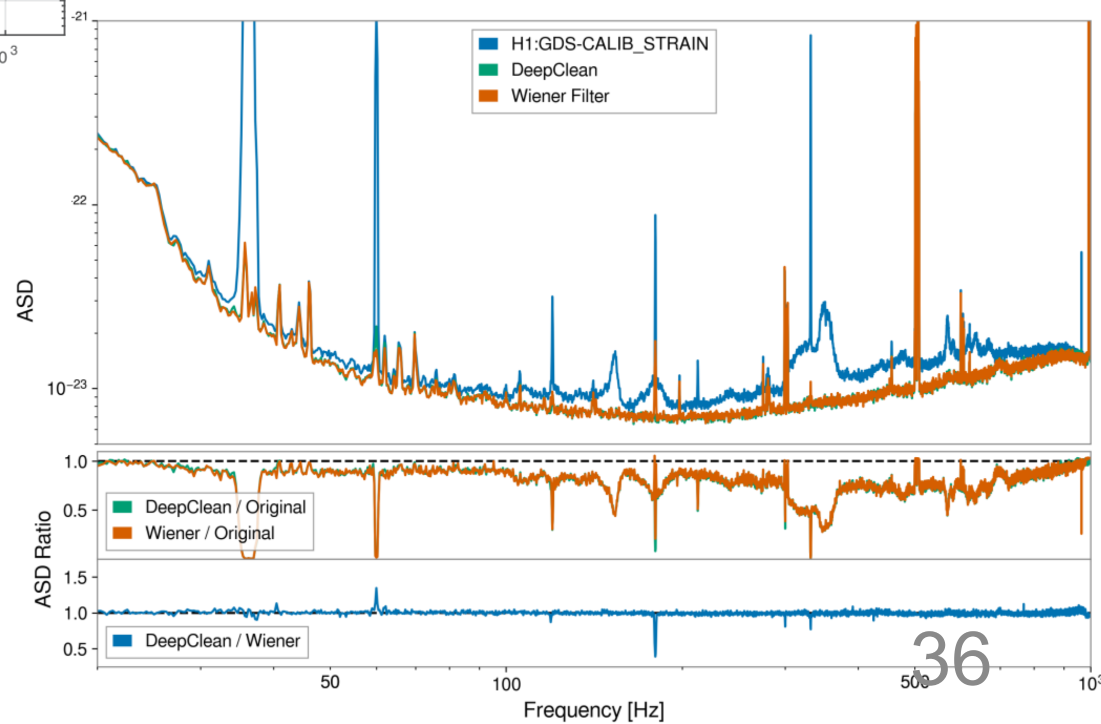
Wiener Filtering and Deep Learning

- Both works nicely for LIGO (especially Hanford)



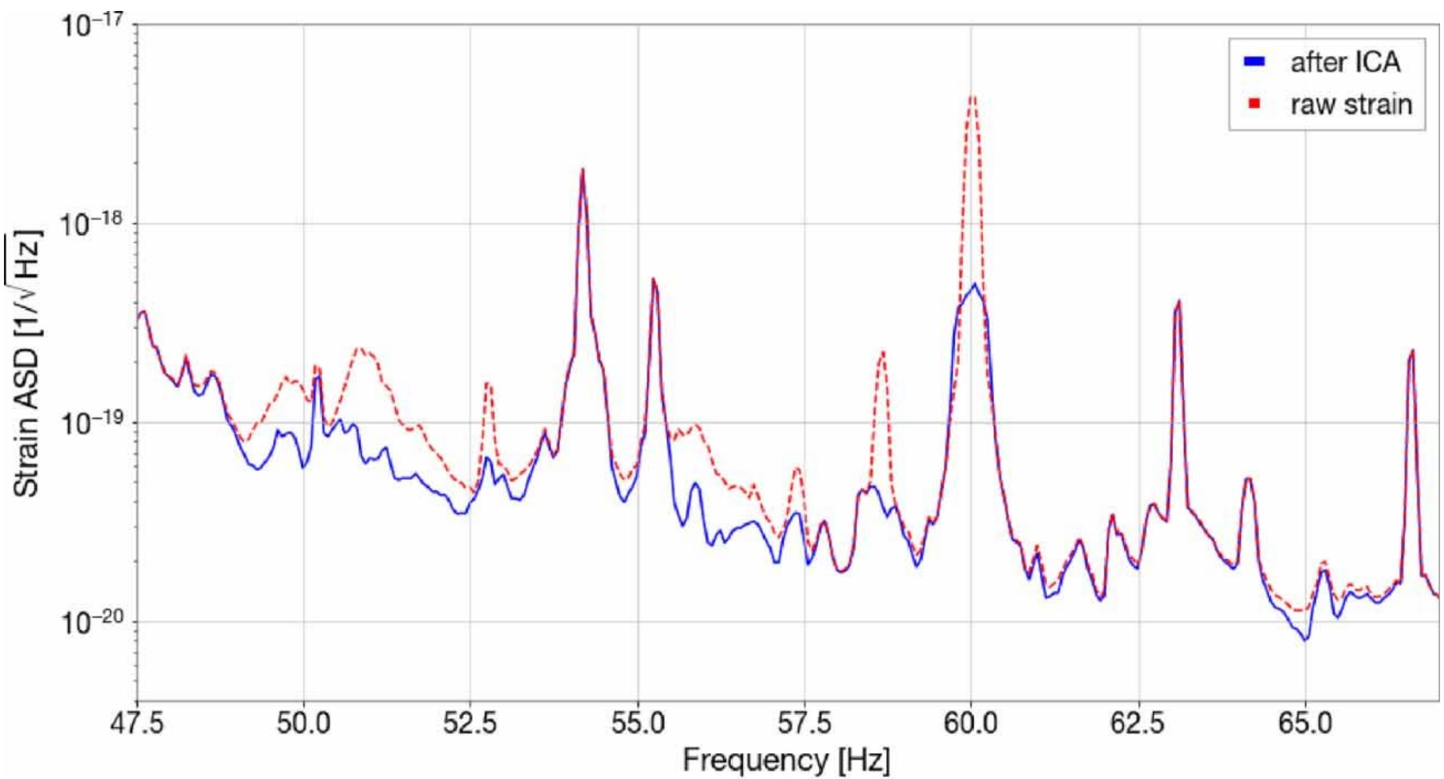
Beam jitter noise subtraction with Wiener Filtering
J. C. Driggers+,
[PRD **99**, 042001 (2019)]

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



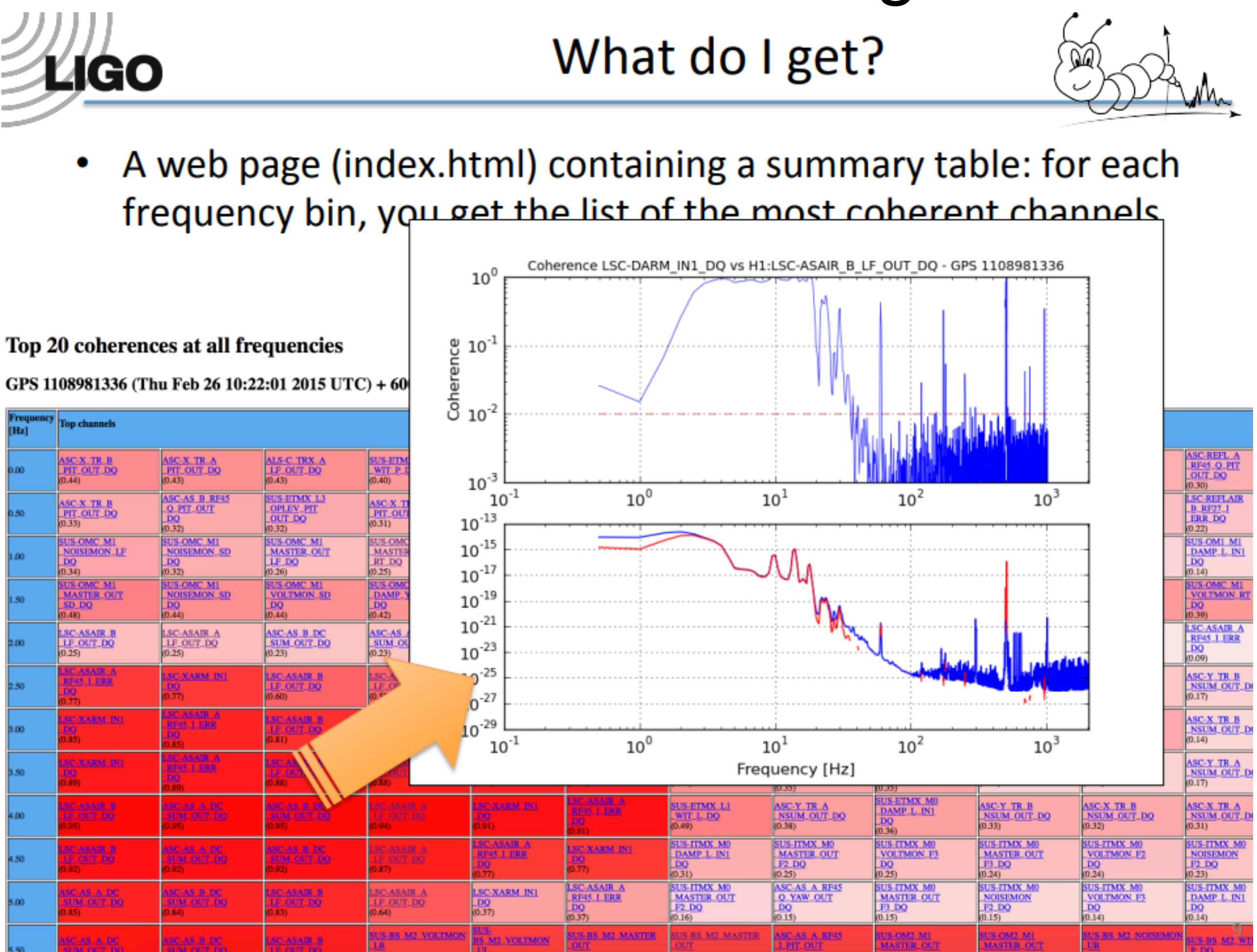
Independent Component Analysis

- 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



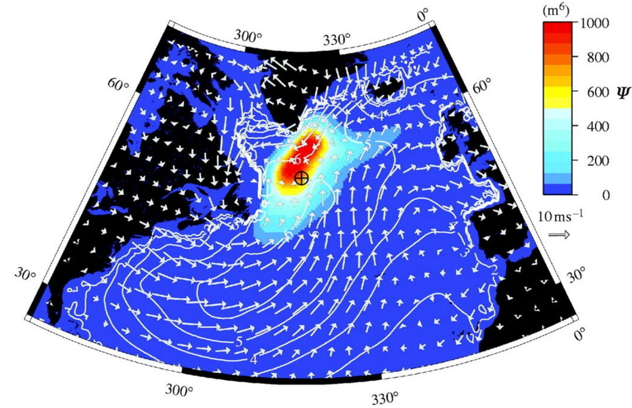
Which Witness Data to Use?

- BruCo: Brute force coherence
  https://github.com/gw-pem/bruco
- Automated noise budget? Non-linear?



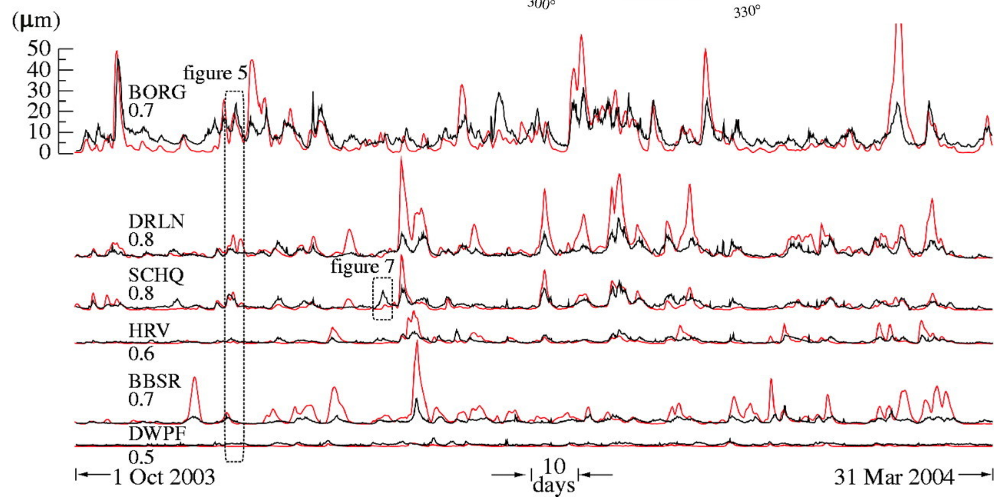
G. Vajente
LIGO-G1500230

Seismic Disturbances



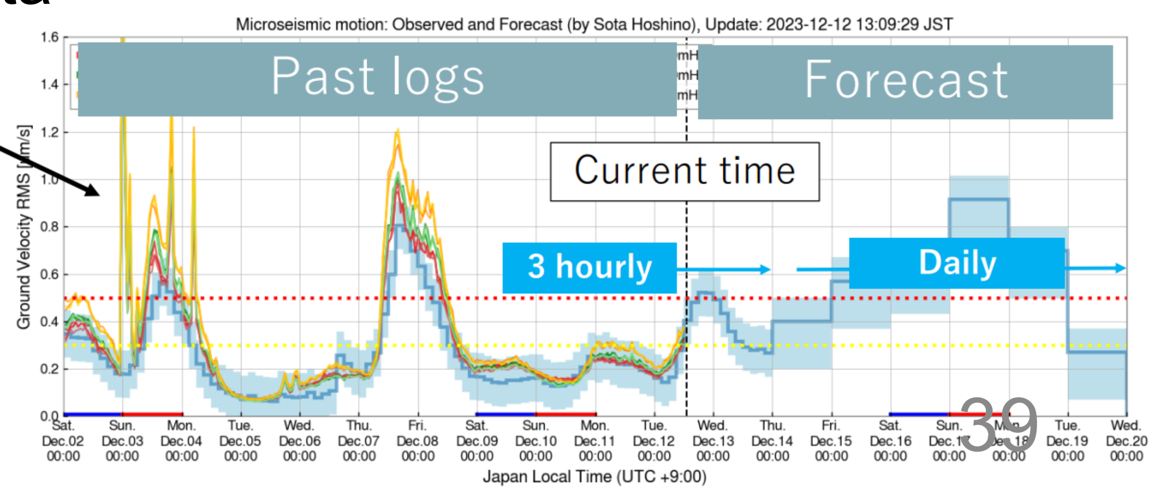
- Microseism at Livingston is affected by weather in Greenland

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



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

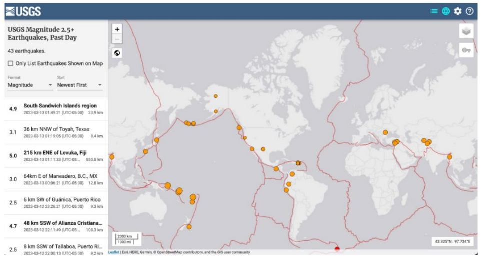
Earthquake



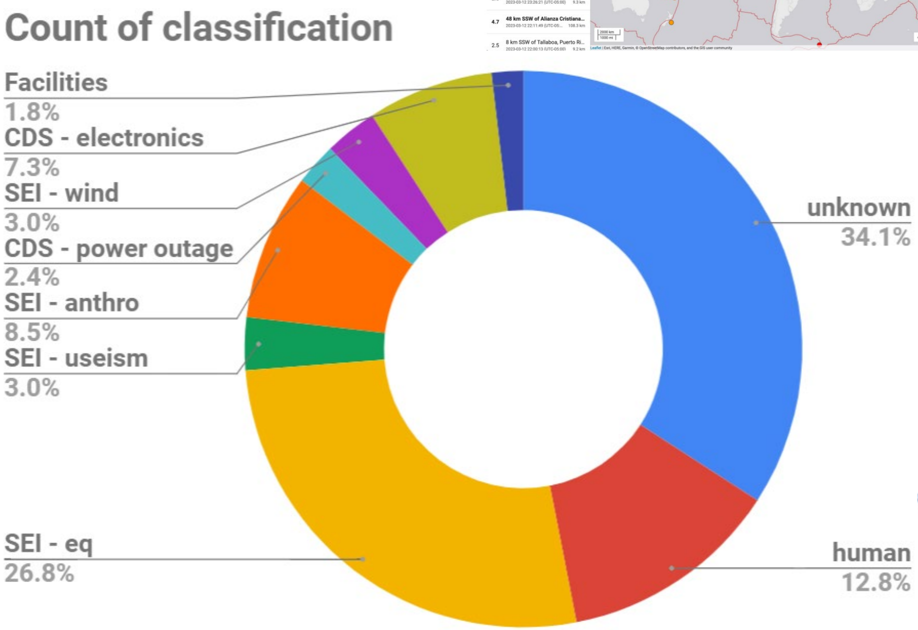
Principal Component Analysis
S. Hoshino+,
[arXiv:2306.12437]
[JGW-G2315480]

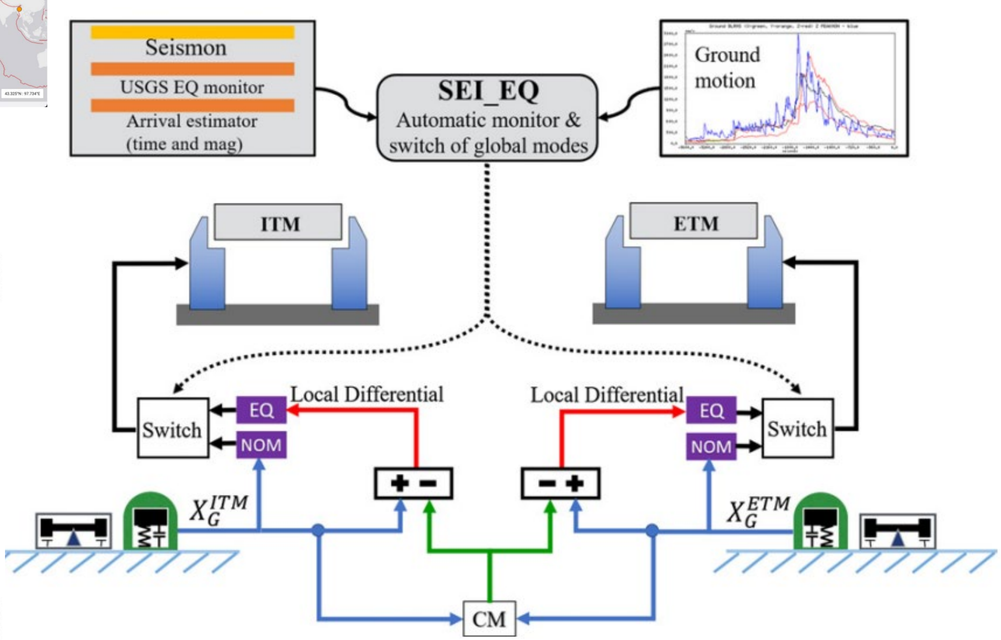
Protection from Seismic

- 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)]()

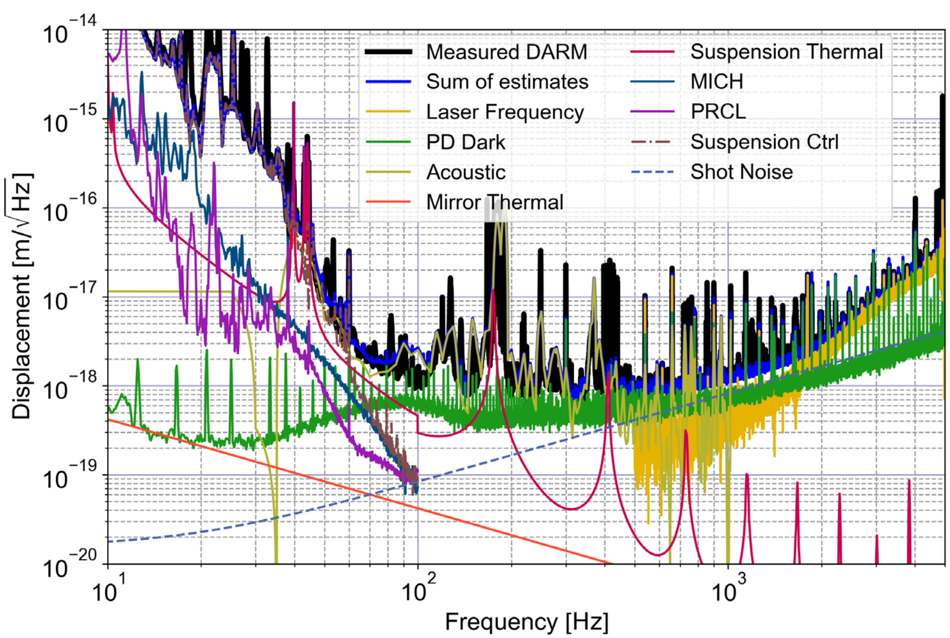


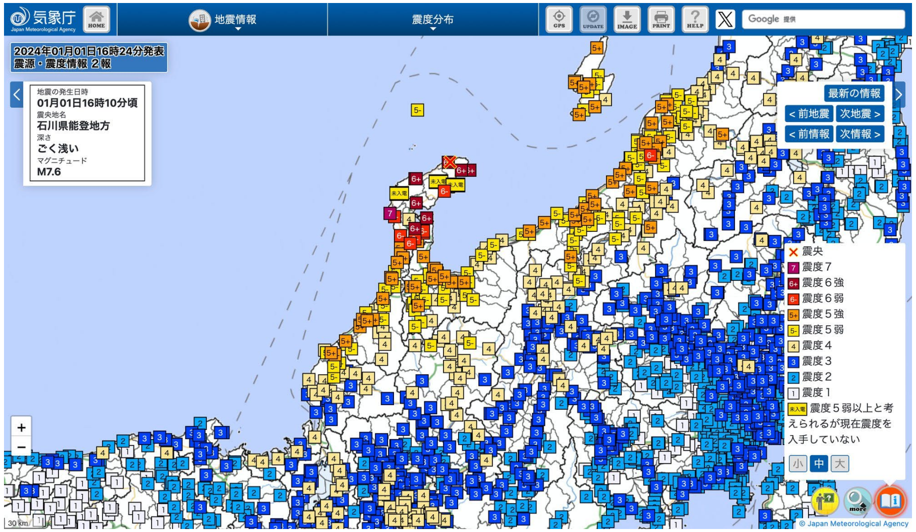


- Useful to improve duty factor

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

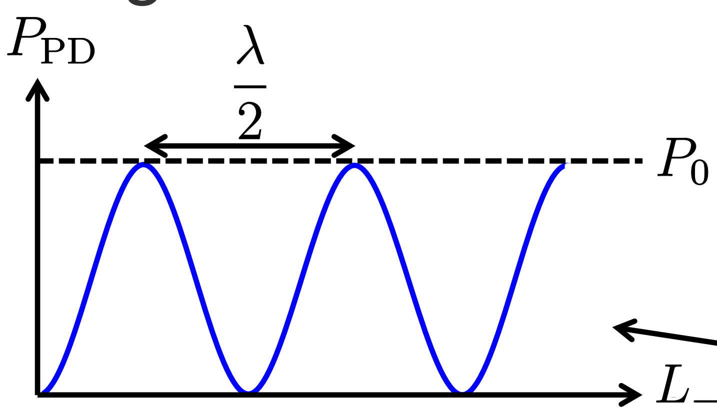


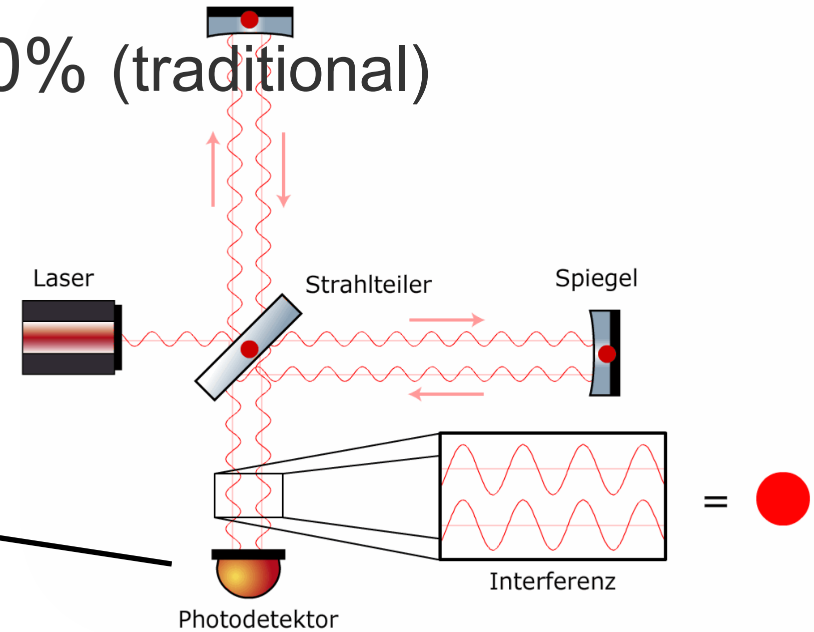


Upgrading Calibration

Brief History of Calibration

- Calibration is crucial for parameter estimation
  - luminosity distance, polarization, localization, NS tidal deformability …
- Michelson Free-swing: ~10% (traditional)
  - 1 fringe = λ/2



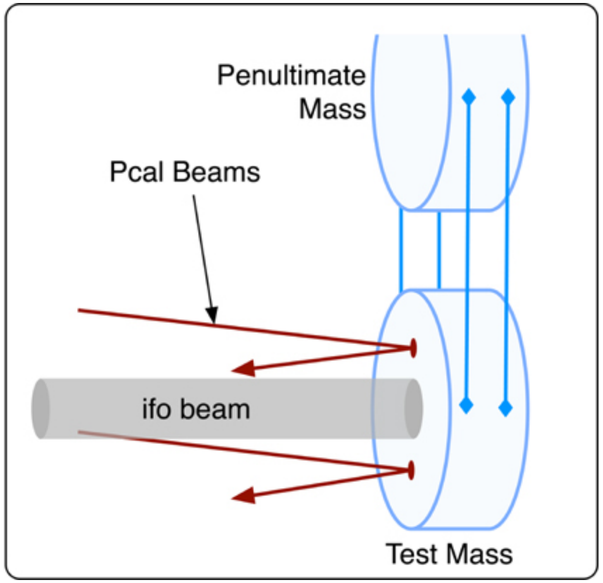


- Photon Calibrator(PCal): 2-5%, 2-5 deg (current)
- Newtonian Calibrator(NCal): 3-5%? (R&D at sites)
- Multicolor Calibrator(SoCal): 0.05-0.4%? (R&D at 40m)
- What's next?

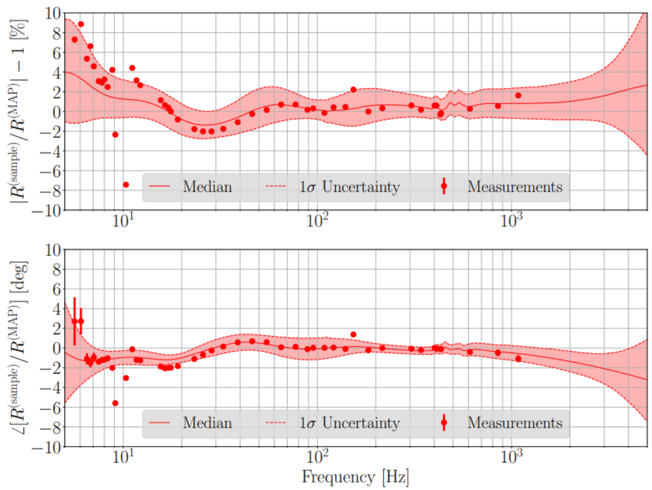
Photon Calibrator (Pcal)

- Shake mirror by radiation pressure from "known" amount of light (current standard)

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

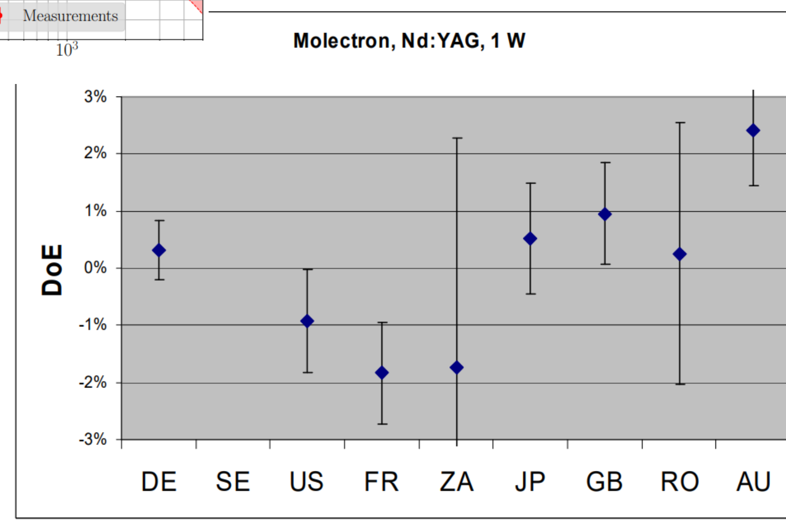


S. Karki+, RSI 87, 114503 (2016)



L. Sun+, CQG **37**, 225008 (2020)

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

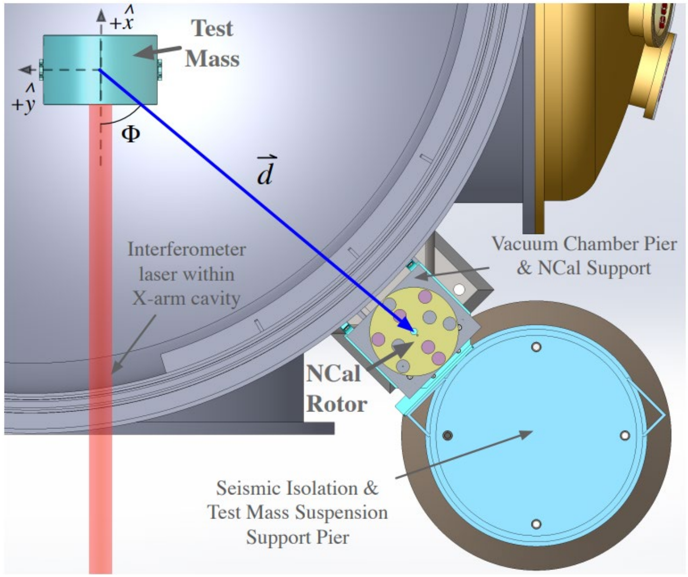


Stefan Kück, Metrologia **47**, 02003 (2010)

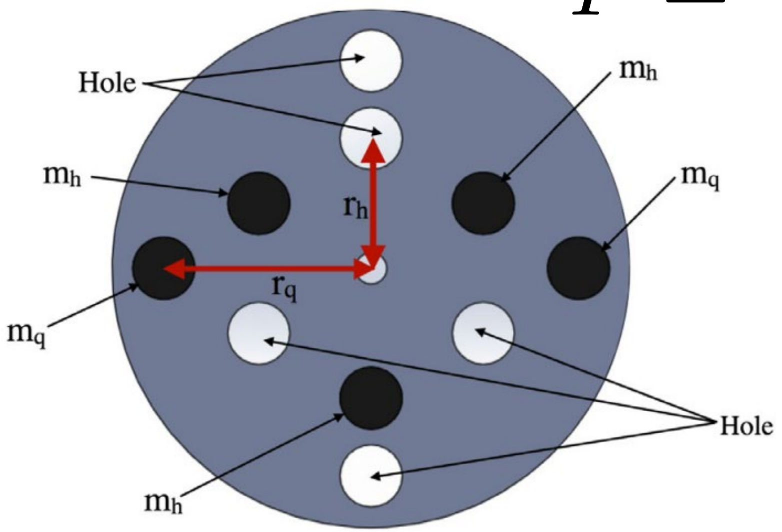
Newtonian Calibrator (NCal or GCal)

- Shake mirror by “known” amount of gravity

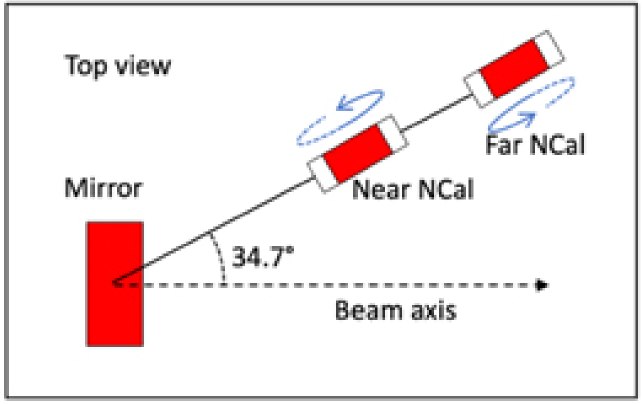
$$F = \frac{GmM}{r^2}$$



LIGO: ~5% below ~30 Hz
M. P. Ross+, arXiv:2107.00141



KAGRA: 0.17% (proposal to combine Pcal and GCal)
Y. Inoue+, PRD **98**, 022005 (2018)



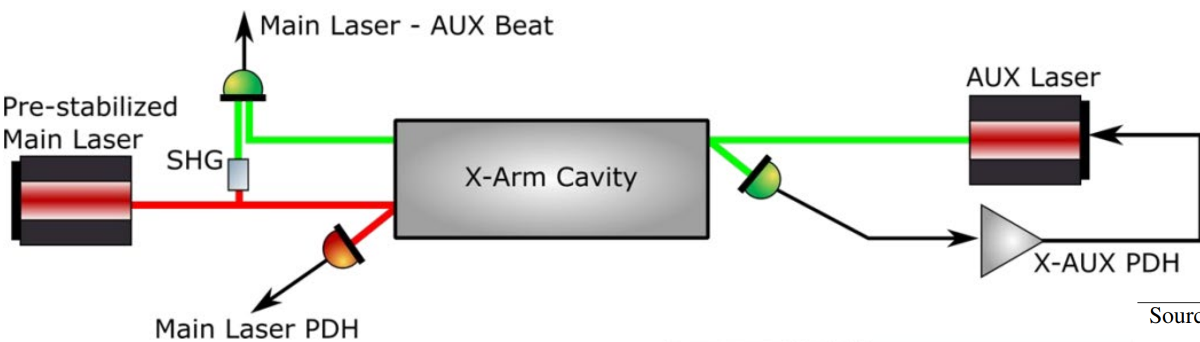
Virgo: ~3% below 120 Hz
D. Estevez+, CQG **38**, 075012 (2021)

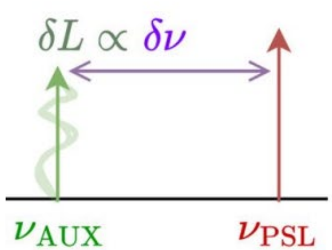
Multi-color Calibrator (McCal)

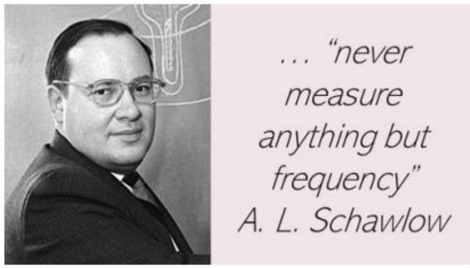
- Based on frequency metrology
  (which is know to be precise)

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

Second Oscillator Calibrator







Statistical uncertainty limited (at 40m prototype)

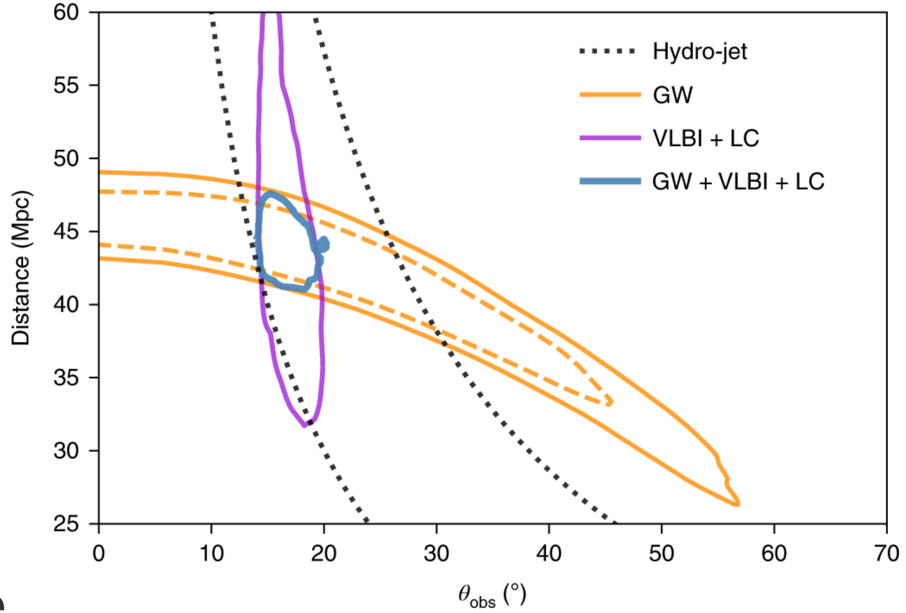
Source	Symbol in Eq. 9.9	Estimated effect on calibration [ppm]				
		33.921 Hz	211.110 Hz	313.31 Hz	575.17 Hz	1418.93 Hz
Laser WaveLength	λ_{main}	100	100	100	100	100
CARM OLTF Drift	H_{OL}	0.071	135.5	0.044	0.051	0.022
AUX OLTF Drift	G_{OL}	12.3	14.9	65.1	224	1043
Beatnote Measurement	$\delta\nu_{beat,i}$	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

Francisco Salces-Carcoba, LIGO-G2302068

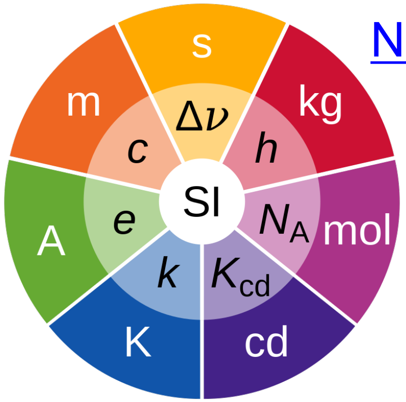
Anchal Gupta, Caltech Thesis (2023)

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 H0, 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

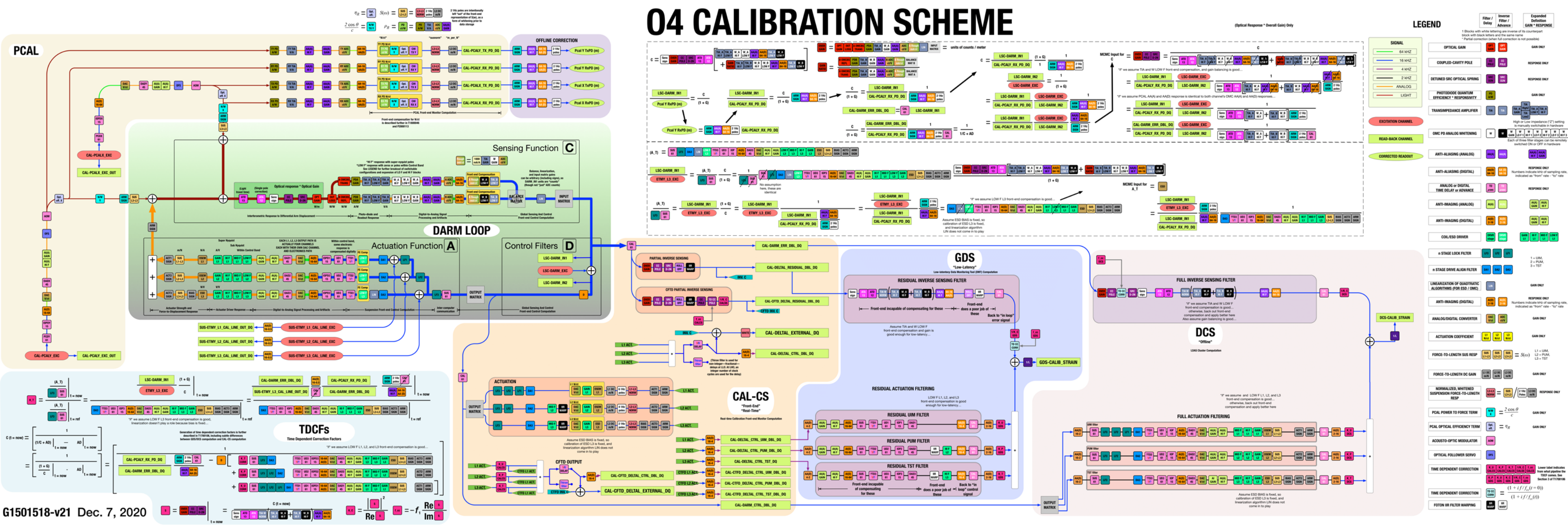


K. Hotokezaka+, [Nature Astronomy **3**, 940 (2019)]



… but it is a lot of work

LIGO O4 Calibration Subway Map



LIGO-G1501518

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)