Ph. D. defense
博士論文審査会

A Study of Baseline Compensation System for Stable Operation of Gravitational-wave Telescopes

(重力波望遠鏡の安定稼働のための基線長補償システムの研究)

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“A Study of Baseline Compensation System for Stable Operation of Gravitational-wave Telescopes”

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- Gravitational-wave (GW) and GW detector
- Problematic seismic motion for stable operation

2. Geophysics Interferometer

- Overview
- Comparison with seismometer

3. Baseline Compensation System

- Concept
- Control design

4. Demonstration and Results

- Setup for demonstration
- Result and discussion

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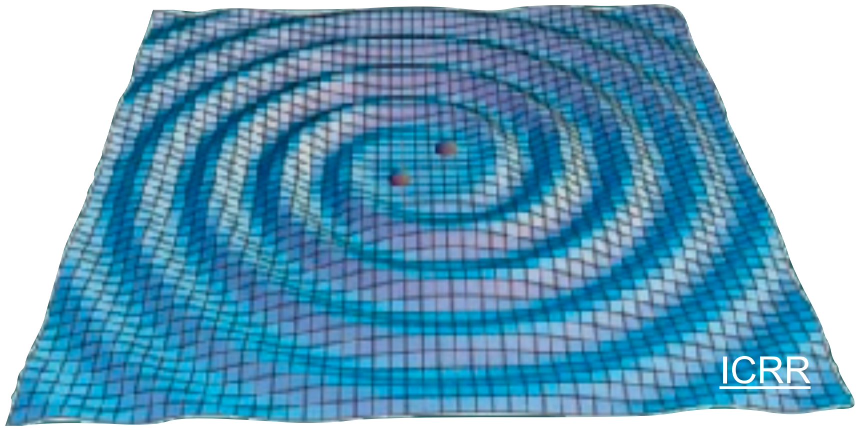
Gravitational-wave (GW)

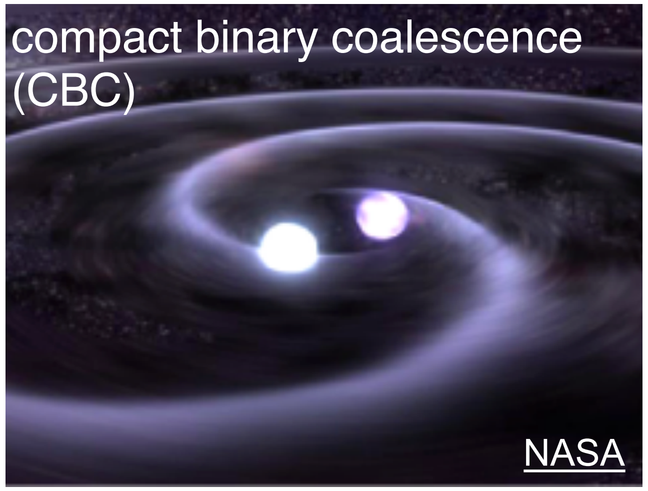


GW is a ripple of the space-time

- Generated by compact and massive objects
- In 2015, First GW detection from BBH
- More 40 events have been observed from CBC.

GW sources

- Binary black hole (BBH) merger
- Binary neutron star (BNS) merger
- Supernovae explosion

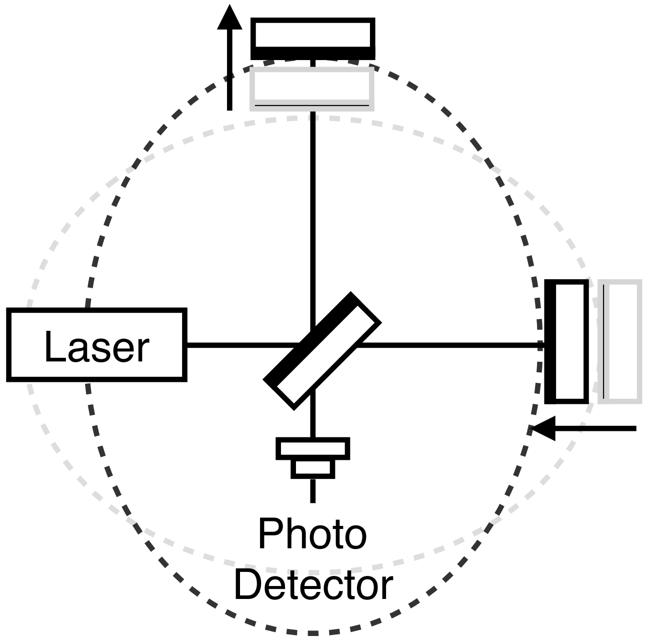


GW has fruitful informations for physics and astrophysics.

- Testing the general relativity in strong-field
- Nuclear equation of state in compact object
- A new observation tool for the astrophysical phenomena

GW observations bring new informations of the universe to us.

GW Detector



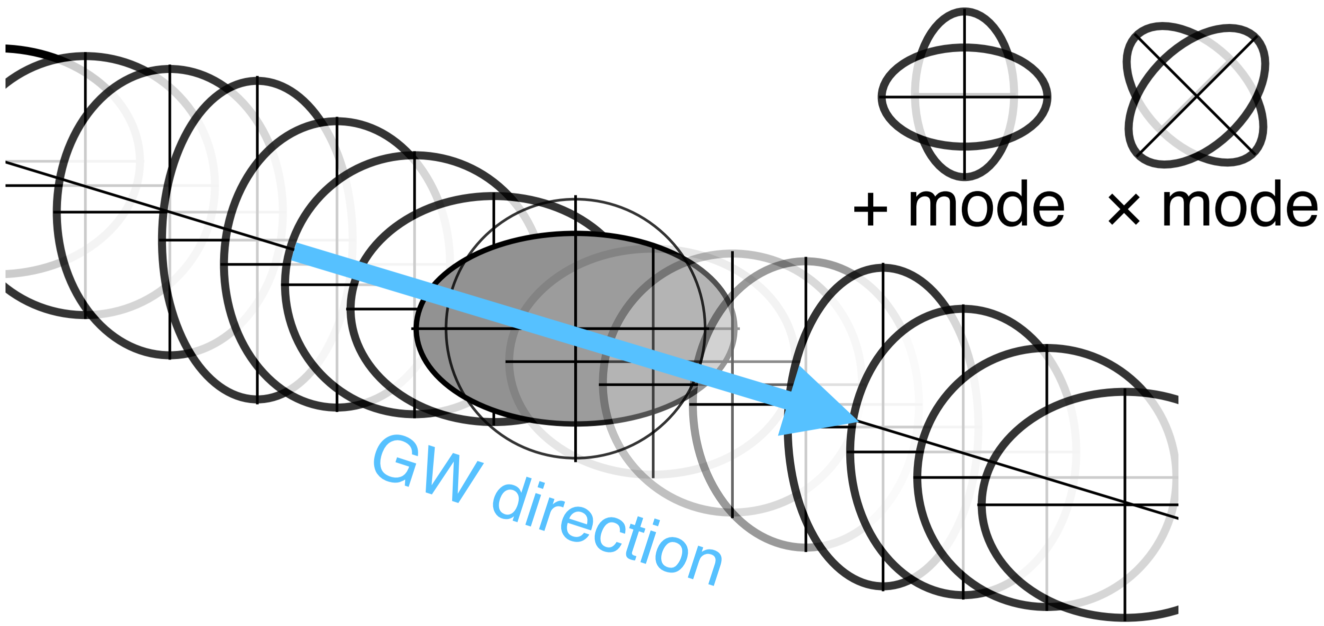
Michelson interferometer

Michelson interferometer

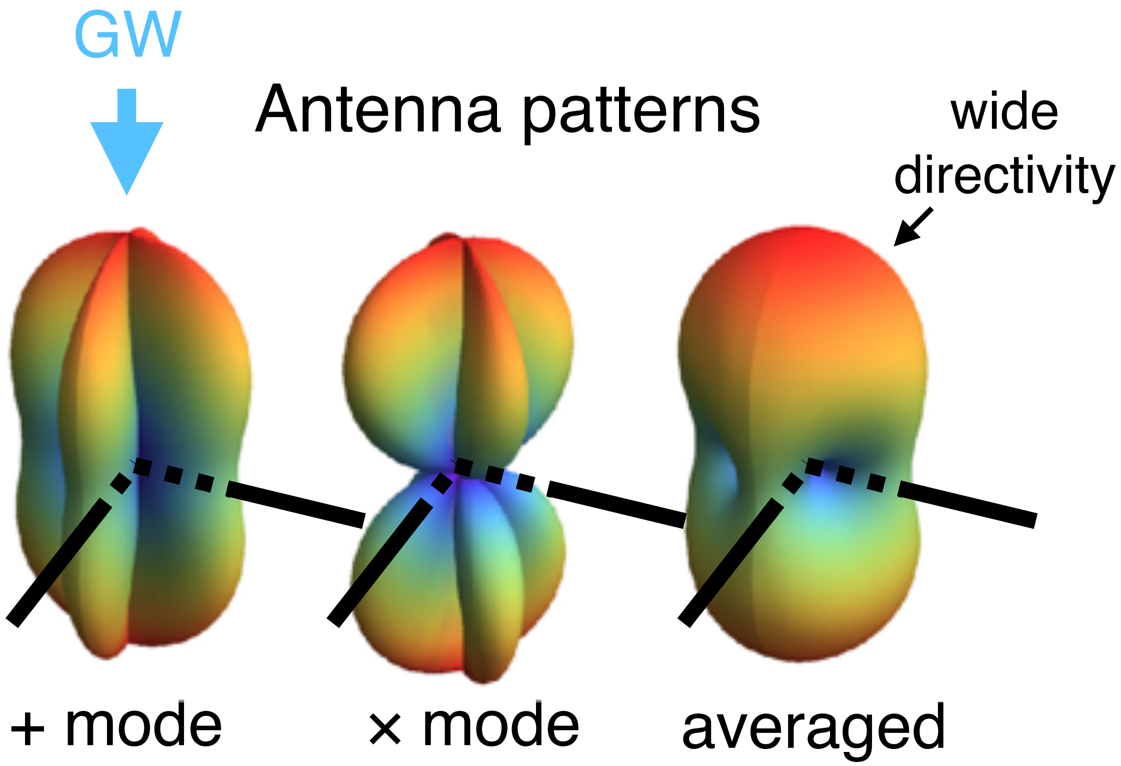
- Sensitive to differential arm length changes deformed by GW
- Sensitive to both ‘+’ and ‘×’ modes
- A wide antenna pattern

GW propagation

Polarizations



Antenna patterns



To determine the direction of GW sources, we need multiple detectors.

GW Detectors

Network Duty Cycle
$\fallingdotseq D_1 \times D_2 \times D_3 \times D_4$

(D_i : duty cycle of the i-th detector)

Multiple detection is needed

- To determine the direction of GW sources
- At least 3 detections are needed

We have to improve the each duty cycle

- Network duty cycle is 50 - 60 %
- Lost of the direction
- Lost of “Near-Earth” event

Duty cycle can be improved

- Limited by the environmental disturbances (seismic motions).

We have to consider about the problem of these motions

Seismic Noise Limiting the Duty Cycle

Problematic seismic motions (< 1Hz)

- Microseismic motions (0.1 - 1 Hz)
- Large earthquakes (0.03 - 0.1 Hz)
- Earth tides (1 day)

Microseismic motions

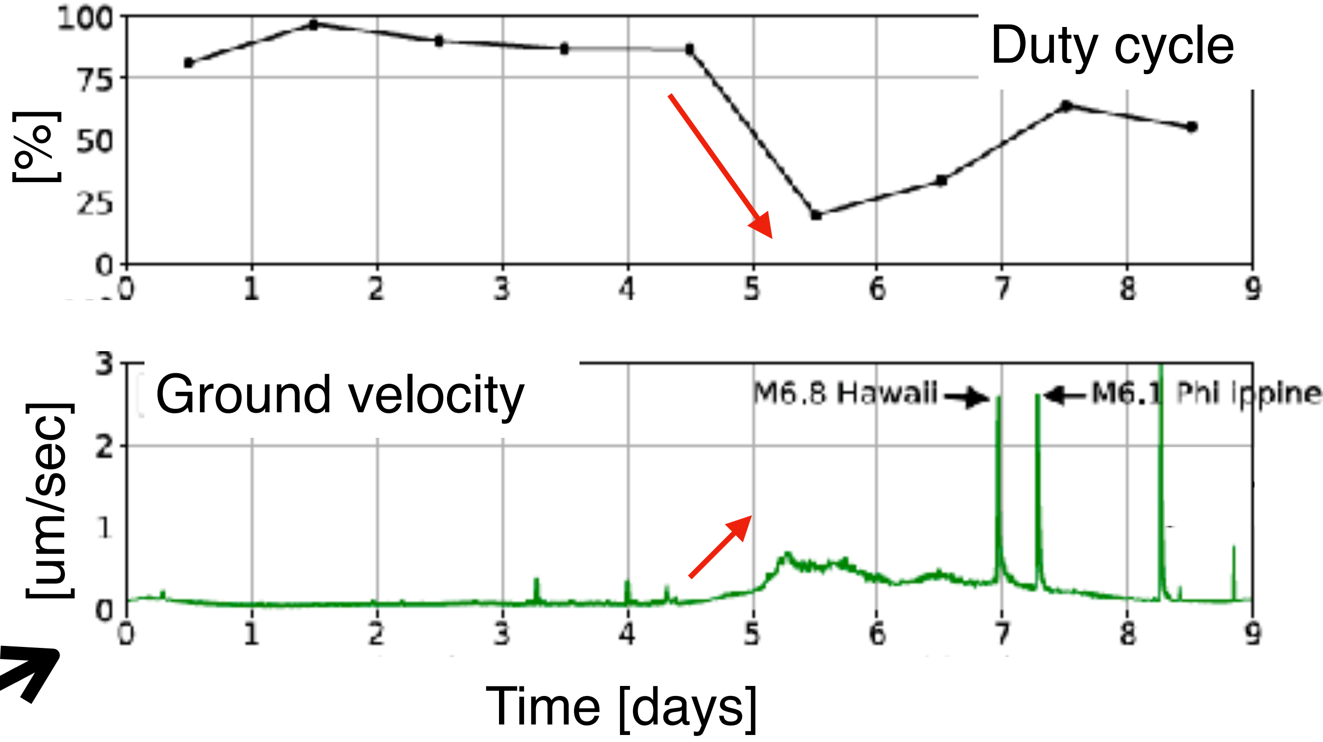
- e.g. KAGRA has been suffering with this motion in bad weather days.

Large earthquakes

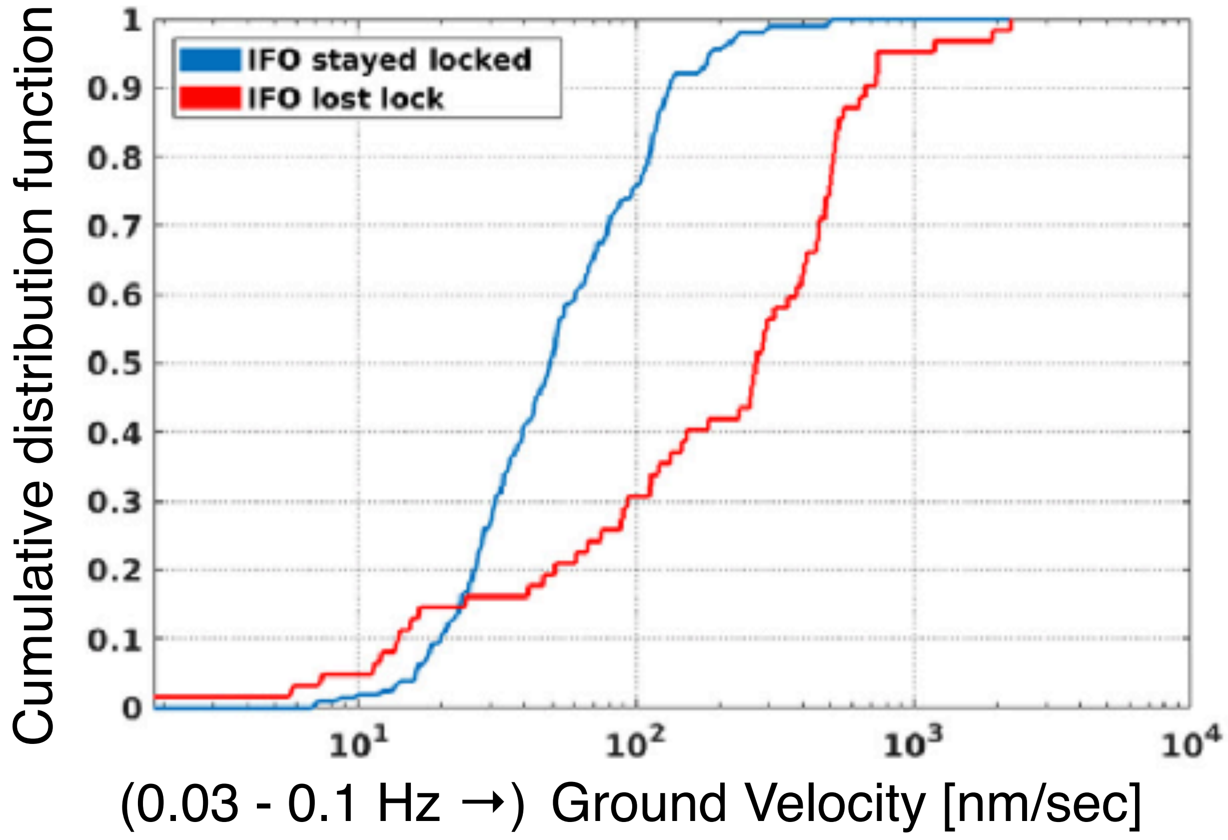
- e.g. LIGO is now suffering with the earthquakes which shakes the ground below 0.1 Hz.
- LIGO becomes unstable at higher velocities

Earth tides

- Large RMS amplitude (>100 um) often saturates the actuator range for seismic isolation control.



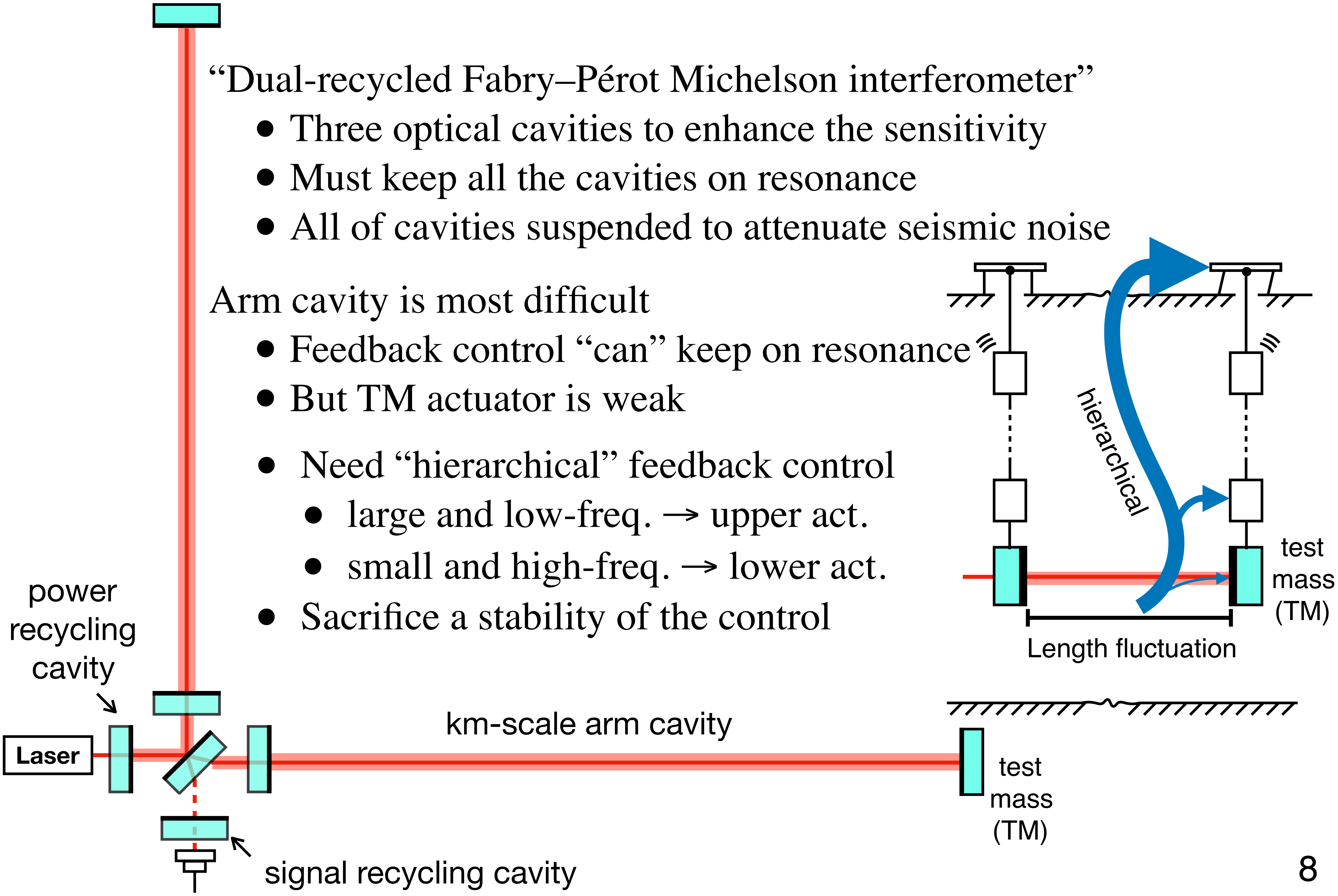
T Akutsu et al. Class. Quantum Grav. 36 (2019) 165008



S Biscans et al. Class. Quantum Grav. 35 (2018) 055004

Interferometer must be isolated from seismic motions below 1Hz.

Difficulties of the GW detector operation



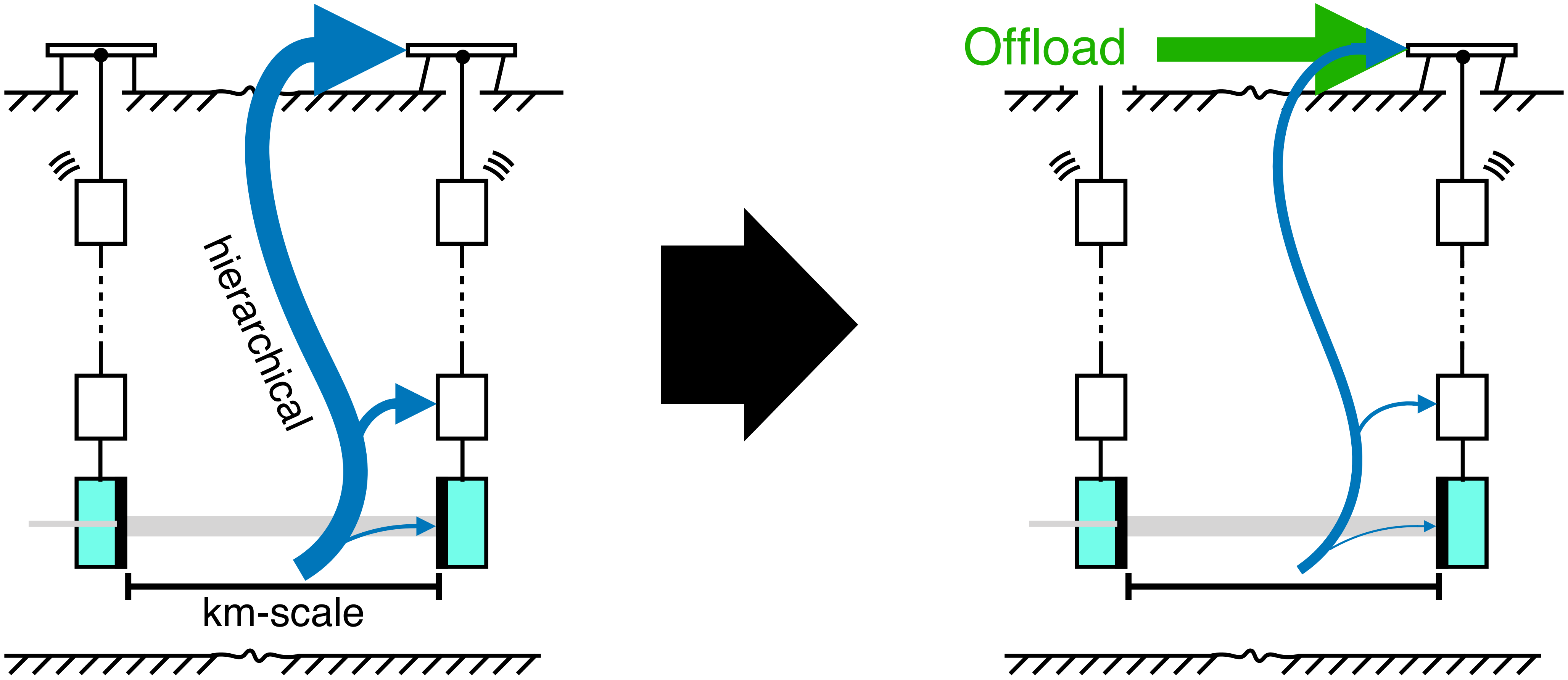
"Dual-recycled Fabry–Pérot Michelson interferometer"

- Three optical cavities to enhance the sensitivity
- Must keep all the cavities on resonance
- All of cavities suspended to attenuate seismic noise

Arm cavity is most difficult

- Feedback control "can" keep on resonance
- But TM actuator is weak
- Need "hierarchical" feedback control
  - large and low-freq. → upper act.
  - small and high-freq. → lower act.
- Sacrifice a stability of the control

Motivation of low-frequency seismic isolation



Offloading the low-freq. motions

- Relax the feedback control

Advantage to offload low-freq. motions

- avoid saturation of weak actuators
- improve stability of control loop

→ become more stable operation

Seismic monitor for low-freq. motions

- In generally, seismometer is used.
- But seismometer have no sensitivity below 0.1 Hz due to sensor noise.
- Microseismic noises only can be offload.

Geophysics interferometer is a good sensor to measure the low-frequency seismic motion.

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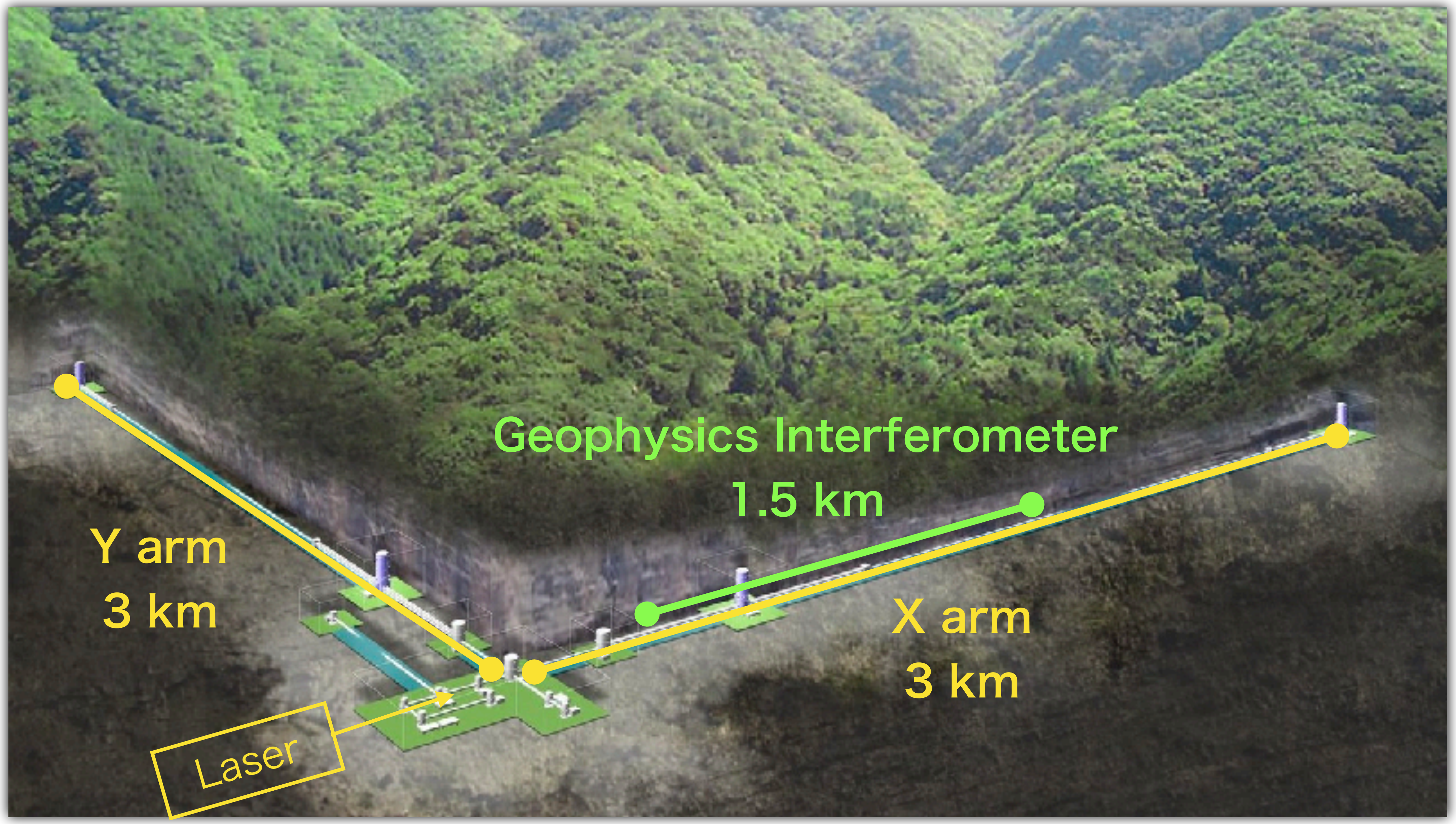
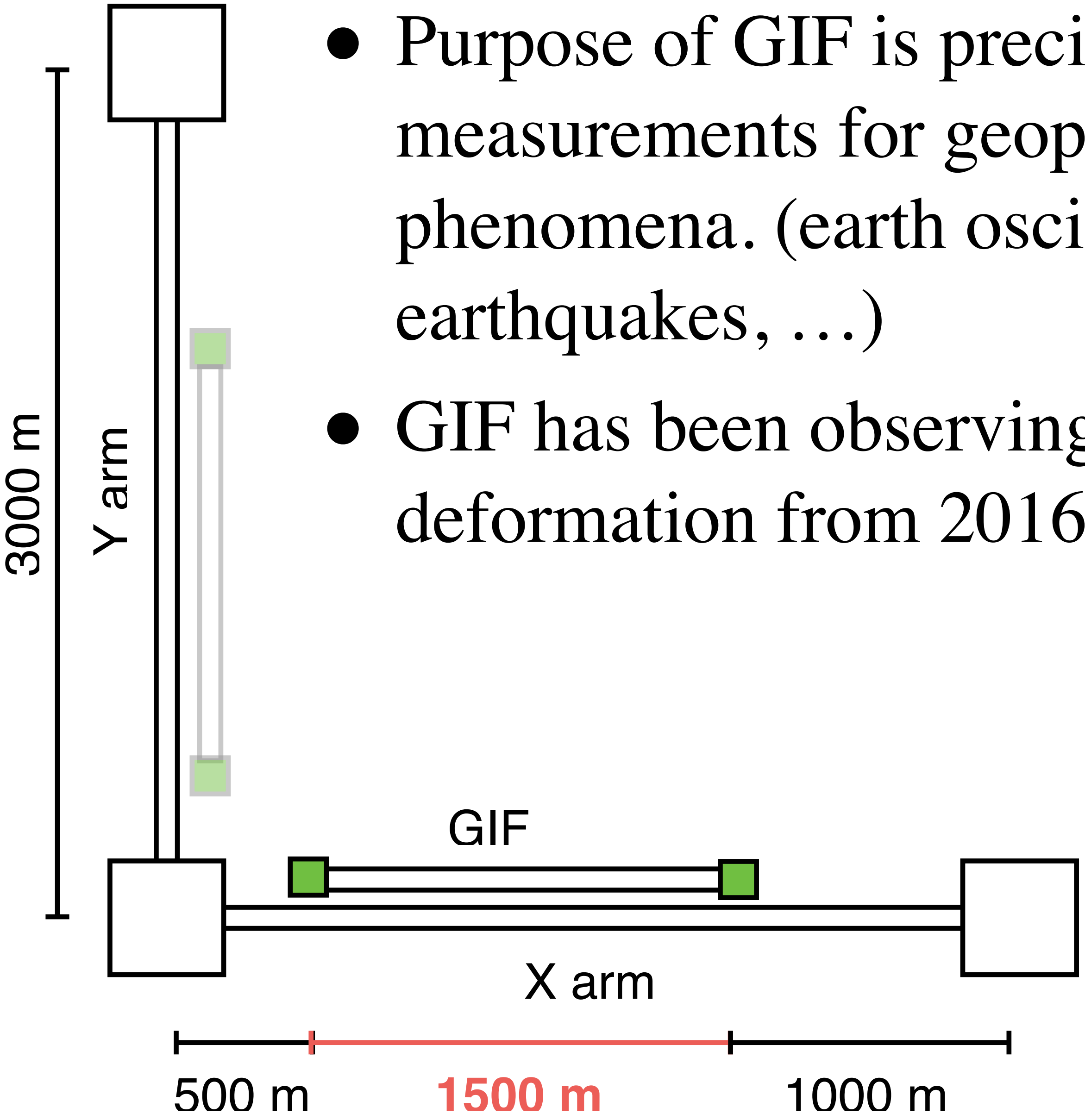
KAGRA and Geophysics Interferometer

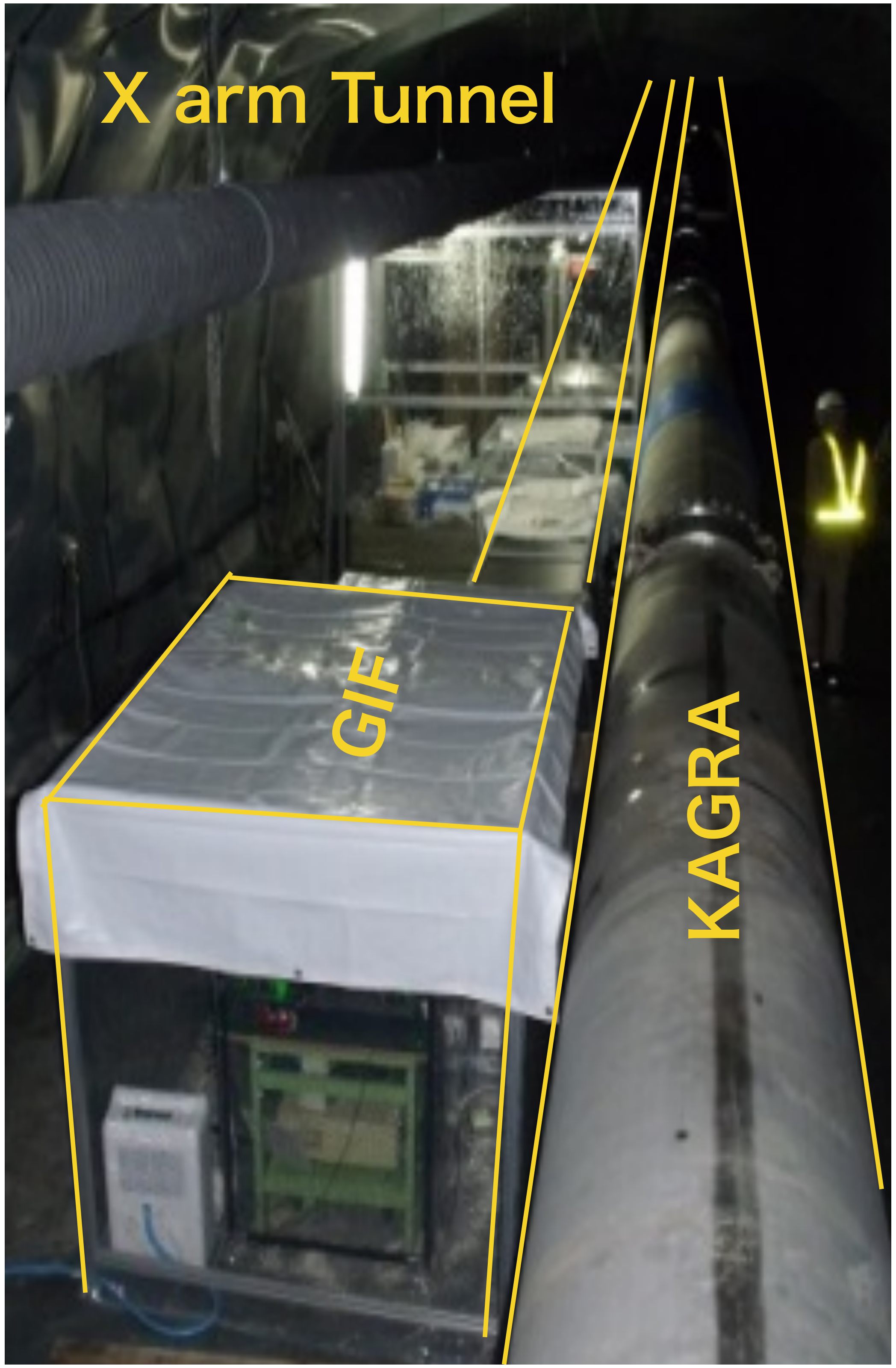


- KAGRA is constructed underground.
- Geophysics Interferometer is installed along the X arm tunnel.

Geophysics Interferometer (GIF)

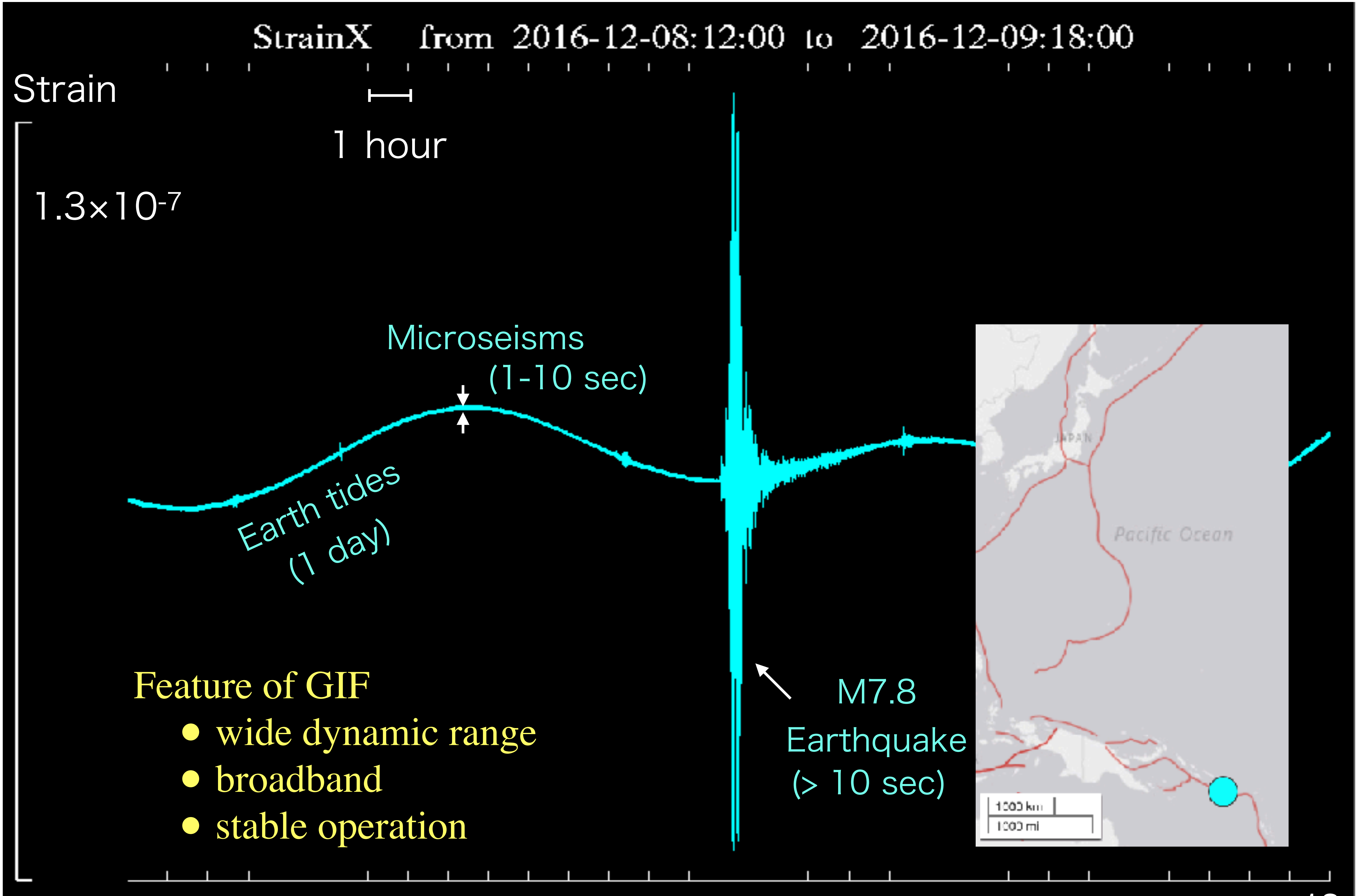
- GIF is a 1500 m laser strainmeter to observe the deformation of the ground. (developed by ERI)
- Purpose of GIF is precise strain measurements for geophysical phenomena. (earth oscillations, earthquakes, …)
- GIF has been observing the deformation from 2016.





ERI : Earthquake Research Institute, University of Tokyo

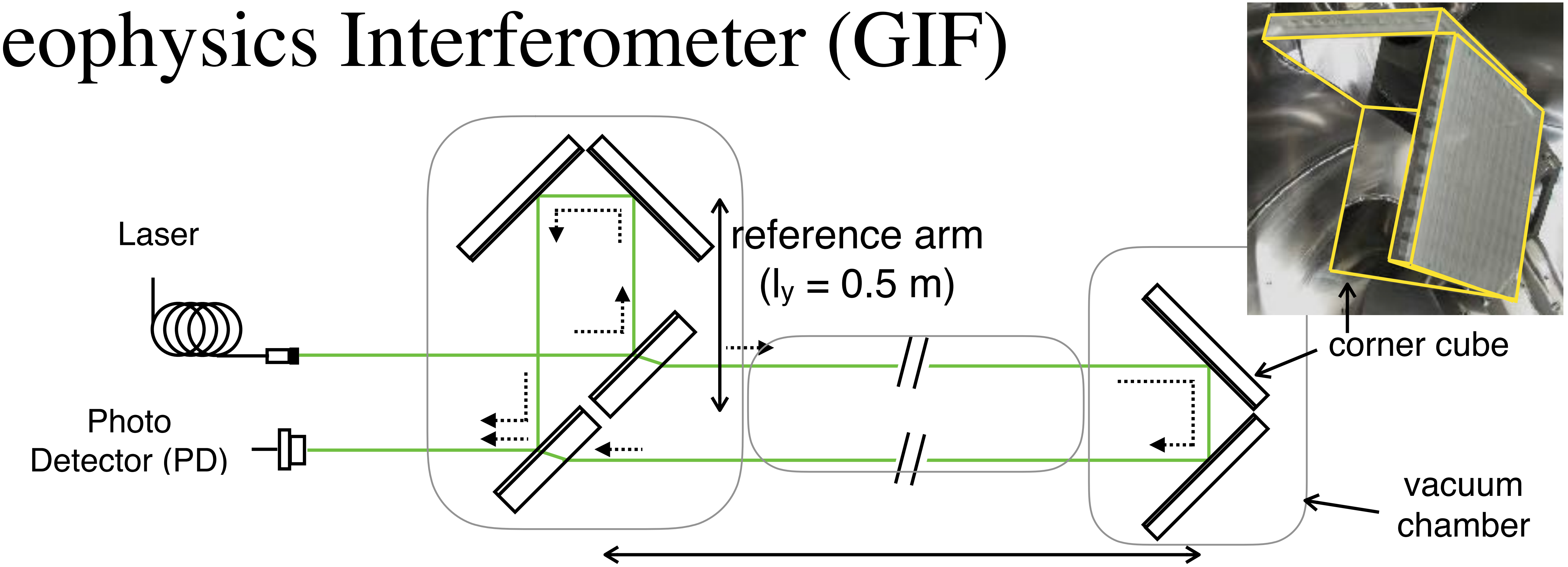
Example

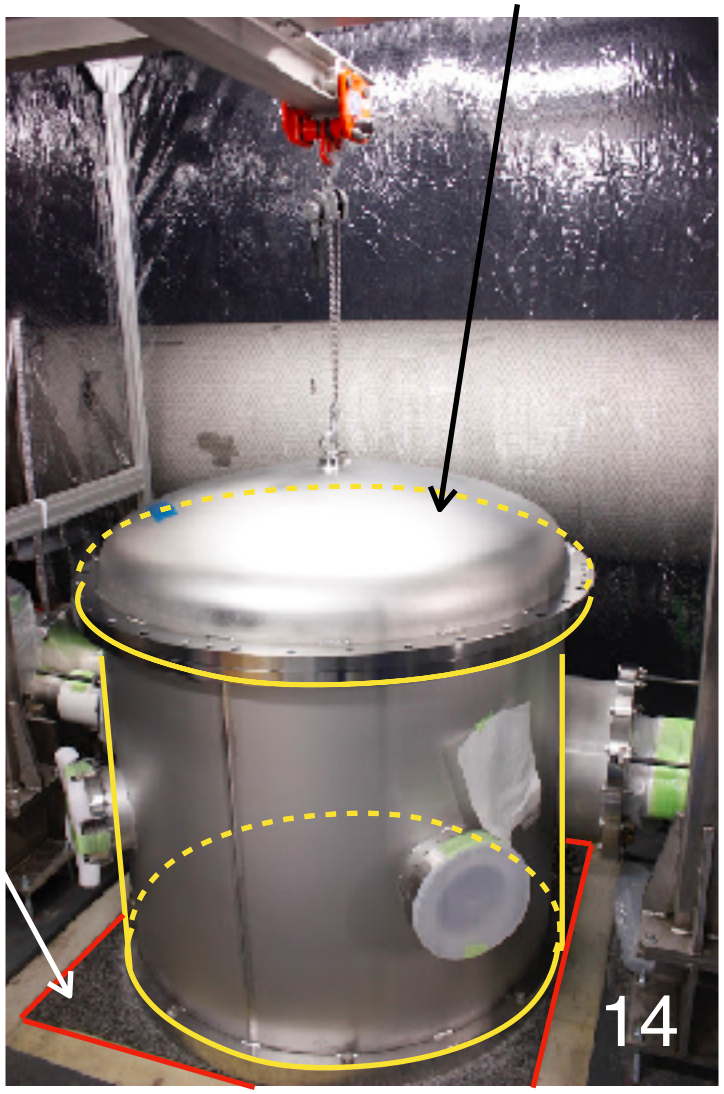


Feature of GIF

- wide dynamic range
- broadband
- stable operation

Geophysics Interferometer (GIF)



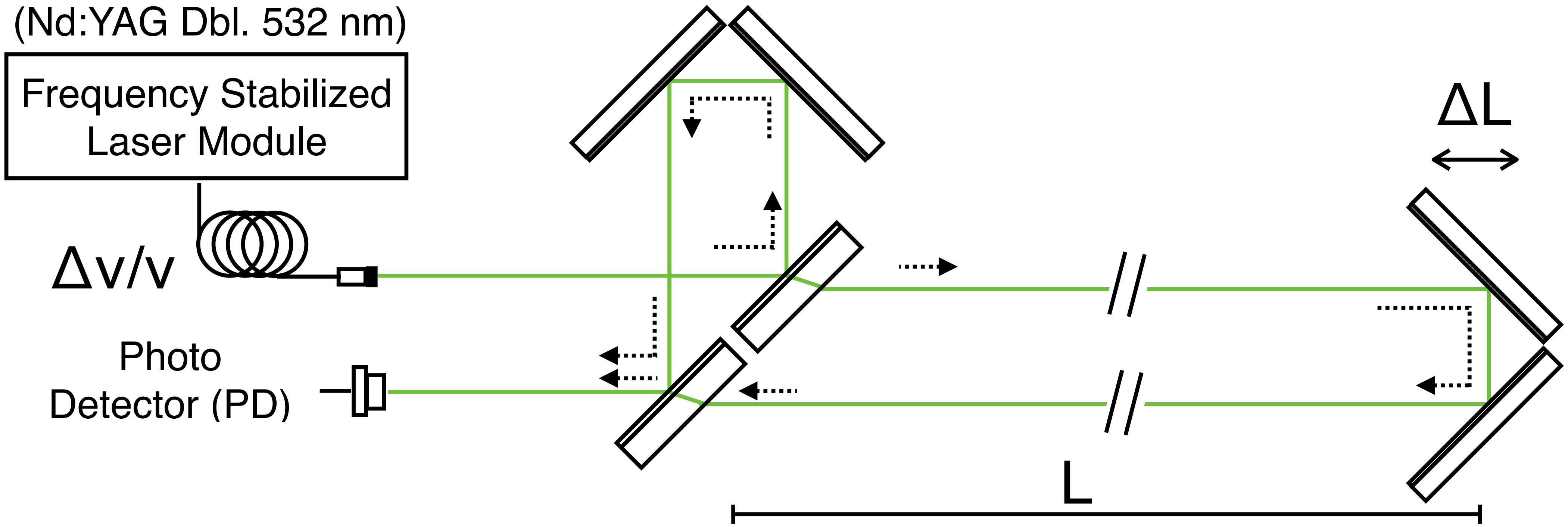


GIF is a 1500 m asymmetric Michelson interferometer.

- Measure the relative length change of baseline and reference arms (l_x - l_y).
- Corner cubes are housed in the vacuum chamber mounted on the ground.
- The corner cubes need no km-scale alignment because they reflect lights in parallel.

→ GIF can measure the baseline length directly and stably.

Main noise source



Asymmetric arms introduces the noise coupling from frequency noise.

strain resolution $\frac{\Delta L}{L} \sim \frac{\Delta \nu}{\nu}$

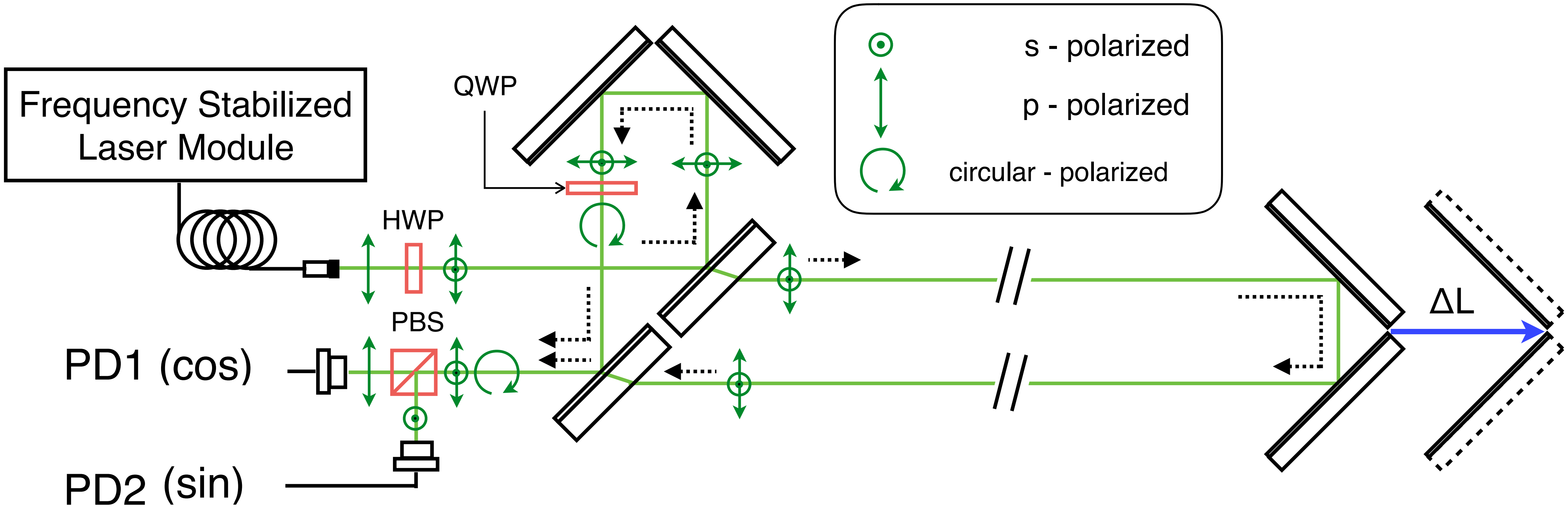
Frequency stabilized laser is used

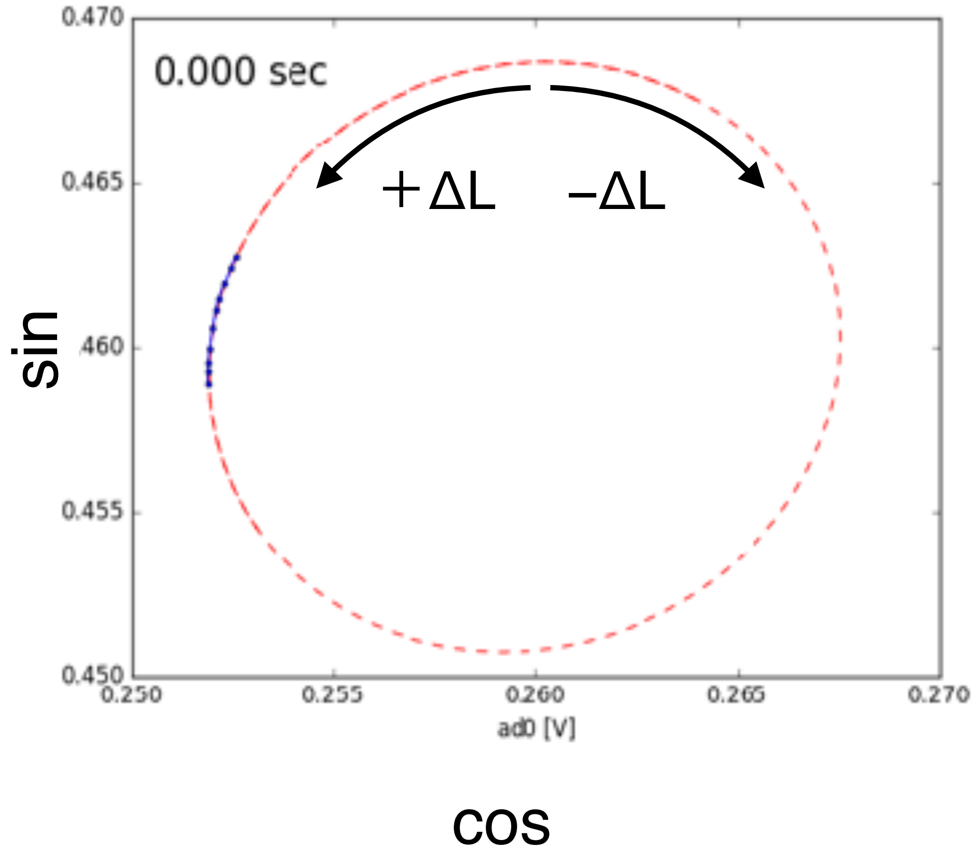
- Laser frequency is stabilized by feeding back the frequency to iodine absorption line.
- $\Delta\nu/\nu \sim 10^{-12}$

GIF can measure the baseline length precisely ($\Delta L/L \sim 10^{-12}$).

e.g. Microseisms $\sim 10^{-10}$ (L = 3km)

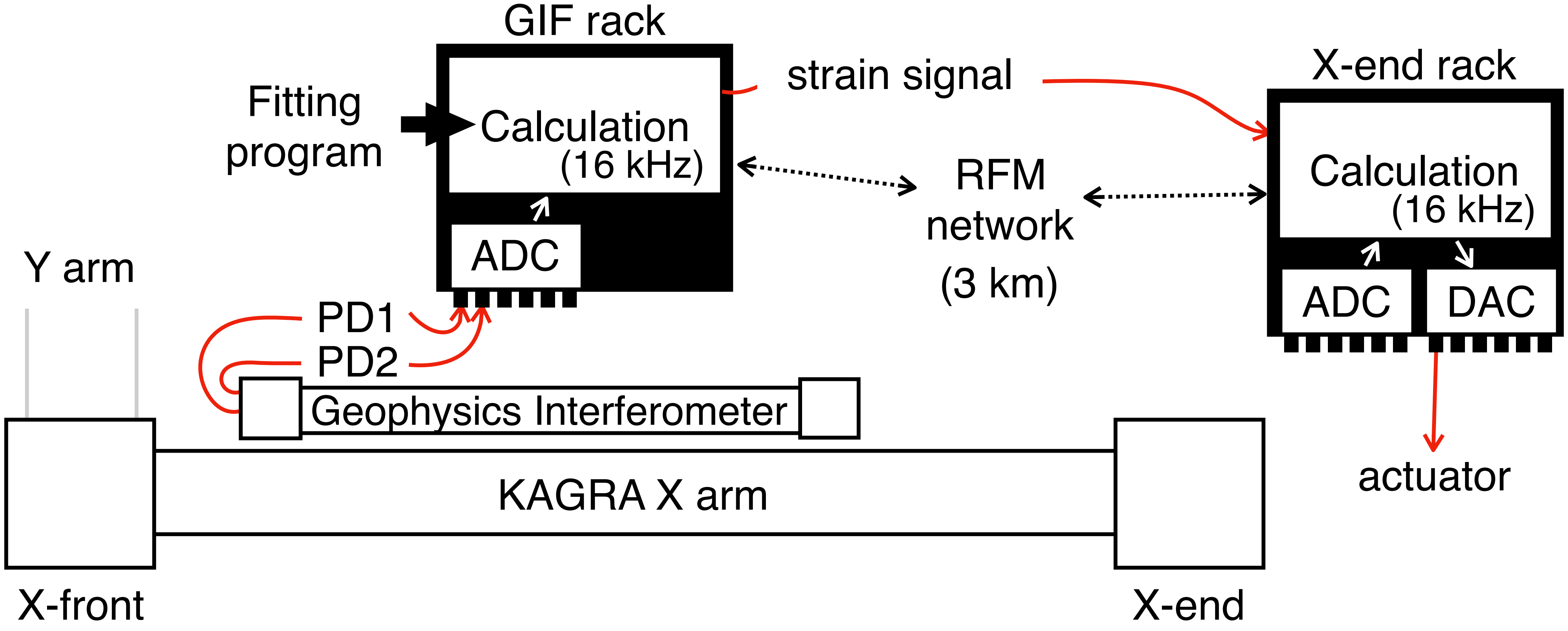
Signal detection





- Use two PD signals shifted 90 degrees from each other (sin, cos)
- Length change ΔL is obtained as a rotation angle in Lissajous figure. → wide dynamic range
- Ellipse curve fitting is needed in realtime.

Realtime signal processing for KAGRA



Strain signal is obtained in realtime

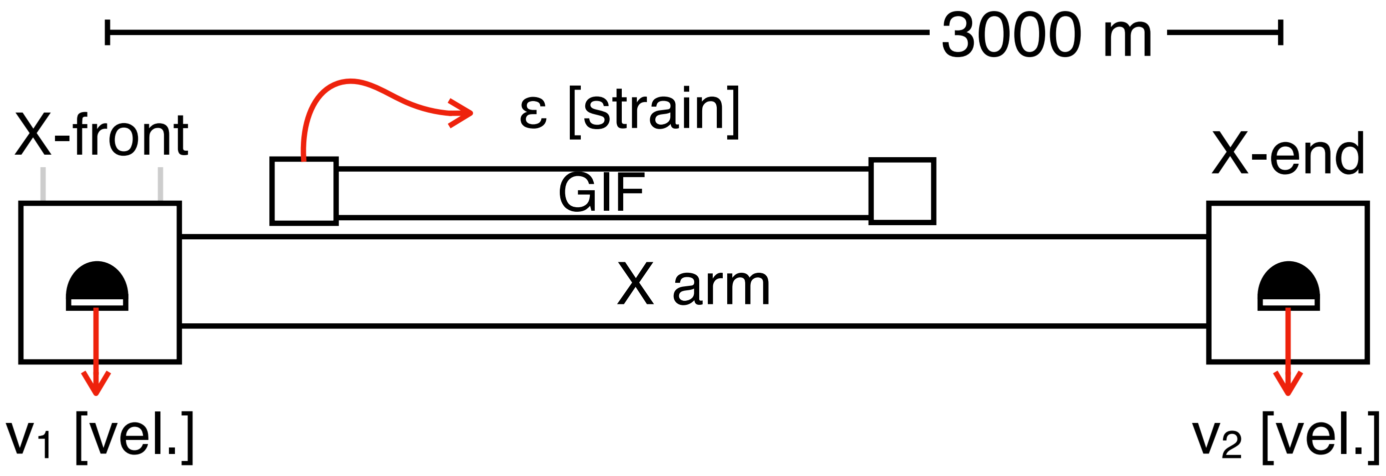
- Fitting program is coded in the KAGRA DAQ system.
- PD outputs are converted to the strain signal.
- This calculation is done every data sampling.

Strain signal is synchronized with the other DAQ rack.

- All racks communicate with the others in RFM network.
- e.g. Strain signal can be sent to an actuator at X-end.

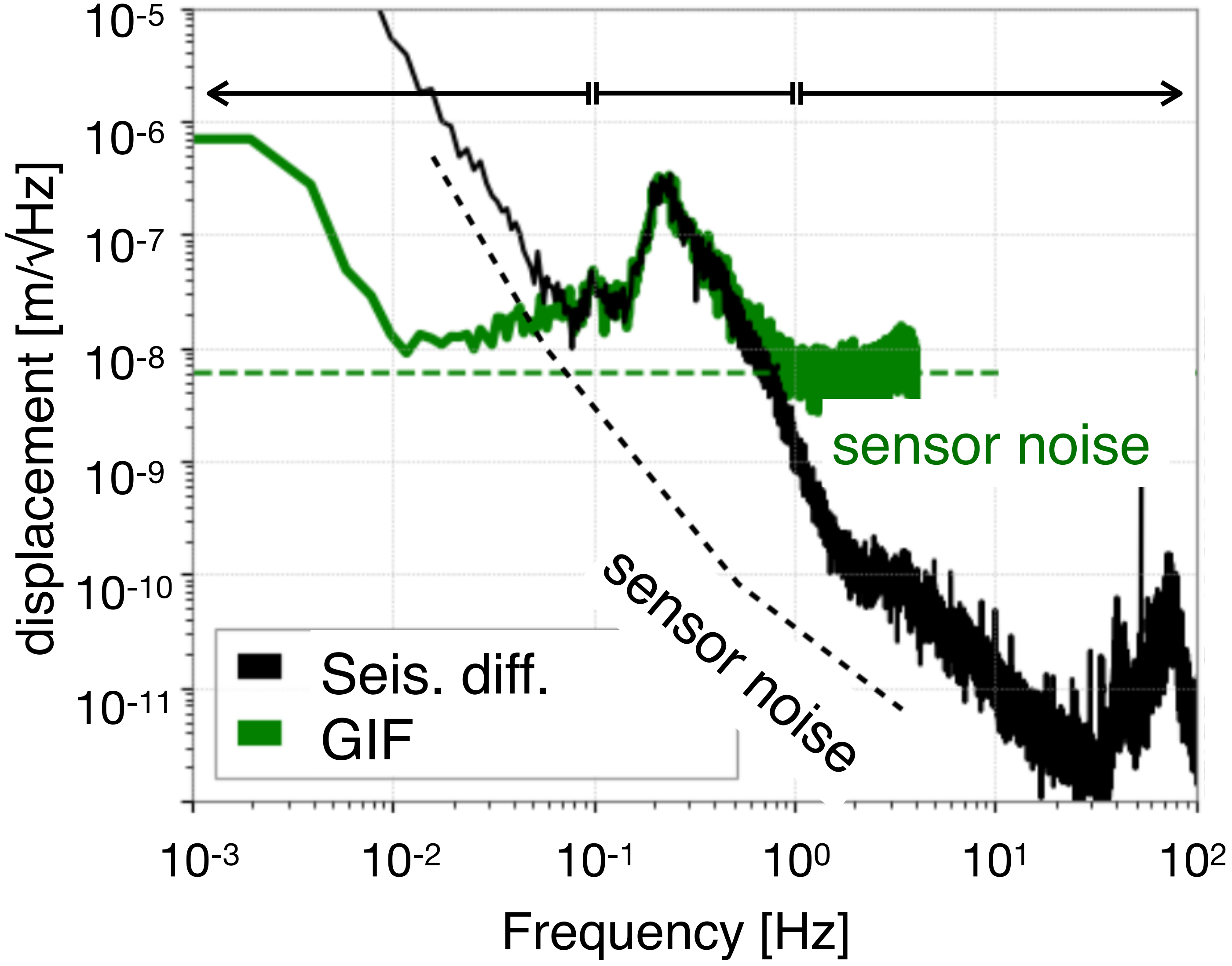
ADC : Analog digital converter DAC : Digital analog converter RFM : Reflective memory

Comparison with seismometer



$\Delta L_{3000} = \varepsilon \times 3000$ … GIF

$\Delta L_{3000} = \int (v_1 - v_2)\, dt$ … Seismometer difference



To confirm the strain calculation, strainmeter is compared with seismometer (Trillium 120QA).

Length fluctuation of the baseline is measured by two ways

Above 1 Hz

- Strainmeter is covered by noise (freq. noise).

0.1 - 1 Hz

- Strainmeter is consistent with seismometer.
- Microseismic motion is measured.

Below 0.1 Hz

- Strainmeter can measure.
- Seismometer is covered by noise.

Strainmeter have a better sensitivity below 0.1 Hz than seismometer

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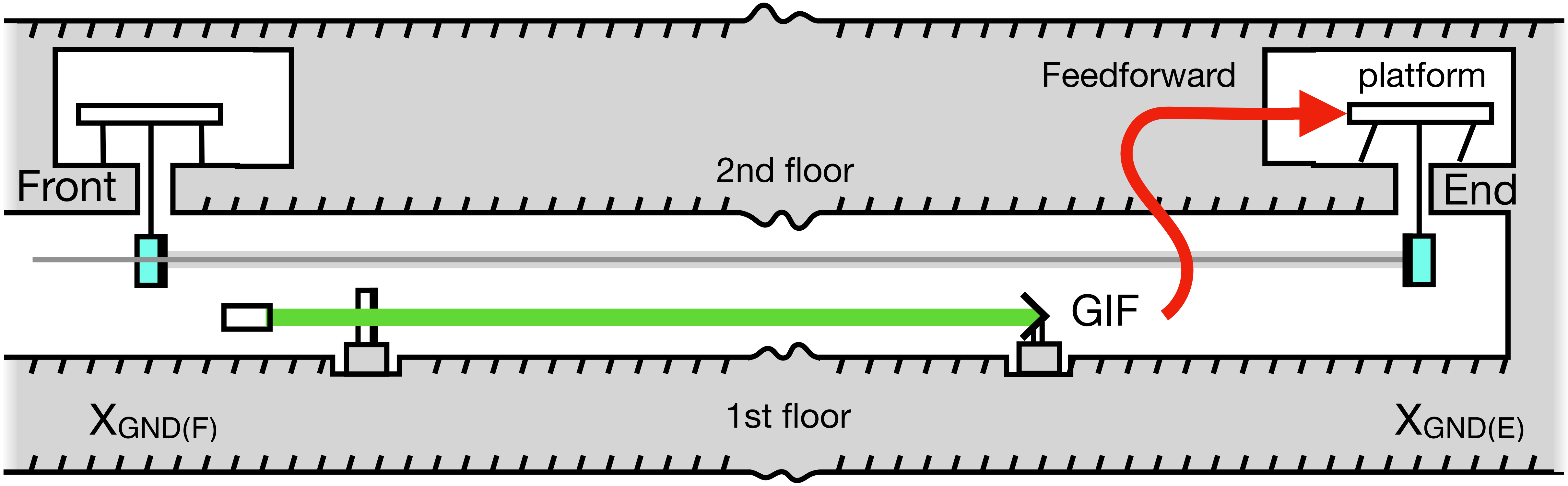
Baseline Compensation System



sectional view of X-arm tunnel

Concept

- Compensate the low-freq. seismic motion (< 1 Hz).
- Because strainmeter have enough sensitivity,
- and the two pendulums have same mechanical response ($f_0 \sim 1$ Hz).

Feedforward control using GIF

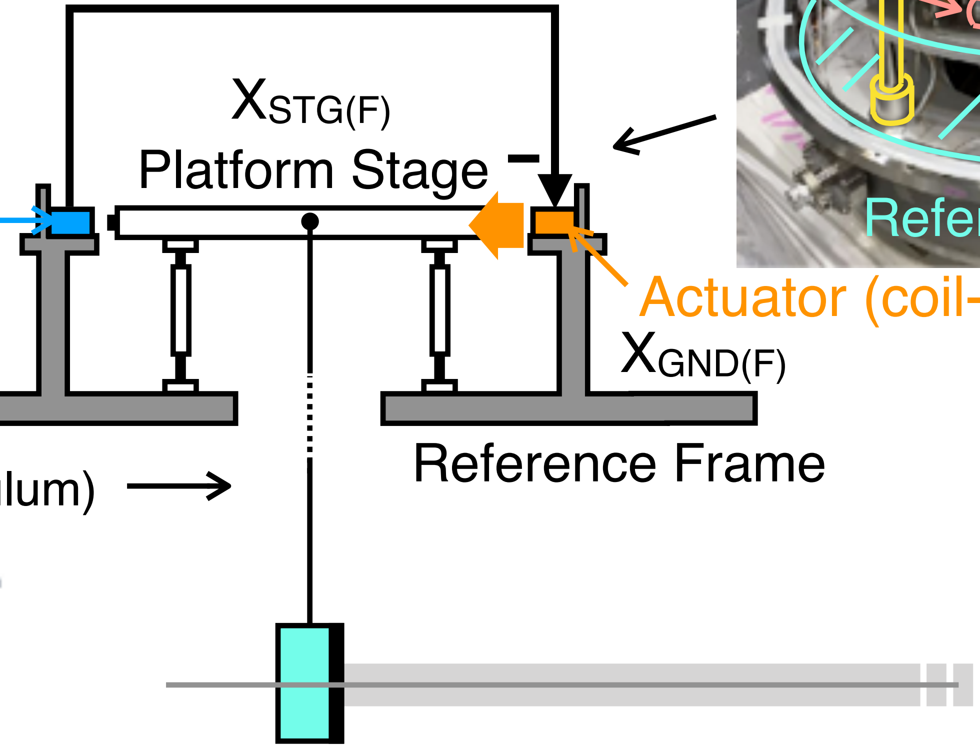
- Below 1 Hz, the strain is the same between 1.5 km and 3 km due to long wavelength (> 5km).
- Feedforward the signal to actuator on the platform stage.

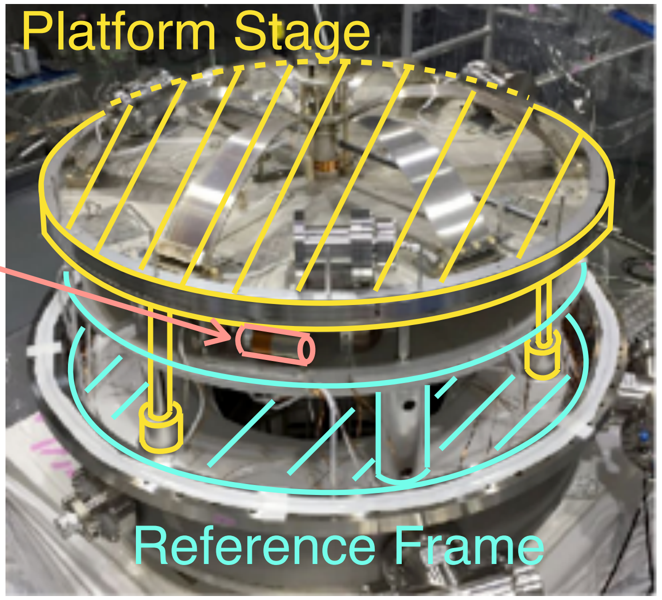
Key point

Move the end stage to follow the front stage for keeping the cavity length

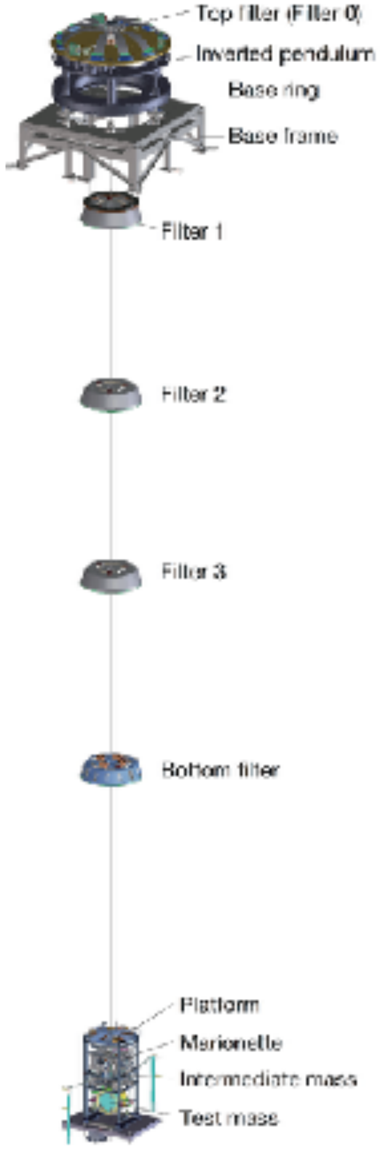
Platform Control

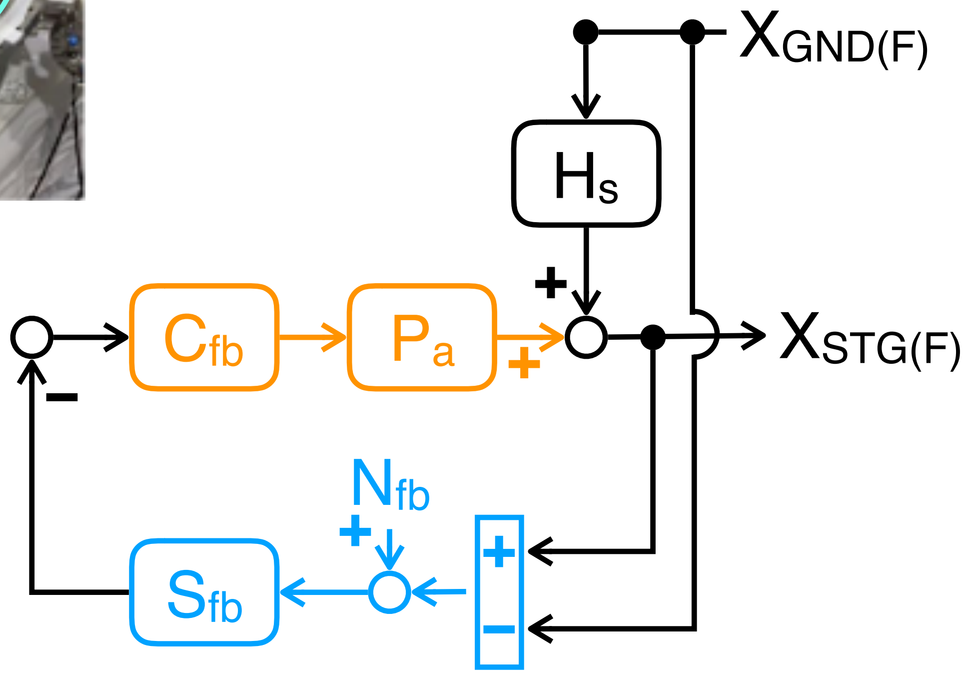
Front platform





(e.g. 13.5 m pendulum) →





$$X_{\mathrm{STG(F)}} = \frac{G}{1+G} X_{\mathrm{GND(F)}} + \frac{1}{1+G} H_{\mathrm{s}} X_{\mathrm{GND(F)}} + \frac{G}{1+G} N_{\mathrm{fb}}$$

$$(G = C_{\mathrm{fb}} P_a S_{\mathrm{fb}})$$

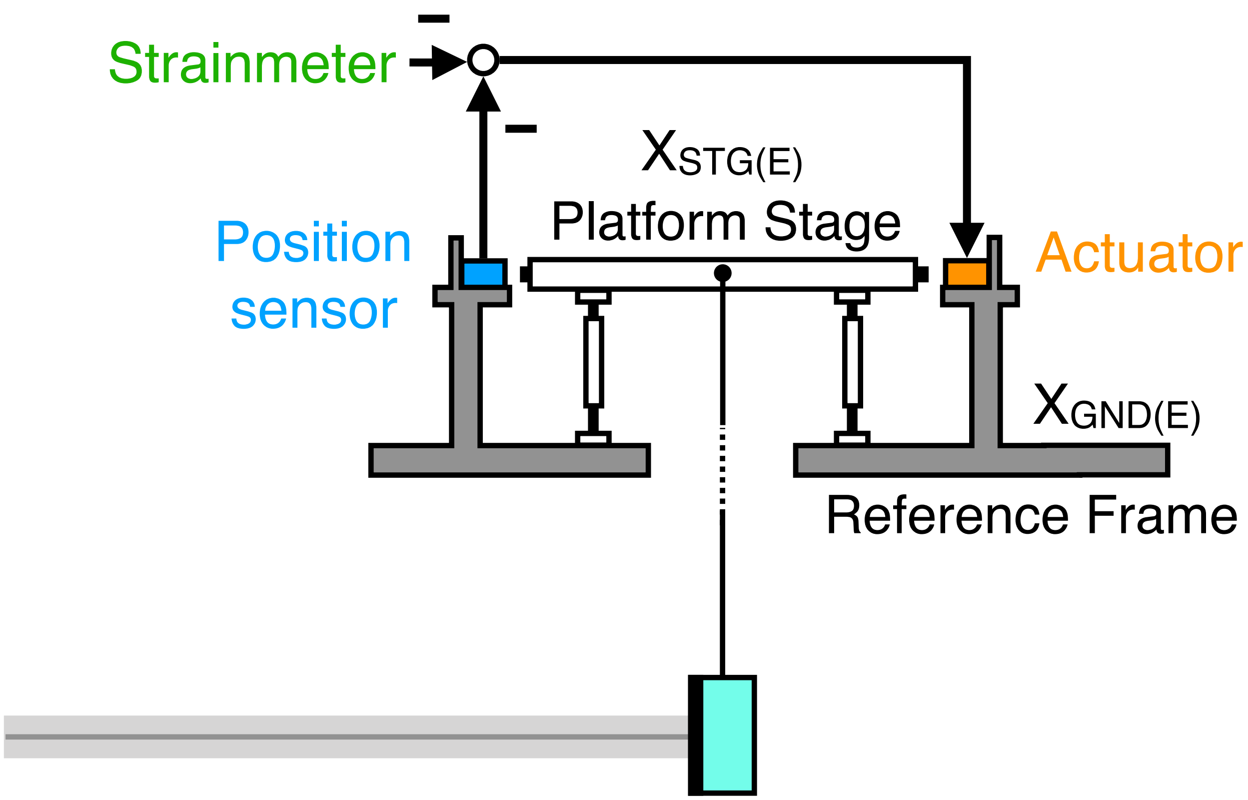
Feedback control is strongly engaged ⇔ G >> 1

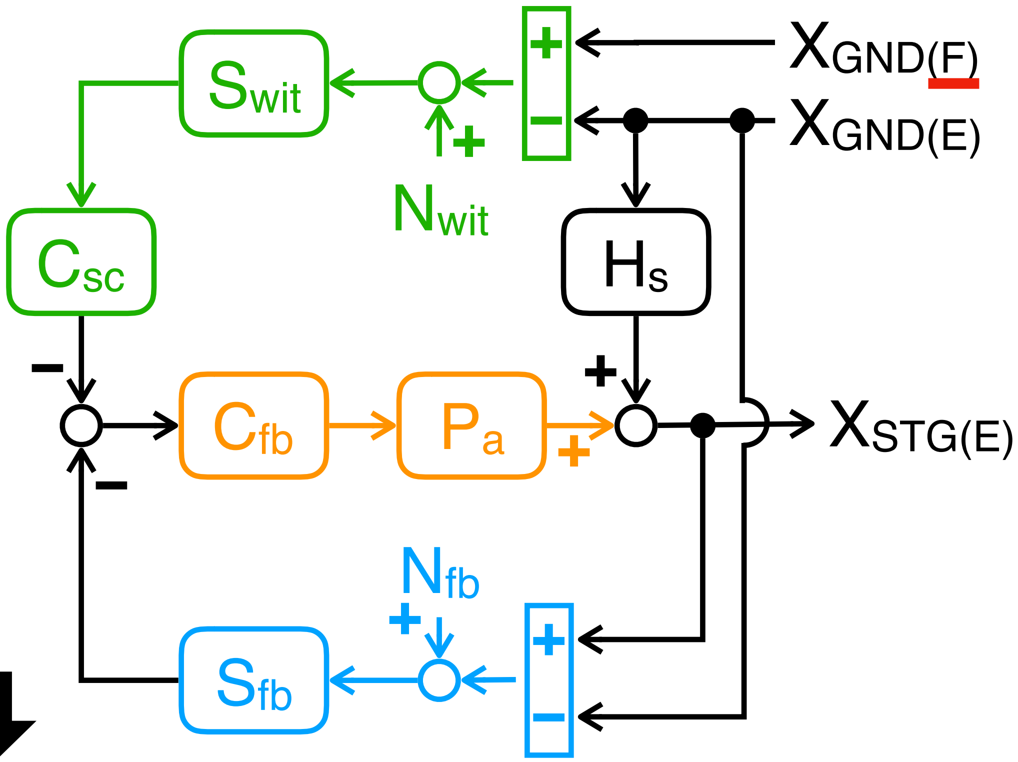
$$X_{\mathrm{STG(F)}} = X_{\mathrm{GND(F)}} + N_{\mathrm{fb}}$$

Front stage is locked to the local ground by feedback control.

Platform Control

End platform





$$X_{\mathrm{STG(E)}} = \frac{G}{1+G}\left(1 - C_{\mathrm{sc}}\frac{S_{\mathrm{wit}}}{S_{\mathrm{fb}}}\right) X_{\mathrm{GND(E)}} + \frac{G}{1+G} X_{\mathrm{GND(F)}}$$

$$+ \frac{1}{1+G} H_{\mathrm{s}} X_{\mathrm{GND(E)}} + \frac{G}{1+G}\left(N_{\mathrm{fb}} - C_{\mathrm{sc}}\frac{S_{\mathrm{wit}}}{S_{\mathrm{fb}}} N_{\mathrm{wit}}\right)$$

G >> 1

$$X_{\mathrm{STG(E)}} = \left(1 - C_{\mathrm{sc}}\frac{S_{\mathrm{wit}}}{S_{\mathrm{fb}}}\right) X_{\mathrm{GND(E)}} + X_{\mathrm{GND(F)}} + \left(N_{\mathrm{fb}} - C_{\mathrm{sc}}\frac{S_{\mathrm{wit}}}{S_{\mathrm{fb}}} N_{\mathrm{wit}}\right)$$

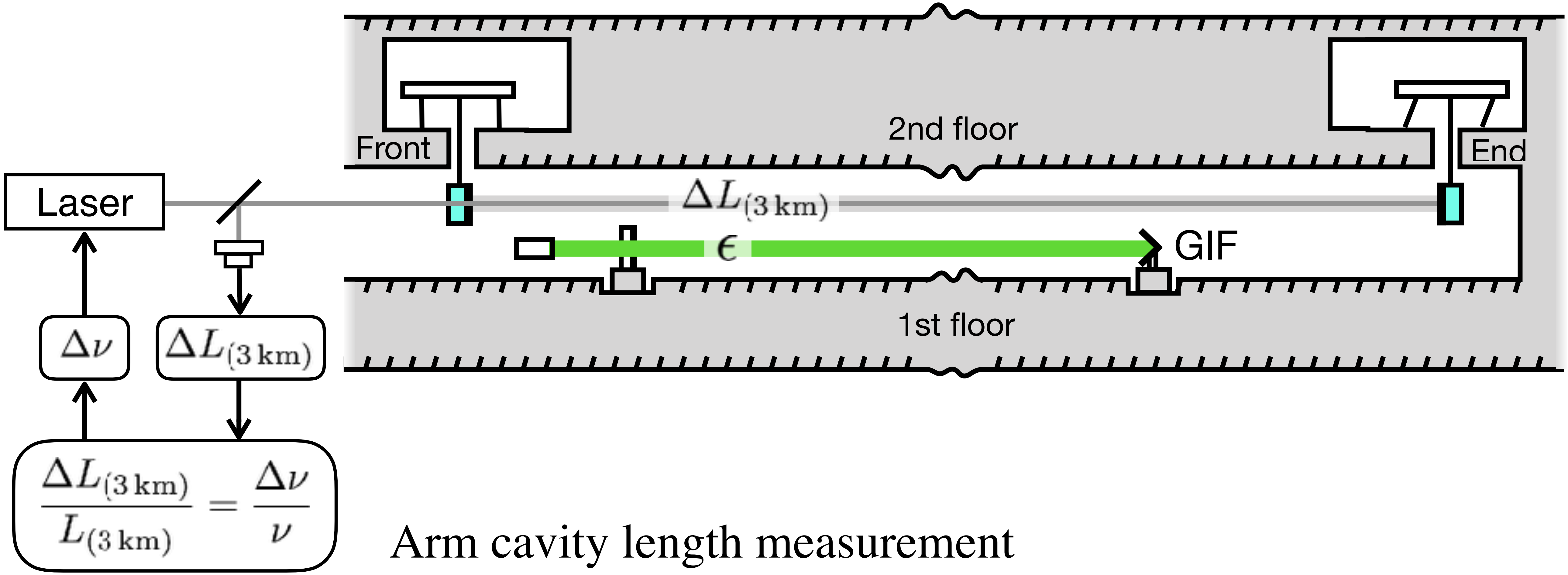
$$C_{\mathrm{sc}} = \frac{S_{\mathrm{fb}}}{S_{\mathrm{wit}}}$$

$$X_{\mathrm{STG}\underline{\mathrm{(E)}}} = X_{\mathrm{GND}\underline{\mathrm{(F)}}} + N_{\mathrm{fb}} - N_{\mathrm{wit}}$$

End stage can follow the front stage motion using GIF signal

Contents

Setup for Demonstration



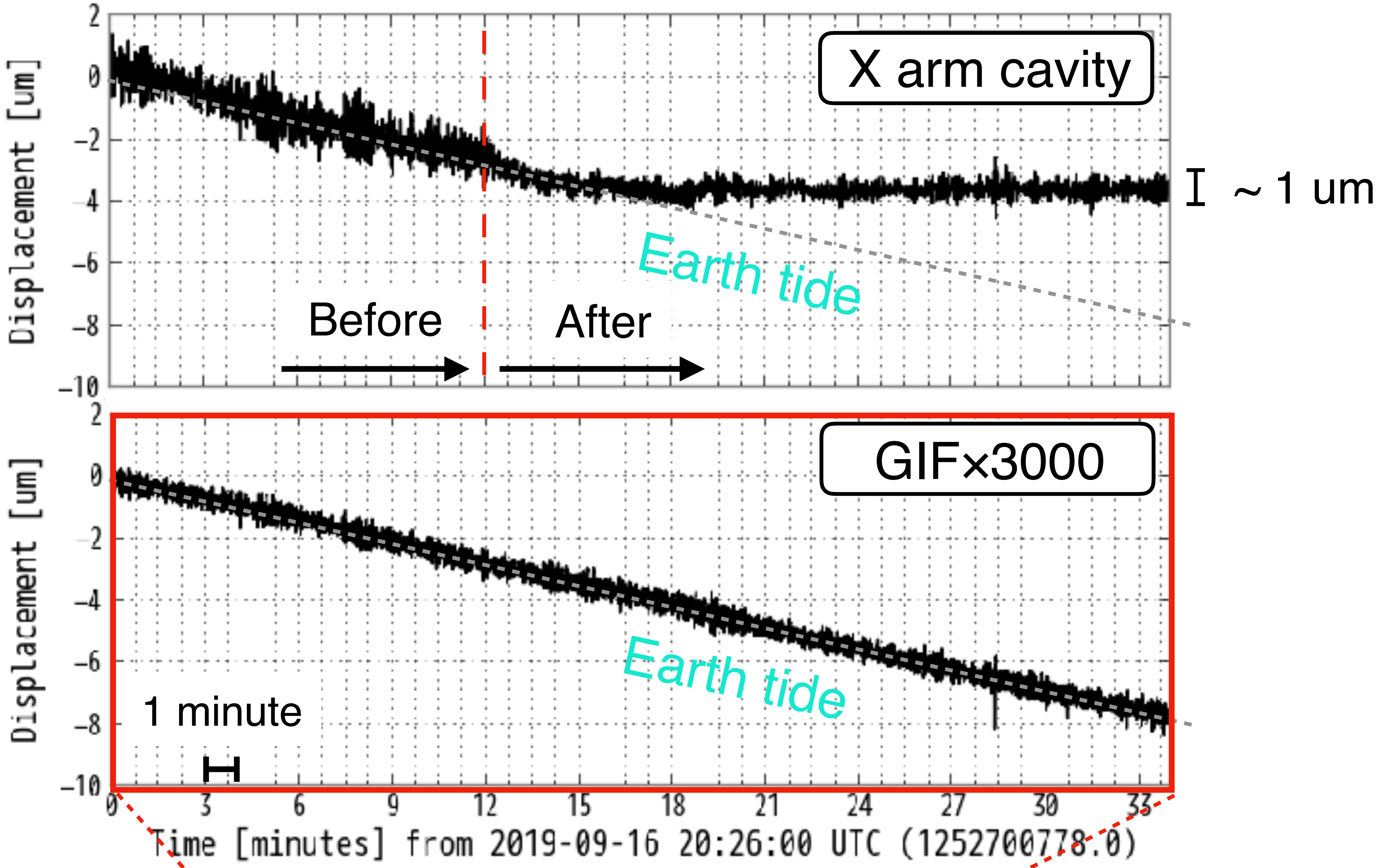
Arm cavity length measurement

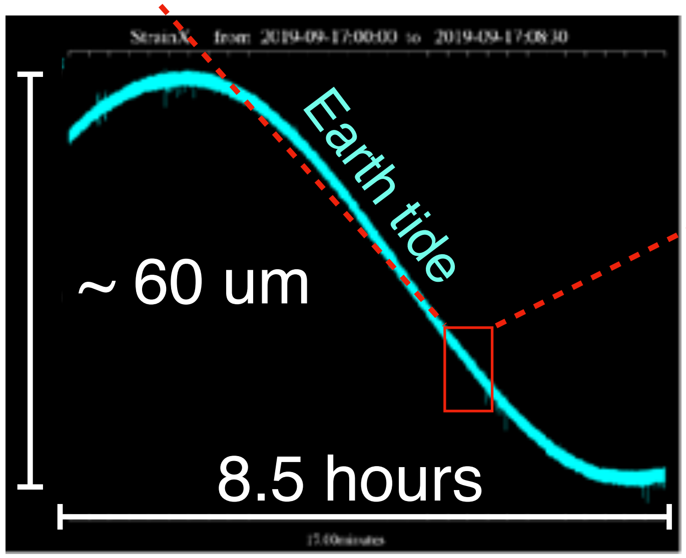
- Cavity was kept on resonance by feedback control.
- Fluctuation of the length $\Delta L_{(3\mathrm{km})}$ was directly calculated from the feedback signal $\Delta\nu$.

Baseline length measurement

- Fluctuation of the baseline length was estimated as $3000 \times \varepsilon$.
- This estimation is true below 1 Hz.

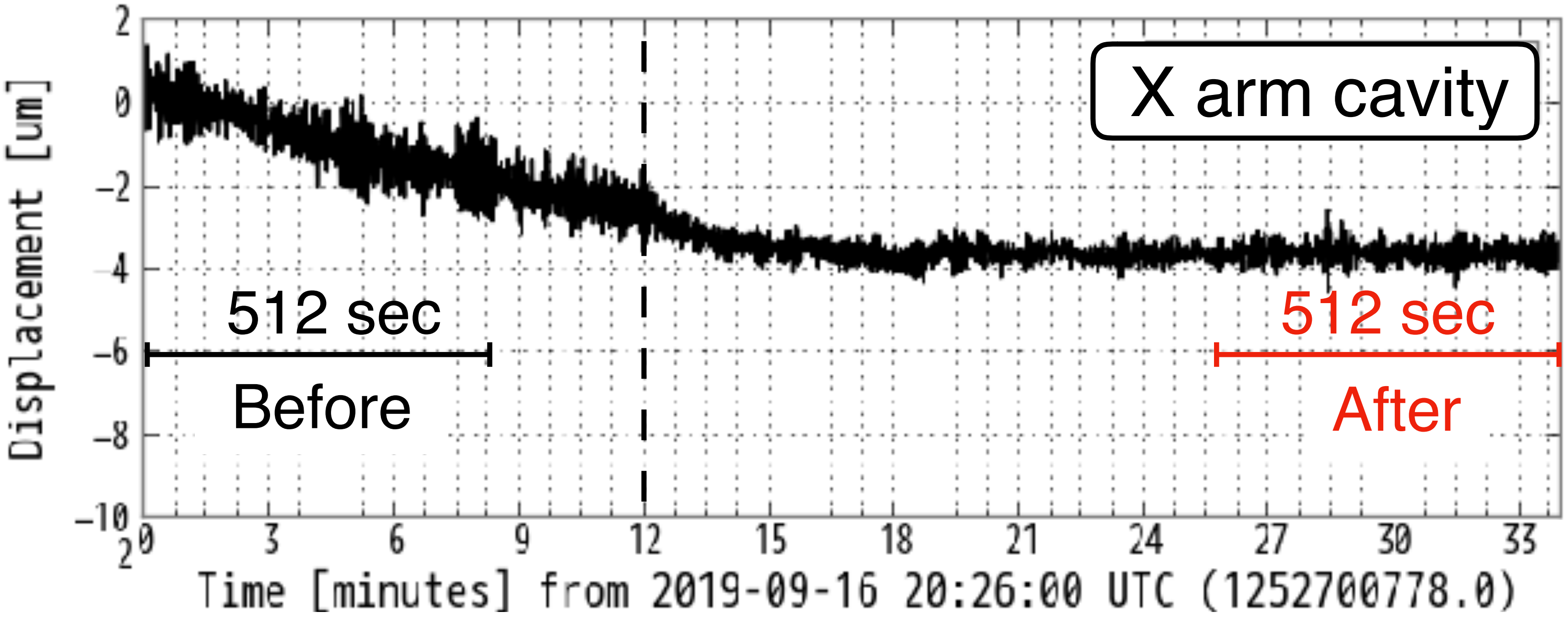
Results : Earth tides bands

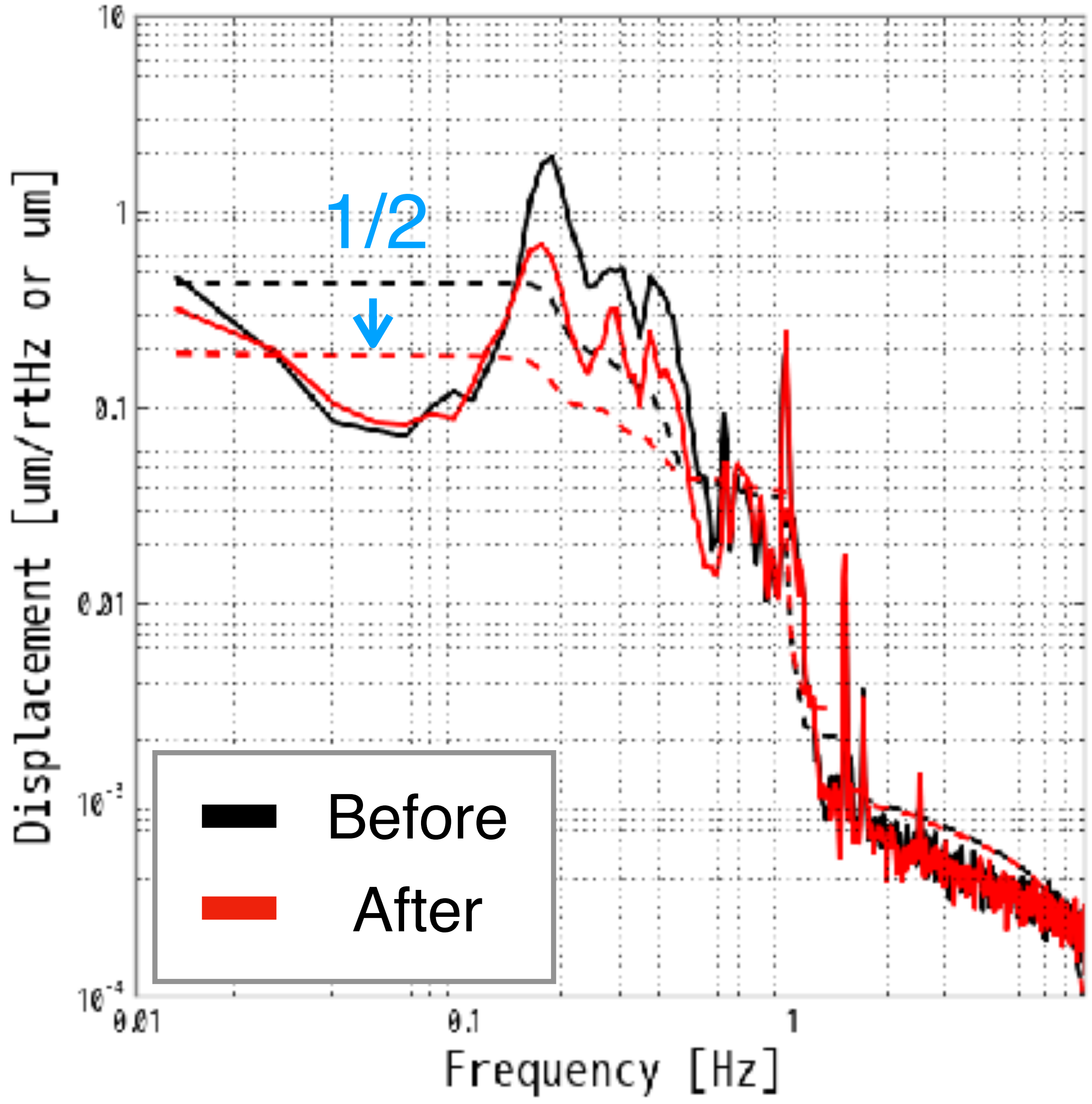




Earth tide would be reduced by at most 1/60 (= -35 dB) if demonstration was continued to several hours.

Results : Above 0.01 Hz





Compare with ASDs [solid line]

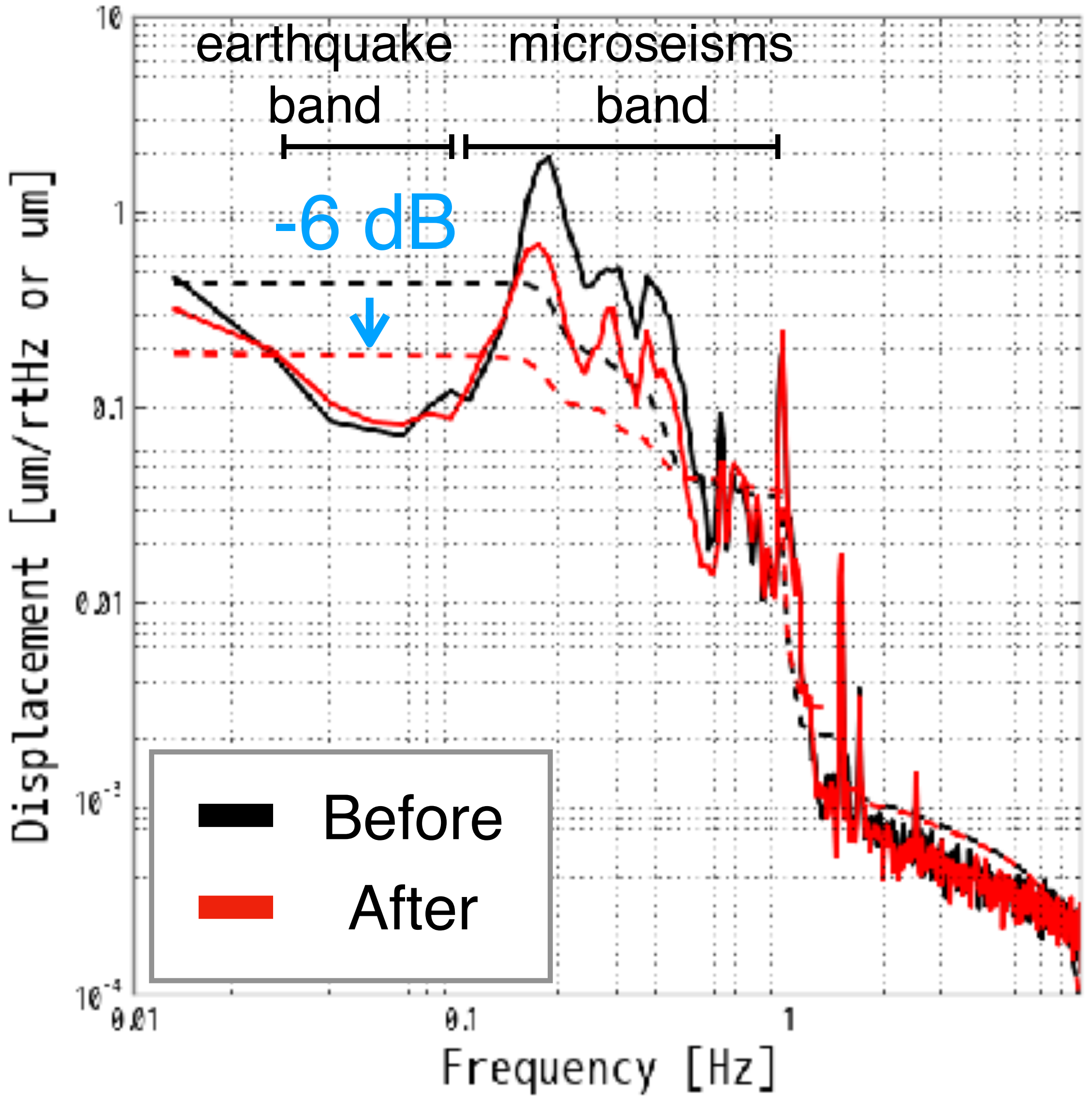
- ASDs have a unit of um/√Hz

Compare with RMS amplitude [dashed line]

- RMS amplitudes have a unit of um
- RMS amplitudes are obtained by integrating the ASDs with frequency.

RMS amplitude above 0.01 Hz was reduced by 1/2 (-6 dB).

Discussion

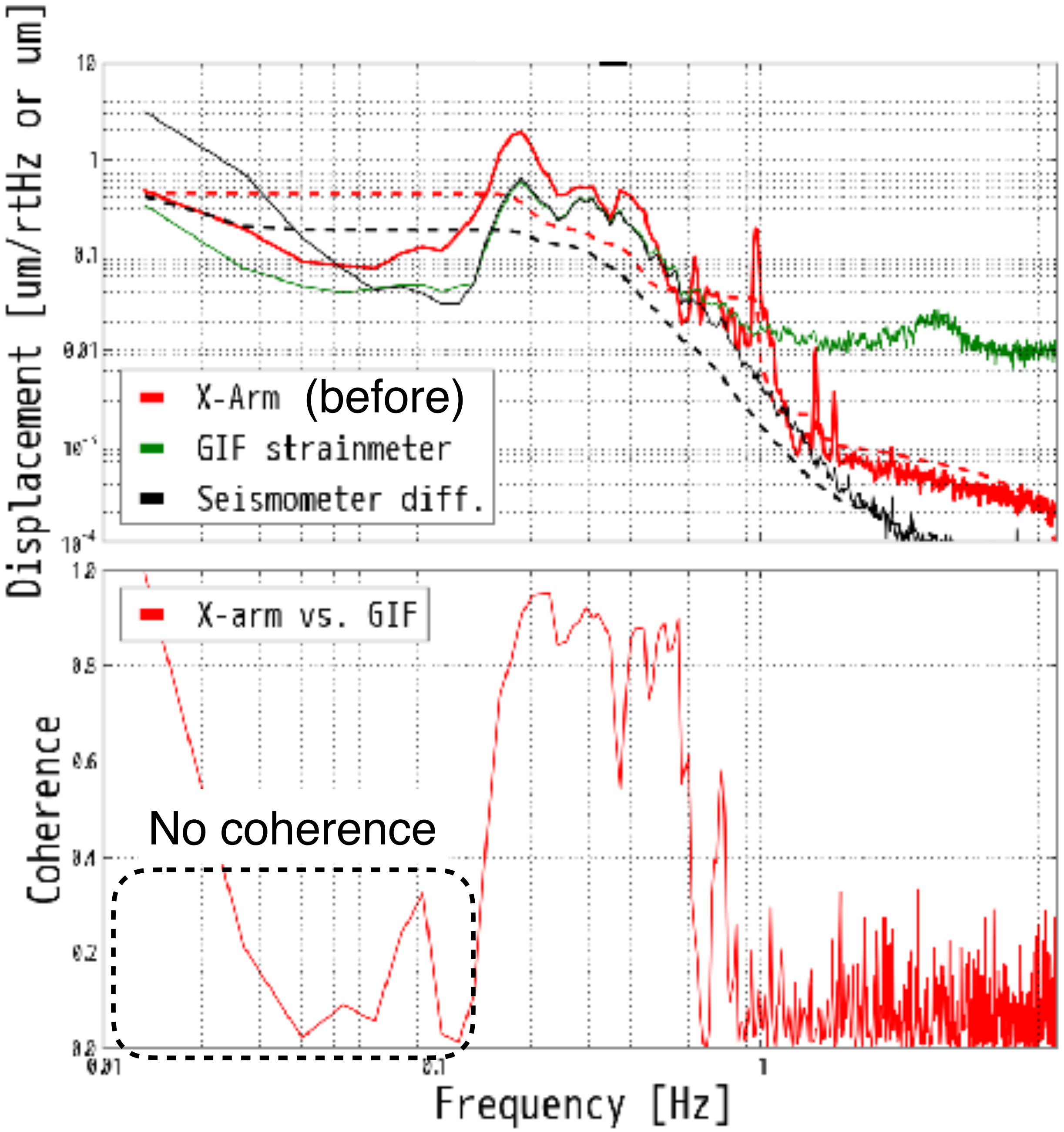


In earthquake band,

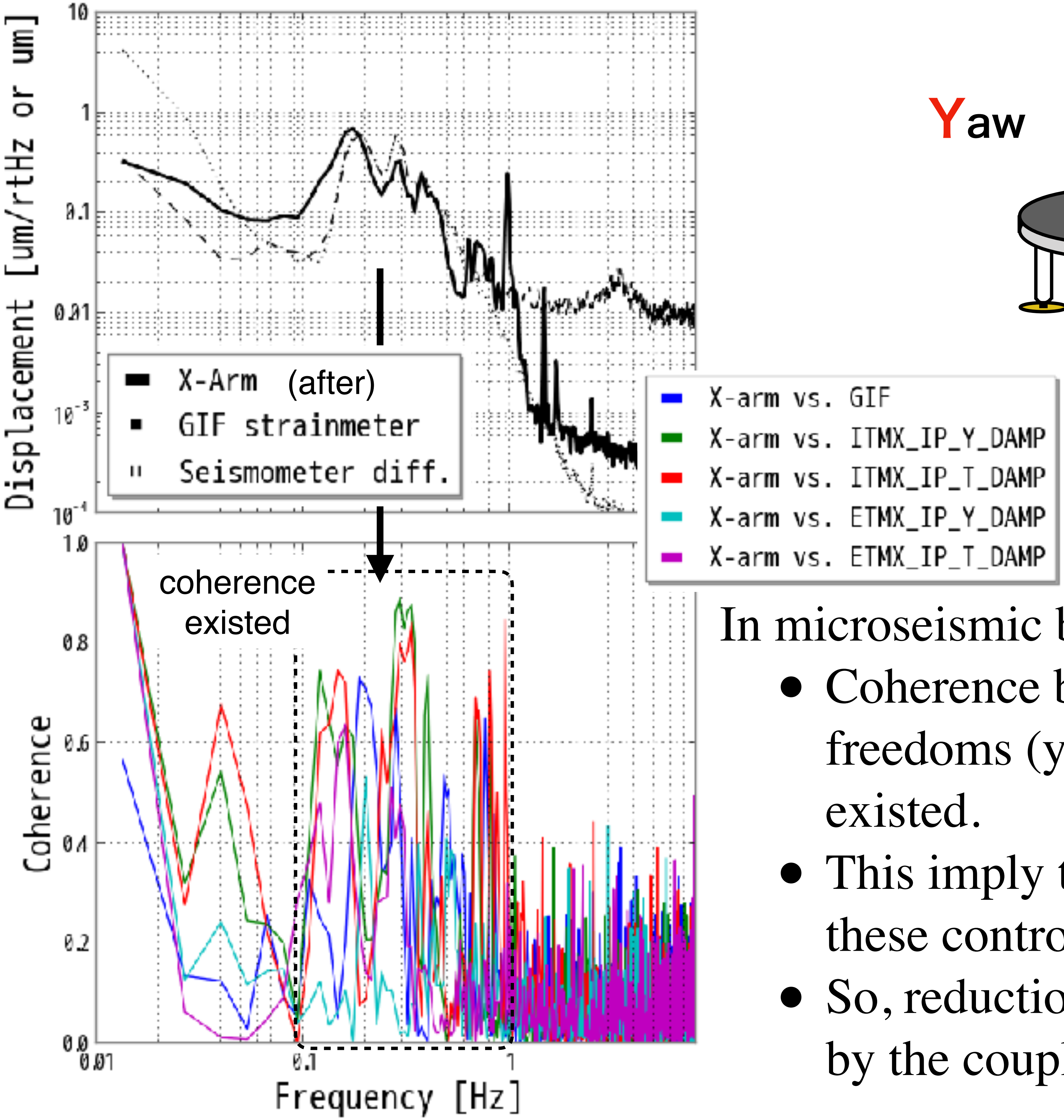
- No coherence
- This indicates that GIF signals was covered by self-noise.
- So, there was few reduction because seismic noise was below the GIF noise.

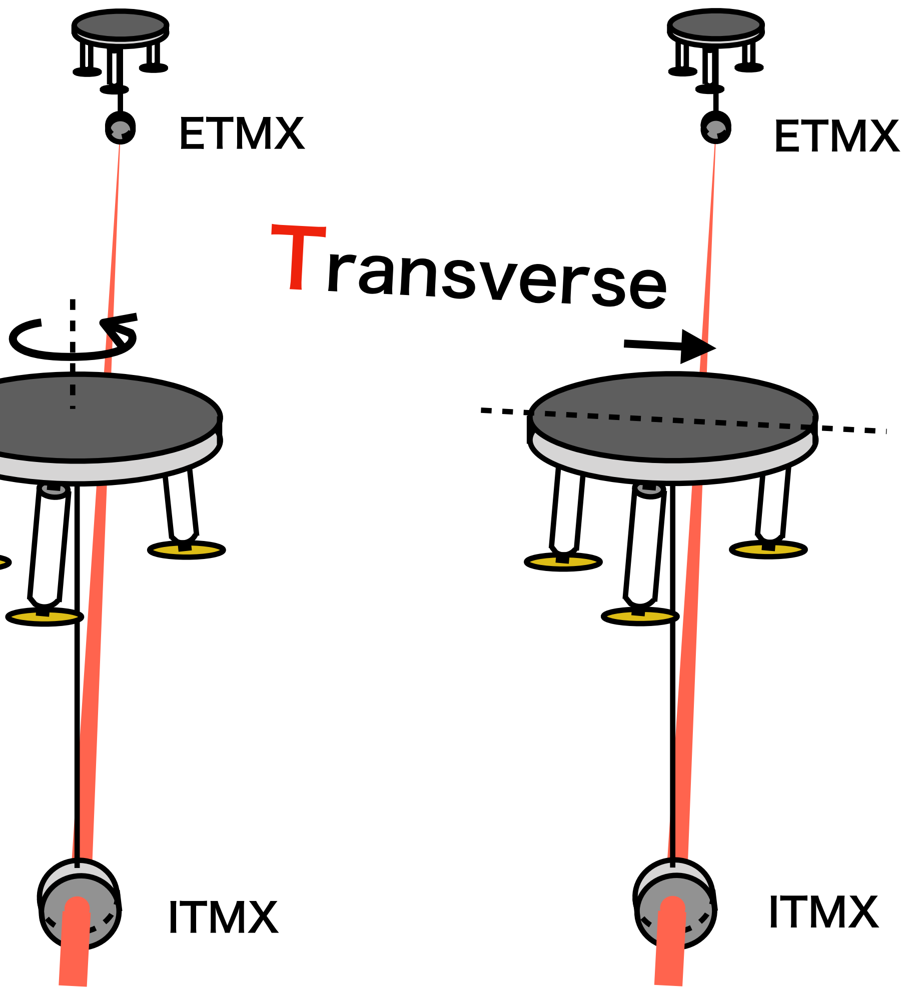
Reduction in 0.03 - 1 Hz

- microseismic band by -6 dB.
- earthquake band was not clearly.



Discussion





In microseismic band,

- Coherence between other degrees of freedoms (yaw, transverse) and X arm existed.
- This imply that signal coupling from these control signals was existed.
- So, reduction of -6 dB might be limited by the couplings.

Contents

Conclusion

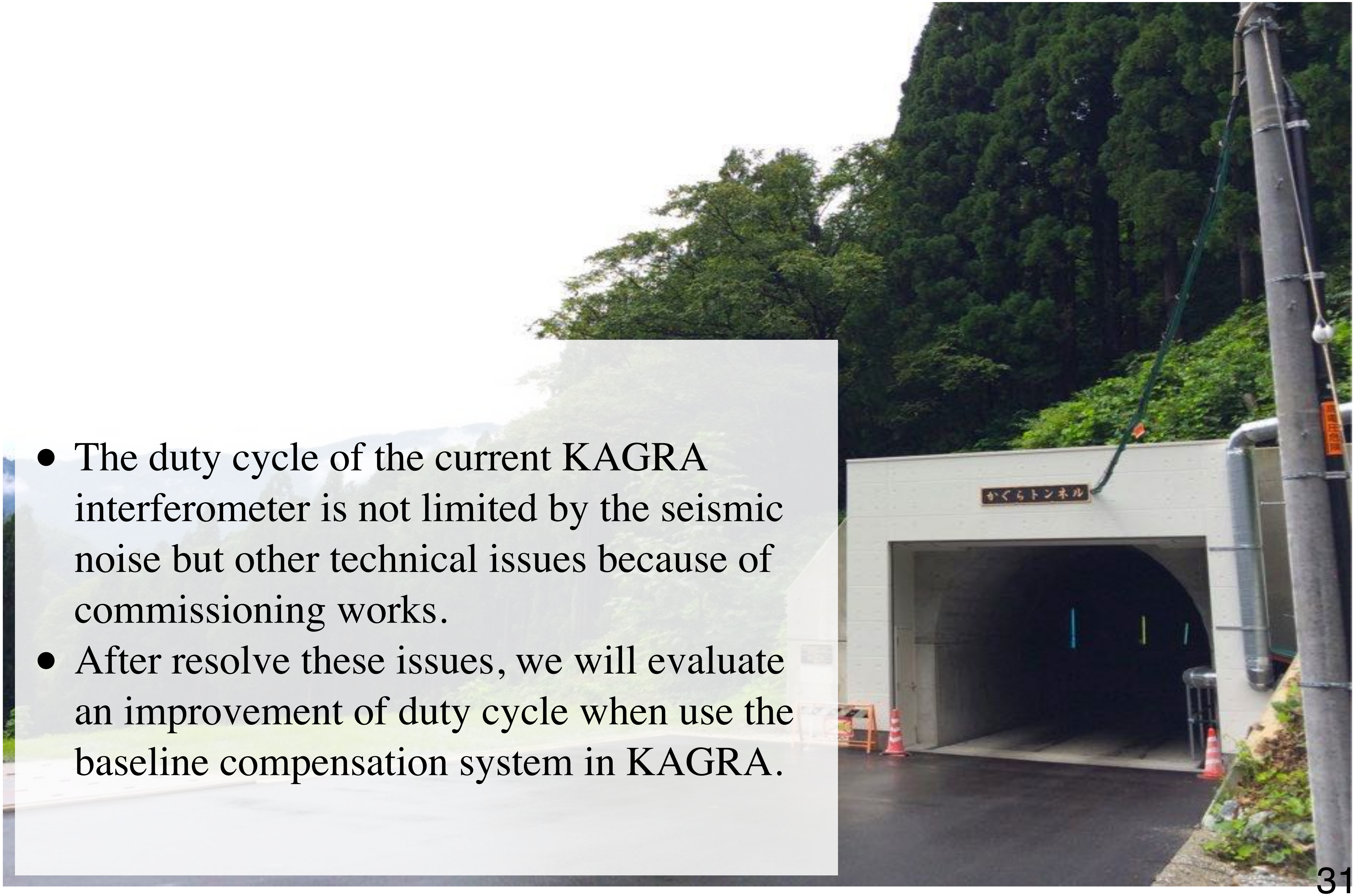
- Duty cycle is limited by low-frequency seismic noises
  - Microseismic noise (0.1 - 1 Hz)
  - Large earthquake (0.03 - 100 mHz)
  - Earth tides (1 day)

- We designed the baseline compensation system and demonstrate its performance by using X-arm cavity of KAGRA.

- As a result, reduction of target seismic noises are
  - Microseismic noise was reduced by -6 dB.
  - Reduction in earthquake band was not seen because the seismic noise was small enough to see the GIF noise.
  - Earth tide was reduced by at most -35 dB.

- This is the first demonstration of the baseline compensation on the km-scale GW detector in the world.

Future Prospects



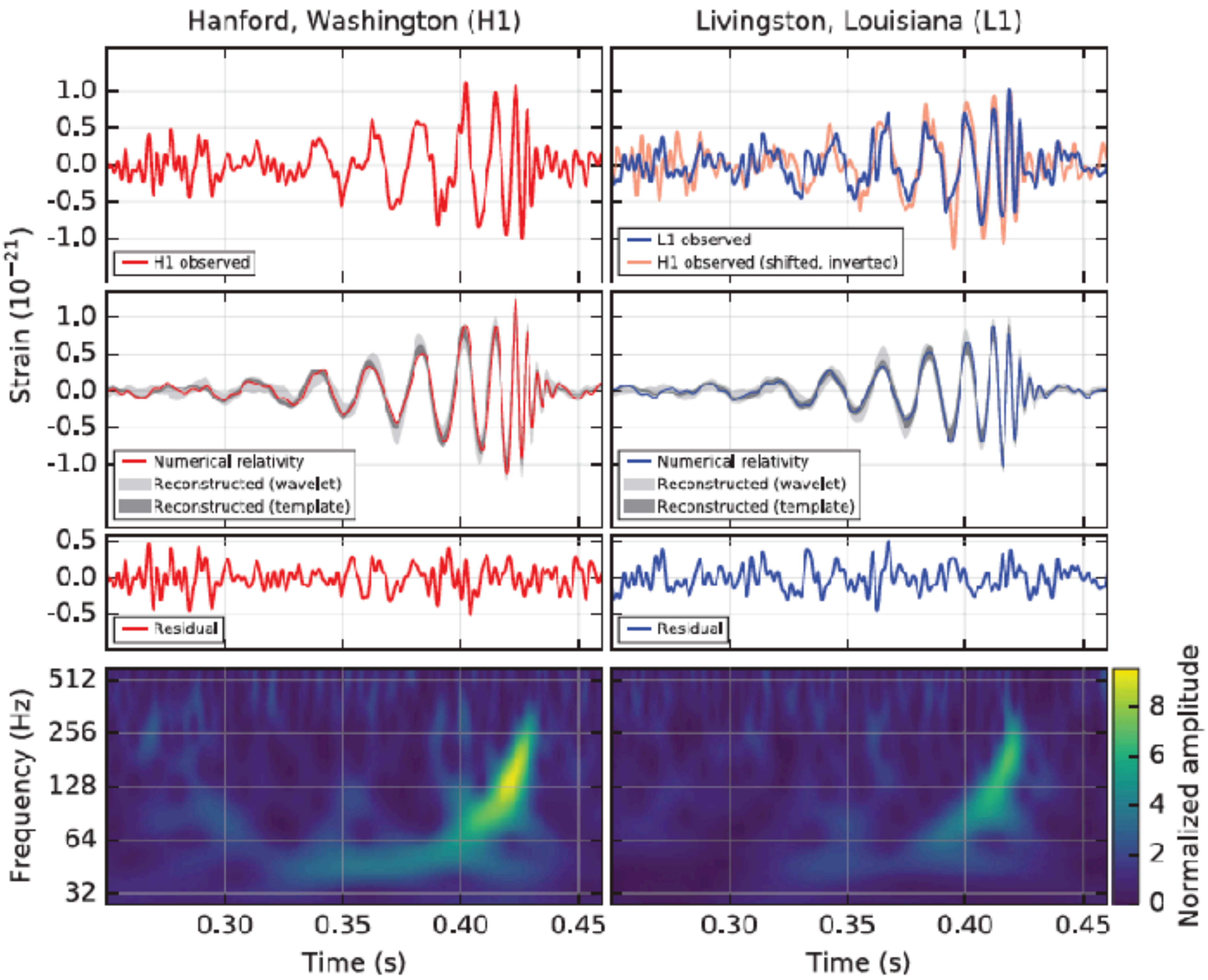
- The duty cycle of the current KAGRA interferometer is not limited by the seismic noise but other technical issues because of commissioning works.
- After resolve these issues, we will evaluate an improvement of duty cycle when use the baseline compensation system in KAGRA.

Backup

要点

- 本研究の目的は、重力波検出器の観測可能期間 (duty cycle) を向上させることである。個々の検出器の duty cycle の向上は、複数台同時観測が必須である重力波観測にとって、重要な課題である。
- Duty cycle は、主に 1 Hz 以下の低周波地面振動によって制限されている。なぜならば現在の防振システムは、制御に使用している慣性センサーの感度不足が原因で、これら地面振動に対して十分な防振性能を持っていないためである。
- 本研究では従来方式の問題点を解決するための新しい防振システムを提案し、それによる防振を実証した。

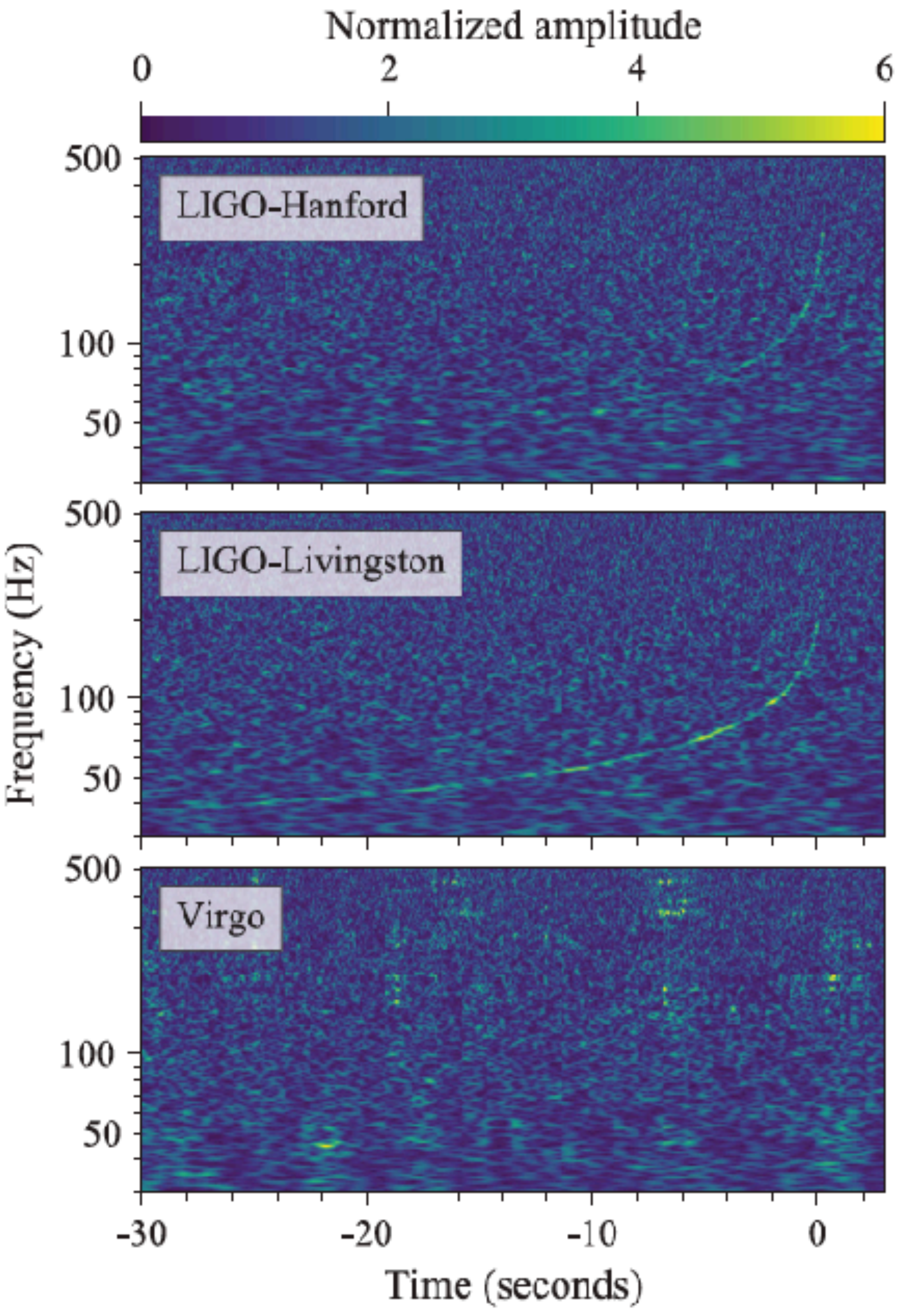
GW150914: binary black hole merger



Abbott, B. P., et al. *Phys. Rev. Lett.* **116**, (2016), 061102.

- Detected by 2 LIGO detectors

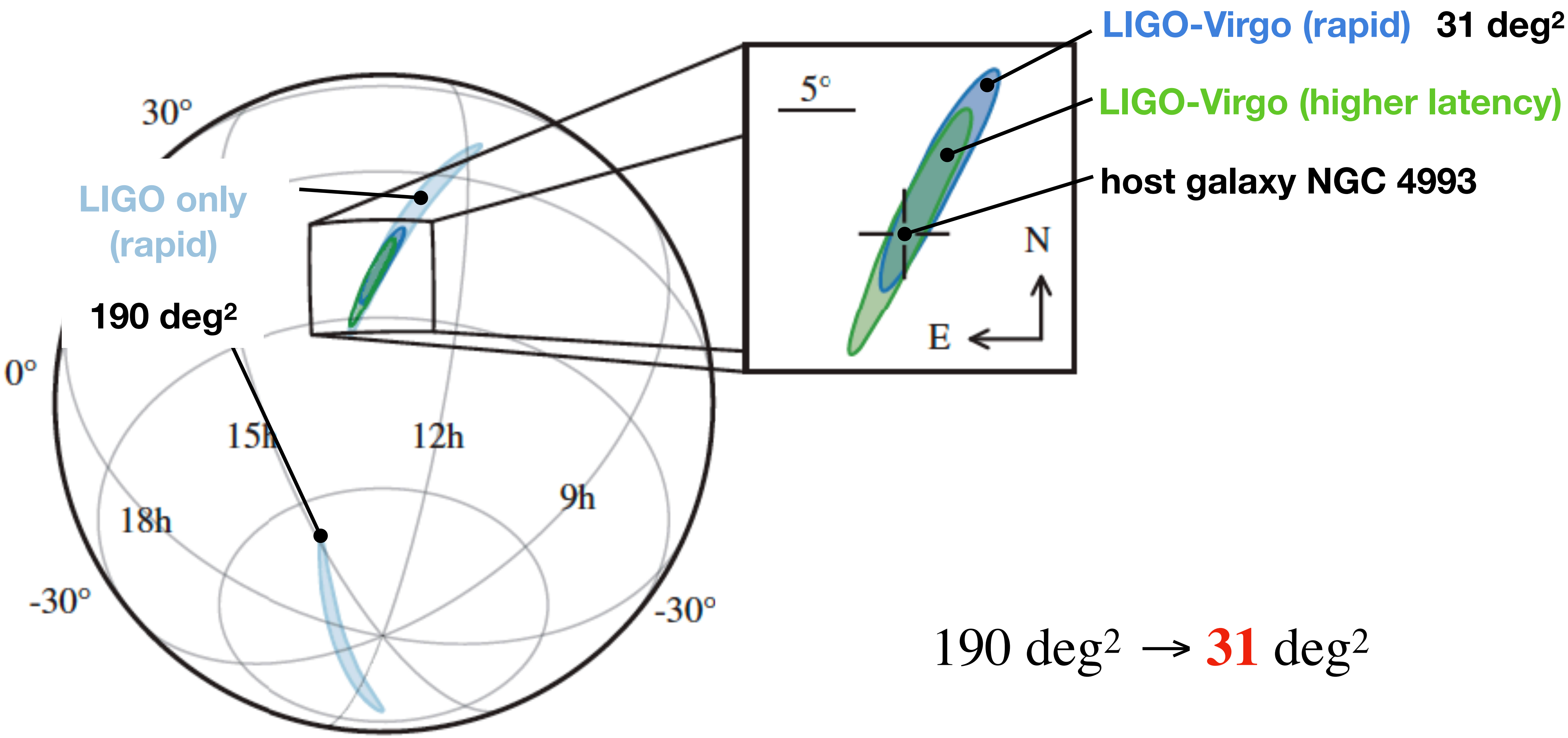
GW170817: binary neutron star inspiral



Abbott, B. P., et al. *Phys. Rev. Lett.* **119**, (2017), 161101.

- Detected by 3 detectors
- LIGOの2台は明瞭にチャープ波形をうけてVirgoは死角にいた。
- しかし3台目のおかげで到来方向を決定する助けになった。

Sky localization of GW170817



LIGO-Virgo (rapid) 31 deg^2

LIGO-Virgo (higher latency)

host galaxy NGC 4993

LIGO only (rapid)

190 deg^2

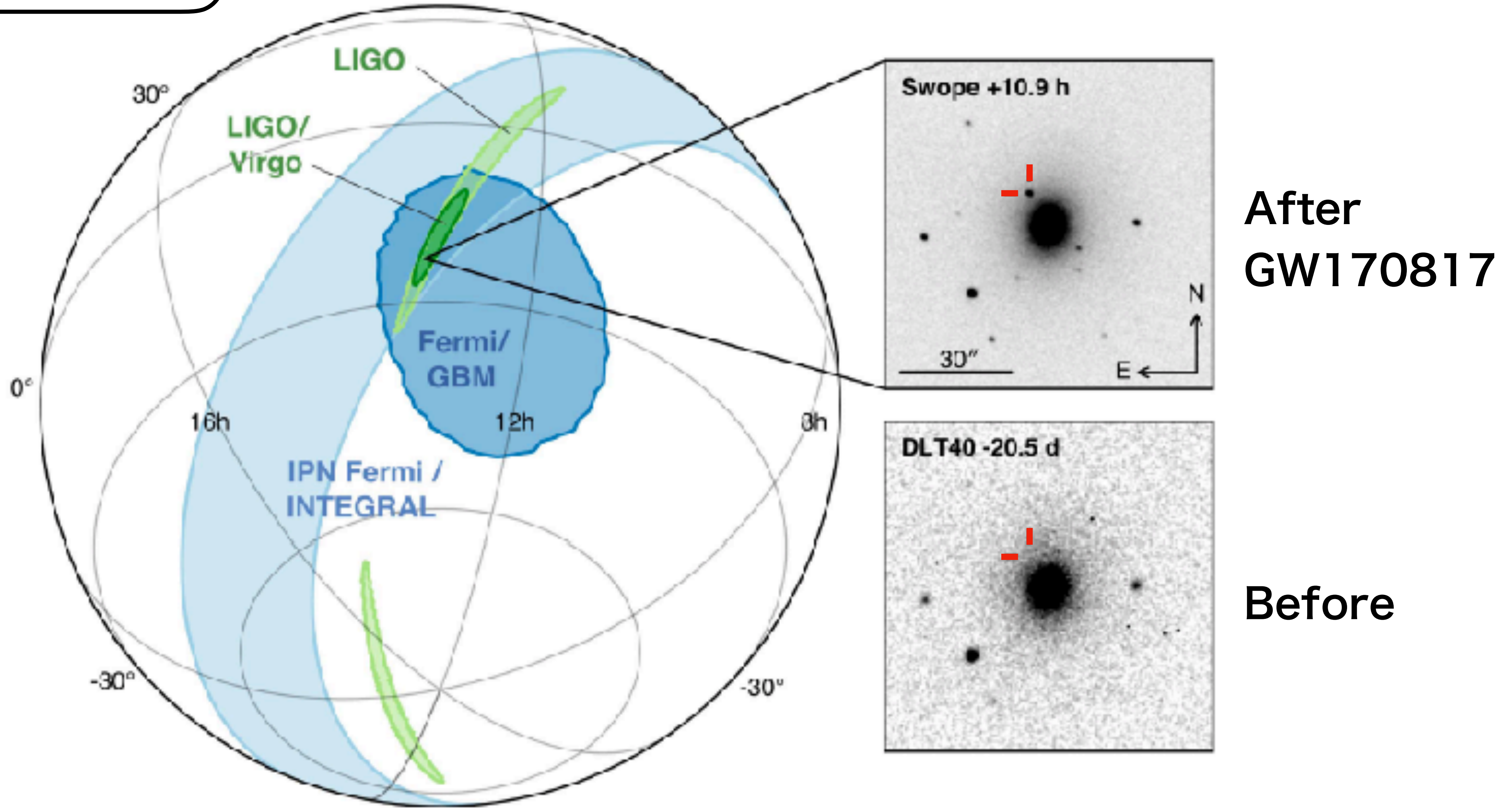
190 deg^2 → **31** deg^2

Abbott, B. P., et al. *Phys. Rev. Lett.* **119**, (2017), 161101.

Multi-messenger observation

LIGO → LIGO & Virgo

190 deg^2 → **31** deg^2

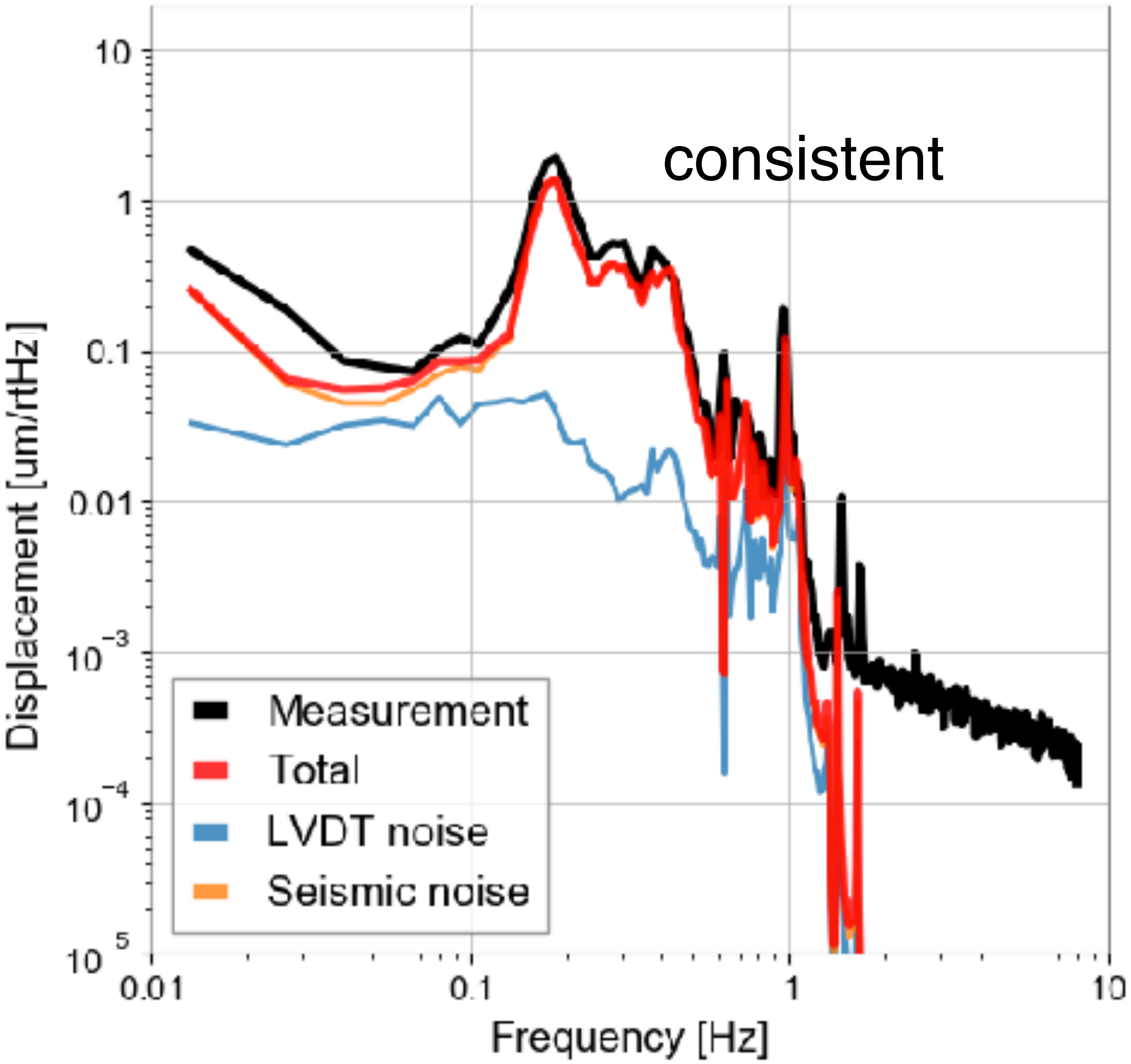


Abbott, B. P., et al. *Astrophys. J. Lett.* **848**, (2017), L12.

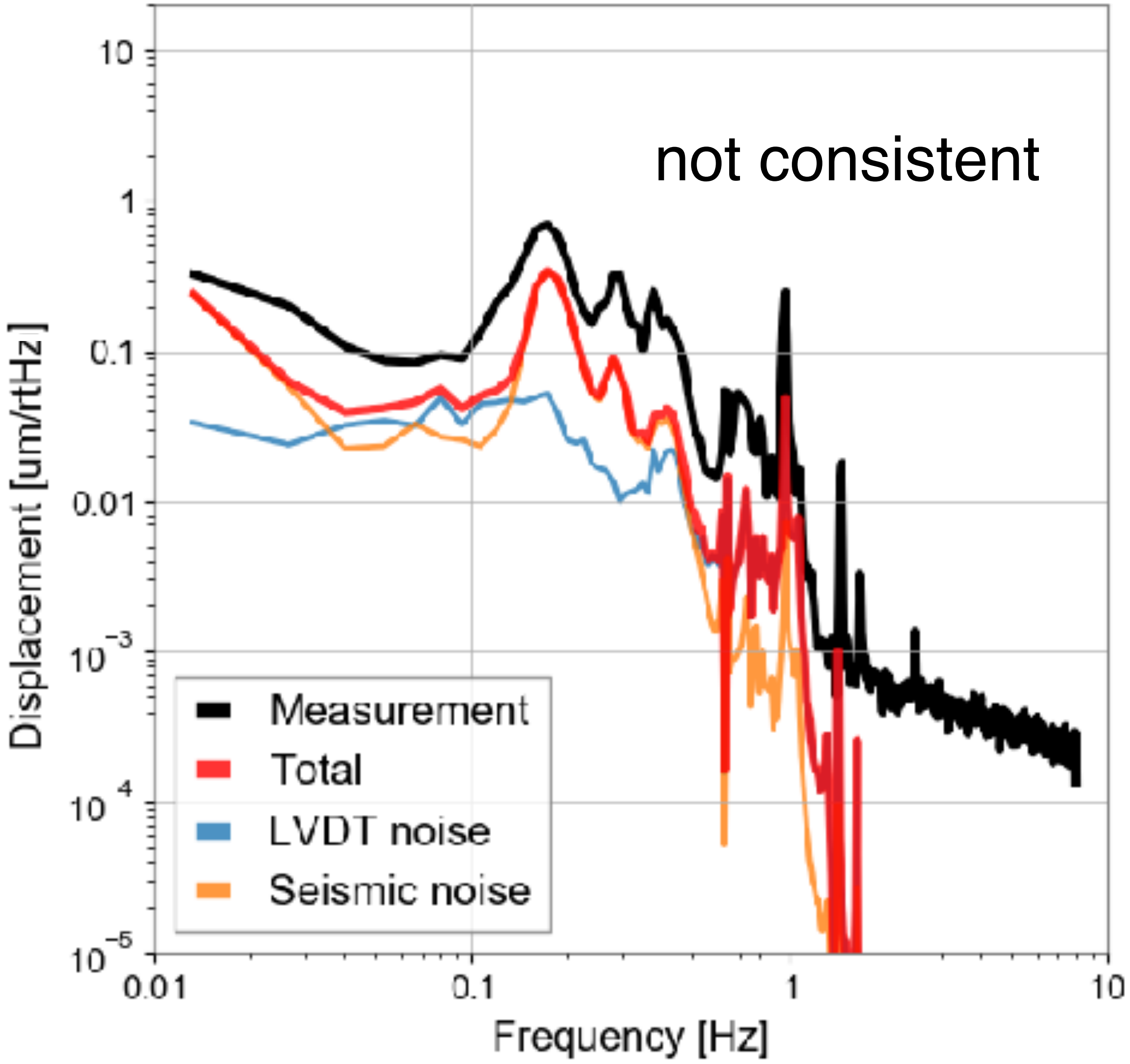
- Many **electromagnetic counterparts discovered** in Ultraviolet, optical, infrared, Gamma-rays, X-rays, and radio.
- To localize the GW sources, we must **operate 3 detectors** simultaneously.

Comparison with the simulation

OFF

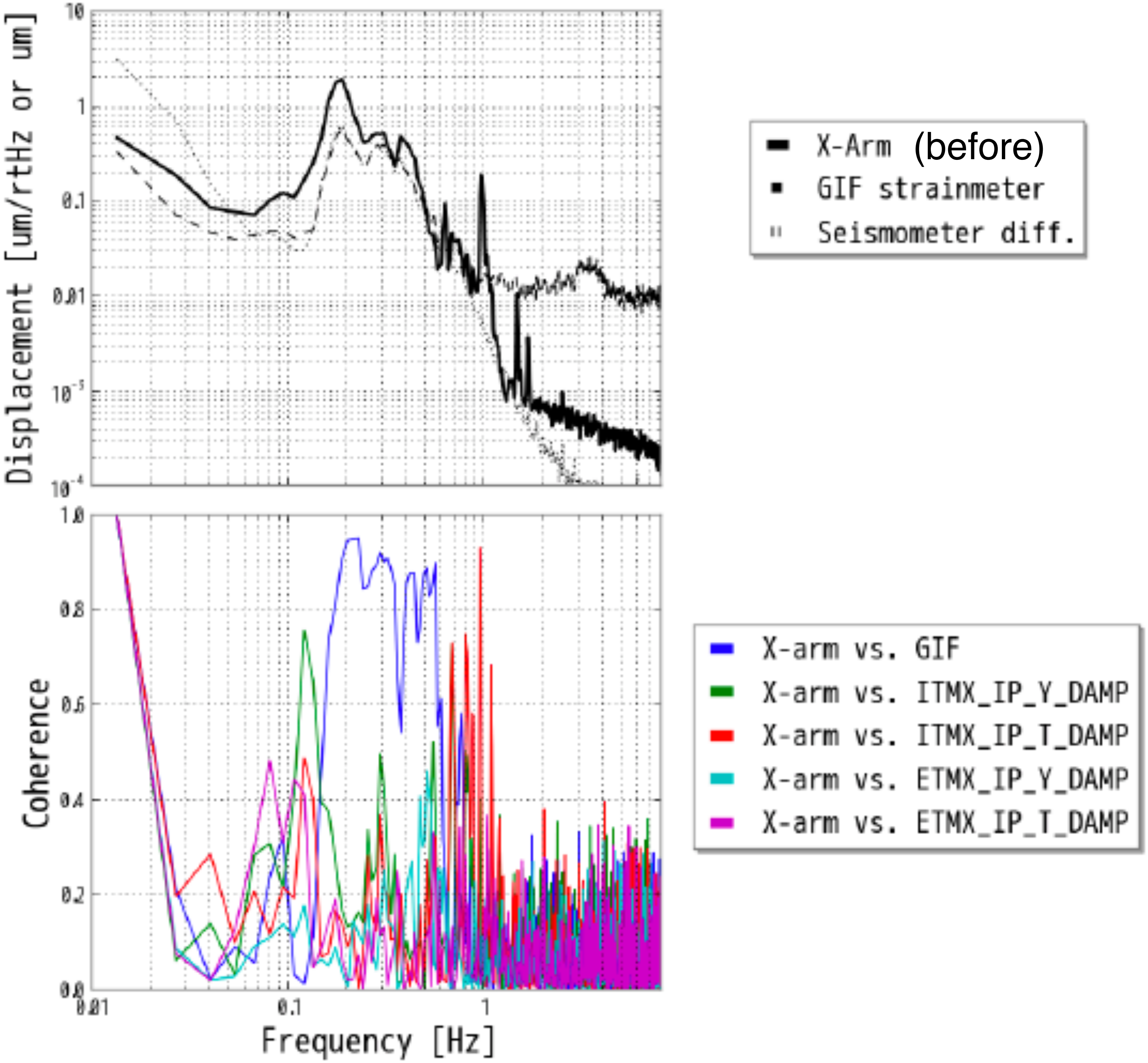

consistent

ON


not consistent

- OFF : Measurement was consistent with the model simulation
- ON : Measurement was not

Discussion: coherences before control



Gravitational-wave (GW) Telescope

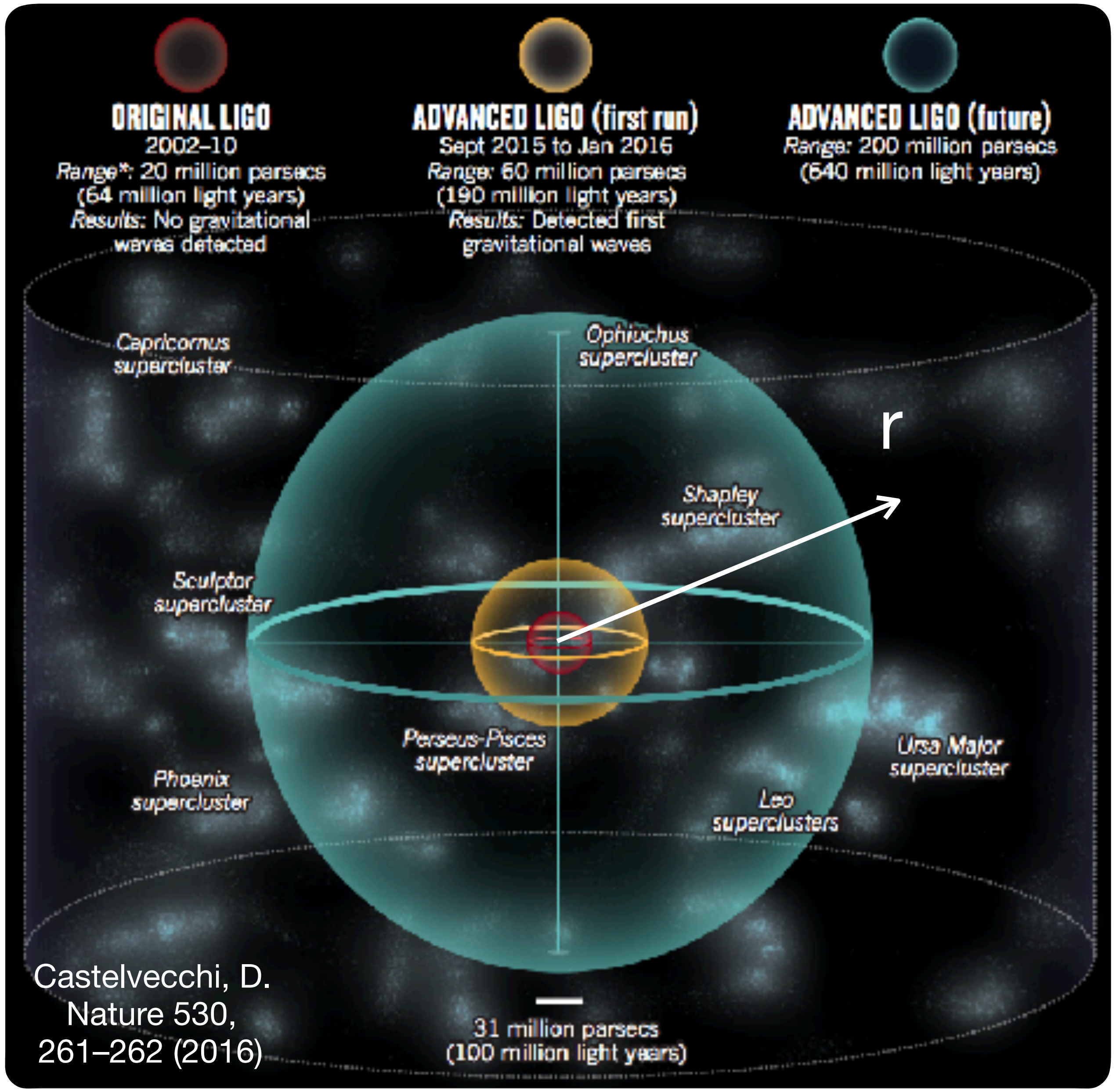
Sensitivity ×10 → Event Rate ×1000

(Operation time)

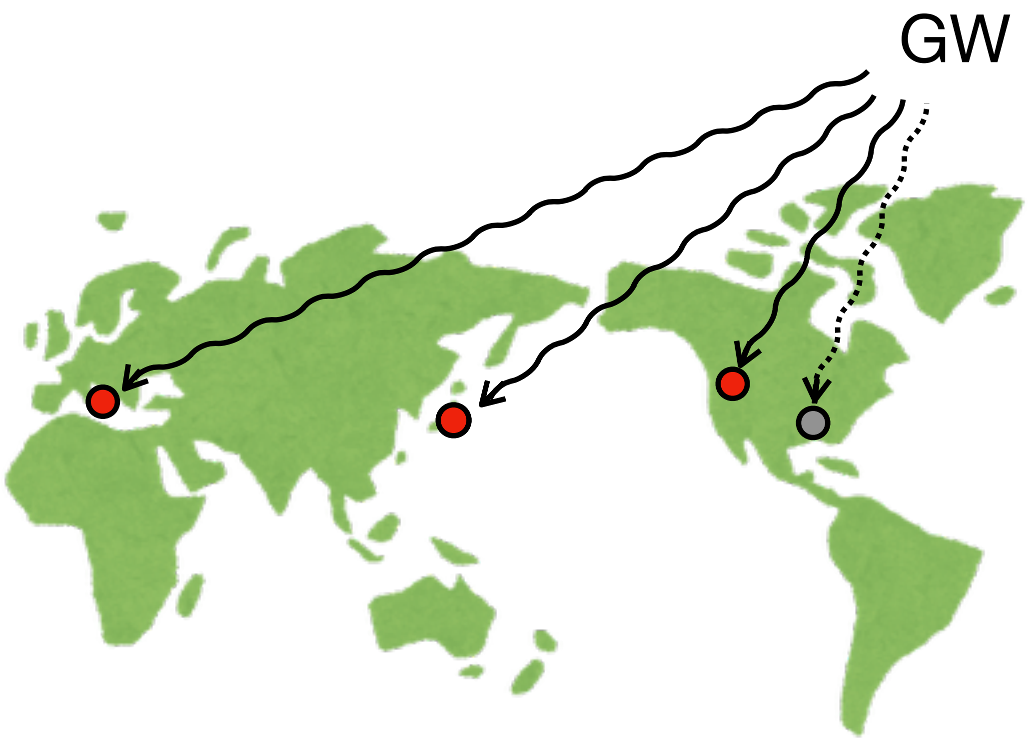
Duty cycle ≒ $D_1 \times D_2 \times D_3 \times \dots$

(D_i : duty cycle of the i-th detector)

e.g. LIGO detector



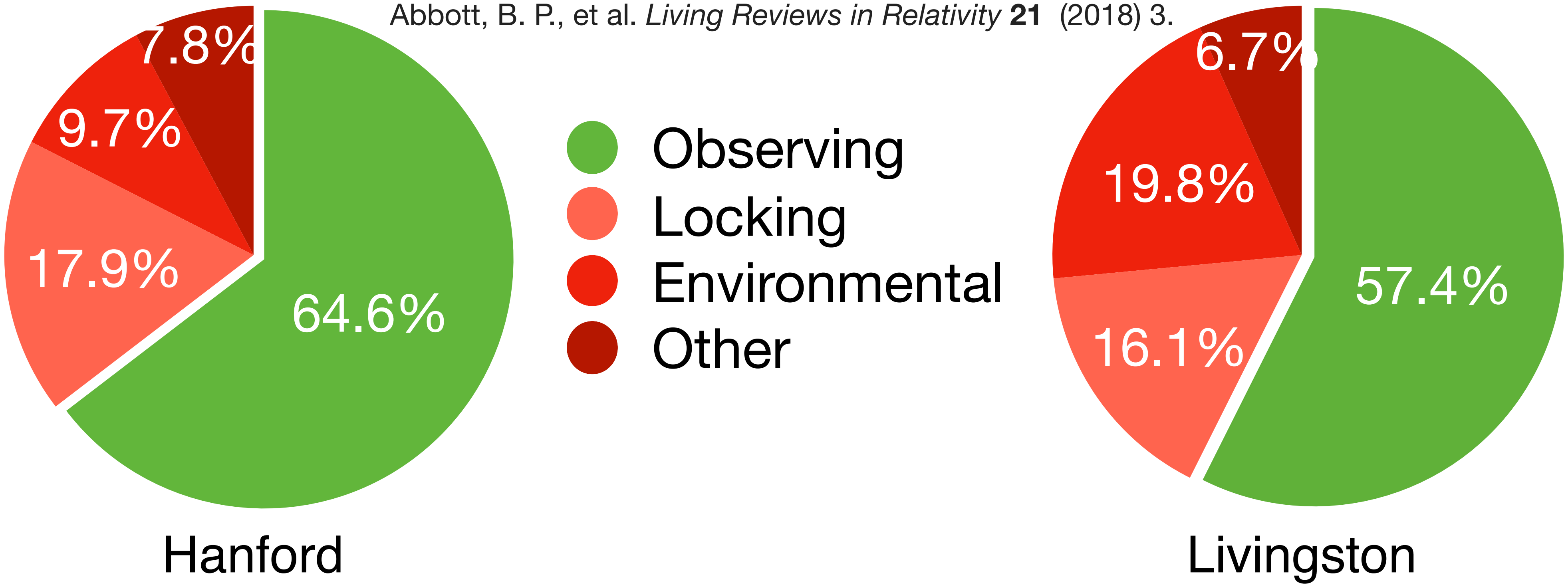
Castelvecchi, D. Nature 530, 261–262 (2016)



At least, 3 detectors must operate simultaneously to determine the direction of arrival.

Duty cycles

e.g. LIGO detectors during the first observation (O1)



Abbott, B. P., et al. *Living Reviews in Relativity* **21** (2018) 3.

Locking

- Transition state from an uncontrolled state to observing state

Environmental

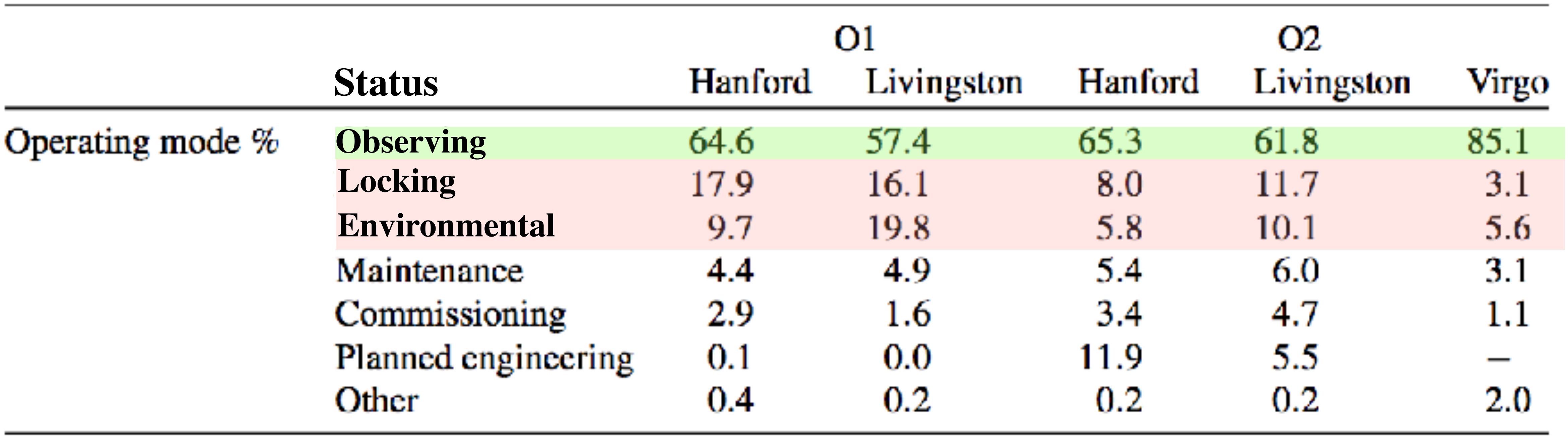
- could not control due to seismic disturbances.

Other

- commissioning or planed maintenances.

Duty cycle in O1 and O2

arXiv:1304.0670v9



		O1		O2		
	Status	Hanford	Livingston	Hanford	Livingston	Virgo
Operating mode %	**Observing**	64.6	57.4	65.3	61.8	85.1
	Locking	17.9	16.1	8.0	11.7	3.1
	Environmental	9.7	19.8	5.8	10.1	5.6
	Maintenance	4.4	4.9	5.4	6.0	3.1
	Commissioning	2.9	1.6	3.4	4.7	1.1
	Planned engineering	0.1	0.0	11.9	5.5	–
	Other	0.4	0.2	0.2	0.2	2.0

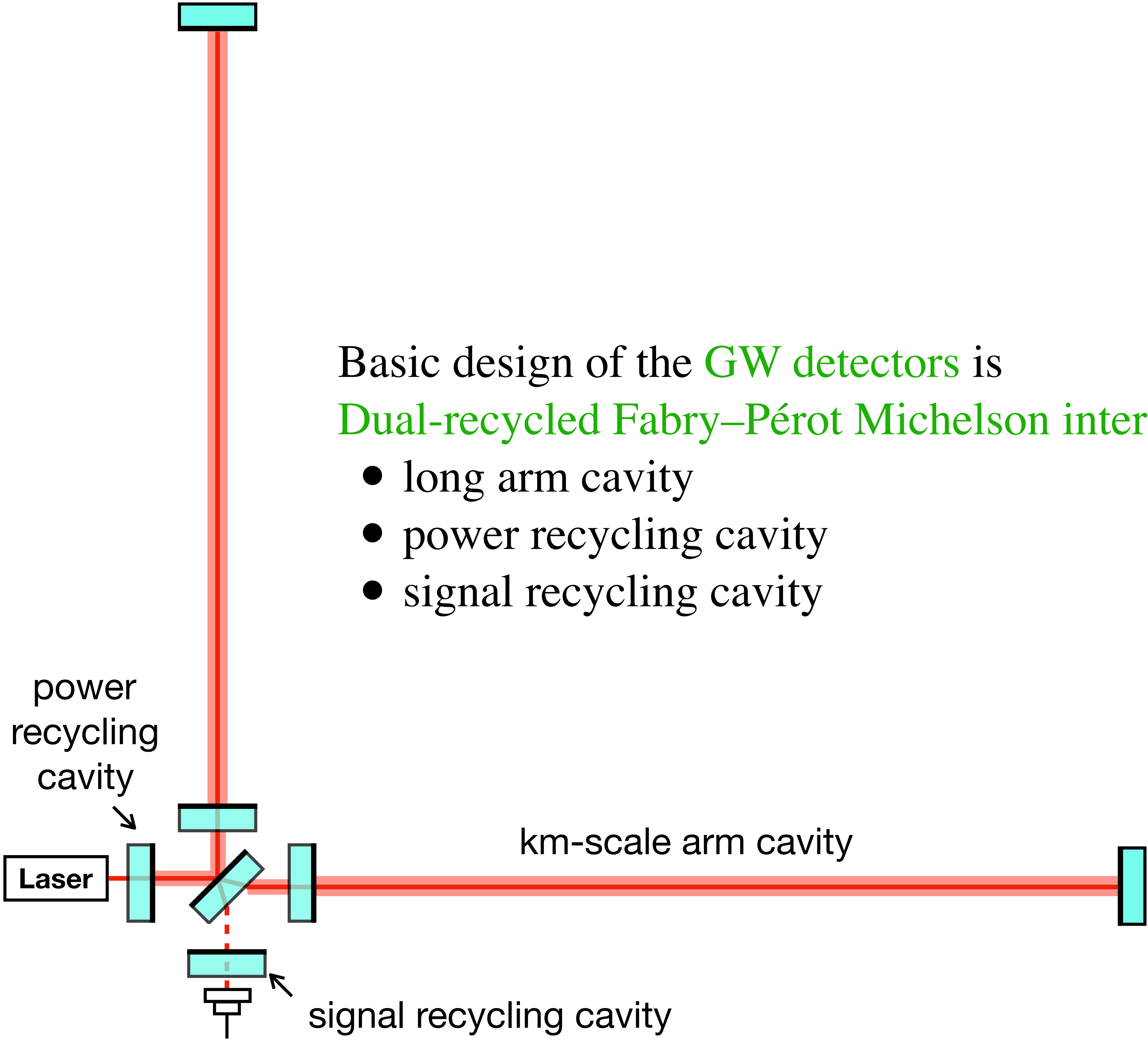
- **“Observing”**
  - Observation status
- **“Locking”**
  - Not observation but just locking the interferometer
- **“Environmental”**
  - Not even locking due to environmental disturbances

- **O1** (49 days)
  - 12 Sep. 2015 - 19 Jan. 2016
  - “Environmental” ratio raised in winter season.
- **O2** (117 days)
  - 30 Nov. 2016 - 25 Aug. 2017
  - AdV join on 1 Aug. 2017
  - Avoided winter season

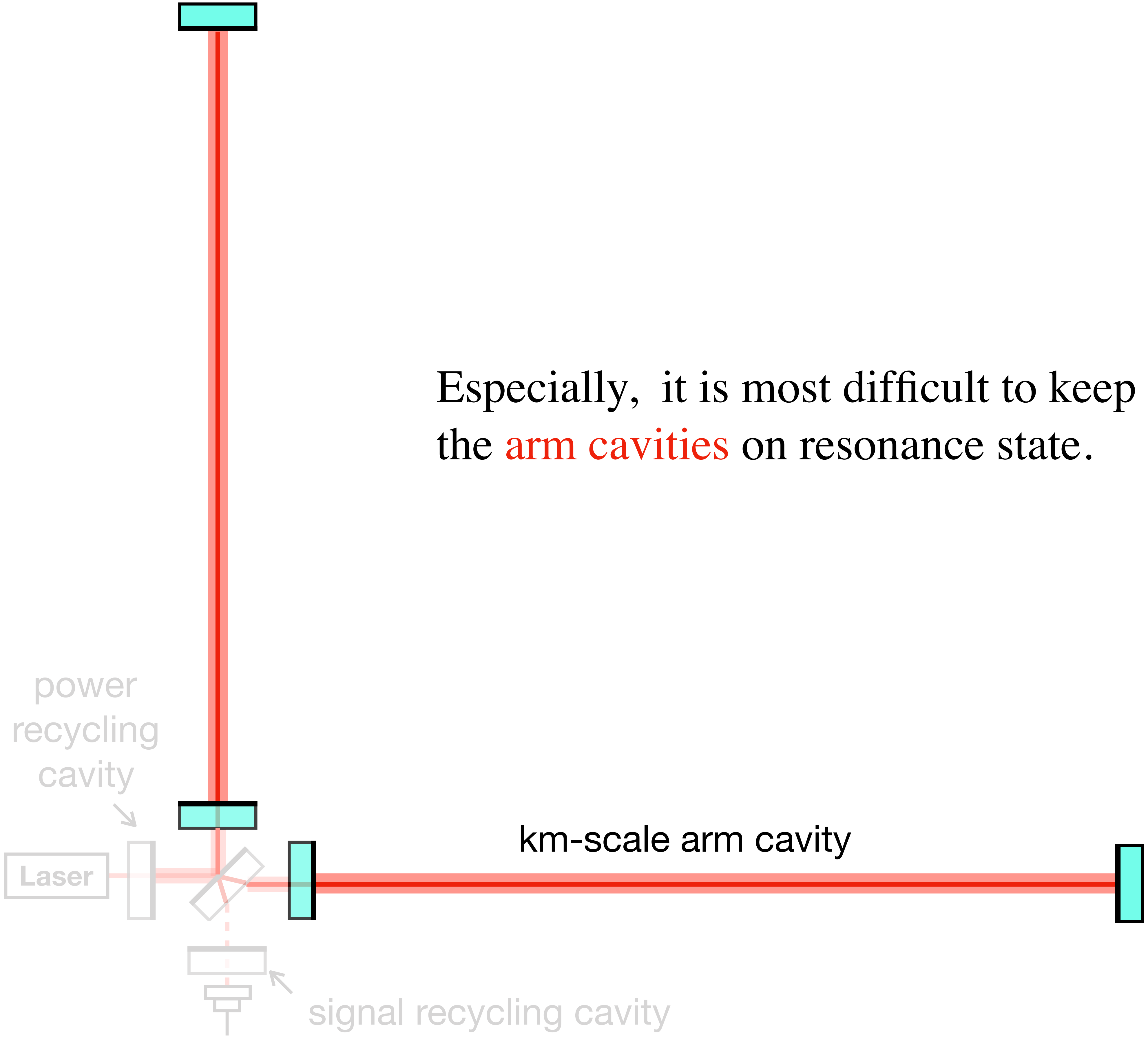
Why GW detectors are weak to seismic disturbances?

Basic design of the GW detectors is
Dual-recycled Fabry–Pérot Michelson interferometer

- long arm cavity
- power recycling cavity
- signal recycling cavity

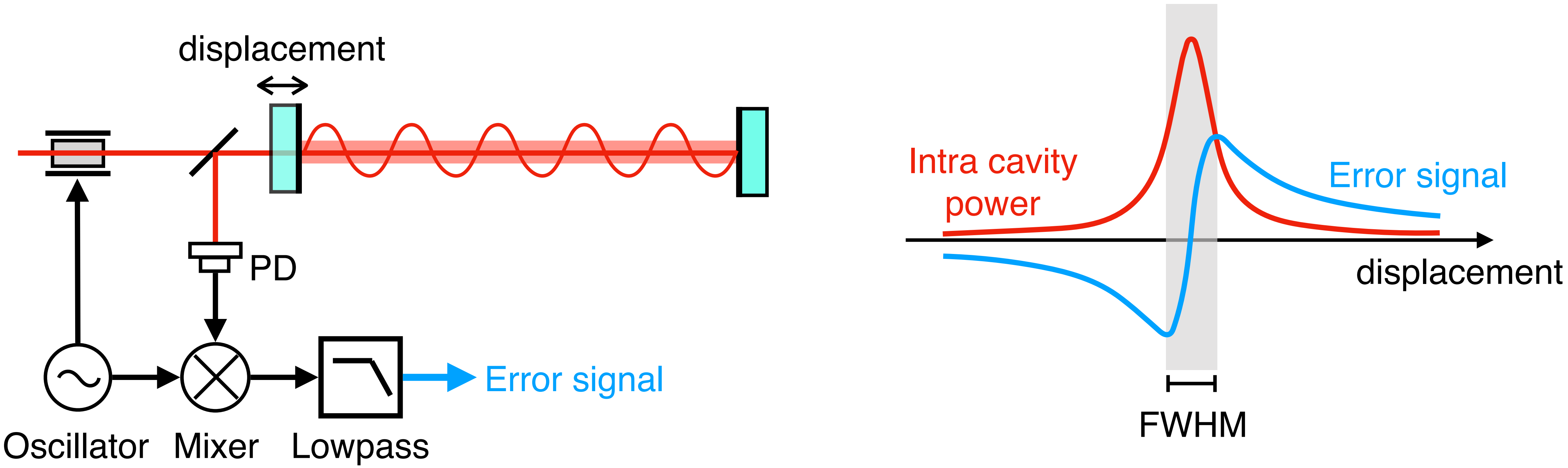


Why GW detectors are weak to seismic disturbances?



Especially, it is most difficult to keep the arm cavities on resonance state.

Difficulties in the cavity control



Pound–Drever–Hall (PDH) technique

Resonant condition

- cavity length = N × wavelength (N = 1, 2, …)

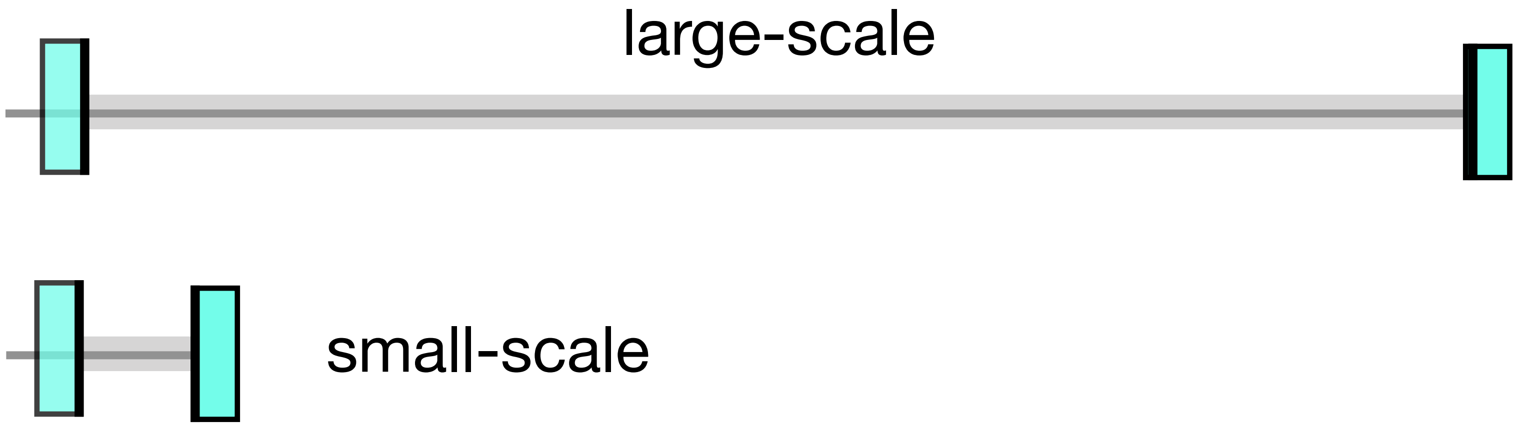
Controlable condition

- Error signal is linear in FWHM range (~ nm).

↓

Seismic disturbances should be attenuate <u>within a few nm.</u>

Difficulties in the long cavity

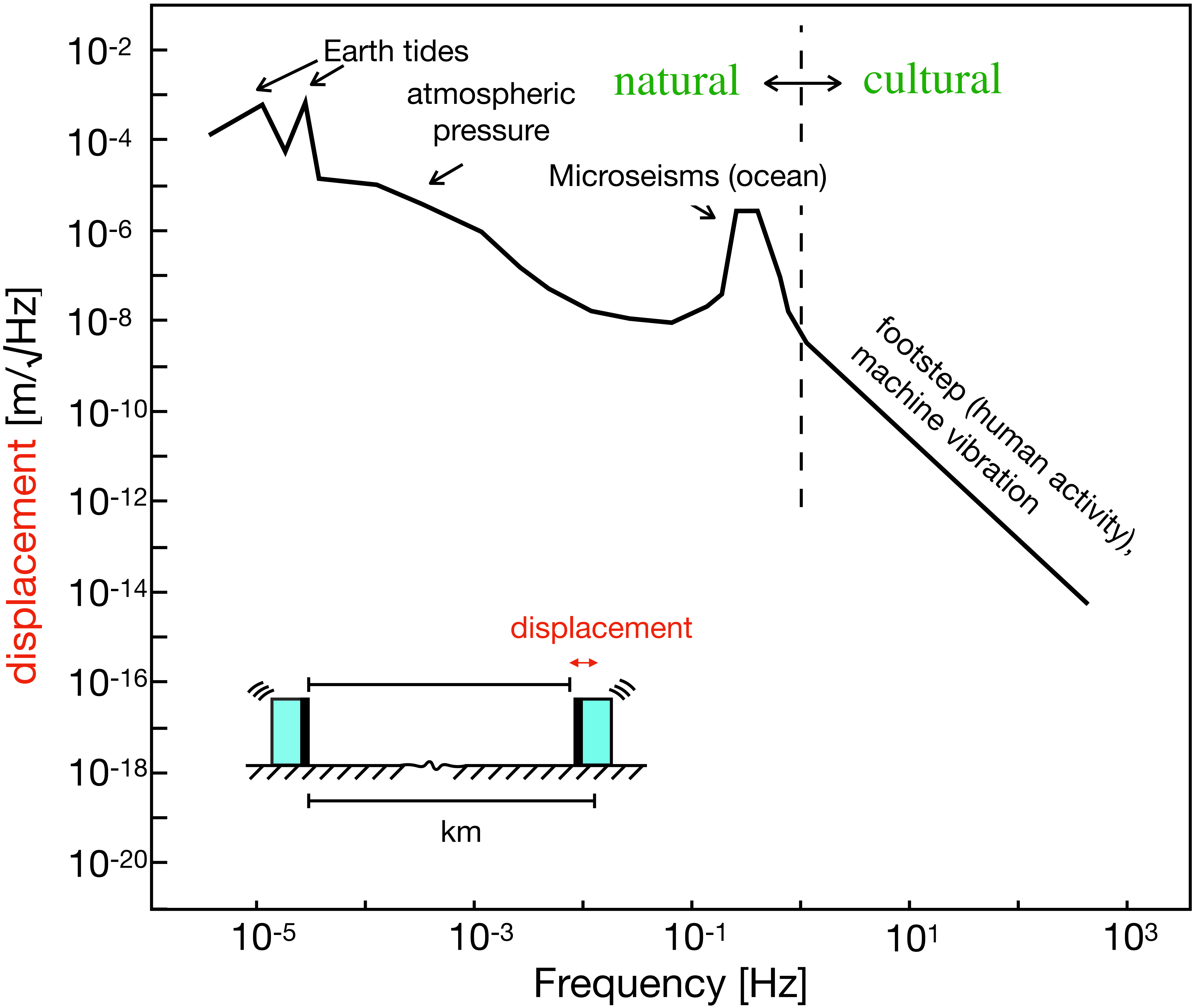


If low-frequency (1 Hz) seismic wave shakes the ground,

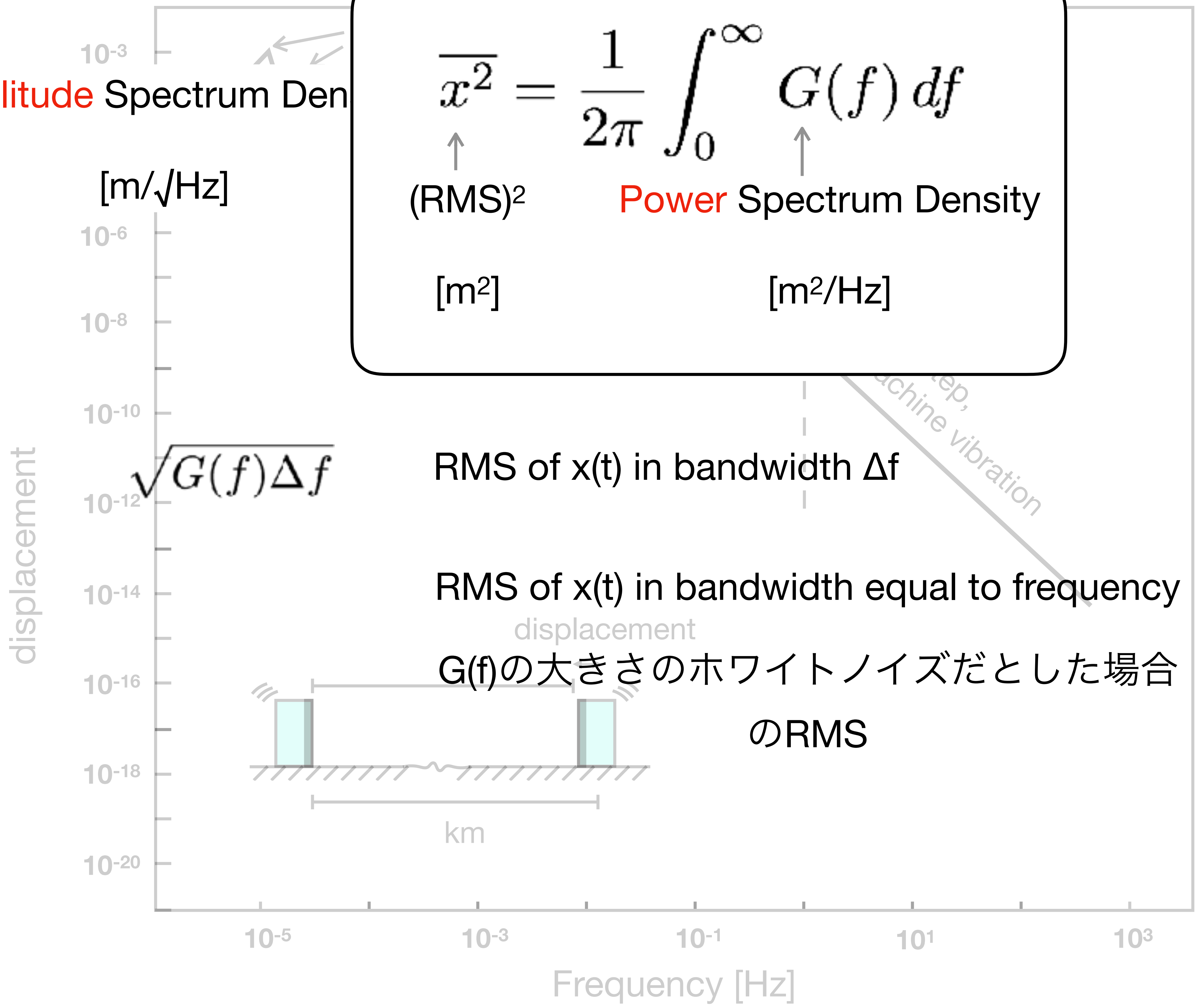
- small-scale cavity moves with common motion → few length change
- large-scale cavity decrease the correlation → appearing length change

Therefore, large-scale arm cavity needs the seismic isolation system in low-frequency.

Seismic Noise (stationary)



Seismic Noise



Amplitude Spectrum Den

[m/√Hz]

$$\overline{x^2} = \frac{1}{2\pi}\int_0^\infty G(f)\,df$$

↑ (RMS)^2

[m^2]

↑ Power Spectrum Density

[m^2/Hz]

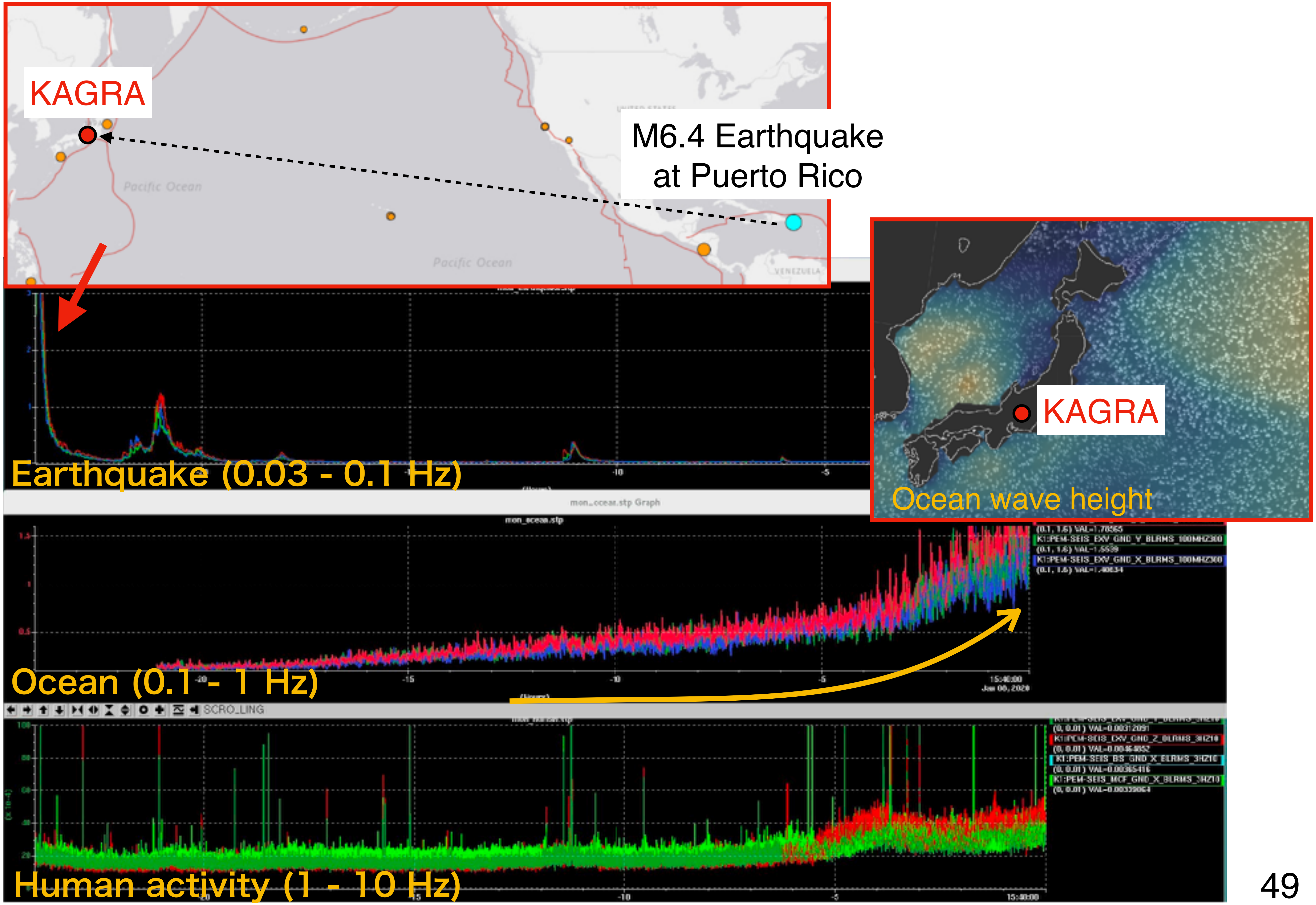
$\sqrt{G(f)\Delta f}$

RMS of x(t) in bandwidth Δf

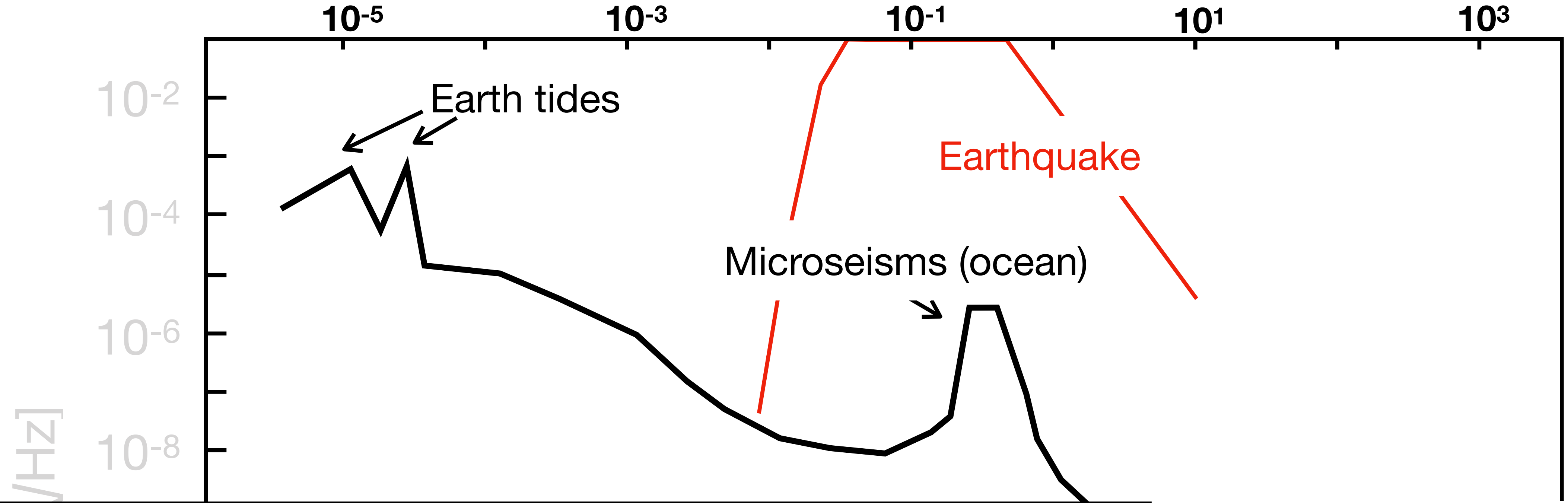
RMS of x(t) in bandwidth equal to frequency

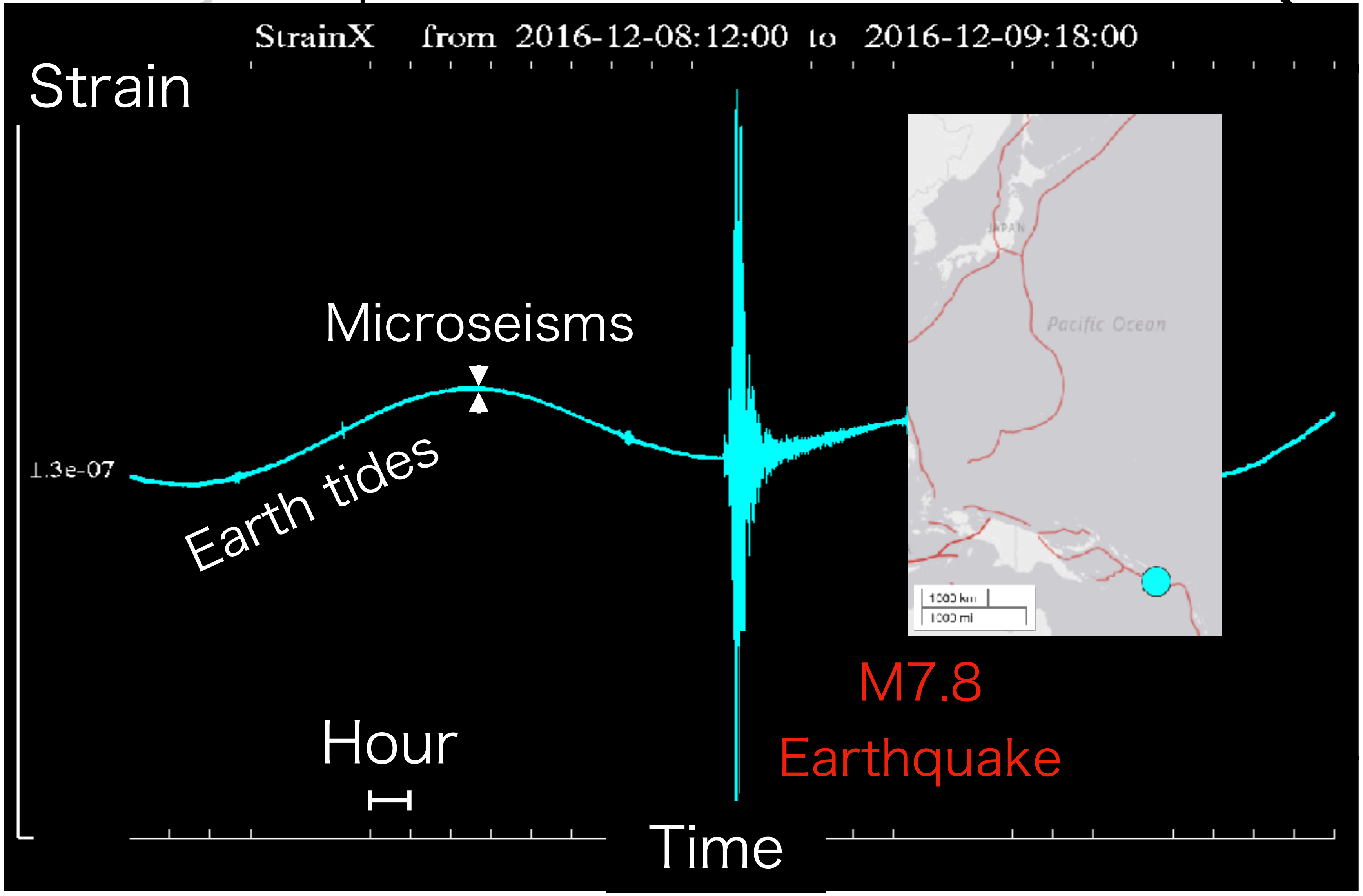
G(f)の大きさのホワイトノイズだとした場合のRMS

e.g. Seismic disturbances at KAGRA



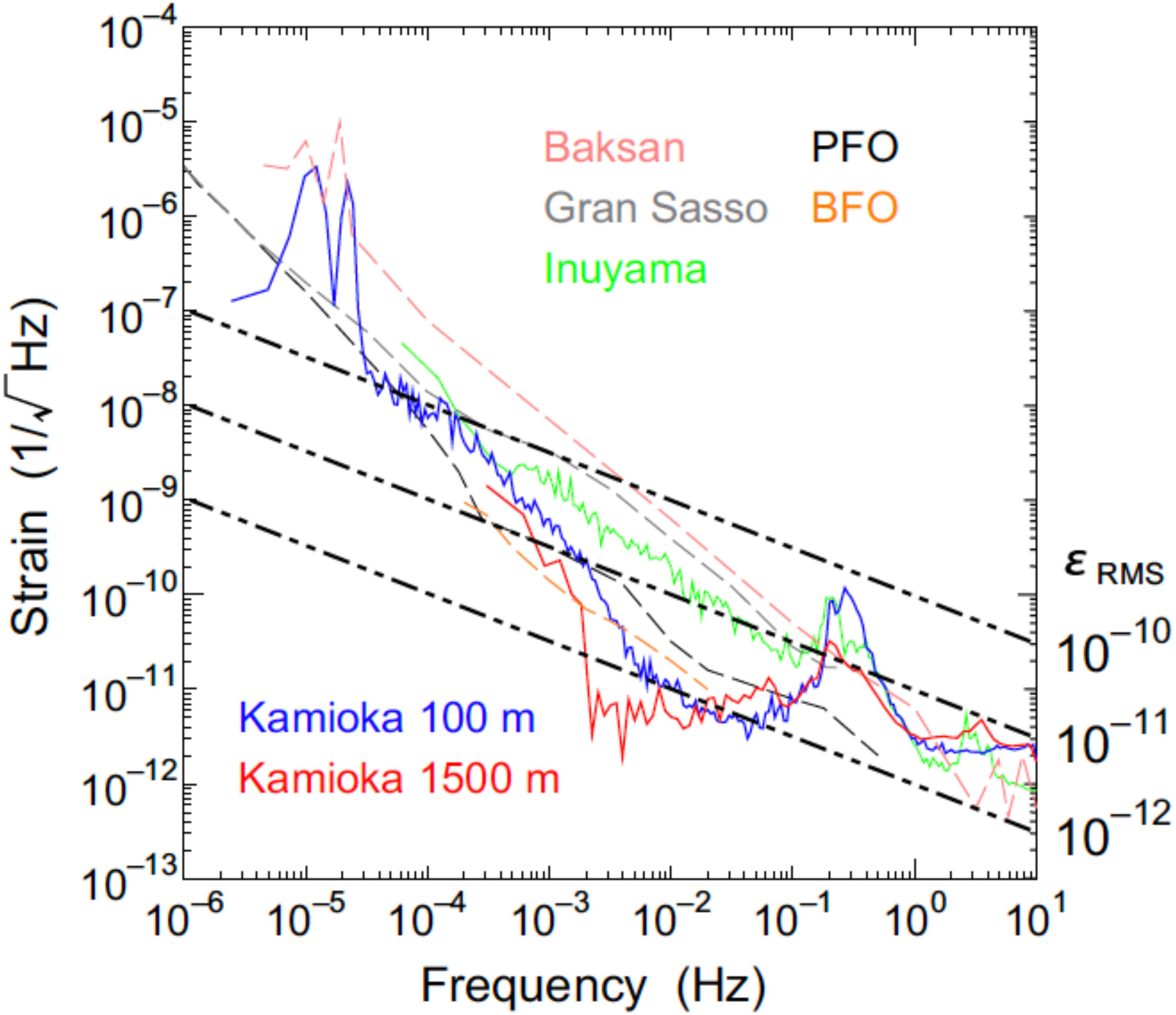
Seismic Noise (transient)



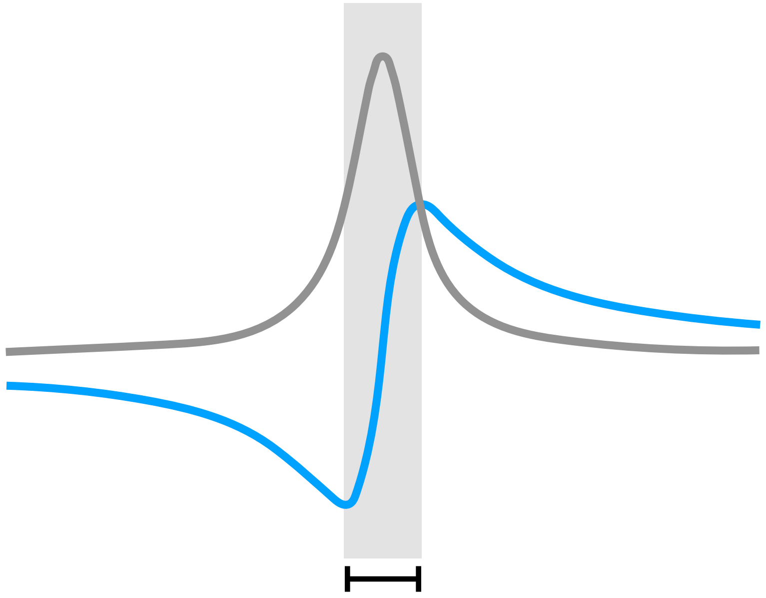


- In generally, earthquake shake the ground above 10 mHz.
- Large earthquake excite the ground with large amplitude and long period, and continues several hours.

Strain spectrum



Requirements of seismic isolation system



Cavity linewidth

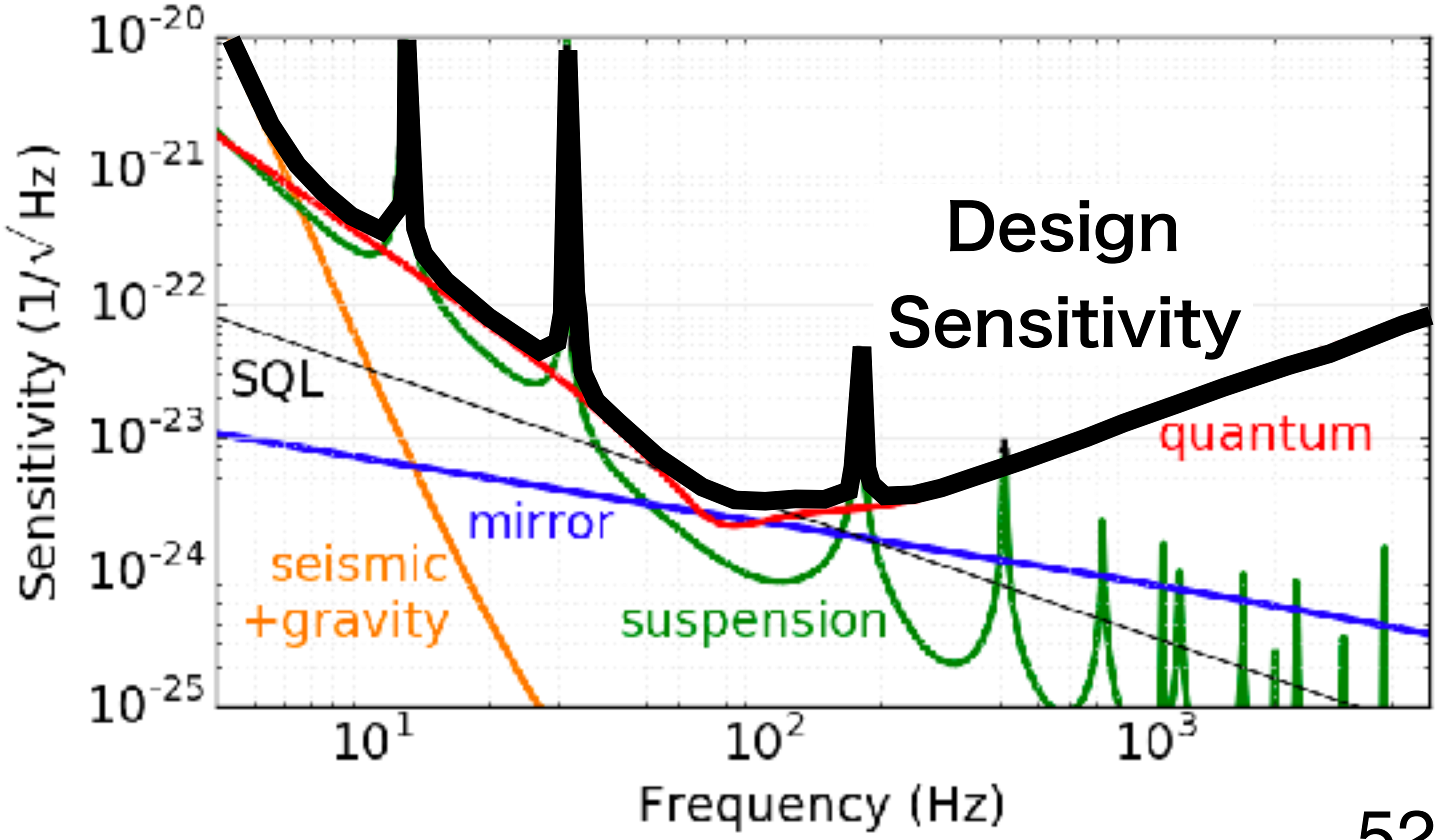
~ 1 nm

RMS requirement

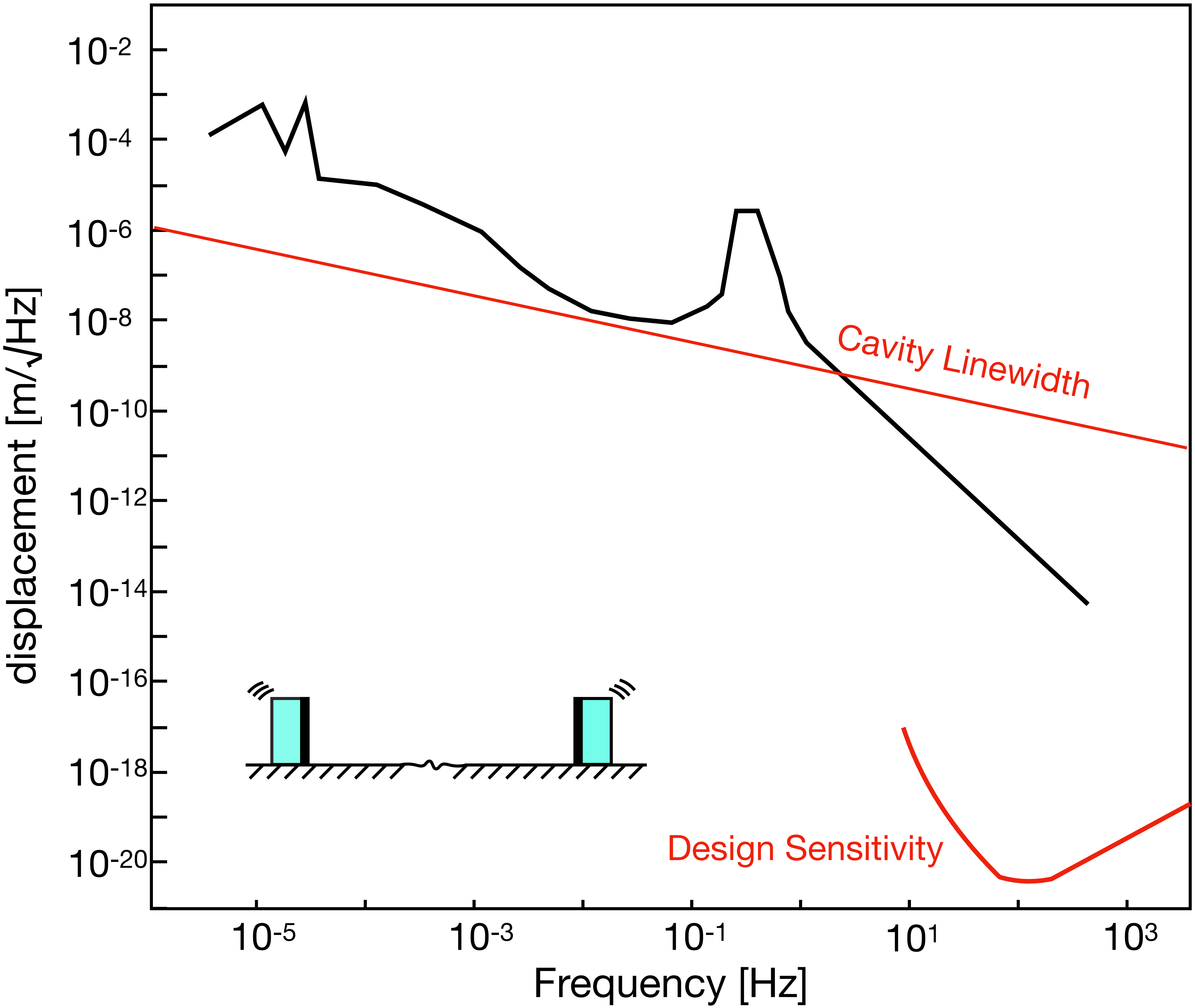
- attenuate the RMS of seismic noise within a few nm.

Noise requirement

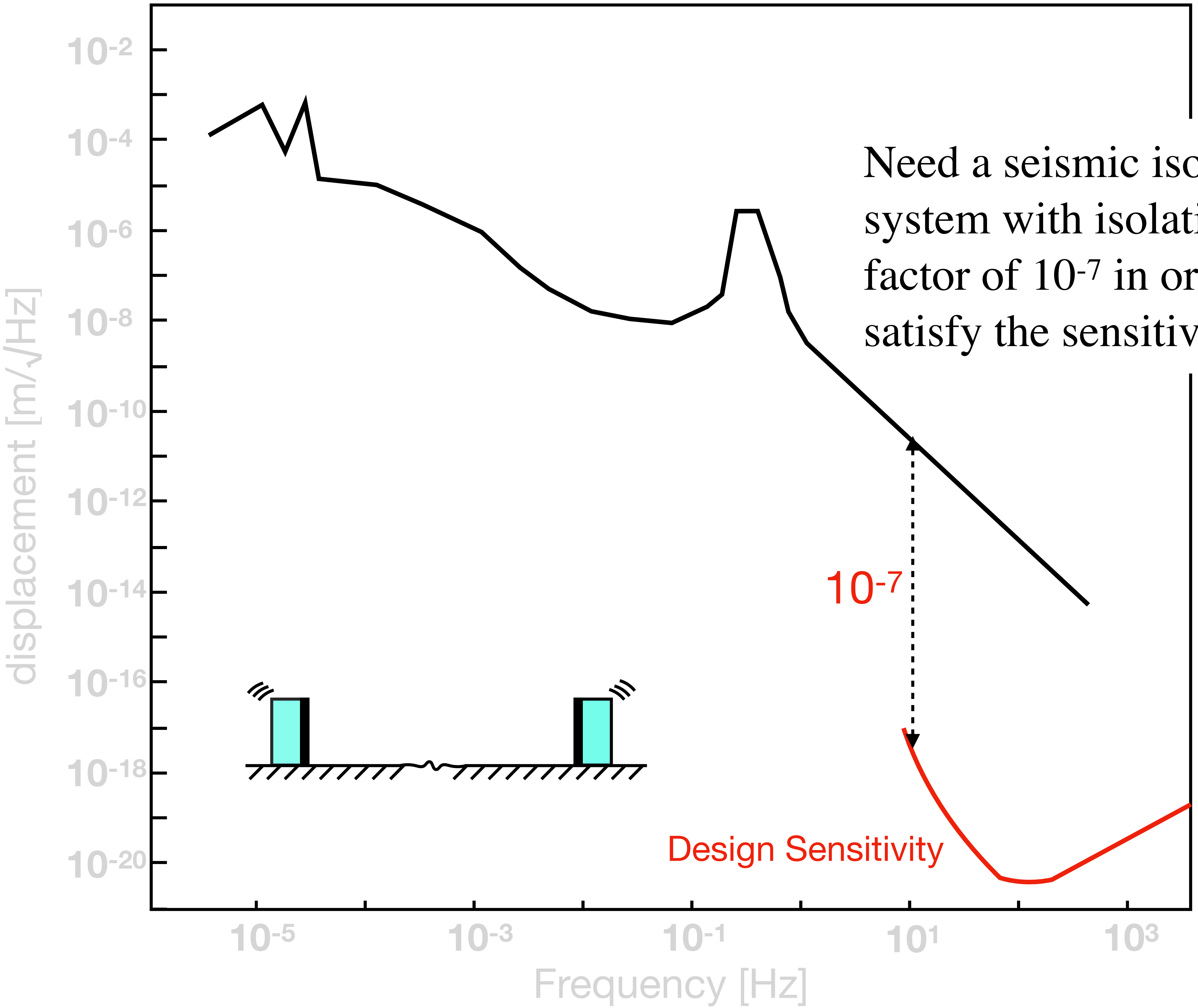
- reduce seismic noise below design sensitivity.



Requirements of seismic isolation system

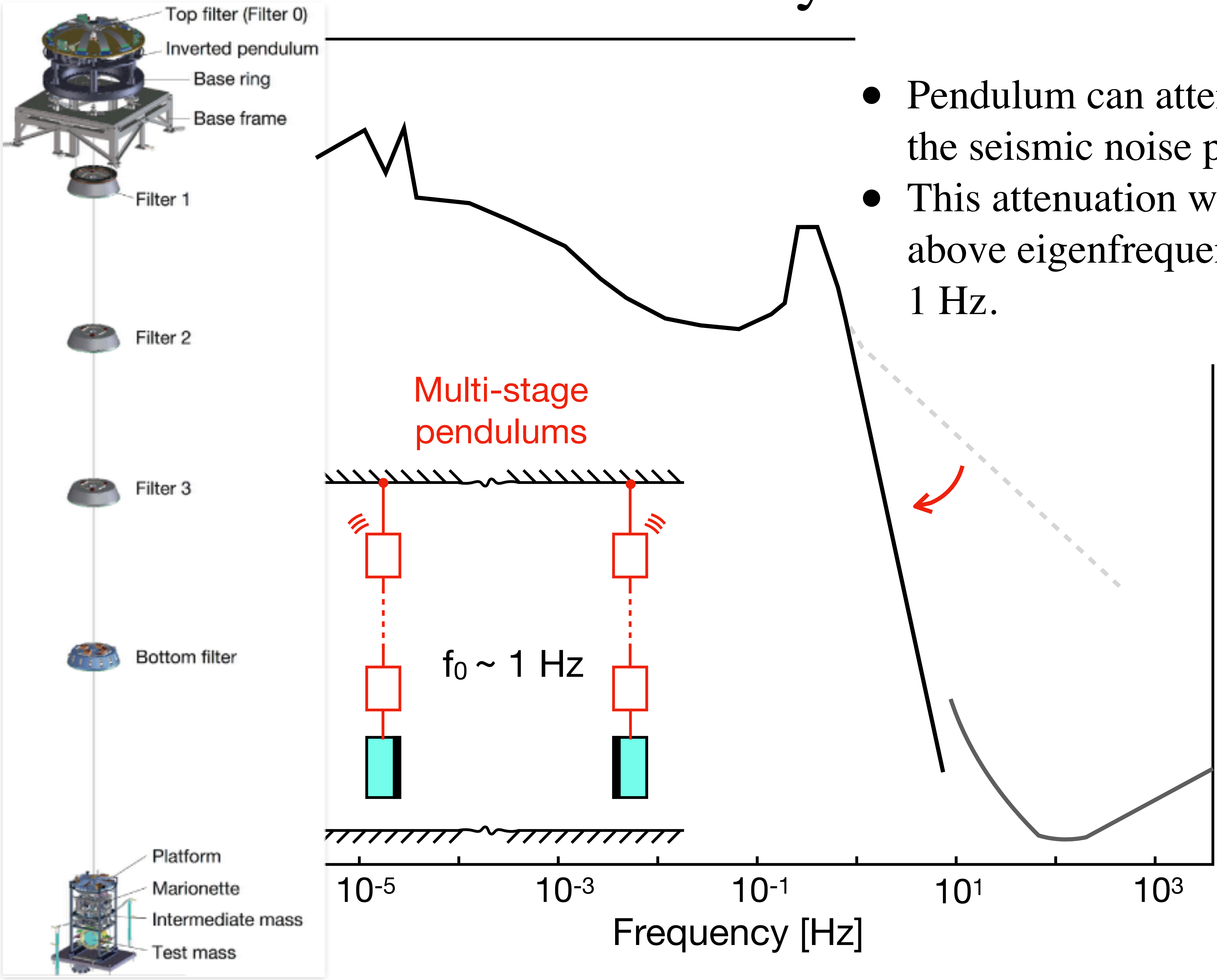


Requirements of seismic isolation system



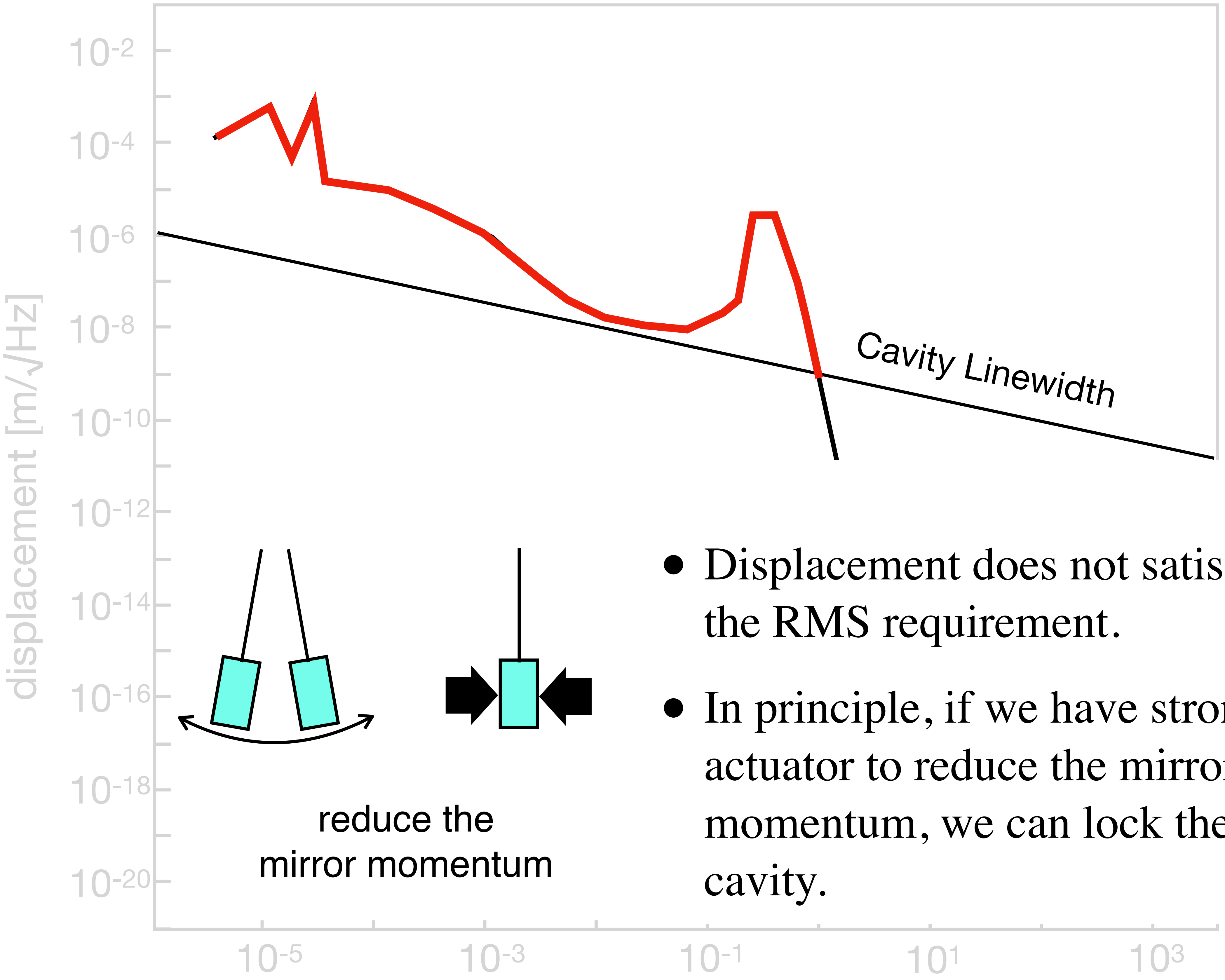
Need a seismic isolation system with isolation factor of 10^{-7} in order to satisfy the sensitivity.

Review : seismic isolation system



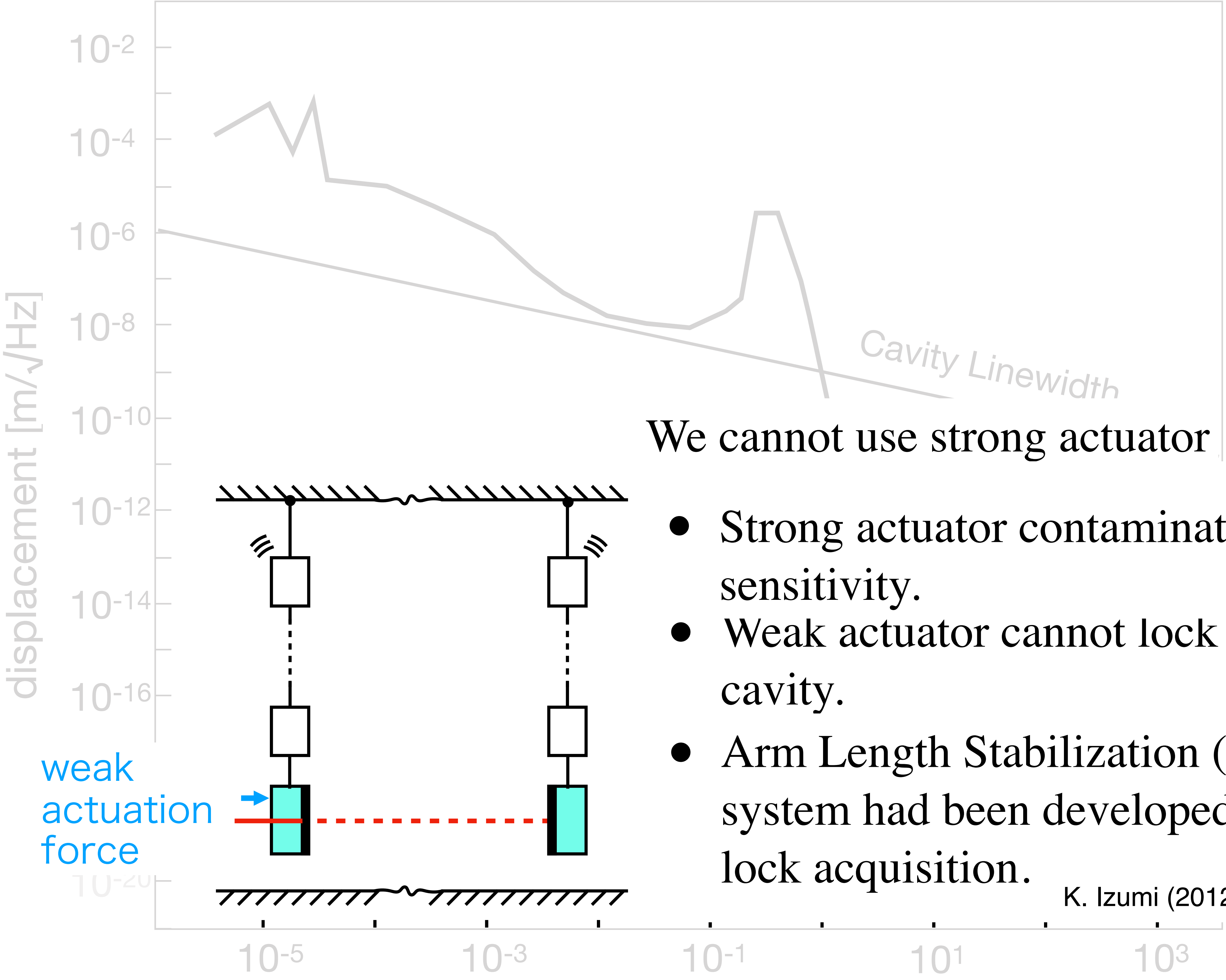
- Pendulum can attenuate the seismic noise passively.
- This attenuation works above eigenfrequency of 1 Hz.

Review : seismic isolation system



- Displacement does not satisfy the RMS requirement.
- In principle, if we have strong actuator to reduce the mirror momentum, we can lock the arm cavity.

Review : seismic isolation system

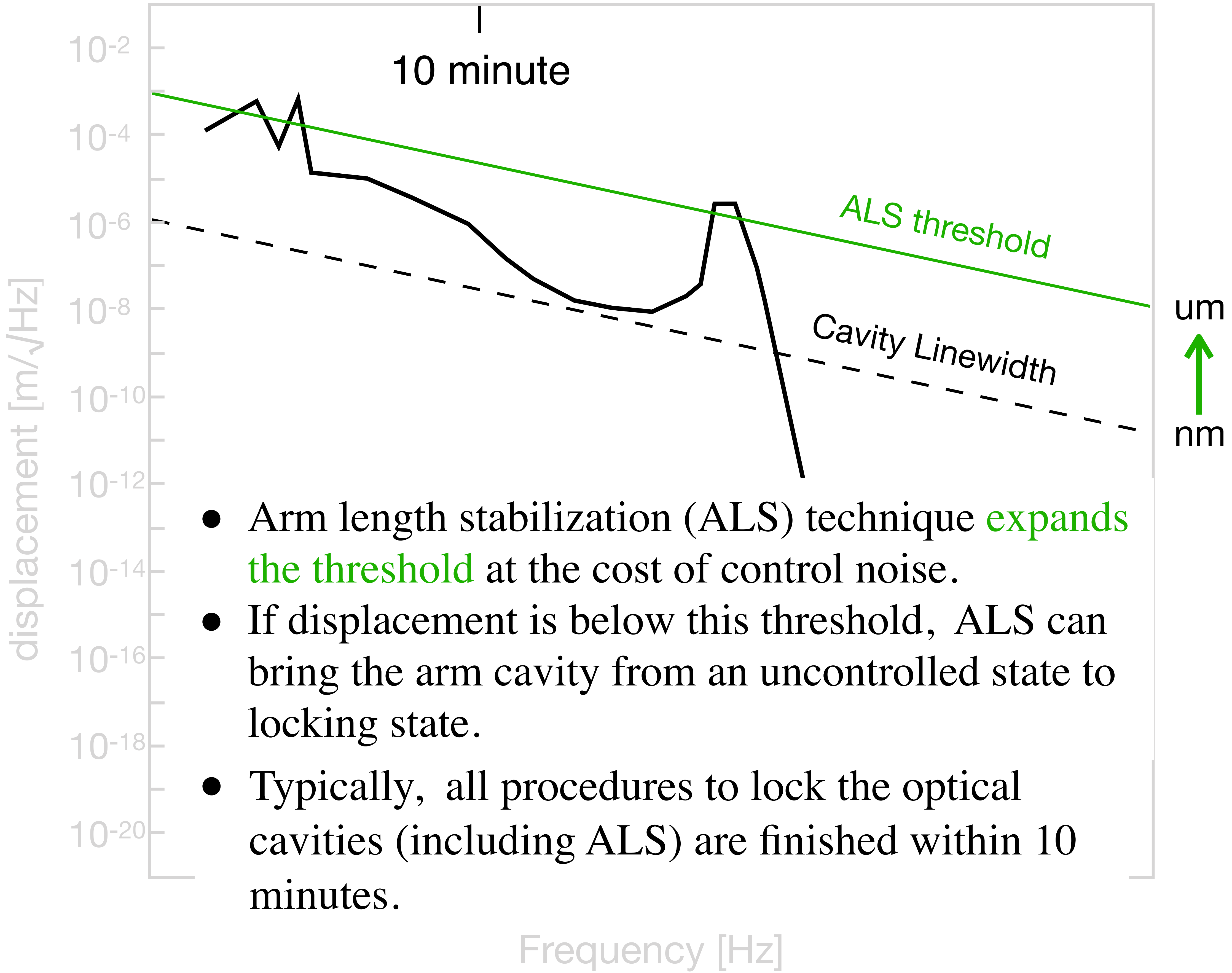


We cannot use strong actuator

- Strong actuator contaminate the sensitivity.
- Weak actuator cannot lock the cavity.
- Arm Length Stabilization (ALS) system had been developed for the lock acquisition.

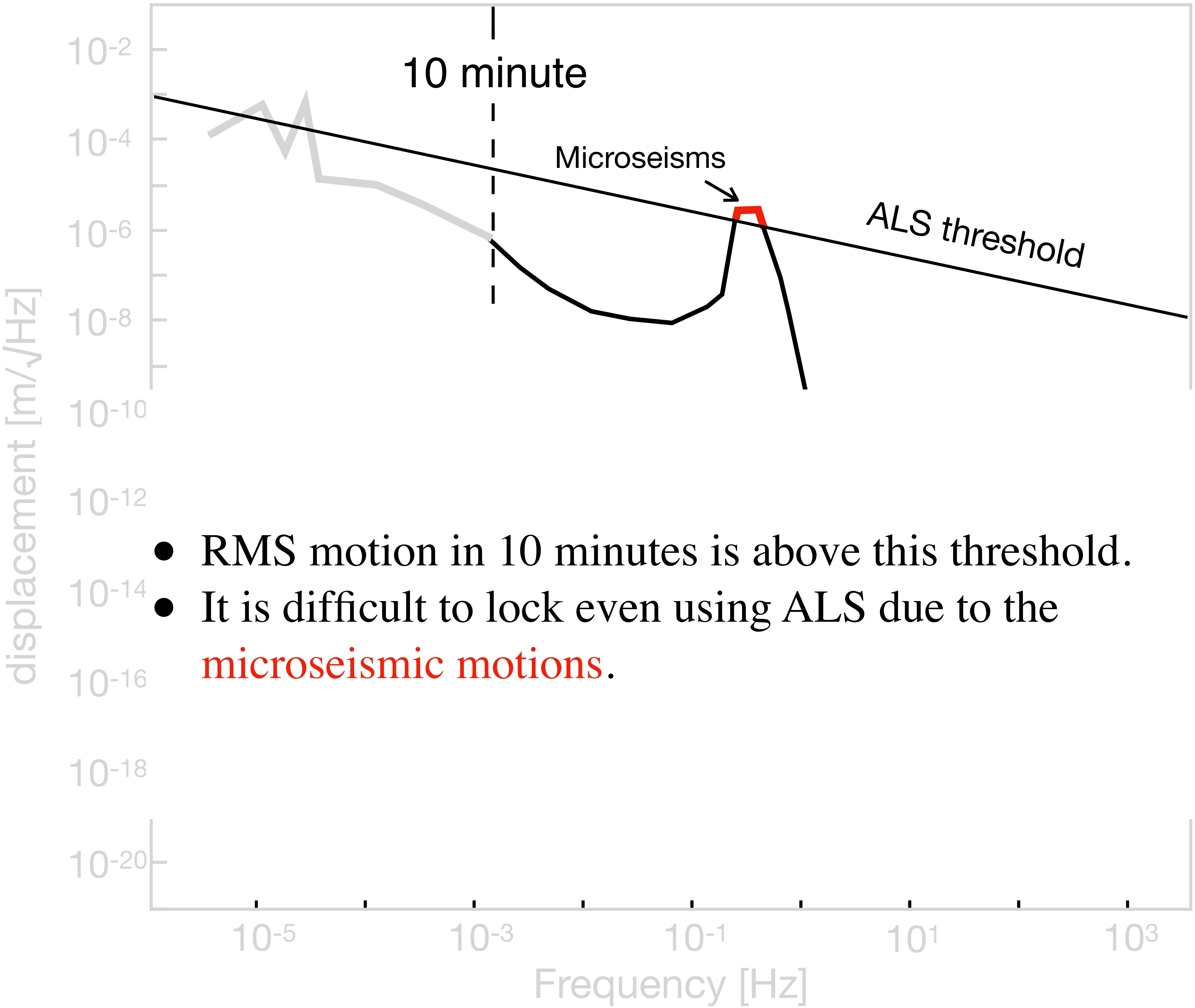
K. Izumi (2012) Ph.D. thesis

Review : seismic isolation system



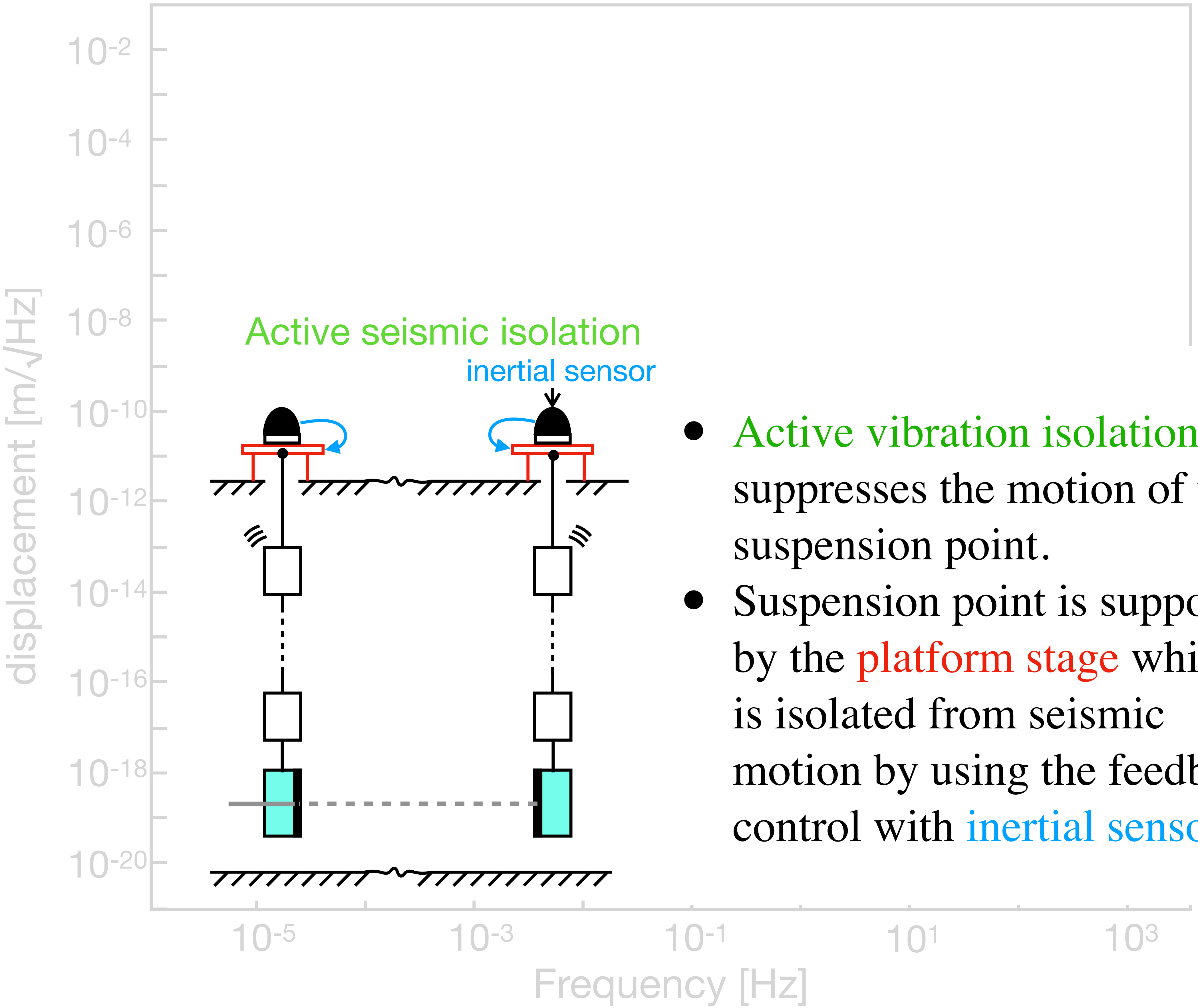
- Arm length stabilization (ALS) technique expands the threshold at the cost of control noise.
- If displacement is below this threshold, ALS can bring the arm cavity from an uncontrolled state to locking state.
- Typically, all procedures to lock the optical cavities (including ALS) are finished within 10 minutes.

Review : seismic isolation system



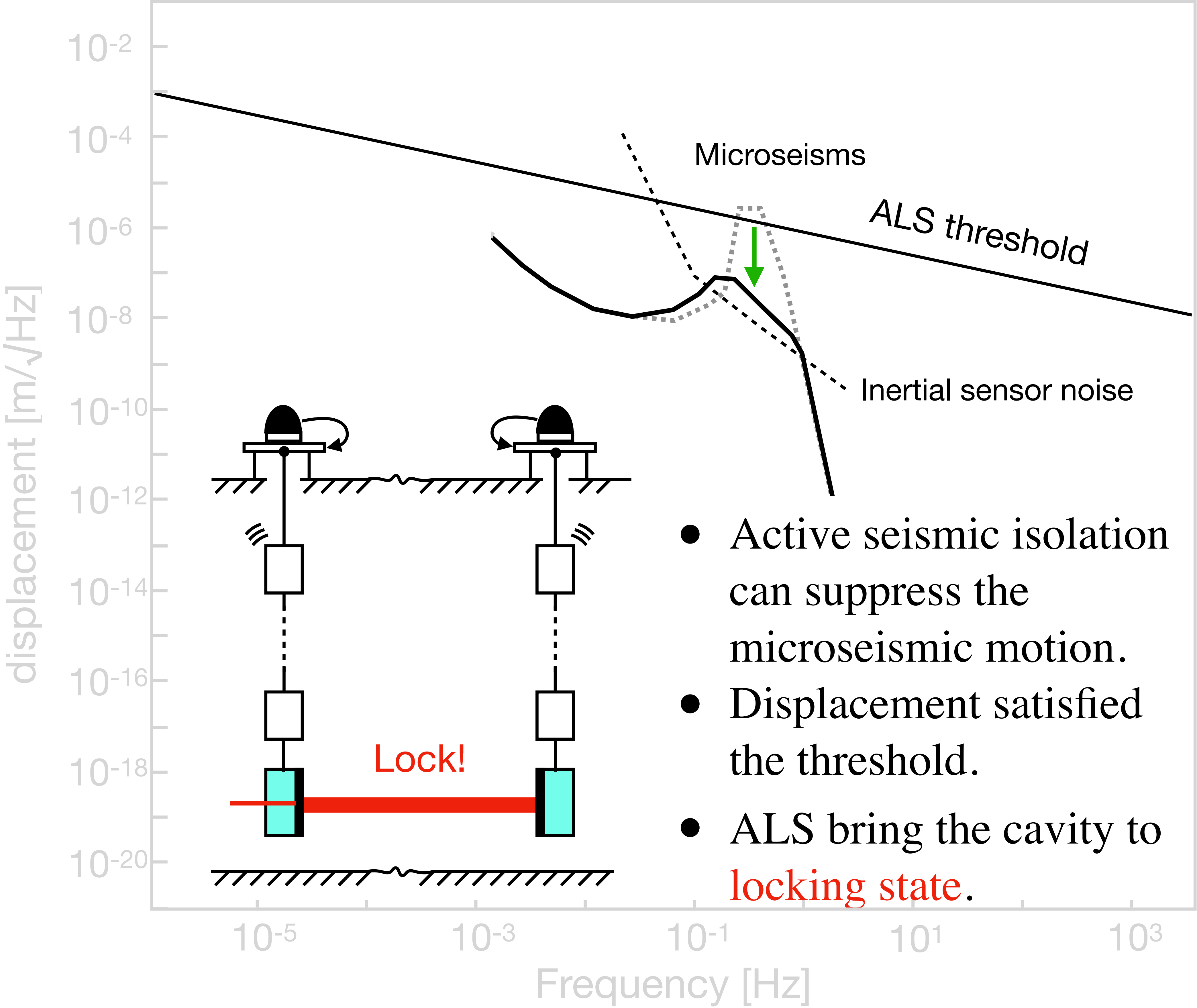
- RMS motion in 10 minutes is above this threshold.
- It is difficult to lock even using ALS due to the microseismic motions.

Review : seismic isolation system



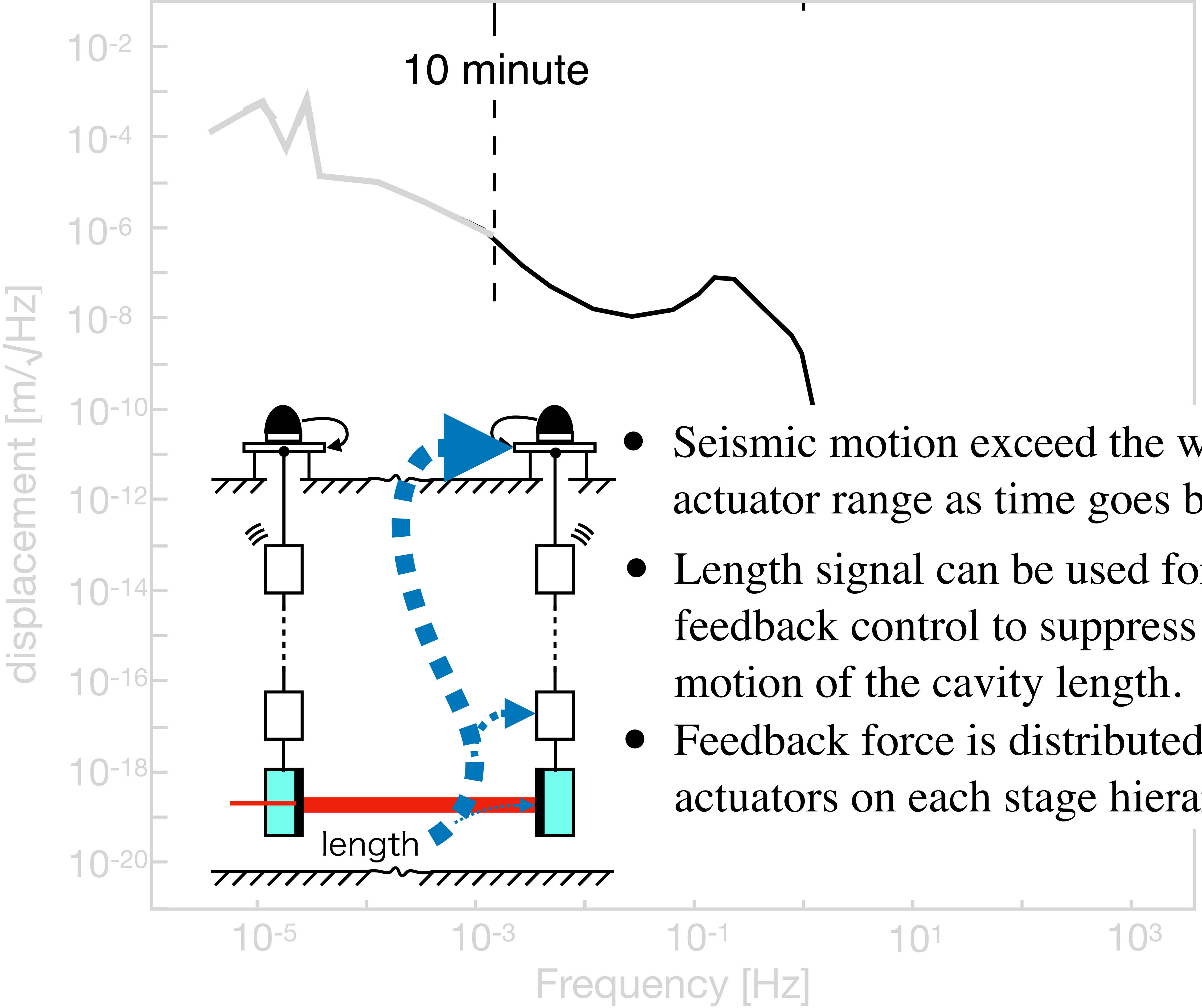
- Active vibration isolation suppresses the motion of the suspension point.
- Suspension point is supported by the platform stage which is isolated from seismic motion by using the feedback control with inertial sensor.

Review : seismic isolation system



- Active seismic isolation can suppress the microseismic motion.
- Displacement satisfied the threshold.
- ALS bring the cavity to locking state.

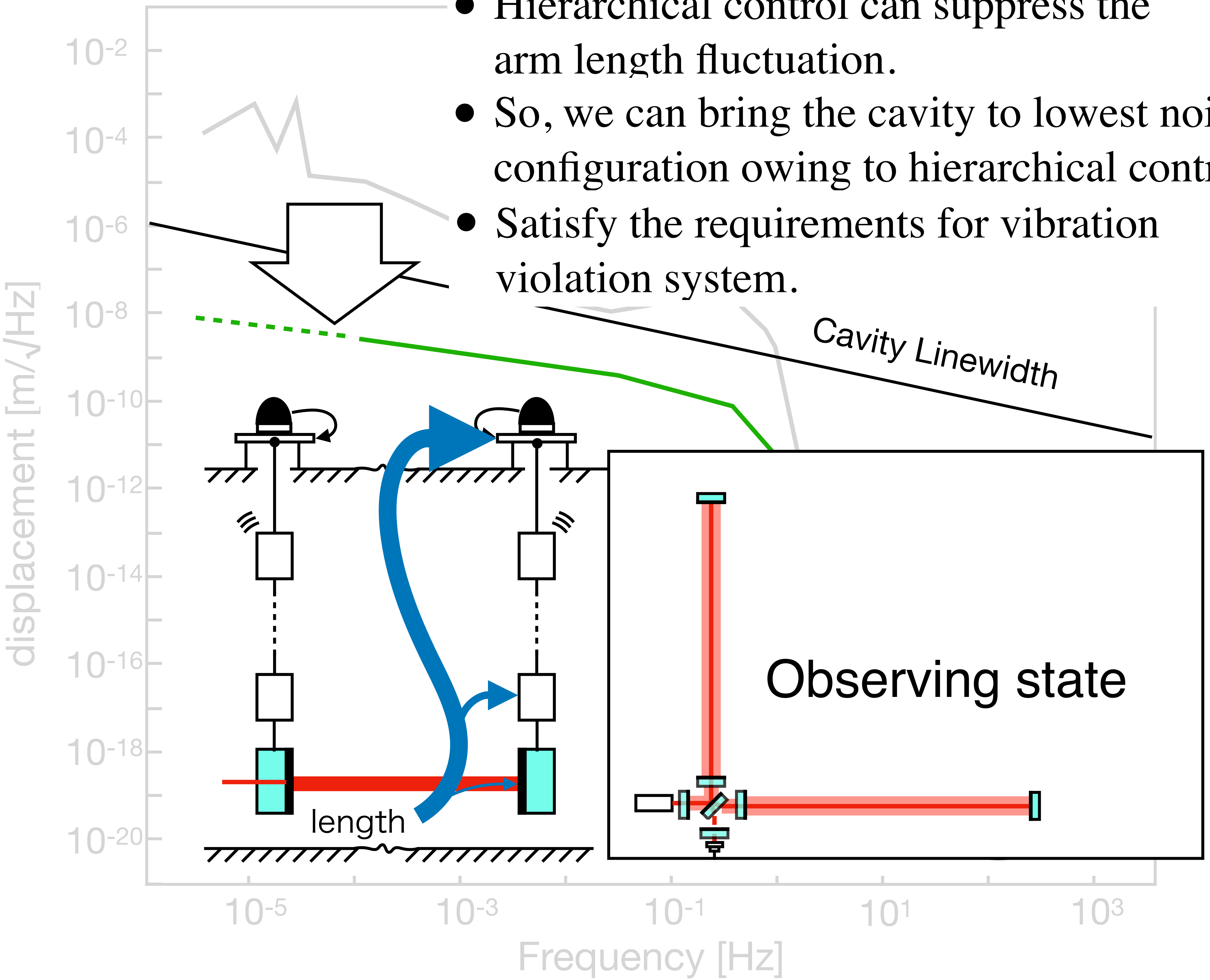
Review : seismic isolation system



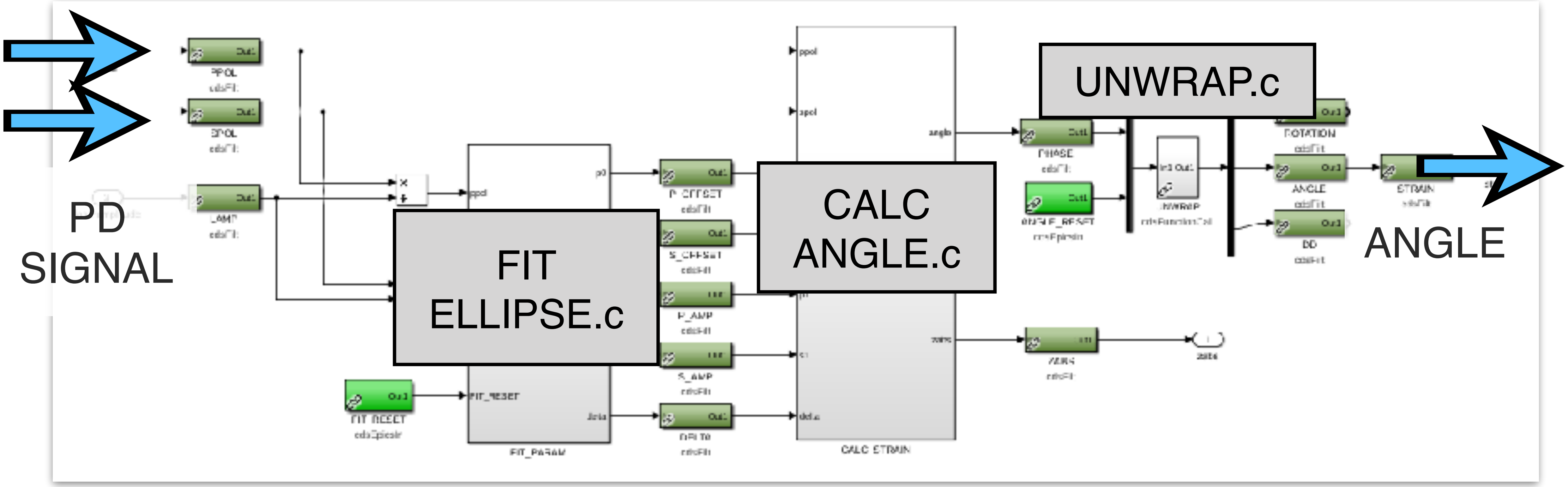
- Seismic motion exceed the weak actuator range as time goes by.
- Length signal can be used for feedback control to suppress the motion of the cavity length.
- Feedback force is distributed to actuators on each stage hierarchically.

Review : seismic isolation system

- Hierarchical control can suppress the arm length fluctuation.
- So, we can bring the cavity to lowest noise configuration owing to hierarchical control
- Satisfy the requirements for vibration violation system.



Realtime signal processing for strainmeter



PD SIGNAL

FIT ELLIPSE.c

CALC ANGLE.c

UNWRAP.c

ANGLE

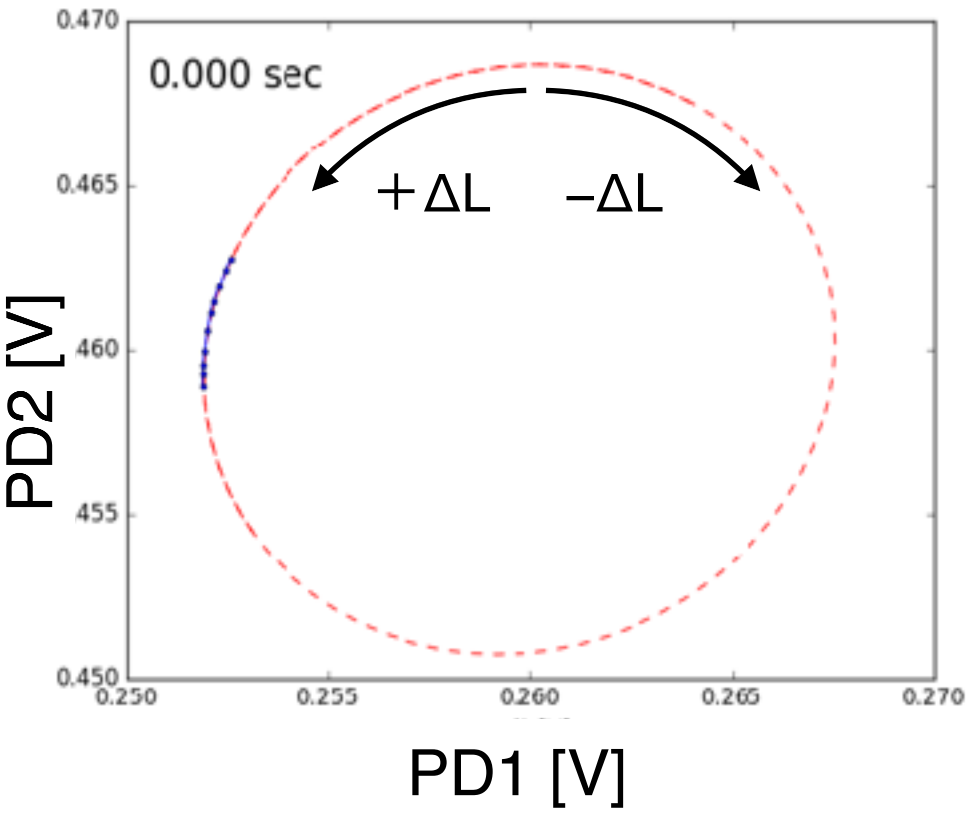
Calculating every 1 clock (16 kHz)

Realtime signal processing code had been developed

- Return the baseline fluctuation signal every 1 clock.
- This signal is synchronized to other KAGRA control signal by using reflective memory (RFM) system.

Strainmeter signal can be send to the KAGRA system

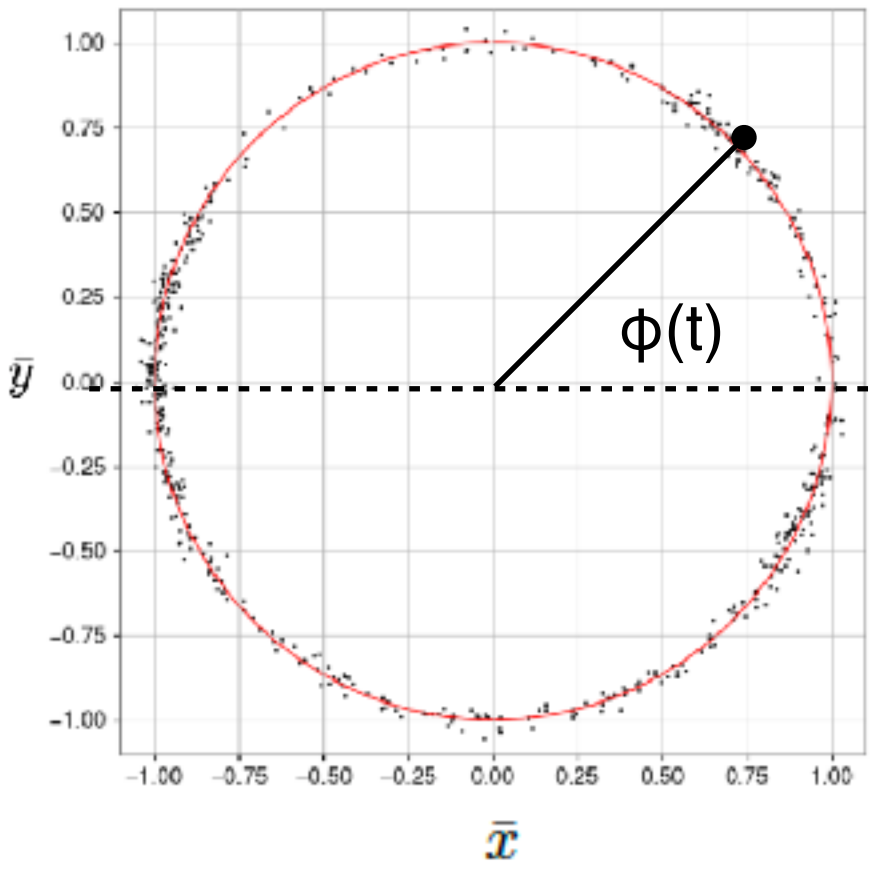
Elipse fitting



$$\bar{Y} = \left(\frac{\bar{y} - \bar{x}\sin\delta}{\cos\delta}\right),$$

$$\bar{x} = \frac{x - x_0}{b} \text{ and } \bar{y} = \frac{y - y_0}{a}.$$

Normalize



PD1 $x(t) = x_0 + b\cos(\phi(t)),$

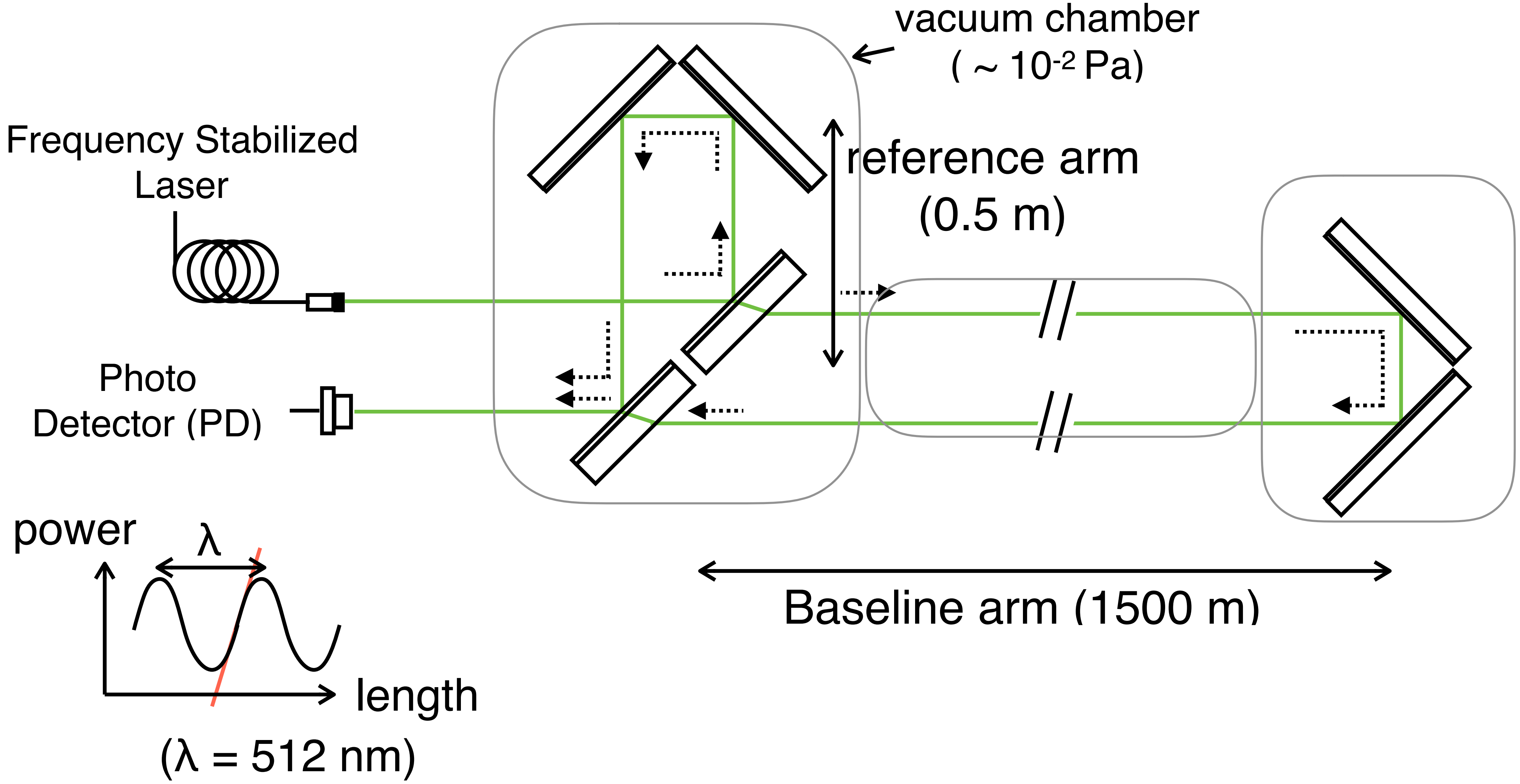
PD2 $y(t) = y_0 + a\sin(\phi(t) + \delta),$

$$\phi = \arctan\frac{Y}{\bar{x}}$$

Zumberge, M A., et al. Applied optics 43.4 (2004): 771-775.

- Fitting the normalized data set with eclipse curve

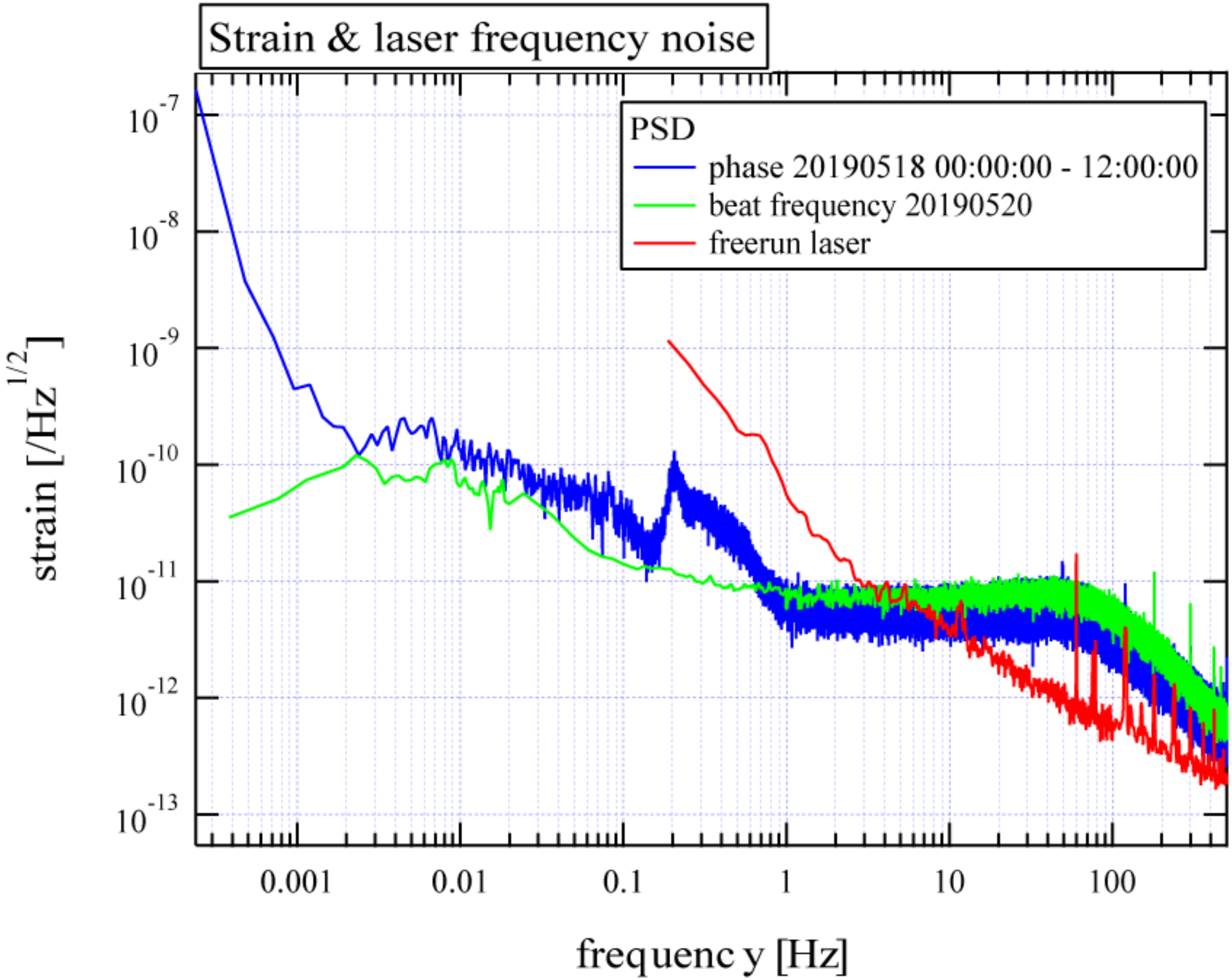
Signal detection



Single PD cannot read the interfered fringe light.

- PD power is not linear to length change.
- Linear range is too small (0.2 um).
- To become wide range, quadrature phase detection technique is used.

タイトルテキスト


Strain & laser frequency noise
PSD
phase 20190518 00:00:00 - 12:00:00
beat frequency 20190520
freerun laser
strain [/Hz$^{1/2}$]
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0.001
0.01
0.1
1
10
100
frequenc y [Hz]

タイトルテキスト

- AAAa