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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三代 浩世希

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JGW-G2011167

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Gravitational-wave (GW) Telescope

Sensitivity → Event Rate

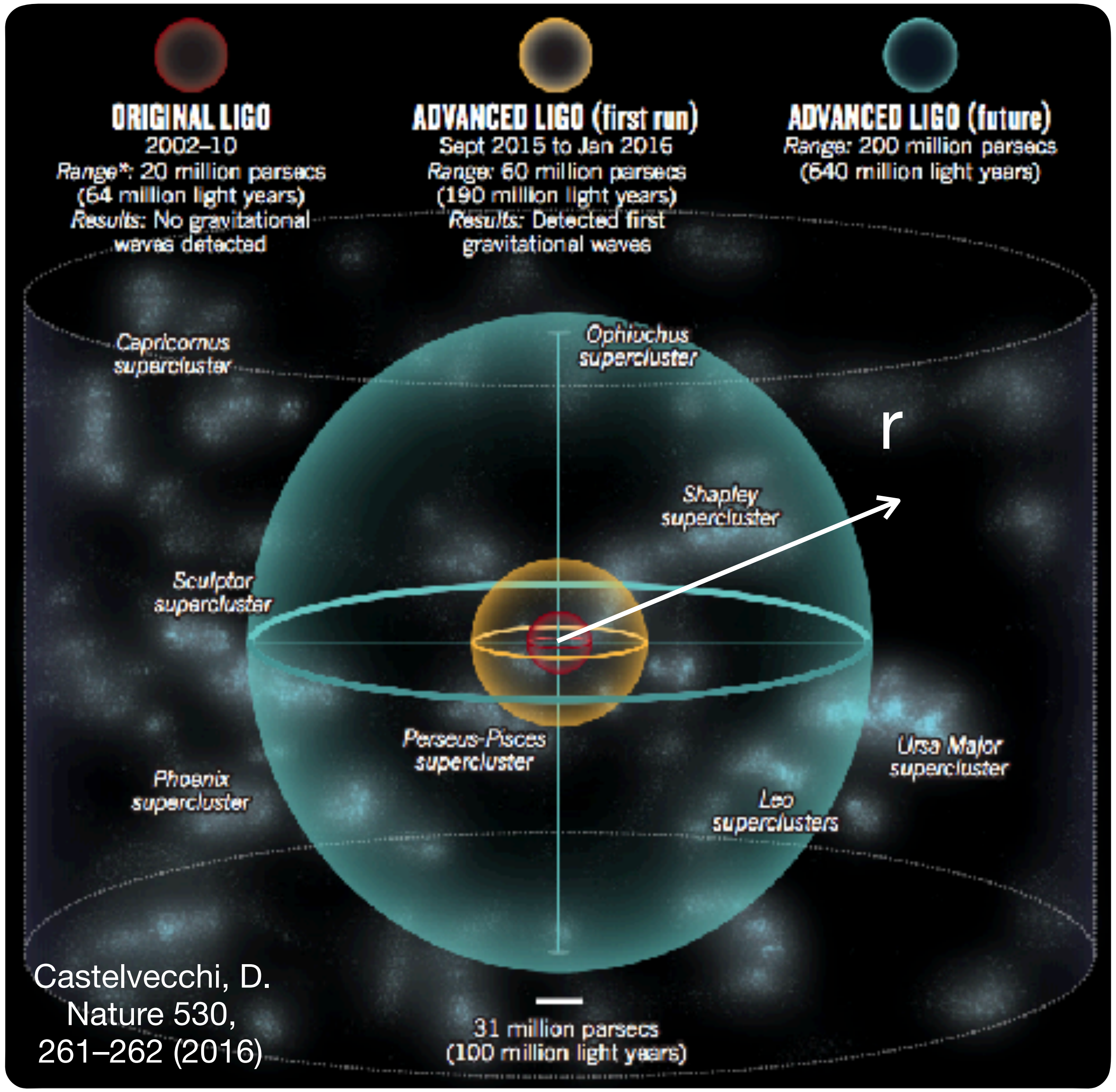
×10 → ×1000

(Operation time)

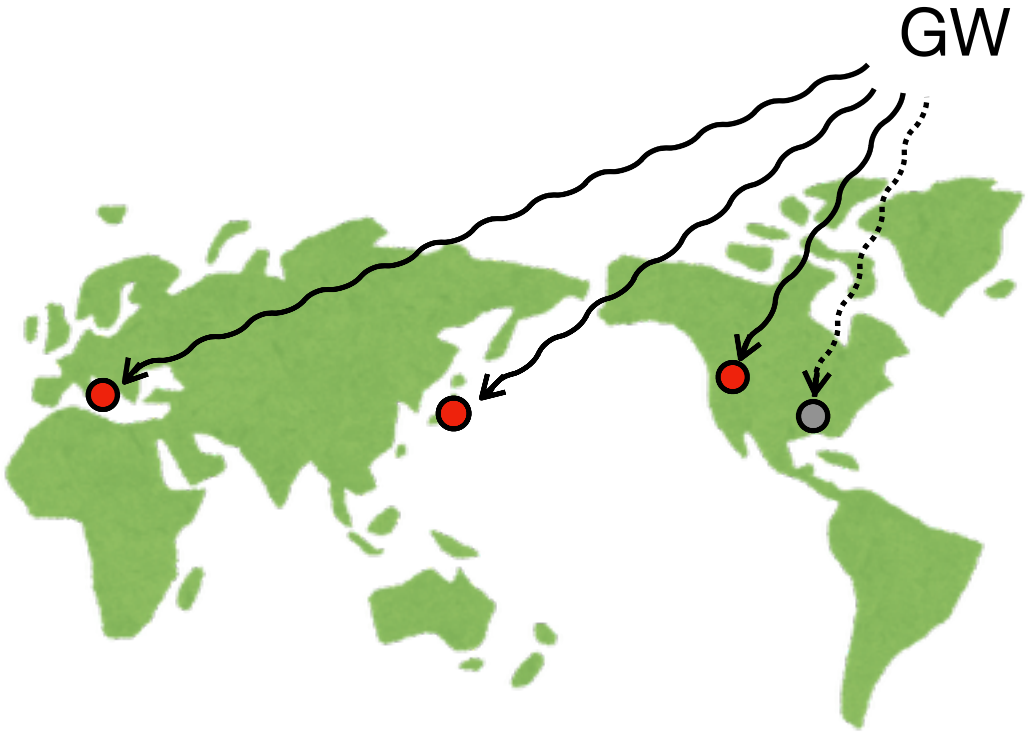
Duty cycle ≒ $D_1 \times D_2 \times D_3 \times \ldots$

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

e.g. LIGO detector



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



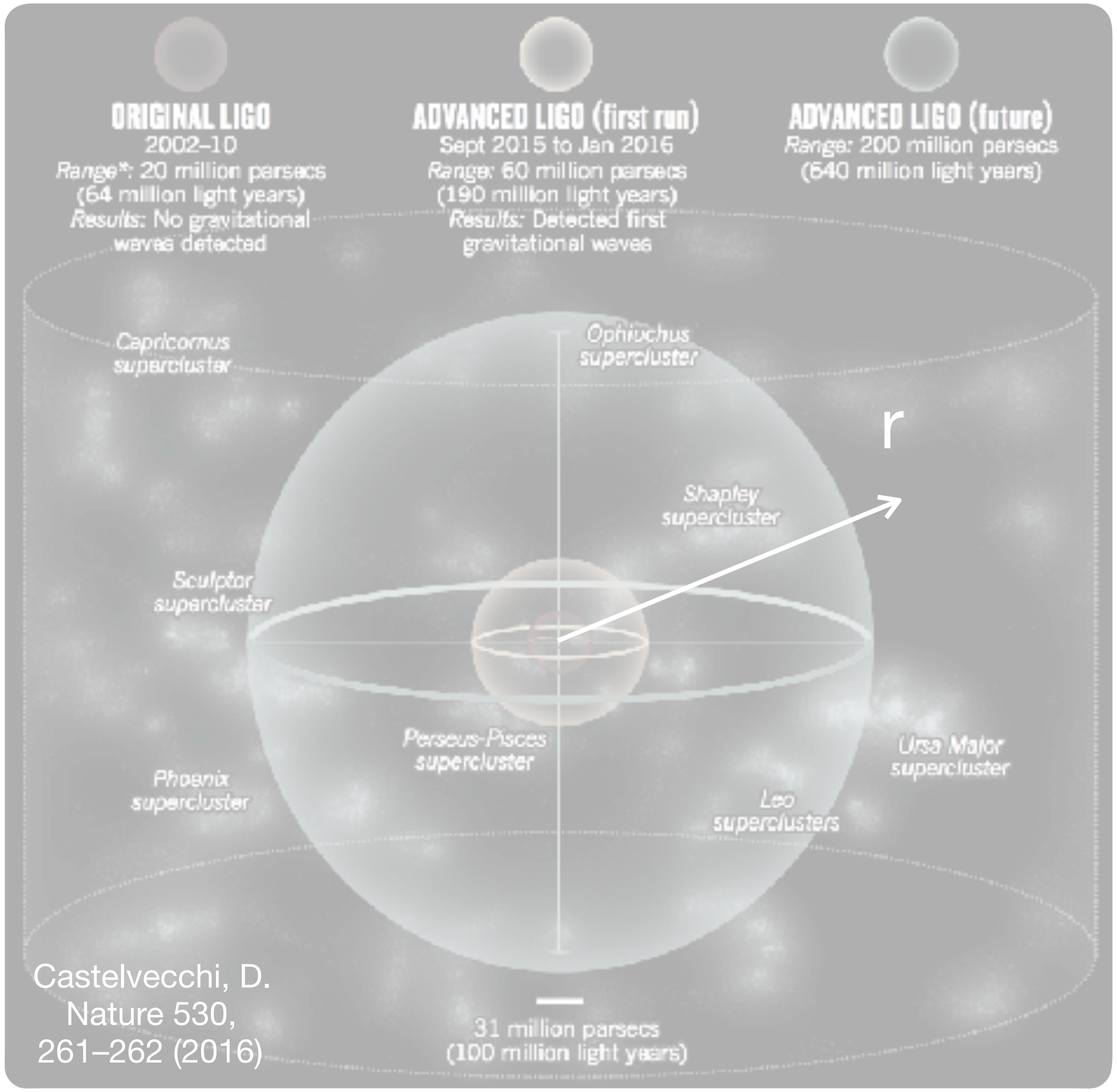
At least, 3 detectors must operate simultaneously to determine the direction of arrival.

Gravitational-wave (GW) Telescope

Sensitivity → Event Rate

10 → 1000

e.g. LIGO detector



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

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

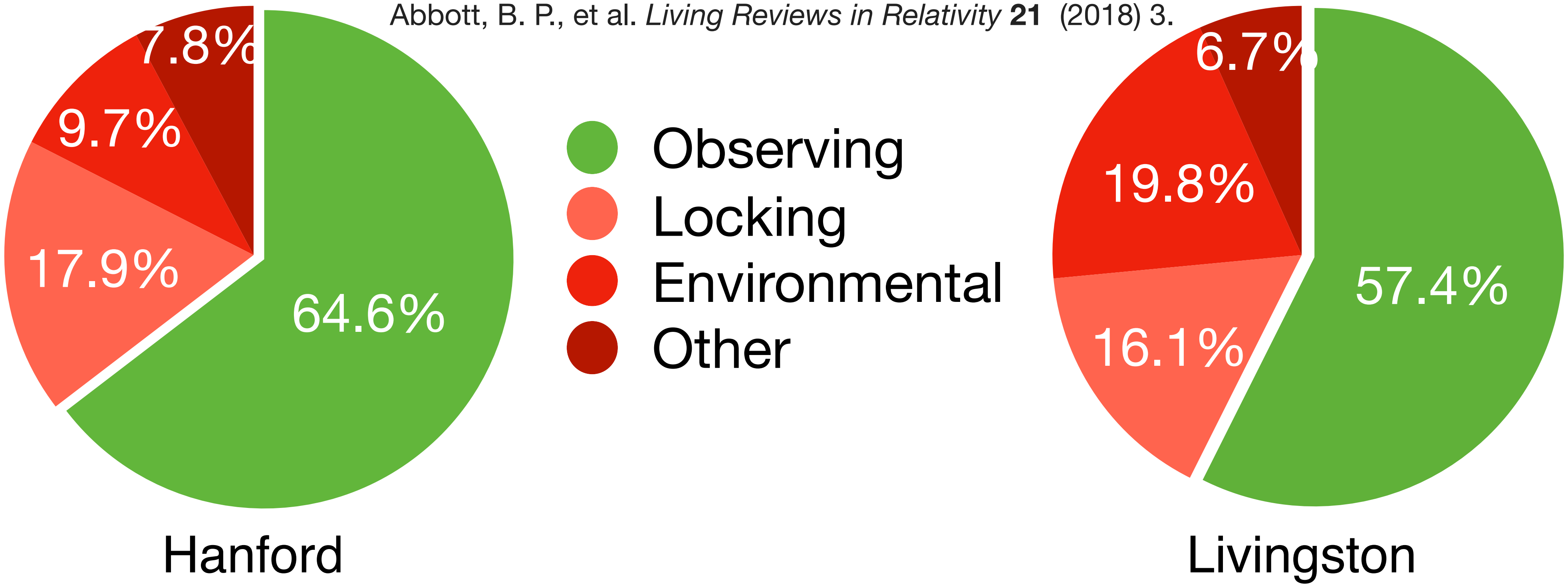
(D_i : duty cycle of the i-th detector)

This study focuses on this

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

Duty cycle

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

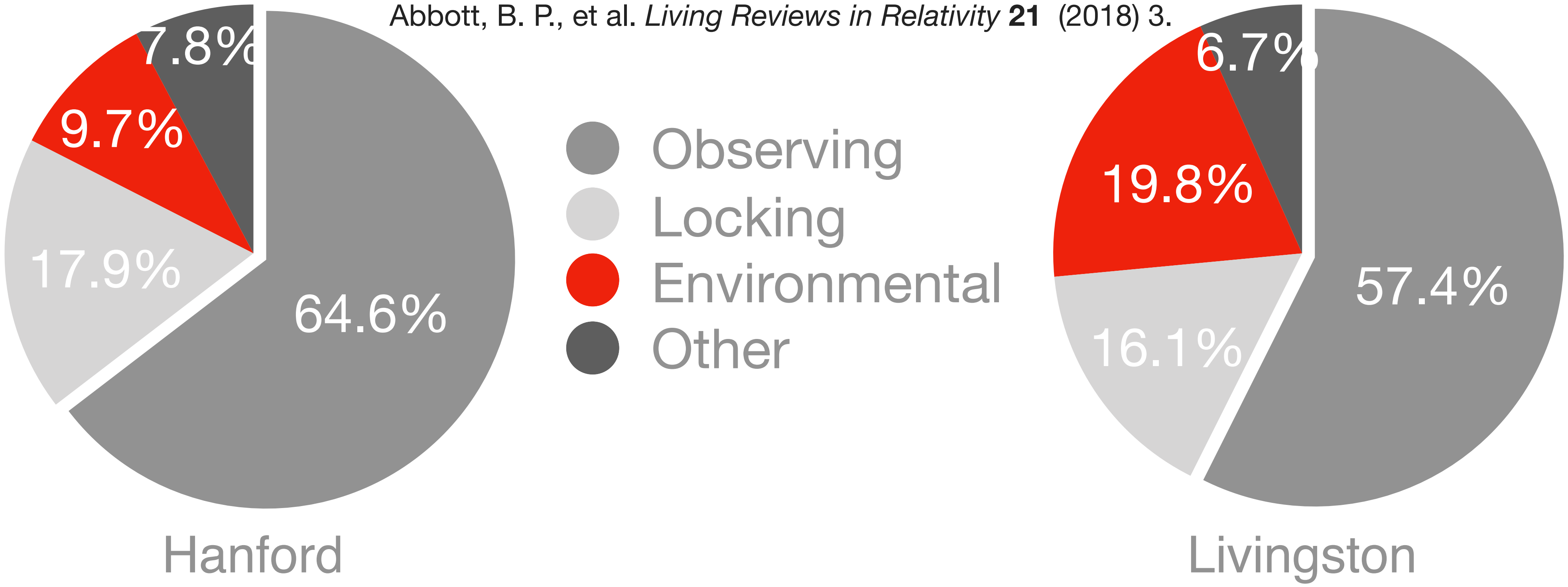
- could not control due to seismic disturbances.

Other

- commissioning or planed maintenances.

Duty cycle

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

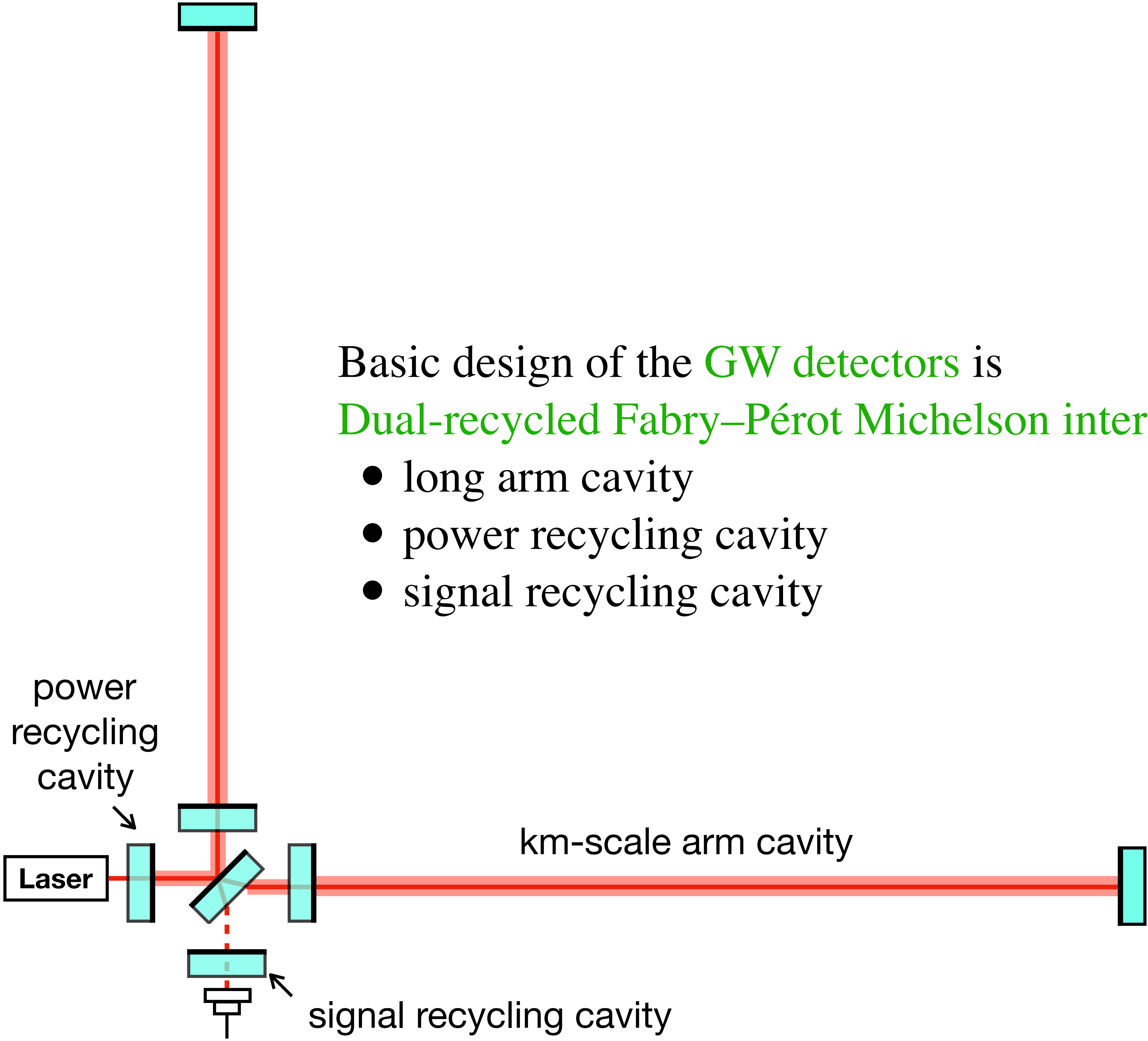
Environmental

- could not control due to seismic disturbances.

Ot

We need further improvement of
the seismic isolation system.

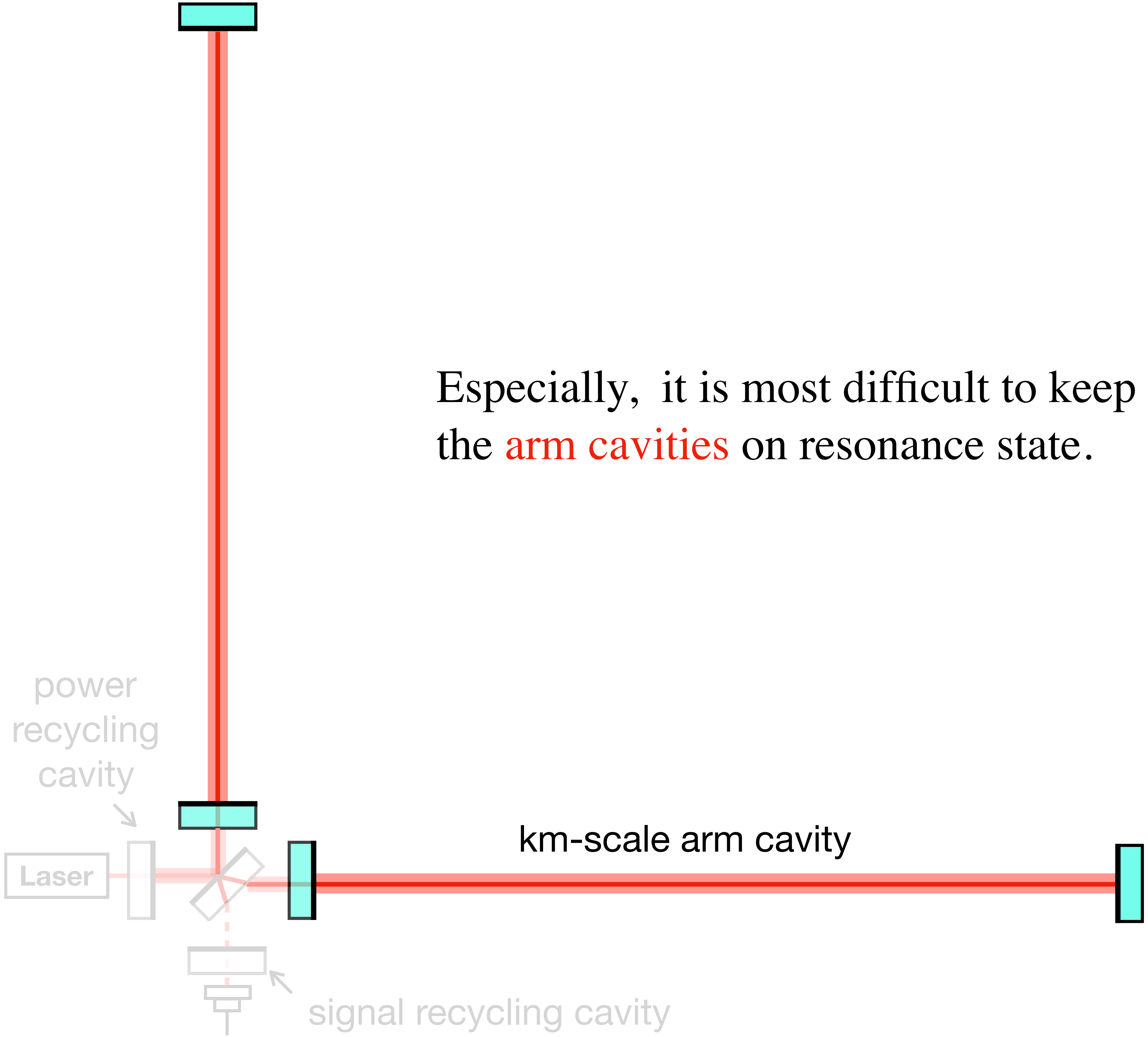
Why GW detectors are weak to seismic disturbances?



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?

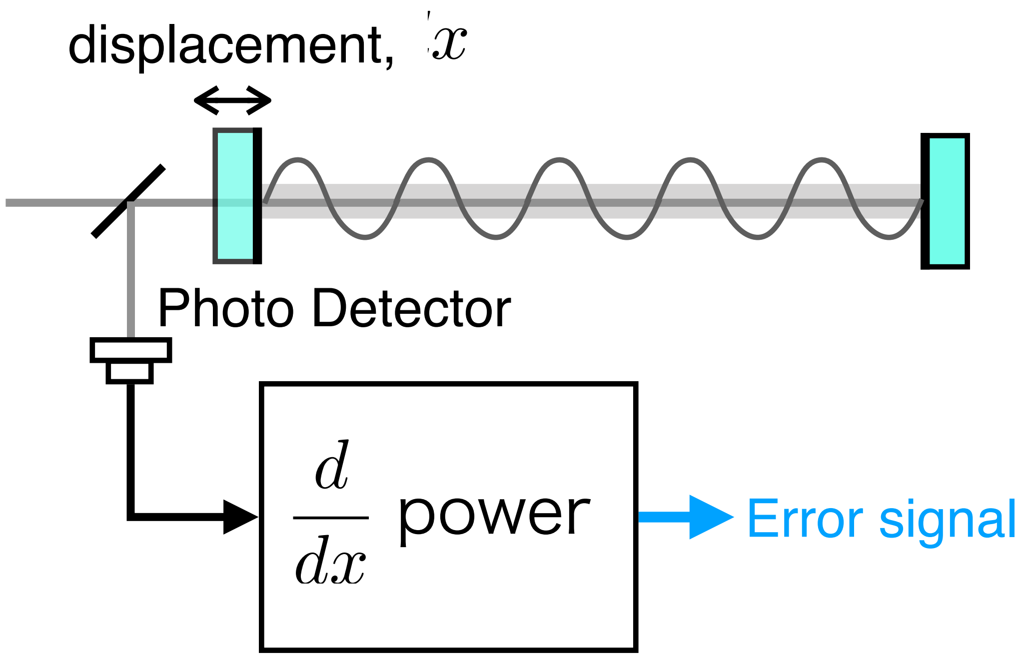


Especially, it is most difficult to keep the arm cavities on resonance state.

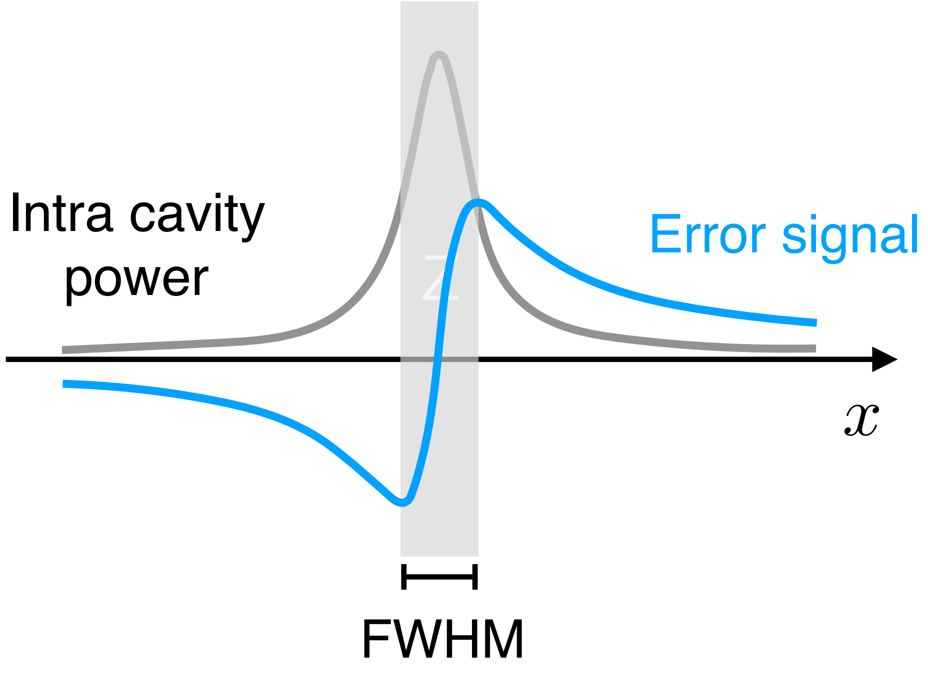
Difficulties in the cavity control

Resonant condition

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



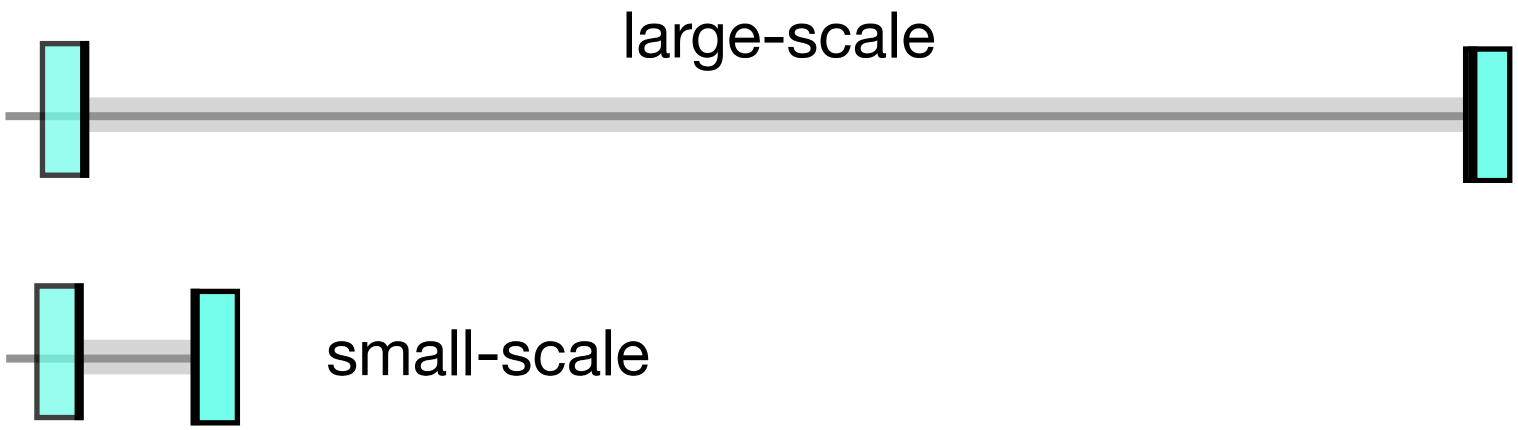
Pound–Drever–Hall (PDH) technique



Feedback control can work within FWHM range (~ nm)

→ Seismic disturbances should be attenuated within a few nm.
in order to lock the cavity using PDH technique.

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.

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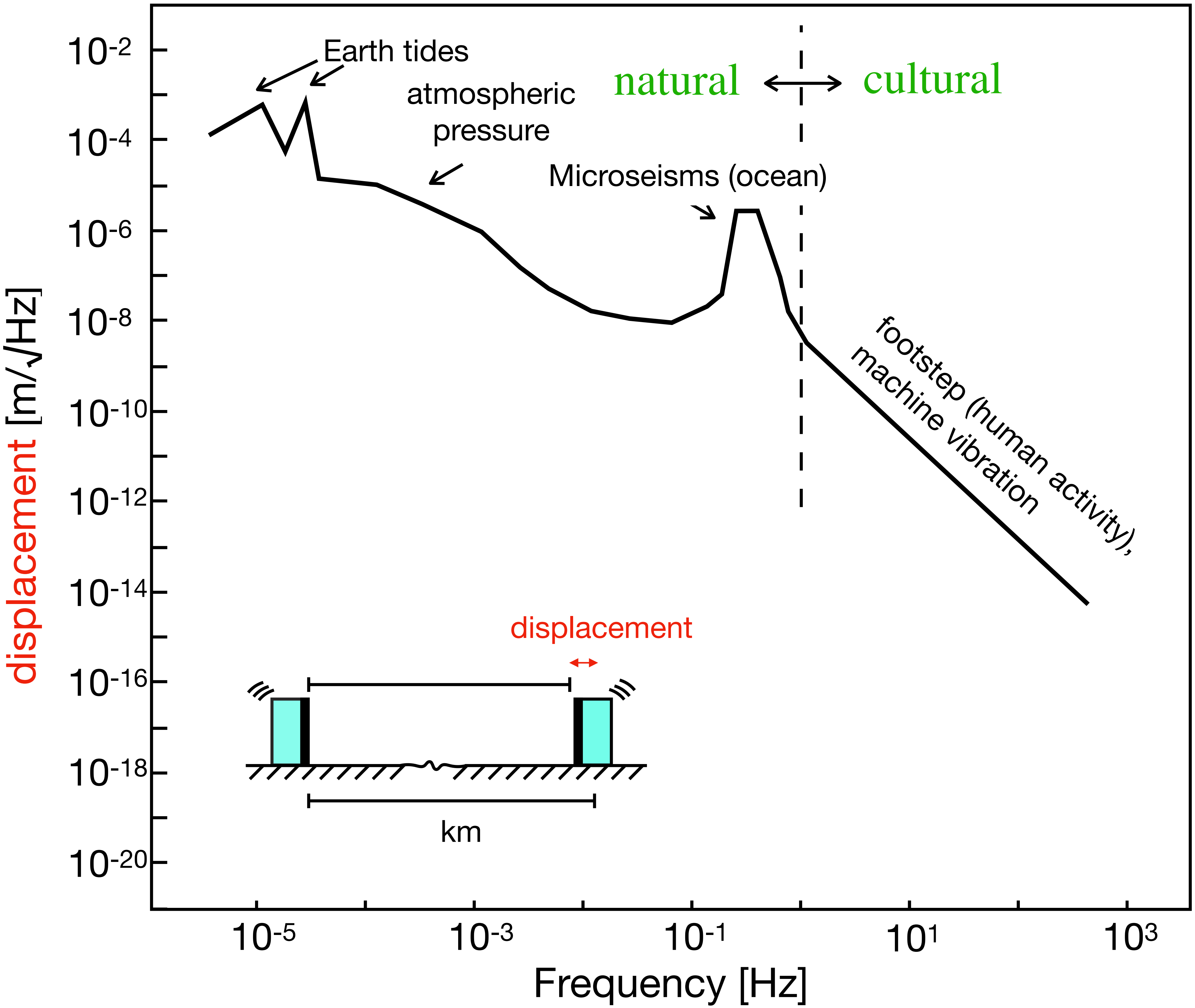
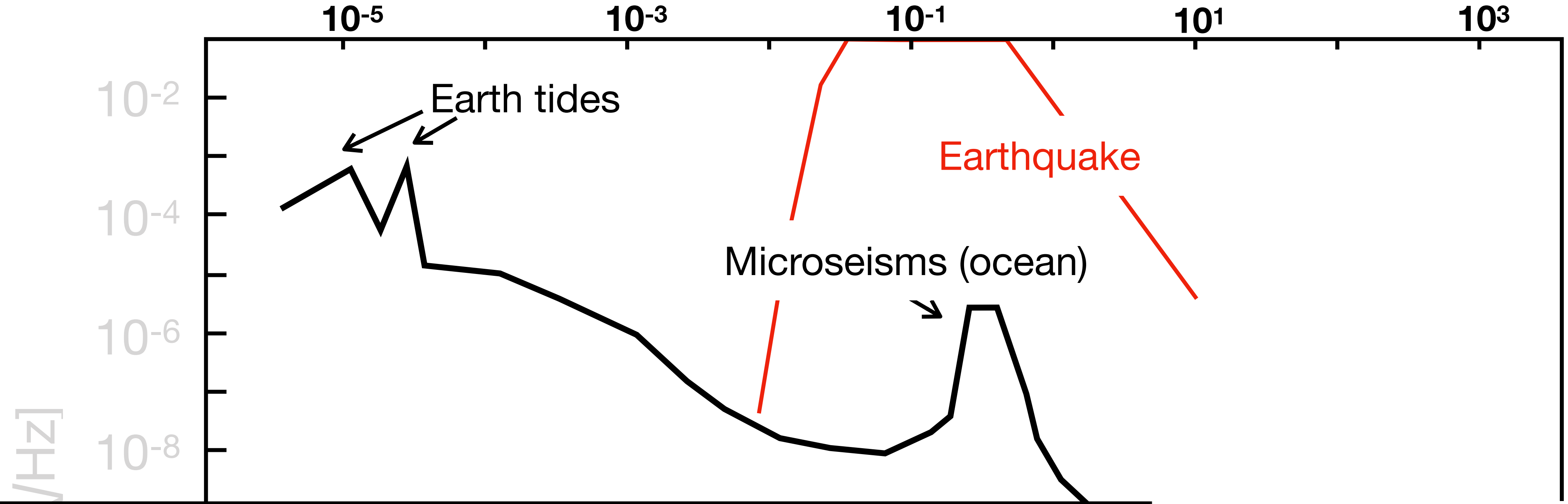
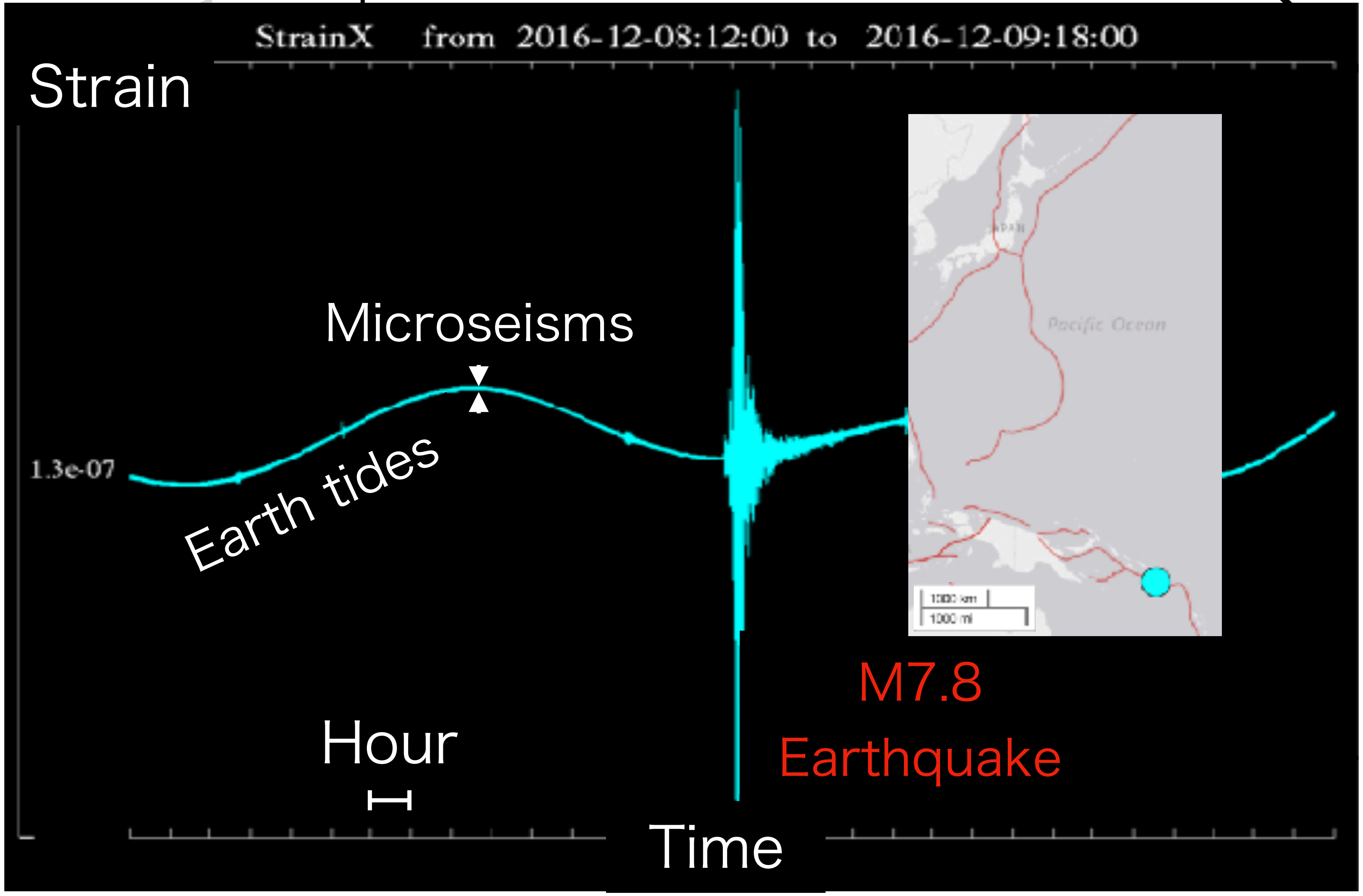
Seismic Noise (stationary)



Seismic Noise (transient)



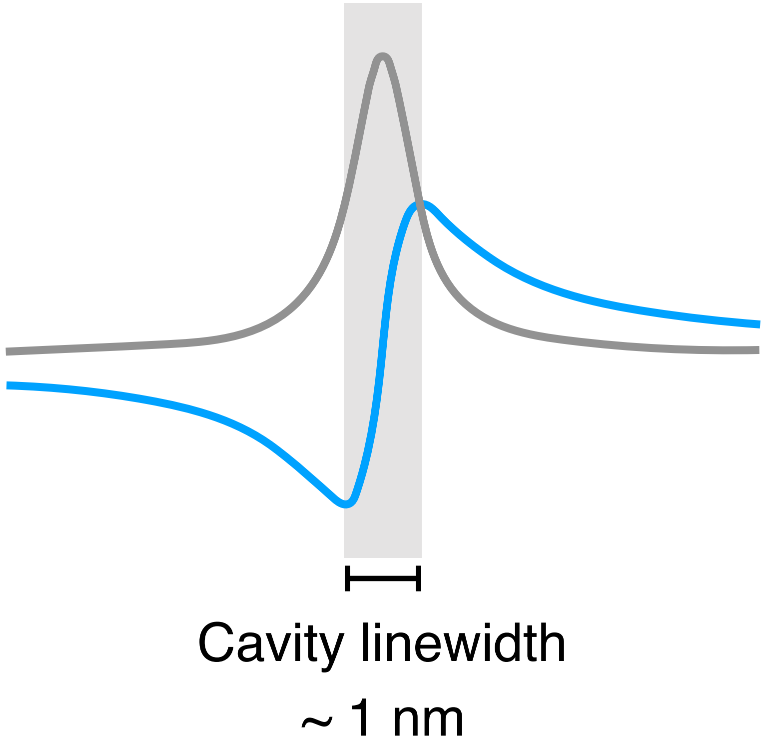


- In generally, earthquake shake the ground above 10 mHz.
- Large earthquake excite the ground with large amplitude and long period, and continues several hours.

Requirements of seismic isolation system

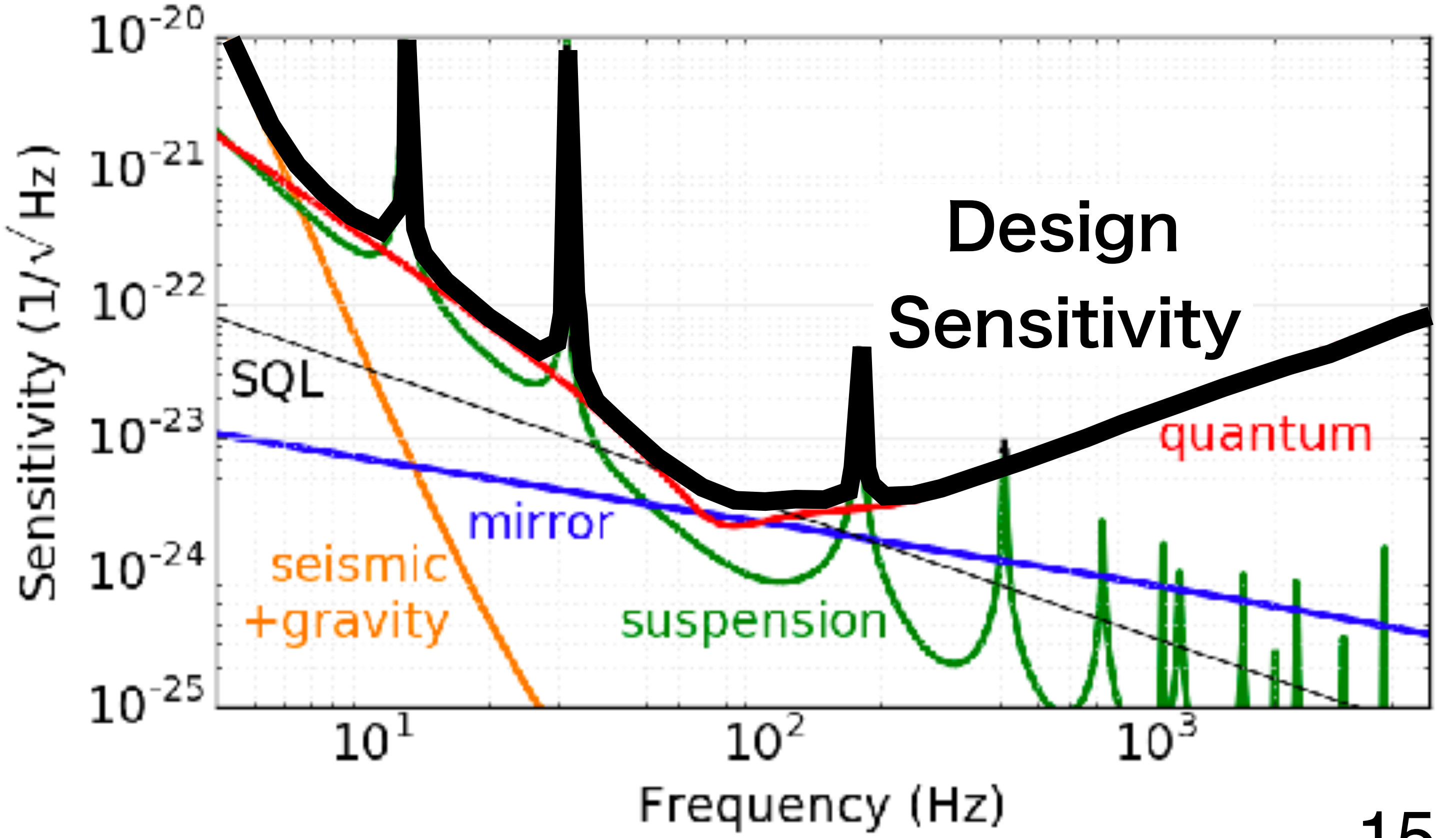
RMS requirement

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

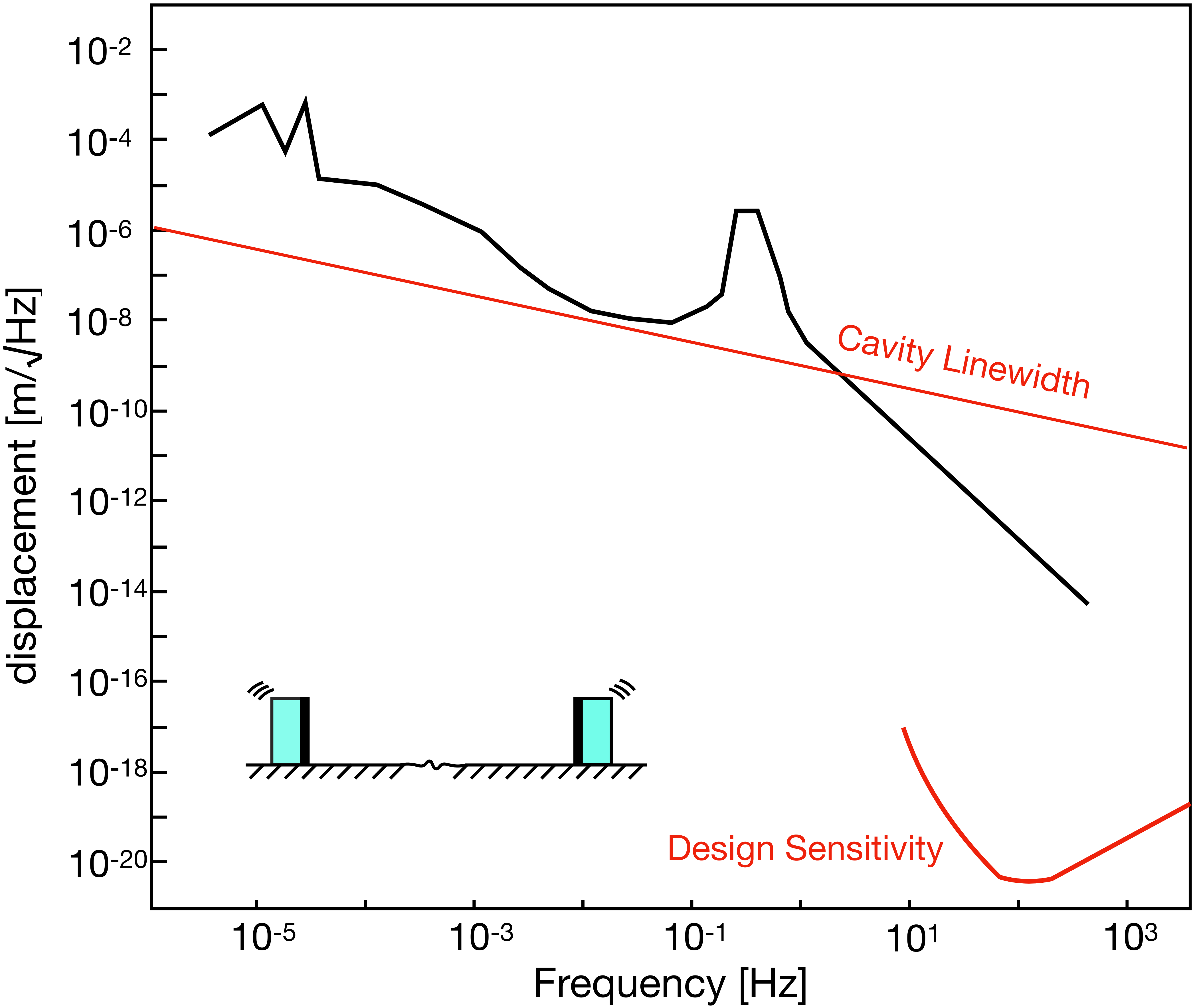


Noise requirement

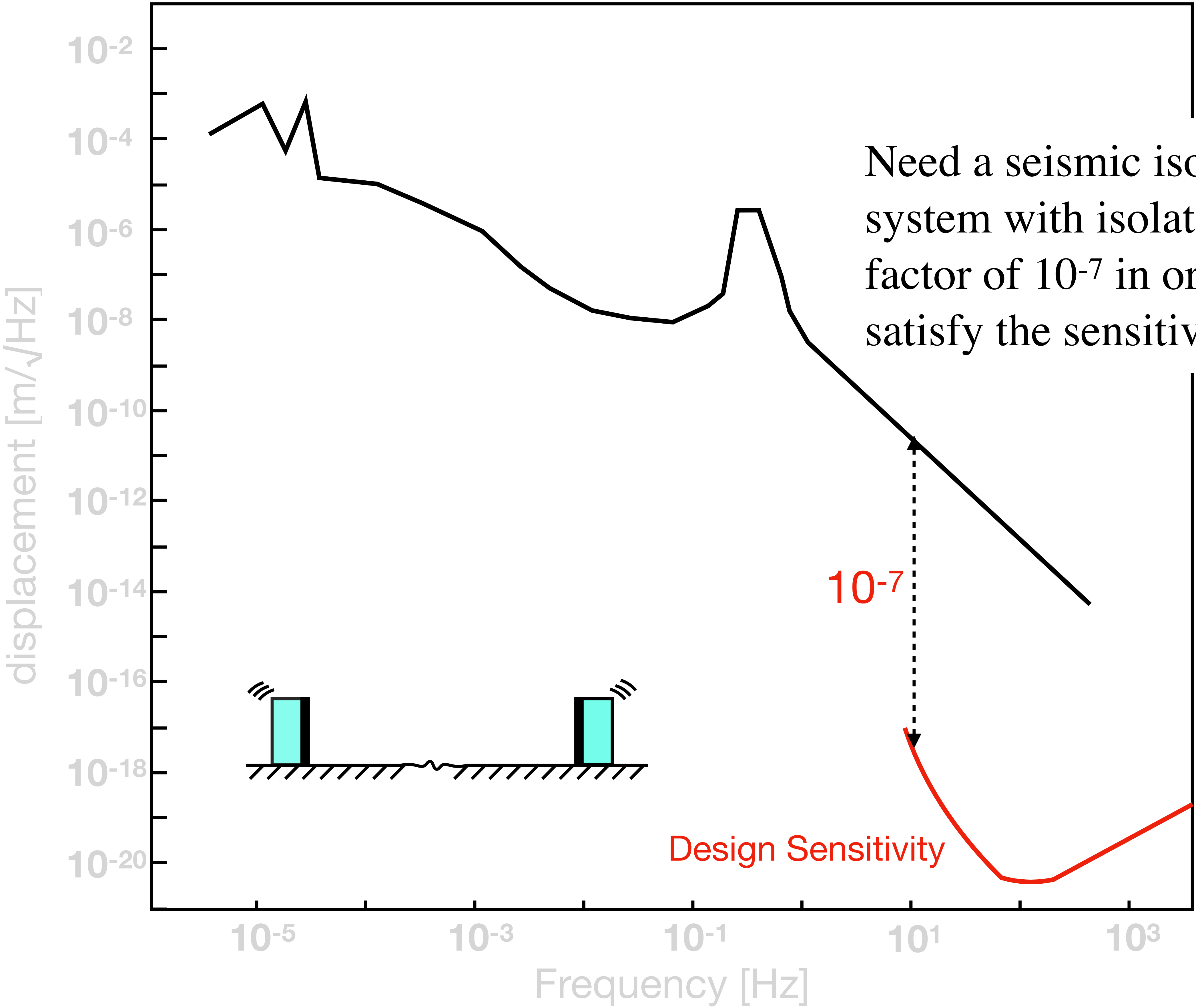
- reduce seismic noise below design sensitivity.



Requirements of seismic isolation system

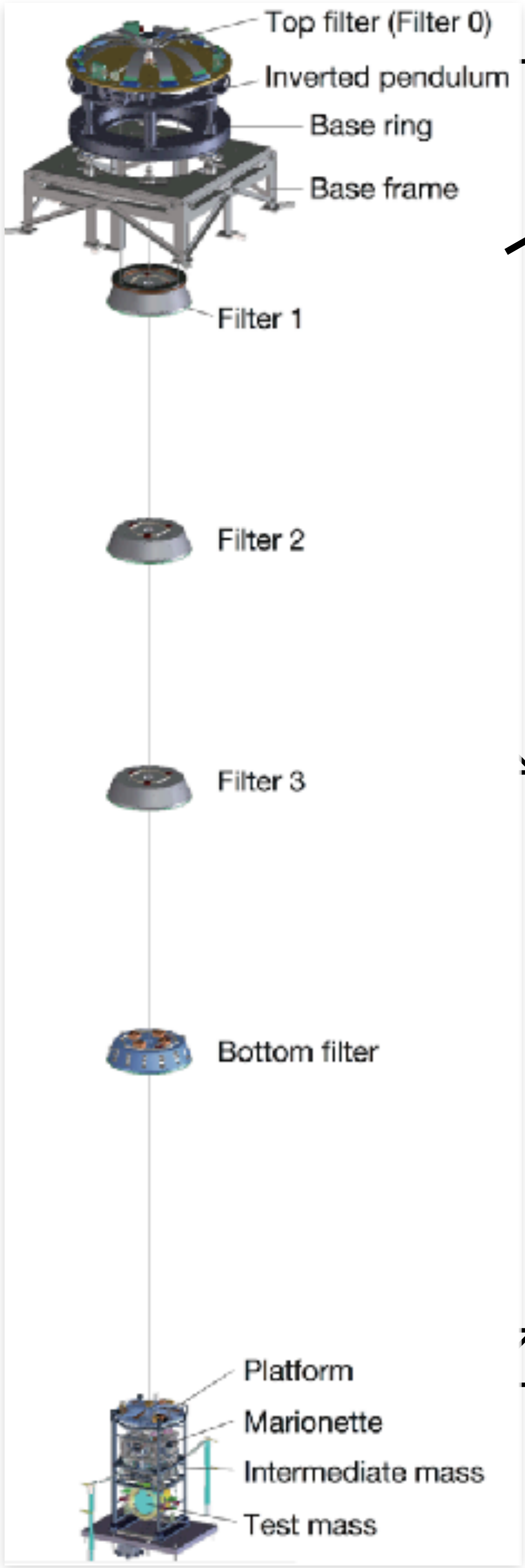


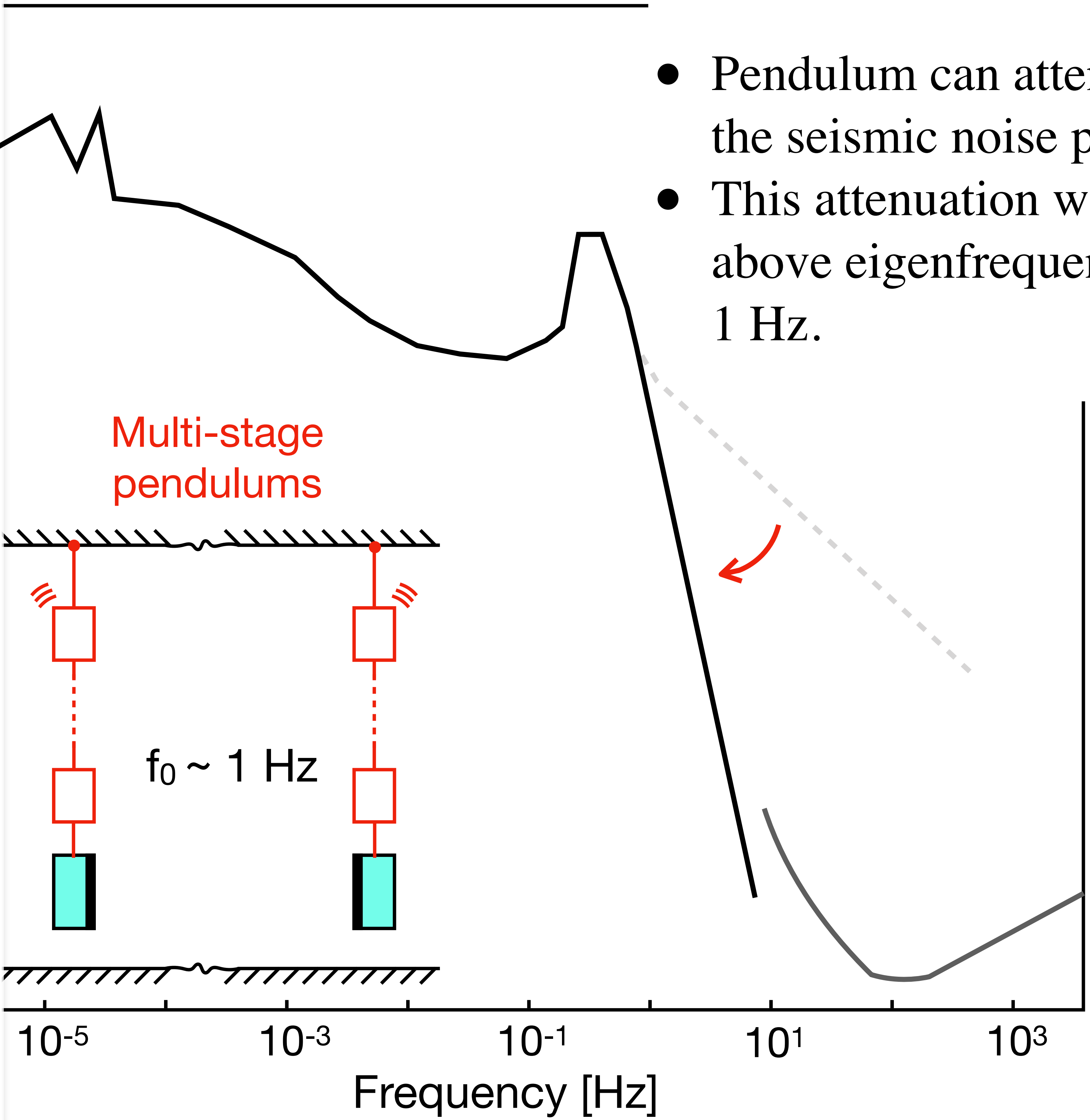
Requirements of seismic isolation system



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

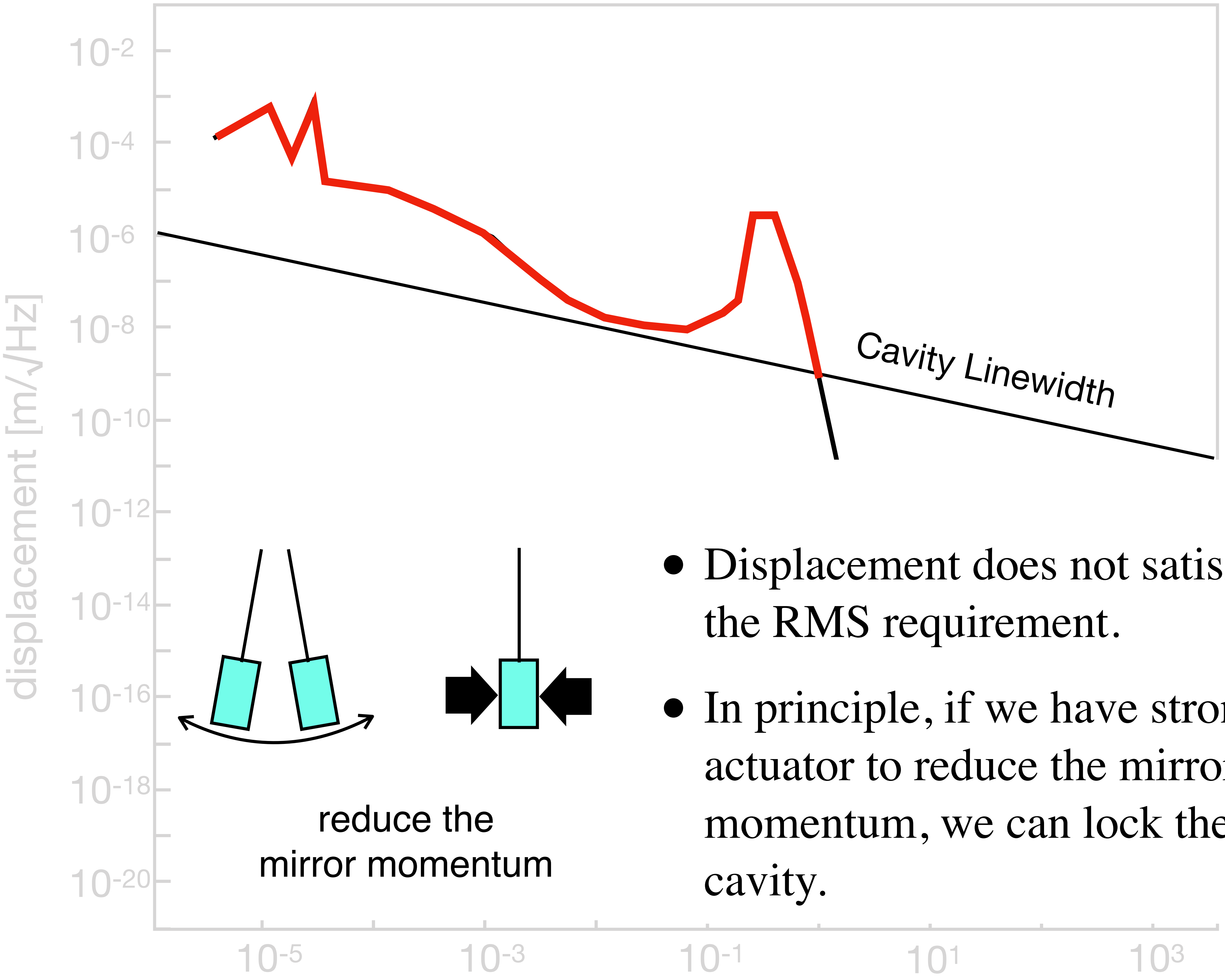
Review : seismic isolation system





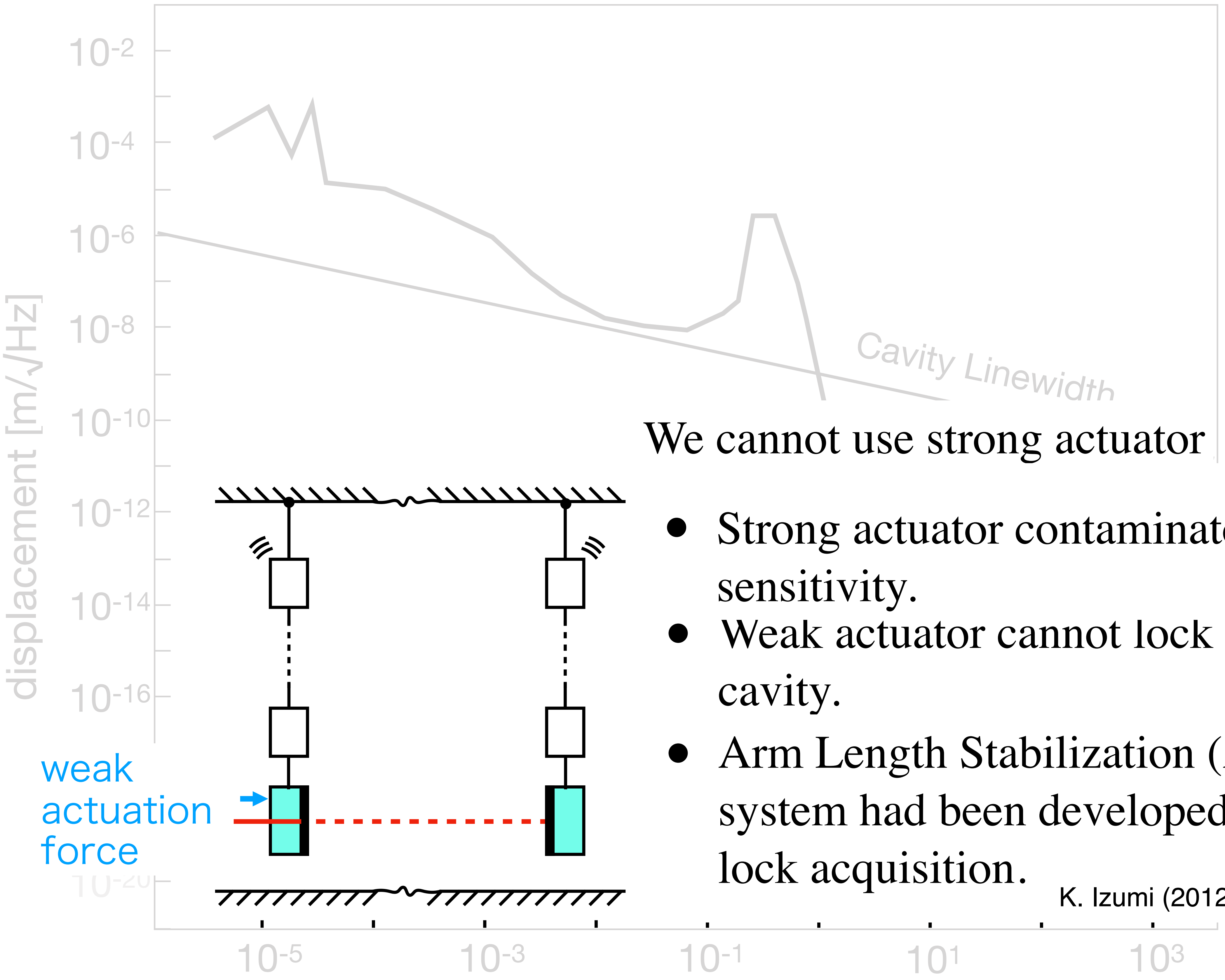
- Pendulum can attenuate the seismic noise passively.
- This attenuation works above eigenfrequency of 1 Hz.

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

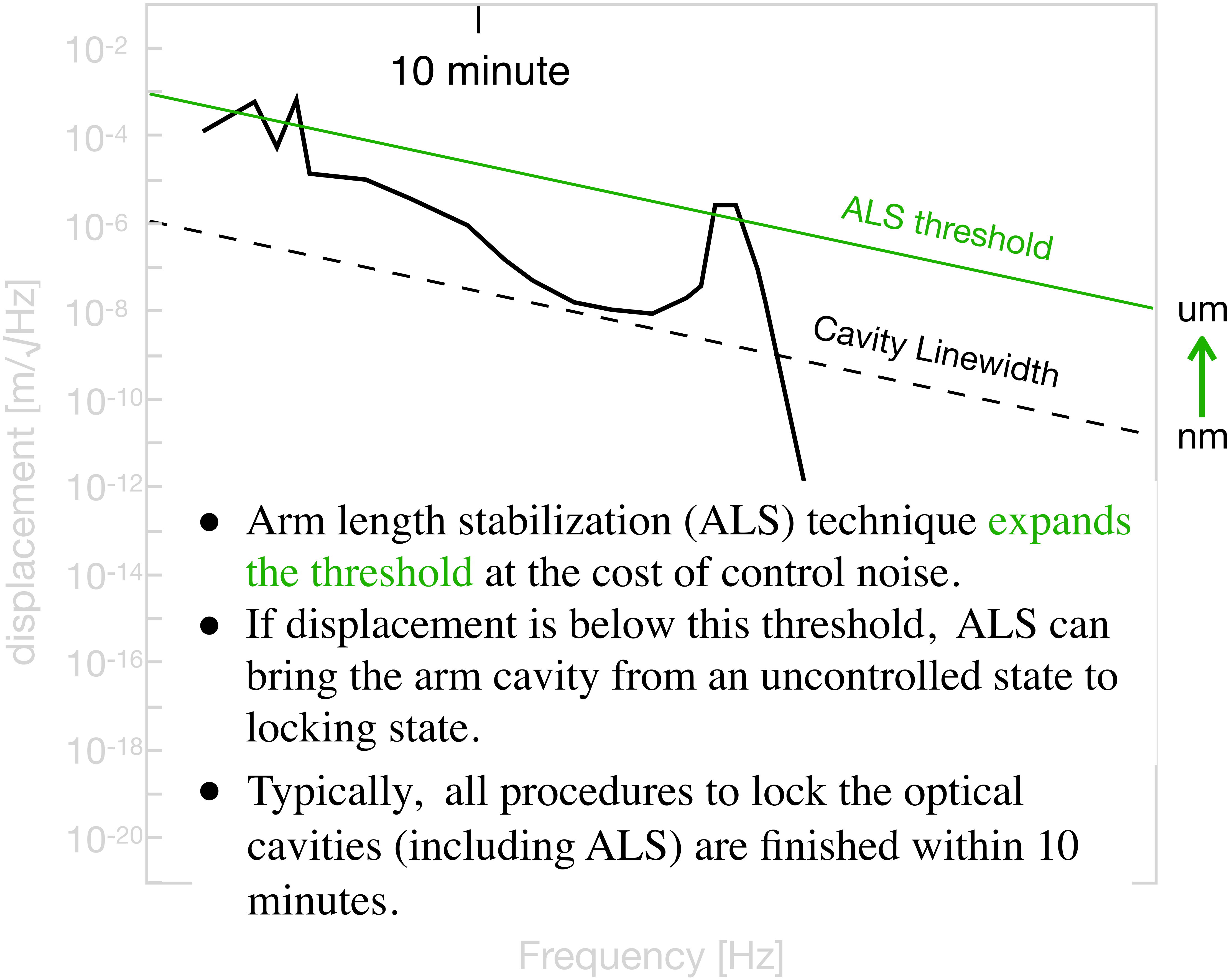


We cannot use strong actuator

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

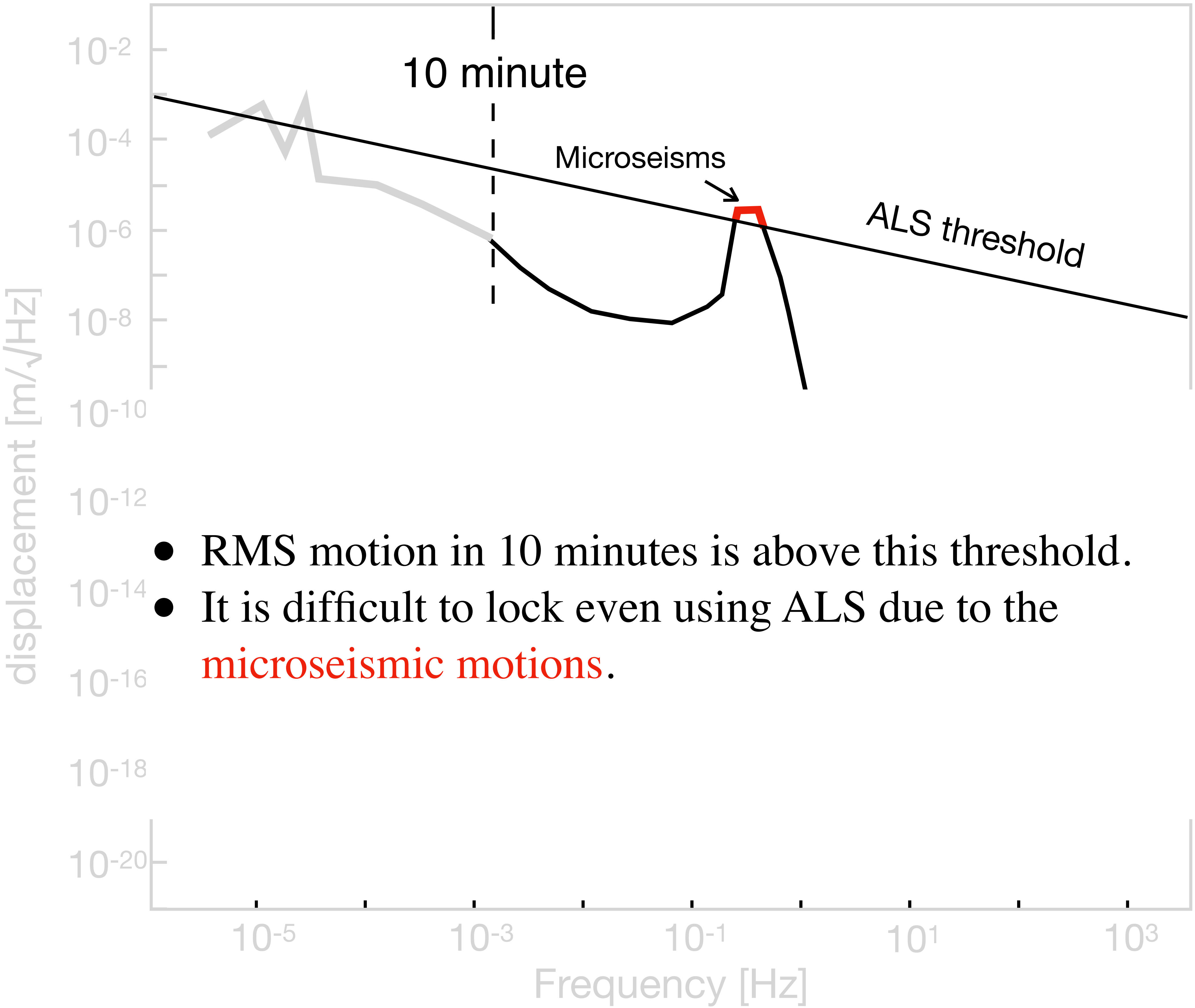
K. Izumi (2012) Ph.D. thesis

Review : seismic isolation system



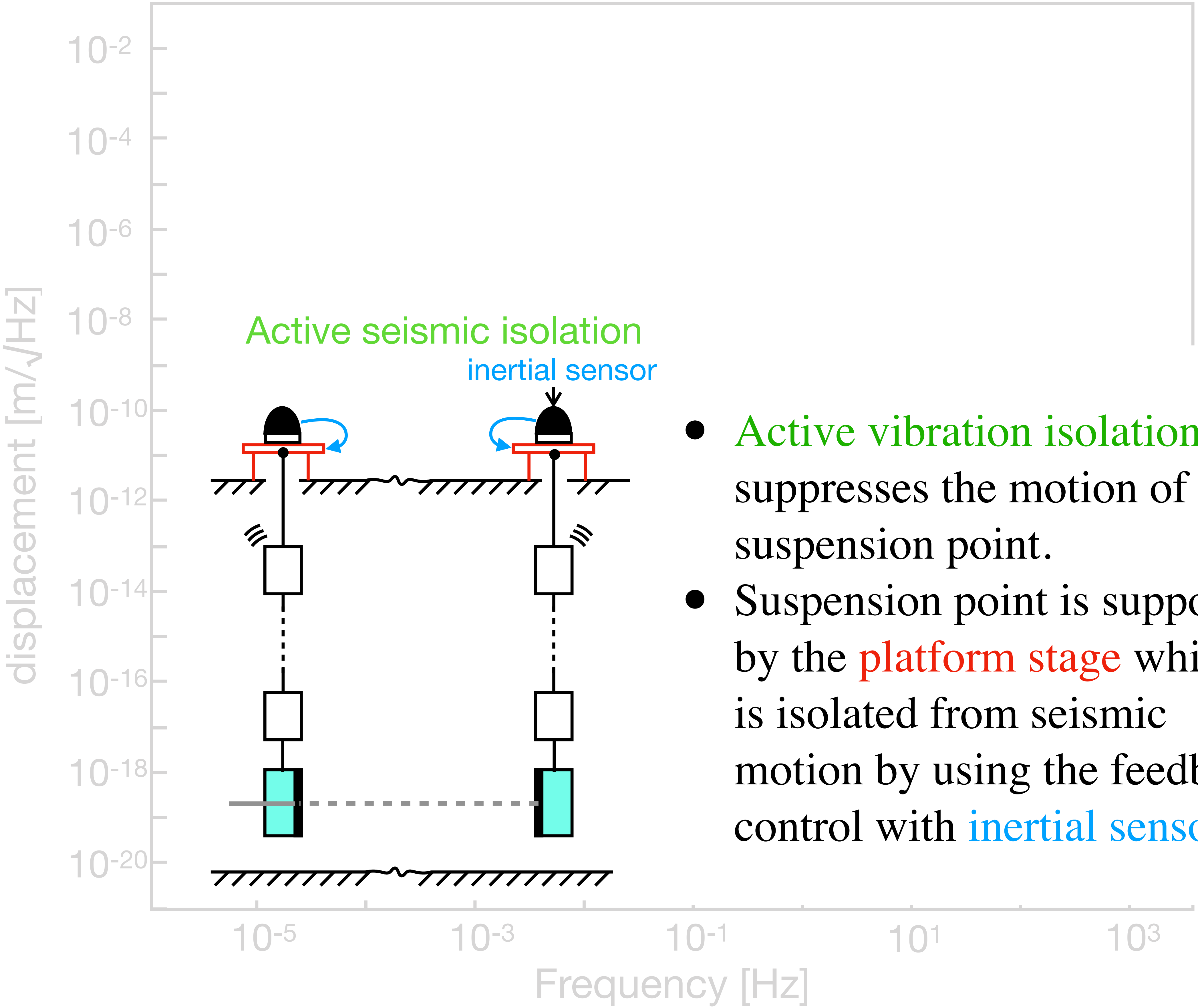
- Arm length stabilization (ALS) technique expands the threshold at the cost of control noise.
- If displacement is below this threshold, ALS can bring the arm cavity from an uncontrolled state to locking state.
- Typically, all procedures to lock the optical cavities (including ALS) are finished within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

Review : seismic isolation system



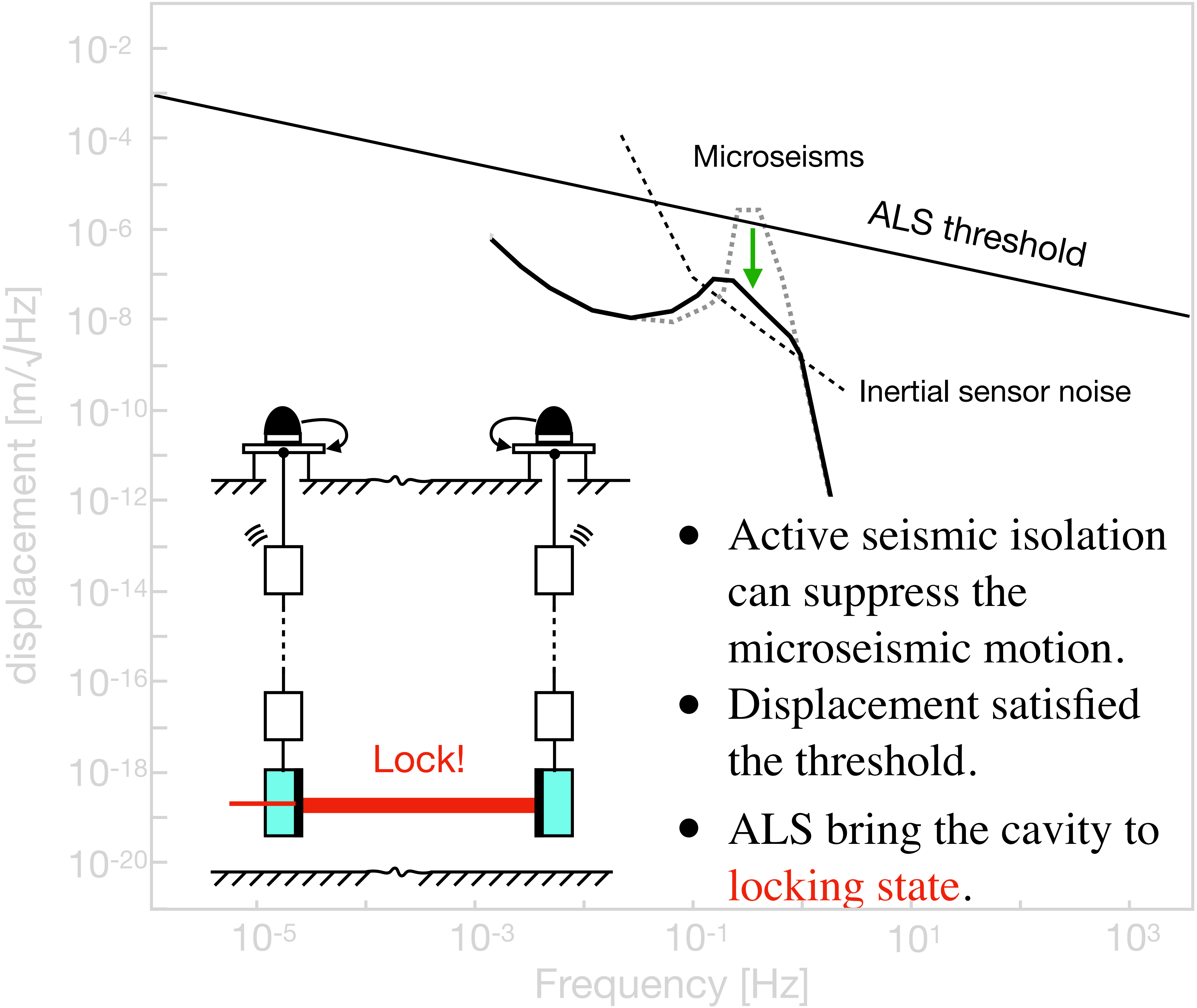
- RMS motion in 10 minutes is above this threshold.
- It is difficult to lock even using ALS due to the microseismic motions.

Review : seismic isolation system



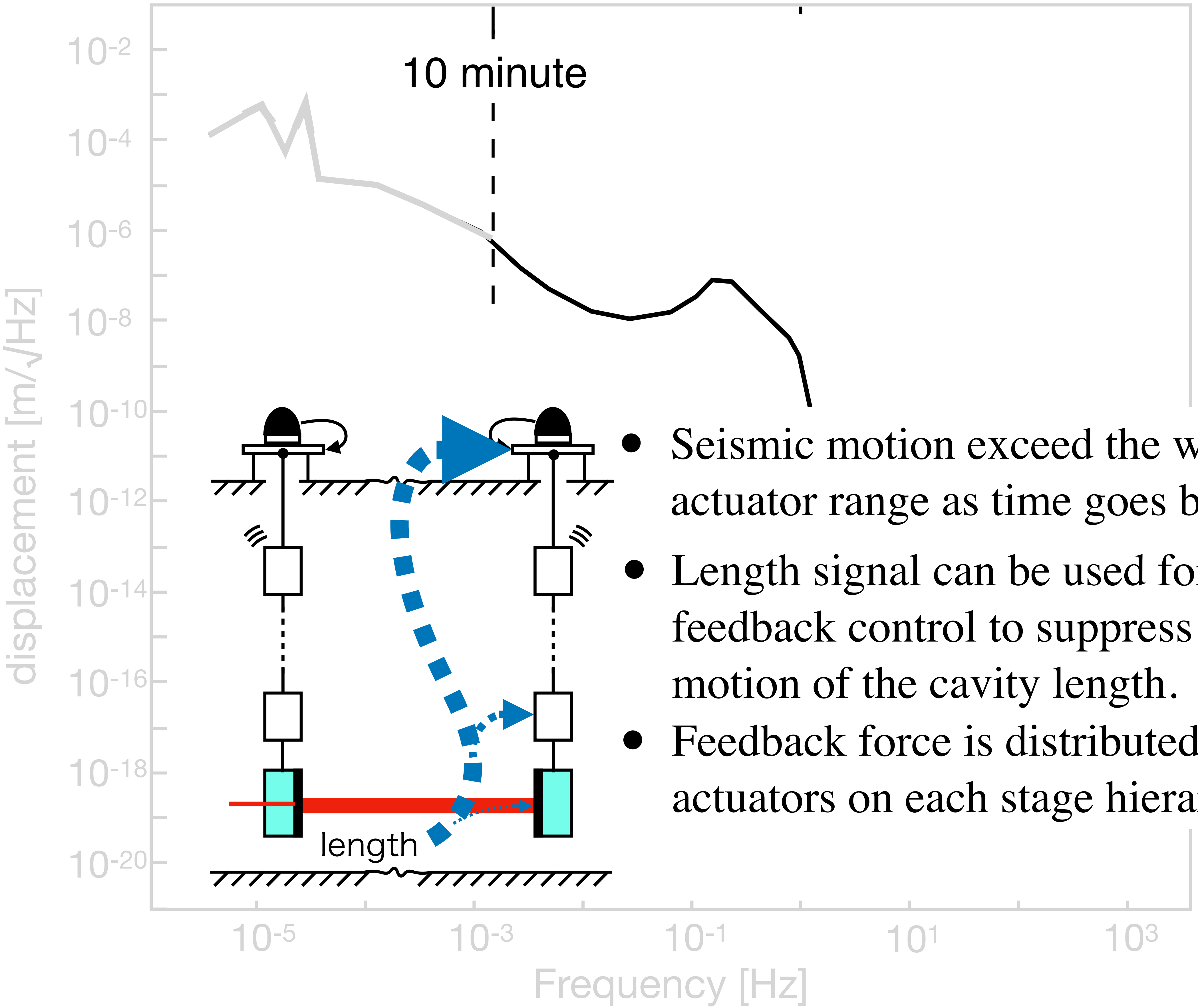
- Active vibration isolation suppresses the motion of the suspension point.
- Suspension point is supported by the platform stage which is isolated from seismic motion by using the feedback control with inertial sensor.

Review : seismic isolation system



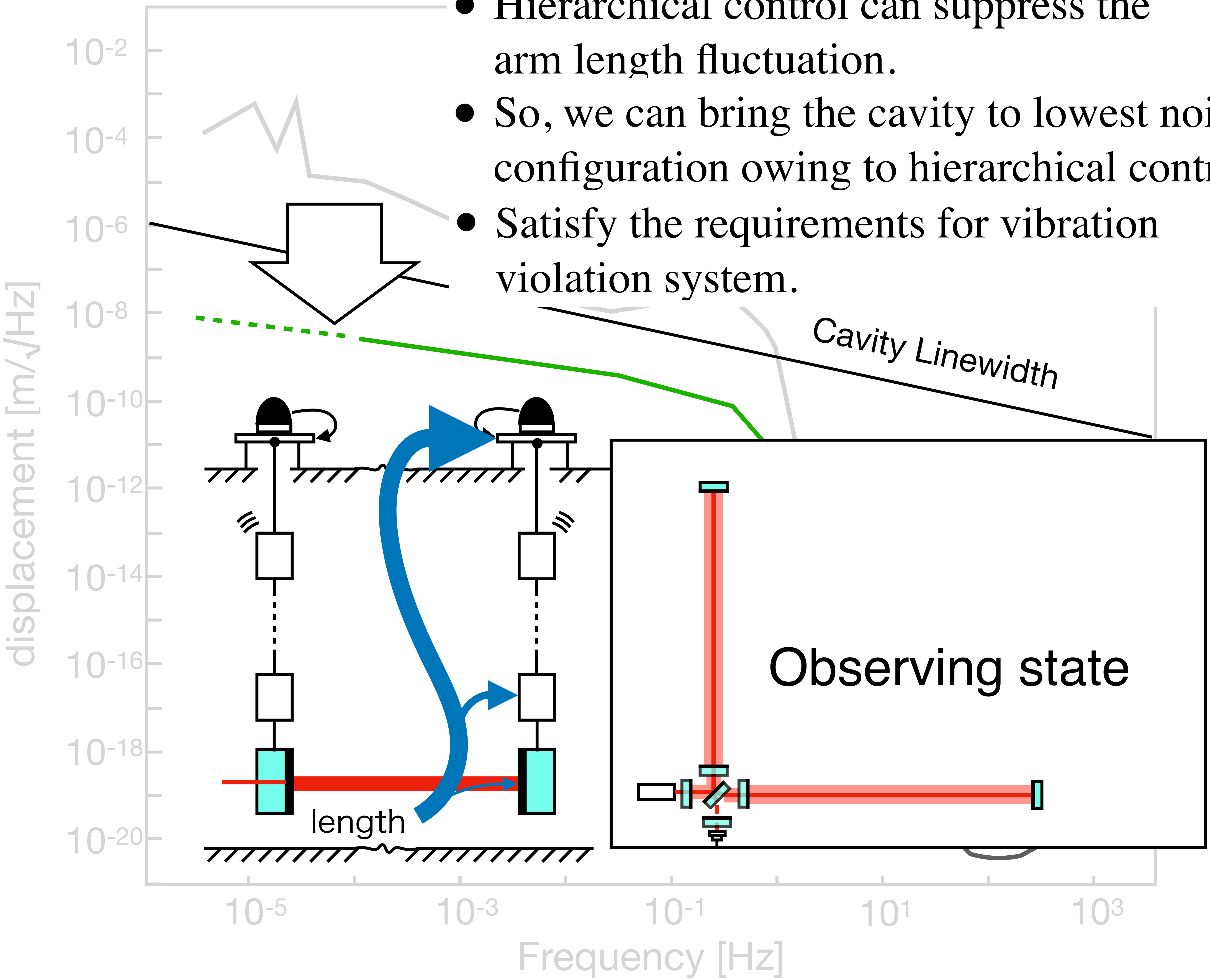
- Active seismic isolation can suppress the microseismic motion.
- Displacement satisfied the threshold.
- ALS bring the cavity to locking state.

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

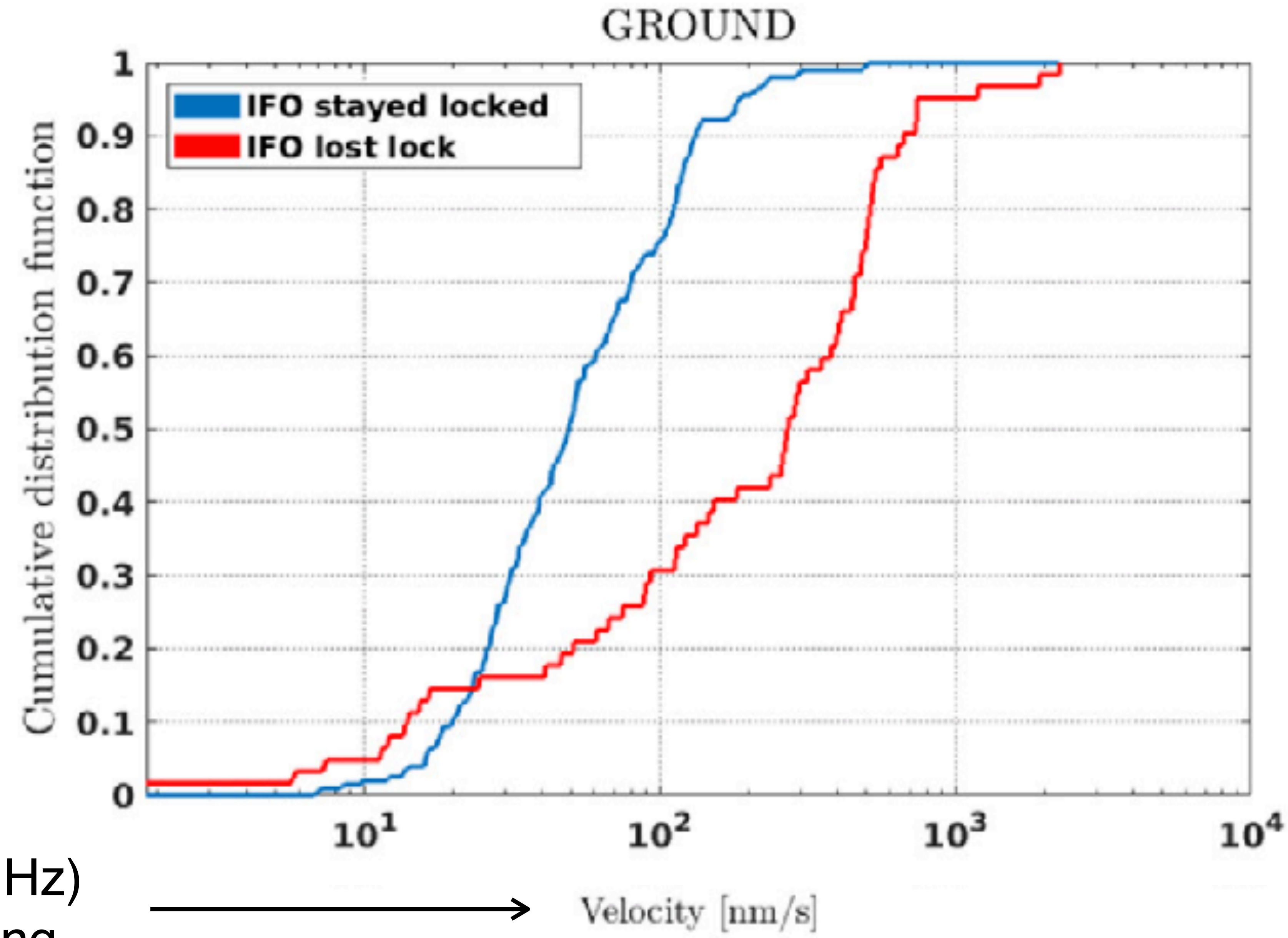


- Hierarchical control can suppress the arm length fluctuation.
- So, we can bring the cavity to lowest noise configuration owing to hierarchical control
- Satisfy the requirements for vibration violation system.

Limit of the current seismic isolation system

- Lockloss is caused by the big earthquakes shaking the ground below 100 mHz.
- LIGO had reported a clear correlation between the lockloss and ground motion enhancement in this frequency region.

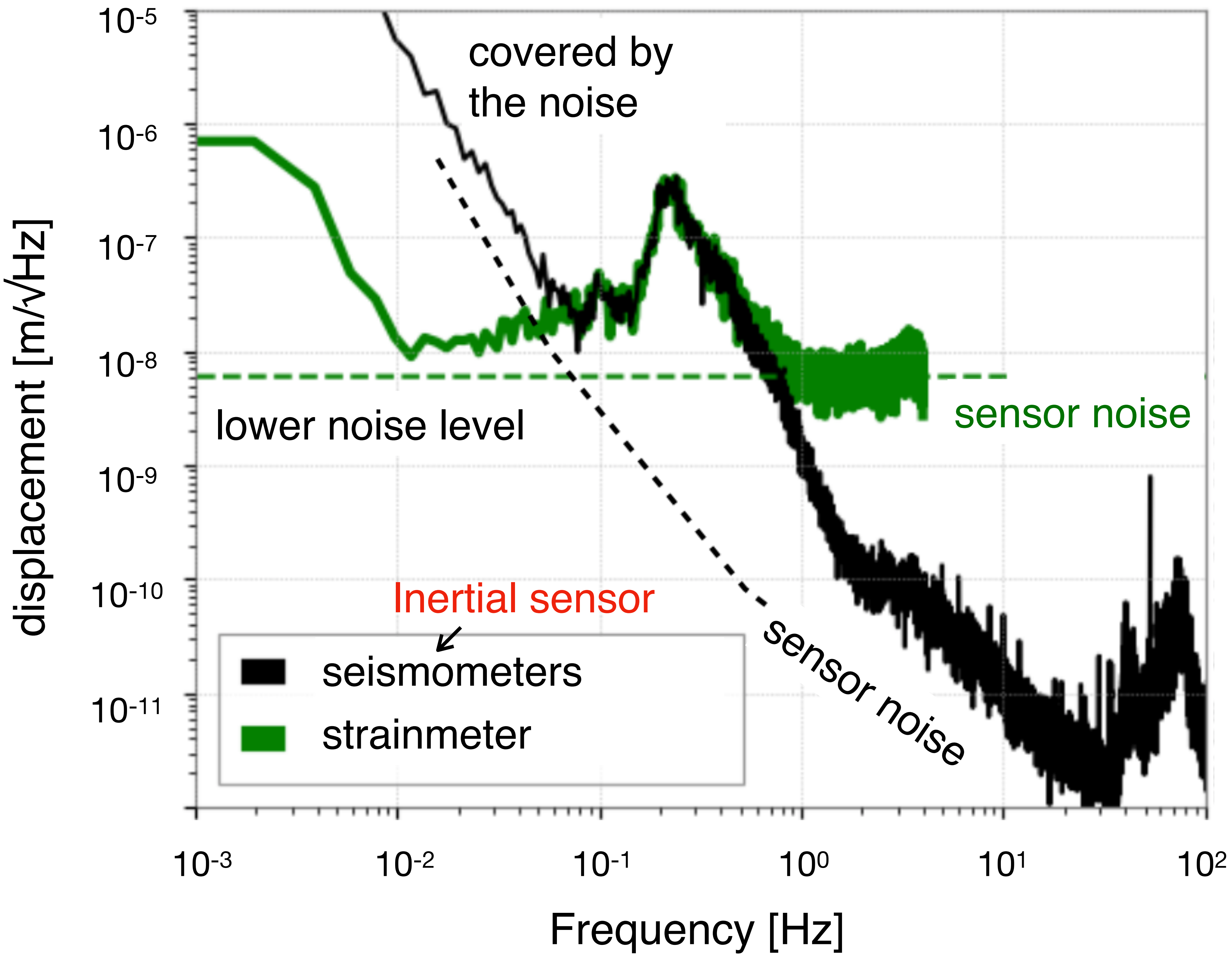
We need a better sensor in low-frequency



ground motion (30 - 100 mHz) when earthquakes are hitting. →

Biscans S. et al., 2018, Class. Quantum Gravity, 35, 055004

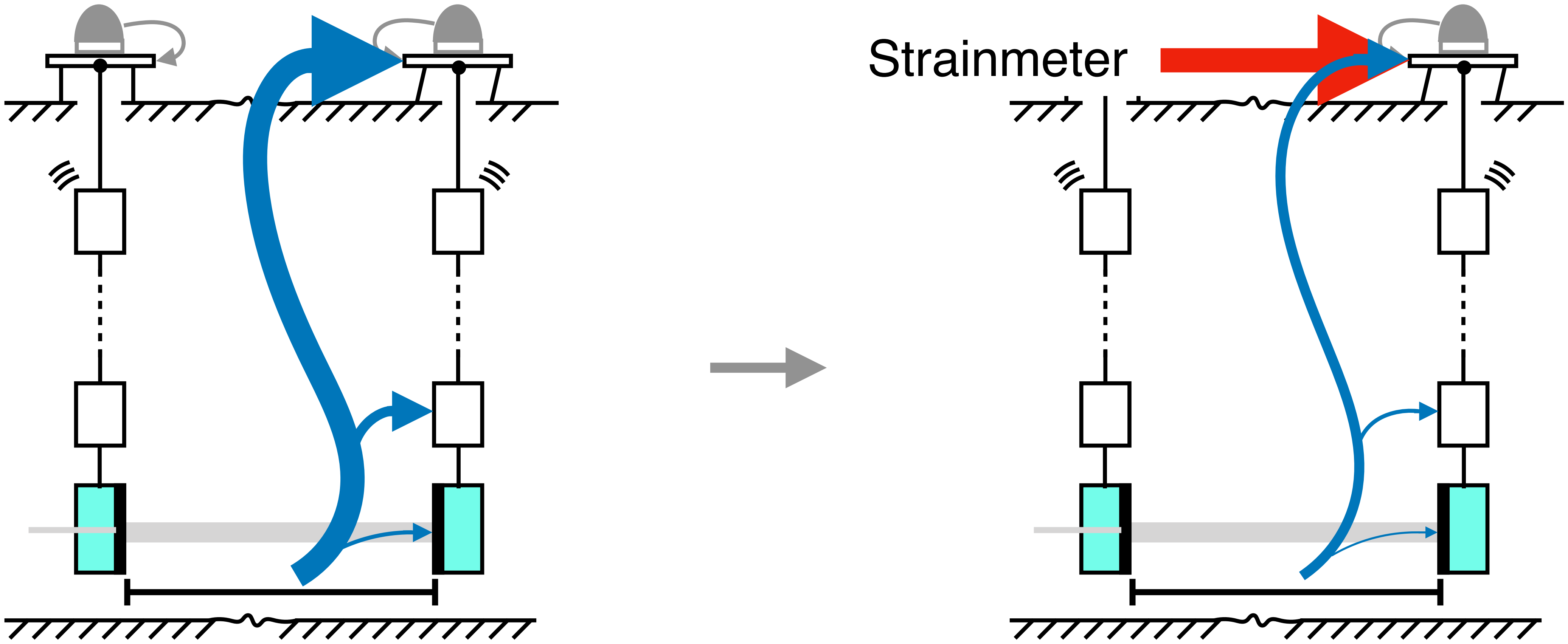
Strainmeter is better sensor



Strainmeter has a better sensitivity in low-frequency band (below 0.1 Hz)

Strainmeter can compensate the low-frequency seismic motion.

Motivation of low-frequency seismic isolation



- Inertial sensor cannot compensate the low-frequency seismic motion
- Rely on the hierarchal feedback control

- Strainmeter can compensate the low-frequency seismic motion
- Relax the feedback control

Relax the feedback control

- Can avoid the saturation of the weak actuator
- Improve stability of the feedback control

→ become more stable operation

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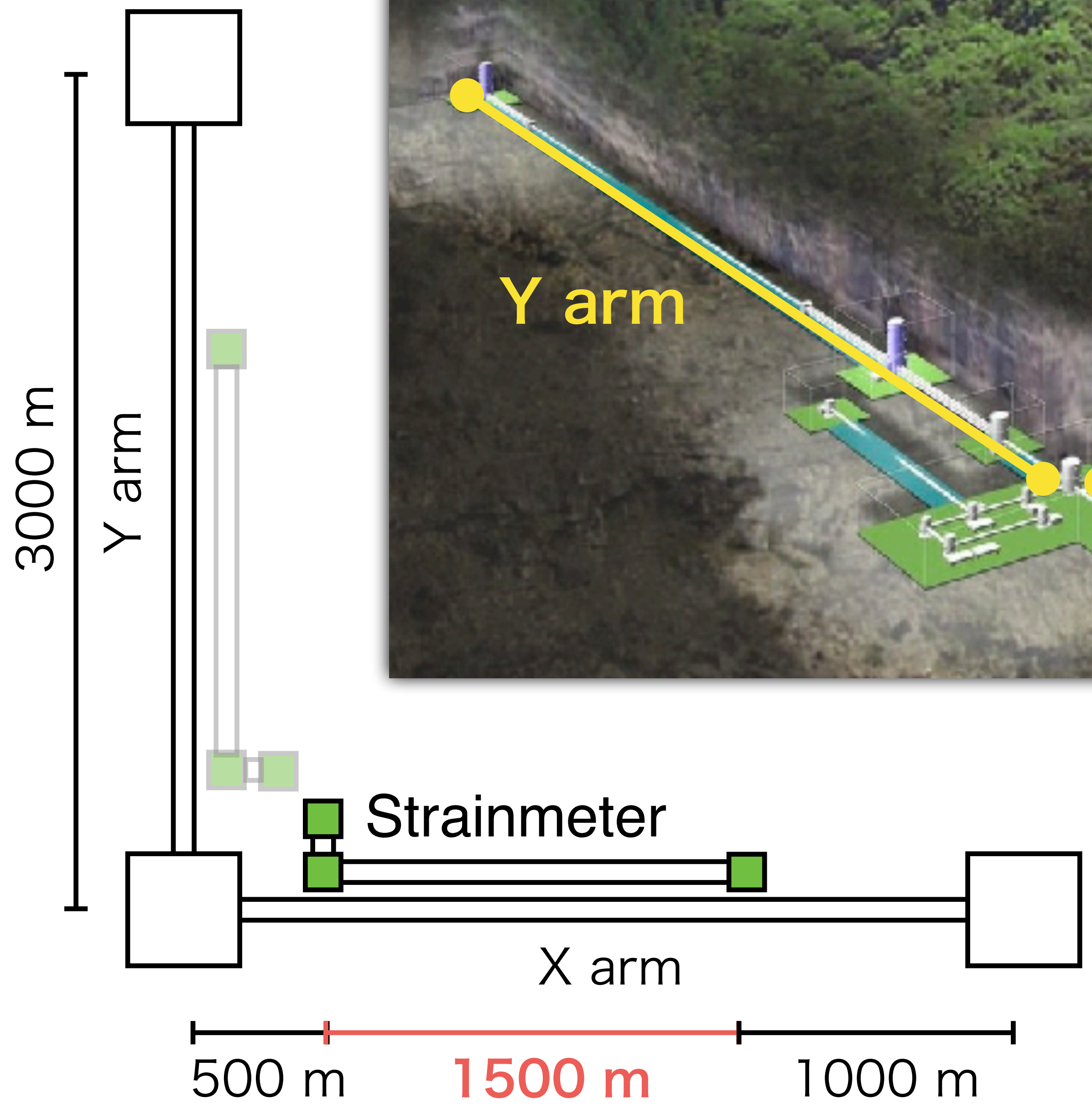
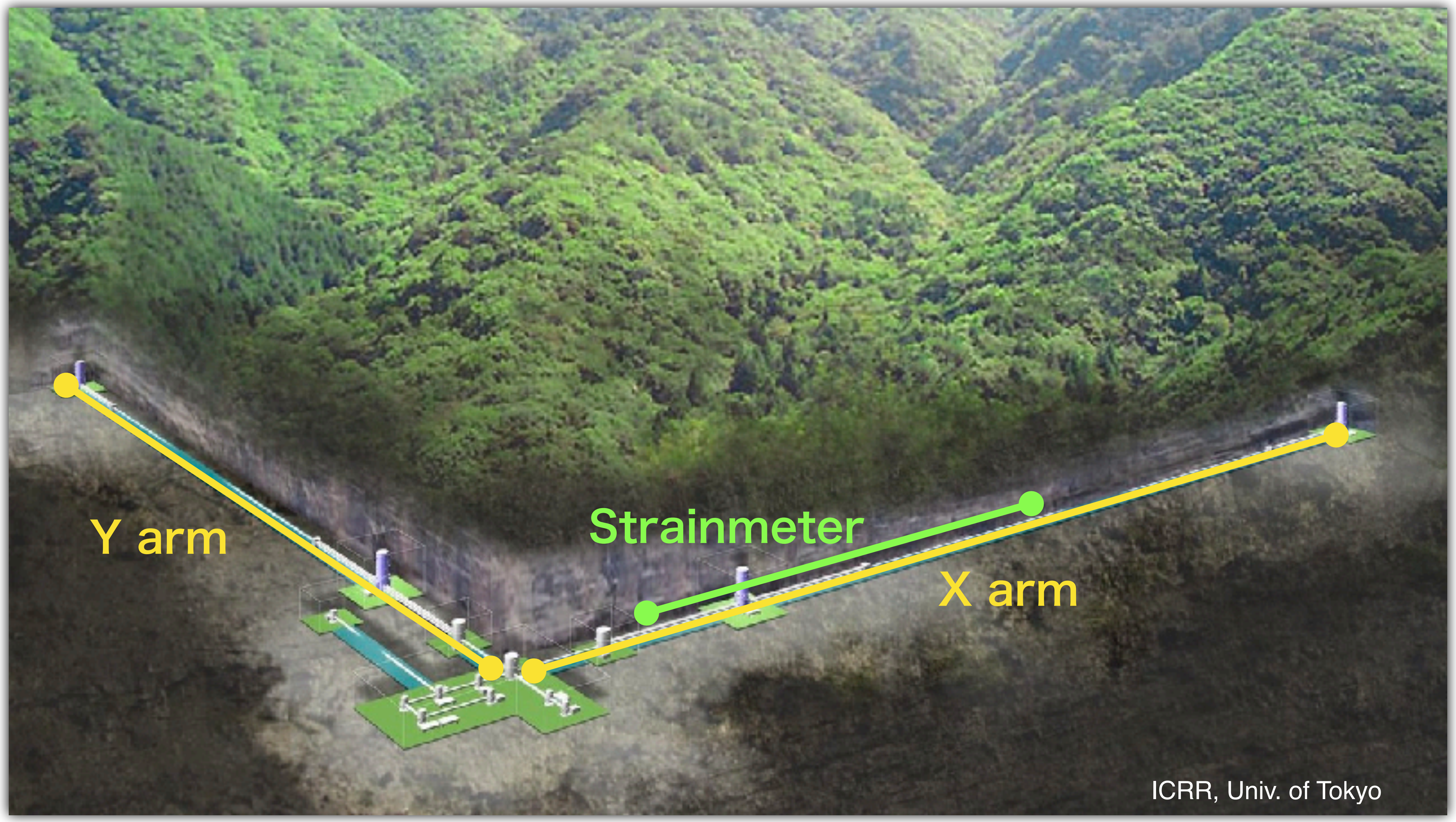
KAGRA and strainmeter



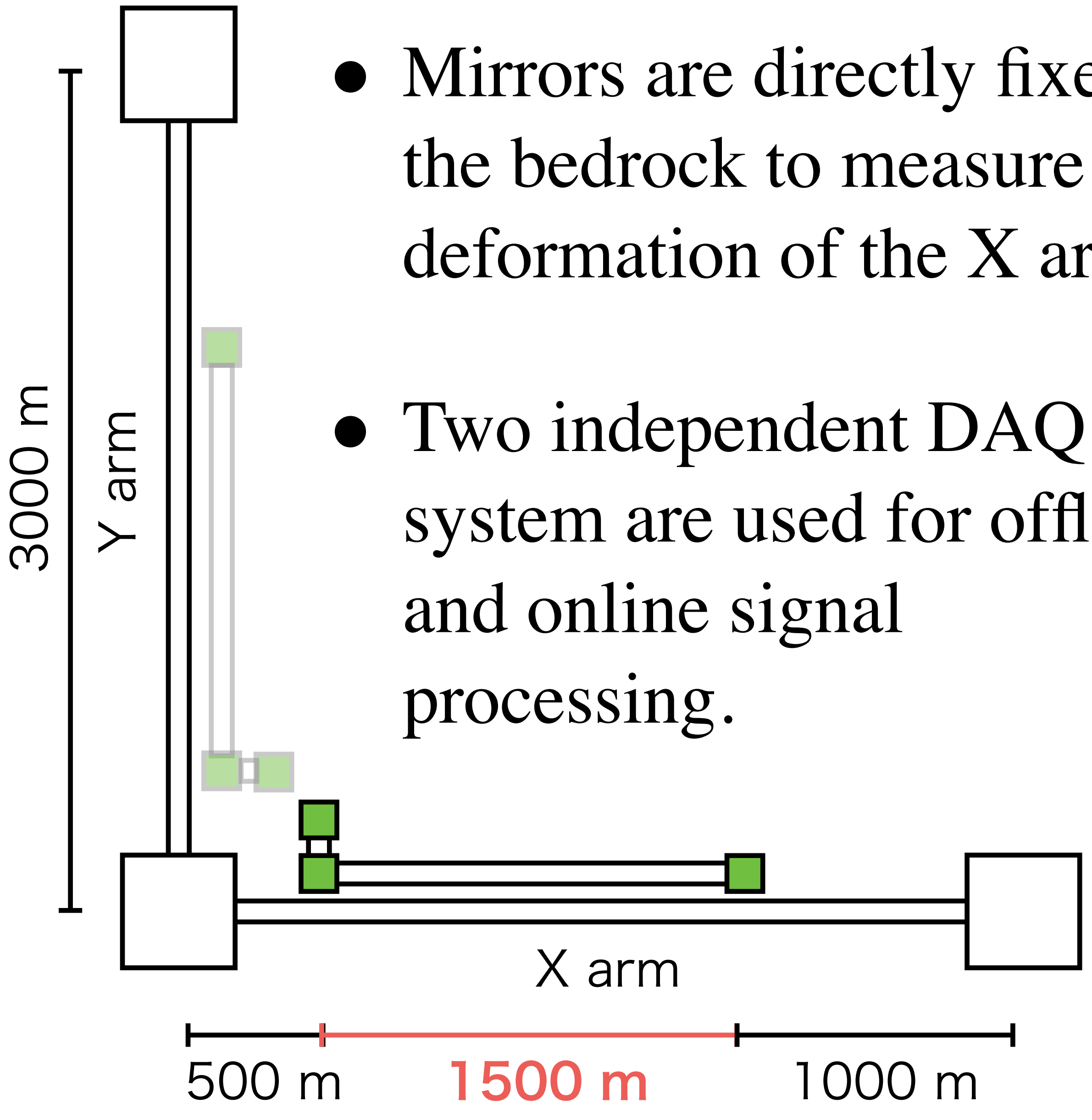


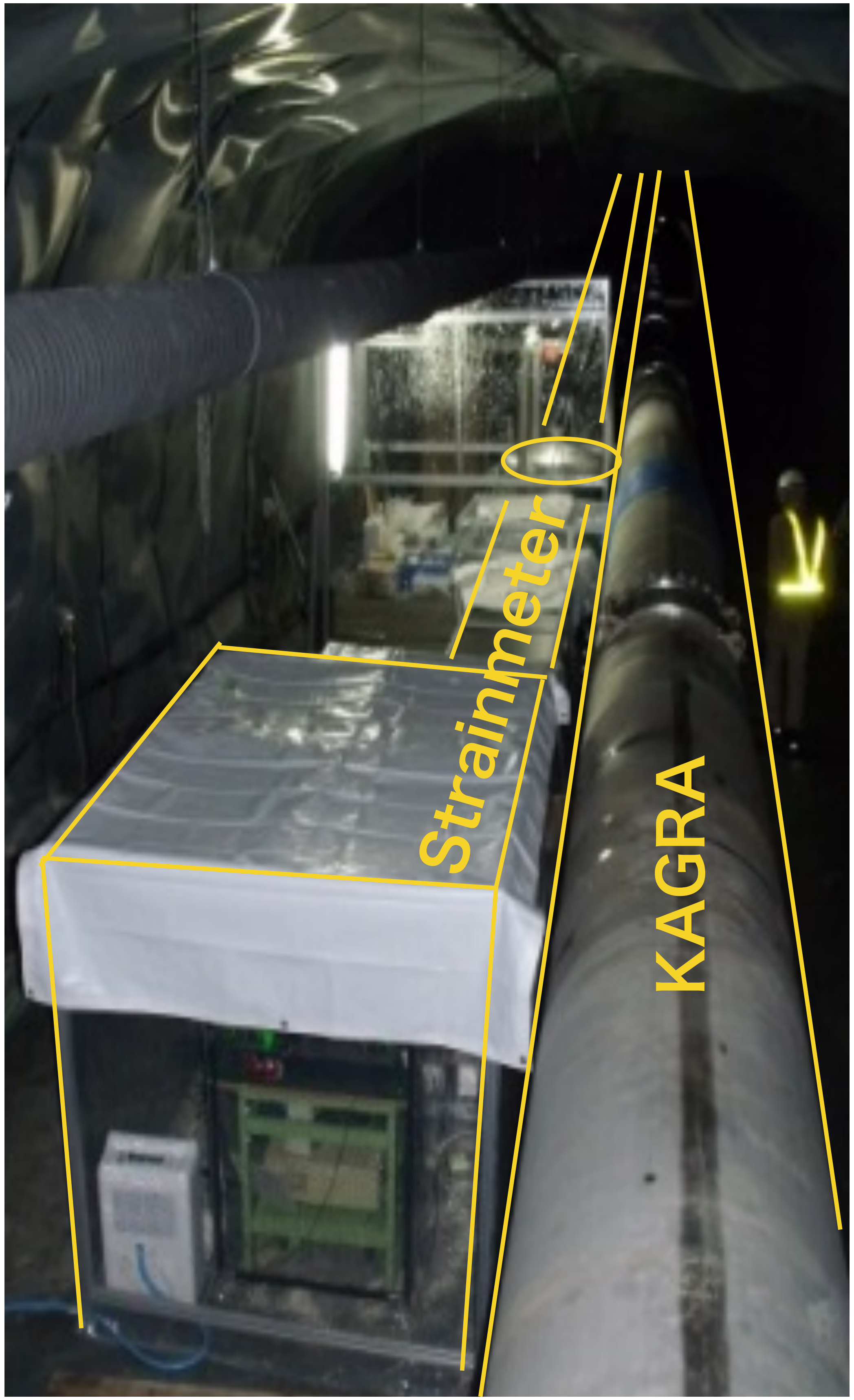
ICRR, Univ. of Tokyo

Strainmeter is an asymmetric 1500 m Michelson interferometer.

Strainmeter

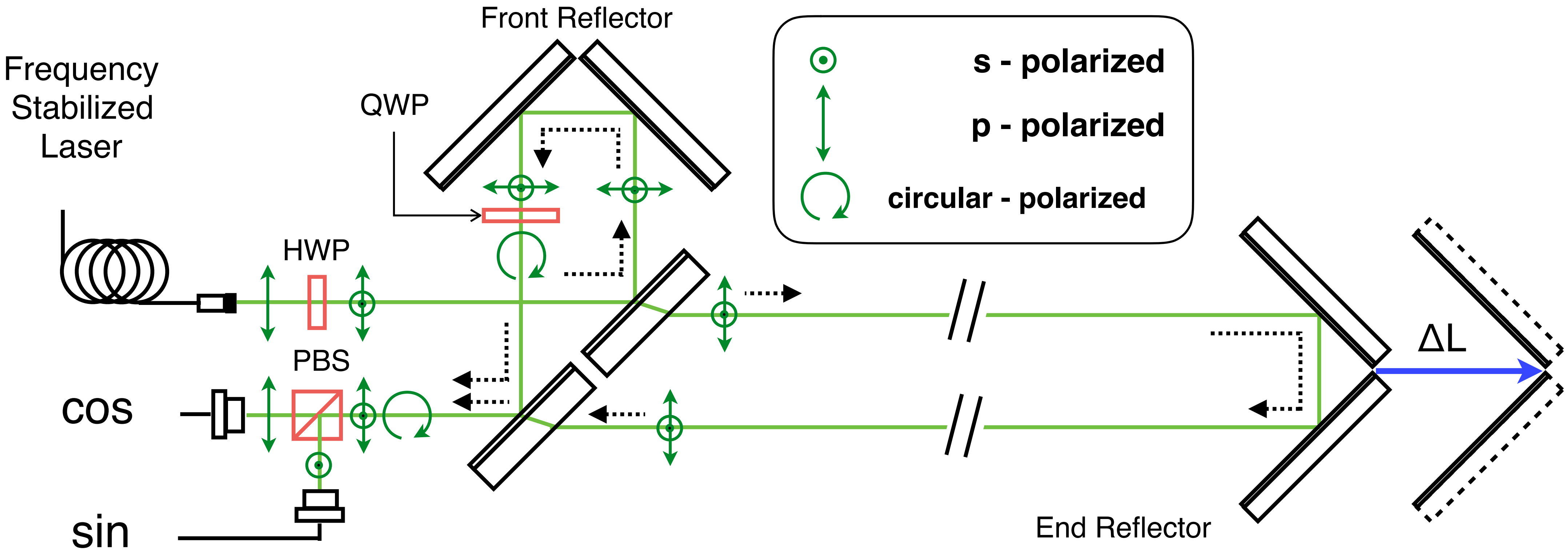
- Strainmeter had been developed for observation of the geophysical phenomena by ERI
- Mirrors are directly fixed on the bedrock to measure the deformation of the X arm.
- Two independent DAQ system are used for offline and online signal processing.

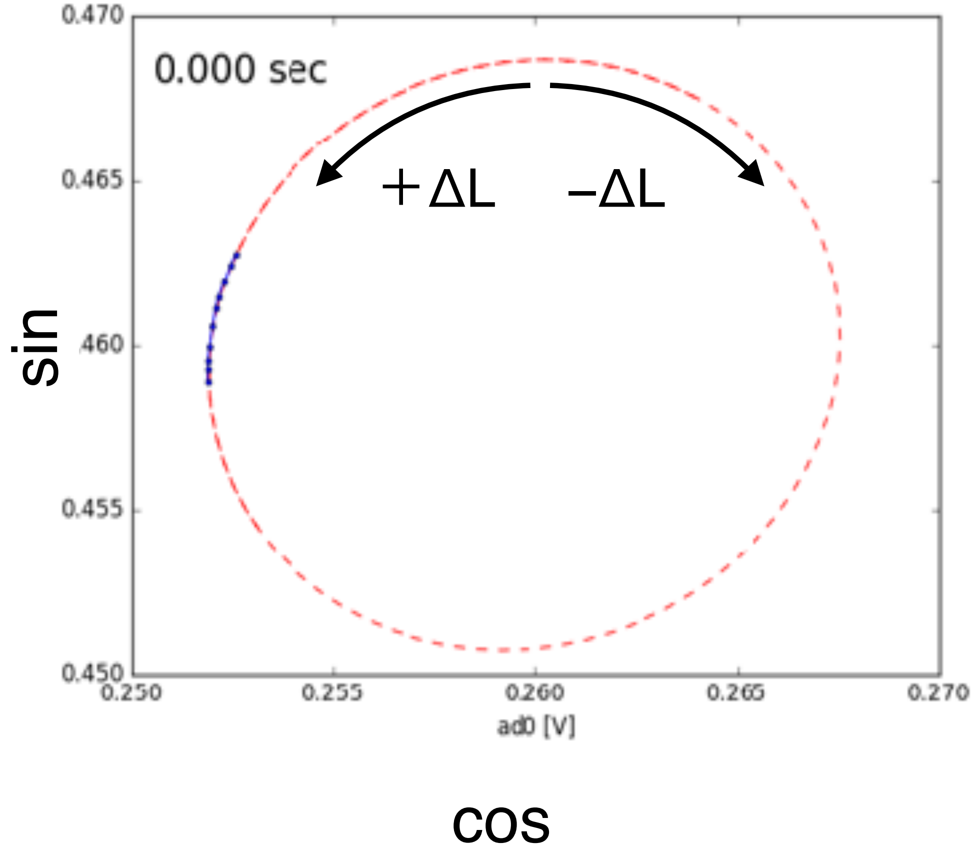




ERI : Earthquake Research Institute, University of Tokyo
DAQ : Data acquisition

The way to measure the baseline fluctuation

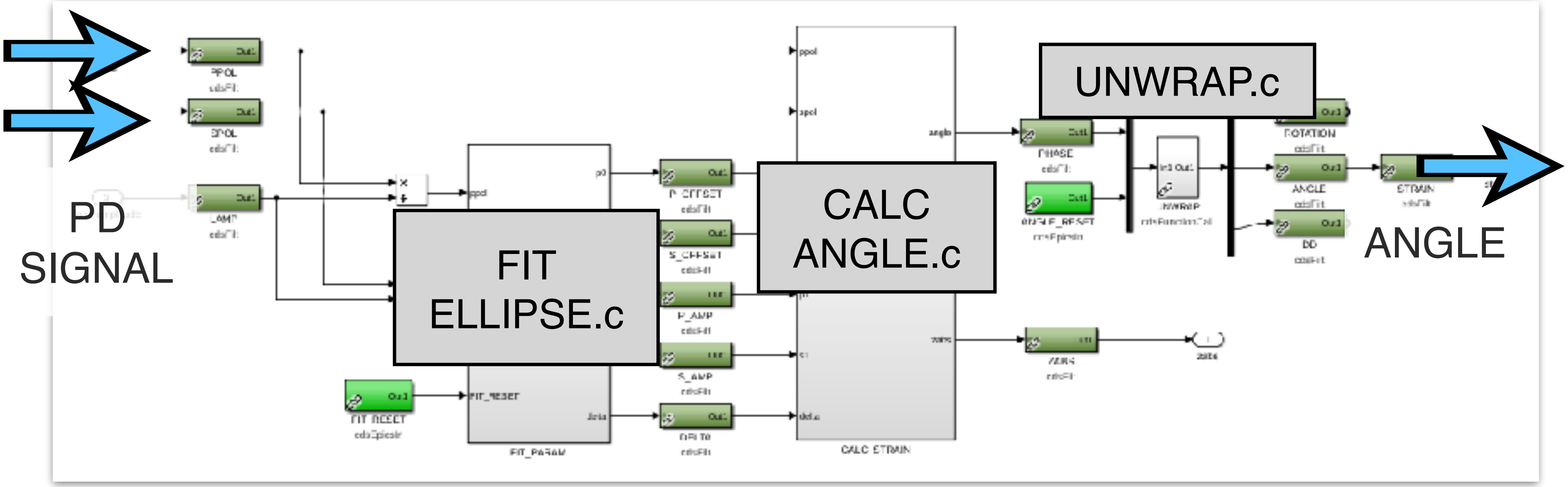




- Baseline fluctuation ΔL is proportional to a rotation angle

- To obtain a rotation angle, we need to fit the data with an ellipse curve.

Realtime signal processing for strainmeter



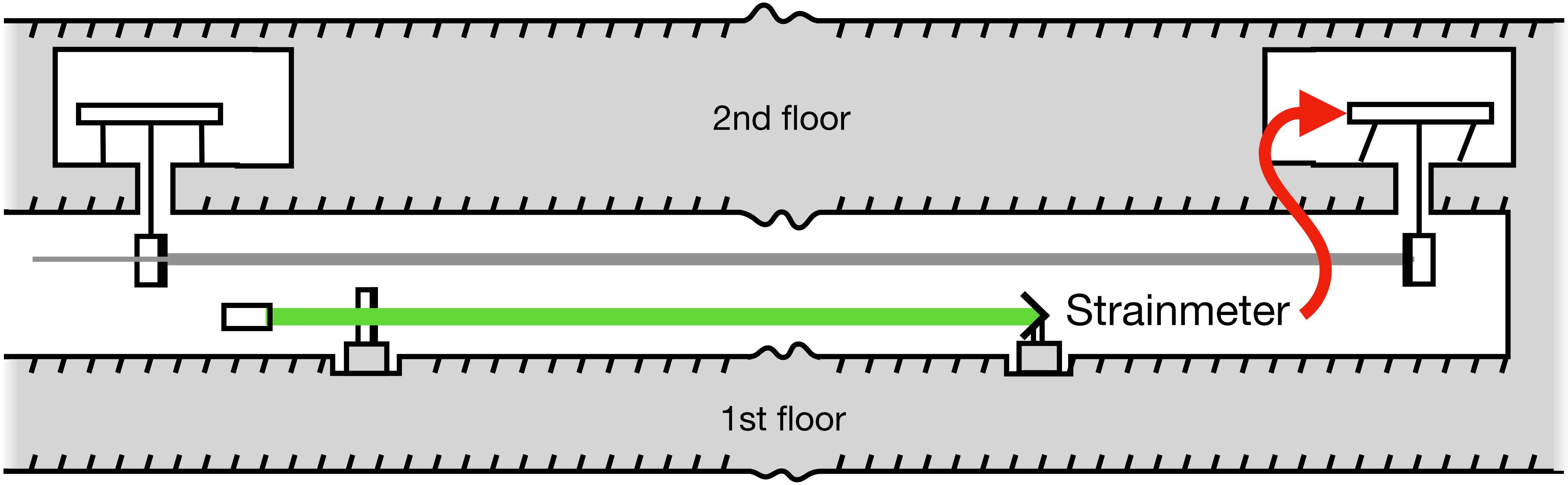
Calculating every 1 clock (16 kHz)

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

Baseline Compensation System



sectional view of X-arm tunnel

Feedforward control using a strainmeter

- compensate for the cavity length by actuating the top stage

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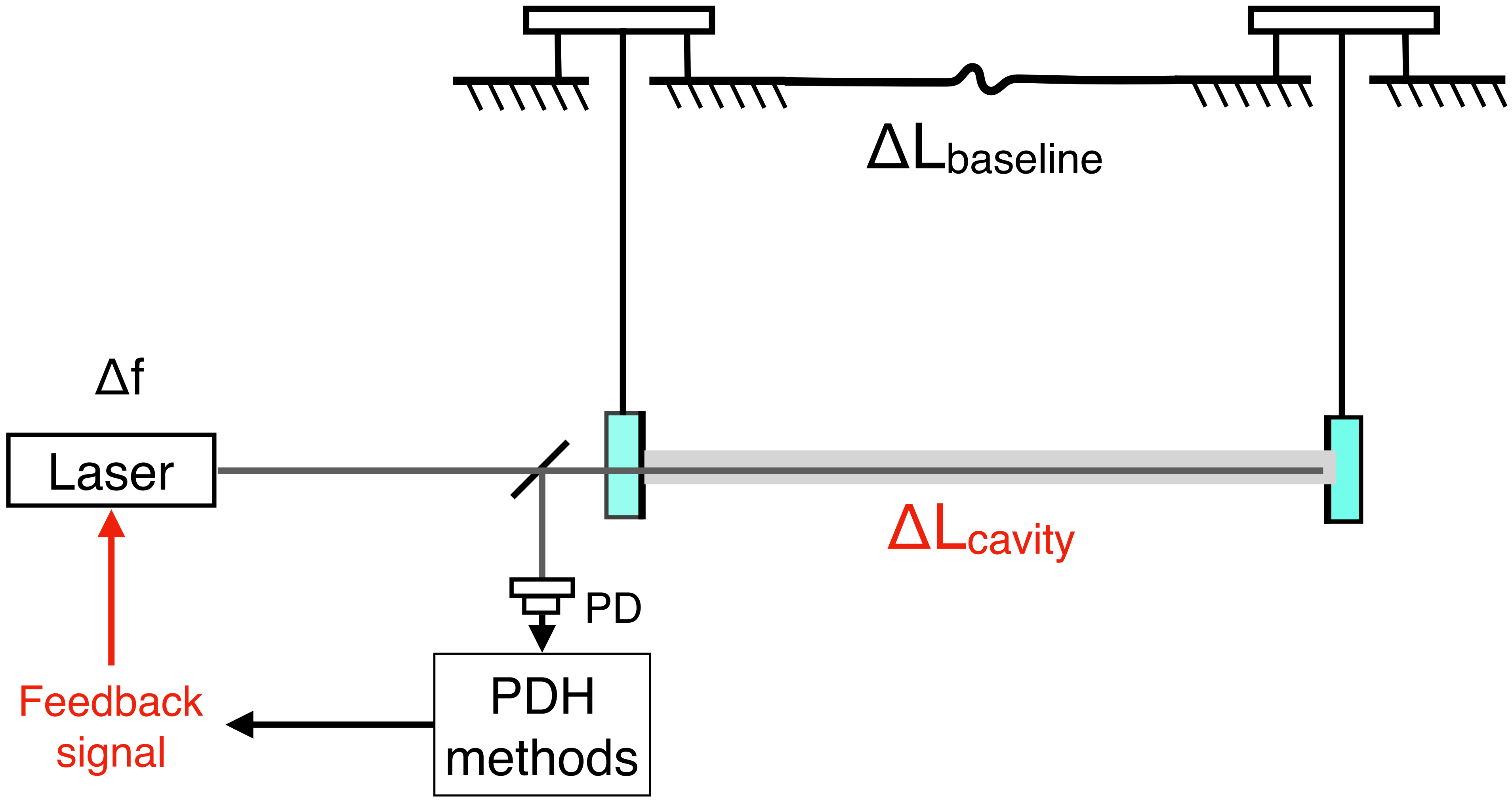
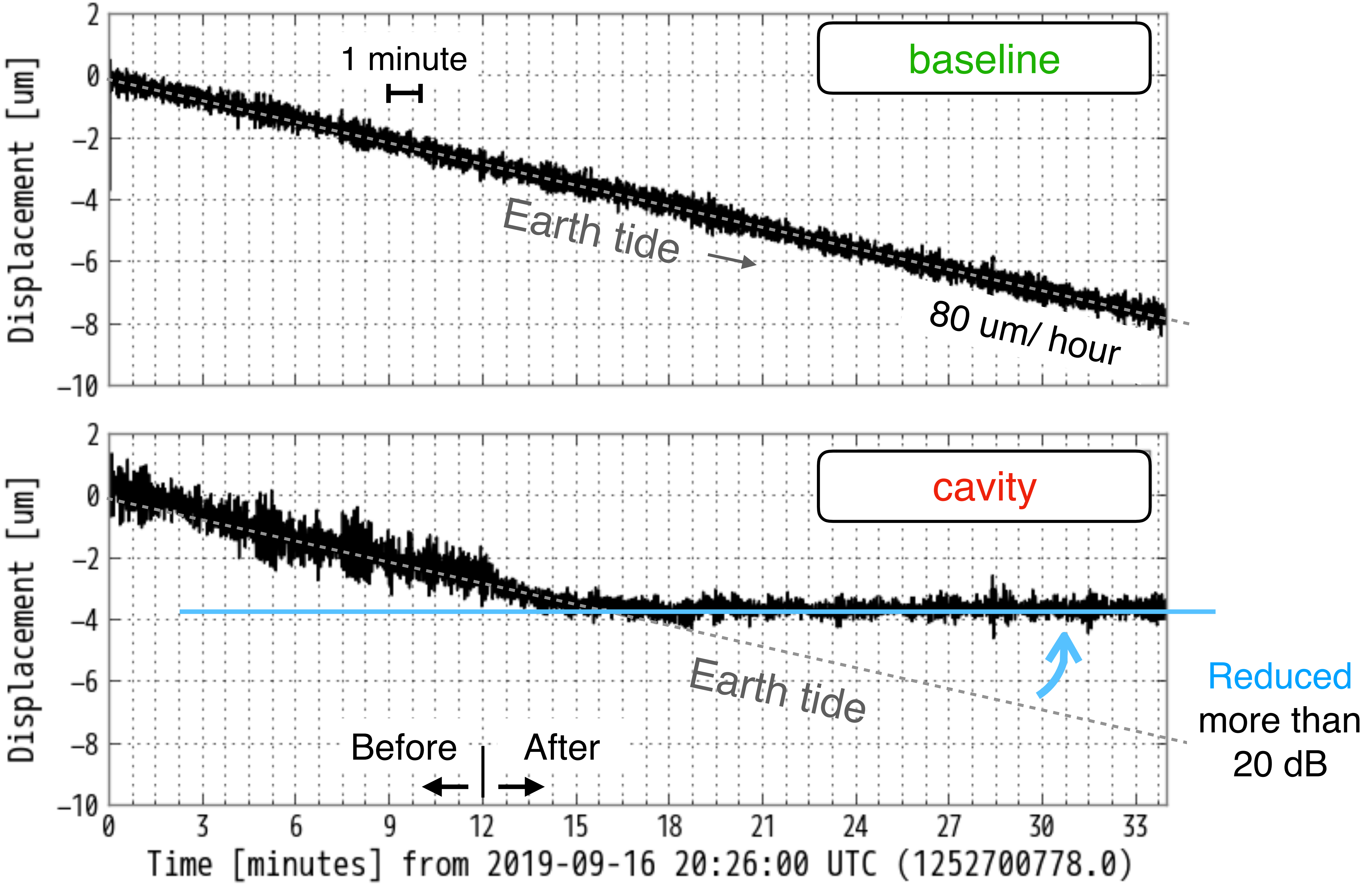
Setup for Demonstration



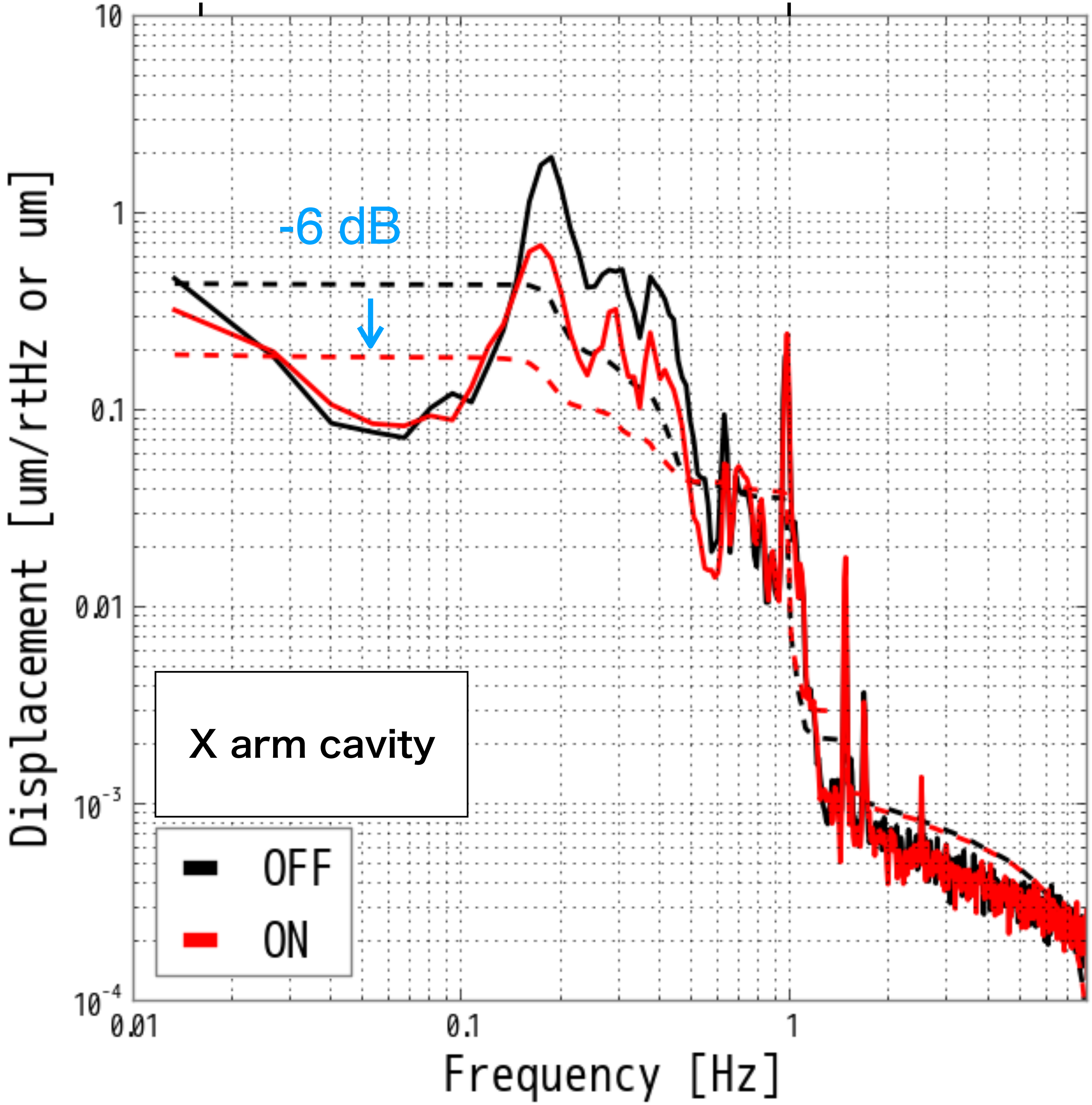
- Keep the X-arm cavity on resonance by changing the laser frequency.
- ΔL_{cavity} is calculated from the feedback signal
- $\Delta L_{baseline}$ is measured by a strainmeter

Results



1 minute
baseline
Earth tide
80 um/ hour
cavity
Earth tide
Before
After
Reduced
more than
20 dB
Displacement [um]
2
0
−2
−4
−6
−8
−10
0
3
6
9
12
15
18
21
24
27
30
33
Time [minutes] from 2019-09-16 20:26:00 UTC (1252700778.0)

Profit in the Microseismic band



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Conclusion

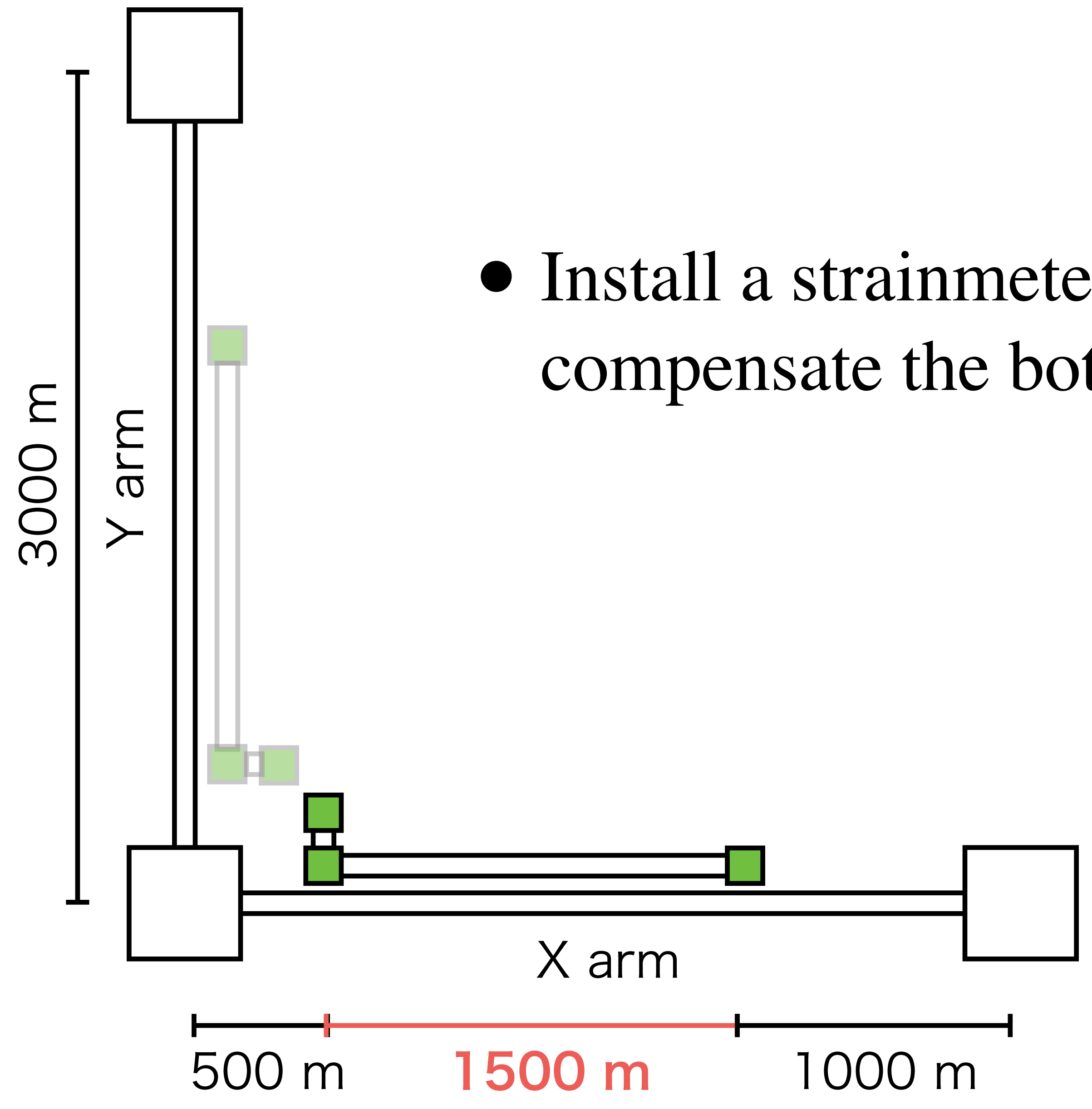
- Duty cycle is limited by low-frequency seismic motions

My work

- We designed the baseline compensation system and demonstrate its performance by using X-arm cavity of KAGRA.
- As a result, this new system had reduced the fluctuation of the arm cavity not only tidal motion (< -20 dB) but also microseismic motion (-6 dB).

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

Future prospects



- Install a strainmeter at the Y-arm and compensate the both arm cavities.

End

Backup

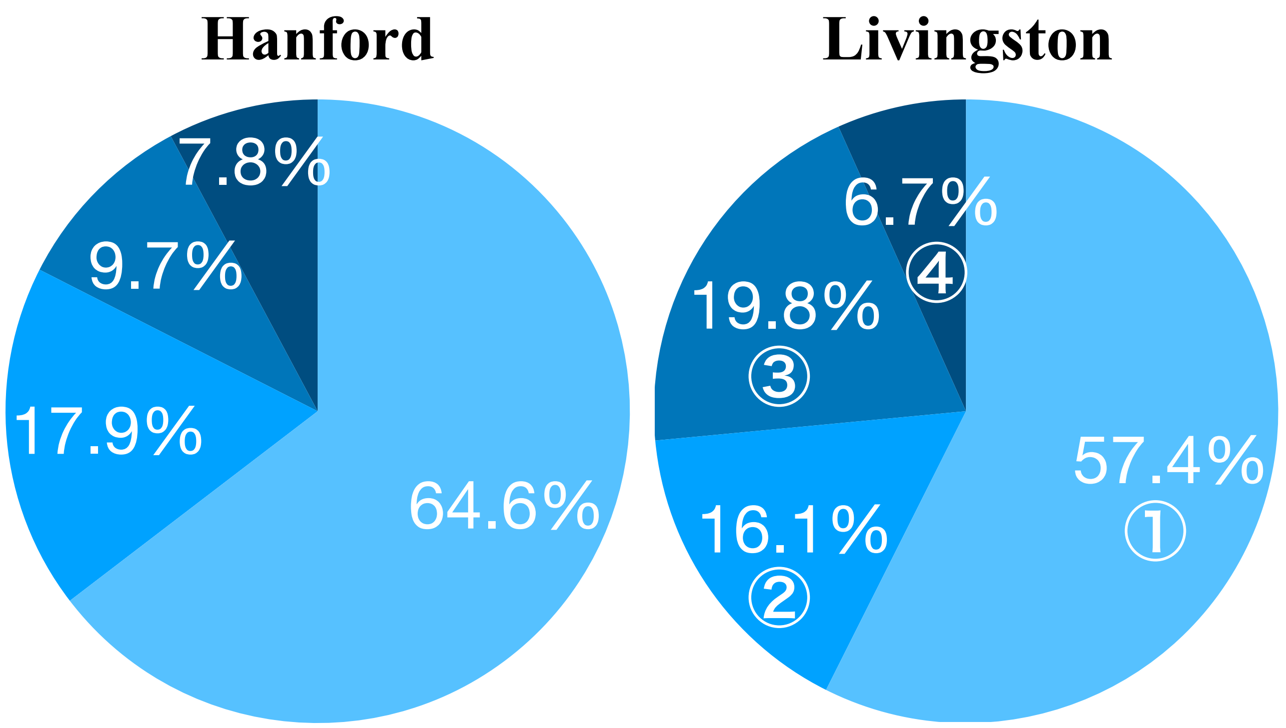
要点

- 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。これにより地面振動で制限されている duty cycle を直接向上させることが期待される。

Duty cycle of GW detectors

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

- **O1 :** 12 Sep. 2015 - 19 Jan. 2016 (49 days)



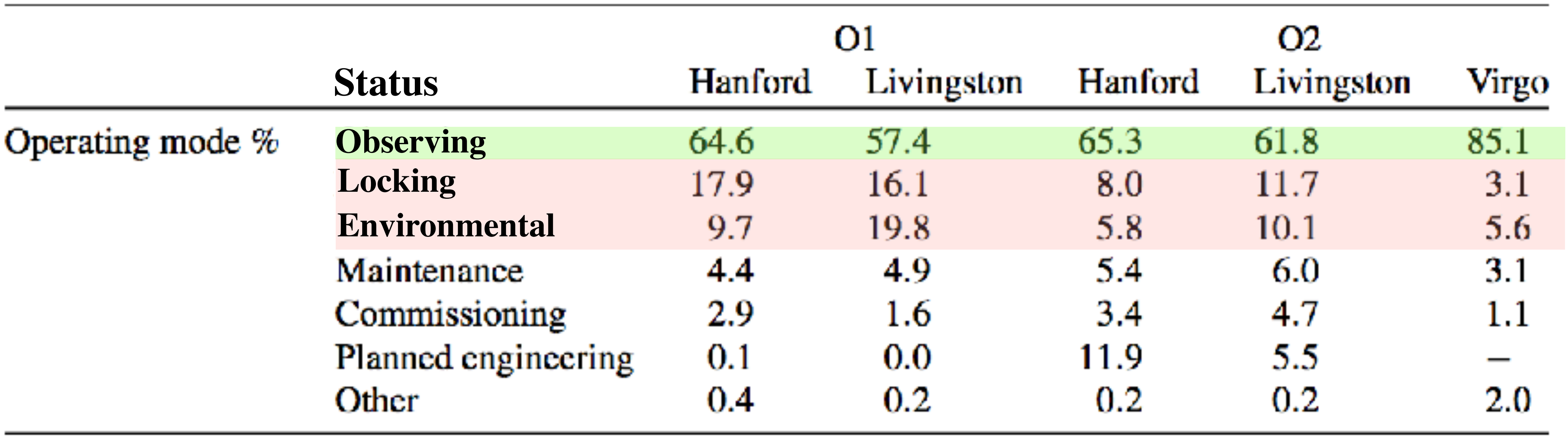
Abbott, B. P., et al. *Living Reviews in Relativity* **21** (2018) 3.

1. **“Observing”**
   - Observation status. (= duty cycle)
2. **“Locking”**
   - Just locking the interferometer but noisy. Can not observe.
3. **“Environmental”**
   - Can not even lock due to environmental disturbances
4. **“Others”**
   - Maintenance and commissioning

- line

Duty cycle of GW detectors

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

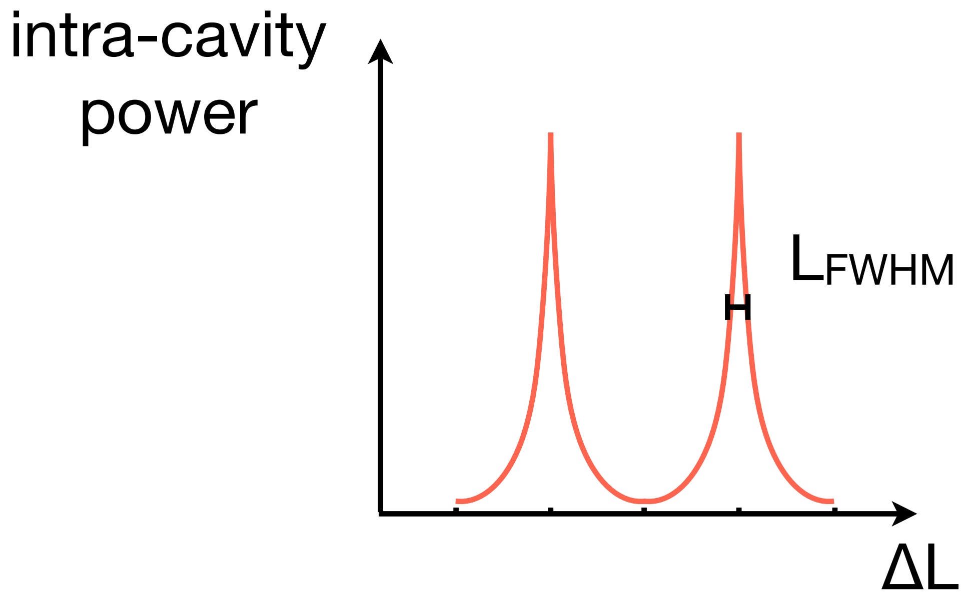
Fabry–Pérot optical resonance cavity

- Resonance condition

- Resonance condition
  - The cavity can resonate within the linewidth which is given by

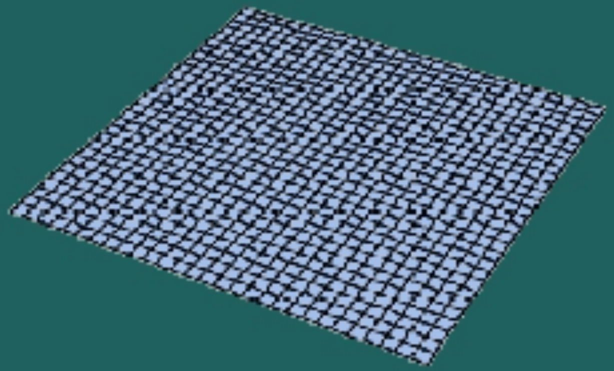
$$L_{\mathrm{FWHM}} = \frac{\lambda}{2\mathscr{F}} \qquad \left(\mathscr{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2}\right)$$

- Arm cavity has the most small linewidth (a few nm)
  - **Arm cavity is a most fragile cavity against the displacement** noise ΔL.

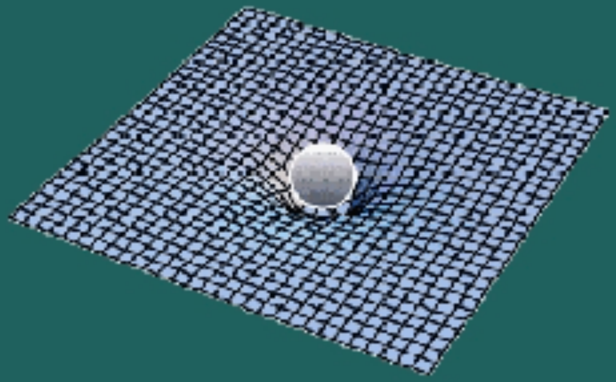


Gravitational-wave (GW)

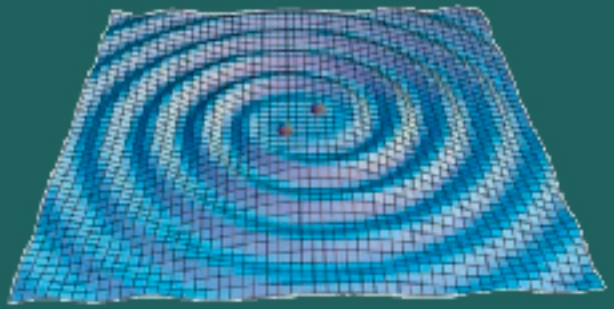
flat space-time



curved space-time



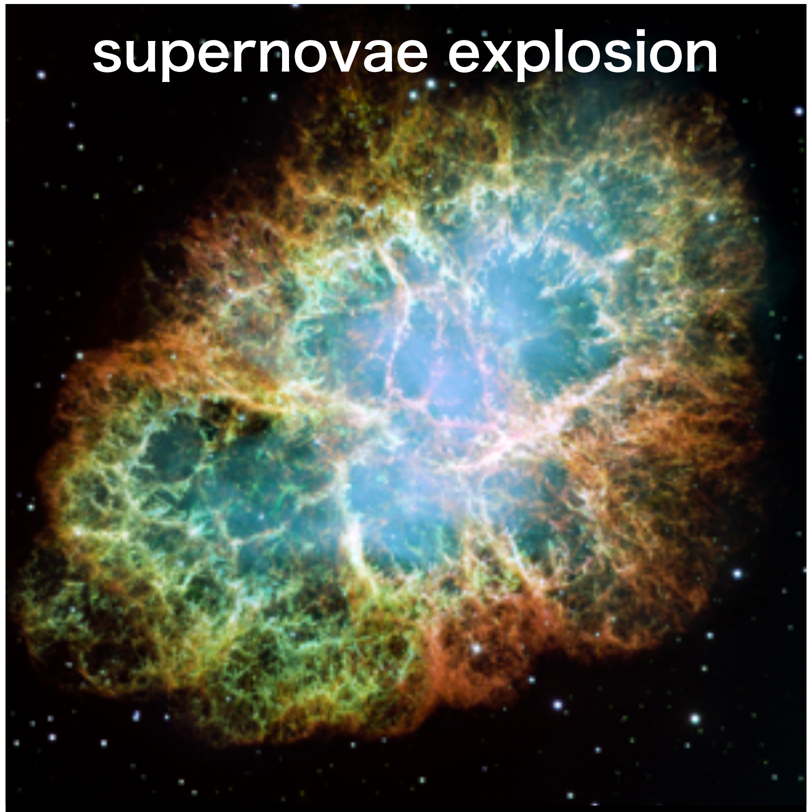
GW emission
(e.g. neutron start binary)



https://gwcenter.icrr.u-tokyo.ac.jp/plan/aboutu-gw

連星合体

supernovae explosion



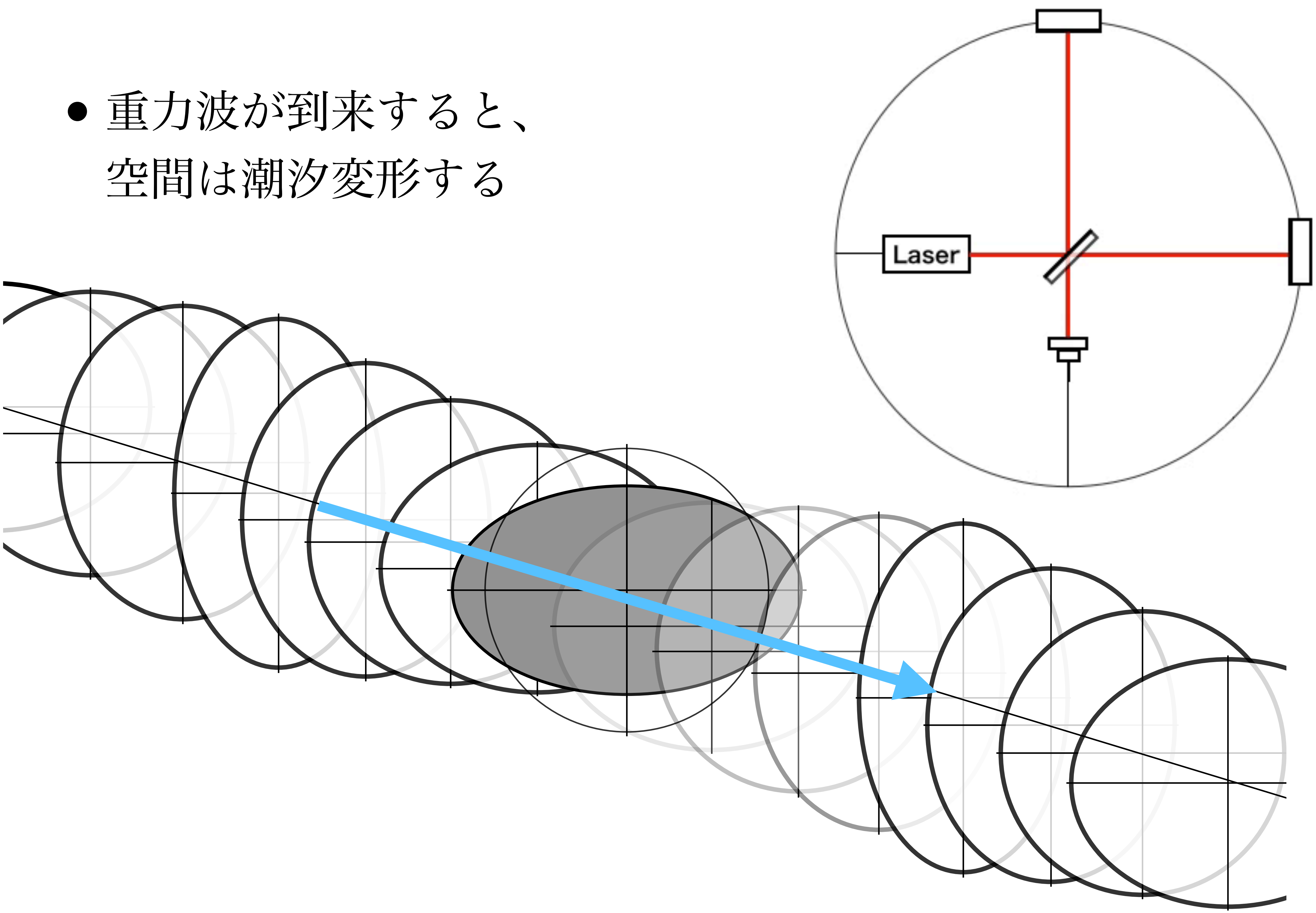
https://www.nasa.gov/multimedia/imagegallery/image_feature_1604.html

パルサー

GW detector

- 重力波が到来すると、
  空間は潮汐変形する

Michelson interferometer



GW detectors network

LIGO Hanford

https://www.ligo.caltech.edu/image/ligo20150731f

Virgo

https://www.ligo.caltech.edu/image/ligo20170927b

LIGO Livingston

https://www.ligo.caltech.edu/image/ligo20150731c

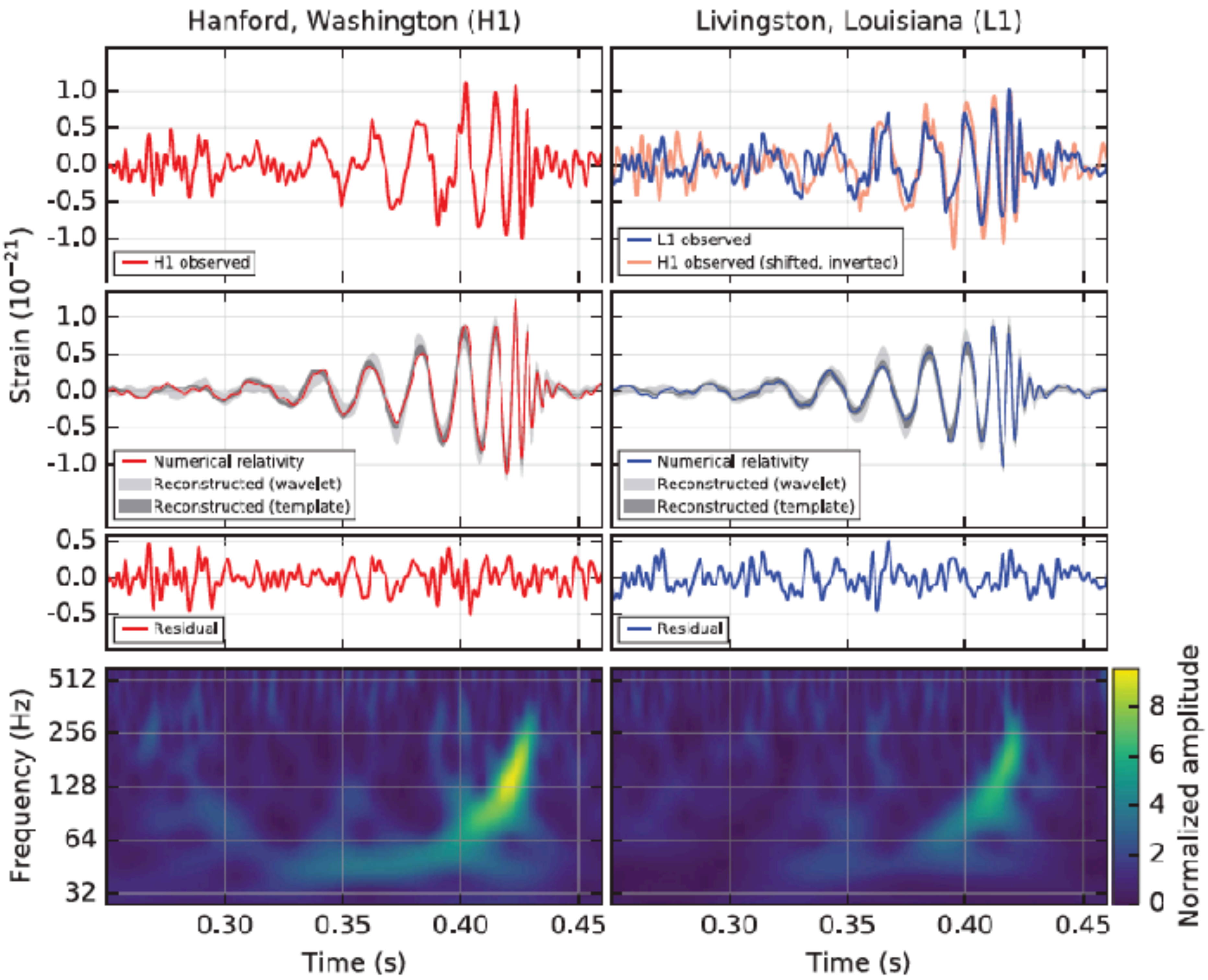
KAGRA

© Institute for Cosmic Ray Research, the University of Tokyo.

Operational
Under Construction
Planned

https://www.ligo.caltech.edu/image/ligo20160211c

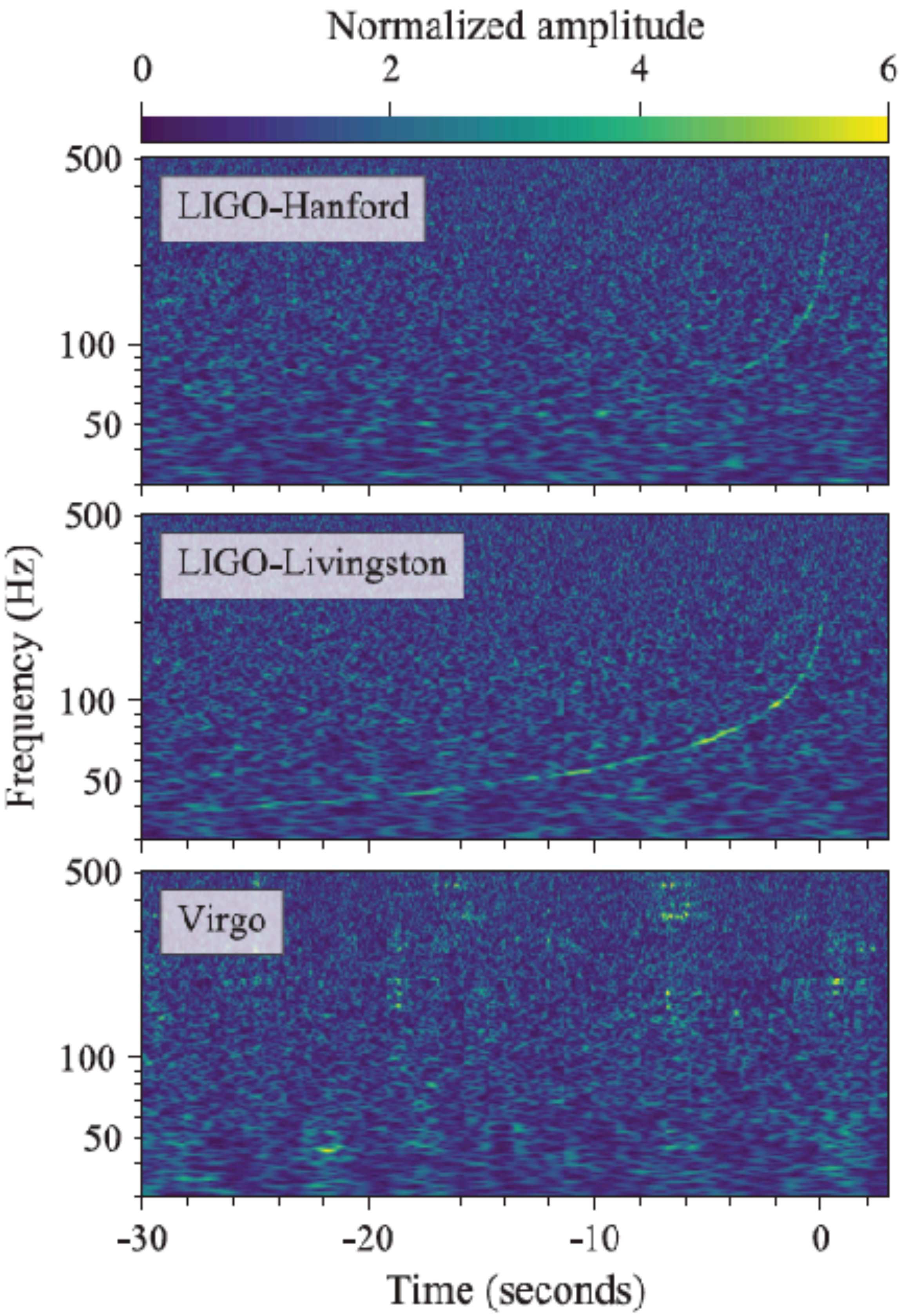
GW150914: binary black hole merger



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

- Detected by 2 LIGO detectors

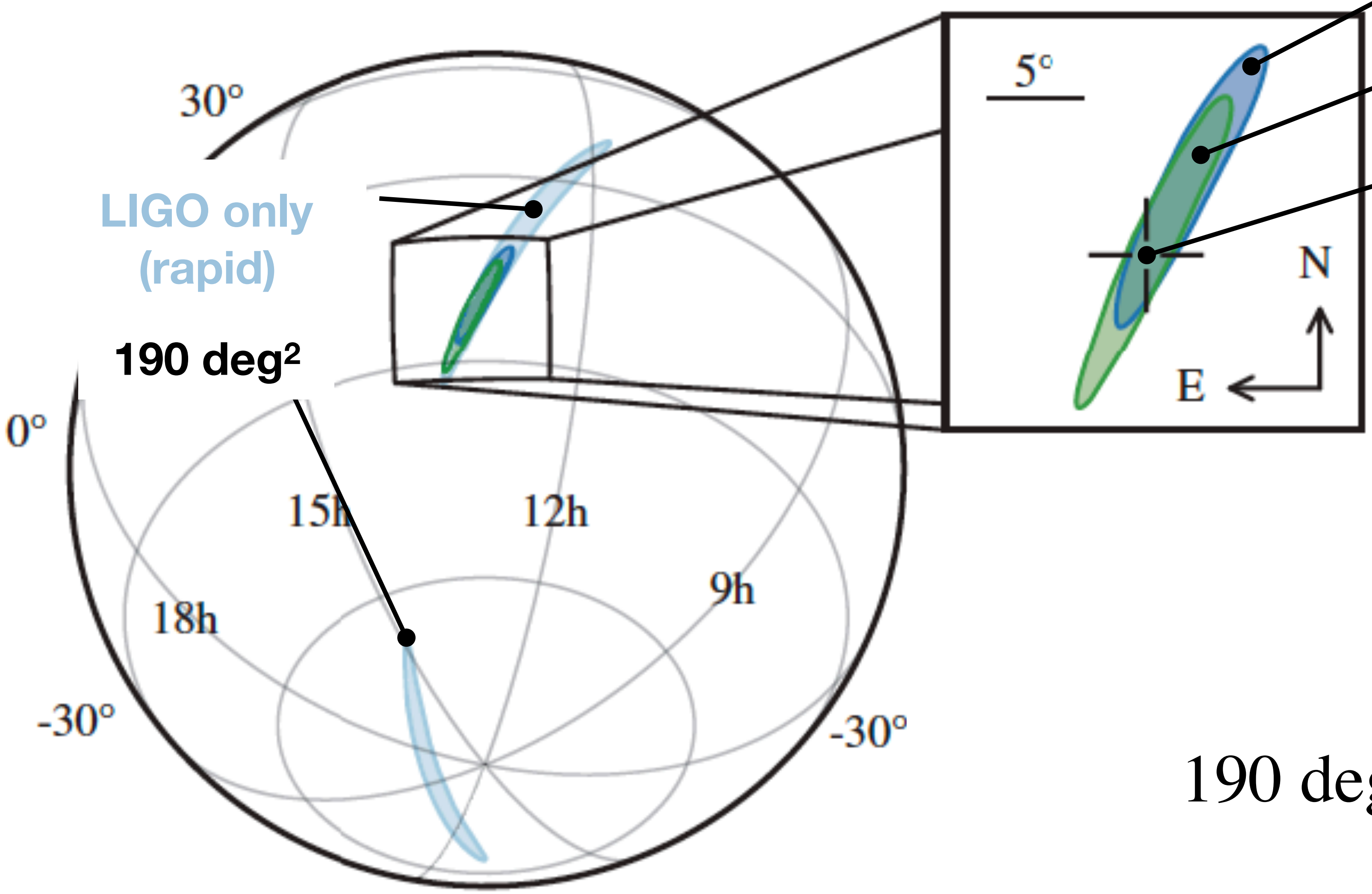
GW170817: binary neutron star inspiral



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 only (rapid)

190 deg^2

LIGO-Virgo (rapid) 31 deg^2

LIGO-Virgo (higher latency)

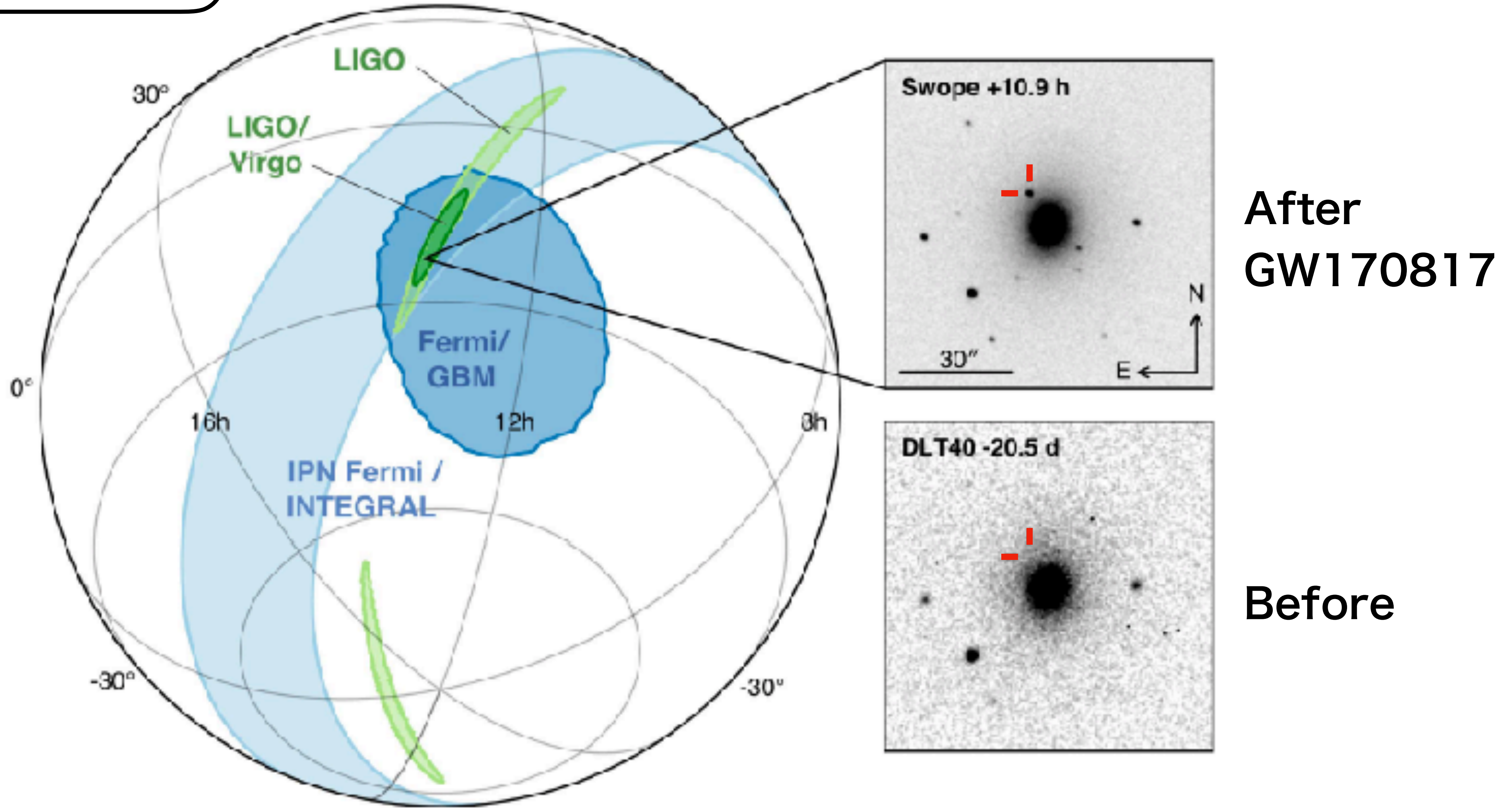
host galaxy NGC 4993

190 deg^2 → **31** deg^2

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

Multi-messenger observation

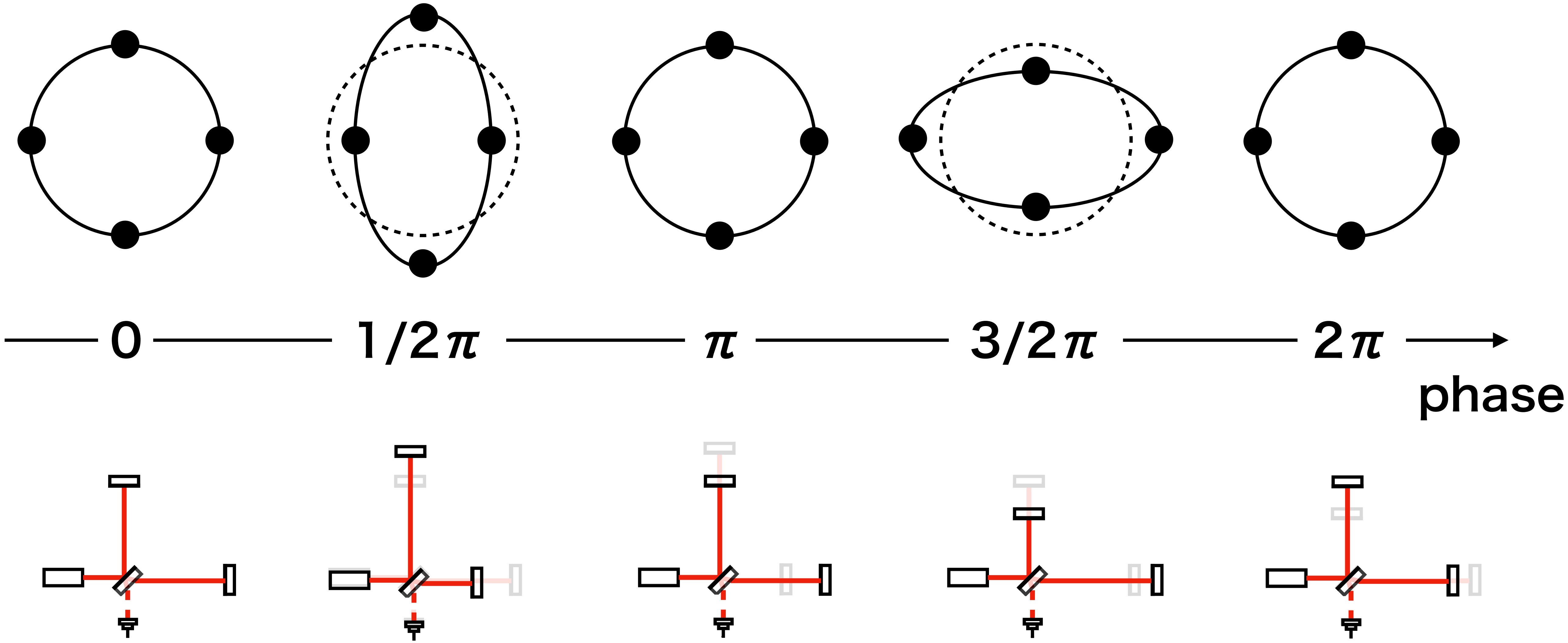
LIGO		LIGO & Virgo
190 deg^2	→	**31** deg^2



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.

Detection principle of GW



- GW
- Michelson interferometer sensitive to the differential arm motion.

DC制御でよくないか？

- 基本的にはそれでいい。LIGOやVirgoはそうしている。
- しかし地震のような大きな外乱で干渉計はロックロスしてしまっている。（技術的なことをいえば、DC制御のための積分器とダンピングのための微分器が交差する周波数帯域ではFBゲインがもっとも小さく、防振が十分ではない。つまりそこを揺らす地震に弱いことを意味する。この交差周波数はおよそ 0.1 Hz程度。）
- できるだけ上の段で粗調し、下の段のFB制御の負担をへらすことが大事。

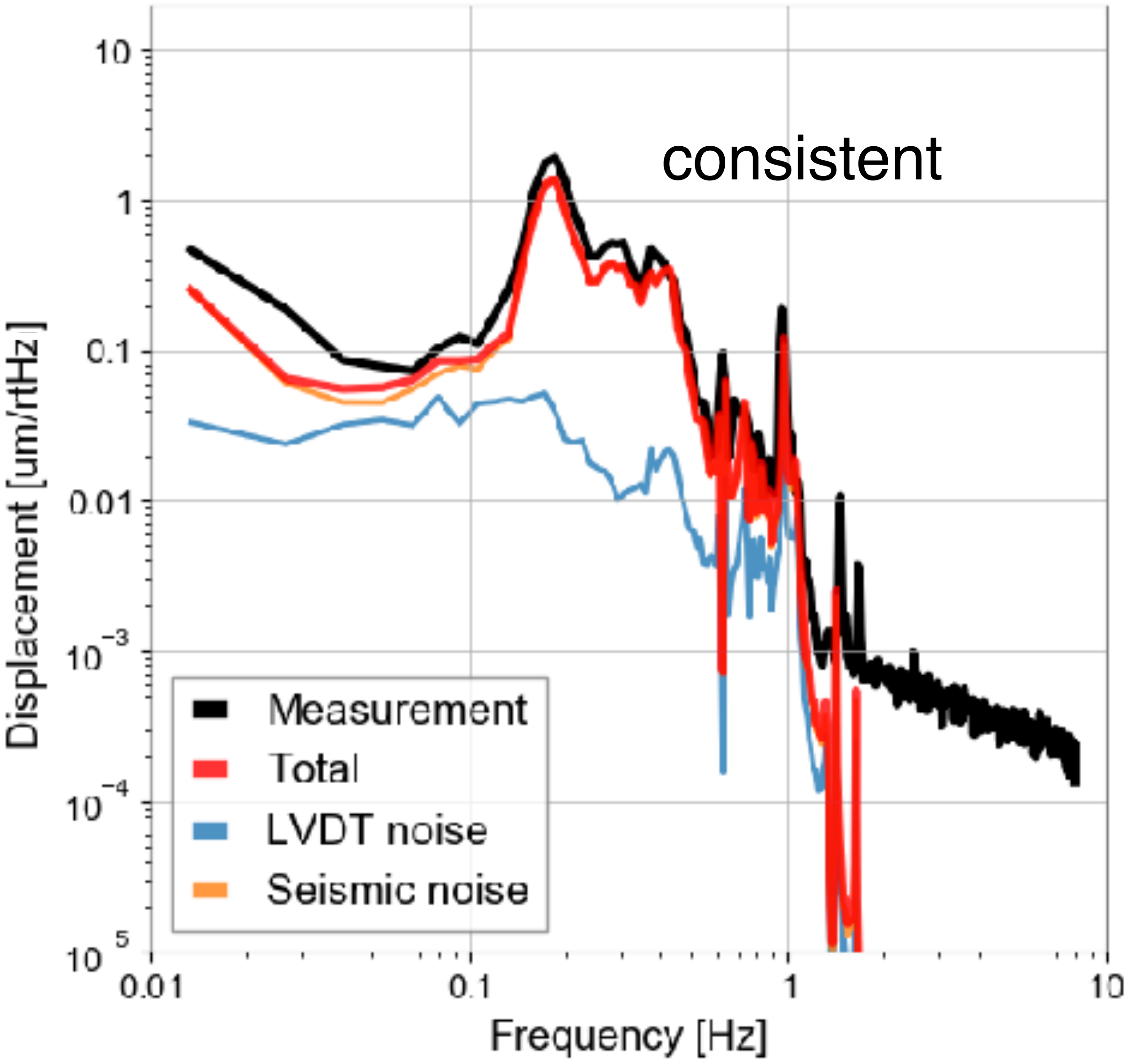
ALSとの比較

- Arm Length Stabilization
  - for lock acquisition
  - cannot use in observation state due to high noise
  - improve “locking” down-time

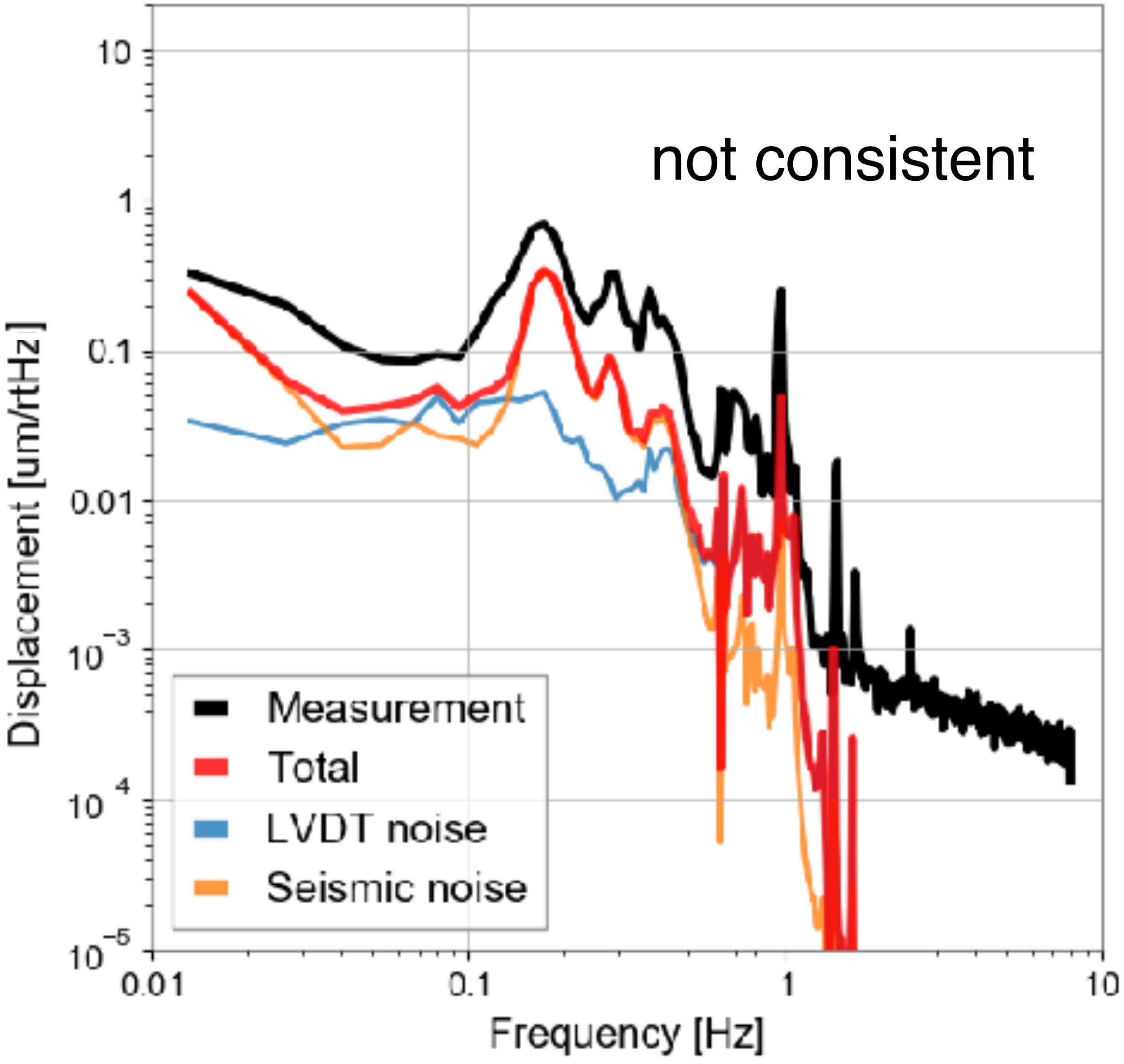
- Baseline Compensation
  - for vibration isolation
  - can use any state
  - improve “environmental” down-time

Comparison with the simulation

OFF

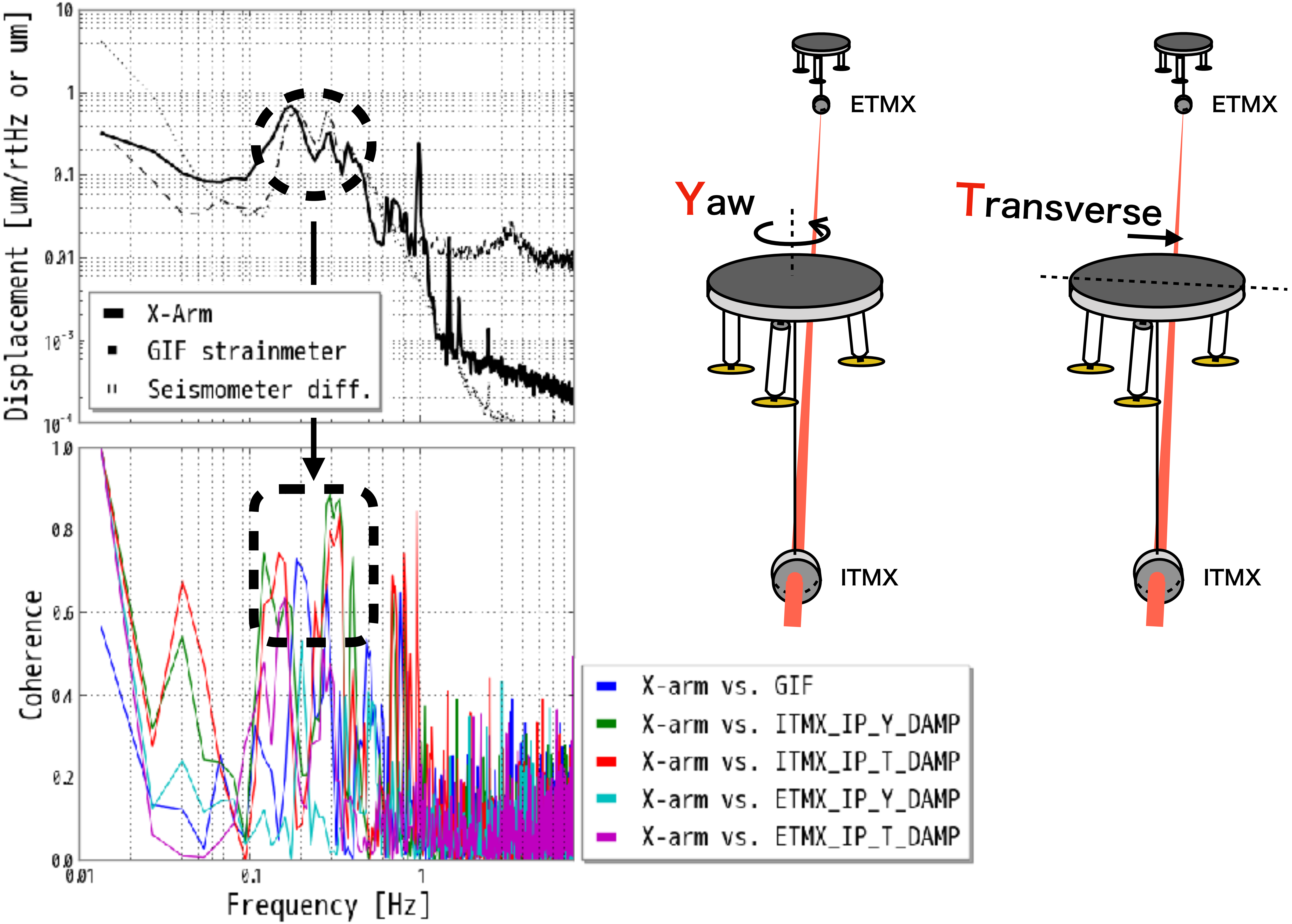


ON

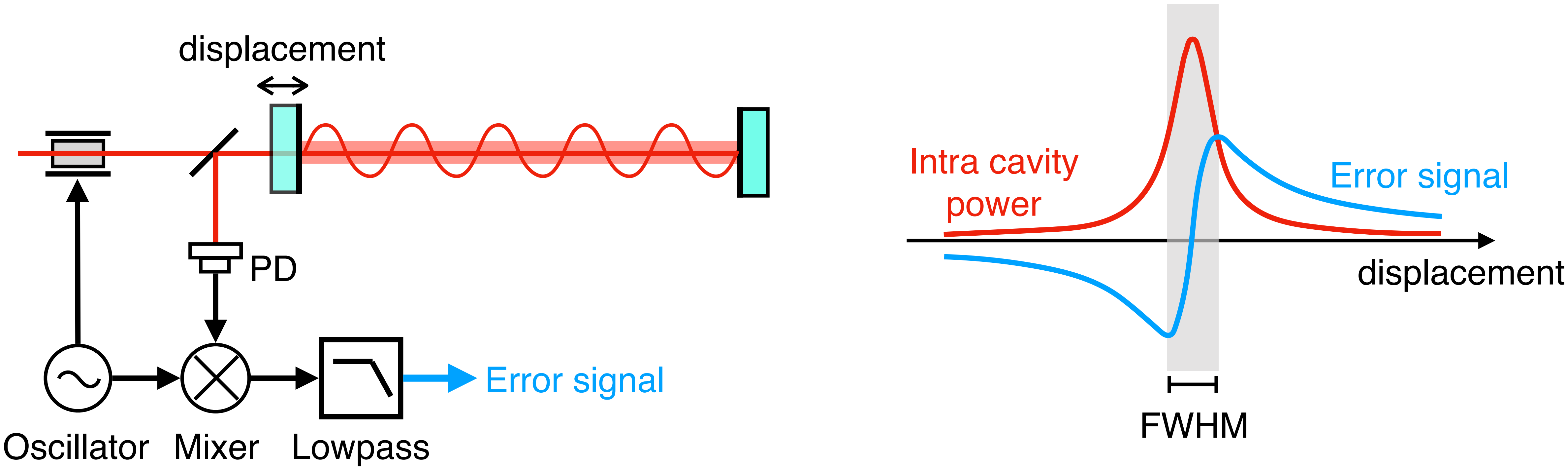


- OFF : Measurement was consistent with the model simulation
- ON : Measurement was not

Discussion


Displacement [um/rtHz or um]
10
1
0.1
0.01
10⁻³
10⁻⁴
X-Arm
GIF strainmeter
Seismometer diff.
Coherence
1.0
0.8
0.6
0.4
0.2
0.0
0.01
0.1
1
Frequency [Hz]
X-arm vs. GIF
X-arm vs. ITMX_IP_Y_DAMP
X-arm vs. ITMX_IP_T_DAMP
X-arm vs. ETMX_IP_Y_DAMP
X-arm vs. ETMX_IP_T_DAMP
ETMX
Yaw
ITMX
ETMX
Transverse
ITMX

Difficulties in the cavity control



Pound–Drever–Hall (PDH) technique

Resonant condition

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

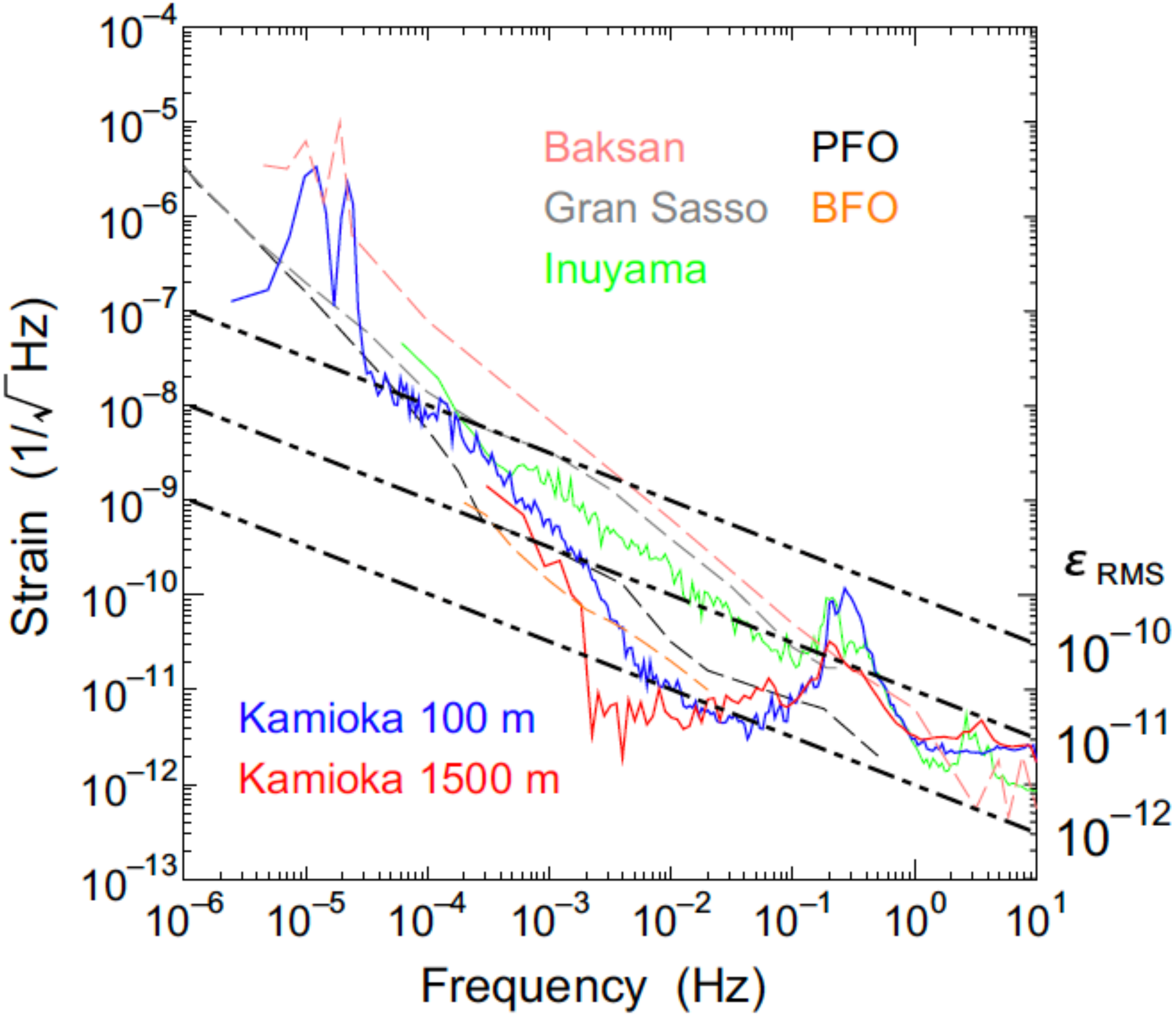
Controlable condition

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

↓

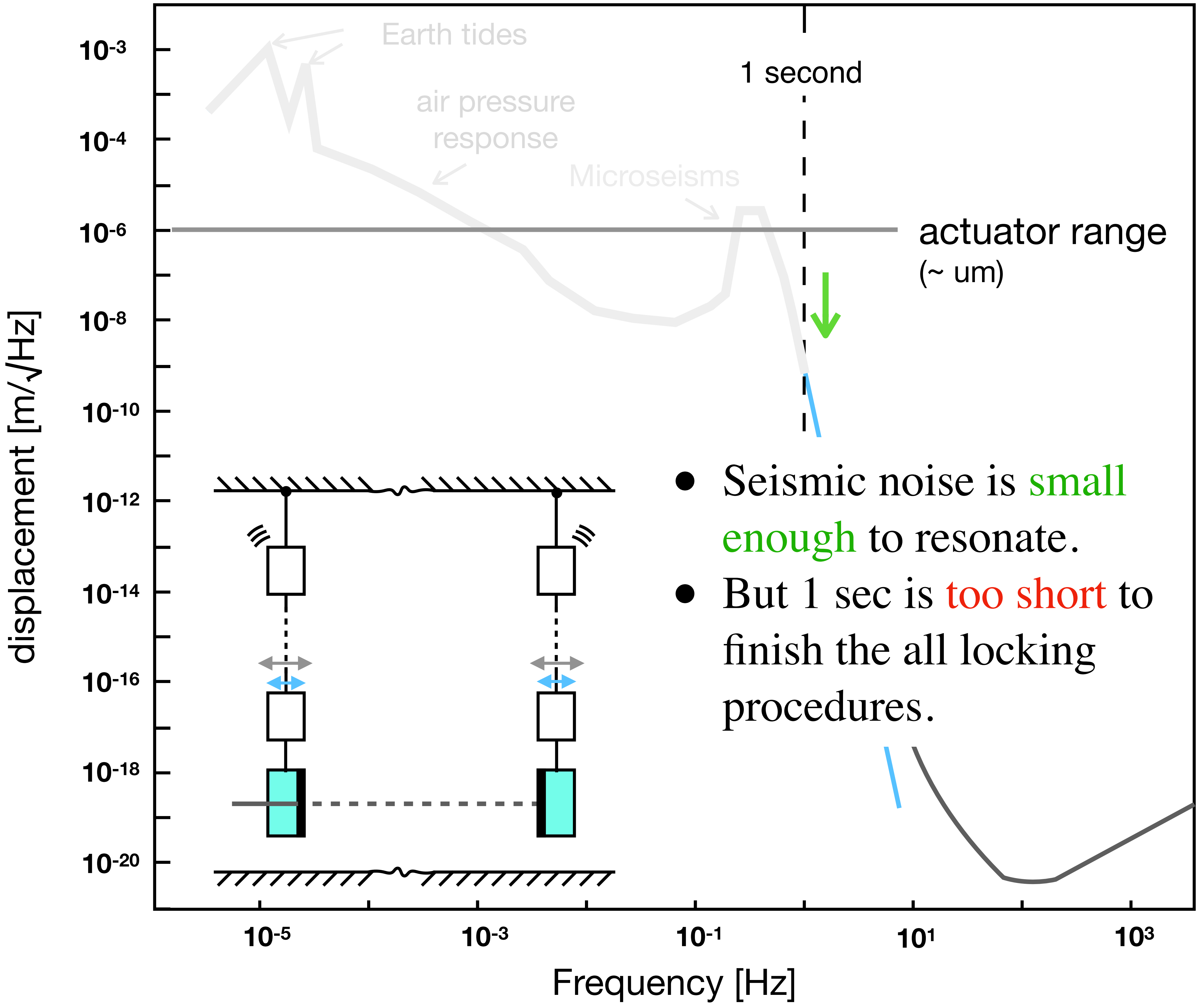
Seismic disturbances should be attenuate <u>within a few nm</u>.

タイトルテキスト



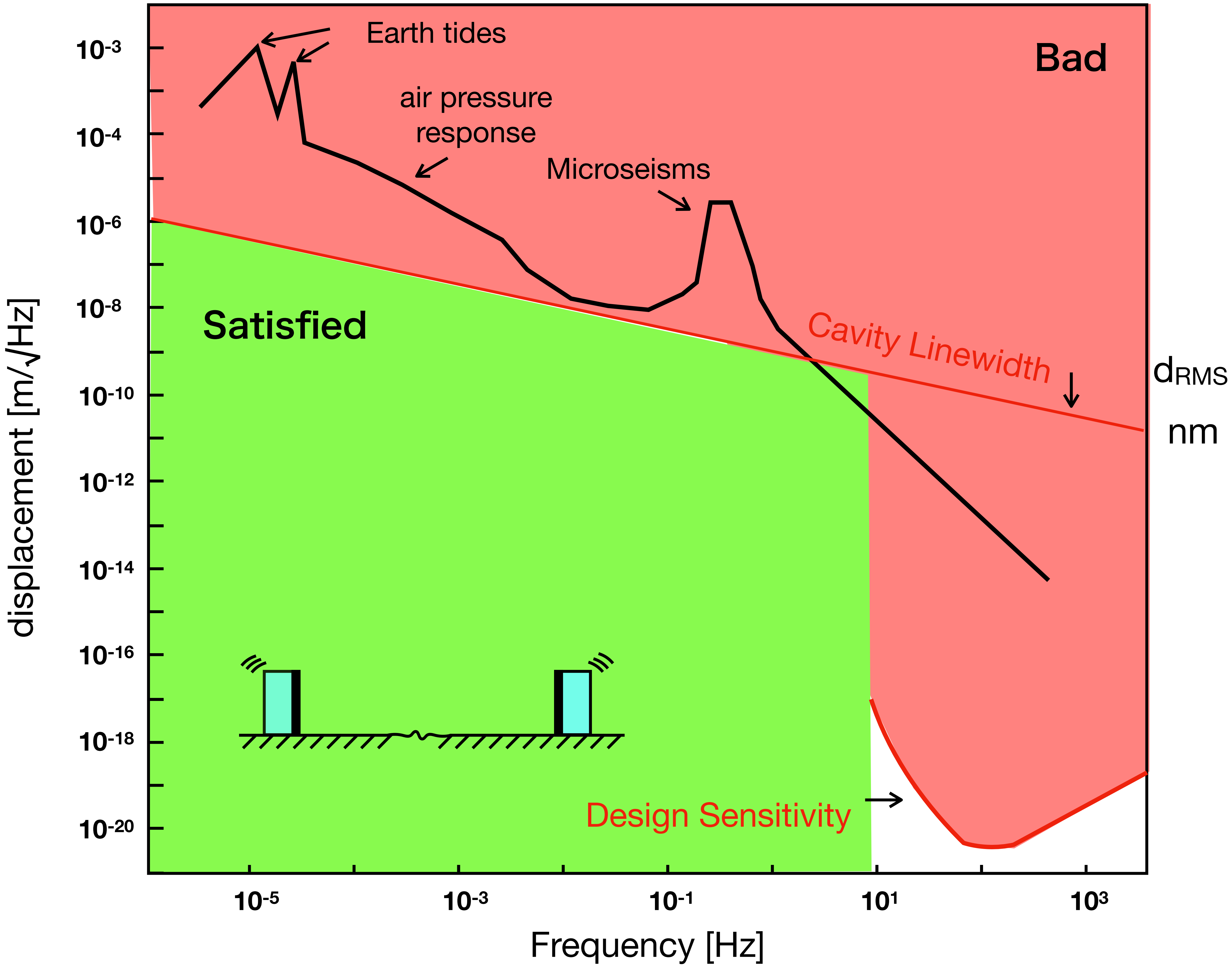
- AAAa

Review : seismic isolation system

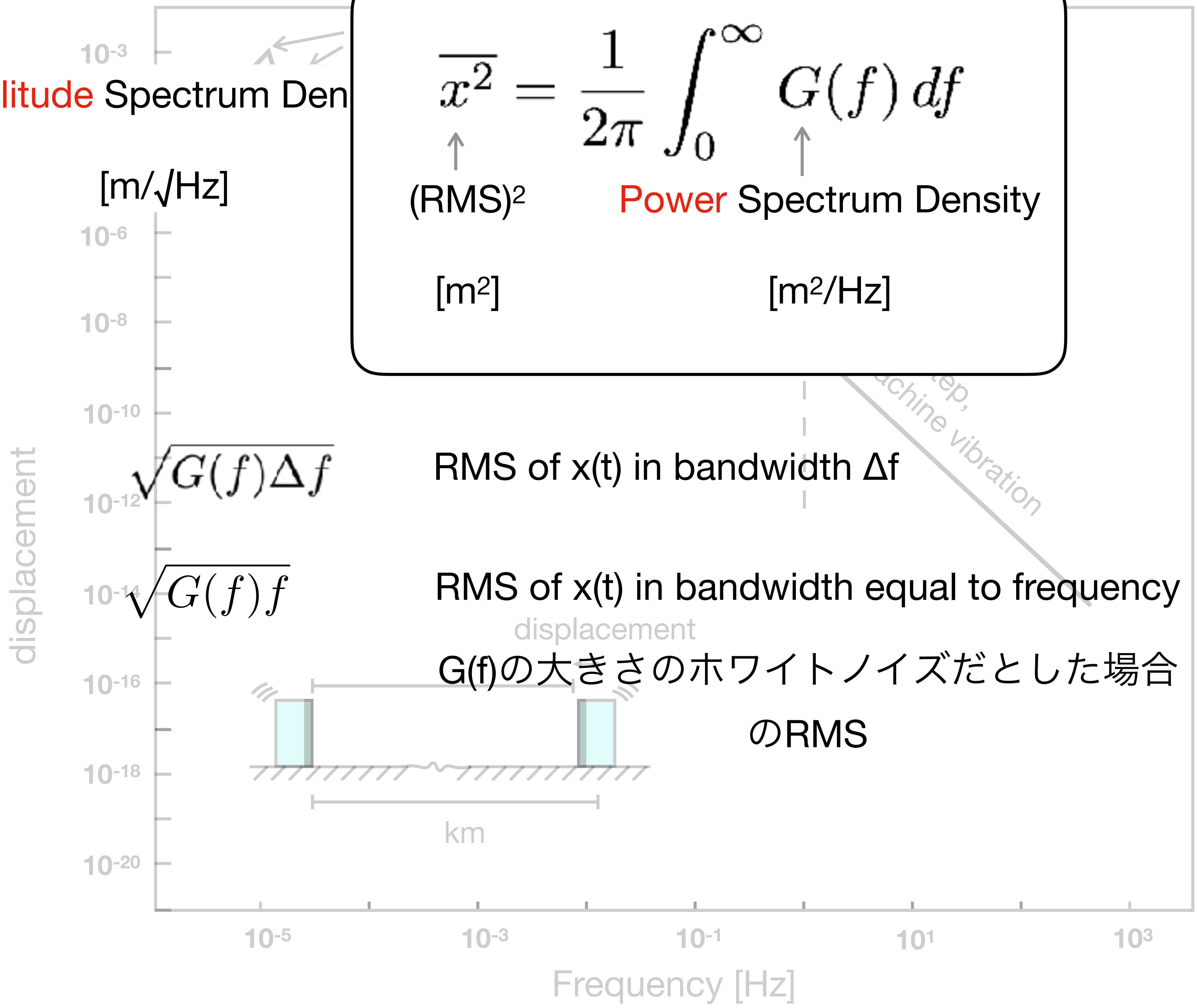


- Seismic noise is small enough to resonate.
- But 1 sec is too short to finish the all locking procedures.

Seismic Noise



Seismic Noise



Amplitude Spectrum Den

[m/√Hz]

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

↑ (RMS)2

[m2]

↑ Power Spectrum Density

[m2/Hz]

$\sqrt{G(f)\Delta f}$ RMS of x(t) in bandwidth Δf

$\sqrt{G(f)f}$ 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