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)

Kouseki Miyo
三代 浩世希

January 15th, 2020

JGW-G2011167

Contents

Contents

Gravitational wave observation

Sensitivity $\propto$ range

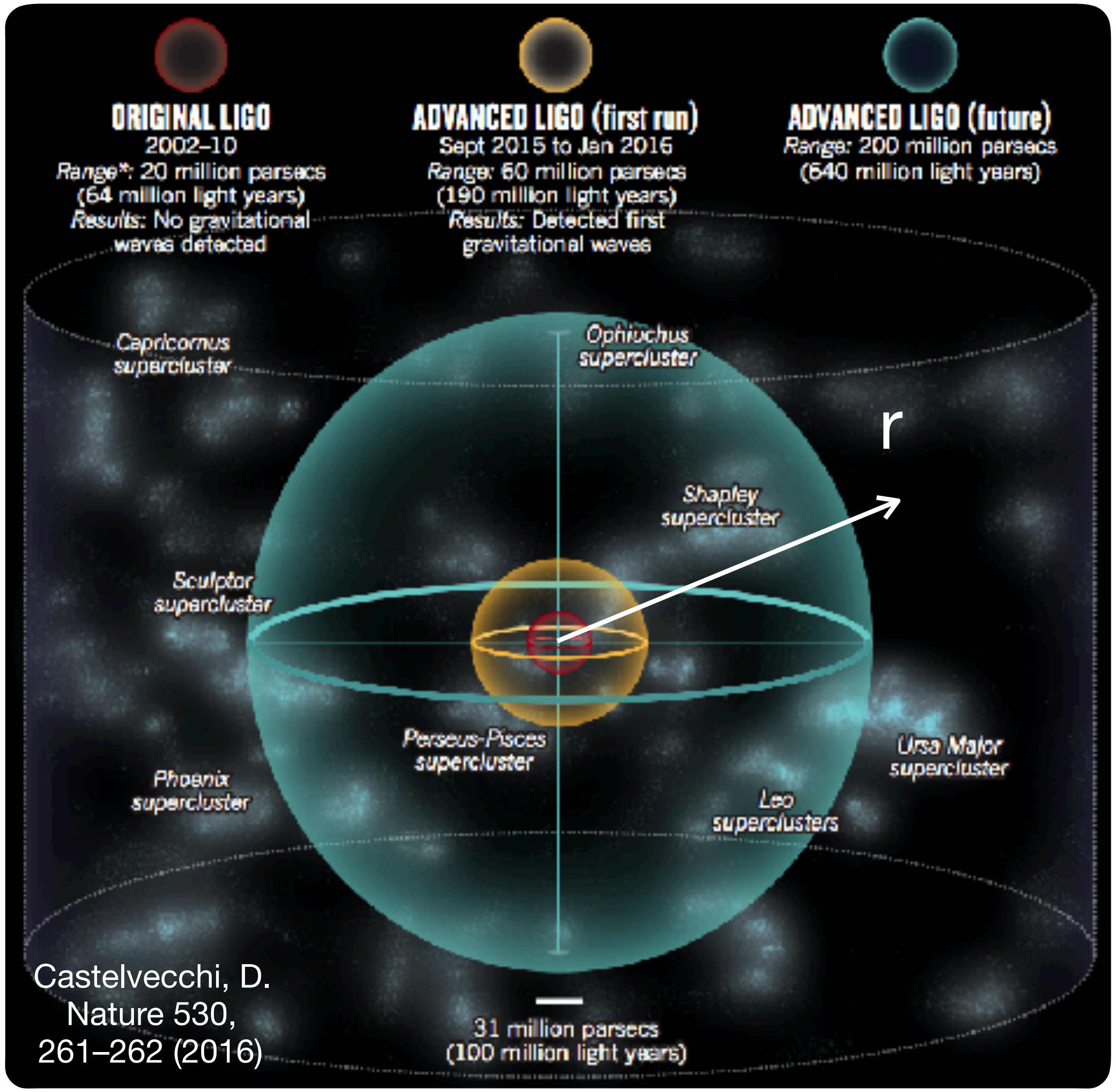
$\propto$ (volume)$^{1/3}$

$\propto$ (event rate)$^{1/3}$

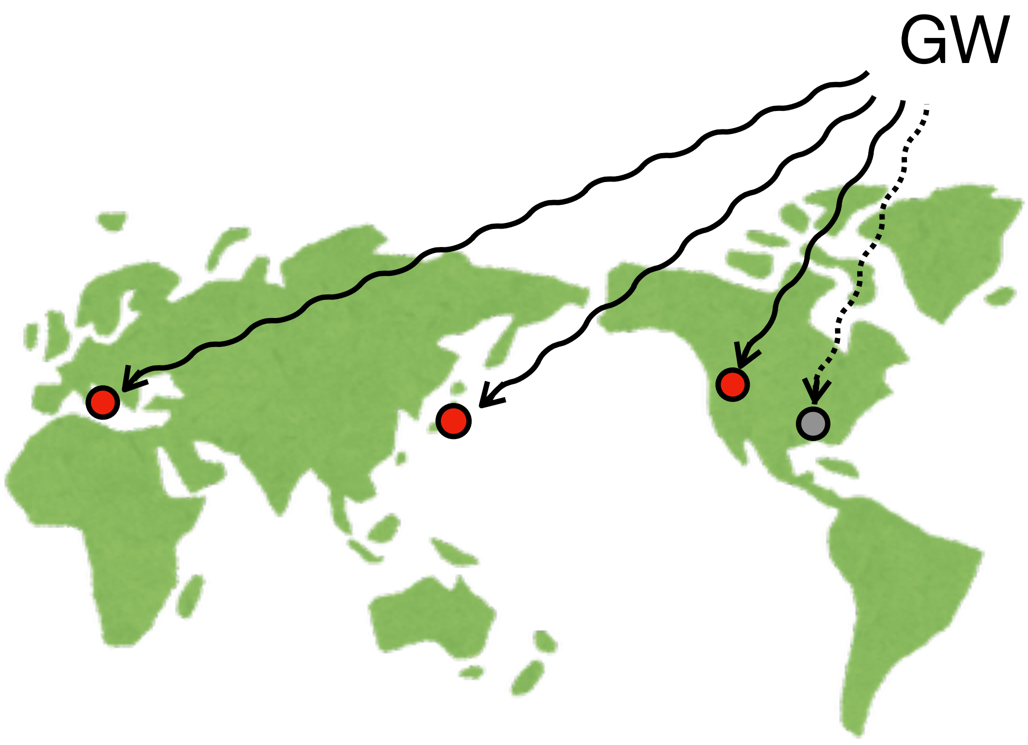
Duty cycle ≒ $D_1 \times D_2 \times D_3 \times \ldots$

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

e.g. LIGO detector



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



Gravitational wave observation

Sensitivity $\propto$ range

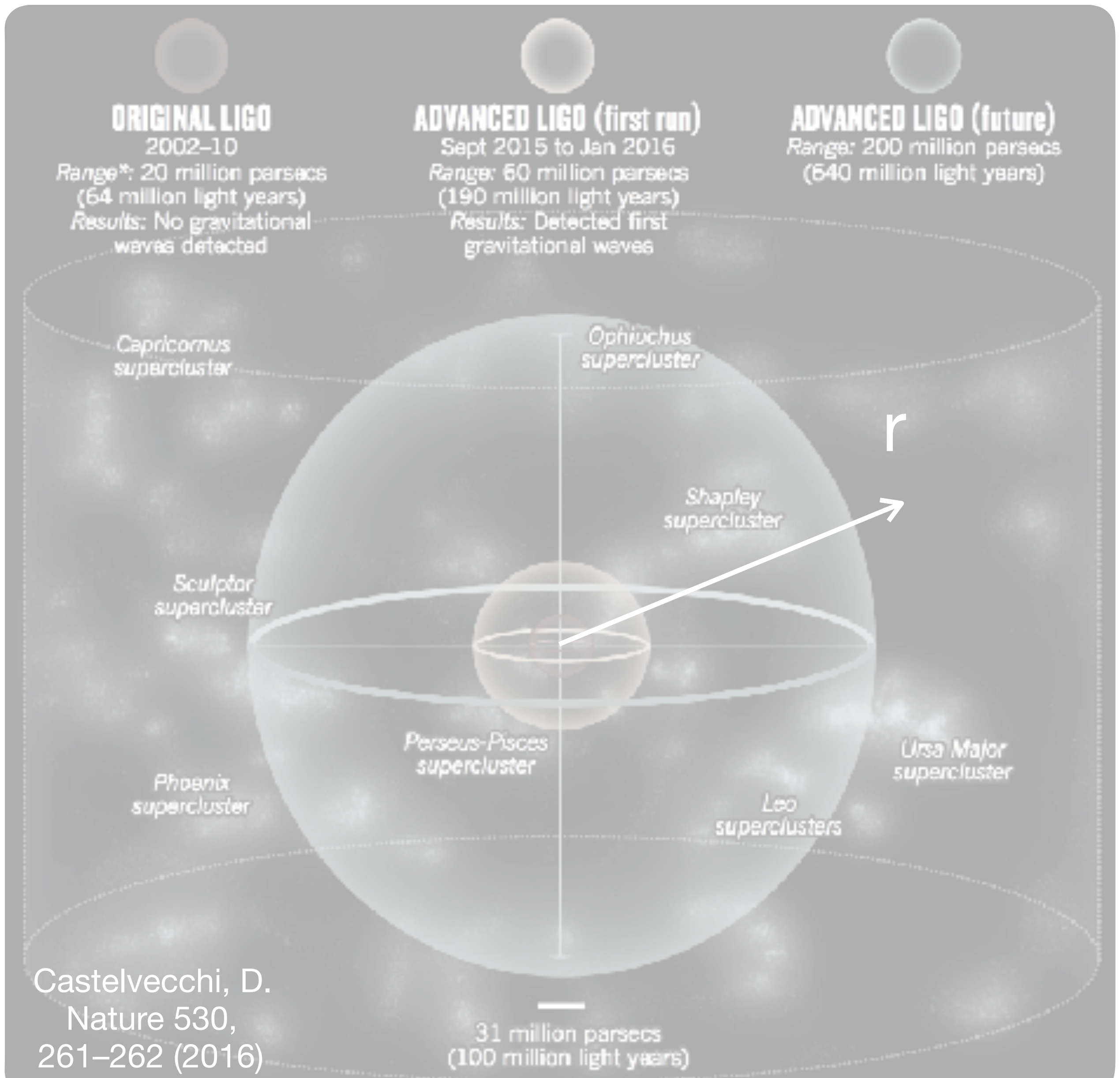
$\propto$ (volume)$^{1/3}$

$\propto$ (event rate)$^{1/3}$

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



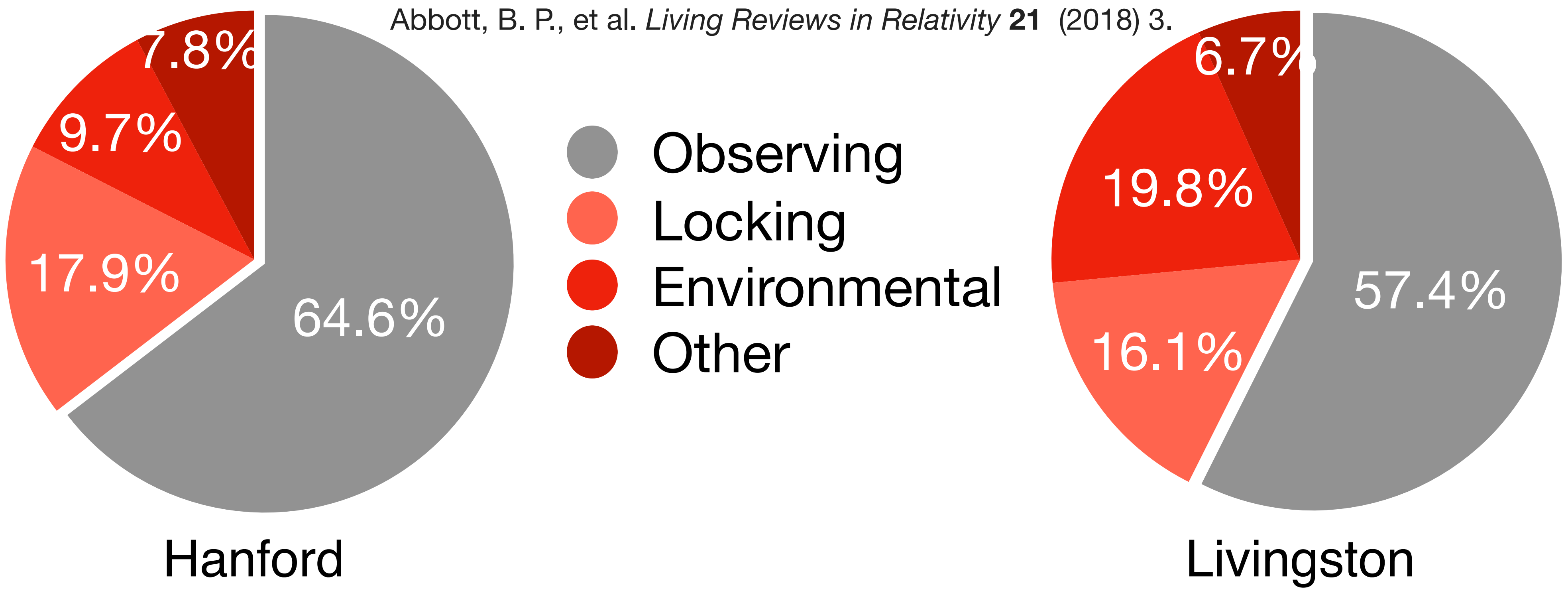
Castelvecchi, D. Nature 530, 261–262 (2016)

This study focuses on this

None-observation state

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

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



Locking

- transition state toward observation state

Environmental

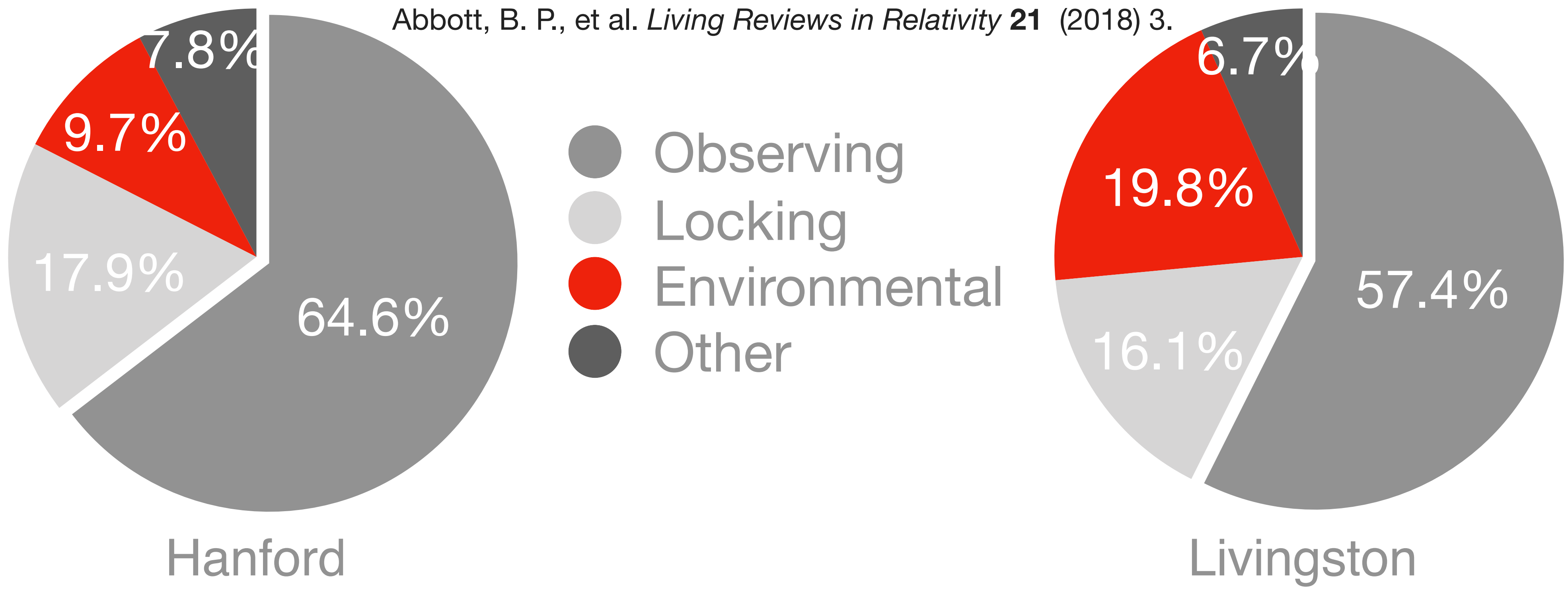
- could not lock due to seismic disturbances.

Other

- commissioning or planed maintenances.

None-observation state

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



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

Locking

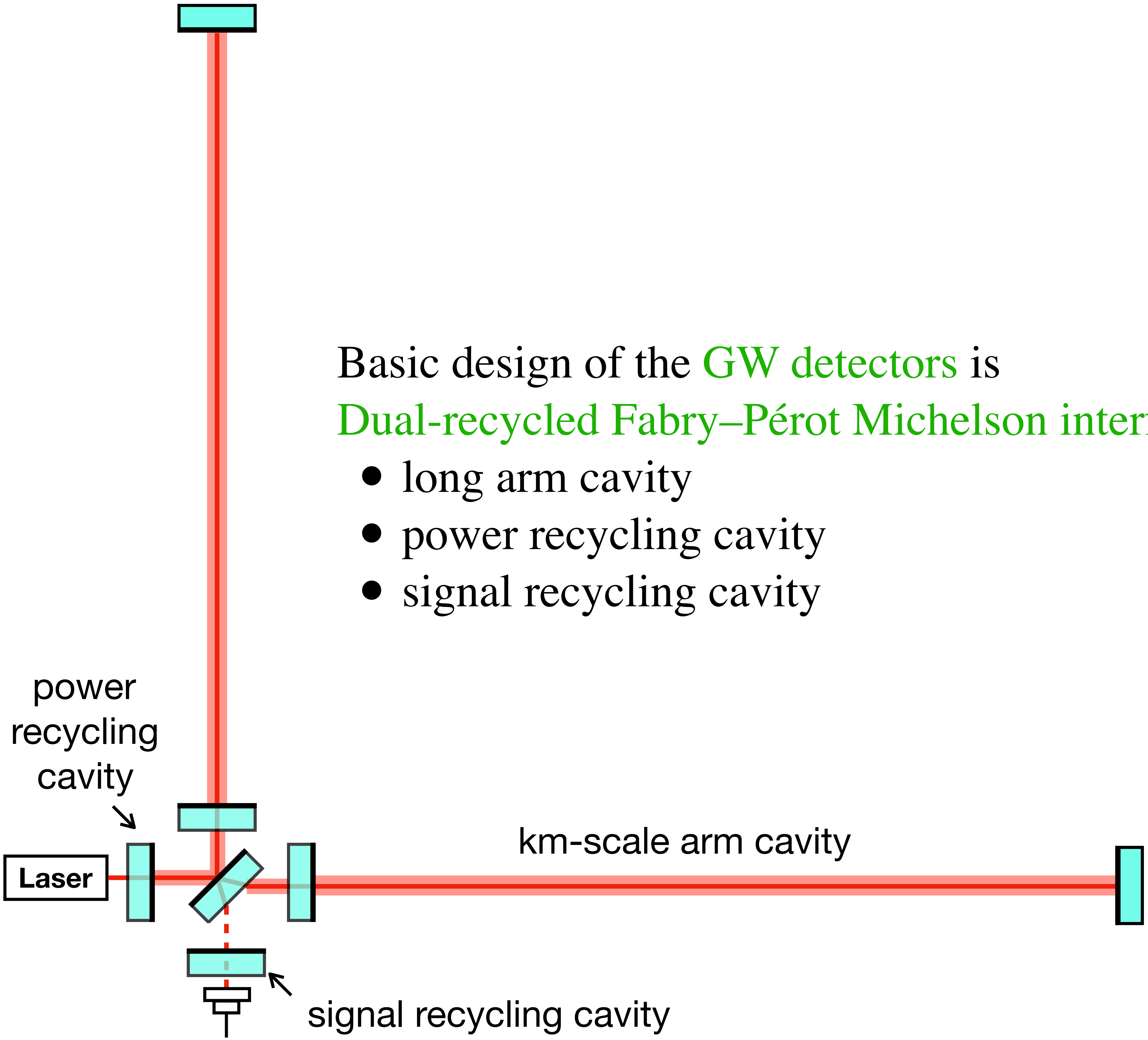
- transition state toward observation state

Environmental

- could not lock due to seismic disturbances.

We need further improvement of
the seismic isolation system.

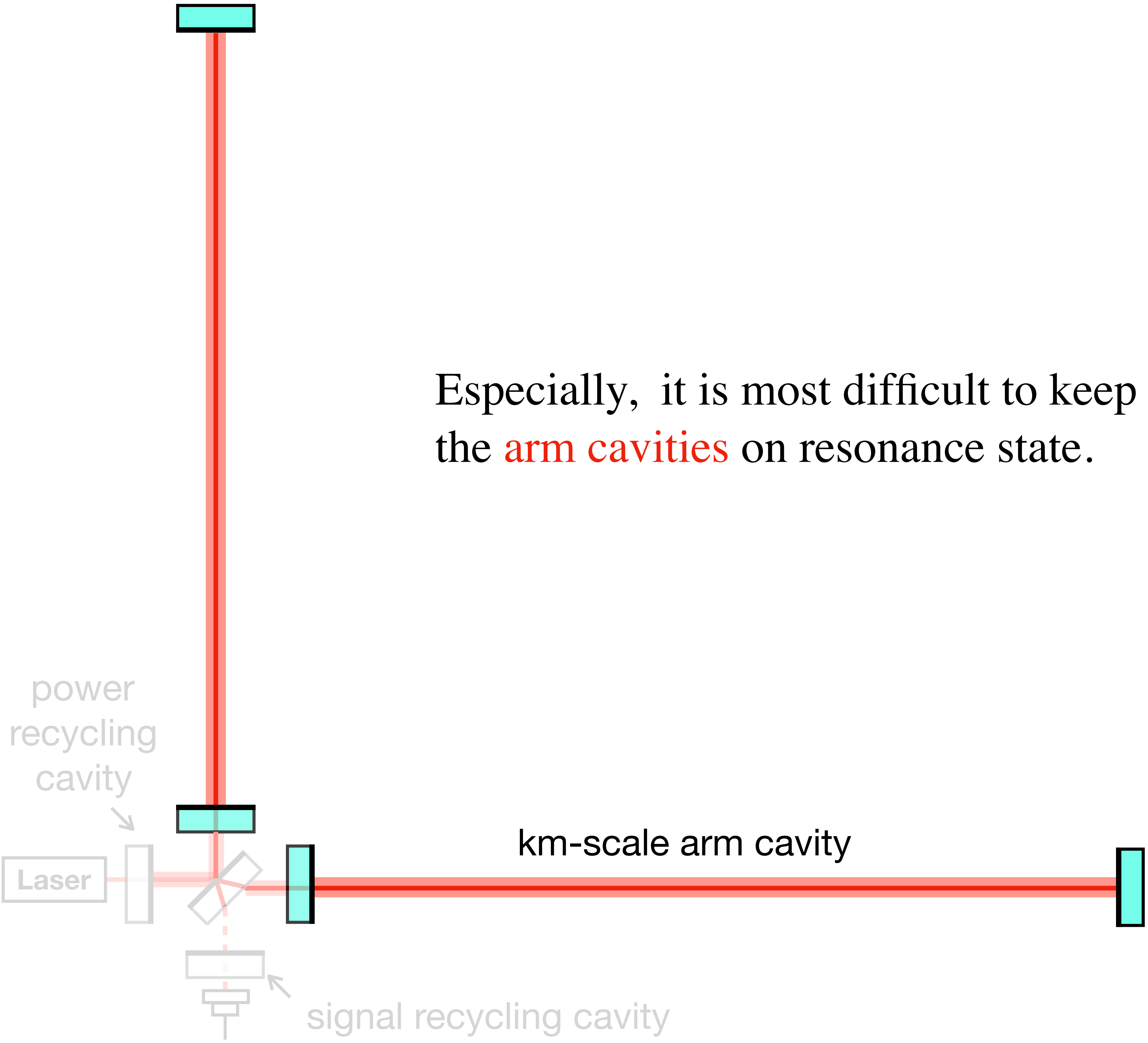
Why GW detectors are weak to seismic disturbances?



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

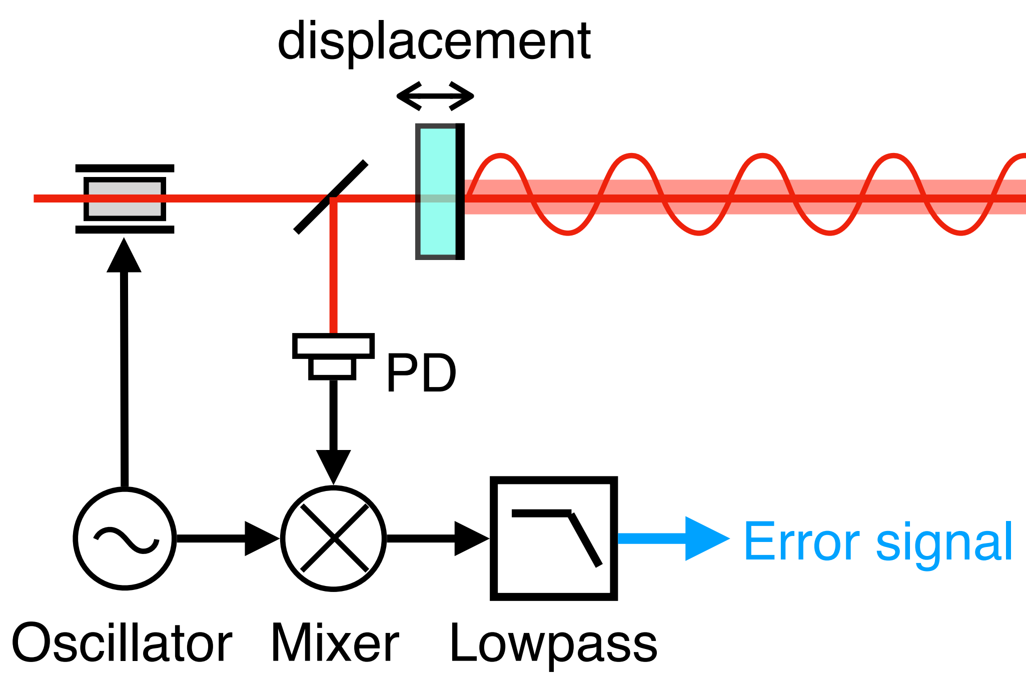
- long arm cavity
- power recycling cavity
- signal recycling cavity

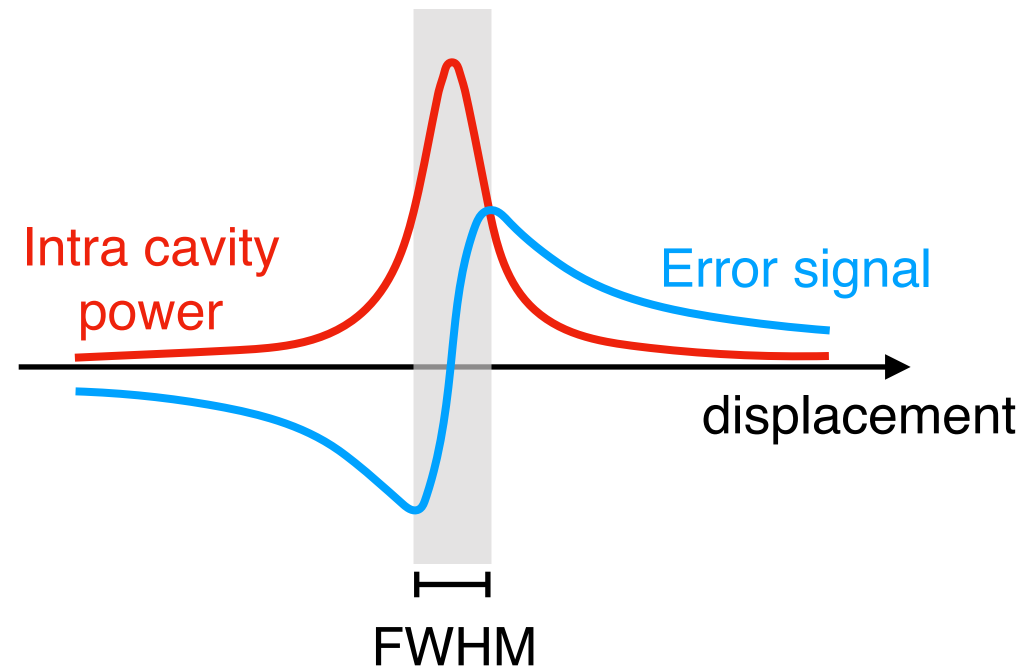
Why GW detectors are weak to seismic disturbances?



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

Difficulties in the cavity control





Pound–Drever–Hall (PDH) technique

Resonant condition

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

Controlable condition

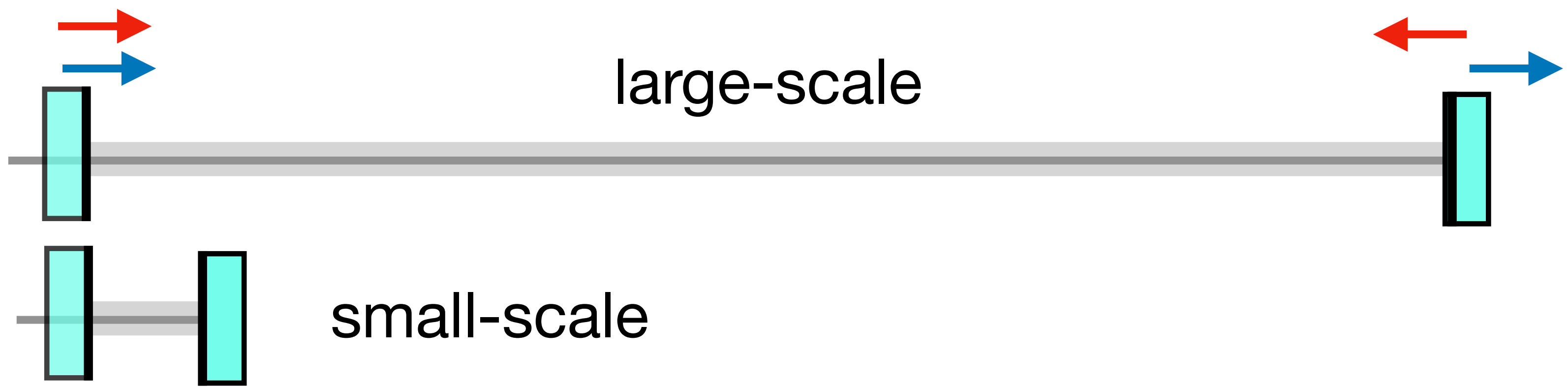
- Error signal is linear in FWHM range (~ nm).

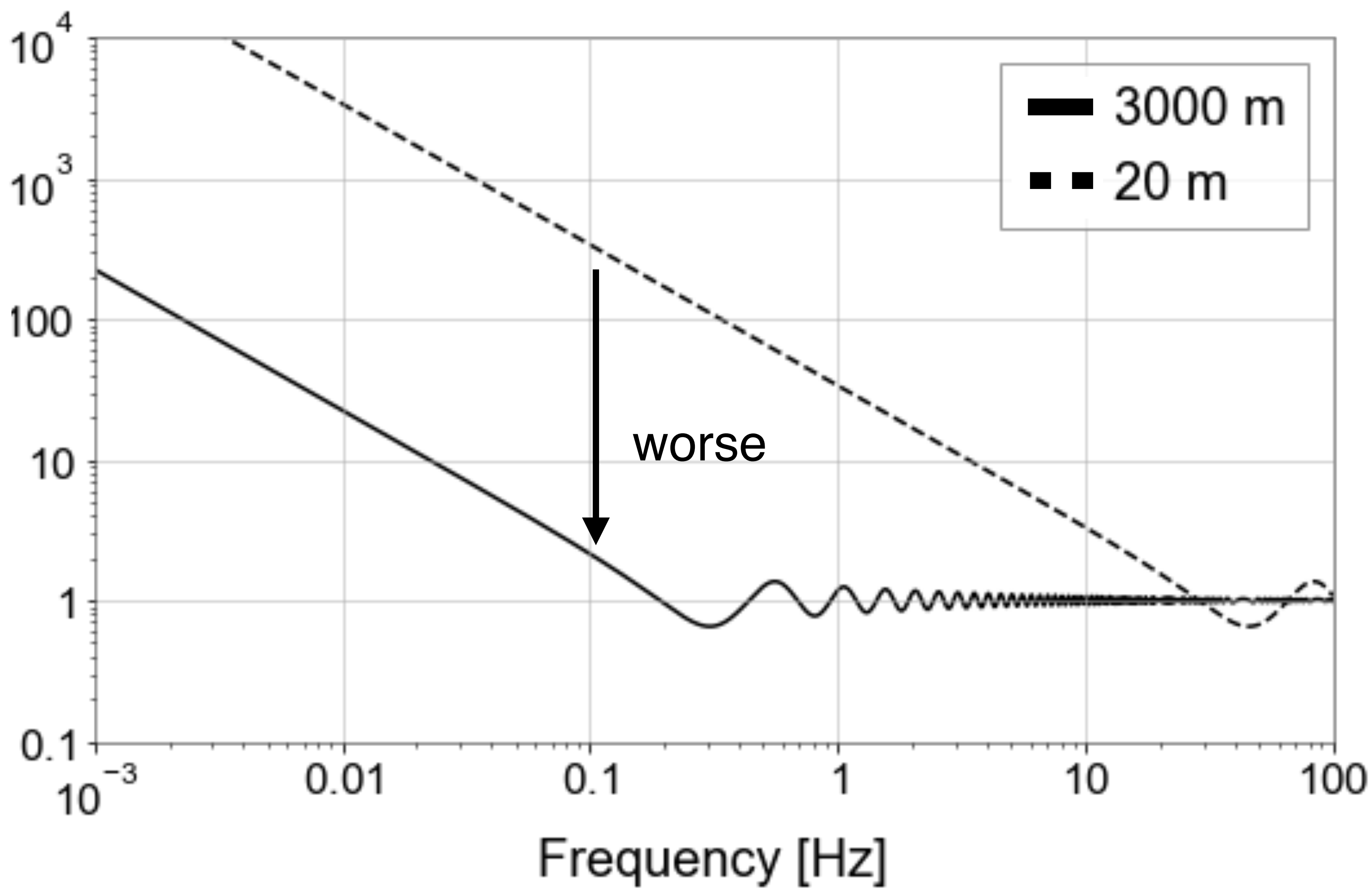
↓

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

Difficulties in the long cavity

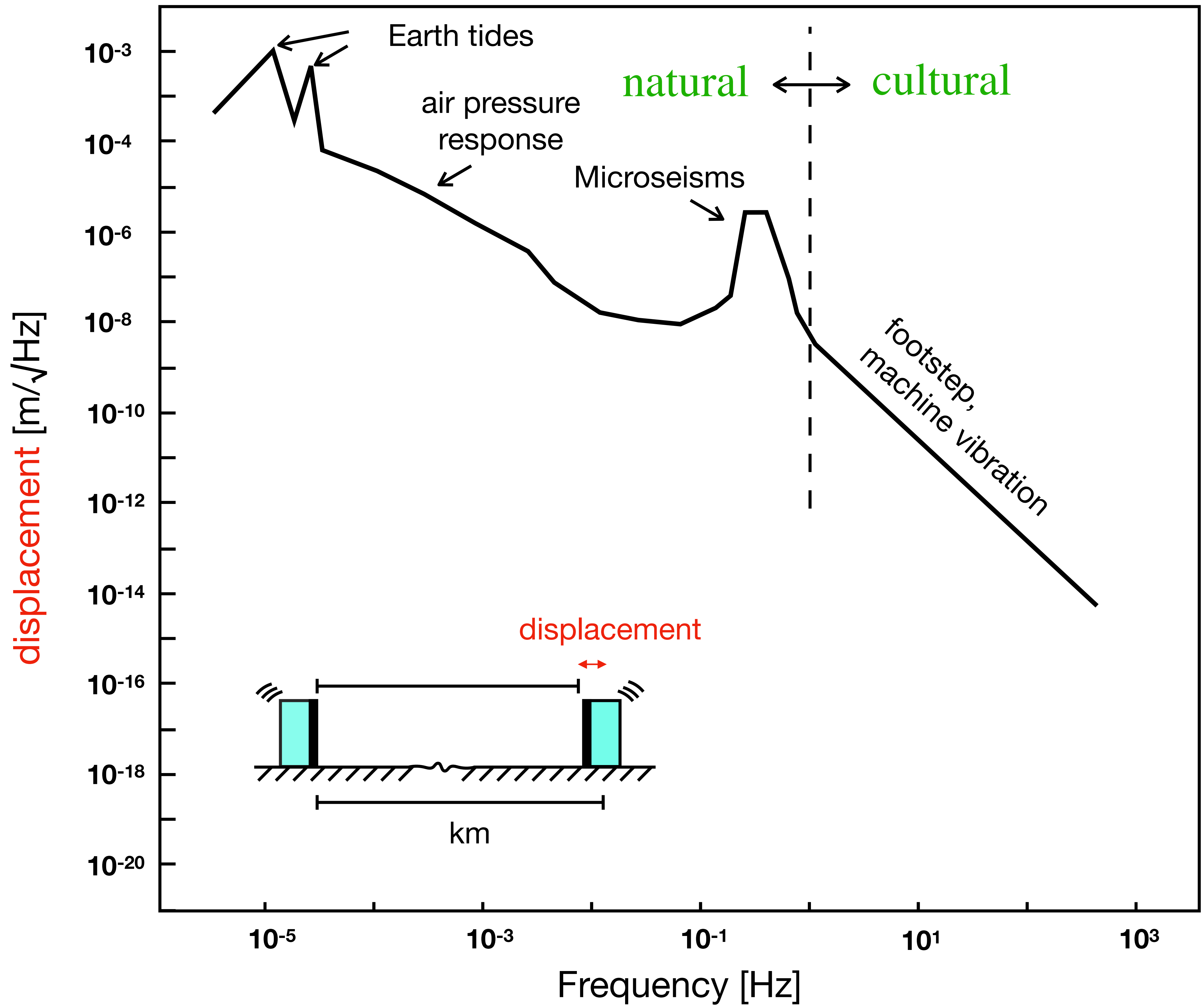
There are few differential motion reduction in the large-scale GW detectors in the low-frequency.



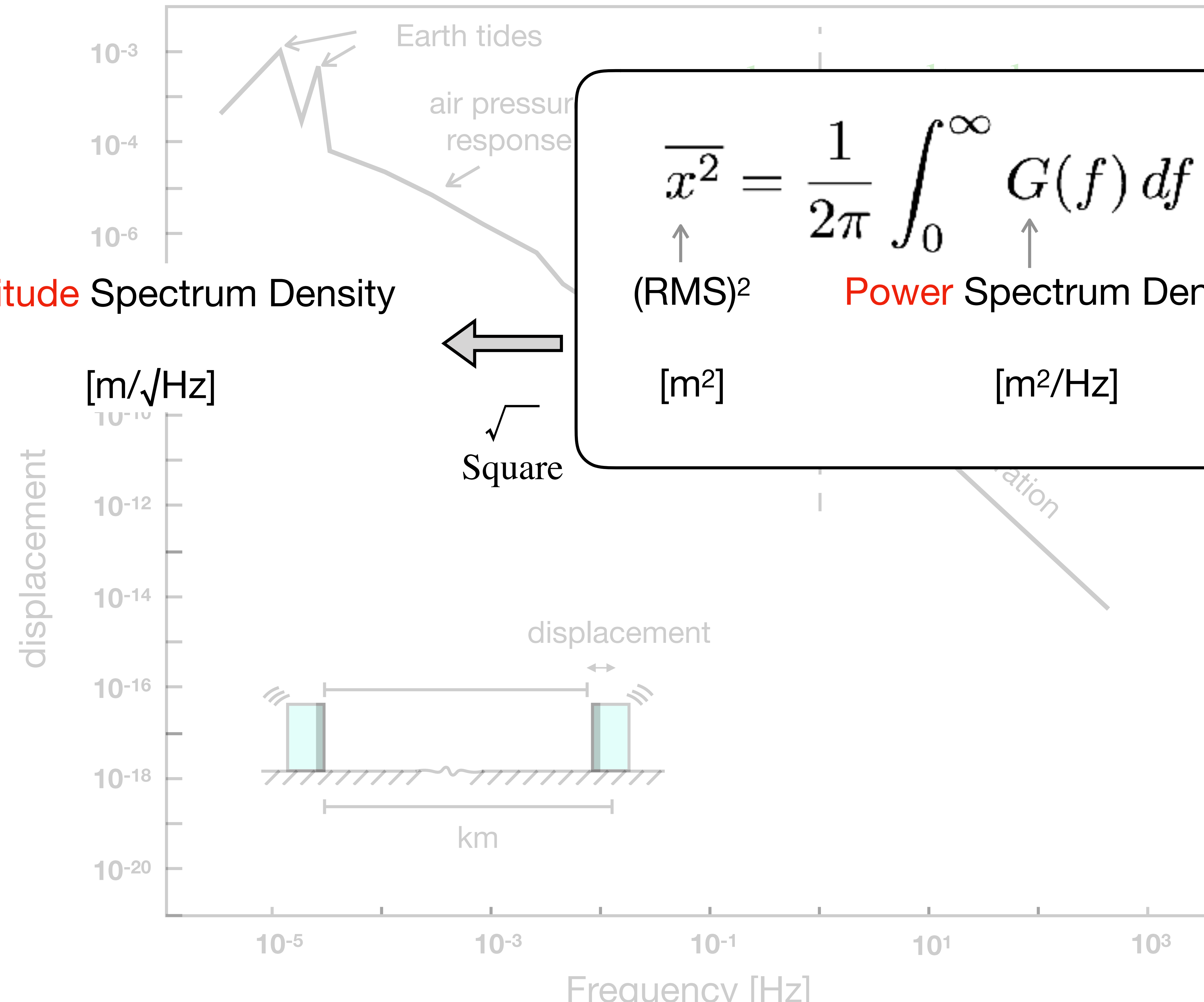


Contents

Seismic Noise



Seismic Noise



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

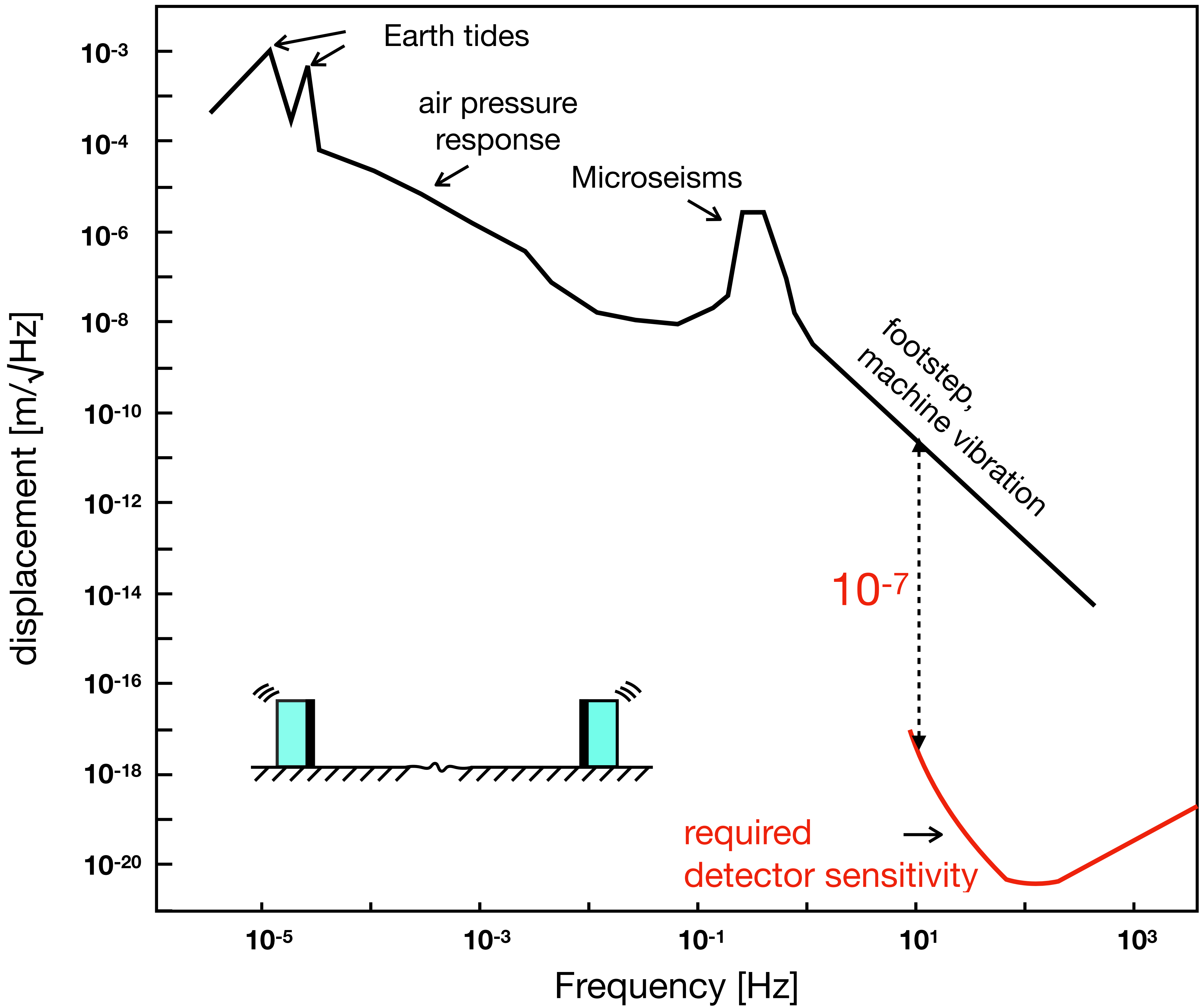
(RMS)^2 — [m^2]

Power Spectrum Density — [m^2/Hz]

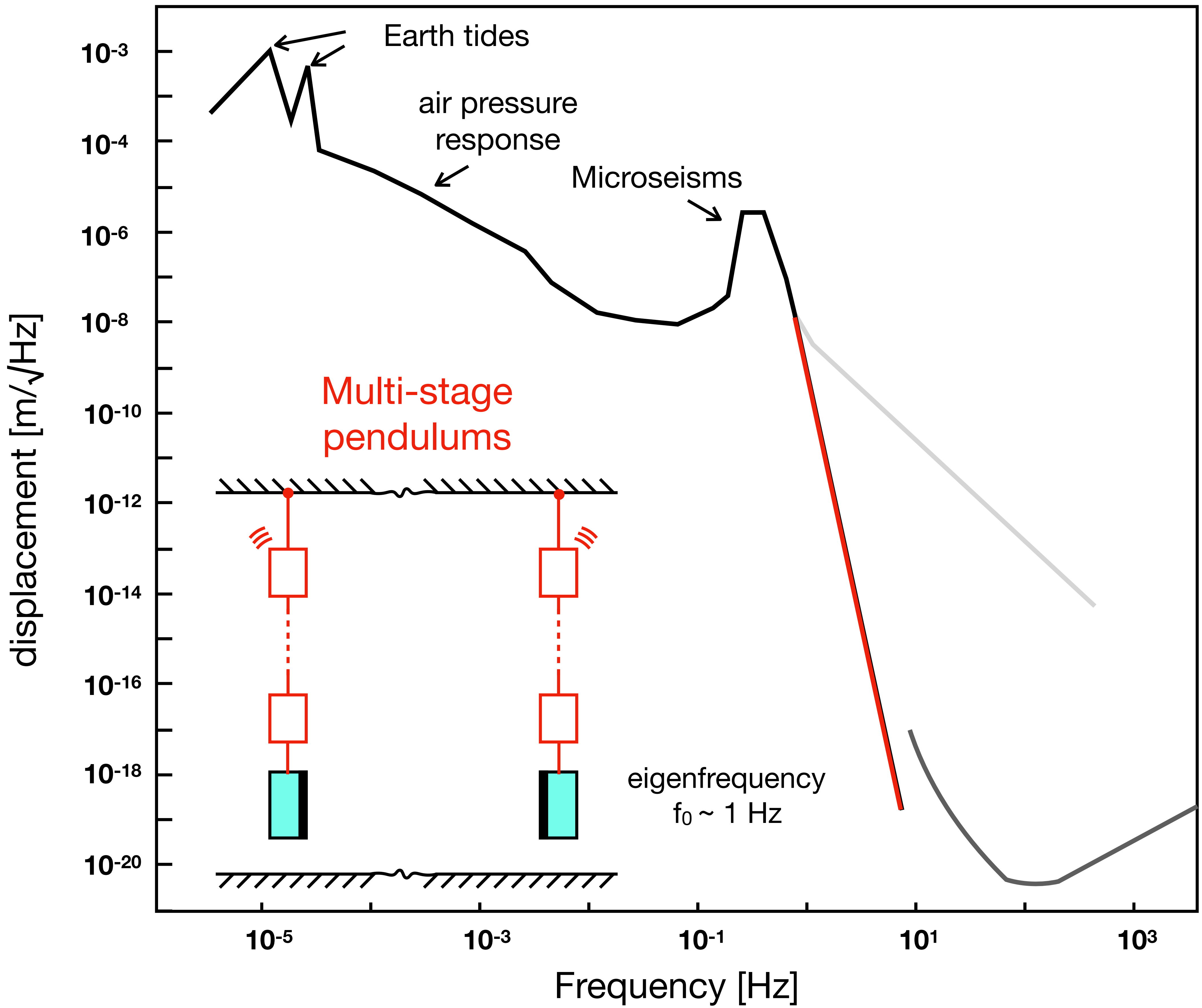
Amplitude Spectrum Density — [m/√Hz]

√ Square

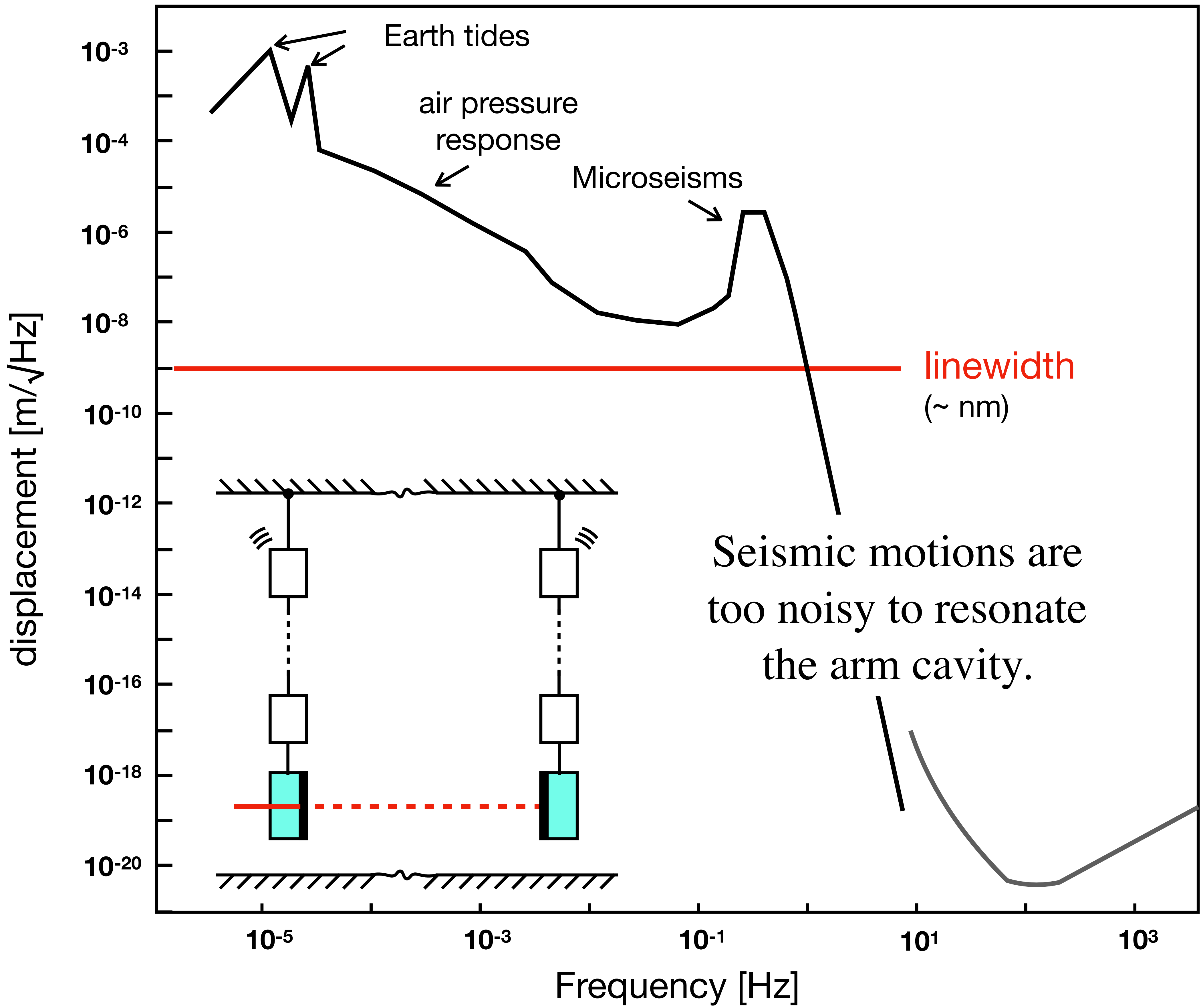
Seismic Noise



Review : seismic isolation system

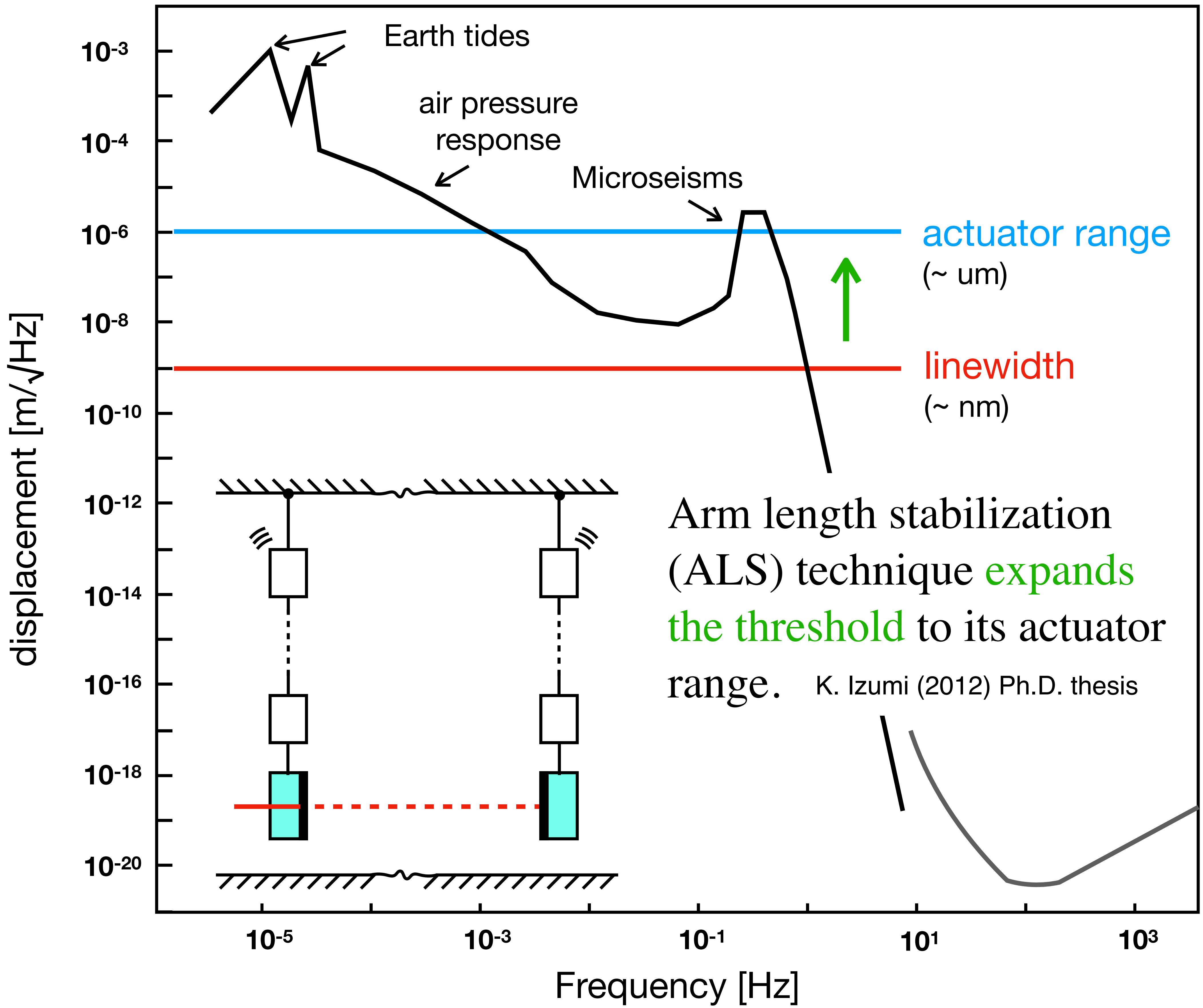


Review : seismic isolation system



Seismic motions are too noisy to resonate the arm cavity.

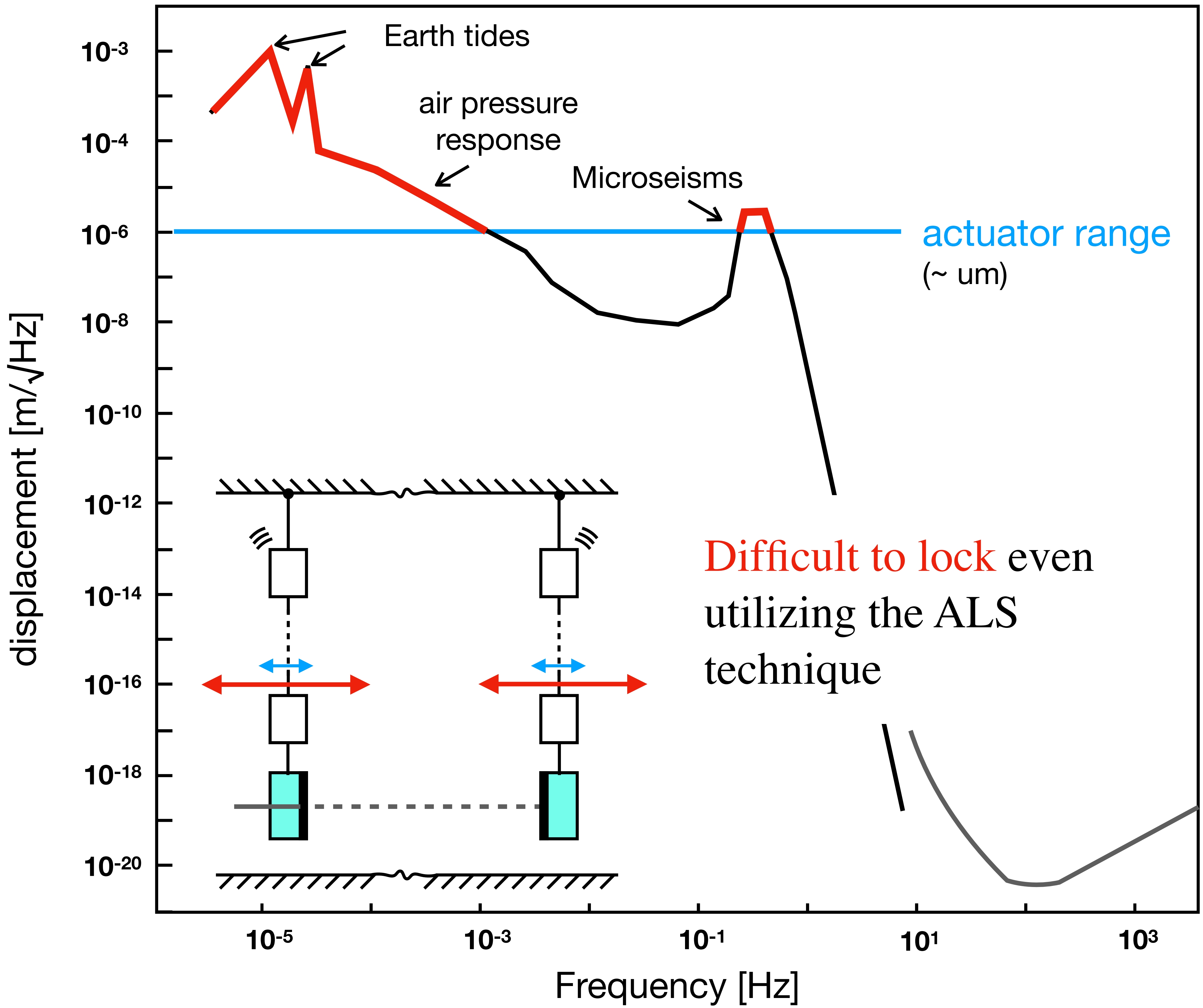
Review : seismic isolation system



Arm length stabilization (ALS) technique expands the threshold to its actuator range.

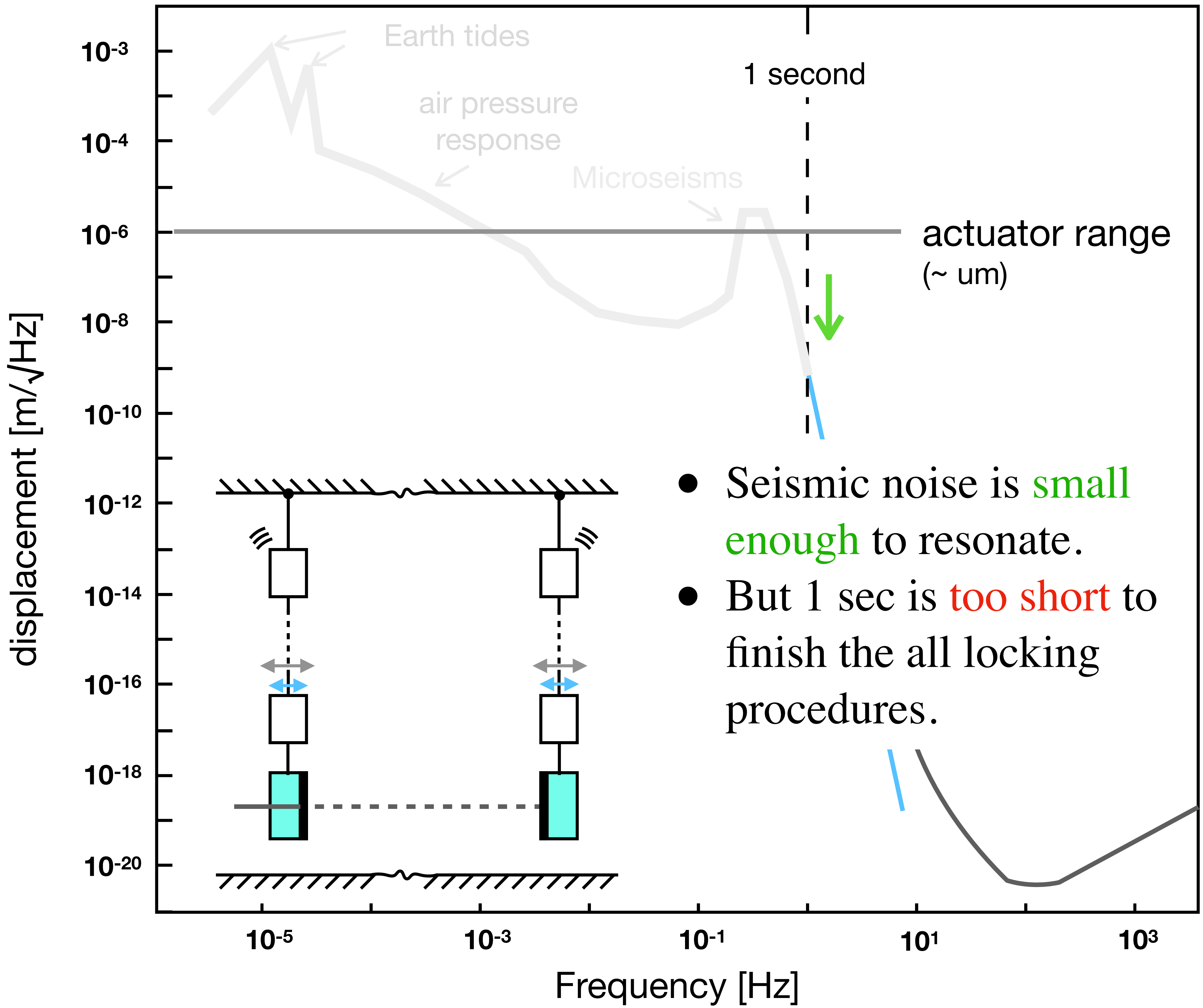
K. Izumi (2012) Ph.D. thesis

Review : seismic isolation system



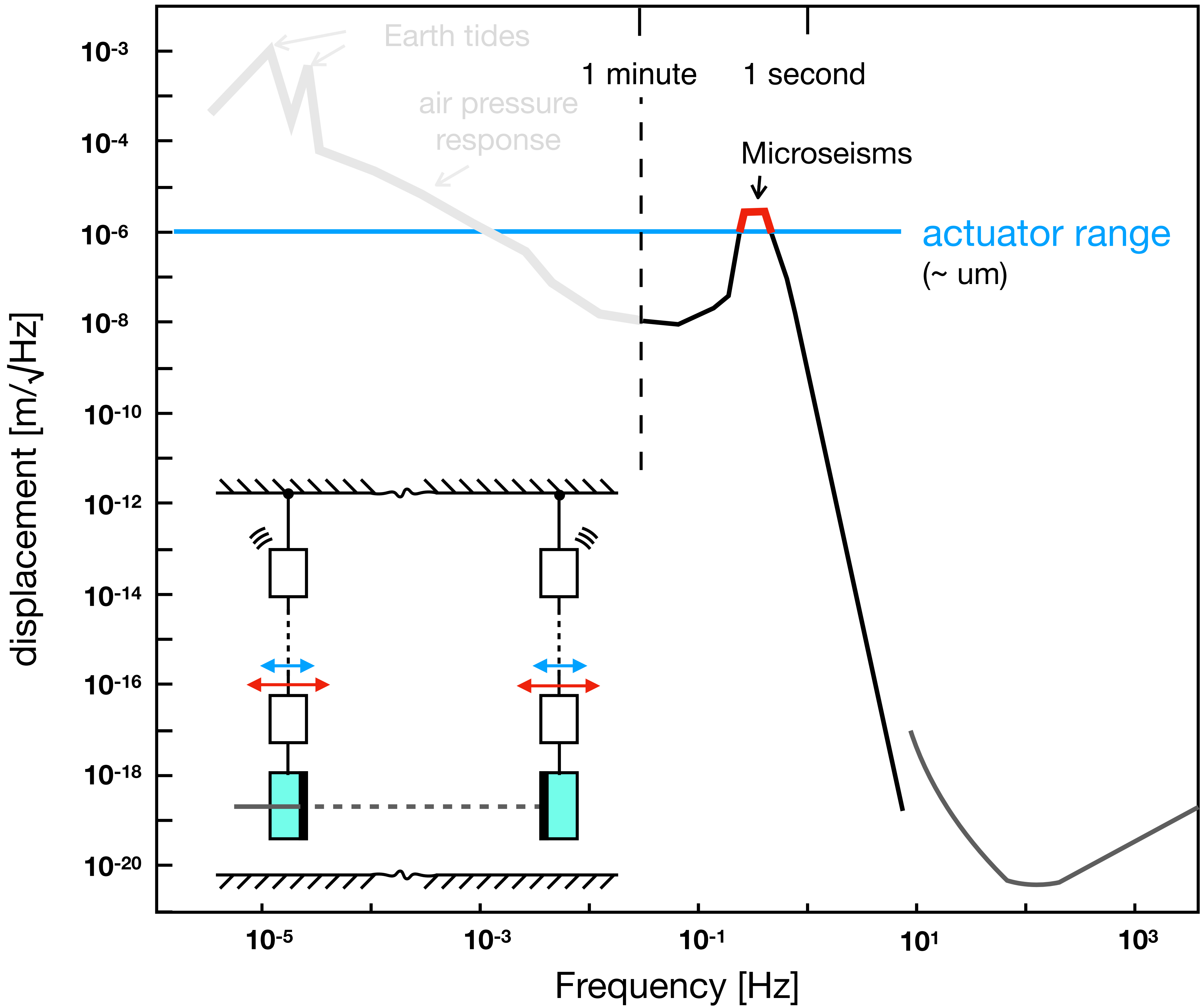
Difficult to lock even utilizing the ALS technique

Review : seismic isolation system

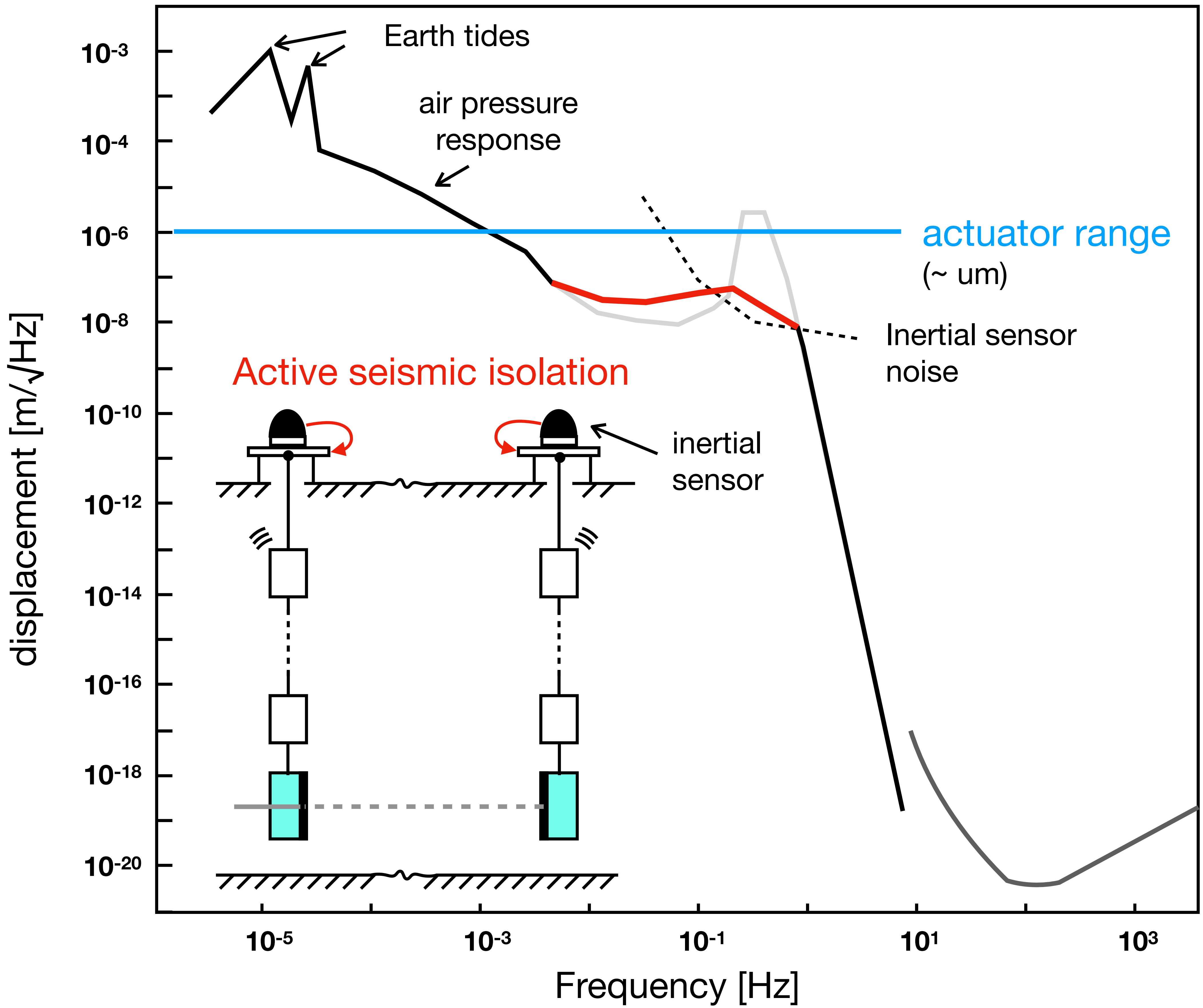


- Seismic noise is small enough to resonate.
- But 1 sec is too short to finish the all locking procedures.

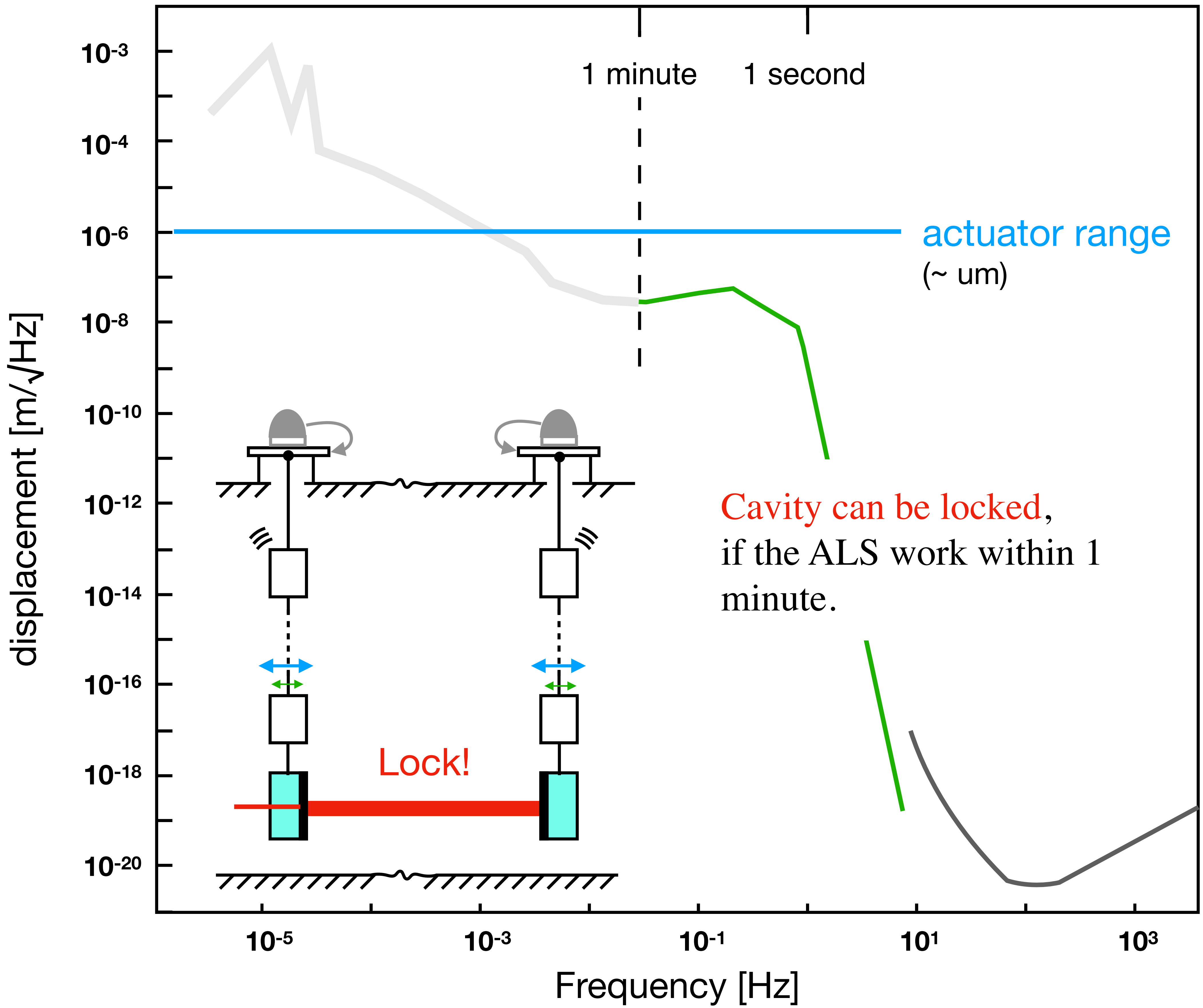
Review : seismic isolation system



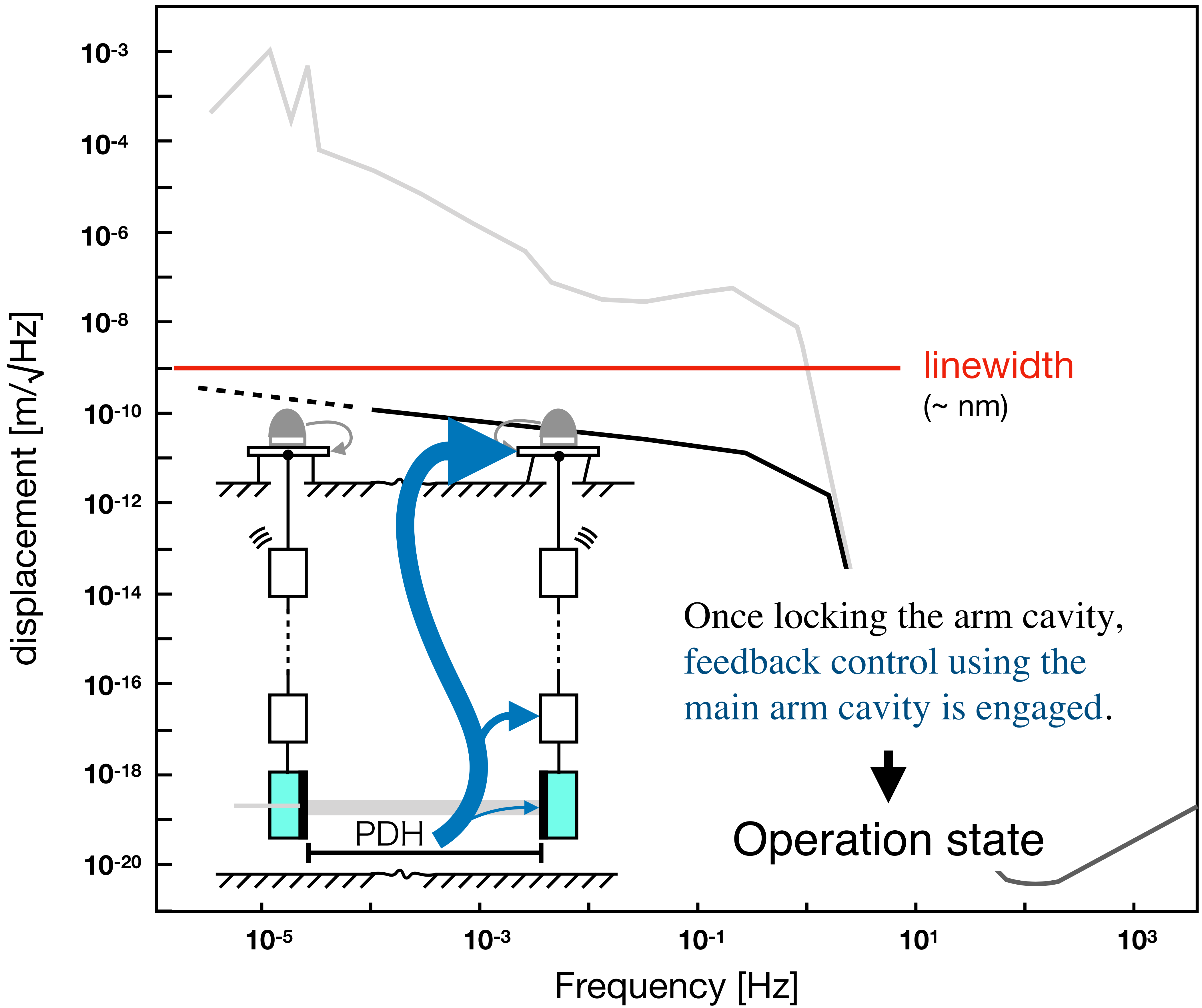
Review : seismic isolation system



Review : seismic isolation system



Review : seismic isolation system



Once locking the arm cavity, feedback control using the main arm cavity is engaged.

↓

Operation state

Current seismic isolation system seems fine, but…

Limit has become apparent **[*]**

- Suspension is weak to seismic disturbance below 100 mHz due to the inertial sensor's noise.
- Earthquake often shakes this band.
- Once lost locking state, it takes several hours to recover.

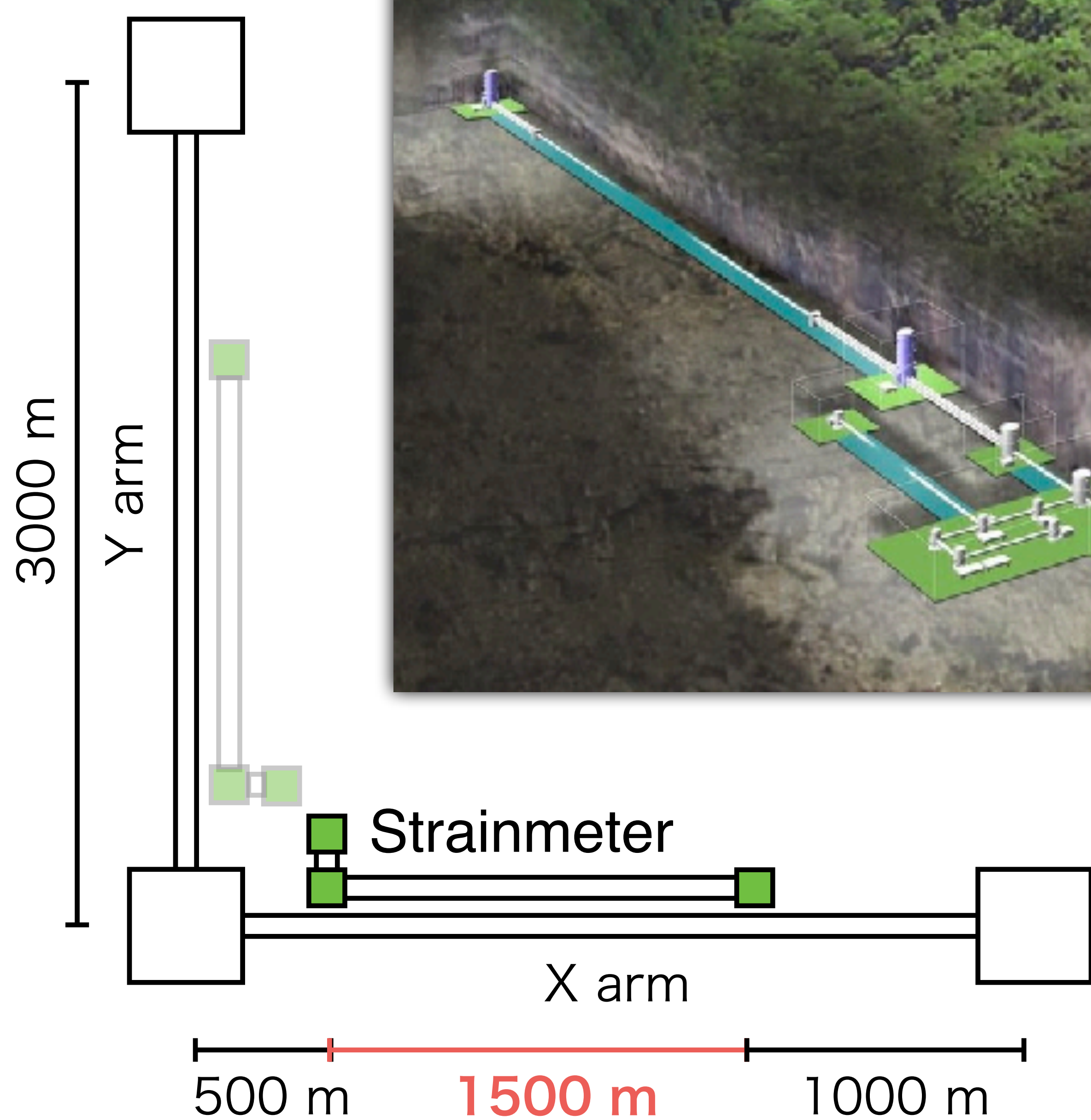
My study resolves this sensor noise problem.

- LIGO is optimizing the control filter in the software because of no better sensitive sensor .
- KAGRA resolves this problem by using a laser strainmeter directly.

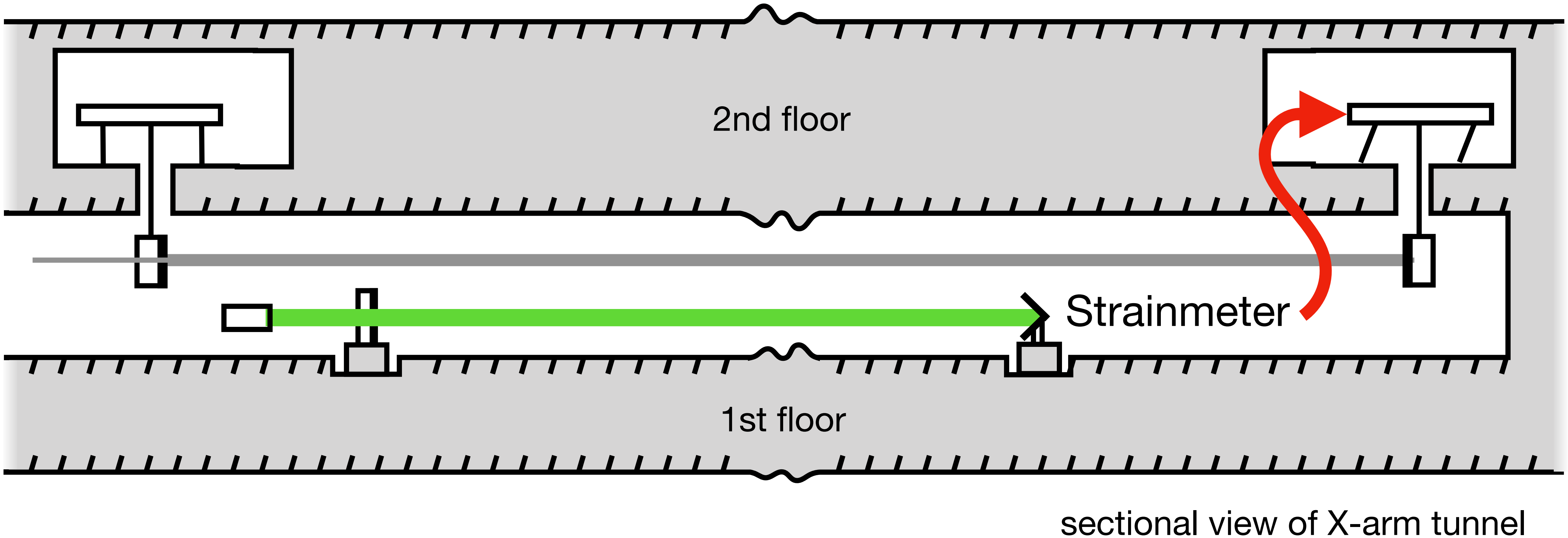
[*] Biscans, Sebastien, et al.
"Control strategy to limit duty cycle impact of earthquakes on the LIGO gravitational-wave detectors."
CQG 35.5 (2018): 055004.

Contents

KAGRA and strainmeter



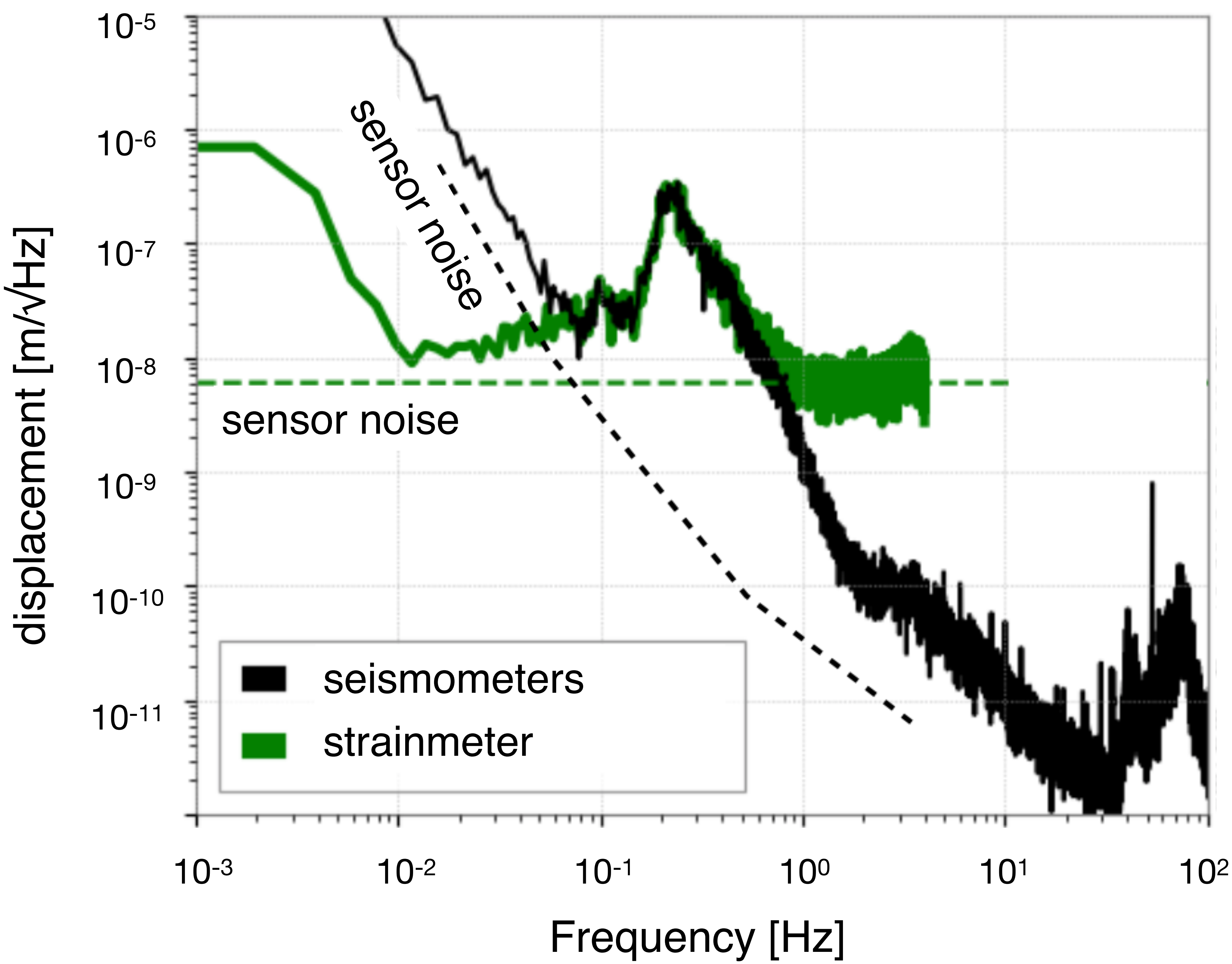
Baseline Compensation System



Feedforward control using a strainmeter

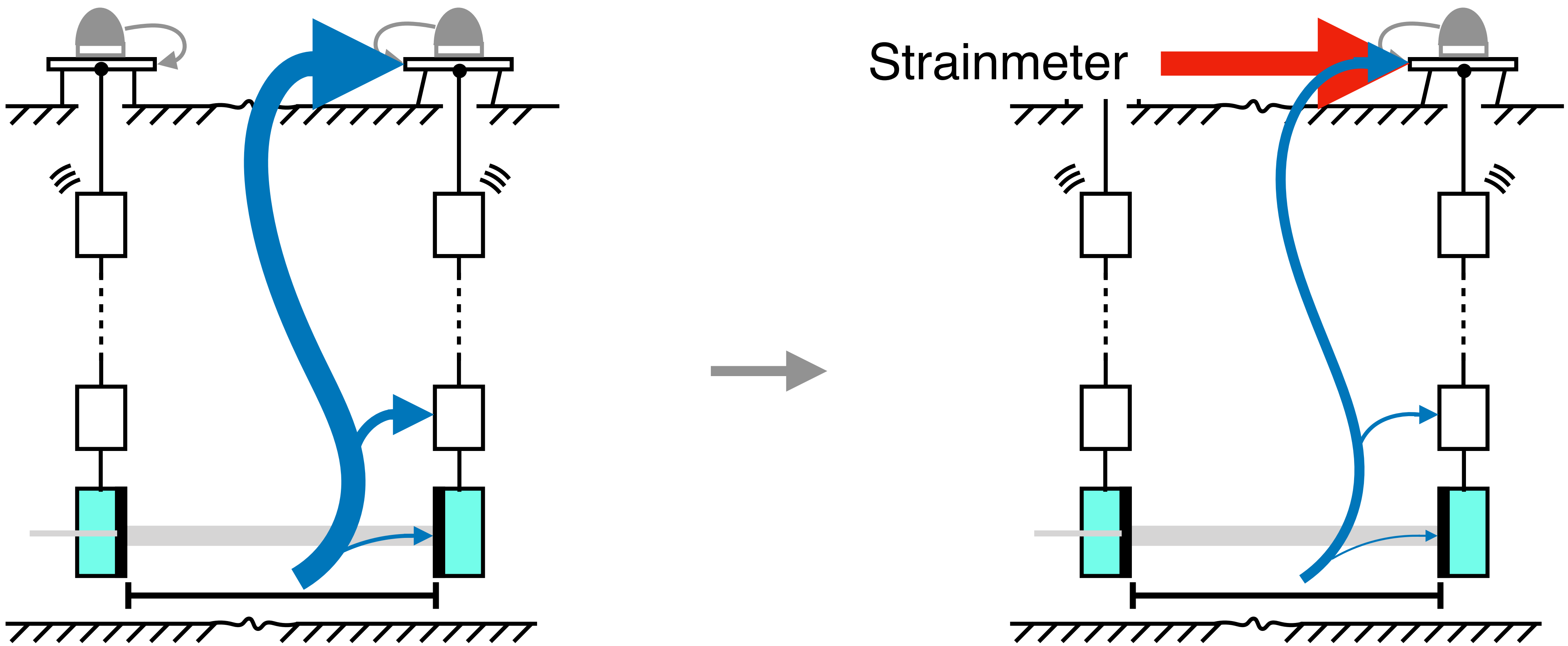
- compensate for the cavity length by actuating the top stage

Comparison between seismometer and strainmeter



Strainmeter has a better sensitivity below 0.1 Hz

Advantage of our system



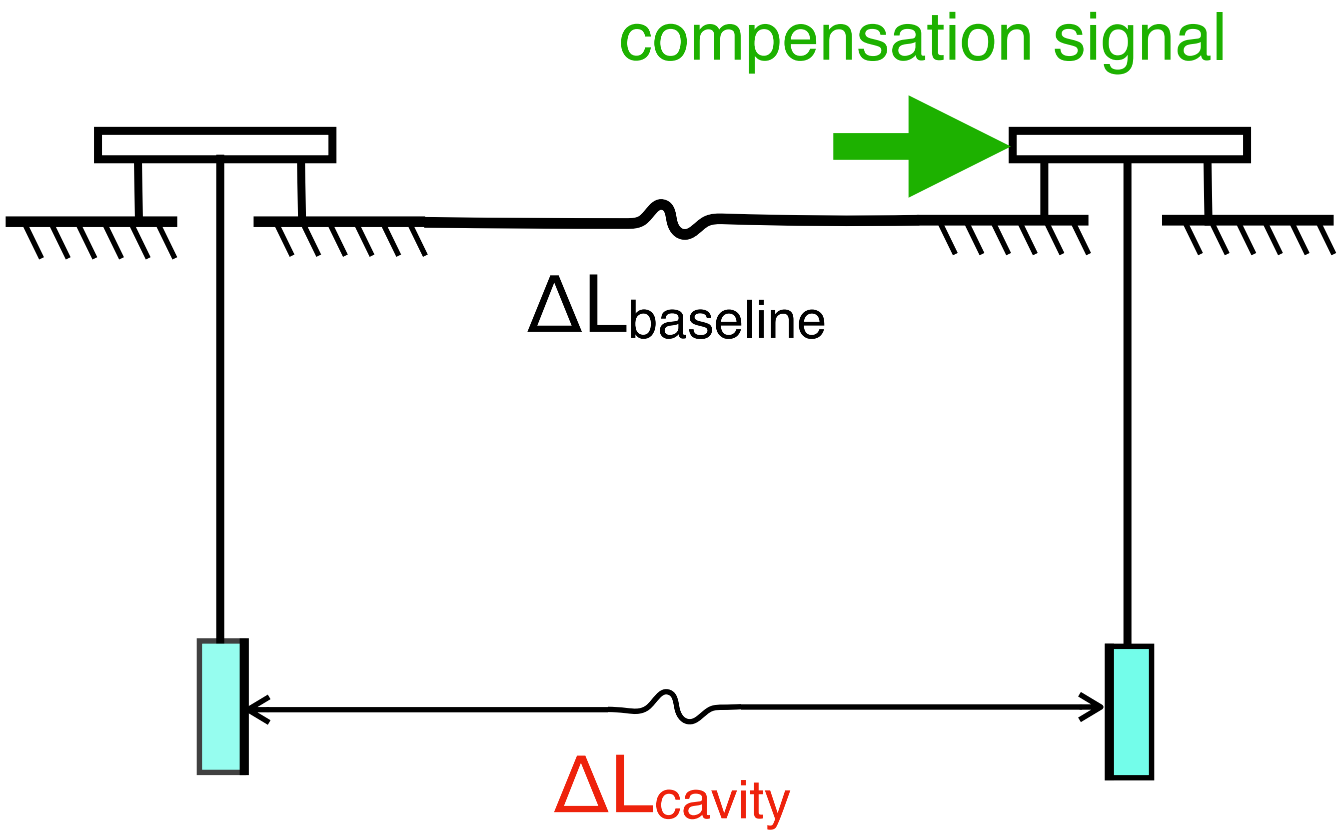
Relax the feedback control

- reduce loads of the actuation forces on lower-stage
- avoid the saturation of the actuation force

→ More stable control

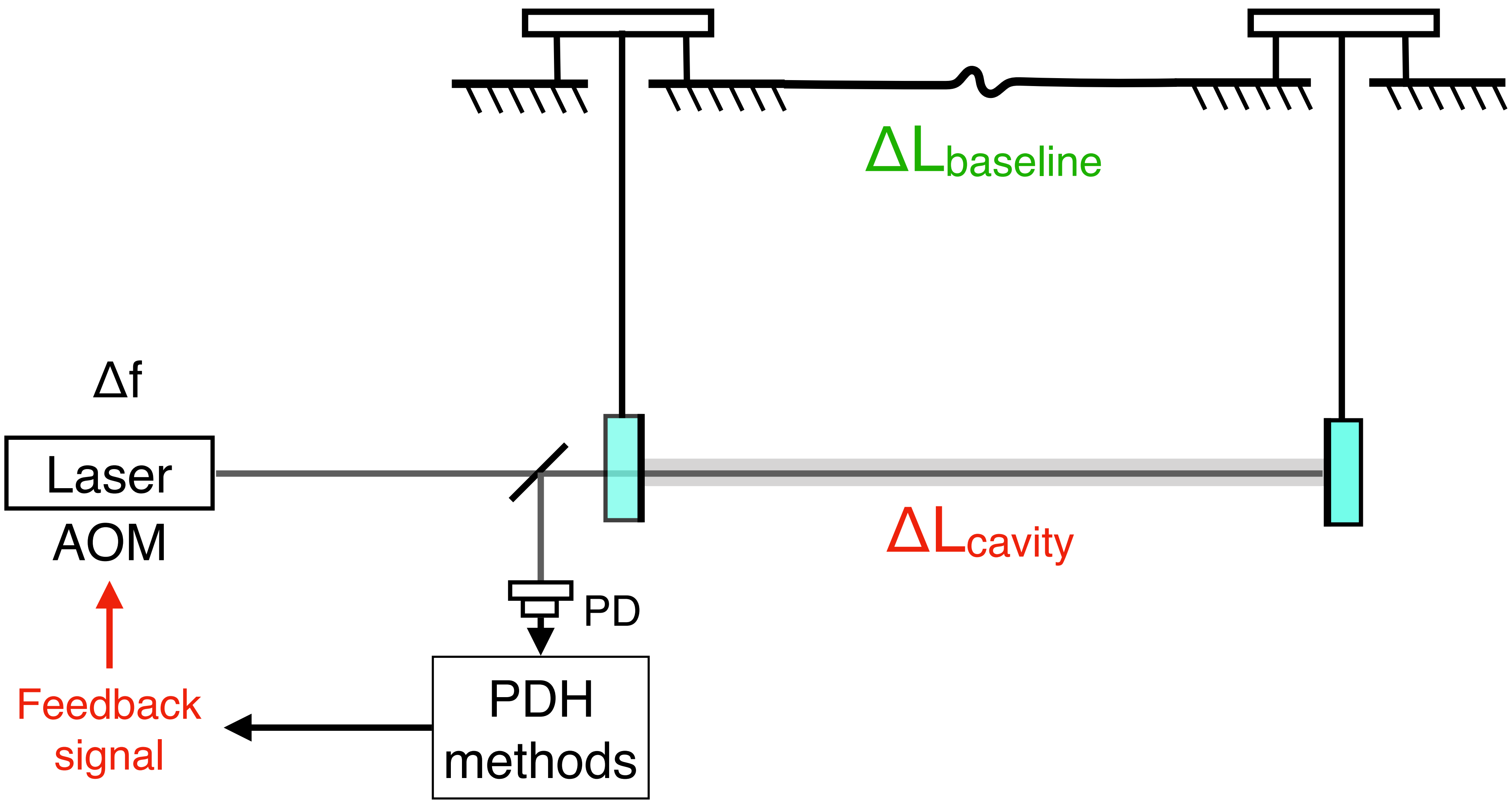
Contents

Setup for Demonstration



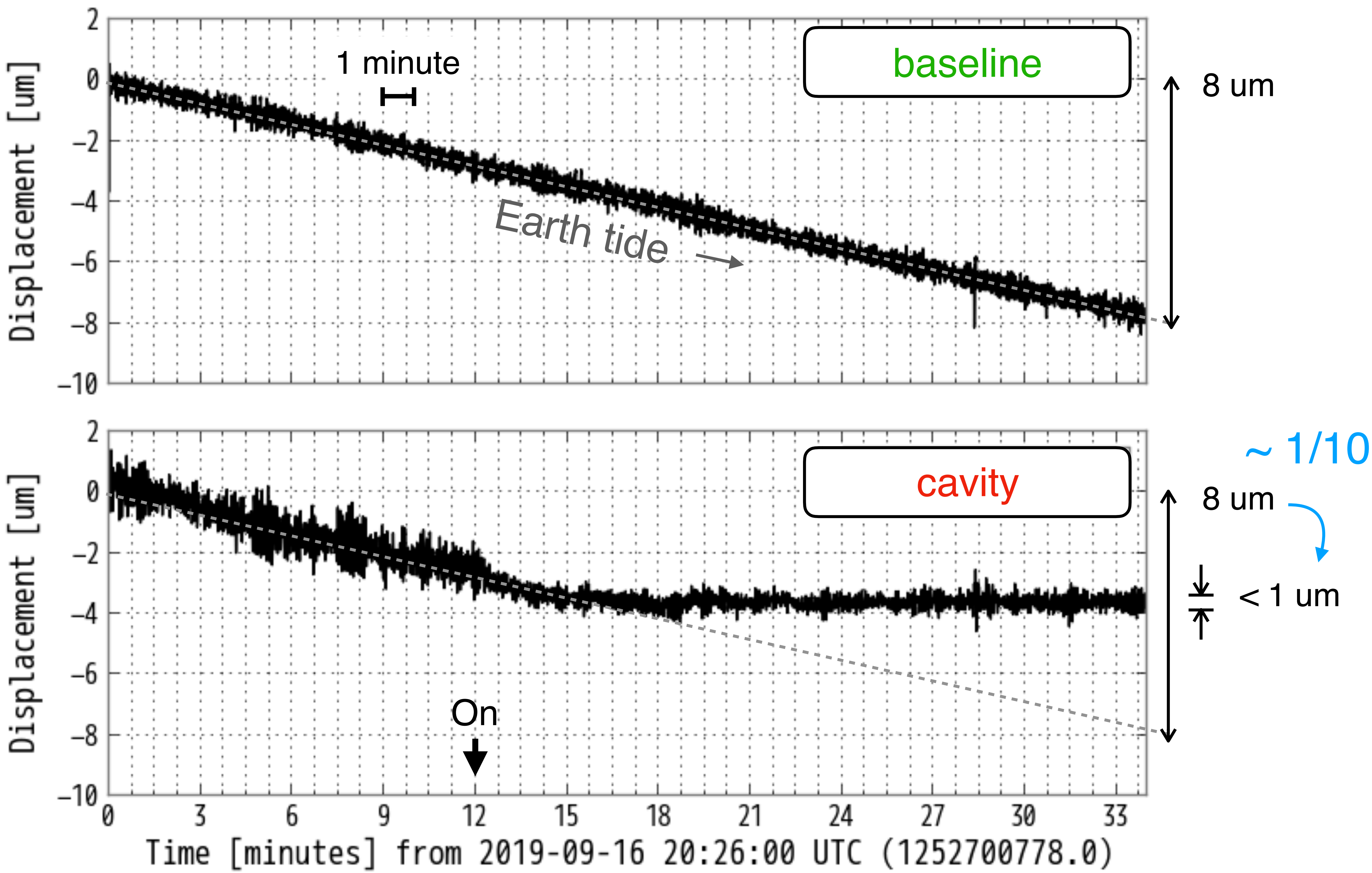
Purpose is to demonstrate the reduction of the cavity length fluctuation when using the baseline compensation system

Setup for Demonstration



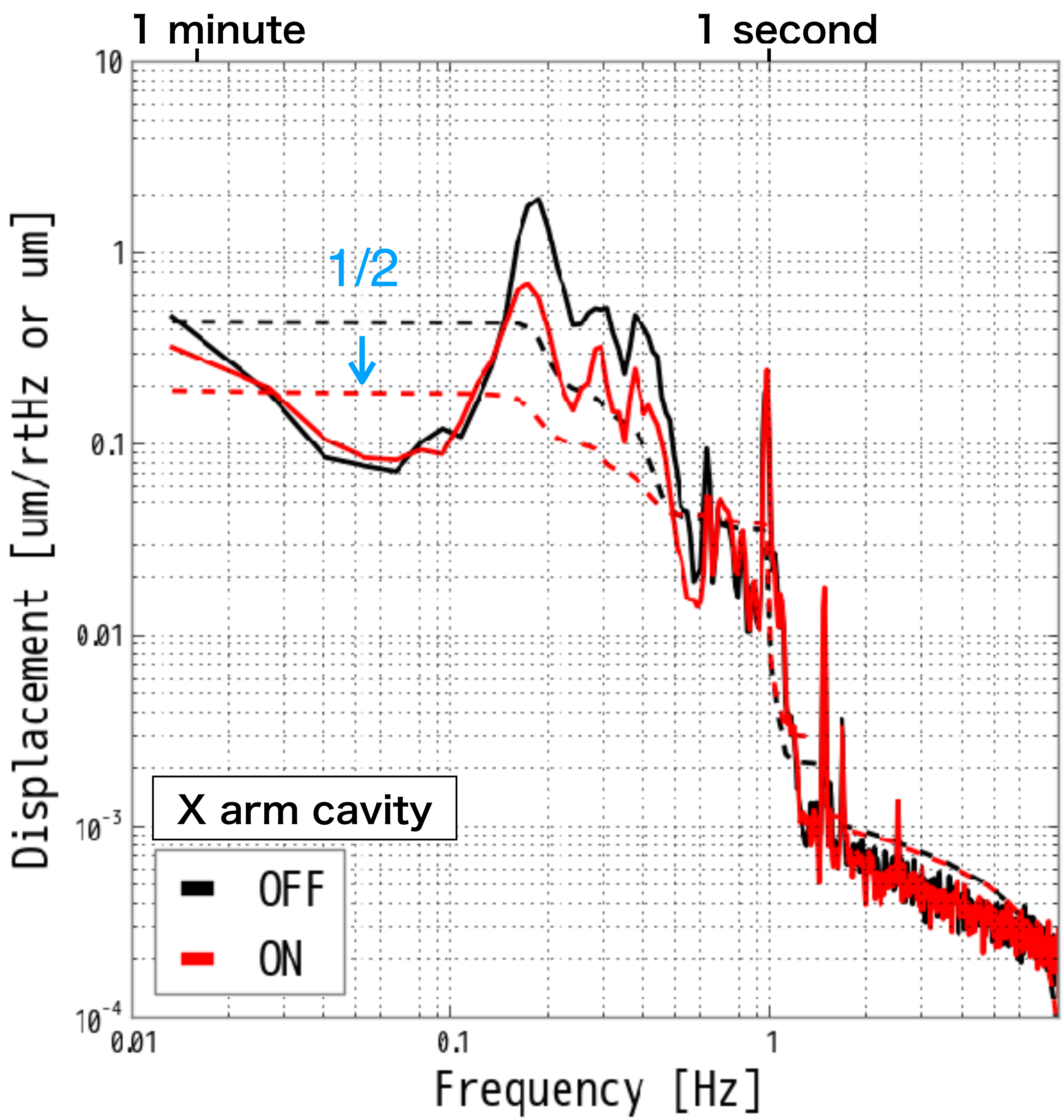
- Keep the X-arm cavity on resonance by feedback control using AOM as a frequency actuator.
- Baseline length fluctuation ΔL_{cavity} is measured by a strainmeter
- cavity length fluctuation ΔL_{cavity} is calculated from the feedback signal

Results

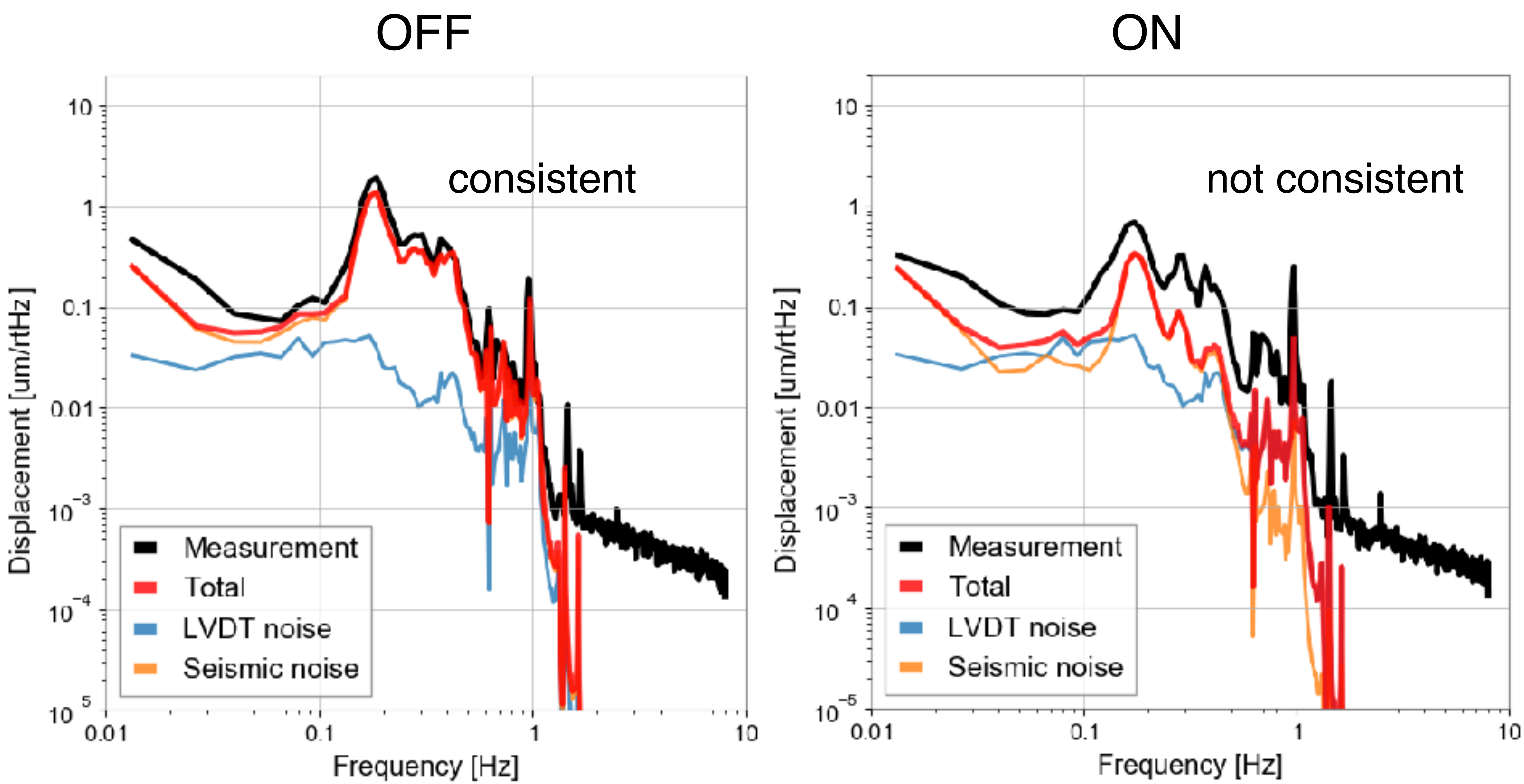


baseline
1 minute
Earth tide
8 um
cavity
~ 1/10
8 um
< 1 um
On
Displacement [um]
Time [minutes] from 2019-09-16 20:26:00 UTC (1252700778.0)

Results

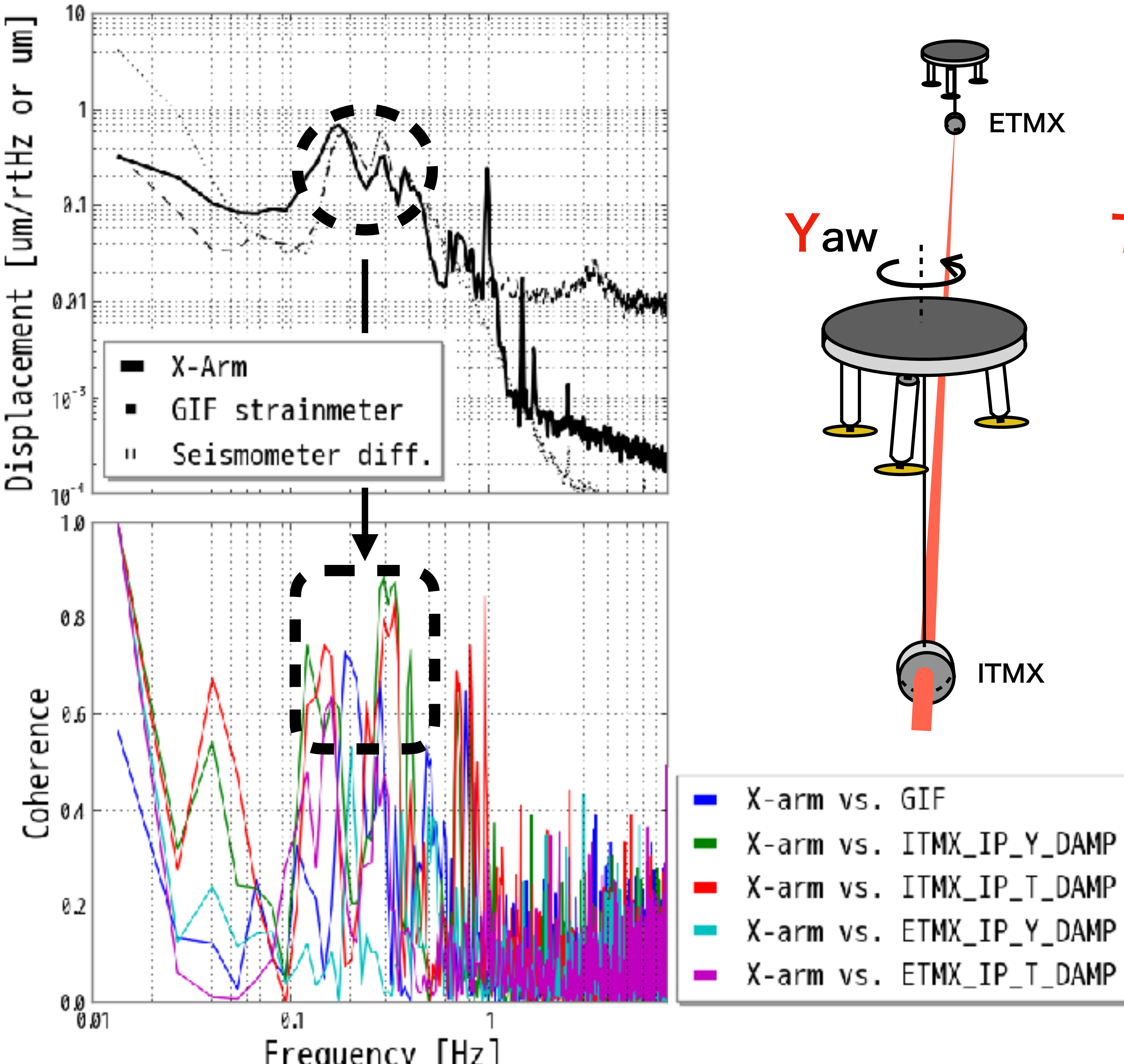

1 minute
1 second
10
1
0.1
0.01
10^{-3}
10^{-4}
Displacement [um/rtHz or um]
1/2
X arm cavity
OFF
ON
0.01
0.1
1
Frequency [Hz]

Comparison with the simulation

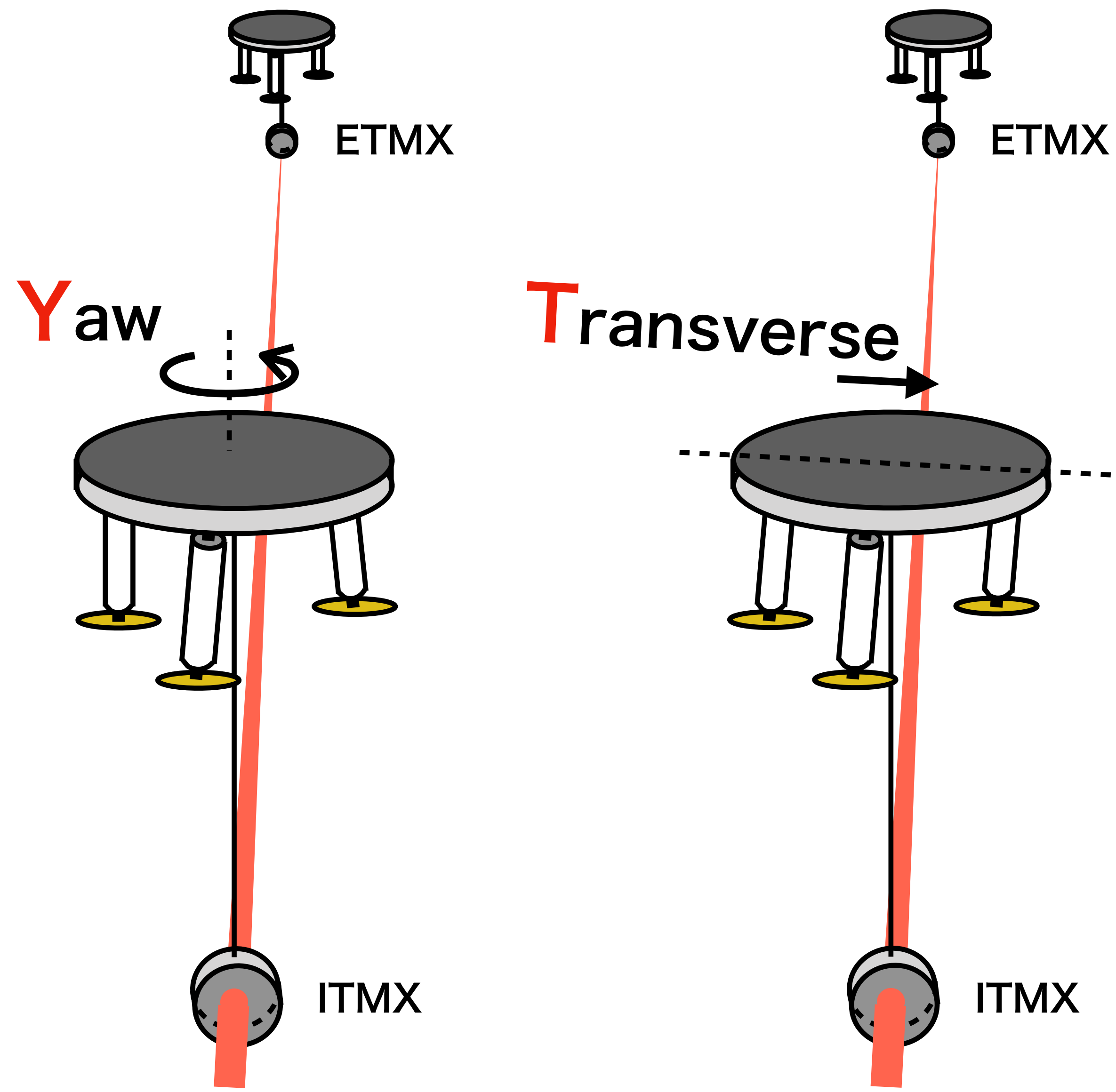


- OFF : Measurement was consistent with the model simulation
- ON : Measurement was not

Discussion



Displacement [um/rtHz or um]
X-Arm
GIF strainmeter
Seismometer diff.
Coherence
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
Frequency [Hz]



ETMX
Yaw
ITMX
ETMX
Transverse
ITMX

Contents

Conclusion

- In order to improve the duty cycle, which is limited by seismic motions on the arm cavity in the low-frequency band, we needs to reduce this disturbances.
- We designed the baseline compensation system and demonstrate its performance by using X-arm cavity of KAGRA.
- As a result, this new system had compensated the fluctuation of the arm cavity.
- This is the first demonstration of the baseline compensation on the km-scale GW detector in the world.

Future prospects

- To eliminate the internal coupling from other degrees of freedoms, we will evaluate the performance of the compensation system in the case that local feedback loops are not engaged. (KAGRA is now under the commissioning of that)

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

End

Backup

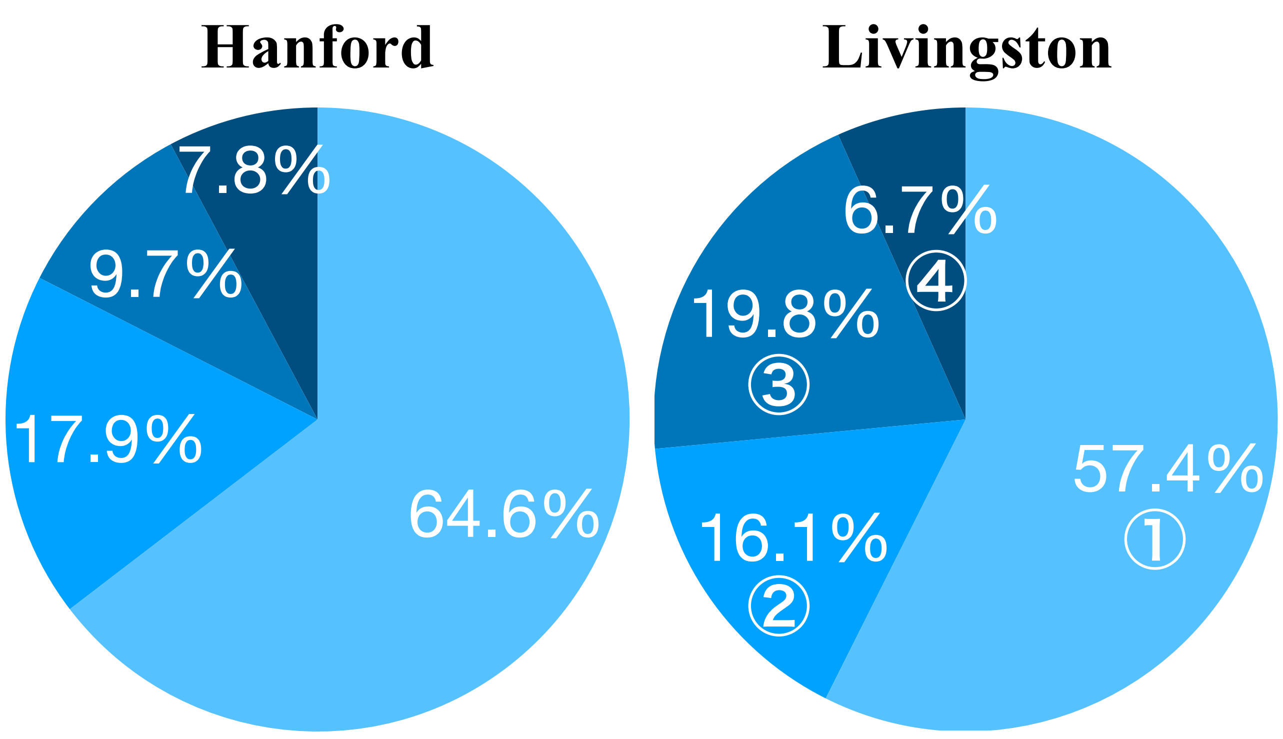
要点

- 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

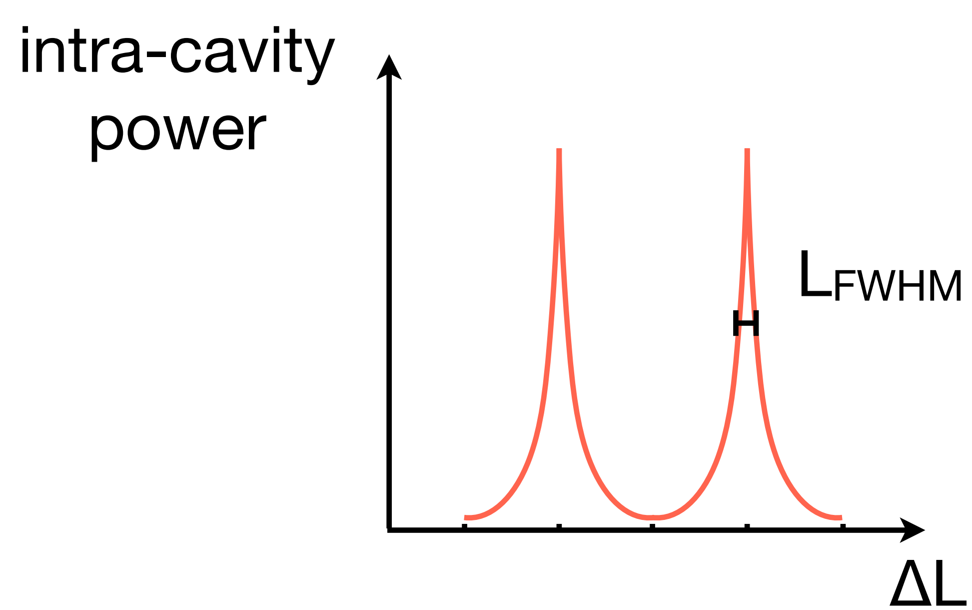
Fabry–Pérot optical resonance cavity

- Resonance condition

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

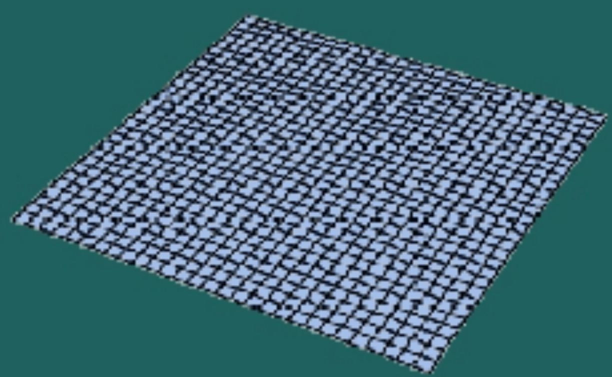
$$L_{\mathrm{FWHM}} = \frac{\lambda}{2\mathscr{F}} \qquad \left(\mathscr{F} = \frac{\pi\sqrt{r_1 r_2}}{1 - r_1 r_2} \right)$$

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

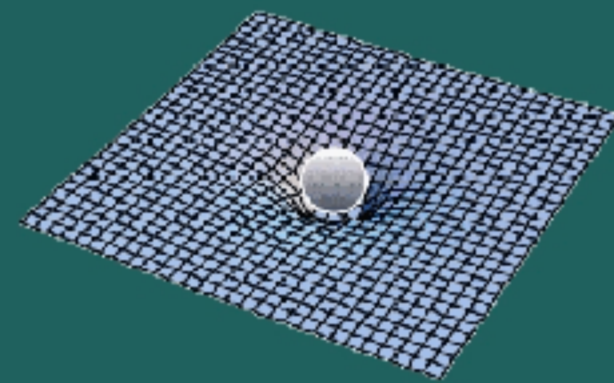


Gravitational-wave (GW)

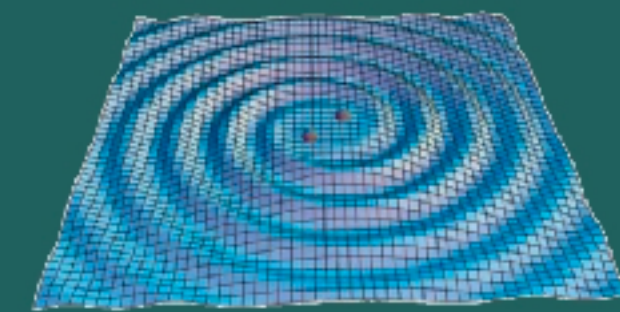
flat space-time



curved space-time



GW emission
(e.g. neutron start binary)



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

連星合体

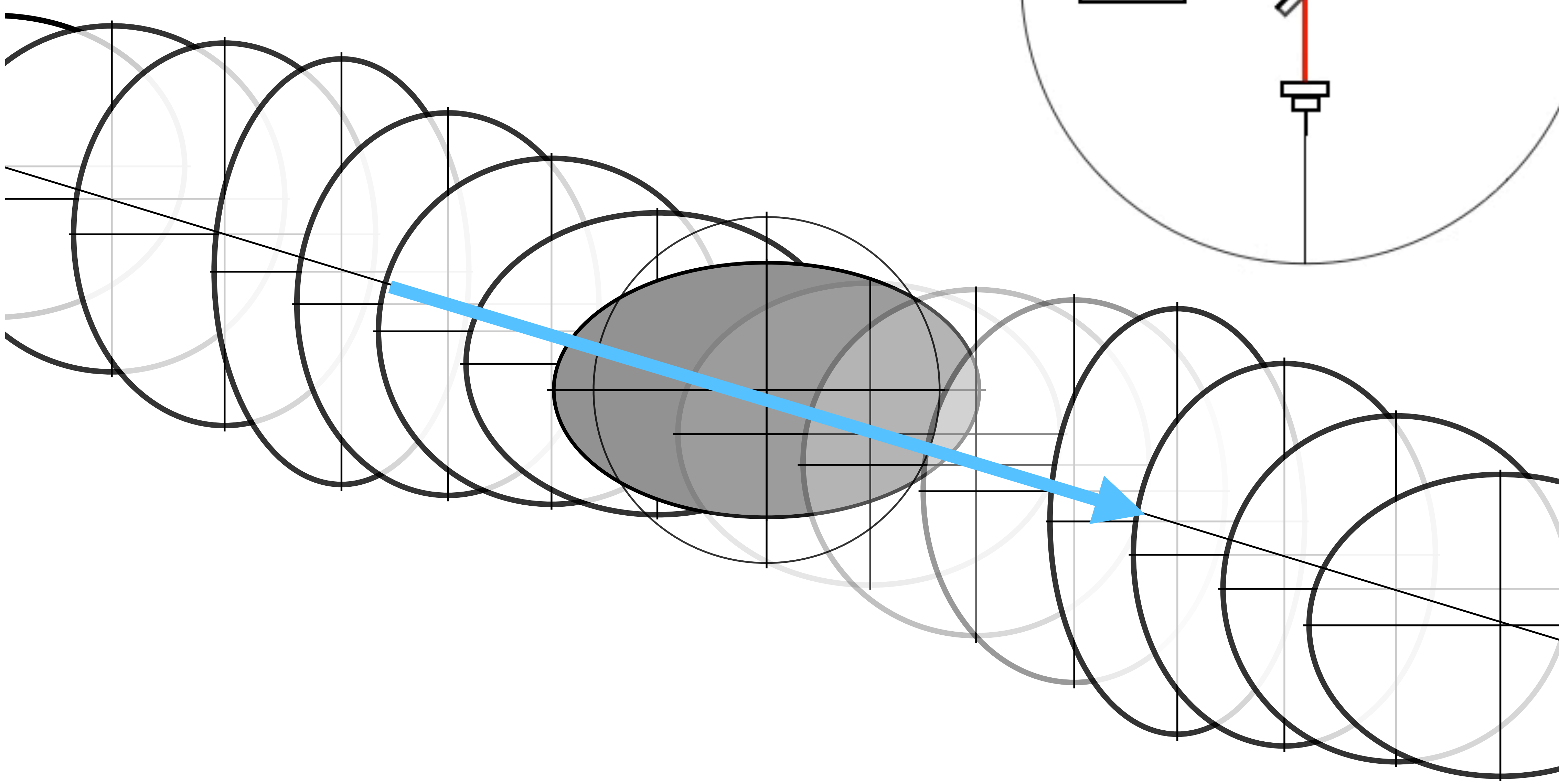
supernovae explosion

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

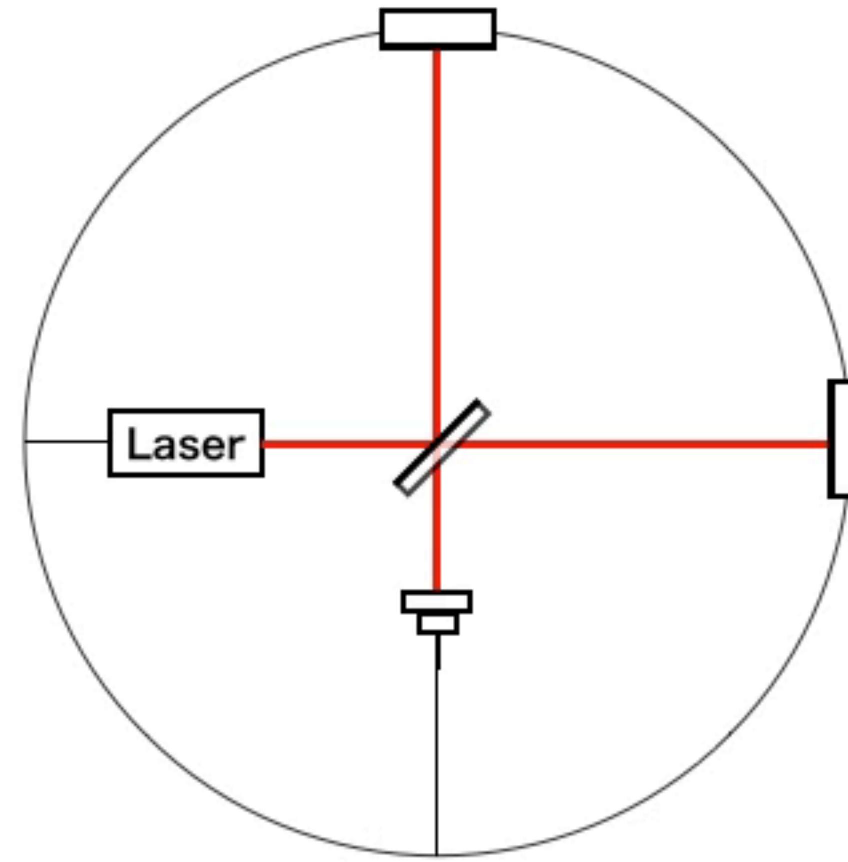
パルサー

GW detector

- 重力波が到来すると、
  空間は潮汐変形する

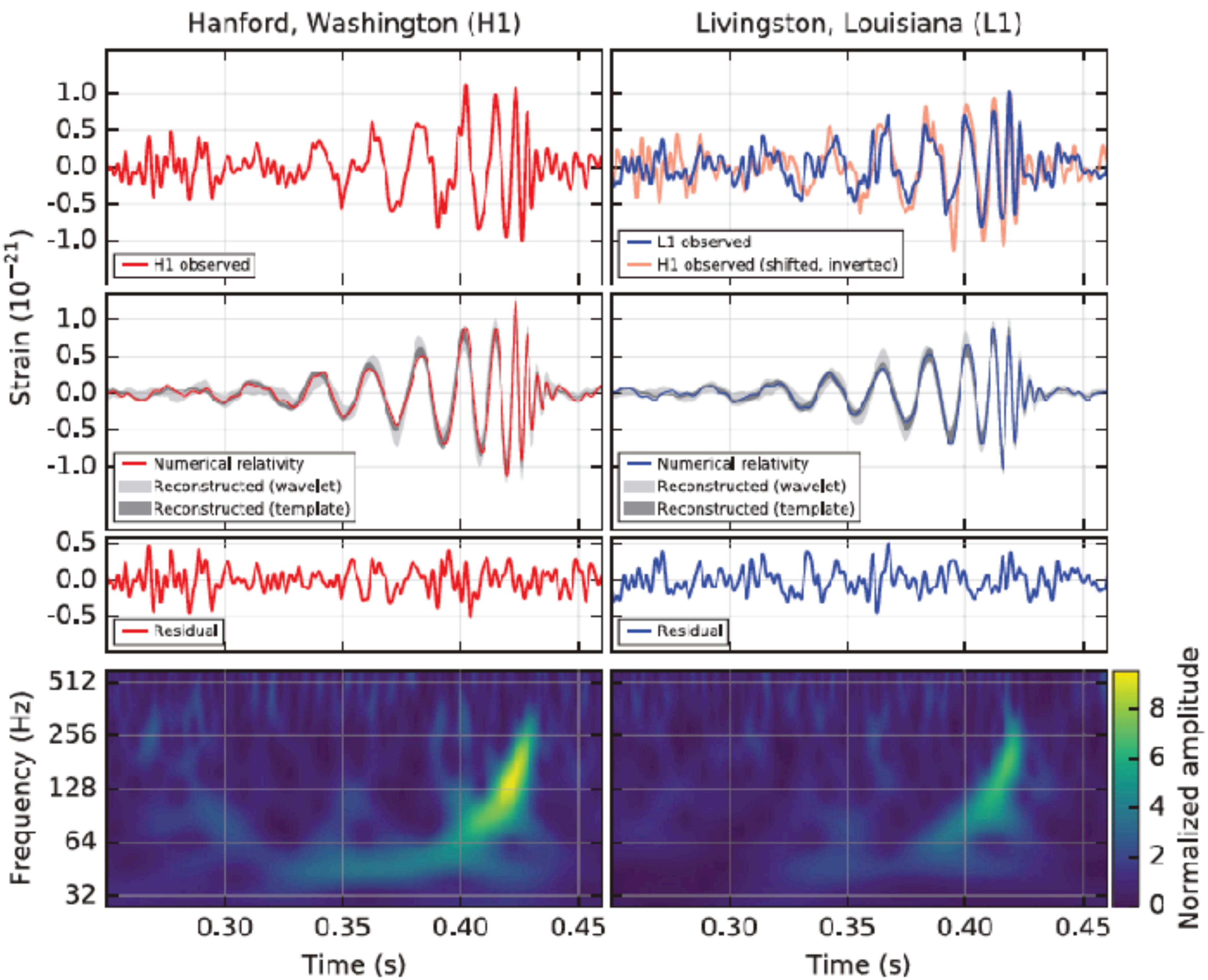


Michelson interferometer



GW detectors network

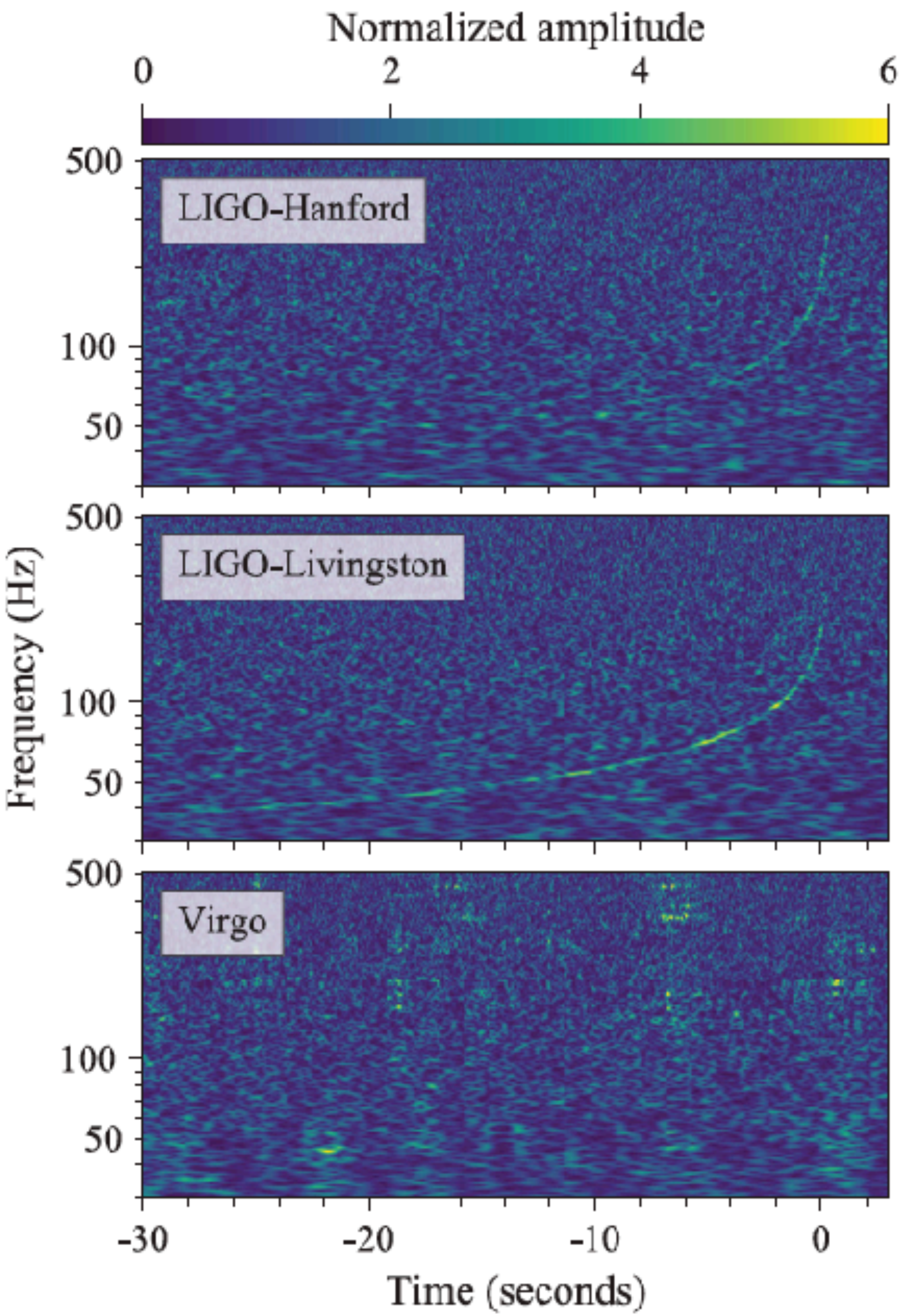
GW150914: binary black hole merger



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

- Detected by 2 LIGO detectors

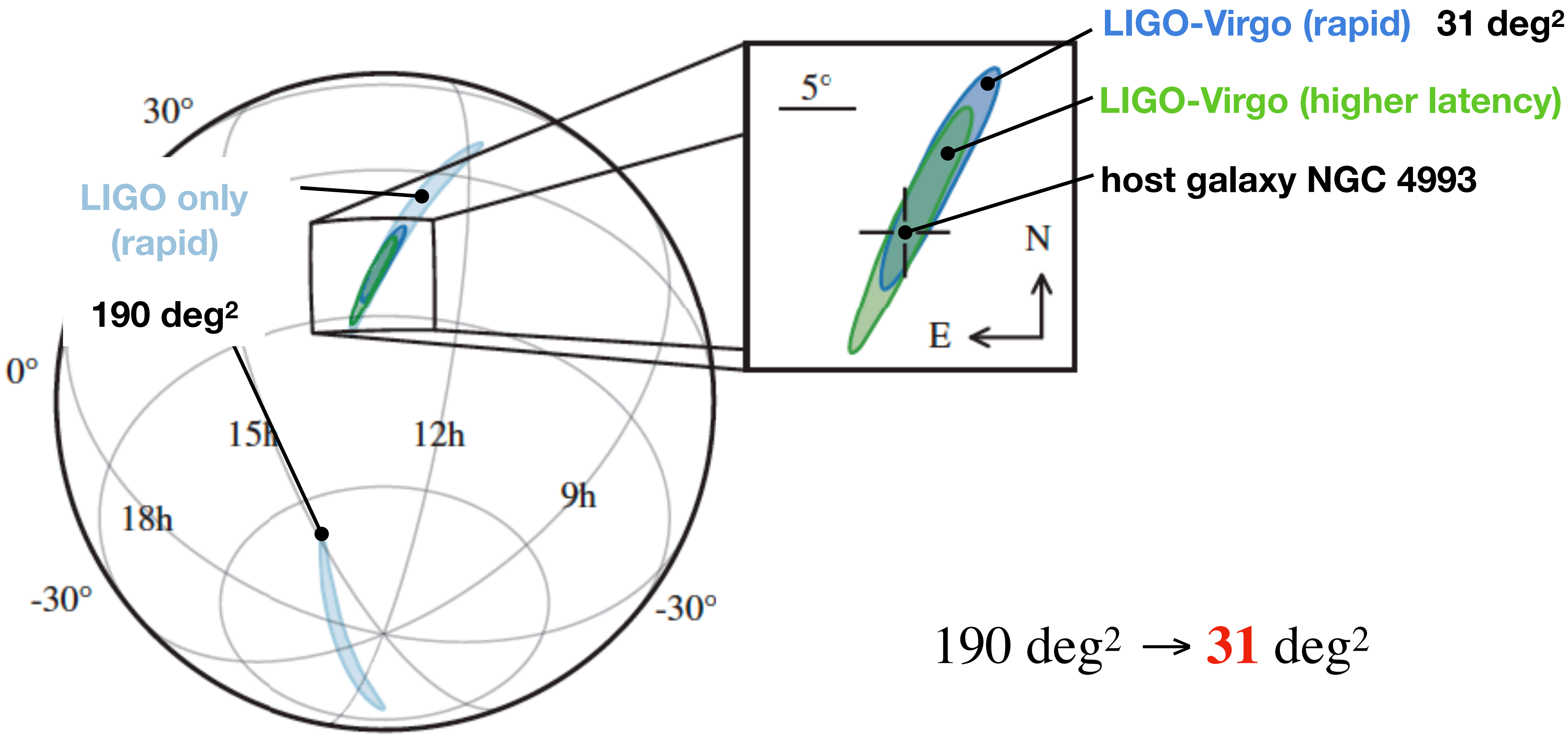
GW170817: binary neutron star inspiral



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

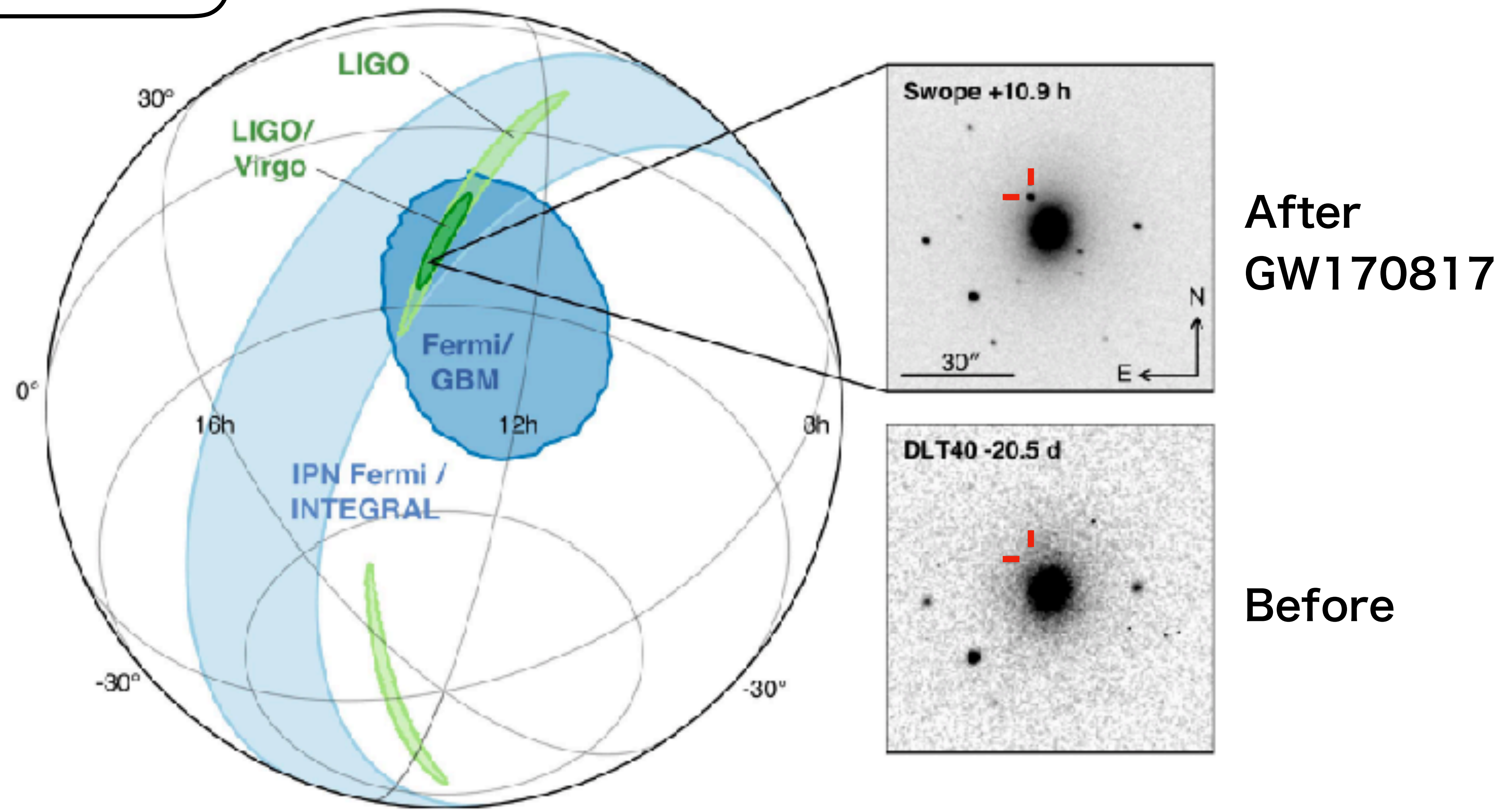


Abbott, B. P., et al. *Phys. Rev. Lett.* **119**, (2017), 161101.

190 deg^2 → **31** deg^2

Multi-messenger observation

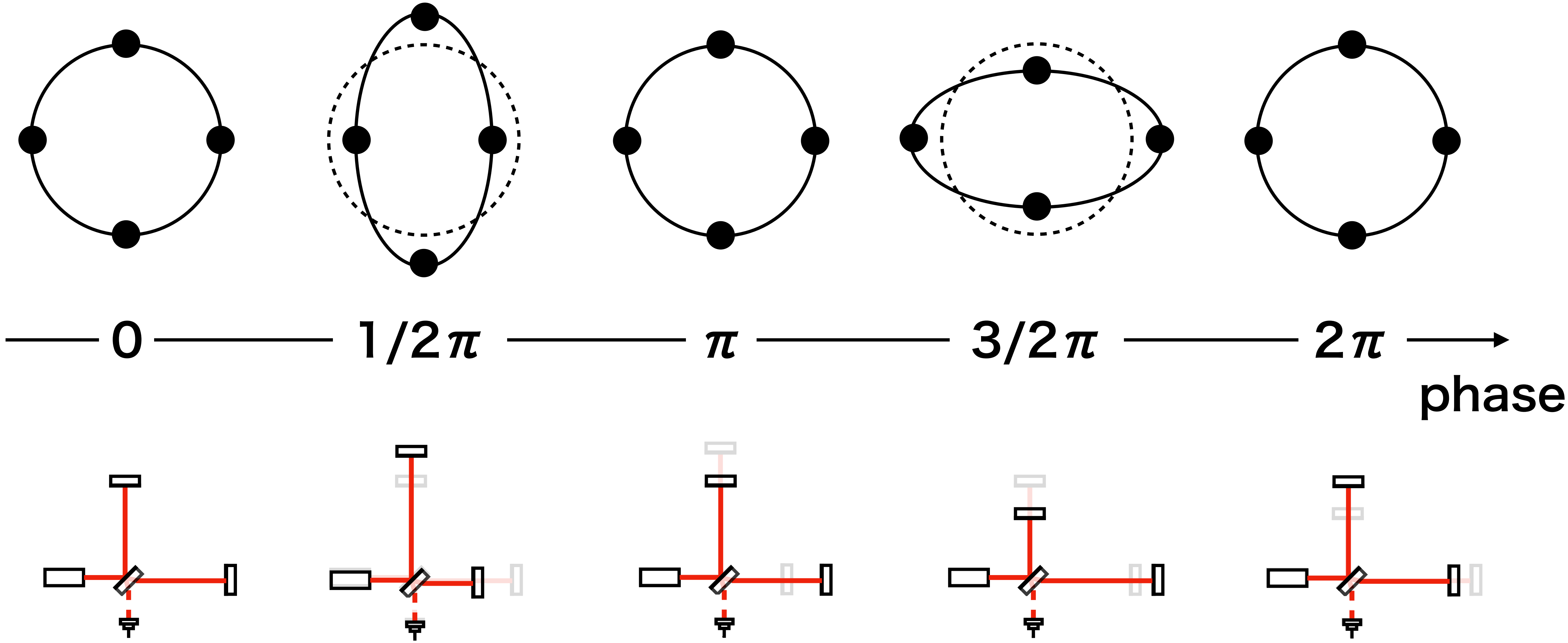
LIGO		LIGO & Virgo
190 deg^2	→	**31** deg^2



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