Characterization and Control of Cryogenic Suspension in KAGRA

(KAGRAにおける低温懸架装置の特性評価と制御)

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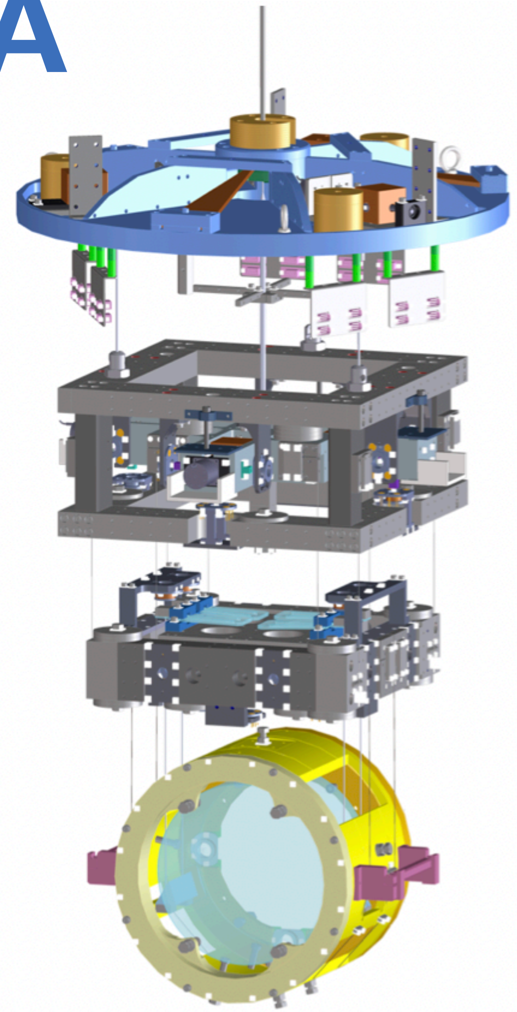

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Abstract

Background

What I did

KAGRA : Gravitational Wave detector with Laser Interferometer

Cryogenic Suspension (pendulum-type) for high sensitivity

Pendulum-type Suspension system

Vibration of the mirror is amplified at resonant frequency

Low noise control

Solution

We designed low noise control filter for observation phase

Damping control

We designed damping control for cryogenic suspensions to suppress the vibration

Control noise

Problem

Control noise limits the sensityvity of KAGRA at 10~50 Hz

Noise reduction

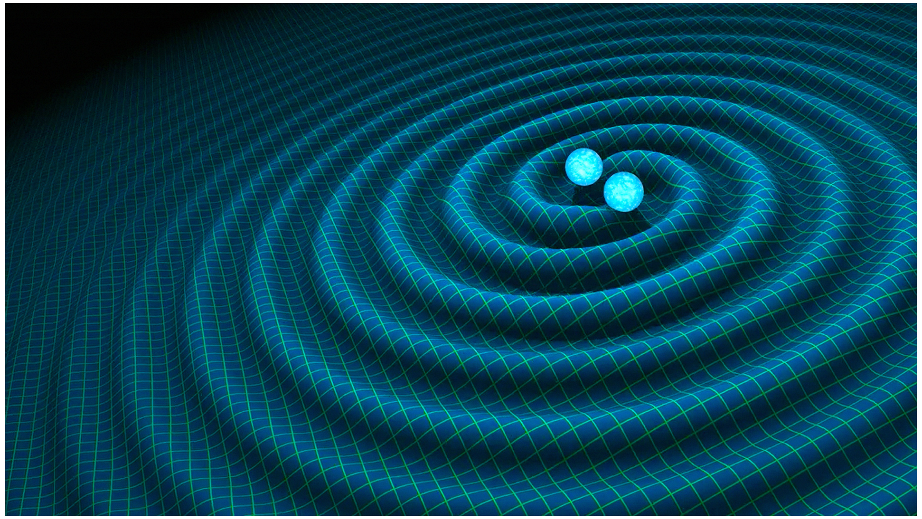
Result

Control noise was reduced by 2~3 orders of magnitude

What is Gravitational Wave?

Gravitational Wave

：Phenomenon that causes expansion and constraction of space-time



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Occurs in the accelerated motion of objects with large masses

(BH Binary, NS Binary, Supernova explosion…)

In 2015, LIGO succeeded in detecting them directly for the first time.

Obsevational significance

：New tool for the measuremment of the universe

Properties completely different from those of electromagnetic waves

→ **Gain new knowledge not previously available**

Properties of BH or NS, Mechanism of supernova explosion, and so on

How can we detect GW?

Gravitational Wave detector with laser interferometer

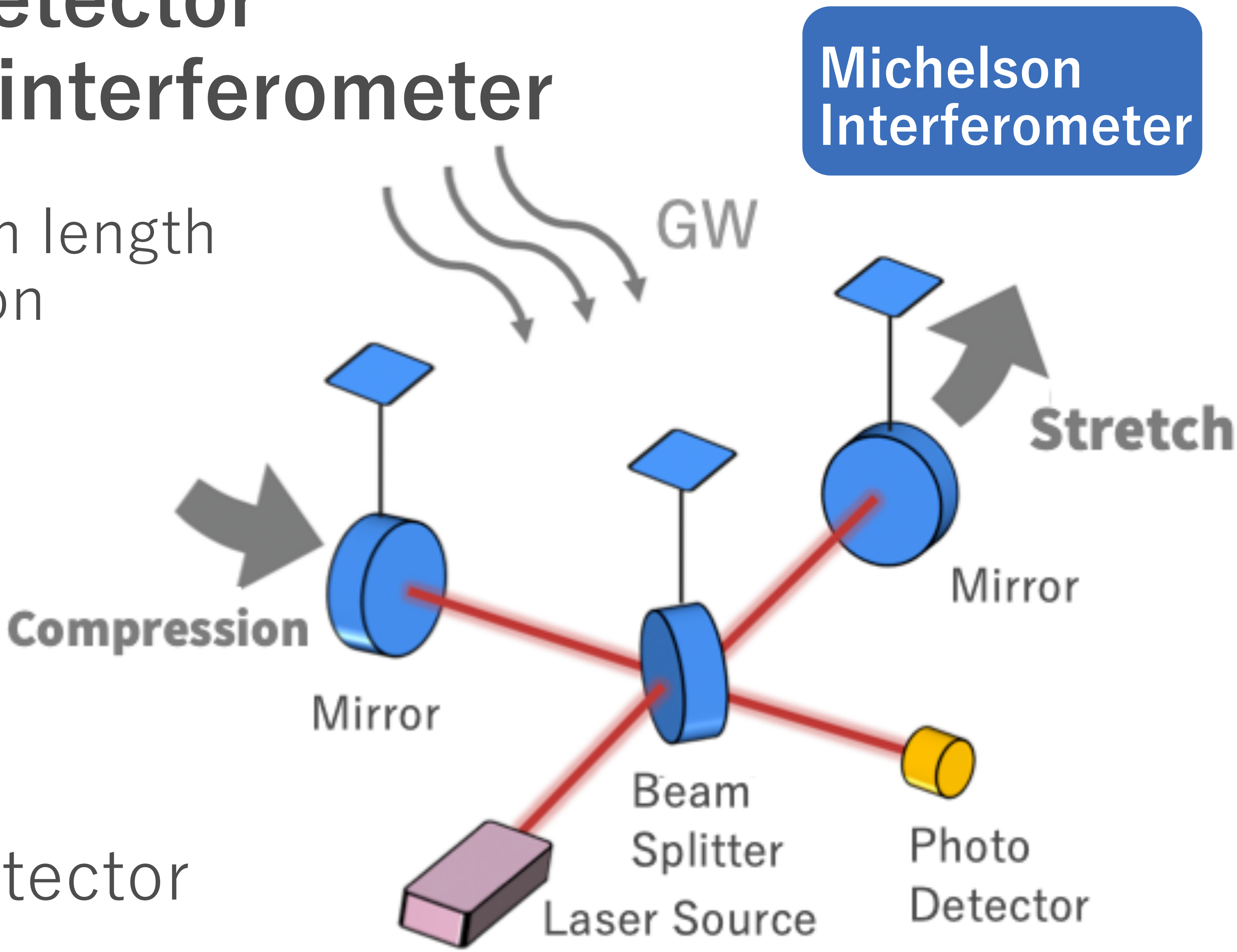
: Differential changes in arm length due to tidal space distortion

↓

Brightness and darkness of the interference light changes

↓

Detected by a photodetector

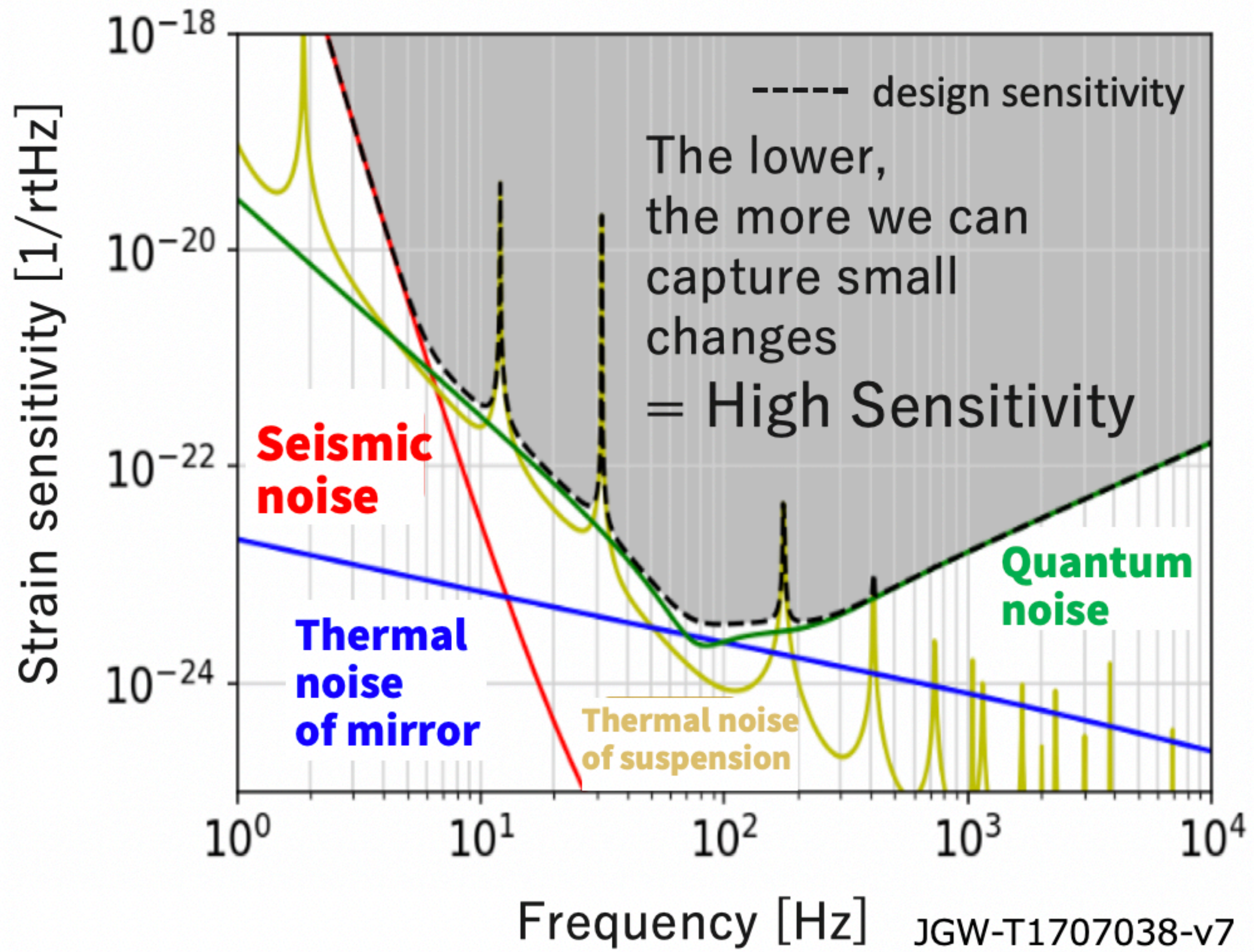


Noise in GW detector

Various Noise Source

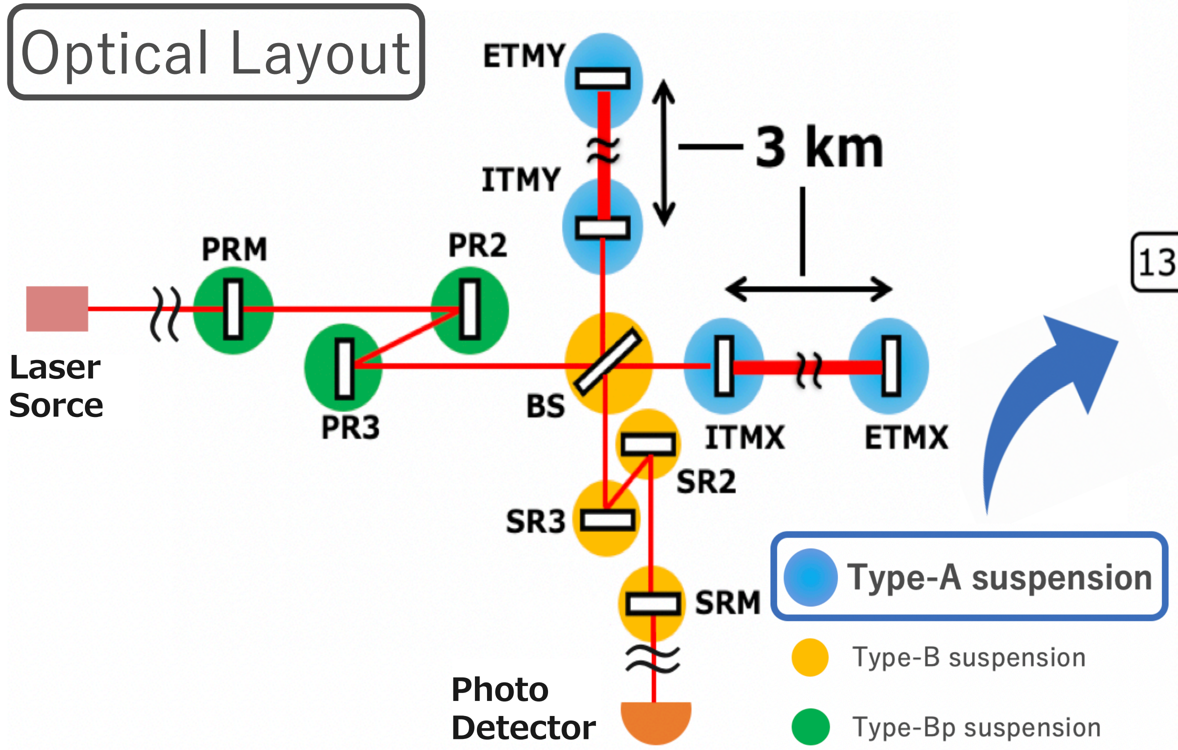
Length variation due to GW is very small, so detectors are limited in sensitivity by various noises

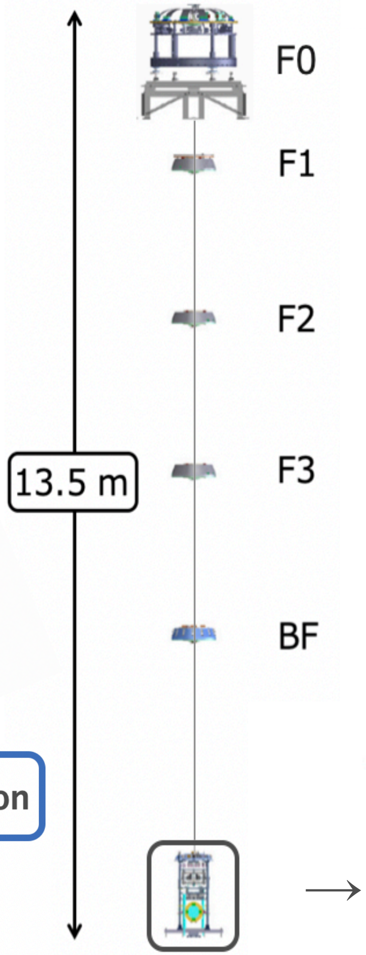
- **Seismic noise**
  : small ground vibration
- **Thermal noise**
  : thermal vibration of atoms which make up mirrors and suspension wires
- **Quantum noise**
  : quantum mechanical fluctuations in laser light



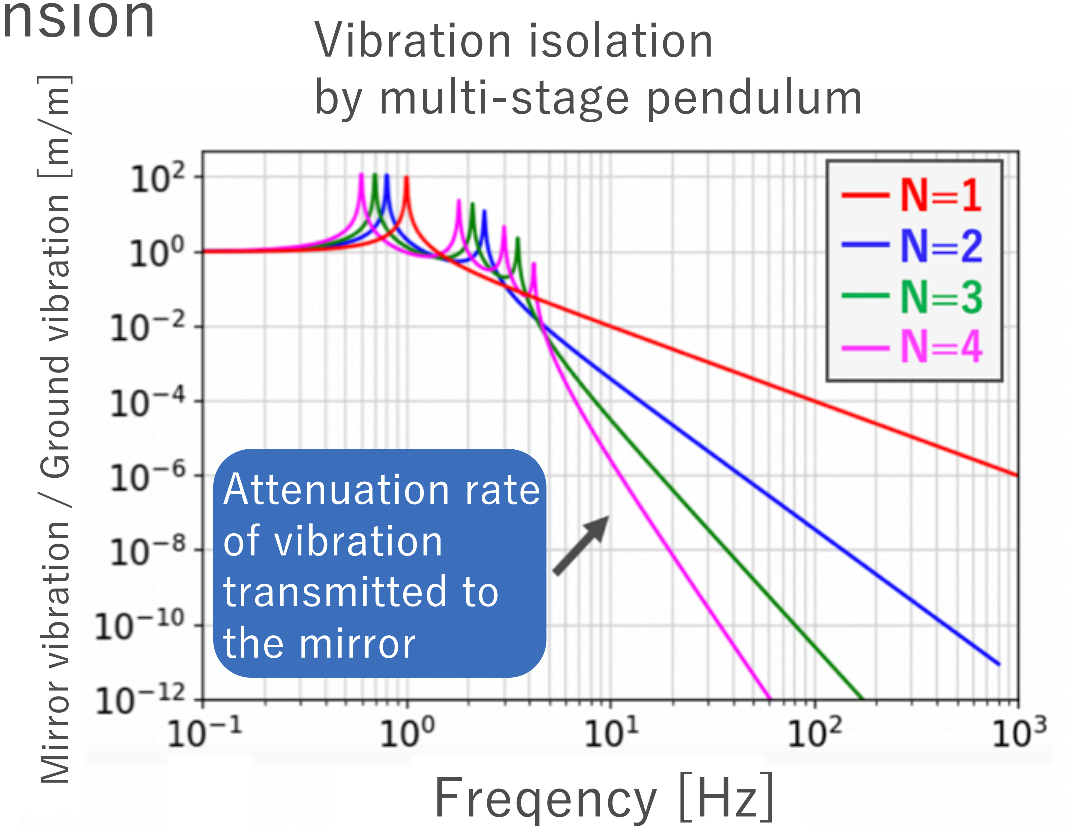
KAGRA (GW detector with interferometer @Kamioka, Hida, Gifu)

- Under ground and multi-stage pendulum suspension
  → Seismic noise redction
- Cool the mirror to 20 K
  → Thermal noise redction



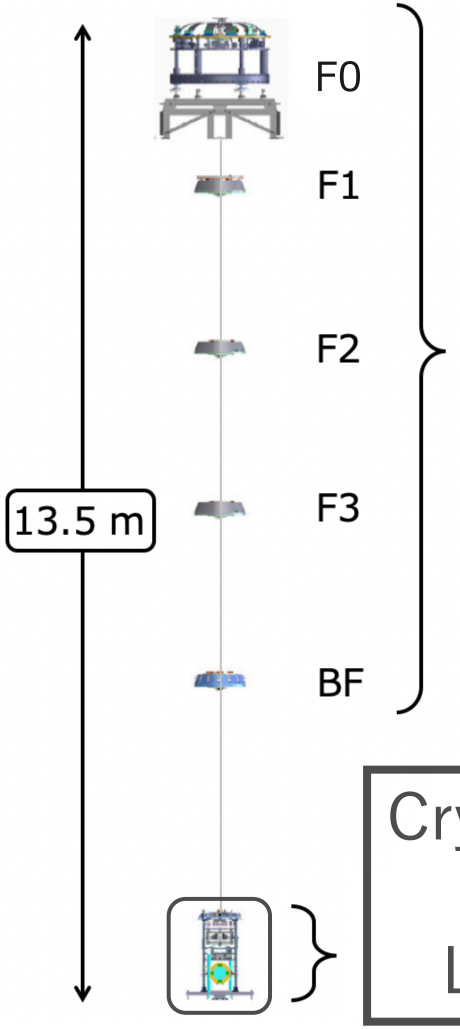


→ Cryogenic Payload



Cryogenic Suspension

Type-A suspension

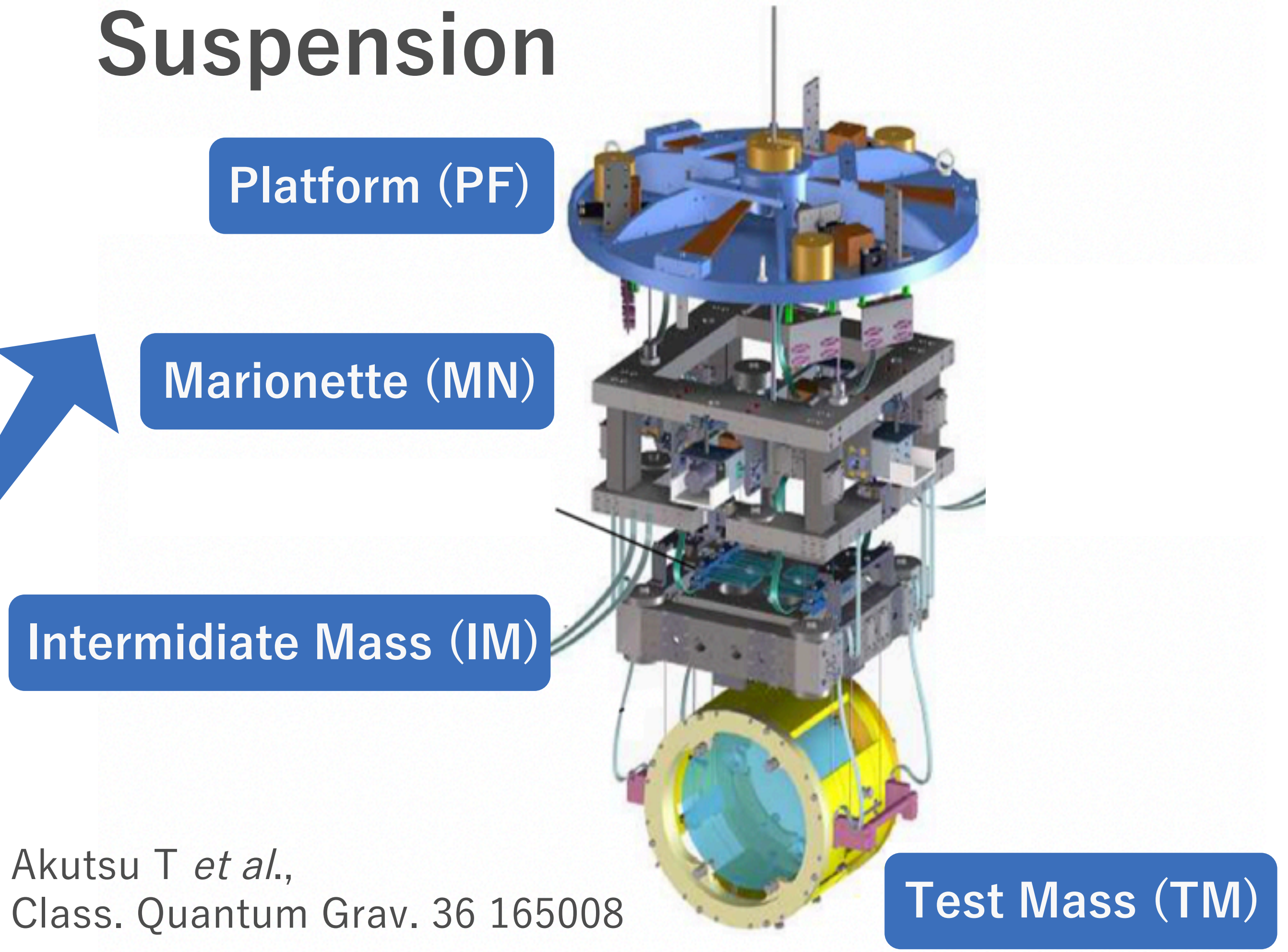


Tower
(Higher 5 stages)
Room Temperature

* System for
low frequency ~ 1Hz

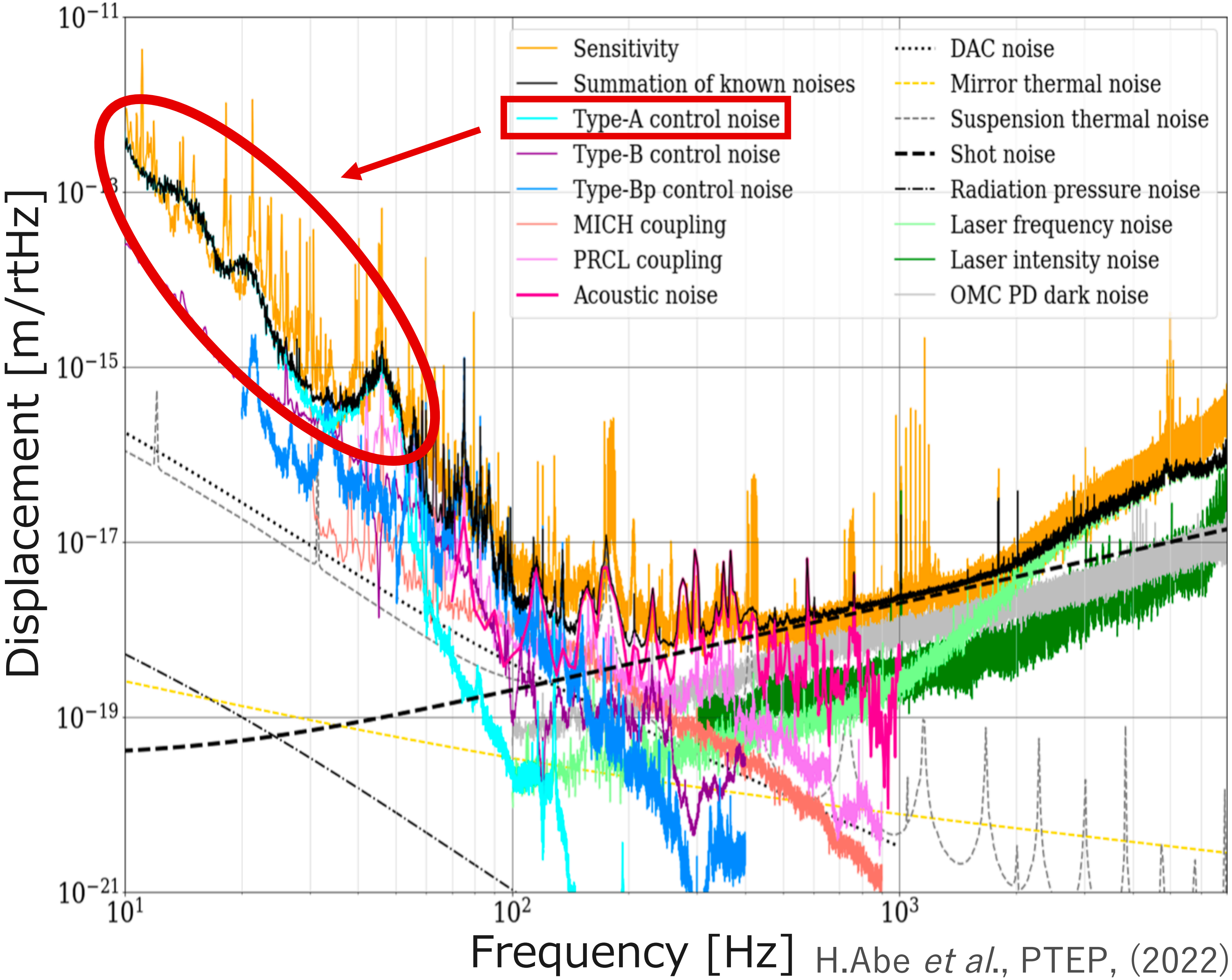
Cryogenic Suspension
(Lower 4 stages)
Low Temperature

Cryogenic Suspension



Akutsu T *et al.*,
Class. Quantum Grav. 36 165008

Problem ― Control Noise ―



H.Abe *et al.*, PTEP, (2022)

Cryogenic suspension

Need to control position and posture to minimize disturbance effects (low frequency below 10 Hz)

The more the disturbance is suppressed, the more the sensor noise is mixed in and shakes the mirror (observation bandwidth above 10 Hz)

＝Control Noise

Problem

In the last observation, control noise for cryogenic suspension limited the sensitivity around 10~50 Hz (circled in red in the left figure)

Control Noise Reduction

Solution： Switching control based on interferometer phase*

＊Several steps must be taken before the interferometer can be moved to the observation phase

Observation-Ready Phase

We want to control the position and posture of the mirror to make it observable

Control focused on suppression of disturbances

The last observation was made with this control

Switching Control

Observation Phase

We want to observe for long periods of time with stability and low noise

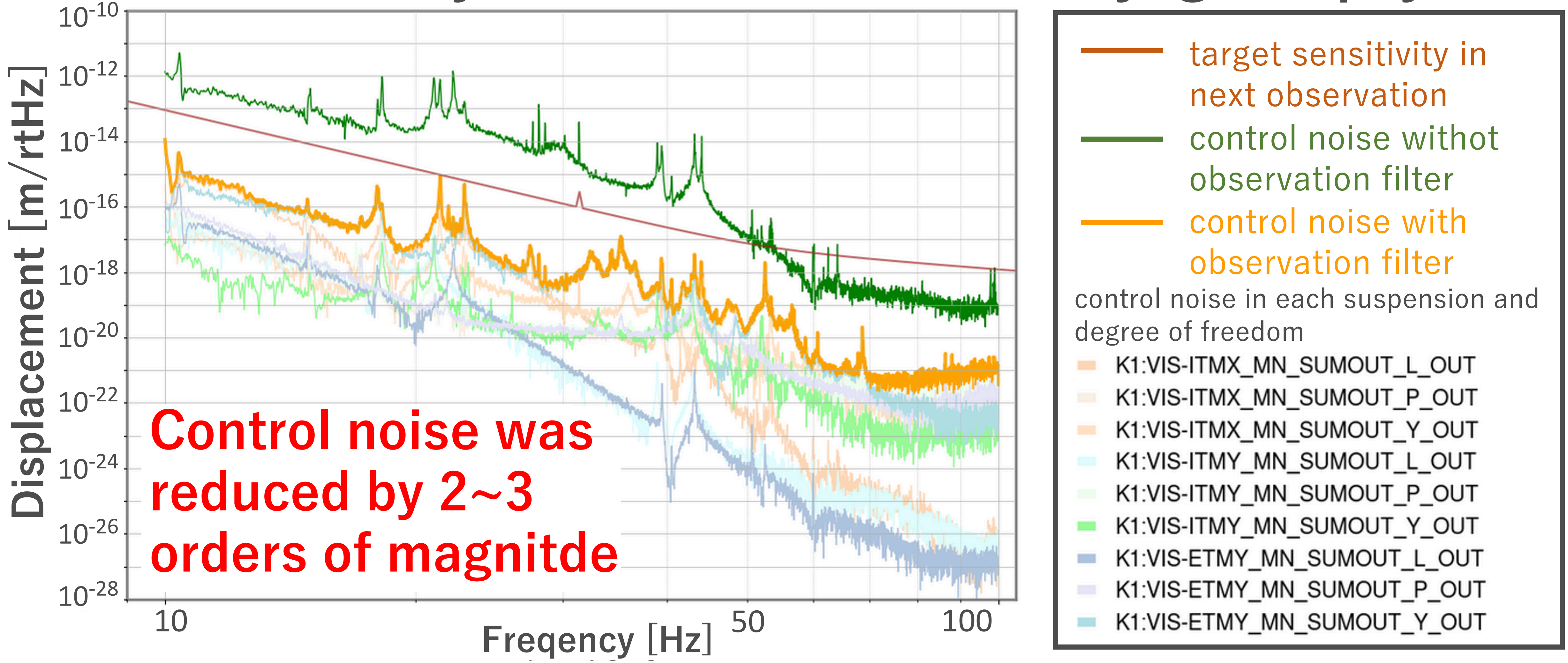
Control focused on low noise and stable operation while suppress disturbance necessary bare minimum

We designed such control

Observation filter (Digital control filter)

Result

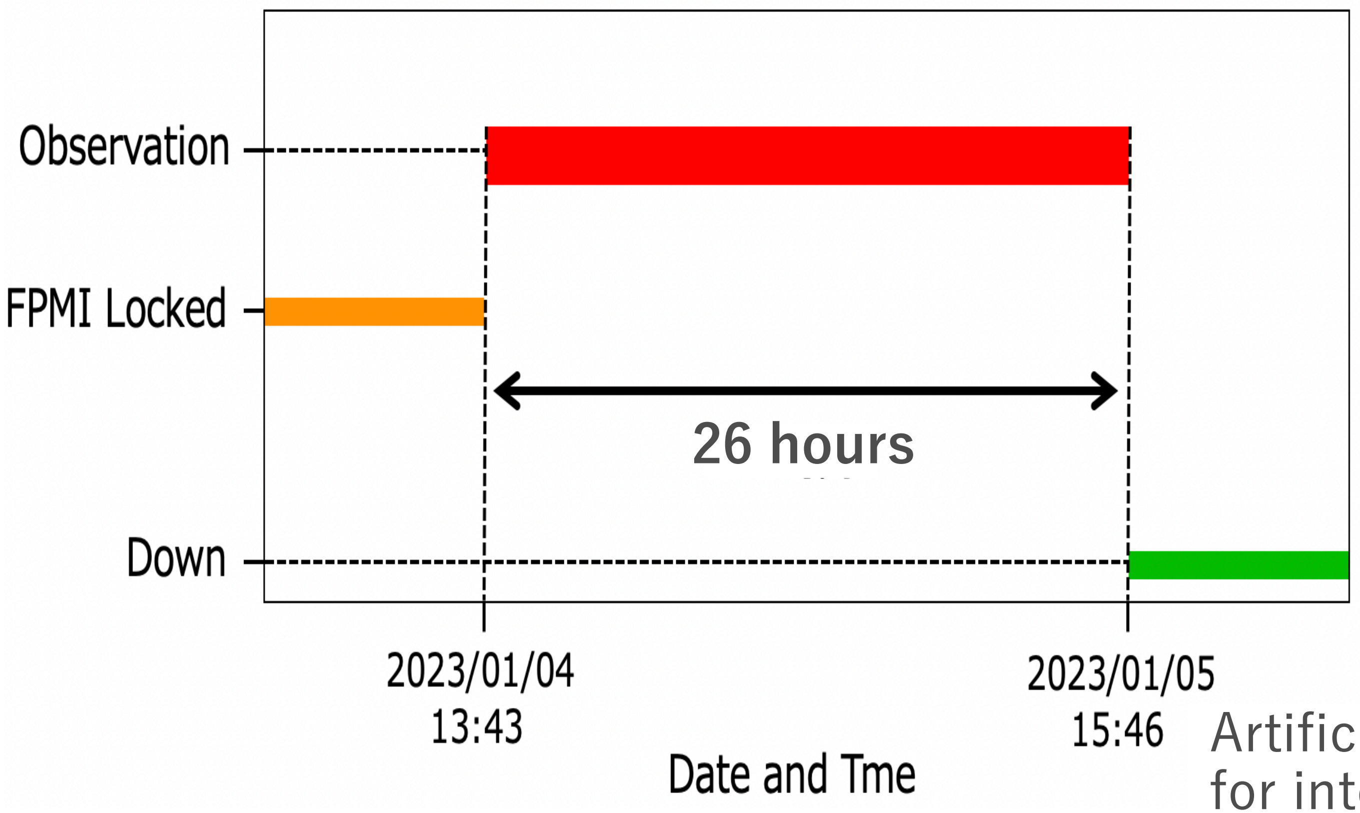
Control noise reduction by Observation filter for cryogenic payload



Result

Control stability with Observation filter

It is necessary to investigate the long-term stability of the control in all cryogenic suspensions with the new control filter



Artificially made Down state for interferometer work

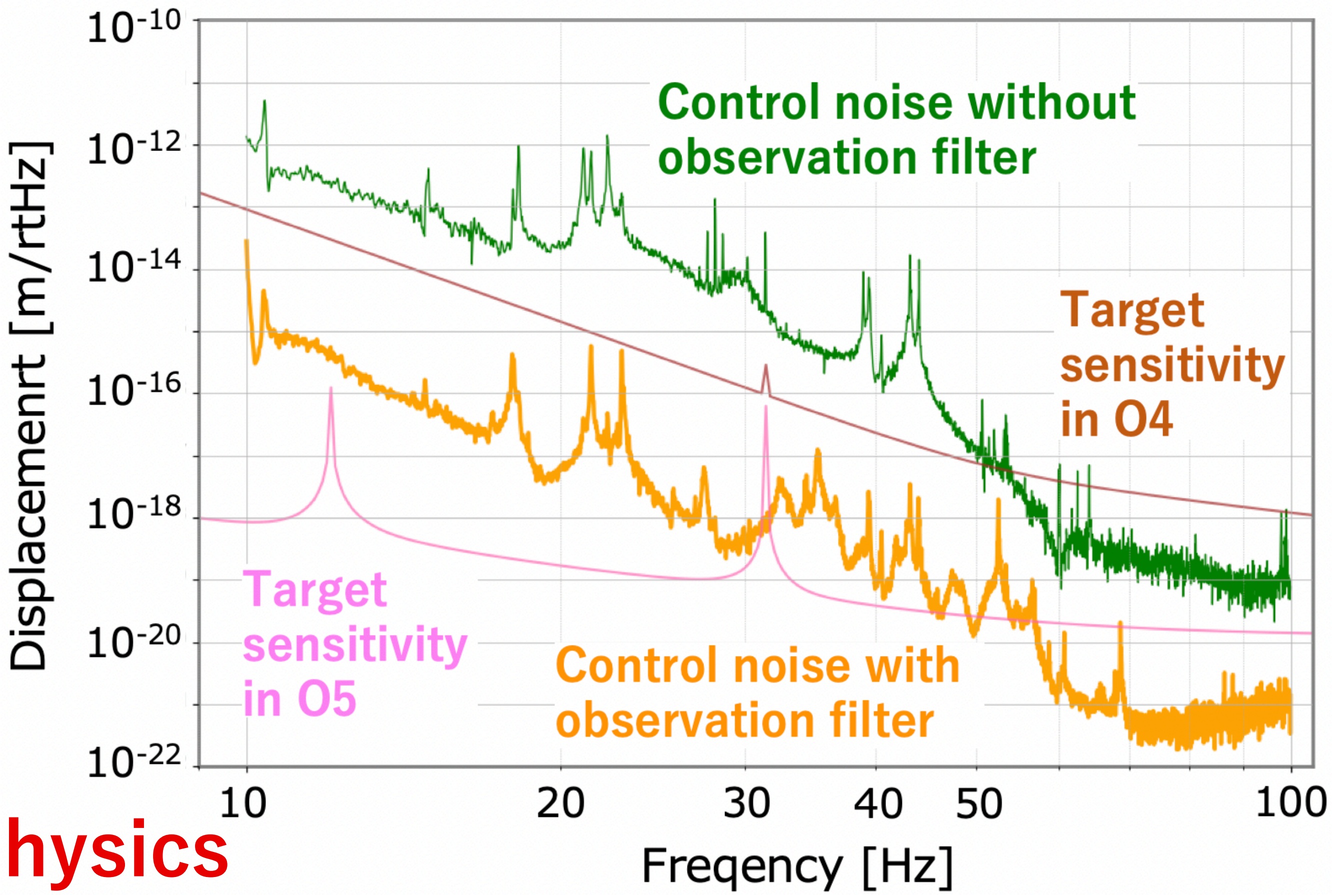
← The interferometer was locked with Observation filter (Observation in the figure), and it was confirmed that **we can operate the interferometer stably for 26 hours**

Conclusion and Future Work

Conclusion

With my newly designed control, the control noise was reduced by 2~3 orders of magnitude while maintaining stable operation of the interferometer for a long time

Target sensitivity for KAGRA's next observation is cleared (at low frequency)



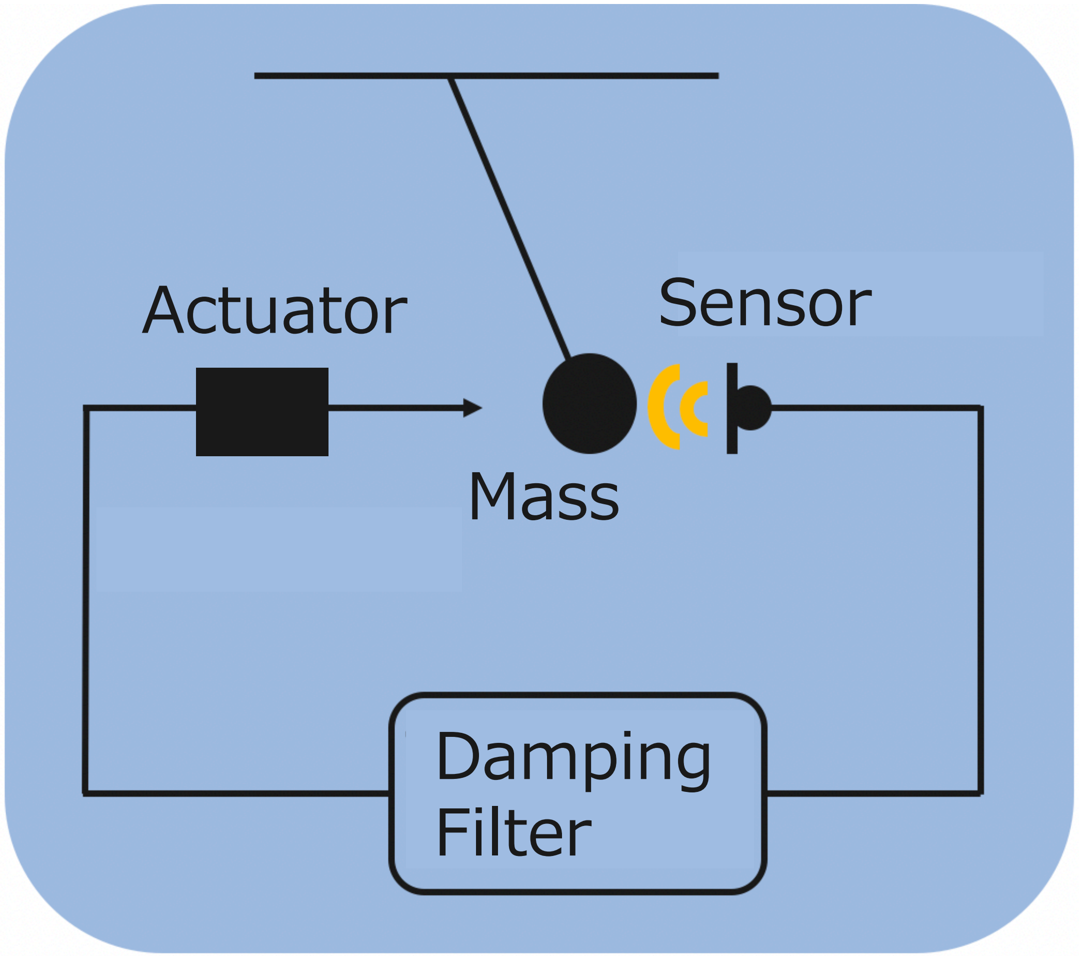
Future Work

Developing a new control method and reducing the control noise to achieve the final target sensitivity of KAGRA → **Contribution to GW physics**

Appendix

What is Damping Control?

Damping Control・・・One of the feed-back controls



Disturbance to the suspension system

↓

Sensors locally detect suspension motion

↓

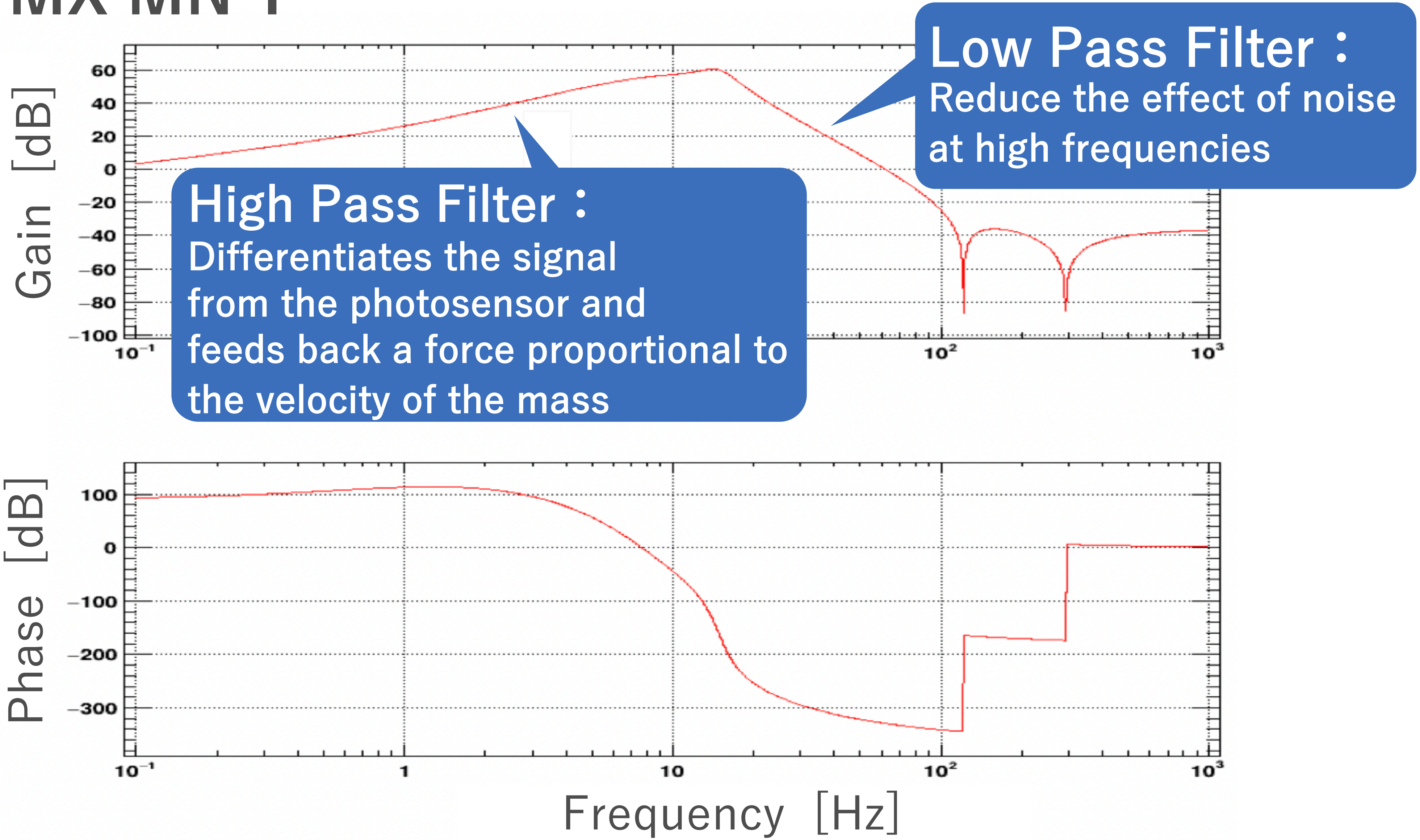
Sends signals to the actuator through damping filter

↓

Applies a force proportional to the velocity of the mass and suppresses shaking caused by external disturbances

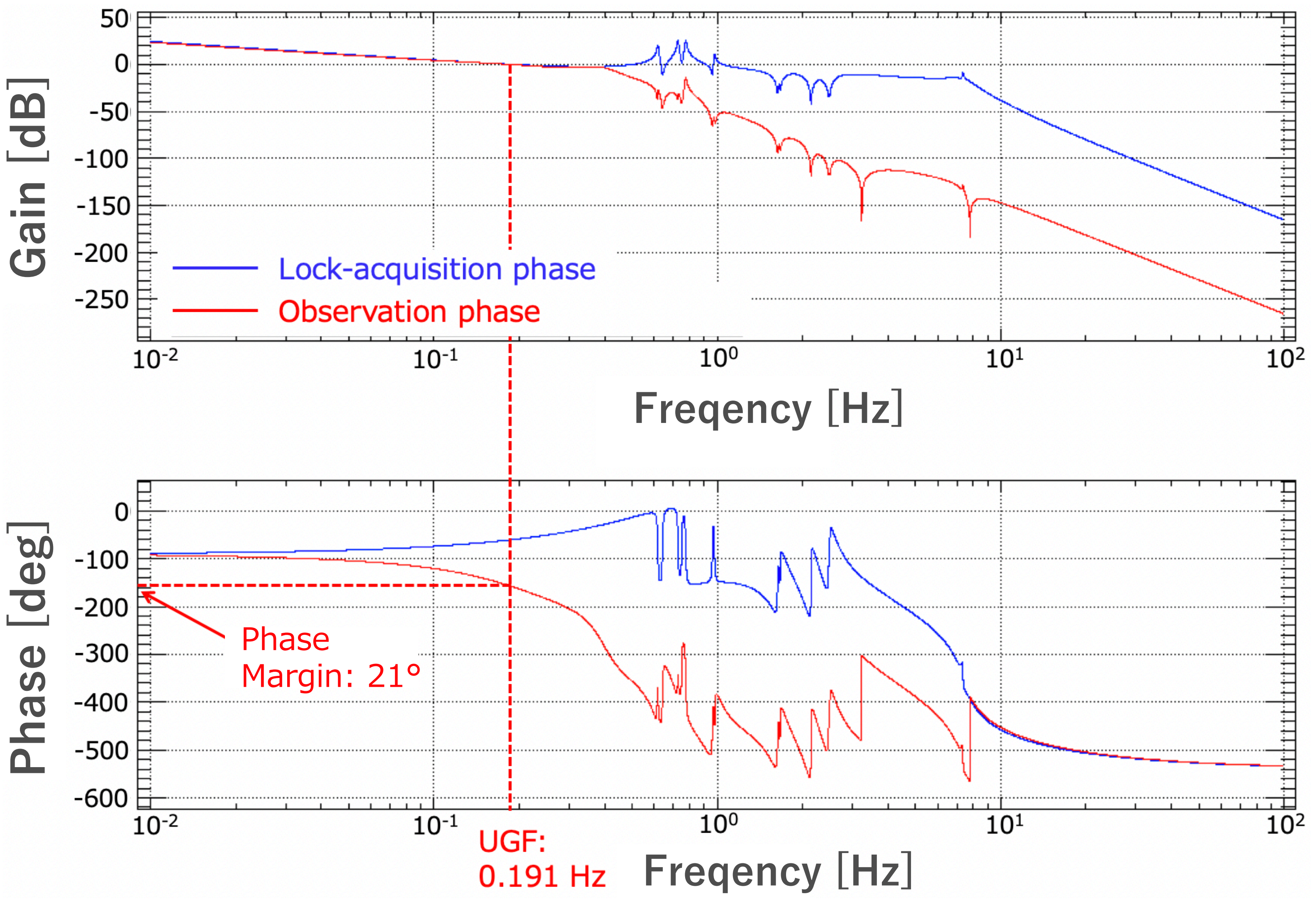
Example of Damping Filter

e.g. ETMX MN Y



Observation Filter

e.g. ITMX MN P Open Loop Transfer Function



Turn off damping control using a photo sensor

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Controlled using optical lever

Reduce gain from lower frequencies than conventional gain reduction with elliptical low-pass filter

Implemented in cryogenic suspension other than ETMX

Future Control (idea)

Modal damping

Conventional control

Feedback control is applied to each stage

Sensor・Actuator Basis

Modal damping

Multi-stage feedback
to match the shape of the **vibration mode**

Modal Decomposition

$$\left(\text{Modal coordinate signal}\right) = E^{-1}\, S \left(\text{Sensor signal}\right)$$

S : Transformation matrix
from the sensor basis
to the physical coordinate system
at each stage

Mode Basis

Future Control (idea)

Advantage and Disadvantage

Conventional control

- ○ Easy to design
- ○ It has worked so far
- × Must be designed for each DoFs
- × Different people uses different design methods

Modal damping

- ○ We can handle multiple DoFs
- ○ Systematic optimization by more accurate simulation is possible
- × Control performance depends on modelling accuracy
- × High accuracy modeling is difficult