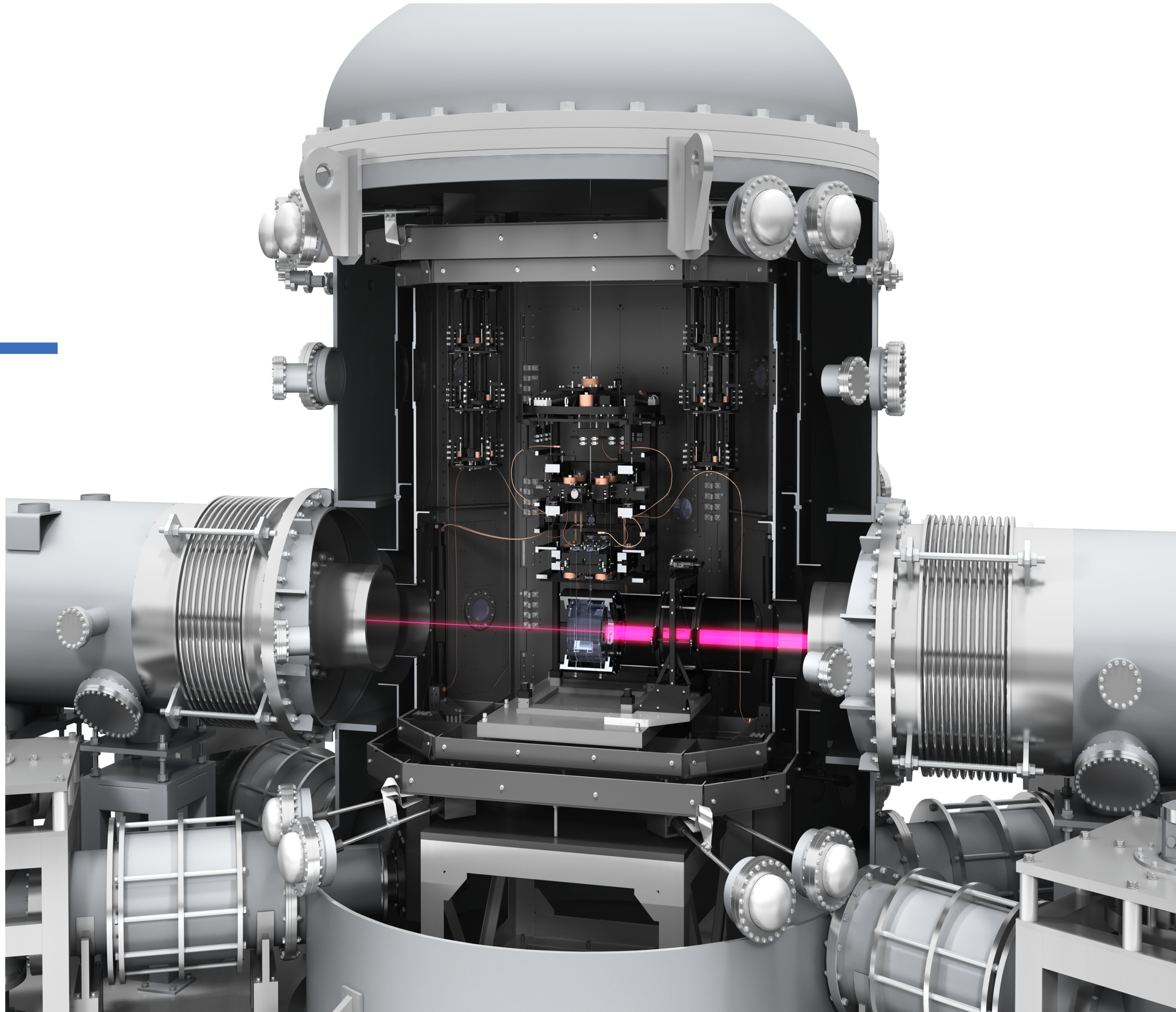
Cryogenics and Cryogenic Payload in KAGRA
- for O4 and future -

Masahide TAMAKI
on behalf of
KAGRA Collaboration

Institute for Cosmic Ray Research

KIW10@NTHU Taiwan 29 May 2023



Introduction

Introduction

<u>KAGRA</u> : 2.5th generation GW Telescope in Japan

Two unique features: **Underground Site** & **Cryogenic**

Quiet Site

For ground vibration reduction

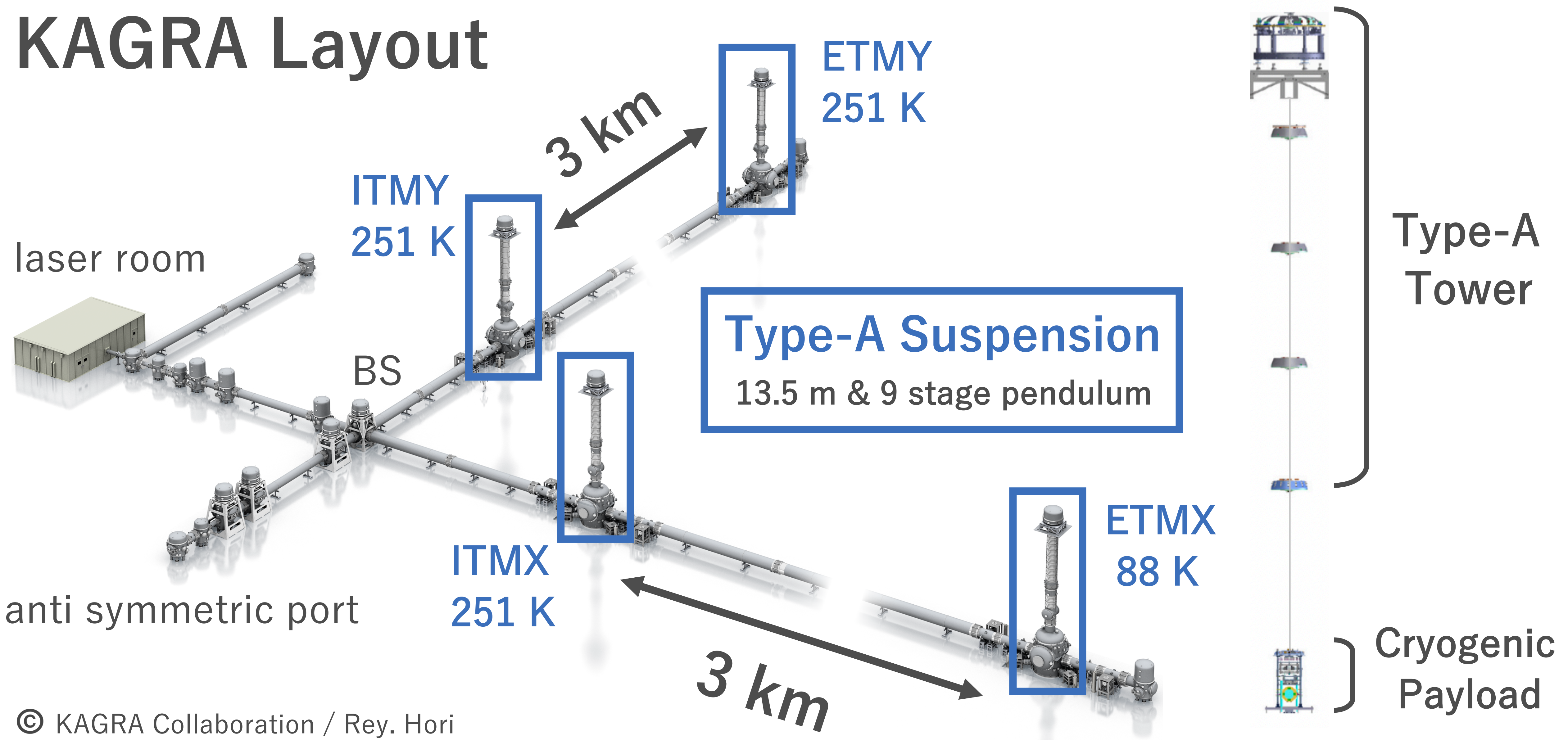
・Ground vibration are 1-2 orders of magnitude lower than ground level

@ 20 K

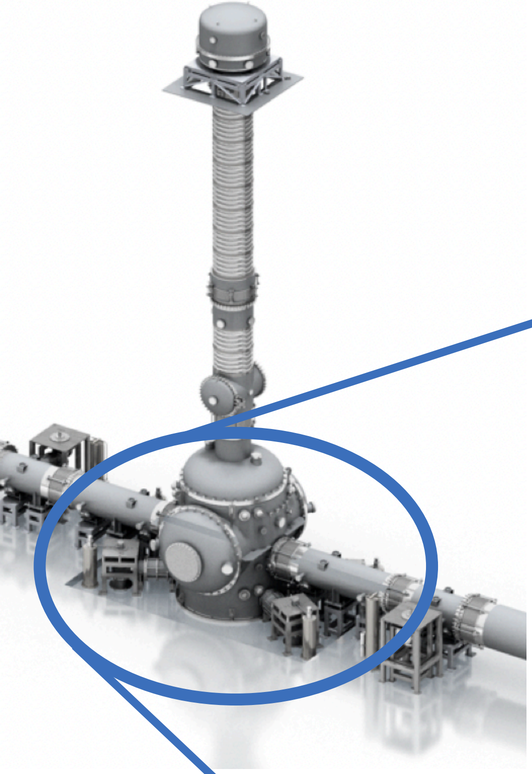
For thermal noise reduction

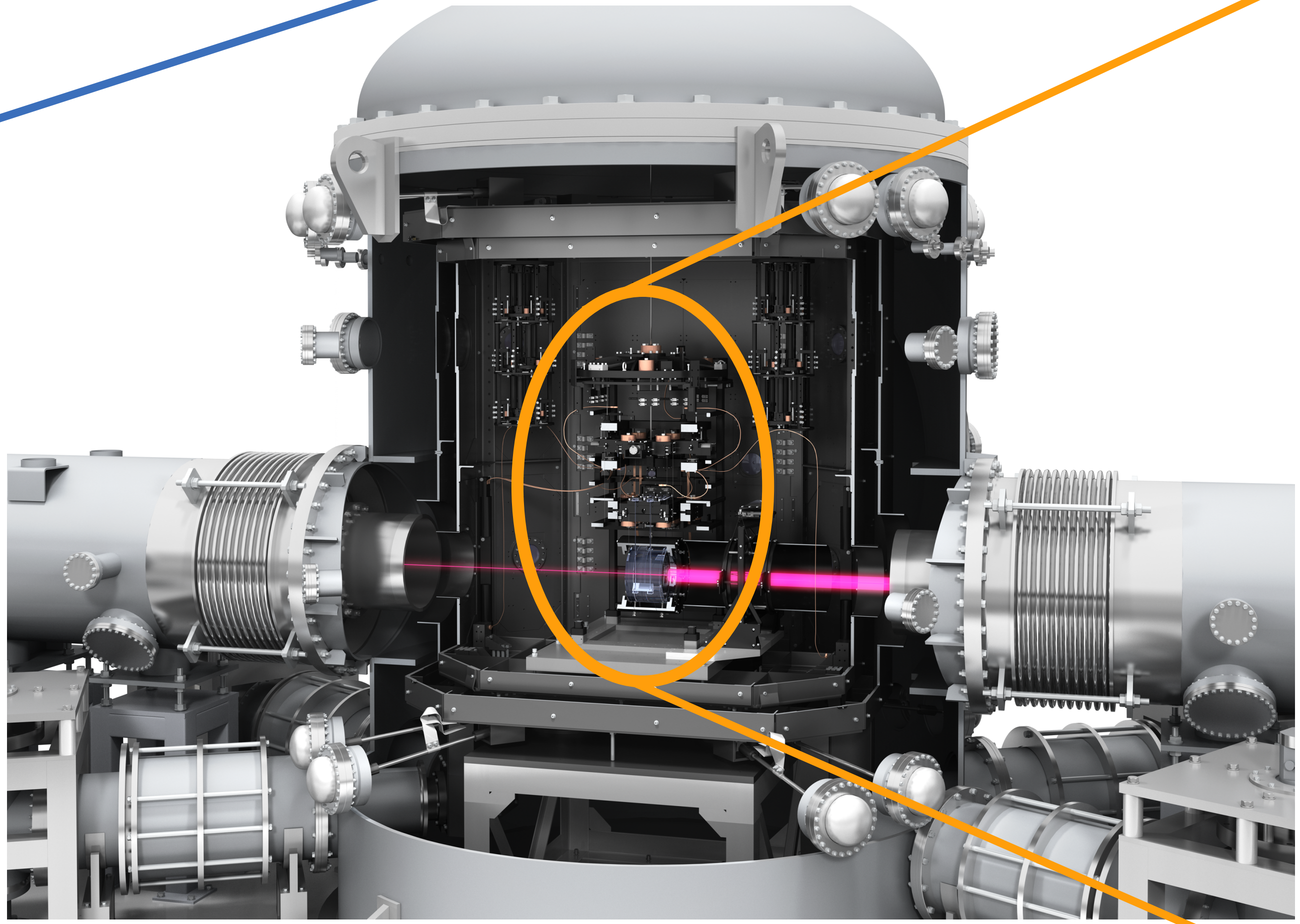
・Sapphire suspension
→ effective heat extraction & high Q

Sapphire Mirror Suspensions

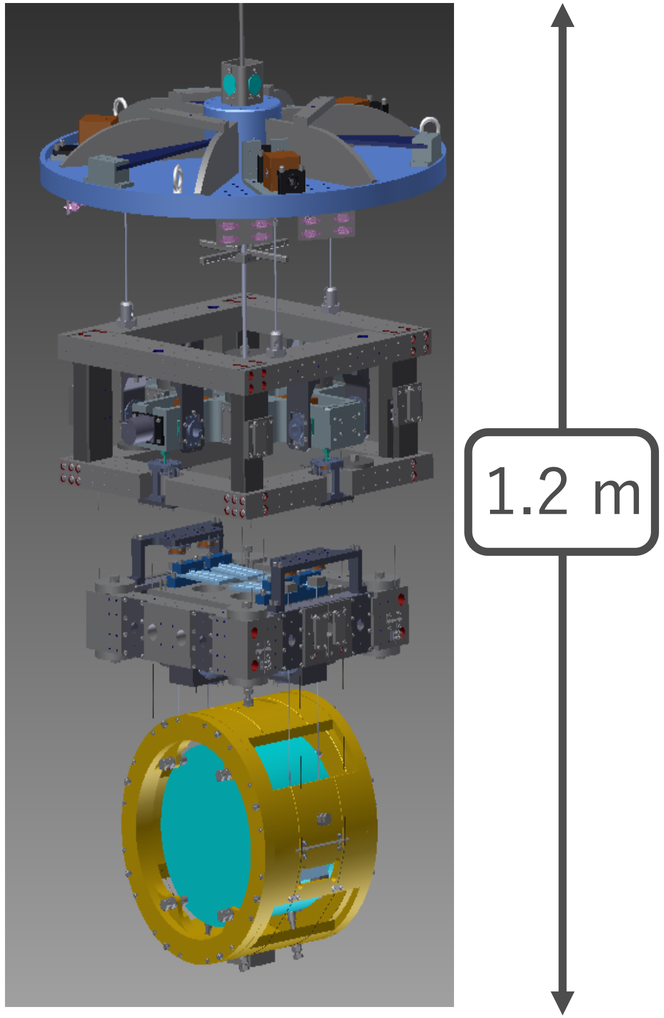


Cryostat & Cryogenic Payload



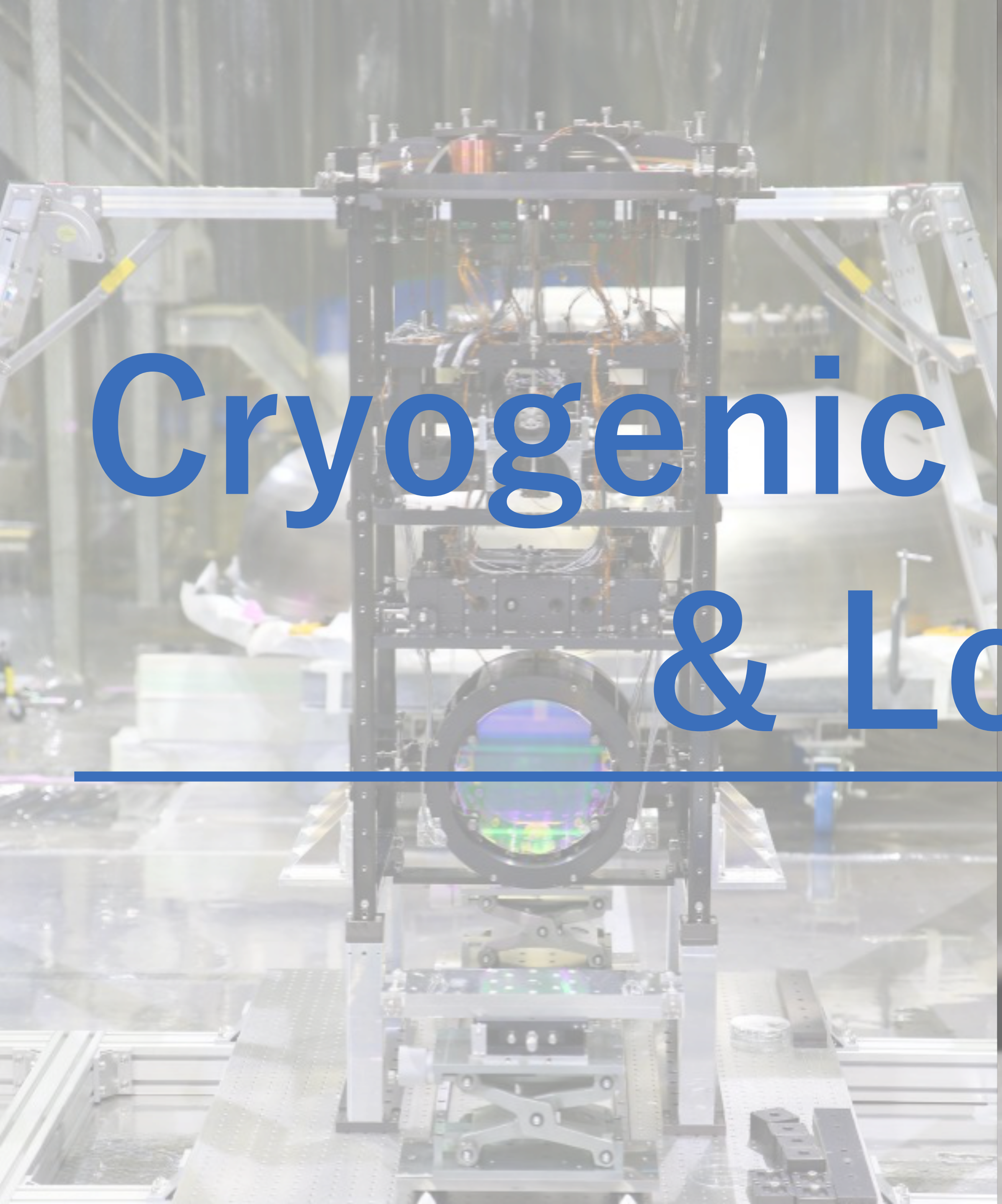


© KAGRA Collaboration / Rey. Hori

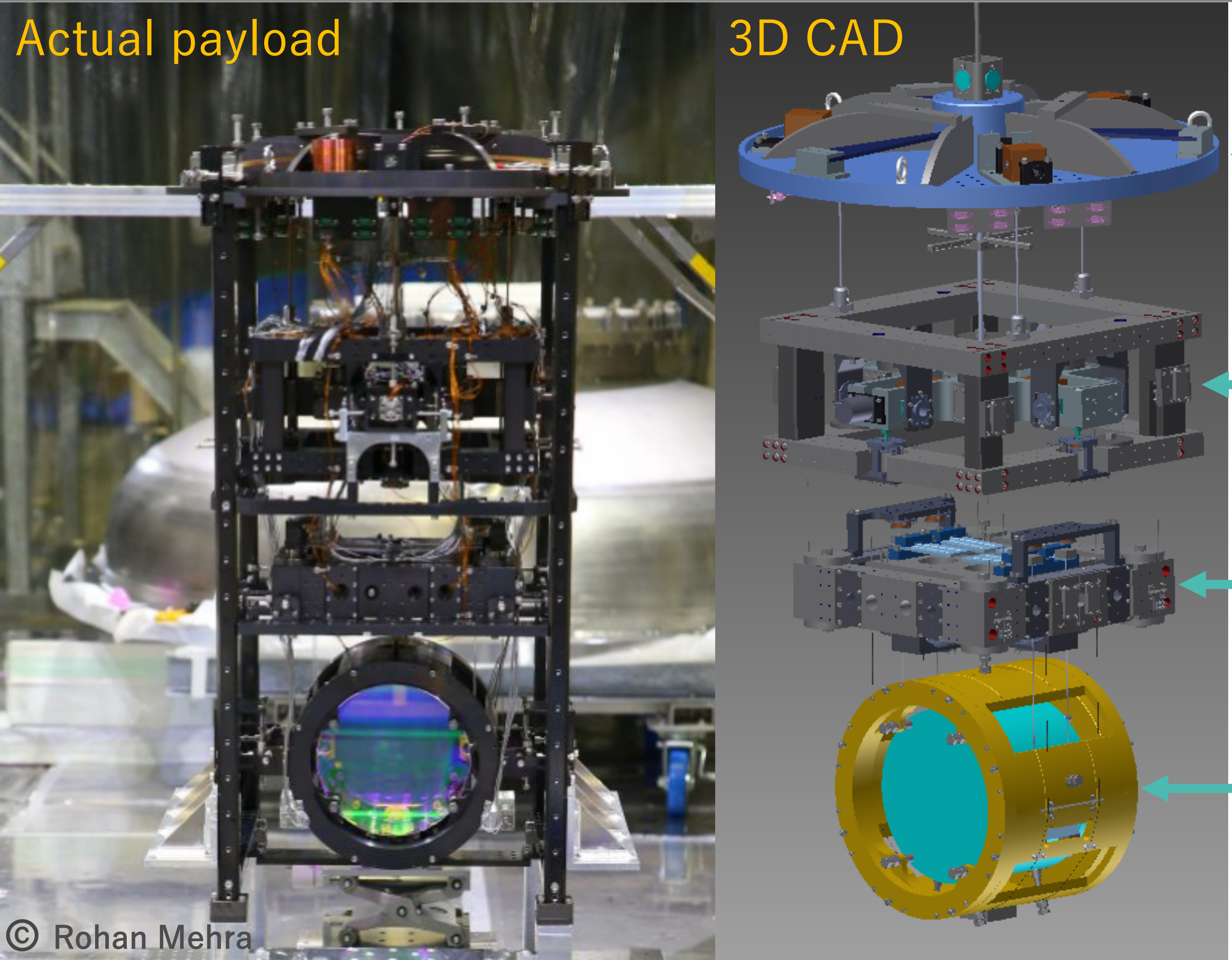


(T. Ushiba, *et. al.*, Class. Quantum, **38**, 085013, 2021)

Cryogenic Payload & Local Control



Cryogenic Payload Design



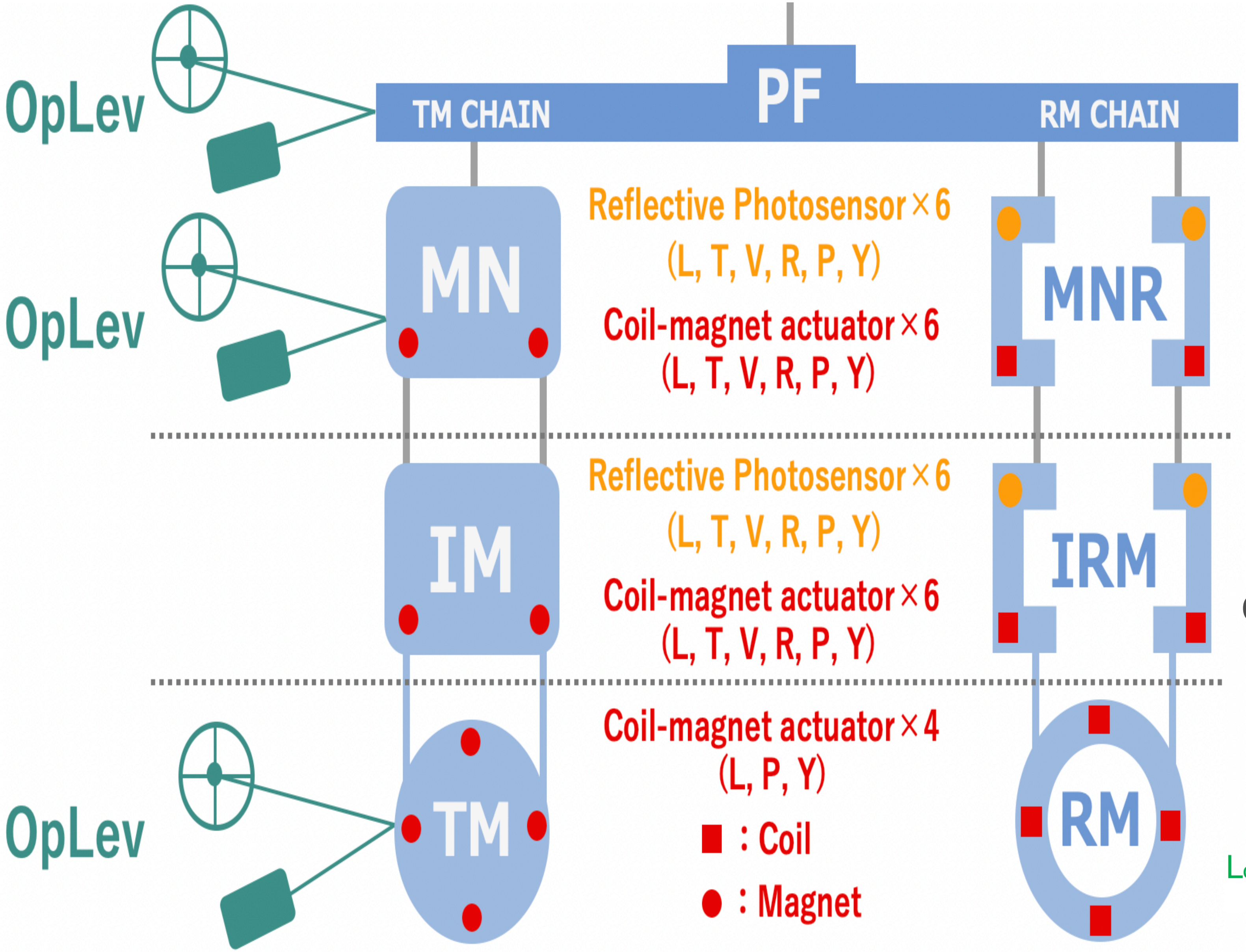
Platform (PF)

Marionette (MN) & Recoil mass

Intermediate mass (IM) & Recoil mass

Test mass (TM) & Recoil mass

Sensors & Actuators on Cryogenic Payload

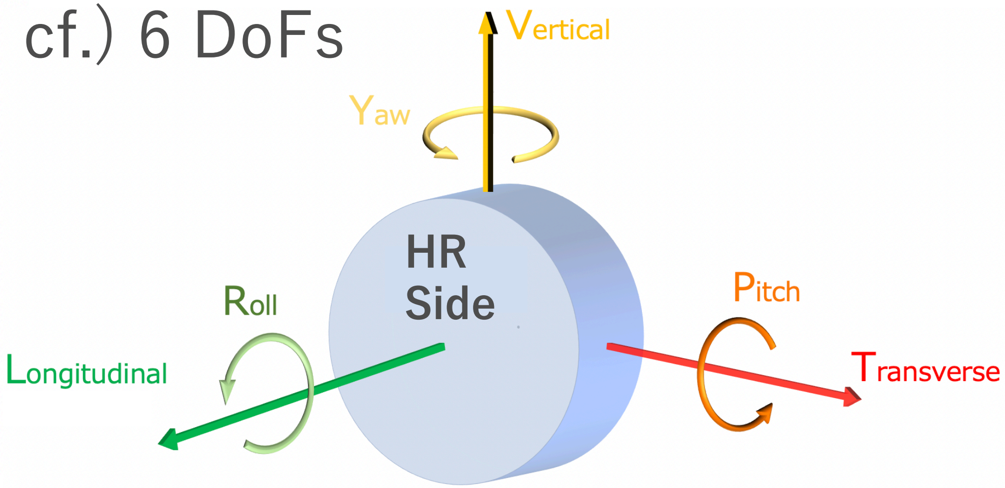


Reflective photosensor
→ Relative displacement of the mass and recoil mass

OpLev
→ Movement of the mass relative to the ground

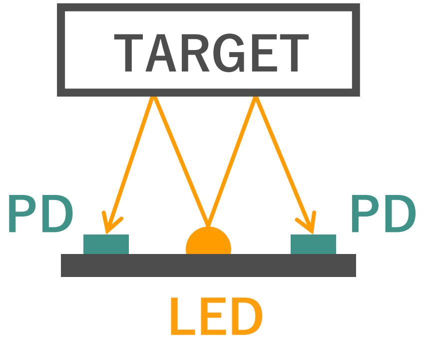
Coil-magnet actuator
→ Apply the force to the mass

cf.) 6 DoFs



Sensors

Reflective Photosensor



Wide dynamic range for use at cryogenic temperature

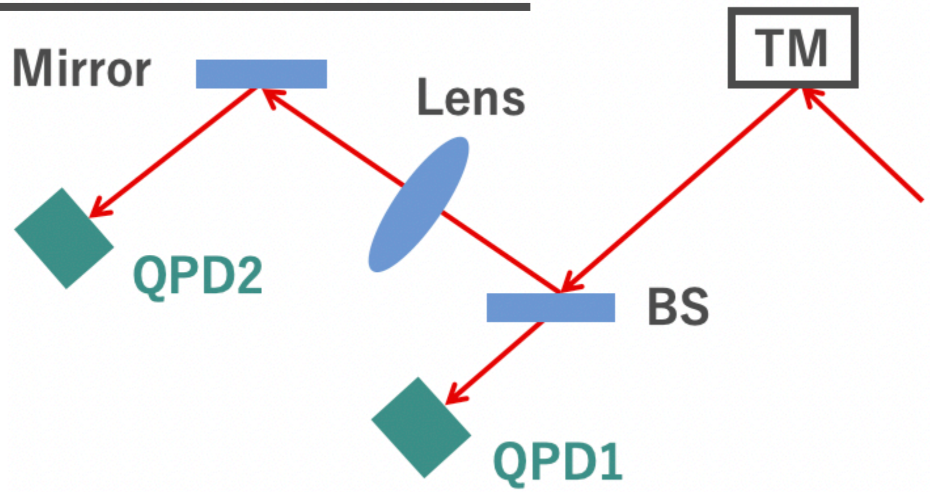
LED: InGaAsP
PD: InGaAs

Direct bandgap type for cryogenic operation

→ 2PDs are for the reduction of angular-to-lateral coupling

- Monitor the changes in relative distance as changes in light intensity

Optical Lever



Gouy phase telescopes in order to distinguish beam shift and tilt

- Monitor the suspension motion with respect to the ground
- Noise level at high frequency is much better than photosensor

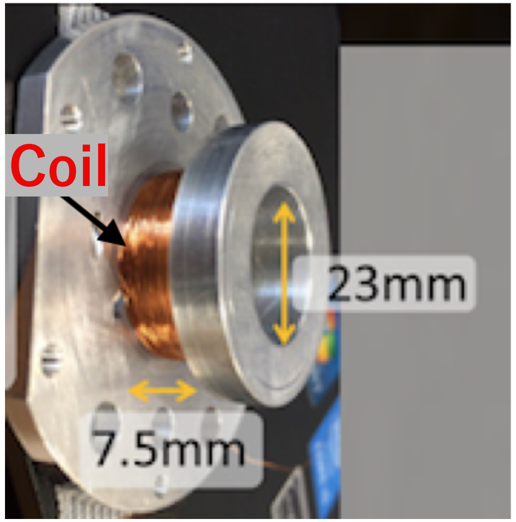
Coil-magnet actuator

Coil (RM chain) + SmCo magnet (TM chain)

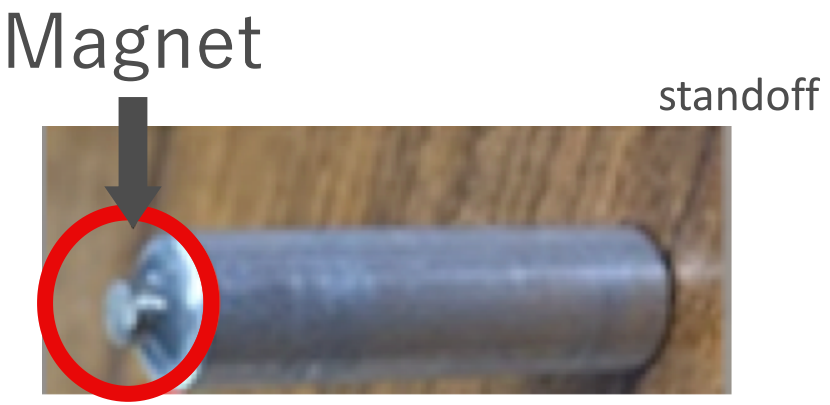
Coils are also vibration isolated

A magnetic field is generated by passing an electric current through the coil

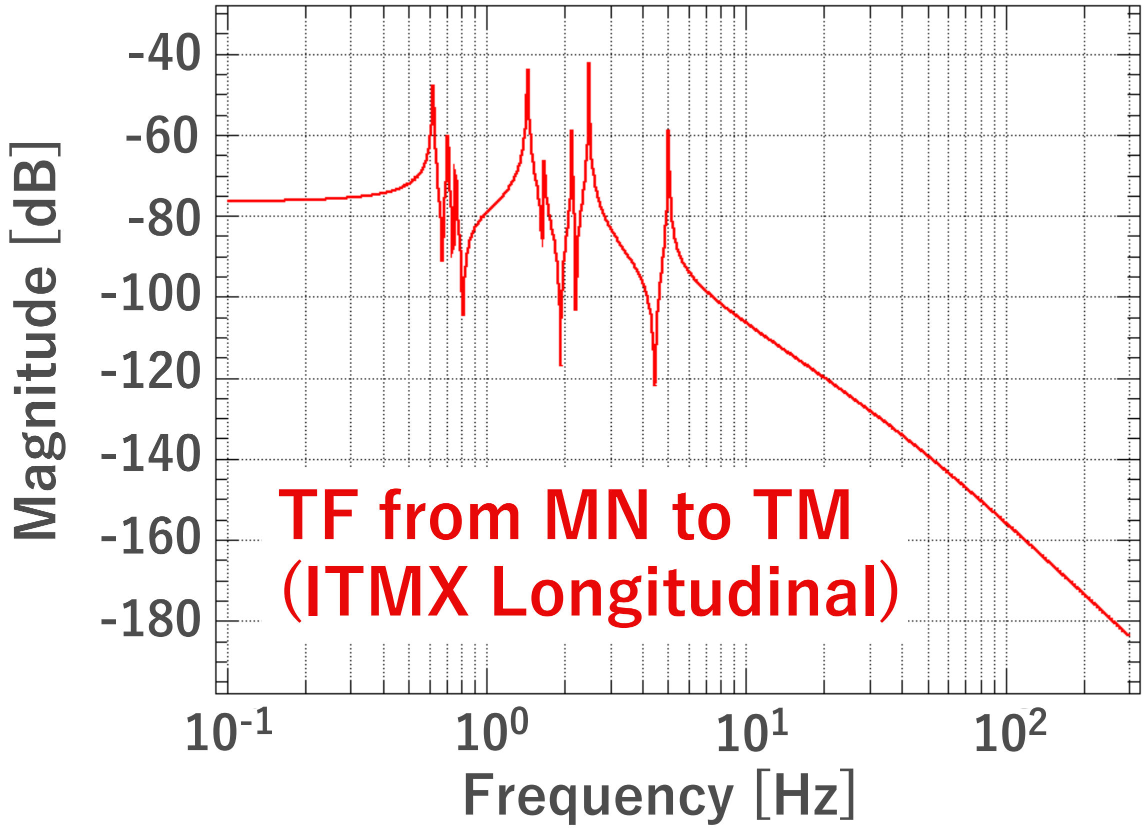
→ Apply the force to the magnet



Magnetization does not decrease significantly even at cryogenic temperatures

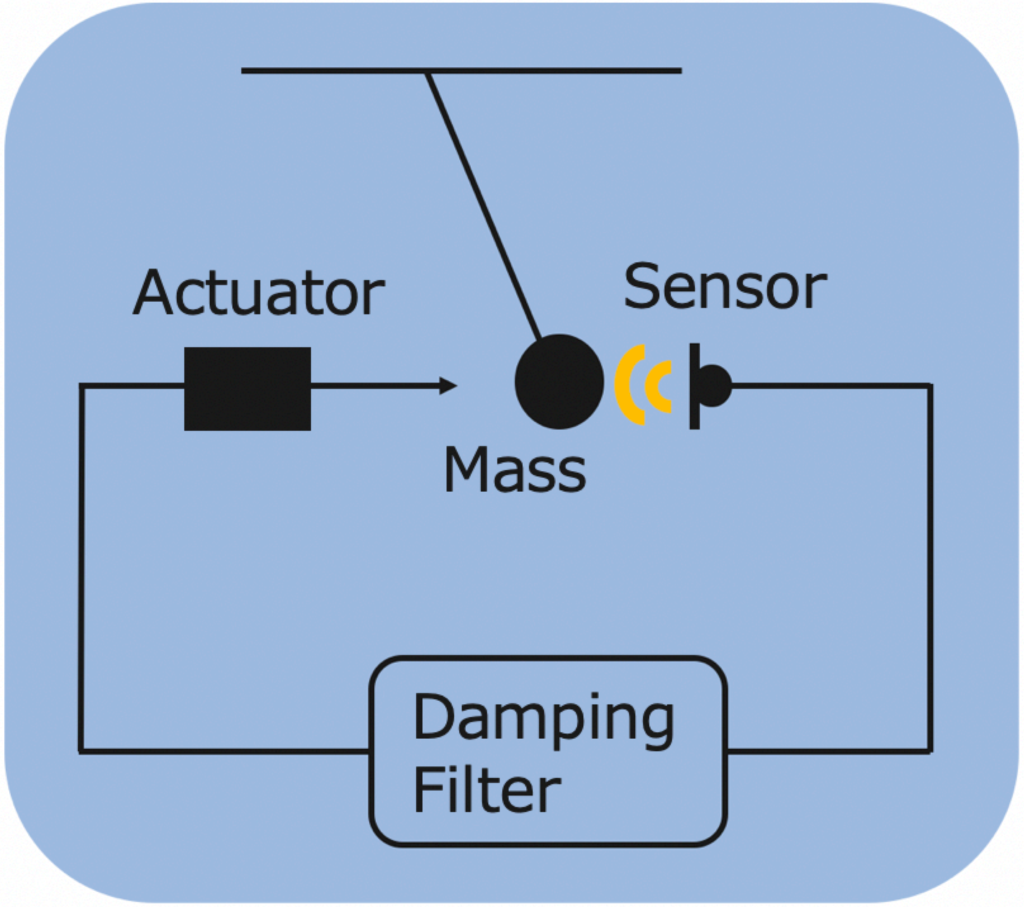


Local Control for Cryogenic Payload



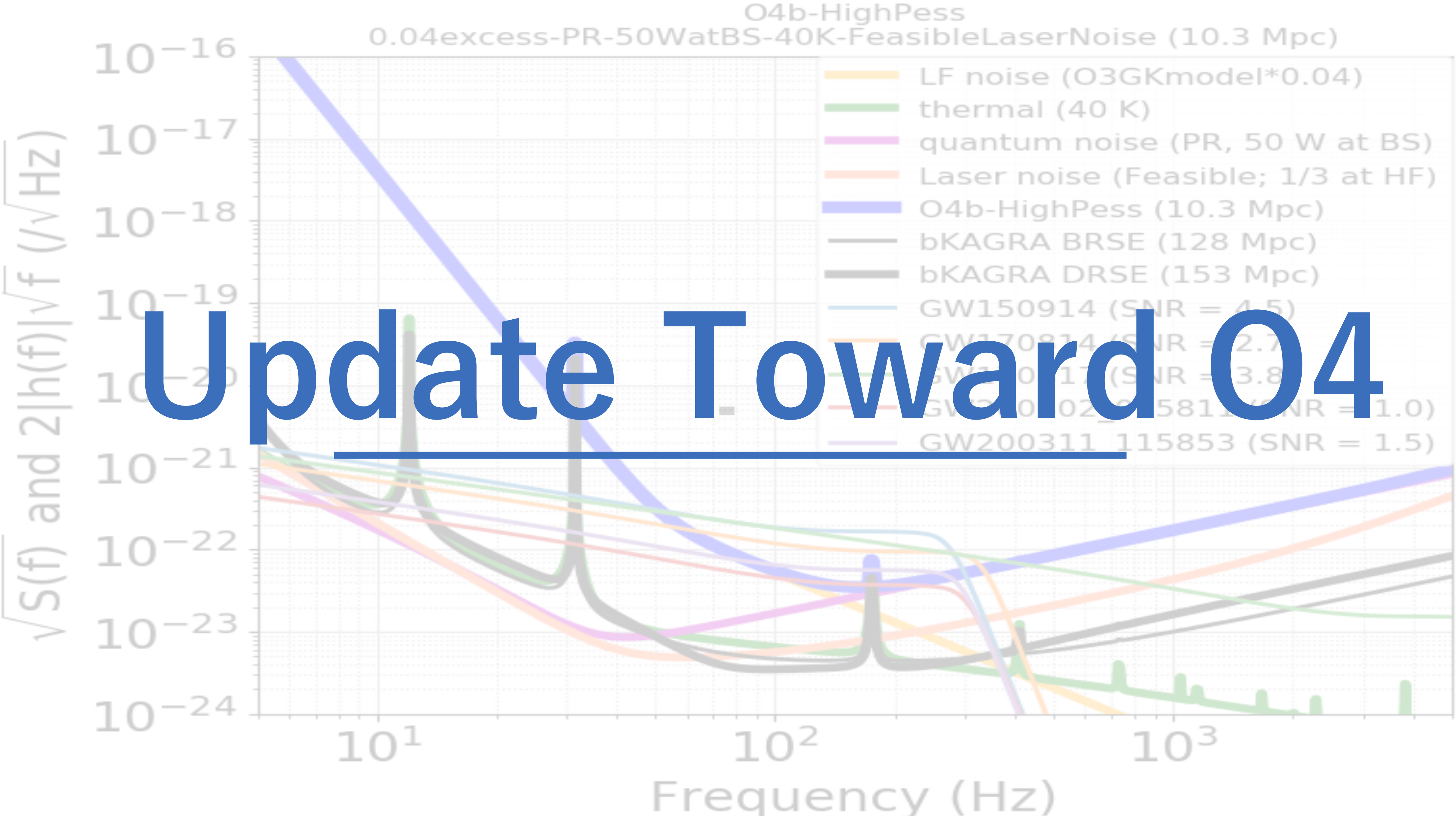
Vibrations transmitted to the mirror are increased at resonant frequencies

→ **Damping control**

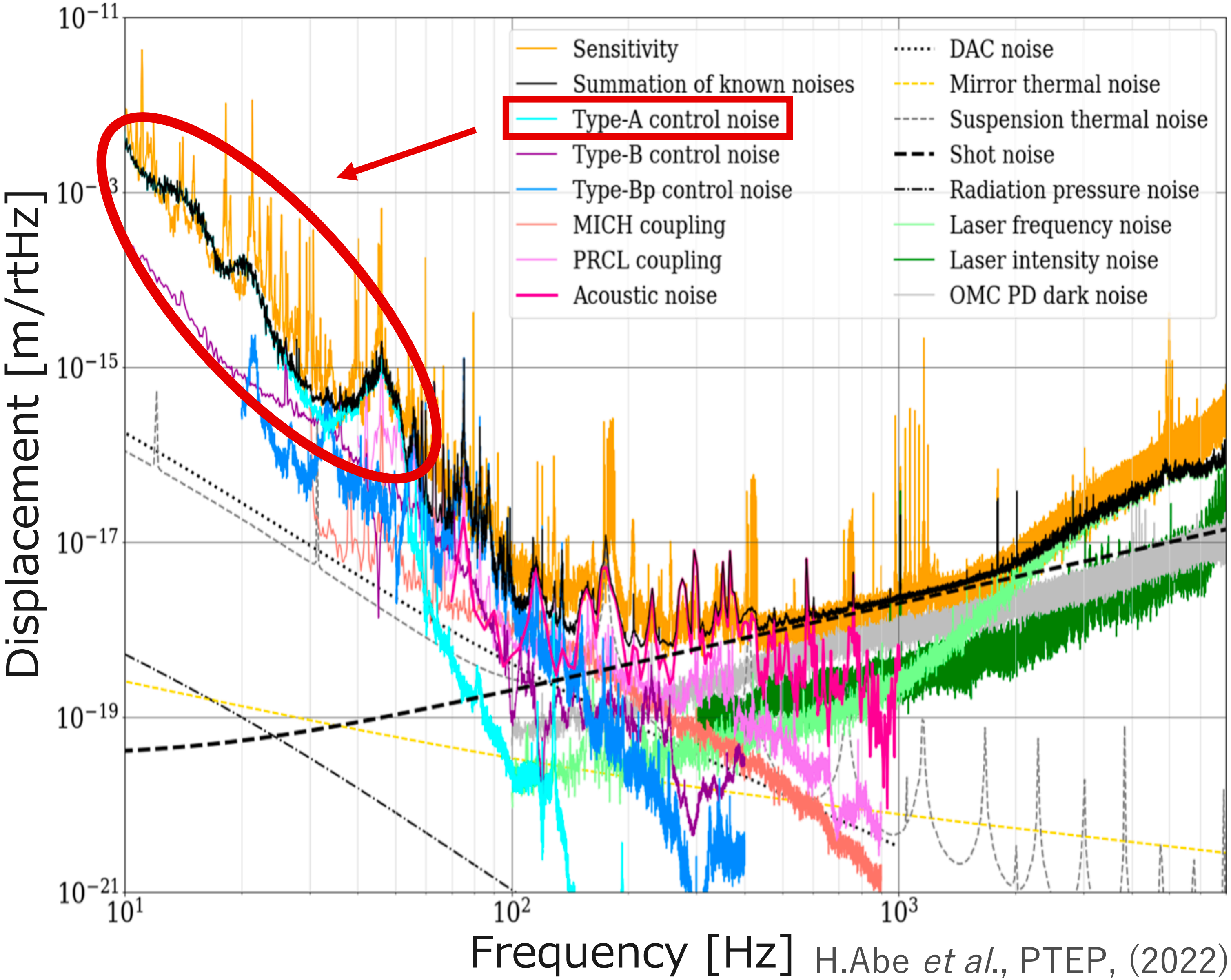


- Sensors detect disturbances
- Actuators apply feedback force

Update Toward O4



Control Noise in Cryogenic Suspension (O3GK)



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

Problem

Control Noise in cryogenic suspension limited the sensitivity around 10~50 Hz

The more we try to suppress disturbance, the more sensor noise is introduced

Solution

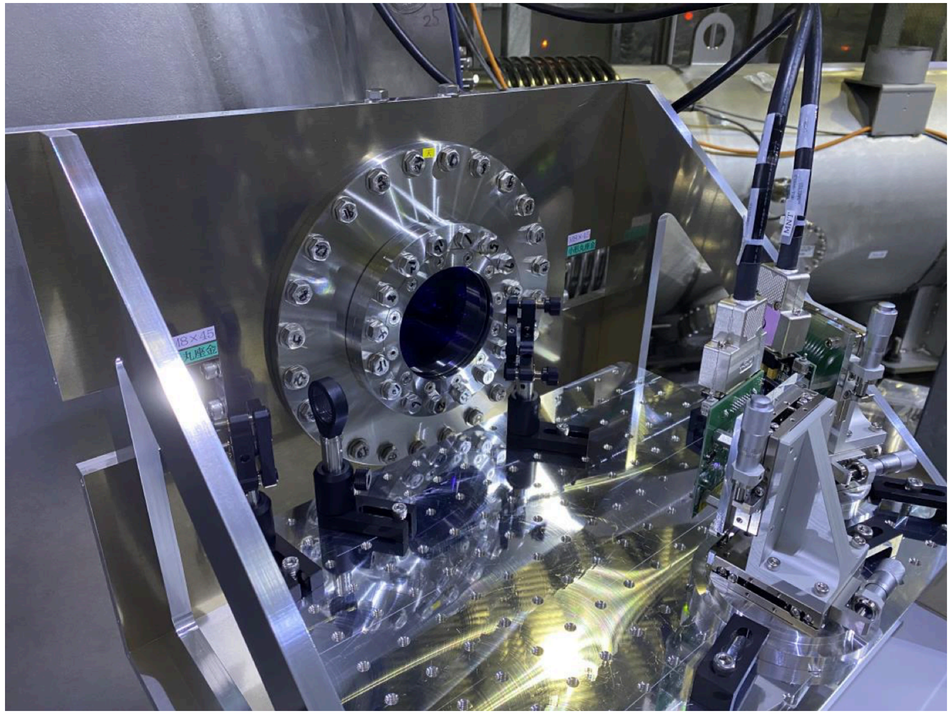
Sensor & Actuator update
Local Control update

Update on Sensor & Actuator

Sensor

New OpLev for PF & MN

→ Better angular sensing



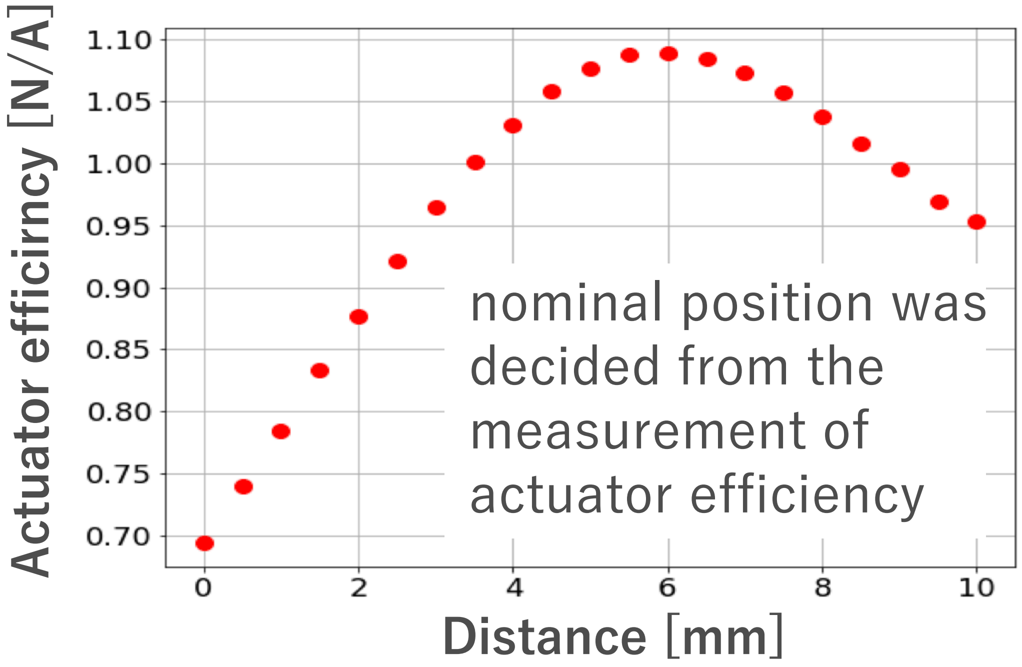
T. Yokozawa, JGW-2214400 -v3

Actuator

We made magnet the bigger

(MN: $\phi 5 \times 13 \rightarrow \phi 7 \times 20$ IM: $\phi 2 \times 2 \rightarrow \phi 2.5 \times 4$)

→ Increase the actuation range for longitudinal motion



Local Control Update (Control Switching)

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

Control focused on suppression of disturbance

- Control the position and posture of the mirror to make it observable asap
- The last observation was conducted with this control

Control Switching

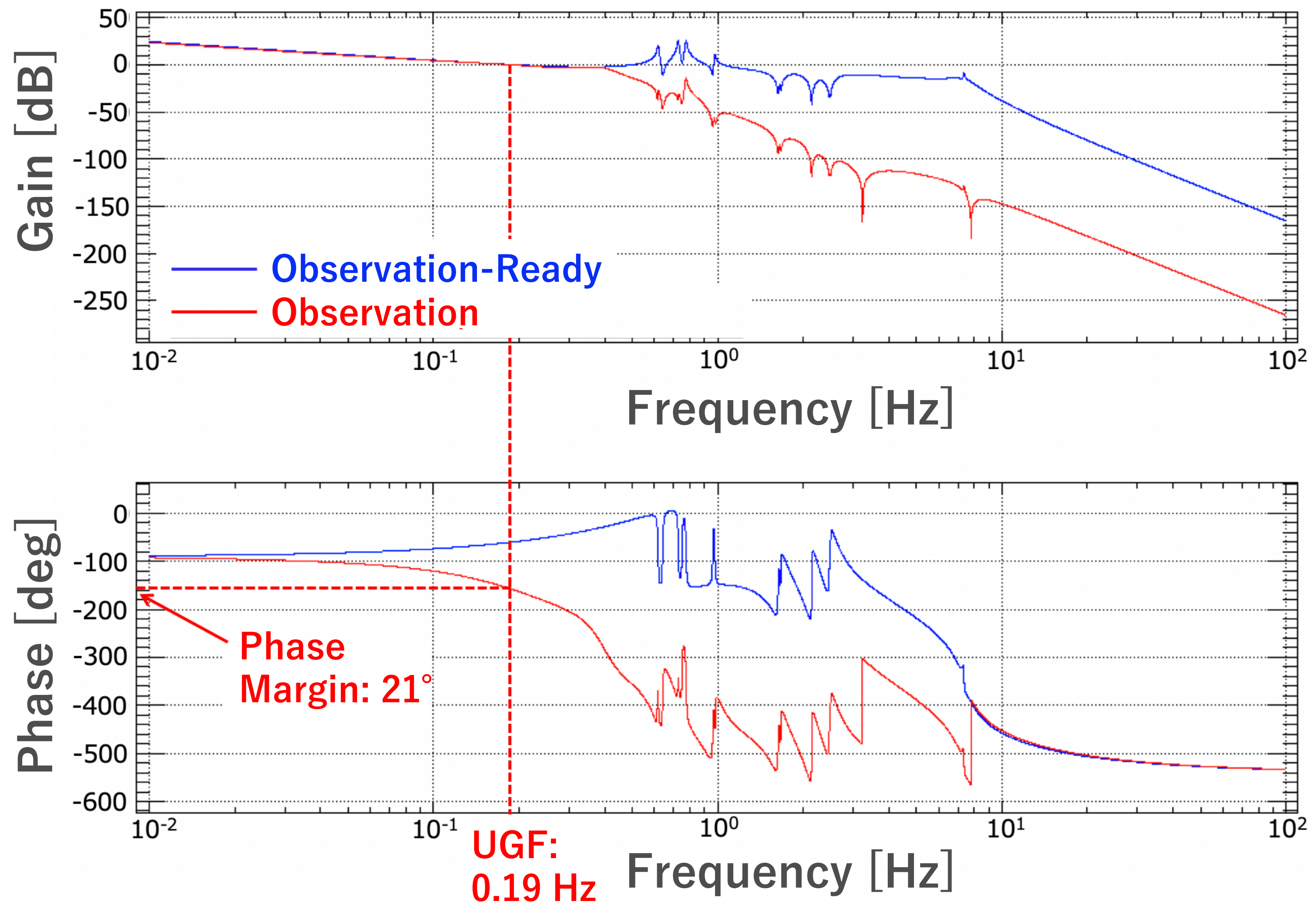
Observation Phase

Control focused on low noise and stable observation

- Low noise control with minimum disturbance suppression
- **We designed such digital control filter** (Observation filter)

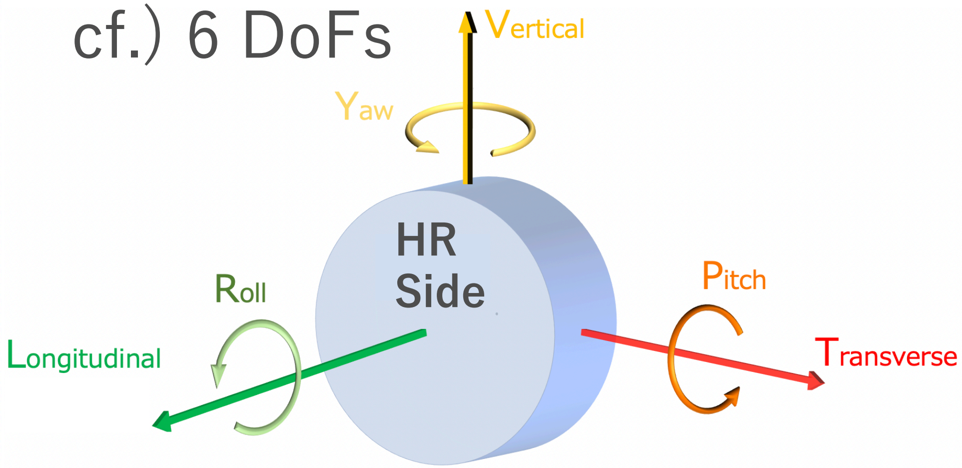
Local Control Update (Observation Filter)

e.g.) ITMX MN Pitch Open Loop TF

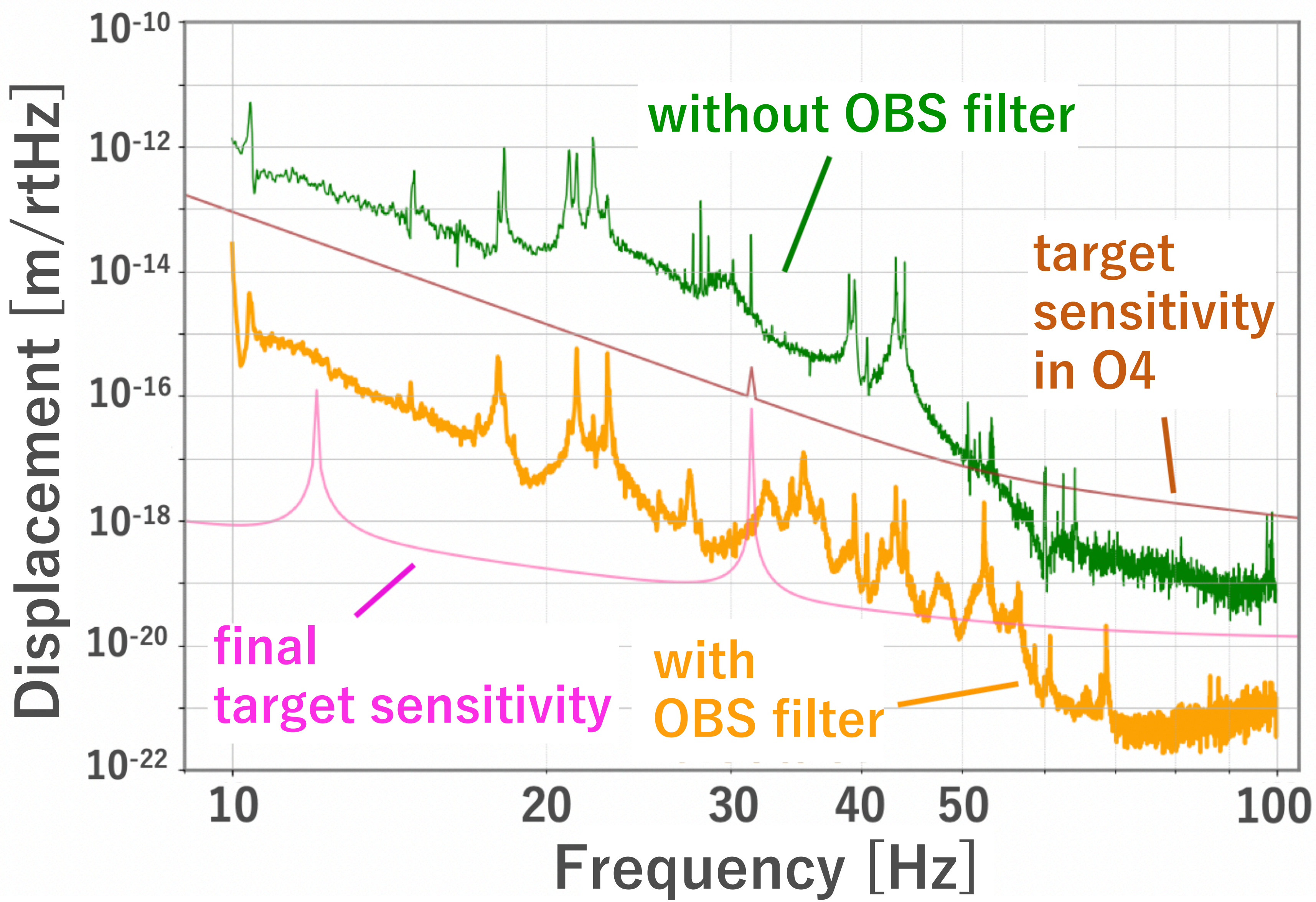


Reduce the control gain from lower frequency than Observation-Ready phase (with Elliptical low-pass filter)

cf.) 6 DoFs



Control Noise Reduction for Cryogenic Payload

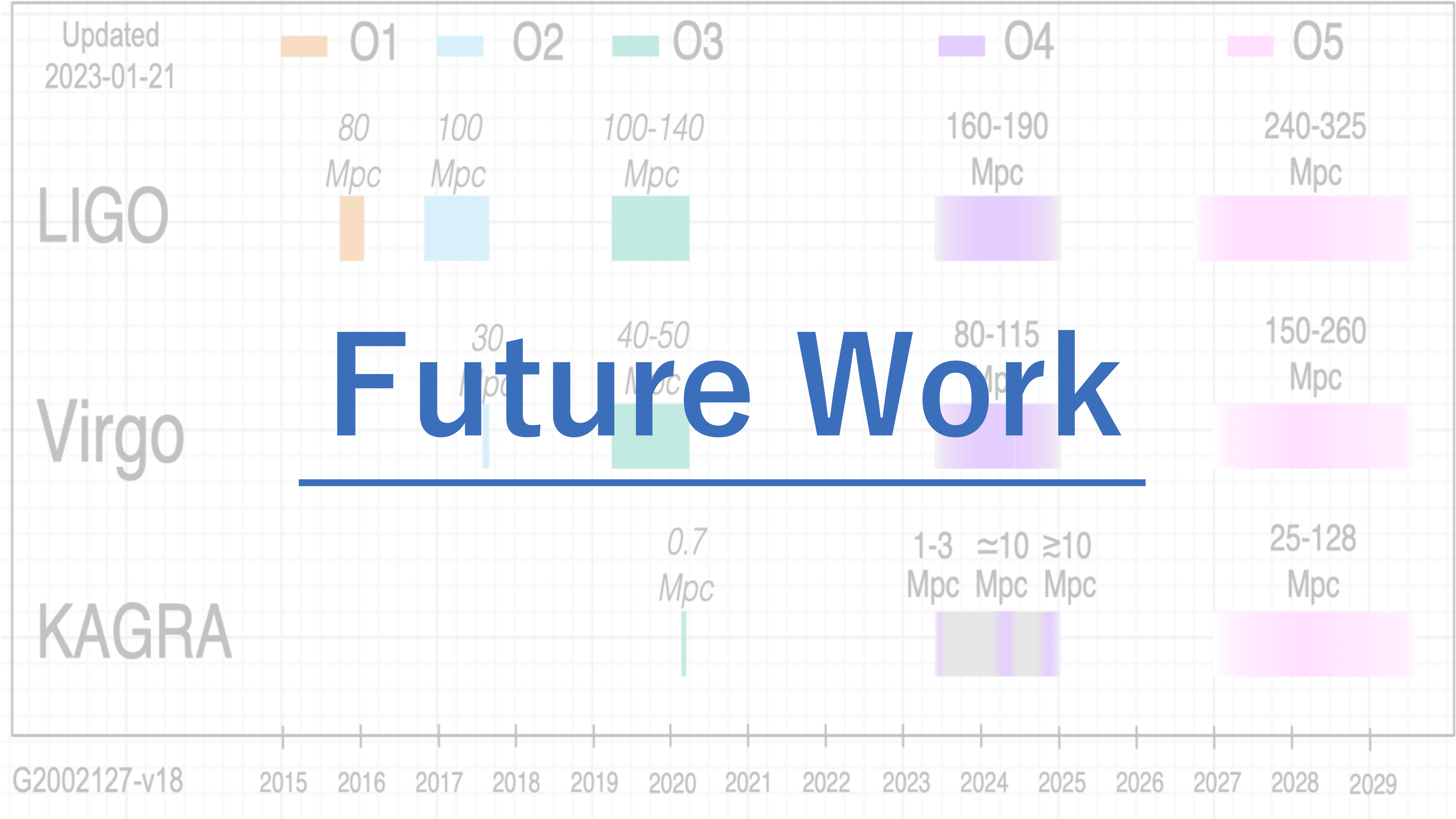


Result

Control noise was reduced by 2~3 order of magnitde

- We could achieve the target sensitivity in O4 with OBS filter
- Improvements are needed to reach the final target sensitivity

Future Work


Updated 2023-01-21
O1
O2
O3
O4
O5
LIGO
80 Mpc
100 Mpc
100-140 Mpc
160-190 Mpc
240-325 Mpc
Virgo
150-260 Mpc
KAGRA
0.7 Mpc
1-3 Mpc
≃10 Mpc
≳10 Mpc
25-128 Mpc
G2002127-v18
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029

Future Work

Toward O4b

We will cool the mirror
to reduce thermal noise

Characteristics of suspension
(resonant frequency,
sensor efficiency, etc...)
will be changed by cooling,
so control filters must
be changed accordingly

* Cooling schedule ・・・ Undecided yet

Further Future

We must update the control of
cryogenic suspension

It is essential to develop
a new cryogenic sensor
(less noise)
and new control scheme
(modal damping or so)
to achieve target sensitivity

* There are many other CRY tasks

Conclusion

Conclusion

For O4

Solution to the problem in O3GK

Control noise

➡ Solved by developing **new control scheme and OBS filter**

- Control noise was reduced **below the taget sensitivity in O4**

Cooling will proceed toward O4b (with new cooling scheme)

＊Cooling schedule for O4b: TBD

For the future

There are many cryogenic tasks besides payload control

KAGRA is the only GW detector operating at cryogenic temperature

⬇

In the future, Einstein Telescope will be operational

Cryogenic techniques in KAGRA will be applied to ET, we hope

Back up

Cryogenic Payload & Cryostat

Heat-Link
Vibration Isolation System

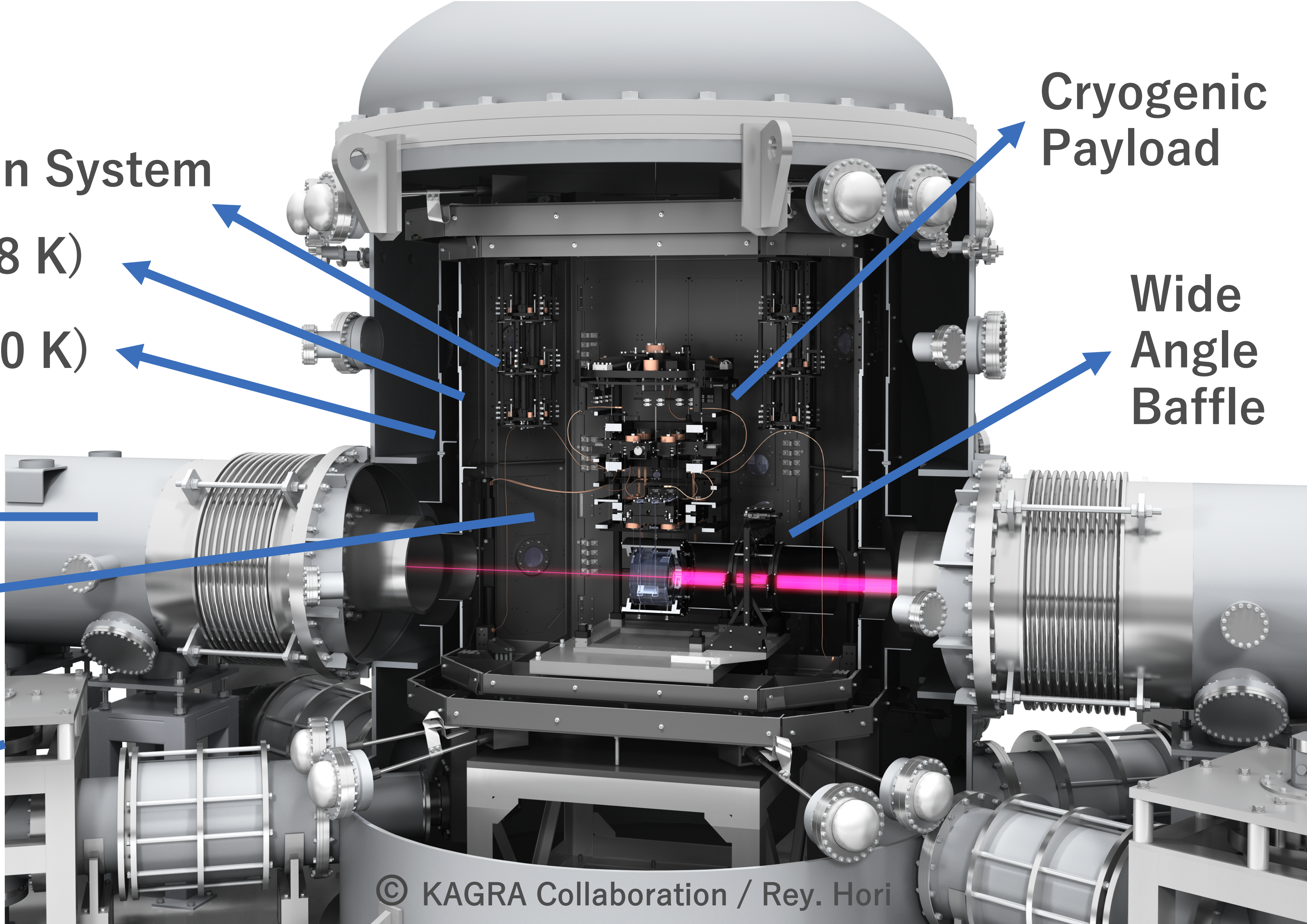
Inner Shield (8 K)

Outer Shield (80 K)

Cryogenic Duct

Heat-Link

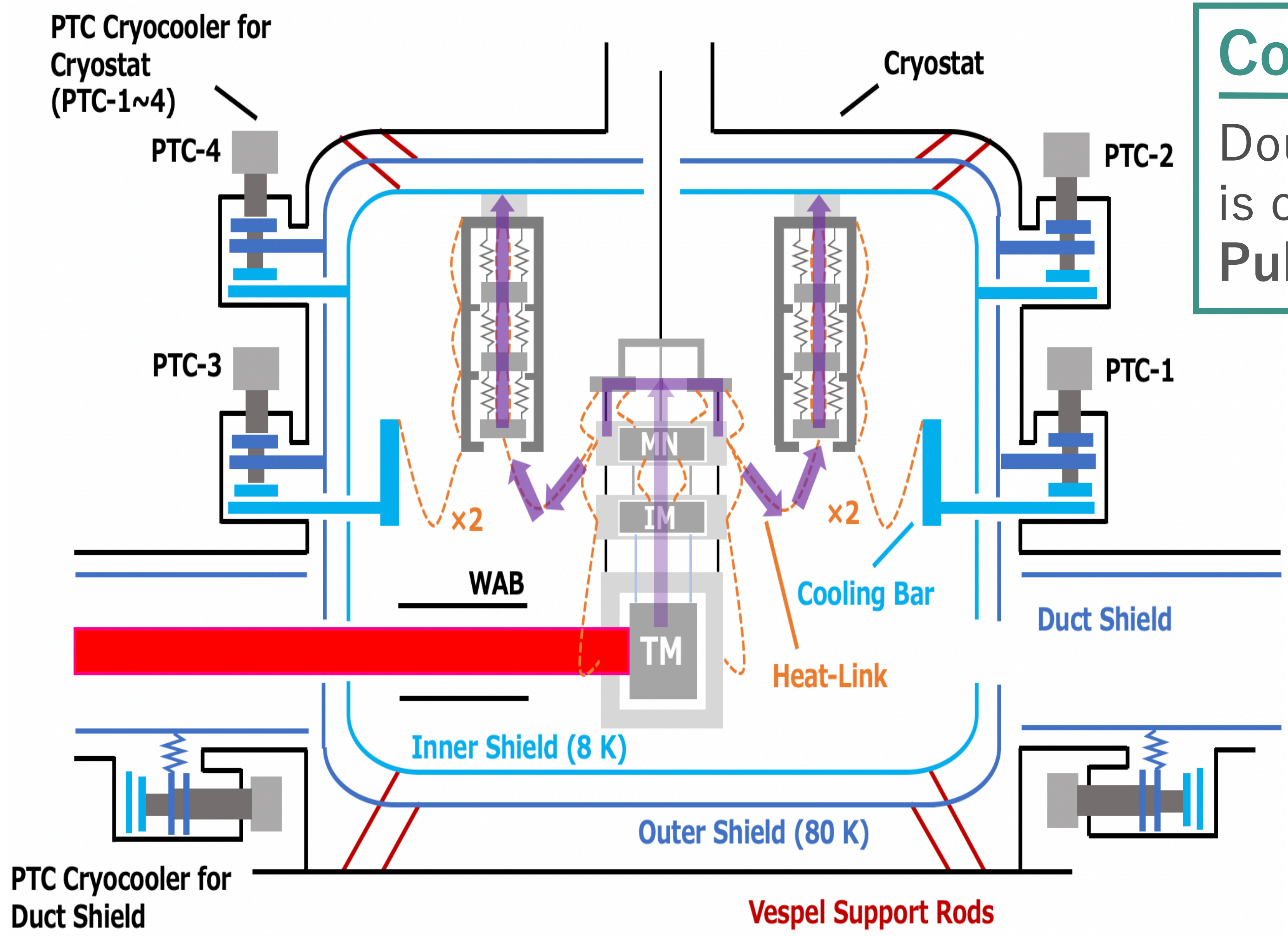
Ultra-low Vibration
Cryocoolers



Cryogenic
Payload

Wide
Angle
Baffle

Cooling Layout



Cooling System

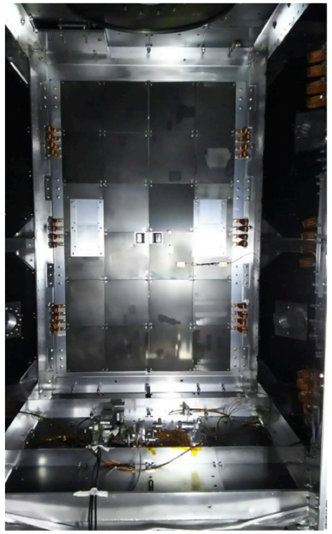
Double radiation shield cryostat is cooled by
Pulse Tube Cryocoolers (PTC)

- **Double Stage PTC (×4)**
  1st Stage → Outer Shield
  2nd Stage → Inner Shield or Cooling Bar
- **Duct Shield PTC (×2)**
  To cool down 5-m duct shield which reduces 300-K radiation
  ＊Change from O3

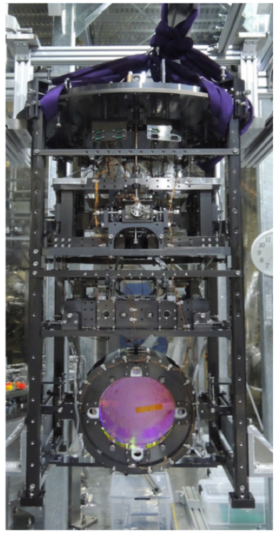
Cooling Process

Thermal Radiative Cooling (300 K → 100 K)

- Non-contact cooling
- Efficient in high temperature
- Black coating for radiation enhancement



DLC

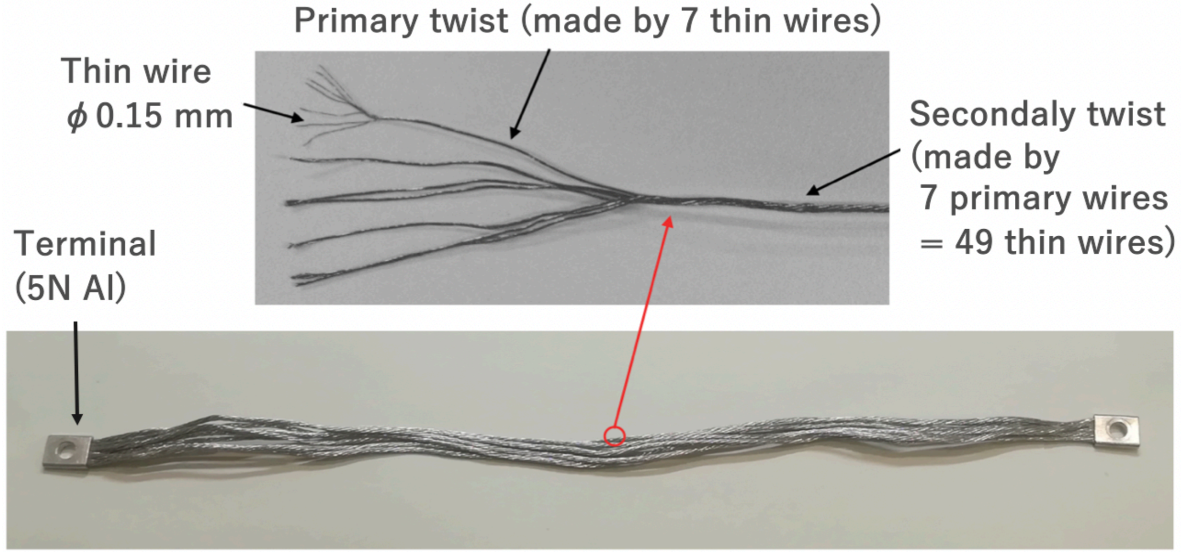


SOLBLACK

(T. Yamada, Ph. D. Thesis, The University of Tokyo, 2021)

Thermal Conductive Cooling (100 K → 20 K)

- Cools TM to ~20 K
- **6N (99.9999% purity) Al Heat Link**



(T. Yamada, *et al.*, Cryogenics, 116, 103280)

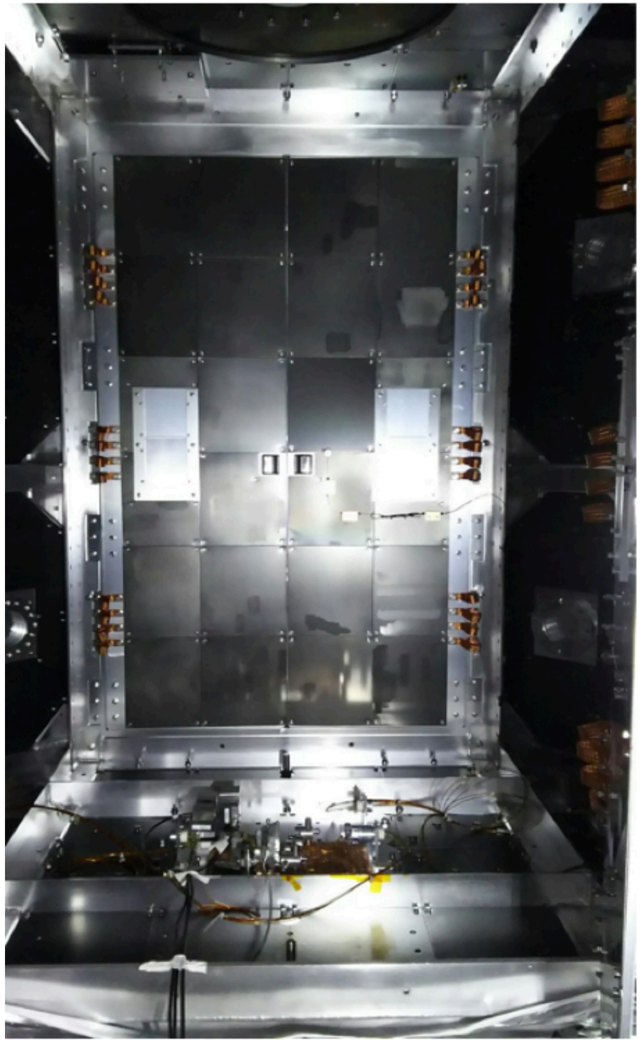
Black coating on cryostat and payload

From room temp to 100 K：
Radiative Cooling

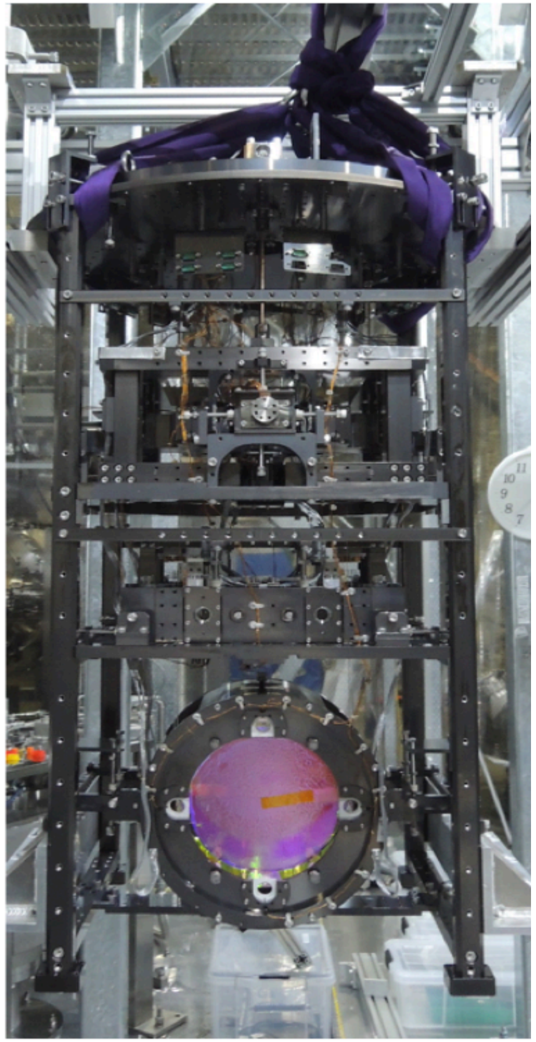
Black coating

on cryostat and payload

- DLC coating for radiation shields
  (Diamond Like Carbon)
  → Increase the emissivity of
  the radiating shield surface
- SOLBLACK coating
  for cryogenic payload
  → Low cost (coating area is large)



DLC



SOLBLACK

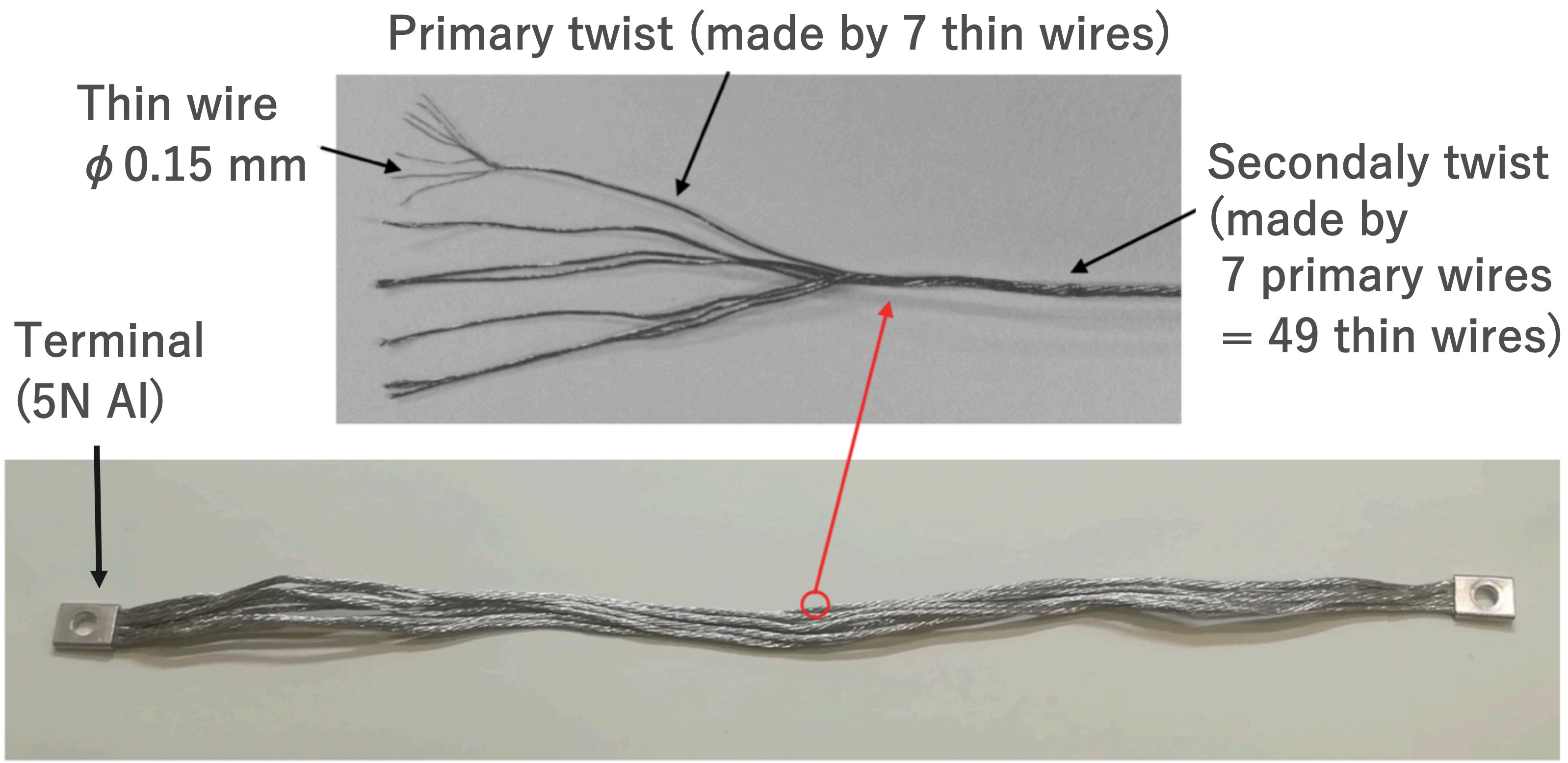
(T. Yamada, Ph. D. Thesis, The University of Tokyo, 2021)

Heat-Link

Below 100 K :
Thermal Conductive Cooling

6N (99.9999% purity) Al Heat-Link is used

- High thermal conductivity
- Low spring constant



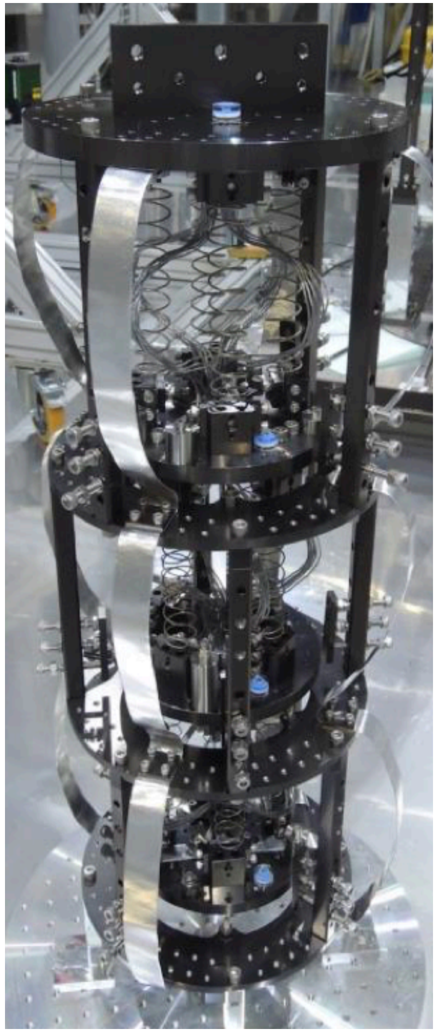
(T. Yamada, *et al.*, Cryogenics, **116**, 103280)

Twisting thin wires together increases cross sectional area and provides high thermal conduction while **reducing spring constant**

Heat-Link VIS

Problem

Vertical vibration isolation for Heat-Link was insufficient



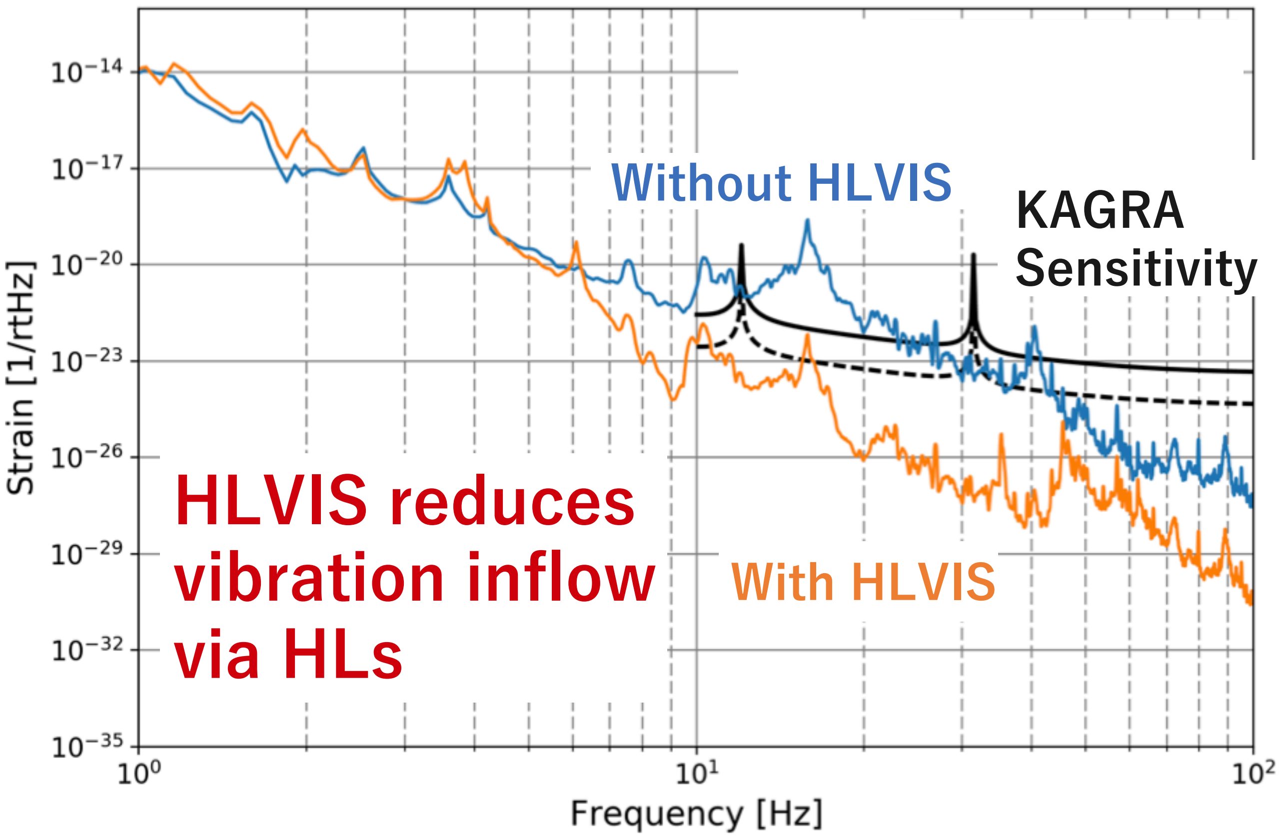
Solution

HLVIS

Simple vertical vibration isolation system for Heat-Link

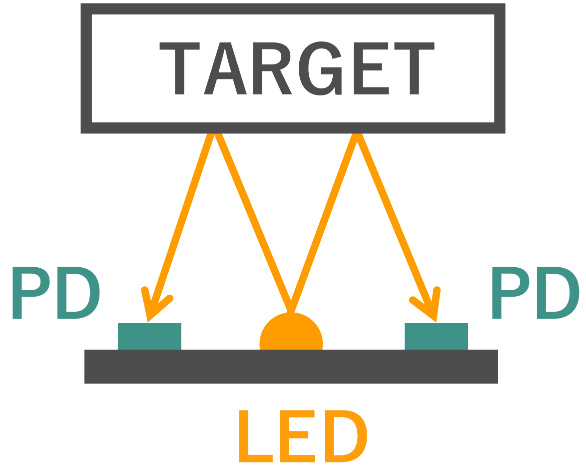
Successfully reduced vibration inflow to a level below the sensitivity curve

Comparision of vibration inflow with/without HLVIS



(T. Yamada, Ph. D. Thesis, The University of Tokyo, 2021)

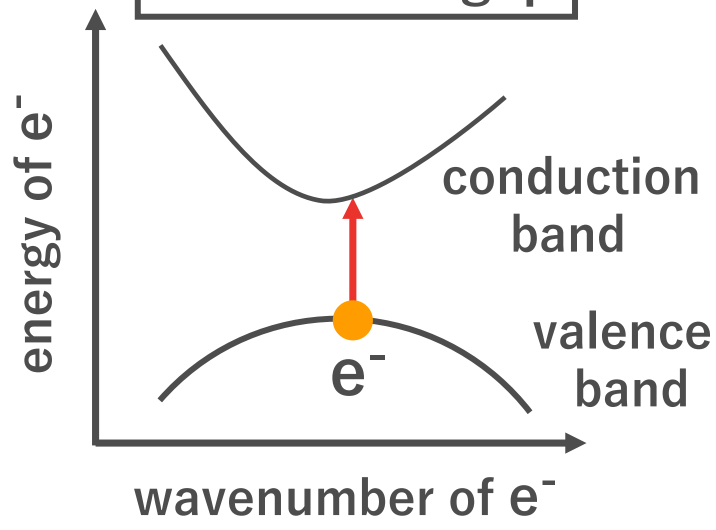
Reflective Photosensor



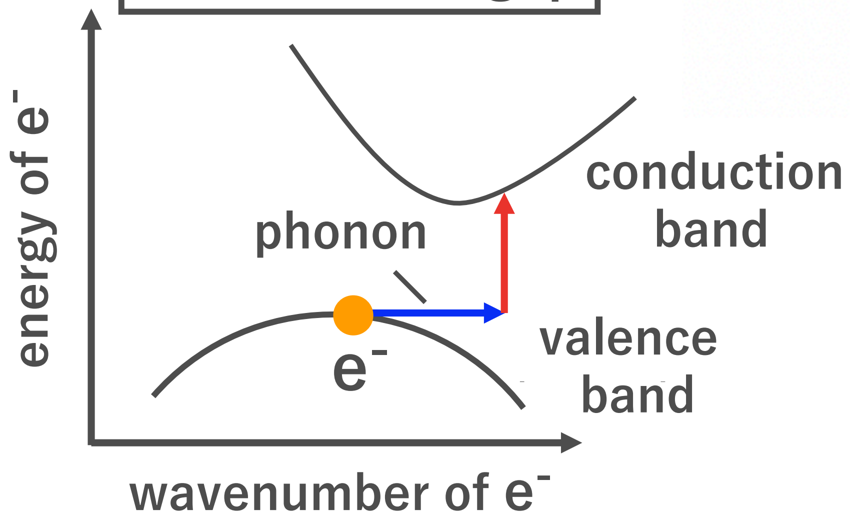
Monitor the changes in relative distance as changes in light intensity

PD: InGaAs LED: InGaAsP → Direct bandgap

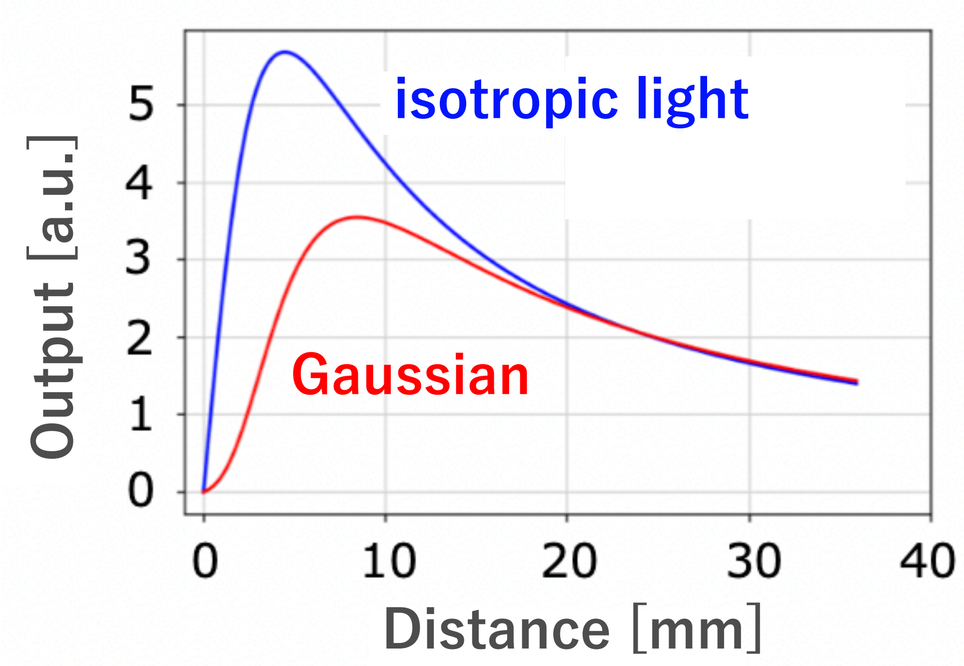
Direct bandgap



Indirect bandgap



Response of photosensor

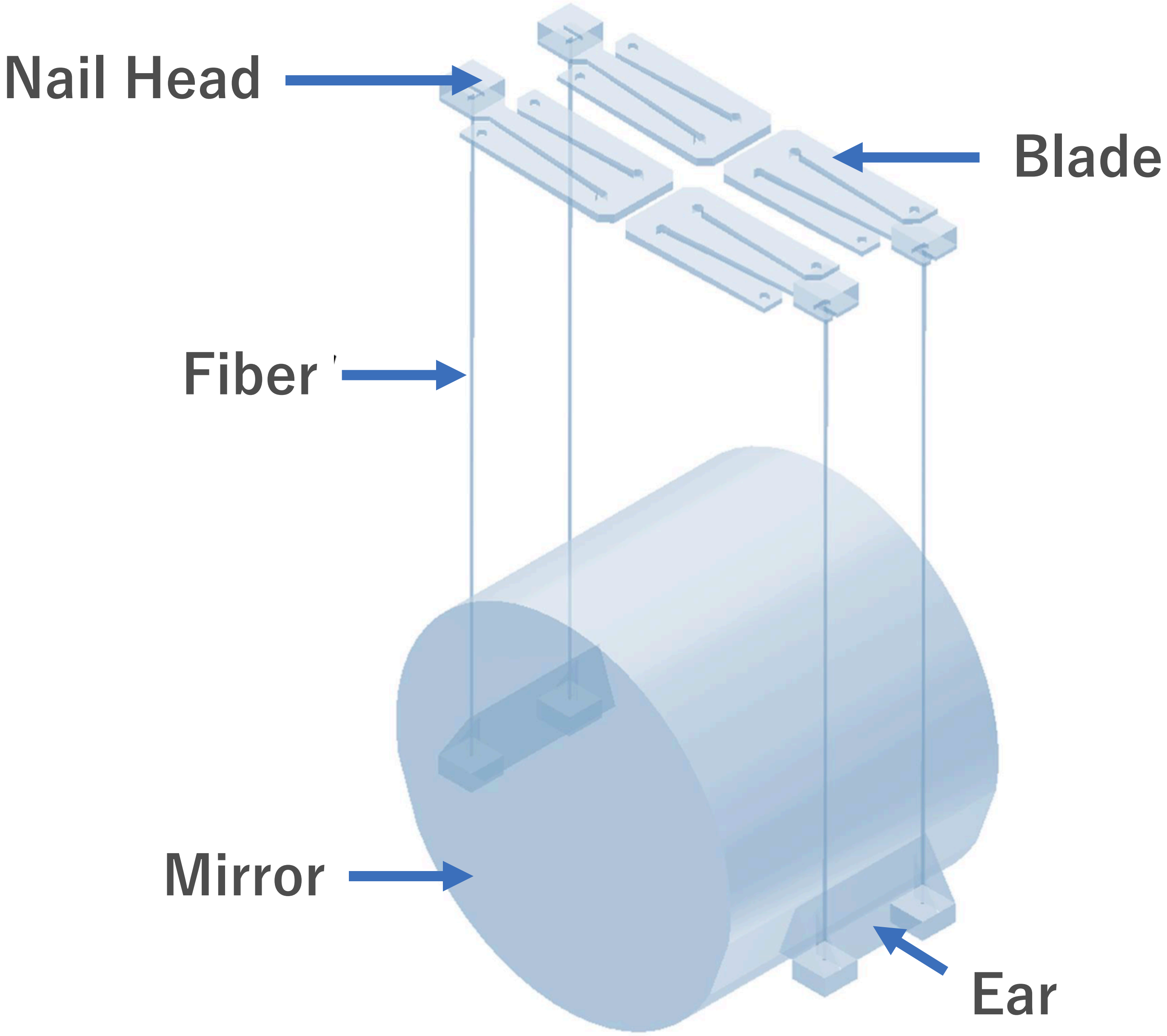


Wide dynamic range for use at cryogenic temperature

Sapphire Suspension

Bottom stage of cryogenic payload

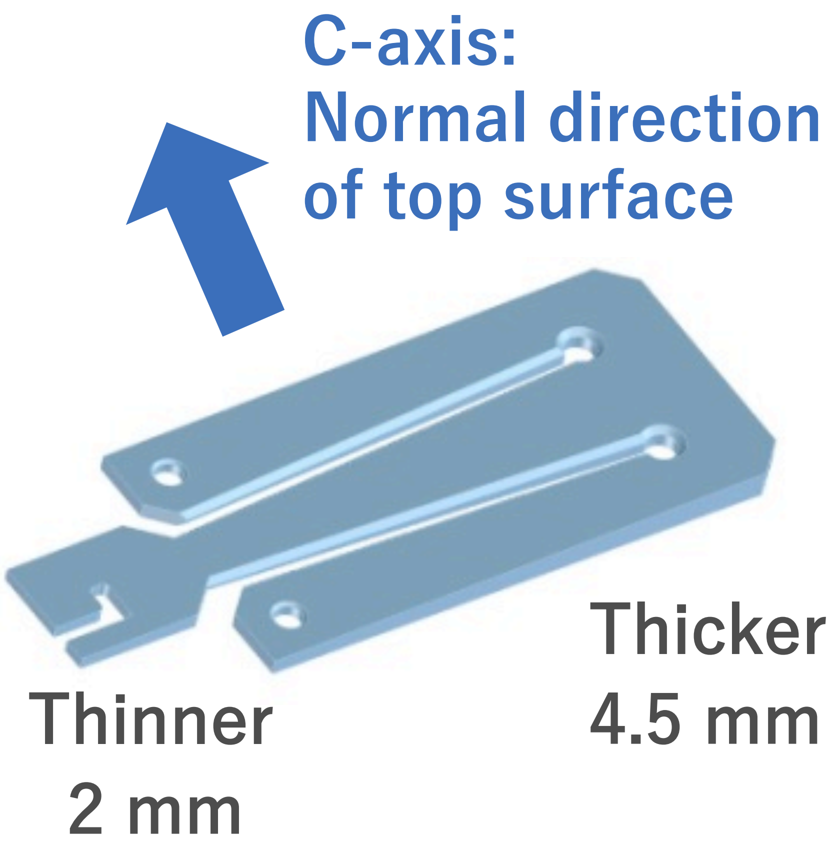
- **High Q value** and **effective heat extraction** at cryogenic temperature
- All 4 sapphire suspensions have been in KAGRA cryostat since 2018 **with no fatal damage**
- Components are bonded with different bonding techniques



Sapphire Blade Springs

KAGRA Sapphire Blade Springs

- Components for aligning sapphire fiber lengths
- Lower the frequency of the violin mode of the sapphire fiber



Problem

Measured loss was 3.5×10^{-5}@9 K

＊Required: 7.0×10^{-7} (T. Yamada, ELiTES, Feb 2017)

Energy might be lost because of

- Measurement setup (loss in the clamps)
- Stresses are concentrated in the unpolished areas of the blade spring → additional losses may occur due to unpolished surfaces

New blade spring was designed and fabricated

Sapphire Fiber

KAGRA Sapphire Fiber

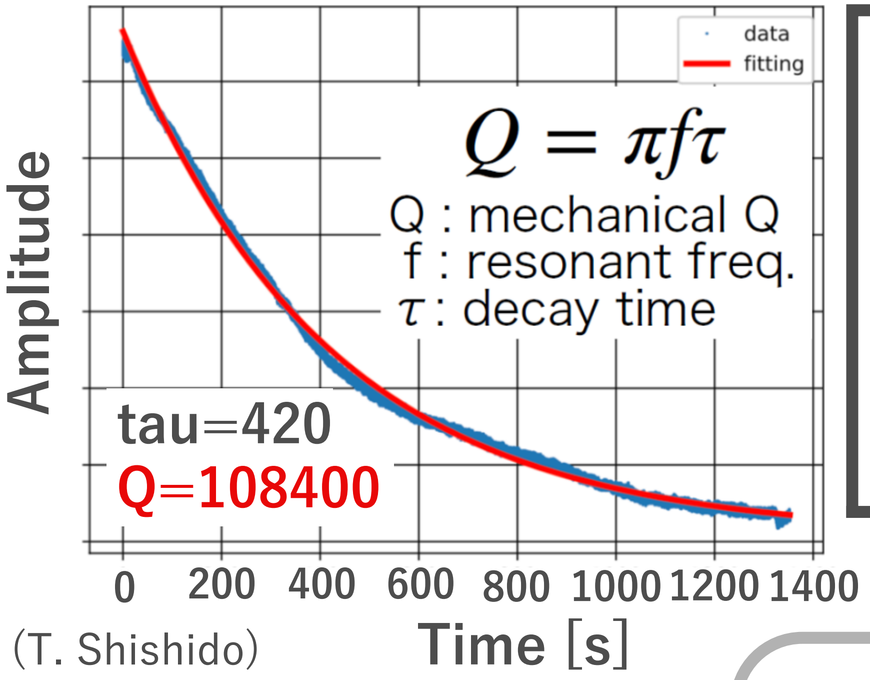
- Extract heat from the mirror
  → **Shorter & Thicker** fiber

- Reduce thermal noise
  → **Longer & Thinner** fiber

High Q & thermal conductivity is necessary for sapphire fiber

Sapphire nail head block (bonded by SUMICERAM)
20 mm × 20 mm × 10 mm

Q Value of Sapphire Fiber



(T. Shishido)

Measured value of SUMICERAM bonded fiber **Q=10^5**

→ a lot smaller than requirement (6×10^6)

However, measuremt reuslt for the sample was very low

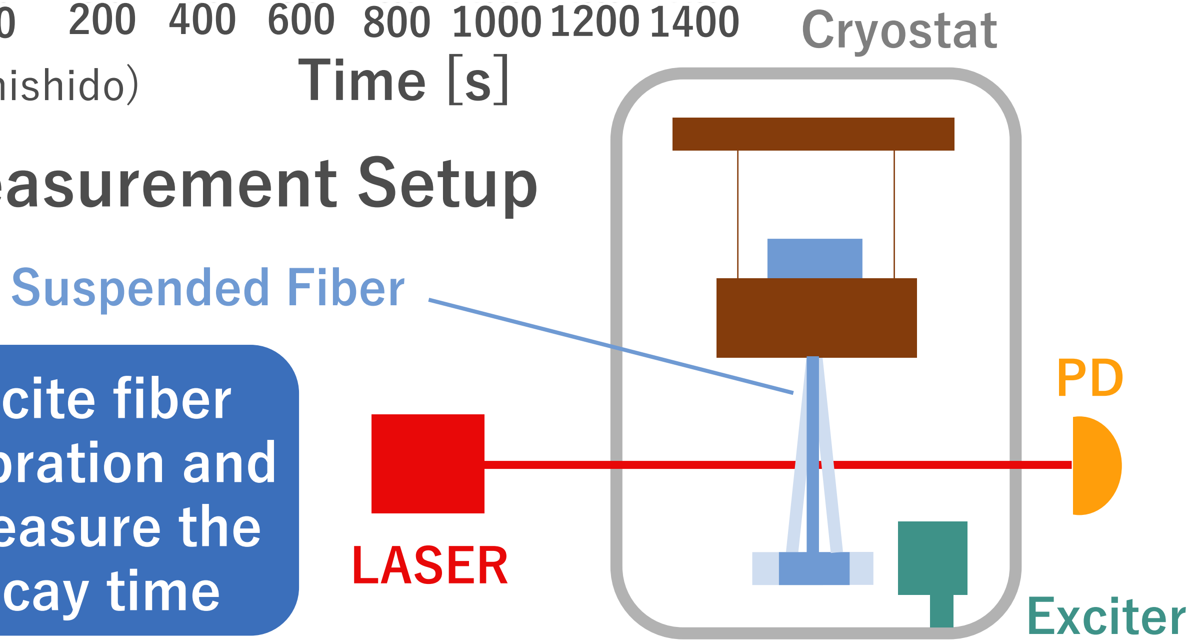
previously recorded Q=10^7

Measurement setup could limit the measured Q value due to internal losses

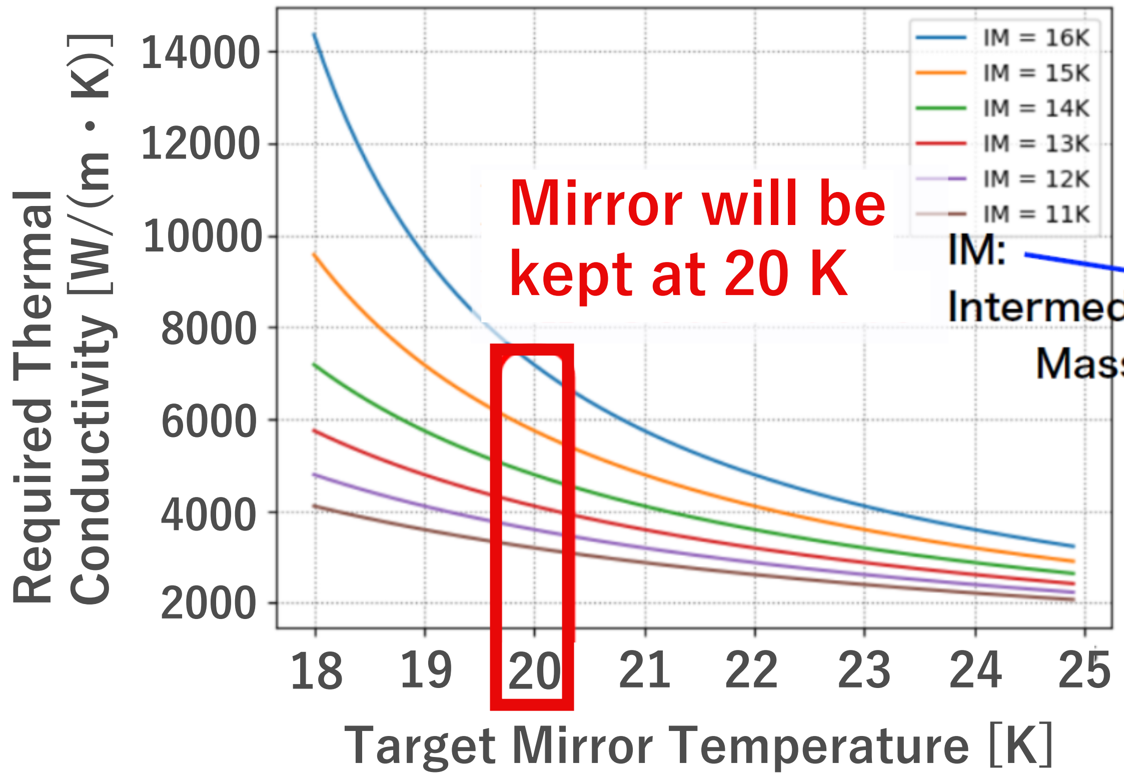
Low loss Q value measurement setup is necessary

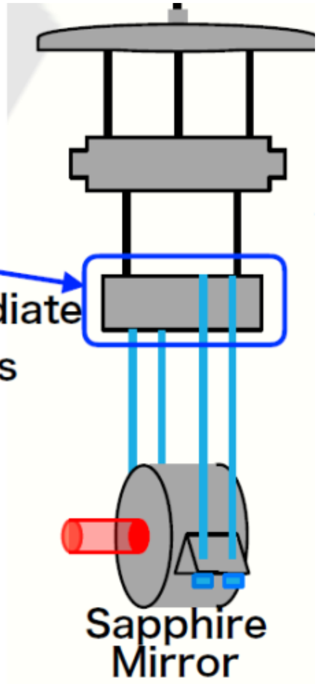
Measurement Setup

Excite fiber vibration and measure the decay time



Thermal Conductivity of Sapphire Fiber





(T. Shishido)

Thermal conductivity was caluculated for several IM temp

IM Temp	Thermal Conductivity
11 K:	3000 W/(m・K)
16 K:	7000 W/(m・K)

Small change in IM temp drastically changes the requirement for conductivity

From Measurement

・SUMICERAM bonded fiber meets the requirement for IM temp < 13K

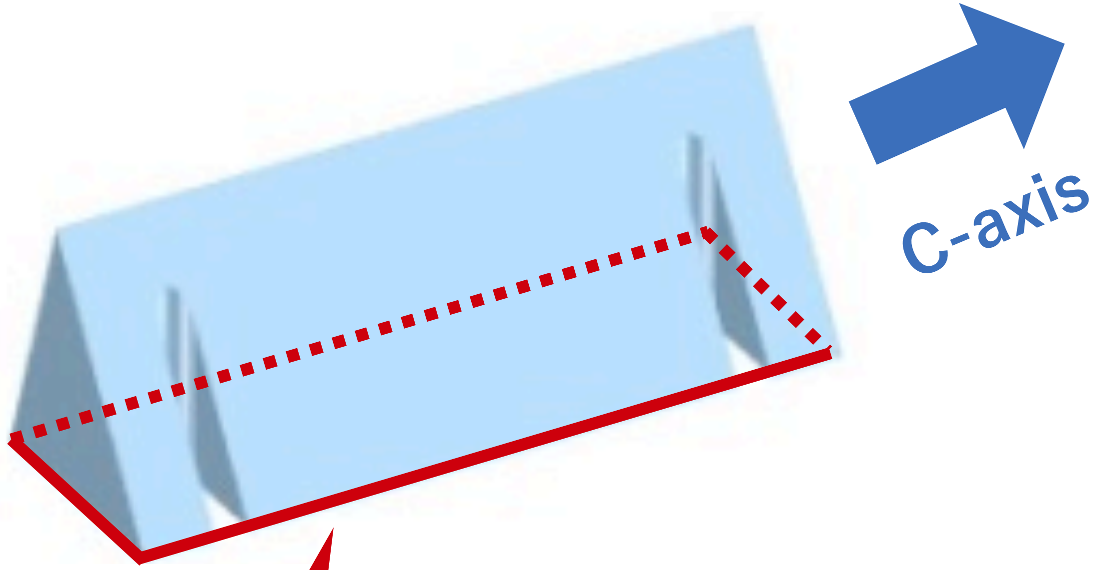
・It is hard to achieve 20-K sapphire mirror with 16-K IM

➡ **Thermal conductivity improvement is significant**

Sapphire Ear

KAGRA Sapphire Ear

- Triangular prism with 2 slits for hooking sapphire fibers
- Very difficult to polish
  → mechanical loss problem for future detector
- HCB between mirror and ear
  → sufficient strength and good thermal contact
- Gallium between fiber and ear
  → good thermal contact and easy disconnection



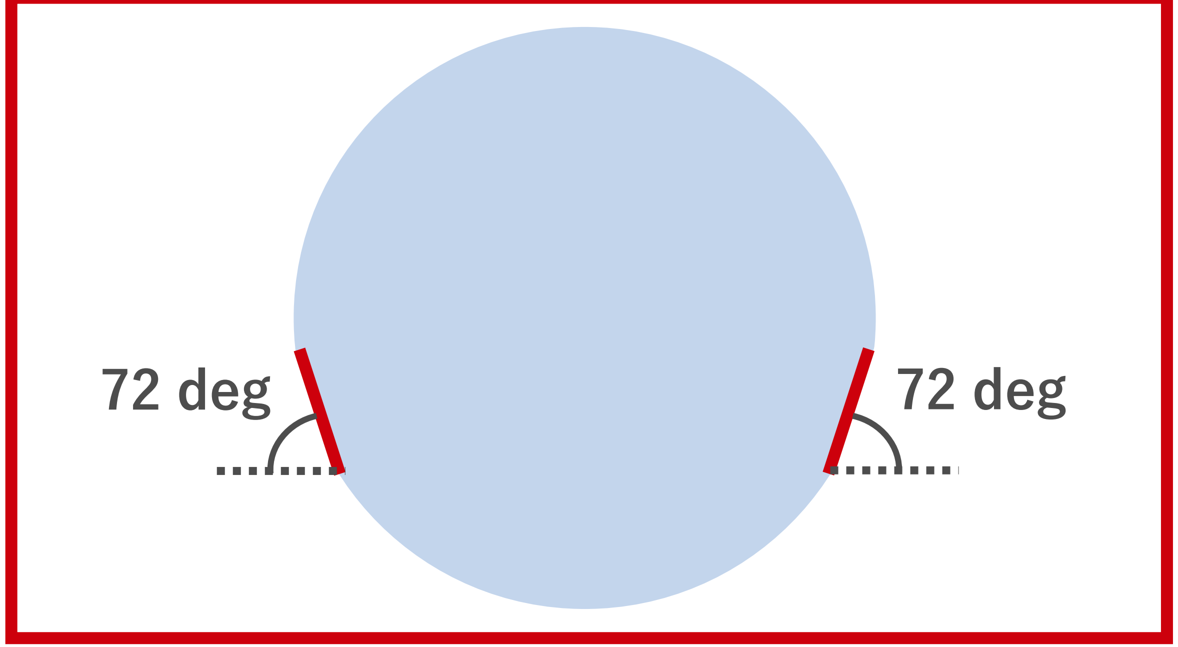
This surface should be 48 mm lower than center of sapphire mirror

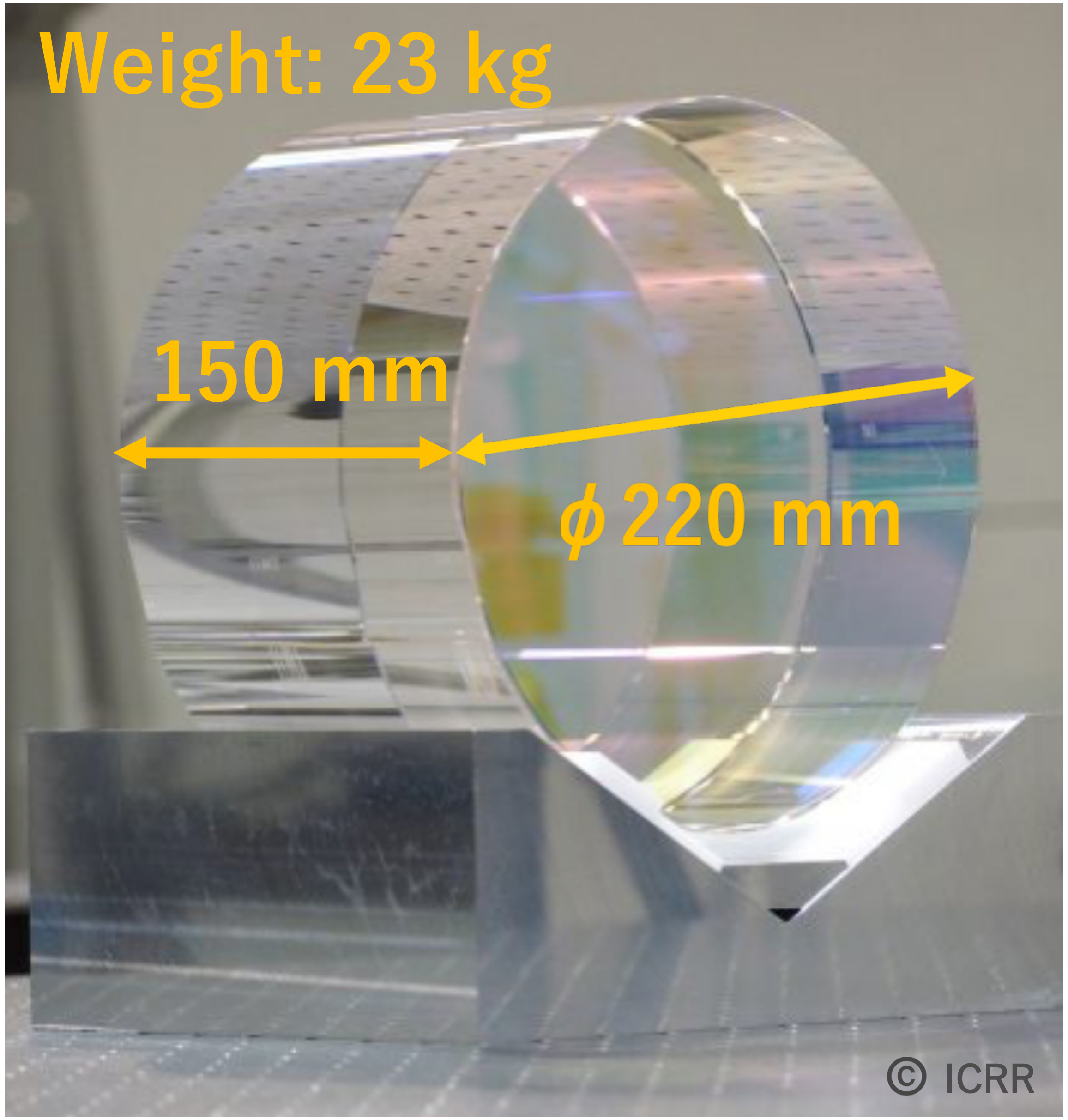
→ **Minimize the Longitudinal to Pitch coupling**

Sapphire Mirror

KAGRA Sapphire Mirror

- Low absorption of 1064-nm light
- High mechanical Q-value (10^8 @20 K)
- 2 **flat cuts** to bond sapphire ear





Bonding Techniques (Advantage and Problem)

Gallium

Fiber & Ears,
Nail Head &
Blade/Fiber

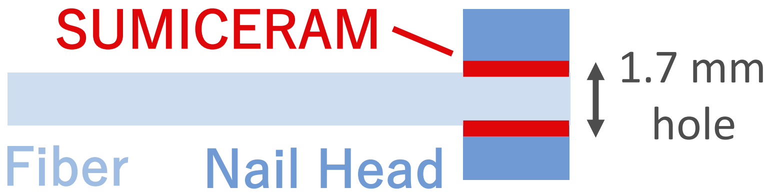
Provide good thermal contact

Removed by melting
→ easy to replace fibers

Ultrasonic soldering is needed to bond sapphire

SUMICERAM

Fiber & Nail Head



Strong enough to suspend KAGRA sapphire mirror even at cryogenic

Thickness > HCB
→ thermal resistance and mechanical loss affect thermal and mechanical performances

HCB

Mirror & Ears

Hydroxide Catalysis Bonding
→ can bond silica, silicon, and sapphire with alkaline solution ($NaOH$, KOH, or Na_2SiO_3)

Cryogenic compatible

Thin bonding thickness (~100 nm)
→ very low thermal resistance at bonding

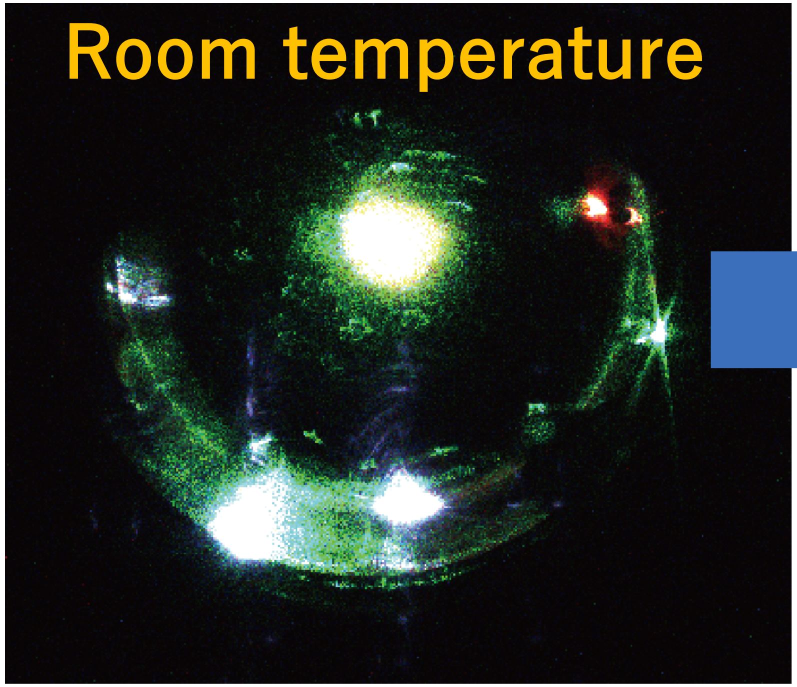
Difficult to separate bonded pieces

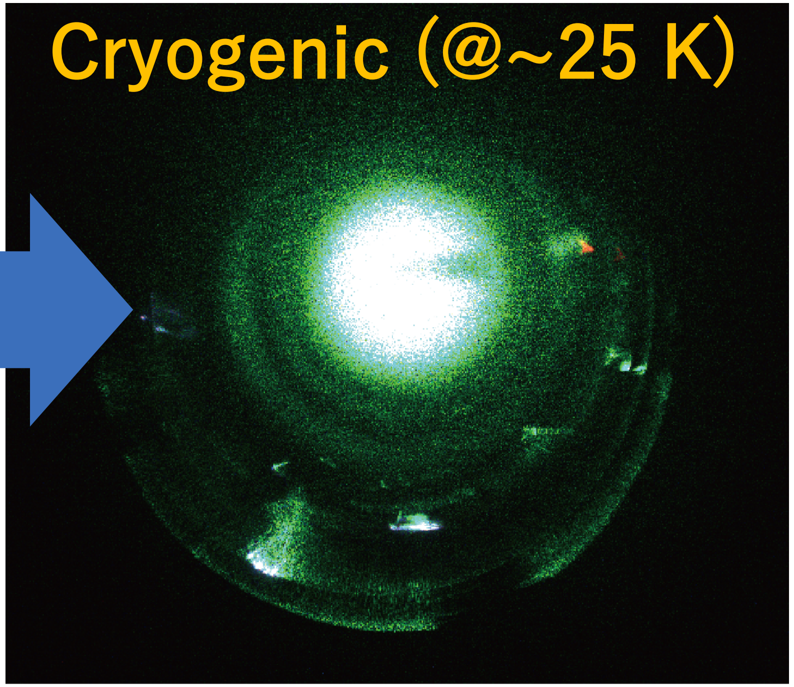
Frosting Issues (during O3)

Problem

During cooling, thick frost formed on the mirrors

Finesse of arm cavity dropped drastically





By warming mirrors
to 70-80 K,
finesse was recoverd

Main component of frost
・・・N_2 (, O_2, H_2O)

camera shots of the mirror during cooling (H. Abe, *et al.*, Galaxies, 10(3), 63, 2022)

New Cooling Scheme in O4

Step 1

Vacuum pumping

until pressure inside cryostat reaches 10^{-4} Pa

3 weeks

Turn on 2 duct coolers

Step 2

Cooling down duct shields

Temp: 90-150 K

To trap H_2O

2-3 weeks

Turn on 2 radiation coolers

Step 3

Cooling down inner/outer shields

Radiation Temp: 20-30 K

To trap N_2 & O_2

3-4 weeks

Turn on 2 payload coolers

Step 4

Cooling down test mass

Goal Temp: 20 K

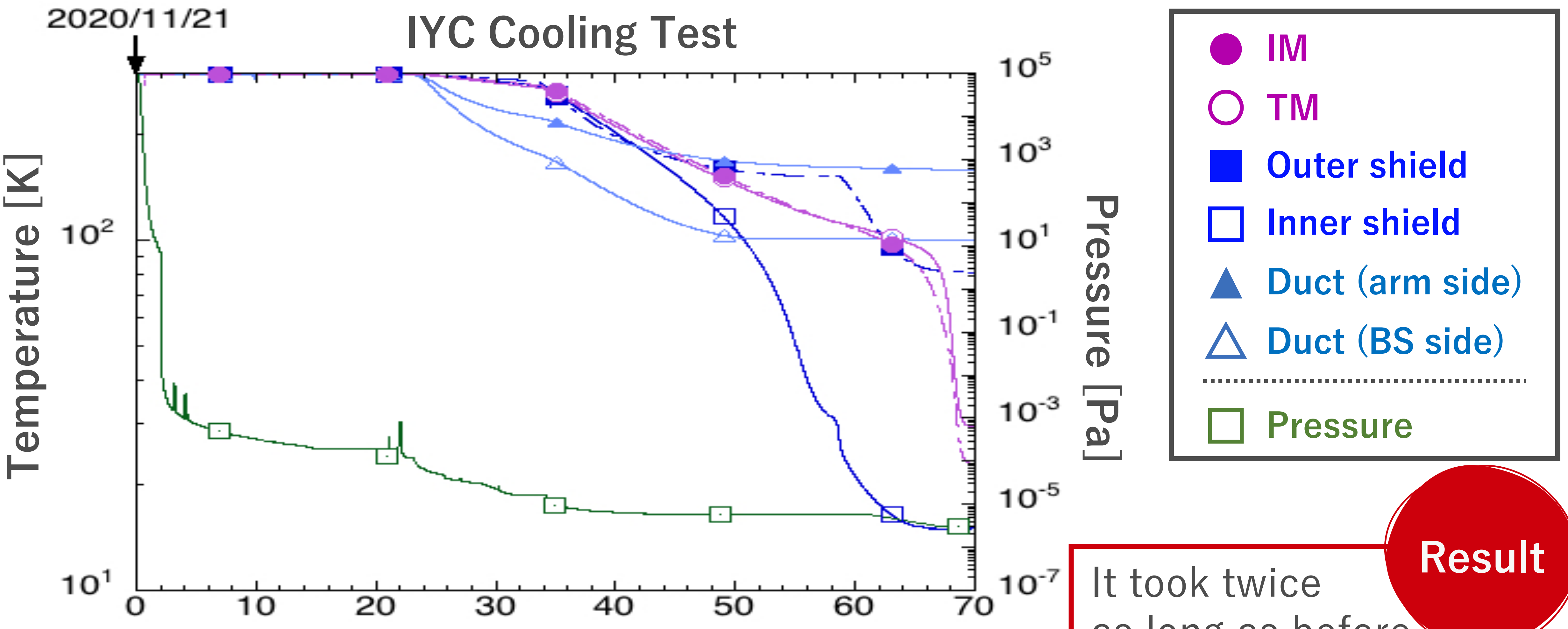
2-3 weeks

Total cooling time : **2.5-3 months** (in O3: 1 months)

Cool down in stage

⇨ the residual gas molecules are adsorbed on the surface of the radiation shield

Test of New Scheme



(N. Kimura, GWAGW, May 2021)

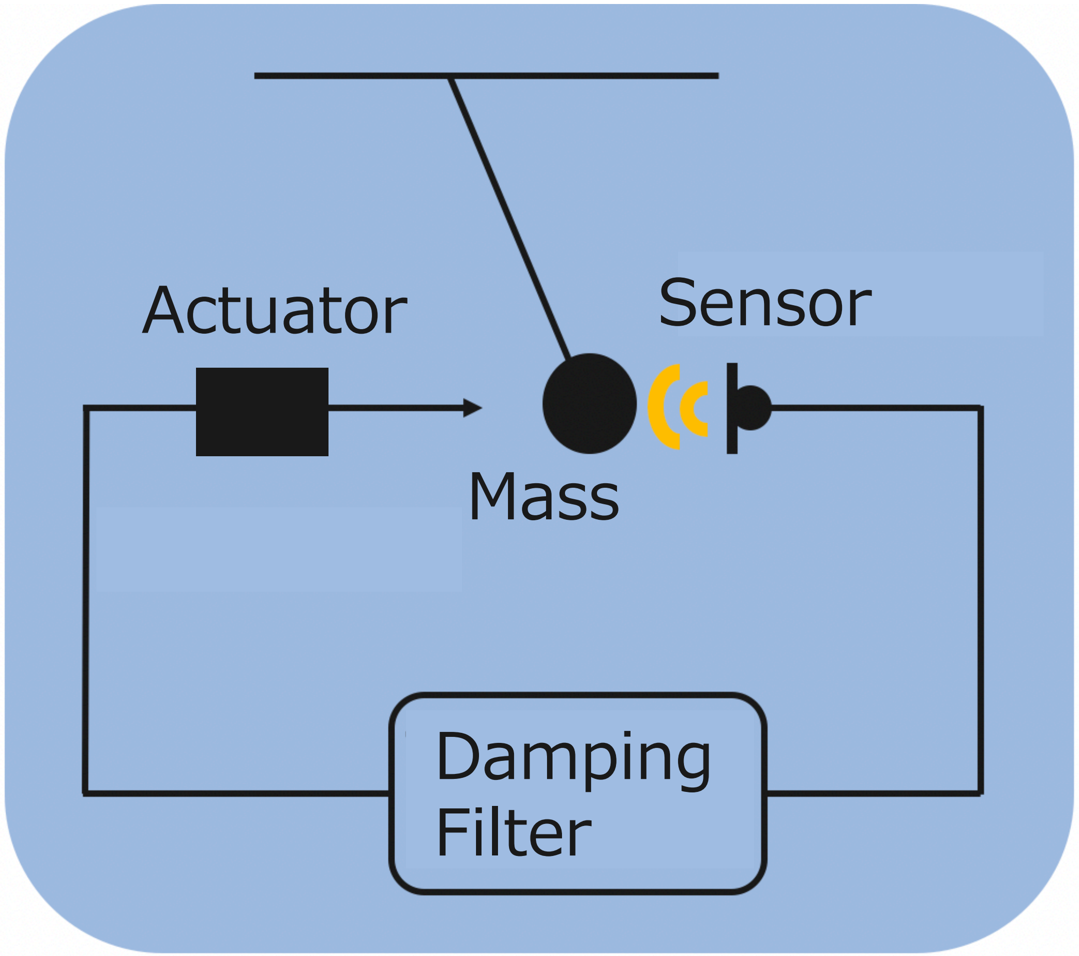
It took **70 days** for the mirror to reach 22 K

Result

It took twice as long as before, but there was **no visibly thick frost**

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

How to Measure Control Noise (FPMI)

1. Lock FPMI
   (Fabry-Perot Michelson Interferometer)

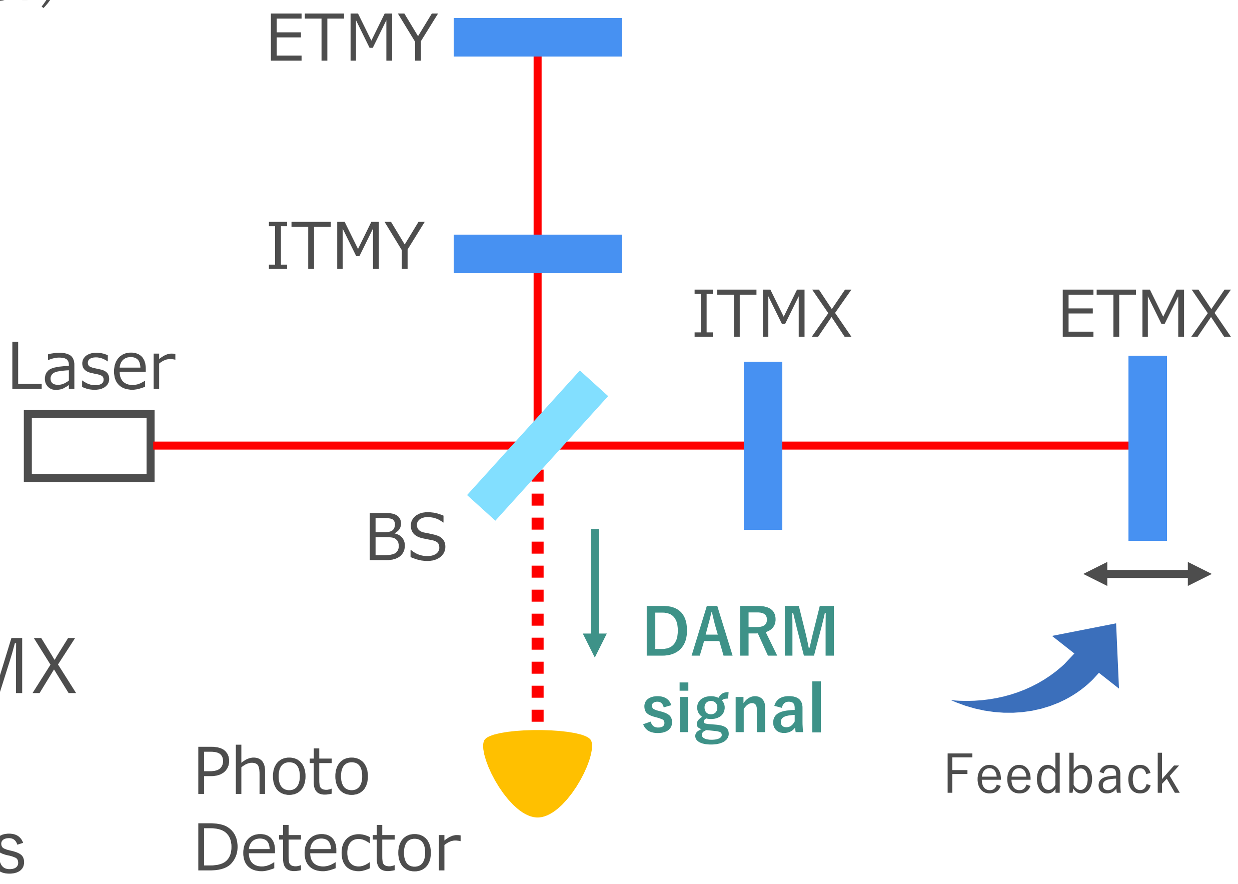
Arm: Fabry-Perot cavity

GW signal = Differential arm signal

DARM signal

Returns feedback signals to ETMX and drives ETMX to maintain differential displacement of arms

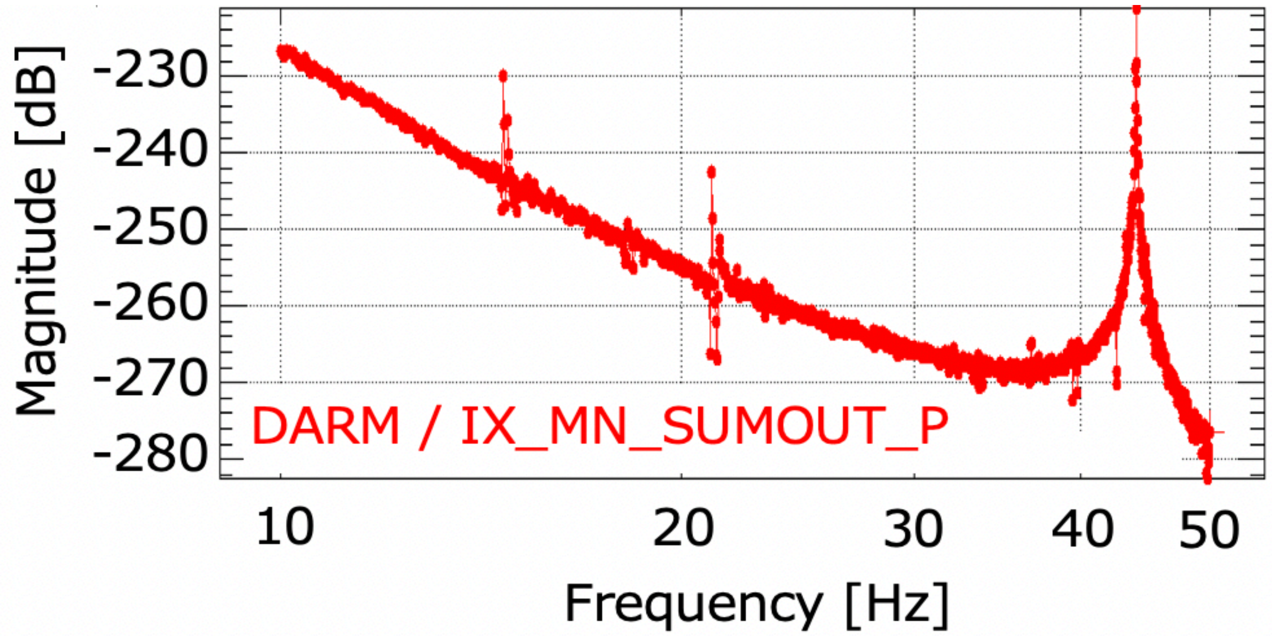
Schematic diagram of FPMI

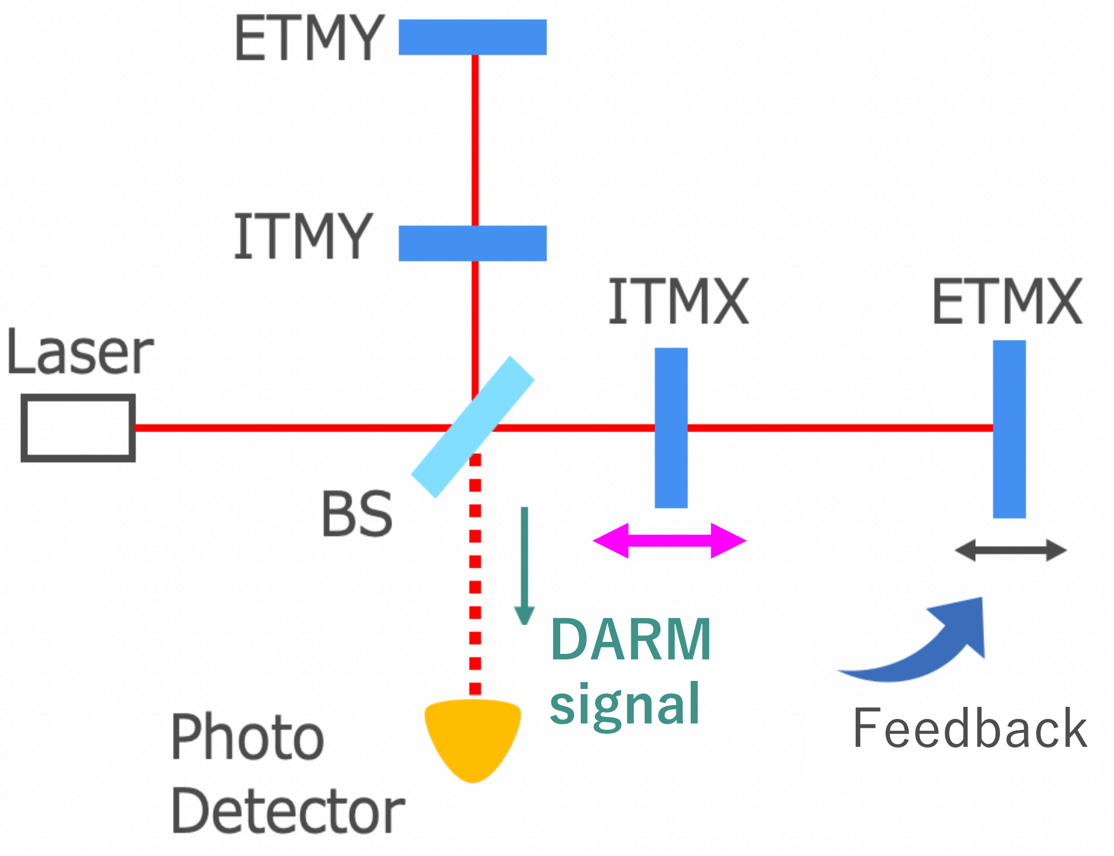


How to Measure Control Noise (FPMI)

2. **Vibrate each suspension**
in each degree of freedom
and measure the transfer function
from the motion to the DARM signal

e.g.) ITMX MN P





How to Measure Control Noise (FPMI)

3. Noise from the sensors
   used for control is always present,
   even when the suspension is not vibrated

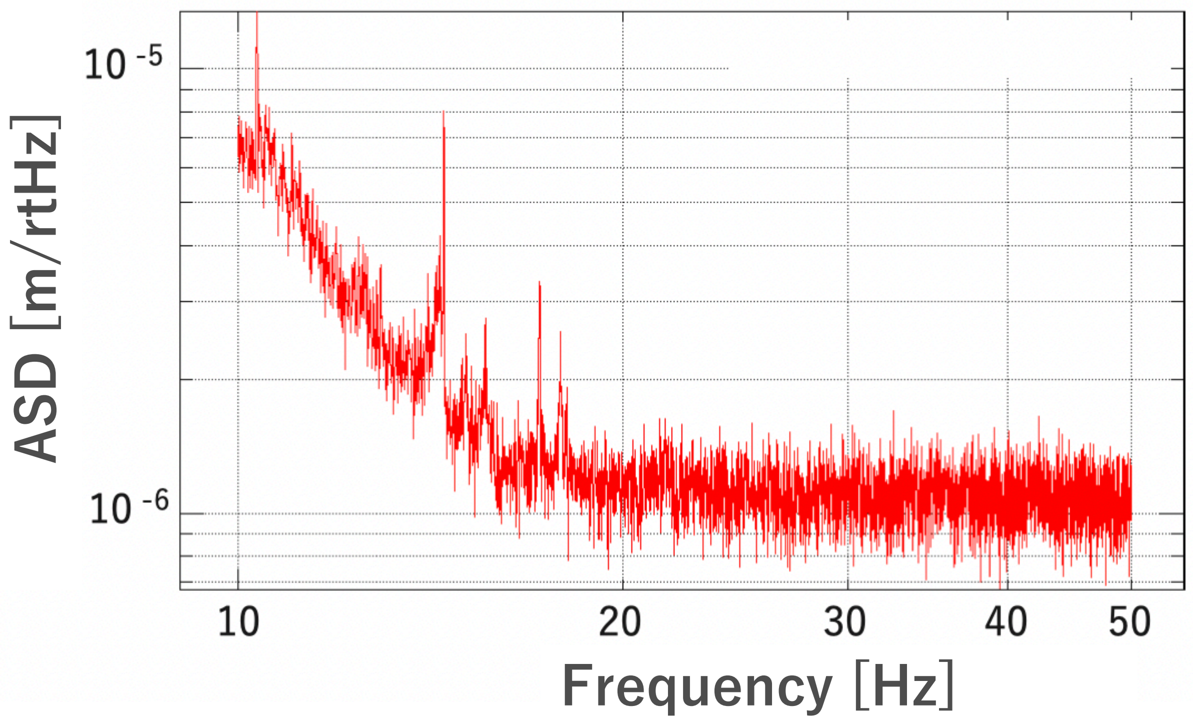
↓

Multiply the
amplitude spectral density
by the measured TF

↓

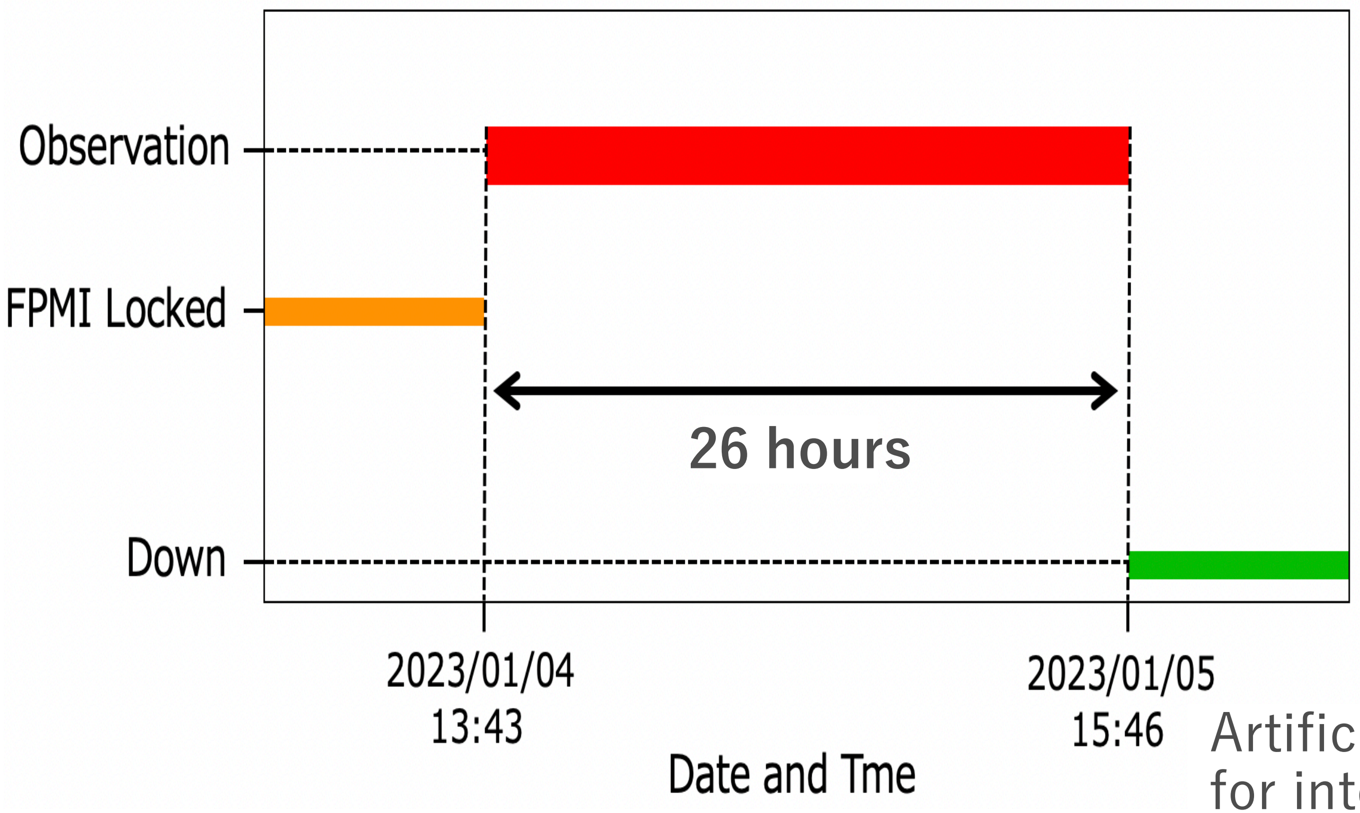
Since the control noise of
each suspension is uncorrelated,
take their sum of squares

ASD of sensor signal (ITMX MN Pitch)



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**

Further noise reduction

Modal damping

Conventional Control

- ○ Easy to design
- ○ Works well for now
- × Must be designed for each DoF
- × Designed for each person

Modal damping

- ○ Can handle multiple DoF
- ○ Systematic optimization through numerical simulation is possible
- × Control performance is dependent on modeling accuracy
- × Difficult to model with high accuracy

Modal Damping

Conventional Control

Feed back signals from
each stage for each stage

Sensor・Actuator basis

Modal damping

Multi-stage feedback
according to the shape of the vibration mode

Mode Decomposition

$$\begin{pmatrix}\text{Mode Coordinate} \\ \text{Signal}\end{pmatrix} = E^{-1} S \begin{pmatrix}\text{Sensor} \\ \text{Signal}\end{pmatrix}$$

E ：Eigenmode Matrix
（Transformation matrix
from modal to physical coordinate system ）

Mode basis

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

Outlook in Cryogenics and Cryogenic Payload

Cryogenics

- Frost removal (CO_2 laser)
- Optical absorption of sapphire
- Reducing the thermal resistance of the HLs
- Identifying the source of unexpected heat flow etc…

Cryogenic Payload

- New fiber
  → sillicon fiber or new shape of sapphire fiber
- New sapphire blade spring
- Bonding techniques
- Control (scheme&sensor) etc…