# Cryogenic mirror suspension in KAGRA


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ICRR, KAGRA Collabration


Octorber 18, 2019, GRASS at Padova, Italy

# Overview

- Introduction of KAGRA and KAGRA mirror suspension

- Difficulties of cryogenics and KAGRA strategy
- Cooling effectively, quickly, and quietly
- Cryogenic compatible suspension development
- Cooling without contamination of mirrors

- Some examples of KAGRA R&D for cryogenics
- Heat link vibration isolation
- Moving mass system
- Cryogenic contamination due to the residual gas

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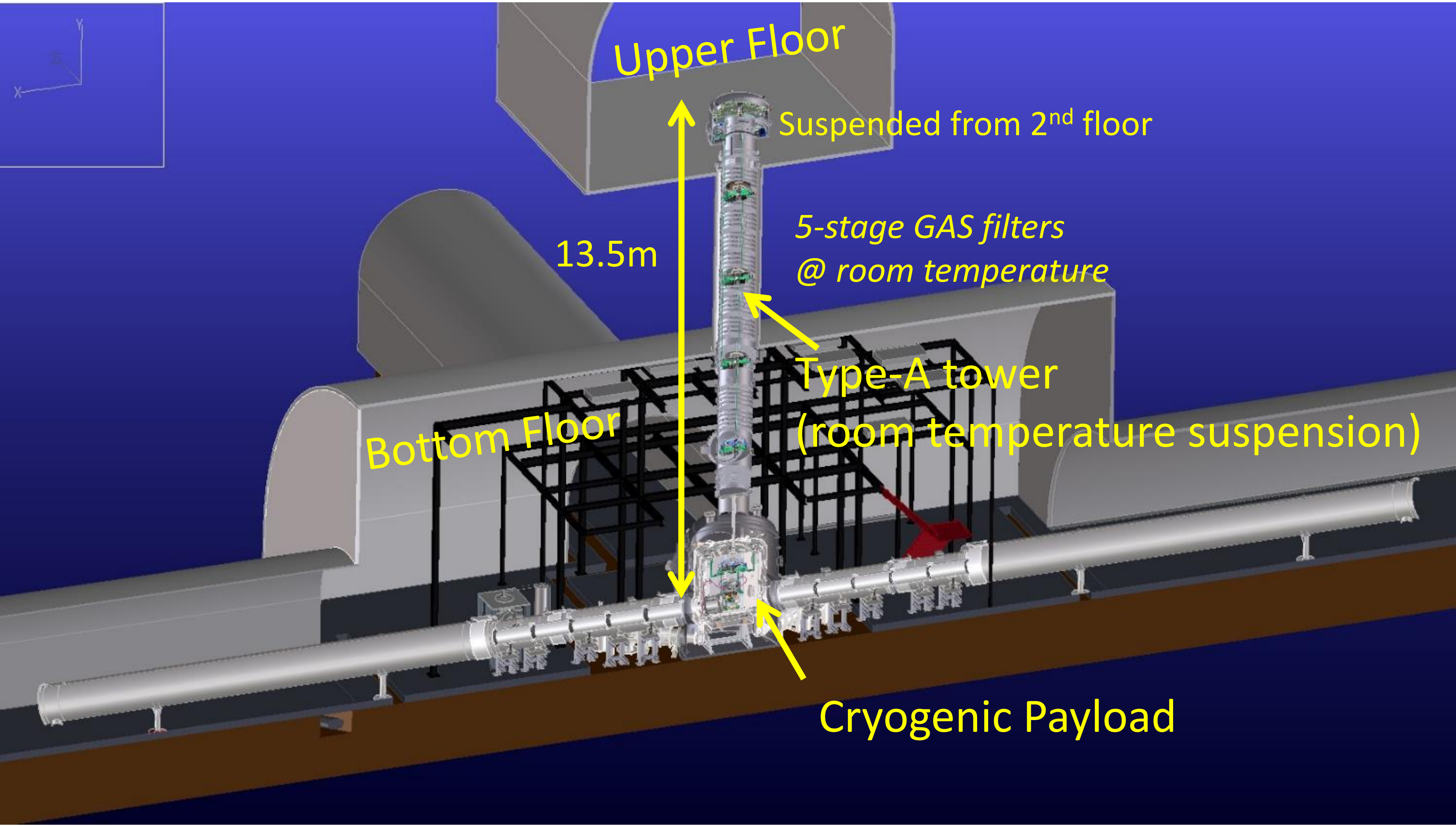
# KAGRA gravitational wave detector

- 3-km arm interferometric gravitational detector.
- Located at Kamioka in Japan near Super Kamiokande.
- Key features:
  - Using underground site
  - Using cryogenic mirrors

These features have a benefit to improve low frequency sensitivity

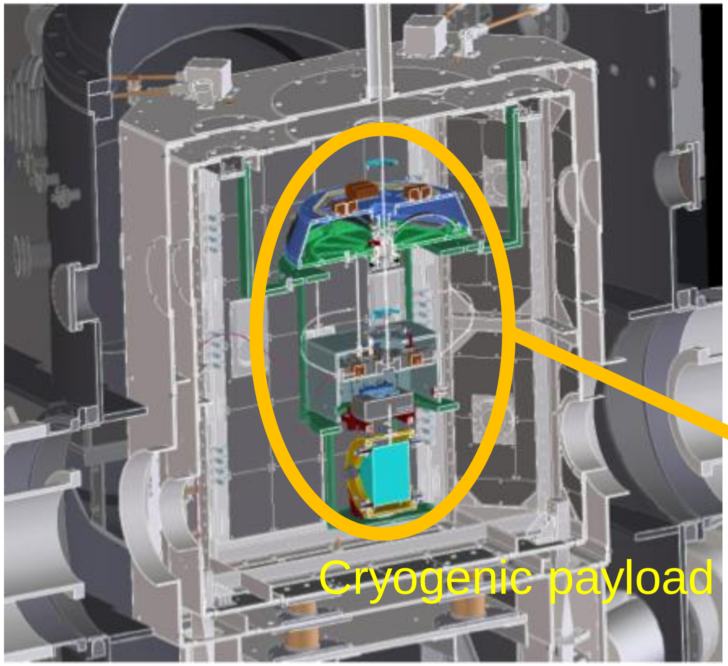
# Test mass suspension (Type-A suspension)

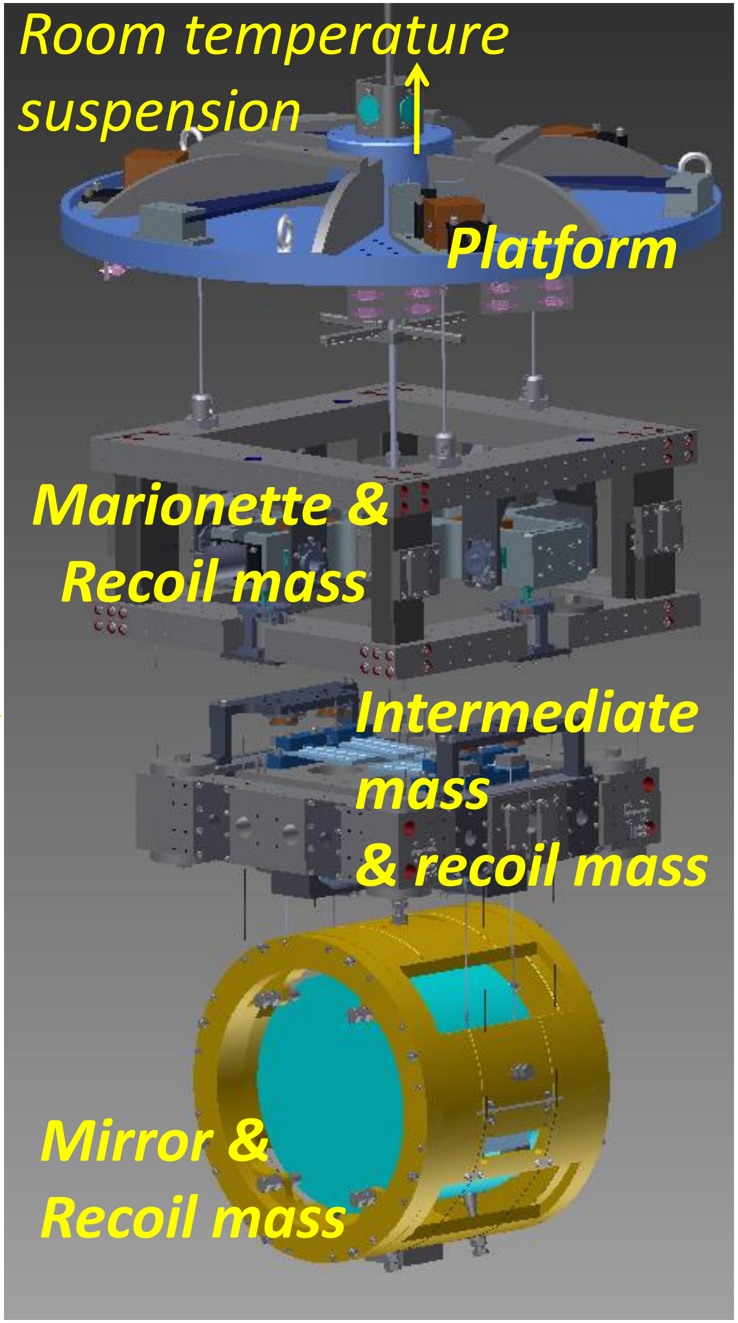
9-stage 13.5-m suspension for vibration isolation with a cryogenic mirror



# Cryogenic payload

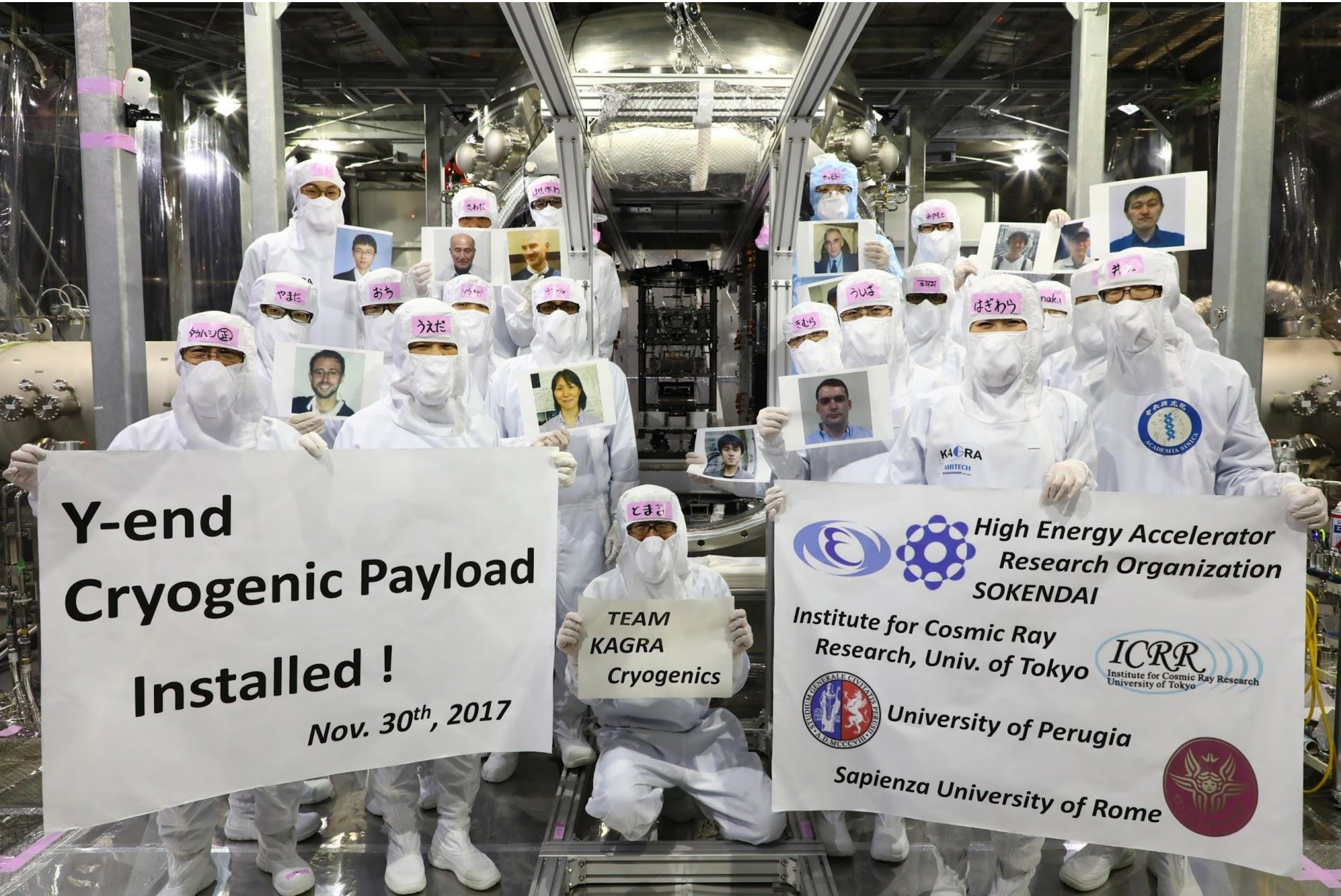
Inside cryostat




- Suspended by single wire from room temperature suspension.
- Surrounded by two layers of radiation shields, one is 80 K and the other is 8 K.

# Installation was succeeded

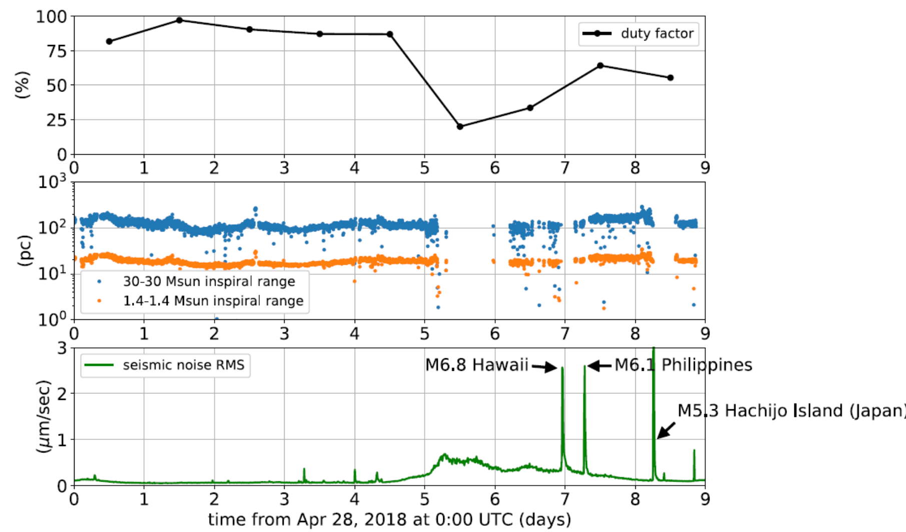


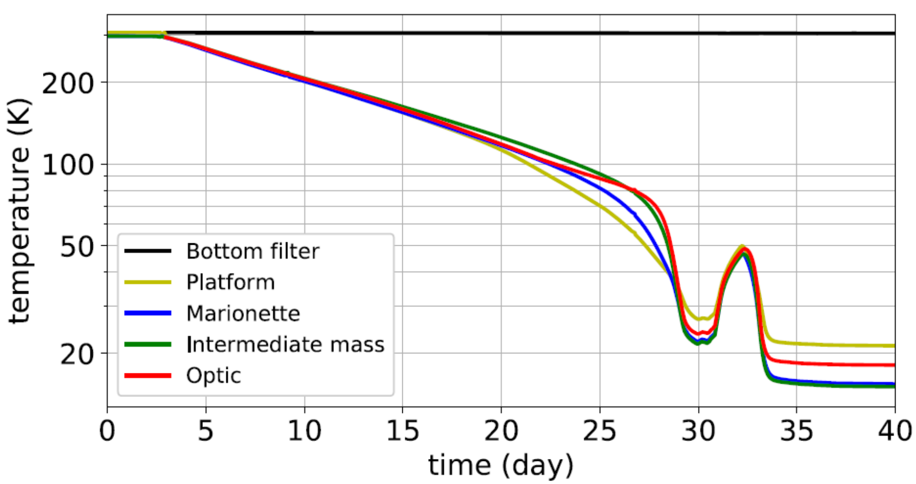
# Passing 3-km interferometer operation

IOP Publishing Classical and Quantum Gravity

Class. Quantum Grav. **36** (2019) 165008 (22pp) https://doi.org/10.1088/1361-6382/ab28a9

# First cryogenic test operation of underground km-scale gravitational-wave observatory KAGRA



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# Technical difficulties for cryogenics

- How to cool effectively

Heat absorption of mirrors, especially at ITMs, are problematic.

- How to cool quickly

Cooling time is one of the longest dead time of the detector.

- How to cool quietly

Cooling can induce the additional vibration to the mirror.

- How to achieve cryogenic compatible suspension

Materials, sensors, actuators, and so on must be cryogenic compatible.

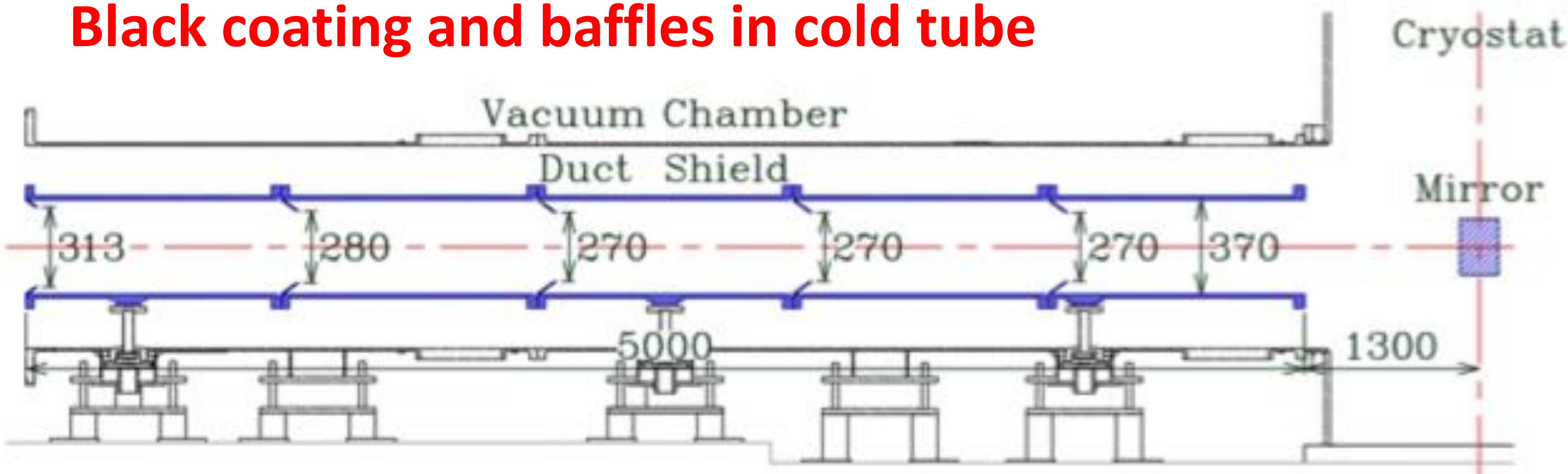
- How to deal with the cryogenic mirror contamination

Cryogenic pumping effect may gather residual gas on the mirror.

# KAGRA strategy for effective cooling I
# －Using cryogenic duct shield in the beam duct－

To reduce the thermal radiation from the beam duct, we installed the 5-m cryogenic duct shield with black coating.

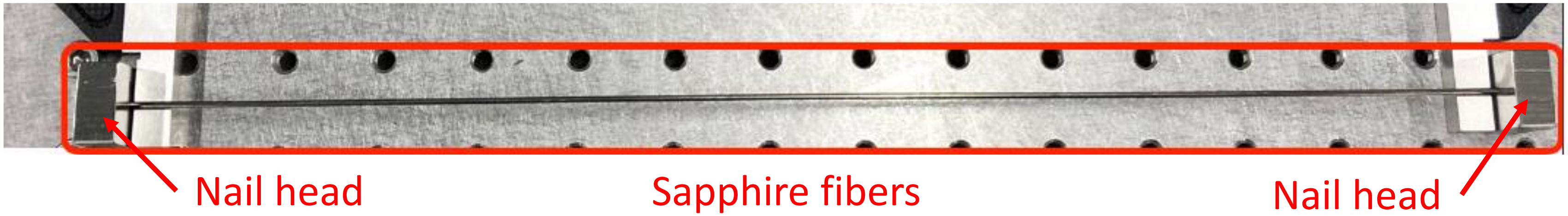

**Black coating and baffles in cold tube**




The cryogenic duct shields reduce the thermal radiation from the room temperature beam duct by 3 orders of magnitude.

# KAGRA strategy for effective cooling II
# － Using high thermal conductivity fibers －

To extract the large amount of heat from the mirror, four 1.6-mm thick sapphire fibers are utilized for the sapphire mirror suspension.



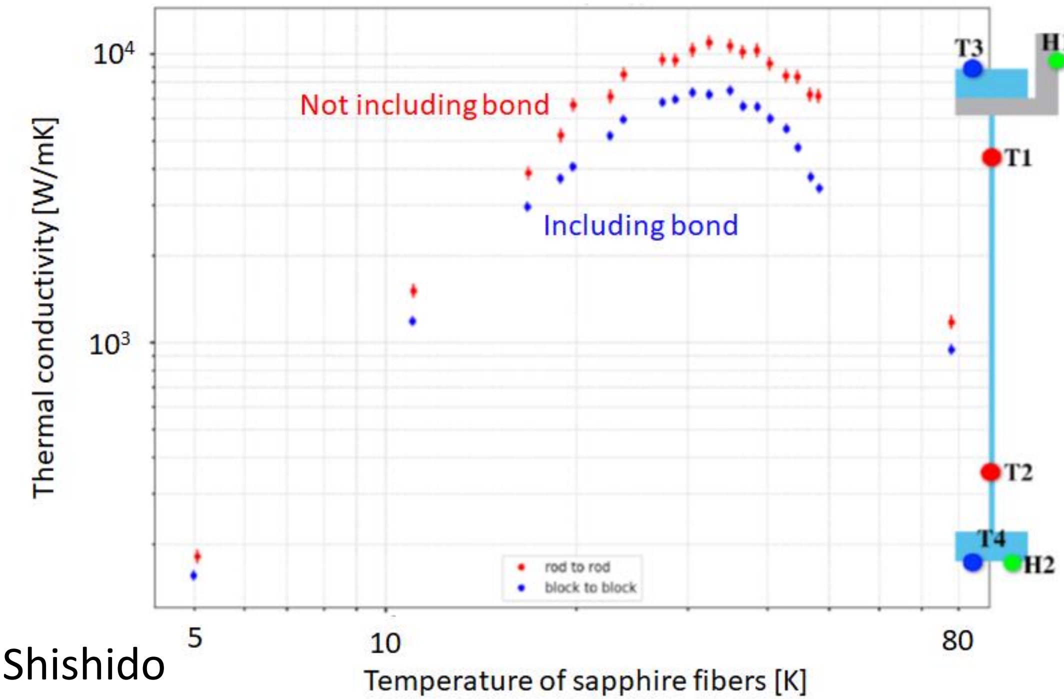

Nail heads are bonded by a kind of adhesives, which mainly consists of silica and alumina and cures at several hundreds degrees.

Thermal conductivity measurement

Not including bond (rod itself):
6000 W/m/K @ 20 K

Including bond (KAGRA fiber):
4000 W/m/K @ 20K

Bonding of the nail head has some thermal resistance.

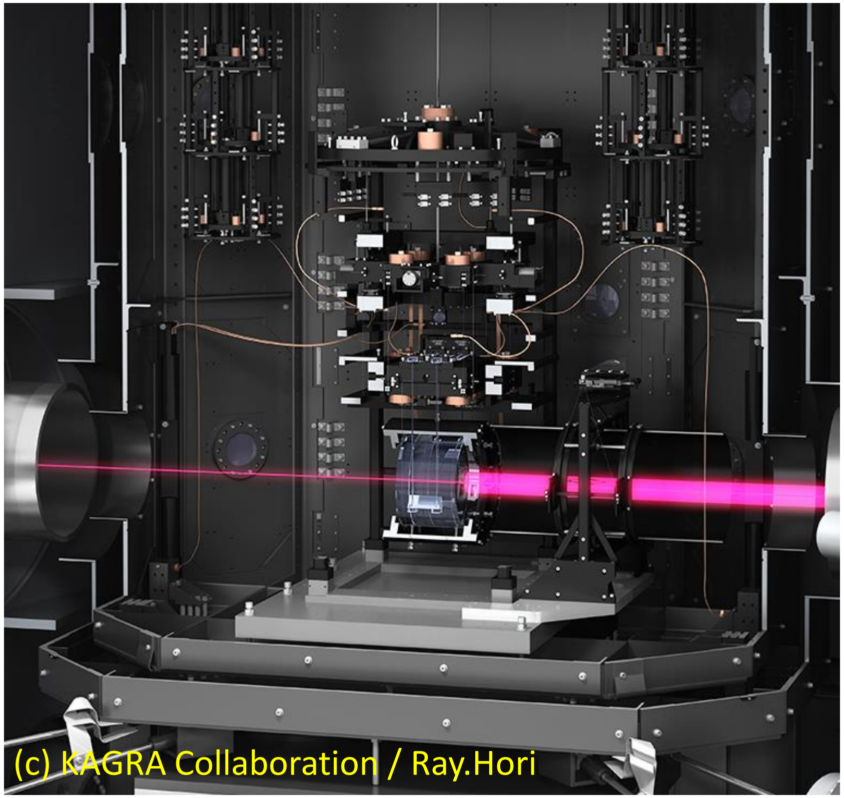



T. Shishido

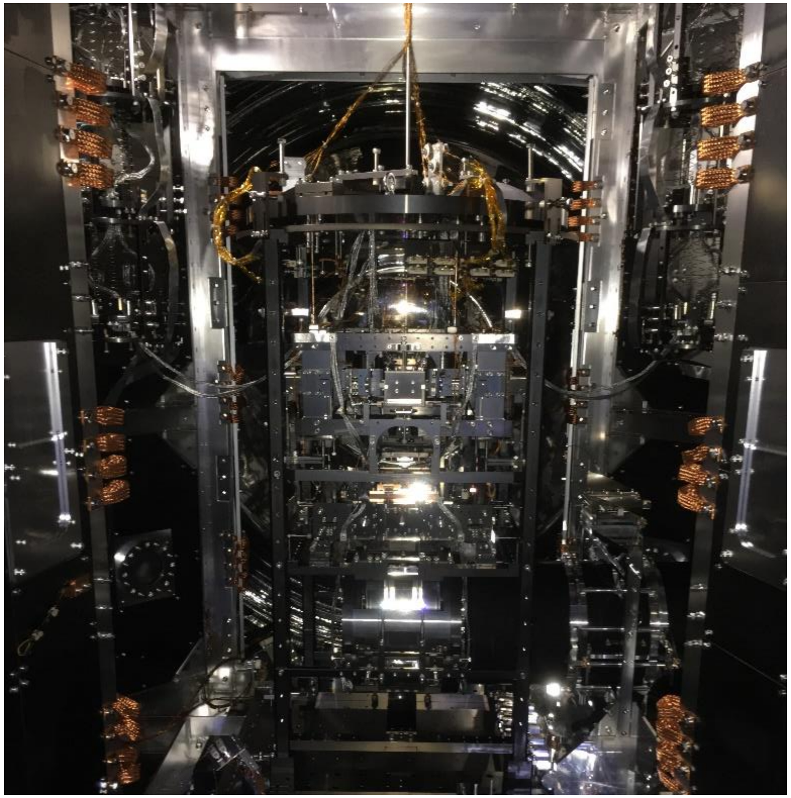
# KAGRA strategy for quick cooling I
## －Using black coating on the cryostat and payload－

To promote the radiation cooling at high temperature region, radiation shields and cryogenic payloads have black coatings.

Radiation shields:
Diamond Like Carbon (DLC) coatings
－low outgas, no magnetism
－only small area, expensive




Cryogenic payloads:
SOLBLACK coating
－low cost, can be coated on large area
－some magnetism, higher outgas



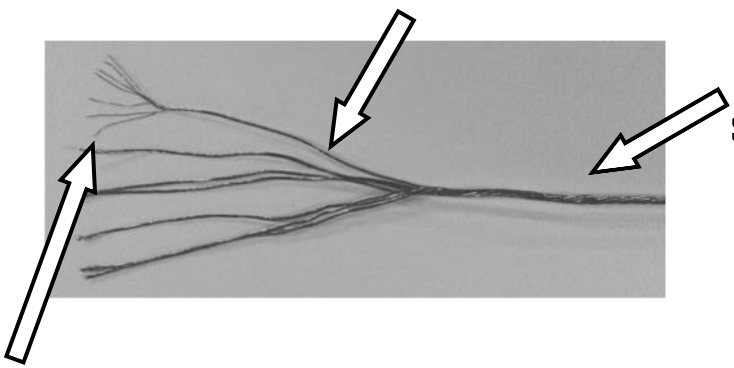
# KAGRA strategy for quick cooling II
# ー Using high purity aluminum for the heat link ー

To accelerate the cooling at low temperature region, high purity aluminum is used for the heat conductor from the cryocoolers.

7 parallels of $\phi$ 0.15 mm $\times$ 7 $\times$ 7 strands

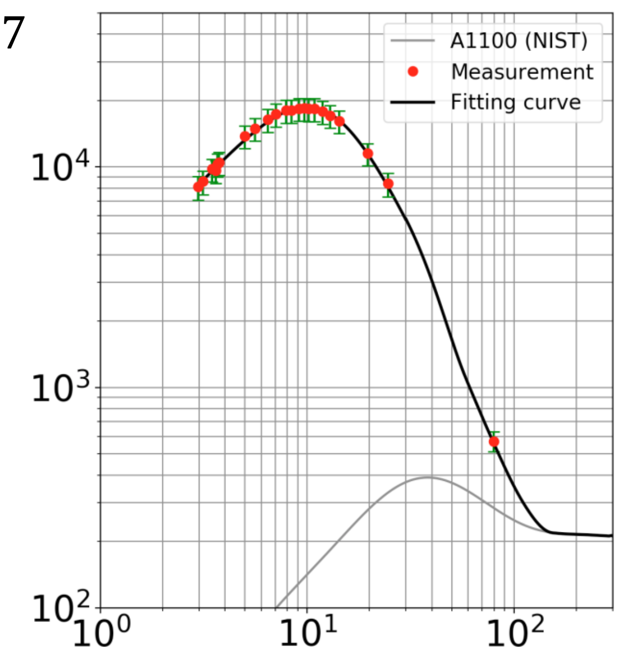
$\phi$ 0.15 mm $\times$ 7 strands

$\phi$ 0.15 mm $\times$ 7 $\times$ 7 strands



$\phi$ 0.15 mm

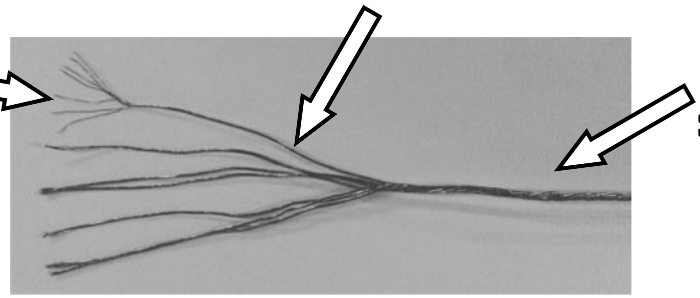
T. Yamada



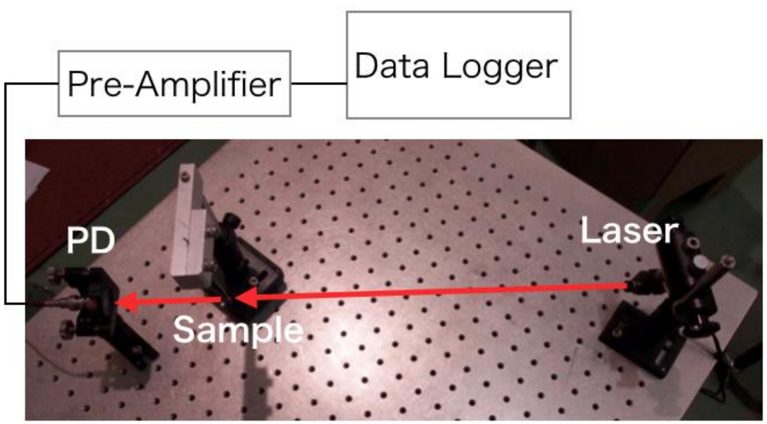

Thermal conductivity of the pure aluminum is much higher than the commercial one.
The peak value is 18500 W/m/K @ 10 K.

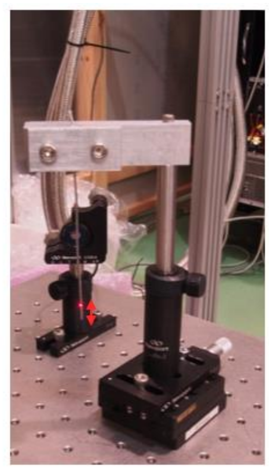
# KAGRA strategy for quiet cooling I
## －Using thin-wire stranded cables for heat link－

Pure aluminum heat conductor also plays an important role for the quiet cooling of the mirror.

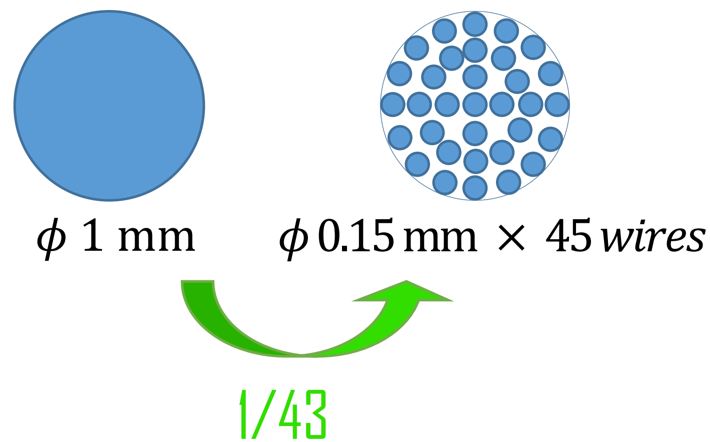



T. Yamada



Spring constant reduction



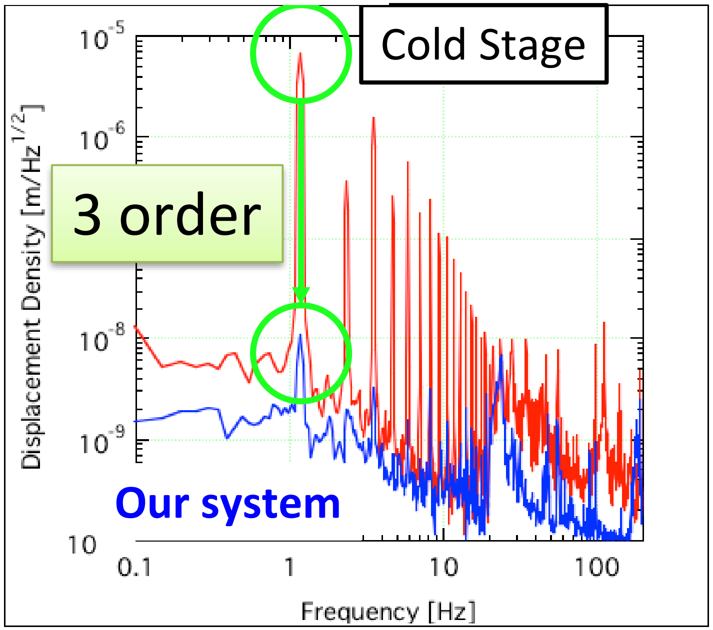

We can balance high thermal conductivity and low stiffness.

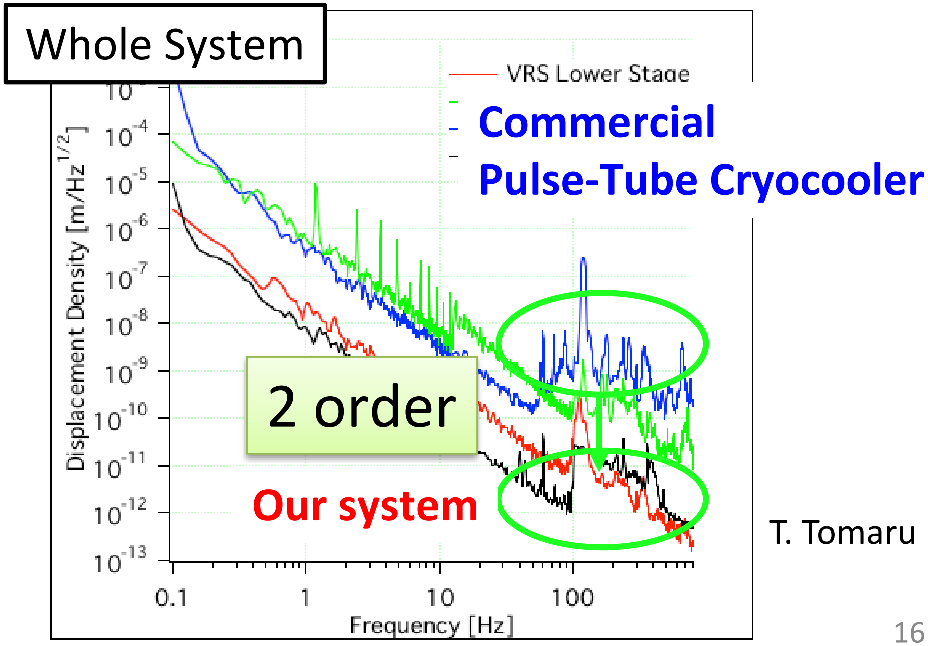
# KAGRA strategy for quiet cooling II
# － Using low vibration pulse-tube cryocoolers －

Low-vibration cryocooler established for the CLIO prototype is also used for KAGRA.

- **nm vibration** at cold stage
- comparable vibration level of whole system with Kamioka seismic vibration.

**Commercial**
**Pulse-Tube Cryocooler**

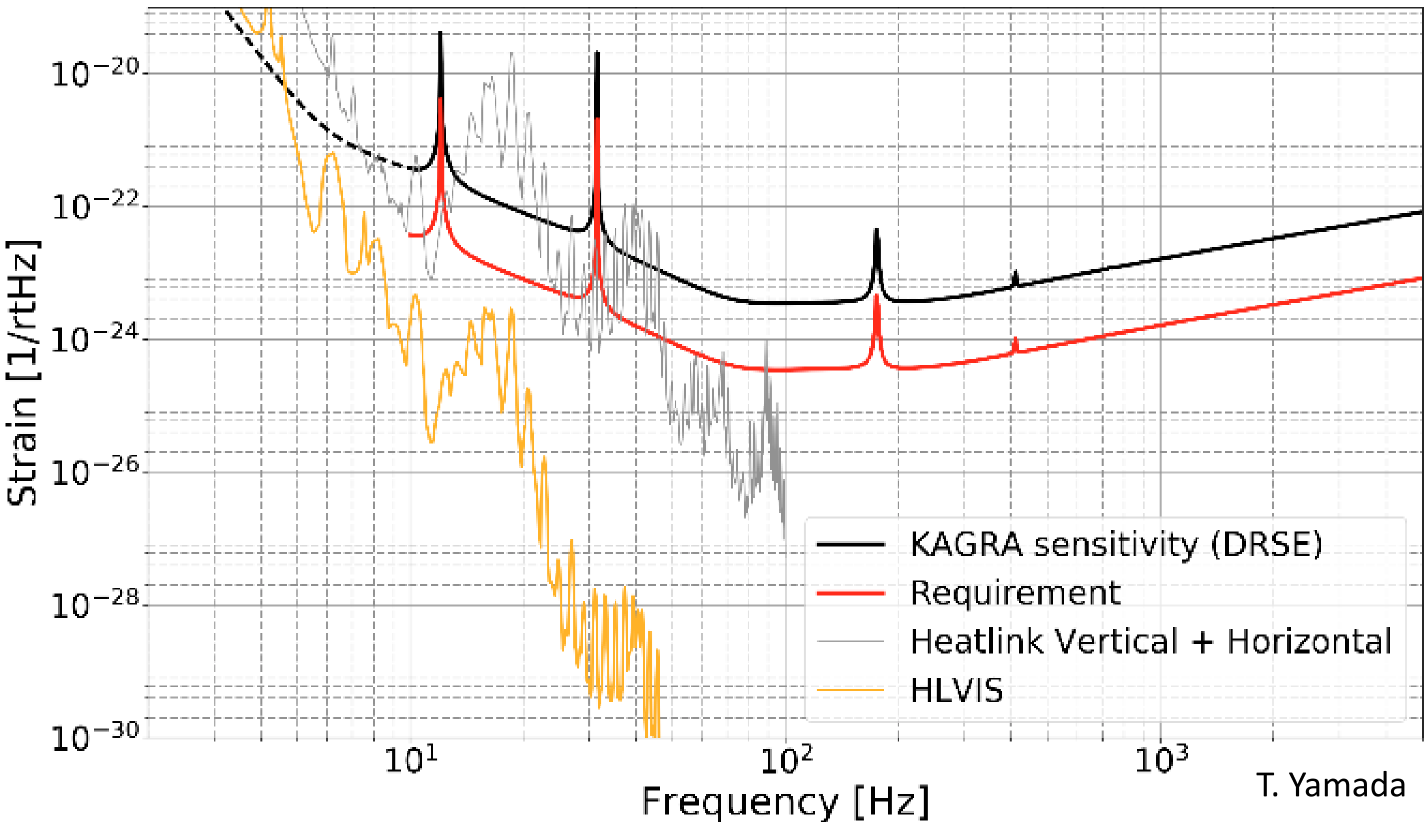


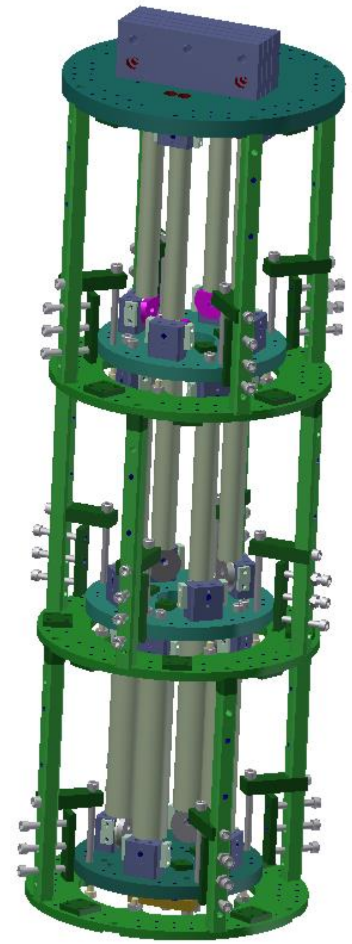

T. Tomaru

# KAGRA strategy for the quiet cooling III
## －Using heat link vibration isolation system－

Three stage vibration isolation system with tension springs is installed for isolating vibration through the heat links




T. Yamada

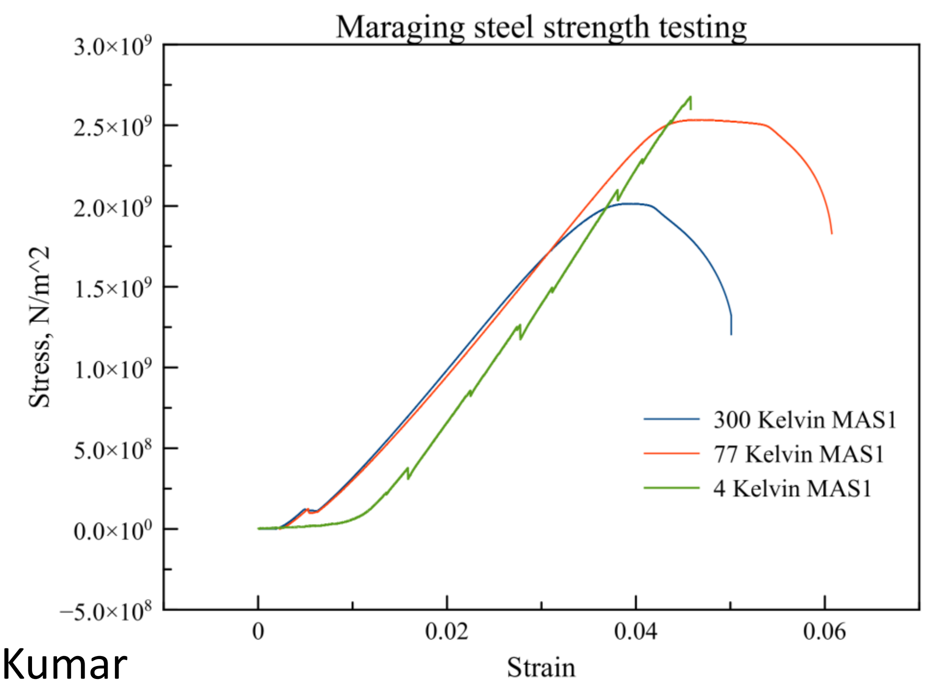


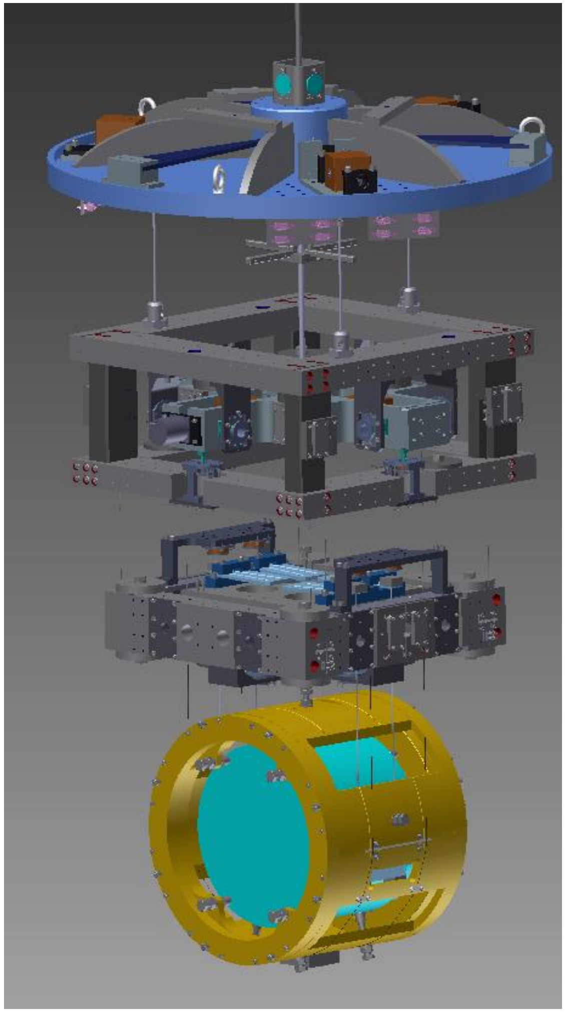
# KAGRA strategy for cryo-compatible suspension I
# ー Using materials without brittleness ー

Using beryllium copper (BeCu) for the leaf sping on the Platform stage of the cryogenic payload.

For vertical vibration isolation, Leaf springs are often used but brittle material is not suitable for this purpose.

Maraging steel, which is used for the GAS filter of KAGRA has brittleness at low temperature.



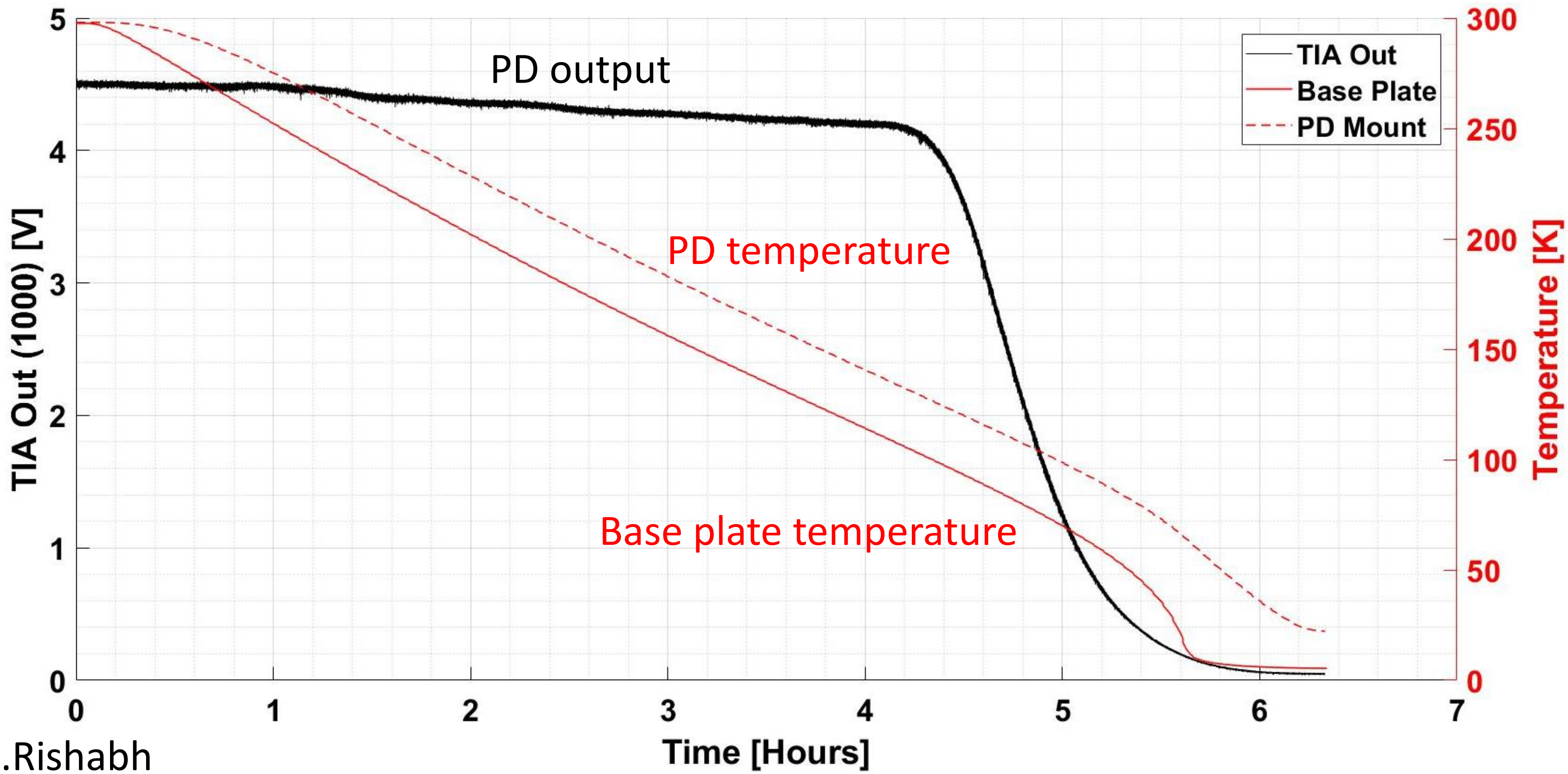
R. Kumar

# KAGRA strategy for cryo-compatible suspension II
## －Using cryogenic compatible sensors－

We selected a pair of PDs and LEDs that can work below 10 K.

PD: FGA21 (Thorlabs), LED: L1200E (Thorlabs)

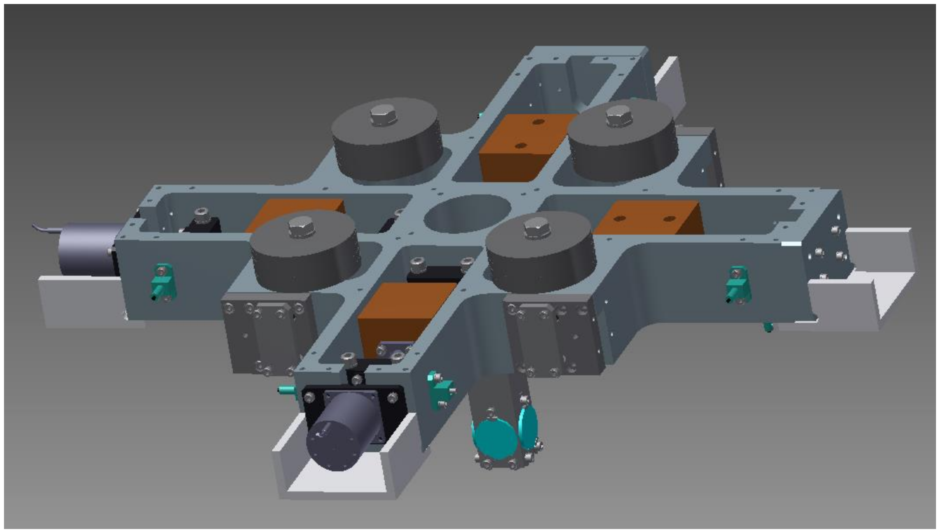
These sets of LEDs and PDs works well during cryogenic operation of KAGRA.
However, if we change the wavelength of light, they do not work anymore.

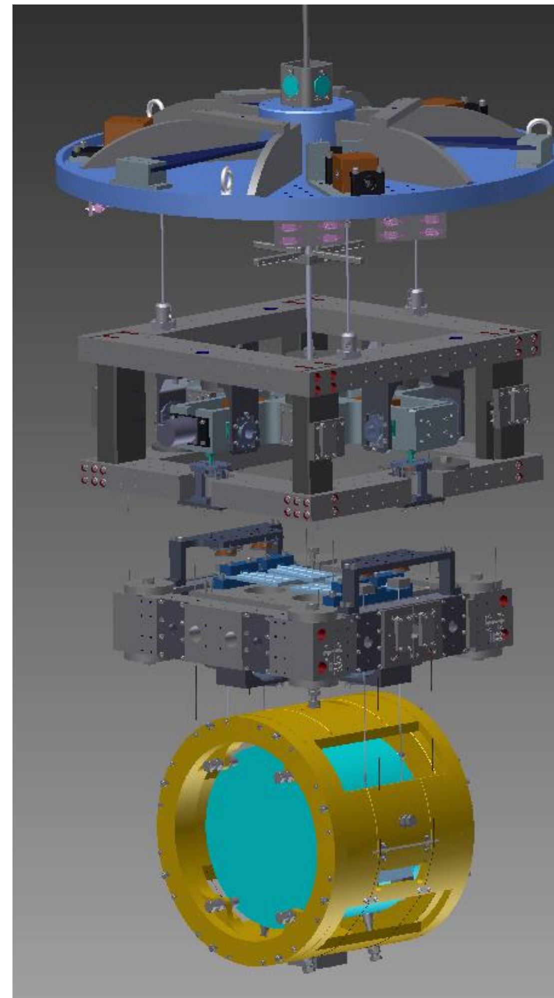


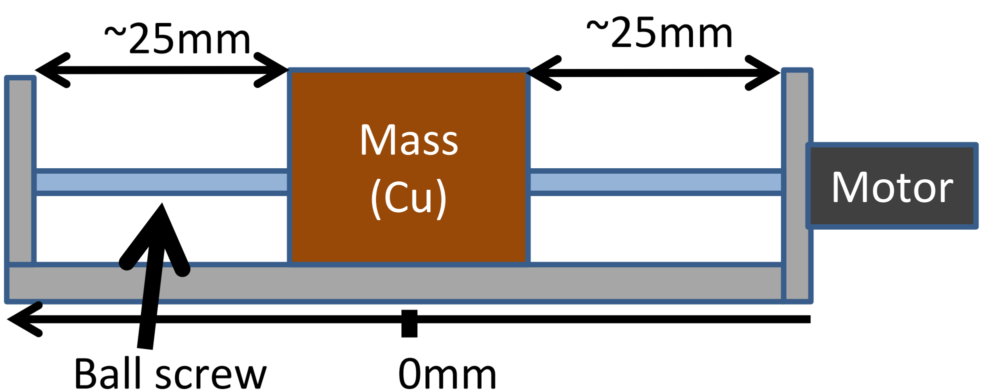

B.Rishabh

# KAGRA strategy for cryo-compatible suspension III
## －Using cryogenic compatible actuators－

We developed large dynamic range mirror inclination adjustment system, moving mass system, with a grease-free ball screw.





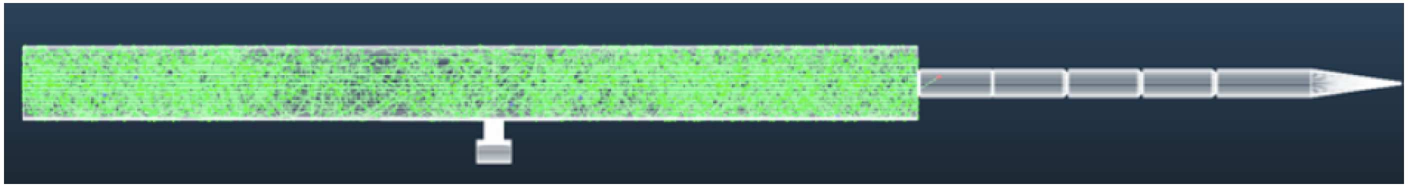


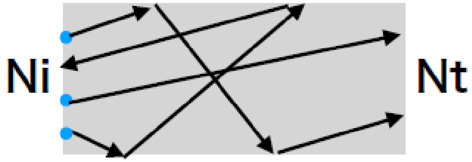
# KAGRA strategy for cryo-mirror contamination
## － Cryogenic contamination R&D －

## Adlayer Formation Rate (2)

K. Hasegawa

The conductance of the system determines the flux of molecules to the cryogenic mirror.






Ni : Number of particles injected to a duct
Nt : Number of particles coming through a duct

| Cond. [m3/s] | ΔP [Pa] | Sim. result | Eep. Result |
|---|---|---|---|
| 0.162 | 6.9×10^{-6} | 42 nm/day | 27.1nm/day |

It's possible and important to design the vacuum and the cryogenic systems from the point of view of the molecular layer formation!

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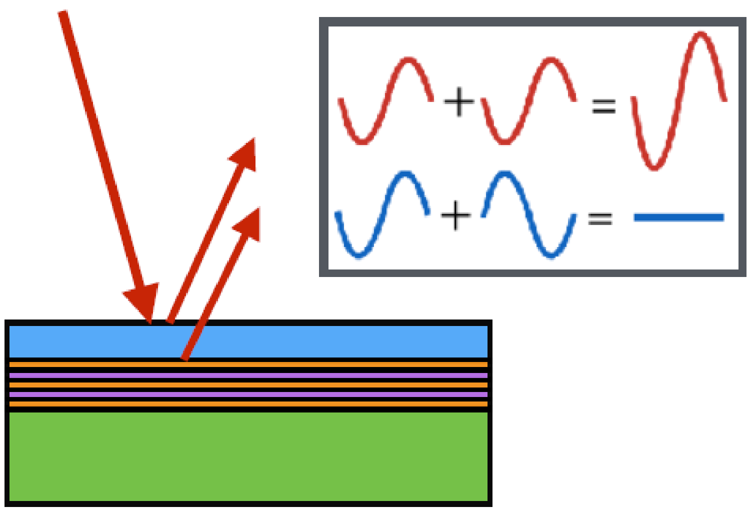
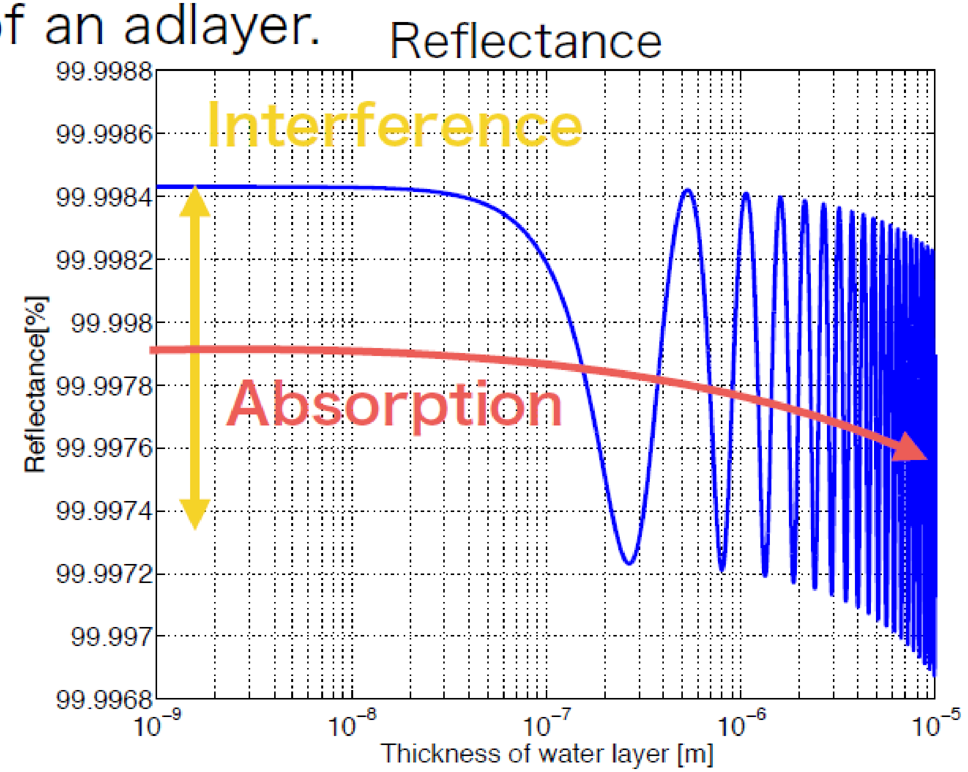
K. Hasegawa
From Amaldi 2019 slide

# Molecular adsorption on a mirror

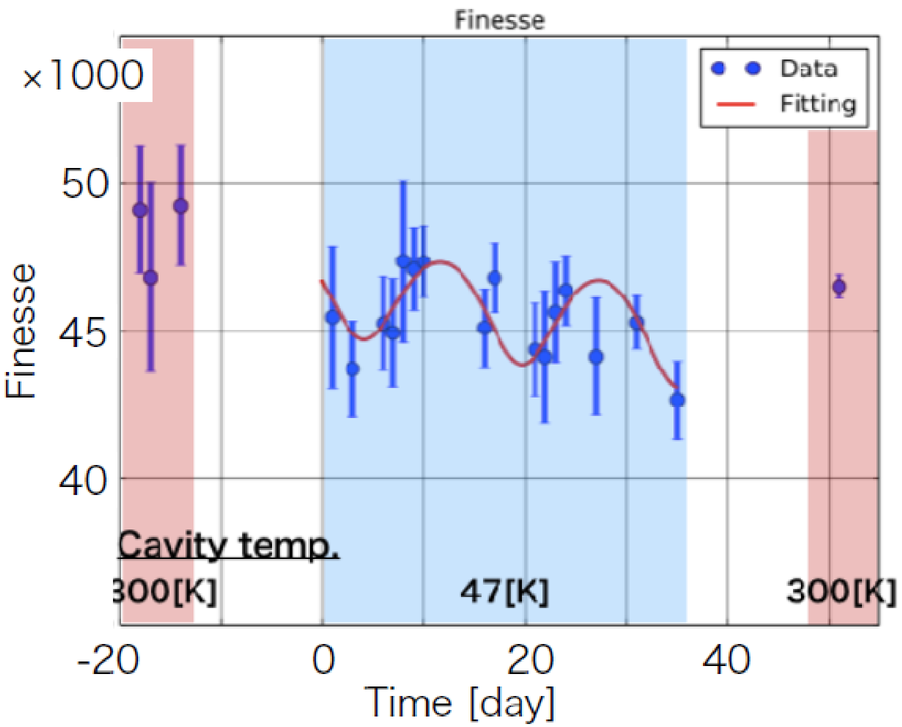
A molecular adsorbed layer expects to work as an optical coating. The parameter of the cryogenic mirror changes depending on the thickness of an adlayer.

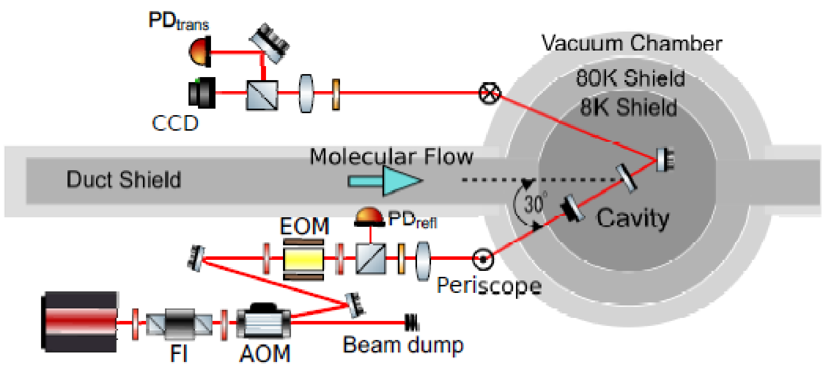




# Adlayer Formation Rate (1)

A molecular adsorbed layer formation rate was measured using the KAGRA cryostat with the high finesse optical cavity.



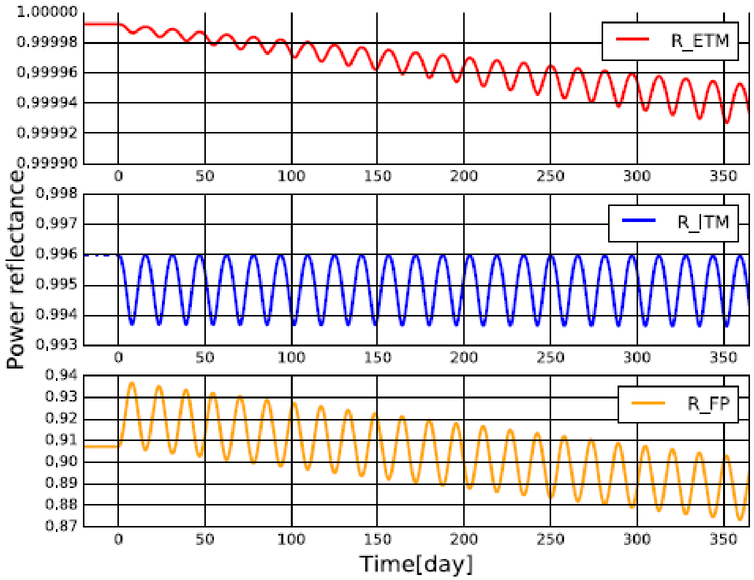



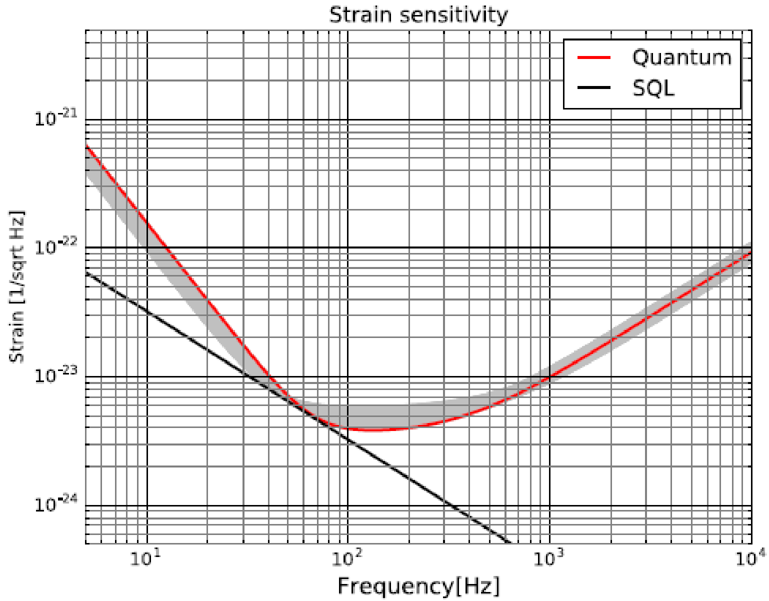

Results:
Formation speed : 27.1 +/- 1.9 nm/day
Refractive index : 1.26 +/- 0.073
 -> Adlayer mainly consists of H2O molecules.

K.Hasegawa et al. Phys. Rev. D **99**, 022003(2019)

# Impacts on the GWD (1)

The optical effects:
The reflectivity changes of the test masses directly change the quantum noise of the detector.



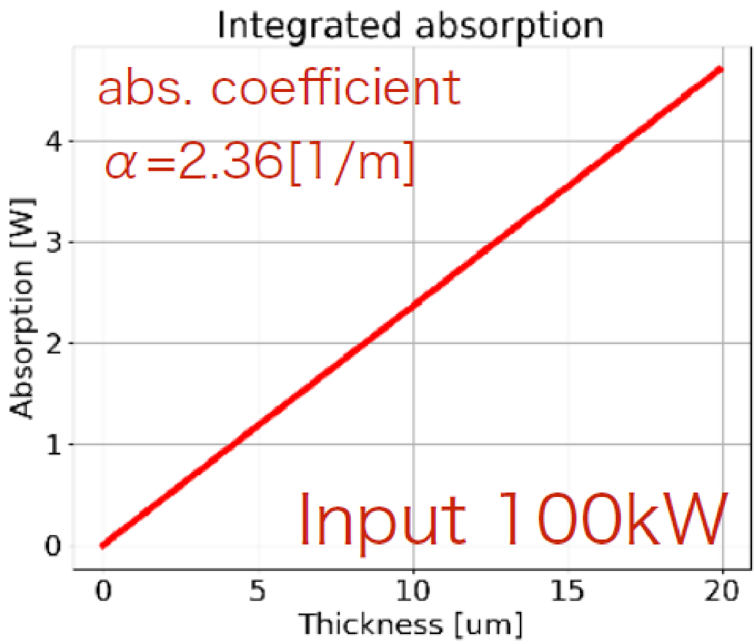

Moreover, the scattering and the inhomogeneity of the adlayer can worsen the sensitivity more…

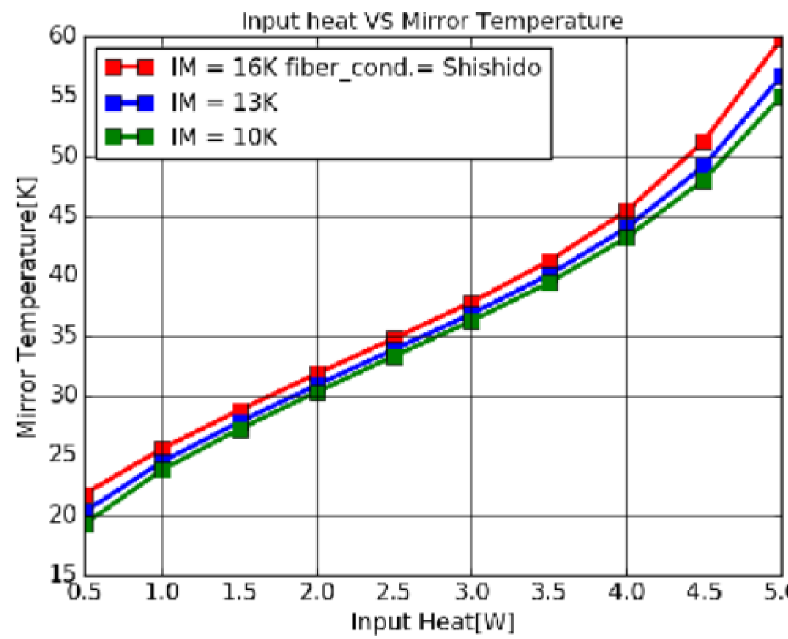
K. Hasegawa
From Amaldi 2019 slide

# Impacts on the GWD (2)

Thermal effects

The optical absorption in the adlayer increases the input heat to the cryogenic system.



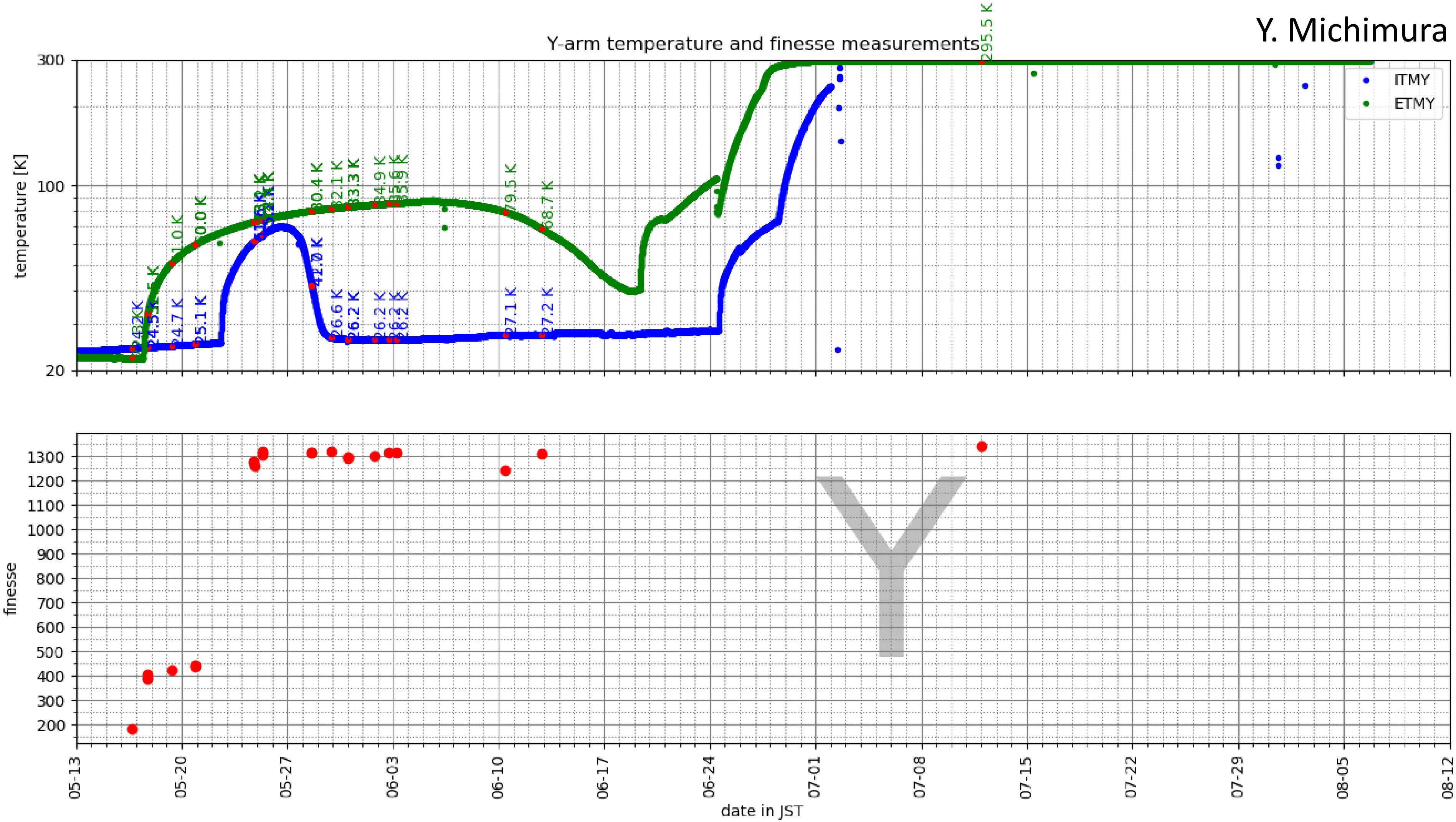




Although it is small absorption, the huge amount of intra-cavity laser power makes large heat to the mirror.

# Finesse drops due to the cryogenic contamination

Cryogenic contamination made finesse of arm cavity worse.

Y. Michimura

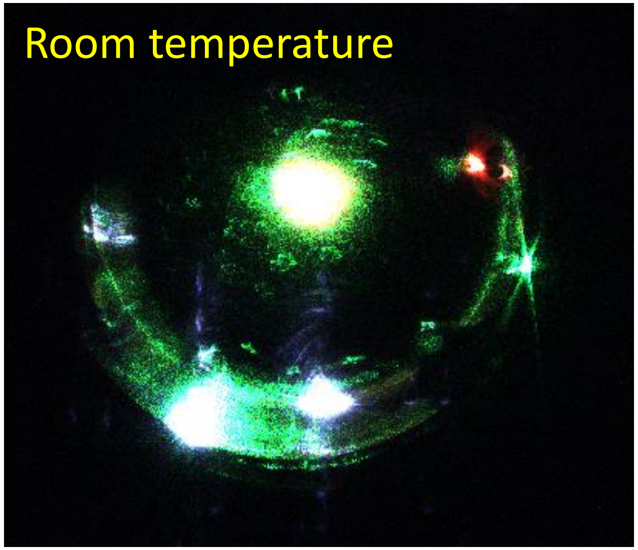


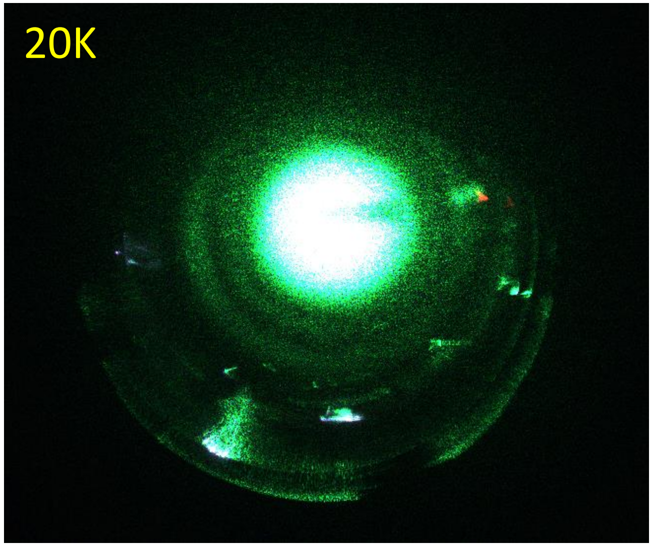

Finesse drop highly depends on the cooling strategy, so we are trying to optimize it

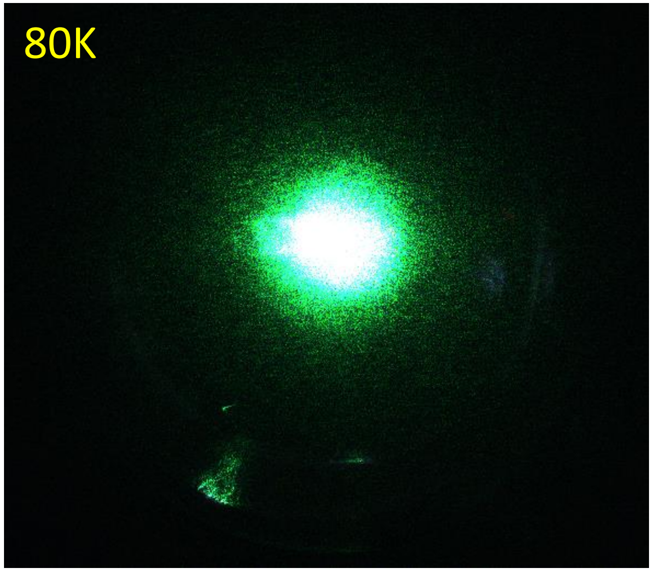
# Camera observed the strange scattering

Real is more problematic than we expected.

Some residual gas formed frosts on the mirror surface




In addition to this, we observed frosts on the  optical viewport for the OpLev.

We should consider how to remove the frost on the mirror and viewport without warming up full suspension.

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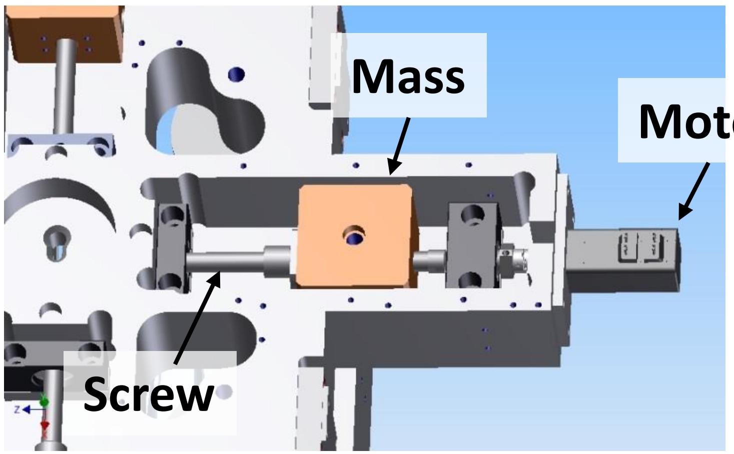
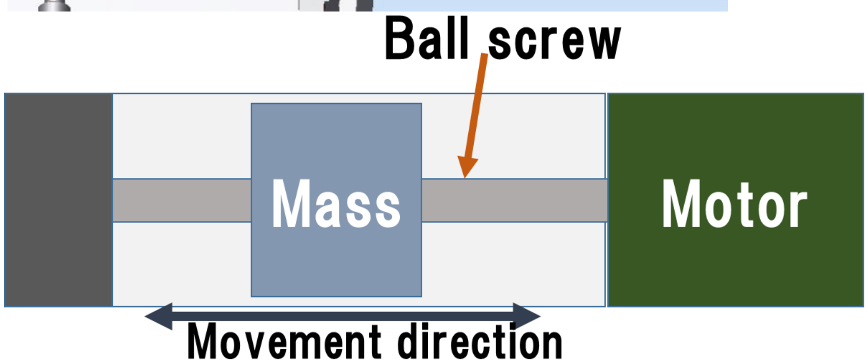
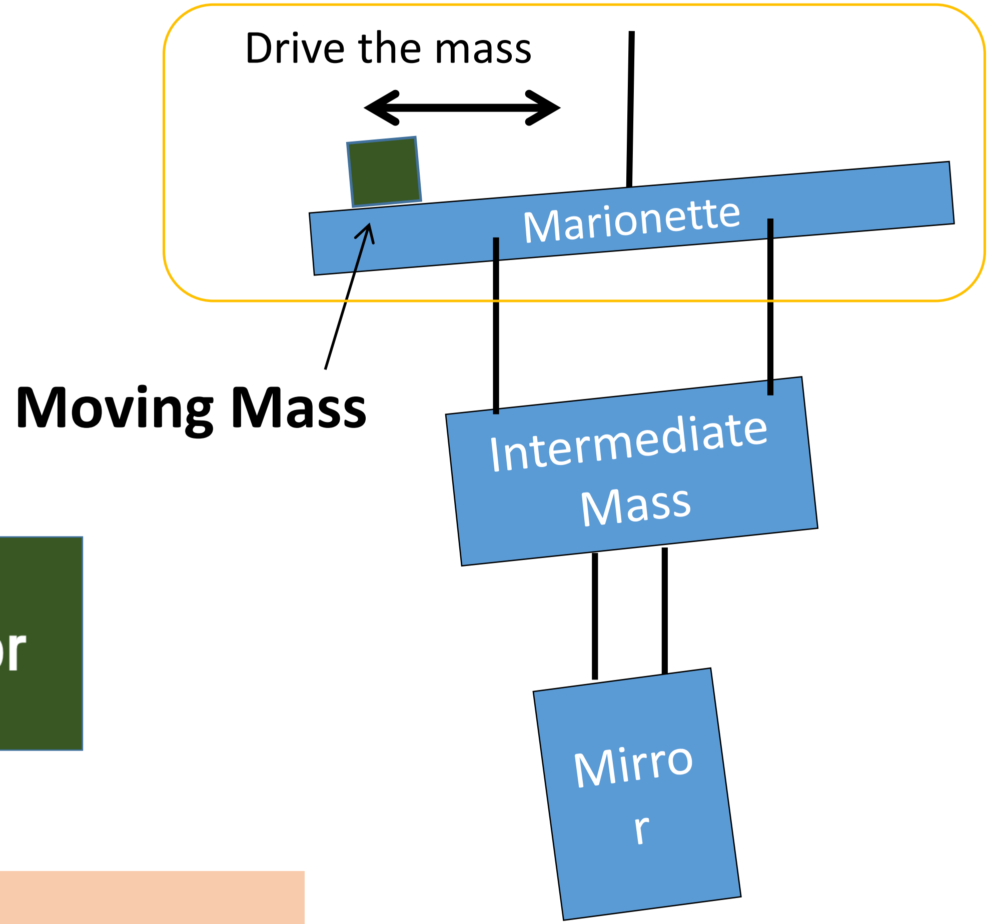
# Moving mass system

Since the Marionette is suspended by single wire, it is necessary to install the tilt actuator at the marionette stage.



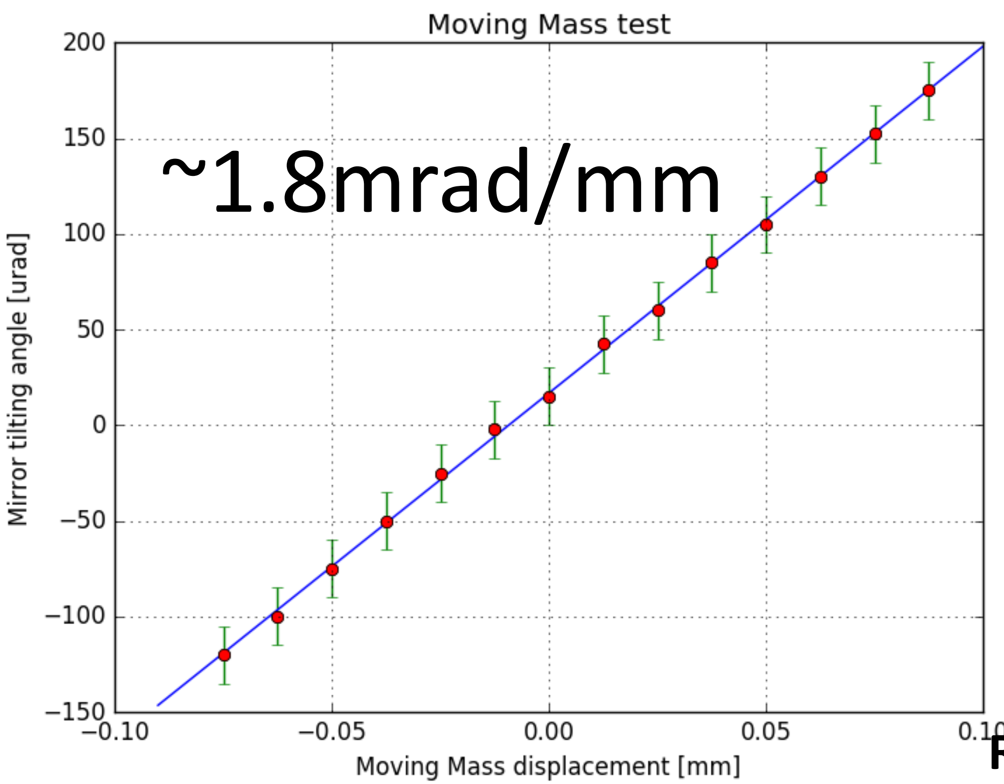



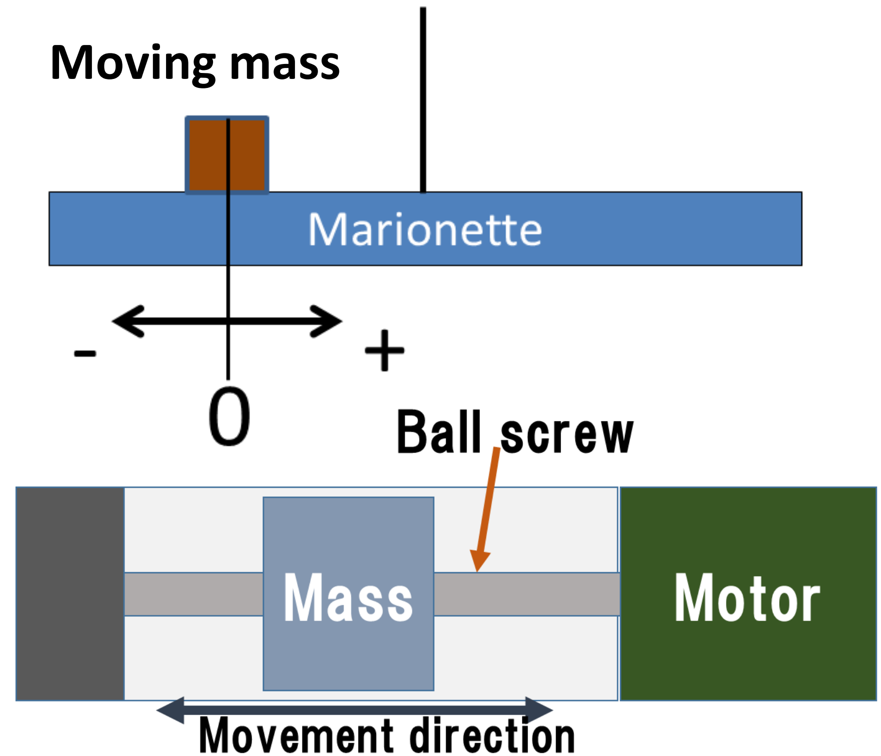

**Schematic view**

Requirement:
Range: 20 mrad, Resolusion: 9 urad

# Moving mass performance

Performance test result at 15 K




Range of motion of this Mass : ±10mm

Evaluated maximum range : **36 mrad > 20 mrad**

Resolution : **0.45 urad < 9 urad**

# Issues on the moving mass system

- Since there is no grease to reduce friction, metal ball inside the ball screw is damaged and sometimes stacks.
- It is necessary to clean up all the setup of the moving mass, when we have a thermal cycle of the payload.
- It is also necessary to replace old one to new one when we have several thermal cycles.
- This issue makes it difficult to achieve the long-term stable operation of the moving mass system (we have already experienced the stack of moving mass system several times).
- So, we started to consider the new mechanism of the moving mass system, which can have easy and simple maintenance.

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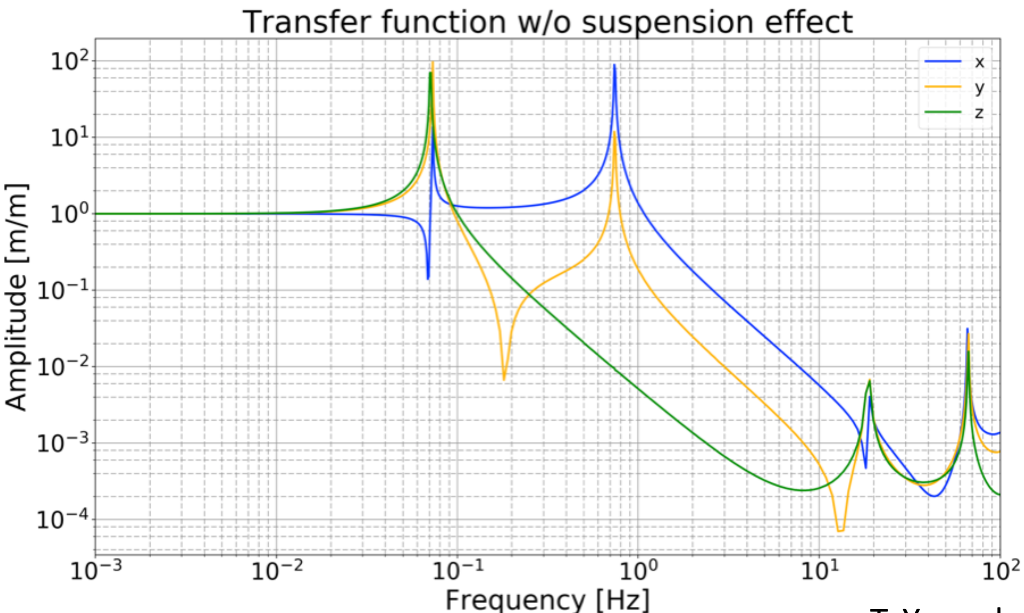
# Vibration transfer via heatlinks

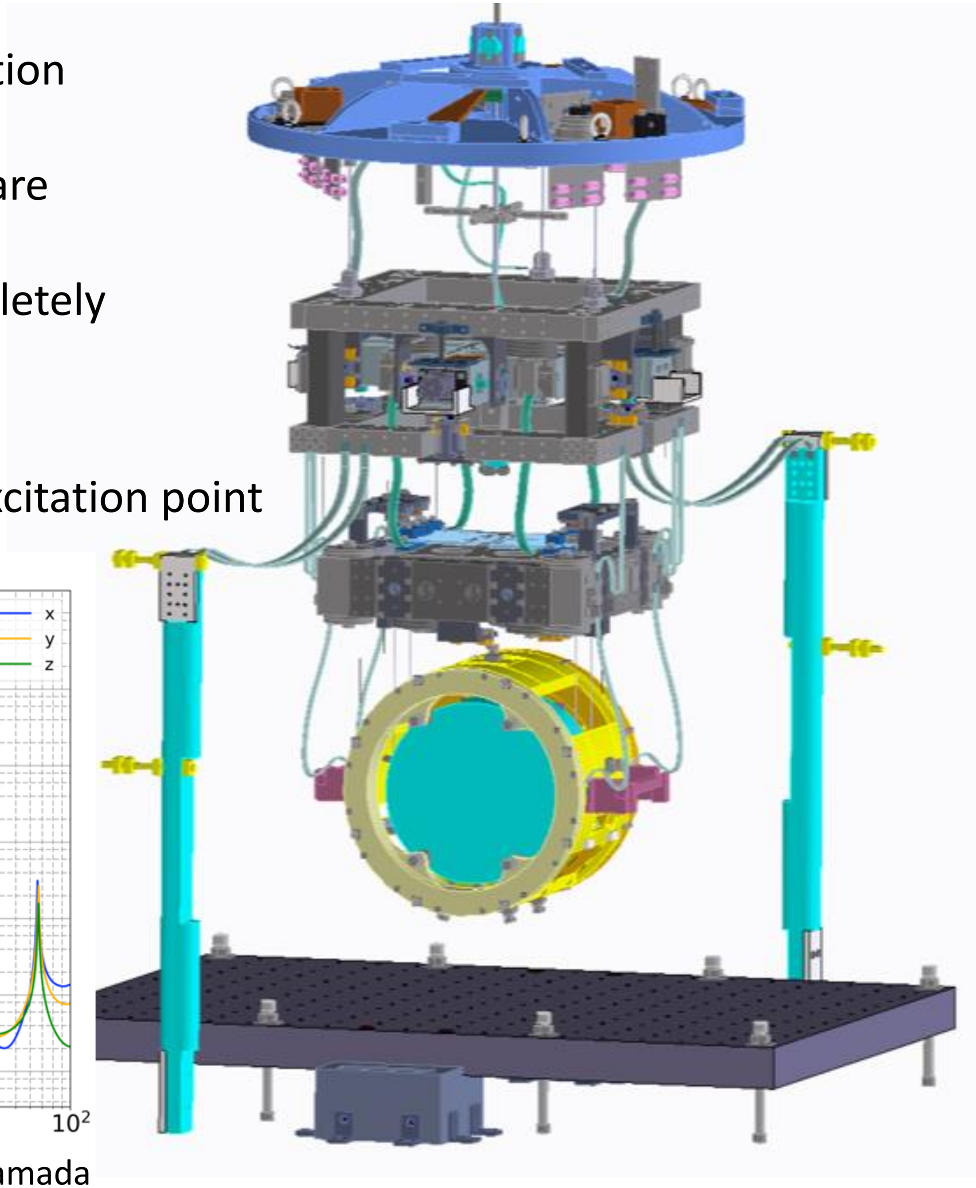
- We calculated the vibration transfer function of the heat links by using ANSYS.
- We assumed that the shape of heatlinks are catenary curve.
- We assumed that the suspension is completely free mass.

Using ANSYS to calculate




T. Yamada

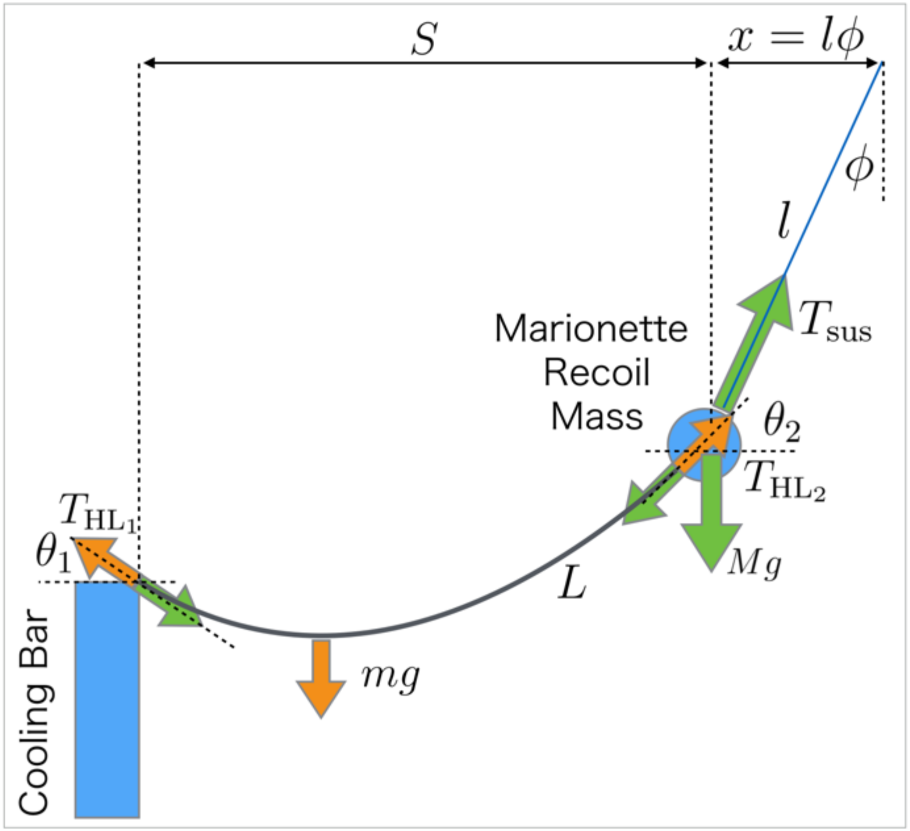
Excitation point

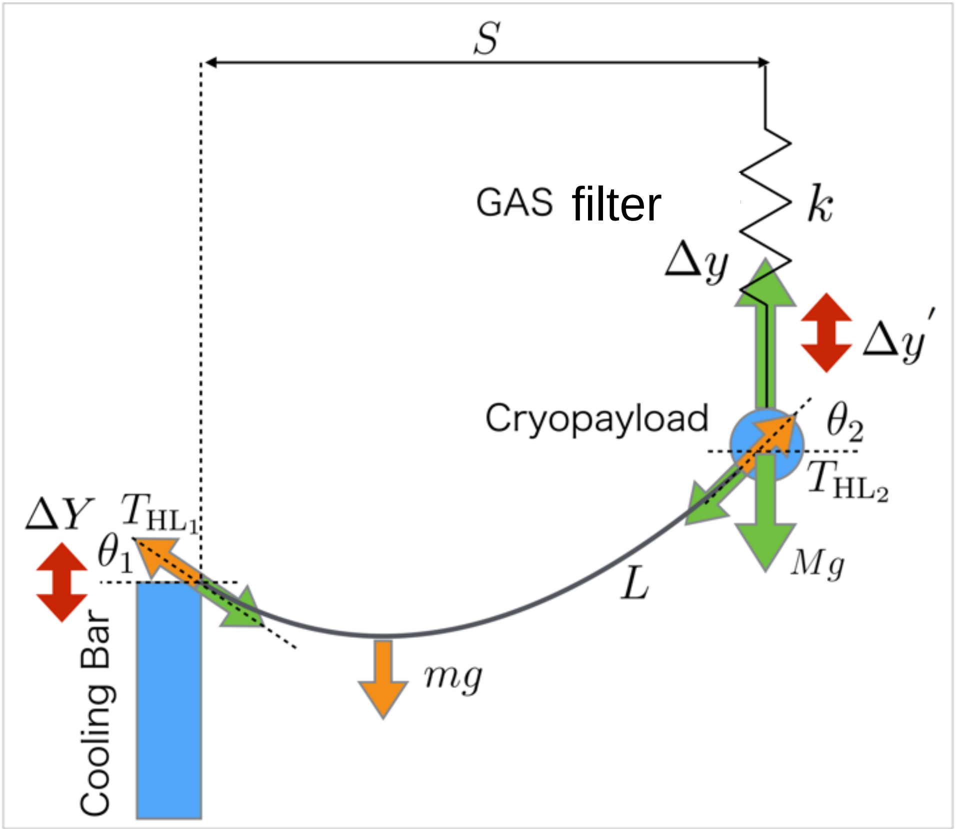


T. Yamada

# Suspended effect

Since the mirror is not a free mass but a suspended mass, we should correct the DC value of the calculated transfer function.

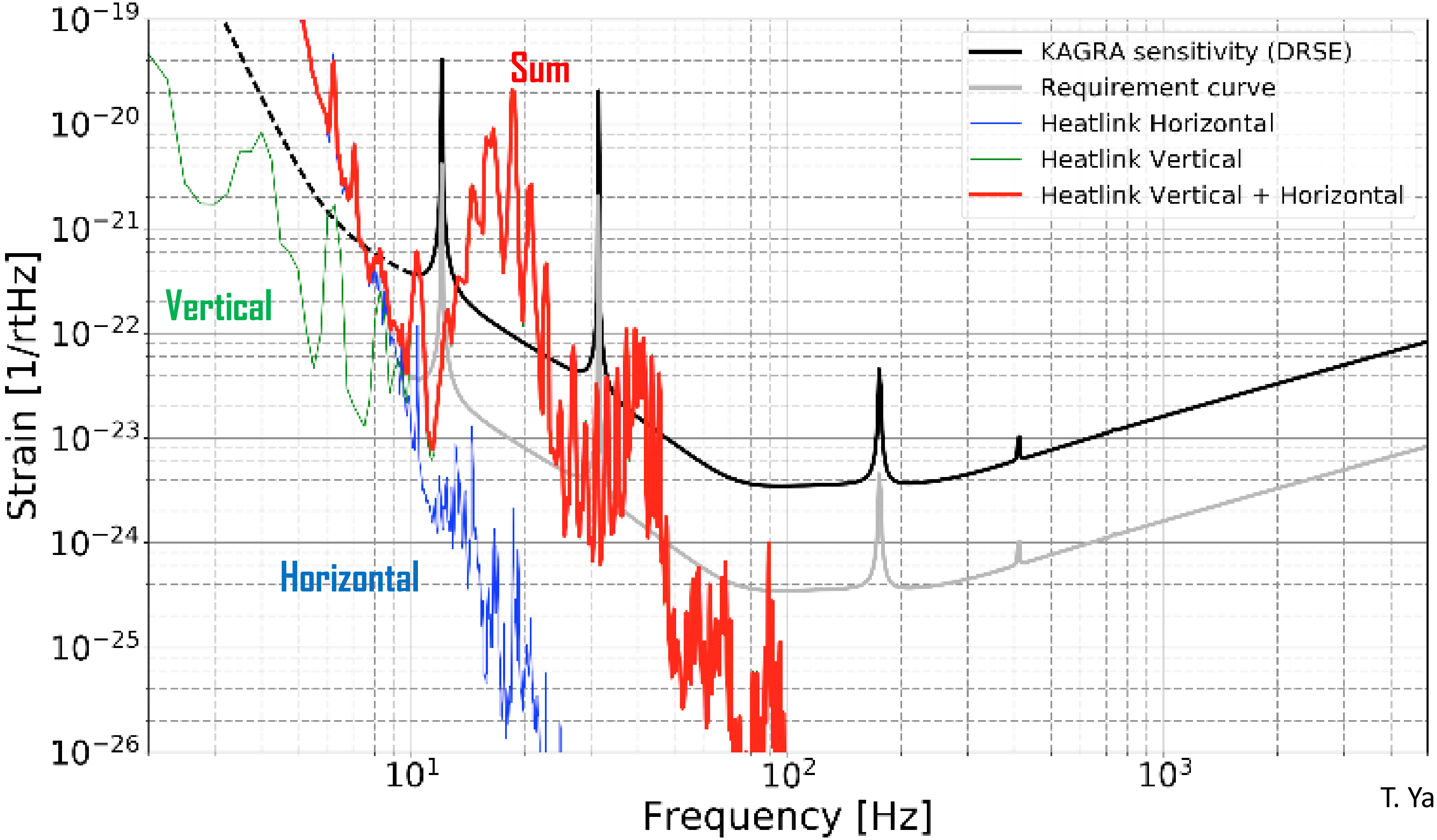



DC vales are related to heat link mass, spring constant of suspension, and also the RMS displacement of the cooling bars.

# Vibration injection at the test mass

1% coupling from vertical motion to longitudinal motion of the mirror is asuumed.

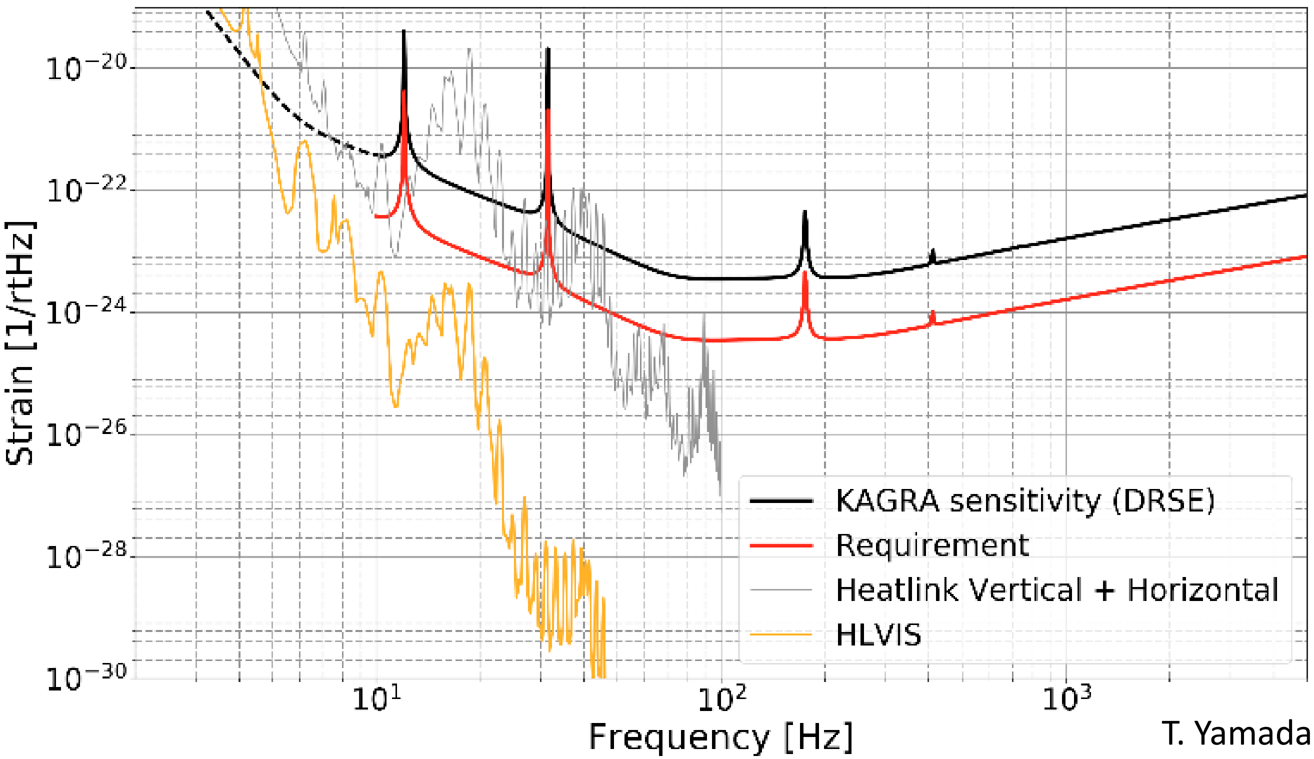



T. Yamada

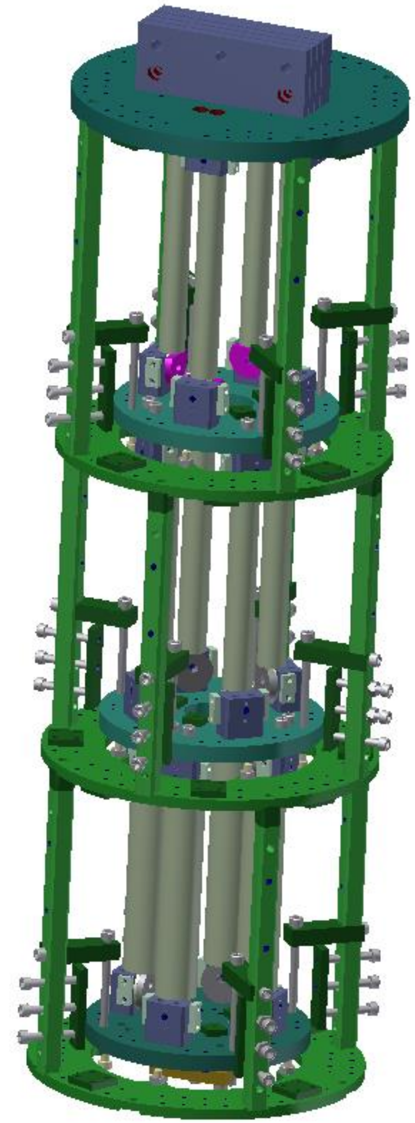
Below 10 Hz, horizontal motion has large impact to the sensitivity.
Above 10 Hz, coupling from vertical motion can contaminate the sensitivity.

# Heat Link Vibration Isolation System (HLVIS) of KAGRA

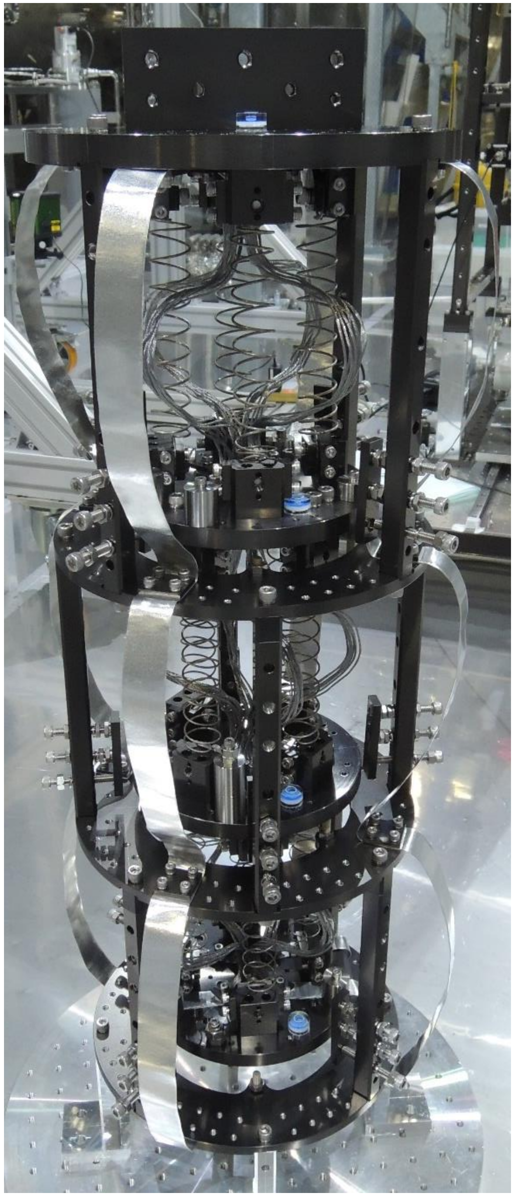
- Three-stage VISs with tension springs are installed.
- Resonant frequency of vertical motion of each stage is 3 Hz.
- Whole mass is about 20 kg and supported from the top of inner radiation shields of KAGRA.

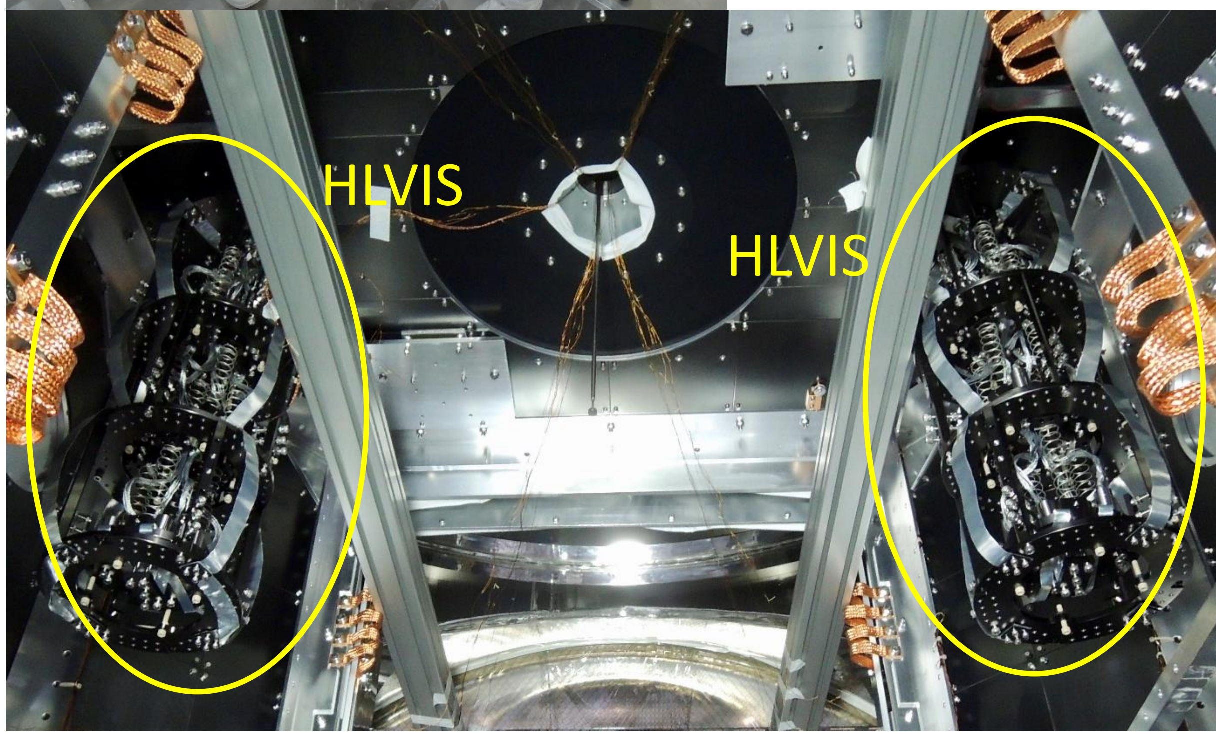



T. Yamada

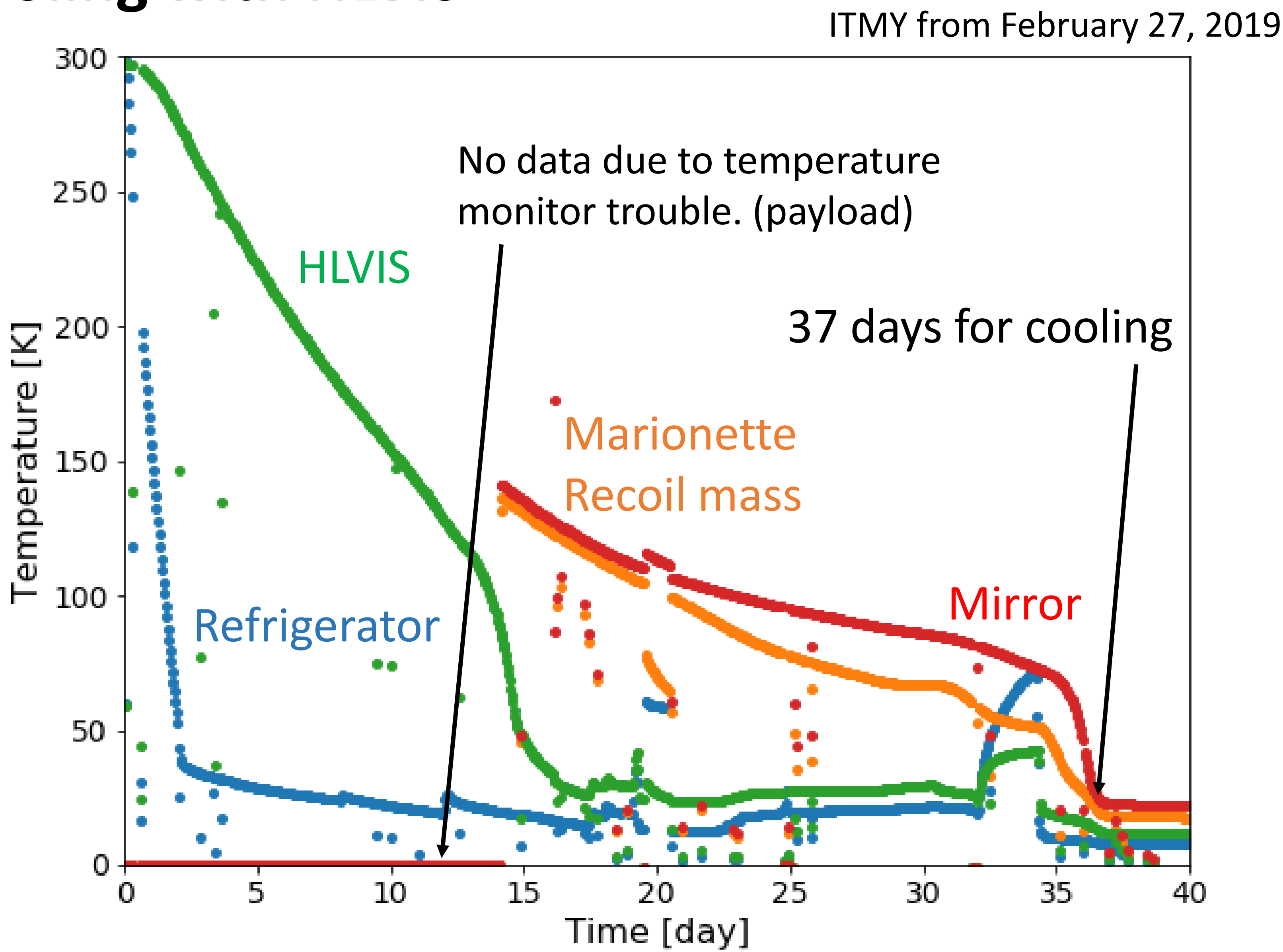


# HLVIS installation at KAGRA site





# Cooling with HLVIS




We could cool the sapphire mirror at around 20 K with HLVIS.

# Summary

- Required technology for applying cryogenics to the gravitational wave detector is very high.

- Cooling effectively, quickly, and quietly
- Cryogenic compatible suspension development
- Cooling without contamination of mirrors

- KAGRA cryogenic payloads have many tricks for achieving cryogenic mirror suspension.

－Still, it is not enough but many important experiences have been obtained.

- Cryo-contamination is one of the most problematic issues we are facing.

- HLVIS is essential for the low frequency sensitivity improvement