Reduction of vibration transfer via heat links in KAGRA cryogenic mirror suspension system

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Introduction

Tow important characteristics in KAGRA

- Underground -> Small seismic noise
- Cryogenic mirror -> Small thermal noise

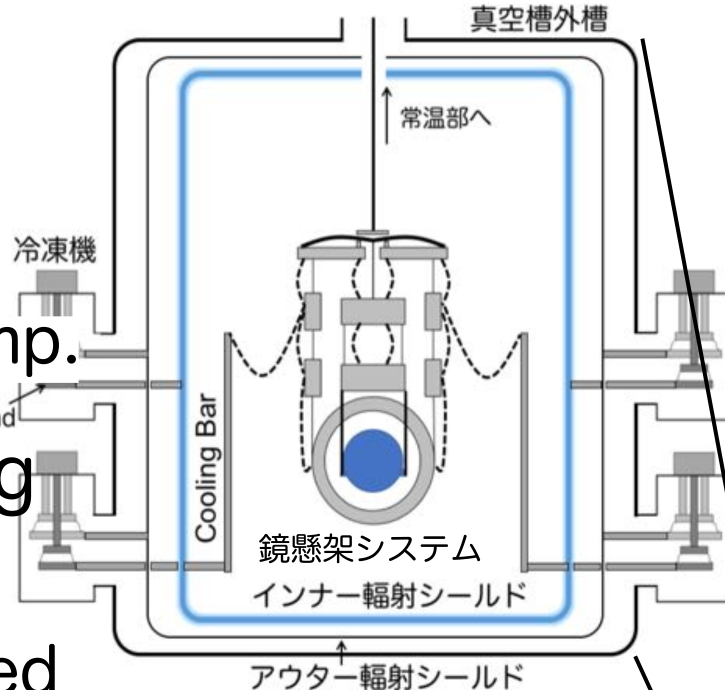
Cooling method

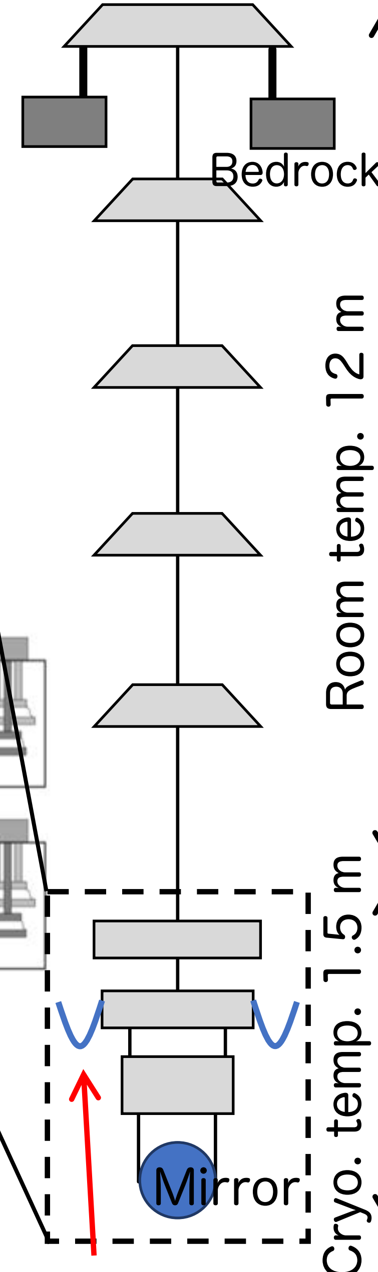
Effective cooling with small vibration

- Radiative cooling

$$P \propto A\varepsilon\left(T_{\mathrm{susp}}^4 - T_{\mathrm{shield}}^4\right)$$

  - Non-contact
  - Effective at high temp.





- Conductive cooling
  - Necessary for 20K
  - Heat link is connected to vibration isolated stage.

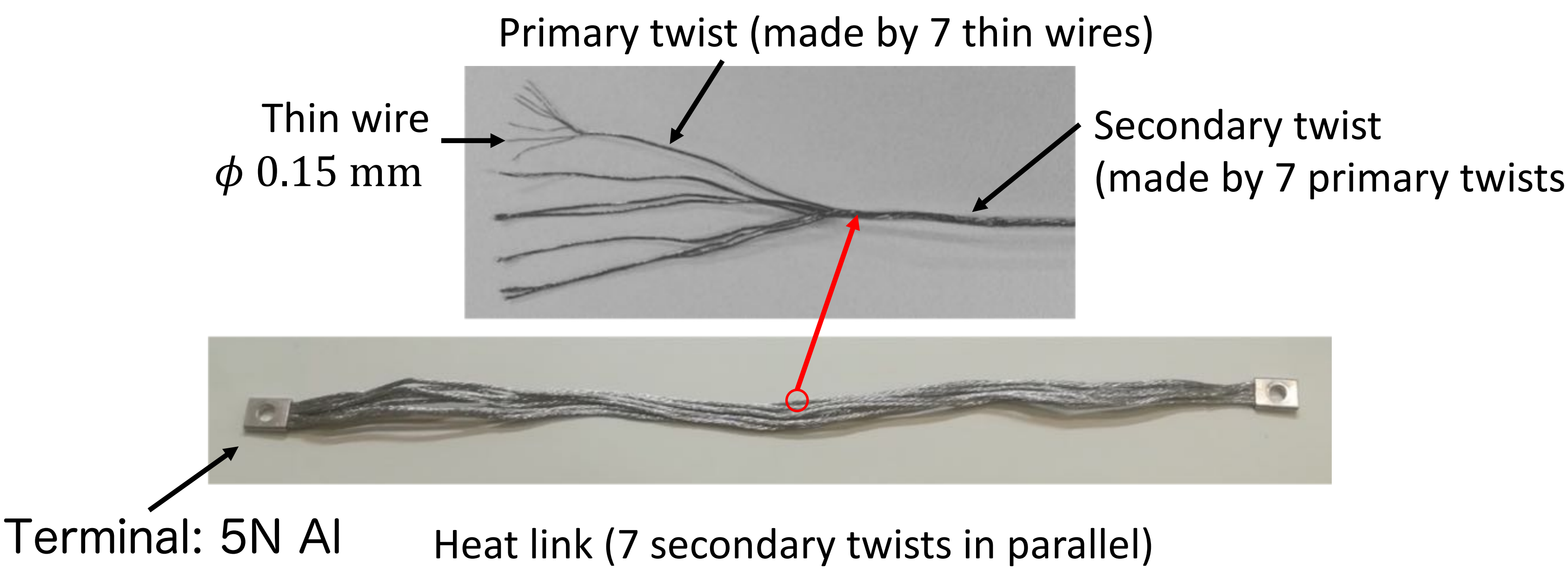
  -> New path of vibration injection

  -> Heat link (HL) must be soft and high thermal conductive at least.

Heat link

T. Yamada *et al.*, Cryogenics 2021

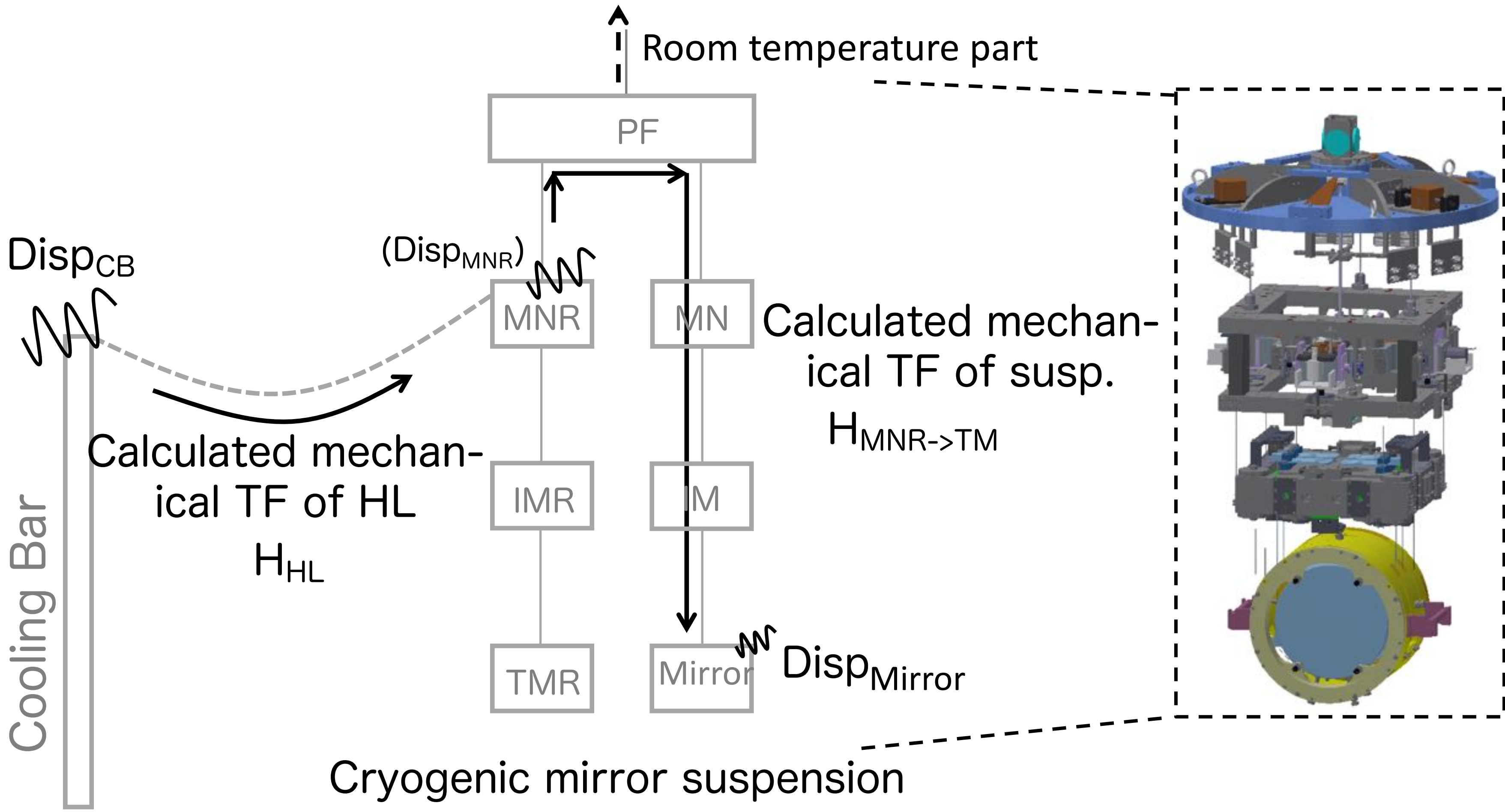
- High purity aluminum (99.9999%, 6N) is used for high thermal conductivity.
- Many thin wires are gathered and stranded for soft spring constant.



Heat link (7 secondary twists in parallel)

⇨ <u>How much vibration inflow via heat link affects the detector sensitivity?</u>

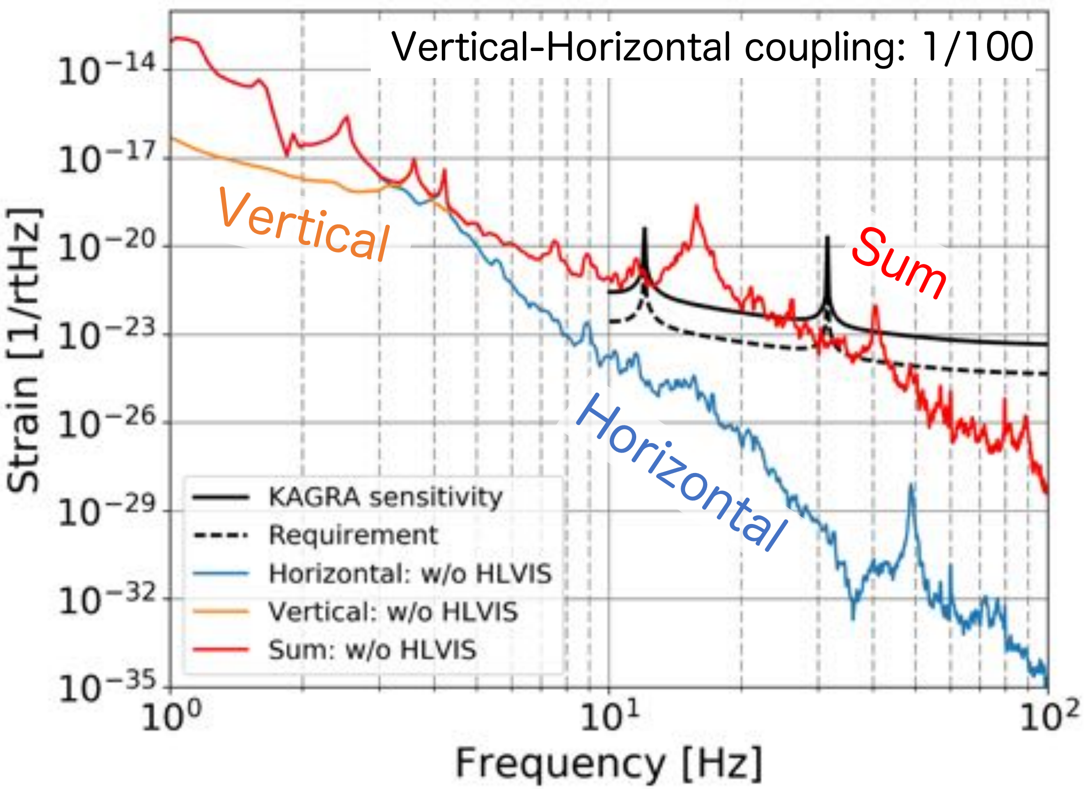
Estimation of vibration inflow

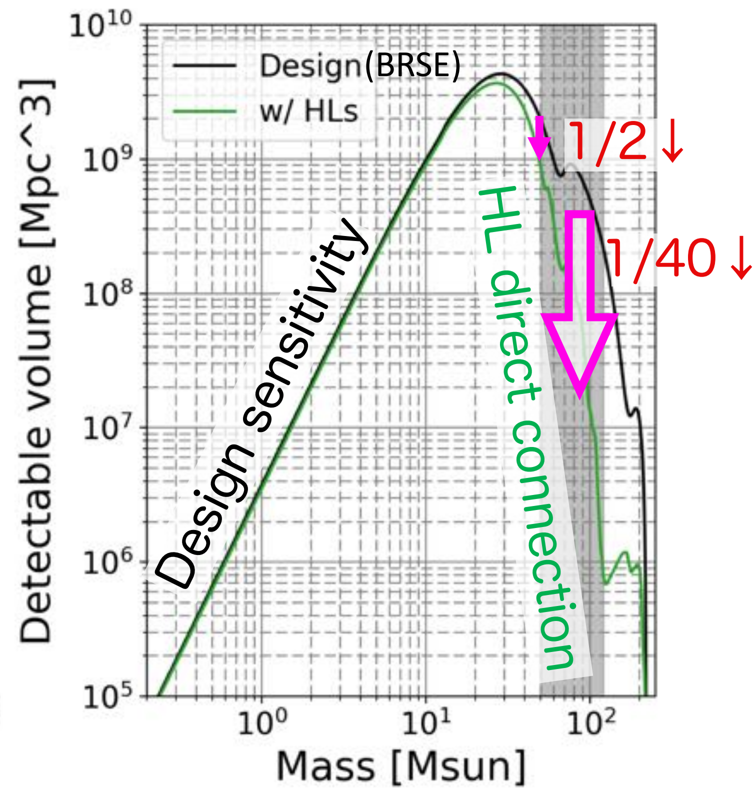


$$\mathrm{Disp_{CB}} \times H_{HL} \times H_{MNR\text{->}TM} = \mathrm{Disp_{Mirror}}$$

(DoF: Horizontal and Vertical)

Vibration inflow via heat links vs. Sensitivity





50–50 $M_\odot$: Approx. 1/2
100–100 $M_\odot$: Approx. 1/40

Vibration inflow via heat links could largely make the sensitivity worse at low frequency, especially for mass gap objects.

-> These vibration must be reduced.

A way to reduce vertical vibration inflow

- $\mathrm{Disp}_{TM} = \underline{\mathrm{Disp}_{CB}} \times \underline{H_{HL}} \times \underline{H_{MNR\text{->}TM}}$

Smaller vibration at Cooling Bar

CB is rigidly connected to cryocooler and radiation shield.
Difficult to reduce CB vib.

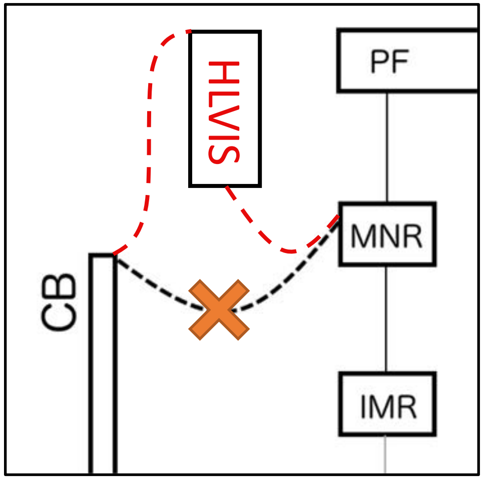
Softer and thinner heat links

- Thickness vs. size effect
- Small number of HL
  <-> Long cooling time

Better vertical vibration isolation in mirror susp.

Soft vertical spring
= Large temperature drift
<-> Suspension control

⊙ $\mathrm{Disp}_{TM} = (\mathrm{Disp}_{CB} \times HL_{VIS}) \times H_{HL} \times H_{MNR\text{->}TM}$



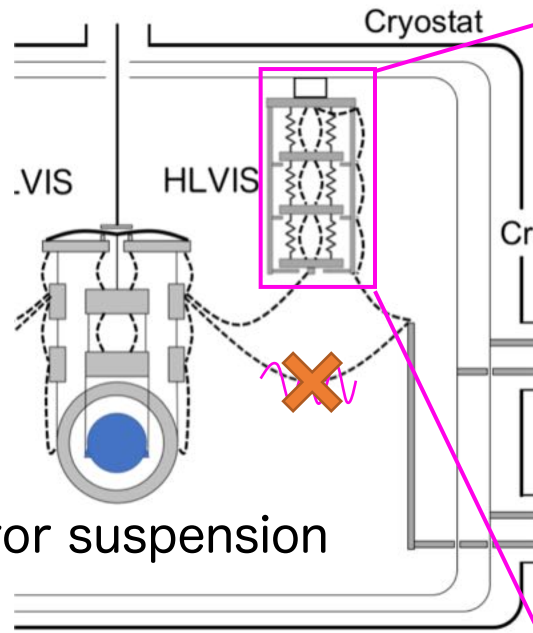
Vibration isolation of HL by new system

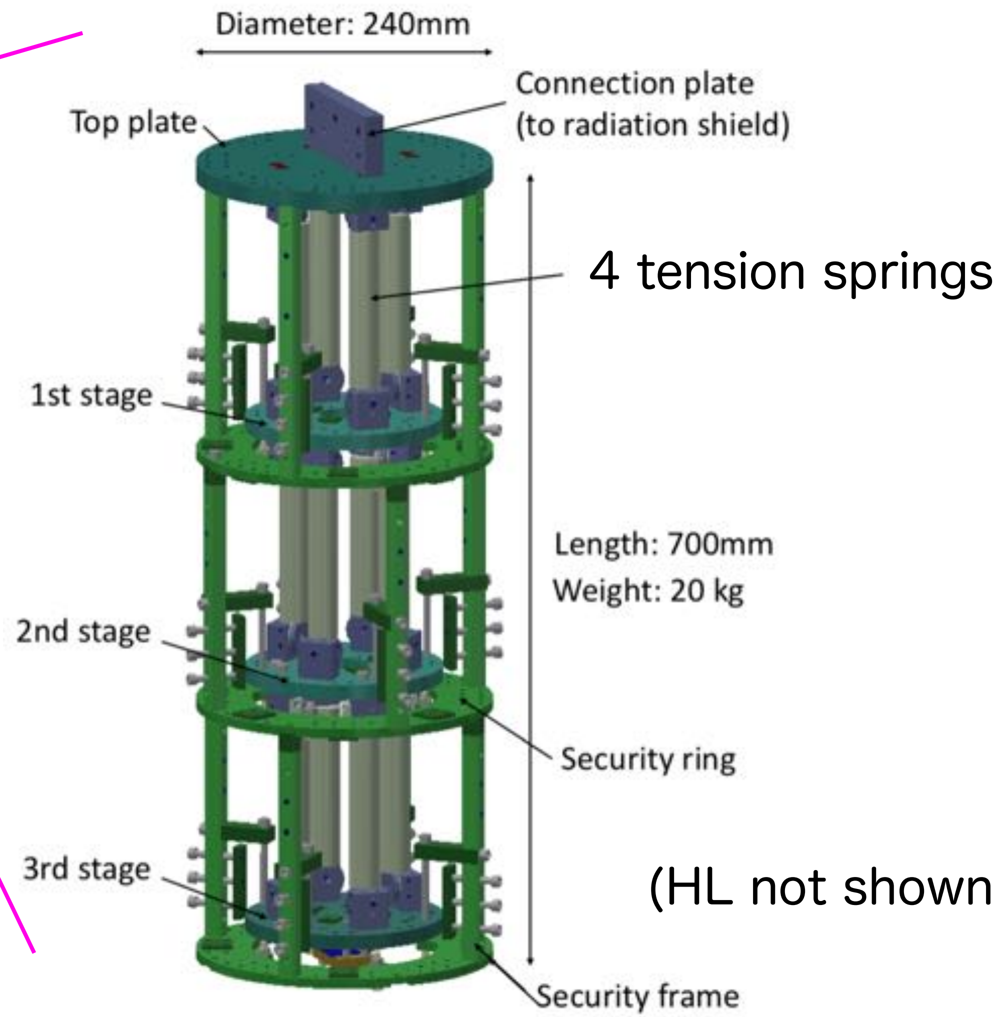
*HLVIS: Heat Link Vibration Isolation System

Merit: High vibration isolation *Mechanical*

Demerit: Increase of thermal resistance *Thermal*

Mechanical design of HLVIS

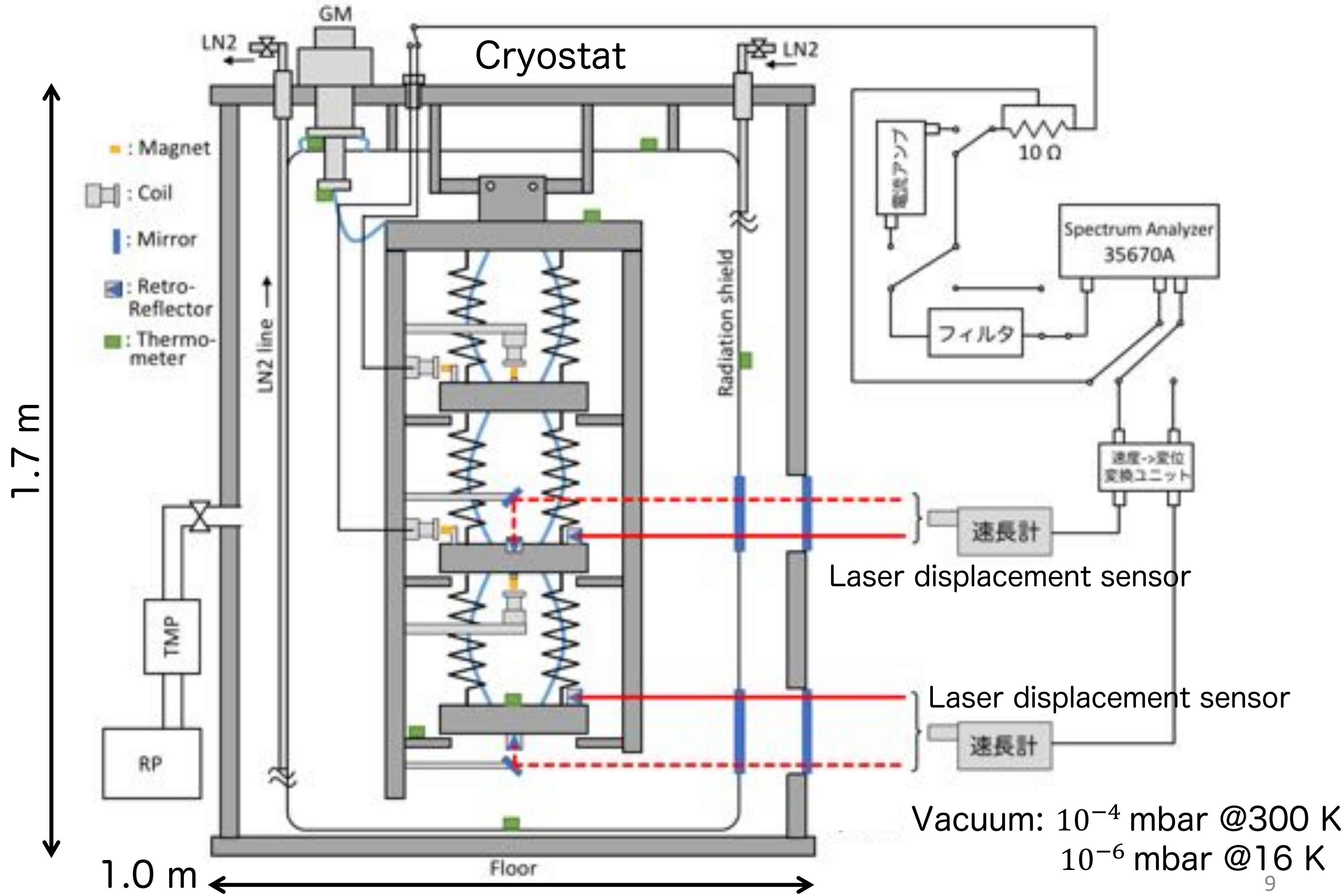




HLVIS was designed to especially reduce vertical vibration.

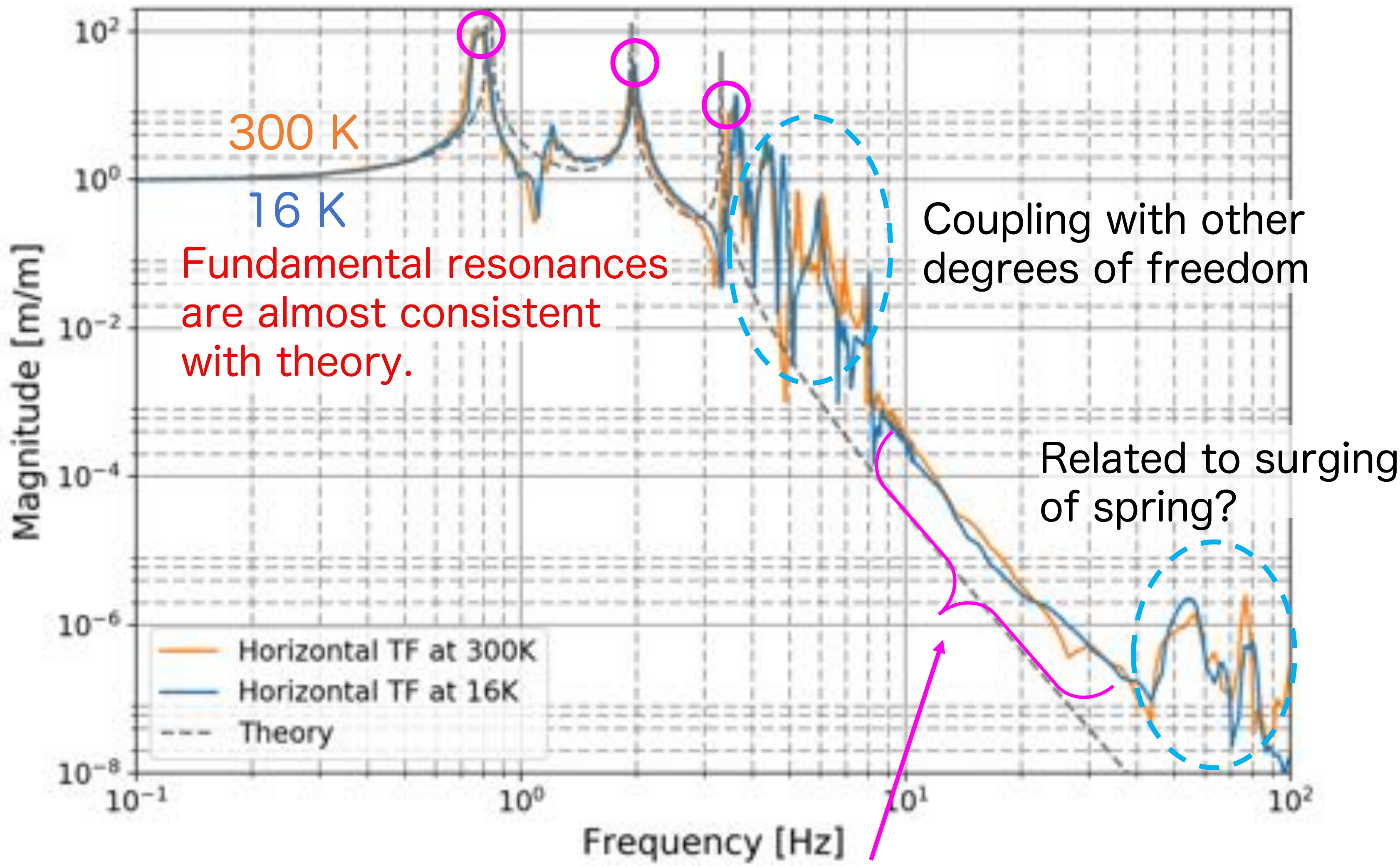
⇨ To evaluate vibration isolation performance, mechanical transfer function was measured at room and cryogenic (16K) temperatures.

Experimental setup



Vacuum: 10^{-4} mbar @300 K
10^{-6} mbar @16 K

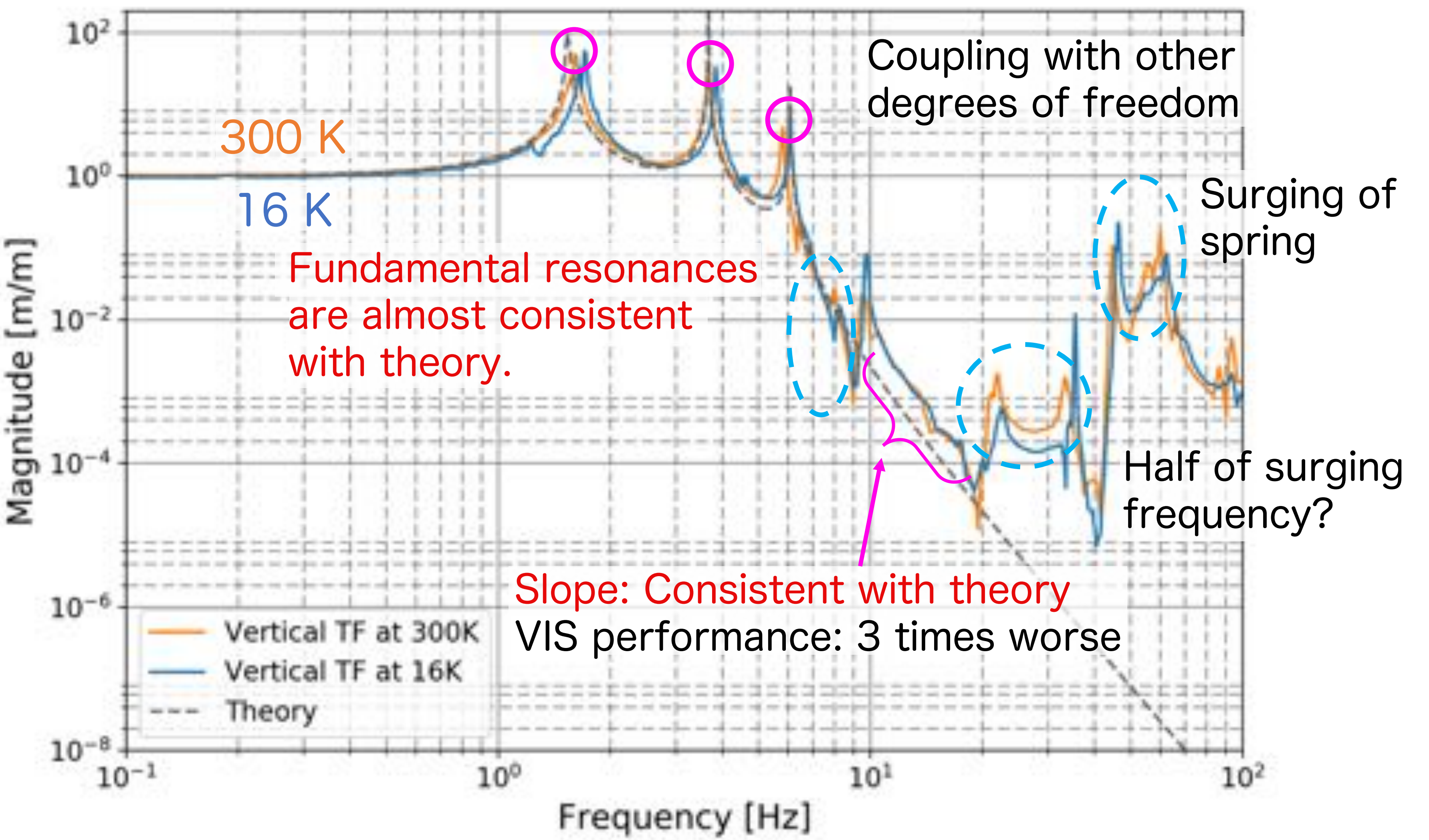
TF measurement result: Horizontal



Slope: Consistent with theory

VIS performance: 4 times worse

TF measurement result: Vertical



A way to reduce vertical vibration inflow

- $Disp_{TM} = \underline{Disp_{CB}} \times \underline{H_{HL}} \times \underline{H_{MNR\text{->}TM}}$

Smaller vibration at Cooling Bar	Softer and thinner heat links	Better vertical vibration isolation in mirror susp.
CB is rigidly connected to cryocooler and radiation shield. Difficult to reduce CB vib.	- Thickness vs. size effect - Small number of HL <-> Long cooling time	Soft vertical spring = Large temperature drift <-> Suspension control

⊙ $Disp_{TM} = (Disp_{CB} \times HL_{VIS}) \times \boxed{H_{HL}} \times H_{MNR\text{->}TM}$

Vibratio

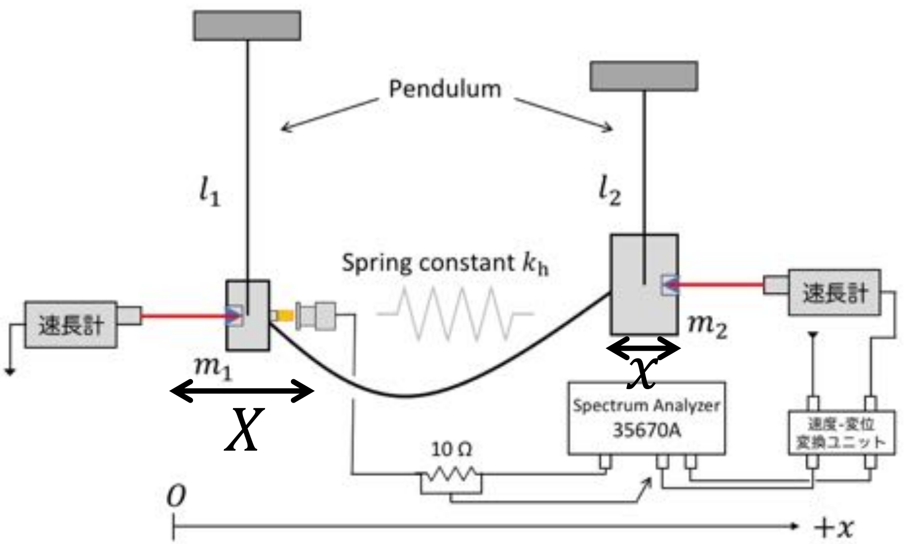
*HLVIS: H

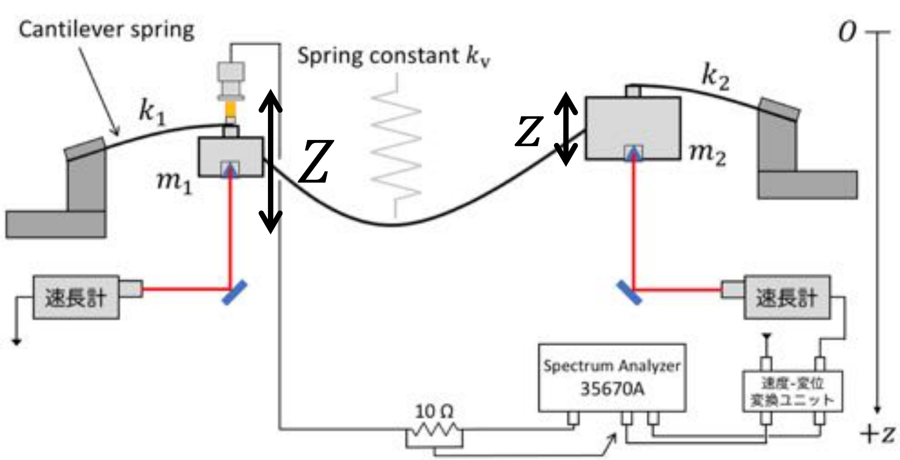
Spring constant of HL was measured for more realistic estimation

Merit: High vibration isolation *Mechanical*

Demerit: Increase of thermal resistance *Thermal*

Spring constant measurement of HL





Exciting left mass, spring constant can be obtained by measuring TF from left to right displacements, namely x/X and z/Z.

$$\frac{\tilde{x}}{\tilde{X}} = (5.06 \pm 0.05)\times 10^{-3}$$

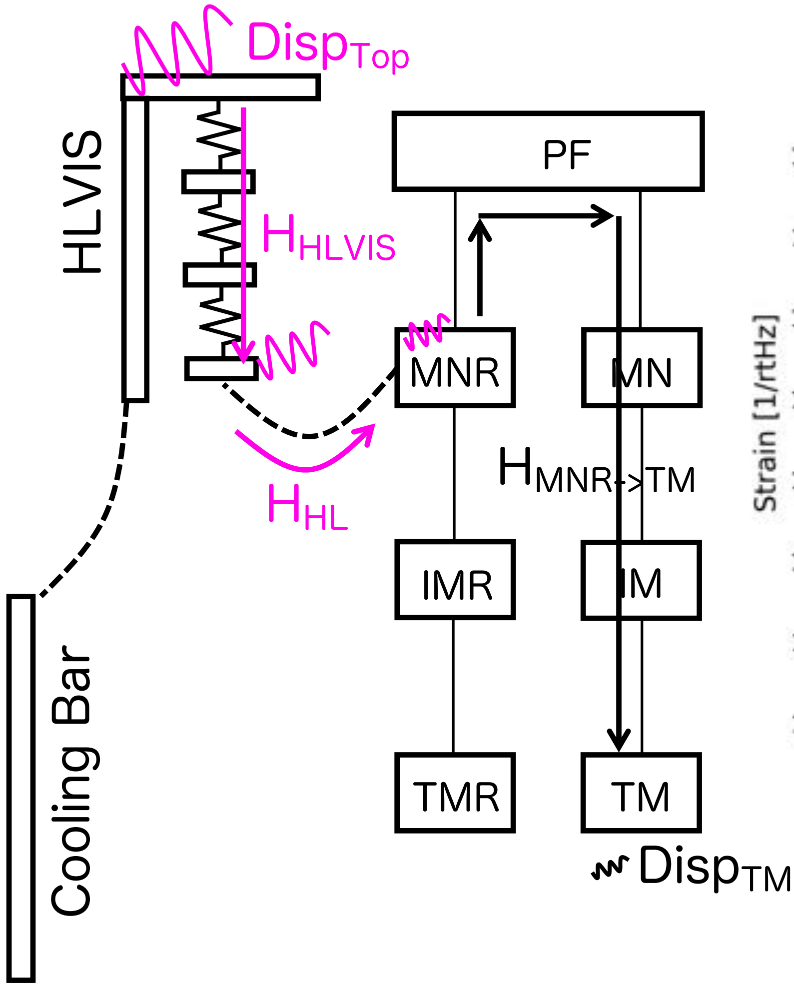
$$\frac{\tilde{z}}{\tilde{Z}} = (1.95 \pm 0.16)\times 10^{-4}$$

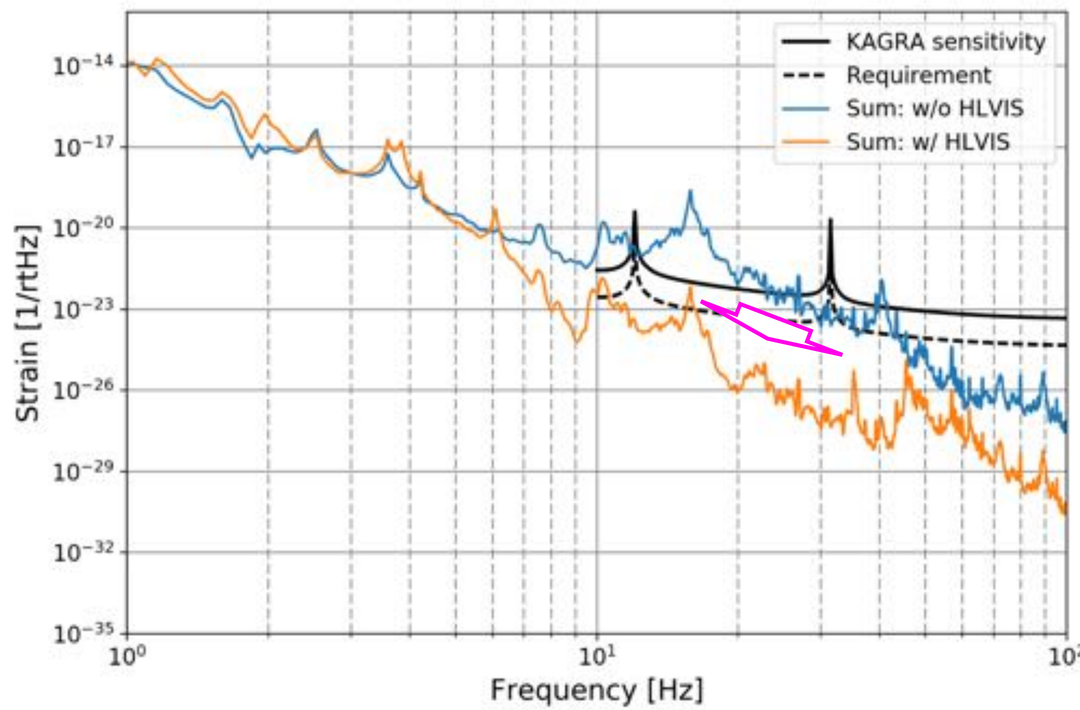
⇩

$k_\mathrm{h} = 1.0\ \mathrm{N/m}$ for 1 HL
<-> $0.72\ \mathrm{N/m}$ by FEM

$k_\mathrm{v} = 0.28\ \mathrm{N/m}$ for 1 HL
<-> $0.17\ \mathrm{N/m}$ by FEM

Reduction of vibration inflow by HLVIS





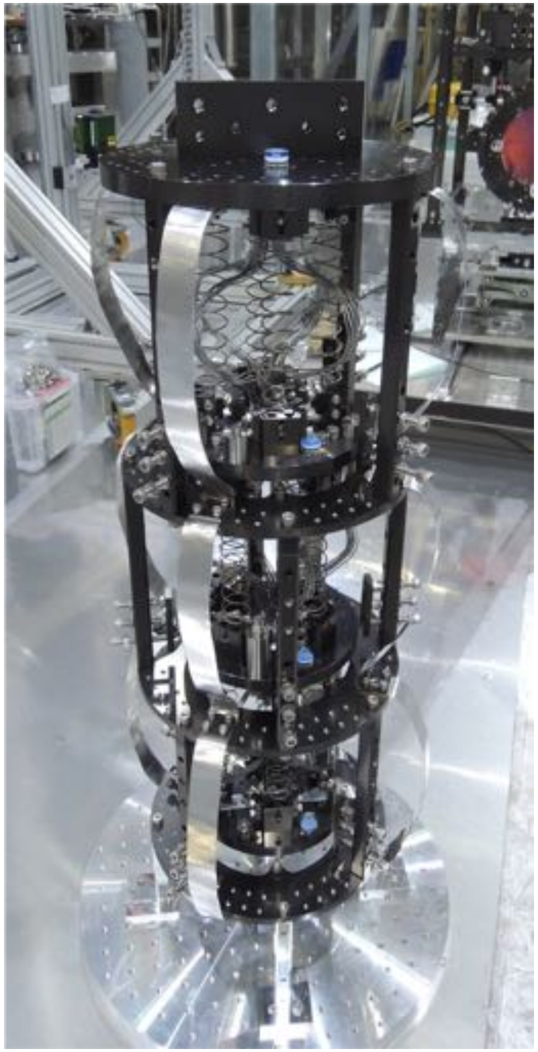
$\mathrm{Disp}_{\mathrm{Top}} \times H_{\mathrm{HLVIS}} \times H_{\mathrm{HL}} \times H_{\mathrm{MNR\text{->}TM}} = \mathrm{Disp}_{\mathrm{TM}}$

Vibration inflow is reduced below the sensitivity curve.

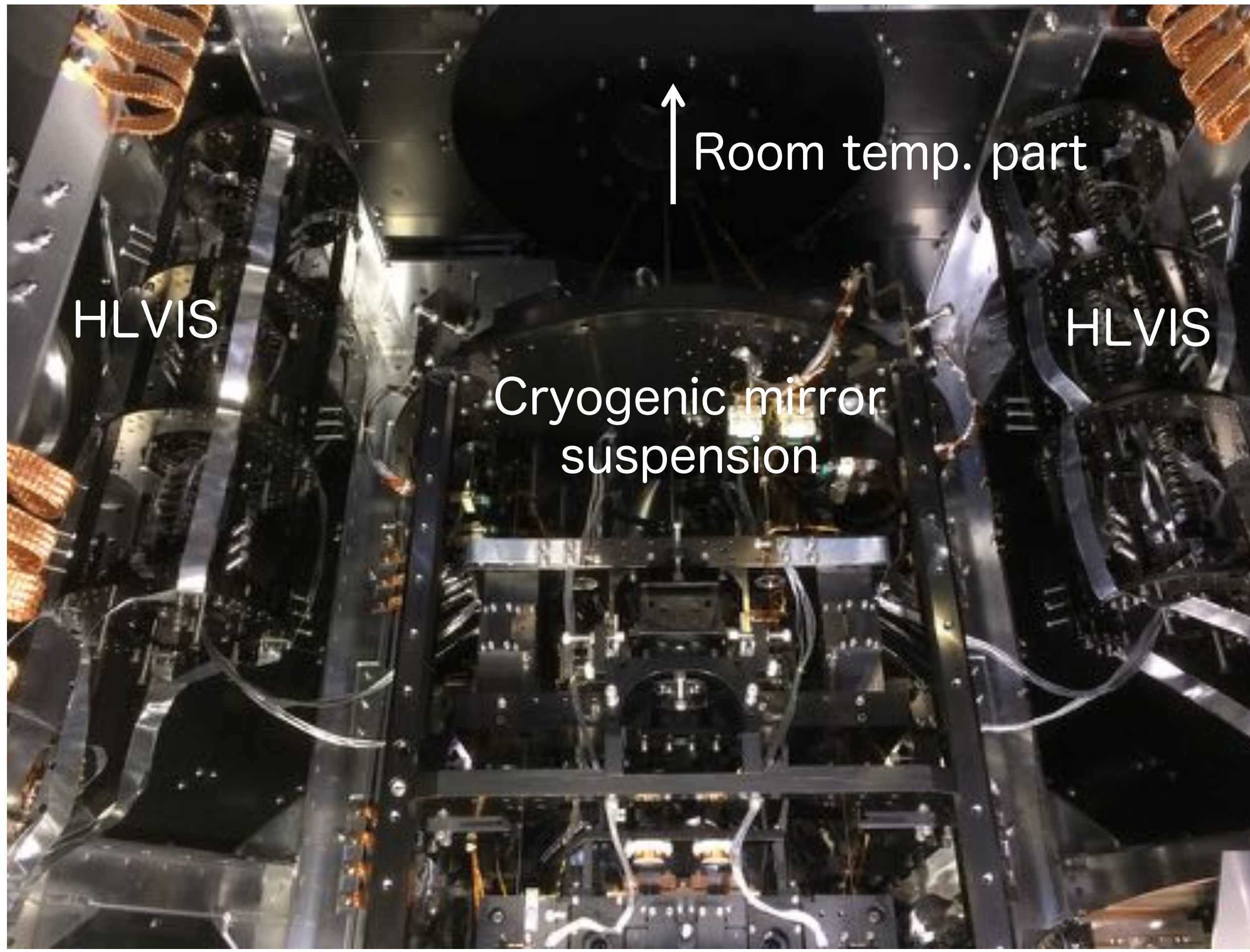
Why the requirement was not satisfied:

- slightly bad VIS performance of HLVIS
- slightly stiff spring constant of HL

Installation of HLVIS into KAGRA



Assembled HLVIS



Layout inside the cryostat

*Coated by Low-magnetism SolBlack Coating

Conclusion

I'm writing a paper about these results.

- New vibration isolation system was developed to reduce vibration inflow via heat links that are essential to achieve 20K sapphire mirror.
- HLVIS can reduce vibration below the sensitivity and largely contribute to increase number of detectable events for mass gap objects.