Study of Newtonian noise from the KAGRA cooling system

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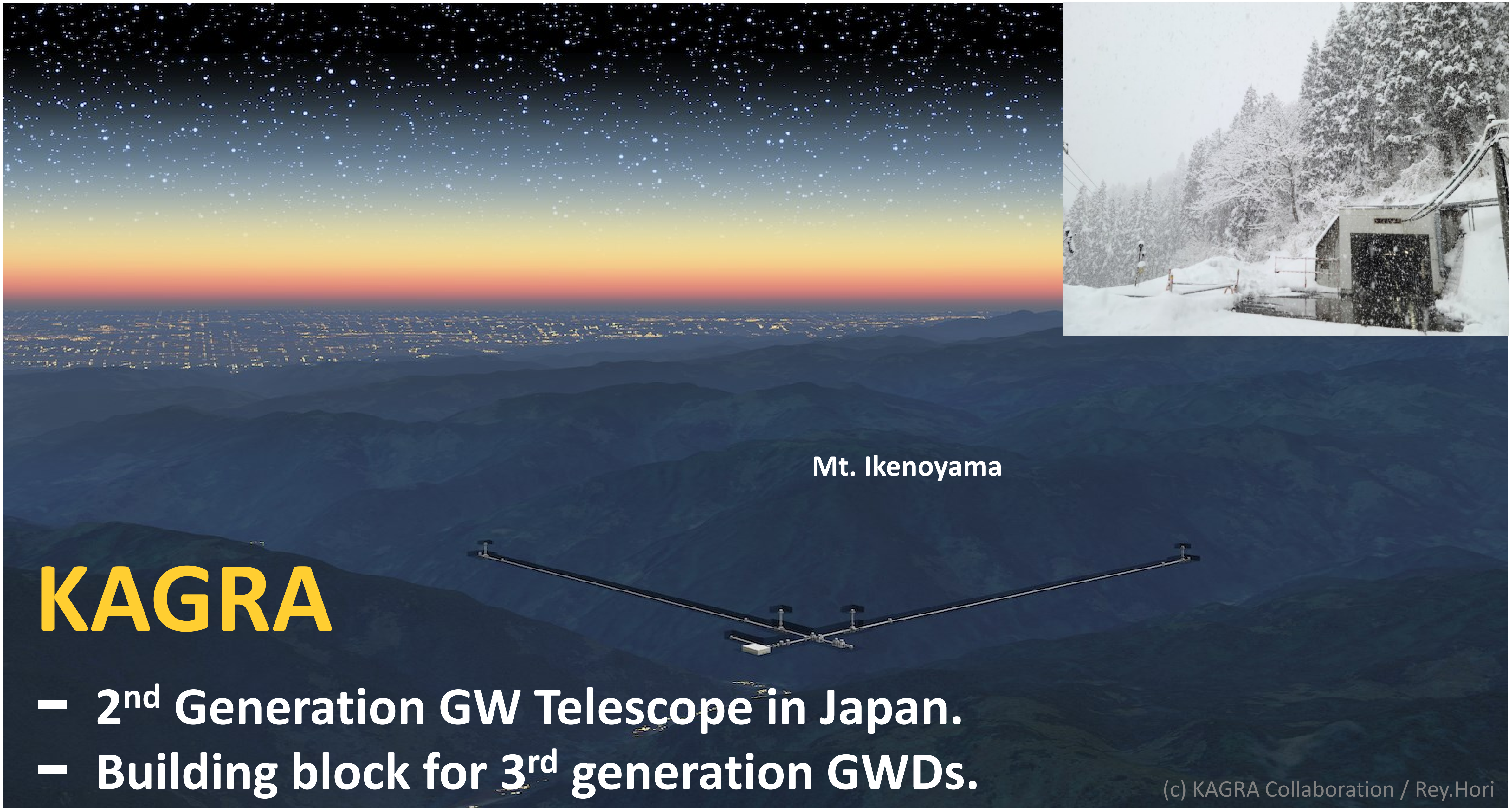
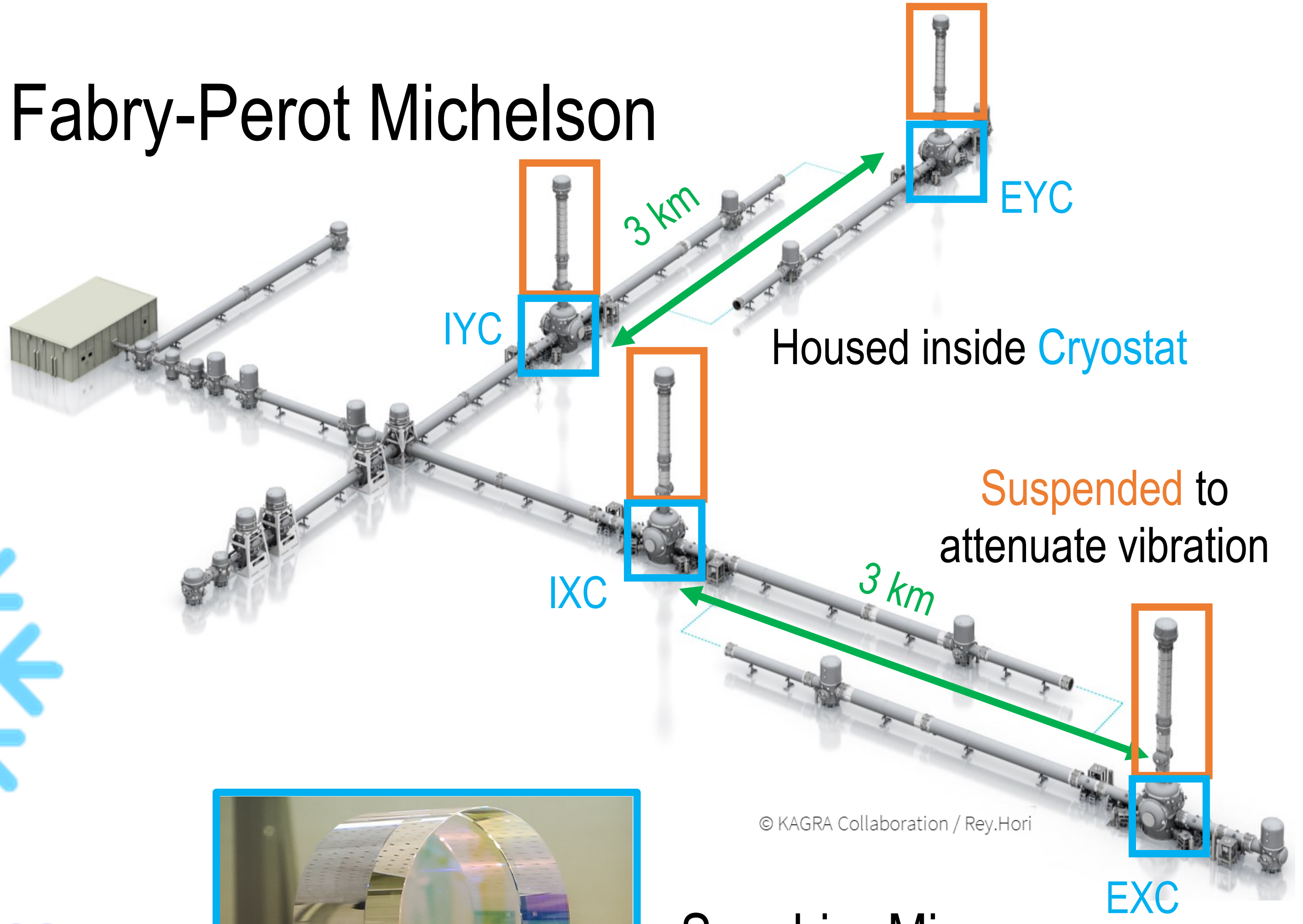


KAGRA

- 2nd Generation GW Telescope in Japan.
- Building block for 3rd generation GWDs.

KAGRA

- Configuration: Dual Recycled Fabry-Perot Michelson
- 3-km arm-length.
- Two unique features:



Underground Site

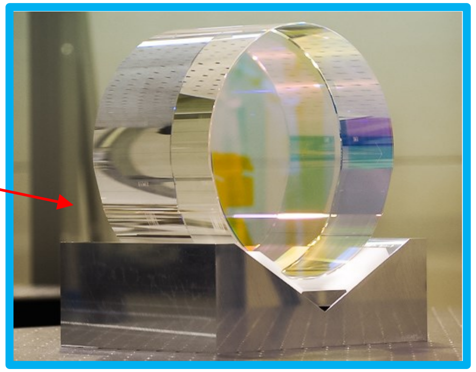
Quiet Site

Reduce Seismic Vibration and Newtonian Noise

Cryogenics

@ 20 K

Reduce thermal noise



Sapphire Mirror

Mass: 23 kg

Diameter: 220 mm

Thickness: 150 mm

Test Mass Suspension

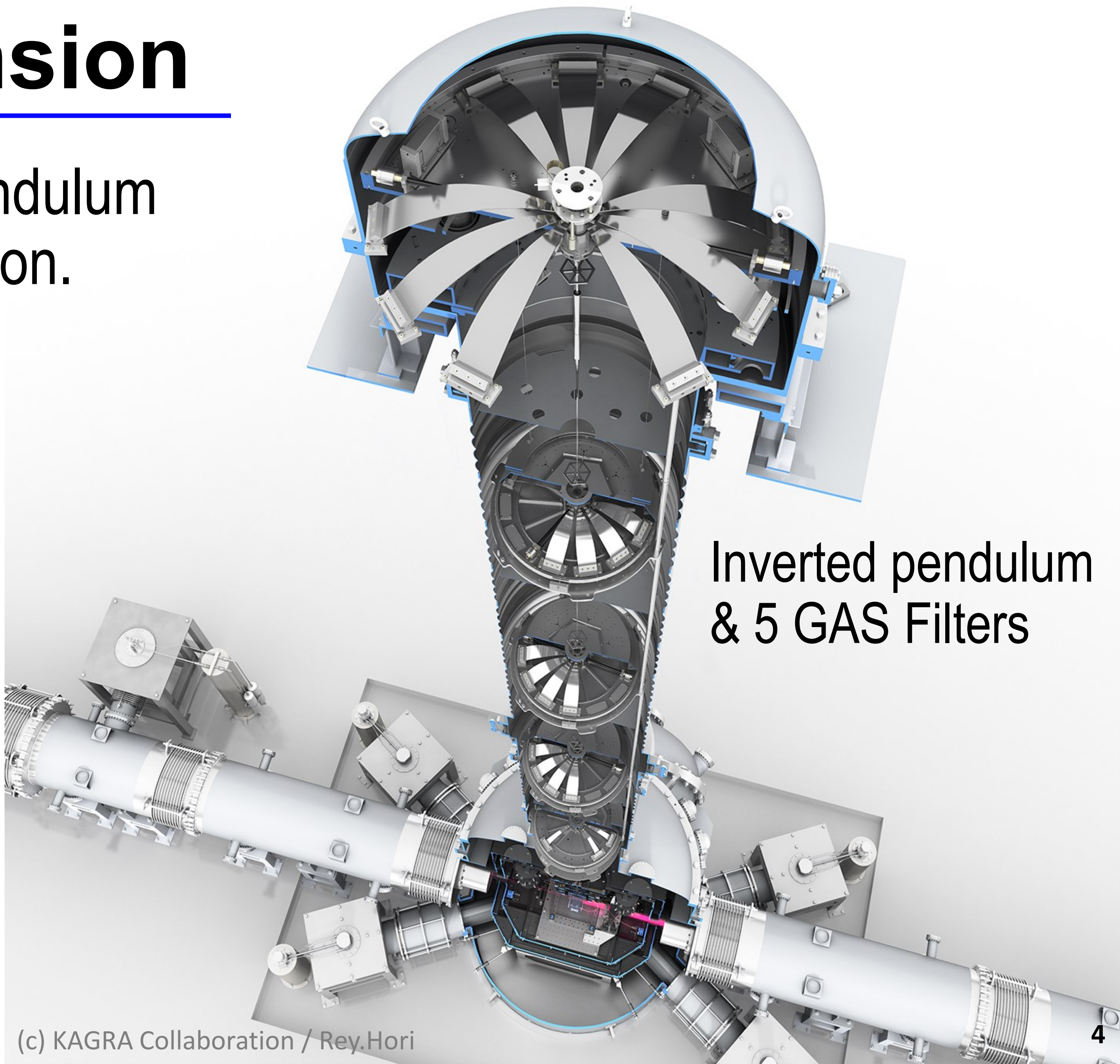
This 13.5 m tower is a 9-stage pendulum and isolates TM from seismic motion.

Type-A Suspension

Type- A Tower:
- Top 5 stages, 12 m
- Room Temperature

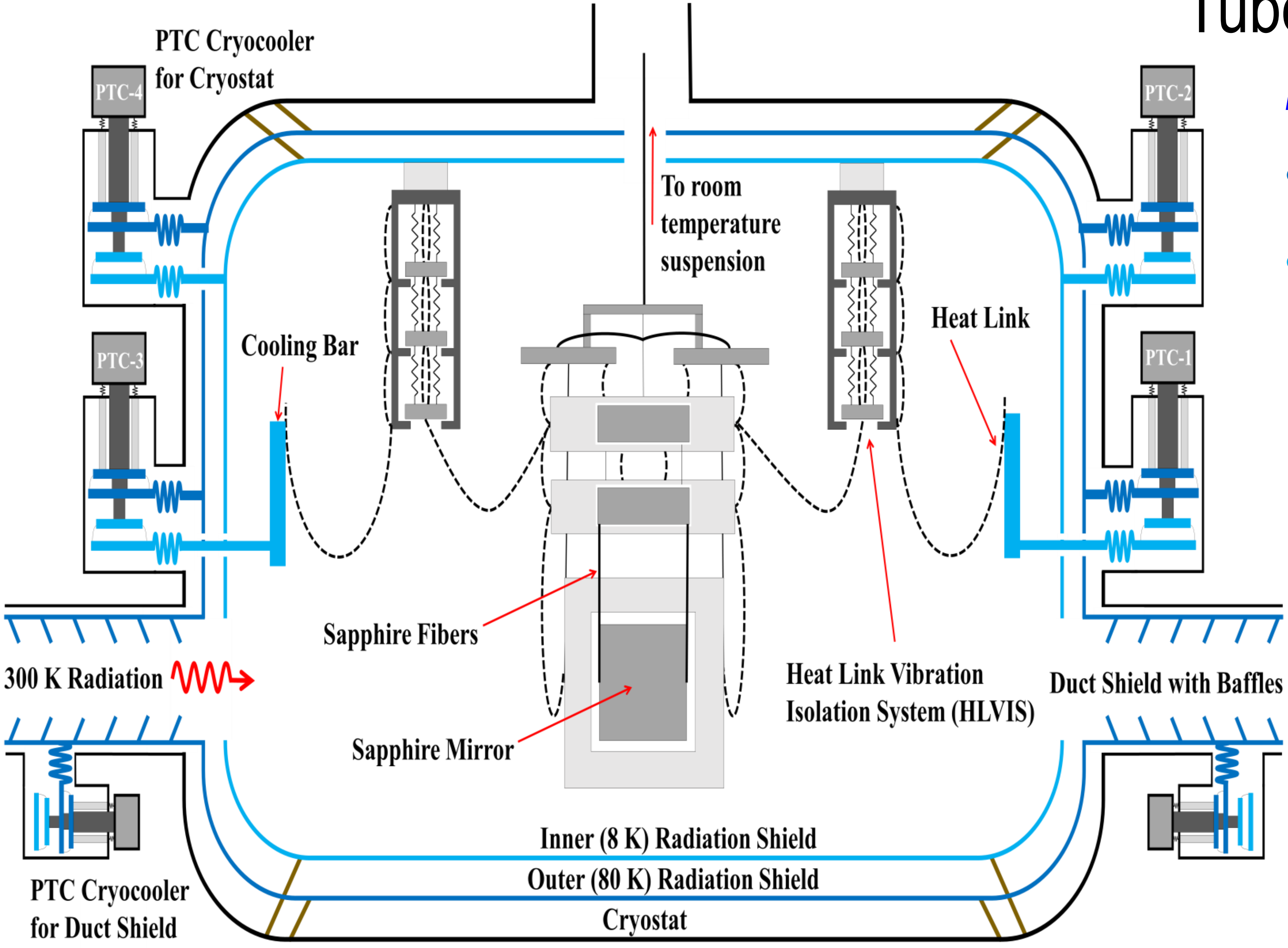
Cryogenic Payload:
- Bottom 4 stages, 1.5 m
- Cryogenic Part

How to cool down TM to 20K and keep vibration isolation?



(c) KAGRA Collaboration / Rey.Hori

Cooling Layout



Cooling System: Double radiation shield cryostat cooled by Pulse Tube Cryocoolers (PTC).

Double Stage PTC: (x4)

- ***1st Stage:*** All 4 → 80-K Shield
- ***2nd Stage:***

  2 → 8-K Shield; 2 → Cooling Bar

Duct shield PTC: (x2)

To cool down 5-m duct shield which reduces 300-K radiation.

Cooling

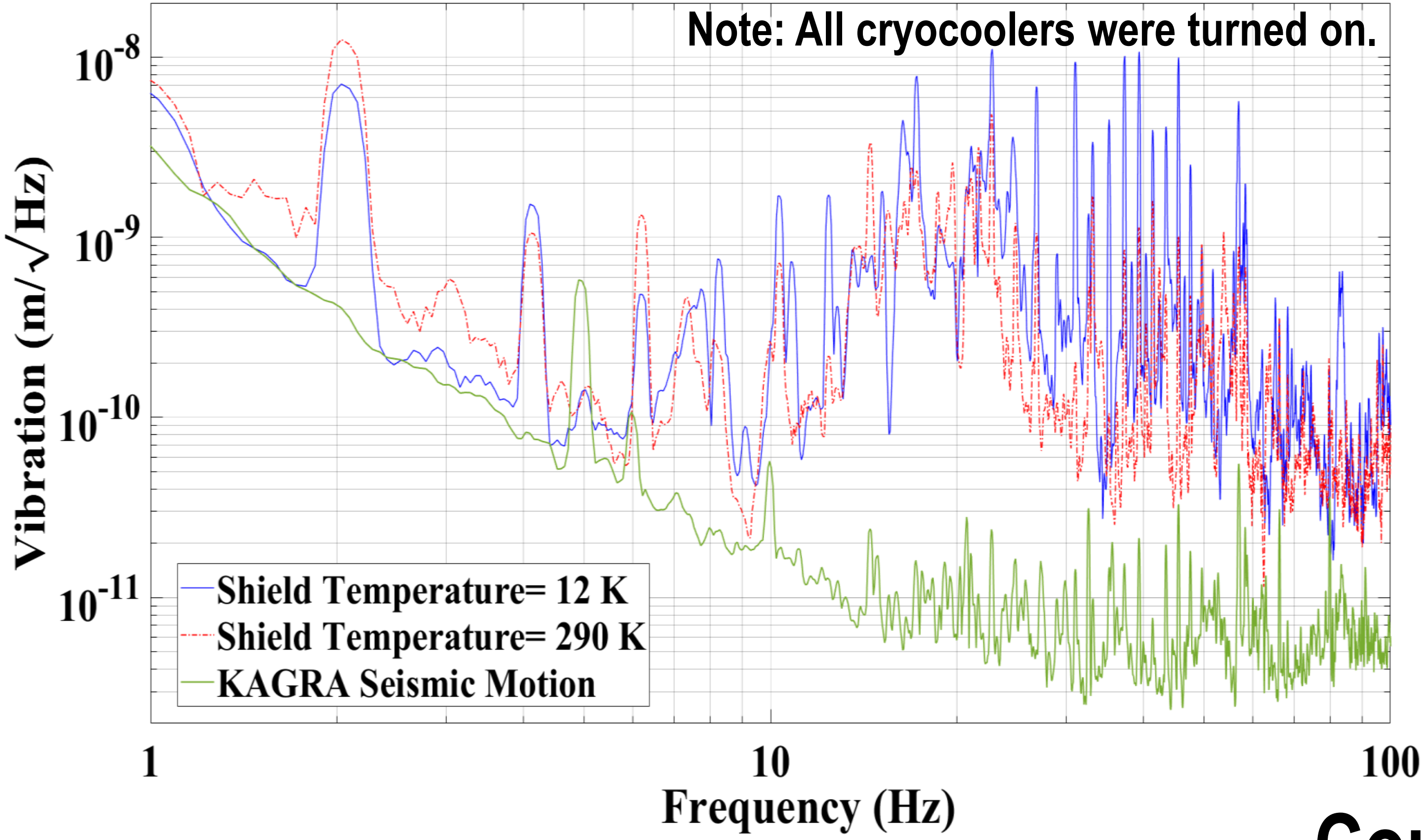
Thermal Radiation to shield:

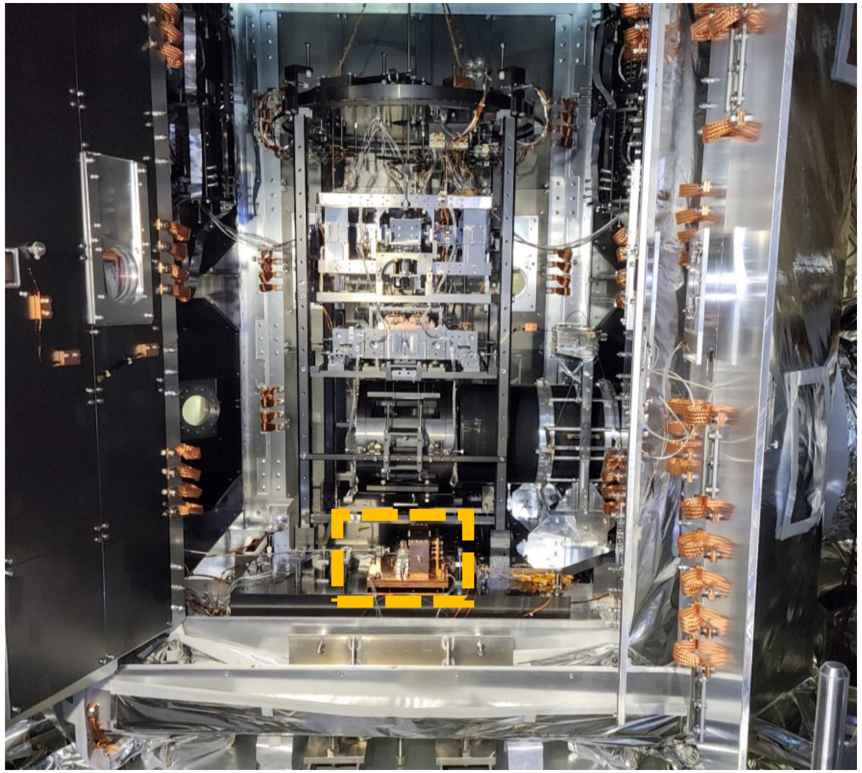
- Cools Payload to ~ 100 K

Conduction cooling via heat-links:

- Cools TM to ~ 20 K

Vibration Spectra of KAGRA Cryostat





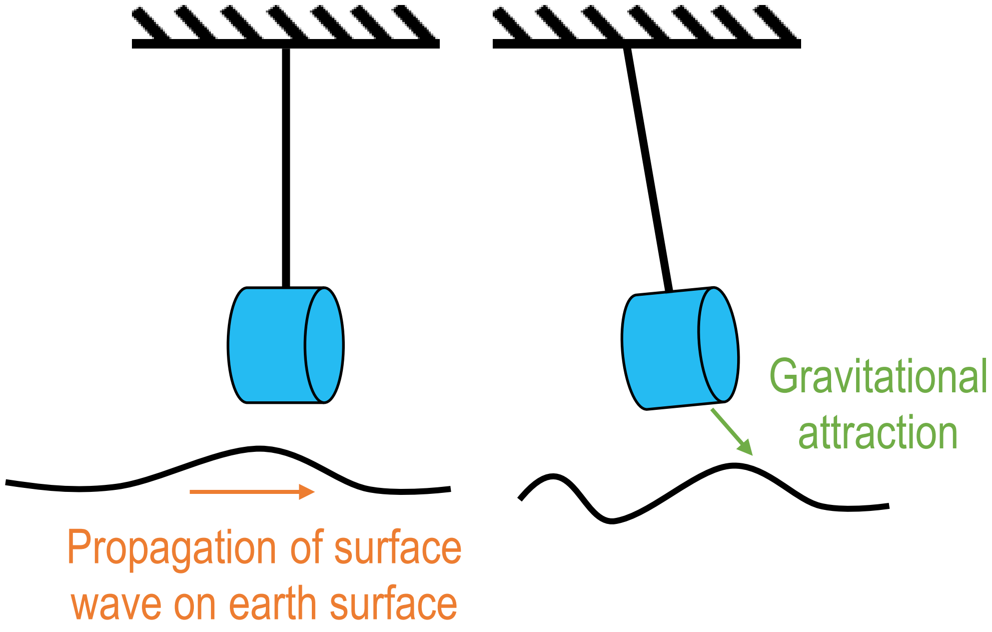
A **significant increase in** radiation **shield vibration** coupling **after cooling** was observed.

R Bajpai *et al* 2022 *Class. Quantum Grav.* **39** 165004

Coupling of this vibration via heat-links is attenuated by HLVIS but Newtonian Noise coupling might be an issue.

Newtonian Noise

- Due to fluctuating mass distribution which causes fluctuating gravitational forces on TM.
- Can't be shielded against or attenuated.
- Sources: Seismic waves, Atmospheric fields, Vibrating Objects



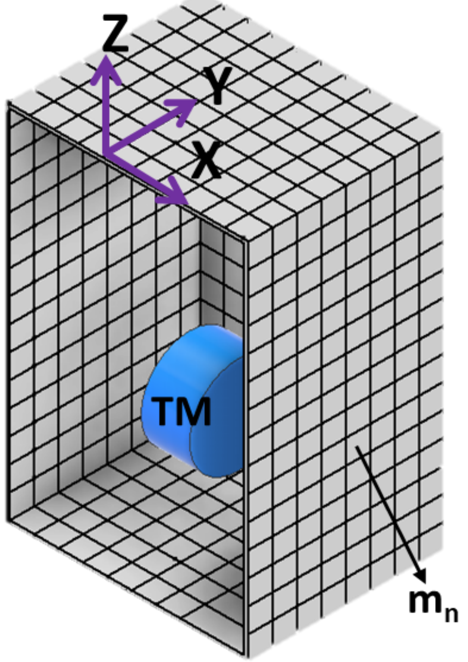
In KAGRA study of NN has been limited to seismic waves, atmospheric fields and underground water.

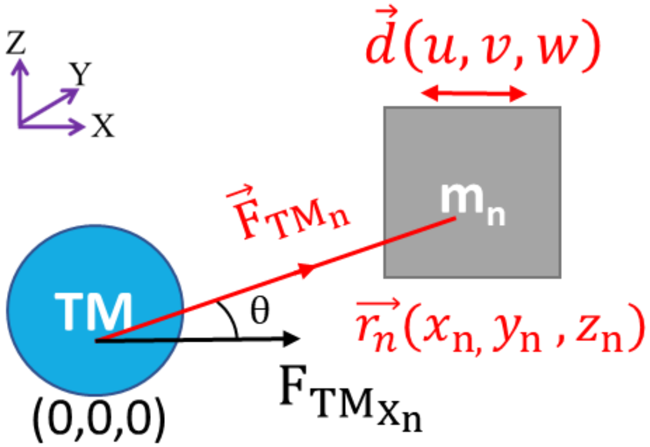
Newtonian Noise ∝
- Mass of the object
- 1/distance^2 (TM - object)
- Vibration magnitude

▪ Cooling System NN:

- Cooling system components are heavy and relatively close to the mirror.
- When components vibrate the Newtonian gravitational force between them and the mirror fluctuates.
- This causes mirror displacement.

Derivation





- Consider a simple hollow cuboid cooling system (CS) with TM (mass: *M*) at origin.
- Split into N element mesh where each element is a point-mass weighing m_n.
- The gravitational force on TM along *X-axis* due to a point-mass located at (x_n, y_n, z_n):

$$F_{\mathrm{TMx_n}} = GMm_n \frac{x_n}{(x_n^2 + y_n^2 + z_n^2)^{\frac{3}{2}}}$$

- When CS vibrates with $\vec{d}(u, v, w)$ force fluctuation will be:

$$\triangle F_{\mathrm{TMx_n}}(t) = \nabla F_{\mathrm{TMx_n}} \cdot \overrightarrow{d}$$

Summate (or Integrate) over the entire cooling system to derive cooling system force fluctuation.

$\Delta F_{\mathrm{TMx_n}}(t)$ — Change in force due to m_n

→ summate / integrate: Σ or $\int$ →

$\Delta F(t)$ — Change in force due entire system

→ Fourier Transform: $\hat{f}(\xi)$ →

$\Delta F(\omega)$ — Change in force in frequency domain

→ (Power Spectral Density)$^{1/2}$: ASD →

$\sqrt{S_F(\omega)}$ — ASD of change in force

→ $\frac{\sqrt{4}}{M\omega^2 L}$ →

$\sqrt{S_h(\omega)}$ — NN Strain

$$\sqrt{S_h(\omega)} = \frac{\sqrt{4}G}{\omega^2 L}\sqrt{A^2 S_u(\omega) + B^2 S_v(\omega) + C^2 S_w(\omega)}$$

$\sqrt{S_h(\omega)}$: Cooling System NN Strain

$\omega = 2\pi f$

L: 3000 m

$$A = \sum_{n=1}^{N} m_n \left[\frac{-2x_n^2 + y_n^2 + z_n^2}{(x_n^2+y_n^2+z_n^2)^{\frac{5}{2}}}\right]$$

$$B = \sum_{n=1}^{N} m_n \left[\frac{-3x_n y_n}{(x_n^2+y_n^2+z_n^2)^{\frac{5}{2}}}\right]$$

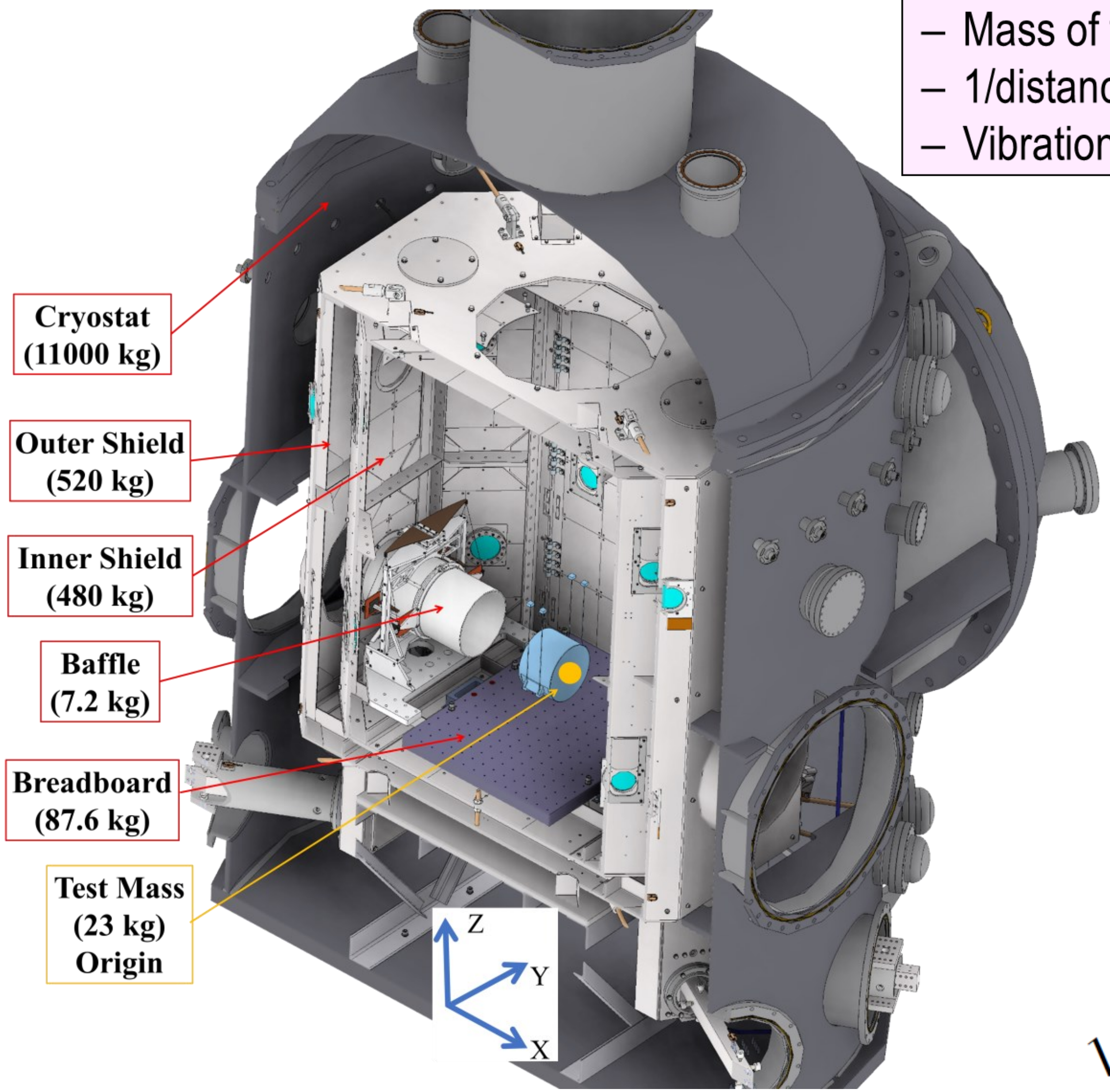
$$C = \sum_{n=1}^{N} m_n \left[\frac{-3z_n x_n}{(x_n^2+y_n^2+z_n^2)^{\frac{5}{2}}}\right]$$

A, *B*, and *C* are constant and depend on the geometry

$S_u(\omega)$	X-axis
$S_v(\omega)$	Y-axis
$S_w(\omega)$	Z-axis

are cooling system Vibration PSD along each axis and are incoherent

KAGRA Cooling System



Newtonian Noise ∝
- Mass of the object
- 1/distance² (TM - object)
- Vibration magnitude

- Values of *A*, *B* and *C* for each component:
  - Evaluated from N element mesh generated on Ansys.

Component	A	B	C
Breadboard	550.69	-5.4×10^{-16}	-1.2×10^{-14}
Baffle	-23.4	-6.97	-0.11
Inner Shield	124.15	-0.28	-4.64
Outer Shield	97.52	0.53	-1.95
Cryostat	-298.34	-6.22	-0.03

A ≫ B or C

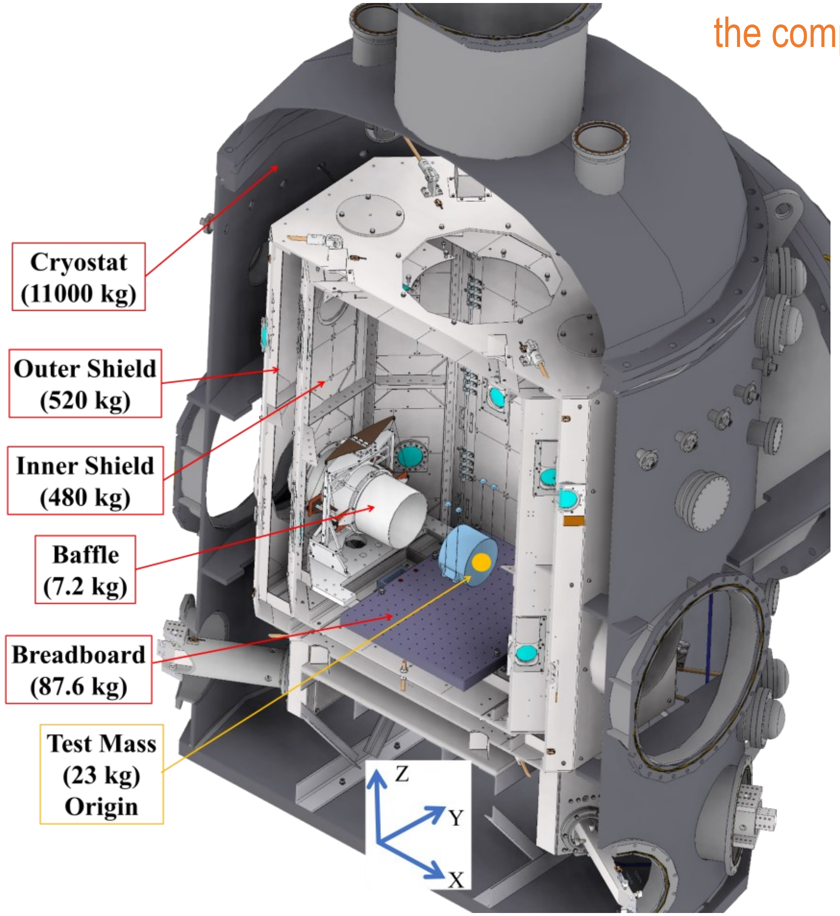
$$\sqrt{S_h(\omega)} = \frac{\sqrt{4G}}{\omega^2 L}\sqrt{A^2 S_u(\omega) + B^2 S_v(\omega) + C^2 S_w(\omega)}$$

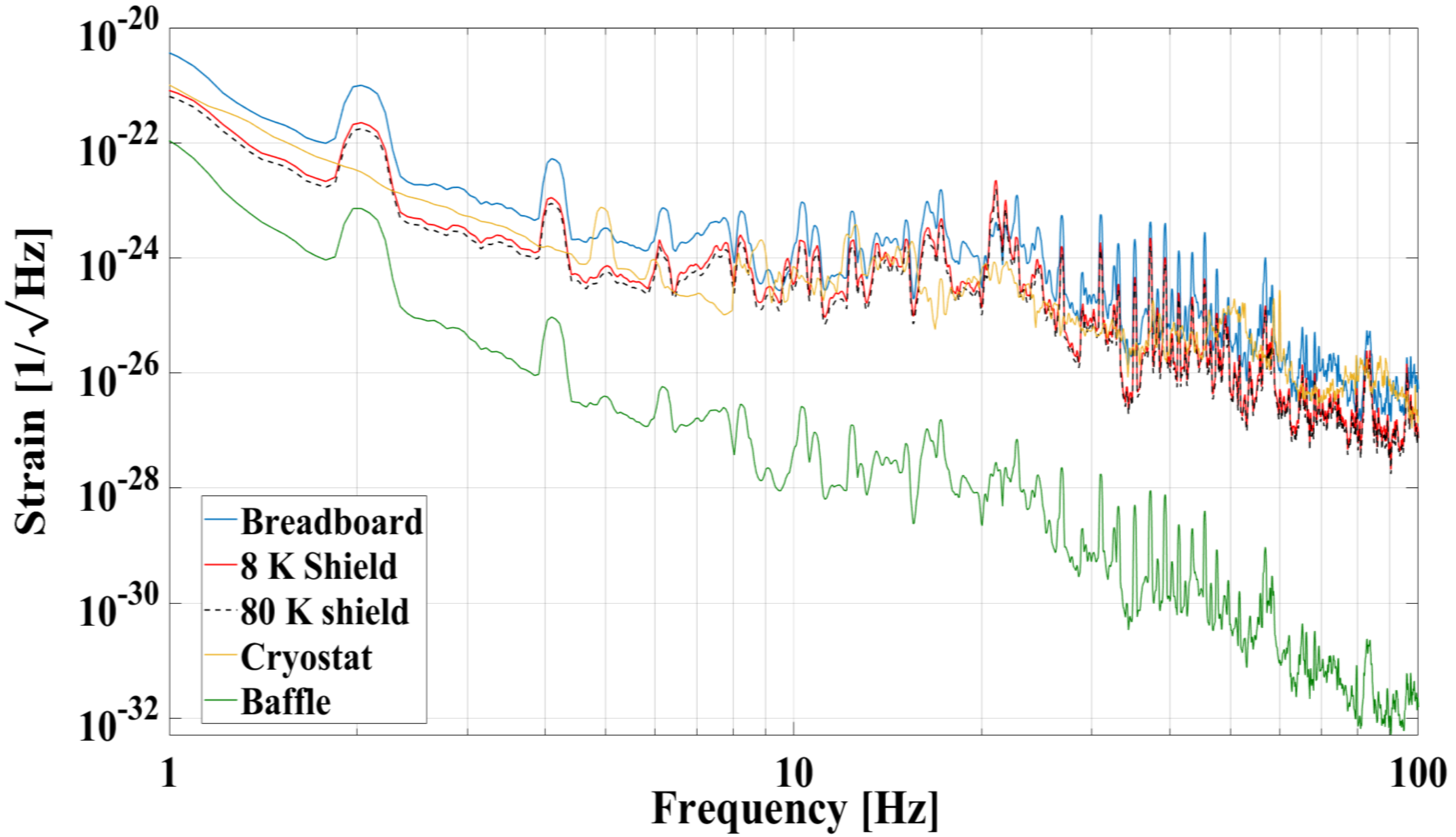
Comparison

NN is estimated as:

$$\sqrt{S_F(\omega)} = \frac{\sqrt{4}G}{\omega^2 L} \times \boxed{\sqrt{S_u(\omega)}} \times A$$

Vibration Spectra of the component

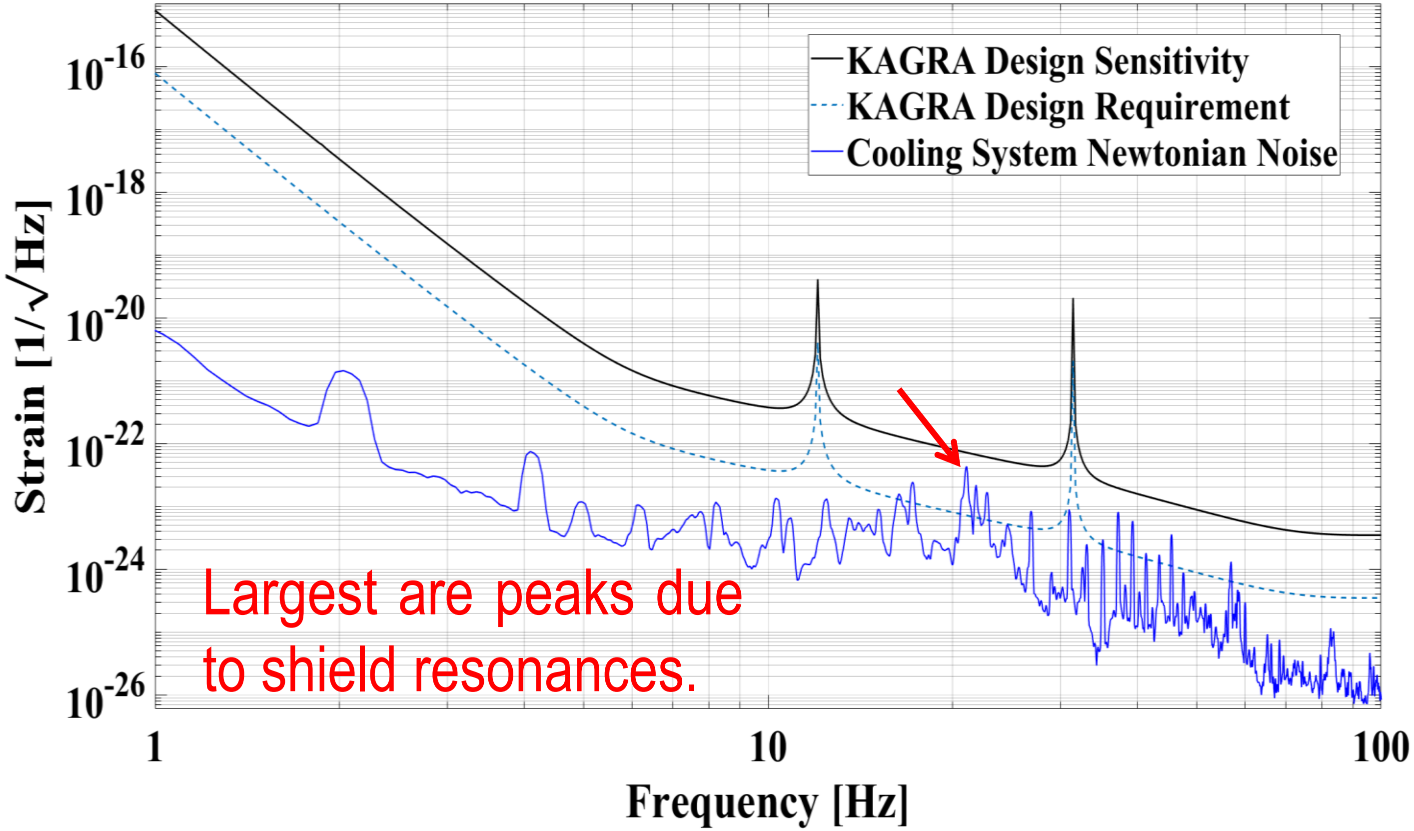




- **Breadboard NN** dominates almost the entire 1-100 Hz band.
- **Radiation shield NN** dominates around 21-23 Hz due to resonance.
- **Chamber NN** is comparable or lower than shield.
- **Baffle NN** is lowest even though it is closest to TM because low mass and smaller vibration.

Impact on Sensitivity

Evaluated as the sum of Newtonian noise from each component.



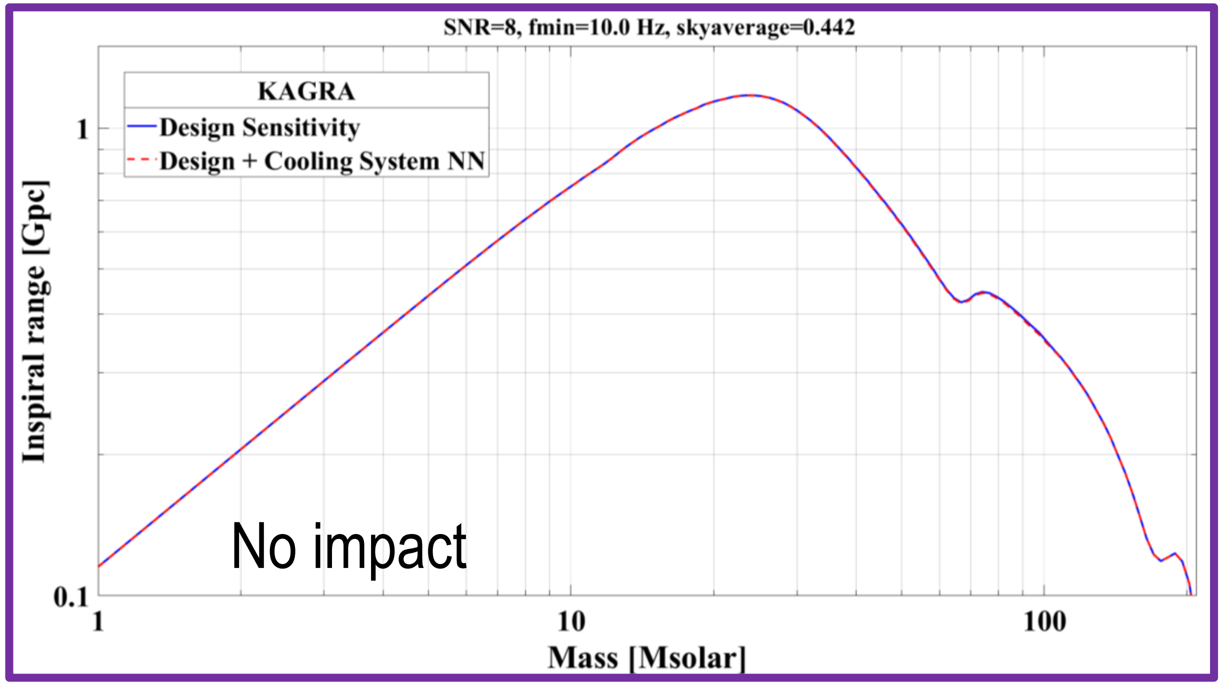
- Cooling system NN is below design sensitivity.
- But several peaks in (16 -50 Hz) are larger than the final requirement.

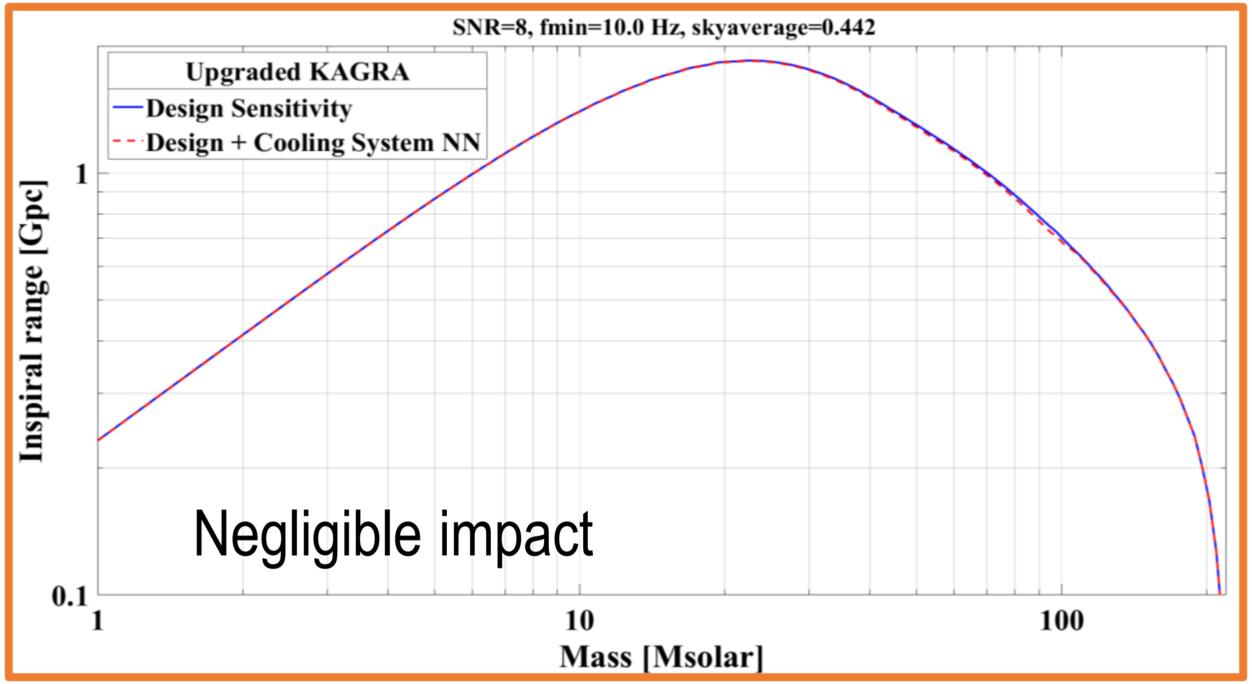
Vibration Source	Frequency (Hz)
Chamber Resonance	17.2, 21.8
Shield Resonance	16.3, 21.1*, 21.8*
Cryocooler Operation	26.8, 35.1, 37.2, 39.3, 41.3, 43.5, 45.5, 47.6, 46.9

R Bajpai *et. al.*, *Phys. Rev. D.* **107**, 042001 (2023)

Code: Internal Document JGW-T1707038-v9
Y Michimura *et. al.*, *Phys. Rev. D.* **102**, 022008 (2020)

Inspiral Range





Current Design Sensitivity

Tech. Upgrade

High power laser, 100 kg mirror and squeezing

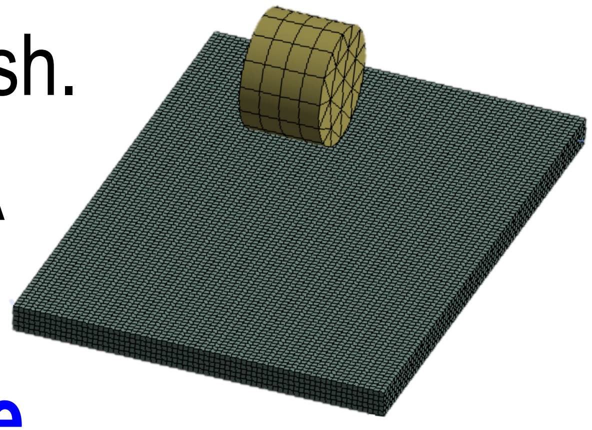
Upgraded Design Sensitivity

*Note: 100 kg test mass is assumed to be point mass

No science is lost due to cooling system Newtonian Noise in KAGRA

Conclusion & Future Work

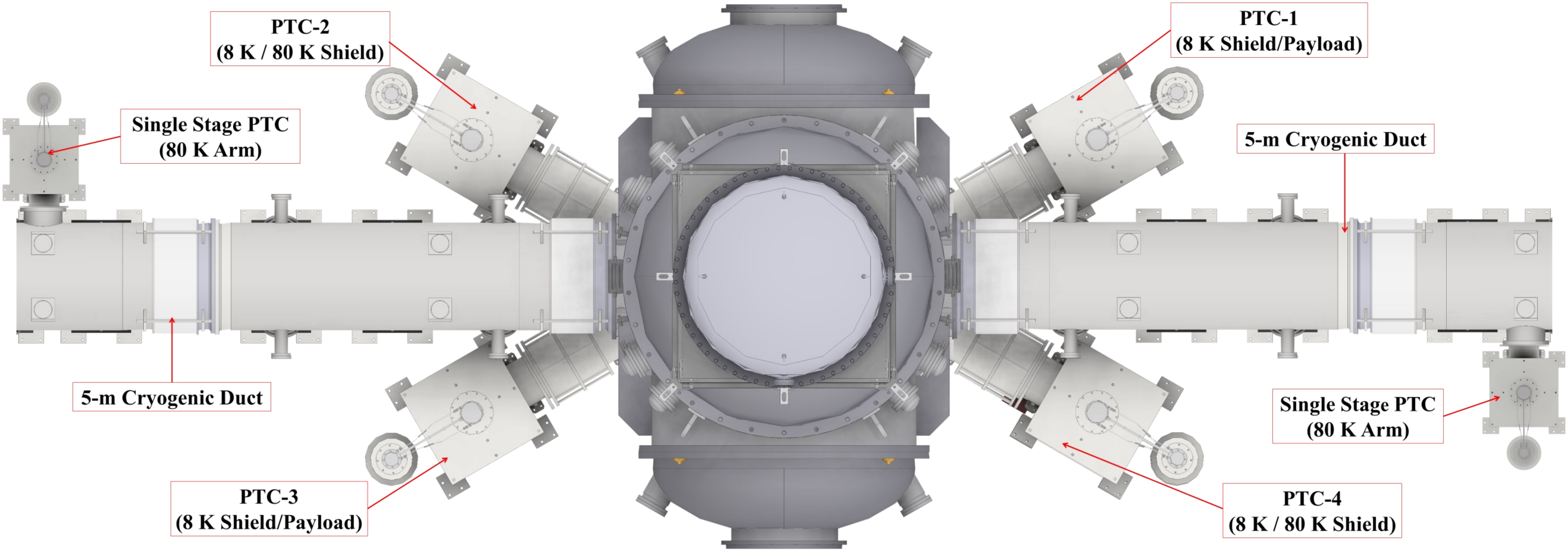
- Significant increase in radiation shield vibration was observed after cooling. Coupling of this vibration via heat-links is sufficiently attenuated.
- Since cooling system components are heavy and relatively close to the mirror, we evaluated the Newtonian noise injected by the cryostat.
- In the current model the size of the test mass is unaccounted for.
- We are improving the model to include the test mass mesh.
- Our calculation shows that NN coupling from KAGRA cryostat has negligible impact on sensitivity.
- But cooling system NN could be a **potential noise source for 3rd generation detector.**

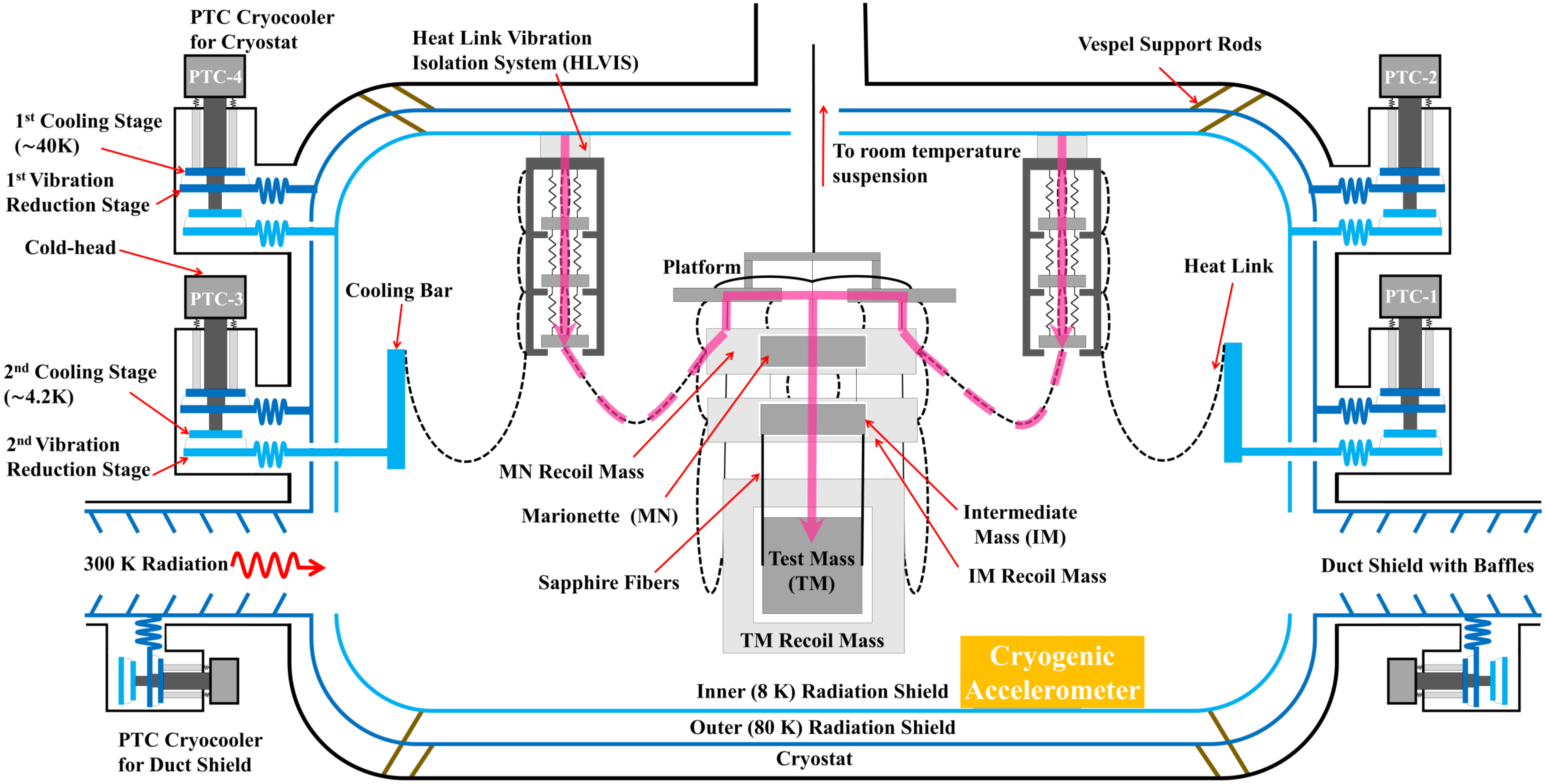


Thank you for your attention

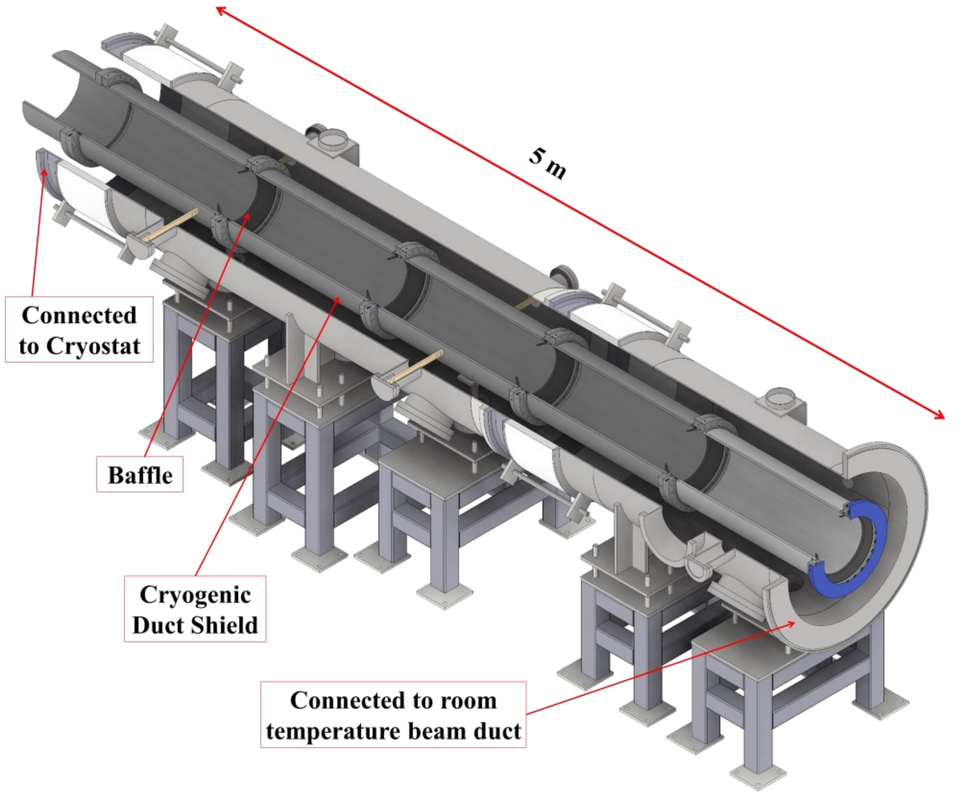
Backup

Cooling System

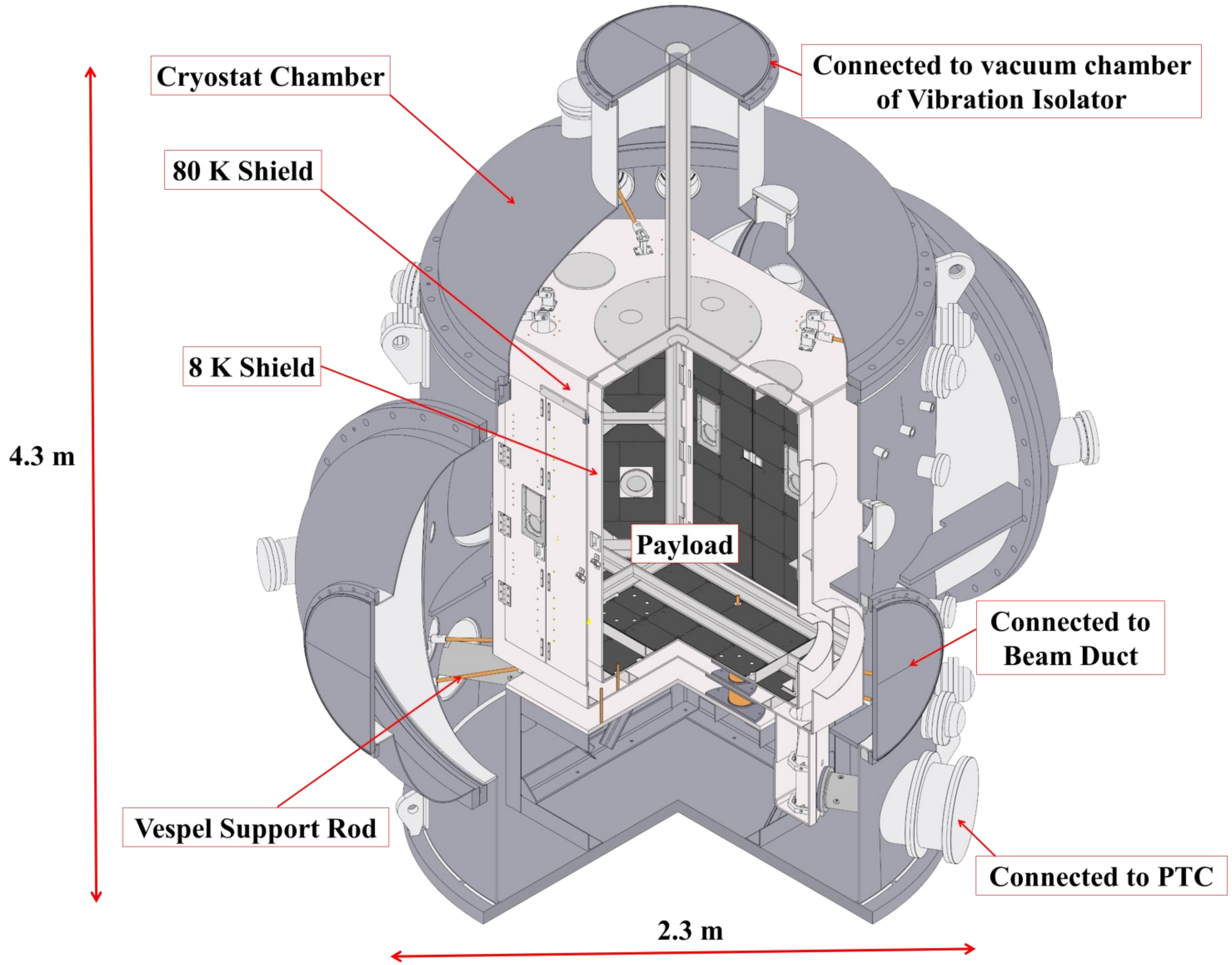



PTC Cryocooler
for Cryostat
PTC-4
Heat Link Vibration
Isolation System (HLVIS)
Vespel Support Rods
PTC-2
1st Cooling Stage
(~40K)
1st Vibration
Reduction Stage
To room temperature
suspension
Cold-head
Platform
Heat Link
PTC-3
Cooling Bar
PTC-1
2nd Cooling Stage
(~4.2K)
2nd Vibration
Reduction Stage
MN Recoil Mass
Marionette (MN)
Intermediate
Mass (IM)
300 K Radiation
Test Mass
(TM)
Sapphire Fibers
IM Recoil Mass
Duct Shield with Baffles
TM Recoil Mass
Cryogenic
Accelerometer
Inner (8 K) Radiation Shield
Outer (80 K) Radiation Shield
Cryostat
PTC Cryocooler
for Duct Shield

Cryostat

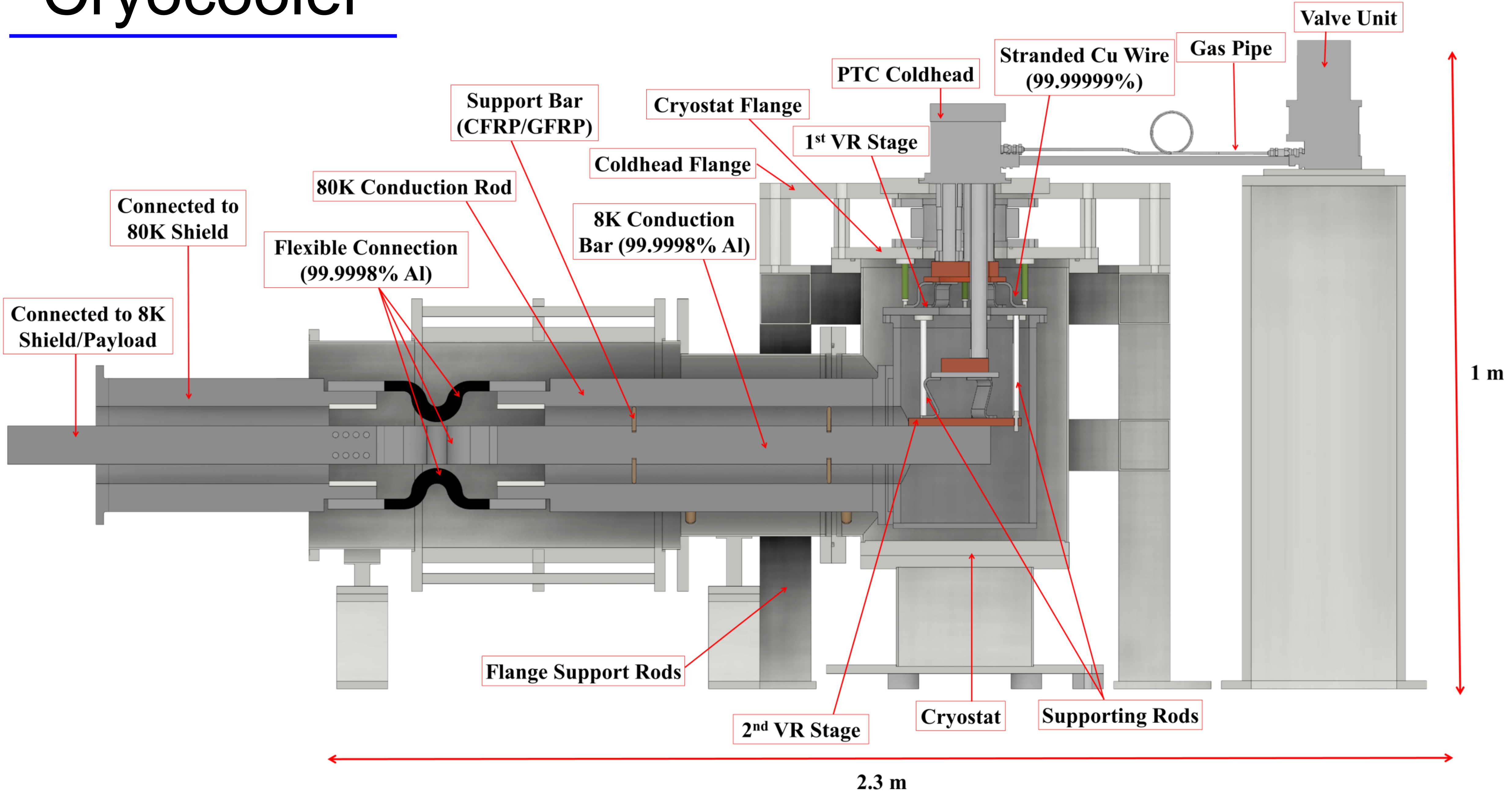


5 m
Connected to Cryostat
Baffle
Cryogenic Duct Shield
Connected to room temperature beam duct



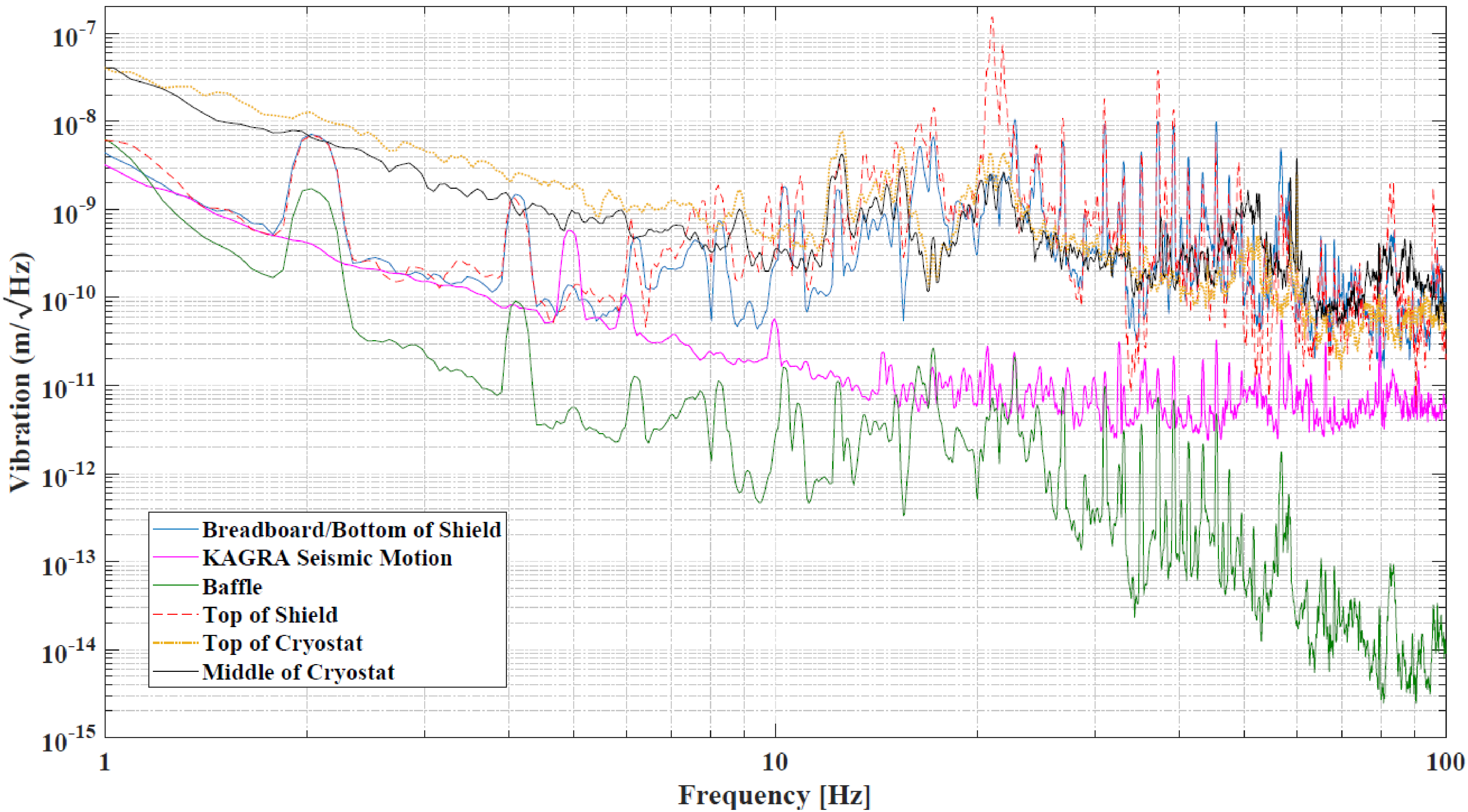
4.3 m
Cryostat Chamber
80 K Shield
8 K Shield
Connected to vacuum chamber of Vibration Isolator
Payload
Connected to Beam Duct
Vespel Support Rod
Connected to PTC
2.3 m

Cryocooler



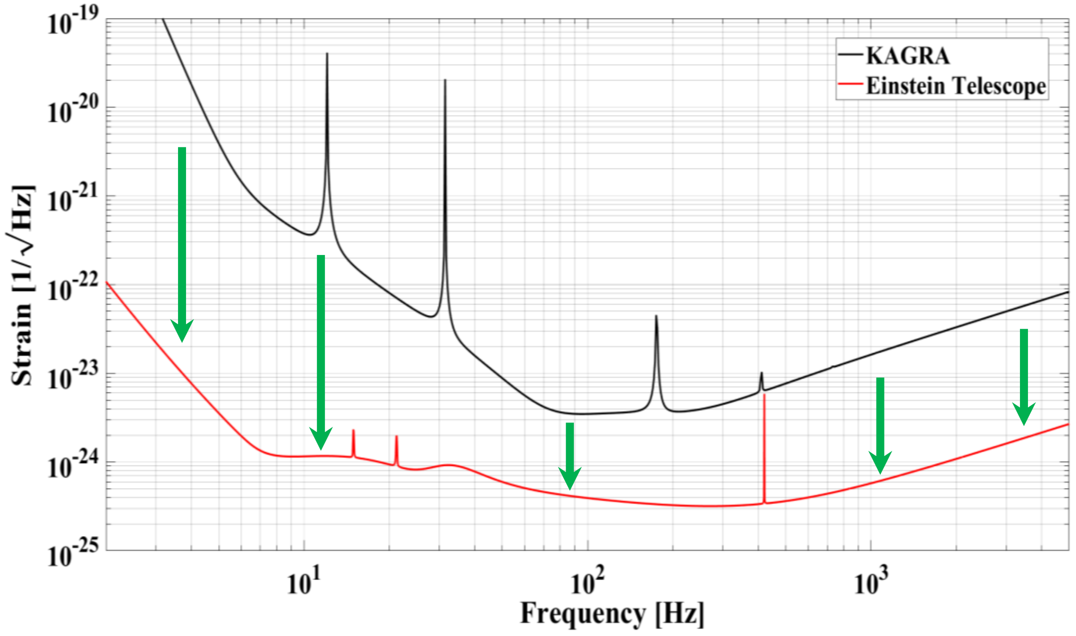
Valve Unit
Gas Pipe
Stranded Cu Wire (99.99999%)
PTC Coldhead
Cryostat Flange
1st VR Stage
Support Bar (CFRP/GFRP)
Coldhead Flange
80K Conduction Rod
8K Conduction Bar (99.9998% Al)
Connected to 80K Shield
Flexible Connection (99.9998% Al)
Connected to 8K Shield/Payload
1 m
Flange Support Rods
2nd VR Stage
Cryostat
Supporting Rods
2.3 m

Vibration Spectra



Einstein Telescope

- 3rd generation GWD in design phase.
- It aims to push the sensitivity of ground-based GWD to its limits by:
  - Longer arm-length →10 Km
  - Constructing detector underground
  - Using cryogenics → <20 K mirrors



- Features unique to KAGRA.
- KAGRA is the building block for Einstein Telescope (ET).

Estimate cooling system NN for ET using KAGRA cooling system.

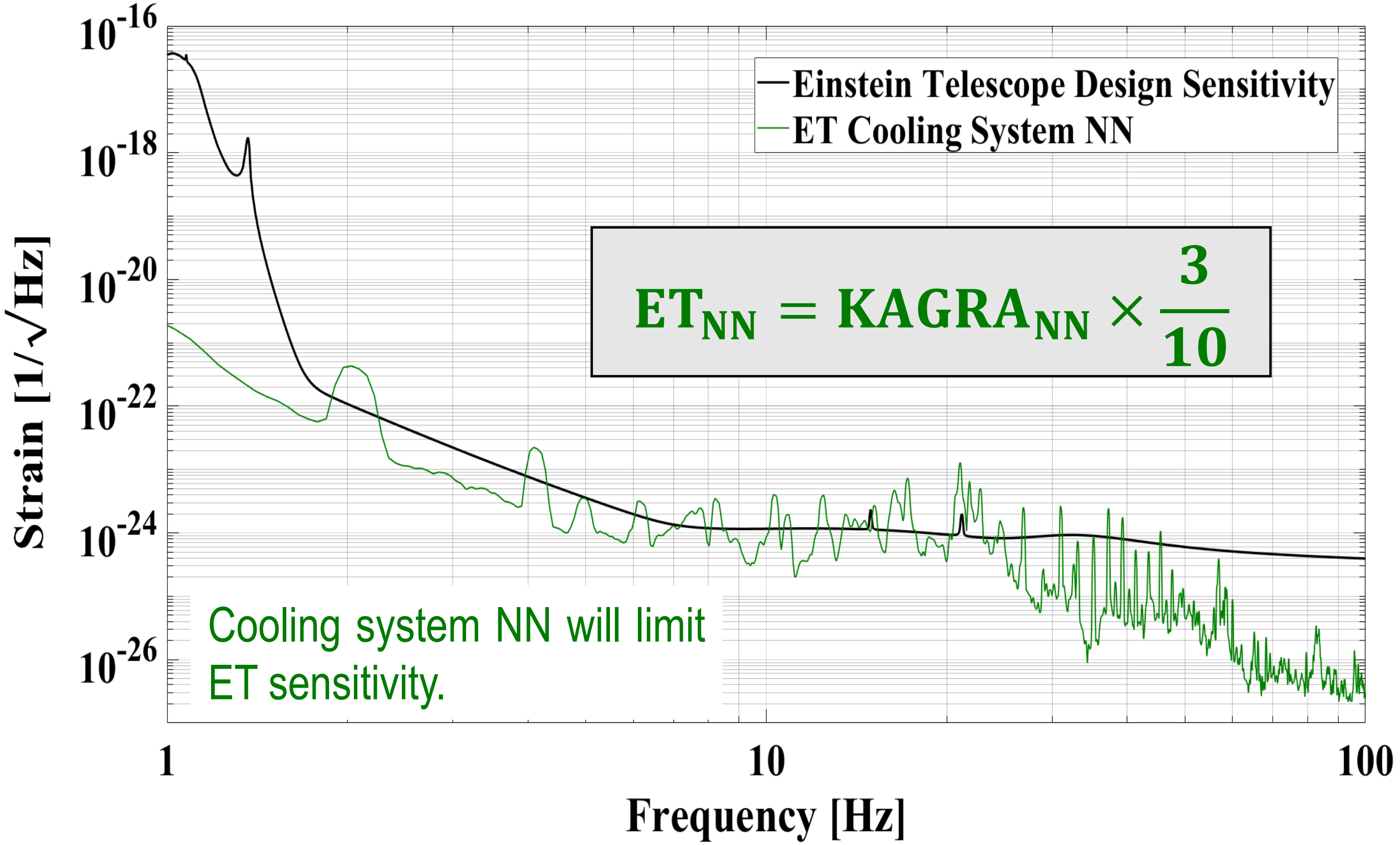
Cooling System NN- ET

- Still in the design phase.
- Substitute KAGRA cooling system as ET's.

NN is estimated as:

$$\sqrt{S_F(\omega)} = \frac{\sqrt{4}G}{\omega^2 L} \times \sqrt{S_u(\omega)} \times A$$

3 km for KAGRA
10 km for ET



Conclusion:

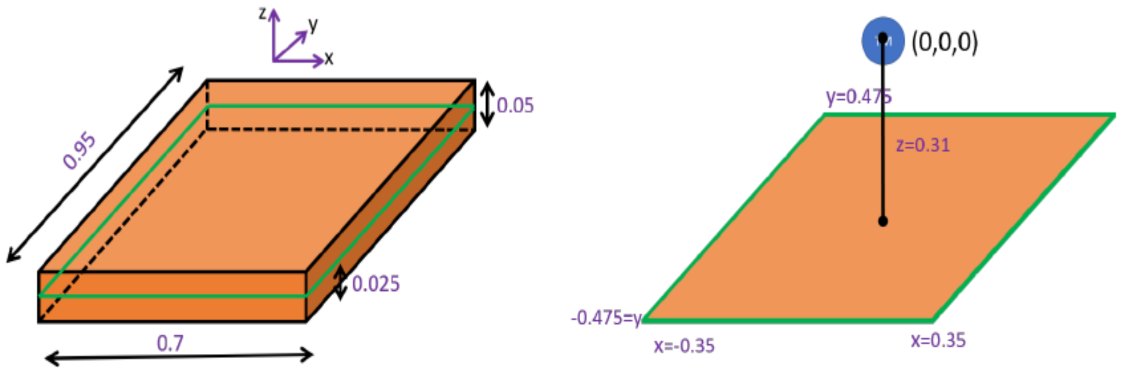
Design of ET cooling system should be carefully considered to minimize NN and achieve design sensitivity.

Breadboard

Integral Calculation

While the breadboard has several M6 tapping to fix the earthquake stopper frame and other components, for NN calculation a simple cuboid as shown in fig. 8.3(a). To simplify the calculation I consider a rectangle of dimension 0.7×0.95 m at the center of cuboid as shown in fig. 8.3(b) with the mass of 87.6 kg evenly distributed across the surface. The distance of this rectangle from the TM is 0.31 m. A small mass dm on this rectangle is $M_{unit}\,dxdy$, where:

$$M_{unit} = \frac{\text{Mass of the breadboard}}{\text{Surface area of the rectangle}} = \frac{87.6}{0.7 \times 0.95} = 139.36 \tag{8.14}$$



(a) (b)

Figure 8.3: (a) Simplified optical breadboard below the test mass for NN calculation. (b) A simple rectangle (green) considered at center if the breadboard to simplify the NN calculation.

From fig. 8.3(b) and eqs. (8.12) and (8.14) the NN strain will be:

$$H_{\text{breadboard}_{\text{integral}}} = \frac{\sqrt{4}.G.M_{unit}.u_{\text{bottom}}}{\omega^2.L} \int_{-0.475}^{0.475} \int_{-0.35}^{0.35} \frac{(-2x^2 + y^2 + z^2)}{(x^2 + y^2 + z^2)^{\frac{5}{2}}} dx\, dy \tag{8.15}$$

where, u_{bottom} is the vibration measured by cryogenic accelerometer.

$$H_{\text{breadboard}_{\text{integral}}} = \frac{4.447 \times 10^{-14}}{\omega^2} \times M_{unit} \times u_{\text{bottom}} \times 4.564 \tag{8.16}$$

$$H_{\text{breadboard}_{\text{integral}}} = 2.828 \times 10^{-11} \times \frac{u_{\text{bottom}}}{\omega^2} \tag{8.17}$$

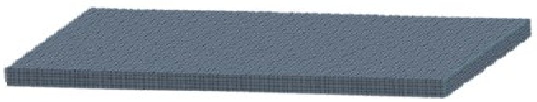
Element Calculation

For elemental method, elements size was set as 0.01 m splitting cuboid into 33250 elements each of weighing 2.634 gm. Figure 8.4(a) shows the generated mesh.

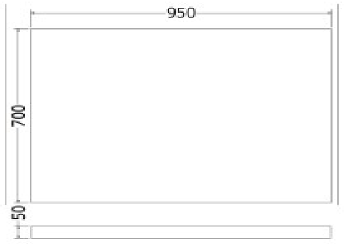
Based on the generated mesh eq. (8.13) becomes:

$$H_{\text{breadboard}_{\text{elemental}}} = \frac{\sqrt{4}.G}{\omega^2.L} \times u_{\text{breadboard}} \sum_{n=1}^{33250} S_{n_{\text{breadboard}}} \tag{8.18}$$

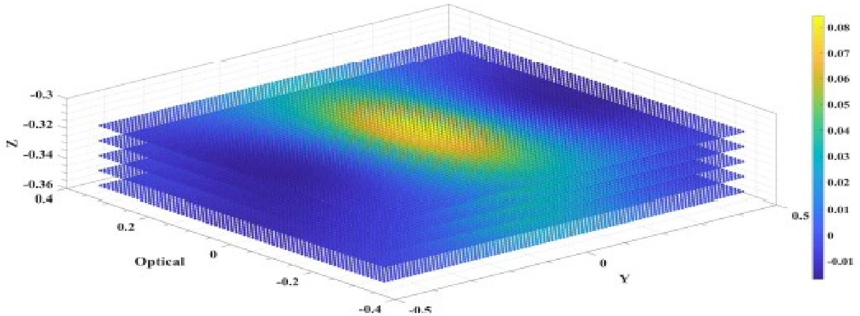
where, m_n is 0.002634 and (x_n, y_n, z_n) are the coordinate of centroid of element n in $S_{n_{\text{breadboard}}}$.



(a)



(b)



(c)

Figure 8.4: (a) Mesh generated for the breadboard. The cuboid is divided into 33,250 elements each weighing 2.634 grams. (c) 2-D drawing of the breadboard. (b) 3-D scatter plot where each dot represents an element n from breadboard mesh while the color is value $S_{n_{\text{breadboard}}}$ of the element in eq. (8.18)

The value of summation is calculated to be $\sum_{n=1}^{33250} = 550.697$, substituting the values in eq. (8.18) we get,

$$H_{\text{breadboard}_{\text{elemental}}} = 2.295 \times 10^{-11} \times \frac{u_{\text{bottom}}}{\omega^2} \tag{8.19}$$

Direct Calculation

A simplified system, shown in fig. 8.5 was considered to confirm the results obtained from elemental and integral method.

Figure 8.5(a) shows the front view of the breadboard. Now if the displacement (vibration) of the breadboard is X m/$\sqrt{\text{Hz}}$ at some frequency f. Now the force acting on the TM

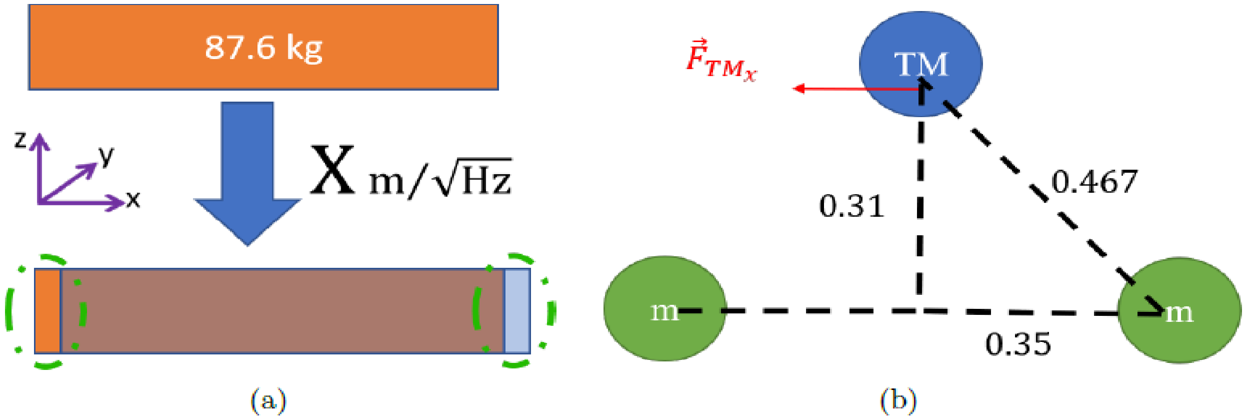


Figure 8.5: (a) Front view of breadboard, being displaced X m/$\sqrt{\text{Hz}}$. Dotted green circle represent mass that cause gravity fluctuations. (b) A simple point mass representation of fig. 8.5(a) showing relative position of Test Mass and breadboard point masses m.

will only be due to the small mass, represented by green dotted circles (in fig. 8.5(a)) displaced at ends of the breadboard. A simplified representation of this is shown in fig. 8.5(b), from which the force on TM along X-axis can be calculated as:

$$\overrightarrow{F}_{TM} = 2.G.M.m.\frac{0.35}{0.467^3} \tag{8.20}$$

where m is 87.6X kg at some frequency f and M is mass of Test Mass From eq. (8.20) the expression for strain can be derived as:

$$H_{\text{breadboard}_{\text{direct}}} = \frac{\sqrt{4}}{\omega^2.L} \times 2 \times G \times 87.6X \times 3.436 \tag{8.21}$$

where, $X = u_{\text{bottom}}$ is the vibration measured by cryogenic accelerometer.

$$H_{\text{breadboard}_{\text{direct}}} = 2.676 \times 10^{-11} \times \frac{u_{\text{bottom}}}{\omega^2} \tag{8.22}$$

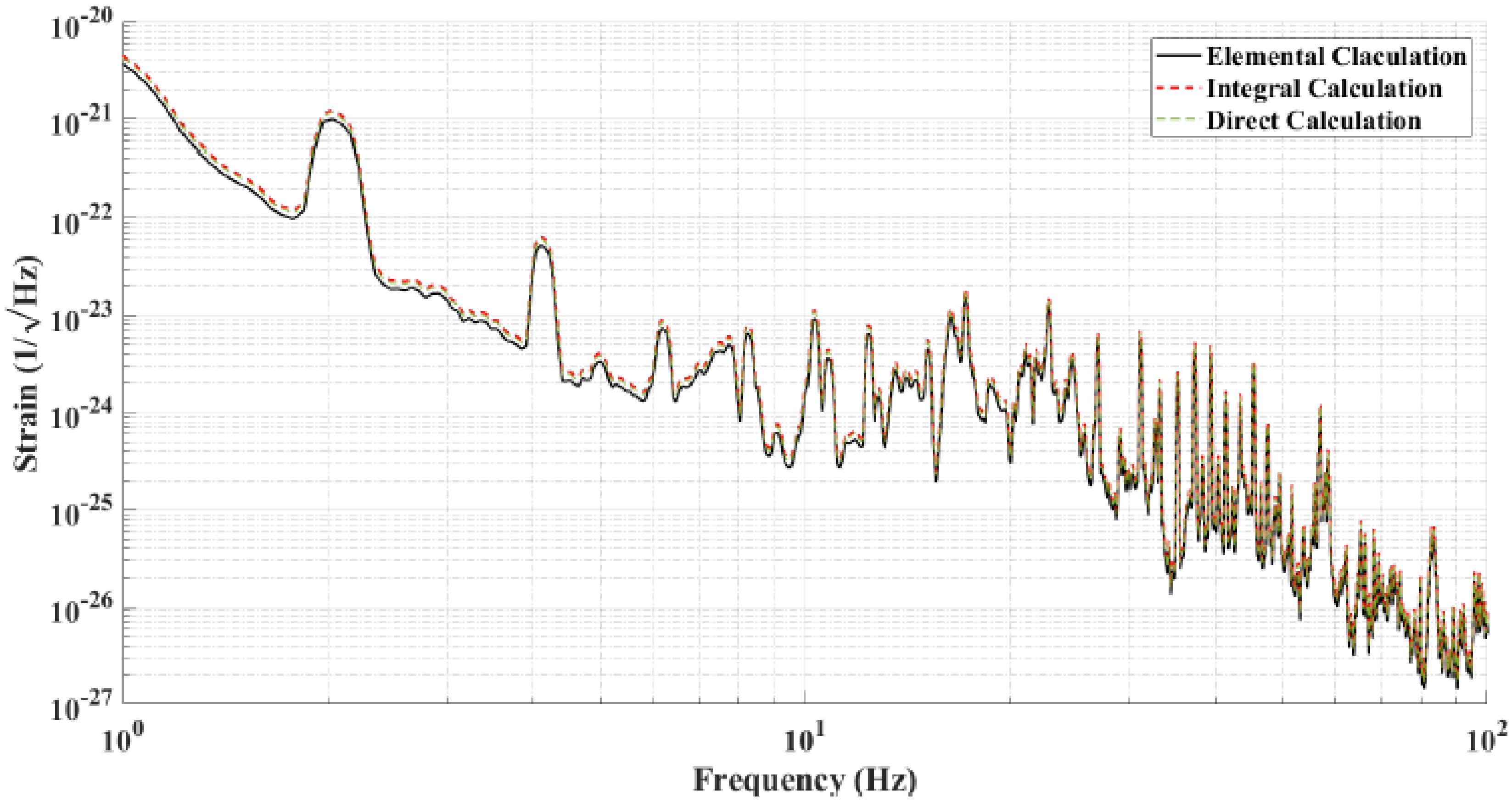
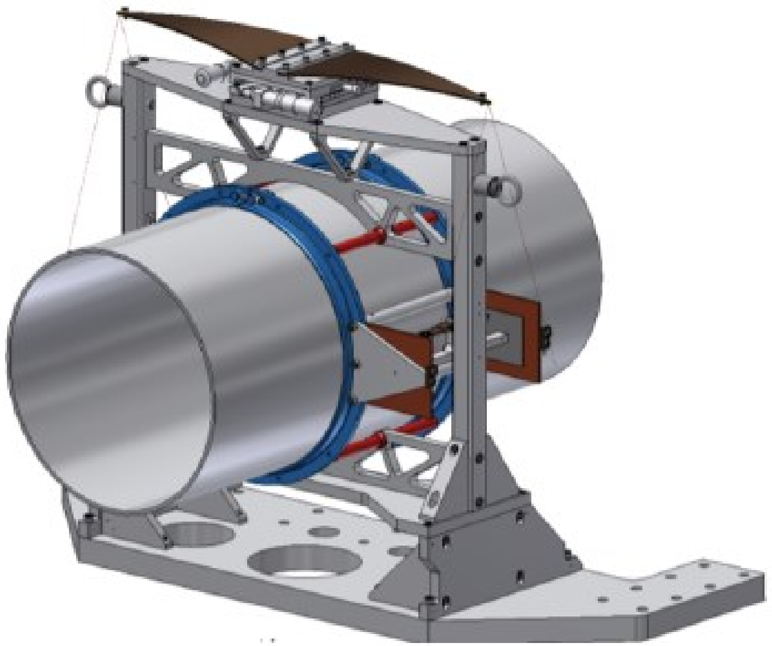


Figure 8.6: Strain of breadboard NN calculated with elemental (black) and integral (red) method. $H_{\text{breadboard}_{\text{integral}}} = 1.05 \times H_{\text{breadboard}_{\text{direct}}} = 1.23 \times H_{\text{breadboard}_{\text{elemental}}}$.

Baffle



Integral Method

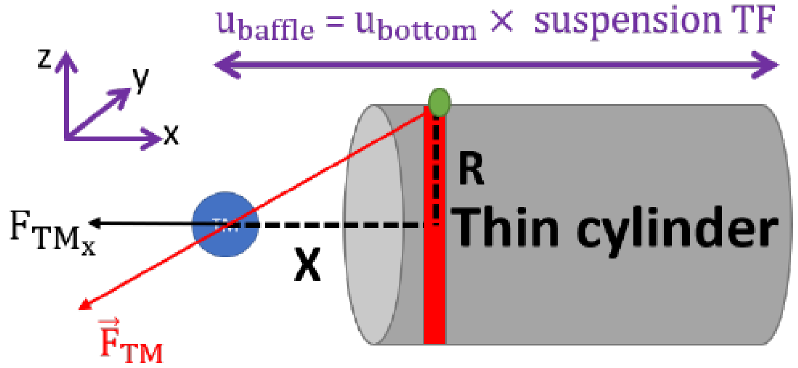


Figure 8.8: Simplified baffle to calculate NN is a thin cylinder of radius, R(=0.128 m) and length, l (=0.57 m). The TM is at distance, X (=0.01 m) from baffle. The green dot is a small mass on the red ring.

To estimate NN from baffle I reduce it to a cylinder of radius (R) 0.128 m and length (l) 0.57 m as shown in fig. 8.8. I consider a thin ring of length dx on the baffle at a distance x from TM. Force on TM due to this red ring along x-axis is:

$$F_{TM_{x_{ring}}} = G.M.m_{ring}.\frac{x}{(x^2+R^2)^{\frac{3}{2}}} \tag{8.23}$$

Gradient of eq. (8.23) is:

$$\nabla F_{TM_{x_{ring}}} = G.M.m_{ring}.\frac{-2x^2+R^2}{(x^2+R^2)^{\frac{2}{2}}}\hat{i} \tag{8.24}$$

Now the ring is being displaced by a small amount $u_{baffle}\hat{i}$. The force due to this small displacement, along x-axis is the scalar product $\nabla F_{TM_{x_{ring}}}.u_{\text{baffle}}$, so:

$$F_{TM_{x_{ring}}} = G.m_{ring}.\frac{-2x^2+R^2}{(x^2+R^2)^{\frac{2}{2}}} \times u_{\text{baffle}} \tag{8.25}$$

Now, $m_{ring} = m_{unit}\, dx$

where,

$$m_{unit} = \frac{\text{Mass of cylinder}}{\text{Length of the cylinder}} = \frac{7.2}{0.57} = 12.63$$

Integrating eq. (8.25) over the length of cylinder we get the force on TM due to baffle as:

$$F_{TM_{z_{\text{baffle}}}} = G.M.m_{unit}.u_{\text{baffle}} \int_{0.01}^{0.58} \frac{-2x^2 + R^2}{(x^2 + R^2)^{\frac{5}{2}}} dx = -1.648 \times 10^{-9} \times u_{baffle} \times M \quad (8.26)$$

So, NN strain for the baffle will be:

$$H_{\text{baffle}_{\text{integral}}} = \frac{\sqrt{4}}{\omega^2.L.M} \times -1.648 \times 10^{-9} \times u_{\text{baffle}} \times M \quad (8.27)$$

$$H_{\text{baffle}_{\text{integral}}} = -1.098 \times 10^{-12} \times \frac{u_{\text{baffle}}}{\omega^2} \quad (8.28)$$

The baffle suspension is rigidly bolted to the breadboard and since the longitudinal mode of the suspended baffle is 0.84 Hz so the transfer function is: $\frac{0.84^2}{f^2}$ for $f > 0.84$ Hz. So, vibration of baffle:

$$u_{\text{baffle}} = u_{\text{bottom}} \times \text{Transfer function of suspension} = u_{\text{bottom}} \times \frac{0.84^2}{f^2} \quad (8.29)$$

From eqs. (8.28) and (8.29) the expression for stain NN becomes:

$$H_{\text{baffle}_{\text{integral}}} = -7.68 \times 10^{-13} \times \frac{u_{\text{bottom}}}{\omega^2.f^2}\ for\ f > 0.84Hz \quad (8.30)$$

Elemental Method

For elemental method, elements size was set as 0.005 m splitting the cylinder into 29,601 elements each of weighing 0.19 gm. Figure 8.9(a) shows the generated mesh. Based on the generated mesh eq. (8.13) becomes:

$$H_{\text{baffle}_{\text{elemntal}}} = \frac{\sqrt{4}.G}{\omega^2.L} \times u_{\text{baffle}} \sum_{n=1}^{37164} S_{n_{\text{baffle}}} \quad (8.31)$$

where, m_n is 0.00019 and (x_n, y_n, z_n) are the coordinate of centroid of element n in $S_{n_{\text{baffle}}}$.

The value of summation is calculated to be $\sum_{n=1}^{29601} = -24.75$, substituting the values in eq. (8.18) we get,

$$H_{\text{baffle}_{\text{elemntal}}} = -6.88 \times 10^{-13} \times \frac{u_{\text{baffle}}}{\omega^2.f^2} \quad (8.32)$$

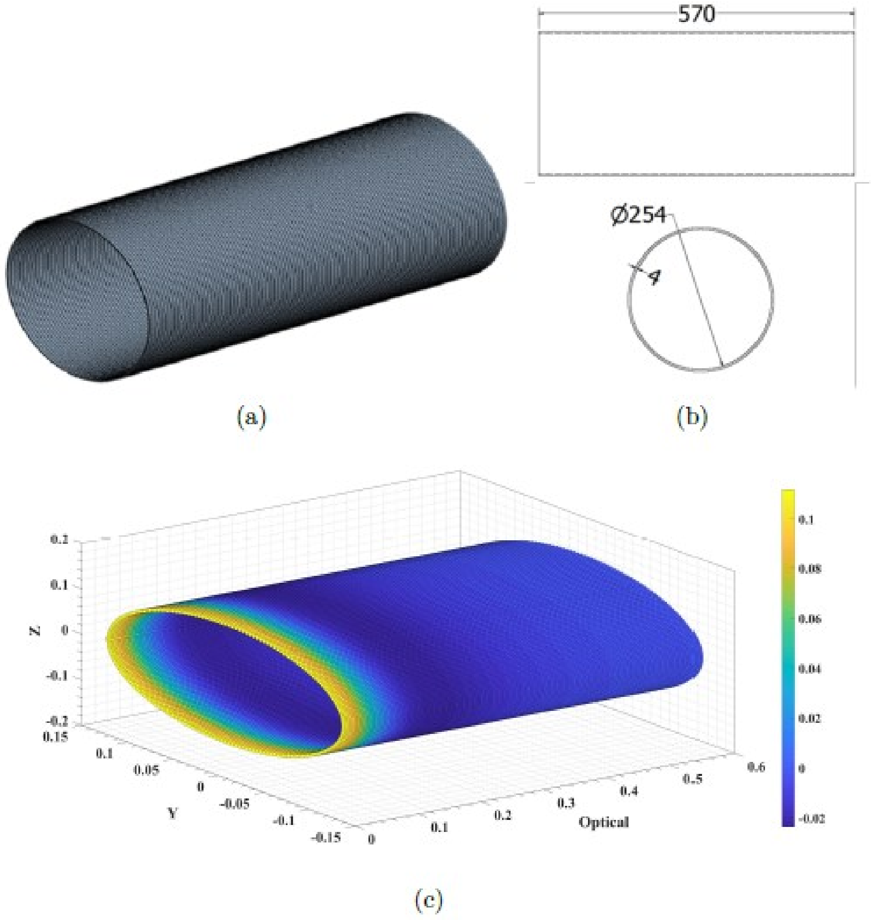


Figure 8.9: (a) Mesh generated for baffle. The cylinder is divided into 29601 elements each weighing 0.24 grams. (c) 2-D drawing of the baffle. (b) 3-D scatter plot where each dot represents an element n from baffle mesh while the color is value $S_{n_{\text{baffle}}}$ of the element in eq. (8.31)

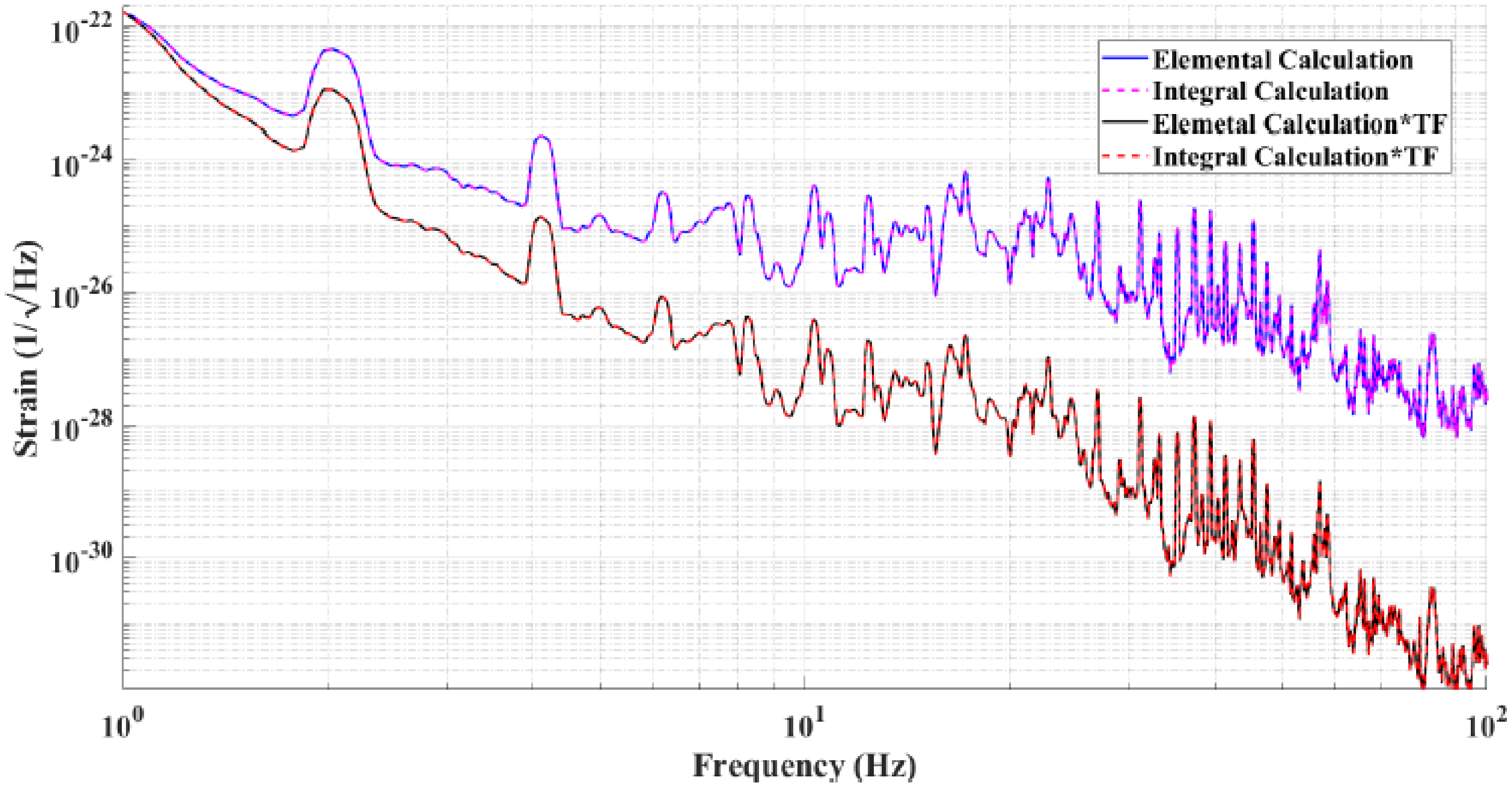


Figure 8.10: Strain of baffle NN calculated with elemental and integral method $H_{\text{baffle}_{\text{integral}}} = 1.125 \times H_{\text{baffle}_{\text{elemntal}}}$.

Radiation Shield

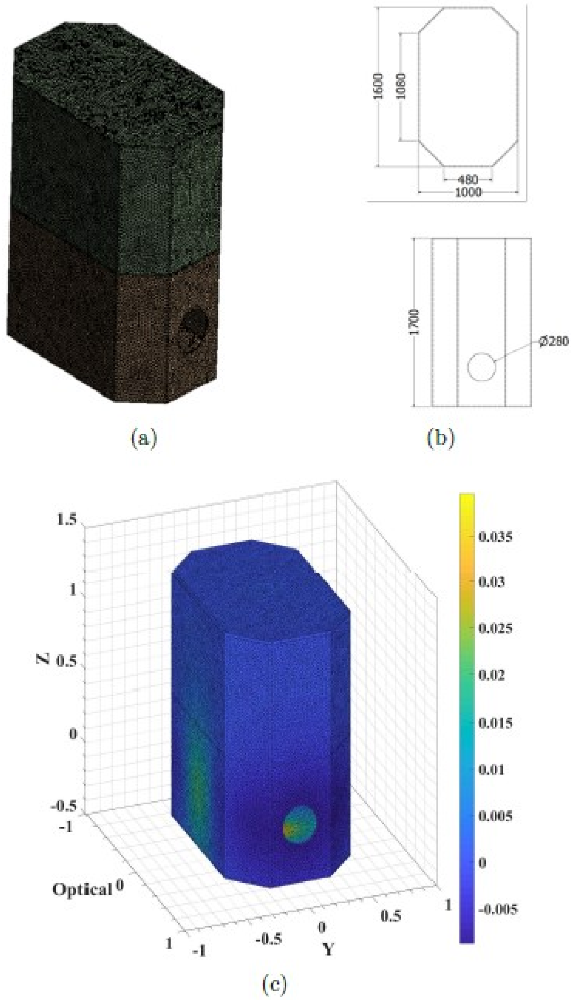


Figure 8.14: (a) Mesh generated for the Inner/8K radiation. The octagonal prism is divided into 200,935 elements each weighing 2.4 grams. (c) 2-D drawing of the inner/8K radiation shield. (b) 3-D scatter plot where each dot represents an element n from inner shield mesh while the color is value of summation expression of the element in eq. (8.39)

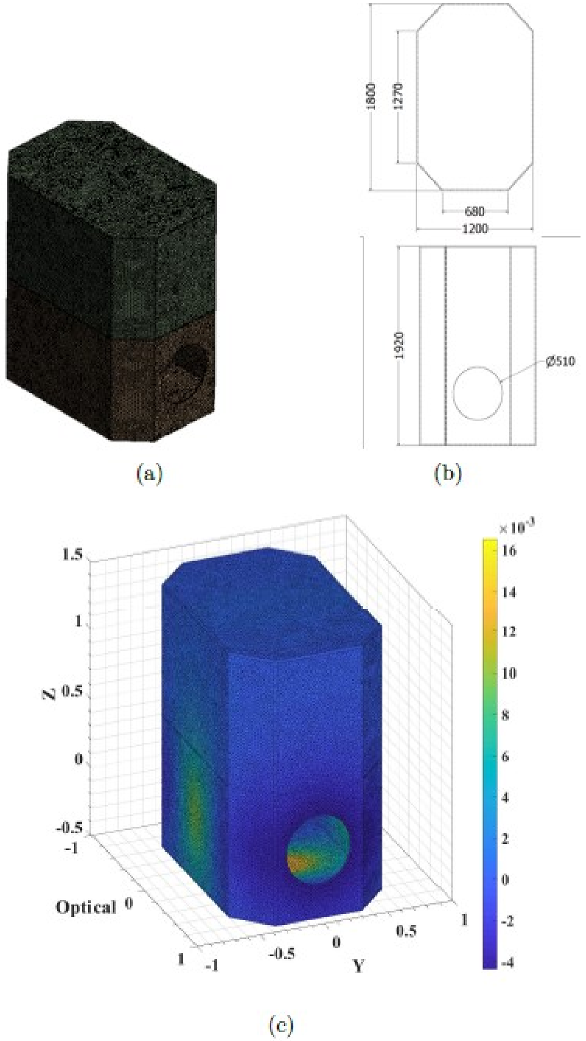


Figure 8.16: (a) Mesh generated for the Outer/80K radiation. The octagonal prism is divided into 262,889 elements each weighing 1.97 grams. (c) 2-D drawing of the outer/80K radiation shield. (b) 3-D scatter plot where each dot represents an element n from outer shield mesh while the color is value of summation expression of the element in eq. (8.43)

Cryostat

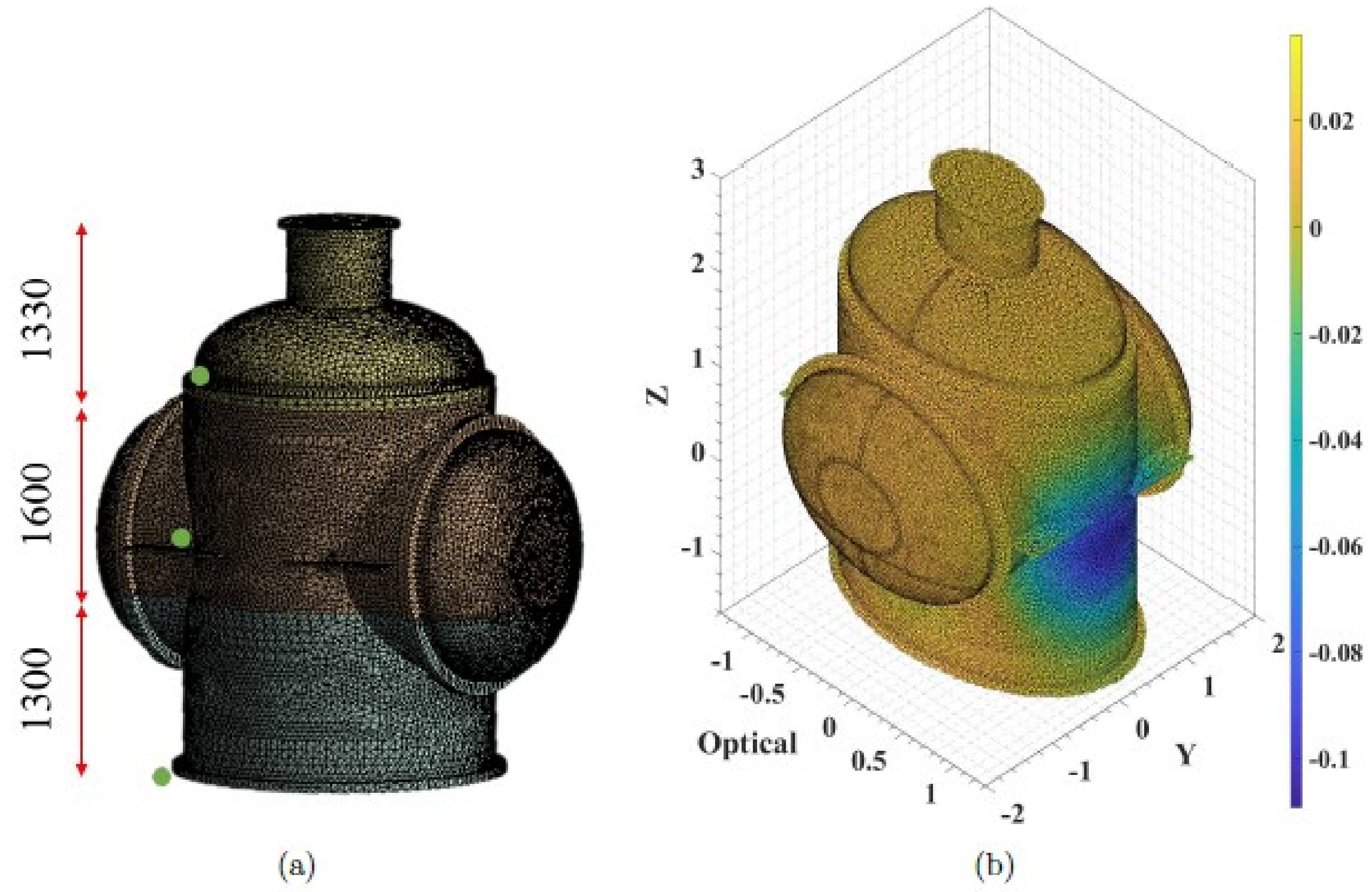
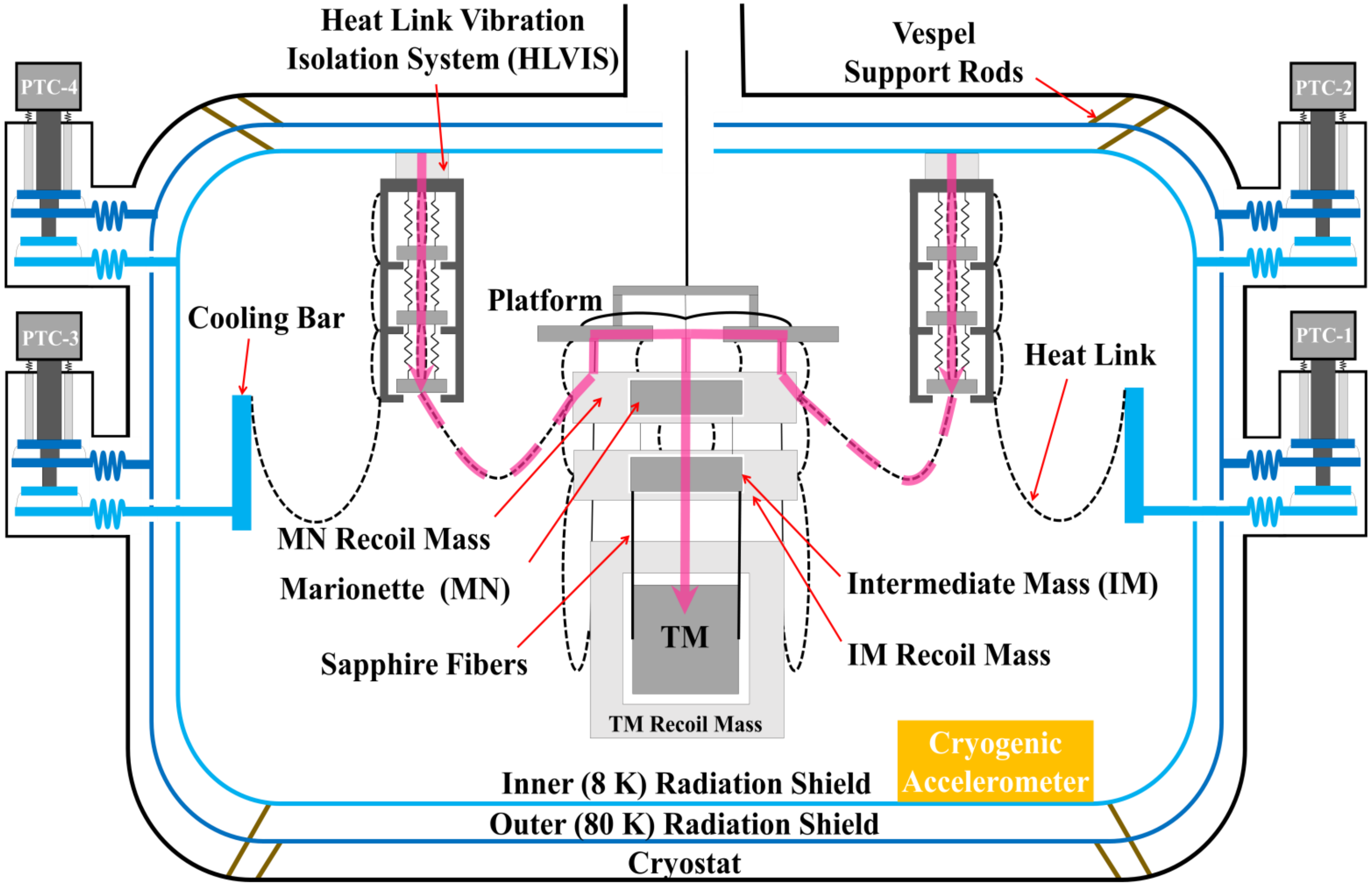


Figure 8.17: (a) Mesh generated for cryostat with 124,795 elements. Cryostat was split into three parts and the green dots represent the position where vibrations u_{top}, u_{middle} and u_{bottom} were measured. (b) 3-D scatter plot where each dot represents an element n from cryostat mesh while the color is value $S_{n_{cryostat}}$ of that element in eq. (8.45)

Vibration Transfer



Radiation shield vibration couples to Test-Mass as:

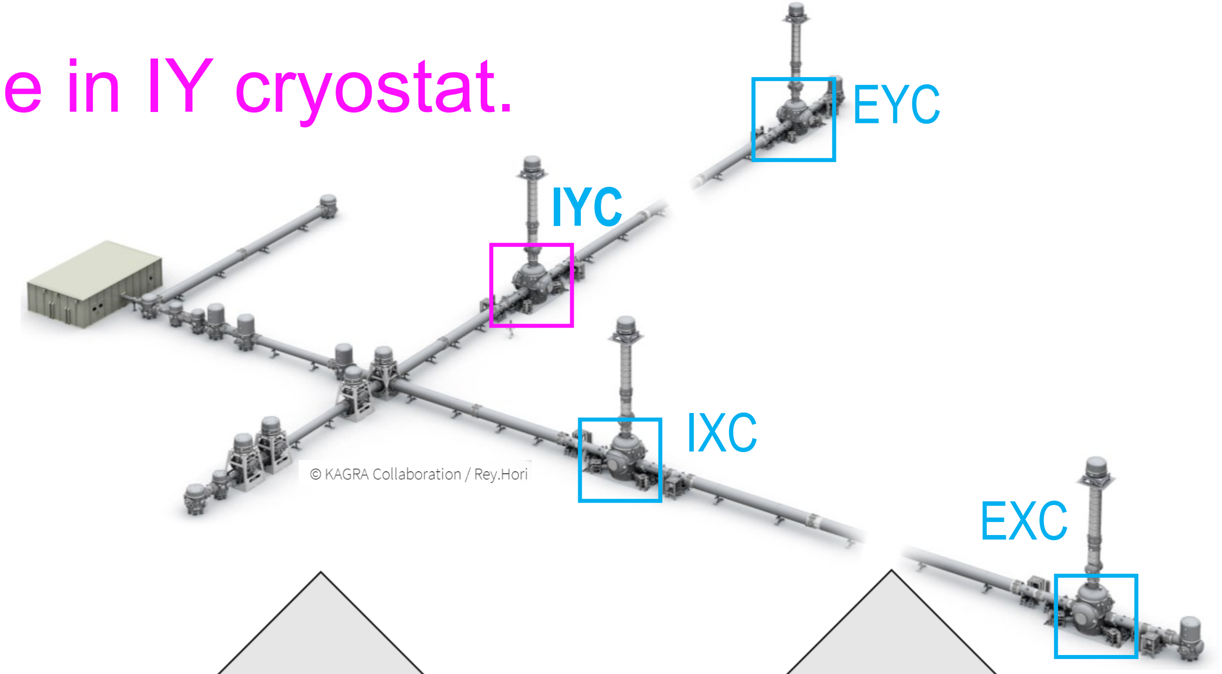
Top of inner shield → HLVIS → HL → MNR → PF → MN → IM → TM

Issues: Current noise budget for this vibration coupling is based on old in vacuum room temperature measurement.

Perform vibration measurement at 12 K.

Setup

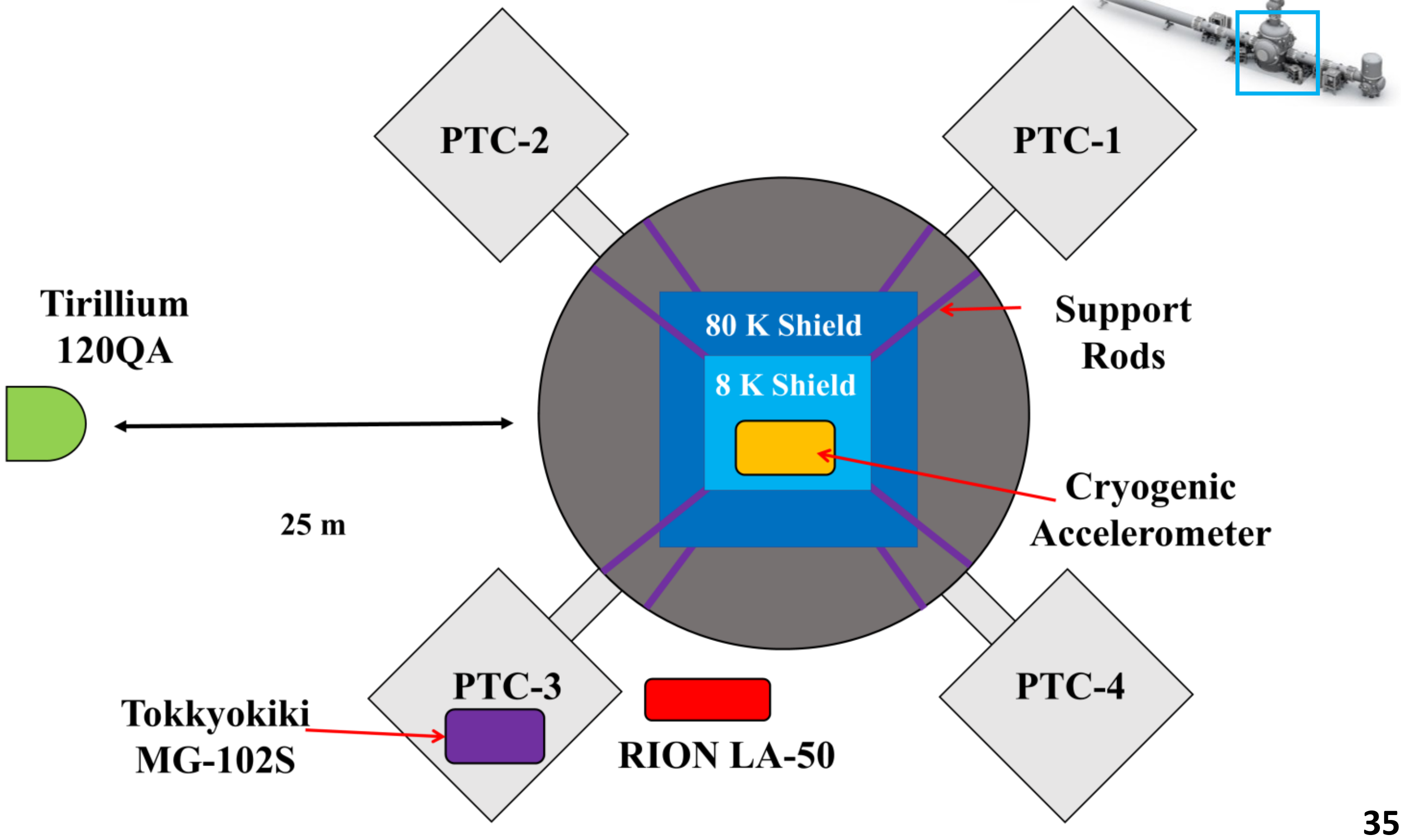
Measurement was done in IY cryostat.

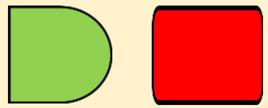
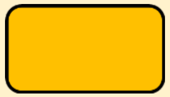


Shield vibration source:

– Seismic Motion. (ground vibration)
– Cryocooler Operation.
– Resonances*: Shield and Chamber

**Enhances the vibration*

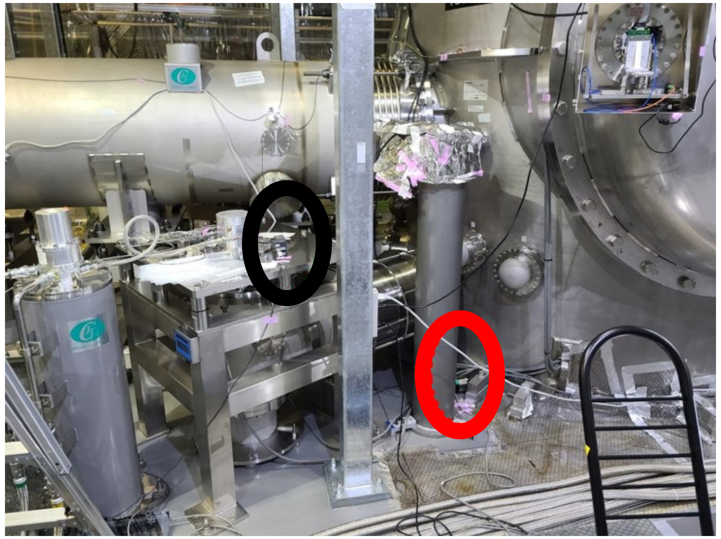


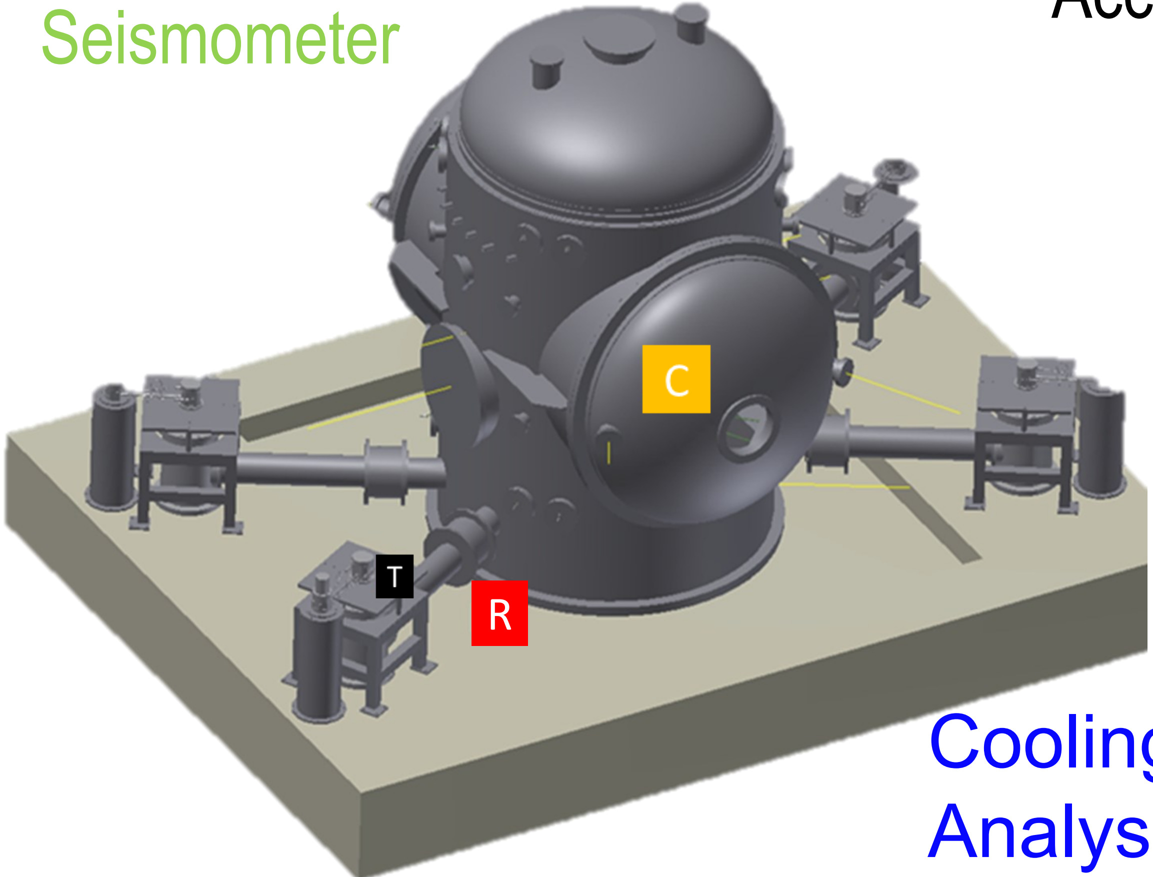
Sensor	Monitors
	Seismic Motion
	Cold-Head Vibration
	Inner Shield Vibration

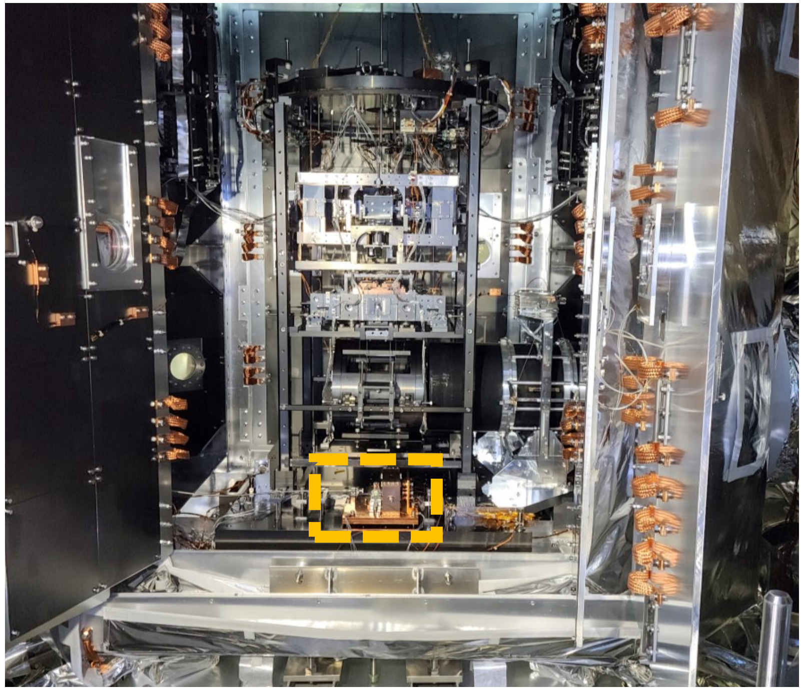
Trillium © nanometrics
120Q/QA
Seismometer

Piezoelectric

Accelerometer





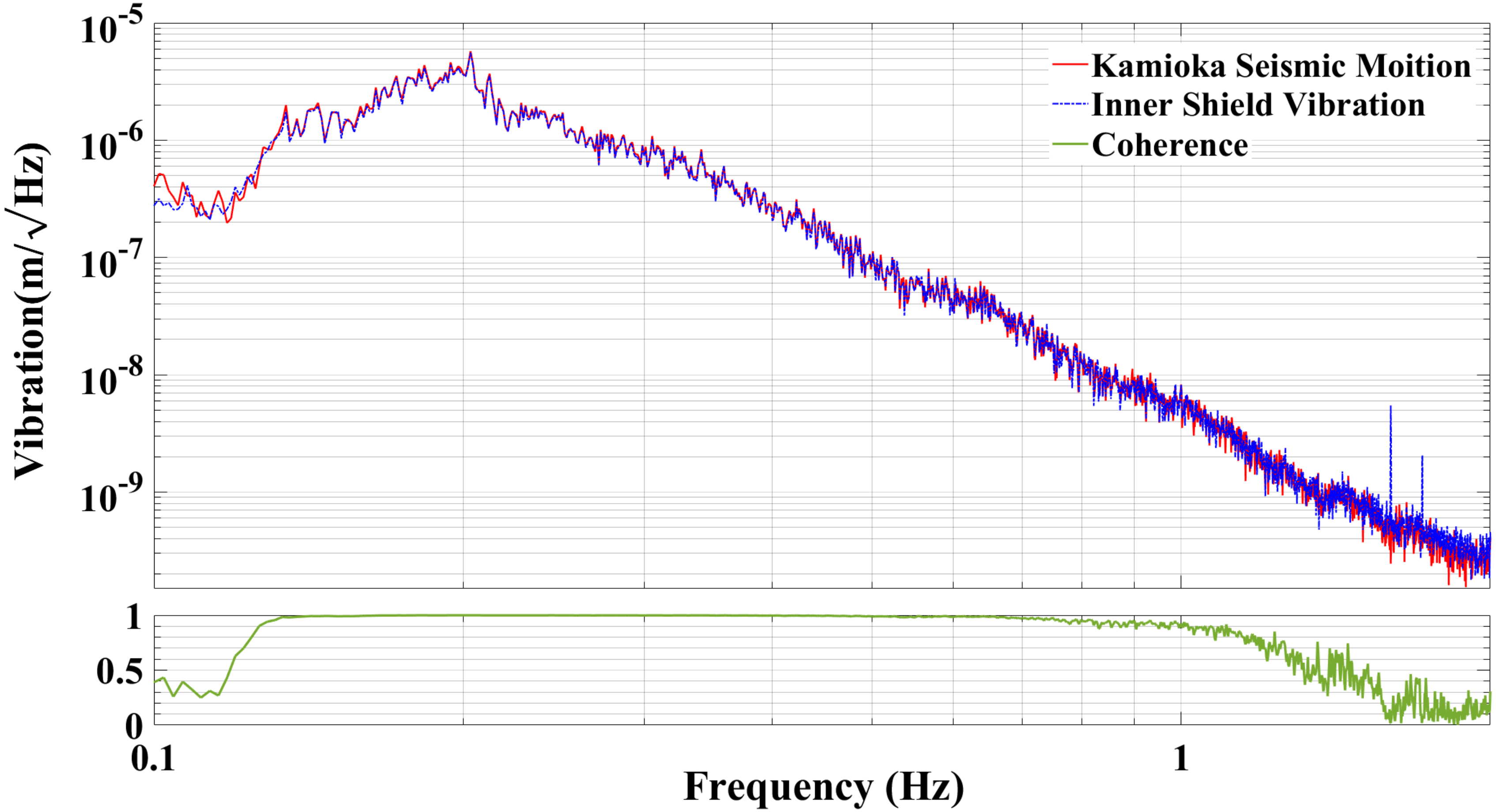


Cooling down to 12 K took 2 months.
Analysis was done after cooling.

Analysis Results

Performed vibration analysis to identify the origin of peaks.

- Influence of Seismic Motion:



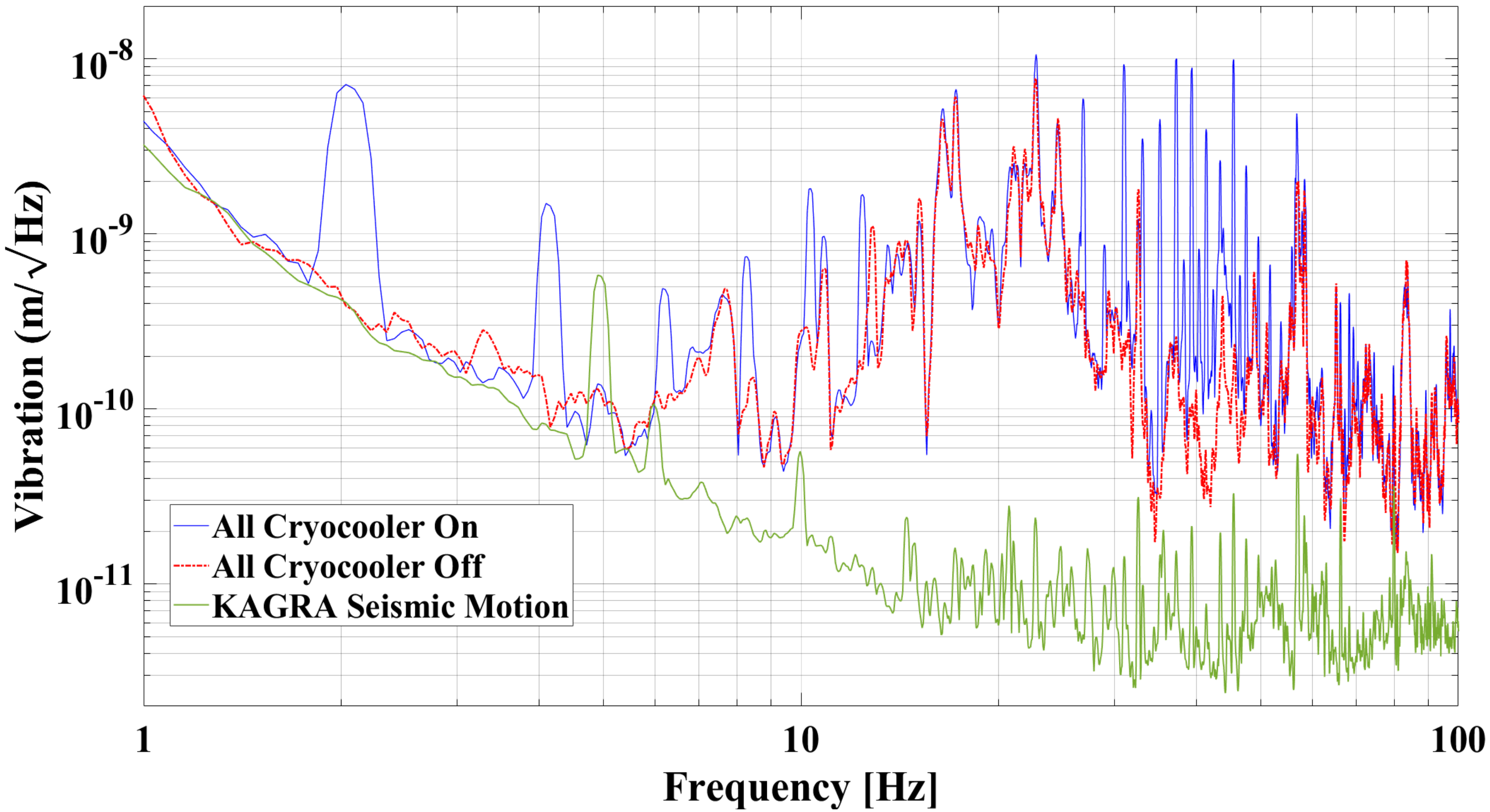
Compare 8 K shield and seismic motion in 0.1-2 Hz.

Measured at: 12 K
Sensor:
Trillium 120QA
Cryogenic Accelerometer

Both spectra below 1 Hz are comparable and coherence is 1.

Conclusion:
Shield follows ground motion below 1 Hz.

▪ Influence of Resonances:



Compare shield vibration when all cryocoolers are on/off and seismic motion.

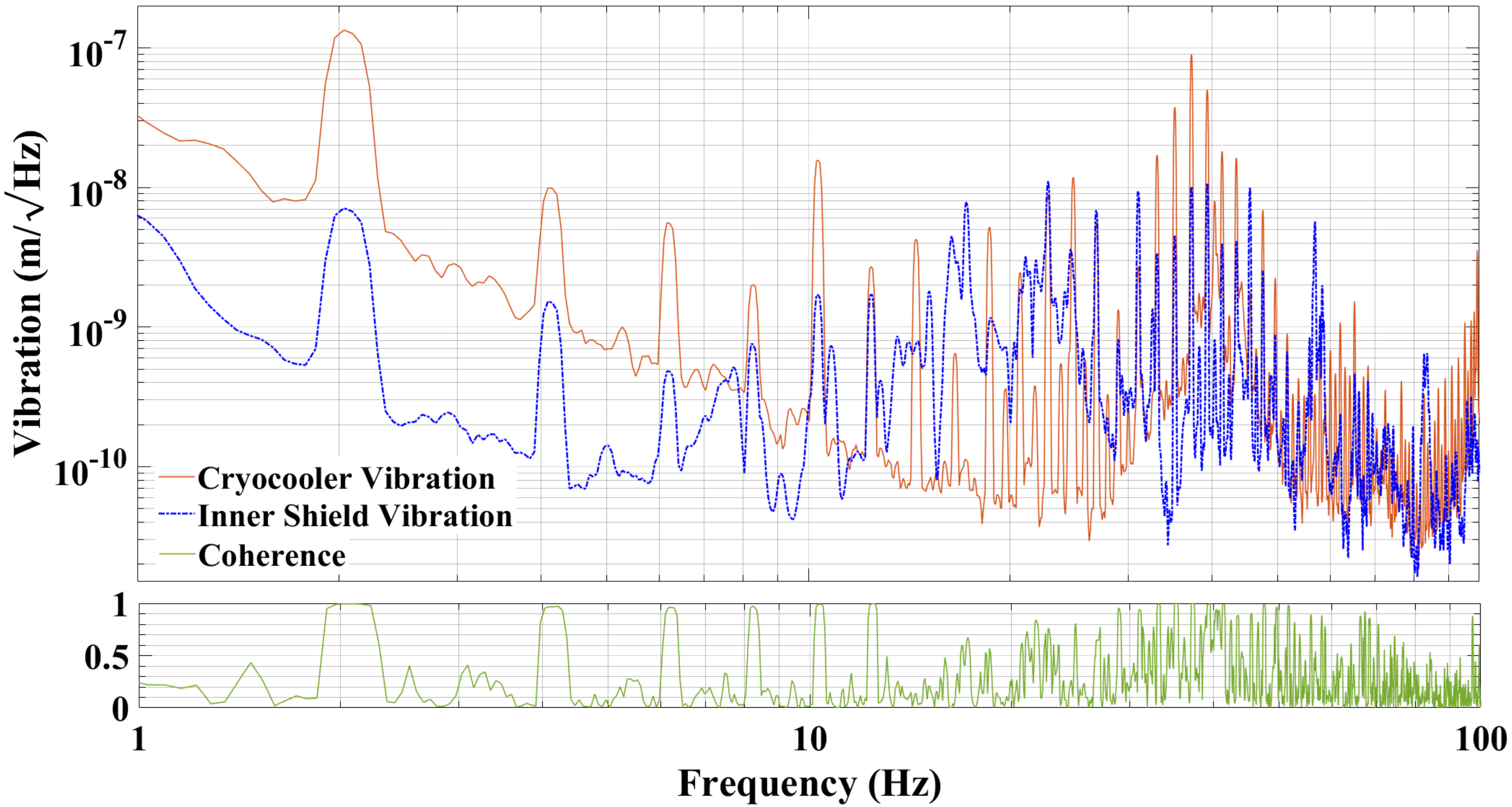
Measured at: 12 K
Sensor:
RION LA-50
Cryogenic Accelerometer

– Cryocoolers off ⇒ peaks due to resonances.
– Origin of peaks identified by hammering test.

Conclusion:

- Shield vibration is 2-3 orders larger than seismic motion.
- Operation of cryocooler doesn't affect noise floor but 2 Hz peaks and it's harmonics appear.

▪ Influence of Cryocooler:



Compare shield vibration with cold-head vibration.

Measured at: 12 K
Sensor:
Tokkyokiki MG-102S
Cryogenic Accelerometer

Cryocooler operation introduces 2.0 Hz and its harmonics over the entire shield vibration spectra

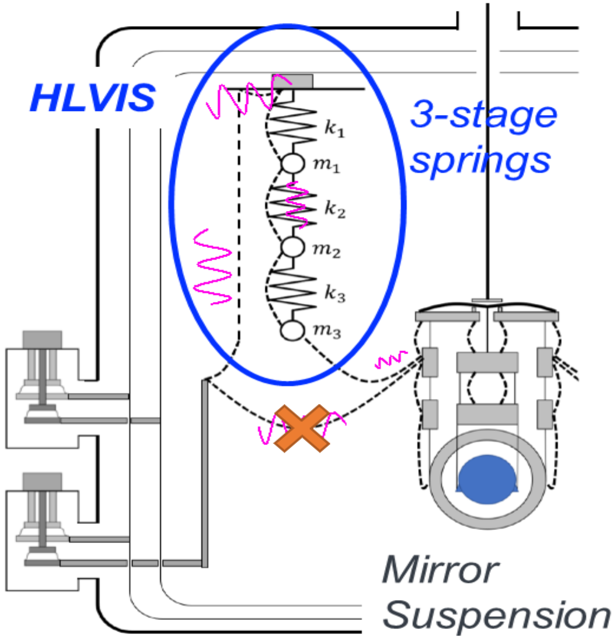
Conclusion:
Shield vibration spectra is dominated by 2.0 Hz peaks in 1-100 Hz however, internal resonance dominate in 10-30 Hz band.

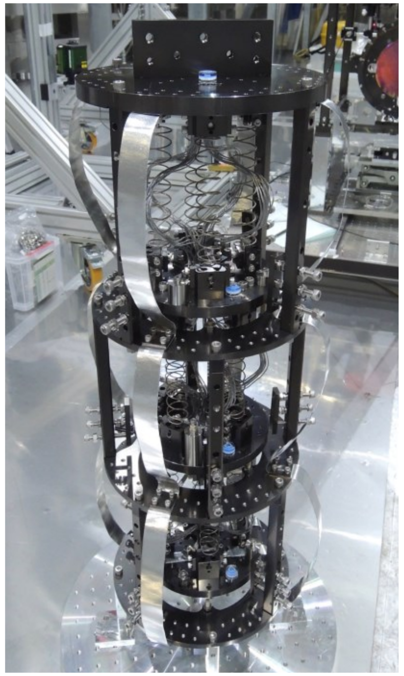
HLVIS

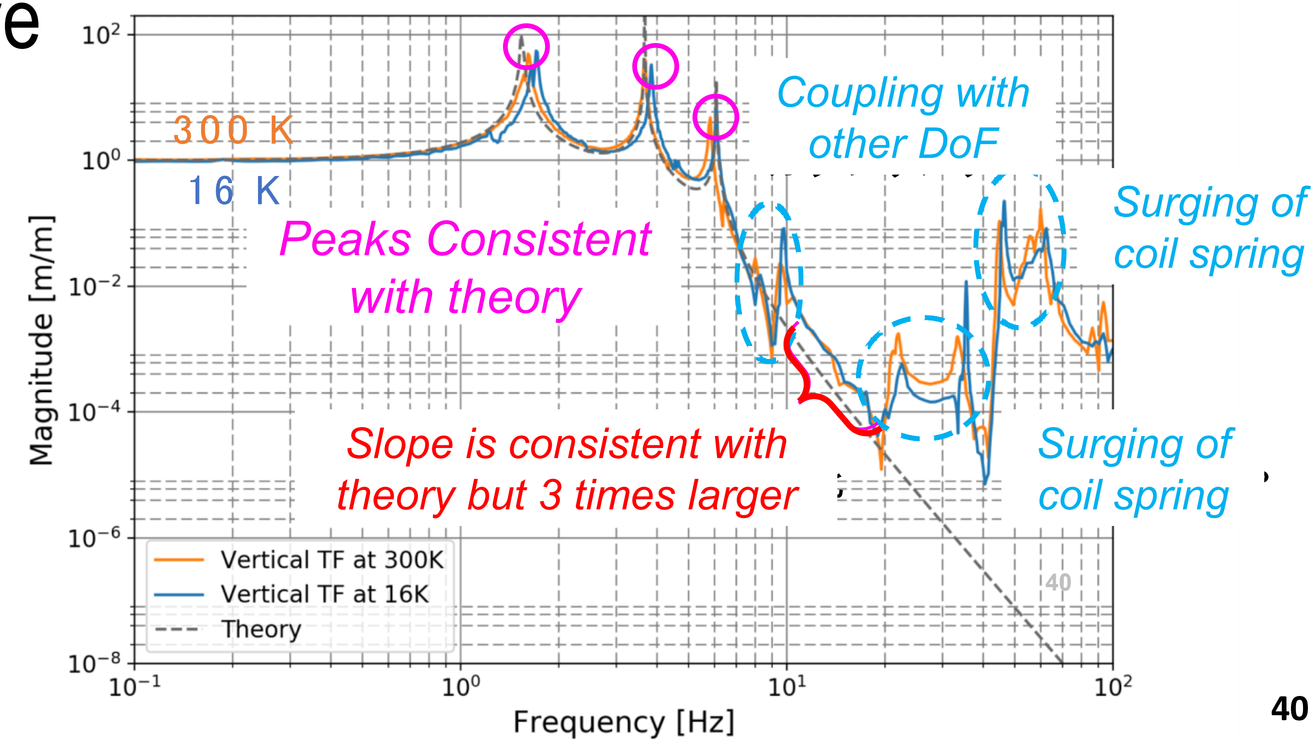
- Heat links should be effective in reducing vibration transfer while keeping sufficient thermal conductivity.
- We found that vertical vibration isolation was insufficient to achieve design sensitivity.

A **simple vertical vibration isolation system was developed** for heat link .

Yamada T., PhD. Thesis, *The University of Tokyo* (2021)







Vibration Coupling

Top of inner shield → Heat-link Vibration Isolation System (×2) → Heat Link (×2) → MNR → PF → MN → IM → TM

TM Displacement due to Horizontal Vibration Coupling

$$\mathrm{Displacement}^{\mathrm{H}}_{\mathrm{TM}} = V^{\mathrm{H}}_{\mathrm{Top}} \times TF^{\mathrm{H}}_{\mathrm{HLVIS}} \times TF^{\mathrm{H}}_{\mathrm{HL}} \times TF^{\mathrm{H}}_{\mathrm{MNR}\rightarrow\mathrm{TM}}$$

Due to 1 heat-link between HLVIS and Payload

$V^{\mathrm{H}}_{\mathrm{Bottom}} \times TF^{\mathrm{H}}_{\mathrm{Bottom}\rightarrow\mathrm{Top}}$

measured

assumption

Measured by Yamada et al.

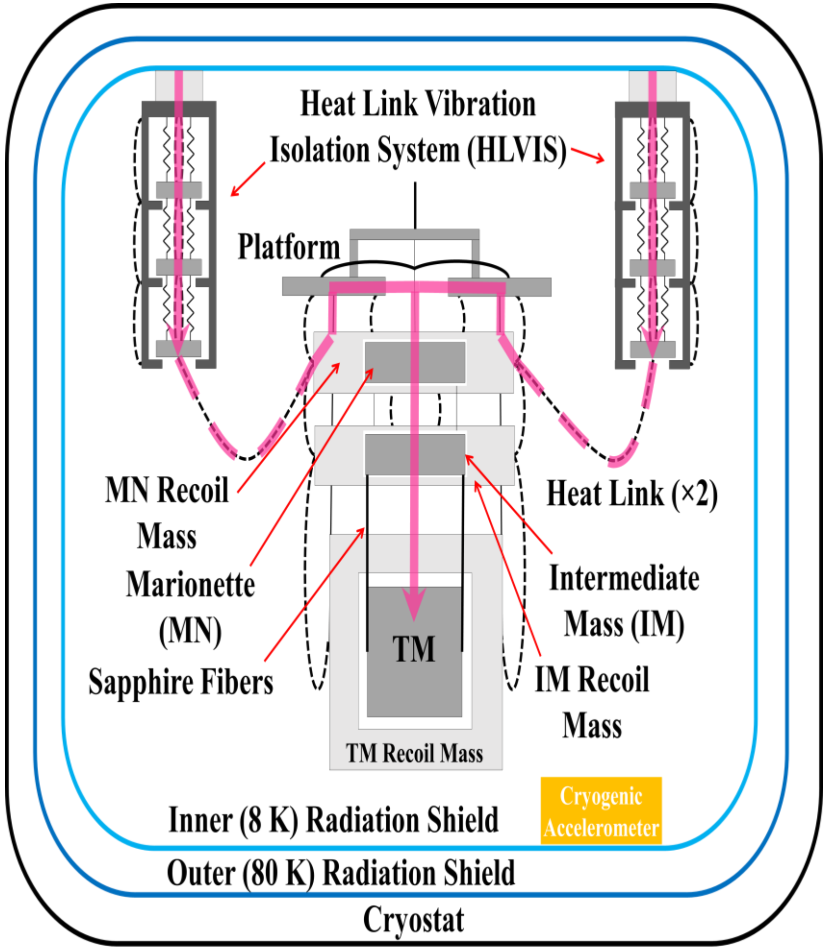
Evaluated using simulation

$$\mathrm{Displacement}^{\mathrm{V}}_{\mathrm{TM}} = V^{\mathrm{V}}_{\mathrm{Top}} \times TF^{\mathrm{V}}_{\mathrm{HLVIS}} \times TF^{\mathrm{V}}_{\mathrm{HL}} \times TF^{\mathrm{V}}_{\mathrm{MNR}\rightarrow\mathrm{TM}} \times 1\%$$

TM Displacement due to Vertical Vibration Coupling

V-H coupling due to 1/300 tunnel slope

assumption (commonly used)



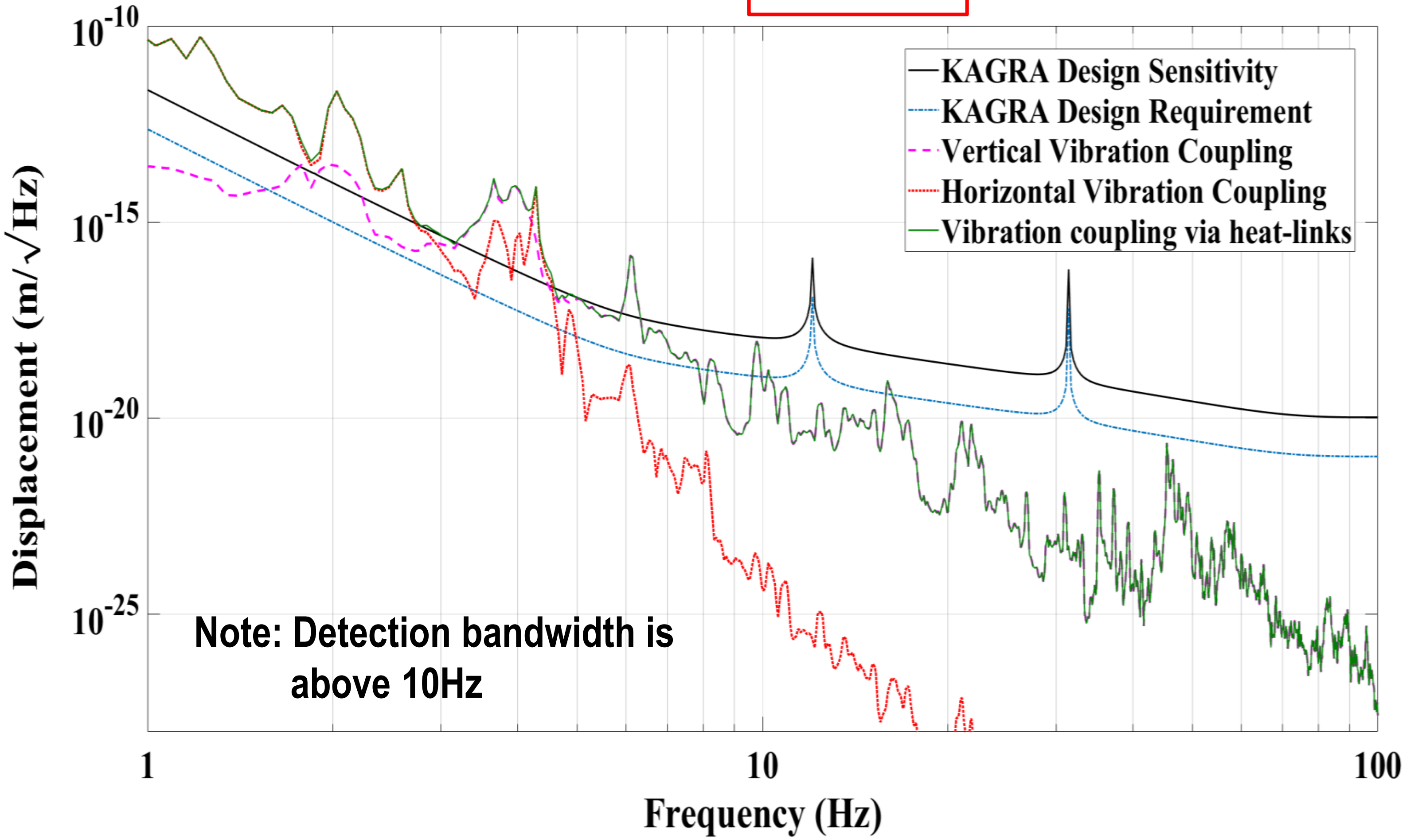
TM Displacement

No correlation between vertical and horizontal vibration
Added in quadrature

similar vibration coupling for all 4 TM with no correlation

$$\text{Displacement}_{\text{TM}} = 4\times\sqrt{4}\times\left[\text{Displacement}_{\text{TM}_V}{}^2 + \text{Displacement}_{\text{TM}_H}{}^2\right]^{1/2}$$

4 heat-links



Conclusion:

Direct vibration coupling via heat-links will not be an issue for KAGRA in the current configuration at 12 K.

The results are summarized in:

R Bajpai *et al* 2022 *Class. Quantum Grav.* 39 165004

Cryogenic Accelerometer

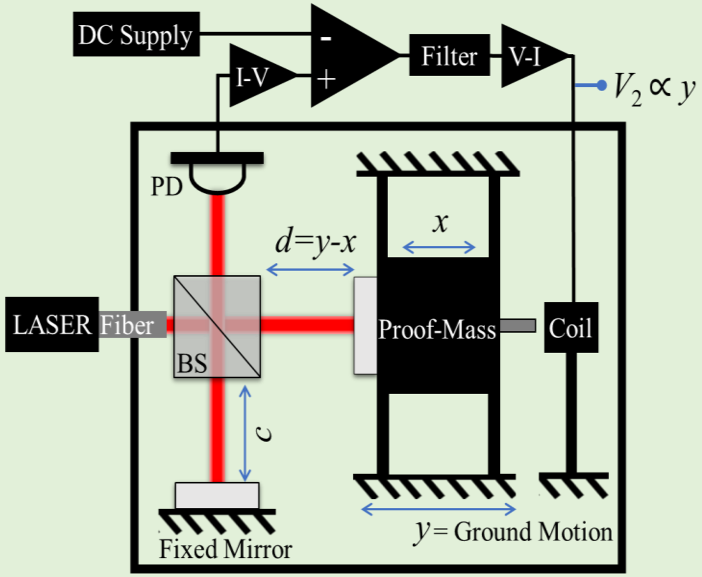
- **Requirements:**

(Cooling may change the Calibration Factor)

– Calibration: Self Calibrating
– Temperature Range < 20 K
– Sensitivity < KAGRA seismic motion in 0.1-100 Hz range

- **Design / Layout:**

– Sensor: Michelson Interferometer
– Interference signal ∝ d



– High Sensitivity can be achieved.
– Laser wavelength can be used for calibration.
– Issue: Loss of interferometer output due to thermal contraction.

- **For cryogenic issues:**

– Identified cryogenic compatible PD.
– Minimum misalignment components:
  - Designed proof-mass.
  - Identified mirror mount.