2012/08/21 Thermal Noise Seminar @ Jena

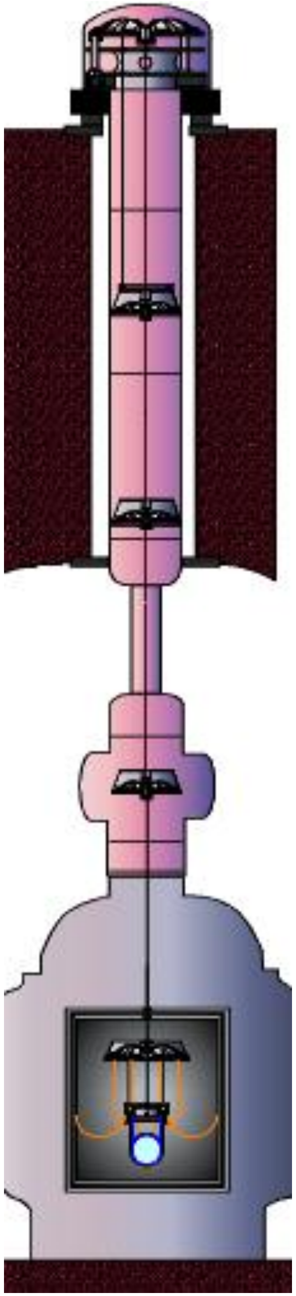
KAGRA

Cryogenic Suspension for KAGRA and Suspension Thermal Noise Issues

D1, ICRR, U. Tokyo

Takanori Sekiguchi

As a member of vibration isolation system (VIS) subgroup for KAGRA



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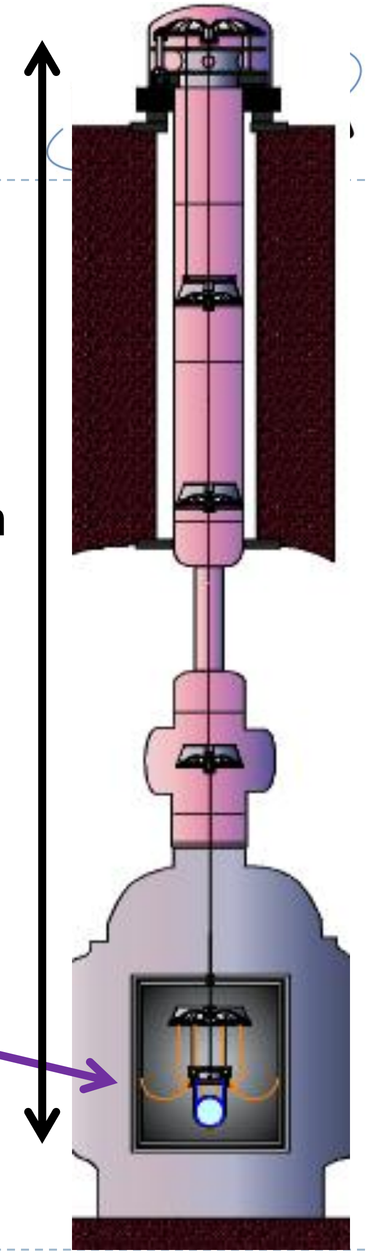
KAGRA Key Features

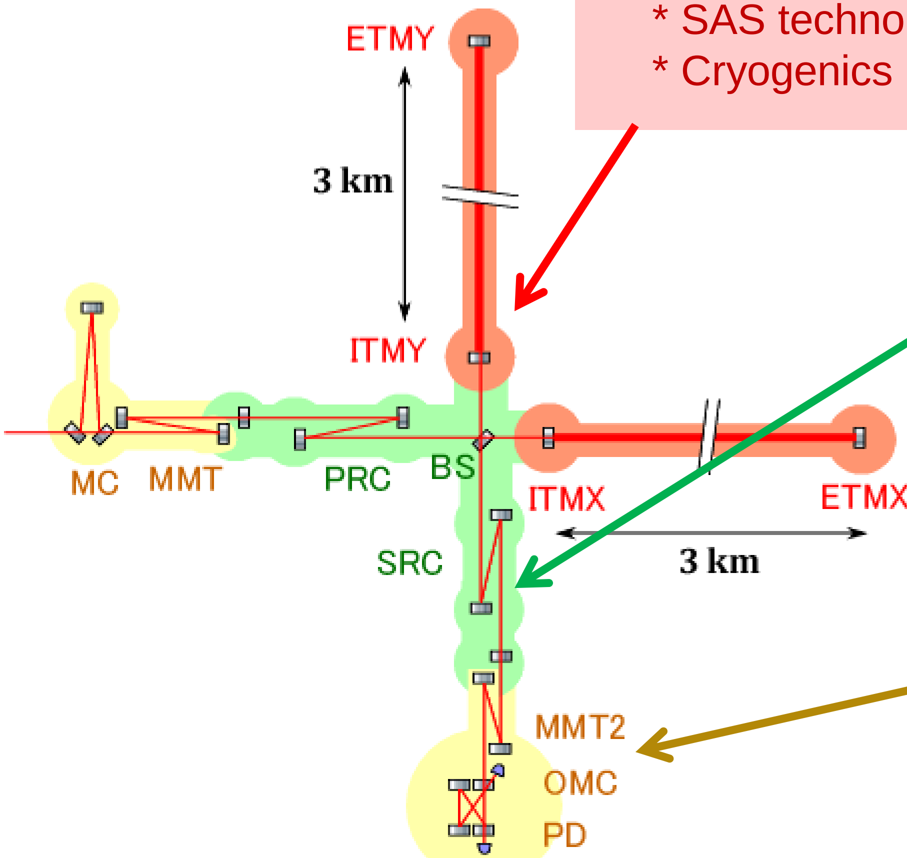
- Cryogenics
- Underground
- Seismic attenuation system (SAS)

- ✓ **Mirror thermal noise ↓**
- ✓ **Expand observation band (~ 10 Hz)**



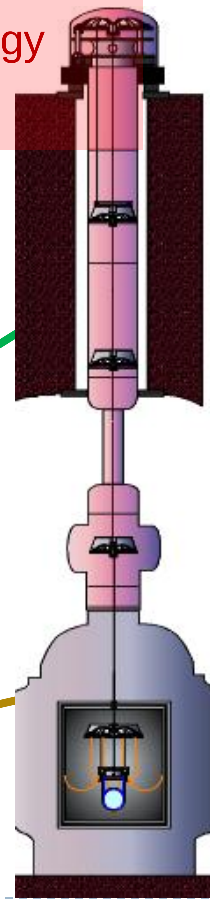
KAGRA-SAS Overview

Suspension systems for KAGRA core optics



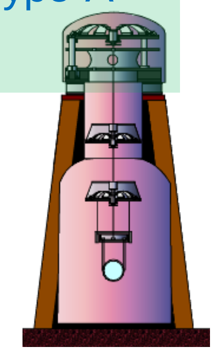
Type-A for test masses

* SAS technology
* Cryogenics



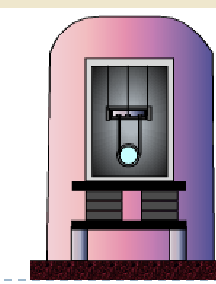
Type-B for recyclers& BS

* Simpler than Type-A
* No cryogenics

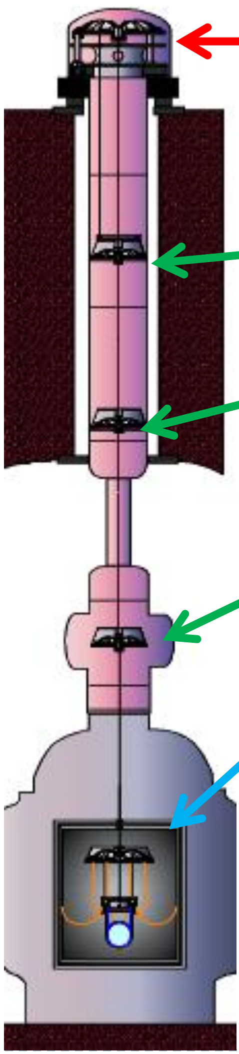


Type-C for smaller optics

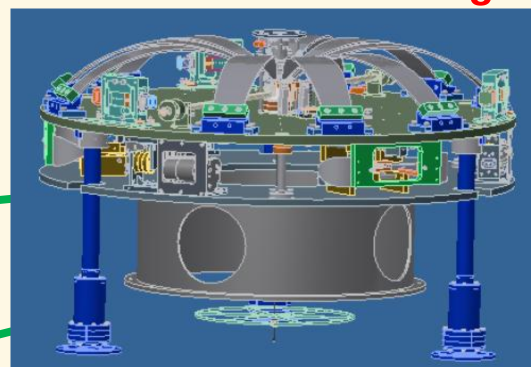
* TAMA-stack
  + simple/double pendulum



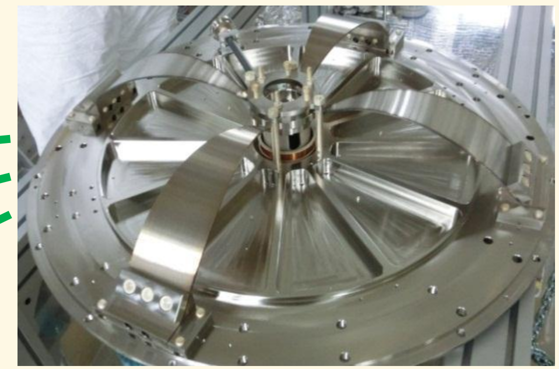
KAGRA-SAS Key Technologies



Inverted Pendulum stage



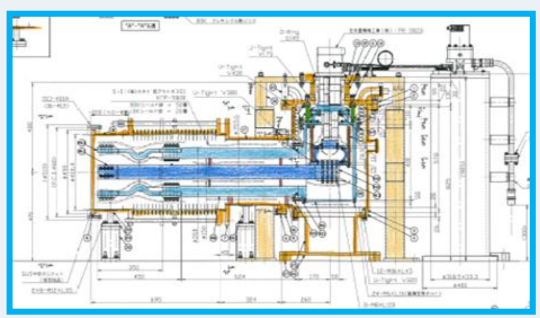
GAS filter chain



Control with LVDTs, accelerometers and voice-coil actuators

Developed in TAMA-SAS, HAM-SAS, AEI-SAS, etc.

Cryogenics



Developed in CLIO.

Low vibration cryocooler
Radiation shields

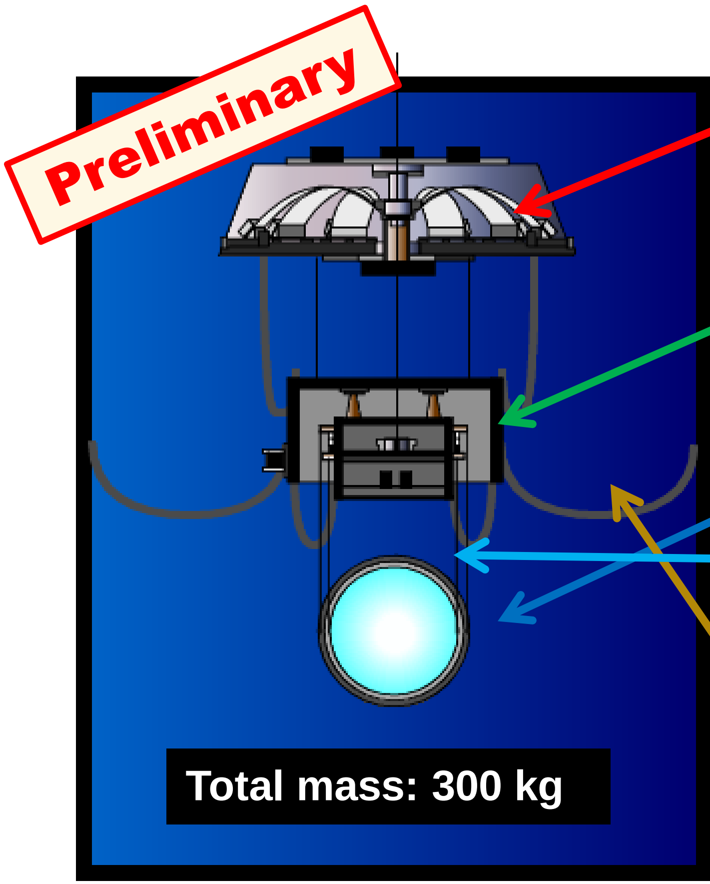
To be developed

Cryogenic sensors
Heat link wiring
Sapphire fibers

Still many R&Ds are necessary for this part !!!

Cryogenic Suspension for KAGRA

KAGRA Cryogenic Payload Schematic Design



Platform with cryogenic spring **(GAS)**

Intermediate mass and its recoil mass for alignment control

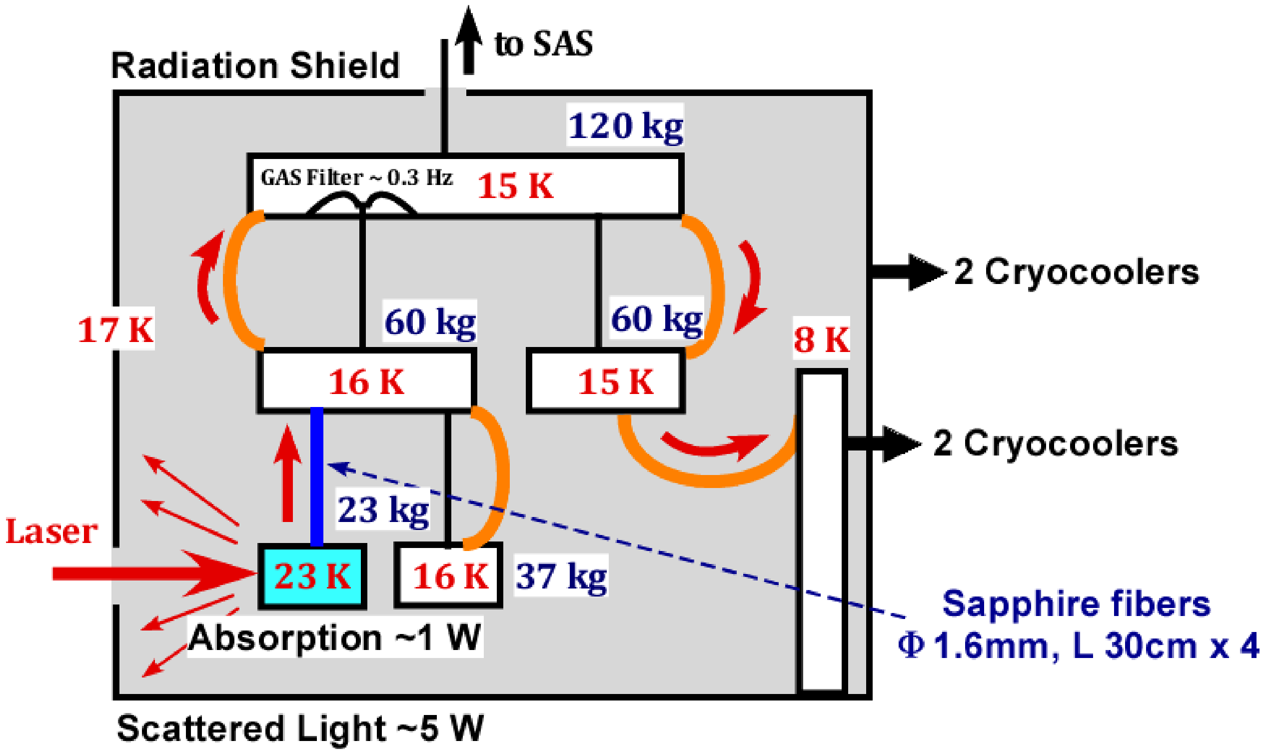
Sapphire test mass and its recoil mass

Sapphire fibers (Φ1.6 mm, L 30 cm)

Aluminum heat links for heat transfer

Heat Subtraction Scheme

KAGRA Cryogenic Payload Heat Flow

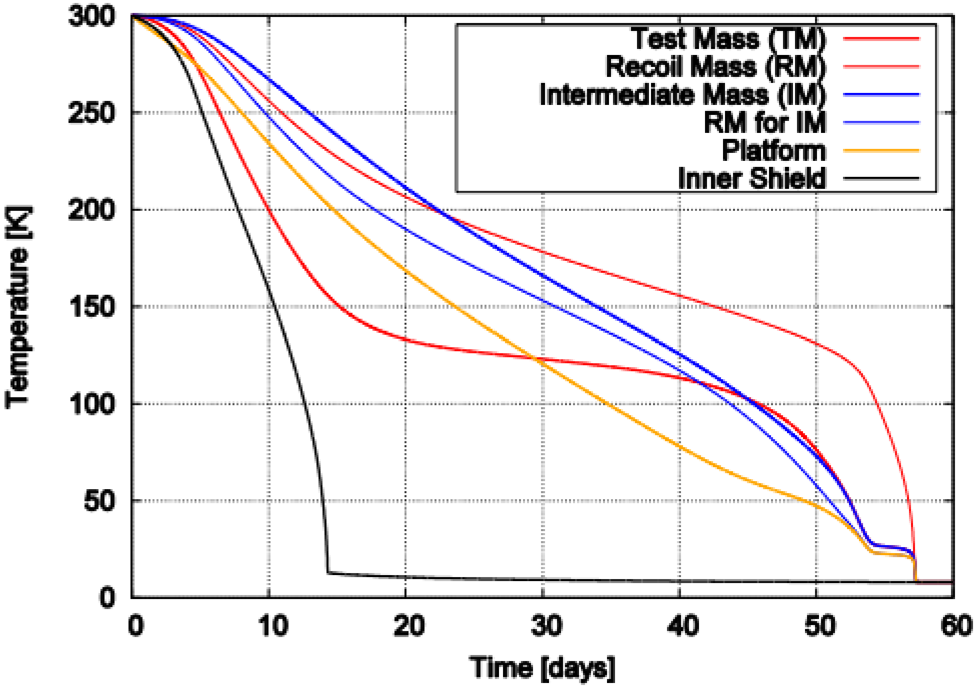


Cryogenic Suspension Problems [1]

Initial cooling time problem

(Discussed by Y. Sakakibara)

- ~ months to reach target temperature



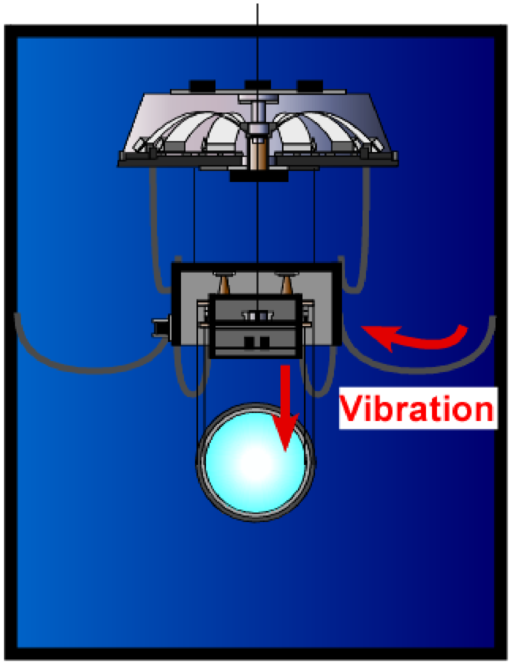
→ Slow down commissioning, reduce duty cycle

Cryogenic Suspension Problems [2]

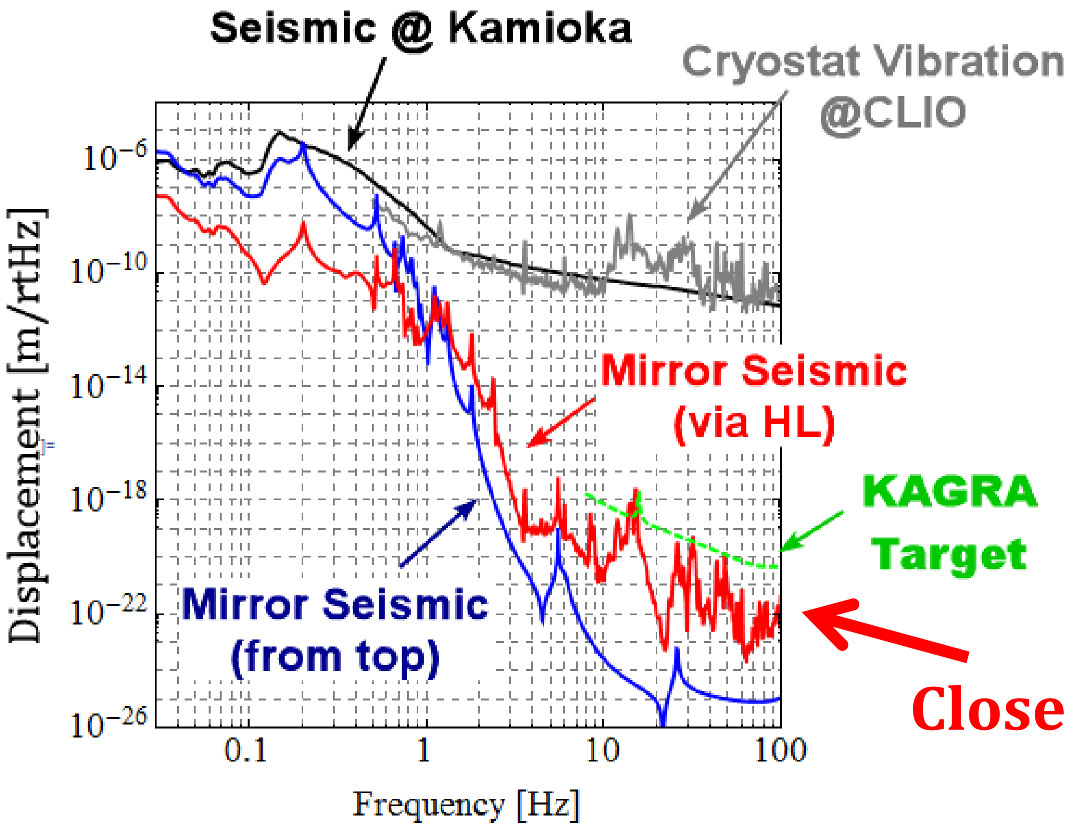
Heat link wiring problem

- Aluminum heat links work as soft mechanical springs (~10 mHz)
- Cryostat vibration is transmitted to the mirror via heat links

→ Spoil the performance of SAS



Cryogenic Suspension Problems [2]



- Cryostat vibration can be larger than seismic vibration

Close to KAGRA sensitivity!!

More details: GWADW2012 presentation, JGW-G1201037

Cryogenic Suspension Problems [3]

KAGRA

Sapphire fiber problem

- **Thick** and **short** sapphire fibers (Φ1.6 mm, L 30 cm).
- Rough surface decreases thermal conductivity
→ Need **surface polishing**
- Sapphire **bonding** may be necessary??

Many difficulties in engineering!!

Cryogenic Suspension Problems [3]

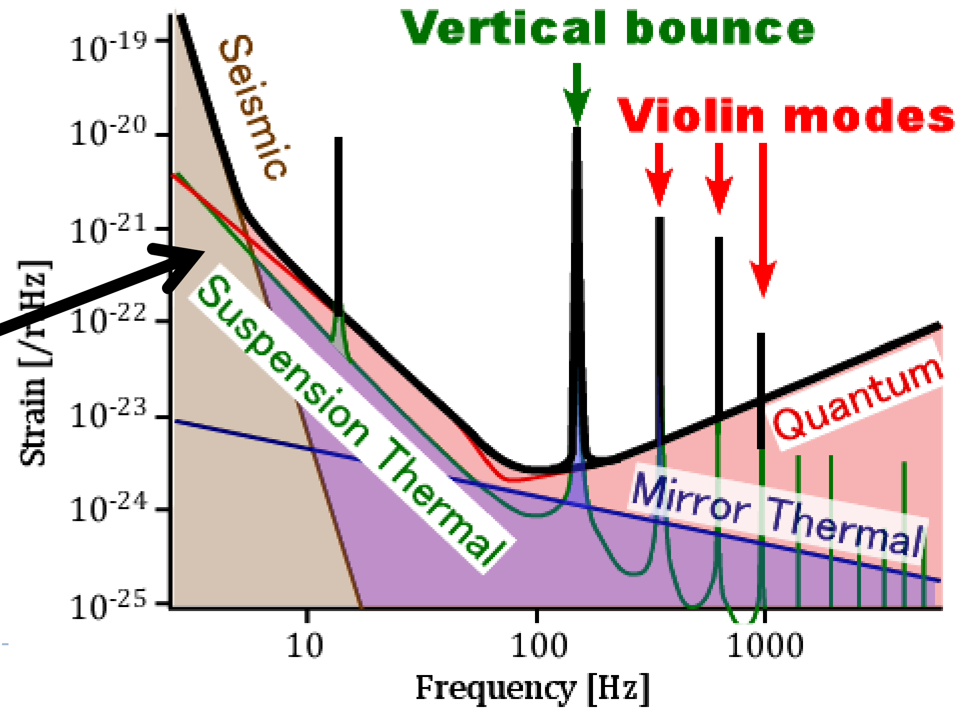
KAGRA

Sapphire fiber problem

- **Vertical bounce mode** and **violin mode** peaks at ~100 Hz.

→ **Pollute detector sensitivity!!**

(Even with low Q sapphire fibers, suspension thermal noise gets large because of small dilution factor.)



Summary

- We use cryogenic suspension for thermal noise reduction.

- Many difficulties have been found.
  - **Initial cooling time** is quite long.
  - **Heat links** introduce non-negligible seismic noise.
  - **Thick sapphire fibers** introduce non-desired peaks around target frequencies.

Still many R&Ds remain!! (but schedule is tight...)

Contents

1. Introduction of KAGRA cryogenic suspensions
2. Suspension thermal noise in KAGRA
3. Ideas to reduce suspension thermal noise in KAGRA
4. Summary and discussion

Suspension Thermal Noise

- Thermal fluctuation of mirror displacement due to mechanical loss of suspension system.

- Power spectrum can be predicted by **fluctuation-dissipation theorem**

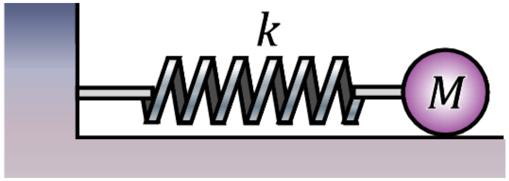
$$x_{\mathrm{therm}}^2(\omega) = \frac{4k_B T}{\omega} \mathrm{Im}[H(\omega)]$$

Imaginary part of force – displacement transfer function

Suspension Thermal Noise

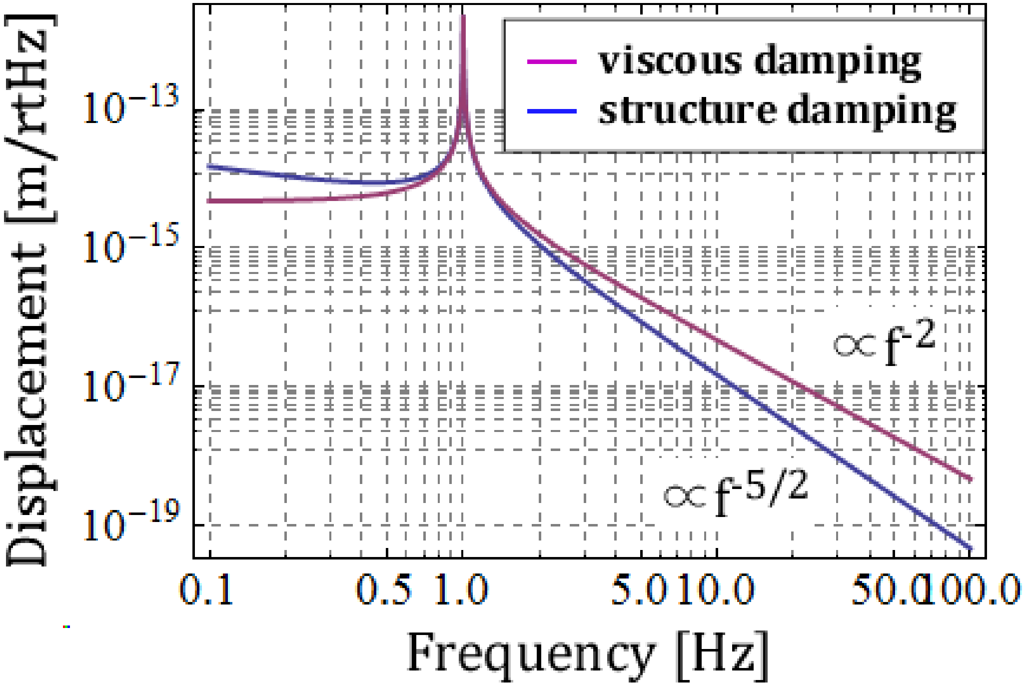
- Thermal fluctuation of simple oscillator

$$f = 1\,\mathrm{Hz},\ Q = 10^5$$



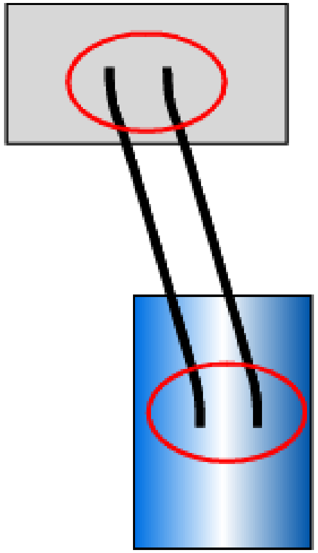
- Material loss: structural damping model

- Pendulum Q is larger than intrinsic material Q (**dissipation dilution**)



Dissipation dilution

- In pendulum, most potential energy stored as lossless gravitational potential energy



Ue: Potential energy stored in the bending of fibers
Ug: Gravitational potential energy (lossless)

$$\phi_{\text{pendulum}} = \phi_{\text{fiber}} \times \frac{U_e}{U_g + U_e}$$

1 / Dilution factor

Dissipation dilution

- Dilution factor gets large for **thin and long** fibers

$$\mathrm{DF} \propto L, d^{-2}$$

L: wire length, d: wire diameter

- However, **thick and short** fibers are used in KAGRA for thermal conduction.

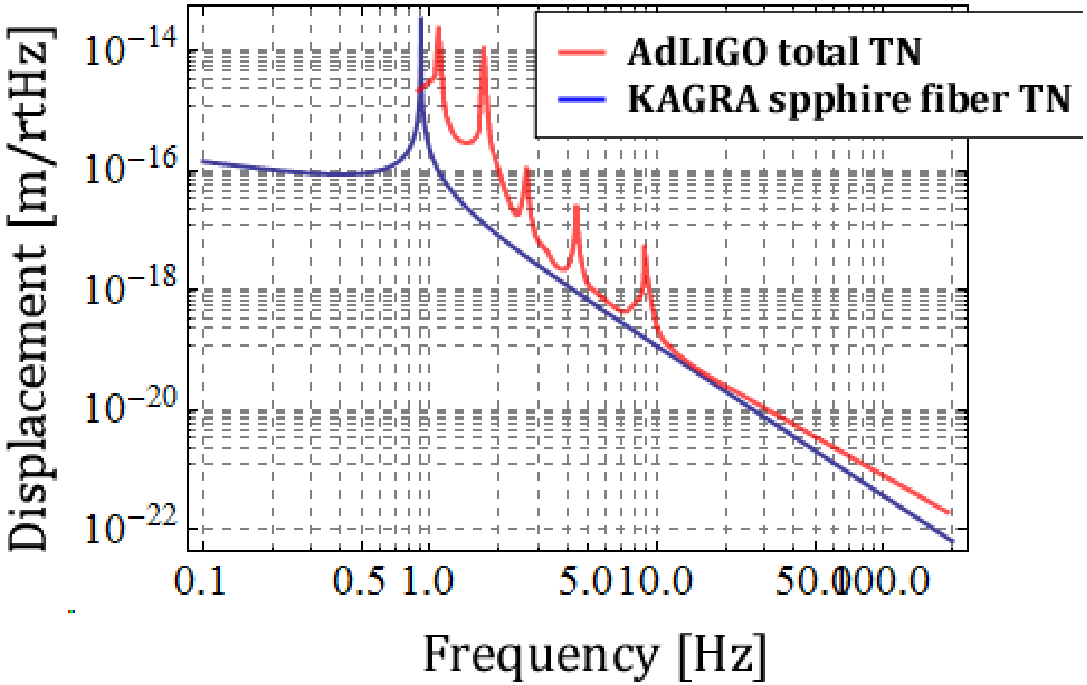
Initial LIGO dilution factor: ~464

KAGRA dilution factor: ~19

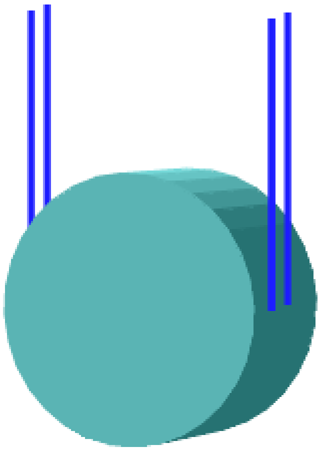
Sapphire Fiber Thermal Noise

- Sapphire fiber thermal noise estimation (pendulum mode)

$$f = 1\,\mathrm{Hz}, \phi = (2\times10^{-7})/19, T = 20\,\mathrm{K}$$



LIGO-G040298



Violin Modes

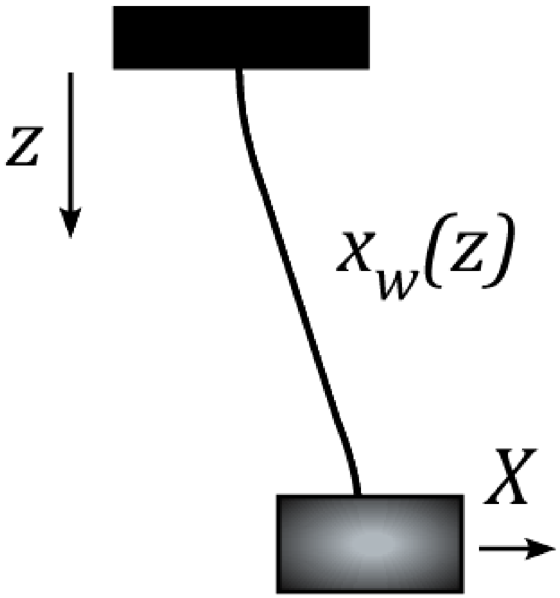
- For high frequency response, violin modes of fiber should be taken into account.

Eq. of motion of fiber

$$\rho \ddot{x}_{\mathrm{w}}(z) = EI \frac{d^4}{dz^4} x_{\mathrm{w}}(z) - T \frac{d^2}{dz^2} x_{\mathrm{w}}(z)$$

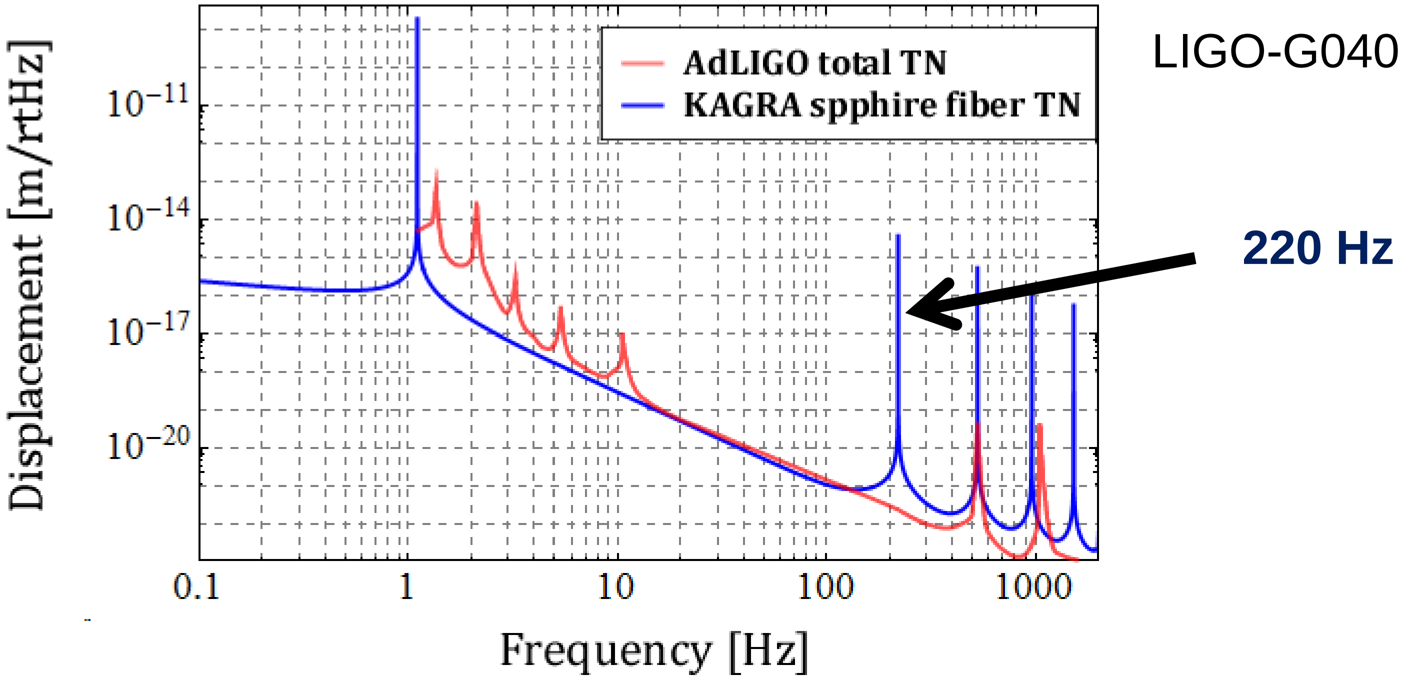
Eq. of motion of suspended mass

$$M\ddot{X} = EI \left. \frac{d^3 x_{\mathrm{w}}(z)}{dz^3} \right|_{z=L} - T \left. \frac{dx_{\mathrm{w}}(z)}{dz} \right|_{z=L}$$



Sapphire Fiber Thermal Noise

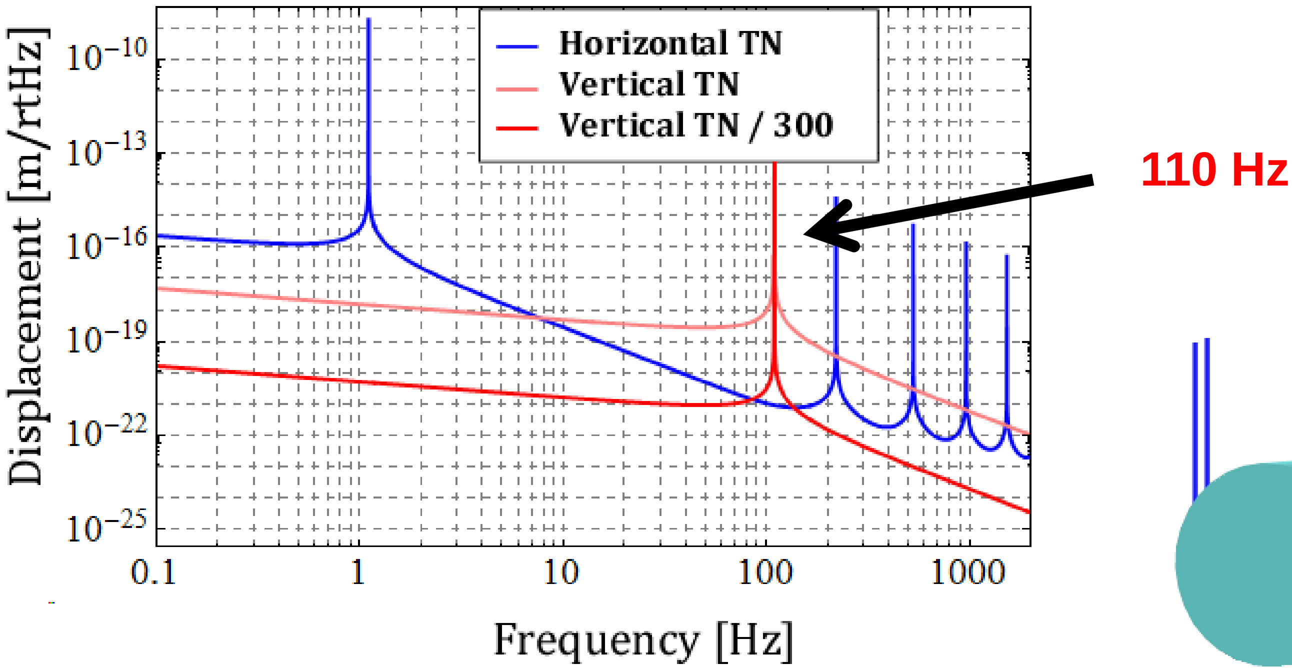
- Sapphire fiber thermal noise estimation (pendulum mode **+ violin modes**)

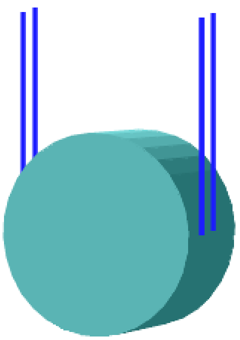


LIGO-G040298

Vertical Thermal Noise

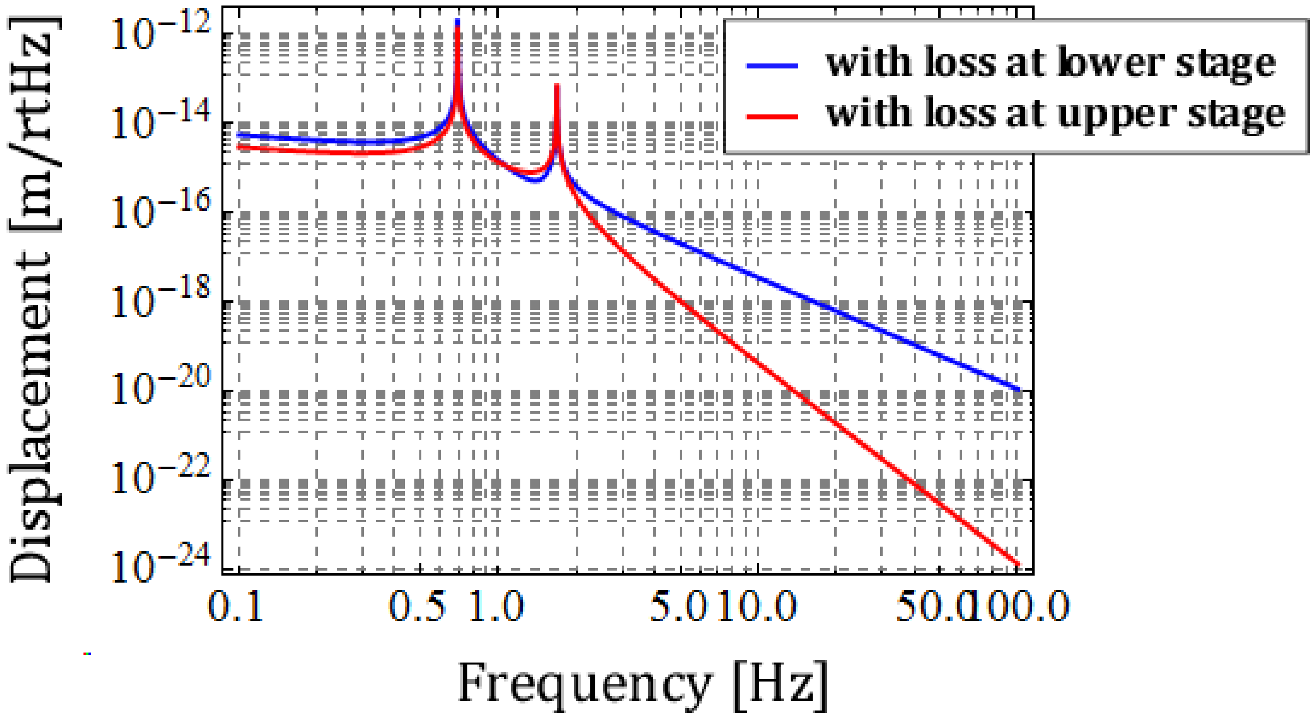
- In KAGRA, we have un-avoidable V-H coupling of 1/300.
- Contribution of vertical thermal fluctuation is not negligible.

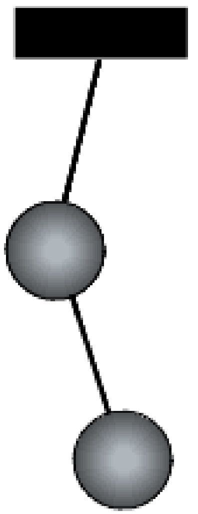




Contribution of Upper Stage Losses

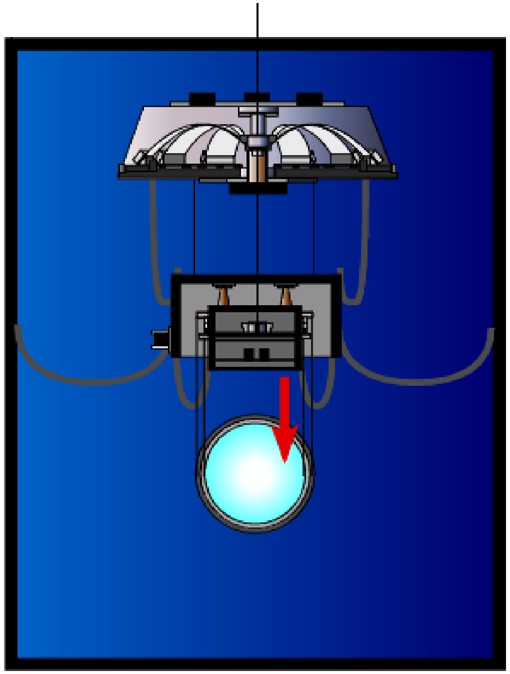
- Generally, thermal noise from upper stage (and recoil mass) loss is cut off at high frequencies.





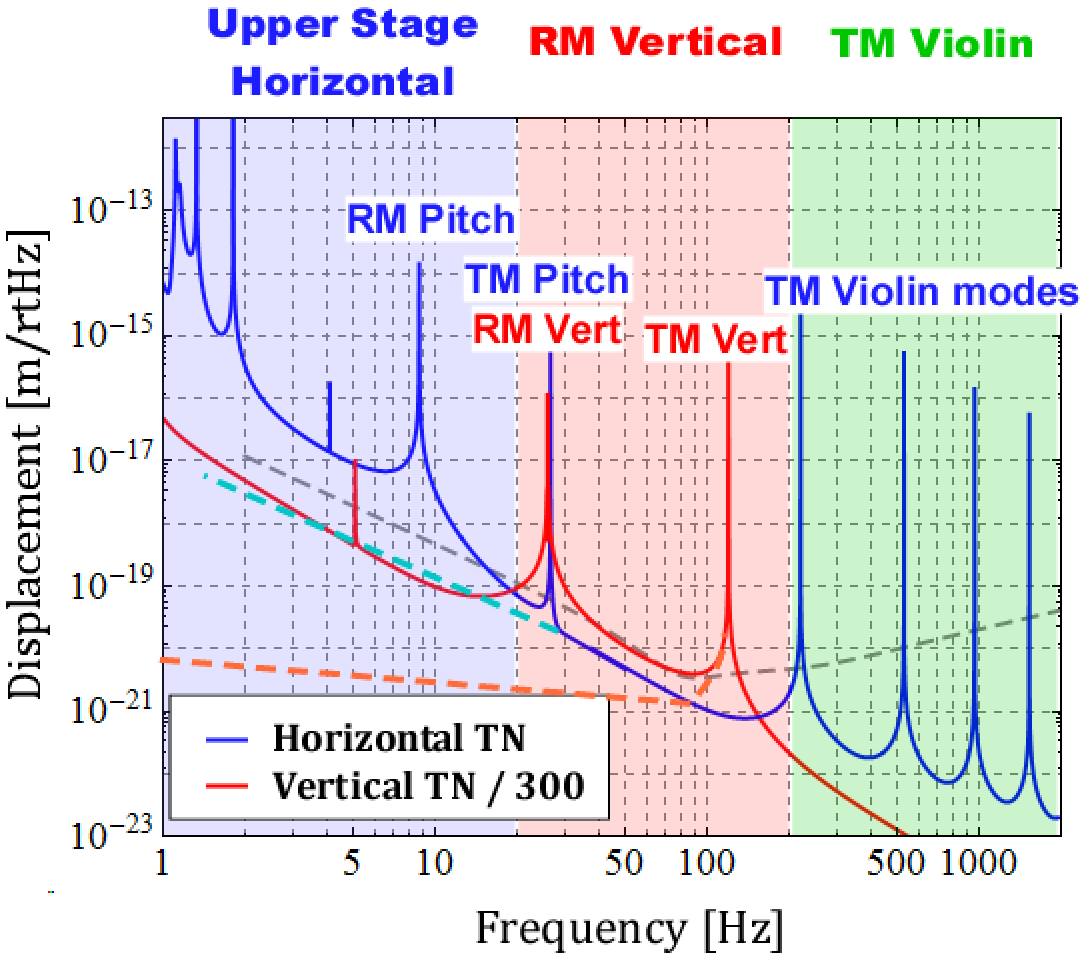
Contribution of Upper Stage Losses

- In KAGRA, due to large stiffness of sapphire fibers, vertical thermal noise from upper stage (and recoil mass) loss **directly** transmits to the mirror.



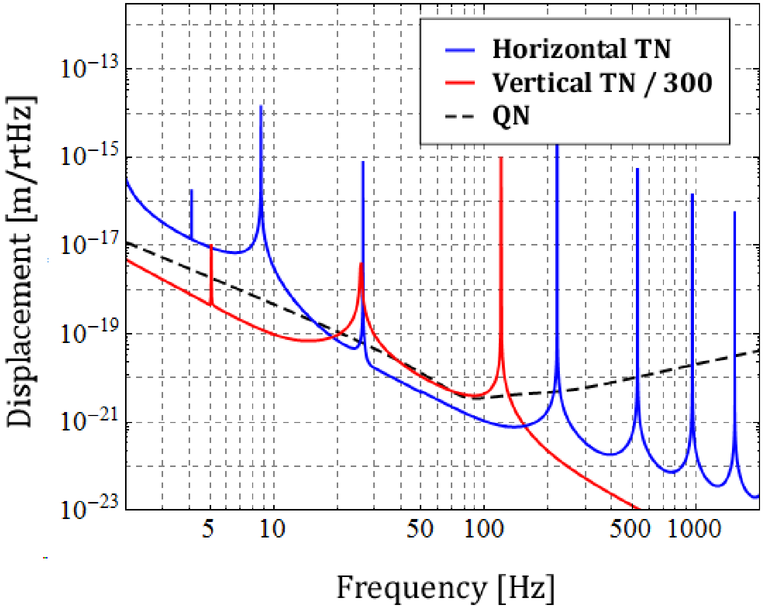
Suspension Thermal Noise in KAGRA

- Thermal noise simulation including upper stages and recoil mass (with intrinsic material Q of ~10^4)



Summary

- Thick sapphire fibers introduce resonant peaks of vertical & violin modes around 100 Hz.
- Thermal noise from upper stages and recoil mass is **not negligible** even at high frequencies.
- Especially, **recoil mass** can introduce large vertical thermal fluctuation at 20-200 Hz.



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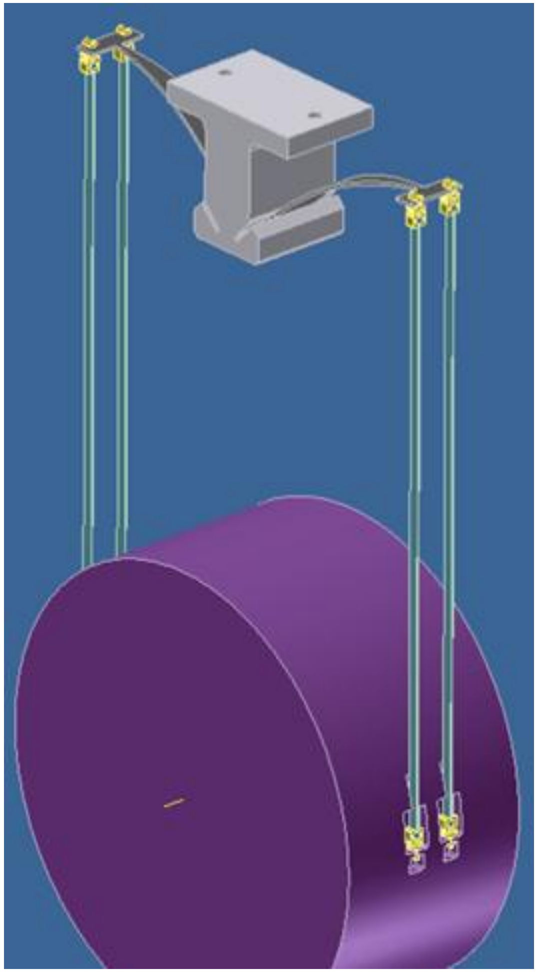
To Reduce Suspension Thermal Noise

- Vertical thermal noise
  - Reduce V-H coupling (1/300)
  - Reduce vertical bounce mode frequency (~100 Hz)
- Horizontal thermal noise
  - Increase dilution factor (~19)
  - Push violin modes to higher frequencies (~200 Hz)
- Loss at recoil mass
  - Improve recoil mass suspension ($Q \sim 10^4$)
  - Remove recoil mass

New Suspension Design

- A fresh approach to the design of low thermal noise cryogenic suspension for KAGRA (and ET)

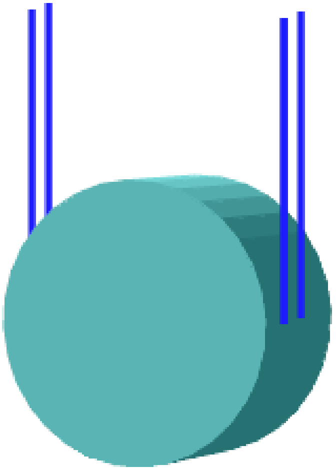
- Design development is conducted by R. DeSalvo



Vertical Thermal Noise

- Vertical stiffness of sapphire fiber introduces:
  - An annoying peak around 100 Hz
  - Large thermal fluctuation from recoil mass stage

- Practically, we cannot equalize tension of four fibers.

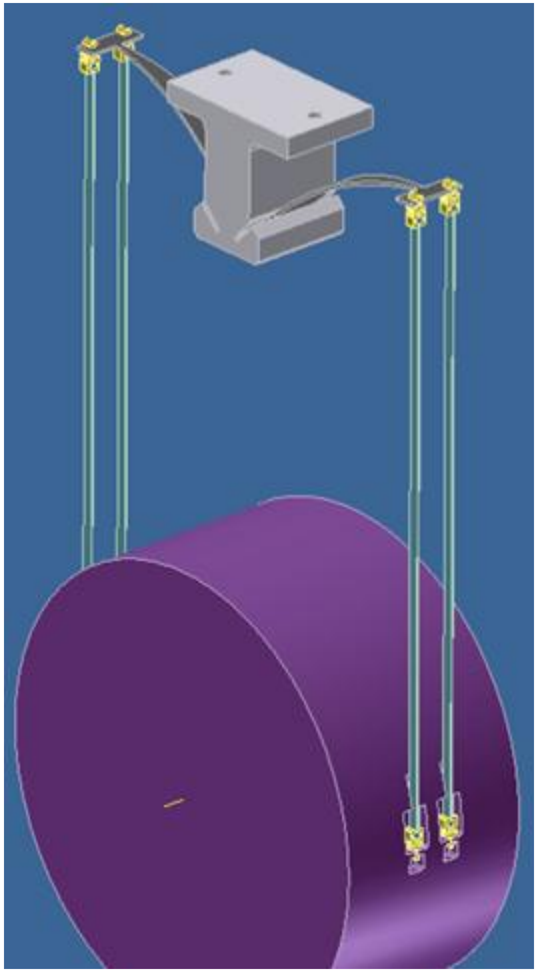


Cantilever Spring

- Hold the mirror from cantilever springs

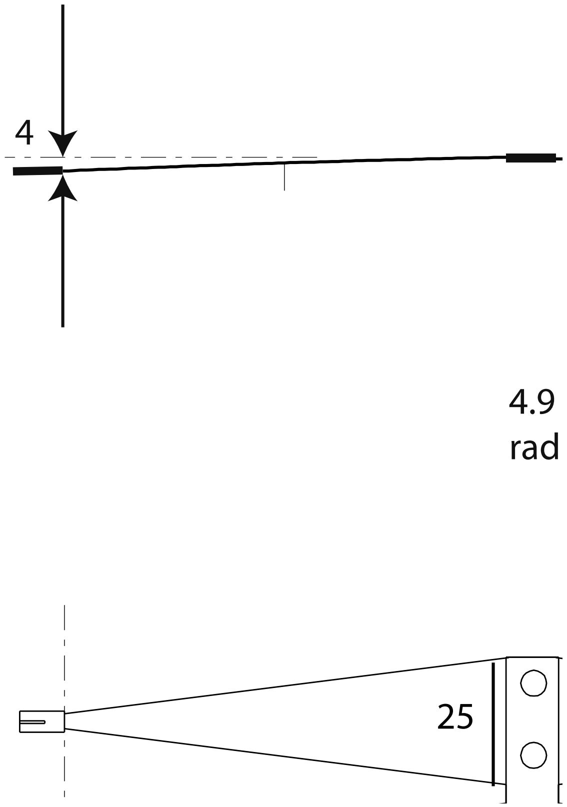
- What material should be used?
  - High Q
  - Large thermal conductivity

→ Candidate: **silicon** cantilever



Silicon cantilever blades

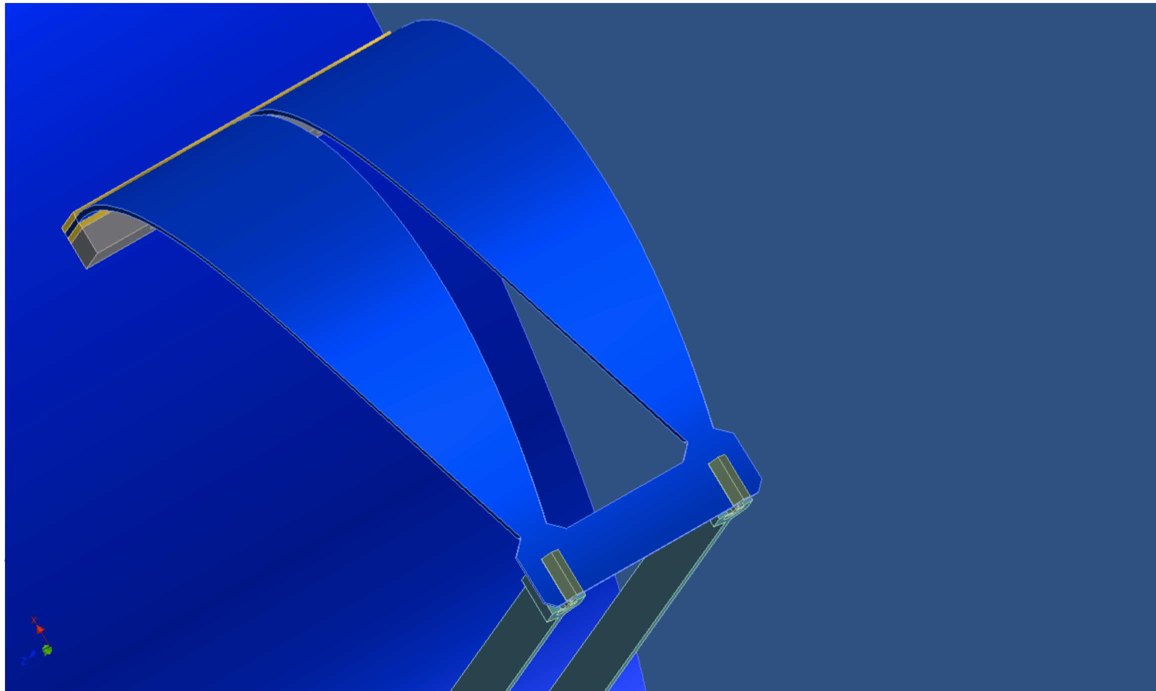
- Etch the bending area
- Leave thick section for clamping and for fiber connection
- With 0.15 Gpa only limited flexure possible (~25 Hz)
- With >1GPa large deflection



Larger stresses possible?

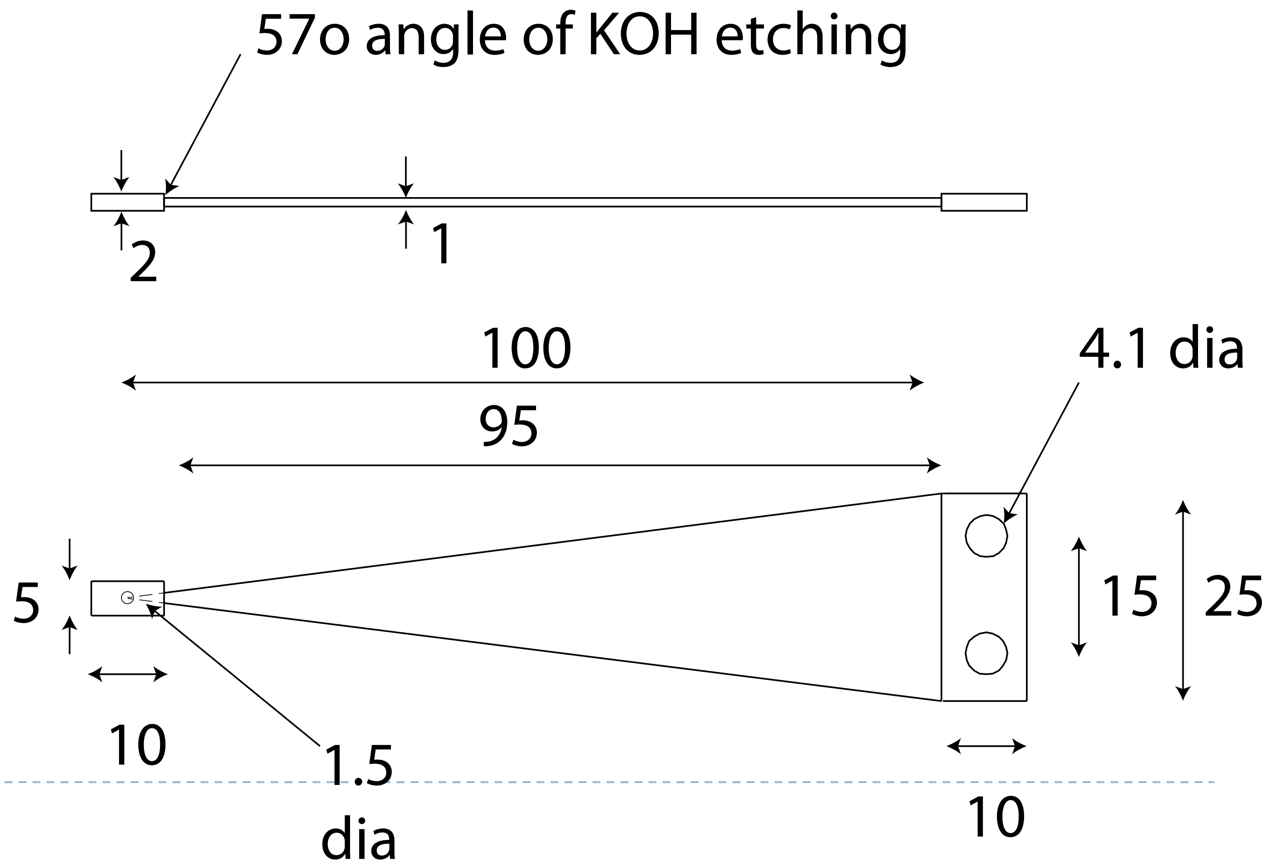
- MEM sensors operating at 1.4 GPa, ~ 10 times higher limit!
- Is etching eliminating surface defect and therefore causing the larger strength?

- if YES, large bends possible!
- Lower frequency bounce modes



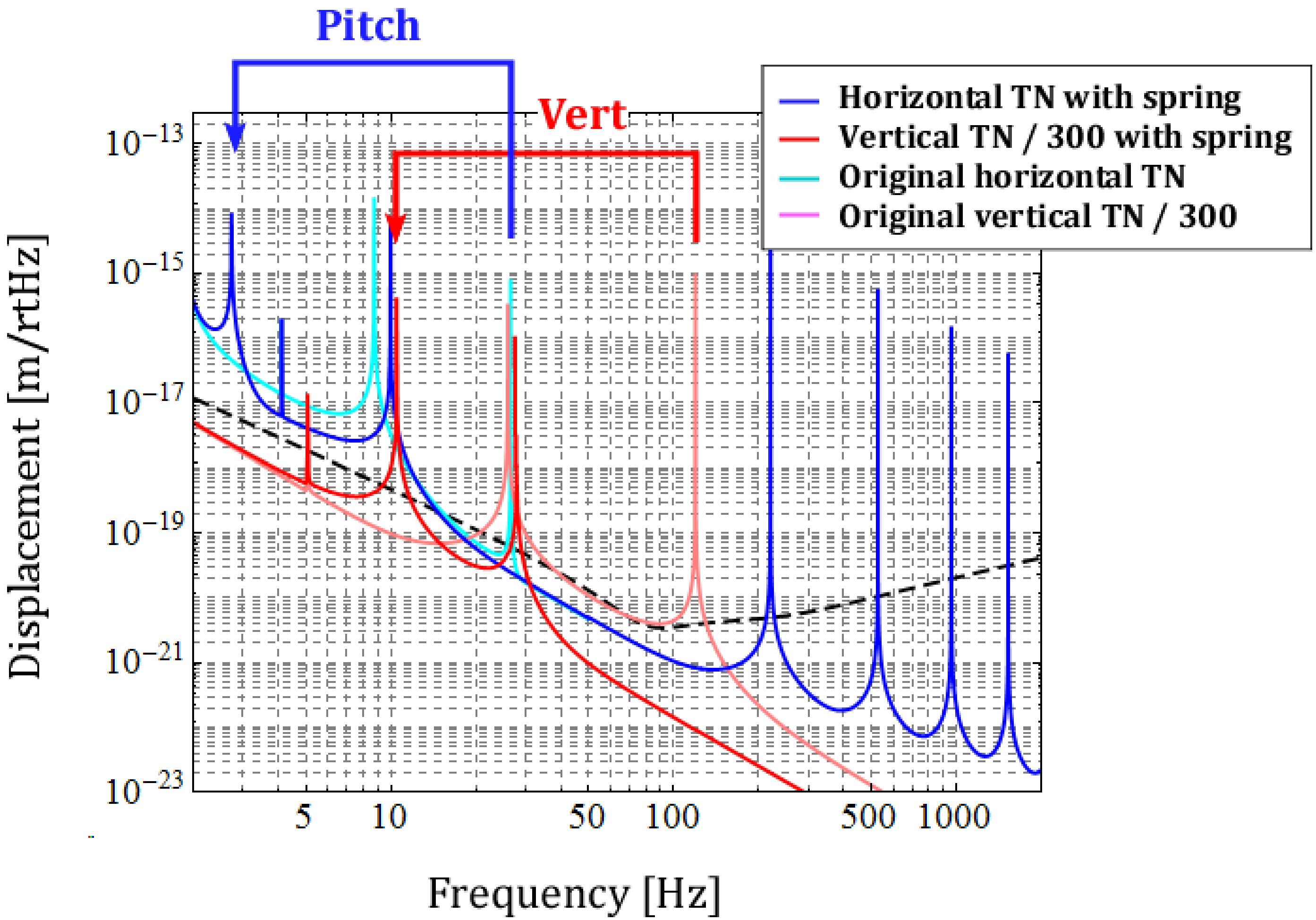
NIKHEF Test

- Produce a number of samples
- Test and see



Silicon Cantilever Solution

- Thermal noise estimation with cantilever spring (assuming f_0 ~10 Hz, Q~10^{-7})



Horizontal Thermal Noise

- Small dilution factor due to thickness of fibers.
- Can we increase **dilution factor** without spoiling **thermal conductivity**?

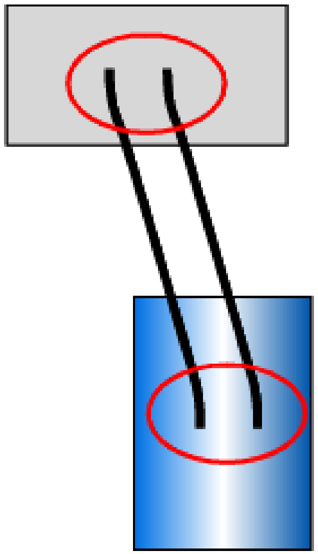
→ Fiber with **flexure** design

Flexure part
For thermal noise reduction

Thick fiber part
For thermal conductivity

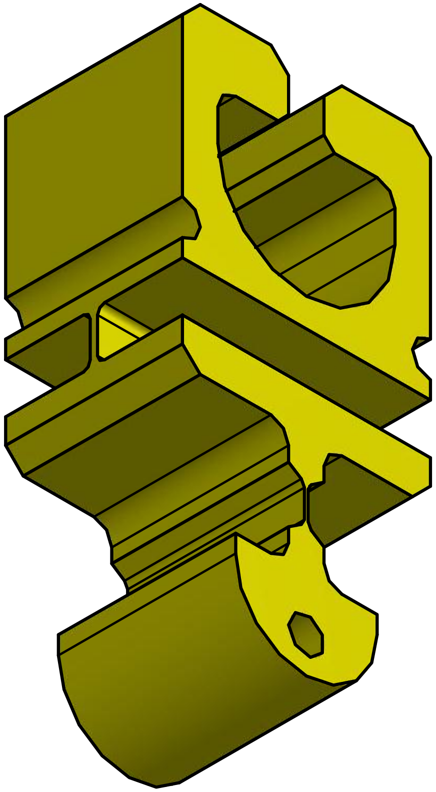
Why Flexure?

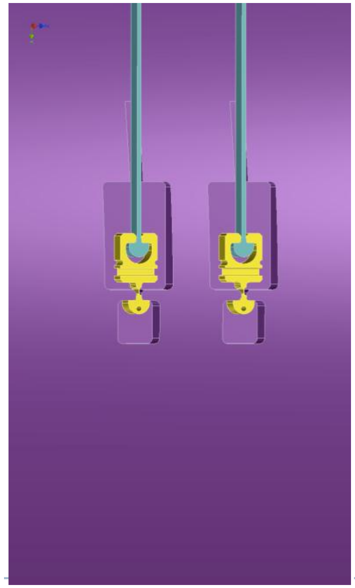
- Most bending energy concentrates on the fiber **ends**
- Bending energy can be reduced by using **soft** fiber in the ends



Flexure Design

- Ultra-Sound Machined structure
- Etching of the flexure surface
- Expected to increase the break point >1GPa



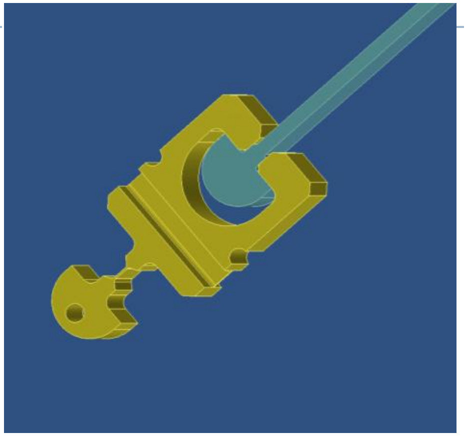


Ribbons Key features:

- Compression joint attachment
- Machined-polished Sapphire ribbons

(from bulk, not grown)

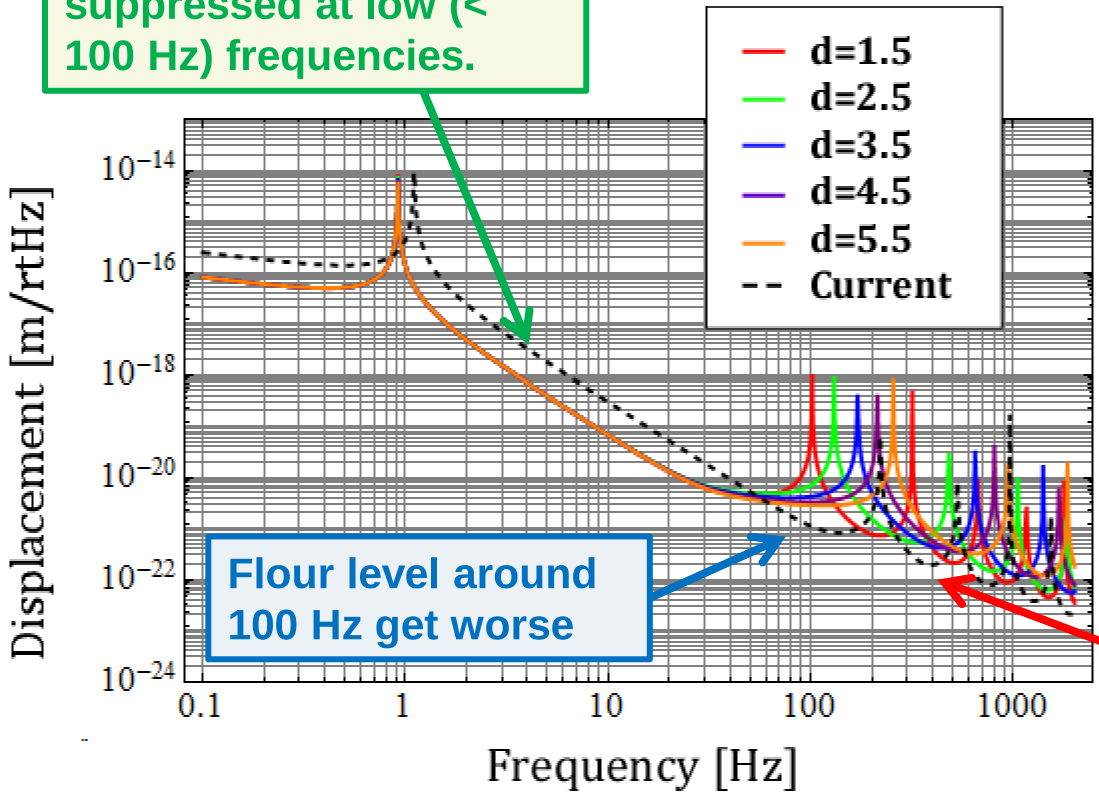
- High quality sapphire
- High quality surface finish (sub-phonon defect size)
- = > High thermal conductivity !



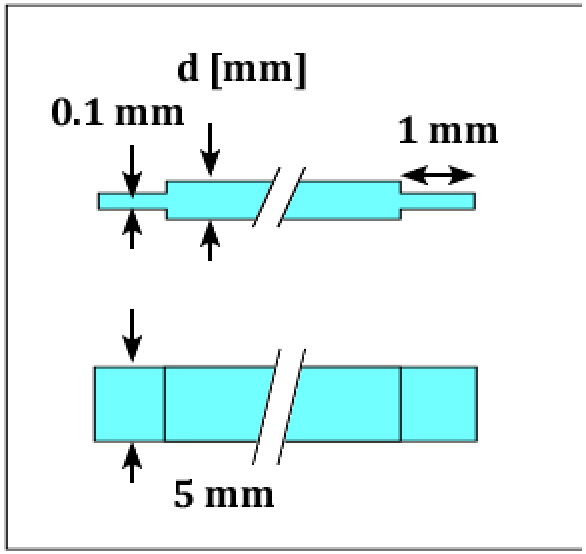
Sapphire Ribbon + Silicon Flexure

- **Preliminary result** (calculated last night…)

The thermal noise is suppressed at low (< 100 Hz) frequencies.



Flour level around 100 Hz get worse



Violin mode frequencies can be pushed to high freq region.

Flexure Design Pro & Con

- 10-50 Hz thermal noise will be improved.

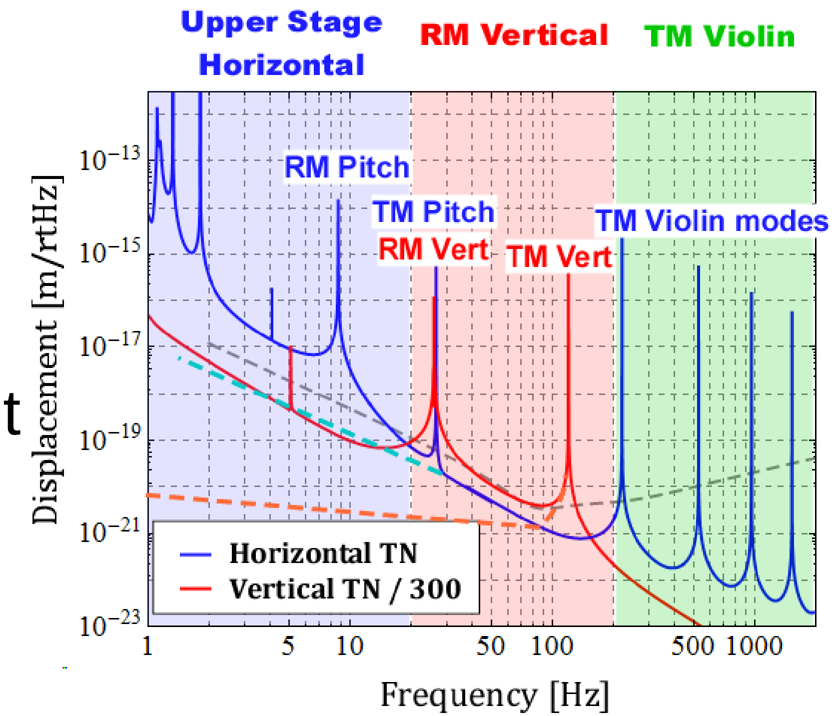
Good, but not so effective?

- 50-200 Hz thermal noise will get worse.

Bad

- We can push the violin modes to higher frequencies.

Good



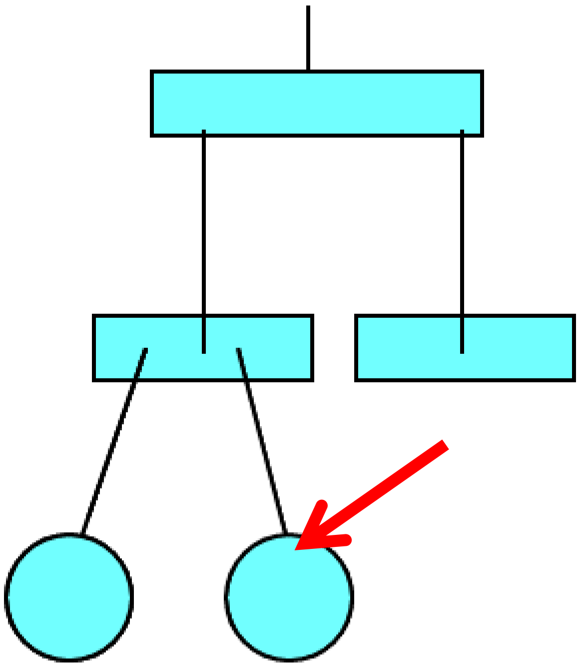
2012/8/21

Can We Remove Recoil Mass ??

- Thermal noise from **RM** suspension loss is quite large.

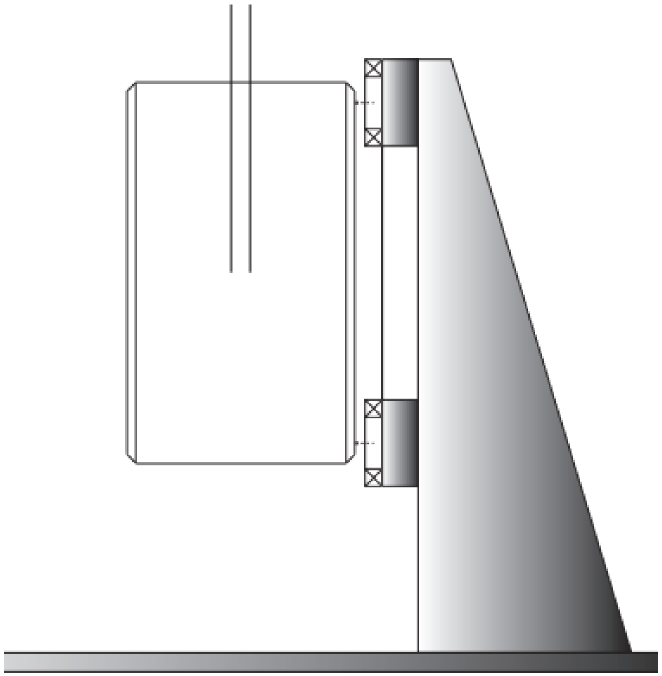
- Can we remove recoil mass??

- In **Virgo**, the actuators on TM are **not** used during operation!! (thanks to large seismic attenuation)



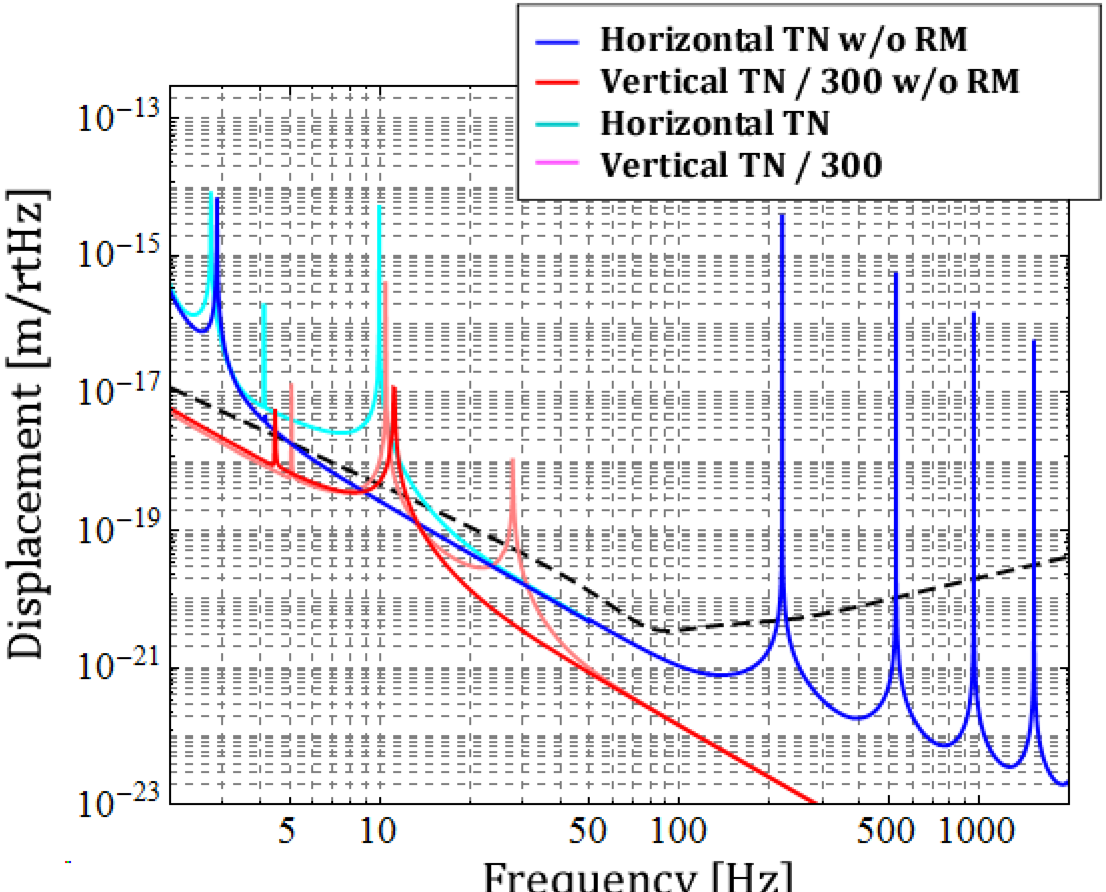
No Suspended Recoil Mass

- **No suspended** recoil mass for TM
- Actuators only used for damping
- Coil should be opened during operation



No Recoil Mass Case

- No peaks at 10-100 Hz!!
- Alternative: also employ springs for RM

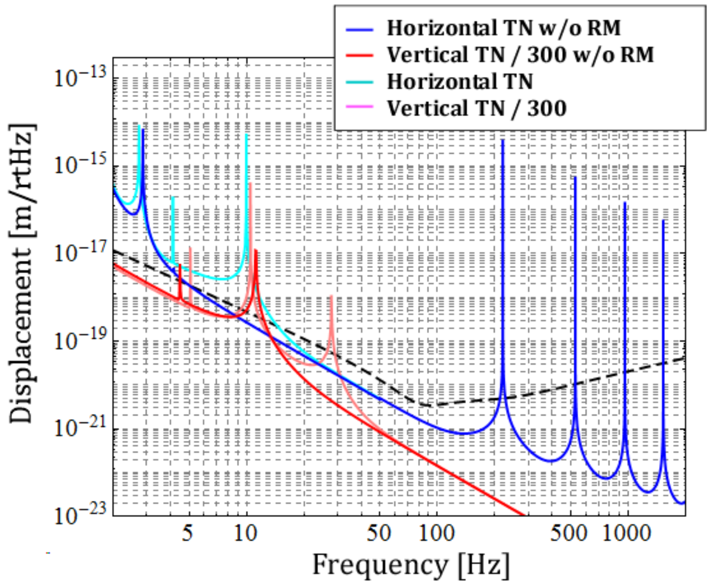


Summary

- Using low-loss cantilevers, vertical thermal noise is dramatically reduced and annoying peak disappears.

- Fibers with flexure design has both profit and demerit.

- Removing RM, or employing cantilever for RM?



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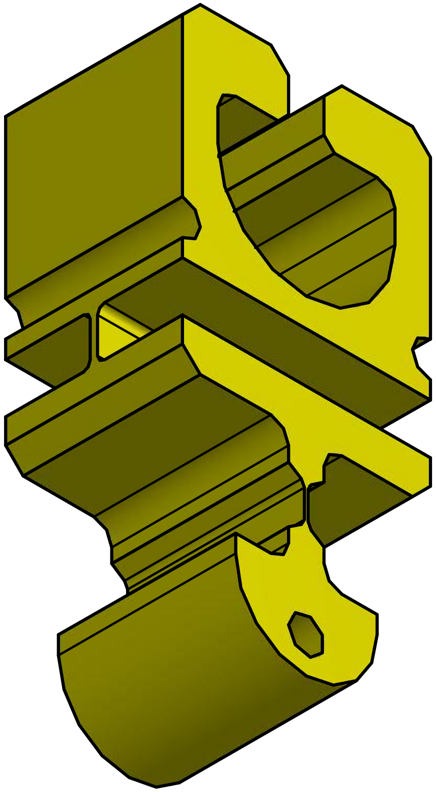
Discussion

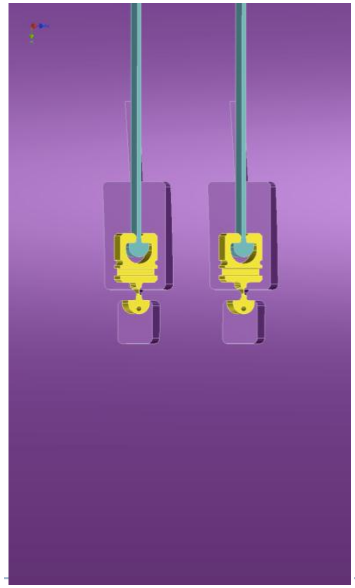
The END

Appendices

Flexure Design

- Ultra-Sound Machined structure
- Etching of the flexure surface
- Expected to increase the break point >1GPa





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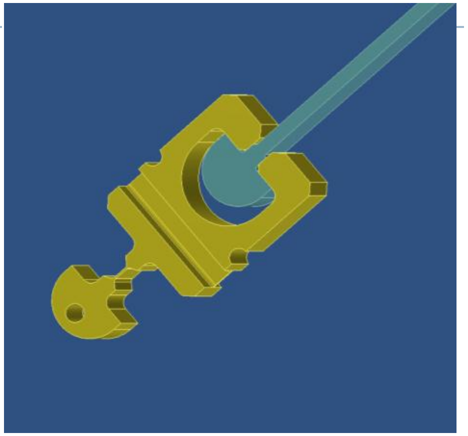
- High quality surface finish (sub-phonon defect size)
- = > High thermal conductivity !



Why Gallium

- Indium proved extremely effective to eliminate friction noise in compression joints (Vladimir Braginsky)
- Melts at relatively high temperature
- May need heating mirror to more than 160^{o}C for disassembly

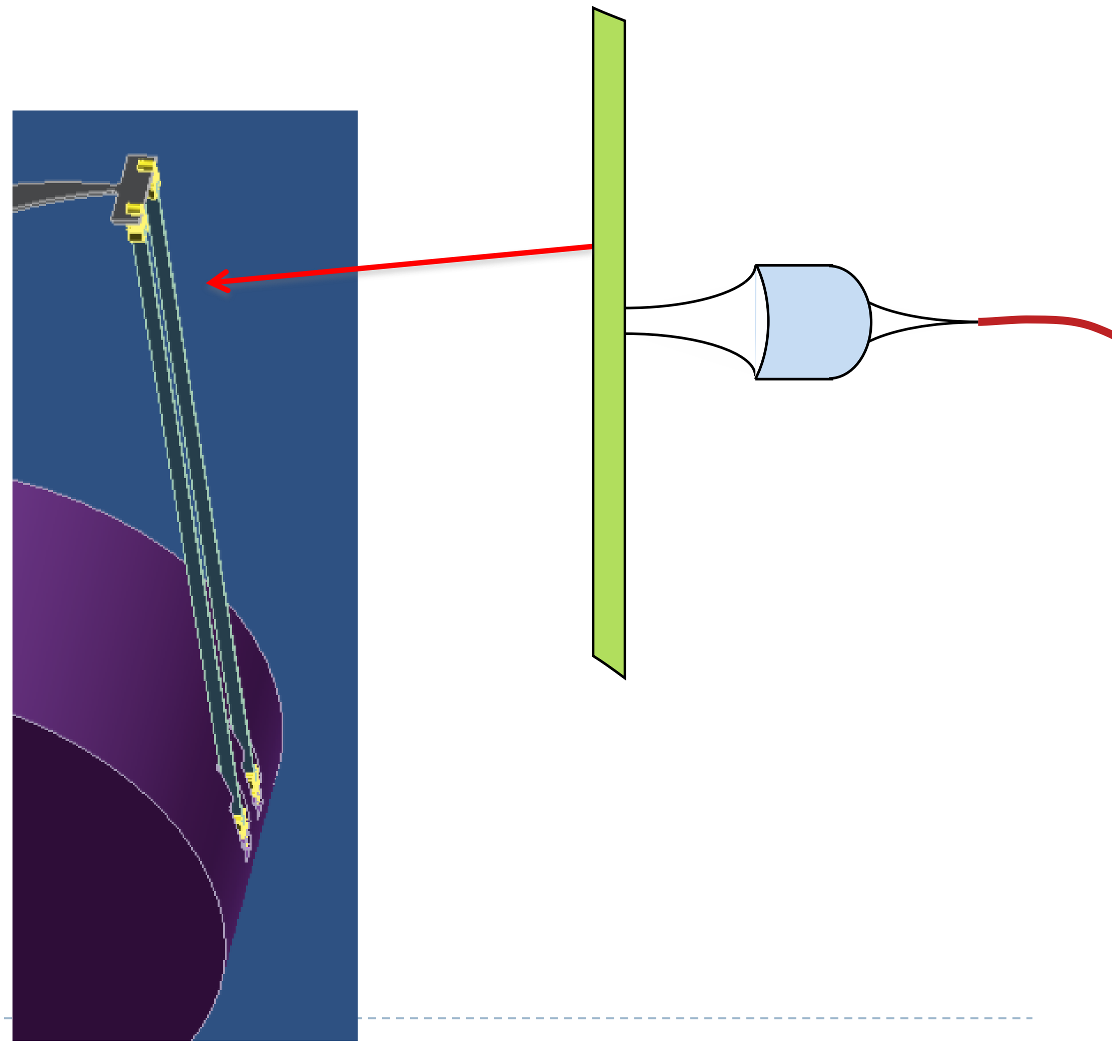
Indium vs. Gallium

Property	Unit	**Indium**	**Gallium**	**score**
Solid density (near r.t.)	$g \cdot cm^{-3}$	7.31	5.91	
Liquid density @ m.p.	$g \cdot cm^{-3}$	7.02	6.095	
Expansion at melting		1.041	0.9696	G
Melting point	°K	429.7485	302.9146	G
Melting point	°C	156.60	29.77	G
Wetting silicates		Yes	Yes	X
Boiling point	K	2345	2477	G
Vapor pressure	Pa	1 @ 1196°K	1 @ 1310°K	G
Vapor pressure	Pa	10@1325°K	10@1448°K	G
Elec. resistivity (20 °C)	nΩ·m	83.7	270	
Thermal conductivity	$W \cdot m^{-1} \cdot K^{-1}$	81.8	40.6	I
Therm. expansion (25 °C)	$\mu m \cdot m^{-1} \cdot K^{-1}$	23.1	18.0	G
Young's modulus	GPa	11	9.8	X
Poisson ratio			0.47	
Brinell hardness	MPa	8.83	60	G
Atomic radius	pm	167	135	
Magnetic ordering		diamagnetic	diamagnetic	X

Violin mode elimination

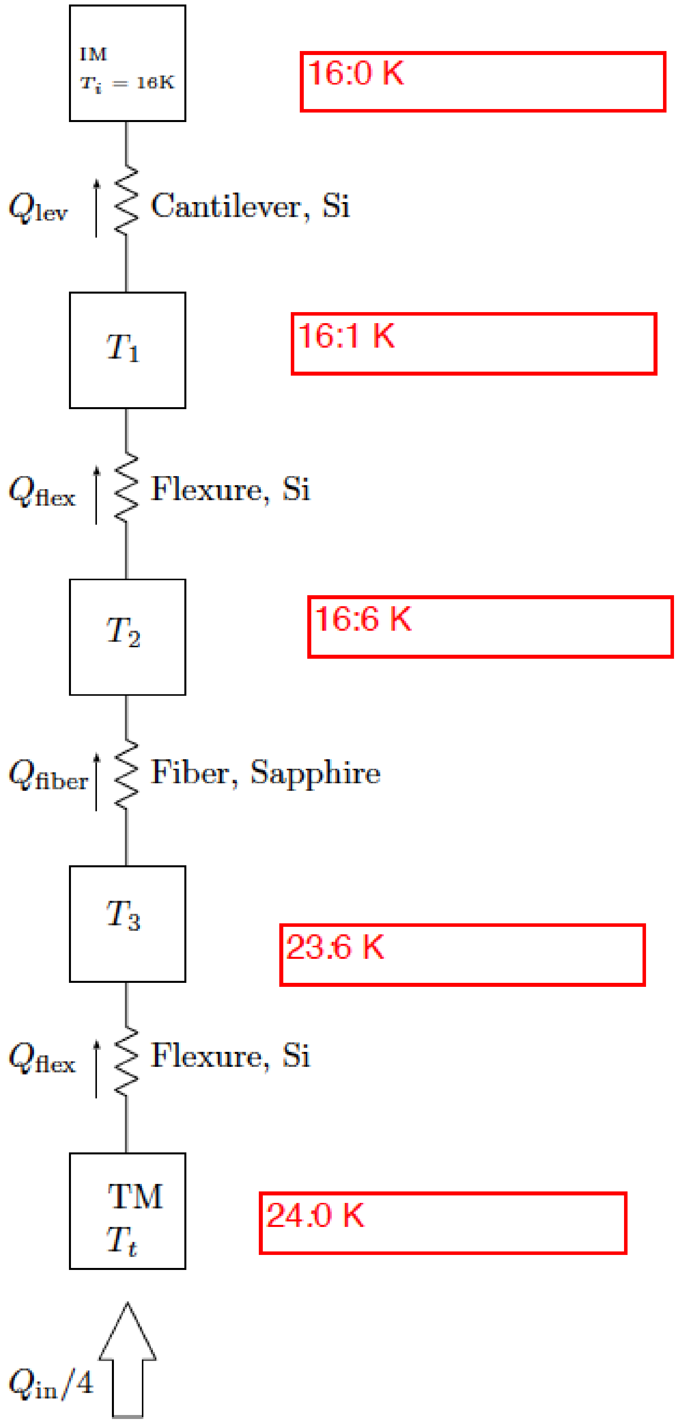
- Fiber-fed
Red-shifted
Fabry-Perot
- Can cool
violin modes
and bounce modes
to mK level

(Same for
Parametric
Instabilities ?)



Conductance budget

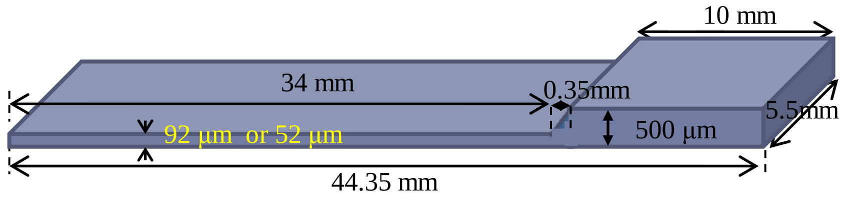
- Preliminary conductance budget from Sakakibara with 1 W load
- Thin ribbon responsible for bulk of loss ! ! !
- Plenty of space for parametric optimization

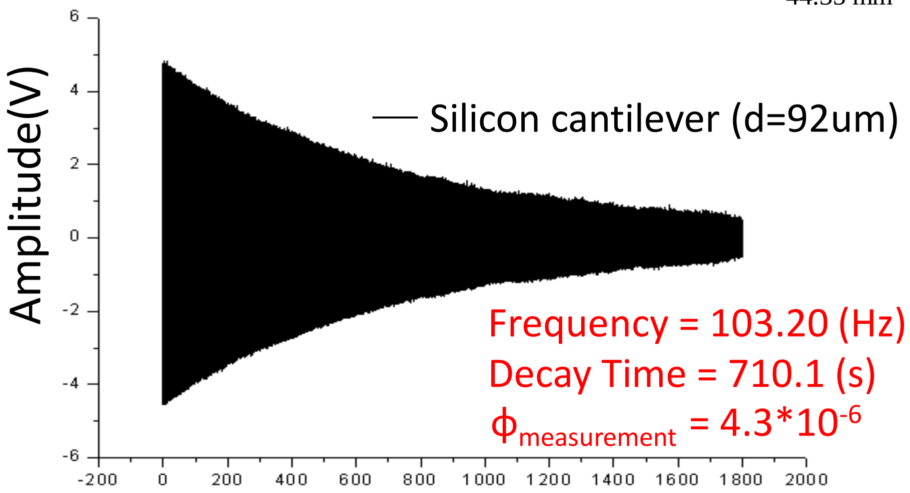


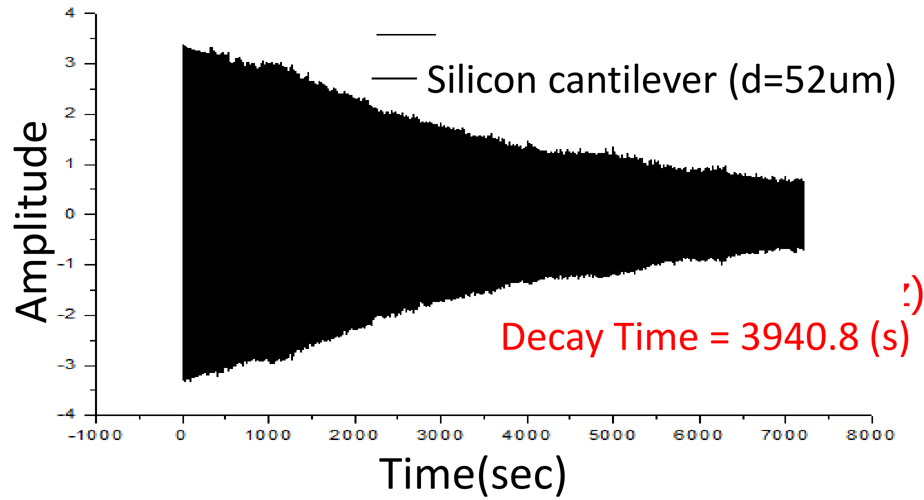
Chao Shiu laboratory, Taiwan

Silicon cantilever with KOH wet etching

4” un-doped double-side polished (001) silicon wafer, 500um thickness etched down to 92 and 52 µm



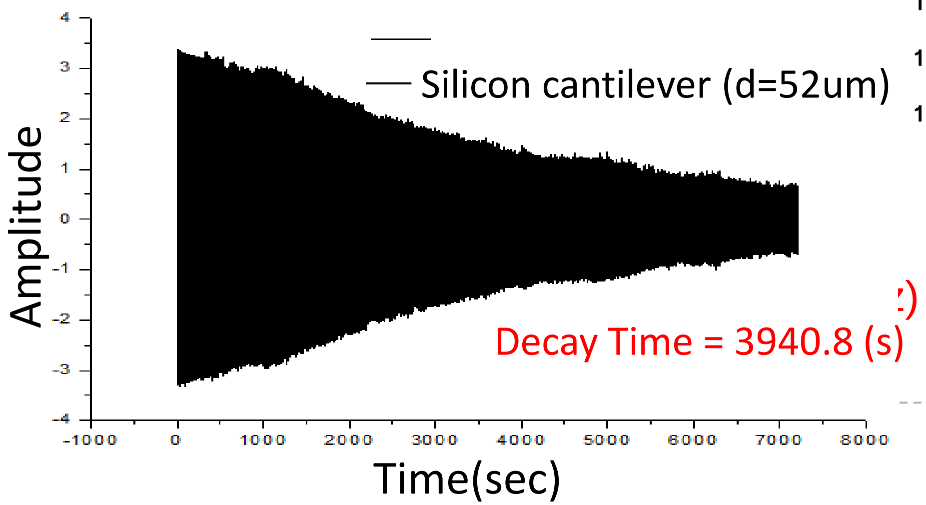


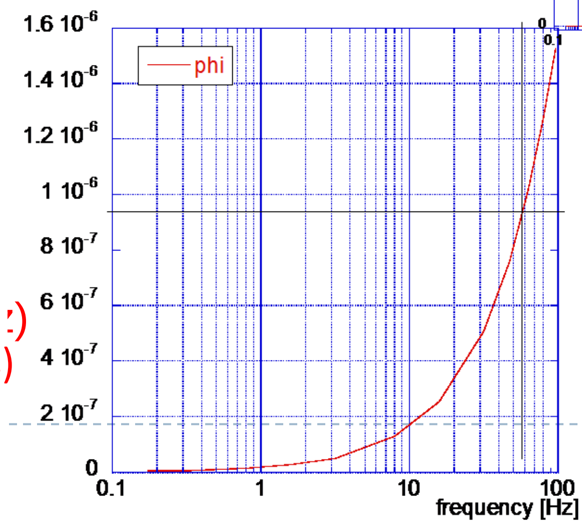


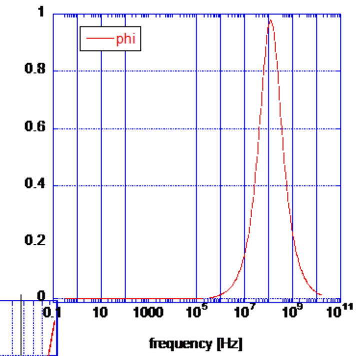
0.3 10^{-6} loss measured from residual gas

Thermo-elastic limit

- **@ 59 Hz 0.945 10^{-6} loss angle predicted (T.E.)**
- **1.3 10^{-6} measured** (-) **0.3 10^{-6} residual gas**
- **1. 10^{-6} loss angle measured**
- => 100% Thermoelastic limited ! ! !

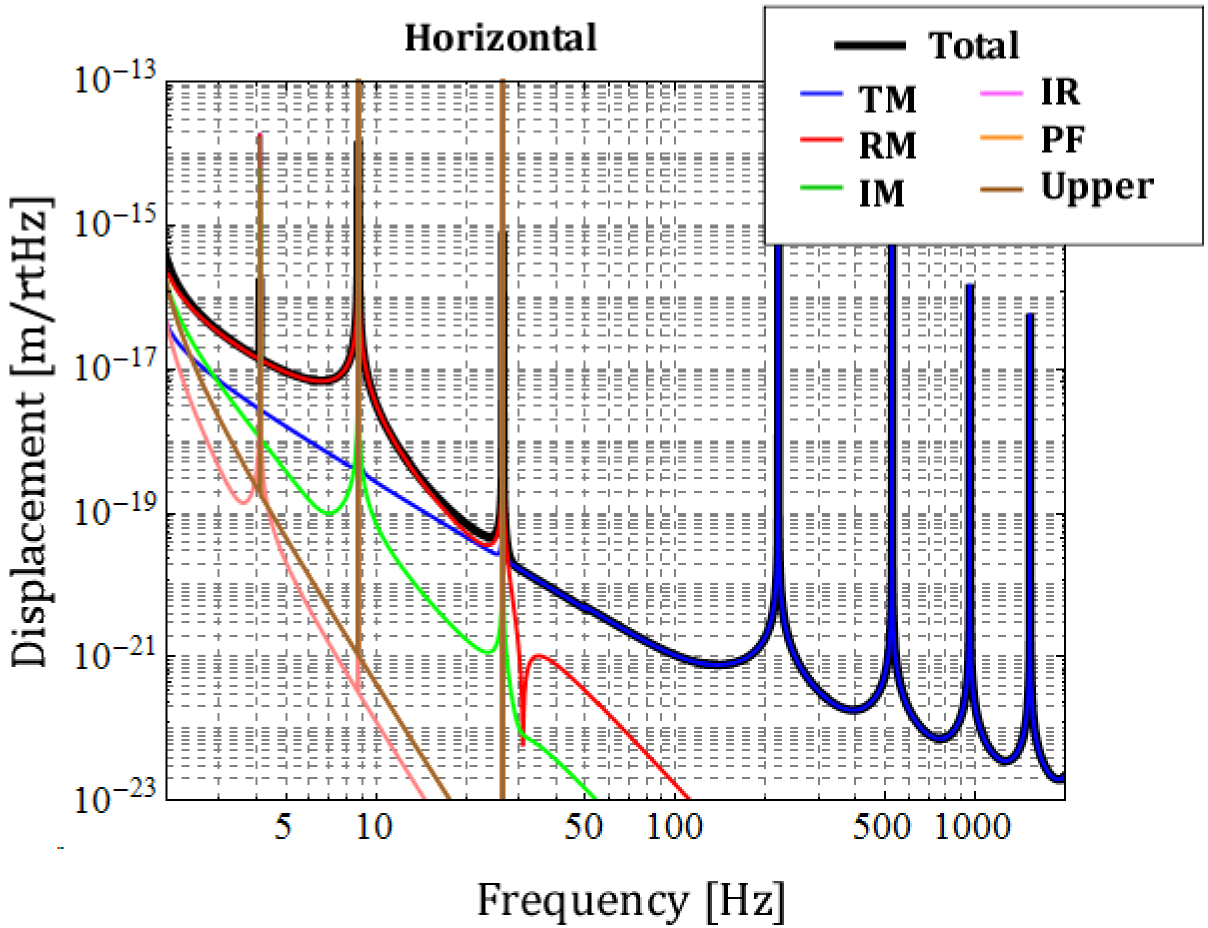






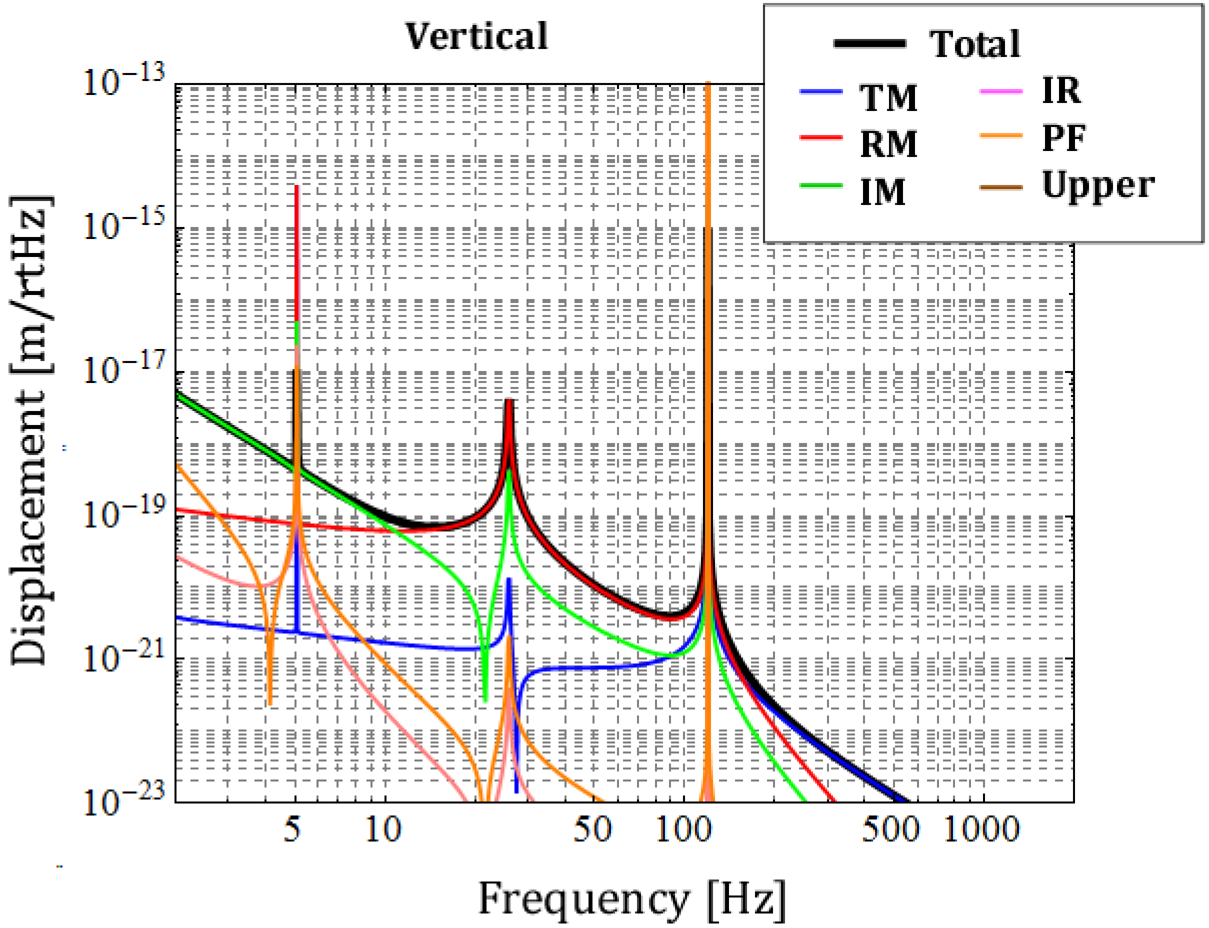
Suspension Thermal Noise in KAGRA

- Distribution of thermal noise source (H)

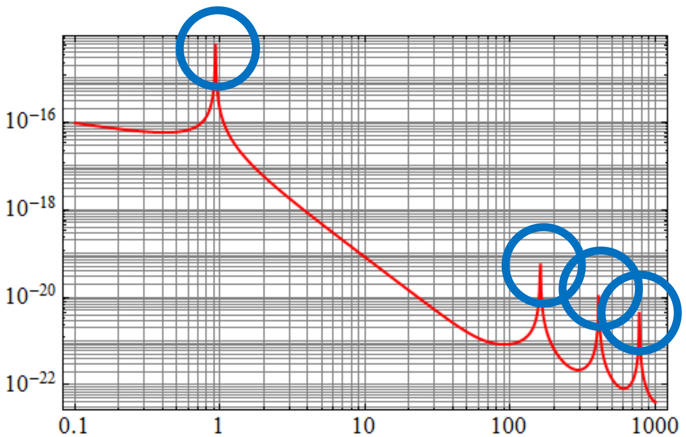


Suspension Thermal Noise in KAGRA

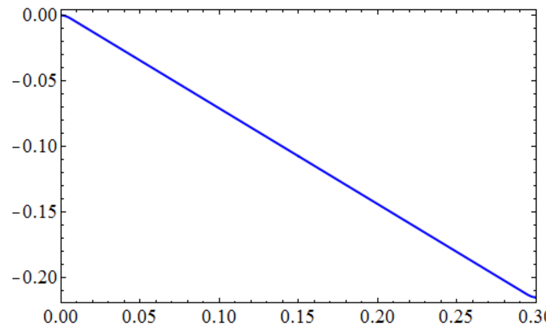
- Distribution of thermal noise source (V)



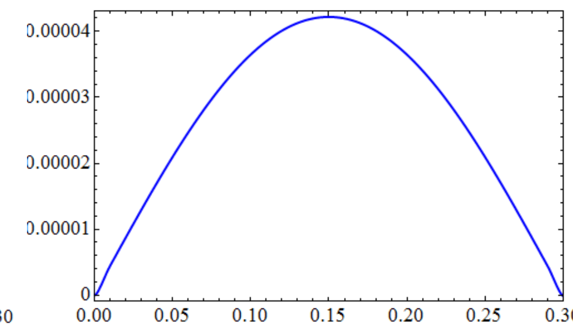
Mode Shape (Beam Profile)

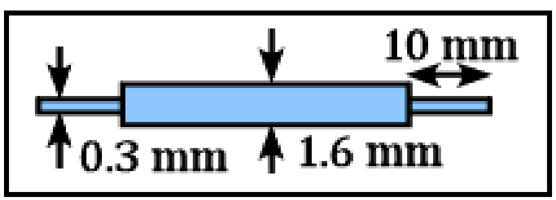


Pendulum Mode

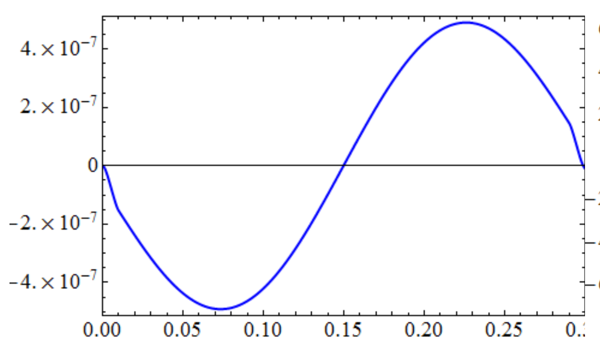


1st Violin Mode





2nd Violin Mode



3rd Violin Mode