Thermal noise in KAGRA

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Contribution

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0. Abstract

I will explain outline of thermal noise of KAGRA (some kinds of lecture or review).

Vivid and latest updates are reported by younger people later.

R. Kumar's talk on Wednesday afternoon
A. Khalaidovski's and D. Chen's talk on Tuesday morning, D. Chen's poster e-1(Thu)

0. Abstract

I will explain outline of thermal noise of KAGRA (some kinds of lecture or review).

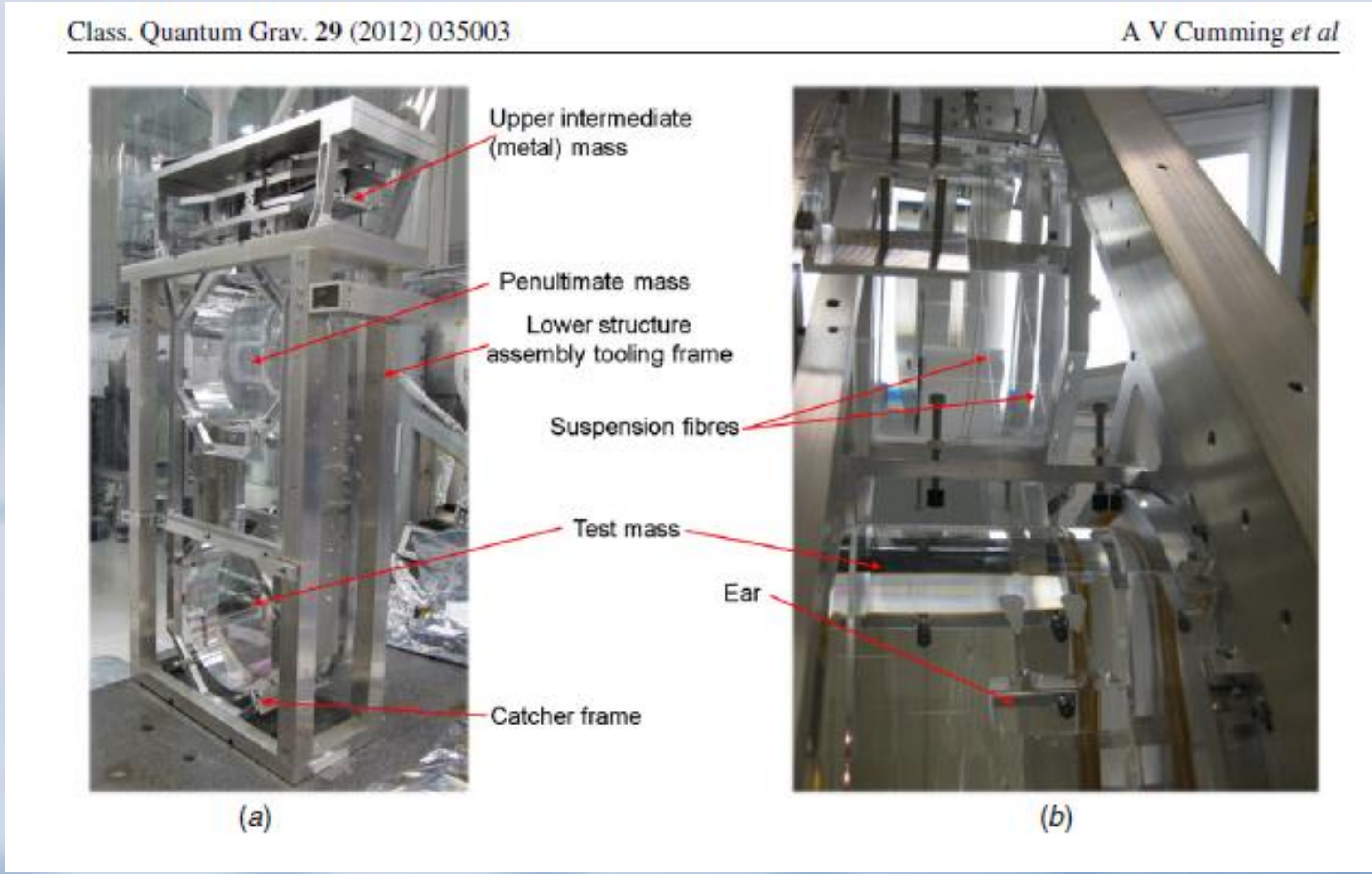
I will show some values to understand outlines, but it is based on calculation based on simple assumption.
If younger people shows slightly different values, please trust them not me.

Contents

1. *Introduction*

Room temperature second generation interferometer

Fused silica mirror suspended by fused silica fibers



1. Introduction

KAGRA (Cryogenic second generation)

Sapphire mirror suspended by sapphire fibers

First feasibility study

T. Uchiyama *et al*., Physics Letters A 242 (1998) 211.

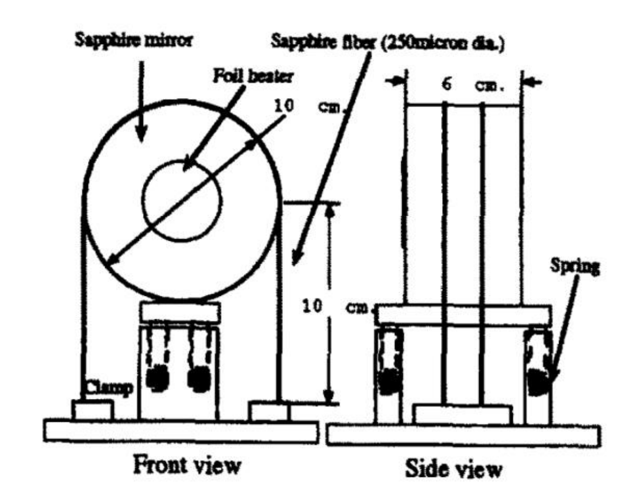


Fig. 1. The experimental setup.

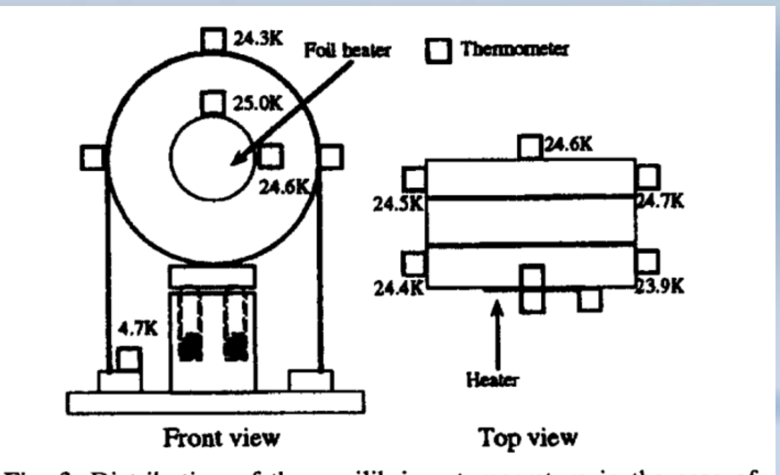


Fig. 3. Distribution of the equilibrium temperature in the case of 29 mW heat power.

Sapphire fiber : High Q-values

and large thermal conductivity

1. Introduction

Development of sapphire suspension

“Initial phase” (R. Kumar’s talk on Wednesday afternoon)

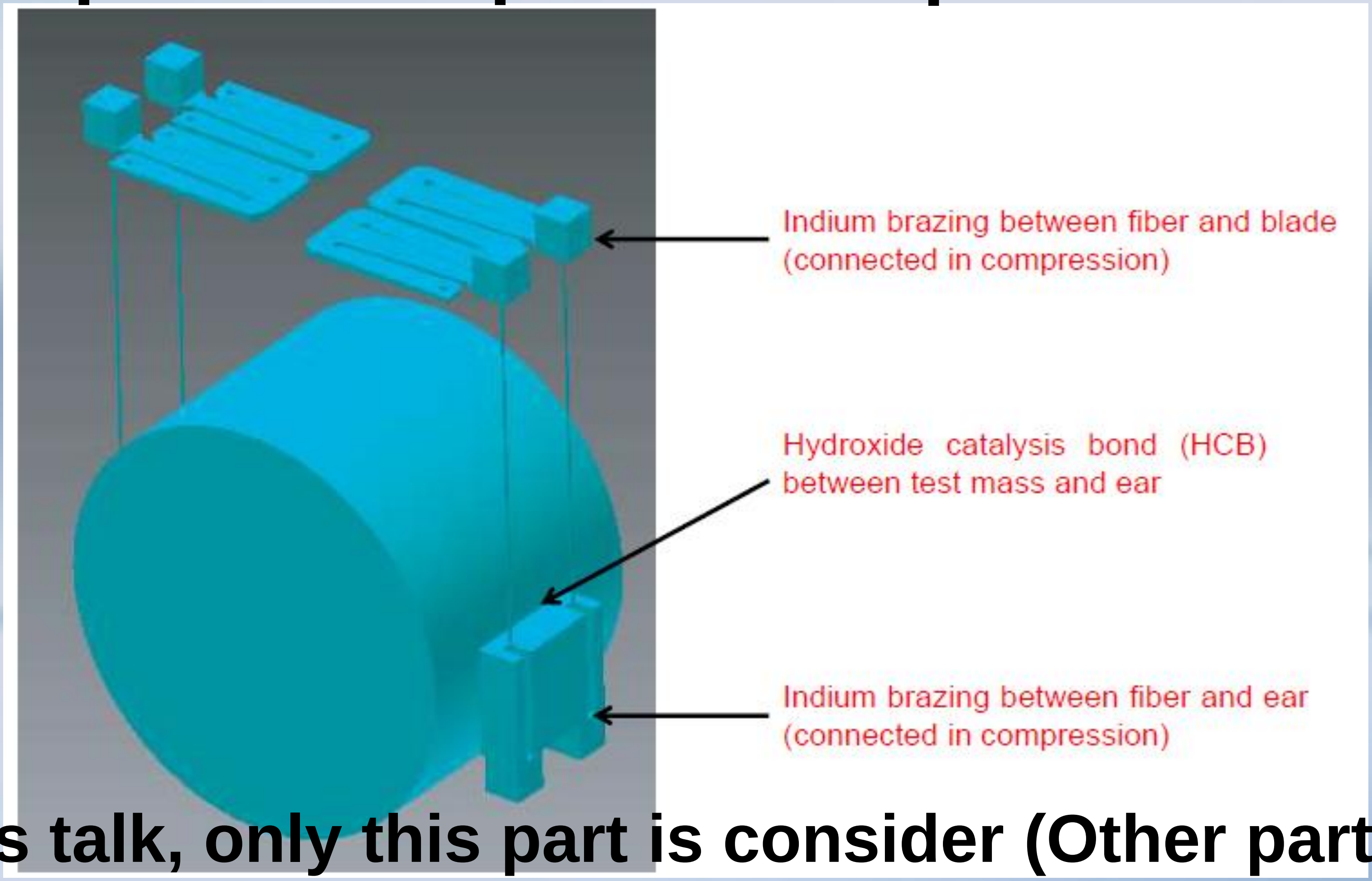
Feasibility

“Final phase” (A. Khalaidovski’s and D. Chen’s talk on Tuesday morning, D. Chen’s poster e-1(Thu))

Small thermal noise

1. Introduction

“Final phase”   lop-eared suspension



In this talk, only this part is consider (Other parts of cryo payload are not discussed here).

2. Mirror

Mechanical dissipation generates thermal noise.

Loss in substrate and coating

Two kinds of loss : Brownian, Thermoelastic

Substrate : Brownian noise

(Unknown frequency independent)

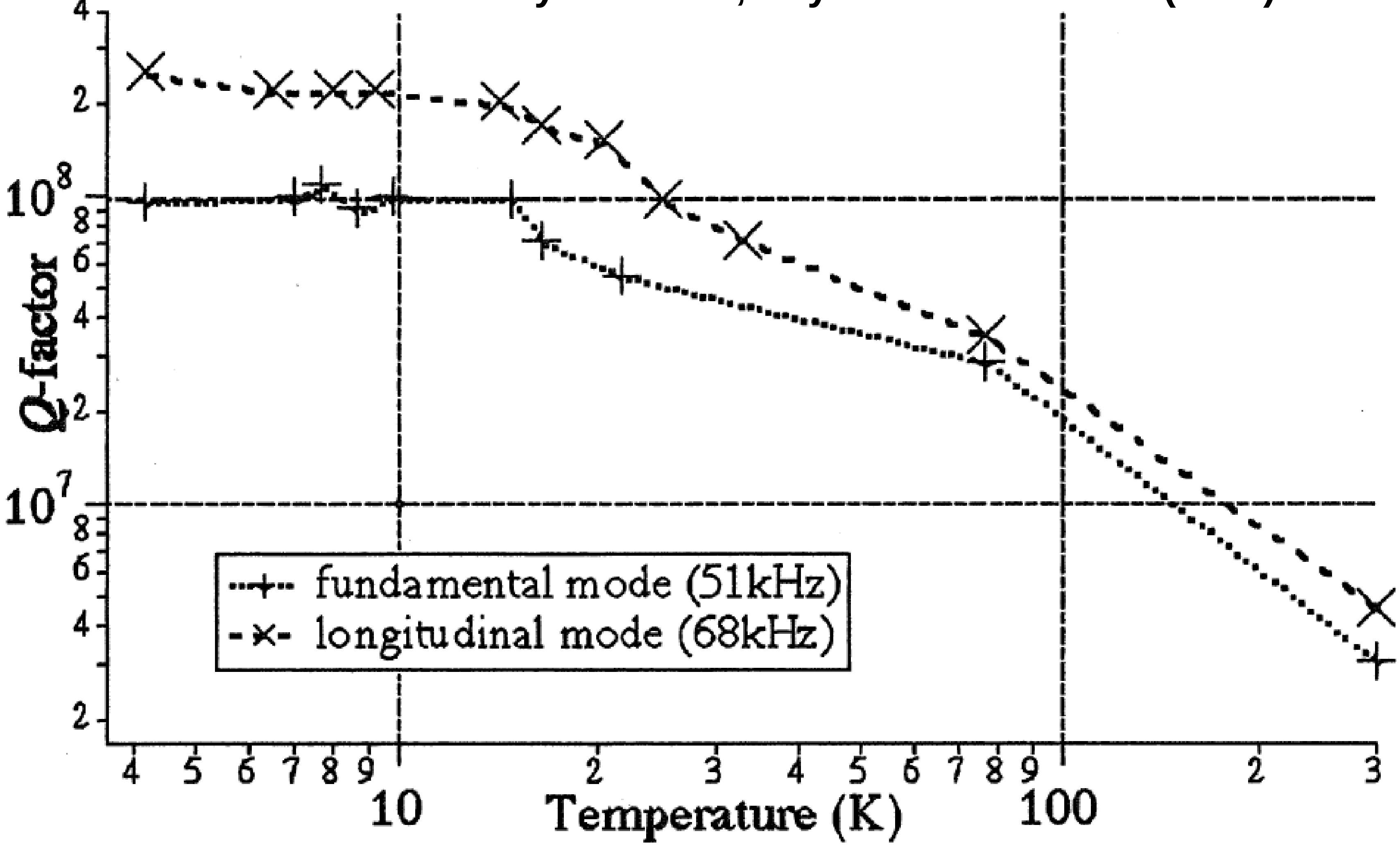
This noise is proportional to $1/Q^{1/2}$ (substrate).

Sapphire *Q* is 10^8 at low temperature.

T. Uchiyama *et al*., Physics Letters A 261(1999)5.

2. Mirror

T. Uchiyama *et al*., Physics Letters A 261(1999)5.



2. Mirror

Mechanical dissipation generates thermal noise.

Loss in substrate and coating

Two kinds of loss : Brownian, Thermoelastic

Substrate : Thermoelastic noise

M. Cerdonio *et al*., Phys. Rev. D 63 (2001) 082003.

Temperature fluctuation

and thermal expansion of substrate

Below 30 K : $T^{5/2}$

Smaller thermal expansion

Phonon mean free path is

independent of temperature.

2. Mirror

Mechanical dissipation generates thermal noise.

Loss in substrate and coating

Two kinds of loss : Brownian, Thermoelastic

Coating : Brownian noise

Y. Levin, Phys. Rev. D 57 (1998) 659.

Coating has large contribution to thermal noise

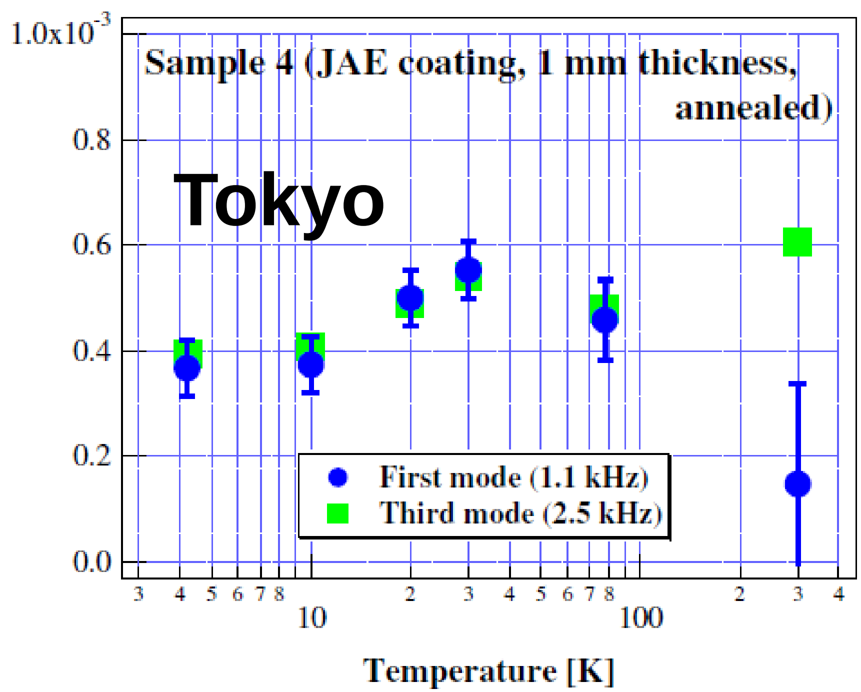
than we expected !

This noise is proportional to $\phi^{1/2}$.

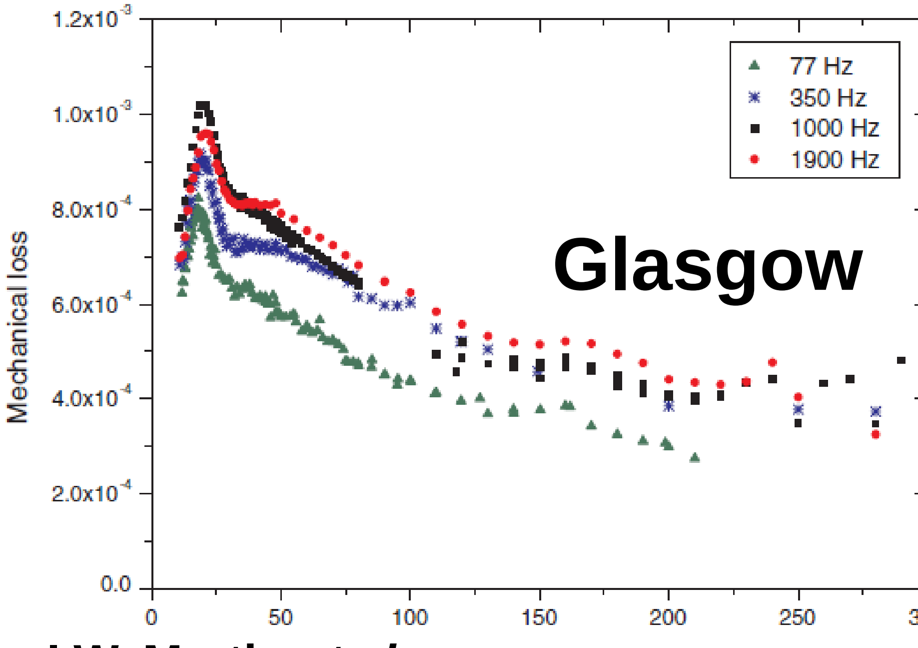
2. Mirror

Coating : Brownian noise (Ta_2O_5/SiO_2)

Discrepancy between Tokyo and Glasgow



K. Yamamoto *et al*.,
Physical Review D 74 (2006) 022002.



I.W. Martin *et al*.,
Classical and Quantum Gravity
27 (2010) 225020.
(Annealing could suppress peak)

Collaboration (Tokyo and Glasgow) for this issue
E. Hirose's talk (Tuesday afternoon)

2. Mirror

Mechanical dissipation generates thermal noise.

Loss in substrate and coating

Two kinds of loss : Brownian, Thermoelastic

Coating : Thermo-optic noise

M. Evans *et al*., Phys. Rev. D 78(2008)102003.

Temperature fluctuation and thermal expansion and temperature coefficient of refractive index of coating

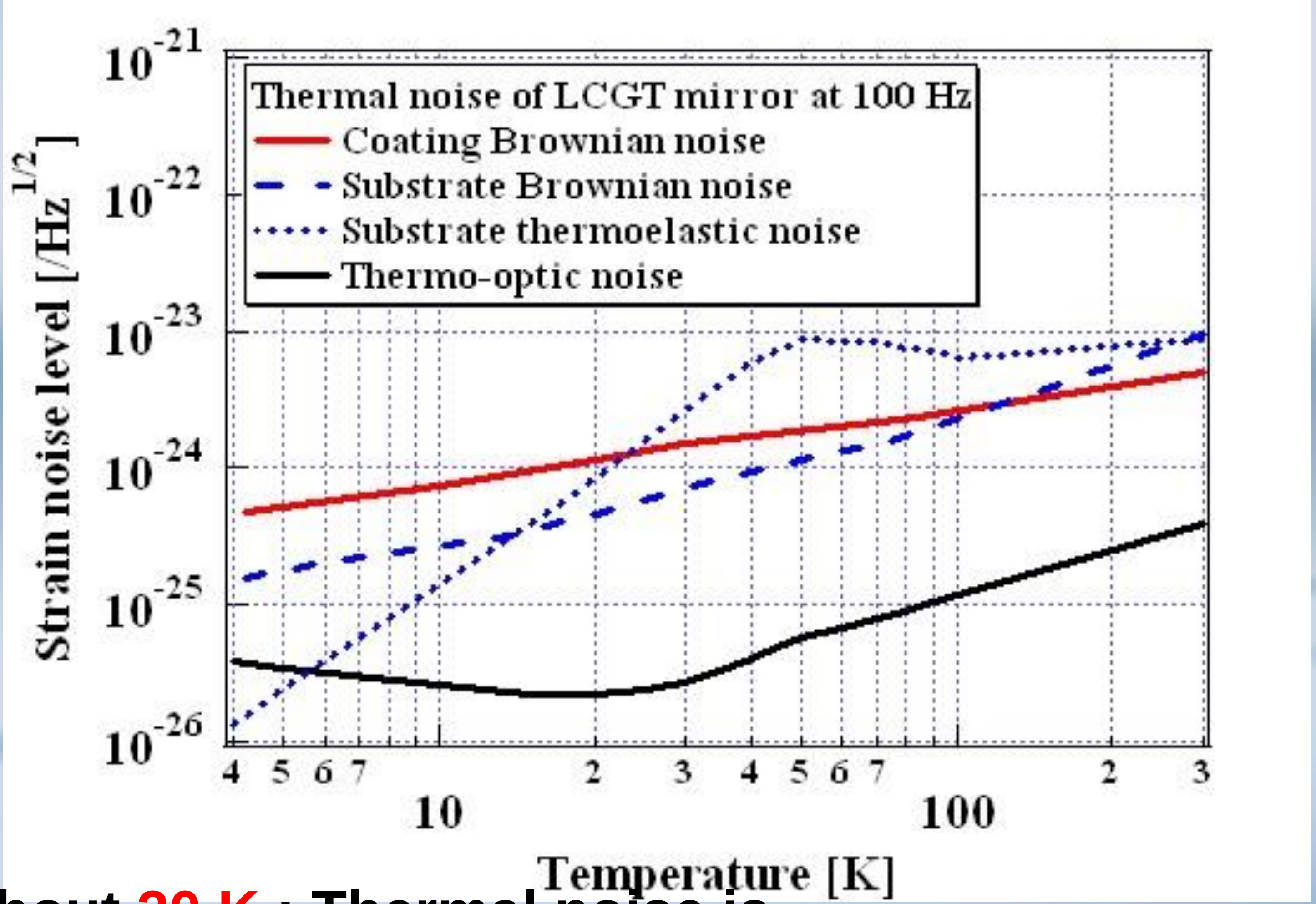
Small thermo-opitc noise at cryogenic temperature

smaller temperature coefficient

longer phonon mean free path

2. Mirror

Temperature of KAGRA mirror



Below about 20 K : Thermal noise is

sufficiently small for KAGRA (~3*10^{-24} /rtHz).

2. Mirror

Other mechanical dissipation

Bonding (and so on …)

Marielle van Veggel's talk (Monday afternoon)

Hydroxide Catalysis Bonding : Mirror and Ears

B. Douglas and Marielle van Veggel's poster (d-3, Thu)

Indium : Ears and Fibers (disassemble)

Dissipation which far from reflective surface has small contribution to thermal noise.

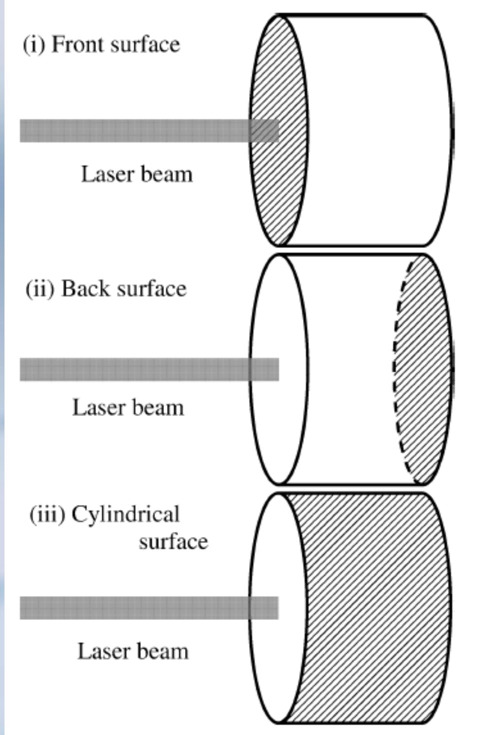
Y. Levin, Phys. Rev. D 57 (1998) 659.

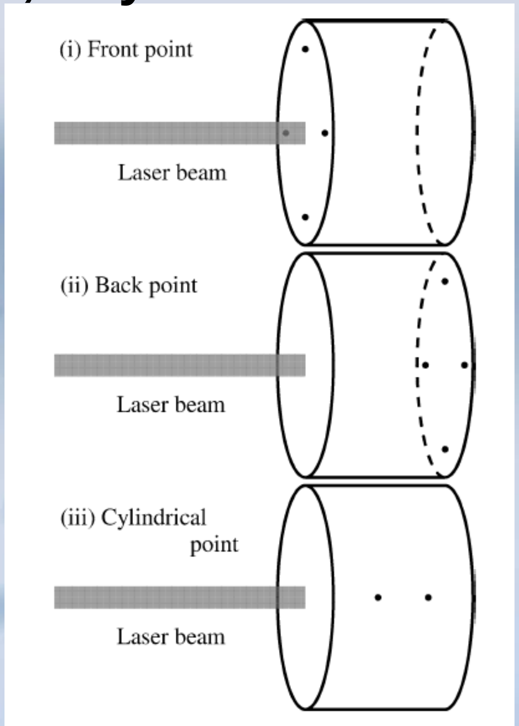
2. Mirror

Other mechanical dissipation

Finite element method is necessary for evaluation.

First paper : K. Yamamoto *et al*., Physics Letter A 305 (2002) 18.





So far, many papers were published

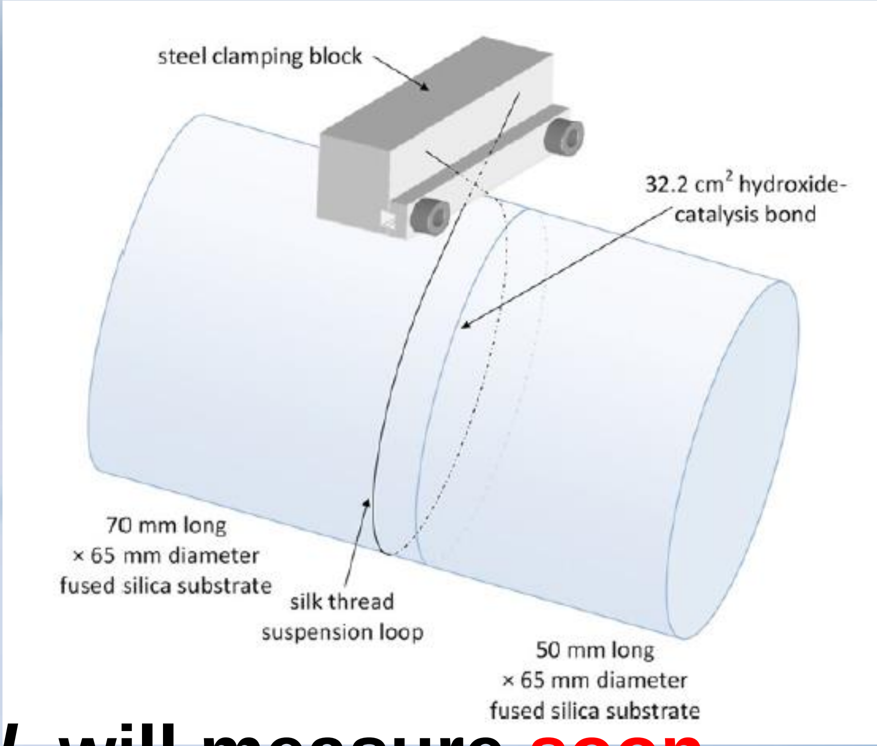
and this is a common method …

2. Mirror

Other mechanical dissipation

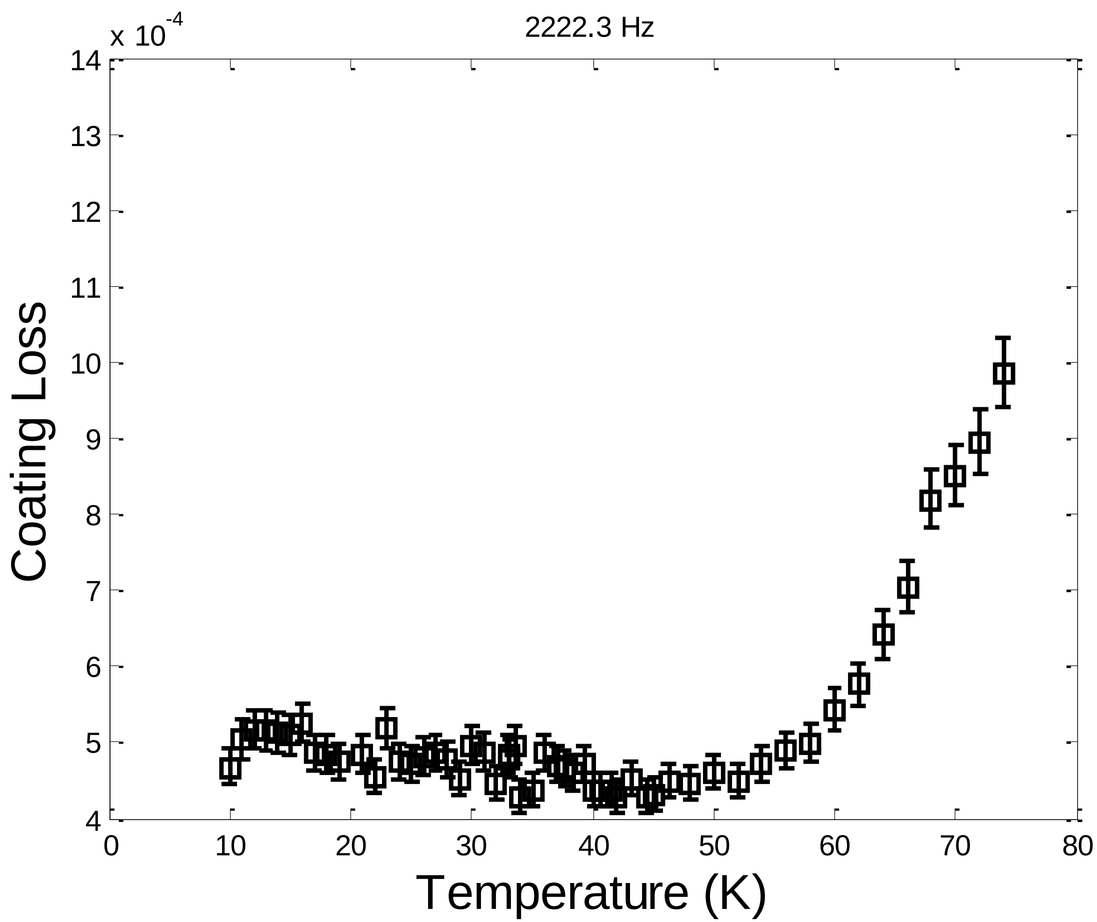
We have plans to measure mechanical dissipation (ELiTES, Jena and Glasgow).

L. Cunningham *et al*., Physics Letters A 374(2010)3993.



D. Chen *et al*. will measure soon.

Loss of indium film at cryogenic temperature



- Loss of approximately 5 x 10^{-4} at a few 10's of K
- Broadly consistent with values from Liu et al (1999)
- FEA models of thermal noise from indium bonds used in an Advanced detector-like suspension geometry at 40K suggest noise would be ~x10 lower than sensitivity of ET.

Mode 4 at f = 2222 Hz

3. Suspension

Assumption

Upper ends of sapphire fibers are fixed rigidly.

(1)In this talk, we discuss only thermal noise from final stage of payload, sapphire main mirror and its fibers.

(2)Resonant frequencies (except for violin modes) are different from the actual system.

They are not exact results, but not so different from the actual contribution of the final stage.

3. Suspension

Strength

Sapphire fibers should support the weight of sapphire mirror.

Mirror : 23 kg
Number of fibers : 4
Tensile strength : 400 MPa
Safety margin : 7

Fiber diameter must be larger than 1.1 mm.

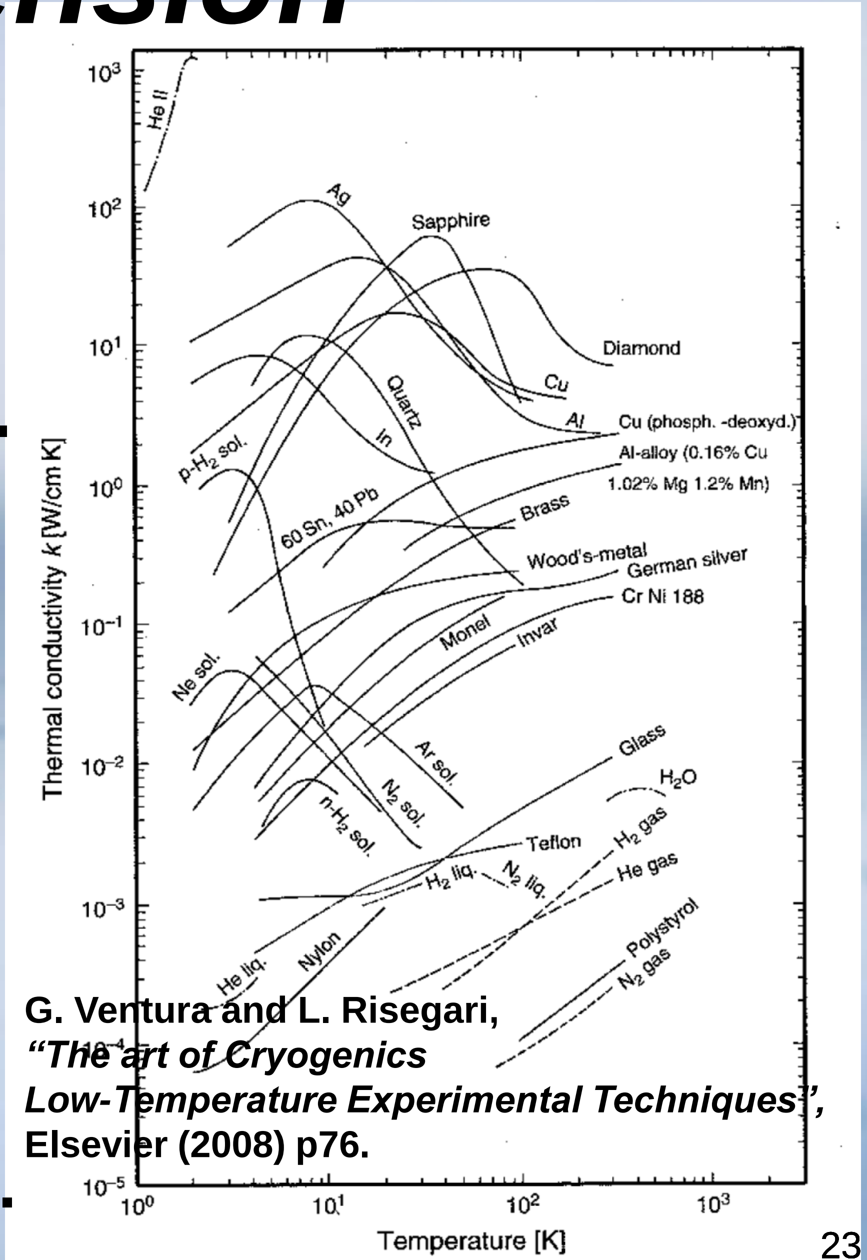
3. Suspension

Thermal conductivity

Fibers should transfer heat (about 1 W).

Crystal (for example, sapphire, silicon) and pure metal (Al, Cu, Ag) : Thermal conductivity is extremely high (> 1000 W/m/K) around 20 K.

Q-values of pure metal is low. Crystals with high Q-values are candidates (sapphire, silicon).



G. Ventura and L. Risegari,
"The art of Cryogenics Low-Temperature Experimental Techniques",
Elsevier (2008) p76.

3. Suspension

Thermal conductivity

Sapphire : Thermal conductivity is maximum around 30 K.
Temperature of KAGRA mirror will be around 20 K.

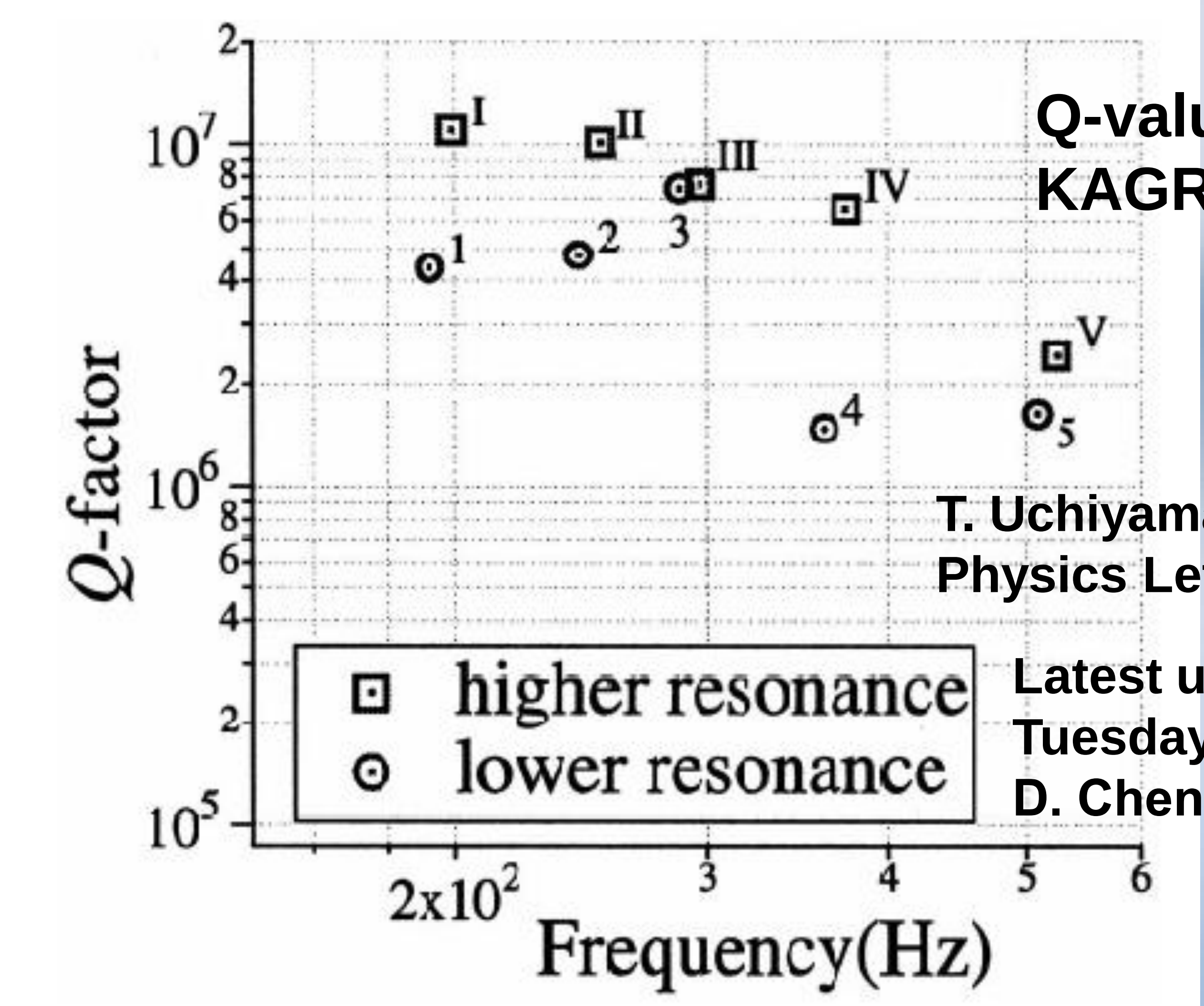
Specification sapphire suspension

Number of fibers : 4
Length of fibers : 0.3 m
Heat generated in a mirror : 1 W
Mirror temperature : 23 K
Temperature at top end of fiber : 16 K
Thermal conductivity : 5500 $(T/20K)^3$ W/m/K

Fiber diameter must be larger than 1.6 mm.
This requirement is severer than that of strength (1.1 mm).

3. Suspension

Q-values of sapphire fibers : 5*10^6



Q-values are 5*10^6.
KAGRA requirement

T. Uchiyama *et al.*,
Physics Letters A 273 (2000) 310.

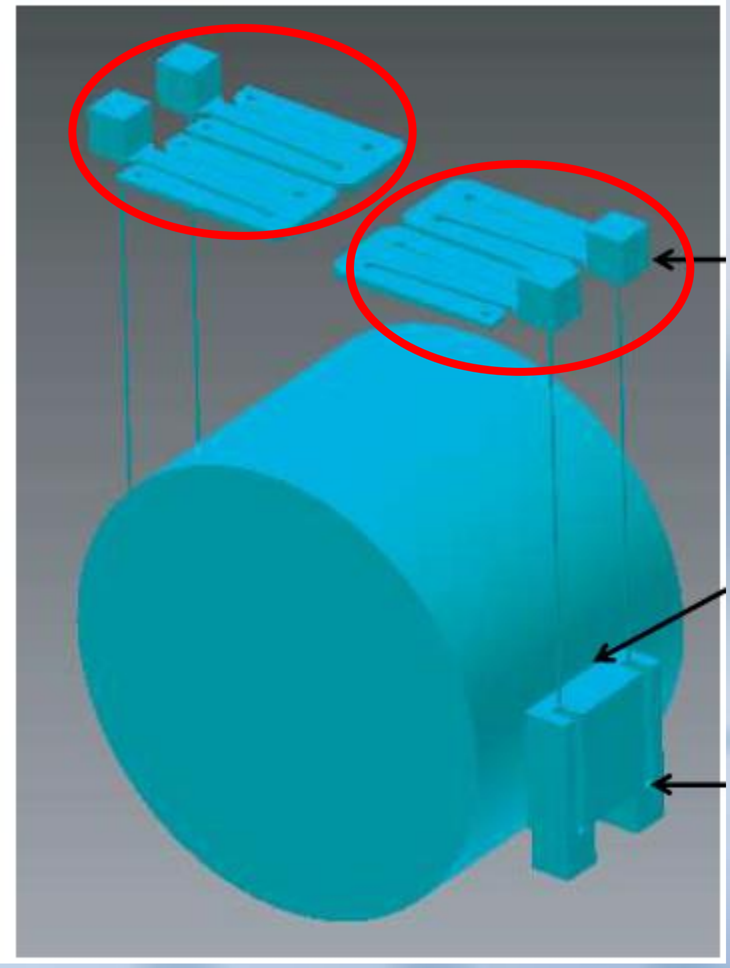
Latest update : D. Chen's talk on Tuesday morning,
D. Chen's poster e-1 (Thu)

3. Suspension

Sapphire **fibers** are **thick**
(1.6 mm in diameter)
for heat transfer.
Stretch by sapphire mirror
weight (23kg) : **21 μm**

If difference between length
of 4 fibers are **larger than 21 μm**,
there is **no tension in one fiber** !

Blade spring is necessary.



3. Suspension

Requirement
Length difference compensation
0.5 mm -> 22 Hz
(Resonant frequency
is inversely proportional
to square root of length difference)

Pulsar search : Vela (22 Hz)

Vela pulsar (Wikipedia: English)

Current design : 14.5 Hz
R. Kumar’s talk
on Wednesday afternoon, S. Barclay and G. Hammond’s poster (d-4, Thu)

3. Suspension

Degrees of freedom

Horizontal motion along optical axis

Pendulum and violin modes

Vertical motion

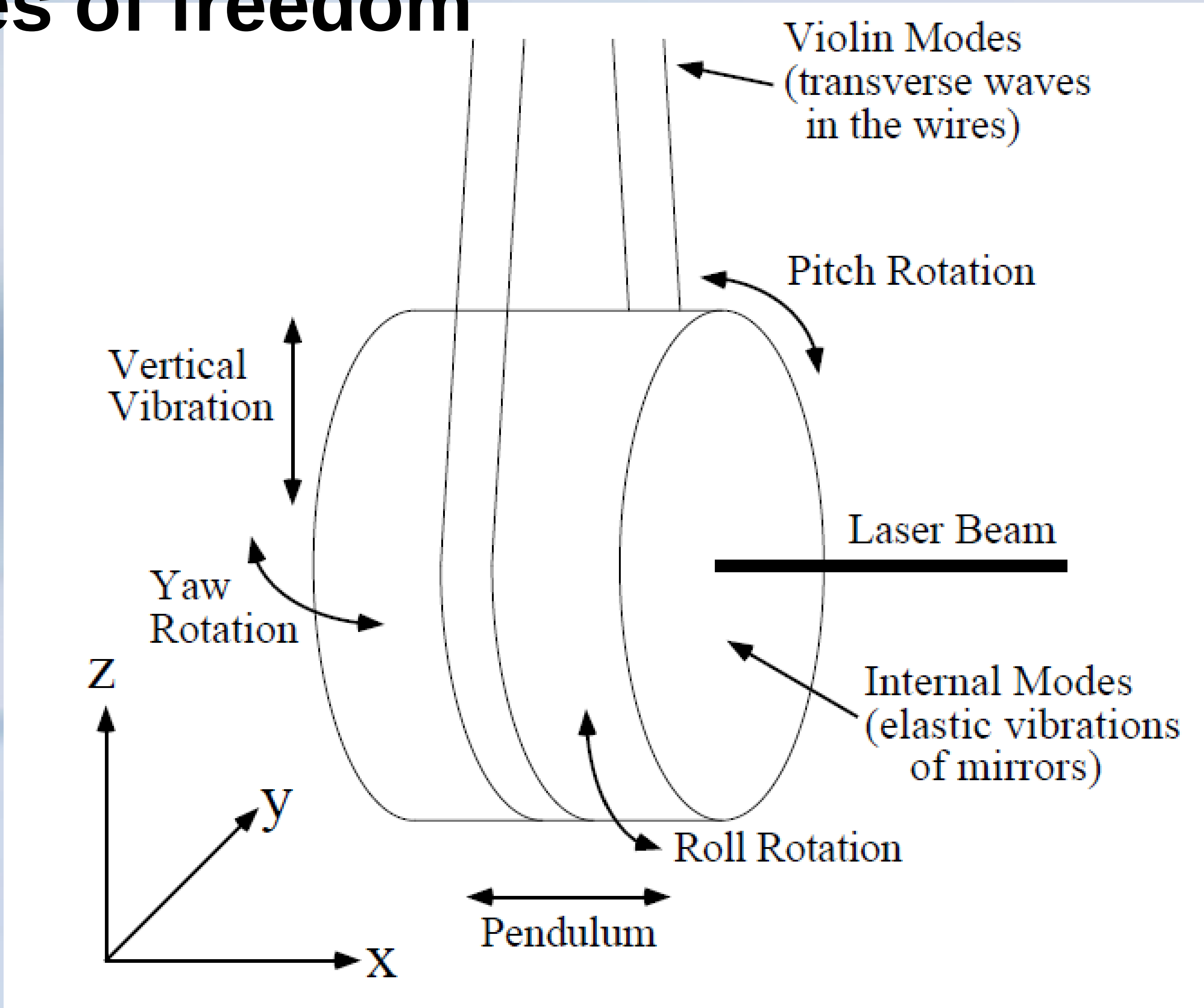
Gradient of interferometer baseline is 1/300
for discharge of water in the mine.

Rotation (Pitch and Yaw)

Distance between optical axis
and center of gravity of mirror is 1 mm.

3. Suspension

Degrees of freedom



3. Suspension

Resonant frequencies and Q-values

T. Sekiguchi, K. Somiya, K, Yamamoto

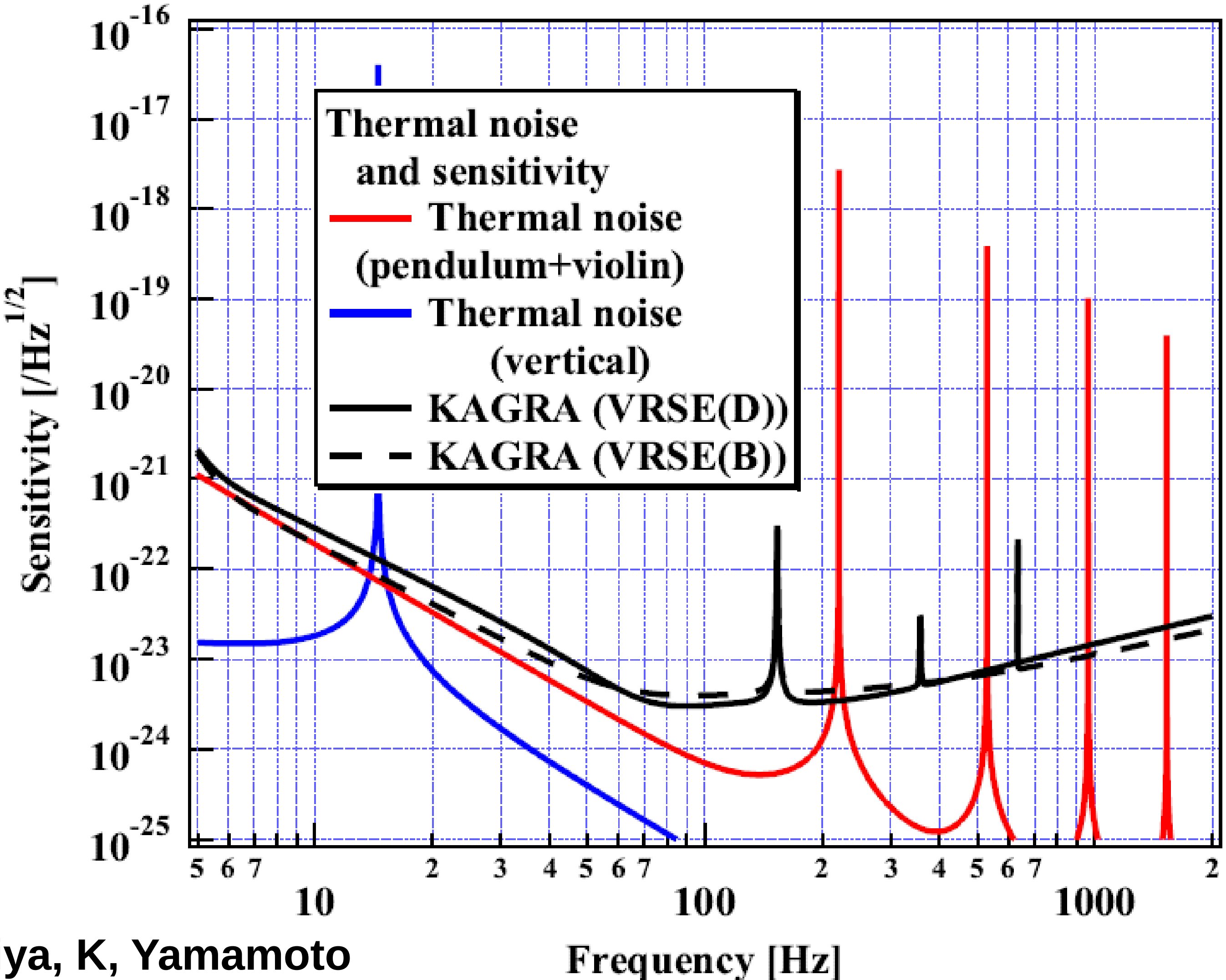
(Analytical calculation with simple assumption)

	Resonant frequencies	Q-values
Pendulum	1.1 Hz	$2*10^7$
1^{st} violin	220 Hz	$1.0*10^7$
Vertical	14.5 Hz	$5*10^6$
Pitch	5.2 Hz	$5*10^6$
Yaw	1.8 Hz	$2.2*10^7$

In the cases of Pendulum (and violin) and Yaw modes, loss dilution factors by gravity were taken into account.
Dilution factors are on the order of unity because of thick fiber (In the case of room temperature interferometer, they are on the order of 100 or 1000).

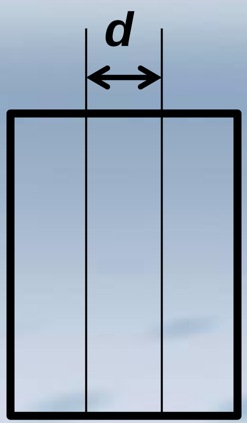
3. Suspension

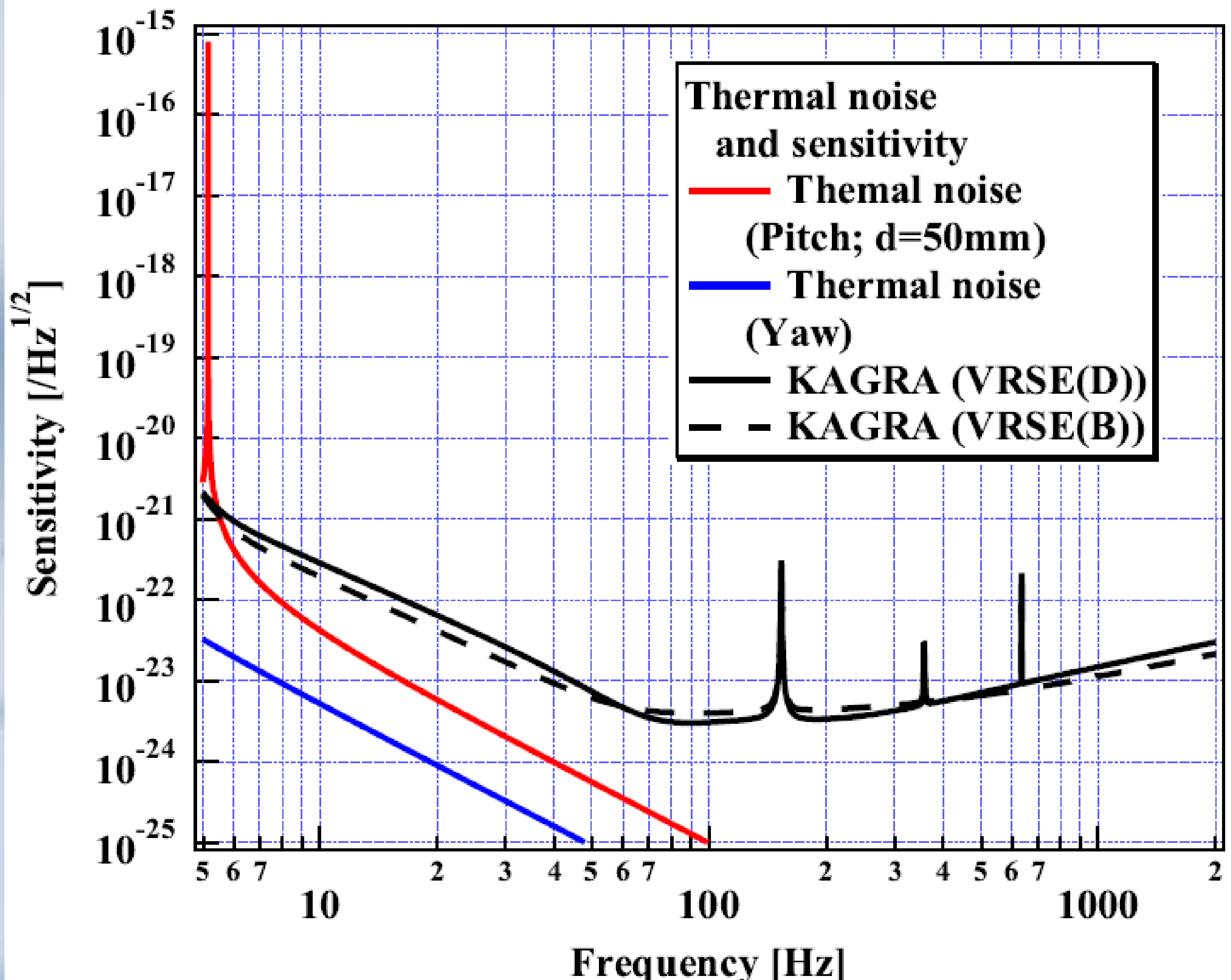
Horizontal and vertical motion



3. Suspension

Pitch and yaw rotation





K, Yamamoto

3. Suspension

In principle, KAGRA sensitivity is **not limited by thermal noise**.

However,
(1)There is not so large margin for pendulum around 10 Hz.
(2)The 1st violin mode is around 220 Hz.
Advanced LIGO : 1st violin around 500 Hz

Thick fiber to transfer heat !

3. Suspension

Thick fiber to transfer heat !

Elasticity is not perturbation in KAGRA.

(1)Thin wire (only tension) :

Violin mode of thicker wire is lower.

KAGRA : Violin mode of thicker fiber is higher owing to elasticity (although it is not strong dependence).

3. Suspension

Thick fiber to transfer heat !

Elasticity is not perturbation in KAGRA.

(2)Frequency of the first violin mode
When we do not take elasticity into account,
1st violin mode is 139 Hz !
Actually, the 1st violin mode is 220 Hz.

3. Suspension

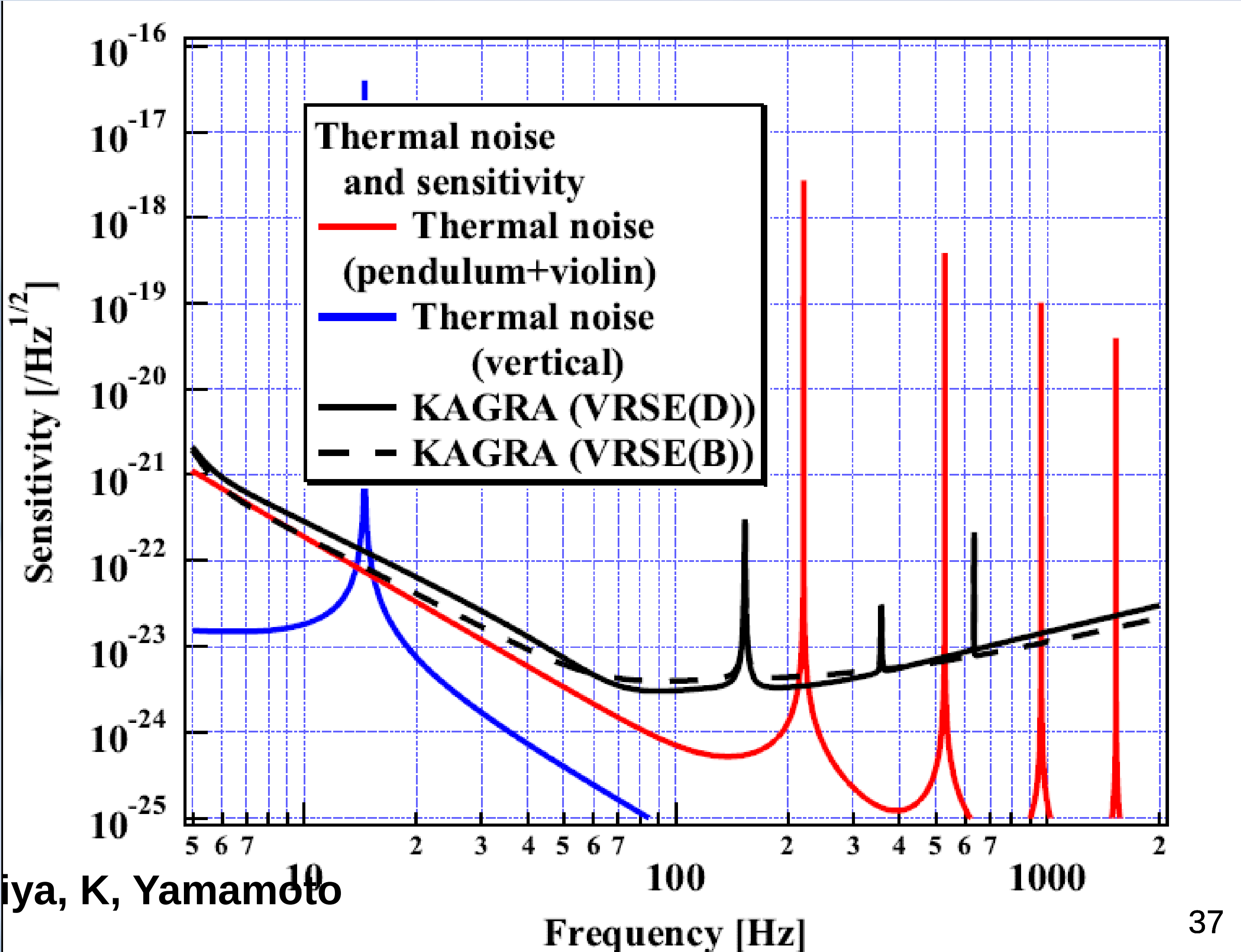
Thick fiber to transfer heat !

Elasticity is not perturbation in KAGRA.

(3)Frequencies of higher violin modes
Thin wire (only tension) : n-th violin frequency is n times higher than fundamental frequency.
Thick wire (only elasticity) : n-th violin frequency is n^2 times higher.

In KAGRA, both of tension and elasticity must be considered.

3. Suspension



T. Sekiguchi, K. Somiya, K, Yamamoto

3. Suspension

Thick fiber to transfer heat !

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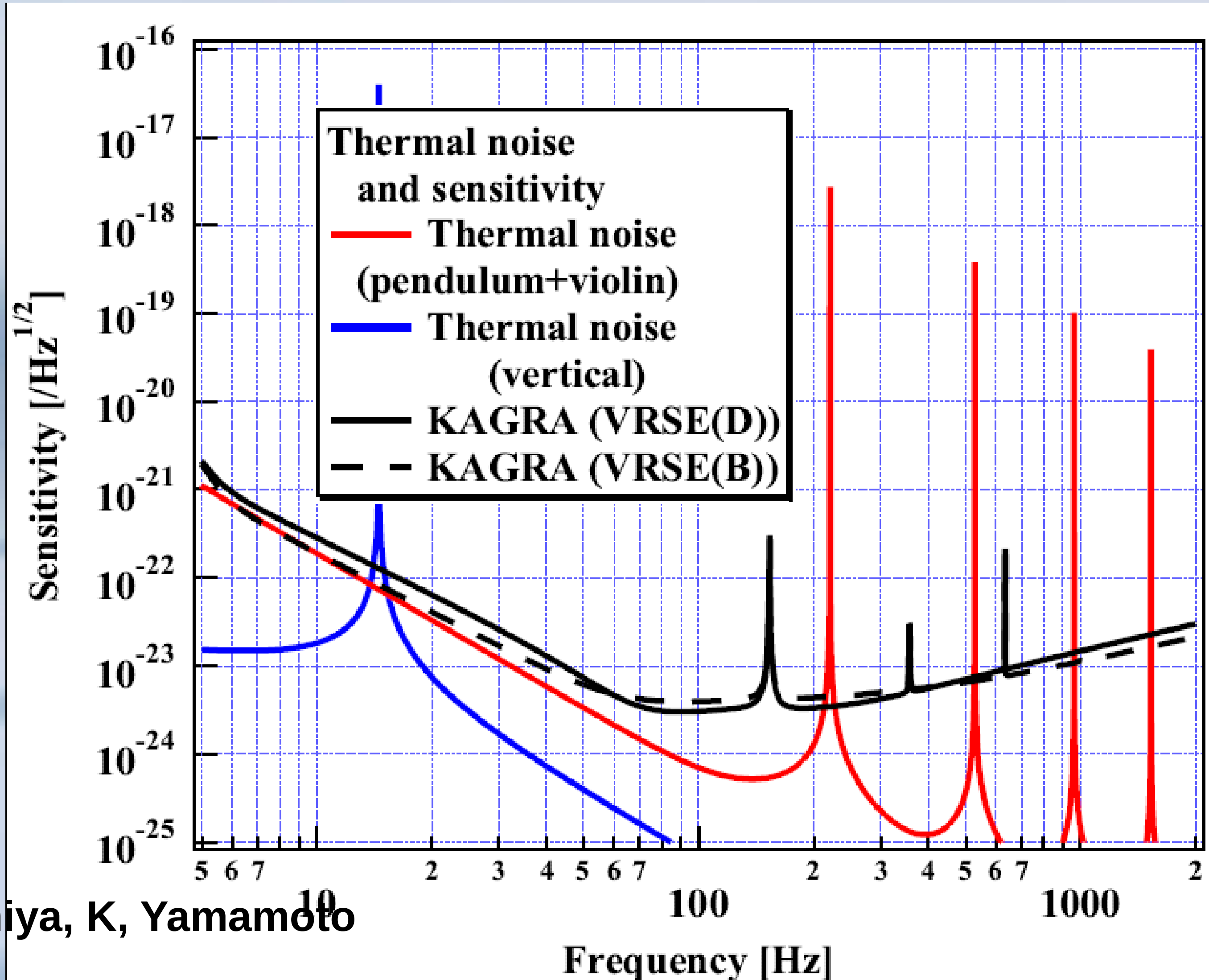

T. Sekiguchi, K. Somiya, K, Yamamoto

3. Suspension

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Thick wire (only elasticity) : n-th violin frequency is n^2 times higher.

In KAGRA, both of tension and elasticity must be considered.

3. Suspension

Higher violin modes ?

Thicker fiber : It is not so effective.
(2.2 mm diameter, 245 Hz)

Shorter fiber :
Pendulum mode thermal noise is larger.

Mirror diameter is 220 mm.
Current design (300mm) fiber
is not so enough long …

3. Suspension

Open questions

Calculation

Coupling to other degree of freedom

Q of pendulum could be spoiled by blade spring ?

Measurement

Bonding mechanical dissipation

Sapphire blade spring

4. ELiTES

ELiTES: ET-LCGT interferometric Telescope Exchange of Scientists

Grant for collaboration about cryogenic between KAGRA and ET

European 7th Framework Programme
Marie Curie action (Mar. 2012 - Feb. 2016)

European people can visit Japan for KAGRA.

4. ELiTES

Measurement of coating mechanical loss
at cryogenic temperature (Glasgow)
nm layer coating (Sannio)

Sapphire fibers with nail heads

Q-value

Measurement in Glasgow, Jena, Rome and Tokyo

Thermal conductivity

Measurement in Jena, Rome and Tokyo

Strength

Measurement in Glasgow

4. ELiTES

Blade spring : Strength test (Glasgow)

S. Barclay and G. Hammond's poster (d-4, Thu)

Bonding

Marielle van Veggel's talk (Monday afternoon)

Hydroxide Catalysis Bonding (Glasgow)

B. Douglas and Marielle van Veggel' poster (d-3, Thu)

Indium (Jena, Glasgow)

5. Summary

Outlines of KAGRA thermal noise (sapphire suspension) were discussed.

Cryogenic technique reduces thermal noise.

Open issues

(1) Coating mechanical loss
Collaboration (Tokyo-Glasgow) is in active.

(2) Measurement of bonding mechanical loss
We have plans in near future (Jena, Glasgow).

(3) Measurement for sapphire blade spring

(4) Precise calculation

5. Summary

ELiTES supports our investigation.

Vivid and latest updates are reported by younger people later.

R. Kumar’s talk on Wednesday afternoon

A. Khalaidovski’s and D. Chen’s talk

on Tuesday morning, D. Chen’s poster e-1(Thu)

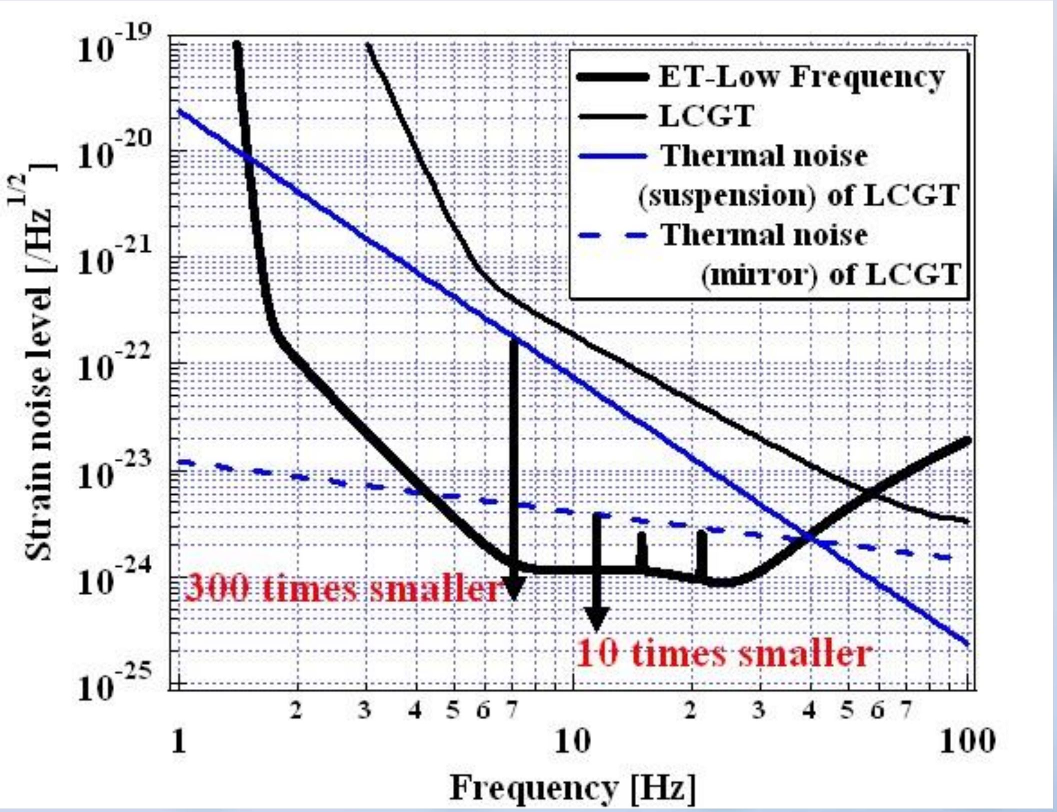
Thank you for your attention !

5. Einstein Telescope

(a) Thermal noise

Mirror thermal noise : 10 times smaller

Suspension thermal noise : 300 times smaller



S. Hild *et al*., Classical and Quantum Gravity 28 (2011) 094013.

R. Nawrodt *et al*., General Relativity and Gravitation 43 (2011) 363.

5. Einstein Telescope

(a) Thermal noise

Mirror thermal noise : 10 times smaller

3 times longer arm (10 km)

3 times larger beam radius (9cm)

Suspension thermal noise : 300 times smaller

3 times longer arm (10 km)

7 times heavier mirror (200 kg)

5 times longer suspension wire (2 m)

100 times smaller dissipation in wires ($Q=10^9$)

4. Challenges for cryogenic

1. Issues of cooling : Reduction of heat load (Absorption in mirror)

In order to keep mirror temperature …
Absorption in mirror : less than 1 W

Coating : 0.4 W (1 ppm)
Substrate : 0.6 W (50 ppm/cm)

Our target of substrate : 20 ppm/cm

Sensitivity of KAGRA

Thermal noise

Assumption (1) : Upper ends of fibers are fixed rigidly.

Resonant frequencies (except for violin modes) are different from the actual system. However, the thermal noise above the resonant frequency is the same.

Assumption (2):

Number of fiber : 4
Fiber length : 0.3 m
Fiber diameter : 0.16 mm
Q-values of sapphire fibers : $5*10^6$

Horizontal motion along optical axis

Pendulum and violin modes

Loss dilution by tension (gravity) must be taken into account.

Sensitivity of KAGRA

Thermal noise

Vertical motion

Gradient of interferometer baseline is 1/300.
Q-values of stretch is assumed to be $5*10^6$.

Pitch motion

Distance between the optical axis and center of gravity of mirror is 1 mm.
Q-values of stretch is assumed to be $5*10^6$.

Yaw motion

Distance between the optical axis and center of gravity of mirror is 1 mm.
Q-values of shear is assumed to be $5*10^6$.
Loss dilution by tension (gravity) must be taken into account.

3. Expected thermal noise

Horizontal and vertical motion

Four sapphire fibers should transfer 1 W heat.

Between 100 Hz and 250 Hz, there are 1st violin mode and vertical mode.

Room temperature interferometer : 1st violin > 300 Hz

vertical mode ~ 10 Hz

Thick fiber to transfer heat !

Thicker fiber : Lager thermal noise (pendulum mode)

Longer fiber : Lower violin mode, lower vertical mode

-> Smaller heat transfer

Shorter fiber : Higher violin mode, higher vertical mode

-> Fiber should be longer than mirror radius.

Known methods of bonding

	Precise polish	Interposition material	Temperature treatment	Sapphire-Sapphire	Thermal conductance	Mechanical loss
AFB, Diffusion	Necessary	none	1300~1400 °C	~~Almost same as bulk~~ ~ 28 MPa	~ 4 W/K/mm^2	Not yet measured
Direct(1), SAB1 (~ 2000)	Necessary	None (Ar$^+$ beam)	300 K	-	-	-
Direct(1), SAB2 (2011)	Necessary	Fe, etc (Ar$^+$ beam)	300 K	Not yet measured	Not yet measured	Not yet measured
Hyroxy-catalysis, silicate	Necessary	KOH, Na_2SiO_3, H_2O	300 K	~ 7 MPa	~ 0.3 W/K/mm^2	Not yet measured
Metalize, soldering	(Not required)	Active metal	< 1000 °C?	~~Not yet measured~~ 50MPa	Not yet measured	Not yet measured
Adhesive	Not required	Al_2O_3, $AlPO_4$, H_2O	~ 500 °C	~20 MPa	Not yet measured	Not yet measured

AFB: Adhesion Free Bonding
SAB: Furface activation Bonding

20MPa
(Ultrasonic soldering)

3. Expected thermal noise

Horizontal and vertical motion

In principle, KAGRA sensitivity is not limited by thermal noise.

However, between 100 Hz and 250 Hz (best sensitivity frequency region), there are peaks of 1st violin mode and vertical mode.
Ratio of frequency of 1st violin mode to that of pendulum mode is smaller than that of room temperature interferometer.

Room temperature interferometer :

1st violin > 300 Hz, vertical mode ~ 10 Hz

Thick fiber to transfer heat !

Note : These peaks make Signal to Noise Ratio of matched filter for neutrons star coalescence about 0.95 times smaller (K. Yamamoto).

Can we push thermal noise peaks away ? (K. Somiya)

3. Expected thermal noise

Pitch and yaw rotation

In principle, KAGRA sensitivity is not limited by thermal noise.

Around 20 Hz, there is peak of pitch mode.
Room temperature interferometer : pitch mode ~ 3 Hz

Thick fiber to transfer heat !

Pitch mode frequency depends on distance between fibers (*d*).

This distance must be as small as possible (15 mm~30 mm).

Note : If this mode is lower than 30 Hz, the effect on Signal to Noise Ratio of matched filter for neutrons star coalescence is small (H. Yuzurihara).

3. Suspension

Diameter of fiber :

Bending length is proportional to square of fiber diameter.

Bending length is about 50 mm

(1.6mm diameter fiber)

Mirror radius : 110 mm

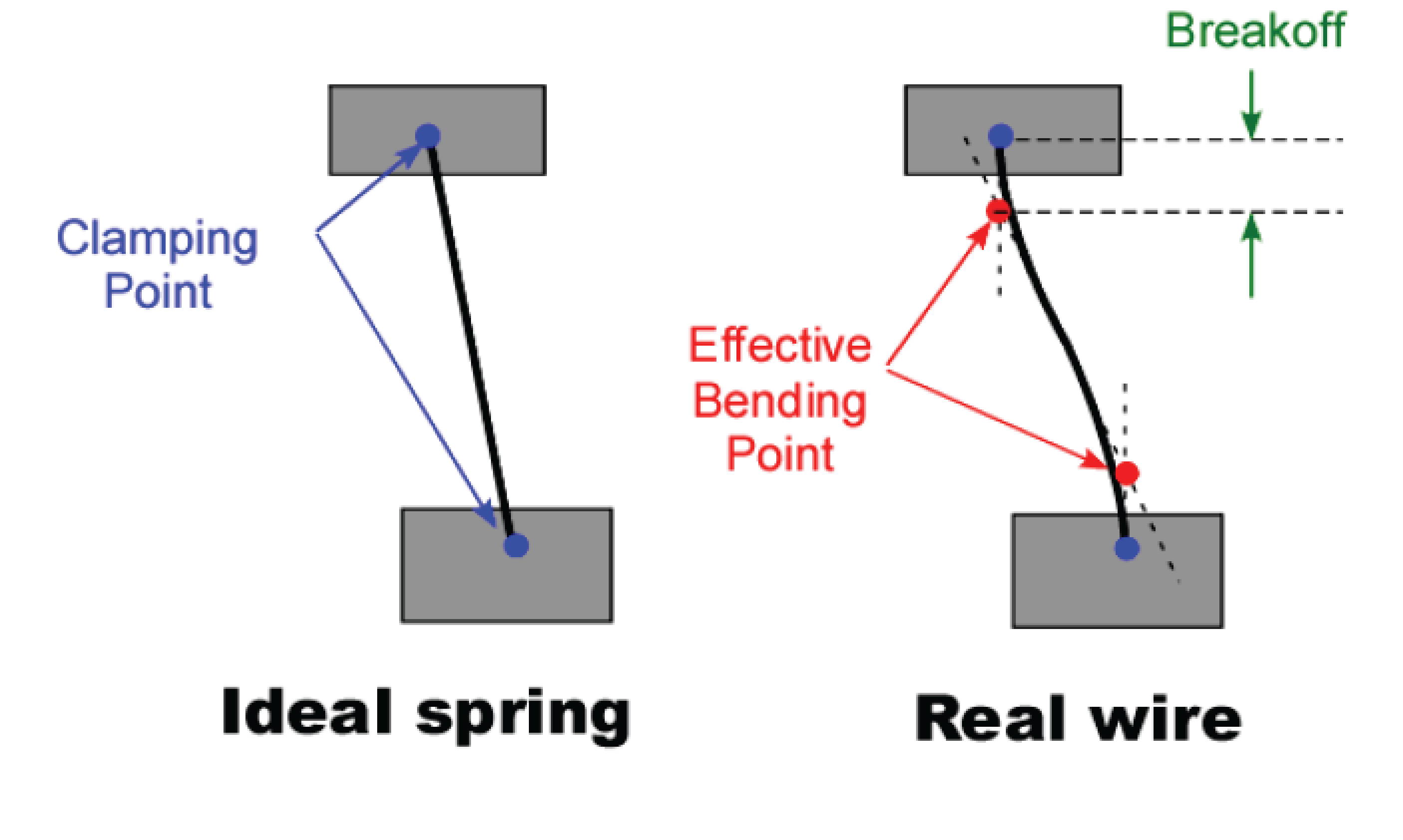
Fiber diameter is smaller than about 2.2 mm.

3. Suspension

Diameter of fiber :

Bending length

T. Sekiguchi, Master thesis (2012)
http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/private/DocDB/ShowDocument?docid=770



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