Design and expected thermal noise of the KAGRA sapphire suspensions

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Contribution

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KAGRA collaboration

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Sannio Univ.[G], INFN[H], Louisiana State Univ.[I] , University of Glasgow[J],
Friedrich-Schiller-Universitaet Jena[K], OCU[L], KAGRA collaboration

0. Abstract

I will explain

(1)How to design sapphire suspension
(2)Expected thermal noise
(3)Recent experimental results

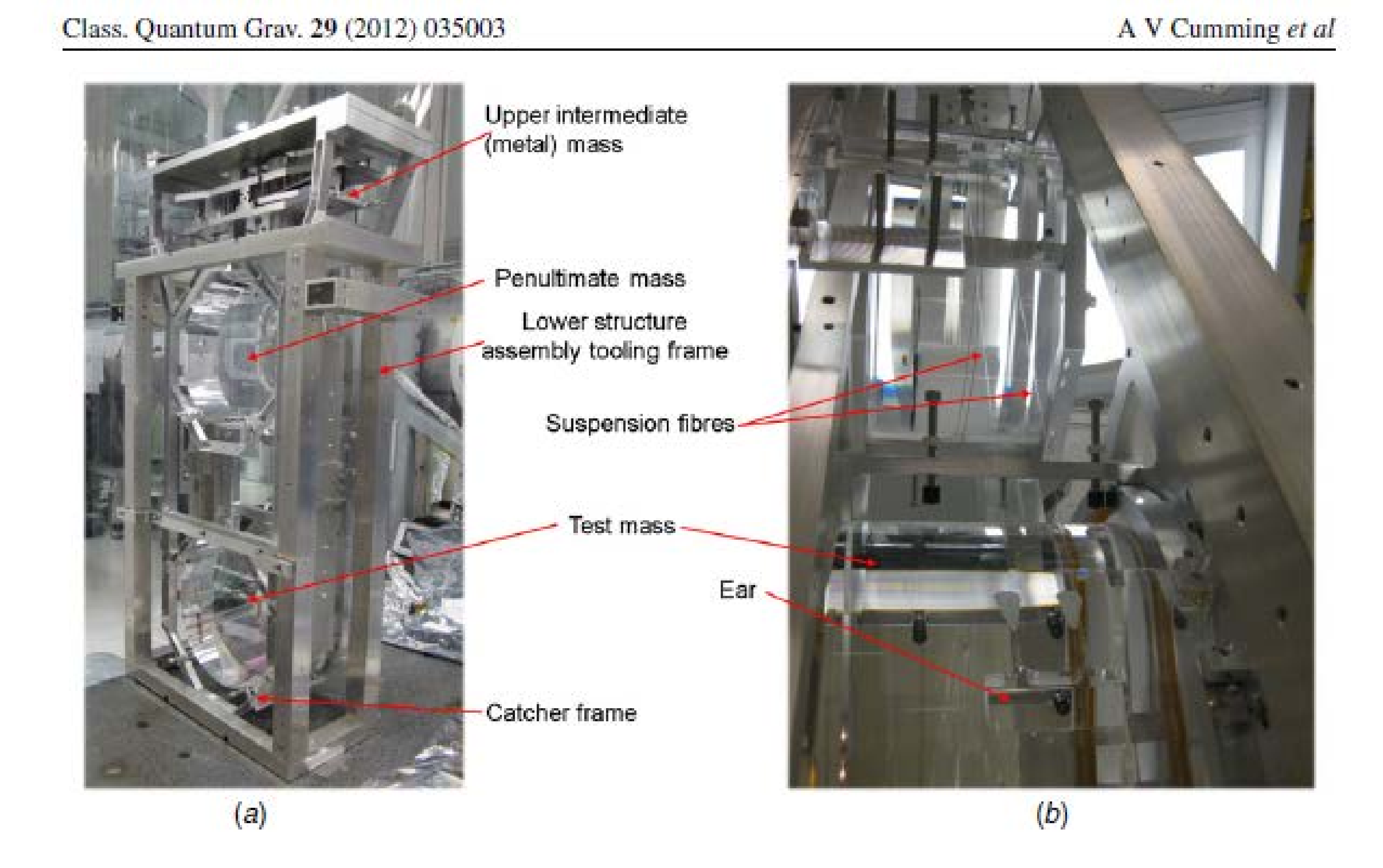
for KAGRA.

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.

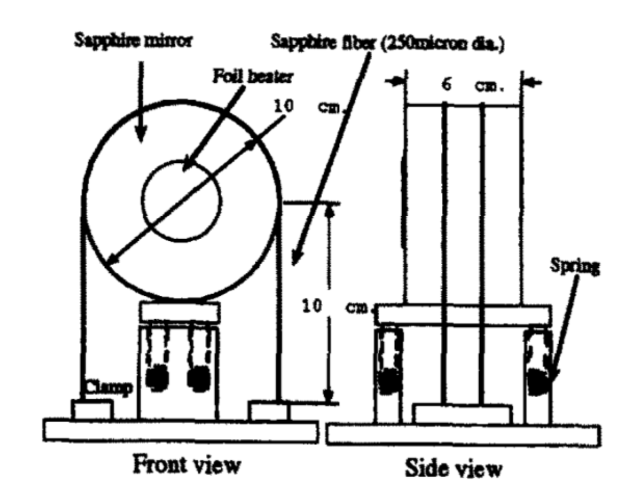


Fig. 1. The experimental setup.

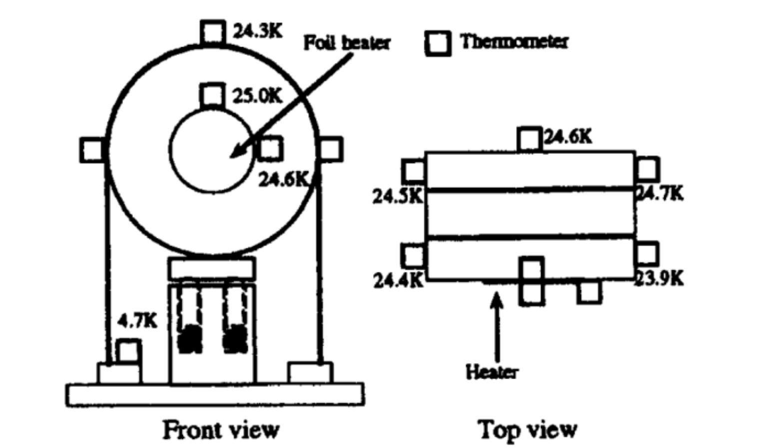


Fig. 3. Distribution of the equilibrium temperature in the case of 29 mW heat power.

Sapphire fiber : High Q-values

and large thermal conductivity

2. Design

Strength

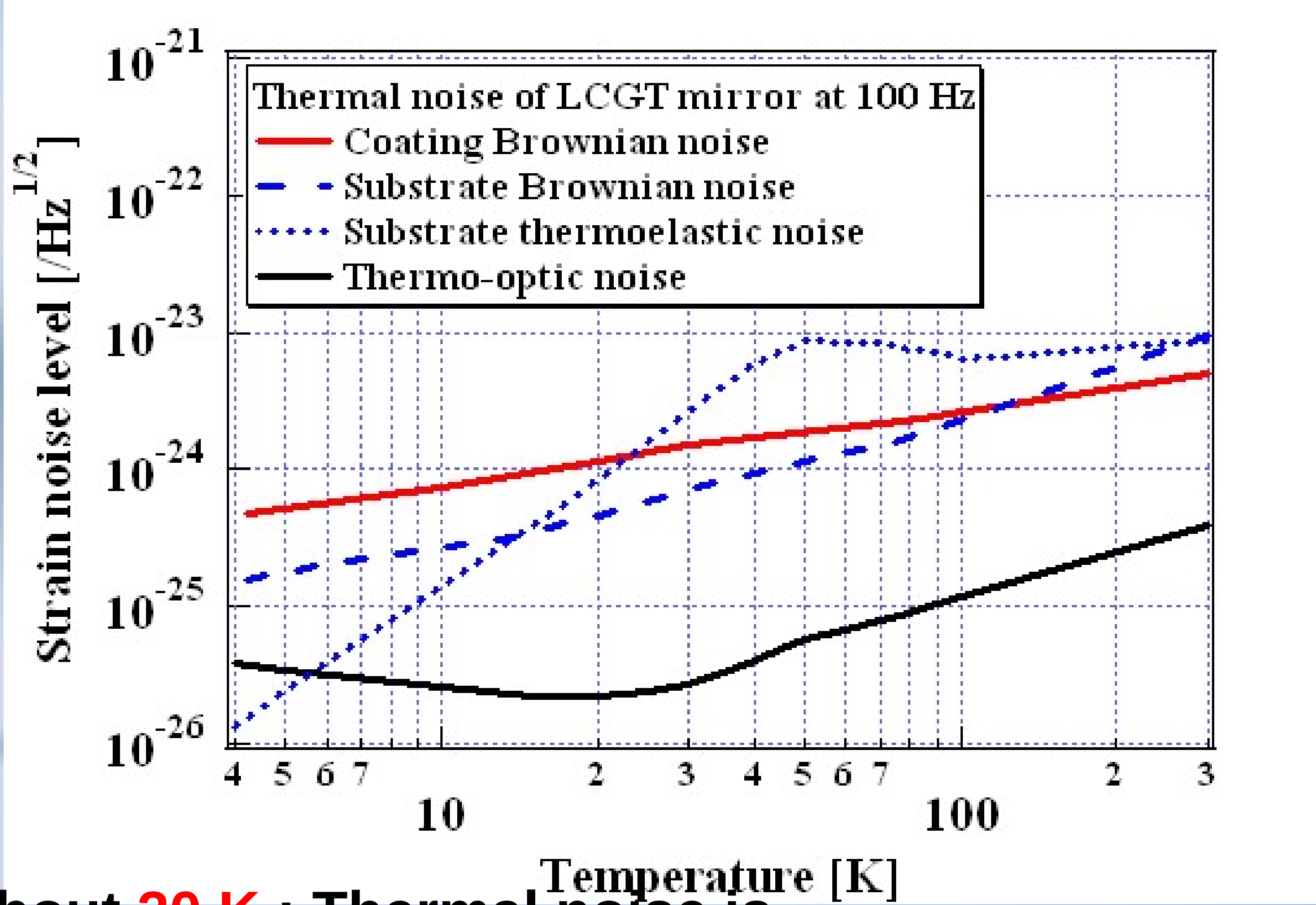
Sapphire fibers should support the weight of sapphire mirror.

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

Fiber diameter must be larger than 1.1 mm.

2. Design

Temperature of KAGRA mirror



Below about **20 K** **: Thermal noise is**

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

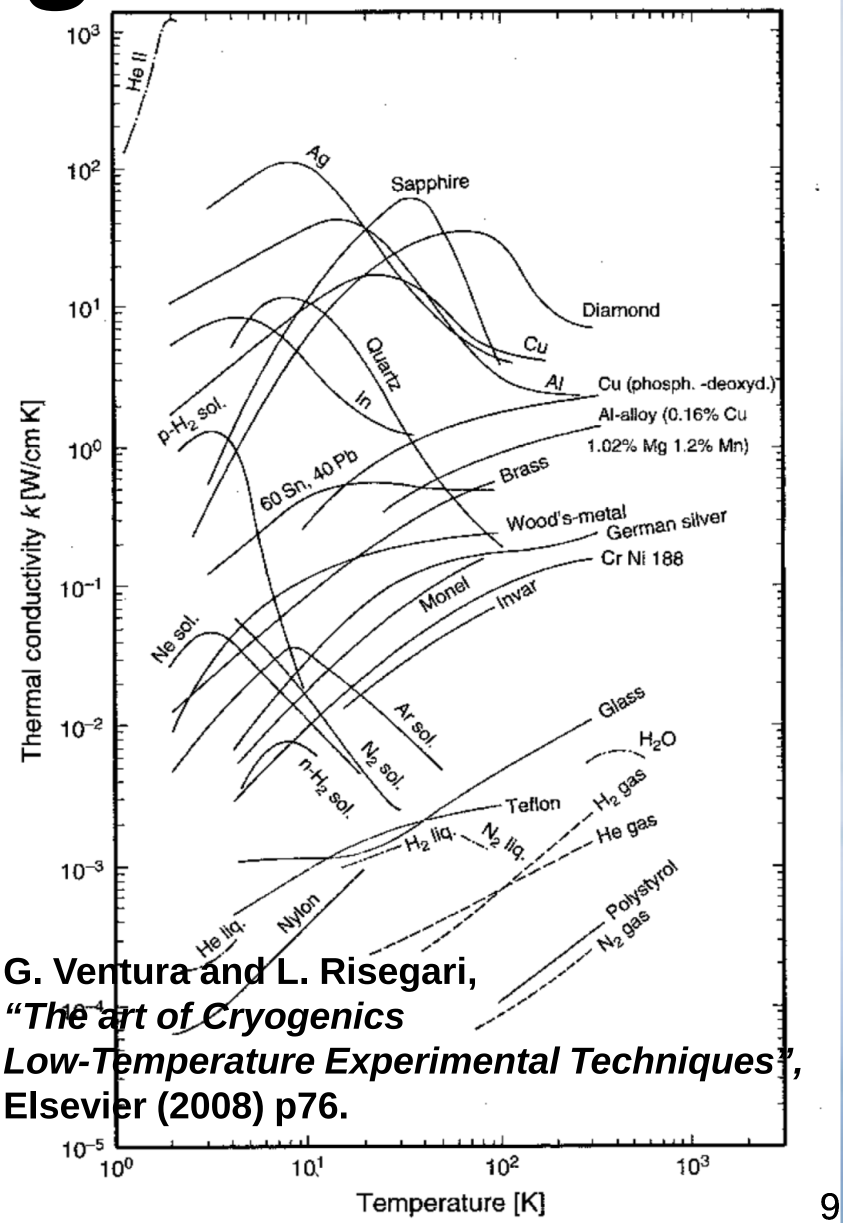
2. Design

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.**

2. Design

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.

3. Expected thermal noise

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. Expected thermal noise

Design

Number of fiber : 4
Fiber length : 0.3 m
Fiber diameter : 1.6 mm
Q-values of sapphire fibers : $5*10^6$

3. Expected thermal noise

Degrees of freedom

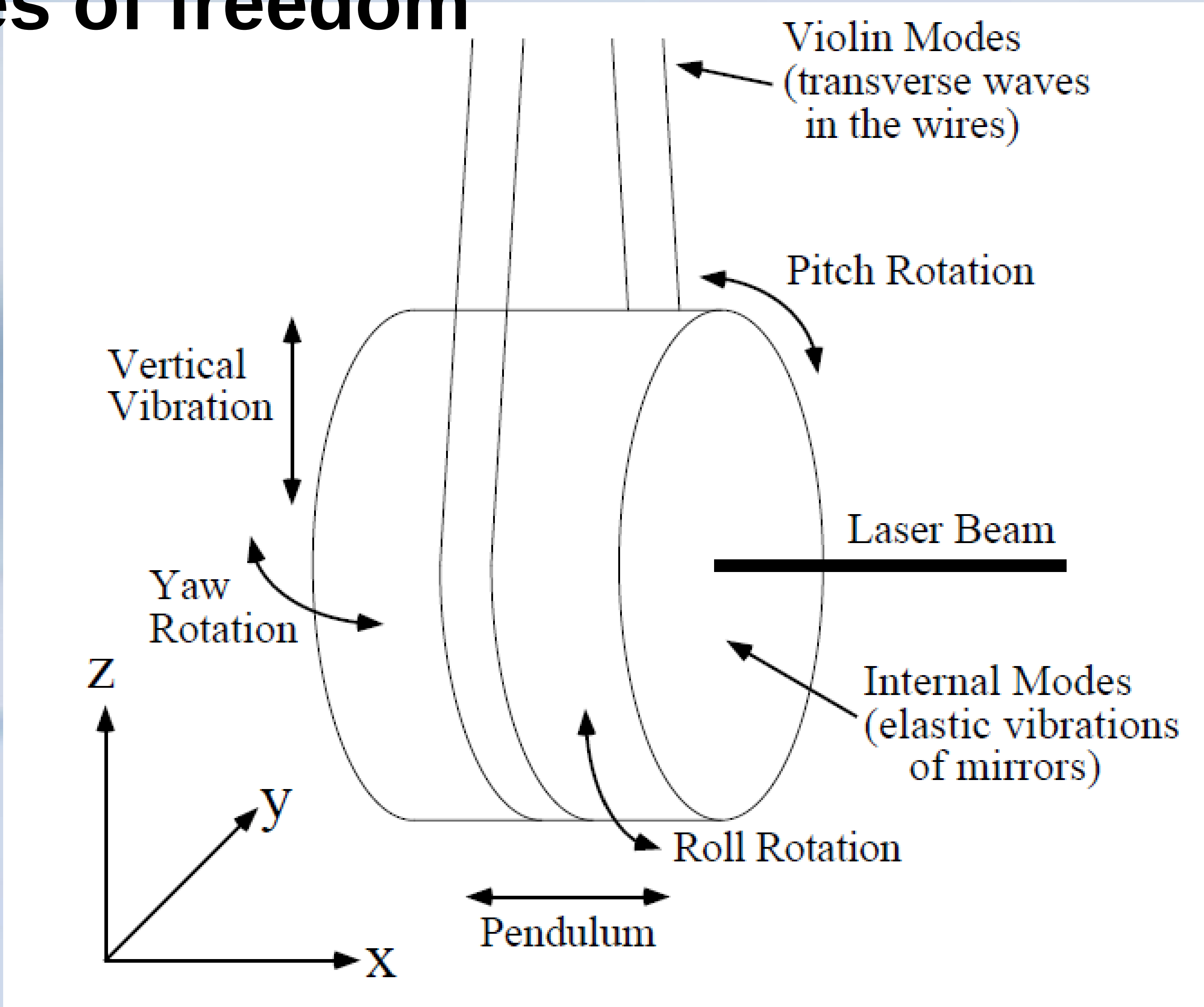
Horizontal motion along optical axis
Pendulum and violin modes

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. Expected thermal noise

Degrees of freedom



3. Expected thermal noise

Resonant frequencies and Q-values

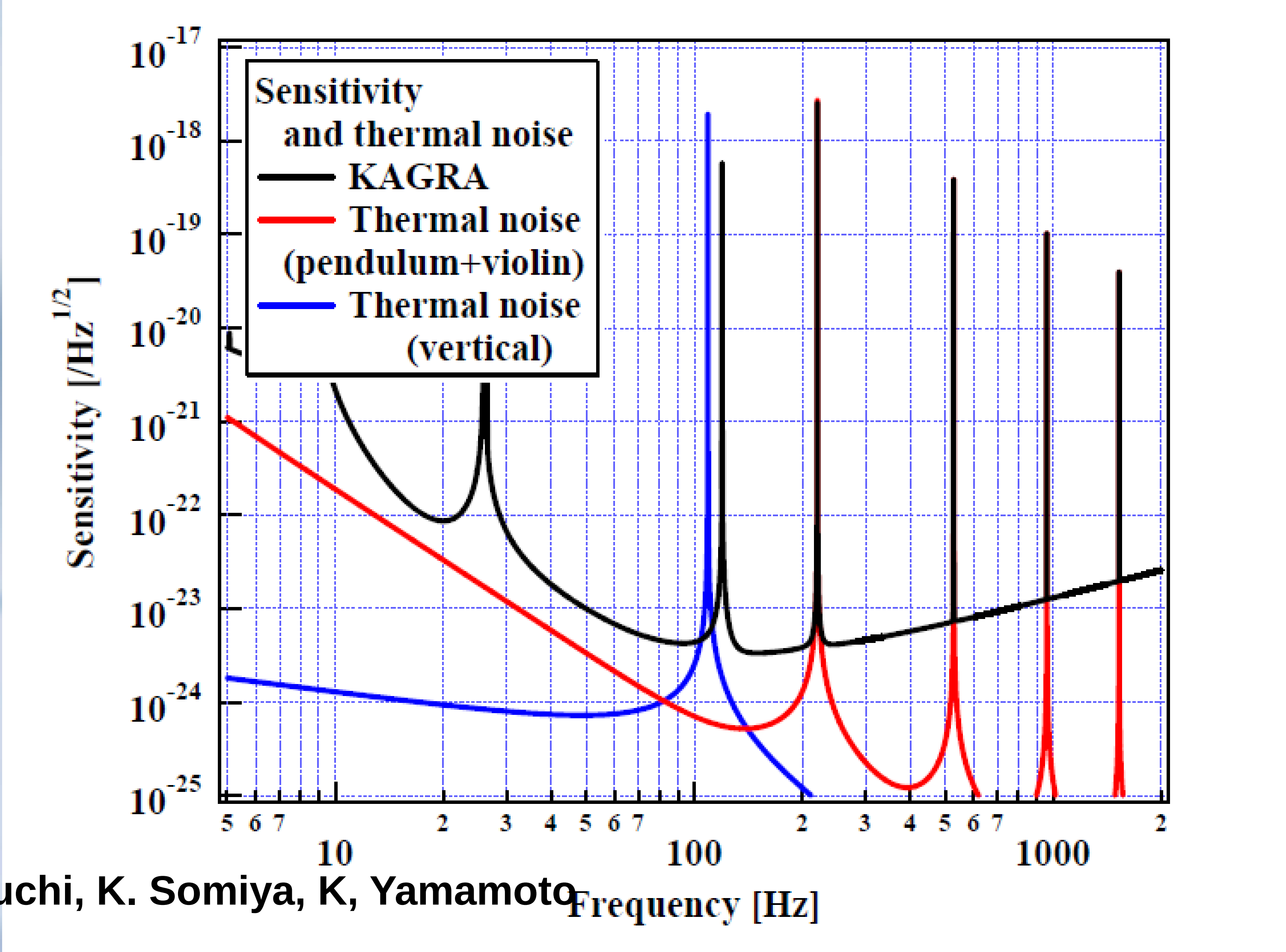
T. Sekiguchi, K. Somiya, K, Yamamoto

	Resonant frequencies	Q-values
Pendulum	1.1 Hz	$2*10^7$
1st violin	220 Hz	$1.0*10^7$
Vertical	109 Hz	$5*10^6$
Pitch	23.4 Hz	$5*10^6$
Yaw	1.8 Hz	$1.3*10^7$

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. Expected thermal noise

Horizontal and vertical motion



T. Sekiguchi, K. Somiya, K, Yamamoto

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.

Room temperature interferometer :

1st violin > 300 Hz, vertical mode ~ 20 Hz

Thick fiber to transfer heat !

Note : Peak of vertical mode makes Signal to Noise Ratio of matched filter for neutrons star coalescence about 0.95 times smaller (K. Yamamoto).
1st violin mode effect is smaller (H. Yuzurihara).

Can we change peak frequencies ? (K. Somiya)

3. Expected thermal noise

Horizontal and vertical motion

Boundary condition

Four sapphire fibers should transfer 1 W heat.
When we adopt thinner fibers, they must be shorter.

In naive case:
Length (l) is proportional to square of radius (a).

In the case with excellent sapphire fibers:
Length (l) is proportional to cubic of radius (a).

Size effect : Thermal conductivity is proportional to fiber diameter. Mean free path of phonon is limited by fiber radius.

Conclusions in both cases are similar.

3. Expected thermal noise

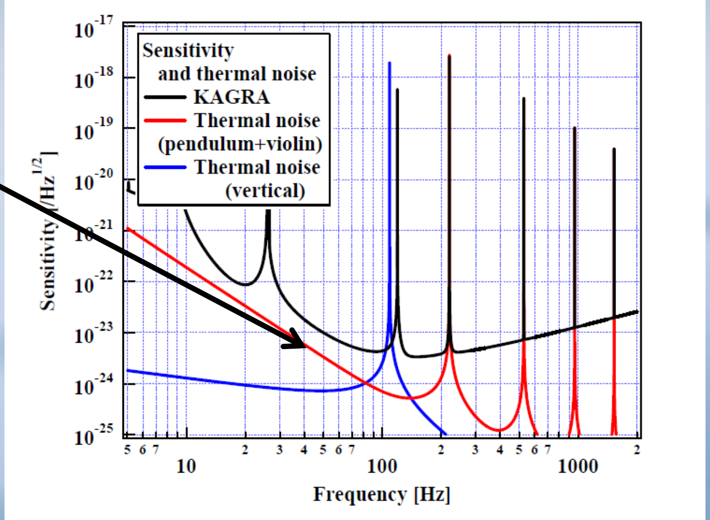
Horizontal and vertical motion

Violin mode

When we adopt too thick and long fibers, frequencies of violin modes are lower. Violin mode forest appear in best sensitivity frequency region (around 100 Hz).

When we adopt too thin and short fibers, thermal noise of pendulum mode is large in best sensitivity frequency region (around 100 Hz).

Our design is based on the optimum case.



3. Expected thermal noise

Horizontal and vertical motion

Vertical mode

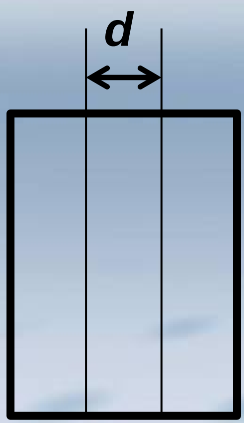
When we adopt thinner fibers, they must be shorter (because they must transfer heat).
We can not change vertical mode frequency so much.

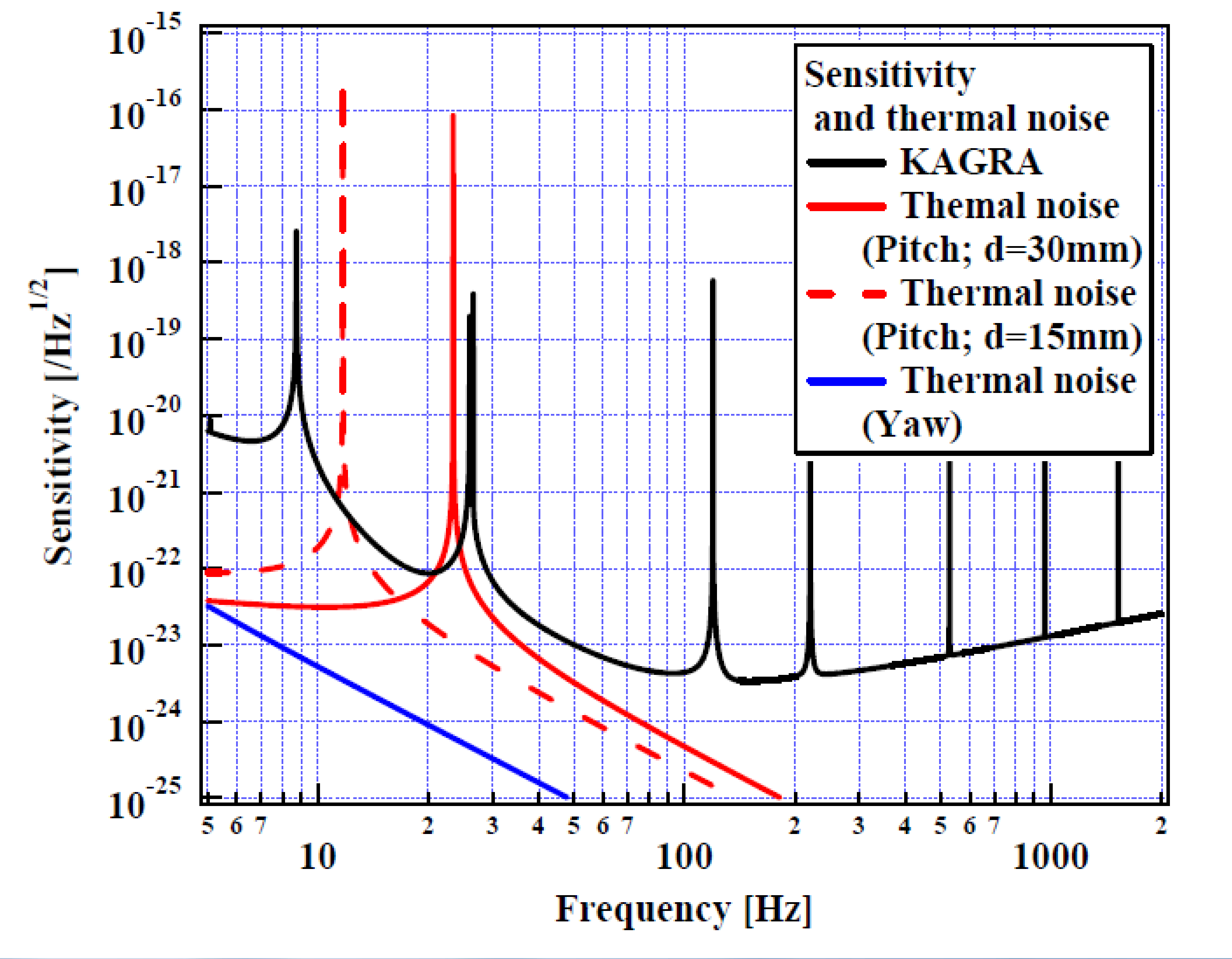
In naive case
Length (l) is proportional to square of radius (a).
Frequency of vertical mode never changes.

In the case with excellent sapphire fibers:
Length (l) is proportional to cubic of radius (a).
Frequency of vertical mode is inversely proportional to $l^{1/6}$.

3. Expected thermal noise

Pitch and yaw rotation





K, Yamamoto

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*).

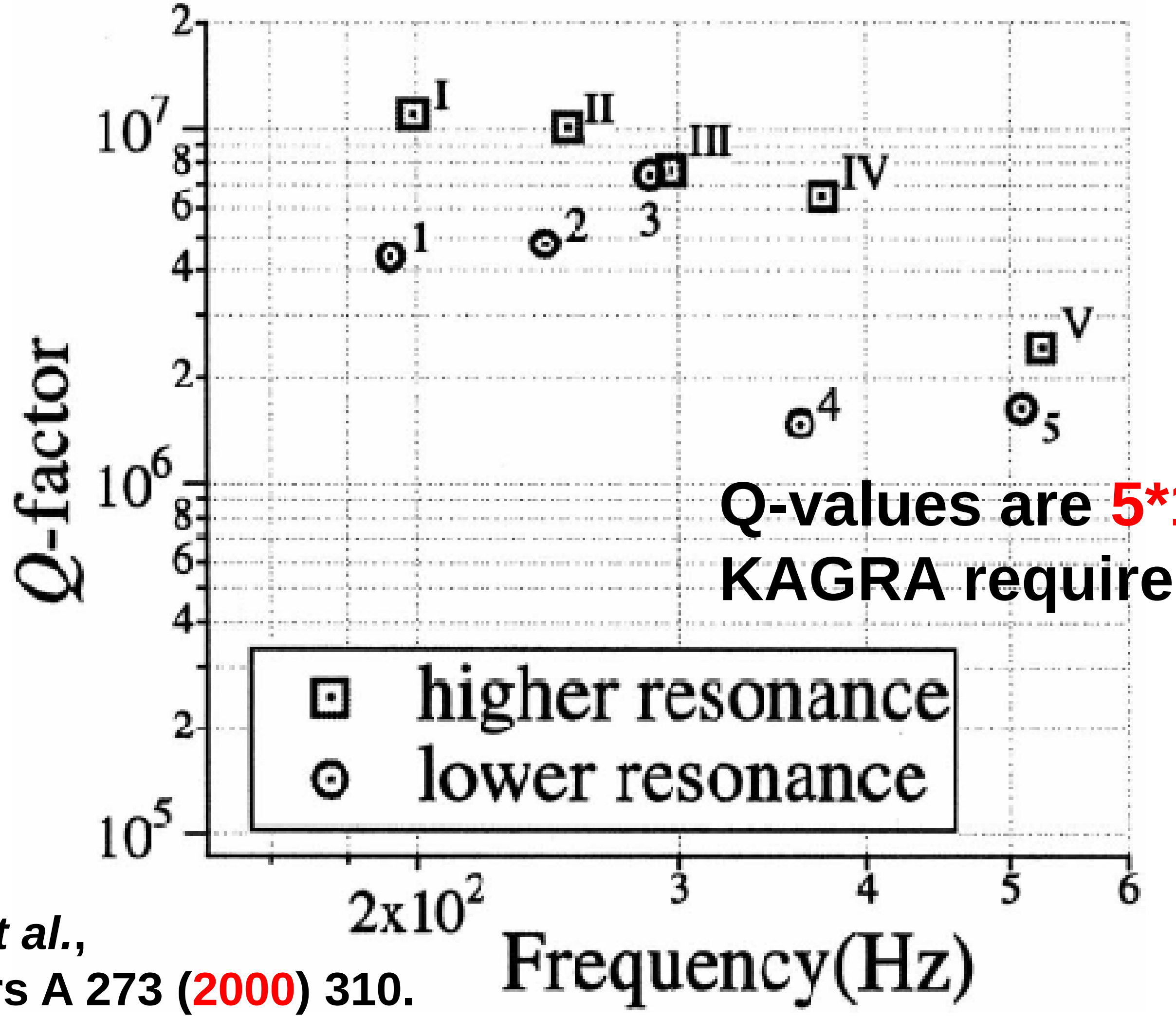
This distance must be as small as possible (15 mm~30 mm).

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).

4. Recent experiments

Our old measurement : Q-values (0.25 mm in diameter)

KAGRA fiber : 1.6 mm in diameter



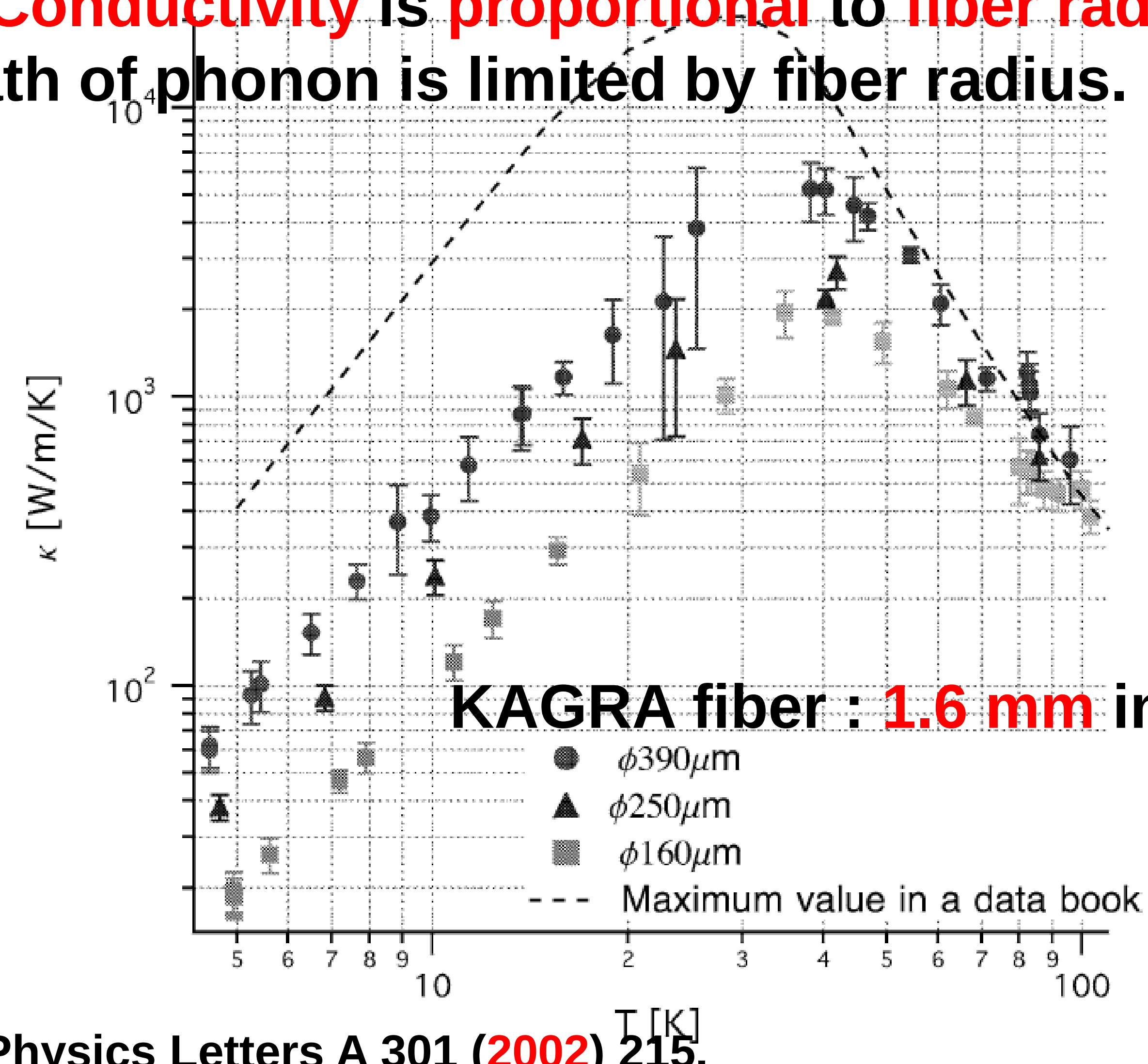
Q-values are $5*10^6$.
KAGRA requirement

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

4. Recent experiments

Our old measurement : Thermal conductivity

Size effect : Conductivity is proportional to fiber radius.
Mean free path of phonon is limited by fiber radius.



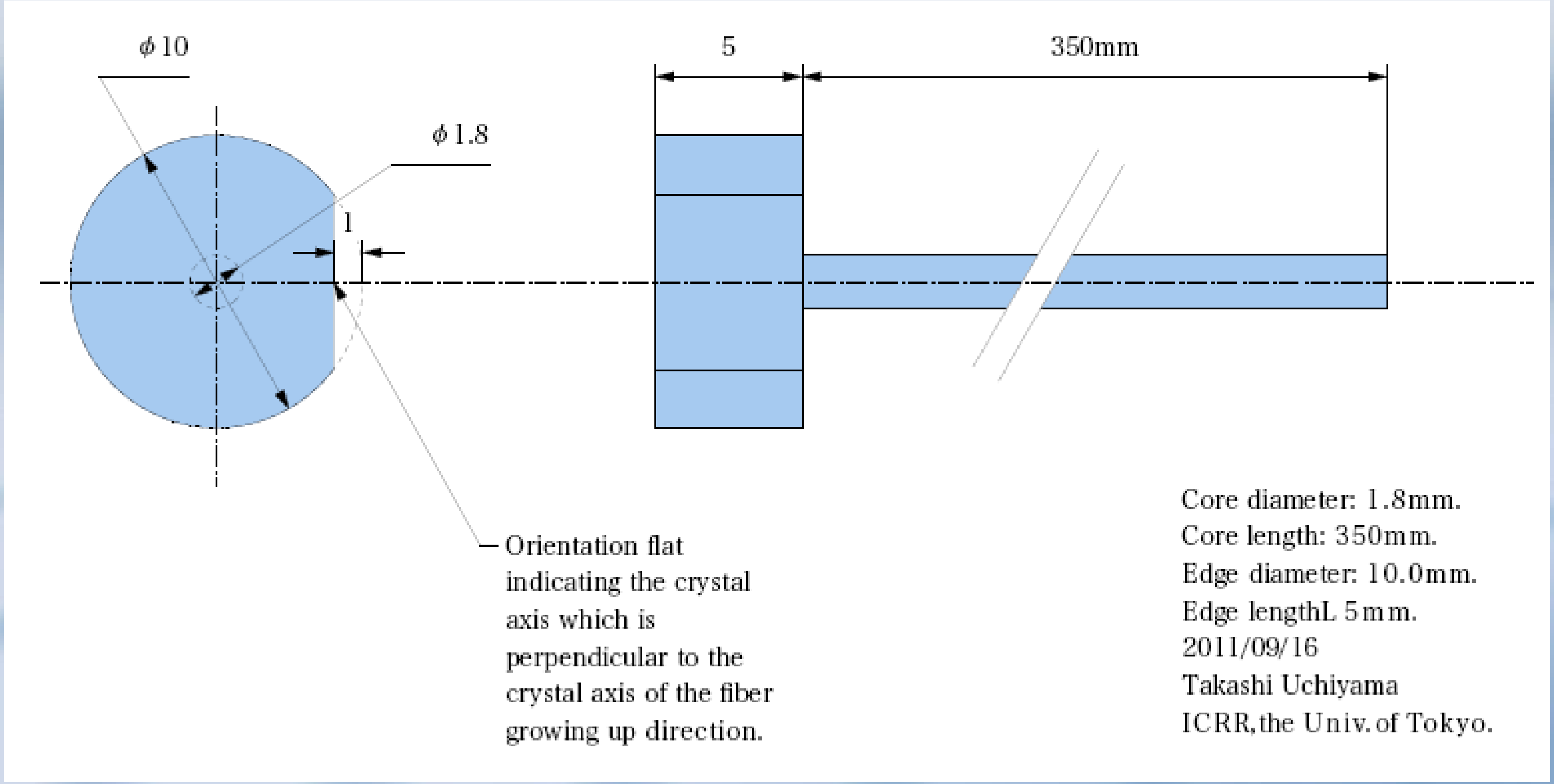
KAGRA fiber : 1.6 mm in diameter

T. Tomaru *et al.*, Physics Letters A 301 (2002) 215.

4. Recent experiments

Thick sapphire fibers (about 1.6 mm in diameter) with nail heads are necessary to suspend mirrors.

Test sample (T. Uchiyama)



4. Recent experiments

T. Uchiyama asked MolTech GmbH (Germany).
Sapphire fibers have already come !

Length = 350 mm diameter = 1.8 mm
Almost as needed in bKAGRA.
Need to check the quality and improvement .

4. Recent experiments

Ettore Majorana asked IMPEX HighTech GmbH (German company).

They made similar fibers (nail heads on the both ends).

100 mm in length

4. Recent experiments

Ettore Majorana asked IMPEX HighTech GmbH (German company).

They made similar fibers (nail heads on the both ends).

300 mm in length

Almost as needed in bKAGRA.
Need to check the quality and improvement .

4. Recent experiments

Quality check under collaboration with ET (ELiTES)

Q-value

Measurement in Glasgow and Jena

Plan for measurement in Rome and Tokyo

(Christian Schwarz and Gerd Hofmann's

visit Japan to export measurement system)

Christian presents a poster.

Thermal conductivity

Measurement in Jena

Plan for measurement in Rome and Tokyo

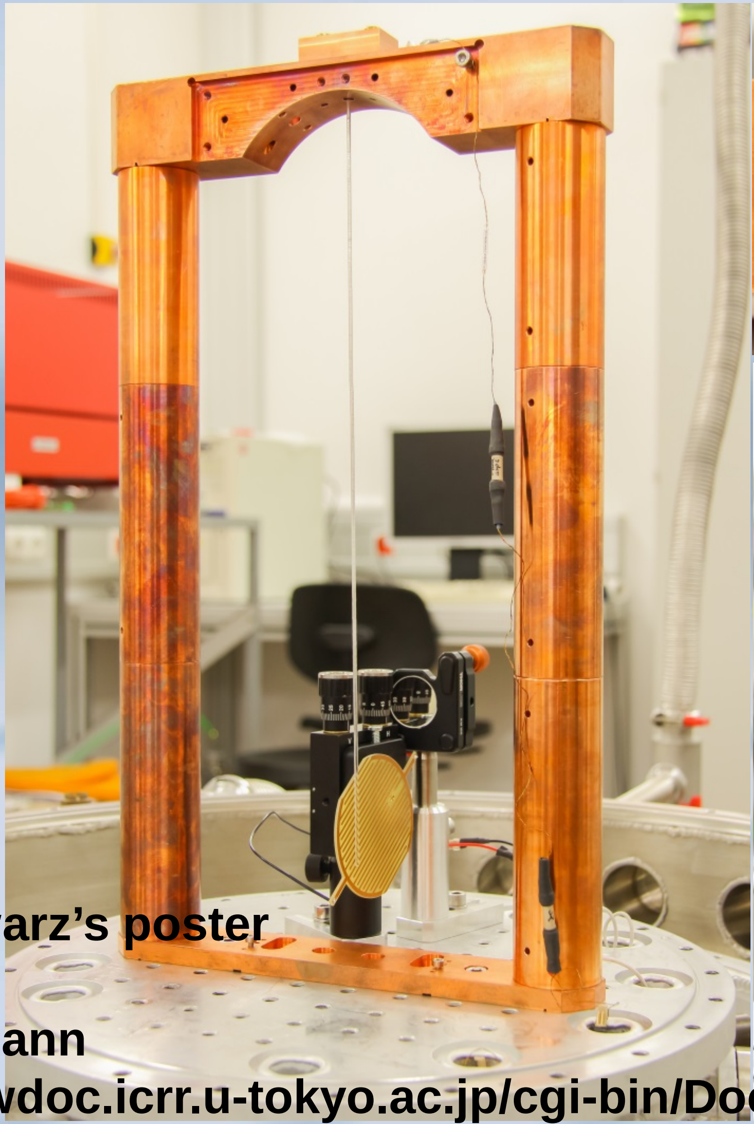
Christian presents a poster.

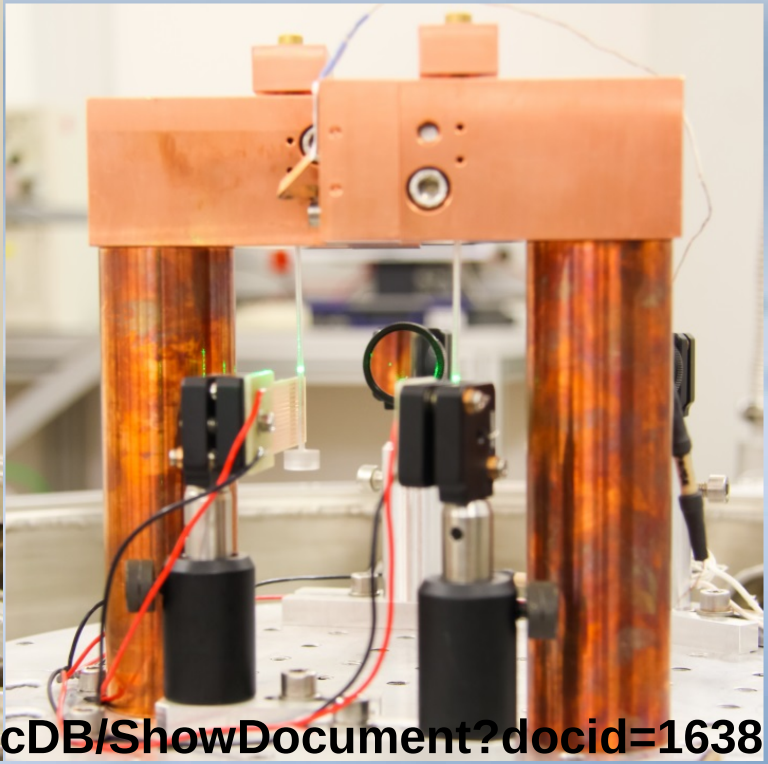
Strength

Discussion with Glasgow (Thanks for E. Hirose)

4. Recent experiments

Apparatus to measure Q-values in cryostat of Jena



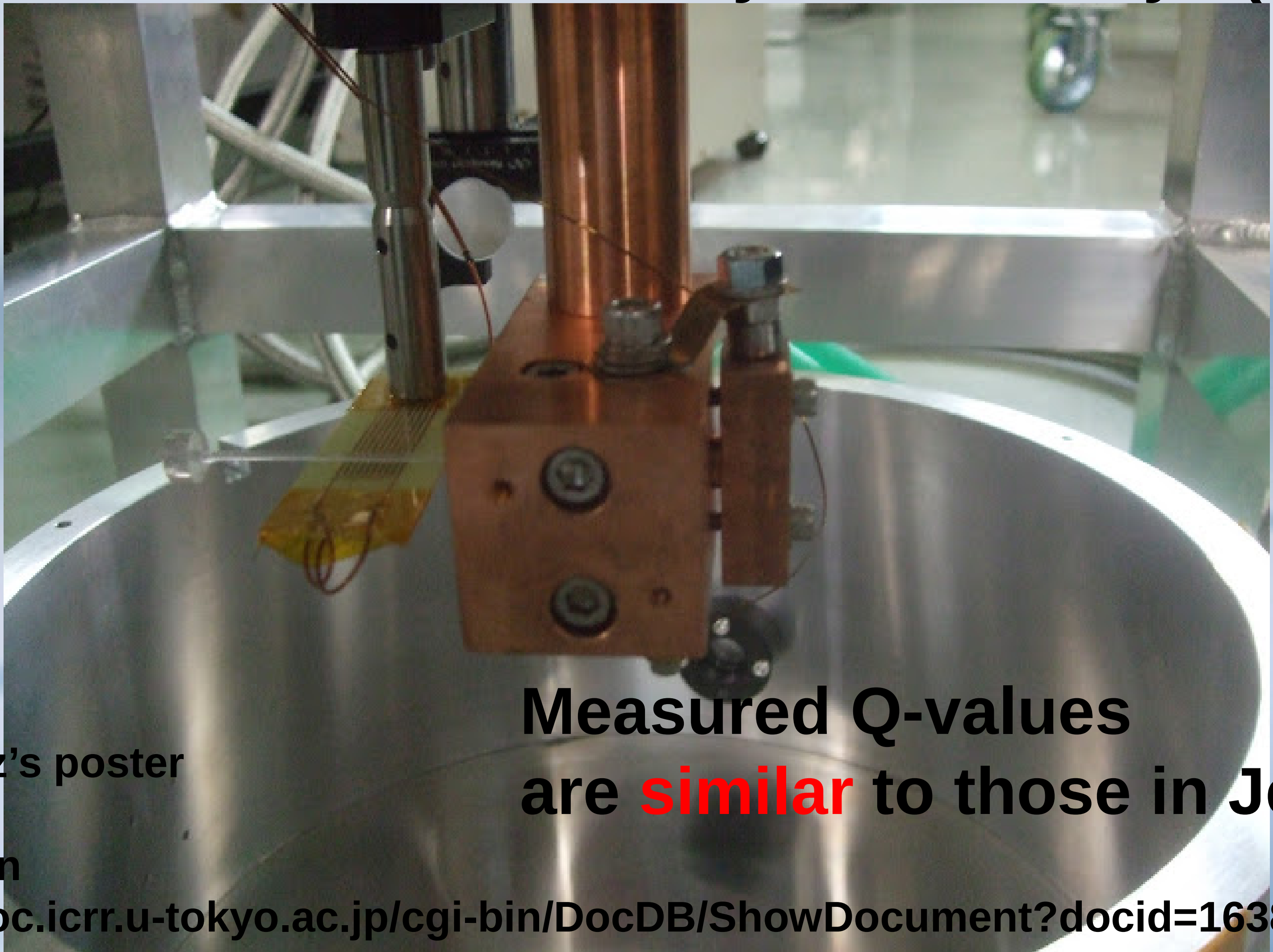


C. Schwarz's poster
or
G. Hofmann
http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=1638

4. Recent experiments

Apparatus to measure Q-values

in cryostat of Tokyo (ICRR)



Measured Q-values
are similar to those in Jena.

C. Schwarz's poster
or
G. Hofmann
http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=1638

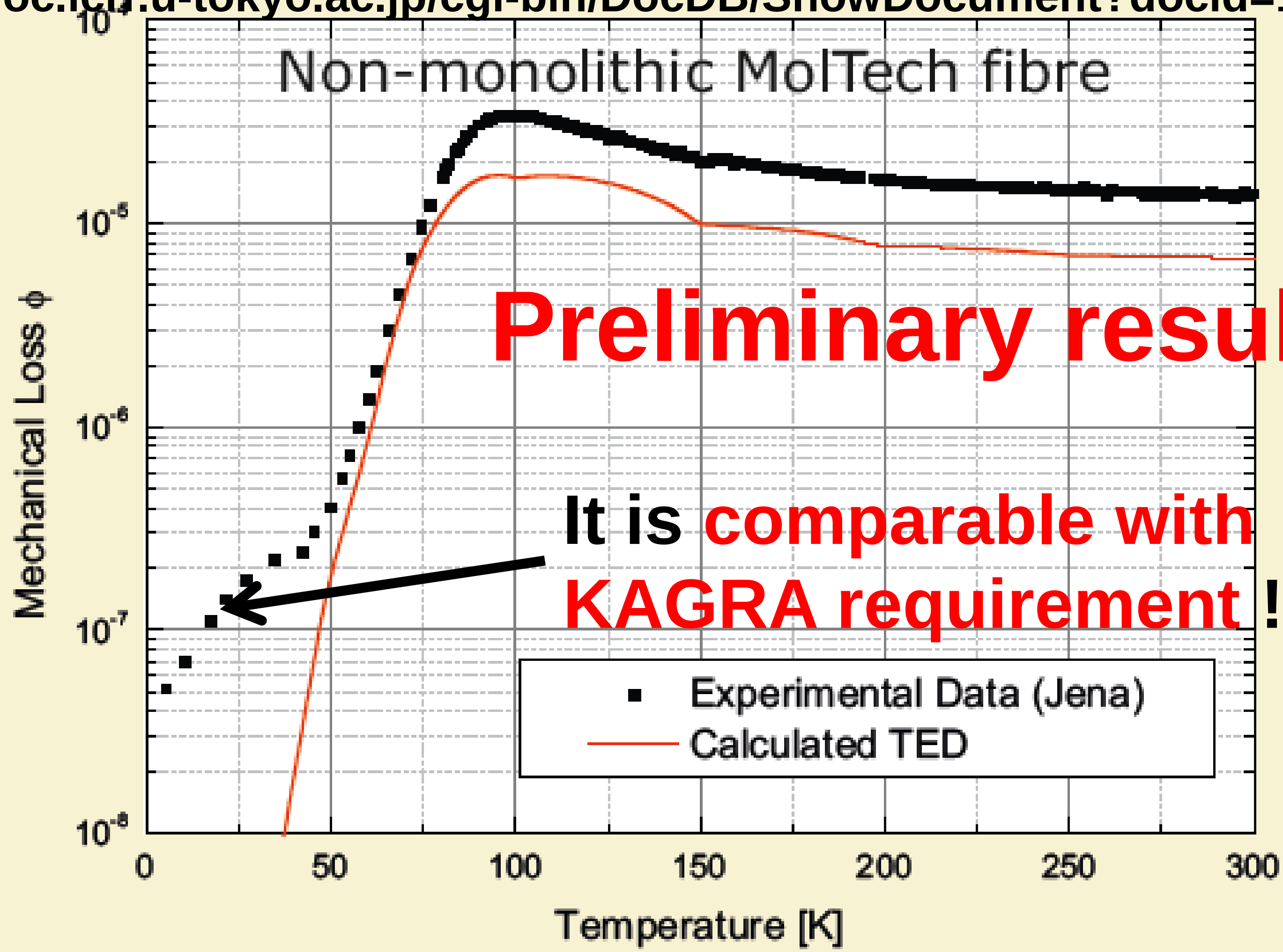
4. Recent experiments

Q measurement in Jena

Moltech

G. Hofmann

http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=1638



Preliminary result

It is comparable with KAGRA requirement !

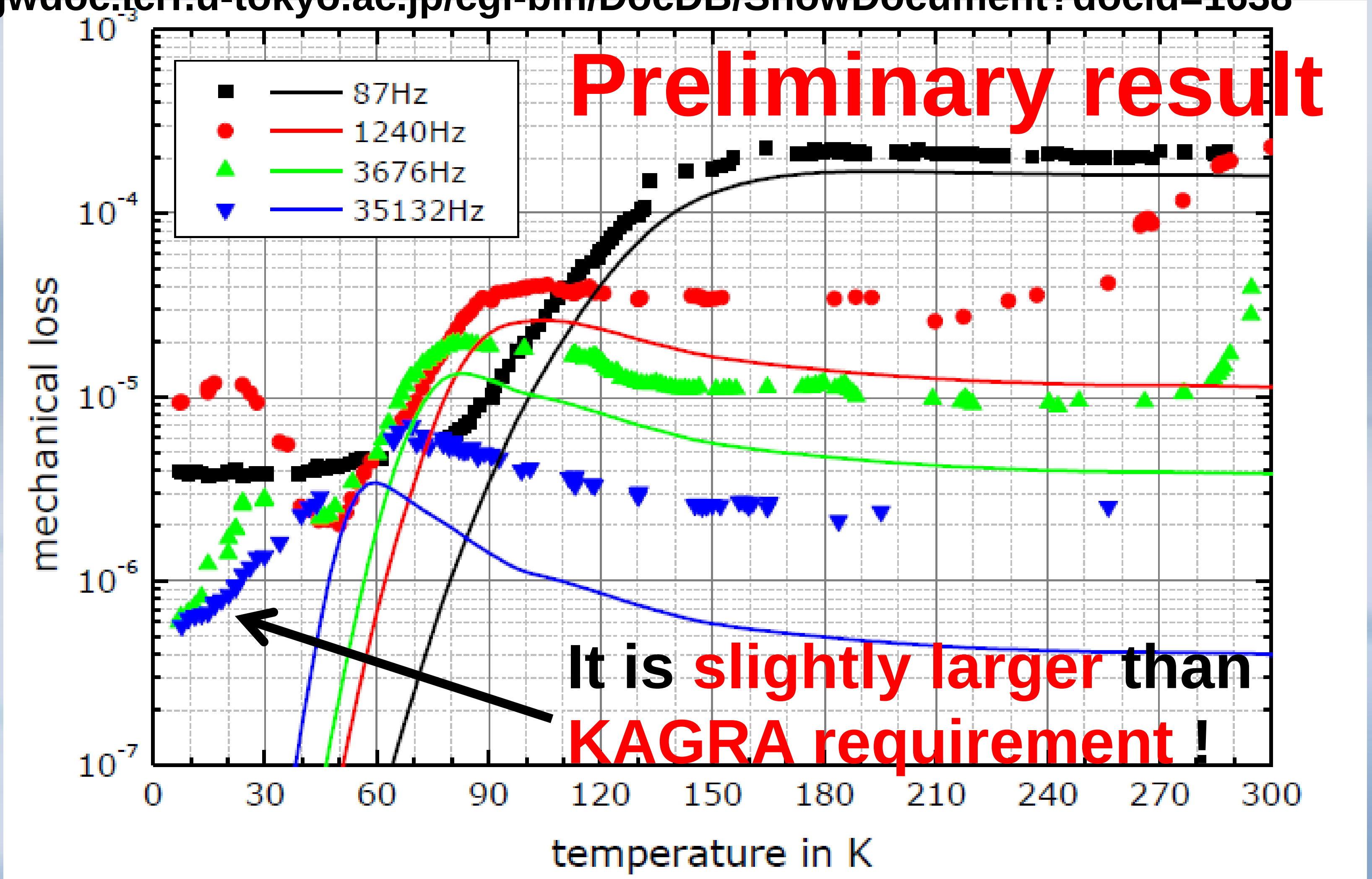
4. Recent experiments

Q measurement in Jena

C. Schwarz's poster or G. Hofmann

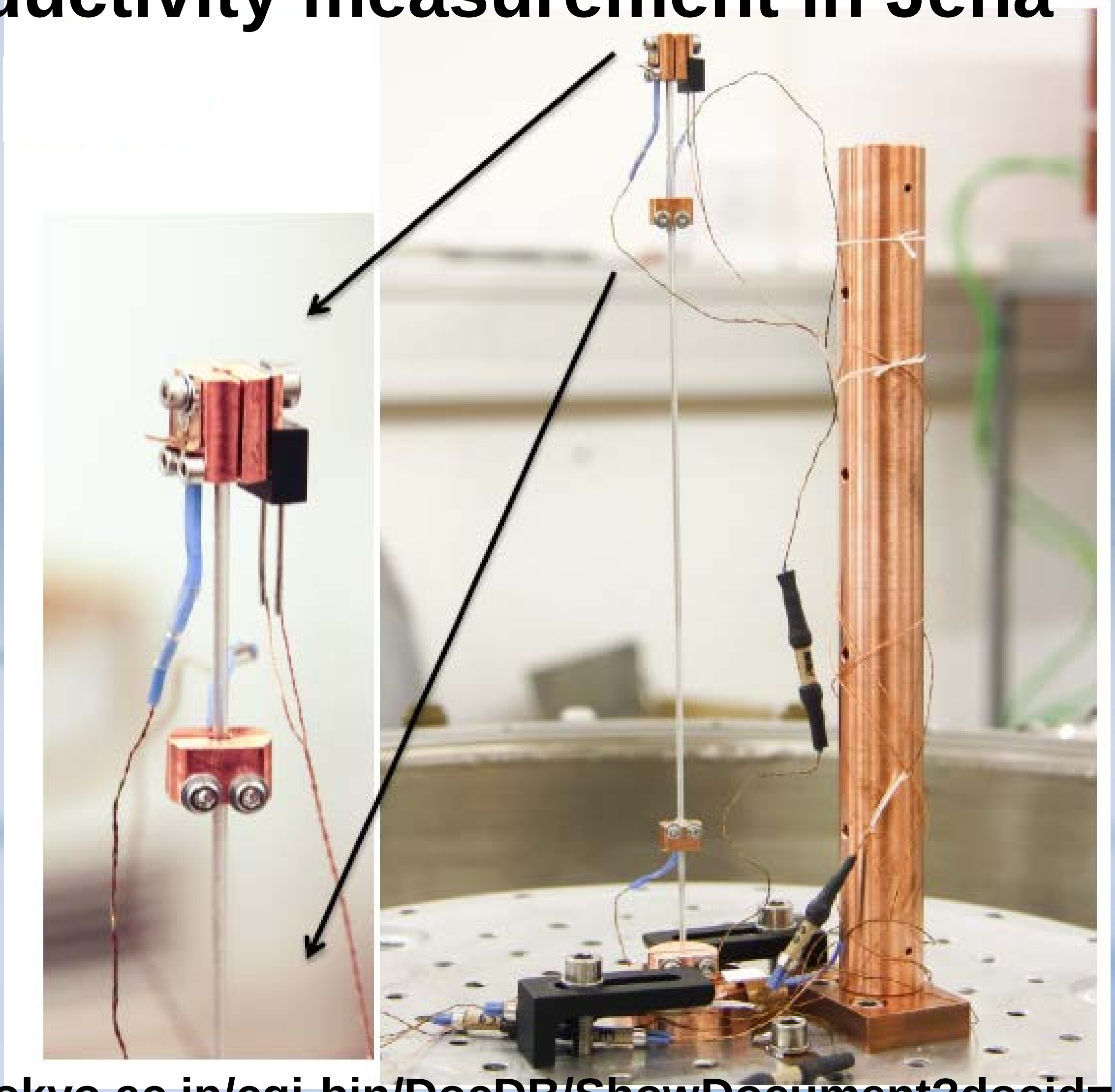
http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=1638

IMPEX



4. Recent experiments

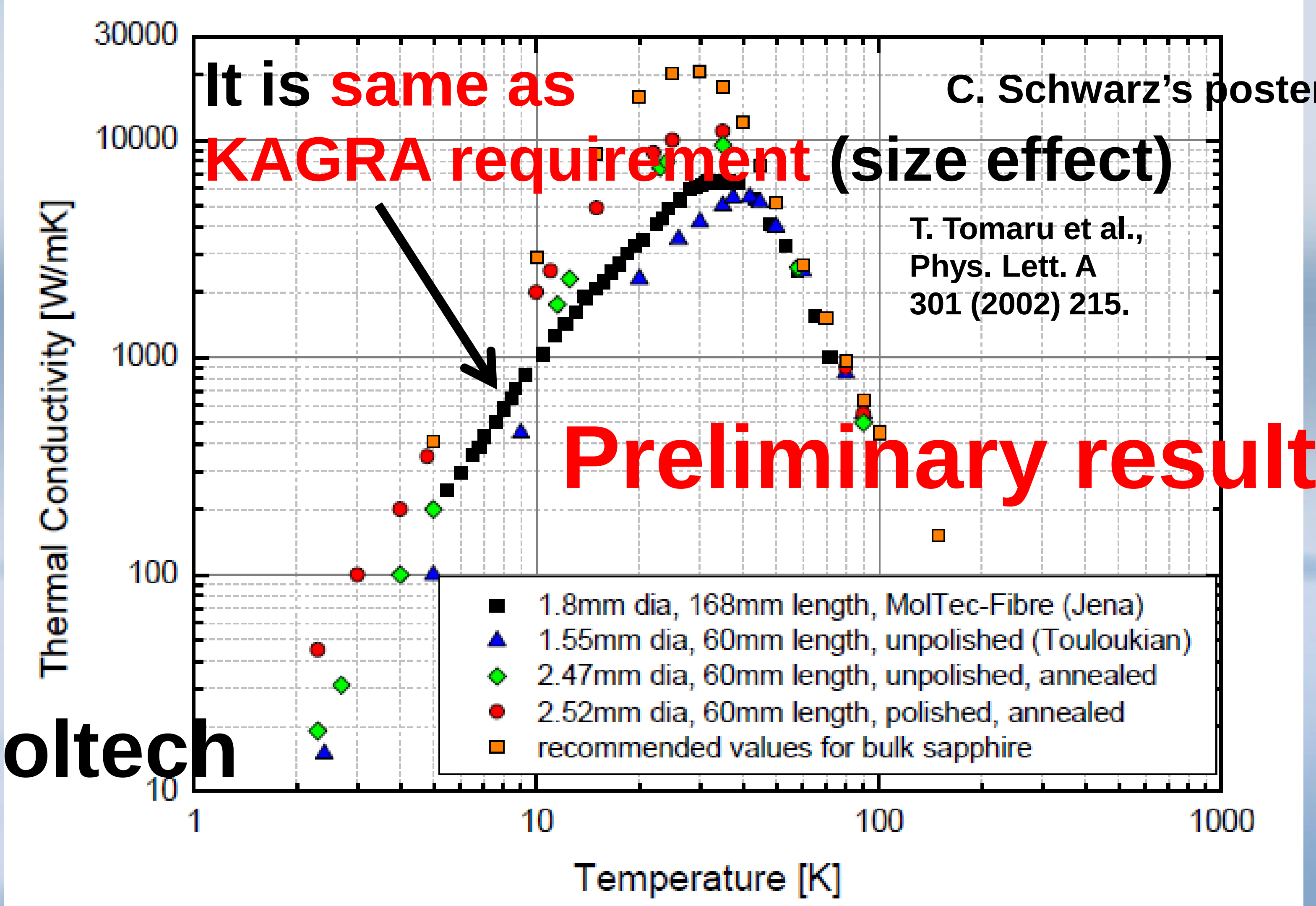
Thermal conductivity measurement in Jena



C. Schwarz's poster
or
G. Hofmann
http://gwdoc.icrr.u-tokyo.ac.jp/cgi-bin/DocDB/ShowDocument?docid=1638

4. Recent experiments

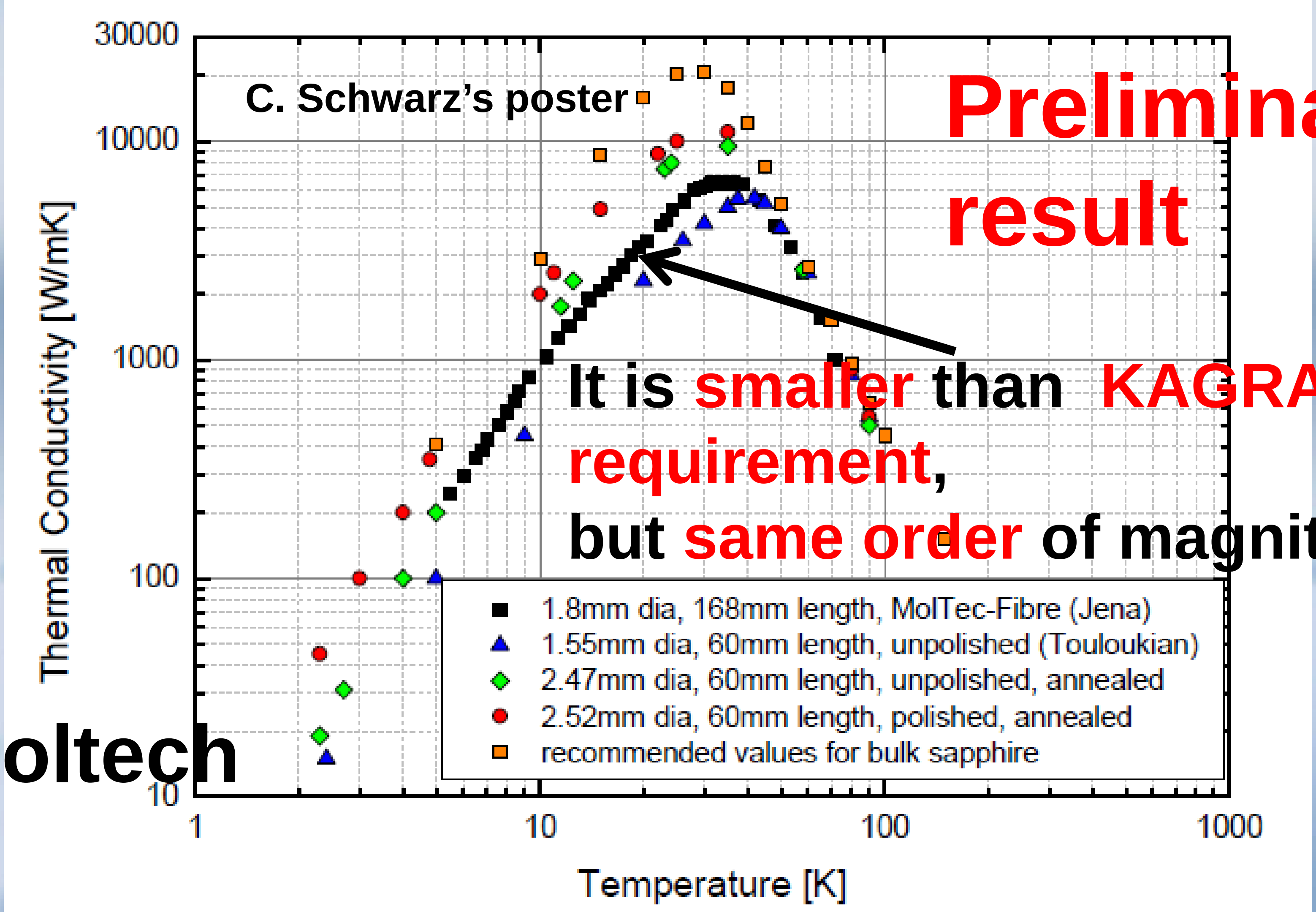
Thermal conductivity measurement in Jena



4. Recent experiments

Thermal conductivity measurement in Jena

Preliminary result



It is smaller than KAGRA requirement, but same order of magnitude.

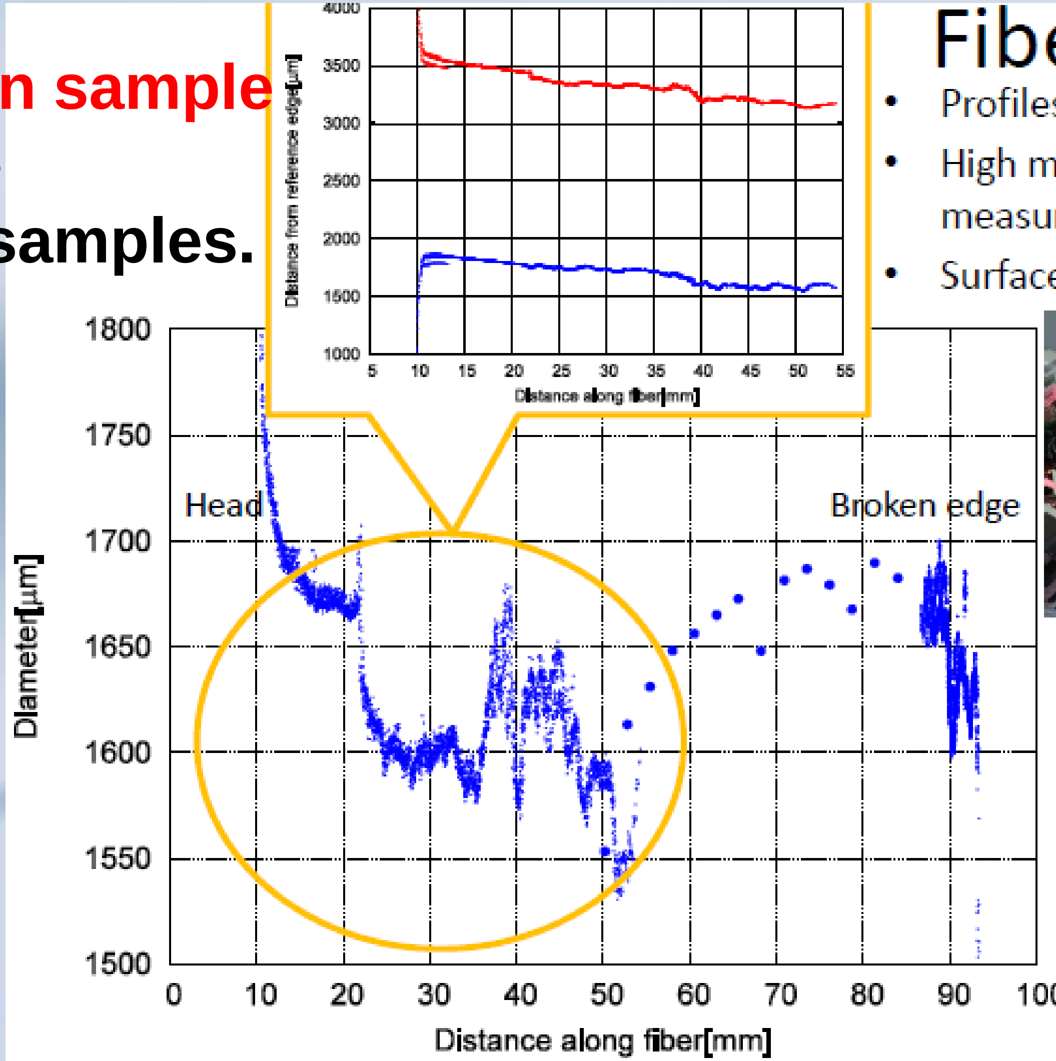
Moltech

4. Recent experiments

Profile measurement in Glasgow

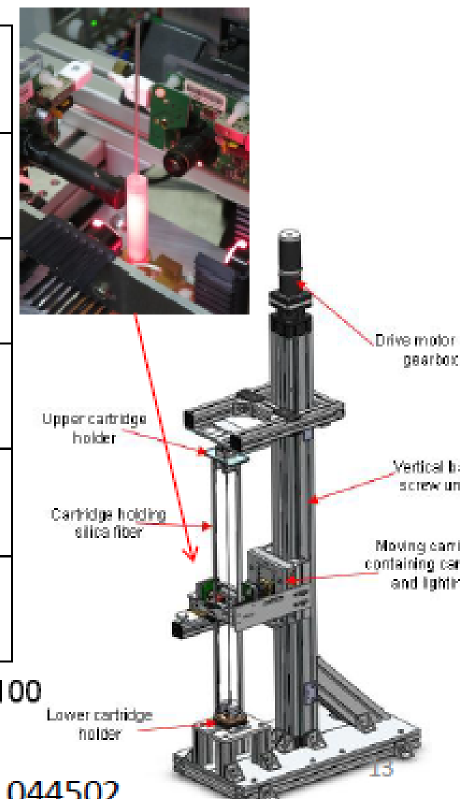
As grown sample

We have
ground samples.



Fiber profiles

- Profiles taken by fiber profiler
- High magnification cameras measure diameter of fiber
- Surface roughness 0.1 mm



A. Cumming et al. Rev. Sci. Instrum. **82** (2011) 044502

4. Recent experiments

Strength test

- **Discussion with Glasgow (4th of April)**
  - **Stretch and bend test**
  - **Some fibers were sent to Glasgow.**

Crystal structure

- **X ray apparatus in Jena**

4. Recent experiments

Bonding between sapphire fibers and mirror

Our old result

T. Suzuki et al., Journal of Physics; Conference Series 32(2006)309.

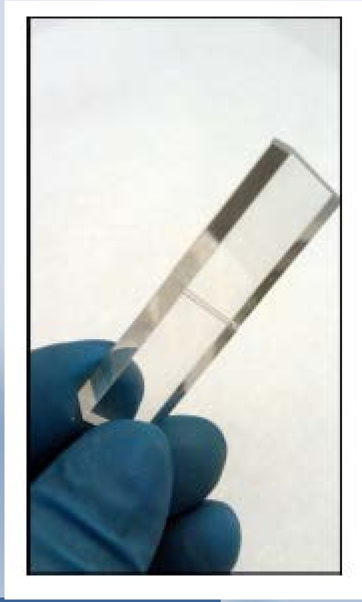
Strength and thermal resistance of Adhesion Free Bonding (Direct bonding) and Hydroxide Catalysis Bonding were measured.

	Direct Bonding	Hydroxide-catalysis Bonding
Shear strength σ_{shear}	28.4 MPa	6.53 MPa
Bonding area $2A_{\frac{Mg}{4}}$	5.06 mm^2	22.0 mm^2
Thermal conductance on $2A_{\frac{Mg}{4}}$	20 W/K	6.6 W/K
ΔT_B for $\dot{q}$=500 mW	25 mK	76 mK

Paper about Hydroxide Catalysis Bonding from Perugia
Classical and Quantum Gravity 27(2010)045010

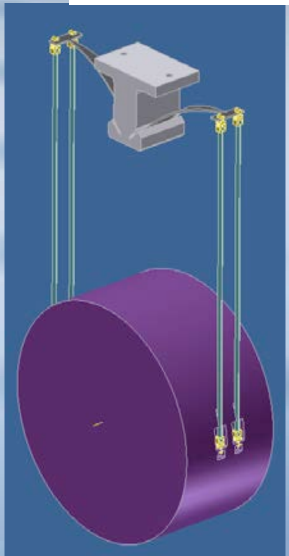
4. Recent experiments

Bonding between fibers and mirror



Investigation of
Hydroxide Catalysis Bonding is
in progress in Glasgow.
Rebecca Douglas presents a poster.

Other type sapphire suspension
(ribbon)



Eric Hennes will report it
on Friday morning.

5. Summary

Design and expected thermal noise

KAGRA sapphire fiber should be thick (1.6 mm in diameter) to transfer heat.

In principle, KAGRA sensitivity is not limited by thermal noise of sapphire suspension stage.

Peak of the vertical mode around 100 Hz is an issue (thick fibers).

Peaks of pitch motion (about 20 Hz) and 1st violin mode (220 Hz) are less serious, but we must pay attention.

5. Summary

Recent experiments

Moltech and IMPEX delivered sapphire fibers with nail heads.

Quality check is in progress under collaboration between ET and Japan (ELiTES) .

Christian Schwarz's poster
Rebecca Douglas's poster
Eric Hennes's talk on Friday morning

Our result is preliminary, but promising (although invesigation for qulity improvement is necessary).

Acknowledgement

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.

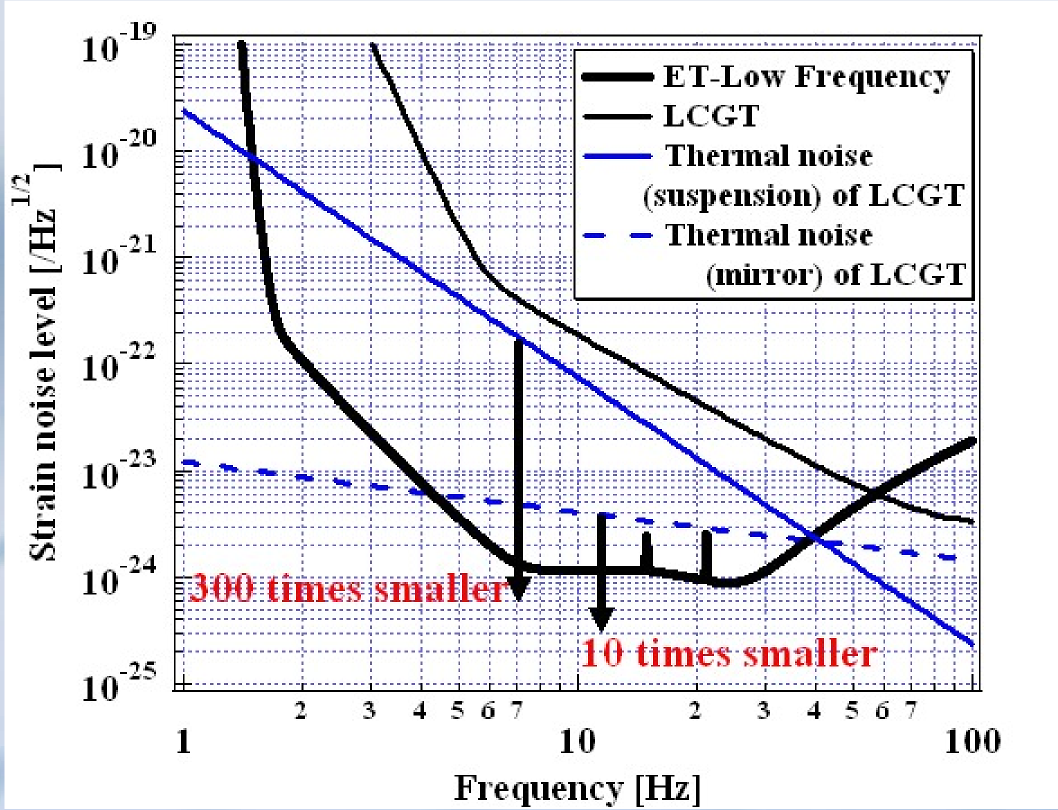
Thank you for your attention !

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)

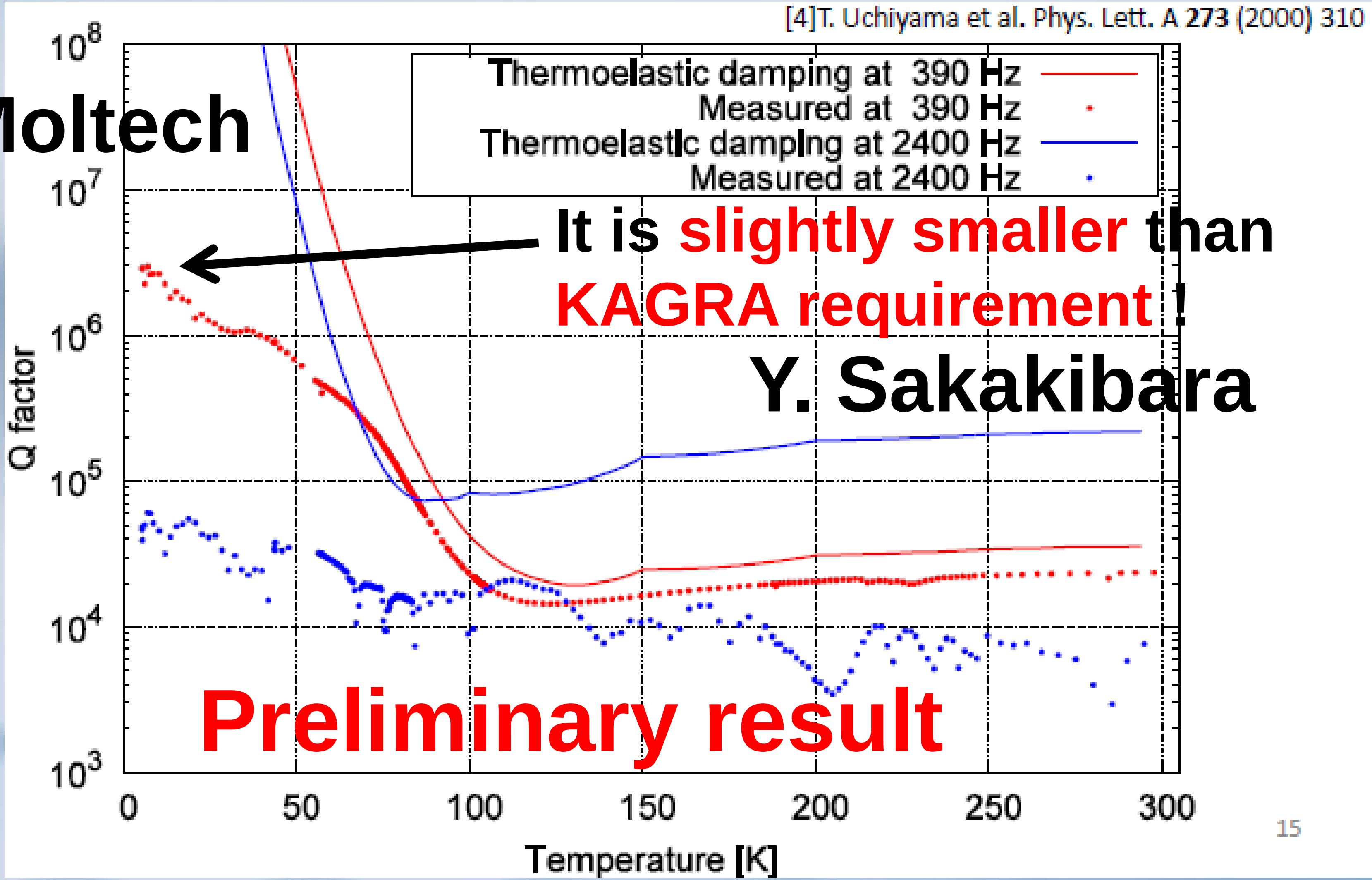
7 times heavier mirror (200 kg)

5 times longer suspension wire (2 m)

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

4. Sapphire fibers

Q measurement in Jena (cool) and Glasgow (300K)



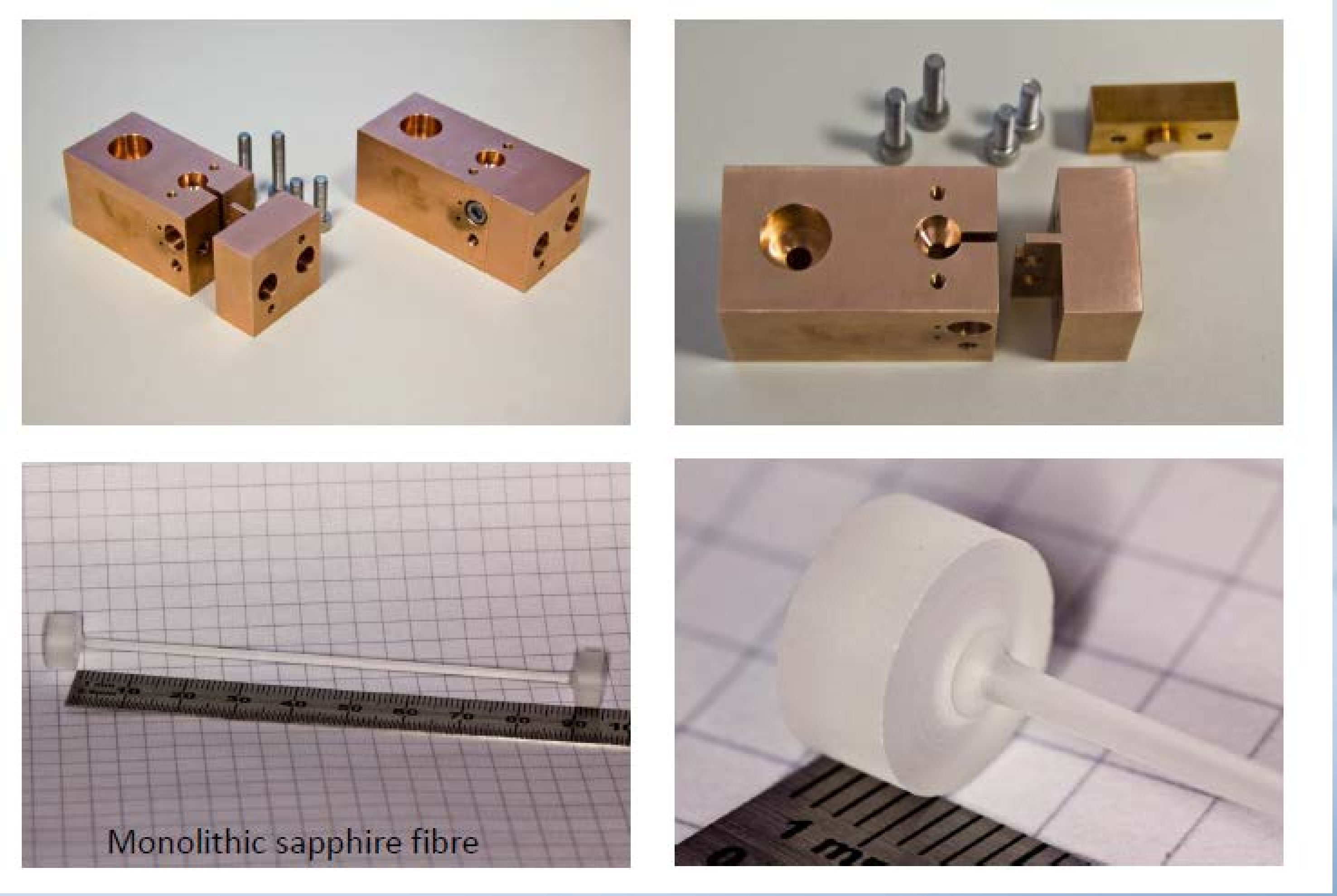
4. Sapphire fibers

Thermal conductivity measurement in Jena

Thermal conductivity of IMPEX fibers will be measured soon.

4. Sapphire fibers

After Yusuke left …. **Clamp for IMPEX fibers in Jena**



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)