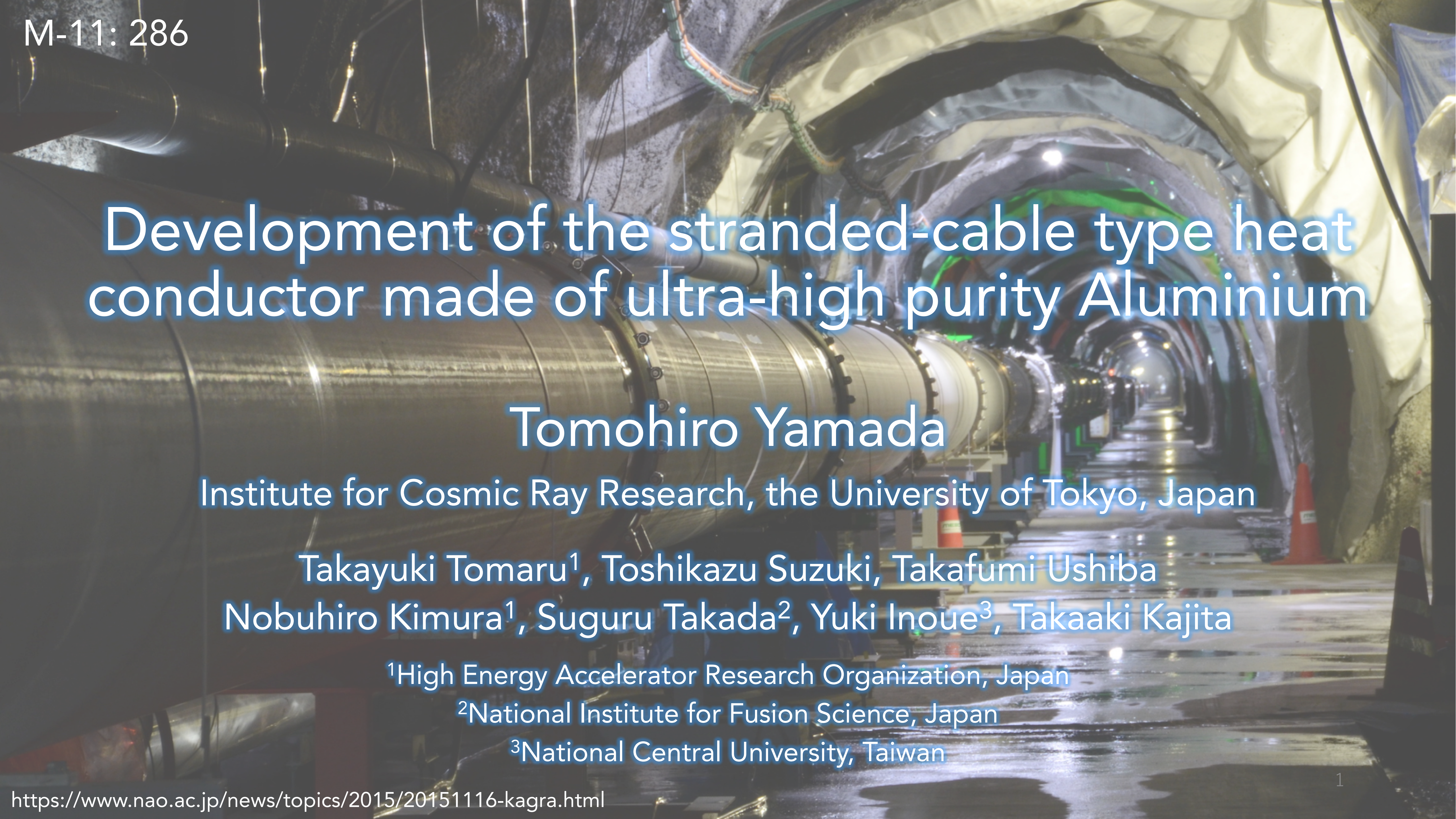

# Development of the stranded-cable type heat conductor made of ultra-high purity Aluminium


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https://www.nao.ac.jp/news/topics/2015/20151116-kagra.html

# Contents

# Contents

- Background
- Developed heat conductor
- Characterization
- Summary

# Refrigeration and Precise measurement

- Cryogenic environment is often adopted for precise measurements.
    - Artificial satellites
    - Cryogenic gravitational wave telescope

  All these precise measurements require quiet-vibration condition.

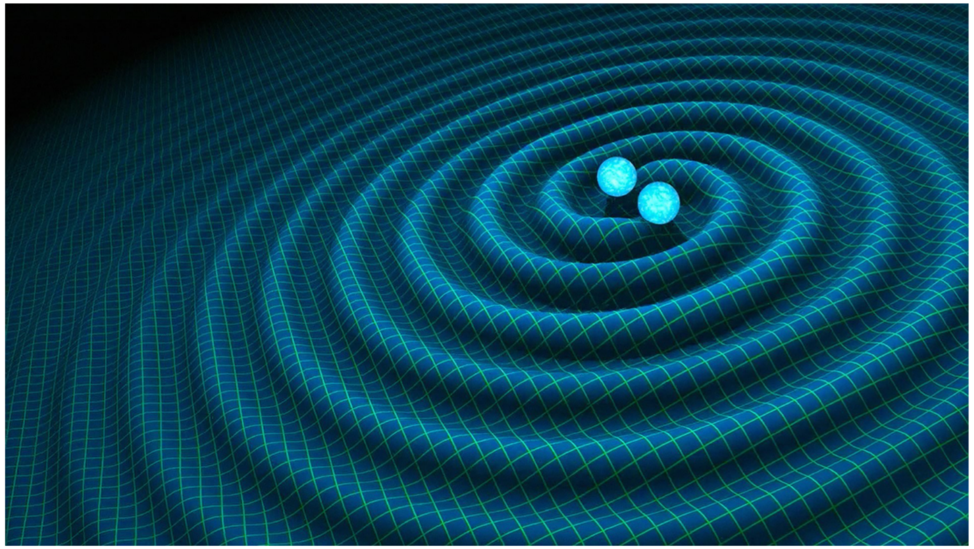
- However, if you connect the heat conductor, it may introduce vibration. In some cases, cryocoolers should be used for cooling. Here, the above problem can be serious.

  ⇨ <u>The heat conductor which has high thermal conductance and low stiffness can be utilized widely.</u>

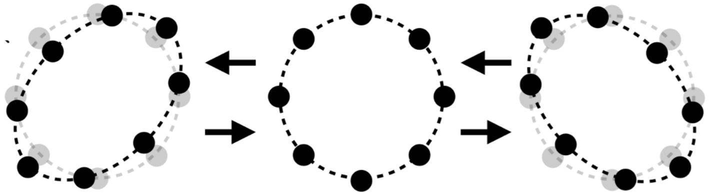
  Originally, this stranded-cable type heat link was developed for "KAGRA".

# Cryogenics and Astrophysics

## KAGRA: Large-scale cryogenic gravitational wave telescope in Japan



http://time.com/4217820/gravitational-waves-history/



Laser interferometer can detect gravitational waves.

Gravitational waves are ripples in space-time.

It changes the distance between cute apples.

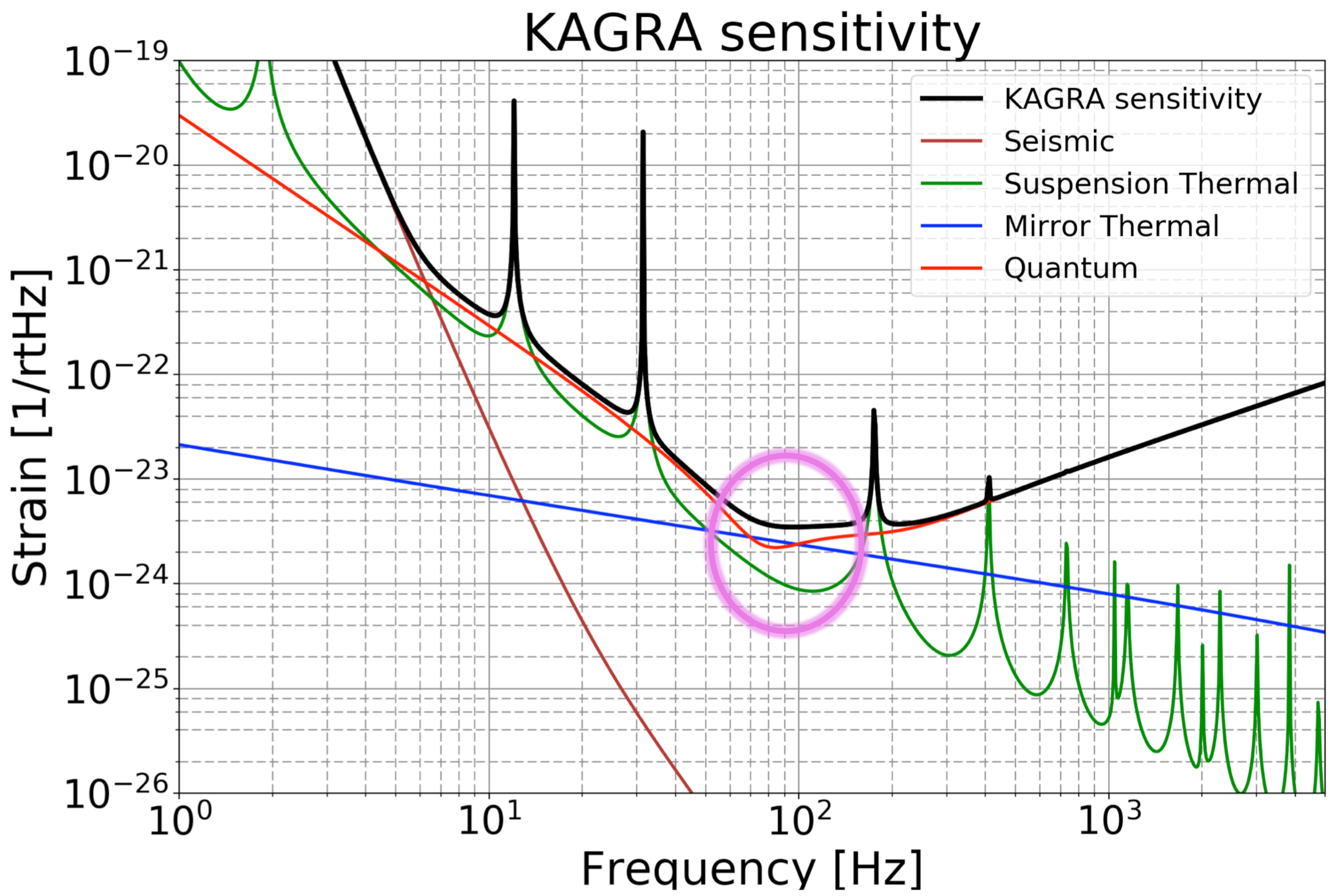
Cute apples must be like free mass.


https://gwcenter.icrr.u-tokyo.ac.jp/plan/history

# Why "Cryogenic"?

- Thermal noise

  Mirror is always fluctuating due to the thermal motion. This thermal noise dominates some sensitivity region.



# Why "Cryogenic"?

- Thermal noise

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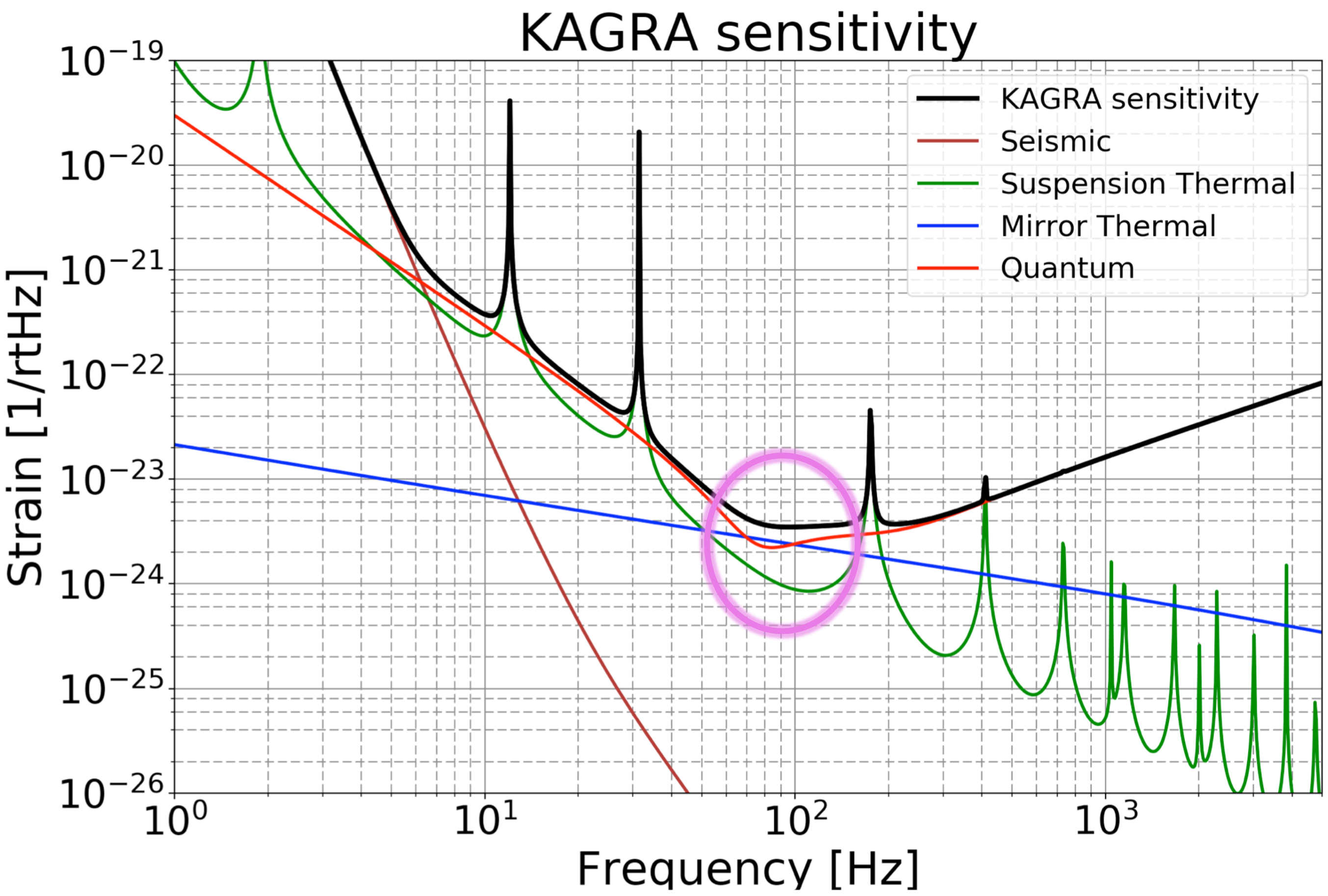
- How can we tackle this issue?

  The simplest way is cooling down mirrors.

**20 K cryogenic sapphire mirror**



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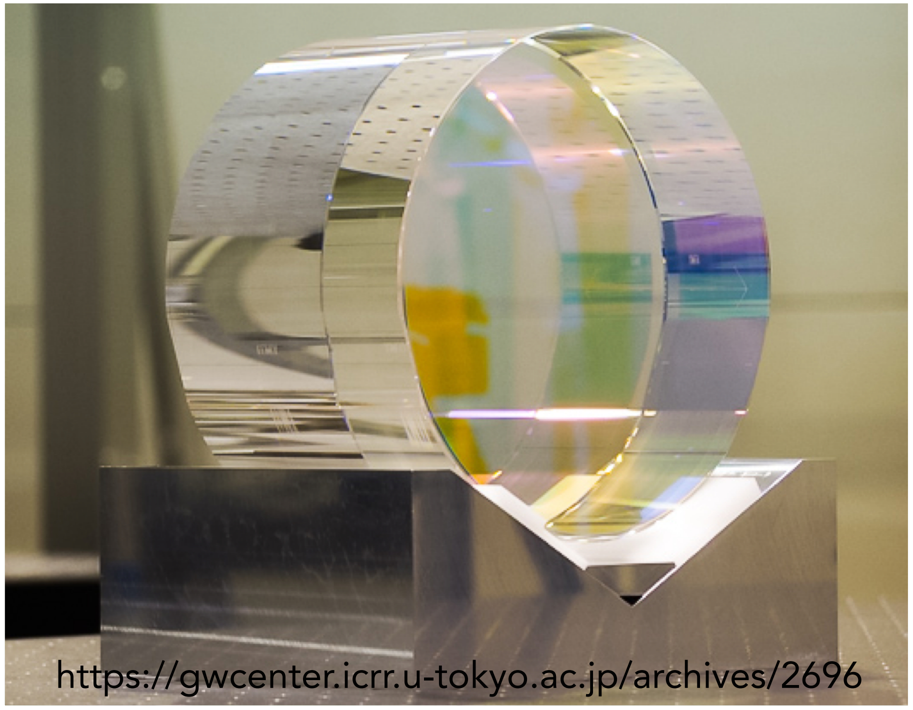
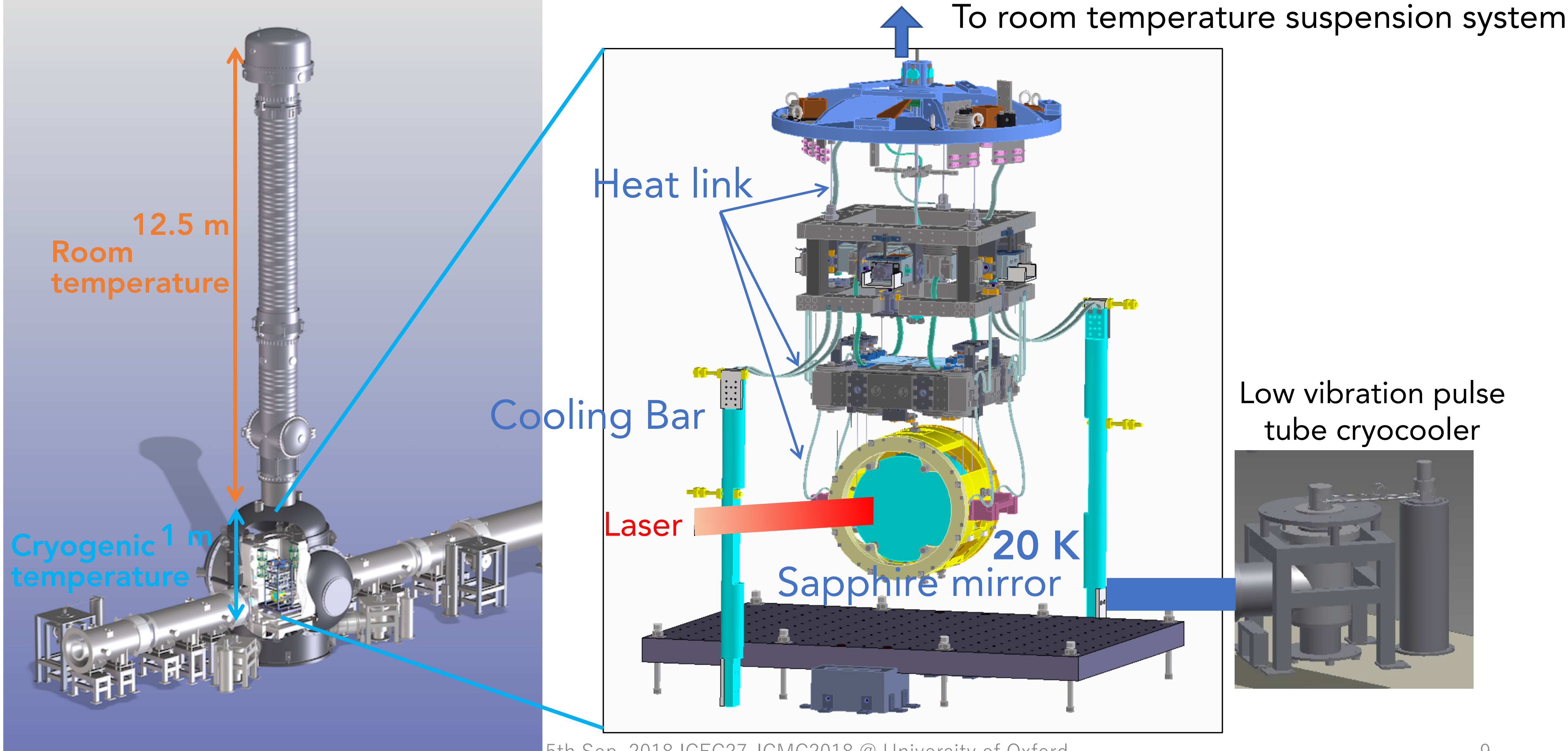


https://gwcenter.icrr.u-tokyo.ac.jp/archives/2696

# Cryogenic mirror suspension system



# Contents

- Background
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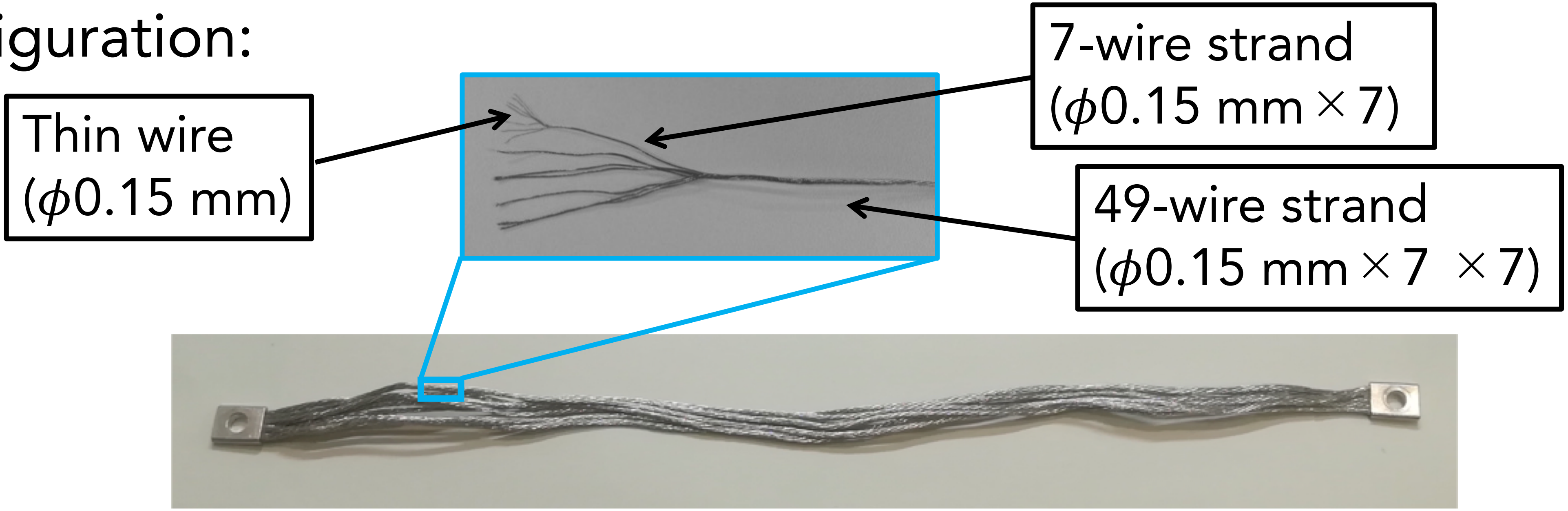
# Details of our heat link

- Material: 99.9999% (6N) Aluminum (Sumitomo Chemical Co., Ltd.)
- Configuration:




Stranded-cable type heat link ($\phi$0.15 mm $\times$ 7 $\times$ 7 $\times$ 7)

If we consider the cantilver shape, from easy discussion, spring constant is driven as $k = \frac{P^2}{N}$. $k$: Spring constant, $P$: Heat, $N$: Number of wires

Our heat link ensures large cross-sectional area by gathering many thin wires.

# Contents

- Background
- Developed heat conductor
- Characterization
  - Residual Resistivity Ratio (RRR)
  - Thermal conductivity
  - Effect of mechanical deformation on the thermal performance
  - Spring constant
- Summary

# RRR: Method

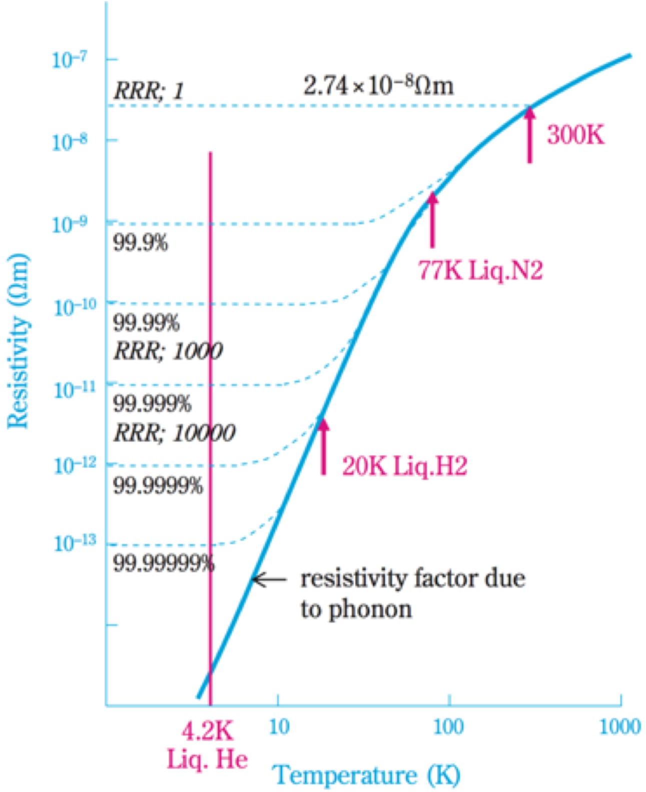
- RRR: Residual Resistivity Ratio

$$\mathrm{RRR} = \frac{\rho_{300\ \mathrm{K}}}{\rho_{4.2\ \mathrm{K}}} = \frac{R_{300\ \mathrm{K}}}{R_{4.2\ \mathrm{K}}}$$

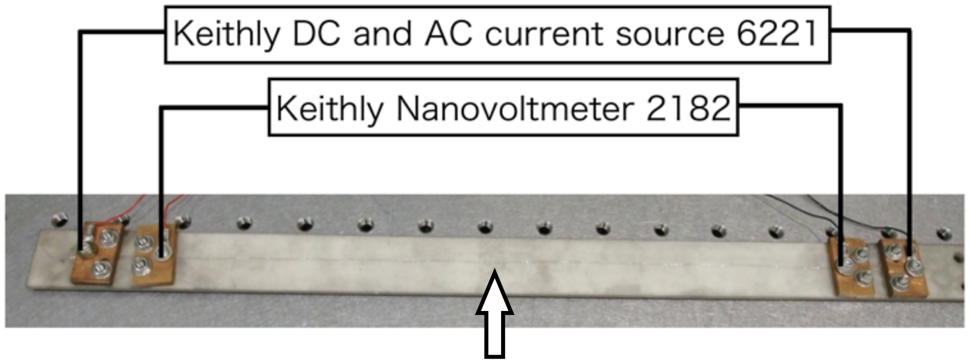
Purity, Size effect, Easy evaluation of t.c..

- 4–wire measurement

We measured electrical resistance of sample at room temp. and liquid helium temp..




Hoshikawa *et al.*, Sumitomo Chemical(2013)




0.15 mm wire was measured

| Measured sample | | |
|---|---|---|
| | 5N | 6N |
| Diameter | 0.15 mm | 0.15 mm |

Annealing: 450 °C, 3 hours, Vacuum

# RRR: Result

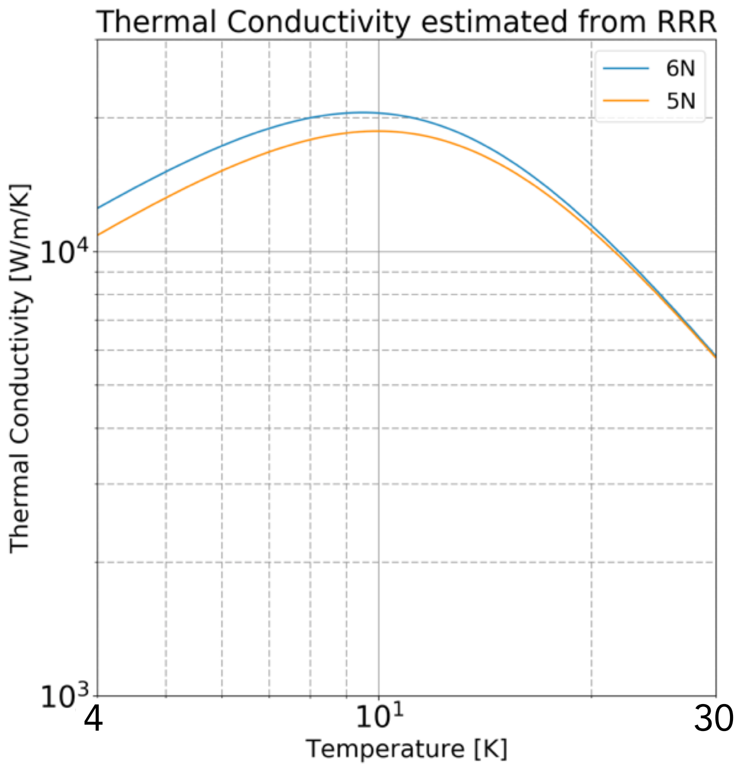
- Result

| | 5N | 6N |
|---|---|---|
| Measured value | 3090 | 3570 |
| Estimated value | 2571 | 3882 |
| Bulk RRR* | 6000 | 22000 |

*by Sumitomo Chemical Co., Ltd.

Size effect:

Occurred due to the limitation of mean-free-path by diameter of sample




- Estimation of thermal conductivity

It is possible to estimate t.c. from RRR.

$$\kappa(T) = \frac{1}{\underbrace{1.8\times10^{-7}T^2}_{\text{Phonon scattering}} + \underbrace{1.1/(\mathrm{RRR}\,T)}_{\text{Impurity \& Lattice defects}}}$$

# Thermal conductivity: Method

- Longitudinal Heat Flow Method

$$P = \kappa \frac{A\Delta T}{l}$$

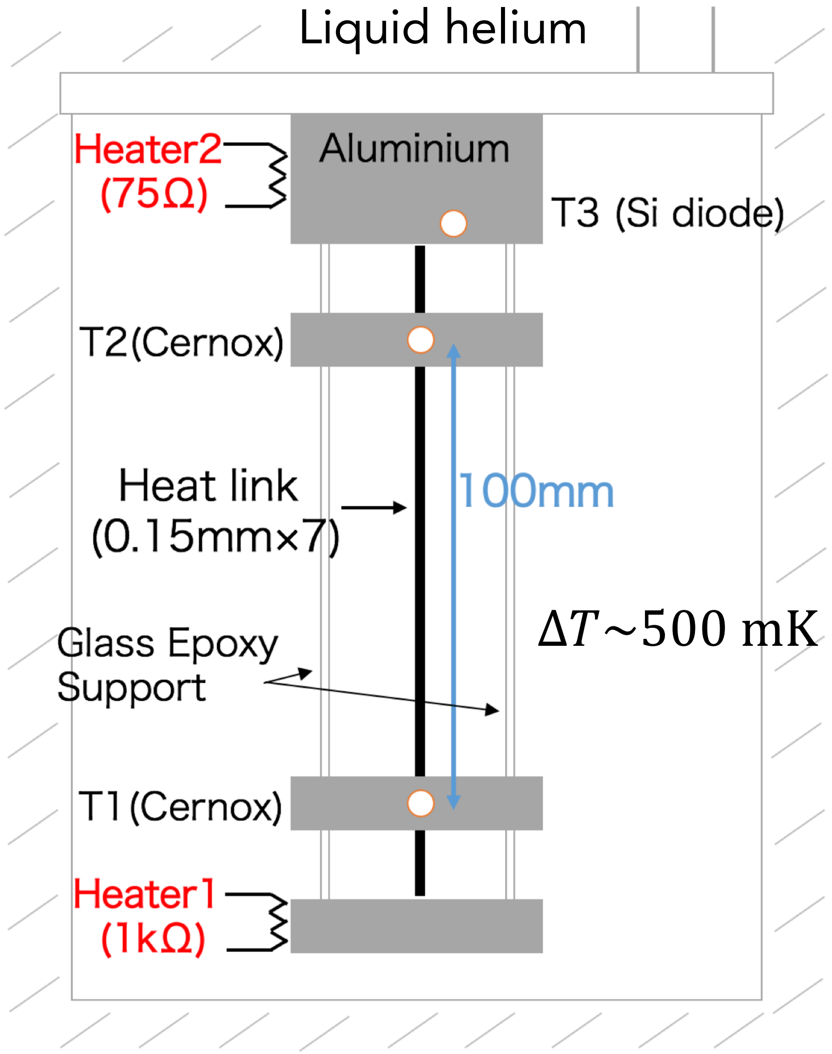
$P$ : Heating value of Heater1

$A$ : Cross-sectional area of heat link

$l$ : Length of heat link

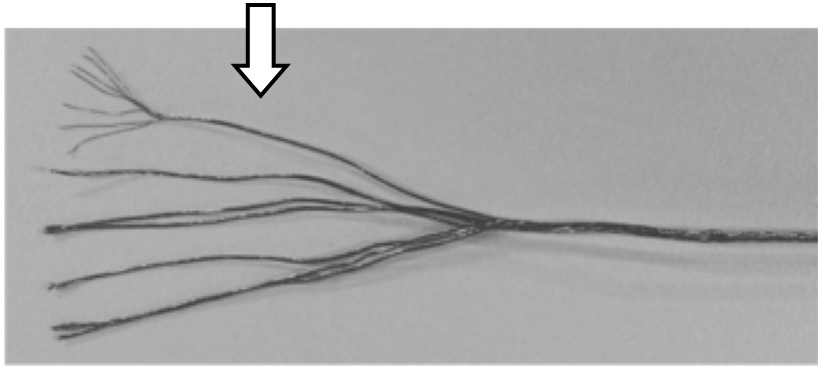
$\Delta T$ : Temperature deference btw T1 and T2

➡ Calculate thermal conductivity $\kappa$



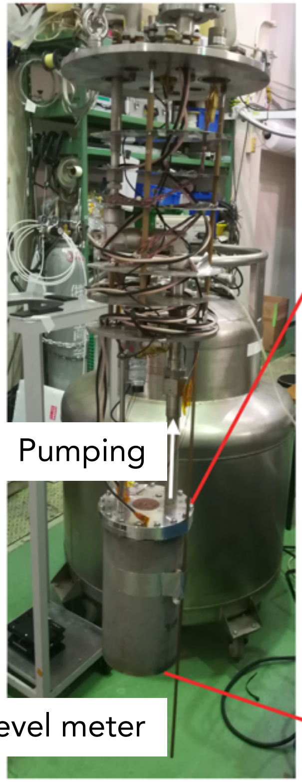
# Thermal conductivity: Setting

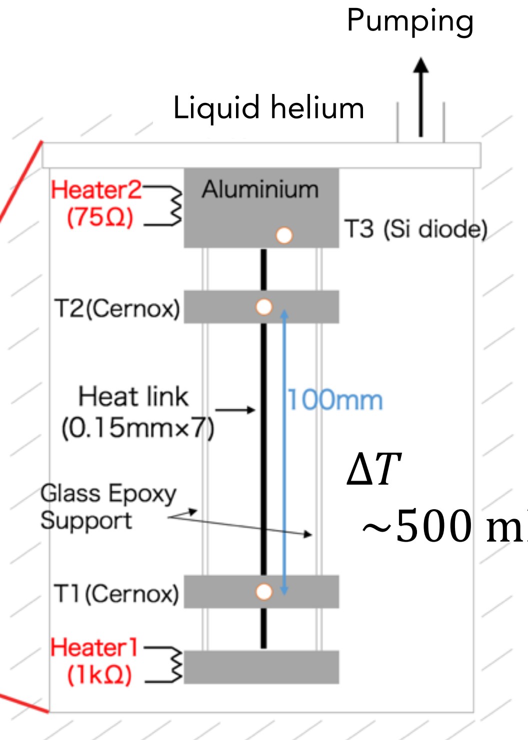
- Liquid helium was used because:
  - temperature is very stable,
  - it is possible to make initial temperature uniform by introducing heat exchange gas.
- 7-wire stranded cable was used.



Liquid helium dewar

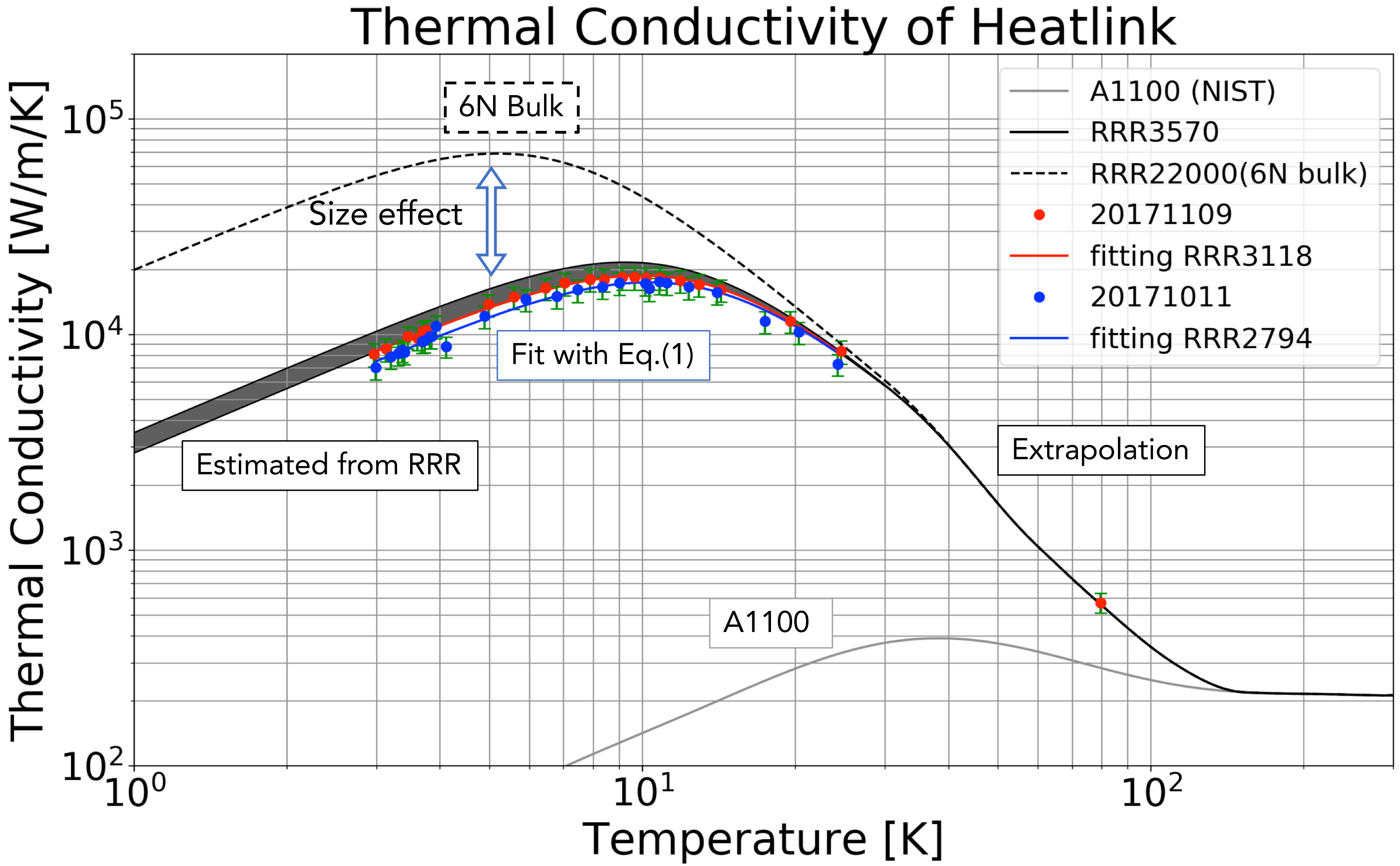
Vacuum tank




$\Delta T$
$\sim 500$ mK

# Thermal conductivity: Result

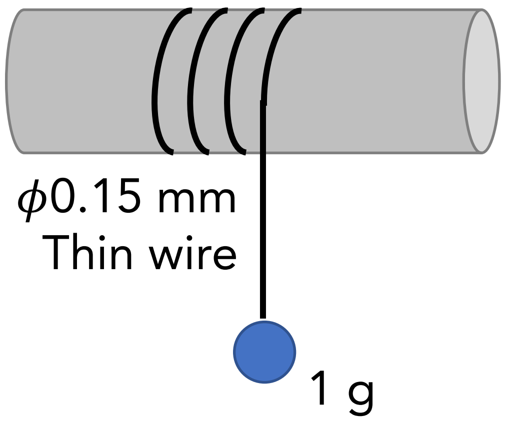


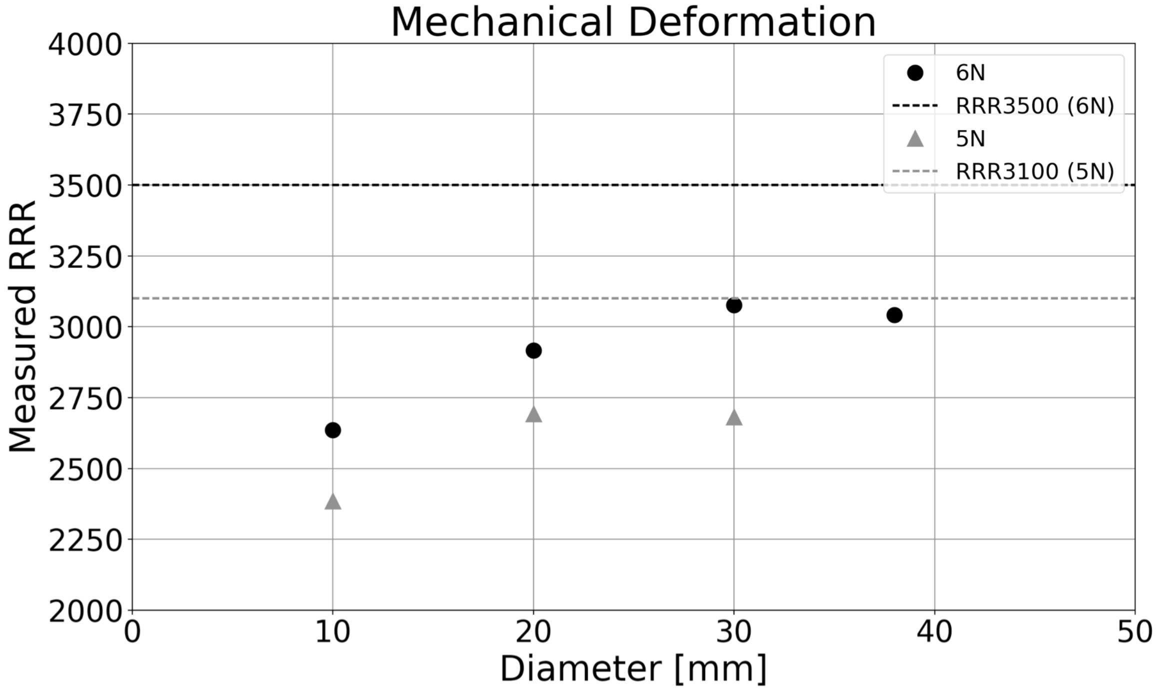
# Effect of mechanical deformation

- Motivation
  - For the practical use, it is difficult to use or install heat link without deformation.
  - However mechanical stress might decrease its thermal performance.

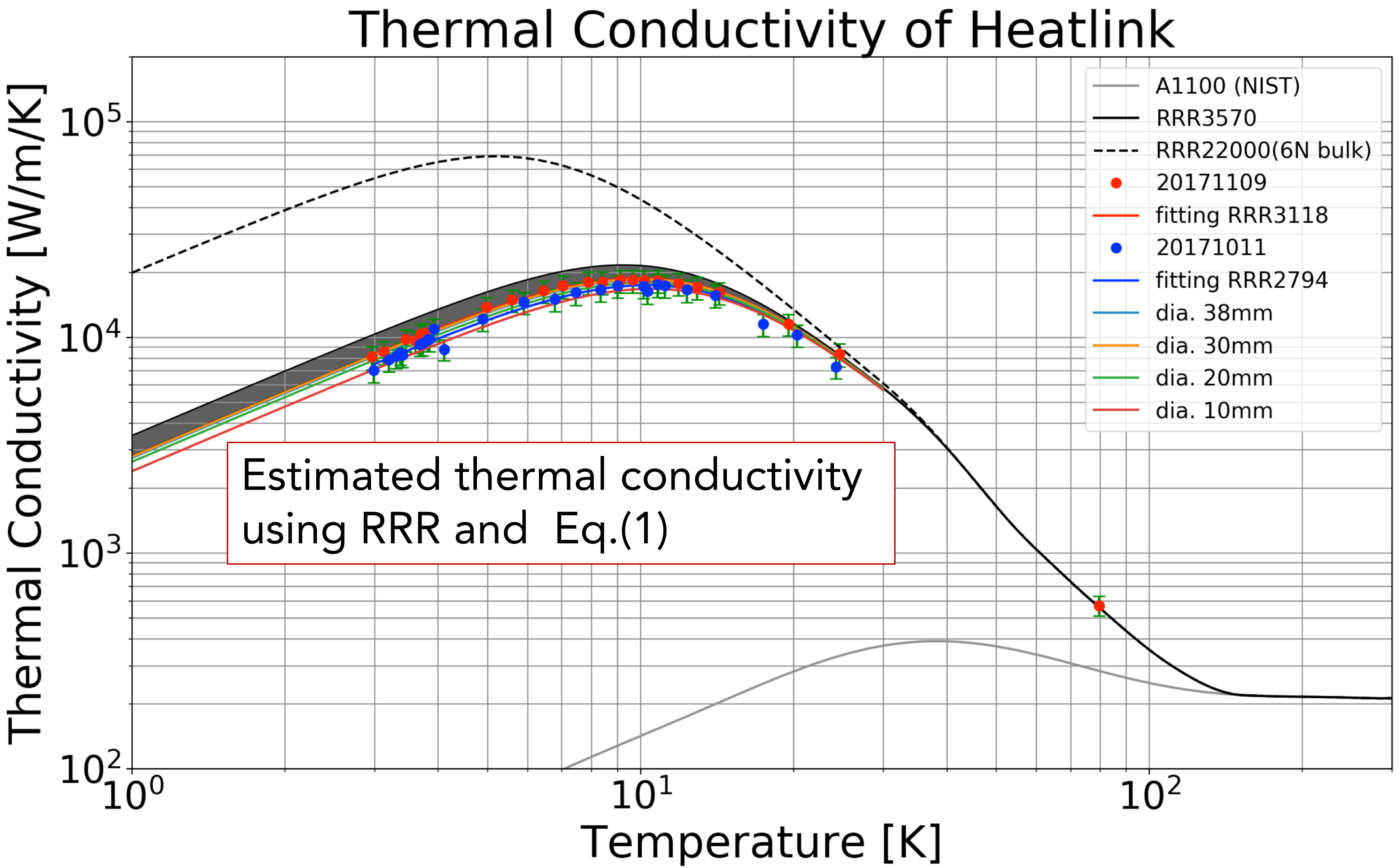
  ➡ We investigated how mechanical stress affect to the RRR.
- Method

  We wrapped a wire to the cylindrical bar and compared RRRs before and after.



# Decrease of thermal conductivity



# Advantage of stranded cable in stiffness

- Evaluation of spring constant

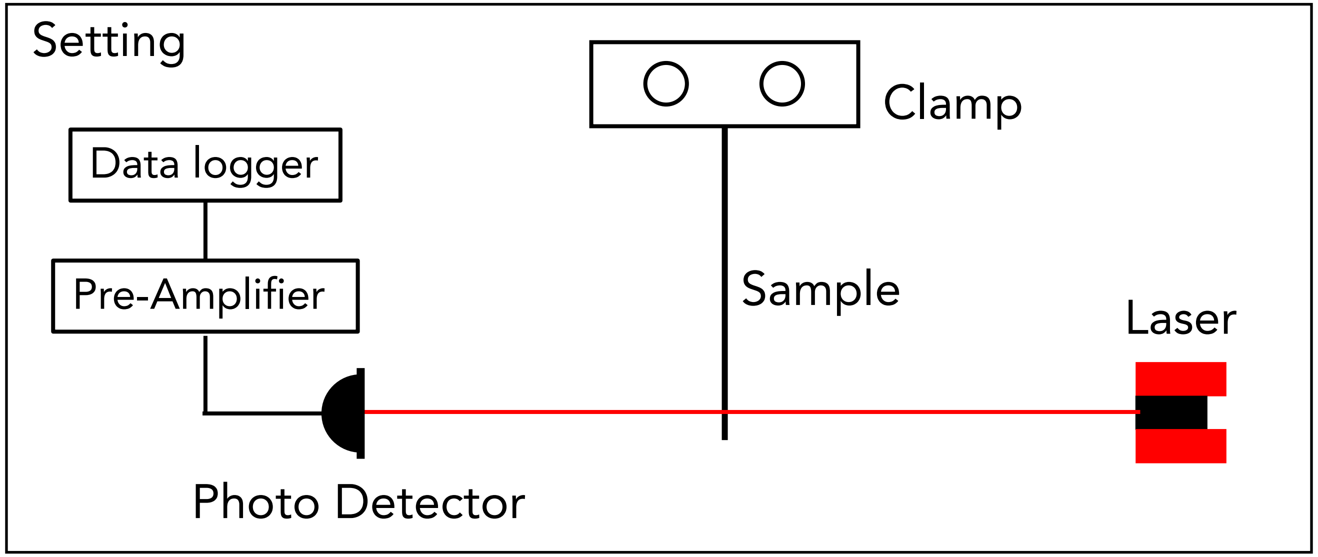
  - Spring constant is index of the stiffness.

  $$k \propto \frac{P^2}{N}$$

  - $k \propto f^2$  $f$: resonant frequency

  - We prepared a single thick wire with same cross-sectional area of stranded cable.

  -> We measured both resonant frequencies.




- Result (Resonant frequency)

| | Area | 5N | 6N |
|---|---|---|---|
| $\phi$1mm single | 0.8 mm$^2$ | 64 Hz | 64 Hz |
| 45 wires strand | 0.8 mm$^2$ | 9.6 Hz | 9.8 Hz |

$\boxed{k \propto f^2}$ 1/6.5

Spring constant: 1/43

**Much lower spring constant and same cross-sectional area**

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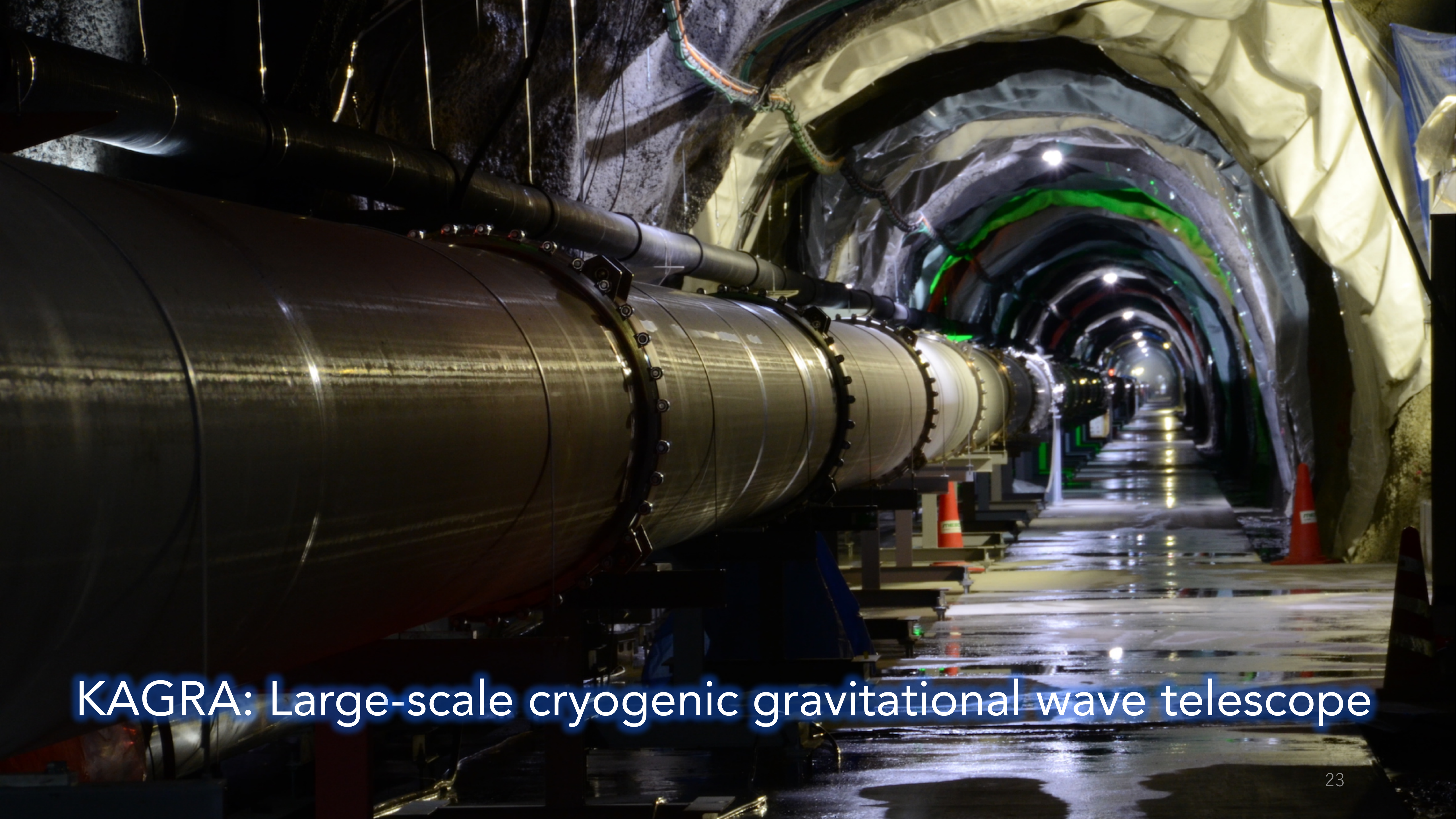
# Summary

- The stranded-cable type heat link was originally developed for KAGRA.

- The measured RRR of 6N aluminum heat link was approximately 3570.
- The measured maximum thermal conductivity was approximately 18500 W/m/K at 10 K.
- The effect of mechanical deformation was verified.
- The spring constant of heat link was 1/43 that of a single thick wire with the same cross sectional area.

- We expect this heat link can be applied to various region.

We thank H. Hoshikawa and A. Nagata in Sumitomo Chemical Co., Ltd. for giving us many advises.



# KAGRA: Large-scale cryogenic gravitational wave telescope

# Estimation of thermal conductivity

For easy evaluation of thermal conductivity

- Wiedemann Franz law

Free electron works as the career of electric charge and heat

$$\frac{\kappa}{\sigma} = \underbrace{\frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2}_{\text{Lorentz number}} T$$

$\kappa$ : Thermal conductivity

$\sigma$ : Electrical conductivity

- Estimation of thermal conductivity from RRR

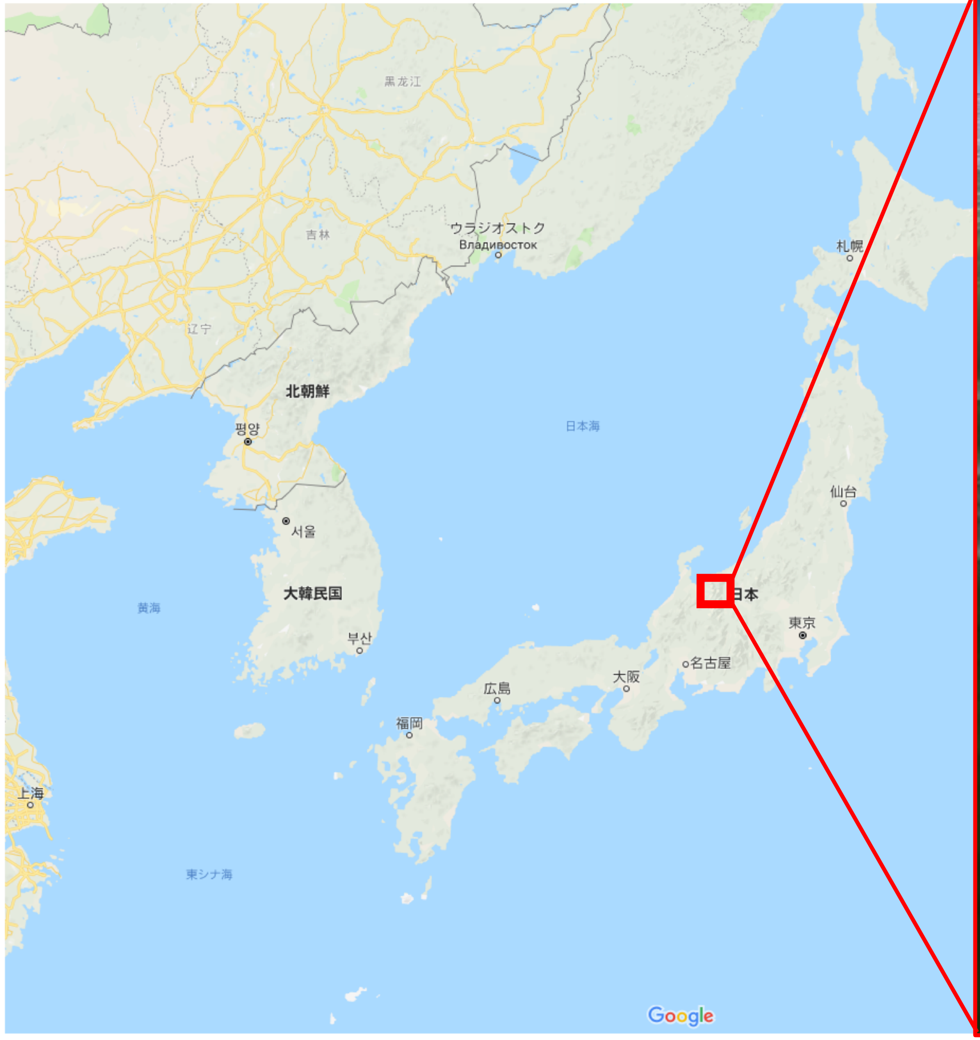
$$\mathrm{RRR} = \frac{\rho_{300\ \mathrm{K}}}{\rho_{4.2\ \mathrm{K}}} = \frac{\sigma_{4.2\ \mathrm{K}}}{\sigma_{300\ \mathrm{K}}}$$

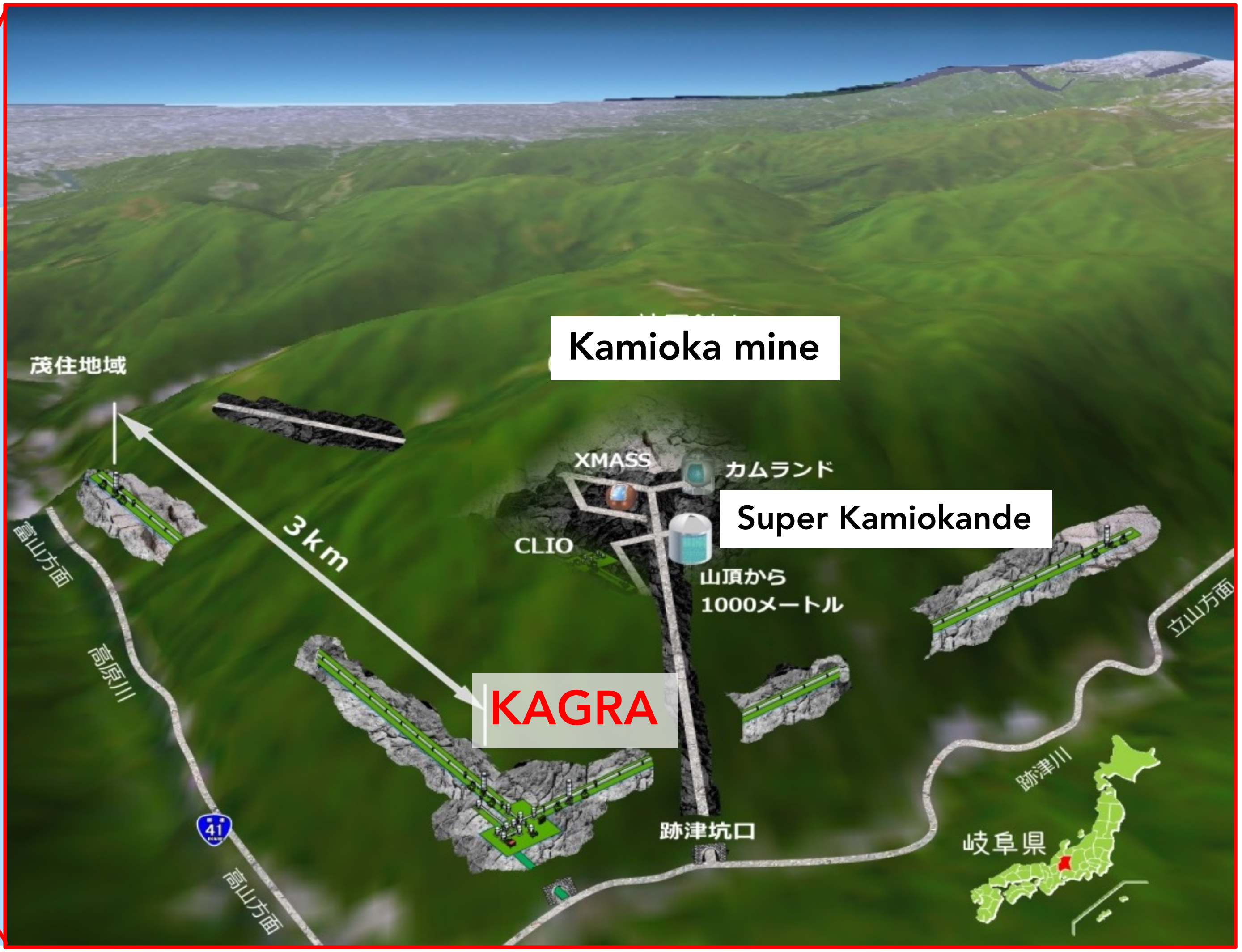
$$\kappa(T) = \frac{1}{1.8\times10^{-7}T^2+1.1/(\mathrm{RRR}\ T)} \quad \dots \text{Eq.(1)}$$

We evaluated the RRR first, then moved thermal conductivity measurement.

# Cryogenics and Astrophysics

## KAGRA: Cryogenic gravitational wave telescope in Japan



# Cryogenics and Astrophysics

## KAGRA: Cryogenic gravitational wave

Key feature1:

- Underground site

  -> Reduction of seismic vibration