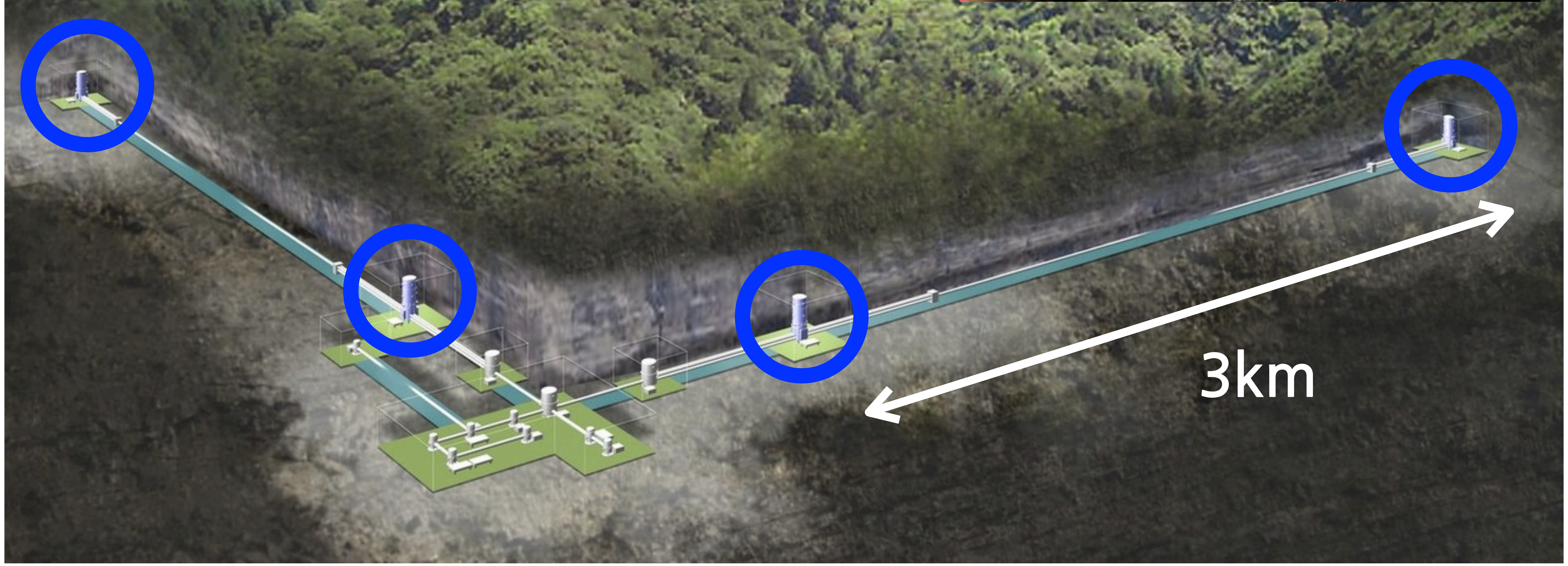
Measurement of the mechanical loss of reflective coatings for Cryogenic Gravitational wave telescope

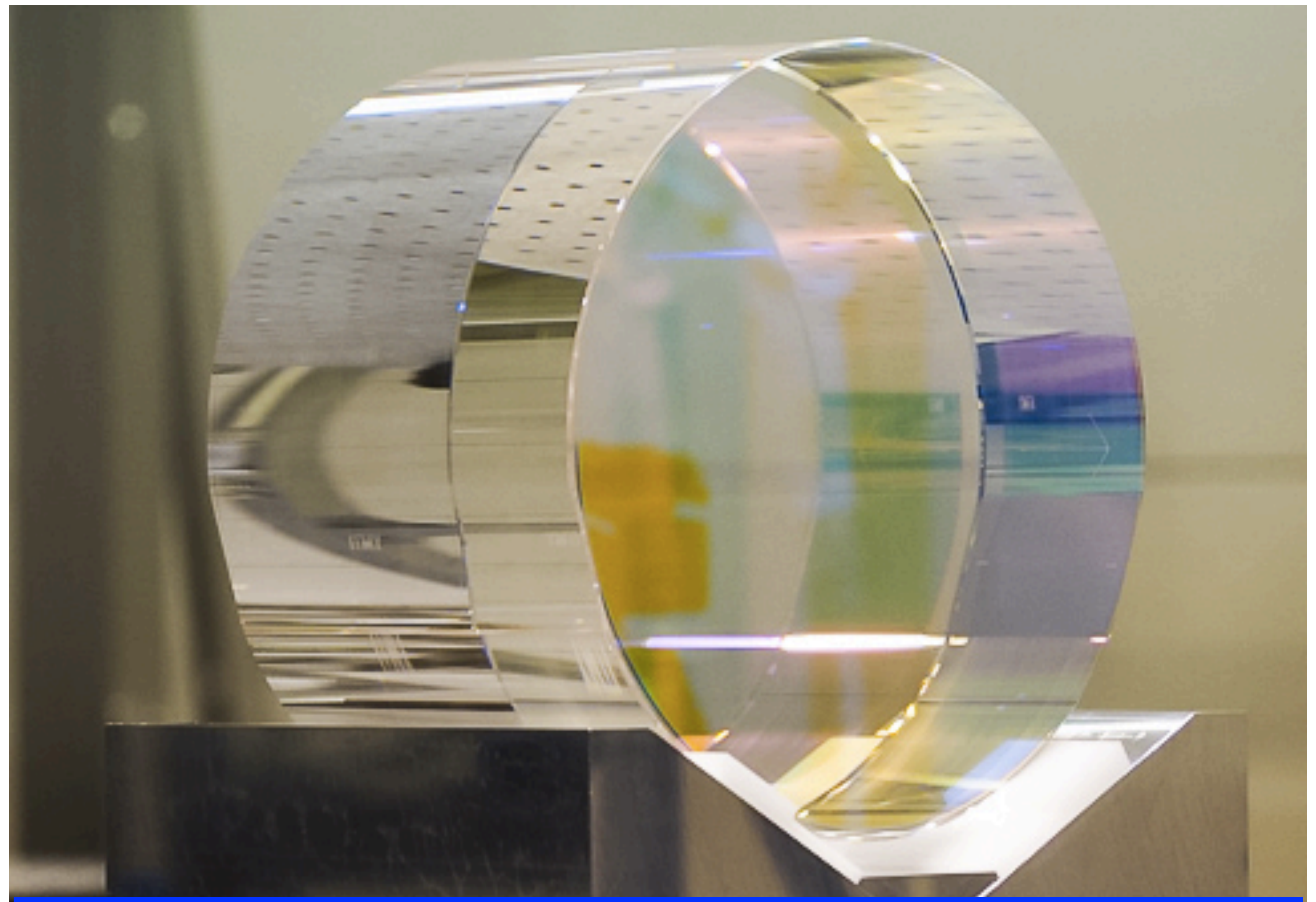
Yukino Mori, Y.Nakayama, K.Yamamoto, T.Ushiba[A]
Univ.Toyama, ICRR[A]

2020/12/19 7th KAGRA International Workshop

Cryogenic Gravitational wave telescope KAGRA

Michelson interferometer with 3 km Fabry-Perot cavity arms in Japan





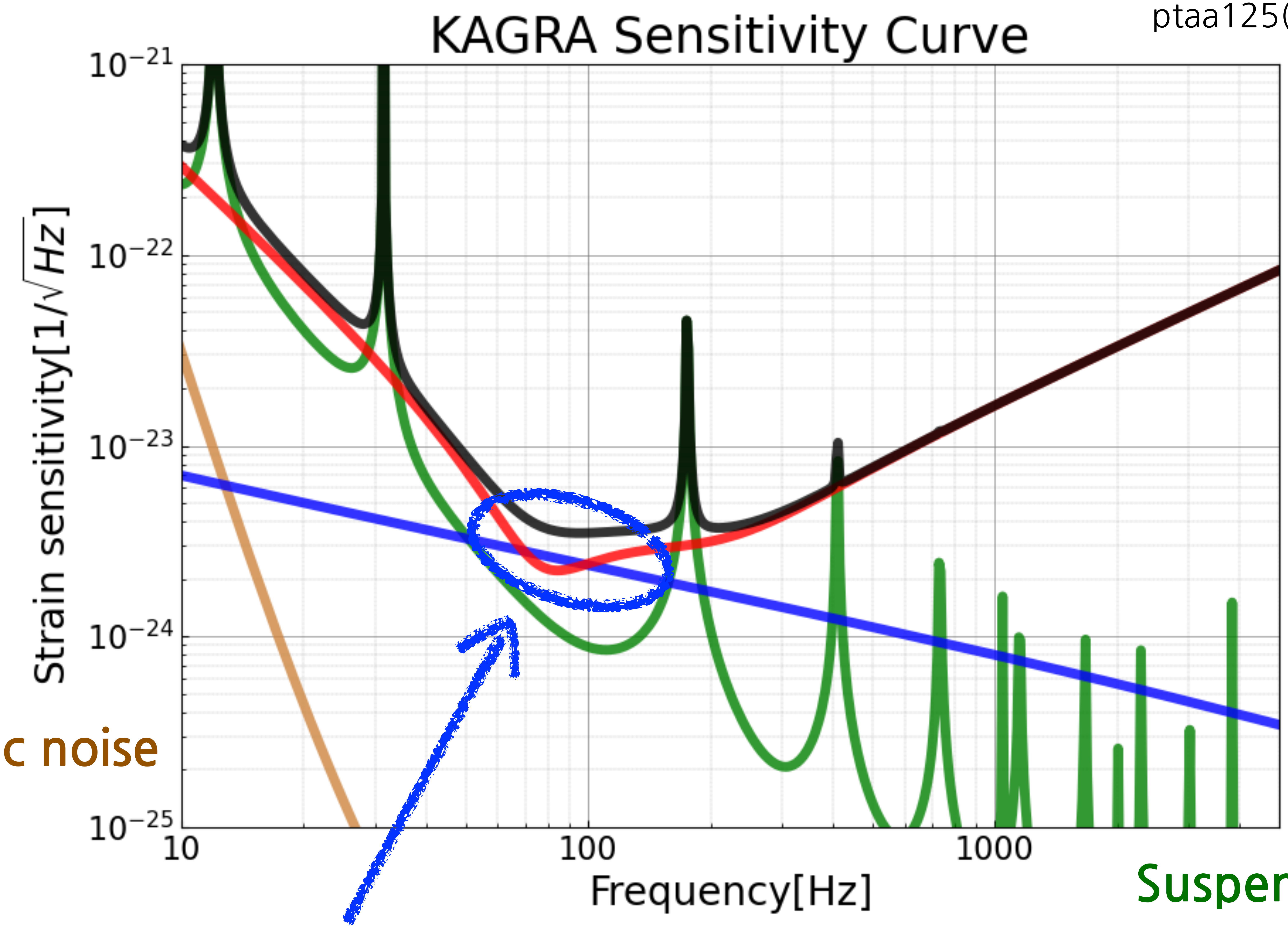
Cryogenic(about 20 K)

Sapphire

Excellent property
at low temperature

KAGRA target sensitivity

Progress of Theoretical and Experimental Physics,
ptaa125(September 18,2017)



Quantum noise

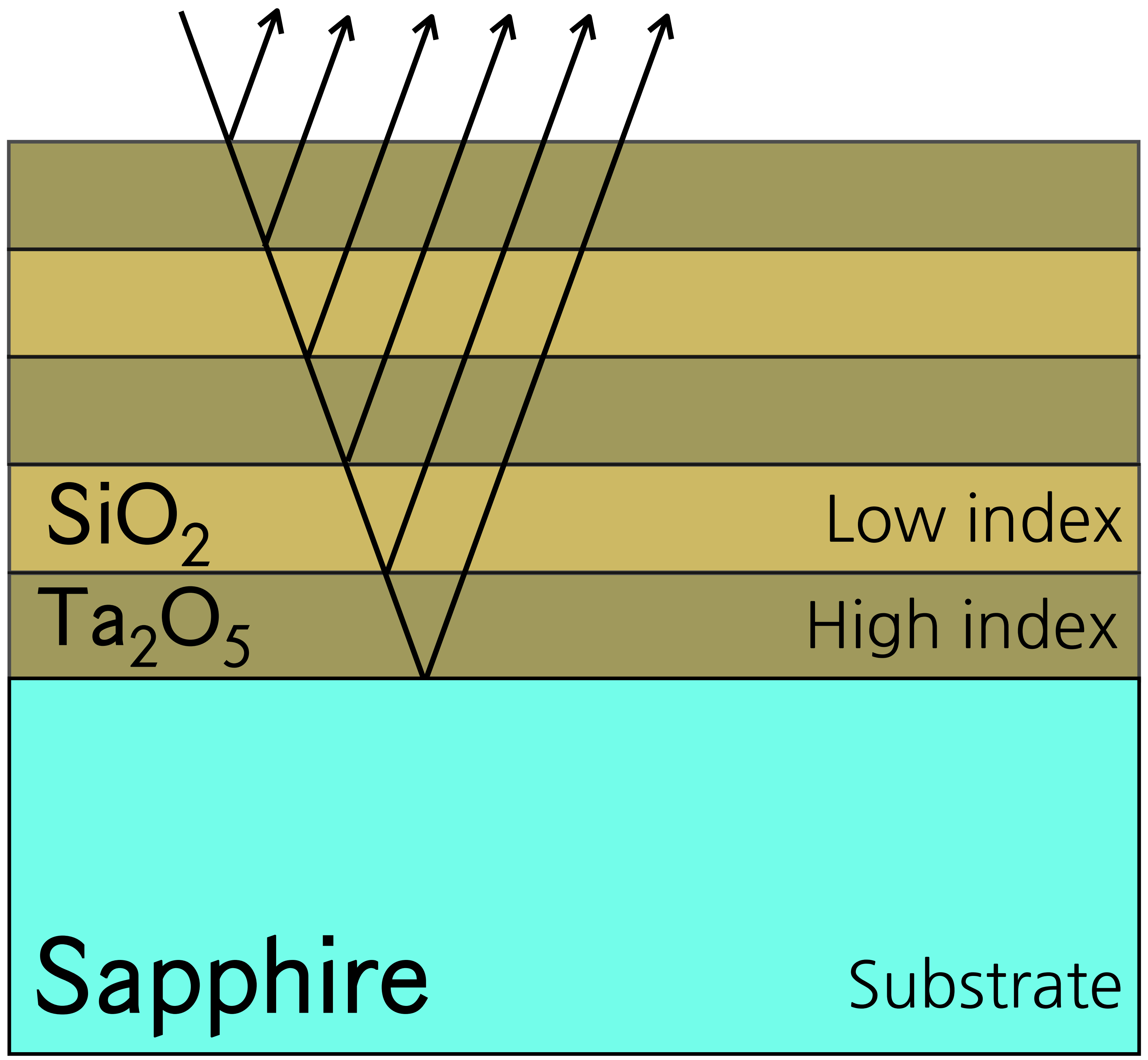
Seismic noise

Suspension thermal noise

Mirror thermal noise mainly comes from **the coating of the mirror**

Coating

The mirror requires high reflectance to reduce the shot noise.
The surface of the mirror is coated with the dielectric multilayer (Coating).



The dielectric multilayer

- Alternating layers of low and high index materials.

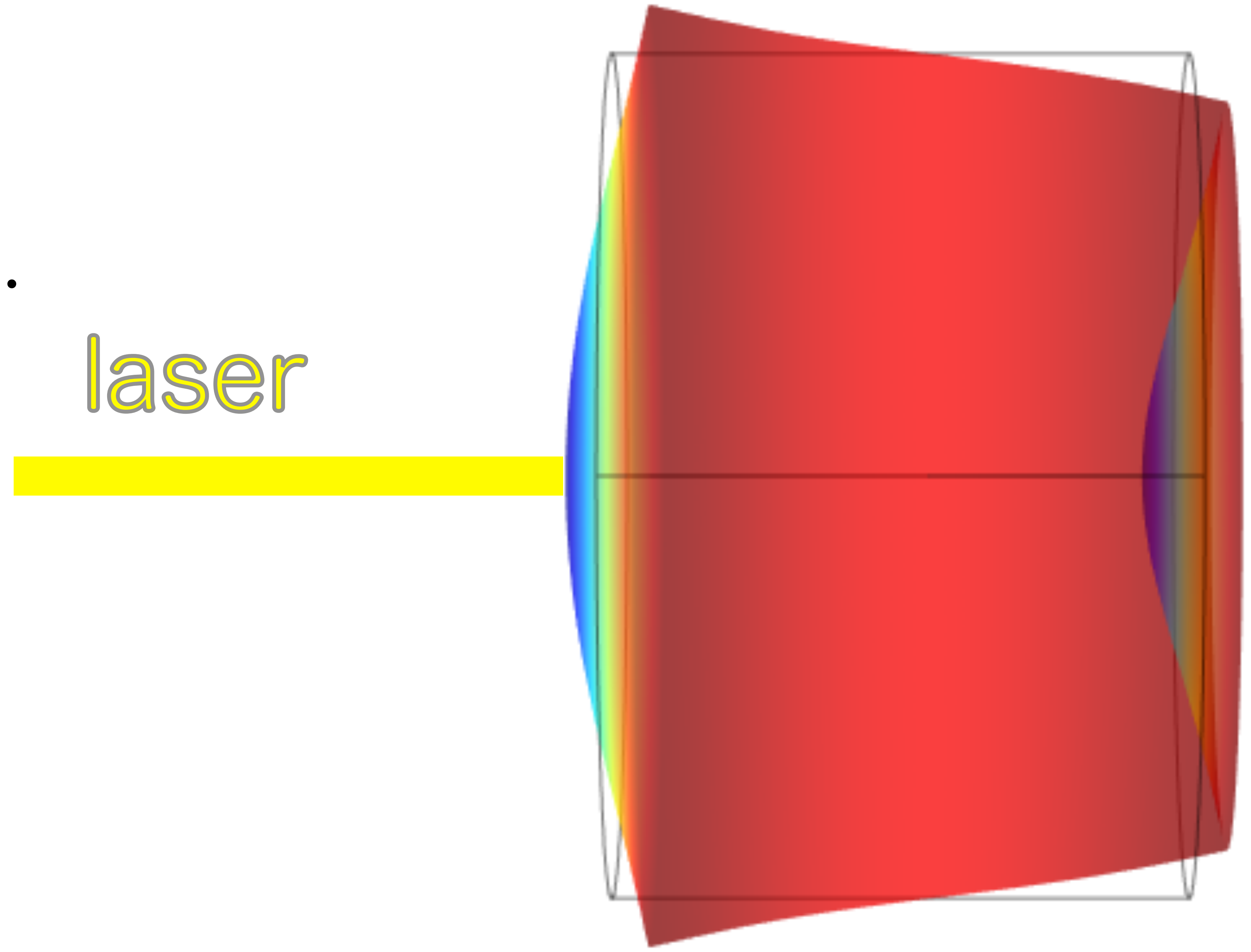
KAGRA of end test mass：40 layers of SiO_2/Ta_2O_5

- The optical thickness of each layer is $\lambda/4$ (λ=1064 nm).
- Since the interferences between reflected light on the layer boundaries are constructive, the reflectance of the coating is quite high.

Mirror thermal noise

Mechanism of mirror thermal noise

— Mirror receives the energy from Heat Bath at random.
— Mirror elastic vibration is excited.
— Mirror surface moves along the laser axis.
— The optical path length changes.



Evaluation of mirror thermal noise

Fluctuation-Dissipation Theorem(FDT)

$$G_{\text{thermal noise}} \propto \sqrt{T\phi_{\text{loss}}(\omega)}$$

Mirror thermal noise (Power spectrum density)

Temperature

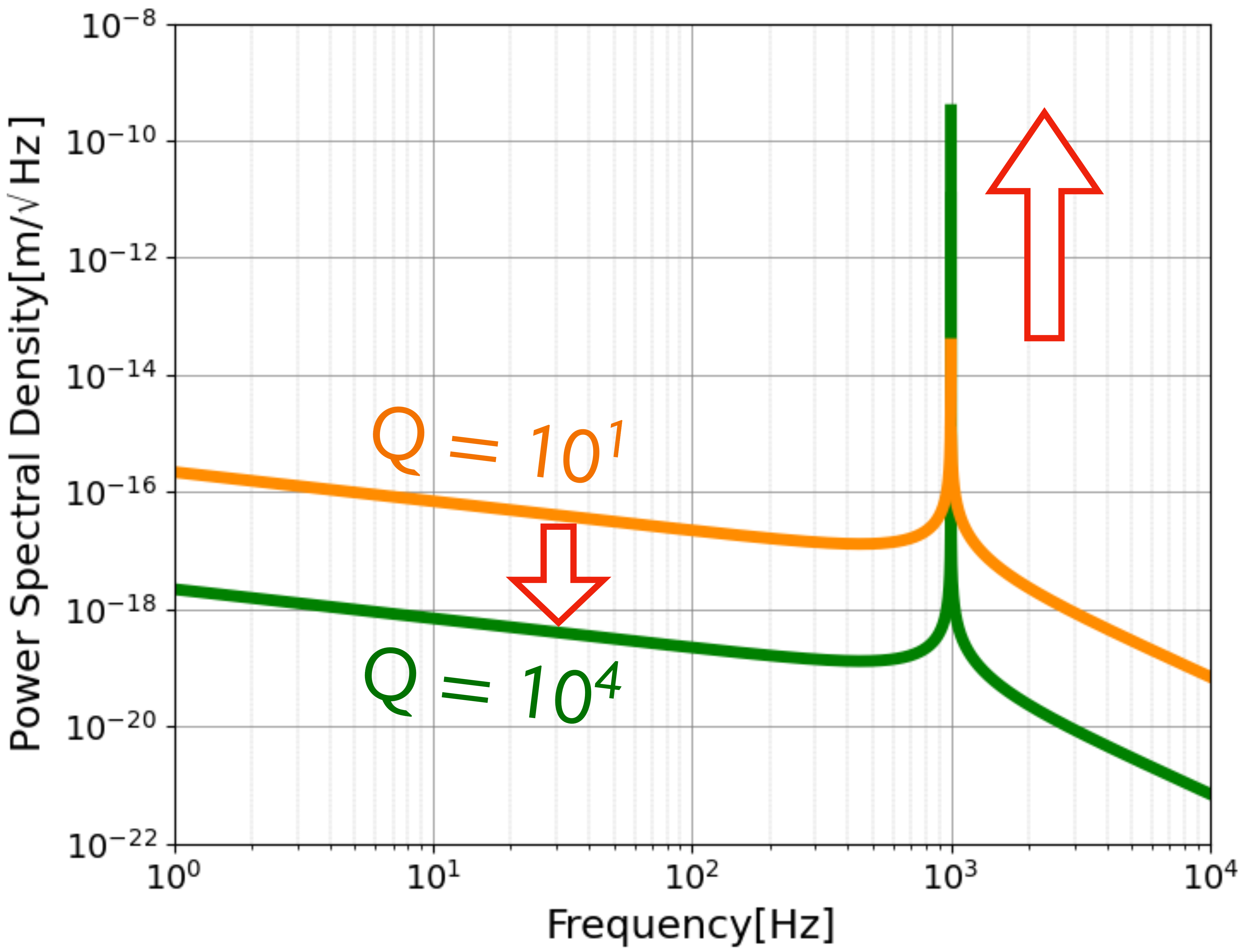
Mechanical loss

Mechanical loss

- Due to the loss of the elastic energy inside the mirror.
- The ratio of the dissipated energy per cycle to total stored energy.

$$\phi = \frac{E_{\text{lost per cycle}}}{2\pi E_{\text{total stored}}} = \frac{1}{Q}$$

Peak sharpness at resonant frequency



Reduce the coating thermal noise
⟶ Use a material with **small mechanical loss in the coating**

Purpose of measurement

The TiO_2 doped coating has a smaller mechanical loss at 300 K.

	Substrate	Coating	Temperature
LIGO and Virgo	Fused silica	SiO_2/Ta_2O_5 doped TiO_2	300 K
KAGRA	Sapphire	SiO_2/Ta_2O_5 undoped TiO_2	about 20 K

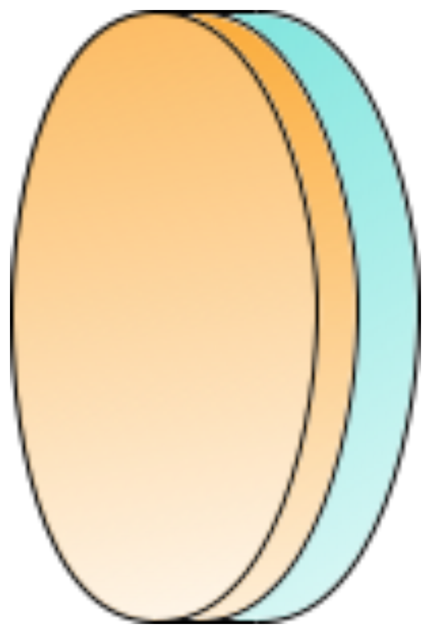
Comparison of the mechanical loss of coating of TiO_2 doped and undoped on sapphire at low temperature.

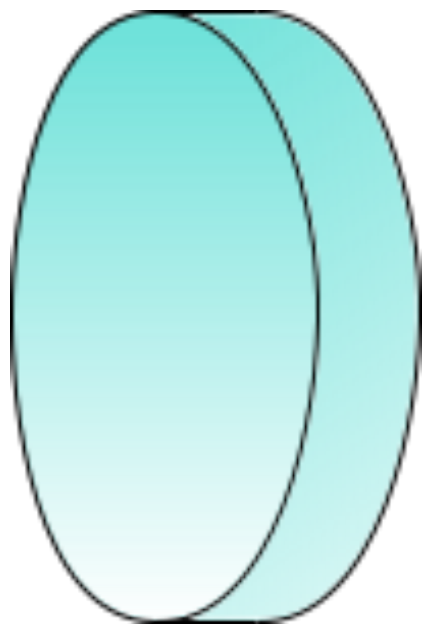
Estimation of coating mechanical loss ϕ

Coating is extremely thin. → We prepare two kind of sapphire disks.

The one sapphire disk is **with coating**, and the other one is **without coating**.
We measure each mechanical loss and take the difference between the two disks.

$$\phi_{\mathrm{coating}} \simeq \frac{E_{\mathrm{sapphire}}}{E_{\mathrm{coating}}}\left(\phi_{\mathrm{with\ coating}} - \phi_{\mathrm{without\ coating}}\right)$$





Elastic strain energy E

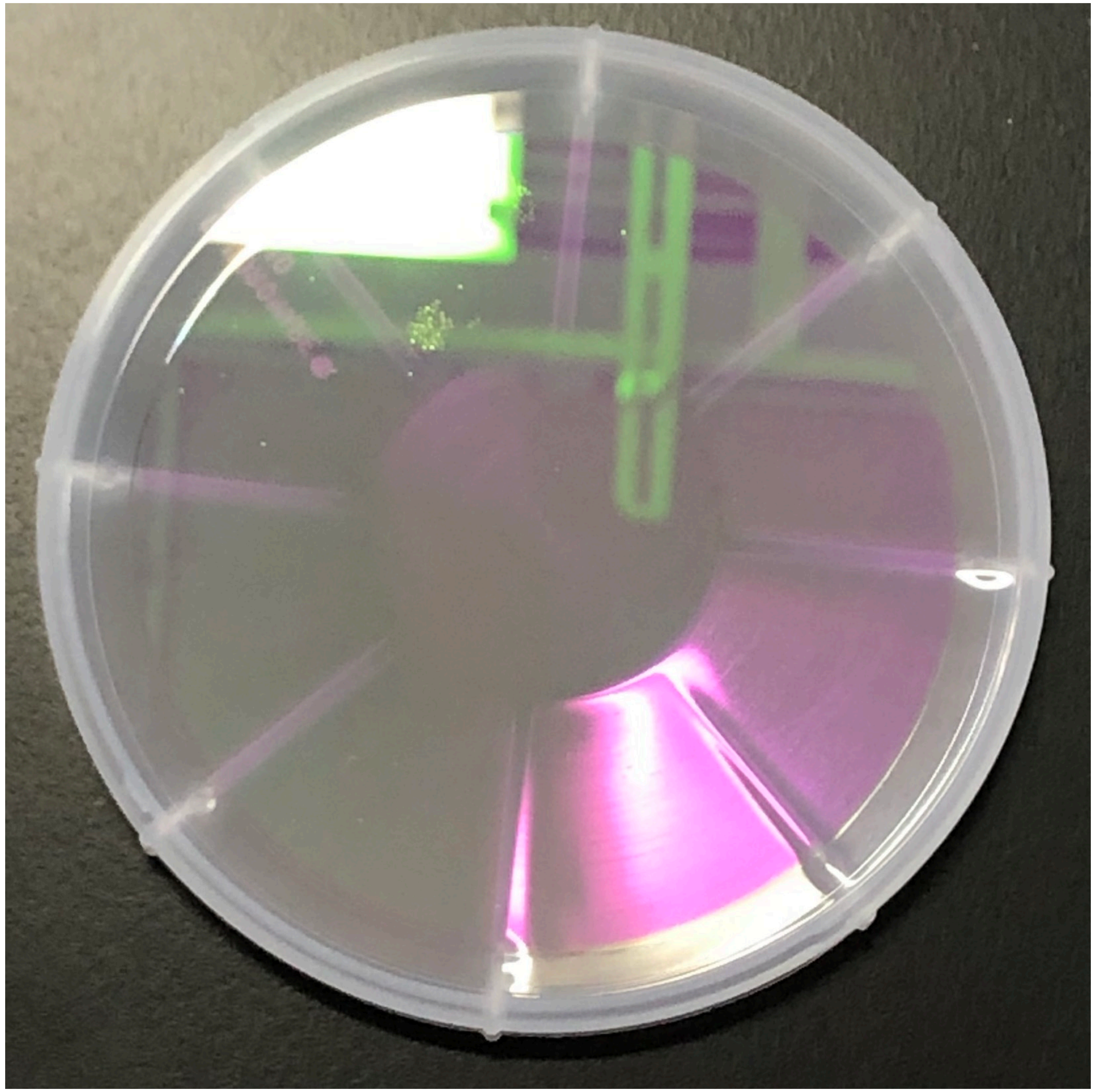
- Stored energy in deformed material.
- The value is calculated using FEM：COMSOL

Sample

Sapphire disk : 100 mm diameter and 0.5 mm thickness

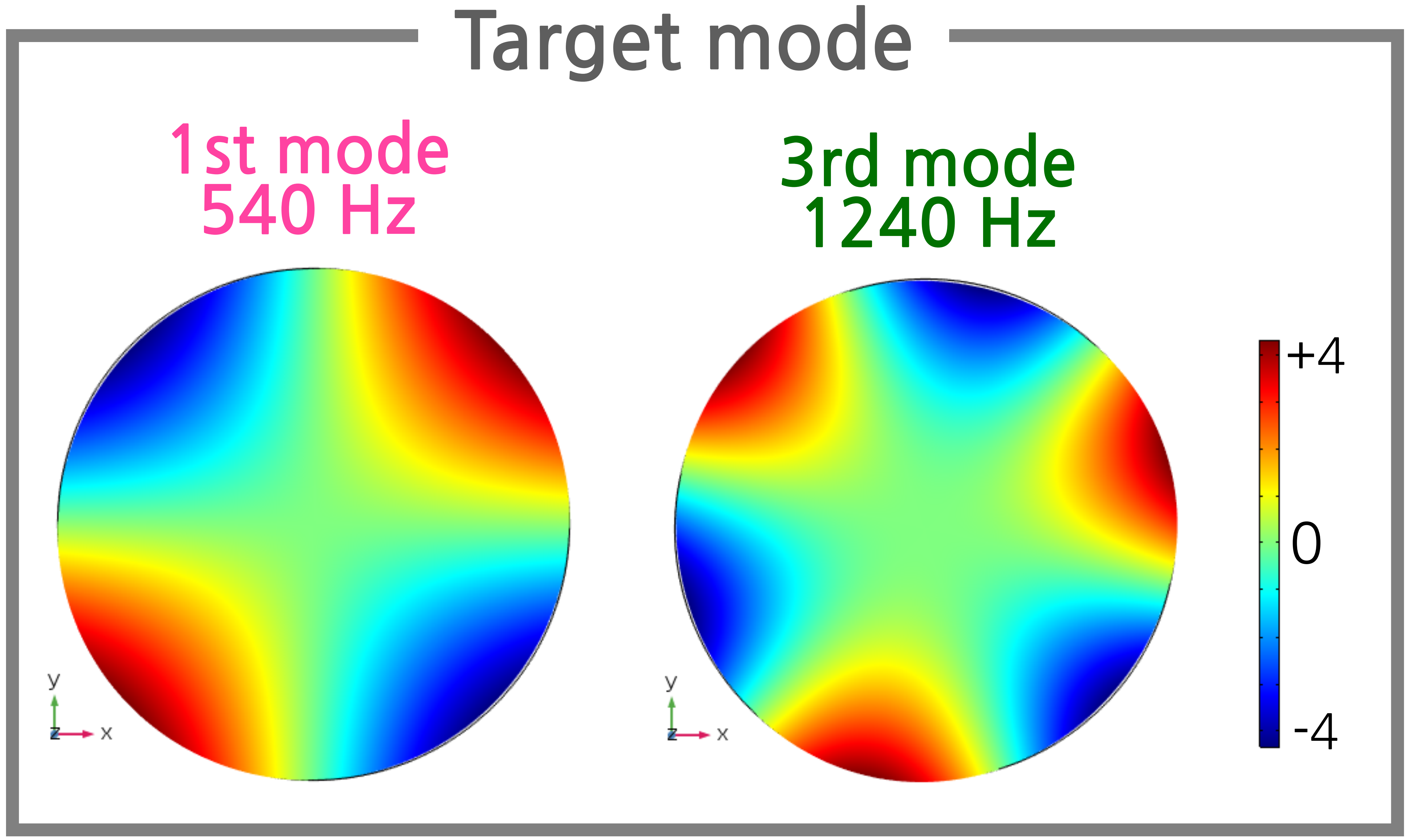
Substrate	Coating
Sapphire	SiO_2/Ta_2O_5 doped TiO_2(38 layers)
Sapphire	SiO_2/Ta_2O_5 undoped TiO_2(40 layers)
Sapphire	Nothing

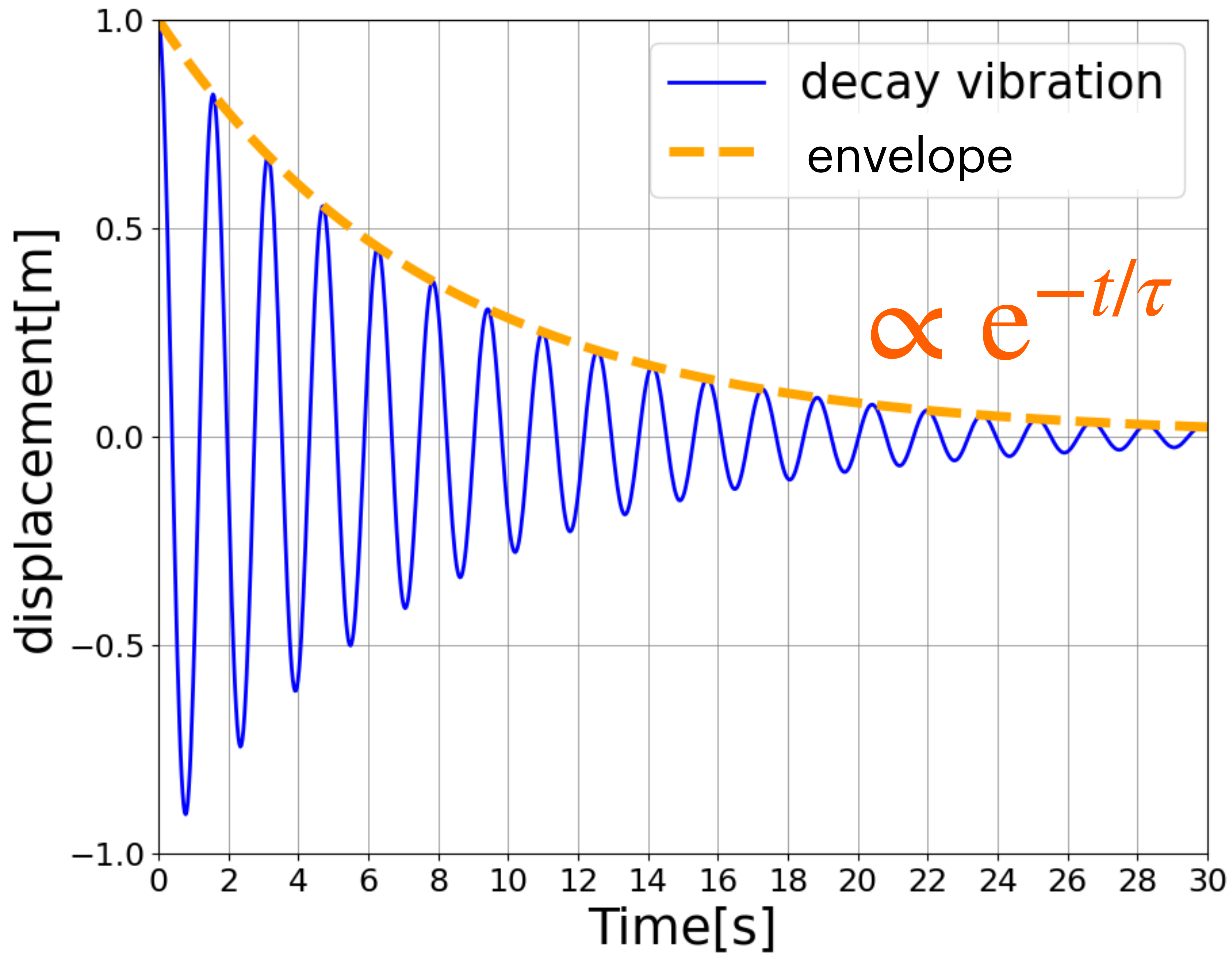
Deposited at LMA(France),
which deposit coating LIGO, Virgo and KAGRA mirrors



Ring down method

1. Exciting the disk at a resonant frequency using an electrostatic actuator.
2. Stop the excitation of the actuator.
3. Measuring the decay time τ by an electrostatic transducer.
4. ϕ is derived from $\phi = 1/f\pi\tau$ (f: resonant frequency).

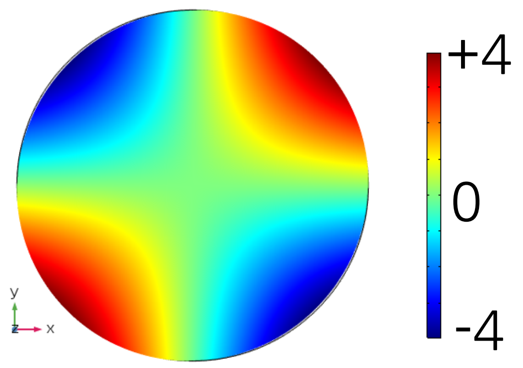




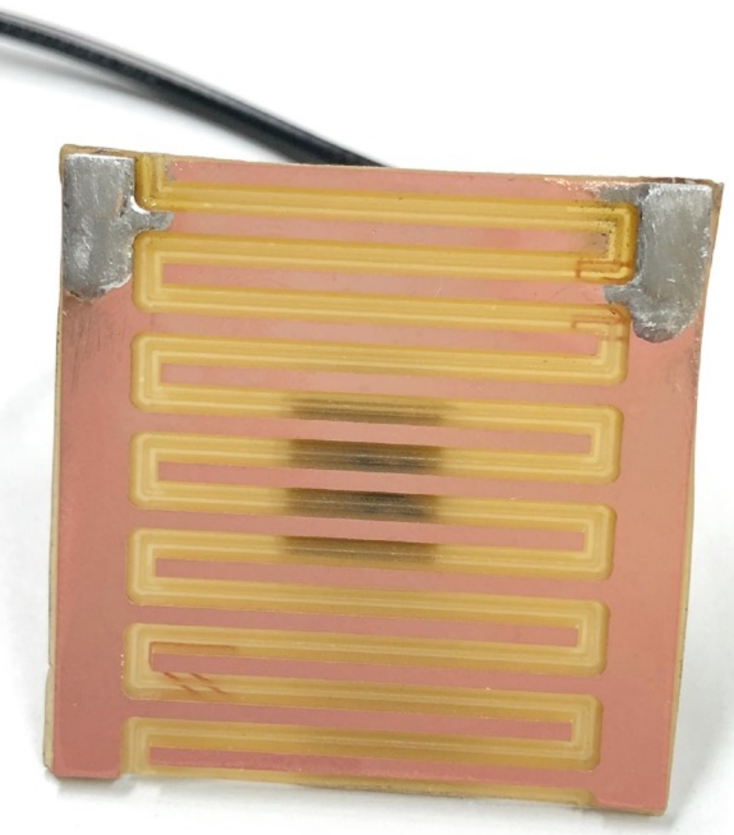
Experiment apparatus in Univ.Toyama

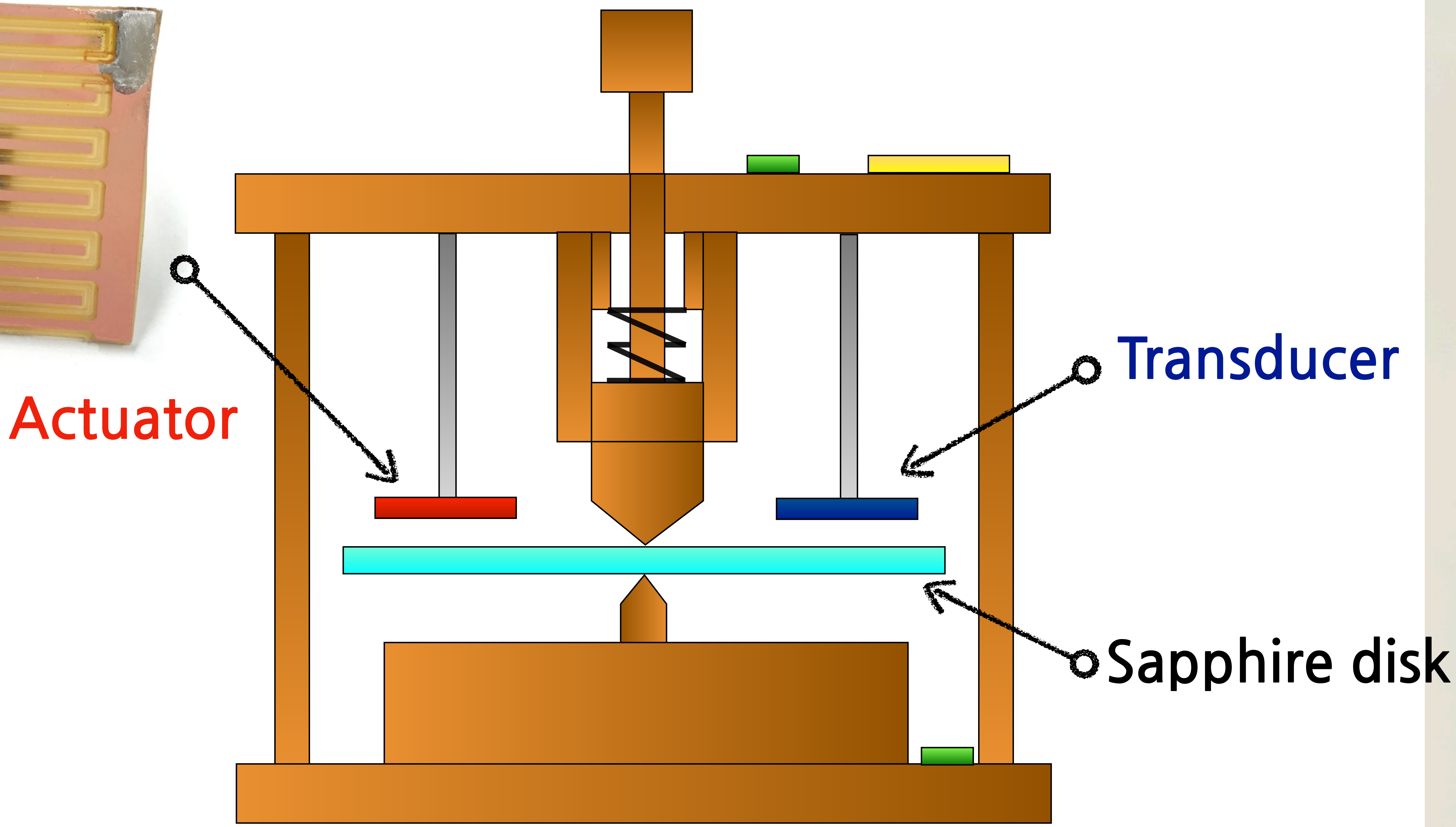
Nodal support system

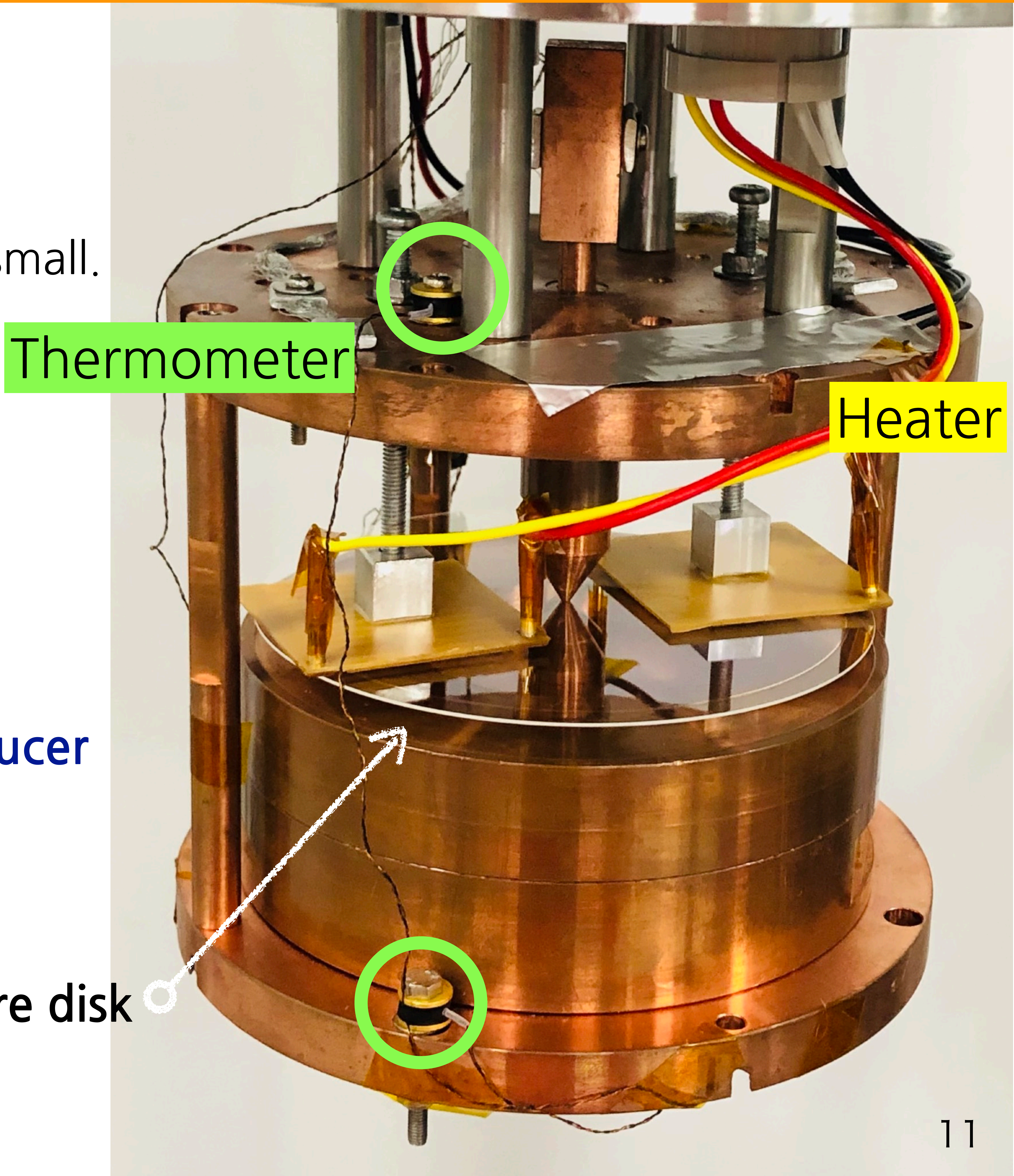
Only the center of the disk is fixed.



→ The center in our measured resonant mode is the node.
The effect of the loss in the support system is extremely small.

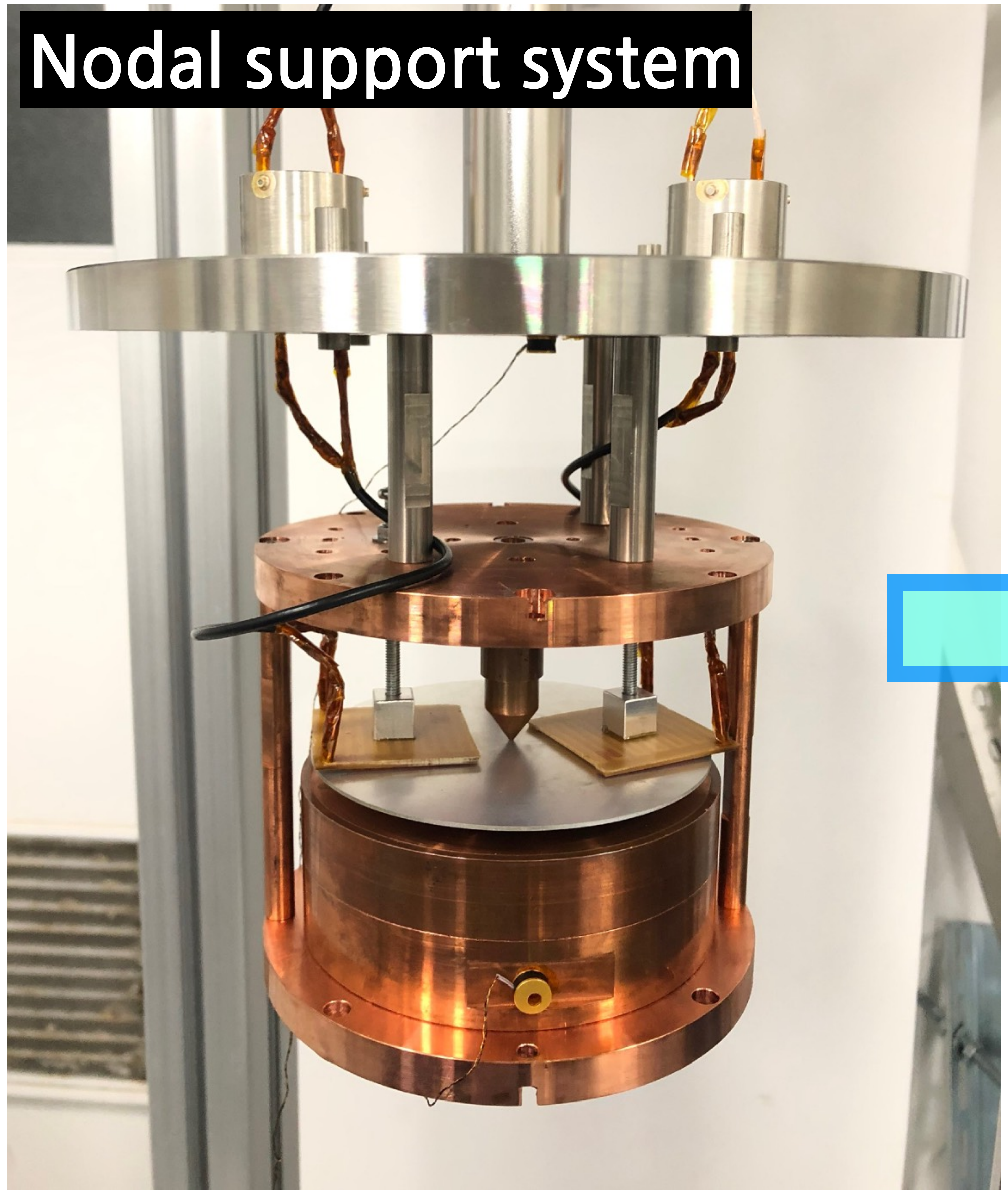


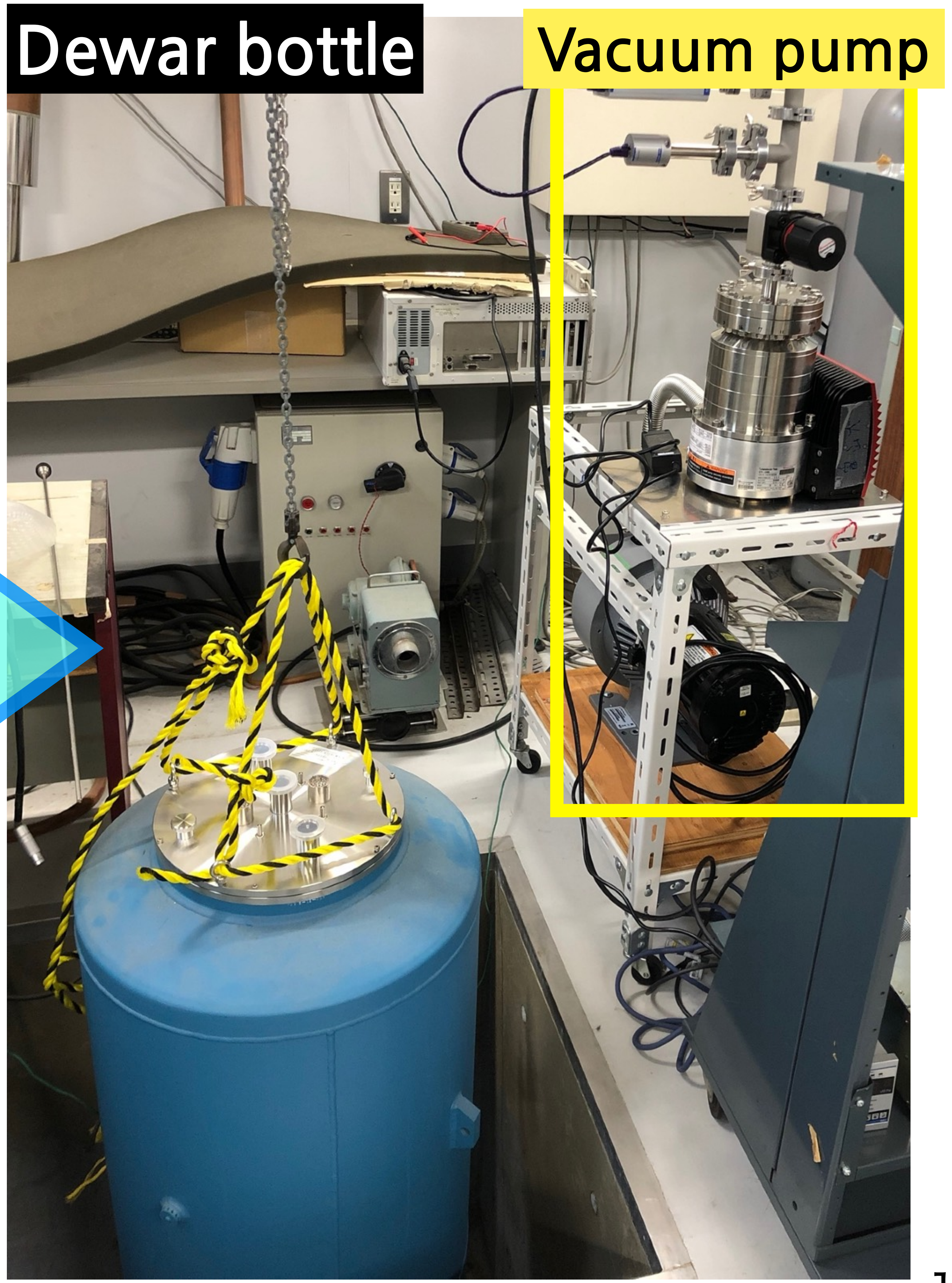




Cooling method

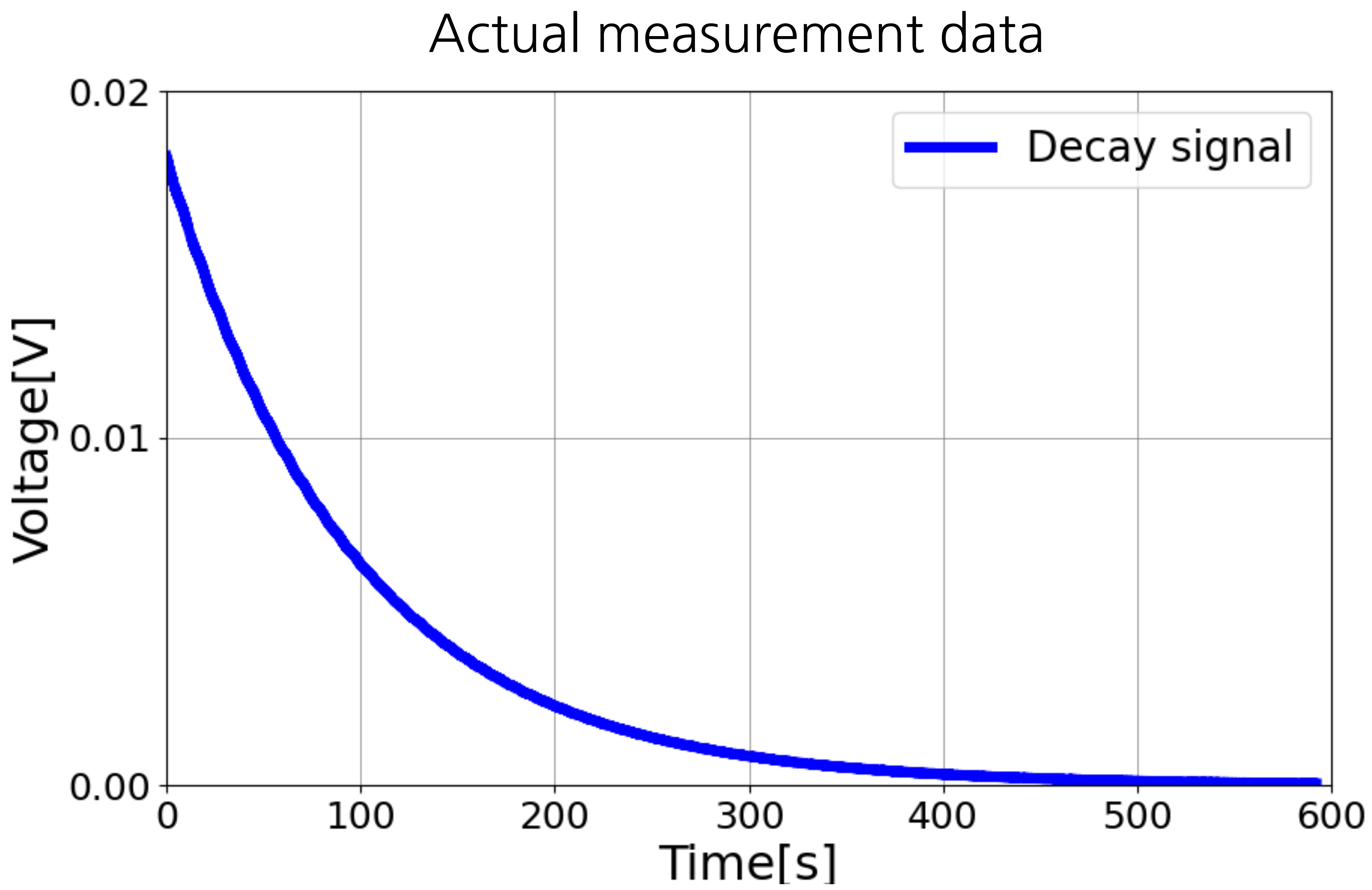
We use liquid nitrogen and liquid helium to cool down our experimental apparatus.





Actual measurement data : ϕ_{with} and $\phi_{without}$

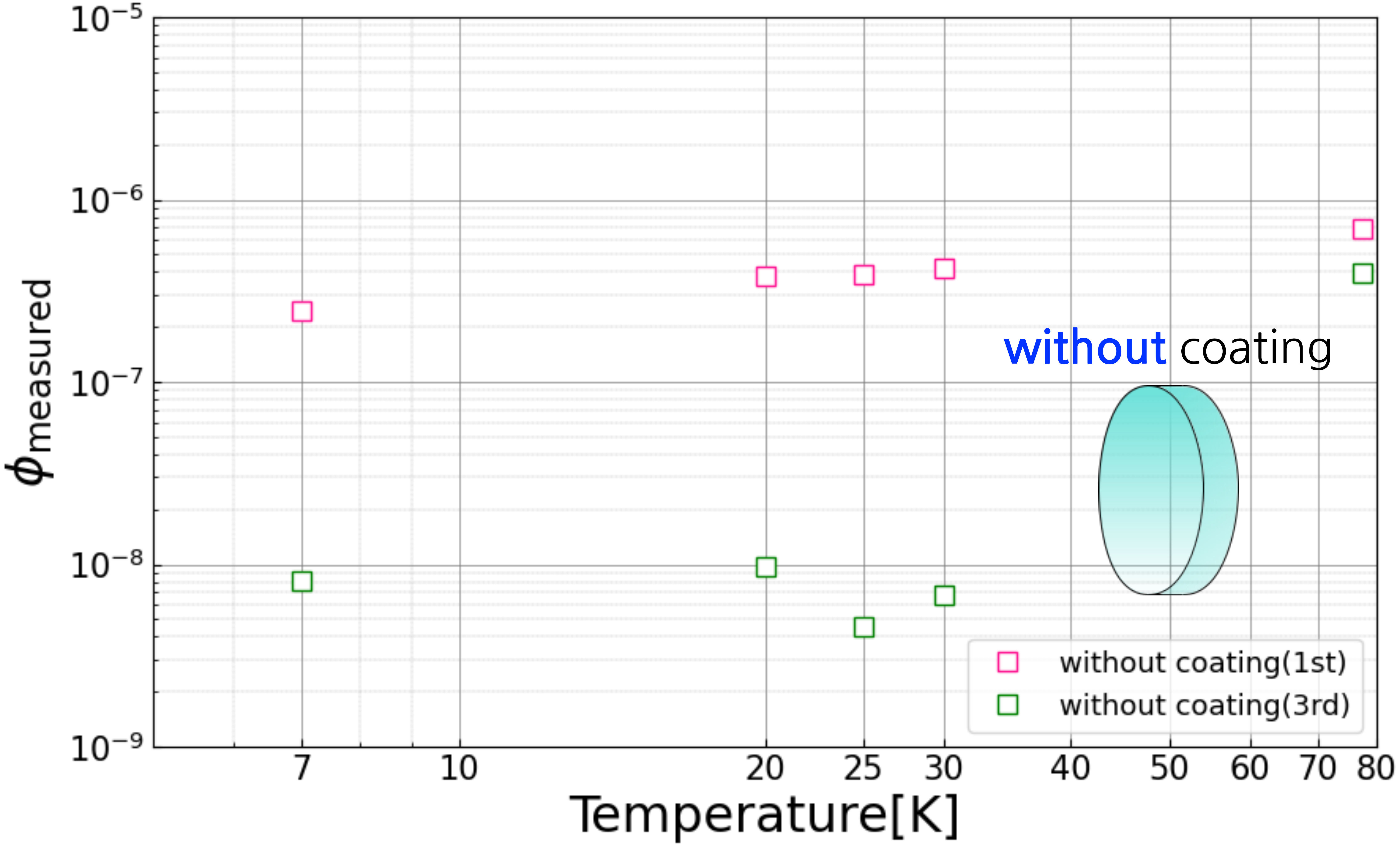
We extract only the resonant frequency components by the lock-in amplifier.

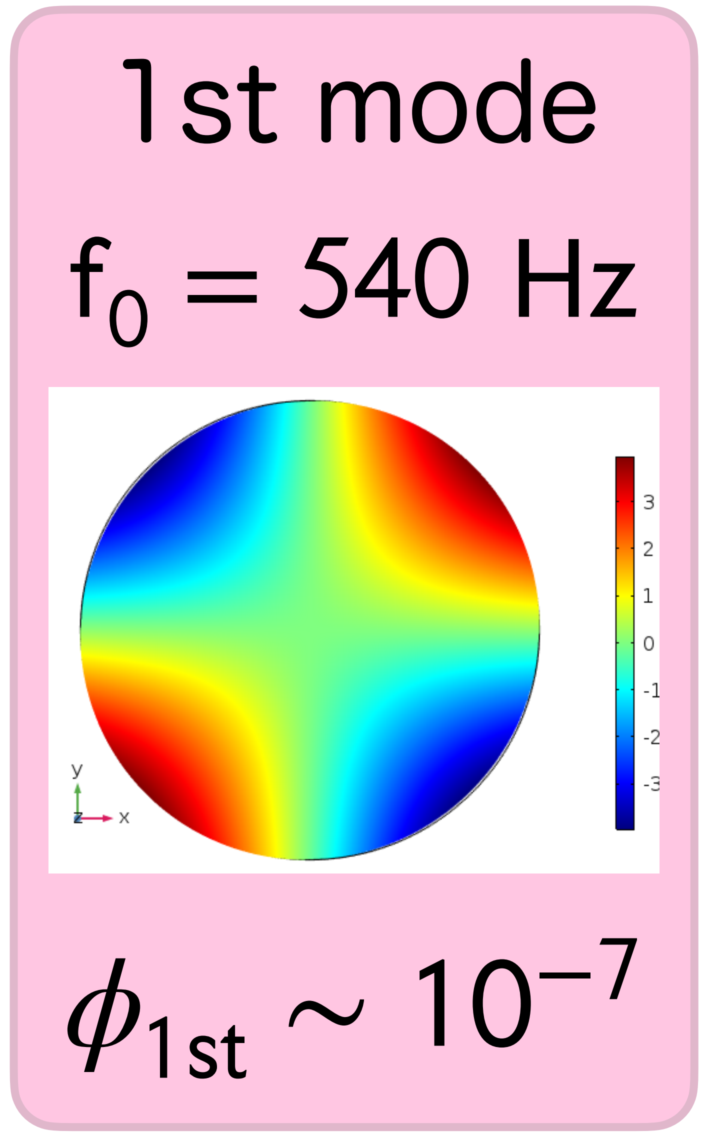


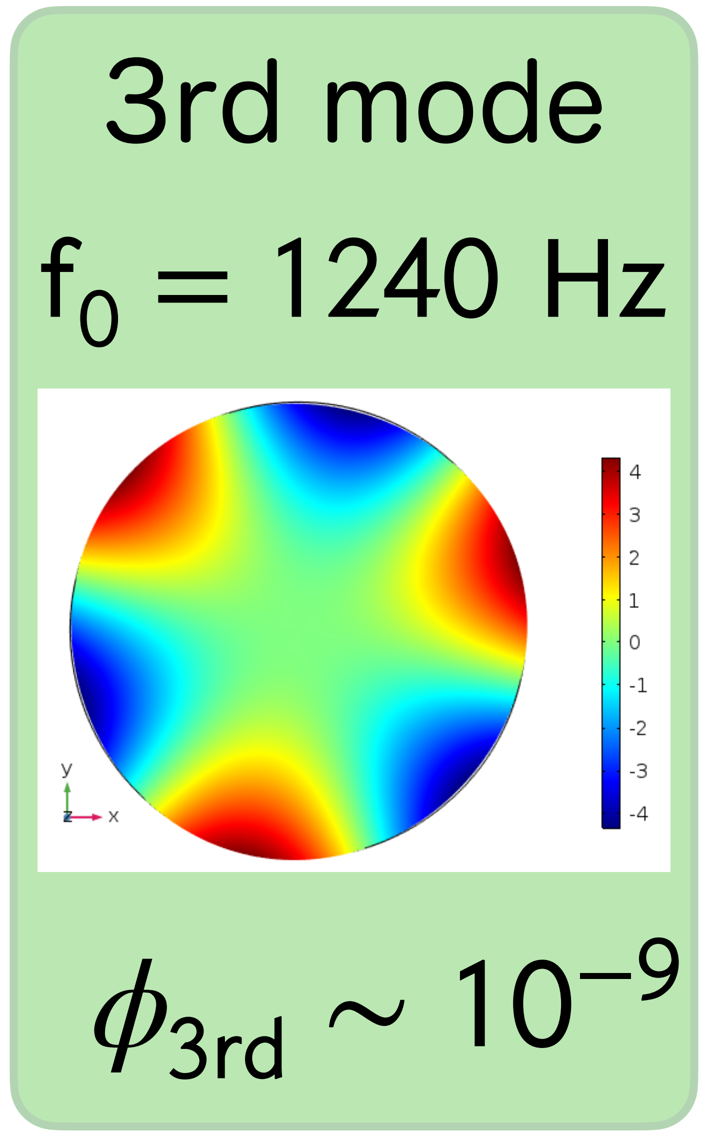
We measure the decay time and estimate the mechanical loss for each disk between 6 K and 77 K.

Result : Measured mechanical loss ϕ_{with} and ϕ_{without}

$$\phi_{\mathrm{coating}} \simeq \frac{E_{\mathrm{sapphire}}}{E_{\mathrm{coating}}}\left(\phi_{\mathrm{with}} - \phi_{\mathrm{without}}\right)$$

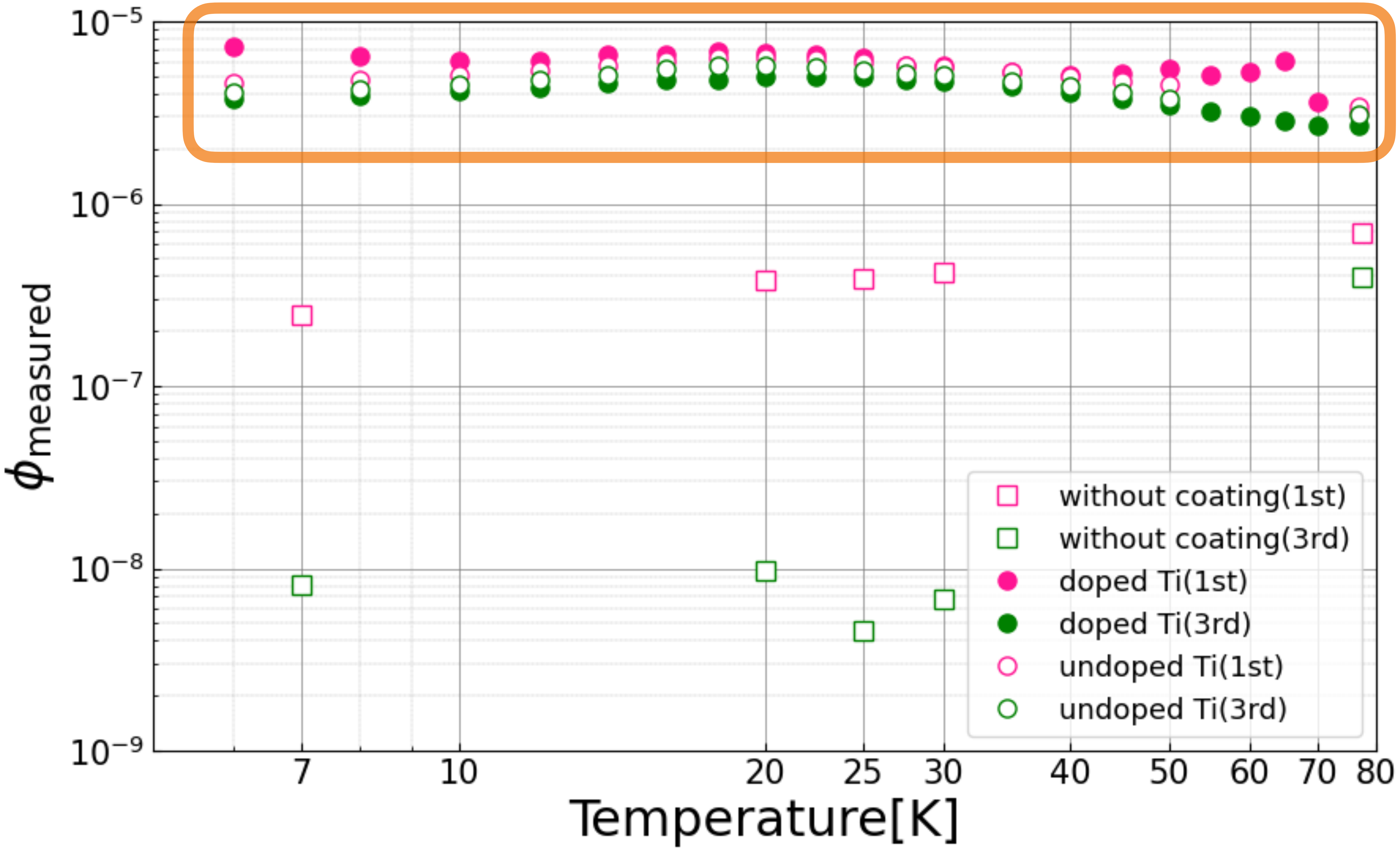




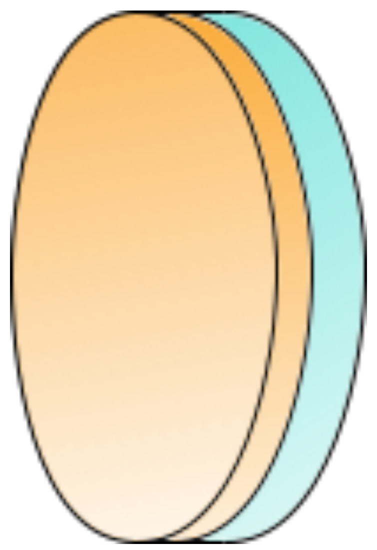


Result : Measured mechanical loss ϕ_{with} and ϕ_{without}

$$\phi_{\mathrm{coating}} \simeq \frac{E_{\mathrm{sapphire}}}{E_{\mathrm{coating}}}\left(\phi_{\mathrm{with}} - \phi_{\mathrm{without}}\right)$$

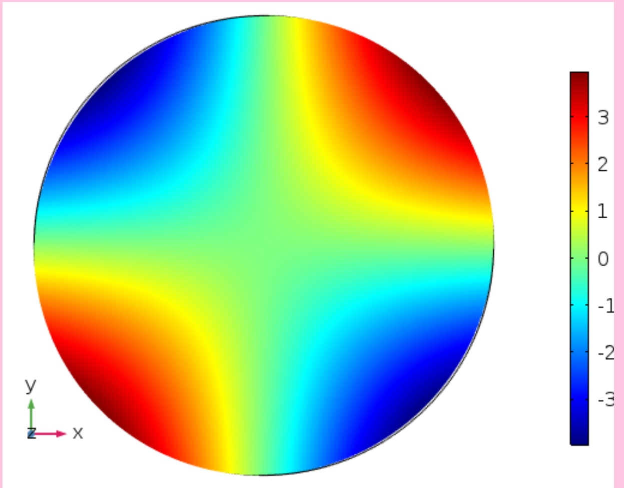


with coating



1st mode

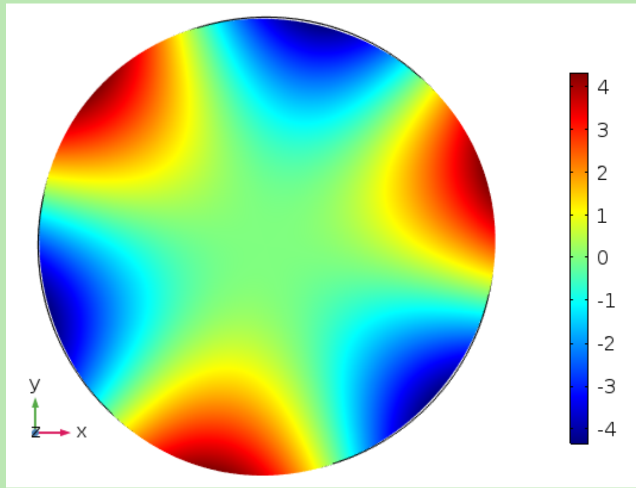
$f_0 = 540$ Hz



$\phi_{1st} \sim 10^{-6}$

3rd mode

$f_0 = 1240$ Hz



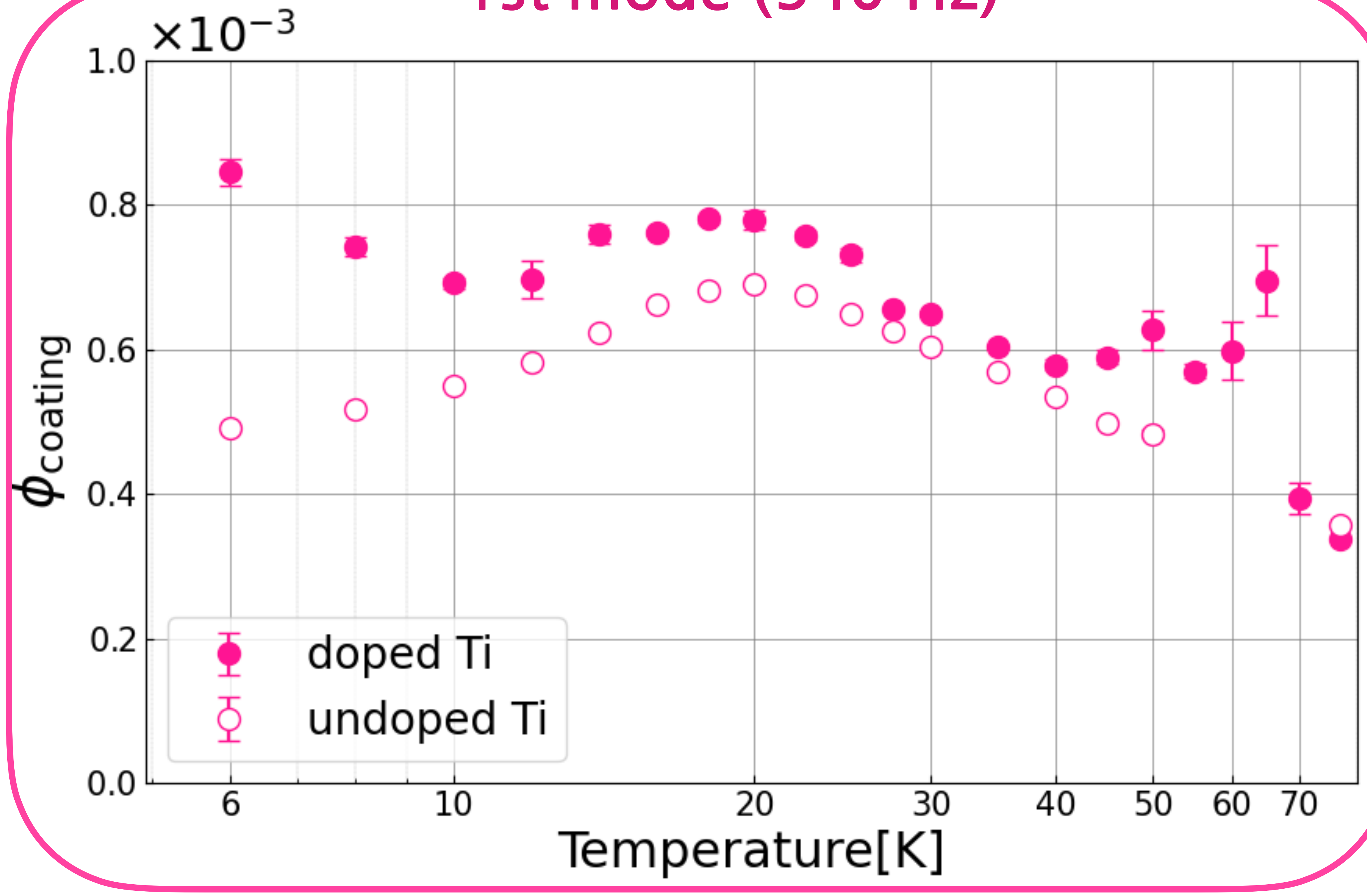
$\phi_{3rd} \sim 10^{-6}$

We can measure ϕ_{with} clearly.

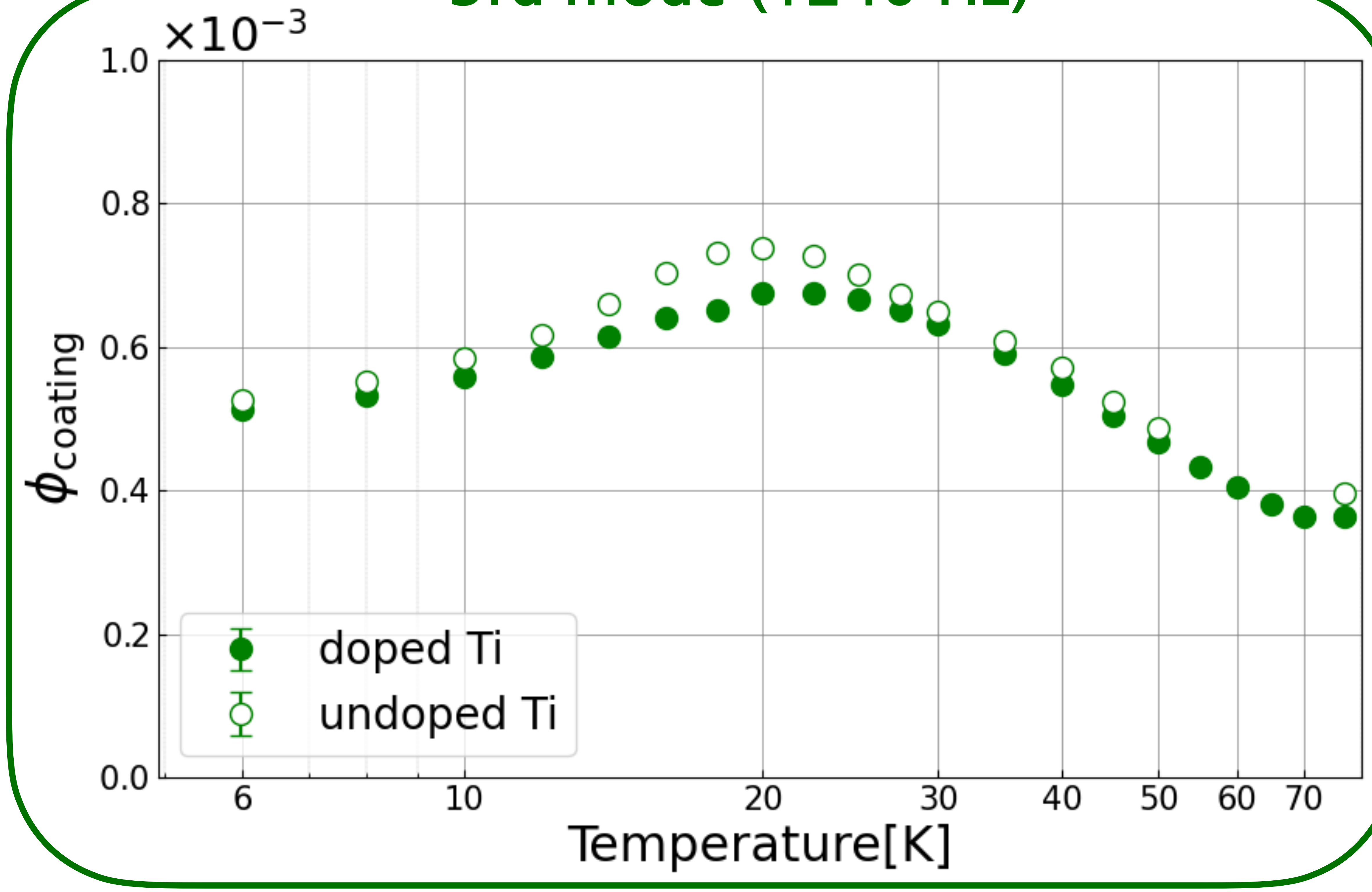
Estimation : Coating mechanical loss $\phi_{coating}$

$$\phi_{coating} \simeq \frac{E_{sapphire}}{E_{coating}} \left(\phi_{with} - \phi_{without} \right)$$

1st mode (540 Hz)



3rd mode (1240 Hz)



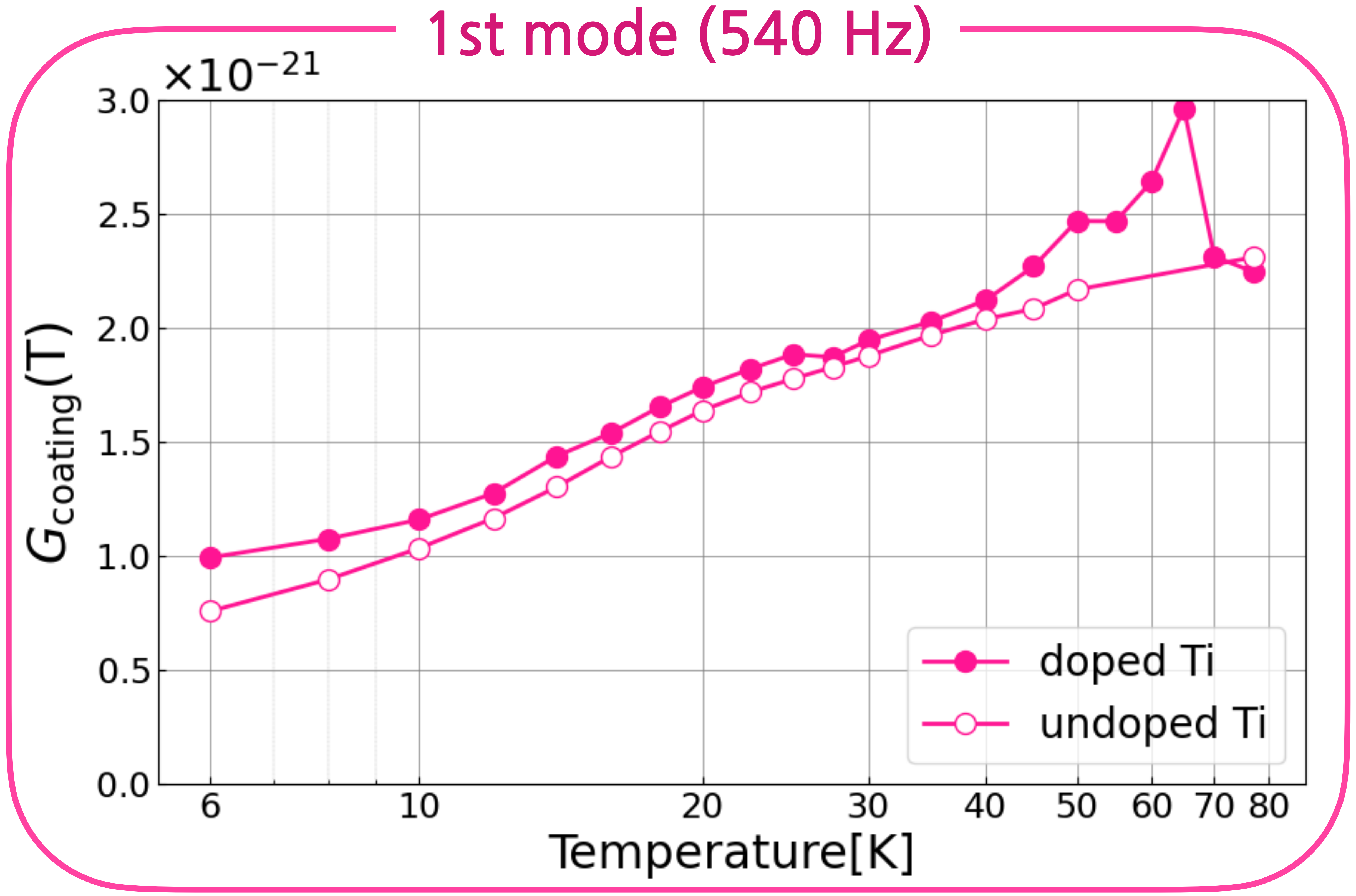
Temperature dependence : Peak at around 20 K

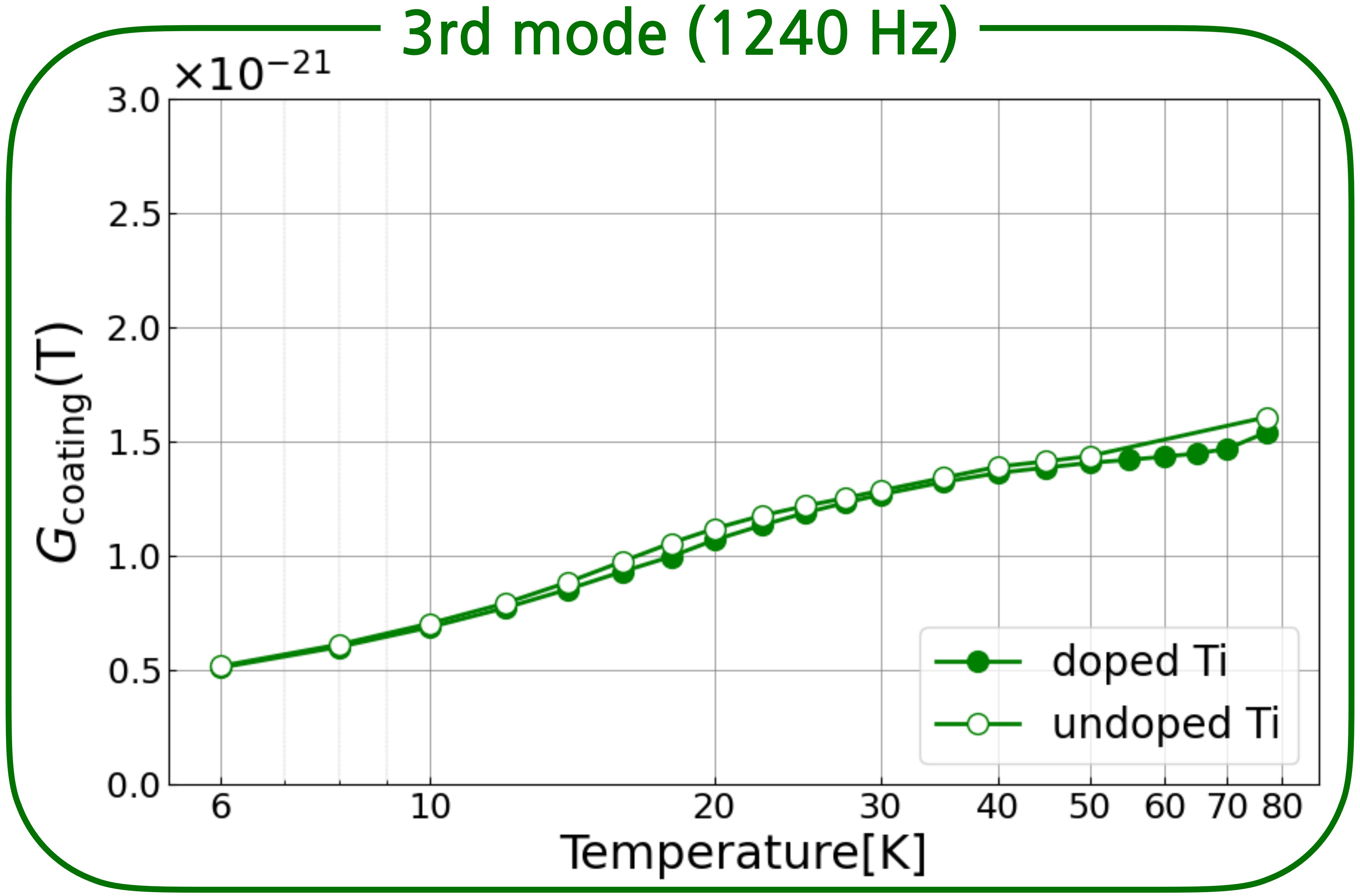
We derive the thermal noise from our result.

- Temperature dependence of coating thermal noise.
- The contribution of TiO_2 doped and undoped coating.

Estimation：Coating thermal noise $G_{\text{coating thermal noise}}$

$$G_{\text{thermal noise}} \simeq \sqrt{\frac{2k_B T}{\pi^2 f}\frac{d}{\omega^2 Y_{\text{sapphire}}}\phi\left(\frac{Y_{\text{coating}}}{Y_{\text{sapphire}}}+\frac{Y_{\text{sapphire}}}{Y_{\text{coating}}}\right)}$$



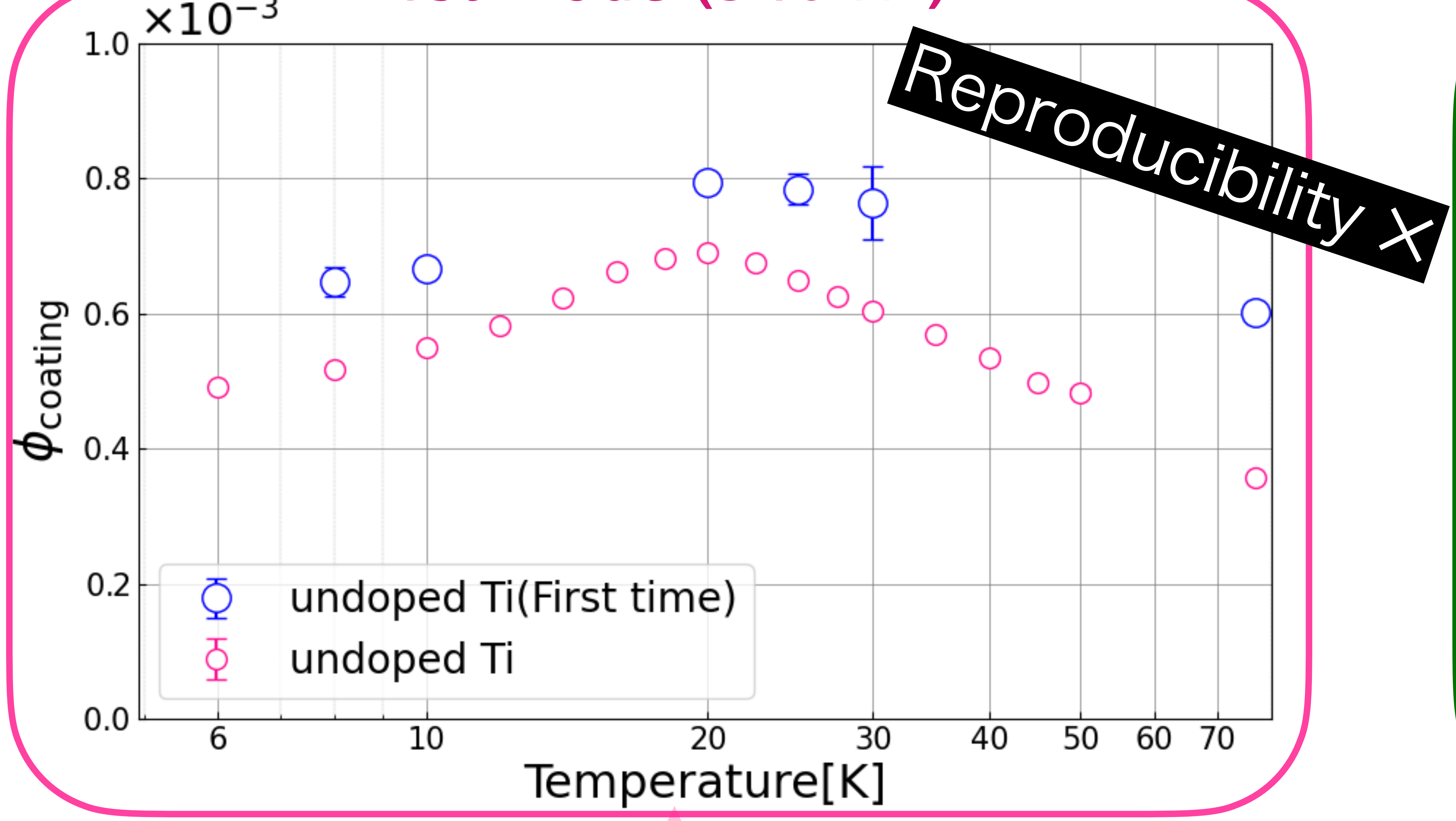


- The coating thermal noise is smaller at lower temperatures.
- Contribution to thermal noise：No large difference between TiO_2 doped and undoped coating.

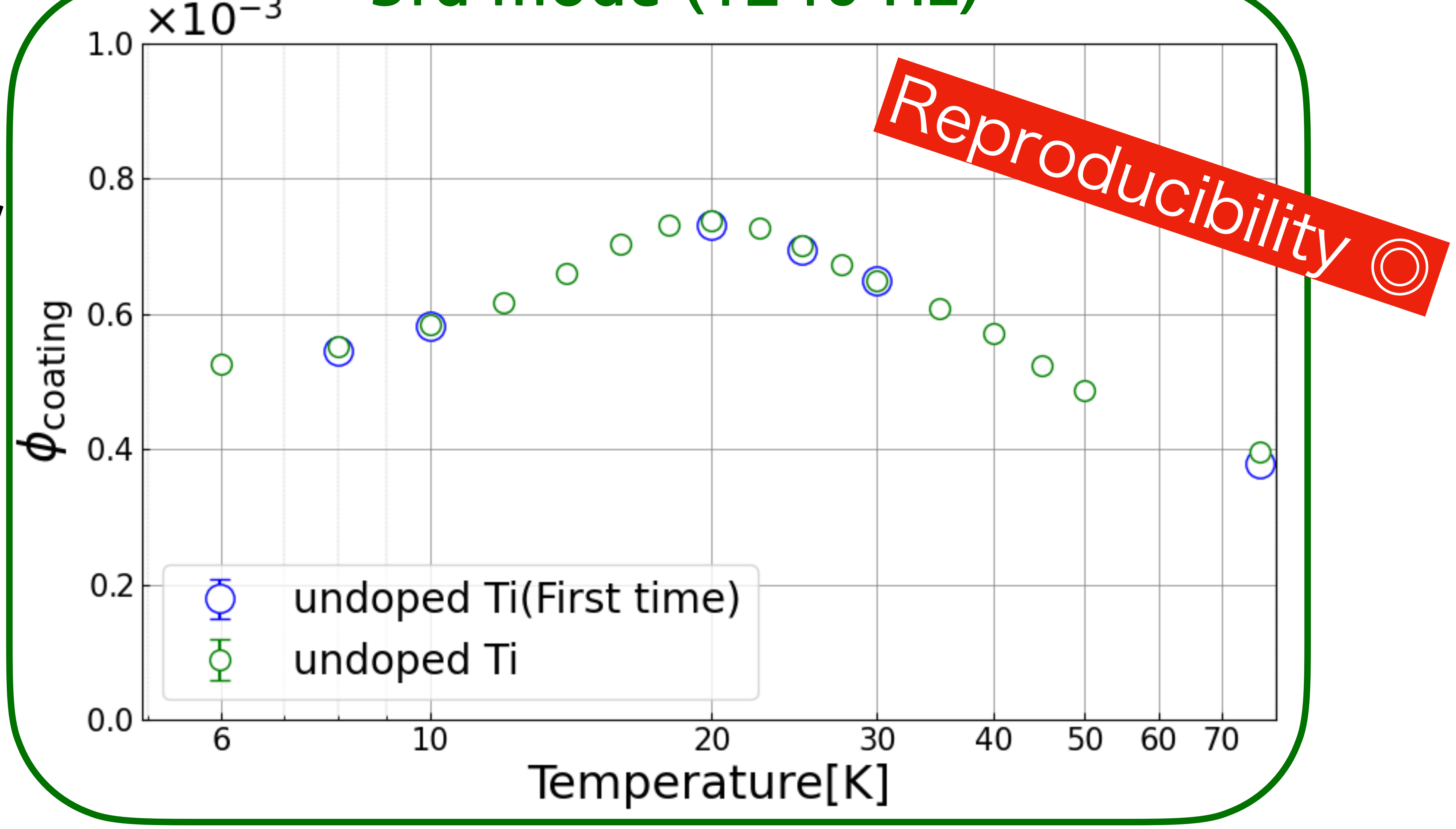
Discussion

The reproducibility of the measurement of ϕ → We measure the same sample twice

1st mode (540 Hz)



3rd mode (1240 Hz)

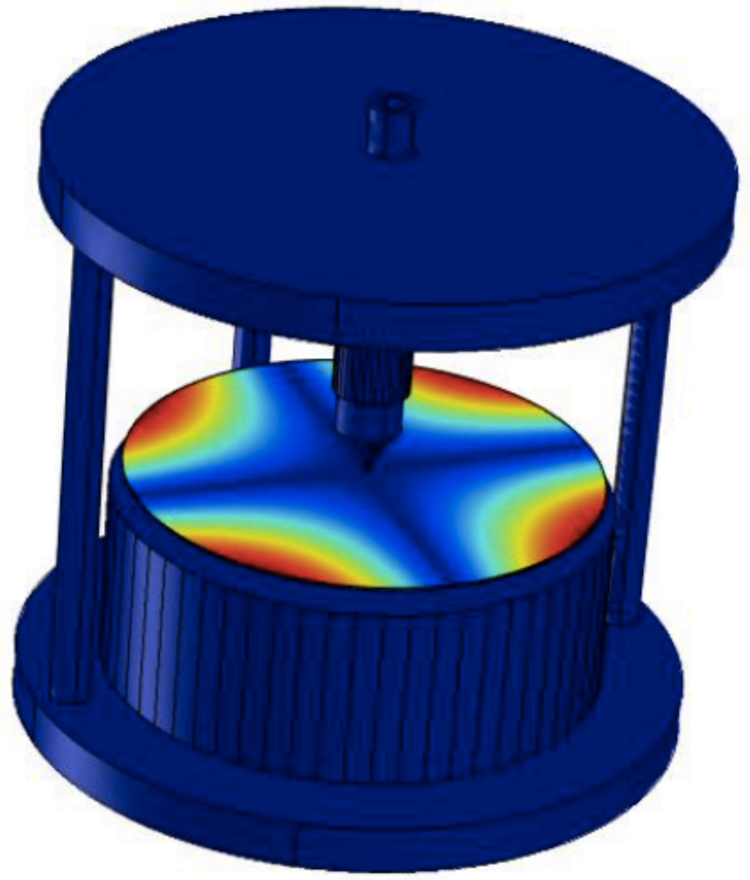


Due to the nodal support system..?

—The amplitude near the center is larger in 1st mode than that in 3rd mode.

—The 1st mode has a large loss originating from the support system

(The 3rd mode is flatter near the center.)



The ϕ depends on how to set the disk to the support system.

This needs further research.

Summary

- The mirror thermal noise mainly comes from the coating around 100 Hz.
- We constructed experimental apparatus at the Univ.Toyama to evaluate the mechanical loss of the coating over a wide temperature range.
- We measure the mechanical loss of the TiO_2 doped and undoped coating on sapphire from 6 K to 77 K.
- Mechanical loss of the coating depends on the temperature : local maximum around 20K
- Contribution to thermal noise :

No large difference between the TiO_2 doped and undoped coating on sapphire.

The thermal noise is smaller at lower temperatures.

Future plan

- Check reproducibility.
- Investigation to reduce the coating mechanical loss.

Thank you for your attention