Levitating Optomechanics

AIC session at LVK March 2021

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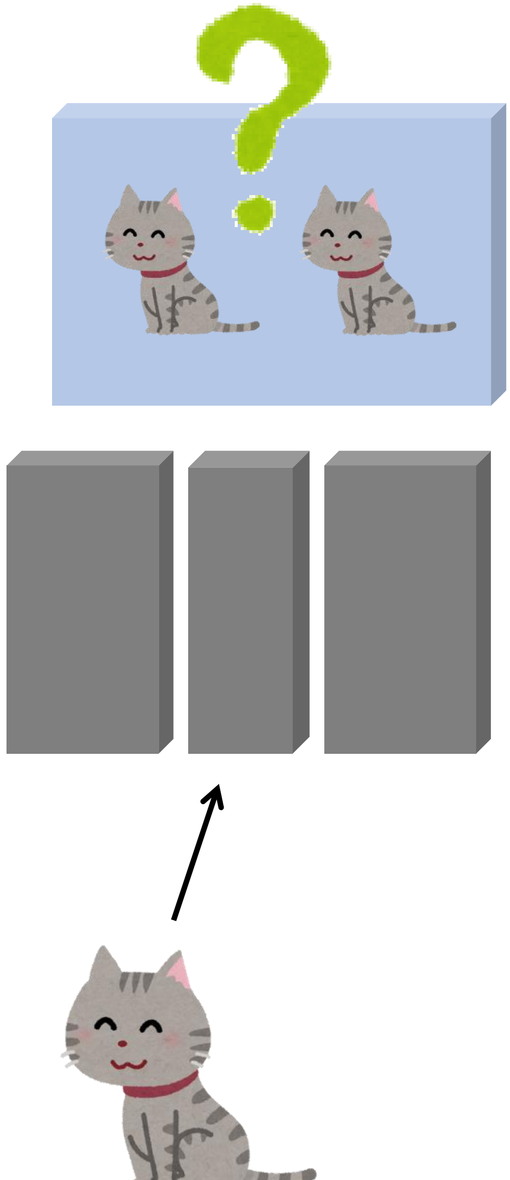
A part of the French-Japanese collaboration program (JST/ANR)
JST CREST #JPMJCR1873

Macroscopic Quantum Measurement

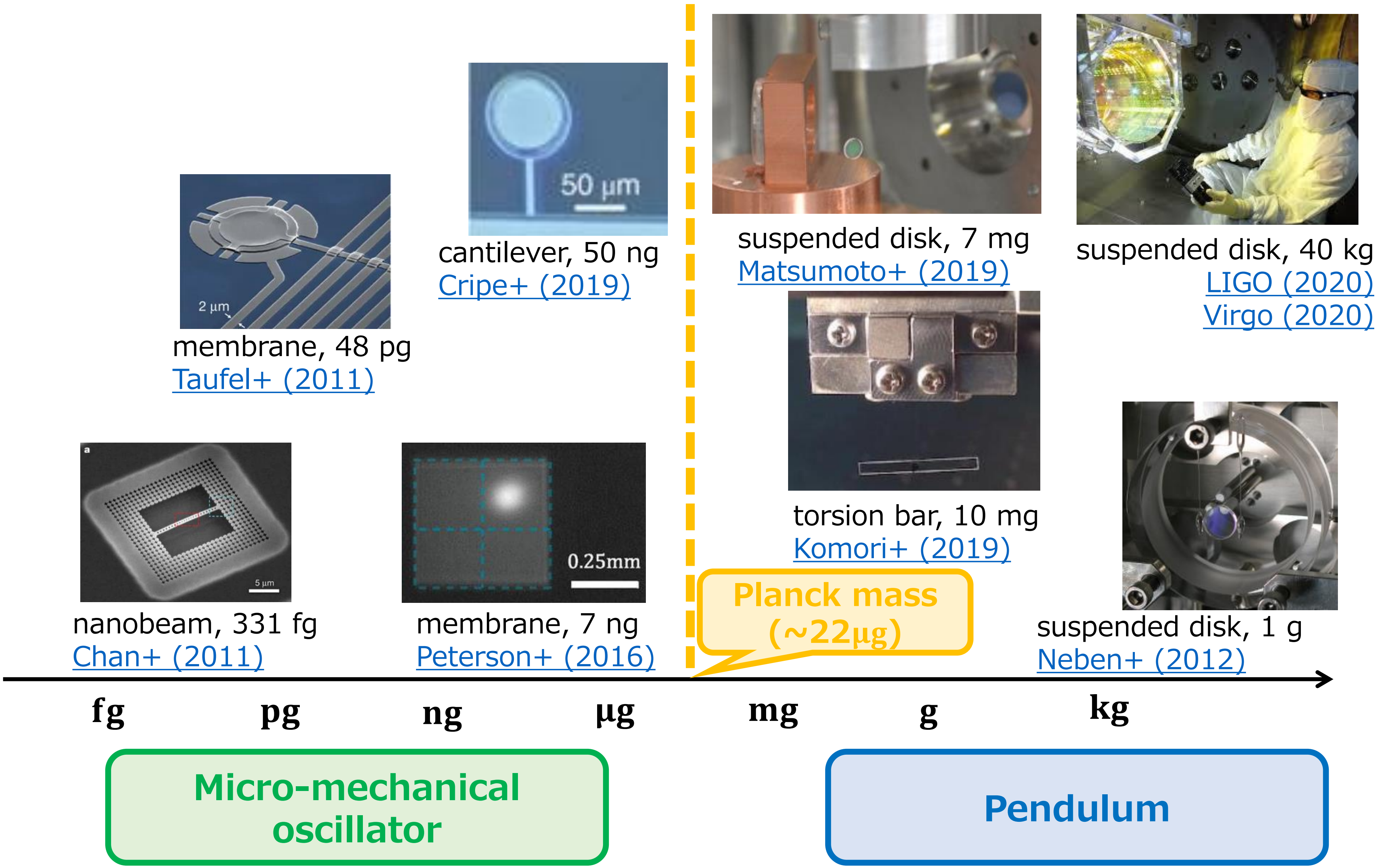


Fundamental difference between micro- and macro-scopic objects?

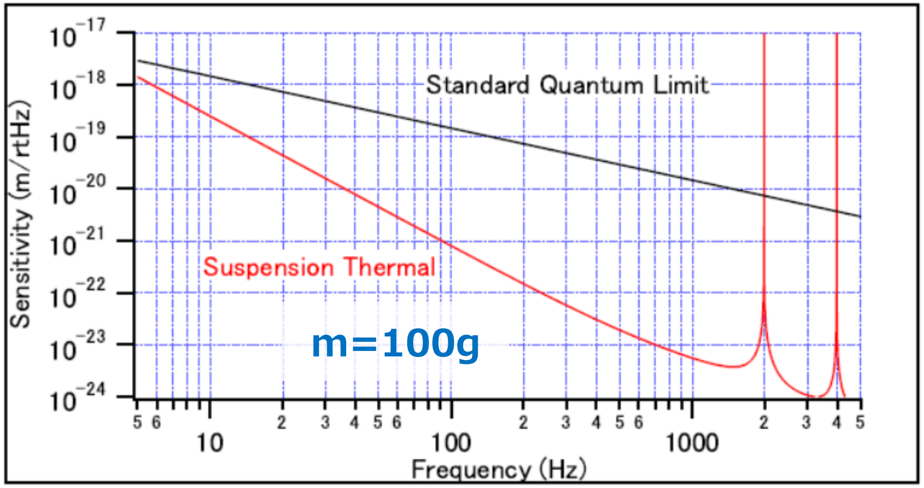
- **Environmental decoherence?**
- **Gravity decoherence?**

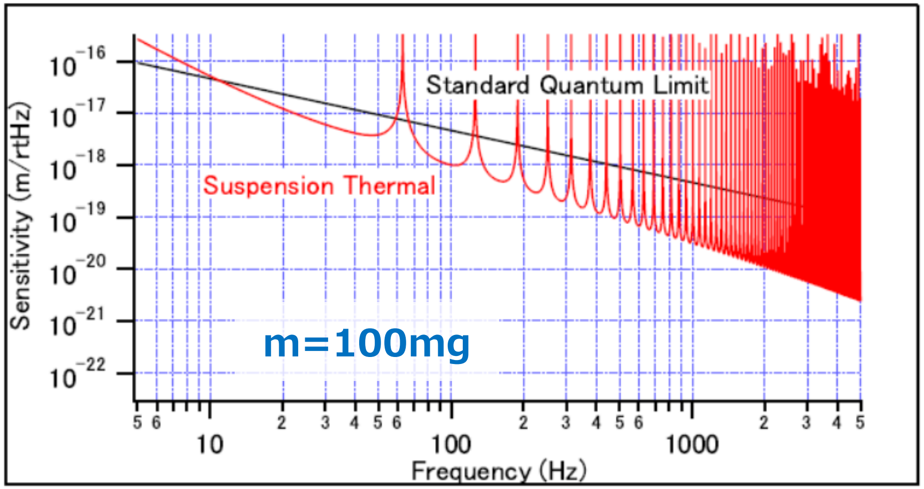
Reaching the standard quantum limit is a necessary condition to observe a quantum behavior of a macroscopic object.

MQM at various scales



Suspension thermal noise





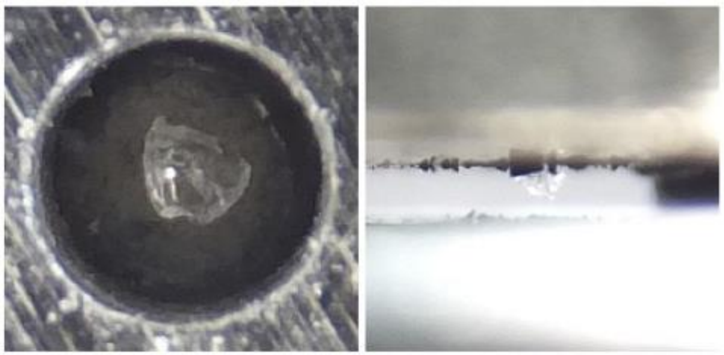
(Parameters used in the calculation above: loss=1e-7, material=silica, fiber diameter=10um.)

For a milligram-scale mass, pendulum's suspension thermal noise can easily exceed the SQL.

⇨ **Can we levitate the mass?**

Levitation experiments

(i) Diamagnetic levitation (Tokyo Tech)



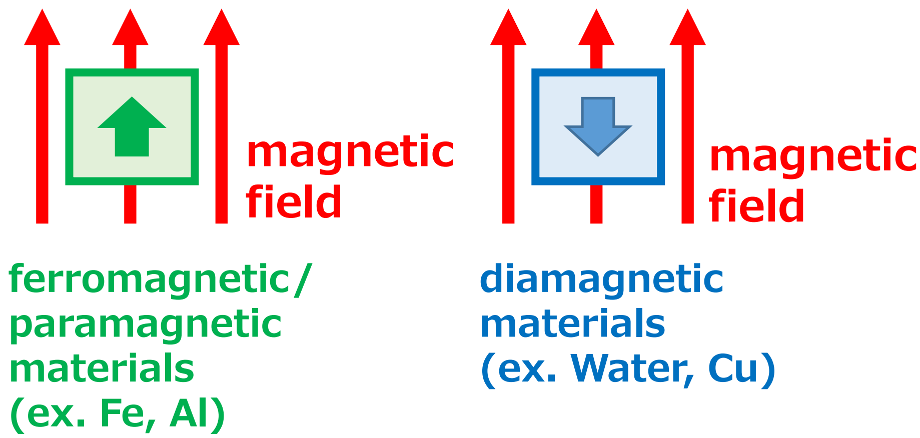
- Some materials can be levitated without an active control.
- We have succeeded in levitating a 1mg silica mass.
- Kentaro will talk about this.

(ii) Optical levitation (U Tokyo)

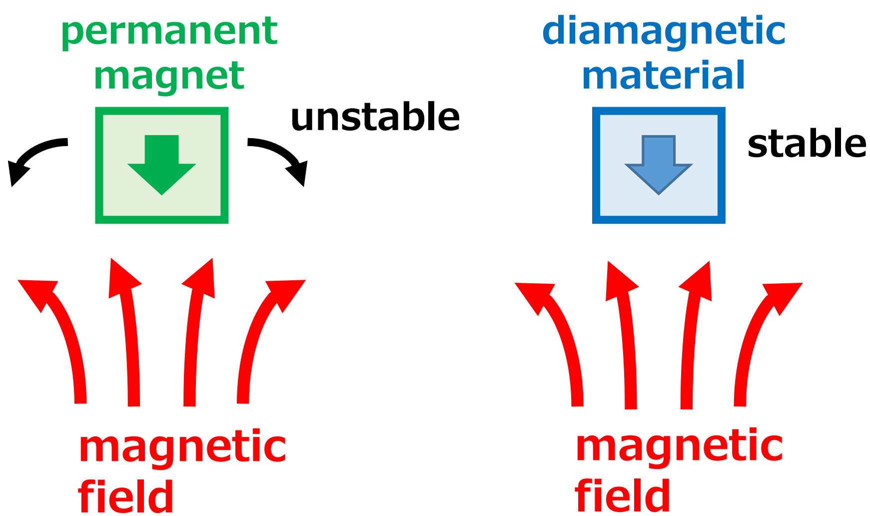
- A curved mirror can be stably levitated with two optomechanical springs.
- We have succeeded in verifying its stability in the horizontal direction.
- Yuta will talk about this.

Diamagnetic levitation (Tokyo Tech)

Diamagnetic levitation



A ferromagnetic material can make a permanent magnet, while diamagnetism appears only when the external magnetic field is applied.

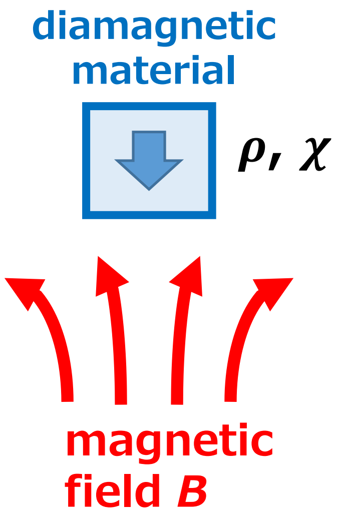


Due to Earnshaw's theorem a permanent magnet <u>cannot be stably levitated.</u>
($\Delta U = -\mu \Delta B = 0$)

A diamagnetic material can be <u>levitated stably</u>.

Levitating force

[Nakashima, PLA (2020)]



The levitating condition is

$$B_z \frac{\partial B_z}{\partial z} = \frac{\mu_0 \rho g}{\chi}$$

and the stability conditions are

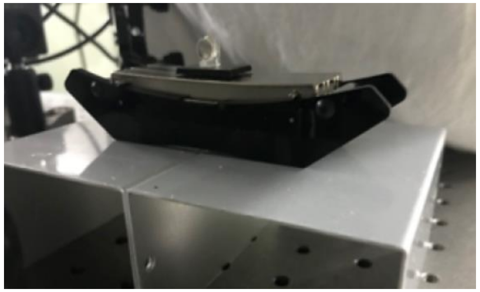
$$\frac{\partial^2 B_x}{\partial x^2} > 0, \quad \frac{\partial^2 B_y}{\partial y^2} > 0, \quad \frac{\partial^2 B_z}{\partial z^2} > 0$$

where μ_0 is permeability, ρ is density, and χ is magnetic susceptibility.

material	density ρ [g/cm^3]	susceptibility χ [10^{-5}]	required $B_z \partial B_z / \partial z$ [T^2/m]
graphite	1.7	20	100
bismuth	9.8	16	730
water	1.0	0.90	1400
silica	2.2	1.4	2000

We demonstrated levitating a graphite mass and a silica mass.

Figure of merit



Levitated graphite and a silica mirror on graphite.

Micro-lens (Sigma-koki); This is actually not silica but LaSF9

Graphite

- **High magnetic susceptibility**
  >> Easy to levitate
- **Electrical resistivity is low ($10^{-6}\Omega/\text{m}$)**
  >> Thermal noise can be large
  >> Need a uniform B_x

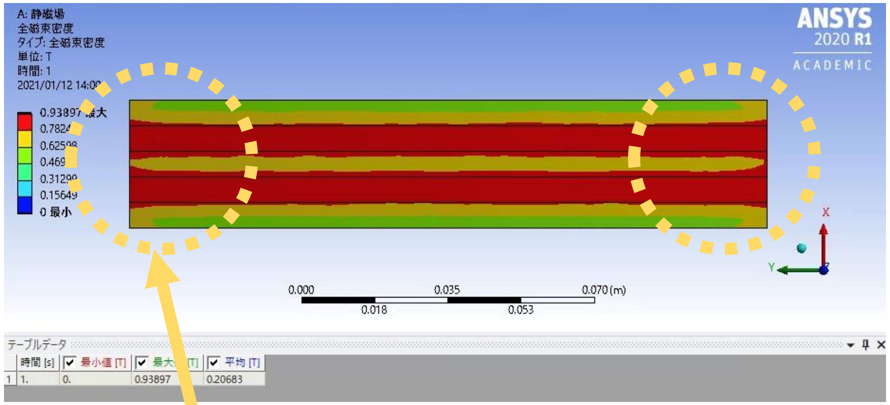
Silica

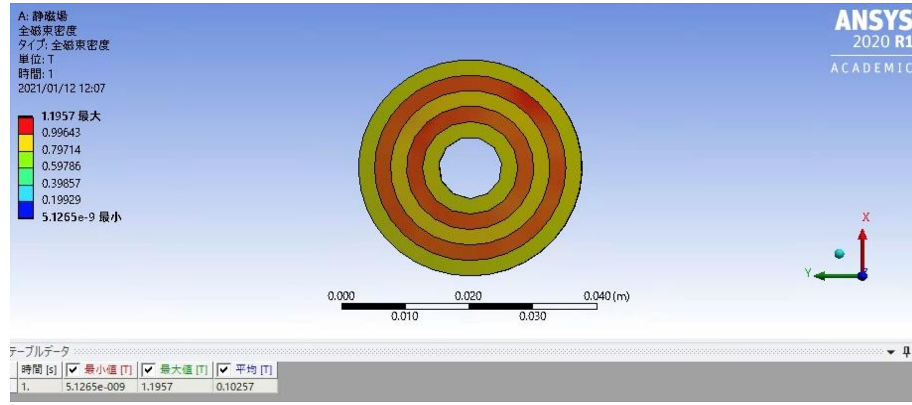
- **Low magnetic susceptibility**
  >> Need to increase $B_z \partial B_z / \partial z$
  >> Small system
- **Electrical resistivity is high ($10^{16}\Omega/\text{m}$)**
  >> Low thermal noise on its surface

A different approach is needed for each experiment.

Ring magnet array for a graphite mass

[Ogawa, thesis (2021)]

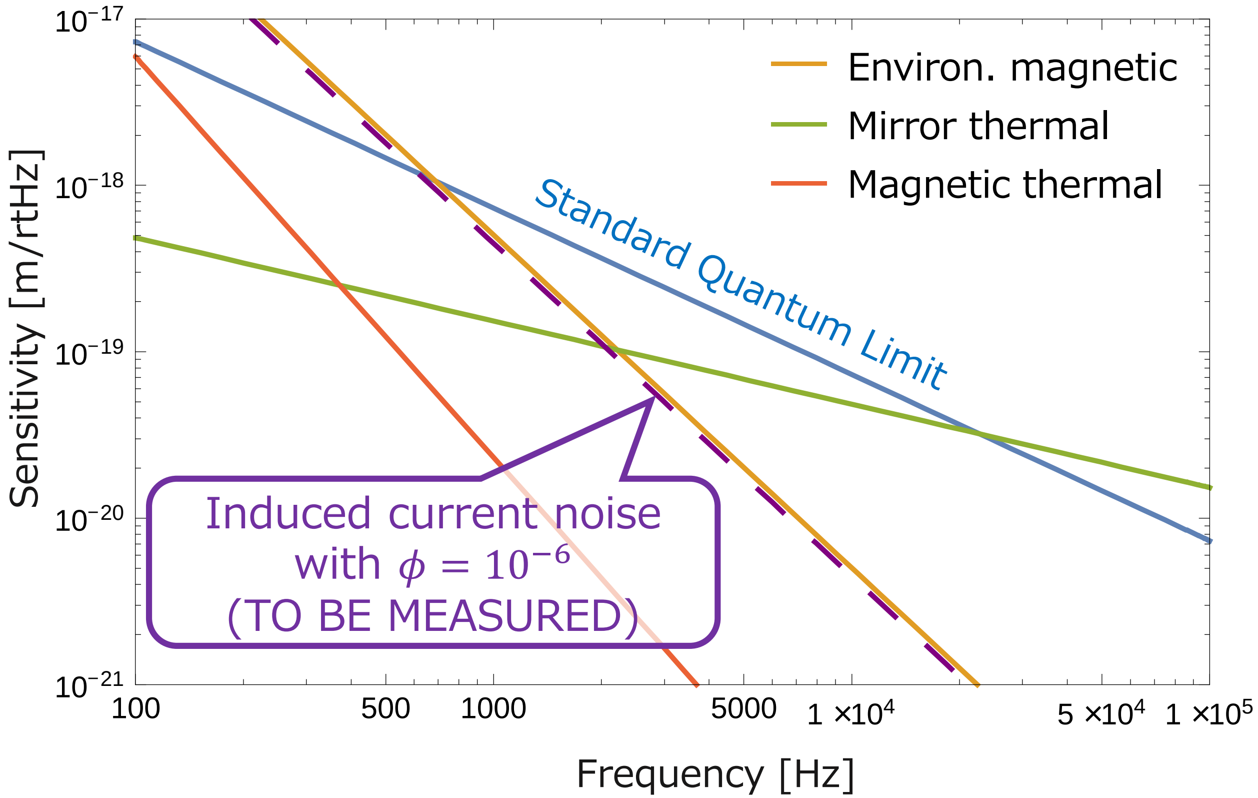




- **Alternating magnet array to increase the vertical magnetic gradient (not the Halbach array).**
- **A linear array has a non-zero horizontal gradient due to the existence of the end.**
- **A ring array does not have the horizontal gradient and ideally its induced-current loss can be zero.**
  >> The actual loss needs to be measured.

Requirement

[Ogawa, thesis (2021)]

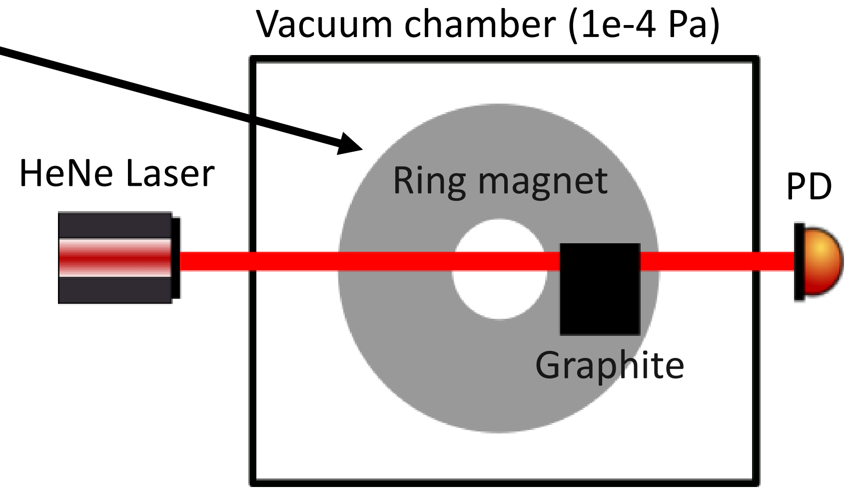


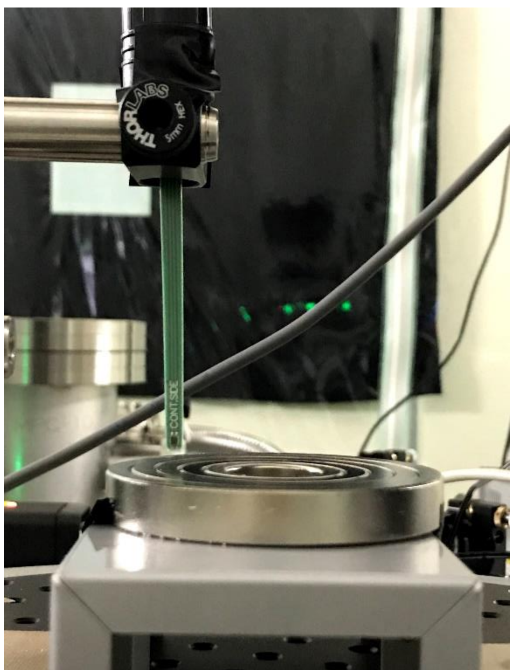
A Sub-SQL measurement will be possible if the induced current loss is as low as 10^{-6}.

(Here the mass is 10mg and $\Delta B_{env} = 10^{-9}[T]$)

Measurements

[Ogawa, thesis (2021)]



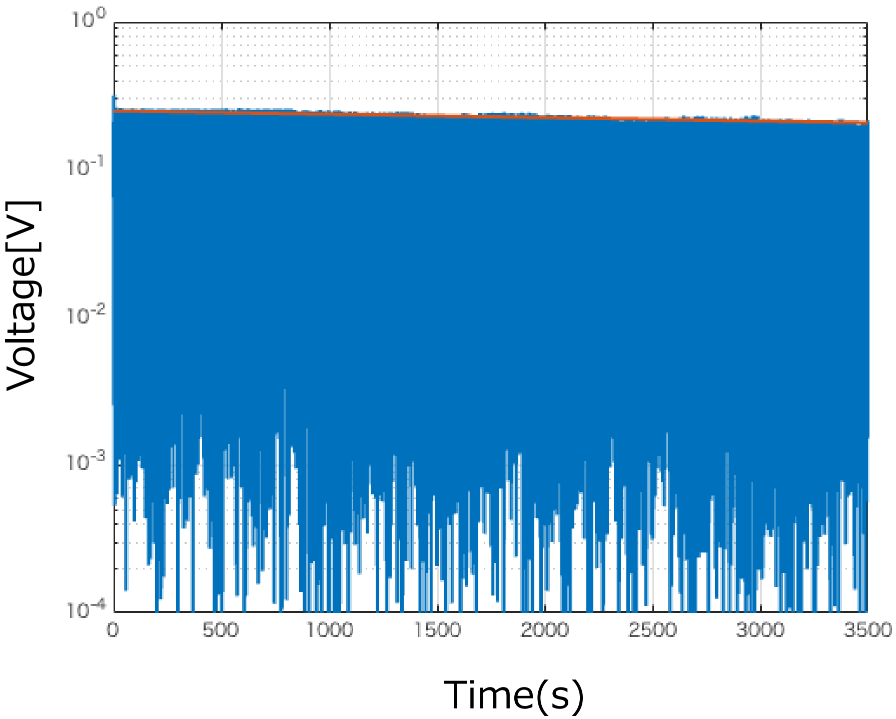


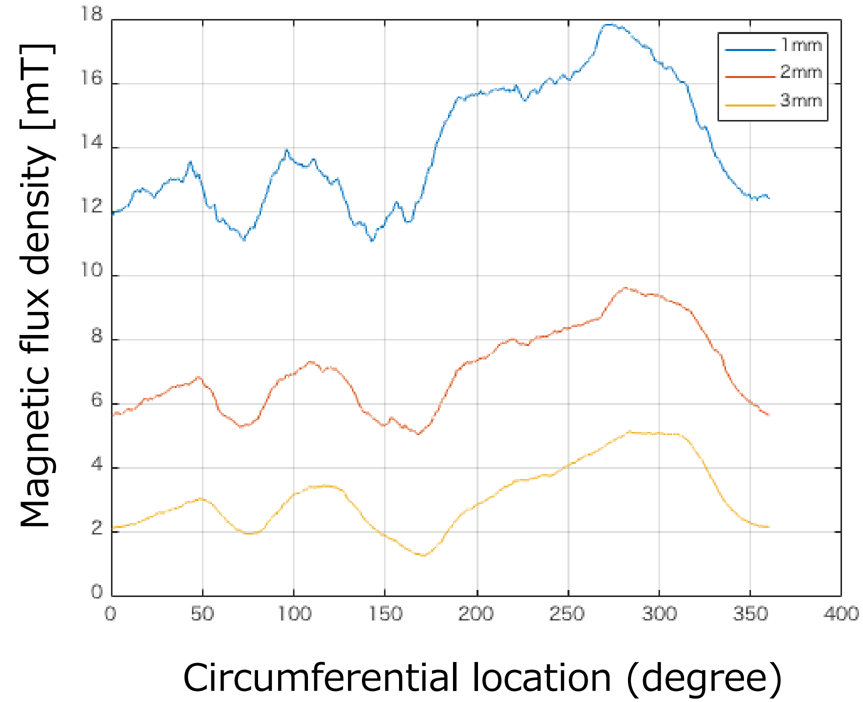
Magnetic field measurement with a Tesla meter.

- **We hit the chamber and measured the ring-down using the graphite itself as a shadow sensor.**
- **We did not have an actuator yet so the graphite was set at a locally stable point.**
- **Uniformity of the magnetic field was also measured with a Tesla meter.**

Results

[Ogawa, thesis (2021)]



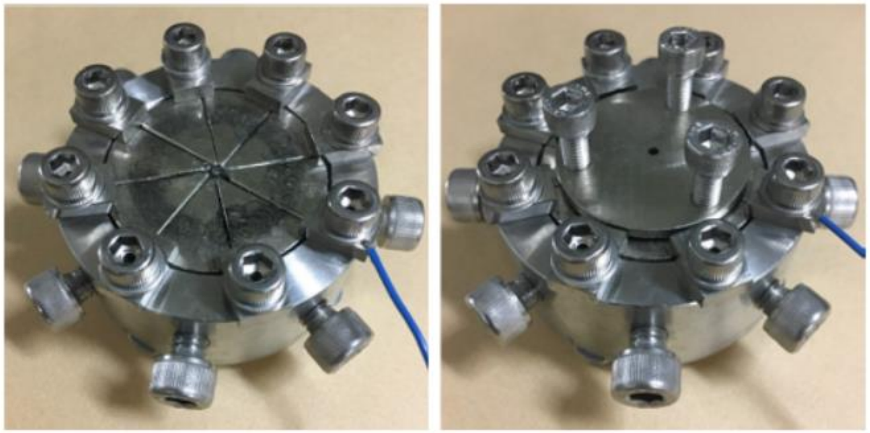


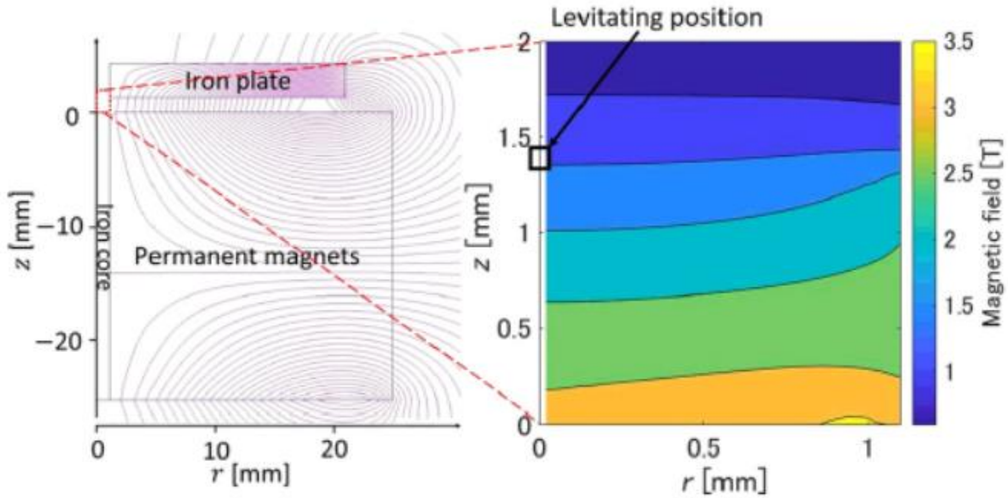
The measured Q-value was 3×10^4.

The measured magnetic gradient at $h = 1\mathrm{mm}$ was 0.23 [T/m] in x and 1.65 [T/m] in z. It corresponds to the Q-value of 2×10^4.

Radial magnets for a silica mass

[Nakashima, PLA (2020)]

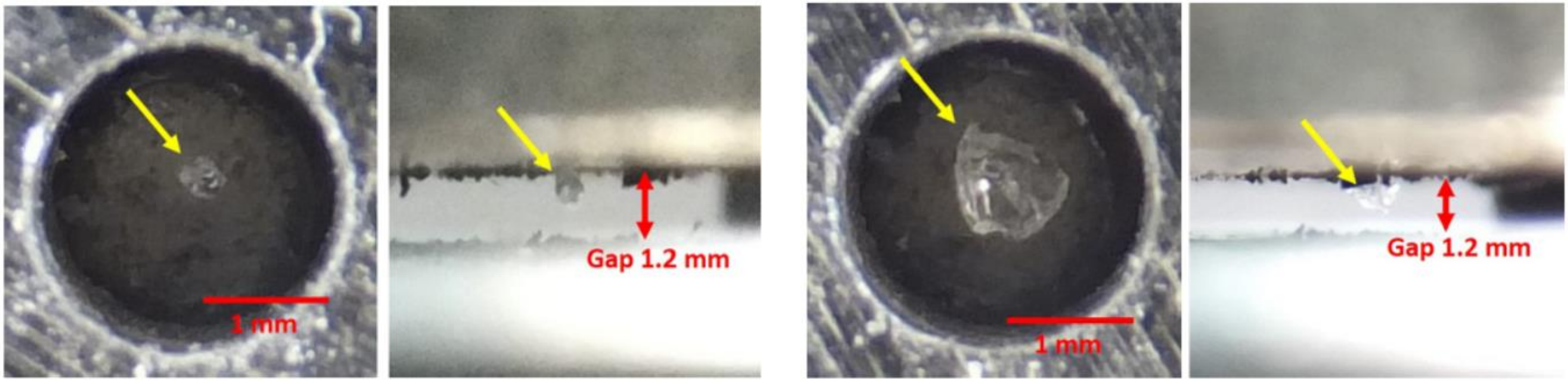




- **We built a compact system with a steep magnetic field gradient to levitate a silica mass of $0.1 \sim 1\mathrm{mg}$.**
- **According to a simulation, the resonant frequencies in vertical and horizontal directions are $10 \sim 20\mathrm{Hz}$ and $1 \sim 6\mathrm{Hz}$, respectively.**

Levitation experiment

[Nakashima, PLA (2020)]



- **Since a polished mirror was not ready, we tried levitation experiments with a broken piece (left: $\sim 0.1\text{mg}$, right: $\sim 1\text{mg}$).**
- **The experimental demonstrations were successful.**
- **We also tried a LaSF9 mirror (coated microlens) but could not levitate it due to its lower susceptibility and higher density.**

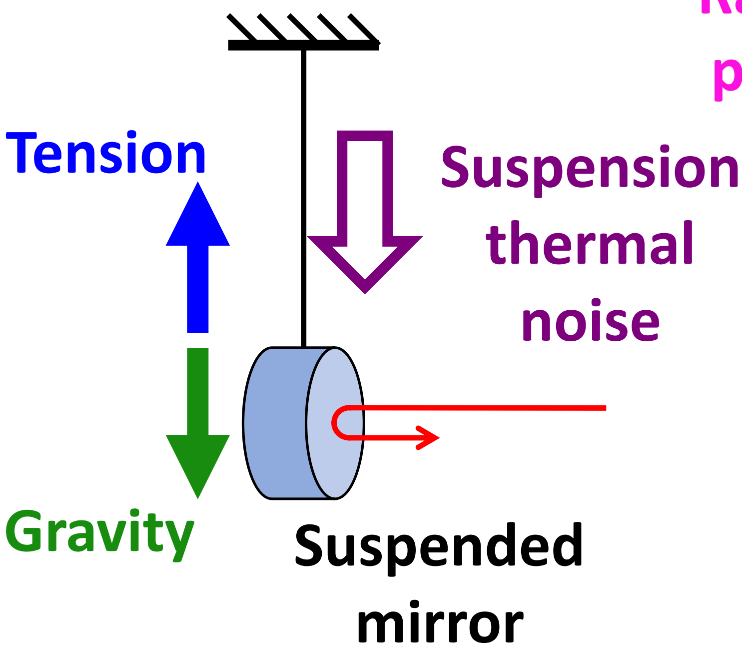
Summary and future plan
(of diamagnetic levitation experiments)

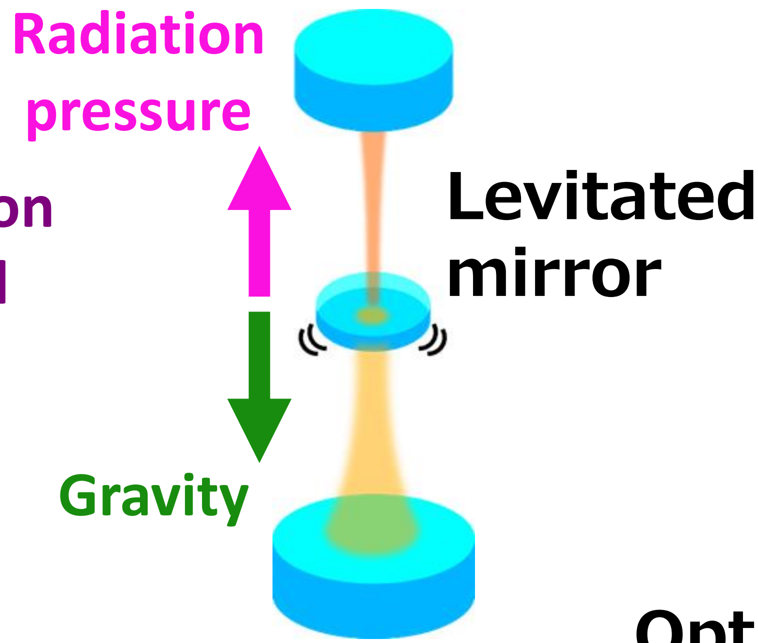
- We succeeded in levitating a graphite mass and measured the Q-value (Q=3e4) on a ring magnet array.
- The low Q-value seems to be caused by a non-uniform magnetic field of the ring magnet. We plan to purchase a better magnet array.
- We succeeded in levitating 0.1mg and 1mg silica masses. The Q-value was not measured.
- We just purchased a 2.3mg polished/coated silica mirror. We plan to levitate it and measure the Q-value.

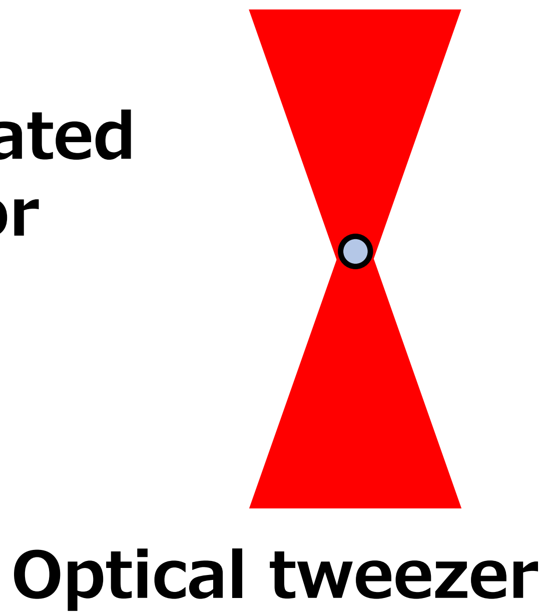
Optical levitation (U of Tokyo)

Optical Levitation of Mirror

- Alternative approach is to support a mirror with radiation pressure alone
- Free from suspension thermal noise
- Large coupling compared with optical tweezers



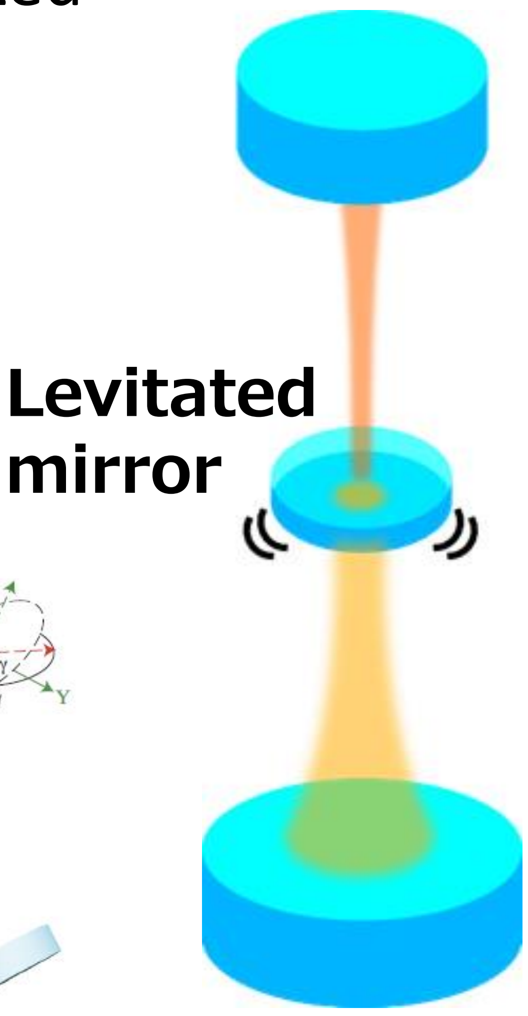


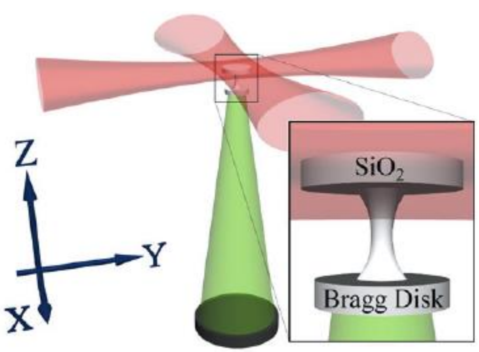


Sandwich Configuration

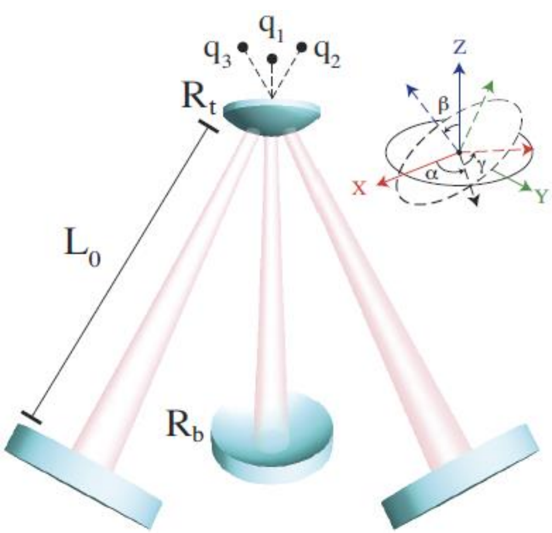
- Mirror levitation have never been realized
- Simpler configuration than previous proposals

  YM, Y. Kuwahara+, [Optics Express 25, 13799 (2017)]
- Proved that stable levitation is possible and SQL can be reached with 0.2 mg mirror





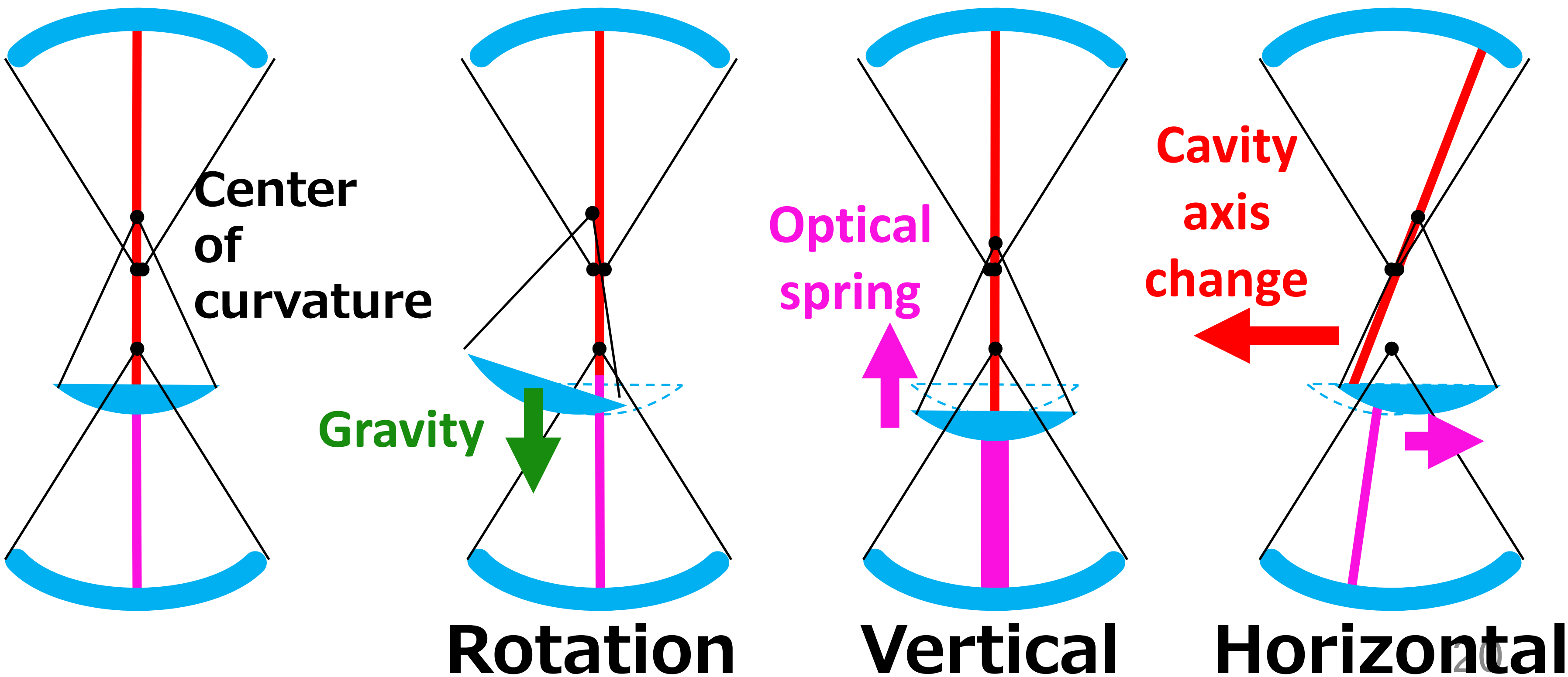
S. Singh+: [PRL 105, 213602 (2010)]



G. Guccione+: [PRL 111, 183001 (2013)]

Stability of Levitation

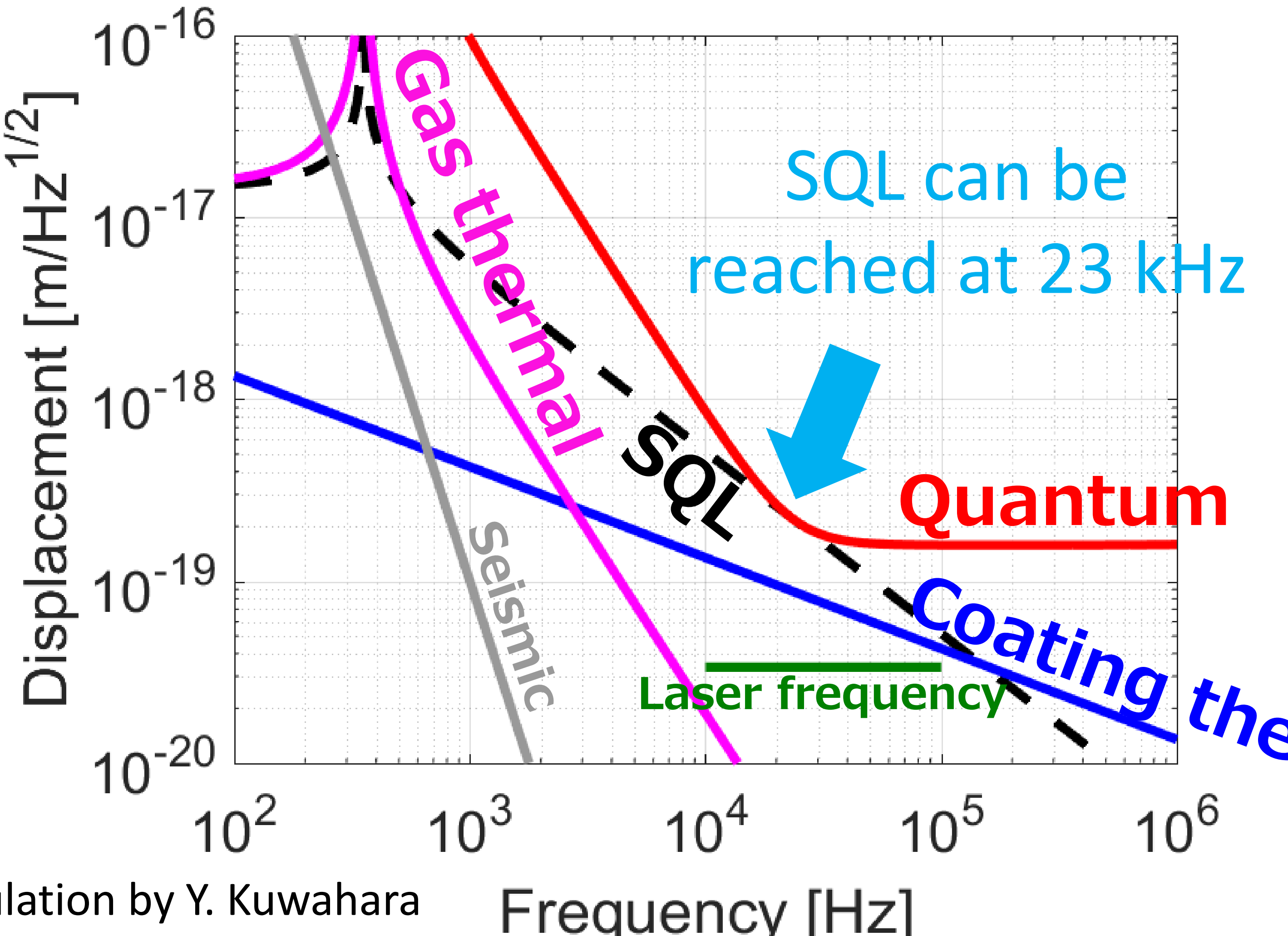
- Rotational motion is stable with gravity
- Vertical motion is stable with optical spring
- Horizontal motion is stable with cavity axis change

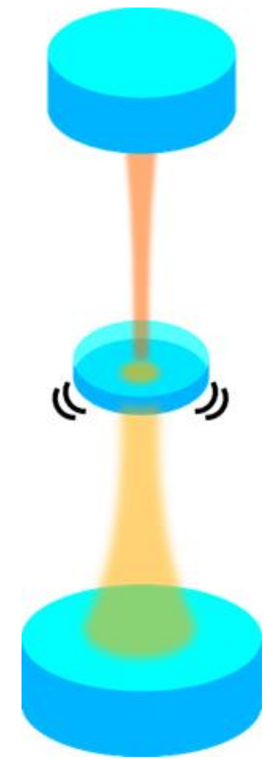


Reaching SQL

- 0.2 mg fused silica mirror, Finesse of 100, 13 W + 4 W input

Low finesse necessary for cavity pole to be higher than SQL reaching frequency



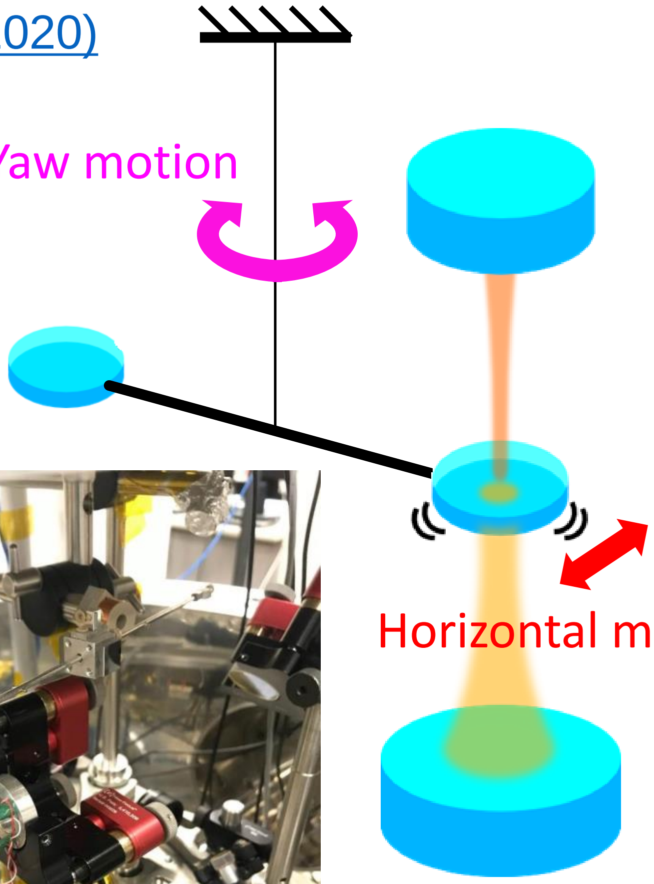


Calculation by Y. Kuwahara

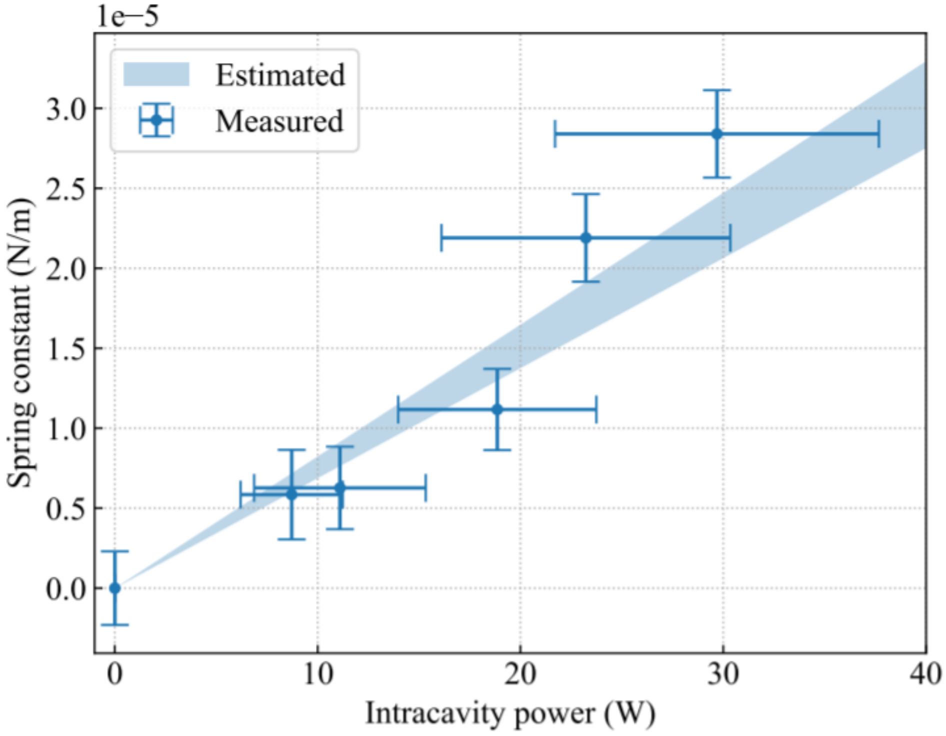
Experiment to Verify the Stability

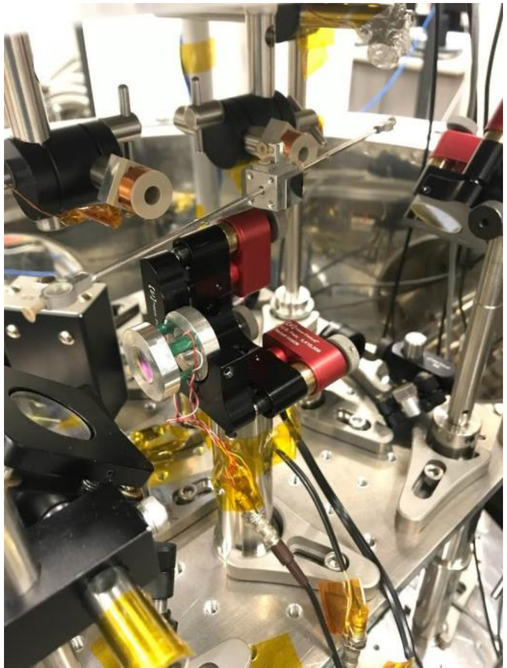
- Verified the stability with a torsion pendulum

T. Kawasaki, …, YM, PRA 102, 053520 (2020)



Measured optical geometrical spring agreed with expectation





Fabrication of Levitation Mirrors

- mg and mm-scale curved mirror necessary
  e.g. For levitation demonstration
  ϕ 3 mm, 0.1 mm thick (~1.6 mg for fused silica)
  RoC = ~30 mm convex
  R > 99.95 %

- Two approaches
  1. Coat thin fused silica mirror

  2. Photonic crystal mirror to create effective curvature

Supported by ANR-JST QFilter project

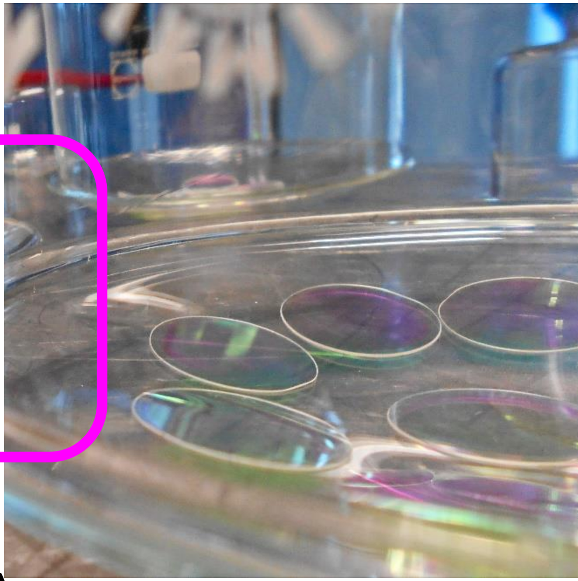
New Approach for Fused Silica

2014 Approach

(1) Make 3 mm dia. lens → (2) Coat → CRACKED!

2020-2021 Approach

(1) Make 1 inch dia. 0.1 mm thick disk → (2) Coat (bend due to stress) → (3) Cut into 3 mm dia.



So far successful upto (2)

- R=92(1)%, RoC=500^{+2000}_{-200} mm
- R=88(1)%, RoC=400^{+800}_{-200} mm

Trying (3) and thicker coating

(would try thinner substrate)

Somehow concave instead of convex

Coating thickness x2

-> RoC x~1/2

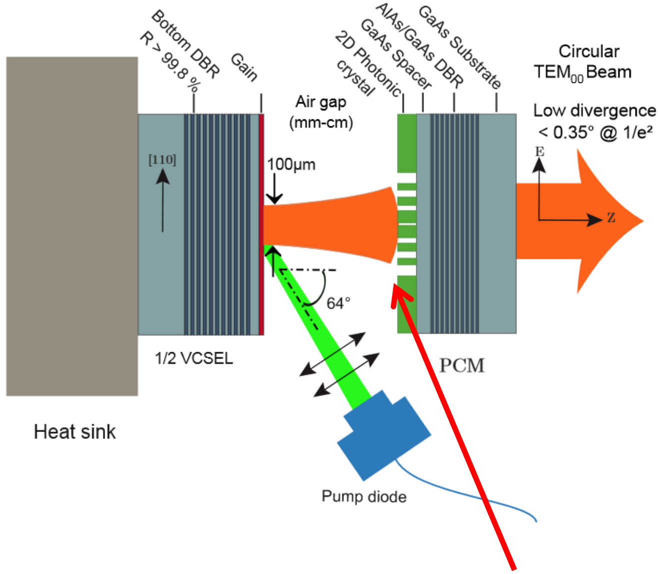
Substrate thickness x1/2

-> RoC x~1/4

Photonic Crystal Mirror

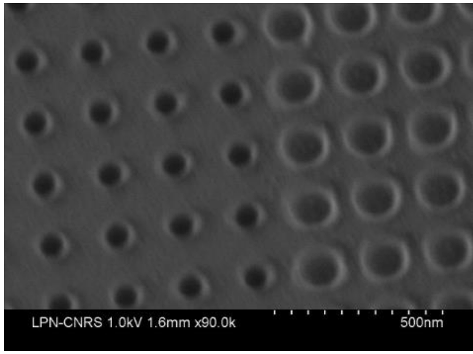
- Effective curvature possible my modulating the filling factor

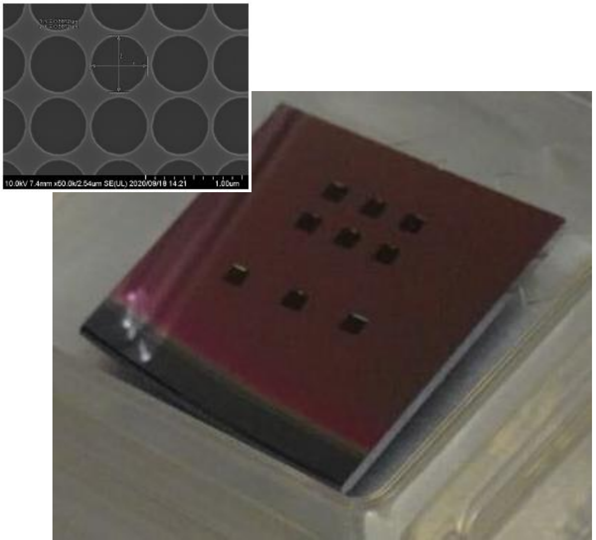
  M. S. Seghilani+,
  [Optics Express 22, 5962 (2014)]

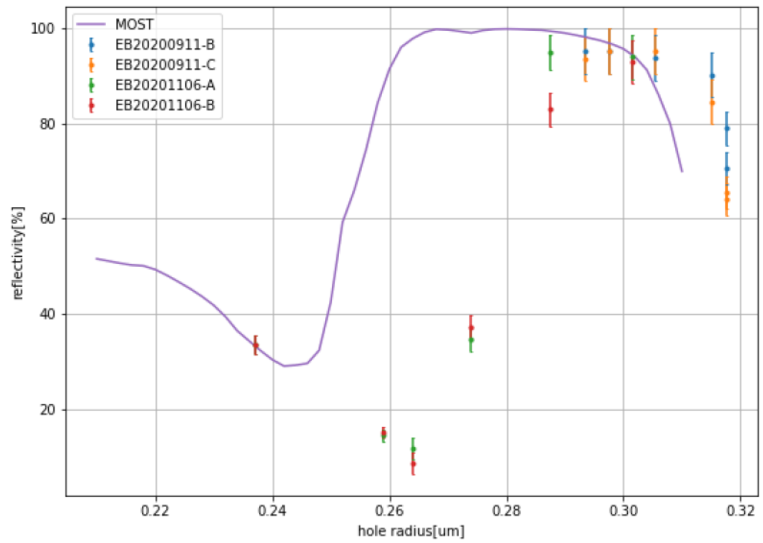


- Currently trying Si photonic crystal mirror without modulation

  So far achieved 95(5) % reflectivity







Summary

- Milligram scale mirror can be levitated with realistic parameters
  YM, Y. Kuwahara+, Optics Express 25, 13799 (2017)
- Succeeded in experimentally verifying the stability of the levitation
  T. Kawasaki, …, YM, PRA 102, 053520 (2020)
- Trying two approaches for the fabrication of a milligram mirror with high reflectivity and curvature
  - Coated thin fused silica mirror
    R~90% achieved with RoC~500 m
    Next: thicker coating and mirror cutting
  - Photonic crystal mirror
    R~95% achieved without modulation
    Next: higher reflectivity and modulation