

Magnetically levitated massive resonators for quantum sensing

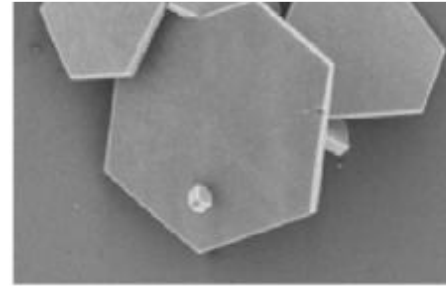
Shilu Tian

Somiya Lab, Institute of Science Tokyo

Why Levitation

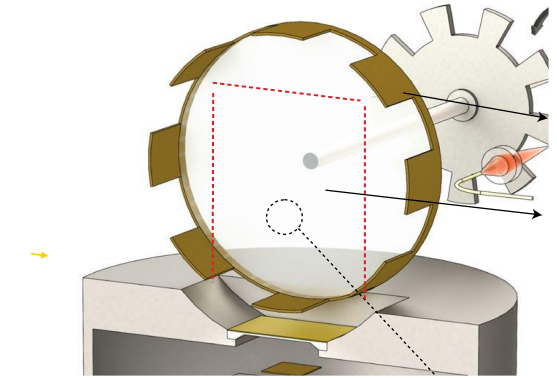
Mechanical systems which are levitated in vacuum can have ultra-low damping and are easy to modulate.

- Ultra-precise sensors: gravimeters, gyroscopes, inertial sensors, sensors for dark matter, magnetometers, gravity waves...
- Fundamental Science: generate really interesting mechanical quantum states – squeezed, Schrodinger Cats
- Gravity&Quantum : Massive systems – can explore the interaction of gravity with quantum!



Optical Trapping of High-Aspect-Ratio NaYF Hexagonal Prisms for kHz-MHz Gravitational Wave Detectors

Geraci, et al, Phys. Rev. Lett. (2022)



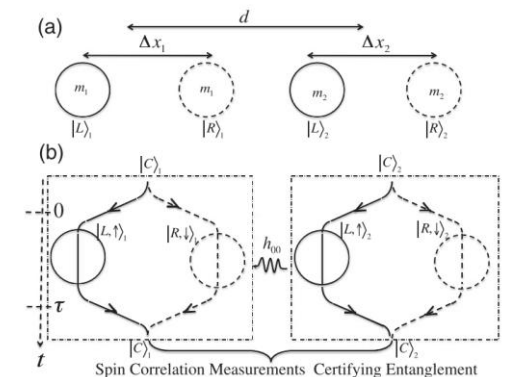
Experiments with levitated force sensor challenge theories of dark energy

Du, et al, Nat Phys (2022)



The superconducting gravimeter

J.M. Goodkind: Rev Sci Inst (1999)



Spin entanglement witness of quantum gravity

Bose, et al, Phys. Rev. Lett. (2017)

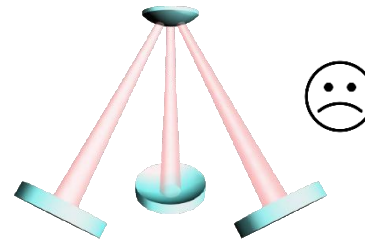
Levitation Platforms

How can we levitate nano-micro sized objects?

Many forms of trapping/levitation are active – they use active power/controls to trap the object

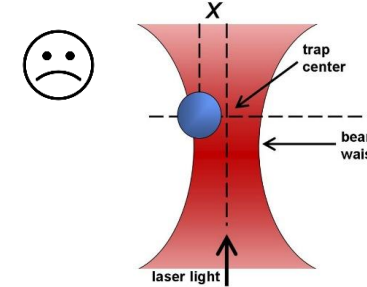
Magnetic levitation can be passive – can levitate a diamagnetic object forever with no power!
Possibly ultra-quiet?

Optomechanical Levitation



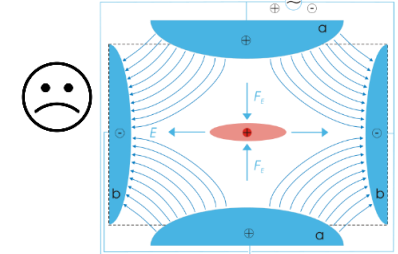
Large laser powers! PRL (2013)

Optical Tweezer



Large laser powers! APL (1976)

Electrodynamic Trap



Micromotion, ZNA (1953)

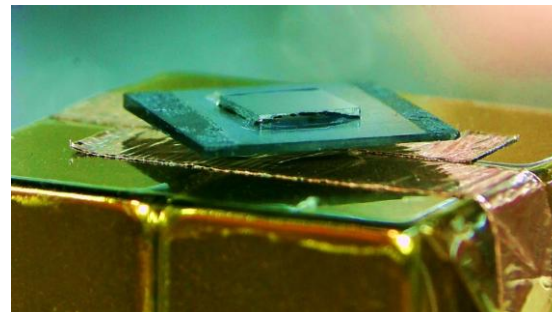
Magnetic Levitation



Diamagnetism!

$$F \propto -\nabla|\mathbf{B} \cdot \mathbf{B}|$$

Diamagnetic Levitation



A flying frog!



Meissner Repulsion



Berry & Geim, Eur. J. Phys. (1997)

Diamagnetic Levitation

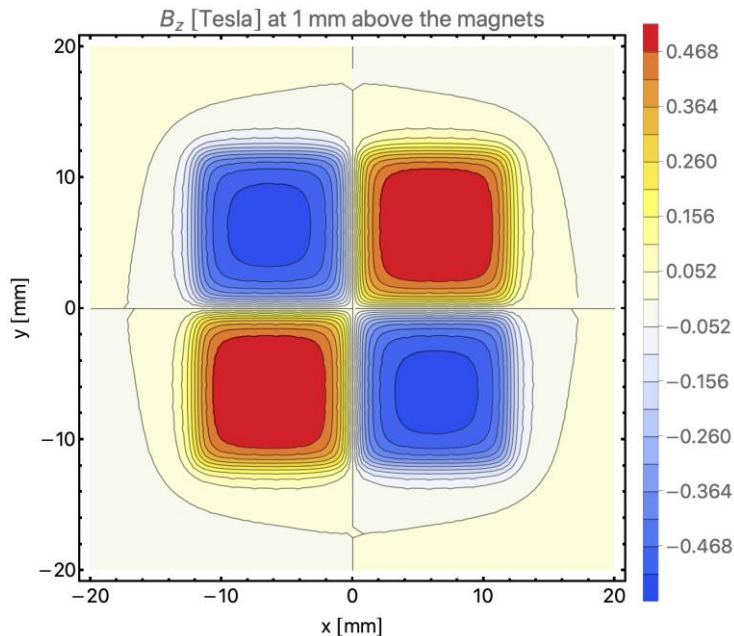
- Highly Oriented Pyrolytic Graphite has largest diamagnetic response at room temp [anisotropic]
- No Cryogenics required
- Can levitate stably over checkerboard magnet array

$$\chi_j = -(8.5, 8.5, 45) \times 10^{-5}$$

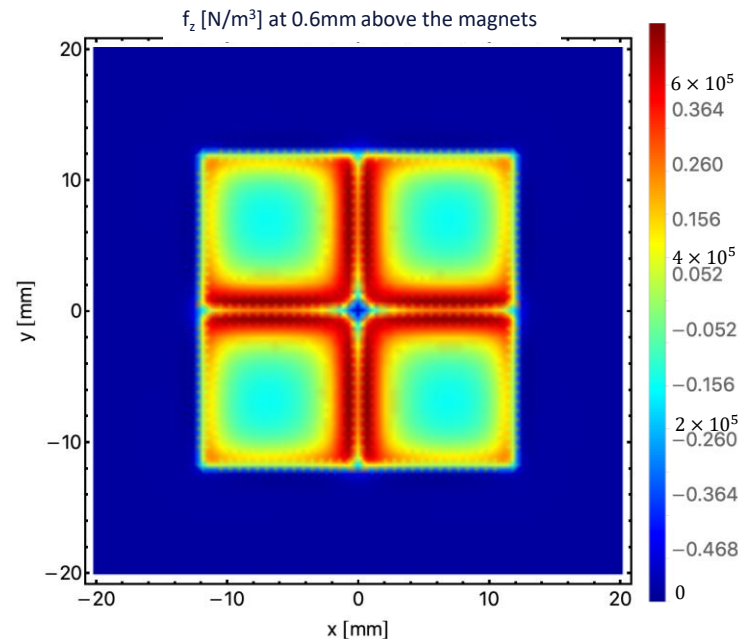


Magnetic Susceptibility

Material	χ [$\times 10^{-5}$ (SI units)]
Superconductor	-10^5
Pyrolytic graphite	-45
Bismuth	-16.6
Mercury	-2.9
Silver	-2.6
Diamond	-2.1
Lead	-1.8
Copper	-1.0
Water	-0.91



B_z above the magnets



Vertical Force Density

$$\mathbf{f} = (\mathbf{M} \cdot \nabla)\mathbf{B} = \frac{1}{2\mu_0} \nabla(\chi_x B_x^2 + \chi_y B_y^2 + \chi_z B_z^2),$$

$$\mathbf{M} = \frac{1}{\mu_0} \chi \cdot \mathbf{B}.$$

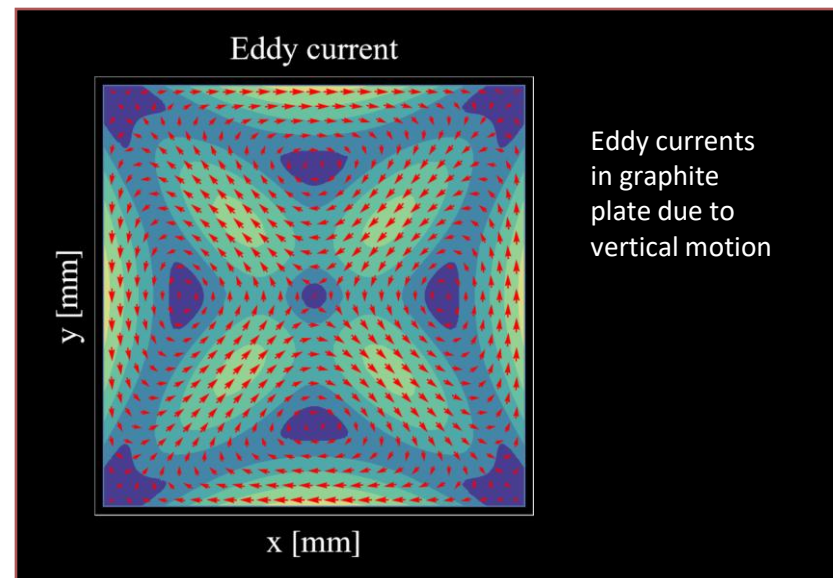
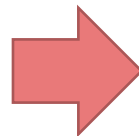
$$\mathbf{F} = \int_V \mathbf{f} dV$$

$$B \frac{\partial B}{\partial z} = \left(\frac{\rho}{\chi} \right) g \mu_0$$

Q-factor ??

Eddy Currents Damping

- Many highly diamagnetic materials are electrical conductors.
- Motion of a conductor in a magnetic field induces **eddy currents and loss** – graphite oscillation even in vacuum has **low motional Q-factor**.
- How to control this – **engineer the eddy currents in the graphite and control the motional Q without losing too much diamagnetic lift?**



Magnetic Susceptibility

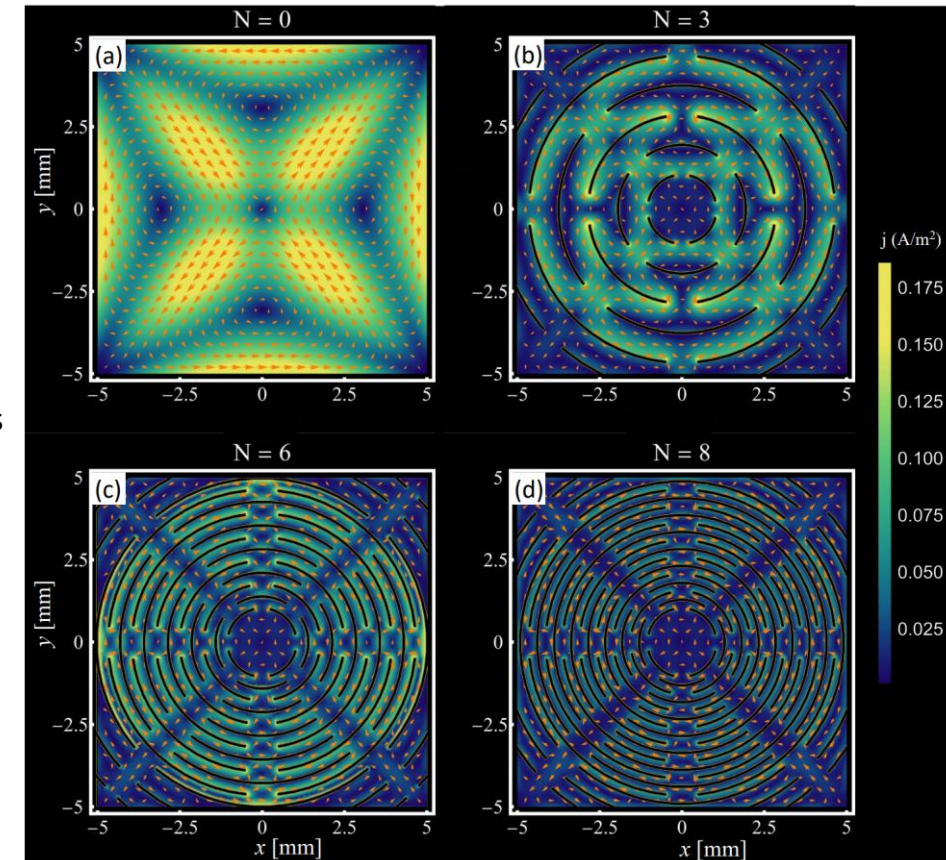
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Q factor ~ 60 !

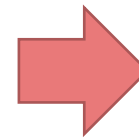


- We follow route similar to how eddy currents are reduced in electrical transformers – physically interrupting the eddy currents.
- Interrupt the eddy currents by physically making tiny slots in the graphite slab

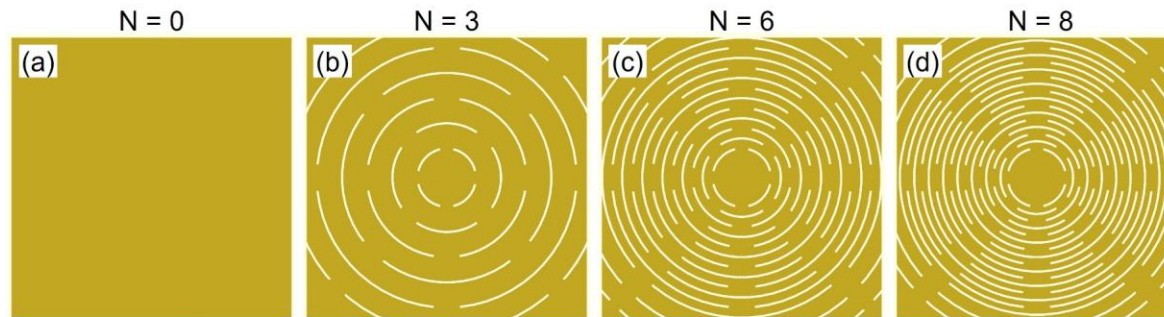
Eddy current simulations [Comsol/Mathematica]



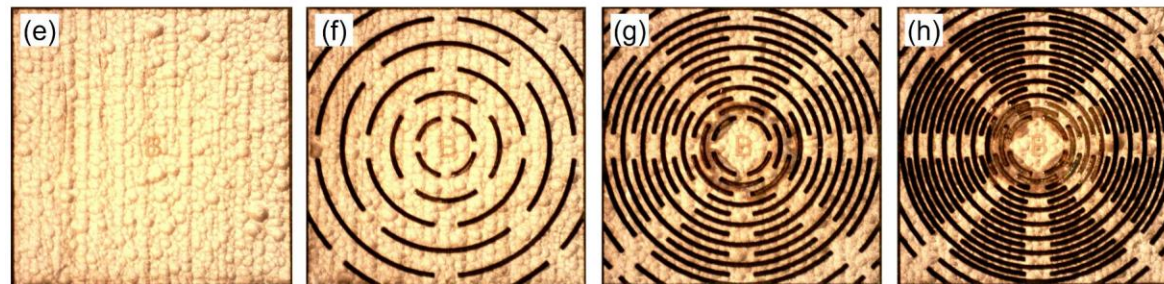
Eddy currents in slotted slabs greatly reduced



CAD design



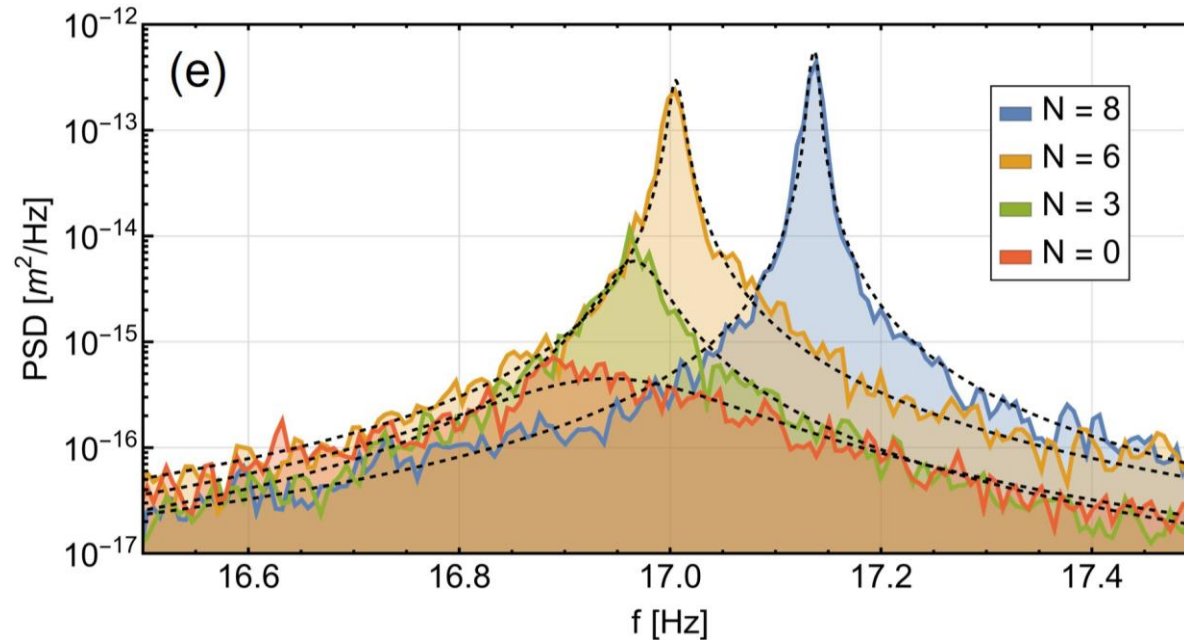
Photos of machined slab



Slotted graphite (10mm square)

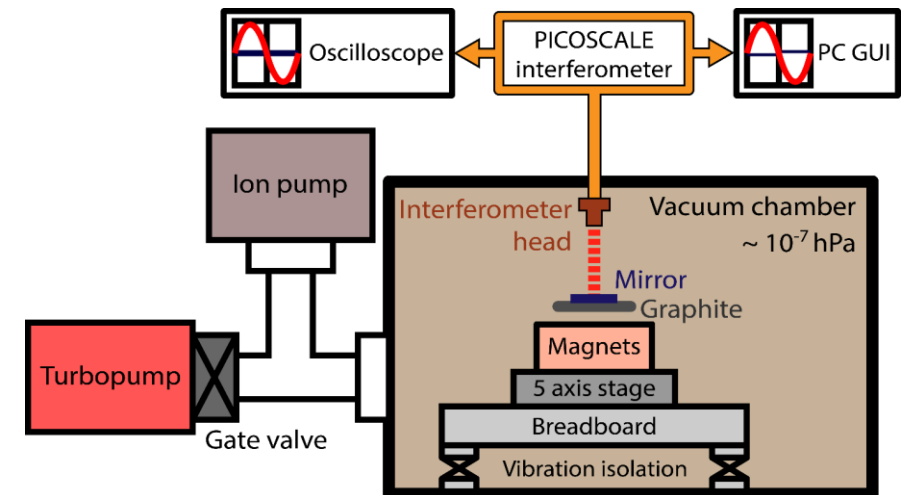
Geometry Engineering

- Measure motion of plate (small mirror attached), using laser displacement interferometer – high vacuum – no pump vibrations using ion pump.



$$S_{zz}(f) = \frac{2k_B T \gamma / m}{((2\pi f_0)^2 - (2\pi f)^2)^2 + (2\pi f \gamma)^2}$$

Schematic of the setup

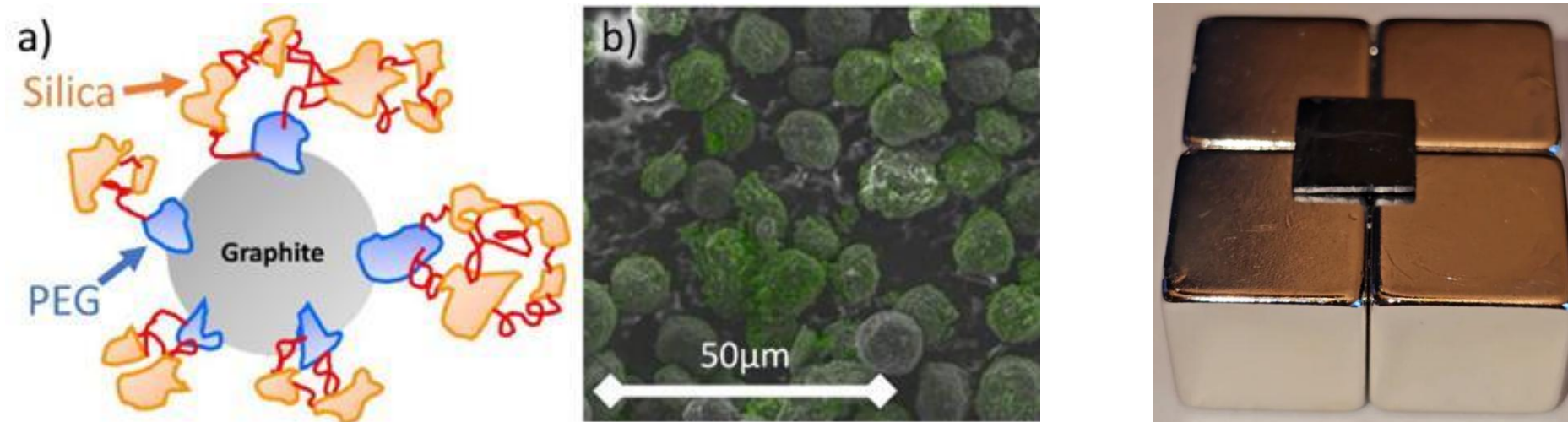


Q-factor increases to ~2500 !



Insulating Composite

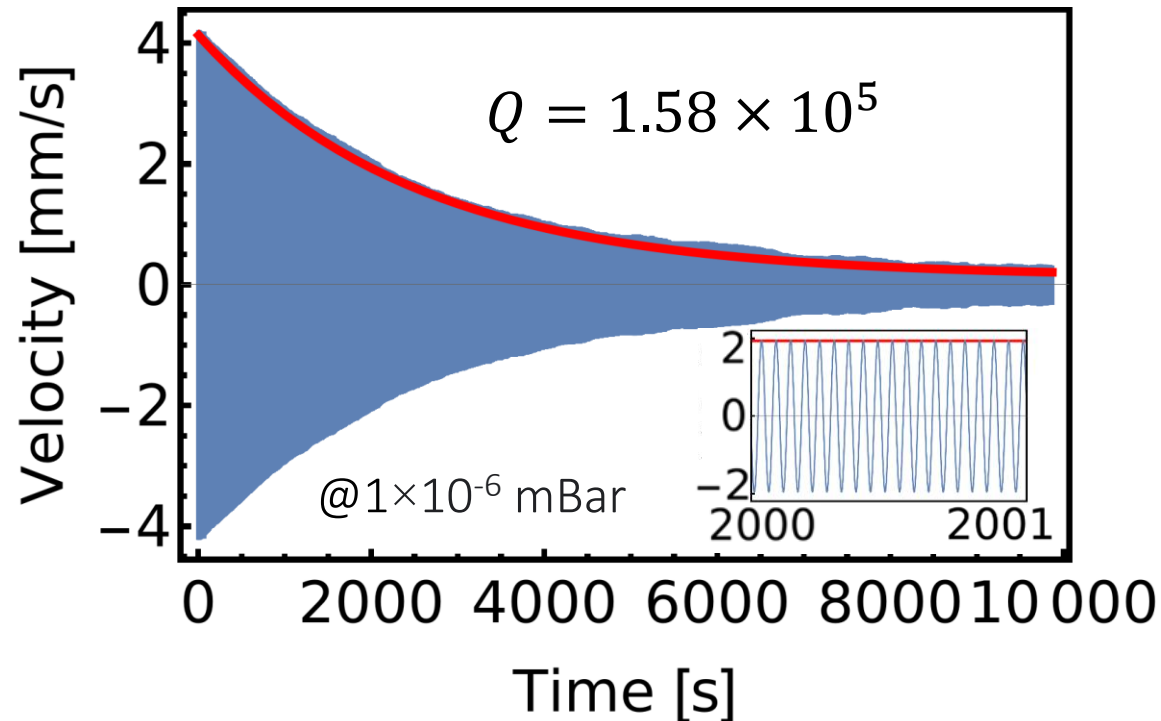
- ‘From top to bottom’ (cut slots) reach a limit. We consider ‘From bottom to top’ (using particles to construct a composite slab).
- To reduce eddy currents, we make the plate out of micron size graphite particles which we coat to make each electrically insulating.



Coated graphite particles and levitated composite slab

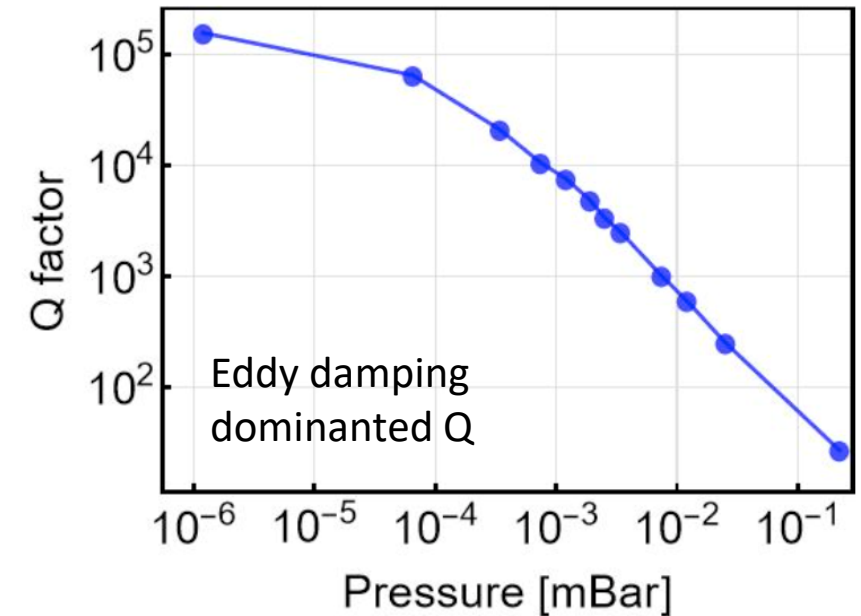
Insulating Composite

- Ringdown measurements yield a motional Q which is very high



Q-factor increase to the scale of 10^5

- Q factors reach a plateau at low pressure, indicating eddy damping is still dominant



High Sensitivity

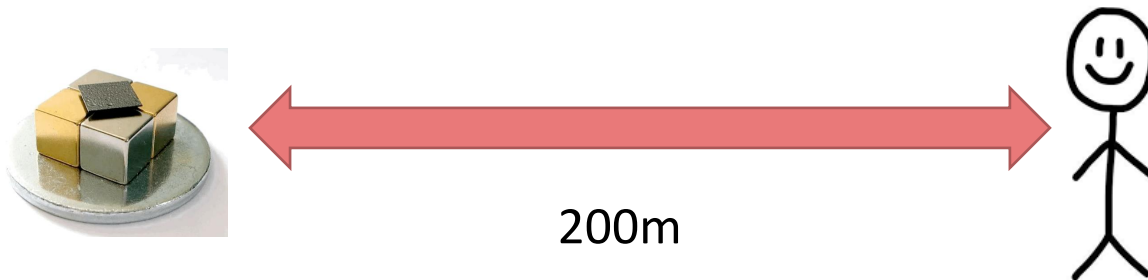
These high-Q massive resonators can make ultraprecise sensors.

Ultra-precise acceleration sensor

- Thermal noise limited acceleration sensitivity for the composite:

$$\sqrt{S_a} = \sqrt{4k_B T \omega_0 / mQ} \sim 1.7 \times 10^{-12} \text{ g}/\sqrt{\text{Hz}}$$

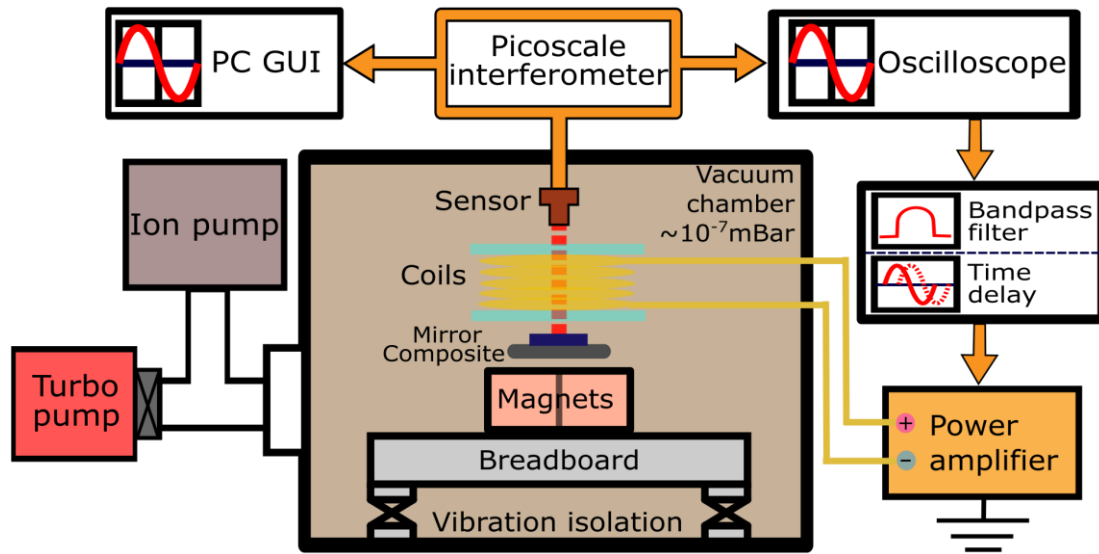
- Detect a 100kg mass 200m away in 1s due to gravity!



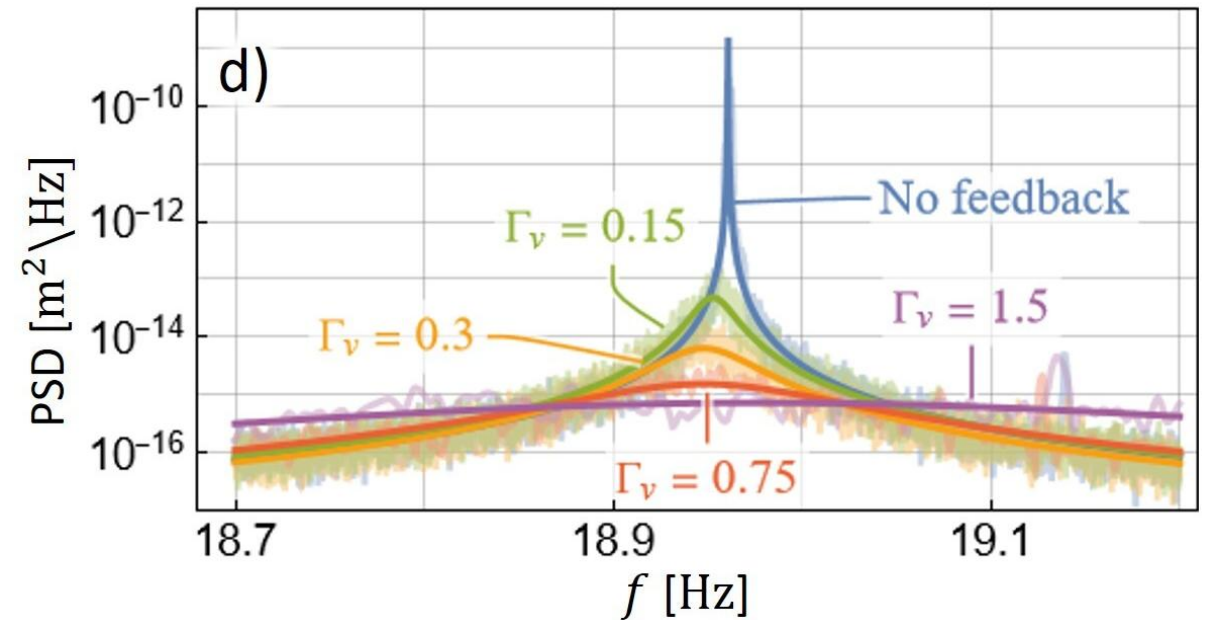
- **Cooling** towards quantum ground state to realize quantum control of macroscopic resonators to test quantum gravity.

Feedback Cooling

- Measure the position with interferometer.
- Feedback the opposite of velocity using magnetic actuation to the resonator.
- COM is cooled by 3 orders of magnitude!



Schematic of experiment setup

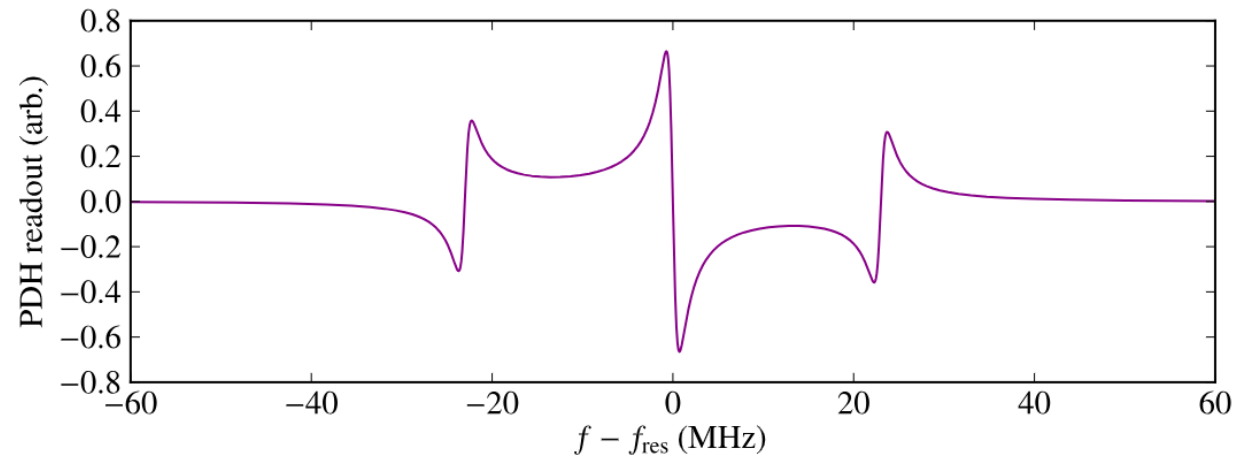
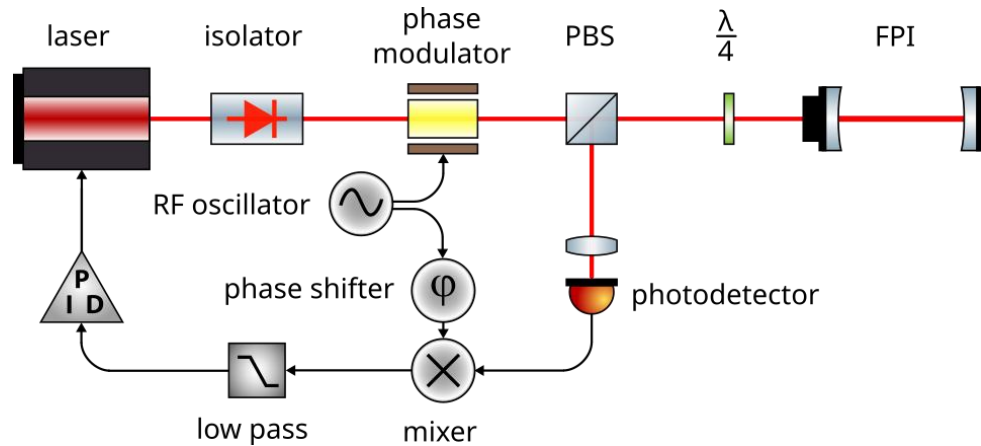


PSD with feedback cooling

Limited by the measurement precision and vibrational noises.

Pound–Drever–Hall Locking

- PDH technique is used to stabilize the frequency of a laser by locking to a stable cavity.
- It can also lock a cavity to a stable laser → Fix the mirror position and precise measurement of the position.



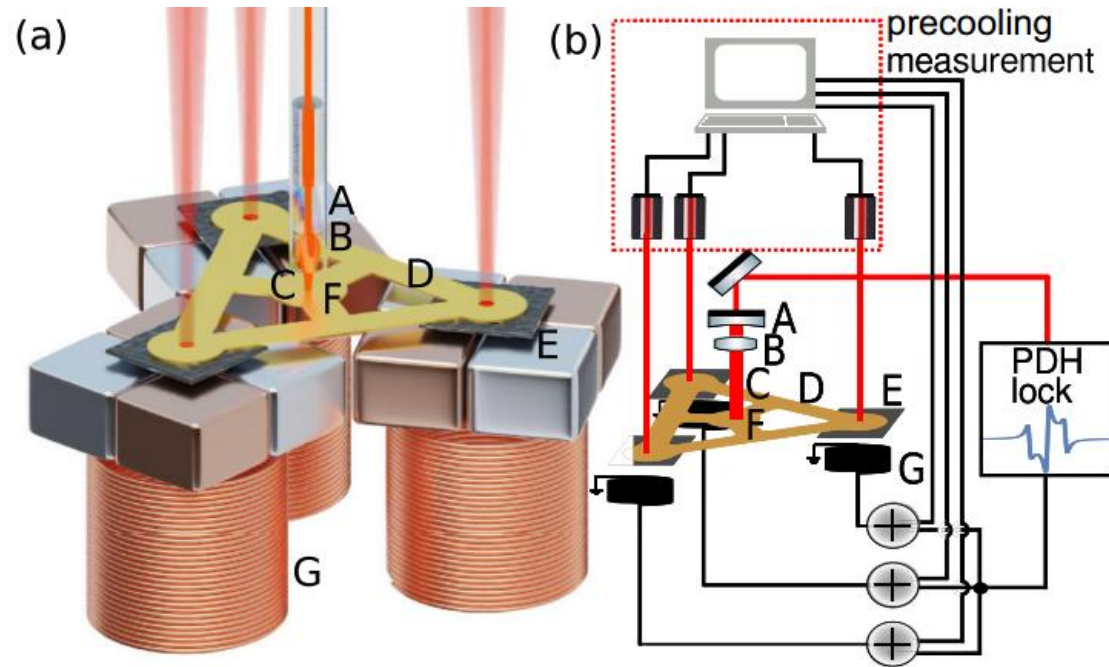
Schematic of PDH setup and error signal (wikipedia)

PDH sensitivity $\sqrt{S_L} = \sqrt{hc\lambda/8F} \sqrt{P_c} \sim 10^{-19} \text{ m}/\sqrt{\text{Hz}} \ll x_{\text{ZPM}} = \sqrt{\hbar/2m\Omega_M} = 5 \times 10^{-17} \text{ m}$

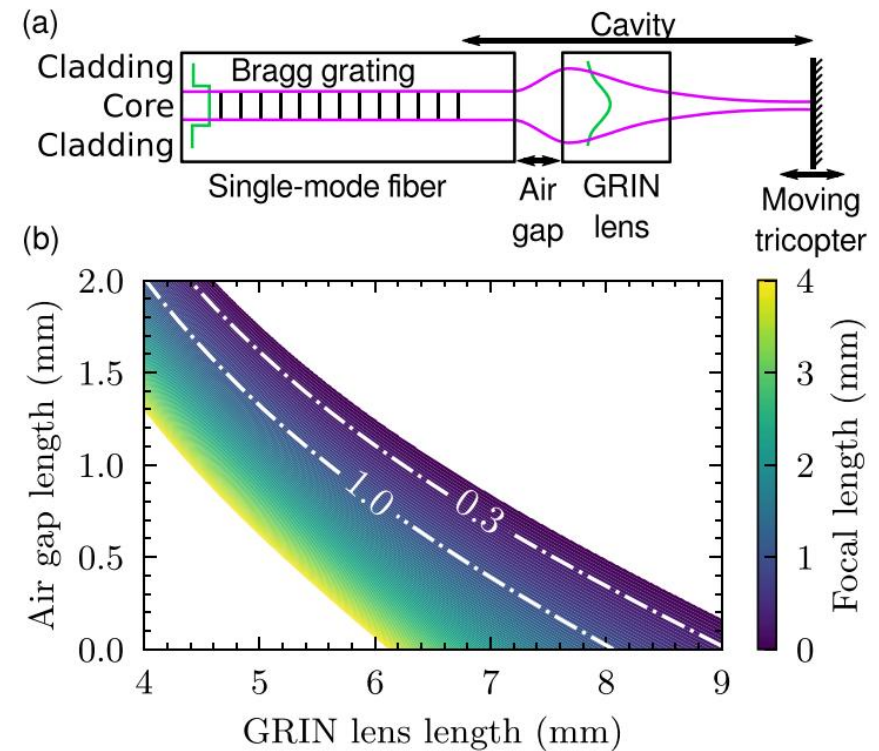
It is extremely sensitive, but linear range is very narrow!

Feedback Cooling – using PDH

- We build a levitated “tricopter” to suppress the tilting and conduct pre-cooling.
- The three corner mirrors are for interferometrically measurement.
- The central mirror is for cavity with fiber Bragg grating.



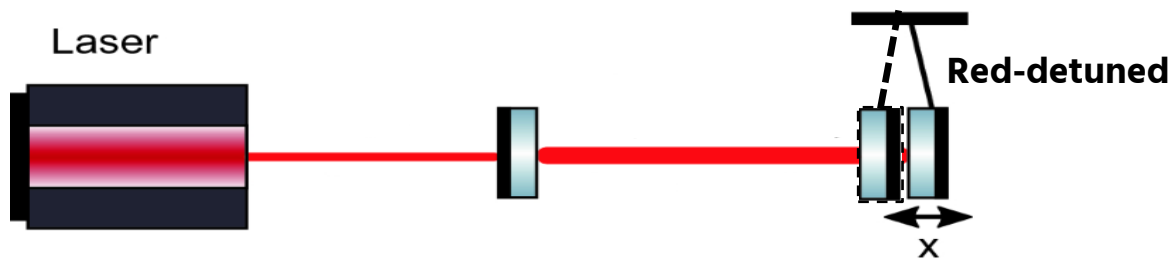
Schematic of the proposed setup



Micro-optomechanical cavity

Optical Spring

- Magnetic levitations usually have low resonant frequencies.
- The optical spring effect can boost the trapping frequency.

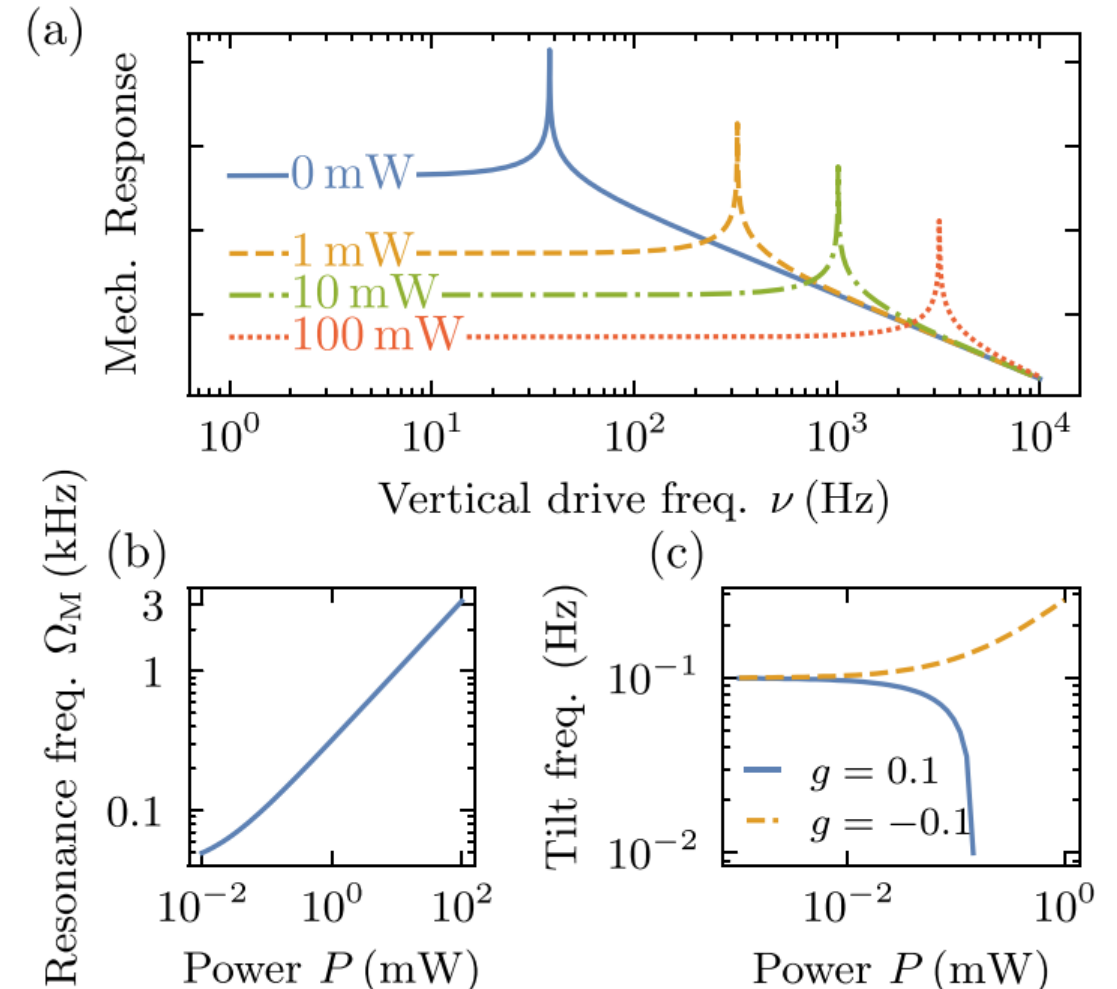


Red-detuned cavity can increase the stiffness

The radiation pressure force can increase the frequency to 3kHz.

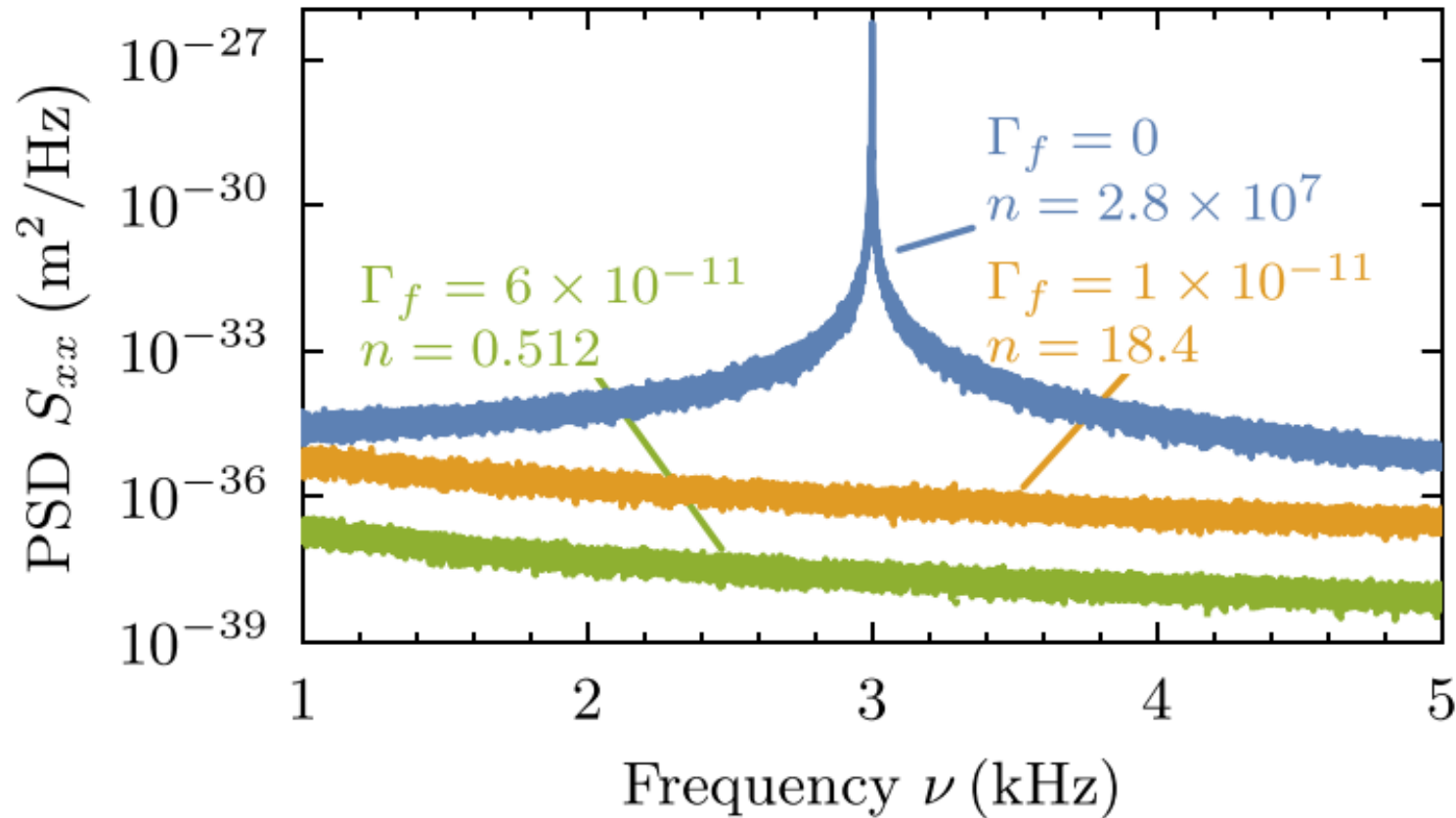
Concave mirror should be used to suppress the caused tilting instability.

- Potential for high-frequency Levitated Sensor Detector (LSD)



Feedback Cooling – using PDH

- The vertical COM of the tricopter can be cooled down to 72 nK;
- Reach phonon occupation number $n < 1$.



Collaborators



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Camila Padilla



Breno Calderoni



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Yuan Ze Univ.

Quantum Machine Unit, OIST

Appl. Phys. Lett. 122, 094102 (2023)

Appl. Phys. Lett. 124, 124002 (2024)

Commun. Phys. 8, 381 (2025)

Phys. Rev. A 113, 033508 (2026)

Thank You!



Thank You!