Research plan I: Optomechanical torsion pendulum

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Lab seminar 2022/09/30

Abstract

- Research plans

- Motivation

- Current status and future of the optomechanical torsion pendulum

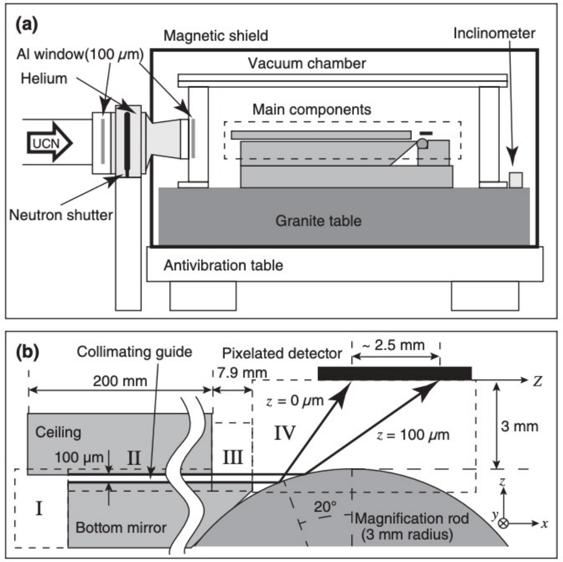
My research plans

- Optomechanical torsion pendulum
  - Research plan I, today's talk

- Sideband cooling of a macroscopic pillar to its ground state
  - Research plan II, probably talking at my next tern
- Demonstration of the long signal recycling cavity and search for high-frequency GWs
  - After the next?
- Test of continuous spontaneous localization with a thin wire
  - Future?

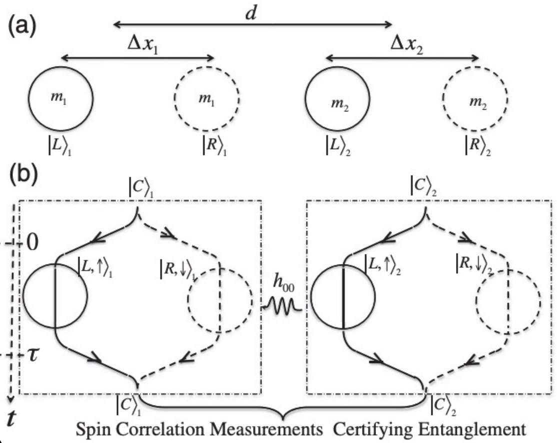
Motivation

- Quantum state in the classical gravity field?
  - Neutrons keep the quantum state in the Earth's gravity



PRL 112, 071101 (2014)

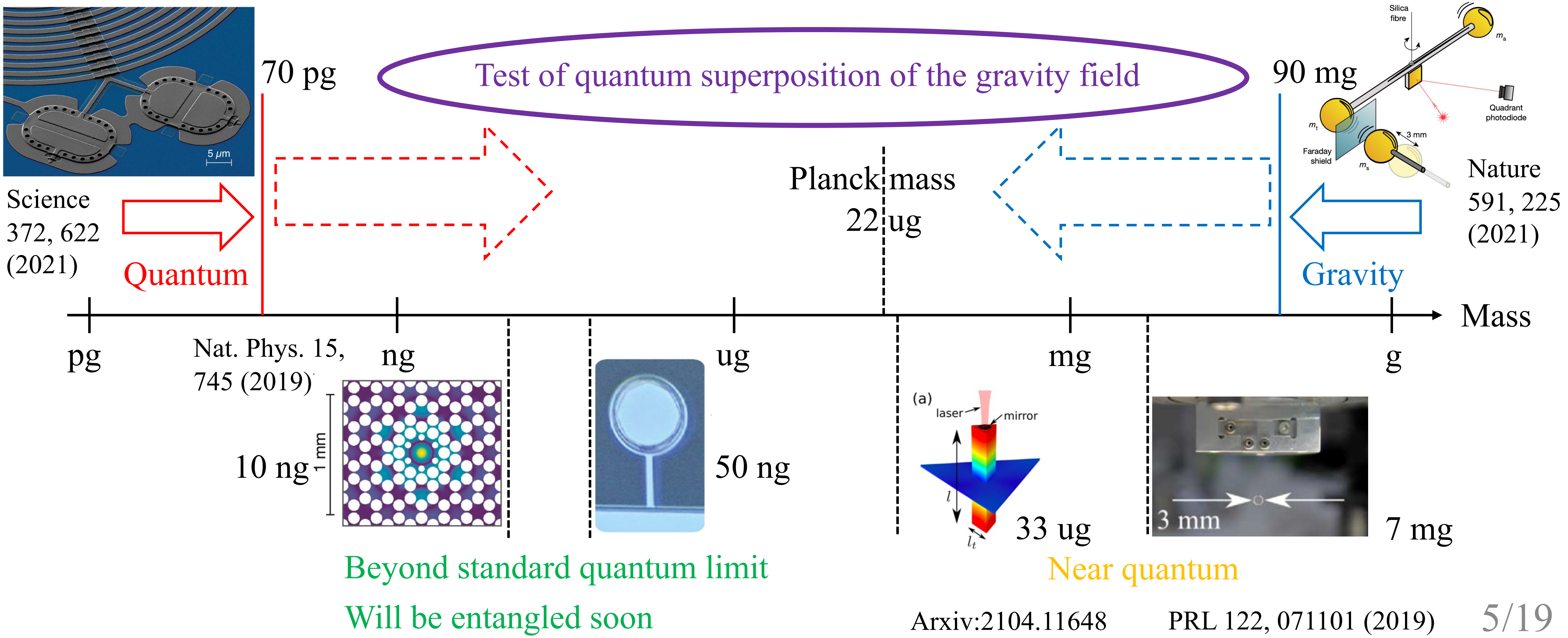
- Should gravity be quantized?
  - Theory of the quantum gravity has not been completed
  - Some experiments are proposed to test it (e.g. spin and matter-wave interferometer)
  - Some counter theories "gravitational decoherence" are also proposed (e.g. CSL, DP model)



PRL 119, 240401 (2017)

Quantum and gravity

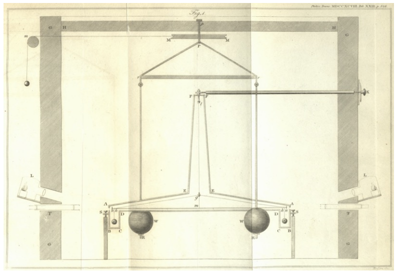
- ➢The massive quantum (70 pg) and the lightest gravity (90 mg)



Torsion pendulum

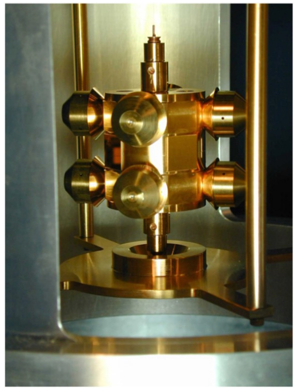
- Very sensitive to tiny force
  - Ultra-small restoring torque: $K \propto \phi^4$
  - Suspension with an O(um) diameter wire leads to O(mHz) resonant frequency

- Gravity measurement
  - Cavendish's experiment (G measurement)



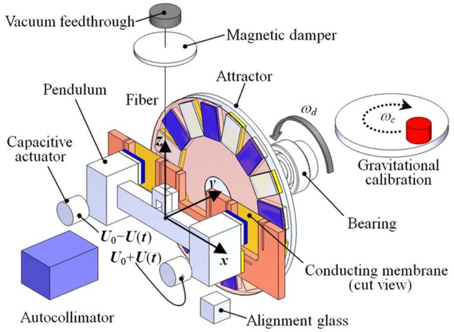
Philos. Trans. R. Soc. London (1798)

  - Equivalence principle



CQG 29, 184002 (2012)

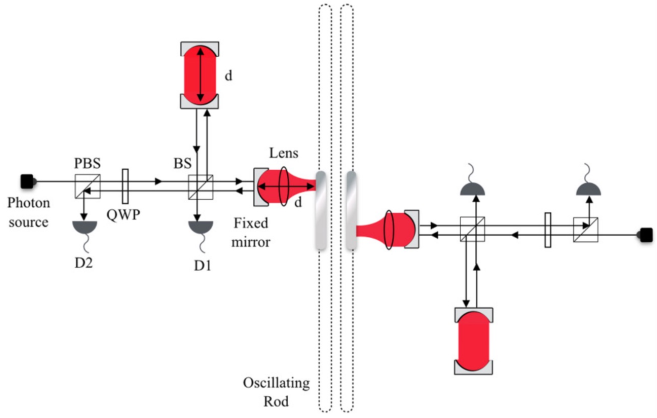
  - Inverse law



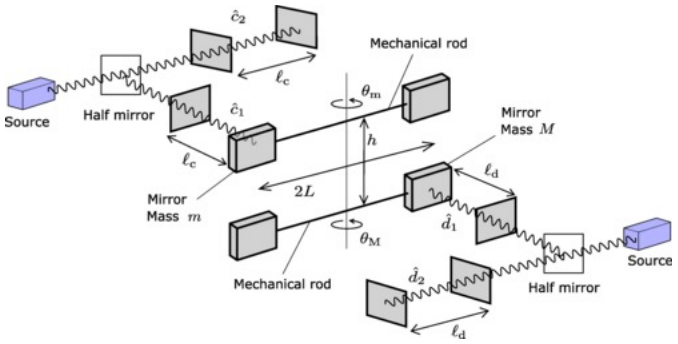
PRL 116, 131101 (2016)

Optomechanical torsion pendulum

- Theoretical proposal
  - Quantum Cavendish (superposition of the torsion pendulum)
  - Test of gravity-induced entanglement

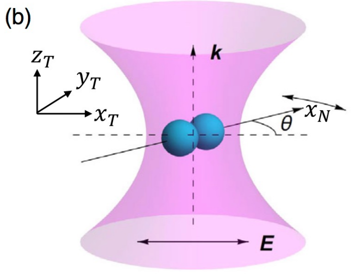


PRA 98, 043811 (2018)

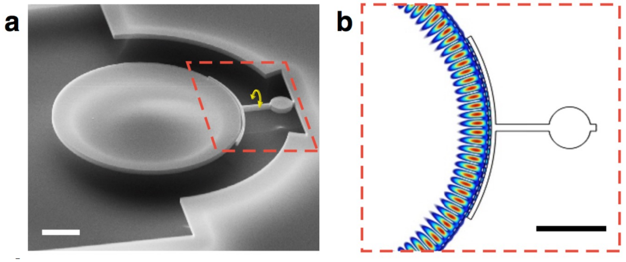


PRD 102, 106021 (2020)

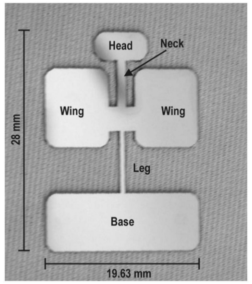
- Experiment
  - GHz nano-rotor
  - Um-pg-torque sensor
  - Mm-mg-scale paddle



PRL 121, 033603 (2018)



Nat. Comm. 7, 13165 (2016)



Rev. Sci. Instrum. 78, 025101 (2007)

My work

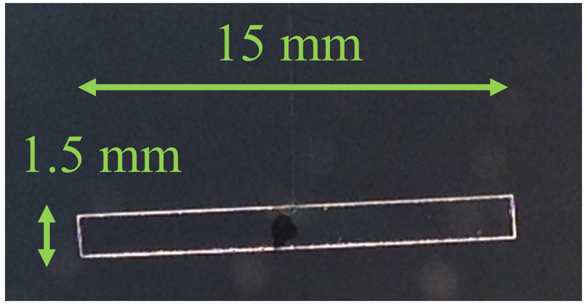
- 10-mg bar mirror suspended by a carbon fiber (6um diameter)
- Triangle cavities avoid the angular instability as similar to Matsumoto-san's triangle cavity
- Low suspension thermal noise because of the low resonant frequency

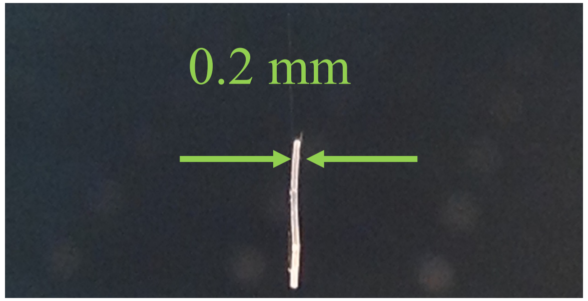
$$S_\tau^{th}(\omega) = 4k_BTI\frac{\omega_m^2}{Q_m\omega}$$

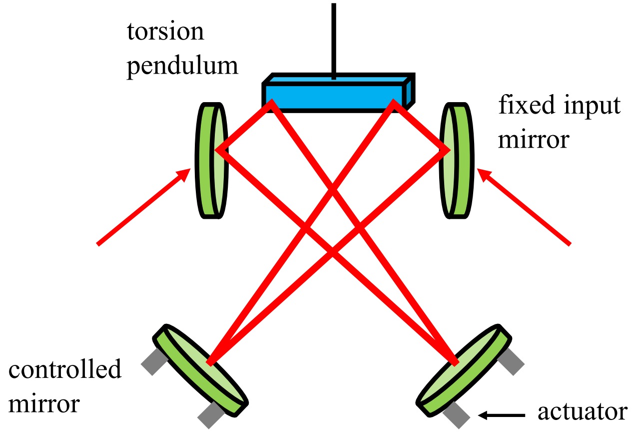
Resonant frequency: quadratic

Q-value: linear

- Subtracting two signals to measure rotational mode and reduce noises from translational mode

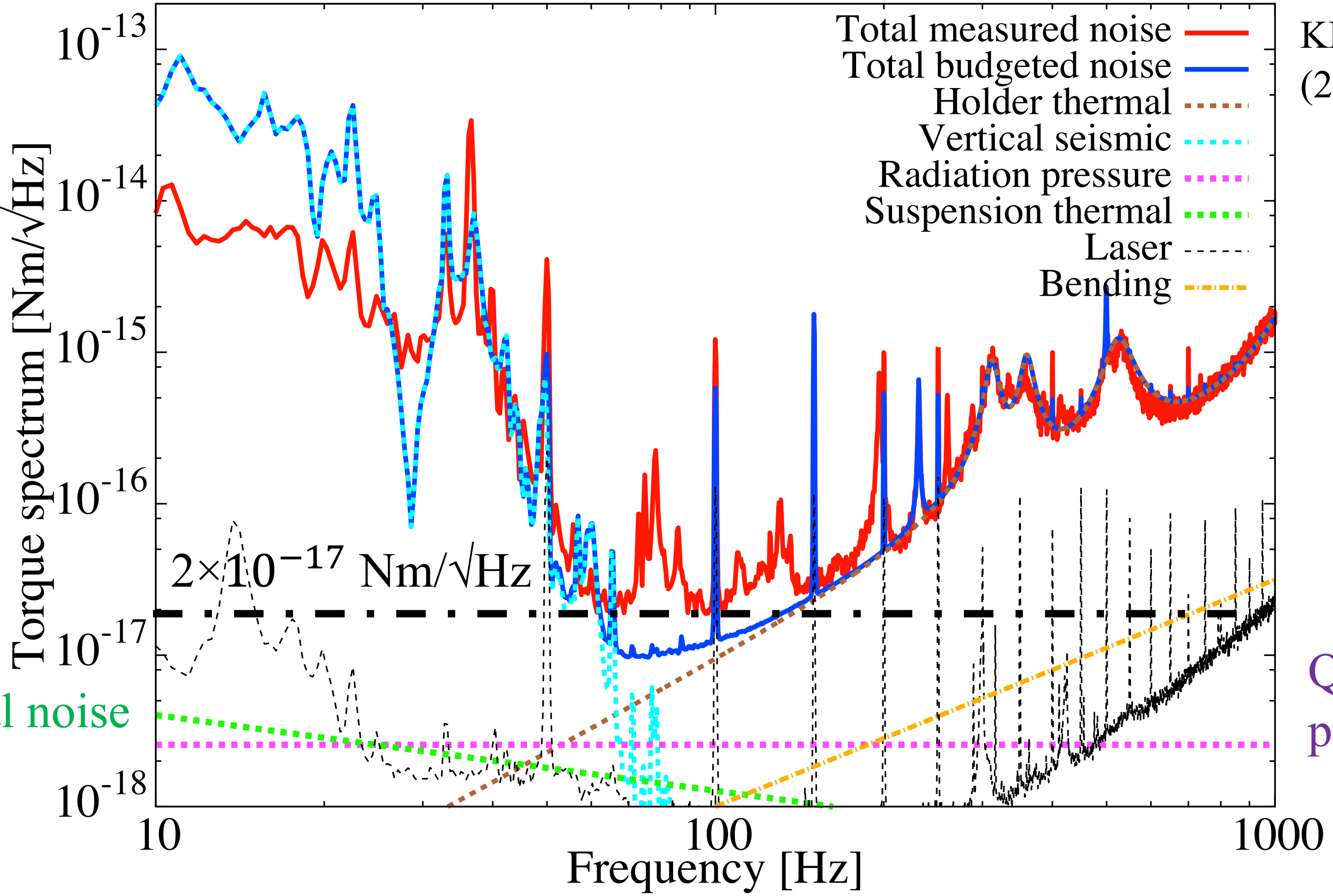






Result

- ➢Best sensitivity of 20 aNm/√Hz in mg-scale torque sensors



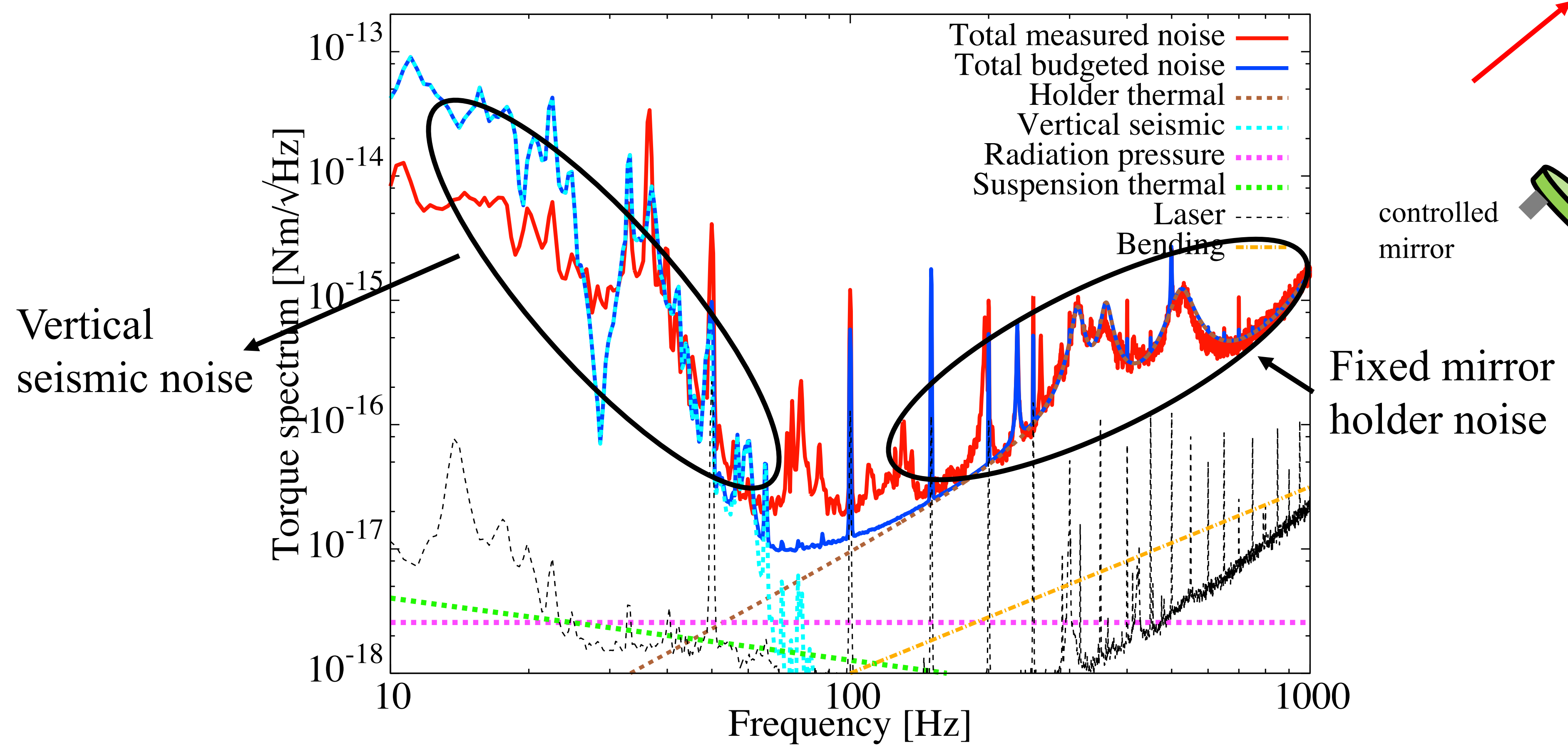
KK+, PRA 101, 011802 (R) (2020)

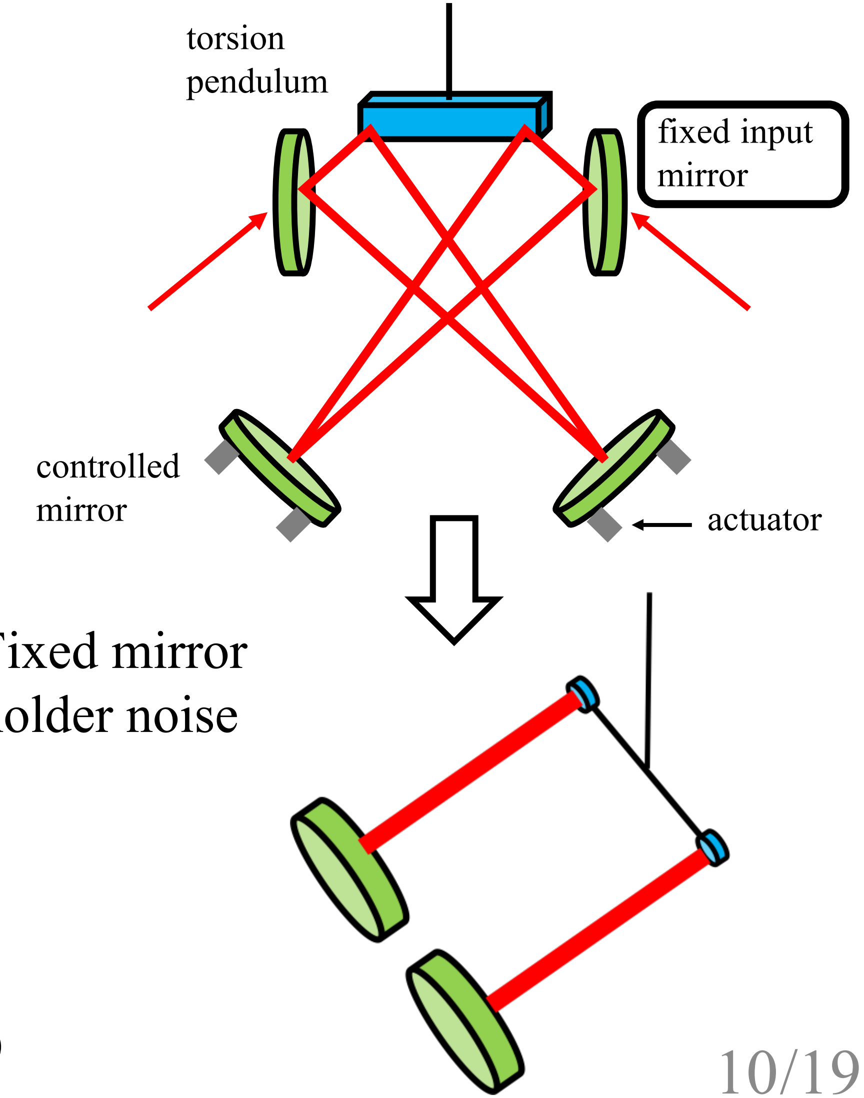
Suspension thermal noise

Quantum radiation pressure noise

Improvement

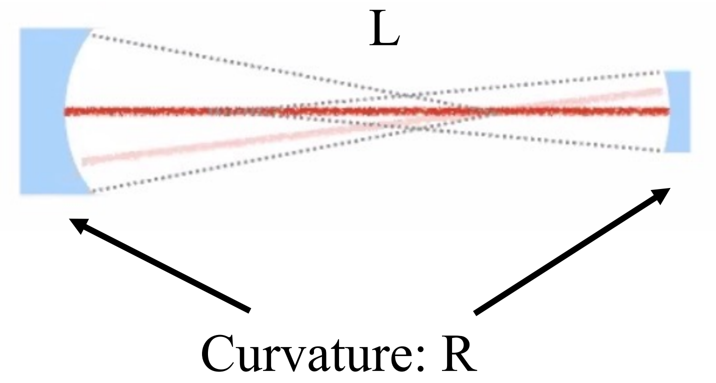
- ➢Removing the fixed mirror to eliminate the holder noise and reduce the vertical coupling



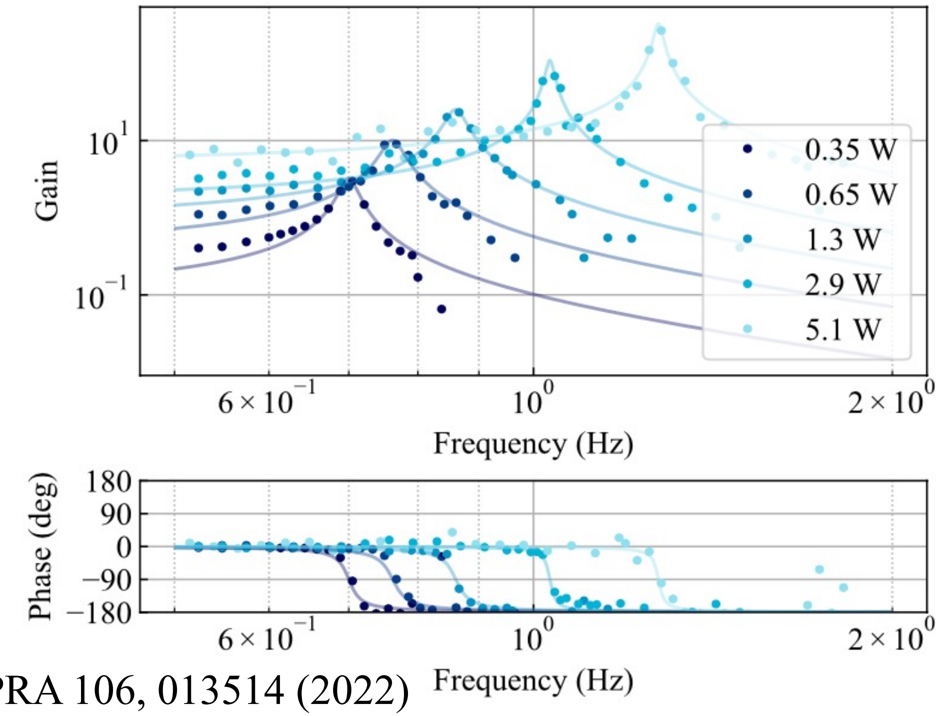


Angular stability

- Demonstration of the angular stability even in the linear cavity
  - Two curved mirrors
  - The curvature smaller than the cavity length leads to the angular stability
  - Larger power increases the resonant frequency of the rotational mode



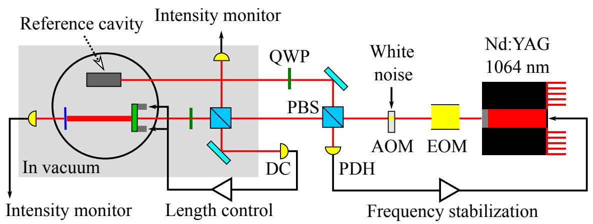
R<L: stable



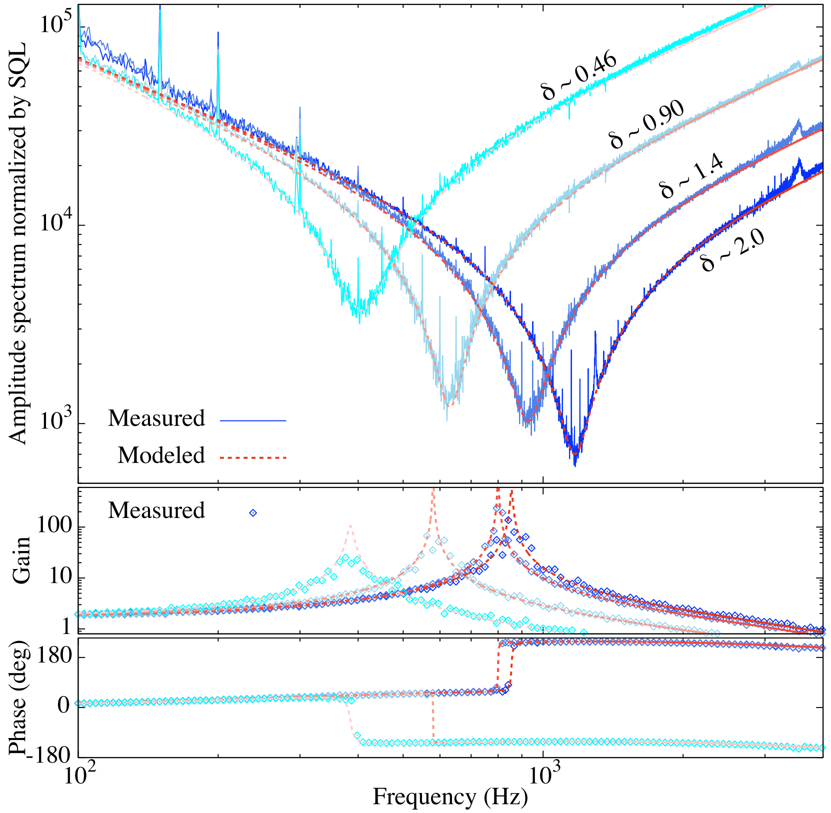
TK, KK+, PRA 106, 013514 (2022)

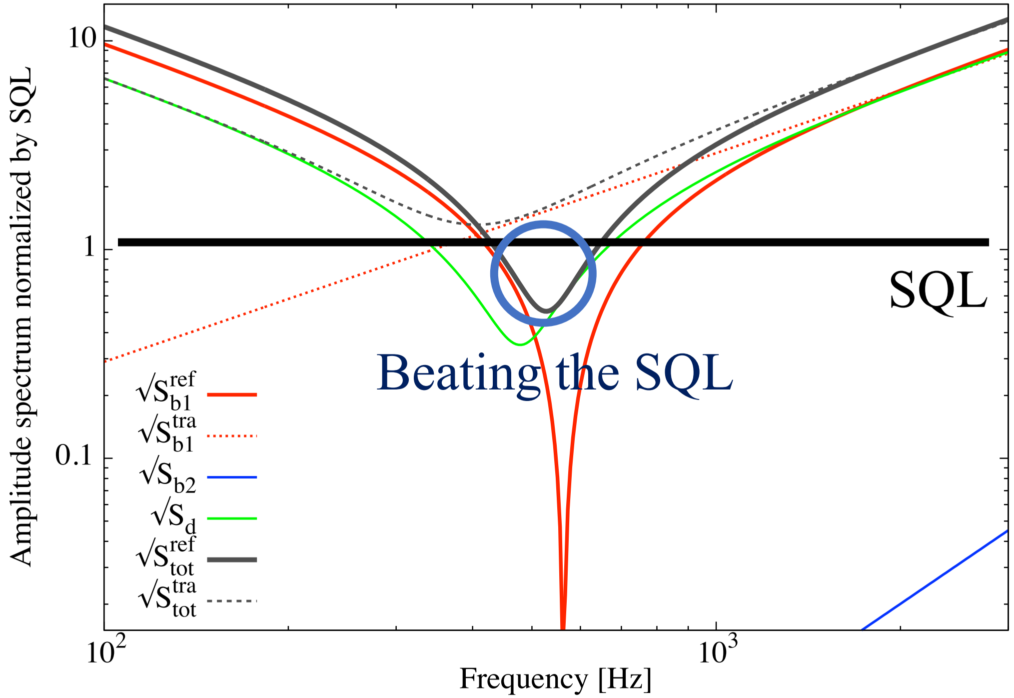
New back-action evasion

- Demonstration of reducing back-action (radiation pressure) noise
  - Just measuring amplitude of reflected light from the cavity
  - The amplitude fluctuation is cancelled at the specific frequency



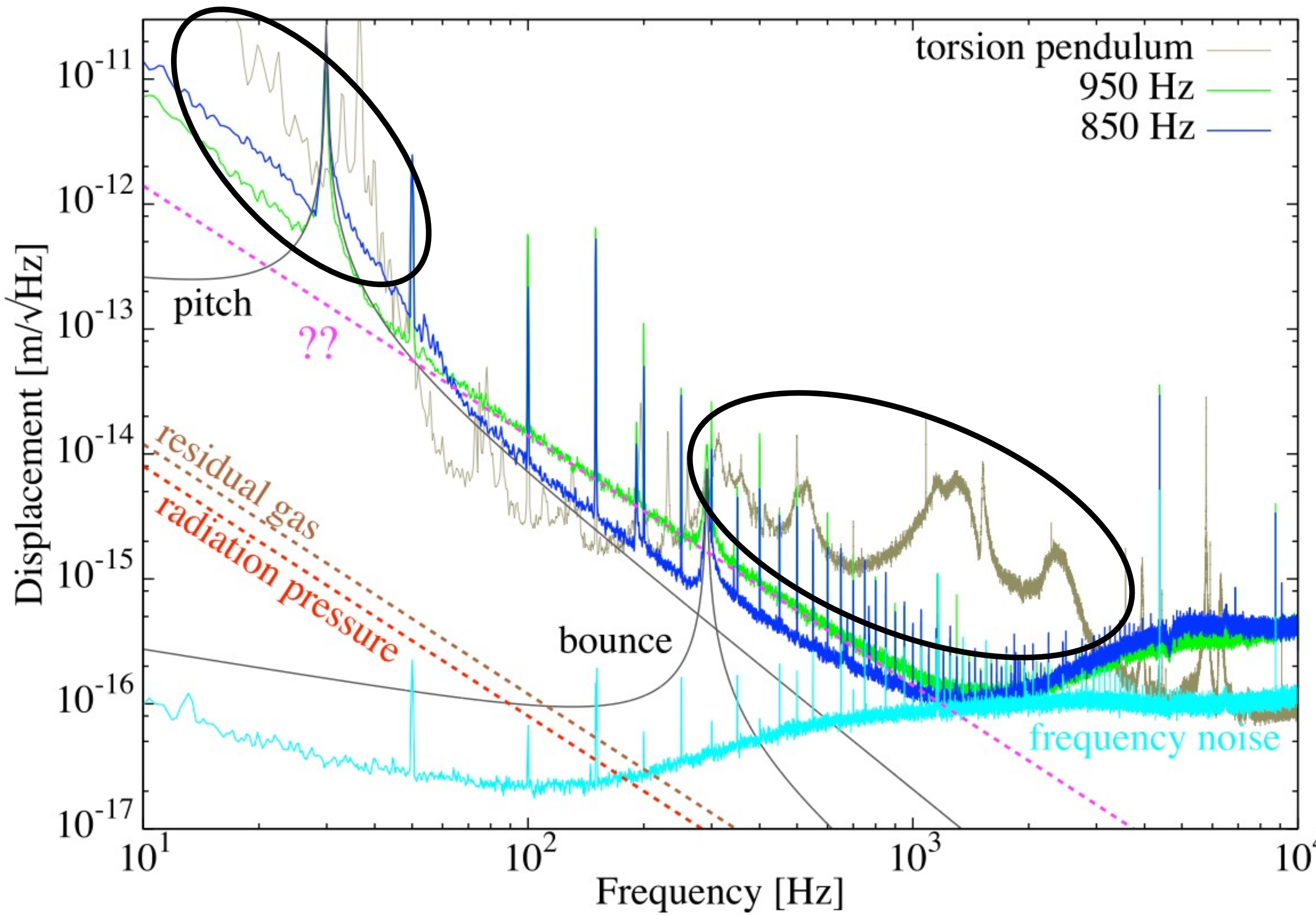
KK+, PRA 104, L031501 (2021)





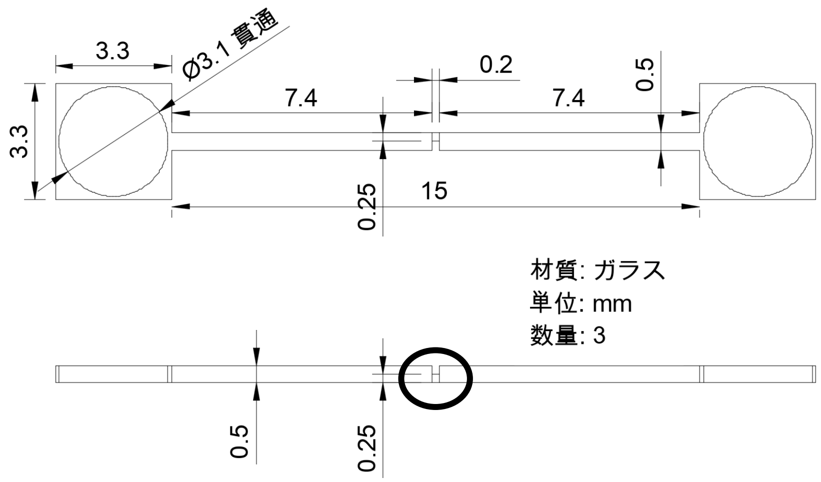
Discussion on the noise

- Comparing the linear cavity and the torsion pendulum triangular cavity
  - No mirror holder noise
  - Much lower vertical seismic noise
  - Adjustment of the beam spot will improve the noise more
  - The dependence of f^{-2} is mysterious

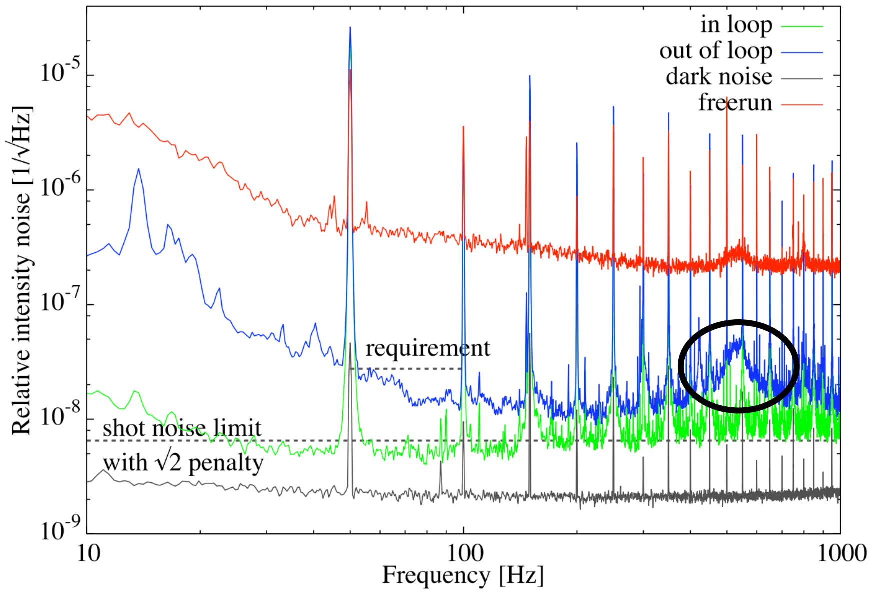


Planned improvement

- New torsion pendulum: dumbbell type
  - Spacer with two holes for the curved mirror at each edge (Opto-science and NSC)
  - Optical contact with the curved mirror and the rectangular solid (Sigma-koki)
  - Suspending at the center of mass to reduce the pitch coupling

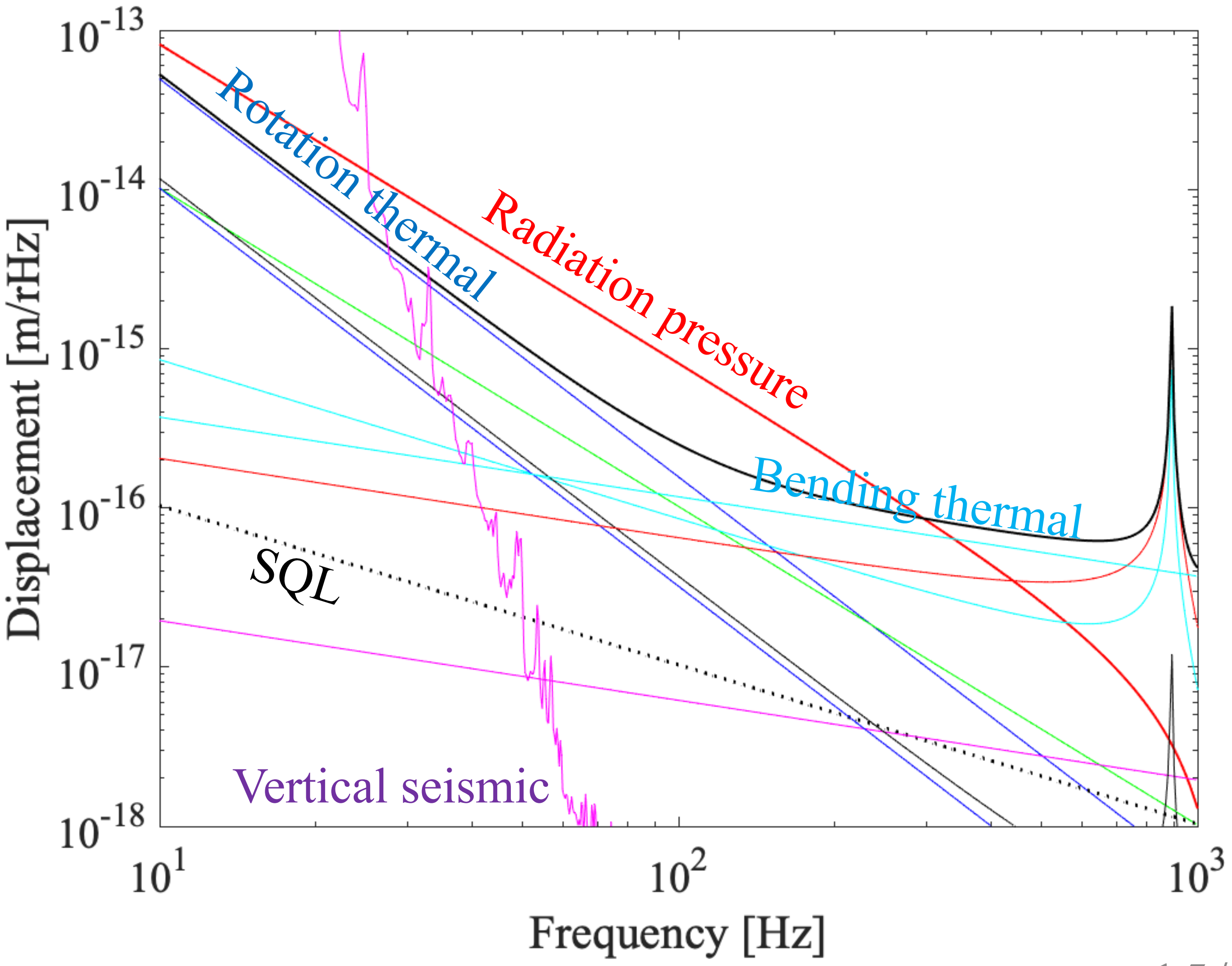


- Intensity stabilization
  - Additional noise from the AOM driver
  - Electrically noisy
  - Replacing the AOM with the EOAM



Design sensitivity

- ➢Radiation pressure dominant from 30 Hz to 300 Hz
- ➢Vertical seismic noise will limit at low frequencies
- ➢Bending thermal noise will limit at high frequencies



Interesting note

- ➢Giving analytical expressions of the radiation pressure noise in the amplitude measurement of reflection

$$S_F^{rad} \simeq \frac{8\hbar\omega_L}{c^2}\frac{P_{in}}{T_{loss}^2} \quad (\omega \ll \omega_{opt})$$

$$S_{b_1}^{\mathrm{ref}} = \frac{(\kappa^2+\Delta^2)\{\Delta\iota - [(\kappa-2\kappa_{\mathrm{in}})^2+\Delta^2]\omega^2\}^2}{16\iota\kappa_{\mathrm{in}}(\kappa-\kappa_{\mathrm{in}})^2\Delta^2\omega^2},$$

$$S_{b_1}^{\mathrm{tra}} = \frac{\kappa_{\mathrm{in}}(\kappa^2+\Delta^2)\omega^2}{\iota\Delta^2},$$

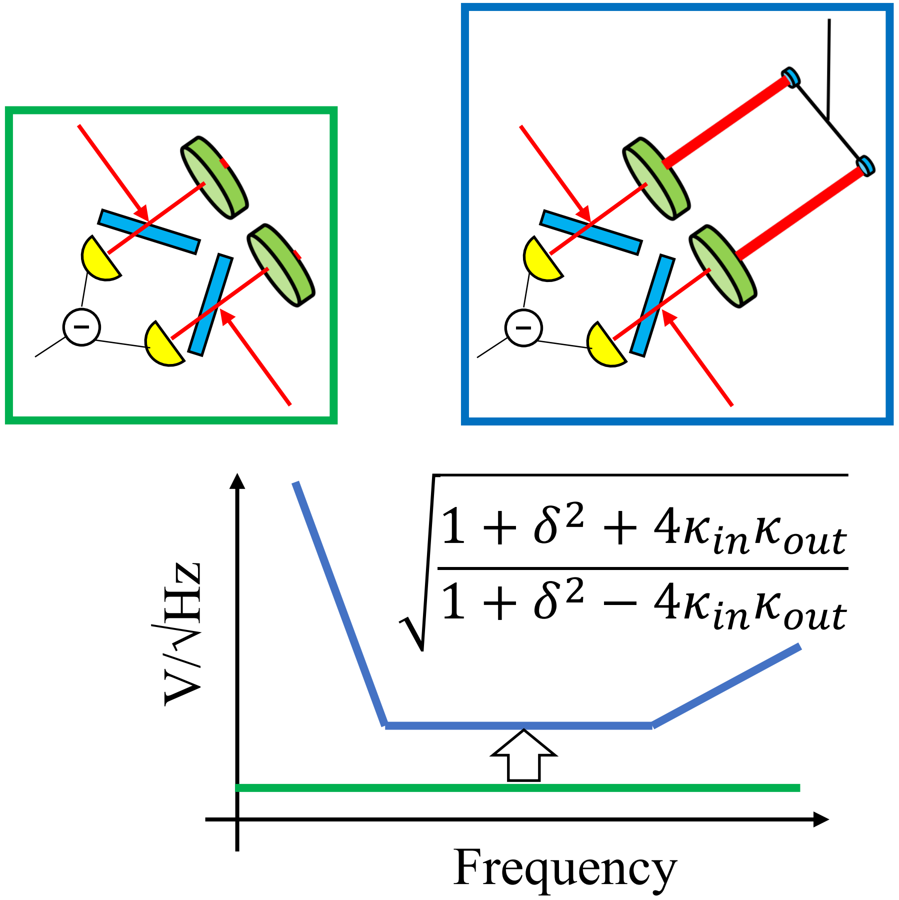
$$S_{b_2} = \frac{\kappa_{\mathrm{in}}\omega^4}{\iota(\kappa^2+\Delta^2)},$$

$$S_d = \frac{[\Delta\iota - (\kappa^2+\Delta^2-2\kappa\kappa_{\mathrm{out}})\omega^2]^2}{4\iota\kappa_{\mathrm{out}}\Delta^2\omega^2} + \frac{\kappa_{\mathrm{out}}\omega^2}{\iota},$$

- ➢Depending only on the optical loss at low frequencies
  - Large T_{in} (smaller finesse) leads to the soft optical spring and the test mass moves more easily
  - Larger finesse means the stiff spring, in the end, the displacement does not change
  - T_{loss} determines how over-coupled the cavity is, so that the slope of the cavity resonance fringe changes linearly in the amplitude (quadratic in the power spectrum)

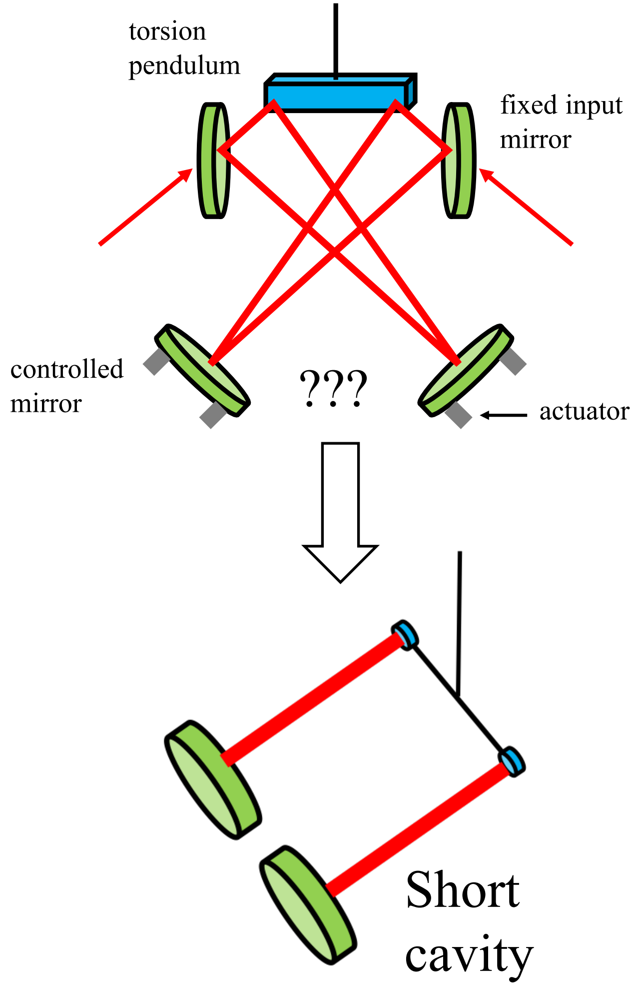
Measured spectrum

- Targeting frequency is around 100 Hz, which is much smaller than the optical spring frequency ~ 1 kHz
- Feedback only around the optical spring and small openloop gain at 100 Hz (error signal measurement)
- Slight increasing from the shot noise without the cavity
  - A factor of ~ 1.3 with $\kappa_{in} = 0.9, \delta = 1/\sqrt{3}$



Recent consideration

- Is the negative g-factor necessary?
- It is necessary for the simple pendulum cavity
- In the case of the torsion pendulum, the optical springs at the edges overwhelm the anti torque spring
- Short cavity (positive g-factor) is still acceptable so that the frequency noise can be reduced?



Summary

- My research plans including the optomechanical torsion pendulum
- Motivation of the macroscopic quantum state
- Current status and future plan toward observation of the quantum radiation pressure fluctuation