The 1st QFilter Workshop @ LMA, Lyon

March 21, 2019

Brief Overview of QFilter Project

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QFilter Project

- Manipulation of an optomechanically coupled oscillator using a quantum filter
- ANR-JST joint research

PI

Antoine Heidmann (Laboratoire Kastler Brossel)

- 0.54Million Euro
- January 2019 – December 2024

PI

Kentaro Somiya (Tokyo Institute of Technology)

- 180Million Yen (~1.4Million Euro)
- October 2018 – March 2024

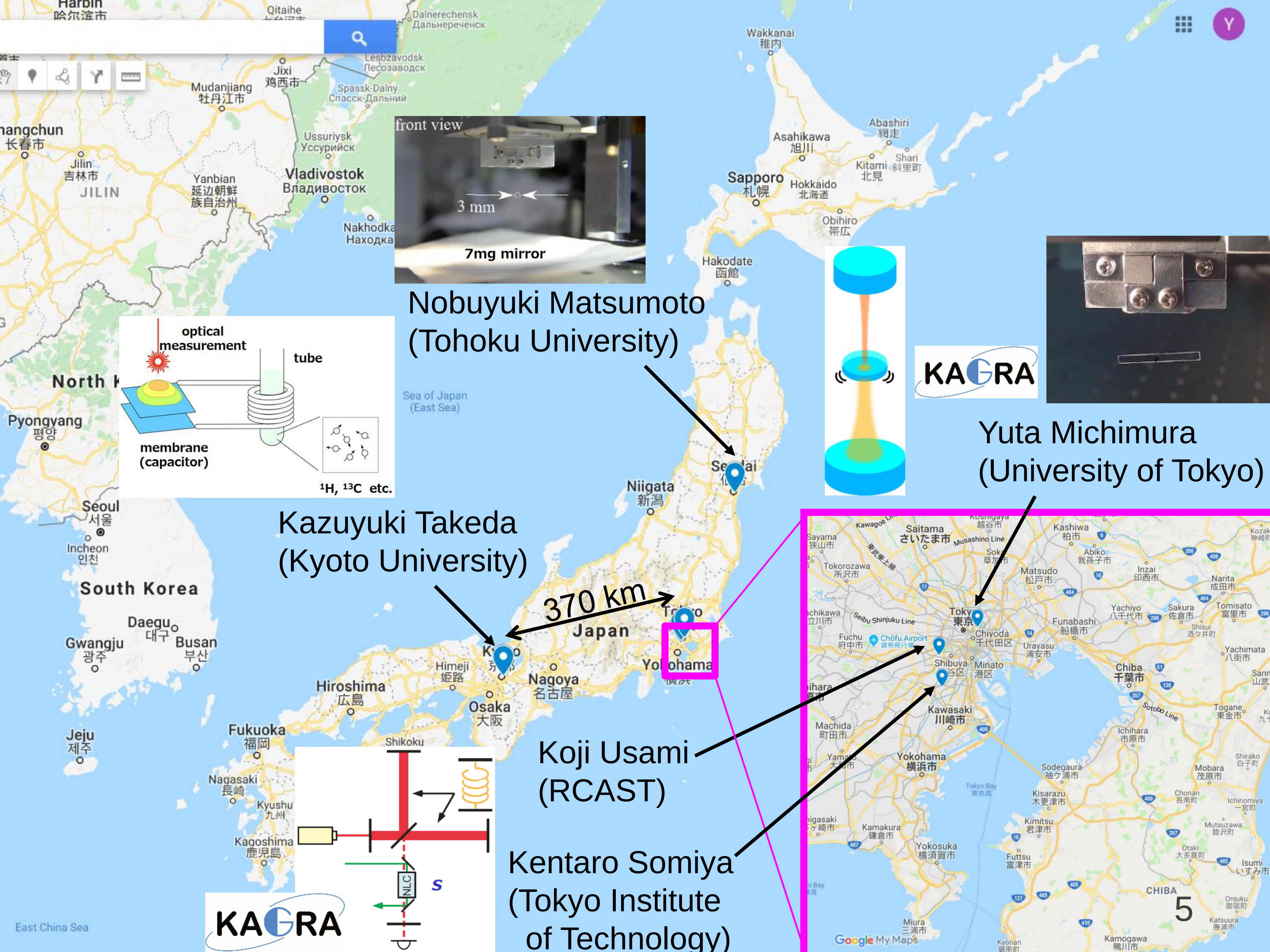
Objectives

- Optomechanics for signal gain and bandwidth enhancement
- Proof of principle experiments
  - signal gain enhancement
  - signal bandwidth enhancement
- Application of these techniques
  - Test of quantum mechanics
  - Gravitational wave detection
  - Nuclear magnetic resonance (NMR) detection

Institutes

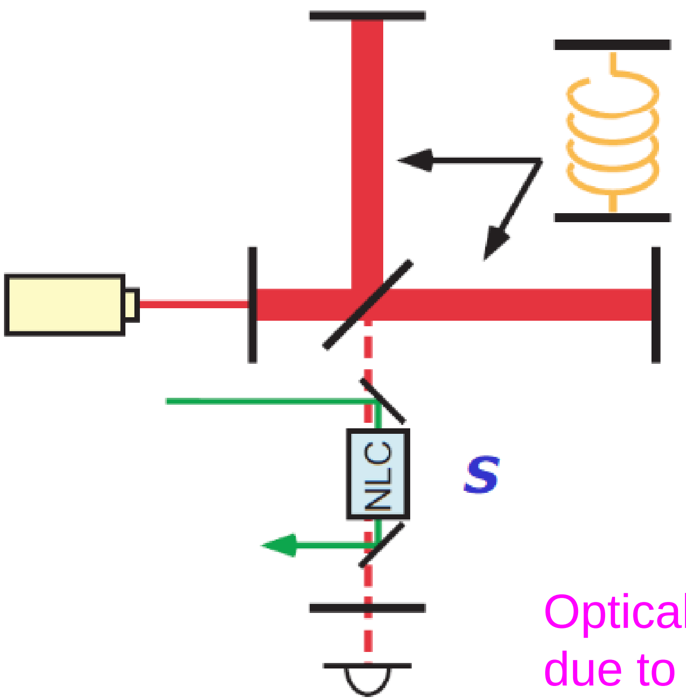
- LKB: Laboratoire Kastler Brossel
- LAL: Laboratoire de l'Accélérateur Linéaire
- LMA: Laboratoire des Matériaux Avancés

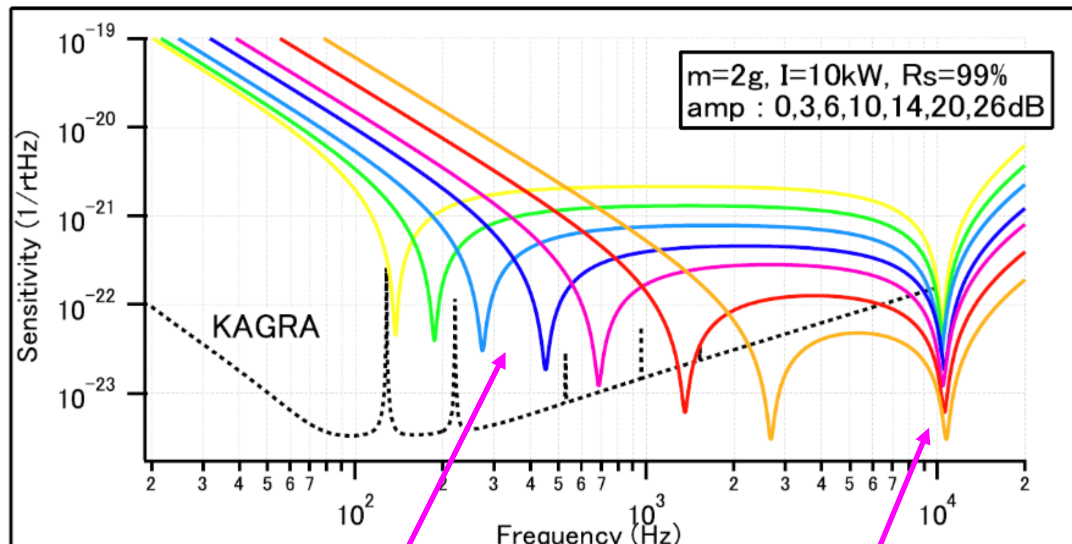
- TT: Tokyo Institute of Technology
- UT: University of Tokyo
- RCAST: Research Center for Advanced Science and Technology, University of Tokyo
- Kyoto: Kyoto University
- Tohoku: Tohoku University


front view
3 mm
7mg mirror
Nobuyuki Matsumoto
(Tohoku University)
optical
measurement
tube
membrane
(capacitor)
^{1}H, ^{13}C etc.
KAGRA
Yuta Michimura
(University of Tokyo)
Kazuyuki Takeda
(Kyoto University)
370 km
Koji Usami
(RCAST)
Kentaro Somiya
(Tokyo Institute
of Technology)
S
NLC
KAGRA

Signal Gain Enhancement

- At TT
- Modify optical spring frequency using a non-linear crystal in signal recycling cavity
- Demonstration experiment on-going





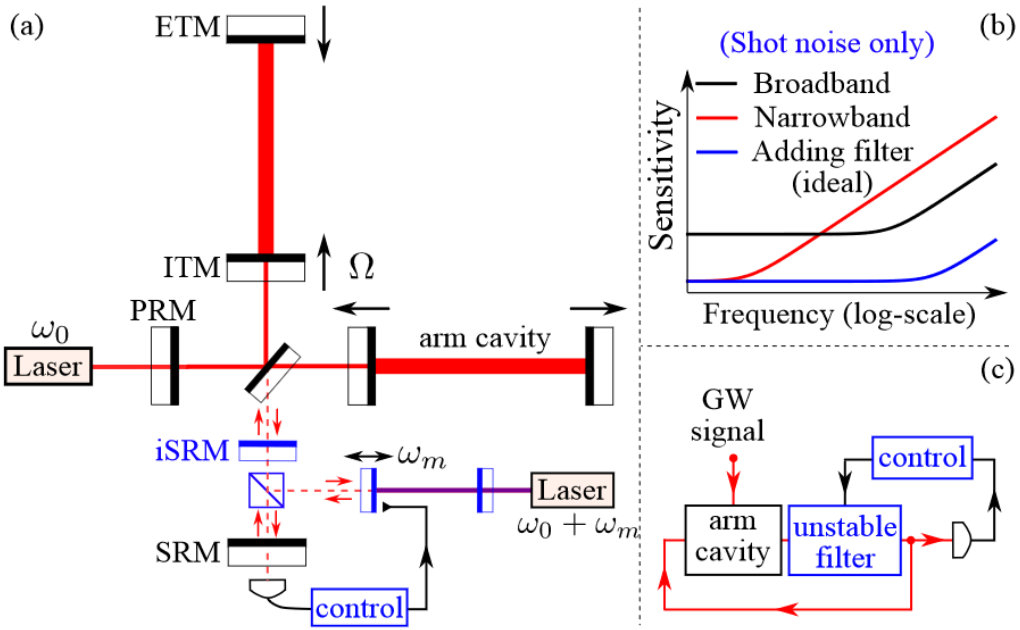
Optical spring frequency shifts due to parametric amplification

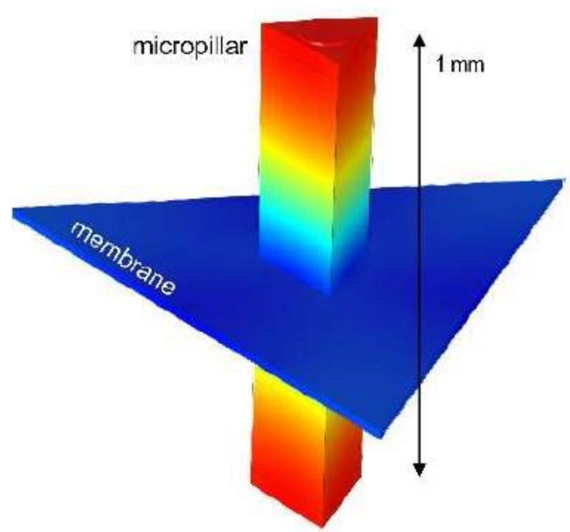
Optical resonance

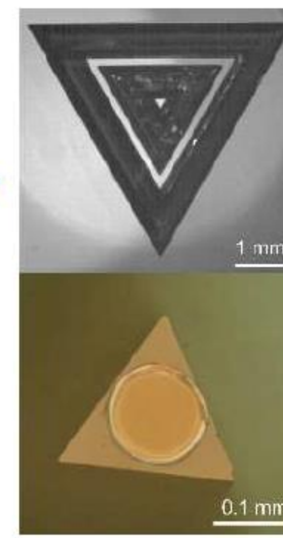
K. Somiya+, [Phys. Lett. A 380, 5 (2016)]

Signal Bandwidth Enhancement

- At LKB
- Bandwidth can be enhanced by compensating the phase delay using negative dispersion of a micro resonator
- Micropillar (30 µg) can be used





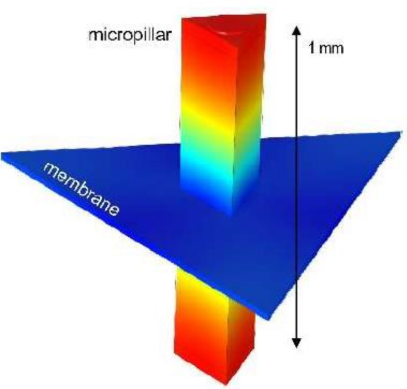


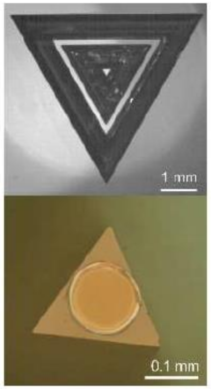
H. Miao+, [PRL 115, 211104 (2015)](PRL 115, 211104 (2015))

Test of Quantum Mechanics

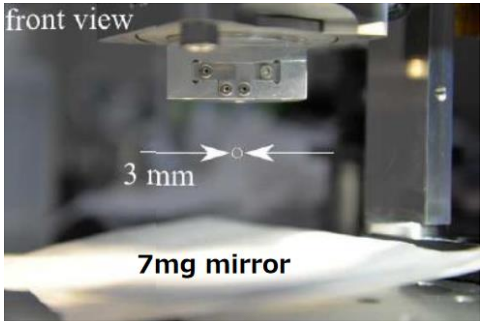
- At LKB, UT and Tohoku
- Test at various scales to look into classical-quantum boundary
- Works for ground state cooling, standard quantum limit measurement on-going

30 μg micropillar





0.2-1 mg levitated mirror

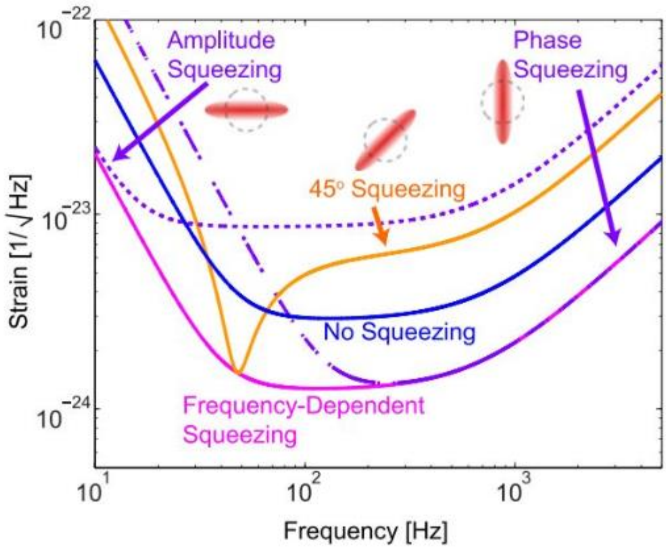


7 mg suspended mirror

10 mg torsion bar

Gravitational Wave Detection

- At LKB, LAL, TT and UT
- Sensitivity enhancement of GW detectors
  - parametric signal amplification
  - bandwidth enhancement
  - frequency dependent squeezing

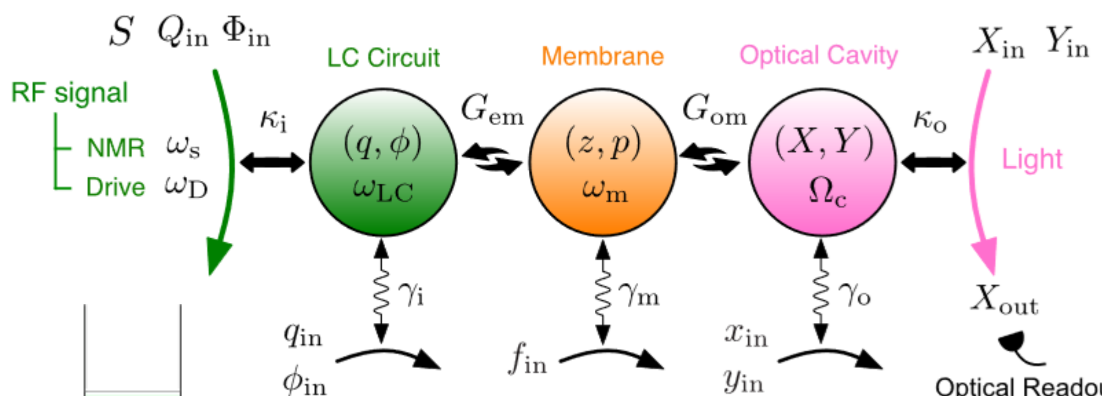


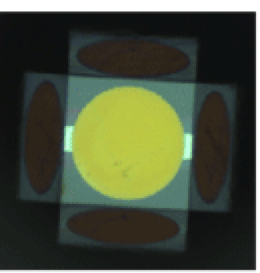
S S Y Chua+, [CQG 31, 183001 (2014)]

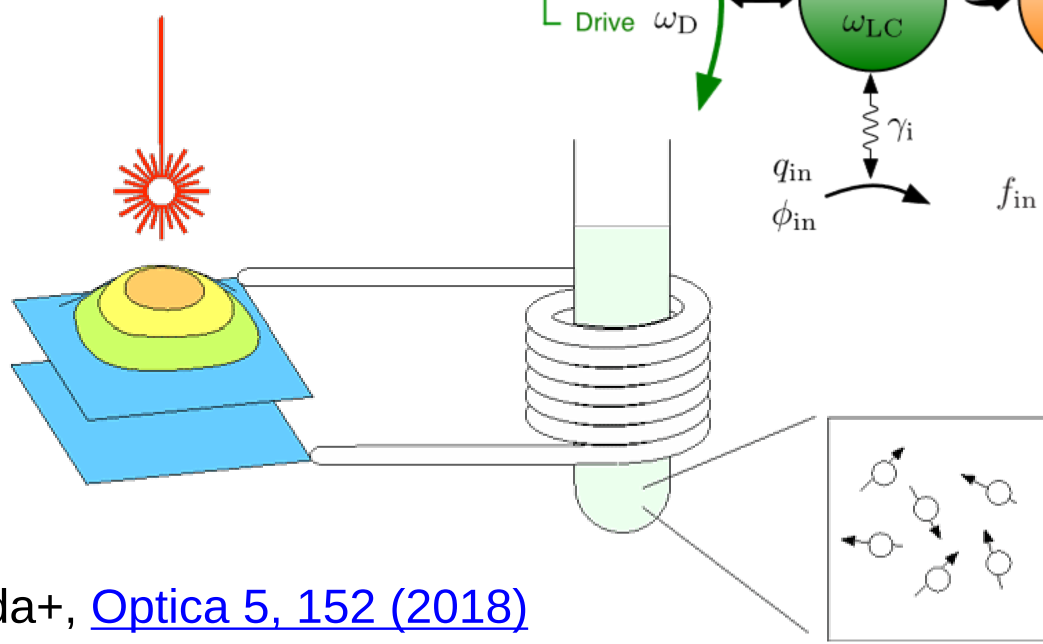
ExSqueez

Nuclear Magnetic Resonance

- At RCAST and Kyoto
- Readout NMR signal optomechanically to increase the sensitivity
- Demonstration done, working on further sensitivity enhancement





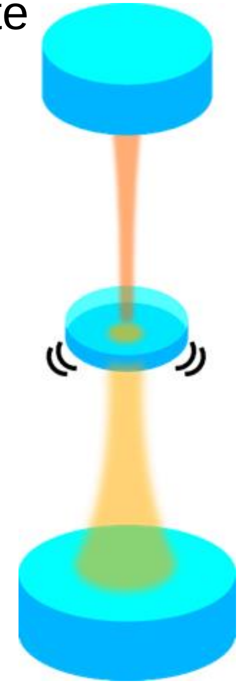


K. Takeda+, [Optica 5, 152 (2018)]

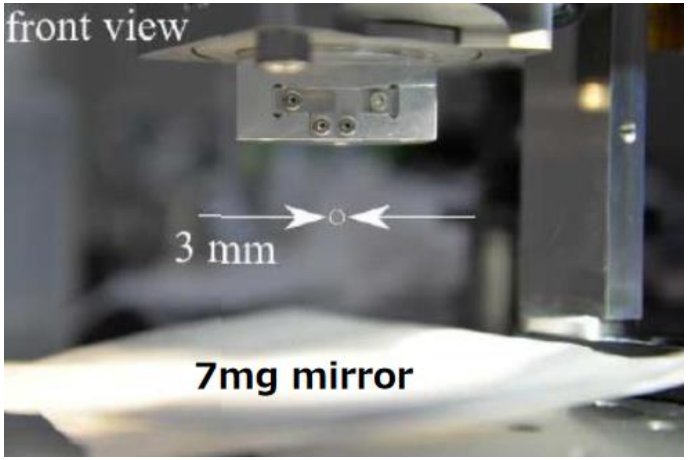
What I Do in the Project

- Test of macroscopic quantum mechanics
- See if superposition of macroscopic objects can be realized
- Focusing on mg-scale, with different approaches

Optical levitation to eliminate suspension thermal noise



Suspended 7mg disc

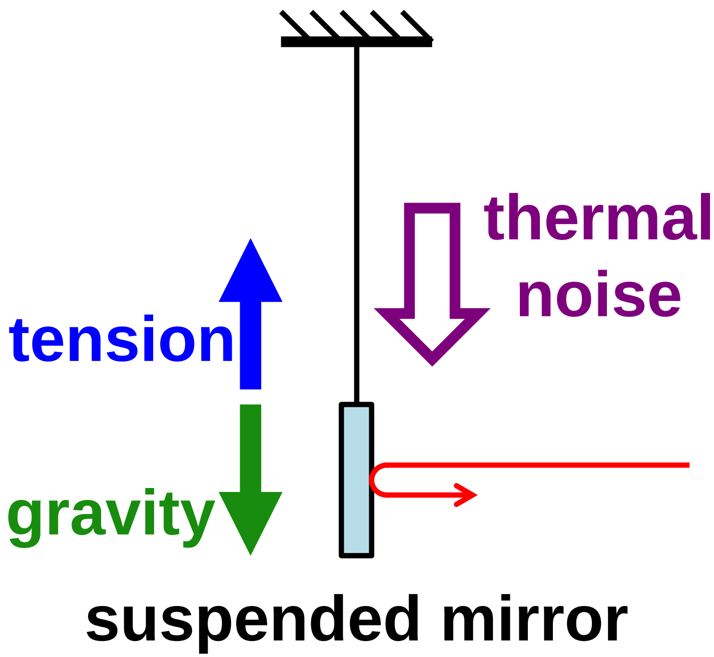


Suspended 10mg bar

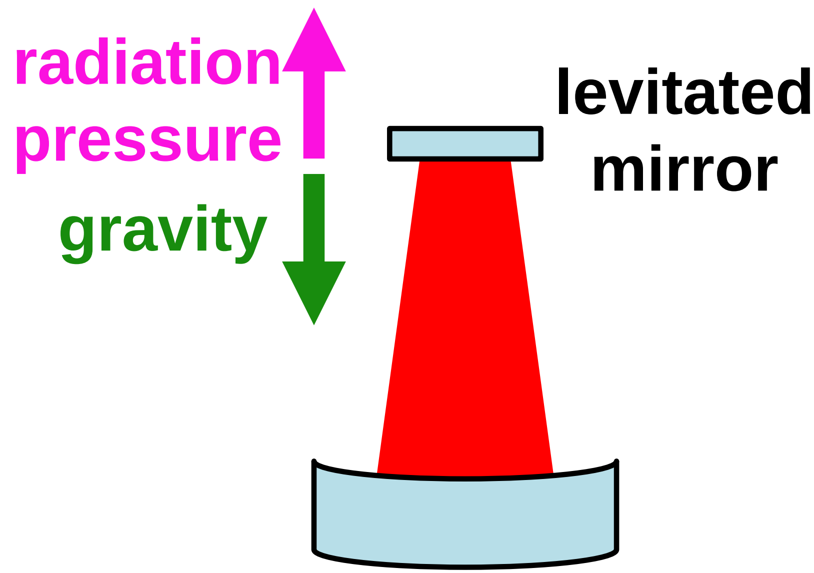
Optical Levitation of a Mirror

- Thermal decoherence due to mechanical support can be avoided with optical levitation

Mechanical Suspension

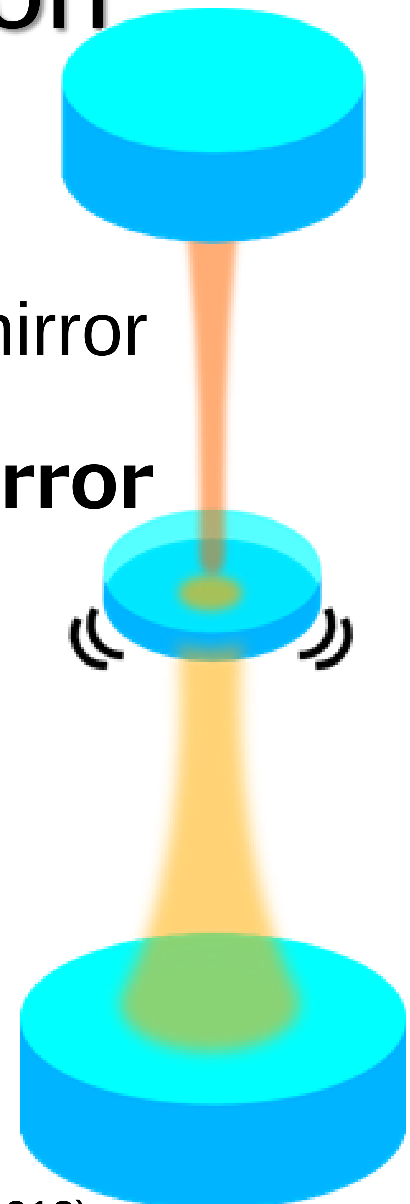


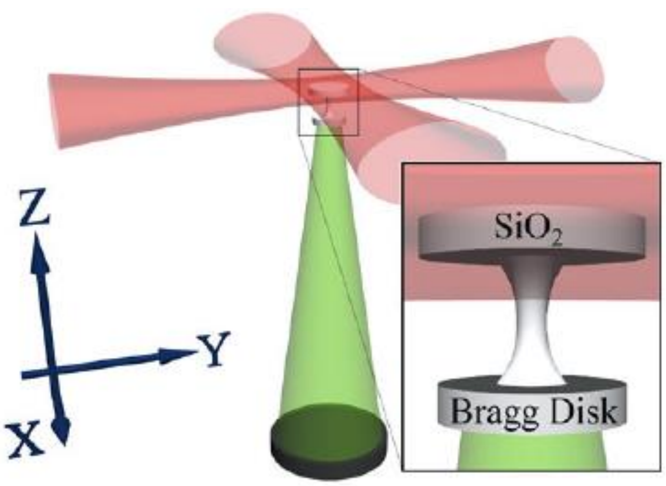
Optical Levitation



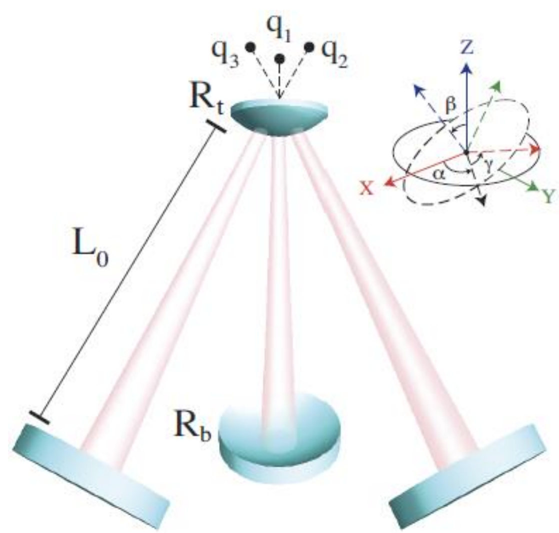
Sandwich Configuration

- Simple configuration than previous proposals
- Upper cavity to stabilize the levitated mirror





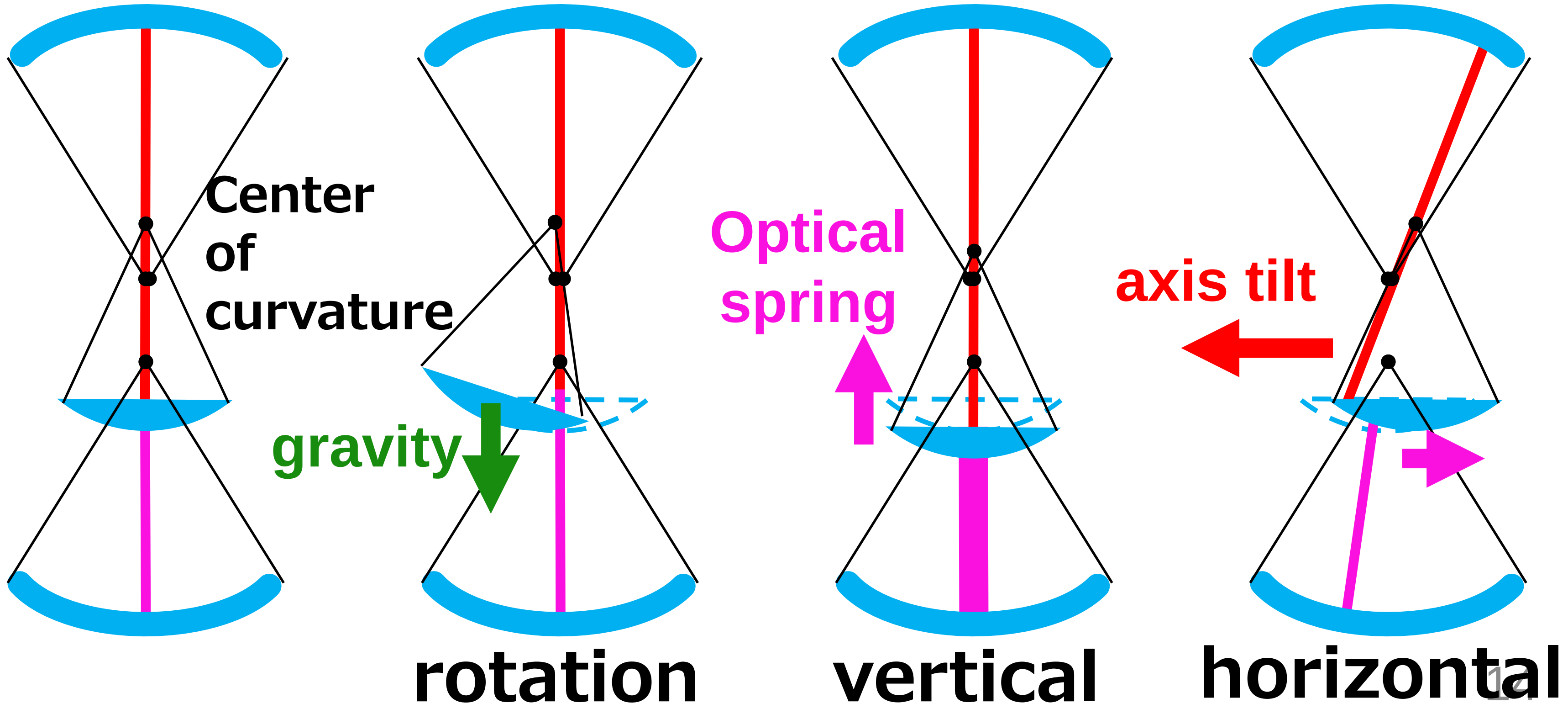
S. Singh+: PRL 105, 213602 (2010)



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

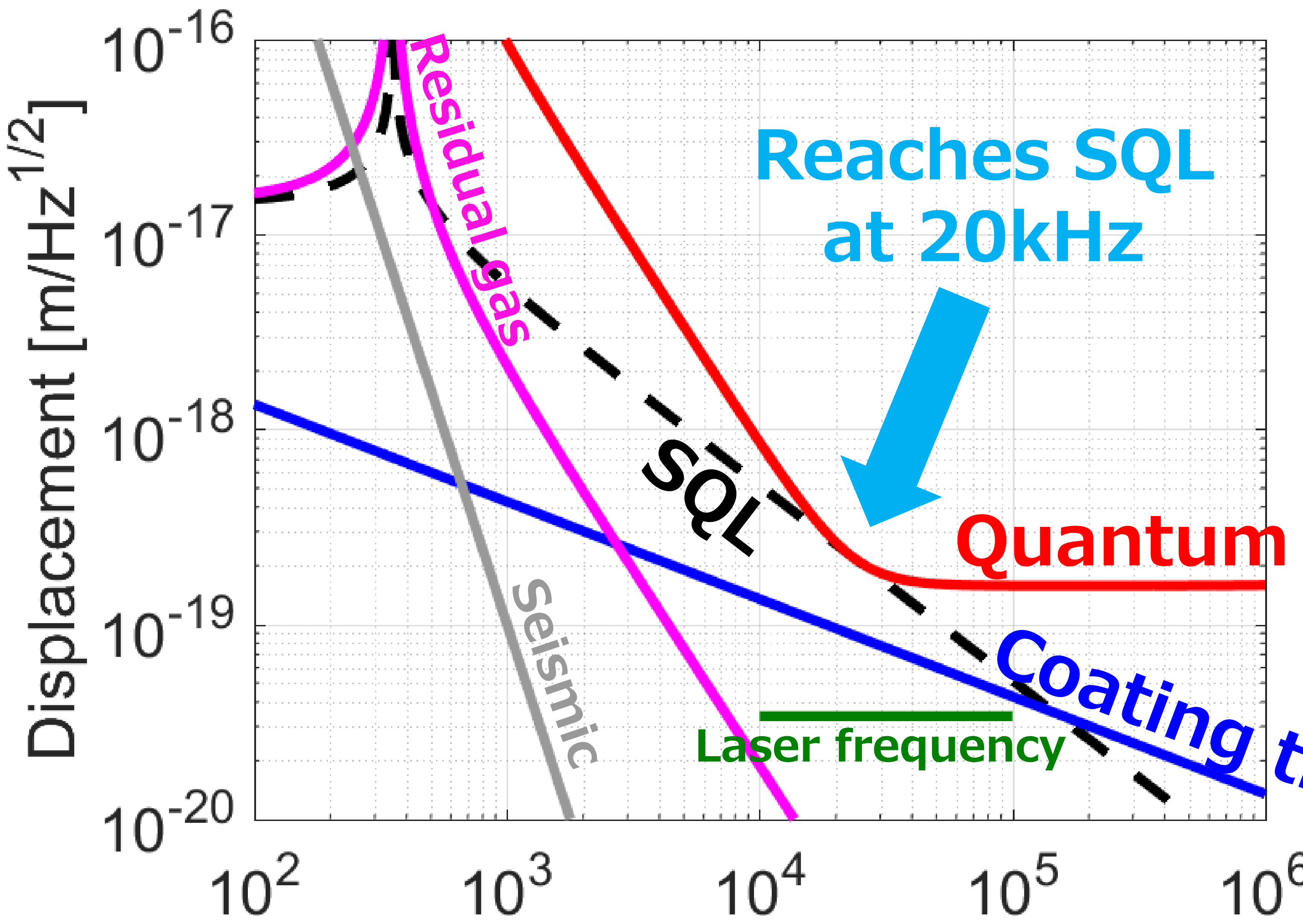
Stability of the Levitation

- Rotationally stable due to gravity
- Vertically stable due to optical spring
- Horizontally stable due to beam axis tilt



Reaching the SQL is Feasible

- 0.2 mg mirror, 13 W + 4 W input, finesse 100



YM+, Opt. Express 25, 13799 (2017)

Technical Challanges

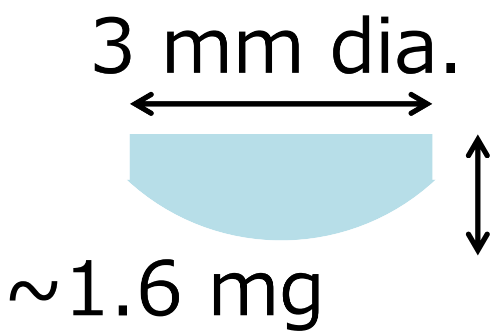
- Fabrication of mg-scale mirrors
  mm-scale diameter, curved, HR/AR coated

- Experimental demonstration of the stability
- Procedure for tuning the alignment, power, detuning for the levitation
  experiment using torsion pendulum ongoing

- Laser frequency noise
  0.1 mHz/$\sqrt{\text{Hz}}$ @ 20 kHz

Mirror We Need

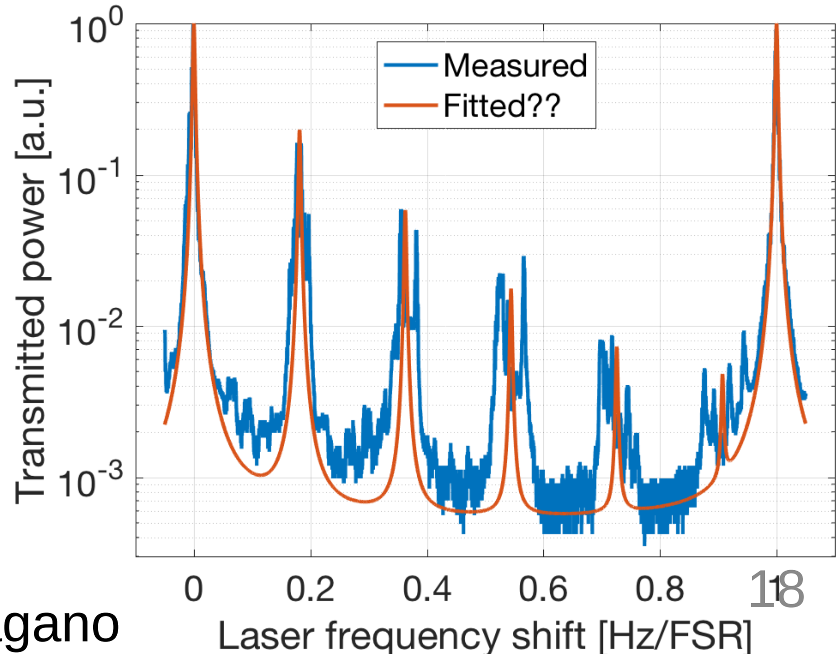
Upper side
- flat
- AR <0.5%



Lower side
- RoC 30 mm
- HR >~99%
  (finesse >~100)

Fabrication Prototype

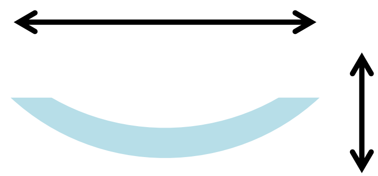
- Ordered (to company S)
  - mass 1.6 mg
  - φ 3mm, t 0.1 mm
  - RoC 30 +/- 10 mm
  - Reflectivity 99.95 %
- Ordered 8, but received 7 (only 1 without cracks)
  - crack during coaing
- Measured
  - RoC 15.9 +/- 0.5 mm
  - Reflectivity >99.5%



Plot by K. Nagano

Alternative Way?

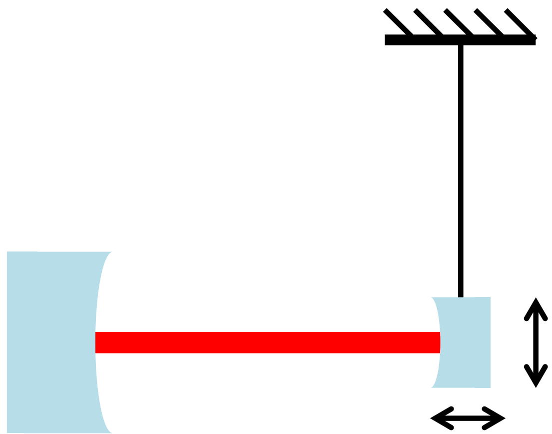
Upper side
- RoC 30 mm
- HR >~99%
  (create an etalon)



Lower side
- RoC 30 mm
- HR >~99%
  (finesse >~100)

Other Approaches

- Curved suspended mirror



- RoC 100 mm
- HR 99.99%

3 mm dia.

0.5 mm thick

~8 mg

- Curved bar

~100 mm long

Supplementary

Parameters for Sensitivity Calc.

Table 1. Parameters for reaching the SQL. The suffix indicates s for the substrate, Ta for the TiO_2:Ta_2O_5 coating layer, Si for the SiO_2 coating layer, L for the lower cavity and U for the upper cavity.

Levitated mirror		
mass	m	0.2 mg
radius	r	0.35 mm
ROC	R	30 mm
beam radius	$w_{\mathrm{L,U}}$	0.14 mm, 0.19 mm
coating thickness	d_{Ta}	91 nm × 7 layers
	d_{Si}	237 nm × 6 layers
Young's modulus	$Y_{\mathrm{s,Ta,Si}}$	73 GPa, 140 GPa, 73 GPa
Poisson ratio	$\nu_{\mathrm{s,Ta,Si}}$	0.17, 0.28, 0.17
loss angle	$\phi_{\mathrm{s,Ta,Si}}$	1×10^{-6}, 2×10^{-4}, 5×10^{-5}
refractive index	$n_{\mathrm{s,Ta,Si}}$	1.45, 2.07, 1.45
Laser		
wavelength	λ	1064 nm
input power	$P^{\mathrm{in}}_{\mathrm{L,U}}$	13 W, 4 W
frequency noise	δf_{a}	0.1 mHz/$\sqrt{\mathrm{Hz}}$
Cavity		
length	$l_{\mathrm{L,U}}$	95 mm, 50 mm
fixed mirror's ROC	$R_{\mathrm{L,U}}$	120 mm, 30 mm
COC distance	$a_{\mathrm{L,U}}$	5.0 mm, 1.3 mm
finesse	$\mathcal{F}_{\mathrm{L,U}}$	100, 100
intracavity power	$P^{\mathrm{circ}}_{\mathrm{L,U}}$	420 W, 130 W
normalized detuning	$\delta_{\mathrm{L,U}}$	−0.005, 0.018
Temperature	T	300 K
Air pressure	P	10^{-5} Pa

YM+, Optics Express 25, 13799 (2017)