OIST Quantum Machines Seminar (Online) January 14, 2021

Optical Levitation of a Mirror for Probing Macroscopic Quantum Mechanics

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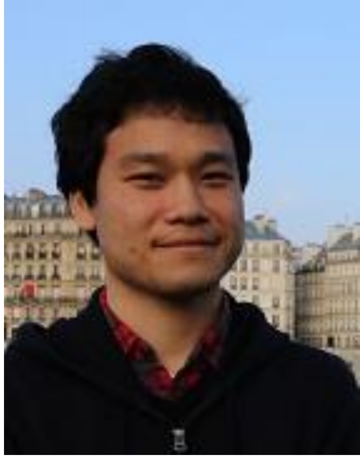
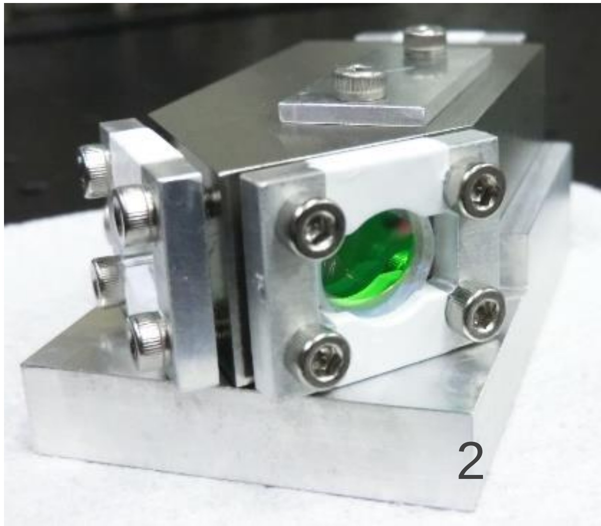
Self Introduction



- Yuta Michimura (道村 唯太)
  Assistant Professor at
  Department of Physics, University of Tokyo

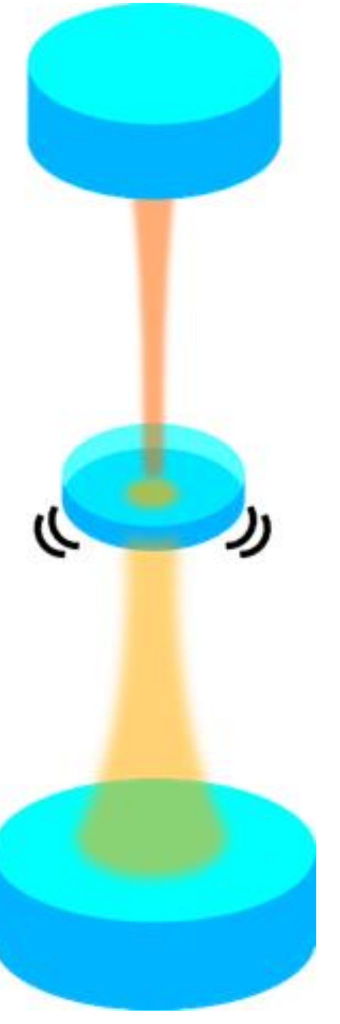
- Laser interferometric gravitational wave detectors
  - KAGRA
  - DECIGO (SILVIA)



- Fundamental physics with laser interferometry
  - Lorentz invariance test
  - Macroscopic quantum mechanics
  - Dark matter search etc…

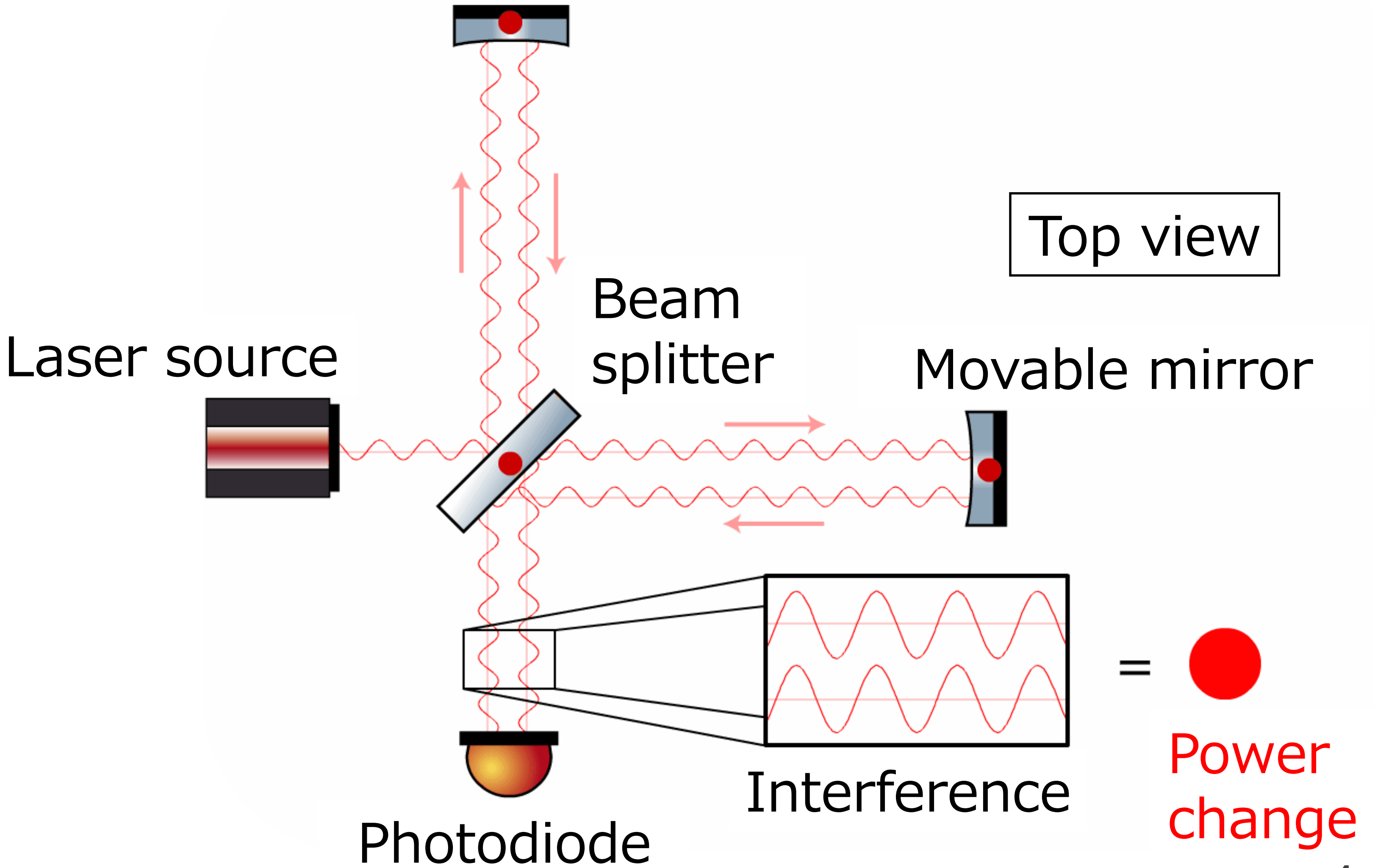
Plan of This Talk

- **Macroscopic Quantum Mechanics**
  - Motivations
  - Standard quantum limit
  - Review of current status of experiments
- **Optical Levitation of a Mirror**
  - Principles
  - Experiment to demonstrate the stability
- **Fabrication of a Levitation Mirror**
  - Past trials and mirror characterization
  - Photonic crystal mirrors
- **Summary**



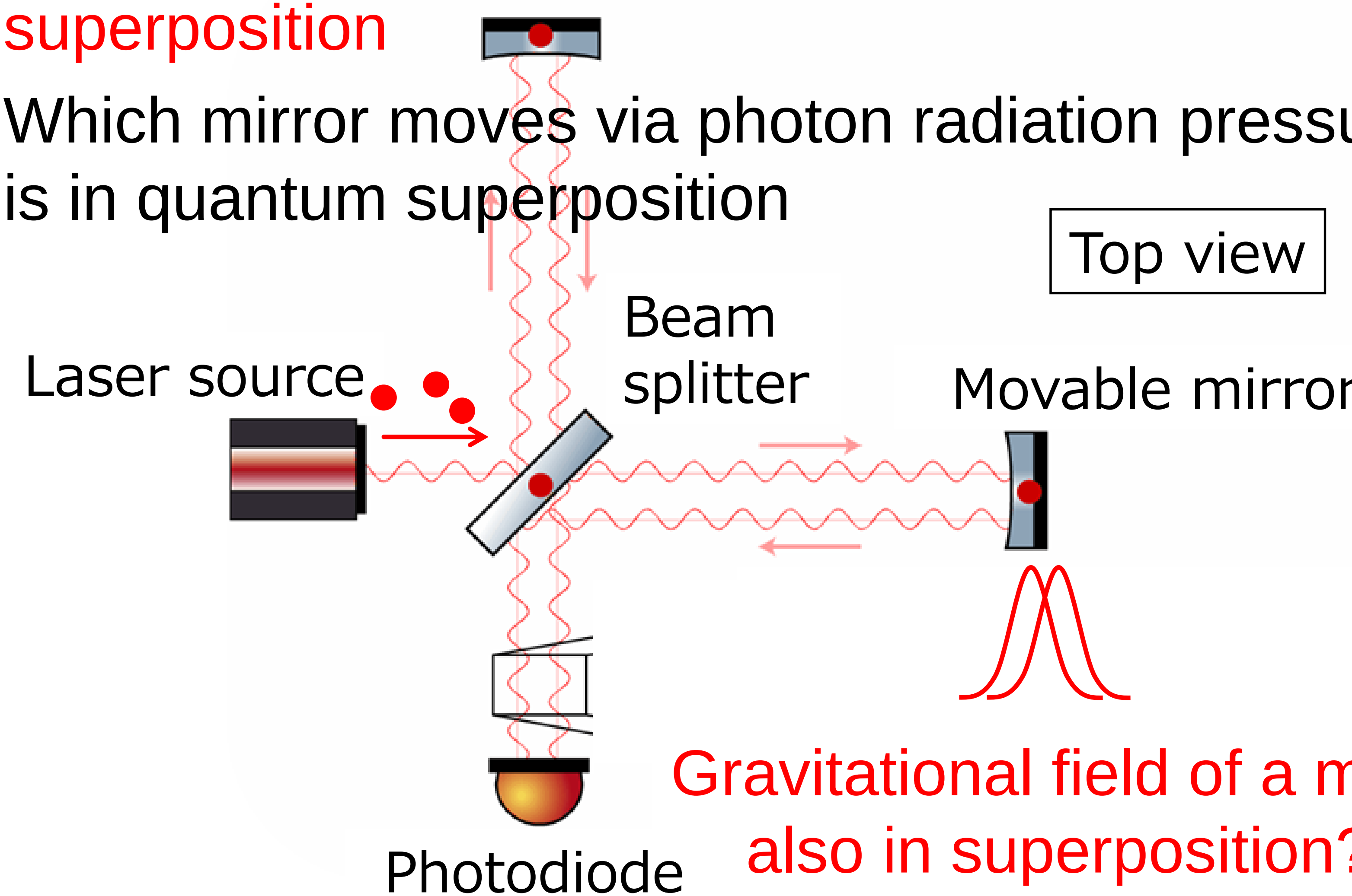
Michelson Interferometer

- Measures the differential arm length change



Quantum Gravity??

- Whether photon goes X-arm or Y-arm is in quantum superposition
- Which mirror moves via photon radiation pressure is in quantum superposition

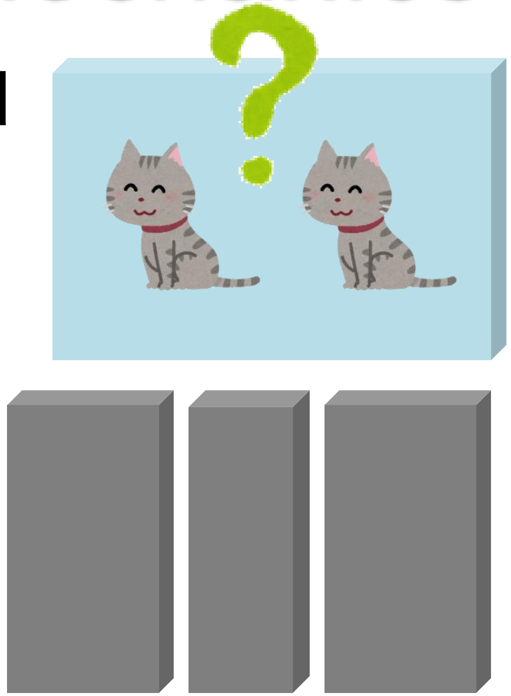


Gravitational field of a mirror also in superposition??

Gravitational Wave Detectors

- 3-4 km Michelson interferometer formed by 20-40 kg suspended mirrors
- Also useful for testing quantum mechanics

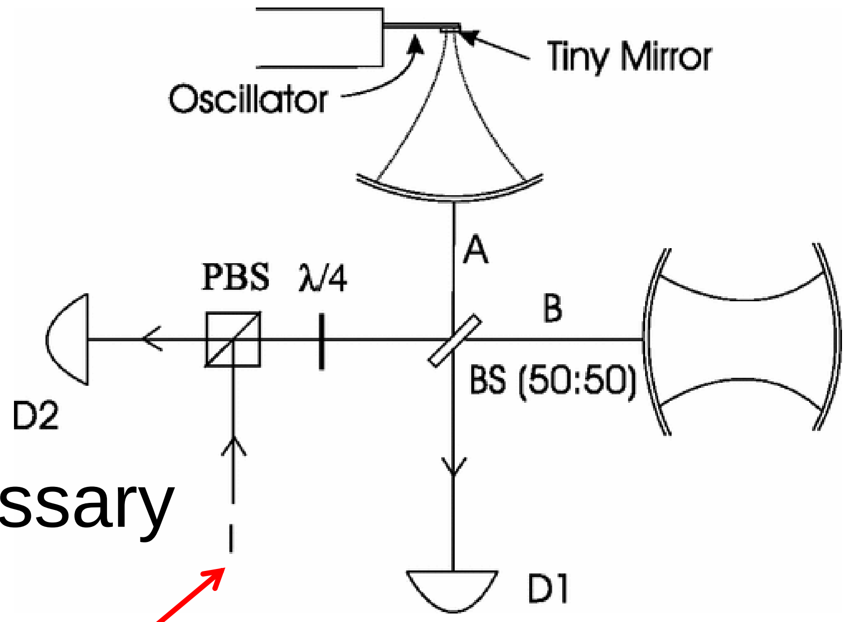
Macroscopic Quantum Mechanics



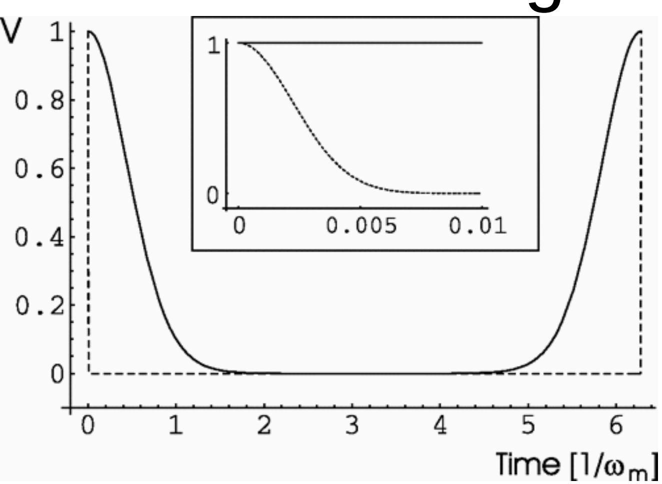
- Quantum mechanics do not depend on scales
- But macroscopic quantum superposition has never been observed (double-slit experiment upto 25 kDa (4e-23 kg)) [Nature Physics **15**, 1242 (2019)]
- Two possibilities at macroscopic scales
  - Quantum mechanics is valid, but too much classical decoherence
  - Quantum mechanics should be modified (e.g. non-linear Schrödinger Eq., Gravitational decoherence …)

Proposed Experiments 1 / 4

- Towards Quantum Superpositions of a Mirror
  Marshall+, PRL 91, 130401 (2003)
- If no decoherence, photon interference fringe should revive at the period of mirror oscillation
- Ground state and ultra-strong coupling necessary



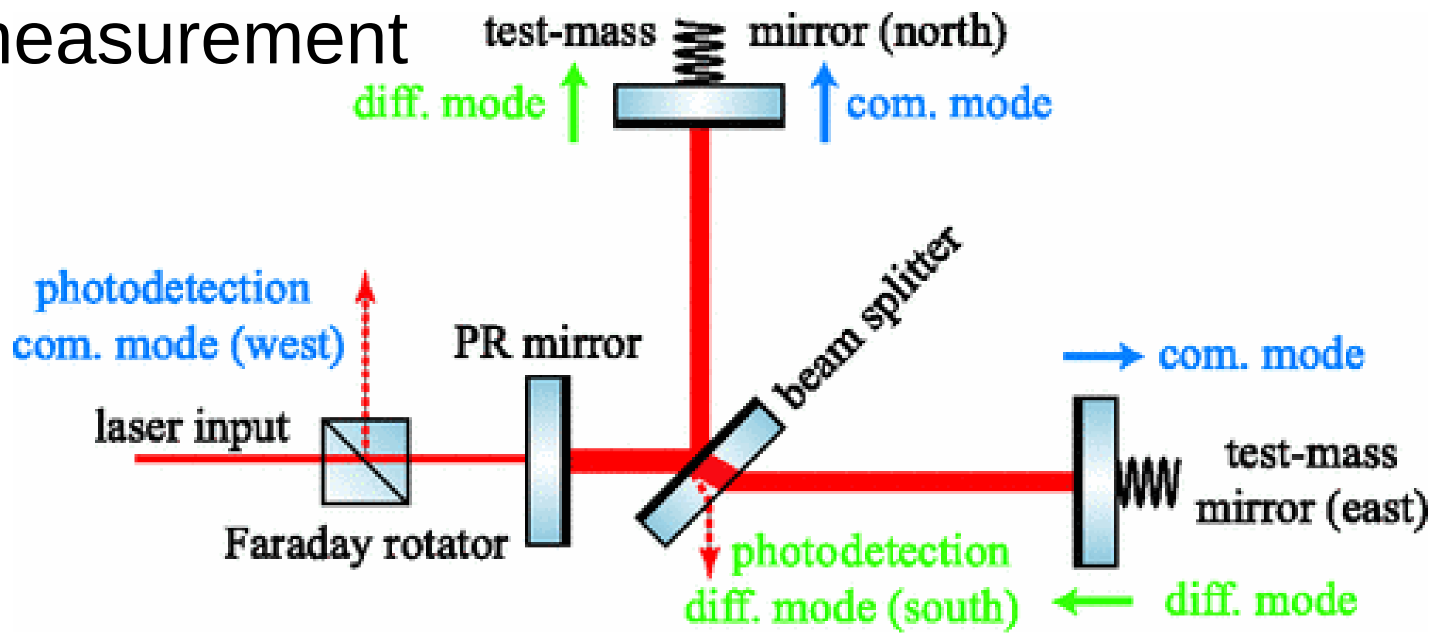
Single photon source



Photon path and mirror motion is entangled
If mirror has decoherence, photon interference fringe will also disappear

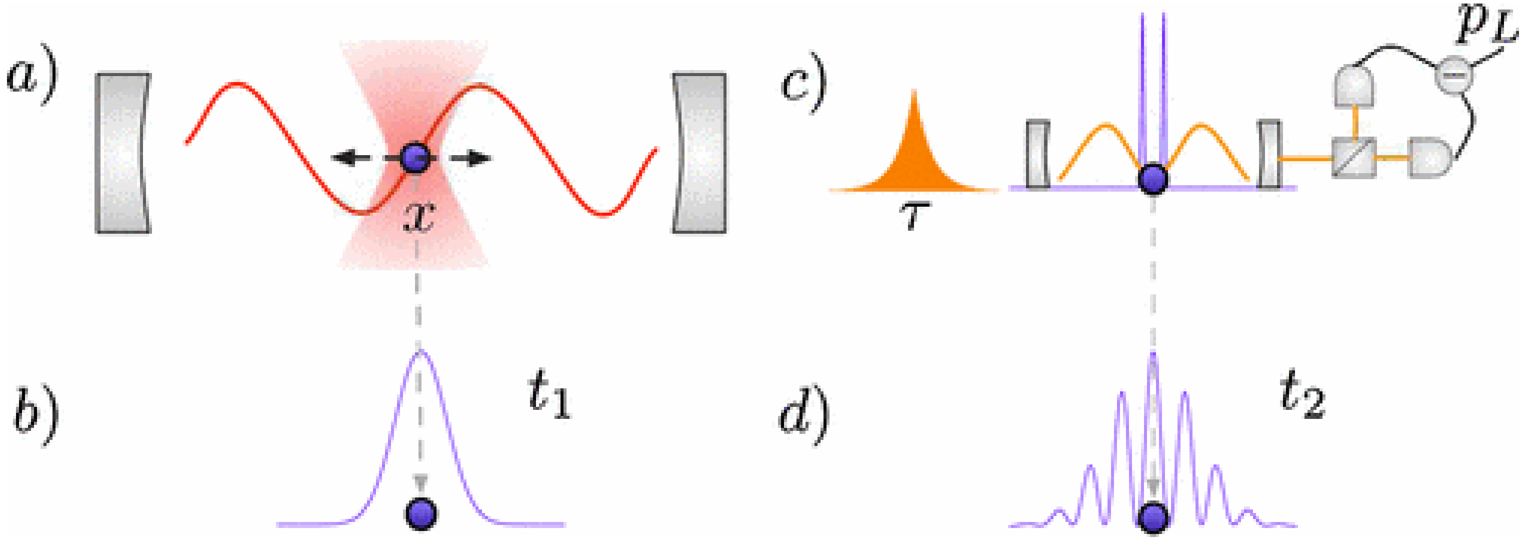
Proposed Experiments 2 / 4

- Entanglement of Macroscopic Test Masses and the Standard Quantum Limit in Laser Interferometry
  Muller-Ebhardt+, PRL 100, 013601 (2008)
- Quantum correlation between mirror common mode and differential mode
- Need to reach SQL for common/differential measurement



Proposed Experiments 3 / 4

- Large Quantum Superpositions and Interference of Massive Nanometer-Sized Objects
Romero-Isart+, PRL 107, 020405 (2011)
- Prepare superposition of nanoparticle at left or right (not at the center), and drop it to see the interference pattern



Proposed Experiments 4 / 4

- Quantum correlation of light mediated by gravity Miao+, arXiv:1901.05827
- Search for quantum correlation between two beams mediated by gravitational coupling of two mirrors
- Thermal noise should be smaller than quantum radiation pressure noise

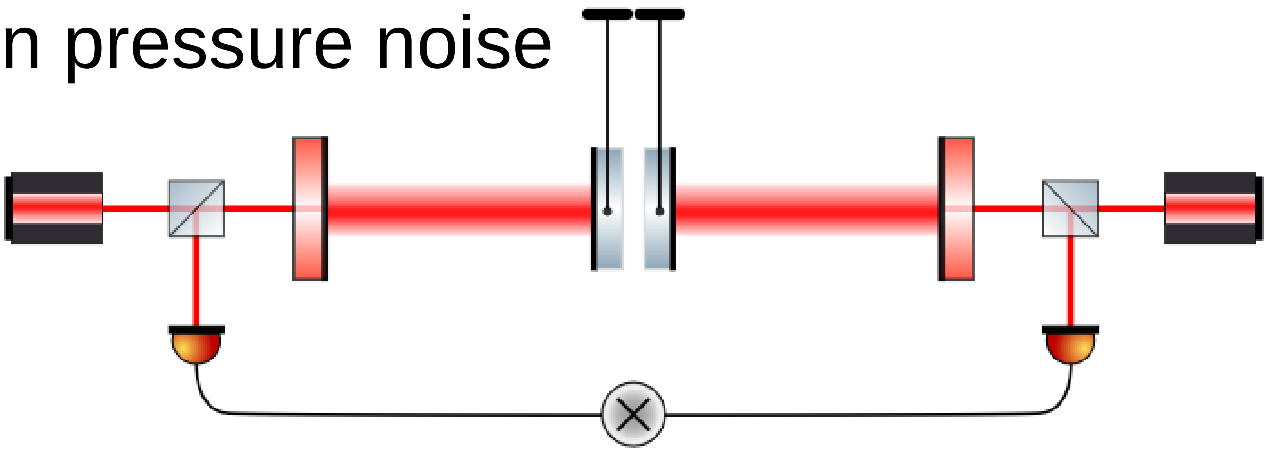
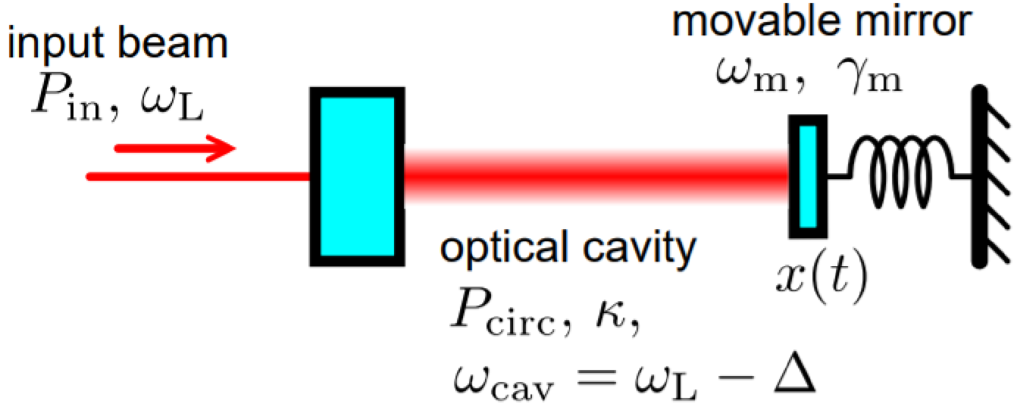


FIG. 1. Schematics showing the setup of two optomechanical cavities with their end mirrors coupled to each other through gravity. The quantum correlation of light is inferred by cross-correlating the readouts of two photodiodes.

Requirements to Optomechanics

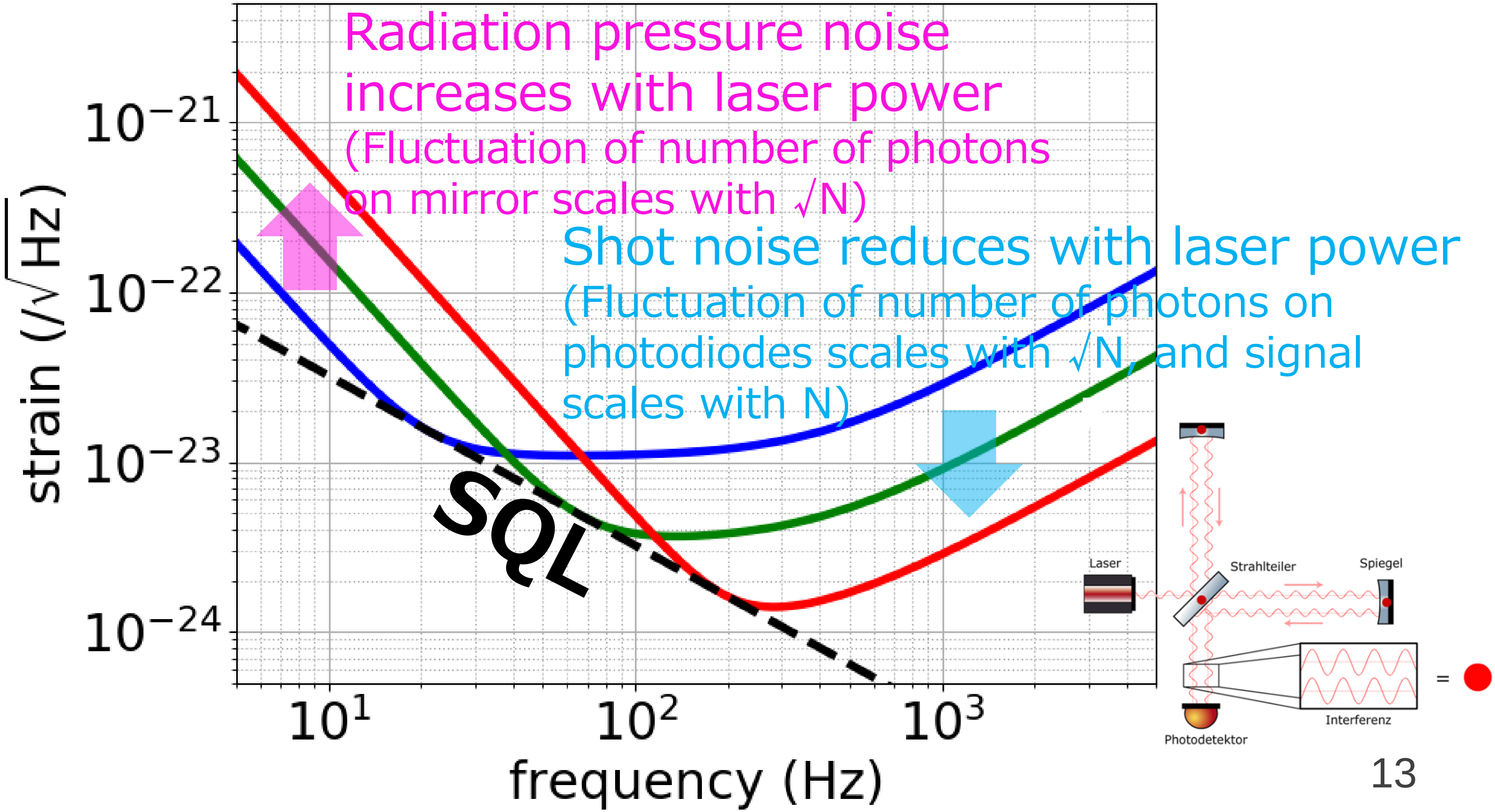
- These systems are called optomechanical systems
  Interaction between light and mechanical oscillator



- Common requirements
  - Make thermal fluctuation smaller than quantum radiation pressure fluctuation (make cooperativity larger than 1)
  - Reach standard quantum limit
  - Ground state cooling of mirror (make phonon number smaller than ~1)

Standard Quantum Limit

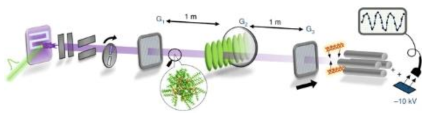
- Displacement sensitivity cannot surpass standard quantum limit just by changing the laser power



Optomechanical Systems

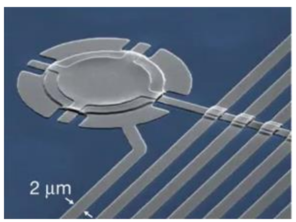
- SQL not yet reached above Planck mass scale

Double-slit



molecules, 40 zg
Fein+ (2019)

Ground state cooling

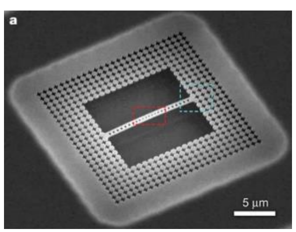


membrane, 48 pg
Taufel+ (2011)

Quantum radiation pressure

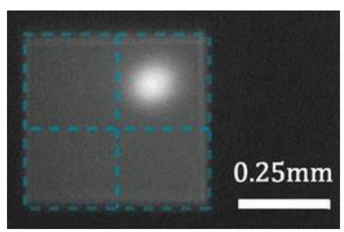
cantilever, 50 ng
Cripe+ (2019)

Ground state cooling



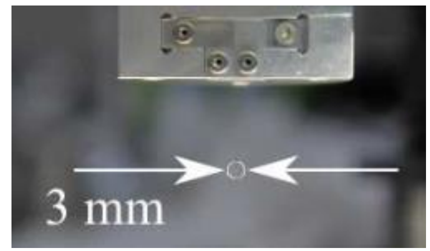
nanobeam, 331 fg
Chan+ (2011)

Ground state cooling



membrane, 7 ng
Peterson+ (2016)

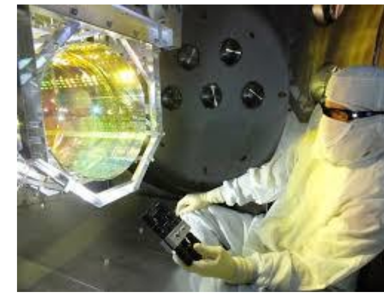
Planck mass (22 ug)



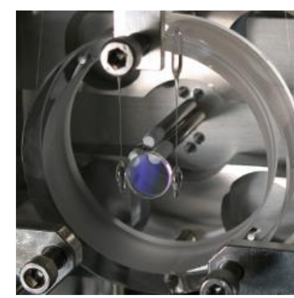
suspended disk, 7 mg
Matsumoto+ (2019)

suspended bar, 10 mg
Komori+ (2020)

Factor of ~3 to SQL



suspended disk, 40 kg
Advanced LIGO



suspended disk, 1 g
Neben+ (2012)

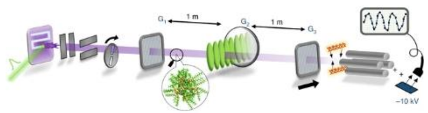
fg pg ng ug mg g kg

Optomechanical Systems

- We focus on milligram scale: mesoscopic scale

YM, K. Komori, EPJD 74, 126 (2020)

Double-slit



molecules, 40 zg
Fein+ (2019)

Planck mass (22 ug)

Quantum radiation pressure

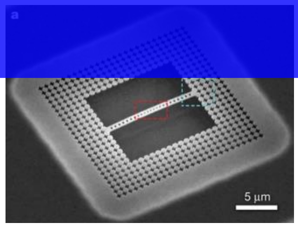
cantilever, 50 ng
Cripe+ (2019)

Ground state cooling

membrane, 48 pg
Taufel+ (2011)

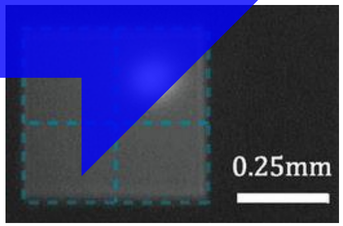
Quantum world

Ground state cooling

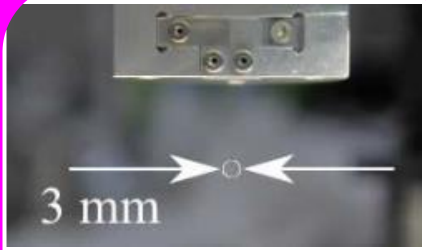


nanobeam, 331 fg
Chan+ (2011)

Ground state cooling



membrane, 7 ng
Peterson+ (2016)

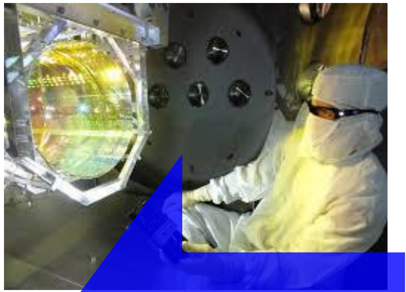


suspended disk, 7 mg
Matsumoto+ (2019)

suspended bar, 10 mg
Komori+ (2020)

Mesoscopic scale

Factor of ~3 to SQL



suspended disk, 40 kg
Advanced LIGO

Gravitational world

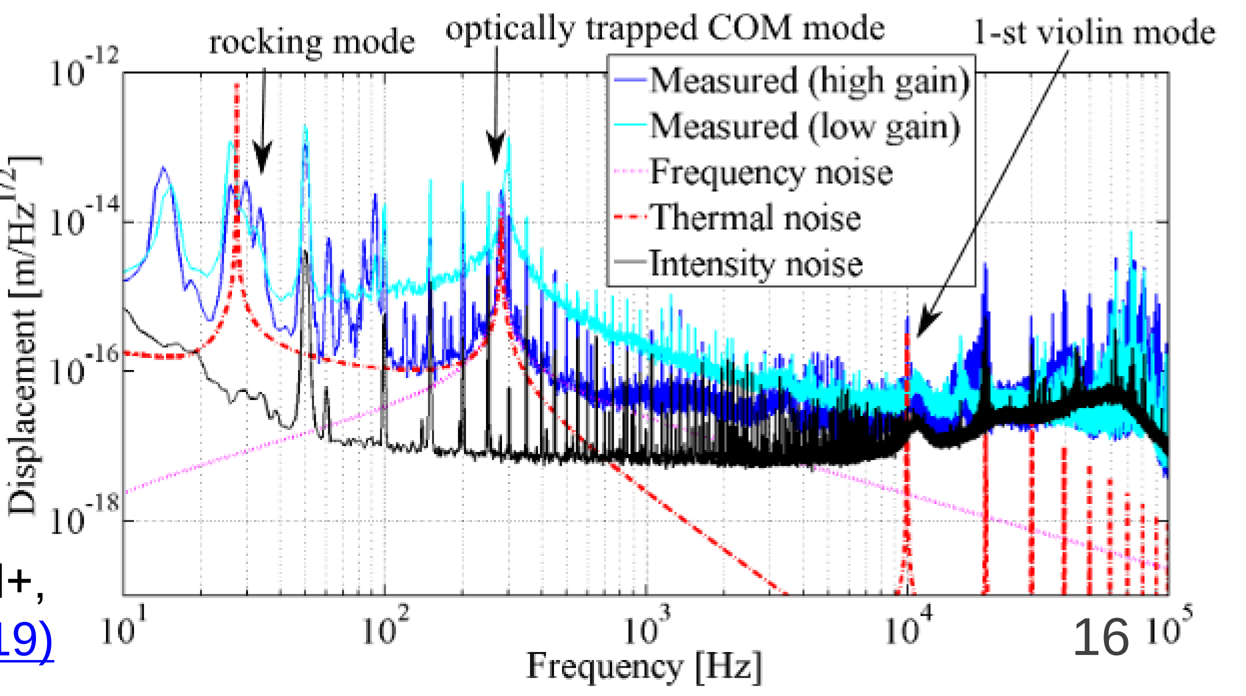
suspended disk, 1 g
Neben+ (2012)

fg pg ng ug mg g kg

7 mg Suspended Disk Experiment

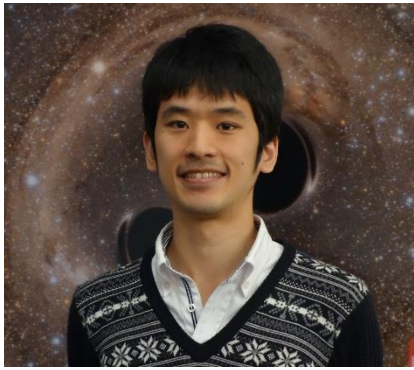
- Displacement sensitivity at 3e-14 m/√Hz @ 280 Hz
- Thermal noise limited (Q=1.1e5)
- Possible to measure 100 mg gravity in a second
- Also developed lower mechanical loss pendulum for better sensitivity (Q=2e6)

PRL 124, 221102 (2020)



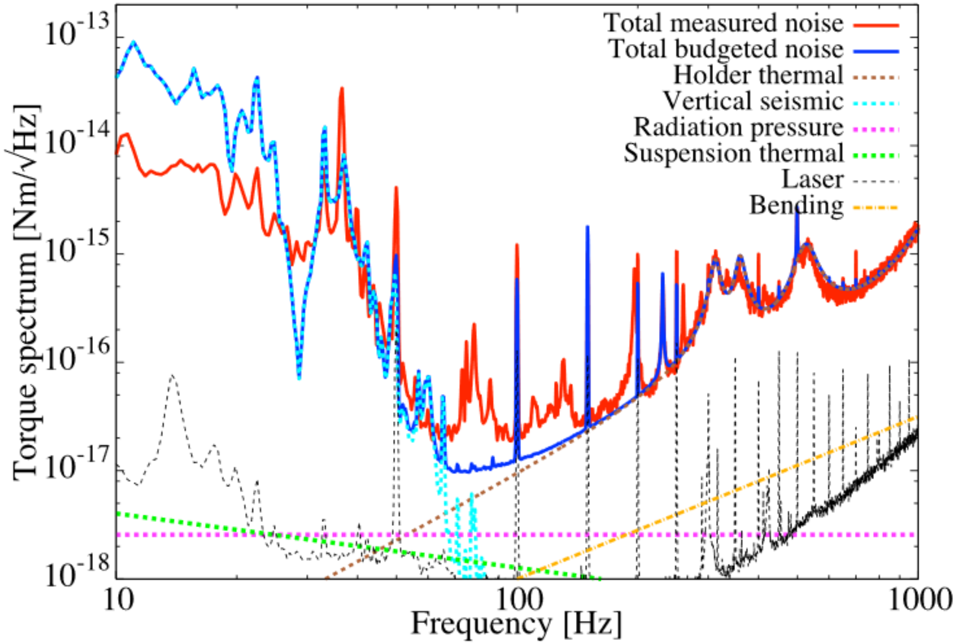
N. Matsumoto, …, YM+, PRL 122, 071101 (2019)

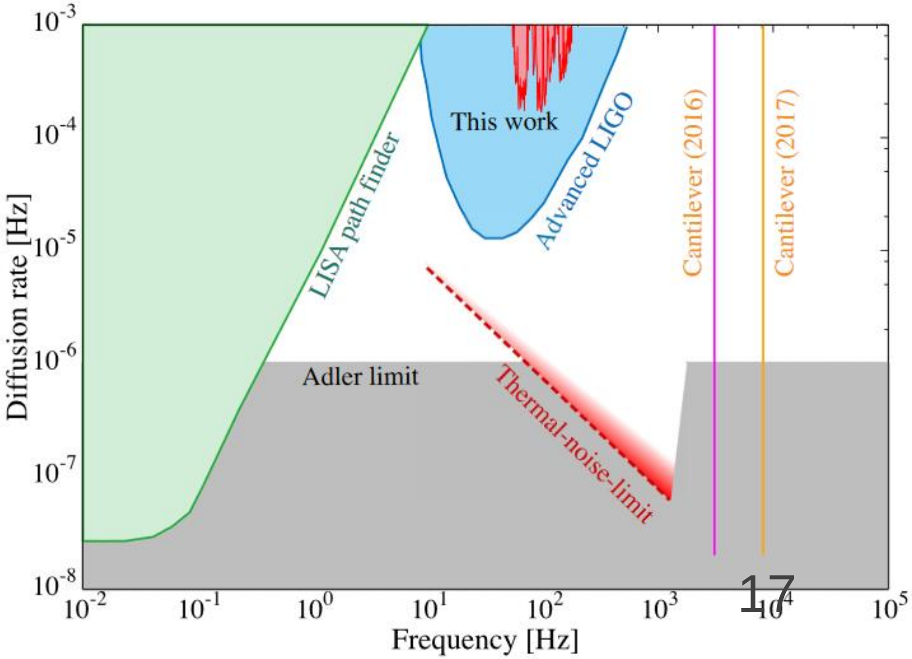
10 mg Suspended Bar Experiment



- Rotation is readout by two cavities
- Highest torque sensitivity at milligram scale
- Limit on parameters of CSL (continuous spontaneous localization) model

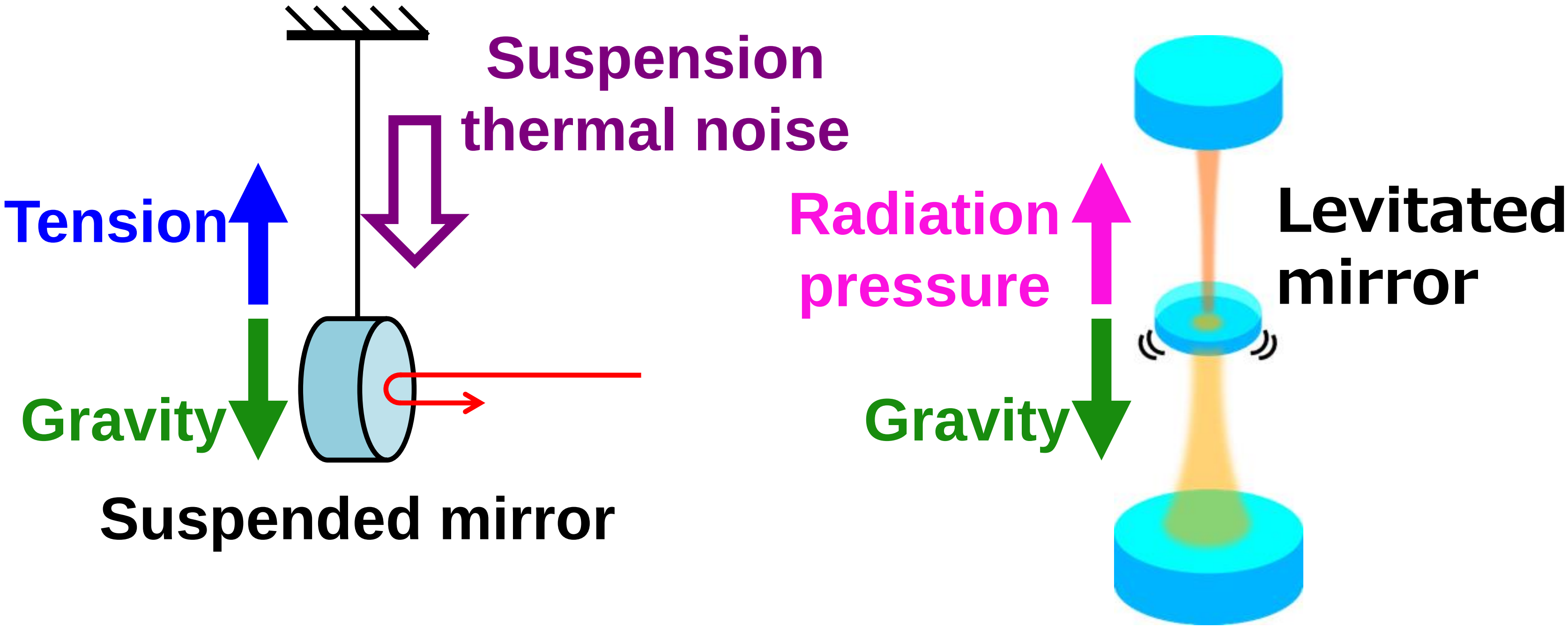
K. Komori,...,YM+, PRA **101**, 011802(R) (2020)





Optical Levitation

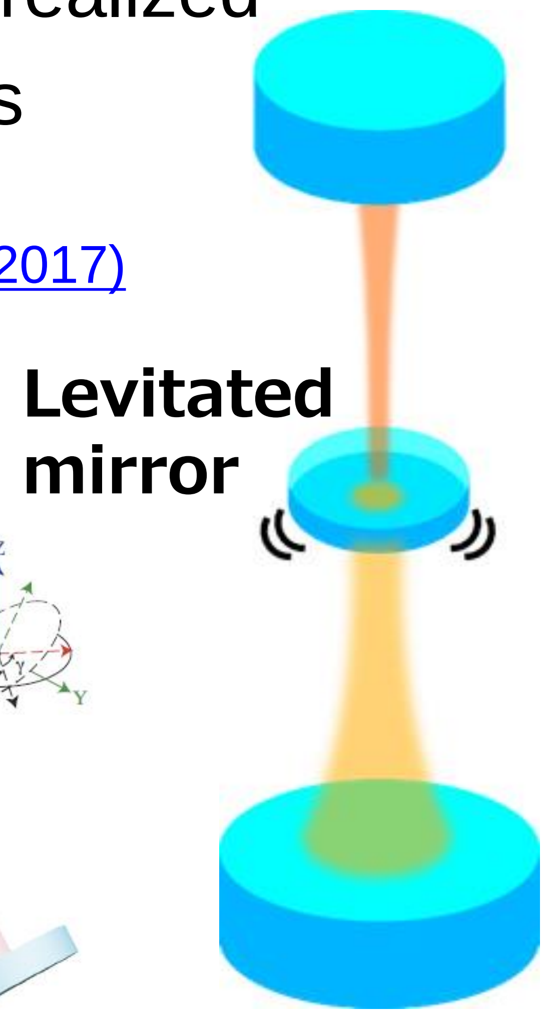
- Alternative approach is to support a mirror with radiation pressure alone
- Both suspended mirror and levitated mirror will be ultimately limited by thermal noise from residual gas and mirror coating

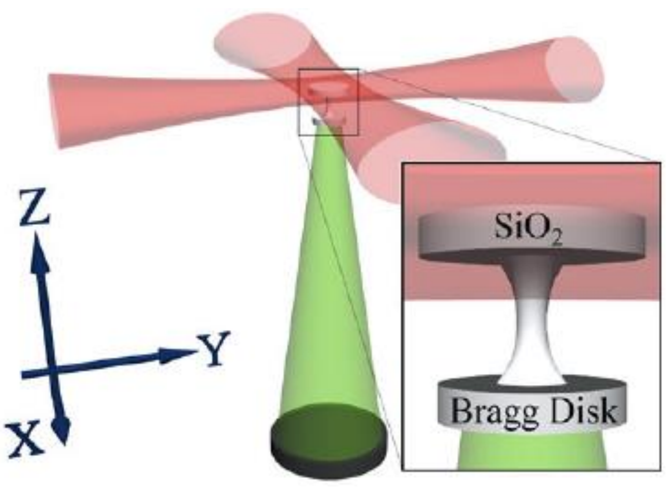


Sandwich Configuration

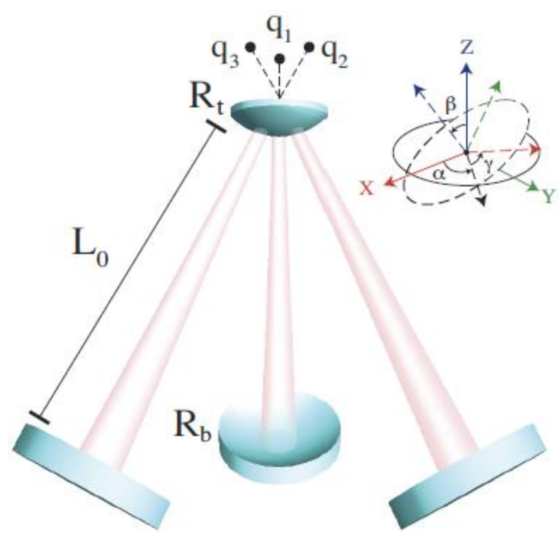
- Optical levitation have never been realized
- Simpler configuration than previous proposals

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





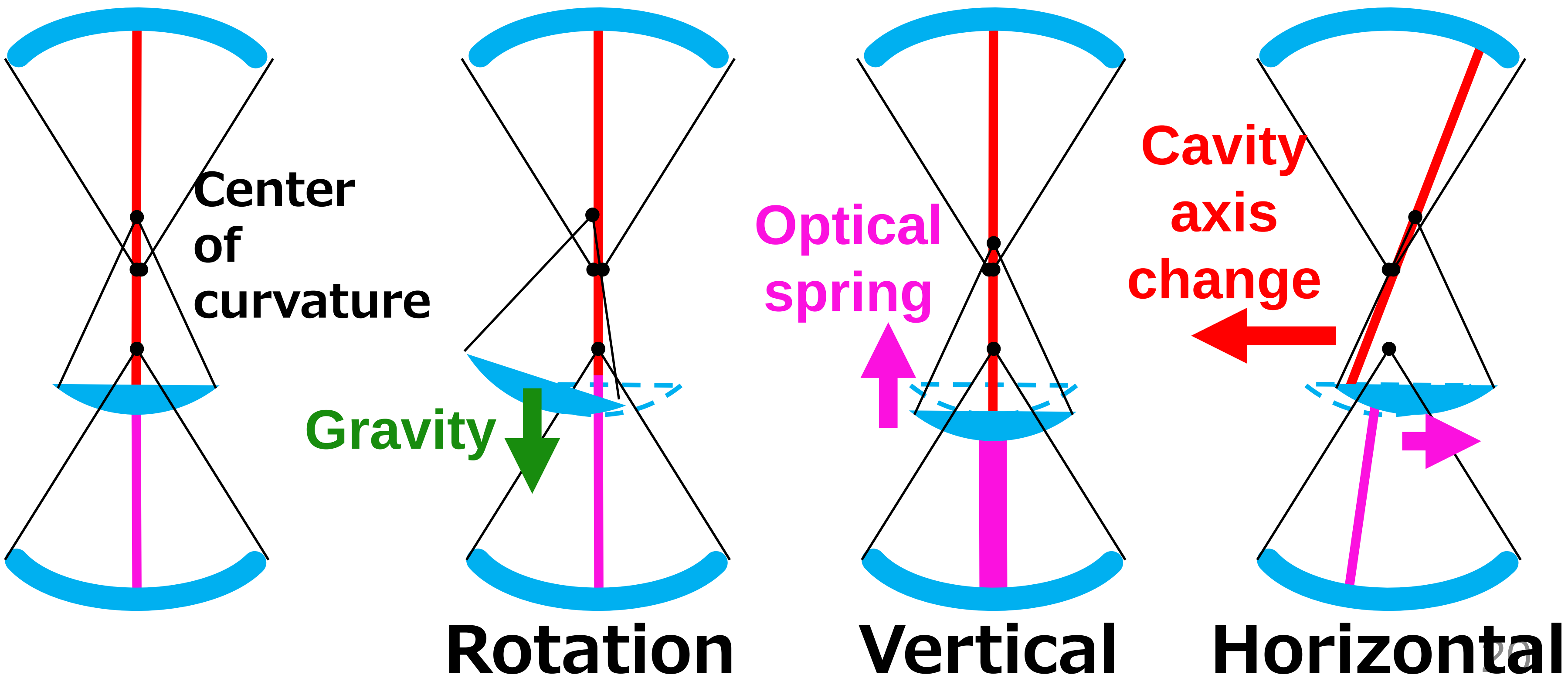
S. Singh+: PRL 105, 213602 (2010)



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

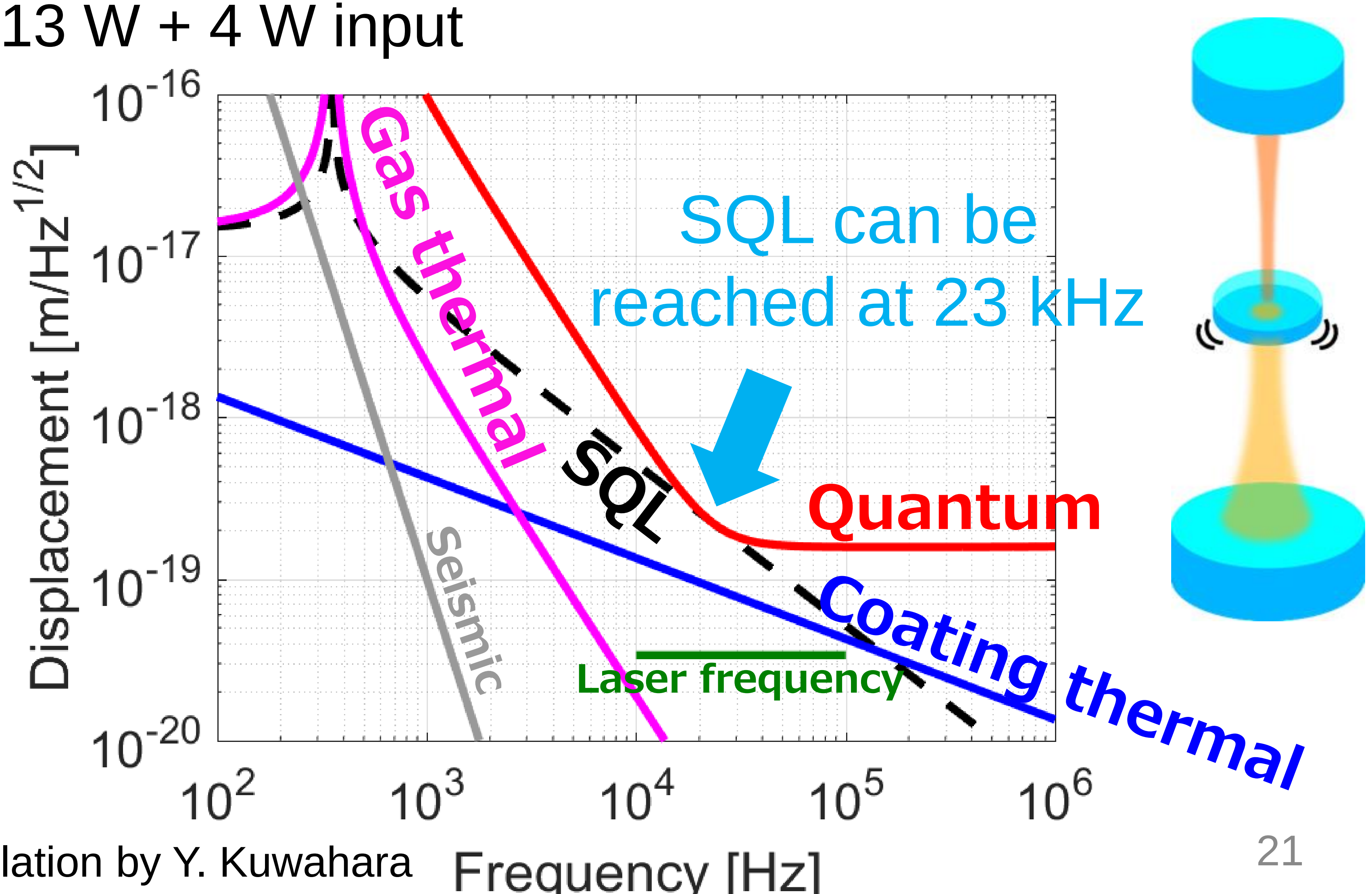
Stability of Levitation

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



Reaching SQL

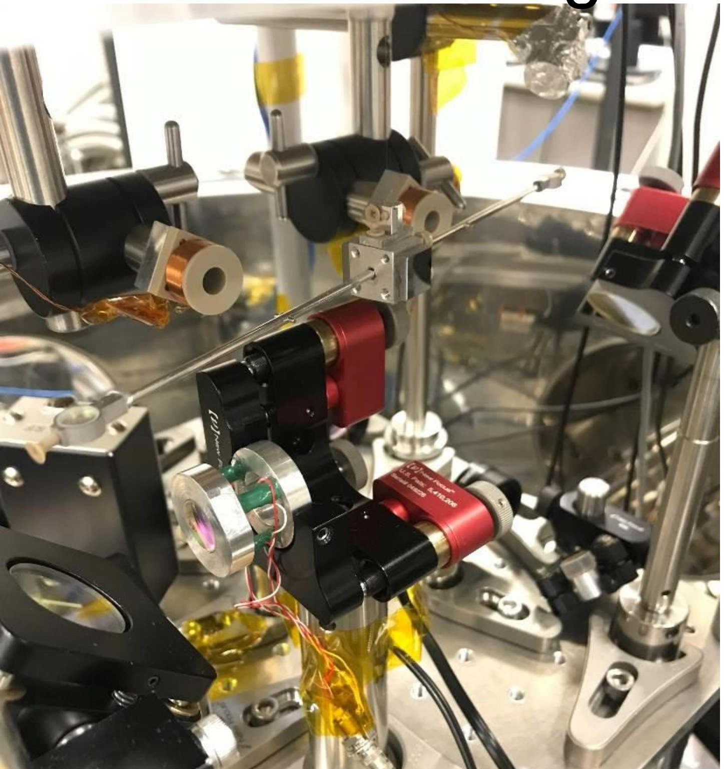
- 0.2 mg fused silica mirror, Finesse of 100, 13 W + 4 W input

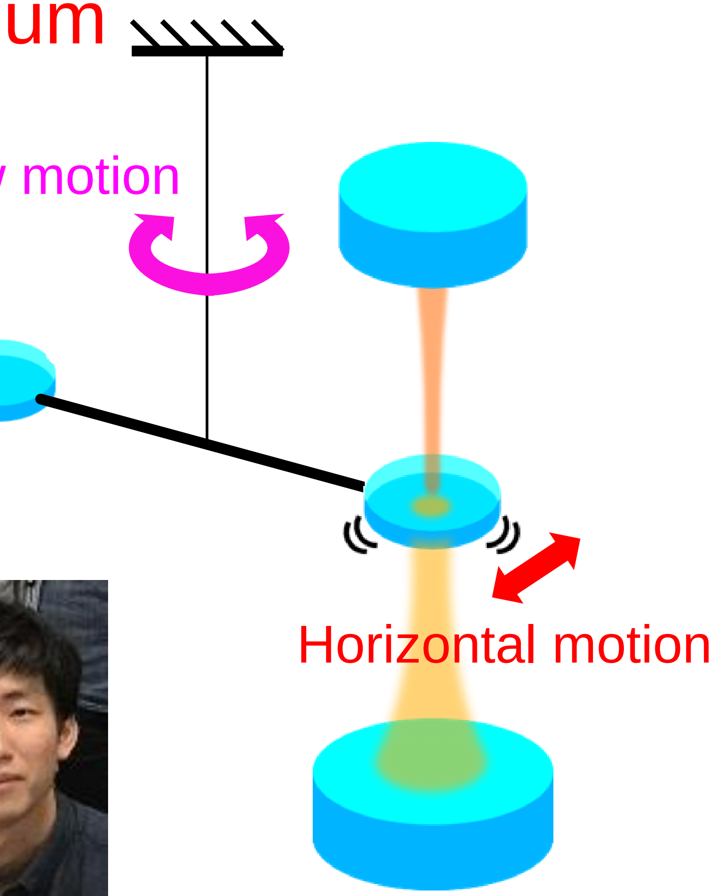


Calculation by Y. Kuwahara

Experiment to Verify the Stability

- Especially, stability of the horizontal motion is special for this sandwich configuration
- Experiment with torsion pendulum was performed to measure the restoring force



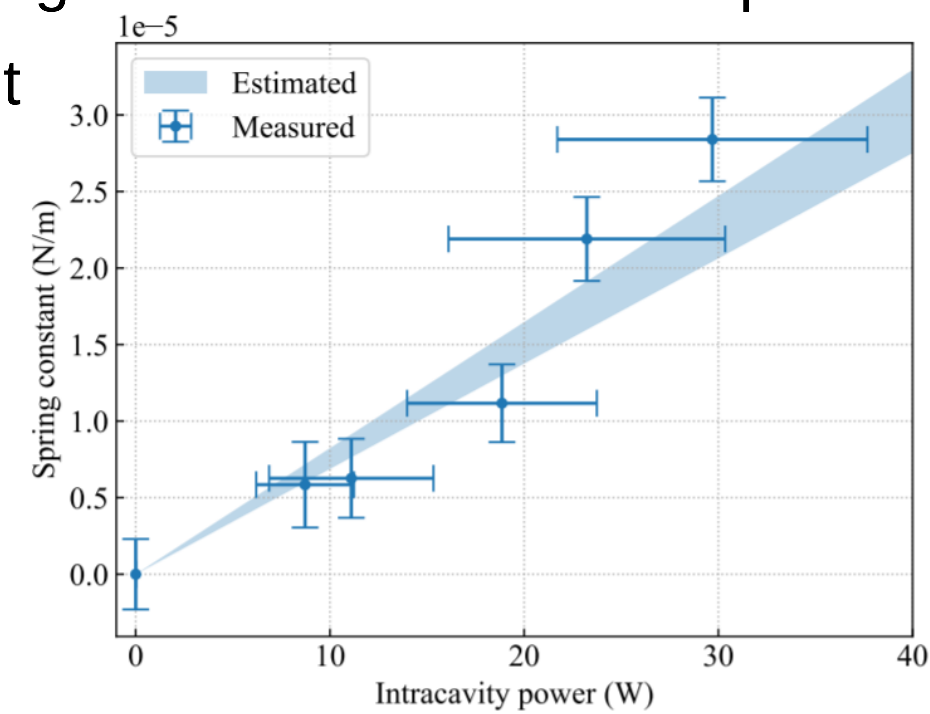


Experiment to Verify the Stability

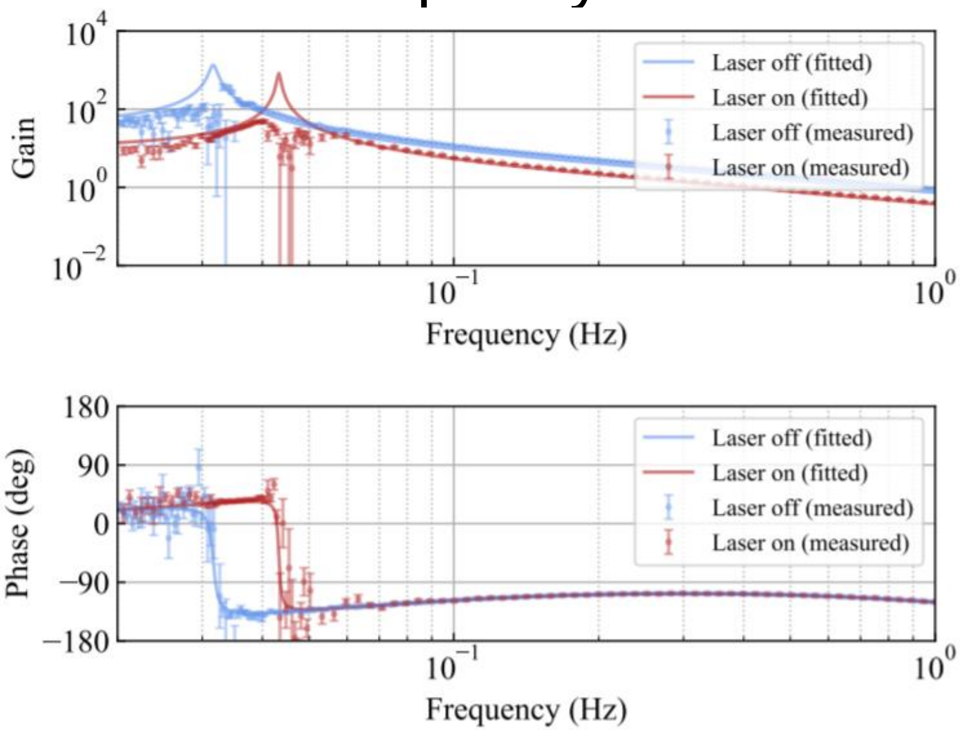
- Resonant frequency of torsion pendulum increased when optical cavity is locked
  → Successfully measured the restoring force

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

Spring constant increase with power



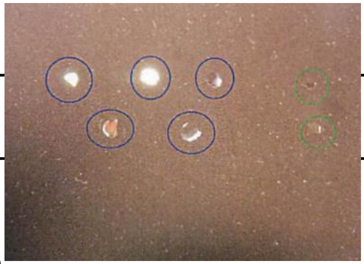
Resonant frequency measurement



Fabrication of Levitation Mirrors

- In 2014, fused silica mirror with dielectric multilayer coating have been tried
- Cracks due to coating stress

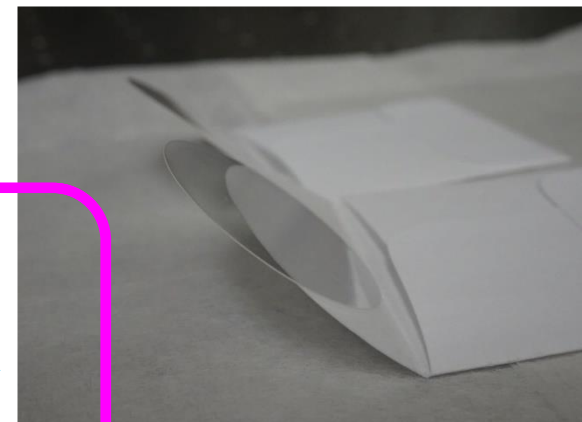
	For SQL	Prototype	For suspended experiment
Mass	0.2 mg	~1.6 mg	~ 7 mg
Size (mm)	φ 0.7 mm t 0.23 mm	φ 3 mm t 0.1 mm	φ 3 mm t 0.5 mm
RoC	30 mm convex	30$\pm$10 mm convex (measured: 15.9$\pm$0.5 mm)	100 mm concave (previously flat ones were used)
Reflectivity	97 % (finesse 100)	>99.95 % (measured: >99.5%)	99.99%
Comment	Optics Express 25, 13799 (2017)	Only one out of 8 without big cracks	Succeeded



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.

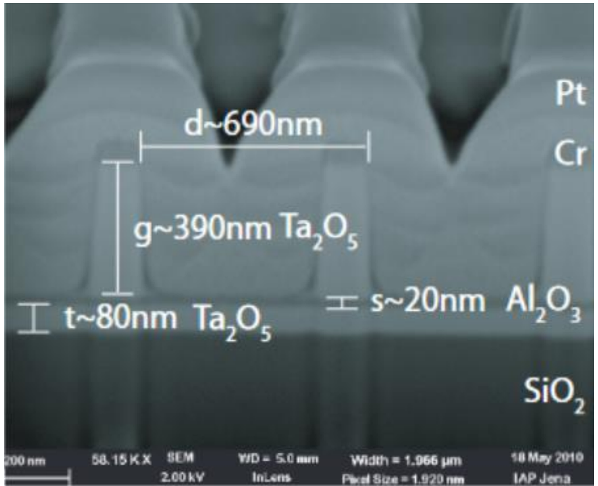
So far successful upto (2)

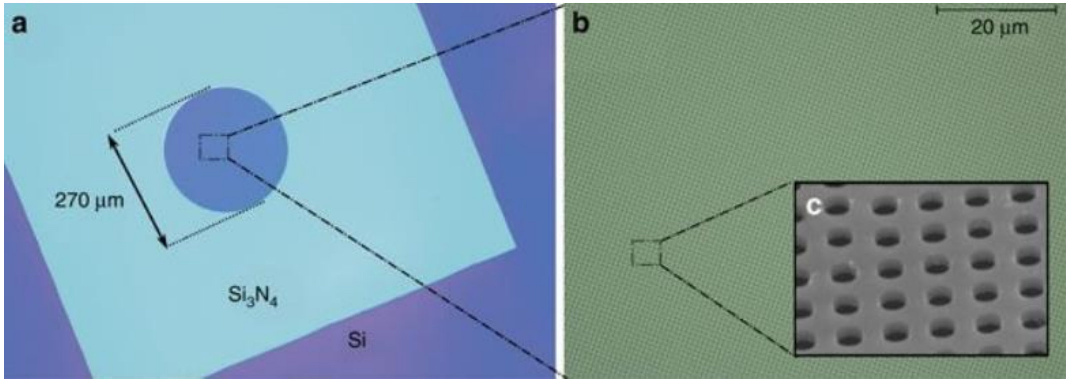
- R=96%, RoC=500 $^{+2000}_{-300}$ mm
- R=94%, RoC=400 $^{+1000}_{-200}$ mm

Trying (3) and thicker coating

Another Approach: Photonic Crystal

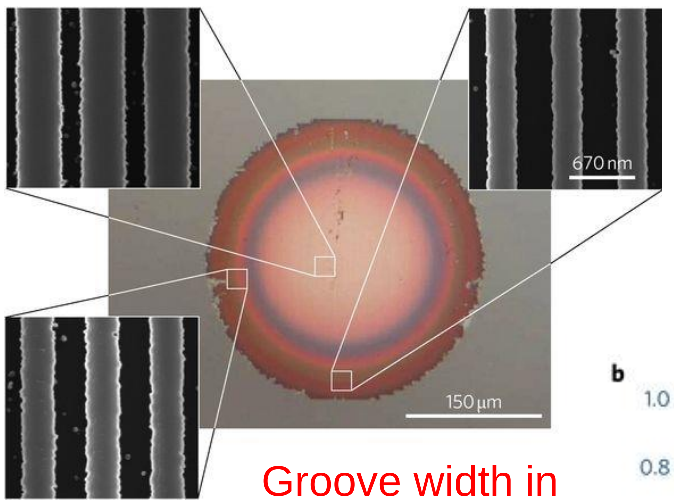
- High reflectivity demonstrated, also in the context of gravitational wave detector to reduce coating thermal noise
  - D. Friedrich+, Optics Express 19, 14955 (2011)
    R=99.2 % @ λ=1064 nm
  - X. Chen+, Light: Science & Applications 6, e16190 (2017)
    R = 0 to 99.9470±0.0025% @ λ=1μm



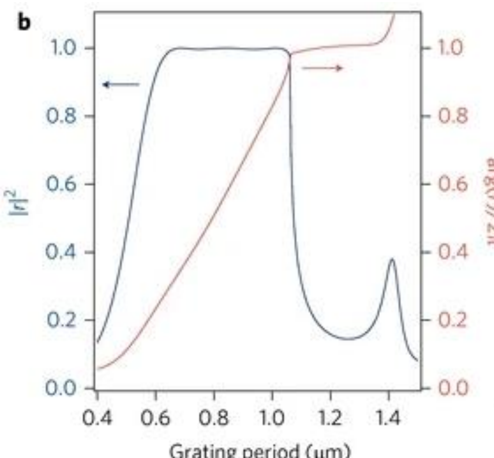


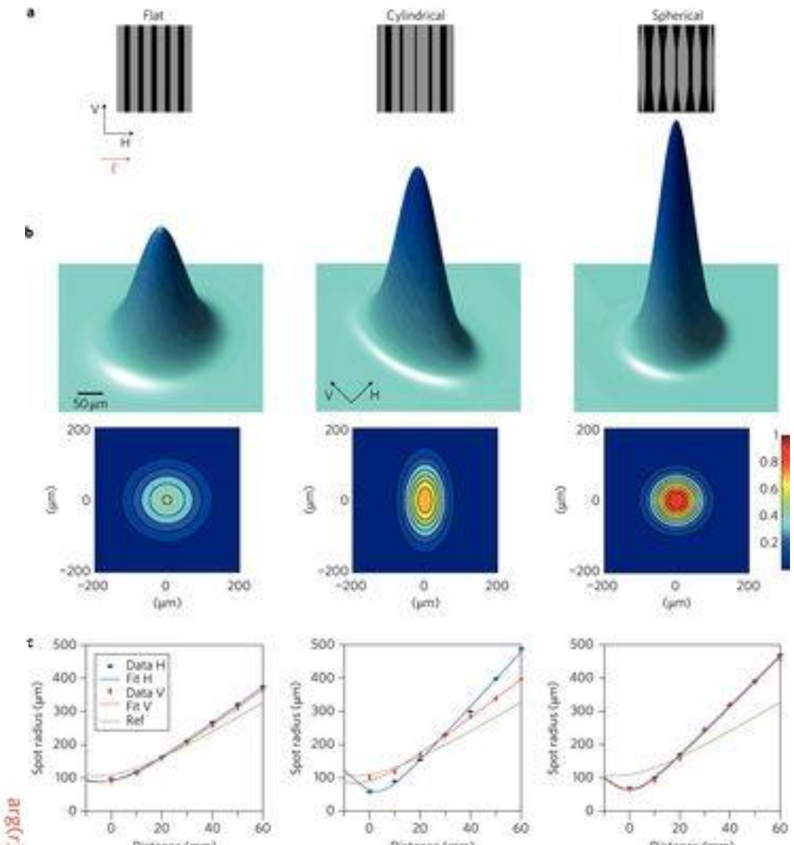
Curved Mirror Seems Possible

- D. Fattal+, [Nature Photonics 4, 466 (2010)]
  R = 80-90%
  RoC = 20 ± 3 mm
- Beam focusing confirmed



Groove width in various locations



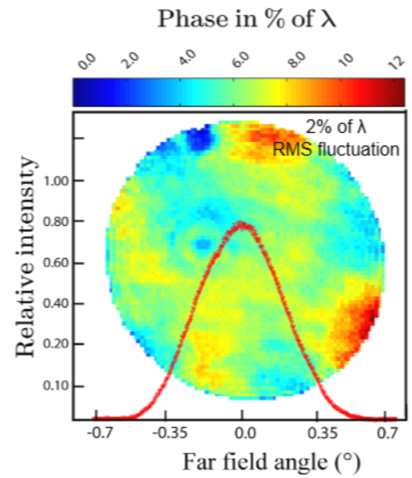


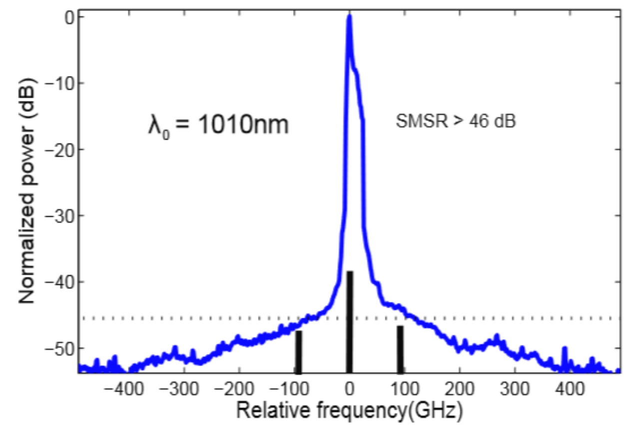
Curved Mirror Seems Possible

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

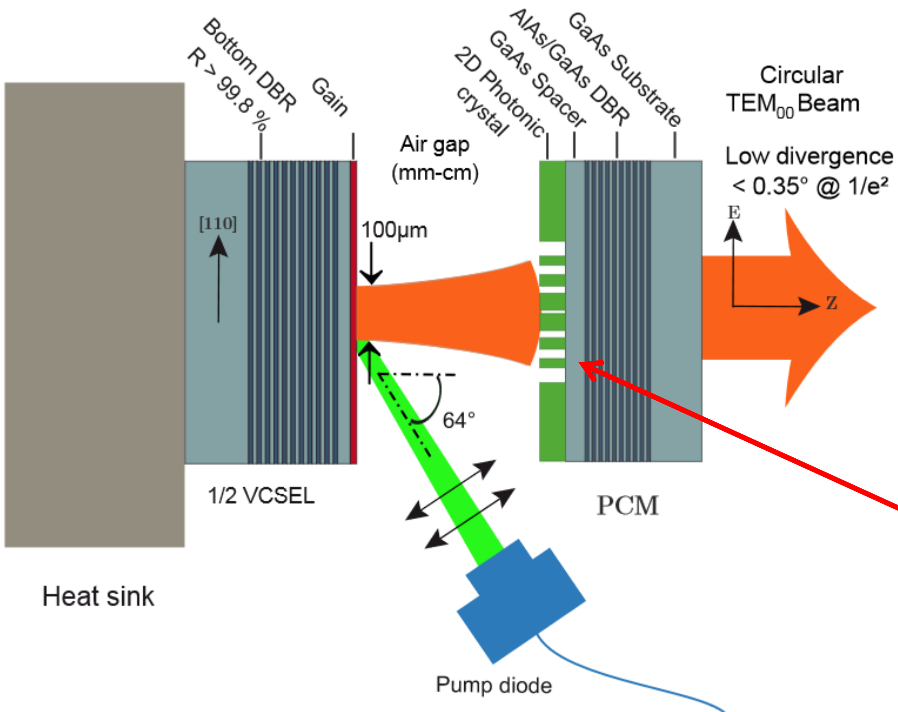
R > 99%

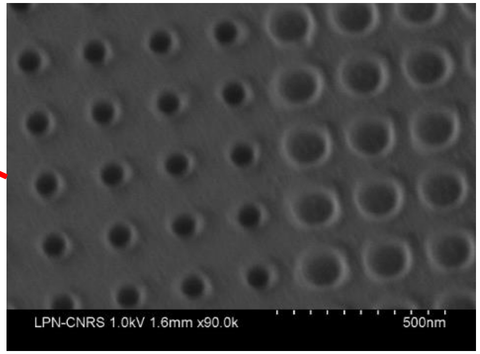
RoC = 20 mm





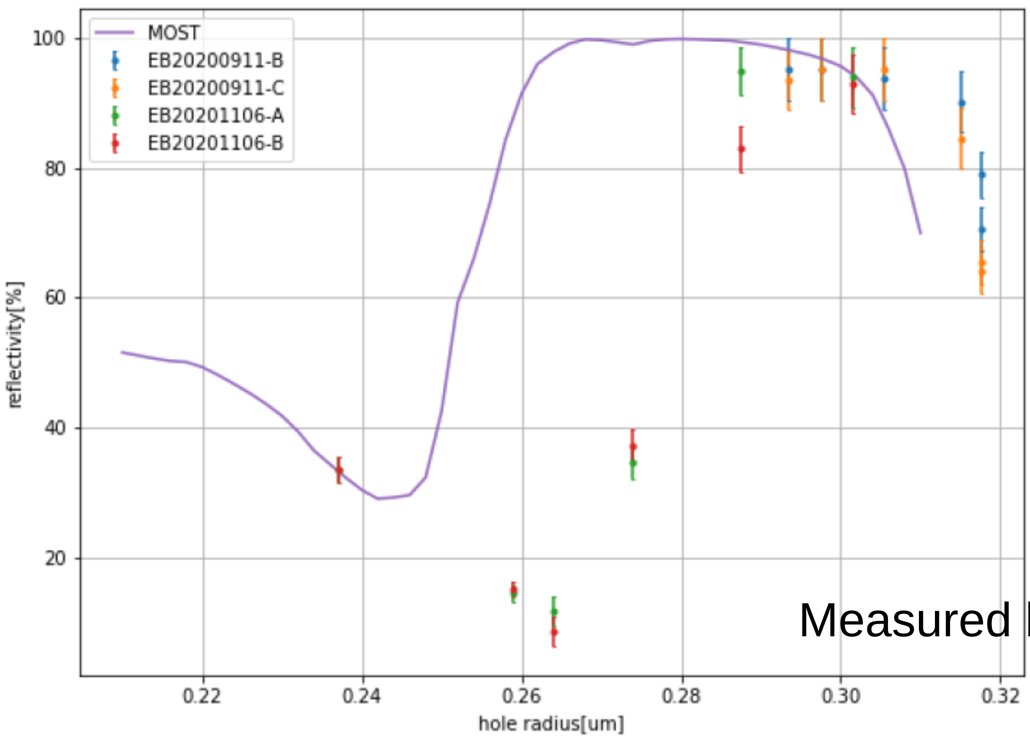
Distributed Bragg reflector (DBR) for high reflectivity

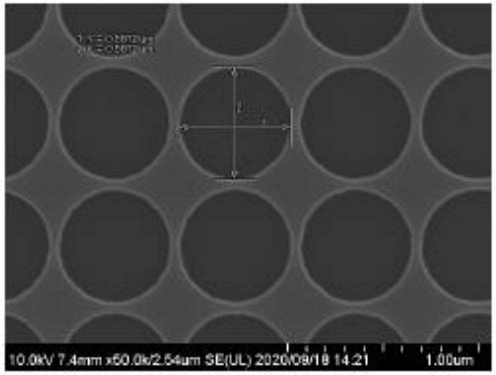


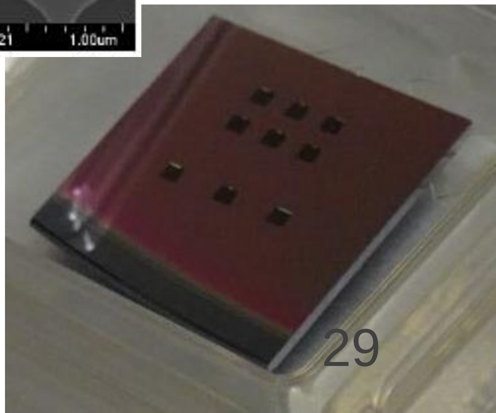


Preliminary Results

- Si photonic crystal mirror samples are fabricated by Iwamoto Group at IIS, UTokyo
- So far achieved R~95% @ 1064 nm with a simple periodic structure (1 mm x 1 mm)
- Next step is to make an effective curvature







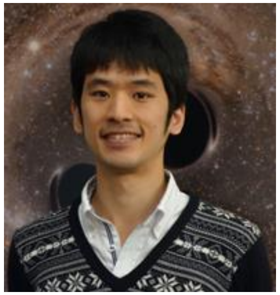
Measured by H. Chiyoda

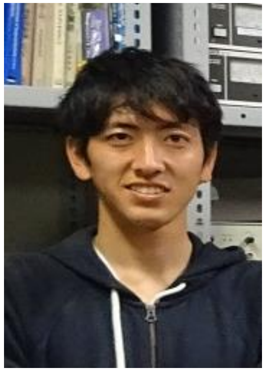
Summary

- Milligram scale is interesting for probing the boundary between classical and quantum world
  YM, K. Komori, EPJD 74, 126 (2020)
- Optical levitation of a mirror is a promising way to prepare a system to test quantum mechanics at macroscopic scales
- 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 different approaches for the fabrication of a milligram mirror with high reflectivity and curvature (thin mirror and photonic crystal mirror)

Acknowledgements

- Students and graduates in Ando Group, UTokyo




- Thin fused silica mirrors are coated by LMA
  Jerome Degallaix
- Photonic crystal mirrors are fabricated at Iwamoto Group @ IIS, UTokyo
  Satoshi Iwamoto, Satomi Ishida
- JSPS Grant-in-Aid for Challenging Research (Exploratory) 18K18763
- JST CREST JPMJCR1873 (ANR-JST joint research)
  - Lead by Kentaro Somiya @ Tokyo Tech
  - Team: Nobuyuki Matsumoto @ Tohoku U (Gakushuin U)
    Koji Usami @ RCAST, UTokyo
    Kazuyuki Takeda @ Kyoto U
    Hiroki Takahashi @ OIST

Bonus Slides

Other Proposals

- Polarization-independent beam focusing by high-contrast grating reflectors
  W. Su+, Optics Communications 325, 5 (2014)
  - curved mirror by grating with parabolic surface
  - ~9 um focal length
  - focusing consistent with diffraction limit

too small for us!

too dirty for us!

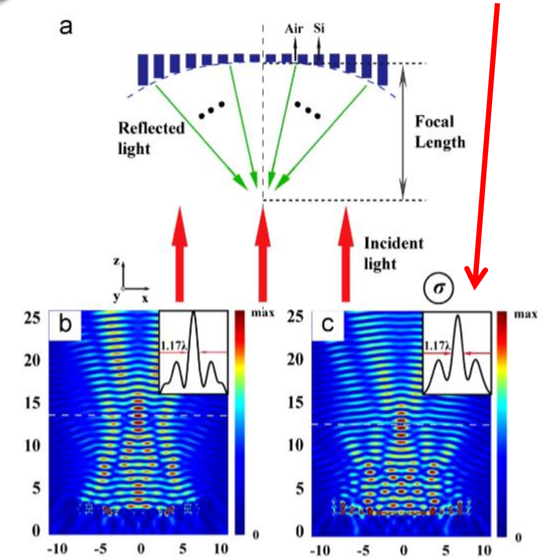
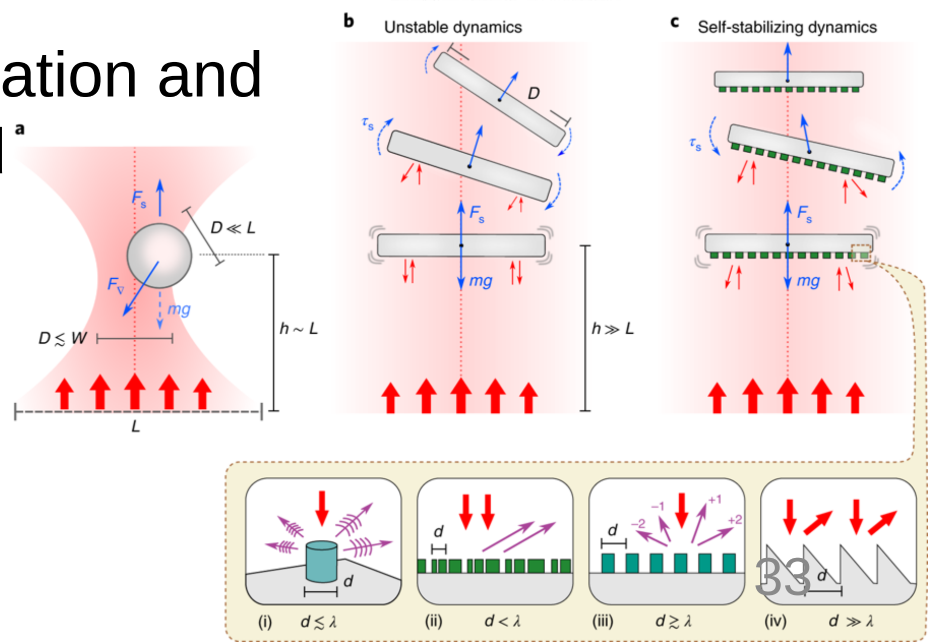


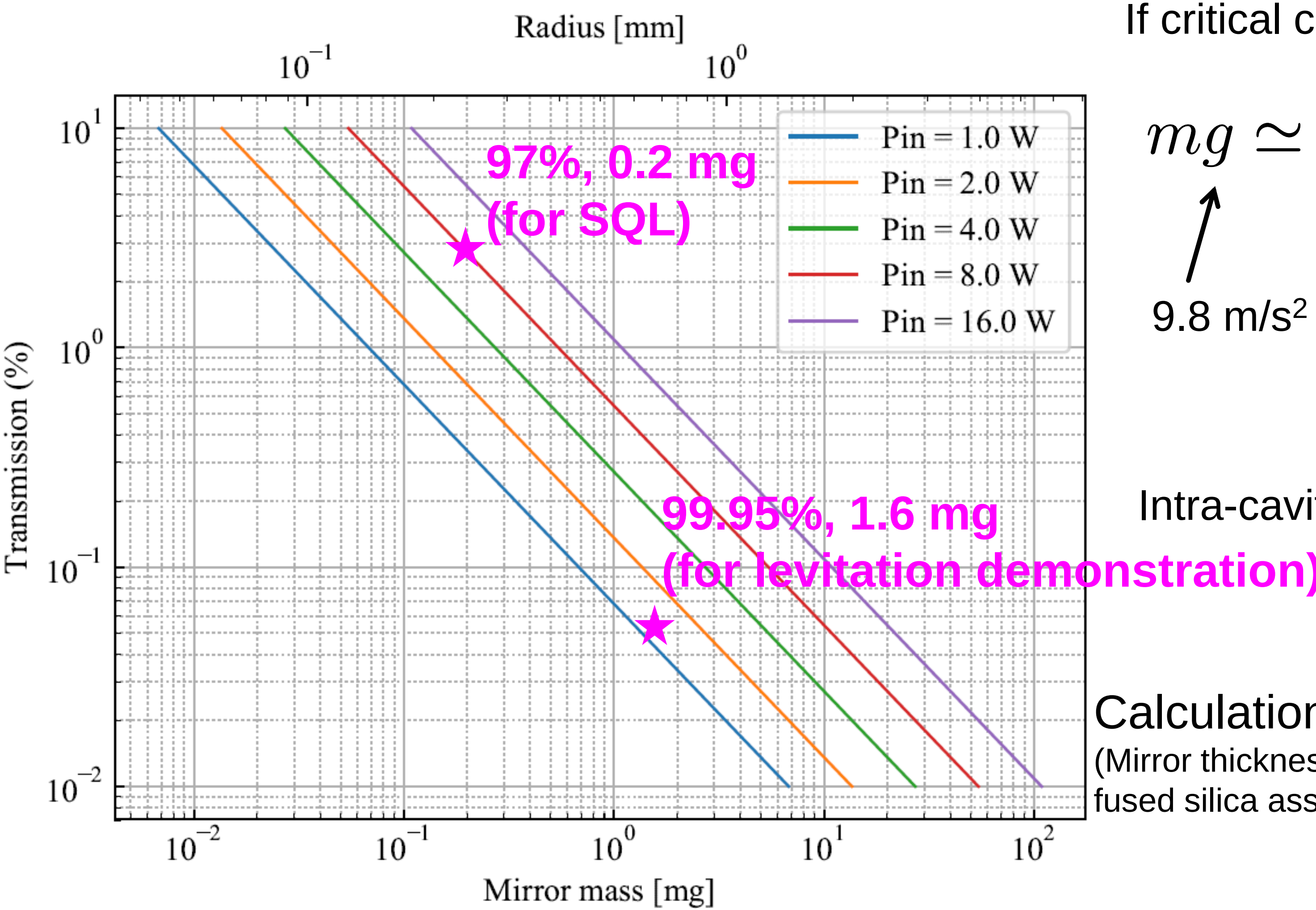
Fig. 2. (a) Schematic of a 2D HCG focusing reflector. The intensity distribution of the focused beam when (b) TE and (c) TM waves illuminate from the bottom side. The wavelength of the incident light is 1.55 μm, and the white line is the position of focal point. FWHMs are both 1.17λ.

- Self-stabilizing photonic levitation and propulsion of nanostructured macroscopic objects
  O. Ilic & H. A. Atwater, Nature Photonics 13, 289 (2019)
  - levitation by tailoring asymmetric scattering of light



Transmission vs Mirror Mass

- Mirror reflectivity can be smaller if the mirror mass is smaller and with higher input power



If critical couple, no detuning

$$mg \simeq \frac{2P_{\mathrm{circ}}}{c} = \frac{2P_{\mathrm{in}}}{cT}$$

9.8 m/s²

Intra-cavity power

Mirror power transmission (R=1-T)

Calculation by T. Kawasaki
(Mirror thickness 0.5 mm, fused silica assumed to calculate radius.)

PhC: Model vs Measurement

- There's a possibility that the structure is tapered when the hole radius is small