The 2nd QFilter Workshop @ Kyoto

February 25, 2020

Recent news from optical levitation experiment

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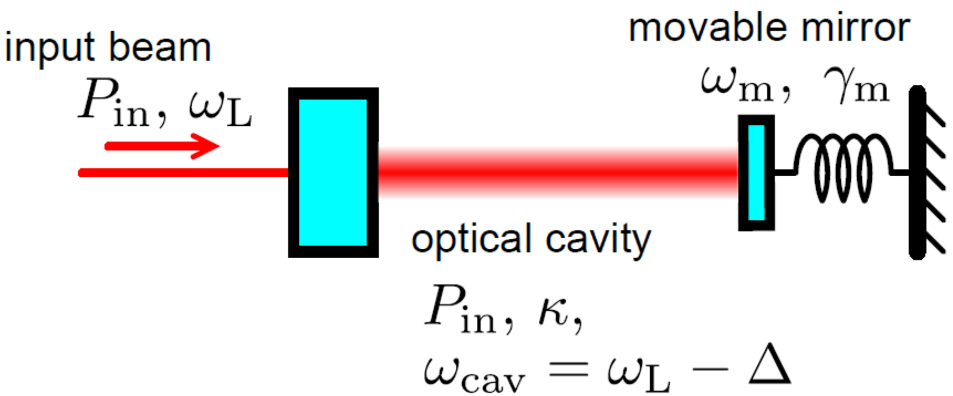
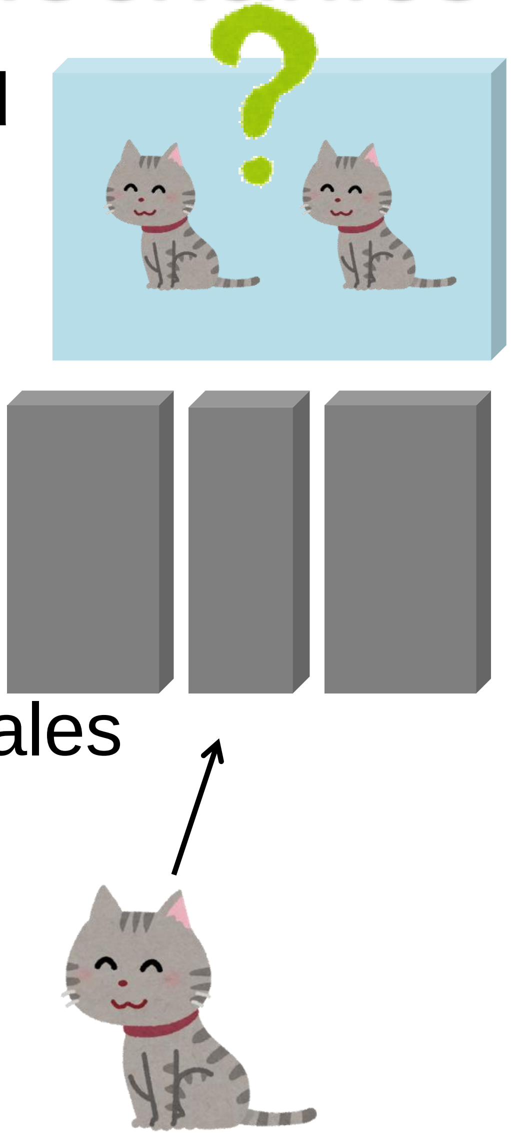
UTokyo Group

- Working on macroscopic quantum mechanics experiments at milligram-scale optomechanical systems
  - optical levitation (this talk)
    experiment mostly done by Naoki Kita
  - suspended disk (Takuya Kawasaki's talk)
- Also frequency dependent squeezing generation experiment at NAOJ Mitaka (Naoki Aritomi's talk)



Macroscopic Quantum Mechanics

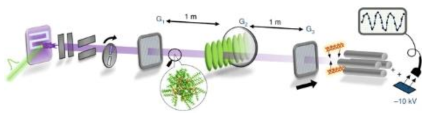
- Quantum mechanics do not depend on scales
- But macroscopic quantum superposition has never been observed (double-slit experiment upto 25 kDa (4e-23 kg)) [Nature Physics **15**, 1242 (2019)]
- Two possibilities at macroscopic scales
  - Quantum mechanics is valid, but too much classical decoherence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



Optomechanical Systems

- SQL not yet reached above Planck mass scale

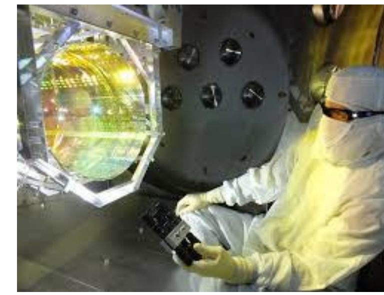
Double-slit



molecules, 40 zg
Fein+ (2019)

Planck mass (22 ug)

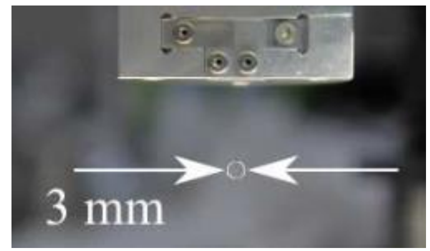
Factor of ~3 to SQL



suspended disk, 40 kg
Advanced LIGO

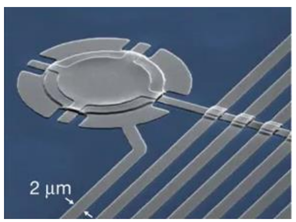
Quantum radiation pressure

cantilever, 50 ng
Cripe+ (2019)



suspended disk, 7 mg
Matsumoto+ (2019)

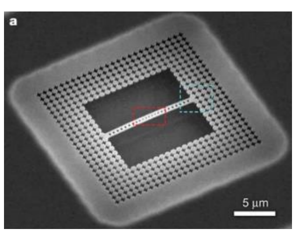
Ground state cooling



membrane, 48 pg
Taufel+ (2011)

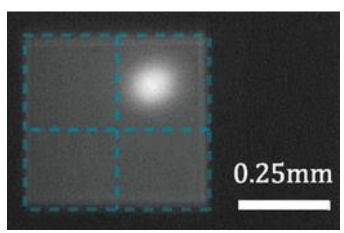
suspended bar, 10 mg
Komori+ (2019)

Ground state cooling

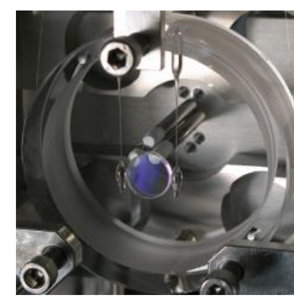


nanobeam, 331 fg
Chan+ (2011)

Ground state cooling



membrane, 7 ng
Peterson+ (2016)



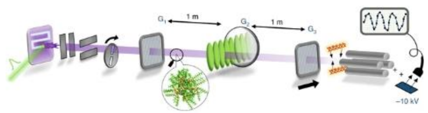
suspended disk, 1 g
Neben+ (2012)

fg pg ng ug mg g kg

Optomechanical Systems

- SQL not yet reached above Planck mass scale

Double-slit



molecules, 40 zg
Fein+ (2019)

Ground state cooling

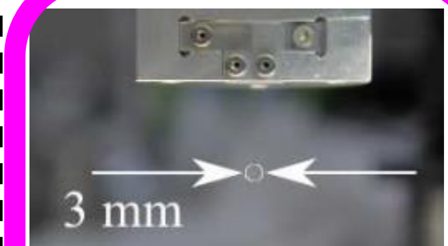
Quantum radiation pressure

We are focusing on mg-scale experiments to probe boundary between quantum world and gravitational world

nanobeam, 331 fg
Chan+ (2011)

membrane, 7 ng
Peterson+ (2016)

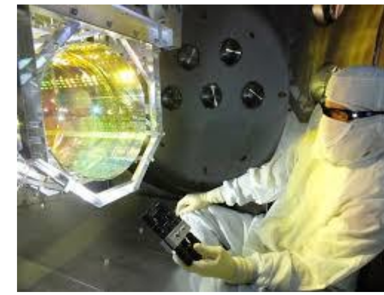
Planck mass (22 ug)



suspended disk, 7 mg
Matsumoto+ (2019)

suspended bar, 10 mg
Komori+ (2019)

Factor of ~3 to SQL



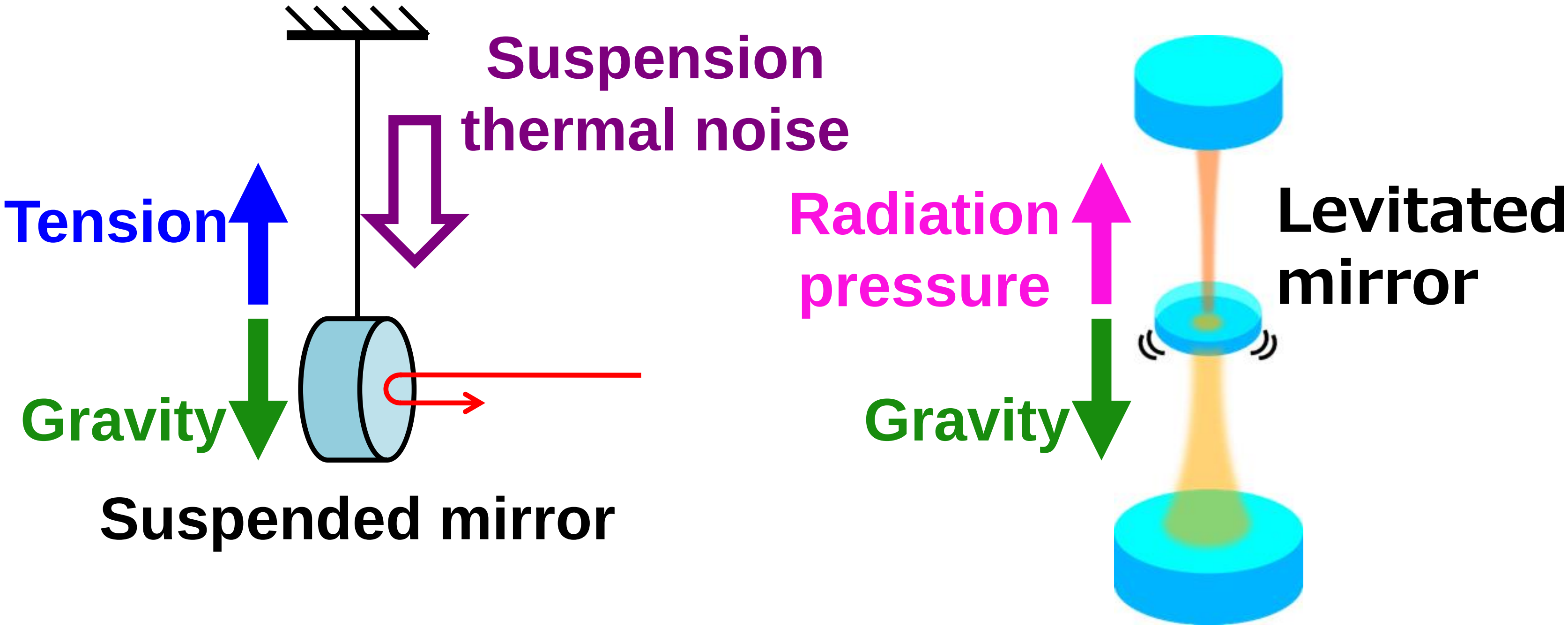
suspended disk, 40 kg
Advanced LIGO

suspended disk, 1 g
Neben+ (2012)

fg pg ng ug mg g kg

Optical Levitation

- Support a mirror with radiation pressure alone, rather than suspending it with a lossy wire
- Both suspended mirror and levitated mirror will be ultimately limited by thermal noise from residual gas and mirror coating

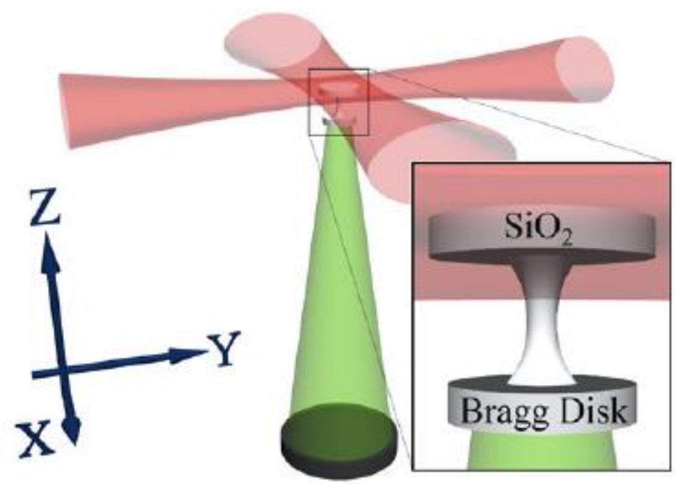


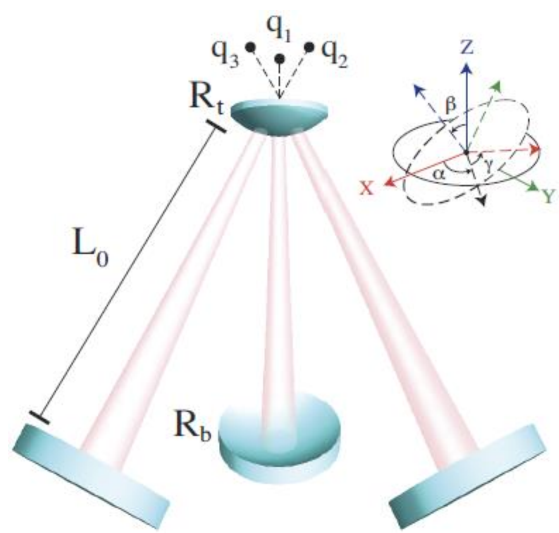
Sandwich Configuration

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

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

Levitated mirror



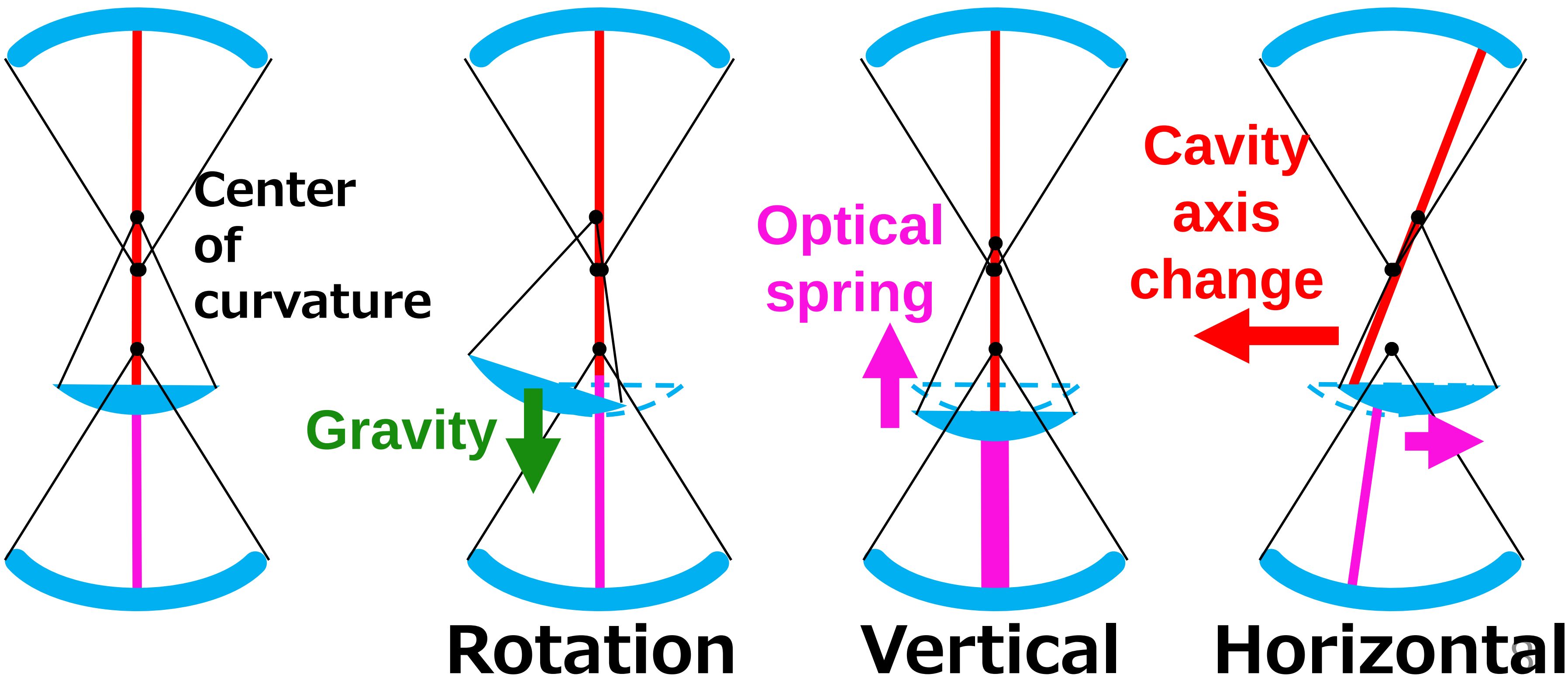


S. Singh+: PRL 105, 213602 (2010)

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

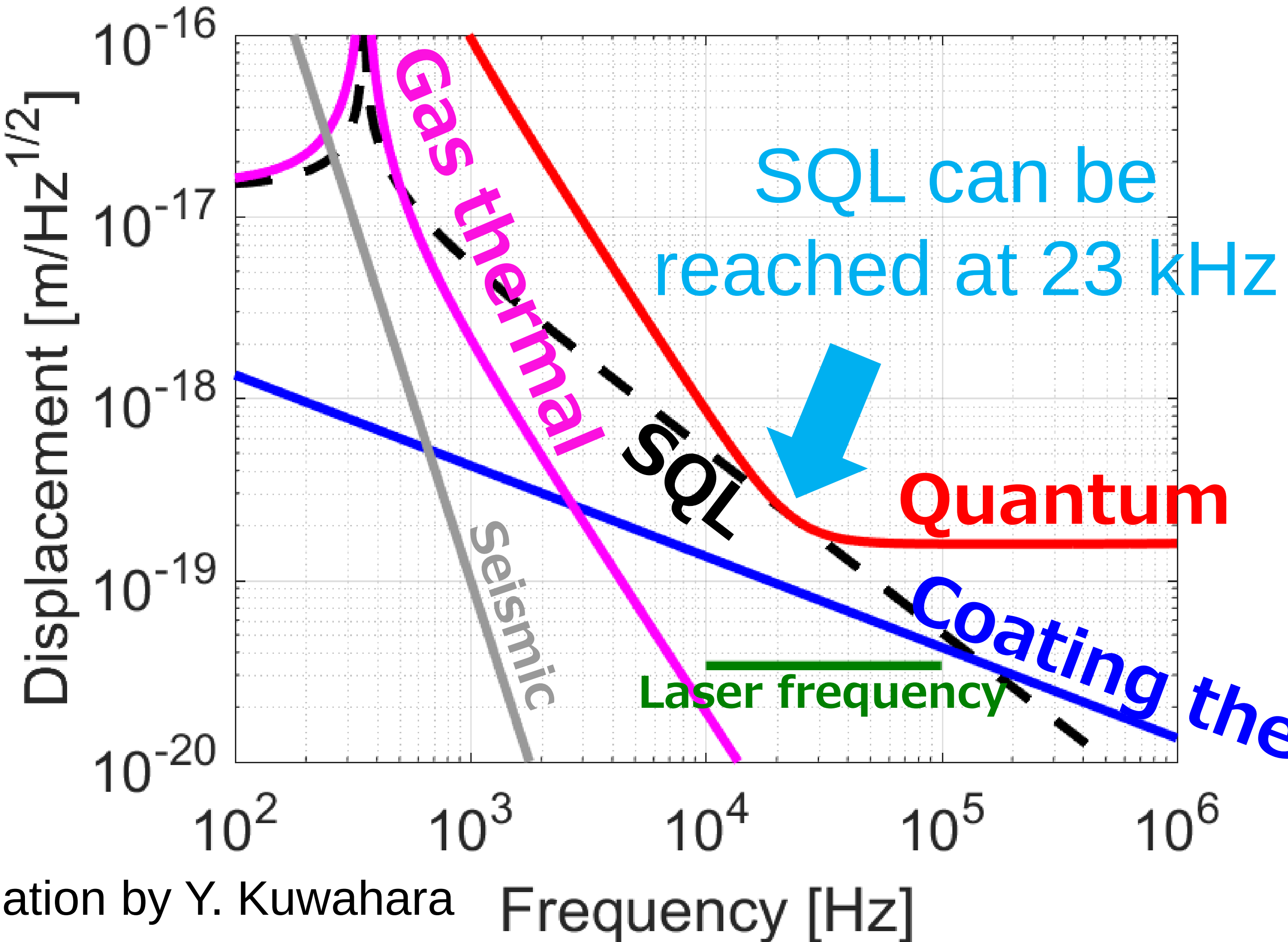
Stability of Levitation

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



Reaching SQL

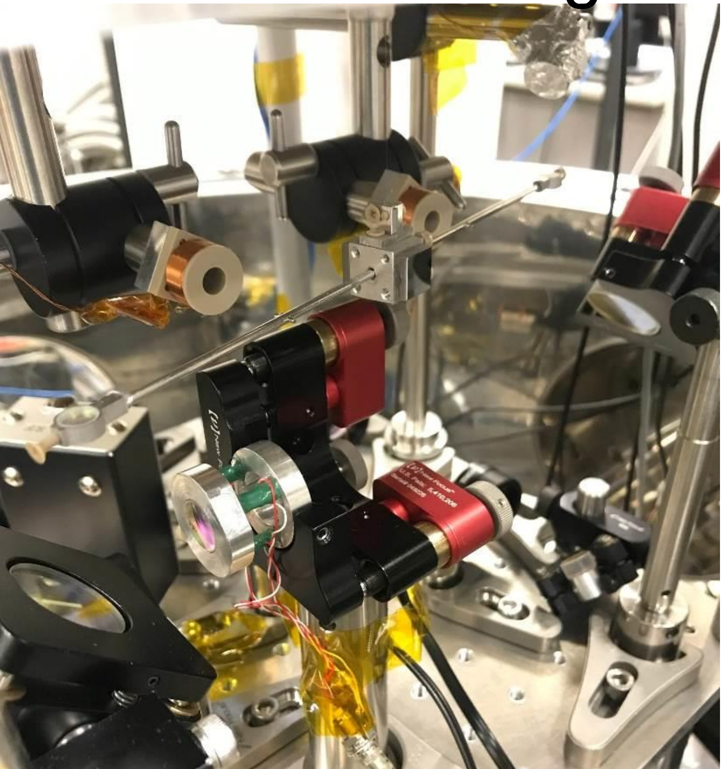
- 0.2 mg fused silica mirror, Finesse of 100, 13 W + 4 W input

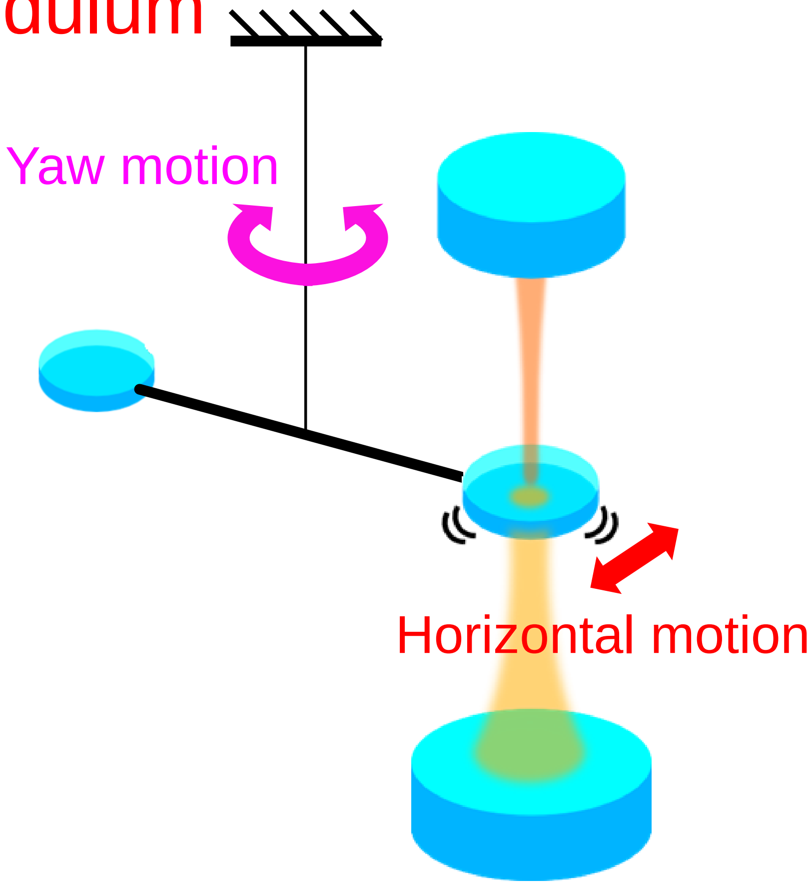


Calculation by Y. Kuwahara

Experiment to Verify the Stability

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



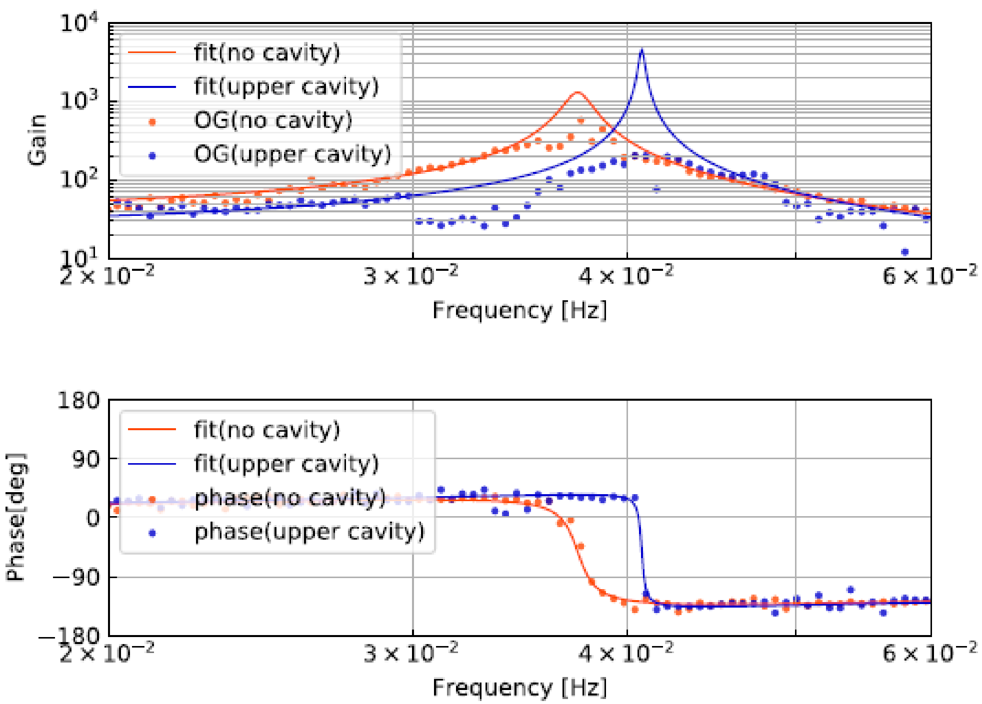


Experiment to Verify the Stability

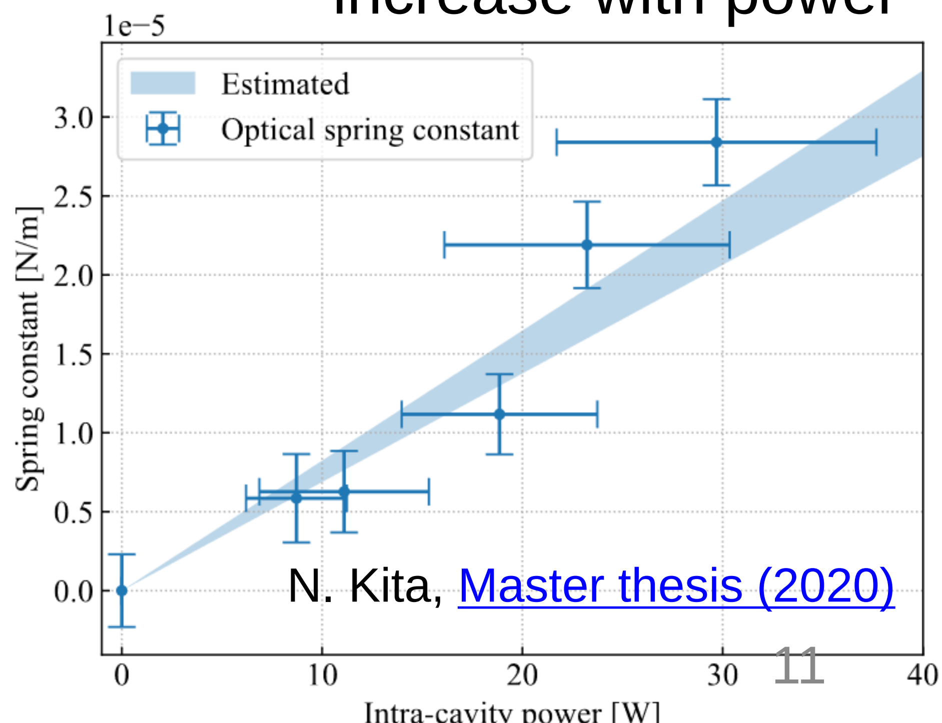
- Resonant frequency of torsion pendulum increased when optical cavity is locked

  → Successfully measured the restoring force

Resonant frequency measurement



Spring constant increase with power

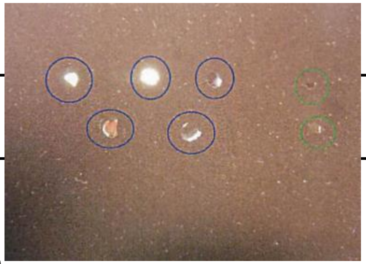


N. Kita, [Master thesis (2020)]

Fabrication of Levitation Mirrors

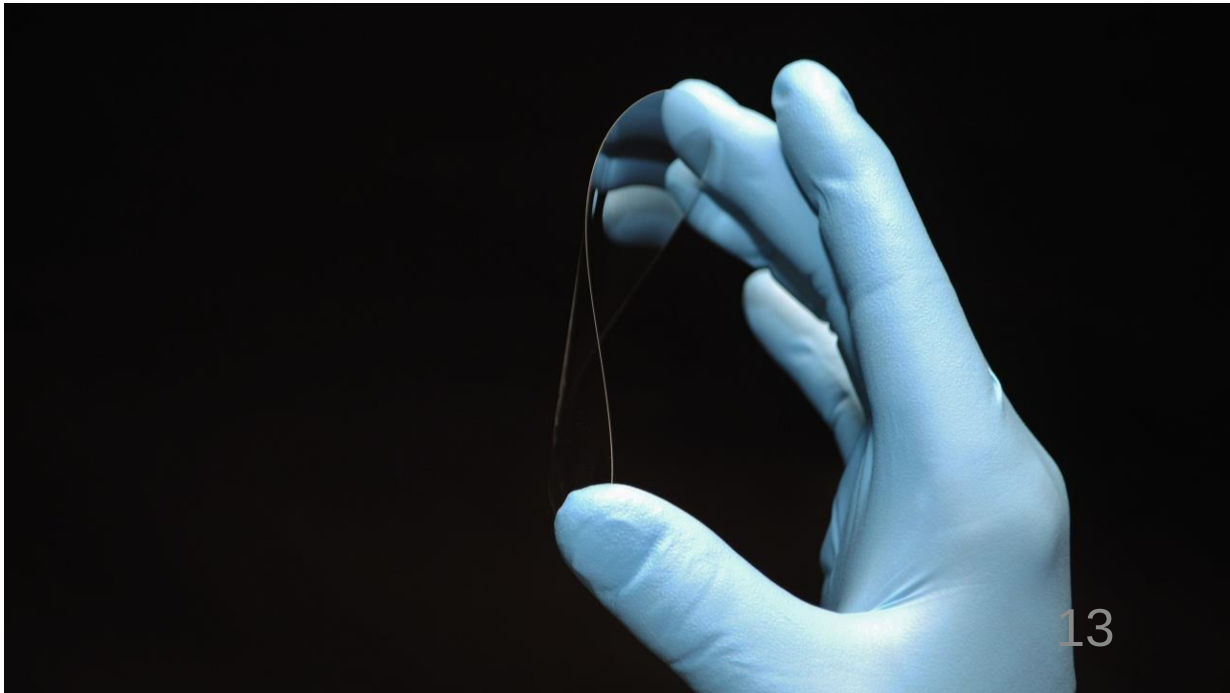
- So far, fused silica mirror with dielectric multilayer coating have been tried
- Cracks due to coating stress

	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±10 mm convex (measured: 15.9±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



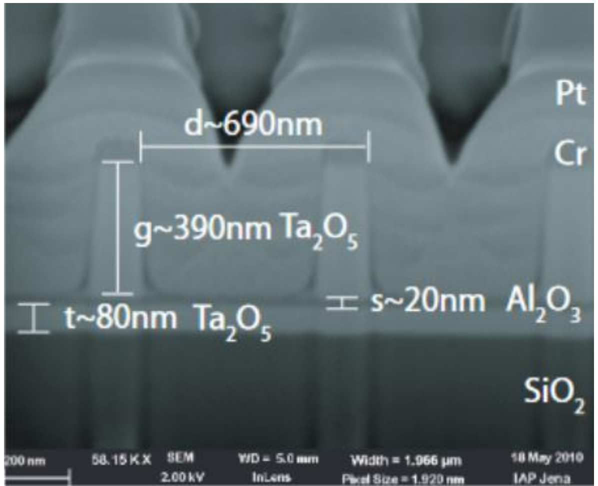
Thin Fused Silica Substrate

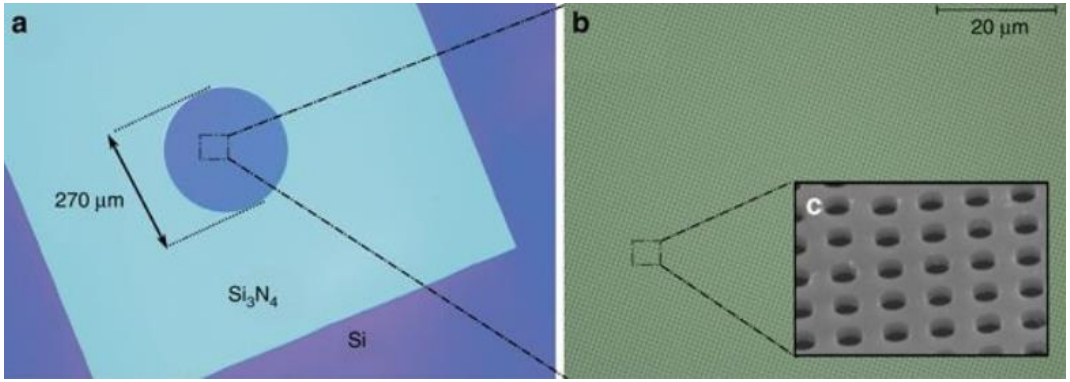
- 1 inch dia. x 0.1 mm thick available from Mark Optics
- Coating stress to introduce curvature
- Possible coating by LMA?
- Substrate procurement next FY



Photonic Crystal Mirror ?

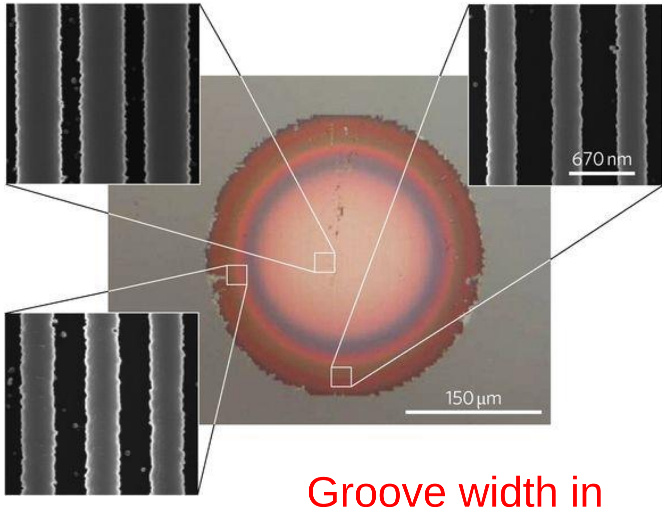
- High reflectivity demonstrated, also in the context of gravitational wave detector to reduce coating thermal noise
  - D. Friedrich+, Optics Express 19, 14955 (2011)
    R=99.2 % @ λ=1064 nm
  - X. Chen+, Light: Science & Applications 6, e16190 (2017)
    R = 0 to 99.9470±0.0025% @ λ=1μm



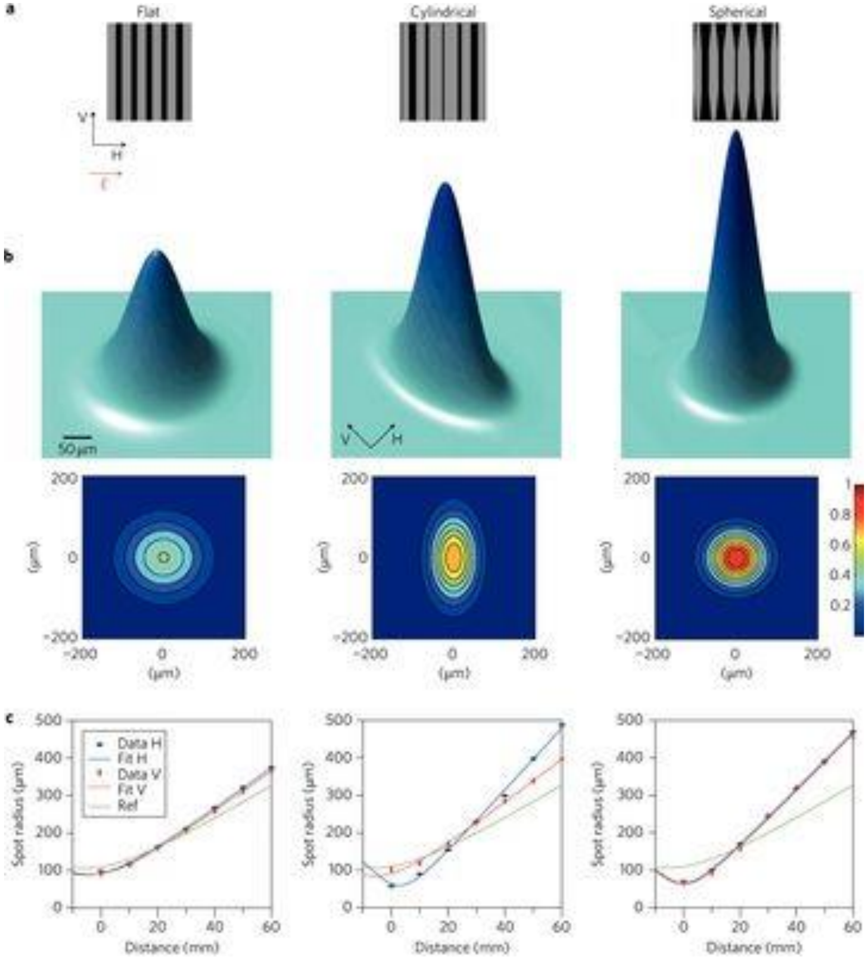


Curved Mirror Seems Possible

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



Groove width in various locations



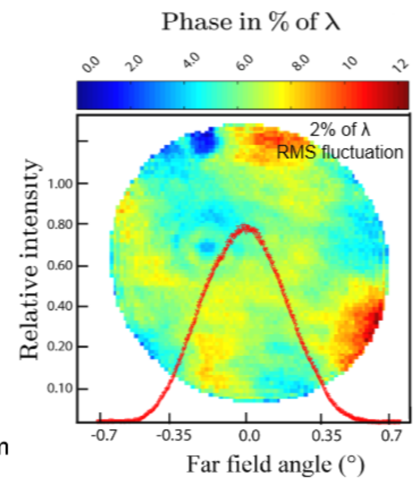
Curved Mirror Seems Possible

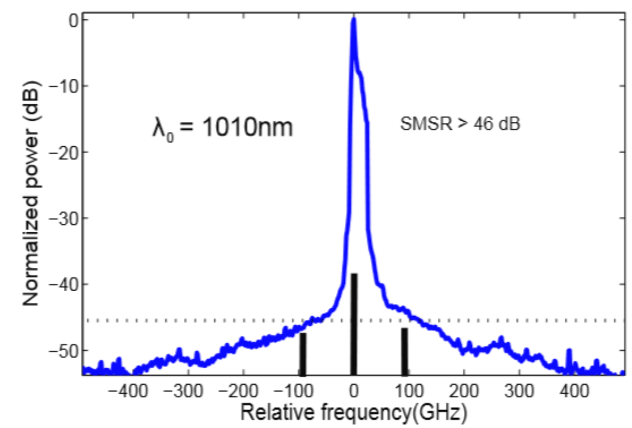
- M. S. Seghilani+, [Optics Express 22, 5962 (2014)]

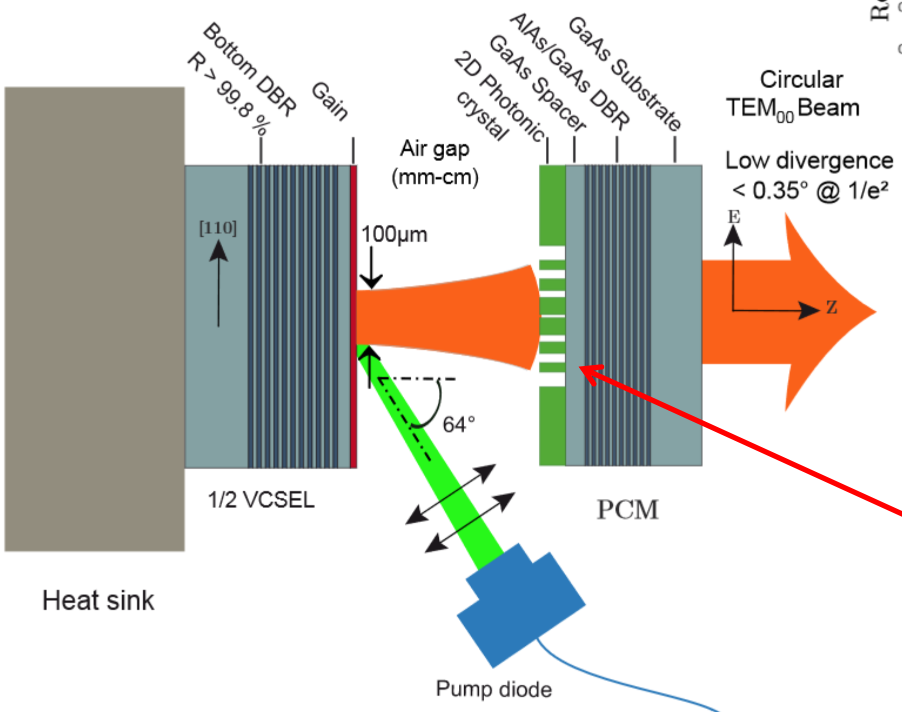
R > 99%

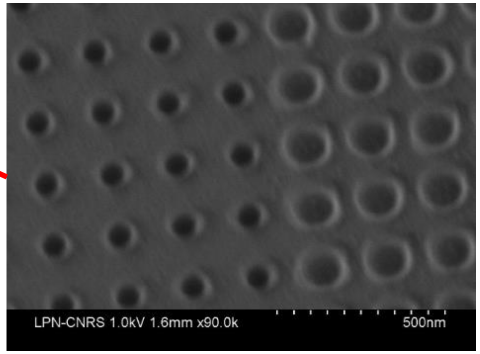
RoC = 20 mm

Distributed Bragg reflector (DBR) for high reflectivity









Other Proposals

too dirty for us!

- 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!

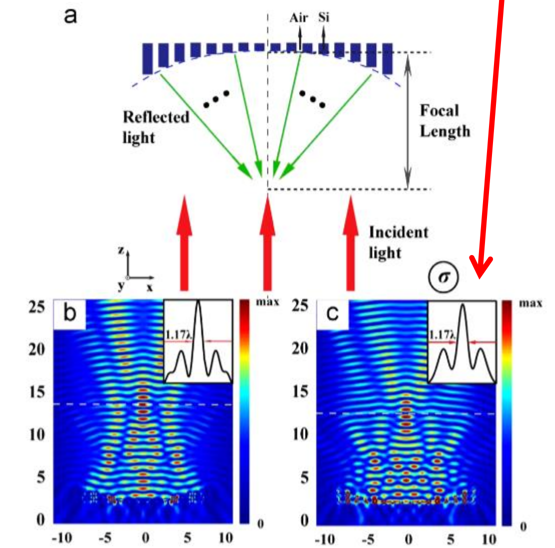
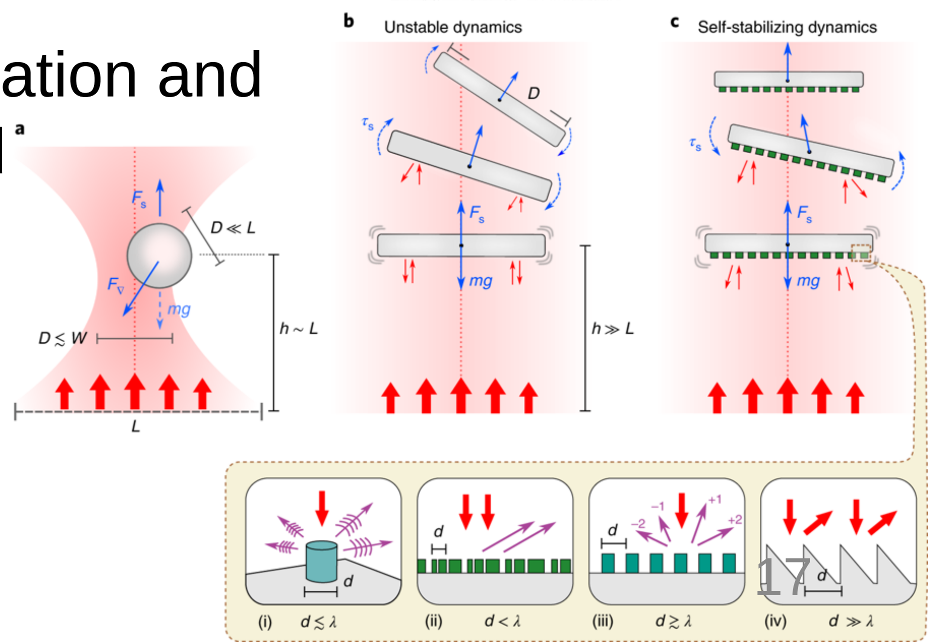


Fig. 2. (a) Schematic of a 2D HCG focusing reflector. The intensity distribution of the focused beam when (b) TE and (c) TM waves illuminate from the bottom side. The wavelength of the incident light is 1.55 μm, and the white line is the position of focal point. FWHMs are both 1.17λ.

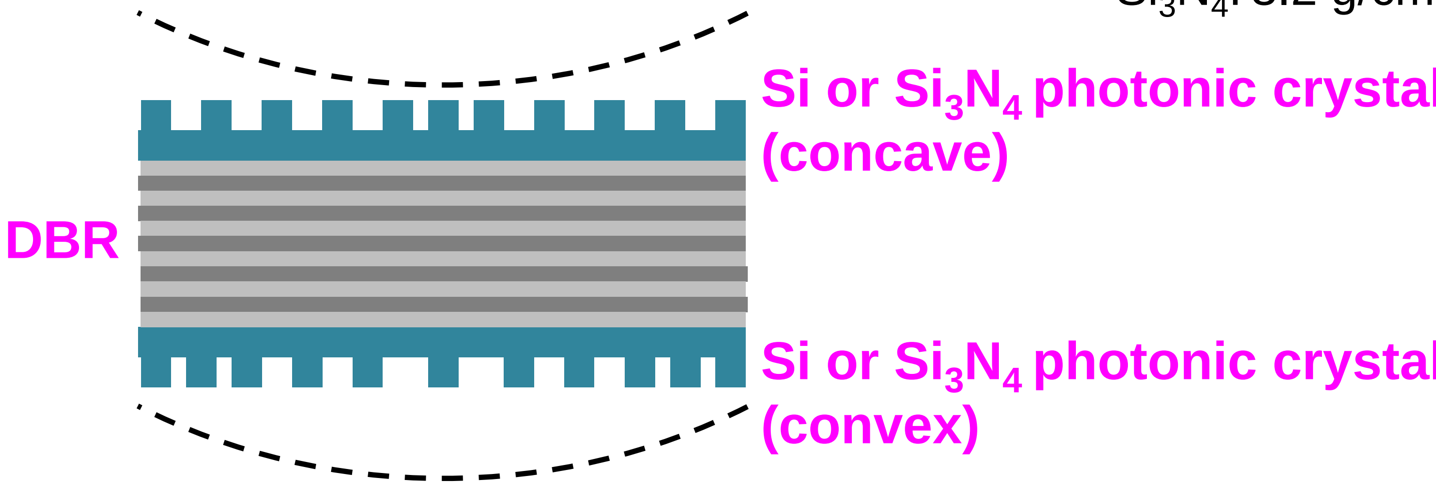
- Self-stabilizing photonic levitation and propulsion of nanostructured macroscopic objects
  O. Ilic & H. A. Atwater, [Nature Photonics 13, 289 (2019)]
  - levitation by tailoring asymmetric scattering of light



Possible Photonic Crystal Mirror

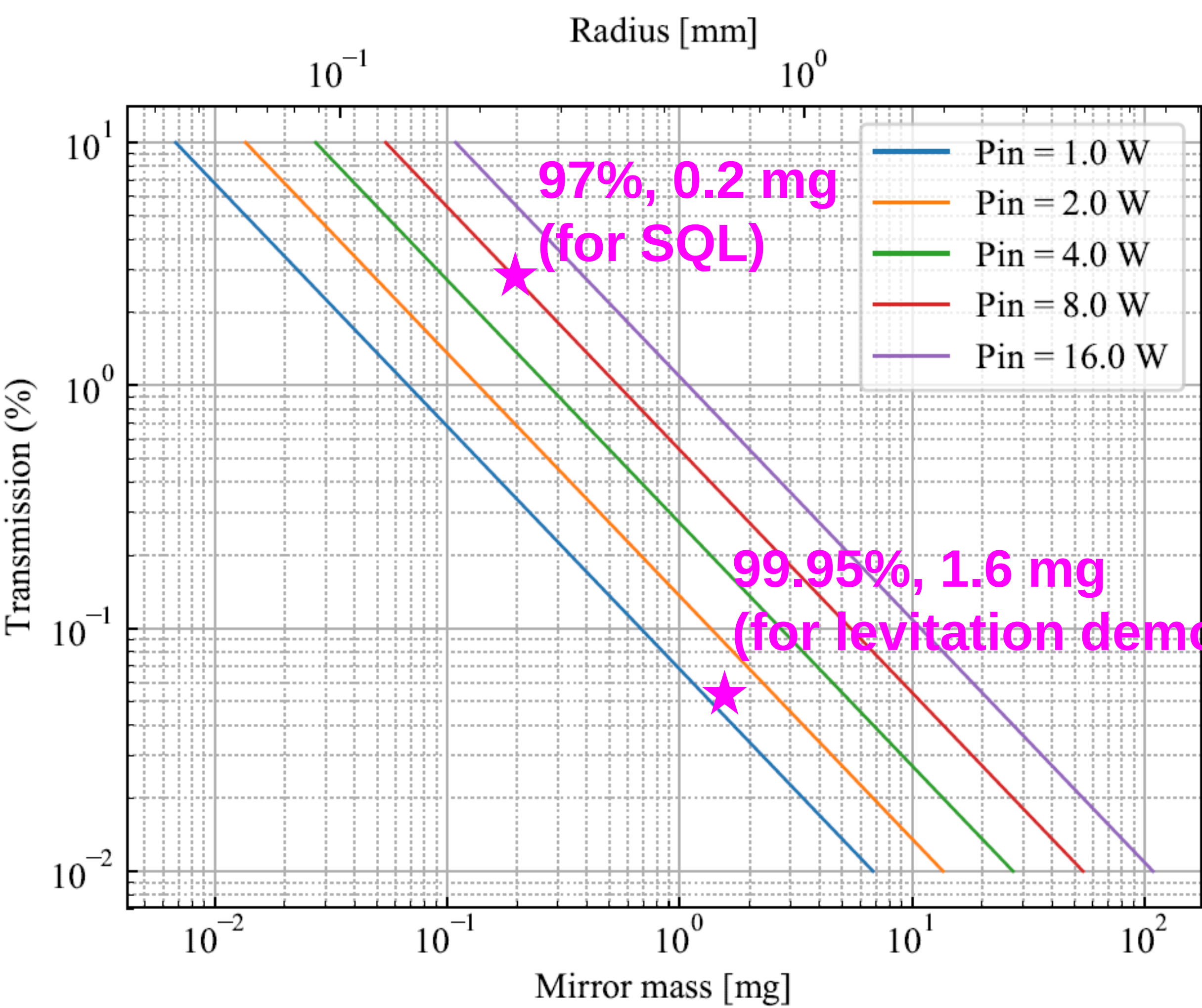
- DBR (distributed Bragg reflector) for high reflectivity, 2D photonic crystal for effective curvature?
- Got Si_3N_4 membrane sample (1 mm x 1 mm x 200 um thick; 0.6 mg only membrane) from Usami group
- Collaboration with Iwamoto group

SiO_2: 2.2g/cm^3, n=1.45
Si: 2.3 g/cm^3, n=3.67
Si_3N_4: 3.2 g/cm^3, n=2.01



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

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

$9.8\ \mathrm{m/s^2}$

Mirror power transmission (R=1-T)

Intra-cavity power

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

Summary

- 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
- Succeeded in experimentally verifying the stability of the levitation
- Next step is the fabrication of a milligram mirror with high reflectivity and curvature
- Will try thin substrate with curvature from coating stress
- Alternative solution: photonic crystal mirror ?