The 1st QFilter Workshop @ LKB, Paris

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Optical Levitation of a Mirror for Realizing Macroscopic Entanglement

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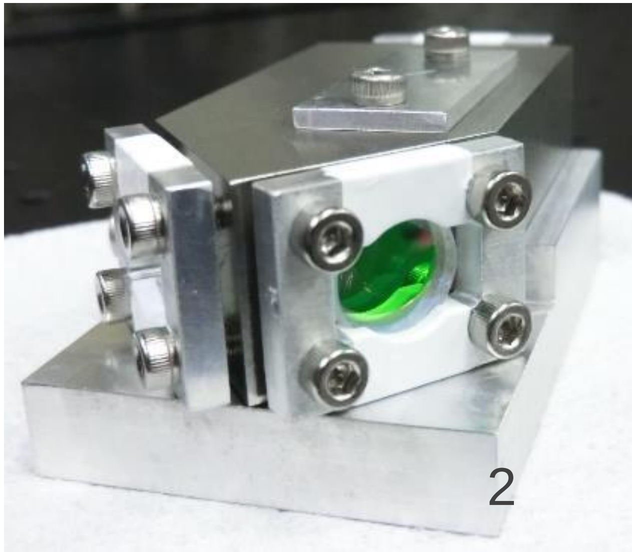
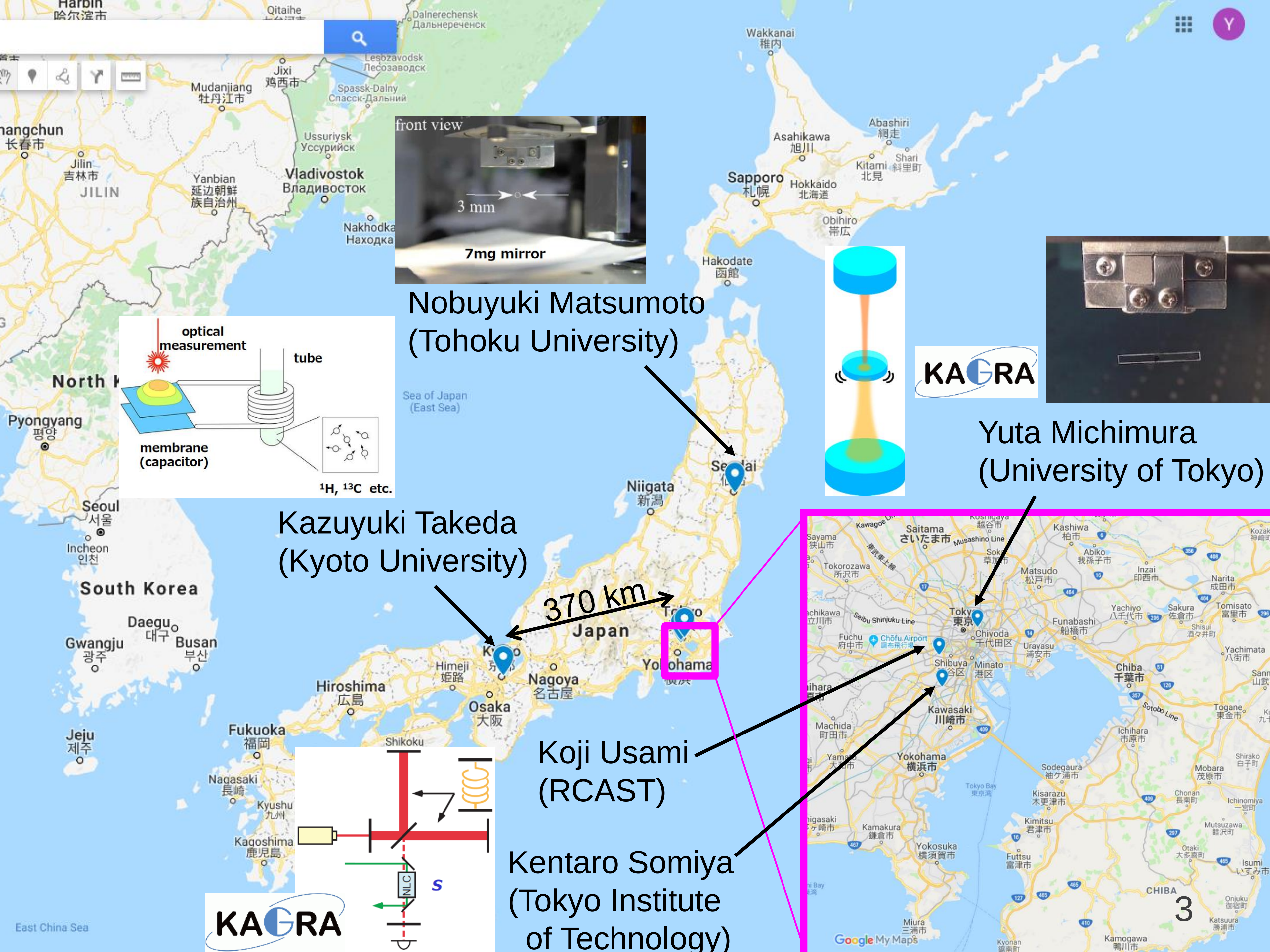
Self Introduction

- Yuta Michimura
  Department of Physics, University of Tokyo

- Interferometry in gravitational wave detectors
  - KAGRA
  - DECIGO
- Test of fundamental physics using laser interferometers
  - Lorentz invariance
  - Macroscopic quantum mechanics
  - Axion search

  etc……





front view
3 mm
7mg mirror
Nobuyuki Matsumoto
(Tohoku University)
optical
measurement
tube
membrane
(capacitor)
¹H, ¹³C 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
Sea of Japan
(East Sea)
Japan
Google My Maps
3

Overview

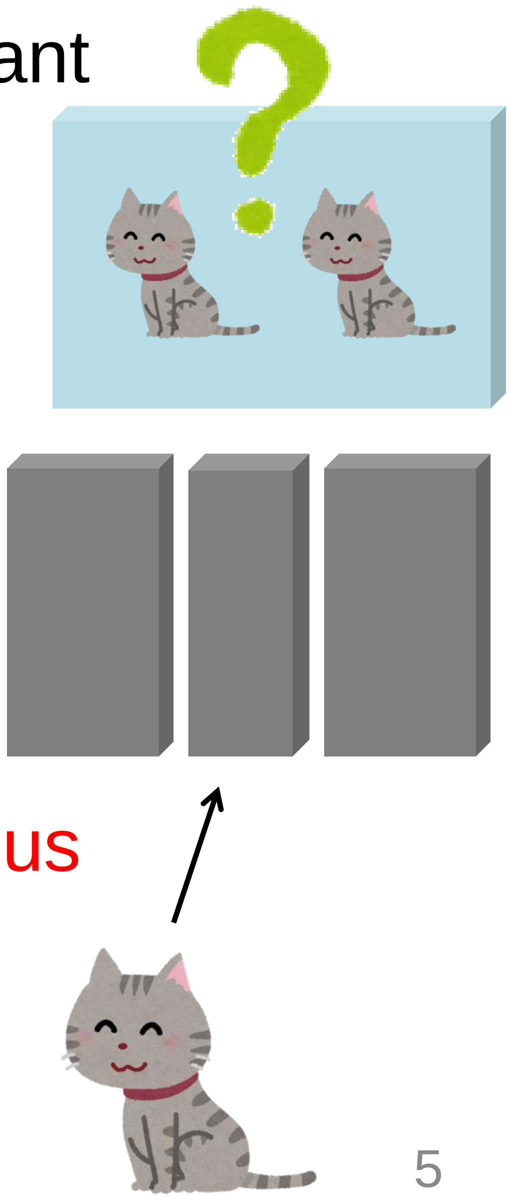
- Test of macroscopic quantum mechanics
  super position of position states of
  mg-scale mirrors
- Optical levitation of a mirror
  no suspension thermal noise
  sandwich configuration
  reaching standard quantum limit is
  feasible

  YM+, [Optics Express 25, 13799 (2017)]

- Technical challenge
  fabrication of mg-scale mirrors

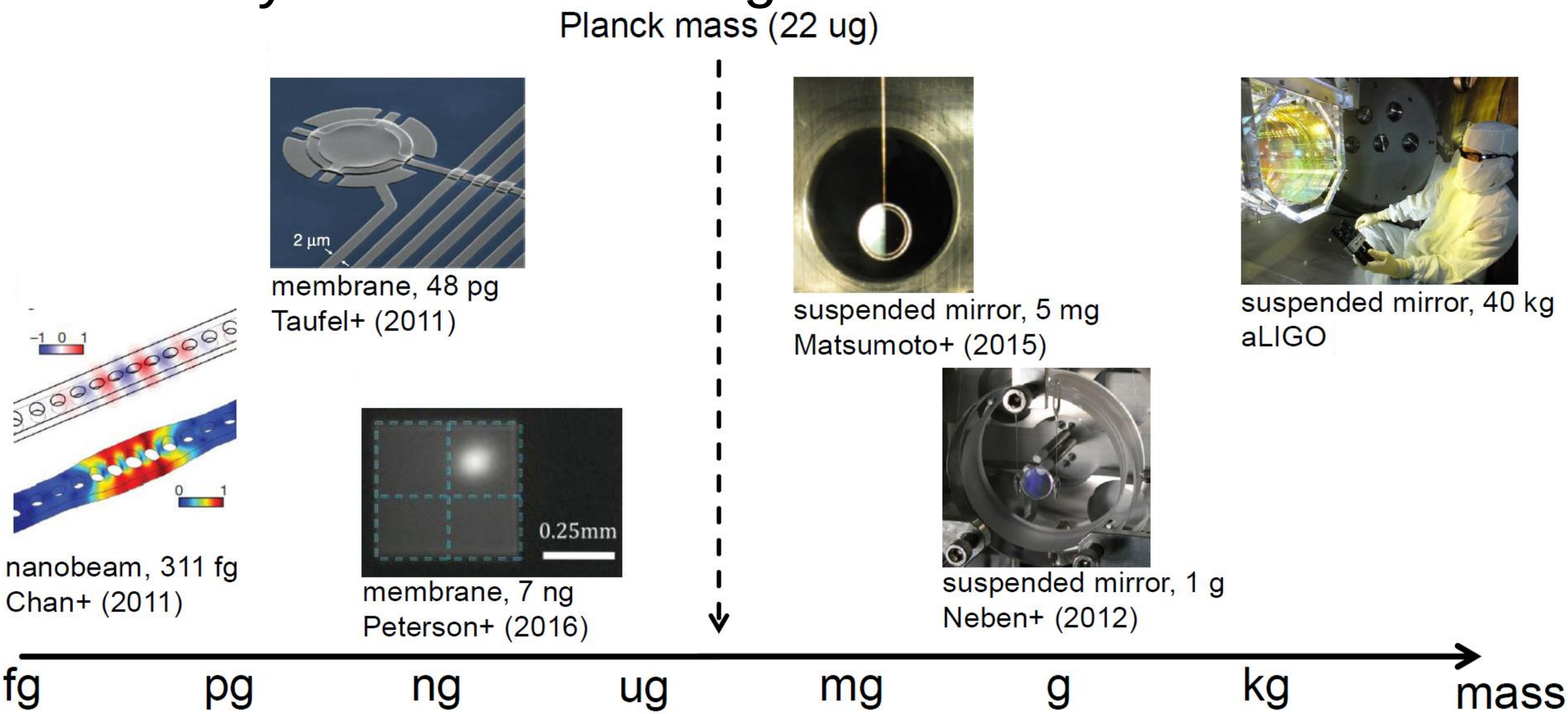
Macroscopic Quantum Mechanics

- Quantum mechanics is scale-invariant
- But superposition of macroscopic objects are not observed
- Many interpretations
  - too much classical decoherence
  - non-linear Schrödinger Eqs.
  - gravity decoherence ……
- Test of quantum mechanics at various scales necessary to look into classical-quantum boundary



Previous Experiments

- Benchmark for realizing quantum mechanics test: reaching the standard quantum limit (SQL)
- Not yet achieved at mg-scale



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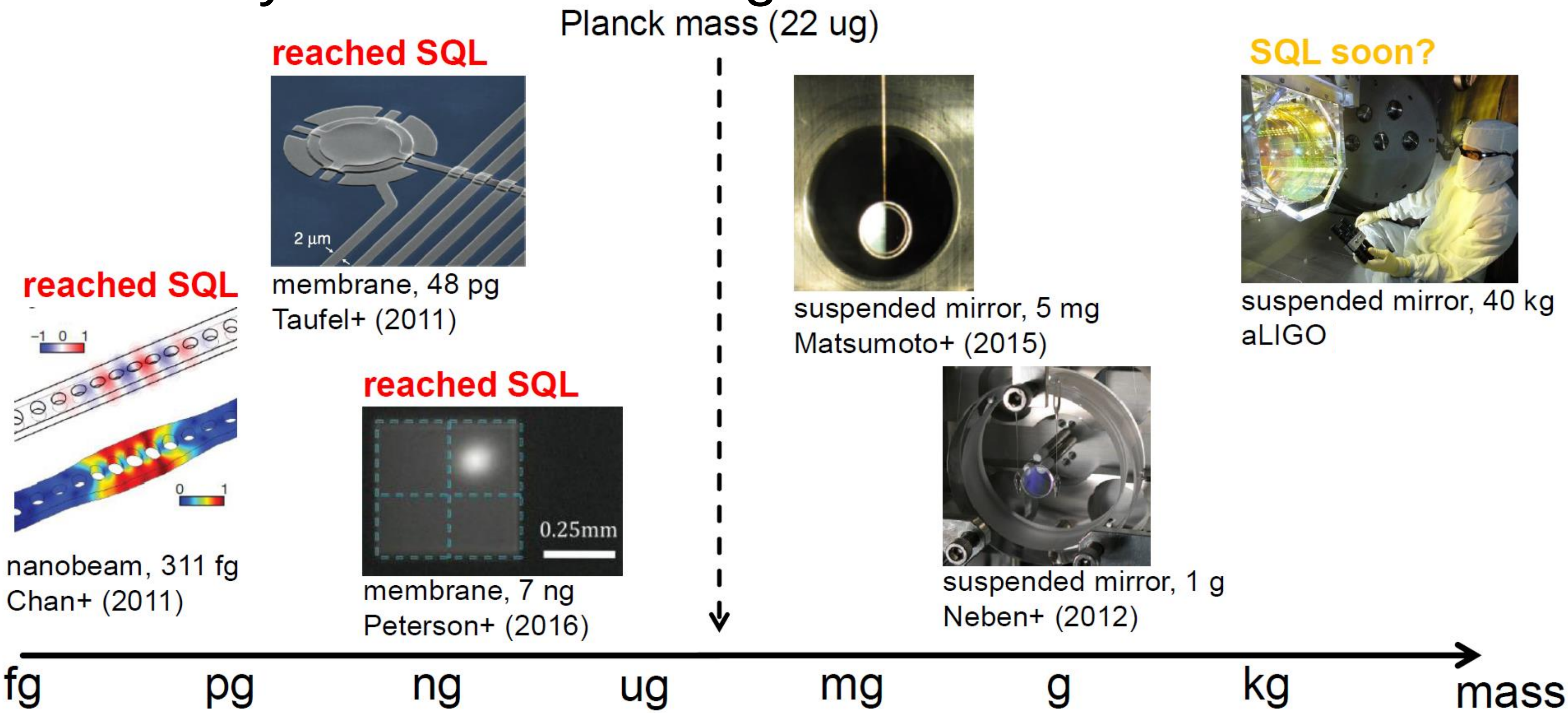

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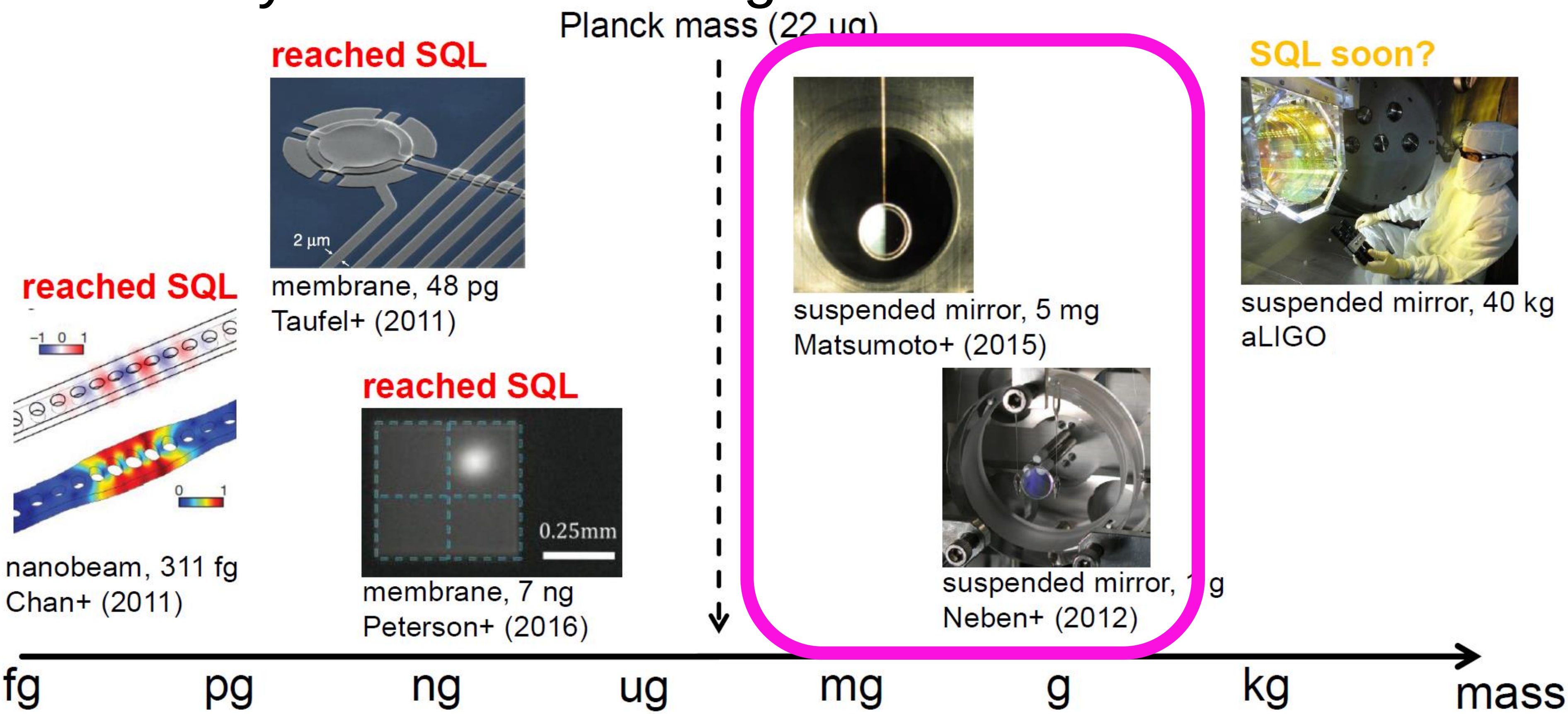
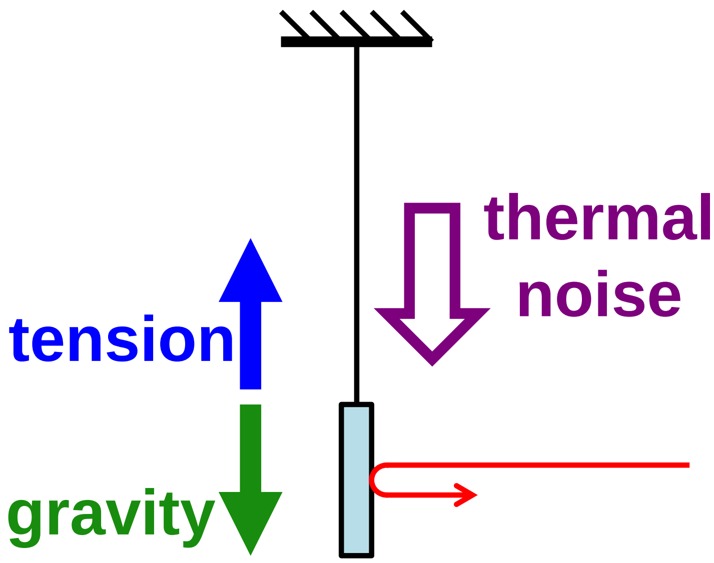


Optical Levitation of a Mirror

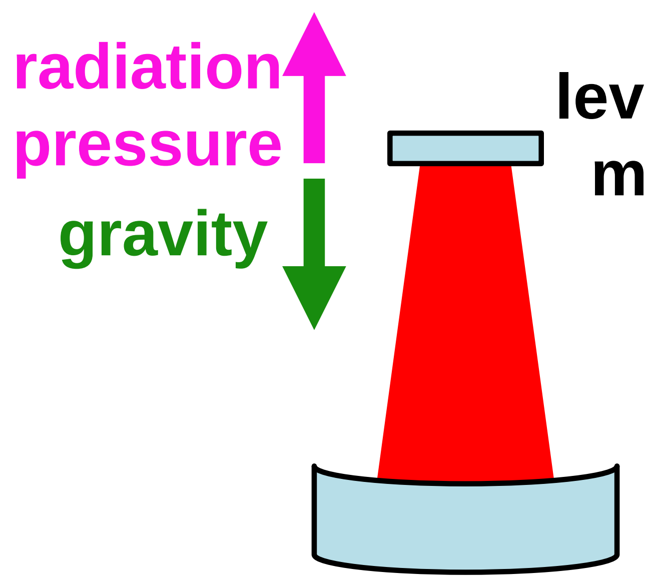
- Thermal decoherence due to mechanical support can be avoided with optical levitation

Mechanical Suspension



suspended mirror

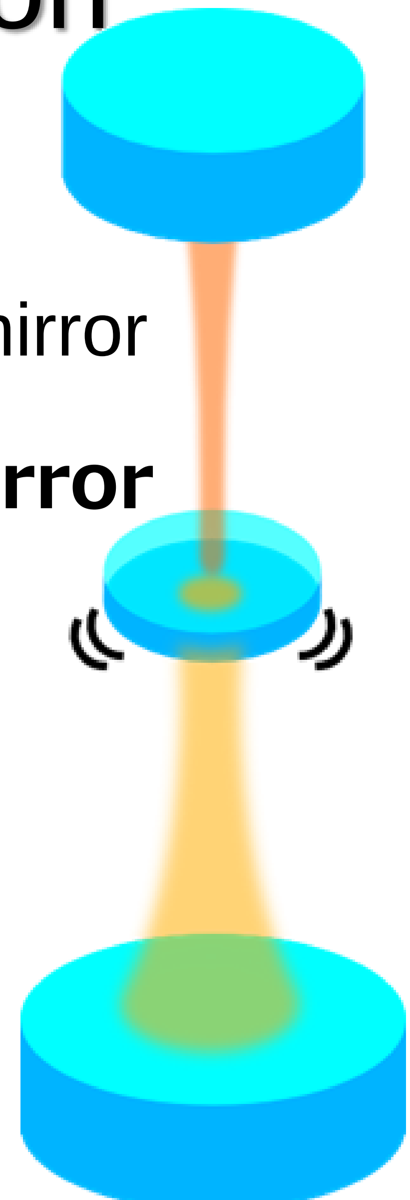
Optical Levitation

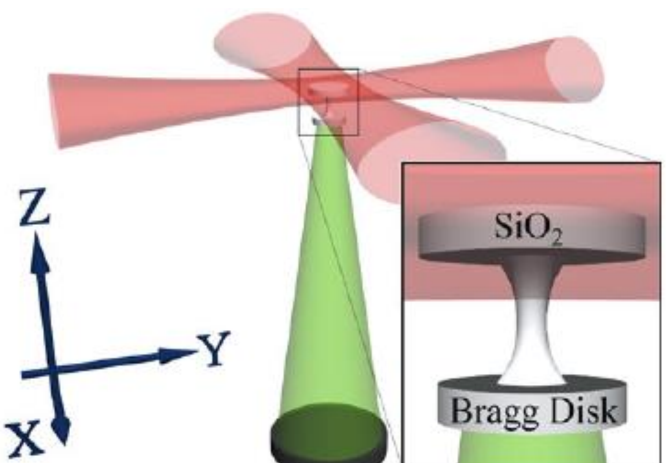


Sandwich Configuration

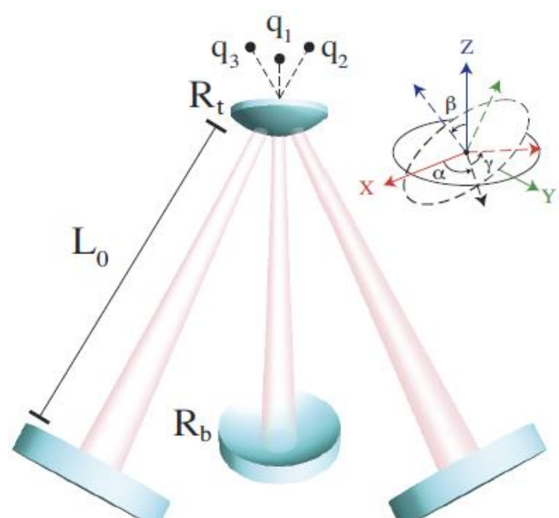
- Simple configuration than previous proposals
- Upper cavity to stabilize the levitated mirror

Levitated mirror





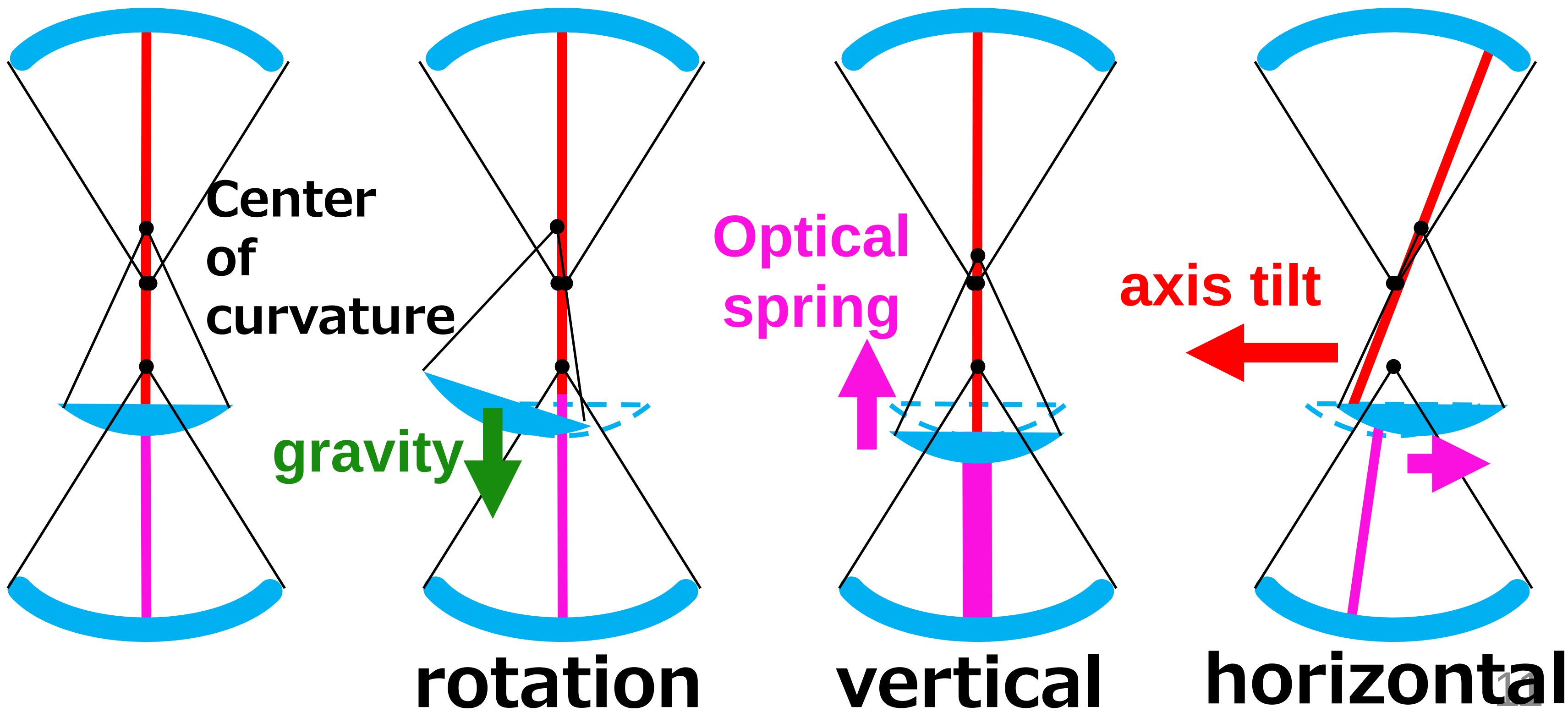
S. Singh+: PRL 105, 213602 (2010)



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

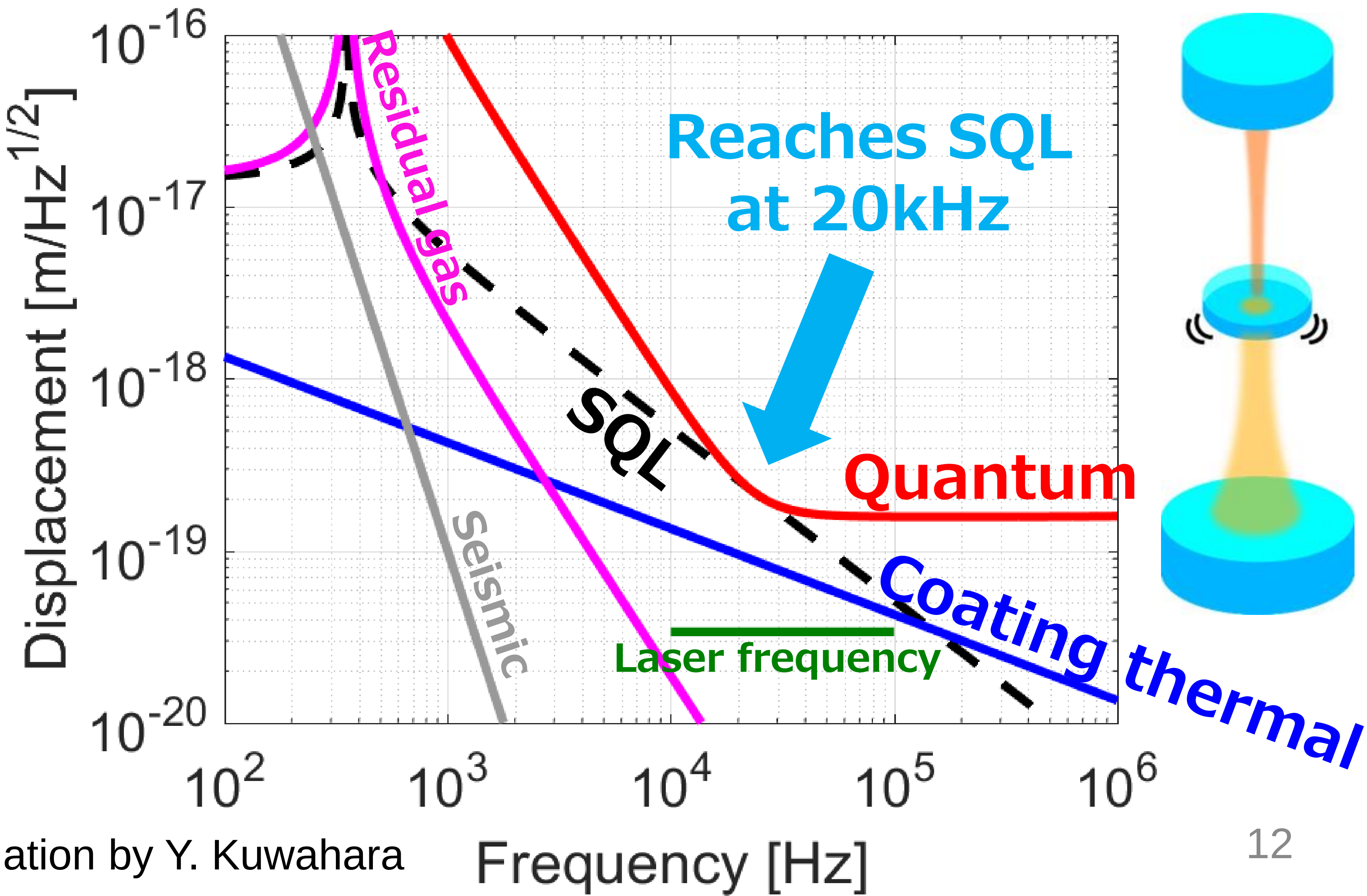
Stability of the Levitation

- 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



Calculation by Y. Kuwahara

Technical Challanges

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

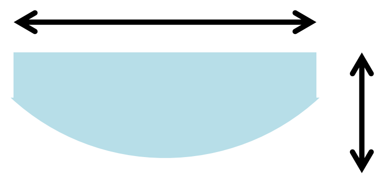
- Experimental demonstration of the stability
- Procedure for tuning the alignment, power, detuning for the levitation
  experiment using torsion pendulum ongoing

- Laser frequency noise
  0.1 mHz/√Hz @ 20 kHz

Mirror We Need

Upper side
- flat
- AR <0.5%

3 mm dia.



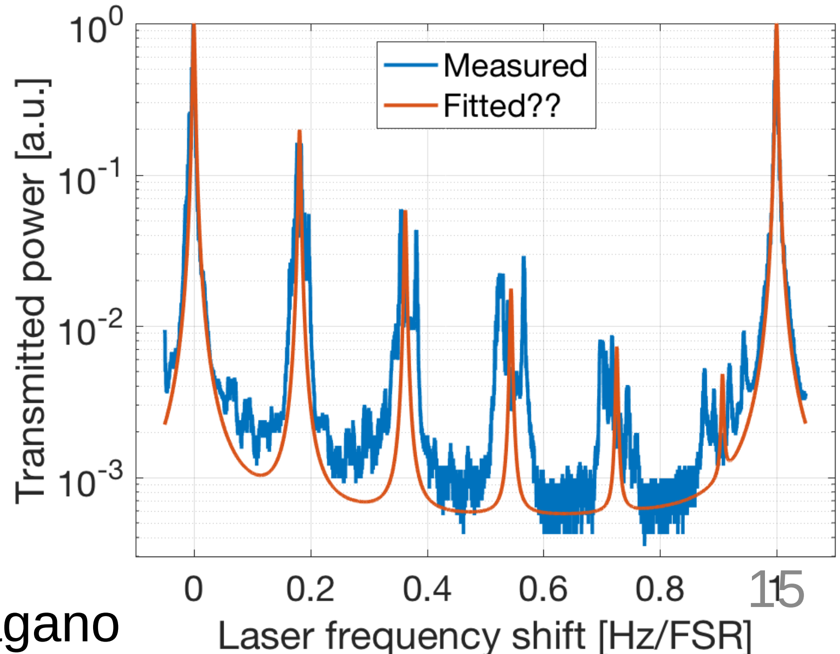
0.1 mm thick

~1.6 mg

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%

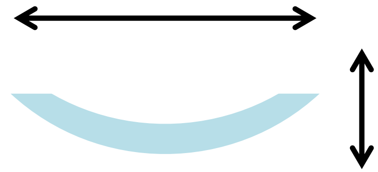


Plot by K. Nagano

Alternative Way?

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

3 mm dia.



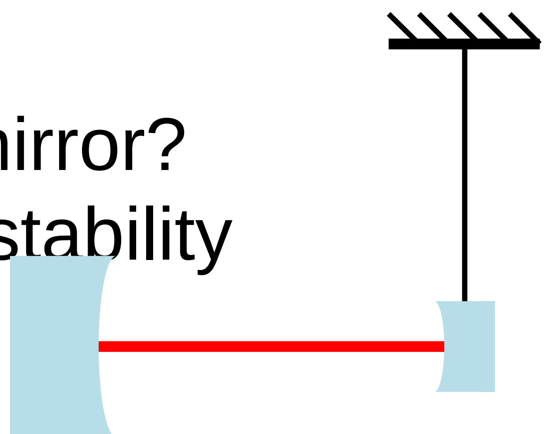
0.1 mm thick

~1.6 mg

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

Any Ideas Welcome!

- We have been focusing on sensing vertical motion of a mirror, but sensitivity design is tough due to intracavity power constraints to levitate a mirror
  $\longrightarrow$ mirror rotation sensing?
- Triangular pyramid mirror?
- Levitate a mirror in space
  - less power since less gravity
  - 50cm cubic, ~50kg satellite could be feasible
- Suspend curved mirror?
  - no alignment instability if curved



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)