The 5th QFilter Workshop (OIST)

November 14, 2022

Unstable optical levitation for testing gravity-induced quantum entanglement

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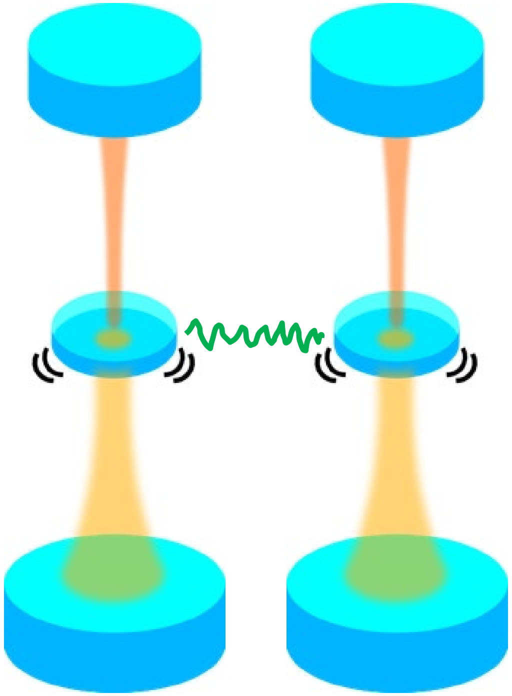


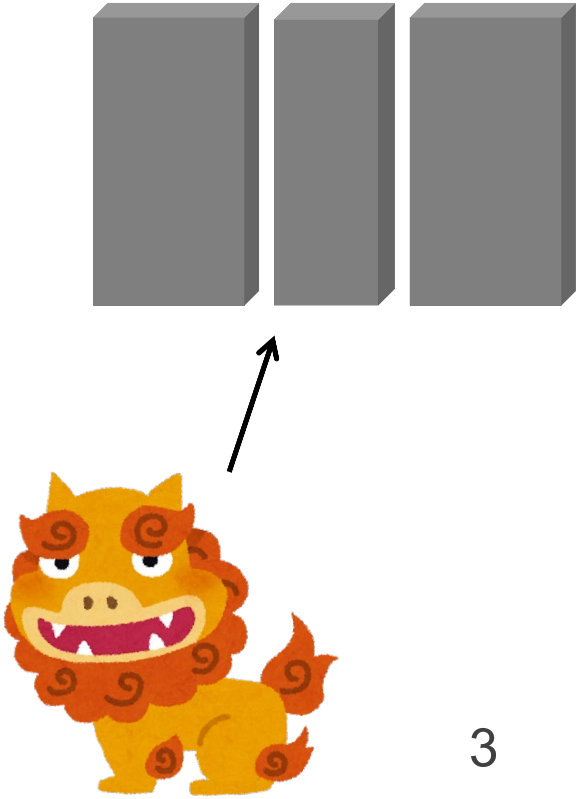
Overview

- We want to test quantum nature of gravity by gravity-induced quantum entanglement
- To seek for the best setup, we estimated the amount of entanglement for trapped/free-falling/inverted oscillators coupled by gravity
- Inverted oscillators are most efficient
  - Generate gravity-induced entanglement exponentially
  - Most resistant to decoherence
- Optical levitation with sandwich configuration is convenient to realize such experiments

T. Fujita, Y. Kaku, A. Matsumura, YM, arXiv:2308.14552

Quantum Gravity?

- Is gravity quantum?
- Will superposition of position states of massive object indicate superposition of gravitational field?

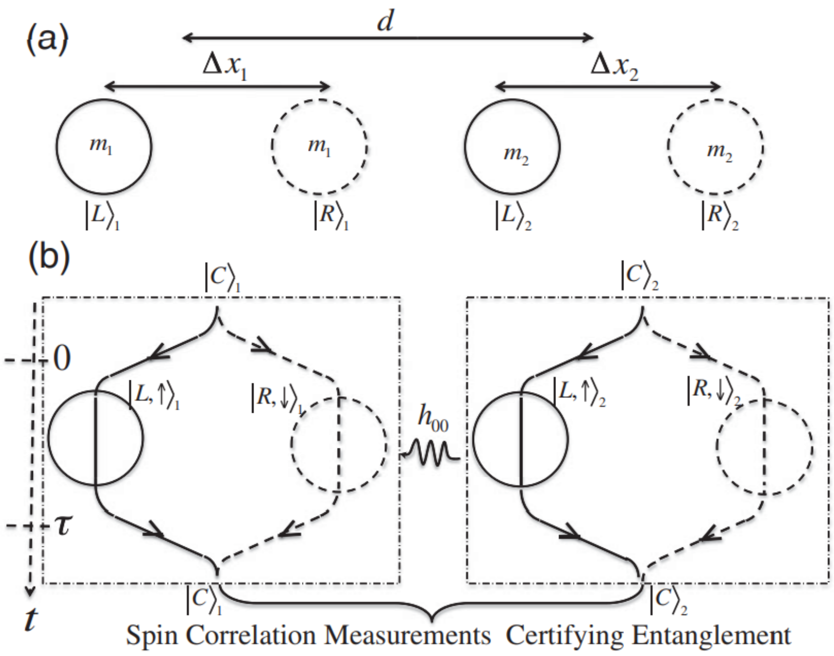


- We need experimental evidences
- As a first step, we can verify if quantum entanglement can be induced by Newtonian gravity

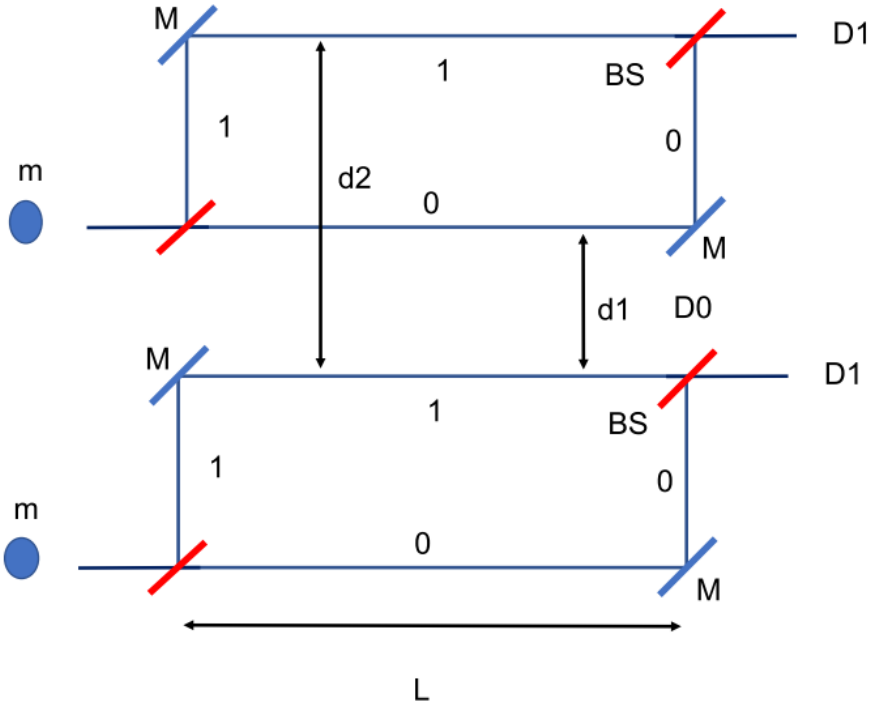
BMV Experiment Proposals

- Gravity-induced entanglement can be tested with adjacent matter interferometers

S. Bose+,
[Phys. Rev. Lett. 119, 240401 (2017)]

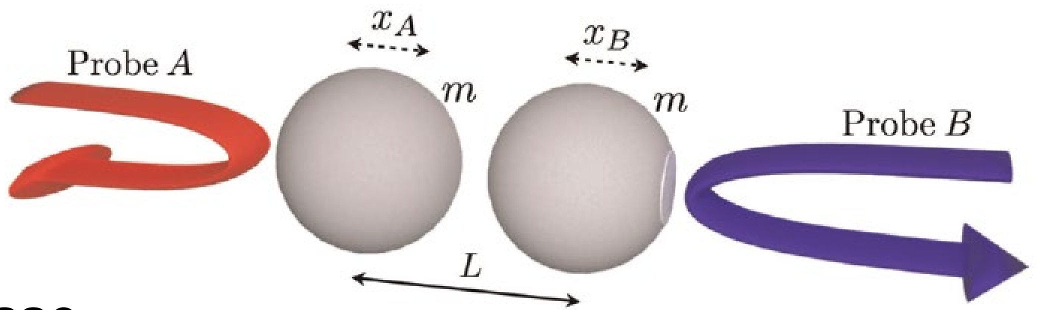


C. Marletto & V. Vedral,
[Phys. Rev. Lett. 119, 240402 (2017)]

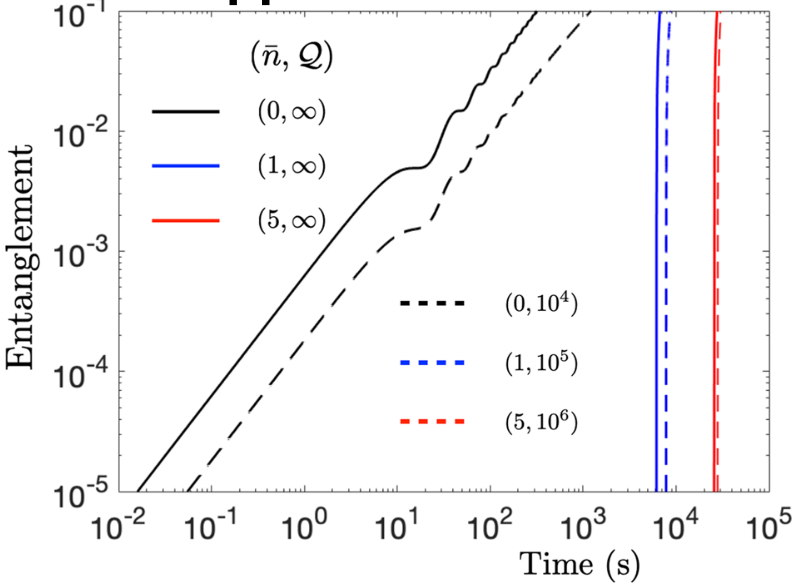


Krisnanda+ Proposal

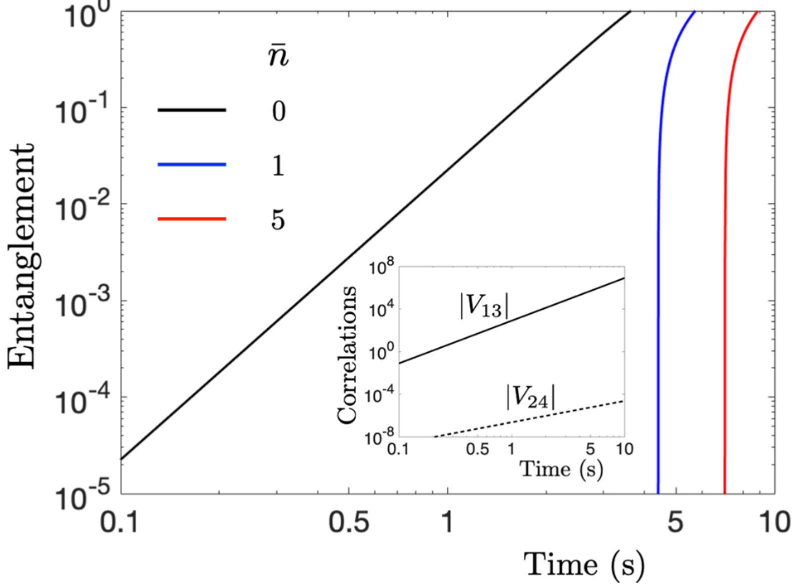
- Free-falling masses can generate gravity-induced entanglement more & faster than trapped masses



Trapped case



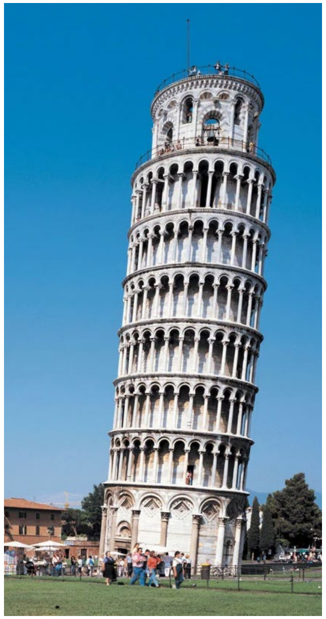
Released case



T. Krisnanda+, [npj Quantum Information **6**, 12 (2020)]

Decoherence Effects

- Decoherence estimates suggest $T < 1$ K and $P < 10^{-16}$ Pa are required
- Also, free-fall time and height are in the orders of ~1 sec and ~10 m
- Sounds tough…



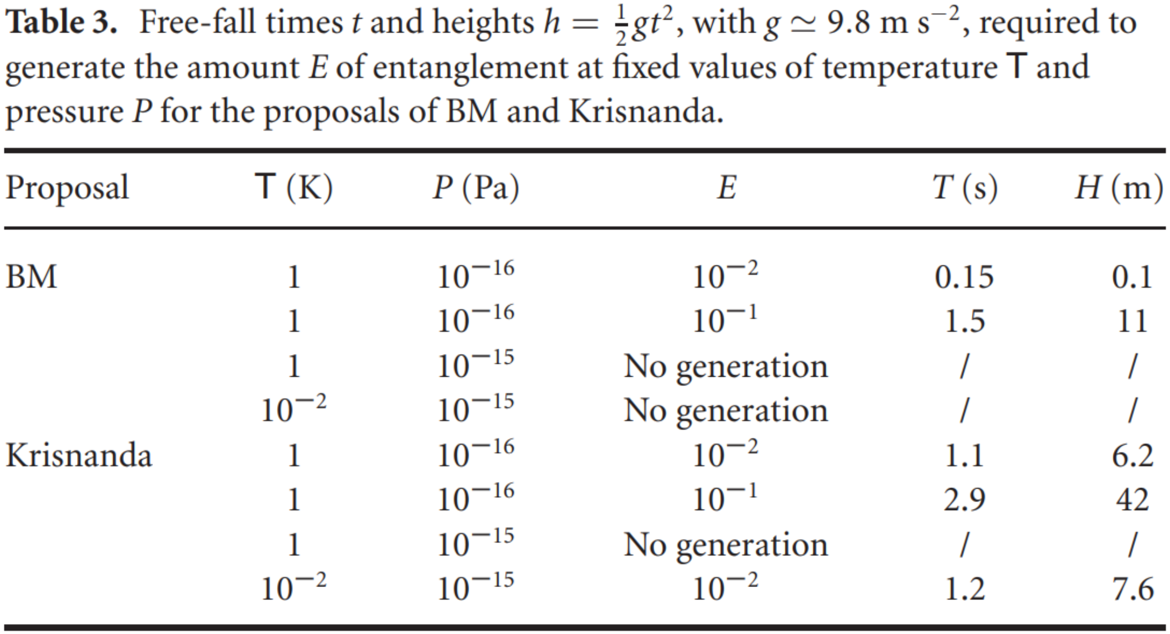


Table 3. Free-fall times t and heights $h = \frac{1}{2}gt^2$, with $g \simeq 9.8$ m s^{-2}, required to generate the amount E of entanglement at fixed values of temperature T and pressure P for the proposals of BM and Krisnanda.

Proposal	T (K)	P (Pa)	E	T (s)	H (m)
BM	1	10^{-16}	10^{-2}	0.15	0.1
	1	10^{-16}	10^{-1}	1.5	11
	1	10^{-15}	No generation	/	/
	10^{-2}	10^{-15}	No generation	/	/
Krisnanda	1	10^{-16}	10^{-2}	1.1	6.2
	1	10^{-16}	10^{-1}	2.9	42
	1	10^{-15}	No generation	/	/
	10^{-2}	10^{-15}	10^{-2}	1.2	7.6

S. Rijavec+, New J. Phys. **23**, 043040 (2021)

What is the Best Oscillator?

- We computed the amount of entanglement for arbitrary quadratic potential
- Hamiltonian

$$H = \sum_{i=1,2}\left(\frac{p_i}{2m} + \frac{1}{2}k_i x_i^2\right) + \frac{Gm^2}{d^3}(x_1 - x_2)^2$$

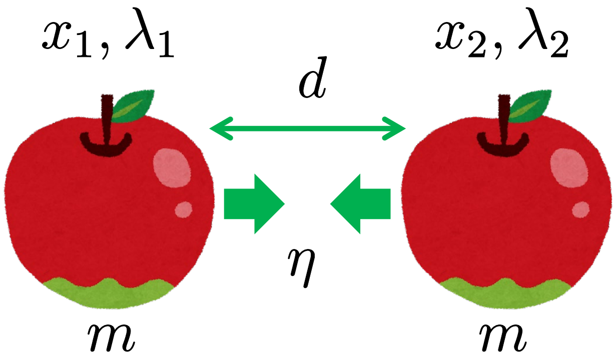
$$= \frac{\omega}{2}\left[\sum_{i=1,2}(P_i + \lambda_i X_i^2) + \eta(x_1 - x_2)^2\right]$$

Distance between masses

Sign of potential
+1 for harmonic
0 for free-falling
-1 for inverted

Strength of gravitational coupling

$$\eta = \frac{2Gm}{\omega^2 d^3}$$



T. Fujita, Y. Kaku, A. Matsumura, YM, arXiv:2308.14552

Inverted Oscillators are the Best

- Logarithmic negativity when $\lambda \equiv \lambda_1 = \lambda_2$

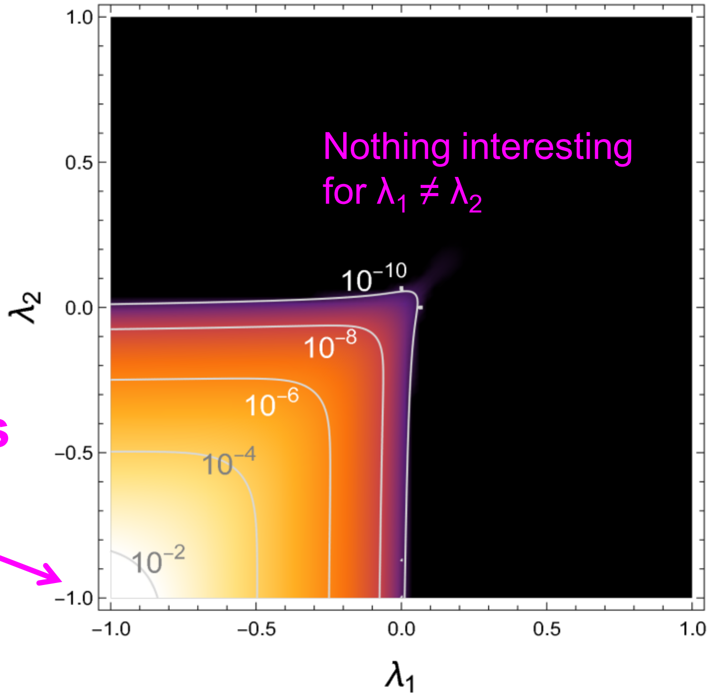
$$E_N \simeq 3[\eta f_{\rm gra}(t) - \mu f_{\rm dec}(t)]$$

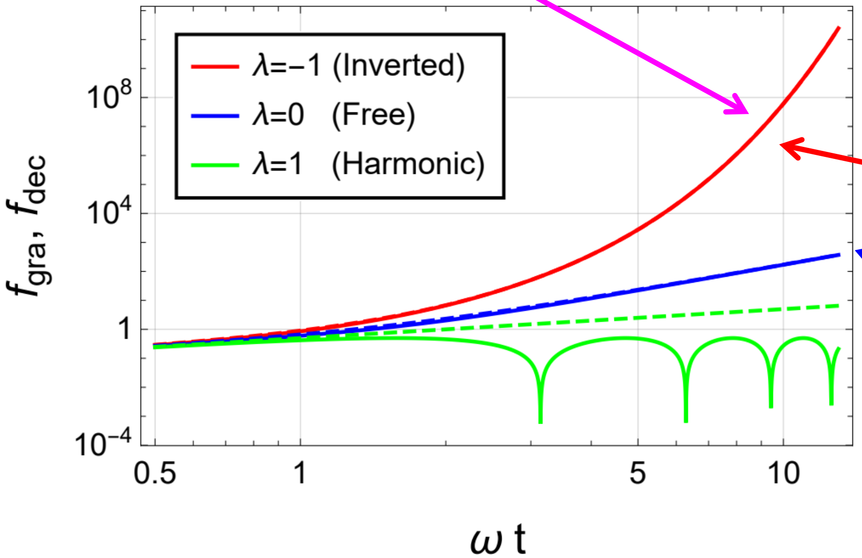
Strength of gravitational coupling

Amount of decoherence

Exponential growth of entanglement

Inverted oscillators are the best


Nothing interesting for $\lambda_1 \neq \lambda_2$



$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8} e^{2\omega t}$$

$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8} (\omega t)^3$$

$$f_{\rm gra}(t) \simeq \frac{1}{2} |\sin(\omega t)|, \ f_{\rm dec}(t) \simeq \frac{1}{2} \omega t$$

Preparing Inverted Oscillators

- Optical anti-spring with detuned cavity
  - Higher power is required for more anti-spring
  - Radiation pressure fluctuation will be a decoherence source
  - In the end, you get

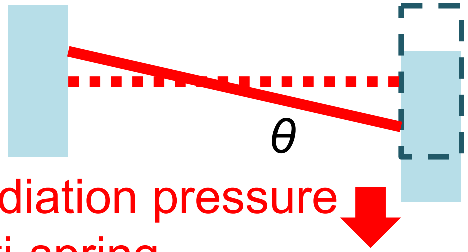
$$\mu_{\mathrm{shot}} = \frac{\kappa}{|\Delta|}$$

Cavity decay rate

Detuning

  - Hard to make this small (we need like $\mu \ll 10^{-13}$)

- Anti-spring in transversal motion
  - Decoherence μ_{shot} is suppressed by θ^2, where θ is cavity axis tilt
  - Transversal motion can be measured by wavefront sensor



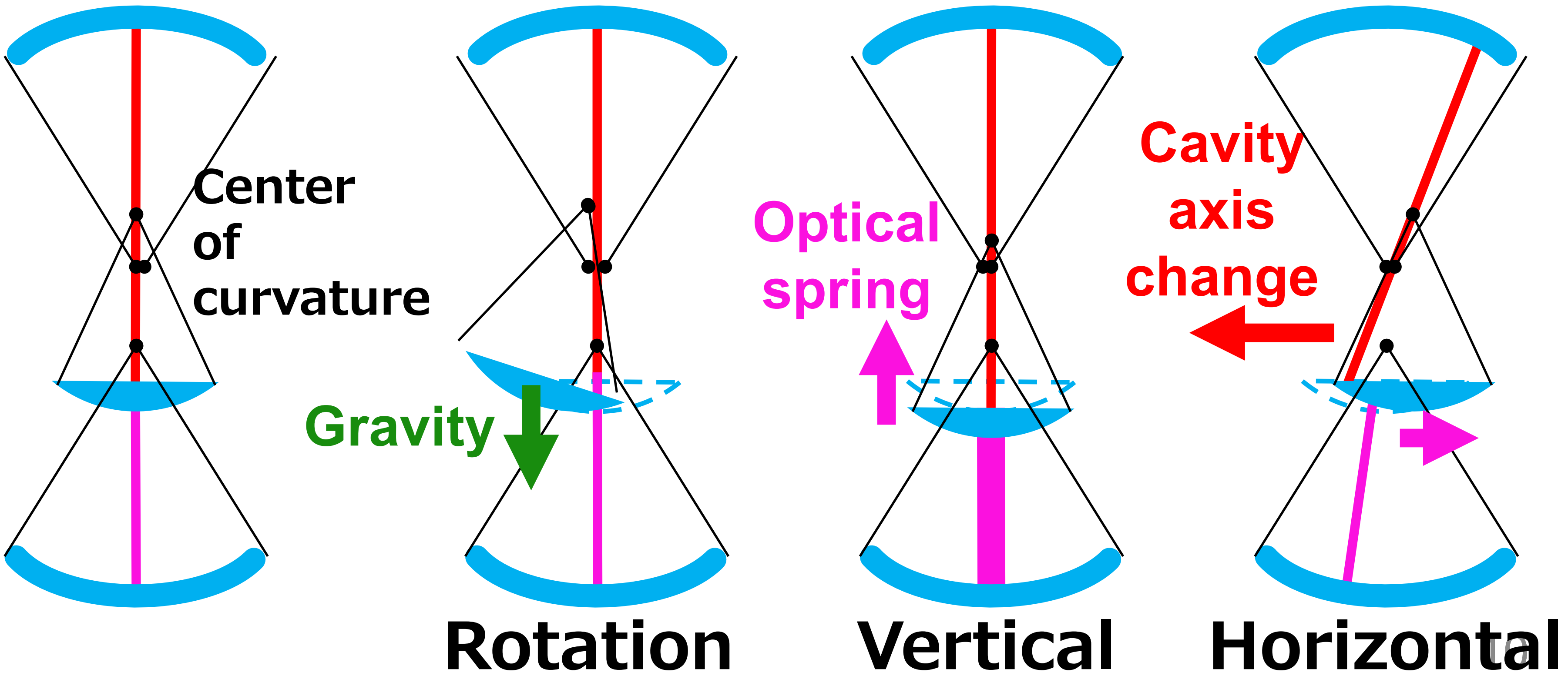
Sandwich Optical Levitation

- Proposed configuration to trap a mirror all optically

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

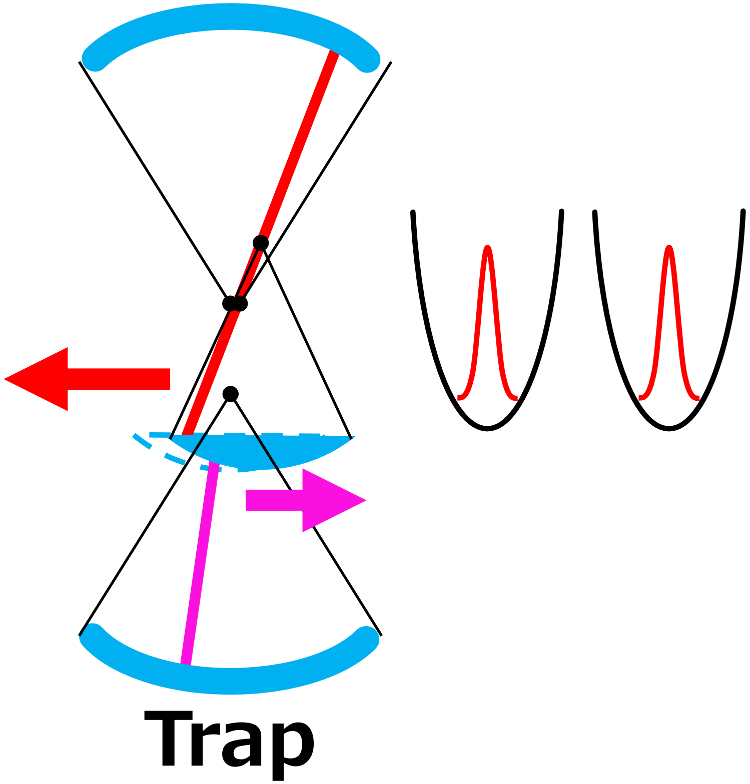
- Trap in transversal motion demonstrated

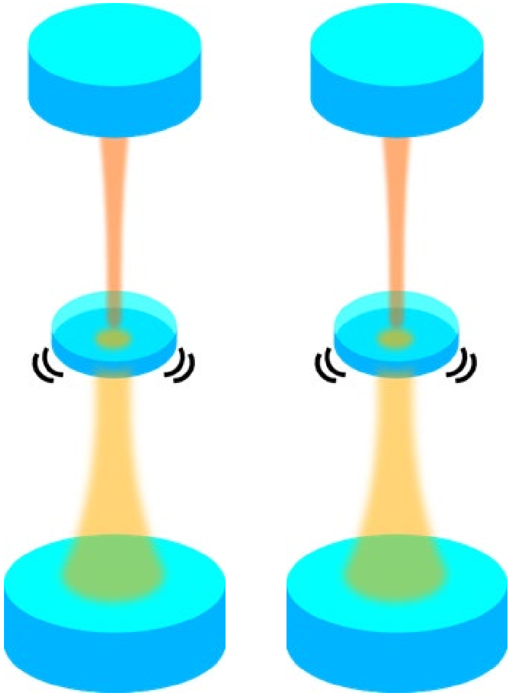
T. Kawasaki+, [PRA 102, 053520 (2020)]



Procedure to Switch the Trap

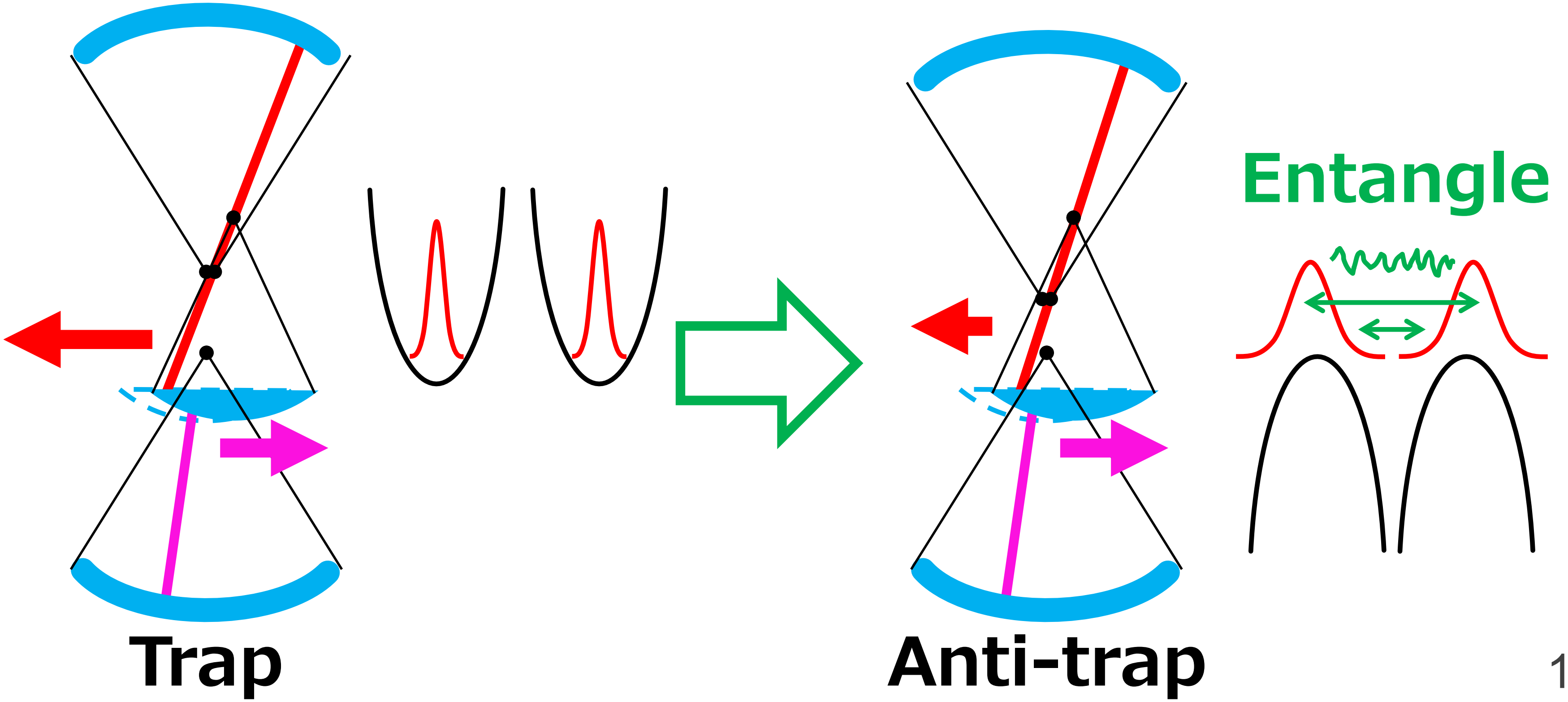
- First, trap strongly to prepare narrow wavefunctions





Procedure to Switch the Trap

- First, trap strongly to prepare narrow wavefunctions
- And then switch to anti-trap to broaden the wavefunction fast (this can be done by effectively switching the cavity geometry)



Example Setup

- To prepare 1 kHz anti-spring for 0.1 mg mirror

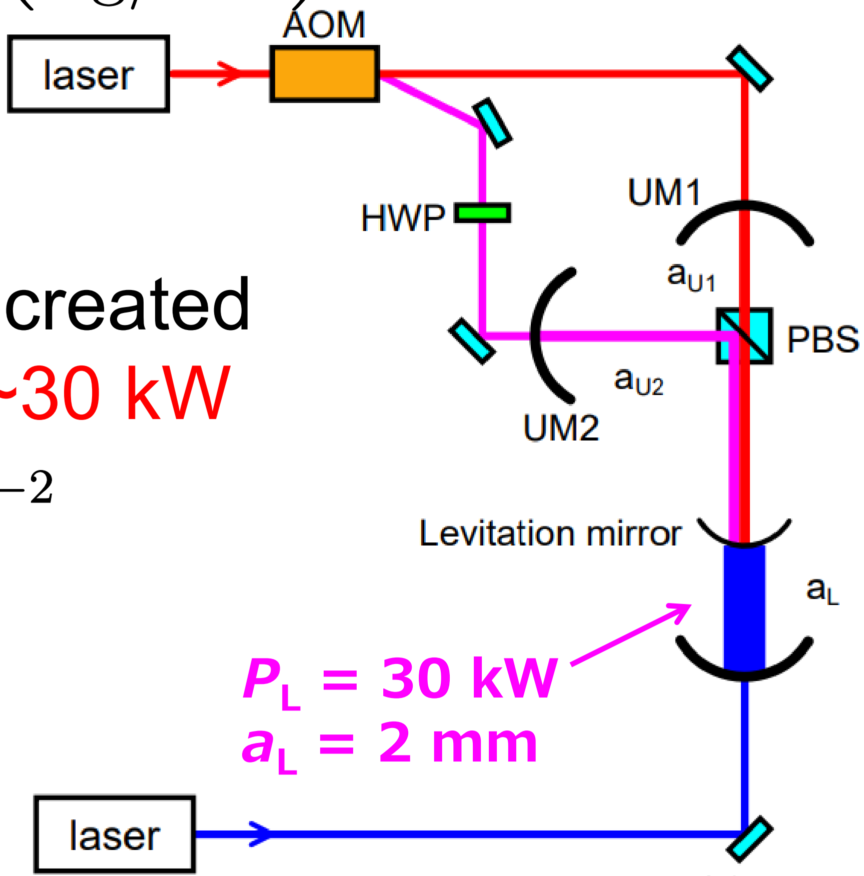
$$\mu << \eta = 2.7 \times 10^{-13} \omega_{\mathrm{kHz}} \left(\frac{m/d^3}{2\,\mathrm{g/cm^3}} \right)$$

- Requires T < ~1 K and P < ~10^{-17} Pa (as usual)
- ~1 kHz anti-spring can be created with intra-cavity power of ~30 kW
- Time to generate $E_N = 10^{-2}$

$$\tau_{\mathrm{ent}} = 4.2 \omega_{\mathrm{kHz}}^{-1/3}\,\mathrm{sec}$$ for free-fall

⬇ *300 times faster*

$$\tau_{\mathrm{ent}} = 1.3 \times 10^{-2} \omega_{\mathrm{kHz}}^{-1/3}\,\mathrm{sec}$$ for inverted



P_L = 30 kW
a_L = 2 mm

Is Fast Good?

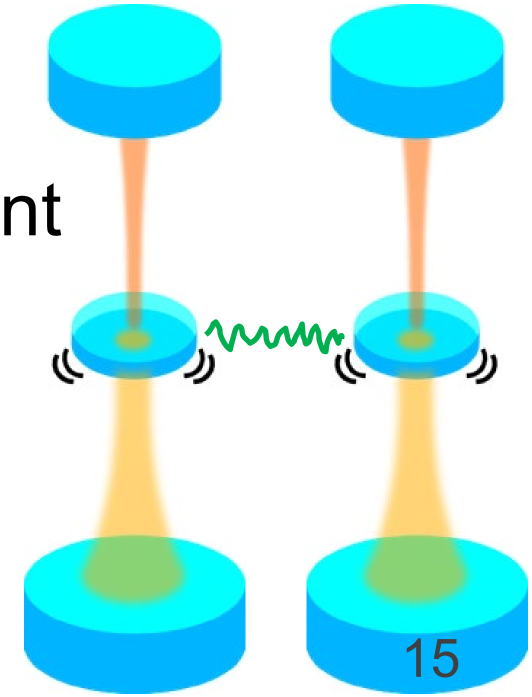
- The process can be repeated multiple times
  - Also, now that the oscillator is not free-falling, height is not required, and repeatable
- Air pressure requirement could be relaxed
  - Entanglement speed is so fast that no molecule will hit the oscillator during the measurement time
  - Mean free time of the scattering

$$\tau_{\mathrm{air}} = 0.64\,\mathrm{sec}\left(\frac{R}{0.2\,\mathrm{mm}}\right)^{-2}\left(\frac{p}{10^{-17}\,\mathrm{Pa}}\right)^{-1}\left(\frac{T}{1\,\mathrm{K}}\right)^{-1/2}$$

  - More rigorous study necessary for treating random force under extremely low pressure

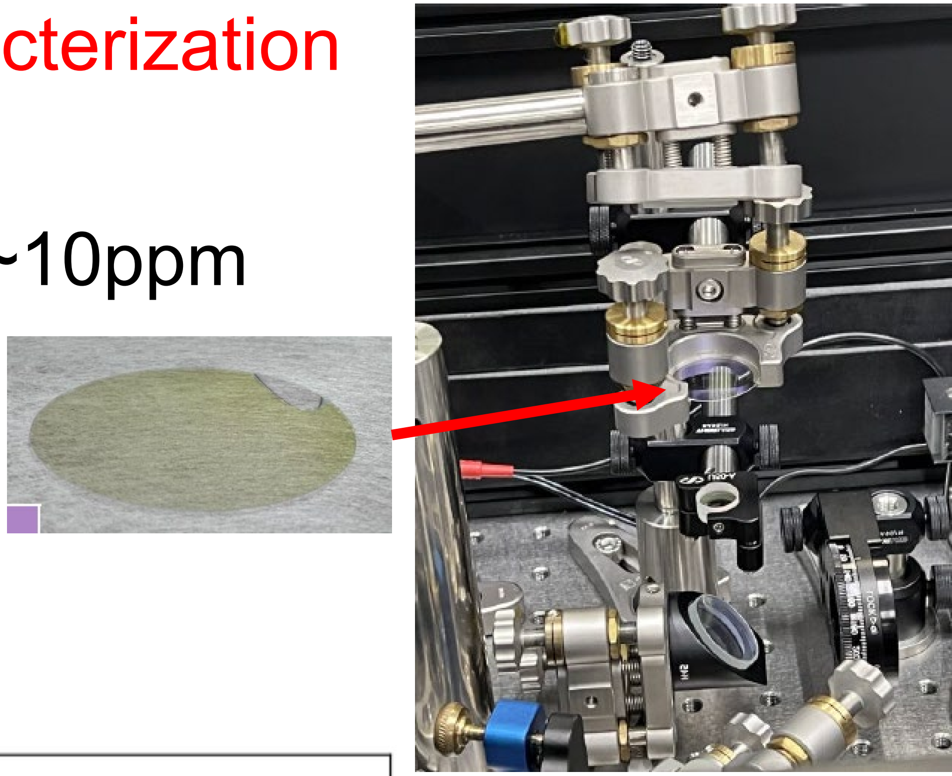
Summary

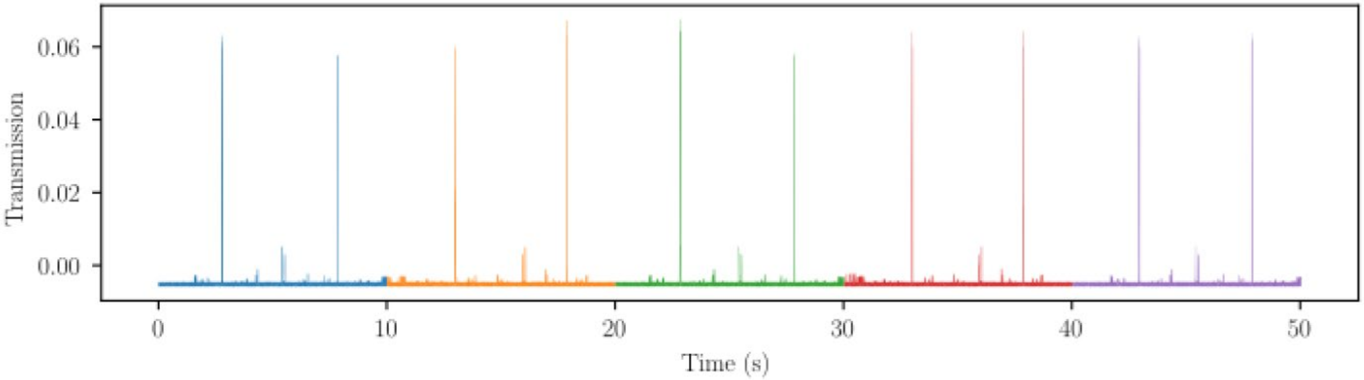
- We want to test quantum nature of gravity by gravity-induced quantum entanglement
- Inverted oscillators are most efficient
  - Generate gravity-induced entanglement exponentially
  - Most resistant to decoherence
- Optical levitation with sandwich configuration is convenient to realize such experiments



Updates on Levitation Mirrors

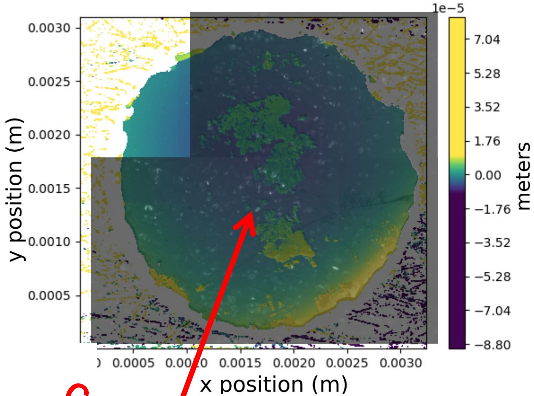
- Chenyue Gu from Ping Koy Lam’s Group visited UTokyo for mirror characterization
- Using cavity scan
- φ1 inch, 25 um thick, T~10ppm
  RoC measured to be
    -250 ± 50 mm in X
    -580 ± 280 mm in Y

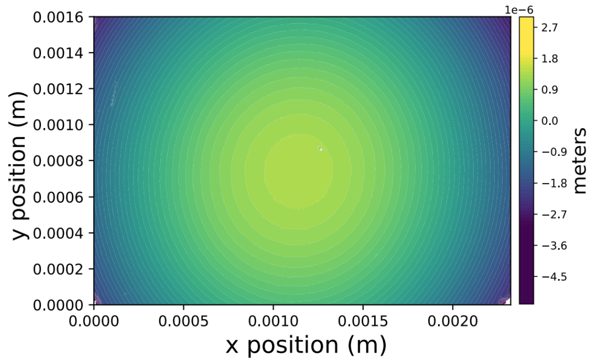




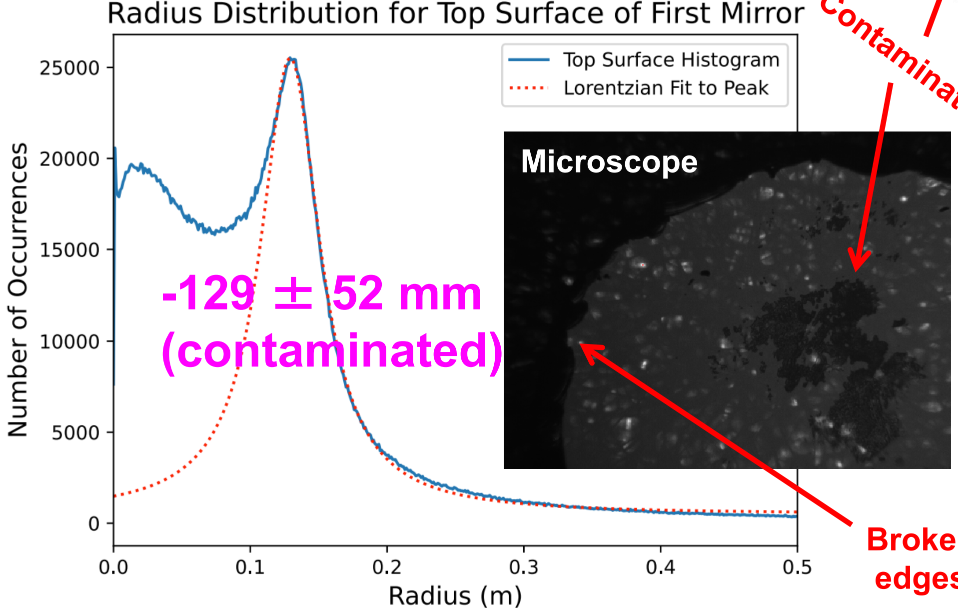
Updates on Levitation Mirrors

- Giovanni Guccione’s team continues to characterize in ANU (both φ1inch and φ3 mm ones)
- RoC of φ3 mm measured with white-light interferometer



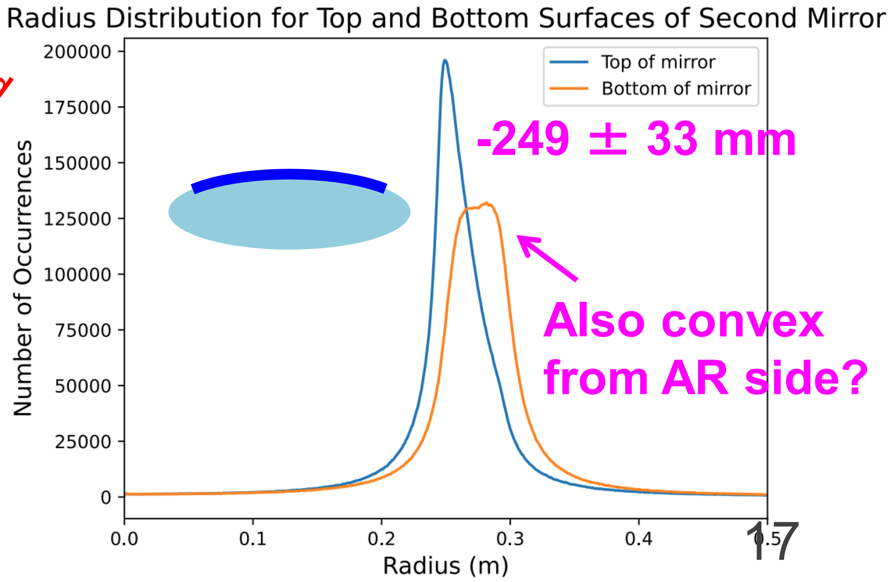


Contaminated



-129 ± 52 mm (contaminated)

Broken edges



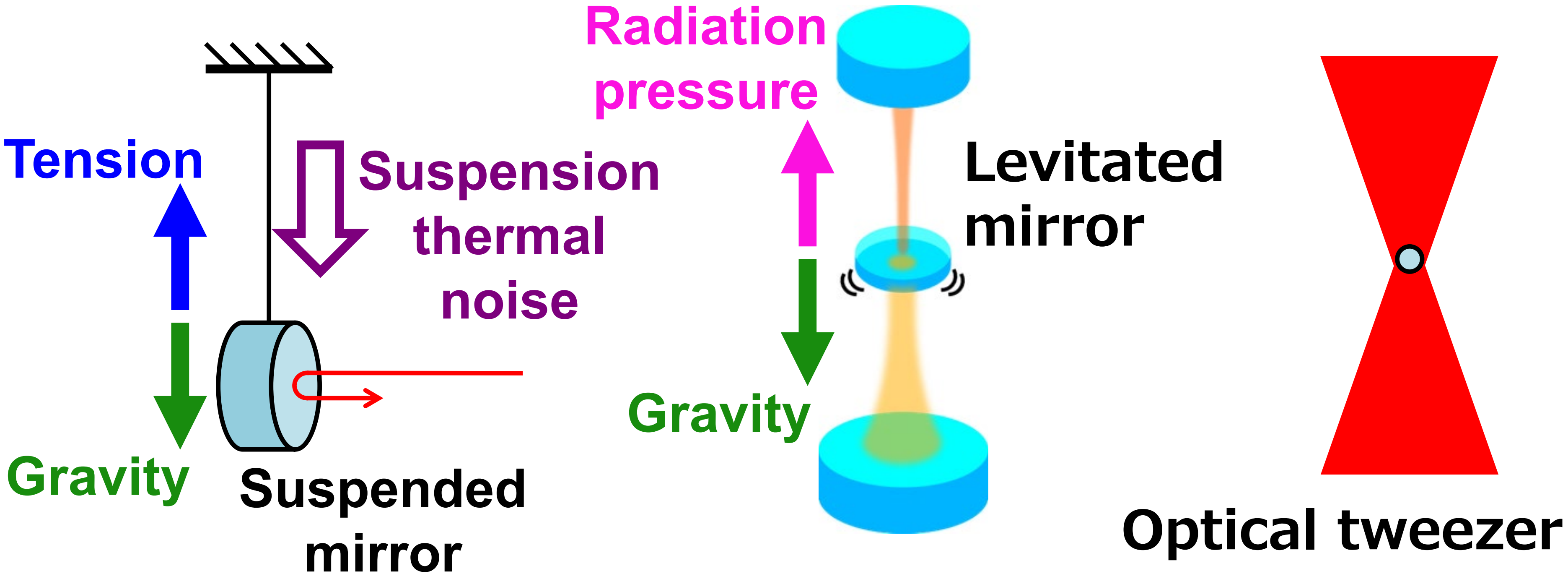
-249 ± 33 mm

Also convex from AR side?

Bonus Slides

Optical Levitation of Mirror

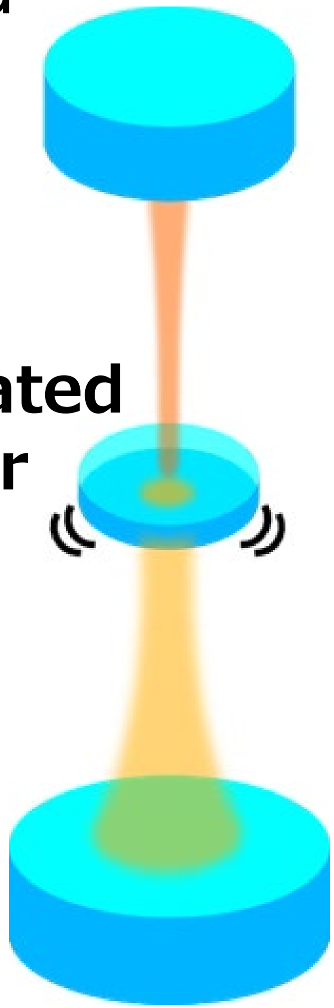
- Support a mirror with radiation pressure alone
- Free from suspension thermal noise
- Large coupling compared with optical tweezers



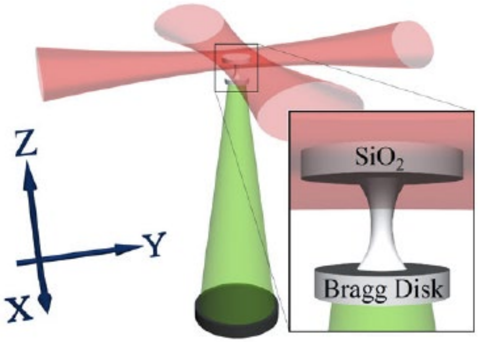
Sandwich Configuration

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

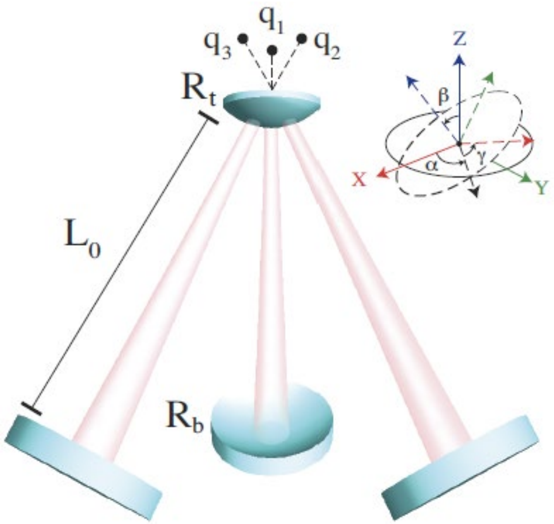
  YM, Y. Kuwahara+, Optics Express 25, 13799 (2017)
- Proved that stable levitation is possible and SQL can be reached with 0.2 mg mirror



Levitated mirror



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

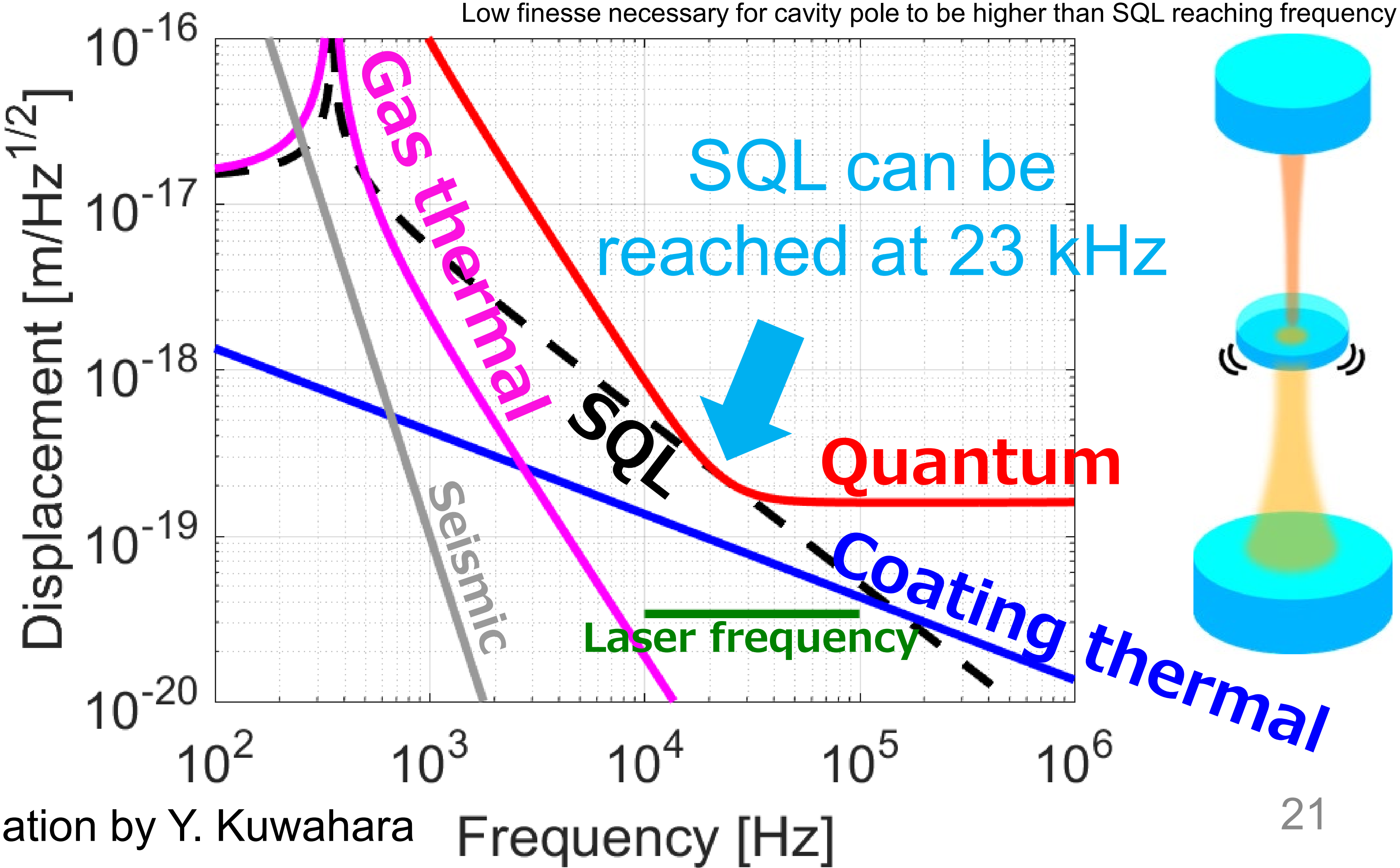


G. Guccione+: PRL 111, 183001 (2013)

Reaching SQL

- Constraint on design: intra-cavity power to support the mass
- 0.2 mg fused silica mirror, Finesse of 100, 13 W + 4 W input

Low finesse necessary for cavity pole to be higher than SQL reaching frequency



SQL can be reached at 23 kHz

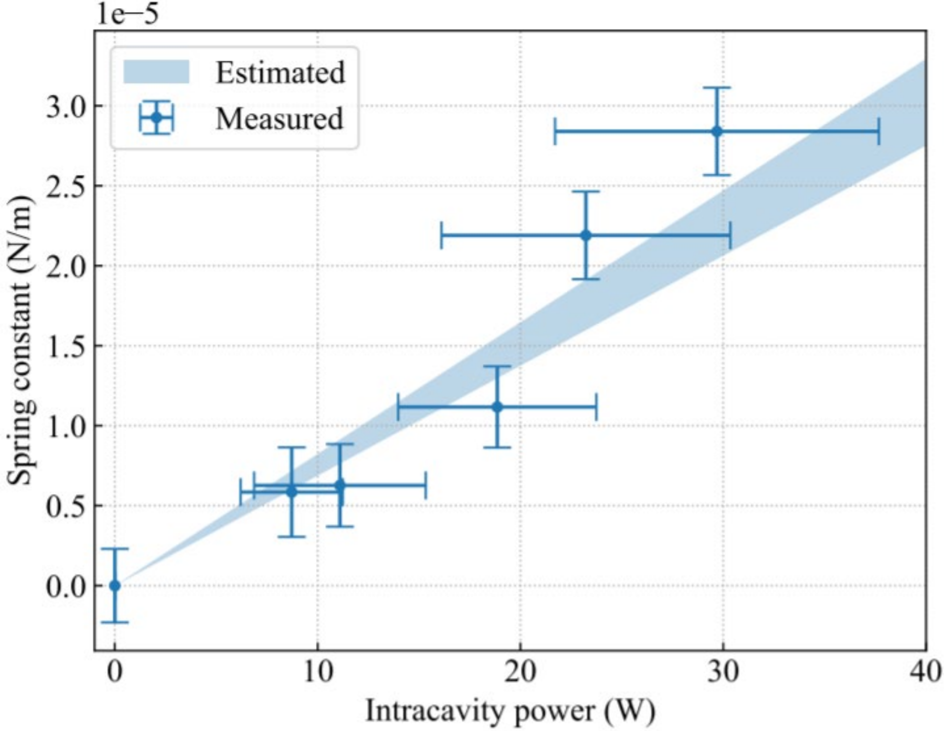
Calculation by Y. Kuwahara

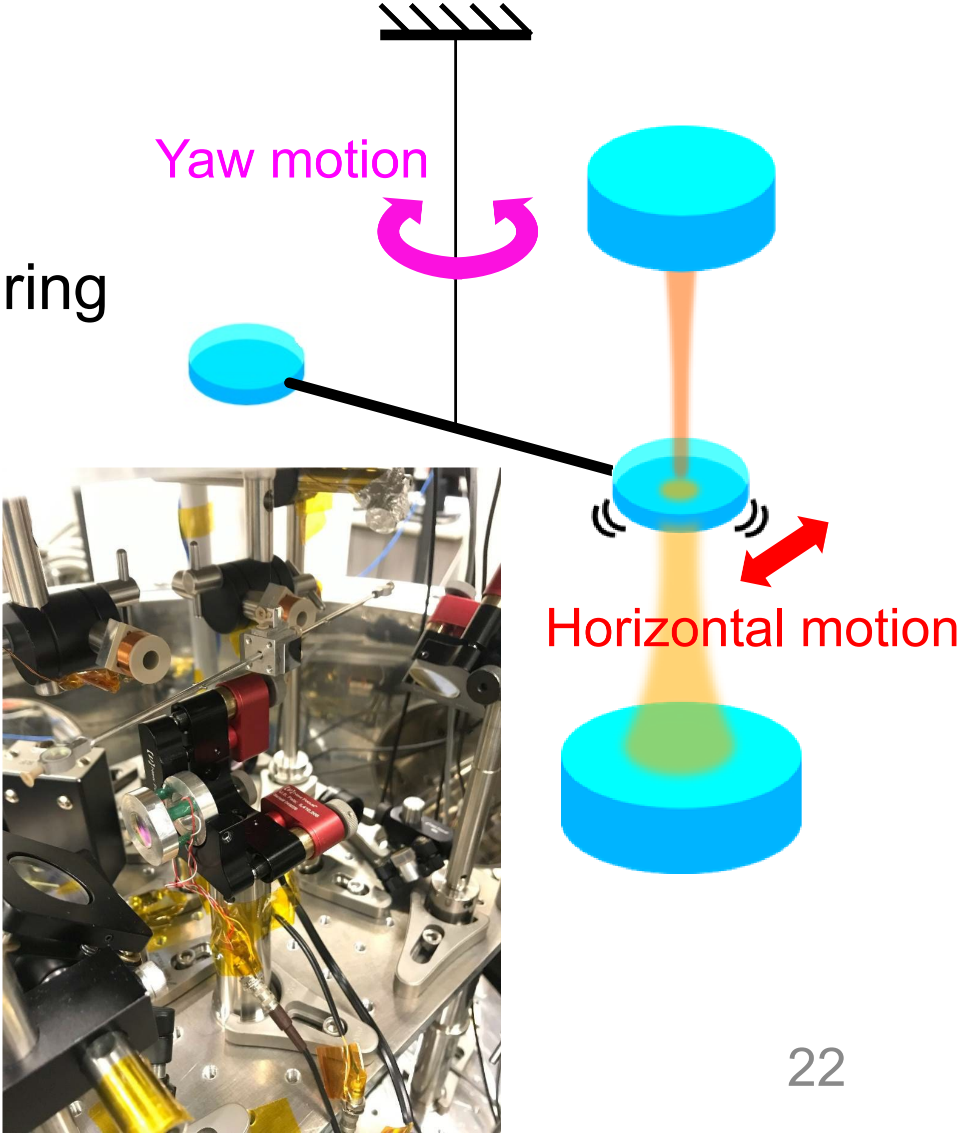
Experiment to Verify the Stability

- Verified the stability with a torsion pendulum and a dummy mirror

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

Measured optical geometrical spring agreed with expectation





Fabrication of Levitation Mirrors

- mg and mm-scale curved mirror necessary

  e.g. For levitation demonstration

  φ 3 mm, 0.1 mm thick (~1.6 mg for fused silica)

  RoC = ~30 mm convex

  R > 99.95 %

- Two approaches

  1. Coat thin fused silica mirror to bend the mirror
  2. Photonic crystal mirror to create effective curvature

mark optics
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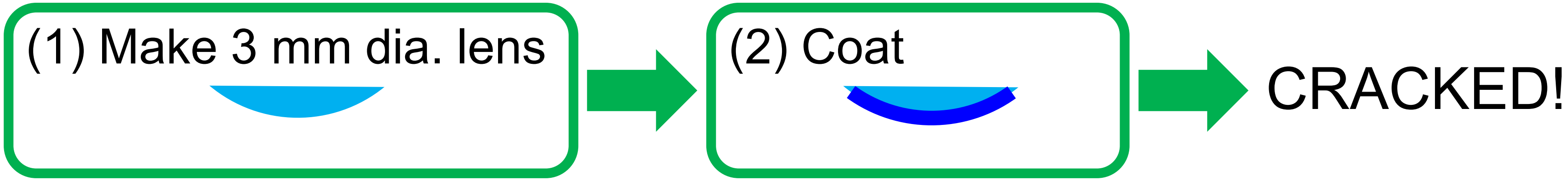
New Approach for Fused Silica

2014 Approach

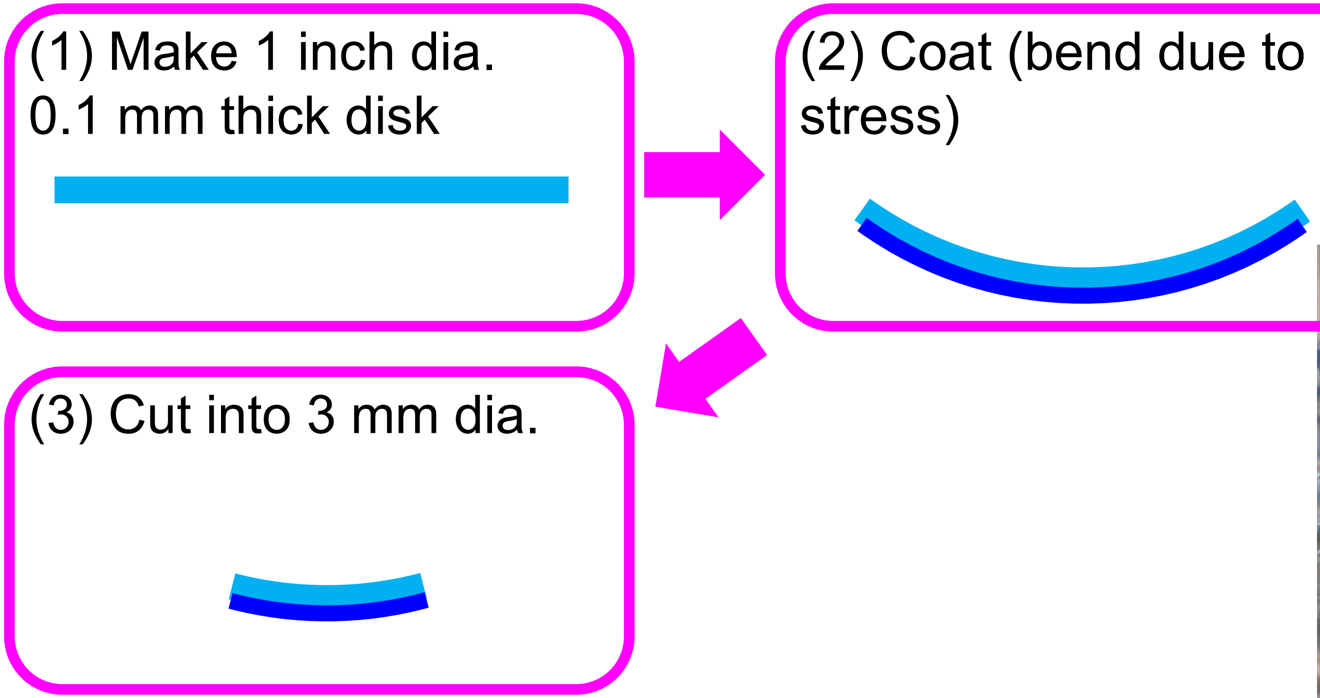


(1) Make 3 mm dia. lens

(2) Coat

CRACKED!

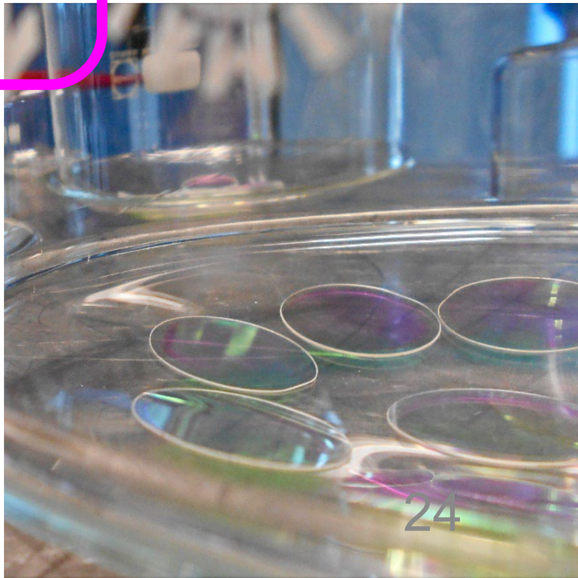
2020-2021 Approach



(1) Make 1 inch dia.
0.1 mm thick disk

(2) Coat (bend due to stress)

(3) Cut into 3 mm dia.



Thin Fused Silica Mirror Updates

- Sep 2020: R>~90% φ1 inch mirrors arrived
  - Two samples, measured to be
    (1) R=92(1)%, RoC=500^{+2000}_{-200} mm
    (2) R=88(1)%, RoC=400^{+800}_{-200} mm
  - Somehow concave, although convex is expected
    probably we measured flipped mirror

No AR coating yet

- Jan 2021: T=10ppm φ1 inch mirrors arrived
  - Expected to have RoC of -450 mm

~6 um thick coating

- June 2021: Cut T=10ppm φ3 mm mirrors arrived
  - 27 remained
  - cleaning of the protective layer wasn't great
    & many broke during the process

Coating thickness x2
-> RoC x~1/2
Substrate thickness x1/4
-> RoC x~1/16
-> Diameter x2

- Oct 2021: φ1 inch 25 um thick wafers arrived
- Jan 2022: Coating made it like a Pringles