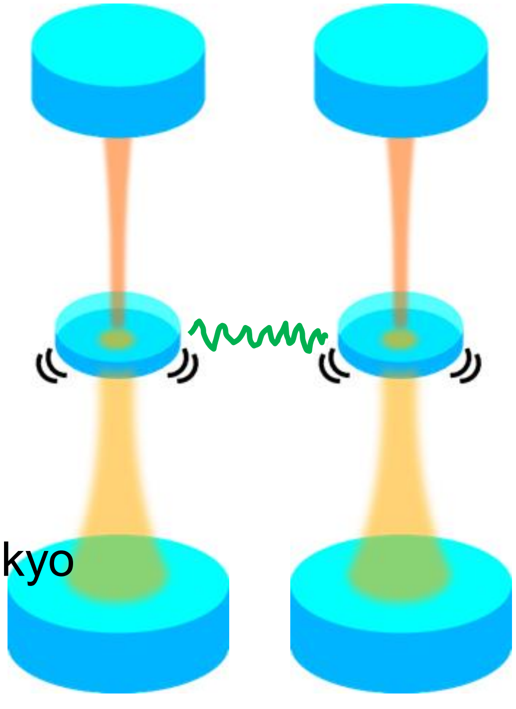
First NEXUS Workshop on Levitated Systems @ UTokyo April 21, 2026

Probing the quantum nature of gravity with levitated mirrors



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NEXUS Japan-Singapore

- Joint call from JST and A*STAR
- Period: April 2026 – March 2029
- 先進的な防振技術による巨視的量子系の実現
  Enabling Macroscopic Quantum Systems through
  Advanced Vibration Damping Technology

Quantum Innovation Centre
A*STAR Q.InC

Japan side

Yuta Michimura (PI)

Kentaro Komori (Co-I)

Masaki Ando (Collaborator)

Singapore side

Tao Wang (PI)

Syed Muhamad Assad (Co-I)

Ping Koy Lam (Collaborator)

NEXUS 日ASEAN科学技術・イノベーション協働連携事業
Networked Exchange, United Strength for Stronger Partnerships between Japan and ASEAN

Workshop Participants from Japan

Ando Group UTokyo

- Masaki Ando
- Naoki Aritomi
- Ryosuke Sugimoto
- Tatsuya Sugioka
- Hinata Takidera

GW, Optomechanics

Aikawa Group UTokyo

- Takuya Kawasaki
- Sotatsu Otabe

Levitated nanoparticles

Somiya Group Institute of Science Tokyo

- Ryo Iden
- Kentaro Somiya
- Shilu Tian

GW, Optomechanics, Magnetic levitation

Michimura Group UTokyo

- Mizuki Honjo
- Ryuta Kataoka
- Kenzaburo Kawaguchi
- Yuta Michimura
- Shogo Okada
- Daiki Watarai

GW, Optical levitation

GW Project NAOJ 国立天文台 National Astronomical Observatory of Japan

- Marc Eisenmann
- Kentaro Komori
- Michael Page
- Yuheng Ye

GW, Metrology

Fujita Group Ochanomizu University

- Tomohiro Fujita

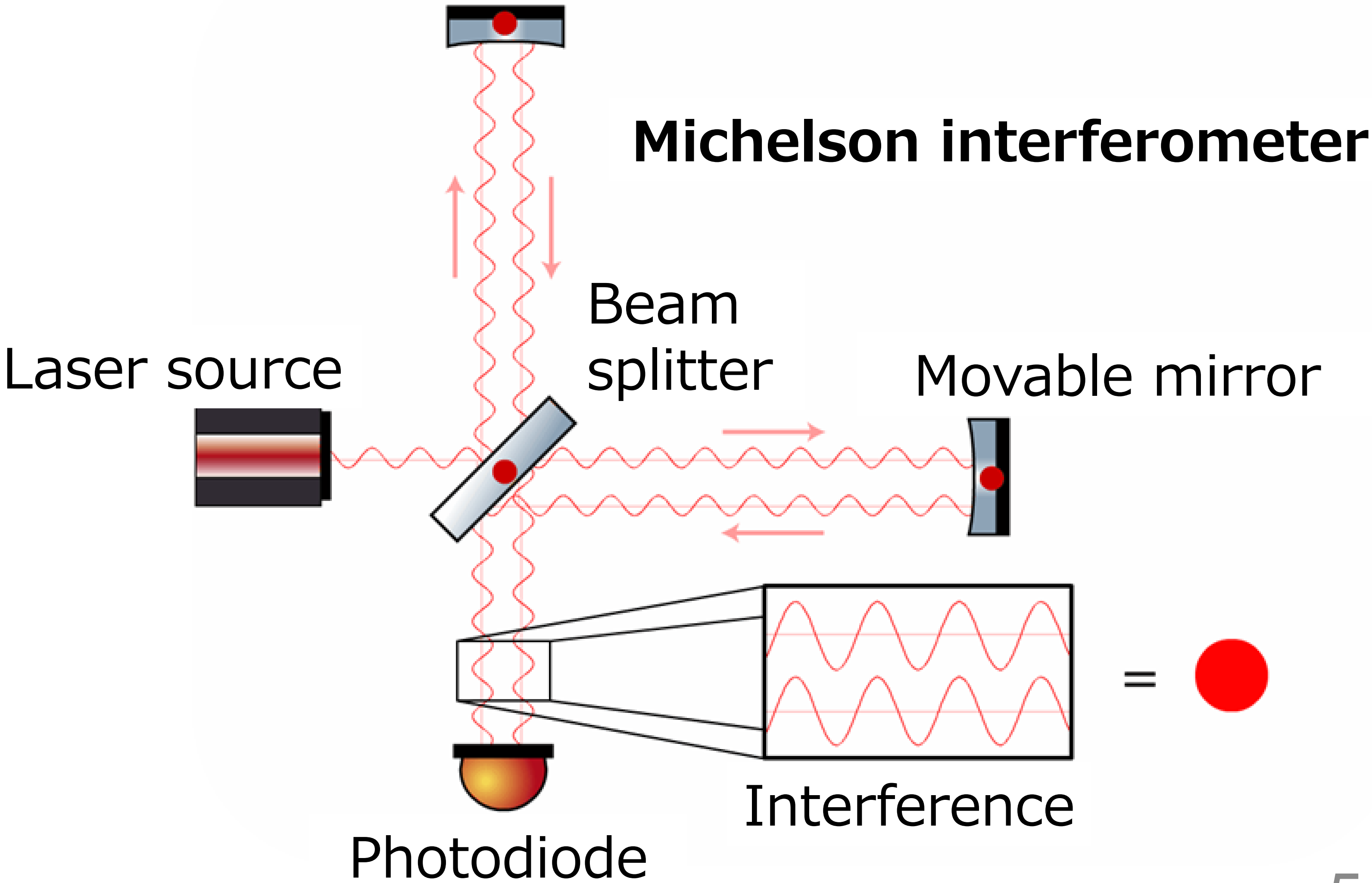
Cosmology, Quantum gravity

Plan of the Talk

- **Laser interferometry and optomechanics**
  - as a tool to probe quantum nature of gravity
- **Optical levitation of mirrors**
  - status of our experiment
- **Inverted oscillators for accelerating gravity induced entanglement generation**
  - T. Fujita, Y. Kaku, A. Matsumura, YM, CQG **42**, 165003 (2025)

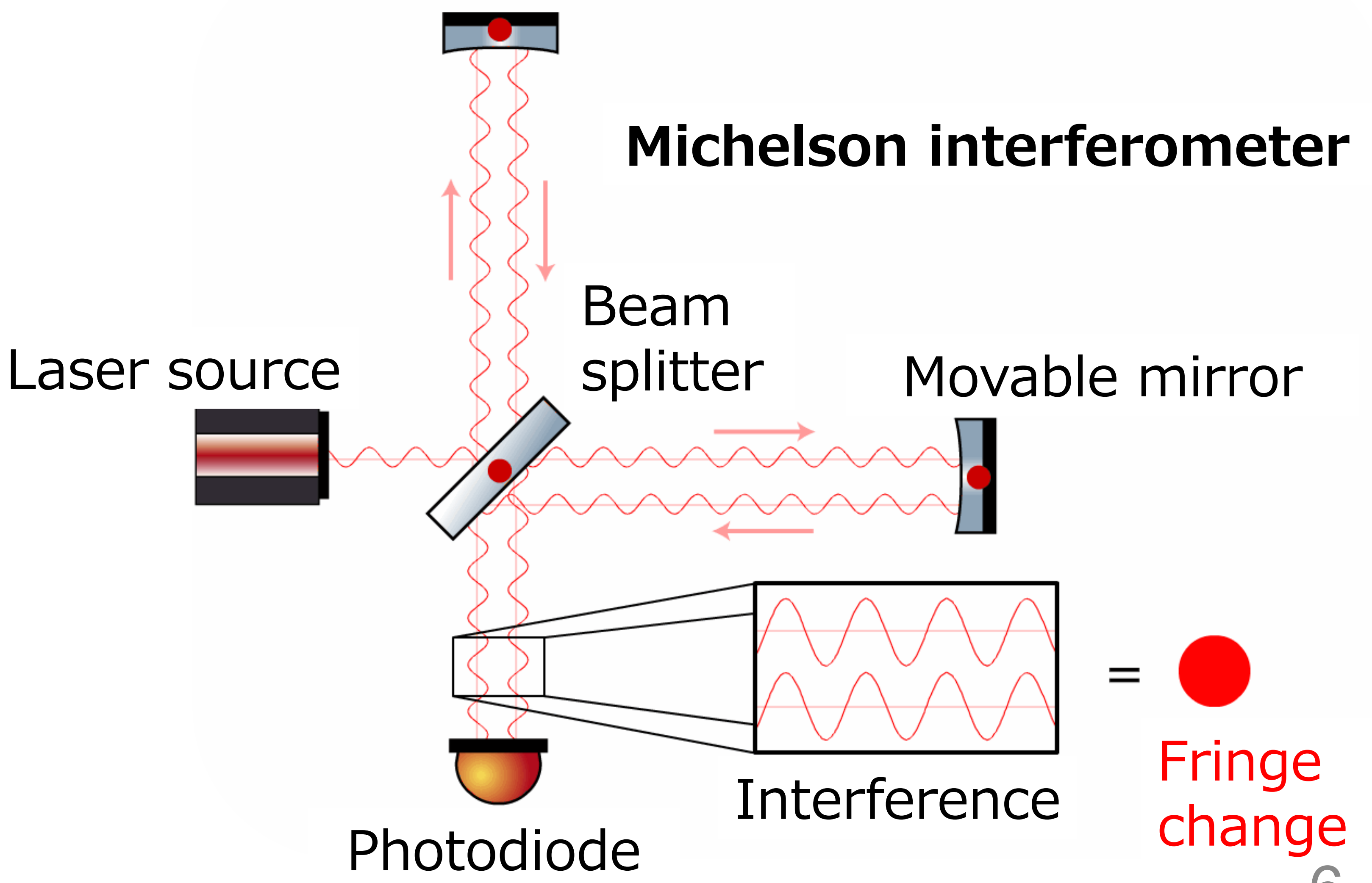
Laser Interferometry

- measures differential arm length change



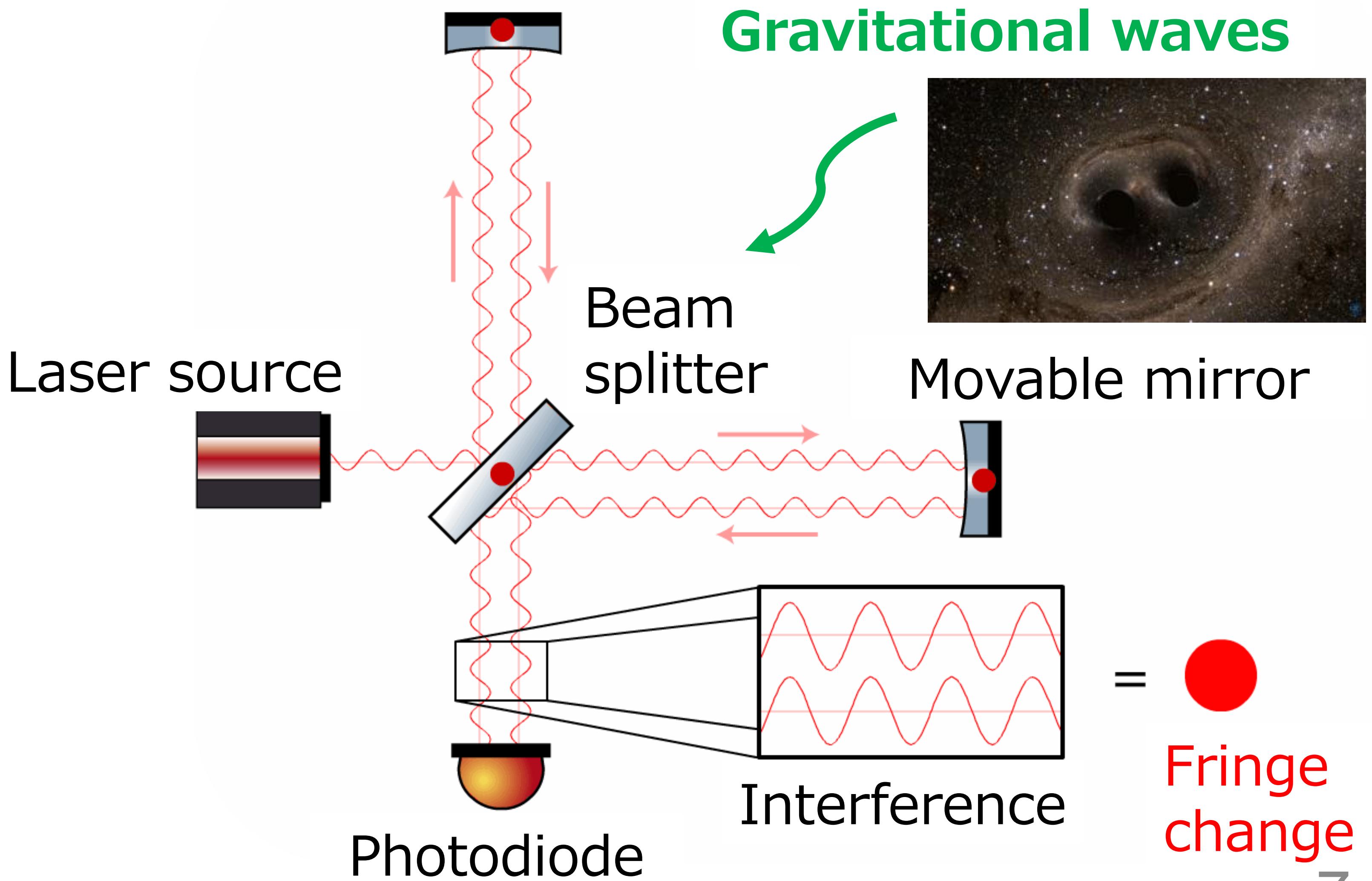
Laser Interferometry

- measures differential arm length change

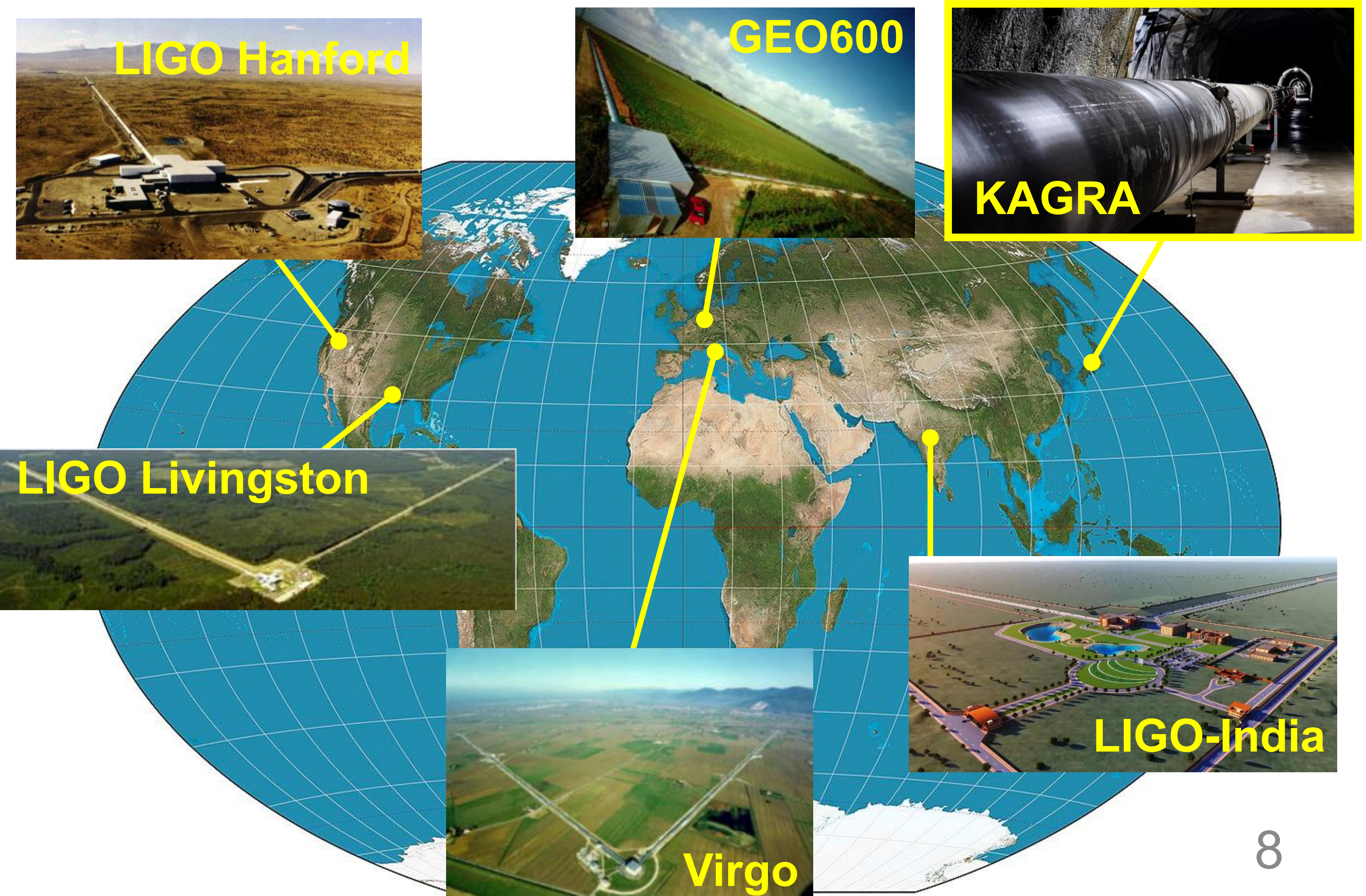


For Gravitational Waves

- measures differential arm length change

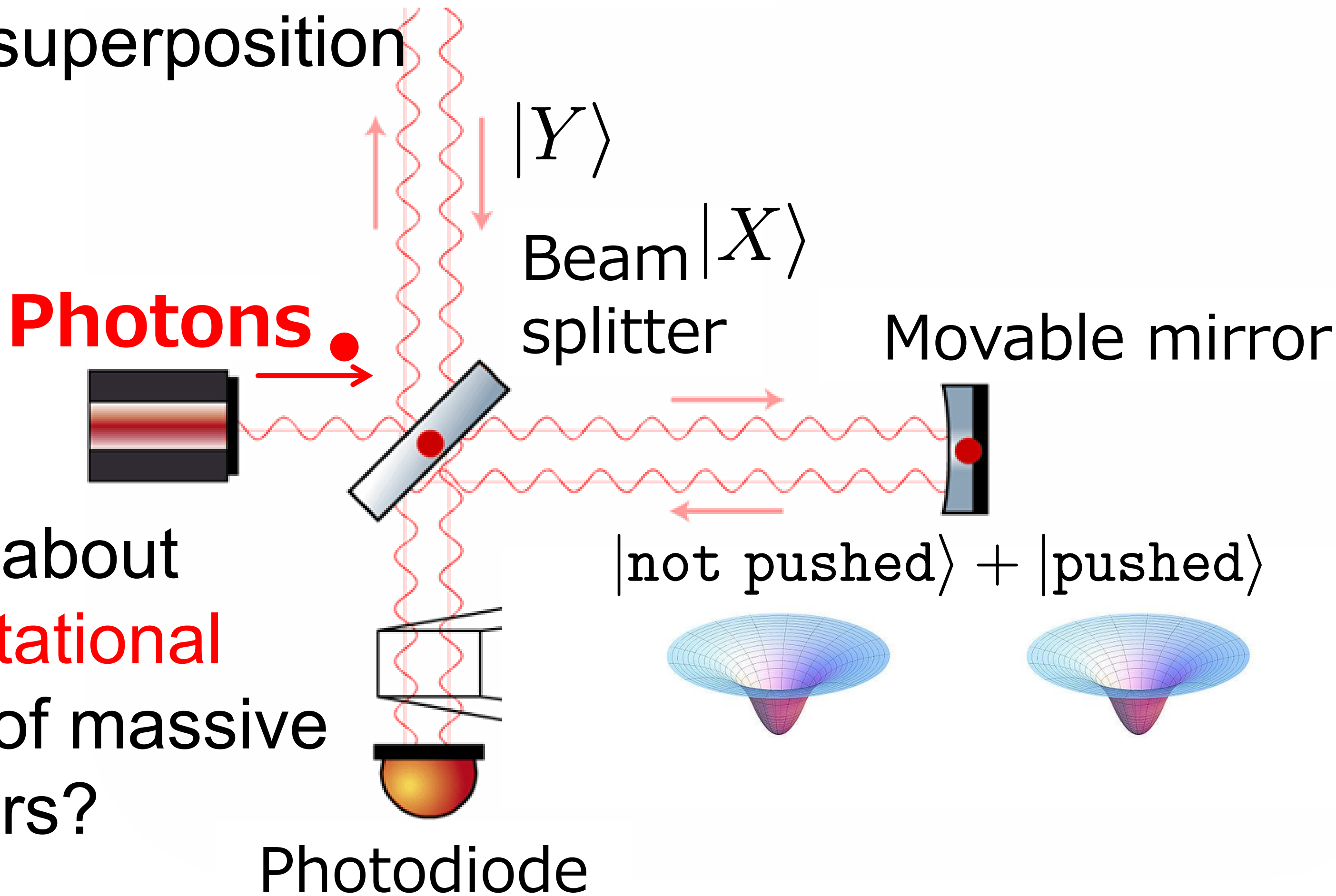


Laser Interferometric GW Detectors



As a Probe of Quantum

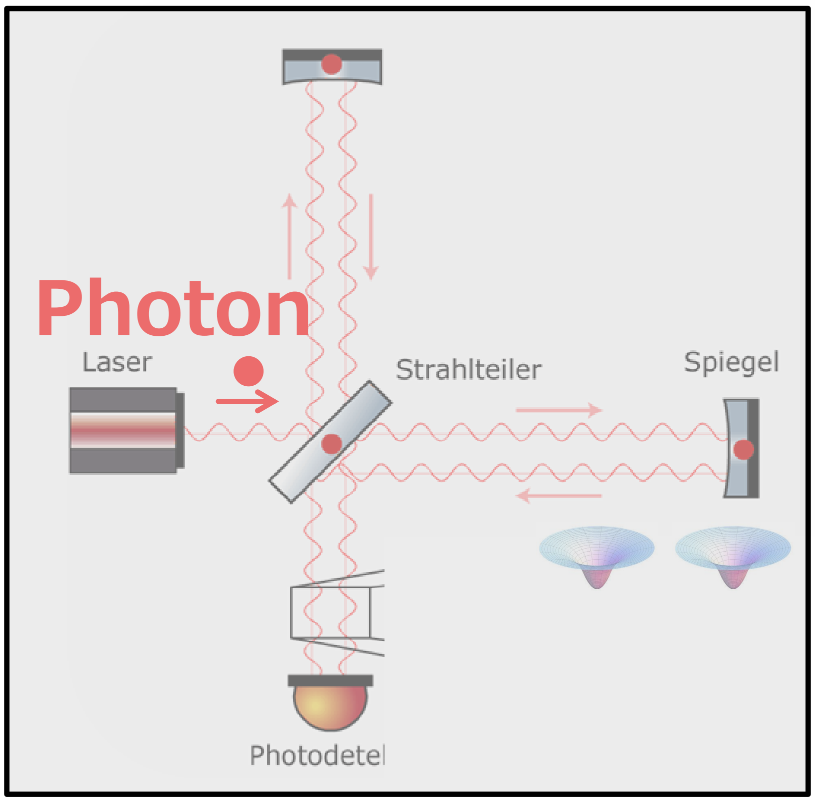
- Photon going to X or Y arm is in superposition
- Mirrors pushed or not pushed by radiation pressure is in superposition

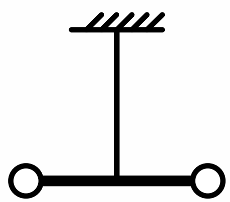


- How about gravitational field of massive mirrors?

Schrödinger's KAGRA

- If you put KAGRA in a box and bring a torsion pendulum close to one of its mirrors, will the torsion pendulum oscillate due to the mirror's gravity, not oscillate at all, or oscillate half???





Schrödinger's KAGRA

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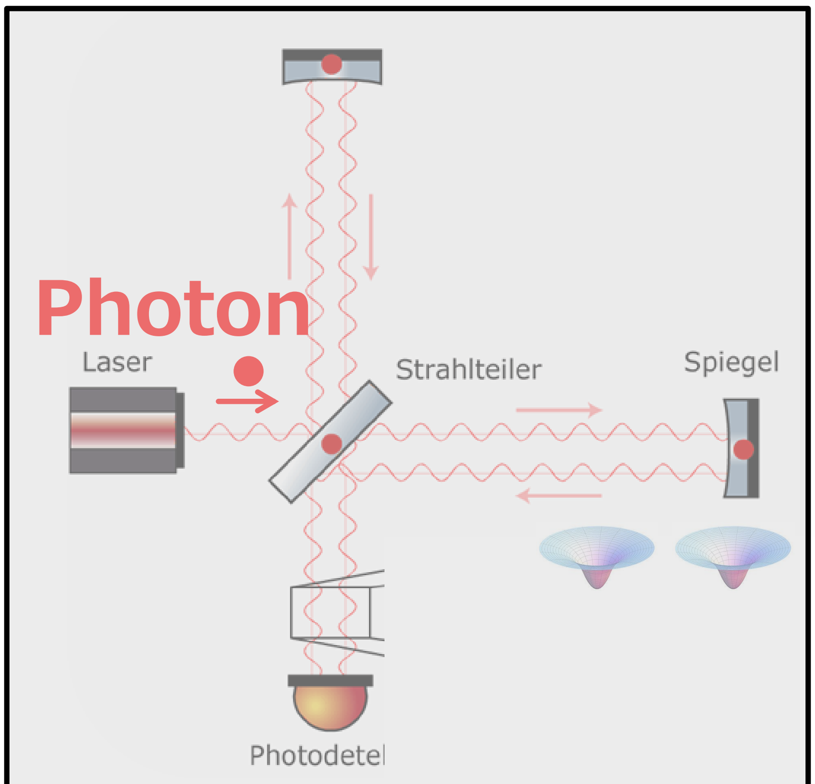
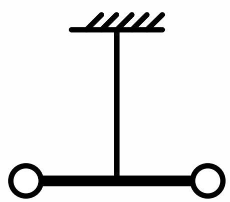


$$\nabla^2\Phi = 4\pi G\left\langle \begin{matrix}\text{Mass}\\ \text{distribution}\end{matrix} \right\rangle$$

Expectation value



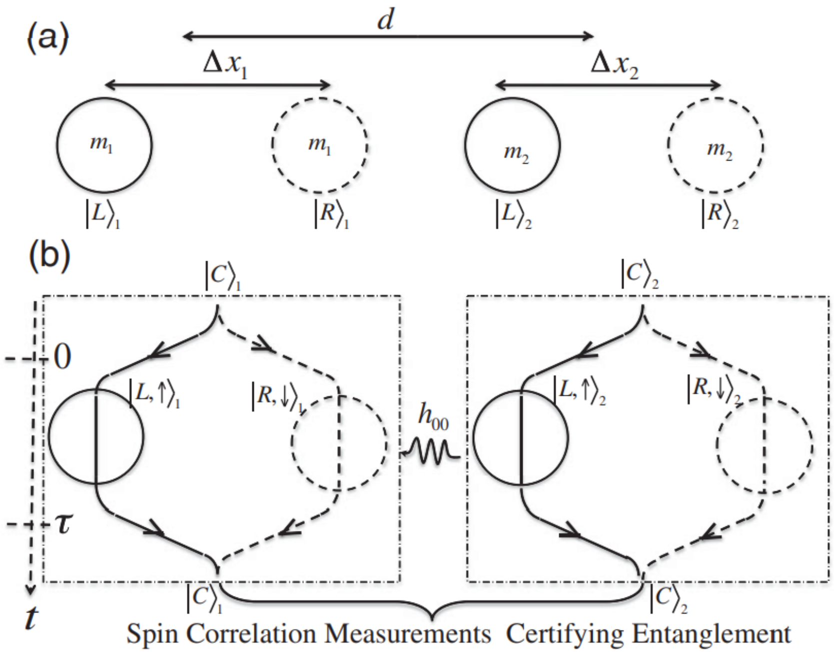
Semiclassical Gravity (Schrödinger-Newton model)

Very strange model, but not falsified experimentally

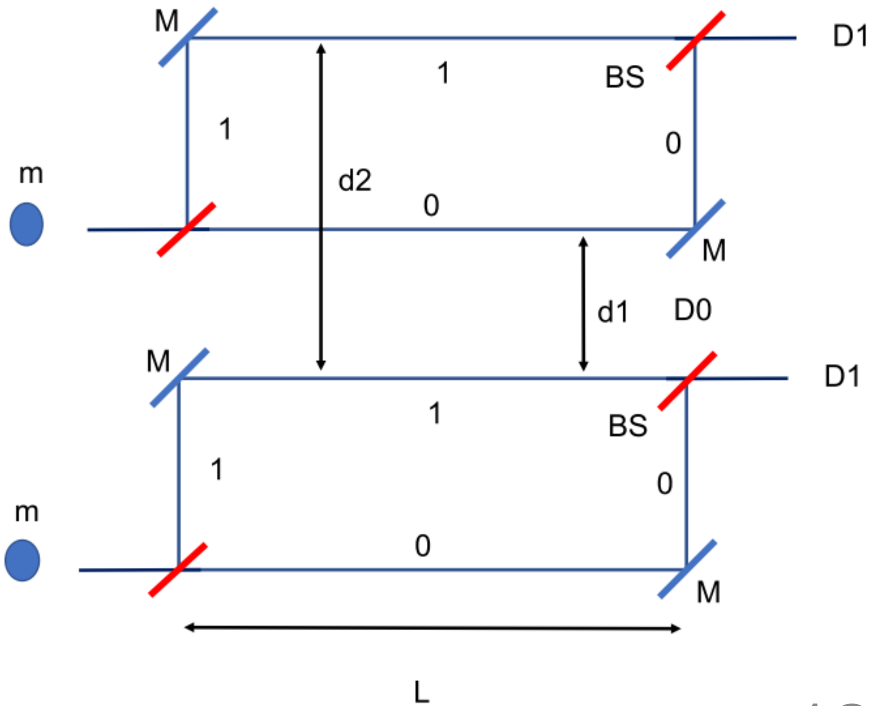
BMV Proposals

- Quantum nature of gravity can be tested by testing gravity-induced entanglement with adjacent matter interferometers

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



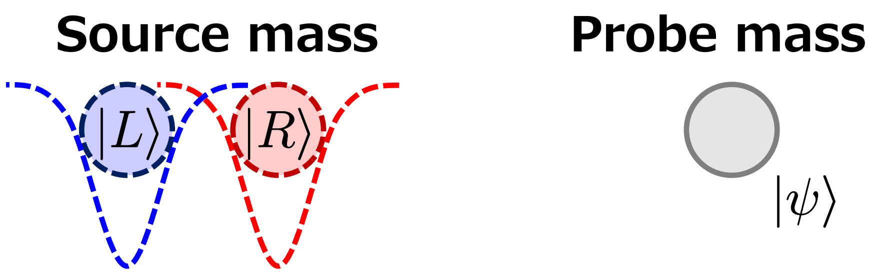
C. Marletto & V. Vedral,
[Phys. Rev. Lett. 119, 240402 (2017)]



Key Idea of BMV Proposals

- If gravity is quantum

$$\Phi(\hat{x}, \hat{X}) = -\frac{GM}{|\hat{x} - \hat{X}|}$$



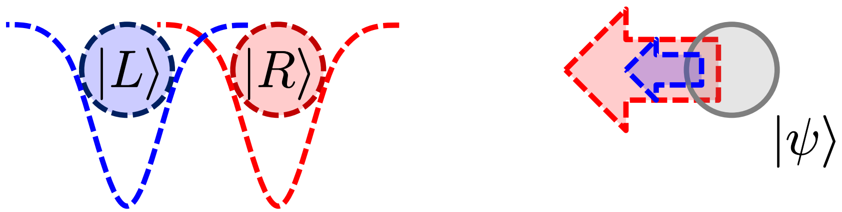
Newtonian potential act as an operator

Key Idea of BMV Proposals

- If gravity is quantum

$$\Phi(\hat{x},\hat{X}) = -\frac{GM}{|\hat{x}-\hat{X}|}$$

Source mass **Probe mass**



Newtonian potential act as an operator

$$e^{\frac{i}{\hbar}m\Phi(\hat{X})t}\frac{1}{\sqrt{2}}(|L\rangle+|R\rangle)\otimes|\psi\rangle$$

$$=\frac{1}{\sqrt{2}}\left(|L\rangle\otimes e^{i\phi_L}|\psi\rangle+|R\rangle\otimes e^{i\phi_R}|\psi\rangle\right)$$

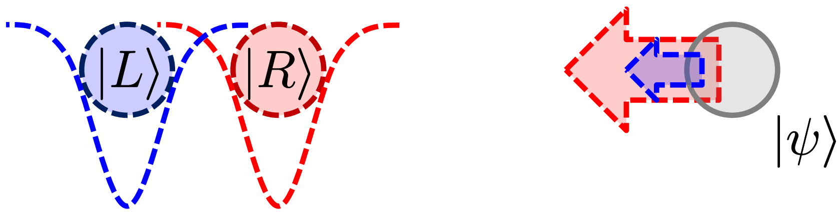
Gravity induced entanglement

Key Idea of BMV Proposals

- If gravity is quantum

$$\Phi(\hat{x}, \hat{X}) = -\frac{GM}{|\hat{x} - \hat{X}|}$$

Source mass **Probe mass**



Newtonian potential act as an operator

$$e^{\frac{i}{\hbar} m\Phi(\hat{X})t} \frac{1}{\sqrt{2}} (|L\rangle + |R\rangle) \otimes |\psi\rangle$$

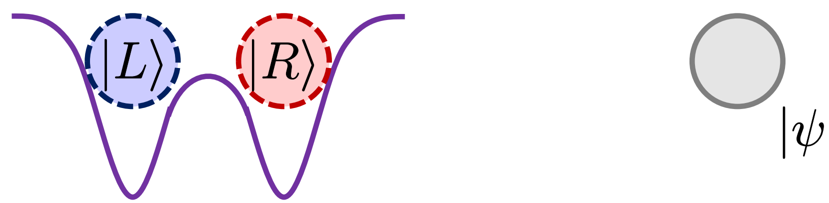
$$= \frac{1}{\sqrt{2}} \left(|L\rangle \otimes e^{i\phi_L} |\psi\rangle + |R\rangle \otimes e^{i\phi_R} |\psi\rangle\right)$$

Gravity induced entanglement

- If gravity is classical

$$\Phi(\hat{x}) = -\left\langle \frac{GM}{|\hat{x} - \hat{X}|} \right\rangle$$

Source mass **Probe mass**



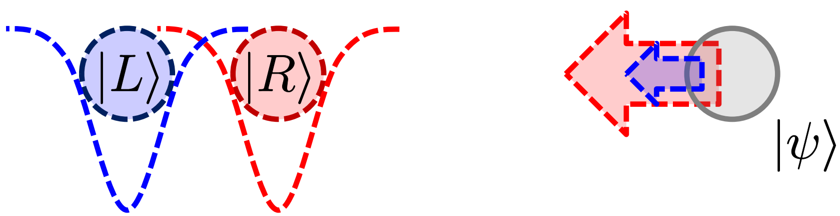
Newtonian potential act as a c-number

Key Idea of BMV Proposals

- If gravity is quantum

$$\Phi(\hat{x}, \hat{X}) = -\frac{GM}{|\hat{x} - \hat{X}|}$$

Source mass **Probe mass**



Newtonian potential act as an operator

$$e^{\frac{i}{\hbar}m\Phi(\hat{X})t}\frac{1}{\sqrt{2}}(|L\rangle + |R\rangle) \otimes |\psi\rangle$$

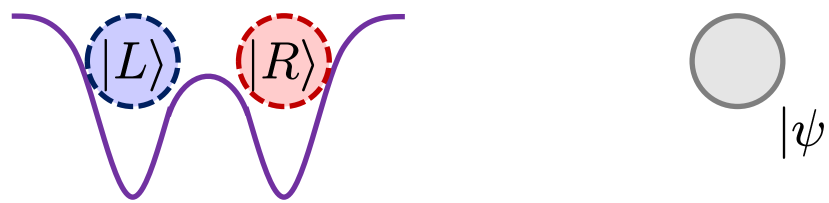
$$= \frac{1}{\sqrt{2}}\left(|L\rangle \otimes e^{i\phi_L}|\psi\rangle + |R\rangle \otimes e^{i\phi_R}|\psi\rangle\right)$$

Gravity induced entanglement

- If gravity is classical

$$\Phi(\hat{x}) = -\left\langle \frac{GM}{|\hat{x} - \hat{X}|} \right\rangle$$

Source mass **Probe mass**



Newtonian potential act as a c-number

$$e^{\frac{i}{\hbar}m\Phi t}\frac{1}{\sqrt{2}}(|L\rangle + |R\rangle) \otimes |\psi\rangle$$

$$= \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle) \otimes e^{\frac{i}{\hbar}m\Phi t}|\psi\rangle$$

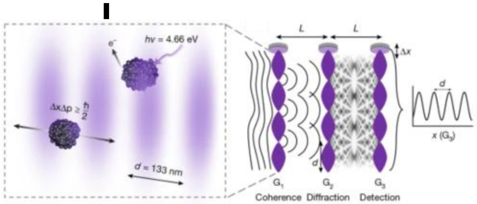
Remains separable

Quantum and Gravity Experiments

Quantum → ← **Gravity**

Mass

Planck mass
22 ug

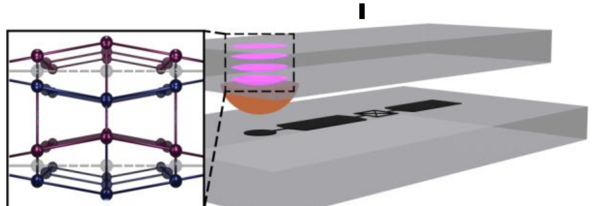


sodium nanoparticles,
3e-19 g
Pedalino+ (2026)

Interference

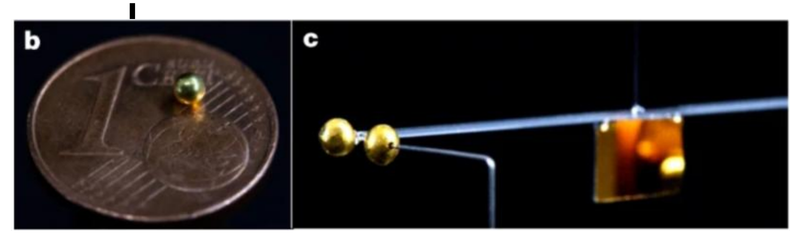
cantilever, 50 ng
Cripe+ (2019)

Backaction



Cat state

acoustic wave, 16 ug
Bild+ (2023)



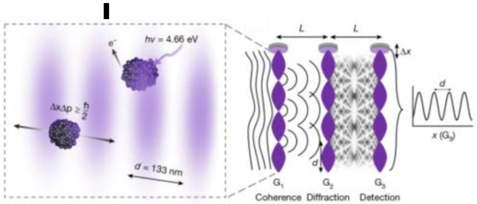
torsion pendulum, 90 mg
Westphal+ (2021)

Quantum and Gravity Experiments

Quantum → **Quantum regime of gravity** ← Gravity

Mass

Planck mass
22 ug



sodium nanoparticles,
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Interference

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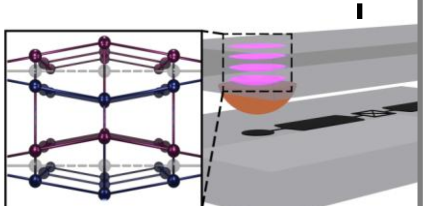
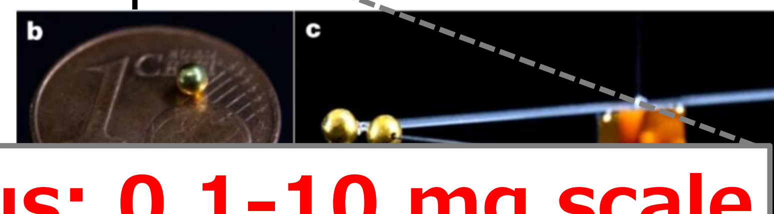


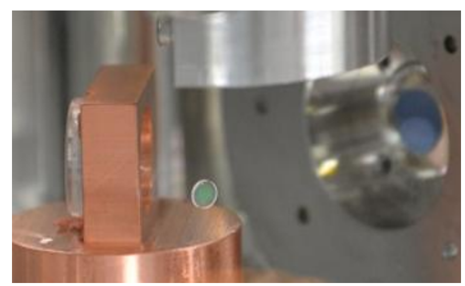
Cat state

acoustic wave,
Bild+ (2023)



Our focus: 0.1-10 mg scale

optical levitation,
~0.2 mg



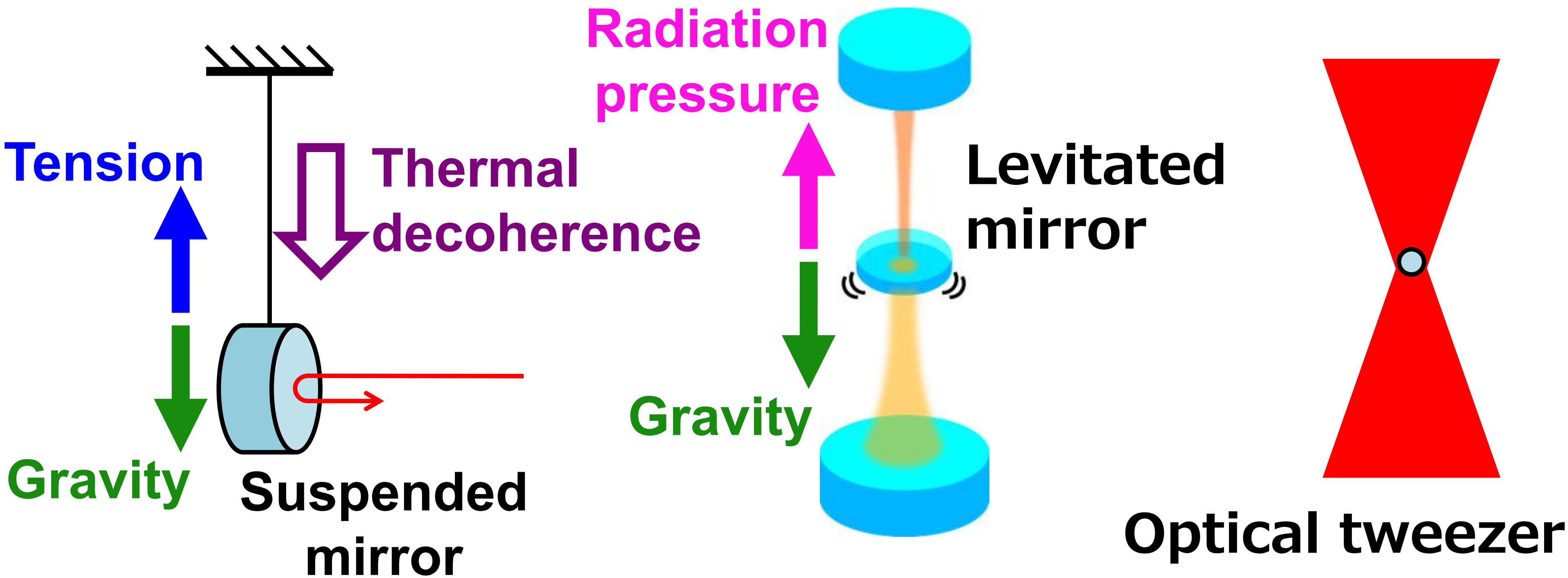
suspended disk, 7 mg
Matsumoto+ (2019)

Ryosuke's talk

suspended bar, 10 mg
Komori+ (2019)

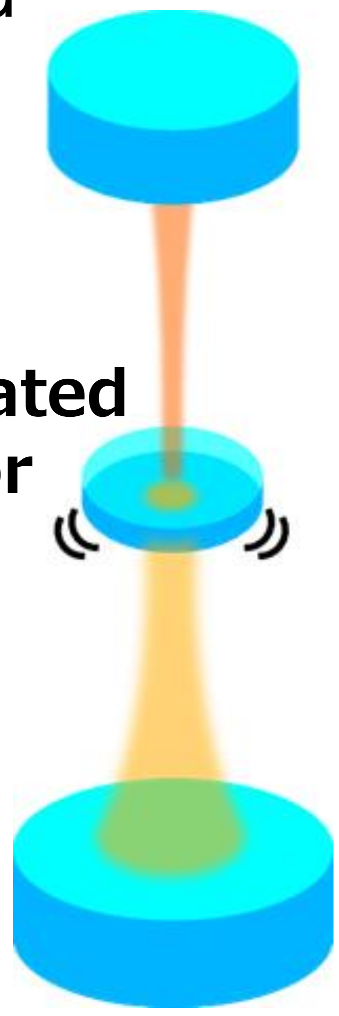
Optical Levitation of Mirrors

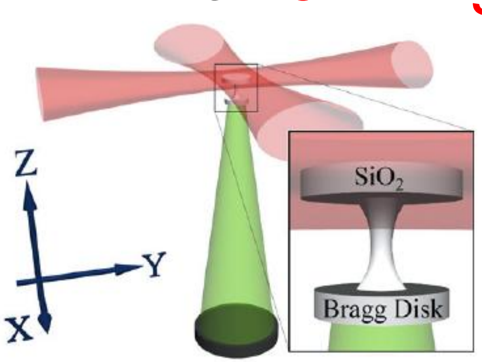
- Support a mirror with radiation pressure alone
- Free from thermal decoherence from mechanical support
- Large coupling compared with optical tweezers



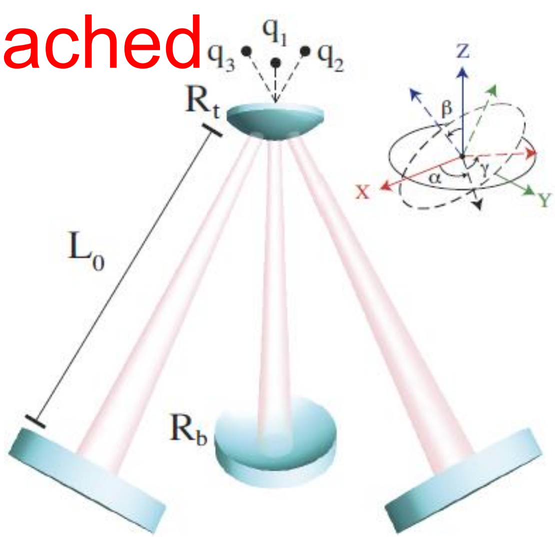
Sandwich Configuration

- 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 standard quantum limit (SQL) can be reached with 0.2 mg mirror





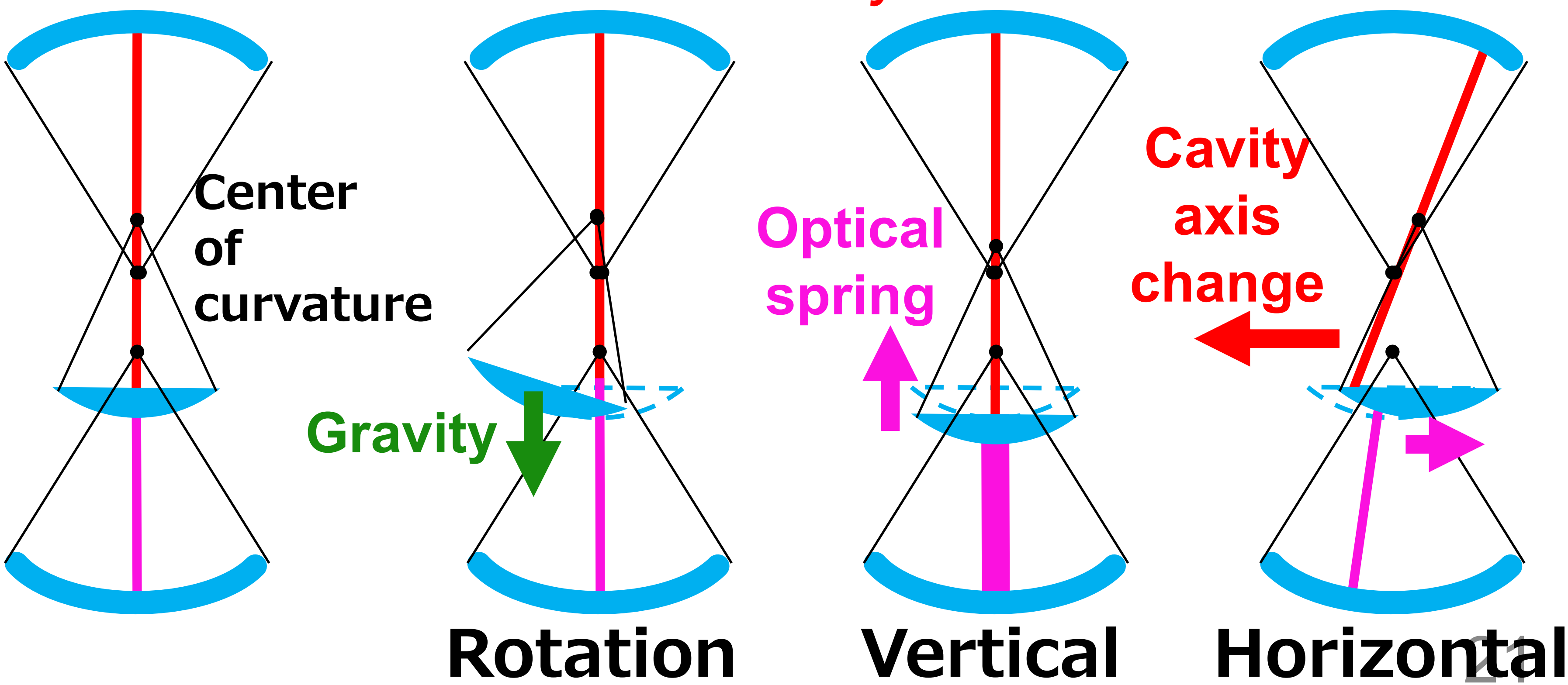
S. Singh+: [PRL 105, 213602 (2010)]



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

Stability of Levitation

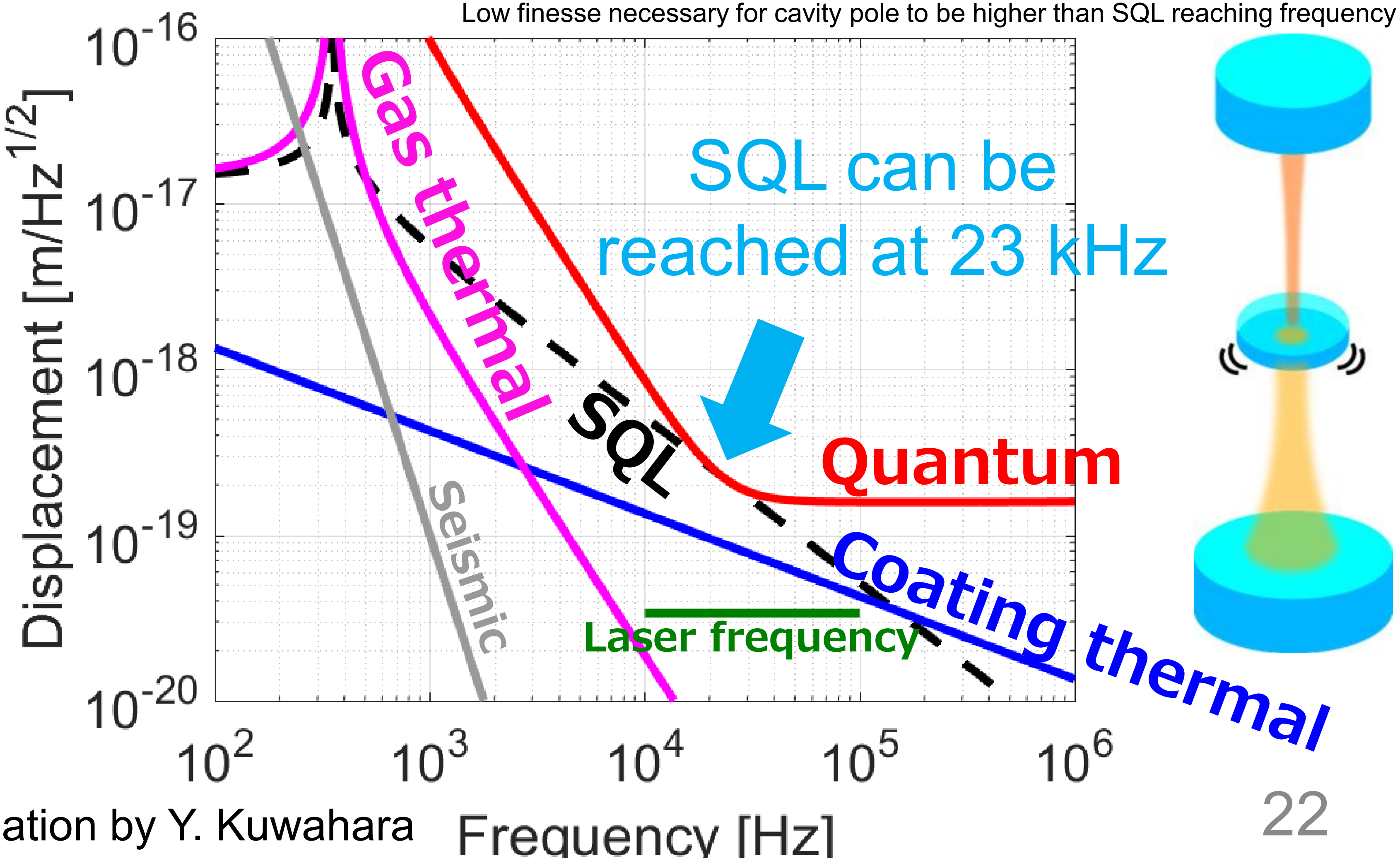
- Rotational motion is stable with gravity
- Vertical motion is stable with optical spring
- Horizontal motion is stable with cavity axis change
- *Curved mirror is necessary!*



Reaching Standard Quantum Limit

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

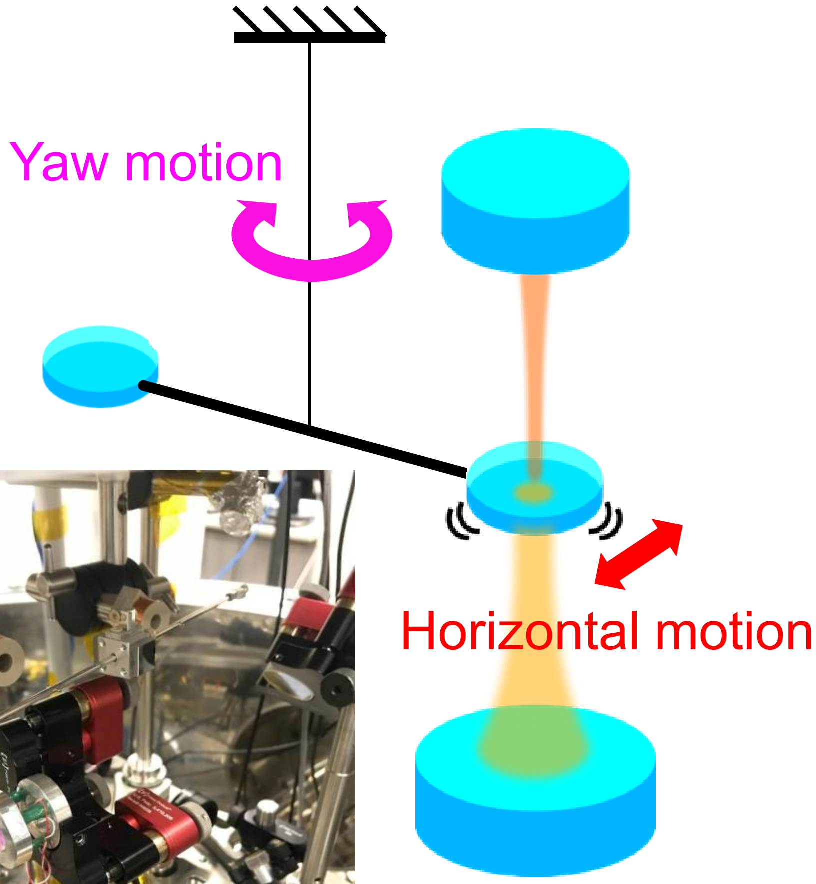
Low finesse necessary for cavity pole to be higher than SQL reaching frequency



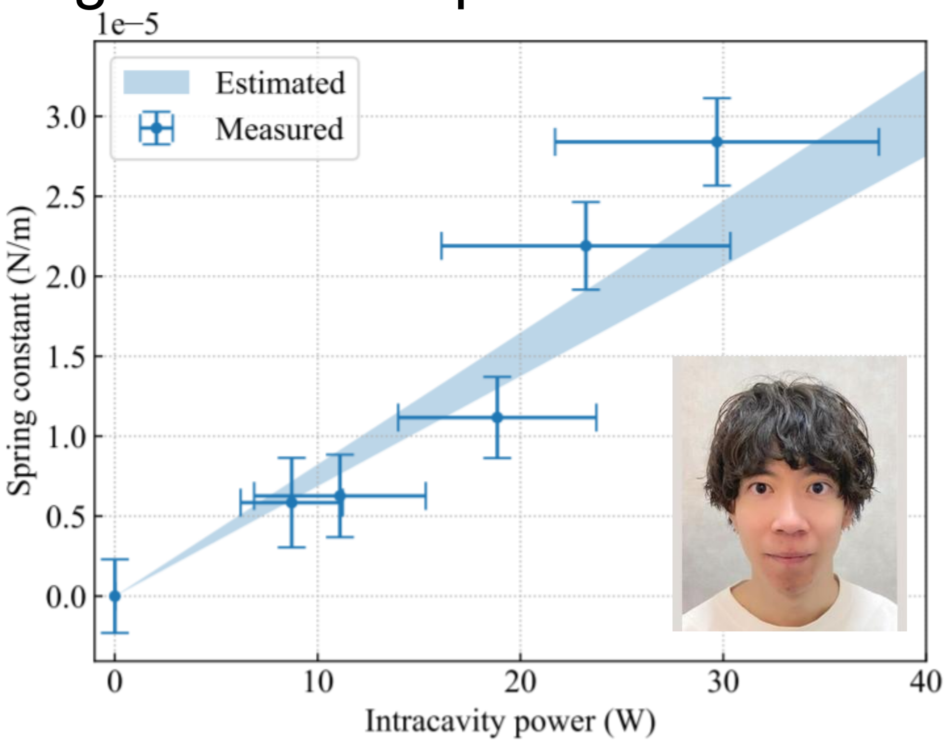
Calculation by Y. Kuwahara

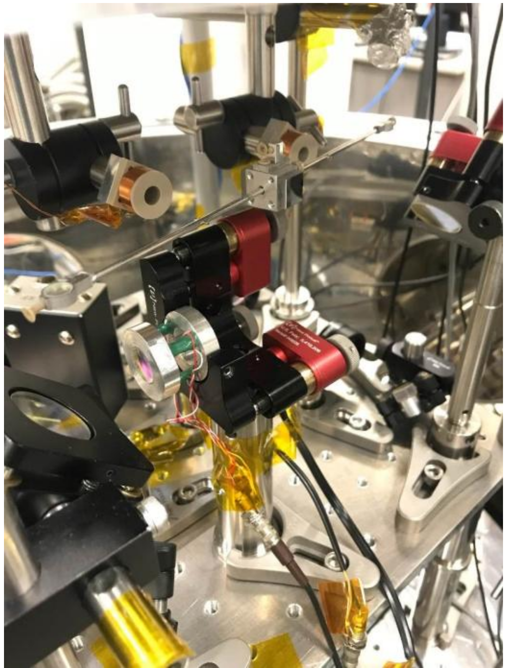
Experiment to Verify the Stability

- 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





Fabricating Milligram Mirrors

- To support the mass:

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

Roughly 1.5 kW of power is required to levitate 1 mg mirror

- Mirror needs to be curved, high reflectivity and low absorption. Our target now is:

φ 3 mm, 0.1 mm thick (~1.6 mg for fused silica)
Curvature RoC = ~30 mm convex
Reflectivity R > 99.95 %
Absorption A < ~0.5 ppm (LIGO, Virgo, KAGRA level)

- Experiment in ANU suggest higher absorption makes the system unstable (photothermal effects)

C. Gu+, New J. Phys. **25**, 123051 (2023)

How to Make Tiny Mirrors

2014 Approach (Company in Japan)

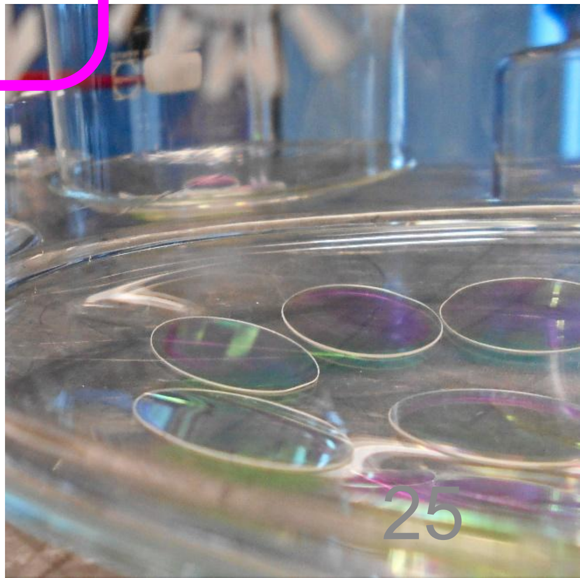
(1) Make 3 mm dia. lens → (2) Coat →

2020- Approach

(2018-2024 JST CREST、
2025-2027 JSPS Bilateral program)

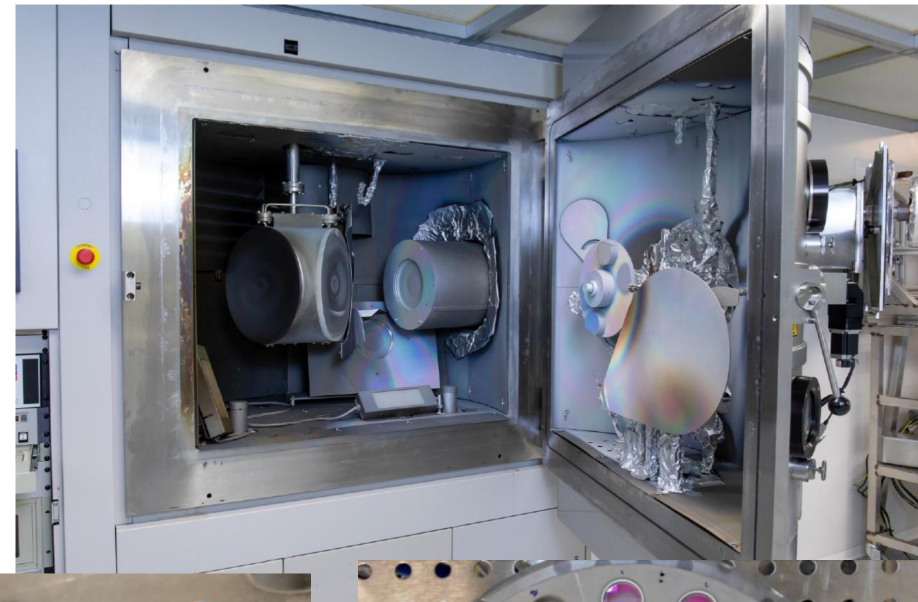
(1) Make 1 inch dia. 0.1 mm thick disk → (2) Coat (bend due to stress) → (3) Cut into 3 mm dia.

LABORATOIRE MATÉRIAUX AVANCÉS

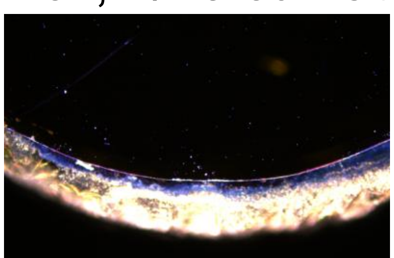


Fabrication Status in LMA

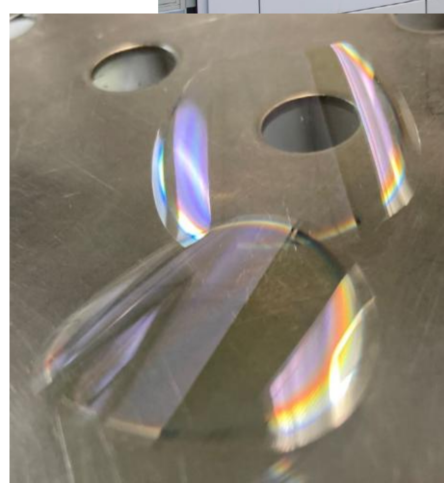
- LIGO/Virgo level high quality coating (Amplitude transmittance T=10 ppm, 6.2 um thick)
- Cut into φ3 mm is tough
- Curvature was not enough *O*(10 cm)
- Now trying thinner substrate (25 um) with laser cutting

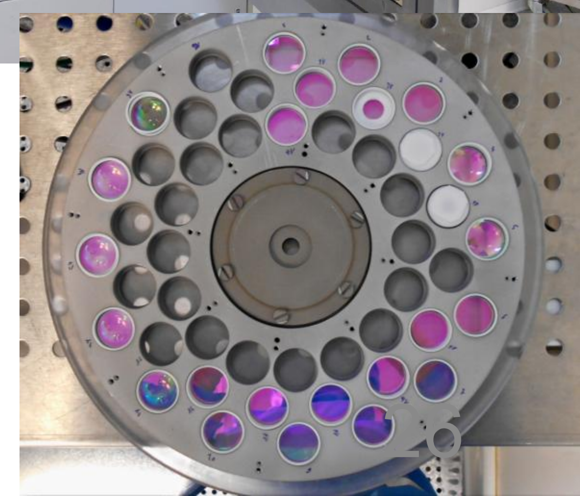


1/4 thick, 1/16 curvature



M. Croquette+, [AVS Quantum Science **5**, 014403 (2023)]

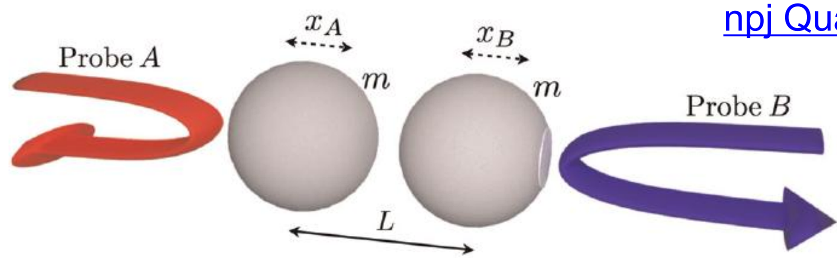




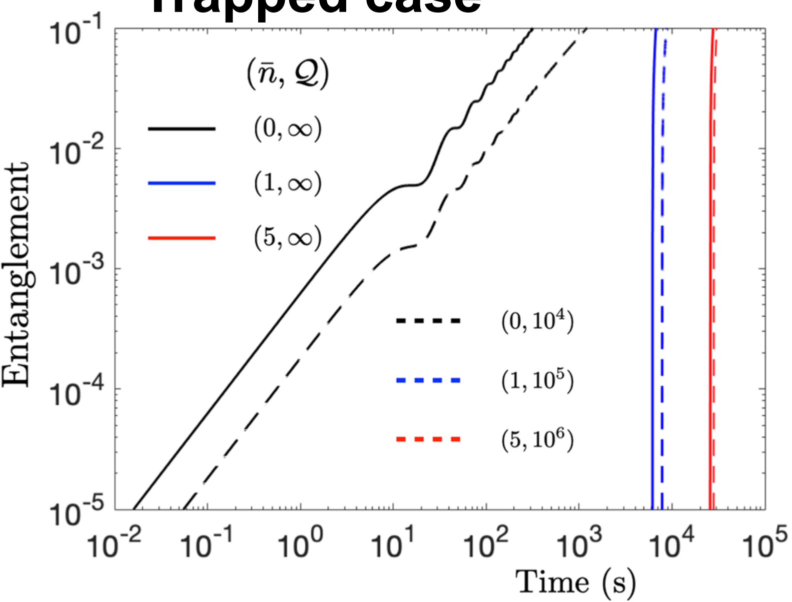
How to Test Gravity Entanglement

- Still far from BMV experiment
- Krisnanda+ proposed free-falling masses can generate gravity-induced entanglement more & faster than trapped masses

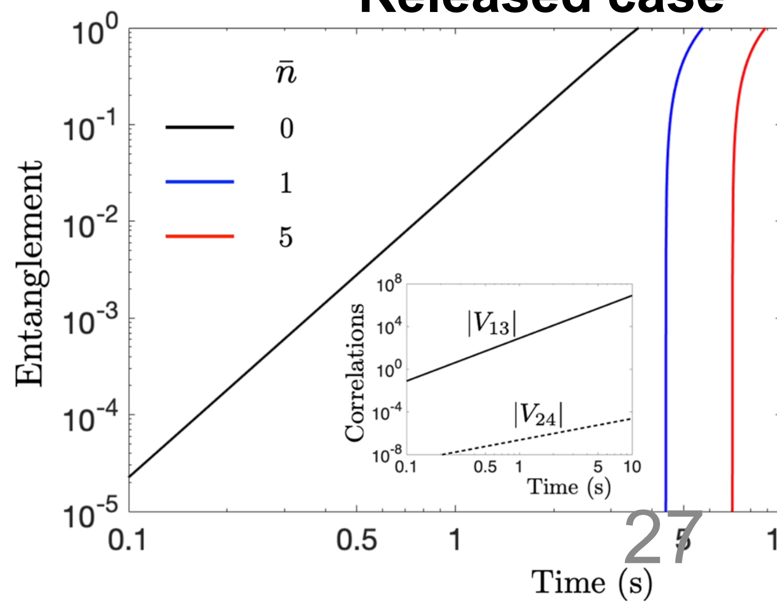
T. Krisnanda+,
[npj Quantum Information **6**, 12 (2020)]



Trapped case



Released case



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…

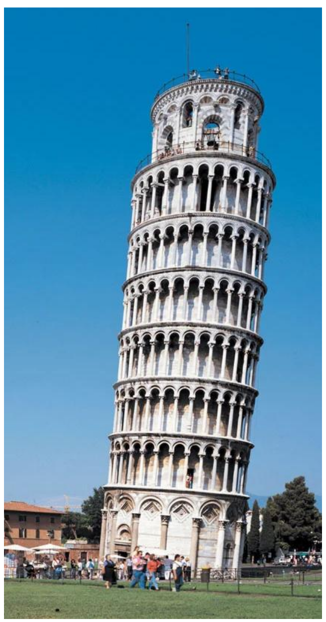


Table 3. Free-fall times t and heights $h = \frac{1}{2}gt^2$, with $g \simeq 9.8$ m s^{-2}, required to generate the amount E of entanglement at fixed values of temperature T and pressure P for the proposals of BM and Krisnanda.

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

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

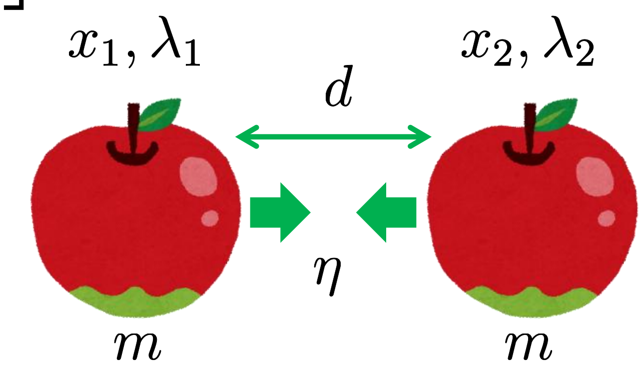
$$= \frac{\omega}{2} \left[\sum_{i=1,2} (P_i + \lambda_i X_i^2) + \eta (x_1 - x_2)^2 \right]$$

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,
CQG **42**, 165003 (2025)

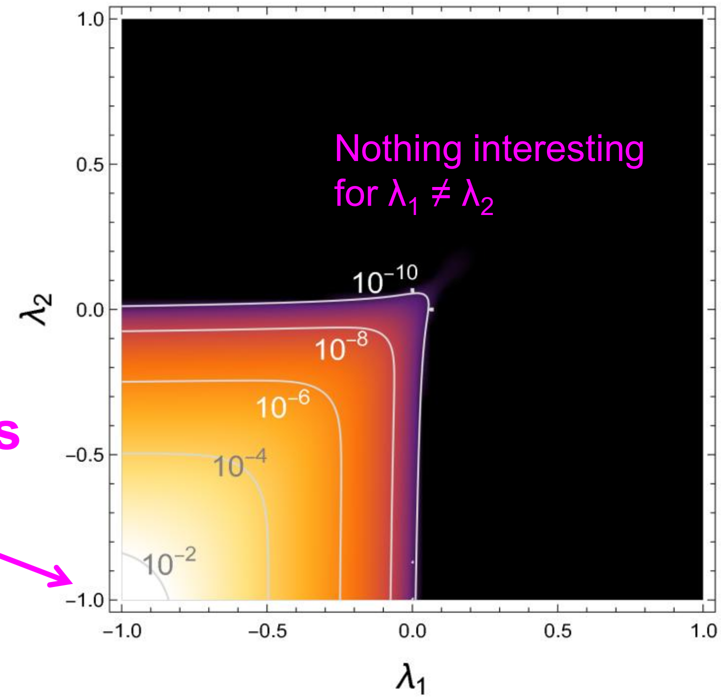
Inverted Oscillators are the Best

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

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

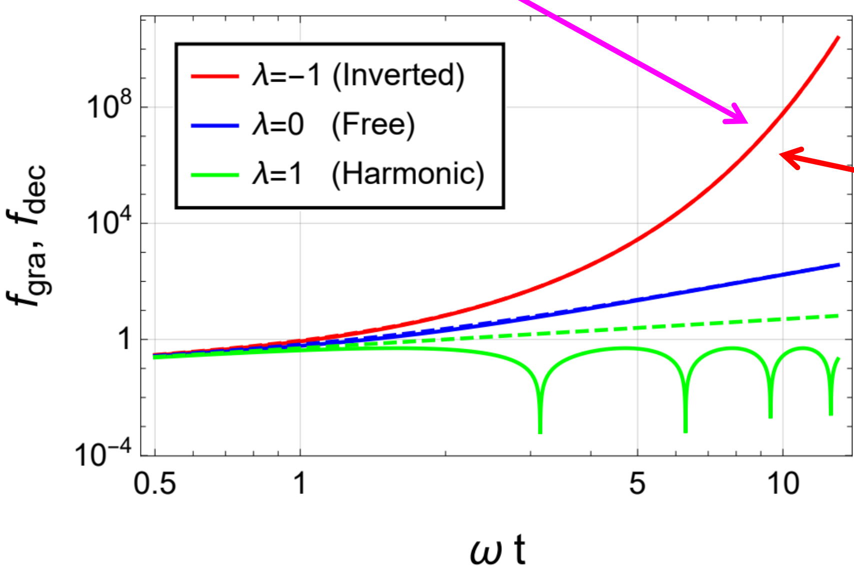
Strength of gravitational coupling

Amount of decoherence



Exponential growth of entanglement

Inverted oscillators are the best



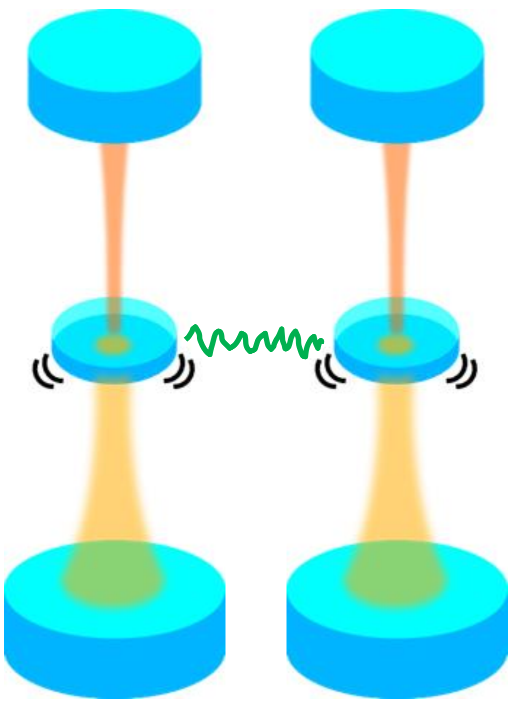
$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8}e^{2\omega t}$$

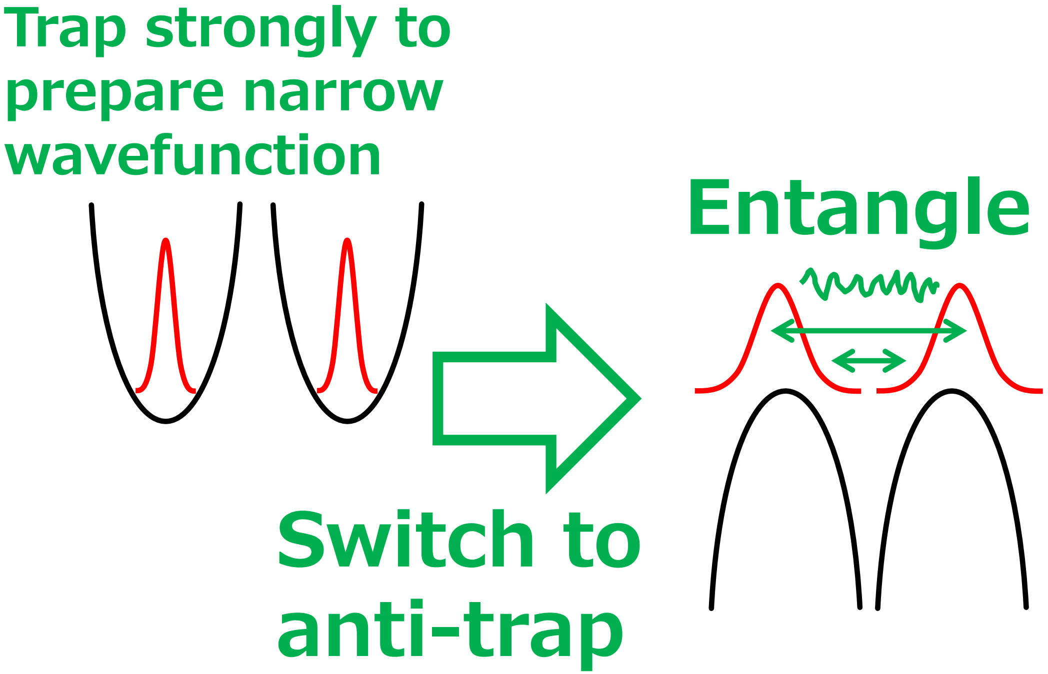
$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8}(\omega t)^3$$

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

Realization with Levitated Mirrors

- Switching between trap and anti-trap is easy with optical levitation
- Entanglement can be tested in horizontal motion
- Can be done similar with other systems





Example Setup

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

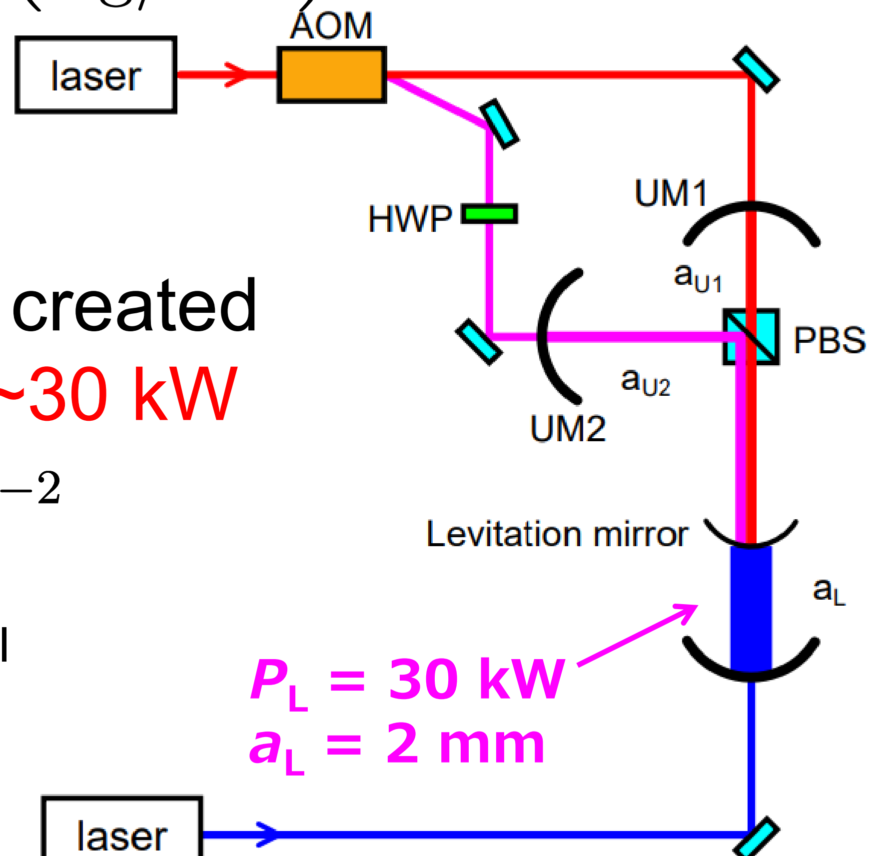
$$\mu << \eta = 2.7 \times 10^{-13} \omega_{\mathrm{kHz}} \left(\frac{m/d^3}{2\,\mathrm{g/cm^3}} \right)$$

- 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



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

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

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

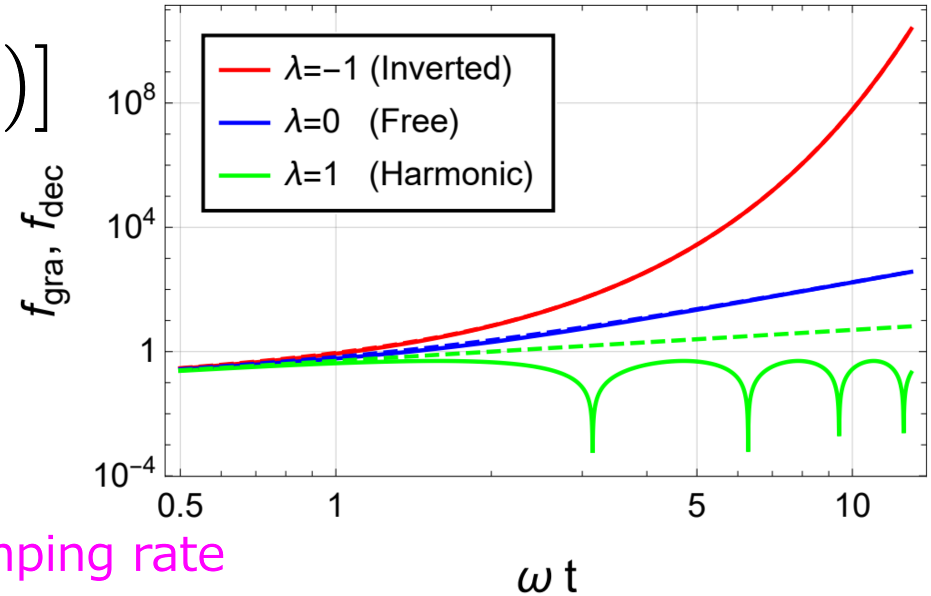
Still, Decoherence is the Issue

- Decoherence effects also increases exponentially with inverted oscillators

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

Gravity Decoherence

Logarithmic negativity

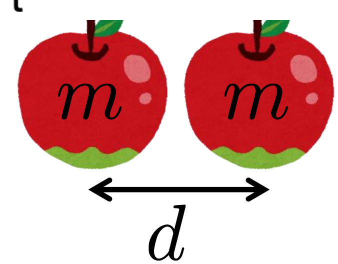


- $\eta > \mu$ is required

Damping rate

$$\frac{2Gm}{\omega_{\rm m} d^3} > \frac{2k_{\rm B}T_{\rm th}\gamma_{\rm m}}{\hbar\omega_{\rm m}}$$

For 300 K
(smaller by ~10 orders of magnitude than state-of-the-art)



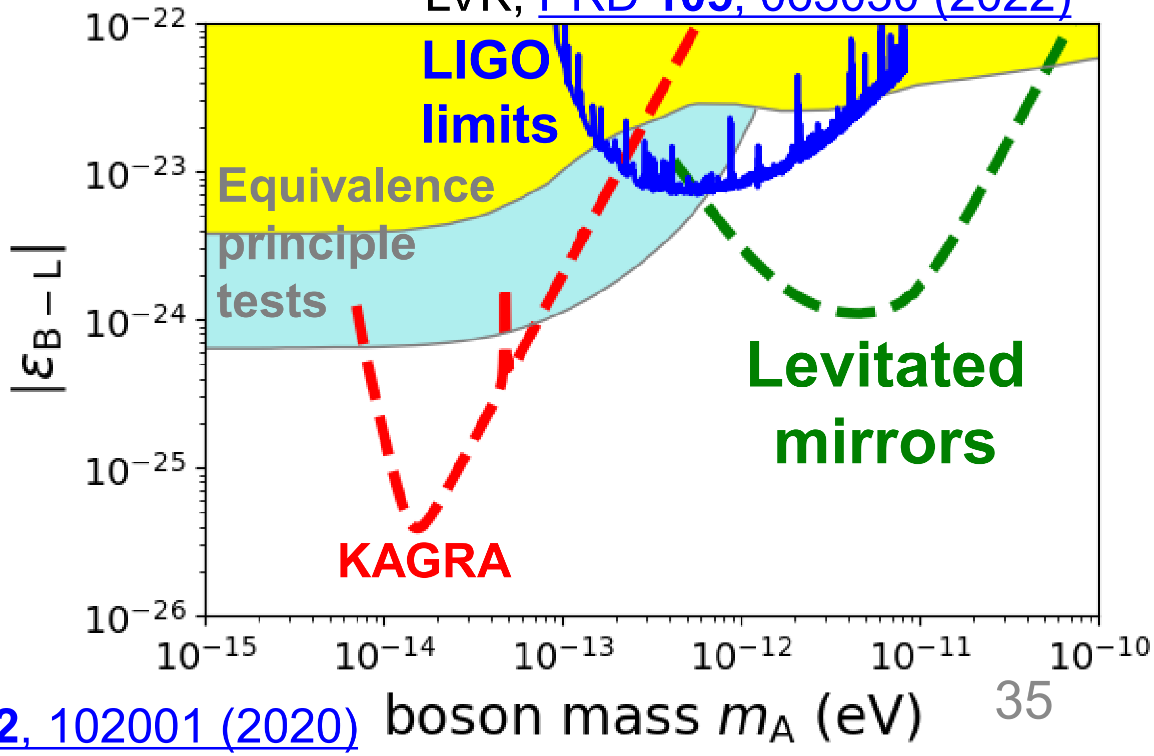
$$\gamma_{\rm m} < \frac{\hbar G m}{k_{\rm B}T_{\rm th}d^3} = 1.7\times 10^{-21}\,{\rm Hz}\frac{m/d^3}{1\,{\rm g/cm^3}}$$

Fused silica: 2 g/cm^3 Osmium: 22 g/cm^3

Plans for now

- Characterization of levitation mirrors
- High power operation and realization of levitation
- New ideas to relax $\eta > \mu$?
- B-L dark matter search also possible

LVK, PRD **105**, 063030 (2022)



YM+, PRD **102**, 102001 (2020)

Summary

- **Remarkable technological advances**:
  Quantum states are now realized in increasingly massive systems (16 μg), while gravity is being measured at ever smaller mass scales (90 mg)
- **Significant theoretical progress**:
  More realistic and experimentally accessible proposals to test the quantum nature of gravity are emerging
- **Still new ideas are required**:
  We must develop methods that evade decoherence and properly account for measurement effects

Japan-Singapore Quantum Collaboration Kick-off Workshop (April 21, 2026)

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