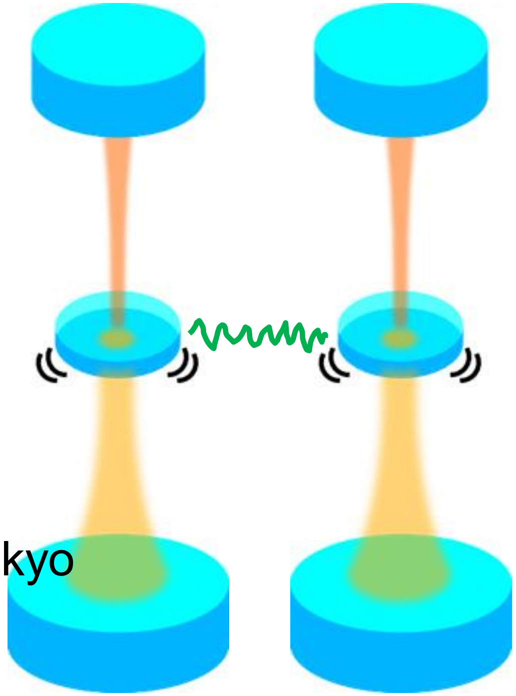
iTHEMS Cosmology Seminar @ RIKEN Wako

February 26, 2026

Testing the quantum nature of gravity with optomechanical systems



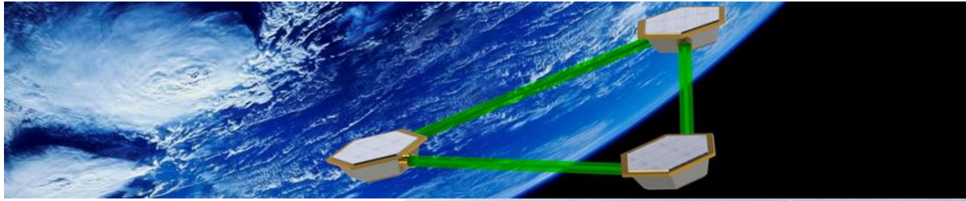
Yuta Michimura

RESCEU, University of Tokyo

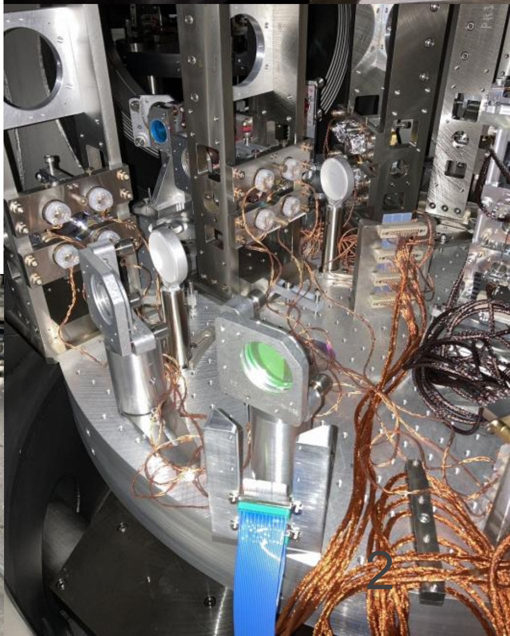
Kavli IPMU, WPI, UTIAS, University of Tokyo

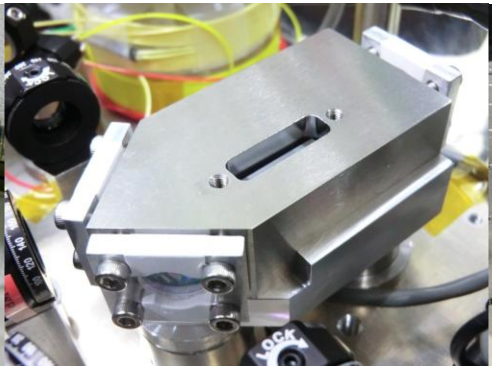
michimura@resceu.s.u-tokyo.ac.jp

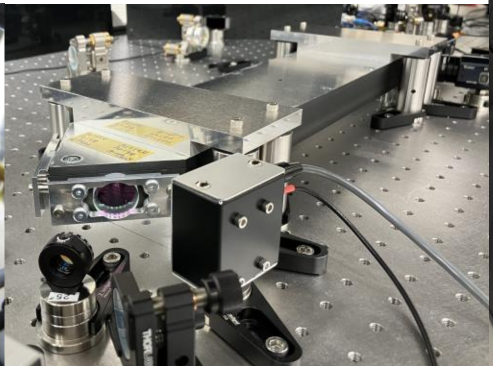
Self Introduction



- Yuta Michimura (道村 唯太)
  - 2015: PhD in Physics, UTokyo
  - 2014-2022: Assistant Prof. at Dept. Physics, UTokyo
  - 2022-2024: Research Scientist at LIGO Caltech
  - 2024-now: Associate Prof. at RESCEU, UTokyo
- Experimental gravitational physics
  - Ground-based and space-based gravitational-wave detectors
    KAGRA, DECIGO, SILVIA …
  - Lorentz invariance test
  - Tests of quantum nature of gravity
  - Dark matter searches …







Advertisement

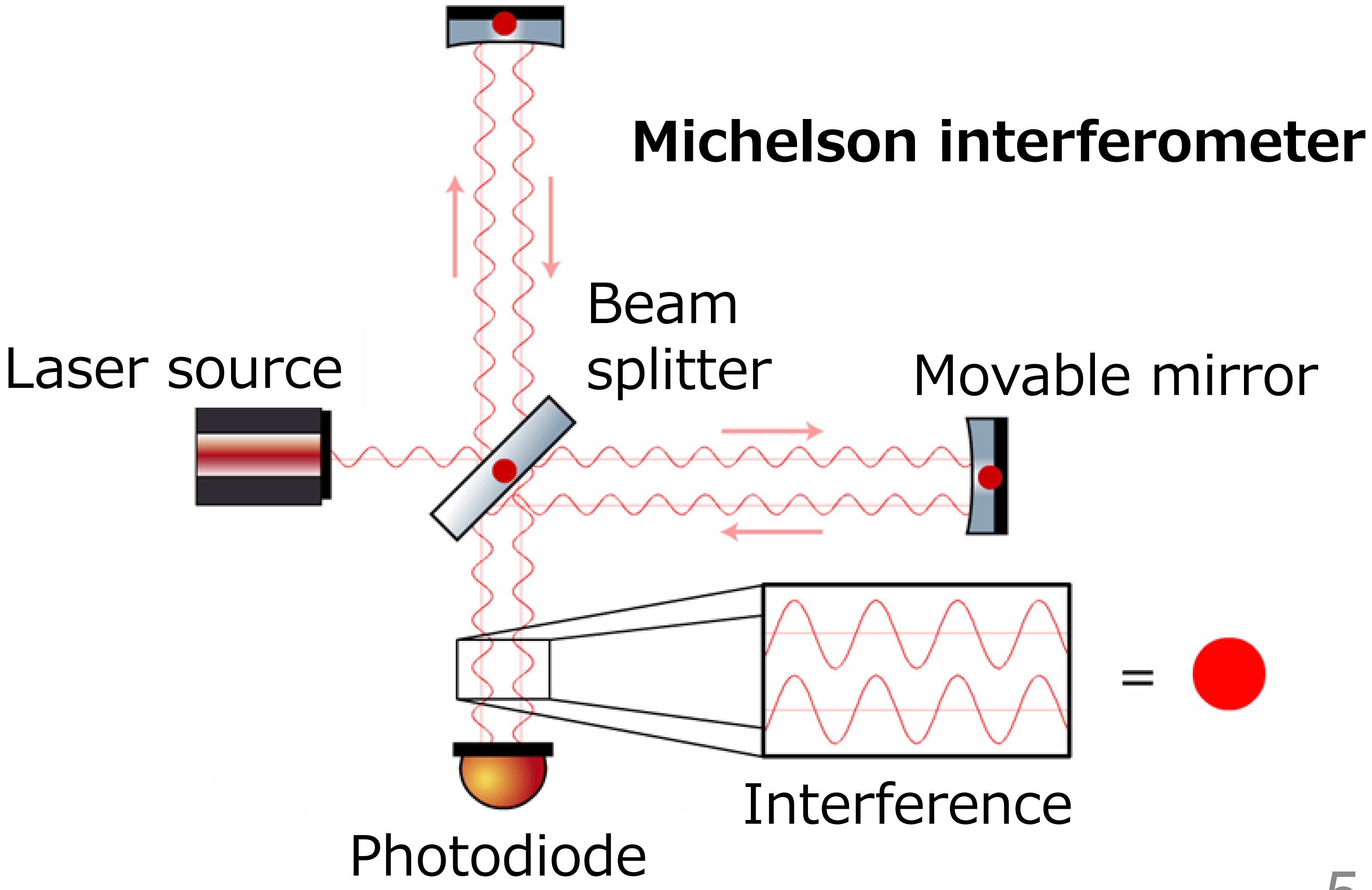
- Transformative Research Areas (A)
  “What is the physical mechanism of the origin of the Universe? - challenges over transcending scales through the integration of theory, observations, and experiments” will start from April 2026 (to March 2031)
  学術変革領域研究(A)「宇宙創生の物理法則はなにか？
  —理論・観測・実験の融合によるスケールを超えた挑戦」
- Our Planned Research C02: “Exploring the origin of the Universe with tabletop laser interferometers and gravitational-wave observatories”
  計画研究C02「テーブルトップレーザー干渉計と重力波望遠鏡で挑む宇宙創生」
- Calls for postdoc etc. positions will be released next month
- Kick-off symposium will be announced soon
- Call for Publicly Offered Research (公募研究) from July

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)
- **Some other new ideas**
  - need help from theorists

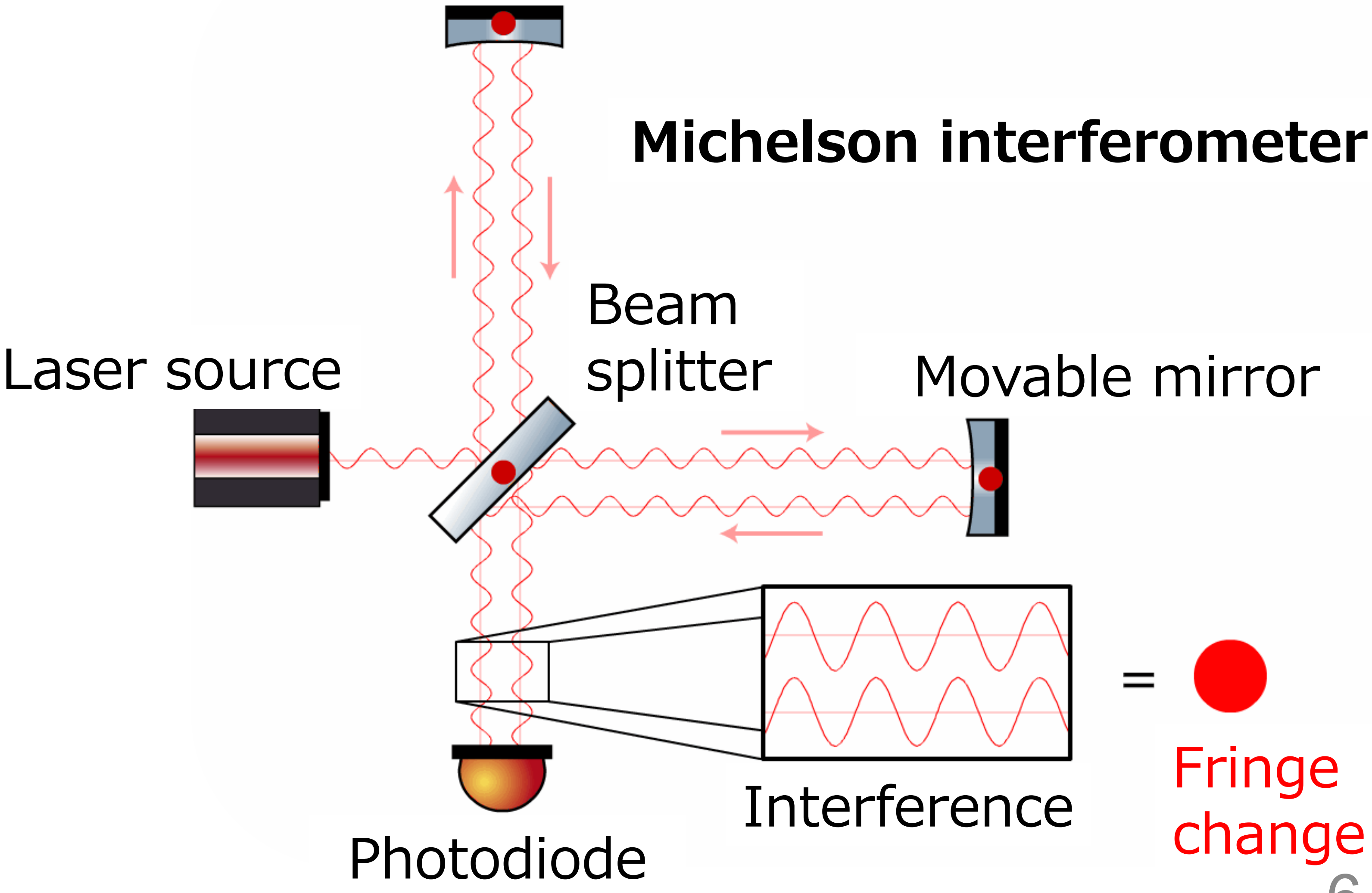
Laser Interferometry

- measures differential arm length change



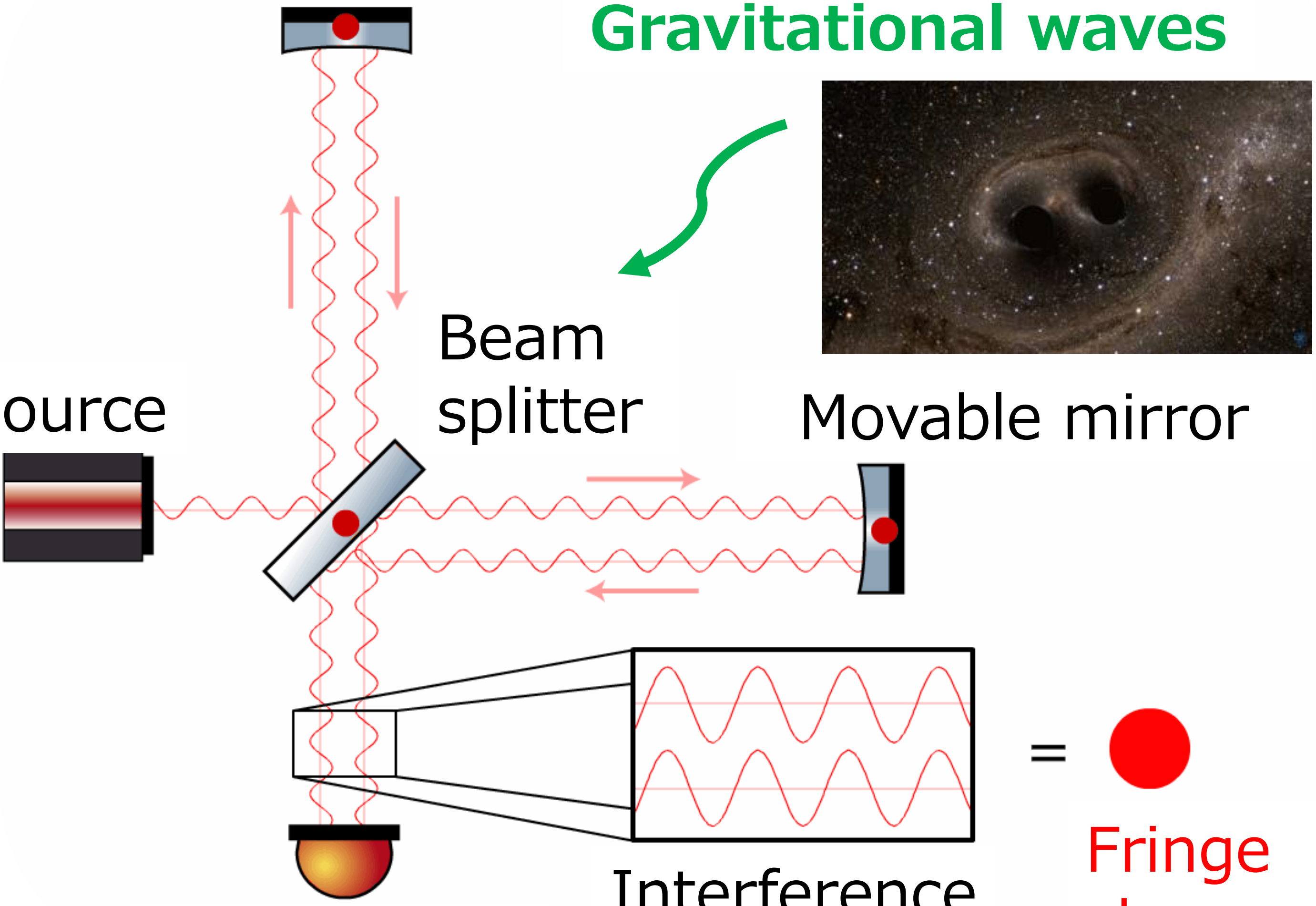
Laser Interferometry

- measures differential arm length change



For Gravitational Waves

- measures differential arm length change



Gravitational waves

Beam splitter

Laser source

Movable mirror

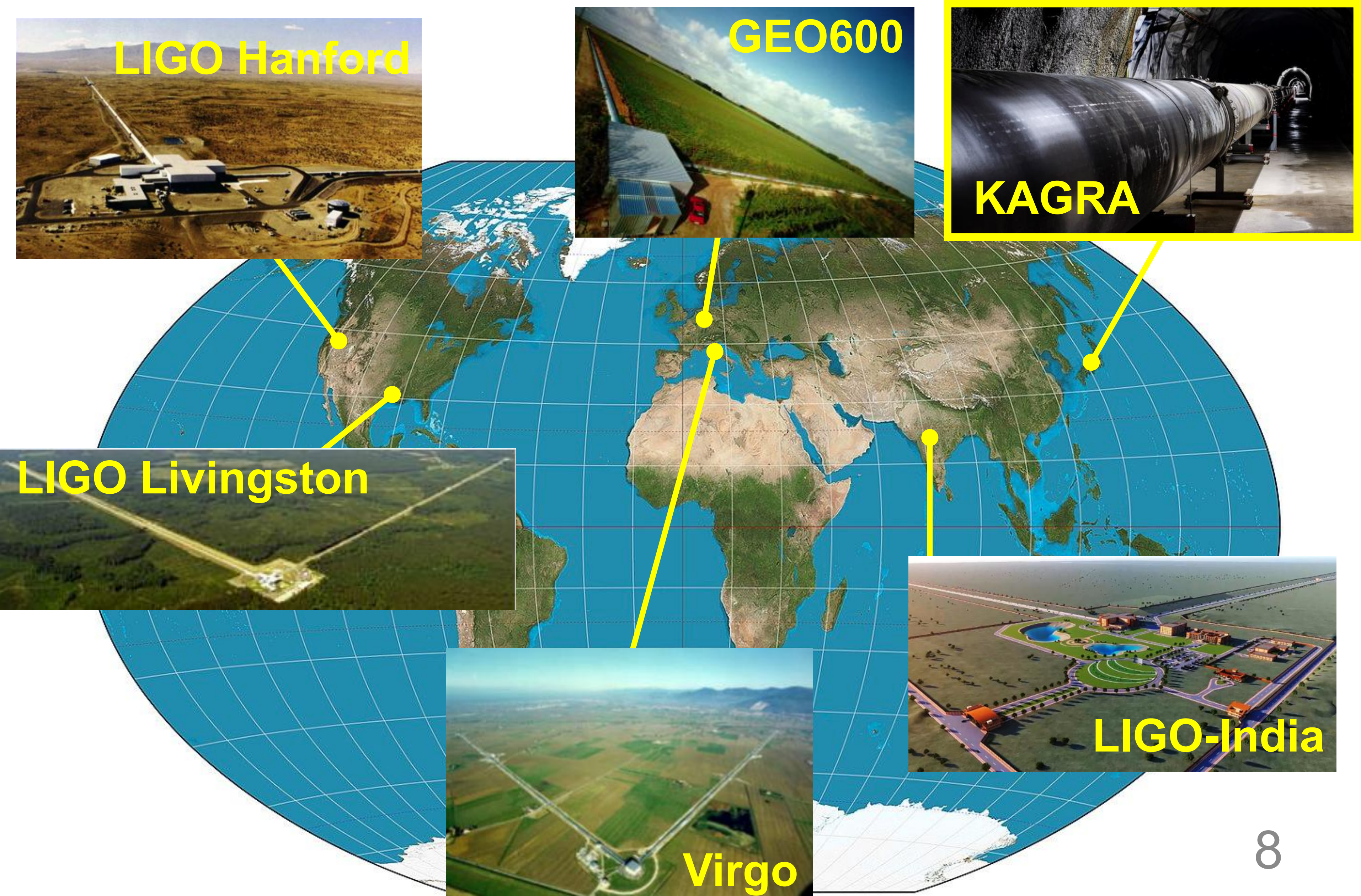
Interference

=

Fringe change

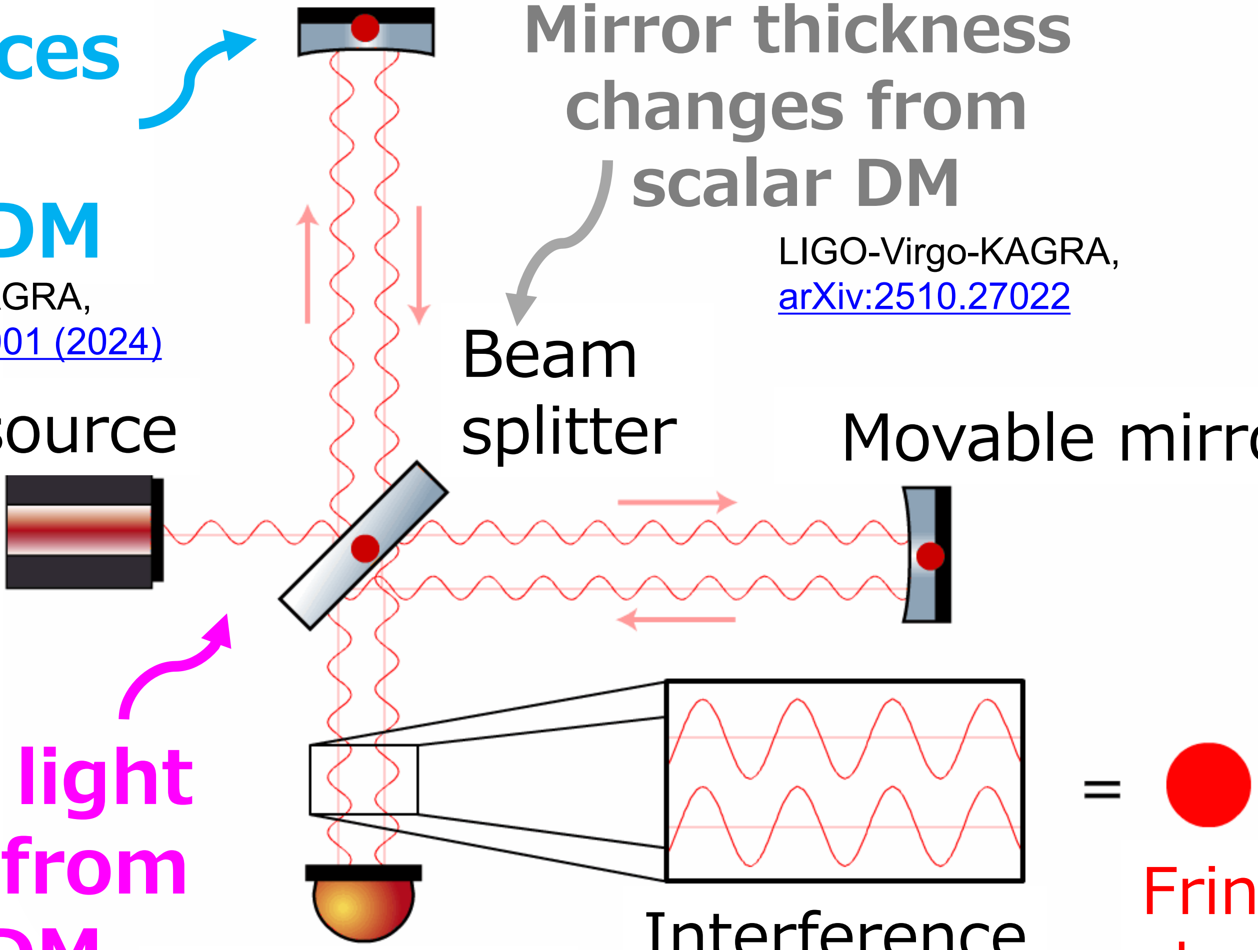
Photodiode

Laser Interferometric GW Detectors



For Dark Matter

- measures differential arm length change



Tiny forces from vector DM

LIGO-Virgo-KAGRA, [PRD 110, 042001 (2024)](https://doi.org/10.1103/PhysRevD.110.042001)

Mirror thickness changes from scalar DM

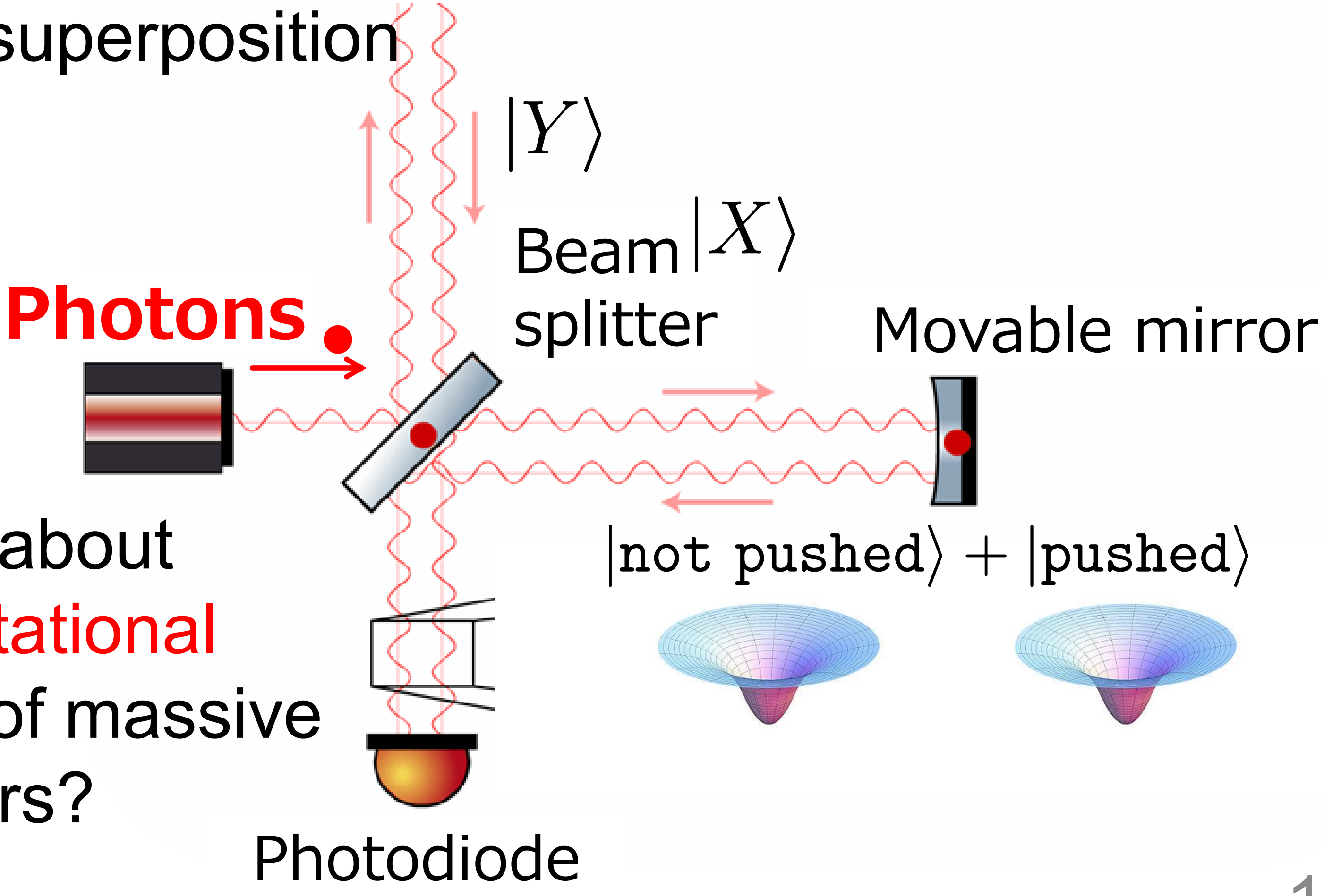
LIGO-Virgo-KAGRA, [arXiv:2510.27022](https://arxiv.org/abs/2510.27022)

Speed of light changes from axion DM

Y. Oshima+, [PRD 108, 072005 (2023)](https://doi.org/10.1103/PhysRevD.108.072005)

As a Probe of Quantum

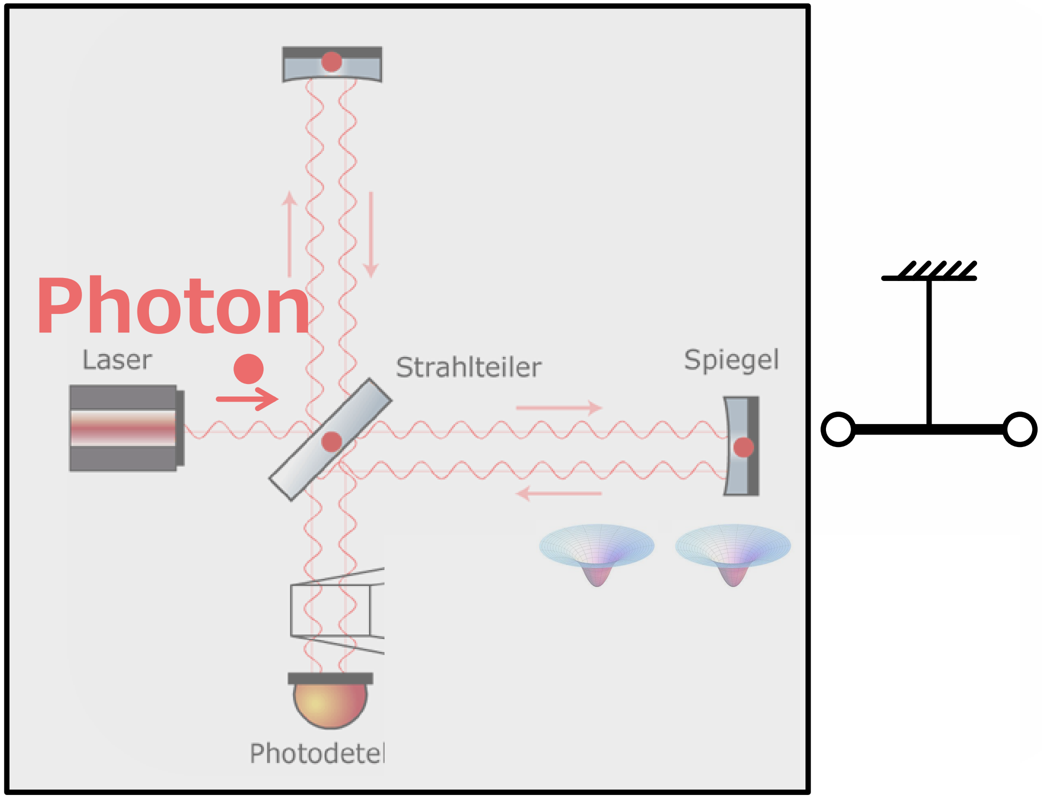
- Photon going to X or Y arm is in superposition
- Mirrors pushed or not pushed by radiation pressure is in superposition



- How about gravitational field of massive mirrors?

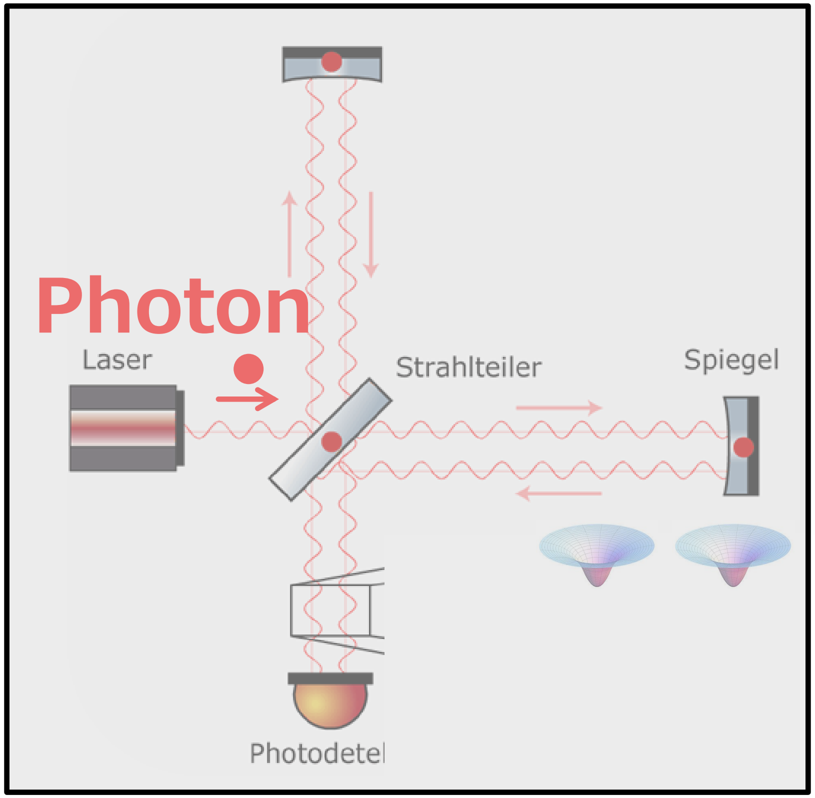
Schrödinger’s KAGRA

- 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???



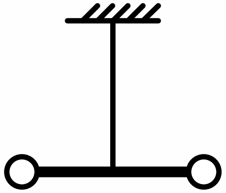
Schrödinger’s KAGRA

- 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???



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

Expectation value



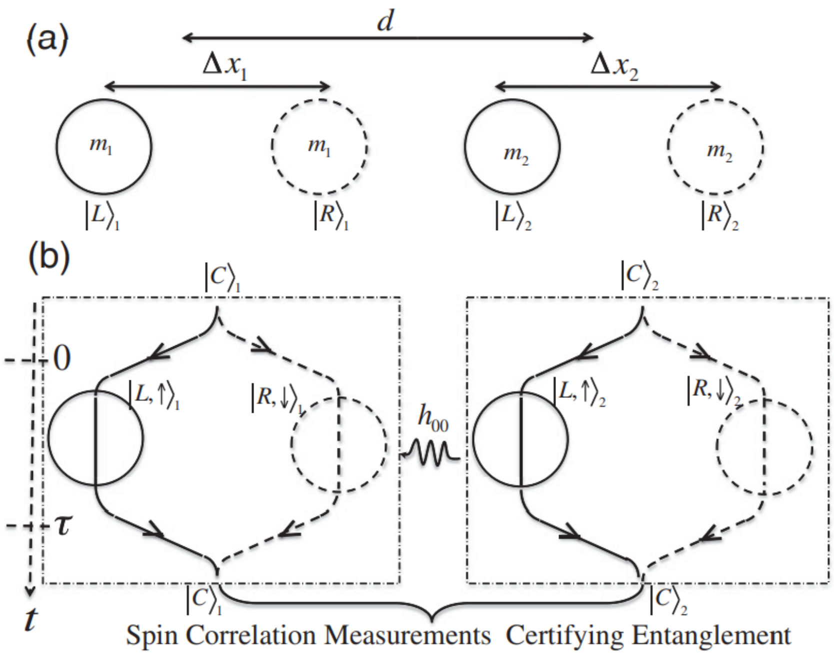
Semiclassical Gravity (Schrödinger-Newton model)

Very strange model, but not falsified experimentally

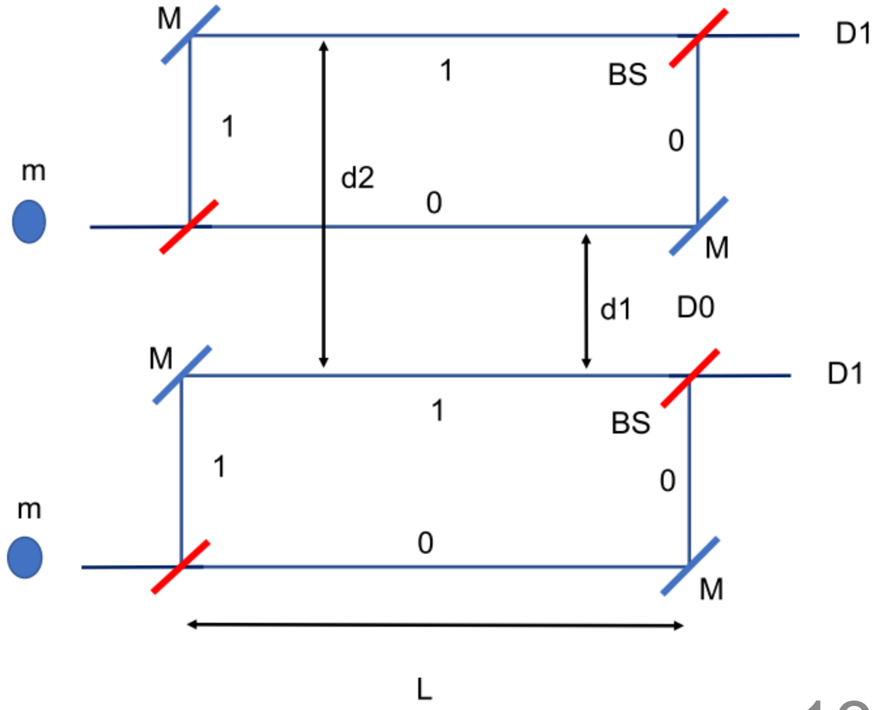
BMV Proposals

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

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



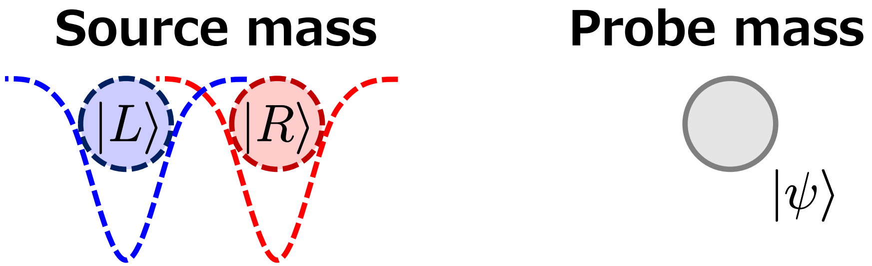
C. Marletto & V. Vedral,
Phys. Rev. Lett. 119, 240402 (2017)



Key Idea of BMV Proposals

- If gravity is quantum

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

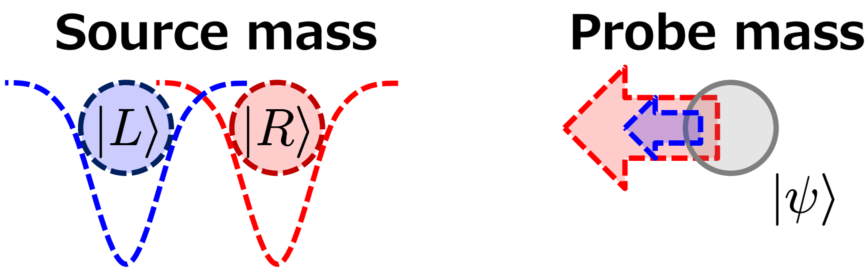


Newtonian potential act as an operator

Key Idea of BMV Proposals

- If gravity is quantum

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



Newtonian potential act as an operator

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

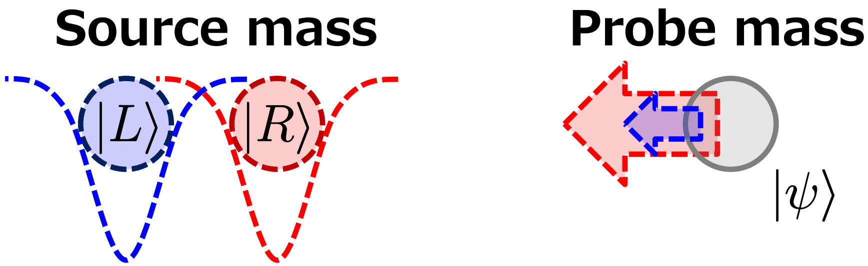
$$= \frac{1}{\sqrt{2}}\left(|L\rangle \otimes e^{i\phi_L}|\psi\rangle + |R\rangle \otimes e^{i\phi_R}|\psi\rangle\right)$$

Gravity induced entanglement

Key Idea of BMV Proposals

- If gravity is quantum

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



Newtonian potential act as an operator

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

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

Gravity induced entanglement

- If gravity is classical

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

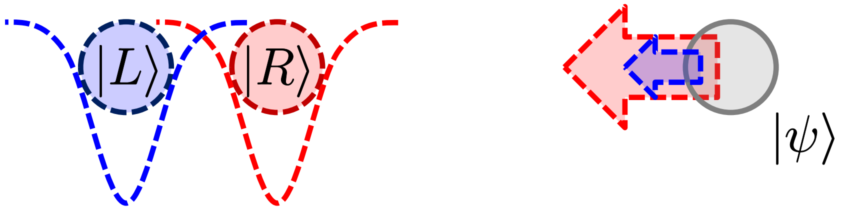
Newtonian potential act as a c-number

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

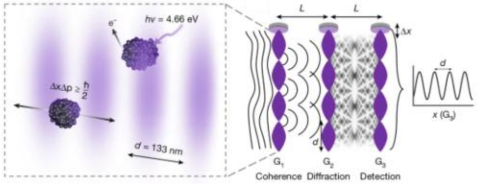
$$e^{\frac{i}{\hbar}m\Phi t}\frac{1}{\sqrt{2}}(|L\rangle+|R\rangle)\otimes|\psi\rangle$$

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

Remains separable

Quantum and Gravity Experiments

Planck mass
22 ug

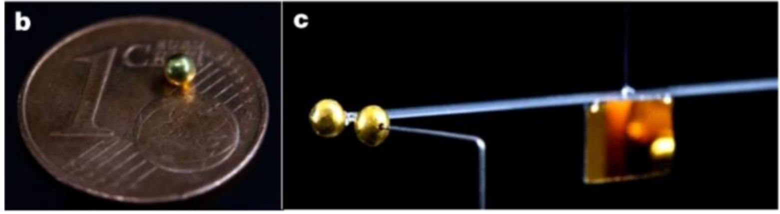


sodium nanoparticles,
3e-19 g
Pedalino+ (2026)

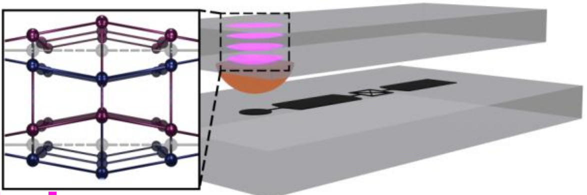
Interference

cantilever, 50 ng
Cripe+ (2019)

Backaction



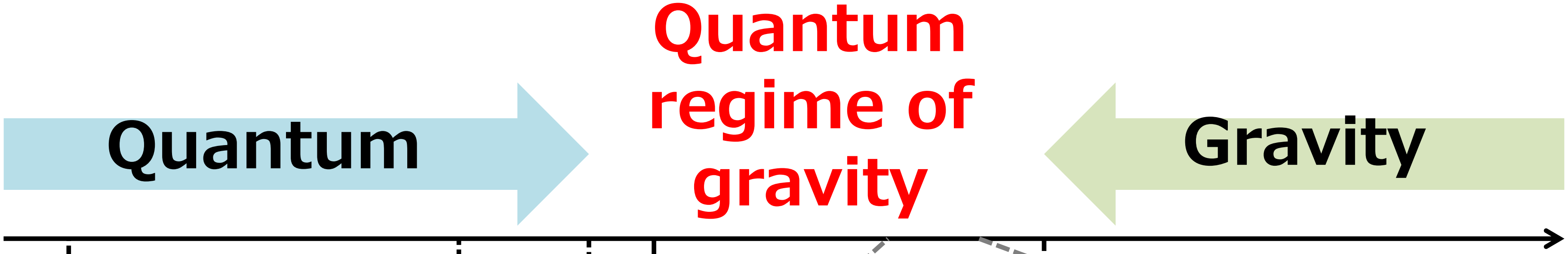
torsion pendulum, 90 mg
Westphal+ (2021)



Cat state

acoustic wave, 16 ug
Bild+ (2023)

Quantum and Gravity Experiments



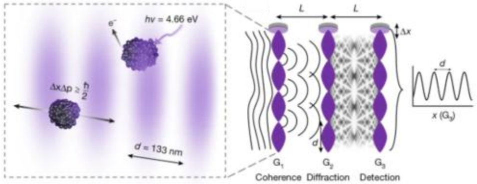
Quantum

Quantum regime of gravity

Gravity

Mass

Planck mass
22 ug

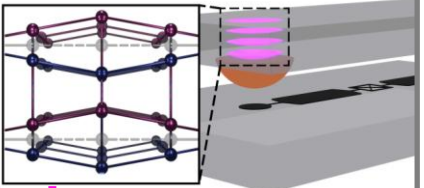


sodium nanoparticles,
3e-19 g
Pedalino+ (2026)

Interference

cantilever, 50 ng
Cripe+ (2019)

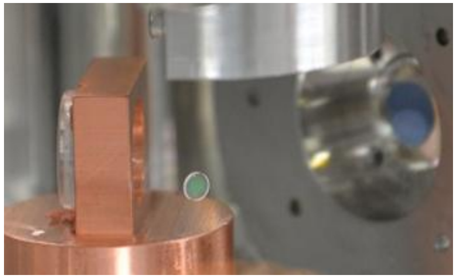
Backaction



Cat state

acoustic wave,
Bild+ (2023)

Our focus: 0.1-10 mg scale



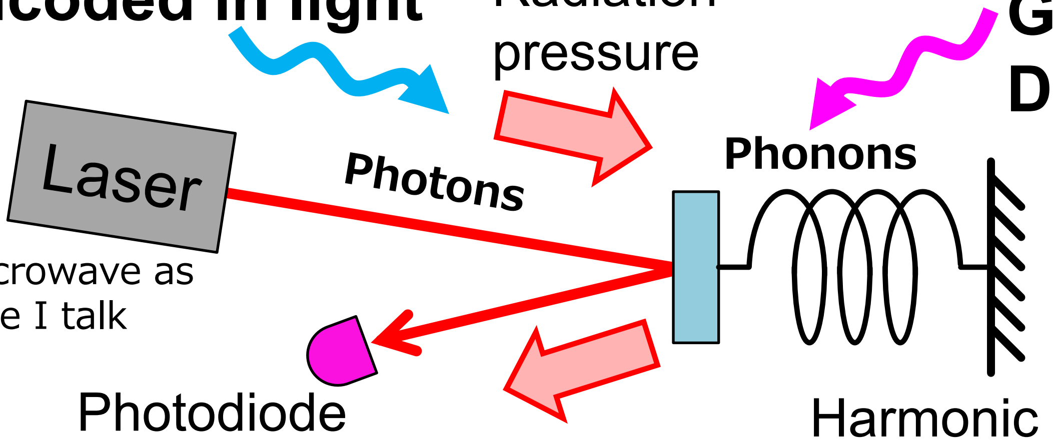
suspended disk, 7 mg
Matsumoto+ (2019)

suspended bar, 10 mg
Komori+ (2019)

optical levitation,
~0.2 mg

Optomechanical Systems

- Interaction between light and mechanical oscillators



Information encoded in light

Radiation pressure

Gravity
Gravitational waves
Dark matter …

It can be microwave as well, but here I talk about light

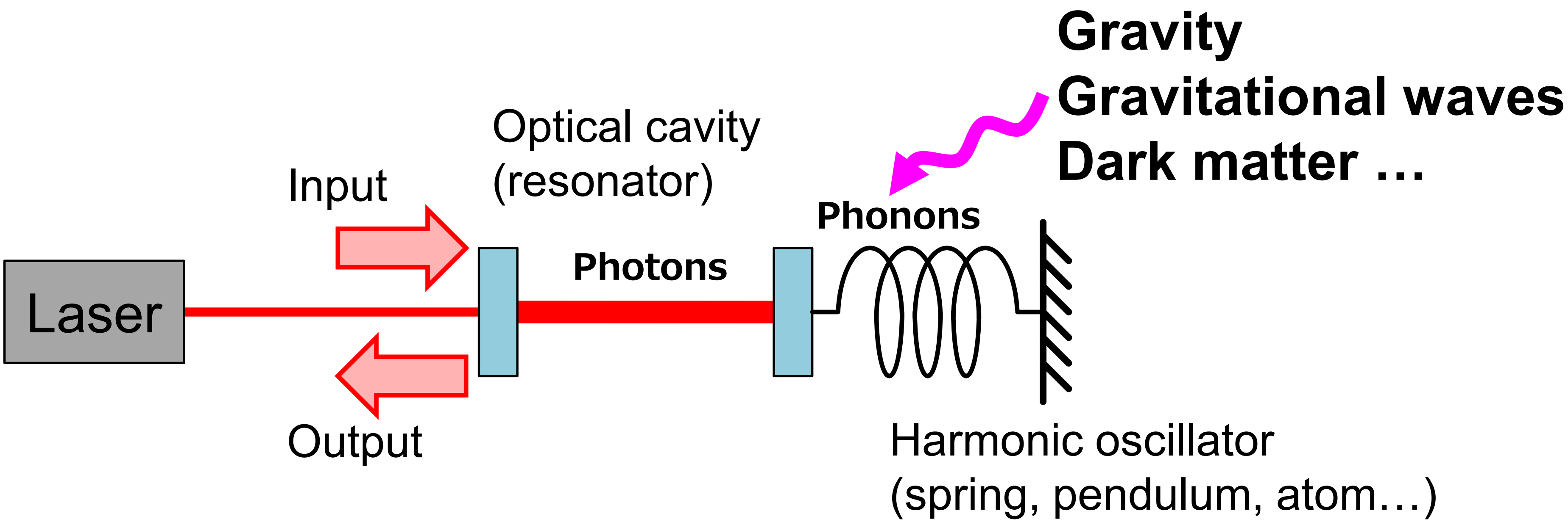
Photodiode

Phase shift
(Frequency shift)

Harmonic oscillator
(spring, pendulum, atom…)

Cavity Optomechanics

- Interaction between light and mechanical oscillators



- Usually, optical cavities are involved to enhance the interaction → Cavity Optomechanics

For a review, see

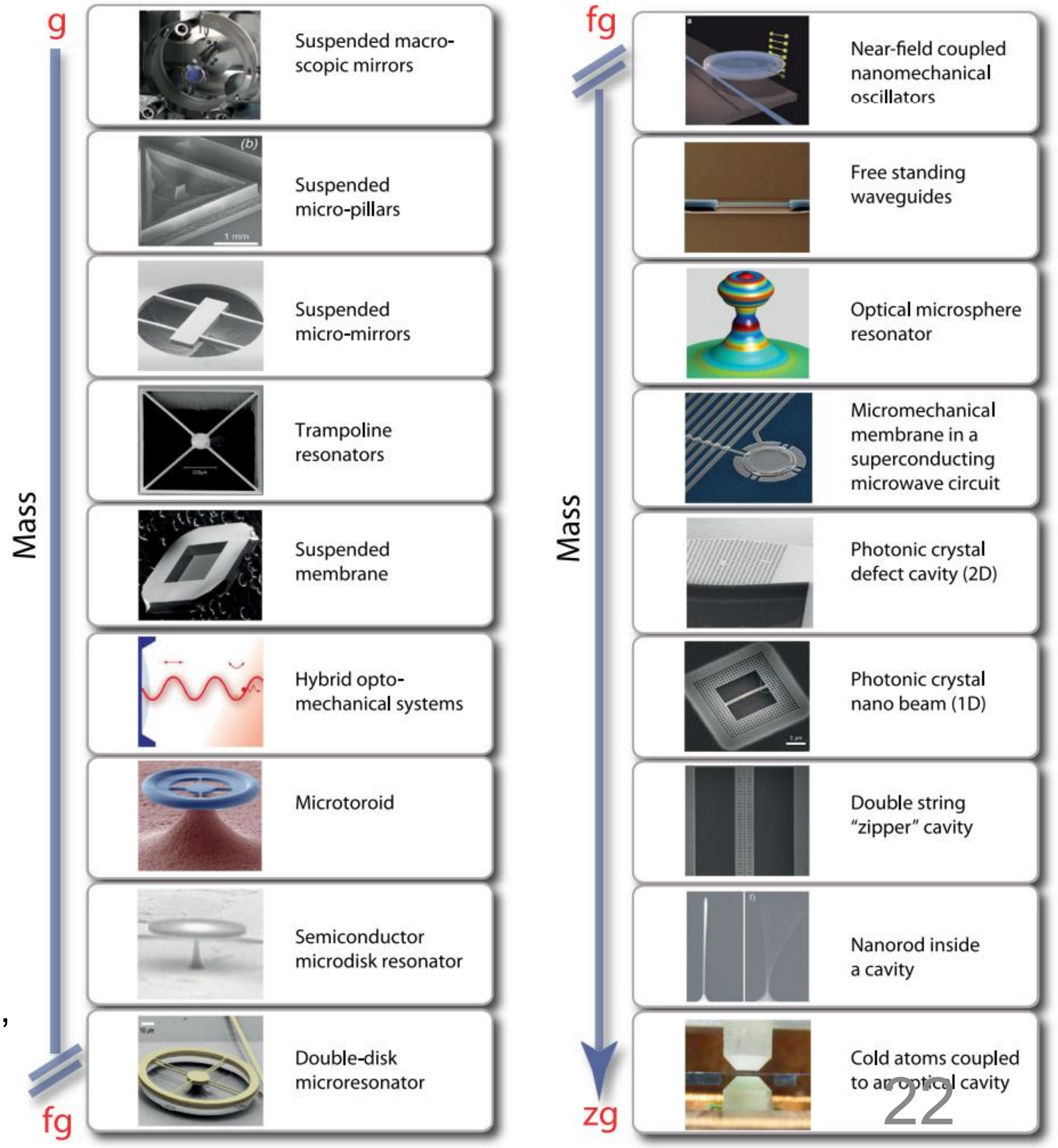
Cavity optomechanics

Aspelmeyer, Kippenberg, Marquardt, Rev. Mod. Phys. 86, 1391 (2014)

Macroscopic Quantum Mechanics

Yanbei Chen, J. Phys. B: At. Mol. Opt. Phys. 46, 104001 (2013)

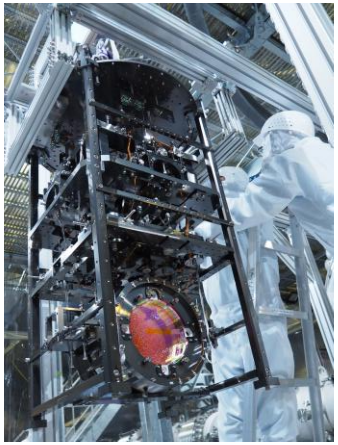
Various Mass Scales



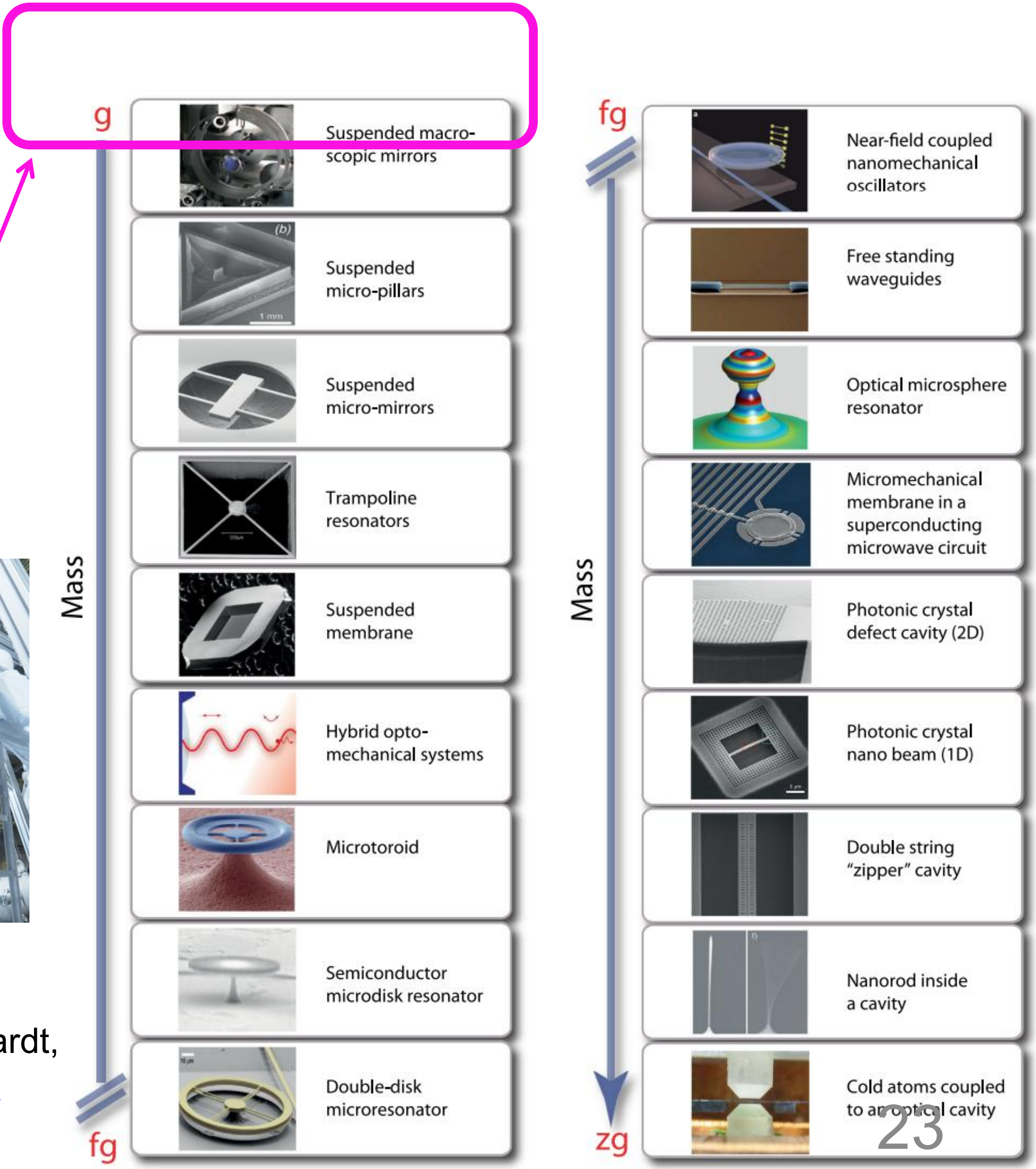
Aspelmeyer, Kippenberg, Marquardt, [Rev. Mod. Phys. 86, 1391 (2014)]

Various Mass Scales

My experiments in mg to kg scale

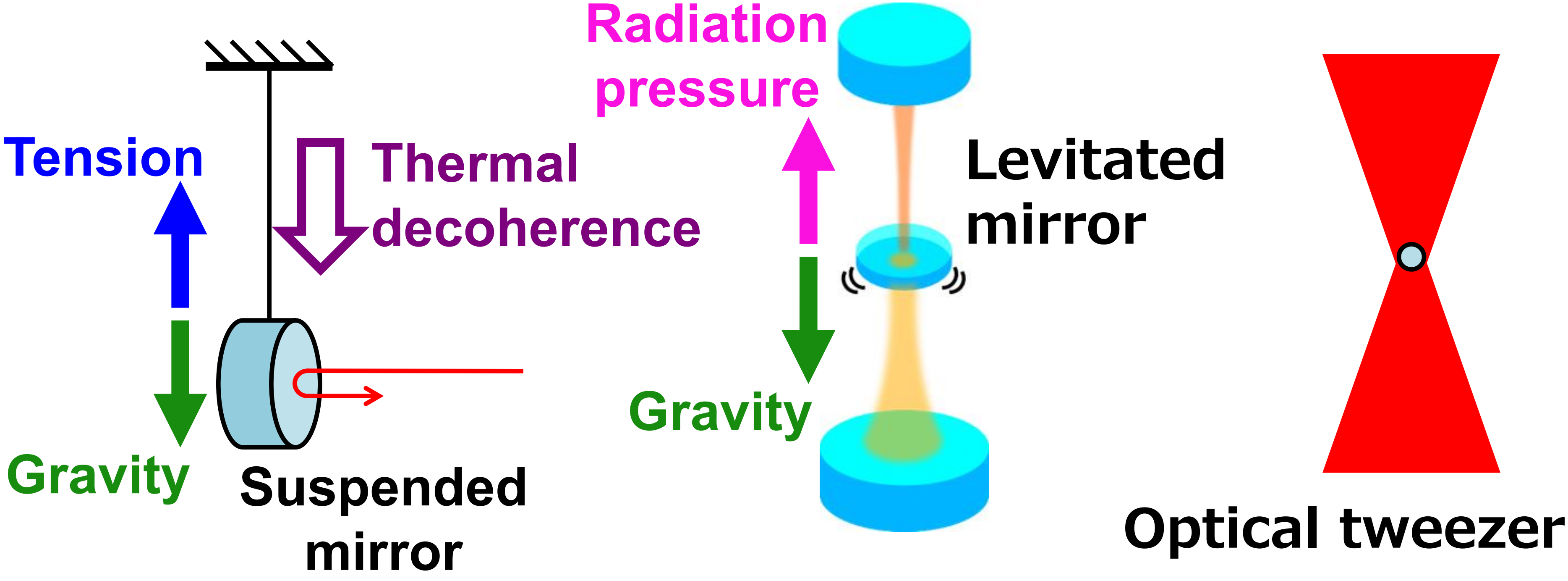


Aspelmeyer, Kippenberg, Marquardt, [Rev. Mod. Phys. 86, 1391 (2014)]



Optical Levitation of Mirrors

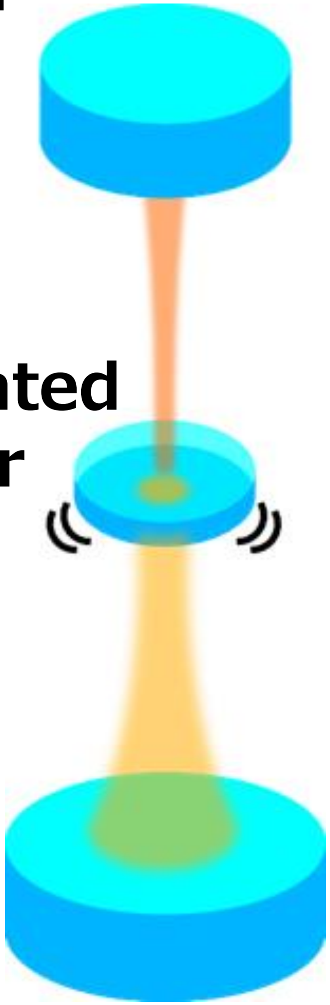
- Support a mirror with radiation pressure alone
- Free from thermal decoherence from mechanical support
- Large coupling compared with optical tweezers



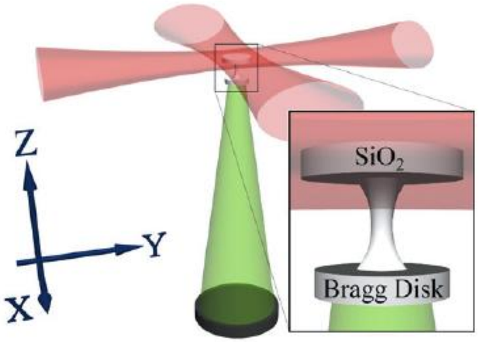
Sandwich Configuration

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

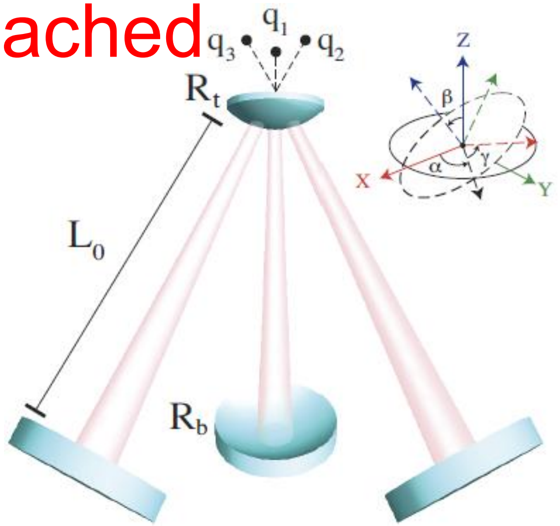
  YM, Y. Kuwahara+, Optics Express 25, 13799 (2017)
- Proved that stable levitation is possible and standard quantum limit (SQL) can be reached with 0.2 mg mirror



Levitated mirror



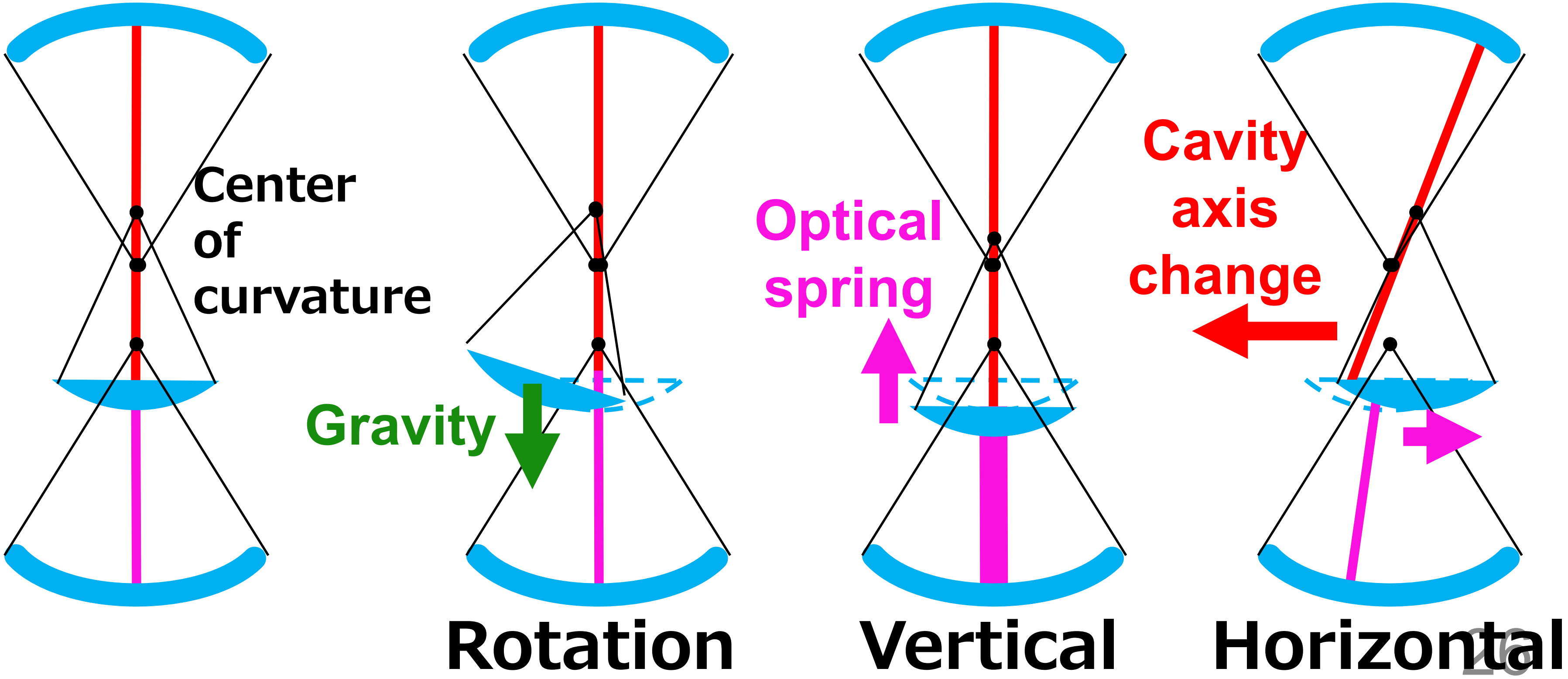
S. Singh+: PRL 105, 213602 (2010)



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

Stability of Levitation

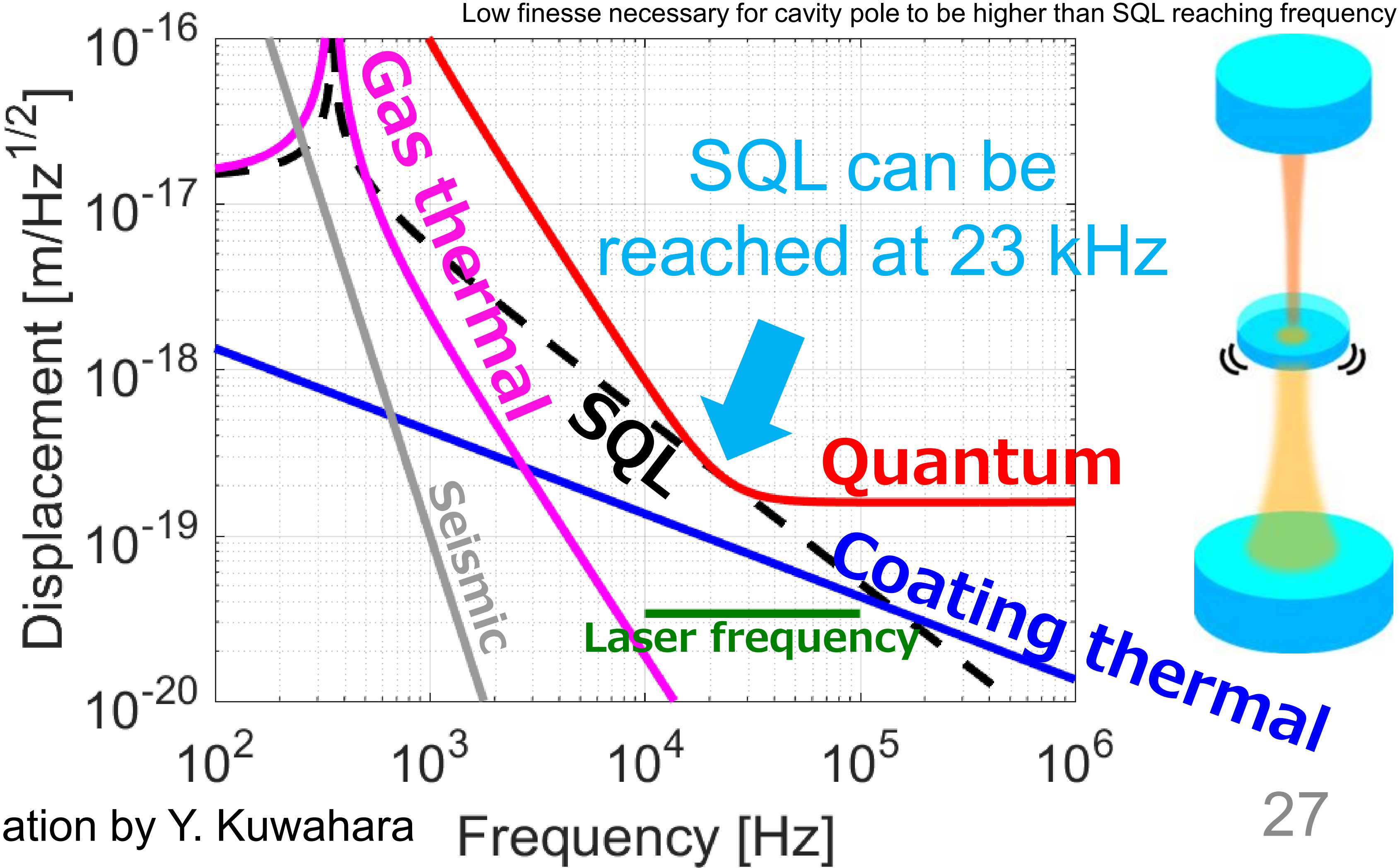
- Rotational motion is stable with gravity
- Vertical motion is stable with optical spring
- Horizontal motion is stable with cavity axis change
- *Curved mirror is necessary!*



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



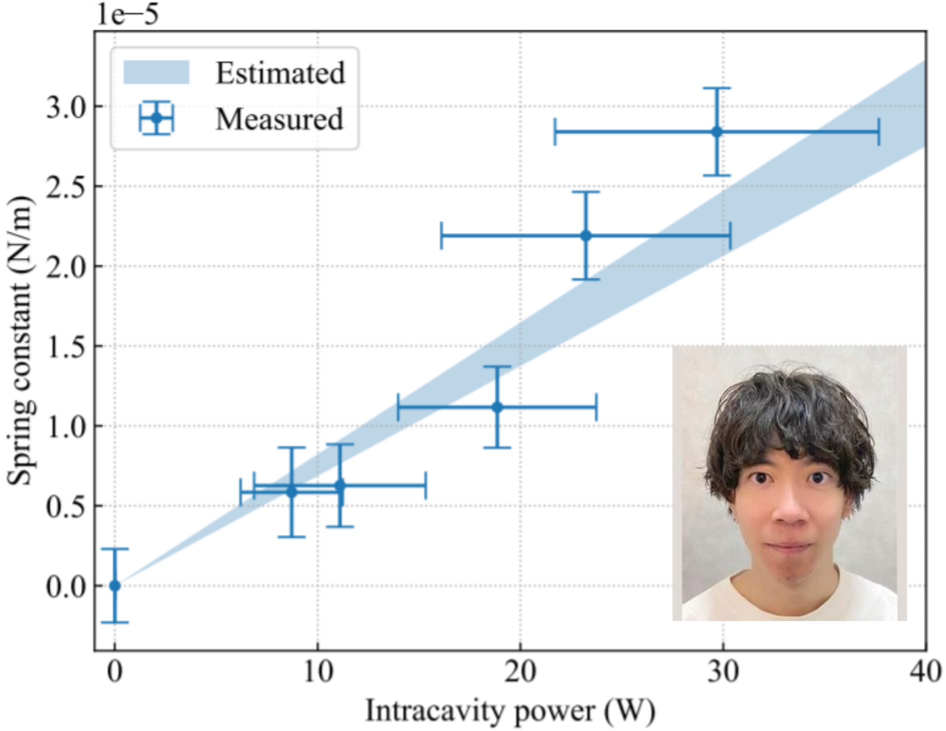
Calculation by Y. Kuwahara

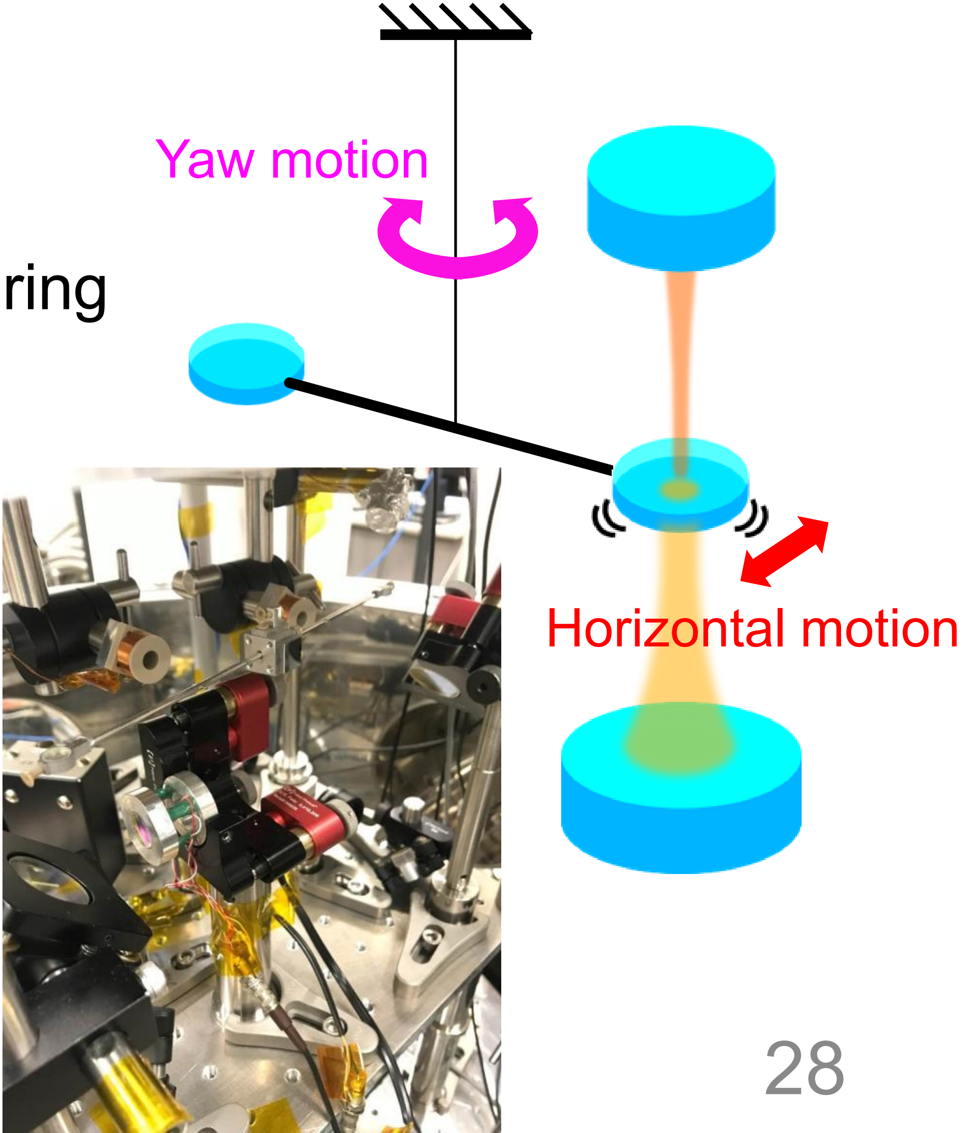
Experiment to Verify the Stability

- 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:

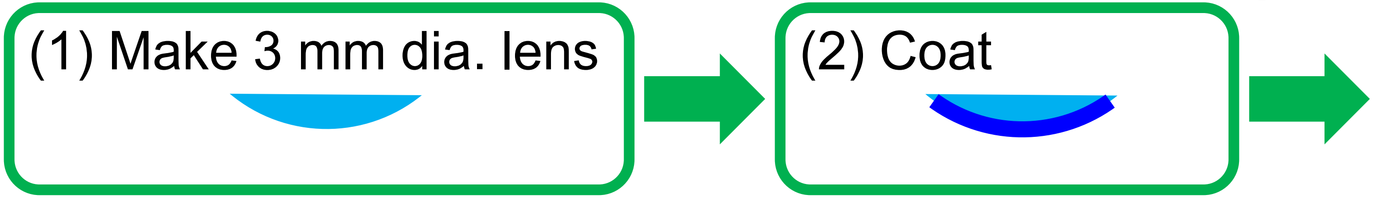
φ 3 mm, 0.1 mm thick (~1.6 mg for fused silica)
Curvature RoC = ~30 mm convex
Reflectivity R > 99.95 %
Absorption A < ~0.5 ppm (LIGO, Virgo, KAGRA level)

- 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

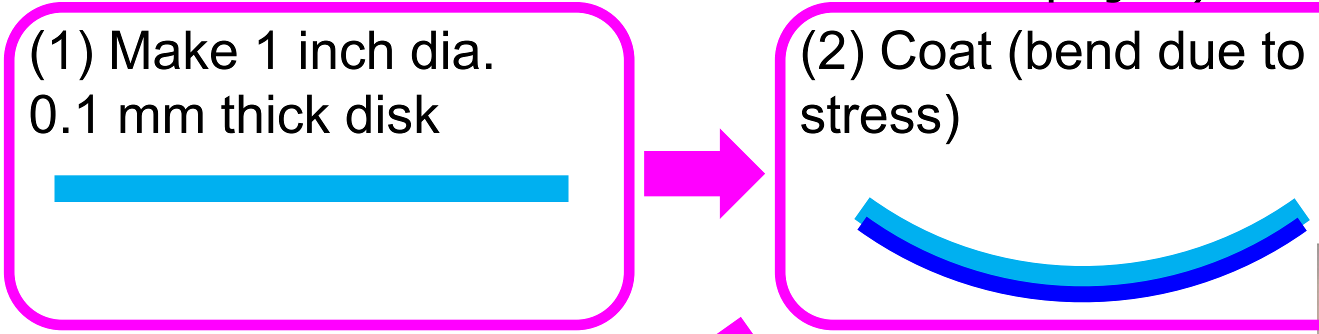
2014 Approach (Company in Japan)


(1) Make 3 mm dia. lens

(2) Coat

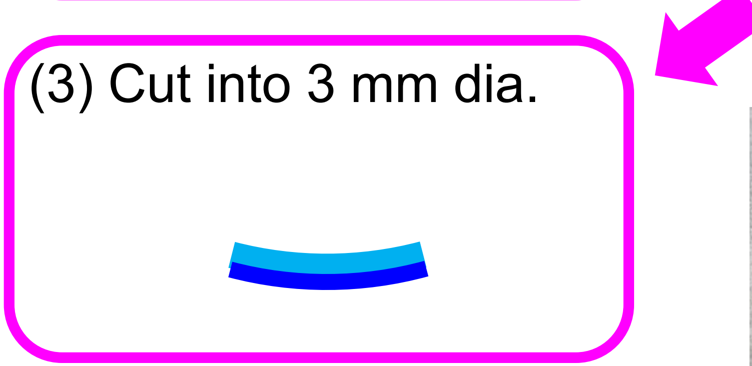
2020- Approach

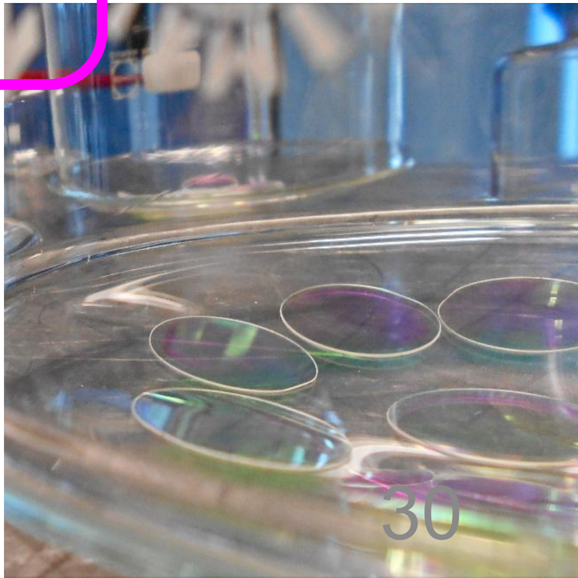
(2018-2024 JST CREST、
2025-2027 JSPS Bilateral program)


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

(2) Coat (bend due to stress)

LABORATOIRE MATÉRIAUX AVANCÉS

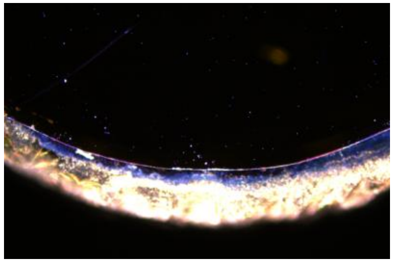

(3) Cut into 3 mm dia.

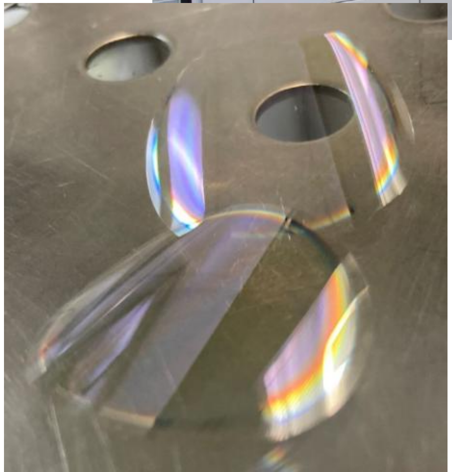


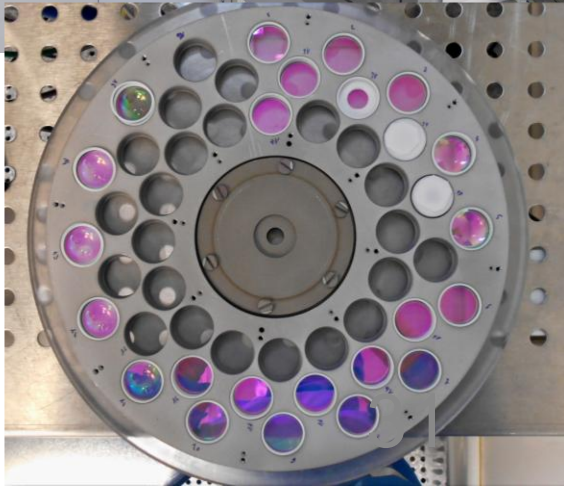
Fabrication Status in LMA

- 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





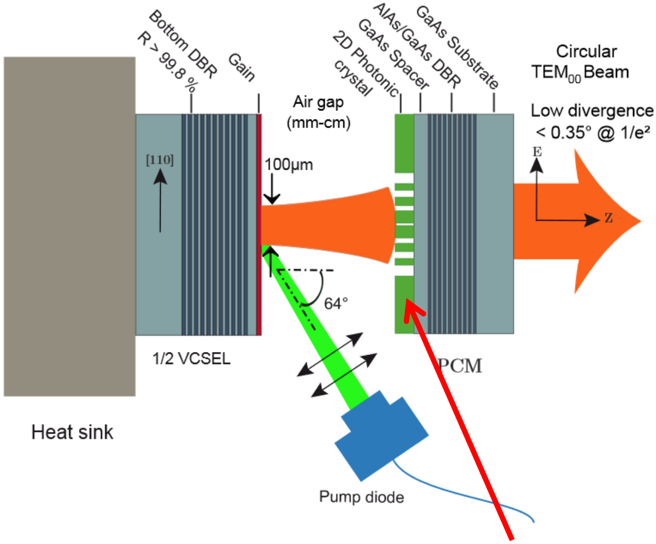


M. Croquette+, AVS Quantum Science **5**, 014403 (2023)

Alternative Approach?

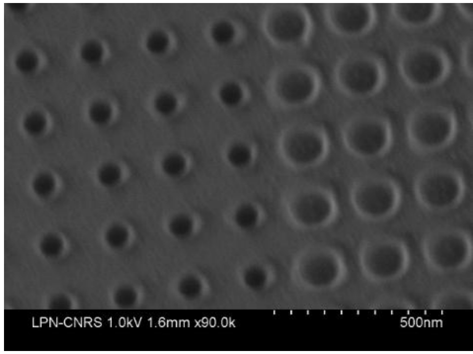
- Photonic crystal (meta-surface) could be used
- By modulating groove width, effective curvature is realized

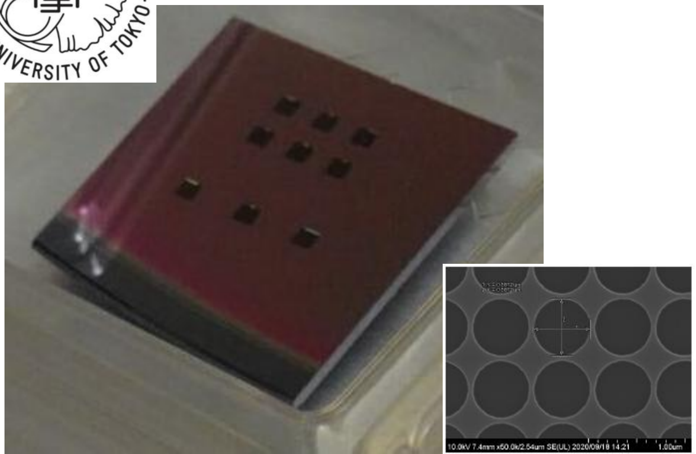
  M. S. Seghilani+,
  [Optics Express 22, 5962 (2014)]()

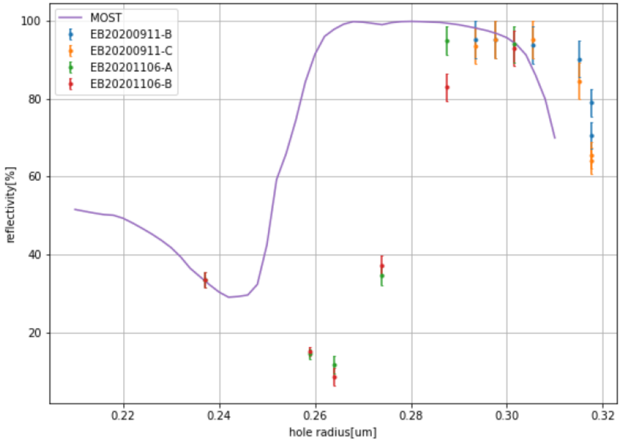


- In 2020, we once tried fabricating Si photonic crystal at Iwamoto Group in IIS, UTokyo

  Achieved R=95(5)% @ 1064 nm



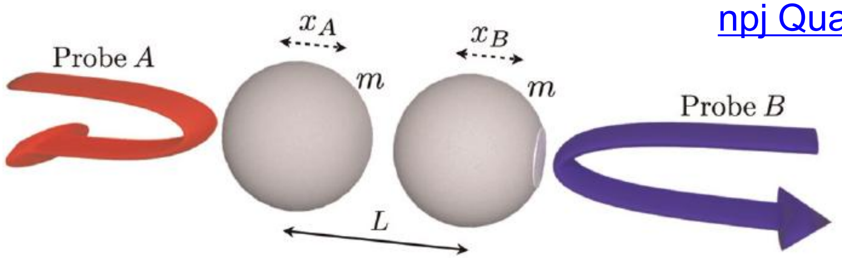




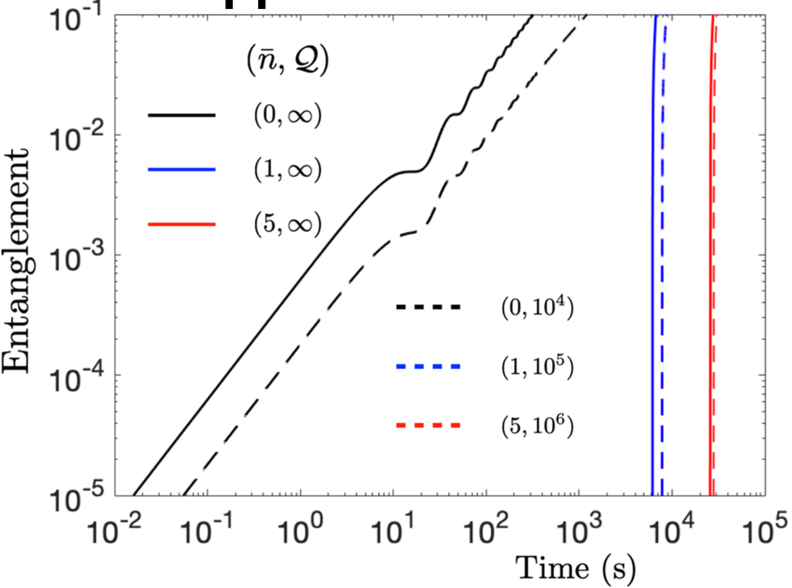
How to Test Gravity Entanglement

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

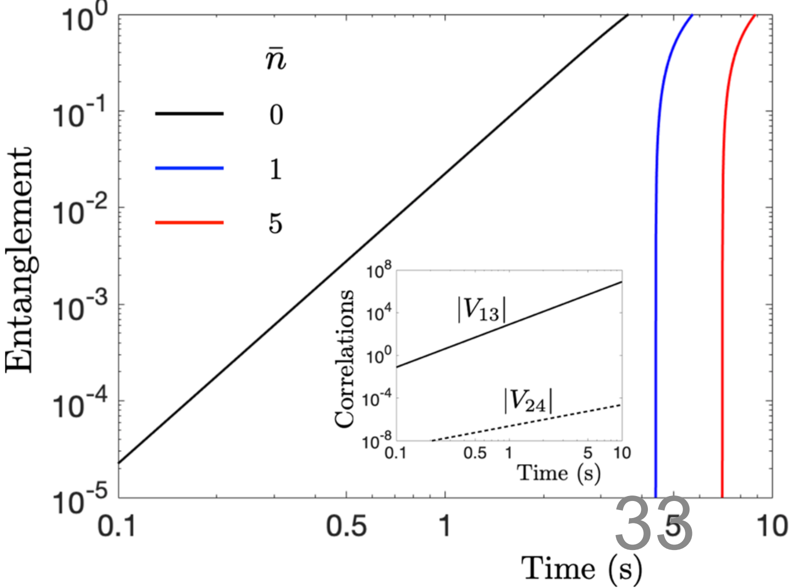
T. Krisnanda+,
npj Quantum Information **6**, 12 (2020)



Trapped case

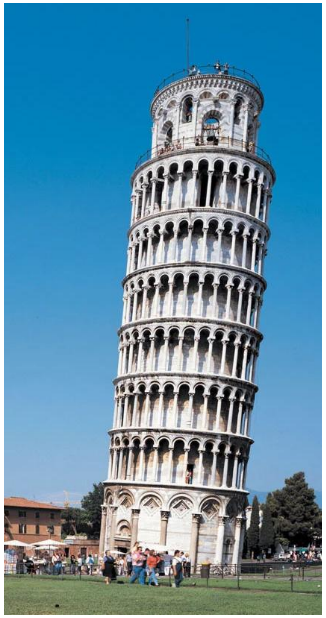


Released case



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…



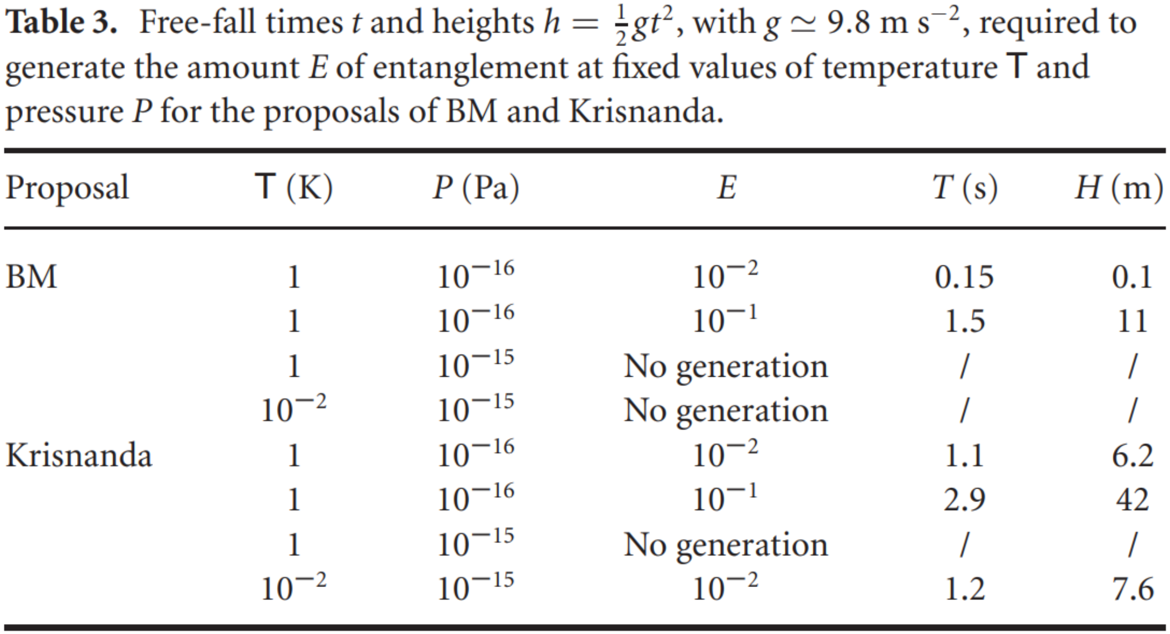


Table 3. Free-fall times t and heights $h = \frac{1}{2}gt^2$, with $g \simeq 9.8$ m s^{-2}, required to generate the amount E of entanglement at fixed values of temperature T and pressure P for the proposals of BM and Krisnanda.

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

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

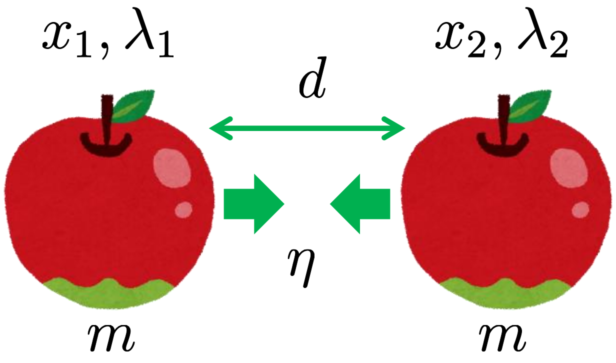
Distance between masses

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

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 $\lambda \equiv \lambda_1 = \lambda_2$

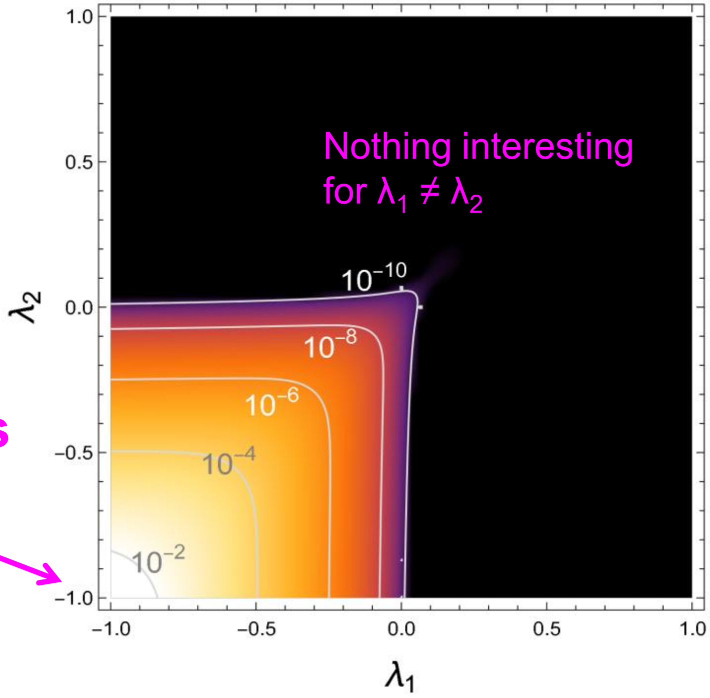
$$E_N \simeq 3[\eta f_{\rm gra}(t) - \mu f_{\rm dec}(t)]$$

Strength of gravitational coupling

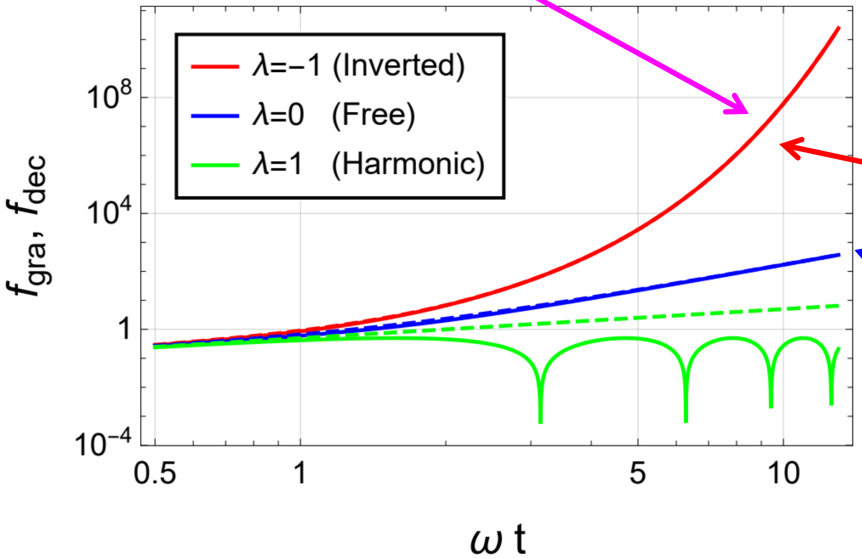
Amount of decoherence

Exponential growth of entanglement

Inverted oscillators are the best



Nothing interesting for $\lambda_1 \neq \lambda_2$



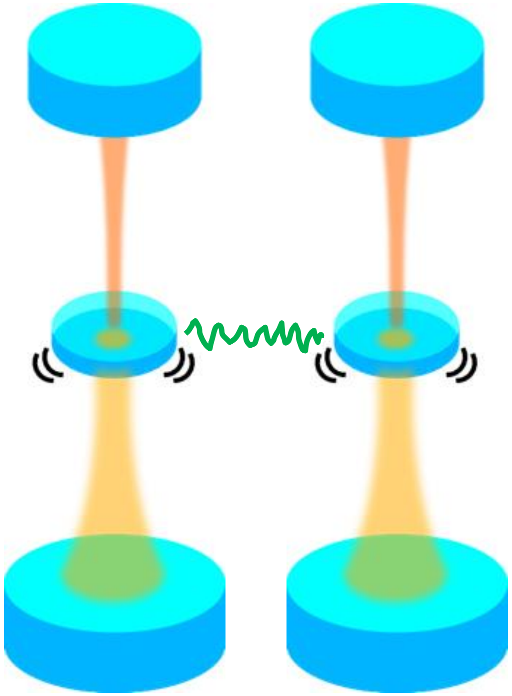
$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8} e^{2\omega t}$$

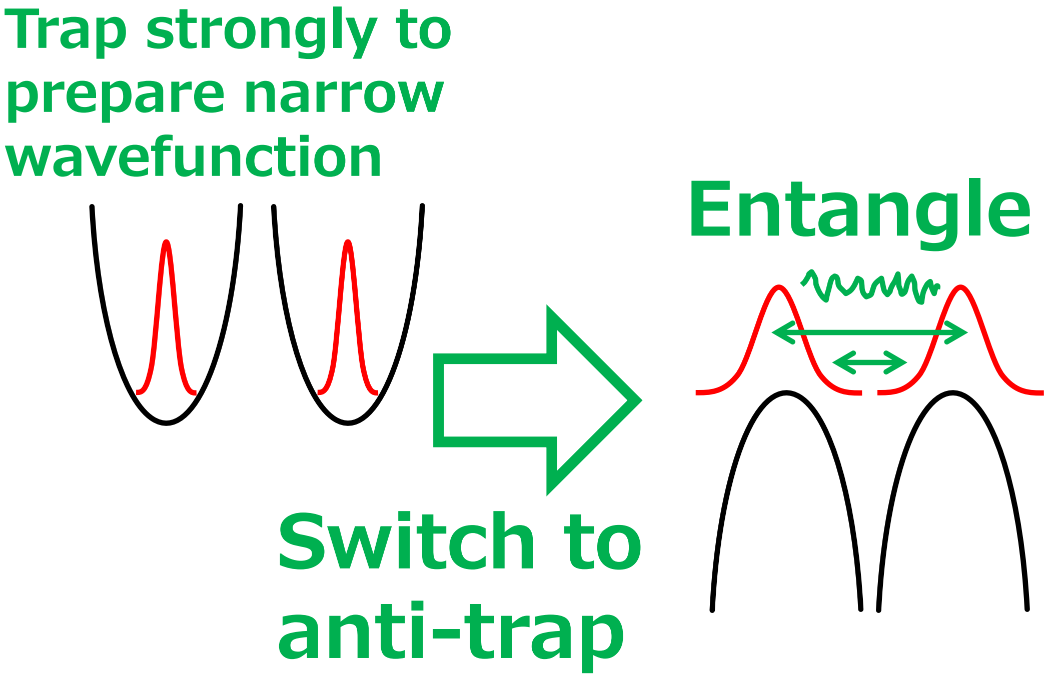
$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8} (\omega t)^3$$

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

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





Trap strongly to prepare narrow wavefunction

Switch to anti-trap

Entangle

Example Setup

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

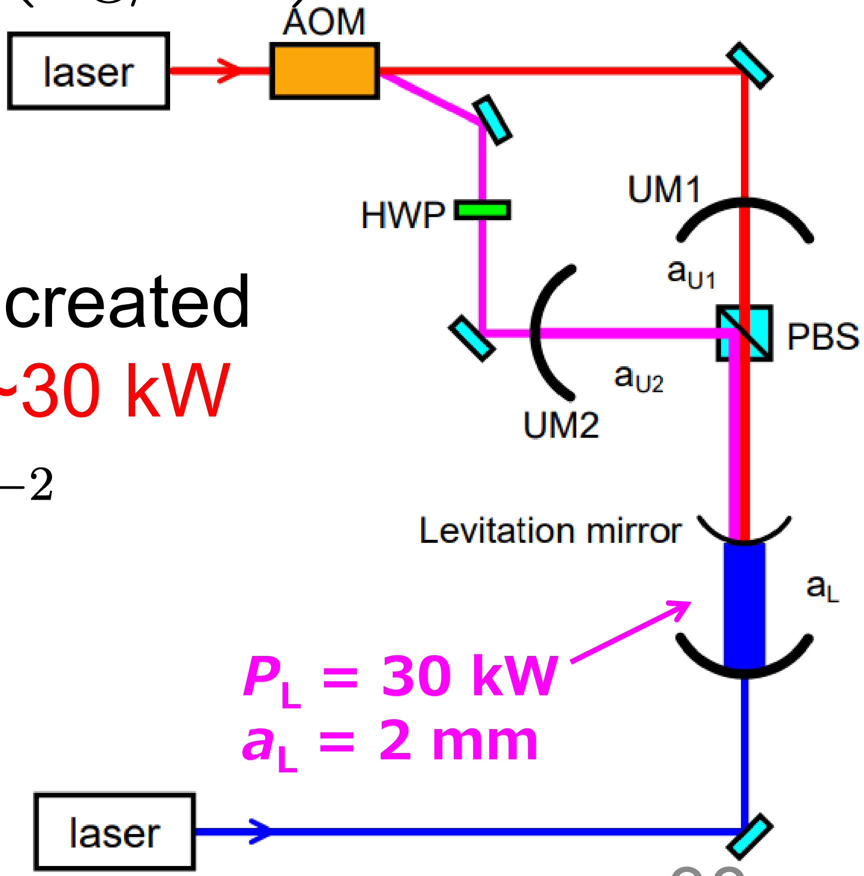
$$\mu << \eta = 2.7 \times 10^{-13}\omega_{\mathrm{kHz}} \left(\frac{m/d^3}{2\,\mathrm{g/cm^3}}\right)$$

- 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

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

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

Still, Decoherence is the Issue

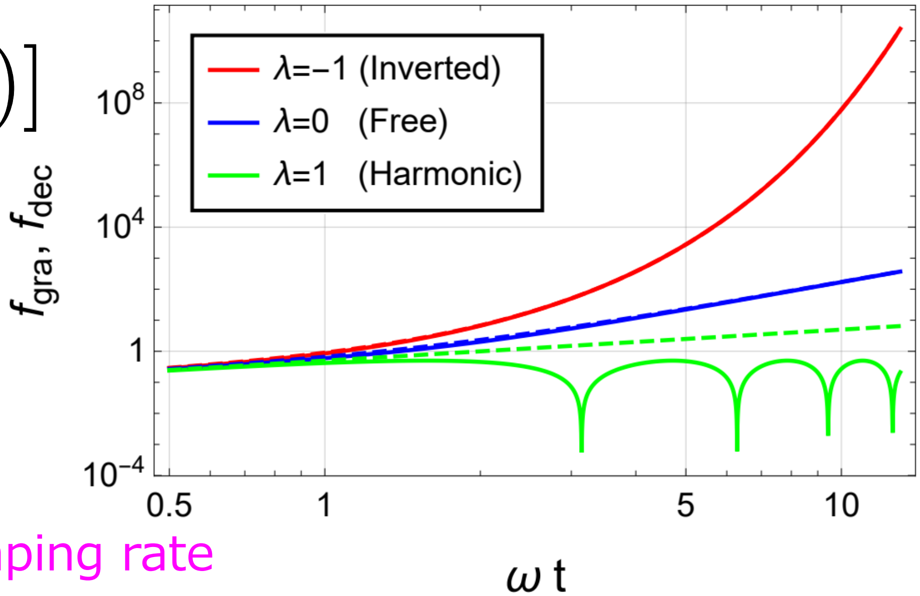
- Decoherence effects also increases exponentially with inverted oscillators

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

Gravity

Decoherence

Logarithmic negativity



- $\eta > \mu$ is required

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

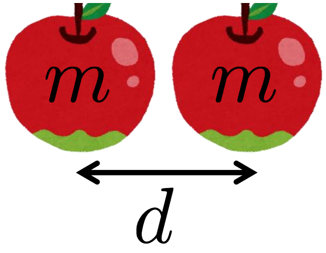
Damping rate

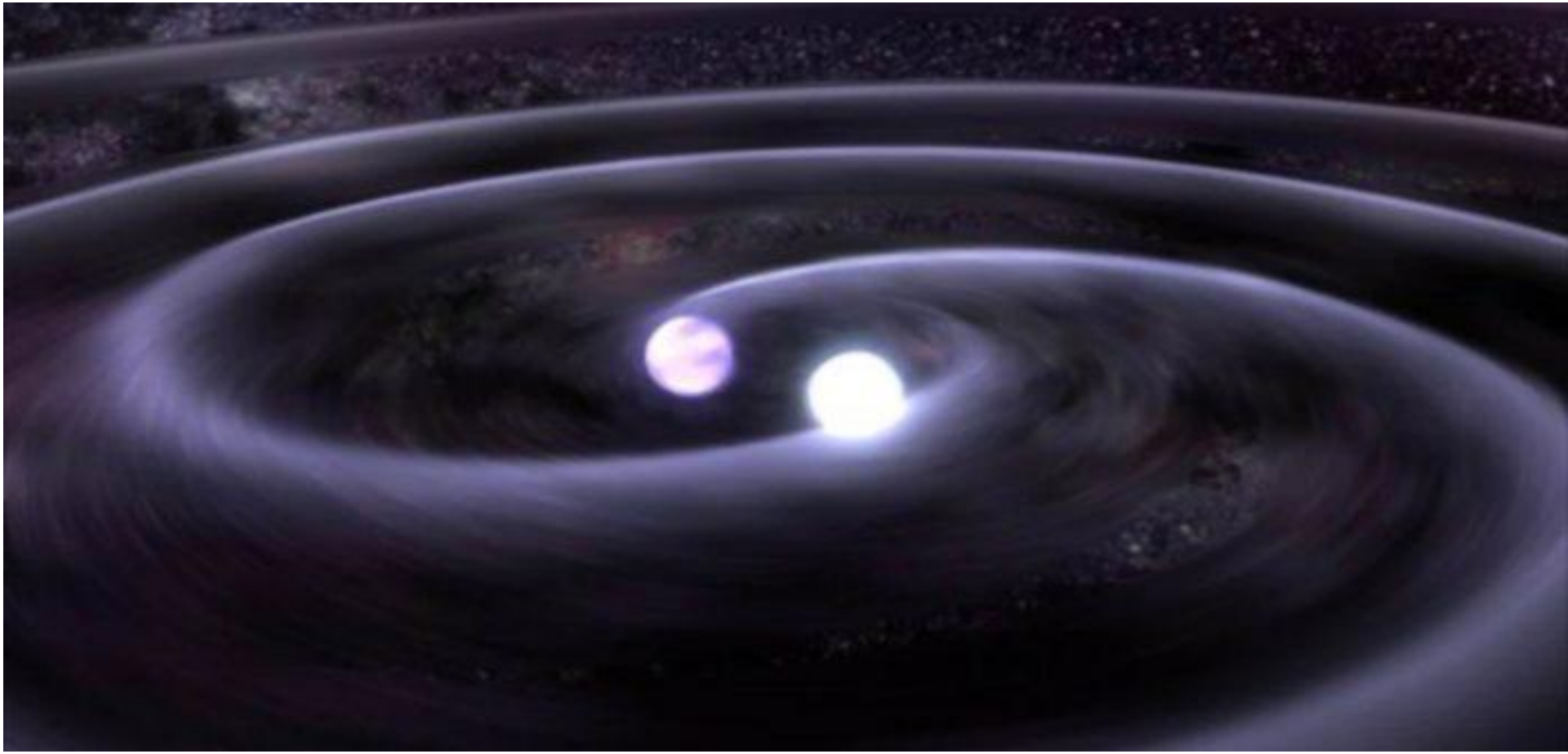
For 300 K

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

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

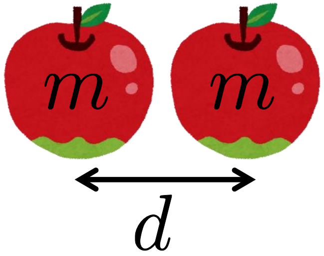
Fused silica: 2 g/cm^3 Osmium: 22 g/cm^3





Neutron star density 10^{15} g/cm^3
and temperature 10^6 K gives

$$\gamma_{\mathrm{m}} < \frac{\hbar G m}{k_{\mathrm{B}} T_{\mathrm{th}} d^3} \sim 10^{-10}\,\mathrm{Hz}\frac{m/d^3}{10^{15}\,\mathrm{g/cm^3}}$$



Comparison with $f \cdot Q$ Criterion

- Necessary condition for ground state cooling

$$f_{\mathrm{m}} Q_{\mathrm{m}} \gg \frac{k_{\mathrm{B}} T_{\mathrm{th}}}{\hbar} \simeq 6 \times 10^{12} \left(\frac{T_{\mathrm{th}}}{300\,\mathrm{K}} \right)$$

Resonant frequency

Q-value

$$Q_{\mathrm{m}} \equiv \frac{\omega_{\mathrm{m}}}{\gamma_{\mathrm{m}}}$$

- Thus,

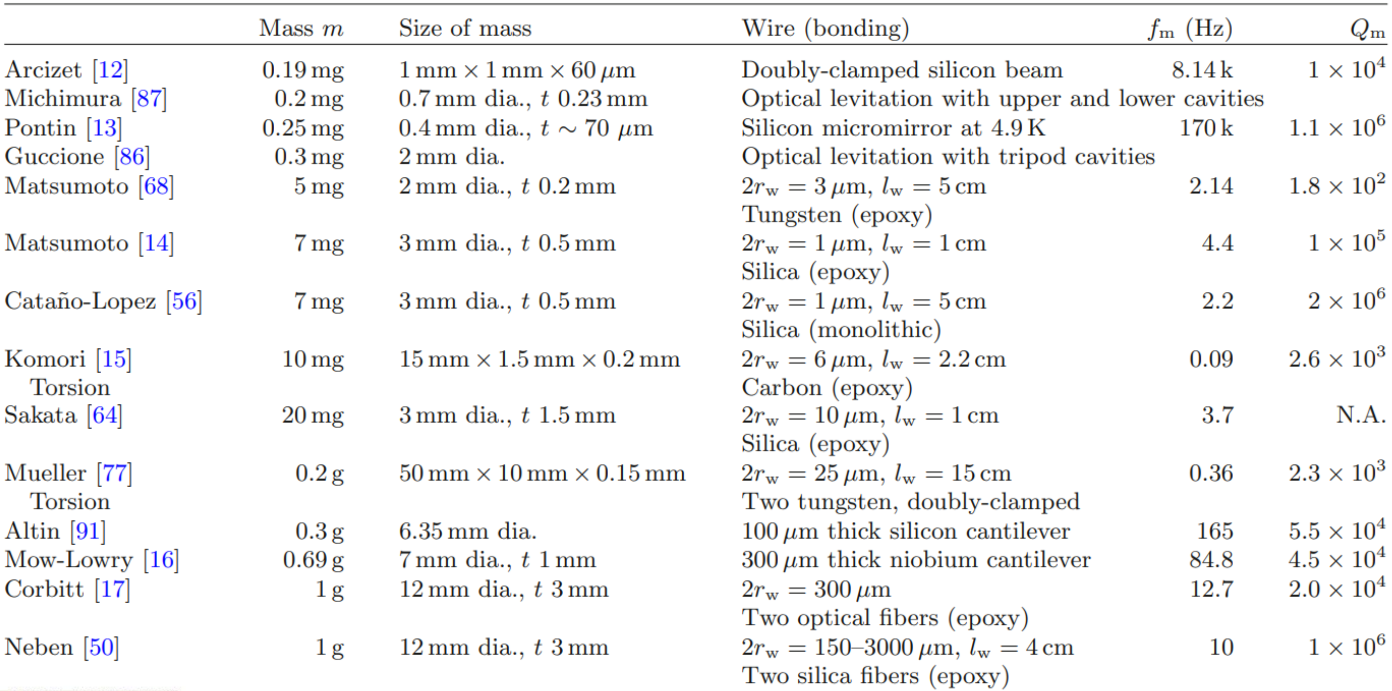
$$\gamma_{m} \ll 1 \times 10^{-12}\,\mathrm{Hz} \left(\frac{f_{\mathrm{m}}}{1\,\mathrm{Hz}} \right) \left(\frac{300\,\mathrm{K}}{T_{\mathrm{th}}} \right)$$

Damping rate

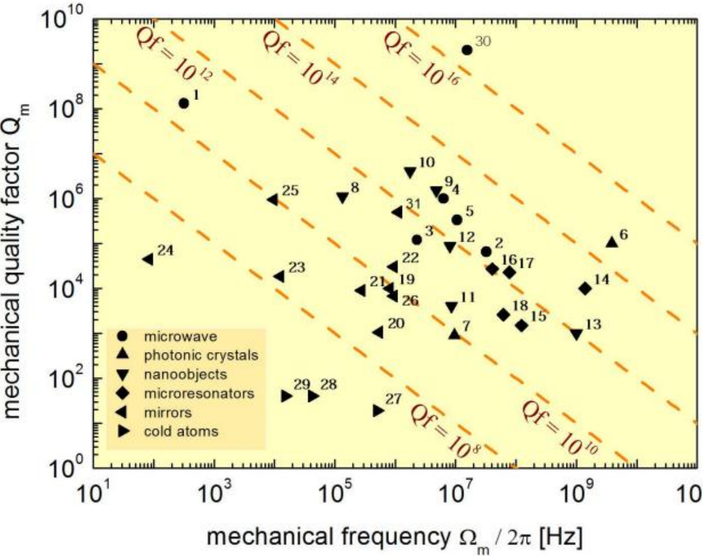
- Criterion for testing gravity induced entanglement is 9 orders of magnitude harder

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

(Outdated) State-of-the-Art



	Mass m	Size of mass	Wire (bonding)	f_m (Hz)	Q_m
Arcizet [12]	0.19 mg	1 mm × 1 mm × 60 μm	Doubly-clamped silicon beam	8.14 k	1×10^4
Michimura [87]	0.2 mg	0.7 mm dia., t 0.23 mm	Optical levitation with upper and lower cavities		
Pontin [13]	0.25 mg	0.4 mm dia., $t \sim 70$ μm	Silicon micromirror at 4.9 K	170 k	1.1×10^6
Guccione [86]	0.3 mg	2 mm dia.	Optical levitation with tripod cavities		
Matsumoto [68]	5 mg	2 mm dia., t 0.2 mm	$2r_\mathrm{w} = 3$ μm, $l_\mathrm{w} = 5$ cm Tungsten (epoxy)	2.14	1.8×10^2
Matsumoto [14]	7 mg	3 mm dia., t 0.5 mm	$2r_\mathrm{w} = 1$ μm, $l_\mathrm{w} = 1$ cm Silica (epoxy)	4.4	1×10^5
Cataño-Lopez [56]	7 mg	3 mm dia., t 0.5 mm	$2r_\mathrm{w} = 1$ μm, $l_\mathrm{w} = 5$ cm Silica (monolithic)	2.2	2×10^6
Komori [15] Torsion	10 mg	15 mm × 1.5 mm × 0.2 mm	$2r_\mathrm{w} = 6$ μm, $l_\mathrm{w} = 2.2$ cm Carbon (epoxy)	0.09	2.6×10^3
Sakata [64]	20 mg	3 mm dia., t 1.5 mm	$2r_\mathrm{w} = 10$ μm, $l_\mathrm{w} = 1$ cm Silica (epoxy)	3.7	N.A.
Mueller [77] Torsion	0.2 g	50 mm × 10 mm × 0.15 mm	$2r_\mathrm{w} = 25$ μm, $l_\mathrm{w} = 15$ cm Two tungsten, doubly-clamped	0.36	2.3×10^3
Altin [91]	0.3 g	6.35 mm dia.	100 μm thick silicon cantilever	165	5.5×10^4
Mow-Lowry [16]	0.69 g	7 mm dia., t 1 mm	300 μm thick niobium cantilever	84.8	4.5×10^4
Corbitt [17]	1 g	12 mm dia., t 3 mm	$2r_\mathrm{w} = 300$ μm Two optical fibers (epoxy)	12.7	2.0×10^4
Neben [50]	1 g	12 mm dia., t 3 mm	$2r_\mathrm{w} = 150$–3000 μm, $l_\mathrm{w} = 4$ cm Two silica fibers (epoxy)	10	1×10^6



In milligram scale

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

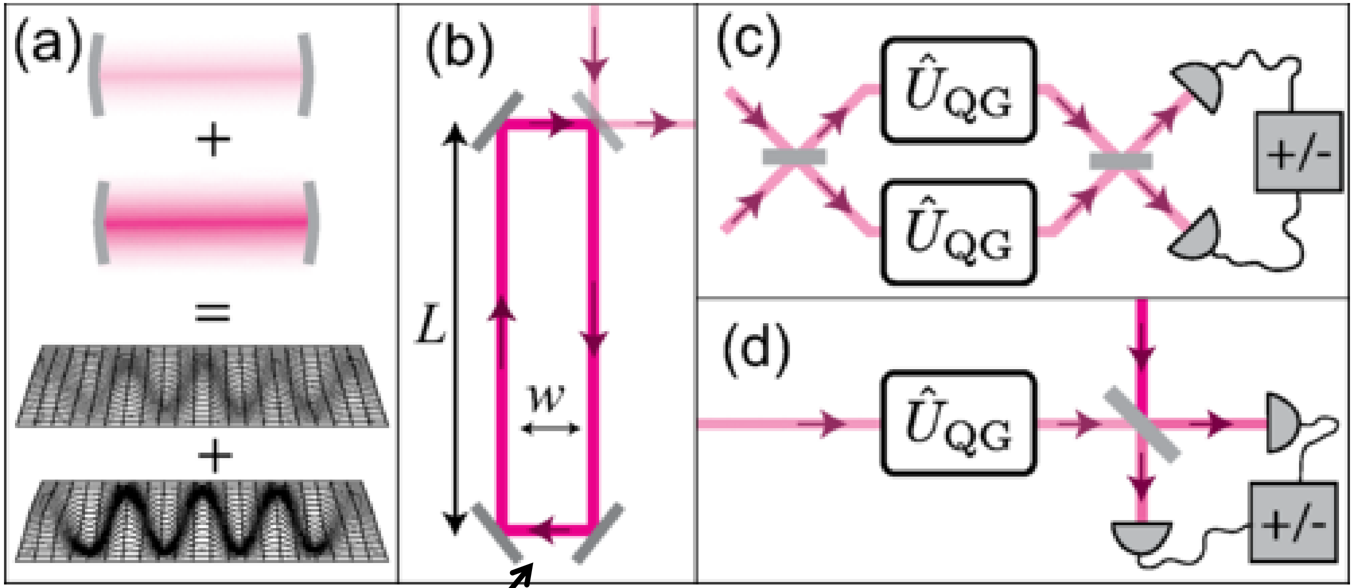
At high frequencies, ground state cooling of 16 μg is realized

Aspelmeyer, Kippenberg, Marquardt, RMP 86, 1391 (2014)

M. Bild+, Science 380, 274 (2023)

Mecha-Free Approach

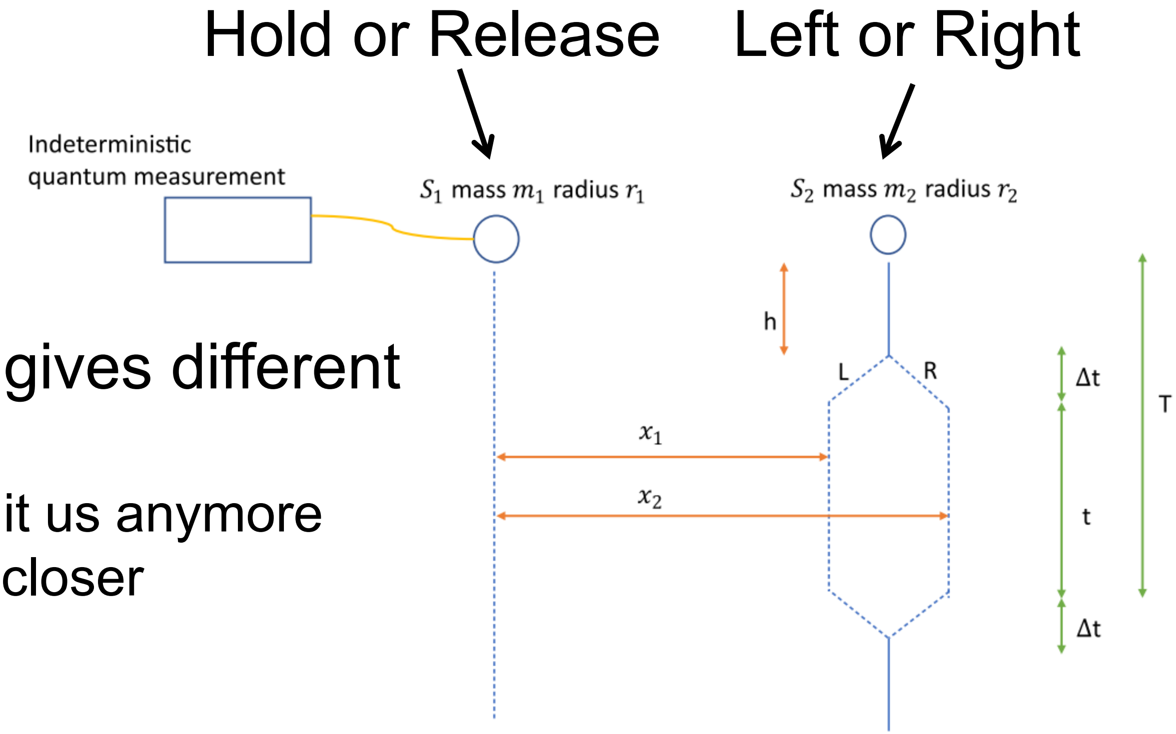
- *Signatures of Quantum Gravity in the Gravitational Self-Interaction of Photons*
  Z. Mehdi+, PRL **130**, 240203 (2023)
- Nonlinear optical effects (Kerr effects, third harmonic generation) from gravity between photons
- Free of QED photon-photon interaction



L=10 km, w=10 cm, 125 MW, for 1 year

Test Near Measurement Event

A. Kent,
PRD **103**, 064038 (2021)



QG and Semiclassical gives different result even S1 is held
- Casimir effect will not limit us anymore
- S1 and S2 can be much closer

	S1 held	S1 released
Quantized gravity	$\lvert\psi(t)\rangle \approx \frac{1}{\sqrt{2}}(\lvert L\rangle + \lvert R\rangle)$	$\lvert\psi(t)\rangle \approx \frac{1}{\sqrt{2}}\exp(i\phi_L t)(\lvert L\rangle + \exp(i(\phi_R - \phi_L)t)\lvert R\rangle)$
Semiclassical gravity	$\lvert\psi(t)\rangle \approx \frac{1}{\sqrt{2}}\exp(i\phi_L t/2)(\lvert L\rangle + \exp(i(\phi_R - \phi_L)t/2)\lvert R\rangle)$	

不射之射

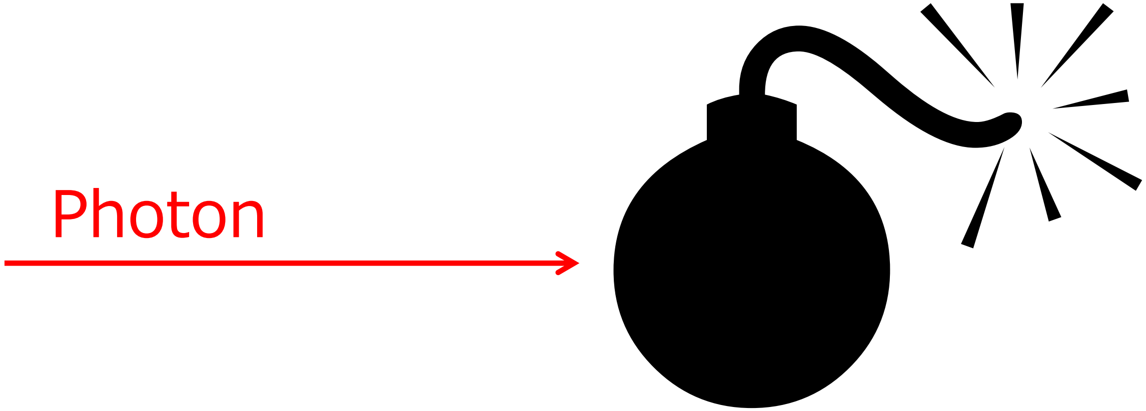
- 弓矢の要る中はまだ射之射じゃ。
  不射之射には、烏漆の弓も粛慎の矢もいらぬ。
  うしつ　しゅくしん

- While one still needs bow and arrow, it is yet “the shooting of shooting.”
  In “the shooting of non-shooting,” no black-lacquered bow and no Sushen arrows are necessary.

Atsushi Nakajima (1942)
The Legend of the Greatest Master

Elitzur-Vaidman Bomb Tester

- Bombs that absorb a photon and explode
- Some bombs are duds
  they do not absorb photons, just transmits
- Can we identify the functional bombs without exploding all of them?



Avshalom C. Elitzur, Lev Vaidman,
[Foundations of Physics 23, 987 (1993)]

Interaction Free Measurement

- Mach-Zehnder interferometer with a single photon
- If detected by A, it is functional bomb (some explodes)

Single photon source

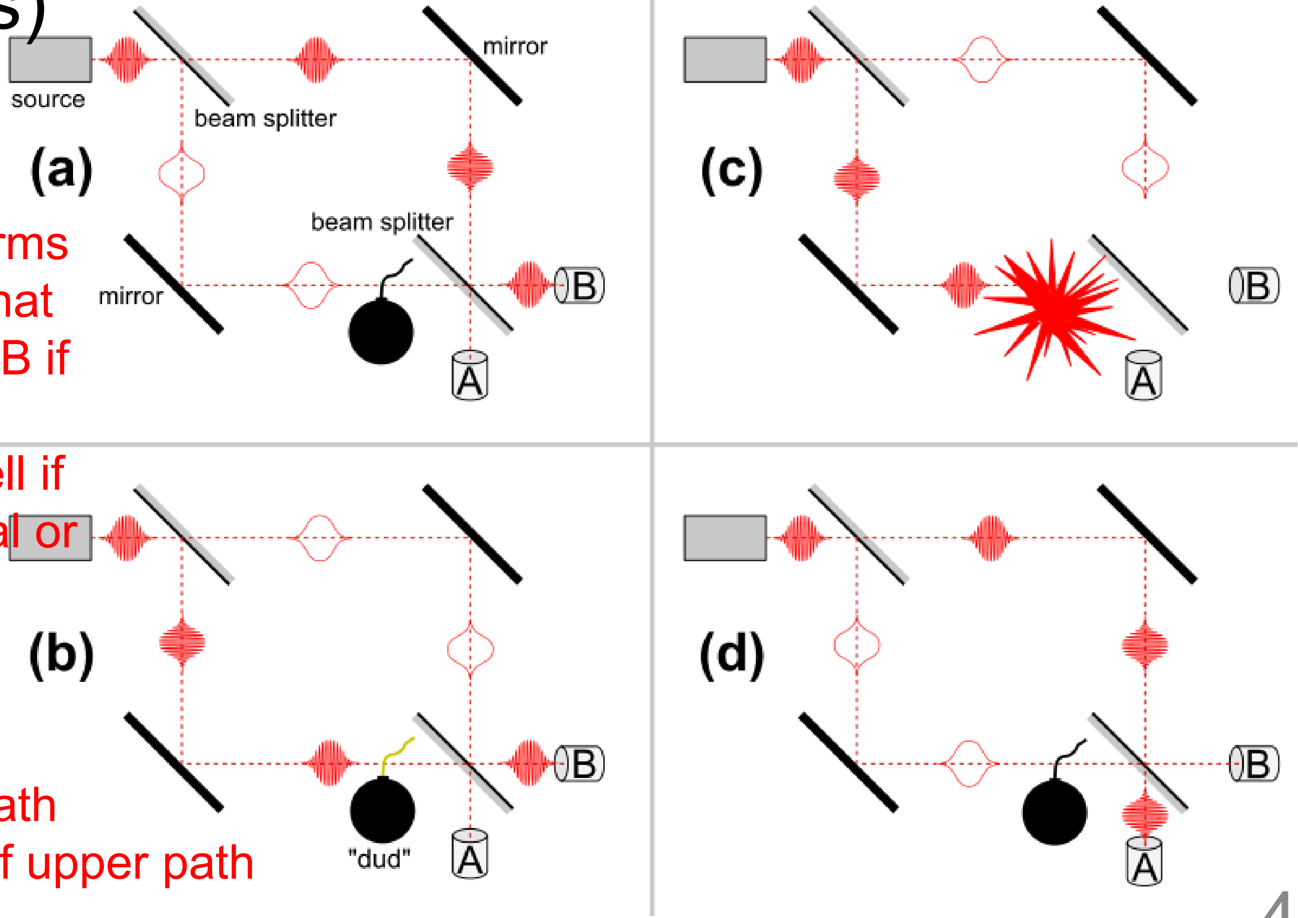
The interferometer arms are controlled such that all the photons go to B if no bomb.

Photon at B do not tell if the bomb is functional or not

For functional bomb

  Explodes if lower path

  Detected at A or B if upper path



https://commons.wikimedia.org/wiki/File:Elitzur-Vaidman_bomb_tester.svg

Experimental Demonstrations

- P. Kwiat+: Phys. Rev. Lett. 74, 4763 (1995)

  Half of functional bombs explodes
- In principle, all of the functional bombs can be distinguished by using quantum Zeno effect

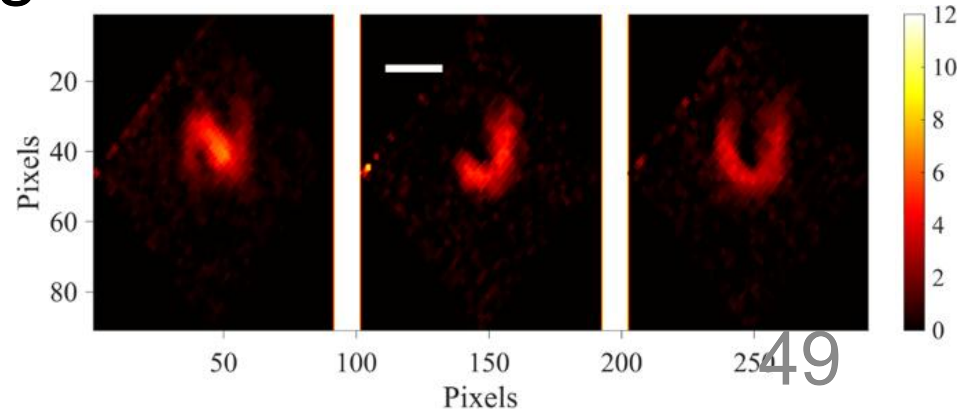
  the suppression of quantum time evolution by frequent measurements

  W. N. Itano+: Phys. Rev. A 41, 2295 (1990)
- Also already demonstrated

  P. G. Kwiat+: Phys. Rev. Lett. 83, 4725 (1999)
- Can be used for imaging

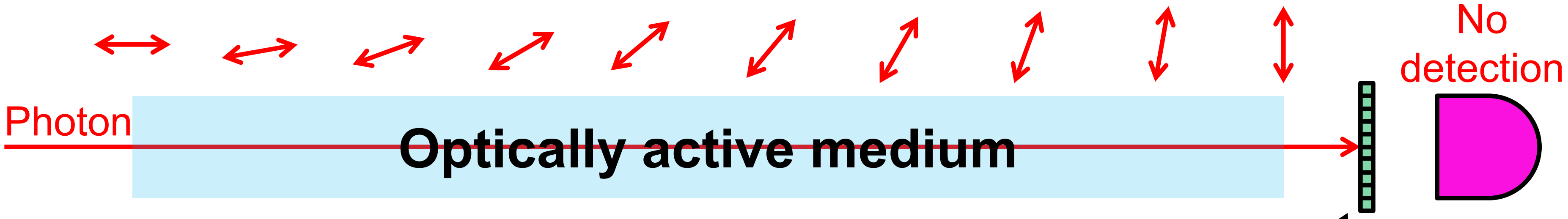
  (cell imaging without illuminating the cell)

  Y. Yang+, npj Quantum Information 9, 2 (2023)

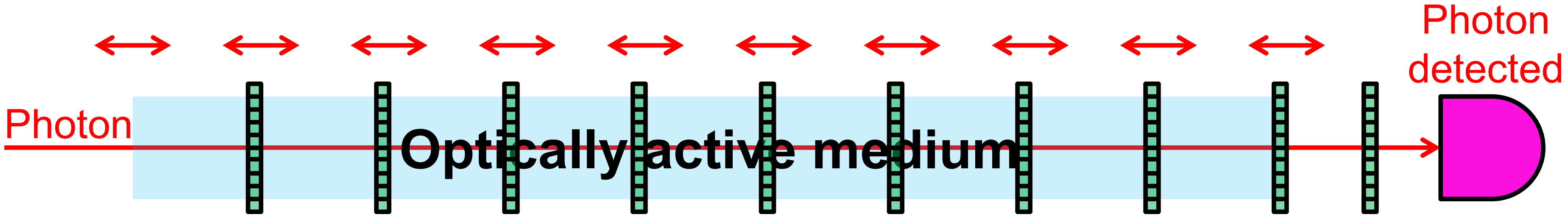


Example of Quantum Zeno Effect

- Polarization do not rotate if frequently measured



$$A = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$



$$A = \left[\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \begin{pmatrix} \cos(\theta/N) & -\sin(\theta/N) \\ \sin(\theta/N) & \cos(\theta/N) \end{pmatrix} \right]^N = \begin{pmatrix} \cos^N(\theta/N) & -\sin^N(\theta/N) \\ 0 & 0 \end{pmatrix}$$

↑ Polarizer

↑ Medium divided into N segments

$$\xrightarrow[N\to\infty]{} \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

Quantum Interrogation Meas.

- Inject p-pol and extract after N round trips
  - If p-pol, functional bomb (frequent measurement)
    From quantum Zeno effect, do not explode if N→∞
  - If s-pol, dud (no measurement)
- Efficiency of 73% achieved with N=15

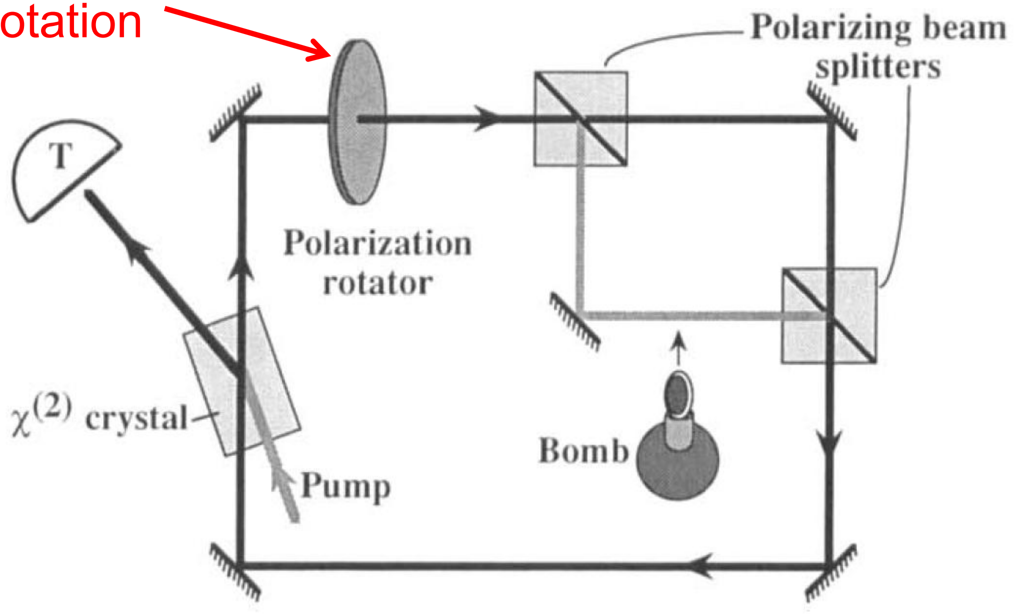


FIGURE 6. Simplified schematic of one method to observe a greater than 50% interaction-free measurement. The downconversion photon makes N cycles before being removed (due to geometry or a fast switch) and its polarization measured.

P. Kwiat+: Ann. N. Y. Acad. Sci. 755, 383 (1995)

Role of Quantum Measurements

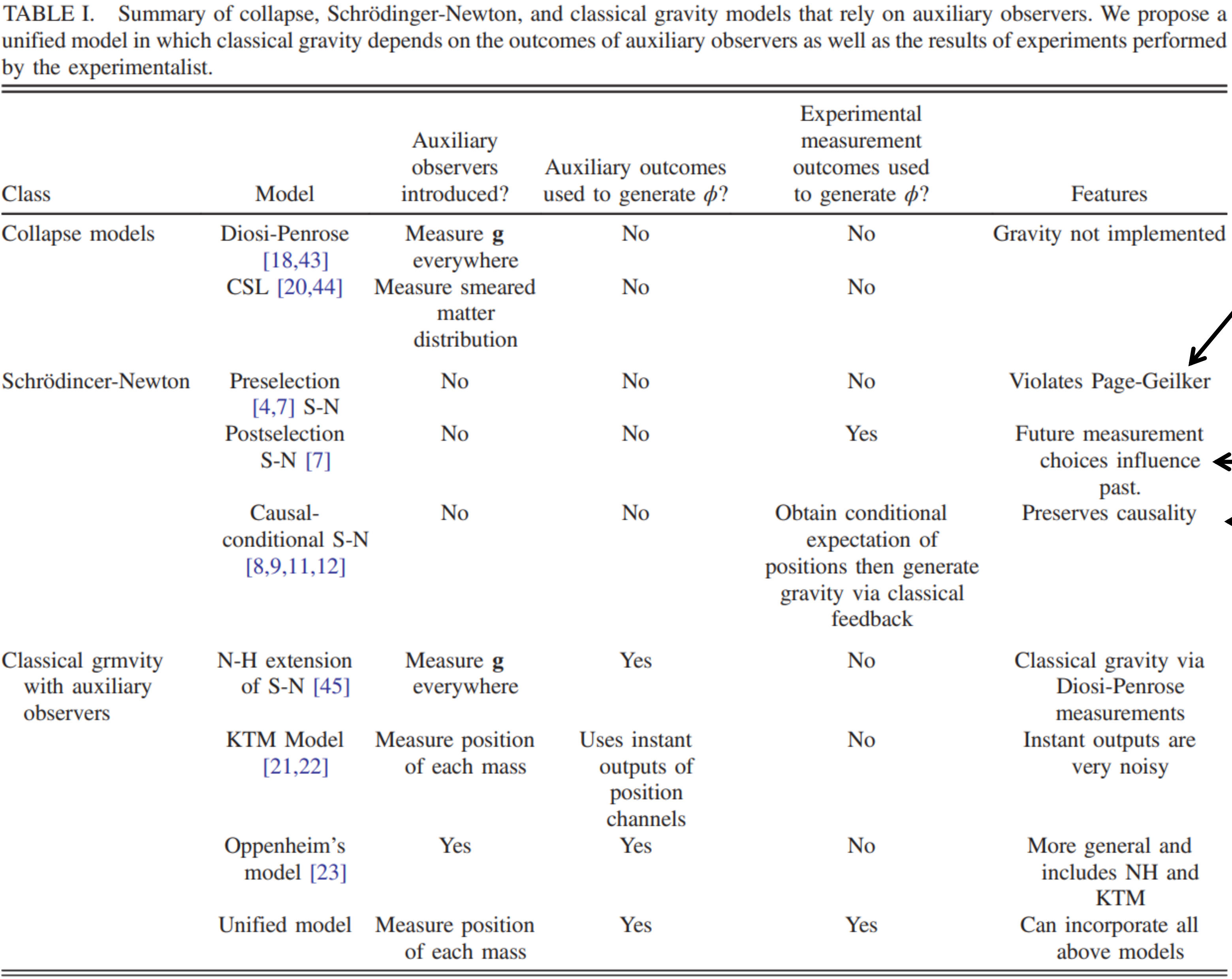


TABLE I. Summary of collapse, Schrödinger-Newton, and classical gravity models that rely on auxiliary observers. We propose a unified model in which classical gravity depends on the outcomes of auxiliary observers as well as the results of experiments performed by the experimentalist.

Class	Model	Auxiliary observers introduced?	Auxiliary outcomes used to generate ϕ?	Experimental measurement outcomes used to generate ϕ?	Features
Collapse models	Diosi-Penrose [18,43]	Measure **g** everywhere	No	No	Gravity not implemented
	CSL [20,44]	Measure smeared matter distribution	No	No	
Schrödincer-Newton	Preselection [4,7] S-N	No	No	No	Violates Page-Geilker
	Postselection S-N [7]	No	No	Yes	Future measurement choices influence past.
	Causal-conditional S-N [8,9,11,12]	No	No	Obtain conditional expectation of positions then generate gravity via classical feedback	Preserves causality
Classical grmvity with auxiliary observers	N-H extension of S-N [45]	Measure **g** everywhere	Yes	No	Classical gravity via Diosi-Penrose measurements
	KTM Model [21,22]	Measure position of each mass	Uses instant outputs of position channels	No	Instant outputs are very noisy
	Oppenheim's model [23]	Yes	Yes	No	More general and includes NH and KTM
	Unified model	Measure position of each mass	Yes	Yes	Can incorporate all above models

This model is falsified by D. N. Page, C. D. Geilker, PRL 47, 979 (1981)

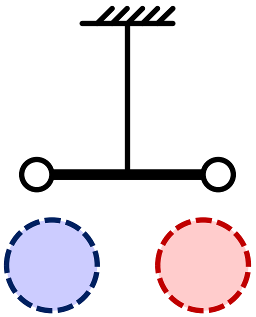
Violates causality

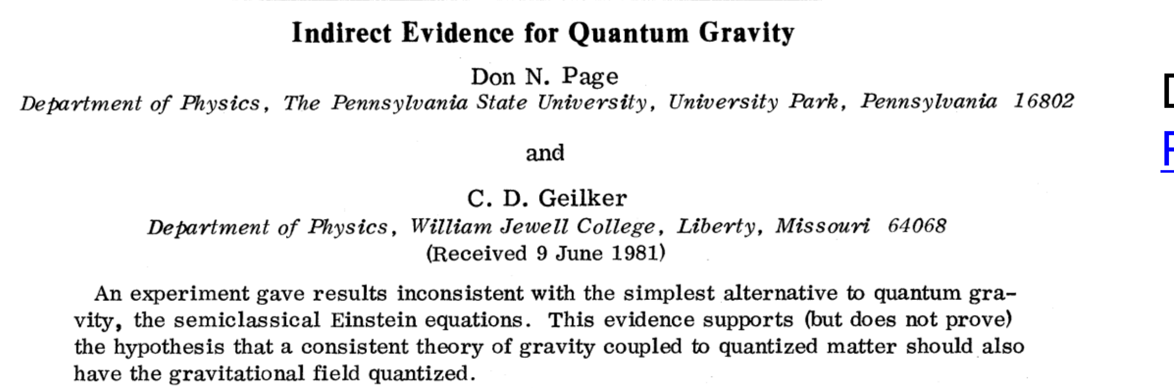
Preserves causality

D. Miki, Y. Kaku, Y. Liu, Y. Ma, Y. Chen, PRD 111, 104084 (2025)

Page-Geilker Experiment

- Source mass was moved according to γ-ray emission from Cobalt 60
  → Torsion correlated with γ-ray emission





VOLUME 47, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1981

Indirect Evidence for Quantum Gravity

Don N. Page
Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802

and

C. D. Geilker
Department of Physics, William Jewell College, Liberty, Missouri 64068

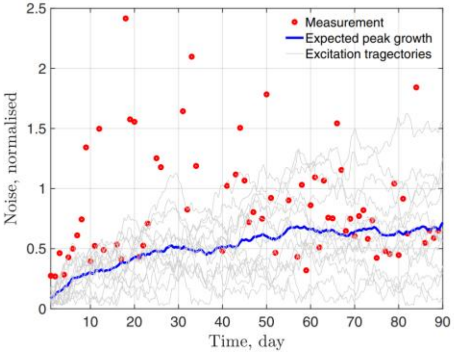
(Received 9 June 1981)

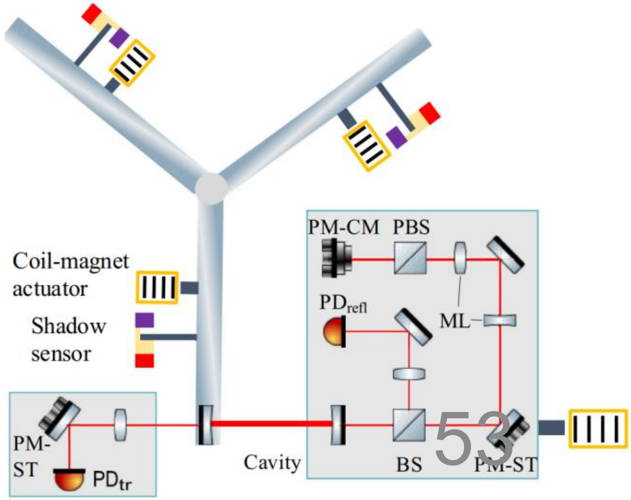
An experiment gave results inconsistent with the simplest alternative to quantum gravity, the semiclassical Einstein equations. This evidence supports (but does not prove) the hypothesis that a consistent theory of gravity coupled to quantized matter should also have the gravitational field quantized.

D. N. Page, C. D. Geilker,
PRL 47, 979 (1981)

- Preselection Schrodinder-Newton also tested more recently
  (resonant frequency shift from self-gravity and the growth in the resonant peak)

T. Yan+,
PRD 111, 082007 (2025)





Plans for now

- Characterization of levitation mirrors
- High power operation and realization of levitation
- B-L dark matter search also possible

創発的研究支援事業
Fusion Oriented REsearch for disruptive Science and Technology

Japan Society for the Promotion of Science
日本学術振興会
日仏二国間交流事業
Japan-France Bilateral Program

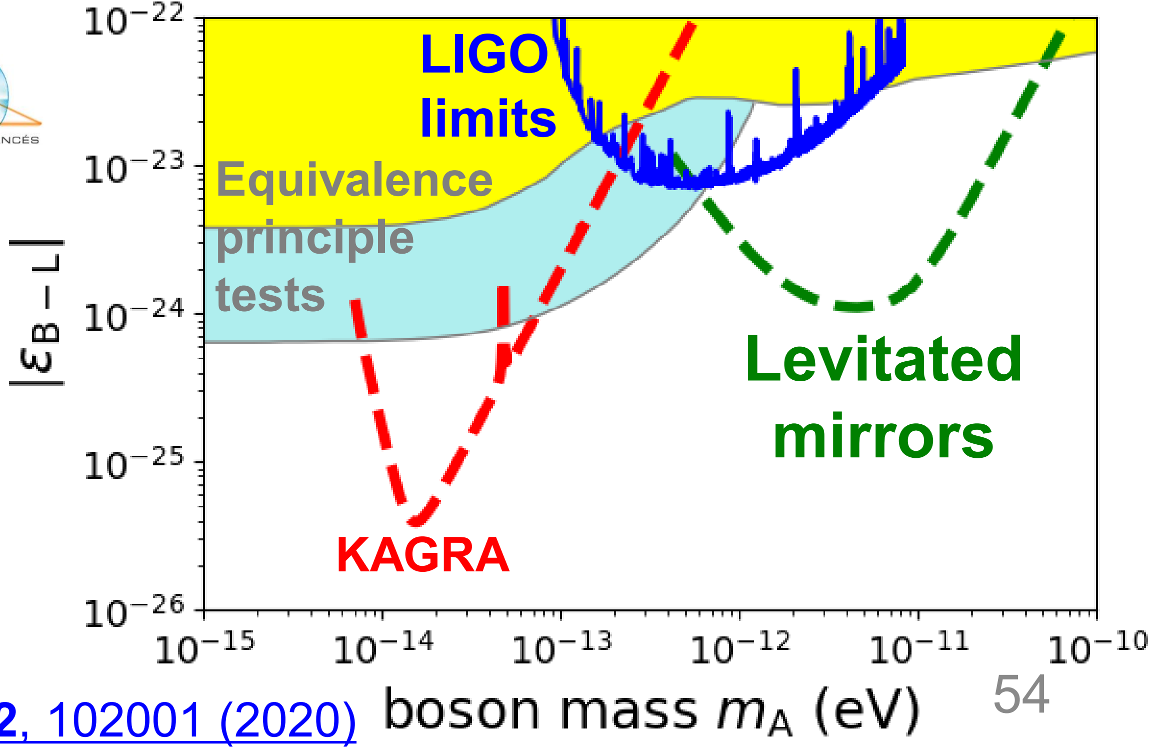
LMA
LABORATOIRE MATÉRIAUX AVANCÉS

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
日星共同研究「量子」
Japan-Singapore joint research

Agency for Science, Technology and Research
SINGAPORE

科研費
KAKENHI
学術変革領域研究(A)
Transformative Research Areas (A)

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