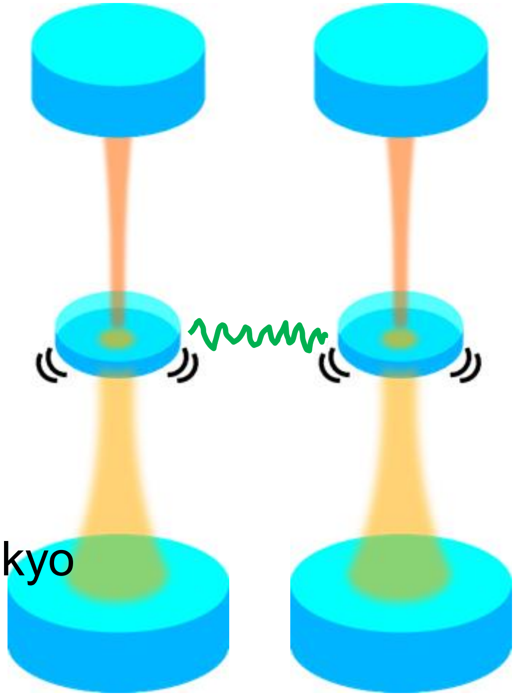
GWADW2026 @ Hotel Hermitage, Isola d'Elba May 21, 2026

Testing the quantum nature of gravity with levitated mirrors



Yuta Michimura

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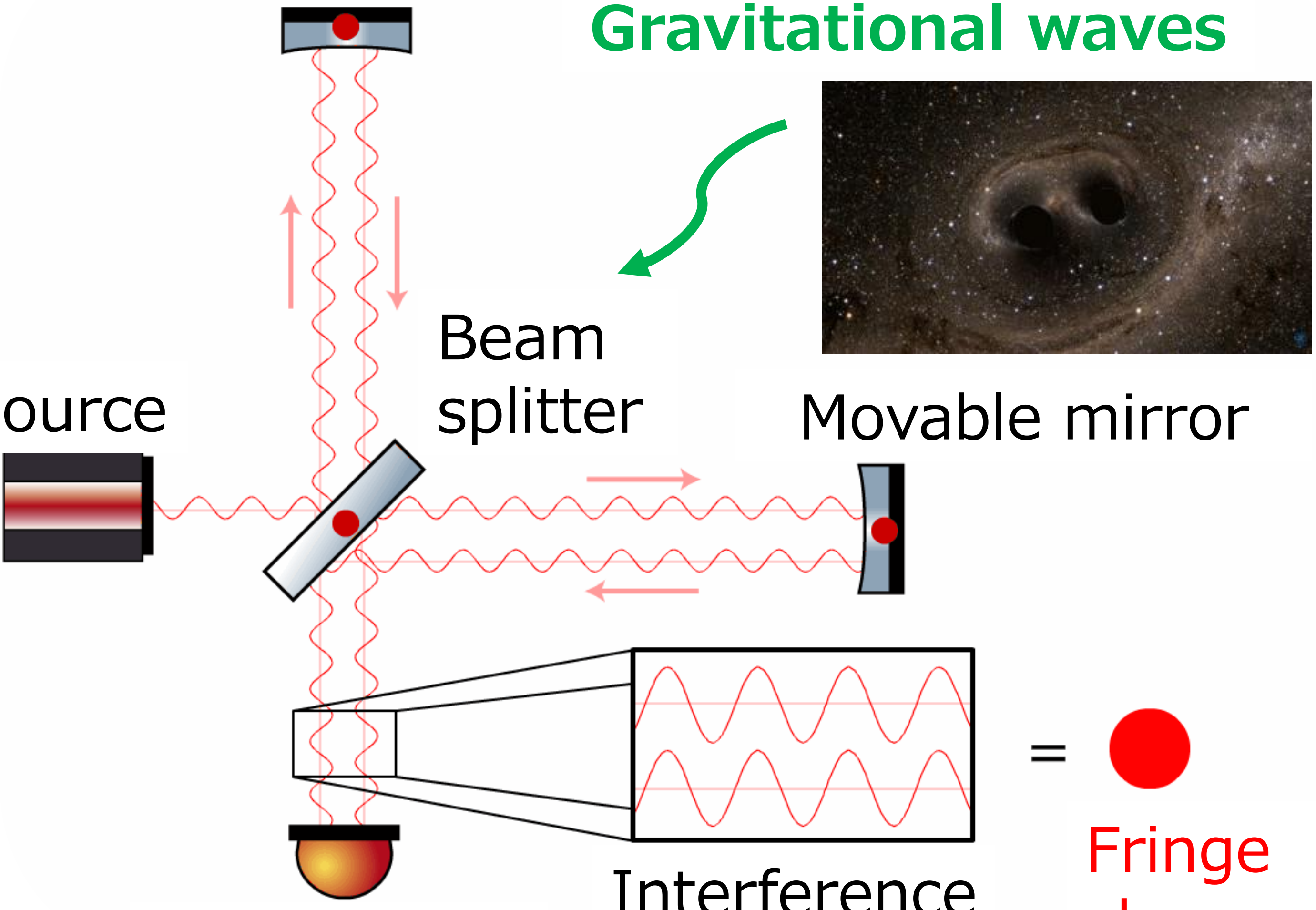
Laser Interferometric GW Detectors

- measures differential arm length change



Gravitational waves

Beam splitter

Laser source

Movable mirror

Interference

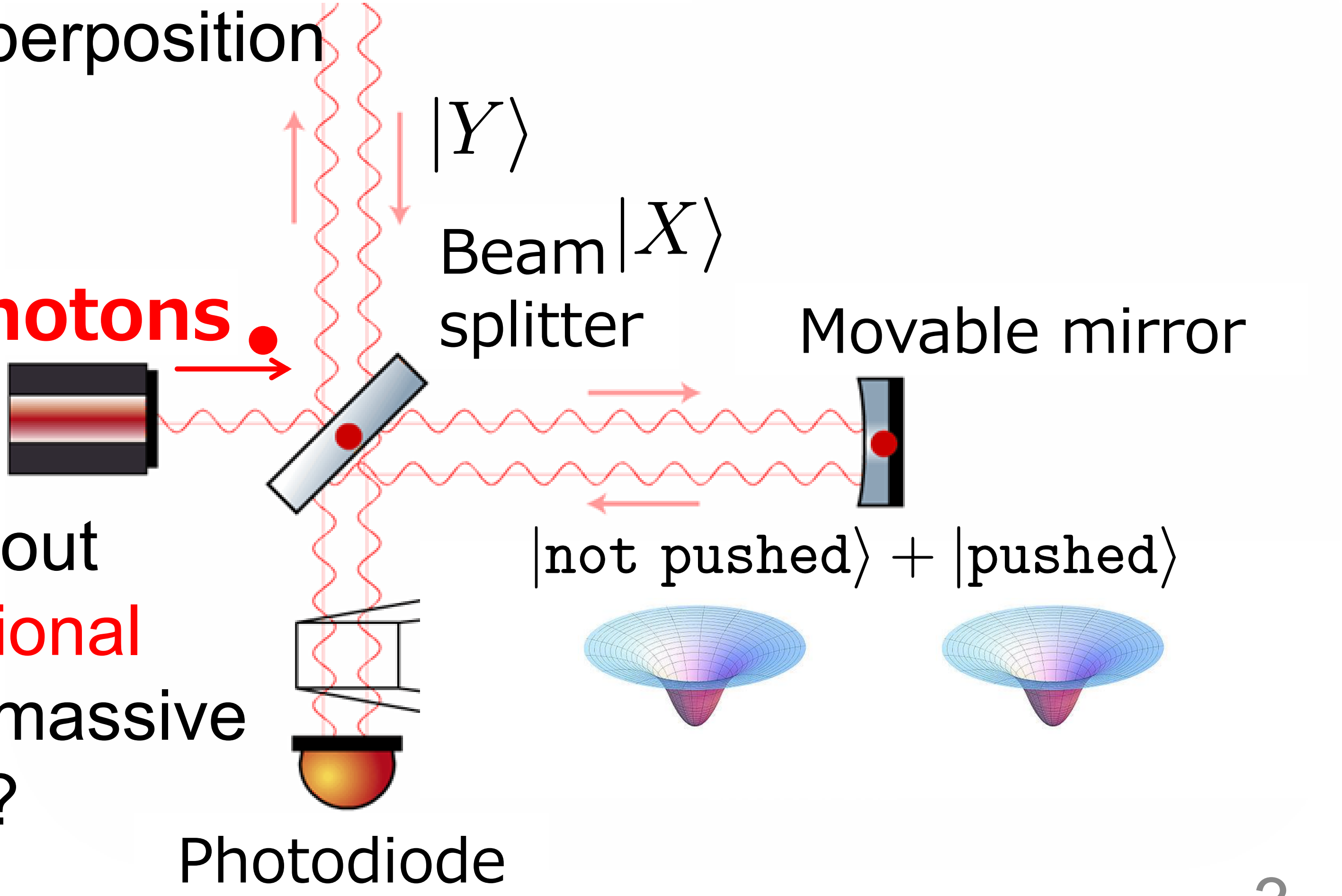
=

Fringe change

Photodiode

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



$|Y\rangle$

Beam splitter $|X\rangle$

Photons

Movable mirror

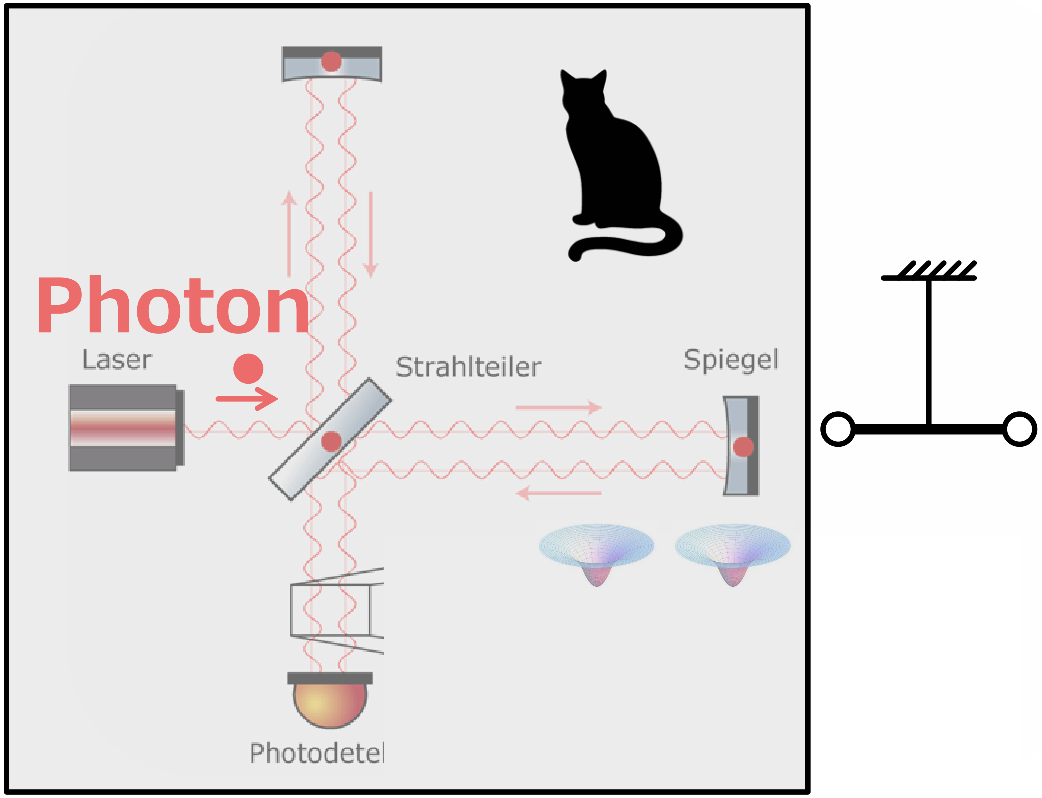
$|\mathtt{not\ pushed}\rangle + |\mathtt{pushed}\rangle$

Photodiode

- How about gravitational field of massive mirrors?

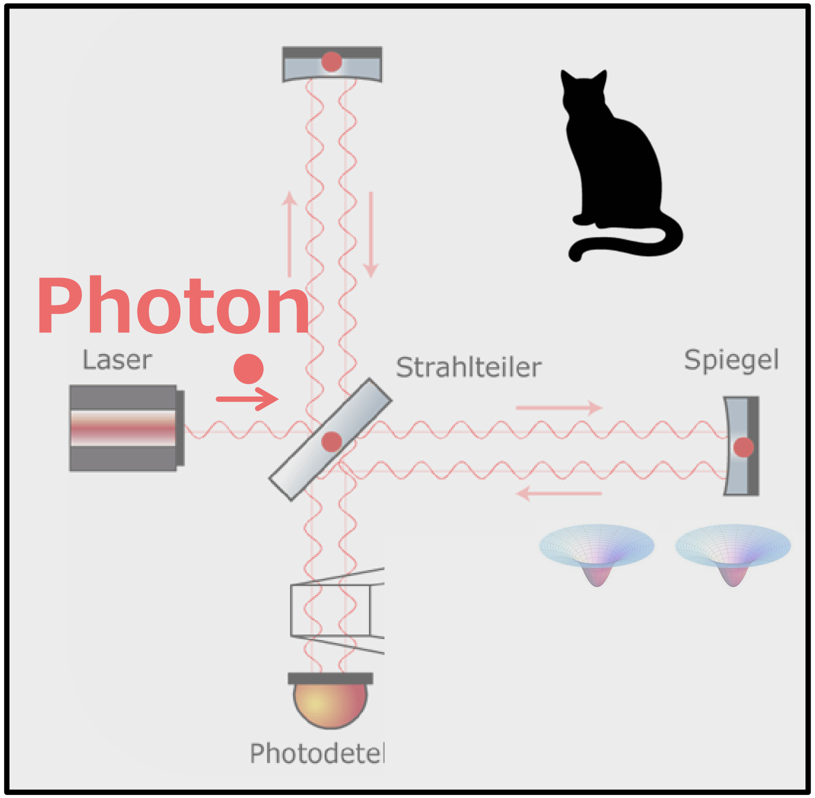
Schrödinger’s KAGRA

- 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???

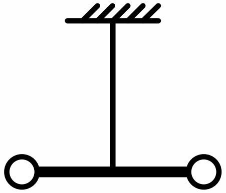


Schrödinger's KAGRA

- 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???



$$\nabla^2\Phi = 4\pi G\underset{\text{Expectation value}}{\langle \text{Mass distribution} \rangle}$$



Semiclassical Gravity
(e.g. Schrödinger-Newton model)

Very strange model, but not experimentally falsified completely.

Various Gravity Models

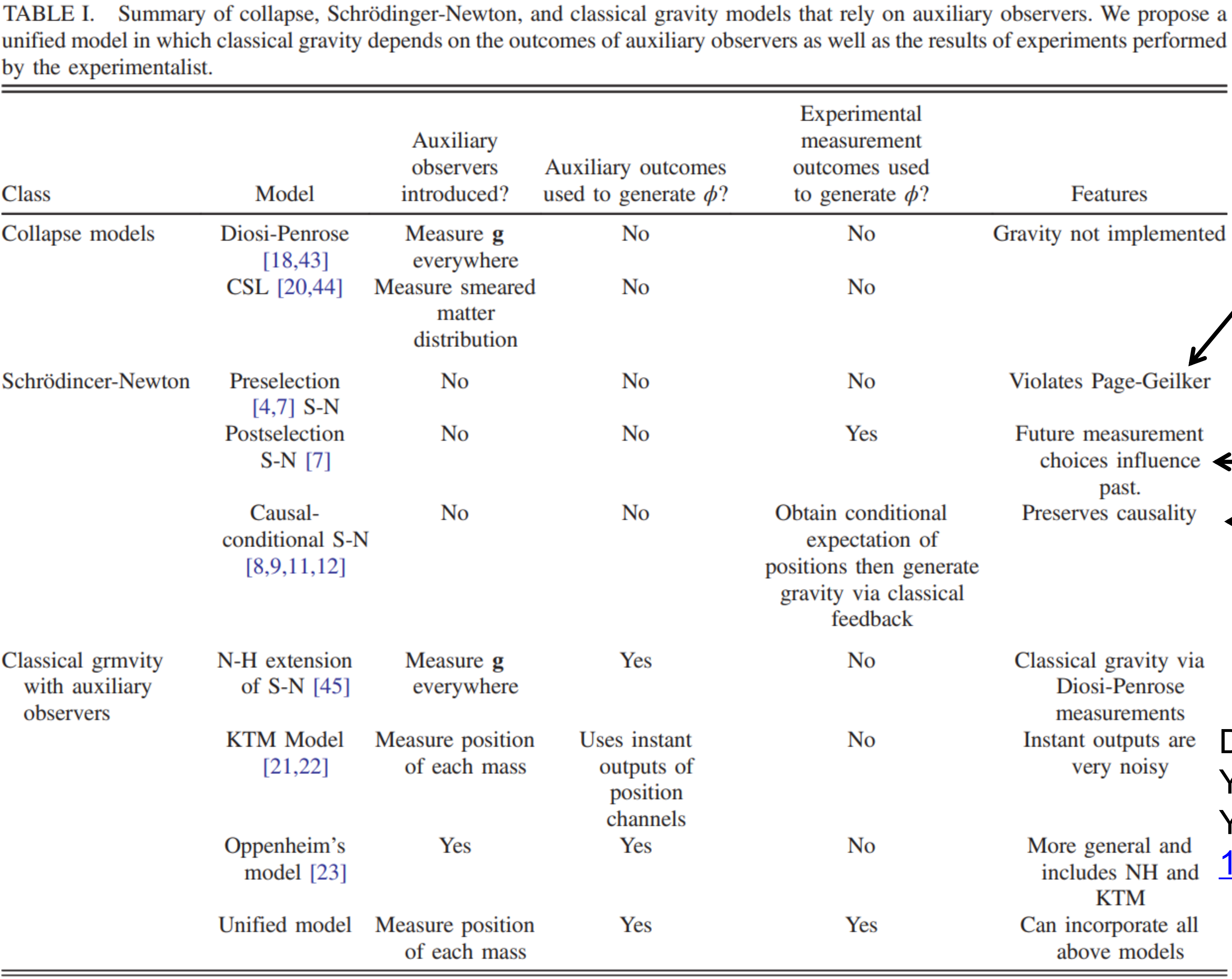


TABLE I. Summary of collapse, Schrödinger-Newton, and classical gravity models that rely on auxiliary observers. We propose a unified model in which classical gravity depends on the outcomes of auxiliary observers as well as the results of experiments performed by the experimentalist.

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

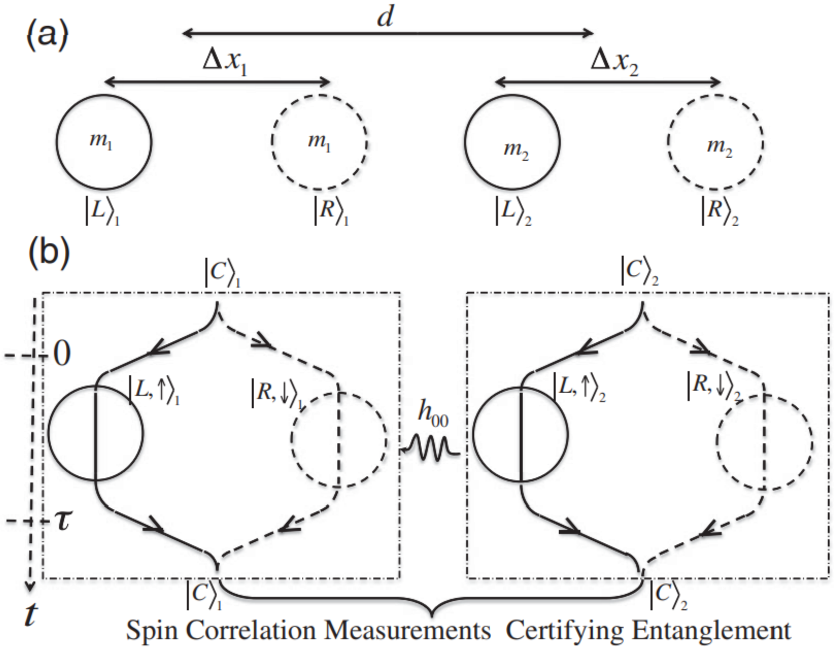
Preserves causality

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

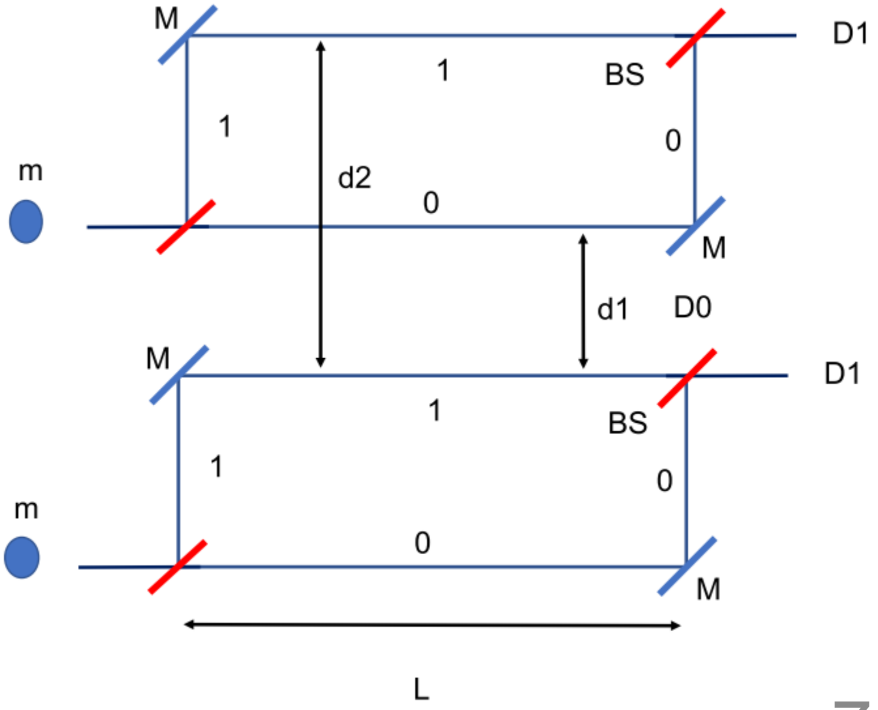
BMV Proposals

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

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



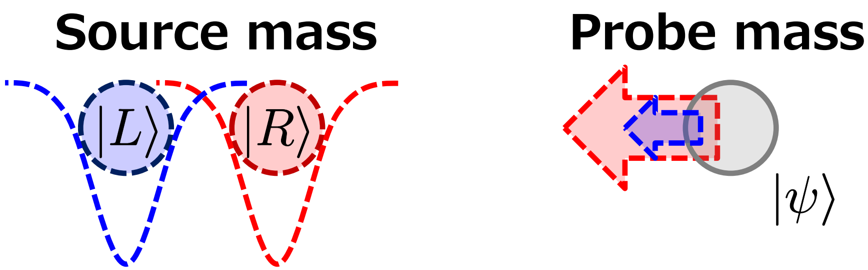
C. Marletto & V. Vedral,
Phys. Rev. Lett. 119, 240402 (2017)



Key Idea of BMV Proposals

- If gravity is quantum

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



Source mass

Probe mass

Newtonian potential act as an operator

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

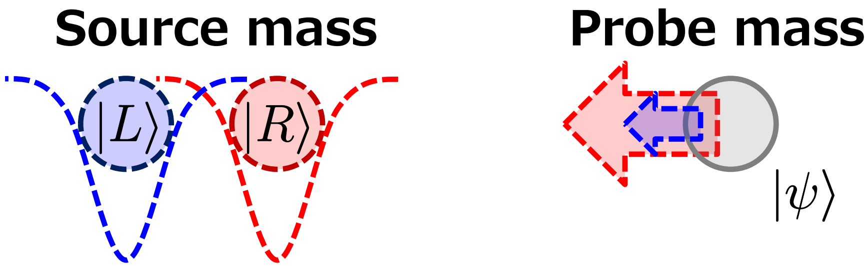
$$= \frac{1}{\sqrt{2}}\left(|L\rangle\otimes e^{i\phi_L}|\psi\rangle + |R\rangle\otimes e^{i\phi_R}|\psi\rangle\right)$$

Gravity induced entanglement

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

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

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

Remains separable

What is the Best Oscillator?

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

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

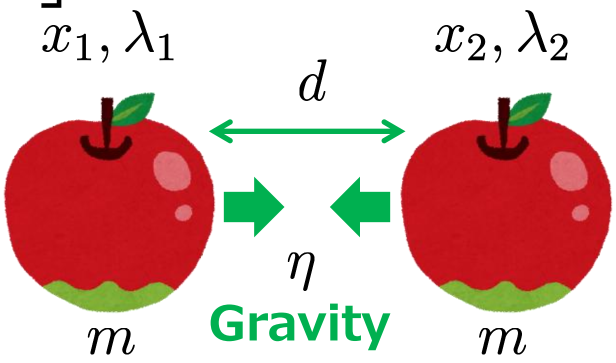
Distance between masses

$$= \frac{\omega}{2}\left[\sum_{i=1,2} (P_i^2 + \lambda_i X_i^2) + \eta (X_1 - X_2)^2\right]$$

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 $\lambda \equiv \lambda_1 = \lambda_2$

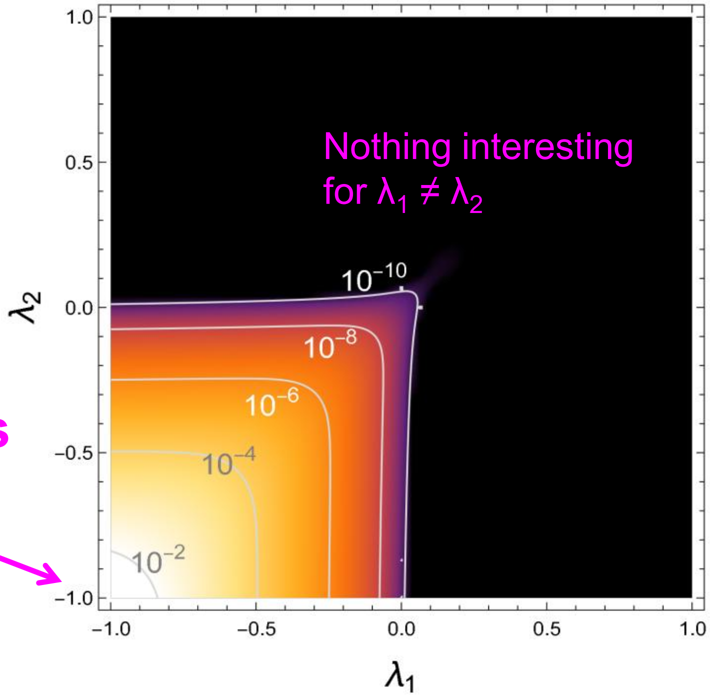
$$E_N \simeq 3[\eta f_{\rm gra}(t) - \mu f_{\rm dec}(t)]$$

Strength of gravitational coupling

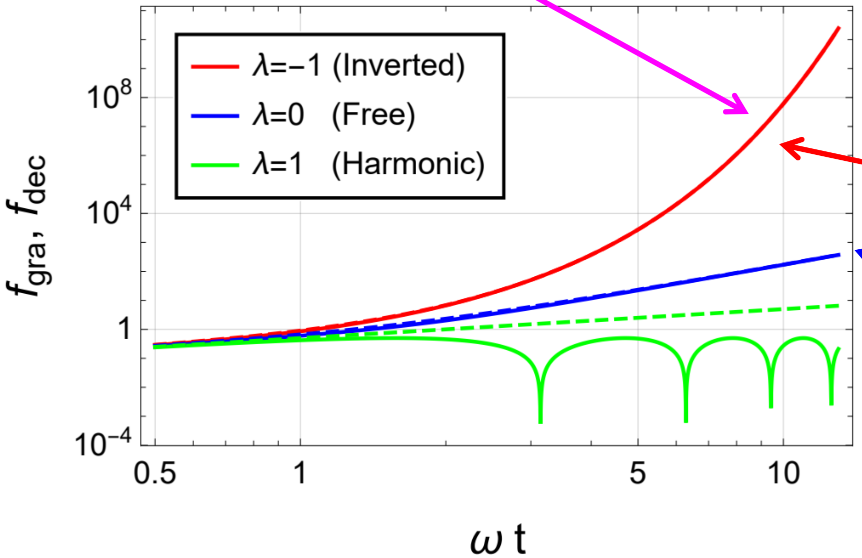
Amount of decoherence

Exponential growth of entanglement

Inverted oscillators are the best



Nothing interesting for $\lambda_1 \neq \lambda_2$



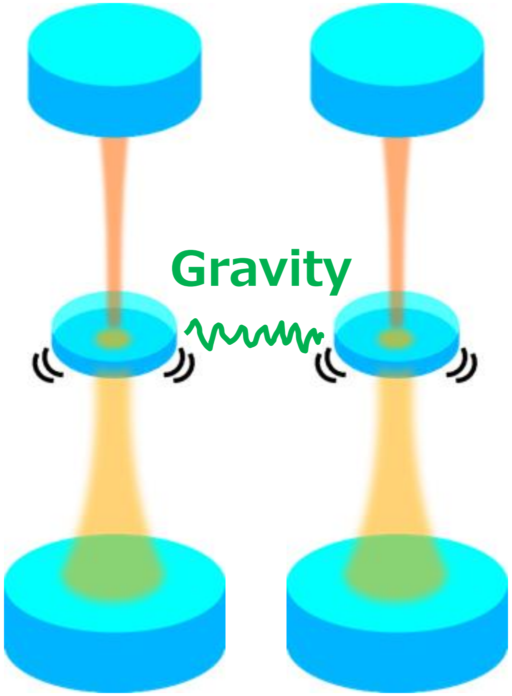
$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8} e^{2\omega t}$$

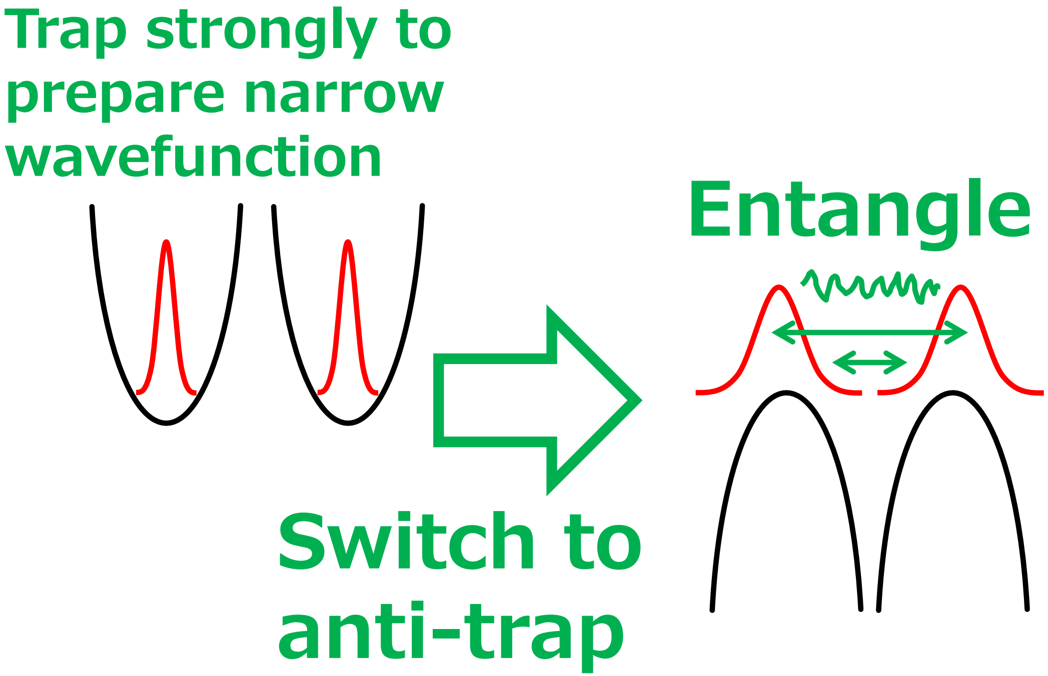
$$f_{\rm gra}(t) \simeq f_{\rm dec}(t) \simeq \frac{1}{8} (\omega t)^3$$

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

Realization with Levitated Mirrors

- Switching between trap and anti-trap is easy with optically levitated mirrors
- 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

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

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 $E_N = 10^{-2}$

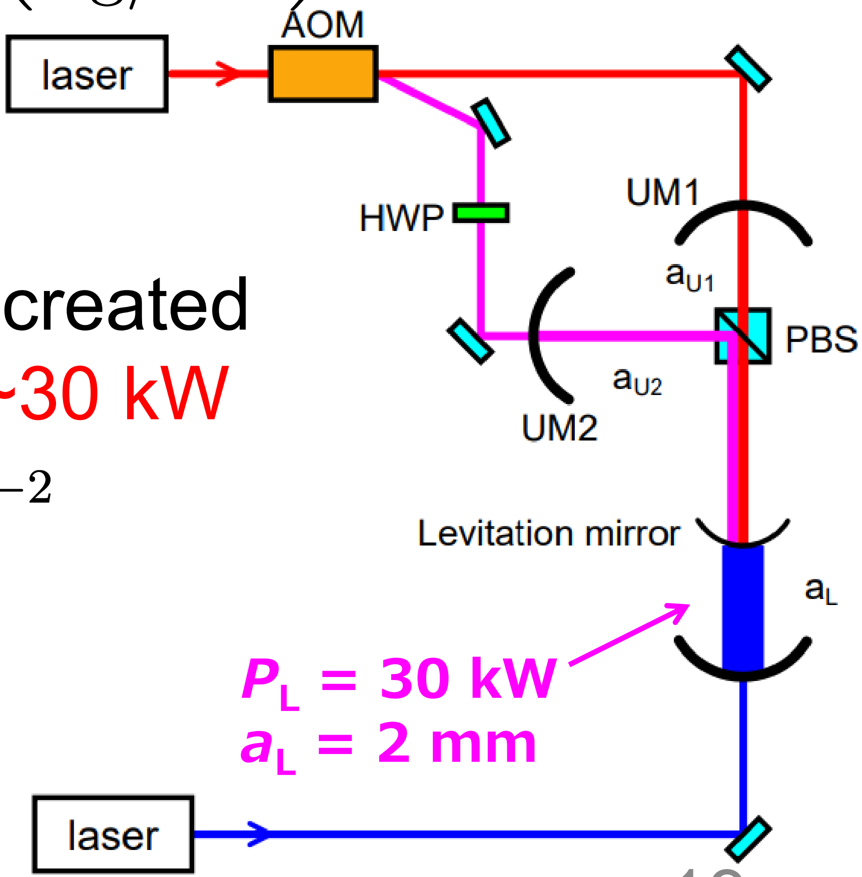
$$\tau_{\mathrm{ent}} = 4.2 \omega_{\mathrm{kHz}}^{-1/3}\ \mathrm{sec}$$

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

Fabricating Mirrors for Levitation

- 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:

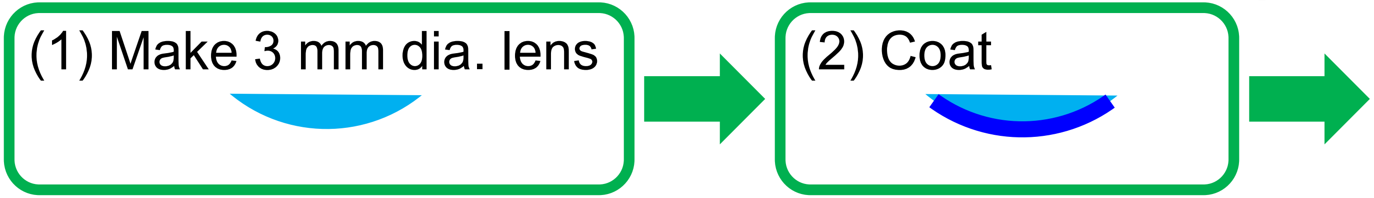
φ 3 mm, 0.1 mm thick (~1.6 mg for fused silica)
Curvature RoC = ~30 mm convex
Reflectivity R > 99.95 %
Absorption A < ~0.5 ppm (LIGO, Virgo, KAGRA level)

- 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

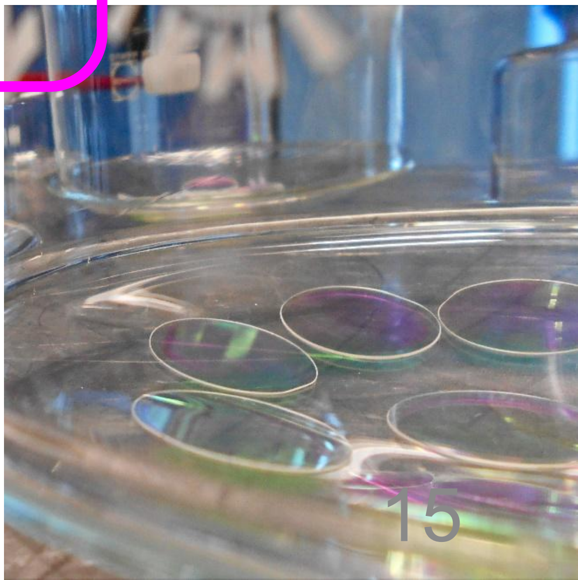
(2018-2024 ANR-JST CREST、
2025-2027 France- Japan JSPS Bilateral program)

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

(2) Coat (bend due to stress)

(3) Cut into 3 mm dia.

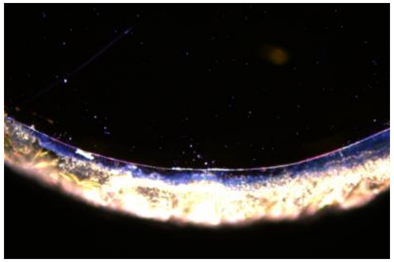
LABORATOIRE MATÉRIAUX AVANCÉS

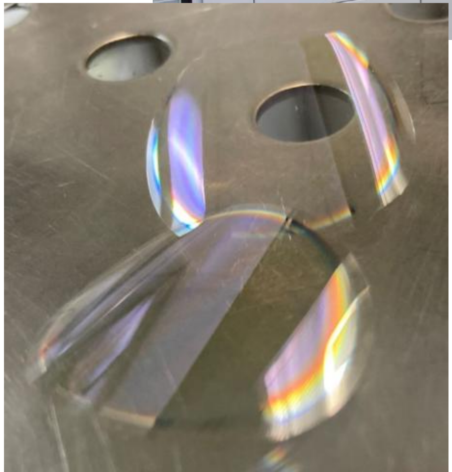


Fabrication Status in LMA

- HR coating with 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

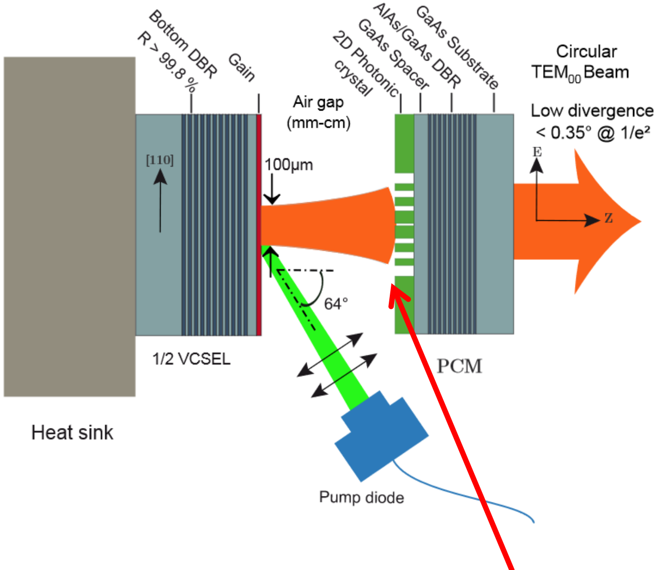




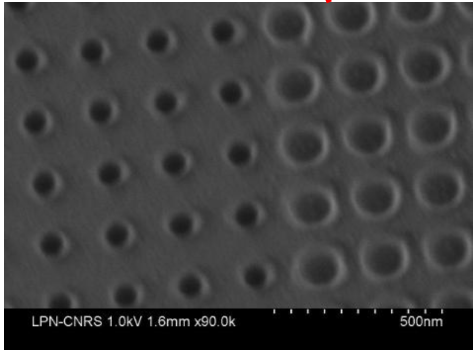
M. Croquette+, AVS Quantum Science **5**, 014403 (2023)

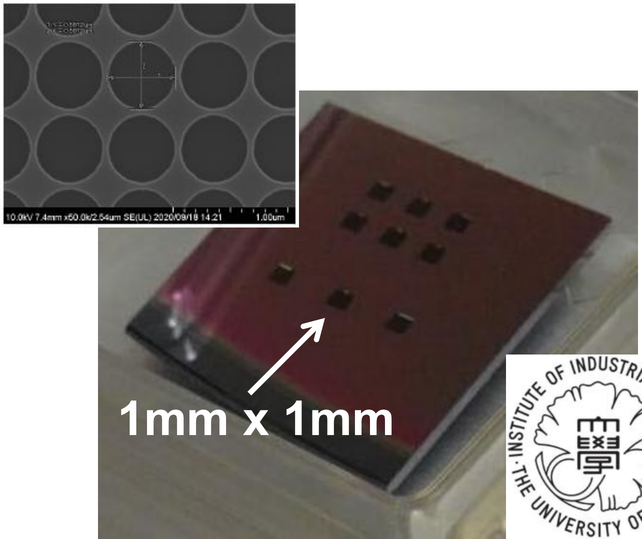
Metasurface Approach

- Effective curvature possible by modulating the filling factor
  M. S. Seghilani+,
  [Optics Express 22, 5962 (2014)]



- Tried with Si with different filling factor
  So far achieved 95(5) % reflectivity





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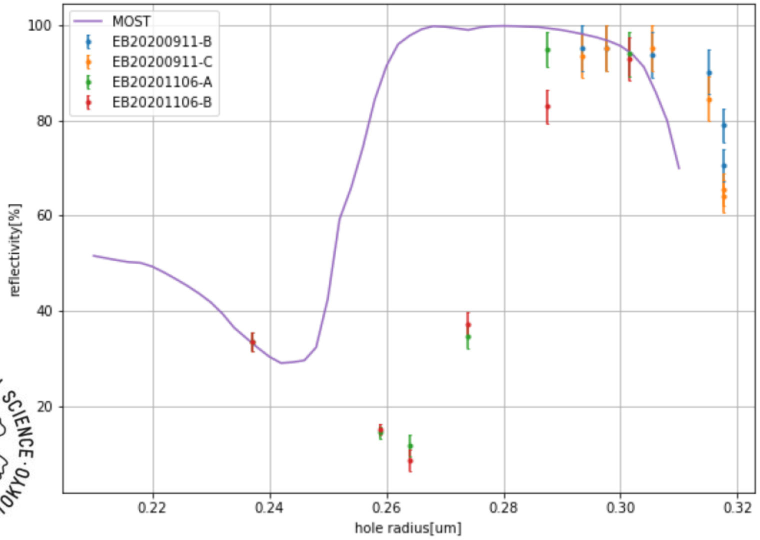
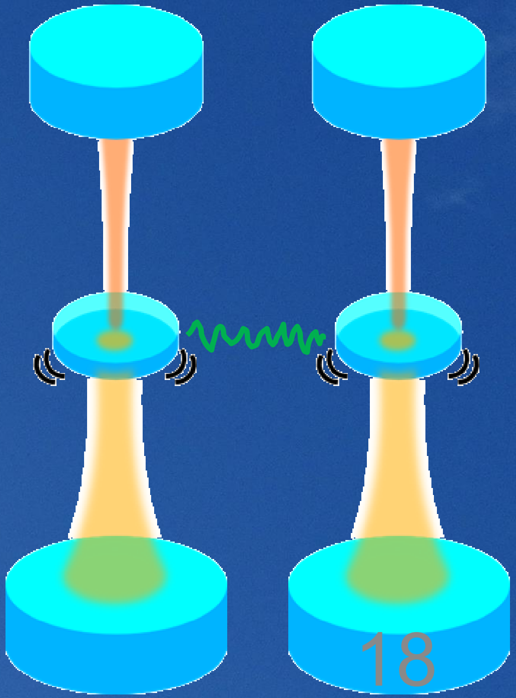


Summary

- Quantum nature of gravity can be tested with **gravity induced entanglement**
- Entanglement generation can be accelerated with **inverted oscillators**

T. Fujita, Y. Kaku, A. Matsumura, YM,
CQG 42, 165003 (2025)

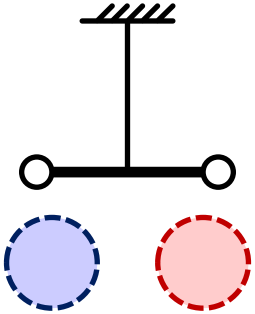
- **Mirror fabrication** is underway to realize optical levitation of mirrors for the first time

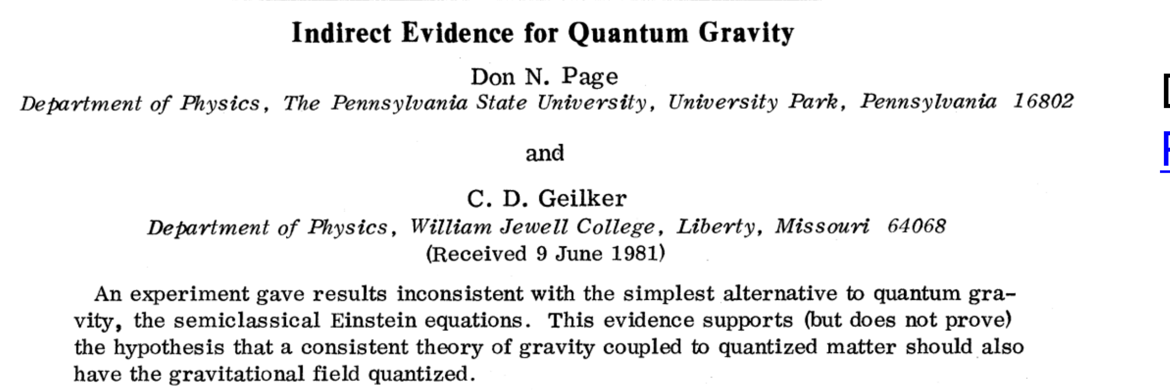


Bonus Slides

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

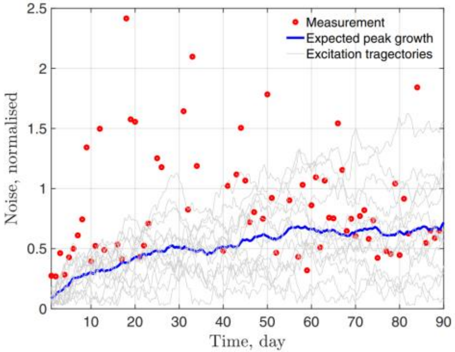
(Received 9 June 1981)

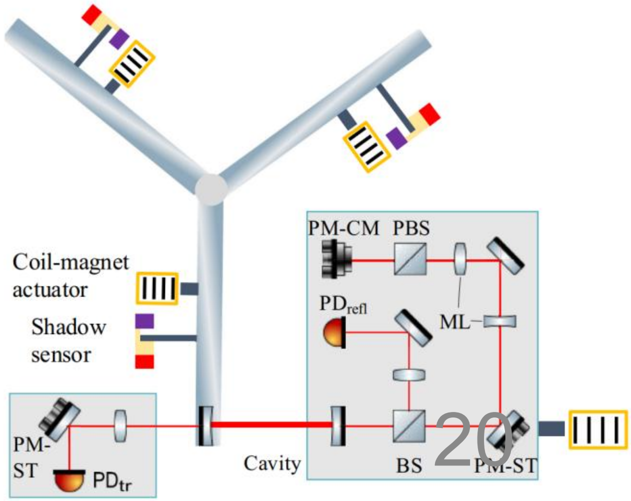
An experiment gave results inconsistent with the simplest alternative to quantum gravity, the semiclassical Einstein equations. This evidence supports (but does not prove) the hypothesis that a consistent theory of gravity coupled to quantized matter should also have the gravitational field quantized.

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)

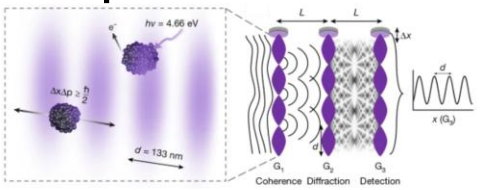
T. Yan+,
PRD 111, 082007 (2025)





Quantum and Gravity Experiments

Mass



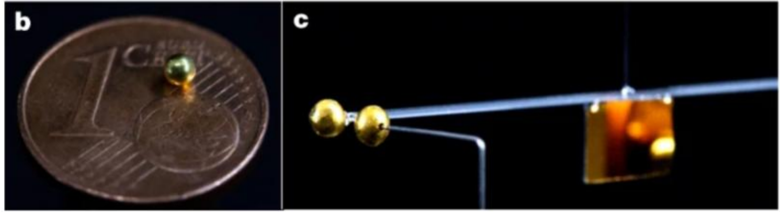
sodium nanoparticles,
3e-19 g
[Pedalino+ (2026)]

Interference

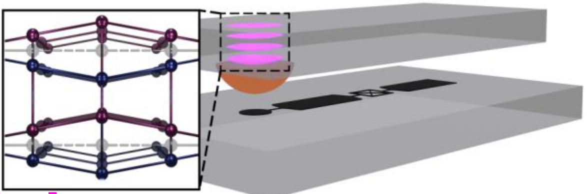
cantilever, 50 ng
[Cripe+ (2019)]

Backaction

Planck mass
22 ug



torsion pendulum, 90 mg
[Westphal+ (2021)]



Cat state

acoustic wave, 16 ug
[Bild+ (2023)]

Quantum and Gravity Experiments

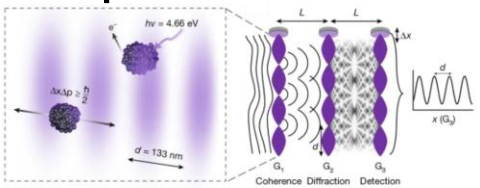
Quantum

Quantum regime of gravity

Gravity

Mass

Planck mass
22 ug

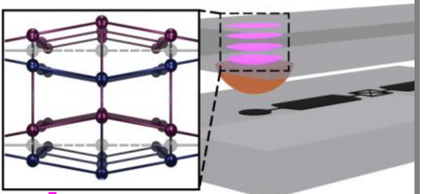


sodium nanoparticles,
3e-19 g
Pedalino+ (2026)

Interference

cantilever, 50 ng
Cripe+ (2019)

Backaction

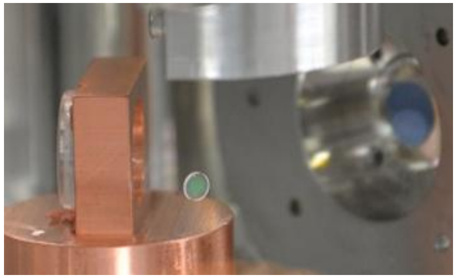


Cat state

acoustic wave,
Bild+ (2023)

Our focus: 0.1-10 mg scale

optical levitation,
~0.2 mg

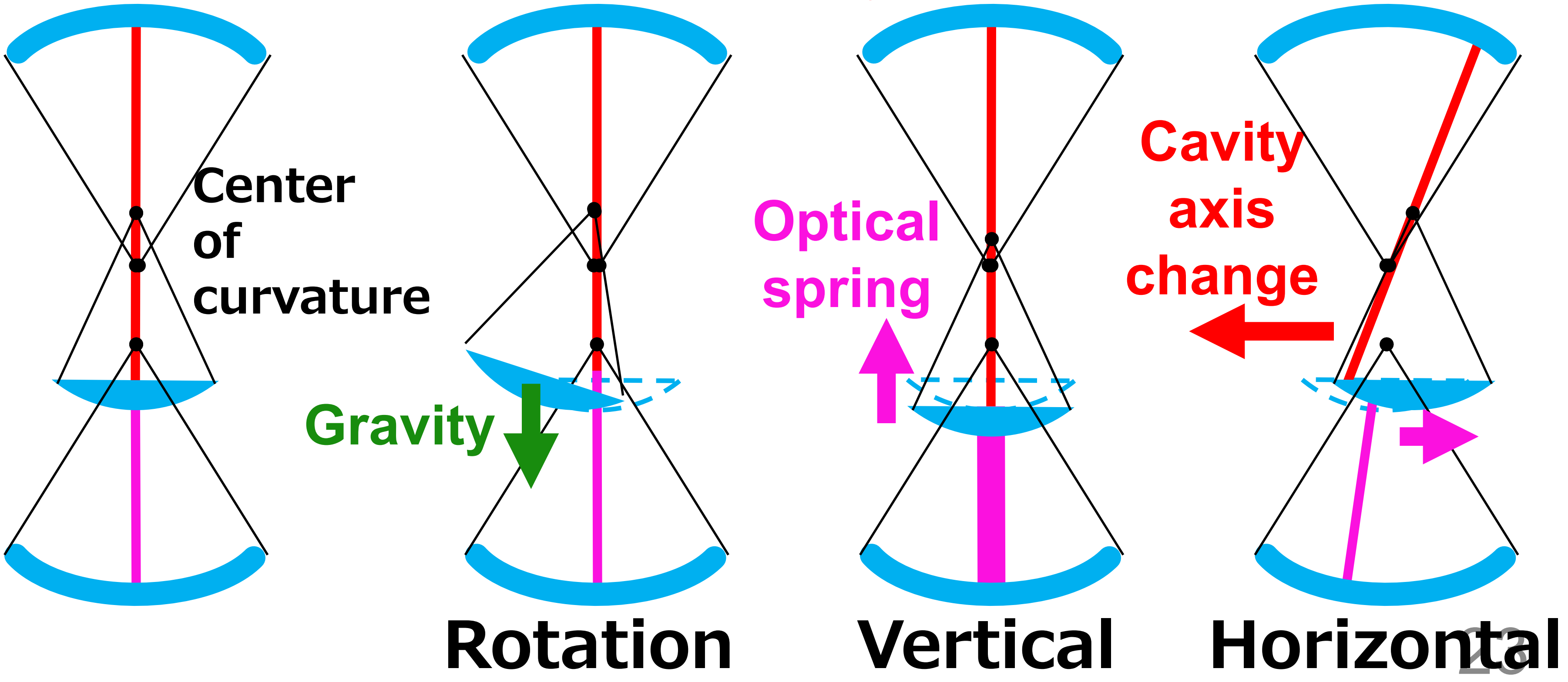


suspended disk, 7 mg
Matsumoto+ (2019)

suspended bar, 10 mg
Komori+ (2019)

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!*

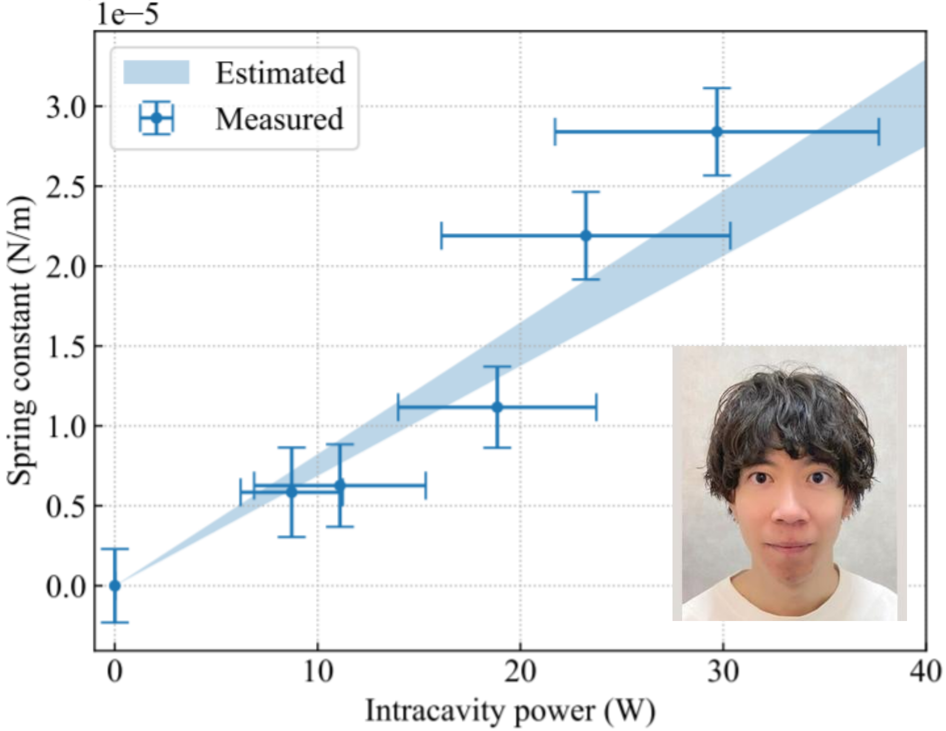


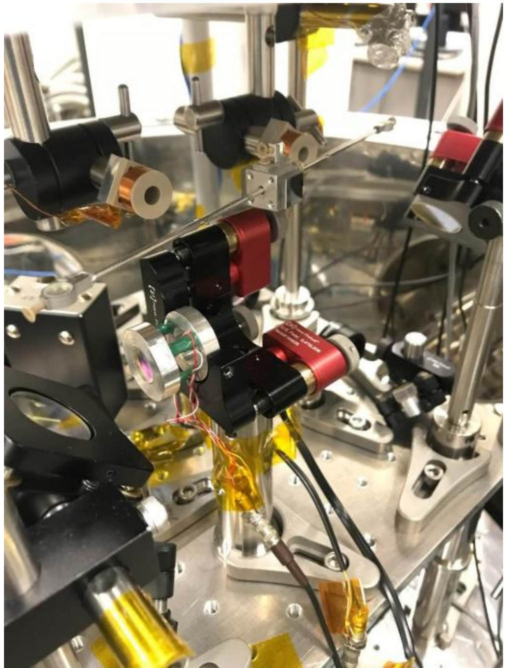
Experiment to Verify the Stability

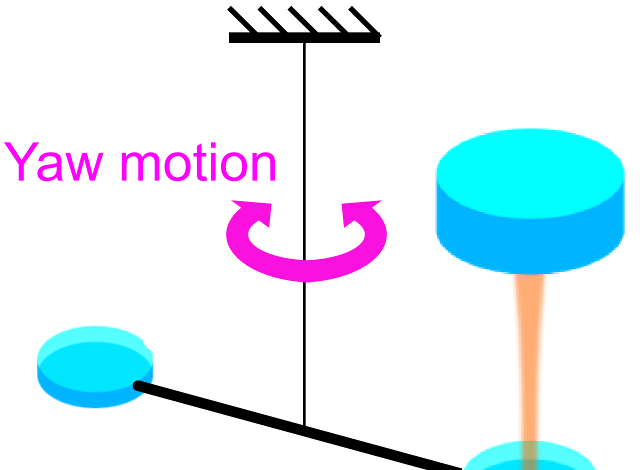
- Verified the stability with a torsion pendulum and a dummy mirror

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

Measured optical geometrical spring agreed with expectation

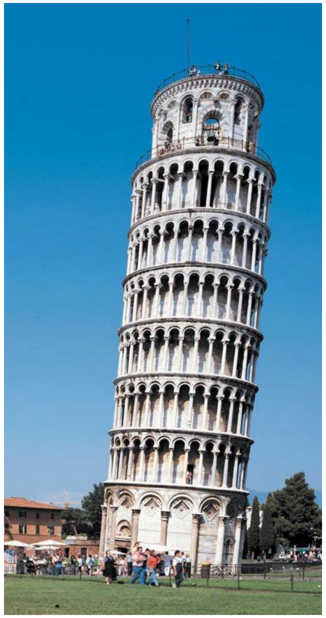






Decoherence Effects

- 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…



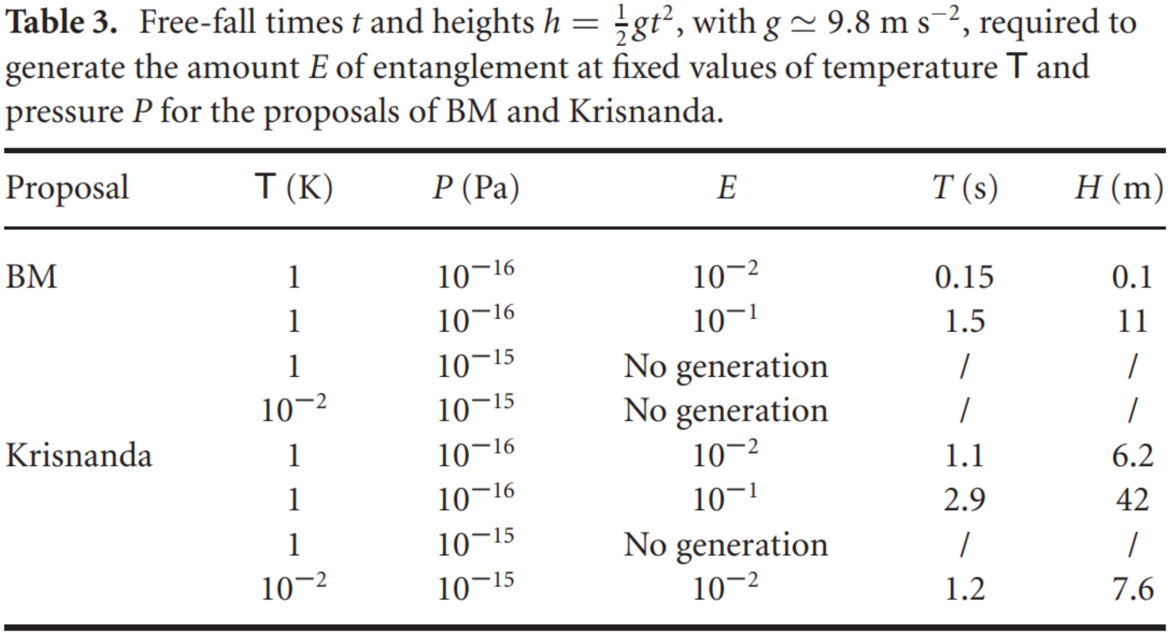


Table 3. Free-fall times t and heights $h = \frac{1}{2}gt^2$, with $g \simeq 9.8$ m s^{-2}, required to generate the amount E of entanglement at fixed values of temperature T and pressure P for the proposals of BM and Krisnanda.

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

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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

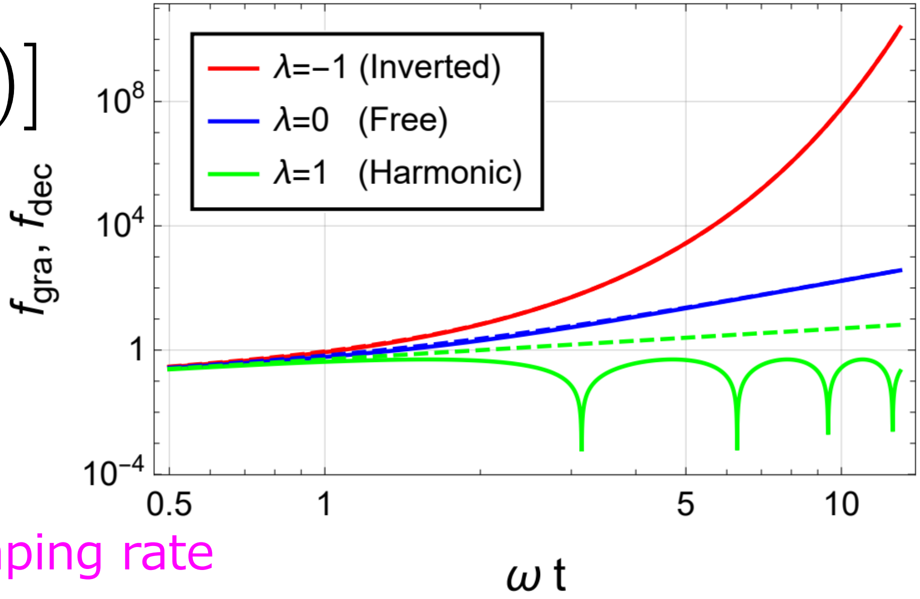
- Decoherence effects also increases exponentially with inverted oscillators

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

Gravity

Decoherence

Logarithmic negativity



- $\eta > \mu$ is required

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

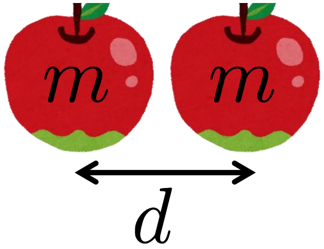
Damping rate

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



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

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