Entanglement mediated by gravity

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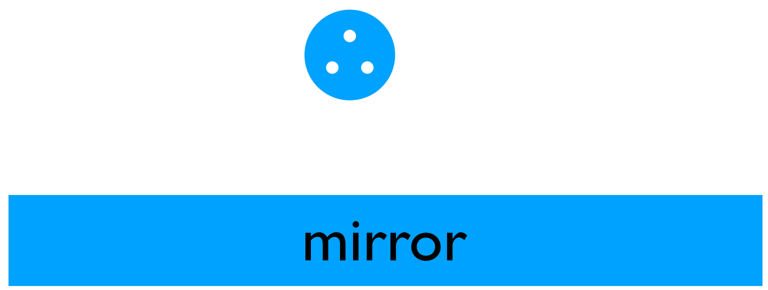
Is gravity quantum?

THINGS FALL… COUNTLESS EXPERIMENTAL EVIDENCE



Quantum states of neutrons in the Earth's gravitational field

Valery V. Nesvizhevsky*, Hans G. Börner*, Alexander K. Petukhov*, Hartmut Abele†, Stefan Baeßler†, Frank J. Rueß†, Thilo Stöferle†, Alexander Westphal†, Alexei M. Gagarski‡, Guennady A. Petrov‡ & Alexander V. Strelkov§

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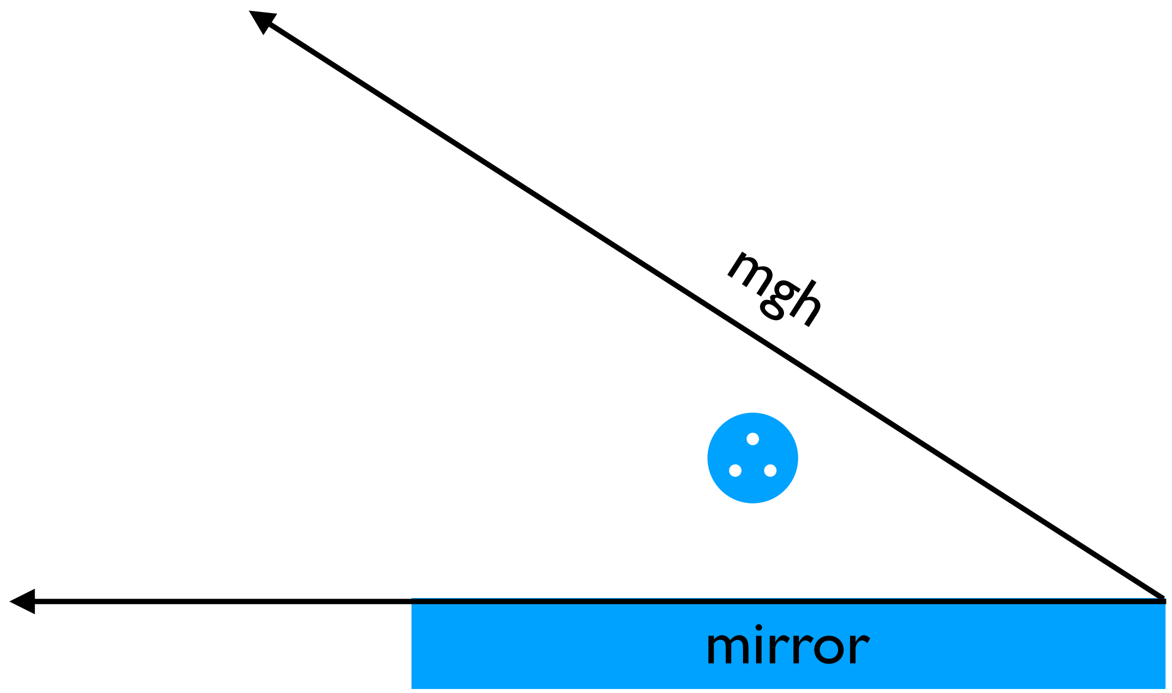
THINGS FALL… COUNTLESS EXPERIMENTAL EVIDENCE



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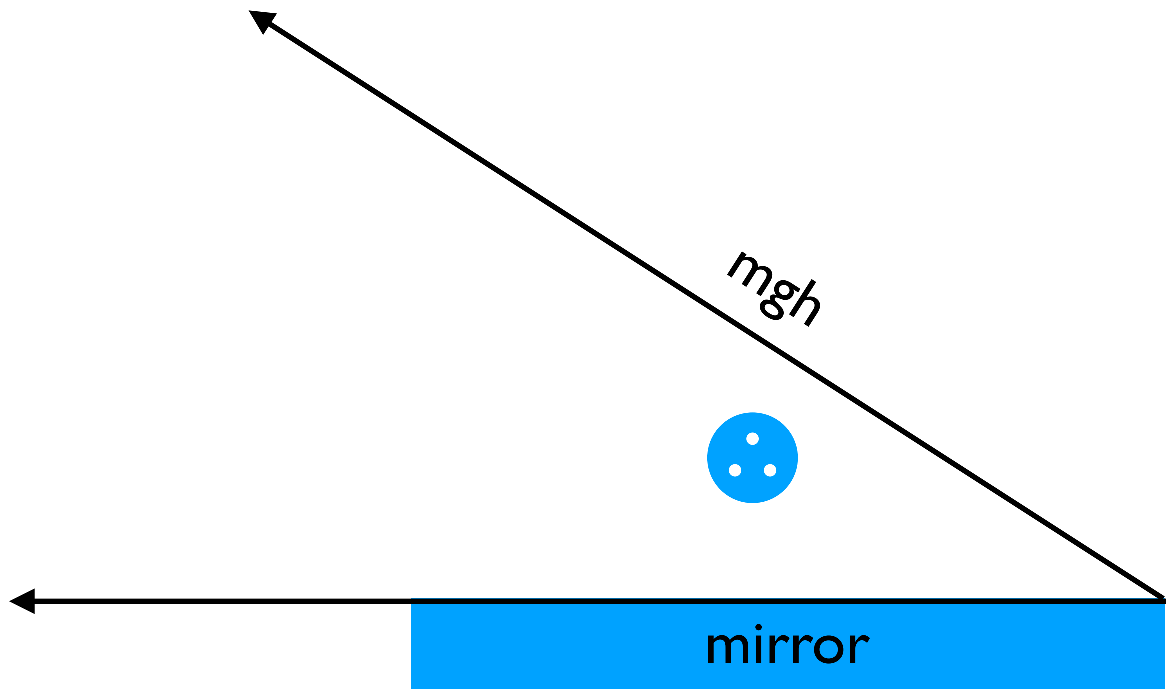

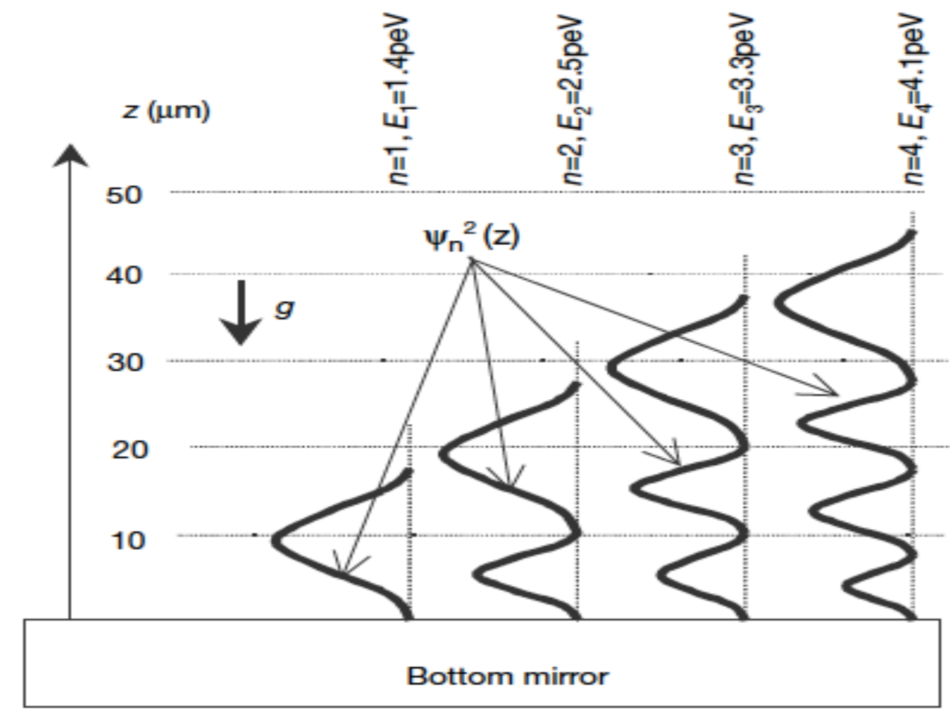

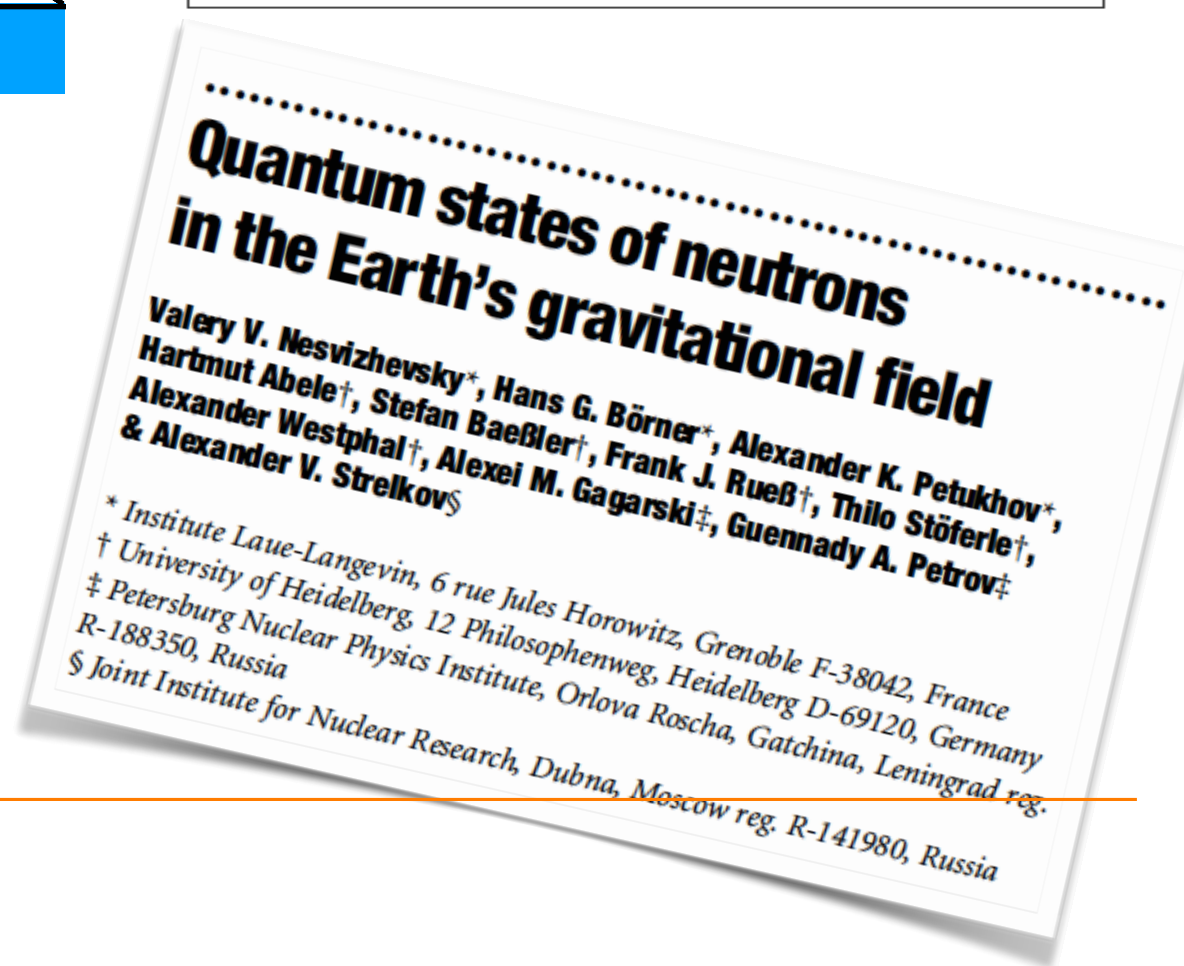

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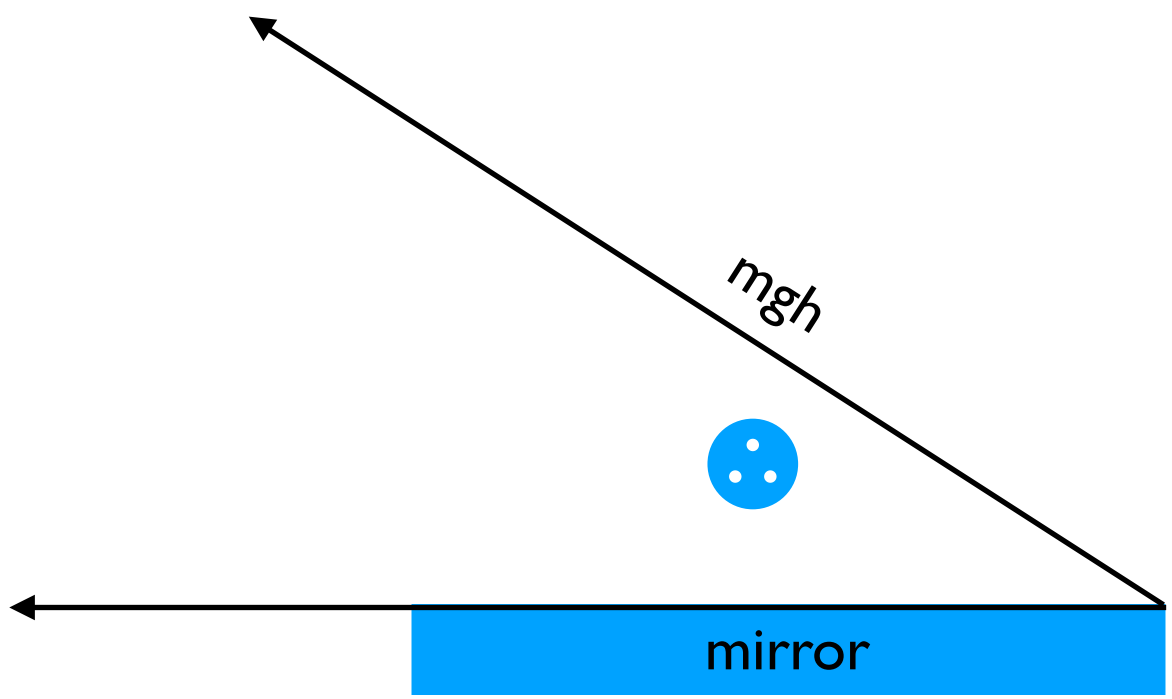
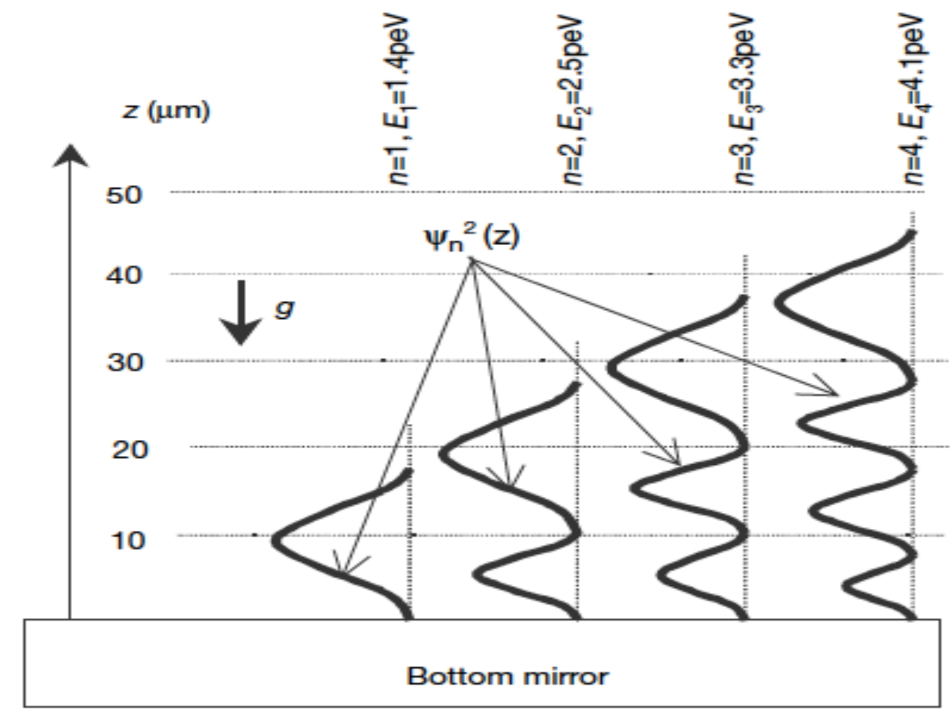
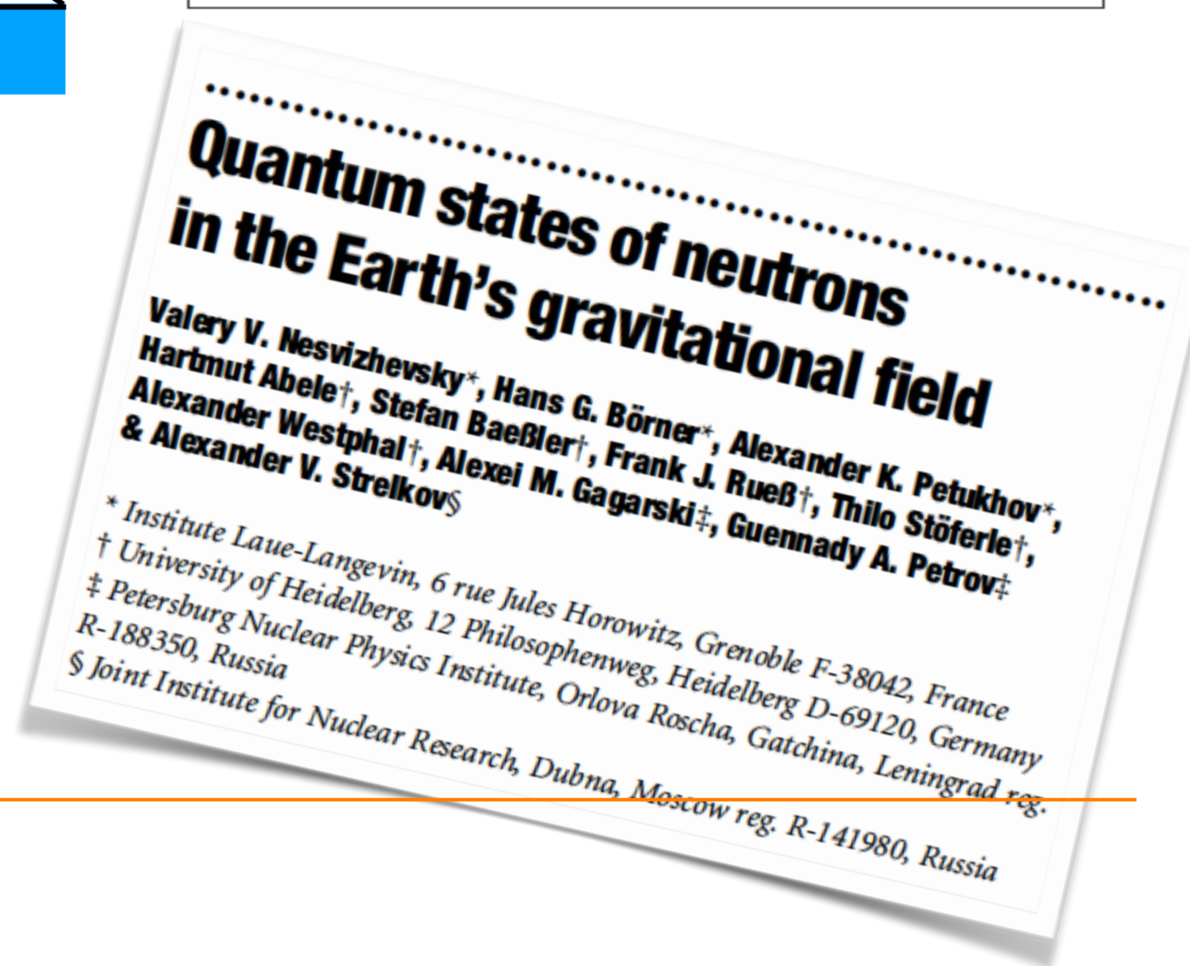


$m\,g\,(10\ um) = 1\ peV$

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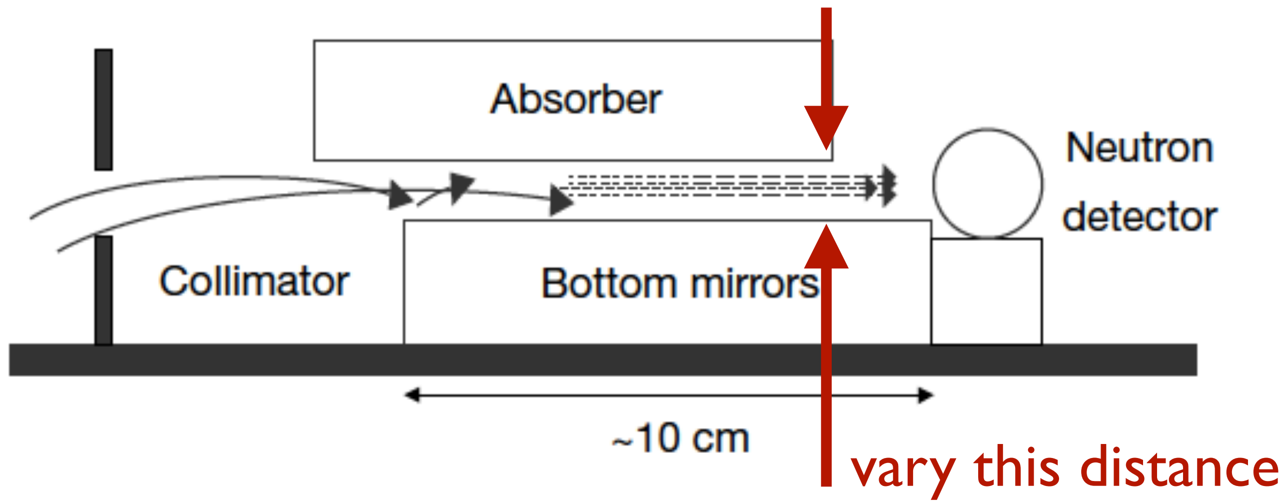
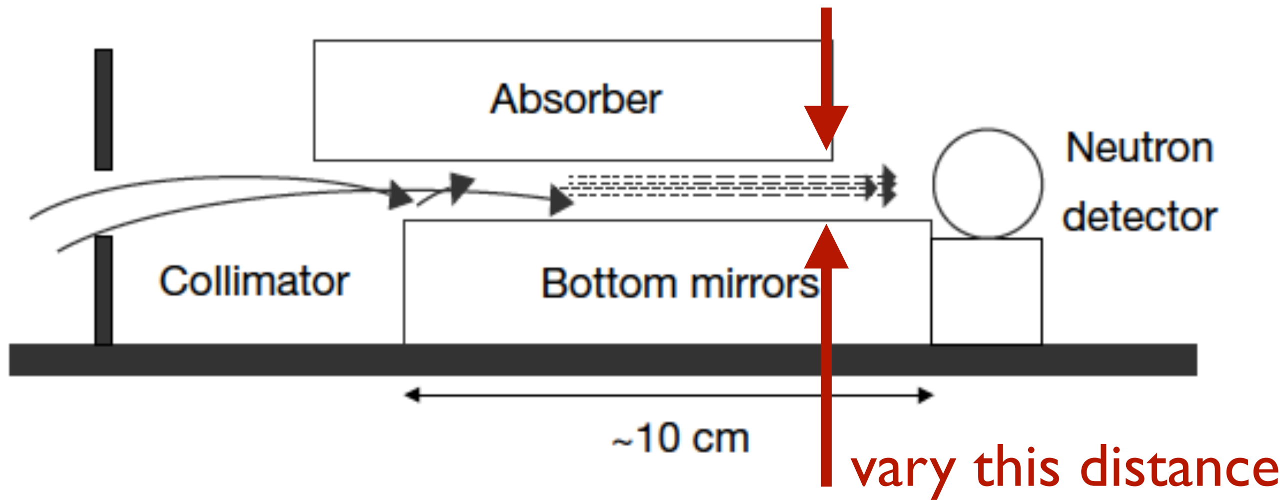
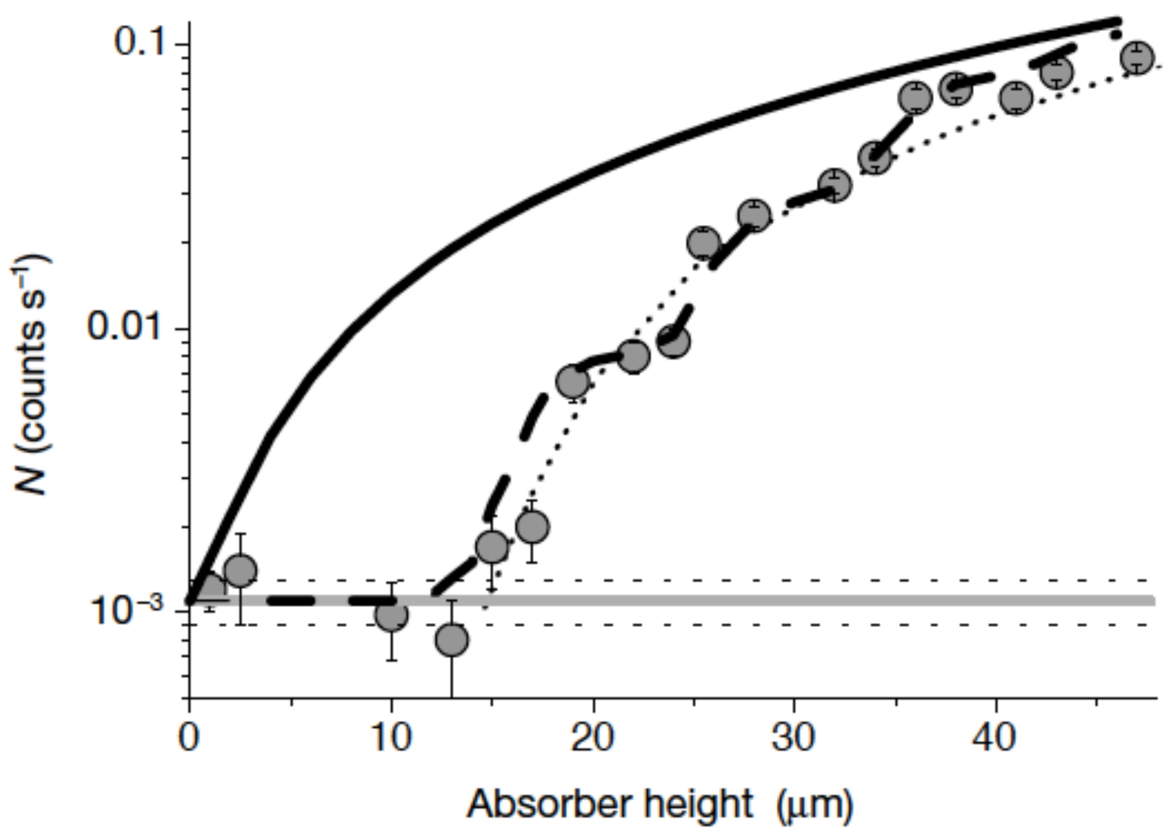

Absorber
Neutron
detector
Collimator
Bottom mirrors
~10 cm
vary this distance

NEUTRONS IN GRAVITATIONAL BOUND STATES





Newtonian gravity

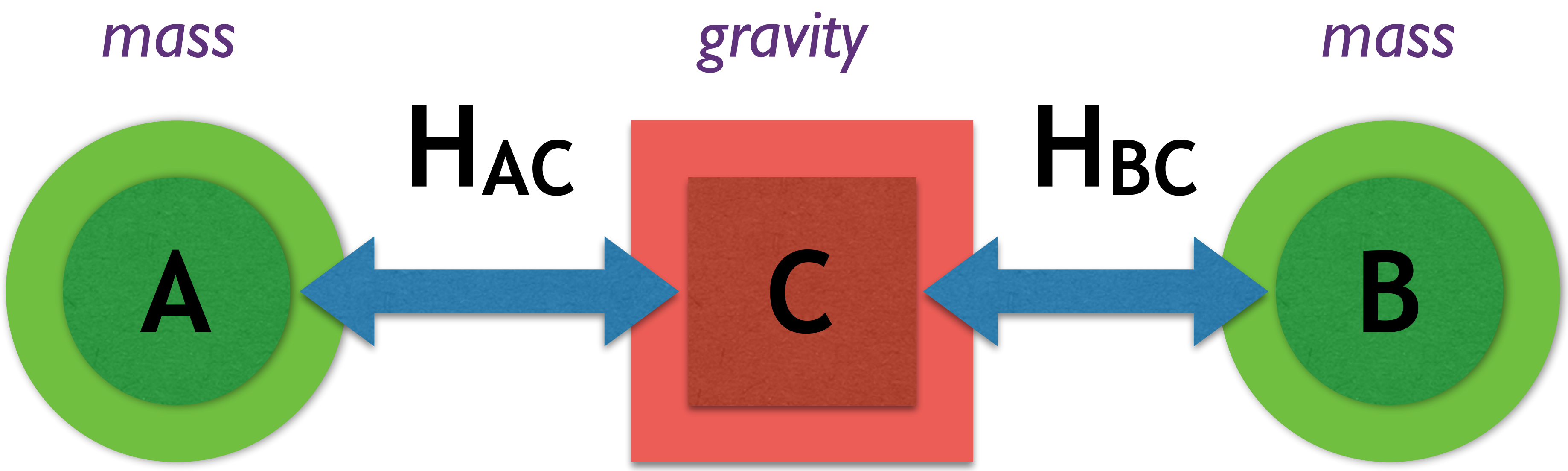
- *neutrons fall* [e.g. Nature **415**, 297 (2002)]
- *vertical interferometers have gravity-dependent phase shift* [PRL **34**, 1472 (1975)]
- *atomic gravimeters* [e.g. Nature **400**, 849 (1999)]

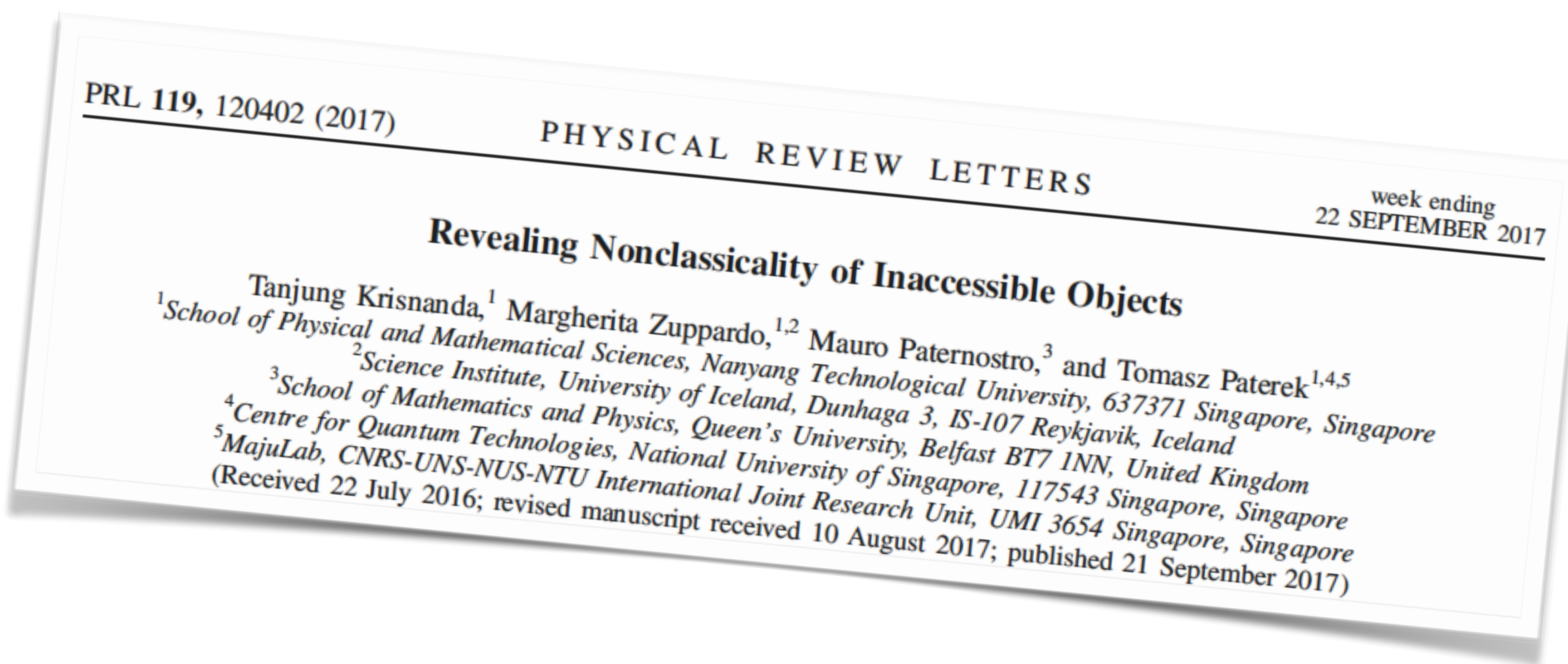
General relativity

- *gravitational redshift* [e.g. PRL **4**, 337 (1960)]
- *atomic clocks tick differently at different heights* [e.g. Science **177**, 168 (1972)]

All explained by classical gravity.

IDEA FOR EXPERIMENT INDICATING QUANTUM GRAVITY




PRL 119, 120402 (2017) PHYSICAL REVIEW LETTERS week ending 22 SEPTEMBER 2017

Revealing Nonclassicality of Inaccessible Objects

Tanjung Krisnanda,[1] Margherita Zuppardo,[1,2] Mauro Paternostro,[3] and Tomasz Paterek[1,4,5]
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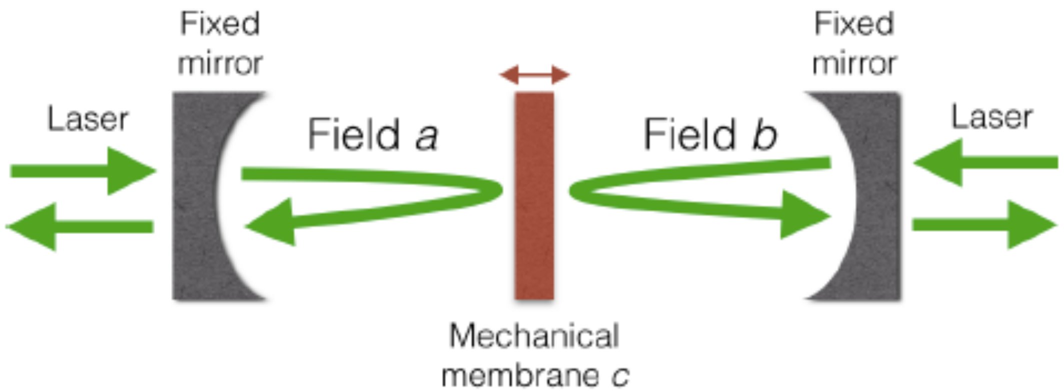
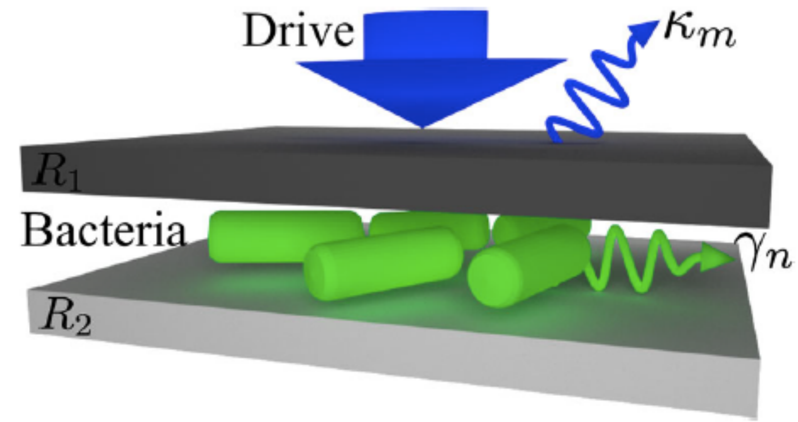
(Received 22 July 2016; revised manuscript received 10 August 2017; published 21 September 2017)

Opto-mechanics



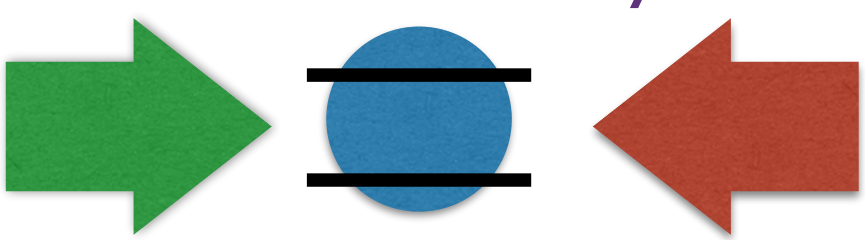
PRL **119**, 120402 (2017)

Quantum bio



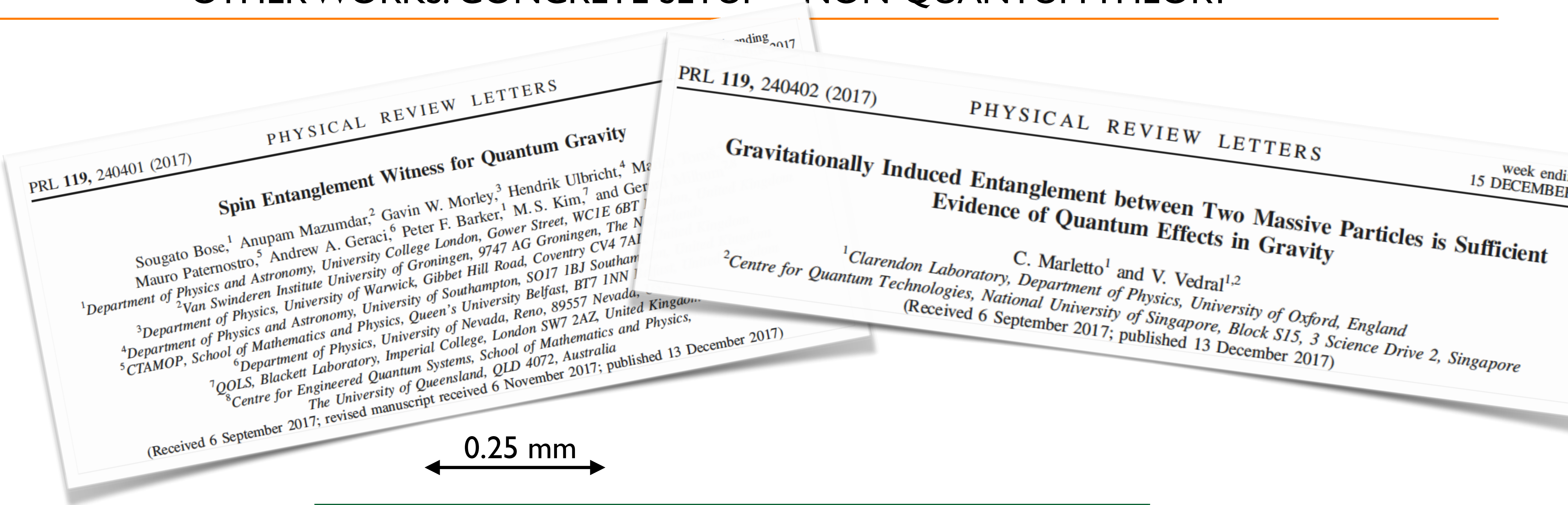
NPJQI **4**, 60 (2018)

Non-commutativity



PRA **98**, 052321 (2018)

OTHER WORKS: CONCRETE SETUP + NON-QUANTUM THEORY



PRL 119, 240401 (2017) PHYSICAL REVIEW LETTERS

Spin Entanglement Witness for Quantum Gravity

Sougato Bose,[1] Anupam Mazumdar,[2] Gavin W. Morley,[3] Hendrik Ulbricht,[4] Ma…
Mauro Paternostro,[5] Andrew A. Geraci,[6] Peter F. Barker,[1] M. S. Kim,[7] and Ger…

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(Received 6 September 2017; revised manuscript received 6 November 2017; published 13 December 2017)

PRL 119, 240402 (2017) PHYSICAL REVIEW LETTERS week ending 15 DECEMBER …

Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

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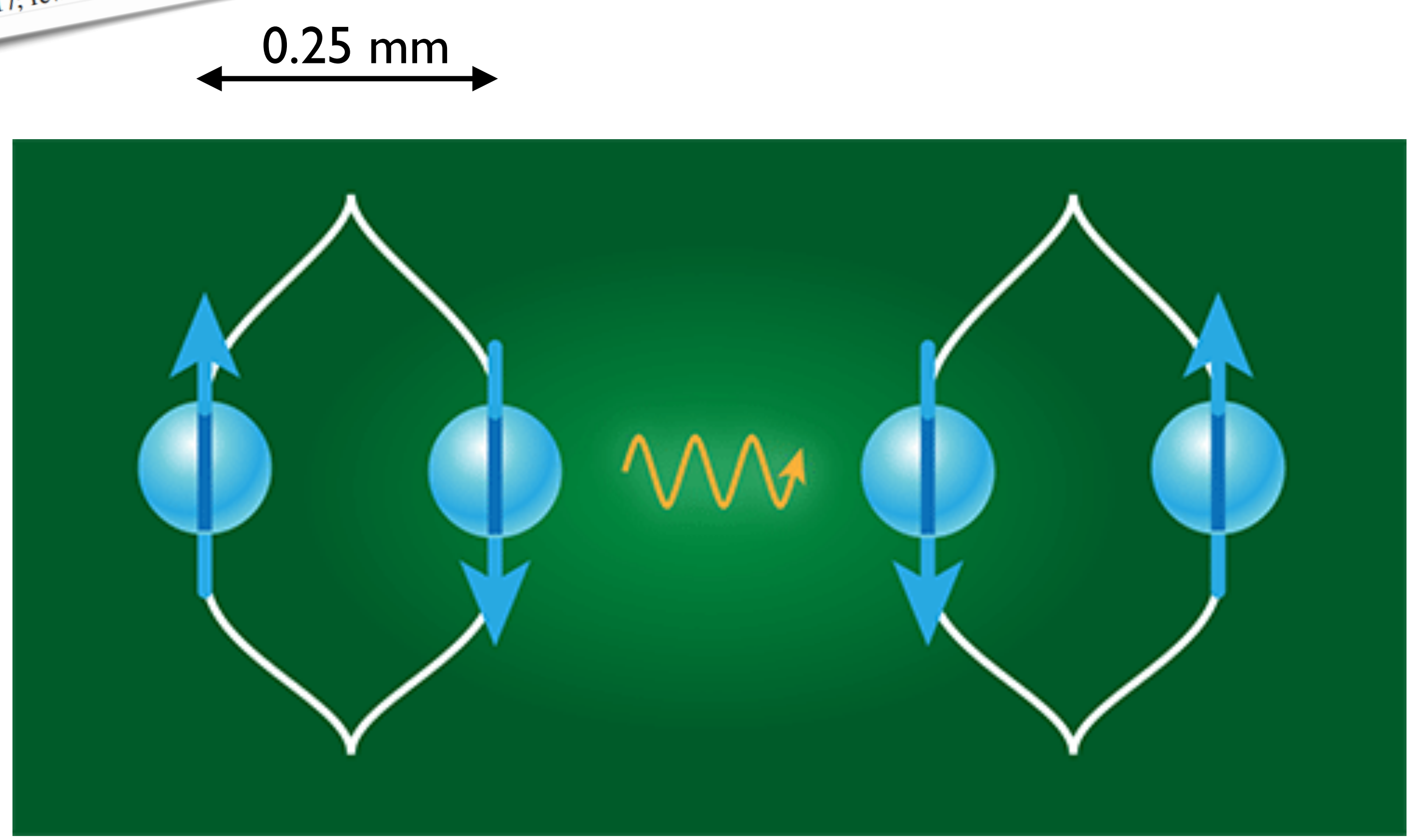
(Received 6 September 2017; published 13 December 2017)

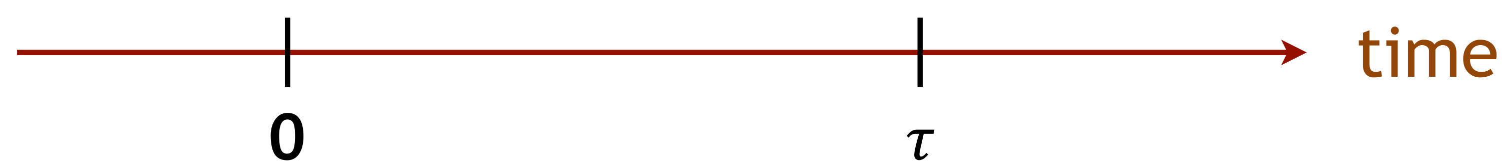


G.W. Morley / University of Warwick and A. Stonebraker / APS

ENTANGLEMENT A:B INDICATES DISCORDED MEDIATOR

If there is no entanglement initially:

$$E_{A:B}(\tau) > E_{A:B}(0) \text{ then } D_{AB|C}(t)>0$$



[note minimalistic assumptions about C and its couplings]

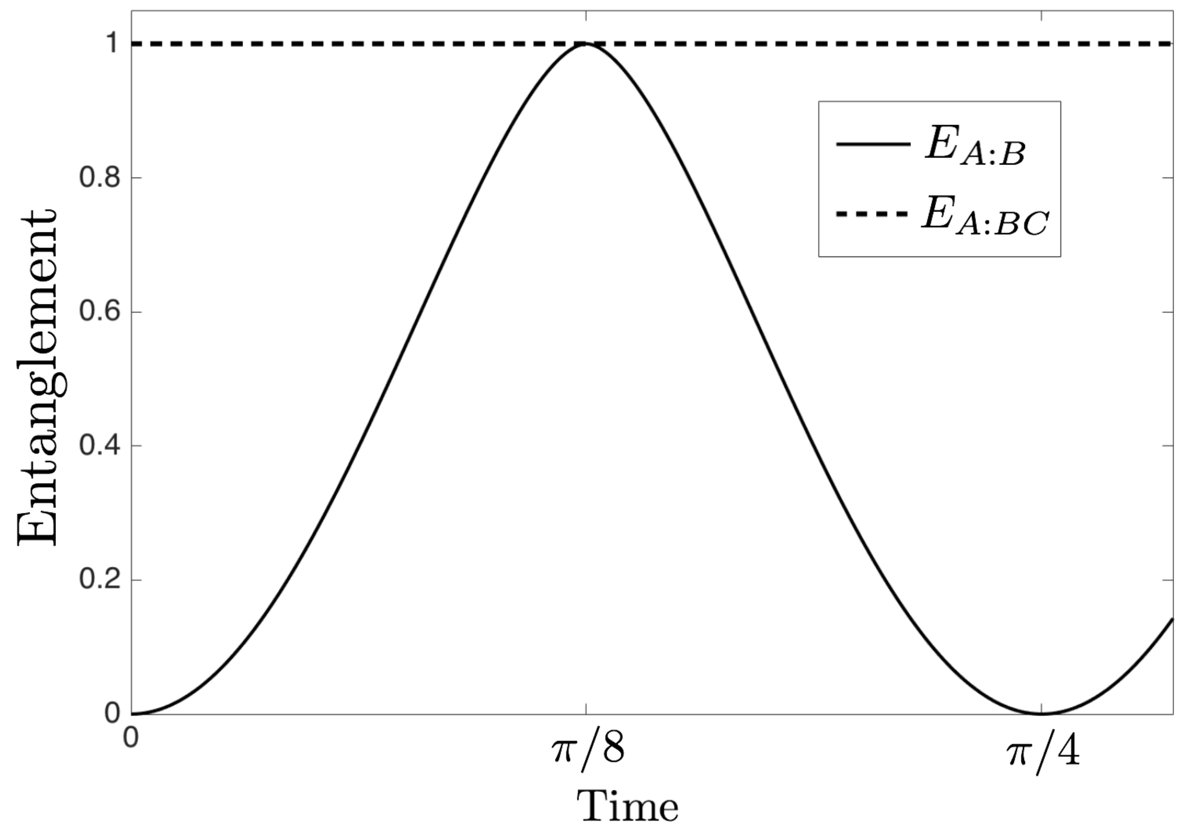
These must be orthogonal → Π_c

$$\rho_{\text{dis}} \neq \sum_c p_c \rho_{AB|c} \otimes \Pi_c$$

There must be non-orthogonal states of C
By operating on A and B one can prepare them

Chitambar, Streltsov, Rana, Bera, Adesso, Lewenstein, PRL **116**, 070402 (2016)

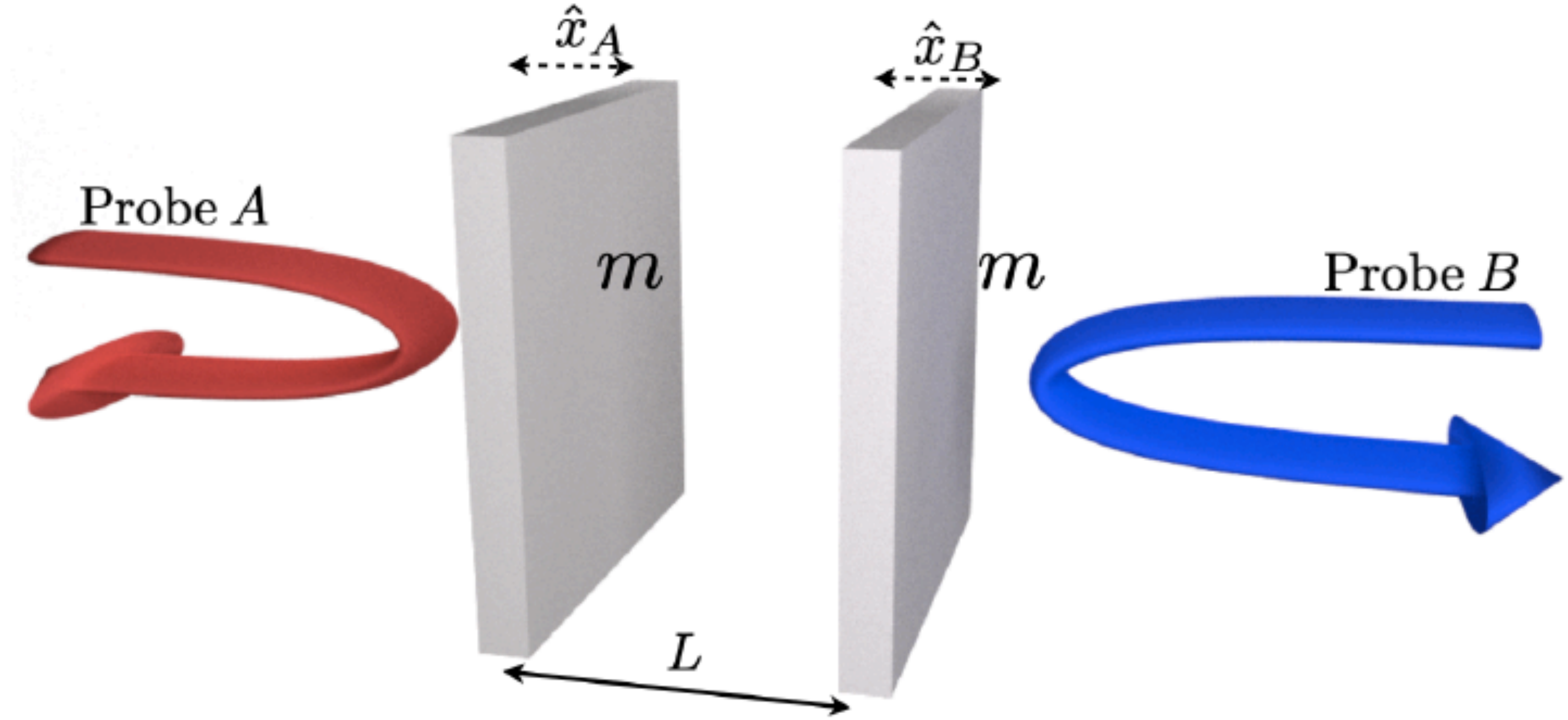
It is possible to localise initial entanglement A:BC to subsystem A:B via classical C.



$$\rho_0 = \frac{1}{2}|\psi^+\rangle\langle\psi^+| \otimes |+\rangle\langle+| + \frac{1}{2}|\phi^+\rangle\langle\phi^+| \otimes |-\rangle\langle-|$$

$$H = X \otimes \mathbb{1} \otimes X + \mathbb{1} \otimes X \otimes X$$

Concrete setup



Cool down close to ground state

Turn off lasers: gravity + noise + Casimir

Probe entanglement

$$H = \frac{\hat{p}_A^2}{2m} + \frac{1}{2}m\omega^2\hat{x}_A^2 + \frac{\hat{p}_B^2}{2m} + \frac{1}{2}m\omega^2\hat{x}_B^2 \; - \frac{Gm^2}{L + (\hat{x}_B - \hat{x}_A)}$$

Each oscillator is spherical.

A and B are directly coupled.
Previous theory not applicable
Incorrect coupling: instantaneous interactions
For two nearby objects very good approximation
Conditions for entanglement the same as with mediator

FIGURE OF MERIT

$$-\frac{Gm^2}{L+(\hat{x}_B-\hat{x}_A)} = -G\frac{m^2}{L}\left(1-\frac{\hat{x}_A-\hat{x}_B}{L}\right)^{-1}$$

$$\simeq -G\frac{m^2}{L}\left(1+\frac{\hat{x}_A-\hat{x}_B}{L}+\frac{(\hat{x}_A-\hat{x}_B)^2}{L^2}\right)$$

Energy shift *Local terms* *Possibility of entanglement*

In order to generate appreciable entanglement the last term needs to be comparable to the energy of each oscillator.

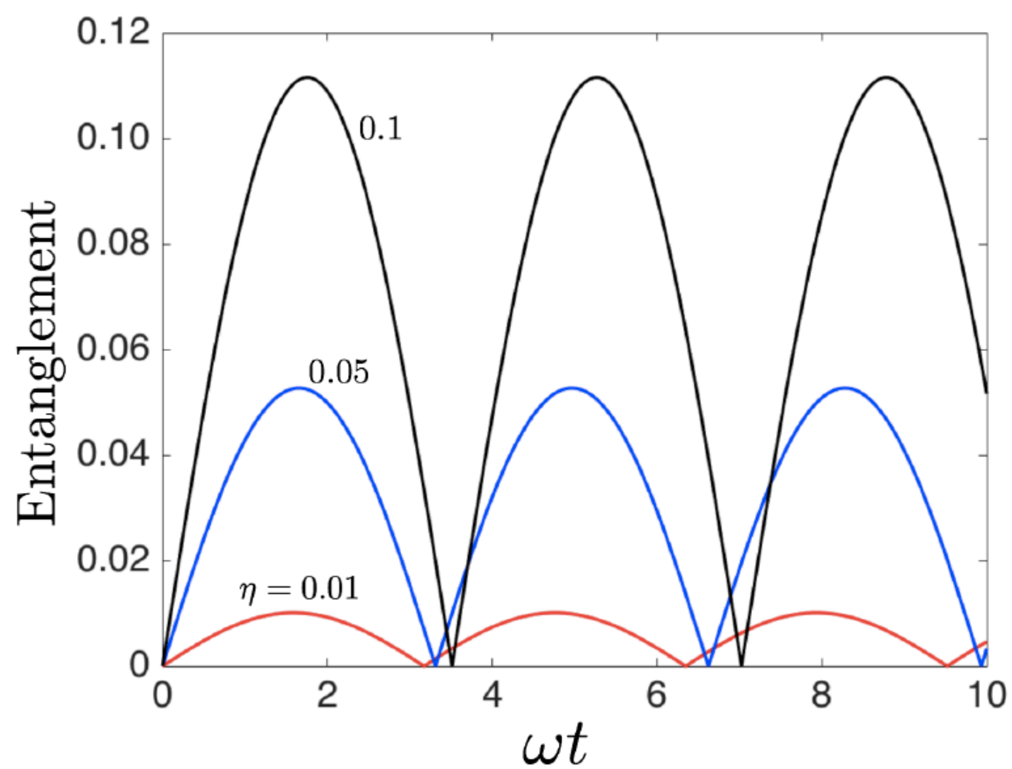
$$\frac{Gm^2(x_A-x_B)^2}{L^3\hbar\omega} \sim \frac{Gm}{\omega^2 L^3}$$

MAXIMUM ENTANGLEMENT AND ENTANGLING TIME

Analytical solution to the amount of logarithmic negativity.

Assumptions: (i) gravitational interaction up to the second order
(ii) small figure of merit

Starting with ground state:



$$E_{\max} \approx \frac{2Gm}{\omega^2 r^3} \equiv \eta$$

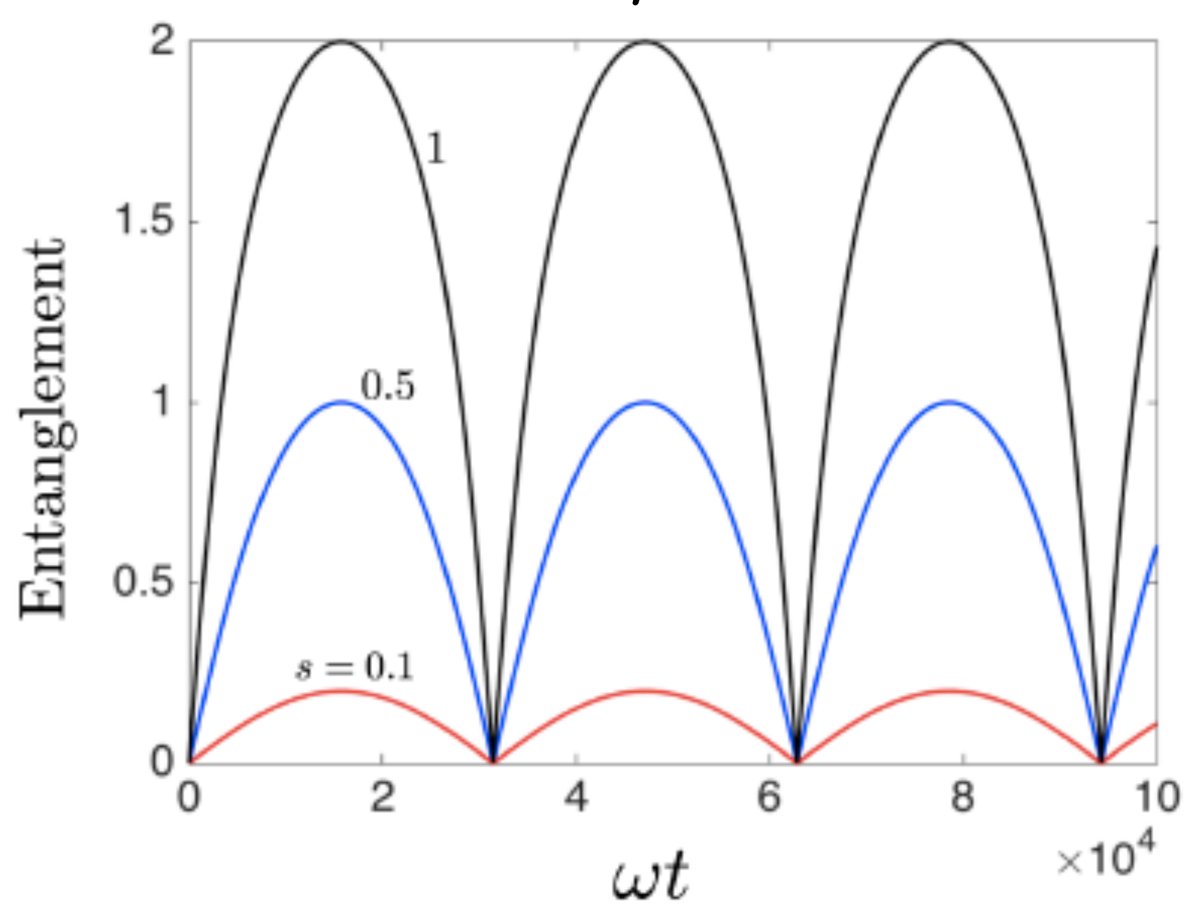
$$\omega t_{\max} \approx \frac{\pi}{2(1-\eta)}$$

MAXIMUM ENTANGLEMENT AND ENTANGLING TIME

Starting with squeezed vacuum (each oscillator independently):

$$E_{\max} \approx |s_1 + s_2| \quad \text{for} \quad s_1, s_2 \gg \eta$$

$$\omega t_{\max} \approx \frac{\pi}{2\eta}$$



$$\eta = 10^{-4}$$

MAXIMUM ENTANGLEMENT

Starting with thermal state: $E_{\max} \approx \eta - \ln(1 + 2\bar{n})$

Starting with squeezed thermal state: $E_{\max} \approx |s_1 + s_2| - \ln(1 + 2\bar{n})$

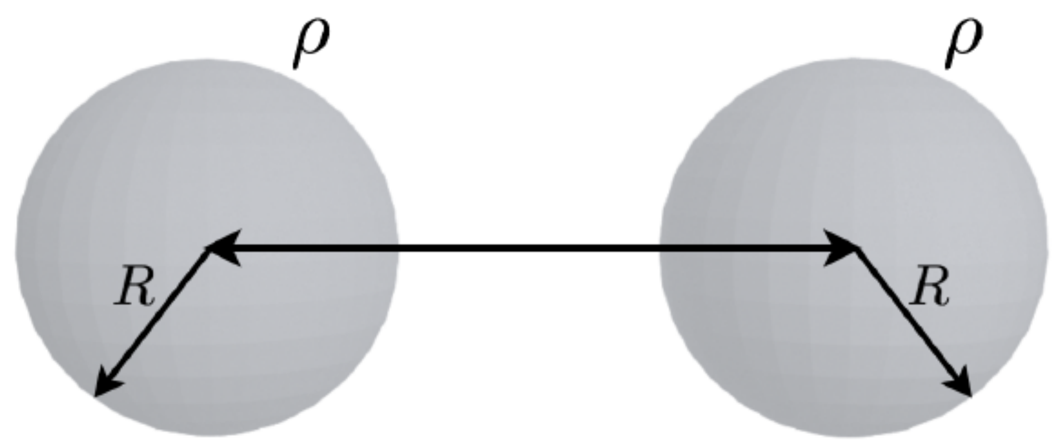
As expected temperature kills entanglement.

Example: for eta = 0.01, no entanglement for n > 0.005.

Hence squeezing is important.

With highest achieved squeezing, s =1.7, no entanglement for n > 14.

Can such experiment be done?

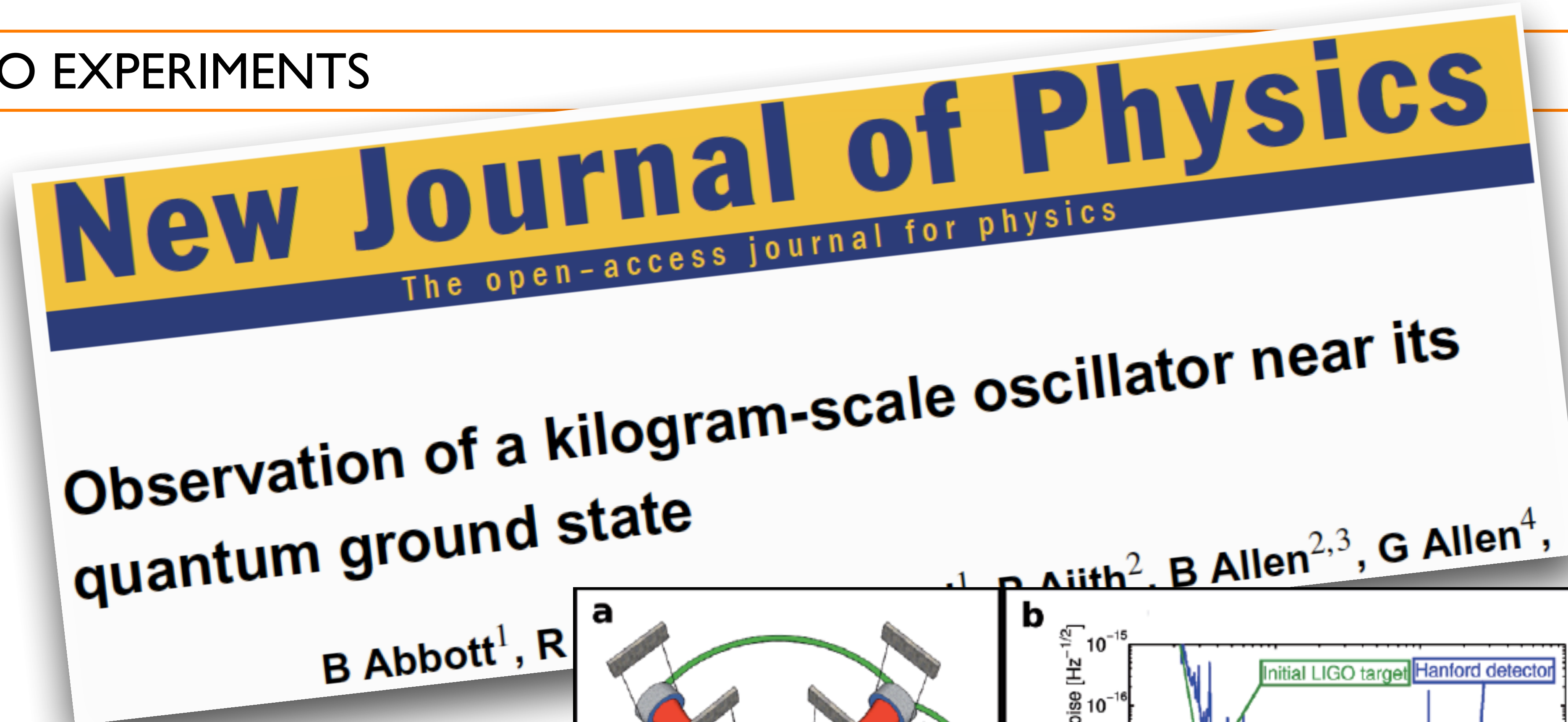


Set L = 2.1 R

$$\eta = \frac{8\pi}{3(2.1)^3}\frac{G\rho}{\omega^2}$$ (mass independent)

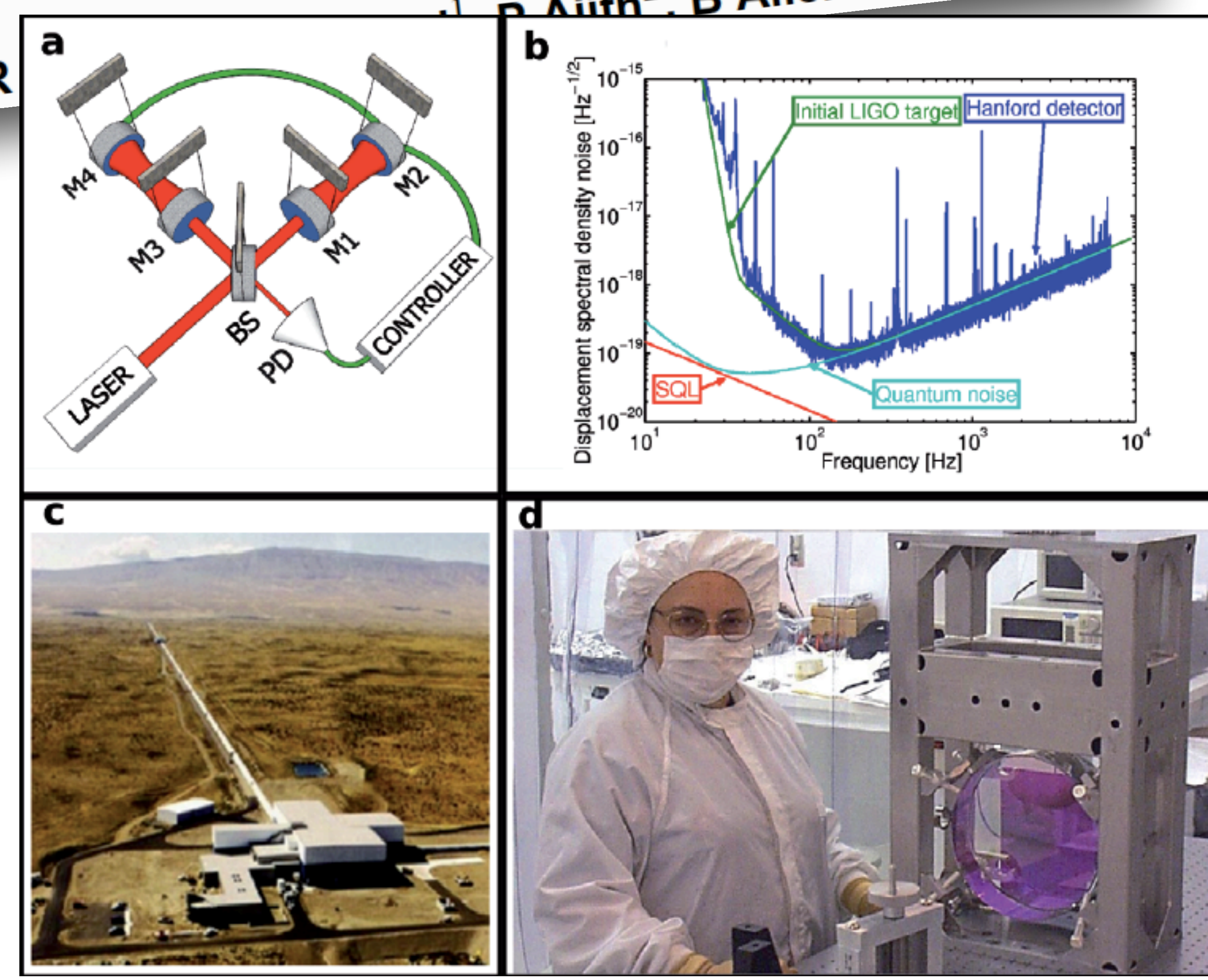
$$\eta(\omega) = 1.36 \times 10^{-6}/\omega^2$$ (with Osmium density)

Conclusion: eta ~ 0.01 requires omega ~ 0.01 Hz
eta ~ 0.0001 requires omega ~ 0.1 Hz


New Journal of Physics
The open-access journal for physics

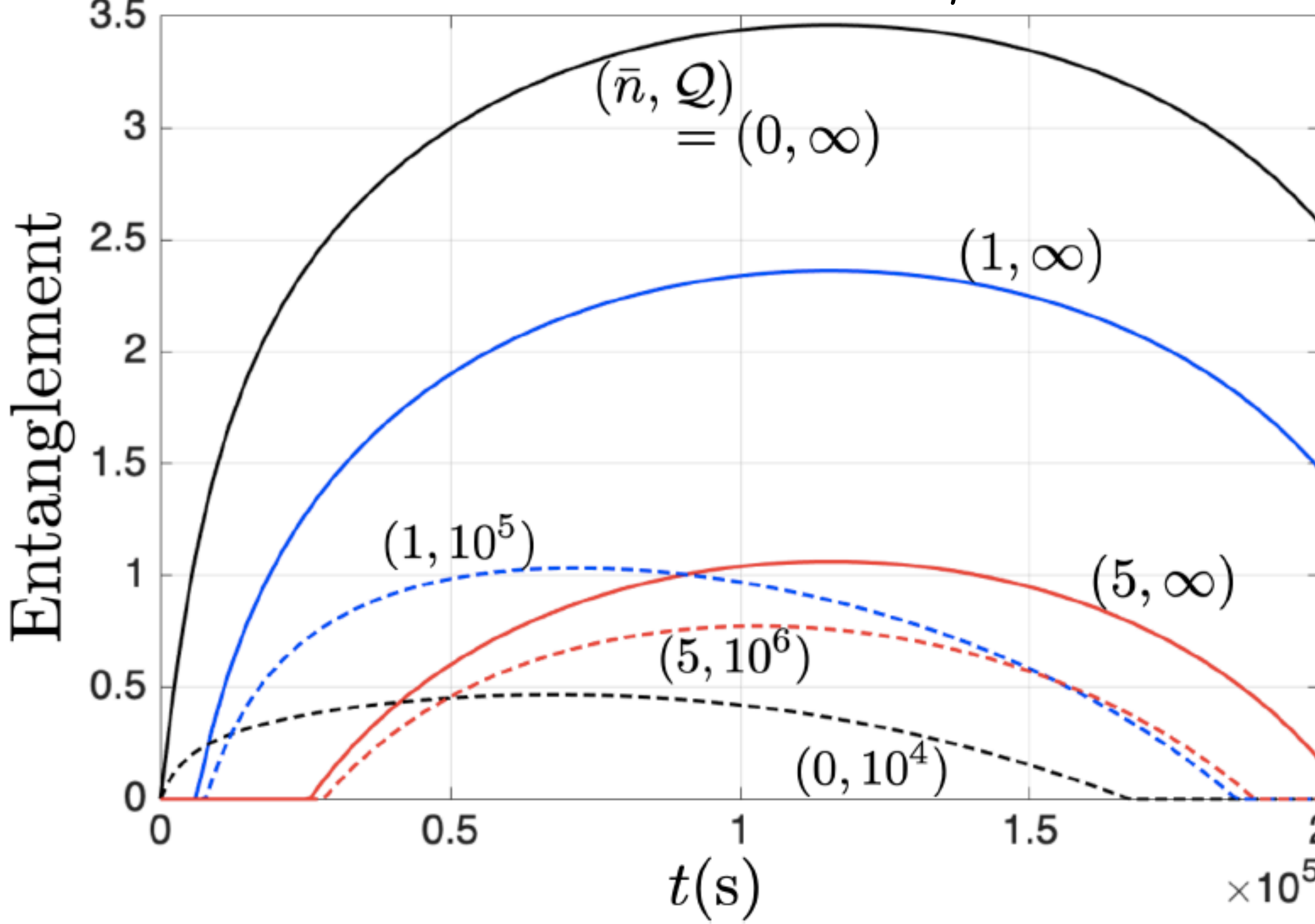
Observation of a kilogram-scale oscillator near its quantum ground state

B Abbott[1], R … P Ajith[2], B Allen[2,3], G Allen[4],

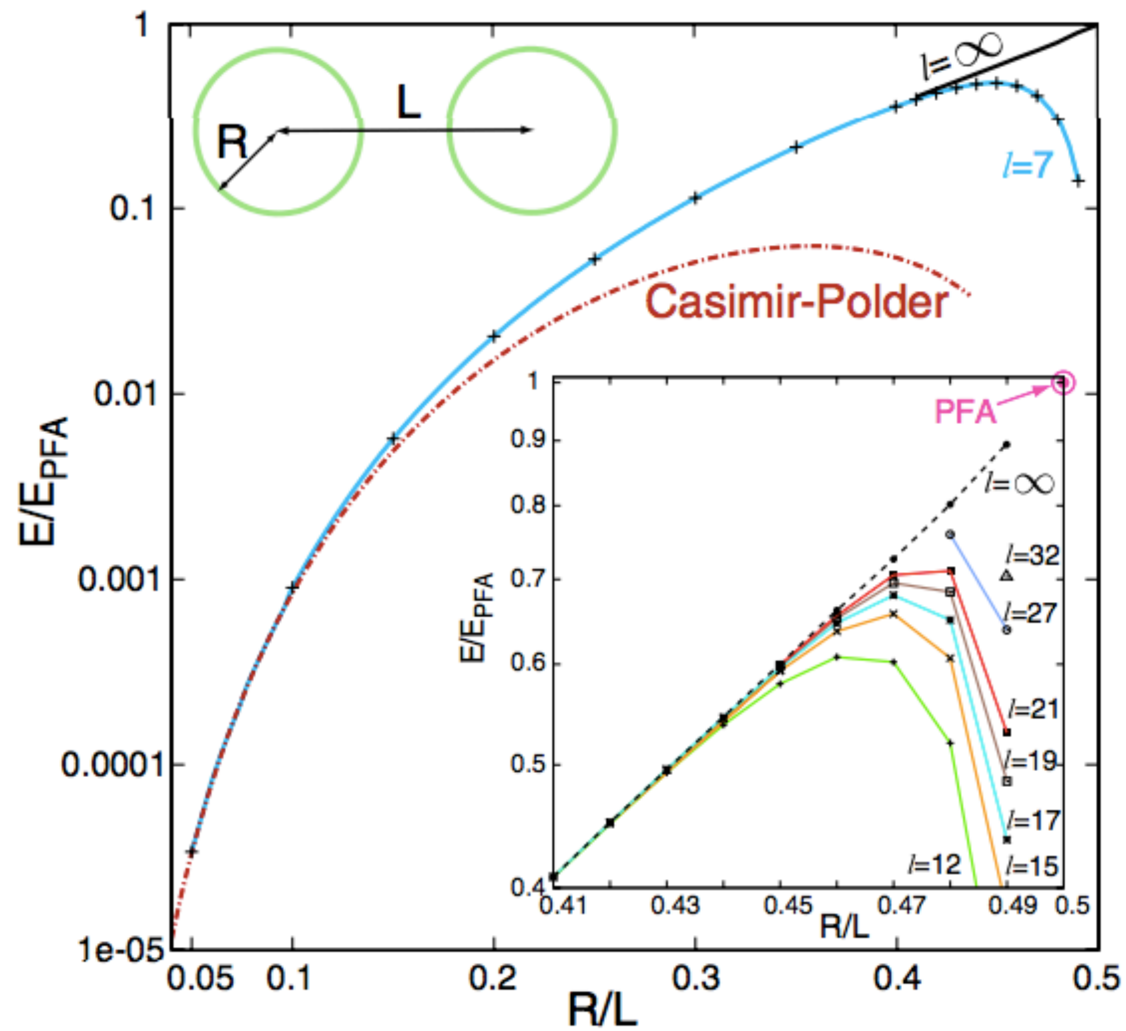


Mirror: 10.8 kg
Frequency: 0.74 Hz
Q factor: 100

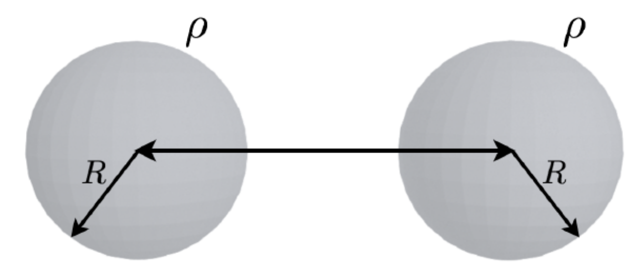
$$\omega = 0.1\text{Hz}$$
$$\eta = 1.36 \times 10^{-4}$$



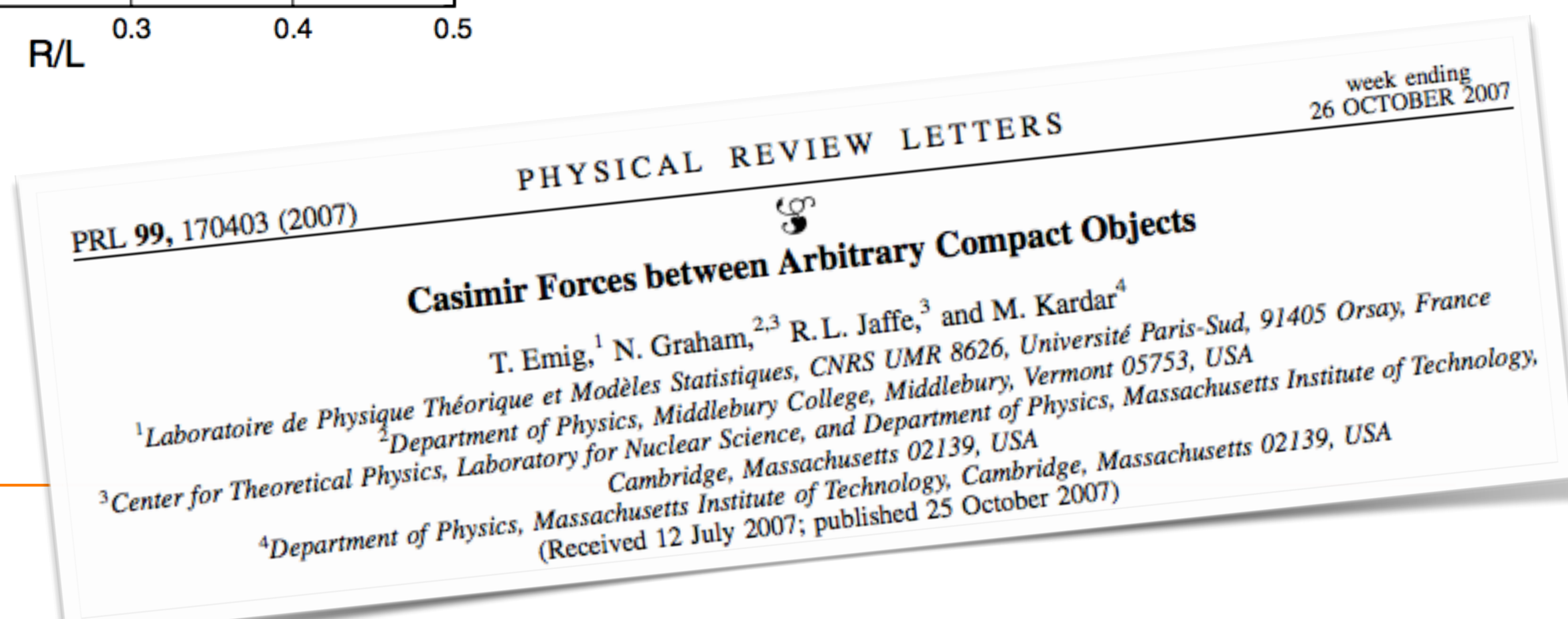
CASIMIR FORCES BETWEEN MACROSCOPIC OBJECTS



$$\mathcal{E}_{\rm PFA} = -\frac{\pi^3}{1440}\frac{\hbar c R}{(L-2R+(x_B-x_A))^2}$$



R = 4 cm


PRL 99, 170403 (2007) PHYSICAL REVIEW LETTERS week ending 26 OCTOBER 2007

Casimir Forces between Arbitrary Compact Objects

T. Emig,[1] N. Graham,[2,3] R. L. Jaffe,[3] and M. Kardar[4]

[1]Laboratoire de Physique Théorique et Modèles Statistiques, CNRS UMR 8626, Université Paris-Sud, 91405 Orsay, France
[2]Department of Physics, Middlebury College, Middlebury, Vermont 05753, USA
[3]Center for Theoretical Physics, Laboratory for Nuclear Science, and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
[4]Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
(Received 12 July 2007; published 25 October 2007)

Expand Casimir energy:

$$\mathcal{E}_{\mathrm{PFA}} = -\frac{\pi^3}{1440}\frac{\hbar c R}{(L-2R+(x_B-x_A))^2}$$

$D = L - 2R \equiv 0.1R$

$$\simeq -\frac{\pi^3}{1440}\frac{\hbar c R}{D^2}\left(1 + 2\frac{x_A - x_B}{D} + 3\frac{(x_A-x_B)^2}{D^2}\right)$$

Energy shift *Local terms* *Entanglement*

Comparison of entangling Casimir and gravitational terms:

$$\frac{\left(\frac{3\pi^3\hbar c R}{1440 L^4}\right)}{\left(\frac{Gm^2}{r^3}\right)} \approx 3\times 10^{-12}\frac{1}{m^2}$$

We need an experiment with an outcome indicating non-classical features of gravity.

Gravity as mediator of entanglement is a possibility.

We provided parameters that are necessary to achieve this for a system of two massive spherical oscillators. LIGO mirrors sound okish, but long coherence time is especially demanding.

Quantitative statements:

How much discord / coherence / … is needed for entanglement gain?

How much non-commutativity is needed for entanglement gain?

Witnesses of direct / indirect interactions:

Is there a way of proving experimentally that these was (no) mediator?