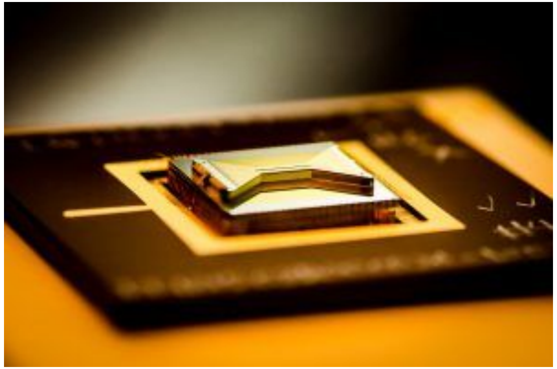
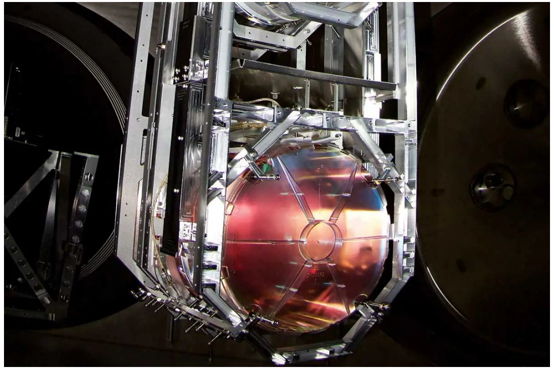
Tabletop experiments in quantum gravity

Daniel Carney
JQI/QuICS, University of Maryland/NIST
Theory Division, Fermilab

→ Berkeley National Lab (spring 2021)

Macroscopic quantum coherence



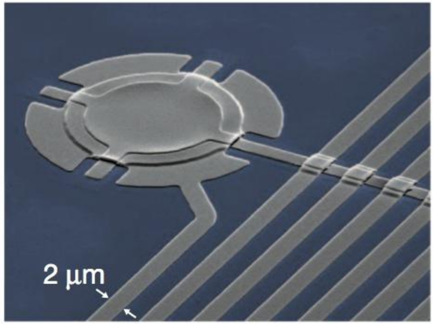


New, open frontier: quantum coherence, entanglement with many particles, large volumes, distances, …

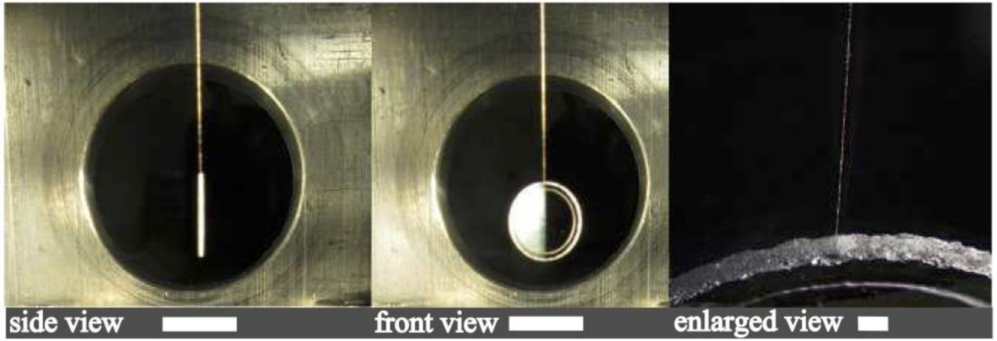
Sensing at the level of vacuum fluctuations of macroscopic objects becoming routine

True quantum control of larger systems possible

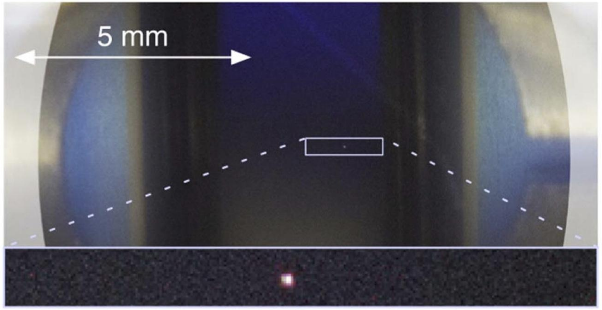
Technology $\longleftrightarrow$ theory



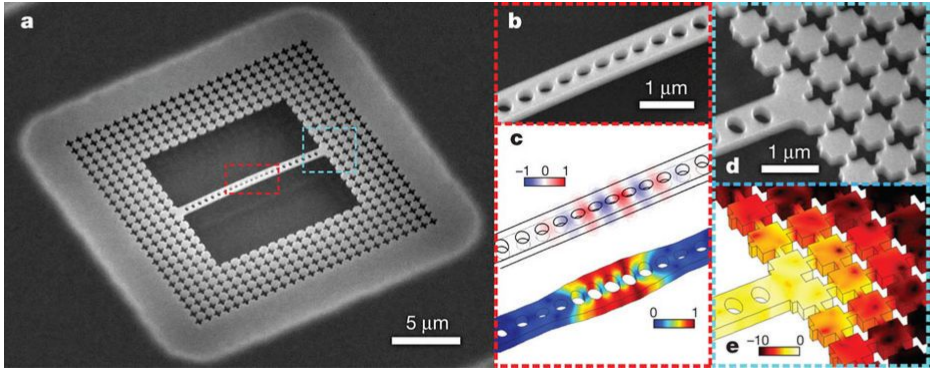
Teufel et al, Nature 2011



Matsumoto et al, PRA 2015



Aspelmeyer ICTP slides 2013



Painter et al, Nature 2011

PHYSICAL REVIEW LETTERS

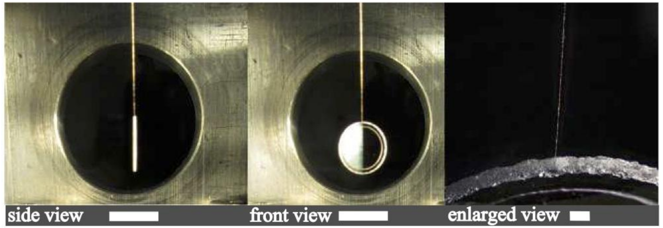
Featured in Physics

Demonstration of Displacement Sensing of a mg-Scale Pendulum for mm- and mg-Scale Gravity Measurements

Nobuyuki Matsumoto, Seth B. Cataño-Lopez, Masakazu Sugawara, Seiya Suzuki, Naofumi Abe, Kentaro Komori, Yuta Michimura, Yoichi Aso, and Keiichi Edamatsu

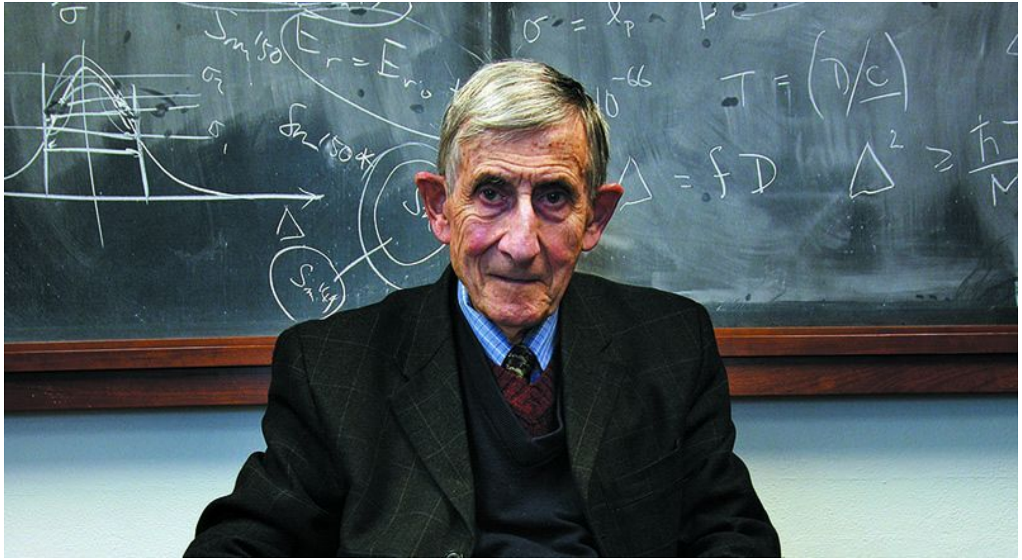
Phys. Rev. Lett. **122**, 071101 – Published 19 February 2019

Physics See Synopsis: Gravity of the Ultralight



$F_{grav} = G_N m^2/d^2 \sim 10^{-17}$ N for two masses m = mg separated by d = mm

cf. 10^{-21} N/√Hz (and better) sensitivities achieved optomechanically



Is a Graviton Detectable?

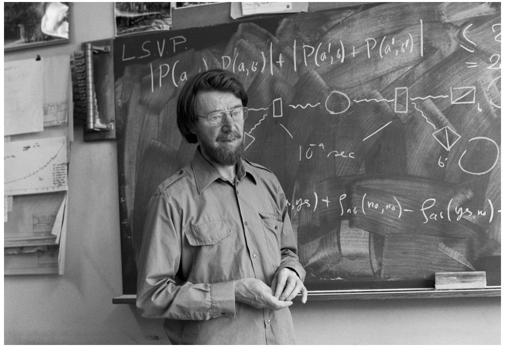
Poincare Prize Lecture

International Congress of Mathematical Physics

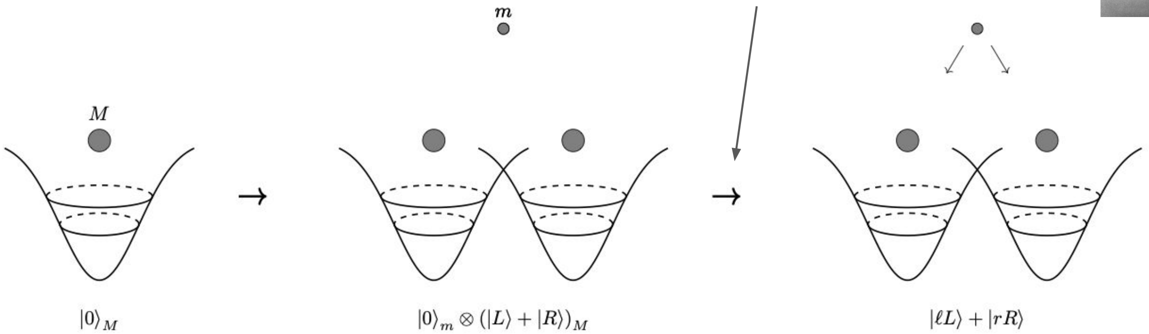
Aalborg, Denmark, August 6, 2012

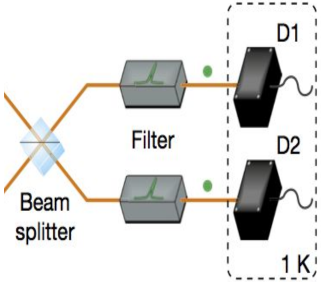
Freeman Dyson, Institute for Advanced Study, Princeton, New Jersey

“Is gravity quantum?”



$$\hat{V} = \frac{G_N m_1 m_2}{|\hat{\mathbf{x}}_1 - \hat{\mathbf{x}}_2|}$$





Concrete goal: demonstrate that gravity can generate entanglement (e.g. violate Bell inequality or similar “witness”). Old idea going back to Feynman, Page & Geilker, etc

Two questions: What would this show? And how exactly would we do it?

Implications

Principled questions this is asking:

- Can the gravitational field be put into quantum superposition?
- Can the gravitational field be used to entangle two quantum systems?

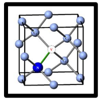
More pheno-y take: in these experiments, $E/M_{pl} << 1$, perturbative quantized GR (viewed as effective QFT) is perfectly good theory. In this model, answer to above is: yes.

But is this the correct theory of nature? Alternatives include:

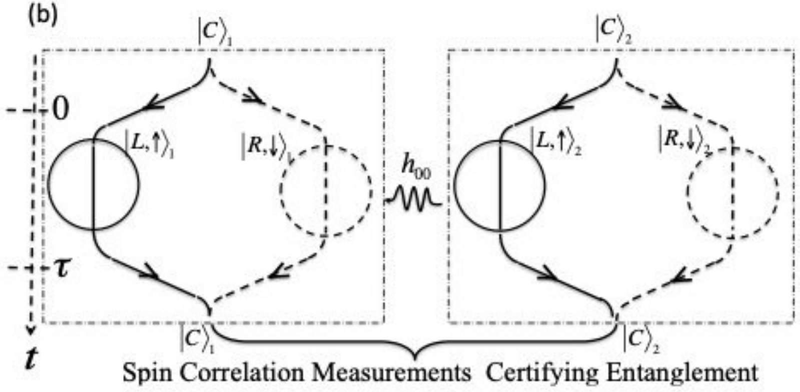
- Gravity is “fundamentally classical” -- interaction cannot entangle objects
- *Gravity is “emergent” -- interaction can maybe entangle objects, depends on details
- Gravity causes a breakdown of quantum mechanics (Penrose, Diosi, ...) -- wild west

*not necessarily an alternative! (eg. AdS/CFT)

Implementation with matter wave interferometery



← NV center diamond (mass with a spin)



GR as effective field theory prediction:

$$|LL\rangle \to |LL\rangle + |LR\rangle + e^{i\Delta\phi}|RL\rangle + |RR\rangle$$

$$\Delta\phi = \frac{G_N m^2 \Delta x \Delta t}{\hbar d^2} \approx 60 \times \left(\frac{m}{1\,\mathrm{ng}}\right)^2 \left(\frac{\Delta x}{1\,\mu\mathrm{m}}\right) \left(\frac{\Delta t}{1\,\mathrm{s}}\right) \left(\frac{1\,\mu\mathrm{m}}{d}\right)^2$$

- Entangled state of the two interferometers, entanglement grows linearly in time
- Verifiable via an entanglement witness: Bell inequality in the spin DOF

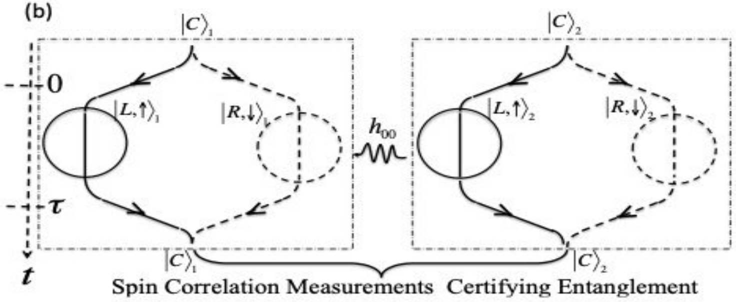
S. Bose et al 1707.06050 (PRL 2017)

Example of alternative: “classical gravity”

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} \langle T_{\mu\nu} \rangle \qquad\qquad i\partial_t |\psi\rangle = (H_{mat} + H_{grav}) |\psi\rangle$$

First equation is in principle OK. Closing it with second is bad, but there are consistent versions now known, at least non-relativistically.

As far as I know, all share one property: no gravitational entanglement!

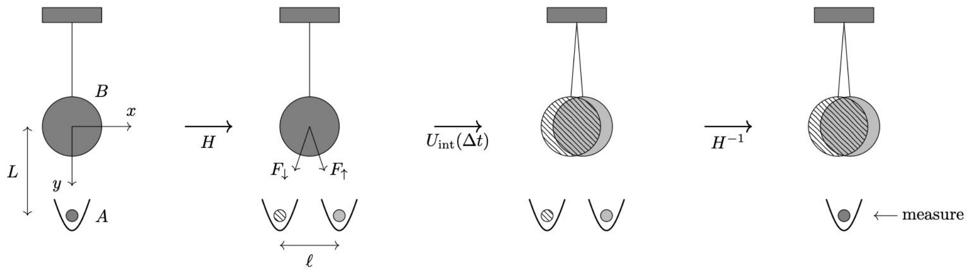


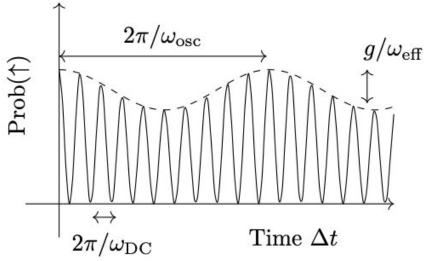
Quantized GR: $|LL\rangle \to |LL\rangle + |LR\rangle + e^{i\Delta\phi}|RL\rangle + |RR\rangle$

“Classical” GR: $|LL\rangle \to \left(|L\rangle + e^{i\Delta\phi}|R\rangle\right)_1 \otimes \left(|L\rangle + e^{-i\Delta\phi}|R\rangle\right)_2$

→ **no entanglement/Bell inequality violation**

Implementation with atom interferometer + mechanics





Per atom → $$\frac{g}{\omega} = \frac{G_N m M \ell x_{ZPF}}{\hbar \omega_{\text{eff}} L^3} \approx 10^{-11} \times \left(\frac{m}{100\ \text{amu}}\right)\left(\frac{M}{1\ \text{mg}}\right)^{1/2}\left(\frac{1\ \text{mHz}}{\omega_{\text{eff}}}\right)$$

- Entangled state of mechanics + atoms, entanglement varies *periodically* in time
- Verification: atom periodically decoheres and recoheres ("wavefunction collapse and revival" similar to NMR/spin echo). **Only need local measurement on atoms!**

Coming soon to arxiv. **D. Carney**, H. Muller, J. Taylor

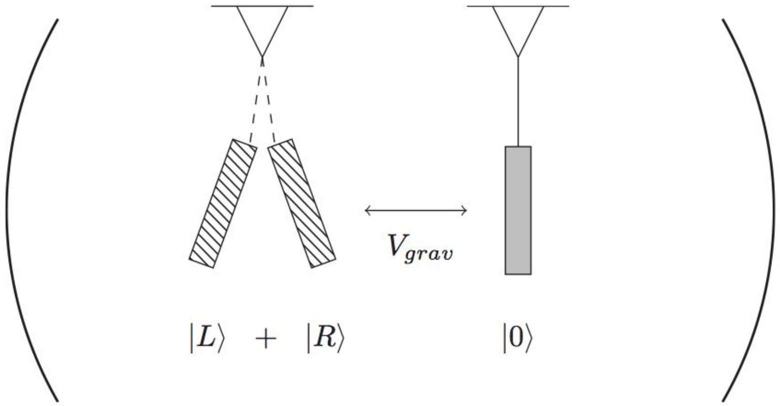
Editorial remarks on the current situation

Bose et al proposal hard: low frequency noise reduction/subtraction, very high B gradients, very high vacuum all needed (all at few orders of magnitude beyond state of art)

Our proposal also hard: more atoms, longer atomic and oscillator coherence times needed (again by few orders of magnitude), also high degree of control on atom state

Some other proposals exist but all look pretty much impossible.

I think the optimum protocol is still not known. My suspicion is you want to use a pair of massive oscillators (thus “large” masses and elimination of low-freq noise), and probably utilizing a form of quantum error correction. This is current work.

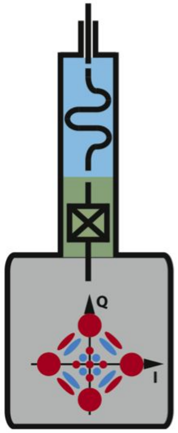


$$H = \sum_{i=1,2} \hbar\omega a_i^\dagger a_i - \hbar\lambda_g(a_1 a_2^\dagger + a_1^\dagger a_2)$$

$$\lambda_g \approx 6\times 10^{-8}\,\mathrm{Hz} \times \left(\frac{m}{1\,\mathrm{ng}}\right)\left(\frac{1\,\mathrm{Hz}}{\omega}\right)\left(\frac{1\,\mu\mathrm{m}}{d}\right)^3$$

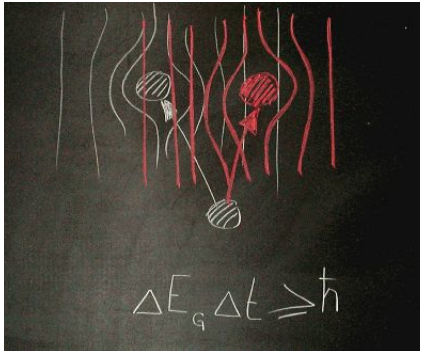
Two central difficulties:

1. Readout--how to see small perturbative effect?
2. State preparation and maintenance--nonlinear control, quantum error correction, ...



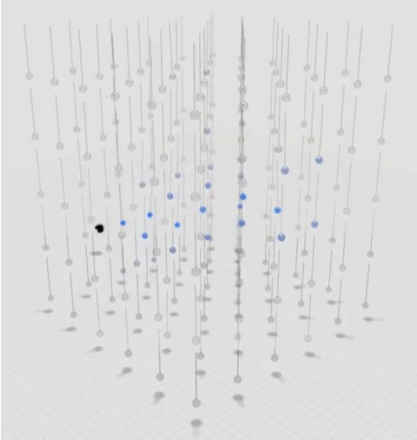
From M. Mirrahimi's notes on "bosonic cat codes"

Related applications with same technology



- Testing other, crazier ideas about gravity + QM which are **NOT** predicted by perturbative quantum GR (e.g. Penrose decoherence)

  Review: **D. Carney**, P. Stamp, J. Taylor 1807.11494
  Snowmass: Theory frontier 1



- Dark matter detection of many flavors (notable: very heavy DM detection purely through gravity)

  Review: **D. Carney**, G. Krnjaic, C. Regal, D. Moore et al 2008.06074
  Snowmass: Instrumentation frontier 1

Open directions

- Is there a better experimental protocol? Noise mitigation techniques?

- If we do see entanglement, does this necessarily imply graviton exists?
(some heuristic arguments in the affirmative, see Belenchia et al 1807.07015, but would be better to have some theorems & understanding of precise statement)

- Models without graviton need to be understood better. For example, microscopic models (even toy models) of emergent gravity, what do they predict?

Thanks! Feel free to reach out with questions: carney@umd.edu.

Review paper on all this & more:
"Tabletop experiments in quantum gravity: a user's manual"
D. Carney, P. Stamp, J. Taylor 1807.11494, Class.Quant.Grav. 36 (2019)

Thanks to collaborators!