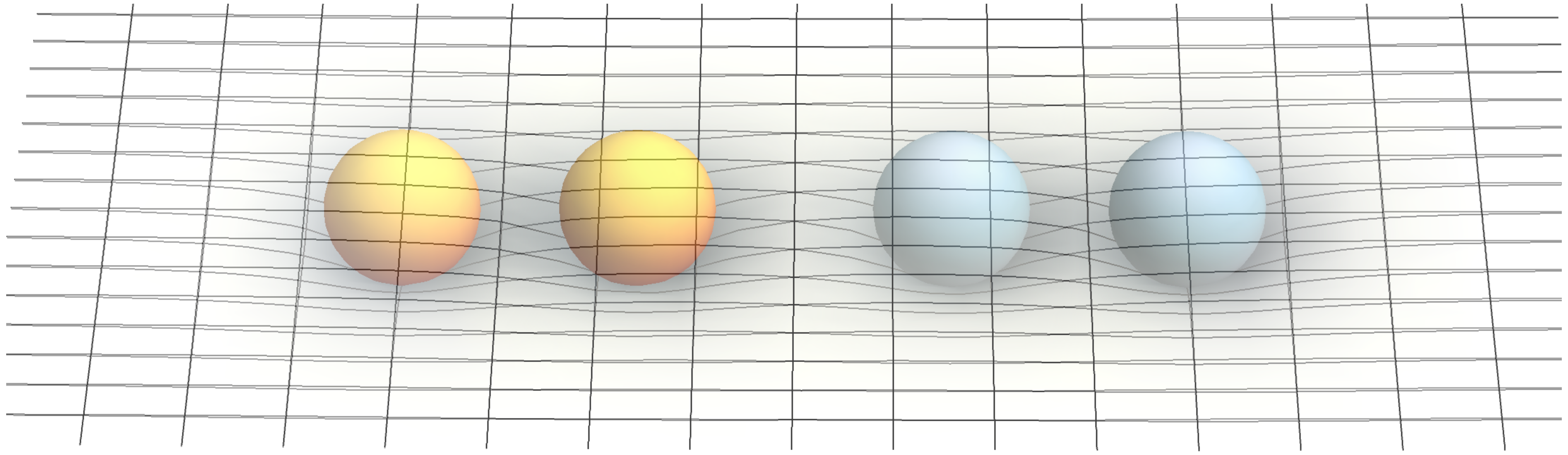
Table-top experiments for Quantum Gravity



Vasileios Fragkos

Ph.D student in the group of
Igor Pikovski

STEVENS INSTITUTE of TECHNOLOGY
1870
THE INNOVATION UNIVERSITY®

UNIVERSITET STOCKHOLMS

COST conference, Rijeka, July 14, 2023

Outline of the talk

Part I: Introduction

- Quantum and Gravity interface.

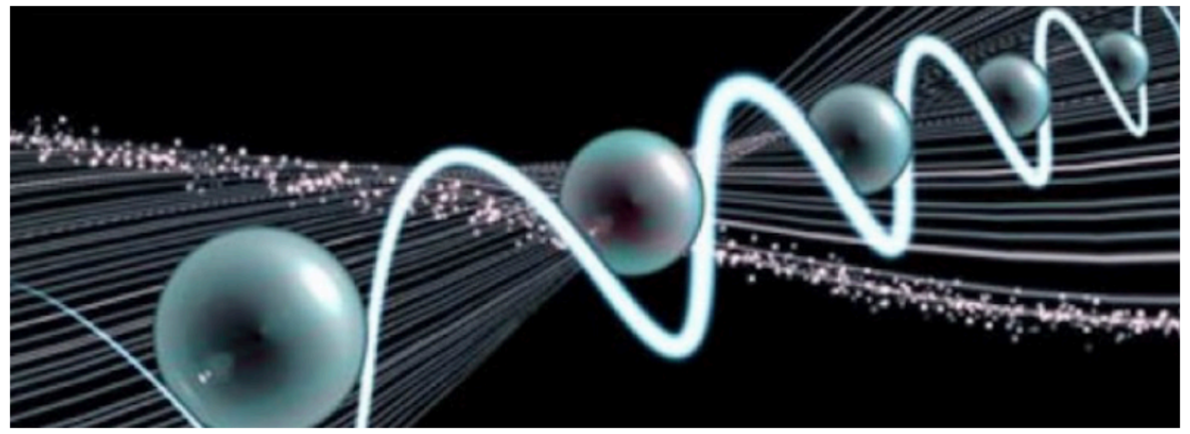
- A brief history of table-top experiments.

Part II: Gravity Induced Entanglement proposal

- What does it teach us about quantum gravity?

Two (very broad) take home messages from this talk

Impressive advances in AMO experimental physics, in control and manipulation of microscopic (and not only) quantum systems, push in new untested regimes. New fundamental phenomena at the interface of quantum and gravity are around the corner.



There are plenty of table-top experimental proposals claiming to *test quantum aspects of gravity*. Nevertheless, *none seems conclusive*.

→

In the second part of the talk, I will zoom in an ambitious proposal from 2017, known as Gravity Induced Entanglement (GIE) proposal, *highlighting its inherent interpretational ambiguity*.

Based on:

On inference of quantization from gravitationally induced entanglement

Cite as: AVS Quantum Sci. **4**, 045601 (2022); doi: 10.1116/5.0101334
Submitted: 31 May 2022 · Accepted: 19 October 2022 ·
Published Online: 29 November 2022

View Online | Export Citation | CrossMark

Vasileios Fragkos,[1,a] Michael Kopp,[1,2,b] and Igor Pikovski[1,3,a]

Research questions on the gravity-quantum interface

- Is gravity fundamentally classical or quantum?

  No experimental input so far.

  - Bottom-up approach → Driven by experiments
  - Top-down approach → Driven by theoretical consistency (Symmetries, Simplicity,…)

- In a theory of quantum gravity, which principles survive and which are abandoned? (e.g. EP, Locality, Lorentz symmetry, superposition principle?)

- Similarly, which principles should be modified/generalised? (e.g Generalised uncertainty relations, Quantum formulation of EP?)

- Are there new (not speculative) effects which have been overlooked?

ARTICLES

PUBLISHED ONLINE: 15 JUNE 2015 | DOI: 10.1038/NPHYS3366

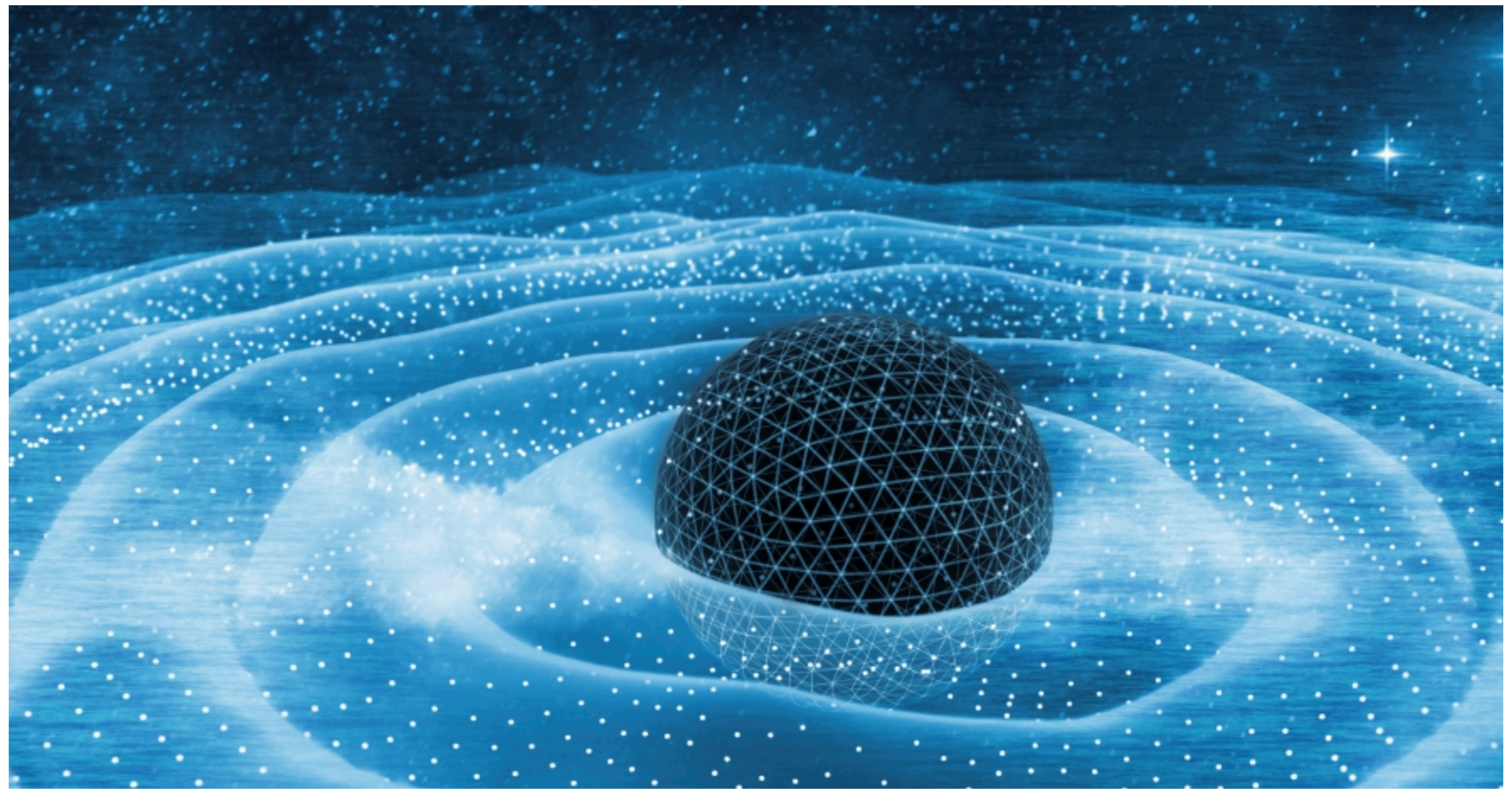
nature physics

Universal decoherence due to gravitational time dilation

Igor Pikovski[1,2,3,4*], Magdalena Zych[1,2,5], Fabio Costa[1,2,5] and Časlav Brukner[1,2]

Motivation for a quantum theory of gravity

- All other fundamental forces in the standard model are quantum in nature.
- General relativity breaks down in the singularities (Black Holes, Big Bang). At these points, the theory loses its predictability.
- Provide a deeper understanding of Hawking radiation, Black hole evaporation, black hole entropy etc…
- Difficulty in consistently coupling classical with quantum systems.



A zoo of quantum gravity approaches

- **String theory**
- **Loop quantum gravity**
- Asymptotic safety in quantum gravity
- Euclidean quantum gravity
- Integral method[59]
- Causal dynamical triangulation[60]
- Causal fermion systems
- Causal Set Theory
- Covariant Feynman path integral approach
- Dilatonic quantum gravity
- Double copy theory
- Group field theory
- Wheeler–DeWitt equation
- Geometrodynamics
- Hořava–Lifshitz gravity
- MacDowell–Mansouri action
- Noncommutative geometry
- Path-integral based models of quantum cosmology[61]
- Regge calculus
- Shape Dynamics
- String-nets and quantum graphity
- Supergravity
- Twistor theory[62]
- Canonical quantum gravity

- *Quantization* of general relativity → Democratic treatment of QM and GR. (Canonical and covariant approach)
- *Gravitization* of quantum physics → GR is fundamental. Forcing QM be compatible with GR.
- Spacetime emergence → Quantum is fundamental and gravity seen as emergent phenomenon
- General relativity and quantum physics as limiting cases → Radical approach. New perspectives in both GR and QM

Is gravity fundamentally classical?

- Lack of experimental evidence has led physicists to question the whole quantum gravity programme.

- Møller-Rosenfeld theory: $$G_{\mu\nu} = 8\pi G \langle \Psi | \hat{T}_{\mu\nu} | \Psi \rangle$$

Møller (1962}
Rosenfeld (1963)

Matter is quantized whereas gravity is *fundamentally* classical

Møller-Rosenfeld theory standard approach to
→ Computation of Hawking radiation
→ Computation of Inflationary power spectrum

Particle Creation by Black Holes

S. W. Hawking

Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, England

Received April 12, 1975

TASI Lectures on Inflation

Daniel Baumann

Department of Physics, Harvard University, Cambridge, MA 02138, USA
School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, USA

However,

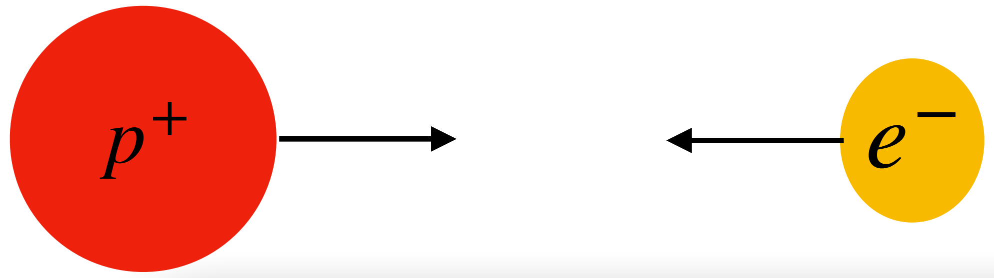
- Conceptual issues with semiclassical gravity, for single particles, as pointed out by Eppley&Hannah (1977) and Page&Geilker (1981).
- Superposition principle (for quantum matter) is lost.

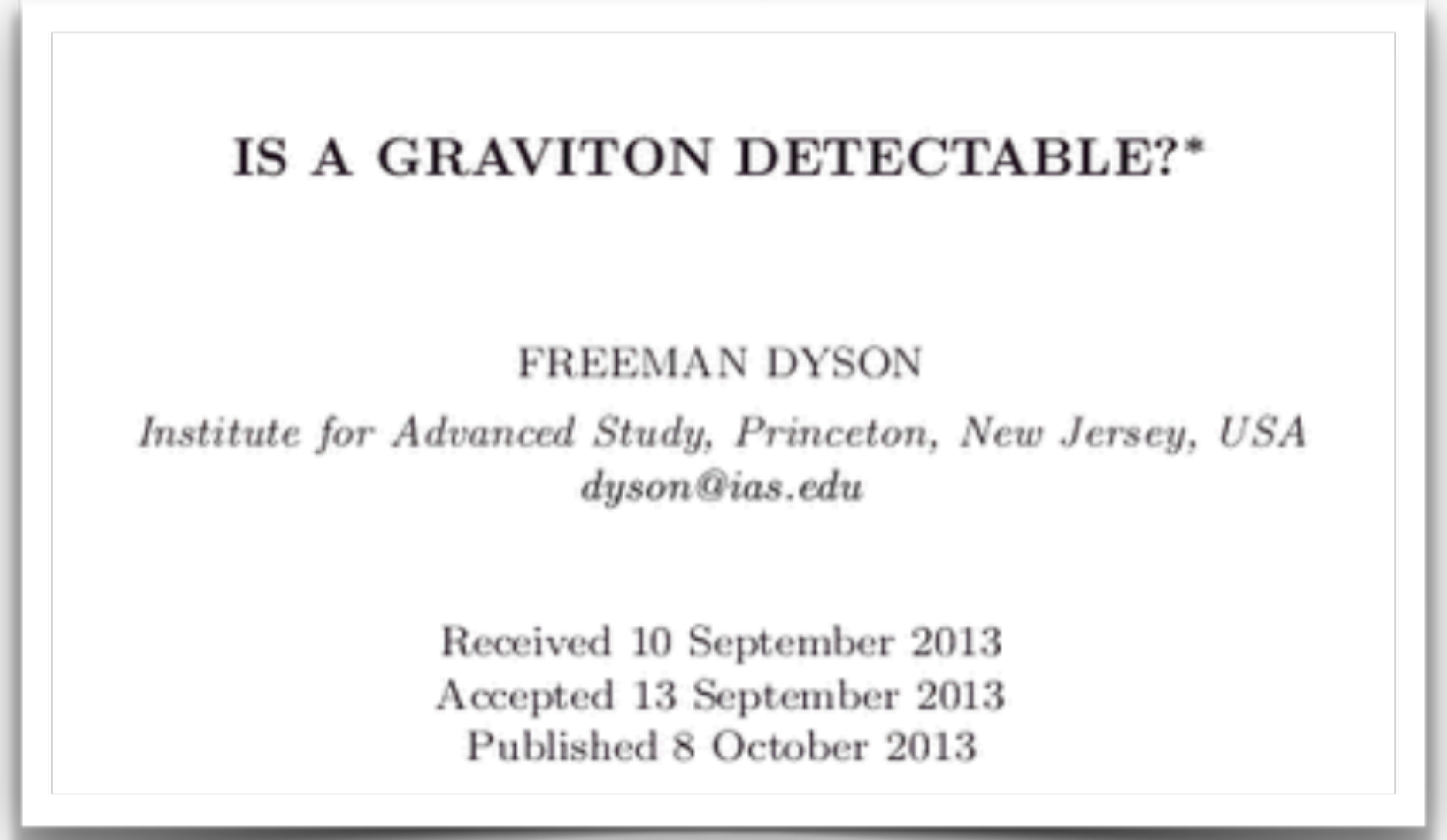
Fundamentally classical gravity may require modifications of QM

Eppley & Hannah (1977)

De-motivation for quantum gravity experiments

- **Gravity is an extremely weak force.** $$\frac{F_G}{F_{EM}} = 10^{-39}$$





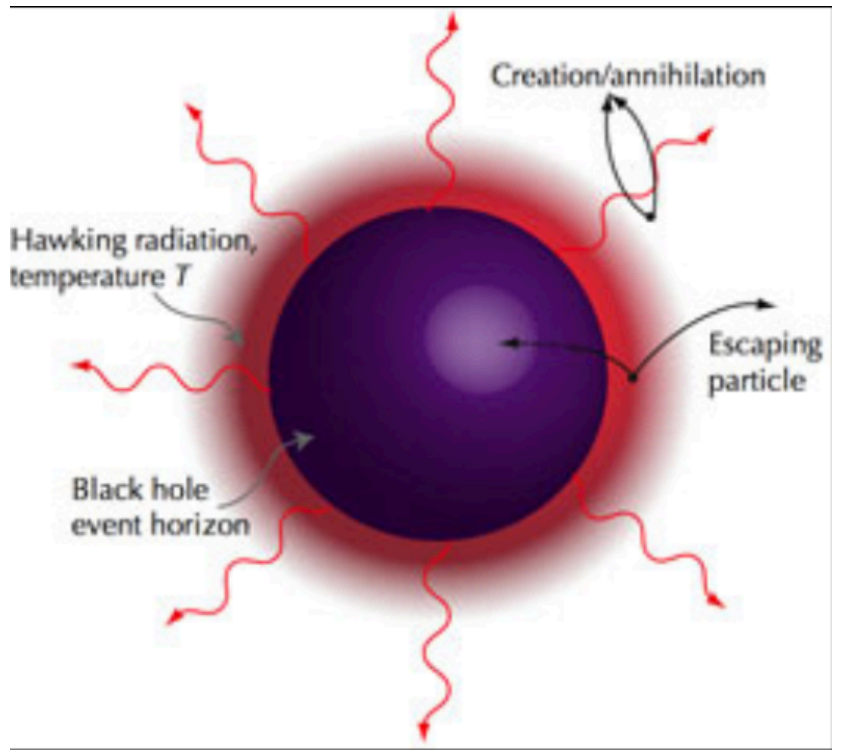
IS A GRAVITON DETECTABLE?*

FREEMAN DYSON
Institute for Advanced Study, Princeton, New Jersey, USA
dyson@ias.edu

Received 10 September 2013
Accepted 13 September 2013
Published 8 October 2013

- **Impossible to detect a single graviton with LIGO.**

- **Hawking radiation:** $T \approx 1nK(\frac{M}{60M_{sun}})^{-1}$

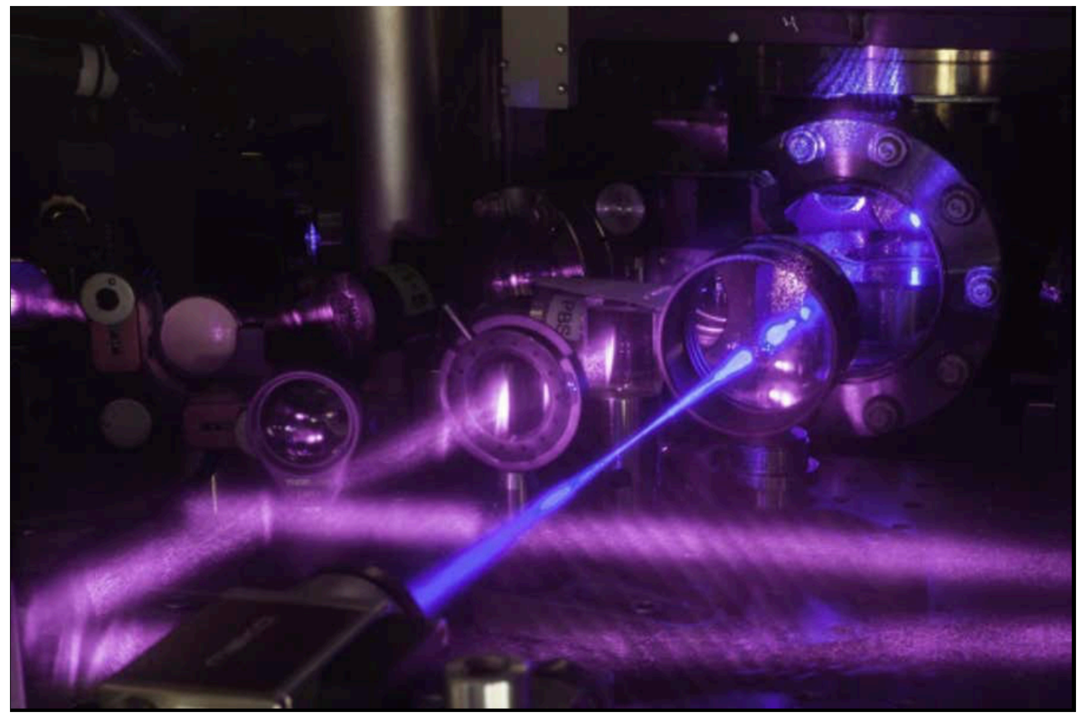


- **LHC runs in energy scales well below Planck scale.**

New experimental capabilities pushing to novel unexplored regimes

Rapid progress in controlling and manipulating quantum systems → Pushing physics to new scales

Atomic clocks



Article

Resolving the gravitational redshift across a millimetre-scale atomic sample

https://doi.org/10.1038/s41586-021-04349-7
Received: 24 September 2021
Accepted: 13 December 2021

Tobias Bothwell[1✉], Colin J. Kennedy[1,2], Alexander Aeppli[1], Dhruv Kedar[1], John M. Robinson[1], Eric Oelker[1,3], Alexander Staron[1] & Jun Ye[1✉]

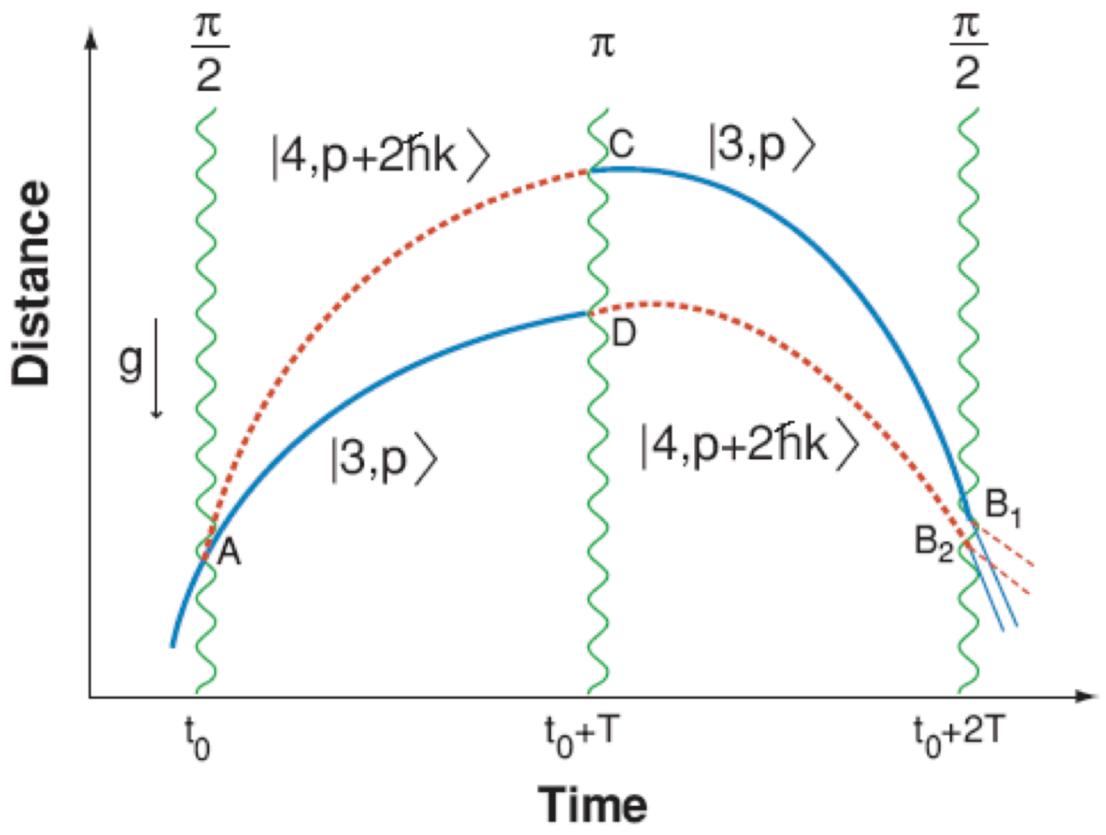
Article

Differential clock comparisons with a multiplexed optical lattice clock

https://doi.org/10.1038/s41586-021-04344-y
Received: 24 September 2021

Xin Zheng[1], Jonathan Dolde[1], Varun Lochab[1], Brett N. Merriman[1], Haoran Li[1] & Shimon Kolkowitz[1✉]

Atomic fountains



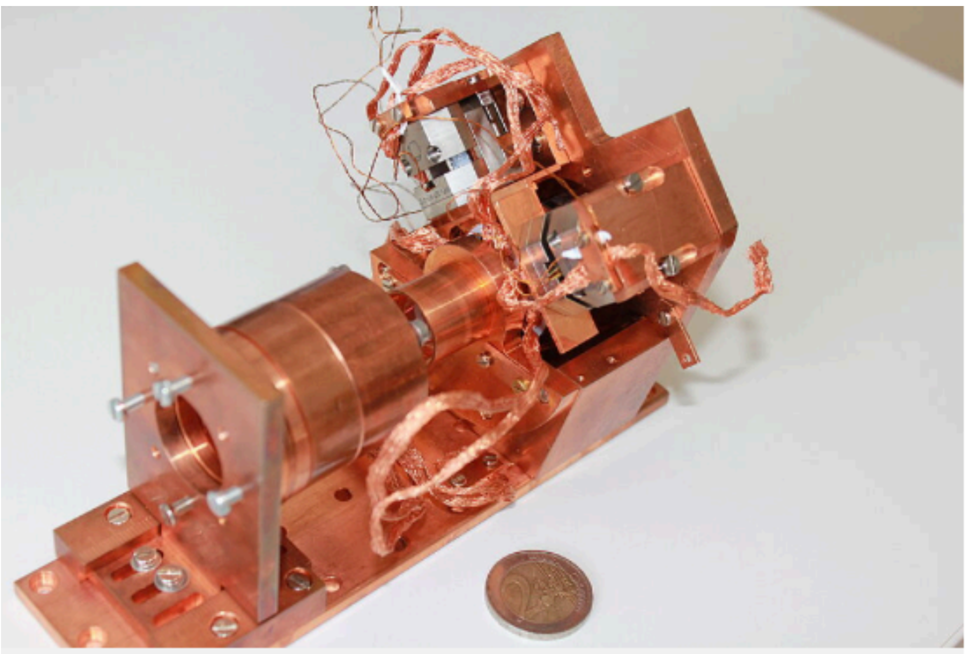
PHYSICAL REVIEW LETTERS **125,** 191101 (2020)

Atom-Interferometric Test of the Equivalence Principle at the 10^{-12} Level

Peter Asenbaum,* Chris Overstreet,* Minjeong Kim, Joseph Curti, and Mark A. Kasevich†
Department of Physics, Stanford University, Stanford, California 94305, USA

(Received 26 June 2020; accepted 5 October 2020; published 2 November 2020)

Quantum Optomechanics



Ultra-stable Fabry-Perot type cavity optomechanical system.

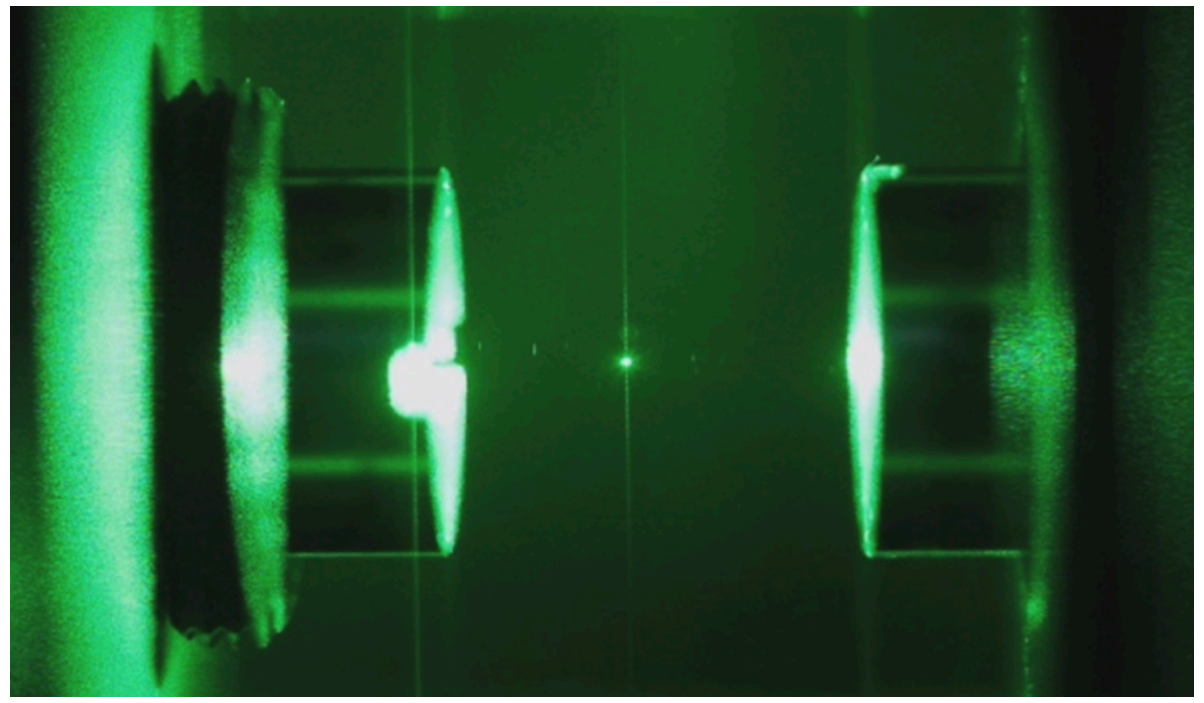
Article

Measurement of gravitational coupling between millimetre-sized masses

https://doi.org/10.1038/s41586-021-03250-7
Received: 17 September 2020

Tobias Westphal[1✉], Hans Hepach[1,4], Jeremias Pfaff[2,4] & Markus Aspelmeyer[1,2,3✉]

Optical tweezers & Levitated particles



PRL **105,** 101101 (2010) PHYSICAL REVIEW LETTERS week ending 3 SEPTEMBER 2010

Short-Range Force Detection Using Optically Cooled Levitated Microspheres

Andrew A. Geraci,* Scott B. Papp, and John Kitching

A brief history of Table-top experiments for Quantum Gravity

1995 **Gravitational wave-function collapse**

On Gravity's Role in Quantum State Reduction

Roger Penrose[1,2]

Received August 22, 1995. Rev. version December 12, 1995

1999 **Experimental proposals test Penrose's idea**

PHYSICAL REVIEW A VOLUME 59, NUMBER 5 MAY 1999

Scheme to probe the decoherence of a macroscopic object

S. Bose, K. Jacobs, and P. L. Knight
Optics Section, The Blackett Laboratory, Imperial College, London SW7 2BZ, England
(Received 28 May 1998)

2003

VOLUME 91, NUMBER 13 PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2003

Towards Quantum Superpositions of a Mirror

William Marshall,[1,2] Christoph Simon,[1] Roger Penrose,[3,4] and Dik Bouwmeester[1,2]

and many more….

A brief history of Table-top experiments for Quantum Gravity

2012 **Table-top quantum gravity phenomenology of new physics** → "Speculative, though educated guesses" (Modification of commutation relations, quantum foam)

nature physics | ARTICLES
PUBLISHED ONLINE: 18 MARCH 2012 | DOI: 10.1038/NPHYS2262

Probing Planck-scale physics with quantum optics

Igor Pikovski[1,2]*, Michael R. Vanner[1,2], Markus Aspelmeyer[1,2], M. S. Kim[3]* and Časlav Brukner[2,4]

PHYSICAL REVIEW D **86**, 124040 (2012)

Is a tabletop search for Planck scale signals feasible?

Jacob D. Bekenstein

2017 **Indirect signatures of quantum gravity**

Featured in Physics

Spin Entanglement Witness for Quantum Gravity

Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toroš, Mauro Paternostro, A. Geraci, Peter F. Barker, M. S. Kim, and Gerard Milburn
Phys. Rev. Lett. **119**, 240401 – Published 13 December 2017

Featured in Physics

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

C. Marletto and V. Vedral
Phys. Rev. Lett. **119**, 240402 – Published 13 December 2017

PRX QUANTUM **2**, 010325 (2021)

Non-Gaussianity as a Signature of a Quantum Theory of Gravity

Richard Howl,[1,2,3,*] Vlatko Vedral,[4,5] Devang Naik,[6] Marios Christodoulou,[2,4] Carlo Rovelli,[7,8,9] and Aditya Iyer[4]

PHYSICAL REVIEW LETTERS **128**, 110401 (2022)

Enhancing Gravitational Interaction between Quantum Systems by a Massive Mediator

Julen S. Pedernales, Kirill Streltsov, and Martin B. Plenio
Institut für Theoretische Physik und IQST, Albert-Einstein-Allee 11, Universität Ulm, D-89081 Ulm, Germany

Principles of quantum physics & gravity in tension

Quantum Mechanics

- Born rule
- Unitarity
- Uncertainty principle
- Superposition principle

Gravity

- Equivalence principle
- Covariance
- Dynamical spacetime

Some observable consequences

Entanglement	Time dilation
Particle interference	Newtonian potential
Violation of Bell's inequalities	Black Holes & Gravitational waves
.	.
.	.
.	.

Both theories: Tremendous success in explaining observable phenomena. However, theoretically challenging to have a unified framework.

One particular example …

Quantum Mechanics

- Born rule
- Unitarity
- Uncertainty principle
- Superposition principle

Gravity

- Equivalence principle
- Covariance
- Dynamical spacetime

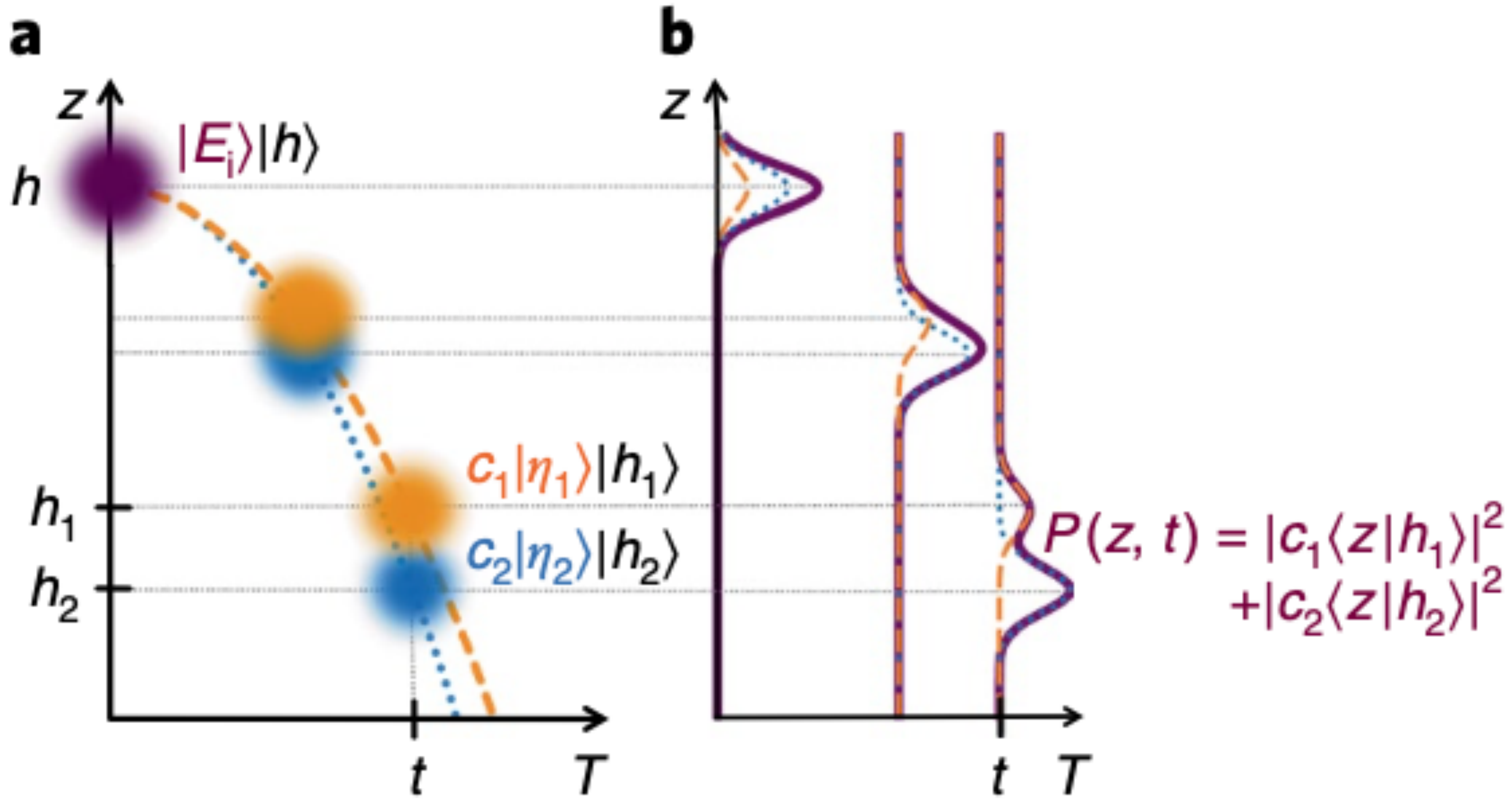
nature physics

ARTICLES

https://doi.org/10.1038/s41567-018-0197-6

Quantum formulation of the Einstein equivalence principle

Magdalena Zych[1*] and Časlav Brukner[2,3]



Superposed trajectories coupled with internal dynamics

Principles of quantum physics & gravity in tension

Quantum Mechanics

- Born rule
- Unitarity
- Uncertainty principle
- Superposition principle

Gravity

- Equivalence principle
- Covariance
- Dynamical spacetime

Some observable consequences

Entanglement

Particle interference ⟷ Newtonian potential

Violation of Bell's inequalities

.
.
.

Time dilation

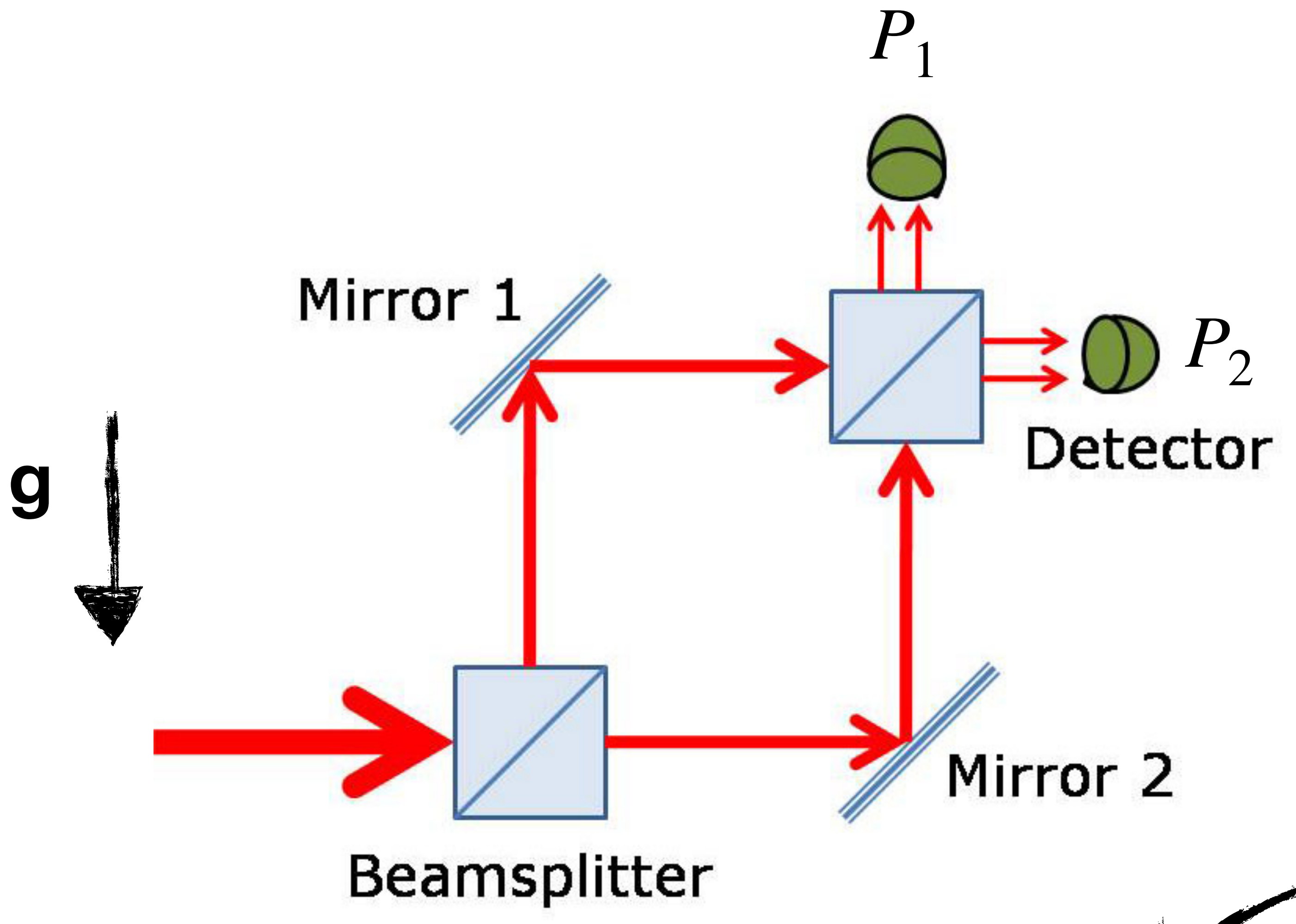
Black Holes & Gravitational waves

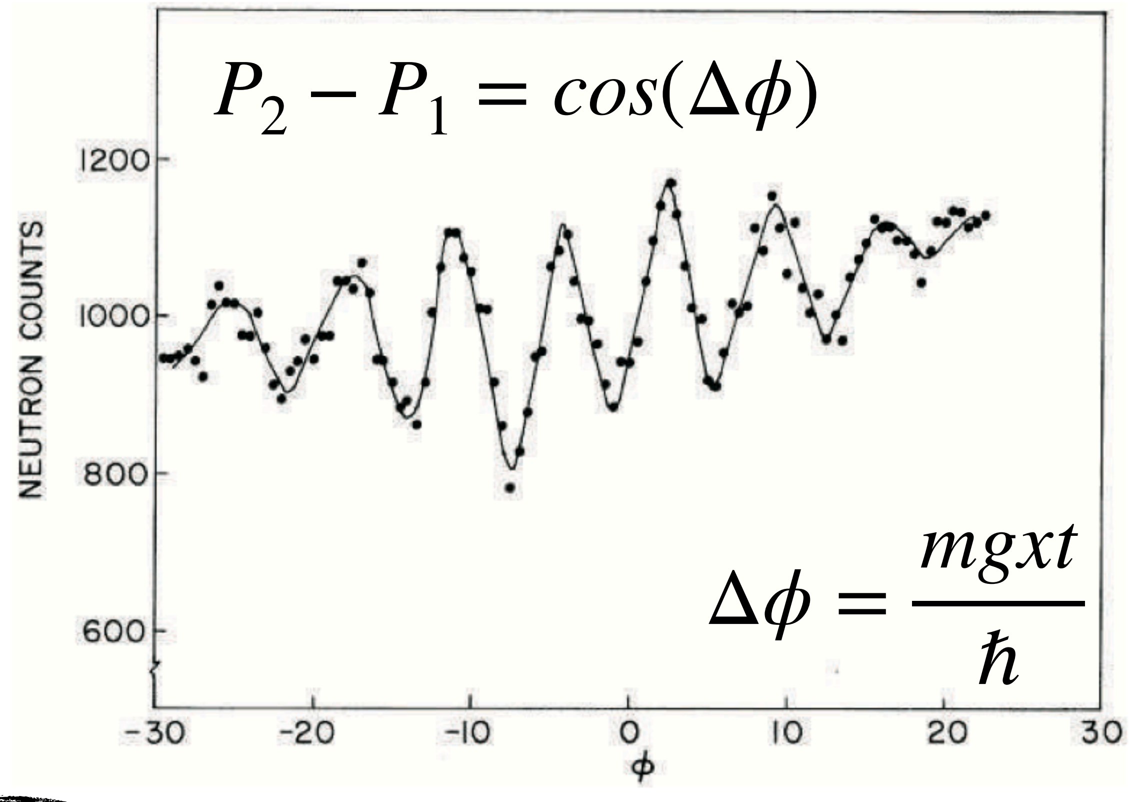
.
.
.

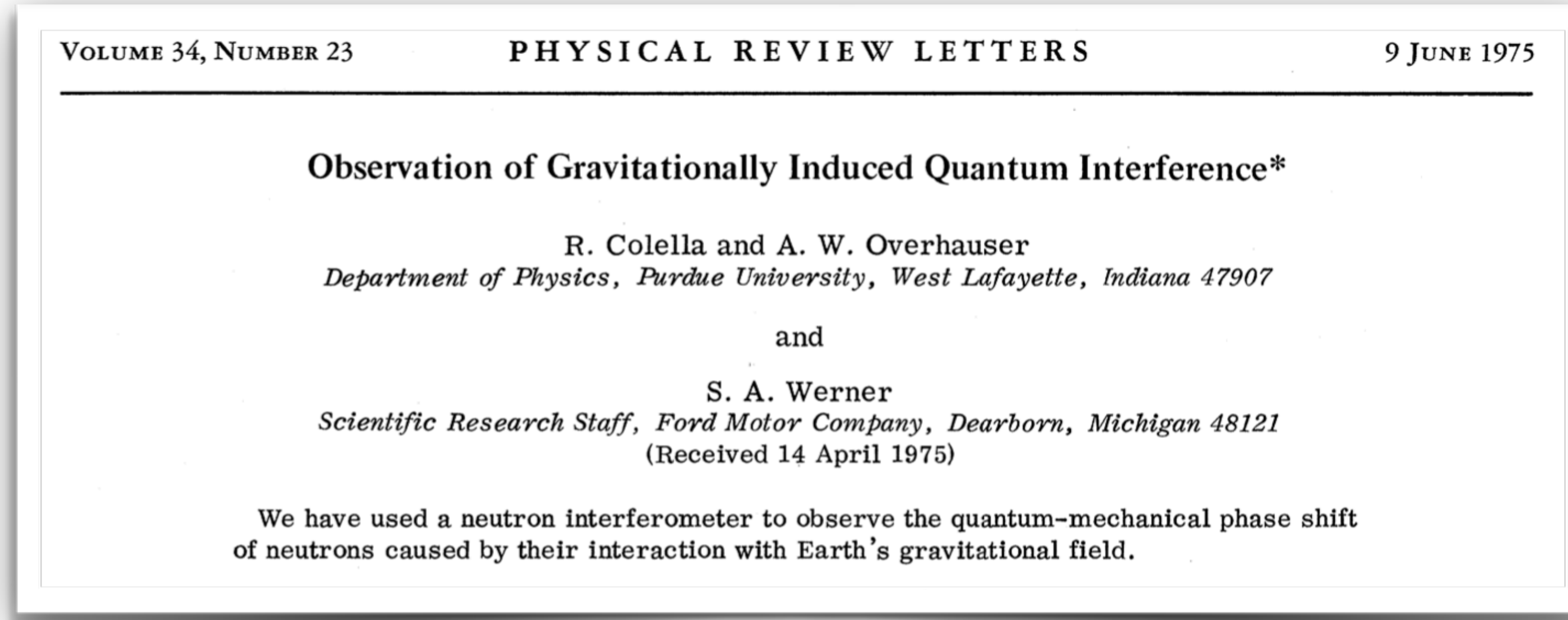
COW experiment!
The only empirical fact we have up to date at the quantum & gravity interface

Influence of gravity on quantum wave-function
Colella-Overhauser-Werner (COW) experiment

Hamiltonian: $H = H_0 + mgx$ — Earth's grav.field






VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

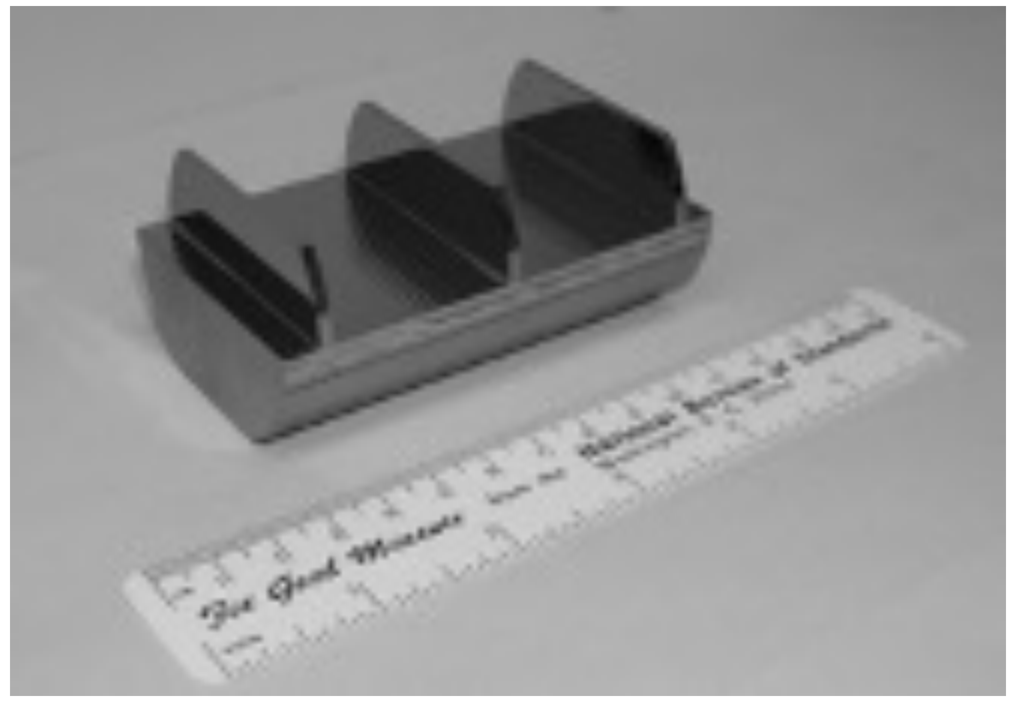
Observation of Gravitationally Induced Quantum Interference*

R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

and

S. A. Werner
Scientific Research Staff, Ford Motor Company, Dearborn, Michigan 48121
(Received 14 April 1975)

We have used a neutron interferometer to observe the quantum-mechanical phase shift of neutrons caused by their interaction with Earth's gravitational field.



$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\psi_{down}\rangle + e^{-i\Delta\phi}|\psi_{up}\rangle\right)$$ — Gravitational phase shift

COW experiment teaches us: Gravitational potential enters Schröndiger equation

BUT nothing about quantum gravity. Gravitational potential is treated entirely as a classical background.

Is there a possible modification of the COW proposal which can address the question of quantisation?

Focus: Gravity Induced Entanglement (GIE) proposals

Featured in Physics

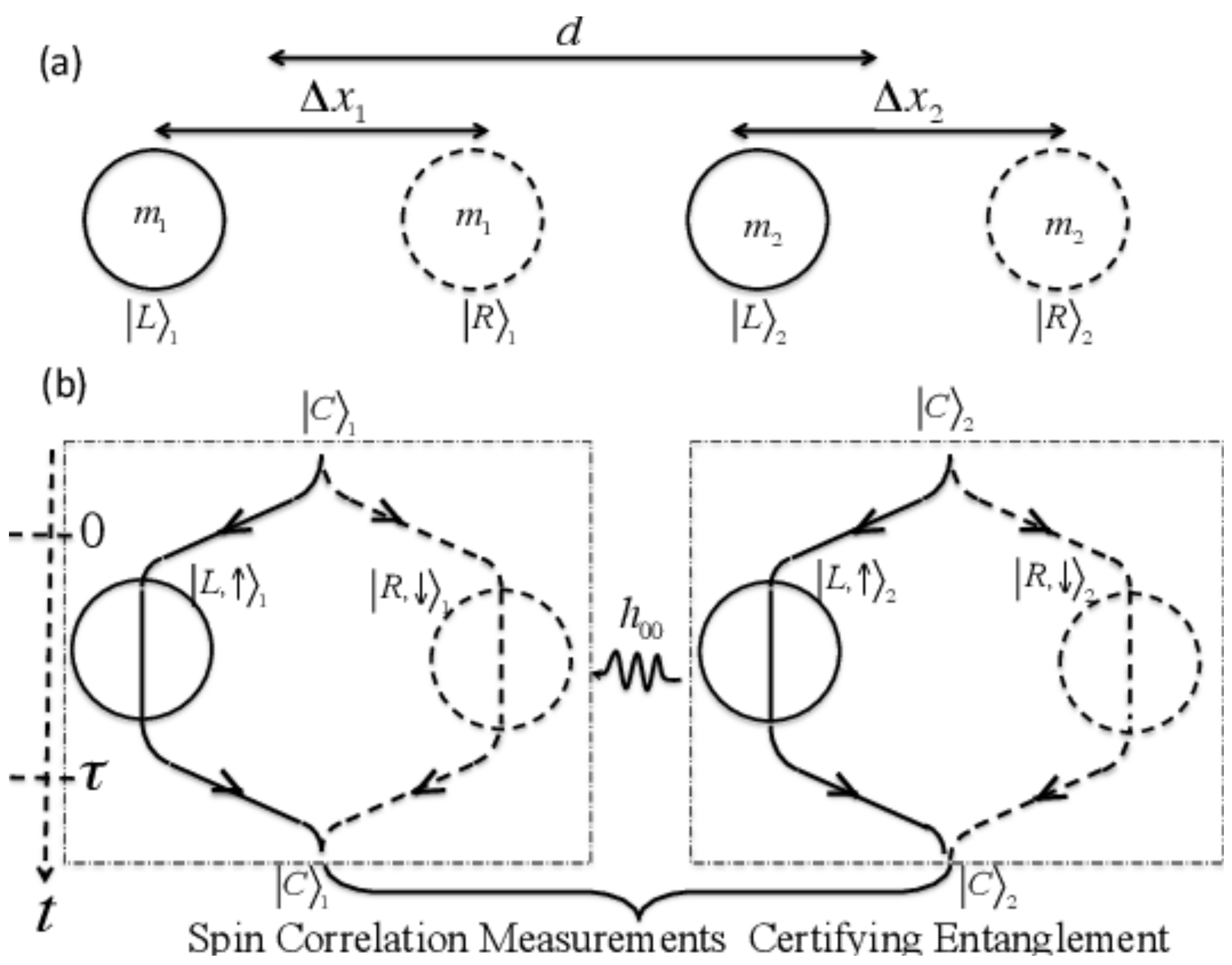
Gravitationally Induced Entanglement between Two Massive Particles is Sufficient Evidence of Quantum Effects in Gravity

C. Marletto and V. Vedral
Phys. Rev. Lett. **119**, 240402 – Published 13 December 2017

Featured in Physics

Spin Entanglement Witness for Quantum Gravity

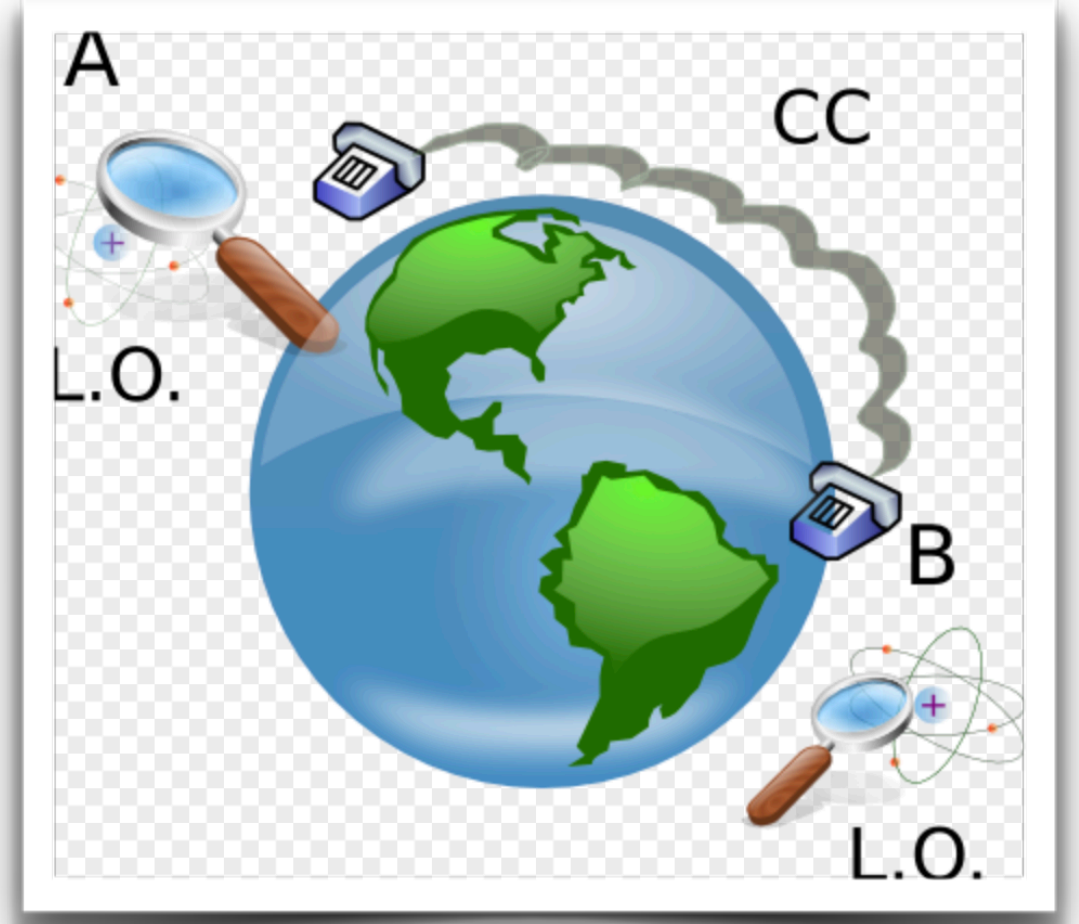
Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toroš, Mauro Paternostro
A. Geraci, Peter F. Barker, M. S. Kim, and Gerard Milburn
Phys. Rev. Lett. **119**, 240401 – Published 13 December 2017



GIE proposal:

If the gravitational interaction generates an entangled state out of the initial product state and (crucially!) we ***assume locality*** of interactions, then, the LOCC argument implies that gravitational field should be quantum mechanical in nature.

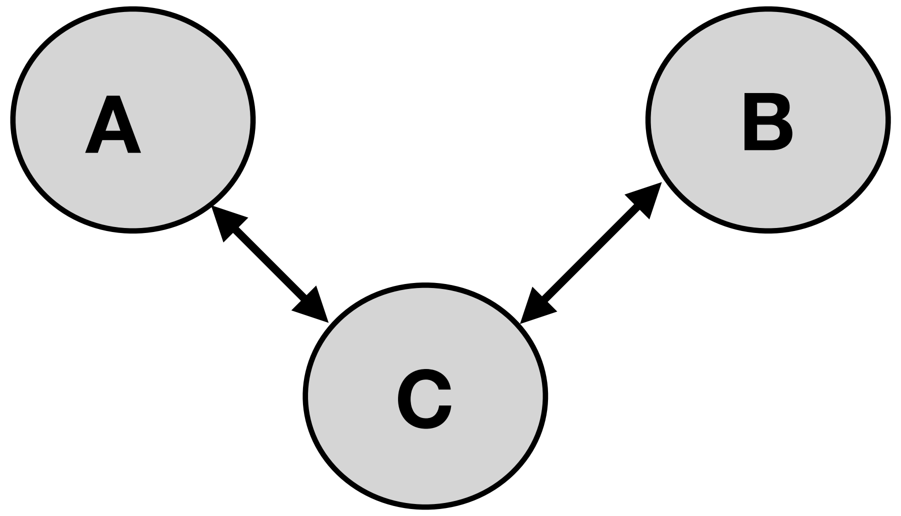
Gravity Induced Entanglement (GIE) proposals



LOCC (Local Operations and Classical Communication) → Cannot increase entanglement between two systems

G.Vidal 1998, "Entanglement monotones"
Horodeckis 2009, "Quantum entanglement"
Peres & Wootters 1991, "Optimal Detection of Quantum Information"

Definition of locality:
(Marletto & Vedral, 2017)



$$H_{int} = H_{AC} + H_{BC}$$

A and B are not allowed to interact directly

C interacts locally with A and B.

A,B: Masses
C: Gravitational mediator

Immediate caveat:

- **Newtonian limit**, $\hat{H}_{int} = \hat{H}_{AB} = -Gm_A m_B / |\hat{x}_A - \hat{x}_B|$ is non-local.
- For the LOCC argument to apply **one needs to assume that fundamentally quantum gravity is a local theory**, which is not tested in this experiment.

Gravity Induced Entanglement (GIE) proposals

Goal: Investigate the problem from different perspectives and understand what conclusions can be drawn from a GIE type of experiment *depending on the initial assumptions.*

How entanglement is generated in different descriptions?

i) Non-Relativistic description → Newtonian theory → Minimal interpretation of GIE.

ii) Relativistic formulations → Weak Field Quantum Gravity →
- Local description
- Non-local description
- Absorber formulation

Take home messages

Weak Field Quantum Gravity admits *both* local and non-local formulations → LOCC cannot be used to infer quantized mediators

GIE tests gravitating source masses in spatial superposition. → Novel, experimentally untested regime.

Newtonian theory: Action-at-a-distance

GIE works in the *Newtonian limit* and refers to *gravitating source masses* which are put *in a spatial superposition*.
How do we make sense of Newtonian potential in superposition?

Hamiltonian for N=2 gravitationally interacting particles

N-body problem

$$\hat{H} = \sum_{i=1}^{N}\left(\frac{\hat{\vec{p}}_i^{\,2}}{2m} - \frac{m^2 G}{2}\sum_{j=1, j\neq i}^{N}\frac{1}{|\hat{\vec{x}}_i - \hat{\vec{x}}_j|}\right)$$

Second quantized formulation

$$\hat{H} = \int d^3x\left(\frac{\hbar^2}{2m}\nabla\hat{\psi}^\dagger(\vec{x})\nabla\hat{\psi}(\vec{x}) + m\hat{\Phi}(\vec{x})\hat{\psi}^\dagger(\vec{x})\hat{\psi}(\vec{x})\right)$$

$$\nabla^2\hat{\Phi}(\vec{x}) = 4\pi G m\hat{\psi}^\dagger(\vec{x})\hat{\psi}(\vec{x})$$

Newtonian potential $\hat{\Phi}(\vec{x})$ is an operator

$$\hat{\Phi}(\vec{x}) = -mG\int d^3x'\frac{\hat{\psi}^\dagger(\vec{x}')\hat{\psi}(\vec{x}')}{|\vec{x} - \vec{x}'|}$$

If sources can be approximated by a mean field, then $\hat{\Phi} \to \Phi$.
(COW experiment)

$$|\Psi\rangle_{COW} = \frac{1}{\sqrt{2}}\Big(|\mathrm{earth}\rangle_1\Big)\Big(|\mathrm{L}\rangle_2 + |\mathrm{R}\rangle_2\Big)$$

Neutron

Colella, Overhauser, Werner (1975, PRL 34)

$$|\Psi\rangle_{GIE} = \frac{1}{2}\Big(|L,\uparrow\rangle_1 + |R,\downarrow\rangle_1\Big)\Big(|L,\uparrow\rangle_2 + |R,\downarrow\rangle_2\Big)$$

Sources of gravity are in superposition

Mean field description inadequate $\hat{\Phi}|\Psi\rangle \neq \langle\Phi\rangle|\Psi\rangle$
Operator nature of $\hat{\Phi}(\vec{x})$ cannot be neglected

GIE probes a new, yet untested regime,
where Newtonian gravitational field is sourced coherently.

Weak field quantum gravity: local or non-local?

Weak field limit of gravity: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}\,, \quad |h_{\mu\nu}| \ll 1$

Interaction Hamiltonian: $H_{int} = -\frac{1}{2}\int d^3r h_{\mu\nu}(\vec{r})T^{\mu\nu}(\vec{r})$

Relativistic formulation #1: Non-local formulation

Poisson gauge ⟶ Fix the gauge classically and quantise only the 2 physical dofs $s_{ij}^{TT} \rightarrow \hat{s}_{ij}^{TT}$

Metric SVT decomposition:

$$h_{00} = -2\phi$$
$$h_{0i} = w_i$$
$$h_{ij} = -2\psi\delta_{ij} + 2s_{ij}$$

Complete gauge fixing: $s_i^i = 0$ **and** $\partial_j s_i^j = 0$ **and** $\partial_i w^i = 0$

Constrained **Hamiltonian *(without redundant degrees of freedom)***

$$\hat{H}_{int} = -\int d^3r\big(\hat{s}_{ij}^{TT}\hat{T}^{ij}\big) - \frac{G}{2}\int\frac{d^3r d^3r'}{|\vec{r}-\vec{r}'|}\Big[-4\hat{f}_{\perp,i}(\vec{r}')\hat{T}^{0i}(\vec{r}) + \hat{T}_{00}(\vec{r}')\big(\hat{T}^{00}(\vec{r}) + \hat{T}_k^k(\vec{r}) - 2\hat{\Pi}^{||}(\vec{r})\big)\Big]$$

- First term: subdominant in GIE
- $\hat{f}_{\perp,i}$ term: $\propto \hat{T}_{\perp}^{0i}$
- $\hat{T}_{00}\hat{T}^{00}$ term: Dominant entangling term
- $\hat{\Pi}^{||}$ term: $\propto$ Traceless stress-energy tensor

In this formulation, entanglement is generated non-locally after removal of unphysical degrees of freedom.

Weak field quantum gravity: local or non-local?

Weak field limit of gravity: $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}\,, \quad |h_{\mu\nu}| \ll 1$

Interaction Hamiltonian: $H_{int} = -\frac{1}{2}\int d^3r h_{\mu\nu}(\vec{r})T^{\mu\nu}(\vec{r})$

Relativistic formulation #2: Local formulation (Gupta 1952,1968)

All (10!) metric components are quantized ⟶ $$\hat{h}_{\mu\nu}(\vec{r}) = \int d^3k\sqrt{\frac{\hbar G}{c^2\pi^2\omega_k}}\left[\hat{a}_{\mu\nu}(\vec{k})e^{i\vec{k}\cdot\vec{r}} + \hat{a}^\dagger_{\mu\nu}(\vec{k})e^{-i\vec{k}\cdot\vec{r}}\right]$$

Hamiltonian gravitational field $$\hat{H}_g = \frac{1}{2}\int d^3k\hbar\omega_k\left[\hat{a}^\dagger_{\mu\nu}(\vec{k})\hat{a}^{\mu\nu}(\vec{k}) - \frac{1}{2}\hat{a}^{\dagger\mu}_{\mu}(\vec{k})\hat{a}^{\nu}_{\nu}(\vec{k})\right]$$

One can impose *subsidiary conditions* in the $\mathscr{H}_{phys}$ to eliminate the redundant dofs. (Gupta 1968)

In presence of matter, redundant "gravitons" can exist in virtual states (Gupta 1952) (Bose et al 2022)

In Lorenz gauge, entanglement is established locally via the exchange of "unphysical" mediators

Interlude: Feynman-Wheeler absorber theory

REVIEWS OF MODERN PHYSICS VOLUME 17, NUMBERS 2 AND 3 APRIL–JULY, 1945

Interaction with the Absorber as the Mechanism of Radiation†*

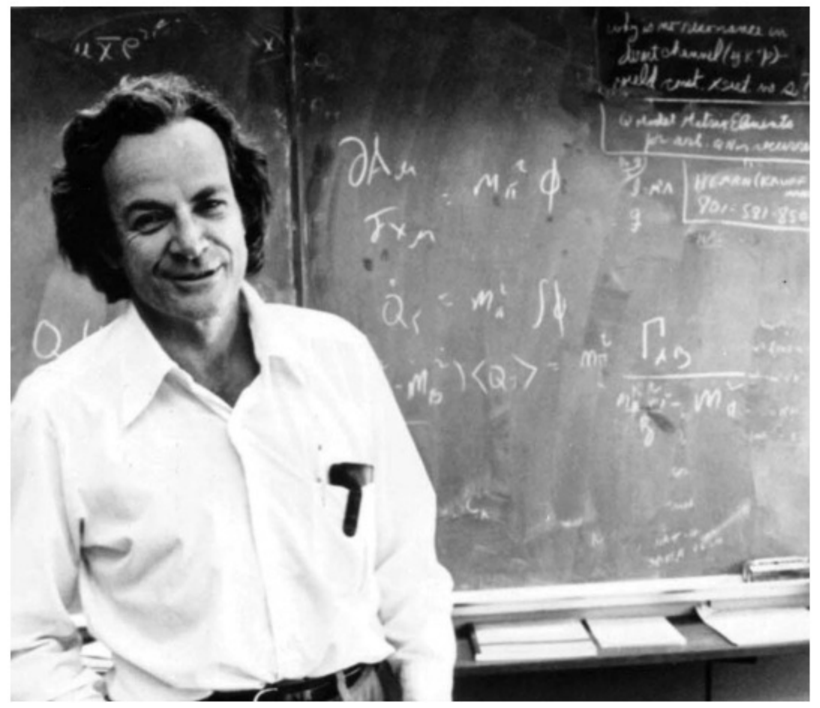
John Archibald Wheeler** and Richard Phillips Feynman***
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey

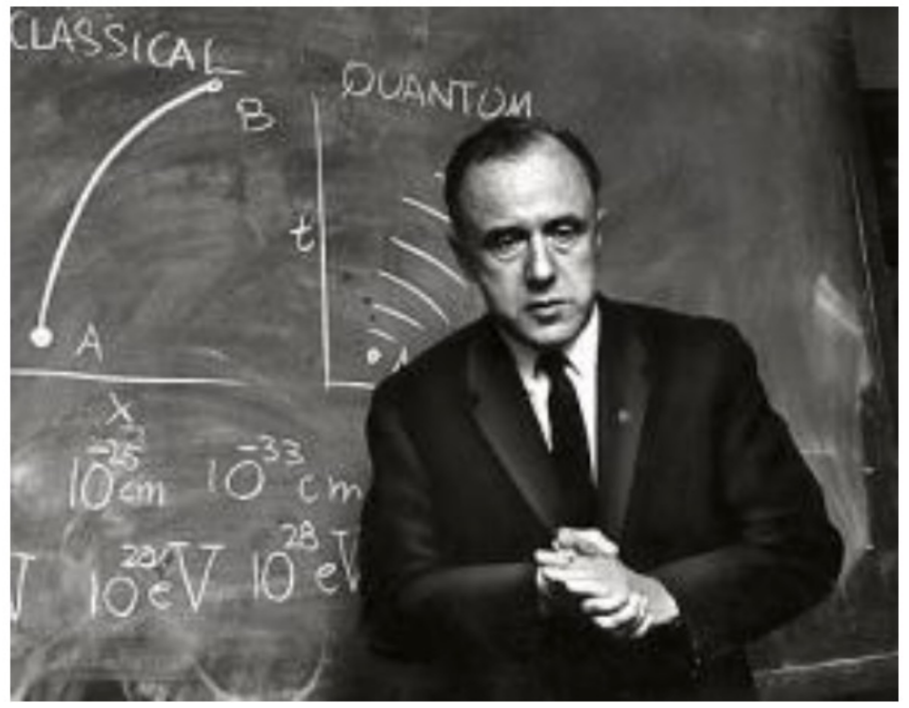
"We must, therefore, be prepared to find that further advance into this region will require a still more extensive renunciation of features which we are accustomed to demand of the space time mode of description."—Niels Bohr[1]

REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 3 JULY, 1949

Classical Electrodynamics in Terms of Direct Interparticle Action[1]

John Archibald Wheeler and Richard Phillips Feynman[2]
Princeton University, Princeton, New Jersey





Equivalent formulations of electrodynamics. Same predictions BUT different ontology.

Quantum Electrodynamics as an absorber theory

Quantum version of Wheeler-Feynman theory: Hoyle-Narlikar (1969, 1971)
P. Davies (1969, 1971, 1972)
Pegg (1975, 1979)

A quantum theory of Wheeler–Feynman electrodynamics

By P. C. W. DAVIES

University College, London

(*Received* 8 *December* 1969)

Abstract. A quantum mechanical theory of the action-at-a-distance electrodynamics of Wheeler and Feynman is given using an S-matrix approach. The response of the universe is introduced, and a perturbation expansion leads to the usual expression for the spontaneous transition rate between atomic energy levels, an effect normally attributed to quantized field oscillators. The Feynman propagator is then recovered, leading to the familiar self-energy formulae. Finally, a comparison of the formal structure of the new theory with the conventional is shown to establish a complete mathematical equivalence to all orders in the expansion.

Conventional QED ⟷ **QED as an absorber theory**

$$\mathscr{L}_{int}(x) = j^{\mu}(x)A_{\mu}(x) \quad \longleftrightarrow \quad \mathscr{L}_{int}(x) = j^{\mu}(x)\int d^4x' j_{\mu}(x')\delta_D\left[(x-x')^2\right]$$

$$\delta_D\left[(x-x')^2\right] \equiv \frac{1}{2}\left(G_+(x-x') + G_-(x-x')\right)$$

Advanced & Retarded Green's function

$$G_{\pm}(x-x') = \frac{\delta_D\left[c(t-t') \pm |\vec{x} - \vec{x}'|\right]}{|\vec{x} - \vec{x}'|}$$

Weak field quantum gravity: local or non-local?

Back to gravity…

Relativistic formulation #3: Absorber formulation of Weak Field Quantum Gravity

An absorber theory exists in the weak field limit of gravity. (Louis-Martinez, 2012) (Rosen 1979)

One can remove the mediators from the theory and end up with a *non-local interaction between matter sources*.

In this formulation, entanglement is established by the sources non-locally. No gravitational mediators exist to be quantized.

Open questions

Beyond WFQG:
i) Does an action-at-a-distance formulation exist?
ii) Is the full quantum theory of gravity a local or non-local theory?

Equivalent formulations of entanglement generation

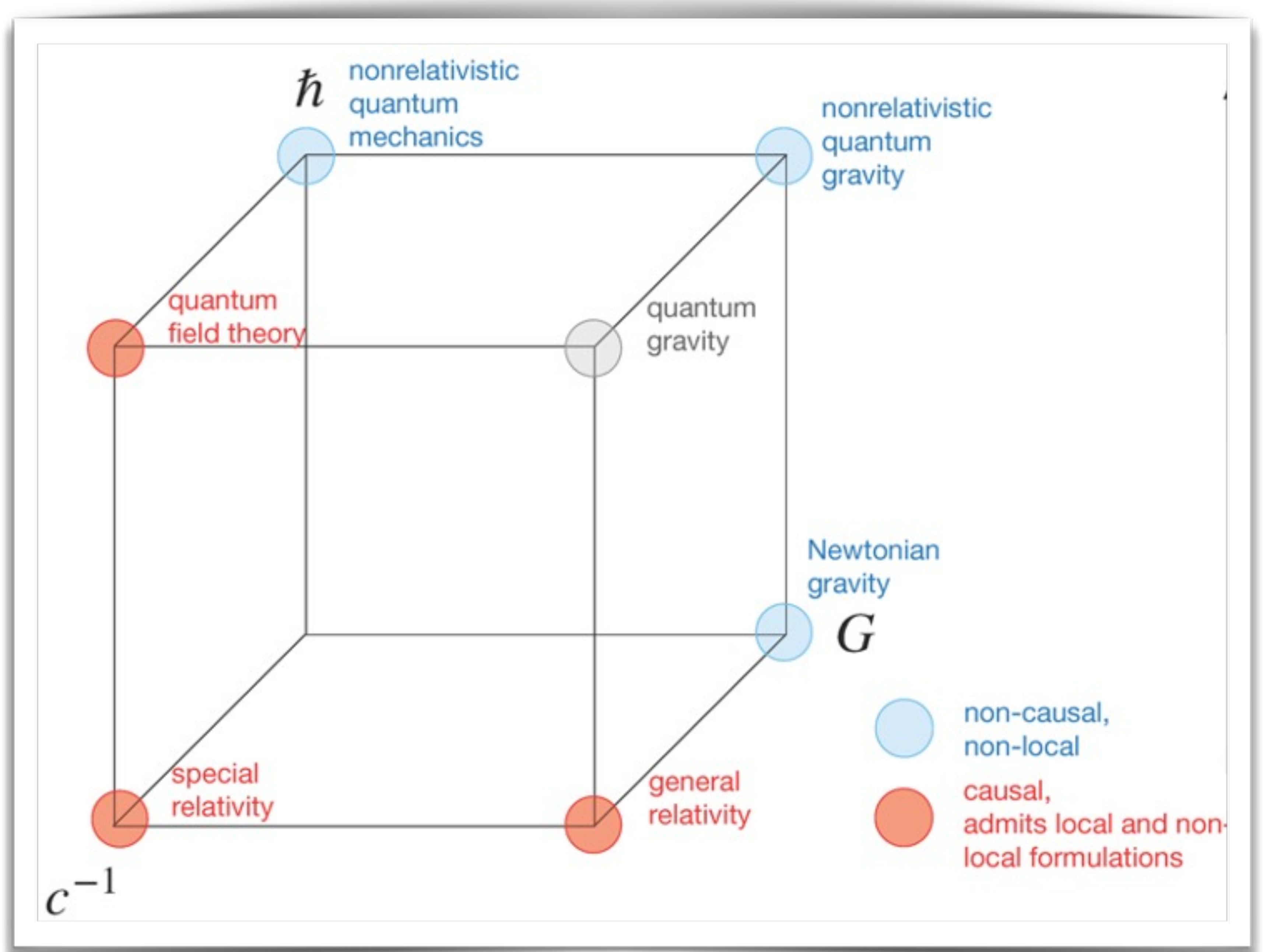
LOCC conclusion about mediators
Relies on *local description*

Deriving the GIE effect in a manifestly local gauge is a *choice.*

Theory	Entanglement	LOCC?	Lorenz Inv.
Non-relativistic Newtonian QG	Yes	~~L~~OCC	No
Weak Field QG (non-local formulation)	Yes	~~L~~OCC	Yes
Weak Field QG (Local formulation)	Yes	LO~~C~~C	Yes
Weak Field QG (Absorber)	Yes	~~L~~OCC	Yes

Bose et al, Phys. Rev. D **105**, 106028 (2022)
Christodoulou et al, 2202.03368 (2022)
Marletto-Vedral 2207.11349 (2022)

Locality is <u>NOT</u> dictated by relativity



Entanglement can be equivalently generated *non-locally BUT still within relativity as we know it.*

AVS Quantum Sci. 4, 045601 (2022)
Hu, Anastopoulos, Classical and Quantum Gravity 37, 235012 (2020).

LOCC cannot be used to *unambiguously* infer quantized mediators

Exactly same conclusions apply to QED

EM analogue of GIE *would not unambiguously* reveal the existence of photons

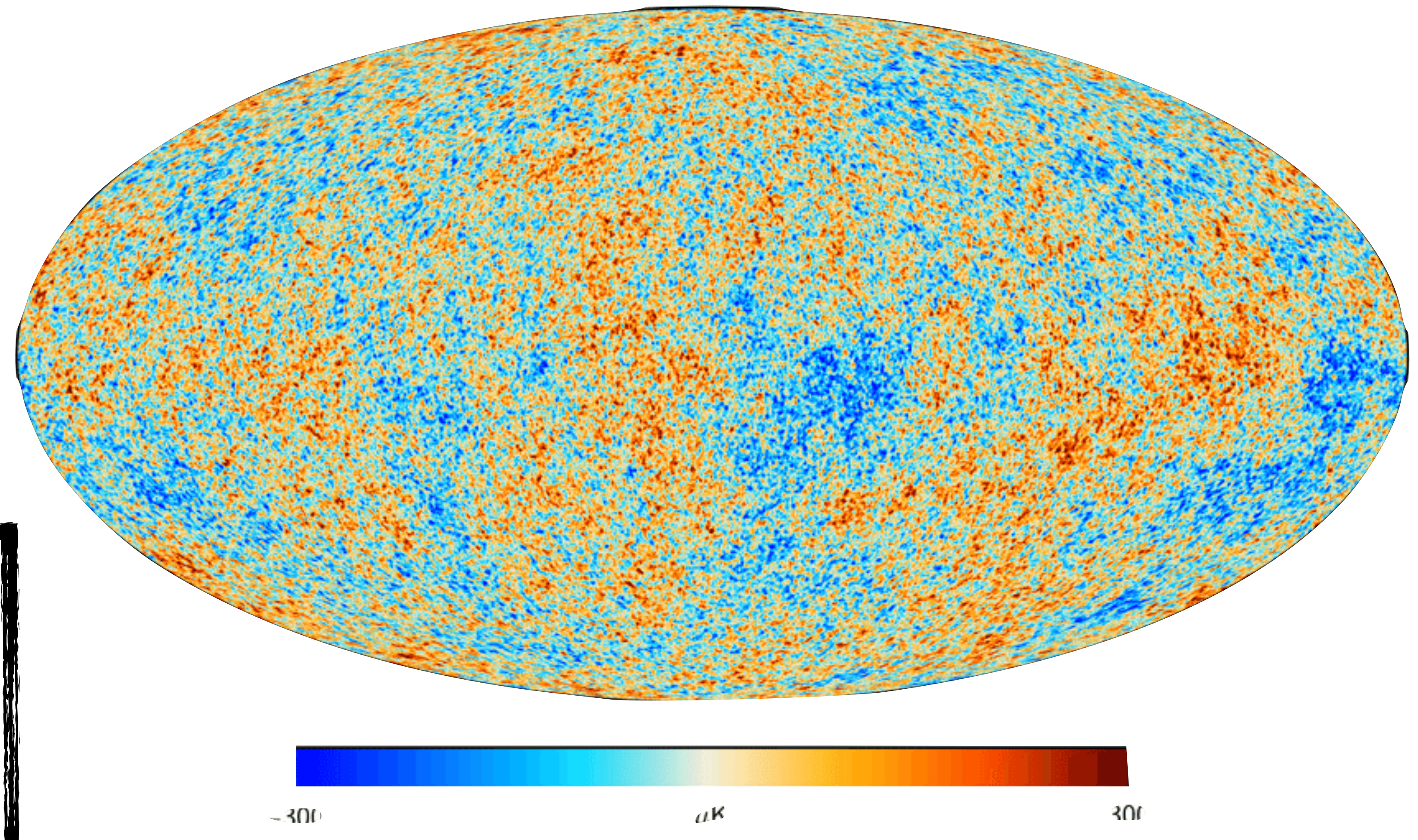
Beyond Mediators: Signatures of weak-field quantum gravity in Cosmology

Standard linear cosmological perturbation theory leads to

Poisson equation

$$\nabla^2\hat{\Phi}(t,\vec{x}) = 4\pi G\frac{\bar{\varphi}'^2}{\mathcal{H}^2}\left(\frac{\hat{v}(t,\vec{x})}{z}\right)'$$

$\hat{\Phi}$ sourced by quantum fluctuations of the metric



$\hat{\Phi}(t,\vec{x})$: Bardeen Potential, scalar part of the metric

$\bar{\varphi}$: The classical inflaton field

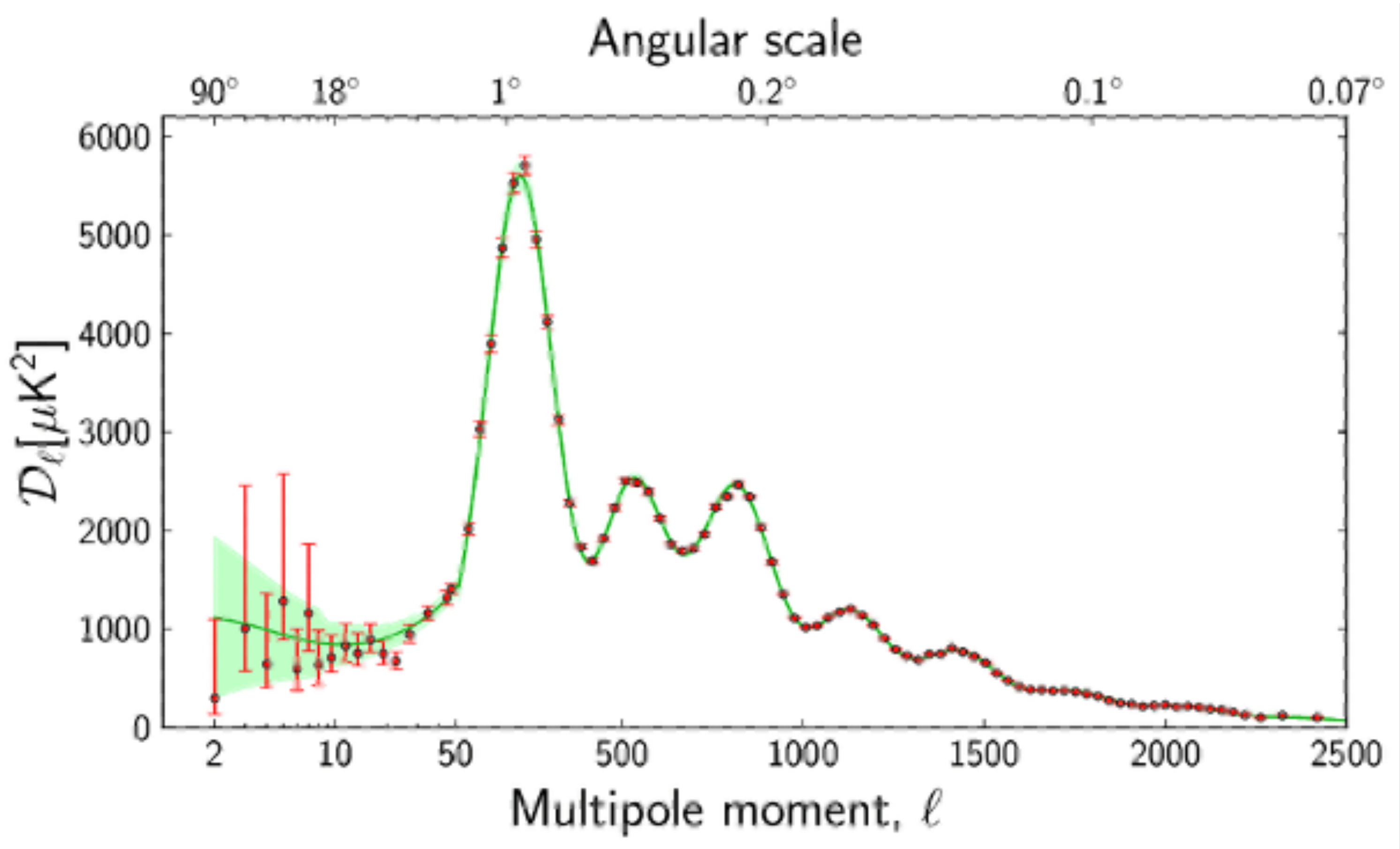
$\hat{v}(t,\vec{x})$: Mukhanov - Sasaki variable → $\hat{v}(t,\vec{x}) = a(\delta\hat{\varphi}(t,\vec{x}) + \hat{\psi}(t,\vec{x})\bar{\varphi}'/\mathcal{H})$

$\delta\hat{\varphi}$: Inflaton fluctuations

$\hat{\psi}$: scalar metric perturbation

$\mathcal{H}, z$: Functions of the scale factor $a(t)$

CMB temperature anisotropy $\propto \langle\hat{\Phi}(t,\vec{x})\hat{\Phi}(t,\vec{x}+\hat{r})\rangle$



Cosmic Microwave Background (CMB) temperature fluctuations already indicate *quantisation of the Newtonian (constrained) part of the metric*.

GIE probes the same regime

Summary of conclusions from entanglement

V.Fragkos , M. Kopp, I. Pikovski.
AVS Quantum Sci. 4, 045601 (2022)

Model	Non-Relativistic Newtonian theory	Weak field Quantum Gravity Poisson gauge	Absorber theory	Weak field Quantum Gravity Lorenz (local) gauge
Entanglement generation	*No mediators Non-local*	*No mediators Non-local*	*No mediators Non-local*	*Mediators exist Local*
Conclusions	Newtonian potential sourced in superposition	Sources in superposition	Sources in superposition	*Quantized mediators LOCC applies*
Caveats	Quantization of the scalar part of the metric already probed by current CMB observations	Quantization of the scalar part of the metric already probed by current CMB observations	There is no absorber formulation for full GR	Mediators are not the standard spin-2 gravitons but auxiliary dofs

Aharonov-Bohm-DeWitt correspondence: Debate on local vs non-local formulations

Aharonov-Bohm: Potentials play a fundamental role in Quantum theory. QED admits a local formulation with the aid of potentials.

> *"We must keep in mind that quantum theory as it is now requires that the interaction of the electron with the EM field **must be a local** one (i.e the field can operate only where the charge is)"*

DeWitt:

> *Which is more significant, the fact that nonlocal formulations of causal theories exist which deal **only with observables**, or the fact that in all known cases local formulations in terms of potentials also exist? In a similar vein the author disagrees with the assertion of Aharonov and Bohm that quantum electrodynamics is ultimately determined by the requirement that it be expressible in a local form. QED is really determined by experiment.*

DeWitt:

> The author is happy to acknowledge a stimulating correspondence with Professor Bohm and, although maintaining a different viewpoint, wishes to express his wholehearted agreement with the effort to shift the controversy over the significance of potentials to the arena of local vs nonlocal theories.

"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are or what your name is. If it doesn't agree with experiment, it's wrong."

Conclusions

- New exciting era for fundamental physics: Control and manipulation of quantum systems provide a new platforms to challenge fundamental theories and push limits to novel regimes.
- Many new experimental proposals probe new *speculative* as well as *expected* physics.
- GIE proposal very exciting. Probes new, untested regime in physics.
- However, interpretation is ambiguous. Relies on the *assumption that entanglement is generated locally*. We saw that standard weak field quantum gravity admits both local and non-local formulations.
- *Locality is not dictated by relativity.* Non-local formulations of QED or weak field quantum gravity, as well as action-at-a-distance formulations *do respect causality*.
- Thus LOCC argument cannot be used to *unambiguously* infer the existence of gravitons, quantised mediators of gravity.
- Weak field quantum gravity has been already indirectly tested by CMB observations. GIE probes the same regime!

V.Fragkos, M. Kopp, I. Pikovski.
AVS Quantum Sci. 4, 045601 (2022)

Extra slides

A useful distinction to keep in mind….

Quantum and gravity interface

ARTICLES | nature physics

PUBLISHED ONLINE: 15 JUNE 2015 | DOI: 10.1038/NPHYS3366

Universal decoherence due to gravitational time dilation

Igor Pikovski[1,2,3,4]*, Magdalena Zych[1,2,5], Fabio Costa[1,2,5] and Časlav Brukner[1,2]

nature physics | ARTICLES

https://doi.org/10.1038/s41567-018-0197-6

Quantum formulation of the Einstein equivalence principle

Magdalena Zych[1]* and Časlav Brukner[2,3]

Not tests of quantum gravity. Test compatibility of GR with QM principles. Indirectly, can teach us something about QG.

Precision tests

PHYSICAL REVIEW LETTERS **124,** 101101 (2020)

New Test of the Gravitational $1/r^2$ Law at Separations down to 52 μm

J. G. Lee, E. G. Adelberger,* T. S. Cook,† S. M. Fleischer,‡ and B. R. Heckel

Center for Experimental Nuclear Physics and Astrophysics, Box 354290, University of Washington, Seattle, Washington 98195-4290 USA

PHYSICAL REVIEW LETTERS **125,** 191101 (2020)

Atom-Interferometric Test of the Equivalence Principle at the 10^{-12} Level

Peter Asenbaum,* Chris Overstreet,* Minjeong Kim, Joseph Curti, and Mark A. Kasevich†

Department of Physics, Stanford University, Stanford, California 94305, USA

(Received 26 June 2020; accepted 5 October 2020; published 2 November 2020)

Not tests of quantum gravity. Indirectly, can teach us something about QG.

Quantum gravity

PRX QUANTUM **2,** 010325 (2021)

Non-Gaussianity as a Signature of a Quantum Theory of Gravity

Richard Howl[1,2,3,*] Vlatko Vedral,[4,5] Devang Naik,[6] Marios Christodoulou,[2,4] Carlo Rovelli,[7,8,9] and Aditya Iyer[4]

Featured in Physics

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

C. Marletto and V. Vedral

Phys. Rev. Lett. **119**, 240402 – Published 13 December 2017

Featured in Physics

Spin Entanglement Witness for Quantum Gravity

Sougato Bose, Anupam Mazumdar, Gavin W. Morley, Hendrik Ulbricht, Marko Toroš, Mauro Paternos
A. Geraci, Peter F. Barker, M. S. Kim, and Gerard Milburn

Phys. Rev. Lett. **119**, 240401 – Published 13 December 2017

In principle, under some assumptions, are tests of quantum gravity.