Gravitating pairs of photons (in waveguides)

Piotr Chrusciel, with some slides by Philip Walther

Research Platform for Testing the Quantum and Gravity Interface (TURIS) &
Faculty of Physics, University of Vienna &

Humboldt Foundation meeting,
Kitzbuehel, June 2022

www.walther.univie.ac.at

www.turis.at

Testing the qUantum and gRavity InterfaSce

Vienna University Research Platform TURIS:

entangled photons (Walther Group)
matter waves (Arndt Group)
nano-mechanical devices (Aspelmeyer Group)
theoretical studies (Chrusciel and co)
causal structures and quantum physics (Brukner Group)
Faculty of Astronomy (Alves Group)

Testing the Quantum and Gravity Interface
Vienna University Research Platform

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TURIS

TURIS‘ big question:

How does gravity act on quantum systems ?

This subquestion:

How does a photon feel time? How do entangled photons feel time?

Experiments at the gravity-quantum interface ?

How does gravity act on massless quantum systems, including quantum entanglement?

And what was done so far?

	Classical physics	***Quantum mechanics***
Newtonian gravity	17^{th}- 19^{th} century	Neutrons (COW) Atoms/BEC
General relativity	Classical test of GR	**Photonic quantum systems**

None of the experiments performed to-date show unique signatures of general relativity and quantum mechanics in a single experiment!

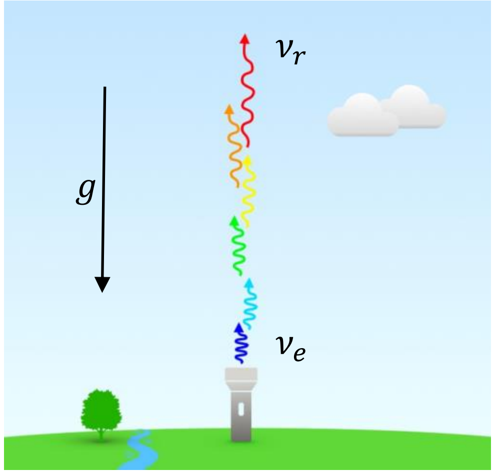
Two «classical» tests of General Relativity involving light

1) Gravitational redshift

Einstein predicted the gravitational redshift of light

$$\nu_r = \nu_e \left(1 - \frac{gh}{c^2}\right)$$

as a direct consequence of the equivalence principle in 1907.



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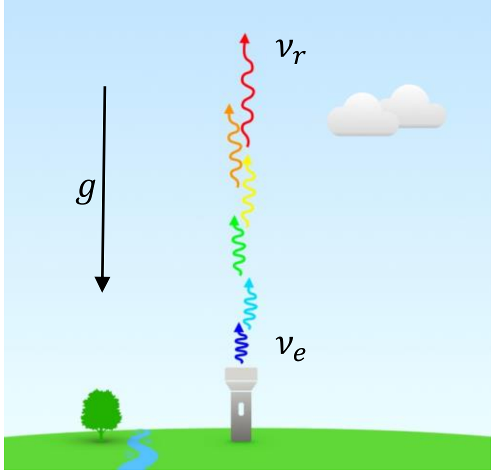

In 1924 *Eddington* pointed out that that this effect might be measured in the spectral lines of a white dwarf star, which has a very high density and gravitational field.

	Redshift
Sirius B (*Adams*, 1925)	$\sim \mathbf{19}\ km/s$
40 Heridani B (*Popper*, 1952)	$\sim \mathbf{21}\ km/s$
Sirius B (*Greenstein et al*, 1971)	$\mathbf{89 \pm 19}\ km/s$
Sirius B (*Hubble ST*, 2005)	$\mathbf{80,4 \pm 4,8}\ km/s$

Two «classical» tests of General Relativity involving light

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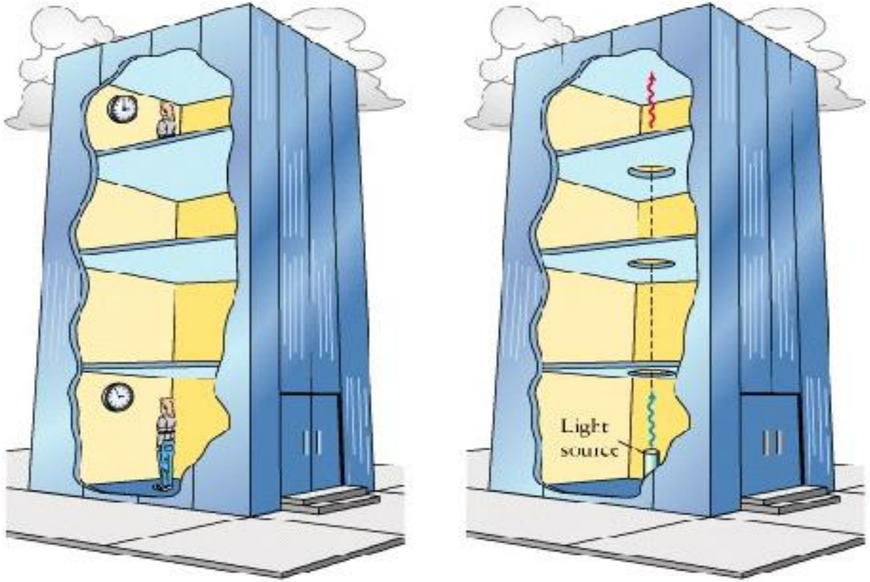
1) Gravitational redshift

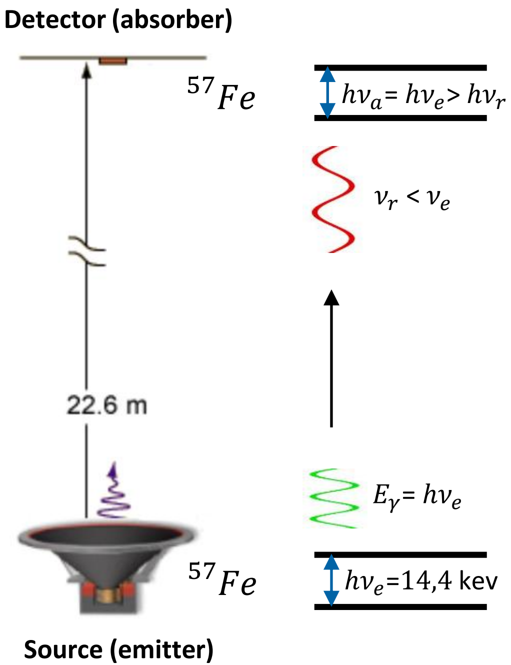
$$\nu_r = \nu_e\left(1 - \frac{gh}{c^2}\right)$$

VOLUME 3, NUMBER 9 PHYSICAL REVIEW LETTERS NOVEMBER 1, 1959

GRAVITATIONAL RED-SHIFT IN NUCLEAR RESONANCE

R. V. Pound and G. A. Rebka, Jr.
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts
(Received October 15, 1959)





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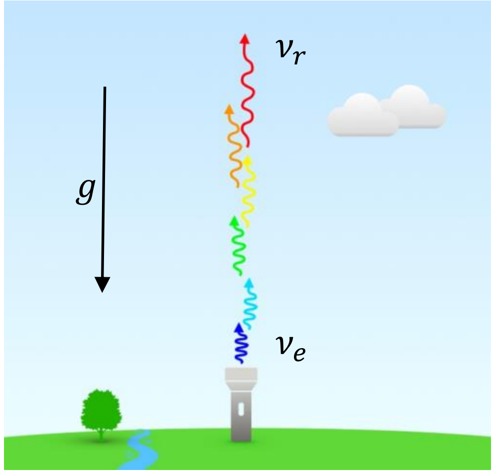

In 1972 *Hafele* and *Keating* brought four cesium-beam atomic clocks aboard of a Boeing 747. They flew twice around the world and ones comparing the clocks with a reference clock placed on Earth, they confirmed gravitational time dilation with a 9% accuracy.

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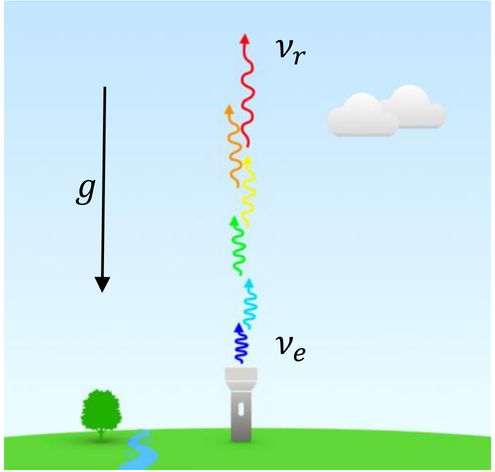

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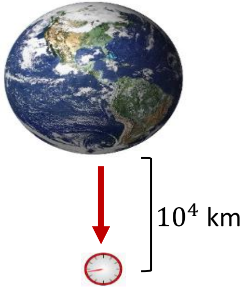
In 1976 a rocket flight with a hydrogen powered maser (atomic clock) on board was launched to a height of 10,000 km. Comparing its rate with an identical clock on the ground, in 1979, *Vessot, Levine et al* confirmed gravitational time dilation with a $\mathbf{7 \cdot 10^{-5}}$ accuracy (**Gravity Probe A**).



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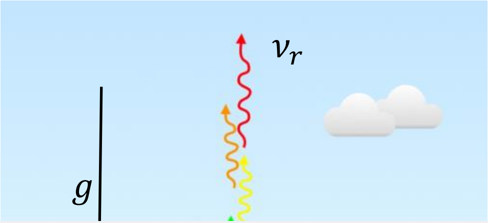
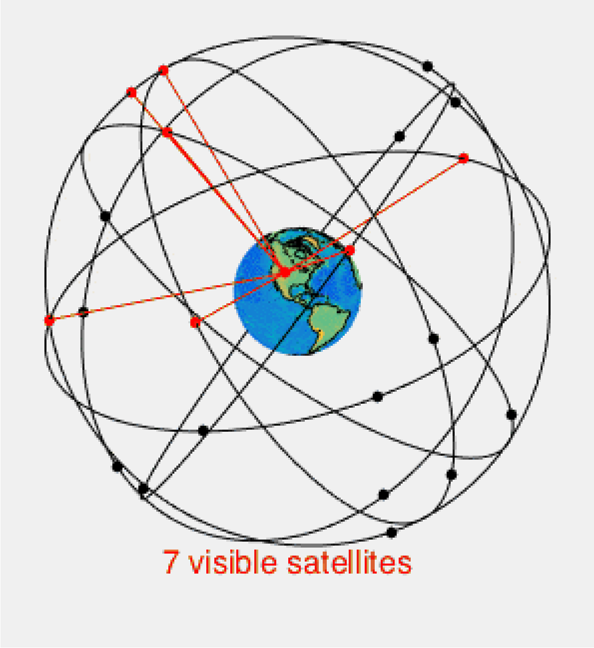


The success of failure:
Doresa (GSAT0201)
and Milena
(GSAT0202)
Soyuz launch in August
2014



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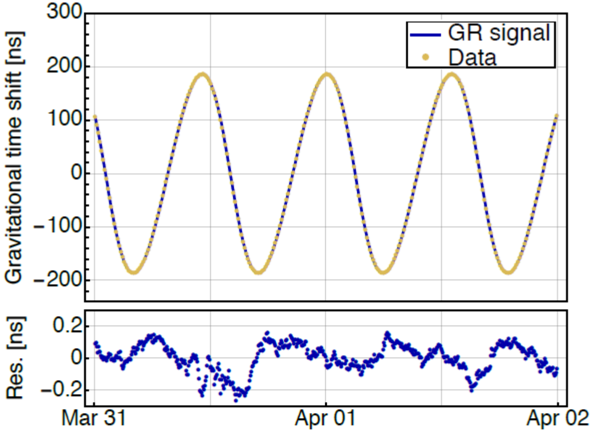

FIG. 4. GR prediction, clock data (after removal of a daily linear fit) and residuals are shown for 2 days from March 31st, 2016. The peak-to-peak effect is around 0.4 μs, therefore the model and systematic effects at orbital period should be controlled down to 4 ps in order to have a 1×10^{-5} uncertainty on the LPI violation parameter α.

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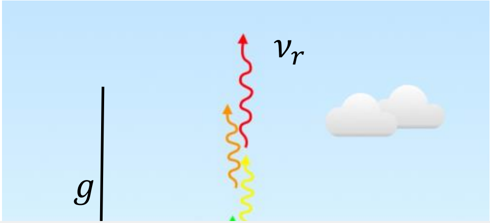

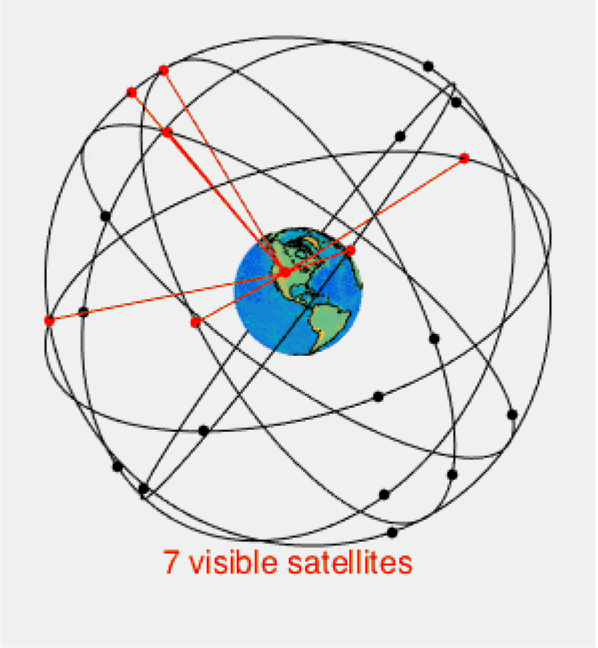

Gravitational Redshift Test Using Eccentric *Galileo* Satellites

P. Delva, N. Puchades, E. Schönemann, F. Dilssner, C. Courde, S. Bertone, F. Gonzalez, A. Hees, Ch. Le Poncin-Lafitte, F. Meynadier, R. Prieto-Cerdeira, B. Sohet, J. Ventura-Traveset, and P. Wolf

Phys. Rev. Lett. **121**, 231101 – Published 4 December 2018

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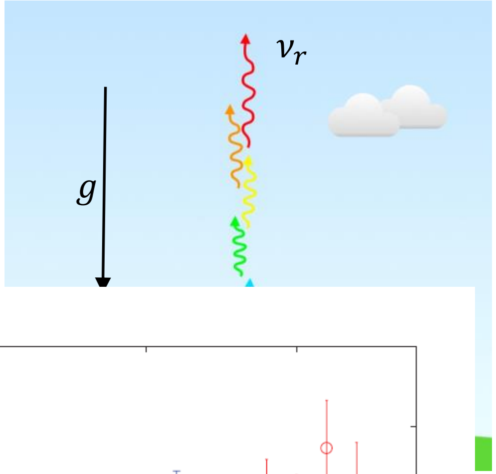
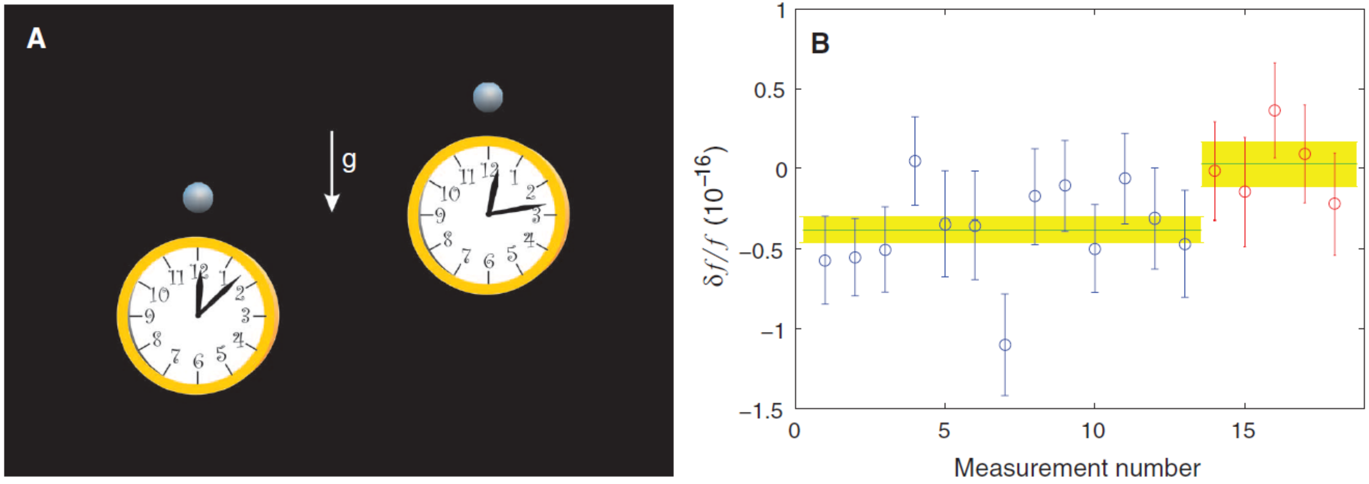


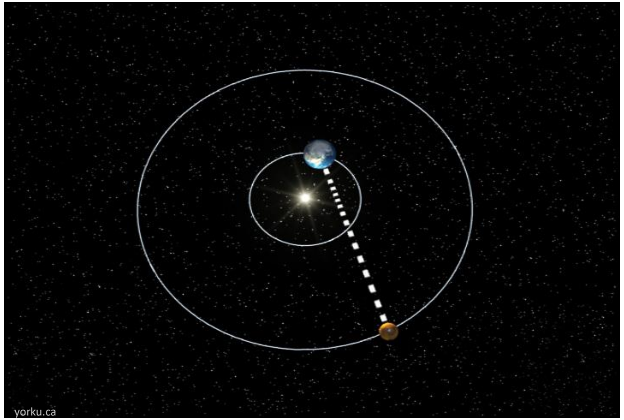
In 2010 *Chou et al* detected ? reported ? time dilation at different gravitational potentials due to a change in height near Earth's surface of less than 1 meter.



Two «classical» tests of General Relativity involving light

2) Shapiro effect

In 1962 *Irwin Shapiro* suggested that, by sending some strong radio signals to Venus, when it is in opposition to the Earth and the Sun, one could observe a time delay effect of 200 μs when measuring the round-trip travel time of the radar beam bouncing off Venus surface.



In 1964, with the 120 foot Haystack antenna in Westford, Shapiro and his team began plans to carry out the experiment.
The experiment first took place from November 1966 until August 1967. The delay was measured by Shapiro with 10% accuracy

Two «classical» tests of General Relativity involving light

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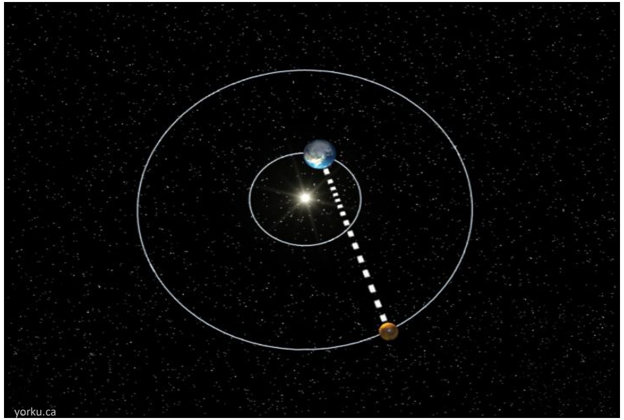
yorku.ca

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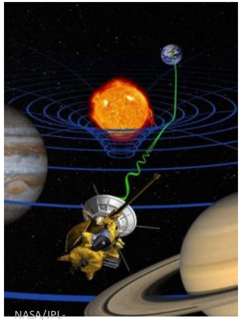
NASA/JPL-

Newer versions of this experiment work with transponders on space probes. Thus with the Viking Mars probe of 1979 the predictions were confirmed to an accuracy of $\mathbf{1}\%$.
In 2003, with the space probe Cassini an accuracy of $\mathbf{1,2 \cdot 10^{-5}}$ was achieved.

But:

- This was all classical physics
- What about quantum physics?

The first quantum test of Newtonian gravity

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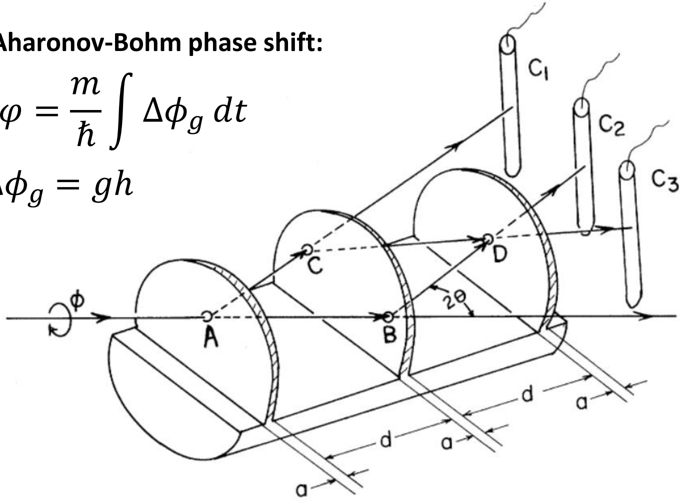
Matter-wave interferometry using neutrons
(the «famous» COW-experiment)

Aharonov-Bohm phase shift:

$$\Delta\varphi = \frac{m}{\hbar}\int \Delta\phi_g \, dt$$

$$\Delta\phi_g = gh$$



Schematic diagram of the neutron interferometer and ^{3}He detectors used in this experiment.

VOLUME 34, NUMBER 23 PHYSICAL REVIEW LETTERS 9 JUNE 1975

Observation of Gravitationally Induced Quantum Interference*

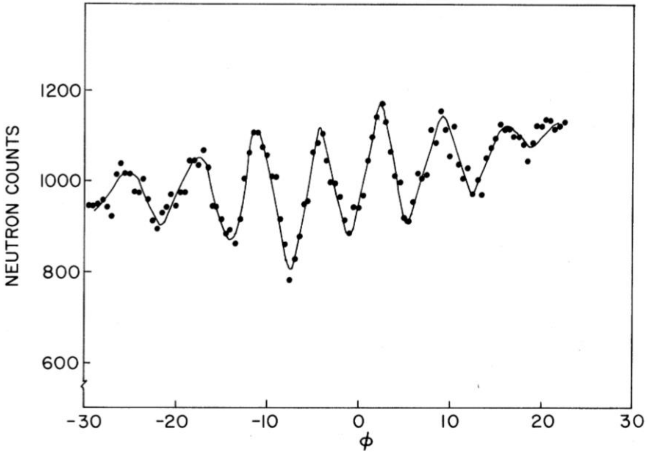
R. Colella and A. W. Overhauser
Department of Physics, Purdue University, West Lafayette, Indiana 47907

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.



Neutrons and Newtonian gravity

Measuring Airy functions (2002);

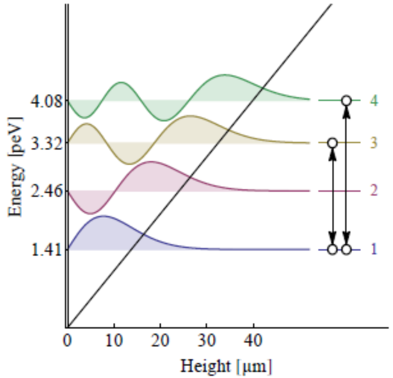
qBounce (2015)

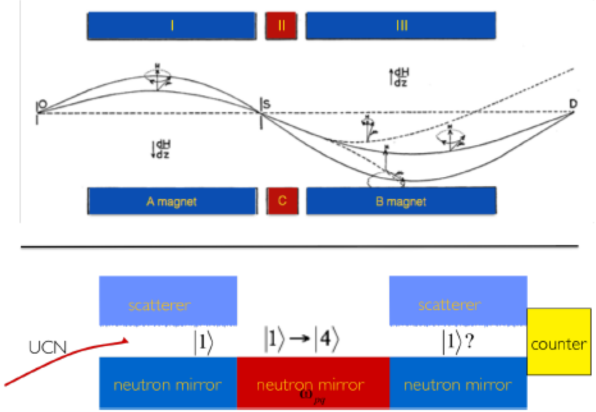
Quantum states of neutrons in the Earth's gravitational field

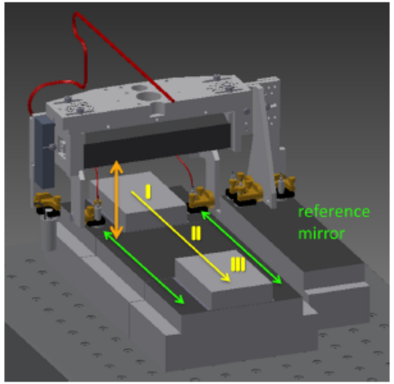
Valery V. Nesvizhevsky*, Hans G. Börner*, Alexander K. Petukhov*, Hartmut Abele†, Stefan Baeßler†, Frank J. Rueß†, Thilo Stöferle†, Alexander Westphal†, Alexei M. Gagarski‡, Guennady A. Petrov‡ & Alexander V. Strelkov§

** Institute Laue-Langevin, 6 rue Jules Horowitz, Grenoble F-38042, France*
† University of Heidelberg, 12 Philosophenweg, Heidelberg D-69120, Germany
‡ Petersburg Nuclear Physics Institute, Orlova Roscha, Gatchina, Leningrad reg. R-188350, Russia
§ Joint Institute for Nuclear Research, Dubna, Moscow reg. R-141980, Russia

A Gravity of Earth measurement with qBOUNCE — Gunther Cronenberg







The first quantum test of Newtonian gravity

Neutron interferometry revisited in 2020

Tests of Fundamental Quantum Mechanics and Dark Interactions with Low Energy Neutrons - Extended Version

Stephan Sponar[1]*, René I.P. Sedmik[1], Mario Pitschmann[1], Hartmut Abele[1], and Yuji Hasegawa[1,2]
[1] Atominstitut, TU Wien, Stadionallee 2, 1020 Vienna, Austria
[2] Department of Applied Physics, Hokkaido University, Kita-ku, Sapporo 060-8628, Japan

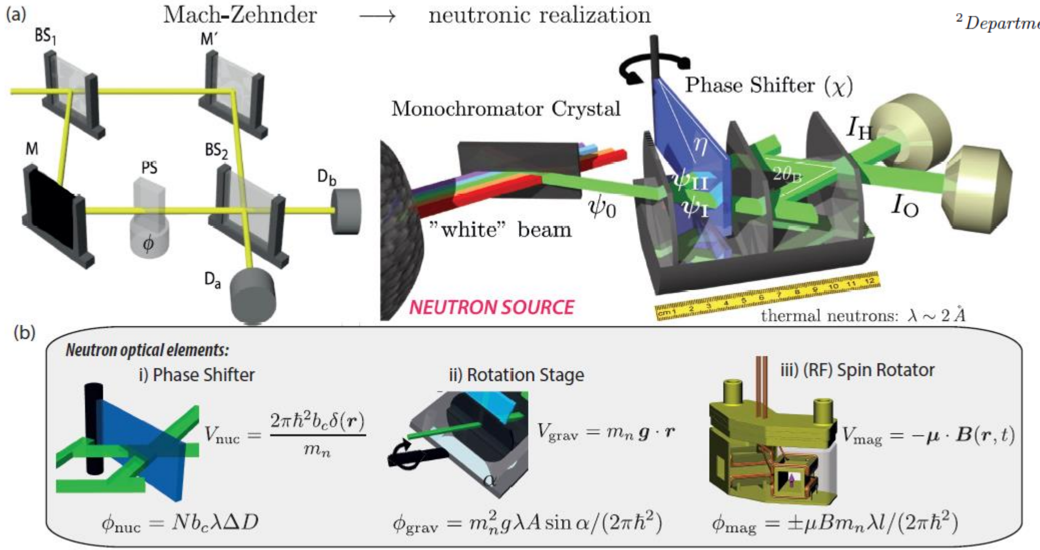


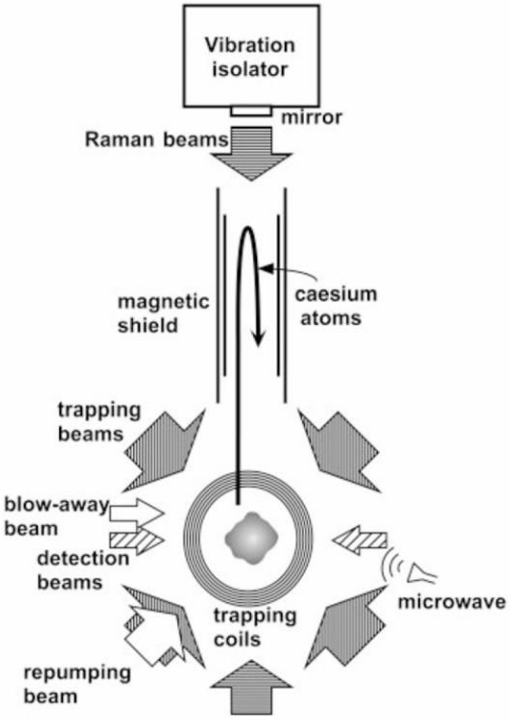
Figure 1 : (a) Optical Mach-Zehnder interferometer compared to a silicon perfect crystal neutron interferometer of Mach-Zehnder type (triple Laue - LLL). (b) Tool box nuclear, gravitational and magnetic phase shifts.

Atomic fountains (1999)

Measurement of gravitational acceleration by dropping atoms

Achim Peters, Keng Yeow Chung & Steven Chu

Physics Department, Stanford University, Stanford, California 94305-4060, USA



gure 1 Overview of the experimental set-up.

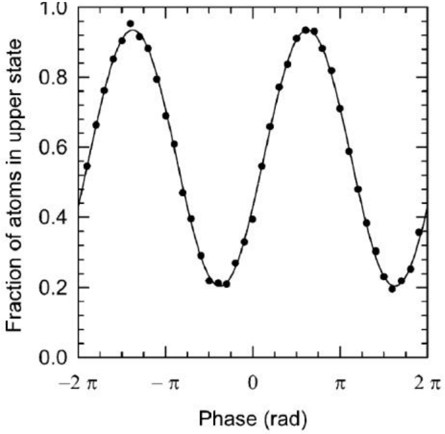


Figure 2 Typical Doppler-sensitive interferometer fringe for $T = 160$ ms. Shown are the 588,638th and 588,639th fringes. Each of the 40 data points represents a single launch of the atoms, spaced 1.3 s apart and taken over a period of 1 min. One full fringe corresponds to $\sim 2 \times 10^6 g$. Performing a least-squares fit determines local gravity to approximately $3 \times 10^{-9} g$.

Atomic fountains (2022)

Science

Current Issue First release papers Archive

HOME > SCIENCE > VOL. 375, NO. 6577 > OBSERVATION OF A GRAVITATIONAL AHARONOV-BOHM EFFECT

REPORT | PHYSICS

Observation of a gravitational Aharonov-Bohm effect

CHRIS OVERSTREET, PETER ASENBAUM, JOSEPH CURTI, MINJEONG KIM, AND, MARK A. KASEVICH Authors Info & Affiliations

SCIENCE • 13 Jan 2022 • Vol 375, Issue 6577 • pp. 226-229 • DOI: 10.1126/science.abl7152

So far all quantum experiments can be explained by the Schroedinger equation with a Newtonian potential

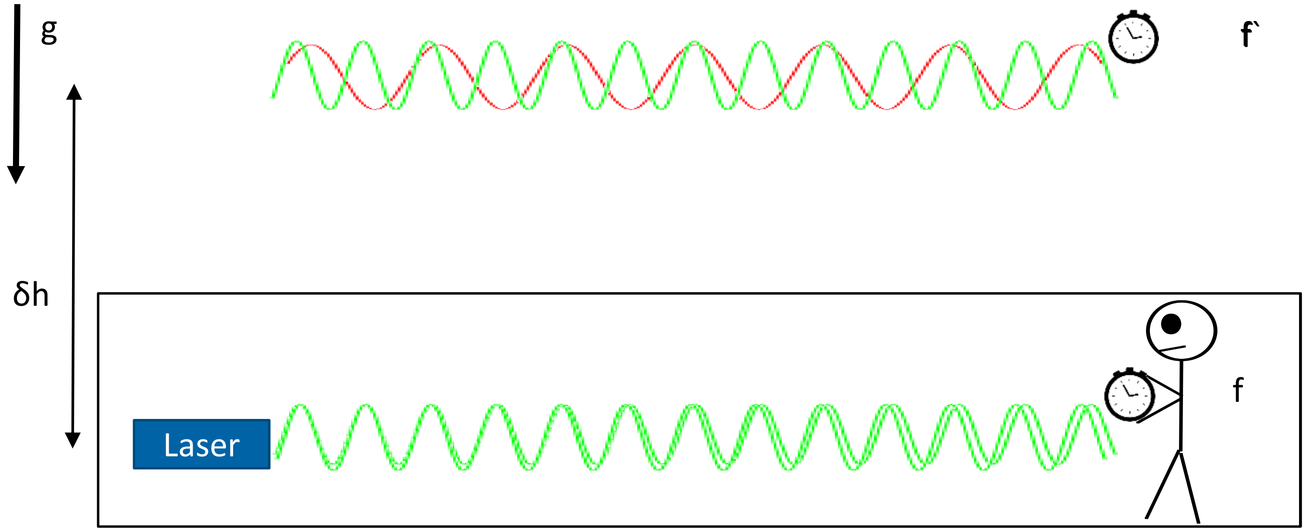
No Newtonian model when photons are used

Photonic quantum interferometry:

a quantum version of the Shapiro? Gravitational

Redshift? experiment

Photons at different heights in a gravit. field



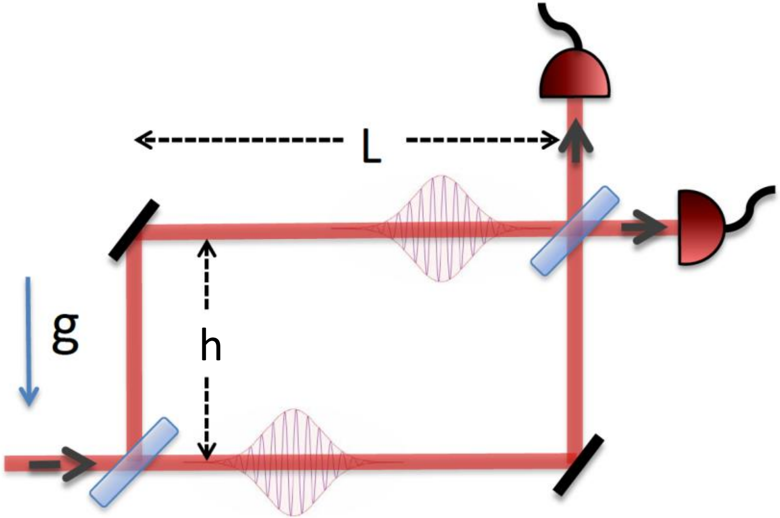
Gravitational interferometry for single photons

New Journal of Physics

Gravitationally induced phase shift on a single photon

Christopher Hilweg , Francesco Massa , Denis Martynov , Nergis Mavalvala , Piotr T Chruściel and Philip Walther

New J. Phys. **19** (2017) 033028

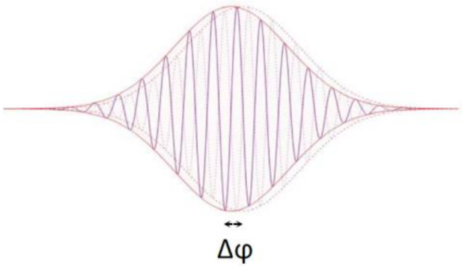


Time delay:

$$\Delta t = \frac{Lgh}{c^3}$$

Phase shift:

$$\Delta\varphi = \frac{2\pi c\Delta t}{\lambda} = \frac{2\pi Lgh}{\lambda c^3}$$



$$\Delta\varphi = \frac{2\pi Lgh}{\lambda c^3}$$

Gravitational interferometry for single photons

- Maxwell equations for a gravitating waveguide predict the following a change of the wave vector:

Weakly gravitating isotropic waveguides

R Beig[1], P T Chruściel[1,2], C Hilweg[4,1,2], P Kornreich[3] and P Walther[1,2]

Published 13 November 2018 • © 2018 IOP Publishing Ltd

Classical and Quantum Gravity, Volume 35, Number 24

$$\delta\beta = \frac{2\,\omega^2 n^2 g\,\delta h}{c^4\,\beta} \approx 1.3\,x10^{-9}\,/m$$

$$\Delta\varphi = \frac{2\pi n L g h}{\lambda c^2}$$

Gravitational interferometry for single photons

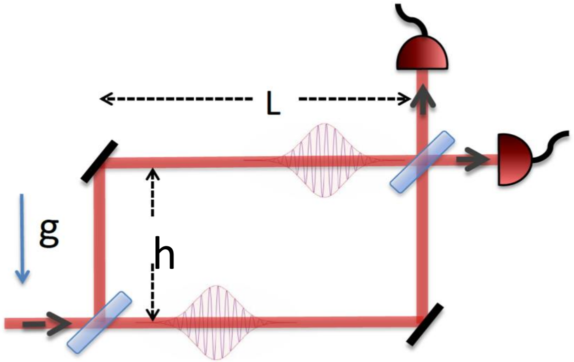
- The gravitational interaction changes the wave vector according to:

$$\delta\beta = \frac{2\,\omega^2 n^2 g\,\delta h}{c^4\,\beta} \approx 1.3\,x10^{-9}\;/m$$

R Beig et al 2018 Class. Quantum Grav. 35 244001

- To get a measuarable signal, the arms of the interferometer need to be of the order of L =100 km:

$$\Delta\phi = \delta\beta\,\mathrm{L} \approx 10^{-4}\,\mathrm{rad}$$



$\mathrm{h} = \mathbf{1}\,m$

$\mathrm{L} = \mathbf{100}\,km$

$$\Delta\varphi = \frac{2\pi nLgh}{\lambda c^2} = \mathbf{10^{-4}}\,rad$$

Gravitational interferometry for single photons

- The gravitational interaction changes the wave vector according to:

$$\delta\beta = \frac{2\,\omega^2 n^2 g\,\delta h}{c^4\,\beta} \approx 1.3\,x10^{-9}\,/m$$

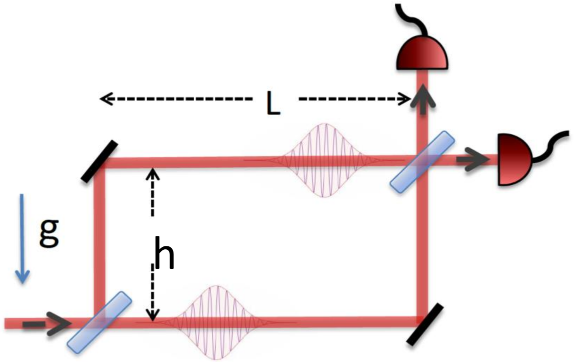
R Beig et al 2018 Class. Quantum Grav. 35 244001

- To get a measurable signal, the arms of the interferometer need to be of the order of L =100 km:

$$\Delta\phi = \delta\beta\,L \approx 10^{-4}\,\text{rad}$$

- Corresponding to a strain sensitivity of $\frac{\Delta L}{L} \approx 10^{-16}$.

- Photon loss in 100km fiber: 20dB (= 1% transmission rate).



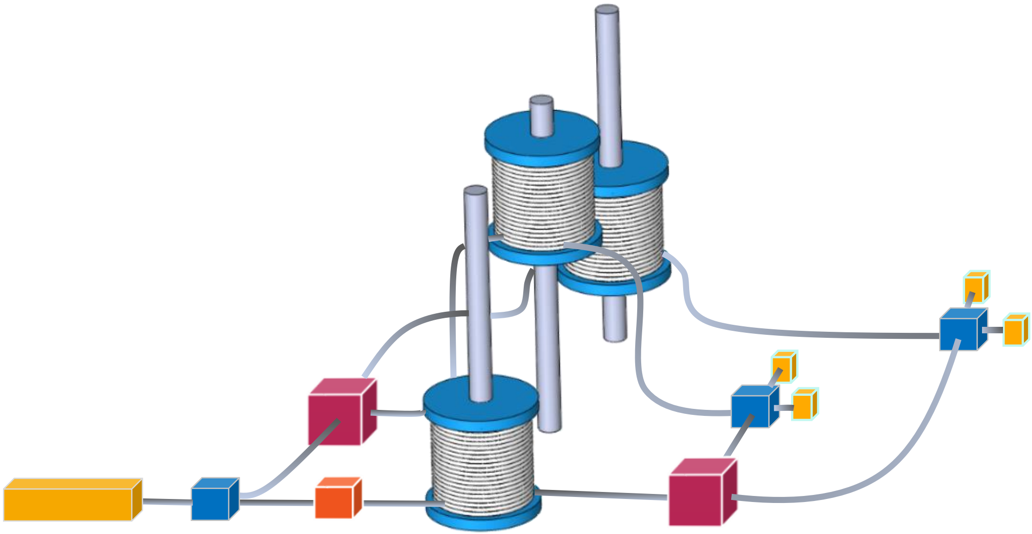
$\Delta\varphi = \mathbf{10^{-5}}\,rad$ ⟷ $\Delta f/f = \mathbf{10^{-17}}$

$h = \mathbf{1}\,m$

$L = \mathbf{100}\,km$

$$\Delta\varphi = \frac{2\pi nLgh}{\lambda c^2} = \mathbf{10^{-4}}\,rad$$

Many challenges in real-world scenario

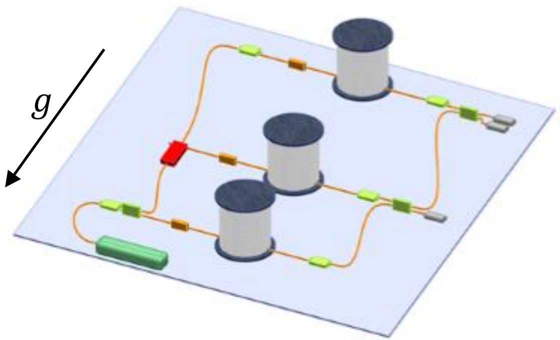


$\Delta\varphi = \mathbf{10^{-5}}\, rad$ ↔ $\Delta f/f = \mathbf{10^{-17}}$

- fiber thermal noise
- systematic errors
- seismic noise
- acoustic noise
- laser noise
- dispersion
- Nonlinear effects
    - self-phase modulation
    - stimulated Raman scattering
    - stimulated Brillouin scattering
    - etc.

Gravitational interferometry for single photons

- **Stabilization scheme**



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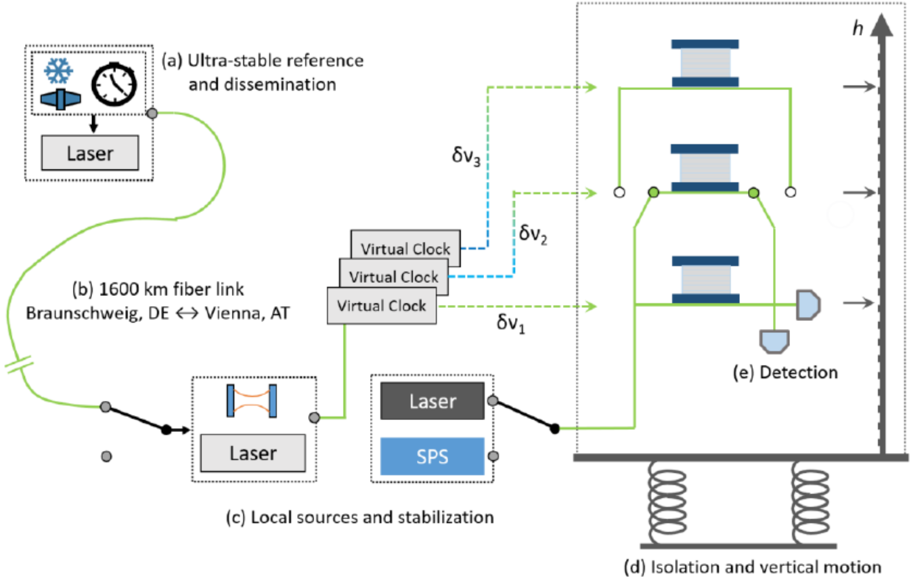


Experimental overview. (a) The ultimate source of stability in the experiment is an ultra-stable cryogenic reference cavity or optical clock at PTB. (b) This reference is transmitted over a fiber link to the University of Vienna. (c) A local laser stabilized to the reference is shifted to provide virtual clocks for stabilization of the 100 km of optical fiber in each arm of the MZI independent of height. (d) The MZI is situated in an environmental isolation system with vertical motion stages to vary the height of each arm. (e) The gravitational phase is read out, using heterodyne detection for the cw-laser experiment (second laser, dark gray), or SNSPDs for the single photon source (SPS).

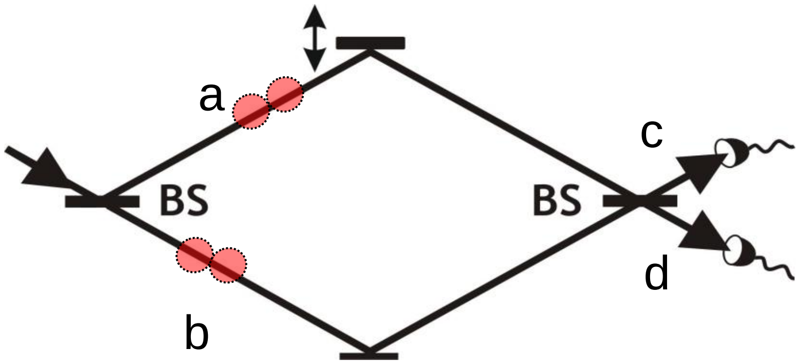
From superposition to quantum entanglement

Gravity effects on quantum entanglement

Path-entangled photon pairs

- Mach-Zehnder setup
- *N*-input particles (photons) are propagating either along mode a *or* b
- $|N>_a|0>_b$ or $|0>|N>_b$ which is called N00N-state
- Oscillation of interference fringes is proportional to *N*

$$\frac{1}{\sqrt{2}}\left(|N\rangle_a|0\rangle_b + e^{iN\Delta\varphi}|0\rangle_a|N\rangle_b\right) \qquad P_{c,d} \propto 1 \pm \cos(N\Delta\varphi)$$



Gravity effects on quantum entanglement

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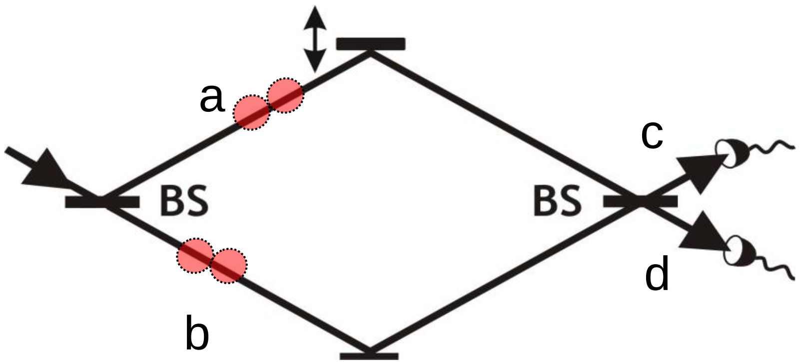
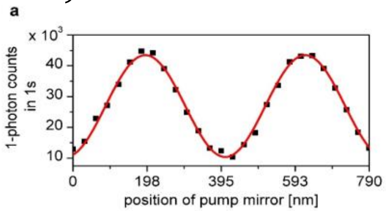
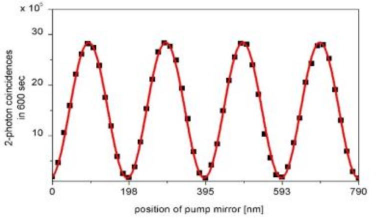
$$\frac{1}{\sqrt{2}}\left(|N\rangle_a|0\rangle_b + e^{iN\Delta\varphi}|0\rangle_a|N\rangle_b\right)$$

$$P_{c,d} \propto 1 \pm \cos(N\Delta\varphi)$$





$$\frac{1}{\sqrt{2}}\left(|1\rangle_a|0\rangle_b + e^{i\Delta\varphi}|0\rangle_a|1\rangle_b\right)$$



$$\frac{1}{\sqrt{2}}\left(|2\rangle_a|0\rangle_b + e^{i2\Delta\varphi}|0\rangle_a|2\rangle_b\right)$$

Walther et al.
Nature 429, 158 (2002)

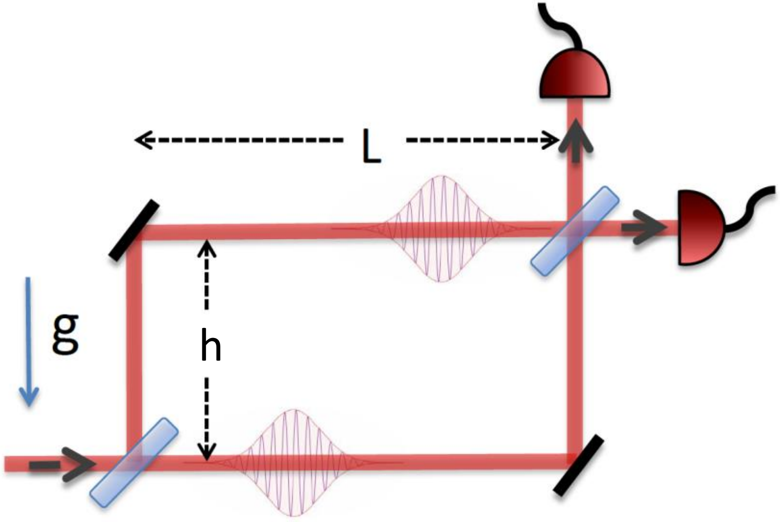
Gravitational interferometry for single photons/pairs of photons

New Journal of Physics

Gravitationally induced phase shift on a single photon

Christopher Hilweg, Francesco Massa, Denis Martynov, Nergis Mavalvala, Piotr T Chruściel and Philip Walther

New J. Phys. **19** (2017) 033028

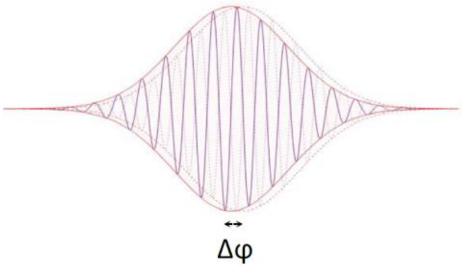


Time delay:

$$\Delta t = \frac{Lgh}{c^3}$$

Phase shift:

$$\Delta\varphi = \frac{2\pi c \Delta t}{\lambda} = \frac{2\pi Lgh}{\lambda c^3}$$



$$\Delta\varphi = \frac{2\pi Lgh}{\lambda c^3}$$

Main effect (3 orders of magnitude): Earth rotation

On the influence of Earth's rotation on light propagation in waveguides

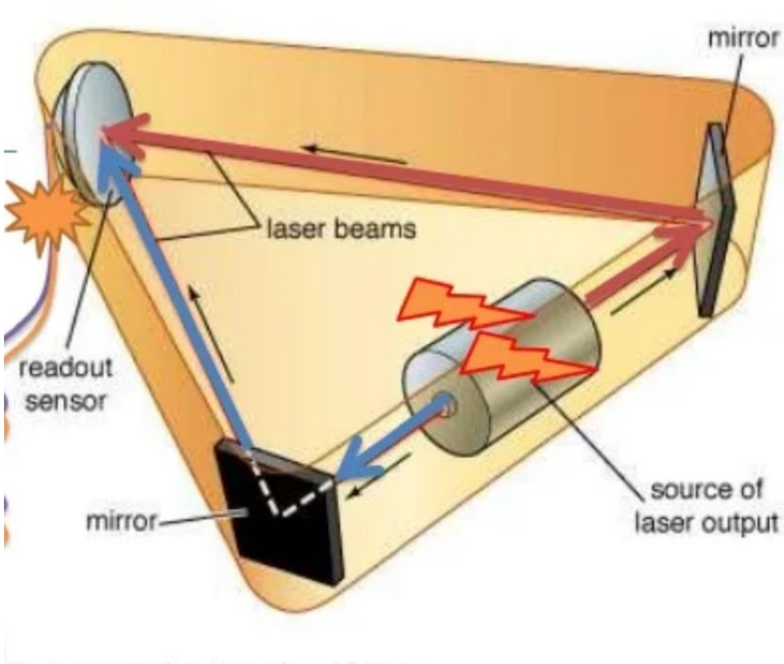
Thomas B Mieling[1]

Published 15 October 2020 •

Classical and Quantum Gravity, Volume 37, Number 22

1^{st} generation experiments: measurement of Earth‘s rotation using quantum light

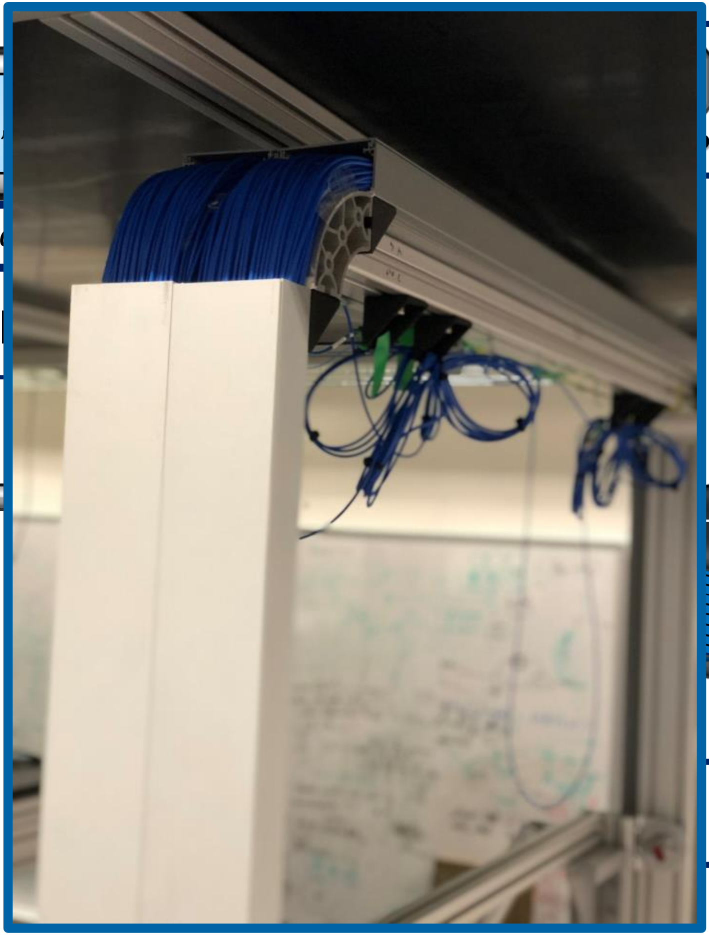
a.k.a: quantum Sagnac gyroscope



Impression from the real experiment

universität wien

TURIS



5%

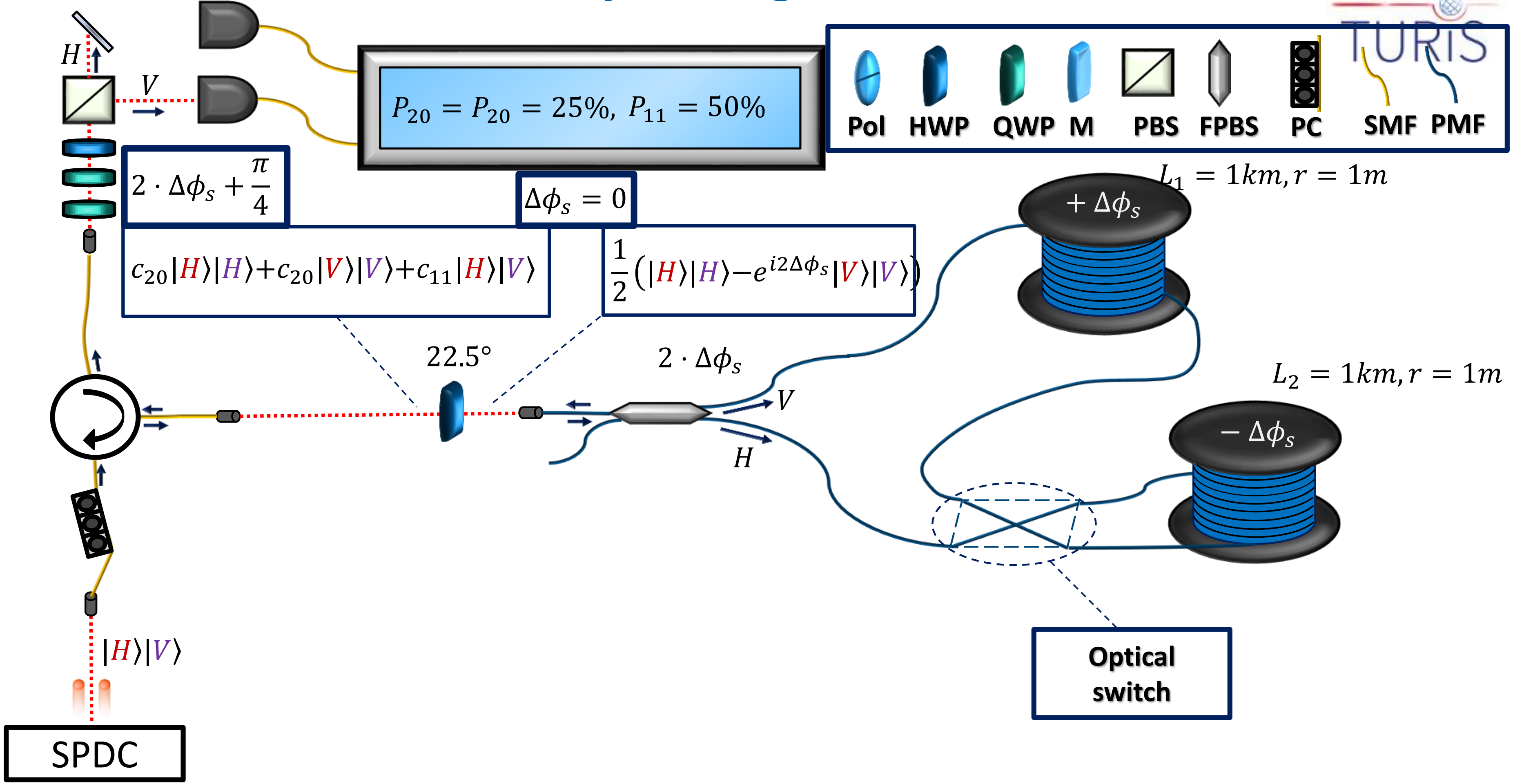
PBS PC SMF PMF

$1km, r = 1m$

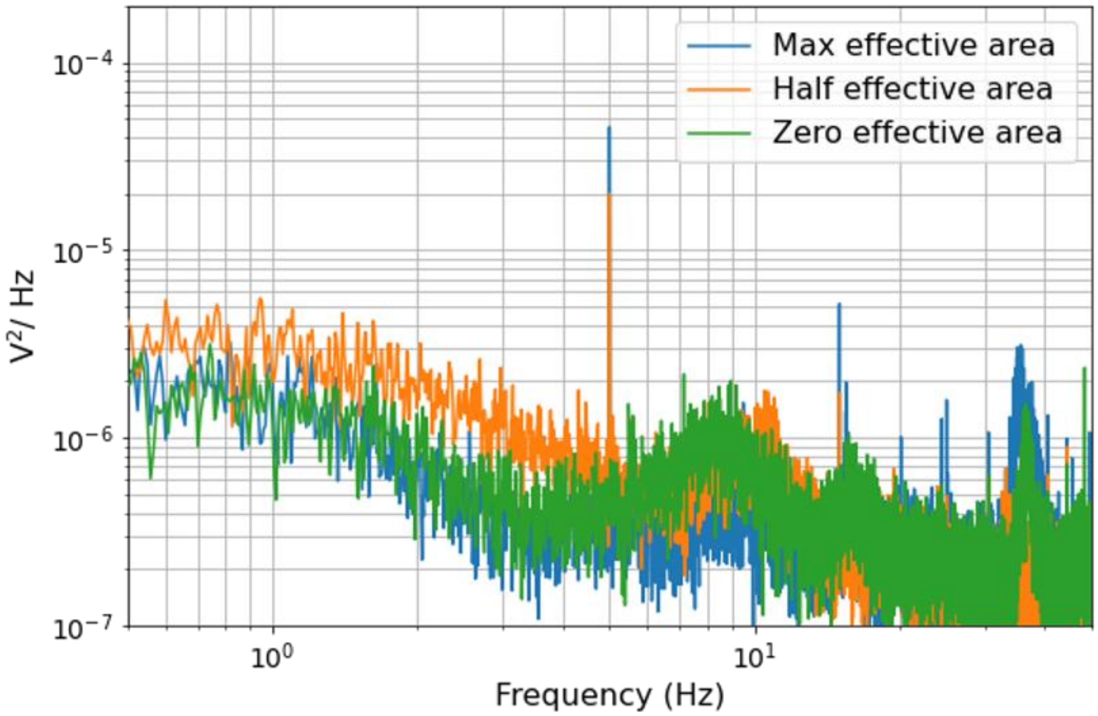
$L_2 = 1km, r = 1m$

$+ \Delta\phi_s$

Quantum interference probing earth rotation



First results with continuous light



Gravitational waves?

The response of optical fibres to gravitational waves

Thomas B Mieling[3,1,2]

Published 2 July 2021 • © 2021 The Author(s). Published by IOP Publishing Ltd

Classical and Quantum Gravity, Volume 38, Number 15

Citation Thomas B Mieling 2021 *Class. Quantum Grav.* **38** 155006

Next steps

- rotation of Earth and single photons (source broke …)
- rotation of Earth and entangled photons (next year?)
- varying h and classical light
- varying h and single photons
- varying h and entangled photons
- Measuring the response of quantum light to spacetime curvature with a satellite experiment

Measuring curvature?

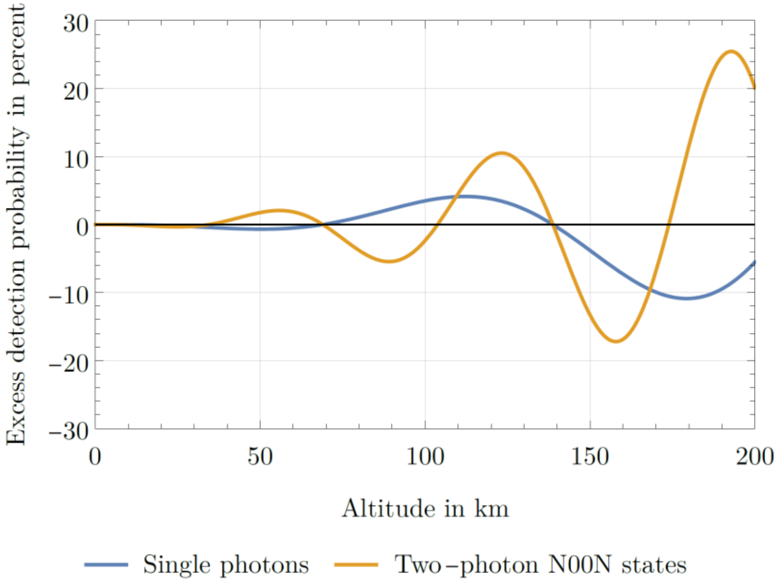
Measuring Space-Time Curvature using Maximally Path-Entangled Quantum States

Thomas Mieling (Vienna U.), Christopher Hilweg (Vienna U. and IQOQI, Vienna), Philip Walther (Vienna U.)

Feb 25, 2022

5 pages

e-Print: 2202.12562 [gr-qc]



Team: Photonic Gravity-Quantum Experiment