Gravitational redshift measurement with two-photon interference of frequency-entangled pairs

Albert Roura

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für Luft- und Raumfahrt
German Aerospace Center

Outline

1. **General relativistic effects in the quantum regime: Matter-wave measurements**
    - Quantum-clock interferometry
    - Spacetime curvature and proper-time difference
    - Alternative: interferometry with quantum states of light
2. **Gravitational redshift measurement with two-photon interferometry**
    - Hong-Ou-Mandel two-photon interference
    - Two-photon interferometry with frequency-entangled pairs
    - Gravitational redshift measurement
3. **Conclusions**

General relativistic effects in the quantum regime:
Matter-wave measurements

DLR

(i) Quantum-clock interferometry

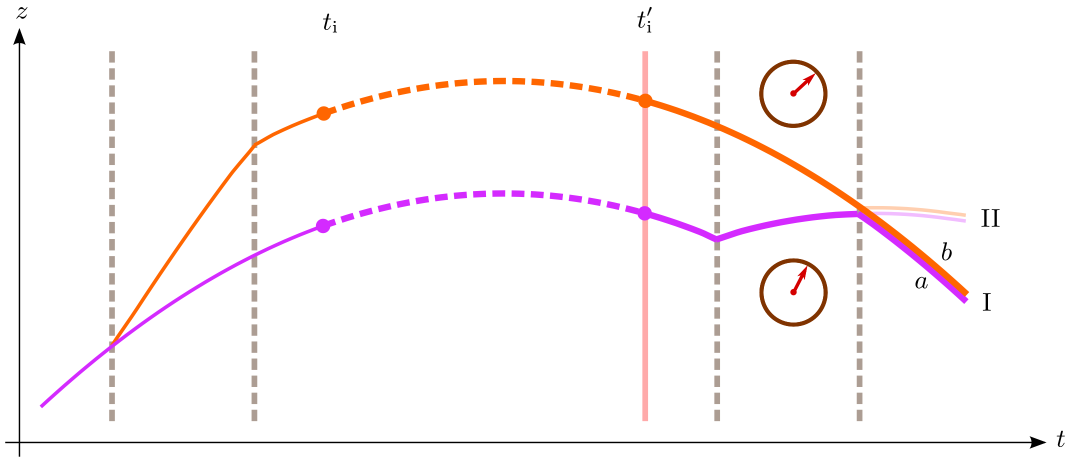
PHYSICAL REVIEW X **10,** 021014 (2020)

Gravitational Redshift in Quantum-Clock Interferometry

Albert Roura

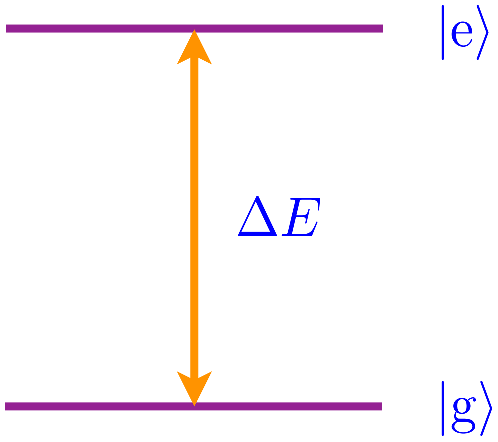
Quantum superposition of a single clock at two different heights

- Initialization pulse after the spatial superposition has been generated.
- Doubly differential measurement:
    - state-selective detection
    - compare different initialization times



Two-level atom as a quantum clock

- Proper time encoded in the relative phase between the two internal states (clock states).



- *Initialization* pulse:

$$|\mathrm{g}\rangle \;\rightarrow\; \big|\Phi(0)\big\rangle = \frac{1}{\sqrt{2}}\Big(|\mathrm{g}\rangle + i\, e^{i\varphi}|\mathrm{e}\rangle\Big)$$

- Evolution:

$$\big|\Phi(\tau)\big\rangle \propto \frac{1}{\sqrt{2}}\Big(|\mathrm{g}\rangle + i\, e^{i\varphi} e^{-i\Delta E\,\tau/\hbar}|\mathrm{e}\rangle\Big)$$

Two-level atom as a quantum clock

- Theoretical description of the clock:
  - two-level atom (internal state):

$$\hat{H} = \hat{H}_1 \otimes |\mathrm{g}\rangle\langle\mathrm{g}| + \hat{H}_2 \otimes |\mathrm{e}\rangle\langle\mathrm{e}|$$

$$m_1 = m_\mathrm{g}$$

$$m_2 = m_\mathrm{g} + \Delta m$$

$$\Delta m = \Delta E / c^2$$

  - classical action for COM motion:

$$S_n\big[x^\mu(\lambda)\big] = -m_n c^2 \int d\tau = -m_n c \int d\lambda \sqrt{-g_{\mu\nu}\frac{dx^\mu}{d\lambda}\frac{dx^\nu}{d\lambda}} \qquad (\, n = 1, 2\,)$$

free fall

Two-level atom as a quantum clock

- Theoretical description of the clock:
  - two-level atom (internal state):

$$\hat{H} = \hat{H}_1 \otimes |\mathrm{g}\rangle\langle\mathrm{g}| + \hat{H}_2 \otimes |\mathrm{e}\rangle\langle\mathrm{e}|$$

$$m_1 = m_\mathrm{g}$$

$$m_2 = m_\mathrm{g} + \Delta m$$

$$\Delta m = \Delta E / c^2$$

  - classical action for COM motion:

$$S_n\big[x^\mu(\lambda)\big] = -m_n c^2 \int d\tau - \int d\tau\, V_n(x^\mu) \qquad (\,n = 1, 2\,)$$

including external forces

(i) Quantum-clock interferometry

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Gravitational Redshift in Quantum-Clock Interferometry

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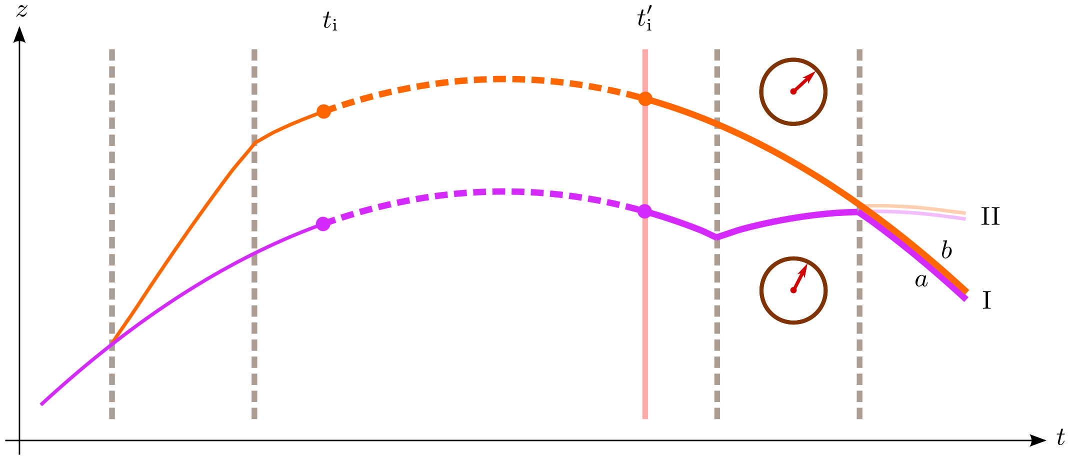


Quantum-clock interferometry

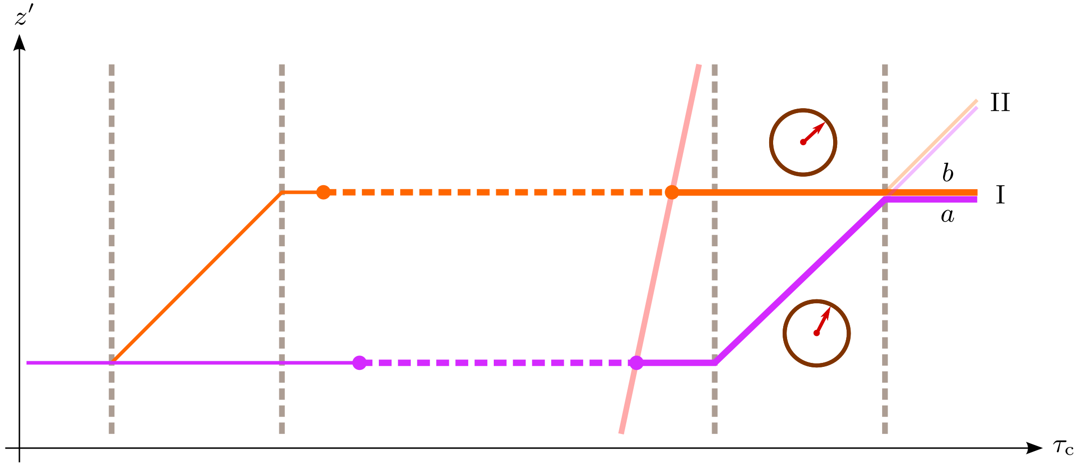
PHYSICAL REVIEW X **10,** 021014 (2020)

Gravitational Redshift in Quantum-Clock Interferometry

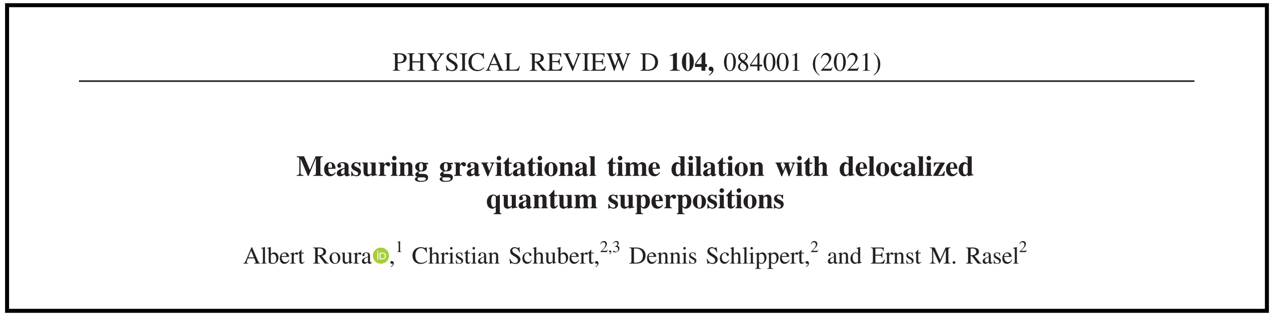
Albert Roura

Quantum superposition of a single clock at two different heights

- *Relativity of simultaneity* for spatially separated events.
- Simultaneous initialization in the lab frame, BUT not in the *freely falling frame*.



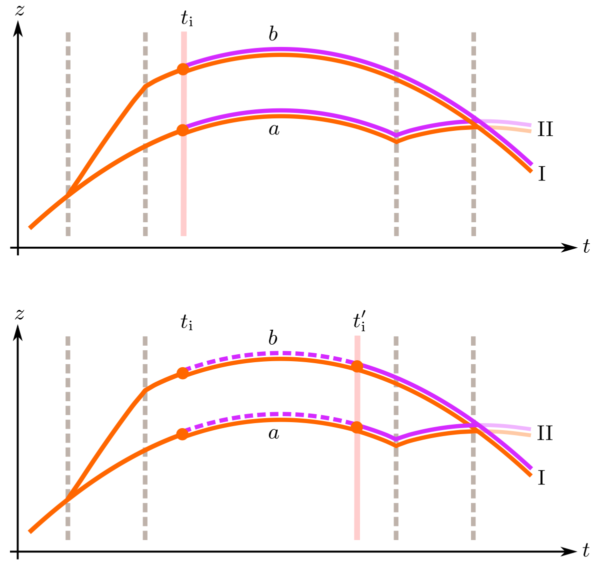
(i) Quantum-clock interferometry

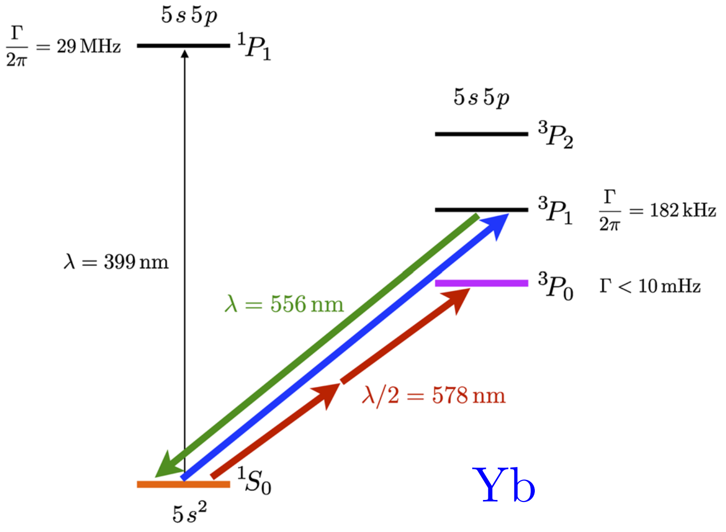


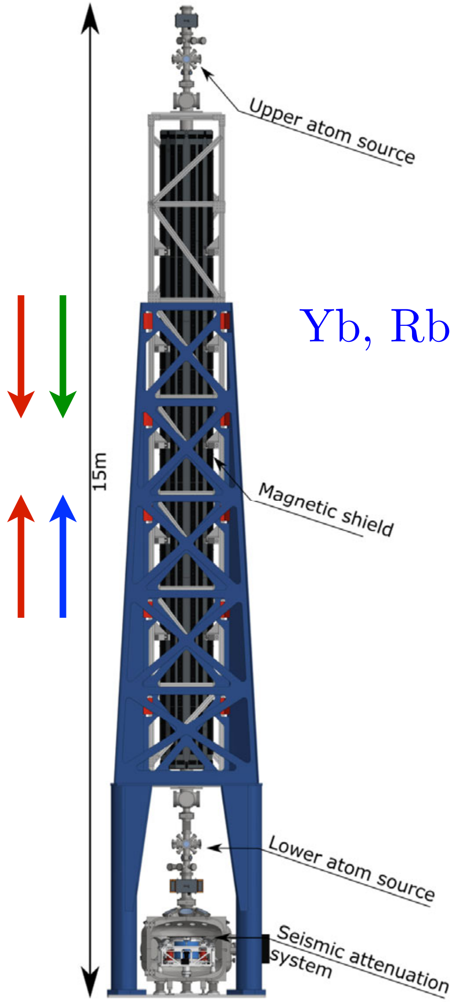
PHYSICAL REVIEW D **104,** 084001 (2021)

Measuring gravitational time dilation with delocalized quantum superpositions

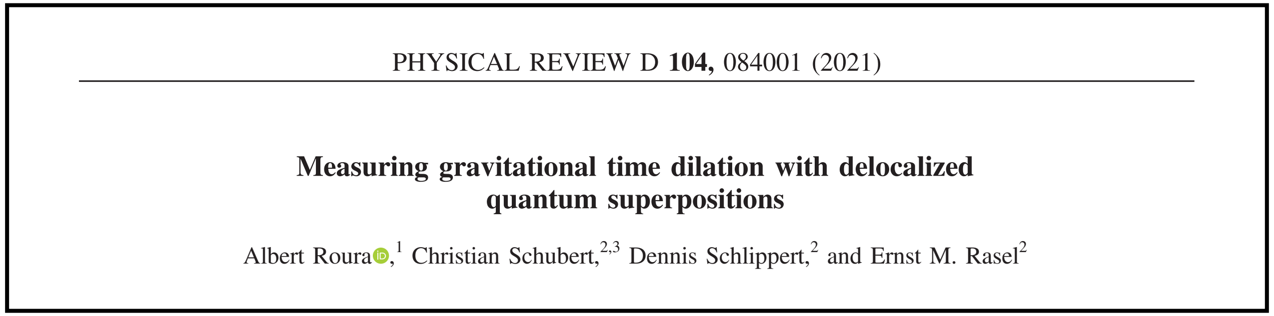
Albert Roura[1] Christian Schubert,[2,3] Dennis Schlippert,[2] and Ernst M. Rasel[2]







(i) Quantum-clock interferometry



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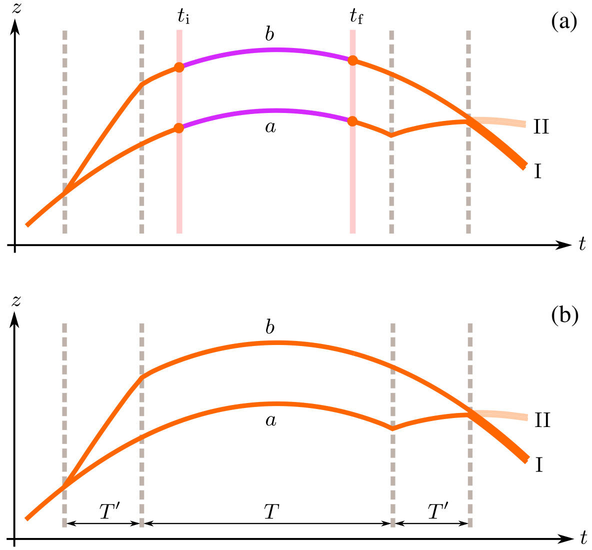
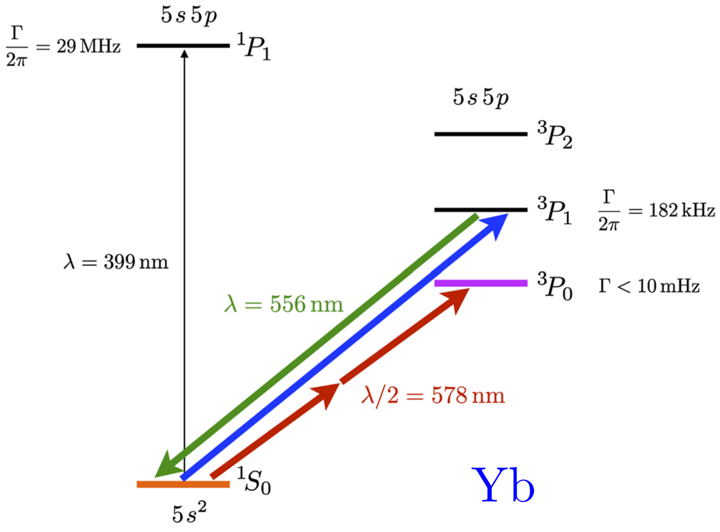
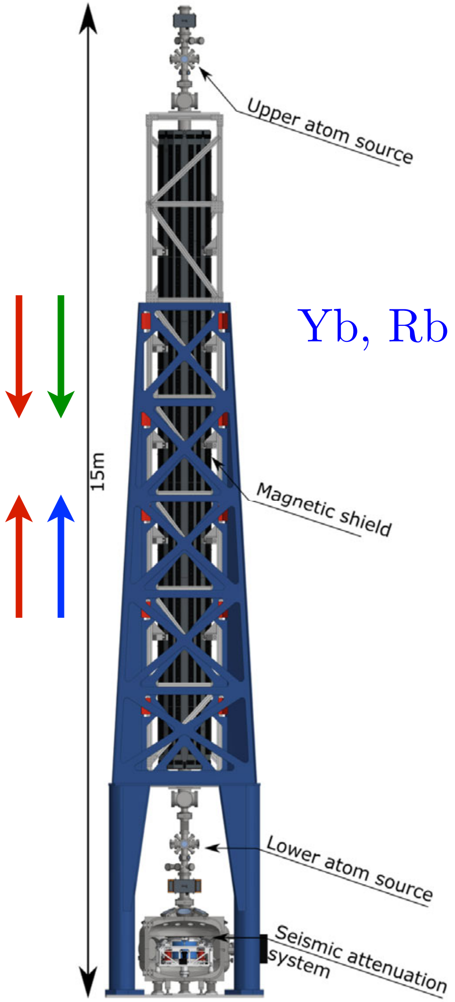
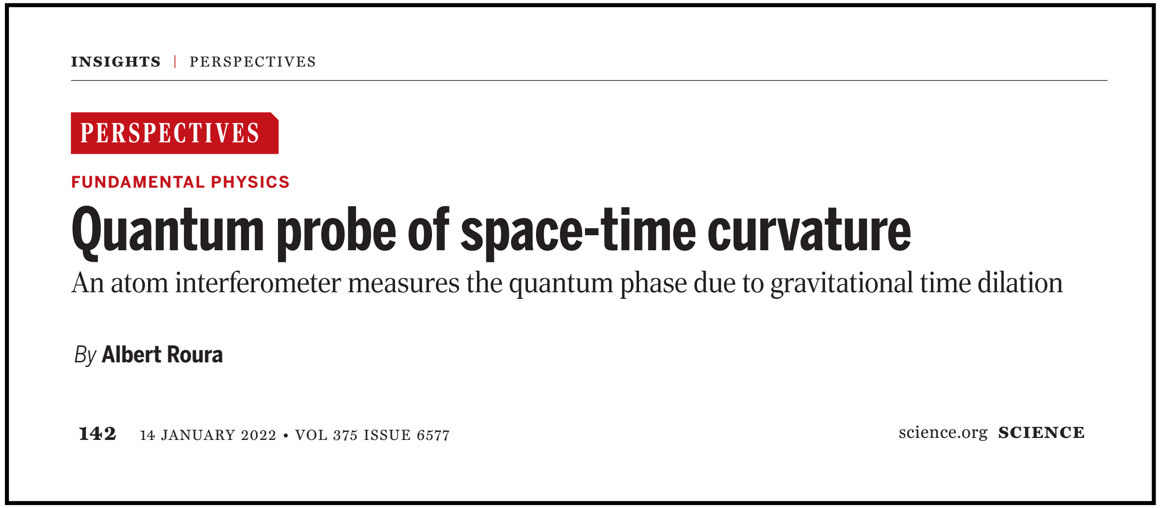






(ii) Spacetime curvature and proper-time difference



INSIGHTS | PERSPECTIVES

PERSPECTIVES

FUNDAMENTAL PHYSICS

Quantum probe of space-time curvature

An atom interferometer measures the quantum phase due to gravitational time dilation

By **Albert Roura**

142 14 JANUARY 2022 • VOL 375 ISSUE 6577 science.org **SCIENCE**

RESEARCH

PHYSICS

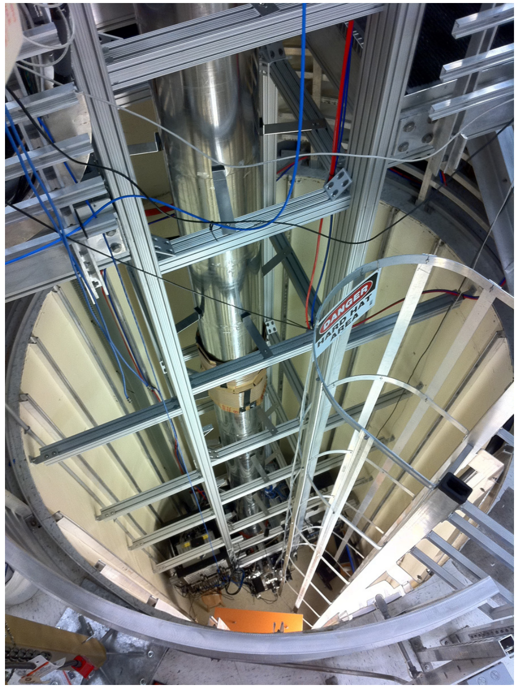
Observation of a gravitational Aharonov-Bohm effect

Chris Overstreet[1]†, Peter Asenbaum[1,2]†, Joseph Curti[1], Minjeong Kim[1], Mark A. Kasevich[1]*

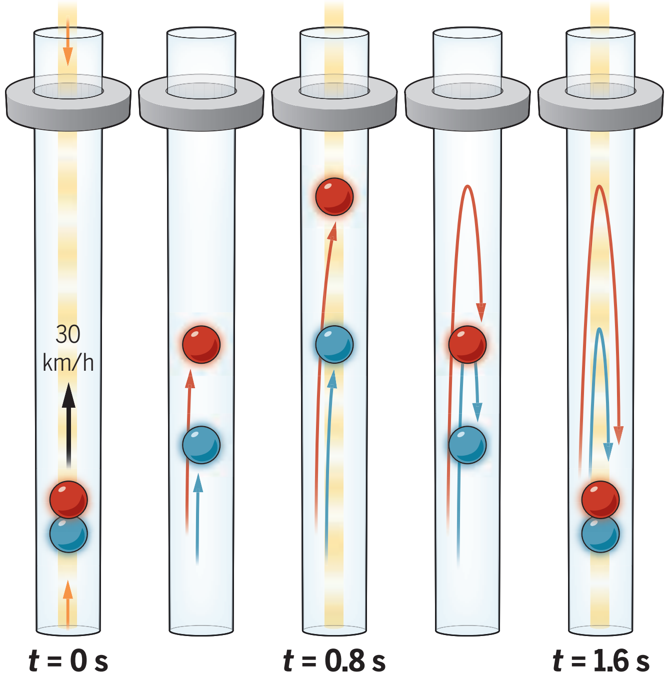
Overstreet *et al.*, *Science* **375**, 226–229 (2022) 14 January 2022

- Effect of spacetime curvature on a delocalized wave function.
- Proper-time time difference between the two atom interferometer arms.
- Gravitational analog of the scalar Aharonov-Bohm effect.

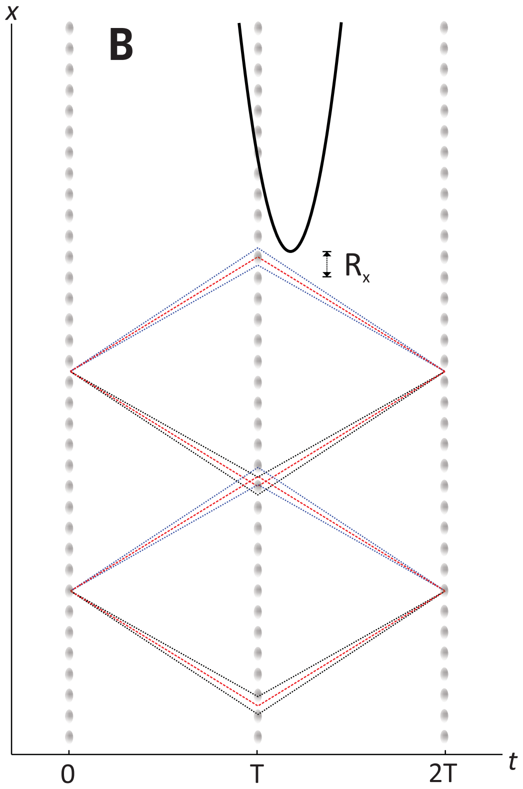
(ii) Spacetime curvature and proper-time difference



Stanford (USA)



lab frame



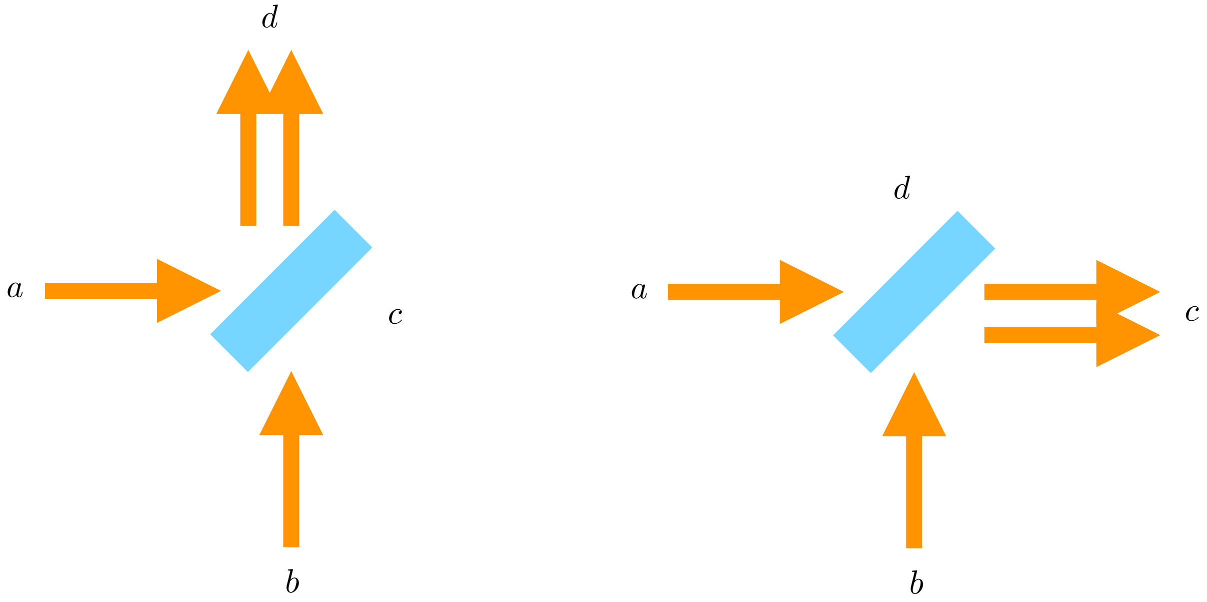
freely falling frame

(iii) Alternative: interferometry with quantum states of light

- Compared to state-of-the-art matter-wave interferometers, optical interferometers with quantum states of light offer the following appealing features:
  - Use of *relativistic* particles → quantum field theory
  - *Multiparticle entanglement* including external degrees of freedom.
  - *Multiparticle interference* with no classical analog.
  - Long baselines and large arm separations (up to hundreds of kilometers or more) → greater sensitivity to *spacetime curvature* effects.

Gravitational redshift measurement with two-photon interferometry

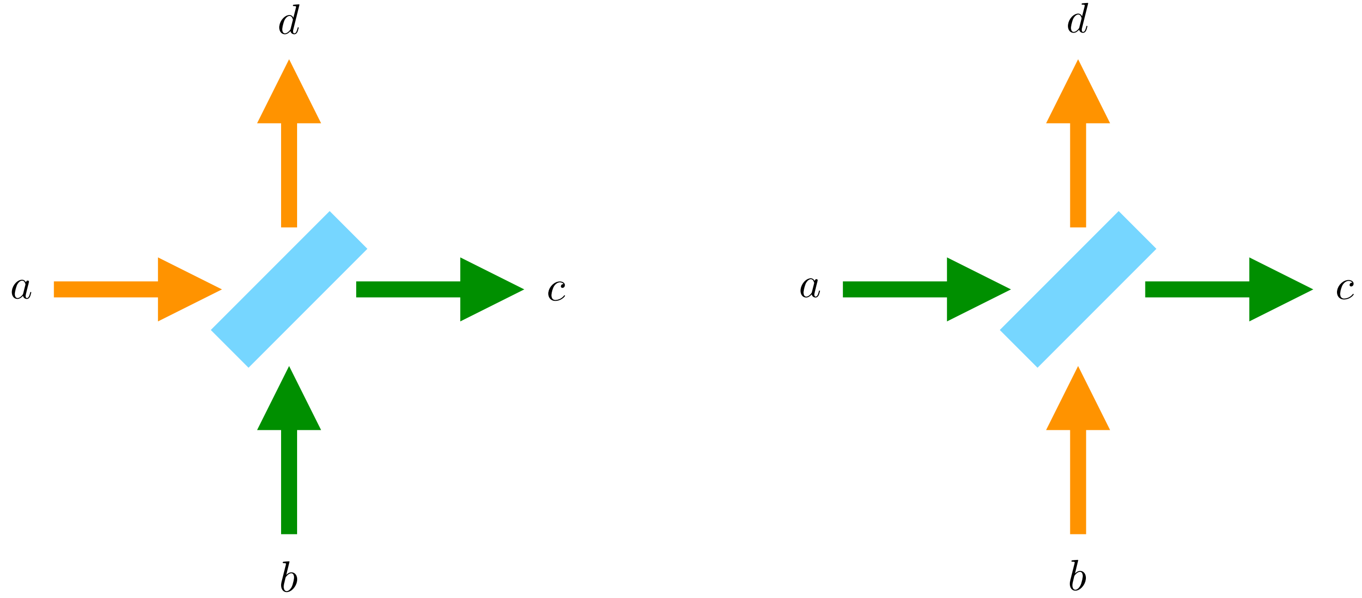
Hong-Ou-Mandel two-photon interference



- Destructive interference of the two possibilities for simultaneous single-photon detection at each port.

- Strong evidence of the quantization of the electromagnetic field.

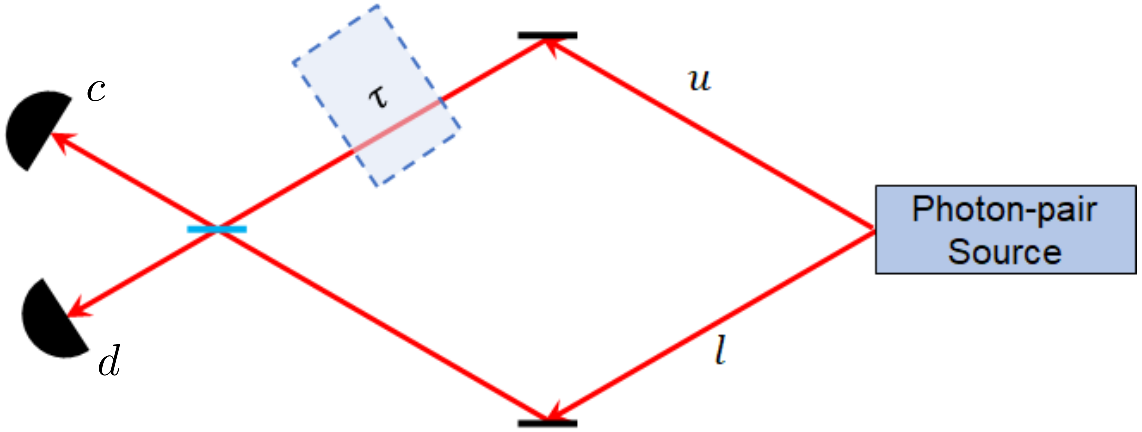
Frequency-entangled photon pair as input state



$$\frac{1}{\sqrt{2}}\Big(|\omega_1\rangle_a\,|\omega_2\rangle_b + e^{i\varphi}|\omega_2\rangle_a\,|\omega_1\rangle_b\Big) \longrightarrow \frac{1}{2}\Big(i^2|\omega_1\rangle_d\,|\omega_2\rangle_c + e^{i\varphi}|\omega_2\rangle_c\,|\omega_1\rangle_d\Big)$$

$$\boxed{P(c,d) = \frac{1}{4}\left(1 - \cos\varphi\right)}$$

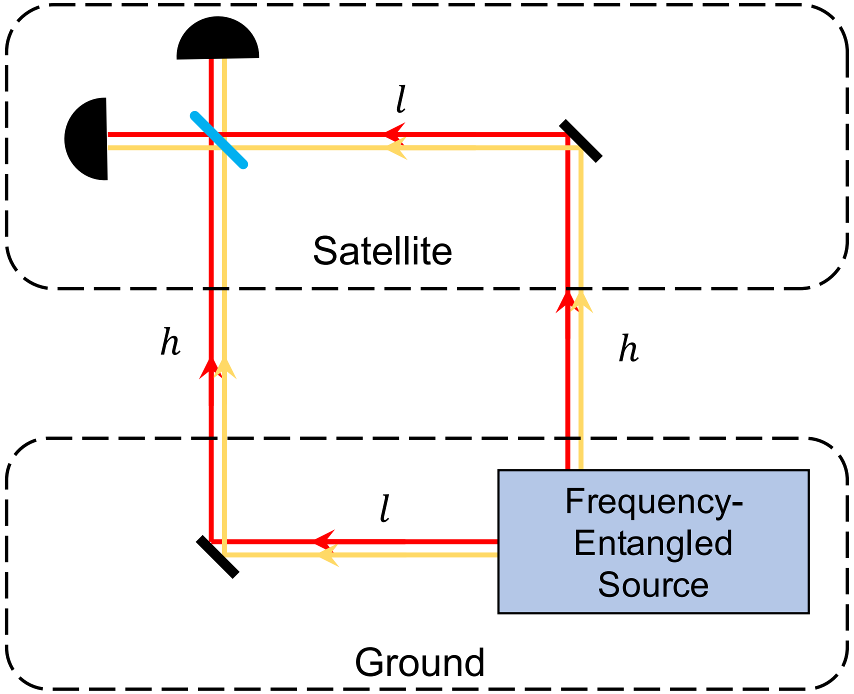
Two-photon interferometer with frequency-entangled pairs



$$\frac{1}{\sqrt{2}}\Big(|\omega_1\rangle_u|\omega_2\rangle_l + |\omega_2\rangle_u|\omega_1\rangle_l\Big) \longrightarrow \frac{1}{\sqrt{2}}\Big(e^{i\omega_1\tau}|\omega_1\rangle_u|\omega_2\rangle_l + e^{i\omega_2\tau}|\omega_2\rangle_u|\omega_1\rangle_l\Big)$$

$$\boxed{P(c,d) = 2 \times \frac{1}{4}\Big(1 - \cos(\omega_1 - \omega_2)\tau\Big)}$$

Gravitational redshift measurement

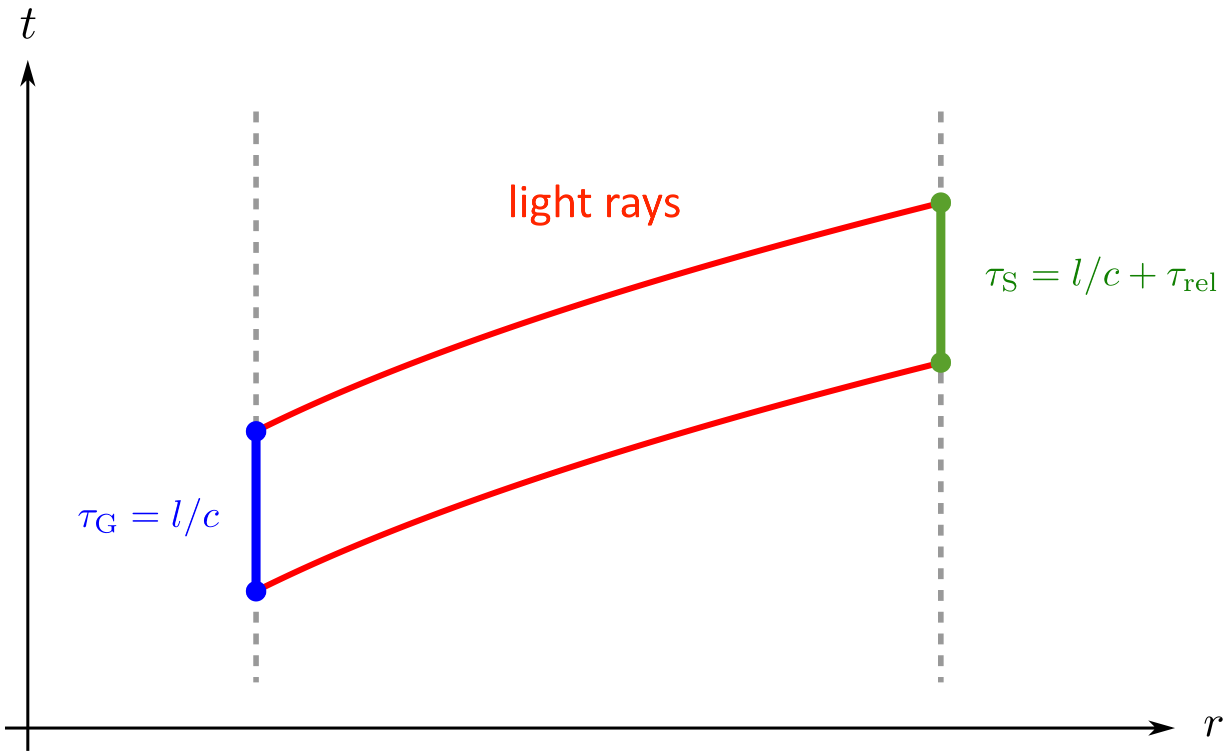


- Equal-length delay lines on Satellite and Ground station.
- Both calibrated and stabilized with identical frequency references.
- Different relativistic time dilation for both delay lines (special relativistic + gravitational).

Gravitational redshift

- Static spacetime with time translation invariance $t \rightarrow t + \Delta t$.
- Proper time spent in each delay line:

$$\tau_{\text{delay}} = l/c$$



$$\tau_{\mathrm{rel}} = \frac{l}{c}\left(\left(\frac{1-(\hat{\mathbf{n}}\cdot\mathbf{v}_{\mathrm{G}})(t_{\mathrm{r}})/c}{1-(\hat{\mathbf{n}}\cdot\mathbf{v}_{\mathrm{S}})(t_{\mathrm{r}})/c}\right)\left(\frac{dt/d\tau_{\mathrm{G}}}{dt/d\tau_{\mathrm{S}}}\right) - 1\right)$$

“classical” Doppler effect

$\sim 10^{-5}$

relativistic time dilation

$\sim 10^{-10}$

$$\left(\frac{dt/d\tau_{\mathrm{S}}}{dt/d\tau_{\mathrm{G}}}\right) \approx 1 + \left(\frac{1}{2}\frac{\mathbf{v}_{\mathrm{S}}^2 - \mathbf{v}_{\mathrm{G}}^2}{c^2} - \frac{U(\mathbf{x}_{\mathrm{S}}) - U(\mathbf{x}_{\mathrm{G}})}{c^2}\right)$$

special relativistic

$\sim 10^{-10}$

gravitational redshift

$\sim 10^{-10}$

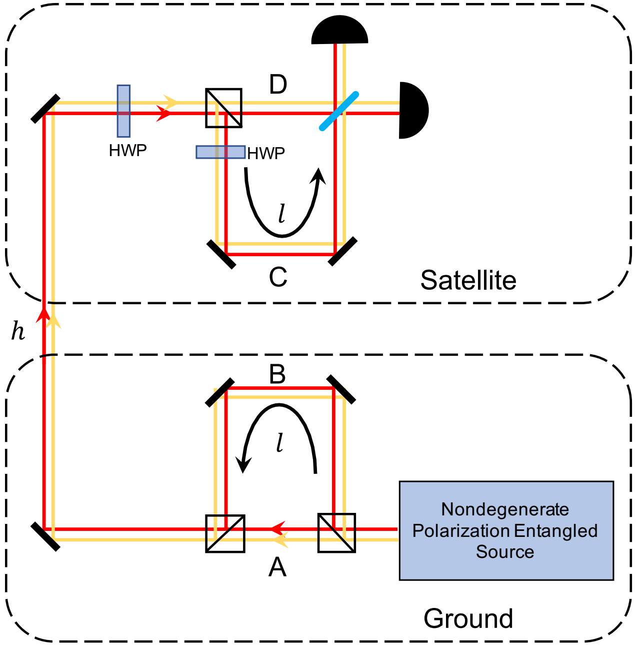
Quantitative estimates

Lunar Gateway → $\tau_{\mathrm{rel}} = 2.3 \times 10^{-15}\,\mathrm{s}\ (l/1\,\mathrm{km})$

$$\delta\varphi = (\omega_1 - \omega_2)\,\tau_{\mathrm{rel}} = 0.2\,\mathrm{rad} \times \left(\frac{\Delta\lambda}{100\,\mathrm{nm}}\right)\left(\frac{1600\,\mathrm{nm}}{\lambda_2}\right)\left(\frac{1500\,\mathrm{nm}}{\lambda_1}\right)\left(\frac{l}{1\,\mathrm{km}}\right)$$

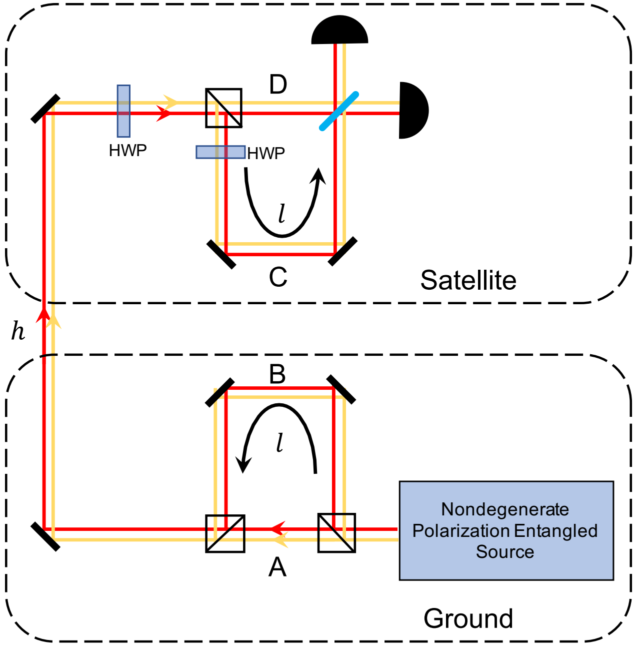
	gravitational redshift	special relativistic
Lunar Gateway	7×10^{-10}	smaller
GEO spacecraft	6×10^{-10}	smaller
LEO spacecraft	4×10^{-11}	-3×10^{-10}

Single-uplink configuration



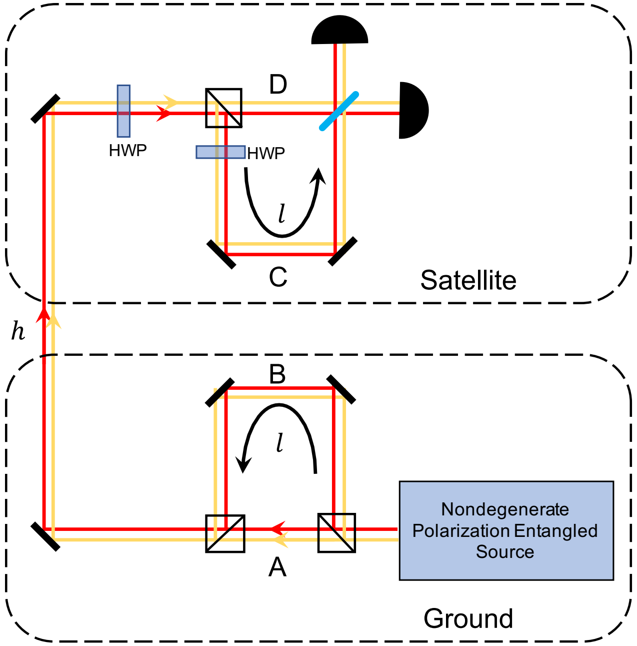
$$|\Psi_0\rangle = \frac{1}{\sqrt{2}}\Big(|\omega_1, H\rangle\,|\omega_2, V\rangle - |\omega_1, V\rangle\,|\omega_2, H\rangle\Big)$$

Single-uplink configuration



$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(e^{i\omega_2\tau_{\mathrm{rel}}}|\omega_1, H\rangle_{BD}\,|\omega_2, V\rangle_{AC} - e^{i\omega_1\tau_{\mathrm{rel}}}|\omega_2, H\rangle_{BD}\,|\omega_1, V\rangle_{AC}\right)$$

Single-uplink configuration



$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(e^{i\omega_2\tau_{\rm rel}}|\omega_1\rangle_{BD}\,|\omega_2\rangle_{AC} - e^{i\omega_1\tau_{\rm rel}}|\omega_2\rangle_{BD}\,|\omega_1\rangle_{AC}\right)\otimes|H\rangle_{BD}\,|H\rangle_{AC}$$

Mohageg et al. *EPJ Quantum Technology* (2022) 9:25
https://doi.org/10.1140/epjqt/s40507-022-00143-0

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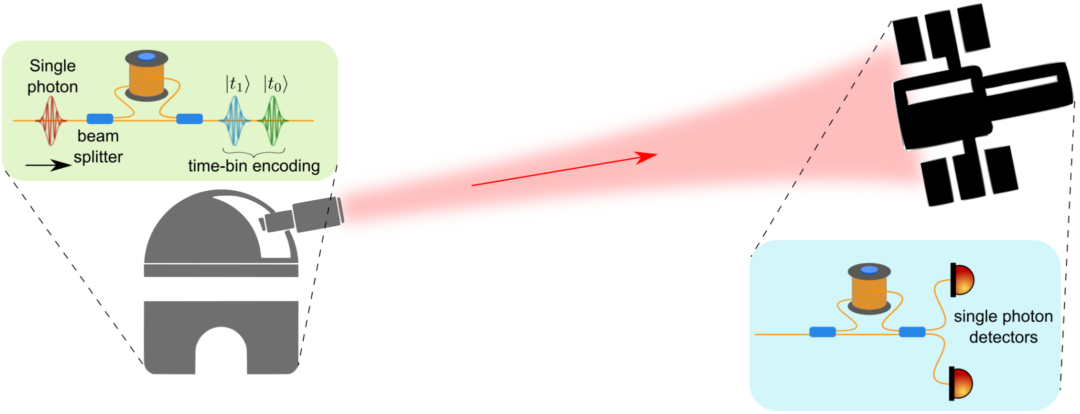
EPJ Quantum Technology
a SpringerOpen Journal

REVIEW **Open Access**

The deep space quantum link: prospective fundamental physics experiments using long-baseline quantum optics

Makan Mohageg[1*], Luca Mazzarella[1], Charis Anastopoulos[2], Jason Gallicchio[3], Bei-Lok Hu[4], Thomas Jennewein[5], Spencer Johnson[6], Shih-Yuin Lin[7], Alexander Ling[8], Christoph Marquardt[9], Matthias Meister[10], Raymond Newell[11], Albert Roura[10], Wolfgang P. Schleich[10,12,13], Christian Schubert[14,15], Dmitry V. Strekalov[1], Giuseppe Vallone[16,17,18], Paolo Villoresi[16,17], Lisa Wörner[10], Nan Yu[1], Aileen Zhai[1] and Paul Kwiat[2*]

- Part of a study by the Science Definition Team for a future space mission.

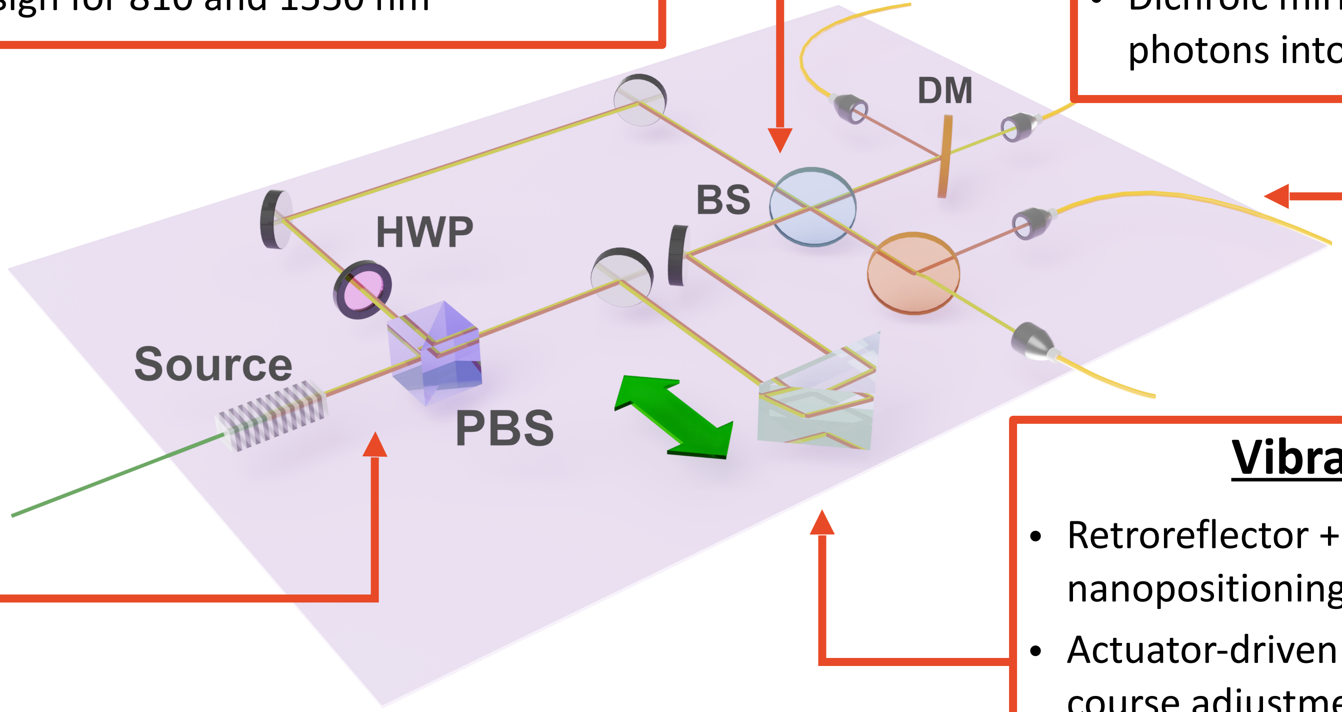


- Recognized with a *NASA Group Achievement Award*.

- Ground-based demonstration experiments in collaboration with
  - Spencer Johnson, Paul Kwiat (University of Illinois Urbana-Champaign)
  - Alex Lohrmann, Makan Mohageg (Jet Propulsion Laboratory)

Experiments in Paul Kwiat’s group (UIUC)

Photon wavelengths of 810 and 1550 nm



Interfering Beamsplitter (BS) & Optics

- Dual-band design for 810 and 1550 nm

Photon Detection

- Superconducting nanowire detectors
- Dichroic mirrors (DM) direct photons into appropriate detectors

Entanglement Generation

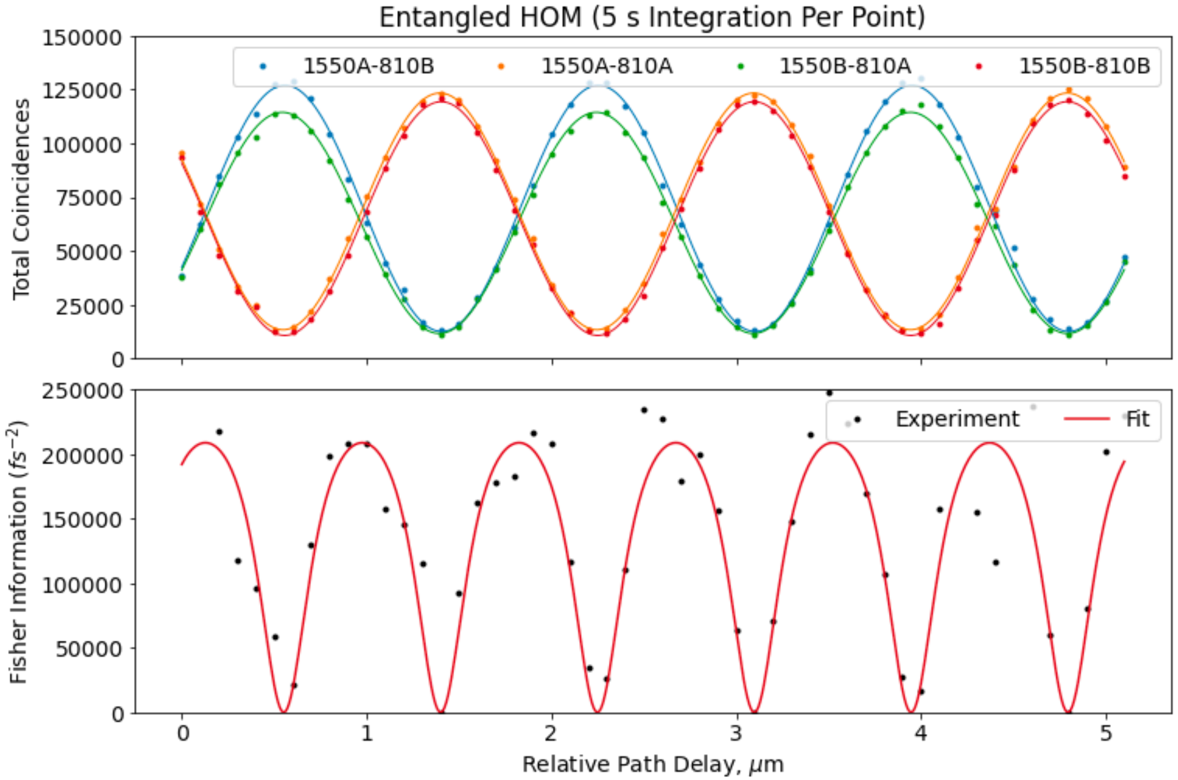
- Source generates non-degenerate polarization entanglement
- Convert to frequency entanglement via polarizing beamsplitter (PBS) and halfwave plate (HWP)

Vibrating Target

- Retroreflector + piezoelectric nanopositioning stage (1-nm resolution)
- Actuator-driven translation stage for course adjustment and path-matching

Recent results for frequency-entangled two-photon interference

Entangled photons at 810 and 1550 nm



System Resolutions

~ 50k photon pairs every second

Current Experiment (fit): **0.7 nm (2.2 attoseconds)**

Theoretical best (with perfect entangled state and optics): **0.6 nm (1.9 attoseconds)**

- Corresponding delay lines capable of resolving the gravitational redshift:
  - Lunar Gateway ⟶ $l > 1\ \mathrm{m}$
  - LEO ⟶ $l > 18\ \mathrm{m}$

Conclusions

- Quantum interferometric measurement of general relativistic time dilation with no classical analog (two-photon interference, entanglement).

- Experimental test of quantum field theory in curved space time.

- Need to suppress the Doppler-shift contribution:
  - satellite laser ranging and post-correction,
  - alternatively, use of a “classical light” beacon as a distributed phase reference.

- For highly elliptical orbits, orbital modulation can be exploited to extract the signal.

Thank you for your attention.

Gefördert durch:

Bundesministerium
für Wirtschaft
und Energie

aufgrund eines Beschlusses
des Deutschen Bundestages

HORIZON 2020

Q-SENSE
European Union H2020 RISE Project

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Deutsches Zentrum
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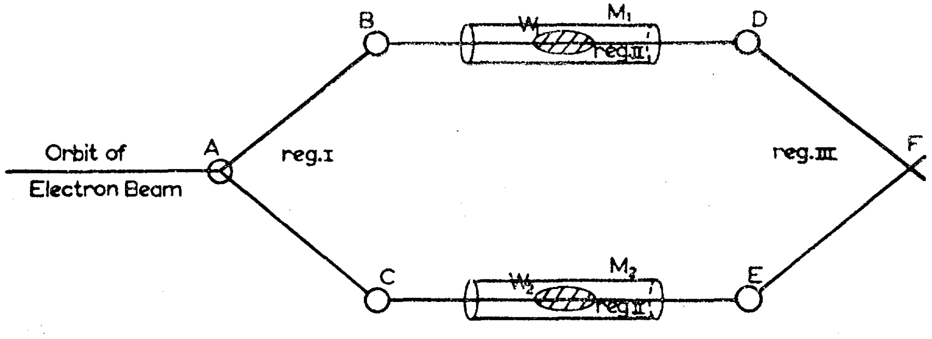
German Aerospace Center

Project Q-GRAV

Scalar Aharonov-Bohm effect

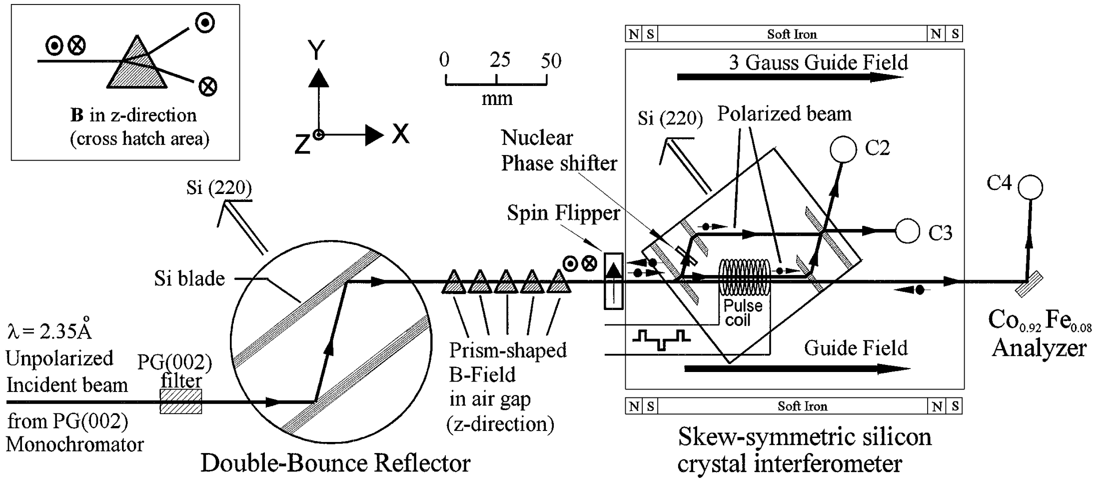
Aharonov & Bohm, Phys. Rev. 115, 485 (1959)

Lee, Motrunich, Allman & Werner, Phys. Rev. Lett. 80, 3165 (1998)



charged particle in a homogeneous electric potential

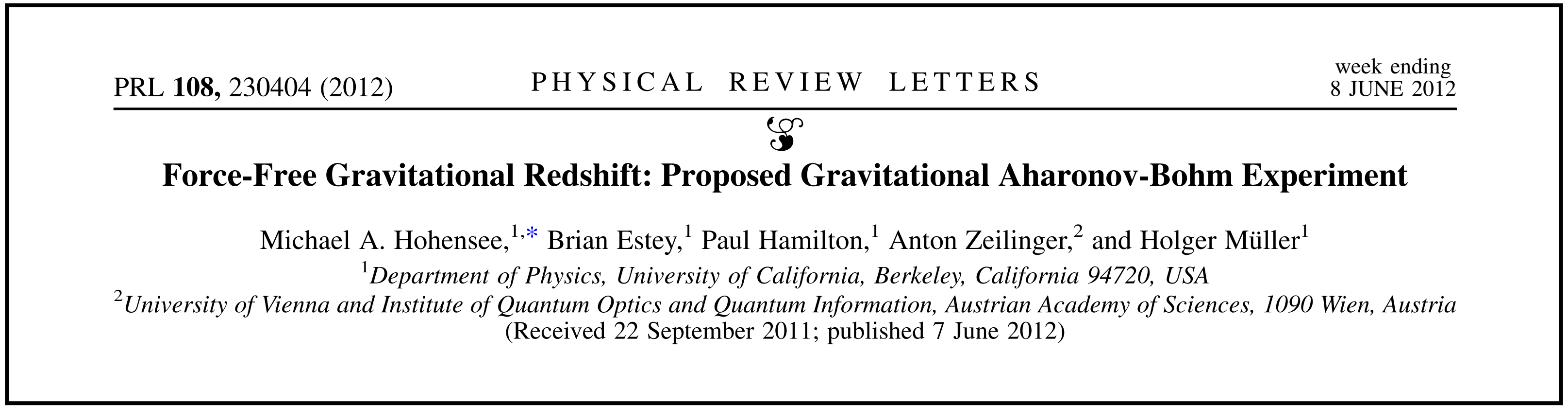
$qV(t)$



experimental realization with neutron interferometry (magnetic dipole in a homogeneous magnetic field)

$\vec{\mu} \cdot \vec{B}(t)$

Proposal for a gravitational version



PRL **108,** 230404 (2012) PHYSICAL REVIEW LETTERS week ending 8 JUNE 2012

Force-Free Gravitational Redshift: Proposed Gravitational Aharonov-Bohm Experiment

Michael A. Hohensee,[1,*] Brian Estey,[1] Paul Hamilton,[1] Anton Zeilinger,[2] and Holger Müller[1]
[1] *Department of Physics, University of California, Berkeley, California 94720, USA*
[2] *University of Vienna and Institute of Quantum Optics and Quantum Information, Austrian Academy of Sciences, 1090 Wien, Austria*

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