Probing gravity with quantum systems

Albert Roura

Institute of Quantum Technologies (Ulm)

DLR Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Search for new physics

- Limitations of particle colliders.

- Alternative probes of *physics beyond the SM* & the *interplay between gravity and quantum mechanics*:
  - cosmology, early universe (indirectly)
  - precision measurements (e.g. eEDM, tests of the equivalence principle)
  - interplay between gravity & QM: quantum test particle / quantum source

- Tools for precision measurements: atomic quantum sensors
  such as atomic clocks and atom interferometers
  (e.g. most accurate measurements of the fine-structure constant)

Outline

1. Tools for precision measurements: atomic clocks & atom interferometers

2. Gravitational measurements for fundamental physics

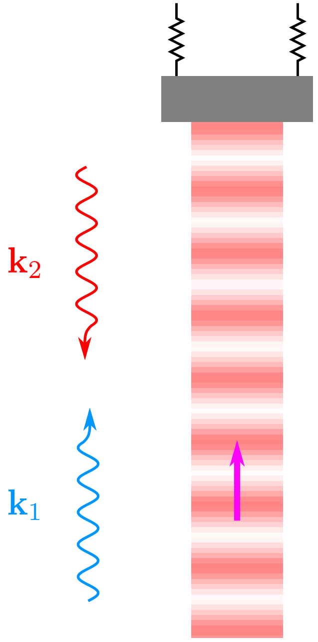
3. General relativistic effects in the quantum regime
   - Quantum-clock interferometry
   - Spacetime curvature and proper-time difference
   - Two-photon interferometry with frequency-entangled pairs

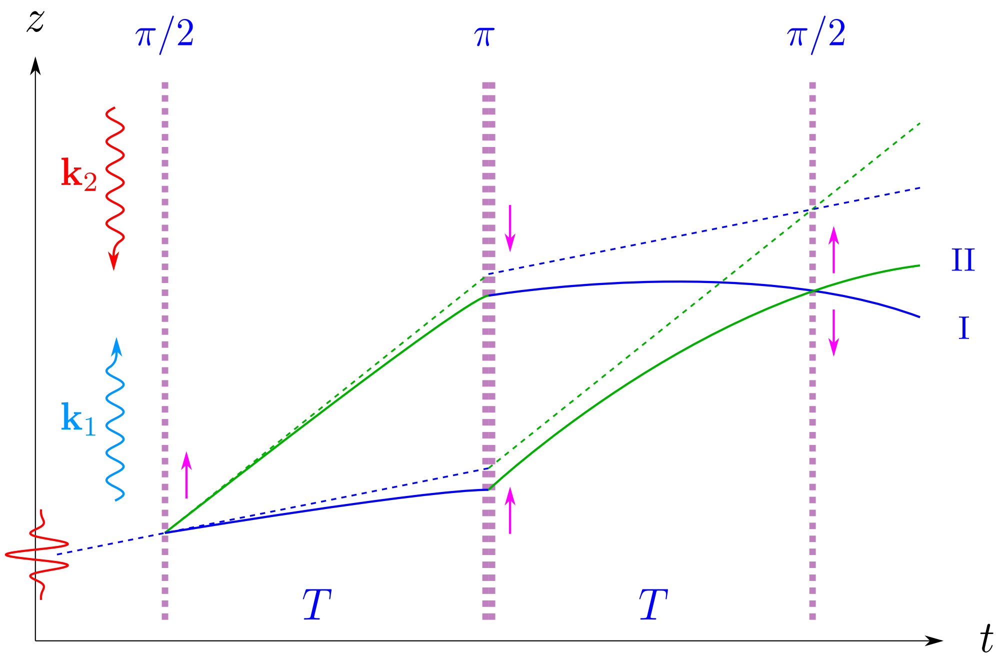
4. Conclusions

Scalar Aharonov-Bohm effect …

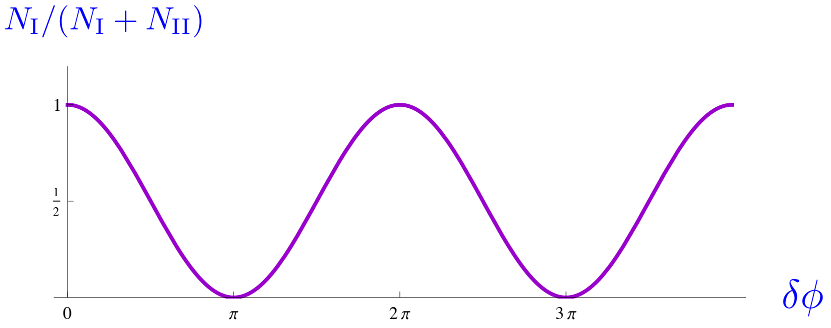
Tools for precision measurements:
atomic clocks & atom interferometers

Atom interferometers as accelerometers





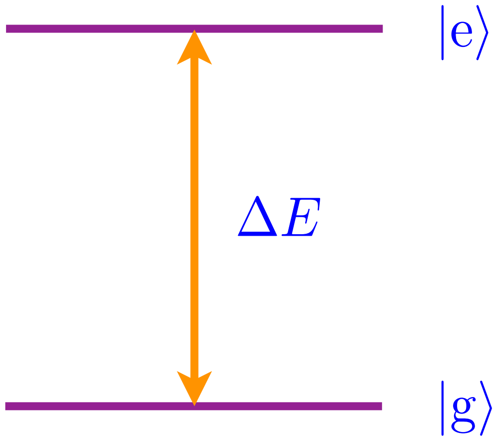
$$\mathbf{k}_{\text{eff}} = \mathbf{k}_1 - \mathbf{k}_2$$



$$\delta\phi = -\,k_{\text{eff}}\; g\, T^2$$

Two-level atom as a quantum clock

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



- *Initialization* pulse:

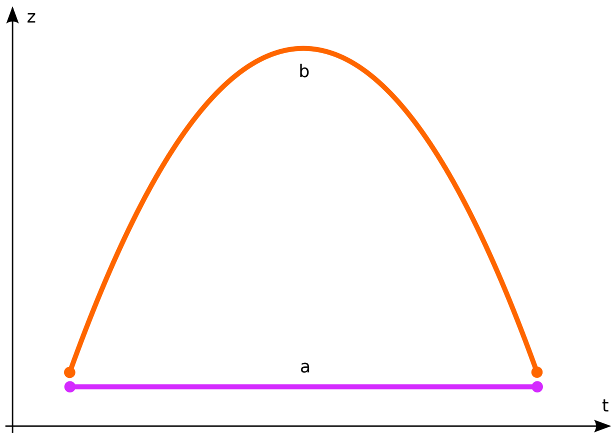
$$|\mathrm{g}\rangle \;\rightarrow\; \big|\Phi(0)\big\rangle = \frac{1}{\sqrt{2}}\Big(|\mathrm{g}\rangle + i\, e^{i\varphi}|\mathrm{e}\rangle\Big)$$

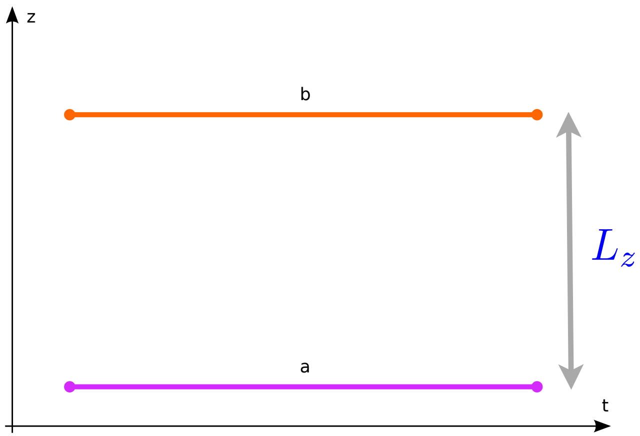
- Evolution:

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

Two-level atom as a quantum clock

- Comparison of independent clocks (after read-out pulse):





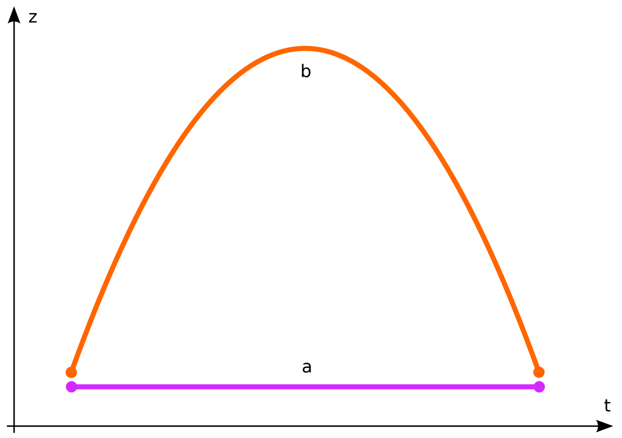
for optical *atomic clocks*

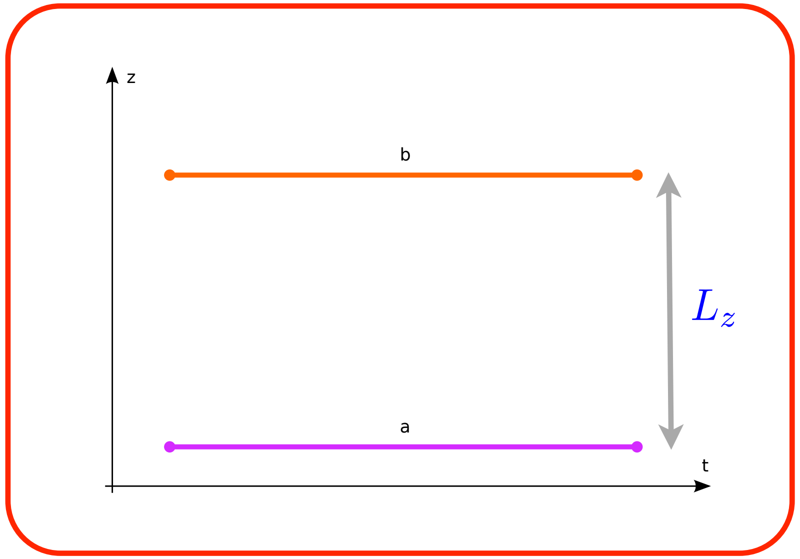
$\Delta E \sim 1\,\mathrm{eV} \qquad L_z \sim 1\,\mathrm{cm}$

$$\Delta\tau_b - \Delta\tau_a \approx \left(g\,L_z/c^2\right)\Delta t$$

Two-level atom as a quantum clock

- Comparison of independent clocks (after read-out pulse):





for optical *atomic clocks*

$\Delta E \sim 1\,\mathrm{eV}$ $L_z \sim 1\,\mathrm{cm}$

$$\Delta\tau_b - \Delta\tau_a \approx \left(g\,L_z/c^2\right)\Delta t$$

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:

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

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:

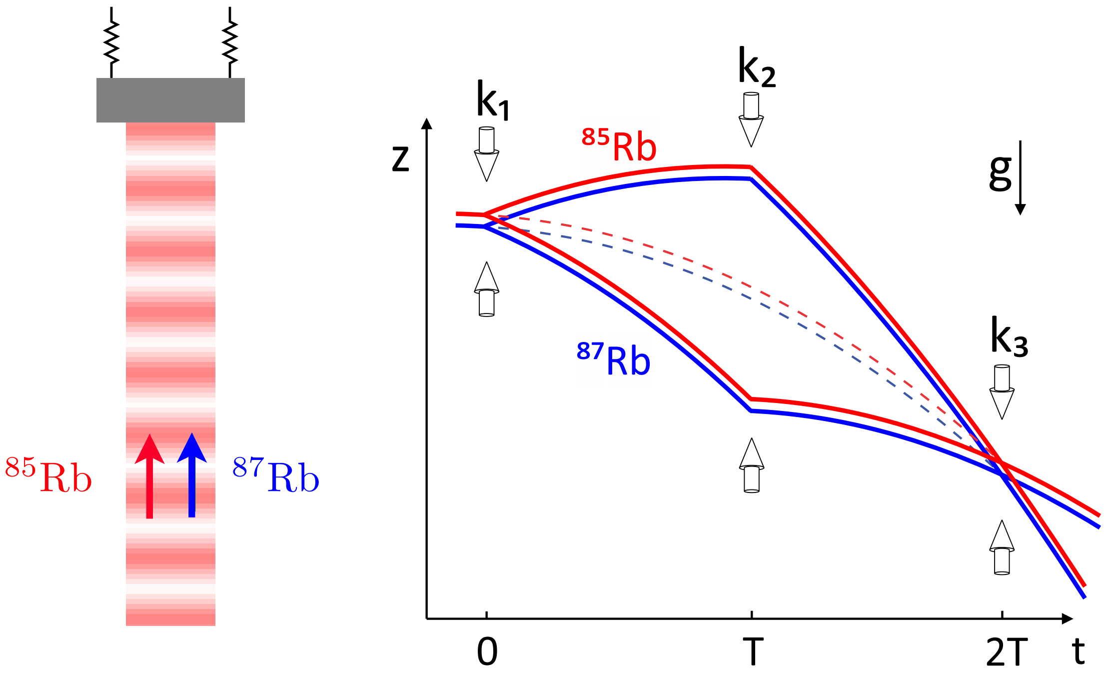
$$S_n\big[x^\mu(\lambda)\big] = -m_n c^2 \int d\tau - \int d\tau\, V_n(x^\mu) \qquad (n = 1, 2)$$

including external forces

Gravitational measurements for fundamental physics

Equivalence principle tests and gravitational constant

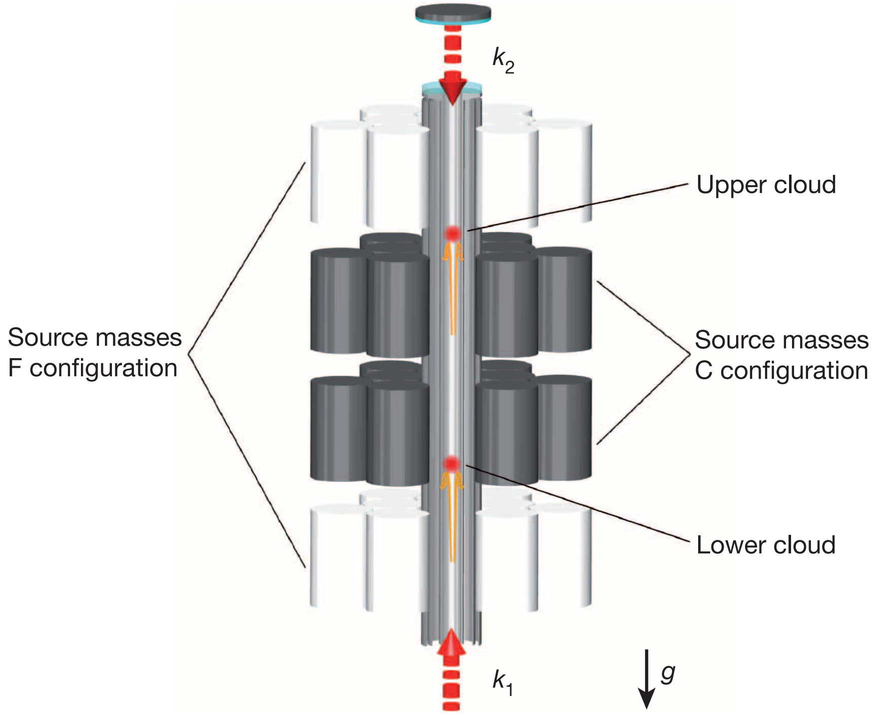
Asenbaum et al., Phys. Rev. Lett. 125, 191101 (2020)



Test of universality of free fall (UFF)

$$\eta_{AB} = 2\,\frac{|g_A - g_B|}{g_A + g_B} \lesssim 10^{-12}$$

Rosi et al., Nature 510, 518 (2014)



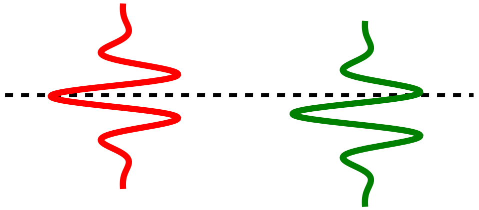
gravitational constant G

$$\Delta G/G = 1.5 \times 10^{-4}$$

Major challenges posed by gravity gradients

- Systematics associated with initial central position & momentum of the two atomic species can mimic a violation of UFF:

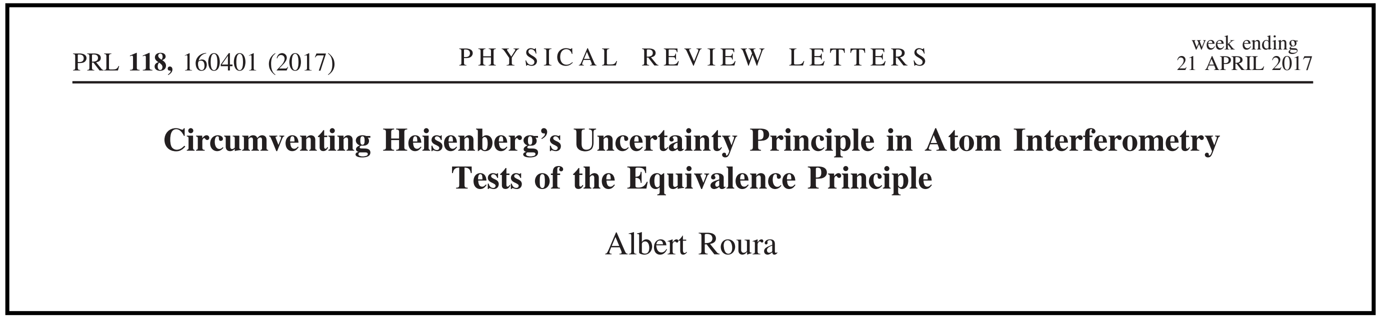
$$\Delta g \sim \Gamma_{zz}\, \Delta z_0 + \Gamma_{zz}\, \Delta v_0\, T \qquad \Gamma_{zz} = -\,\partial^2 U/\partial z^2 \;\approx\; 3 \times 10^{-6}\, \mathrm{s}^2$$



$$\frac{\Delta g}{g} \lesssim 10^{-15} \;\longrightarrow\; \begin{array}{l} \Delta z_0 \lesssim 1\,\mathrm{nm} \\ \Delta v_0 \lesssim 10^2\,\mathrm{pm/s} \end{array}$$

- Such sensitivity to initial conditions due to gravity gradients is one of the main systematic effects in most precision measurements based on atom interferometry.

Major challenges posed by gravity gradients


PRL **118,** 160401 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

Circumventing Heisenberg's Uncertainty Principle in Atom Interferometry Tests of the Equivalence Principle

Albert Roura

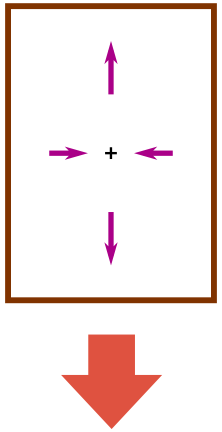
- Tidal forces lead to an open interferometer:

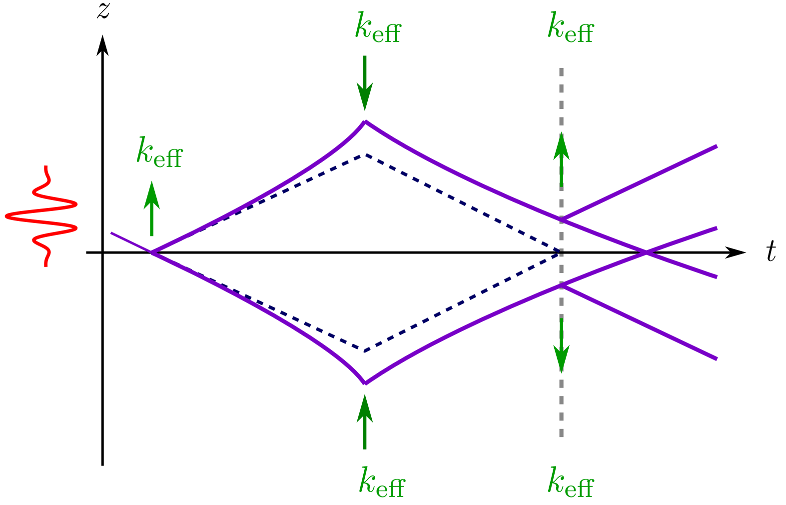
$$\delta z = \left(\Gamma_{zz}\, T^2\right) v_{\text{rec}}\, T$$

$$\delta p = \left(\Gamma_{zz}\, T^2\right) m\, v_{\text{rec}}$$

- Sensitivity to initial conditions directly related to such relative displacement between the two interfering wave packets at each exit port.

freely falling frame
(Einstein elevator)





Major challenges posed by gravity gradients

PRL **118,** 160401 (2017) PHYSICAL REVIEW LETTERS week ending 21 APRIL 2017

Circumventing Heisenberg's Uncertainty Principle in Atom Interferometry Tests of the Equivalence Principle

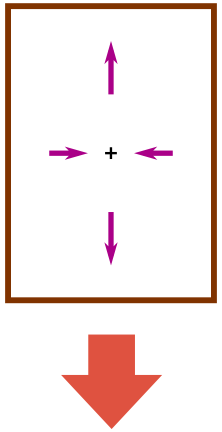
Albert Roura

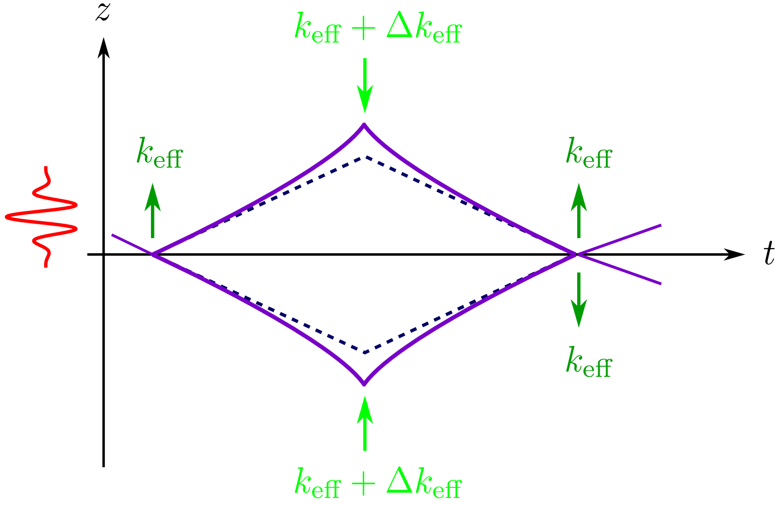
- Suitable frequency change of central pulse

$$\Delta k_{\mathrm{eff}} = \left(\Gamma_{zz}\, T^2/2\right) k_{\mathrm{eff}}$$

leads to closed interferometer and removes sensitivity to initial conditions.

freely falling frame
(Einstein elevator)





General relativistic effects in the quantum regime

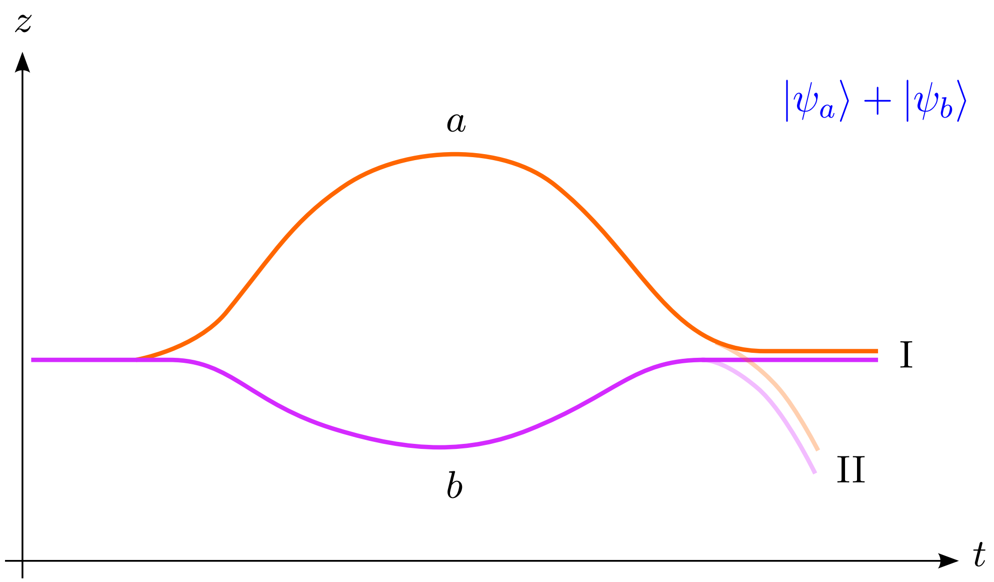
(i) Quantum-clock interferometry

- Quantum particle with internal degrees of freedom acting as a clock.
- Difference of proper time along the two interferometer arms → effect on the interference signal
- However, light-pulse atom interferometers in a uniform gravitational field → *insensitive* to gravitational time dilation.

  (easily seen in the freely falling frame)

Sinha & Samuel, Class. Quantum Grav. 28, 145018 (2011)

Zych et al., Nat. Commun. 2, 505 (2011)



(i) Quantum-clock interferometry

- Quantum particle with internal degrees of freedom acting as a clock.
- Difference of proper time along the two interferometer arms ⟶ effect on the interference signal
- However, light-pulse atom interferometers in a uniform gravitational field ⟶ *insensitive* to gravitational time dilation.

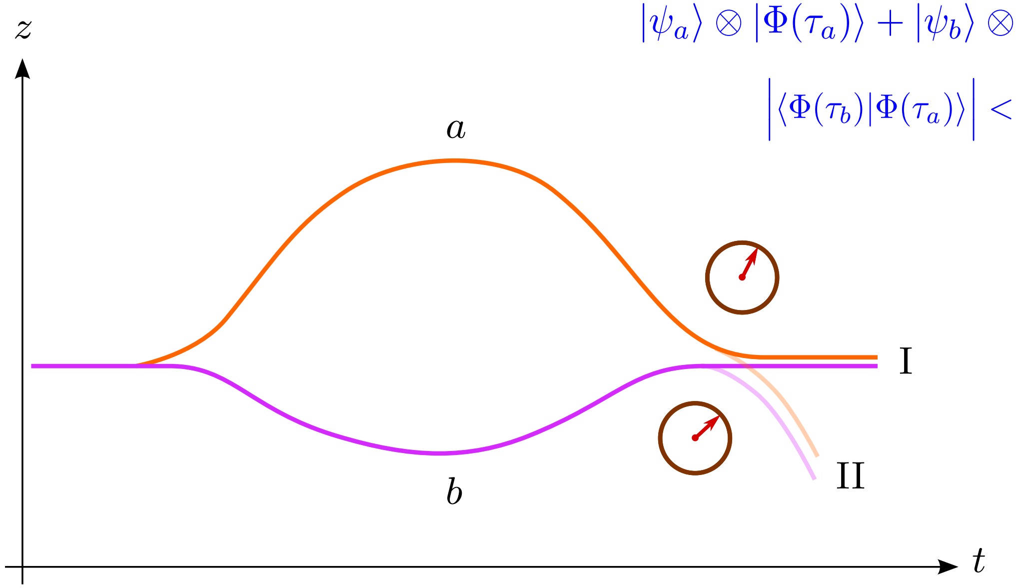
  (easily seen in the freely falling frame)

Sinha & Samuel, Class. Quantum Grav. 28, 145018 (2011)

Zych et al., Nat. Commun. 2, 505 (2011)

$$|\psi_a\rangle \otimes |\Phi(\tau_a)\rangle + |\psi_b\rangle \otimes |\Phi(\tau_b)\rangle$$

$$\big|\langle\Phi(\tau_b)|\Phi(\tau_a)\rangle\big| < 1$$



(i) Quantum-clock interferometry

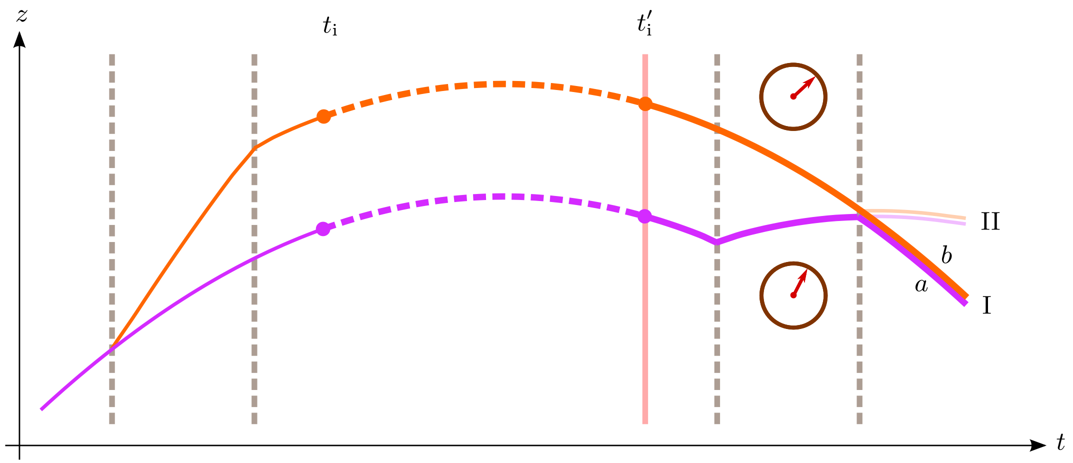
PHYSICAL REVIEW X **10,** 021014 (2020)

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



(i) Quantum-clock interferometry

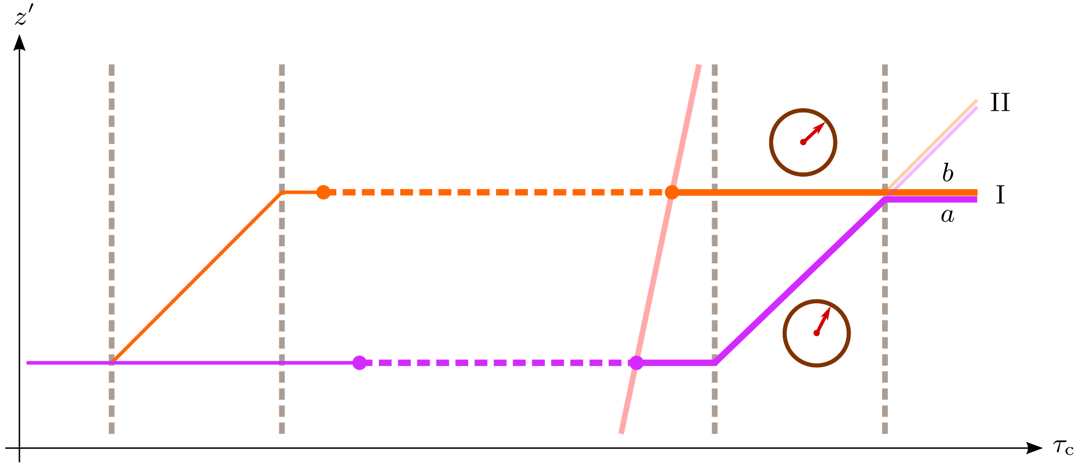
PHYSICAL REVIEW X **10,** 021014 (2020)

Gravitational Redshift in Quantum-Clock Interferometry

Albert Roura

Quantum superposition of a single clock at two different heights

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

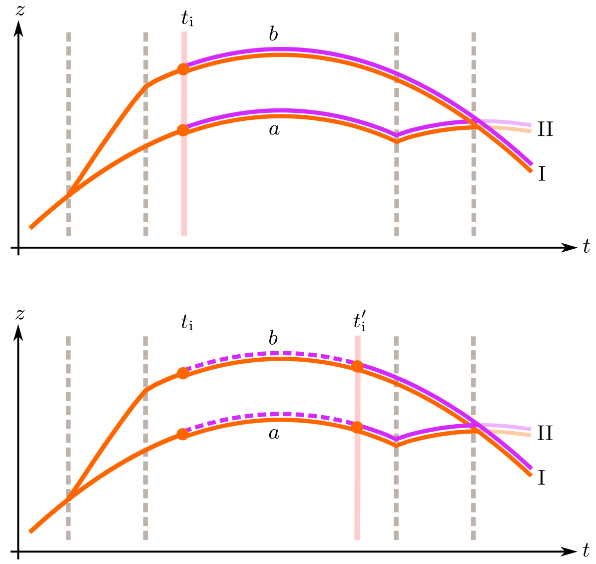


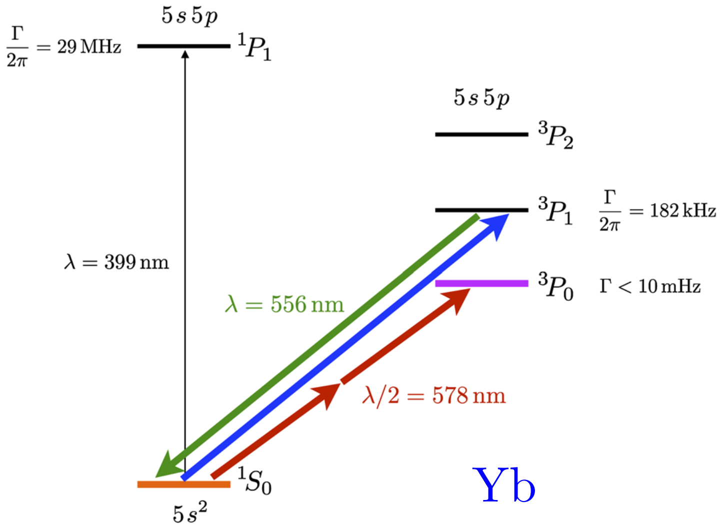
(i) Quantum-clock interferometry

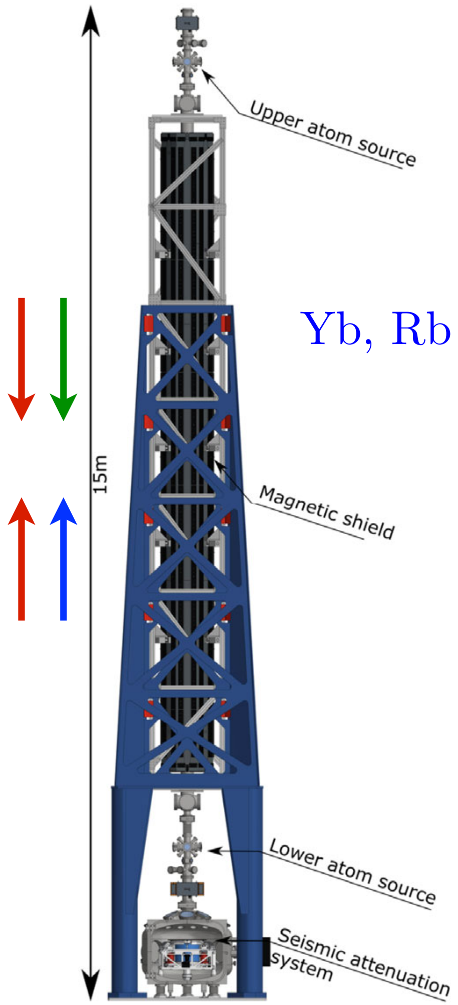
PHYSICAL REVIEW D **104,** 084001 (2021)

Measuring gravitational time dilation with delocalized quantum superpositions

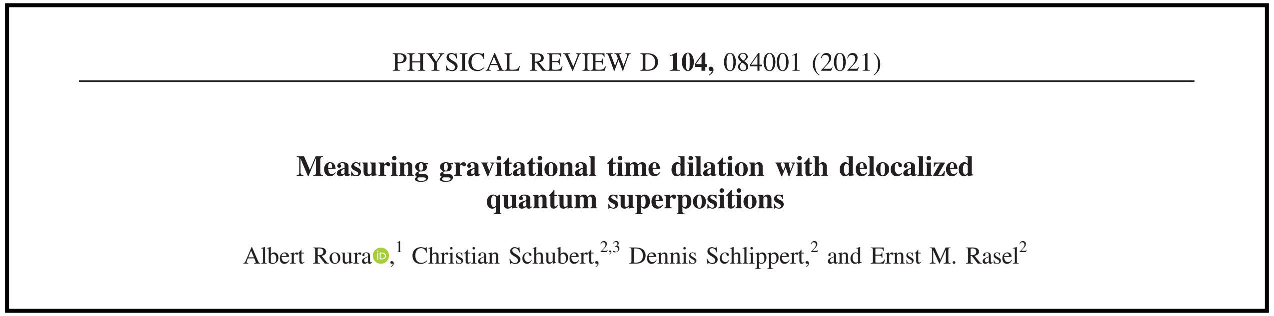
Albert Roura,[1] Christian Schubert,[2,3] Dennis Schlippert,[2] and Ernst M. Rasel[2]





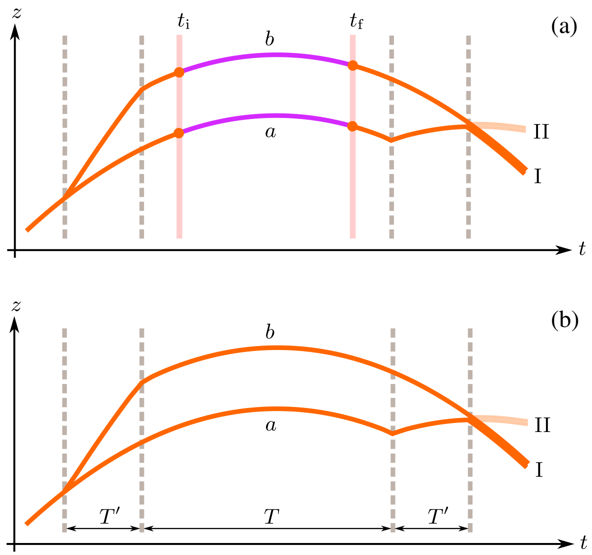


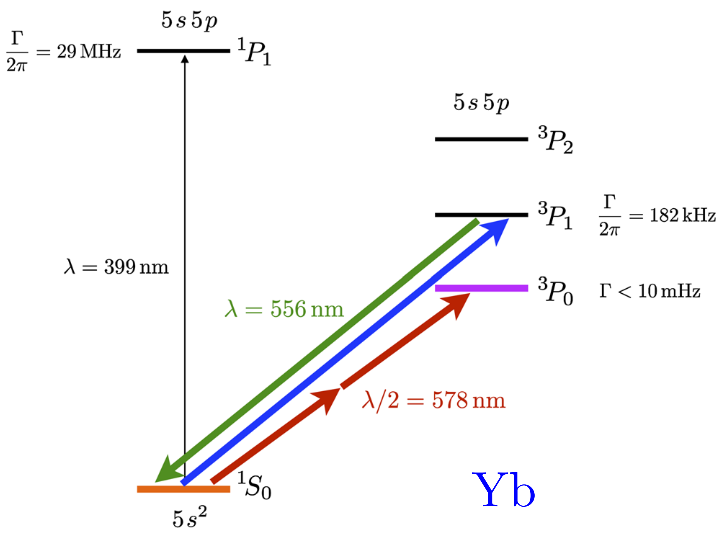
(i) Quantum-clock interferometry

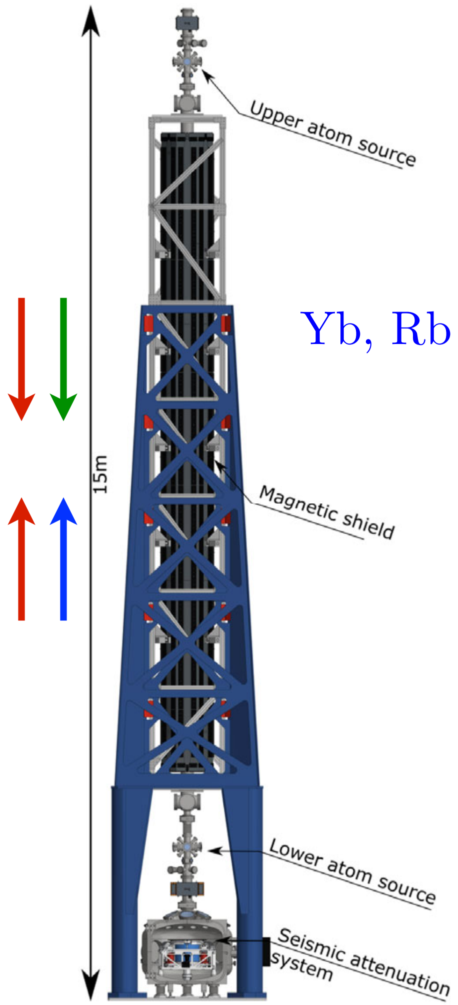

PHYSICAL REVIEW D **104,** 084001 (2021)

Measuring gravitational time dilation with delocalized quantum superpositions

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







(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

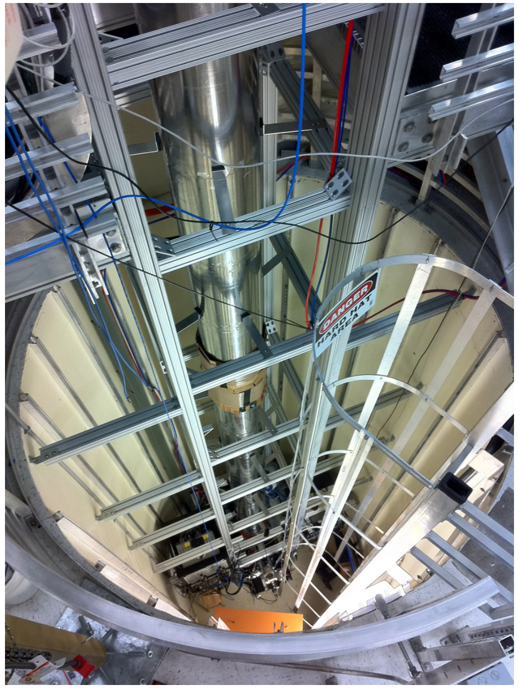
Chris Overstreet[1]†, Peter Asenbaum[1,2]†, Joseph Curti[1], Minjeong Kim[1], Mark A. Kasevich[1]*

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

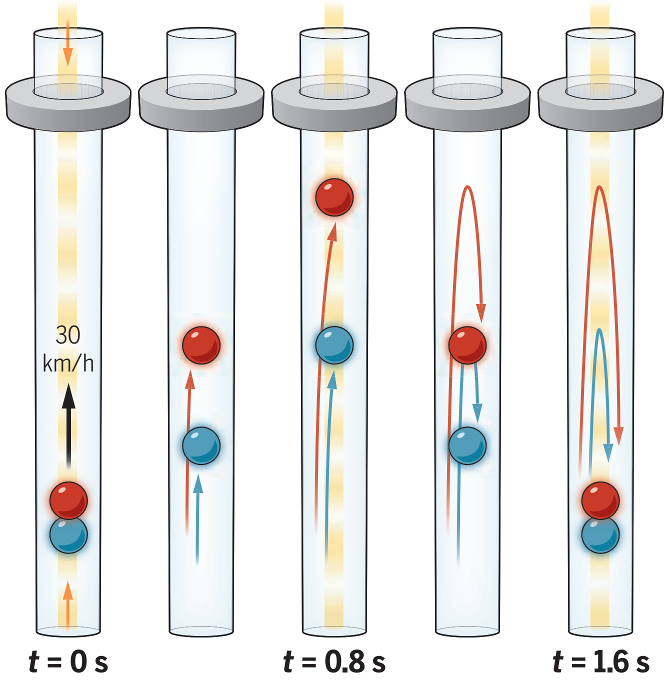
- Effect of spacetime curvature on a delocalized wave function.
- Proper-time time difference between the two interferometer arms.
- Gravitational analog of the scalar Aharonov-Bohm effect.

DLR

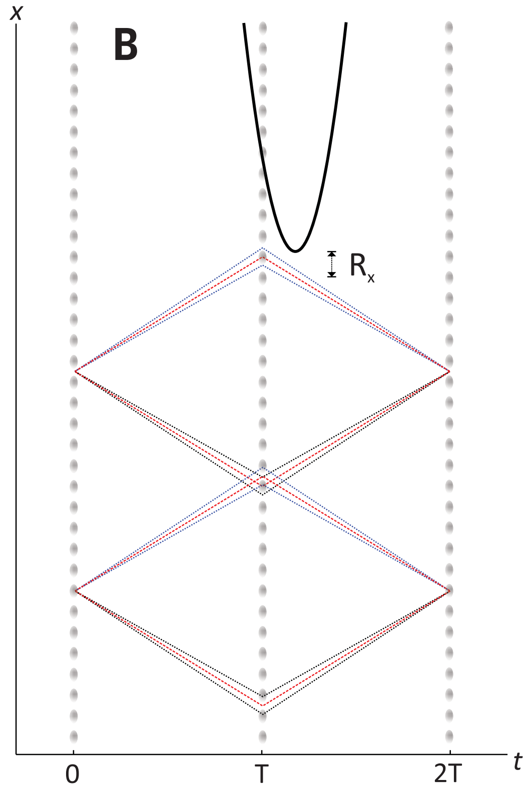
(ii) Spacetime curvature and proper-time difference



Stanford (USA)



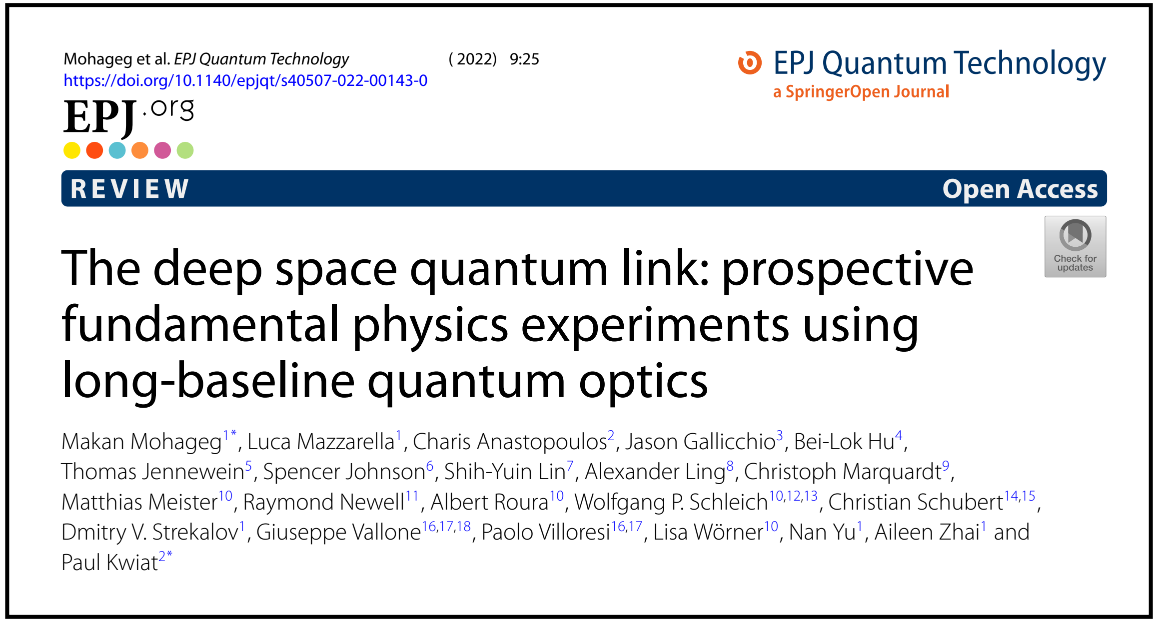
lab frame



freely falling frame

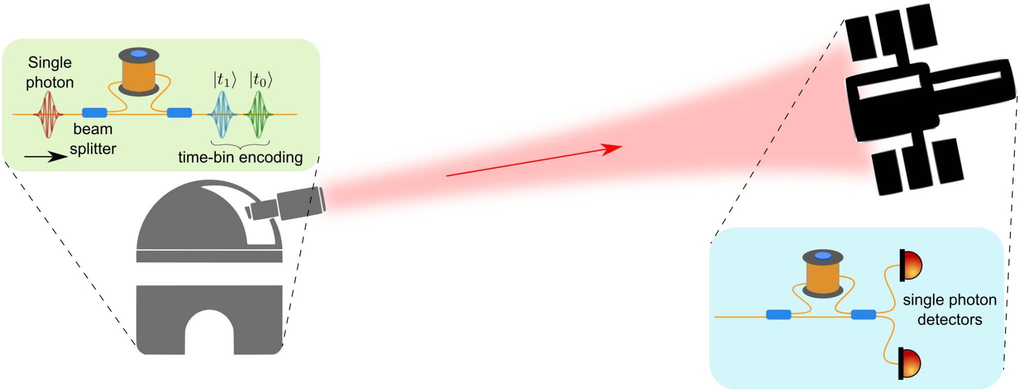
DLR

(iii) Two-photon interferometry with frequency-entangled pairs


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

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

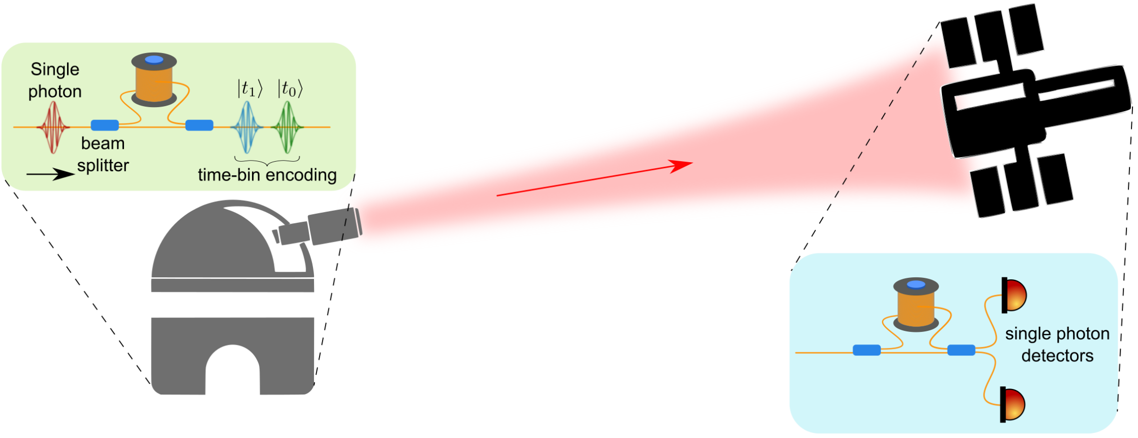
Makan Mohageg[1*], Luca Mazzarella[1], Charis Anastopoulos[2], Jason Gallicchio[3], Bei-Lok Hu[4], Thomas Jennewein[5], Spencer Johnson[6], Shih-Yuin Lin[7], Alexander Ling[8], Christoph Marquardt[9], Matthias Meister[10], Raymond Newell[11], Albert Roura[10], Wolfgang P. Schleich[10,12,13], Christian 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*]

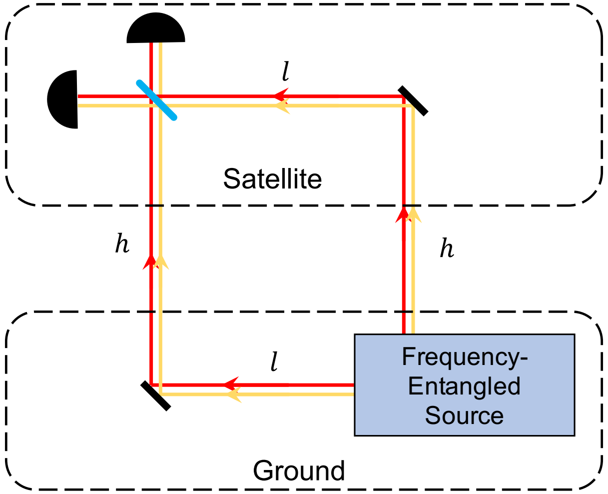


- Two-photon interference (similar to Hong-Ou-Mandel) with frequency-entangled pairs.
- Genuinely quantum interferometer with no classical analog.

(iii) Two-photon interferometry with frequency-entangled pairs

- Identically calibrated optical delay lines in spacecraft and ground station.
- Sensitive to the gravitational redshift.

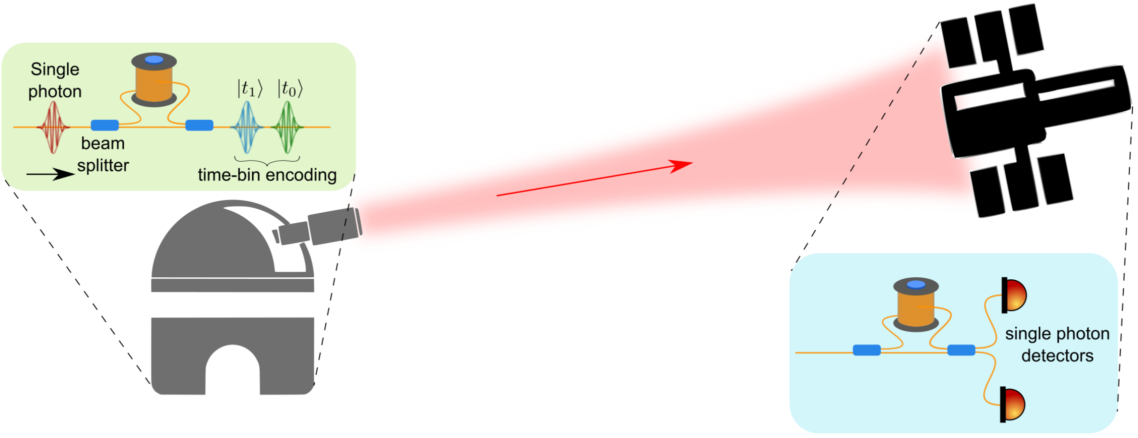


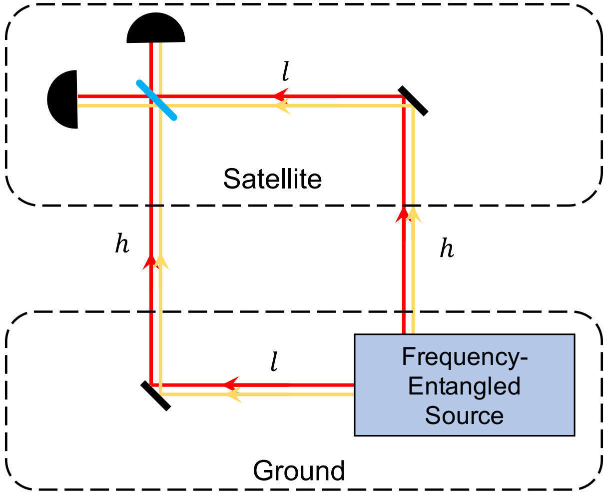


$$\frac{1}{\sqrt{2}}\left(|\omega_1\rangle_a + e^{i\varphi}|\omega_1\rangle_b\right)$$

(iii) Two-photon interferometry with frequency-entangled pairs

- Identically calibrated optical delay lines in spacecraft and ground station.
- Sensitive to the gravitational redshift.

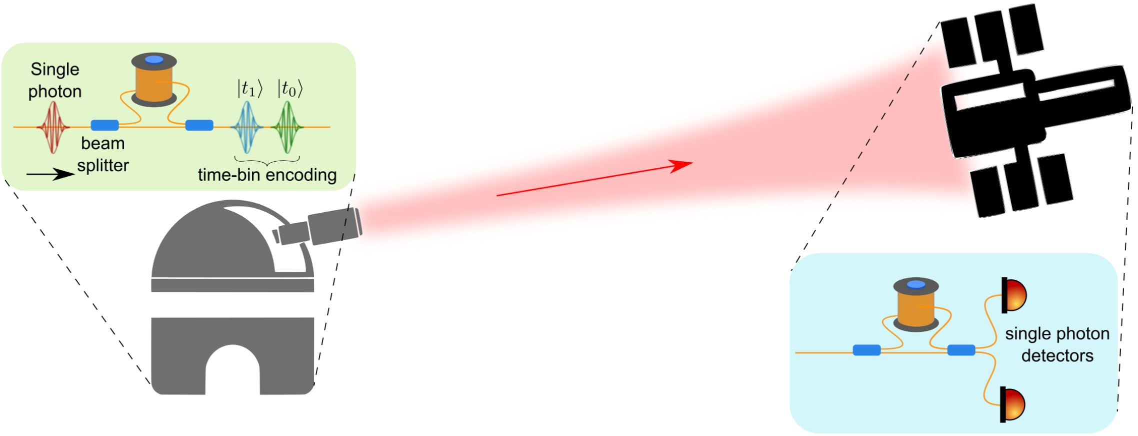


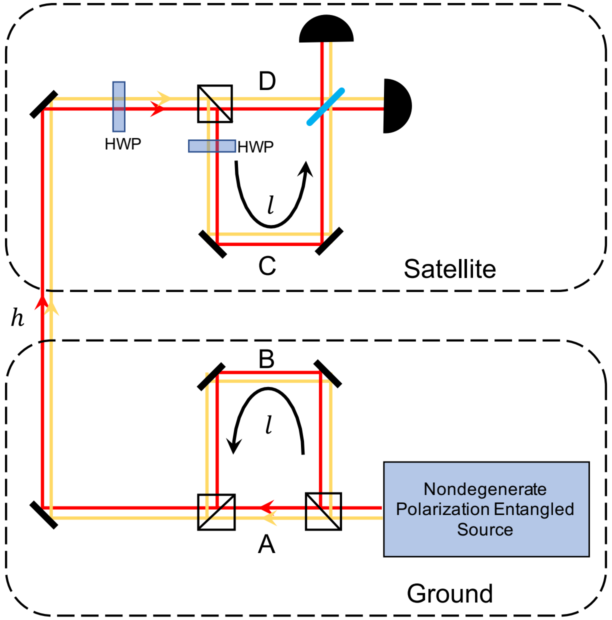


$$\frac{1}{\sqrt{2}}\left(|\omega_1\rangle_a|\omega_2\rangle_b + e^{i\varphi}|\omega_2\rangle_a|\omega_1\rangle_b\right)$$

(iii) Two-photon interferometry with frequency-entangled pairs

- Single-baseline version:
  - correlated frequency and polarization
  - polarizing beam splitters + half-wave plates





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

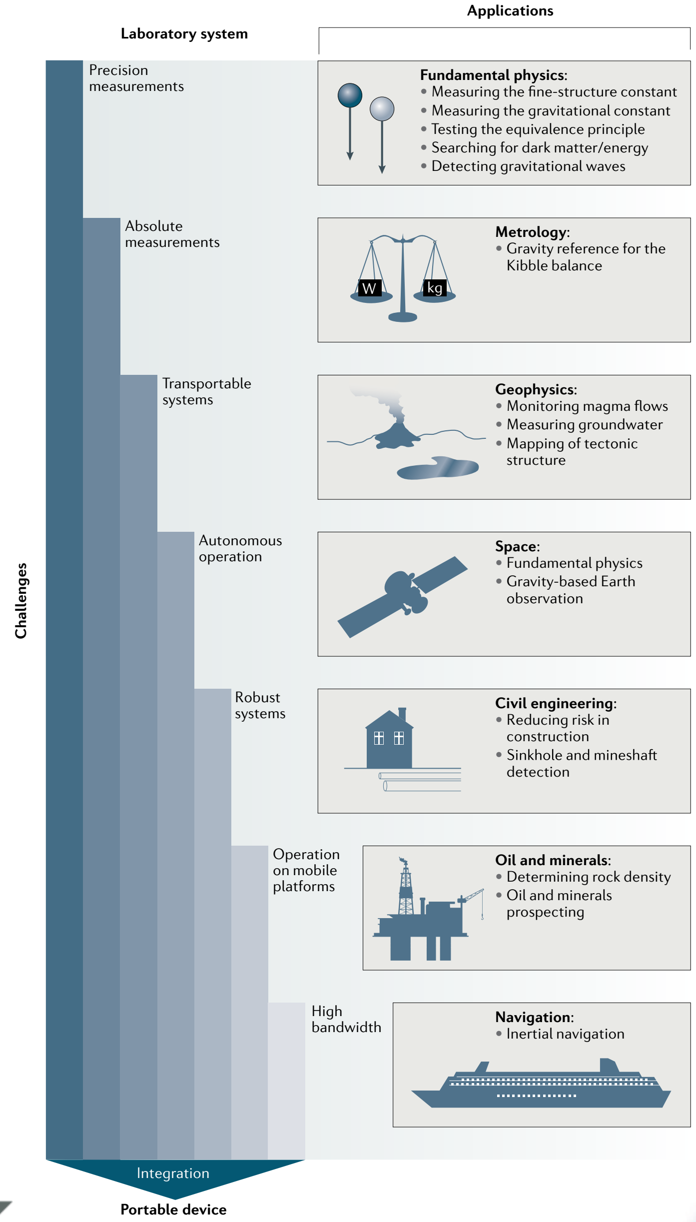
Conclusions

- Atomic clocks and atom interferometers are powerful tools for precision measurements in fundamental physics.

- Other applications:
  - search of ultralight dark matter
  - search of light dark-energy candidates (chameleons, symmetrons)

- The sensitivity and accuracy of atomic quantum sensors can also be exploited for practical applications: geophysics, Earth observation, civil engineering, navigation …

Fundamental physics and practical applications



Taking atom interferometric quantum sensors from the laboratory to real-world applications

PERSPECTIVES

Kai Bongs, Michael Holynski, Jamie Vovrosh, Philippe Bouyer, Gabriel Condon, Ernst Rasel, Christian Schubert, Wolfgang P. Schleich and Albert Roura

NATURE REVIEWS | **PHYSICS** VOLUME 1 | DECEMBER 2019 | **731**

recent commercial availability

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

QTSpace is supported by COST

cost
EUROPEAN COOPERATION
IN SCIENCE AND TECHNOLOGY

DLR
Deutsches Zentrum
für Luft- und Raumfahrt
German Aerospace Center

Project Q-GRAV