Probing gravity with quantum sensors

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German Aerospace Center (DLR)
Institute of Quantum Technologies, Ulm

DLR

Project Leader at Institute of Quantum Technologies

German Aerospace Center (DLR)

Co-Leader of WG on *Gravitational Quantum Physics and Metrology*

COST Action *Relativistic Quantum Information*

Co-Chair of ESA's *Physical Sciences Working Group* (PSWG)

Ex officio member of ESA's *Space Science Advisory Committee* (SSAC)

Member of the ACES Scientific Collaboration

Probing gravity with quantum sensors

1. Atom interferometry

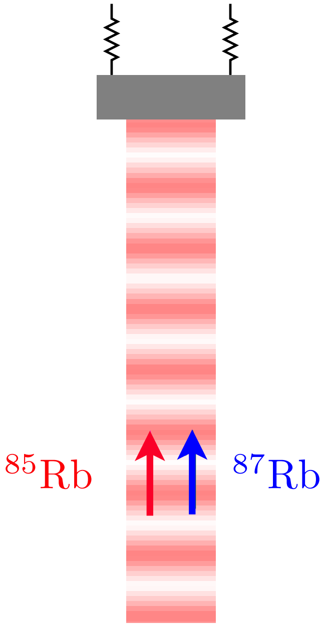
2. Atomic clocks and time / frequency links

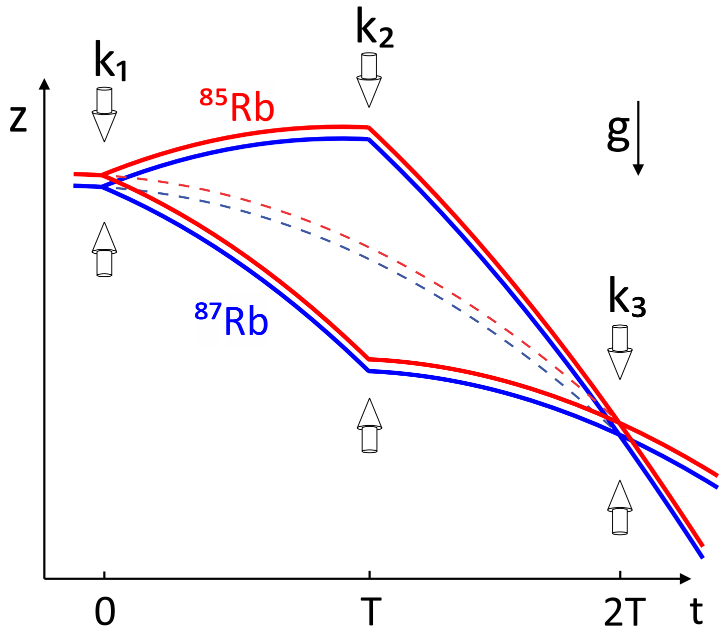
3. General relativistic effects in the quantum regime:
    - Quantum-clock interferometry
    - Atom interferometer as a freely falling clock
    - Interferometry with quantum states of light

Atom interferometry

Equivalence principle tests and gravitational constant

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

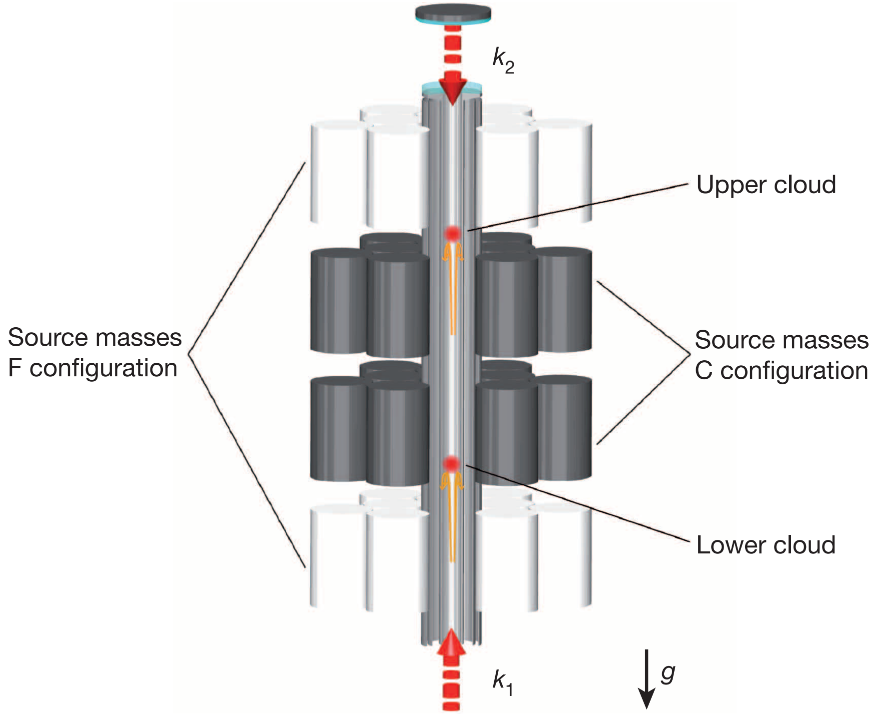




Test of universality of free fall (UFF)

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

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



gravitational constant G

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

Equivalence principle tests and gravitational constant

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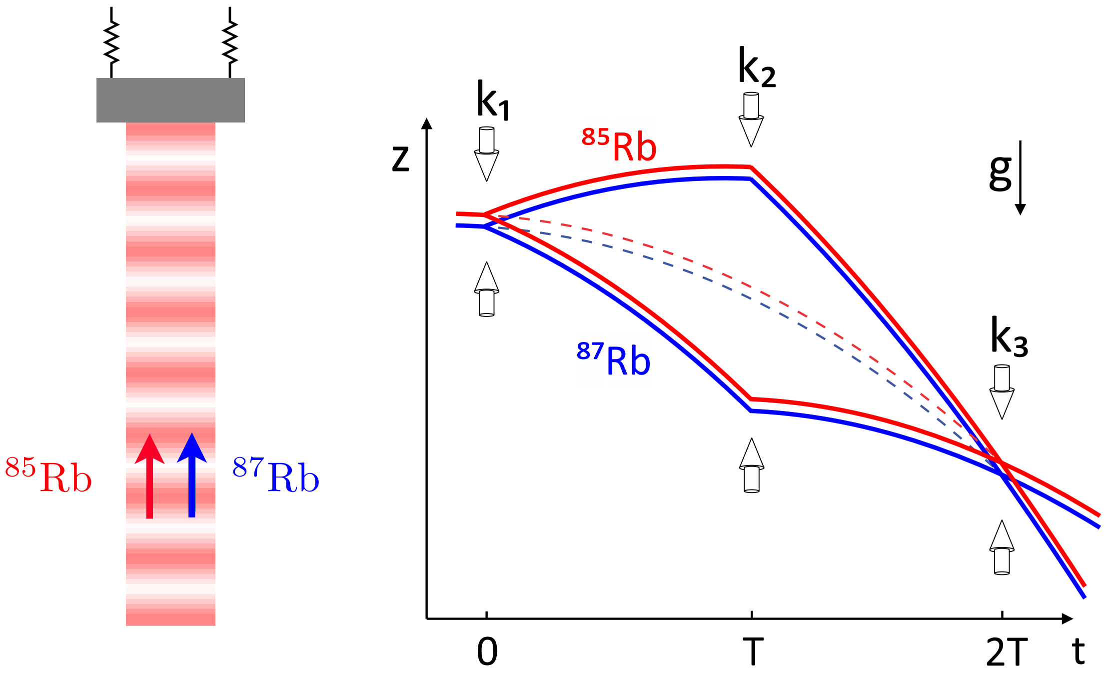

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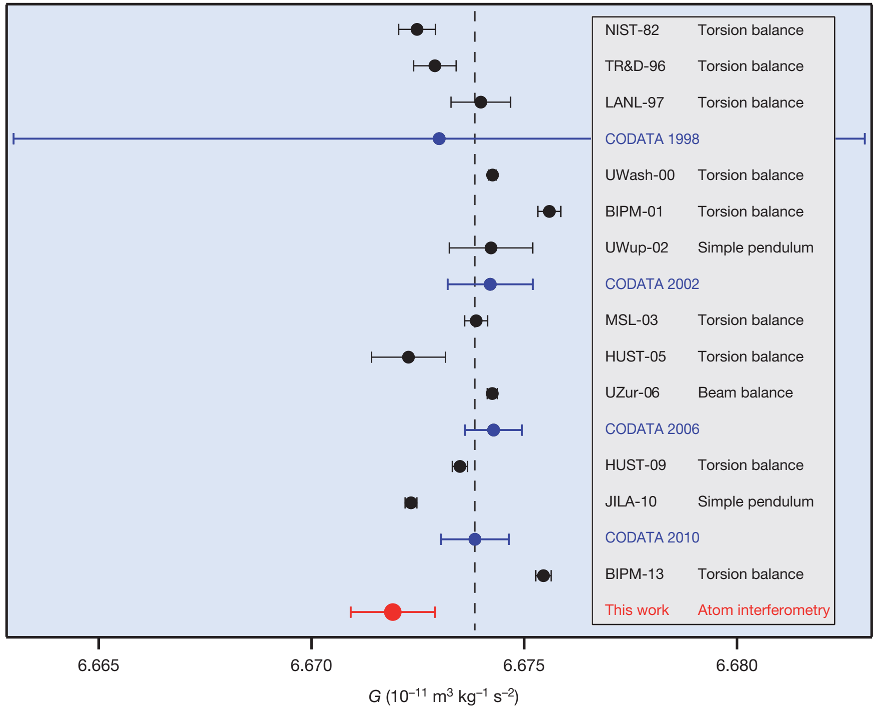

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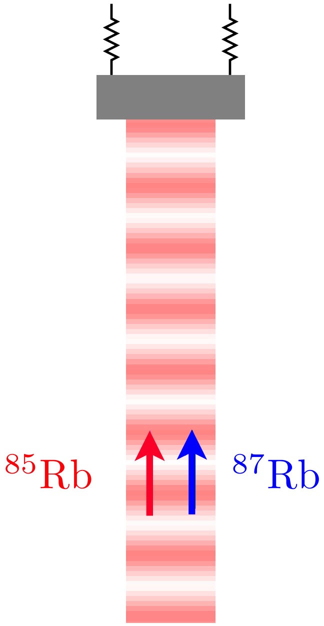

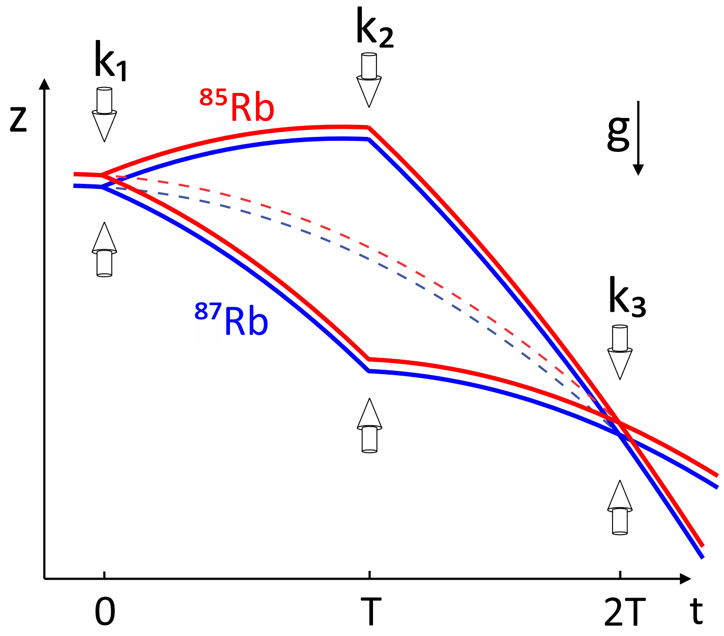

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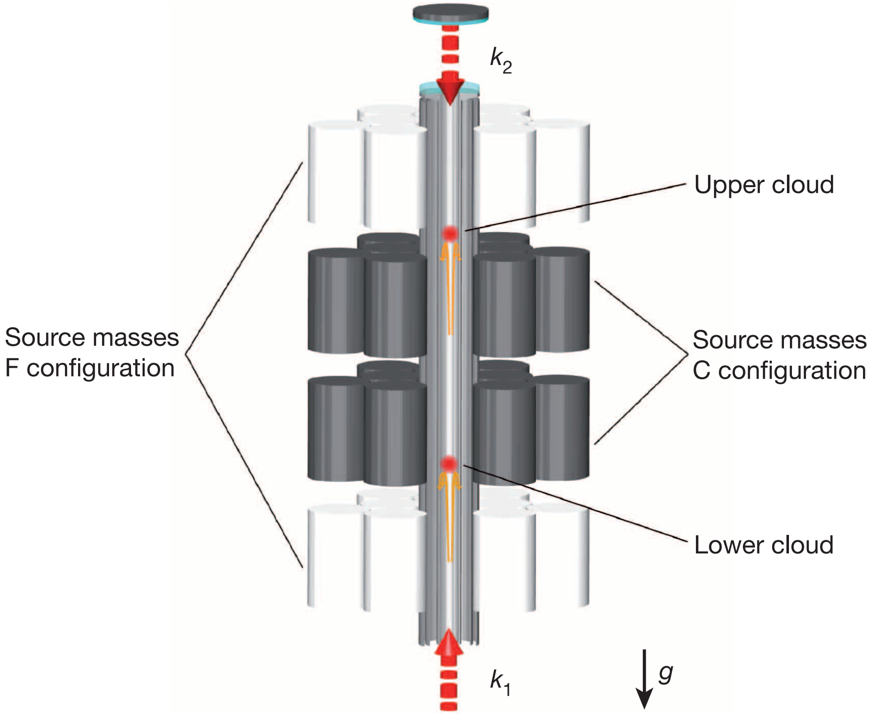

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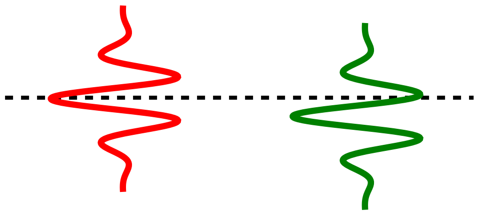
$$\Delta G/G = 1.5 \times 10^{-4}$$

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

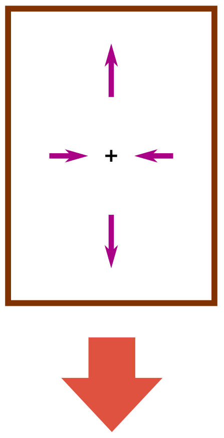
- Tidal forces lead to an open interferometer:

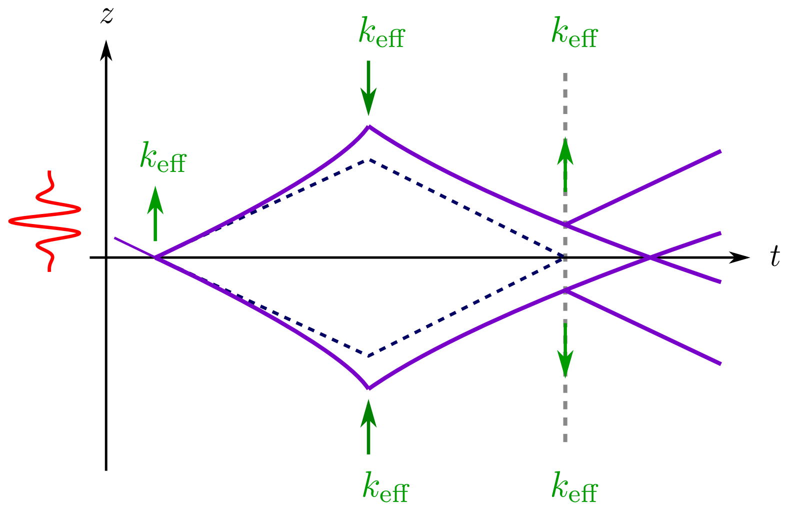
$$\delta z = \left(\Gamma_{zz}\, T^2\right) v_{\mathrm{rec}}\, T$$

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

- 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

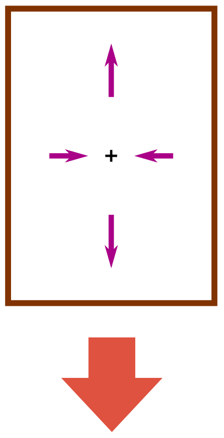
Albert Roura

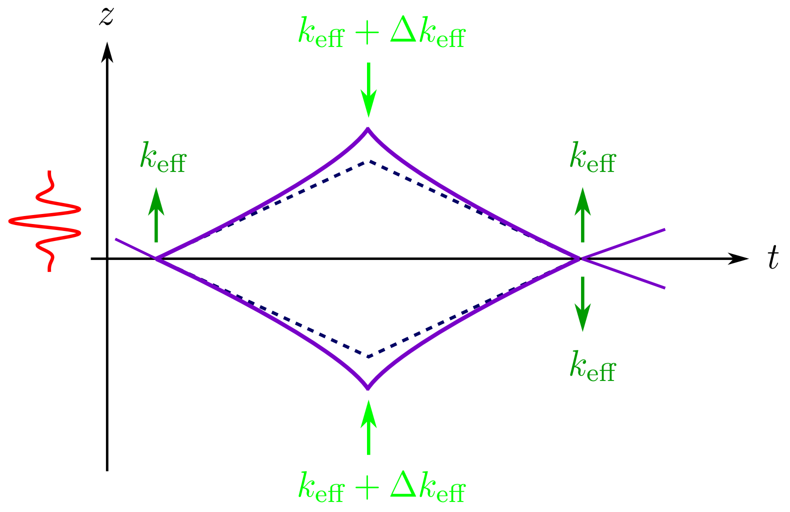
- Suitable frequency change of central pulse

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

leads to closed interferometer and removes sensitivity to initial conditions.

freely falling frame
(*Einstein elevator*)





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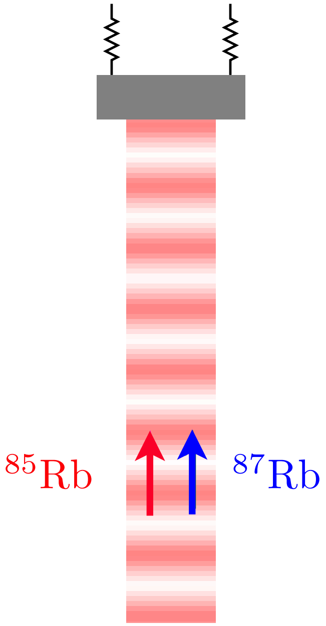

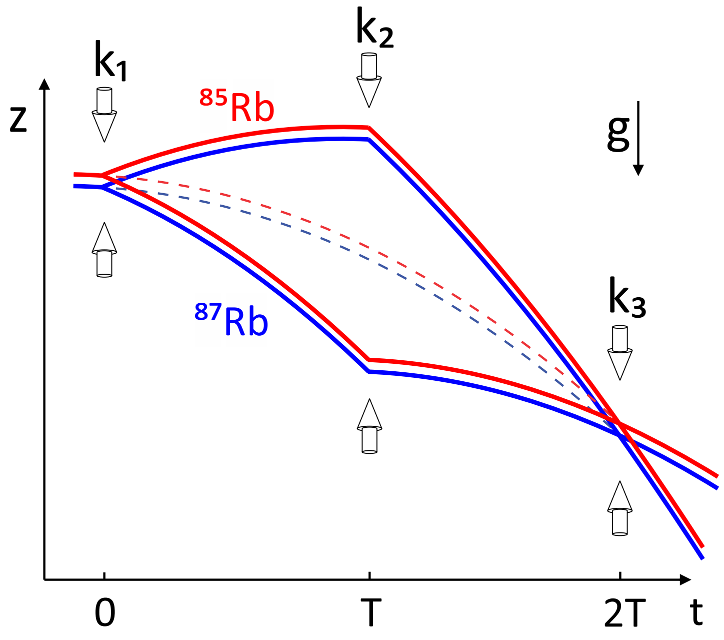

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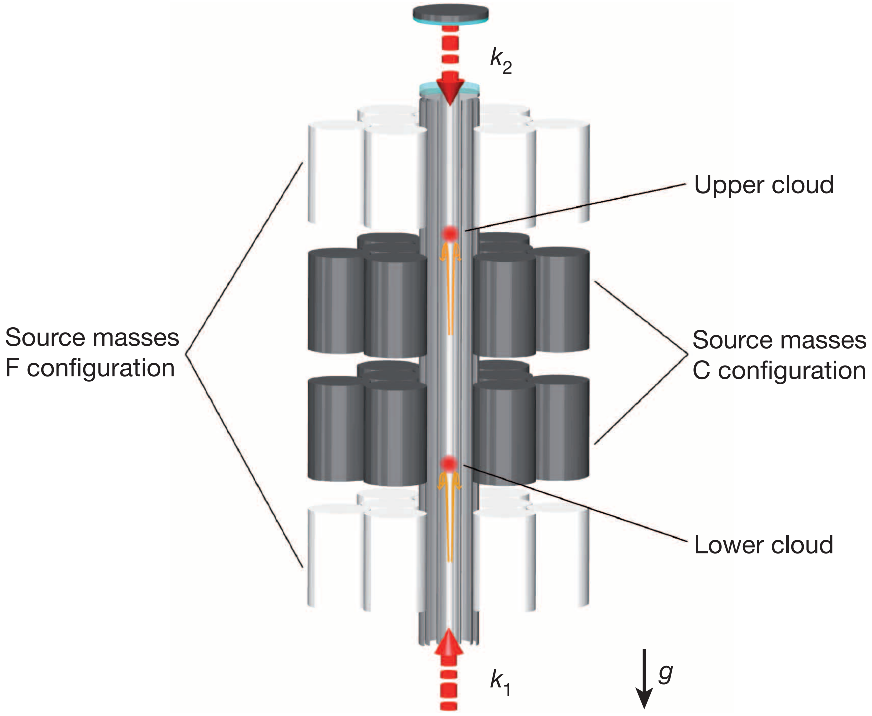


gravitational constant G

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

Atomic clocks and time/frequency links

Time & frequency distribution from space

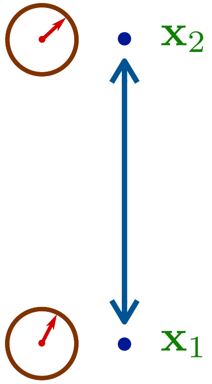
- Next-generation GNSS.
- Clock comparisons for *metrological* and *fundamental physics* applications.
- Intercontinental comparisons.
- Eventually *master clock* in space.
- Global coverage.
- Chronometric geodesy.

Gravitational redshift

- General relativistic effect:

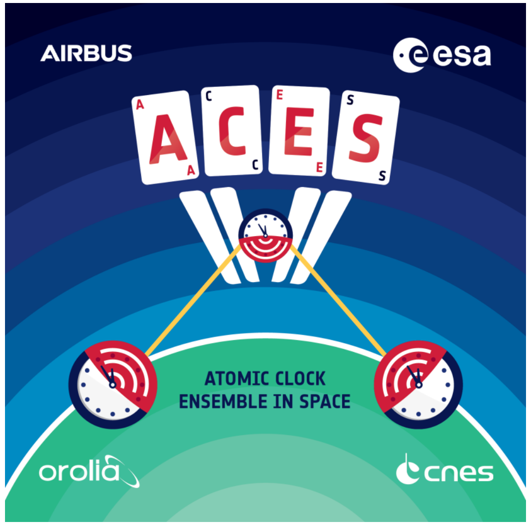
$$\frac{\Delta\tau}{\tau} \approx -\frac{\Delta f}{f} \approx (1+\alpha)\,\Delta U/c^2$$

$$\Delta U = U(\mathbf{x}_2) - U(\mathbf{x}_1)$$



- Test of Equivalence Principle: $\alpha = 0$?
- Must be taken into account in practical applications (e.g. GNSS).
- It can be exploited itself.

ACES (Atomic Clock Ensemble in Space)



Project scientist: Luigi Cacciapuoti

PI: Christophe Salomon

- Target: first high-precision measurements with cold atoms in space.
- Important milestone for future ESA missions with cold atoms.
- Main scientific goals:
  - measuring gravitational redshift at 10^{-6} level
  - searching for dark matter, variations of fundamental constants
  - intercontinental clock comparison at 10^{-17} level
  - demonstration of chronometric geodesy at $10\,\text{cm}$ level

Successful launch on 21 April 2025
Space X, Falcon 9 rocket

Bartolomeo platform
outside the ISS Columbus module

ACES

Atomic Clock Ensemble in Space

A European facility to test fundamental physics from outside ESA's Columbus module on the International Space Station. By creating a "network of clocks", ACES links its own precise timepieces, PHARAO and SHM, with the most accurate clocks on Earth to compare them and measure the flow of time.

1 **PHARAO**
a clock which uses laser-cooled caesium atoms

2 **SHM**
Space Hydrogen Maser, a clock which uses hydrogen atoms

3 **External payload computer (XLPC)**
ACES computer

4 **PHARAO on-board management unit (OMU)**
PHARAO clock's on-board computer

5 **PHARAO laser source**
cools caesium atoms for the PHARAO clock

6 **Single photon avalanche diode (SPAD)**
a highly sensitive device that can detect single photons of light

7 **Global navigation satellite system (GNSS) antenna**
provides orbit determination of ACES to perform fundamental physics tests

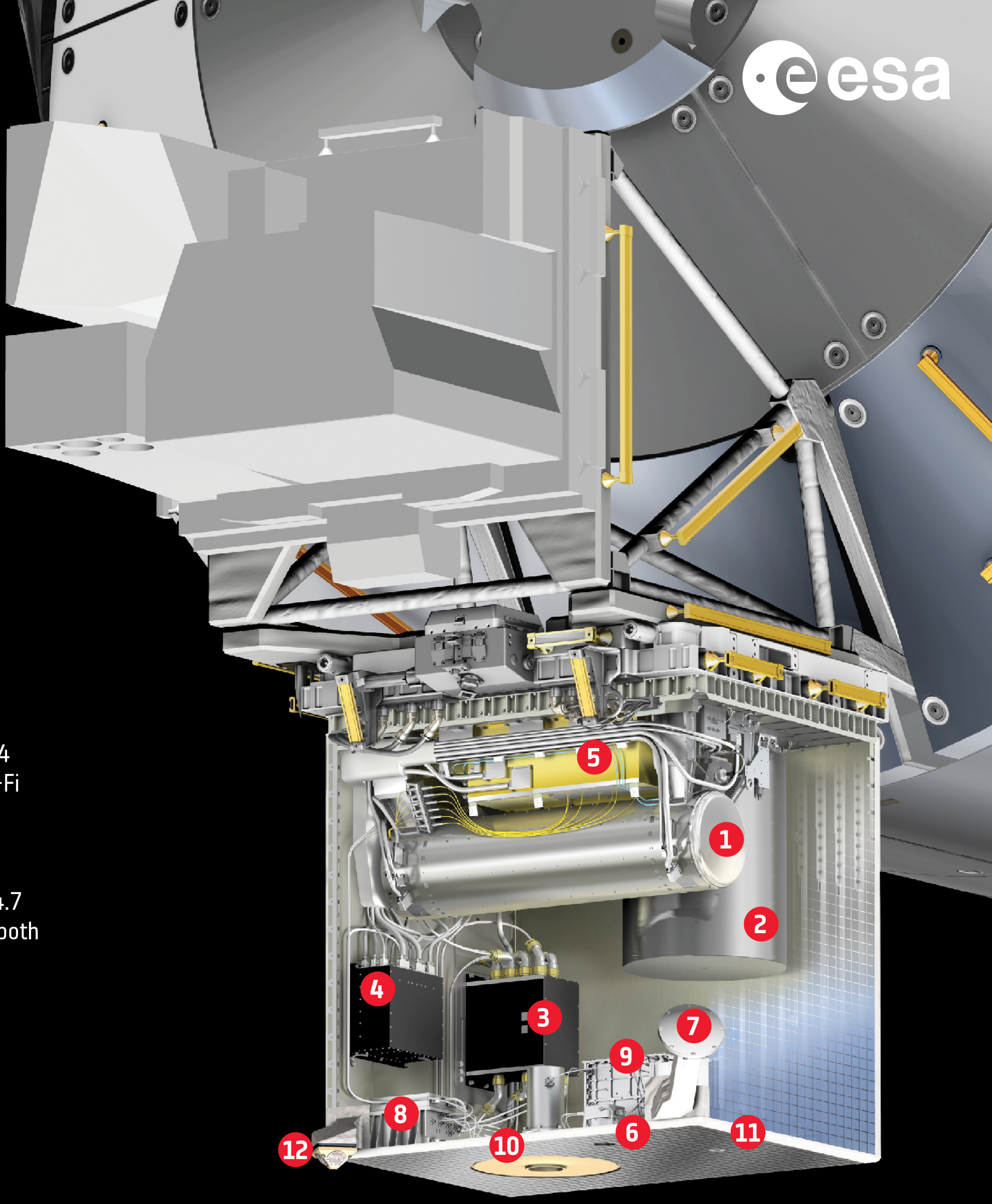
8 **Frequency comparison and distribution package (FCDP)**
compares PHARAO and SHM and sends the ACES clock signal to the microwave link electronics

9 **Microwave link (MWL)**
enables the comparison of clocks on Earth and in space through the exchange of microwave signals

10 **S-band microwave link antenna**
transmits microwave signals with a frequency of 2.4 GHz, within the 2-4 GHz S-band range used for Wi-Fi and mobile phone communications

11 **Ku-band microwave link antenna**
transmits microwave signals with a frequency of 14.7 GHz a receives signals at a frequency of 13.5 GHz, both within the Ku-band range used mostly for satellite communications

12 **European Laser Timing (ELT) reflector**
enables the comparison of clocks on Earth and in space by using laser pulses



General relativistic effects in the quantum regime

(i) Quantum-clock interferometry

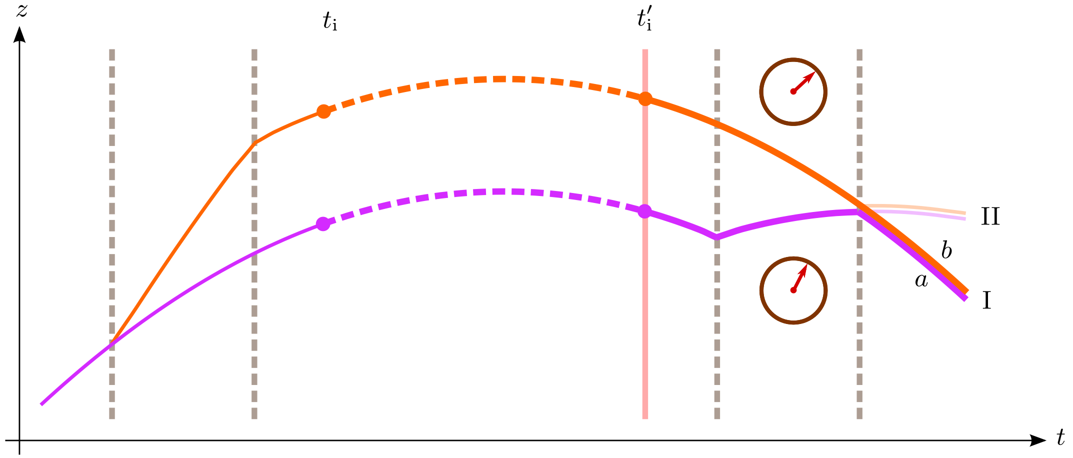
PHYSICAL REVIEW X **10,** 021014 (2020)

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

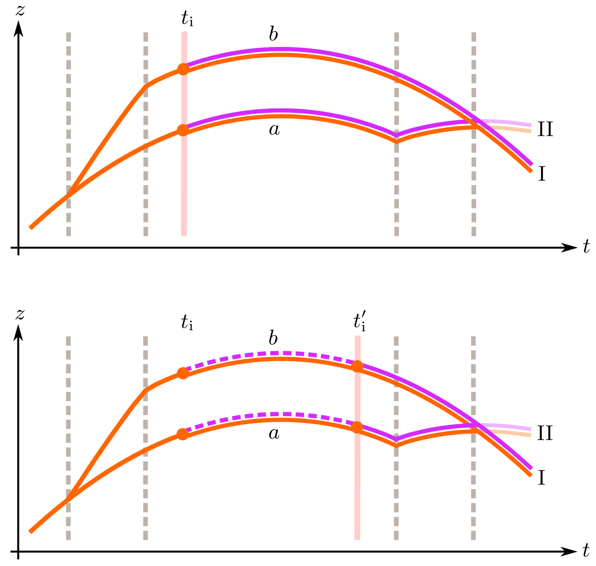


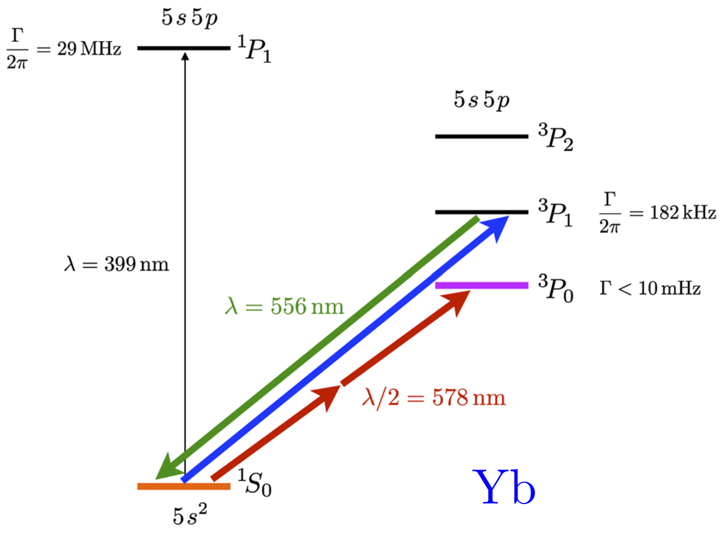
(i) Quantum-clock interferometry

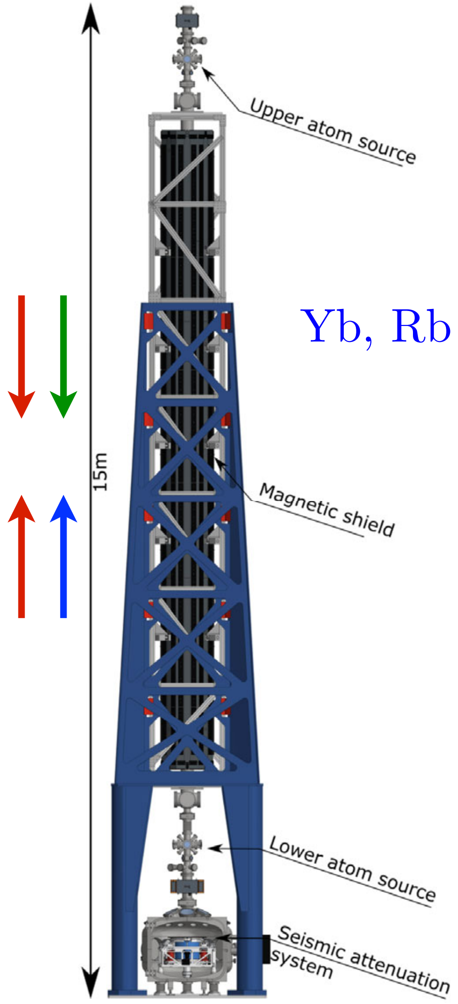
PHYSICAL REVIEW D **104,** 084001 (2021)

Measuring gravitational time dilation with delocalized quantum superpositions

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







(ii) Atom interferometer as a freely falling clock

Quantum Sci. Technol. **10** (2025) 025004 https://doi.org/10.1088/2058-9565/ad9e2e

Quantum Science and Technology

PAPER

Atom interferometer as a freely falling clock for time-dilation measurements

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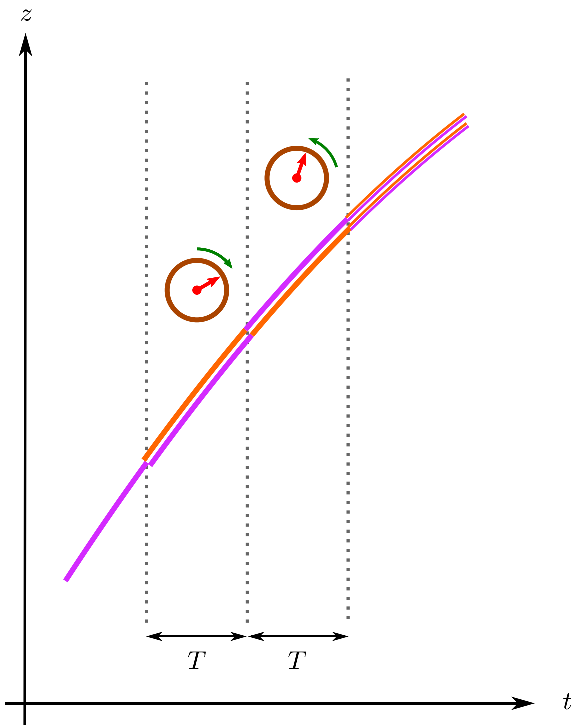
E-mail: albert.roura@dlr.de

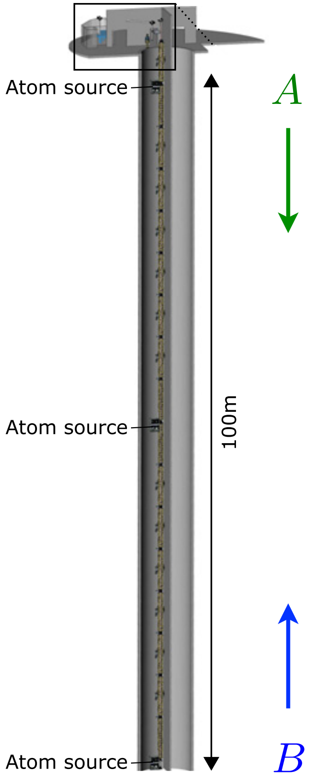
Keywords: atom interferometry, relativistic time dilation, gravitational and relativistic measurements, long-baseline facilities, single-photon clock transition



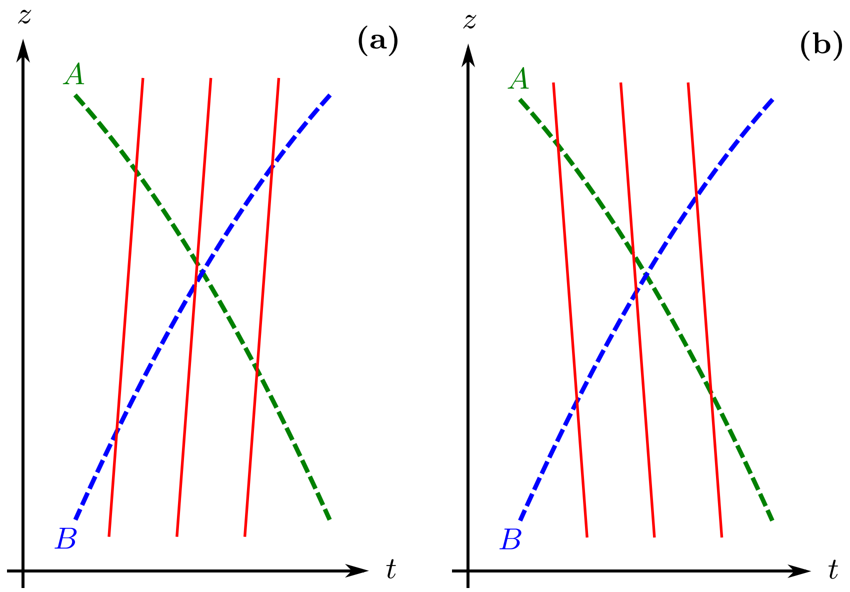
Clock ticks backwards after intermediate time. Imbalance due to relativistic time-dilation effects.

(ii) Atom interferometer as a freely falling clock

Abe *et al.*, QST **6**, 044003 (2021)



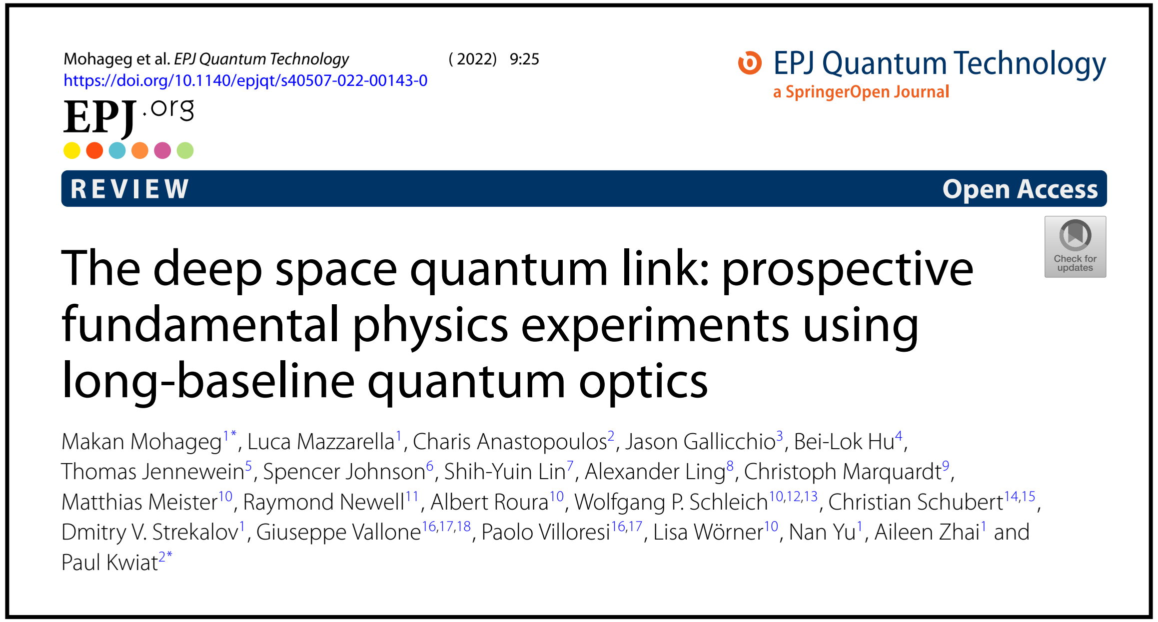
MAGIS-100



"gradiometric" configuration suppresses laser phase noise and effect of mirror vibrations

$$\delta\phi_A - \delta\phi_B = -2\,(\Delta E/\hbar)\,\left(\bar{\mathbf{v}}_0^A - \bar{\mathbf{v}}_0^B\right)\cdot\mathbf{g}\,T^2/c^2$$

(iv) Two-photon interference with frequency-entangled pairs



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

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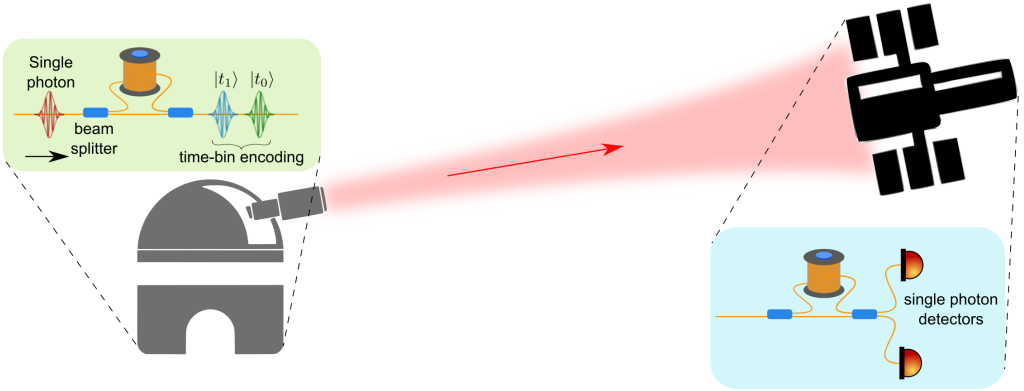
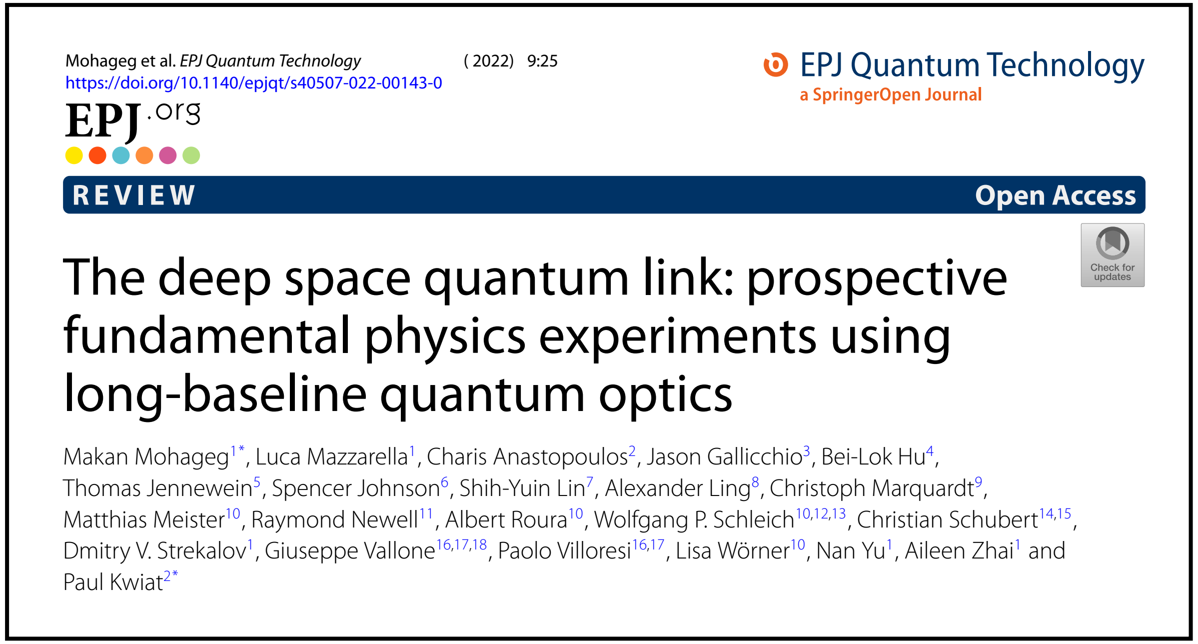
The deep space quantum link: prospective fundamental physics experiments using long-baseline quantum optics

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.



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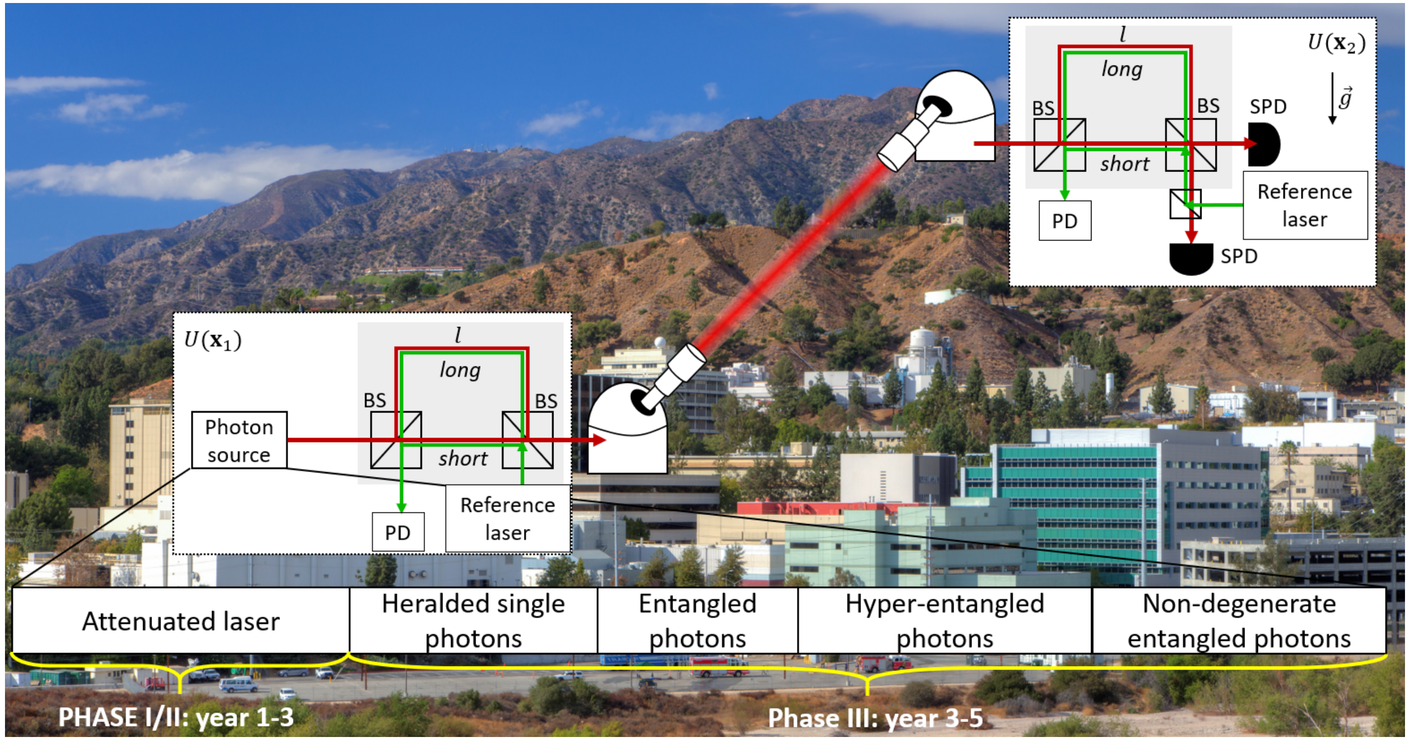
- Part of a study by the Science Definition Team for a future space mission.
- Recognized with a *NASA Group Achievement Award*.

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

Ground-based implementation



- 10-km free-space link between Jet Propulsion Laboratory and Mt. Wilson (1.2 km height difference)
- Collaboration with Paul Kwiat, Makan Mohageg, Alex Lohrmann and Spencer Johnson.

DLR

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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German Aerospace Center

Project Q-GRAV

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Relativistic Quantum Information
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