Quantum Technologies in Space

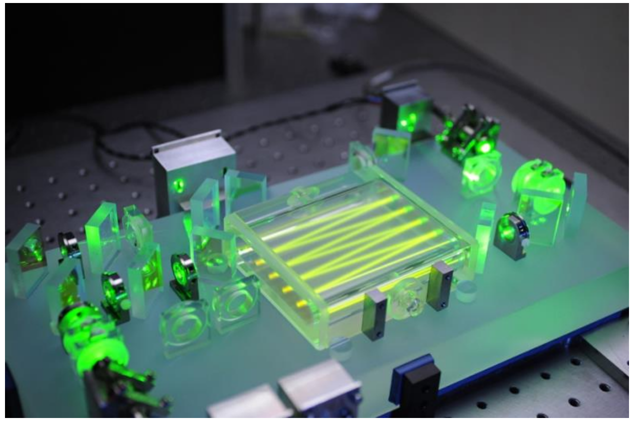
Albert Roura

Institute of Quantum Technologies (Ulm)

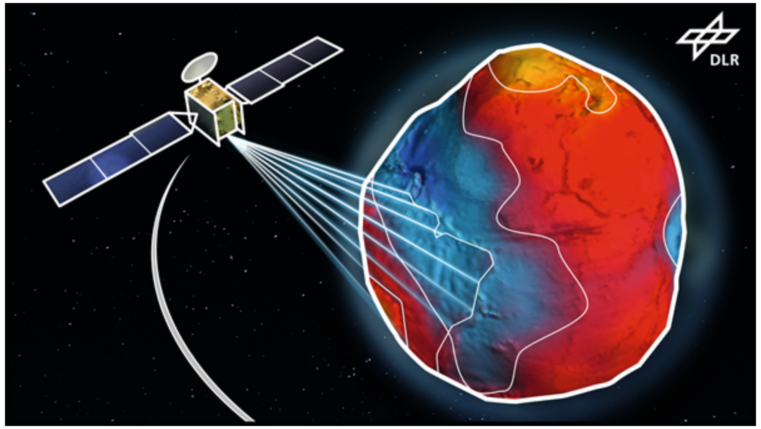
DLR
Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Quantum Technologies + (New) Space

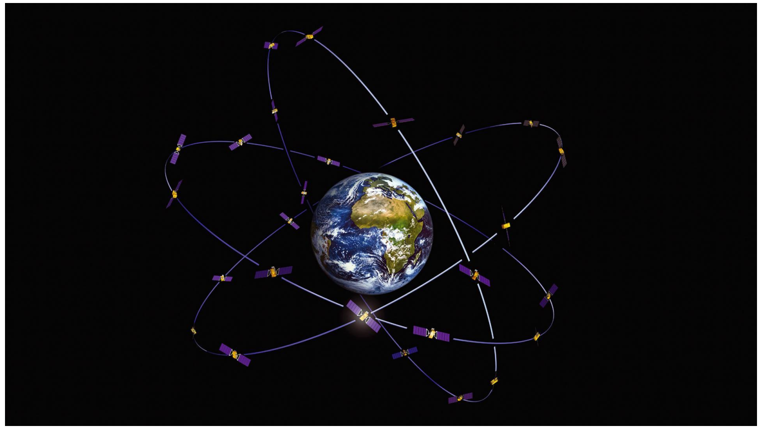
3 new Institutes recently established by the German Aerospace Center (DLR)



Institute of Quantum Technologies (Ulm)



Institute for Satellite Geodesy and Inertial Sensing (Hannover)



Galileo Competence Center (Oberpfaffenhofen)

Advantages of Space

- Global coverage.
- Intercontinental links.
- Microgravity conditions.
- Gravitationally quiet environment.

Important Synergies

Fundamental Physics + Practical Applications

I. Quantum Communication

II. Time & Frequency distribution

III. Quantum Sensing

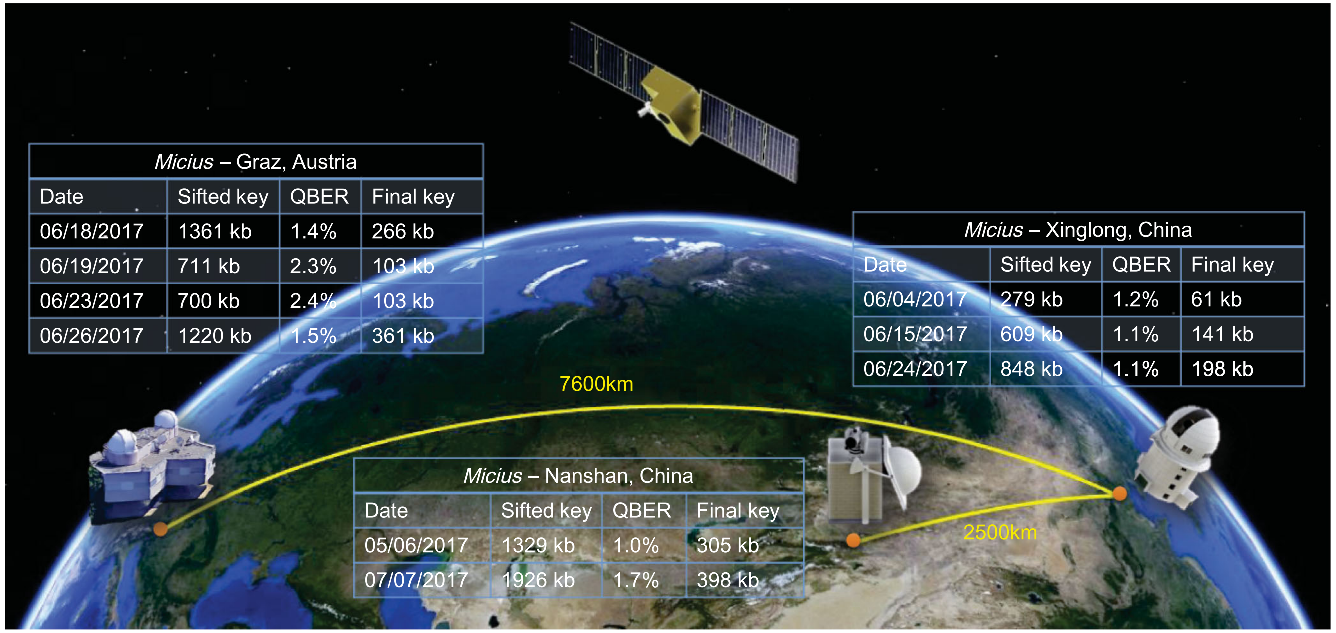
IV. Earth Observation

Quantum Communication

Quantum Key Distribution from space

- Free-space optical links instead of optical fibers (limited to tens of km without quantum repeaters).
- Intercontinental QKD.
- Global coverage.

Micius satellite



Micius – Graz, Austria			
Date	Sifted key	QBER	Final key
06/18/2017	1361 kb	1.4%	266 kb
06/19/2017	711 kb	2.3%	103 kb
06/23/2017	700 kb	2.4%	103 kb
06/26/2017	1220 kb	1.5%	361 kb

Micius – Xinglong, China			
Date	Sifted key	QBER	Final key
06/04/2017	279 kb	1.2%	61 kb
06/15/2017	609 kb	1.1%	141 kb
06/24/2017	848 kb	1.1%	198 kb

Micius – Nanshan, China			
Date	Sifted key	QBER	Final key
05/06/2017	1329 kb	1.0%	305 kb
07/07/2017	1926 kb	1.7%	398 kb

S.-K. Liao *et al.* (2017)

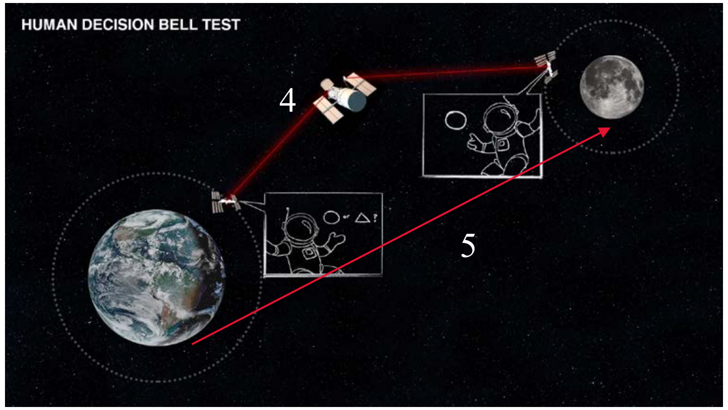
Satellite-relayed intercontinental Quantum Key Distribution (QKD)

Also demonstration of satellite-based *entanglement distribution* and ground-to-satellite *quantum teleportation.*

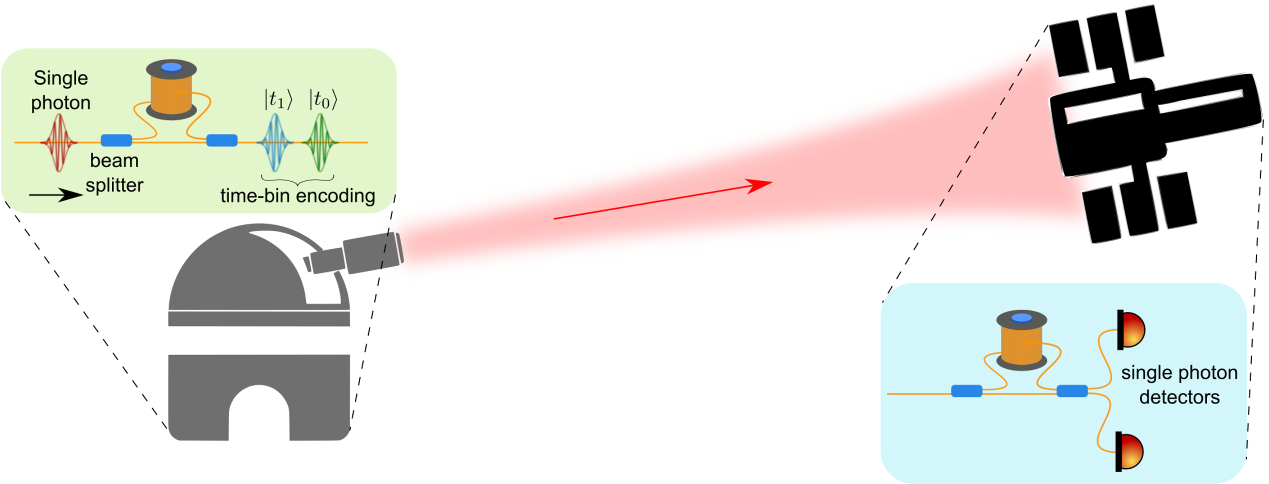
RESEARCH

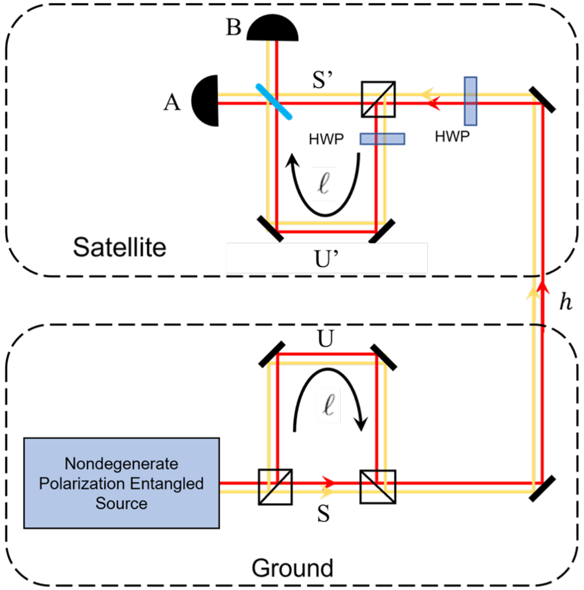
The Deep Space Quantum Link: Prospective Fundamental Physics Experiments using Long-Baseline Quantum Optics

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



Mohageg, Kwiat





Time & Frequency distribution

Time & frequency distribution from space

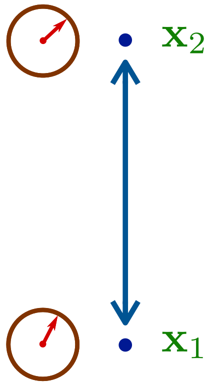
- Next-generation GNSS.
- Clock comparisons for *metrological* and *fundamental physics* applications.
- Intercontinental comparisons.
- Eventually *master clock* in space.
- Global coverage.
- Chronometric geodesy.

Gravitational redshift

- General relativistic effect:

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

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

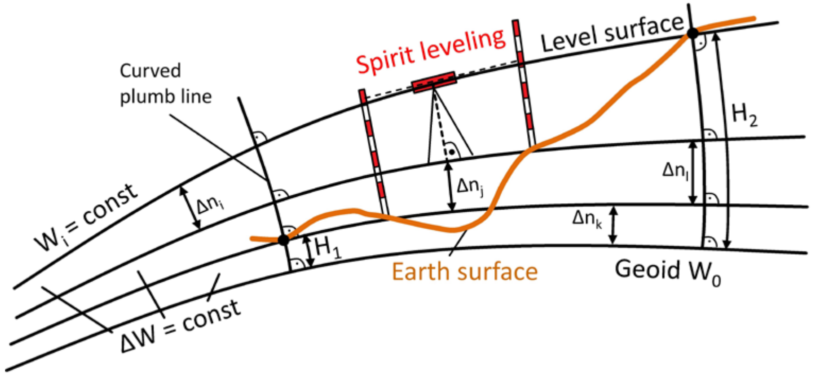


- Test of Equivalence Principle: $\alpha = 0$?
- Must be taken into account in practical applications (e.g. GNSS).
- It can be exploited itself.

Chronometric (relativistic) geodesy

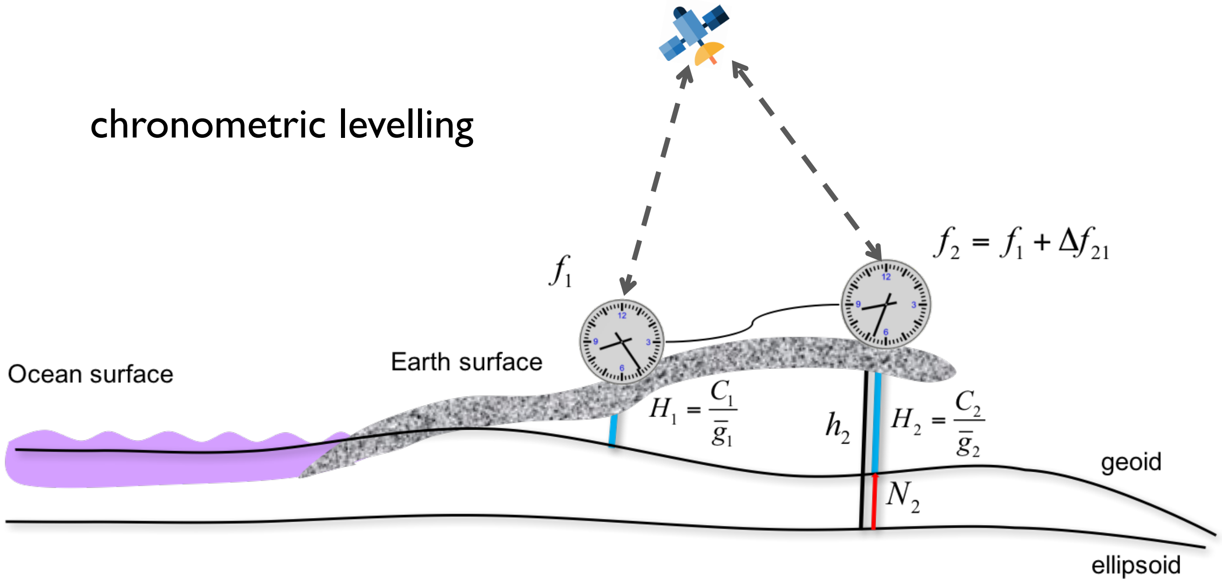
- Gravitational redshift: $\Delta f/f \approx 10^{-18} \longrightarrow \Delta H \approx 1\,\mathrm{cm}$
- Chronometric levelling: comparison between a *transportable clock* and a *fixed reference*.
- Optical links to satellite $\longrightarrow$ global coverage

T. Mehlstäubler *et al.* (2018)



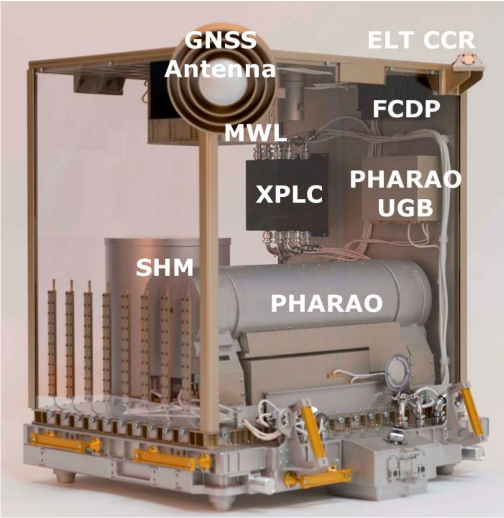
geometric levelling

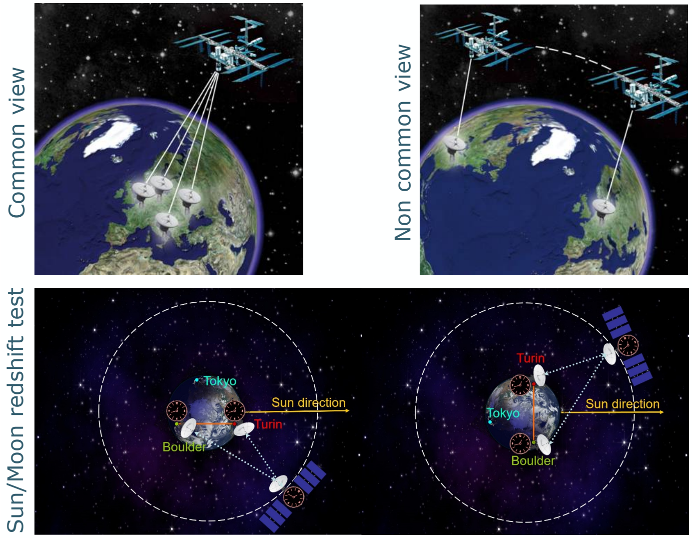
chronometric levelling



H. Wu, J. Müller

L. Cacciapuoti





ACES

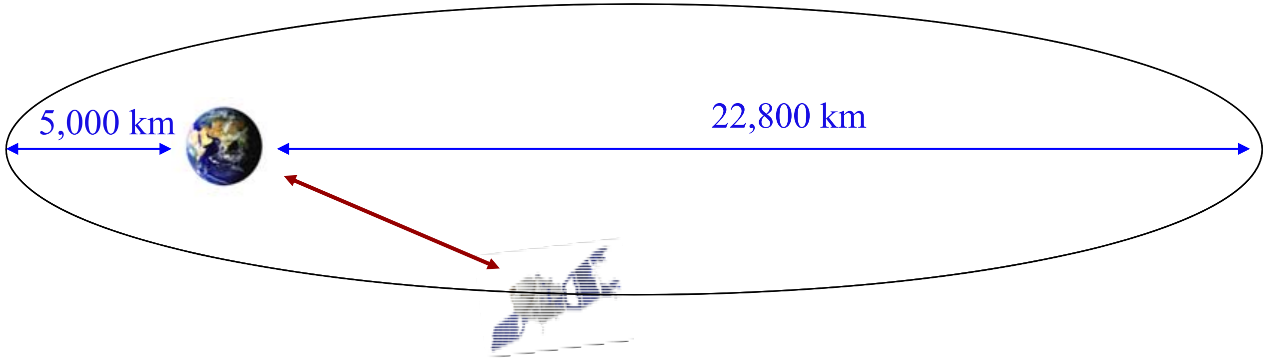
(Atomic Clock Ensemble in Space)

- H-maser + Cs cold-atom microwave clock.
- Microwave & optical time/frequency links.
- Expected launch in 2022.

FOCOS

(Fundamental physics with an Optical Clock Orbiting in Space)

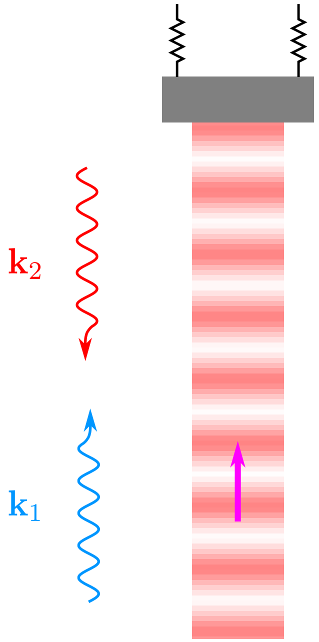
- Dual Yb optical clock.
- Two-way optical time/frequency link.
- Future mission proposal.

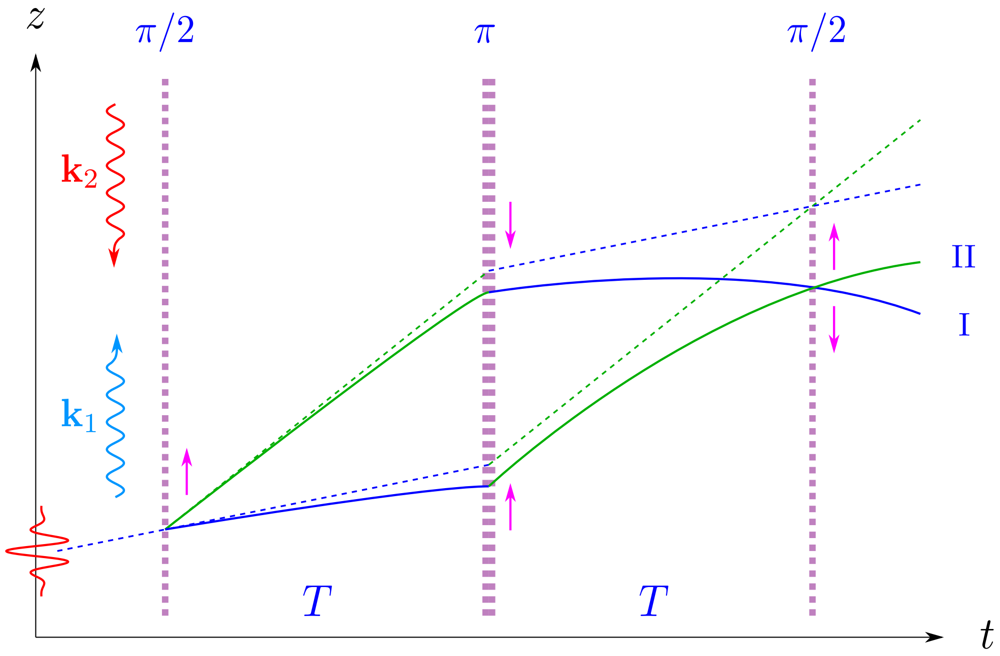


C. Oates *et al.*

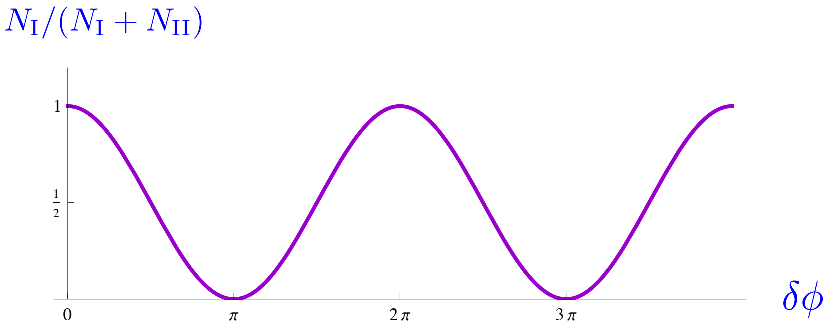
Quantum Sensing

Atom interferometers as accelerometers

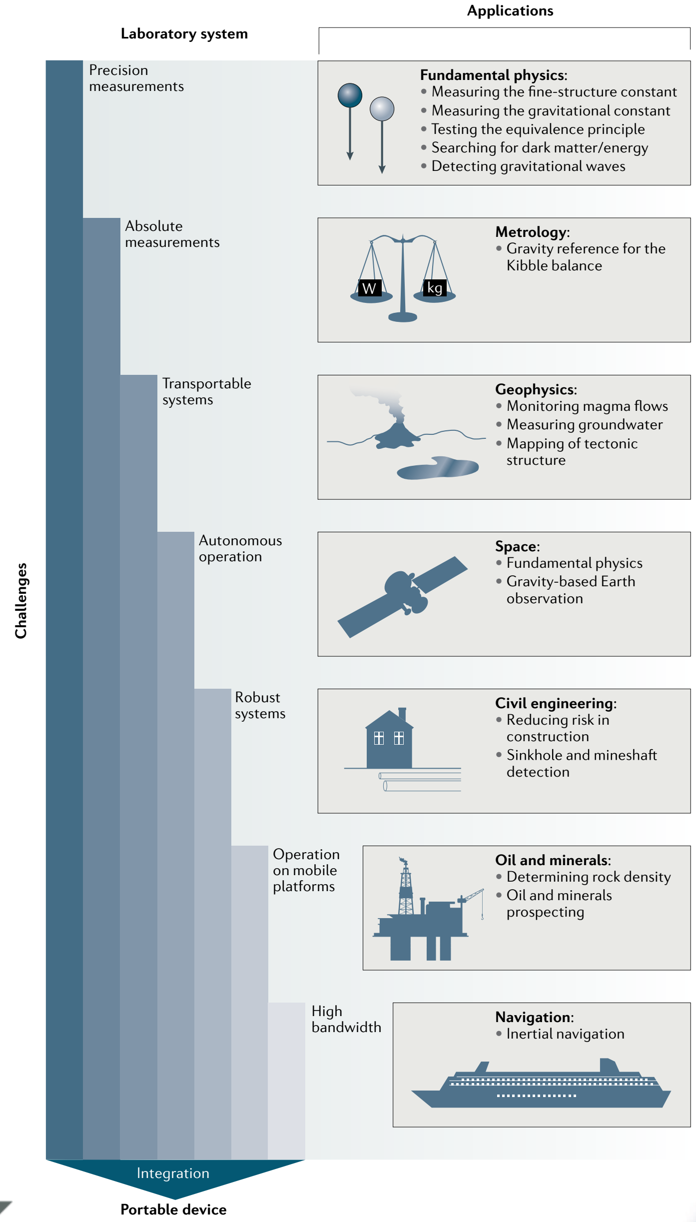




$$\mathbf{k}_{\text{eff}} = \mathbf{k}_1 - \mathbf{k}_2$$



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



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

μQUANS

AOSense Sensors for a Quantum World

M SQUARED

recent commercial availability

DLR

Fundamental physics measurements

LETTER

Precision measurement of the Newtonian gravitational constant using cold atoms

G. Rosi[1], F. Sorrentino[1], L. Cacciapuoti[2], M. Prevedelli[3] & G. M. Tino[1]

518 | NATURE | VOL 510 | 26 JUNE 2014

The least accurately determined fundamental constant by several orders of magnitude.

PRL **112,** 203002 (2014) PHYSICAL REVIEW LETTERS week ending 23 MAY 2014

Quantum Test of the Universality of Free Fall

D. Schlippert,[1] J. Hartwig,[1] H. Albers,[1] L. L. Richardson,[1] C. Schubert,[1] A. Roura,[2] W. P. Schleich,[2,3] W. Ertmer,[1] and E. M. Rasel[1*]

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

The Equivalence Principle is a cornerstone of General Relativity

Fundamental physics measurements

LETTER

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

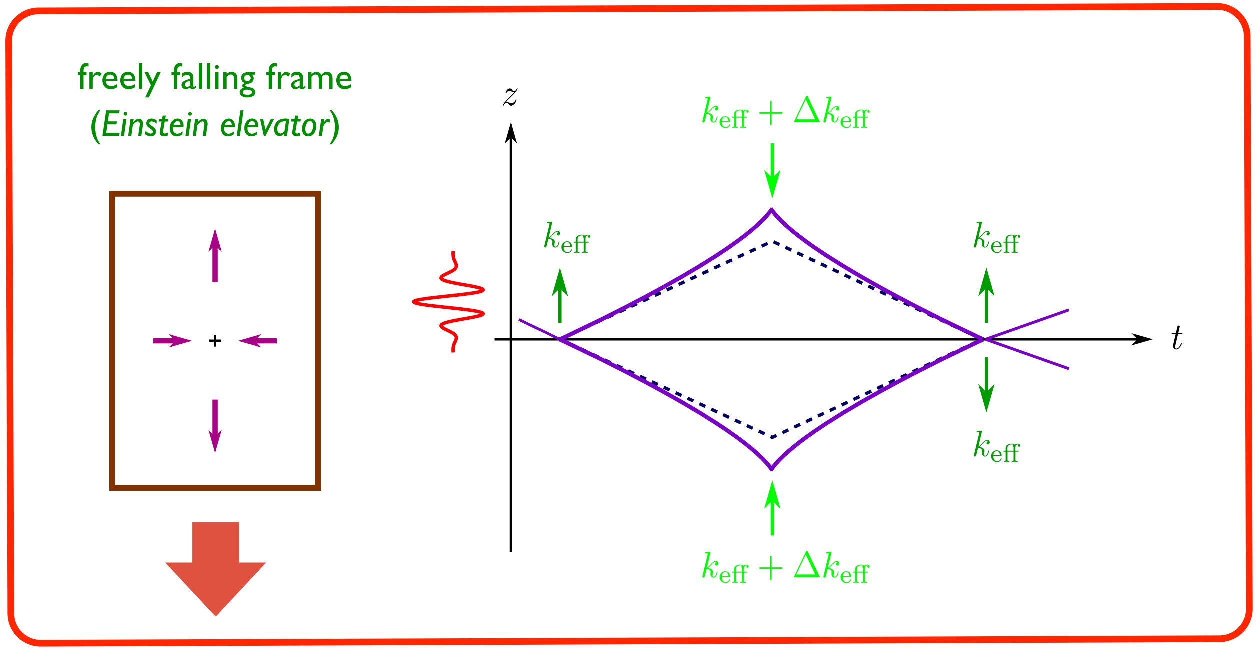
Major systematic effect due to gravity gradients.

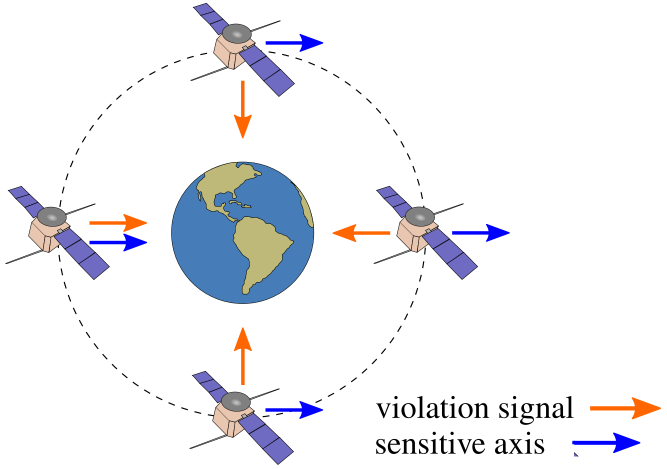
Mitigation techniques for gravity gradients

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





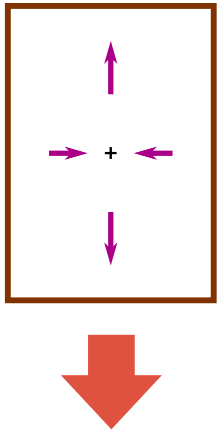
Mitigation techniques for gravity gradients

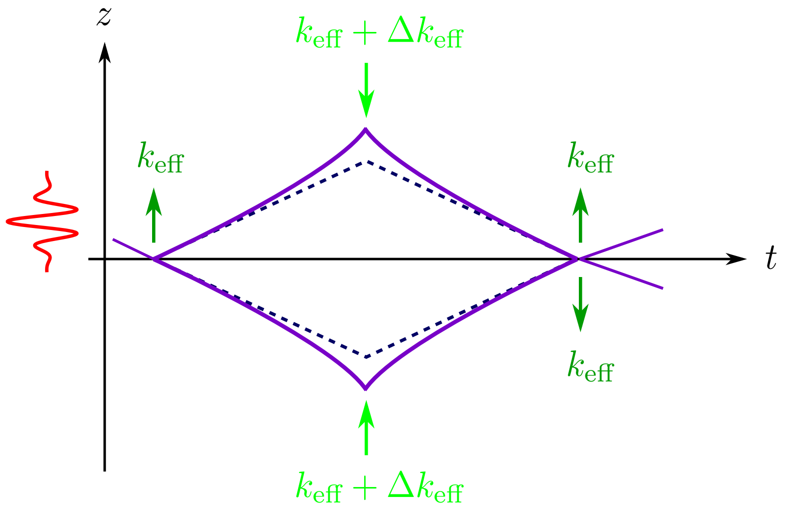
PHYSICAL REVIEW D **102,** 124043 (2020)

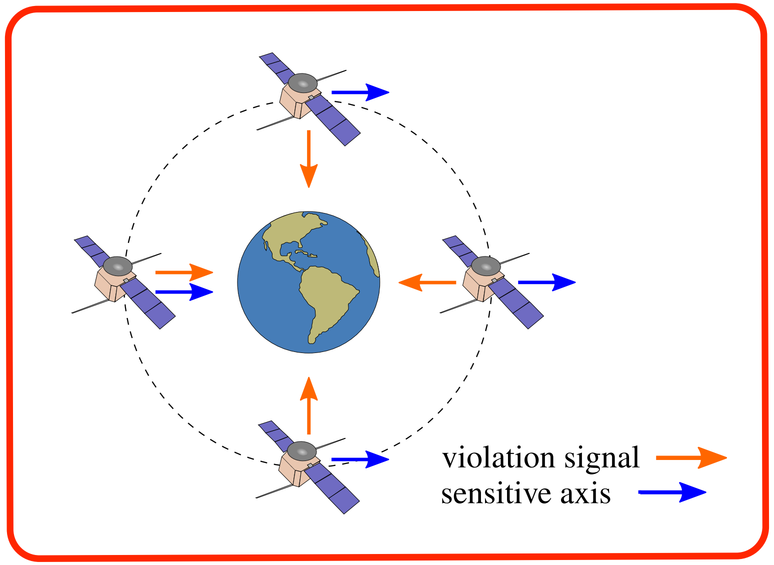
Resolution of the colocation problem in satellite quantum tests of the universality of free fall

Sina Loriani,[1,*] Christian Schubert,[1,3] Dennis Schlippert,[1] Wolfgang Ertmer,[1,3] Franck Pereira Dos Santos,[2] Ernst Maria Rasel,[1] Naceur Gaalou,[1,†] and Peter Wolf[2,‡]

freely falling frame
(*Einstein elevator*)







arXiv:2107.03709

Advantages of space

- Microgravity conditions:
  - Long free evolution times.
  - No gravitational sag.
  - Long times close to source masses possible.
- Gravitationally quiet environment.
- Access to larger *gravitational potential* and *velocity* variations.
- Orbital modulation techniques.

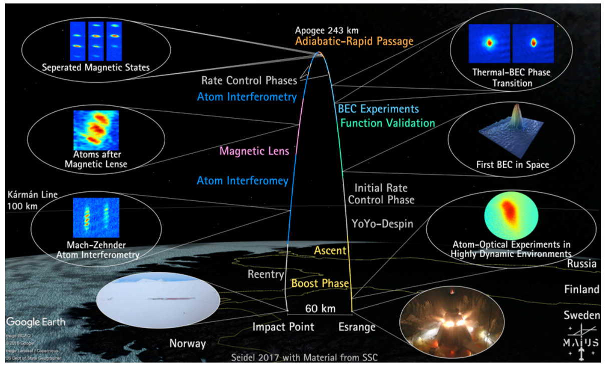
Ultracold atoms in space

LETTER

Space-borne Bose–Einstein condensation for precision interferometry

Dennis Becker *et al.*

18 OCTOBER 2018 | VOL 562 | NATURE | 391



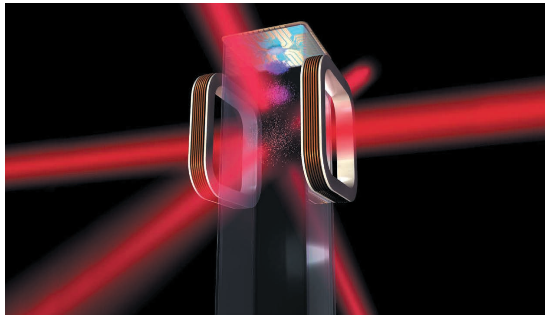
MAIUS / QUANTUS

Article

Observation of Bose–Einstein condensates in an Earth-orbiting research lab

David Aveline *et al.*

Nature | Vol 582 | 11 June 2020 | **193**



NASA (CAL)

Frye et al. *EPJ Quantum Technology* (2021) 8:1

EPJ Quantum Technology
a SpringerOpen Journal

RESEARCH Open Access

The Bose-Einstein Condensate and Cold Atom Laboratory

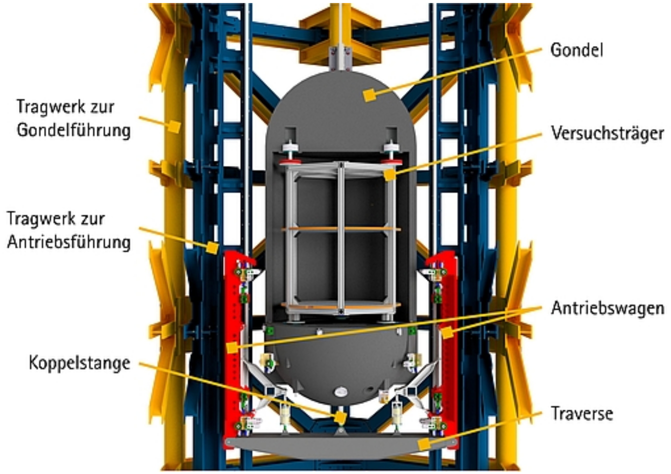
DLR – NASA

DLR

Ground-based microgravity platforms

ZARM drop tower (Bremen)

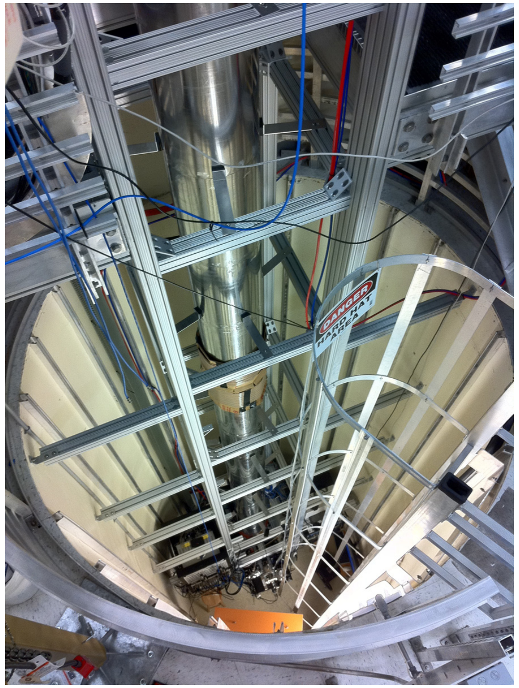
5 s / 10 s microgravity



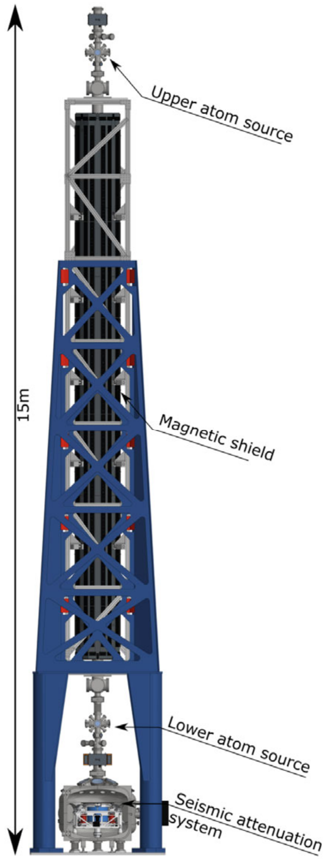
Einstein elevator at the HITec building (Hannover)

4 s microgravity, 300 shots/day

10-meter atomic fountains



Stanford (USA)



VLBAI, Hannover (Germany)

Wuhan (China)

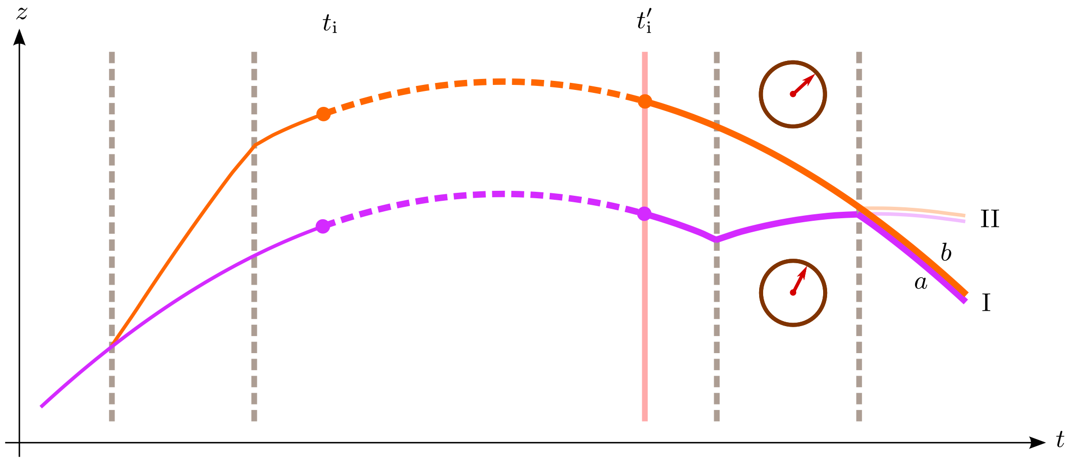
Testing general relativity in the quantum regime

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

Gravitational Redshift in Quantum-Clock Interferometry

Albert Roura

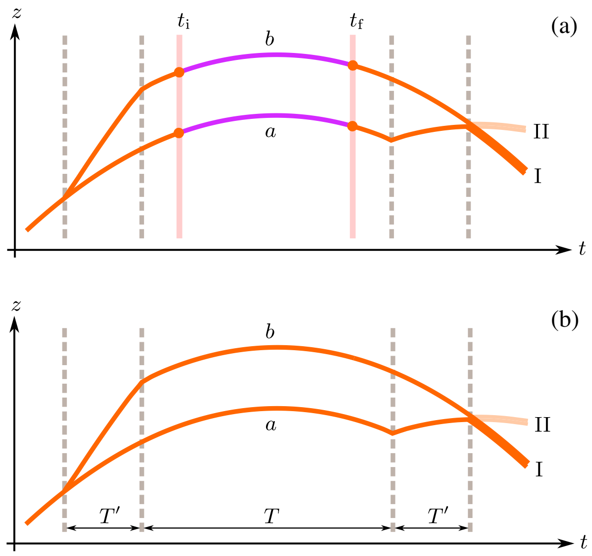
Quantum superposition of a single clock
at two different heights

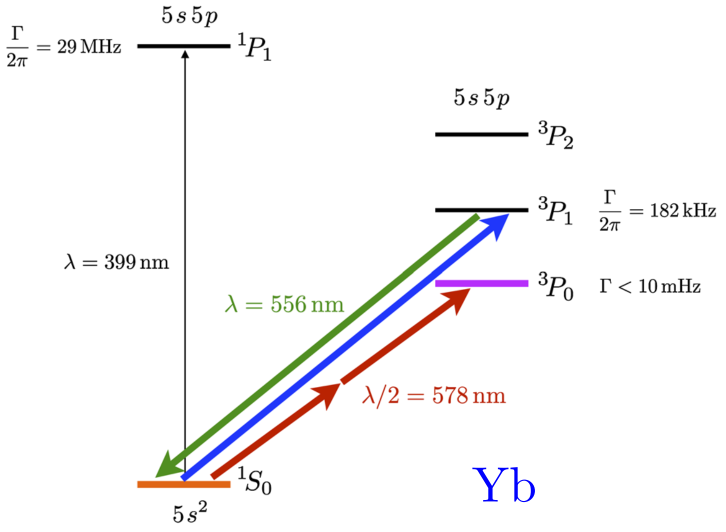


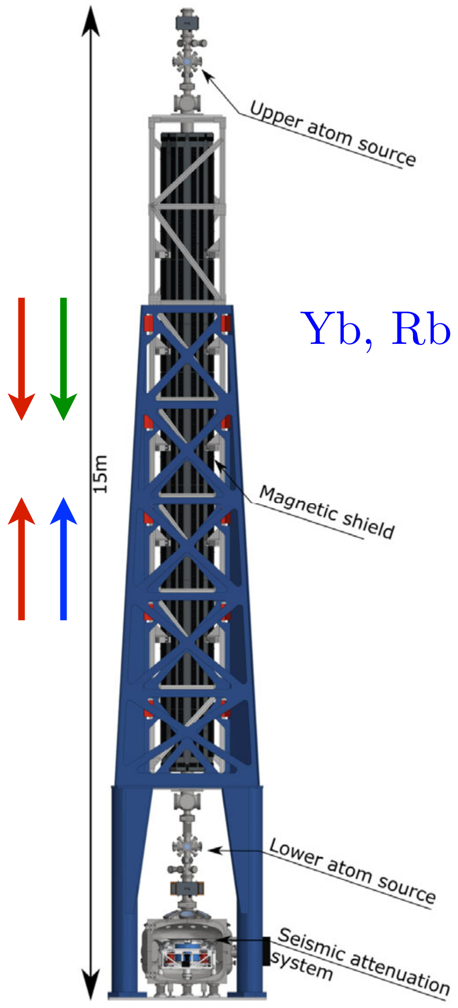
PHYSICAL REVIEW D **104**, 084001 (2021)

Measuring gravitational time dilation with delocalized quantum superpositions

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

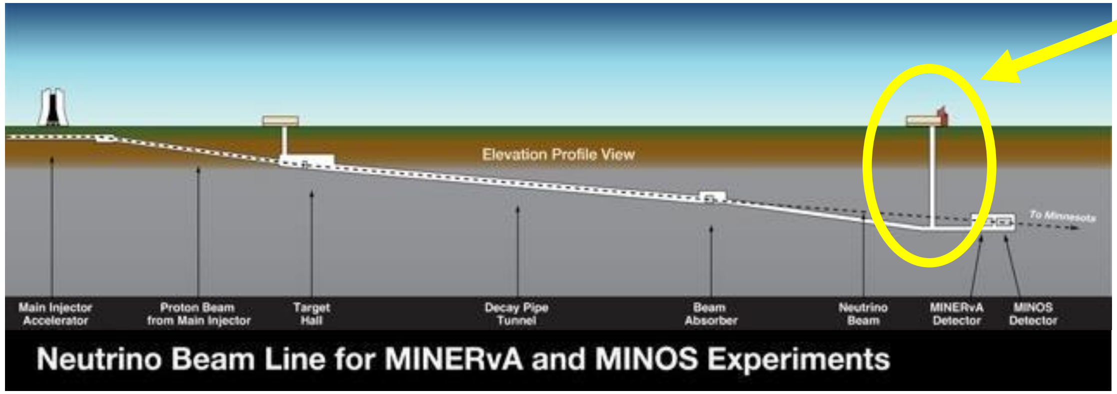






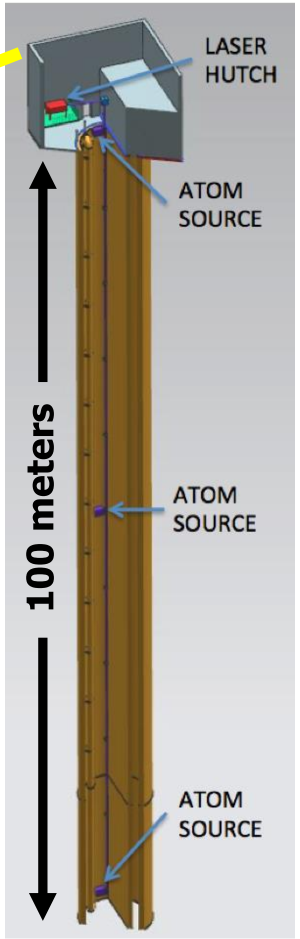
MAGIS-100: GW detector prototype at Fermilab

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor



- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Probes for ultralight scalar dark matter beyond current limits (Hz range)
- Extreme quantum superposition states: >meter wavepacket separation, up to 9 seconds duration

STANFORD Fermilab BERKELEY UNIVERSITY OF LIVERPOOL Northwestern University Northern Illinois University

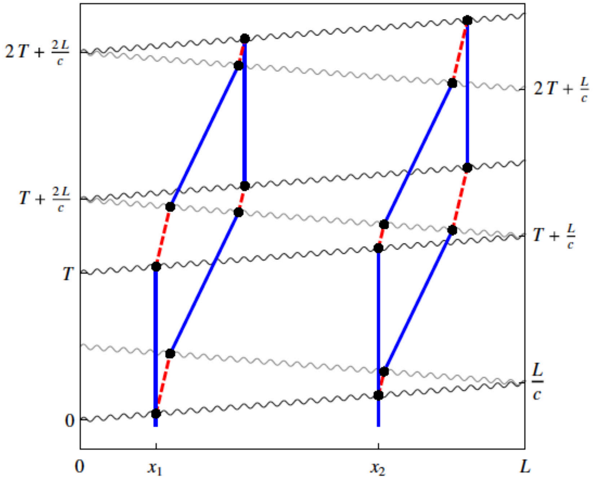


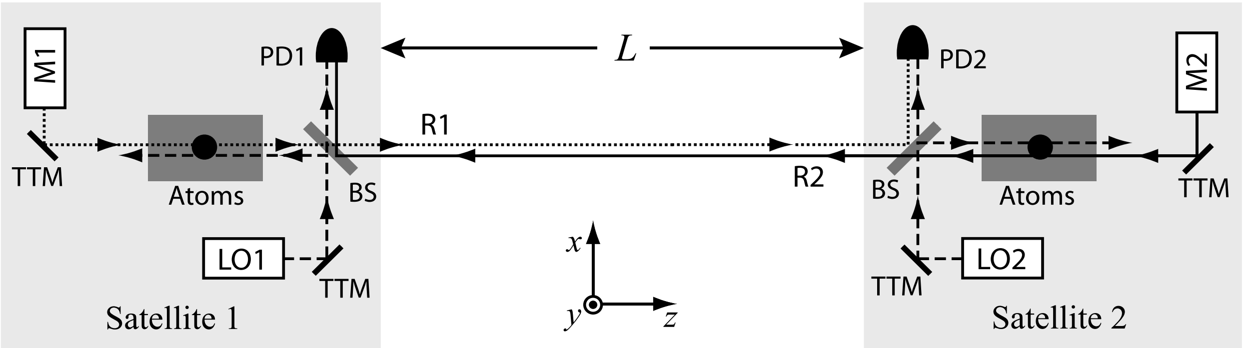
El-Neaj et al. *EPJ Quantum Technology* (2020) 7:6
https://doi.org/10.1140/epjqt/s40507-020-0080-0

EPJ Quantum Technology
a SpringerOpen Journal

RESEARCH Open Access

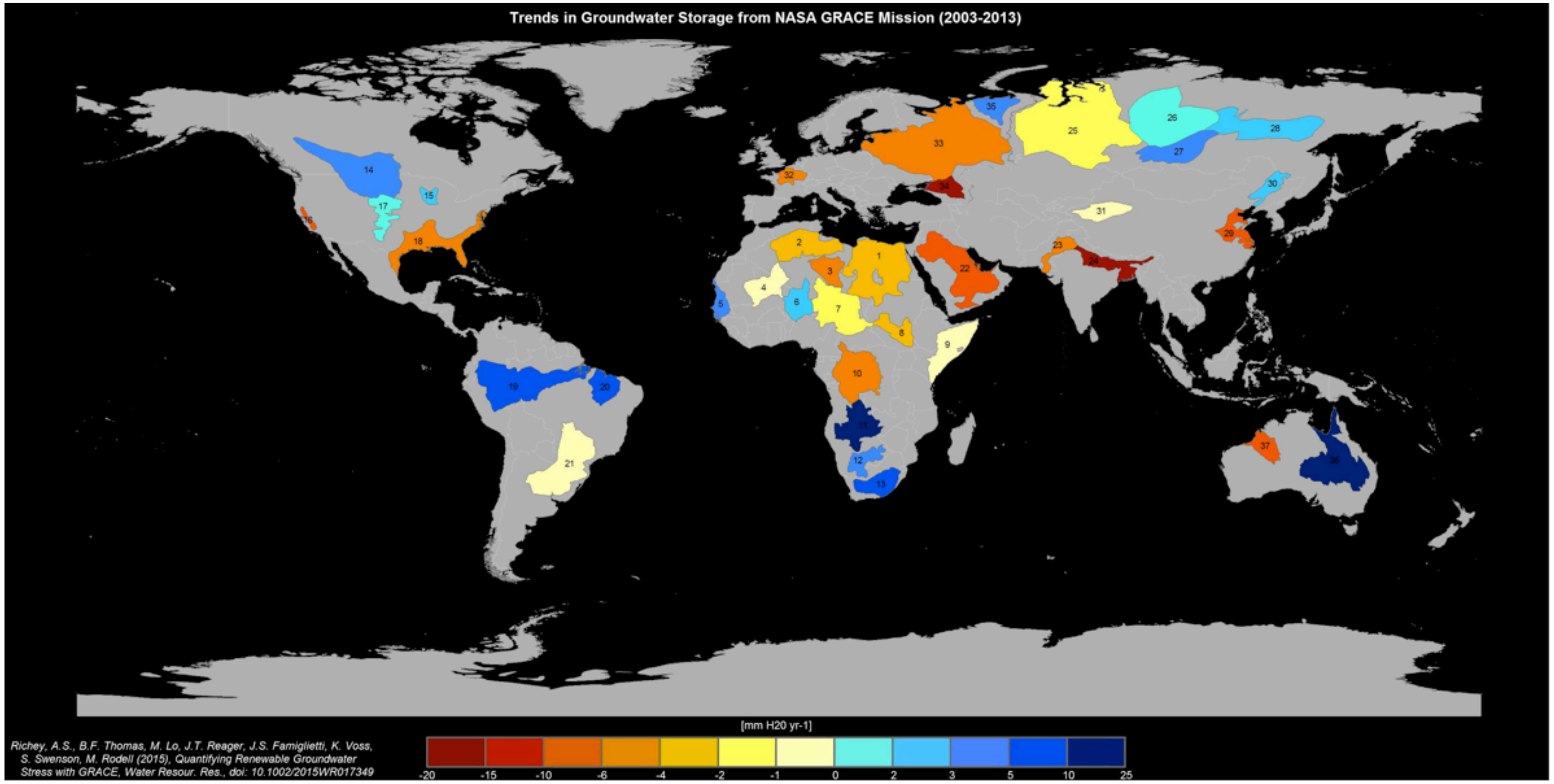
AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration in Space





Earth Observation

Monitoring groundwater aquifers from space through gravitational measurements:

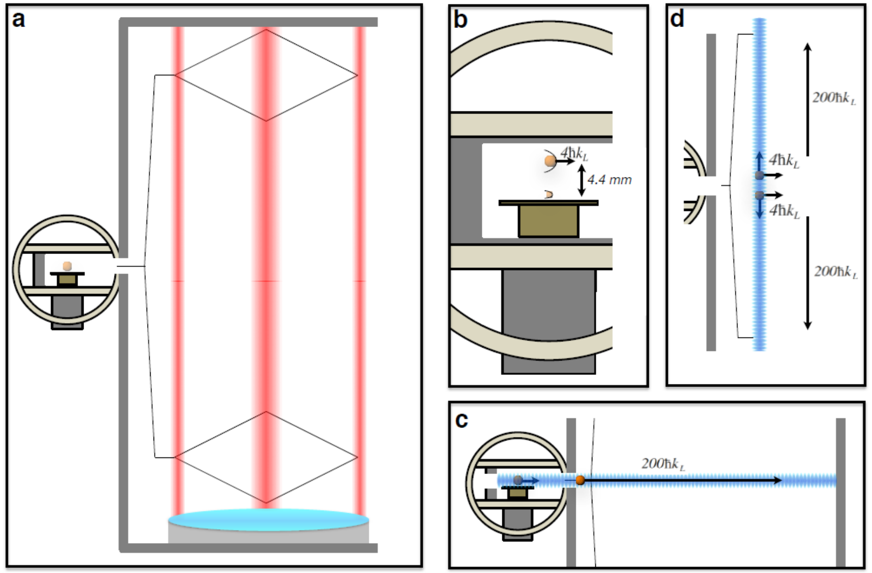


NASA GRACE Mission

Next Generation Gravity Mission (NGGM)

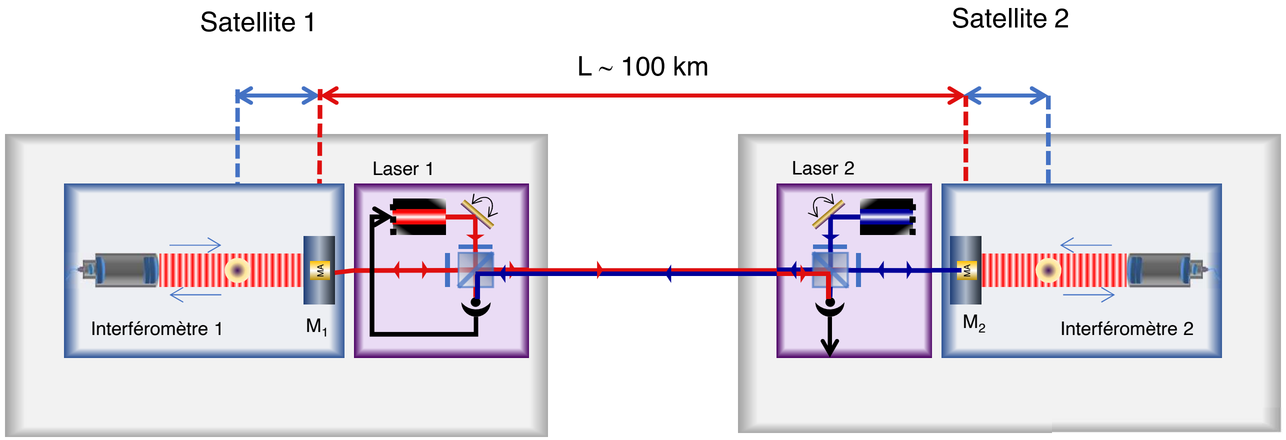
CAI gradiometer

F. Pereira dos Santos



$3\,\mathrm{mE\,Hz}^{-1/2}$

GRICE



T. Lévêque

$10\,\mu\mathrm{E\,Hz}^{-1/2}$

Summary

- Quantum communication
  (quantum key distribution, tests of QFT in curved spacetime, …)

- Time and frequency distribution
  (metrological applications, chronometric geodesy, gravitational redshift tests, …)

- Quantum sensing
  (gravimetry, tests of equivalence principle, dark-matter searches, …)

- Earth observation

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