Quantum Test of the Universality of Free Fall in Earth's Orbit

Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032
Research Campaign White Paper

Jason Williams[*1], David Aveline[1], Nicholas Bigelow[2,3], Sheng-wey Chiow[1], Ethan Elliott[1], Peter Engels[4], Naceur Gaaloul[5], James Kohel[1], Markus Krutzik[6], Nathan Lundblad[7], Matthias Meister[8], Ernst Rasel[5], Albert Roura[8], Cass Sackett[9], Matteo Sbroscia[1], Wolfgang Schleich[8,10,11,12,13], Robert Thompson[1], Lisa Wörner[14], and Nan Yu[1]

[*]Primary Author: jrwillia@jpl.nasa.gov, Phone: (818)354-8872
[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA
[2]Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA
[3]Center for Coherence and Quantum Optics, University of Rochester, Rochester, NY 14627, USA
[4]Department of Physics and Astronomy, Washington State University, Pullman, WA 99164, USA
[5]Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany
[6]Humboldt-Universität zu Berlin, Berlin, Germany
[7]Department of Physics and Astronomy, Bates College, Lewiston, ME 04240, USA
[8]Institute of Quantum Technologies, German Aerospace Center (DLR), Ulm, Germany
[9]Physics Department, University of Virginia, Charlottesville, VA 22904 USA
[10]Institut fur Quantenphysik and Center for Integrated Quantum Science and Technology (IQST), Ulm, Germany
[11]Hagler Institute for Advanced Study, Texas AM University, College Station, TX, USA
[12]Texas AM AgriLife Research, Texas AM University, College Station, TX, USA.
[13]Institute for Quantum Science and Engineering (IQSE), Department of Physics and Astronomy, Texas AM University, College Station, TX, USA.
[14]German Aerospace Center, Institute for Quantum Technologies (DLR-QT), Ulm, Germany

December 23, 2021

Abstract

Precision tests of Einstein's equivalence principle (EP) are essential to guide cutting-edge gravity theories. We propose an atom interferometer mission on an Earth-orbiting space station, with the primary objective of testing the universality of free-fall with two rubidium isotopes with a precision better than 10^{-15}. The space-station-based quantum EP test can also probe spin-gravity couplings and study coherent wave packets with large spatial separation. Moreover, they are postulated to be sensitive to ultralight dark-matter candidates and can explore the influence of gravity in quantum mechanics.

A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

1 Introduction

The lack of a comprehensive quantum theory of gravity and the unexplained origins of dark matter and dark energy hint that our understanding of gravity may not be complete. Testing the equivalence principle (EP) is one of the key methods for probing the fundamental nature of gravity. Without the EP, general relativity cannot be correct. However, the EP is (or may be) violated in many theories that attempt to join gravity with the standard model of particle physics (e.g., string theory, loop quantum gravity, higher dimensions, brane worlds) [1–4]. Tests of the EP are also sensitive to new physics, such as dilatons or moduli [5], and thus could be one of the best chances to detect new physics beyond the standard model.

Recent advances in ultra-cold atom physics and atom interferometry have provided new measurement capabilities [6–16], enabling tests of the EP with unprecedented precision. Already, laboratory experimental investigations have been carried out with atomic matter waves for tests of the Universality of Free-Fall (UFF) [17–22], for precise photon recoil measurements [23–25], for tests of inverse square laws of gravity [26–28], and for searches for "fifth" forces not explained by the Standard Model [29]. Notably, NASA's Cold Atom Lab (CAL) has been operating onboard the International Space Station (ISS) since 2018 [30]. A recent upgrade enabled atom interferometry to be demonstrated for the first time in orbit with single-species ultracold rubidium gases. Efforts are now ongoing to use this facility to mature the technology for future high-precision space-based EP tests.

The Quantum Test of the UFF in Earth's Orbit will fundamentally be a series of light-pulse atom interferometer (AI) experiments operating onboard a space station such as the ISS or similar platforms expected to be available in the near future. Its primary science objective would be to measure the differential gravitational acceleration between ^{87}Rb and ^{85}Rb to a precision better than one part in 10^{15}. In contrast to classical bulk-matter EP tests, AI-based measurements could allow access to rare isotopes, probe spin-gravity coupling, study coherent quantum wave packets, and explore the influence of gravity in quantum mechanics [31]. A secondary science objective is to achieve unprecedented photon recoil measurements. This can be accomplished by simply changing the interferometer measurement sequences. The improvement in the photon recoil measurement will result in the most stringent test of quantum electrodynamics by verifying the electron's gyromagnetic ratio, the most precise prediction made in any science [32], and can lead to the best realization of the unit of mass in the revised international system of units [33].

2 Flight Concept

The proposed space-station-based test of the EP in Earth's orbit derives from a Pre-Phase A concept study titled "Quantum Test of the Equivalence Principle and Space Time (QTEST)" [34], but is adapted to include recently developed cold-atom technologies for precision gravity science and updated with results from CAL and MAIUS (Matter-Wave Interferometry in Microgravity) space-based quantum gas and AI missions [30, 35, 36]. Notably, much of the precision gain of the mission concept over the ground experiments comes from the microgravity environment in orbit. The most recognized benefit is the extended free fall duration, allowing long interrogation times while minimizing the necessary length of the atom trajectories in the frame of reference of the instrument and, therefore, simplifying and enhancing environmental isolation and control.

Since, for Mach-Zehnder AI, the inertial-measurement sensitivity scales quadratically with the interrogation time (see Section 2.1), the sensitivity gain can be significant. Just as important for this mission concept is the ability to modulate gravity by rotating the setup on a rotation stage, which helps strongly reduce the systematic errors by phase sensitive detection (see Figure 2) [34]. Furthermore, a space environment will provide opportunities for new science. The high relative velocity of space stations makes it possible to perform precision tests of the relativistic properties of gravity [37, 38], i.e., terms in test theories that enter the signal proportional to the gravitational acceleration and a power of the velocity with respect to the source mass of the gravitational potential. Finally, the long interrogation time in a stable environment makes the mission optimally sensitive to time-dependent EP violating terms that will narrow the range of feasible dark matter candidates [39].

2.1 Quantum Test of the Weak Equivalence Principle

The observation that gravity appears to accelerate all objects in the same way, regardless of their structure, mass, charge, or composition (the UFF), serves as a cornerstone for modern gravitational theories. For the Einstein Equivalence Principle, this observation is central to the postulate that gravity is locally equivalent to being in an accelerated frame of reference. "Equivalence" here means that there is no experiment that can tell the two apart. Violations to the UFF are quantified by the Eötvös parameter η, which gives the normalized differential acceleration of two bodies (A and B) under the influence of gravity

$$\eta(A,B) = 2\frac{g^A - g^B}{g^A + g^B}$$

The mission will primarily seek for possible violations to the UFF ($\eta \neq 0$) using ultracold gases of A = ^{87}Rb and B = ^{85}Rb as quantum test masses. By a quantum test, we mean an experiment in which the wavelike properties of matter are used to measure the influence of gravity (e.g., based on matter-wave interferometers). One fundamental difference of quantum tests, as compared to classical ones, is that they are sensitive to the interference of matter waves as they evolve over time. In that way, they go beyond testing the UFF, and also probe the behavior of quantum mechanics on macroscopic length scales. The known discrepancies between general relativity and quantum mechanics are strong motivation for precision tests of quantum systems where gravity is important. As with atomic clocks, this quantum test would use the well-understood and controlled properties of ultracold atoms to mitigate systematic errors. All atoms of one species are alike and their interactions with the environment (magnetic and electric fields, radiation, background gas collisions, etc.) can be controlled to high precision. Neutral atoms are a close approximation to the textbook concept of a light, isolated, non-interacting point mass.

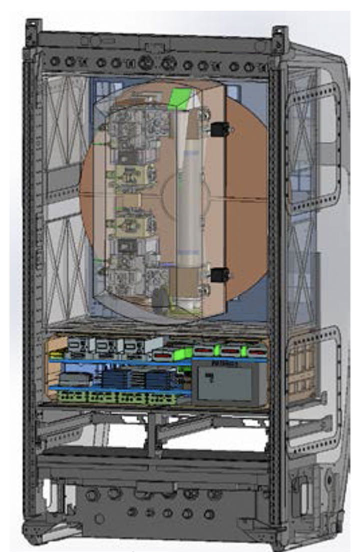

Figure 1: Engineering concept of the QTEST payload hosted in a Basic ISS Express Rack. The physics experiment module is mounted on a turntable at the top with two double lockers housing lasers, electronics, and the control system near the bottom.

AIs are highly sensitive to accelerations $\mathbf{a}$, with accumulated phase response in Mach-Zehnder configuration given by $\phi = (\mathbf{k}_{\text{eff}} \cdot \mathbf{a})T^2$, where $\mathbf{k}_{\text{eff}}$ is the effective wavevector and T is the free-evolution-time between interferometer pulses. The gravity-induced evolution of the relative atomic wavefunctions is measured by reading out the interference pattern in the atomic density distributions. We consider a cycle time of $T_c = 70$ s, given by reasonable microgravity-enabled interferometry interrogation times $2T = 20$ s and up to 50 s for atomic cloud sample preparation, cooling, state manipulation, detection, and positioning of the atoms and the rotating platform. Assuming each interferometer has a beam near-resonant to the D_2 transition in rubidium (i.e., $k_{\text{eff}} = 2\pi/(780 \text{ nm})$), contrasts in excess of 50%, and $N > 10^6$ detected atoms, the per-shot acceleration sensitivity for each rubidium AI is approximated as

$$\sigma = \sqrt{\frac{1}{N}}\frac{1}{Ck_{\text{eff}}T^2} \sim 10^{-13}g$$

The mission concept relies on differential measurements of two simultaneously interrogated atom interferometers (^{85}Rb and ^{87}Rb) to search for relevant violations of the UFF. For a total measurement time on orbit of 12 months, allowing for multiple $\tau = 3$-month measurement sets for noise reduction, the integrated acceleration sensitivity for each differential UFF measurement set is

$$\sigma_\eta = \sqrt{\frac{T_C(\sigma_{85}^2 + \sigma_{87}^2)}{\tau}} \sim 5 \times 10^{-16}g$$

It is anticipated that the Quantum Test of the Universality of Free Fall in Earth's Orbit will provide over two orders of magnitude improvement in constraining the Eötvös parameter over any previous quantum test of the UFF [17]. This station-based mission is expected to be a first-of-its-kind precision quantum sensor operating in space for searches of physics beyond the standard model. It will further serve as a path-finder and technology maturation platform for enabling high-precision quantum technologies that will enable new science in follow-on missions both on station-based and free-flyer platforms for the coming decades.

2.2 Space Station Enabled Flight Hardware

The experiment payload will mainly consist of the atom interferometer physics package (AIPP), a rotating platform, a laser and optics subsystem assembly, electronics, and control system. It is anticipated that the payload will closely resemble the notional hardware design developed for the QTEST concept (see Figure 1). The AIPP design is illustrated in Figure 2. Here, dual-species (^{85}Rb, ^{87}Rb) 2D Magneto Optical Traps (MOT) feed two identical atom-source regions at opposing sides of the vacuum chamber. The cold Rb beams are collected and simultaneously laser-cooled in 3D MOTs and subsequently evaporatively cooled (^{87}Rb) or sympathetically cooled (^{85}Rb) in Quadrupole Ioffee Pritchard magnetic traps [40, 41]. A final delta-kick cooling stage [42, 7, 13, 15] will reduce the kinetic energy of each atomic species, at each trap, to reach an effective temperature of less than 1 nK. Subsequent transfer to the $m_F = 0$ state will then mitigate the sensitivity of the clouds to magnetic fields and gradients.

After the complete cooling and preparation process, the ultra-cold atom clouds are transported to the science chamber, where AI measurements take place in a well-controlled and isolated environment, using an optical Bloch oscillation (OBO) technique. OBO is considered not only for its ability to transport atom ensembles without heating [43], but also with large momentum for reduced transport time. OBO of cold atoms in a moving optical lattice has transferred $> 1000\hbar k$ photon momenta in 10 ms for precision metrology [25, 43]. Interferometry for the two species will then be performed in the science chamber with a sequence of Bragg laser pulses at the so-called "magic wavelength", where the two-photon Rabi frequencies for ^{85}Rb and ^{87}Rb are identical [34]. With the planned interferometer interrogation time of $T = 10$ s, spatially inhomogeneous forces, including gravity gradients and rotations, would likely be sufficiently large to reduce the total contrast to zero. To mitigate these issues and still have the ability to take advantage of the long interrogation times accessible in space, this campaign would integrate rotation-compensating piezo-electric actuators on the AI retro mirror [44], laser frequency compensation to correct for gravity gradients [45], and imaging detection of the clouds with open interferometry [46, 9] to recover the contrast loss due to inhomogeneities. These demonstrated techniques will allow to recover spatially dependent phase shifts in long-time AIs that would otherwise be completely washed out with state-detection over the entire clouds.

2.3 Control and Suppression of Error Sources

High-sensitivity measurements of gravitational accelerations with AIs require extensive mitigation of systematic shifts to achieve their ultimate accuracy. As was already considered for QTEST, common-mode suppression of systematic errors will be maximized by using a highly symmetric measurement approach. This includes the use of two Rb isotopes with a single Bragg laser beam addressing both isotopes simultaneously. This helps to suppress the sensitivity to vibrational noise, which is necessary on the ISS and likely for all upcoming space station platforms. It will also use two dual-species sources, enabling two dual-species atom interferometers (four AIs in total) to be interrogated simultaneously in a time-reversed configuration. This reduces systematic error sources that are sensitive to the photon recoil and to the AI laser orientations. These are the key design points that would enable to achieve the primary science objectives.

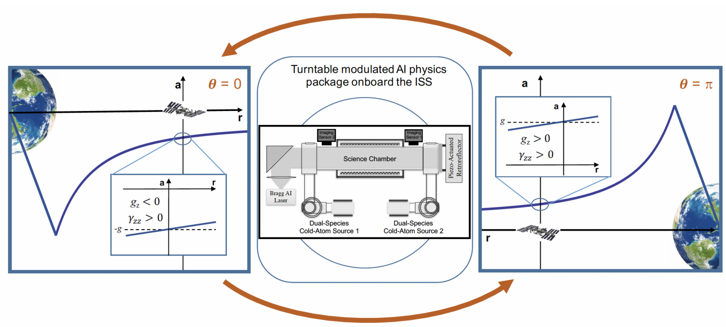

Figure 2: Illustration of the gravity modulation scheme in the context of the QTEST concept. The center figure is the atom interferometer EP experimental setup on a turntable which is modulated between 0 and π along the nadir direction z. In the reference frame of the turntable (experiment), the projection of the Earth's gravitational acceleration along z (g_z), and therefore the EP signal ($\eta k_{\text{eff}} g T^2$), changes sign as the turntable is modulated from $\Theta = 0$ (left) to $\Theta = \pi$ (right). On the other hand, the gravity gradient from Earth γ_{zz} remains the same under the modulation (by definition, the gravity and the gravity gradient of the instrument remain constant in the experiment reference frame). Therefore, the gravity gradient effects can be effectively suppressed in differential measurements. The insets emphasize that the modulation changes the relative sign between the gravitational acceleration g_z and gravity gradient γ_{zz}. Hence, gravity gradient sources both inside and external to the experimental apparatus can be distinguished from the gravity signal via demodulation.

The gravity gradient is expected to be the most serious systematic effect for cold atom based (quantum) EP tests. Here, species-dependent accelerations arise due to imperfect spatial overlap of test masses [34, 45, 47–50]. Various measures are necessary to control this systematic, e.g., extensive in-flight calibrations [47–49] or environmental control [50].

However, the effectiveness of these mitigations is not at all obvious. In Ref. [51], we reported that the gravity gradient dependent systematics, including those due to the instrument self gravity gradient and from the Earth itself, can be highly suppressed in AI-based EP tests when the apparatus is inverted by a turnable table (see Figure 2). When combined with the gravity-gradient compensation technique proposed in Ref.[45] and recently demonstrated [17], systematic shifts from the imperfect overlap of the atomic test masses (^{85}Rb and ^{87}Rb) are no longer a leading error source [52]. See Refs. [53–56] for a discussion of suppression techniques for the remaining significant error sources.

3 Notional Cost and Schedule

The proposed space-station-based quantum sensor for testing the UFF would rely heavily on the predecessor station-based cold atom facilities: CAL [30] and BECCAL [57]. The physics package, laser and optical subassemblies, electronics, and control system would all build on flight heritage hardware and are expected to be TRL 7 or above before the start of Phase A. However, a significant effort is still necessary before Phase B to mature the concept, reduce technological risk, and mitigate error sources that could degrade the science goals. Notably:

- Ultracold ^{85}Rb atom source (TRL 3)
- High precision matter-wave splitting and transport (TRL 3)
- Magnetic field systematic suppression (TRL 2)
- Imaging analysis and detection errors (TRL 3)
- Practical implementation of gravity modulation (TRL 3)
- Analyses of systematic error sources and space-enabled system performance

These risks will be mitigated and the hardware or techniques matured to TRL 6 by a concentrated 2-year ground-test campaign using a development testbed at JPL, collaboration with university researchers, CAL and BECCAL ground facilities and expertise, as well as European partners for possible collaborative risk reduction efforts. A high-level summary of the cost and schedule for the QTEST mission before launch is summarized in Table 1.

Table 1: QTEST mission cost estimate

Phase A	**Phase B**	**Phase C**		**Phase D**
Year 1	**Year 2**	**Year 3**	**Year 4**	**Year 5**
$8M	$14M	$41M	$35M	$15M

The $113M pre-flight cost is developed by a Grass Roots estimate using vendor quotes and reference to the actuals of the NASA CAL project where applicable with the assumptions that a) this will be a Class D mission b) the costs are adjusted for 3.1% annual inflation with an assumed start date of 2024, c) it includes payload development, integration, and operation only. No science NRA is included, d) no Onboard Replacement Units are included, e) it includes 10% funded schedule reserve and f) 30% project reserve, and g) the cost of the launch vehicle is not included. Note that the cost and schedule information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

References

[1] James Overduin, Francis Everitt, John Mester, and Paul Worden. The science case for STEP. Advances in Space Research, 43(10):1532–1537, 2009. ISSN 0273-1177. doi:https://doi.org/10.1016/j.asr.2009.02.012. URL https://www.sciencedirect.com/science/article/pii/S0273117709001458.

[2] Claus Lämmerzahl. The Einstein equivalence principle and the search for new physics. In Domenico J. W. Giulini, Claus Kiefer, and Claus Lämmerzahl, editors, Quantum Gravity: From Theory to Experimental Search, volume 631, pages 367–394. Springer, Berlin, Heidelberg, 2003. ISBN 978-3-540-45230-0. doi:10.1007/978-3-540-45230-0_11. URL https://doi.org/10.1007/978-3-540-45230-0_11.

[3] Thibault Damour. Theoretical aspects of the equivalence principle. Classical and Quantum Gravity, 29(18):184001, 2012. doi:10.1088/0264-9381/29/18/184001. URL https://doi.org/10.1088/0264-9381/29/18/184001.

[4] Ertan Göklü and Claus Lämmerzahl. Metric fluctuations and the weak equivalence principle. Classical and Quantum Gravity, 25(10):105012, 2008. doi:10.1088/0264-9381/25/10/105012. URL https://doi.org/10.1088/0264-9381/25/10/105012.

[5] Todd A. Wagner, S. Schlamminger, J. H. Gundlach, and E. G. Adelberger. Torsion-balance tests of the weak equivalence principle. Classical and Quantum Gravity, 29 (18):184002, 2012. doi:10.1088/0264-9381/29/18/184002. URL https://doi.org/10.1088/0264-9381/29/18/184002.

[6] Christian Deppner, Waldemar Herr, Merle Cornelius, Peter Stromberger, Tammo Sternke, Christoph Grzeschik, Alexander Grote, Jan Rudolph, Sven Herrmann, Markus Krutzik, André Wenzlawski, Robin Corgier, Eric Charron, David Guéry-Odelin, Naceur Gaaloul, Claus Lämmerzahl, Achim Peters, Patrick Windpassinger, and Ernst M. Rasel. Collective-mode enhanced matter-wave optics. Phys. Rev. Lett., 127:100401, Aug 2021. doi:10.1103/PhysRevLett.127.100401. URL https://link.aps.org/doi/10.1103/PhysRevLett.127.100401.

[7] Susannah M. Dickerson, Jason M. Hogan, Alex Sugarbaker, David M. S. Johnson, and Mark A. Kasevich. Multiaxis inertial sensing with long-time point source atom interferometry. Phys. Rev. Lett., 111:083001, Aug 2013. doi:10.1103/PhysRevLett.111.083001. URL https://link.aps.org/doi/10.1103/PhysRevLett.111.083001.

[8] Tim Kovachy, Jason M. Hogan, Alex Sugarbaker, Susannah M. Dickerson, Christine A. Donnelly, Chris Overstreet, and Mark A. Kasevich. Matter wave lensing to picokelvin temperatures. Phys. Rev. Lett., 114:143004, Apr 2015. doi:10.1103/PhysRevLett.114.143004. URL https://link.aps.org/doi/10.1103/PhysRevLett.114.143004.

[9] Alex Sugarbaker, Susannah M. Dickerson, Jason M. Hogan, David M. S. Johnson, and Mark A. Kasevich. Enhanced atom interferometer readout through the application of phase shear. Phys. Rev. Lett., 111:113002, Sep 2013.

doi:10.1103/PhysRevLett.111.113002. URL https://link.aps.org/doi/10.1103/PhysRevLett.111.113002.

[10] Sheng-wey Chiow, Tim Kovachy, Hui-Chun Chien, and Mark A. Kasevich. $102\hbar k$ large area atom interferometers. Phys. Rev. Lett., 107:130403, 2011. doi:10.1103/PhysRevLett.107.130403. URL https://link.aps.org/doi/10.1103/PhysRevLett.107.130403.

[11] Fiodor Sorrentino, Kai Bongs, Philippe Bouyer, Luigi Cacciapuoti, Marella de Angelis, Hansjoerg Dittus, Wolfgang Ertmer, A. Giorgini, J. Hartwig, Matthias Hauth, Sven Herrmann, Massimo Inguscio, Endre Kajari, Thorben T. Könemann, Claus Lämmerzahl, Arnaud Landragin, Giovanni Modugno, Frank Pereira dos Santos, Achmin Peters, Marco Prevedelli, Ernst M. Rasel, Wolfgang P. Schleich, Malte Schmidt, Alexander Senger, Klaus Sengstock, Guillaume Stern, Guglielmo Maria Tino, and Reinhold Walser. A compact atom interferometer for future space missions. Microgravity Science and Technology, 22(4):551–561, 2010. doi:10.1007/s12217-010-9240-7. URL https://doi.org/10.1007/s12217-010-9240-7.

[12] C. C. N. Kuhn, G. D. McDonald, K. S. Hardman, S. Bennetts, P. J. Everitt, P. A. Altin, J. E. Debs, J. D. Close, and N. P. Robins. A Bose-condensed, simultaneous dual-species Mach-Zehnder atom interferometer. New Journal of Physics, 16(7):073035, 2014. doi:10.1088/1367-2630/16/7/073035.

[13] H. Müntinga, H. Ahlers, M. Krutzik, A. Wenzlawski, S. Arnold, D. Becker, K. Bongs, H. Dittus, H. Duncker, N. Gaaloul, C. Gherasim, E. Giese, C. Grzeschik, T. W. Hänsch, O. Hellmig, W. Herr, S. Herrmann, E. Kajari, S. Kleinert, C. Lämmerzahl, W. Lewoczko-Adamczyk, J. Malcolm, N. Meyer, R. Nolte, A. Peters, M. Popp, J. Reichel, A. Roura, J. Rudolph, M. Schiemangk, M. Schneider, S. T. Seidel, K. Sengstock, V. Tamma, T. Valenzuela, A. Vogel, R. Walser, T. Wendrich, P. Windpassinger, W. Zeller, T. van Zoest, W. Ertmer, W. P. Schleich, and E. M. Rasel. Interferometry with Bose-Einstein condensates in microgravity. Phys. Rev. Lett., 110:093602, Feb 2013. doi:10.1103/PhysRevLett.110.093602. URL https://link.aps.org/doi/10.1103/PhysRevLett.110.093602.

[14] T. Mazzoni, X. Zhang, R. Del Aguila, L. Salvi, N. Poli, and G. M. Tino. Large-momentum-transfer Bragg interferometer with strontium atoms. Phys. Rev. A, 92:053619, Nov 2015. doi:10.1103/PhysRevA.92.053619. URL https://link.aps.org/doi/10.1103/PhysRevA.92.053619.

[15] Simon Kanthak, Martina Gebbe, Matthias Gersemann, Sven Abend, Ernst M Rasel, and Markus Krutzik. Time-domain optics for atomic quantum matter. New Journal of Physics, 23(9):093002, sep 2021. doi:10.1088/1367-2630/ac1285. URL https://doi.org/10.1088/1367-2630/ac1285.

[16] Peter Asenbaum, Chris Overstreet, Tim Kovachy, Daniel D. Brown, Jason M. Hogan, and Mark A. Kasevich. Phase shift in an atom interferometer due to spacetime curvature across its wave function. Phys. Rev. Lett., 118:183602, May 2017. doi:10.1103/PhysRevLett.118.183602. URL https://link.aps.org/doi/10.1103/PhysRevLett.118.183602.

[17] Peter Asenbaum, Chris Overstreet, Minjeong Kim, Joseph Curti, and Mark A. Kasevich. Atom-interferometric test of the equivalence principle at the 10^{-12} level. Phys. Rev. Lett., 125:191101, Nov 2020. doi:10.1103/PhysRevLett.125.191101. URL https://link.aps.org/doi/10.1103/PhysRevLett.125.191101.

[18] Sebastian Fray and Martin Weitz. Atom-based test of the equivalence principle. Space Science Reviews, 148(1):225–232, 2009. doi:10.1007/s11214-009-9566-x.

[19] A. Bonnin, N. Zahzam, Y. Bidel, and A. Bresson. Simultaneous dual-species matter-wave accelerometer. Phys. Rev. A, 88:043615, Oct 2013. doi:10.1103/PhysRevA.88.043615. URL https://link.aps.org/doi/10.1103/PhysRevA.88.043615.

[20] D. Schlippert, J. Hartwig, H. Albers, L. L. Richardson, C. Schubert, A. Roura, W. P. Schleich, W. Ertmer, and E. M. Rasel. Quantum test of the universality of free fall. Phys. Rev. Lett., 112:203002, May 2014. doi:10.1103/PhysRevLett.112.203002. URL https://link.aps.org/doi/10.1103/PhysRevLett.112.203002.

[21] Lin Zhou, Shitong Long, Biao Tang, Xi Chen, Fen Gao, Wencui Peng, Weitao Duan, Jiaqi Zhong, Zongyuan Xiong, Jin Wang, Yuanzhong Zhang, and Mingsheng Zhan. Test of equivalence principle at 10^{-8} level by a dual-species double-diffraction Raman atom interferometer. Phys. Rev. Lett., 115:013004, Jul 2015. doi:10.1103/PhysRevLett.115.013004. URL https://link.aps.org/doi/10.1103/PhysRevLett.115.013004.

[22] M. G. Tarallo, T. Mazzoni, N. Poli, D. V. Sutyrin, X. Zhang, and G. M. Tino. Test of Einstein equivalence principle for 0-spin and half-integer-spin atoms: Search for spin-gravity coupling effects. Phys. Rev. Lett., 113:023005, Jul 2014. doi:10.1103/PhysRevLett.113.023005. URL https://link.aps.org/doi/10.1103/PhysRevLett.113.023005.

[23] Léo Morel, Zhibin Yao, Pierre Cladé, and Saïda Guellati-Khélifa. Determination of the fine-structure constant with an accuracy of 81 parts per trillion. Nature, 588 (7836):61–65, 2020. ISSN 1476-4687. doi:10.1038/s41586-020-2964-7. URL https://doi.org/10.1038/s41586-020-2964-7.

[24] Richard H. Parker, Chenghui Yu, Weicheng Zhong, Brian Estey, and Holger Müller. Measurement of the fine-structure constant as a test of the standard model. Science, 360(6385):191–195, 2018. doi:10.1126/science.aap7706. URL https://www.science.org/doi/abs/10.1126/science.aap7706.

[25] Pierre Cladé, Estefania de Mirandes, Malo Cadoret, Saïda Guellati-Khélifa, Catherine Schwob, François Nez, Lucile Julien, and François Biraben. Precise measurement of h/m_{Rb} using Bloch oscillations in a vertical optical lattice: Determination of the fine-structure constant. Phys. Rev. A, 74:052109, 2006. doi:10.1103/PhysRevA.74.052109. URL https://link.aps.org/doi/10.1103/PhysRevA.74.052109.

[26] G. W. Biedermann, X. Wu, L. Deslauriers, S. Roy, C. Mahadeswaraswamy, and M. A. Kasevich. Testing gravity with cold-atom interferometers. Phys. Rev. A, 91:033629,

Mar 2015. doi:10.1103/PhysRevA.91.033629. URL https://link.aps.org/doi/10.1103/PhysRevA.91.033629.

[27] G. Ferrari, N. Poli, F. Sorrentino, and G. M. Tino. Long-lived Bloch oscillations with bosonic Sr atoms and application to gravity measurement at the micrometer scale. Phys. Rev. Lett., 97:060402, Aug 2006. doi:10.1103/PhysRevLett.97.060402. URL https://link.aps.org/doi/10.1103/PhysRevLett.97.060402.

[28] P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Müller, and J. Khoury. Atom-interferometry constraints on dark energy. Science, 349(6250):849–851, 2015. doi:10.1126/science.aaa8883. URL https://www.science.org/doi/abs/10.1126/science.aaa8883.

[29] Matt Jaffe, Philipp Haslinger, Victoria Xu, Paul Hamilton, Amol Upadhye, Benjamin Elder, Justin Khoury, and Holger Müller. Testing sub-gravitational forces on atoms from a miniature in-vacuum source mass. Nature Physics, 13(10):938–942, 2017. ISSN 1745-2481. doi:10.1038/nphys4189. URL https://doi.org/10.1038/nphys4189.

[30] David C. Aveline, Jason R. Williams, Ethan R. Elliott, Chelsea Dutenhoffer, James R. Kellogg, James M. Kohel, Norman E. Lay, Kamal Oudrhiri, Robert F. Shotwell, Nan Yu, and Robert J. Thompson. Observation of Bose-Einstein condensates in an Earth-orbiting research lab. Nature, 582(7811):193–197, 2020. doi:10.1038/s41586-020-2346-1. URL https://doi.org/10.1038/s41586-020-2346-1.

[31] Brett Altschul, Quentin G. Bailey, Luc Blanchet, Kai Bongs, Philippe Bouyer, Luigi Cacciapuoti, Salvatore Capozziello, Naceur Gaaloul, Domenico Giulini, Jonas Hartwig, Luciano Iess, Philippe Jetzer, Arnaud Landragin, Ernst Rasel, Serge Reynaud, Stephan Schiller, Christian Schubert, Fiodor Sorrentino, Uwe Sterr, Jay D. Tasson, Guglielmo M. Tino, Philip Tuckey, and Peter Wolf. Quantum tests of the Einstein Equivalence Principle with the STE-QUEST space mission. Advances in Space Research, 55(1):501–524, 2015. ISSN 0273-1177. doi:https://doi.org/10.1016/j.asr.2014.07.014. URL https://www.sciencedirect.com/science/article/pii/S0273117714004384.

[32] Tatsumi Aoyama, Masashi Hayakawa, Toichiro Kinoshita, and Makiko Nio. Tenth-order QED contribution to the electron $g-2$ and an improved value of the fine structure constant. Phys. Rev. Lett., 109:111807, Sep 2012. doi:10.1103/PhysRevLett.109.111807. URL https://link.aps.org/doi/10.1103/PhysRevLett.109.111807.

[33] Shau-Yu Lan, Pei-Chen Kuan, Brian Estey, Damon English, Justin M. Brown, Michael A. Hohensee, and Holger Müller. A clock directly linking time to a particle's mass. Science, 339(6119):554–557, 2013. doi:10.1126/science.1230767. URL https://www.science.org/doi/abs/10.1126/science.1230767.

[34] Jason Williams, Sheng-wey Chiow, Nan Yu, and Holger Müller. Quantum test of the equivalence principle and space-time aboard the International Space Station. New J. Phys., 18:025018, 2016. doi:10.1088/1367-2630/18/2/025018.

[35] Dennis Becker, Maike D. Lachmann, Stephan T. Seidel, Holger Ahlers, Aline N. Dinkelaker, Jens Grosse, Ortwin Hellmig, Hauke Müntinga, Vladimir Schkolnik, Thijs Wendrich, André Wenzlawski, Benjamin Weps, Robin Corgier, Tobias Franz, Naceur Gaaloul, Waldemar Herr, Daniel Lüdtke, Manuel Popp, Sirine Amri, Hannes Duncker, Maik Erbe, Anja Kohfeldt, André Kubelka-Lange, Claus Braxmaier, Eric Charron, Wolfgang Ertmer, Markus Krutzik, Claus Lämmerzahl, Achim Peters, Wolfgang P. Schleich, Klaus Sengstock, Reinhold Walser, Andreas Wicht, Patrick Windpassinger, and Ernst M. Rasel. Space-borne Bose-Einstein condensation for precision interferometry. Nature, 562(7727):391–395, 2018. doi:10.1038/s41586-018-0605-1. URL `https://doi.org/10.1038/s41586-018-0605-1`.

[36] Maike D. Lachmann, Holger Ahlers, Dennis Becker, Aline N. Dinkelaker, Jens Grosse, Ortwin Hellmig, Hauke Müntinga, Vladimir Schkolnik, Stephan T. Seidel, Thijs Wendrich, André Wenzlawski, Benjamin Carrick, Naceur Gaaloul, Daniel Lüdtke, Claus Braxmaier, Wolfgang Ertmer, Markus Krutzik, Claus Lämmerzahl, Achim Peters, Wolfgang P. Schleich, Klaus Sengstock, Andreas Wicht, Patrick Windpassinger, and Ernst M. Rasel. Ultracold atom interferometry in space. Nature Communications, 12(1):1317, 2021. doi:10.1038/s41467-021-21628-z. URL `https://doi.org/10.1038/s41467-021-21628-z`.

[37] Peter W. Graham, David E. Kaplan, Jeremy Mardon, Surjeet Rajendran, and William A. Terrano. Dark matter direct detection with accelerometers. Phys. Rev. D, 93:075029, Apr 2016. doi:10.1103/PhysRevD.93.075029. URL `https://link.aps.org/doi/10.1103/PhysRevD.93.075029`.

[38] Dawid Brzeminski, Zackaria Chacko, Abhish Dev, and Anson Hook. Time-varying fine structure constant from naturally ultralight dark matter. Phys. Rev. D, 104:075019, Oct 2021. doi:10.1103/PhysRevD.104.075019. URL `https://link.aps.org/doi/10.1103/PhysRevD.104.075019`.

[39] Clifford M. Will. Theory and Experiment in Gravitational Physics. Cambridge University Press, 2 edition, 2018. ISBN 9781316338612. doi:10.1017/9781316338612.

[40] Immanuel Bloch, Markus Greiner, Olaf Mandel, Theodor W. Hänsch, and Tilman Esslinger. Sympathetic cooling of ^{85}Rb and ^{87}Rb. Phys. Rev. A, 64:021402, Jul 2001. doi:10.1103/PhysRevA.64.021402. URL `https://link.aps.org/doi/10.1103/PhysRevA.64.021402`.

[41] P. A. Altin, N. P. Robins, D. Döring, J. E. Debs, R. Poldy, C. Figl, and J. D. Close. ^{85}Rb tunable-interaction Bose-Einstein condensate machine. Review of Scientific Instruments, 81(6):063103, 2010. doi:10.1063/1.3430538. URL `https://doi.org/10.1063/1.3430538`.

[42] Hubert Ammann and Nelson Christensen. Delta kick cooling: A new method for cooling atoms. Phys. Rev. Lett., 78:2088–2091, Mar 1997. doi:10.1103/PhysRevLett.78.2088. URL `https://link.aps.org/doi/10.1103/PhysRevLett.78.2088`.

[43] Pierre Cladé. Bloch oscillations in atom interferometry, 2015. URL `https://arxiv.org/abs/10.1393/ncr/i2015-10111-3`.

[44] Shau-Yu Lan, Pei-Chen Kuan, Brian Estey, Philipp Haslinger, and Holger Müller. Influence of the Coriolis force in atom interferometry. Phys. Rev. Lett., 108:090402, Feb 2012. doi:10.1103/PhysRevLett.108.090402. URL https://link.aps.org/doi/10.1103/PhysRevLett.108.090402.

[45] Albert Roura. Circumventing Heisenberg's uncertainty principle in atom interferometry tests of the equivalence principle. Phys. Rev. Lett., 118:160401, Apr 2017. doi:10.1103/PhysRevLett.118.160401. URL https://link.aps.org/doi/10.1103/PhysRevLett.118.160401.

[46] Albert Roura, Wolfgang Zeller, and Wolfgang P. Schleich. Overcoming loss of contrast in atom interferometry due to gravity gradients. New Journal of Physics, 16 (12):123012, 2014. doi:10.1088/1367-2630/16/12/123012. URL https://doi.org/10.1088/1367-2630/16/12/123012.

[47] P. Touboul, G. Métris, V. Lebat, and A. Robert. The MICROSCOPE experiment, ready for the in-orbit test of the equivalence principle. Classical and Quantum Gravity, 29(18):184010, 2012. doi:10.1088/0264-9381/29/18/184010. URL https://doi.org/10.1088/0264-9381/29/18/184010.

[48] Émilie Hardy, Agnès Levy, Manuel Rodrigues, Pierre Touboul, and Gilles Métris. Validation of the in-flight calibration procedures for the MICROSCOPE space mission. Advances in Space Research, 52(9):1634–1646, 2013. ISSN 0273-1177. doi:https://doi.org/10.1016/j.asr.2013.07.042. URL https://www.sciencedirect.com/science/article/pii/S0273117713004717.

[49] Pierre Touboul, Gilles Métris, Manuel Rodrigues, Yves André, Quentin Baghi, Joel Bergé, Damien Boulanger, Stefanie Bremer, Ratana Chhun, Bruno Christophe, Valerio Cipolla, Thibault Damour, Pascale Danto, Hansjoerg Dittus, Pierre Fayet, Bernard Foulon, Pierre-Yves Guidotti, Emilie Hardy, Phuong-Anh Huynh, Claus Lämmerzahl, Vincent Lebat, Françoise Liorzou, Meike List, Isabelle Panet, Sandrine Pires, Benjamin Pouilloux, Pascal Prieur, Serge Reynaud, Benny Rievers, Alain Robert, Hanns Selig, Laura Serron, Timothy Sumner, and Pieter Visser. Space test of the equivalence principle: first results of the MICROSCOPE mission. Classical and Quantum Gravity, 36(22):225006, Oct 2019. doi:10.1088/1361-6382/ab4707. URL https://doi.org/10.1088/1361-6382/ab4707.

[50] Jason M. Hogan, David M. S. Johnson, and Mark A. Kasevich. Light-pulse atom interferometry. In Proceedings of the International School of Physics "Enrico Fermi", volume 168, 2009. doi:10.3254/978-1-58603-990-5-411.

[51] Sheng-wey Chiow, Jason Williams, Nan Yu, and Holger Müller. Gravity-gradient suppression in spaceborne atomic tests of the equivalence principle. Phys. Rev. A, 95: 021603, 2017. doi:10.1103/PhysRevA.95.021603. URL https://link.aps.org/doi/10.1103/PhysRevA.95.021603.

[52] Sina Loriani, Christian Schubert, Dennis Schlippert, Wolfgang Ertmer, Franck Pereira Dos Santos, Ernst Maria Rasel, Naceur Gaaloul, and Peter Wolf. Resolution of the colocation problem in satellite quantum tests of the universality of free fall. Phys. Rev.

D, 102:124043, Dec 2020. doi:10.1103/PhysRevD.102.124043. URL https://link.aps.org/doi/10.1103/PhysRevD.102.124043.

[53] Jian-Gong Hu, Xi Chen, Li-Yong Wang, Qing-Hong Liao, and Qing-Nian Wang. Systematic error suppression scheme of the weak equivalence principle test by dual atom interferometers in space based on spectral correlation. Chinese Physics B, 29(11):110305, 2020. doi:10.1088/1674-1056/aba609. URL https://doi.org/10.1088/1674-1056/aba609.

[54] Anna M. Nobili. Fundamental limitations to high-precision tests of the universality of free fall by dropping atoms. Phys. Rev. A, 93:023617, Feb 2016. doi:10.1103/PhysRevA.93.023617. URL https://link.aps.org/doi/10.1103/PhysRevA.93.023617.

[55] Anna M. Nobili, Alberto Anselmi, and Raffaello Pegna. Systematic errors in high-precision gravity measurements by light-pulse atom interferometry on the ground and in space. Phys. Rev. Research, 2:012036, Feb 2020. doi:10.1103/PhysRevResearch.2.012036. URL https://link.aps.org/doi/10.1103/PhysRevResearch.2.012036.

[56] Christian Ufrecht. Generalized gravity-gradient mitigation scheme. Phys. Rev. A, 103:023305, Feb 2021. doi:10.1103/PhysRevA.103.023305. URL https://link.aps.org/doi/10.1103/PhysRevA.103.023305.

[57] Kai Frye, Sven Abend, Wolfgang Bartosch, Ahmad Bawamia, Dennis Becker, Holger Blume, Claus Braxmaier, Sheng-Wey Chiow, Maxim A Efremov, Wolfgang Ertmer, Peter Fierlinger, Tobias Franz, Naceur Gaaloul, Jens Grosse, Christoph Grzeschik, Ortwin Hellmig, Victoria A Henderson, Waldemar Herr, Ulf Israelsson, James Kohel, Markus Krutzik, Christian Kürbis, Claus Lämmerzahl, Meike List, Daniel Lüdtke, Nathan Lundblad, J Pierre Marburger, Matthias Meister, Moritz Mihm, Holger Müller, Hauke Müntinga, Ayush M Nepal, Tim Oberschulte, Alexandros Papakonstantinou, Jaka Perovsek, Achim Peters, Arnau Prat, Ernst M Rasel, Albert Roura, Matteo Sbroscia, Wolfgang P Schleich, Christian Schubert, Stephan T Seidel, Jan Sommer, Christian Spindeldreier, Dan Stamper-Kurn, Benjamin K Stuhl, Marvin Warner, Thijs Wendrich, André Wenzlawski, Andreas Wicht, Patrick Windpassinger, Nan Yu, and Lisa Wörner. The Bose-Einstein Condensate and Cold Atom Laboratory. EPJ Quantum Technology, 8(1):1, 2021. ISSN 2196-0763. doi:10.1140/epjqt/s40507-020-00090-8. URL https://doi.org/10.1140/epjqt/s40507-020-00090-8.