Topical Whitepaper for BPS Decadal Survey 2021

Title: Atomic dark energy detection in space

Authors: Sheng-wey Chiow[1], Nan Yu[1], Albert Roura[2], Maike D. Lachmann[3], Ernst M. Rasel[3], Vladimir Schkolnik[4]

Institutions:

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

[2]Institute of Quantum Technologies, German Aerospace Center (DLR), Söflinger Straße 100, D-89077 Ulm, Germany

[3]Institute of Quantum Optics, QUEST-Leibniz Research School, Leibniz University Hannover, Welfengarten 1, 30167 Hannover, Germany

[4]Joint Lab Integrated Quantum Sensors, Humboldt-Universität zu Berlin, Institute of Physics, Newtonstraße 15, 12489 Berlin, Germany

Overview

We advocate pursuing atom-interferometric tests of thin-shell theories of dark energy in prolonged microgravity environments. The endeavor can utilize platforms and facilities including drop towers, the International Space Station (ISS) or alike, and free-flyers. The anticipated advancement in the understanding of nature of dark energy will complement results from future terrestrial and space telescopes where some models are indistinguishable [1, 2]. In the past decade, atom interferometry technology has matured from prestige labs to some microgravity platforms. In the coming decade, directed efforts from NASA on testing thin-shell models of dark energy in space will leverage previous NASA investments and achievements, and will improve constraints on dark energy model by orders of magnitude.

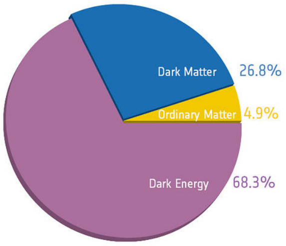

Figure 1. Constituents of our Universe [3].

Dark energy – the missing piece of the Universe

To the best of human knowledge to date, dark energy contributes 68% of the average energy density of the physical Universe [3] (Figure 1). Normal matter, as we can see and manipulate, makes up about only 5% of the energy content of the Universe. Dark matter, a Nobel Prize winning discovery [4], is responsible for the additional gravity that helps form the astonishing spiral shape of a galaxy. It contributes another 27% of the Universe. Although the exact underlying nature of dark matter is still unknown, its presence is genuine and observable. Dark energy, another Nobel Prize winning discovery [5], is characterized by a large negative pressure that gives rise to an accelerated cosmological expansion and hence of the separation between distant galaxies. An important class of dark energy models involve very light scalar fields. However, such light fields would mediate long-range interactions that would result in a "fifth force" that has never been observed on Earth or in the solar system. This difficulty can be circumvented through a "screening mechanism" of the dark energy field near normal matter [6-9], and it is a prerequisite for viable dark energy models of this kind.

Dark energy searches have been focused on better observations of universe expansion over cosmological timescales, efforts including the Rubin Observatory (terrestrial) [10], the Euclid mission (ESA) [11], and the Roman space telescope (NASA) [12]. However, observational data may not elucidate the underlying physical cause of the accelerating expansion.

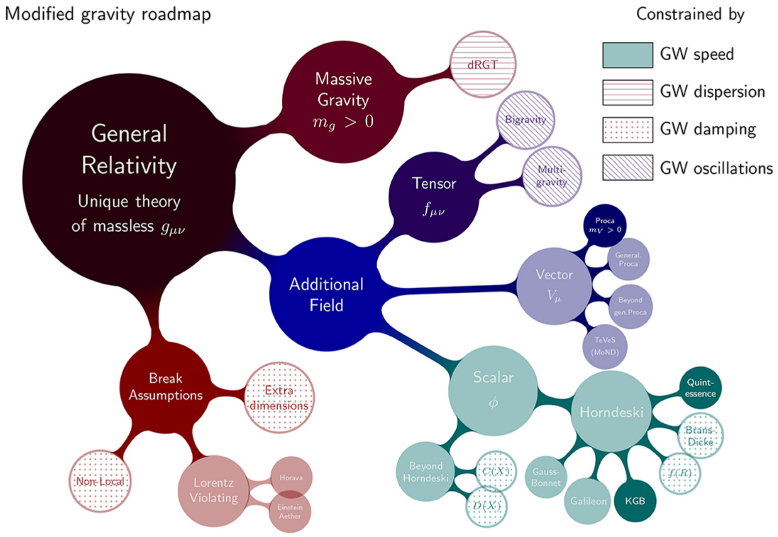

Figure 2. Modified gravity theories, adapted from [13].

Modified gravity theories have been developed to describe dark energy [13]. Figure 2 illustrates the richness of the area of research, and also the lack of knowledge. Among them, theories based on additional scalar fields are attractive [9, 14-16]. Scalar fields of low-order nonlinearity, such as the chameleon model and the symmetron model [17], are of particular interest. Indeed, both chameleon and symmetron feature short penetration depths (thin-shell) of the scalar field into normal matter, and thus naturally facilitate the screening mechanism.

Recently, researchers identified that thin-shell models can be verified/invalidated in lab and discerned from other models by precise force measurements [6-8, 18-22]. Given the same thin-shell thickness, small objects would have fractionally larger volume experiencing the dark energy field than larger objects, and thus larger dark energy induced accelerations. This readily violates the Equivalence Principle. Moreover, in gravity measurements, this extra force will violate the inverse square law of gravity. Most interestingly, in thin-shell models, single atoms are at least a billion times more prone to the hypothetical scalar fields, which makes it feasible to directly detect dark energy in a laboratory setting [6]. This is in sharp contrast to passive observation of the evolution of Universe, and thus pioneers a new path in the investigation of dark energy.

Atom interferometry as a direct probe for dark energy

Atom interferometry employs the wave nature of single atoms for interferometric measurements [23-26]. The operating principle is well-described by quantum mechanics, and essentially includes only free evolution of a particle and atom-light interactions that are based merely on the atomic structure and fundamental constants. Due to the simplicity of the physical mechanism, atom interferometers exhibit both accuracy and precision, and also direct sensitivity to fundamental phenomena such as variation of physical constants [27].

One can easily perceive the synergy of testing thin-shell models by using atom interferometry. Indeed, the concept has been explored in laboratories [18, 28-31]. Forces other than gravity were sought by implementing atomic gravimeters near a source mass. Null results would then exclude parameter space of the model of interest, where detectable forces would have emerged if the parameters were valid. As an example, Figure 3 shows one of such experimental tests [31]. Atoms are launched vertically inside an ultrahigh-vacuum chamber. During

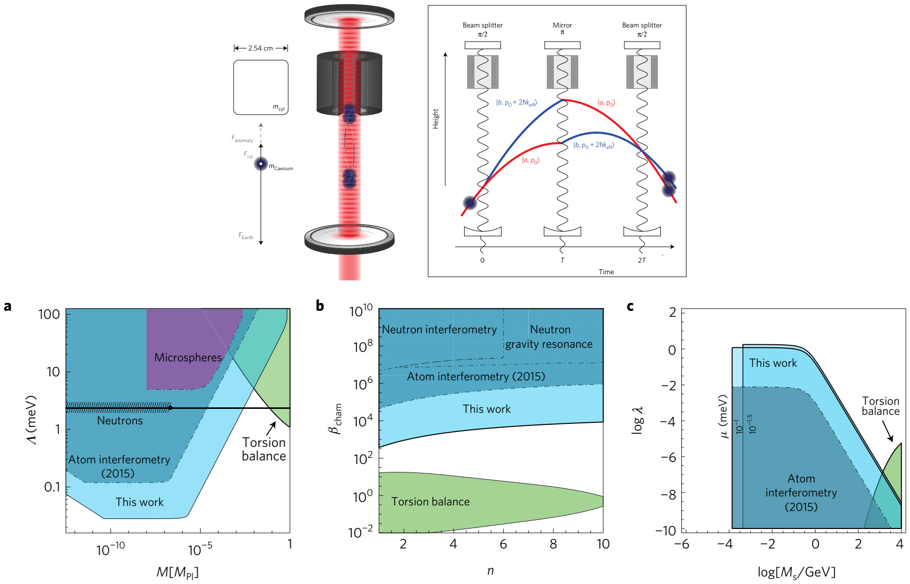

Figure 3. Atom interferometric constrains on thin-shell models, adapted from [31]. Upper panel: depiction of experimental sequence where light pulse atom interferometers are performed near a source mass. Lower panel: exclusion in parameter space of chameleon and symmetron models.

the free fall, an atom interferometer is realized using three laser pulses. Without the source mass, the atom interferometer measures local gravity. With the source mass placed near the apogee, the atoms would experience both the gravity of the source mass and an additional force as predicted by the thin-shell models. By comparing results with and without the source mass, and by estimating the density distribution of the source mass, one can bound the magnitude of extra force, and thus constrains models of interest. As shown in the bottom panel of Figure 3, the excluded parameter space of the chameleon model is complementary to and significantly surpasses tests using bulk objects (e.g., the torsion balance tests). Similar improvements on symmetron model constraints were also achieved.

Despite the success of demonstrating the approach and establishing the most stringent constraints, the ultimate performance of ground tests is limited by two factors. The first one is the finite interaction time of atoms with the scalar field sourced by the source mass. Atoms fall under gravity while the source mass is fixed to the lab, so the duration that the atoms are exposed to the short-ranged dark energy force is brief, even if the atom interferometer itself can have long interrogation time. The second factor is the uncertainty of the gravitational force of the source mass. Differential force measurement of the source mass at two locations yields the gravitational force of the source mass. Bounds of the extra force are limited by the uncertainty of the absolute gravity. Fundamentally, the gravitational constant *G* is only known to 20 parts per million [32], while dark energy forces are anticipated to be orders of magnitude less than gravity. Thus, revolutionary performance enhancement in laboratories is impeded by both sensitivity and systematics of the measurement scheme.

Proposed investigation

The full potential of atomic tests of thin-shell models can be unleashed by adapting the concept detailed in [33] (Figure 4). In the proposed concept, the experiment will be performed under microgravity, where atoms and the source mass can remain in close proximity as long as feasible and not limited by Earth gravity. Moreover, instead of moving the source mass to modulate the detected signal, where both gravity and the dark energy force are modulated, atom interferometers will be conducted in a multi-loop fashion through a structured source mass. In a periodically structured source mass, both the gravity and the scalar field force are spatially modulated. A multi-loop atom interferometer will synchronously pick up the periodic modulation, analogous to the functioning of an electronic lock-in amplifier. This way, spatial and temporal potential variations not induced by the source mass will be significantly suppressed in each measurement run, and thus the measurement will be largely insensitive to environmental disturbances and practical imperfections. In addition, the effects of rotations and external gravity gradients can be mitigated by employing interferometers with an even number of loops combined with the compensation technique proposed in [34].

Furthermore, the gravitational effect of the source mass itself will be suppressed by engineering its shape, e.g., by adding trim rings, so that the gravity contribution at the structural periodicity can be nulled. The suppression is not limited by the absolute value of gravity or the precision of *G*, but by machining tolerance and homogeneity of the source mass. The dark energy signal is only minimally affected by the trim mass, thanks to the short-range nature of dark energy force near normal matter.

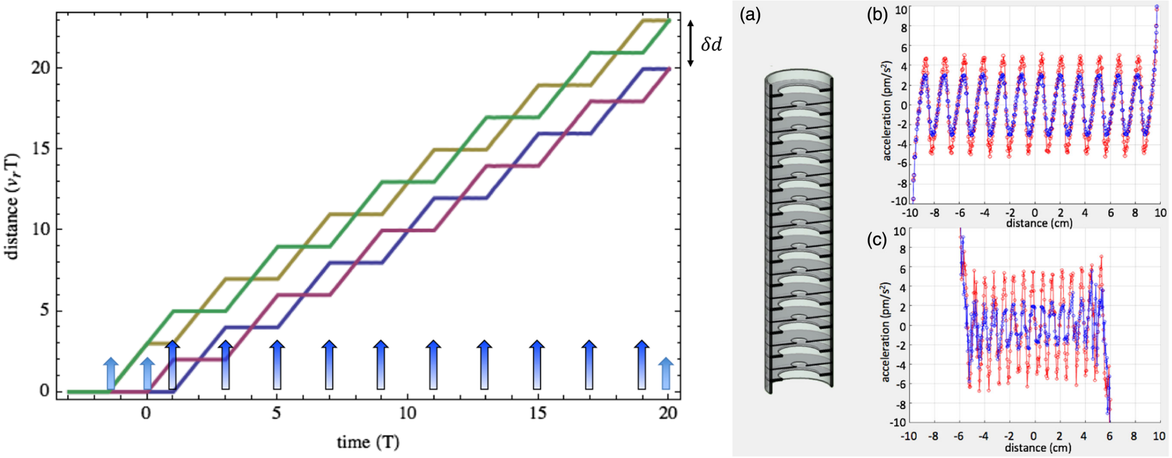

Figure 4. Multiloop atom interferometers in a structured source mass, adapted from [33]. Left: Space-time diagram of two atom interferometers. The size of each double-loop matches the periodicity of the source mass, and the separation between interferometers equates half of the periodicity. Right: (a) depiction of a sample structure. (b) anticipated chameleon acceleration vs axial position. (c) estimated gravitational acceleration vs axial position. Note that gravitational acceleration is smaller in amplitude than the chameleon acceleration, and has twice the spatial frequency.

The science impact will be significant. As estimated in [33], in a conceptual mission based on currently demonstrated atom interferometer capabilities, three days of continuous data collection of such an experiment on the ISS would improve the constraints of the chameleon model by more than a factor of 10 (Figure 5). More advanced atom interferometer technology or longer mission time will have sensitivities far better than the estimate in the reference. Note that for $\Lambda = 2.4$meV, which is the value of the observed present-day dark energy density, a gap in exclusion exists in the chameleon parameter space (Figure 3, Figure 5). Closing the gap with high fidelity would decisively test the model as a candidate of dark energy.

Microgravity justification and roadmap

The proposed measurement concept exploits the weightlessness to achieve sensitivities that are not attainable in terrestrial laboratories. However, it does not need a space mission to demonstrate the feasibility and capability. In fact, a technology development and demonstration project based on this concept is in progress [27]. **D3E3** (**D**irect **D**etection of **D**ark **E**nergy on **E**instein **E**levator)/**DESIRE** (**D**ark **E**nergy **S**earch by Atom **I**nterferomet**r**y in the **E**instein-Elevator) is a NASA/DLR collaborative effort that utilizes the drop tower of the Einstein-Elevator facility [35, 36] at the Hannover Institute of Technology, Germany, which features 4 s of free-fall time and up to 300 runs a day. The payload of the previously flown MAIUS-1 sounding rocket mission [37, 38] will be modified to implement the concept of structured source mass and multi-loop atom

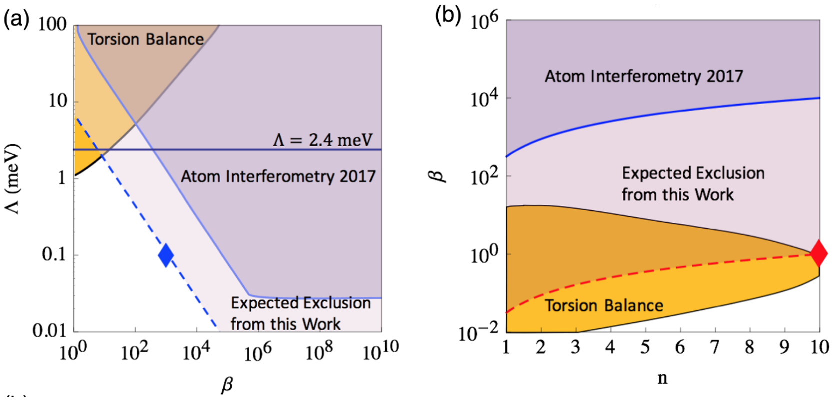

Figure 5. Projected science return of a conceptual mission on the ISS [33].

interferometers, and accommodated as a payload for the Einstein-Elevator. The success of D3E3/DESIRE will not only validate the proposed concept and extend the excluded parameter range of chameleon by a factor of 10, but will also improve the technology readiness level of multi-loop atom interferometry in microgravity. It will be the first stepping stone on the technology development roadmap for spaceborne missions on atomic dark energy detections, while leveraging technology maturation of all subsystems in NASA-funded Cold Atom Lab (CAL) [39, 40] and BECCAL [41, 42] missions.

We envision a full-scale space mission to be implemented as a payload on the ISS or on the Gateway of the Artemis program, where a controlled environment and electric power are available while the attitude of the spacecraft has no impact to the mission. In addition to the concept demonstration of D3E3/DESIRE, we advocate for technology studies to advance the following capabilities:

- Ultracold atom source: the short-term sensitivity of an atom interferometer is determined by the number of participating atoms. The state-of-the-art atom source in space is 10^5 atoms at < 1 nK per run [39, 43, 44], which limits the signal-to-noise ratio (SNR) to about 300. A compact, bright source of 10^8 atoms will improve the SNR to ~10,000, which directly translates to > 10x better constraints on dark energy models.
- Long interrogation time atom interferometers: the measurement time of free-fall atom interferometers have been demonstrated up to ~2 s [45]. While researchers gain more understanding as microgravity environments are becoming available, such as the Bremen drop tower [46], sounding rockets [37, 38], zero-g flights [47], the Einstein-Elevator [35, 36], CAL [39, 40], and BECCAL [41, 42], continuous programmatic support and focused investigations on second-scale atom interferometers are essential to improve technology maturity.

Conclusion

Dark energy is one of the greatest mysteries in modern physics. Observatories may not provide a complete answer about its underlying nature. The capability of direct detection of dark energy in a human-made environment will be a powerful tool to help tackle the problem. We point out that atom interferometry in space will substantially improve the constraints on thin-shell models of dark energy, such as the chameleon and the symmetron fields, leading to decisive (in)validation of such models.

A mission on a space platform using atom interferometers inside a structured source mass will strengthen the constraints on chameleon and symmetron by orders of magnitude in few days of operation. Technological advances on cold atom manipulation will further improve the sensitivity by orders of magnitude. This game-changing capability of validating dark energy models can only be achieved in space, and can be realized in the next decade with dedicated technology maturation efforts.

A. R. is supported by the Q-GRAV Project within the Space Research and Technology Program of the German Aerospace Center (DLR). This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

References

[1] A. Ferté *et al.*, "Categorizing models using Self-Organizing Maps: an application to modified gravity theories probed by cosmic shear," p. arXiv:2110.13171 https://ui.adsabs.harvard.edu/abs/2021arXiv211013171F

[2] M. Ishak *et al.*, "Modified Gravity and Dark Energy models Beyond $w(z)$CDM Testable by LSST," p. arXiv:1905.09687 https://ui.adsabs.harvard.edu/abs/2019arXiv190509687I

[3] "What is Dark Energy." https://science.nasa.gov/astrophysics/focus-areas/what-is-dark-energy.

[4] "Nobel Prize in Physics 2019." https://www.nobelprize.org/prizes/physics/2019/summary/.

[5] "Nobel Prize in Physics 2011." https://www.nobelprize.org/prizes/physics/2011/summary/.

[6] C. Burrage and J. Sakstein, "Tests of chameleon gravity," *Living Reviews in Relativity,* vol. 21, no. 1, p. 1, 2018. DOI: http://doi.org/10.1007/s41114-018-0011-x

[7] C. Burrage, A. Kuribayashi-Coleman, J. Stevenson, and B. Thrussell, "Constraining symmetron fields with atom interferometry," *J Cosmol Astropart P,* vol. 2016, no. 12, pp. 041, Dec 2016. DOI: http://doi.org/10.1088/1475-7516/2016/12/041

[8] C. Burrage, E. J. Copeland, and E. A. Hinds, "Probing dark energy with atom interferometry," *J Cosmol Astropart P,* vol. 2015, no. 3, pp. 042, Mar 2015. DOI: http://doi.org/10.1088/1475-7516/2015/03/042

[9] K. Hinterbichler and J. Khoury, "Screening long-range forces through local symmetry restoration," *Phys Rev Lett,* vol. 104, no. 23, p. 231301, Jun 11 2010. DOI: http://doi.org/10.1103/PhysRevLett.104.231301

[10] "Rubin Observatory." https://www.lsst.org/.

[11] "Euclid Mission." https://www.jpl.nasa.gov/missions/euclid.

[12] "Roman Space Telescope." https://roman.gsfc.nasa.gov/.

[13] J. M. Ezquiaga and M. Zumalacárregui, "Dark Energy in Light of Multi-Messenger Gravitational-Wave Astronomy," *Frontiers in Astronomy and Space Sciences,* vol. 5, Dec 21 2018. DOI: http://doi.org/10.3389/fspas.2018.00044

[14] K. Hinterbichler, J. Khoury, A. Levy, and A. Matas, "Symmetron cosmology," *Phys Rev D,* vol. 84, no. 10, Nov 18 2011. DOI: http://doi.org/10.1103/PhysRevD.84.103521

[15] J. Khoury and A. Weltman, "Chameleon cosmology," *Phys Rev D,* vol. 69, no. 4, Feb 2004. DOI: http://doi.org/10.1103/PhysRevD.69.044026

[16] J. Khoury and A. Weltman, "Chameleon fields: awaiting surprises for tests of gravity in space," *Phys Rev Lett,* vol. 93, no. 17, p. 171104, Oct 22 2004. DOI: http://doi.org/10.1103/PhysRevLett.93.171104

[17] A. Joyce, B. Jain, J. Khoury, and M. Trodden, "Beyond the cosmological standard model," *Phys Rep,* vol. 568, pp. 1, Mar 22 2015. DOI: http://doi.org/10.1016/j.physrep.2014.12.002

[18] D. O. Sabulsky, I. Dutta, E. A. Hinds, B. Elder, C. Burrage, and E. J. Copeland, "Experiment to Detect Dark Energy Forces Using Atom Interferometry," *Phys Rev Lett,* vol. 123, no. 6, p. 061102, Aug 6 2019. DOI: http://doi.org/10.1103/PhysRevLett.123.061102

[19] C. Burrage, E. J. Copeland, A. Moss, and J. A. Stevenson, "The shape dependence of chameleon screening," *J Cosmol Astropart P,* no. 1, Jan 2018. DOI: http://doi.org/10.1088/1475-7516/2018/01/056

[20] C. Burrage and J. Sakstein, "A compendium of chameleon constraints," *J Cosmol Astropart P,* no. 11, Nov 2016. DOI: http://doi.org/10.1088/1475-7516/2016/11/045

[21] C. Burrage and E. J. Copeland, "Using atom interferometry to detect dark energy," *Contemp Phys,* vol. 57, no. 2, pp. 164, 2016. DOI: http://doi.org/10.1080/00107514.2015.1060058

[22] P. Brax, C. Burrage, and A. C. Davis, "Shining light on modifications of gravity," *J Cosmol Astropart P,* vol. 2012, no. 10, pp. 016, Oct 2012. DOI: http://doi.org/10.1088/1475-7516/2012/10/016

[23] G. M. Tino and M. A. Kasevich, *Atom interferometry*. IOS Press, 2014.

[24] P. R. Berman, *Atom interferometry*. Academic press, 1997.

[25] A. D. Cronin, J. Schmiedmayer, and D. E. Pritchard, "Optics and interferometry with atoms and molecules," *Rev Mod Phys,* vol. 81, no. 3, pp. 1051, Jul-Sep 2009. DOI: http://doi.org/10.1103/RevModPhys.81.1051

[26] S. Kleinert, E. Kajari, A. Roura, and W. P. Schleich, "Representation-free description of light-pulse atom interferometry including non-inertial effects," *Physics Reports,* vol. 605, pp. 1, Dec 30 2015. DOI: http://doi.org/10.1016/j.physrep.2015.09.004

[27] A. Belenchia *et al.*, "Quantum Physics in Space," p. arXiv:2108.01435 https://ui.adsabs.harvard.edu/abs/2021arXiv210801435B

[28] M. Jaffe, V. Xu, P. Haslinger, H. Müller, and P. Hamilton, "Efficient Adiabatic Spin-Dependent Kicks in an Atom Interferometer," *Phys Rev Lett,* vol. 121, no. 4, p. 040402, Jul 27 2018. DOI: http://doi.org/10.1103/PhysRevLett.121.040402

[29] P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Müller, and J. Khoury, "ASTROPHYSICS. Atom-interferometry constraints on dark energy," *Science,* vol. 349, no. 6250, pp. 849, Aug 21 2015. DOI: http://doi.org/10.1126/science.aaa8883

[30] B. Elder, J. Khoury, P. Haslinger, M. Jaffe, H. Müller, and P. Hamilton, "Chameleon dark energy and atom interferometry," *Phys Rev D,* vol. 94, no. 4, Aug 25 2016. DOI: http://doi.org/10.1103/PhysRevD.94.044051

[31] M. Jaffe *et al.*, "Testing sub-gravitational forces on atoms from a miniature in-vacuum source mass," *Nat Phys,* vol. 13, no. 10, pp. 938, Oct 2017. DOI: http://doi.org/10.1038/nphys4189

[32] P. J. Mohr, D. B. Newell, and B. N. Taylor, "CODATA Recommended Values of the Fundamental Physical Constants: 2014," *J Phys Chem Ref Data,* vol. 45, no. 4, 2016. DOI: http://doi.org/10.1063/1.4954402

[33] S.-w. Chiow and N. Yu, "Multiloop atom interferometer measurements of chameleon dark energy in microgravity," *Phys Rev D,* vol. 97, no. 4, Feb 28 2018. DOI: http://doi.org/10.1103/PhysRevD.97.044043

[34] A. Roura, "Circumventing Heisenberg's Uncertainty Principle in Atom Interferometry Tests of the Equivalence Principle," *Phys Rev Lett,* vol. 118, no. 16, p. 160401, Apr 21 2017. DOI: http://doi.org/10.1103/PhysRevLett.118.160401

[35] "EE@HITec." https://www.hitec.uni-hannover.de/en/large-scale-equipment/einstein-elevator/.

[36] C. Lotz, T. Froböse, A. Wanner, L. Overmeyer, and W. Ertmer, "Einstein-Elevator: A New Facility for Research from µg to 5 g," *Gravitational and Space Research,* vol. 5, no. 2, pp. 11, 2017. DOI: http://doi.org/10.2478/gsr-2017-0007

[37] M. D. Lachmann *et al.*, "Ultracold atom interferometry in space," *Nat Commun,* vol. 12, no. 1, p. 1317, Feb 26 2021. DOI: http://doi.org/10.1038/s41467-021-21628-z

[38] "MAIUS project." https://www.zarm.uni-bremen.de/en/research/space-technologies/space-systems/projects/quantus-iv-maius.html.

[39] D. C. Aveline *et al.*, "Observation of Bose–Einstein condensates in an Earth-orbiting research lab," *Nature,* vol. 582, no. 7811, pp. 193, Jun 2020. DOI: http://doi.org/10.1038/s41586-020-2346-1

[40] "CAL." https://coldatomlab.jpl.nasa.gov.

[41] K. Frye *et al.*, "The Bose-Einstein Condensate and Cold Atom Laboratory," *Epj Quantum Technol,* vol. 8, no. 1, Jan 2021. DOI: http://doi.org/10.1140/epjqt/s40507-020-00090-8

[42] "BECCAL." https://www.zarm.uni-bremen.de/en/research/space-technologies/space-systems/projects/quantus-iv-maius.html.

[43] E. R. Elliott, M. C. Krutzik, J. R. Williams, R. J. Thompson, and D. C. Aveline, "NASA's Cold Atom Lab (CAL): system development and ground test status," *NPJ Microgravity,* vol. 4, no. 1, p. 16, 2018. DOI: http://doi.org/10.1038/s41526-018-0049-9

[44] D. Becker *et al.*, "Space-borne Bose–Einstein condensation for precision interferometry," *Nature,* vol. 562, no. 7727, pp. 391, Oct 2018. DOI: http://doi.org/10.1038/s41586-018-0605-1

[45] S. M. Dickerson, J. M. Hogan, A. Sugarbaker, D. M. S. Johnson, and M. A. Kasevich, "Multiaxis Inertial Sensing with Long-Time Point Source Atom Interferometry," *Phys Rev Lett,* vol. 111, no. 8, p. 083001, Aug 23 2013. DOI: http://doi.org/10.1103/PhysRevLett.111.083001

[46] H. Müntinga *et al.*, "Interferometry with Bose-Einstein Condensates in Microgravity," *Phys Rev Lett,* vol. 110, no. 9, p. 093602, Mar 1 2013. DOI: http://doi.org/10.1103/PhysRevLett.110.093602

[47] G. Stern *et al.*, "Light-pulse atom interferometry in microgravity," *Eur Phys J D,* vol. 53, no. 3, pp. 353, Jun 2009. DOI: http://doi.org/10.1140/epjd/e2009-00150-5