Space Laboratory Experiments For Probing Dark Energy and Fundamental Physics

Thematic Areas:

☒ Space Project
☒ Technological Development Activity
☒ State of the Profession Consideration

Principal Author:

Name: Nan Yu
Institution: Jet Propulsion Laboratory, California Institute of Technology
Email: nan.yu@jpl.nasa.gov
Phone: (818)-354-4093

Co-authors: (names and institutions)

Sheng-wey Chiow, Curt J. Cutler, Olivier P. Dore, Eric M. Huff, Ulf E. Israelsson, Jeffrey B. Jewell, Jason D. Rhodes, Slava G. Turyshev, and Jason R. Williams (Jet Propulsion Laboratory)
Justin Khoury and Jeremy Sakstein (University of Pennsylvania)
Kazuya Koyama (University of Portsmouth)
Clare Burrage and Benjamin Elder (University of Nottingham)
Paul Hamilton (University of California, Los Angeles)
Holger Mueller (University of California, Berkeley)
Phil Bull (Queen Mary University of London)
Joel Bergé (ONERA, Université Paris Saclay)

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

Space Laboratory Experiments For Probing Dark Energy and Fundamental Physics

Synopsis: This white paper (1) highlights important scientific discover roles of space laboratory measurements in astrophysics and fundamental physics, and the need to establish a corresponding healthy program for continued science investigations and technology developments in the area, and (2) describes a laboratory science measurement mission concept, Gravity Observation and Detection of Dark energy Explorer in Solar System (GODDESS), for understanding the nature of dark energy using the solar system as the laboratory. The proposed tetrahedra spacecraft configuration with precise differential inertial force measurements will also provide rich scientific data for mid-band gravitational waves, ultra-light dark matter detection, and other non-Newtonian gravity exploration.

1) State of Cosmology, Astrophysics, and Fundamental Physics, and Their Connections

Highlighted by the discovery of dark energy and dark matter, growing observational evidence points to the need for new physics aimed at answering important questions related to the most fundamental laws of Nature [1]. Efforts to discover new fundamental symmetries, investigations of limits of established symmetries, tests of the general theory of relativity, and attempts to understand the nature of dark energy were among the top priorities of scientific research in the new century, as clearly stated in the 2003 NRC report "Connecting Quarks with the Cosmos – Eleven Science Questions for the New Century" [2]. These questions are emphasized in NASA's science strategic plans [3] [4] accordingly.

The greatest mystery in science today is that we only know less than 5% of the constituents of our universe. Dark energy, together with dark matter, make up the rest and are only observed indirectly. What exactly is dark energy? The nature of dark energy itself is obscure and completely unknown today. It could simply be Einstein's cosmological constant. Yet this poses a conundrum, because straightforward arguments from quantum field theory suggest that the cosmological constant should be more than one hundred orders of magnitude larger than what is observed and attributed to dark energy [5]. The solution to this so-called cosmological constant problem clearly lies outside the known realms of gravity as described by the general theory of relativity and the standard model of particle physics. Even well-studied extensions of the standard model, such as supersymmetry, fail to provide answers [6]. Dark matter also remains mysterious. Is it some stable supersymmetric particle, or axions, or a signature of modified gravity?

The connection between the dark sector in astrophysics and tests of fundamental physics is clear: Theoretical models of the kinds of new physics that can solve the problems above typically involve new physical interactions, some of which could manifest themselves as a violation of the Equivalence Principle, variation of fundamental constants, modification of the inverse square law of gravity at various distances, Lorentz-symmetry breaking, or large-scale gravitational phenomena. Each of these manifestations offers an opportunity for a major discovery.

2) Space Laboratory Science Program for Astrophysics

Astronomical observations have long been successfully used for understanding where we are and how Nature works. It remains one of the most powerful ways to explore and understand the universe. WFIRST for dark energy and dark matter [7], and LISA for gravitational wave detections [8] are prime new mission examples. At the same time, to understand new fields and new interactions, high energy (accelerator) physics plays a crucial role to understand fundamental interactions and how the world is put together. The Large Hadron Collider (LHC) has been trying to detect light supersymmetry particles of dark matter, though it seems now that a higher energy may be needed [9]. While the particle colliders can't probe gravity and would miss ultra-light dark matter particles, precision laboratory experiments can complement with entirely different approaches. Through ever increasing precision that test interactions and dynamics predicted by the established laws of physics, including possible interactions from dark energy and dark matter, laboratory measurements have the ability to seek the smallest violations and probe physics at the Planck scale.

In the last few decades, there has been an explosion of new technologies that provide exquisite tools for precision measurements. Highly accurate optical clocks approaching one part per 10^{19} for time and frequency measurements [10], and atom interferometers for weak force measurements capable of attometer precision [11] are the two major breakthrough developments. Applying these precision measurement tools in space environment greatly increase the technical capabilities and scientific exploration space at the same time.

On the one hand, precision measurement tools, such as clocks and atom interferometers can benefit enormously from operation on a space platform [12] [13]. In particular, atom interferometers use laser-cooled atomic particles as totally free-fall test masses. This exploits the quantum nature of atomic particles as matter waves and forms matter-wave interferometers for sensitive and stable inertial force measurements. The measurement sensitivity increases quadratically with the interaction time. With the possibility of many seconds of free fall time in space (vs a fraction of second in a typical ground laboratory), very sensitive inertial force measurements can be made. In fact, atom interferometer technology is derived from that of atomic clocks. They are two sides of the same coin, the same precision measurement basics. On the other hand, access to space provide large gravity variation, large spatial separation, speed and orientation typically favorable for science measurements. Thus, conducting space laboratory precision measurements provides a unique ability to explore unknown physics, complementary to both the observational science in astronomy and accelerator science in high energy physics, and generates science data and knowledge that are not available from either of the two.

Laboratory experiments are often associated with Fundamental physics measurements, which has been an integral part of the NASA astrophysics program [14]. Unfortunately, laboratory measurement types of mission have not been emphasized since Gravity Probe-B (GP-B) [15]. The scientific outcome and programmatic issues of GP-B may have made NASA reluctant to consider fundamental physics missions. But new advances in atom interferometry and optical clocks warrant a fresh look at the discovery potential in the broad field of fundamental physics, including dark energy, dark matter and gravitational waves. Currently, the fundamental physics program is largely being supported through the microgravity physical science programs in NASA HEOMD, albeit with severe disruptions over the last two decades. Thanks to the NRC Life and Physical Sciences Decadal [16] and a strong interest in the fundamental physics community, the program is getting re-built up. The NASA Cold Atom Laboratory (CAL) launched last May and operating on ISS is an initial but great success story. One of the most significant beneficiaries of the current fundamental physics program will be astrophysics, as the resulting science and technology developments will lead to more dedicated and much more sophisticated missions for hunting dark energy and dark matter, and gravitational wave detection, much at the heart of astrophysics.

The strong and direct connection to Astrophysics in both science and technology, and the potential for discovery of new physics, calls for a coordinated program within NASA for space laboratory astrophysics and fundamental physics. Such programs should have clear science goals, concrete strategy and development plan, and meaningful funding priorities. Similar scientific and program interests are shared within ESA and other national space agencies, as well as the respective science communities. International collaborations are strongly encouraged, and indeed already exist in the current Fundamental Physics Program.

3) Hunting for Dark Energy as a Mission of Space Laboratory Measurements

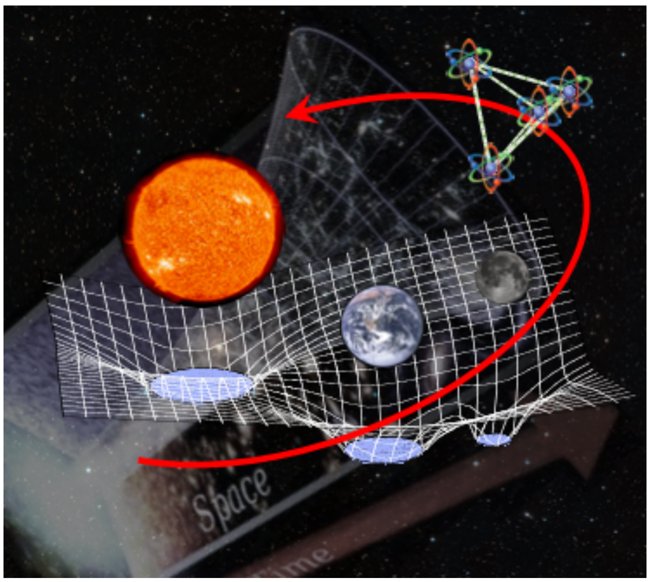

Fig.1. A tetrahedral constellation of satellites with atomic test masses traversing the spatial distribution of dark energy fields, search for signs of space-dependent non-zero trace of the gravity gradient tensor. The baseline separation of 100s km of the formation and the measurement sensitivity also make it an excellent gravitation wave antenna in the mid-band just below LISA.

Using the latest precision measurement tools such as atomic clocks and atom interferometer sensors, several salient proposals have been put forward for fundamental physics tests and gravitational wave detections through laboratory precision measurements. A non-exhaustive list includes the Quantum Weak Equivalence Principle (QWEP) [17] and Quantum Test of Equivalence and Space Time (QTEST) [18] for testing equivalence principle including dark matter search, STE-Quest in ESA Cosmic Vision [19], Atomic Interferometric Gravitational-wave Space Observatory (AIGSO) [20] for gravitational wave detection, Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS) [21] for dark matter detection, and GODDESS [22]. It should also be mentioned that CNES just completed Microscope [23] [24] [25], which has put a new limit at one part per 10^{14} on the Einstein equivalence principle as well as certain models of dark energy. Below, we will focus on the discussion of the GODDESS mission concept.

The primary science objectives of GODDESS, *Gravity Observation and Detection of Dark energy Explorer in Solar System*, is to seek direct detection of dark energy scalar field in the solar system laboratory. Phenomenologically, dark energy assumes an energy density in space-time with an effective negative pressure that can drive cosmic acceleration. In the "standard cosmological model," ΛCDM, the cosmological constant has to be fine-tuned to be consistent with astrophysics observations. Its explanation or a broader theoretical framework encounters daunting difficulties [5]. In some modified gravity models, general relativity (GR) is modified to encompass the cosmic acceleration without dark energy, but they are severely restricted [26] [27]. In quintessence theories, a new scalar field is introduced to account for the cosmic acceleration. Contrary to the cosmological constant, the quintessence field can vary in space and time [28] [29].

There has been much activity recently both on the theoretical front [30] [31] [32] [33] [34] [35] [36] [37] [38] [39] and experimental activities [32] [33] [40] [41] [42] for understanding the dark energy as a new scalar field. It is well known that GR has been stringently tested without any sign of violation so far both with solar system observations and laboratory precision measurements. Therefore, any new interaction and the resulting unknown forces from dark energy must be highly suppressed on solar system scales; otherwise, it would contradict various precision tests of GR that have been performed to date. Viable scalar field theories of dark energy achieve this suppression by making the interaction between normal matter and dark energy environment-dependent. The mechanism for doing this is called screening, and works by changing the coupling between matter and dark energy to be dependent on the local mass density or other environmental factors. Three general screening mechanisms have been proposed [36]. Chameleon screening increases the effective mass at high local mass densities, reducing the range of the fifth force [31]; Symmetron models undergo a symmetry-restoring phase transition at high densities decoupling the field from matter [35]; and Vainshtein screening such as in galileon models depends environmentally on the kinetic energy of the field, effectively reducing their matter couplings [43].

While Chameleon and symmetron forces may be measured in a typical laboratory scale experiments because of the thin-shell effects [38], space laboratory experiments can significantly improve the measurement precision, to the levels that these models can be either validated (detecting a non-Newtonian signal) or completely ruled out [41]. On the other than, galileon is a long range force, with the so-call Vainshtein radius on the order of 100's of parsecs. Measuring this force seems hopeless in a lab scale setting. However, as a recent simulation shows that the predicted galileon force on the order of 10^{-10} of that of the solar gravitational force at 1 AU distance away from the Sun [44]. It also has signature spatial distributions in the solar system. Using the solar system as a laboratory, one can take advantage of such spatial variations in hunting the dark energy field.

In the proposed GODDESS measurement scheme (Fig. 1), a tetrahedral constellation of four spacecraft orbiting around the Sun measures the force gradients along the trajectory. Cold atoms onboard each spacecraft are used as test masses and quantum sensors, and laser ranging interferometers between the spacecraft measure relative displacements to yield force gradient. Gradient measurements are then combined to yield the force gradient tensor. The Newtonian gravitational force, which follows the inverse-square law, has no divergence and contributes zero to the trace of the gradient tensor. Thus, by summing over the diagonal elements of the gradient tensor, one can detect any non-zero trace signals, revealing the galileon influence or confirmation of non-Newtonian gravity. The trace measurement scheme completely mitigates the effects of the much stronger gravity backgrounds and allows the spacecraft to fly freely in the tetrahedral formation without the need for precise orbit control. The use of cold free fall atomic test masses enable innovative mitigation of spacecraft local disturbances without flying spacecraft drag-free, and achieve the necessary inertial force measurement stability and precision. A preliminary analysis shows that 3 years of accumulative data collection in a 1 AU orbit around the Sun will detect the galileon force with a signal to noise of 3, based on the cosmologically observed Hubble's constant that governs the galileon model. It will also be able severely constrain Chameleon and Symmetron fields [45].

Moreover, the tetrahedra constellation of precise differential gravity gradient measurements in GODDESS offers the opportunity to achieve other significant science objectives. The measurements from GODDESS would also provide rich and diverse scientific data for testing gravity field theories in general beyond Newtonian gravity, hunting for ultra-light fields of dark matter [46] [47], as well as detecting gravitational waves in the mid band frequency spectrum between those of LIGO and LISA [48] with the GODDESS baseline separation of 100s kilometers.

4) State of Needed Technology and Maturation

The key enabling technology is the precision test mass measurements without flying spacecraft drag-free. Historically, in space gravity science measurements, the spacecraft itself is often used as the test mass, but this technique suffers from unknown non-gravitational forces, often referred as drag-force (recall the infamous Pioneer Anomaly [49]). A mass-spring accelerometer is also often used for inertial force measurements [50] [51] [52]. The bulk test mass and the associated sensing and configurations are limited by mechanical and thermal instabilities, and drift, limiting achievable results. The finite spring stiffness also limits low frequency responses. The most advanced test mass system today, as in GOCE [53] and in that planned for LISA [8], operates at the center of mass of the spacecraft and requires flying the spacecraft drag-free with a complex spacecraft system of micro-thrusters and consumable fuels.

The novel atomic test mass concept stems from the advent of laser cooling of atomic particles and the quantum mechanical nature of atom waves for matter-wave interferometers. The atomic particles are ideal test masses and atom interferometers are employed as sensors for small motional changes of atoms [54]. Identical atomic particles are collected, laser-cooled, and set in free fall in ultra-high vacuum with no external perturbation (and no spring attachment) other than gravity/inertial forces. Laser-cooling produces the atomic test masses of temperatures ranging from μK to nK. No cryogenics and no mechanical moving parts are needed and make this system ideally adapted to the microgravity space operation environment. Matter-wave interference for displacement measurements through interactions of lasers and atoms can be achieved with better than pm/Hz$^{1/2}$ sensitivity in space. The atomic sensor scheme is akin to atomic clocks, capable of providing superior intrinsic high-stability and high-accuracy, guaranteeing low frequency performance and long averaging time that are not achievable by conventional bulk test masses. Identical atomic particles can be regenerated or even operated in space vacuum away from spacecraft for reduced self-gravity gradients, making it possible to eliminate the need for flying drag-free spacecraft while increasing sensitivity performance. Indeed, as described in the detailed in Ref. [22], GODDESS is only enabled by these features of atomic test masses.

The atomic sensor technology has been demonstrated in research laboratories worldwide, commercialized for terrestrial applications, and matured for space deployment. In particular, NASA CAL is currently operating on ISS as a multi-user facility, and serves as a pathfinder for future atomic sensors in space [55]. In addition, the atom interferometer experiments have been demonstrated in 0-*g* flights by CNES and on sounding rockets by DLR [56] [57]. On the other hand, to achieve the performance needed for the GODDESS measurements at the level better than $1x10^{-14}$ m/s^2/Hz$^{1/2}$, the atomic test mass and atom interferometer technology must be further advanced beyond those demonstrated today, both in space and on the ground, as well as in performance and maturity. Among the major areas of technology gaps include high-flux ultra-cold atom sources, robust large momentum transfer schemes, as the ability to control and operate atomic test masses in the nature space vacuum environment outside spacecraft. The last area may require a specific space mission for the demonstration and validation in a deep space environment. In addition, much of the laser and optical systems for atomic experiments have little or no space heritage. Significant efforts are needed for maturing and space qualifying the laser and optical systems to support a mission like GODDESS.

Synergistically, there are broad applications of atomic test masses, from fundamental physics [18], to earth science [58], to planetary science [59] as well as other non-NASA space platforms. There are active activities and investments in all these areas. In addition, there exist a strong and healthy laboratory research programs in a similar area [60]. Nevertheless, the dark energy mission of GODDESS, perhaps together with AIGSO, presents the most demanding and challenging ones. Focused technology programs should be established, as these mission concepts mature, to support these kinds of missions in the next 15 to 20 years.

5) GODDESS Mission Development

GODDESS is very technically challenging, a mission with the technical sophistication and complexity beyond LISA in laser ranging, drag-free control and spacecraft formation flight. While the expected dark energy force is not unmeasurably small against the projected instrument sensitivities. Suppressing the gravity and other systematic effects by 10 orders of magnitude with corresponding control of systematics is at the heart of the challenge. As a result, four spacecraft with pair-wise inter-spacecraft laser ranging similar to LISA are required. On the other hand, GODDESS spacecraft does not have a complicated drag-free disturbance reduction system, thanks to the advent of atomic sensors. Instead, it carries a set of drag-free atomic test masses in the atom interferometer instrument configuration for inter-spacecraft differential gravity measurements. This may lead to a billion dollar class mission similar to LISA and MMS [61].

Currently, GODDESS is at the early concept formulation stage. Science requirements, mission concept, and technology require further development and maturation. Dark energy science measurements are already being simulated in detail. Secondary science objects need careful study to make the mission a multi-science measurement campaign and to maximize the values and science returns of such a large mission. As the science requirements are better defined, the mission concept and measurement configurations can be matured and optimized with a comprehensive analysis of system performance requirements and error budgets. More specific technology gaps can be articulated and identified, and developed and matured enough for mission implementation. The mission concept maturation may require a dedicated technology demonstration mission to validate the full capability of drag-free atomic sensor in space in the next decade. In the same decade, Euclid [62] and WFIRST will have provided the most precise astrophysics observables from dark energy and dark matter, in time for a new mission to elucidate the true nature of dark energy and indeed to discover new physics.

Acronyms

AIGSO – Atomic Interferometric Gravitational-wave Space Observatory
CAL – Cold Atom Laboratory
CNES – The National Centre for Space Studies is the French government space agency
DLR – The German Aerospace Center
ESA – European Space Agency
GOCE – Gravity Field and Steady-State Ocean Circulation Explorer
GODDESS – Gravity Observation and Detection of Dark energy Explorer in Solar System

GP-B – Gravity Probe B
GR – General Relativity
HEOMD – The Human Exploration and Operations Mission Directorate
LHC – Large Hadron Collider
LIGO – The Laser Interferometer Gravitational-Wave Observatory
LISA – Laser Interferometer Space Antenna
MAGIS – Matter-wave Atomic Gradiometer Interferometric Sensor
MMS – Magnetospheric Multiscale Mission
NRC – National Research Council
QWEP – Quantum Weak Equivalence Principle
QTEST – Quantum Test of Equivalence Principle and Space Time
STE-Quest – Space-Time Explorer and Quantum Equivalence Principle Space Test
WFIRST – Wide Field Infrared Survey Telescope

References

[1] S. G. Turyshev, J. Thomas W. Murphy, E. G. Adelberger, J. Battat, D. Currie, W. M. Folkner, J. Gundlach, S. M. Merkowitz, K. L. Nordtvedt, R. D. Reasenberg, I. I. Shapiro, M. Shao, C. W. Stubbs, M. Tinto, J. G. Williams and N. Yu, "Opportunities for Probing Fundamental Gravity with Solar System Experiments," 17 2 2009.

[2] N. R. Council, Connecting Quarks with the Cosmos: Eleven Science Questions for the New Century, Washington, DC: The National Academies Press, 2003.

[3] NASA 2014 Science Plan, 2014.

[4] NASA 2018 Strategic Plan, 2018.

[5] S. M. Carroll, "The Cosmological Constant," *Living Reviews in Relativity,* vol. 4, 2 2001.

[6] J. Wess and J. Bagger, Supersymmetry and supergravity, Princeton university press, 1992.

[7] *https://wfirst.gsfc.nasa.gov/.*

[8] *https://lisa.nasa.gov/.*

[9] J. Conrad and O. Reimer, "Indirect dark matter searches in gamma and cosmic rays," *Nature Physics,* vol. 13, pp. 224-231, 31 3 2017.

[10] E. Oelker, R. B. Hutson, C. J. Kennedy, L. Sonderhouse, T. Bothwell, A. Goban, D. Kedar, C. Sanner, J. M. Robinson, G. E. Marti, D. G. Matei, T. Legero, M. Giunta, R. Holzwarth, F. Riehle, U. Sterr and J. Ye, "Optical clock intercomparison with 6×10^{-19} precision in one hour," 7 2 2019.

[11] P. W. Graham, J. M. Hogan, M. A. Kasevich and S. Rajendran, "New method for gravitational wave detection with atomic sensors," *Physical Review Letters,* vol. 110, p. 171102, 4 2013.

[12] S. Schiller, P. Lemonde, G. M. Tino, U. Sterr, C. Lisdat, A. Görlitz, N. Poli, A. Nevsky and C. Salomon, "The space optical clocks project," *International Conference on Space Optics --- ICSO 2010,* 11 2017.

[13] F. Sorrentino, K. Bongs, P. Bouyer, L. Cacciapuoti, M. Angelis, H. Dittus, W. Ertmer, J. Hartwig, M. Hauth, S. Herrmann, K. Huang, M. Inguscio, E. Kajari, T. Könemann, C. Lämmerzahl, A. Landragin, G. Modugno, F. P. Santos, A. Peters, M. Prevedelli, E. M. Rasel, W. P. Schleich, M. Schmidt, A. Senger, K. Sengstock, G. Stern, G. M. Tino, T. Valenzuela, R. Walser and P. Windpassinger, "The Space Atom Interferometer project: status and prospects," *Journal of Physics: Conference Series,* vol. 327, p. 012050, 12 2011.

[14] National Academies of Sciences and Medicine, New Worlds, New Horizons: A Midterm Assessment, The National Academies Press, 2016.

[15] C. W. F. Everitt, D. B. DeBra, B. W. Parkinson, J. P. Turneaure, J. W. Conklin, M. I. Heifetz, G. M. Keiser, A. S. Silbergleit, T. Holmes, J. Kolodziejczak, M. Al-Meshari, J. C. Mester, B. Muhlfelder, V. G. Solomonik, K. Stahl, P. W. Worden, W. Bencze, S. Buchman, B. Clarke, A. Al-Jadaan, H. Al-Jibreen, J. Li, J. A. Lipa, J. M. Lockhart, B. Al-Suwaidan, M. Taber and S. Wang, "Gravity probe B: final results of a space experiment to test general relativity," *Physical Review Letters,* vol. 106, p. 221101, 5 2011.

[16] Recapturing a Future for Space Exploration, Life and Physical Sciences Research for a New Era (2011), National Academies Press, 2011.

[17] G. M. Tino, F. Sorrentino, D. Aguilera, B. Battelier, A. Bertoldi, Q. Bodart, K. Bongs, P. Bouyer, C. Braxmaier, L. Cacciapuoti, N. Gaaloul, N. Gürlebeck, M. Hauth, S. Herrmann, M. Krutzik, A. Kubelka, A. Landragin, A. Milke, A. Peters, E. M. Rasel, E. Rocco, C. Schubert, T. Schuldt, K. Sengstock and A. Wicht, "Precision gravity tests with atom interferometry in space," *Nuclear Physics B-Proceedings Supplements,* vol. 243, pp. 203-217, 10 2013.

[18] J. Williams, S.-w. Chiow, N. Yu and H. Müller, "Quantum test of the equivalence principle and space-time aboard the international space station," *New Journal of Physics,* vol. 18, p. 025018, 2016.

[19] B. Altschul, Q. G. Bailey, L. Blanchet, K. Bongs, P. Bouyer, L. Cacciapuoti, S. Capozziello, N. Gaaloul, D. Giulini, J. Hartwig, L. Iess, P. Jetzer, A. Landragin, E. Rasel, S. Reynaud, S. Schiller, C. Schubert, F. Sorrentino, U. Sterr, J. D. Tasson, G. M. Tino, P. Tuckey and P. Wolf, "Quantum tests of the Einstein Equivalence Principle with the STE--QUEST space mission," *Advances in Space Research,* vol. 55, pp. 501-524, 1 2015.

[20] D.-F. Gao, J. Wang and M.-S. Zhan, "Atomic interferometric gravitational-wave space observatory (aigso)," *Communications in Theoretical Physics,* vol. 69, p. 37, 2018.

[21] J. Coleman, "MAGIS-100 at Fermilab," *arXiv preprint arXiv:1812.00482,* 2018.

[22] N. Yu, "Direct probe of dark energy interactions with a Solar System laboratory," NIAC Phase 1 Report, 2019.

[23] P. Touboul, G. Métris, M. Rodrigues, Y. André, Q. Baghi, J. Bergé, D. Boulanger, S. Bremer, P. Carle, R. Chhun, B. Christophe, V. Cipolla, T. Damour, P. Danto, H. Dittus, P. Fayet, B. Foulon, C. Gageant, P.-Y. Guidotti, D. Hagedorn, E. Hardy, P.-A. Huynh, H. Inchauspe, P. Kayser, S. Lala, C. Lämmerzahl, V. Lebat, P. Leseur, F. ç. ç. Liorzou, M. List, F. Löffler, I. Panet, B. Pouilloux, P. Prieur, A. Rebray, S. Reynaud, B. Rievers, A. Robert, H. Selig, L. Serron, T. Sumner, N. Tanguy and P. Visser, "MICROSCOPE Mission: First Results of a Space Test of the Equivalence Principle," *Phys. Rev. Lett.,* vol. 119, no. 23, p. 231101, 12 2017.

[24] P. Fayet, "MICROSCOPE limits for new long-range forces and implications for unified theories," *Physical Review D,* vol. 97, 3 2018.

[25] P. Fayet, "MICROSCOPE limits on the strength of a new force with comparisons to gravity and electromagnetism," *Physical Review D,* vol. 99, 3 2019.

[26] P. Creminelli, "Dark Energy after GW170817 and GRB170817A," *Physical Review Letters,* vol. 119, 2017.

[27] J. M. Ezquiaga and M. Zumalacárregui, "Dark energy after GW170817: dead ends and the road ahead," *Physical review letters,* vol. 119, p. 251304, 2017.

[28] S. M. Carroll, "Quintessence and the Rest of the World: Suppressing Long-Range Interactions," *Physical Review Letters,* vol. 81, pp. 3067-3070, 1998.

[29] I. Zlatev, L. Wang and P. J. Steinhardt, "Quintessence, cosmic coincidence, and the cosmological constant," *Physical Review Letters,* vol. 82, p. 896, 1999.

[30] B. Jain, V. Vikram and J. Sakstein, "Astrophysical tests of modified gravity: constraints from distance indicators in the nearby universe," *The Astrophysical Journal,* vol. 779, p. 39, 2013.

[31] C. Burrage and J. Sakstein, "Tests of chameleon gravity," *Living Reviews in Relativity,* vol. 21, p. 1, 2018.

[32] C. Burrage, E. J. Copeland and E. A. Hinds, "Probing dark energy with atom interferometry," *Journal of Cosmology and Astroparticle Physics,* vol. 2015, p. 042, 2015.

[33] C. Burrage, A. Kuribayashi-Coleman, J. Stevenson and B. Thrussell, "Constraining symmetron fields with atom interferometry," *Journal of Cosmology and Astroparticle Physics,* vol. 2016, p. 041, 2016.

[34] K. Hinterbichler and J. Khoury, "Screening long-range forces through local symmetry restoration," *Physical review letters,* vol. 104, p. 231301, 2010.

[35] K. Hinterbichler, J. Khoury, A. Levy and A. Matas, "Symmetron cosmology," *Physical Review D,* vol. 84, p. 103521, 2011.

[36] A. Joyce, B. Jain, J. Khoury and M. Trodden, "Beyond the cosmological standard model," *Physics Reports,* vol. 568, pp. 1-98, 2015.

[37] J. Khoury and A. Weltman, "Chameleon Fields: Awaiting Surprises for Tests of Gravity in Space," *Phys. Rev. Lett.,* vol. 93, no. 17, p. 171104, 10 2004.

[38] J. Sakstein, "Tests of Gravity with Future Space-Based Experiments," *arXiv preprint arXiv:1710.03156,* 2017.

[39] V. Vikram, J. Sakstein, C. Davis and A. Neil, "Astrophysical tests of modified gravity: stellar and gaseous rotation curves in dwarf galaxies," *arXiv preprint arXiv:1407.6044,* 2014.

[40] P. Hamilton, M. Jaffe, P. Haslinger, Q. Simmons, H. Müller and J. Khoury, "Atom-interferometry constraints on dark energy," *Science,* vol. 349, pp. 849-851, 2015.

[41] M. Jaffe, P. Haslinger, V. Xu, P. Hamilton, A. Upadhye, B. Elder, J. Khoury and H. Müller, "Testing sub-gravitational forces on atoms from a miniature in-vacuum source mass," *Nature Physics,* vol. 13, pp. 938-942, 2017.

[42] D. Sabulsky, I. Dutta, E. A. Hinds, B. Elder, C. Burrage and E. J. Copeland, "Experiment to detect dark energy forces using atom interferometry," *arXiv preprint arXiv:1812.08244,* 2018.

[43] A. Barreira, B. Li, W. A. Hellwing, C. M. Baugh and S. Pascoli, "Nonlinear structure formation in the cubic Galileon gravity model," *Journal of Cosmology and Astroparticle Physics,* vol. 2013, pp. 27-27, 10 2013.

[44] N. White, et al, "Accurate numerical simulation of the Vainshtein mechanism at Solar System scales," In preparation.

[45] 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, p. 044051, 8 2016.

[46] T. Kalaydzhyan and N. Yu, "Extracting dark matter signatures from atomic clock stability measurements," *Phys. Rev. D,* vol. 96, no. 7, p. 075007, 10 2017.

[47] T. Kalaydzhyan and N. Yu, "Searching for Stochastic Background of Ultra-Light Fields with Atomic Sensors," *Universe,* vol. 4, p. 99, 9 2018.

[48] J. M. Hogan and M. A. Kasevich, "Atom-interferometric gravitational-wave detection using heterodyne laser links," *Physical Review A,* vol. 94, p. 033632, 2016.

[49] S. G. Turyshev, V. T. Toth, G. Kinsella, S.-C. Lee, S. M. Lok and J. Ellis, "Support for the thermal origin of the Pioneer anomaly," *Physical review letters,* vol. 108, p. 241101, 2012.

[50] B. Christophe, B. Foulon, F. Liorzou, V. Lebat, D. Boulanger, P.-A. Huynh, N. Zahzam, Y. Bidel and A. Bresson, "Status of Development of the Future Accelerometers for Next Generation Gravity Missions," in *International Symposium on Advancing Geodesy in a Changing World*, Springer International Publishing, 2018, pp. 85-89.

[51] B. Lenoir, B. Christophe and S. Reynaud, "Unbiased acceleration measurements with an electrostatic accelerometer on a rotating platform," *Advances in Space Research,* vol. 51, pp. 188-197, 1 2013.

[52] P. Abrykosov, R. Pail, T. Gruber, N. Zahzam, A. Bresson, E. Hardy, B. Christophe, Y. Bidel, O. Carraz and C. Siemes, "Impact of a novel hybrid accelerometer on satellite gravimetry performance," *Advances in Space Research,* vol. 63, pp. 3235-3248, 5 2019.

[53] *https://www.esa.int/Our_Activities/Observingthe_Earth/GOCE.*

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

[55] *http://coldatomlab.jpl.nasa.gov.*

[56] D. Becker, M. D. Lachmann, S. T. Seidel, H. Ahlers, A. N. Dinkelaker, J. Grosse, O. Hellmig, H. Müntinga, V. Schkolnik, T. Wendrich and et al., "Space-borne Bose--Einstein condensation for precision interferometry," *Nature,* vol. 562, pp. 391-395, 10 2018.

[57] V. Schkolnik, O. Hellmig, A. Wenzlawski, J. Grosse, A. Kohfeldt, K. Döringshoff, A. Wicht, P. Windpassinger, K. Sengstock, C. Braxmaier and et al., "A compact and robust diode laser system for atom interferometry on a sounding rocket," *Applied Physics B,* vol. 122, 7 2016.

[58] S.-w. Chiow, J. Williams and N. Yu, "Noise reduction in differential phase extraction of dual atom interferometers using an active servo loop," *Physical Review A,* vol. 93, p. 013602, 2016.

[59] S.-w. Chiow and N. Yu, "Compact atom interferometer using single laser," *Applied Physics B,* vol. 124, 5 2018.

[60] G. M. Tino and M. A. Kasevich, Atom interferometry, vol. 188, IOS Press, 2014.

[61] *https://mms.gsfc.nasa.gov/.*

[62] *https://www.jpl.nasa.gov/missions/euclid/.*