Topical: Advanced Tests of Fundamental Physics with State-of-the-Art Optical Clocks/Two-Way Time Links in Space

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Advanced Tests of Fundamental Physics with State-of-the-Art Optical Clocks/Two-Way Time Links in Space

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Recent advances in optical atomic clocks and optical time transfer have enabled new possibilities in precision metrology for both tests of fundamental physics and timing applications. Space offers both the potential to vary significantly the gravitational potential in which experiments operate and a microgravity environment free from local earth fluctuations. As a result, spaceborne optical clock tests of fundamental physics could achieve sensitivities four (or more) orders of magnitude beyond those of current tests of relativity. Additional fundamental test opportunities include enhanced searches for dark matter and drifts in fundamental constants.

Introduction

Atomic clocks have a long history of serving as one of the most sensitive means for testing the fundamental theories of physics. Many of the most stringent limits on possible deviations from our standard theories have been set through clock comparisons, on earth and in space. Here we describe how recent breakthroughs in time transfer and atomic clock performance have enabled new opportunities for spaceborne clock missions to test fundamental physics with orders of magnitude more precision than was possible even a few years ago. Indeed, such missions may be one of the most promising avenues we have for discovering new physics.

Advances in Time Metrology – Beyond the 18th Digit

Time is an omnipresent concept in modern society and plays a central role in the foundations of physics and our understanding of the cosmos. Atomic clocks keep international time and their quantum measurements are, by orders of magnitude, the most accurate measurements of any physical observable. Figure 1 shows the dramatic improvement of the accuracy of atomic clocks over the last 20 years, far faster than in the last half of the 20th century. This extremely rapid improvement of clocks at optical frequencies resulted from advancements in the manipulation of atomic quantum systems, as well as advanced techniques in laser cooling/trapping and the development of fs-laser frequency combs in 2000, which enabled the reliable counting of the ticks of the cycles of laser light at 10^{15} cycles per second [1–3]. The most accurate versions of these optical clocks use trapped quantum absorbers (either ions or lattice-confined neutral atoms) and now have fractional frequency uncertainties approaching or exceeding 1 part in 10^{18} [4–9], which enable transformational advances in a variety of tests of fundamental physics, including searches for dark matter [10], violation of Lorentz invariance [3], and possible variation of fundamental constants [11], as well as stringent tests of general relativity [9]. Future atomic clocks are also proposed for gravitational wave detection [12,13]. Indeed, with no foreseeable barriers to continued improvement along the recent trend in Figure 1, clock accuracies could reach 10^{-19} in 2027, 10^{-20} by 2034, and 10^{-21} in two decades, at which point gravitational waves could be directly observed in the tick rates of individual clocks.

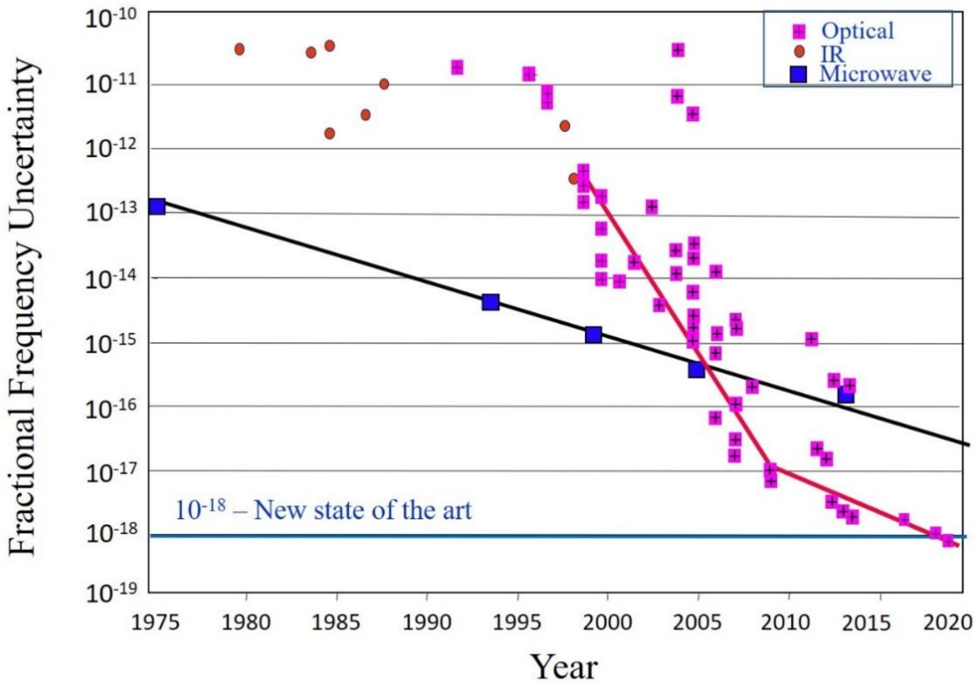

Figure 1. Historical accuracy of atomic clocks. Since 2000, the uncertainty of optical atomic standards have rapidly improved to, and beyond, 1 part in 10^{18}.

In general relativity (GR), the tick rate of time is no longer universal, but slows in the presence of massive bodies. As a result, further advances in clock accuracies and stabilities will soon surpass the instability of time itself on the surface of earth due to gravitational fluctuations, for example, from tides and noise. A straightforward solution is to locate one or more clocks in orbits around the Earth, thereby avoiding Earth's tidal motion/gravitational noise and reducing the sensitivity to Earth's gravity for middle-Earth and high Earth orbits. An orbiting platform as such could provide a low-noise environment that could enable atomic clocks to perform at the nineteenth digit and beyond. As a result, anticipated improvements in clock performance could be realized for a variety of applications, including dramatically advancing aforementioned tests of fundamental physics.

These motivations have led to a number of international projects on orbiting clocks. A laser-cooled microwave clock, CACES, is currently orbiting on the Chinese space station [14], and the ESA project ACES with a cold atom clock is scheduled to launch in the coming year. For over a decade ESA has also been developing optical clocks for space as part of their ISOC program [15], and the Chinese Space Agency aims to demonstrate an optical lattice clock in orbit on their next generation space station. These missions, however, were proposed before recent breakthroughs in time transfer that would have supported the inclusion of the highest performing clocks. Recent demonstrations of free space optical time transfer have exhibited stability at or beyond that of the highest performing optical clocks over distances beyond ten kilometers through turbulent air, involving both stationary and slowly moving receivers. These two-way techniques should be scalable over longer distances with fast moving vehicles, thus opening the door to space-based clock comparisons at the 10^{-18} level or below. As a result, future space-clock missions could serve as ultra-sensitive space-time probes for testing fundamental physics, with uncertainties reduced orders-of-magnitude beyond current limits.

Testing Fundamental Physics with Atomic Clocks

To understand the significance of these new opportunities, let's briefly consider the current state of fundamental physics tests. The Standard Model and General Relativity describe a vast array of physical phenomena and have essentially passed every precision test to date (with a few reported anomalies, e.g. results from the muon g-2 collaboration[16]). However, these theories cannot coexist in their present form to provide a quantum description of gravity and are unable to account for key phenomena such as dark energy, dark matter, the matter/anti-matter imbalance, and the unique direction of time. Indeed, arguably the most significant problems facing physics today are connected to these conundrums. Thus, there is a strong motivation to find new theories or extend existing ones to address these gaps. However, such extensions have thus far proven elusive. New physics can appear either at extremely high energy scales (energy frontier), where new particles can appear as distinct resonances, or at low energies where the colliders are blind to new physics with feeble couplings to standard particles due to background rejection (high precision frontier) [17]. At low energies, the competing "new physics" theories have indicated possible places where the Standard Model of particle physics might fail, including the three components of the Einstein Equivalence Principle (EEP): (1) weak equivalence principle (WEP) and, therefore, universality of free fall, local Lorentz invariance (LLI), and the local position invariance (LPI) [18]. As a result, over the past decades there has been a notable increase in proposed and experimental tests of these basic theories that look for new physics or gaps in our existing physics [17,19]. Many of these tests are based on time/frequency metrology, which is a direct consequence of the capability to measure time nearly a billion times more precisely than other base SI units. Consequently, atomic clocks are presently one of the tools of choice to pursue more stringent tests of fundamental theories.

As just one example, we show in Figure 2 the measurement history of one of the classic tests of fundamental physics, the gravitational redshift, which is a direct consequence of Local Position Invariance of EEP [see [9] and references therein]. For a difference in gravitational potential, ΔU, α, in $\frac{\Delta\nu}{\nu} = (1+\alpha)\frac{\Delta U}{c^2}$, represents a measure of the deviation of a given fractional frequency measurement ($\Delta\nu/\nu$) from the predictions of GR. Bounds on α have been tightened through the years with ground- and space-based measurements. We note from Figure 2 that the high precision atomic clock measurements provide more stringent constraints on the gravitational redshift than astrophysical measurements (black triangles), even though they are performed in the relatively weak gravity field of Earth. (In fact, the redshift measurements of stars may be more useful in determining the mass of the star by taking advantage of the low uncertainty from the clock measurements of the red shift [20].) We note also that since the initial tower-based measurement in 1960 [21], tighter constraints have come via experiments that put clocks in a space environment [22–24]. But perhaps the most significant takeaway from Figure 2 is that, because such experiments are difficult and expensive, the overall progress in the reduction of the constraints on α has been relatively slow, with less than a factor of 10 improvement over 40 years. For comparison, Figure 1 shows the reduction of atomic clock uncertainties by a factor of almost a million over a similar period.

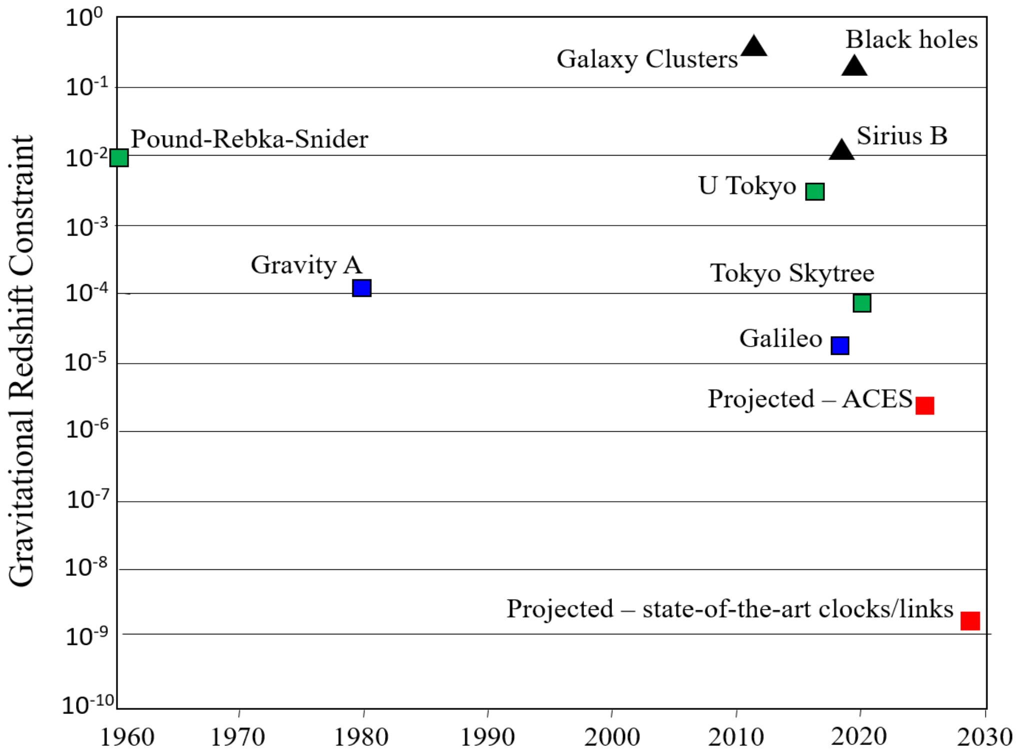

Figure 2: Constraints on the gravitational redshift parameter α over the past six decades. Green circles represent Earth-based measurements, blue squares represent space-based measurements, black triangles represent astronomical measurements, and red squares represent projected sensitivity for the ISS-based ACES mission and for a mission based on state-of-the-art clocks and links as described in this paper. Combining the recent rapid advances of optical clocks with a large change in gravitational potential enables a dramatically improved test of General Relativity, with a projected constraint on the redshift near 10^{-9}.

Given that the sensitivities of many fundamental tests, such as the redshift, are proportional to the clock precision, we now have a golden opportunity: by strategically locating 10^{-18} clocks in space, we can leverage this new level of clock performance via the new time-transfer links to enable new tests of GR and the Standard Model with a leap in sensitivity, thereby significantly tightening constraints on key parameters. For the example of the gravitational redshift, we project that a 10^{-18} clock in an elliptical orbit (with a perigee of ~ 5000 km and an apogee of 23,000 km) could tighten the constraint on alpha by more than a factor of 10,000. (A proposed mission[25] based on this concept, termed **F**undamental physics with an **O**ptical **C**lock **O**rbiting in **S**pace, is described in more detail in a Mission Campaign White Paper; another concept proposes using two clocks in different orbits[26]). Many of these parameter constraints are connected to Planck scale physics, and possibly new fields and forces, complementary to those explored by high energy accelerator physics and astrophysics observatories. Precision measurements enabled by clocks and frequency control can quantify the yet unconstrained parameters space of possible new physics, thereby providing perhaps the best prospects to elucidate science mysteries and discover new physics.

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References

(1) Abdel-Hafiz, M.; Ablewski, P.; Al-Masoudi, A.; Martínez, H. Á.; Balling, P.; Barwood, G.; Benkler, E.; Bober, M.; Borkowski, M.; Bowden, W.; Ciuryło, R.; Cybulski, H.; Didier, A.; Doležal, M.; Dörscher, S.; Falke, S.; Godun, R. M.; Hamid, R.; Hill, I. R.; Hobson, R.; Huntemann, N.; Coq, Y. L.; Targat, R. L.; Legero, T.; Lindvall, T.; Lisdat, C.; Lodewyck, J.; Margolis, H. S.; Mehlstäubler, T. E.; Peik, E.; Pelzer, L.; Pizzocaro, M.; Rauf, B.; Rolland, A.; Scharnhorst, N.; Schioppo, M.; Schmidt, P. O.; Schwarz, R.; Şenel, Ç.; Spethmann, N.; Sterr, U.; Tamm, C.; Thomsen, J. W.; Vianello, A.; Zawada, M. Guidelines for Developing Optical Clocks with 10^{-18} Fractional Frequency Uncertainty. *ArXiv190611495 Phys.* **2019**.

(2) Ludlow, A. D.; Boyd, M. M.; Ye, J.; Peik, E.; Schmidt, P. O. Optical Atomic Clocks. *Rev. Mod. Phys.* **2015**, *87* (2), 637–701. https://doi.org/10.1103/RevModPhys.87.637.

(3) Sanner, C.; Huntemann, N.; Lange, R.; Tamm, C.; Peik, E.; Safronova, M. S.; Porsev, S. G. Optical Clock Comparison for Lorentz Symmetry Testing. *Nature* **2019**, *567* (7747), 204. https://doi.org/10.1038/s41586-019-0972-2.

(4) Bothwell, T.; Kedar, D.; Oelker, E.; Robinson, J. M.; Bromley, S. L.; Tew, W. L.; Ye, J.; Kennedy, C. J. JILA SrI Optical Lattice Clock with Uncertainty of 2.0×10^{-18}. *Metrologia* **2019**, *56* (6), 065004. https://doi.org/10.1088/1681-7575/ab4089.

(5) Brewer, S. M.; Chen, J.-S.; Hankin, A. M.; Clements, E. R.; Chou, C. W.; Wineland, D. J.; Hume, D. B.; Leibrandt, D. R. $^{27}{\mathrm{Al}}^{+}$ Quantum-Logic Clock with a Systematic Uncertainty below ${10}^{\ensuremath{-}18}$. *Phys. Rev. Lett.* **2019**, *123* (3), 033201. https://doi.org/10.1103/PhysRevLett.123.033201.

(6) Godun, R. M.; Nisbet-Jones, P. B. R.; Jones, J. M.; King, S. A.; Johnson, L. A. M.; Margolis, H. S.; Szymaniec, K.; Lea, S. N.; Bongs, K.; Gill, P. Frequency Ratio of Two Optical Clock Transitions in $^{171}Yb^{+}$ and Constraints on the Time Variation of Fundamental Constants. *Phys. Rev. Lett.* **2014**, *113* (21), 210801. https://doi.org/10.1103/PhysRevLett.113.210801.

(7) Huntemann, N.; Sanner, C.; Lipphardt, B.; Tamm, Chr.; Peik, E. Single-Ion Atomic Clock with $3x10^{-18}$ Systematic Uncertainty. *Phys. Rev. Lett.* **2016**, *116* (6), 063001. https://doi.org/10.1103/PhysRevLett.116.063001.

(8) McGrew, W. F.; Zhang, X.; Fasano, R. J.; Schäffer, S. A.; Beloy, K.; Nicolodi, D.; Brown, R. C.; Hinkley, N.; Milani, G.; Schioppo, M.; Yoon, T. H.; Ludlow, A. D. Atomic Clock Performance Enabling Geodesy below the Centimetre Level. *Nature* **2018**, *564* (7734), 87. https://doi.org/10.1038/s41586-018-0738-2.

(9) Takamoto, M.; Ushijima, I.; Ohmae, N.; Yahagi, T.; Kokado, K.; Shinkai, H.; Katori, H. Test of General Relativity by a Pair of Transportable Optical Lattice Clocks. *Nat. Photonics* **2020**, 1–5. https://doi.org/10.1038/s41566-020-0619-8.

(10) Kennedy, C. J.; Oelker, E.; Robinson, J. M.; Bothwell, T.; Kedar, D.; Milner, W. R.; Marti, G. E.; Derevianko, A.; Ye, J. Precision Metrology Meets Cosmology: Improved Constraints on Ultralight Dark Matter from Atom-Cavity Frequency Comparisons. *Phys. Rev. Lett.* **2020**, *125* (20), 201302. https://doi.org/10.1103/PhysRevLett.125.201302.

(11) Lange, R.; Huntemann, N.; Rahm, J. M.; Sanner, C.; Shao, H.; Lipphardt, B.; Tamm, Chr.; Weyers, S.; Peik, E. Improved Limits for Violations of Local Position Invariance from Atomic Clock Comparisons. *Phys. Rev. Lett.* **2021**, *126* (1), 011102. https://doi.org/10.1103/PhysRevLett.126.011102.

(12) Ebisuzaki, T.; Katori, H.; Makino, J.; Noda, A.; Shinkai, H.; Tamagawa, T. INO: Interplanetary Network of Optical Lattice Clocks. *Int. J. Mod. Phys. D* **2019**, *29* (04), 1940002. https://doi.org/10.1142/S0218271819400029.

(13) Kolkowitz, S.; Pikovski, I.; Langellier, N.; Lukin, M. D.; Walsworth, R. L.; Ye, J. Gravitational Wave Detection with Optical Lattice Atomic Clocks. *Phys. Rev. D* **2016**, *94* (12), 124043. https://doi.org/10.1103/PhysRevD.94.124043.

(14) Liu, L.; Lü, D.-S.; Chen, W.-B.; Li, T.; Qu, Q.-Z.; Wang, B.; Li, L.; Ren, W.; Dong, Z.-R.; Zhao, J.-B.; Xia, W.-B.; Zhao, X.; Ji, J.-W.; Ye, M.-F.; Sun, Y.-G.; Yao, Y.-Y.; Song, D.; Liang, Z.-G.; Hu, S.-J.; Yu, D.-H.; Hou, X.; Shi, W.; Zang, H.-G.; Xiang, J.-F.; Peng, X.-K.; Wang, Y.-Z. In-Orbit Operation of an Atomic Clock Based on Laser-Cooled 87 Rb Atoms. *Nat. Commun.* **2018**, *9* (1), 1–8. https://doi.org/10.1038/s41467-018-05219-z.

(15) Schiller, S.; Görlitz, A.; Nevsky, A.; Alighanbari, S.; Vasilyev, S.; Abou-Jaoudeh, C.; Mura, G.; Franzen, T.; Sterr, U.; Falke, S.; Lisdat, Ch.; Rasel, E.; Kulosa, A.; Bize, S.; Lodewyck, J.; Tino, G. M.; Poli, N.; Schioppo, M.; Bongs, K.; Singh, Y.; Gill, P.; Barwood, G.; Ovchinnikov, Y.; Stuhler, J.; Kaenders, W.; Braxmaier, C.; Holzwarth, R.; Donati, A.; Lecomte, S.; Calonico, D.; Levi, F. The Space Optical Clocks Project: Development of High-Performance Transportable and Breadboard Optical Clocks and Advanced Subsystems. In *2012 European Frequency and Time Forum*; 2012; pp 412–418. https://doi.org/10.1109/EFTF.2012.6502414.

(16) Muon g−2 Collaboration; Abi, B.; Albahri, T.; Al-Kilani, S.; Allspach, D.; Alonzi, L. P.; Anastasi, A.; Anisenkov, A.; Azfar, F.; Badgley, K.; Baeßler, S.; Bailey, I.; Baranov, V. A.; Barlas-Yucel, E.; Barrett, T.; Barzi, E.; Basti, A.; Bedeschi, F.; Behnke, A.; Berz, M.; Bhattacharya, M.; Binney, H. P.; Bjorkquist, R.; Bloom, P.; Bono, J.; Bottalico, E.; Bowcock, T.; Boyden, D.; Cantatore, G.; Carey, R. M.; Carroll, J.; Casey, B. C. K.; Cauz, D.; Ceravolo, S.; Chakraborty, R.; Chang, S. P.; Chapelain, A.; Chappa, S.; Charity, S.; Chislett, R.; Choi, J.; Chu, Z.; Chupp, T. E.; Convery, M. E.; Conway, A.; Corradi, G.; Corrodi, S.; Cotrozzi, L.; Crnkovic, J. D.; Dabagov, S.; De Lurgio, P. M.; Debevec, P. T.; Di Falco, S.; Di Meo, P.; Di Sciascio, G.; Di Stefano, R.; Drendel, B.; Driutti, A.; Duginov, V. N.; Eads, M.; Eggert, N.; Epps, A.; Esquivel, J.; Farooq, M.; Fatemi, R.; Ferrari, C.; Fertl, M.; Fiedler, A.; Fienberg, A. T.; Fioretti, A.; Flay, D.; Foster, S. B.; Friedsam, H.; Frlež, E.; Froemming, N. S.; Fry, J.; Fu, C.; Gabbanini, C.; Galati, M. D.; Ganguly, S.; Garcia, A.; Gastler, D. E.; George, J.; Gibbons, L. K.; Gioiosa, A.; Giovanetti, K. L.; Girotti, P.; Gohn, W.; Gorringe, T.; Grange, J.; Grant, S.; Gray, F.; Haciomeroglu, S.; Hahn, D.; Halewood-Leagas, T.; Hampai, D.; Han, F.; Hazen, E.; Hempstead, J.; Henry, S.; Herrod, A. T.; Hertzog, D. W.; Hesketh, G.; Hibbert, A.; Hodge, Z.; Holzbauer, J. L.; Hong, K. W.; Hong, R.; Iacovacci, M.; Incagli, M.; Johnstone, C.; Johnstone, J. A.; Kammel, P.; Kargiantoulakis, M.; Karuza, M.; Kaspar, J.; Kawall, D.; Kelton, L.; Keshavarzi, A.; Kessler, D.; Khaw, K. S.; Khechadoorian, Z.; Khomutov, N. V.; Kiburg, B.; Kiburg, M.; Kim, O.; Kim, S. C.; Kim, Y. I.; King, B.; Kinnaird, N.; Korostelev, M.; Kourbanis, I.; Kraegeloh, E.; Krylov, V. A.; Kuchibhotla, A.; Kuchinskiy, N. A.; Labe, K. R.; LaBounty, J.; Lancaster, M.; Lee, M. J.; Lee, S.; Leo, S.; Li, B.; Li, D.; Li, L.; Logashenko, I.; Lorente Campos, A.; Lucà, A.; Lukicov, G.; Luo, G.; Lusiani, A.; Lyon, A. L.; MacCoy, B.; Madrak, R.; Makino, K.; Marignetti, F.; Mastroianni, S.; Maxfield, S.; McEvoy, M.; Merritt, W.; Mikhailichenko, A. A.; Miller, J. P.; Miozzi, S.; Morgan, J. P.; Morse, W. M.; Mott, J.; Motuk, E.; Nath, A.; Newton, D.; Nguyen, H.; Oberling, M.; Osofsky, R.; Ostiguy, J.-F.; Park, S.; Pauletta, G.; Piacentino, G. M.; Pilato,

R. N.; Pitts, K. T.; Plaster, B.; Počanić, D.; Pohlman, N.; Polly, C. C.; Popovic, M.; Price, J.; Quinn, B.; Raha, N.; Ramachandran, S.; Ramberg, E.; Rider, N. T.; Ritchie, J. L.; Roberts, B. L.; Rubin, D. L.; Santi, L.; Sathyan, D.; Schellman, H.; Schlesier, C.; Schreckenberger, A.; Semertzidis, Y. K.; Shatunov, Y. M.; Shemyakin, D.; Shenk, M.; Sim, D.; Smith, M. W.; Smith, A.; Soha, A. K.; Sorbara, M.; Stöckinger, D.; Stapleton, J.; Still, D.; Stoughton, C.; Stratakis, D.; Strohman, C.; Stuttard, T.; Swanson, H. E.; Sweetmore, G.; Sweigart, D. A.; Syphers, M. J.; Tarazona, D. A.; Teubner, T.; Tewsley-Booth, A. E.; Thomson, K.; Tishchenko, V.; Tran, N. H.; Turner, W.; Valetov, E.; Vasilkova, D.; Venanzoni, G.; Volnykh, V. P.; Walton, T.; Warren, M.; Weisskopf, A.; Welty-Rieger, L.; Whitley, M.; Winter, P.; Wolski, A.; Wormald, M.; Wu, W.; Yoshikawa, C. Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 Ppm. *Phys. Rev. Lett.* **2021**, *126* (14), 141801. https://doi.org/10.1103/PhysRevLett.126.141801.

(17) Safronova, M. S.; Budker, D.; DeMille, D.; Kimball, D. F. J.; Derevianko, A.; Clark, C. W. Search for New Physics with Atoms and Molecules. *Rev. Mod. Phys.* **2018**, *90* (2), 025008. https://doi.org/10.1103/RevModPhys.90.025008.

(18) Will, C. M. The Confrontation between General Relativity and Experiment. *Living Rev. Relativ.* **2014**, *17* (1), 4. https://doi.org/10.12942/lrr-2014-4.

(19) Delva, P.; Hees, A.; Wolf, P. Clocks in Space for Tests of Fundamental Physics. *Space Sci. Rev.* **2017**, *212* (3), 1385–1421. https://doi.org/10.1007/s11214-017-0361-9.

(20) Do, T.; Hees, A.; Ghez, A.; Martinez, G. D.; Chu, D. S.; Jia, S.; Sakai, S.; Lu, J. R.; Gautam, A. K.; O'Neil, K. K.; Becklin, E. E.; Morris, M. R.; Matthews, K.; Nishiyama, S.; Campbell, R.; Chappell, S.; Chen, Z.; Ciurlo, A.; Dehghanfar, A.; Gallego-Cano, E.; Kerzendorf, W. E.; Lyke, J. E.; Naoz, S.; Saida, H.; Schödel, R.; Takahashi, M.; Takamori, Y.; Witzel, G.; Wizinowich, P. Relativistic Redshift of the Star S0-2 Orbiting the Galactic Center Supermassive Black Hole. *Science* **2019**, *365* (6454), 664–668. https://doi.org/10.1126/science.aav8137.

(21) Pound, R. V.; Snider, J. L. Effect of Gravity on Gamma Radiation. *Phys. Rev.* **1965**, *140* (3B), B788–B803. https://doi.org/10.1103/PhysRev.140.B788.

(22) Delva, P.; Puchades, N.; Schönemann, E.; Dilssner, F.; Courde, C.; Bertone, S.; Gonzalez, F.; Hees, A.; Le Poncin-Lafitte, Ch.; Meynadier, F.; Prieto-Cerdeira, R.; Sohet, B.; Ventura-Traveset, J.; Wolf, P. Gravitational Redshift Test Using Eccentric Galileo Satellites. *Phys. Rev. Lett.* **2018**, *121* (23), 231101. https://doi.org/10.1103/PhysRevLett.121.231101.

(23) Herrmann, S.; Finke, F.; Lülf, M.; Kichakova, O.; Puetzfeld, D.; Knickmann, D.; List, M.; Rievers, B.; Giorgi, G.; Günther, C.; Dittus, H.; Prieto-Cerdeira, R.; Dilssner, F.; Gonzalez, F.; Schönemann, E.; Ventura-Traveset, J.; Lämmerzahl, C. Test of the Gravitational Redshift with Galileo Satellites in an Eccentric Orbit. *Phys. Rev. Lett.* **2018**, *121* (23), 231102. https://doi.org/10.1103/PhysRevLett.121.231102.

(24) Vessot, R. F. C.; Levine, M. W.; Mattison, E. M.; Blomberg, E. L.; Hoffman, T. E.; Nystrom, G. U.; Farrel, B. F.; Decher, R.; Eby, P. B.; Baugher, C. R.; Watts, J. W.; Teuber, D. L.; Wills, F. D. Test of Relativistic Gravitation with a Space-Borne Hydrogen Maser. *Phys. Rev. Lett.* **1980**, *45* (26), 2081–2084. https://doi.org/10.1103/PhysRevLett.45.2081.

(25) Oates, C. W.; Gibble, K.; Hollberg, L.; Newbury, N. R.; Derevianko, A.; Safronova, M. S.; Sinclair, L. C. FOCOS – Fundamental Physics with an Optical Clock Orbiting in

Space. *ASGSR Decadal Surv. Workshop Ser.* https://drive.google.com/file/d/1N3Gtwnnevz_OOMeqks8um6UpFPPzgU9J/view?usp=sharing&usp=embed_facebook.

(26) Litvinov, D.; Pilipenko, S. Testing the Einstein Equivalence Principle with Two Earth-Orbiting Clocks. *Class. Quantum Gravity* **2021**. https://doi.org/10.1088/1361-6382/abf895.