

# Quantum Science and Technology



## PAPER

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











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# Optical atomic clock aboard an Earth-orbiting space station (OACCESS): enhancing searches for physics beyond the standard model in space

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## Abstract

We present a concept for a high-precision optical atomic clock (OAC) operating on an Earth-orbiting space station. This pathfinder science mission will compare the space-based OAC with one or more ultra-stable terrestrial OACs to search for space-time-dependent signatures of dark scalar fields that manifest as anomalies in the relative frequencies of station-based and ground-based clocks. This opens the possibility of probing models of new physics that are inaccessible to purely ground-based OAC experiments where a dark scalar field may potentially be strongly screened near Earth's surface. This unique enhancement of sensitivity to potential dark matter candidates harnesses the potential of space-based OACs.

## 1. Introduction

Clocks play a critical role in communications technology, synchronization of large data networks and radio telescopes, and in generating reference signals for global satellite navigation systems. Recent advances in optical atomic clocks (OAC) provide new measurement capabilities with which the standard model (SM) and general relativity can be tested to unprecedented precision [1–4]. These clocks utilize ensembles of laser-cooled atoms as frequency references. The clock signal is derived from an ultra-stable laser which is frequency-locked to a narrow atomic transition at optical frequencies of 100's of THz [5, 6]. Terrestrial OAC have now achieved a fractional frequency uncertainty at the  $10^{-18}$  level [3, 7–14], orders of magnitude better than the record caesium microwave frequency standards [15]. It is envisioned that future precision OAC operating in Earth's orbit will serve as invaluable infrastructure for a global quantum network of clocks with enabling capabilities for a range of scientific and technical applications [16]. Future generations of global navigation satellite systems consisting of advanced OACs could be used also for deep space

navigation in our Solar System. In addition, such a system would generate scientific data for dark matter searches at the same time [17].

It has recently been realized that space-based clocks should offer a significant advantage over ground-based clocks to test certain models of dark-sector particles, fields, or entities (such as dark matter and dark energy) which are absent in the SM; specifically, for dark scalar fields where the scalar field is strongly screened near Earth's surface [18–20] (see also [21–23] for earlier work on screening in scalar-field models). The Optical Atomic Clock aboard an Earth-orbiting Space Station (OACCESS) concept therefore addresses two priorities for NASA [24]: (1) by establishing high-precision OAC and ground-to-space time-transfer technologies in Earth's orbit, it provides capabilities for science that could profit strongly if done in space, with anticipated value to humans on Earth, and (2) the possibility of detecting dark fields which are screened near Earth's surface enables scientific experiments that, with current technologies, can only be done in space.

We propose a strontium OAC operating aboard an Earth-orbiting space station as a pathfinder science mission to enable unprecedented capabilities in searches for signatures of physics beyond the SM. Comparison of the OACCESS clock with terrestrial OAC via leading-edge optical time-frequency transfer techniques [15, 25–30] will enable tests of temporal and spatial variations of the fundamental constants of nature that can arise in various dark-sector models, including ultra-low-mass dark matter and dark energy, as well as in quantum gravity. In this way, OACCESS will serve as a pathfinder for dedicated missions (e.g., FOCOS [31]) to establish high-precision OAC as space-time references in space.

As a space-station-based multi-user research campaign, we also consider the inclusion of high-precision sensors for complementary searches for dark-matter signatures, including magnetometers, accelerometers, optical cavities, and interferometers. Additional sensors or measurement combinations allow for complementary searches for dark-matter signatures. Vapor-cell-based magnetometers are routinely used in both space mission and ground based applications [32, 33]. Mature laser technology, microfabricated cells, and optical assembly techniques also allow for a compact low size, weight, and power (SWaP) piggyback device.

## 2. Probing the dark sector with space-based clocks

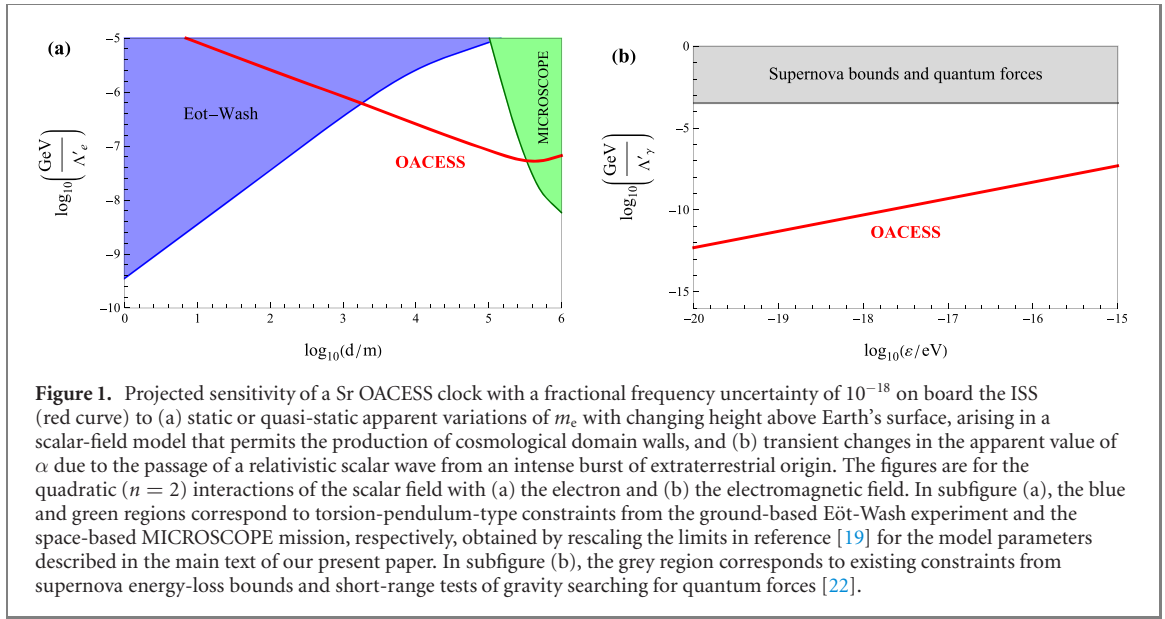
Determining the properties of dark matter and dark energy is one of the grand challenges of our time. Ultra-low-mass (sub-eV) bosons are excellent candidates to explain the dark matter and dark energy, and can also serve as more general dark-sector components that do not necessarily play a significant role in cosmology. Atomic clocks have been proposed as sensitive probes of dark scalar (spin-0) fields that induce temporal or spatial variations of the fundamental constants of nature, including in models of dark matter [18, 34–36], solitons [19, 37], and bursts of relativistic scalar particles [20, 38].

Let us consider the following interaction Lagrangian describing the coupling of a real scalar field  $\phi$  to ordinary matter at low energies (see, e.g., [35, 36]):

$$\mathcal{L}_{\text{int}}^{(n)} = \left( \frac{\phi}{\Lambda_{\gamma,n}} \right)^n \frac{F_{\mu\nu} F^{\mu\nu}}{4} - \left( \frac{\phi}{\Lambda_{e,n}} \right)^n m_e \bar{\psi}_e \psi_e - \left( \frac{\phi}{\Lambda_{N,n}} \right)^n m_N \bar{\psi}_N \psi_N, \quad (1)$$

where  $F$  is the electromagnetic field tensor,  $\psi_e$  denotes the electron field, and  $\psi_N$  denote the nucleon fields. The parameters  $\Lambda_{i,n}$  denote the effective new-physics energy scales of the underlying model, with  $n$  being a positive integer; higher energy scales correspond to feebler interactions between the scalar field and SM fields. In this section, we employ the natural units  $\hbar = c = 1$ .

The most commonly considered values of  $n$  in equation (1) are  $n = 1$  (*linear portal*) and  $n = 2$  (*quadratic portal*). The linear portal is generally devoid of screening effects and linear interactions are absent altogether, e.g., in models with an underlying  $Z_2$  symmetry (which precludes interactions with an odd power of  $\phi$ ). The quadratic portal is of particular interest to experiments employing at least one atomic clock in space, since the scalar field can be strongly screened near the surface of and inside Earth as well as other large dense bodies [18–23]. When the scalar field is strongly screened inside Earth, the scalar-field amplitude can be suppressed by the factor of  $\sim h/R$  near the surface of a spherical dense body, where  $h$  is the height above the surface of the body and  $R$  is the radius of the body; for a typical height of a ground-based atomic clock of  $h \sim 1$  m, we have  $h/R_{\oplus} \sim 10^{-7}$ , which means that the utilisation of space-based clocks, such as in OACCESS, can provide an enormous advantage. In the case of clocks on board the ISS, e.g., the suppression factor is only  $\approx 0.06$ , but can be practically evaded altogether at higher altitudes (e.g., in geosynchronous orbit).



The Lagrangian (1) induces the following changes in the apparent values of the electromagnetic fine-structure constant  $\alpha$  and the fermion masses [35, 36]:

$$\frac{\delta\alpha}{\alpha} \approx \left(\frac{\phi}{\Lambda_{\gamma,n}}\right)^n, \quad \frac{\delta m_e}{m_e} = \left(\frac{\phi}{\Lambda_{e,n}}\right)^n, \quad \frac{\delta m_N}{m_N} = \left(\frac{\phi}{\Lambda_{N,n}}\right)^n. \quad (2)$$

The response of a clock transition frequency  $\nu$  to apparent variations of one or more of the fundamental constants  $X = \alpha, m_e, m_N$  can be parameterised in terms of the *relative sensitivity coefficients*  $K_X$ , according to:

$$\frac{\delta\nu}{\nu} = \sum_X K_X \frac{\delta X}{X}. \quad (3)$$

In the non-relativistic limit, an archetypal optical atomic transition frequency scales proportionally to the Rydberg constant,  $\nu \propto m_e \alpha^2$ , and so  $K_\alpha = +2$ ,  $K_{m_e} = +1$  and  $K_{m_N} = 0$ . In frequency comparisons of two *co-located* optical atomic transitions, the Rydberg constant cancels in the frequency ratio and sensitivity to variations of  $\alpha$  arises from differences in the relativistic correction factors associated with the two transitions [39, 40], which have been calculated extensively [39–44]; e.g., the relativistic factor (in  $K_\alpha$  equivalent) is +0.06 in the case of the Sr  $^1S_0 - ^3P_0$  optical clock transition, but can have a significantly larger magnitude for transitions in heavier atomic species (e.g., Yb, Hg). The overall sensitivity coefficient typically remains dominated by the non-relativistic contribution  $K_\alpha = +2$  in our proposed measurements, so in general there is only a modest benefit in terms of the sensitivity coefficient when using atomic species heavier than Sr.

On the other hand, in ground-to-space comparisons of a *single* optical clock transition, which involve an independent determination of the clock height difference e.g. via a combination of laser ranging and either orbital position or gravimeter data, the effective sensitivity coefficients are  $K_\alpha^{\text{eff}} \approx +2$ ,  $K_{m_e}^{\text{eff}} \approx +1$ ,  $K_{m_N}^{\text{eff}} \approx -1$  in the non-relativistic limit [19]; here the sensitivity to  $\delta\alpha$  and  $\delta m_e$  mainly comes from the Rydberg constant associated with the optical transition, while the sensitivity to  $\delta m_N$  mainly comes from the dominant nucleon content of the test masses or bodies. Compared to optical atomic transitions, in the non-relativistic limit, an archetypal hyperfine atomic transition has larger relative sensitivity coefficients ( $K_\alpha = +4$ ,  $K_{m_e} = +2$  and  $K_{m_N} = -1$ ), due to the short-range nature of the magnetic hyperfine interaction and the participation of the nuclear magnetic moment.

In figures 1(a) and (b), we present the projected sensitivity of a clock operating in low Earth orbit (e.g., ISS), assuming a fractional frequency stability of  $2 \times 10^{-16} / \sqrt{\tau}$  s and a fractional frequency uncertainty of  $10^{-18}$ , in the context of two different scalar-field models:

- In figure 1(a), static or quasi-static apparent variations of  $m_e$  with changing height above Earth's surface, arising in a scalar-field model that permits the production of cosmological domain walls [19]. Here we have chosen model parameters such that a single cosmological domain wall would contribute to the present-day mass-energy fraction of the Universe at the level of one part in  $10^{20}$ , with the presence of a single domain wall motivated by results of numerical simulations [45–47] and the choice of mass-energy fraction consistent with cosmological observations [19, 48]; however, our

sensitivity estimate also equally applies if there are no domain walls of cosmological origin. The apparent value of  $m_e$  changes over a characteristic height of  $\sim \min(d, R_\oplus)$  away from Earth's surface, where  $d$  is the thickness of a (possible) domain wall of cosmological origin, and so the comparison of the space-based OACCESS clock with another Sr clock on the ground can offer an enormous advantage over purely ground-based clock comparisons such as in reference [49] for  $d \gtrsim 1$  km.

- In figure 1(b), transient changes in the apparent value of  $\alpha$  due to the passage of a relativistic scalar wave from an intense burst of extraterrestrial origin [20, 38]. Here we have chosen burst parameters that yield a coherent burst over the entire relevant range of scalar particle energies  $\varepsilon$  and have assumed that the same type of scalar particle makes no contribution towards the matter-energy content of the Universe (beyond the negligible fraction due to the bursts themselves). The use of a space-based clock network with multiple nodes would allow for the determination of the direction to the burst source.

In both cases, analogous ground-based clock experiments have insufficient sensitivity to probe the relevant parameter space in these models due to strong screening of the scalar field by Earth's atmosphere (see references [19, 20] for details). Experiments utilising space-based optical clocks therefore open up possibilities that are currently inaccessible to purely ground-based experiments.

### 3. Space station enabled optical clock hardware

Key components for a space-based OAC payload include the science module (in which the atoms are produced, cooled, and interrogated), the laser and optical system (including the ultra-high-stability clock laser), and the clock-signal distribution system (including the optical frequency comb (OFC) for down-converting high-precision clock signals from the optical domain and space-to-ground comparison via an optical link). The payload is illustrated in figure 2. In the following, we briefly discuss the primary components for OACCESS and the ongoing efforts from various institutions worldwide towards supporting a near-term Earth-orbiting optical clock mission.

#### 3.1. Science module

OACCESS will require a rugged science module that incorporates the physics package (vacuum chamber), magnetic coils, optomechanics, magnetic shields, and thermal control systems in a low-SWaP design. The physics package will consist of a low-power, high-flux atom source and an ultra-high-vacuum (UHV) (better than  $10^{-10}$  Torr) 'science cell' with exceptional optical access to accommodate three retro-reflected pairs of laser beams for a two-stage magneto-optical trap (MOT), an 813 nm lattice laser, a clock laser, optical pumping beams, and an independent imaging path. Mature solutions currently exist for the miniaturized Sr source [50, 51].

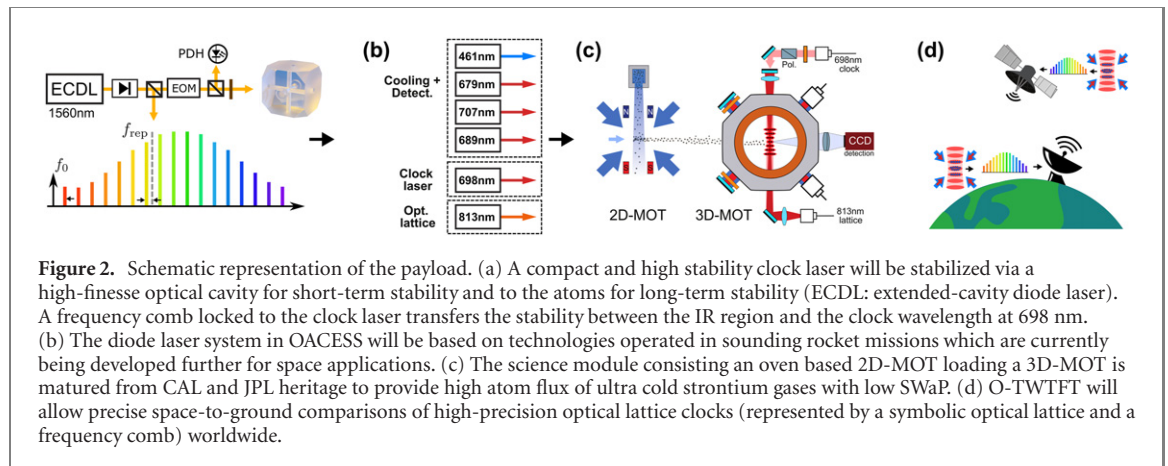
We envision that the science cell, vacuum pumps, magnetic coils, opto-mechanics, magnetic shields, cooling, electronics, and control/imaging systems can all strongly leverage the heritage established from NASA's Cold Atom Lab (CAL) [52] as well as ongoing DLR activities (SOLIS-1G). The latter aims to develop a compact, low-SWaP 2D-MOT atomic source and a 3D-MOT based on an aluminum alloy with maximized optical access. The non-magnetic alloy has a low level of helium permeability, allowing to reach low UHV levels without high temperature baking and high pumping speed pumps. Adaptations that might be beneficial for OACCESS, like a pyramidal single beam 3D-MOT assembly or an integrated enhancement cavity for the optical lattice will be investigated [53, 54].

However, because some types of OACCESS dark-sector searches rely on time-dependent comparisons of ultra-high-precision clocks, it will require unprecedented environmental control with respect to space-based quantum sensors. Influences and mitigation plans for the leading clock systematic errors will therefore be an integral part of this study. The development and use of ground testbeds for analyzing/testing OACCESS designs for functionality and unanticipated systematic shifts will be critical.

#### 3.2. Laser and optical system

The operation of OACCESS requires a laser system capable of two-stage laser cooling, state preparation, coherent transfer of atoms and trapping in an optical lattice at the magic wavelength, and ultra-stable interrogation of the clock transition [7]. The required wavelengths are shown in figure 2. Here, the ultra-stable clock laser system will combine mature cavity-stabilized laser designs from terrestrial labs [7–14] with flight-qualified laser system designs (e.g. for the GRACE-FO mission [55]).

Strontium optical clock technologies have matured to the point where all necessary wavelengths can be provided by diode lasers. Diode-laser-based systems already operate in experiments at the Bremen drop tower, on sounding rockets, and in CAL to study ultra-cold rubidium and potassium atoms [52, 56–58]. Laser payloads and optical frequency references have been developed for operation on sounding rockets



and reached TRL 9 on such sub-orbital vehicles through flight mission operation [59–62]. These payloads feature diode laser systems which are based on a micro-integrated laser technology platform, providing compact, robust and energy-efficient semiconductor laser modules. Moreover, a system for laser cooling and atom interferometry with  $^{87}\text{Rb}$  atoms was launched in 2017 (MAIUS) [63] and a high-performance optical frequency reference based on molecular iodine (JOKARUS mission) has also been launched [64, 65]. Currently, laser systems with even lower SWaP are under development for future operation on CubeSats [66], integrated into standalone piggyback devices [67] where flexible field-programmable-gate-array-based tools are used for automatic lock point selection and autonomously optimising spectroscopy parameters [68].

As part of the ongoing DLR SOLIS-IG activities, DBR lasers optimized for strontium lattice clocks, at 689.449 nm were fabricated. The devices achieve a laser power output of 80 mW as well as a spectral linewidth of 0.4 MHz [69]. Extending the wavelength range from 679 nm to 707 nm would allow for a highly integrated and intrinsically stable laser system. A space qualified frequency comb (Menlo Systems) as well as SMD-based light modulators (QUBIG) are being developed or first prototypes exist.

Development of a robust, low SWaP clock laser system will benefit from early development of ground test-beds to validate the design and performance of the optical clock.

### 3.3. Frequency comparison

We consider frequency-comb-based optical two-way time-frequency transfer (O-TWTFT) [15, 25] as one highly promising method for achieving space-to-ground clock comparisons below the  $10^{-18}$  level. Here, laser light stabilized by the optical clocks would be transmitted to OFCs. OFC pulses from Earth-based clocks and from the space-based clock would then be simultaneously exchanged via a free-space optical link. This approach mirrors conventional RF two-way satellite transfer but achieves much higher precision by use of short optical pulses. In this two-way approach, the time-of-flight fluctuations are canceled to yield just the relative clock offsets. Recent demonstrations have compared state-of-the-art optical clocks at JILA and NIST, where the residual instability contribution from the O-TWTFT comparison was well below  $10^{-18}$  [15, 25]. O-TWTFT has also been demonstrated over a link to a flying quad-copter at closing velocities of up to  $20 \text{ m s}^{-1}$  with no observable degradation from velocity-dependent systematics [70].

Frequency combs have already been operated on suborbital vehicles and optical frequency measurements were successfully demonstrated on two sounding rocket flights [61] and are currently being developed for operation on the Bartolomeo platform attached to the ISS (COMPASSO). Using fiber amplifiers and second-harmonic generation, the spectrum from 400 nm–2000 nm can be covered. In this way, all lasers required for clock operation could be referenced directly to the comb, allowing for additional stabilized laser sources for high-performance space-based optical-to-ground links. For this mission, mature designs for a robust, low-SWaP frequency comb will need to be space qualified. In addition, the promising O-TWTFT transfer scheme needs to be validated for orders of magnitude longer length scales and Doppler shifts for the ground-to-space OAC comparisons.

A modified version of the O-TWTFT technique shows promise for operation at significantly lower received powers [71], which should enable operation at low power-aperture products over the long path lengths between a clock in low-earth orbit and on the ground. However, this new approach will require further development to operate at the high closing velocities associated with low-earth-orbit satellites.

## 4. Summary

OACCESS aims to serve as a pathfinder science mission to search for space-time-dependent signatures of dark scalar fields while establishing the technologies for high-precision OACs in space. This mission will directly leverage the developments and lessons learned from the recent and ongoing campaigns of NASA's CAL, several DLR sounding rocket missions that demonstrated laser systems, BEC-based interferometry, optical atomic and molecular frequency references, as well as future missions under development like the NASA/DLR BECCAL. As summarized in the BPS Topical White paper 'Space-Time Referencing: atomic clocks, laser links and applications' [26], space-based clocks and Earth-space timing links, building off of the technologies matured by OACCESS, can provide enabling capabilities for geodesy, Earth sciences, navigation, world-wide time transfer, and fundamental physics including testing the foundations of general relativity and searching for physics beyond the standard model.

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## Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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## References

- [1] Safronova M *et al* 2018 Search for new physics with atoms and molecules *Rev. Mod. Phys.* **90** 025008
- [2] Antypas D *et al* 2022 New horizons: scalar and vector ultralight dark matter (arXiv:2203.14915)
- [3] Bothwell T, Kennedy C J, Aeppli A, Kedar D, Robinson J M, Oelker E, Staron A and Ye J 2022 Resolving the gravitational redshift across a millimetre-scale atomic sample *Nature* **602** 420
- [4] Zheng X, Dolde J, Lochab V, Merriman B N, Li H and Kolkowitz S 2022 Differential clock comparisons with a multiplexed optical lattice clock *Nature* **602** 425
- [5] Matei D *et al* 2017 1.5  $\mu\text{m}$  lasers with sub-10 mHz linewidth *Phys. Rev. Lett.* **118** 263202
- [6] Zhang W *et al* 2017 Ultrastable silicon cavity in a continuously operating closed-cycle cryostat at 4 K *Phys. Rev. Lett.* **119** 243601
- [7] Ludlow A, Boyd M M, Ye J, Peik E and Schmidt P O 2015 Optical atomic clocks *Rev. Mod. Phys.* **87** 637
- [8] Campbell S L *et al* 2017 A Fermi-degenerate three-dimensional optical lattice clock *Science* **358** 6359
- [9] McGrew W F *et al* 2018 Atomic clock performance enabling geodesy below the centimetre level *Nature* **564** 87–90
- [10] Schioppo M *et al* 2017 Ultrastable optical clock with two cold-atom ensembles *Nat. Photon.* **11** 48–52
- [11] Oelker E *et al* 2019 Demonstration of  $4.8 \times 10^{-17}$  stability at 1 s for two independent optical clocks *Nat. Photon.* **13** 714–9
- [12] Hinkley N, Sherman J A, Phillips N B, Schioppo M, Lemke N D, Beloy K, Pizzocaro M, Oates C W and Ludlow A D 2013 An atomic clock with  $10^{-18}$  instability *Science* **341** 1215–8
- [13] Marti G E, Hutson R B, Goban A, Campbell S L, Poli N and Ye J 2018 Imaging optical frequencies with 100  $\mu\text{Hz}$  precision and 1.1  $\mu\text{m}$  resolution *Phys. Rev. Lett.* **120** 103201
- [14] Bothwell T, Kedar D, Oelker E, Robinson J M, Bromley S L, Tew W L, Ye J and Kennedy C J 2019 JILA SrI optical lattice clock with uncertainty of  $2.0 \times 10^{-18}$  *Metrologia* **56** 065004
- [15] Boulder Atomic Clock Optical Network (BACON) Collaboration 2021 Frequency ratio measurements at 18-digit accuracy using an optical clock network *Nature* **591** 564
- [16] Kómár P, Kessler E M, Bishof M, Jiang L, Sørensen A S, Ye J and Lukin M D 2014 A quantum network of clocks *Nat. Phys.* **10** 582
- [17] Schuldt T *et al* 2021 Optical clock technologies for global navigation satellite systems *GPS Solut.* **25** 83
- [18] Hees A, Minazzoli O, Savalle E, Stadnik Y V and Wolf P 2018 Violation of the equivalence principle from light scalar dark matter *Phys. Rev. D* **98** 064051
- [19] Stadnik Y V 2020 New bounds on macroscopic scalar-field topological defects from nontransient signatures due to environmental dependence and spatial variations of the fundamental constants *Phys. Rev. D* **102** 115016
- [20] Stadnik Y V 2021 Comment on ‘Quantum sensor networks as exotic field telescopes for multi-messenger astronomy’ (arXiv:2111.14351)
- [21] Damour T and Esposito-Farèse G 1993 Nonperturbative strong-field effects in tensor–scalar theories of gravitation *Phys. Rev. Lett.* **70** 2220
- [22] Olive K A and Pospelov M 2008 Environmental dependence of masses and coupling constants *Phys. Rev. D* **77** 043524
- [23] Hinterbichler K and Khoury J 2010 Screening long-range forces through local symmetry restoration *Phys. Rev. Lett.* **104** 231301
- [24] Feryl R and Van Vliet K 2021 *Call to the Biological and Physical Sciences in Space Community for White Papers* (NASA)
- [25] Bodine M I *et al* 2020 Optical atomic clock comparison through turbulent air *Phys. Rev. Res.* **2** 033395
- [26] Hollberg L *et al* 2021 Space-time referencing: atomic clocks, laser links and applications *A Topic White Paper Submitted to the NASA Decadal Survey on Biological and Physical Sciences Research in Space 2023–2032* (NASA)
- [27] Berceau P *et al* 2016 Space-time reference with an optical link *Class. Quantum Grav.* **33** 135007
- [28] Robert C, Conan J-M and Wolf P 2016 Impact of turbulence on high-precision ground-satellite frequency transfer with two-way coherent optical links *Phys. Rev. A* **93** 033860
- [29] Taylor M T, Hollberg L and Kahn J M 2017 Effect of atmospheric anisoplanatism on earth-to-satellite time transfer over laser communication links *Opt. Express* **25** 15676–86
- [30] Taylor M T *et al* 2020 Effect of atmospheric turbulence on timing instability for partially reciprocal two-way optical time transfer links *Phys. Rev. A* **101** 033843
- [31] Derevianko A *et al* 2022 Fundamental physics with a state-of-the-art optical clock in space *Quantum Sci. Technol.* **7** 044002
- [32] Acuña M H 2002 Space-based magnetometers *Rev. Sci. Instrum.* **73** 3717
- [33] Korth H, Strohhahn K, Tejada F, Andreou A G, Kitching J, Knappe S, Lehtonen S J, London S M and Kafel M 2016 Miniature atomic scalar magnetometer for space based on the rubidium isotope  $^{87}\text{Rb}$  *JGR Space Phys.* **121** 7870–80
- [34] Arvanitaki A, Huang J and Van Tilburg K 2015 Searching for dilaton dark matter with atomic clocks *Phys. Rev. D* **91** 015015
- [35] Stadnik Y V and Flambaum V V 2015 Searching for dark matter and variation of fundamental constants with laser and maser interferometry *Phys. Rev. Lett.* **114** 161301
- [36] Stadnik Y V and Flambaum V V 2015 Can dark matter induce cosmological evolution of the fundamental constants of nature? *Phys. Rev. Lett.* **115** 201301
- [37] Derevianko A and Pospelov M 2014 Hunting for topological dark matter with atomic clocks *Nat. Phys.* **10** 933
- [38] Dailey C, Bradley C, Jackson Kimball D F, Sulai I A, Pustelny S, Wickenbrock A and Derevianko A 2021 Quantum sensor networks as exotic field telescopes for multi-messenger astronomy *Nat. Astron.* **5** 150
- [39] Dzuba V A, Flambaum V V and Webb J K 1999 Space-time variation of physical constants and relativistic corrections in atoms *Phys. Rev. Lett.* **82** 888
- [40] Dzuba V A, Flambaum V V and Webb J K 1999 Calculations of the relativistic effects in many-electron atoms and space-time variation of fundamental constants *Phys. Rev. A* **59** 230
- [41] Dzuba V A, Flambaum V V and Marchenko M V 2003 Relativistic effects in Sr, Dy, Yb II, and Yb III and search for variation of the fine-structure constant *Phys. Rev. A* **68** 022506
- [42] Angstmann E J, Dzuba V A and Flambaum V V 2004 Relativistic effects in two valence-electron atoms and ions and the search for variation of the fine-structure constant *Phys. Rev. A* **70** 014102
- [43] Flambaum V V and Tedesco A F 2006 Dependence of nuclear magnetic moments on quark masses and limits on temporal variation of fundamental constants from atomic clock experiments *Phys. Rev. C* **73** 055501
- [44] Dzuba V A and Flambaum V V 2008 Relativistic corrections to transition frequencies of Ag I, Dy I, Ho I, Yb II, Yb III, Au I, and Hg II and search for variation of the fine-structure constant *Phys. Rev. A* **77** 012515
- [45] Garagounis T and Hindmarsh M 2003 Scaling in numerical simulations of domain walls *Phys. Rev. D* **68** 103506

- [46] Oliveira J C R E, Martins C J A P and Avelino P P 2005 The cosmological evolution of domain wall networks *Phys. Rev. D* **71** 083509
- [47] Avelino P P, Oliveira J C R E and Martins C J A P 2005 Understanding domain wall network evolution *Phys. Lett. B* **610** 1
- [48] Press W H, Ryden B S and Spergel D N 1989 Dynamical evolution of domain walls in an expanding Universe *Astrophys. J.* **347** 590
- [49] Takamoto M, Ushijima I, Ohmae N, Yahagi T, Kokado K, Shinkai H and Katori H 2020 Test of general relativity by a pair of transportable optical lattice clocks *Nat. Photon.* **14** 411
- [50] <https://aosense.com/product/cold-atomic-beam-system-reload/>
- [51] Schioppo M, Poli N, Prevedelli M, Falke S, Lisdat C, Sterr U and Tino G M 2012 A compact and efficient strontium oven for laser-cooling experiments *Rev. Sci. Instrum.* **83** 103101
- [52] Avelino D *et al* 2020 Observation of Bose–Einstein condensates in an Earth-orbiting research lab *Nature* **582** 193–7
- [53] Bowden W, Hobson R, Hill I R, Vianello A, Schioppo M, Silva A, Margolis H S, Baird P E G and Gill P 2019 A pyramid MOT with integrated optical cavities as a cold atom platform for an optical lattice clock *Sci. Rep.* **9** 11704
- [54] Ohmae N *et al* 2021 Transportable strontium optical lattice clocks operated outside laboratory at the level of  $10^{-18}$  uncertainty *Adv Quantum Technol.* **4** 2100015
- [55] Thompson R *et al* 2011 A flight-like optical reference cavity for GRACE follow-on laser frequency stabilization *Joint Conf. IEEE Int. Frequency Control and the European Frequency and Time Forum (FCS) Proc.* pp 1–2
- [56] Schiemangk M *et al* 2015 High-power, micro-integrated diode laser modules at 767 and 780 nm for portable quantum gas experiments *Appl. Opt.* **54** 5332–8
- [57] Pahl J, Dinkelaker A N, Grzeschik C, Kluge J, Schiemangk M, Wicht A, Peters A and Krutzik M 2019 Compact and robust diode laser system technology for dual-species ultracold atom experiments with rubidium and potassium in microgravity *Appl. Opt.* **58** 5456–64
- [58] Becker D *et al* 2018 Space-borne Bose–Einstein condensation for precision interferometry *Nature* **562** 391–5
- [59] Kohfeldt A *et al* 2016 Compact narrow linewidth diode laser modules for precision quantum optics experiments on board of sounding rockets *SPIE Photonics Europe 2016* pp 203–12
- [60] Luvsandamdin E, Kürbis C, Schiemangk M, Sahn A, Wicht A, Peters A, Erbert G and Tränkle G 2014 Micro-integrated extended cavity diode lasers for precision potassium spectroscopy in space *Opt. Express* **22** 7790–8
- [61] Lezius M *et al* 2016 Space-borne frequency comb metrology *Optica* **3** 1381–7
- [62] Dinkelaker A *et al* 2017 Autonomous frequency stabilization of two extended-cavity diode lasers at the potassium wavelength on a sounding rocket *Appl. Opt.* **56** 1388–96
- [63] Schkolnik V *et al* 2016 A compact and robust diode laser system for atom interferometry on a sounding rocket *Appl. Phys. B* **122** 217
- [64] Doeringshoff K *et al* 2019 Iodine frequency reference on a sounding rocket *Phys. Rev. Appl.* **11** 054068
- [65] Schkolnik V *et al* 2017 JOKARUS—design of a compact optical iodine frequency reference for a sounding rocket mission *EPJ Quantum Technol.* **4** 9
- [66] Strangfeld A, Kanthak S, Schiemangk M, Wiegand B, Wicht A, Ling A and Krutzik M 2021 Prototype of a compact rubidium-based optical frequency reference for operation on nanosatellites *J. Opt. Soc. Am. B* **38** 1885–91
- [67] Strangfeld A, Wiegand B, Kluge J, Schoch M and Krutzik M 2022 Compact plug and play optical frequency reference device based on Doppler-free spectroscopy of rubidium vapor *Opt. Express* **30** 12039
- [68] Wiegand B, Leykauf B, Jördens R and Krutzik M 2022 Linien: a versatile, user-friendly, open-source FPGA-based tool for frequency stabilization and spectroscopy parameter optimization *Rev. Sci. Instrum.* **93** 063001
- [69] Pyrlík C *et al* 2022 High power distributed Bragg reflector lasers at 689.45 nm for quantum technology applications *IEEE Photon. Technol. Lett.* **34** 679–82
- [70] Bergeron H, Sinclair L C, Swann W C, Khader I, Cossel K C, Cermak M, Deschênes J-D and Newbury N R 2019 Femtosecond time synchronization of optical clocks off of a flying quadcopter *Nat. Commun.* **10** 1819
- [71] Caldwell E, Sinclair L, Swann W, Newbury N, Stuhl B and Deschenes J 2022 Photon efficient optical time transfer *EFTF-IFCS, Timekeeping, T & F Transfer, Telecom, GNSS and Applications* vol 5036