ARC DECRA Fellow, The University of Queensland, QLD 4072, Australia
@: b.roberts@uq.edu.au
www: broberts.io/
ORCID: 0000-0002-0345-6375
INSPIRE HEP: B.M.Roberts.1
arXiv profile: arxiv.org/a/roberts_b_1

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I. Research Articles

[1] *Ultralight Dark Matter Search with Space-Time Separated Atomic Clocks and Cavities*,
Melina Filzinger[1], Ashlee R. Caddell[†2], Dhruv Jani[*2], Martin Steinel[1], Leonardo Giani[2], Nils Huntemann[1], and B. M. Roberts[2]. [1] *Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany;* [2] *The University of Queensland, QLD 4072, Australia.*
[arXiv:2312.13723].

We devise and demonstrate a method to search for non-gravitational couplings of ultralight dark matter to standard model particles using space-time separated atomic clocks and cavity-stabilized lasers. By making use of space-time separated sensors, which probe different values of an oscillating dark matter field, we can search for couplings that cancel in typical local experiments. We demonstrate this method using existing data from a frequency comparison of lasers stabilized to two optical cavities connected via a 2220 km fiber link [Schioppo et al., Nat. Commun. **13***, 212 (2022)]. The absence of significant oscillations in the data results in constraints on the coupling of scalar dark matter to electrons, d_{m_e}, for masses between $10^{-19}\,\mathrm{eV}/c^2$ and $2\times10^{-15}\,\mathrm{eV}/c^2$. These are the first constraints on d_{m_e} alone in this mass range, and improve the dark matter constraints on any scalar-Fermion coupling by up to two orders of magnitude.*

[2] *Accurate electron-recoil ionization factors for dark matter direct detection in xenon, krypton and argon*,
A. R. Caddell[†1], V. V. Flambaum[2], and B. M. Roberts[1]. [1] *The University of Queensland, QLD 4072, Australia;* [2] *UNSW, Sydney, NSW 2052, Australia.*
Physical Review D **108**, 083030 (2023). [arXiv:2305.05125].

While most scintillation-based dark matter experiments search for weakly interacting massive particles (WIMPs), a sub-GeV WIMP-like particle may also be detectable in these experiments. While dark matter of this type and scale would not leave appreciable nuclear recoil signals, it may instead induce ionization of atomic electrons. Accurate modeling of the atomic wave functions is key to investigating this possibility, with incorrect treatment leading to a large suppression in the atomic excitation factors. We have calculated these atomic factors for argon, krypton, and xenon and present the tabulated results for use with a range of dark matter models. This is made possible by the separability of the atomic and dark matter form factor, allowing the atomic factors to be calculated for general couplings; we include tables for vector, scalar, pseudovector, and pseudoscalar electron couplings. Additionally, we calculate electron-impact total ionization cross sections for xenon using the tabulated results as a test of accuracy. Lastly, we provide an example calculation of the event rate for dark matter scattering on electrons in XENON1T and show that these calculations depend heavily on how the low-energy response of the detector is modeled.

[3] *Electric-dipole transition amplitudes for atoms and ions with one valence electron*,
B. M. Roberts, C. J. Fairhall[†], and J. S. M. Ginges. *The University of Queensland, QLD 4072, Australia.*
Physical Review A **107**, 052812 (2023). [arXiv:2211.11134].

Motivated by recent measurements for several alkali-metal atoms and alkali-metal-like ions, we perform a detailed study of electric dipole (E1) transition amplitudes in K, Ca^+, Rb, Sr^+, Cs, Ba^+, Fr, and Ra^+, which are of interest for studies of atomic parity violation, electric dipole moments, and polarizabilities. Using the all-orders correlation potential method, we perform high-precision calculations of E1 transition amplitudes between low-lying s, p, and d states. We perform a robust error analysis, and compare our calculations to many amplitudes for which there are

[†] My PhD students, [*] My honours students

high-precision experimental determinations. We find excellent agreement, with deviations at the level of $\sim 0.1\%$. We also compare our results to other theoretical evaluations, and discuss the implications for uncertainty analyses. Further, combining calculations of branching ratios with recent measurements, we extract high-precision values for several E1 amplitudes of Ca^+, Sr^+, Cs, Fr, and Ra^+.

[4] *Experimental and theoretical study of dynamic polarizabilities in the $5S_{1/2}-5D_{5/2}$ clock transition in rubidium-87 and determination of E1 matrix elements*,
R. Hamilton[1], B. M. Roberts[2], S. Scholten[1], C. Locke[1], A. N. Luiten[1], J. S. M. Ginges[2], and C. Perrella[1].
[1]*Institute for Photonics and Advanced Sensing (IPAS) and School of Physical Sciences, University of Adelaide, Adelaide SA 5005, Australia;* [2]*The University of Queensland, QLD 4072, Australia.*
Physical Review Applied **19**, 054059 (2023). [arXiv:2212.10743].
The interaction between light and an atom causes a perturbation in the atom's energy levels, known as the light-shift. These light-shifts are a key source of inaccuracy in atomic clocks, and can also deteriorate their precision. We present a study of light-shifts and associated dynamic polarizabilities for a two-photon atomic clock based on the $5S_{1/2}$ – $5D_{5/2}$ transition in rubidium-87 over the range 770 nm to 800 nm. We determine experimental and theoretical values for a magic wavelength in this range and the electric dipole (E1) matrix element for the $5P_{3/2}-5D_{5/2}$ transition. We find a magic wavelength of 776.179(5) nm (experimental) and 776.21 nm (theoretical) in the vicinity of the $5P_{3/2}-5D_{5/2}$ resonance, and the corresponding reduced E1 matrix element $1.80(6)\,ea_0$ (experimental) and $1.96(15)\,ea_0$ (theoretical). These values resolve a previous discrepancy between theory and experiment.

[5] *QED radiative corrections to electric dipole amplitudes in heavy atoms*,
C. J. Fairhall[†], B. M. Roberts, and J. S. M. Ginges. *The University of Queensland, QLD 4072, Australia.*
Physical Review A **107**, 022813 (2023). [arXiv:2212.11490].
We use the radiative potential method to perform a detailed study of quantum electrodynamics (QED) radiative corrections to electric dipole (E1) transition amplitudes in heavy alkali-metal atoms Rb, Cs, Fr, and alkali-metal-like ions Sr^+, Ba^+, and Ra^+. The validity of the method is checked by comparing with the results of rigorous QED in simple atomic potentials. We study the effects of core relaxation, polarization of the core by the E1 field, and valence-core correlations on QED, which are shown to be important in some cases. We identify several transitions in Cs for which the QED contribution exceeds the deviation between atomic theory and experiment.

[6] *Empirical determination of the Bohr-Weisskopf effect in cesium and improved tests of precision atomic theory in searches for new physics*,
G. Sanamyan*, B. M. Roberts, and J. S. M. Ginges. *The University of Queensland, QLD 4072, Australia.*
Physical Review Letters 130, 053001 (2023). [arXiv:2209.05099].
The finite distribution of the nuclear magnetic moment across the nucleus gives a contribution to the hyperfine structure known as the Bohr-Weisskopf (BW) effect. We have obtained an empirical value of -0.24(18)% for this effect in the ground and excited s states of atomic Cs-133. This value is found from historical muonic-atom measurements in combination with our muonic-atom and atomic many-body calculations. The effect differs by 0.5% in the hyperfine structure from the value found using the uniform magnetization distribution, which has been commonly employed in the precision heavy-atom community over the last several decades. We also deduce accurate values for the BW effect in other isotopes and states of cesium. These results enable cesium atomic wave functions to be tested in the nuclear region at an unprecedented 0.2% level, and are needed for the development of precision atomic many-body methods. This is important for increasing the discovery potential of precision atomic searches for new physics, in particular for atomic parity violation in cesium.

- Covered in *The Brisbane Times*: *'Unusual' atom helps search for dark matter – and a quicker car ride*, as well as *The Sydney Morning Herald*, *The Age*, and *WA Today*. Also featured in *phys.org* and others

[7] *The Bohr-Weisskopf effect: from hydrogenlike-ion experiments to heavy-atom calculations of hyperfine structure*,
B. M. Roberts, P. G. Ranclaud*, and J. S. M. Ginges. *The University of Queensland, QLD 4072, Australia.*
Physical Review A **105**, 052802 (2022). [arXiv:2111.12954].
In this paper we study the influence of electron screening on the Bohr-Weisskopf (BW) effect in many-electron atoms. The BW effect gives the finite-nucleus magnetization contribution to the hyperfine structure. Relativistic atomic many-body calculations are performed for s and $p_{1/2}$ states of several systems of interest for studies of atomic parity violation and time-reversal-violating electric dipole moments – Rb, Cs, Fr, Ba^+, Ra^+, and Tl. For s states, electron screening effects are small, and the relative BW correction for hydrogenlike ions and neutral atoms is approximately the same. We relate the ground-state BW effect in H-like ions, which may be cleanly extracted from experiments, to the BW effect in s and $p_{1/2}$ states of neutral and near neutral atoms through an electronic screening factor. This allows the BW effect extracted from measurements with H-like ions to be used, with screening factors, in atomic calculations without recourse to modelled nuclear structure input. It opens the way for unprecedented accuracy in accounting for the BW effect in heavy atoms. The efficacy of this approach is demonstrated using available experimental data for H-like and neutral ^{203}Tl and ^{205}Tl.

[8] *Comment on "New physics constraints from atomic parity violation in ^{133}Cs"*,
B. M. Roberts and J. S. M. Ginges. *The University of Queensland, QLD 4072, Australia.*
Physical Review D **105**, 018301 (2022). [arXiv:2110.11621].

In a recent Letter, B. K. Sahoo, B. P. Das, and H. Spiesberger, Phys. Rev. D **103**, *L111303 (2021), a calculation of the parity violating $6S-7S$ E1 amplitude in Cs is reported, claiming an uncertainty of just 0.3%. In this Comment, we point out that key contributions have been omitted, and the theoretical uncertainty has been significantly underestimated. In particular, the contribution of missed QED radiative corrections amounts to several times the claimed uncertainty.*

[9] *The hyperfine anomaly in heavy atoms and its role in precision atomic searches for new physics*,
B. M. Roberts and J. S. M. Ginges. *The University of Queensland, QLD 4072, Australia.*
Physical Review A **104**, 022823 (2021). [arXiv:2101.09924].

We report on our calculations of differential hyperfine anomalies in the nuclear single-particle model for a number of atoms and ions of interest for studies of fundamental symmetries violations. Comparison with available experimental data allows one to discriminate between different nuclear magnetization models, and this data supports the use of the nuclear single-particle model over the commonly-used uniform ball model. Accurate modelling of the nuclear magnetization distribution is important for testing atomic theory through hyperfine comparisons. The magnetization distribution must be adequately understood and modelled, with uncertainties well under the atomic theory uncertainty, for hyperfine comparisons to be meaningful. This has not been the case for a number of atoms of particular interest for precision studies, including Cs. Our work demonstrates the validity of the nuclear single-particle model for Cs, and this has implications for the theory analysis of atomic parity violation in this atom.

[10] *Searching for Dark Matter with an Optical Cavity and an Unequal-Delay Interferometer*,
E. Savalle[1], A. Hees[1], F. Frank[1], E. Cantin[1], P.-E. Pottie[1], B. M. Roberts[2], L. Cros[1,3], B. T. McAllister[4], and P. Wolf[1]. [1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France;* [2]*The University of Queensland, QLD 4072, Australia;* [3]*MINES ParisTech, Université PSL, 75006 Paris, France;* [4]*ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, University of Western Australia, Crawley WA 6009, Australia.*
Physical Review Letters 126, 051301 (2021). [arXiv:2006.07055].

We report an experiment that compares the frequency of a clock (an ultra-stable optical cavity in this case) at time t to its own frequency some time $t-T$ earlier, by "storing" the output signal (photons) in a fibre delay line. In ultra-light oscillating dark matter (DM) models such an experiment is sensitive to coupling of DM to the standard model fields, through oscillations of the cavity and fibre lengths and of the fibre refractive index. Additionally, the sensitivity is significantly enhanced around the mechanical resonances of the cavity. We report no evidence of DM for masses in the 4.1×10^{-11}, 8.3×10^{-10} eV region. In addition, we improve constraints on the involved coupling constants by one order of magnitude in a standard galactic DM model, at the mass corresponding to the resonant frequency of our cavity. In a recently proposed model of a DM relaxation halo around the Earth we improve on existing constraints over the whole DM mass range, by up to 6 orders of magnitude.

- Top 5% by citations for category/year (Scopus)

[11] *Precision measurement noise asymmetry and its annual modulation as a dark matter signature*,
B. M. Roberts[1,2], and A. Derevianko[1]. [1]*University of Nevada, Reno 89557, Nevada, USA;* [2]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire 75014 Paris, France.*
Universe (Open Access) **7**, 50 (2021). [arXiv:1803.00617].

Dark matter may be composed of self-interacting ultralight quantum fields that form macroscopic objects. An example of which includes Q-balls, compact non-topological solitons predicted by a range of theories that are viable dark matter candidates. As the Earth moves through the galaxy, interactions with such objects may leave transient perturbations in terrestrial experiments. Here we propose a new dark matter signature: an asymmetry (and other non-Gaussianities) that may thereby be induced in the noise distributions of precision quantum sensors, such as atomic clocks, magnetometers, and interferometers. Further, we demonstrate that there would be a sizeable annual modulation in these signatures due to the annual variation of the Earth velocity with respect to dark matter halo. As an illustration of our formalism, we apply our method to 6 years of data from the atomic clocks on board GPS satellites and place constraints on couplings for macroscopic dark matter objects with radii $R<10^4$ km, the region that is otherwise inaccessible using relatively sparse global networks.

[12] *Nuclear magnetic moments of francium 207–213 from precision hyperfine comparisons*,
B. M. Roberts and J. S. M. Ginges. *The University of Queensland, QLD 4072, Australia.*
Physical Review Letters 125, 063002 (2020). [arXiv:2001.01907].

We report a fourfold improvement in the determination of nuclear magnetic moments for neutron-deficient isotopes of francium-207–213, reducing the uncertainties from 2% for most isotopes to 0.5%. These are found by comparing our high-precision calculations of hyperfine structure constants for the ground states with experimental values. In particular, we show the importance of a careful modelling of the Bohr-Weisskopf effect, which arises due to the finite *nuclear magnetization distribution. This effect is particularly large in Fr and until now has not been modelled with sufficiently high accuracy. An improved understanding of the nuclear magnetic moments and Bohr-Weisskopf effect are crucial for benchmarking the atomic theory required in precision tests of the standard model, in particular atomic parity violation studies, that are underway in francium.*

- Featured in phys.org: *Improved modelling of nuclear structure in francium aids searches for new physics*

[13] *Search for a variation of the fine-structure constant around the supermassive Black Hole in our Galactic Center*,
A. Hees[1], T. Do[2], B. M. Roberts[1,3], Andrea M. Ghez[2], S. Nishiyama[4], R. O. Bentley[2], A. K. Gautam[2], S. Jia[5], T. Kara[4], J. R. Lu[5], H. Saida[6], S. Sakai[2], M. Takahashi[7], and Y. Takamori[8]. [1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France;* [2]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA;* [3]*The University of Queensland, QLD 4072, Australia;* [4]*Miyagi University of Education, 149 Aramaki-aza-aoba, Aoba-ku, Sendai, Miyagi 980-0845, Japan;* [5]*Astronomy Department, University of California, Berkeley, CA 94720, USA;* [6]*Daido University, 10-3 Takiharu-cho, Minami-ku, Nagoya, Aichi 457-8530, Japan;* [7]*Aichi University of Education, 1 Hirosawa, Igaya-cho, Kariya, Aichi 448-8542, Japan;* [8]*National Institute of Technology, Wakayama College, 77 Noshima, Nada-cho, Gobo, Wakayama 644-0023, Japan.*
Physical Review Letters 124, 081101 (2020). [arXiv:2002.11567].

Searching for space-time variations of the constants of Nature is a promising way to search for new physics beyond General Relativity and the standard model motivated by unification theories and models of dark matter and dark energy. We propose a new way to search for a variation of the fine-structure constant using measurements of late-type evolved giant stars from the S-star cluster orbiting the supermassive black hole in our Galactic Center. A measurement of the difference between distinct absorption lines (with different sensitivity to the fine structure constant) from a star leads to a direct estimate of a variation of the fine structure constant between the star's location and Earth. Using spectroscopic measurements of 5 stars, we obtain a constraint on the relative variation of the fine structure constant below 10^{-5}*. This is the first time a variation of the fine structure constant is searched for around a black hole and in a high gravitational potential. This analysis shows new ways the monitoring of stars in the Galactic Center can be used to probe fundamental physics.*

- Editors' Suggestion; Featured in Physics Synopsis (APS) [*Constants Still Constant Near Black Holes*]
- Covered in Spektrum (DE), Science News, and others
- Top 5% by citations for category/year (Scopus)

[14] *Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks*,
B. M. Roberts[1,8], P. Delva[1], A. Al-Masoudi[2], A. Amy-Klein[4], C. Bærentsen[1], C. F. A. Baynham[3], S. Bize[1], E. Benkler[2], S. Bilicki[1], W. Bowden[3], E. Cantin[14], J. Calvert[1], V. Cambier[1], E. A. Curtis[3], S. Dörscher[2], M. Favier[1], F. Frank[1], P. Gill[3], R. M. Godun[3], G. Grosche[2], C. Guo[1], A. Hees[1], I. R. Hill[3], R. Hobson[3], N. Huntemann[2], J. Kronjäger[3], S. Koke[2], A. Kuhl[2], R. Lange[2], T. Legero[2], B. Lipphardt[2], C. Lisdat[2], J. Lodewyck[1], O. Lopez[4], H. S. Margolis[3], H. Álvarez-Martínez[1,5], F. Meynadier[1,6], F. Ozimek[3], E. Peik[2], P.-E. Pottie[1], N. Quintin[7], C. Sanner[2], L. De Sarlo[1], M. Schioppo[3], R. Schwarz[2], A. Silva[3], U. Sterr[2], Chr. Tamm[2], R. Le Targat[1], P. Tuckey[1], G. Vallet[1], T. Waterholter[2], D. Xu[1], and P. Wolf[1]. [1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France;* [2]*Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany;* [3]*National Physical Laboratory, Hampton Road, Teddington TW11 0LW, United Kingdom;* [4]*Laboratoire de Physique des Lasers, Université Paris 13, Sorbonne Paris Cité, CNRS, 99 Avenue Jean-Baptiste Clément, 93430 Villetaneuse, France;* [5]*Sección de Hora, Real Instituto y Observatorio de la Armada, San Fernando, Spain;* [6]*Bureau International des Poids et Mesures, BIPM, Pavillon de Breteuil, 92312 Sèvres, France;* [7]*Réseau National de télécommunications pour la Technologie, l'Enseignement et la Recherche, 23–25 Rue Daviel, 75013 Paris, France* [8]*The University of Queensland, QLD 4072, Australia..*
New Journal of Physics **22**, 093010 (2020). [arXiv:1907.02661].

We search for transient variations of the fine structure constant using data from a European network of fiber-linked optical atomic clocks. By searching for coherent variations in the recorded clock frequency comparisons across the network, we significantly improve the constraints on transient variations of the fine structure constant. For example, we constrain the variation to $|\delta\alpha/\alpha| < 5\times10^{-17}$ *for transients of duration* 10^3 *s. This analysis also presents a possibility to search for dark matter, the mysterious substance hypothesised to explain galaxy dynamics and other astrophysical phenomena that is thought to dominate the matter density of the universe. At the current sensitivity level, we find no evidence for dark matter in the form of topological defects (or, more generally, any macroscopic objects), and we thus place constraints on certain potential couplings between the dark matter and standard model particles, substantially improving upon the existing constraints, particularly for large (*$\gtrsim 10^4$ *km) objects.*

- Featured Article (chosen by the editors for "novelty, significance and potential impact")
- Top 5% by citations for category/year (Reuters Web of Science/Scopus)

[15] *Applying matched-filter technique to the search for dark matter transients with networks of quantum sensors*,
G. Panelli[1], B. M. Roberts[1,2], and A. Derevianko[1]. [1]*University of Nevada, Reno 89557, Nevada, USA;* [2]*The University of Queensland, QLD 4072, Australia.*

EPJ Quantum Technology **7**, 5 (2020). [arXiv:1908.03320].

There are several networks of precision sensors in existence, including networks of atomic clocks, magnetometers, and gravitational wave detectors. These networks can be re-purposed for searches of exotic physics, such as direct dark matter searches. Here we explore a detection strategy for macroscopic dark matter objects with such networks using the matched-filter technique. Such "clumpy" dark matter objects would register as transients sweeping through the network at galactic velocities. As a specific example, we consider a network of atomic clocks aboard the Global Positioning System (GPS) satellites. We apply the matched-filter technique to simulated GPS atomic clock data and study its utility and performance. The analysis and the developed methodology have a wide applicability to other networks of quantum sensors.

[16] *Correlation trends in the hyperfine structure for Rb, Cs, and Fr, and high-accuracy predictions for hyperfine constants*,
S. J. Grunefeld, B. M. Roberts, and J. S. M. Ginges. *The University of Queensland, QLD 4072, Australia.*
Physical Review A **100**, 042506 (2019). [arXiv:1907.02657].

We have performed high-precision calculations of the hyperfine structure for $n\,S_{1/2}$ and $n\,P_{1/2}$ states of the alkali-metal atoms Rb, Cs, and Fr across principal quantum number n, and studied the trend in the size of the correlations. Our calculations were performed in the all-orders correlation potential method. We demonstrate that the relative correlation corrections fall off quickly with n and tend towards constant and non-zero values for highly-excited states. This trend is supported by experiment, and we utilize the smooth dependence on n to make high-accuracy predictions of the hyperfine constants, with uncertainties to within 0.1% for most states of Rb and Cs.

[17] *Novel approaches to dark-matter detection using space-time separated clocks*,
E. Savalle[1], B. M. Roberts[1], F. Frank[1], P.-E. Pottie[1], B. T. McAllister[2], C. B. Dailey[3], A. Derevianko[3], and P. Wolf[1]. [1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France;* [2]*ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, University of Western Australia, Crawley WA 6009, Australia;* [3]*University of Nevada, Reno 89557, Nevada, USA.*
[arXiv:1902.07192].

We discuss the theoretical analysis and interpretation of space-time separated clock experiments in the context of a space-time varying scalar field that is non-universally coupled to the standard model fields. If massive, such a field is a candidate for dark matter and could be detected in laboratory experiments. We show that space-time separated experiments have the potential to probe a fundamentally different parameter space from more common co-located experiments, allowing decorrelation of previously necessarily correlated parameters. Finally, we describe such a space-time separated clock experiment currently running at the Paris Observatory, and present some preliminary results as a proof of principle.

[18] *Electron-interacting dark matter: Implications from DAMA/LIBRA-phase2 and prospects for liquid xenon detectors and NaI detectors*,
B. M. Roberts[1,2] and V. V. Flambaum[3,4]. [1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France;* [2]*The University of Queensland, QLD 4072, Australia;* [3]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [4]*Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany.*
Physical Review D **100**, 063017 (2019). [arXiv:1904.07127].

We investigate the possibility for the direct detection of low mass (GeV scale) WIMP dark matter in scintillation experiments. Such WIMPs are typically too light to leave appreciable nuclear recoils, but may be detected via their scattering off atomic electrons. In particular, the DAMA Collaboration [R. Bernabei et al., Nucl. Phys. At. Energy **19***, 307 (2018)] has recently presented strong evidence of an annual modulation in the scintillation rate observed at energies as low as 1 keV. Despite a strong enhancement in the calculated event rate at low energies, we find that an interpretation in terms of electron-interacting WIMPs cannot be consistent with existing constraints. We also demonstrate the importance of correct treatment of the atomic wavefunctions, and show the resulting event rate is very sensitive to the low-energy performance of the detectors, meaning it is crucial that the detector uncertainties be taken into account. Finally, we demonstrate that the potential scintillation event rate can be much larger than may otherwise be expected, meaning that competitive searches can be performed for $m_\chi \sim 1\,$GeV scale WIMPs using the conventional prompt ($S1$) scintillation signals. This is important given the recent and upcoming very large liquid xenon detectors.*

- Top 5% by citations for category/year (Scopus)

[19] *Calculations of the atomic structure for the low-lying states of actinium*,
V. A. Dzuba[1], V. V. Flambaum[1], and B. M. Roberts[2]. [1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [2]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France.*
Physical Review A **100**, 022504 (2019). [arXiv:1905.02365].

We employ a technique that combines the configuration interaction method with the singles-doubles coupled-cluster method to perform calculation of the energy levels, transition amplitudes, lifetimes, g-factors, and magnetic

dipole and electric quadrupole hyperfine structure constants for many low-lying states of neutral actinium. We find very good agreement with existing experimental energy levels and make accurate predictions for missing levels. It has been noted that some of the levels have been previously misidentified; our analysis supports this claim. If spectroscopy is performed with actinium-225, our calculations will lead to values for nuclear structure constants. The accuracy of this can be constrained by comparing with actinium-227.

[20] *Search for transient ultralight dark matter signatures with networks of precision measurement devices using a Bayesian statistics method*,
B. M. Roberts[1], G. Blewitt[1,2], C. Dailey*[1], and A. Derevianko[1]. [1]*University of Nevada, Reno 89557, Nevada, USA;* [2]*Nevada Geodetic Laboratory, Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, USA.*
Physical Review D **97**, 083009 (2018). [arXiv:1803.10264].
We analyze the prospects of employing a distributed global network of precision measurement devices as a dark matter and exotic physics observatory. In particular, we consider the atomic clocks of the global positioning system (GPS), consisting of a constellation of 32 medium-Earth orbit satellites equipped with either Cs or Rb microwave clocks and a number of Earth-based receiver stations, some of which employ highly-stable H-maser atomic clocks. High-accuracy timing data is available for almost two decades. By analyzing the satellite and terrestrial atomic clock data, it is possible to search for transient signatures of exotic physics, such as "clumpy" dark matter and dark energy, effectively transforming the GPS constellation into a 50,000 km aperture sensor array. Here we characterize the noise of the GPS satellite atomic clocks, describe the search method based on Bayesian statistics, and test the method using simulated clock data. We present the projected discovery reach using our method, and demonstrate that it can surpass the existing constrains by several order of magnitude for certain models. Our method is not limited in scope to GPS or atomic clock networks, and can also be applied to other networks of precision measurement devices.

[21] *Search for domain wall dark matter with atomic clocks on board Global Positioning System satellites*,
B. M. Roberts[1], G. Blewitt[1,2], C. Dailey*[1], M. Murphy[1], M. Pospelov[3,4], A. Rollings[1], J. Sherman[5], W. Williams*[1], and A. Derevianko[1]. [1]*University of Nevada, Reno 89557, Nevada, USA;* [2]*Nevada Geodetic Laboratory, Nevada Bureau of Mines and Geology, University of Nevada, Reno, NV 89557, USA;* [3]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8P 5C2, Canada;* [4]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2J 2W9, Canada;* [5]*National Institute of Standards and Technology, Boulder, CO 80305, USA.*
Nature Communications 8, 1195 (2017). [arXiv:1704.06844].
Cosmological observations indicate that dark matter makes up 85% of all matter in the universe yet its microscopic composition remains a mystery. Dark matter could arise from ultralight quantum fields that form macroscopic objects. Here we use the global positioning system as a $\sim$ 50,000 km aperture dark matter detector to search for such objects in the form of domain walls. Global positioning system navigation relies on precision timing signals furnished by atomic clocks. As the Earth moves through the galactic dark matter halo, interactions with domain walls could cause a sequence of atomic clock perturbations that propagate through the satellite constellation at galactic velocities $\sim$ 300 km/s. Mining 16 years of archival data, we find no evidence for domain walls at our current sensitivity level. This improves the limits on certain quadratic scalar couplings of domain wall dark matter to standard model particles by several orders of magnitude.
- Covered in Science [doi: 10.1126/science.aal0676], and Eos (AGU) [doi: 10.1029/2018EO104623]
- Also covered in Quanta, NBC News, Cosmos Magazine, MIT Tech. Review, and others
- Top 5% by citations for category/year (Reuters Web of Science/Scopus)

[22] *Comment on "Axion induced oscillating electric dipole moments"*,
V. V. Flambaum, B. M. Roberts, and Y. V. Stadnik. *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia.*
Physical Review D **95**, 058701 (2017).

[23] *Reply to 'Comment on "Ionization of Atoms by Slow Heavy Particles, Including Dark Matter"'*,
B. M. Roberts[1], V. V. Flambaum[2], and G. F. Gribakin[3]. [1]*University of Nevada, Reno 89557, Nevada, USA;* [2]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [3]*Queen's University, Belfast BT7 1NN, United Kingdom.*
Physical Review Letters 117, 089302 (2016).

[24] *Dark matter scattering on electrons: Accurate calculations of atomic excitations and implications for the DAMA signal*,
B. M. Roberts[1], Y. V. Stadnik[2], V. A. Dzuba[2], V. V. Flambaum[2], and M. Pospelov[3,4]. [1]*University of Nevada, Reno 89557, USA;* [2]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [3]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia V8P 5C2, Canada;* [4]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2J 2W9, Canada.*
Physical Review D **93**, 115037 (2016). [arXiv:1604.04559].
We revisit the WIMP-type dark matter scattering on electrons that results in atomic ionization and can manifest

itself in a variety of existing direct-detection experiments. Unlike the WIMP-nucleon scattering, where current experiments probe typical interaction strengths much smaller than the Fermi constant, the scattering on electrons requires a much stronger interaction to be detectable, which in turn requires new light force carriers. We account for such new forces explicitly, by introducing a mediator particle with scalar or vector couplings to dark matter and to electrons. We then perform state-of-the-art numerical calculations of atomic ionization relevant to the existing experiments. Our goals are to consistently take into account the atomic physics aspect of the problem (e.g., the relativistic effects, which can be quite significant) and to scan the parameter space—the dark matter mass, the mediator mass, and the effective coupling strength—to see if there is any part of the parameter space that could potentially explain the DAMA modulation signal. While we find that the modulation fraction of all events with energy deposition above 2 keV in NaI can be quite significant, reaching $\sim 50\%$*, the relevant parts of the parameter space are excluded by the XENON10 and XENON100 experiments.*

- Top 5% by citations for category/year (Scopus)

[25] *Atomic ionization by slow heavy particles, including dark matter*,
B. M. Roberts[1], V. V. Flambaum[1,2], and G. F. Gribakin[3]. [1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [2]*Mainz Institute for Theoretical Physics, Johannes Gutenberg University, 55099 Mainz, Germany;* [3]*Queen's University, Belfast BT7 1NN, United Kingdom.*
Physical Review Letters 116, 023201 (2016). [arXiv:1509.09044].

Atoms and molecules can become ionized during the scattering of a slow, heavy particle off a bound electron. Such an interaction involving leptophilic weakly interacting massive particle (WIMP) dark matter is a promising possible explanation for the anomalous 9σ *annual modulation in the DAMA dark matter direct detection experiment [R. Bernabei et al., Eur. Phys. J. C* **73***, 2648 (2013)]. We demonstrate the applicability of the Born approximation for such an interaction by showing its equivalence to the semiclassical adiabatic treatment of atomic ionization by slow-moving WIMPs. Conventional wisdom has it that the ionization probability for such a process should be exponentially small. We show, however, that due to nonanalytic, cusp-like behaviour of Coulomb functions close to the nucleus this suppression is removed, leading to an effective atomic structure enhancement.*

[26] *Parity and Time-Reversal Violation in Atomic Systems*,
B. M. Roberts, V. A. Dzuba, and V. V. Flambaum. *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia.*
Annual Review of Nuclear and Particle Science **65**, 63 (2015). [arXiv:1412.6644].

Studying the violation of parity and time-reversal invariance in atomic systems has proven to be a very effective means for testing the electroweak theory at low energy and searching for physics beyond it. Recent developments in both atomic theory and experimental methods have led to the ability to make extremely precise theoretical calculations and experimental measurements of these effects. Such studies are complementary to direct high-energy searches, and can be performed for just a fraction of the cost. We review the recent progress in the field of parity and time-reversal violation in atoms, molecules, and nuclei, and examine the implications for physics beyond the Standard Model, with an emphasis on possible areas for development in the near future.

- Top 5% by citations for category/year in Nuclear and High Energy Physics (Scopus)

[27] *Parity-violating interactions of cosmic fields with atoms, molecules, and nuclei: Concepts and calculations for laboratory searches and extracting limits*,
B. M. Roberts[1], Y. V. Stadnik[1], V. A. Dzuba[1], V. V. Flambaum[1], N. Leefer[2], and D. Budker[2,3,4]. [1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [2]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany;* [3]*University of California at Berkeley, Berkeley, CA 94720-7300, USA;* [4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.*
Physical Review D **90**, 096005 (2014). [arXiv:1409.2564].

We propose methods and present calculations that can be used to search for evidence of cosmic fields by investigating the parity-violating effects, including parity nonconservation amplitudes and electric dipole moments, that they induce in atoms. The results are used to constrain important fundamental parameters describing the strength of the interaction of various cosmic fields with electrons, protons, and neutrons. Candidates for such fields are dark matter (including axions) and dark energy, as well as several more exotic sources described by standard-model extensions. Calculations of the effects induced by pseudoscalar and pseudovector fields are performed for H, Li, Na, K, Cu, Rb, Ag, Cs, Ba, Ba^+*, Dy, Yb, Au, Tl, Fr, and* Ra^+*. Existing parity nonconservation experiments in Cs, Dy, Yb, and Tl are combined with these calculations to directly place limits on the interaction strength between the temporal component,* b_0*, of a static pseudovector cosmic field and the atomic electrons, with the most stringent limit of* $|b_0^e| < 7\times10^{-15}$ *GeV, in the laboratory frame of reference, coming from Dy. From a measurement of the nuclear anapole moment of Cs, and a limit on its value for Tl, we also extract limits on the interaction strength between the temporal component of this cosmic field, as well as a related tensor cosmic-field component* d_{00}*, with protons and neutrons. The most stringent limits of* $|b_0^p| < 4\times10^{-8}$ *GeV and* $|d_{00}^p| < 5\times10^{-8}$ *for protons, and* $|b_0^n| < 1\times10^{-7}$ *GeV and* $|d_{00}^n| < 1\times10^{-7}$ *for neutrons (in the laboratory frame) come from the results using Cs. Axions may induce oscillating parity- and time-*

reversal-violating effects in atoms and molecules through the generation of oscillating nuclear magnetic quadrupole and Schiff moments, which arise from P- and T-odd intranuclear forces and from the electric dipole moments of constituent nucleons. Nuclear-spin-independent parity nonconservation effects may be enhanced in diatomic molecules possessing close pairs of opposite-parity levels in the presence of time-dependent interactions.

- Editors' Suggestion
- Covered in *Physics Today* [doi: 10.1063/PT.3.2896]
- Top 10% by citations for category/year (Scopus)

[28] *Tests of CPT and Lorentz symmetry from muon anomalous magnetic dipole moment*,
Y. V. Stadnik, B. M. Roberts, V. V. Flambaum. *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia.*
Physical Review D **90**, 045035 (2014). [arXiv:1407.5728].
We derive the relativistic factor for splitting of the g-factors of a fermion and its anti-fermion partner, which is important for placing constraints on dimension-five, CPT-odd and Lorentz-invariance-violating interactions from experiments performed in a cyclotron. From existing data, we extract limits (1σ) on the coupling strengths of the temporal component, f^0, of a background field (including the field amplitude), which is responsible for such g-factor splitting, with an electron, proton, and muon: $|f_e^0| < 2.3 \times 10^{-12}\ \mu_B$, $|f_p^0| < 4 \times 10^{-9}\ \mu_B$, and $|f_\mu^0| < 8 \times 10^{-11}\ \mu_B$, respectively, in the laboratory frame (μ_B is the Bohr magneton). From existing data, we also extract limits on the coupling strengths of the spatial components, $d^\perp$, of related dimension-five interactions of a background field with an electron, proton, neutron, and muon: $|d_e^\perp| \lesssim 10^{-9}\ \mu_B$, $|d_p^\perp| \lesssim 10^{-9}\ \mu_B$, $|d_n^\perp| \lesssim 10^{-10}\ \mu_B$, and $|d_\mu^\perp| \lesssim 10^{-9}\ \mu_B$, respectively, in the laboratory frame.

[29] *Limiting P-odd interactions of cosmic fields with electrons, protons, and neutrons*,
B. M. Roberts[1], Y. V. Stadnik[1], V. A. Dzuba[1], V. V. Flambaum[1], N. Leefer[2], and D. Budker[2,3,4]. [1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [2]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany;* [3]*University of California at Berkeley, Berkeley, CA 94720-7300, USA;* [4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA.*
Physical Review Letters 113, 081601 (2014). [arXiv:1404.2723].
We propose methods for extracting limits on the strength of P-odd interactions of pseudoscalar and pseudovector cosmic fields with electrons, protons, and neutrons, by exploiting the static and dynamic parity-nonconserving amplitudes and electric dipole moments they induce in atoms. Candidates for such fields are dark matter (including axions) and dark energy, as well as several more exotic sources described by Lorentz-violating standard model extensions. Atomic calculations are performed for H, Li, Na, K, Rb, Cs, Ba^+, Tl, Dy, Fr, and Ra^+. From these calculations and existing measurements in Dy, Cs, and Tl, we constrain the interaction strengths of the parity-violating static pseudovector cosmic field to be 7×10^{-15} GeV with an electron, and 3×10^{-8} GeV with a proton.

- Top 10% by citations for category/year (Reuters Web of Science/Scopus)

[30] *Strongly enhanced atomic parity violation due to close levels of opposite parity*,
B. M. Roberts, V. A. Dzuba, and V. V. Flambaum. *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia.*
Physical Review A **89**, 042509 (2014). [arXiv:1401.6262].
We present calculations of nuclear-spin-dependent and nuclear-spin-independent parity violating amplitudes in Ba, Ra, Ac^+, Th and Pa. Parity nonconservation in these systems is greatly enhanced due to the presence of very close electronic energy levels of opposite parity, large nuclear charge, and strong nuclear enhancement of parity-violating effects. The presented amplitudes constitute several of the largest atomic parity-violating signals predicted so far. Experiments using these systems may be performed to determine values for the nuclear anapole moment, a P-odd T-even nuclear moment given rise to by parity-violating nuclear forces. Such measurements may prove to be valuable tools in the study of parity violation in the hadron sector. The considered spin-independent transitions could also be used to measure the ratio of weak charges for different isotopes of the same atom, the results of which would serve as a test of the standard model and also of neutron distributions. Barium, with seven stable isotopes, is particularly promising in this regard.

[31] *Nuclear-spin-dependent parity nonconservation in s-$d_{5/2}$ and s-$d_{3/2}$ transitions*,
B. M. Roberts, V. A. Dzuba, and V. V. Flambaum. *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia.*
Physical Review A **89**, 012502 (2014). [arXiv:1311.2373].
We perform calculations of s-$d_{5/2}$ nuclear-spin-dependent parity nonconservation amplitudes for Rb, Cs, Ba^+, Yb^+, Fr, Ra^+ and Ac^{2+}. These systems prove to be good candidates for the use in atomic experiments to extract the so-called anapole moment, a P-odd T-even nuclear moment important for the study of parity violating nuclear forces. We also extend our previous works by calculating the missed spin-dependent amplitudes for the s-$d_{3/2}$ transitions in the above systems.

[32] *Double-core-polarization contribution to atomic parity-nonconservation and electric-dipole-moment calculations*,
B. M. Roberts, V. A. Dzuba, and V. V. Flambaum. *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia.*
Physical Review A **88**, 042507 (2013). [arXiv:1309.3371].
We present a detailed study of the effect of double core polarization (the polarization of core electrons due to the simultaneous action of the electric dipole and parity-violating weak fields) for amplitudes of the ss and sd parity non-conserving transitions in Rb, Cs, Ba^+, La^{2+}, Tl, Fr, Ra^+, Ac^{2+} and Th^{3+} as well as electron electric-dipole-moment enhancement factors for the ground states of the above neutral atoms and Au. This effect is quite large and has the potential to resolve some disagreement between calculations in the literature. It also has significant consequences for the use of experimental data in the accuracy analysis.

[33] *Parity nonconservation in Fr-like actinide and Cs-like rare-earth-metal ions*,
B. M. Roberts, V. A. Dzuba, and V. V. Flambaum. *School of Physics, University of New South Wales, Sydney, NSW 2052, Australia.*
Physical Review A **88**, 012510 (2013). [arXiv:1304.7591].
Parity nonconservation amplitudes are calculated for the $7s$-$6d_{3/2}$ transitions of the francium isoelectronic sequence (Fr, Ra^+, Ac^{2+}, Th^{3+}, Pa^{4+}, U^{5+} and Np^{6+}) and for the $6s$-$5d_{3/2}$ transitions of the cesium isoelectronic sequence (Cs, Ba^+, La^{2+}, Ce^{3+} and Pr^{4+}). We show in particular that isotopes of La^{2+}, Ac^{2+} and Th^{3+} ions have strong potential in the search for new physics beyond the standard model: the PNC amplitudes are large, the calculations are accurate and the nuclei are practically stable. In addition, $^{232}Th^{3+}$ ions have recently been trapped and cooled [C. J. Campbell et al., *Phys. Rev. Lett. 102, 233004 (2009)]. We also extend previous works by calculating the s-s PNC transitions in Ra^+ and Ba^+, and provide calculations of several energy levels, and electric dipole and quadrupole transition amplitudes for the Fr-like actinide ions.*

[34] *Quantum electrodynamics corrections to energies, transition amplitudes and parity nonconservation in Rb, Cs, Ba^+, Tl, Fr and Ra^+*,
B. M. Roberts[1], V. A. Dzuba[1], and V. V. Flambaum[1,2]. [1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [2]*Centre for Theoretical Chemistry and Physics, New Zealand Institute for Advanced Study, Massey University, Auckland 0745, New Zealand.*
Physical Review A **87**, 054502 (2013). [arXiv:1302.0593].
We use the previously developed radiative potential method to calculate quantum electrodynamic (QED) corrections to energy levels and electric dipole transition amplitudes for atoms which are used for the study of the parity nonconservation (PNC) in atoms. The QED shift in energies and dipole amplitudes leads to noticeable change in the PNC amplitudes. This study compliments the previously considered QED corrections to the weak matrix elements. We demonstrate that the QED corrections due to the change in energies and dipole matrix elements are comparable in value to those due to change in weak matrix elements, and therefore must be included.
- Top 10% by citations for category/year (Scopus)

[35] *Calculation of the parity-violating $5s$-$6s$ $E1$ amplitude in the rubidium atom*,
V. A. Dzuba, V. V. Flambaum, and B. M. Roberts. *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia.*
Physical Review A **86**, 062512 (2012). [arXiv:1211.0075].
Currently, the theoretical uncertainty limits the interpretation of the atomic parity nonconservation (PNC) measurements.We calculate the PNC $5s$-$6s$ electric dipole transition amplitude in rubidium and demonstrate that rubidium is a good candidate to search for new physics beyond the standard model since accuracy of the atomic calculations in rubidium can be higher than in cesium. PNC in cesium is currently the best low-energy test of the standard model; therefore, similar measurements for rubidium present a good option for further progress in the field.We also calculate the nuclear spin-dependent part of the PNC amplitude, which is needed for the extraction of the nuclear anapole moment from the PNC measurements.

[36] *Revisiting Parity Nonconservation in Cesium*,
V. A. Dzuba, J. C. Berengut, V. V. Flambaum, and B. M. Roberts. *School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia.*
Physical Review Letters 109, 203003 (2012). [arXiv:1207.5864].
*We apply the sum-over-states approach to calculate partial contributions to parity nonconservation (PNC) in cesium [*Porsev, Beloy, and Derevianko, *Phys. Rev. Lett. 102, 181601 (2009)]. We find significant corrections to two nondominating terms coming from the contribution of the core and highly excited states ($n > 9$, the so called tail). When these differences are taken into account the result of* Porsev et al.*, $E_{PNC} = 0.8906(24) \times 10^{-11} i(-Q_W/N)$ changes to $0.8977(40)$, coming into good agreement with our previous calculations, $0.8980(45)$. The interpretation of the PNC measurements in cesium still indicates reasonable agreement with the standard model (1.5σ); however, it gives new constraints on physics beyond it.*

- Top 5% by citations for category/year (Reuters Web of Science/Scopus)

II. Conference Proceedings

[37] *Testing Fundamental Physics With Stellar Orbits at the Galactic Center*,
T. Do, A. Hees, Andrea Ghez, G. D. Martinez, D. S. Chu, S. Jia, S. Sakai, J. R. Lu, A. K. Gautam, K. K. O'Neil, E. E. Becklin, M. R. Morris, K. Matthews, S. Nishiyama, R. Campbell, S. Chappell, Z. Chen, A. Ciurlo, A. Witzel, E. Gallego-Cano, W. E. Kerzendorf, J. E. Lyke, S. Naoz, H. Saida, R. Schödel, M. Takahashi, Y. Takamori, G. Witzel, P. Wizinowich, and B. M. Roberts.
ASP Conference Series: New Horizons in Galactic Center Astronomy and Beyond **528**, 249 (2019)
The closest approach of the star S0-2 to the supermassive black hole Sgr A in 2018 opened a new era of tests of gravity with stellar orbits at the Galactic Center. Using radial velocity and astrometry measurements from 24 years of data, including data from 2018, we are able to measure the relativistic redshift from S0-2. In addition, the stars in orbit around Sgr A* can be used to search for variations in the fundamental constants of nature around a supermassive black hole. Using the spectral features of late-type giants in orbit around the black hole, we present limits on the variation of fine structure constant in the gravitational field of a supermassive black hole. Both the relativistic redshift measurement and the limits on the fine structure constant allows us to test Einstein's Equivalence Principle, a fundamental component of General Relativity. We find that both of these tests are consistent with the predictions of GR. Improvements in stellar orbital measurements as well as high spectral-resolution measurements will significantly improve the power of these tests in the future.*

[38] *DAMNED - DArk Matter from Non Equal Delays: New test of the fundamental constants variation*,
E. Savalle[1], B. M. Roberts[1], F. Frank[1], P.-E. Pottie[1], B. T. McAllister[2], C. B. Dailey[3], A. Derevianko[3], and P. Wolf[1]. [1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France;* [2]*ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, University of Western Australia, Crawley WA 6009, Australia;* [3]*University of Nevada, Reno 89557, Nevada, USA.*
Joint Conference of the IEEE International Frequency Control Symposium and European Frequency and Time Forum (EFTF/IFC) **2019**, 1 (2019).
"DArk Matter from Non Equal Delays" (DAMNED) is a new experiment that aims to check for space or time variation of physics fundamental constants. This 3 arm Mach-Zender experiment allows us to compare an ultra-stable cavity to itself in the past through the delay created by a multi kilometer long optical fiber. A massive scalar dark matter field (DM) would be seen on the experiment beat and we aim to constrain a new combination of the DM coupling constants.

[39] *Violation of the equivalence principle from light scalar fields: from Dark Matter candidates to scalarized black holes*,
A. Hees[1], O. Minazzoli[2,3], E. Savalle[1], Y. V. Stadnik[4], P. Wolf[1], and B. M. Roberts[1]. [1]*SYRTE, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, 61 avenue de l'Observatoire, 75014 Paris, France;* [2]*Centre Scientifique de Monaco, 8 Quai Antoine 1er, 98000 Monaco, Monaco;* [3]*Artemis, Université Cote d'Azur, CNRS, Observatoire Cote d'Azur, BP4229, 06304, Nice, France;* [4]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany.* Proceedings of the 2019 Gravitation session of the 54th Rencontres de Moriond (available: moriond.in2p3.fr/previous-sessions.html) [arXiv:1905.08524].
Tensor-scalar theory is a wide class of alternative theory of gravitation that can be motivated by higher dimensional theories, by models of dark matter or dark energy. In the general case, the scalar field will couple non-universally to matter producing a violation of the equivalence principle. In this communication, we review a microscopic model of scalar/matter coupling and its observable consequences in terms of universality of free fall, of frequencies comparison and of redshifts tests. We then focus on two models: (i) a model of ultralight scalar dark matter and (ii) a model of scalarized black hole in our Galactic Center. For both these models, we present constraints using recent measurements: atomic clocks comparisons, universality of free fall measurements, measurement of the relativistic redshift with the short period star S0-2 orbiting the supermassive black hole in our Galactic Center.

[40] *New Atomic Methods for Dark Matter Detection*,
B. M. Roberts[1], Y. V. Stadnik[1], V. A. Dzuba[1], V. V. Flambaum[1], N. Leefer[2], and D. Budker[2,3,4]. [1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [2]*Helmholtz Institute Mainz, Johannes Gutenberg University, 55099 Mainz, Germany;* [3]*University of California at Berkeley, Berkeley, CA 94720-7300, USA;* [4]*Nuclear Science Division, Lawrence Berkeley National Laboratory, CA 94720, USA.*
J. Phys. Conf. Ser. **635**, 022033 (2015).
We calculate the parity and time-reversal violating effects that are induced in atoms, nuclei, and molecules by their interaction with various background cosmic fields, such as axion dark matter or dark energy.

[41] *Searching for Axion Dark Matter in Atoms: Oscillating Electric Dipole Moments and Spin-Precession Effects*, B. M. Roberts[1], Y. V. Stadnik[1], V. V. Flambaum[1,2], and V. A. Dzuba[1]. [1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia,* [2]*Mainz Institute for Theoretical Physics, Johannes Gutenberg University, 55099 Mainz, Germany.* Proceedings of the 11th Patras Workshop on Axions, WIMPs and WISPs (doi: 10.3204/DESY-PROC-2015-02/roberts_benjamin) [arXiv:1511.04098].

We propose to search for axion dark matter via the oscillating electric dipole moments that axions induce in atoms and molecules. These moments are produced through the intrinsic oscillating electric dipole moments of nucleons and through the P, T -violating nucleon-nucleon interaction mediated by pion exchange, both of which arise due to the axion-gluon coupling, and also directly through the axion-electron interaction. Axion dark matter may also be sought for through the spin-precession effects that axions produce by directly coupling to fermion spins.

[42] *Searching for Scalar Dark Matter in Atoms and Astrophysical Phenomena: Variation of Fundamental Constants*,
Y. V. Stadnik[1], B. M. Roberts[1], V. V. Flambaum[1,2], and V. A. Dzuba[1]. [1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [2]*Mainz Institute for Theoretical Physics, Johannes Gutenberg University, 55099 Mainz, Germany.* Proceedings of the 11th Patras Workshop on Axions, WIMPs and WISPs (doi: 10.3204/DESY-PROC-2015-02/roberts_benjamin_axions) [arXiv:1511.04100].

We propose to search for scalar dark matter via its effects on the electromagnetic fine- structure constant and particle masses. Scalar dark matter that forms an oscillating classical field produces 'slow' linear-in-time drifts and oscillating variations of the fundamental constants, while scalar dark matter that forms topological defects produces transient-in- time variations of the constants of Nature. These variations can be sought for with atomic clock, laser interferometer and pulsar timing measurements. Atomic spectroscopy and Big Bang nucleosynthesis measurements already give improved bounds on the quadratic interaction parameters of scalar dark matter with the photon and light quarks by up to 15 orders of magnitude, while Big Bang nucleosynthesis measurements provide the first such constraints on the interaction parameters of scalar dark matter with the massive vector bosons.

[43] *Atomic Ionization by Dark Matter Particles*,
V. V. Flambaum[1], V. A. Dzuba[1], M. Pospelov[2,3], A. Derevianko[4], and B. M. Roberts[1]. [1]*School of Physics, University of New South Wales, Sydney, New South Wales 2052, Australia;* [2]*Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, V8P IAI, Canada;* [3]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2J 2W9, Canada;* [4]*University of Nevada, Reno, Nevada 89557, USA.*
J. Phys. Conf. Ser. **635**, 022012 (2015).

Using the relativistic Hartree-Fock approximation, we calculate the rates of atomic ionization by absorption of axions and other Dark matter candidates. We also calculate atomic ionization by scattering of heavy Dark matter particles on electrons. The results are used to interpret possible detection of Dark matter by DAMA collaboration.

III. Other research outputs: public software projects

[44] AtomicIonisation, A. R. Caddell† and B. M. Roberts (2023). An example C++ and python program to calculate example DM-electron-induced ionisation rates. Also provides tables of high-accuracy atomic ionisation factors (matrix elements), which are required to calculate atomic ionisation rates, including from dark matter electron scattering. github.com/benroberts999/AtomicIonisation
- Companion code to paper: A. R. Caddell, V. V. Flambaum, and B. M. Roberts, *Accurate electron-recoil ionization factors for dark matter direct detection in xenon, krypton and argon* [arXiv:2305.05125].

[45] AdamsMoulton, B. M. Roberts (2023). A C++ implementation of the Adams-Moulton method for solving general second-order ODEs. github.com/benroberts999/AdamsMoulton

[46] ampsci, B. M. Roberts (2022). A C++ program for high-precision atomic structure calculations of single-valence systems. github.com/benroberts999/ampsci
- Used in many papers, including by other groups; first major publication: B. M. Roberts, C. J. Fairhall†, and J. S. M. Ginges, *Electric dipole transition amplitudes for atoms and ions with one valence electron*, Physical Review A (in press, 2023) [arXiv:2211.11134].

[47] FGRP, B. M. Roberts (2022). A C++ implementation of the Flambaum-Ginges radiative potential method, a method for including radiative quantum electrodynamics effects into calculations of atomic wavefunctions, including finite nuclear size corrections. github.com/benroberts999/FGRP
- Used in: C. J. Fairhall†, B. M. Roberts, and J. S. M. Ginges, *QED radiative corrections to electric dipole amplitudes in heavy atoms*, Physical Review A **107**, 022813 (2023). Also used by other group in: H. B. Tran Tan and A. Derevianko, Physical Review A **107**, 042809 (2023).

[48] transientDM, B. M. Roberts (2019). A C++ program for searching for transient dark matter signals in data from atomic clock networks. github.com/benroberts999/transientDM
- Companion code to paper: B. M. Roberts *et al.*, *Search for transient variations of the fine structure constant and dark matter using fiber-linked optical atomic clocks*, New Journal of Physics **22**, 093010 (2020). [arXiv:1907.02661].

[49] DM-ClockAsymmetry, B. M. Roberts (2018). A python program for simulating dark matter induced asymmetries in atomic clock data, and their annual modulation. github.com/benroberts999/DM-ClockAsymmetry
- Companion code to paper: B. M. Roberts and A. Derevianko, *Precision measurement noise asymmetry and its annual modulation as a dark matter signature*, Universe **7**, 50 (2021). [arXiv:1803.00617].

[50] InverseNumericalCDF, B. M. Roberts (2017). A C++ program that finds the inverse of numerical cumulative distribution functions for inverse transform sampling in Monte-Carlo methods. github.com/benroberts999/InverseNumericalCDF
- Used in: B. M. Roberts *et al.*, *Search for domain wall dark matter with atomic clocks on board Global Positioning System satellites*, **Nature Communications 8**, 1195 (2017). [arXiv:1704.06844].

IV. Invited seminars, colloquiums, and public talks

[1] Invited Seminar: **University of Sussex, UK, QSNET Seminar (presented virtually), February 2024**. Talk: *Search for scalar dark matter and variation of fundamental constants with spatially separated sensors* [Slides available]

[2] Public Lecture: National Quantum and Dark Matter Roadshow [qdmroadtrip.org/event/public-lecture-brisbane/], Brisbane QLD, August 2023. Talk: *Enlightening the search for dark matter*

[3] Colloquium: **University of Melbourne, Astrophysics Colloquium (presented virtually), August 2023**.
Talk: *Variation of fundamental constants: Search for new physics around a supermassive black hole*

[4] Colloquium: **University of Queensland, Physics Colloquium, August 2023**.
Talk: *Enlightening the search for dark matter (and exotic physics)* [Slides available]

[5] Summer school lecture: **PhysTeV 2023, Physics at TeV Colliders and Beyond the Standard Model, Les Houches, France, June 2023**.
Lecture for "precision low-energy school": *Atomic parity violation as a low-energy probe of electroweak theory*

[6] Public Talk: **UQ ASA (student society) outreach talk, University of Queensland, Australia, April 2022**.
Talk: *Variation of fundamental constants: Search for new physics around a supermassive black hole* [Slides available]

[7] Invited Seminar: **University of Melbourne, particle physics seminar (virtual), March 2022**.
Talk: *Dark matter induced atomic ionisation* [Slides available]

[8] Invited Seminar: **Observatoire de Paris, Seminaire Temps & Frequencies (SYRTE seminar), May 2018**.
Talk: *Searching for dark matter with GPS and global networks of atomic clocks*

V. Conferences, including invited talks

[1] **2023 AIP Summer Meeting, ANU, Canberra, Australia, December 2023**.
Talk: *Atomic phenomena in the search for GeV scale WIMPs: enlightening the search for dark matter* [Slides]

[2] **9th Symposium on Frequency Standards and Metrology, Kingscliff, NSW, Australia, October 2023**.
Poster: *Electric-dipole transition amplitudes for atoms and ions with one valence electron* [Poster]

[3] **Invited: 2023 MIAPbP (Munich Institute for Astro-, Particle, and Bio Physics) program: Particle & AMO physicists discussing quantum sensors and new physics 2023), Munich, Germany, September 2023**.

[4] **PhysTeV 2023, Physics at TeV Colliders and Beyond the Standard Model, Les Houches, France, June 2023**.
Lecture: Atomic parity violation as a low-energy probe of electroweak theory

[5] **DAMOP 2023 (APS Division of Atomic, Molecular and Optical Physics), Spokane, WA, USA, June 2023**.
Talk: *Using atomic phenomena to search for GeV scale dark matter* [Slides]
Talk: *Hyperfine anomaly in cesium: From exotic atoms to improved searches for new physics* [Slides]
Poster: *Electric-dipole transition amplitudes for atoms and ions with one valence electron* [Poster]

[6] **AIP2022, Australian Institute of Physics Congress, Adelaide, December 2022**.
Talk: *Search for a Variation of the Fine Structure Constant around the Supermassive Black Hole in Our Galactic Centre*
Poster: *High-precision study of E1 transition amplitudes for single-valence atoms and ions* [Poster]

[7] **DSU2022, The Dark Side of the Universe, University of New South Wales, Sydney, Australia, December 2022**.
Talk: *Search for a Variation of the Fine Structure Constant around the Supermassive Black Hole in Our Galactic Centre* [Slides]

[8] **Invited: APV2022, The International Workshop on Atomic Parity Violation (virtual), November 2022**.
Talk: *Study of electric dipole amplitudes for alkali-like atoms and implications for atomic parity violation* [Slides]

[9] **Australian Institute of Physics (AIP) Summer Meeting, QUT, Brisbane, December 2021**.
Talk: *Search for a variation of the fine-structure constant around the supermassive Black Hole in our Galactic Centre*

[10] **ASA2021, Astronomical Society of Australia Science Meeting, University of Melbourne (virtual), July 2021**.
Talk: *Search for a variation of the fine-structure constant around the supermassive Black Hole in our Galactic Centre* [Slides available]

[11] **DAMOP, Portland, Oregon, USA (held virtually), June 2020**.
Talk: *Electron-interacting dark matter: prospects for liquid xenon detectors and NaI detectors*
Poster: *Do constants remain constant around a Supermassive Black hole?*
[Slides available: meetings.aps.org/Meeting/DAMOP20/Session/J07.10, Poster available: .../E01.155]

[12] **Invited: ATMOP (AIP) Summer Workshop, Australian National University, Canberra, February 2020**.
Invited talk: *Signatures of GeV-scale dark matter in liquid xenon experiments due to scattering off electrons and atomic ionisation*

[13] **Invited: Frontiers in Quantum Matter Workshop: Electric Dipole Moments, Australian National University (ANU), Canberra, November 2019**.
Invited talk: *Dark matter signatures in EDM and precision physics experiments*

[14] **CHEP 2019, 24th International Conference on Computing in High Energy and Nuclear Physics, Adelaide, Australia, November 2019**.
Talk: *Searching for dark matter signatures in 20 years of GPS atomic clock data*

[15] **Invited: 7th International Colloquium on Scientific and Fundamental Aspects of GNSS, ESA (European Space Agency), ETH Zürich, Zurich, Switzerland, September 2019**.
Invited talk: *Searching for dark matter and exotic physics with space and ground-based atomic clocks*

[16] **Rencontres de Moriond, Gravitation Session, La Thuile, Valle d'Aosta, Italy, March 2019**.
Talk: *Search for dark matter and transient variations in α using fibre-linked optical atomic clocks*
[Slides available: moriond.in2p3.fr/2019/Gravitation/Program.html]

[17] **AIP2018, Australian Institute of Physics Congress, University of Western Australia, Perth, December 2018**.
Talk: *Searching for transient dark matter signatures with atomic clock networks*
Talk: *Ionisation signatures of GeV–scale dark matter due to absorption and scattering off electrons*

[18] **ACES Workshop, Technical University of Munich, Germany, October 2018**.
Talk: *Searching for transient dark matter signatures with atomic clock networks*

[19] **Invited: MG15 – Fifteenth Marcel Grossmann Meeting, University of Rome, La Sapienza, Rome, July 2018**.
Invited talk: *Searching for transient dark matter signatures with atomic clocks*

[20] **NASA Fundamental Physics Workshop, La Jolla, CA, USA, April 2018**.
Talk: *Searching for dark matter and exotic physics with atomic clocks and GPS*
[Slides available: https://icpi.nasaprs.com/fpws2018]

[21] **Invited: New Directions in Dark Matter and Neutrino Physics, Perimeter Institute for Theoretical Physics, Waterloo, Canada, July 2017**.
Invited talk: *Searching for dark matter with GPS and global networks of atomic clocks* [Recording and slides available: PIRSA Number: 17070027]

[22] **DAMOP (APS Division of Atomic, Molecular and Optical Physics), Sacramento Convention Center, CA, USA, June 2017**.
Talk: *Searching for dark matter and exotic physics with atomic clocks and the GPS constellation*
Poster: *Electron-interacting WIMPs: Can dark matter scattering on electrons explain the DAMA annual modulation signal?* [Slides available at doi:10.13140/RG.2.2.11038.95045]

[23] **APS April Meeting, Marriott Wardman Park, Washington DC, USA, January 2017**.
Poster: *Electron-interacting WIMPs: Can dark matter scattering on electrons explain the DAMA annual modulation signal?* [Poster available at doi:10.13140/RG.2.2.11038.95045]
Talk: *First Results of the GPS.DM Observatory: Search for Dark Matter and exotic Physics with Atomic Clocks and GPS Constellation*
- Talk was the focus of an article in *Science* Magazine [10.1126/science.aal0676].

[24] **GPMFC Workshop (Topical Group on Precision Measurement & Fundamental Constants Pre-Meeting Workshop: Ultralight Dark Matter), Marriott Wardman Park, Washington DC, USA, January 2017**.
Poster: *GPS.DM: Search for Dark Matter and Exotic Physics with Atomic Clocks and GPS Constellation*

[25] **CosPA (13th Conference in the Symposium on Cosmology and Particle Astrophysics), Sydney Nanoscience Hub, University of Sydney, Australia, December 2016**.
Talk: *First Results of the GPS.DM Observatory: Search for Dark Matter and Exotic Physics with Atomic Clocks and GPS Constellation*

[26] **DAMOP 2016 (APS Division of Atomic, Molecular and Optical Physics), Rhode Island Convention Center, Providence, RI, USA, May 2016**.
Talk: *Atomic ionization from dark matter–electron scattering: Implications for DAMA and XENON interpretation*
Poster: *GPS.DM: Search for Dark Matter and Exotic Physics with Atomic Clocks and GPS Constellation*

[27] **PATRAS (11th Patras Workshop on Axions, WIMPs and WISPs), Universidad de Zaragoza, Spain, June 2015**.
Talk: *Axion and WIMP phenomena in atomic systems* [Slides available at doi:10.13140/RG.2.1.4458.8963]
Talk: *New Effects of Dark Matter which are Linear in the Interaction Strength (on behalf of Victor Flambaum)* [Slides available at doi:10.13140/RG.2.1.2130.5448]
Poster: *Axion Dark Matter: New atomic detection schemes*

[28] **Invited: The Ultra-Light Frontier, Mainz Institute for Theoretical Physics, Johannes Gutenberg University, Mainz, Germany, June 2015**.
Invited talk: *Axion-induced EDMs in paramagnetic systems* [Slides available at doi:10.13140/RG.2.1.3410.3204]

[29] **SSP (6th International Symposium on Symmetries in Subatomic Physics), Victoria BC, Canada, June 2015**.
Talk: *Atomic Methods for Dark Matter Detection* [Slides available at doi:10.13140/RG.2.1.2623.8880]

Poster: *Axion Dark Matter: New atomic detection schemes*
Poster: *Atomic Symmetry Violation: New applications for tests of fundamental physics*

[30] **CosPA (10th Conference in the Symposium on Cosmology and Particle Astrophysics Series), University of Auckland, New Zealand, December 2014**.
Talk: *Manifestations of dark matter and cosmic fields in atomic phenomena*
[Slides available at doi:10.13140/2.1.1158.8167]

[31] **AIP2014, Australian Institute of Physics Congress, Australian National University, Canberra, December 2014**.
Talk: *Violations of fundamental symmetries in atoms and tests of unification theories*
[Slides available at doi:10.13140/2.1.3829.4083]
Poster: *Limits on P-odd interactions of cosmic fields with electrons, protons and neutrons*

[32] **Australian Institute of Physics Congress, UNSW Australia, December 2012**.
Poster: *Parity nonconservation in cesium and the search for physics beyond the standard model*

VI. Selected coverage in popular press

[1] *'Unusual' atom helps search for dark matter – and a quicker car ride*,
Stuart Layt. The Brisbane Times, 28 February 2023.
"Queensland researchers have used an "unusual" atom of caesium to reveal the fundamental forces at work in the universe..."

[2] *A Minimalist Approach to the Hunt for Dark Matter*,
Sophia Chen. WIRED, 2 August 2022
"In one notable example, physicists recast atomic clocks to look for dark matter instead of for timekeeping."

[3] *Improved modelling of nuclear structure in francium aids searches for new physics*, phys.org, 5 August 2020.
"...By combining precision experiments in atoms with high-precision atomic theory, we get a powerful way to search for new physics"

[4] *This fundamental constant of nature remains the same even near a black hole*,
Emily Conover. Science News, 28 March 2020.
"...'The work is very important because it denotes the beginning of a new type of study' says physicist John Webb"

[5] *Im Angesicht des Schwarzen Lochs (In the face of the black hole)*,
Robert Gast. Spectrum [DE], 3 March 2020.
"...The astrophysicists have looked at radiation that comes from the center of the Milky Way....to determine the size of the so-called fine structure constant" (translated)

[6] *Constants Still Constant Near Black Holes*,
M. Stephens. Physics (APS) Synopsis, 26 February 2020.
"...A spectral analysis of stars at our Galaxy's center sets the first constraints on how much the fine-structure constant varies in the vicinity of a supermassive black hole."

[7] *Harnessing the GPS Data Explosion for Interdisciplinary Science*,
G. Blewitt, W. C. Hammond and C. Kreemer. Eos (American Geophysical Union), 24 September 2018.
"...even fundamental physics is fair game, as we collaborate with physicists using the constellation of GPS atomic clocks (on board GPS satellites) as a giant dark matter detector [Roberts et al., 2017]."

[8] *Is This A Good Time To Start Looking For Dark Matter?*,
C. Orzel. Forbes, 4 June 2018.
"...Other experiments, like the GPS-based dark matter search developed by Andrei Derevianko's group, don't even require new apparatus. They're looking through years of records from the clocks on the Global Positioning system satellites..."

[9] *Ultra-Accurate Clocks Lead Search for New Laws of Physics*,
G. Popkin. Quanta, 16 April 2018.
"...reported in fall 2017 that they had found no dark matter-induced hiccups in 16 years' worth of GPS data, tightening the lid on theories of such "topological" dark matter by a factor of 10^3 to 10^5..."

[10] *GPS satellites "the largest dark matter detector ever built"*,
R. A. Lovett. Cosmos, 10 November 2017.
"...'The electrons and the nucleus 'feel' the effect of the dark matter, and this can change their properties temporarily,' says Benjamin Roberts, an Australian postdoctoral researcher working with Derevianko in Reno...."

[11] *The search for dark matter just took a big step forward*,
Brad Bergan. NBC News, 3 November 2017.
"...'While there is no definitive evidence after looking at 16 years of data, it could be that the interaction is weaker or that the defects cross paths with the Earth less often,' Benjamin Roberts, lead author of team's paper..."

[12] *Astrophysicists turn GPS constellation into giant dark matter detector*,
MIT Technology Review, 4 May 2017.
"...Enter Roberts and co. They start with a different vision of what dark matter may consist of. Instead of small particles, another option is that dark matter may take the form of topological defects in space-time left over from the Big Bang..."

[13] *Hunting dark matter with GPS data*,
Adrian Cho. Science, 30 January 2017.
"...Now, Benjamin Roberts and Andrei Derevianko, two physicists at the University of Nevada in Reno, and their colleagues say they have performed the most stringent search yet for topological dark matter, using archival data from the constellation of 31 orbiting GPS satellites..."