Precision Frequency Techniques to Search for Dark Matter and New Physics with Photonic, Phononic and Atomic Oscillators

William M. Campbell, Ben T. McAllister, Maxim Goryachev, Eugene N. Ivanov and Michael E. Tobar*
ARC Centre of Excellence for Engineered Quantum Systems and ARC Centre of Excellence for Dark Matter Particle Physics,
Department of Physics, The University of Western Australia, 35 Stirling Hwy, Crawley, Western Australia 6009, Australia

Abstract—**In these proceedings we summarise a collection of recent experimental results in which high precision photonic, phononic and atomic oscillators are used to probe for new physics, such as searching for wave-like dark matter, performing Lorentz invariance tests, looking for high frequency gravitational waves and more. We focus our discussions on summarising our most recent work on a new method for constraining scalar dark matter using a photonic microwave cavity, phononic quartz mechanical resonator and atomic hydrogen transition in conjunction, while also briefly summarising various other experimental results.**

I. Introduction

Precision frequency techniques and metrology is a necessary cornerstone in fundamental physics research, providing the means and accuracy to meaningfully constrain physical parameters as well as provide the ability to experimentally test new theories and physics. The zoo of resonators, oscillators and clocks that envelops photonic microwave cavities, phononic bulk and surface acoustic wave resonators, LC circuits, bulk and spin-torque magnon resonators, and atomic transitions [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11] , provides a broad experimental tool-kit to test and constrain the enormous amount of new theoretical physics that is constantly arising. Due to the precision nature of these metrological devices; they are typically of a small spatial footprint, allowing more accessibility for researchers to provide critical contributions to some of the most pressing questions in physics.

One such question is as to the nature and composition of dark matter (DM) as well as its interaction properties on a particle level, which despite decades of cosmological and astronomical evidence supporting the existence of DM[12] , these properties still remain largely unknown and loosely constrained. Many different flavours of DM candidates have been proposed, leading to an ensemble of corresponding detection experiments operating across a broad frequency space[13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24]. Despite the growing number of DM detectors, a strong claim of detection of any kind is yet to be made, however; the unconstrained parameter space for many DM candidates remains large and relatively unexplored, providing motivation for new experiments, a few of which we will briefly summarise.

Cryogenic microwave cavities can be placed in strong DC magnetic fields to search for Axion DM, a dark matter candidate particle arising from a proposed solution to the strong CP problem. The ORGAN experiment [23] at The University of Western Australia (UWA), is a cavity based Axion DM detector currently operational in the 15-16 GHz range and is a part of the ADMX collaboration [25]. In another active experiment, a dual-mode photonic microwave oscillator cavity is used to search for Axions at lower frequencies ($<$ 240 MHz) using upconversion [26].

Of course the use of precision frequency devices for tests of new physics is not constrained to DM searches, the Acoustic Lorentz Invariance ExperimeNt (ALIEN) utilises two state-of-the-art OCXOs [27] mounted on a rotation stage in order to place constraints on Lorentz violations, thus constraining beyond-the-standard-model physics such as many unification theories. Finally, a high frequency gravitational wave (HFGW) detector based on a quartz bulk acoustic wave (BAW) antenna held at cryogenic temperatures is currently operational and sensitive to gravitational radiation at MHz frequencies [28], [29], at which many theories predict sources may exist. This device utilises the extremely high quality factors attributed to cryogenic quartz BAWs (10^7-10^9) in order to detect impinging strain fields induced by gravitational radiation, and has in fact recorded several candidate signal events already. As one of the only active gravitational wave detectors in this frequency range, with potential to extend its

978-1-6654-3935-0/21/$31.00 ©2021 IEEE

operational frequencies into completely unexplored parameter space, this experiment represents an exciting probe into unexplored physics.

Here we limit our discussion to a detailed summary of just one of our recent works performing experimental tests of new physics using precision frequency devices; a new technique to search for scalar DM utilising photonic, phononic and atomic oscillators [30]. Scalar DM refers to a class of DM models in which an ultra light scalar field with non-trivial couplings is added to the standard model and attributed to the majority of the local DM density. In previous works it has been shown that the introduction of a weakly coupled scalar field, such as the string theory dilaton or moduli fields, to the standard model would produce some small scale oscillations in the fundamental constants of nature. In the technique we present here this effect is exploited by utilising a combination of a Hydrogen maser, cryogenic sapphire oscillator (CSO), and notably an oven controlled quartz oscillator (OCXO) in order to constrain fundamental constant oscillations, and thus Scalar DM coupling, to some level. The novelty in the method lies in the fact that multiple oscillators of varying physical architecture can be used to provide individual limits on the variation of multiple different fundamental constants via coefficient separation. This is in contrast to many other previous works in the field, which must ignore the coupling of DM to many other constants in order to extract meaningful limits, using the approximative technique of maximum reach analysis. With this work we further demonstrate how extreme precision acoustic oscillators can be utilised for future DM search experiments.

II. Methods/Results

In [30] we considered the Scalar field model of Darmour and Donoghue [31], in which a dimensionless massive scalar field φ is introduced into the effective action that described physics of ground state nuclei. Each term in this effective action can then couple to φ in some non-trivial way, in most cases linear couplings are seen as the most 'simple' and therefore are often explored, however other couplings can also be considered. We are thus given a Lagrangian density term that describes the introduced scalar fields interactions with the standard model, it takes a form where the interaction of the scalar field with the standard model is parametrised by d_j for $j = m_u, m_d, m_e, g, e$, which are dimensionless coupling parameters that define the strength of the interaction between the scalar field and each standard model sector, their introduction into this Lagrangian density term modifies each corresponding standard model sector's fundamental physical constant such that they display φ dependence:

$$\alpha(\varphi) = \alpha\left(1 + d_e\varphi\right), \tag{1}$$

$$m_i(\varphi) = m_i\left(1 + d_{m_i}\varphi\right), \quad \text{for } i = e, u, d \tag{2}$$

$$\Lambda_{\mathrm{QCD}}(\varphi) = \Lambda_{\mathrm{QCD}}\left(1 + d_g\varphi\right). \tag{3}$$

Where α is the fine structure constant, m_i denotes fermion mass (electron (e), up (u) or down (d) quarks), and Λ_{QCD} represents the QCD mass scale.

If we identify this new scalar field as attributing for the majority of the local dark matter density ρ_{DM} as described in [32], with a periodic evolution given by the cosmological string-theory dilaton model of [33], we see that the DM scalar field take the form:

$$\varphi = \frac{4\pi G\sigma\hbar^2}{m_\varphi^2 c^6} + \varphi_0 \cos(\omega_\varphi t + \phi), \ \text{ with } \omega_\varphi = \frac{m_\varphi c^2}{\hbar}. \tag{4}$$

where m_φ represents the scalar field mass and σ is a cosmological source term that is assumed to be constant.

In this form it is clear that the introduction of a scalar field to the standard model, that is also attributed to the local galactic DM density, will cause periodic variation in fundamental constants of nature, with amplitudes parametrised by the coupling constants d_j and frequency determined by the field's mass m_φ. As a result; many experiments have begun searches for scalar field-like DM by searching for variations in dimensionless ratios such as $m_u/\Lambda_{\mathrm{QCD}}$, $m_d/\Lambda_{\mathrm{QCD}}$, $m_e/\Lambda_{\mathrm{QCD}}$ and α. Searching for these small variations naturally leads to the use of high precision frequency and metrology techniques. Indeed, the most well developed experiments in this field make use of ongoing comparison measurements between extremely stable frequency standards that exhibit fundamental frequencies which depend on a combination of the aforementioned dimensionless ratios. These types of experiments will thus be able to probe and further place exclusion limits on a combination of Scalar DM field couplings linear in d_e and $d_{m_i} - d_g$, however difficulty arises when attempting to extract a limit on one coupling constant alone due to these potential combinations. There are two such methods to deal with this difficulty, this first and most common among recent experimental work is known as 'maximum reach analysis' (MRA) in which it is initially assumed that the DM field only couples to one standard model sector, with all other coupling constants being made to vanish. The other method is to take multiple sets of data with differing dependencies on fundamental constant ratios, so that one can separate linear combinations of different parameters. This technique is known as 'coefficient separation' and is the novelty that we applied experimentally in our recent work [30]; by introducing a mechanical oscillator, which depends on a different combination of fundamental constants with respect to atomic and photonic oscillators, we can extract limits on individual constants via coefficient separation.

In order to place exclusion limits on individual scalar field DM coupling constants we monitored fluctuations in phase difference $\delta\phi_{21}$ of the mixed signal between a 10 MHz NEL Frequency Controls Inc. ultralow phase noise OCXO and a 10 MHz synthesised signal originating from a microwave CSO, as well as the mixed signal between the same OCXO and a 10 MHz reference signal supplied from a Kvarz CH1-75A active Hydrogen maser. For the first comparison the synthesised CSO signal was achieved by shifting its frequency by 39 MHz to get it within a few tens of Hz of 11200 MHz, where it could be divided down to give a stable 10 MHz signal. The auxiliary 39 MHz signal was supplied by a direct digital synthesizer phase locked to the active Hydrogen maser. In order to make long term measurements of the mixed signal between the OCXO and either CSO or maser, a phase-locked loop was employed, this helps stabilise the mean OCXO frequency so it does not drift over time. The spectral density of phase fluctuations $\delta\phi_{21}$ could be inferred from the spectrum of the phase locked loop correction voltage δu_{corr} through the loop transfer function. Thus, continuous monitoring of the loop correction voltage allowed for monitoring of the the phase noise variations of the mixed signal, which gave the variation in the beat frequency $\delta f_{21} = \delta f_2 - \delta f_1$ between the two oscillators.

As the resonant frequency of the OCXO f_{Q}, CSO f_{CSO} and maser f_{HM} all depend differently on the considered fundamental constants α, m_e, m_p and Λ_{QCD} the fractional frequency variation of each two-oscillator system was given by,

$$\begin{aligned} \frac{\delta f_{\text{CSO}} - \delta f_{\text{Q}}}{f_0} &= -\frac{\delta\alpha}{\alpha} - \frac{1}{2}\left(\frac{\delta m_e}{m_e} - \frac{\delta\Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}}\right) \\ &= -\left[d_e + \frac{1}{2}\left(d_{m_e} - d_g\right)\right]\varphi_0, \end{aligned} \tag{5a}$$

$$\begin{aligned} \frac{\delta f_{\text{HM}} - \delta f_{\text{Q}}}{f_0} &= 2\frac{\delta\alpha}{\alpha} + \frac{1}{2}\left(\frac{\delta m_e}{m_e} - \frac{\delta\Lambda_{\text{QCD}}}{\Lambda_{\text{QCD}}}\right) \\ &= \left[2d_e + \frac{1}{2}\left(d_{m_e} - d_g\right)\right]\varphi_0. \end{aligned} \tag{5b}$$

These two linear equations where then solved to extract the coupling constants d_e and $d_{m_e} - d_g$.

For the CSO-OCXO comparison; the loop correction voltage was sampled at 2.2 Hz for 2 days, while fo the HM-OCXO comparison it was sampled at the same rate for 16 days. The result of this data collection gave two sets of data from which the spectral density of fractional frequency noise $S_{y_{21}}$ could be determined. Using monte-carlo simulation the fractional frequency noise amplitude that could be excluded from containing a noise peak synonymous with a DM signal to 95% confidence for each noise bin was estimated, giving exclusion limits across frequency space. Substituting these limits into the left hand side of equations (5) and performing the linear separation resulted in exclusion limits on d_e and $d_{m_e} - d_g$ over a range of scalar field DM masses corresponding to the measured Fourier frequencies.

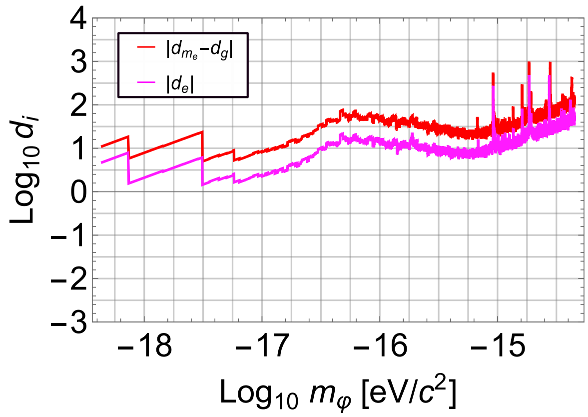

Fig. 1. Exclusion limits on scalar dark matter coupling constants d_e and $d_{m_e} - d_g$ determined from the CSO-OCXO and HM-OCXO comparisons are shown.

III. Discussion/Interpretation

Exclusion limits place on the dimensionless coupling constants in the work we summarise here were not as sensitive as those that have been determined by previous experiments which utilised torsion balances comparisons or atomic transitions. However we note that this work was of a different and complementary significance to those previous results as use of coefficient separation was used, while all other limits in the region were found using maximum reach analysis. As these limits did not require any one coupling of scalar DM to a standard model sector to be made to vanish, they provide a further more conclusive argument to the exclusion of a small region of DM parameter space.

As this experiment was only limited to a few days of data collection, due to oscillator availability, this does not represent the maximum sensitivity achievable using this scheme. By making use of the next generation of ultra low phase and frequency noise oscillators, and a longer experimental run time, this technique is capable of placing world leading exclusion limits on the coupling constants of interest, without the need for approximative maximum reach analysis.

IV. Conclusion

We have summarised in detail our recent work [30] on a new technique with experimental results showing how an ensemble of low-noise oscillators of differing architecture, namely photonic, phononic and atomic, can be used as powerful tools for probing dark matter. We highlight the fact that using a collection of such oscillators, rather than just one, can allow for a significant advantage in the use of coefficient separation, which isn't subject to the idealistic approximations of the more widely used maximum reach analysis. We have also highlighted a few of our other works that further show how precision metrology tools and frequency techniques can be used as highly sensitive probes for new physics.

The natural next step in improving sensitivity of experiments such as the one we present here as well as many others, leads us to furthering the development of our oscillators and frequency references by improving their phase noise and frequency stability. To this end, recent advancements in CSO performance [34], [35] as well as further research into designing stable cryogenic quartz oscillators [6], [7], [36], are important steps towards building the next generation of highly sensitive detection experiments.

REFERENCES

[1] K. Van Tilburg, N. Leefer, L. Bougas, and D. Budker, "Search for ultralight scalar dark matter with atomic spectroscopy," *Phys. Rev. Lett.*, vol. 115, p. 011802, Jun 2015. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevLett.115.011802

[2] A. Arvanitaki, J. Huang, and K. V. Tilburg, "Searching for dilaton dark matter with atomic clocks," *Physical Review D*, vol. 91, no. 1, jan 2015.

[3] M. E. Tobar, P. L. Stanwix, J. J. McFerran, J. Guena, M. Abgrall, S. Bize, A. Clairon, P. Laurent, P. Rosenbusch, D. Rovera, and G. Santarelli, "Testing local position and fundamental constant invariance due to periodic gravitational and boost using long-term comparison of the SYRTE atomic fountains and H-masers," *Physical Review D*, vol. 87, no. 12, June 2013.

[4] M. E. Tobar, P. Wolf, S. Bize, G. Santarelli, and V. Flambaum, "Testing local lorentz and position invariance and variation of fundamental constants by searching the derivative of the comparison frequency between a cryogenic sapphire oscillator and hydrogen maser," *Physical Review D*, vol. 81, no. 2, Jan 2010.

[5] A. Arvanitaki, S. Dimopoulos, and K. V. Tilburg, "Sound of dark matter: Searching for light scalars with resonant-mass detectors," *Physical Review Letters*, vol. 116, no. 3, jan 2016.

[6] M. Goryachev, Z. Kuang, E. N. Ivanov, P. Haslinger, H. Muller, and M. E. Tobar, "Next generation of phonon tests of lorentz invariance using quartz BAW resonators," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 65, no. 6, pp. 991–1000, jun 2018.

[7] A. Lo, P. Haslinger, E. Mizrachi, L. Anderegg, H. Müller, M. Hohensee, M. Goryachev, and M. E. Tobar, "Acoustic tests of lorentz symmetry using quartz oscillators," *Physical Review X*, vol. 6, no. 1, feb 2016.

[8] S. Galliou, M. Goryachev, R. Bourquin, P. Abbé, J. P. Aubry, and M. E. Tobar, "Extremely low loss phonon-trapping cryogenic acoustic cavities for future physical experiments," *Scientific Reports*, vol. 3, pp. 1–6, 2013.

[9] M. Abgrall, J. Guéna, M. Lours, G. Santarelli, M. E. Tobar, S. Bize, S. Grop, B. Dubois, C. Fluhr, and V. Giordano, "High-stability comparison of atomic fountains using two different cryogenic oscillators," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 63, no. 8, pp. 1198–1203, 2016.

[10] J. G. Hartnett, N. R. Nand, and C. Lu, "Ultra-low-phase-noise cryocooled microwave dielectric-sapphire-resonator oscillators," *Applied Physics Letters*, vol. 100, no. 18, p. 183501, 2012. [Online]. Available: https://doi.org/10.1063/1.4709479

[11] G. Flower, M. Goryachev, J. Bourhill, and M. E. Tobar, "Experimental implementations of cavity-magnon systems: from ultra strong coupling to applications in precision measurement," *New Journal of Physics*, vol. 21, no. 9, p. 095004, sep 2019.

[12] P. J. McMillan, "Mass models of the milky way," *Monthly Notices of the Royal Astronomical Society*, vol. 414, no. 3, pp. 2446–2457, apr 2011.

[13] E. Armengaud, C. Augier, A. Benoît, L. Bergé, T. Bergmann, J. Blümer, A. Broniatowski, V. Brudanin, B. Censier, M. Chapellier, F. Charlieux, F. Couëdo, P. Coulter, G. A. Cox, J. Domange, A. A. Drillien, L. Dumoulin, K. Eitel, D. Filosofov, N. Fourches, J. Gascon, G. Gerbier, J. Gironnet, M. Gros, S. Henry, G. Heuermann, S. Hervé, A. Juillard, M. Kleifges, H. Kluck, V. Kozlov, H. Kraus, V. A. Kudryavtsev, H. L. Sueur, P. Loaiza, S. Marnieros, A. Menshikov, X.-F. Navick, C. Nones, E. Olivieri, P. Pari, B. Paul, M. Robinson, S. Rozov, V. Sanglard, B. Schmidt, B. Siebenborn, D. Tcherniakhovski, A. S. Torrento-Coello, L. Vagneron, R. J. Walker, M. Weber, E. Yakushev, and X. Zhang, "Search for low-mass WIMPs with EDELWEISS-II heat-and-ionization detectors," *Physical Review D*, vol. 86, no. 5, sep 2012.

[14] C. E. Aalseth, P. S. Barbeau, J. Colaresi, J. I. Collar, J. D. Leon, J. E. Fast, N. E. Fields, T. W. Hossbach, A. Knecht, M. S. Kos, M. G. Marino, H. S. Miley, M. L. Miller, J. L. Orrell, and K. M. Y. and, "CoGeNT: A search for low-mass dark matter usingp-type point contact germanium detectors," *Physical Review D*, vol. 88, no. 1, jul 2013.

[15] R. Essig and etal, "Dark sectors and new, light, weakly-coupled particles," *arXiv:1311.0029 [hep-ph]*, 2013.

[16] G. Angloher, A. Bento, C. Bucci, L. Canonica, X. Defay, A. Erb, F. von Feilitzsch, N. F. Iachellini, P. Gorla, A. Gütlein, D. Hauff, J. Jochum, M. Kiefer, H. Kluck, H. Kraus, J. C. Lanfranchi, J. Loebell, A. Münster, C. Pagliarone, F. Petricca, W. Potzel, F. Pröbst, F. Reindl, K. Schäffner, J. Schieck, S. Schönert, W. Seidel, L. Stodolsky, C. Strandhagen, R. Strauss, A. Tanzke, H. H. T. Thi, C. Türkoğlu, M. Uffinger, A. Ulrich, I. Usherov, S. Wawoczny, M. Willers, M. Wüstrich, and A. Zöller, "Results on light dark matter particles with a low-threshold CRESST-II detector," *The European Physical Journal C*, vol. 76, no. 1, jan 2016.

[17] J. M. Gaskins, "A review of indirect searches for particle dark matter," *Contemporary Physics*, vol. 57, no. 4, pp. 496–525, 2016. [Online]. Available: https://doi.org/10.1080/00107514.2016.1175160

[18] N. Du, N. Force, R. Khatiwada, E. Lentz, R. Ottens, L. Rosenberg, G. Rybka, G. Carosi, N. Woollett, D. Bowring, A. Chou, A. Sonnenschein, W. Wester, C. Boutan, N. Oblath, R. Bradley, E. Daw, A. Dixit, J. Clarke, S. O'Kelley, N. Crisosto, J. Gleason, S. Jois, P. Sikivie, I. Stern, N. Sullivan, D. Tanner, and G. H. and, "Search for invisible axion dark matter with the axion dark matter experiment," *Physical Review Letters*, vol. 120, no. 15, apr 2018.

[19] L. Zhong, S. A. Kenany, K. Backes, B. Brubaker, S. Cahn, G. Carosi, Y. Gurevich, W. Kindel, S. Lamoreaux, K. Lehnert, S. Lewis, M. Malnou, R. Maruyama, D. Palken, N. Rapidis, J. Root, M. Simanovskaia, T. Shokair, D. Speller, I. Urdinaran, and K. van Bibber, "Results from phase 1 of the HAYSTAC microwave cavity axion experiment," *Physical Review D*, vol. 97, no. 9, may 2018.

[20] P. Sikivie, "Invisible axion search methods," *arXiv:2003.02206 [hep-ph]*, 2020.

[21] S. Gori, G. Perez, and K. Tobioka, "Koto vs. na62 dark scalar searches," 2020.

[22] L. Badurina, E. Bentine, D. Blas, K. Bongs, D. Bortoletto, T. Bowcock, K. Bridges, W. Bowden, O. Buchmueller, C. Burrage, J. Coleman, G. Elertas, J. Ellis, C. Foot, V. Gibson, M. Haehnelt, T. Harte, S. Hedges, R. Hobson, M. Holynski, T. Jones, M. Langlois, S. Lellouch, M. Lewicki, R. Maiolino, P. Majewski, S. Malik, J. March-Russell, C. McCabe, D. Newbold, B. Sauer, U. Schneider, I. Shipsey, Y. Singh, M. Uchida, T. Valenzuela, M. van der Grinten, V. Vaskonen, J. Vossebeld, D. Weatherill, and I. Wilmut, "AION: an atom interferometer observatory and network," *Journal of Cosmology and Astroparticle Physics*, vol. 2020, no. 05, pp. 011–011, may 2020. [Online]. Available: https://doi.org/10.1088%2F1475-7516%2F2020%2F05%2F011

[23] B. T. McAllister, G. Flower, E. N. Ivanov, M. Goryachev, J. Bourhill, and M. E. Tobar, "The organ experiment: An axion haloscope above 15 ghz," *Physics of the Dark Universe*, vol. 18, pp. 67 – 72, 2017. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S2212686417300602

[24] A. Caldwell, G. Dvali, B. Majorovits, A. Millar, G. Raffelt, J. Redondo, O. Reimann, F. Simon, and F. Steffen, "Dielectric haloscopes: A new way to detect axion dark matter," *Phys. Rev. Lett.*, vol. 118, p. 091801, Mar 2017. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevLett.118.091801

[25] S. J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L. J. Rosenberg, G. Rybka, J. Hoskins, J. Hwang, P. Sikivie, D. B. Tanner, R. Bradley, and J. Clarke, "SQUID-based microwave cavity search for dark-matter axions," *Physical Review Letters*, vol. 104, no. 4, p. 041301, jan 2010.

[26] C. A. Thomson, B. T. McAllister, M. Goryachev, E. N. Ivanov, and M. E. Tobar, "Upconversion loop oscillator axion detection experiment: A precision frequency interferometric axion dark matter search with a cylindrical microwave cavity," *Physical Review Letters*, vol. 126, no. 8, p. 081803, feb 2021.

[27] M. Goryachev, Z. Kuang, E. N. Ivanov, P. Haslinger, H. Müller, and M. E. Tobar, "Next generation of phonon tests of lorentz invariance using quartz baw resonators," *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 65, no. 6, pp. 991–1000, 2018.

[28] M. Goryachev and M. E. Tobar, "Gravitational wave detection with high frequency phonon trapping acoustic cavities," *Physical Review*

D, vol. 90, no. 10, pp. 102 005–, 11 2014. [Online]. Available: https://link.aps.org/doi/10.1103/PhysRevD.90.102005

[29] M. Goryachev, W. M. Campbell, I. S. Heng, S. Galliou, E. N. Ivanov, and M. E. Tobar, "Rare events detected with a bulk acoustic wave high frequency gravitational wave antenna," 2021.

[30] W. M. Campbell, B. T. McAllister, M. Goryachev, E. N. Ivanov, and M. E. Tobar, "Searching for scalar dark matter via coupling to fundamental constants with photonic, atomic, and mechanical oscillators," *Physical Review Letters*, vol. 126, no. 7, p. 071301, feb 2021.

[31] T. Damour and J. F. Donoghue, "Equivalence principle violations and couplings of a light dilaton," *Physical Review D*, vol. 82, no. 8, oct 2010.

[32] A. Hees, J. Guéna, M. Abgrall, S. Bize, and P. Wolf, "Searching for an oscillating massive scalar field as a dark matter candidate using atomic hyperfine frequency comparisons," *Physical Review Letters*, vol. 117, no. 6, aug 2016.

[33] T. Damour and A. Polyakov, "The string dilation and a least coupling principle," *Nuclear Physics B*, vol. 423, no. 2-3, pp. 532–558, jul 1994.

[34] E. N. Ivanov and M. E. Tobar, "Generation of spectrally pure microwave signals," 2020, arXiv:2003.09117 [physics.ins-det].

[35] ——, "Noise suppression with cryogenic resonators," *IEEE Microwave and Wireless Components Letters*, vol. 31, no. 4, pp. 405–408, apr 2021.

[36] E. Ivanov, M. Goryachev, M. Tobar, and S. Galliou, "Pound stabilized cryogenic bulk acoustic wave resonator-oscillator," in *2018 IEEE International Frequency Control Symposium (IFCS 2018)*.