# Development of a PZT-based experimental bench for potential detection of the piezoaxionic effect in axion dark matter research

Mahmoud Addouche*, Nathalie Cholley, Fabrice Sthal, Patrice Salzenstein*
Centre National de la Recherche Scientifique (CNRS), Université Marie et Louis Pasteur (UMLP),
FEMTO-ST Institute, 15B avenue des Montboucons, F25030 Besançon Cedex, FRANCE
***Corresponding author's e-mail:*** mahmoud.addouche@femto-st.fr , patrice.salzenstein@cnrs.fr

## ABSTRACT

The detection of axion dark matter has traditionally relied on electromagnetic resonant techniques such as haloscopes and dielectric resonators. Recently, the proposal of a piezoaxionic effect—an axion-induced mechanical strain in piezoelectric materials—has opened a new experimental avenue. In this context, we have introduced an original experimental strategy based on high-Q PZT resonators engineered with bound states in the continuum (BICs). Their work constitutes one of the first systematic attempts to bridge axion field theory, piezoelectric material science, and tunable mechanical resonator engineering. This paper reviews the scientific context, theoretical basis, experimental approach, and originality of their contribution, highlighting its significance for future axion detection experiments.

**Keywords:** PZT, Axion, Dark matter.

## 1. INTRODUCTION

The search for axions, hypothetical particles proposed as constituents of dark matter, has stimulated innovative approaches leveraging advanced sensing techniques. One emerging concept is the piezoaxionic effect, wherein axion induced interactions may generate measurable mechanical or electrical responses in piezoelectric materials. Building on our previous work on high-Q PZT resonators [1], we report the ongoing development of an experimental bench designed to explore this effect under controlled conditions. The bench integrates piezoelectric transducers (PZT) with precision excitation and detection systems, enabling the monitoring of extremely small displacements and electric signals potentially induced by axion interactions. Key challenges addressed in the design include maximizing resonator quality factors, minimizing environmental noise, and implementing tunable configurations to scan a wide range of potential axion masses. The approach exploits bound states in the continuum (BIC) in PZT resonators to enhance signal sensitivity, providing a promising pathway for detecting weak couplings associated with dark matter axions. Preliminary simulations should indicate that the system can resolve mechanical or electrical perturbations at levels consistent with theoretical predictions of the piezoaxionic effect. The bench is also designed to be modular, allowing integration with complementary detection techniques, such as optical interferometry or superconducting sensors, thereby offering a versatile platform for cross validation of potential signals. While the experimental realization is ongoing, this work establishes a foundational methodology for probing axion induced phenomena via piezoelectric transduction. Successful detection of the predicted effects would not only provide evidence for axion dark matter but also open a new frontier in the application of piezoelectric resonators in fundamental physics research. This development represents a significant step toward bridging theoretical predictions of axion interactions with experimentally accessible observables.

Recent studies suggest gravitational lensing anomalies are better explained if dark matter consists of axions rather than WIMPs [2]. Direct-detection experiments such as *DarkSide* in Italy use liquid argon detectors deep underground to search for dark matter [3]. At CERN, the CAST experiment has been adapted to look for axions in the Milky Way's dark matter halo [4]. In strong magnetic fields, axions may convert into photons in the 4.8–5.4 GHz range, corresponding to masses of 19.7–22.5 μeV. CAST scanned this band in 200 kHz steps, while other experiments are now probing even lower frequencies, down to 100–600 MHz [5].

Axions and axion-like particles (ALPs) remain among the most compelling candidates for dark matter, motivated by both cosmology and the strong CP problem in quantum chromodynamics. Experimental efforts to detect axions have historically focused on axion–photon coupling, notably through resonant microwave cavities. However, this approach faces challenges at higher axion masses due to shrinking cavity volumes and reduced signal strength.

The recent theoretical proposal of the piezoaxionic effect suggests that axions may also couple to mechanical degrees of freedom in piezoelectric materials, inducing strain oscillations at the axion Compton frequency. This paradigm shift motivates the exploration of mechanical resonators as axion detectors.

Within this emerging framework, our work represents a novel and technically grounded contribution, proposing PZT-based resonators with engineered high-quality factors and tunability as realistic platforms for axion detection.

The sensitivity of such experiments depends critically on two factors:

- High quality factor (Q): to maximize the signal-to-noise ratio.
- Broad frequency tunability: to scan the axion mass range, typically corresponding to frequencies from kilo Hertz up to hundreds of Mega Hertz.

Traditional resonator arrays meet these requirements only partially, as switching among multiple high-Q devices is technically complex and time-consuming. We propose an alternative strategy: implementing bound states in the continuum (BICs) in coupled PZT resonators, which simultaneously yield ultra-high-Q and tunability. The nature of axion is illustrated in Fig. 1.

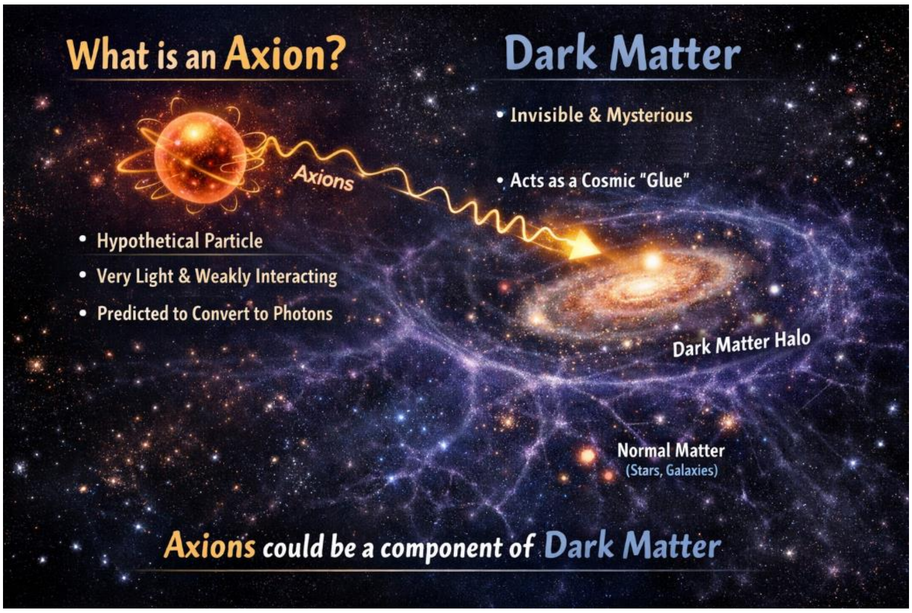

**Fig. 1:** What is an axion? Dark matter could explain why the rotational speed of a galaxy is larger than expected.

The amount of axions a detector receives varies over time. This temporal modulation is a key signature predicted by dark matter models and is central to axion detection experiments, which attempt to identify both annual and daily (23 h 56 min) modulation [6-10].

Traditional axion detection strategies have primarily focused on the axion-photon coupling via the Primakoff effect, exemplified by cavity haloscope experiments such as the Axion Dark Matter eXperiment (ADMX) [11-13]. However, these approaches face significant technical challenges when targeting certain mass ranges, particularly below 1 μeV and in the intermediate range between $10^{-11}$ and $10^{-7}$ eV [14]. The recent theoretical proposal of the piezoaxionic effect by Arvanitaki represents a paradigm shift in axion detection methodology, offering an innovative approach that exploits the interaction between axion dark matter and piezoelectric crystals [13,14]. This work presents the piezoaxionic effect as arising from the fundamental property that axion dark matter constitutes an oscillating background field that violates both parity and time-reversal symmetries. When this axion field permeates a piezoelectric crystal—a material in which parity is spontaneously broken—it induces a mechanical stress that oscillates at the Compton frequency of the axion. This stress can be resonantly enhanced when the axion frequency matches a bulk acoustic normal mode of the crystal and subsequently read out electrically via the conventional piezoelectric effect.

If axion dark matter exists, it forms a coherent oscillating field throughout the galaxy with a characteristic frequency determined by the axion mass via the relation $\omega = m\_a c^2/\hbar$ [16]. The amplitude of this axion field is constrained by the local dark matter density, resulting in extremely weak coupling forces with ordinary matter [17]. This fundamental weakness of axion interactions necessitates highly sensitive detection techniques with substantial signal amplification mechanisms [11]. Traditional cavity haloscopes exploit the axion-photon coupling in strong magnetic fields, converting axions into photons when the cavity resonance matches the axion mass [11]. However, these experiments face practical limitations regarding cavity size and tuning range, making certain mass windows technically difficult to explore.

Arvanitaki proposes a fundamentally new mechanism, predicting that a decisive coupling of the QCD axion occurs via the strong-sector anomaly, particularly its interaction with gluons [13,14]. This coupling gives rise to various detection signatures depending on the experimental setup and target material. The advantage of this coupling is that the mass range of interest lies between $10^{-11}$ and $10^{-7}$ eV (corresponding to frequencies of approximately 2 kHz to 20 GHz), which presents particular experimental difficulties for conventional detection methods. This challenging intermediate mass range motivates the development of alternative detection strategies, including the piezoaxionic effect, which offers a complementary approach with technical requirements distinct from haloscope-based methods.

The piezoaxionic stress can be phenomenologically expressed as causing mechanical deformations in the crystal, which are typically extremely small due to the weakness of axionic interactions [14,15]. However, when the axion frequency matches a normal acoustic mode of the piezoelectric crystal, the mechanical response is resonantly amplified by the quality factor Q of that mode. The resonantly amplified mechanical deformation is then converted into an electrical signal via the conventional piezoelectric effect, where mechanical strain induces charge separation and generates a voltage across the crystal. This two-step transduction—axion to mechanical strain via the piezoaxionic effect, then mechanical strain to voltage via the piezoelectric effect—allows electrical readout of the axion signal using standard low-noise amplification techniques. The overall signal strength depends on the product of the piezoaxionic coupling, the mechanical quality factor, and the piezoelectric coupling coefficient, making material selection and resonator design critical for detector performance.

Lead zirconate titanate (PZT) exhibits strong electromechanical coupling with high piezoelectric coefficients, and its fabrication processes are well established. Selecting piezoelectric materials for axion detection requires balancing several competing factors. High piezoelectric coefficients are essential for efficient conversion of mechanical strain to electrical signals, directly impacting detector sensitivity. The electromechanical coupling coefficient, which quantifies energy conversion efficiency between mechanical and electrical domains, should be maximized to enhance signal transduction. Mechanical quality factors Q determine the resonant amplification of axion-induced stress and must be as high as possible to amplify the weak axion signal. When the quality factor is insufficient, it can be improved by lowering the temperature of the piezoelectric resonator, as is the case for PZT-5A, which is widely used in actuators and sensors and exhibits stable properties at cryogenic temperatures where thermal noise is minimized and detector sensitivity is optimized. Indeed, dielectric loss, quantified by the loss tangent $\tan(\delta)$, generally decreases at lower temperatures, contributing to improved quality factors and reduced dissipation. PZT-5A offers a good balance of piezoelectric performance, mechanical quality factor, and can be fabricated in various geometries, including bulk resonators, thin films, and composite structures, offering design flexibility [16]. Below 30 K, quality factors exceeding $10^6$ are achievable [17]. However, the cryogenic regime requires careful attention to mounting techniques, wiring, and thermal isolation and stabilization.

Although this technique potentially represents the ultimate solution for axion detection, other avenues are exploitable, such as the use of bound states in the continuum (BICs) to achieve ultra-high Q factors in resonators. BICs are resonant modes that remain localized despite existing within a continuum of radiating modes, effectively trapping energy inside the resonator and suppressing dissipation.

## 2. SCIENTIFIC CONTEXT

### *2.1. Axion Detection Beyond Electromagnetic Haloscopes*

Traditional axion haloscopes exploit the axion–photon coupling in strong magnetic fields. While highly sensitive, these experiments face scaling limitations and frequency coverage challenges. As a result, alternative coupling channels, spin, phonon, and mechanical, have gained attention. The proposal by Arvanitaki et al. [14] introduced the piezoaxionic effect, whereby the axion field induces an effective stress tensor in piezoelectric crystals, generating a measurable voltage or mechanical vibration.

### *2.2. Piezoelectric Materials as Axion Sensors*

Piezoelectric materials such as quartz, lithium niobate, and PZT are well known for their strong electromechanical coupling and mature fabrication technologies. However, prior to our work, the use of PZT resonators explicitly optimized for axion detection had not been systematically explored.

## 3. THEORETICAL FRAMEWORK

The axion field $a(t)$ couples to nuclear spins and manifests as an effective oscillatory force density in piezoelectric media. Following [1], the induced stress can be written as:

$$\sigma_{ij}(t) \propto g_{qNN} < S_N > a_0 \cos(\omega_a t) \qquad \text{(Equation 1)}$$

where:

- $g_{aNN}$ is the axion-nucleon coupling constant,
- $< S_N >$ is the average nuclear spin polarization,
- $a_0$ is the local axion field amplitude,
- $\omega_a = \frac{m_a c^2}{\hbar}$ is the axion angular frequency.

When $\omega_a$ matches the resonance frequency of a bulk acoustic mode $\omega_r$, the stress resonantly excites vibrations with amplitude enhanced by the quality factor $Q$:

$$A \propto \frac{1}{\sqrt{(\omega_a - \omega_r)^2 + \left(\frac{\omega_r}{Q}\right)^2}} \qquad \text{(Equation 2)}$$

Thus, maximizing $Q$ directly boosts sensitivity to axion signals.
The piezoaxionic effect predicts that an oscillating axion field $a(t)$ couples to lattice deformations via an effective interaction of the form:

$$\pounds_{axion-phonon} = g_a a(t) u \text{ (Equation 3)}$$

where $u$ is the displacement field of the crystal lattice and $g_a$ is an effective axion–phonon coupling constant.

In a piezoelectric medium, this strain induces an electric polarization, allowing the conversion of axion-induced mechanical motion into an electrical signal. Resonant enhancement occurs when the mechanical eigenfrequency of the resonator matches the axion Compton frequency. The originality of our work lies in recognizing that high-Q mechanical resonators with engineered mode confinement are essential to amplify this weak coupling to detectable levels. Bound states in the continuum (BICs) arise when destructive interference prevents radiative losses in a resonant system, despite the resonance frequency lying within the radiation continuum. In mechanical and acoustic systems, BICs allow for the trapping of vibrational energy with minimal leakage, thereby boosting the effective Q-factor. Recent studies have demonstrated ultra-high-Q resonators based on BICs in the ultrasound regime [14]. Translating this concept to the piezoaxionic context, we consider the coupling of two centimetre-scale PZT resonators. By carefully tuning the geometric and boundary conditions, the coupled system supports quasi-BIC modes, where energy dissipation is strongly suppressed. The resulting Q-factors can exceed those of single resonators by an order of magnitude, a crucial advantage for weak signal detection. In open systems, resonant modes typically couple to radiation channels, leading to energy leakage and finite Q. However, under specific symmetry or interference conditions, radiative losses cancel, yielding bound states in the continuum [4]. For two coupled piezoelectric resonators, the effective Hamiltonian can be written as:

$$H = \begin{pmatrix} \omega_1 - i\gamma & \kappa \\ \kappa & \omega_1 - i\gamma \end{pmatrix} \qquad \text{(Equation 4)}$$

where $\omega_{1,2}$ are the uncoupled resonance frequencies, $\gamma$ represents intrinsic losses, and $\kappa$ is the coupling coefficient. At the BIC condition, destructive interference eliminates radiation leakage, yielding a mode with decay rate limited only by intrinsic losses:

$$Q_{BIC} \approx \frac{\omega}{2\gamma} \qquad \text{(Equation 5)}$$

This results in an order-of-magnitude increase in $Q$ compared to single-resonator configurations. Concept of axion-induced stress is illustrated in Fig. 2.

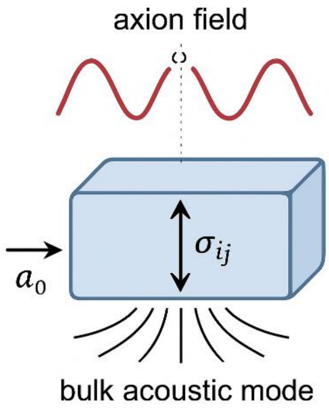

**Fig. 2:** Concept of axion-induced stress in a piezoelectric crystal.

## 4. EXPERIMENTAL CONCEPT AND METHODOLOGY

### *4.1. Use of PZT Resonators*

PZT offers exceptionally strong piezoelectric coefficients compared to natural crystals, making it particularly attractive for axion-induced strain detection. However, PZT also suffers from intrinsic losses that can limit the quality factor Q. We address this challenge by proposing geometrical and modal engineering rather than relying solely on material purity. Lead zirconate titanate (PZT) is an excellent material for axion searches due to its:

- Strong piezoelectric coupling,
- Robust mechanical properties,
- Established fabrication scalability.

By coupling two centimeter-scale PZT resonators with controlled separation, we engineer quasi-BIC modes. Figure 2 (conceptual) illustrates the setup, where symmetric and antisymmetric hybridization of BAMs leads to destructive interference in the radiation continuum. Additionally, BIC-enabled PZT resonators are compatible with electrical frequency tuning. Adding passive inductive (L) and capacitive (C) loads modifies the effective resonance:

$$\omega_{eff} = \frac{1}{\sqrt{L(C_0+C)}} \qquad \text{(Equation 6)}$$

where $C_0$ is the intrinsic capacitance of the resonator. This allows scanning across wide frequency bands without switching between separate devices. In this work we rely on our experience in stable signal oscillators [18-21] or waveguides [22]. We also rely on our knowledge on metrology requirements [23,24].

### *4.2. Bound States in the Continuum (BICs)*

In a previous paper [1], we introduce the use of bound states in the continuum in PZT resonators. BICs are non-radiative modes embedded in the continuous spectrum that exhibit extremely high quality factors due to symmetry protection or destructive interference [25]. By tailoring resonator geometry, they demonstrate the feasibility of:

- Strong suppression of acoustic radiation losses,
- Tunable resonance frequencies,
- Substantially enhanced Q-factors suitable for axion searches.

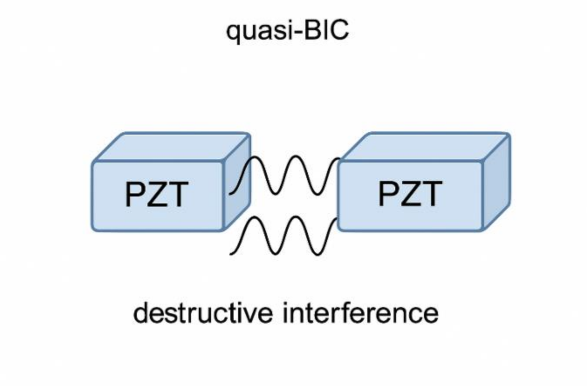

**Fig. 3:** Two coupled PZT resonators forming a quasi-BIC

This represents a conceptual transfer of BIC physics, traditionally used in photonics, into the domain of mechanical axion detectors. The concept of two coupled PZT resonators is given in Fig. 3. The idea is that a PZT resonator (in a blade configuration to induce Lamb waves) exhibits Q values that can increase with increasing mode order, and these values can be very high if no mechanical constraints are applied. However, in reality, such boundary conditions are obviously not achievable. Fixing them drastically reduces the Q value. Therefore, we propose using a phononic (PN) crystal [26,27], which exhibits a frequency gap where no Lamb mode can exist. In our case, the originality lies in using two PN structures (see Fig. 4) as elastic insulators to hold a PZT resonator. This means that, although they are fixed on one side, the resonator experiences confined vibrations with specific boundary conditions that allow it to reach even higher Q values (See Fig. 5).

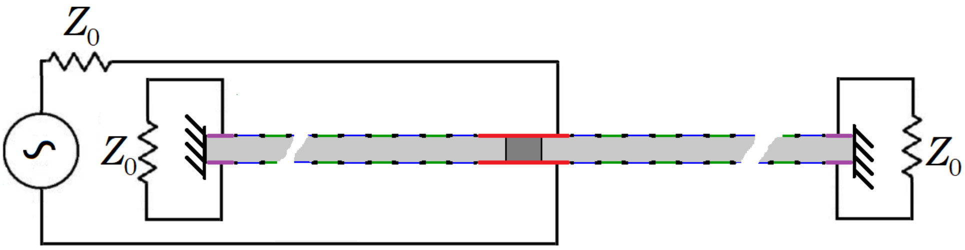

**Fig. 4:** Structures composed of two phononic crystals (PCs) connected by a PZT-5A layer (dark gray), which constitutes the resonator to be isolated and can also be regarded as a defect in the middle of this composite phononic crystal.

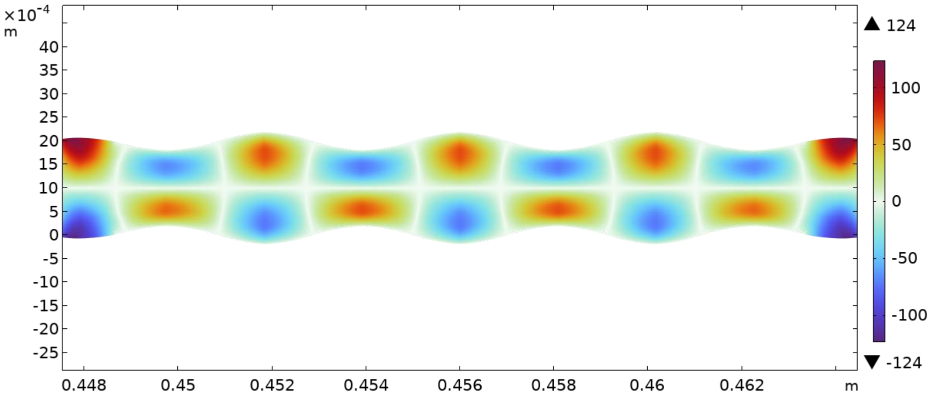

**Fig. 5:** Calculated color map of the electric potential and mode deformation shape associated to S4 wave for a clamped PZT-5A slab resonator at frequency fr4=645.79 kHz.

## 5. CONCLUSION

The originality of our work lies in the introduction of piezoelectric bound states in the continuum (BIC) resonators as a dedicated platform for axion detection. Rather than adapting piezoelectric devices designed for conventional sensing, they explicitly optimize PZT resonators for the piezoaxionic effect, marking one of the first focused efforts in this direction. By importing the concept of mechanical BICs into axion physics, their approach is both conceptually novel and strongly interdisciplinary, leveraging high-Q resonator engineering to enhance sensitivity in a domain traditionally dominated by electromagnetic techniques. A key strength of their contribution is the clear bridge it establishes between theory and experimental feasibility. The proposed devices rely on industrially mature PZT materials and realistic fabrication strategies, demonstrating that the piezoaxionic effect can be explored with manufacturable and scalable resonators. In addition, the intrinsic frequency tunability of these mechanical systems directly addresses one of the central challenges in axion searches: the need to scan across an unknown axion mass range without compromising sensitivity. In this sense, their work defines a credible experimental roadmap rather than a purely conceptual proposal. While no axion detection is claimed, we provide essential groundwork for transforming the piezoaxionic effect from a theoretical idea into a testable experimental framework. Their results open clear paths for future developments, including cryogenic operation to reduce the mechanical dissipation, integration with quantum - limited readout electronics, hybrid electromagnetic–mechanical detection schemes, and exploration of alternative low-loss piezoelectric materials. Overall, this approach significantly broadens the experimental landscape of axion physics and strengthens the case for phonon- and strain-based dark matter detection as a serious and competitive methodology.

## REFERENCES

[1] M. Addouche, P. Salzenstein, "Bound states in the continuum for tunable high-Q PZT resonators in axion dark matter detection," Proc. SPIE 13720, Optical Metrology and Inspection for Industrial Applications XII, 137201R (2025). https://doi.org/10.1117/12.3076654.

[2] Alfred Amruth et al., "Einstein rings modulated by wavelike dark matter from anomalies in gravitationally lensed images," Nature Astronomy, 7, 736–747 (2023). https://doi.org/10.1038/s41550-023-01943-9.

[3] P. Agnes et al. (DarkSide Collaboration), "Low-Mass Dark Matter Search with the DarkSide-50 Experiment," Phys. Rev. Lett. 121, 081307 (2023). https://doi.org/10.1103/PhysRevLett.121.081307.

[4] Adair, C.M., Altenmüller, K., Anastassopoulos, V. et al. Search for Dark Matter Axions with CAST-CAPP. Nat Commun 13, 6180 (2022). https://doi.org/10.1038/s41467-022-33913-6.

[5] Chakrabarty S. et al, "Low frequency, 100–600 MHz, searches with axion cavity haloscopes," Phys. Rev. D 109, 042004 (2024). http://dx.doi.org/10.1103/PhysRevD.109.042004.

[6] Xunyu Liang, Alexander Mead, Md Shahriar Rahim Siddiqui, Ludovic Van Waerbeke, Ariel Zhitnitsky, “Axion Quark Nugget Dark Matter: Time Modulations and Amplifications,” Phys. Rev. D 101, 043512 (2020). https://doi.org/10.1103/PhysRevD.101.043512.

[7] F. Caspers et al, “Daily modulations and broadband strategy in axion searches: An application with the CAST-CAPP detector,” Phys. Rev. D 111, 082009 (2025). https://doi.org/10.1103/PhysRevD.111.082009.

[8] Fu-Sin Ling, Pierre Sikivie, and Stuart Wick, “Diurnal and annual modulation of cold dark matter signals,” Phys. Rev. D 70, 123503 (2004). https://doi.org/10.1103/PhysRevD.70.123503.

[9] Xiangjun Tan, Zhanning Wang, “Annual-modulation fingerprint of the axion wind induced sideband triplet in quantum dot spin qubit sensors,” Phys. Rev. D 113, 016001 (2026). https://doi.org/10.1103/886r-126m.

[10] Kahn et al., "Broadband and Resonant Approaches to Axion Dark Matter Detection," Physical Review Letters, vol. 117, 2016. https://doi.org/10.1103/PHYSREVLETT.117.141801.

[11] Thomson et al., "Upconversion Loop Oscillator Axion Detection Experiment: A Precision Frequency Interferometric Axion Dark Matter Search with a Cylindrical Microwave Cavity," Physical Review Letters, vol. 126, 2021. https://doi.org/10.1103/PHYSREVLETT.126.081803.

[12] Stern, "ADMX Status," 2016. https://doi.org/10.22323/1.282.0198.

[13] Asimina Arvanitaki et al, “Dark QED from inflation,” Journal of High Energy Physics 11, 106 (2021). https://doi.org/10.1007/JHEP11(2021)106.

[14] A. Arvanitaki, A. Madden, K. Van Tilburg, The Piezoaxionic Effect, Phys. Rev. D 109, 072009 (2024). http://dx.doi.org/10.1103/PhysRevD.109.072009.

[15] Francesca Chadha-Day, John Ellis, David J.E. Marsh, “Axion dark matter: What is it and why now?,” Science Advances 8, eabj3618 (2022). https://doi.org/10.1126/sciadv.abj3618.

[16] Butt et al., "Generation of electrical energy using lead zirconate titanate (PZT-5A) piezoelectric material: Analytical, numerical and experimental verifications," Journal of Mechanical Science and Technology, 2016. https://doi.org/10.1007/S12206-016-0715-3.

[17] Islam, "Piezoelectric and Dielectric Properties of LiNbO3, PMN-PT, and PZT-5A Materials at Cryogenic Temperatures," 2018. https://doi.org/10.7939/R3TM72H2P.

[18] Salzenstein P., Cholley N., Kuna A., Abbé P., Lardet-Vieudrin F., Sojdr L. and Chauvin J., "Distributed amplified ultra-stable signal quartz oscillator based," Measurement 45(7), 1937–1939 (2012). https://doi.org/10.1016/j.measurement.2012.03.035.

[19] Pavlyuchenko E., Salzenstein, P., "Application of modern method of calculating uncertainty to microwaves and opto-electronics," Laser Optics, 2014 International Conference, Saint Petersburg, Russia, June 30 2014-July 4 (2014). http://dx.doi.org/10.1109/LO.2014.6886449.

[20] Salzenstein P., Mortier M., Sérier-Brault H., Henriet R., Coillet A., Chembo Y. K., Rasoloniaina A., Dumeige Y., Féron P., "Coupling of high quality factor optical resonators," Physica Scripta, T157, 014024 (2013). http://dx.doi.org/10.1088/0031-8949/2013/T157/014024.

[21] Henriet, R., Salzenstein, P., Ristic, D., Coillet, A., Mortier, M., Rasoloniaina, A., Saleh, K., Cibiel, G., Dumeige, Y., Ferrari, M., Chembo, Y. K., Llopis, O., Féron, P., "High quality factor optical resonators," Physica Scripta, T162, 014032 (2014). http://dx.doi.org/10.1088/0031-8949/2014/T162/014032.

[22] Salzenstein P., Dupuis O., Helal M., Lheurette E., Vanbésien O., Mounaix P., Lippens D., "Coplanar waveguides on dielectric membranes micromachined on GaAs substrate," Electronics Letters 32(9), 821-822 (1996). http://dx.doi.org/10.1049/el:19960564.

[23] Salzenstein P., Wu T. Y., "Uncertainty estimation for the Brillouin frequency shift measurement using a scanning tandem Fabry-Pérot interferometer," Micromachines 14(7), 1429 (2023). https://doi.org/10.3390/mi14071429.

[24] Salzenstein P., Wu Thomas Y., Pavlyuchenko, E., "The Critical Role of International Comparisons in Global Metrology System: An Overview," Metrology 5(4), 74 (2025). https://www.mdpi.com/2673-8244/5/4/74.

[25] M. Farhat, Y. Achaoui, J. A. I. Martínez, M. Addouche, Y. Wu, A. Khelif, "Observation of Ultra-High-Q Resonators in the Ultrasound via Bound States in the Continuum," Adv. Sci. 2024, 11, 2402917. http://dx.doi.org/10.1002/advs.202402917.

[26] N. Kherraz, L. Haumesser, F. Levassort, P. Benard, B. Morvan, "Controlling Bragg gaps induced by electric boundary conditions in phononic piezoelectric plates," Applied Physics Letters 108, 093503 (2016). https://doi.org/10.1063/1.4943138.

[27] S. Degraeve, C. Granger, B. Dubus, J. O. Vasseur, M. Pham Thi, A.-C. Hladky-Hennion, "Bragg band gaps tunability in an homogeneous piezoelectric rod with periodic electrical boundary conditions," J. Appl. Phys. 115, 194508 (2014). https://doi.org/10.1063/1.4876757.