

Quantum Semiconductor Heterostructures for meV Axion Dark Matter Detection

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We propose a novel strategy and a new class of detectors for the direct detection of axion dark matter in the meV mass range, based on resonantly enhanced axion-photon conversion through the inverse Primakoff effect in engineered radiometers composed of quantum semiconductor heterostructures. Semiconductor-Quantum-Well Axion Radiometer Experiments (SQWAREs) are multiple quantum well structures forming magnetoplasmonic cavities, containing high-mobility two-dimensional electron gases, realizing tunable epsilon-near-zero resonances in the terahertz frequency range. By controlling the orientation of the cavity within a strong external magnetic field, both the resonance frequency and the axion-induced current are optimized *in situ*, enabling efficient scanning across a broad mass range without the need for complex mechanical adjustments. The axion-induced electromagnetic signal radiatively emitted from the cavity is then detected by a photodetector. We present the theoretical basis for resonant enhancement, detail the experimental design and benchmarks through extensive simulations, project the sensitivity of an example SQWARE for several realistic configurations, and demonstrate the modularity and flexibility of the design to fit reasonably with any lab's existing capabilities and target unique axion mass ranges. Our results demonstrate that the SQWAREs can probe the well-motivated quantum chromodynamics axion parameter space and close a critical gap in direct searches at meV masses.

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Introduction—The axion, originally proposed to solve the strong charge-parity problem in quantum chromodynamics (QCD), remains a leading candidate for dark matter (DM) [1–4]. Axionlike particles, which we will also call axions, appear ubiquitous in string theory [5]. Searches probing various portions of the axion mass m_a use photons as the primary probe through the axion-photon coupling $g_{a\gamma\gamma}$ in planned colliders, beam dumps, astrophysical systems, and an array of tabletop experiments [6]. Masses in the meV range lie on the edge of favorability for postinflationary production of axions and correspond to maximal misalignment in the preinflationary scenario [7,8].

Direct detection of axion DM at meV masses poses a significant experimental challenge. Traditional vacuum cavity haloscopes like ADMX, CAPP, and QUAX are highly sensitive at microwave frequencies, with high

quality factors $Q \sim 10^4$ – 10^5 but narrow tuning bandwidth [9]. At THz frequencies corresponding to meV masses, however, the quality factor and cavity volume drop significantly [10]. Metallic cavities like Fabry-Perot have experimentally demonstrated up to $Q \sim 89$ [11], and while Tamm and photonic crystal cavities reach $Q \sim 10^3$ – 10^4 , they have low form factor, further reducing the signal [12,13]. Mechanical tuning mechanisms involving dielectric rods and/or multicavity systems become difficult to implement with smaller structures due to shorter wavelengths and in smaller sample spaces that are common in high field magnets [14]. Novel strategies, including dielectric haloscopes [15,16] and plasmonic cavity designs [17–19], have extended the reach of axion searches, but mechanical tuning and structural constraints limit their scalability at higher frequencies. Meanwhile, detectors based on material resonances, such as phonon-polariton [20,21] and axion quasiparticle devices [22–25], are restricted by the scarcity of well-characterized, low-loss materials with tunable resonances at meV energies [26]. Broadband approaches like Broadband Reflector Experiment for Axion Detection, which uses parabolic reflectors, are promising but require a very large detector volume [27].

Here, we propose a novel detection strategy, the Semiconductor-Quantum-Well Axion Radiometer Experiments (SQWAREs), that leverages advances in quantum semiconductor heterostructures to overcome these obstacles. Our proposed experimental design utilizes a magnetoplasmonic cavity based on high-mobility two-dimensional electron gases (2DEGs) in a multiple quantum well (MQW) structure in a strong magnetic field engineered with a tunable epsilon-near-zero (ENZ) response in the THz band, where the axion-photon conversion signal can be resonantly and electromagnetically enhanced. In contrast to previous methods, the resonant frequency is scanned *in situ* simply by reorienting the MQW in the magnetic field. This approach enables efficient exploration of the previously inaccessible meV axion mass window, with projected sensitivities that can approach the well-motivated QCD axion parameter space under the Dine-Fischler-Srednicki-Zhitnitsky and Kim-Shifman-Vainshtein-Zakharov models [8]. The modular design also allows labs with different resource availabilities, including weaker magnets and alternative growth methods and semiconductor materials, to target unique mass ranges. The combination of using known high-quality materials with wide tunability and flexible, scalable fabrication methods marks a major step toward closing the experimental gap in axion DM searches.

The SQWARE concept consists of an MQW structure functioning as a magnetoplasmonic cavity with centimeter-scale thickness and diameter placed in a static magnetic field. The relevant physical scales (electromagnetic wavelength $\lambda \sim \text{mm}$, frequency $f \sim \text{THz}$, and axion mass $m_a \sim \text{meV}$, for example) are well-matched to the engineered ENZ resonance of the MQW, where the permittivity approaches

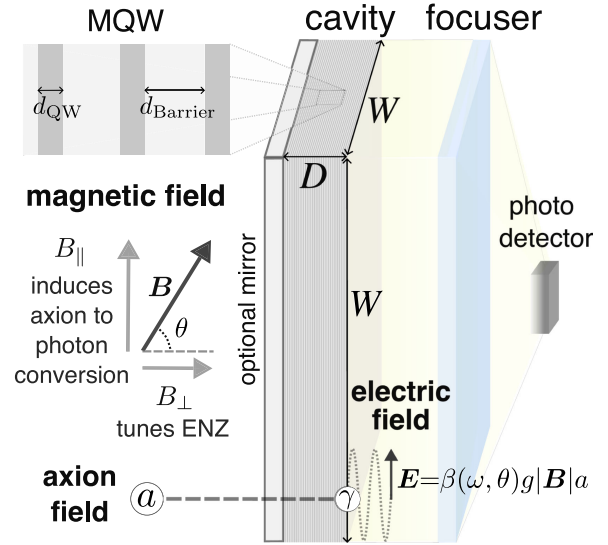


FIG. 1. Schematic of a possible SQWARE detector. A magneto-plasmonic cavity with area W^2 and thickness D is an MQW structure consisting of high-mobility 2DEGs in quantum wells with thickness d_{QW} and insulating dielectric barriers with thickness d_{Barrier} . An applied magnetic field $\mathbf{B}$ with tilt angle θ induces electromagnetic radiation from the axion DM (via component $B_{\parallel}$) and sweeps the ENZ resonance frequency (via $B_{\perp}$). Electromagnetic radiation from the surface of the cavity is focused onto a photodetector.

zero. Under these conditions, the axion-induced electric field inside the material is resonantly enhanced, substantially increasing the emitted electromagnetic power on the order of $\sim 10^4$, which can be measured with a photodetector coupled to the device. Crucially, the ENZ resonance is tunable. By varying the orientation of the MQW within the external magnetic field, one can independently optimize the magnetic field components due to the anisotropic permittivity tensor of the material: the component parallel to the sample controls the axion-induced current and thus the signal strength, while the component perpendicular to the sample tunes the ENZ frequency, allowing for mass scanning. This dual control enables efficient exploration of the $(m_a, g_{a\gamma\gamma})$ parameter space without complicated mechanical adjustment. Figure 1 illustrates the core SQWARE concept. The remainder of this Letter details the underlying physical principles and presents projected sensitivities to axion DM across the meV mass window for an example ideal SQWARE configuration.

General concept—The axion-photon coupling modifies Maxwell’s equations by introducing a source term proportional to the axion field and external magnetic field; see Sec. I A in Supplemental Material (SM) [28]. For a nonrelativistic axion DM background, the axion field can be approximated as spatially homogeneous on the scale of the experiment, $a(t) = a_0 e^{-im_a t}$, with amplitude $a_0 = \sqrt{2\rho_a}/m_a$, where ρ_a is the local axion DM density. In a medium with a complex electric permittivity tensor

$\epsilon(\omega)$ (real part ϵ' and imaginary part ϵ''), the induced electric field with vector amplitude $\mathbf{E}$ oscillates at the axion Compton frequency $\omega_a = m_a$,

$$\epsilon(\omega)\mathbf{E}e^{-i\omega_a t} = -g_{a\gamma\gamma}\mathbf{B}a_0e^{-im_a t}, \quad (1)$$

where $\mathbf{B}$ is the applied dc magnetic field vector.

The axion-induced electric field can be dramatically amplified in media where the permittivity approaches zero. In this regime, the field in the medium E_{med} is enhanced by a factor,

$$\frac{E_{\text{med}}}{E_{\text{vac}}} = \frac{1}{|\epsilon|}, \quad (2)$$

where $E_{\text{vac}} = g_{a\gamma\gamma}|\mathbf{B}|a_0$ is the axion-induced field in vacuum [15]. Thus, minimizing $|\epsilon|$ produces a large electromagnetic response to the axion; see Sec. I B in SM [28]. This enhancement is central to the SQUIRE concept: by engineering a tunable ENZ resonance in a semiconductor magnetoplasma, the signal can be resonantly boosted and efficiently measured by a photodetector.

Boost factor—Whereas the homogeneous electric field in an infinite medium is enhanced by a factor of $1/|\epsilon|$, the boost factor is somewhat reduced when considering the propagating radiation emitted from a finite volume in a real experiment. The SQUIRE design uses an anisotropic magnetoplasmonic cavity at an angle θ relative to the applied magnetic field to generate a tunable ENZ mode in one of the two chiral permittivity components. Following similar steps as Ref. [15], the boost factor β in the radiated field from such a cavity is

$$\beta(\omega, \theta) = \left| -\frac{(1 - \epsilon) \sin(\Delta/2)}{\epsilon \sin(\Delta/2) + i\sqrt{\epsilon} \cos(\Delta/2)} \right| \frac{\sin \theta}{\sqrt{2}}, \quad (3)$$

where $\Delta = 2\pi D/\lambda_{\text{med}}$ is the phase depth of a cavity with thickness D , $\lambda_{\text{med}} = \lambda_{\text{vac}}/n_{\text{med}}$ is the in-medium wavelength, $n_{\text{med}} = \sqrt{\epsilon}$ is the complex refractive index, and $\lambda_{\text{vac}} = 2\pi c/\omega$ is the vacuum wavelength.

The boost factor is now maximized at a finite real part of the permittivity ϵ' (still ENZ). For negligible $\text{Im}[\Delta]$, resonant enhancement occurs when $\text{Re}[\Delta] \approx M\pi$, where M is an odd integer, and the boost factor on resonance is $(1 - \epsilon) \sin \theta / \sqrt{2}\epsilon$. The boost factor is modified with the addition of a mirror to redirect the radiation from both sides of the magnetoplasmonic cavity toward the photodetector. See Secs. I D and I E in SM [28] for the derivation of the boost factors [28]. A critical parameter governing the enhancement is the loss, which is proportional to the imaginary part of the permittivity, ϵ'' . High loss broadens and suppresses the resonance, significantly reducing β and the detectable signal, illustrated in Fig. 2. SQUIRE must be designed with optimized material parameters to achieve low-loss, high-boost performance in the ENZ regime.

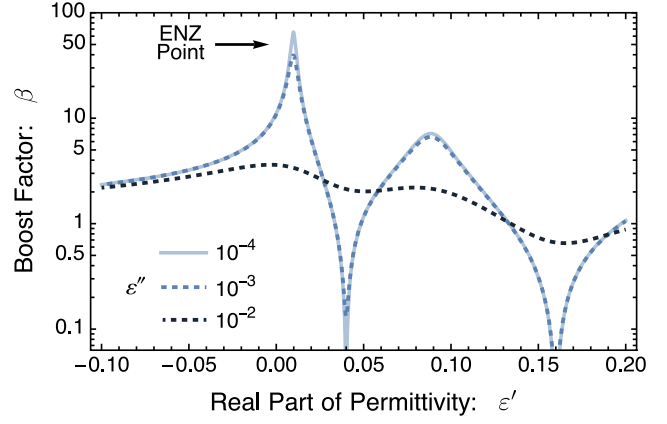


FIG. 2. The boost factor β , given by Eq. (3), from a plasmonic cavity with a fixed thickness $D = 5\lambda_{\text{vac}}$ as a function of the complex permittivity $\epsilon = \epsilon' + i\epsilon''$, evaluated at $\theta = 90^\circ$. The resonant boost factor occurs at the ENZ point, and decreasing loss (or equivalently ϵ'') maximizes the achievable boost, which can be quite large.

MQW—The SQUIRE detector concept exploits well-characterized engineered MQWs, such as a GaAs/AlGaAs system with ultrahigh mobility formed from molecular beam epitaxy (MBE), a well-developed and high-quality fabrication method, to create a magnetoplasmonic cavity with sharp, tunable ENZ response at the frequency of interest. Each quantum well consists of a thin layer of a doped degenerate semiconductor (thickness d_{QW}) separated by thicker insulating dielectric barrier layers (thickness d_{Barrier}), forming periodic 2DEGs with characteristic electron surface density n_e and scattering time τ that is directly proportional to the material's intrinsic mobility $\mu_e = e\tau/m^*$, both determined by currently achievable values in high-quality (ultrahigh-mobility) systems. n_e is set by an atomically thin silicon doping layer providing electrons to the nearby quantum well, while τ is governed by impurities (which are on the order 10^{13} cm^{-3} in high-quality samples) and thermal phonons [29]. Cryogenic temperatures ($T = 0.3 \text{ K}$) are necessary to ensure negligible thermal noise as well as long scattering times, which results in lower loss and a stronger, sharper resonance. The collective electronic response of a 2DEG, which can occur on timescales faster than the axion coherence time [30], may be described by the Drude model, from which a frequency and magnetic field dependent electric permittivity tensor may be obtained [31,32]. When subjected to an external magnetic field $\mathbf{B}$, cyclotron resonance allows for multiple polarized ENZ points in the permittivity tensor ϵ within the relevant axion mass window.

The key tuning parameter is the cyclotron frequency, $\omega_c = eB_{\perp}/m^*$, where $B_{\perp} = |\mathbf{B}| \cos \theta$ is the magnetic field component normal to the quantum well surface, e is the electron charge, and m^* is the effective electron mass [33]. The independent chiral components of the permittivity

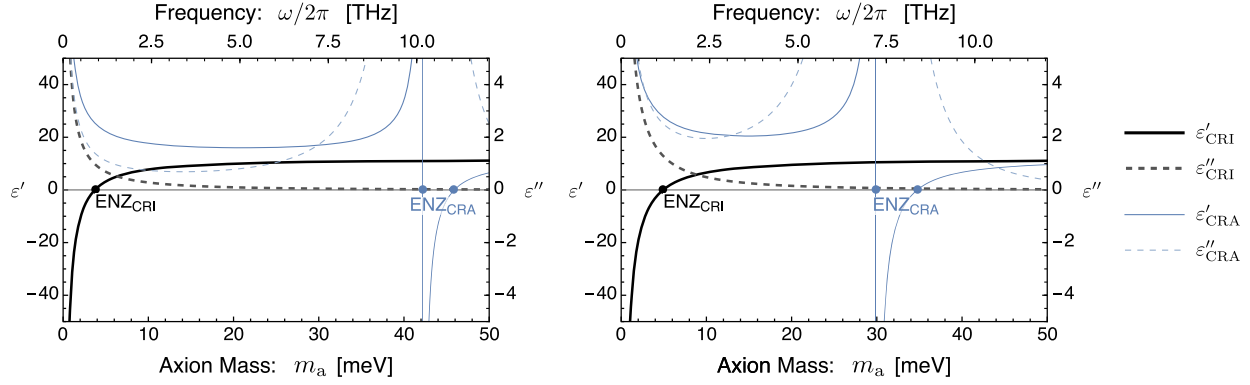


FIG. 3. The CRI and CRA permittivity components in a single GaAs-AlGaAs quantum well as a function of electromagnetic frequency for two magnetic fields are plotted. We plot the real and imaginary parts, $\epsilon = \epsilon' + i\epsilon''$, evaluated at $\mathbf{k} = \mathbf{0}$ and $\omega = m_a$. We take the SQUARE Config. 2's material parameters, with magnetic field $|\mathbf{B}_{\text{ext}}| = 36$ T orientated at angle $\theta = 45^\circ$ (left) and $\theta = 60^\circ$ (right) from the 2DEG's surface normal. A larger angle and normal magnetic field $B_\perp$ shifts the CRI's ENZ point to higher frequency and vice versa for CRA.

tensor, cyclotron resonance inactive (CRI) and cyclotron resonance active (CRA), are normal to the stacking direction and respond uniquely to $B_\perp$. Typically, the CRI component is most relevant for detection as it exhibits a sharper ENZ resonance with minimal loss, while the CRA mode is strongly damped by absorption represented by a large imaginary permittivity near resonance. The CRI permittivity in the quantum well is given by [34,35] (see Sec. I C in SM [28])

$$\epsilon_{\text{CRI}} = \epsilon_{\text{bg}} + \frac{in_e e^2 \tau}{m^* \omega d_{\text{QW}} [1 - i(\omega + \omega_c) \tau]}, \quad (4)$$

where ϵ_{bg} is the dielectric constant of the doped semiconductor—for example, GaAs [36]. As the cyclotron resonance frequency ω_c increases as the result of an increasing $B_\perp$, the ENZ point will shift toward lower frequencies and the signal will resonate at lower axion masses, leading to the unique scaling $B_\perp \propto 1/m_a$, where $m_a = \omega$ when $\omega \ll \omega_c$, $\omega \ll \sigma_0$, and $1 \ll \omega_c \tau$. See Fig. 3 for the complex permittivity tensor and ENZ points for a single GaAs-AlGaAs quantum well as a function of frequency at two different magnetic fields.

From effective medium theory (EMT) under the Maxwell-Garnett approximation [37–40], the overall permittivity components normal to the stacking direction ($\epsilon_{\text{eff,CRI}}$ and $\epsilon_{\text{eff,CRA}}$) are the weighted average of the quantum well and barrier layers, ϵ_{QW} (either ϵ_{CRI} or ϵ_{CRA}) and $\epsilon_{\text{Barrier}}$, the isotropic dielectric constant of the barrier, e.g., AlGaAs [41,42],

$$\epsilon_{\text{eff,CRI}} = \frac{\epsilon_{\text{Barrier}} d_{\text{Barrier}} + \epsilon_{\text{CRI}} d_{\text{QW}}}{d_{\text{Barrier}} + d_{\text{QW}}}. \quad (5)$$

EMT is valid when individual layer thicknesses are small compared to in-medium electromagnetic wavelengths (see End Matter) and the doped semiconductor layers remain

2DEGs [43,44]. Equation (5) substitutes the permittivity in Eq. (3) to calculate signal boost. To achieve effective ENZ, the quantum well's permittivity must approach a large negative value to compensate for the thicker barrier's positive permittivity. THz ENZ has been observed in MQWs [35]. All parameters in the boost $\beta(\omega, \theta)$ are fixed, except for the magnetic field orientation angle θ and the axion or photon frequency ω . The signal enhancement is maximized at optimal configurations of the two variables, giving a continuum of ENZ points. The tuning of the ENZ point across a range of frequencies is achieved *in situ* by simply tilting the orientation of the plasmonic cavity relative to the magnetic field. Because of electron confinement in a 2DEG or MQW, only the normal component $B_\perp$ controls the cyclotron resonance and is responsible for tuning the ENZ and parallel permittivity components. From Eq. (1), this means that the parallel component $B_\parallel$ is mainly responsible for and directly proportional to the boosted axion-induced current and can theoretically be as large as possible at each resonance frequency in order to maximize the signal. The independent control in tuning and signal enhancement with two magnetic field components allows the SQUARE to rapidly scan across axion masses efficiently in the meV regime without complex mechanical movement or structural modification as in the Magnetized Disk and Mirror Axion Experiment (MADMAX) [15,16] nor be constrained in frequency range by the strength of the magnetic field responsible for axion-photon conversion as in TOpological Resonant Axion Detection (TOORAD) [22–25].

The MQW approach is further enabled by advances in material growth and thick wafer-scale fabrication, which now allow for high-purity, low-loss structures with engineered electron densities and barrier configurations [45–52]. For the frequency range of interest, the MQW structure behaves as a plasmonic cavity with highly tunable resonance and low dissipation, verified both analytically and numerically; see simulation details in SM [28]. The optimization

of the boost and resonance quality, and chosen material parameters, is central to achieving the projected SQUIRE sensitivity.

Design modularity—We demonstrate the prospect of a conventional MQW forming a single magnetoplasmonic cavity to radiate photons in the presence of an axion field, tunable simply with the background magnetic field. Multiple MQWs in series with optimal spacing may also be designed for an enhanced coherent signal strength, as described in MADMAX [15,16]. Additionally, more complex optimization of the structural design can be accomplished with machine learning, especially if the MQWs require thousands of layers, each fabricated with unique thickness, doping and electro-optical properties to enhance the axion-induced signal [53,54]. The unique adaptability of the SQUIRE provides the advantage for labs with varying growth capabilities to target new mass ranges by designing their own MQWs using GaAs/AlGaAs, InGaAs/InP, GaN/AlGaN, or other magnetoplasmonic systems based on material availability and optimize structural parameters based on magnetic field limitations and desired axion targets. For example, smaller-scale MQWs with fewer layers can target shorter wavelengths, and lower magnetic fields are typically sensitive to higher axion masses.

Example SQUIRE—We consider three example configurations to specifically target the ~ 1 meV mass range, which correspond to currently available components for Config. 1 or high mass (HM) targeting 2–5 meV masses, near-future improvements for Config. 2 or low mass (LM) targeting 0.6–2 meV masses with thicker MQW cavities and more efficient photodetectors, and more ambitious, longer-term advances for Config. 3 or low mass sensitive (LM-S) also targeting 0.6–2 meV masses with even thicker, larger, and high-quality MQWs, more sensitive photodetectors, and stronger magnets, achievable with anticipated technological advances in the next decade. Key parameters are accessible in Table I; see more details in Sec. III in SM [28].

MQW structure and geometry—The square-shaped MQW heterostructure may be fabricated by MBE or similar growth processes. The total thickness D and width W set the plasmonic volume: larger areas linearly enhance the signal power, while the total layer thickness is optimized for ENZ resonance in the desired axion mass range. See Sec. II C in SM [28] for effects of finite area on boost factor and Sec. II D in SM [28] for effects of finite area under an axion field with finite axion coherence length [28]. The axion field is modeled using Ref. [55]. Each example MQW configuration uses a GaAs/AlGaAs system and fixes $d_{\text{QW}} = 30$ nm and $n_e = 3 \times 10^{11} \text{ cm}^{-2}$, while discretely varying D , W , and τ according to technological feasibility, and optimizing d_{Barrier} to 90 nm for Configs. 1 and 3 and 150 nm for Config. 2. Standard fabrication of MQWs (in MBE) yields up to $W = 5$ cm, used in Config. 3, while a

TABLE I. Summary of parameters for three example benchmark SQUIRE configurations: HM (high mass), LM (low mass), and LM-S (low mass sensitive). For all example scenarios, the temperature $T = 0.3$ K, electron density $n_e = 3 \times 10^{11} \text{ cm}^{-2}$, quantum well width $d_{\text{QW}} = 30$ nm, and total observation time $t_{\text{tot}} = 300$ d. As MQW cavities get larger and scattering times increase, larger signal boosts are possible at lower frequencies and sharper resonances result in shorter integration times.

Parameter	Config. 1 (HM)	Config. 2 (LM)	Config. 3 (LM-S)
D [mm]	2	10	20
W [cm]	3	3	5
d_{Barrier} [nm]	90	150	90
B [T]	36	36	50
τ [ns]	1.7	1.7	4
Γ_{dark} [mHz]	1	1	0.1
η [%]	7	20	35
t_{obs} [min]	84	34	7

more conservative value of $W = 3$ cm is used for Configs. 1 and 2, to fit in the small sample space of currently available magnets. Configuration 1 utilizes a $D = 2$ mm thick MQW and targets the 2–5 meV axion mass range. Configurations 2 and 3 use thicker MQWs with $D = 10$ and $D = 20$ mm, respectively, allowing for smaller permittivities and larger signal boosts at lower frequencies, i.e., 0.6–2 meV mass range. Configurations 1 and 2 utilize experimentally obtained values for mobility ($\mu_e = 44 \times 10^6 \text{ cm}^2/\text{Vs}$ [47]), corresponding to $\tau = 1.7$ ns for a GaAs 2DEG (for which $m^* \approx 0.067m_e$, where m_e is the electron mass), while Config. 3 uses theoretically achievable values [48,56], $\mu_e = 100 \times 10^6 \text{ cm}^2/\text{Vs}$ or $\tau = 4$ ns, for lower loss and better sensitivity. See Sec. II F in SM [28] for the effects of expected electron density nonuniformity in the 2DEGs [29,57–60] on the boost factor [28].

Magnetic field—A strong uniform dc magnetic field B is crucial both for maximizing axion-photon conversion and for tuning the ENZ resonance. A key requirement for the SQUIRE is magnetic field homogeneity across the plasmonic cavity. The ENZ point typically exhibits sharp resonance, depending on the material quality, making the signal highly sensitive to variations in B . Inhomogeneities of even a hundred ppm across the sample can broaden or shift the resonance, reducing the effective signal and degrading sensitivity (see Sec. II E in SM [28]). To scan axion masses with zero mechanical movement, the magnet could be dynamically tuned using the current, with a fixed sample orientation, or using vector magnets [61], but this may sacrifice the sensitivity at higher masses, which would require decreasing the entire magnetic field strength for tuning and neglects the available strength in the magnetic field for axion-photon production instead. The SQUIRE example configurations assume a rotatable sample stage in

a fixed high-field magnet, allowing the sample to tilt such that $B_{\perp}$ and $B_{\parallel}$ can be adjusted for efficient mass scanning. Both Configs. 1 and 2 utilize the 36-T NMR magnet at the National High Magnetic Field Laboratory, which boasts a 1-ppm inhomogeneity over a 3-cm sample region [14], with an optional tilting probe available, while Config. 3 assumes a next-generation 5-cm, 50-T magnet to generate larger signals [62]. Future studies may be done on the use of weaker magnets and a combination of higher electron density wells ($n_e \gtrsim 10 \times 10^{11} \text{ cm}^{-2}$) and thinner barriers ($d_{\text{Barrier}} \lesssim 60 \text{ nm}$) to target the same mass range, albeit weaker sensitivity.

Operation and scanning—Mass scanning can be easily performed by varying the angle θ between the surface normal of the magnetoplasmonic cavity and the magnetic field, thereby shifting the ENZ point and resonance frequency to optimize the boost. The overall maximum boost for each example configuration is $\beta_{\text{max}} = 70, 115$, and 390, which occur at masses $m_a = 5.0, 1.6$, and 1.1 meV, corresponding to angles $\theta = 86^\circ, 72^\circ$, and 60° , respectively. The scan rate is determined by the full-width-half-maximum or quality factor Q of the boost factor as a function of frequency at a fixed angle. Several axion masses within a frequency band can be searched simultaneously when the detector's minimum resonance width, set by the maximum quality factor, which is $Q_{\text{max}} = 6 \times 10^3, 1 \times 10^4$, and 5×10^4 for the example configurations, respectively, is wider than the cold DM axion linewidth, which has quality factor $\mathcal{O}(10^6)$ [4]. With optimized MQW geometry and magnetic field control, the experiment can efficiently scan large regions of parameter space in a practical runtime, for total measurement scan time t_{tot} and integration time per resonance frequency t_{obs} (see more details on scanning in Sec. I F in SM [28]). The scan protocol can be adapted to prioritize regions of greatest theoretical or experimental interest. The experiment can be dynamically calibrated using ellipsometry or similar reflection or transmission spectroscopy measurement to account for drifts and shifted resonances as well as boost and quality factors [63,64].

Lens and photodetector—Signal photons emitted from the magnetoplasmonic cavity are focused with ideal efficiency simply set to 100%, as parabolic mirrors or metalens can reach focus efficiencies above 90% realistically [65–69]. The photons are then measured with a THz photodetector, whose dark count and quantum efficiency directly set the experiment's sensitivity. Quantum dot detectors offer state-of-the-art quantum efficiency η and low dark count rates Γ_{dark} in the $\sim \mathcal{O}(1)$ meV range [70–74]. Configurations 1 and 2 assume $\eta \sim 0.07$ (shown experimentally) and $\eta \sim 0.2$ (with better antenna coupler), respectively, both with $\Gamma_{\text{dark}} \sim 1 \text{ mHz}$ [72], while Config. 3 assumes $\eta \sim 0.35$ (shown experimentally for higher frequencies) [75], with $\Gamma_{\text{dark}} \sim 0.1 \text{ mHz}$, which may be feasible in the future, as theoretically expected dark counts reach μHz for next-generation quantum dot detectors [72].

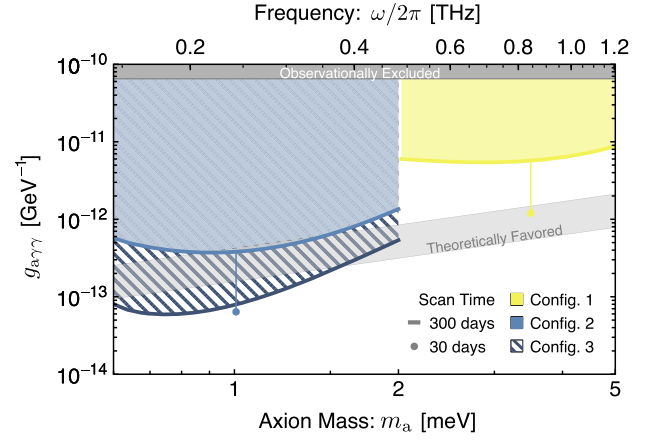


FIG. 4. Projected sensitivity of an example SQWARE to the axion mass m_a and axion-photon coupling $g_{a\gamma\gamma}$ for three configurations (in yellow, blue, and striped navy) for $t_{\text{tot}} = 300$ -d wide mass sweeps or 30-d single resonance runs, generating significant coverage of the axion parameter space beyond current experimental constraints, with CAST limits in the top gray band [4]. For optimistic configurations, theoretically favorable QCD axion models may be probed, with Dine-Fischler-Srednicki-Zhitnitsky and Kim-Shifman-Vainshtein-Zakharov benchmarks [8] in the diagonal light gray band.

Sensitivity—The projected example SQWARE sensitivity to axion DM is set by requiring a 95% confidence exclusion. In the background-dominant scenario, the expected axion signal must exceed twice the standard deviation of detector noise, approximated from Poisson statistics. The dominant noise is the photodetector's dark count rate Γ_{dark} , with other sources (e.g., thermal photons or cosmic rays) rendered negligible by sub-Kelvin operation and sufficient shielding. The minimum detectable signal rate is thus $\Gamma_{\text{signal}} > 2\sqrt{\Gamma_{\text{dark}}/t_{\text{obs}}}$, where t_{obs} is the integration time [24,76]. In background-free scenarios (e.g., with a next-generation detector with dark count less than 1 per t_{obs}), a threshold of three detected photons is required [7,27]. Assuming ideal focusing, the signal rate detected by a photodetector with quantum efficiency η , boost factor β , magnetic field $|\mathbf{B}|$, and plasmonic cavity area W^2 is $\Gamma_{\text{signal}} = \eta |\mathbf{E}|^2 W^2 / 2\omega$, where $|\mathbf{E}| = \beta g_{a\gamma\gamma} |\mathbf{B}| a_0$. The sensitivity to the axion-photon coupling in the background-dominated regime, over integration time, t_{obs} , is therefore

$$g_{a\gamma\gamma} > 5 \times 10^{-14} \text{ GeV}^{-1} \left[\frac{36 \text{ T}}{|\mathbf{B}|} \right] \left[\frac{100}{\beta(m_a)} \right] \left[\frac{20\%}{\eta} \right]^{\frac{1}{2}} \times \left[\frac{9 \text{ cm}^2}{W^2} \right]^{\frac{1}{2}} \left[\frac{\Gamma_{\text{dark}}}{1 \text{ mHz}} \right]^{\frac{1}{4}} \left[\frac{m_a}{1 \text{ meV}} \right]^{\frac{3}{2}} \left[\frac{30 \text{ d}}{t_{\text{obs}}} \right]^{\frac{1}{4}}. \quad (6)$$

The boost factor $\beta(\omega, \theta) = \beta(m_a)$ depends on the axion mass m_a implicitly through the resonance frequency $\omega = m_a$ and angle θ . A similar formula can be derived

for the background-free regime, which applies to Config. 3 for wide scans.

In Fig. 4, we show the projected sensitivity of an example SQUIRE for the three benchmark configurations provided in Table I. For narrow scans, we assume a total exposure time of $t_{\text{tot}} = 30$ d, where the detector sits at a fixed angle and resonance frequency, portrayed as narrow lines at $m_a = 1$ and 3.5 meV for Configs. 1 and 2, respectively. For wide scans, we assume a $t_{\text{tot}} = 300$ d sweep over a range of axion masses corresponding to several thousand scans, each with integration time $t_{\text{obs}} = 84, 34$, and 7 min, for the three example configurations, respectively. The conservative and realistic designs of Configs. 1 and 2 are already projected to achieve leading limits, surpassing the CERN Axion Solar Telescope (CAST) helioscope for axion masses 0.6–5 meV, and the aggressive Config. 3 can probe the favored QCD axion band at axion masses of 0.6–2 meV [4]. The SQUIRE can simultaneously probe dark photon DM, which does not require a magnetic field for photon-dark photon conversion [77,78]; see End Matter for projected sensitivities of the three configurations.

Conclusion—We have introduced the SQUIRE, a new approach for direct axion DM detection at meV masses, leveraging recent advances in quantum semiconductor heterostructures to create high-quality magnetoplasmonic cavities with ENZ response and simple tuning mechanisms. This platform offers a feasible path for experimental laboratories to design and probe the unexplored axion parameter space, including the QCD axion band, with near-term technology. Experiment design details, extended calculations, and simulations are provided in SM [28].

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of

preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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End Matter

Validation of effective medium theory—The analytical boost factor from Eq. (3) assumes an averaged or effective permittivity, given by Eq. (5), under the approximations of effective medium theory (EMT). To validate EMT for an example SQWARE, the discrete layers of GaAs quantum wells (QWs) and AlGaAs barriers, with permittivities ϵ_{QW} and $\epsilon_{\text{Barrier}}$ respectively, are simulated in a 1D COMSOL simulation, (see Sec. II A in SM [28] for details, including how the axion field can be modeled following MADMAX’s technique [79]). The numerically solved electric field enhancement is compared with the analytical expression of boost factor as a function of the effective permittivity. The two individual layer thicknesses d_{QW} and d_{Barrier} are varied for two cases, while the total thickness D and the ratio between the two are kept constant. The imaginary part of the permittivity ϵ''_{QW} is fixed while the real part ϵ'_{QW} is tuned to locate the maximum boost.

As shown in Fig. 5, the analytical boost factor in Eq. (3) closely matches the results when individual layers are much thinner than the in-medium wavelength, confirming the validity of EMT. For thicker layers, EMT breaks down, but the maximum achievable boost and shape of the boost factor vs permittivity curves are maintained (realized at a more negative real part of the permittivity), further illustrated in Sec. II B in SM [28]. For all MQW structures in the example SQWARE configurations, EMT is an excellent

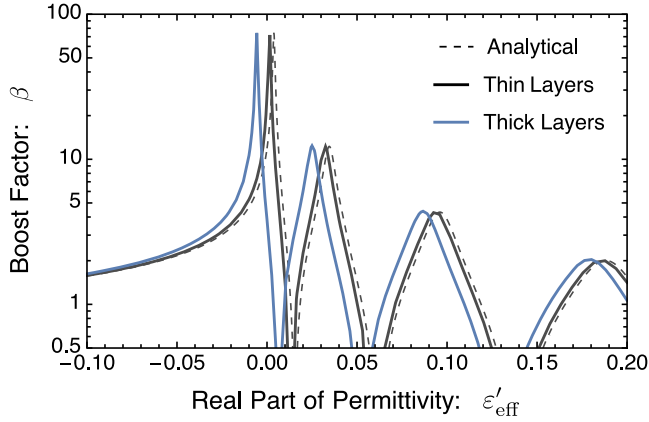


FIG. 5. Validation of EMT for an example MQW structure in COMSOL. The dashed black line shows the analytical boost factor as a function of the real part of the effective permittivity ϵ'_{eff} , while the imaginary part is ϵ''_{eff} is fixed at 2×10^{-4} , while the black and blue solid lines show numerical results for thin layers, where $d_{\text{Barrier}} = 0.0025\lambda_{\text{vac}}$ and $d_{\text{QW}} = 0.0005\lambda_{\text{vac}}$, and thicker layers where $d_{\text{Barrier}} = 0.005\lambda_{\text{vac}}$ and $d_{\text{QW}} = 0.001\lambda_{\text{vac}}$, respectively, both with total thickness $D = 1$ cm. Thinner layers emulate EMT; thicker layers break down EMT and shift the resonance toward negative permittivities, with peak boost factor preserved.

approximation, as the layer thicknesses are on the order of tens of nm, much smaller than the in-medium wavelengths on the order of hundreds of μm .

Sensitivity of SQWARE to dark photon dark matter—Dark photons may interact with ordinary electromagnetic photons through a kinetic mixing, which is parametrized by a dimensionless mixing parameter χ [77]. Unlike axion-photon conversion, dark photon-photon conversion occurs spontaneously without a magnetic field. The SQWARE, like many axion search strategies, can search for dark photon DM at the same time as it searches for axion DM [78]. As the plasmonic cavity is rotated in a magnetic field, the resonance frequency varies, scanning across DM masses. Alternatively, one could optimize the search for dark photon DM by holding the cavity fixed, with the magnetic field normal to its surface, and scan across dark photon masses by varying the field strength.

We estimate the projected sensitivity of an example SQWARE to dark photon DM following Ref. [27]. The formula for axion DM in Eq. (6) is modified with the replacements

$$g_{a\gamma\gamma} B_{\parallel} \rightarrow m_{A'} \chi, \quad (\text{B1a})$$

$$m_a \rightarrow m_{A'}, \quad (\text{B1b})$$

$$a_0 \rightarrow a_0 / \sqrt{3}, \quad (\text{B1c})$$

where $m_{A'}$ is the dark photon mass, and the factor of $\sqrt{3}$ accounts for the dark photon’s random polarization.

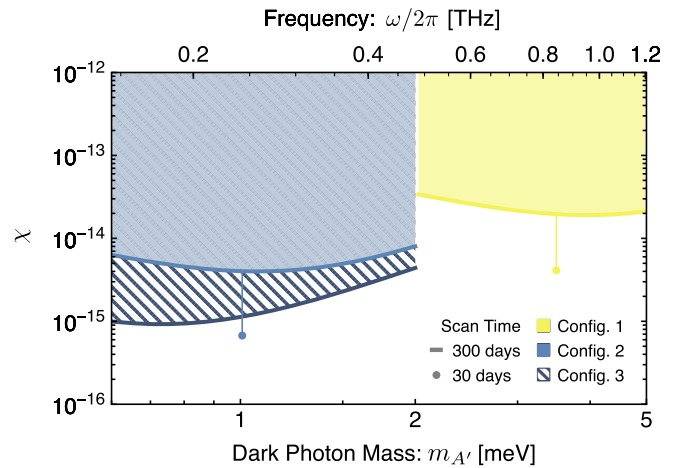


FIG. 6. Projected sensitivity of an example SQWARE to the dark photon mass $m_{A'}$ and dark photon-photon mixing χ for three configurations (in yellow, blue, and striped navy) for $t_{\text{tot}} = 300$ -d wide mass sweeps or 30-d single resonance runs.

The dark photon sensitivity is

$$\chi > 6 \times 10^{-16} \left[\frac{100}{\beta(m_{A'})} \right] \left[\frac{0.2}{\eta} \right]^{\frac{1}{2}} \times \left[\frac{9 \text{ cm}^2}{w^2} \right]^{\frac{1}{2}} \left[\frac{\Gamma_{\text{dark}}}{1 \text{ mHz}} \right]^{\frac{1}{4}} \left[\frac{m_{A'}}{1 \text{ meV}} \right]^{\frac{1}{2}} \left[\frac{30 \text{ d}}{t_{\text{obs}}} \right]^{\frac{1}{4}}. \quad (\text{B2})$$

In Fig. 6 we show the projected sensitivity of an example SQUIRE to dark photon DM for the three design configurations in Table I. By comparing data from runs optimized for axion sensitivity, the SQUIRE can place competitive limits on dark photon DM in the meV mass range simultaneously.