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(BREAD Collaboration)

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# Broadband solenoidal haloscope for terahertz axion detection

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We introduce the Broadband Reflector Experiment for Axion Detection (BREAD) conceptual design and science program. This haloscope plans to search for bosonic dark matter across the  $[10^{-3}, 1]$  eV ( $[0.24, 240]$  THz) mass range. BREAD proposes a cylindrical metal barrel to convert dark matter into photons, which a novel parabolic reflector design focuses onto a photosensor. This unique geometry enables enclosure in standard cryostats and high-field solenoids, overcoming limitations of current dish antennas. A pilot  $0.7 \text{ m}^2$  barrel experiment planned at Fermilab is projected to surpass existing dark photon coupling constraints by over a decade with one-day runtime. Axion sensitivity requires  $< 10^{-20} \text{ W}/\sqrt{\text{Hz}}$  sensor noise equivalent power with a 10 T solenoid and  $10 \text{ m}^2$  barrel. We project BREAD sensitivity for various sensor technologies and discuss future prospects.

## I. INTRODUCTION

Astrophysical evidence for dark matter (DM) is unambiguous [1–6], but its particle properties remain enigmatic. Recent efforts are expanding bosonic DM searches for  $m_{\text{DM}} \lesssim 1 \text{ eV}$  masses [7] predicted by many extensions of the Standard Model (SM) [8–14], complementing higher-mass searches [15–24]. Notably, the unobserved neutron electric dipole moment [25–28] motivates the quantum chromodynamics (QCD) axion  $a$  predicted by the Peccei–Quinn solution of the strong charge–parity problem [29–31]. Dark photons  $A'$  are also sought-after candidates arising in string theory scenarios [32–35]. These states have compelling early-universe production mechanisms and their field oscillations with frequency  $\nu = m_{\text{DM}}/2\pi$  exhibit DM properties [36–41]. Nonzero DM–photon couplings enable laboratory detection via electromagnetic (EM) effects.

The most-sensitive detection strategy today is the radio-frequency resonant-cavity haloscope [42–45], where ADMX [46–52], CAPP [53–55], HAYSTAC [56–59] probe QCD axions within  $[1.8, 24] \mu\text{eV}$  masses. However, this strategy has longstanding obstacles from (i) narrow-band tuning to unknown  $m_{\text{DM}}$  and (ii) impractical high-mass scaling for  $m_{\text{DM}} \gtrsim 40 \mu\text{eV}$ . Scan rates fall precipitously with photon frequency  $R_{\text{scan}} \sim \nu^{-14/3}$  [59] and the number of required resonators scales unfavorably with effective volume  $\sim m_{\text{DM}}^3$ . Proposed dielectric haloscopes could probe  $[40, 400] \mu\text{eV}$  [60–62] and

$[0.1, 10] \text{ eV}$  [63] masses, while topological insulators target  $[0.7, 3.5] \text{ meV}$  [64]. Significant sensitivity gaps persist across  $[10^{-4}, 1] \text{ eV}$  masses, favored by several theoretical scenarios [65–67], motivating broadband approaches.

This paper introduces the Broadband Reflector Experiment for Axion Detection (BREAD) conceptual design to search multiple decades of DM mass without tuning to  $m_{\text{DM}}$ . BREAD proposes a novel experimental design that optimally realizes dish-antenna haloscopes [68]. Its hallmark is a cylindrical metal barrel for broadband DM-to-photon conversion with a coaxial parabolic reflector that focuses signal photons onto a sensor. In contrast to existing dish antennas using spherical or flat surfaces [69–73], our geometry is optimized for enclosure in standard cryostats and compact high-field solenoids. This enhances signal-to-noise, ensures the emitting surface and magnetic field are parallel, and keeps costs practical. We delineate the optical properties of this novel geometry with detailed ray tracing and numerical simulation. While photoconversion is broadband, photosensor performance governs final discovery reach. We assess various state-of-the-art sensors and discuss the advances required in quantum sensing technology for next-generation devices to fulfill BREAD science goals with broad anticipated impact in astronomy and beyond [74].

## II. DARK MATTER SIGNAL

Sub-eV-mass bosonic DM behave as classical fields, whose coherent oscillations generate the local halo energy

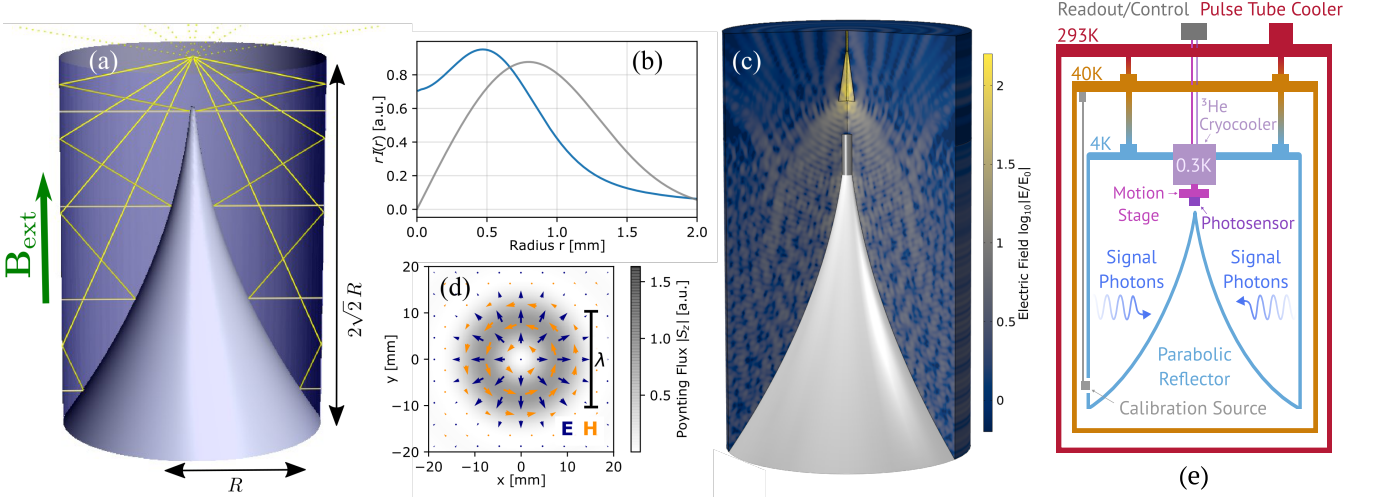


FIG. 1. (a) BREAD reflector geometry: rays (yellow lines) emitted from the cylindrical barrel, which is parallel to an external magnetic field  $\mathbf{B}_{\text{ext}}$  from a surrounding solenoid (not shown) and focused at the vertex by a parabolic surface of revolution. (b) Radial intensity distribution  $rI(r)$  expected from DM velocity effects in the  $xy$ -plane at the focal spot using ray tracing, for the BREAD geometry as in (a) with  $R = 20$  cm (blue) and for a conventional plane-parabolic mirror setup used in other experiments [69–73] with the same emitting surface area (gray). (c) Full field simulation at around 15 GHz including a preliminary coaxial horn design. (d) Electric (blue) and magnetic (orange) field distribution and time-averaged Poynting-flux along the  $z$ -direction in the  $xy$ -plane at the focal spot. (e) Schematic setup in cryostat for pilot dark photon searches.

density  $\rho_{\text{DM}}$ , which we assume to be  $0.45 \text{ GeV cm}^{-3}$  [75]. We consider scenarios where either axions or dark photons exclusively saturate the halo DM. The DM–photon interaction augments the Ampère–Maxwell equation with an effective source current  $\mathbf{J}_{\text{DM}}$  [9]

$$\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{J}_{\text{DM}}. \quad (1)$$

A nonzero  $\mathbf{J}_{\text{DM}}$  induces a small EM field that causes a discontinuity at the interface of media with different electric permittivity, such as a conducting dish in vacuum. To satisfy the  $\mathbf{E}_{\parallel} = 0$  boundary condition parallel to the dish surface, a compensating EM wave with amplitude  $|\mathbf{E}_0|$  must be emitted perpendicular to the surface. These waves transmit  $P_{\text{DM}} = \frac{1}{2} |\mathbf{E}_0|^2 A_{\text{dish}}$  of power for dish area  $A_{\text{dish}}$ . For axions with  $g_{a\gamma\gamma}$  coupling to photons, the current is  $\mathbf{J}_a = g_{a\gamma\gamma} \sqrt{2\rho_{\text{DM}}} \mathbf{B}_{\text{ext}}^{\parallel} \cos(m_a t)$  given an external magnetic field  $\mathbf{B}_{\text{ext}}^{\parallel}$  with nonzero component parallel to the plate, resulting in  $P_a = \frac{1}{2} \rho_{\text{DM}} (B_{\text{ext}}^{\parallel} g_{a\gamma\gamma} / m_a)^2 A_{\text{dish}}$  emitted power [68]. QCD axion models [76–80] relate  $g_{a\gamma\gamma}$  to the mass by  $g_{a\gamma\gamma} \sim 10^{-13} (m_a / \text{meV}) \text{ GeV}^{-1}$ , giving  $m_a$ -independent power. For dark photons with  $A'$ -SM kinetic mixing  $\kappa$  and polarization  $\hat{\mathbf{n}}$ , the current is  $\mathbf{J}_{A'} = \kappa m_{A'} \sqrt{2\rho_{\text{DM}}} \hat{\mathbf{n}} \cos(m_{A'} t)$ , yielding  $P_{A'} = \frac{1}{2} \rho_{\text{DM}} \kappa^2 A_{\text{dish}} \alpha_{\text{pol}}^2$  power. The factor  $\alpha_{\text{pol}} = \sqrt{2/3}$  averages over  $A'$  polarizations [68].  $P_{A'}$  is  $m_{A'}$ -independent and persists even when  $\mathbf{B}_{\text{ext}} = \mathbf{0}$ . Signal emission occurs independent of frequency in principle, allowing searches across several mass decades in single runs.

Practically, DM-detection sensitivity also depends on the signal emission-to-detection efficiency  $\epsilon_s$ , photosensor noise equivalent power (NEP), and runtime  $\Delta t$ . NEP is

defined as the incident signal power required to achieve unit signal-to-noise ratio (SNR) in a one Hertz bandwidth. We estimate sensitivity to  $g_{a\gamma\gamma}$  and  $\kappa$  (squared) as the SNR exceeding five  $\text{SNR} = (\epsilon_s P_{\text{DM}} \sqrt{\Delta t}) / \text{NEP} > 5$ , where we assume sensors have sufficiently-fast readout bandwidth  $\mathcal{O}(100 \text{ kHz})$ :

$$\left\{ \left( \frac{g_{a\gamma\gamma}}{10^{-11}} \right)^2 \right\} = \left\{ \frac{1.9}{\text{GeV}^2} \left( \frac{m_a}{\text{meV}} \frac{10 \text{ T}}{B_{\text{ext}}} \right)^2 \right\} \frac{10 \text{ m}^2}{A_{\text{dish}}} \left( \frac{\text{hour}}{\Delta t} \right)^{1/2} \times \frac{\text{SNR } 0.5}{5} \frac{\text{NEP}}{\epsilon_s} \frac{0.45 \text{ GeV/cm}^3}{\rho_{\text{DM}}} \frac{1}{10^{-21} \text{ W}/\sqrt{\text{Hz}}}. \quad (2)$$

At high masses, shot noise is relevant due to insufficient signal photons  $N_{\text{signal}} = (\epsilon_s P_{\text{DM}} \Delta t) / m_{\text{DM}} < 5$ . For the nominal  $A_{\text{dish}} = 10 \text{ m}^2$ ,  $B_{\text{ext}} = 10 \text{ T}$  configuration, QCD axions induce a few 1 eV photons  $\text{week}^{-1}$  so month-long runtimes render shot noise subdominant for  $m_{\text{DM}} \lesssim 1 \text{ eV}$ .

In photon-counting regimes, sensors with dark count rate DCR detect photons emitted at rate  $R_{\text{DM}} = P_{\text{DM}} / m_{\text{DM}}$ . We use the counting-statistics significance  $Z = N_{\text{signal}} / \sqrt{N_{\text{noise}}} = (\epsilon_s R_{\text{DM}} \Delta t) / \sqrt{\text{DCR} \Delta t} > 5$  to estimate sensitivity in the background-limited regime. In the background-free photon-counting limit, the coupling sensitivity scales faster  $g_{a\gamma\gamma}^{\text{sens}} \propto (\Delta t)^{-1/2}$ . With nominal photoconversion rates down to 1 photon per day, scaling as  $R_{\gamma} \approx 10^{-5} (1 \text{ eV}/m_a) \text{ Hz}$ , the photosensors considered are background limited. We thus constrain our projections to this scenario, where appendix ?? discusses requirements of background-free experiments.

### III. COAXIAL HALOSCOPE DESIGN

BREAD proposes a cylindrical barrel as the emitting surface and a novel reflector geometry comprising a coaxial parabolic surface of rotation around its tangent. This focuses the emitted radiation to a photosensor located on-axis at the parabola's vertex as shown in Fig. 1 (a). DM-to-photon conversion also occurs at the parabolic surface but is not focused on the vertex. For a barrel with radius  $R$  and length  $L = 2\sqrt{2}R$ , the effective emitting area is  $A_{\text{dish}} = 2\pi RL$ . This aspect ratio suits enclosure in conventional high-field solenoid magnets and ensures  $\mathbf{B}_{\text{ext}}$  is parallel to the emitting surface. Such magnets are widely used in basic or applied applications with fields reaching 10 T or higher [81, 82].

While photoconversion occurs regardless of  $m_{\text{DM}}$ , sensitivity is limited at high (low) masses by focusing (diffraction) effects. Both effects broaden the focal spot and reduce the geometric signal efficiency due to finite photosensor size. In the high-mass limit  $\lambda_{\text{dB}} \ll R$ , DM-to-photon conversion occurs incoherently as the DM de Broglie wavelength  $\lambda_{\text{dB}}$  is smaller than the radius of the barrel  $R \sim 1$  m. Here, the DM-halo velocity  $v \simeq 10^{-3}$  smears out the focal spot size [83–85] on length scales larger than the signal-photon wavelength  $\lambda_{\text{sig}}$ , rendering diffraction effects negligible. The blue line in Fig. 1 (b) shows the expected intensity distribution at the focal spot for the most conservative case where the DM wind points along the least favorable direction. The gray line refers to a planar conversion surface of the same area comparable to other dish-antenna experiments [69–73] with an on-axis parabolic mirror at 1 m distance. Since rays impinge the focal plane from a larger solid angle, BREAD achieves improved focusing.

In the opposite low-mass limit  $\lambda_{\text{dB}} \gg R$ , such defocusing effects are negligible and the signal can be detected coherently. Figure 1 (c) shows the result of a COMSOL simulation at around 15 GHz. Here the full modified Maxwell wave equation is solved to verify that there are no spurious sources or resonances excited that may interfere destructively with the signal. Figure 1 (d) shows the diffraction-limited electromagnetic fields at the focal plane. The electric field polarized along the radial direction can be picked up by coaxial horn antennas [86, 87]. Receiver designs based on microwave and submillimeter astronomy projects could be considered for signal collection. Proof-of-principle pilot experiments near both these limits are in preparation. The radio-frequency pilot targeting 10s of GHz masses, called GigaBREAD, will be detailed in future work.

Figure 1 (e) shows the proposed experimental design for the pilot  $A'$  search at infrared (IR) frequencies, called InfraBREAD. Cooling the conducting surfaces to 4 K suppresses thermal noise and we identified a large cryostat at Fermilab built to test ADMX resonators, which will be available in 2022. The barrel is constructed from aluminum with  $A_{\text{dish}} = 0.7 \text{ m}^2$  ( $10 \text{ m}^2$ ) for the pilot (upgrade). A 4 K blackbody with  $0.7 \text{ m}^2$  area and unit emis-

sivity emits  $\sim 10^{-8}$  W of power above 1 THz (4 meV). Simulation shows that thermal radiation is evenly distributed across the focal plane and so suppressed by  $A_{\text{sens}}/A_{\text{dish}} \sim 10^{-6}$  for active sensor area  $A_{\text{sens}}$ . For  $A_{\text{dish}} = 0.7 \text{ m}^2$ ,  $A_{\text{sens}} = 0.5 \times 0.5 \text{ mm}^2$  yields 50% (25%) signal efficiency  $\epsilon_s$  for optimistic (pessimistic) DM-wind alignment; see appendix ?? for further discussion. For absolute alignment of the photosensor in the reflector, we propose a piezoelectric motion stage to fine-tune the sensor position at the focus. Off focus, the signal is not enhanced. This enables in-situ noise measurements by moving the single photosensor off axis or installing a second off-axis photosensor. A monochromatic laser or bandpass-filtered blackbody source can inject photons via a small hole in the barrel for absolute calibration of the reflector–photosensor setup. A room-temperature spectrometer at UChicago is available to characterize sources and filters [88].

Various upgrades and optimizations could be implemented to improve sensitivity of the proposed experimental concept. A small secondary mirror near the focal point could guide the signal toward a low-field region where, e.g. a chopper and/or spectrometer could be installed. The optics may optimize the radiation polarization and incident angle on the photosensors. A detector array or photon imager [89] could also provide spatial resolution to correlate any observed signals with the astrophysical DM distribution. Specifically, the focal point and signal undergo diurnal and annual modulations due to the rotating DM velocity vector in the lab frame [90] and possibly  $A'$  polarization [91]. The total  $A_{\text{dish}}$  could be increased within the same available volume by combining the signals from an array of smaller BREAD-like barrels, but this increases complexity significantly. Cosmic-ray muons are a suggested noise source for photon counters [92]; in-situ vetoes at the sensor or barrel exterior, and/or underground operation are mitigation strategies. Studying these options is deferred to future work.

### IV. PHOTOSENSOR TECHNOLOGIES

The expected DM signal rates and optical geometry imply stringent photosensor requirements: broad spectral response  $\Delta E/E > 1$ , ultralow noise NEP  $< 10^{-20} \text{ W Hz}^{-1/2}$  or DCR  $< 10^{-3} \text{ Hz}$ , and millimeter-size active area. Bolometers are promising because they directly measure absorbed photon power, only the absorbing material or structures limit spectral response, and are established technology with diverse applications [93, 94]. They comprise a thermally-isolated absorbing element with low heat capacity, sensitive thermometer and weak link to a cold thermal bath. They can measure photon energies from  $10^{-5} \text{ eV}$  [95] to  $10^6 \text{ eV}$ . Bolometers are typically insensitive to static (DC) radiation due to instrumental low-frequency ( $1/f$ ) noise, so input signals must be time-modulated with e.g. a chopper that shifts the signal to a frequency where  $1/f$  noise is subdominant

TABLE I. Illustrative photosensor performance: spectral energy  $E$ , operating temperature  $T_{\text{op}}$ , active area  $A_{\text{sens}}$ . Bolometers (photocounters) report noise equivalent power NEP (dark count rate DCR).

Photosensor	$E$ meV	$T_{\text{op}}$ K	NEP $\text{W}/\sqrt{\text{Hz}}$	$A_{\text{sens}}$ $\text{mm}^2$
GENTEC [97]	[0.4, 120]	293	$1 \cdot 10^{-8}$	$\pi 2.5^2$
IR LABS [98]	[0.24, 248]	1.6	$5 \cdot 10^{-14}$	$1.5^2$
KID/TES [99, 100]	[0.2, 125]	0.3	$2 \cdot 10^{-19}$	$0.2^2$
QCDet [101, 102]	[2, 125]	0.015	$\frac{\text{DCR}}{\text{Hz}} = 4$	$0.06^2$
SNSPD [103, 104]	[124, 830]	0.3	$\frac{\text{DCR}}{\text{Hz}} = 10^{-4}$	$0.4^2$

and SNR increases  $\propto (\Delta t)^{1/2}$ .

Photon-counting devices (photocounters) are potentially more sensitive than total-power bolometry, since simple signal-processing techniques, e.g. thresholding and pulse fitting, can suppress noise. Small devices achieve nearly background-free single-photon counting at thresholds  $\gtrsim 1$  eV. For lower energies, numerous devices exploit athermal breaking of Cooper pairs, including kinetic inductance detectors (KID), superconducting nanowire single photon detectors (SNSPD), and quantum capacitance detectors (QCDet) [96].

We now discuss specific technologies motivating the values in Table I assumed for our projections. We display typical  $A_{\text{sens}}$ , but later set  $\epsilon_s = 50\%$  for simplicity assuming sensor development will enable scaling to required sizes. Room-temperature (GENTEC pyroelectric [97]) and cryogenic (IR LABS semiconducting thermistor [98]) devices exemplify commercial performance.

Superconducting titanium-gold Transition Edge Sensors (TES) [105–107] report down to  $2 \times 10^{-19} \text{ W Hz}^{-1/2}$  NEP in arrays of  $200 \times 200 \mu\text{m}^2$  pixels [99]. TESs have broad spectral response, where a molybdenum-gold device reporting  $4 \times 10^{-19} \text{ W Hz}^{-1/2}$  NEP covers 1-4  $\mu\text{m}$  to 160-960  $\mu\text{m}$  (eV to meV) [108]. Elsewhere, small 10  $\mu\text{m}$  superconducting/normal-metal junction bolometers report  $2 \times 10^{-20} \text{ W Hz}^{-1/2}$  NEP [109], which may be promising if active areas are scalable to millimeters [110].

KIDs [112–114] are thin-film resonators, whose surface inductance is sensitive to Cooper-pair-breaking photons above the band gap  $\Delta \simeq 0.2$  meV. Titanium-nitride KIDs are scalable to  $50 \times 50 \text{ mm}^2$  kilopixel arrays with  $3 \times 10^{-19} \text{ W Hz}^{-1/2}$  NEP [100], which are antenna coupled and optimized to [3.4, 12] meV [115]. For cosmic microwave background (CMB) applications ( $0.2 \lesssim E \lesssim 2$  meV), KIDs are limited by signal power rather than sensor noise at NEP  $\sim 10^{-17} \text{ W Hz}^{-1/2}$  [116], and therefore could have better performance in such frequencies than current sensors targeting CMB science. Given KID and TES devices report similar NEP in each application, we amalgamate their presentation in our projections for simplicity. We extrapolate the  $2 \times 10^{-19} \text{ W Hz}^{-1/2}$  NEP [99] into the [0.2, 125] meV range where we expect KID/TES

devices to operate bolometrically, but this will require experimental demonstration.

QCDets [117–119] recently report  $3 \times 10^{-21} \text{ W Hz}^{-1/2}$  NEP at 1.5 THz (6.2 meV) [101]. These are scalable to 441 pixel arrays and simulation indicates  $1\text{--}4 \times 10^{-20} \text{ W Hz}^{-1/2}$  NEP for [2, 125] meV [102], driven by e.g. Origins Space Telescope goals [120]. Such performance is promising, and for simplicity, we assume constant  $3 \times 10^{-21} \text{ W Hz}^{-1/2}$  NEP in our projections. We convert this to DCR = 4 Hz using NEP =  $(E/\eta)\sqrt{2 \cdot \text{DCR}}$  [121] for  $E = 6.2$  meV and optical efficiency  $\eta = 0.9$  [101].

SNSPDs [121–123] comprise sub-micron-width wires wound across thin-film substrates that count photons above an energy threshold. Superconductivity is momentarily lost upon photon absorption, leading to a measurable voltage pulse. Such devices achieve  $> 90\%$  efficiency [124] and recently, a  $400 \times 400 \mu\text{m}^2$  tungsten-silicide device reports DCR  $< 10^{-4}$  Hz for 0.8 eV threshold [103]. Using Fermilab refrigerators [125], we are preparing to test similar SNSPDs fabricated at MIT. Recent advances important for BREAD include extending up to 10  $\mu\text{m}$  (0.12 eV) [104] and developing large  $3.1 \times 3.1 \text{ mm}^2$  single pixels [126]. Continued research to lower thresholds is motivated given axions with  $m_a \lesssim 60$  meV are disfavored by supernova constraints [127].

Photocounting is also possible using KIDs [128, 129] and TESs [130–132], with the benefit of per-photon energy resolution. With e.g. 10% energy resolution determined by detector resolution, the monochromatic DM signal occupies one energy bin but noise can be spread across 10 bins, improving SNR after sufficient  $\Delta t$  up to a trials factor. Exploring this in BREAD requires more detailed resolution and noise models, which is deferred to future work.

## V. SENSITIVITY AND DISCUSSION

We project BREAD sensitivity to dark photons in Fig. 2 (left) using Eq. (2) assuming the spectral and noise benchmarks in Table I. Existing constraints following Ref. [91] (blue shading) include stellar astrophysics [133, 134], cosmology [40, 135, 136], and  $\gamma \rightarrow A'$  conversion that includes laboratory probes [137, 138]. With just 1 day runtime assuming  $A_{\text{dish}} = 0.7 \text{ m}^2$ , the gray thin line shows the BREAD pilot could surpass existing  $\kappa$  constraints by one decade around 1 meV using the commercial IR LABS sensor. The reach of BREAD is substantially broader compared with two existing dish antennas, SHUKET [139] and Tokyo [71] (dark blue). Importantly, BREAD probes higher masses than existing haloscopes ADMX [47, 48], CAPP [53–55], HAYSTAC [58, 59], transmon qubit [140], and WIS-PDMX [141], whose results are recasted for  $A'$  following Ref. [91]. Scaling to  $A_{\text{dish}} = 10 \text{ m}^2$  and using KID/TES sensors could open two decades further  $\kappa$  sensitivity, while SNSPDs could achieve three decades gain

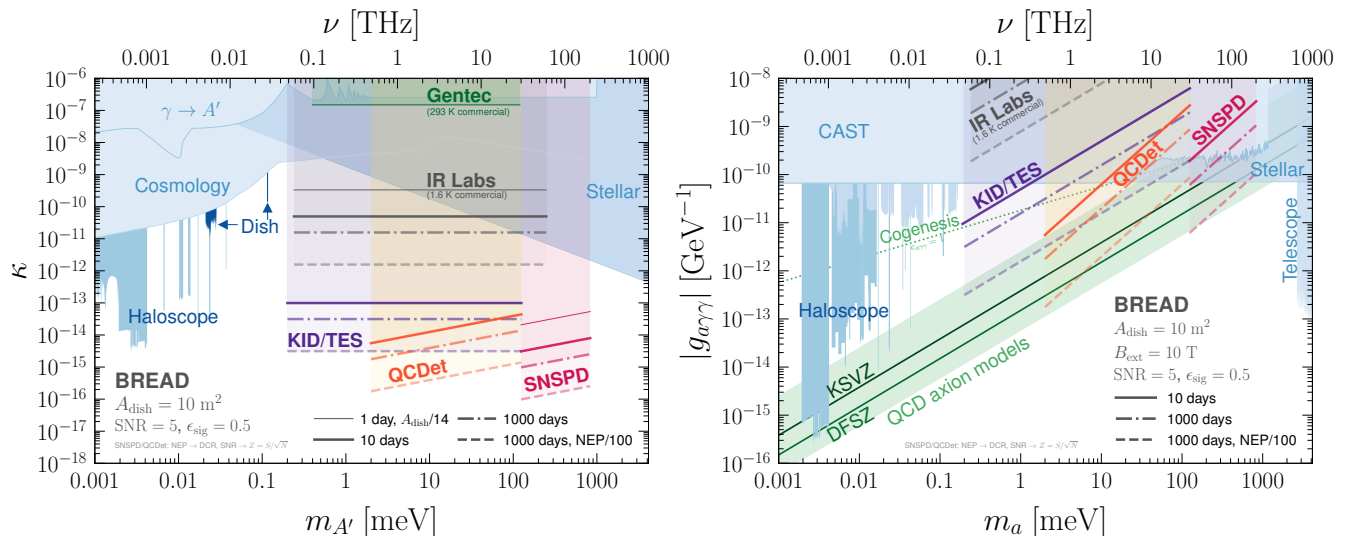


FIG. 2. Projected BREAD sensitivity by sensor technology (bold labels, see Table I) for dark photons  $A'$  (left) and axions  $a$  (right). This assumes signal-to-noise ratio  $\text{SNR} = 5$  (significance  $Z = 5$  for photocounters), signal efficiency  $\epsilon_{\text{sig}} = 0.5$ , and dish area  $A_{\text{dish}} = 10 \text{ m}^2$ . Blue shading shows existing constraints from Ref. [91]. Benchmark axion predictions include QCD axion models [111] (green band), cogenesis [67] (green dots), KSVZ [78, 79] and DFSZ [76, 77] (green lines). Sensitivity scaling assumes background-limited operation where signal-power limits scale as  $\sqrt{\Delta t}$  for runtime  $\Delta t$  and linearly with improved NEP.

for  $m_{A'} \gtrsim 0.1 \text{ eV}$ . Extending runtime to  $\Delta t = 10^3$  days enables  $\kappa$  sensitivity to reach six (four) decades beyond existing constraints for  $m_{A'} \sim 0.4$  (200) meV.

Axion sensitivity is illustrated in Fig. 2 (right). Existing constraints [91] additionally include the CAST helioscope [142, 143], telescopes [144, 145], neutron stars [146–148], alongside ORGAN [149] QUAX [150, 151] RADES [152] and URF [43–45] haloscopes. While challenging with commercial devices, 10 day runtimes using KID/TES sensors with  $\text{NEP} \sim 10^{-19} \text{ W Hz}^{-1/2}$  could surpass CAST sensitivity for  $m_a \lesssim 10 \text{ meV}$ . Longer runtimes could test cogenesis predictions for the  $c_{a\gamma\gamma} = 1$  benchmark [67]. Increasing  $A_{\text{dish}}$  ( $B_{\text{ext}}$ ) beyond  $10 \text{ m}^2$  (10 T) is financially unfavorable, requiring custom cryostats and magnets. Thus practically probing QCD axion models [111] requires longer runtime and lower sensor noise. Coupling sensitivity scales slowly with runtime  $g_{a\gamma\gamma}^{\text{sens}} \sim (\Delta t)^{-1/4}$ , i.e. halving  $g_{a\gamma\gamma}^{\text{sens}}$  requires  $16\times$  longer runtimes. For  $\Delta t = 10^3$  days, reaching KSVZ [78, 79] (DFSZ [76, 77]) demands  $1$  ( $0.2$ )  $\times 10^{-22} \text{ W Hz}^{-1/2}$  NEP. Achieving this NEP for wide spectral ranges is challenging and a key science driver for sensor development. This may be attainable above  $0.1 \text{ meV}$  for photocounters, e.g. SNSPDs, motivating dedicated measurements in preparation, and next-generation bolometers at lower masses given a recent TES-based device reports  $8 \times 10^{-22} \text{ W Hz}^{-1/2}$  electrical NEP [153]. Maintaining signal efficiency when upgrading  $A_{\text{dish}} = 0.7 \rightarrow 10 \text{ m}^2$  requires quadrupling the active sensor width. Overcoming these challenges promises significant scientific payoff given the multidecade improvements in search coverage that has long eluded cavity haloscopes. Post-discovery,

the DM signal will always persist, enabling cross checks with resonant techniques and measurements to elucidate its particle physics and astrophysical properties [70, 91].

In summary, we proposed BREAD to improve sub-eV-mass DM reach by several decades. We introduced the novel coaxial design optimized for embedding in standard solenoids and cryostats, in contrast to existing dish antennas, then detailed numerical optics simulation and examined photosensor candidates. Realizing BREAD into a cornerstone DM experiment will catalyze synergies across quantum technology and astroparticle physics.

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