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Prospects of Laboratory Searches for Physics Beyond the Standard Model with Single-Photon Detectors in RF Cavities

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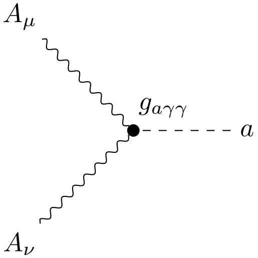
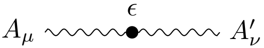
Introduction

- Dark photons (DP) and axion-like particles (ALPs) are hypothetical particles appearing in SM extensions.
- Well motivated candidates for dark matter content.
- Interaction with photons:

$$\mathcal{L}_{\mathrm{ALPs}} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}\, a^2 - \frac{g_{a\gamma\gamma}}{4}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu}.$$

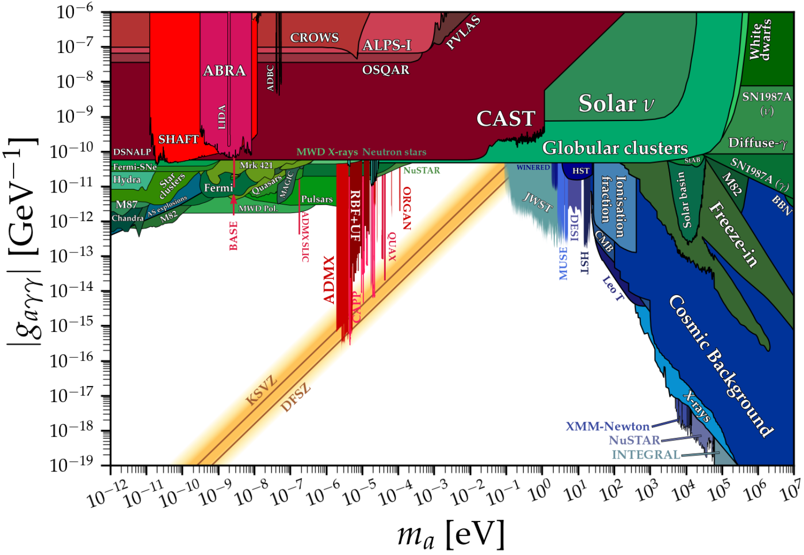


$$\mathcal{L}_{\mathrm{DP}} = -\frac{1}{4}F'^2_{\mu\nu} + \frac{m_{A'}^2}{2}A'^2_\mu - \frac{\epsilon}{2}F^{\mu\nu}F'_{\mu\nu}.$$



Current constraints on ALPs

Caputo et al., 2105.04565



Current constraints on DP

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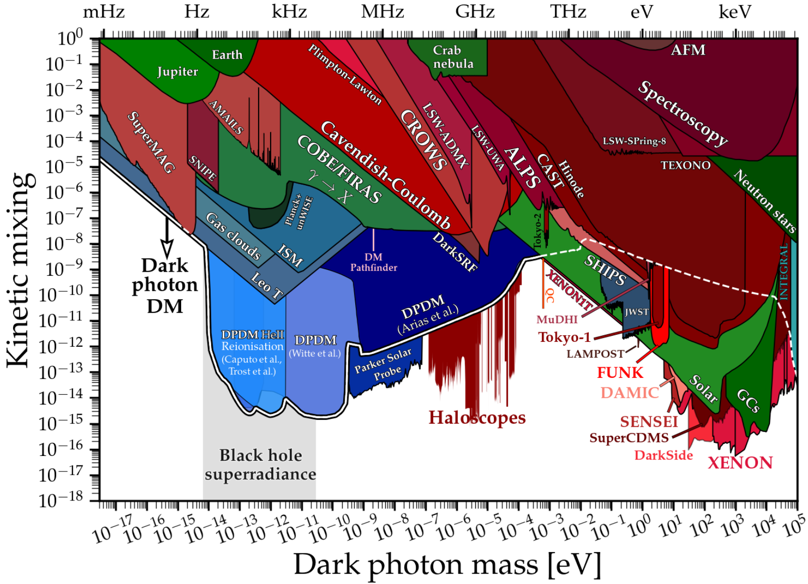
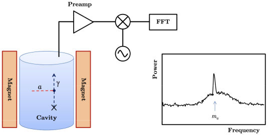
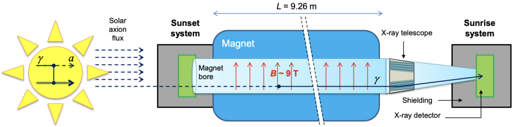
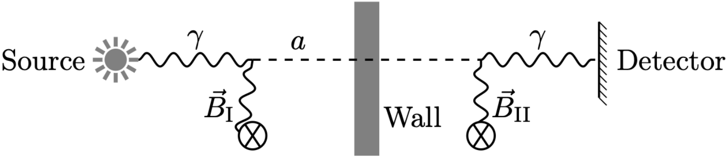


Search strategies

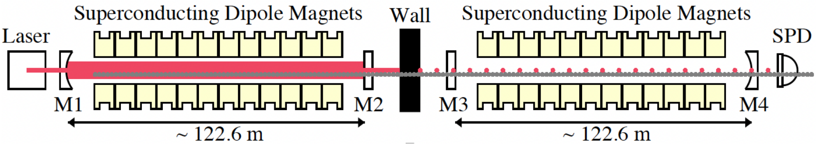
- Haloscopes target DP and ALPs as constituents of the local dark matter halo (depending on the DM fraction and ρ_{DM}).
- Helioscopes search for DP and ALPs emitted by the Sun (depending on the production model in the Sun).
- Purely laboratory-based experiments aim to produce and detect DP and ALPs within a single setup – light-shining-through-wall (LSW) (model independent).







Laser-based LSW experiment



Parameter	Value
Wavelength	(1064.5 ± 0.1) nm
Vacuum-tube length bf. wall	$L_{\mathrm{V}} = (123.00 \pm 0.01)$ m
Cavity length behind wall	$L_{\mathrm{RC}} = (122.6012 \pm 0.0001)$ m
Laser power injected	$P_{\mathrm{i}} \approx 25$ W
Cavity res. enhancement	$\beta \approx 7000$
Cavity free spectral range	FSR ≈ 1.22263 MHz
Spatial & spectral matching of HPL to the RC Eigenmode	$\lvert\eta\rvert^2 \approx 0.9$
Vacuum system gas pressure	$< 10^{-9}$ mbar

TABLE II. Parameters of the optical system. P_{i} denotes the laser power traversing the magnet string before the wall. P_{i}, β and $\lvert\eta\rvert^2$ varied during data taking (see [47]). L_{RC} is measured via the free spectral range of the cavity.

Figure 1 – Any Light Particle Search (ALPS) is a dual optical cavity enhanced light-shining-through-awall (LSW) experiment at DESY in Hamburg. ALPS-I: Phys.Lett.B689:149-155, 2010; ALPS-II: arXiv:2512.14110

RF cavity LSW experiment

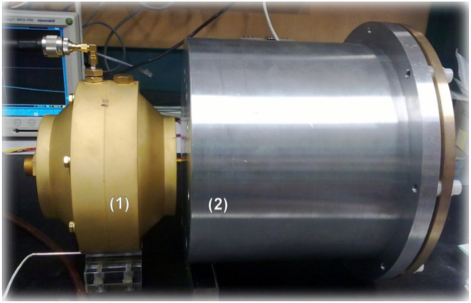


FIG. 7: Photo of emitting cavity (1) and shielding enclosure (2) containing the identical detecting cavity. For ALP search, both parts were placed in the bore of a solenoid magnet with the same arrangement as shown in the picture.

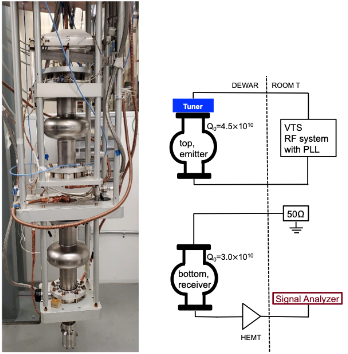
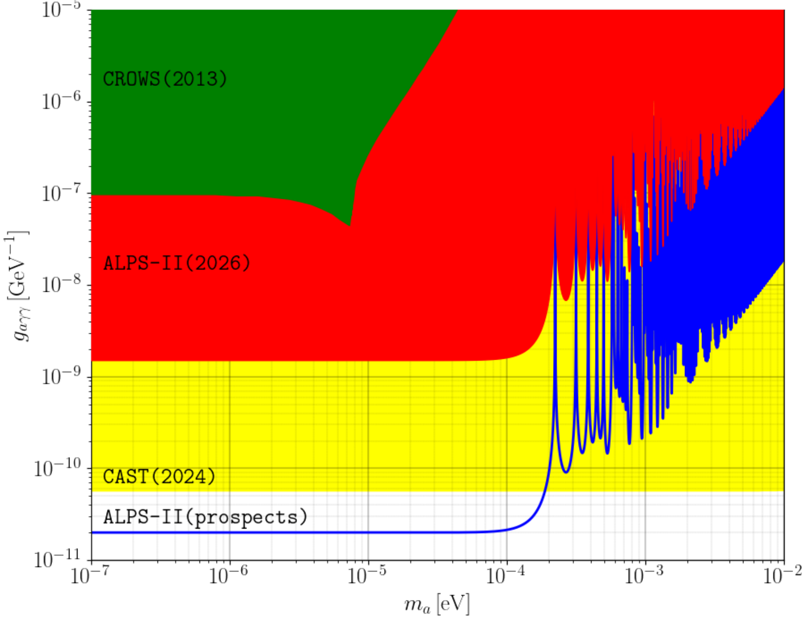


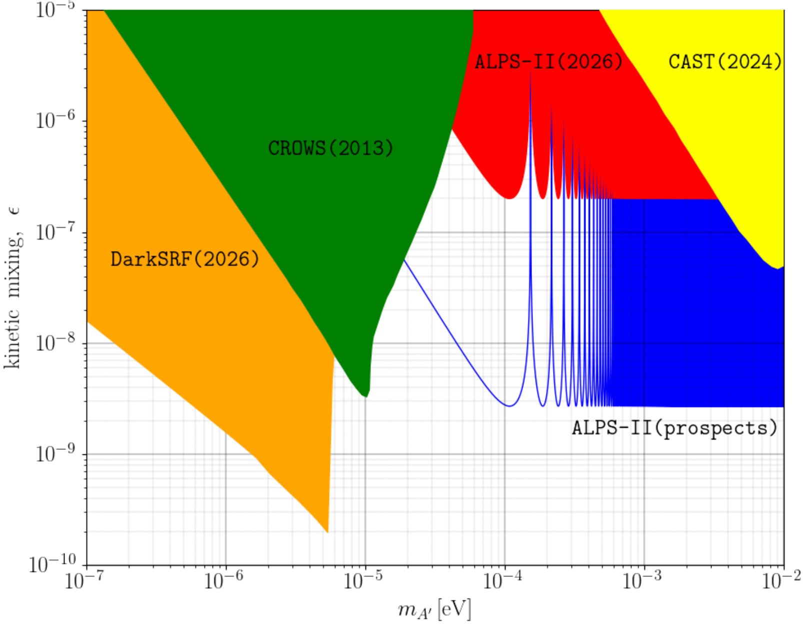
FIG. 1. Left: The experimental setup for the Dark SRF experiment consisting of two 1.3 GHz cavities. Right: A sketch of the Dark SRF electronic system.

Figure 2 – CROWS experiment at CERN, Phys.Rev.D 88 (2013). Dark SRF at Fermilab Phys. Rev. Lett. 130, 261801 (2023), Phys. Rev. Lett. 136, 111802 (2026).

Current laboratory constraints on ALPs & CAST



Current laboratory constraints on DP & CAST



Single photon detector & Linear amplifier

■ Linear amplifier (LA) and standard quantum limit (SQL)

$$\mathrm{SNR} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}}\sqrt{t\,\delta f} = \frac{P_{\mathrm{signal}}}{T_{\mathrm{eff}}}\sqrt{\frac{t}{\delta f}}, \tag{1}$$

$$T_{\mathrm{eff}} = \omega\left[\frac{1}{e^{\omega/T_{\mathrm{phys}}}-1}+1\right] \geq 50\,\mathrm{mK}\cdot\left(\frac{f}{\mathrm{GHz}}\right), \tag{2}$$

$$\delta f = \frac{f}{Q};\quad \delta f \simeq \frac{1\,\mathrm{GHz}}{10^5} \simeq 10^4\,\mathrm{Hz}; \tag{3}$$

■ Single photon detector (SPD)

$$\mathrm{SNR} \simeq \frac{N_{\mathrm{signal}}}{\sqrt{N_{\mathrm{noise}}}} = \frac{P_{\mathrm{signal}}}{\omega}\sqrt{\frac{t}{R_{\mathrm{dc}}}},\quad R_{\mathrm{dc}} \sim 10^{-2}\mathrm{Hz}. \tag{4}$$

■ Efficiency of SPD comparing to LA:

$$\frac{T_{\mathrm{eff}}}{\omega}\sqrt{\frac{\delta f}{R_{\mathrm{dc}}}} \simeq \frac{5\,\mathrm{K}}{50\,\mathrm{mK}}\sqrt{\frac{10^4\,\mathrm{Hz}}{10^{-2}\,\mathrm{Hz}}} \simeq 10^5. \tag{5}$$

Signal power

- DP

$$P_{\rm signal} = P_{\rm em} \times Q^2 V^2 \omega^2 \times \mathcal{G}^2_{\rm DP}(m_{A'}) \times \epsilon^4 m^4_{A'}, \qquad (6)$$

$$\mathcal{G}_{\rm DP} = \int\limits_{V_{\rm rec}} \frac{d^3x}{V_{\rm rec}} \int\limits_{V_{\rm em}} \frac{d^3x'}{V_{\rm em}} \, \mathcal{E}^{i*}_{\rm rec}(\vec{x}) \mathcal{E}^{j}_{\rm em}(\vec{x}') \frac{(\delta_{ij} m^2_{A'} - \partial_i \partial_j)}{\omega^2} \frac{e^{ik_{A'}|\vec{x}-\vec{x}'-\vec{l}|}}{4\pi\omega|\vec{x}-\vec{x}'-\vec{l}|}$$

$$\mathcal{G}_{\rm DP}(m_{A'}) \propto \begin{cases} m^{0\div 2}_{A'}, & m_{A'} \ll \omega; \\ m^{-(3\div 4)}_{A'} \times \exp(-m_{A'} d), & m_{A'} \gg \omega. \end{cases}$$

- ALPs

$$P_{\rm signal} = P_{\rm em} \times B^4_{\rm ext} Q^2 V^2 \omega^2 \times \mathcal{G}^2_{\rm ALPs}(m_a) \times g^4_{a\gamma\gamma}, \qquad (7)$$

$$\mathcal{G}_{\rm ALPs} = \int\limits_{V_{\rm rec}} \frac{d^3x}{V_{\rm rec}} \int\limits_{V_{\rm em}} \frac{d^3x'}{V_{\rm em}} \, \mathcal{E}^{*{\rm rec}}_{B}(\vec{x}) \mathcal{E}^{\rm em}_{B}(\vec{x}') \frac{e^{ik_a|\vec{x}-\vec{x}'-\vec{l}|}}{4\pi\omega|\vec{x}-\vec{x}'-\vec{l}|},$$

$$\mathcal{G}_{\rm ALPs}(m_a) \propto \begin{cases} \text{Const}, & m_a \ll \omega; \\ m_a^{-(3\div 4)} \times \exp(-m_a d), & m_a \gg \omega. \end{cases}$$

- Sensitivity improvement: $(10^5)^{1/4} \simeq 20$.

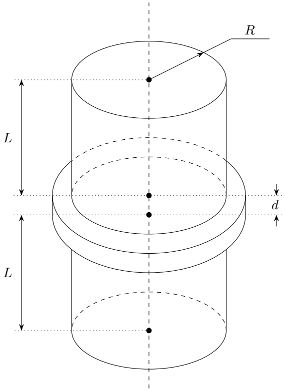
Setup parameters for sensitivity estimation

$$P_{\rm em} = 1\,{\rm kW}, \quad Q = Q_{\rm em} = Q_{\rm rec} = 10^5, \quad B_{\rm ext} = 10\,{\rm T}, \quad t = 1\,{\rm day},$$

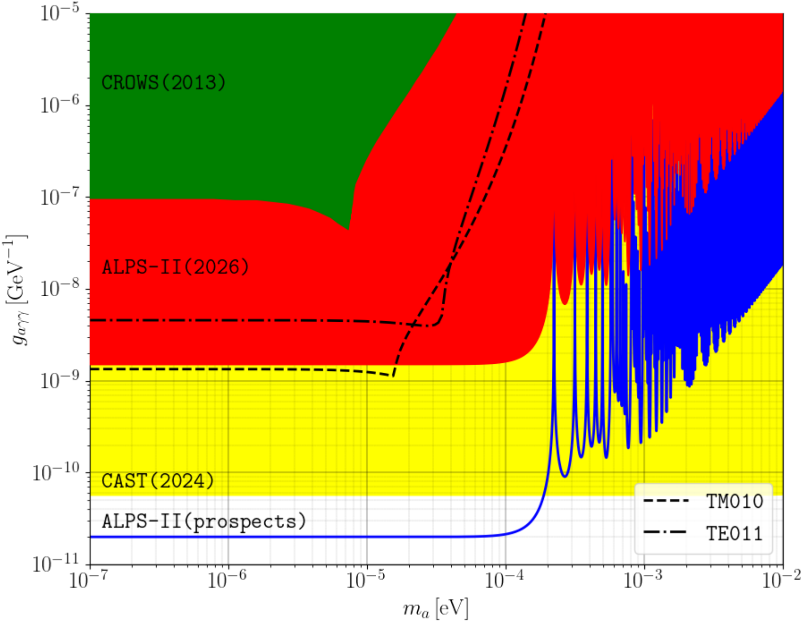
$$R = 30\,{\rm mm}, \quad L = 25\,{\rm mm}, \quad d = 10\,{\rm mm},$$

$$\mathrm{SNR} = 1.65\,(\mathrm{one\,side\,95\%\,C.L.}),$$

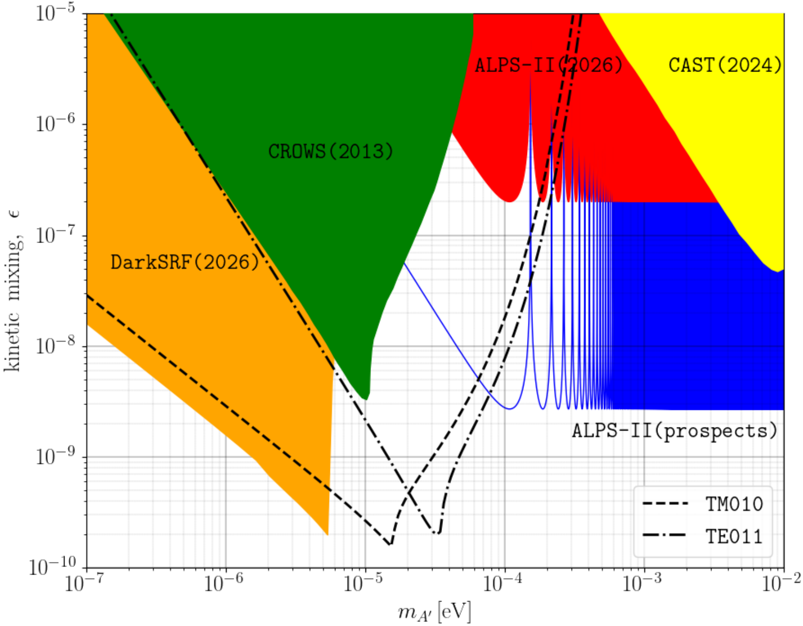
$$R_{\rm dc} = 10^{-2}\,{\rm Hz}, \quad f({\rm TM}_{010}) = 3.82\,{\rm GHz}, \quad f({\rm TE}_{011}) = 8.55\,{\rm GHz}.$$



Estimation on ALPs constraints



Estimation on DP constraints



Conclusions

- Single-photon detectors operating at frequencies of 1-10 GHz can increase sensitivity of RF cavity lsw setups by an order of magnitude comparing to linear amplifiers.
- The estimated sensitivity to ALPs merely reproduces the existing ALPS-II constraints but does not improve them significantly, therefore conducting an experiment aimed at ALPs searches is hardly justified.
- In the case of DP, an experimental setup can cover unconstrained areas and seems more motivated.

Thank you!