Pacific Northwest NATIONAL LABORATORY

PNNL-32283

# ALP Experiment Sensitivity Exploration

## Preliminary Findings

December 3, 2021

Erik W. Lentz

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
Under contract DE-AC05-76RL01830

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# 1.0 Introduction and Baseline Sensitivities

This report presents an exploration of sensitivity estimates for multiple prominent proposed techniques to search for axion-like particles (ALPs). The sensitivities are plotted over particle mass $(m_a)$ and coupling $(g_{a\gamma\gamma})$ parameter space. Explorations include variation over detector type, integration time, background cosmology, and size of the apparatus.

Let us start with an explanation of the approaches presented and their baseline sensitivities, Fig. 1.

- Helioscope: Base figures were pulled from the IAXO proposal [3, 2], using magnetic chamber of length 20 m, collecting area of 2.4 m$^2$). The coupling sensitivity on this concept is not a simple power law, but I assumed it to be for this preliminary study. Not all the structure of the collaboration projections are captured. This could be updated without too much difficulty.
- Light through Wall: Base figures were pulled from ALPSII and JURA [21], using a magnetic length of 426 m, laser light frequency of 300 THz, and laser power of 150 kW.
- Ferromagnetic Haloscope: Base figures were pulled from the QUAX proposal [5, 8], using YiG volume of 0.001 liters, and cavity Q of $10^5$. The range of this approach is limited to frequencies of 10-100 GHz.
- Cavity Haloscope: Base figures were pulled from ADMX proposals [9, 1, 10], using cavity Q of 50,000, form factor of 0.4, and cavity size set to twice Compton scale to accommodate a tuning rod. The range of this approach is limited to frequencies of 100 MHz-10 GHz.
- Current Loop Haloscope: Base figures were pulled from ABRACADABRA proposal [15, 18], with toroid radius of 0.85 m, and operating in a broadband configuration. The range of this approach is limited to frequencies of 1 kHz-100 MHz.
- Dish Antenna Haloscope: Base figures were pulled from BRASS proposal [13, 14], operating in a broadband configuration. The range of this approach is limited to frequencies of 1 GHz-1 THz.
- Dielectric Train Haloscope: Base figures were pulled from MADMAX proposal [7, 6], using 80 disks, a boost structure Q-width of 400, and root boost factor of 100. The range of this approach is limited to frequencies of 4-400 GHz.
- NMR Haloscope: Base figures were pulled from CASPEr-Electric proposal [16, 12], using a one liter polarized gas volume, $10^28$ spins per m$^3$, and Q width of 500. The range of this approach is limited to frequencies of 1 kHz-100 MHz.

The relevant operational parameters common to each approach are:

- Integration time: 1 year
- Size: one Compton length on each relevant dimension for haloscopes; the coherence scale length for helioscopes; the base design length of JURA for light-through-wall
- Detector: a heterodyne/homodyne detector is assumed for narrowband/broadband searches and is operating at the SQL (standard quantum limit). Noise bandwidth of narrowband search is set by Q-width of the axion.

- System noise temperature: the base noise temperature scales with the quantum thermal limit $\overline{h}\nu/2k_B = T$, save for the broadband helioscope and light-through-wall searches, where it is set to 4 Kelvin.
- Noise bandwidth: Set by the width of the axion signal for narrowband searches ($f_a/Q_a$), and set to the total bandwidth of the search for broadband searches.
- Axion signal width: $Q_a = 10^6$
- Dark matter density: 0.3 GeV/cc
- Magnetic fields: 10 Tesla for every search

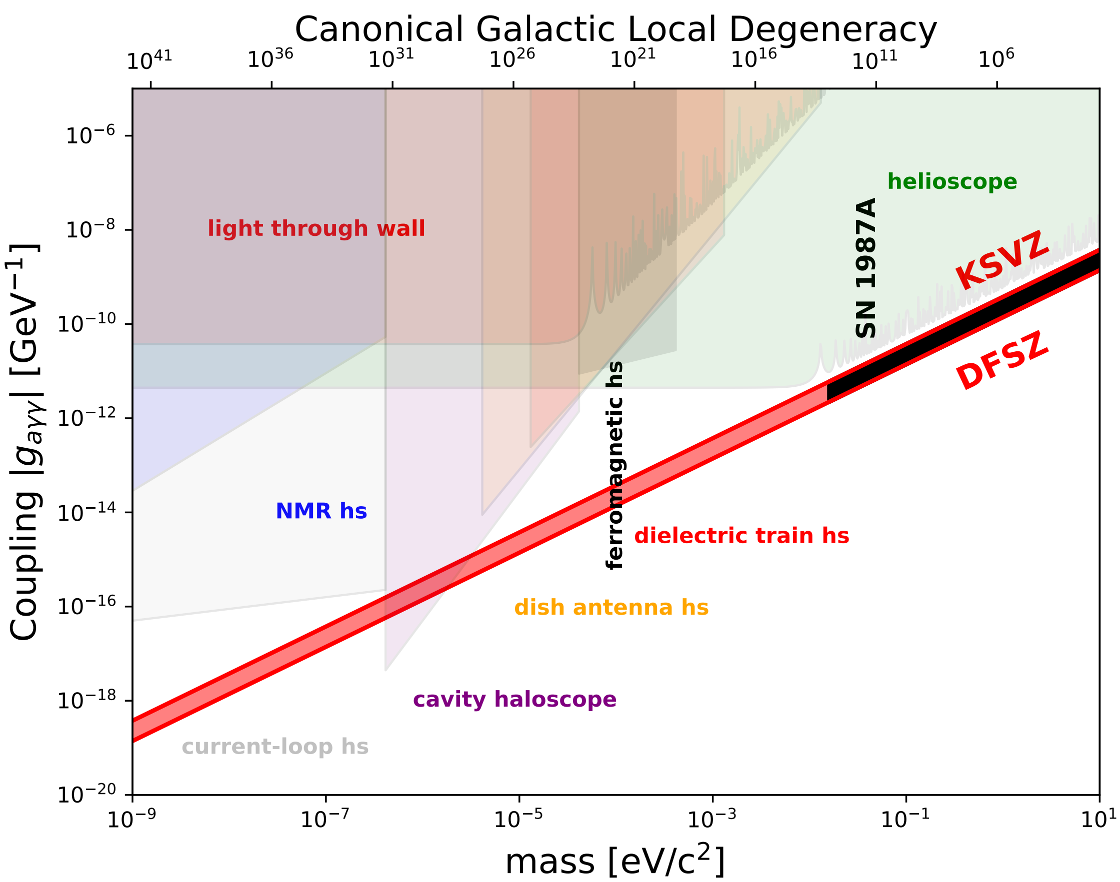


Figure 1: Baseline sensitivity plot. Details for each search type are given in the text above.

# 2.0 Detector Type Exploration

Varying the detector type is the first parameter explored in this study, Fig. 2. Three different detector types were implemented:

- Heterodyne/Homodyne: Depending on the narrowband or broadband nature of the search, the detector used will respectively be of (super-)herterodyne or homodyne type, with background noise given by the radiometer equation.
- Single Photon Detector (SPD): For a given bandwidth, the SPD is assumed to have a dark photon rate of 0.1 Hz and a detection efficiency of 100%.
- Squeezed SPD: For a given bandwidth, the SPD is assumed to have a dark photon rate of 0.1 Hz, a detection efficiency of 100%, and a squeezing advantage factor of 10.

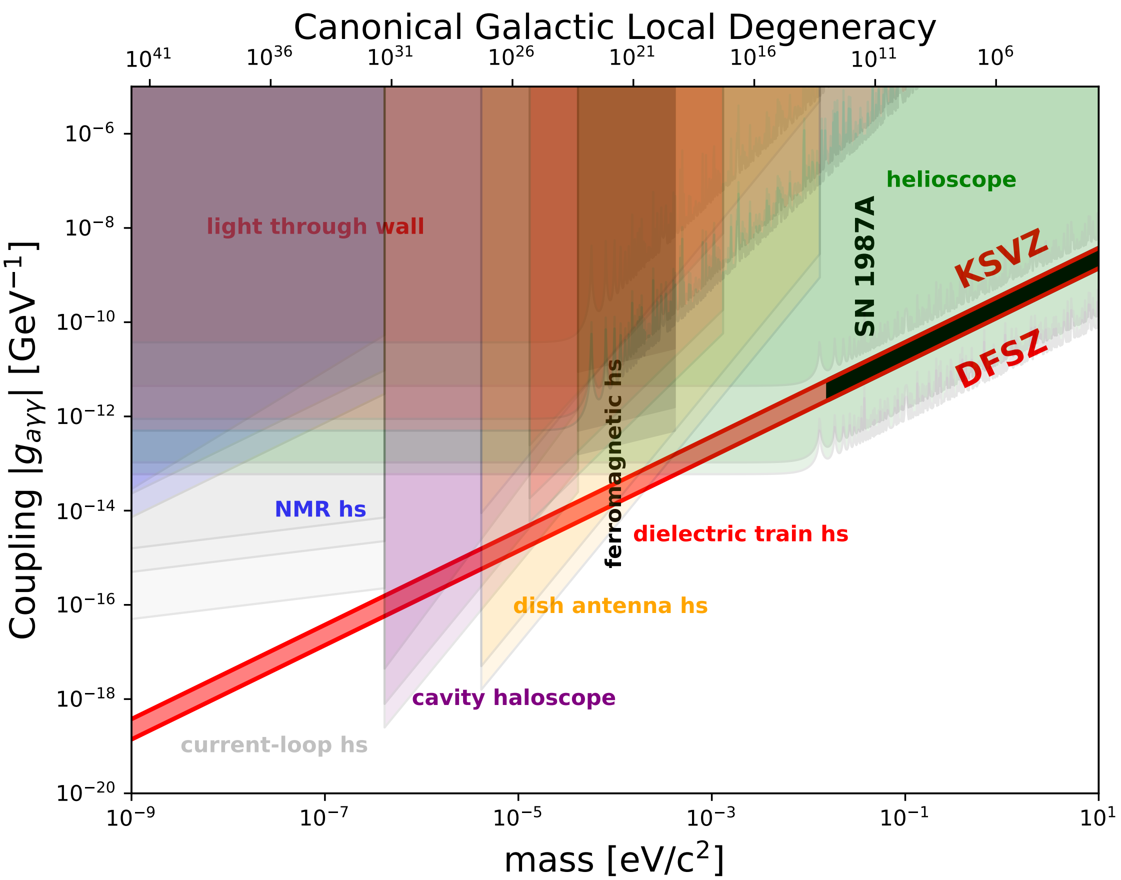


Figure 2: Detector type exploration plot. Each detector is given its own sensitivity estimate, with an approach's least sensitive estimate generally corresponding to the heterodyne/homodyne detector, the middle estimate corresponding to the unsqueezed single photon detector, and the most sensitive estimate corresponding to the squeezed single photon detector. See the text above for details.

## 3.0 Increasing Integration Time

The next parameter to be explored is integration time. This is the total observation time for an approach to observe its entire band. Note that this time is for observation only, and does not include the time taken for R&D, commissioning, tuning, or other operations that would interrupt observation. The times explored here are 1 year, 10 years, and 100 years.

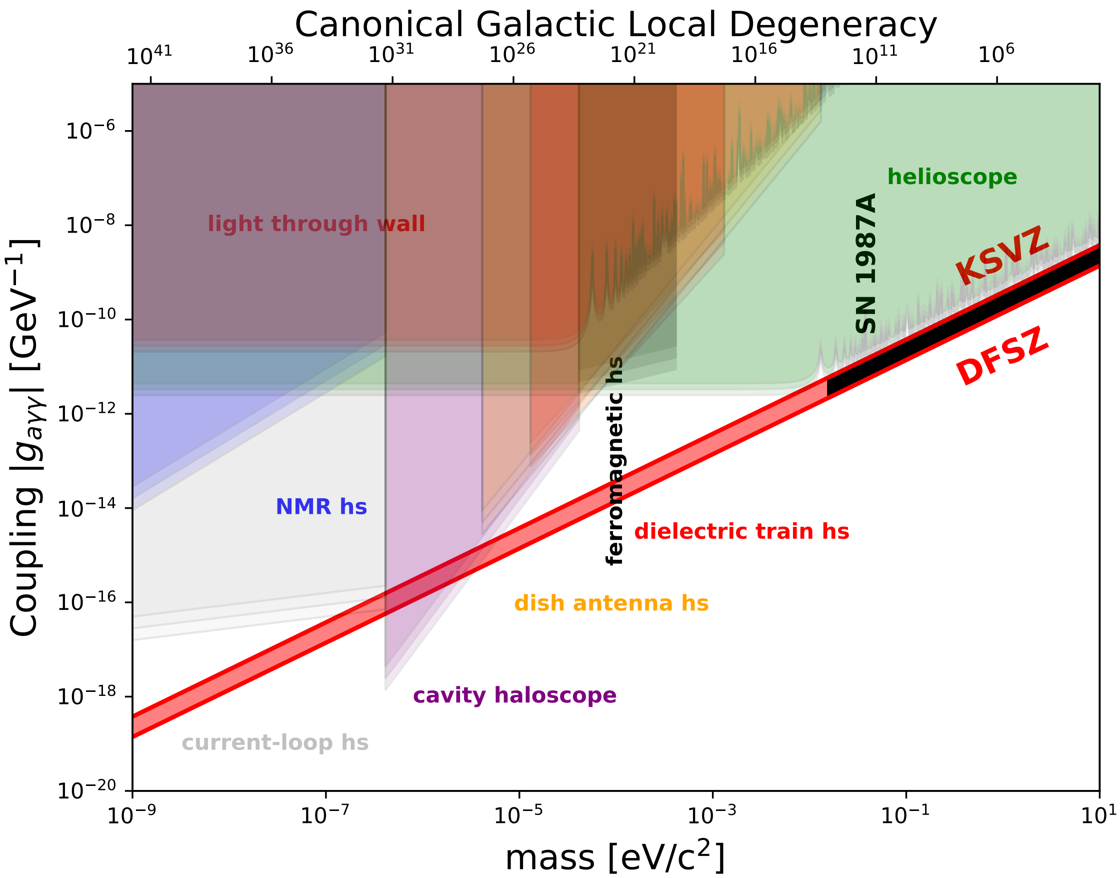


Figure 3: Integration time exploration plot. Each integration span is given its own sensitivity estimate, with an approach's least sensitive estimate corresponding the baseline of 1 year continuous integration, the middle estimate having 10 years of integration, and the most sensitive estimate having 100 years of integration time. See the text above for details.

# 4.0 Sample Cosmologies

The cosmology variation consist of exploring a range of cosmologies and the impact it would have on an incoming relic axion signal's width ($Q_a$) and local mean density ($\rho_a$). Transient events such as the passing of an axion star or minicluster were not considered. Current instances include:

- "Minicluster": Based on a cosmos where miniclusters have taken up 90% of the baseline local density ($\rho = 0.03$ GeV/cc, $Q_a = 10^6$)
- "Baseline": $\rho = 0.3$ GeV/cc, $Q_a = 10^6$
- "N-Body": Based on the MW halo model motivated by [17] ($\rho = 0.6$ GeV/cc, $Q_a = 2 \times 10^6$)
- "Big Flow": Based on Pierre Sikivie et al.'s model of a local DM density dominated by the flows of a caustic ring [19, 11, 20, 4].

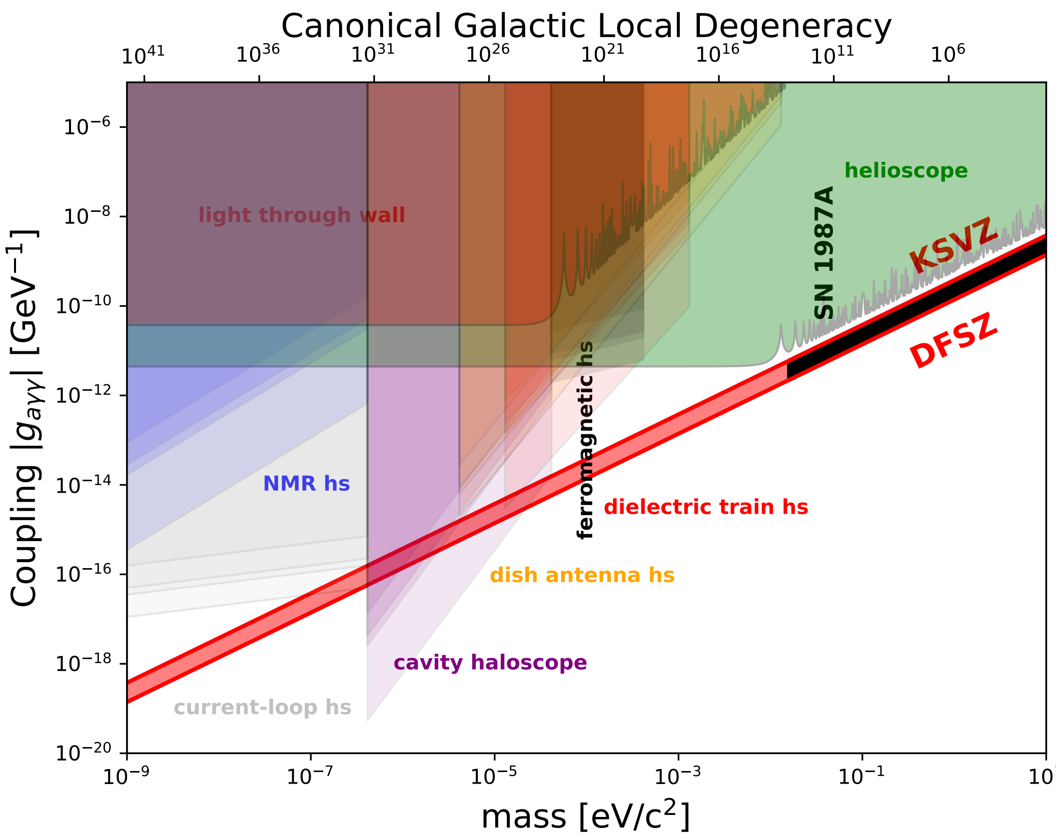


Figure 4: Cosmology type exploration plot. Each cosmology is given its own sensitivity estimate, with an approach's least sensitive estimate corresponding to a cosmology where the long-lived local dark matter density has been depleted by axion mini-clusters, followed by the baseline cosmology, the N-Body inspired halo model of [17], and the cosmology resulting in highest sensitivity is given by a "Big Flow" model similar to those proposed in [19, 11, 20, 4]. See the text above for details.

## 5.0 Increasing Apparatus Size

The last parameter explored here is the size of the apparatus. Where applicable, the size of the detector is increased from its base size (usually set by the Compton scale), to 10x larger, to 100x larger in each relevant dimension. We stop at 100x as any larger would reach an appreciable fraction of a coherence length, compromising conversion efficiency. Note that proposals for the Dish Antenna and Dielectric Train approaches both have maximized the area of their disks to take advantage of this. Also note that cavity haloscope power goes like scaling cubed, but the light-through-wall experiment is invariant as its size is set by parameters other than the relic axion kinematics.

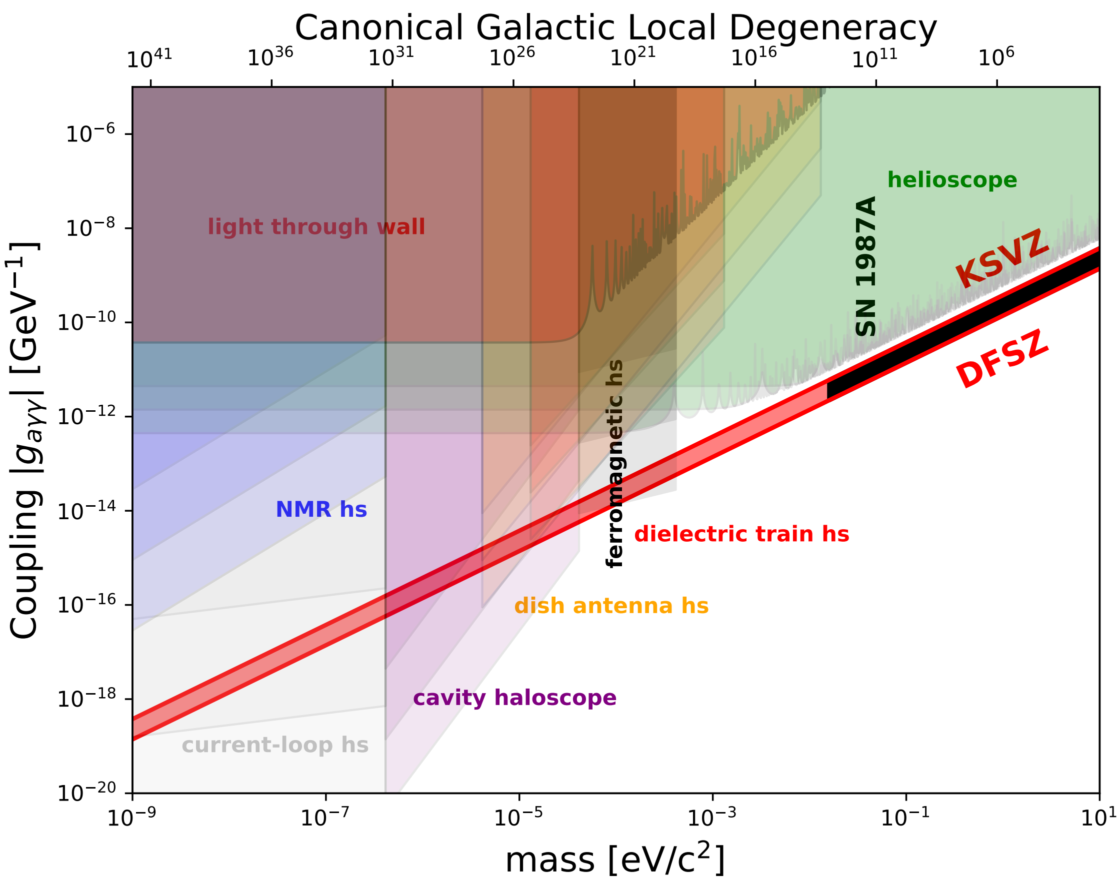


Figure 5: Size exploration plot. Each apparatus size is given its own sensitivity estimate, with an approach's least sensitive estimate corresponding the baseline size, the middle estimate being expanded in each relative dimension by a factor of 10, and the most sensitive estimate being expanded by a factor of 100. See the text above for details.

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