# Snowmass2021 - Letter of Interest

*UP-conversion Loop Oscillator Axion Detectors (UPLOAD)*

**Thematic Areas:** (check all that apply □/■)
■ (CF2) Dark Matter: Wavelike
■ (IF1) Quantum Sensors


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**Abstract:** (maximum 200 words)

Special configurations of dual-mode resonator-oscillators have been shown to be sensitive to low mass axions through the principle of upconversion and precision frequency metrology [1;2]. The signal sensitivity is derived from the two-photon axion process given by $a+\gamma_1+\gamma_2 \rightarrow a+\gamma_1'+\gamma_2'$, which does not destroy the axion, but causes frequency modulation of the photon frequencies inside the resonator. This is effectively an axion non-demolition technique with enhanced sensitivity by searching the spectrum of frequency fluctuations of one of the oscillators. A first simple table-top demonstration has been achieved, placing exclusion limits of $5 \times 10^{-7}$ 1/GeV in the range of 7.44 - 19.38 neV after a measurement time of only 2.5 hours [2]. In the future, a frequency-stabilized cryogenic version of this technique will achieve best limits in an axion mass range of less than $1\mu eV$, and it is possible that an optical version will place competitive limits in the $50-400\mu$eV range. These group of projects will continue in concurrent stages: 1) Frequency stabilized oscillators [3–5] based on an invar silver plated microwave cavity operating in vacuum, will start operation by 2021, with the ability to test ALP Cogenesis [6] in the mass range less than $10neV$: 2) A cryogenic version of the experiment based on high-Q superconducting Tesla cavities designed by Fermilab [7], with a proof of principle experiment to begin in 2020. This will be followed up with a properly designed system able to test QCD axions below $10^{-11}eV$ and conventional alignment mechanisms below $10^{-8}eV$, tentatively scheduled to begin in 2022 after the necessary R&D. 3) In parallel, due to the lessons learnt at microwaves, we have started to design a dual mode optical cavity with a similar enhanced sensitivity. The goal of this experiment will be to search at a difference frequency compatible with the $50-400\mu$ eV range, where the necessary size of the microwave cavities become problematic to attain QCD sensitivity. This work will be undertaken with researches from the LIGO collaboration at the University of Western Australia (UWA) and Caltech.

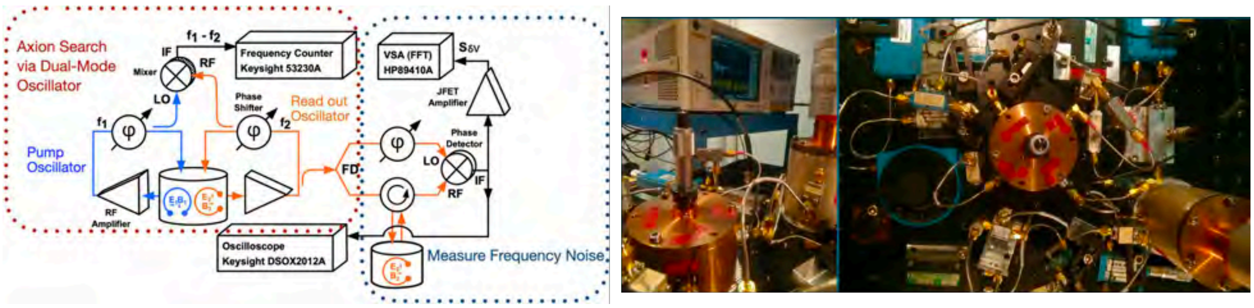


Figure 1: Table-top UPLOAD-MC pilot experiment[2]. **Left)** Schematic of the experiment with frequency readout system. **Right)** Photograph of the table top experiment in operation. Loop oscillators support the microwave modes in the main resonator allowing axion conversion while a frequency counter records the frequency difference, $|f_2 - f_1|$. The TM mode acts as the readout mode with constant known $f_2$, while the TE mode acts as a tunable pump at $f_1$. The frequency noise is continuously scanned with a high-Q frequency discriminator based on a a duplicate cavity, creating the dispersion required for frequency to voltage noise conversion for detection at the mixer output.

## Preliminary Work and Background

The UPLOAD-MC (UPconversion Loop Oscillator Axion Detection with a Microwave Cavity) experiment is similar to traditional haloscopes. It is the first in a new class based on frequency metrology[1;2], instead of power detection. Most haloscopes attempt to create photons by interacting axions with a virtual photon source, but the Primakoff process also generates products in the presence of real photons, as first noted by Sikivie in 2010[8]. AC haloscopes based on the two-photon process are capable of detecting axions near the sum and difference frequency of two photonic oscillators. The method implemented here allows detection via precision frequency measurements due to the $a + \gamma_1 + \gamma_2 \rightarrow a + \gamma_1' + \gamma_2'$ process[1;2] causing frequency modulations without destroying axions. In contrast, proposed power measurements based on the $a + \gamma \rightarrow \gamma$ process destroy axions to create a photon and are inherently less sensitive[8–11]. Moreover, precision oscillators of the type proposed here have been used in the past for some of the best tests of fundamental physics, including variations in fundamental constants and local position invariance[12–14], as well as tests of Lorentz invariance violation[15–17], with proven long-term performance of up to eight years[14], and if designed properly the sensitivity will be determined by the white noise frequency floor of the frequency stabilization system[15]. In particular the UWA team leading this project are world experts in developing low noise microwave and radio frequency oscillators[3–5;18] based on low noise phase detection[19;20], and using them to test fundamental physics[13–17;21;22]. This is evidenced by the fact that the technology developed in their lab is now present in all of Raytheon's defence radar[23].

## Sensitivity

The sensitivity of this experiment is proportional to the resonant cavity mode overlap functions $\xi_\pm$[1;2;8], if the axion mass is close to the sum and difference of the two photon frequencies, $|f_2 \pm f_1|$. In a resonant cavity, if the two photon modes are properly chosen, the overlap function will be of order unity (many mode pairs have zero overlap). The mode pair in use for the current experiment is the $TM_{020}$ and $TE_{011}$ mode pair, which when tuned close in frequency have an overlap function $\xi_-$ of magnitude 0.874, while $\xi_+$ is supressed. This means the experiment is sensitive to low mass axions near the difference frequency of the modes when the two photon modes are tuned close in frequency, and in general will cause frequency modulations of rms amplitude $\left\langle \frac{\delta f_{a_2}}{f_2} \right\rangle_- = |k_{a-}| g_{a\gamma\gamma} \langle a_0 \rangle$, where $k_{a-} = \pi\sqrt{\frac{f_1 P_{c1}}{f_2 P_{c2}}}\xi_-$ is the conversion ratio from axion-photon theta angle, $\theta = g_{a\gamma\gamma} a$, to fractional frequency shift, $\frac{\delta f_{a2}}{f_2}$, $P_{c1}$ is the circulating power of the pump mode and $P_{c2}$ is the circulating carrier power of the readout mode, which are dependent on resonator mode couplings and Q-factors[1;2]. The oscillator spectral density of fractional frequency fluctuations, $S_y$ (related to phase noise), in a stabilised oscillator is determined by the noise temperature of the phase detector used to cancel frequency fluctuations so that the signal to noise ratio is given by is given by

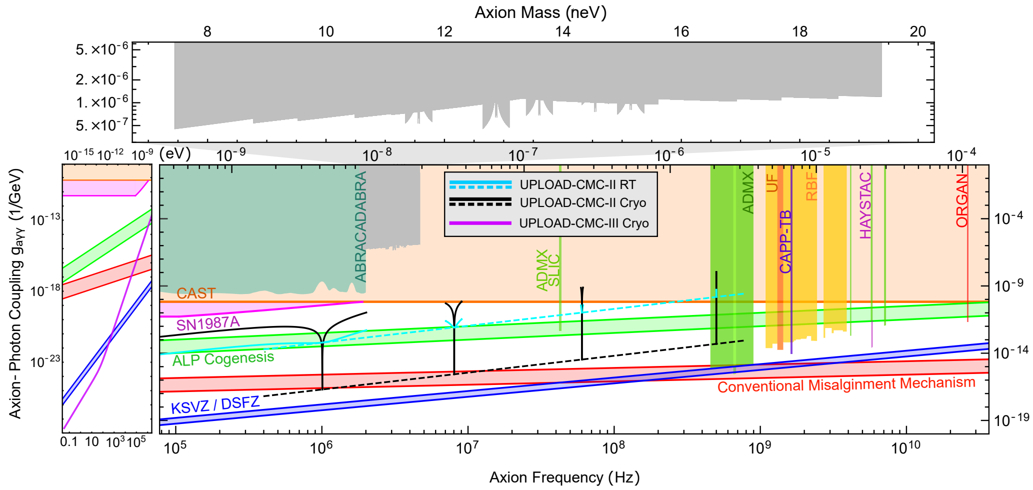


Figure 2: 95% confidence exclusion zone (gray) for our first table-top experiment with respect to already set experimental limits and QCD axion models in blue [24;25], red (conventional ALP misalignment), and green (ALP cogenesis) [6;26]. Projected upconversion limits for future experiments are dashed, 1) UPLOAD-MC-II-RT, a silver plated invar resonator with frequency stabilization (FS) at room temperature (RT); 2) UPLOAD-MC-II-Cryo, cryogenic superconducting cavities with FS below 4K. The Fourier span of a single measurement allows a 1 MHz span before tuning, and are represented in bold for a measurement period of 30 days per MHz. Projections are based on readily constructible setups with available equipment and standard techniques. 3) UPLOAD-MC-III-Cryo is a cryogenic version of the experiment, with possible QCD axion sensitivity at ultra-light axion mass. By tuning the orthogonal modes to coincide in resonant frequency and creating oscillator degenerate mode synchronisation, we expect to reach QCD axion limits at $< 1.8$ kHz ($7.7 \times 10^{-12}$ eV), illustrated in the left sub-plot with1.3 years of data acquisition.

$SNR_{\pm} = g_{a\gamma\gamma}|k_{a\pm}|\frac{\left(\frac{10^6 t}{f_{a_\pm}}\right)^{\frac{1}{4}}\sqrt{\rho_{DM}c^3}}{2\pi f_{a_\pm}\sqrt{S_{y_2}}}$, assuming the measurement time, $t$ is greater than the axion coherence time so that $t > \frac{10^6}{f_{a_\pm}}$. Note, for the upconversion case, $f_{a-}$, may be significantly lower than the microwave carrier frequencies ($f_{1,2}$), in which case the SNR is enhanced, being inversely proportional to $f_a$, and the time of integration may be longer before the bandwidth of the axion starts to reduce the sensitivity.

## Research Plan

Now that the initial pilot experiment is complete[2], stage 2 is to run a new room temperature experiment (UPLOAD-MC-II-RT), set up for long term operation and data collection, with the minimization of all possible noise sources. This experiment will be capable of testing ALP cogenisis, and will use a cylindrical silver plated invar cavity in vacuum to limit effects of pressure and temperature fluctuations. Long-term data taking procedures will be developed along with the development of tuning procedures to allow scanning of the desired axion mass ranges. For these future experiments, phase/frequency noise data will be most likely measured using the more sensitive two-oscillator technique. Techniques to create degenerate oscillator mode synchronisation will also be developed, which will uniquely allow the search for ultra-light axion dark matter. Stage 3 will be the construction of the ultimate cryogenic version of the experiment, and will importantly require collaboration with experts from Fermi Lab. During 2020 a proof of principle experiment will begin, with two oscillator modes excited in an existing superconducting cavity. Thus, a low phase noise dual-mode oscillator will be built, with the ability to set limits of axion mass at about 180 and/or 70 MHz (depending on the mode pair) with about a 1 MHz scan bandwidth. From the knowledge gained in concurrent stage 2 and 3 experiments, an extremely sensitive cryogenically scannable experiment will be designed (UPLOAD-MC-III-Cryo), along with a degenerate mode version to search for ultra-light axions. Concurrently, from the knowledge we have gained from the microwave systems, we are designing a system based on an Optical Cavity (UPLOAD-OC). This has been achieved by understanding 3D resonator modes in the limit of a large number of anti-nodes, and from our initial calculations a sensitive design is possible. The final design will be defined in collaborations with experts from the LIGO collaboration in the USA and Australia and will use state-of-the-art high-Q optical resonators and frequency stabilization systems.

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