Davis Dark E-Field Radio Experiment: Progress Towards Run 1A

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1 Introduction

Dark matter remains one of the great unsolved mysteries of modern physics. Its unknown mass splits nicely into two regimes; waves and particles. At a mass of order 1eV the inter-particle spacing $\approx$ wavelength. Lighter than this, it is more convenient to think of dark matter as a wave. Alternatively, dark matter candidates heavier than this are more conveniently modeled as exhibiting particle-like behavior. Particle-like dark matter detectors have dominated the budgets and schedules of dark matter search programs but have yet to report any positive findings. In light of this, the 2017 community report on dark matter [1] highlights a need for a multi-experiment program in which many small scale experiments ($<$ \$10M) split up to cover the vast landscape of potential dark matter candidates (see Fig. 1). Since very little is known about dark matter, it is a playground for theoretical physicists to invent candidates. This overwhelming search should be narrowed down.

The Dark E-Field Radio Experiment at UC Davis is a direct detection experiment searching for dark photon dark matter at neV to meV mass scales (tens of MHz to hundreds of GHz). The experiment relies on an antenna to couple to the E-field of the local dark matter density. We have completed a pilot experiment, which covers 50 to 300MHz and was published in 2021 [2]. In the pilot run, we probed the electromagnetic coupling of photons to dark photon dark matter (ϵ) down to approximately 10^{-12}. I have spent the past 18 months completing upgrades in preparation for preparing for Run 1A, which will be taking data in May 2023. Run 1A will cover the same 50 to 300MHz span, but with ϵ sensitivity of closer to 10^{-13}. The completed upgrades, which are described in the following sections, represent the most

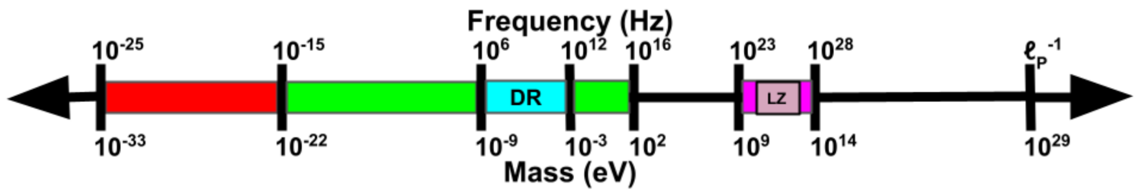

Figure 1: Cartoon depicting the mass scales over which dark matter may be found. Corresponding frequencies shown above. At heavy mass scales $> \mathcal{O}(1\,\mathrm{eV})$ the dark matter would behave like a particle, while on the lighter end it would behave like a wave. The Dark Radio Experiment searches at radio/microwave frequencies (blue) for a hidden photon using an antenna and spectrum analyzer. LUX-ZEPLIN Experiment (LZ) also shown.

technically challenging in the sub ≈14GHz regime. With very minor upgrades we will cover 300MHz to 1GHz (run 1B). Approximately 6 months of further upgrades will push us up to 8GHz (run 2A), and very minor upgrades will push up to 14GHz (run 2B). Beyond this we hit challenges which are beyond my timeline as a grad student, but which nonetheless represent an exciting opportunity.

This write up is laid out as follows. Section two is dedicated to briefly bringing the reader up to speed on dark photon physics as it applies to our detection technique and provides references for further reading. Section three provides an experimental overview including general pointers for improving sensitivity. Section four provides an overview of the past 18 months of work, which have brought us to the point of beginning to collect run 1A data.

2 Dark Photon Overview

The dark photon is a hypothetical, low-mass, vector boson. They are theorized to have been produced from a vector field during inflation [3]. By allowing an additional U(1) symmetry in the Standard Model Lagrangian there can be a weak coupling between the dark field and standard electromagnetism (EM) [4];

$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{\gamma'}A'_{\mu}A'^{\mu} - \frac{1}{2}\epsilon F'_{\mu\nu}F^{\mu\nu}_{EM} + \mathcal{L}_{SM} \tag{1}$$

This *kinetic mixing* may provide a portal to detection by coupling to classical EM at $\mathcal{O}(\epsilon)$, namely

$$E = \epsilon\, E^{'} \tag{2}$$

where $E^{'}$ is the hidden field and E is the detectable field.

3 Detecting Dark Photons

Given the local dark matter density, $\rho_{\rm DM} = 0.3 \pm 0.1$GeV/cc [5] and using elementary EM to relate the local dark matter energy density to the energy density of the dark field,

$$E^{'}_{\rm DM} = \sqrt{2\rho_{\rm DM}/\varepsilon_0} \approx 3\,{\rm kV/m}. \tag{3}$$

(Note ε_0 is the permittivity of free space, not to be confused with ϵ, the coupling). When combined with Eq. 2 we realize that if our dark photon hypothesis were correct, and if $\epsilon \approx \mathcal{O}(1)$, we would be subject to kV/m radio frequency fields, which we would surely detect. This allows us to place our first limit,

$$\epsilon < 1$$

More stringent limits can be set through other experiments or cosmological observations and are shown in Fig. 2.

Our experimental design involves using an antenna to detect high-Q E-fields at radio frequencies. The antenna is placed in a shielded room to prevent radio frequency interference (RFI) from external RF sources such as local broadcast radio and switching power supplies. The incident power spectrum is read out on a spectrum analyzer. This is performed many times and the spectra are averaged together to improve the signal-to-noise (SNR) ratio of a coherent, monochromatic signal riding on a background of white noise. Measured power is converted to a constraining E-field, which can be converted to a limit on the kinetic coupling constant. The frequency of the measured power is a proxy for the mass. See Fig. 3 for a schematic and simulated dark photon detection.

There are four main principals we use to see deep into the thermal noise:

- Reduce EMI by placing antenna in shielded room
- Apply gain before the signal is measured in order to swamp the internal noise of the spectrum analyzer with the thermal background seen by the antenna due to the temperature of the room ≈ 300K.
- Reduce the frequency width of each bin, $\delta\nu$. A narrow bin will capture less power from the underlying flat spectral density (white noise) and result in a lower noise floor. This is is known as resolution bandwidth (RBW). Note that reducing the RBW to below that of the dark

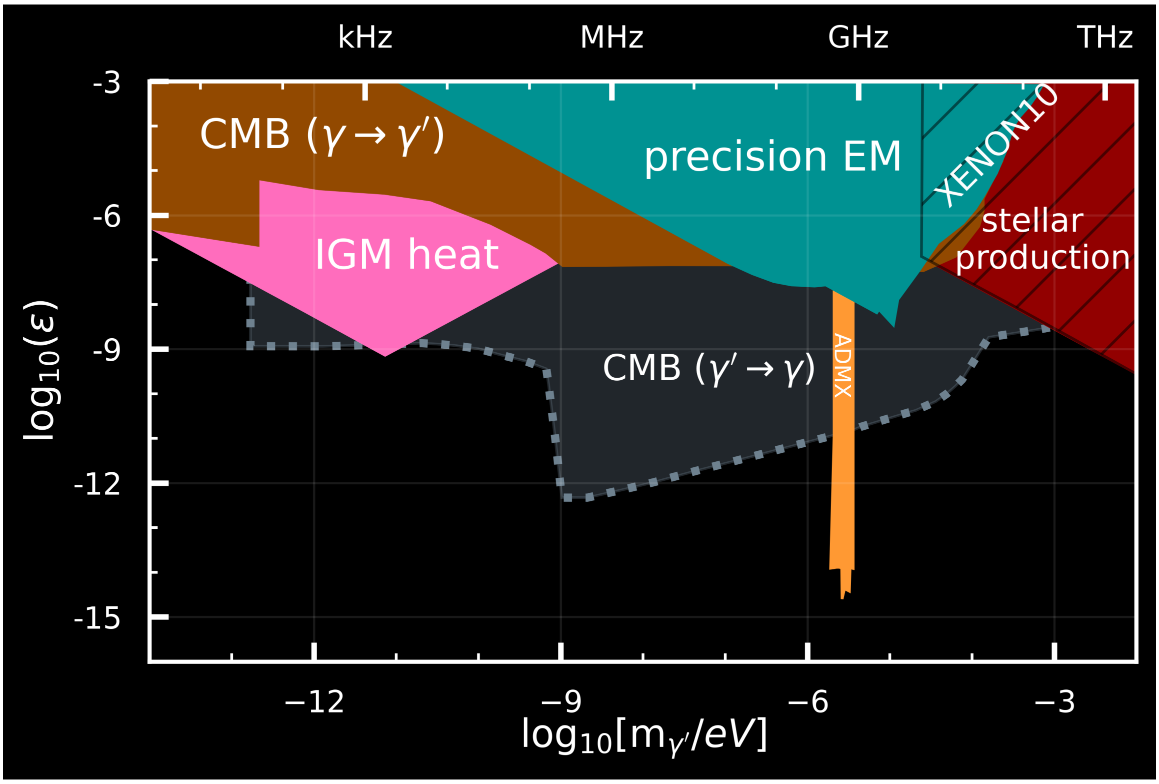

Figure 2: Constraints placed on the $\epsilon, m_{\gamma'}$ parameter space.

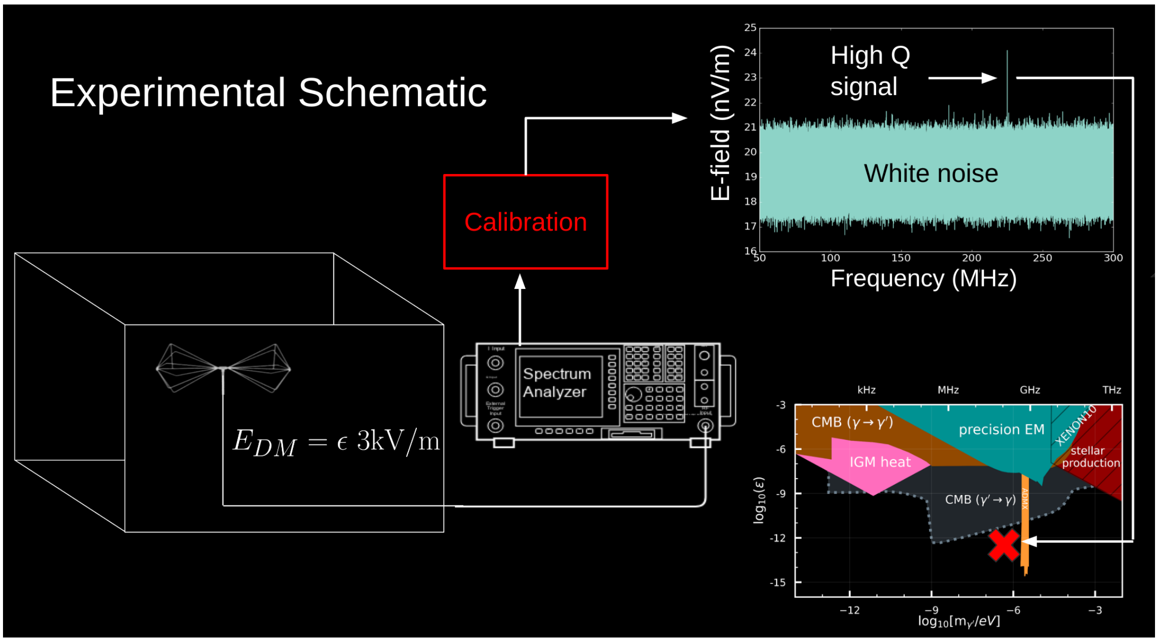

Figure 3: Simplified schematic of the experiment showing a simulated dark photon detection and how it would appear on the constraint plot of Fig. 2.

photon's line width begins to split power between bins causing SNR to remain constant. However, to get a smaller RBW requires longer FFTs meaning we can take less of them in a given time. This sets a lower limit on RBW below which we lose sensitivity.

- Average as many spectra as possible. Noise goes like $1/\sqrt{N}$ while our limit goes like $1/\sqrt[4]{N}$ (because we are averaging power spectra and $P \propto E^2$). Averaging works until we are able to resolve the non-white, noise floor of our spectrum analyzers or begin to see high Q interfering signals which make it through the shielding. We have struggled with this, but recently have reduced the level of interference that we should be able to average for about 1 year before this becomes an issue.

4 Progress towards run 1

We have completed many short runs (1-12 hours) and three "real" data runs, which turned out to have various issues. In this iterative process, we have streamlined analysis and optimized the experiment in a way which I believe will make the next run the actual data set.

4.1 DAQ Improvements

A large portion of the past year was spent integrating a new digitizer (Teledyne ADQ32) into our DAQ pipeline. This gives us the capability of direct writing time domain sampled data onto a GPU where we can perform a large FFT significantly faster than data are collected. As a point of reference, we can perform a 2^{24} point FFT in 2ms, while it takes $2^{24}/2.5\text{GHz} = 6.7\text{ms}$ to collect the data (using the maximum sampling rate).

The Teledyne digitizer has an exceptionally low noise floor, which eliminates many spurious signals we observe on other digitizers and spectrum analyzers. We are able to simulate the effects these "spurs" will have on longer averaging periods by applying less gain before the ADC, and have found we won't start to see any until about one year of averaging. Currently we perform 9-day runs, and since epsilon $\propto 1/\sqrt[4]{N}$, we will likely never run much longer than than a month.

4.2 Analysis pipeline

Because the antenna and balun don't provide a perfect match to the 50Ω transmission line, we see wide wiggles on our baseline that are hundreds of kHz to tens of MHz wide. When searching for a narrow candidate, a filter can be applied to frequency domain data to discriminate based on signal width in the frequency domain. We came to this solution on our own, but are validated by others using a similar technique performing similar searches (see for example [6] or [7]).

High-pass filtering data removes wide frequency domain features, while admitting narrow candidates. In fact, this functions as baseline subtraction and the (gain corrected) standard deviation on the filtered spectrum gives the sensitivity of the experiment after taking N averages. While the filtered spectrum is not normally distributed (due to impedance match issues), any small section of it is. Taking a rolling standard deviation of filtered data gives a nice Nσ line, above which we have confidence there is an excess of power. This does not tell us what the source of the power is. Up until early May 2023 we had thousands of bins greater than 5σ. However, recent improvements outlined in this write up have brought that list down to zero, meaning we are ready to take data.

4.3 Reduction of Interfering Signals

Many of the signals we observed were caused by clocks sourced by various pieces of the DAQ chain radiating and entering the shielding room. After much struggling to reduce RFI, the solution was simply to clean the brass finger stock on the door of the shielded room, and the stainless steel doorjamb it mates to. We have improved isolation from about 70-80dB to greater than 110dB over the 50 to 300MHz range of run 1A. Performing injection tests with a transmit antenna in the lab have shown we should only expect to see about ten very large radio stations in a month long run, all of which are well known and monitored in real time using an external "veto" antenna. After several years we will begin to be sensitive to the various clocks present in the lab, but this is beyond the scope of our experiment.

References

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