A Radio for Dark Matter

Joseph Levine

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1 Introduction

It is believed that a large majority of the mass in the universe comes from an as yet undetected source [2, 4]. This claim stems from observations of galaxies spinning far too quickly to be held together by the gravity of the directly observed sources as shown in Fig. 1. The only connection to the outside universe is through the electromagnetic radiation that is emitted which is observed using various forms of telescopes. If radiation emitted from "light matter" (stars) is observed to be following a trajectory that is not consistent with the theories of gravitation, it is thought there is some "dark matter" invisibly pulling on these trajectories. By this same token, gravitational lensing is observed, distorting the observed radiation from known sources. This dark matter does not emit enough (if any) electromagnetic radiation in a known waveband to be observed directly, but should exist to account for secondary observations.

Since very little is known about the dark matter, it is a playground for theoretical physicists to invent candidates. This overwhelming search should

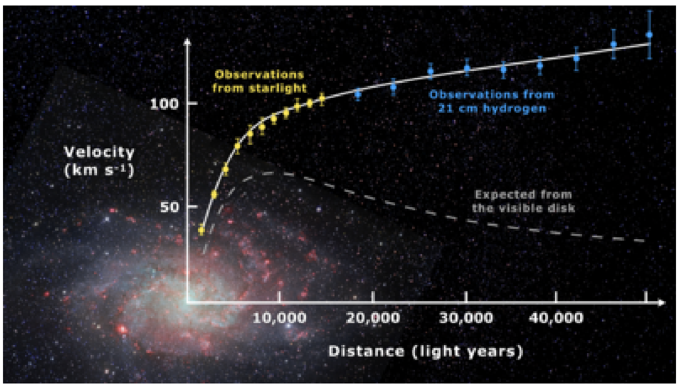


Figure 1: Expected vs observed velocity distributions of M33

be narrowed down. The focus of this paper is the hidden photon, a light massive particle in the neV to meV range. Specifically, what hidden photons are, how they are expected to behave and various attempts to detect them. While they are as-of-yet undetected there are many ongoing efforts to confirm their existence.

2 Hidden Photon

Falling on the light end of the mass scale, the hidden photon behaves as a coherent field and can be detected electromagnetically. An interesting feature of the massive photon is its ability to penetrate conductors [5]. Because of weak coupling to E&M, the signal that would indicate the presence of the hidden photon would be extremely weak. The strength of this coupling is given by the parameter ϵ. We expect our detector (discussed in sections 2.1.2 and 3) to be sensitive to $\epsilon \approx 10^{-15}$ at its peak sensitivity. It is important to equip the detector with a filter to prevent becoming overwhelmed by classical E&M fields that would exist simultaneously such as local radio stations and the proposed cell towers to be installed on the roof of the UC Davis Physics building. The property of penetrating conductors allows a Faraday cage to act as just this sort of filter.

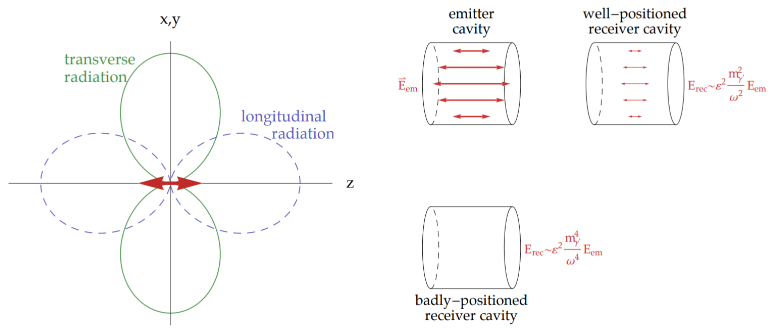
2.1 Generation and Detection

Many efforts are in place to detect the massive photon. These include efforts to generate *and* detect it, as well as to detect naturally occurring hidden fields (ie, the dark matter).

2.1.1 Light-Shining-Through-a-Wall Experiment

The Light-Shining-Through-a-Wall Experiment is a pedagogical thought experiment to demonstrate how massive photons may be created and then detected, though several experiments are based on the concept. The idea is to generate electromagnetic radiation and place a detector inside of a shield. The radiation generated will be composed of both classical and hidden fields. The hidden field is able to penetrate and be detected, while the classical field is filtered out.

An important phenomena in the creation of hidden fields is the radiation pattern of the longitudinal mode. Since this mode penetrates conductors by a factor of $\frac{\omega^2}{m_\gamma^2}$ greater than the transverse mode [5] it would be easier to detect. Longitudinal radiation is emitted parallel to an oscillating electric



(a) Radiation pattern from an oscillating EDM.

(b) Good and bad cavity positioning.

Figure 2: (a) shows the radiation pattern for transverse and longitudinal modes of an electric dipole. (b) shows the positioning of a detector that would permit the maximum field to penetrate. Image from [5]

dipole Fig 2 (a), so a well positioned receiver as shown in Fig 2 (b) would receive a stronger signal.

2.1.2 Detectors

A complication in detecting natural hidden photons is the huge parameter space that must be searched as shown in Fig. 3. For this reason it may be beneficial to generate and detect hidden photons of a known frequency. However, experiments of this type have not yet been successful.

Resonant detector The principal of resonant detectors is to build some kind of resonant apparatus with high Q and sweep across frequency space looking for a spike. The ADMX experiment [7] is one such device. It uses a resonant microwave cavity and a small antenna to look for microwave axions. The LC resonator described in [3] is another such device. A major disadvantage is such a high Q means it takes a very long time to sweep through such a large frequency span.

"Dark Radio" - Tyson Group at UC Davis The Dark Radio experiment is in progress at UC Davis [1]. Its main advantage is the ability to listen to a large frequency space using a broadband antenna, and using a cutting edge FPGA based FFT (ROACH2), integrate the signal over a long period (one to three months) which would allow a persistent signal of constant frequency to be seen over the noise. This broadband architecture allows a relatively quick scan over frequency space, pausing only to swap out antennas and amplifiers. The setup is sensitive down to femtovolts where thermal

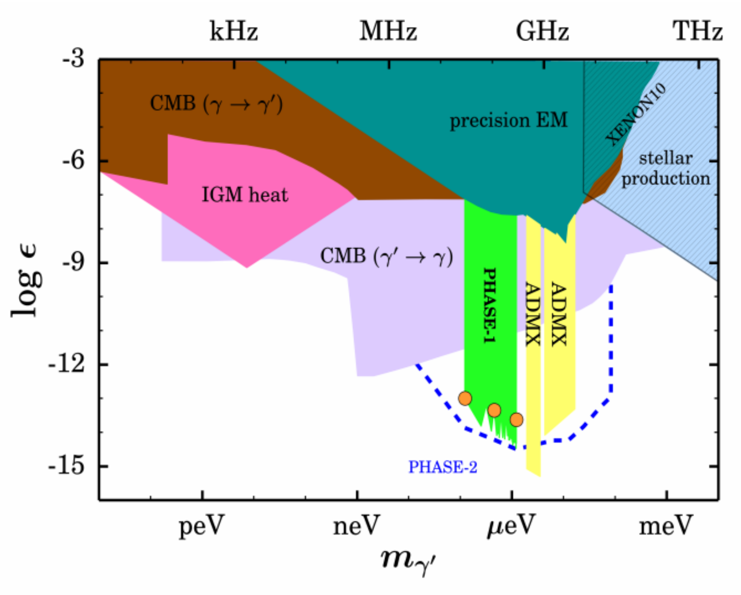


Figure 3: The ϵ, ω parameter space. From Tyson Group at UC Davis. Phase 1 refers to the completed first run, and phase 2 was completed summer 2019. Various limits on this parameter space are set by experiments and production methods as shown in variety of colors. Image from [1].

noise begins to become significant. This is combated by cooling the preamplifier with liquid nitrogen. See Fig. 4 for experimental schematic.

3 REU Summer 2019, Tyson Group at UC Davis

Progress during the 2019 summer REU was made in the areas of simulation of the detector using COMSOL, completion of phase 2 run, signal injection test, and construction of temperature probe. Simulation is mainly discussed in [6].

3.1 Phase 2 run

The output of the spectrum is shown in Figure 5. This plot is the result the spectrum analyzer looking at one of about 200 small frequency windows for 10 seconds at a time before moving to the next window. It sweeps up and down the full 50 to 300 MHz spectrum for a total of 10^5 seconds per window, then each window is averaged together with those of the same frequency range

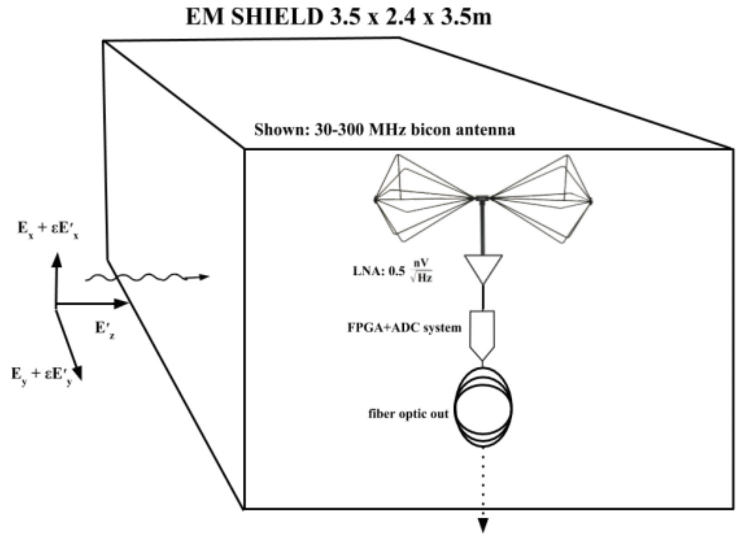


Figure 4: Experimental schematic for Tyson Dark Radio experiment. Image from [1].

to produce the plot. All of the averaging is to reduce the random noise so that, if present, a small but persistent signal will show up above the noise. Because the proposed Q (loosely, the width) of the signal is known to be on the order of 10^6 [3], the Q of each bin can be set. The limiting factor is that the spectrum analyzer can only listen to about 1000 frequency bins at one time. Accounting for down time, the actual time to get 10^5 seconds of data per window was around two months. Future designs include a FPGA based FFT that can listen to all of the frequency bins simultaneously on one big window, cutting experimental time by a factor of about 200.

3.2 Signal Injection Test

In order to test sensitivity to small signals over noise, a small signal was injected with a small dipole antenna. Figure 6 shows one window after 10 seconds of averaging, while Figure 7 shows the same window with 3520 seconds of averaging. The random noise is greatly decreased after the additional averaging because random noise is proportional to $\frac{1}{\sqrt{N}}$.

To detect a bin that is higher than the noise indicating the presence of a high Q, persistent signal we can calculate the Z-score of each bin relative to the other bins in the window. This is shown in Figure 8. The known injected frequency shows up at 5.24σ. However, due to a non uniform frequency response of the spectrum analyzer the signal could have been missed had it

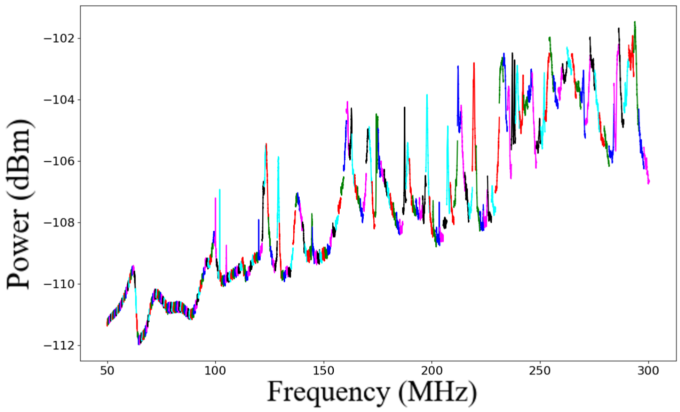


Figure 5: Power vs frequency for first phase 2 run.

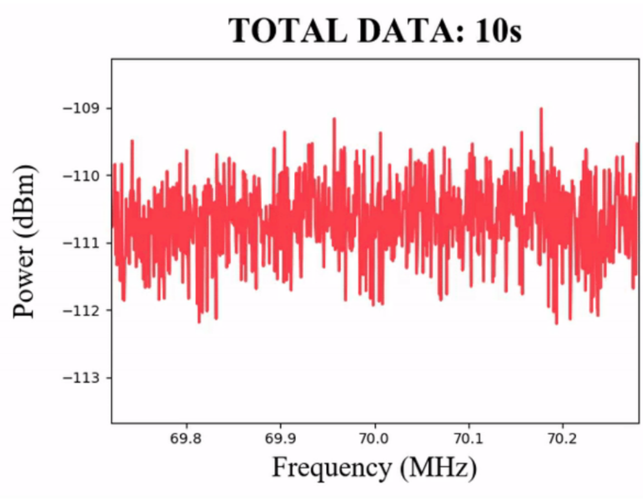


Figure 6: 10 seconds of averaging for one window

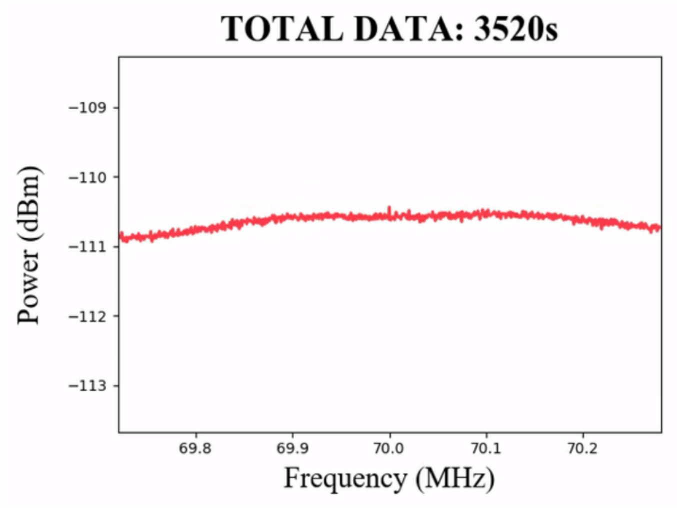


Figure 7: 3520 seconds of averaging for one window

shown up out of the peak sensitivity. To avoid this problem, Figure 9 shows a proposed filter that provides a weight for the z score. Using this filtering technique each bin is compared to it's nearest neighbors. This optimal filter design is the next goal of the group.

3.3 Construction of Temperature Probe

The final contribution of the 2019 summer REU students was to implement an Arduino based temperature collection probe to monitor the ambient temperature which may possibly be used in future analysis. The arduino itself is shown in Figure 10, and some sample temperature data in Figure 11.

4 Conclusion

While there remain many unanswered questions about dark matter, the Dark Radio experiment is probing the hidden photon as one possible answer. As more data are collected and analyzed there will either be confirmation of this theory or it can be cast aside to allow other theories to be investigated.

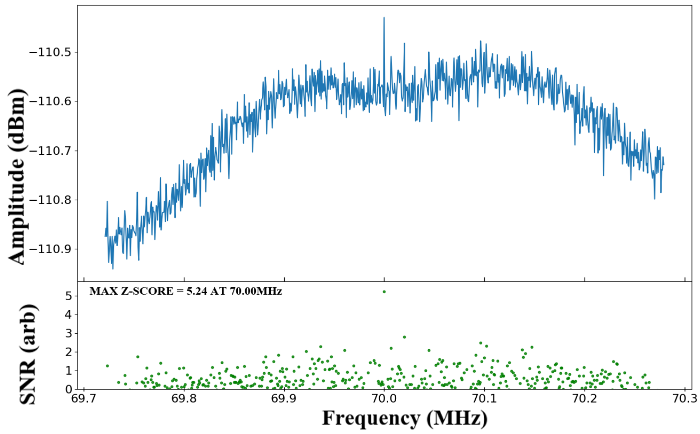


Figure 8: Z score of each bin

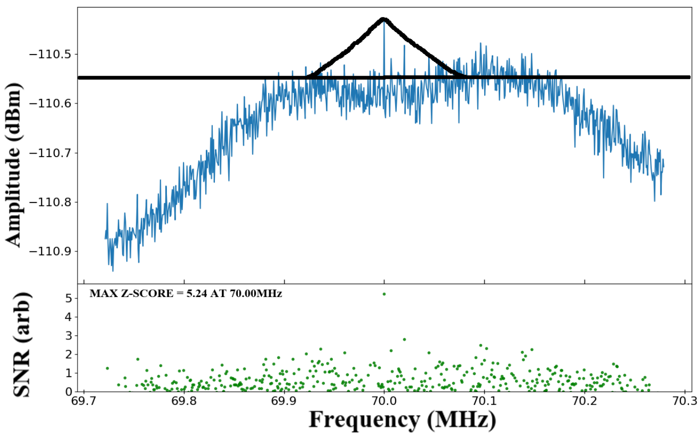


Figure 9: proposed filtering to only compare each bin to it's nearest neighbors.

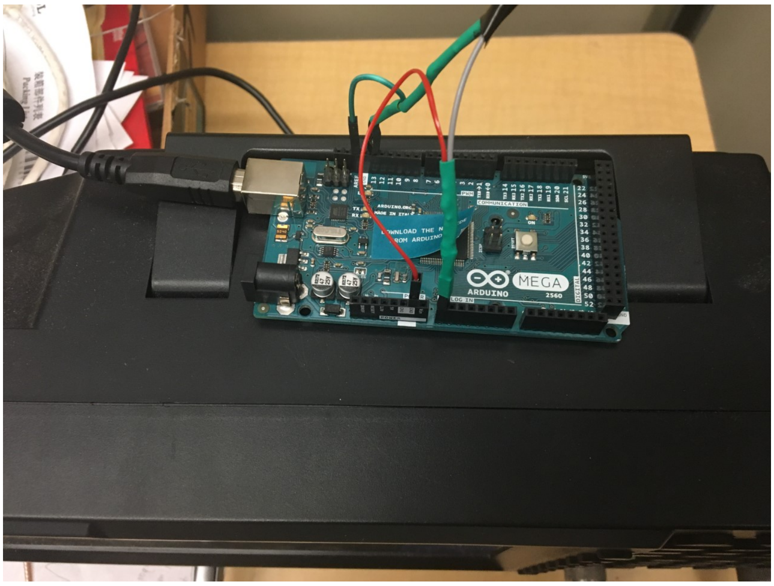


Figure 10: The Arduino based temperature collection system. The actual probe was placed on top of the shielded room close to an exhaust fan.

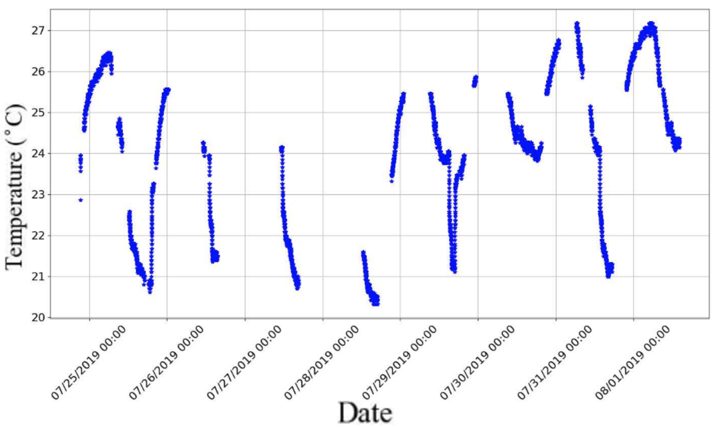


Figure 11: The temperature vs time measured by the probe. Large gaps in data show the high percentage of down time in the data acquisition system.

References

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