Listening for Dark Photons

HEP-Exchange

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12/2/17

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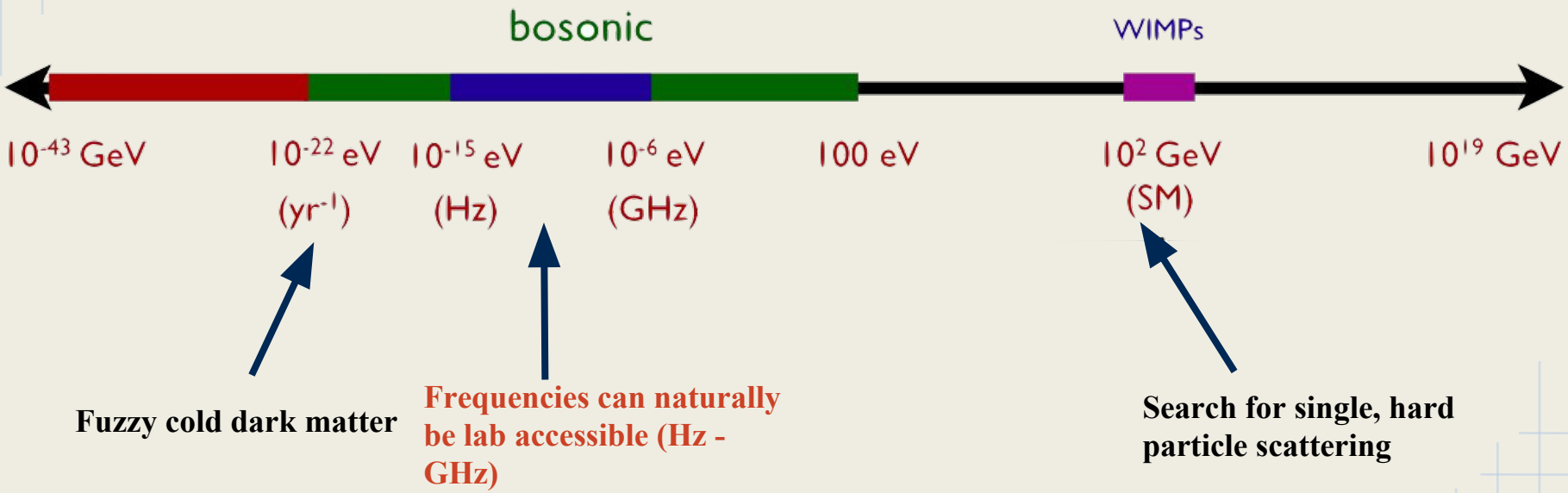
What is Dark Matter?

- Really hard question to answer
- Cosmological and astronomical observations (flat rotation curves, weak lensing, Bullet cluster, etc.) provide indirect evidence
- No direct evidence but not for lack of trying

Dark Matter Landscape



Moral of the story: Lots of unexplored phase space in the low mass regime

Portal to the Dark Sector

- Ultralight massive vector boson (*dark photon*) could be a messenger to the dark sector and may even constitute dark matter
  - Old idea: Dates back to 1986 (Holdom, Phy. Lett B166)

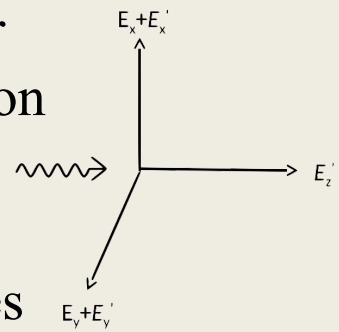
- Would kinetically mix with the (normal) photon

- Naturally produced by quantum fluctuations during inflation

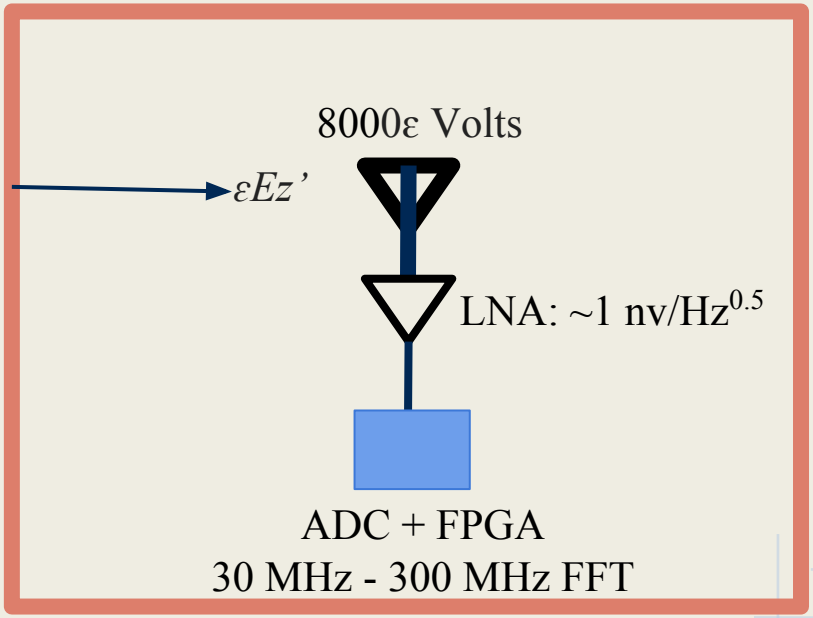
- Question: How do we detect this dark matter candidate?
  - What is its mass?
  - How strongly does it couple to the photon?

UC Davis Experiment

- Femtovolt search for ultra-light dark photon
- Massive photon will contain longitudinal *and* transverse modes (Proca equation)
- Classical/dark transverse modes shielded

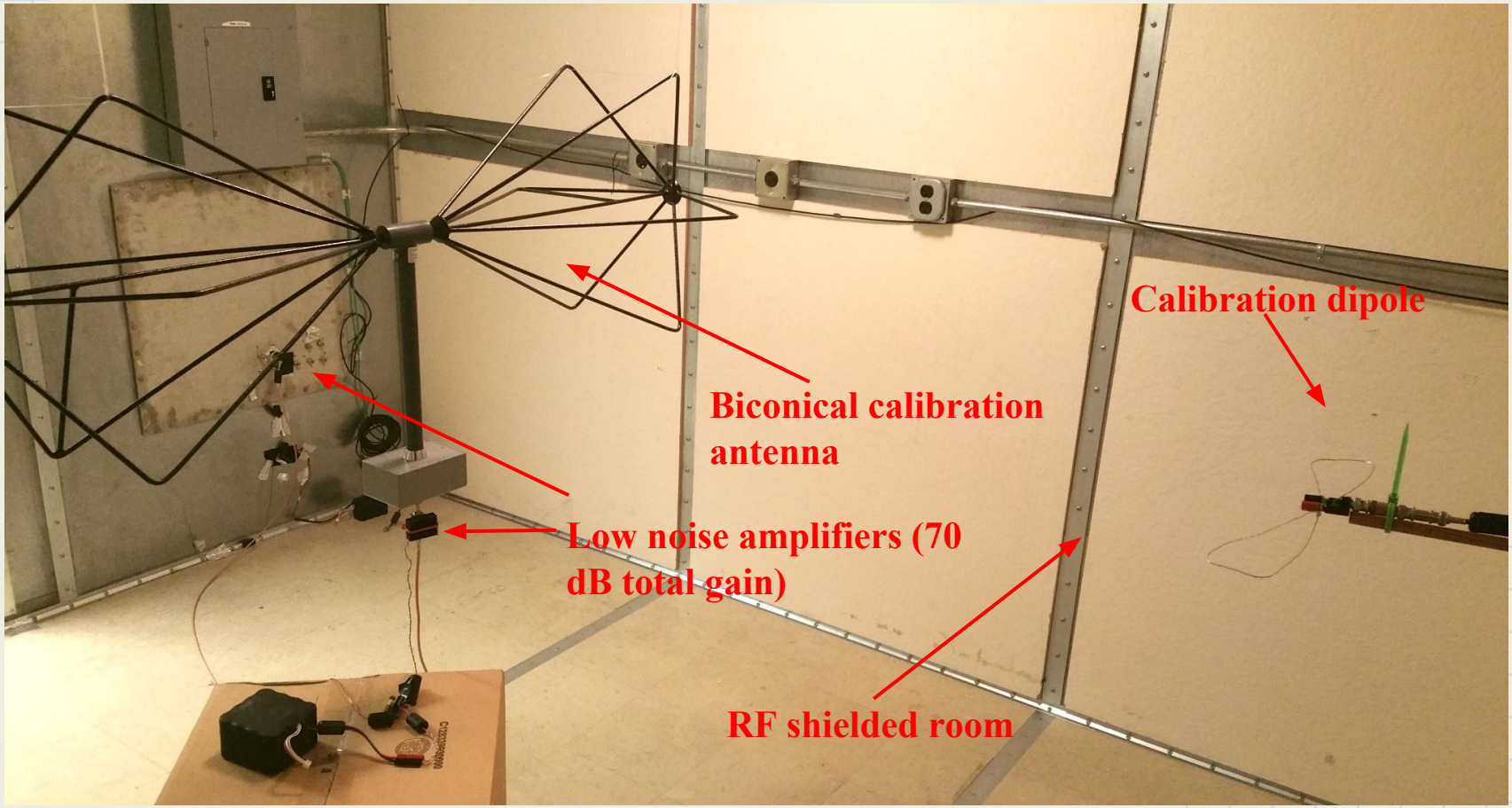


Inner EM shield 3.5m x 2.4m x 3.5m



- Assuming a large shield (compared to de Broglie wavelength) longitudinal mode unaffected
- Search through frequency space for unknown frequency looking for an anomalous source of EM power
- Rather than tune high Q detector over wide frequency range, do parallel FFT search for high Q signal

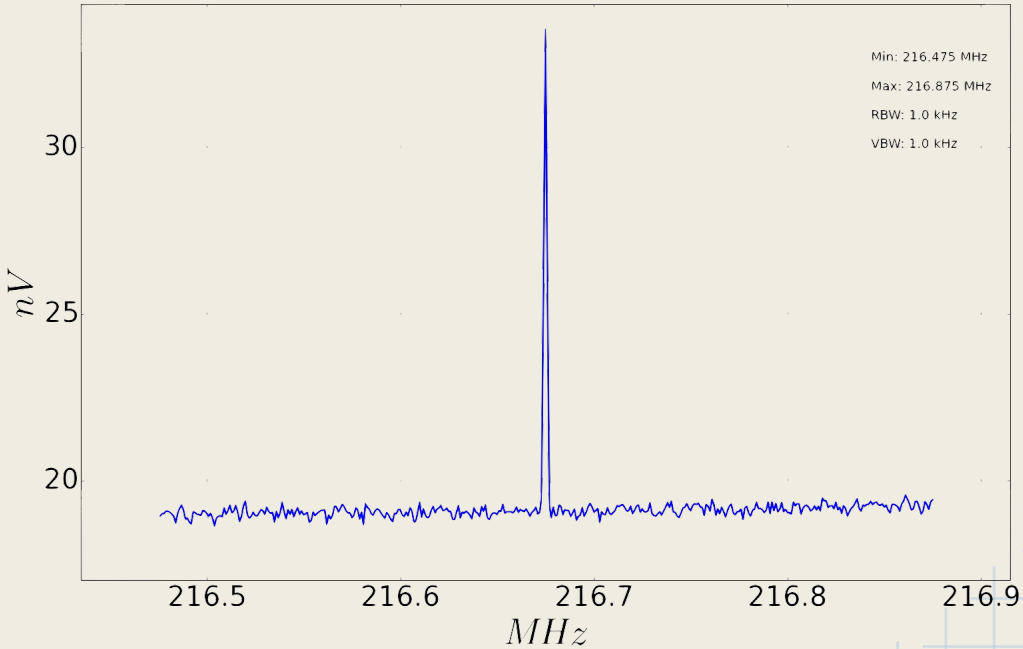
Picture of Current Setup



Calibration setup

What Will The Signal Look Like?

- Velocity spread of dark matter field gives frequency spread of $\sim 10^{-6}$
- At 100 MHz → $\Delta\nu$ = 100Hz
- Resolution bandwidth ~1kHz
- Candidate signal will look like a δ-spike at the frequency of interest



Output from system with -115 dBm = 3.16 fW injected signal at 216.675 MHz

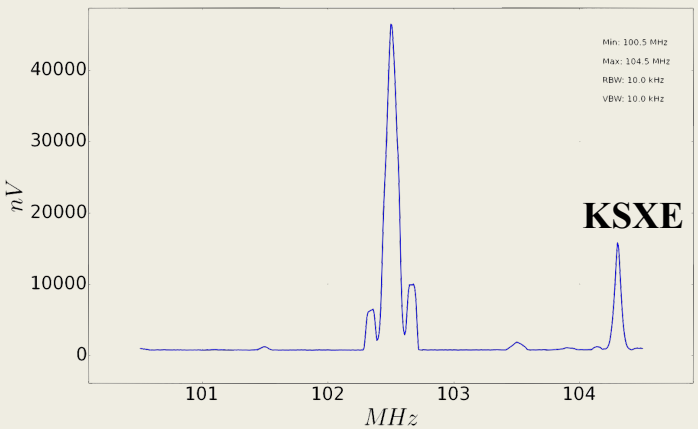
How Large a Signal Do We Predict?

- Dark photon has a high enough number density that it acts like a coherent field (*hidden electric field*)
- From cosmological/astronomical observations: $\rho_{DM} = 0.3\frac{\mathrm{GeV}}{\mathrm{cm}^3} = 4.6 * 10^{-5}\frac{\mathrm{J}}{\mathrm{m}^3}$
- Assume energy in antenna as capacitor: $\frac{1}{2}\int_C \epsilon_0 E_{obs} d^3x = \frac{1}{2}CV^2$ where $E_{obs} = \epsilon E' = \epsilon\sqrt{\epsilon_0 \rho_{DM}}$ and ε is the coupling strength
- For a short antenna of total length, *l*, modeled as a capacitor of area *A* the effective volume is *Al* and the capacitance is $C = \epsilon_0 \frac{A}{l}$
- Then **V_{obs} ~8000ε for l = 1m** → **your cellphone (or multimeter) has already set limits on m and ε**

How Large a Signal Can We See?

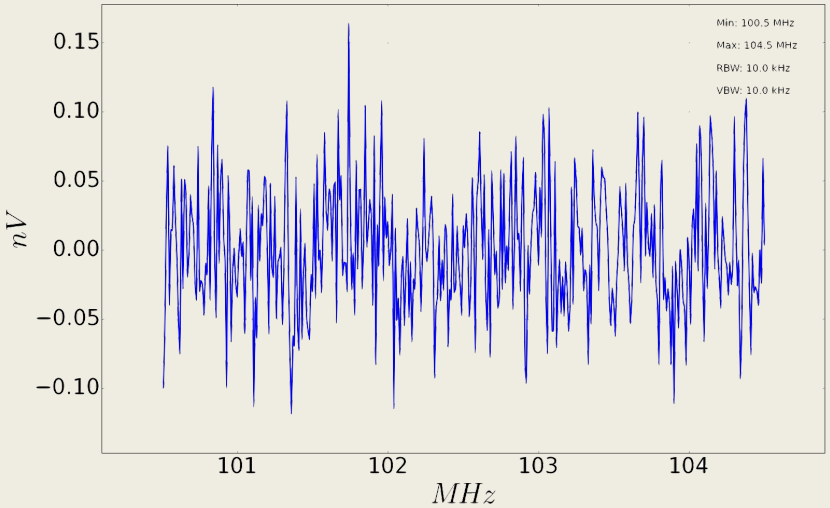
Depends, in part, on the shielding capability of our room

KSFM



Listening to KSFM (50 kW transmitter ~ 10 miles from the lab) at 102.5 MHz with the shielded room door open

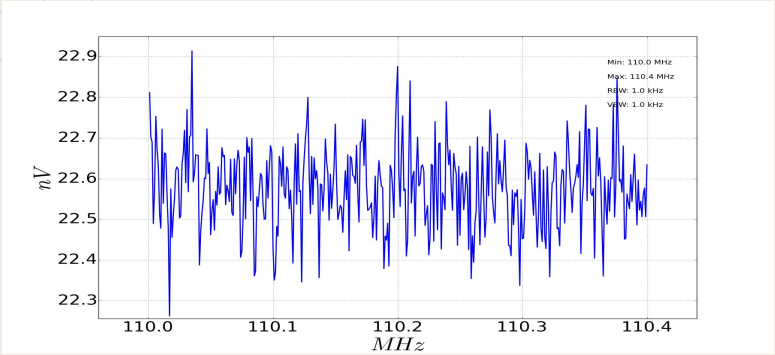
RMS: 47.1 pV



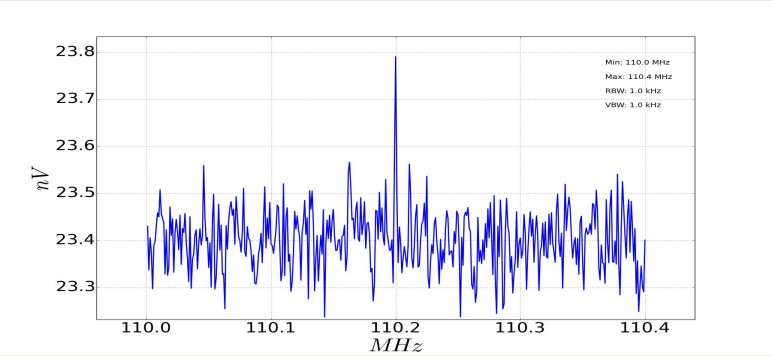
Listening to KSFM with the door closed (baseline offset removed)

SHIELDING ABILITY
5σ detection limit:
$20*\log_{10}(46{,}440/(5*0.0471)) =$ 106 dB lower limit
Typical RF background of 1mV/m attenuated to 5 nV/m

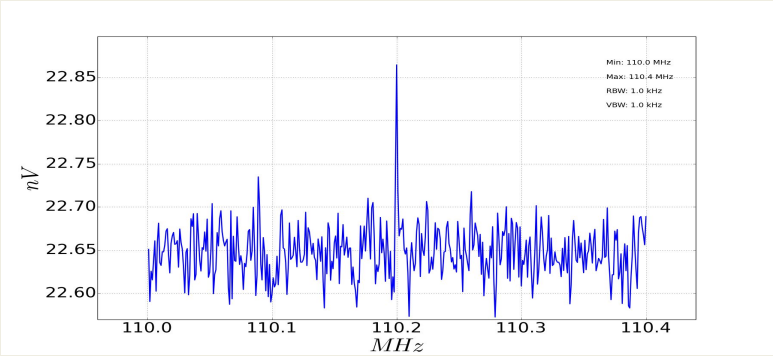
How Long Do We Take Data For?



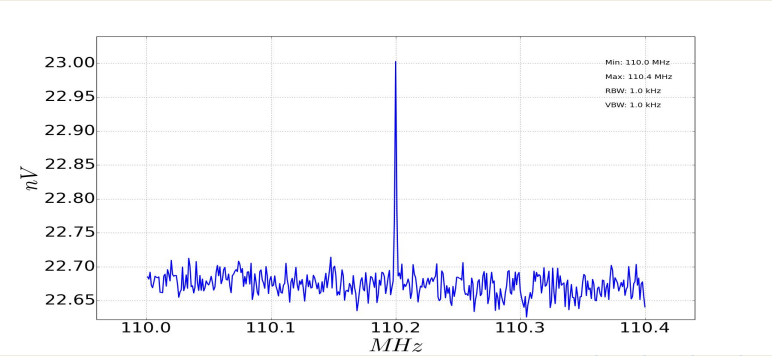
6 seconds



12 seconds



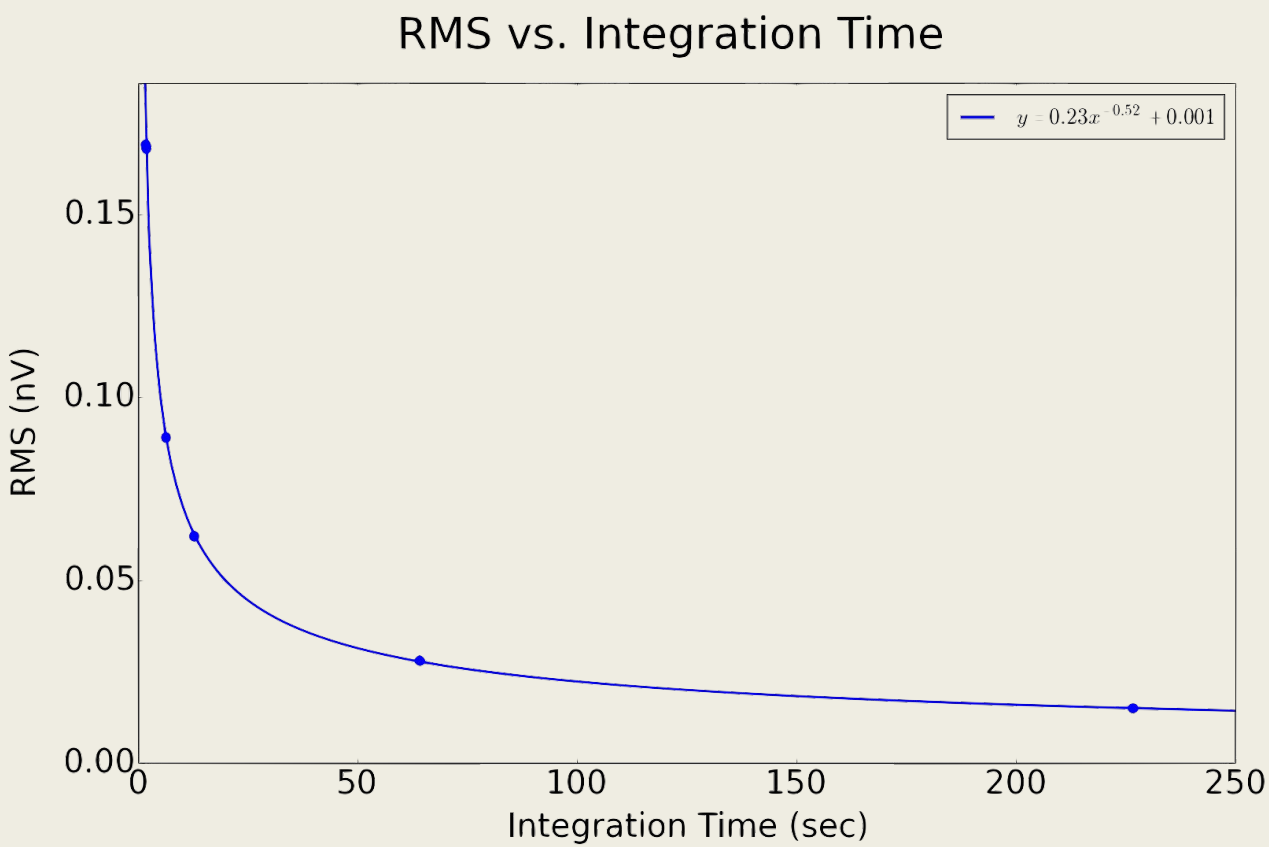
1 minute



3.75 minutes

Pulling a -117 dBm = 2fW signal at 110.2 MHz out of the noise by increasing integration time

RMS Dependence on Integration Time



Noise RMS proportional to square root of integration time

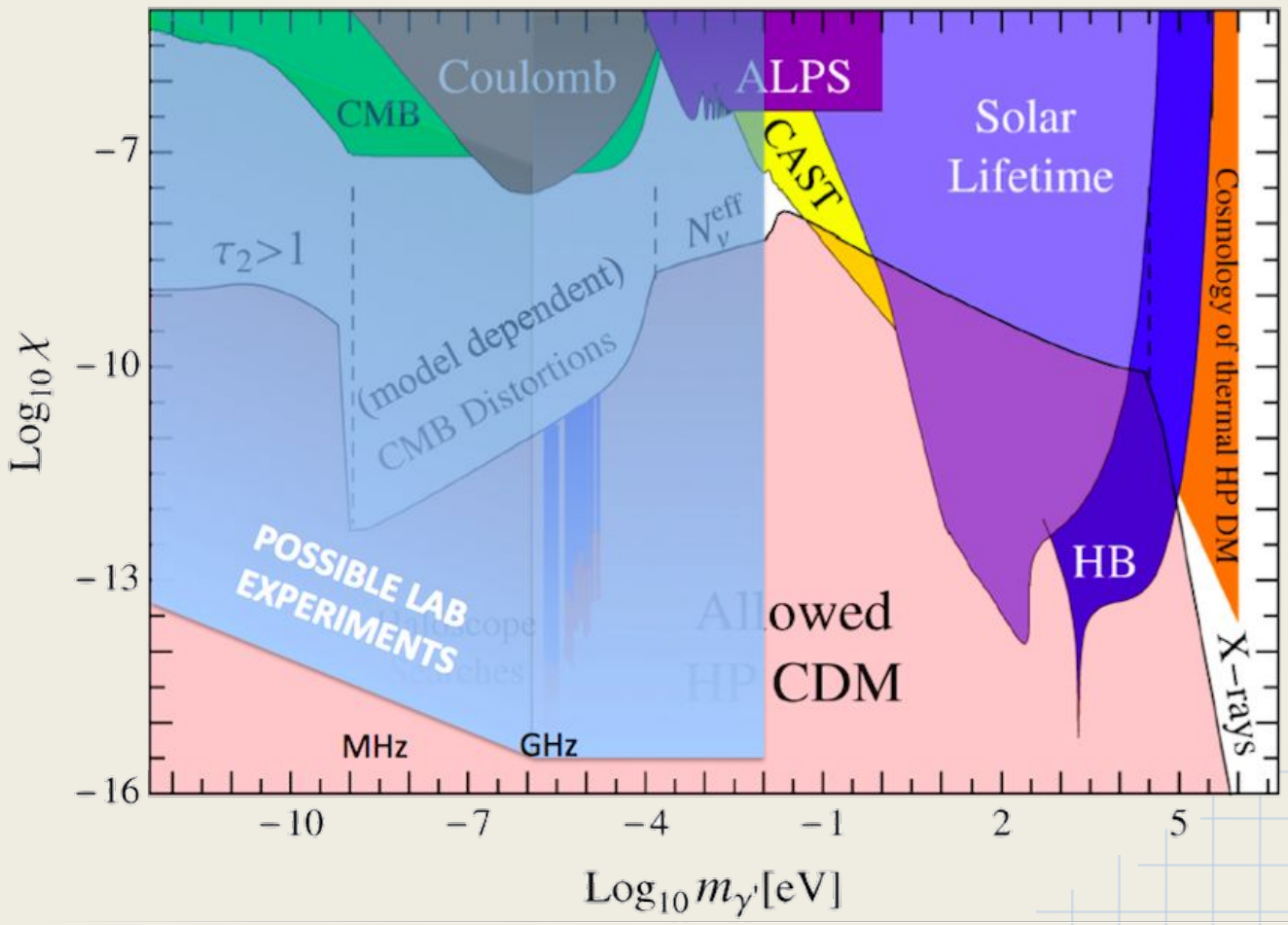
What Does This Say About The Limits We Can Set on ε?

Total Integration Time (10 MHz bandwidth)	Total Experiment Time	ε
1 hr	1 day	5.5E-14
10 hr	1.5 weeks	2.6E-16
1 day	1 month	2.1E-16
1 week	6 months	1.6E-16
1 month	2 years	1.4E-16

Limits on ε assuming resonant dipole with 10MHz bandwidth and mass search range from 30MHz to 300MHz

* Rough estimate (assumes 100% duty cycle and 1m dipole)

How Competitive are These Limits?



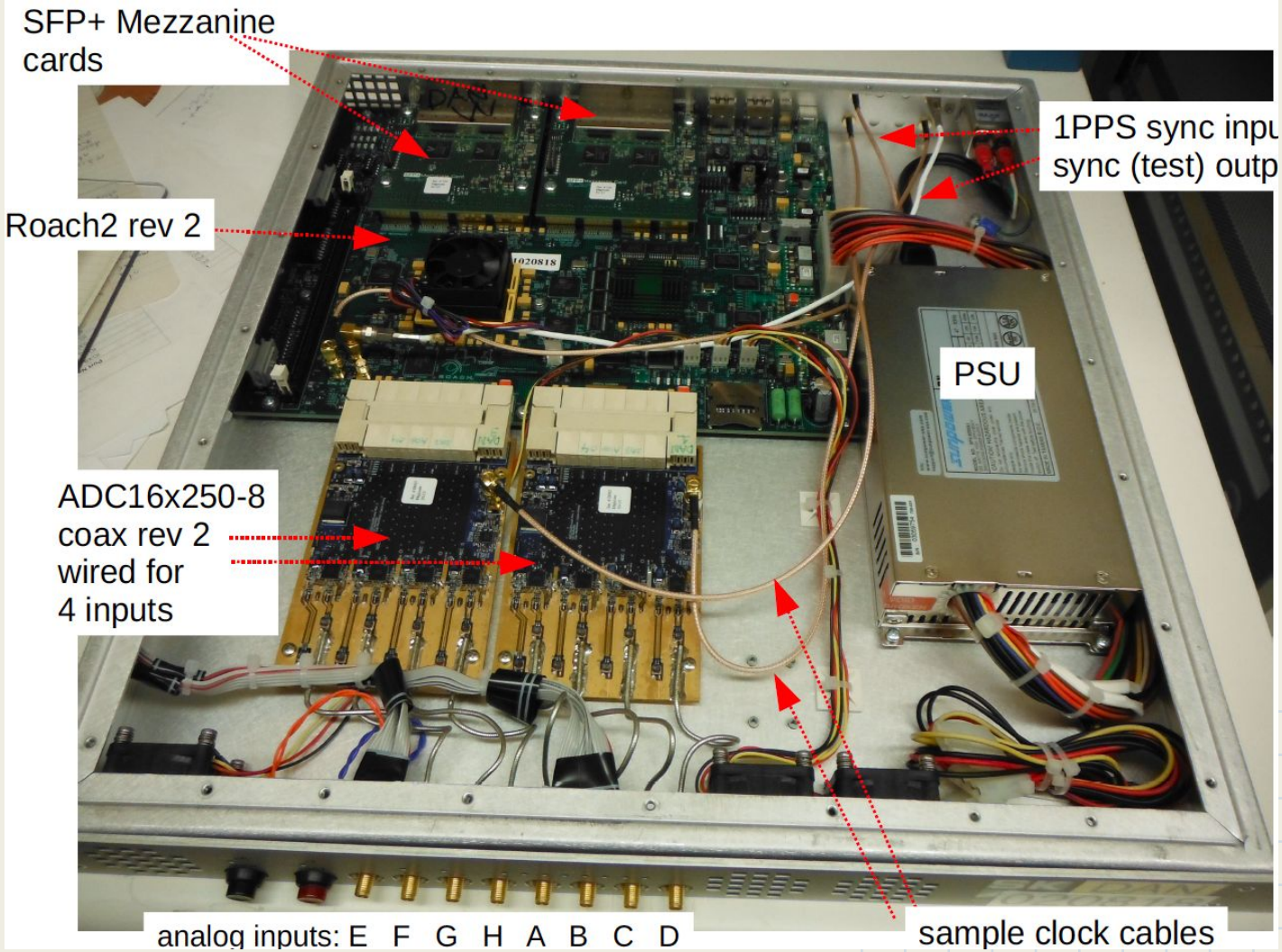
Data Acquisition System

- Currently using an Agilent spectrum analyzer for data acquisition
  - No FFT capabilities (slow)

- Installing a ROACH-2 test machine for data acquisition
  - Dedicated FPGA for sampling above 100Msps
  - Commercial design (hardware already designed)
  - Wide 100 kHz - 300 MHz FFT range
  - Front end ADC

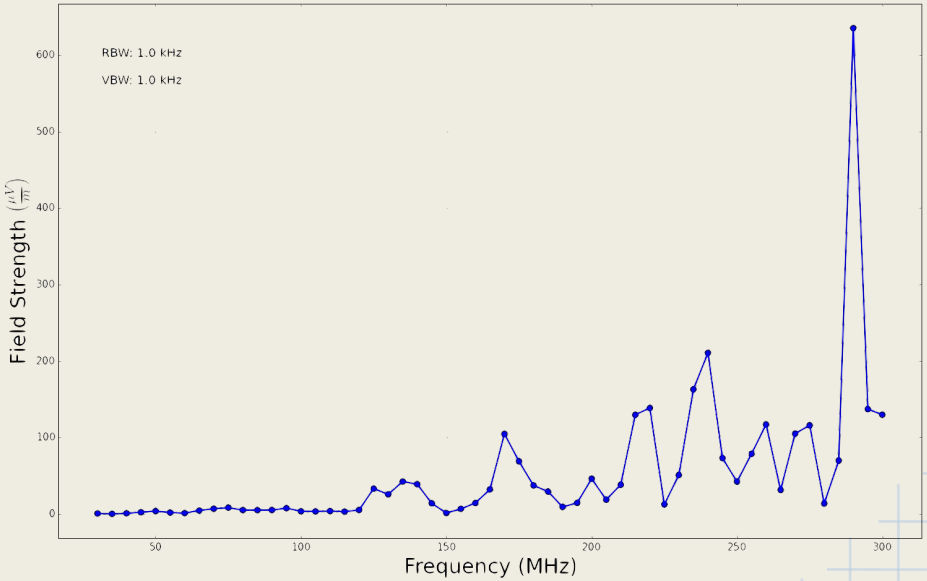
- Will store raw waveforms for offline data analysis (system still being designed)

Upgraded Data Acquisition System



What are We Doing Now?

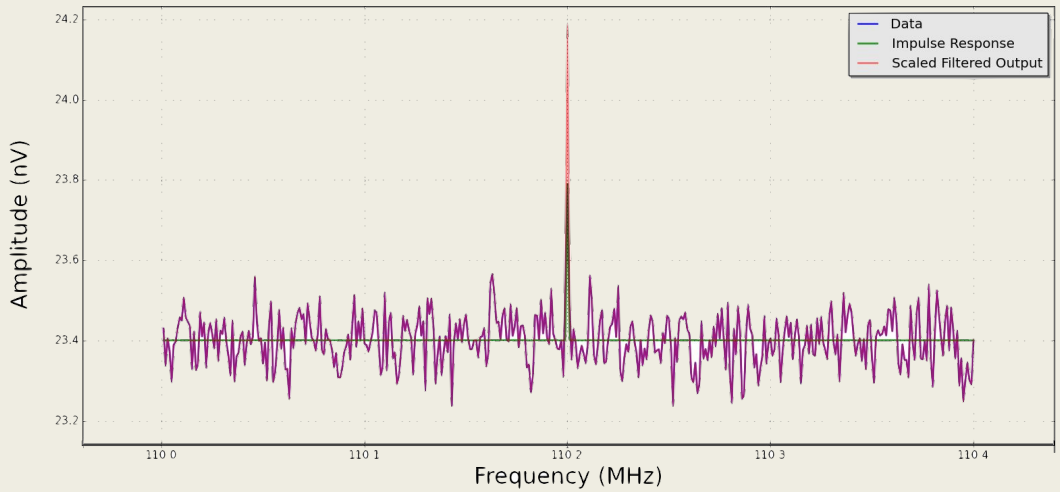
- Calibration
  - Ultimate design will have a series of resonant dipoles that need to be calibrated
  - Need to have a good understanding of the electric field at the dipole to be able to extract a coupling value
- Using a calibrated biconical antenna, we use a calibration dipole to inject signal into the room and determine field strength



Electric field strength at biconical antenna for an input power of 25 nW

What are We Doing Now?

- Since the shape of the signal is known can we use a matched filtering technique to maximize SNR?
- Go through each frequency bin and apply the (constant energy) template
- Set threshold to determine detection



Proposed filter: Constant baseline set to average of all data not at frequency of interest

Conclusions

- The dark photon is an interesting non-WIMP dark matter candidate with strong theoretical motivation
- Experimental setup is simple and based on well established techniques
- Currently deploying hardware and finishing calibrations to start taking data