Recent Results and Current Efforts from BREAD

Astroparticle Symposium 2025

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6 November, 2025

Concept and Motivation

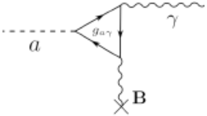
The BREAD Reflector Concept

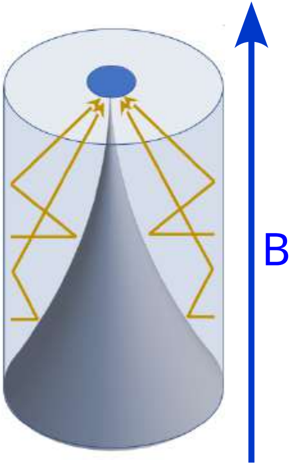
- In the presence of a strong magnetic field, axions cause the emission of photons at the conductive walls of the reflector.
- A parabolic reflector is placed in the middle of the cylinder to focus the photons onto a point.

Axion induced *E*-field:

$$\boldsymbol{E}_a = -\frac{1}{\varepsilon} g_{a\gamma\gamma} \boldsymbol{B}_{\mathrm{ext}} a$$

Coupling through Primakoff Effect:





Reflector compared to Resonant Cavity

Resonant Cavity:

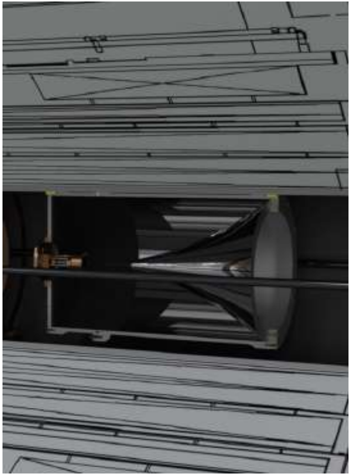
- $P_{\text{sig}} \propto QB^2V$
- Narrowband
- Resonant enhancement
- Volume becomes very small for short wavelength signals

Reflector:

- $P_{\text{sig}} \propto B^2A$
- Broadband
- Minimal to no resonant enhancement
- Area can be kept large even for short wavelength signals

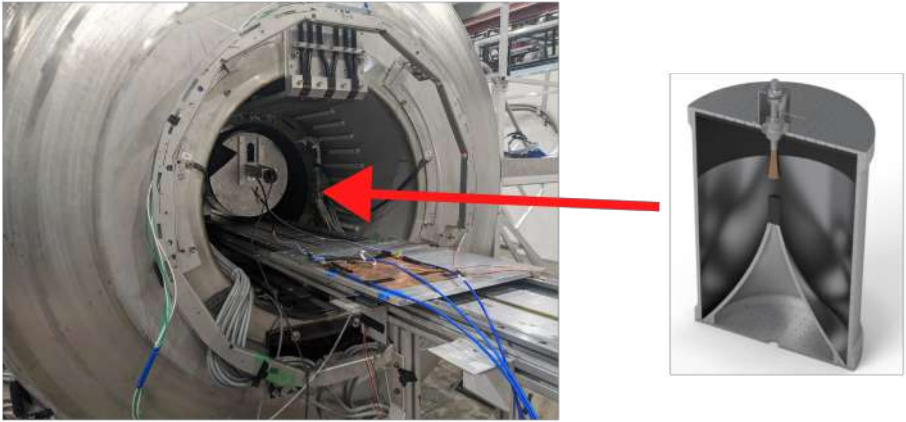
$\implies$ Reflectors are a compelling technology to push axion sensitivity to mm-wave and beyond!

A Reflector Designed to Fit Inside Large Solenoid Magnets

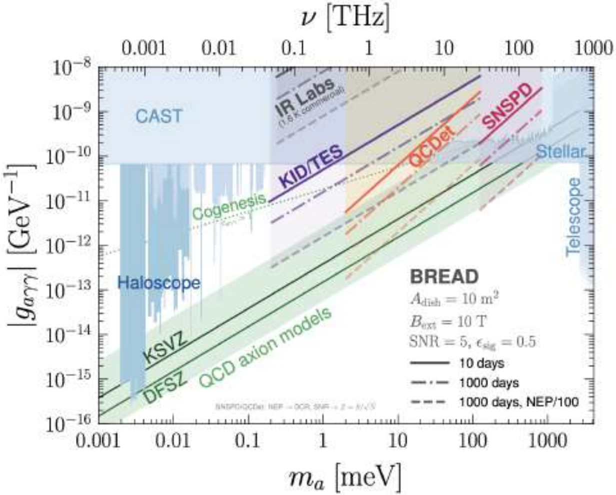


A Reflector Designed to Fit Inside Large Solenoid Magnets

- A BREAD reflector in a real solenoid magnet at Argonne National Laboratory!



BREAD as a Platform for Different Sensor Technologies

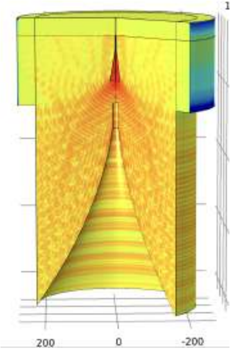


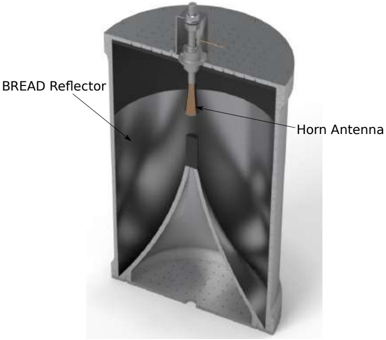
GigaBREAD Pilot

GigaBREAD

- GigaBREAD is the GHz BREAD pilot designed to look for axions and dark photons in the 10.7-12.5 GHz range
- In the GHz regime, the reflector can be coupled to a microwave horn antenna

COMSOL RF Simulation





Custom coaxial horn antenna

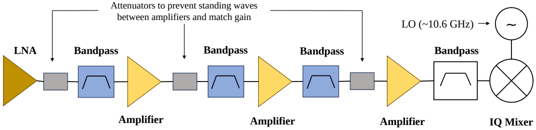
The GigaBREAD Reflector

$A = 0.5\ \mathrm{m}^2$

Amplifier Chain And DAQ

- Low noise receiver chain using off-the-shelf parts.

GigaBREAD RF Amplifier Chain



LNA: +28 dB
LNF-LNR10-30A
$T_N = 120K$

Bandpass Filters: -8 dB each
ZXHF-K14M + ZXLF-K133

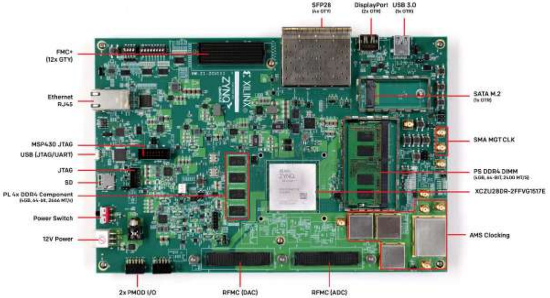
Amplifiers: +27 dB each
ZX60-24A-S

IQ Mixer: -12 dB
MMIQ-0520HS

Attenuators: -3 dB each

Total gain: ~70 dB

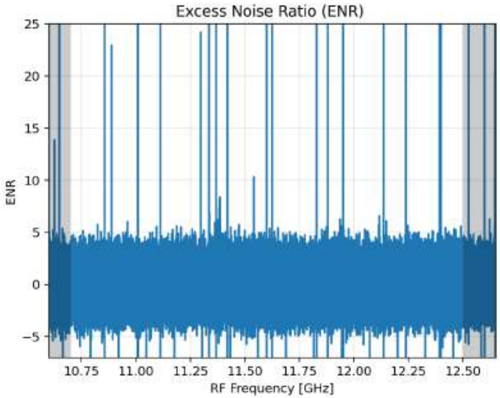
- FPGA board with qick firmware performs realtime fast fourier transforms using a 4 GSPS ADC allowing for a 2 GHz bandwidth.



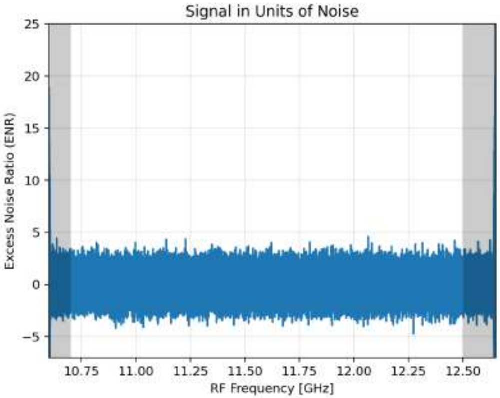
LO Frequency Hopping: RFI Rejection Scheme

- Shifting the LO frequency while taking data can reduce RFI from the readout band

Without LO hopping:

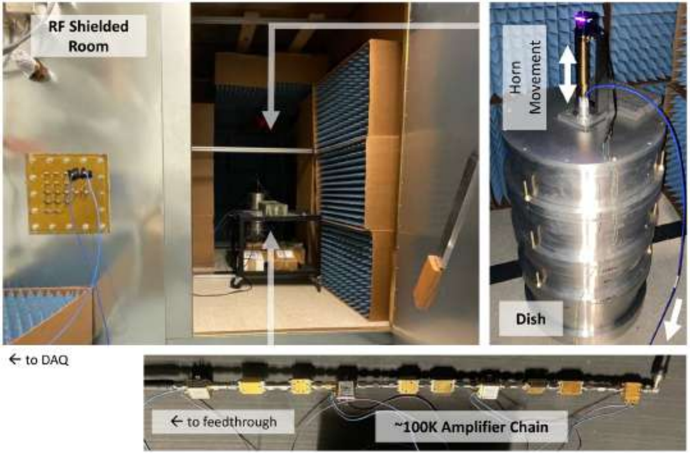


With LO hopping:



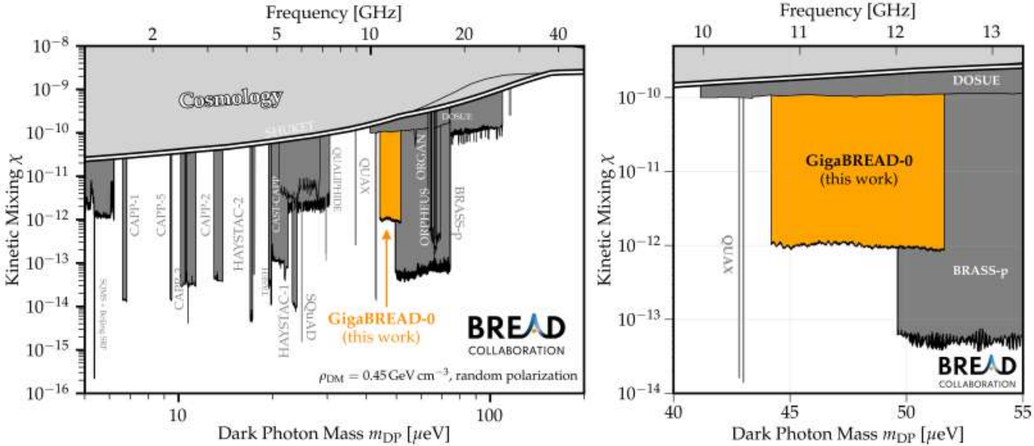
Setup

- Data was taken for $\sim$ 24 days
- During data taking, the reflector, antenna, and amplifier chain were inside an RF-shielded room
- Data is taken at different antenna positions
- Antenna passes through the focal spot every $\sim$ 4 hours



Dark Photon Limit

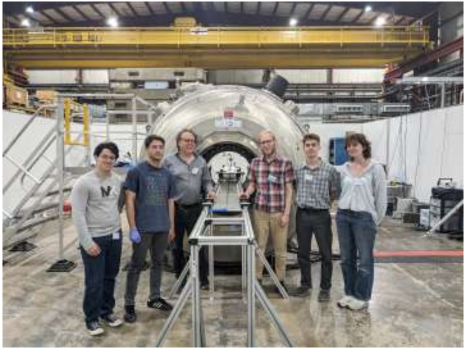
PRL 132 (2024) 131004



Plots modified from `https://cajohare.github.io/AxionLimits/`

ALPs at Argonne

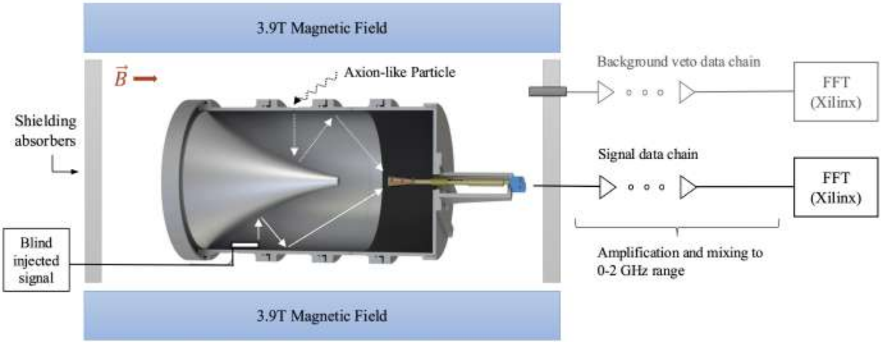
- We took data in a 3.9 T field using an MRI magnet at Argonne National Laboratory
- We were able to take $\sim$ 3 days of data at a system noise temperature of ~ 400 K and $\sim$ 27 days at a system noise temperature of ~ 600 K.



Installing Shielding

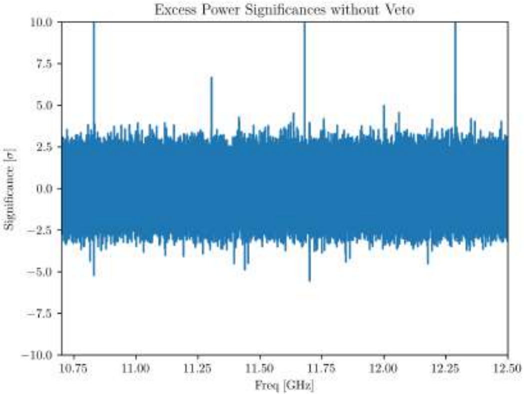
Background Veto Antenna for ALPs at Argonne

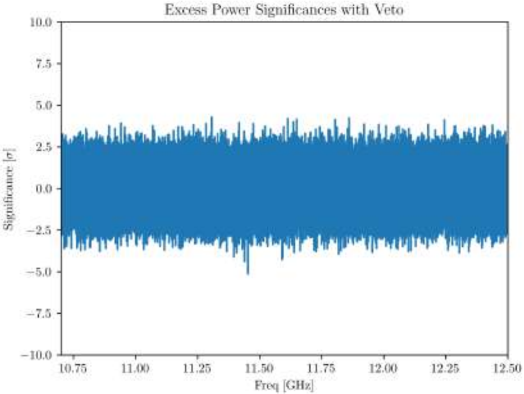
- The environment around the ANL MRI magnet was full of backgrounds
- To mitigate backgrounds, a second antenna was used to mask frequency bins with significant backgrounds



High Frequency Background Rejection

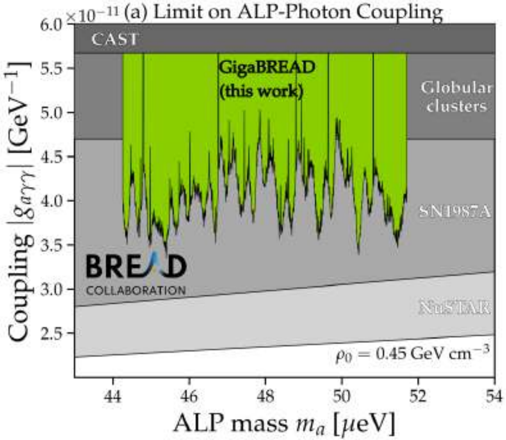
- For the ALP search at Argonne, a separate antenna and amplifier chain was used to monitor backgrounds and mask bins accordingly

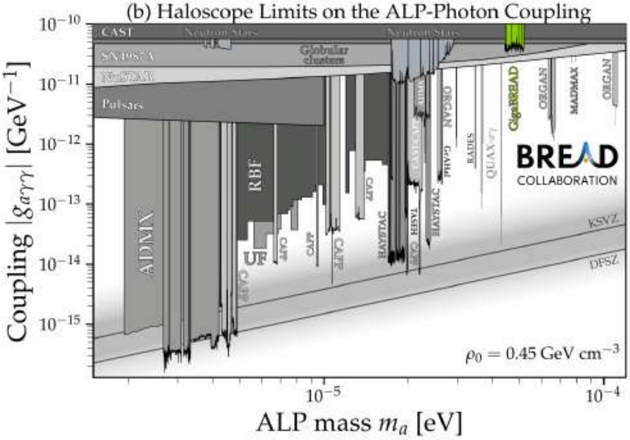




ALP Limit

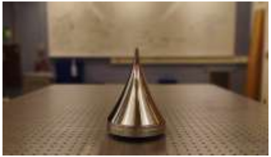
PRL 134 (2025) 171002

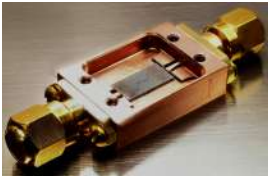


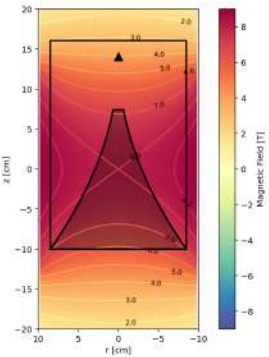


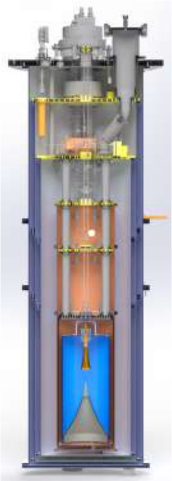
Work in Progress and Next Steps

Quantum-Limited GigaBREAD



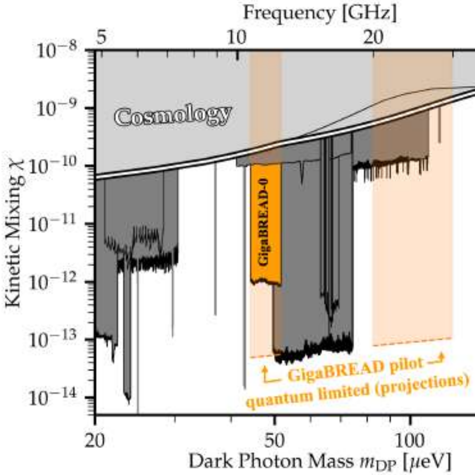


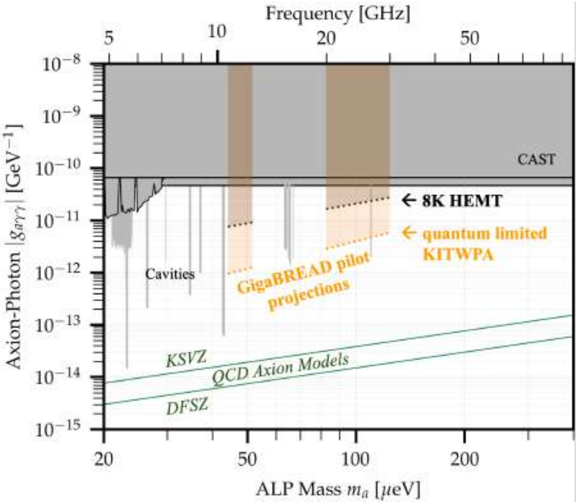




- Our collaborators at Harvard are developing a quantum-limited, cryogenic version of GigaBREAD using a smaller reflector, a KI-TWPA from NIST, a dilution refridgerator, and an 8 T magnet.

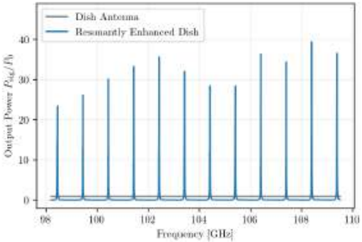
Projected Sensitivities

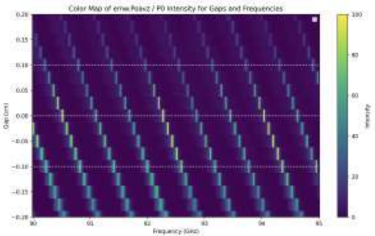




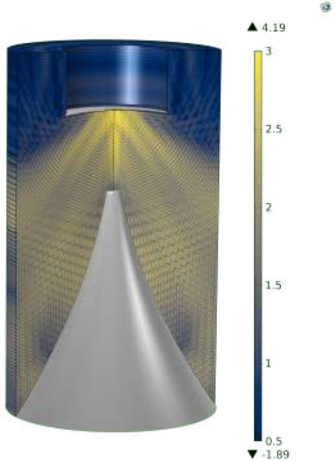
QualityBREAD

- Replacing an antenna with a secondary mirror we can add a small resonant enhancement.

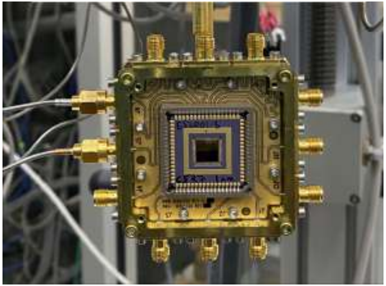


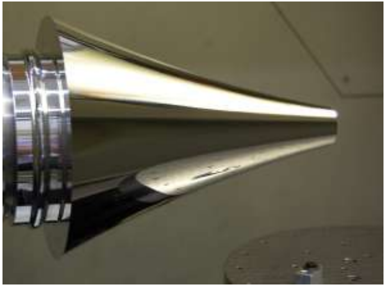


- Resonances can be tuned by changing the separation between the mirrors.



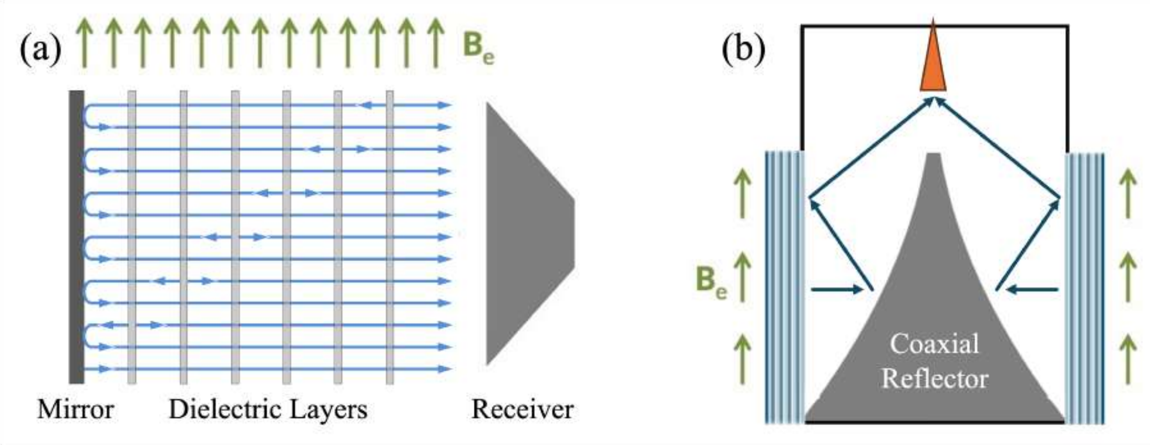
InfraBREAD



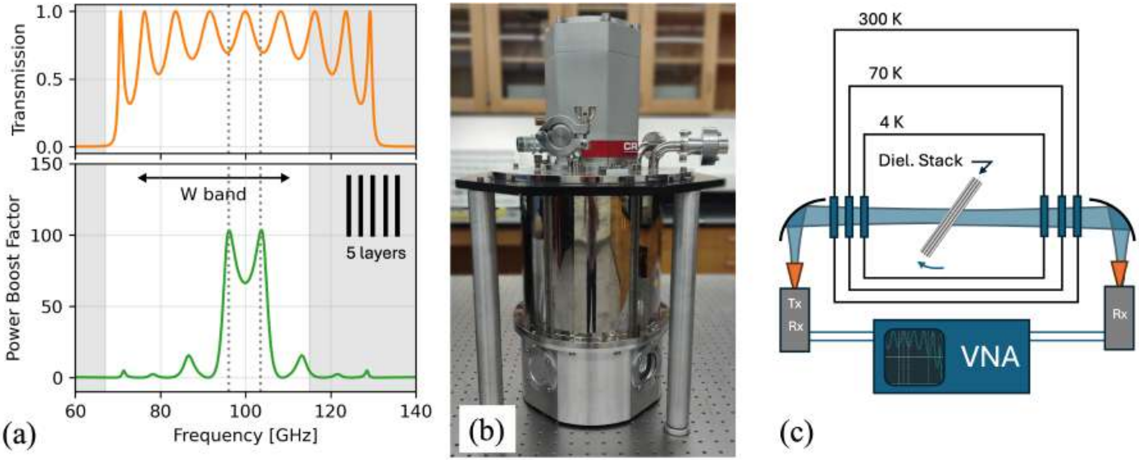


- SNSPDs with 1 mm^2 active area and lower threshold are being tested for use with BREAD.
- An optical-grade reflector has been diamond-turned at Lawrence Livermore National Laboratory.
- Efforts are underway to characterize the beam of the InfraBREAD reflector at FNAL.

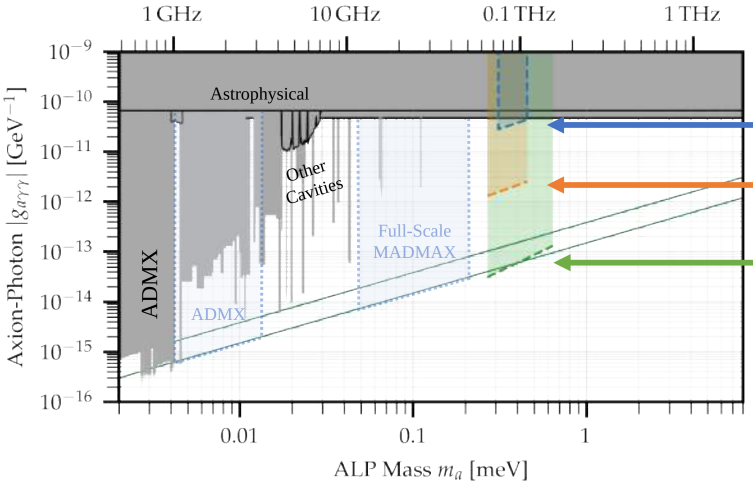
Dielectric Enhancement



Dielectric Characterization



Future Prospects



TeraBREAD Phase I
e.g., QualityBREAD

TeraBREAD Phase II
$A = 2\text{m}^2, B = 9.4\text{T},$
$\beta^2 \sim 100$
off-the-shelf amplifiers

TeraBREAD Phase III
$A = 7\text{m}^2, B = 20\text{T},$
$\beta^2 \sim 1{,}000$
quantum limited amplifier

Large-Scale Facility at FNAL

Fermilab Dark Wave Lab Workshop

Apr 15 – 16, 2024
Fermilab

ADMX AXION DARK MATTER EXPERIMENT

BREAD

MADMAX

UNIVERSITY of WASHINGTON

DESY.

東京大学 THE UNIVERSITY OF TOKYO

9.4 T Magnet at FNAL

Thanks!

BREAD Collaboration:

Pete Barry, Clarence Chang, Juliang Li, *Argonne National Laboratory*

Jesse Liu, *University of Cambridge*

Kristin Dona, Gabe Hoshino, Alex Lapuente, Mira Littmann, David Miller, Max Olberding, *University of Chicago*

Daniel Bowring, Gustavo I Cancelo, Claudio Chavez, Aaron Chou, Mohamed Hassan, Benjamin Knepper, Stefan Knirck, Samantha Lewis, Matthew Malaker, Cristian Pena, Andrew Sonnenschein, Leonardo Stefanazzi, Christina Wang, Kevin Zvonarek, *Fermilab*

Rakshya Khatiwada, Jialin Yu, *Fermilab and Illinois Institute of Technology*

Stefan Knirck, Alex Buzzi, I-see Jaidee, Grant McIntyre, Larom Segev, Johnny Miri, Jasmine Palma, Steven Su, Jian Wang-Munoz, *Harvard University*

Gianpaolo Carosi, *Lawrence Livermore National Laboratory*

Karl Berggren, Dip Joti Paul, Tony (Xu) Zhou, *Massachusetts Institute of Technology*

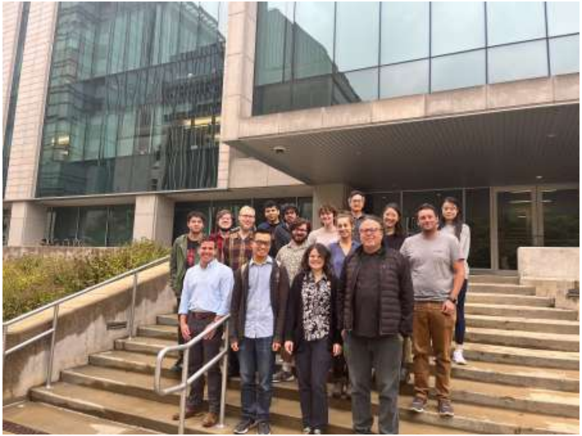
Omid Noroozian, *NASA Goddard Space Flight Center*

Sae Woo Nam, *National Institute of Standards and Technology*

Huma Jafree, *Randolph-Macon College*

Chiara Salemi, *University of California Berkeley*

Noah Kurinsky, *SLAC*



Also Special Thanks to:

Peter Winter, Simon Corrodi, *Argonne National Laboratory, Muon g-2*

Backup

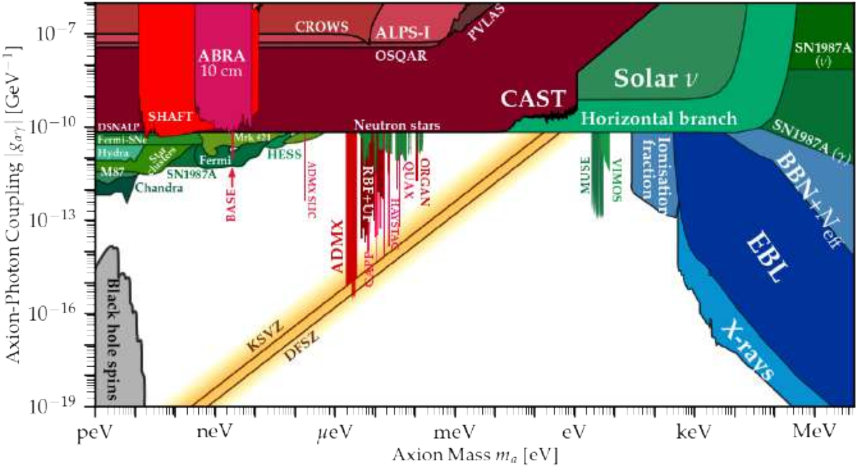
The QCD Axion

- The strong force is expected to violate CP symmetry via the following term in the QCD Lagrangian:

$$\mathcal{L}_{\mathrm{QCD}} \supset \theta \frac{g^2}{32\pi^2} G\tilde{G}$$

- Roberto Peccei and Helen Quinn have explained the lack of any observed CP violation by introducing the axion.
- Couplings between the axion and standard model particles can be feeble, making it a good dark matter candidate.

Axion Parameter Space



https://cajohare.github.io/AxionLimits/

Setting up the Simulation in COMSOL

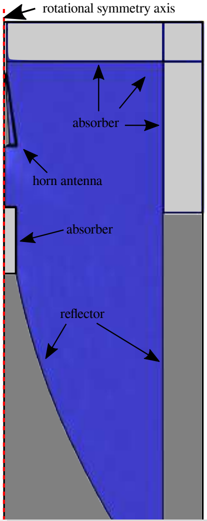
- The axion and dark photon fields modify Maxwell's equations by adding new sources for EM fields.
- We implement this in COMSOL by treating the axion/dark photon excitations as a space-filling oscillating current with a direction which is parallel/anti-parallel to the direction of the magnetic field in the experiment.

$$\frac{\partial^2 \vec{E}}{\partial t^2} - \nabla^2 \vec{E} = -\frac{\partial \vec{J}_{\text{eff}}}{\partial t}$$

$$\frac{\partial^2 \vec{B}}{\partial t^2} - \nabla^2 \vec{B} = \nabla \times \vec{J}_{\text{eff}}$$

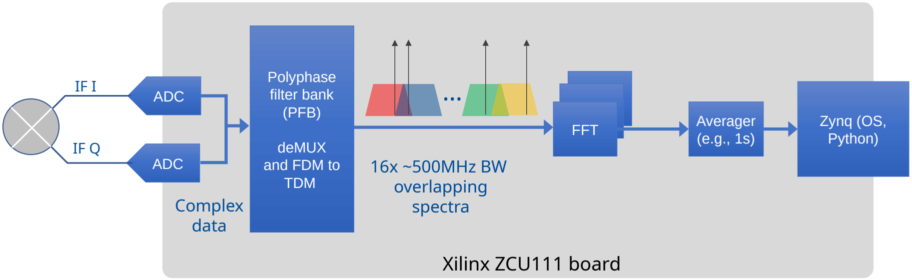
Setting up the Simulation in COMSOL

- Simulations are performed using the RF module in COMSOL.
- The rotational symmetry of our reflector allows us to solve for the EM fields in 2D.
- Boundary conditions are set for the reflector and horn antenna based on their material properties.
- Absorbers are implemented using scattering boundary conditions and perfectly matched layers.



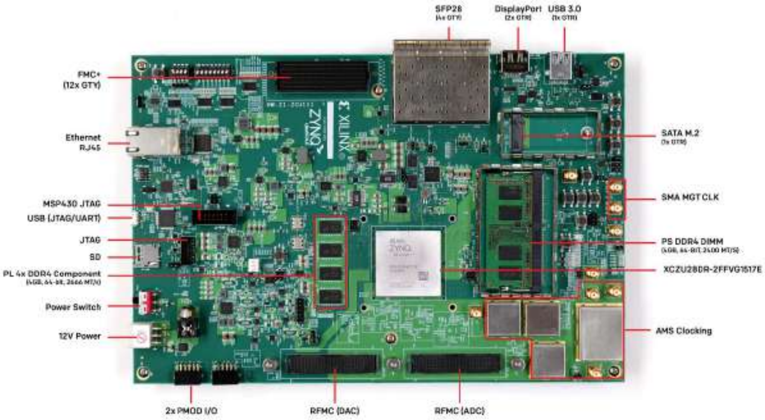
Block Diagram

- The board can sample a 2 GHz bandwidth at a time using a ~ 4 GSPS ADC

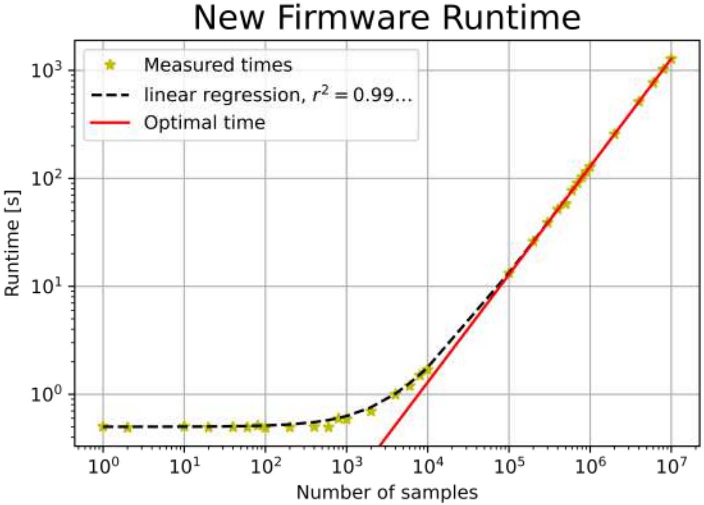


Xilinx ZCU111 Board

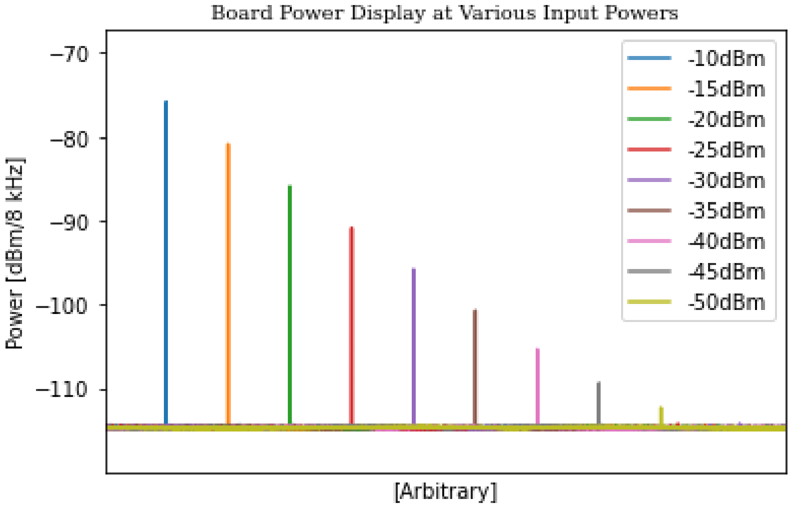
- Performs realtime fast fourier transforms and averaging implemented in the FPGA firmware



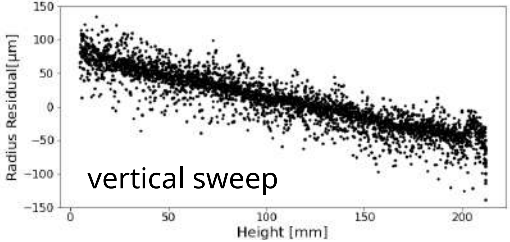
DAQ Firmware Deadtime

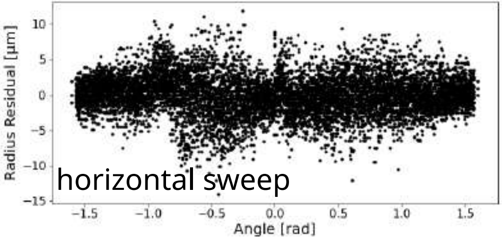


DAQ Firmware Signal Injection



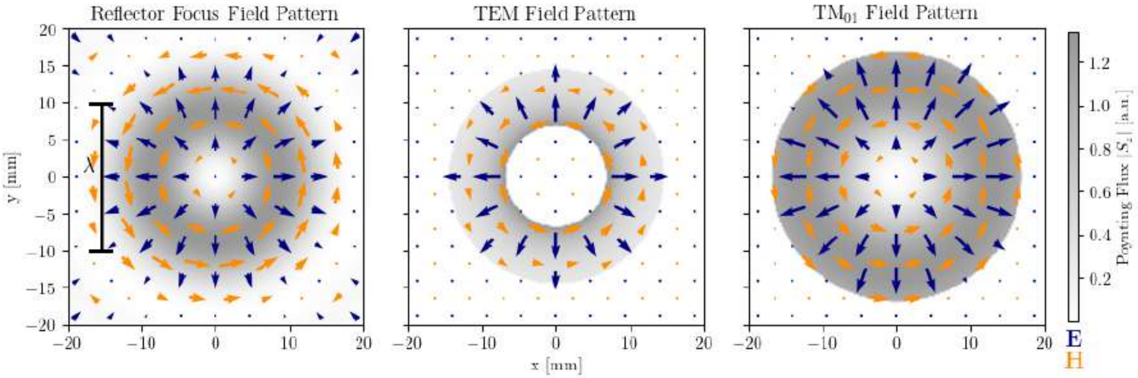
Reflector Surface Characterization with CMM





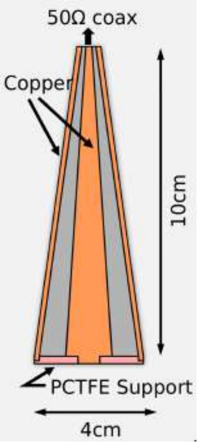
Matching Antenna to the Reflector Beam Shape

- In order to get the best performance, we look for an antenna with a near-field pattern similar to that of the reflector.



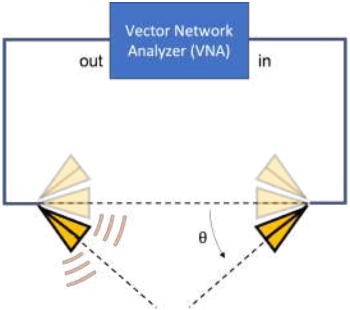
Coaxial Antenna

- Coaxial horn design used for GigaBREAD



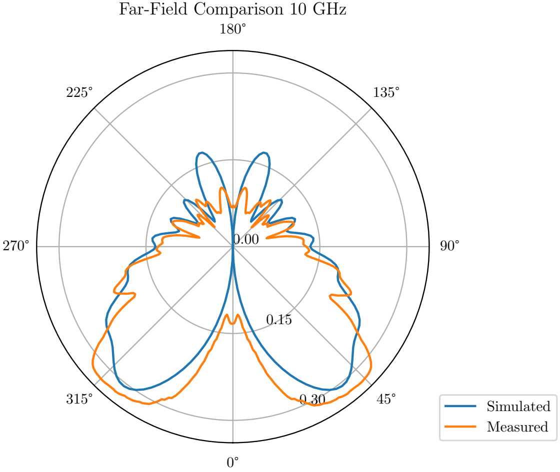
Far-Field Measurement Setup

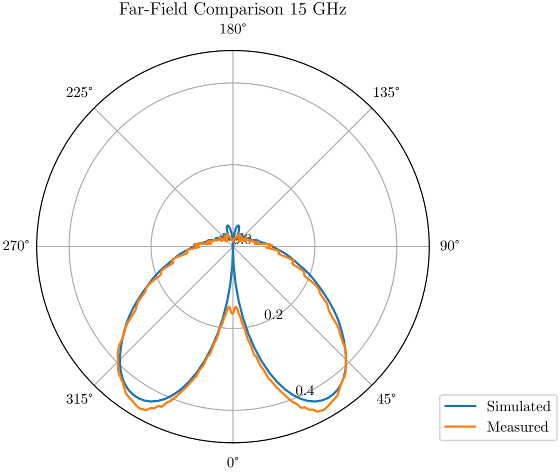
- Horns are mounted on robotic arms in the RF isolation chamber.
- The robotic arms can be made to rotate together as shown on the right which allows us to determine the far-field transmission at different angles.



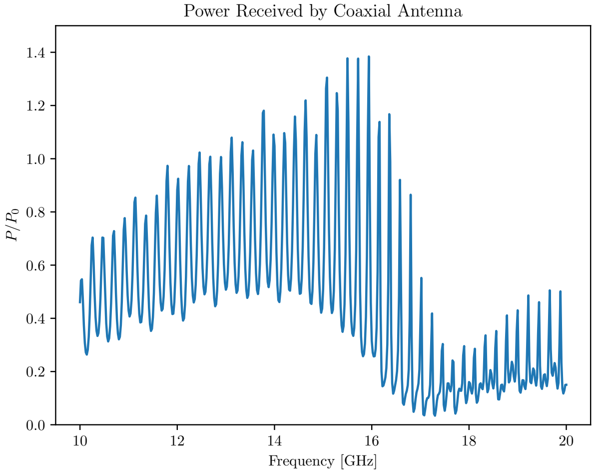
Far-Field Measurement Setup

Far-Field Measurement Results



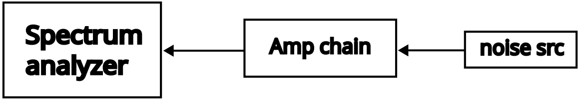


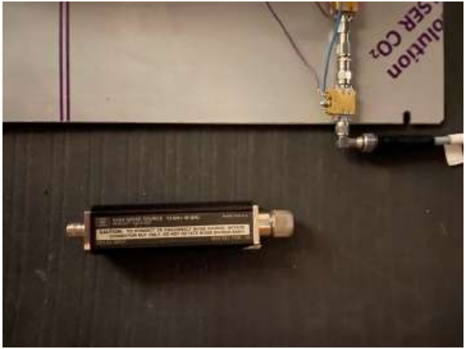
Horn Efficiency



Y-factor Method

- The Y-factor method is a method for measuring the system noise temperature.
- This method is convenient because it allows for the system noise temperature to be measured without first measuring the exact gain of the amplifier chain.
- Using a calibrated noise source which adds a known amount of noise to the amplifier chain input, the noise added by the amplifier chain can be determined.



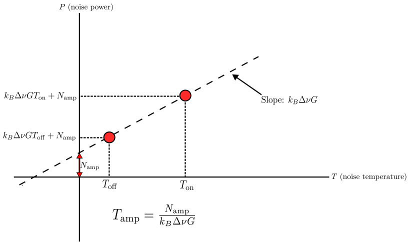


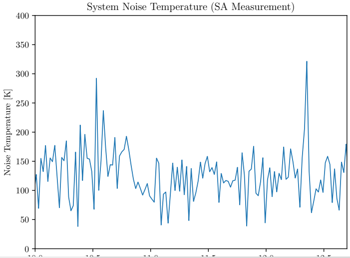
Y-factor Method

- Power spectrum was measured with a noise source connected and either on or off.
- The two measurements were then used to calculate the noise temperature:

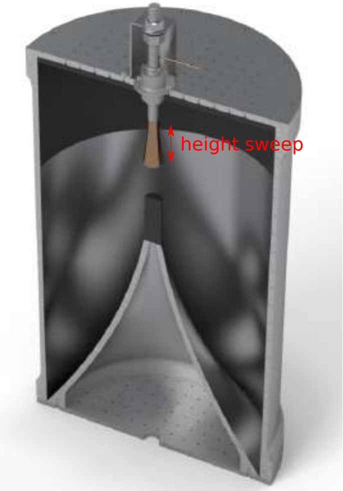
$$Y = \frac{P_{\text{on}}}{P_{\text{off}}}$$

$$T_{\text{amp}} = \frac{(290\text{ K})(\text{ENR}) - (Y-1)(290\text{ K})}{Y-1}$$

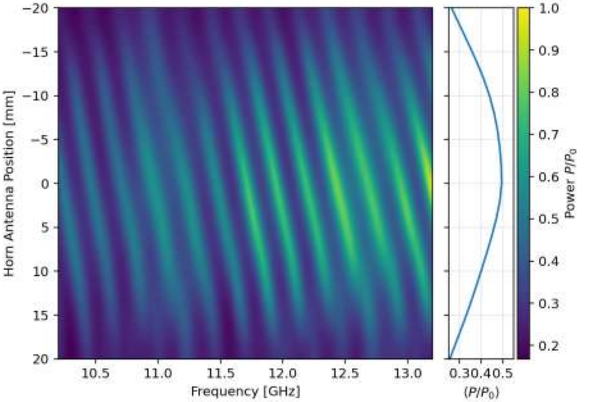




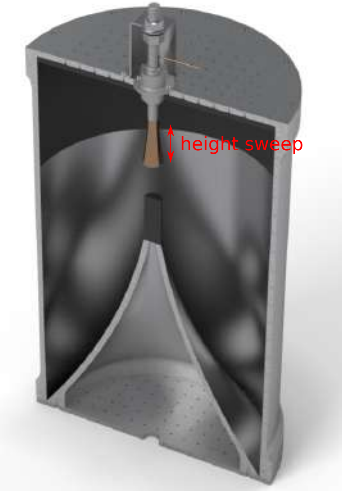
Horn Position Calibration



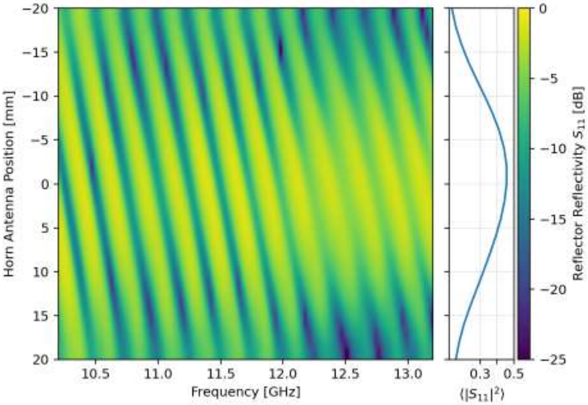
Efficiency as a function of antenna position (simulated)



Horn Position Calibration

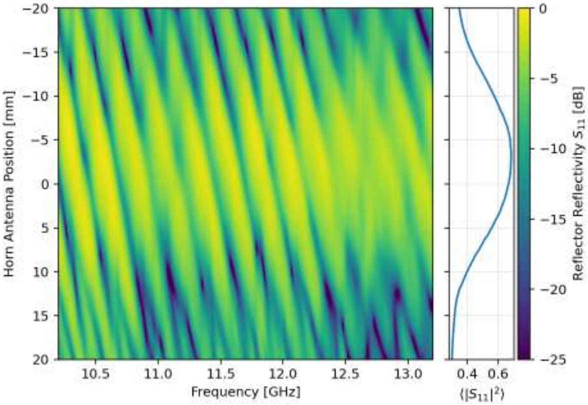


Reflectivity as a function of antenna position (simulated)



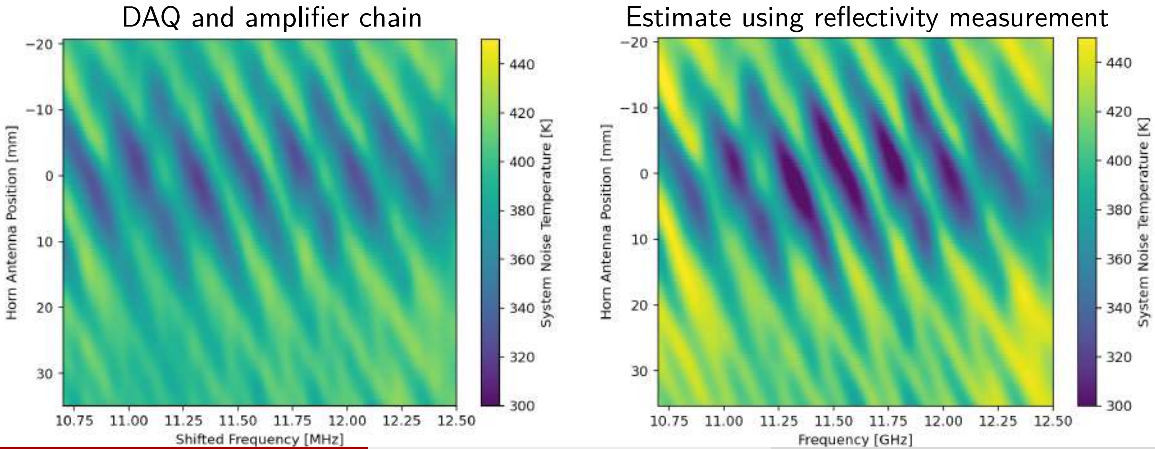
Horn Position Calibration

Reflectivity as a function of antenna position (measured)

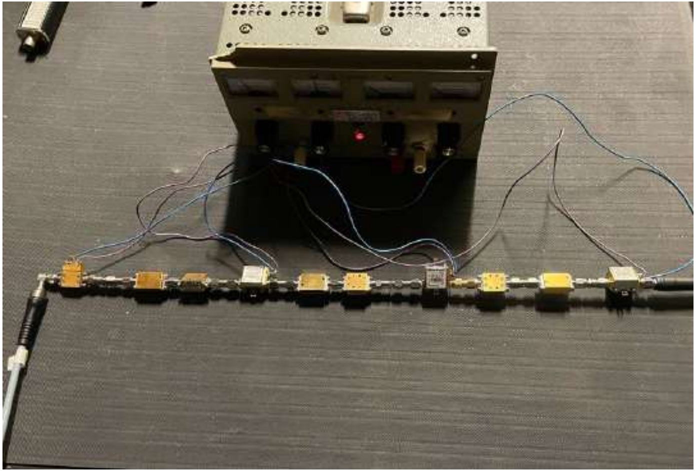


Thermal Measurement and S_{11} Comparison

- We can check measurements made with our DAQ and amplifier chain against reflectivity measurements done with a network analyzer.

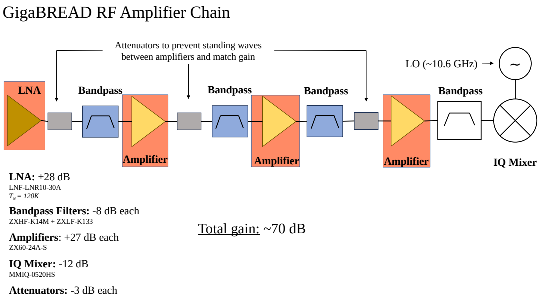


Amplifier Chain



Amplifier Chain

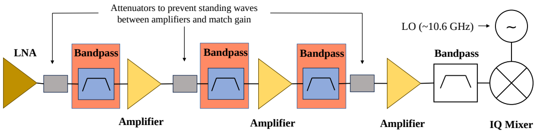
- Consists of one low noise amplifier followed by three additional amplifiers.
- All amplifiers are operated at room temperature.



Amplifier Chain

- To avoid saturation effects, a bandpass is placed between the amplifiers.

GigaBREAD RF Amplifier Chain



LNA: +28 dB
LNF-LNR10-30A
$T_N = 120K$

Bandpass Filters: -8 dB each
ZXHF-K14M + ZXLF-K133

Amplifiers: +27 dB each
ZX60-24A-S

IQ Mixer: -12 dB
MMIQ-0520HS

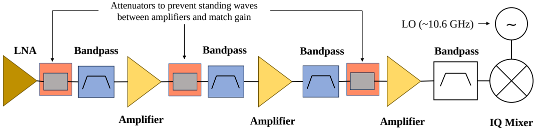
Attenuators: -3 dB each

Total gain: ~70 dB

Amplifier Chain

- 3 dB attenuators are placed between the amplifiers to attenuate standing waves.

GigaBREAD RF Amplifier Chain



LNA: +28 dB
LNF-LNR10-30A
$T_N = 120K$

Bandpass Filters: -8 dB each
ZXHF-K14M + ZXLF-K133

Amplifiers: +27 dB each
ZX60-24A-S

IQ Mixer: -12 dB
MMIQ-0520HS

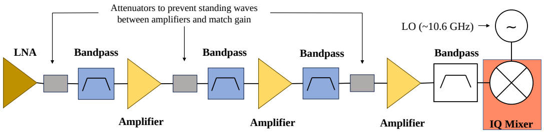
Attenuators: -3 dB each

Total gain: ~70 dB

Amplifier Chain

- A mixer converts the 10.7-12.5 GHz signal into a 0.1-1.9 GHz signal.

GigaBREAD RF Amplifier Chain



LNA: +28 dB
LNF-LNR10-30A
$T_N = 120K$

Bandpass Filters: -8 dB each
ZXHF-K14M + ZXLF-K133

Amplifiers: +27 dB each
ZX60-24A-S

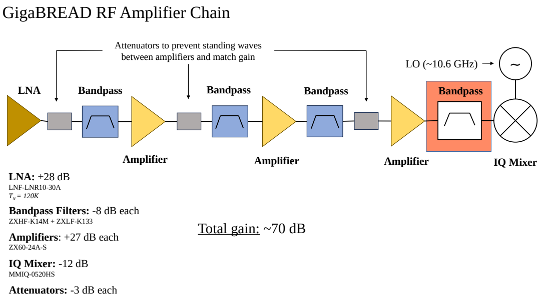
IQ Mixer: -12 dB
MMIQ-0520HS

Attenuators: -3 dB each

Total gain: ~70 dB

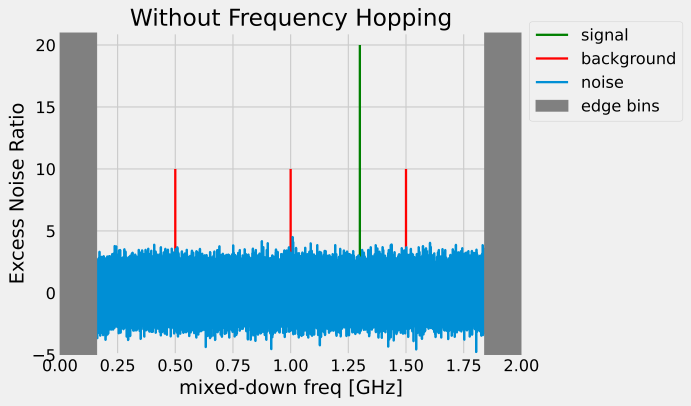
Amplifier Chain

- A cavity filter bandpass blocks the unwanted sideband of the mixer below 10.6 GHz.



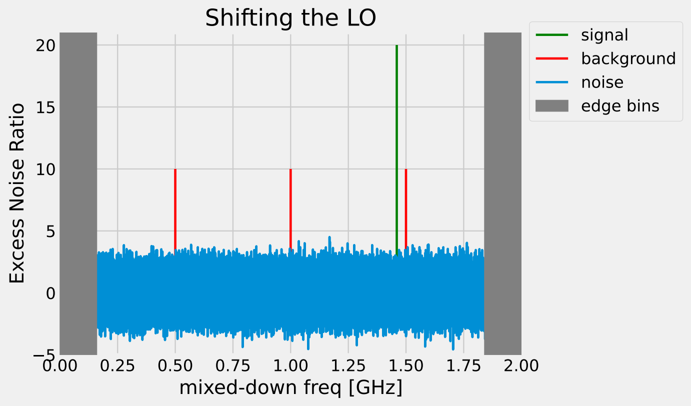
Frequency Hopping Scheme

- Frequency hopping can reduce low frequency background that.



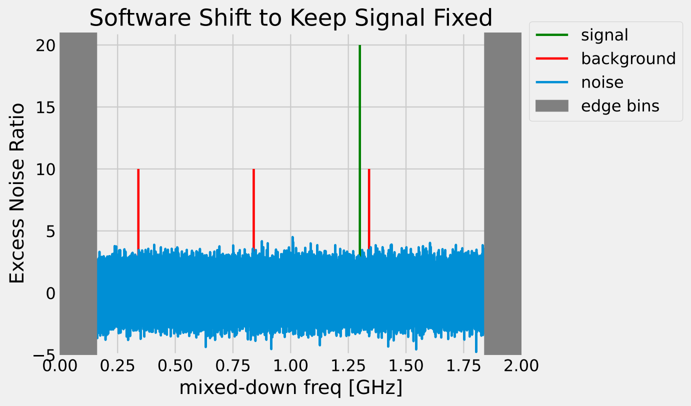
Frequency Hopping Scheme

- LO shifting moves high frequency signal peaks with respect to the background.



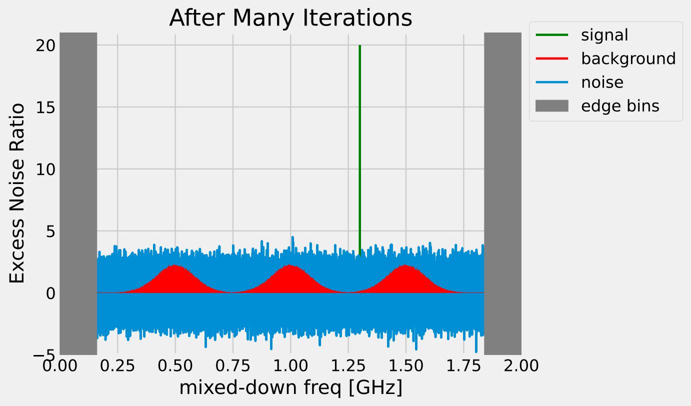
Frequency Hopping Scheme

- Software shift keeps high frequency signal peaks fixed.



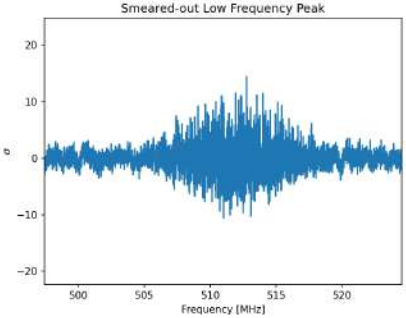
Frequency Hopping Scheme

- Hopping is repeated many times.
- Size of hopping is drawn from a Gaussian distribution.
- Background smeared out and becomes less significant than noise.

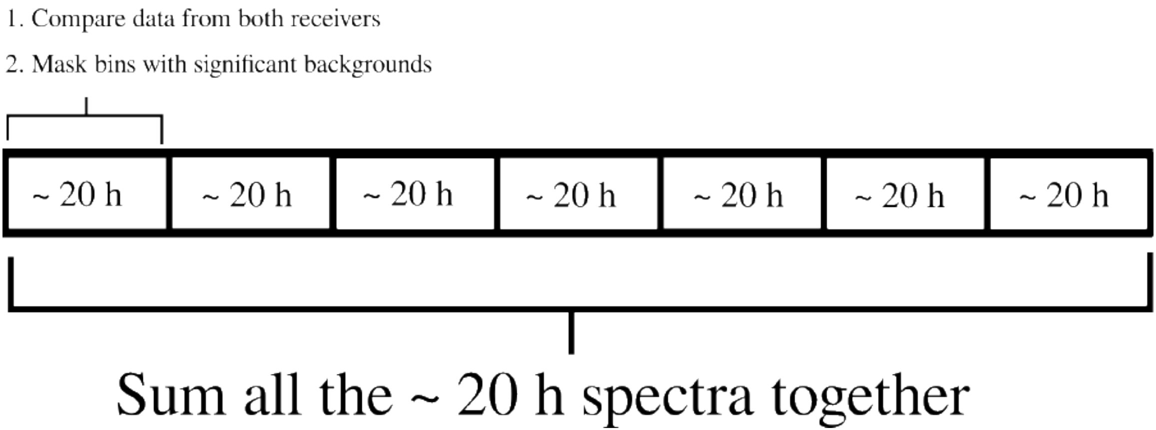


Example of Smeared Out Peak

- This is an example of a peak that is too big to mitigated with this method because it increases the noise non-negligibly in the bins around it. It is still a nice visualization of what happens to low frequency backgrounds due to frequency hopping.

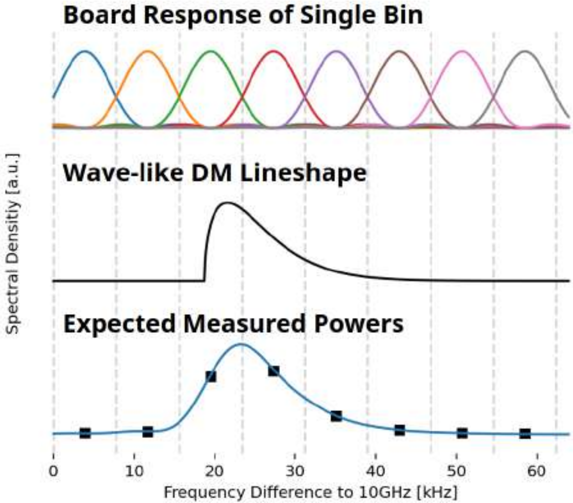


Background Veto Procedure



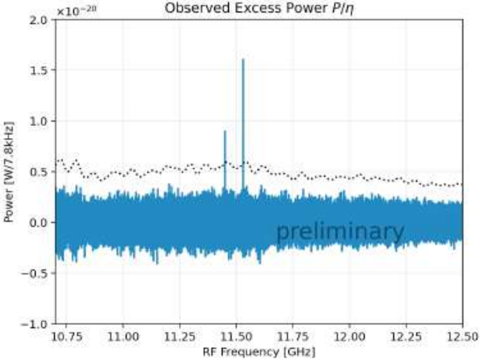
Accounting for Dark Matter Lineshape

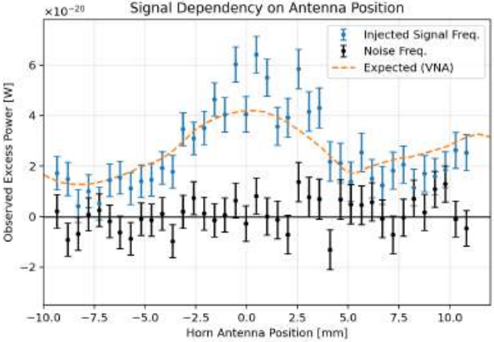
- The lineshape of axions and dark photons means that our expected signal spills over into multiple bins
- We can account for this by performing a cross-correlation with the lineshape at each frequency



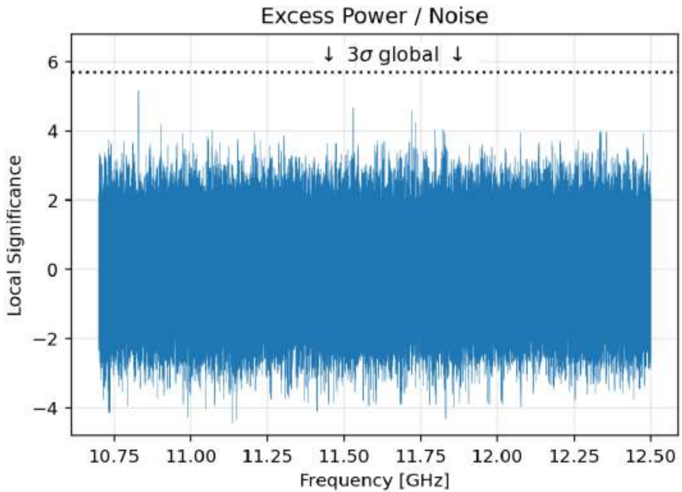
Finding the Blind Injected Signals

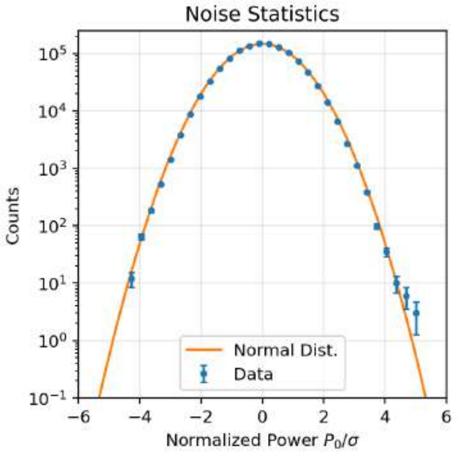
- Test signals at two frequencies were injected using a pin antenna during data taking



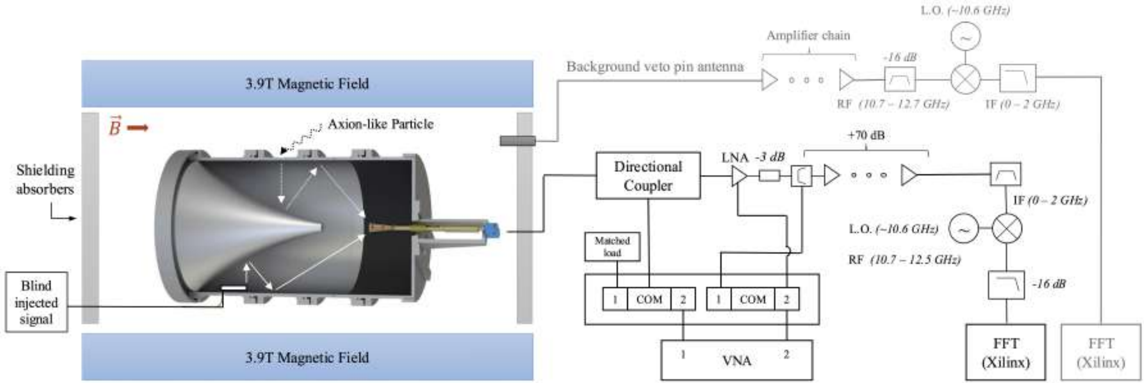


Final Excess Power



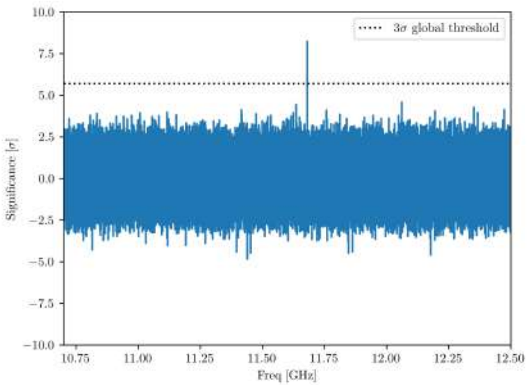


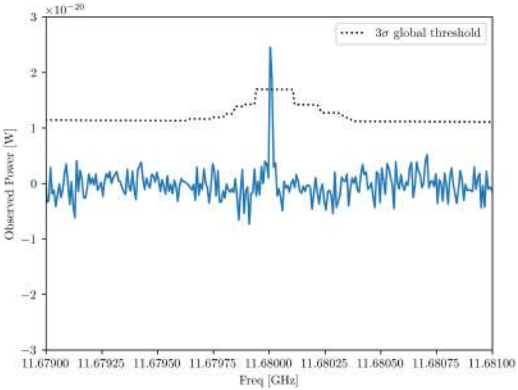
ALP Setup at ANL: More Detailed View



Finding the Blind Injected Signal

- During both the dark photon and ALP experiment, blind signal was injected during data taking using a pin antenna.





Final Excess Power