Update and Recent Results from GigaBREAD

19th Patras Workshop on Axions, WIMPs, and WISPs

Gabe Hoshino

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THE UNIVERSITY OF CHICAGO

BREAD COLLABORATION

Fermilab

Concept and Motivation

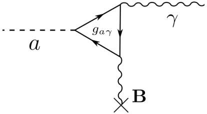
The BREAD Reflector Concept

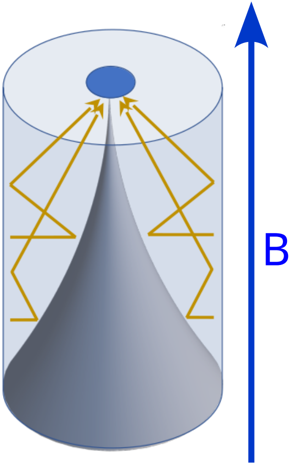
- In the presence of a strong magnetic field, axions cause the emission of photons at the conductive walls of the reflector.
- A parabolic reflector is placed in the middle of the cylinder to focus the photons onto a point.

Axion induced *E*-field:

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

Coupling through Primakoff Effect:





Reflector compared to Resonant Cavity

Resonant Cavity:

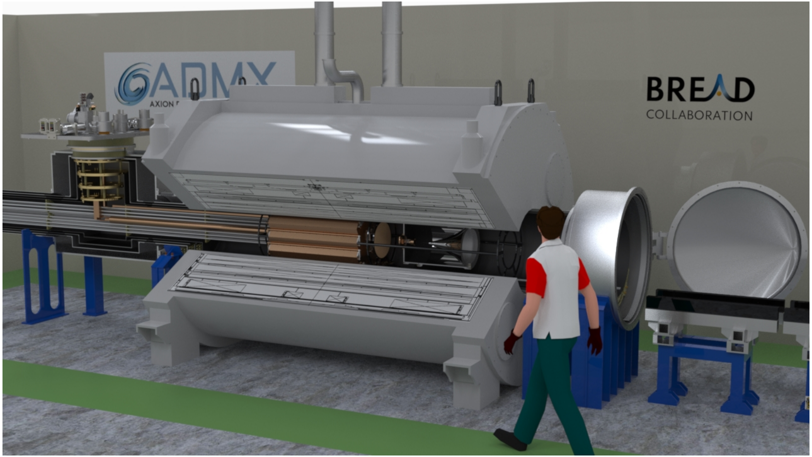
- $P_{\mathrm{sig}} \propto QB^2V$
- Narrowband
- Resonant enhancement
- Volume becomes very small for short wavelength signals

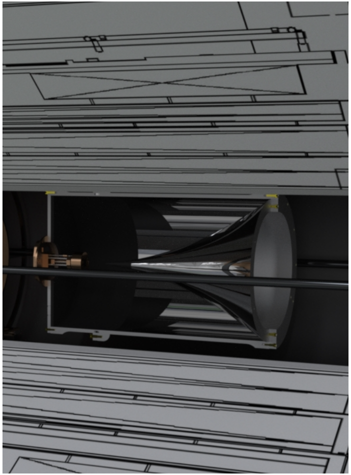
Reflector:

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

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

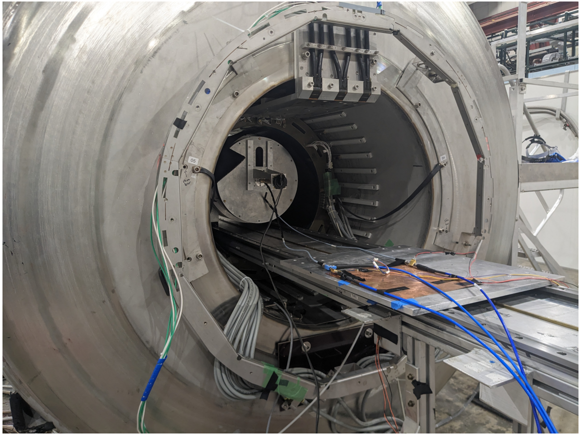
A Reflector Designed to Fit Inside Large Solenoid Magnets



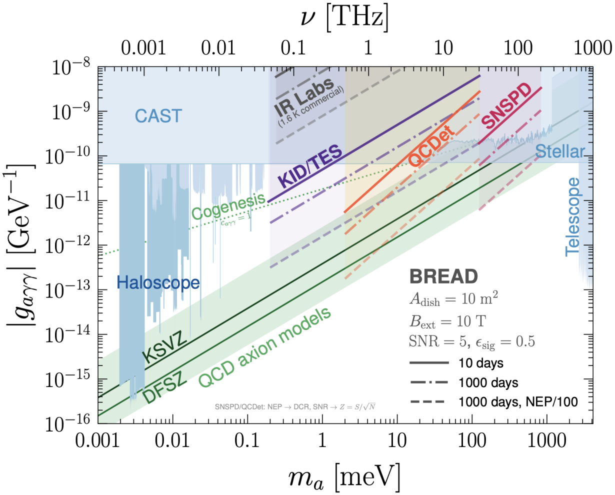


A Reflector Designed to Fit Inside Large Solenoid Magnets

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



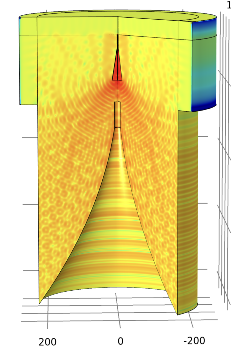
BREAD as a Platform for Different Sensor Technologies

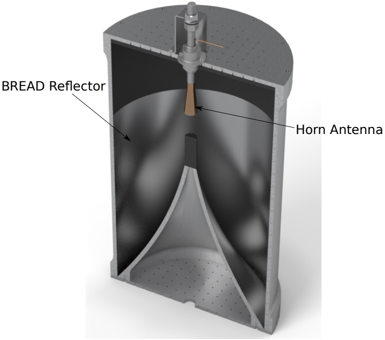


GigaBREAD

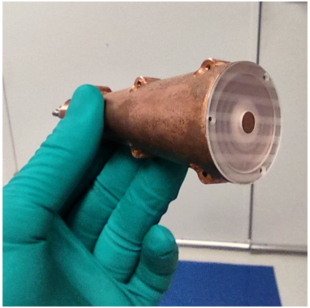
- GigaBREAD is the GHz BREAD pilot designed to look for axions and dark photons in the 10.7-12.5 GHz range
- In the GHz regime, the reflector can be coupled to a microwave horn antenna

COMSOL RF Simulation



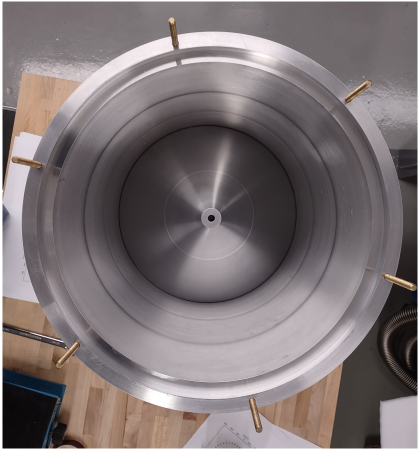


Custom coaxial horn antenna

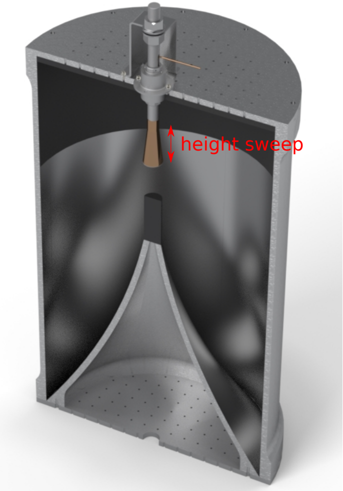


The GigaBREAD Reflector

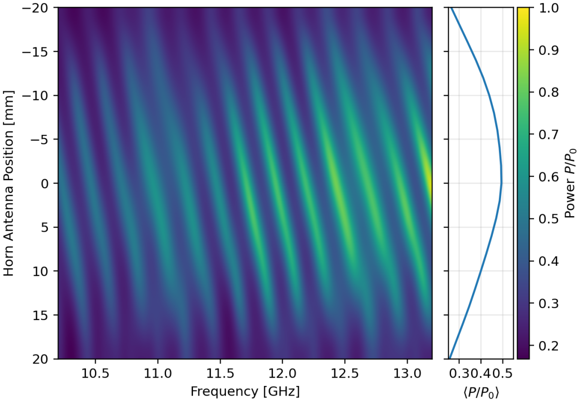
$A = 0.5\ \mathrm{m}^2$



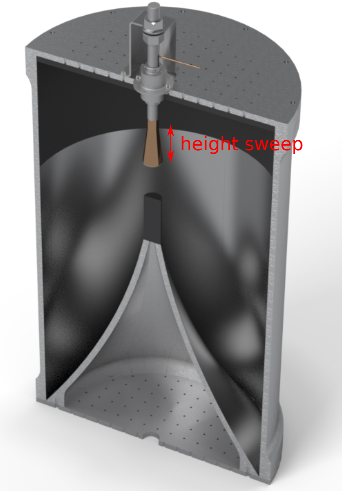
Horn Position Calibration



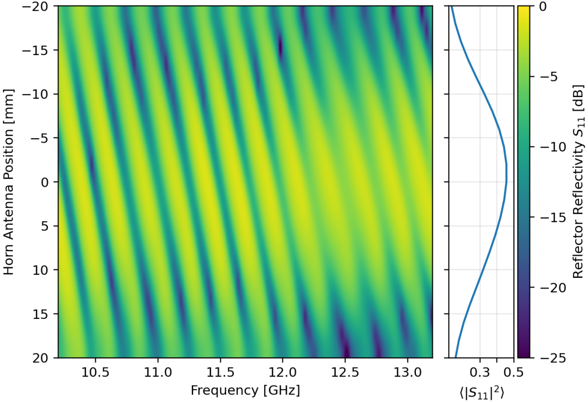
Efficiency as a function of antenna position (simulated)



Horn Position Calibration

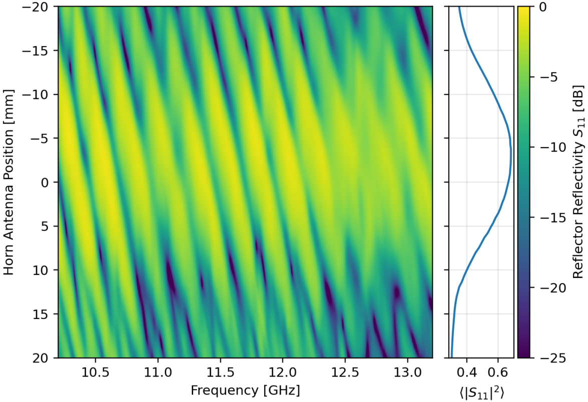


Reflectivity as a function of antenna position (simulated)



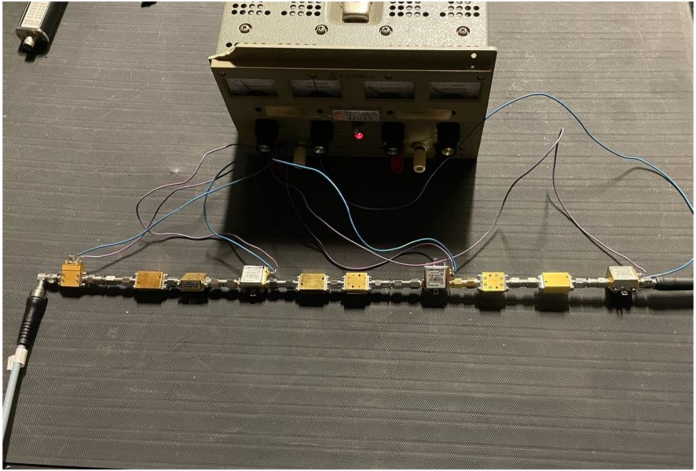
Horn Position Calibration

Reflectivity as a function of antenna position (measured)



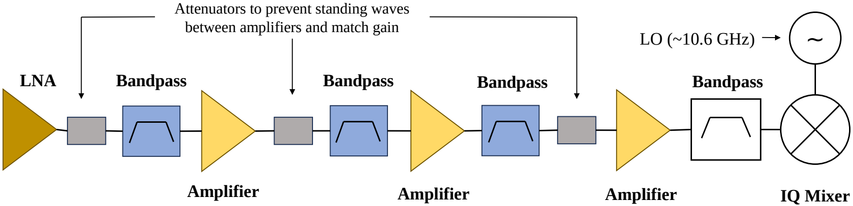
Amplifier Chain and DAQ

Amplifier Chain



Amplifier Chain

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

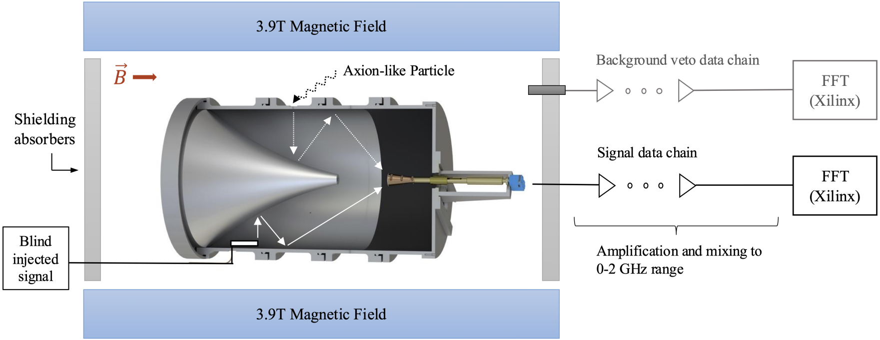
IQ Mixer: -12 dB
MMIQ-0520HS

Attenuators: -3 dB each

Total gain: ~70 dB

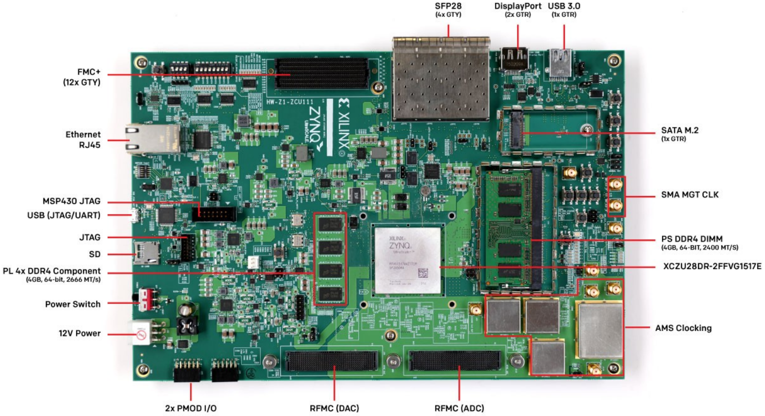
Background Veto Antenna for ALPs at Argonne

- 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



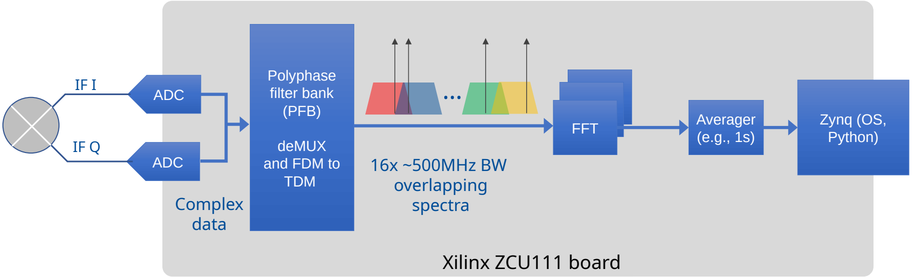
Xilinx ZCU111 Board

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



Block Diagram

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

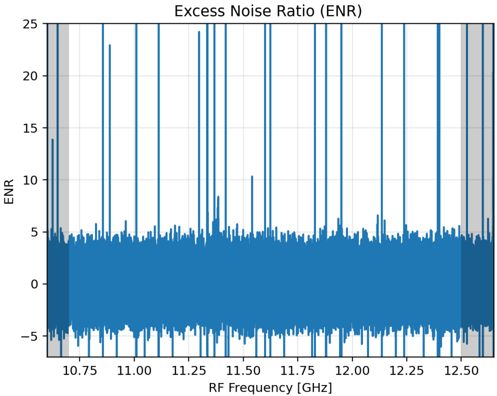


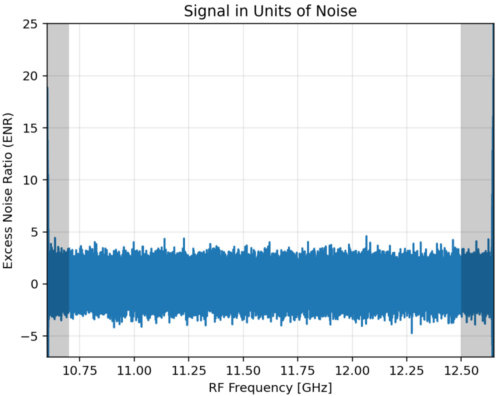
LO Frequency Hopping: RFI Rejection Scheme

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

Without LO hopping:

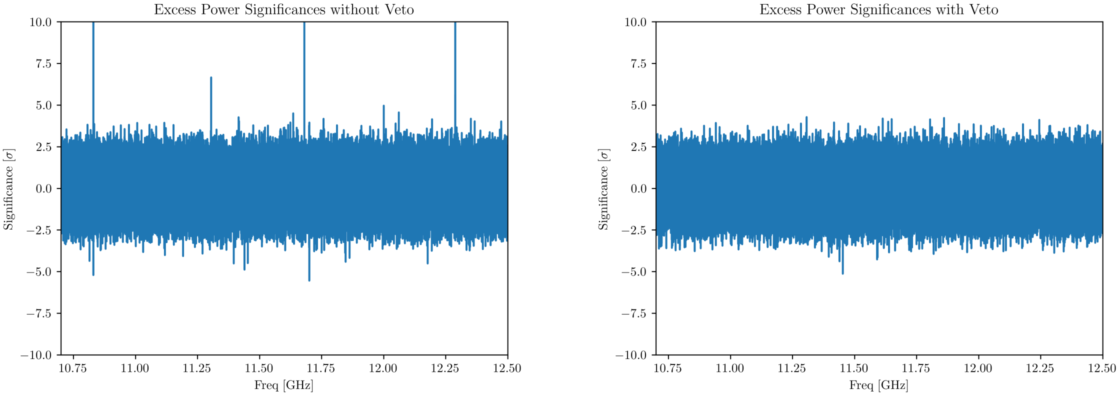
With LO hopping:





High Frequency Background Rejection

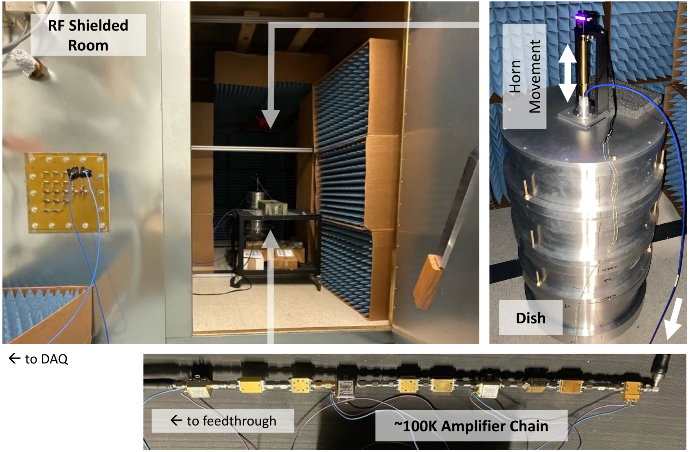
- For the ALP search at Argonne, a separate antenna and amplifier chain was used to monitor backgrounds and mask bins accordingly



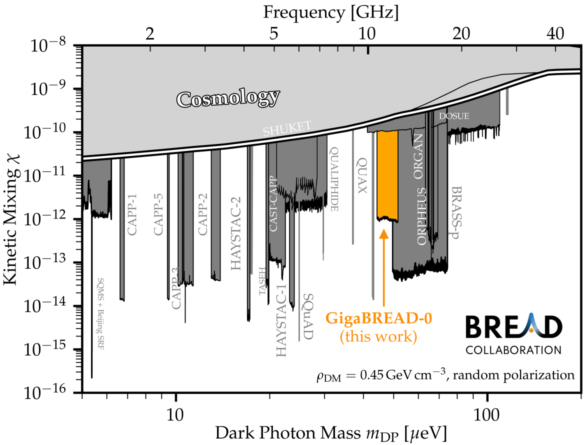
Dark Photon Search

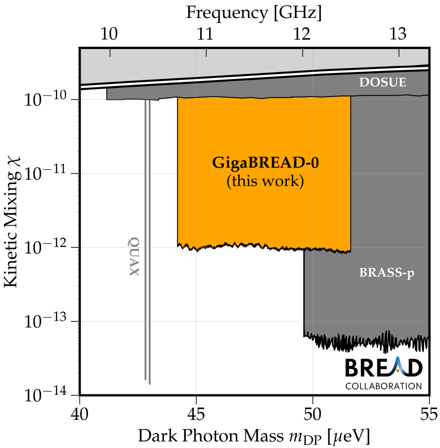
Setup

- 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



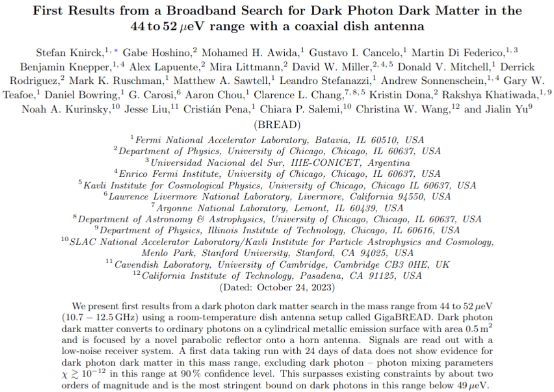
Dark Photon Limit





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

Read more about this result in PRL!



First Results from a Broadband Search for Dark Photon Dark Matter in the 44 to 52 μeV range with a coaxial dish antenna

Stefan Knirck,[1,*] Gabe Hoshino,[2] Mohamed H. Awida,[1] Gustavo I. Cancelo,[1] Martin Di Federico,[1,3] Benjamin Knepper,[1,4] Alex Lapuente,[2] Mira Littmann,[2] David W. Miller,[2,4,5] Donald V. Mitchell,[1] Derrick Rodriguez,[2] Mark K. Ruschman,[1] Matthew A. Sawtell,[1] Leandro Stefanazzi,[1] Andrew Sonnenschein,[1,4] Gary W. Teafoe,[1] Daniel Bowring,[1] G. Carosi,[6] Aaron Chou,[1] Clarence L. Chang,[7,8,5] Kristin Dona,[2] Rakshya Khatiwada,[1,9] Noah A. Kurinsky,[10] Jesse Liu,[11] Cristián Pena,[1] Chiara P. Salemi,[10] Christina W. Wang,[12] and Jialin Yu[9]

(BREAD)

[1] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[2] *Department of Physics, University of Chicago, Chicago, IL 60637, USA*
[3] *Universidad Nacional del Sur, IIIE-CONICET, Argentina*
[4] *Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[5] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago IL 60637, USA*
[6] *Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[7] *Argonne National Laboratory, Lemont, IL 60439, USA*
[8] *Department of Astronomy & Astrophysics, University of Chicago, Chicago, IL 60637, USA*
[9] *Department of Physics, Illinois Institute of Technology, Chicago, IL 60616, USA*
[10] *SLAC National Accelerator Laboratory/Kavli Institute for Particle Astrophysics and Cosmology, Menlo Park, Stanford University, Stanford, CA 94025, USA*
[11] *Cavendish Laboratory, University of Cambridge, Cambridge CB3 0HE, UK*
[12] *California Institute of Technology, Pasadena, CA 91125, USA*

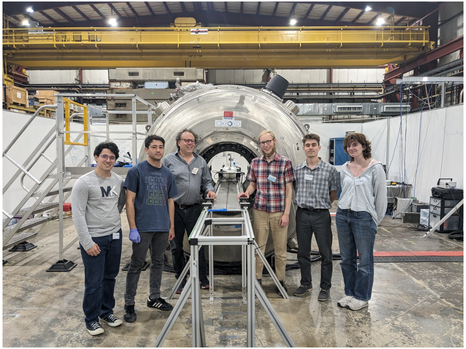
(Dated: October 24, 2023)

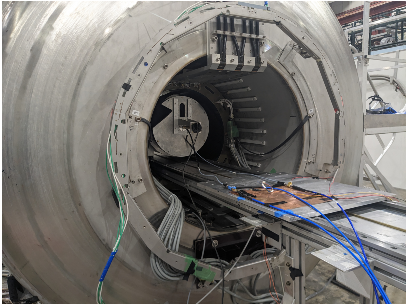
We present first results from a dark photon dark matter search in the mass range from 44 to 52 μeV ($10.7 - 12.5$ GHz) using a room-temperature dish antenna setup called GigaBREAD. Dark photon dark matter converts to ordinary photons on a cylindrical metallic emission surface with area $0.5\,\mathrm{m}^2$ and is focused by a novel parabolic reflector onto a horn antenna. Signals are read out with a low-noise receiver system. A first data taking run with 24 days of data does not show evidence for dark photon dark matter in this mass range, excluding dark photon – photon mixing parameters $\chi \gtrsim 10^{-12}$ in this range at 90 % confidence level. This surpasses existing constraints by about two orders of magnitude and is the most stringent bound on dark photons in this range below 49 μeV.

Axion-Like Particle Search

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 $\sim 400\ \mathrm{K}$ and $\sim$ 27 days at a system noise temperature of $\sim 600\ \mathrm{K}$.

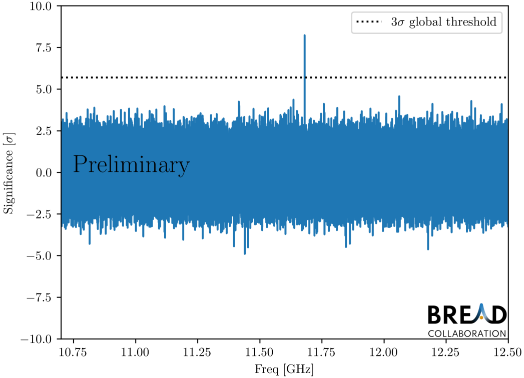


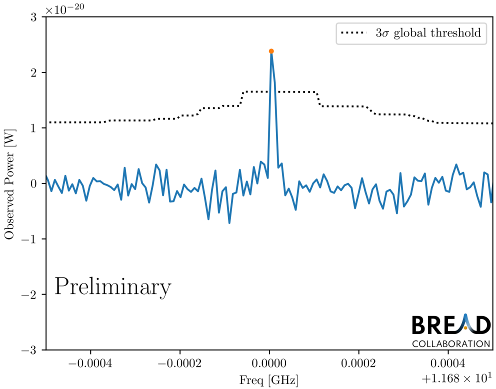


Installing Shielding

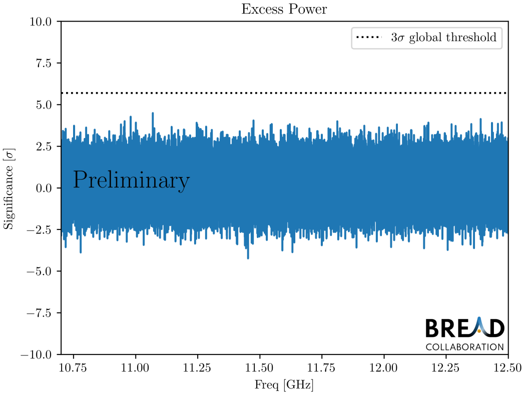
Finding the Blind Injected Signal

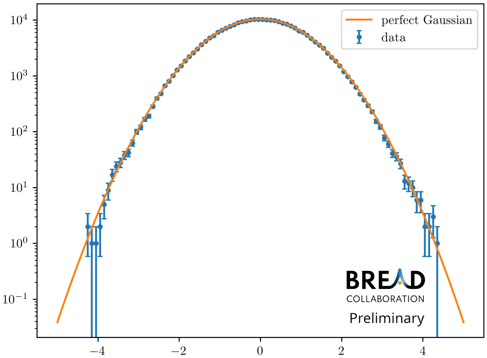
- During both the dark photon and ALP experiment, blind signal was injected during data taking using a pin antenna.



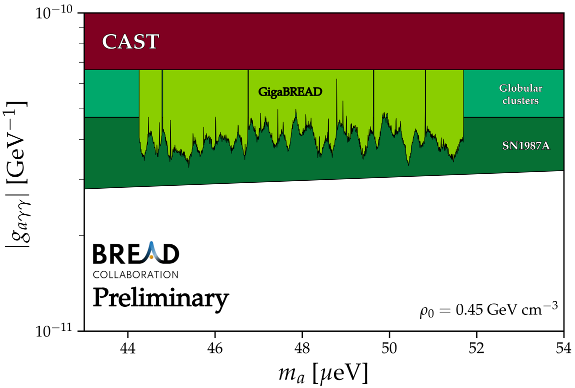


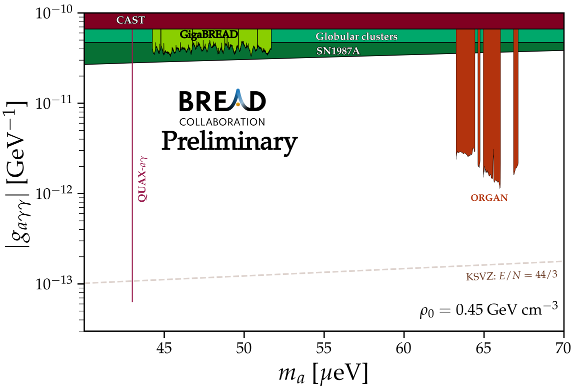
Final Excess Power





Preliminary ALP Limit



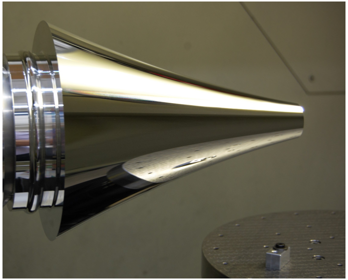


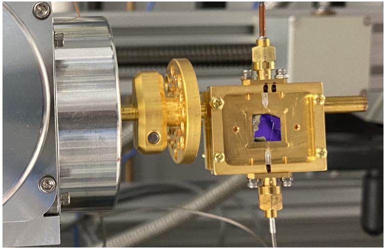
Plots modified from `https://cajohare.github.io/AxionLimits/`

Future Plans

Next Steps

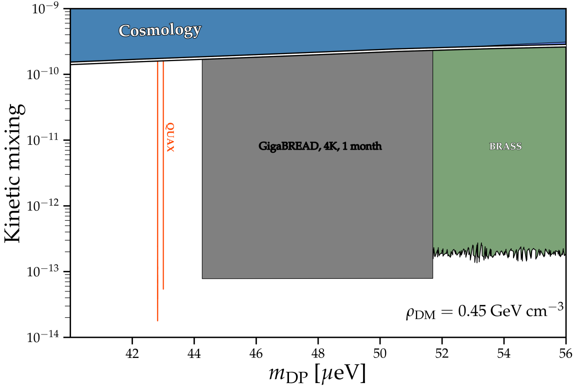
- A GigaBREAD run in a 9.4 T solenoid magnet at Fermilab may be possible in the near future
- We may consider making the experiment cryogenic and using quantum-limited amplification
- Additionally, higher frequency versions of BREAD are being developed operating in mm-wave, terahertz, and infrared regimes



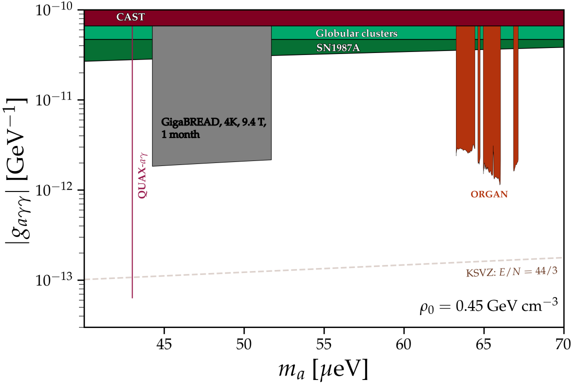


Future GigaBREAD Projections

Dark Photon:



ALP:



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

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*

Gianpaolo Carosi, *Lawrence Livermore National Laboratory*

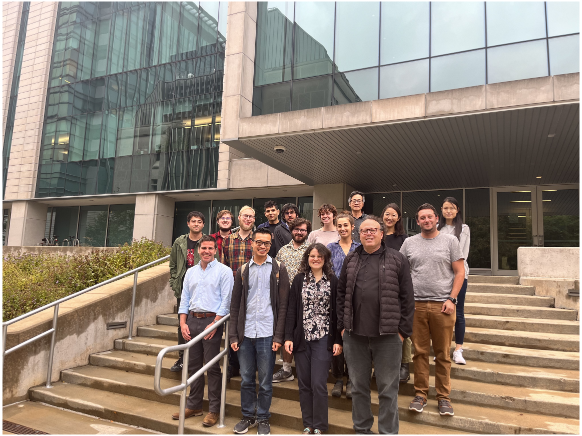
Karl Berggren, Dip Joti Paul, Tony (Xu) Zhou, *Massachusetts Institute of Technology*

Omid Noroozian, *NASA Goddard Space Flight Center*

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

Huma Jafree, *Randolph-Macon College*

Chiara Salemi, Noah Kurinsky, *SLAC*



Also Special Thanks to:

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

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Backup

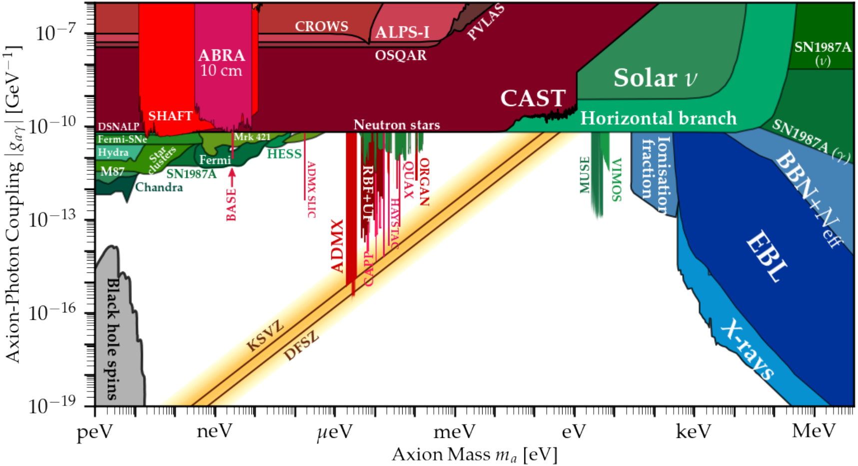
The QCD Axion

- 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

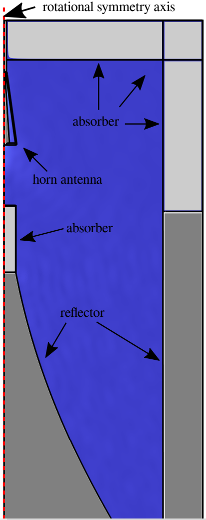
- The axion and dark photon fields modify Maxwell's equations by adding new sources for EM fields.
- We implement this in COMSOL by treating the axion/dark photon excitations as a space-filling oscillating current with a direction which is parallel/anti-parallel to the direction of the magnetic field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

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

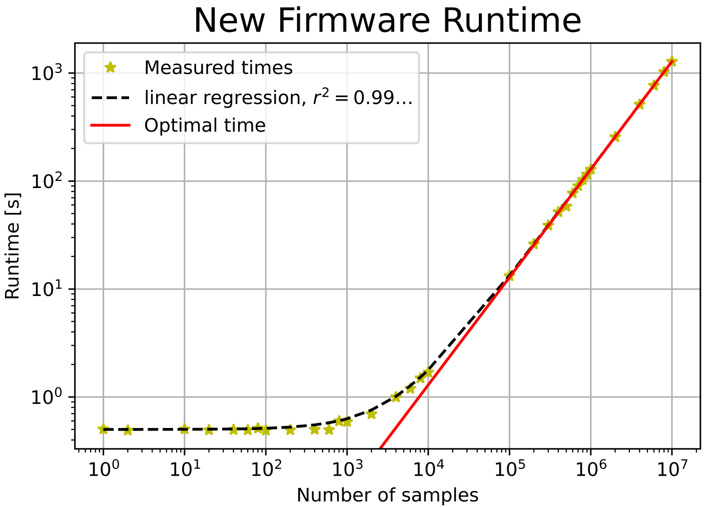
$$\frac{\partial^2 \vec{B}}{\partial t^2} - \nabla^2 \vec{B} = \nabla \times \vec{J}_{\mathrm{eff}}$$

Setting up the Simulation in COMSOL

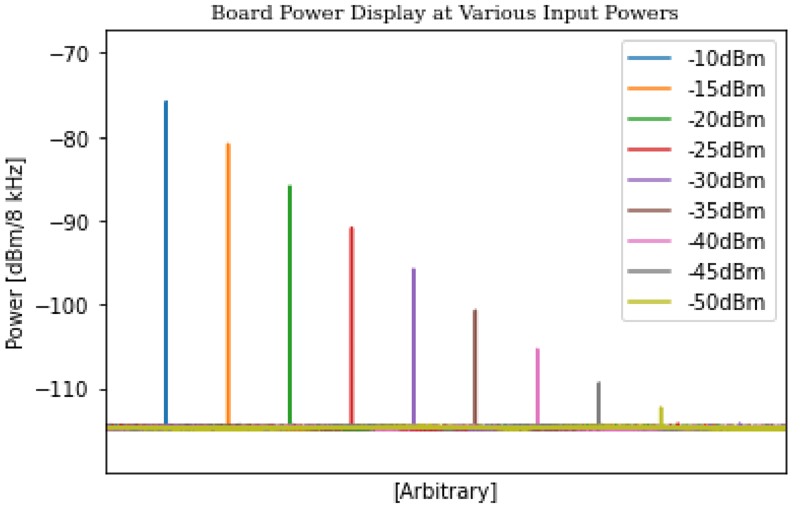
- Simulations are performed using the RF module in COMSOL.
- The rotational symmetry of our reflector allows us to solve for the EM fields in 2D.
- Boundary conditions are set for the reflector and horn antenna based on their material properties.
- Absorbers are implemented using scattering boundary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



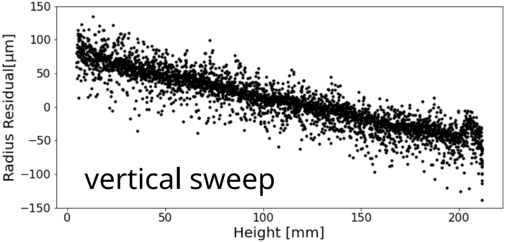
DAQ Firmware Deadtime

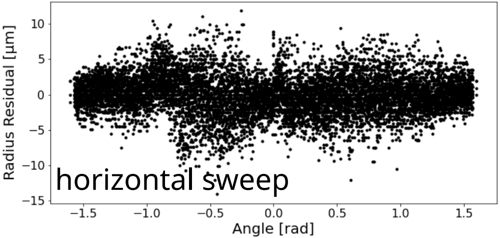


DAQ Firmware Signal Injection



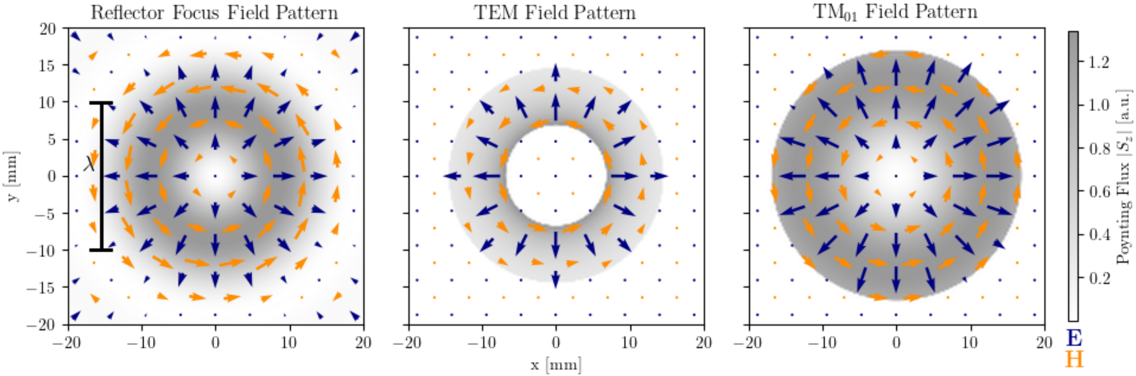
Reflector Surface Characterization with CMM





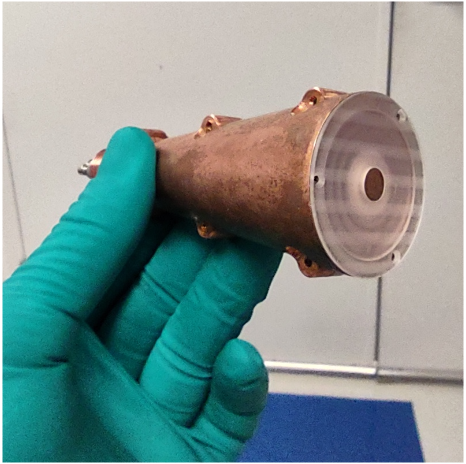
Matching Antenna to the Reflector Beam Shape

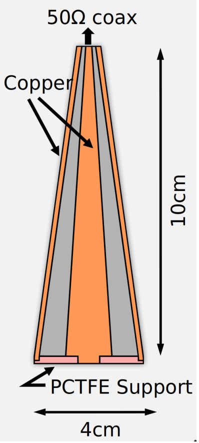
- In order to get the best performance, we look for an antenna with a near-field pattern similar to that of the reflector.



Coaxial Antenna

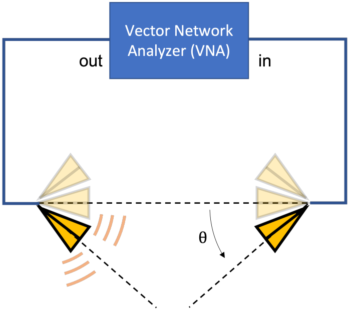
- Coaxial horn design used for GigaBREAD



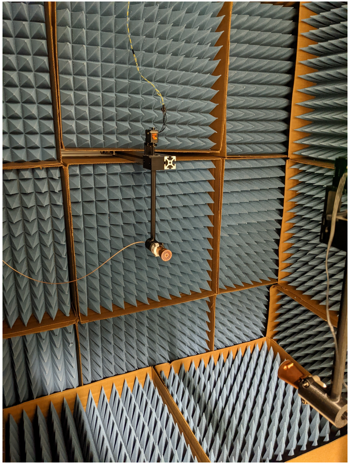


Far-Field Measurement Setup

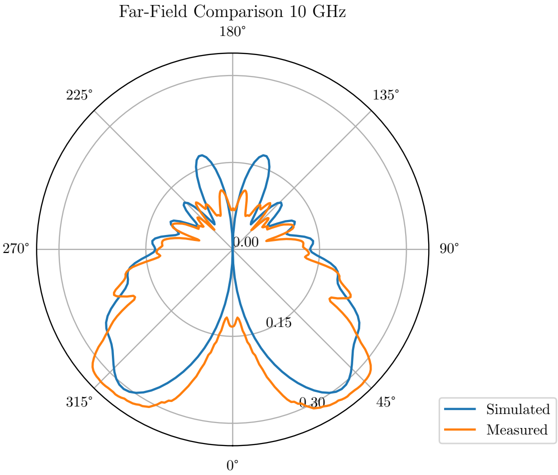
- Horns are mounted on robotic arms in the RF isolation chamber.
- The robotic arms can be made to rotate together as shown on the right which allows us to determine the far-field transmission at different angles.

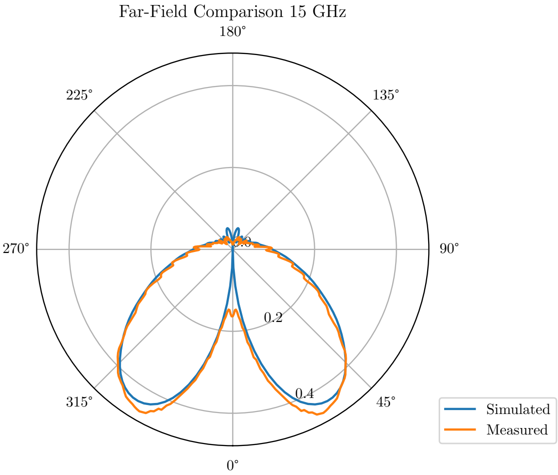


Far-Field Measurement Setup

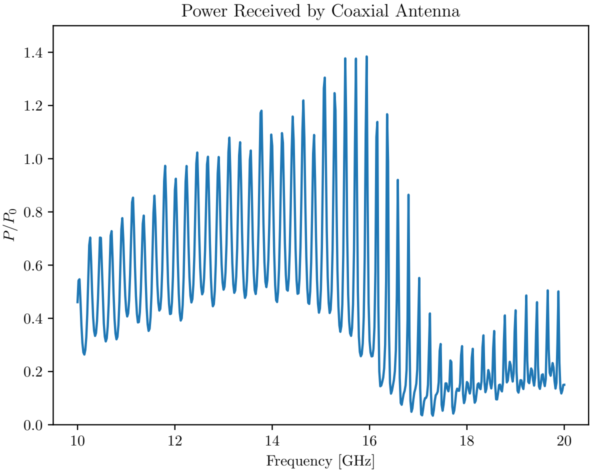


Far-Field Measurement Results


Far-Field Comparison 10 GHz

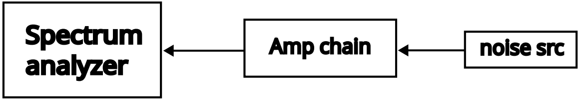

Far-Field Comparison 15 GHz

Horn Efficiency

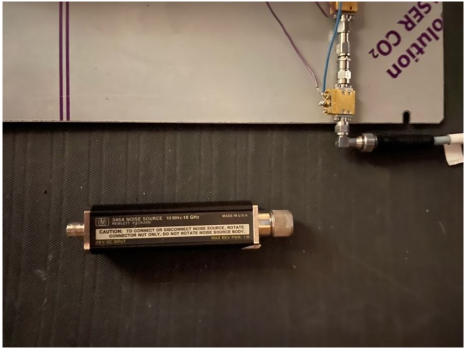


Y-factor Method

- 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.



Spectrum analyzer ← **Amp chain** ← **noise src**

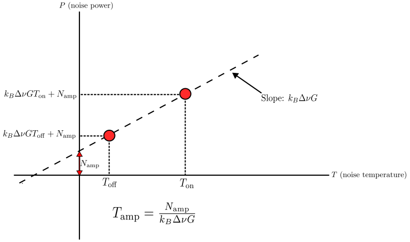


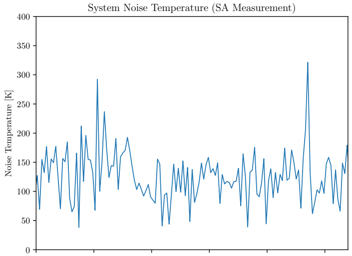
Y-factor Method

- 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:

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

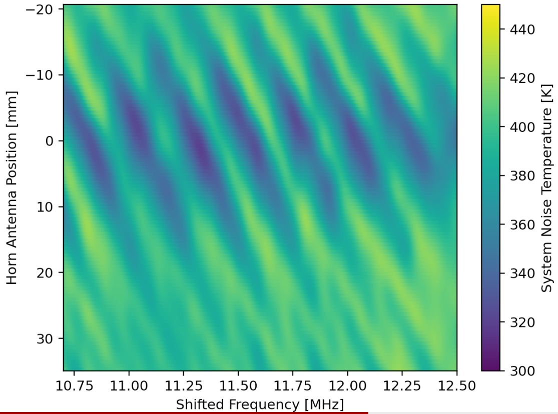
$$T_{\text{amp}} = \frac{(290\text{ K})(\text{ENR}) - (Y-1)(290\text{ K})}{Y-1}$$

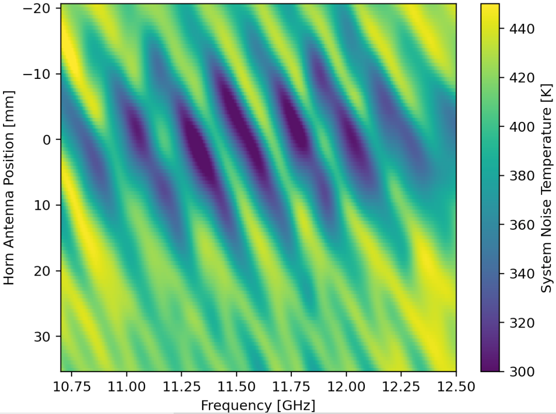




Thermal Measurement and S_{11} Comparison

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

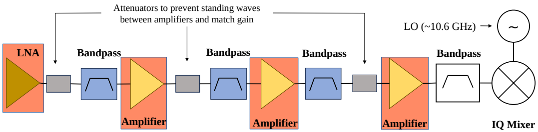

DAQ and amplifier chain


Estimate using reflectivity measurement

Amplifier Chain

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

GigaBREAD RF Amplifier Chain


Attenuators to prevent standing waves between amplifiers and match gain

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

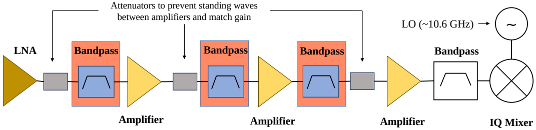
Attenuators: -3 dB each

Total gain: ~70 dB

Amplifier Chain

- 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

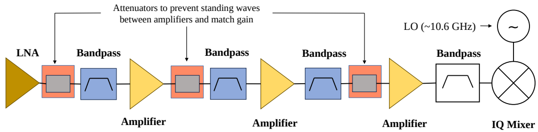
Attenuators: -3 dB each

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

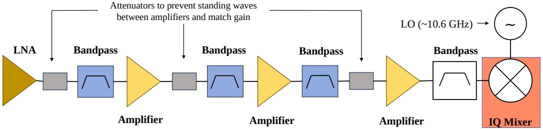
Attenuators: -3 dB each

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

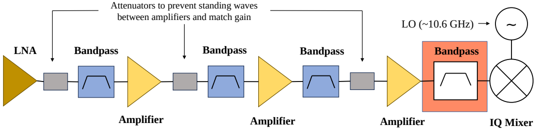
Attenuators: -3 dB each

<u>Total gain:</u> ~70 dB

Amplifier Chain

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

GigaBREAD RF Amplifier Chain



Attenuators to prevent standing waves
between amplifiers and match gain

LO (~10.6 GHz) →

LNA

Bandpass

Bandpass

Bandpass

Bandpass

Amplifier

Amplifier

Amplifier

IQ Mixer

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

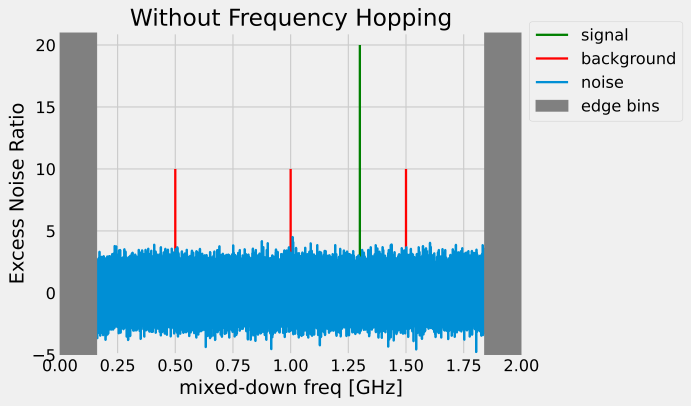
IQ Mixer: -12 dB
MMIQ-0520HS

Attenuators: -3 dB each

Total gain: ~70 dB

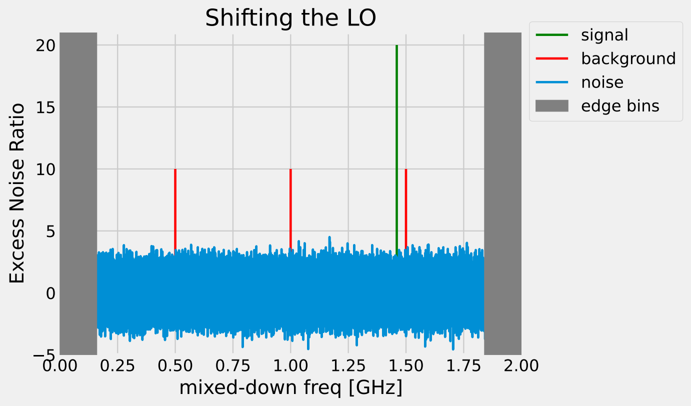
Frequency Hopping Scheme

- Frequency hopping can reduce low frequency background that.



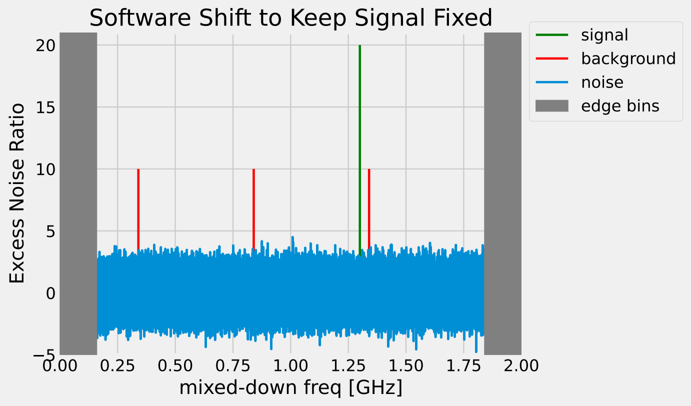
Frequency Hopping Scheme

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



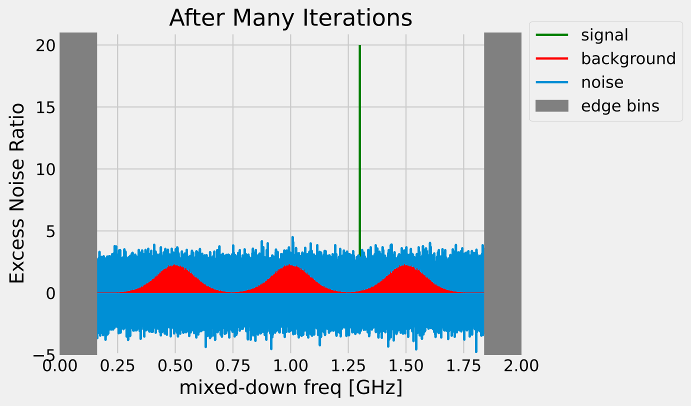
Frequency Hopping Scheme

- Software shift keeps high frequency signal peaks fixed.



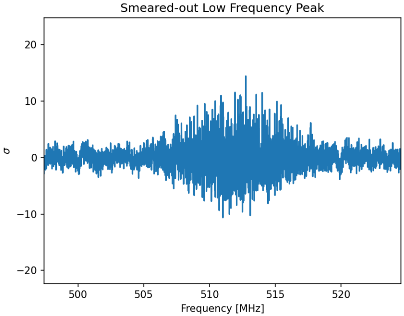
Frequency Hopping Scheme

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



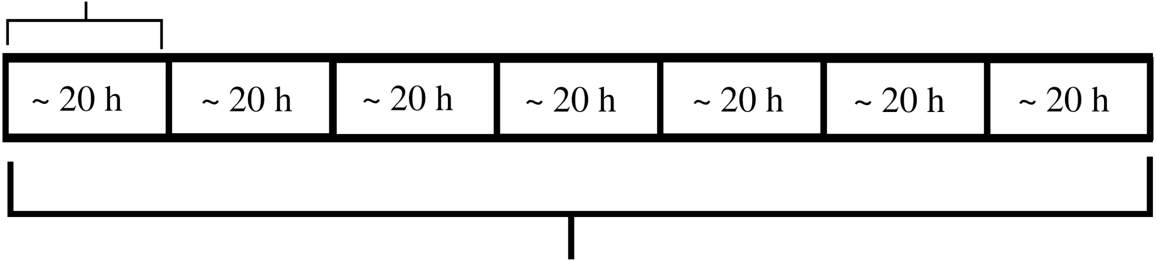
Example of Smeared Out Peak

- 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

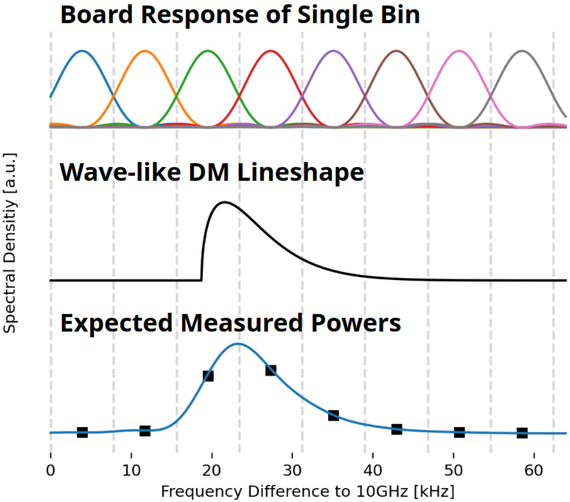
1. Compare data from both receivers
2. Mask bins with significant backgrounds



Sum all the ~ 20 h spectra together

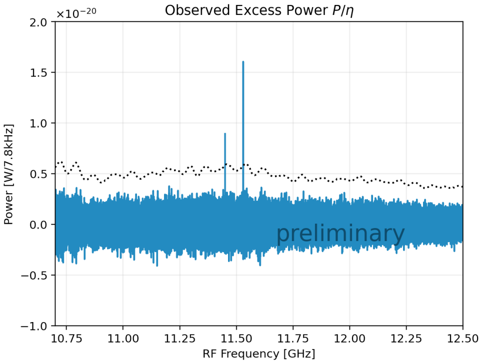
Accounting for Dark Matter Lineshape

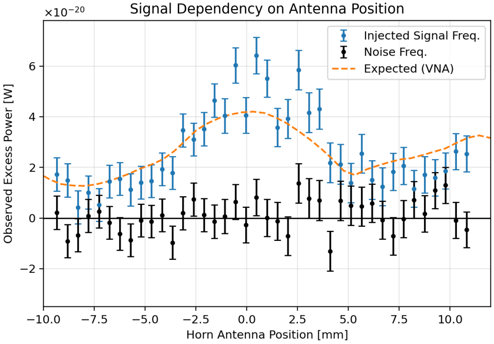
- The lineshape of axions and dark photons means that our expected signal spills over into multiple bins
- We can account for this by performing a cross-correlation with the lineshape at each frequency



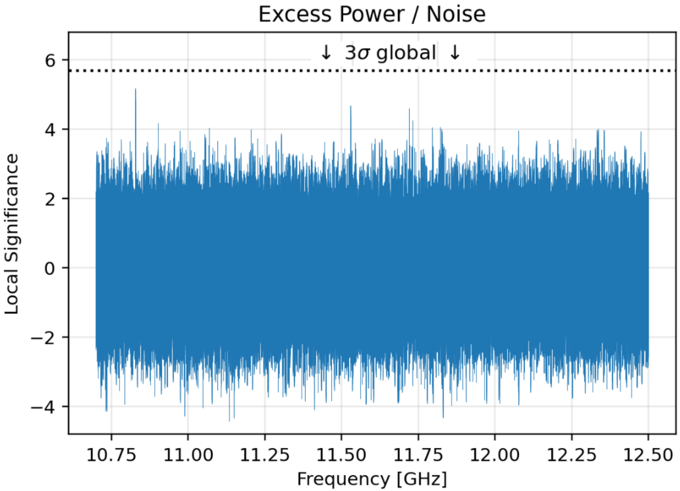
Finding the Blind Injected Signals

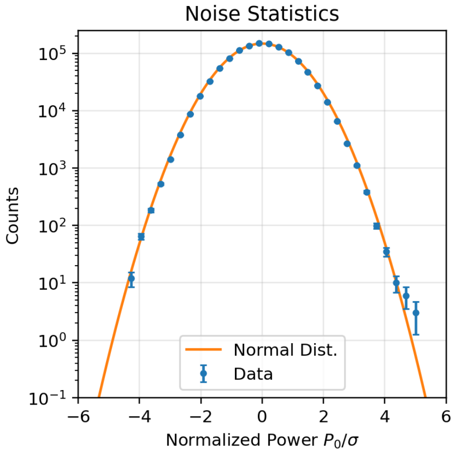
- Test signals at two frequencies were injected using a pin antenna during data taking





Final Excess Power





ALP Setup at ANL: More Detailed View