Broadband Reflector Experiment for Axion Detection (BREAD)

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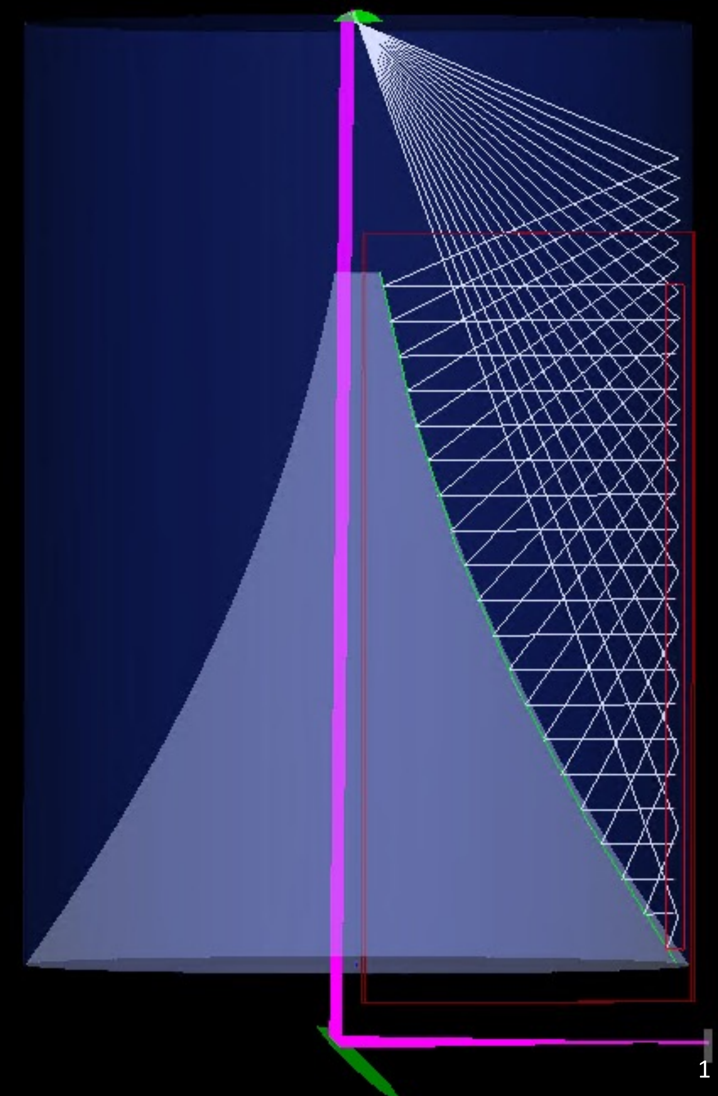
Fermilab

Quantum Technologies for Fundamental Physics

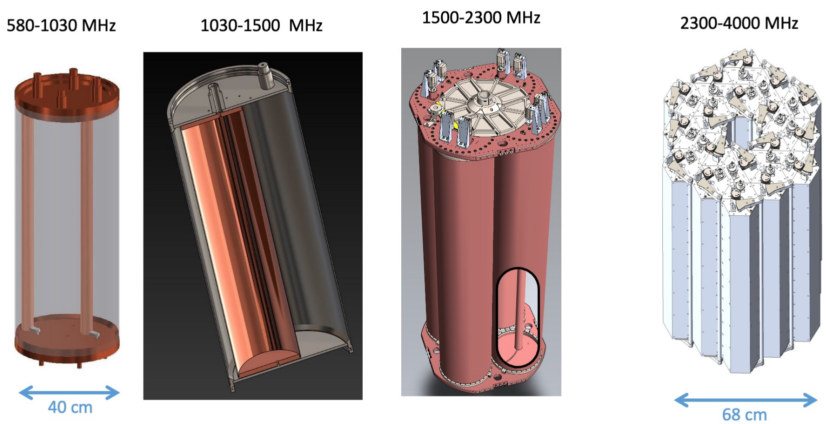
Sept 3, 2023

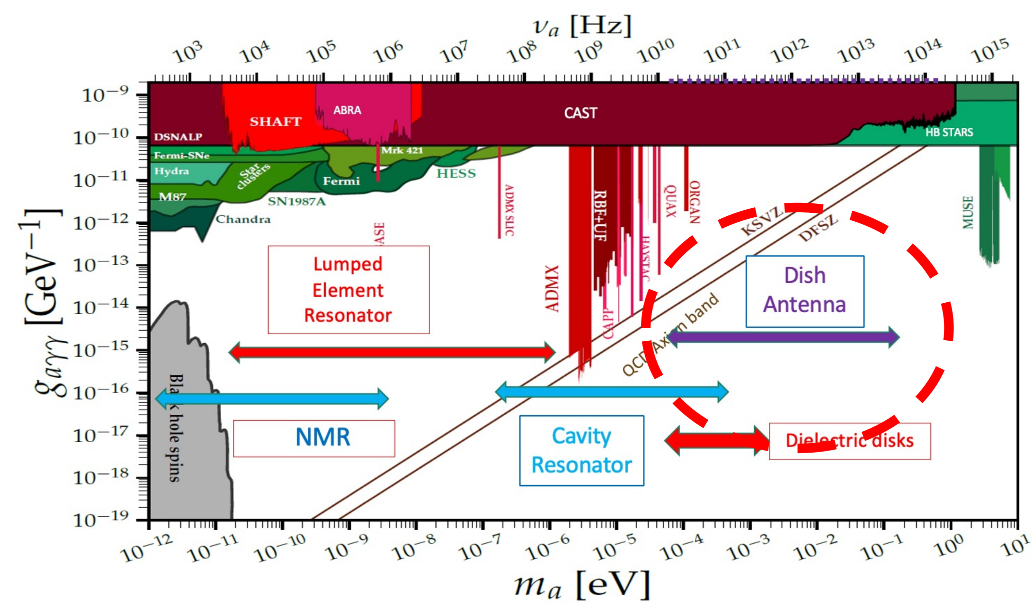


Motivation: Cavity Experiments Scale Poorly to High Mass

- Sensitivity of resonant cavity axion search technique doesn't scale favorably with mass:
  - Cavity size matched to axion Compton wavelength $\lambda = h/m_a c$
  - Axion to photon conversion power proportional to volume $\propto \lambda^3 \propto 1/m_a^3$
- "Swiss watch problem"– need large numbers of small cavities to maintain signal power as mass increases.

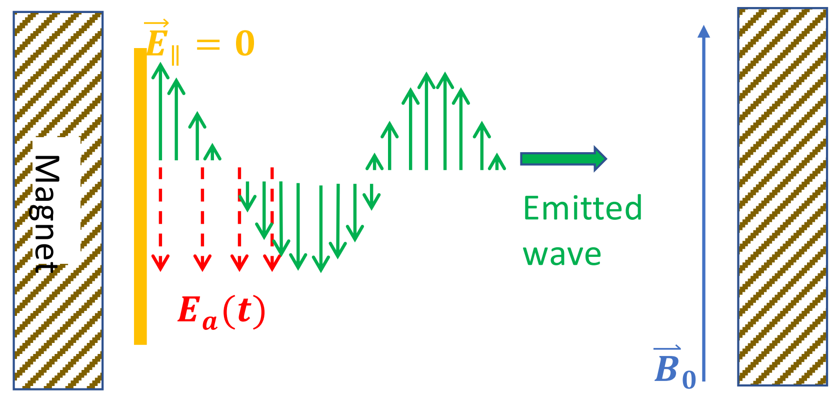
ADMX cavity designs for increasing mass ranges





Axion-Induced Electromagnetic Radiation from Conducting Surface in Magnetic Field

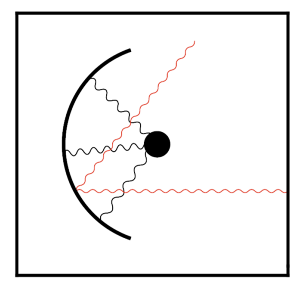
- Axions interact with a static magnetic field producing an oscillating parallel electric field in free space
- A conducting surface in this field emits a plane wave perpendicular to surface.



- Radiated power is low:

$$P_{signal} = 8.27 \cdot 10^{-26} W \cdot \left(\frac{A}{10\ m^2}\right)\left(\frac{B_\parallel}{10\ \text{Tesla}}\right)^2 \left(\frac{\rho_{DM}}{0.3\ GeV/cm^3}\right)\left(\frac{g_{a\gamma\gamma}}{3.92 \cdot 10^{-16}\ GeV^{-1}}\right)^2 \left(\frac{1\ \mu eV}{m_a}\right)^2$$

- But no detector tuning is required.

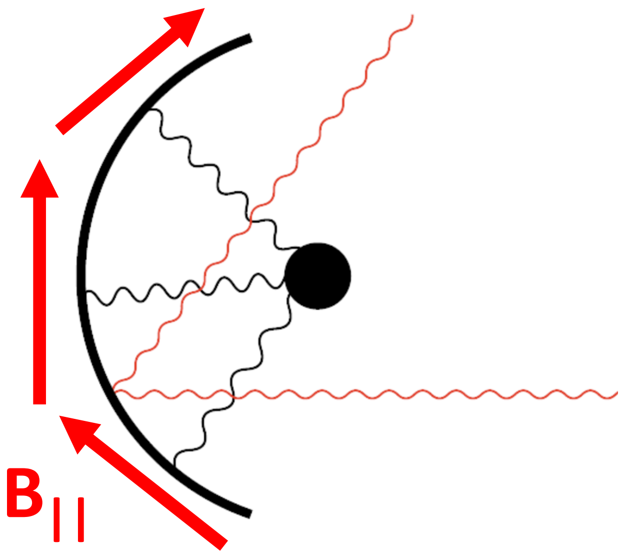


“Dish Antenna” Horns, Jaeckel, Lindner, Lobanov, Redondo & Ringwald, 2012

Magnetic Field Configuration

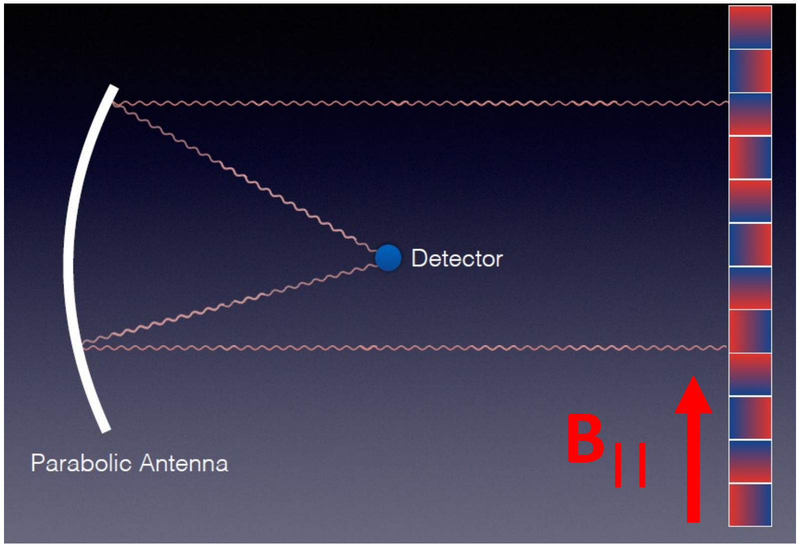
- Need to maximize component of magnetic field parallel to radiating surface $B_{||}$
- Spherical dish geometry not a good match to conventional magnet types.

Spherical dish radiator from Horns *et al.* concept paper:



"Dish antenna" (Horns et al., 2012)

BRASS experiment: Planar array of permanent magnets



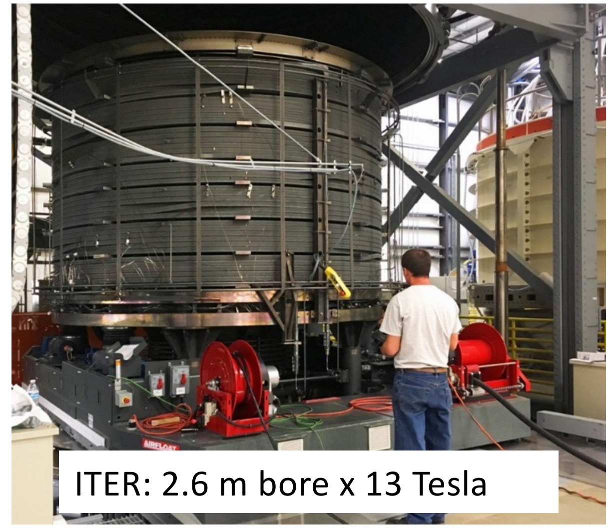
Le Hoang Nguyen, Patras 2019
http://wwwiexp.desy.de/groups/astroparticle/brass/brassweb.htm

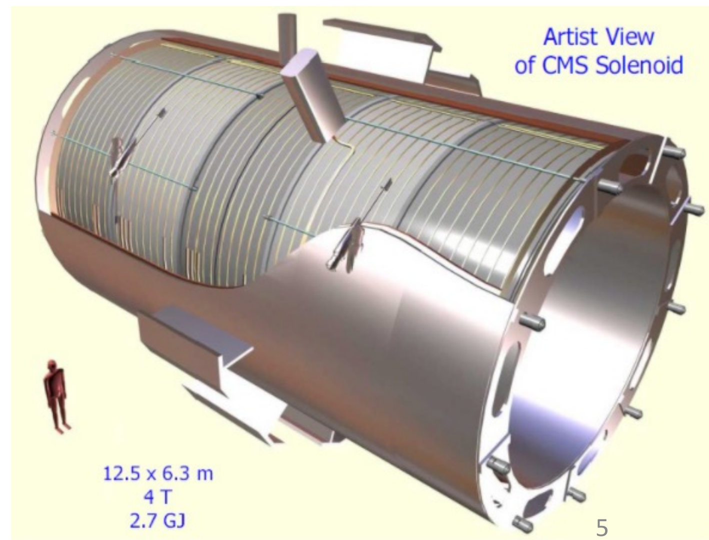
Large Solenoids

- How to use large volume solenoids to detect axions?

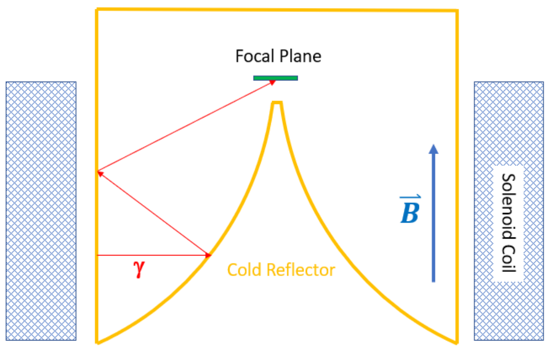
B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*	*MRI/Ti SRC*	*CEA*	*11.75*	*1*	*4*	*338*	
320	ITER CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
290	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	
250	*Magnex*	*MRI/Mono*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	Magnex	MRI/Mono	Juelich	9.4	0.9	3	190	
70	45 T out	HF/Nb_3Sn CICC	MagLab	14	0.7	1	100	14
12	ADMX	Axion/NbTi mono	U Wash	7	0.5	1.1	14	0.4
5	900 MHz	NMR/Sn mono	MagLab	21.1	0.11	0.6	40	15

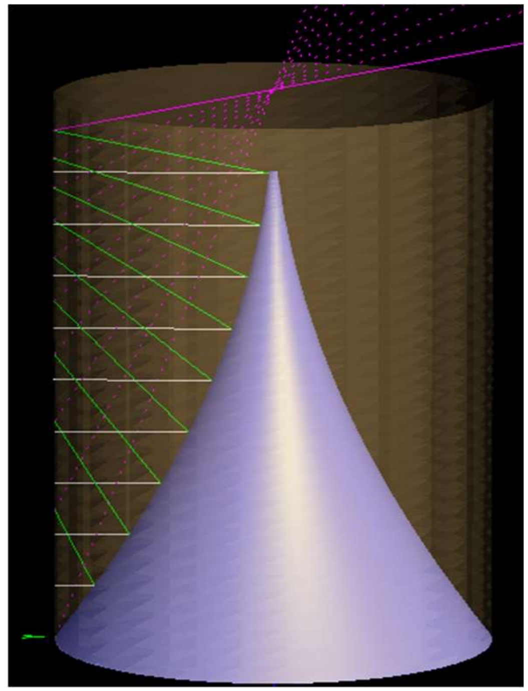
Compilation by Mark Bird, NHMFL

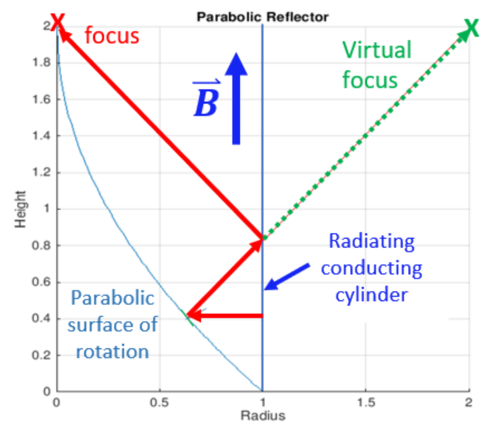




“Coaxial Dish”: Optical Concentrator for Solenoid Magnets

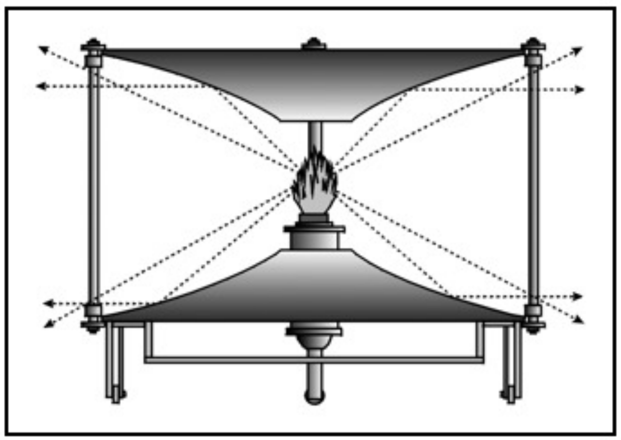






- Rays emitted from cylindrical inner surface of solenoid are focused to a point after two reflections.

Design Legacy- 19th Century Lighthouse Mirrors



Bordier-Marcet's 'Fanal Sidereal Reflector. (1809)

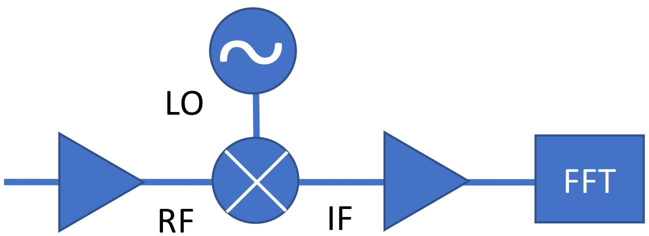
Fanal Sidereal Lantern. (1811)

In 1809, Bordier-Marcet invented the 'Fanal Sidereal' reflector where two parabolic reflecting surfaces were placed one above the other. Each of the reflecting surfaces had a central hole where the lamp flame was placed. The Fanal Sidereal reflector was first used in the harbor lighthouse in Honfleur, France and the design was patented in 1812.

From https://uslhs.org/reflectors

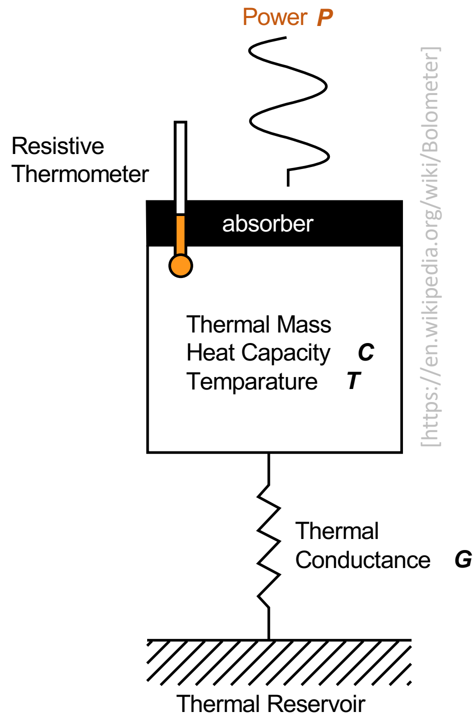
Three Strategies to Measure Signal

Heterodyne



- high resolution
- **Standard Quantum Limit (SQL):** $k_B\, T_{noise} = hf$

Bolometer



[https://en.wikipedia.org/wiki/Bolometer]

NEP ~ $10^{-20}\ W/\sqrt{Hz}$

Single Photon Counting

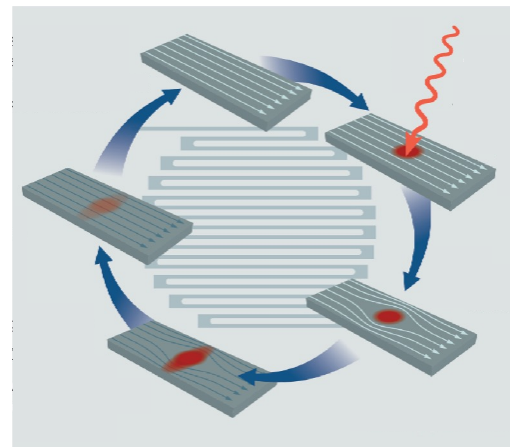


Fig.: Sae Woo Nam (NIST)

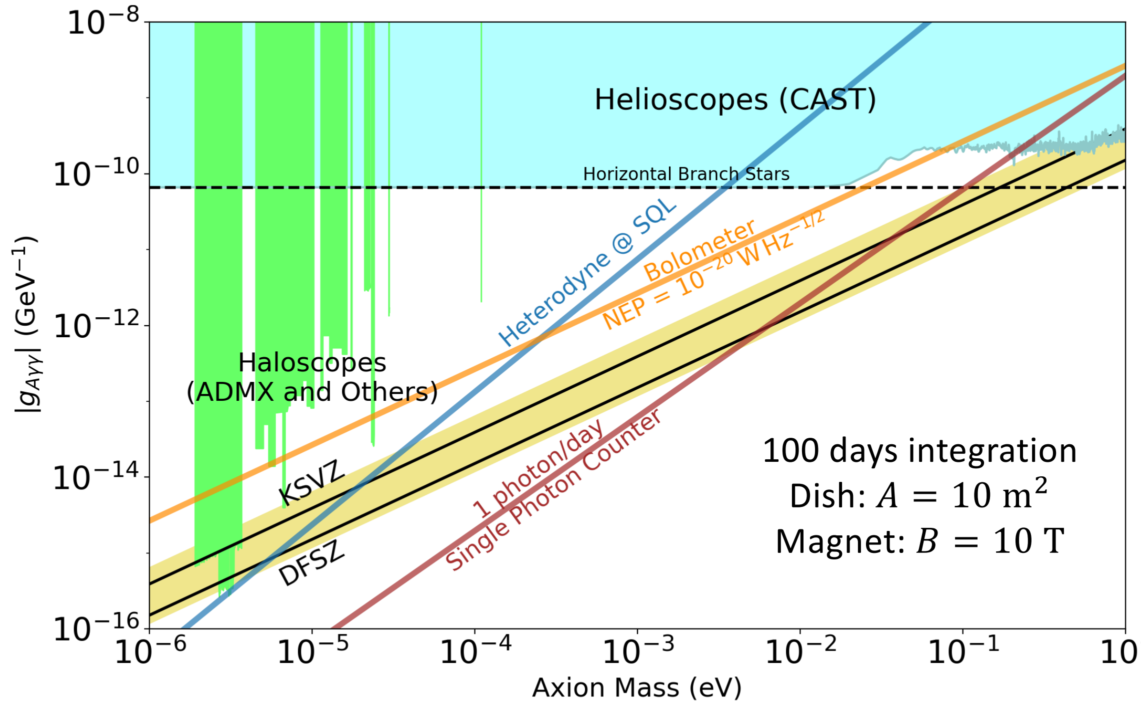
e.g., nanowire detectors

SNSPDs, KIDs, QCDs, …

down to ~ 1 photon/day

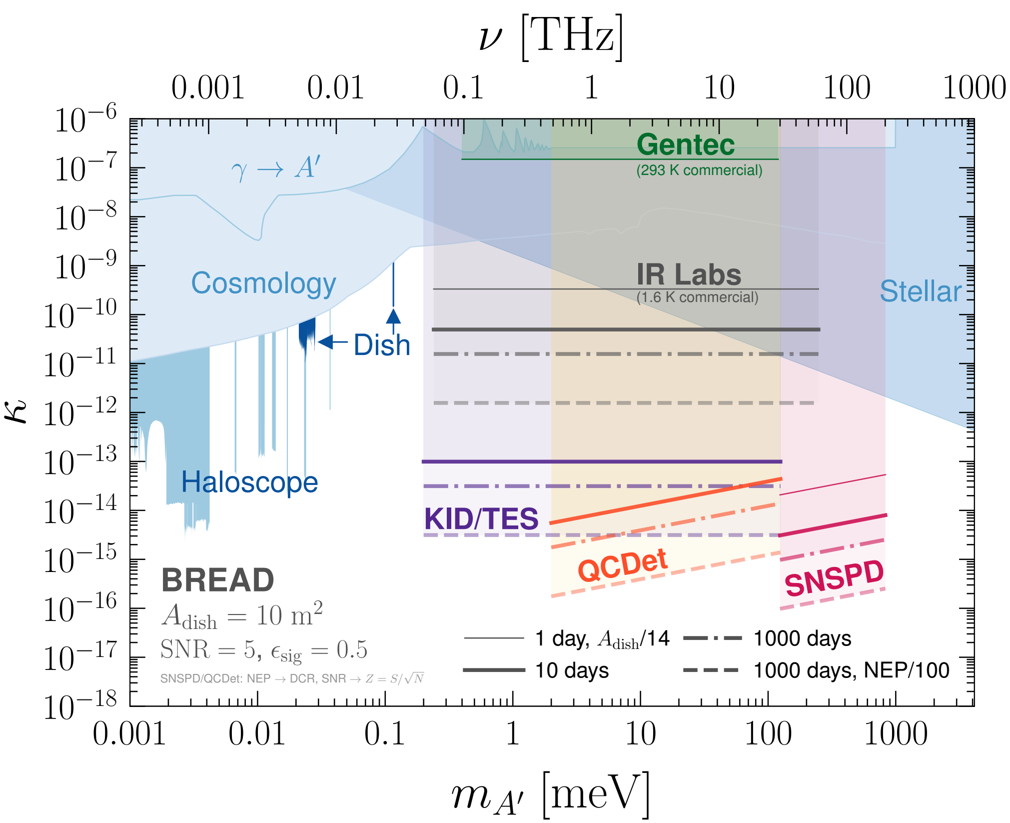
Sensitivity Projections-- Futuristic

- Assume the use of largest magnets currently available.
- 10 Tesla field x 10 m^2 bore area -> 10^{-25} W signal power for KSVZ axions.
- Not enough signal power for detection with current state-of-art sensors. E.g. bolometer with 10^{-20} W/Sqrt(Hz) noise equivalent power.
- However, sensor field is rapidly changing- new quantum technologies.

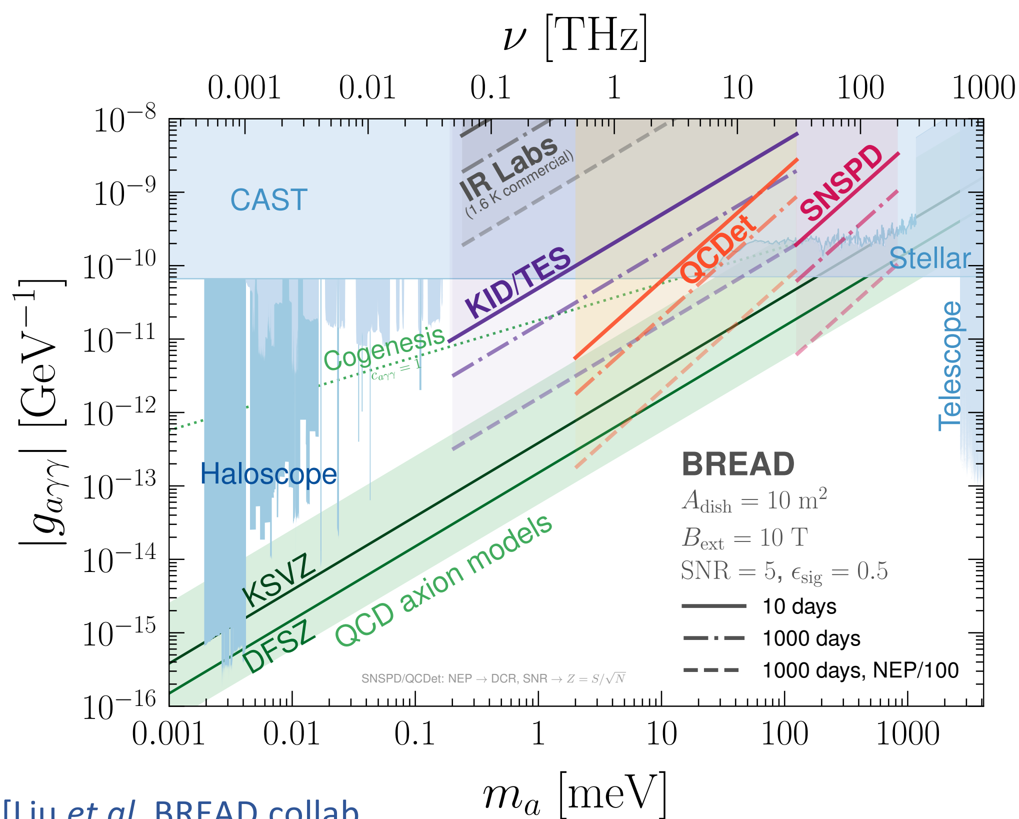


BREAD Sensitivity with State of Art THz Sensors

Dark Photons



Axions



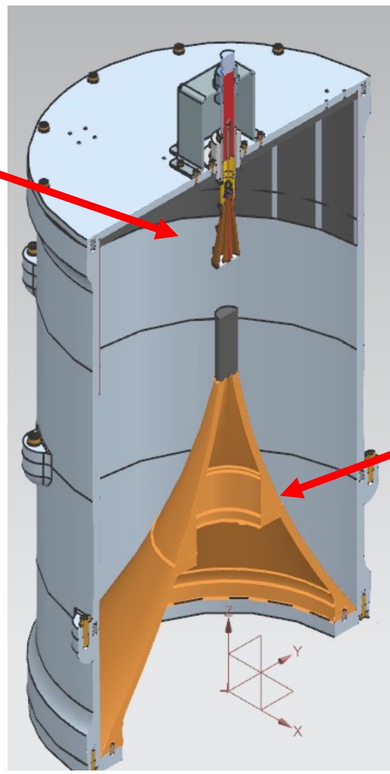
[Liu *et al*, BREAD collab.,
arXiv:2111.12103, PRL 128 (2022) 131801]

Proof of Concept Experiments: GigaBREAD and InfraBREAD

GigaBREAD: 10-20 GHz experiment with HEMT amplifier

Horn Antenna with Axial position adjustment

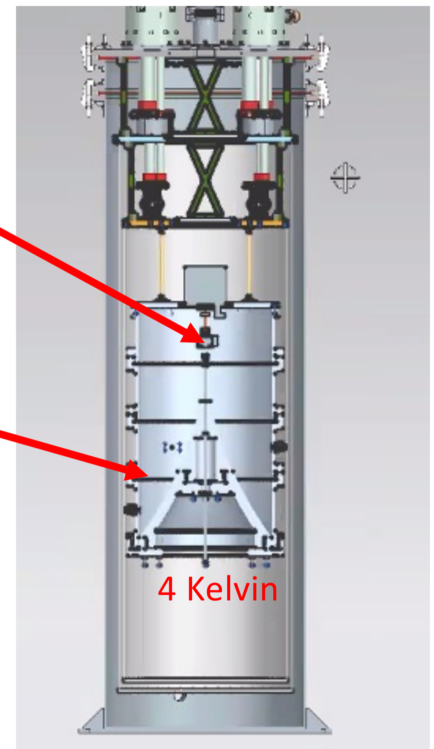
Room temperature



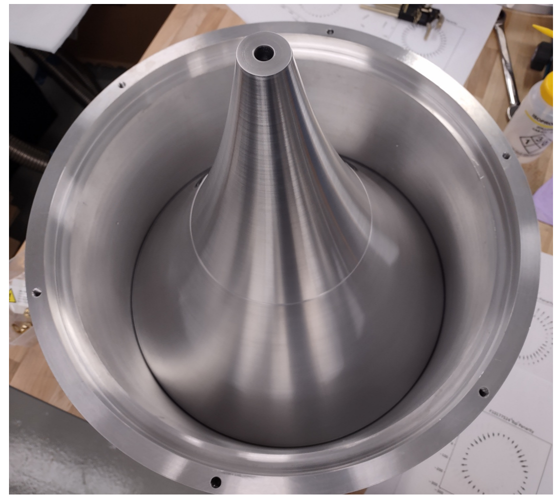
400 mm diameter Coaxial Dish

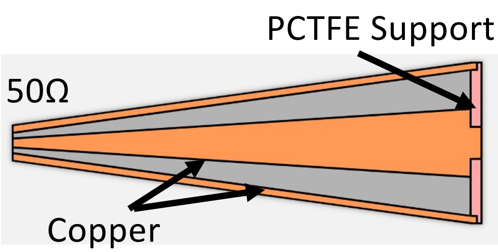
InfraBREAD: 300 THz experiment (~1 micron) with Superconducting Nanowire Detectors (SNSPDs)

SNSPD @ 800 mK



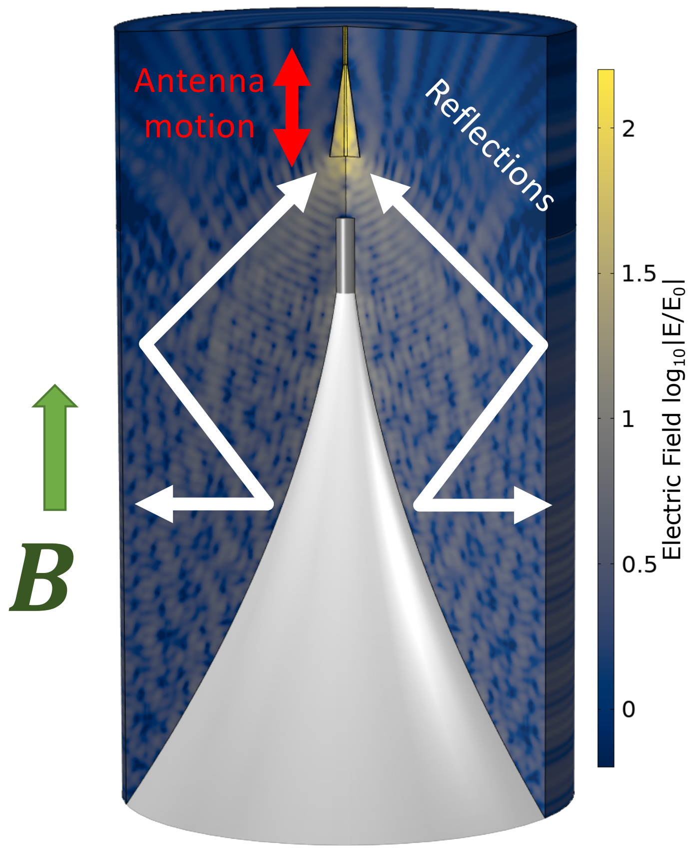
GigaBREAD Parts & Assembly

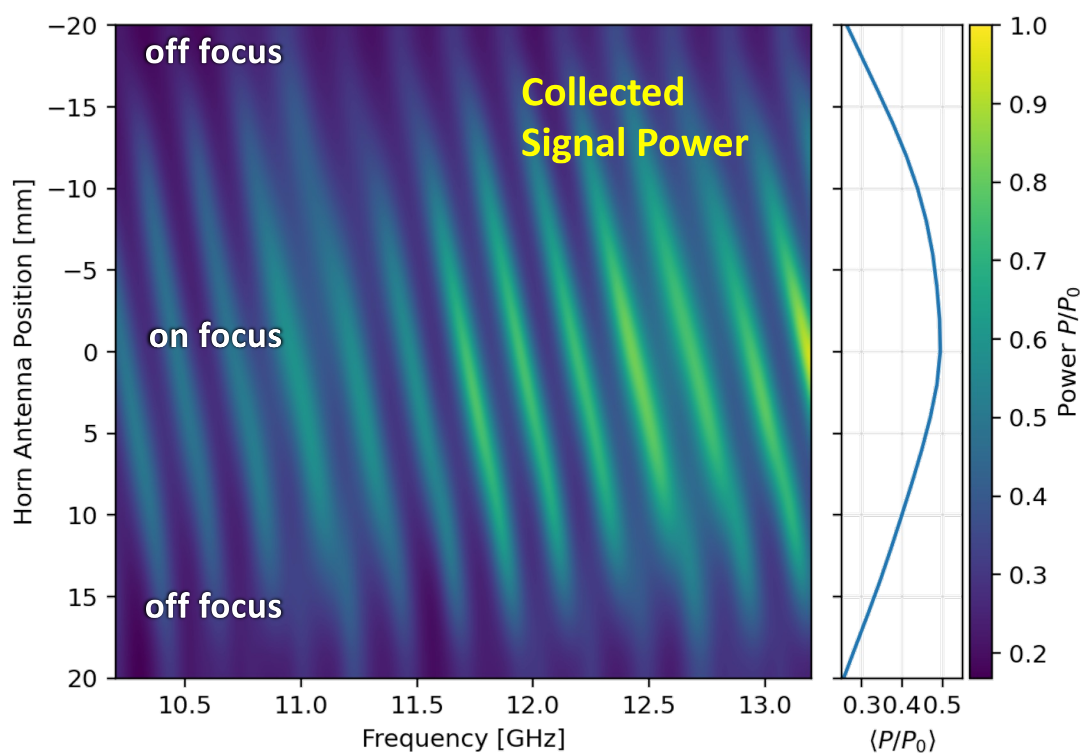




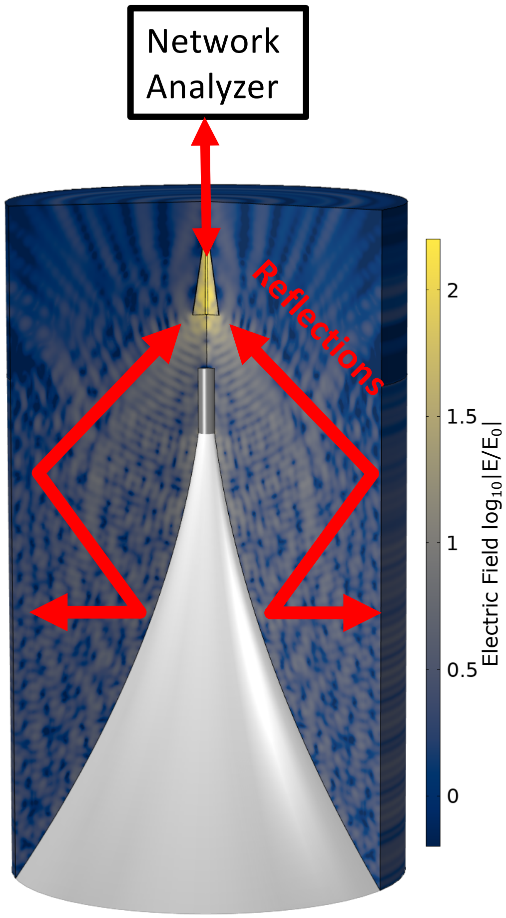
Simulation of GigaBREAD Axion Response

- COMSOL Simulation of system response to axion-induced oscillating electric field.
- Includes effect of horn antenna impedance mismatch to signal mode.

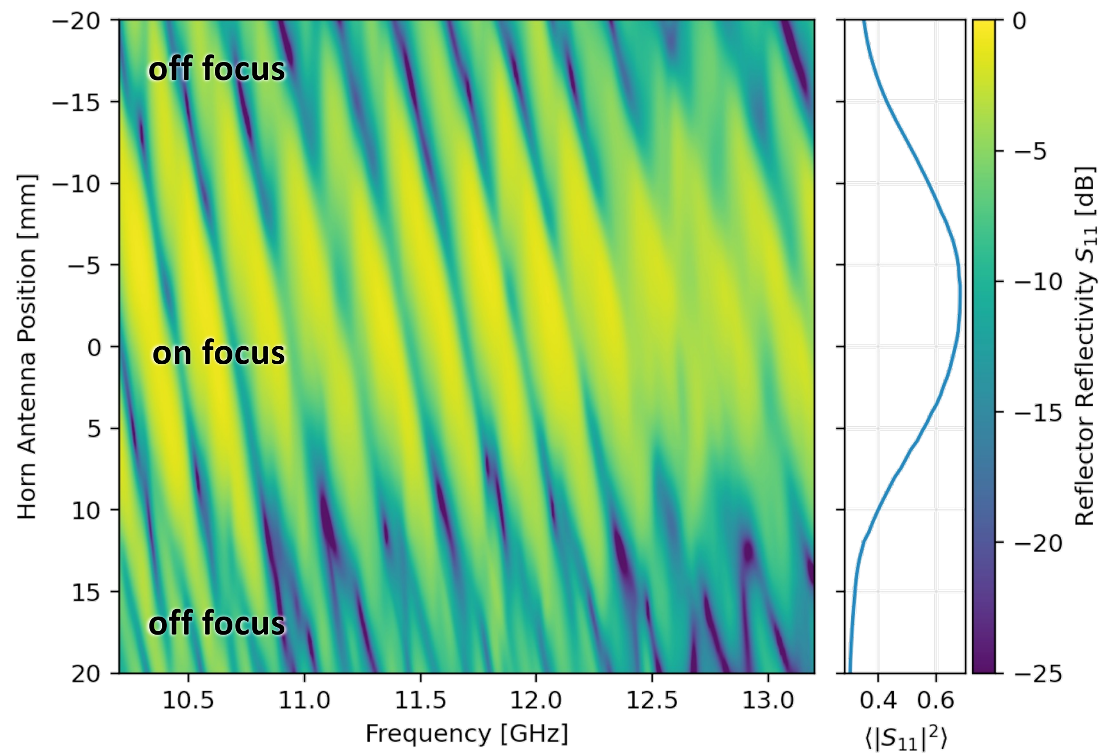




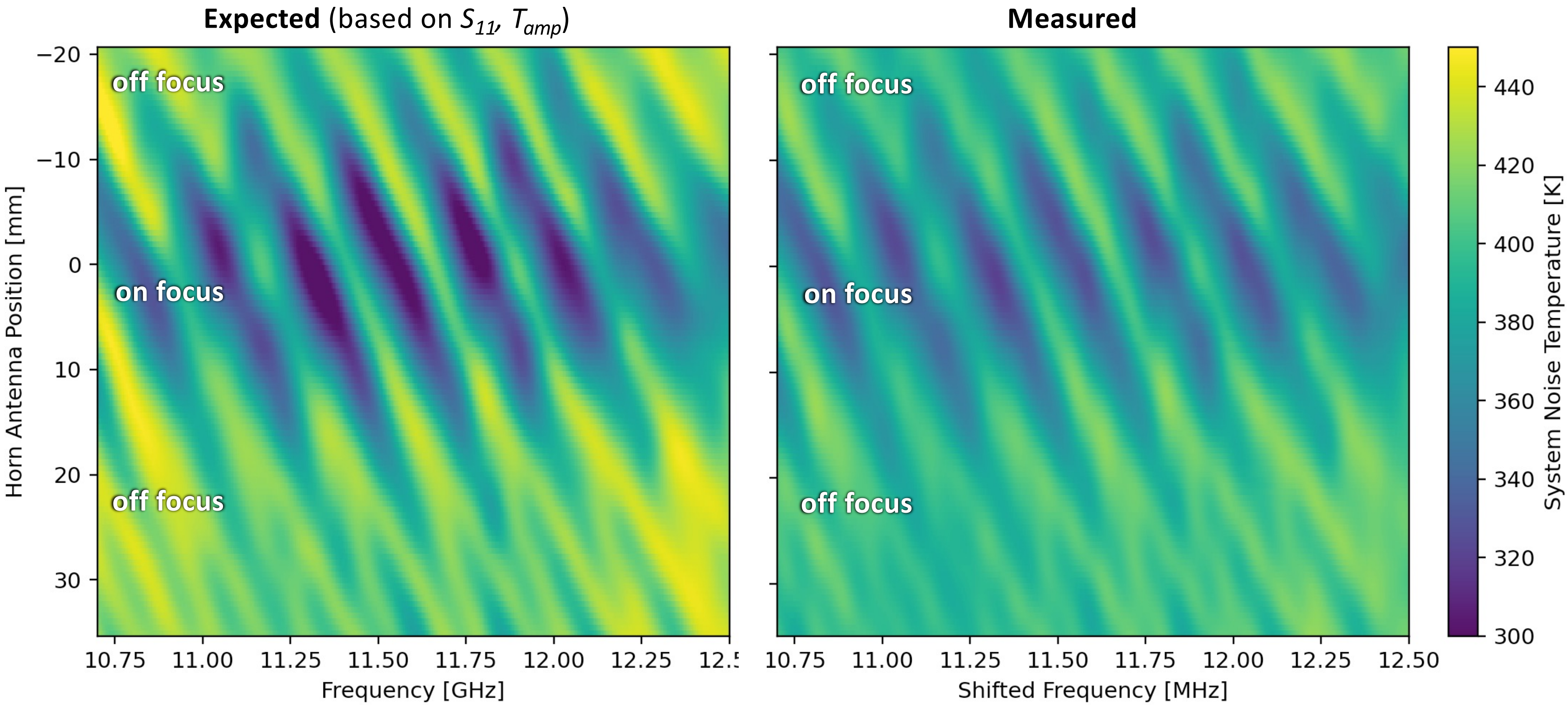
GigaBREAD Reflection Measurements



- Measure reflected RF power with network analyzer (S_{11})



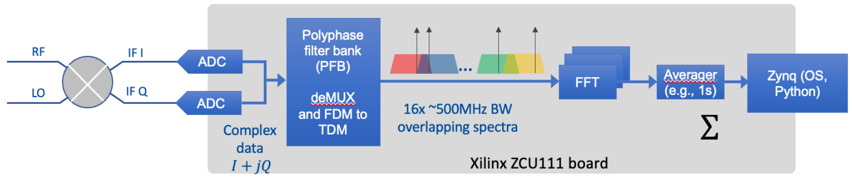
Thermal Emission from Dish at Room Temperature

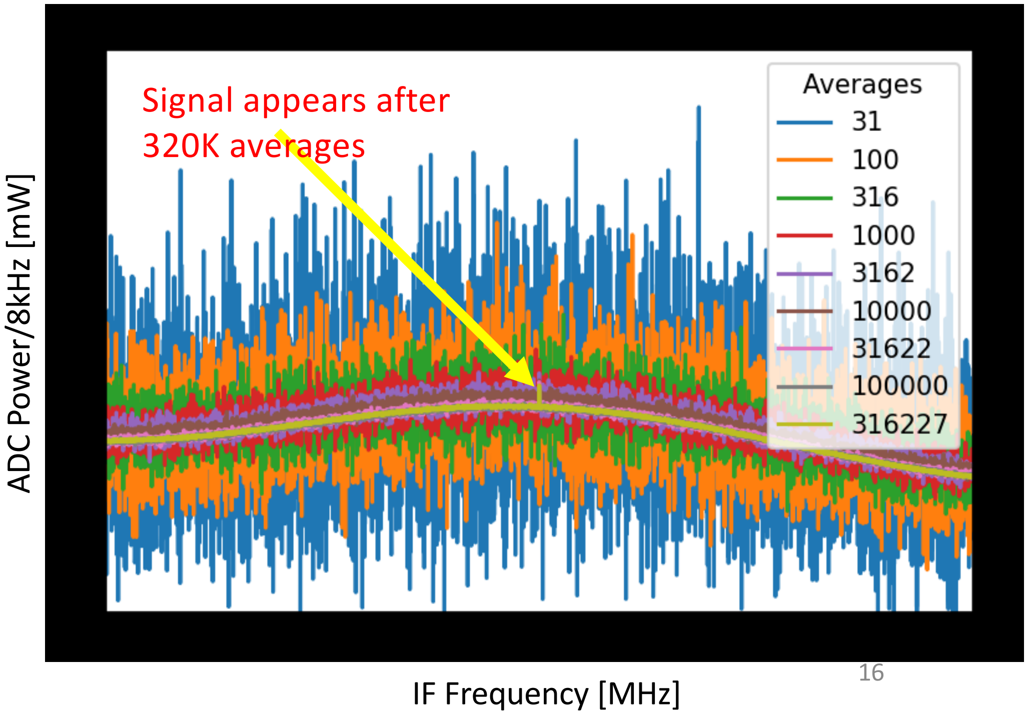


FPGA- Based Data Acquisition

- Off-the-shelf Xylinx FPGA board averages 4 million frequency channels in real time.
- Can search for a 1- MHz wide signal over 2-GHz bandwidth with negligible dead time.

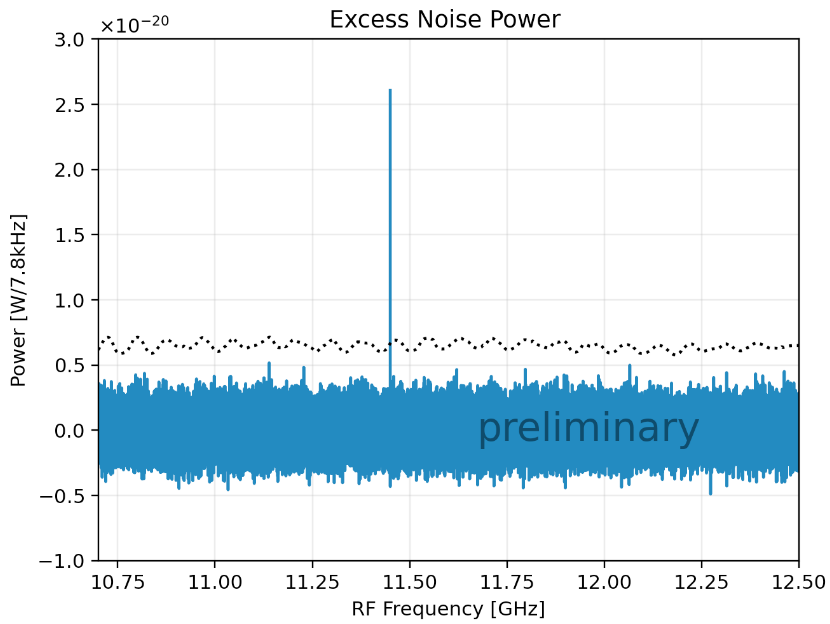
Real-Time Averager

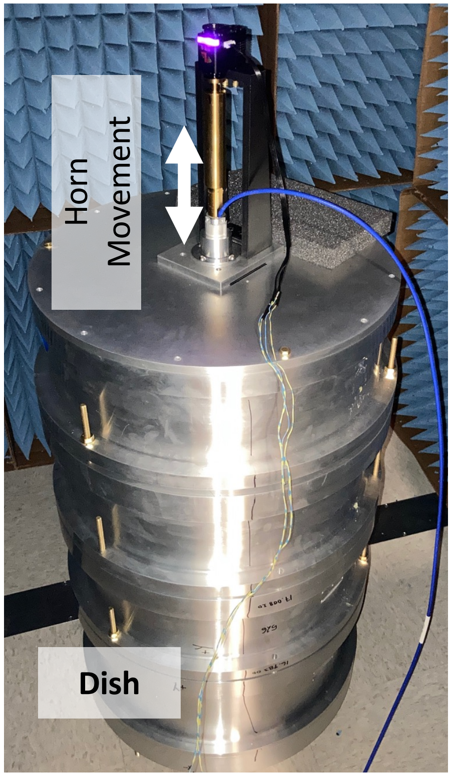




First Dark Matter Search with GigaBREAD

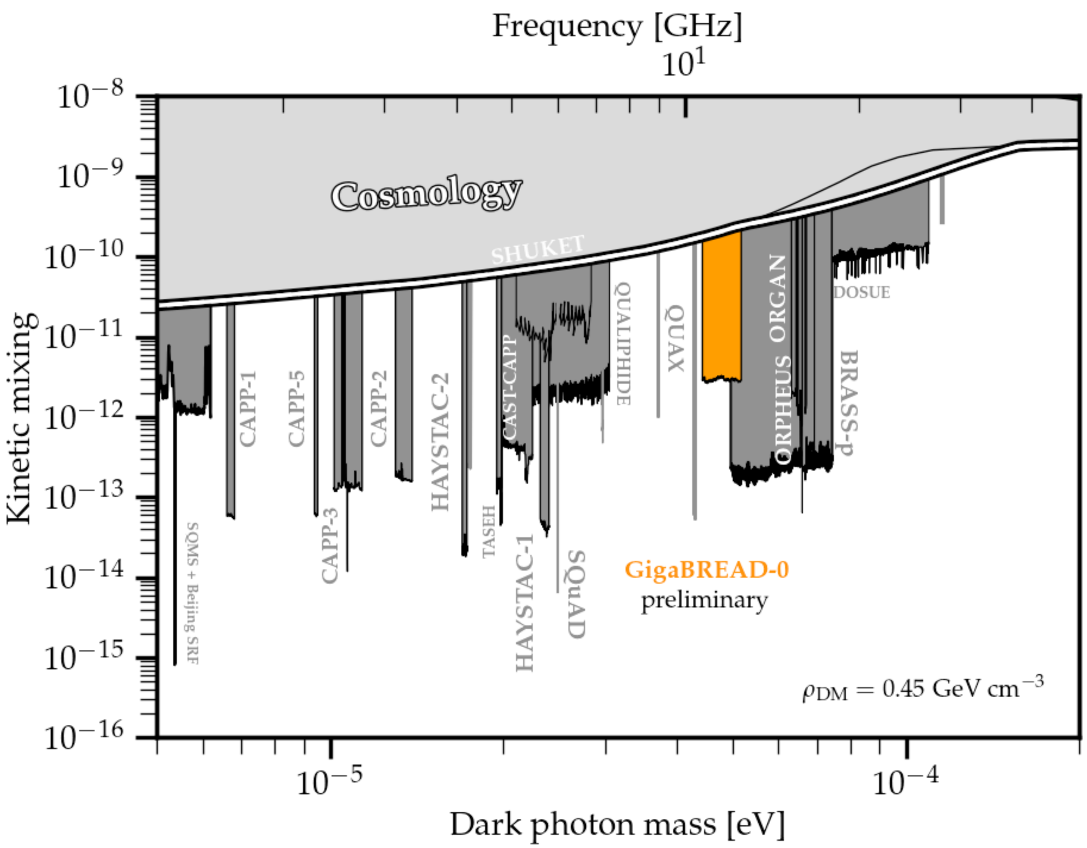
- 3.5 day run in an RF shielded room at University of Chicago.
- 10.7- 12.5 GHz
- Room temperature
- Off-the-shelf HEMT amplifier ~100 Kelvin added noise.
- No magnet (dark photon search)
- Scanning of vertical horn antenna position.

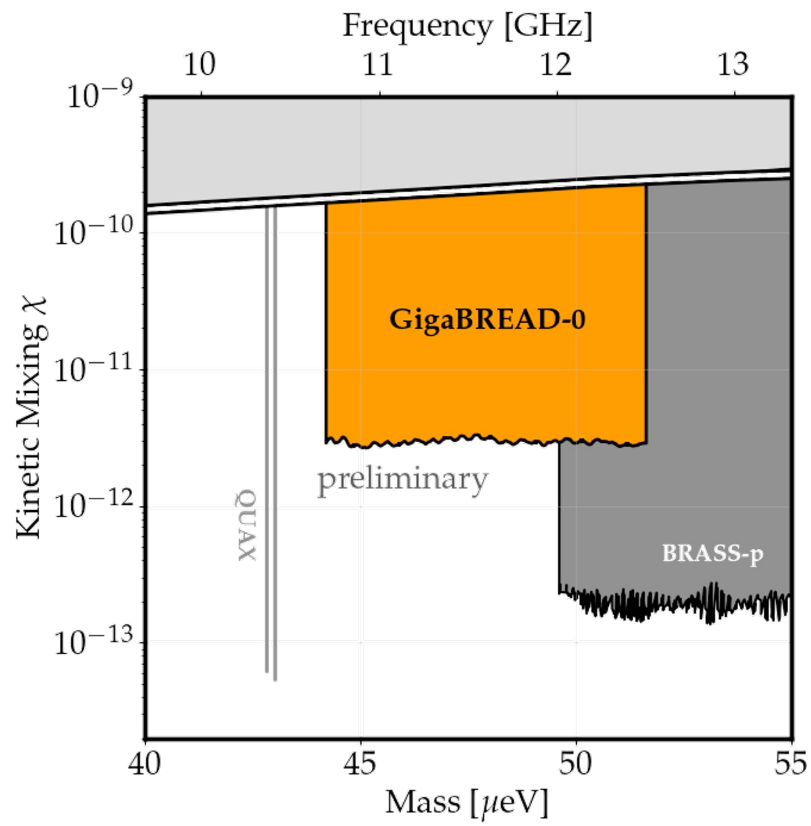




First Dark Photon Search with GigaBREAD

- 3.5 days of scanning at room temperature.

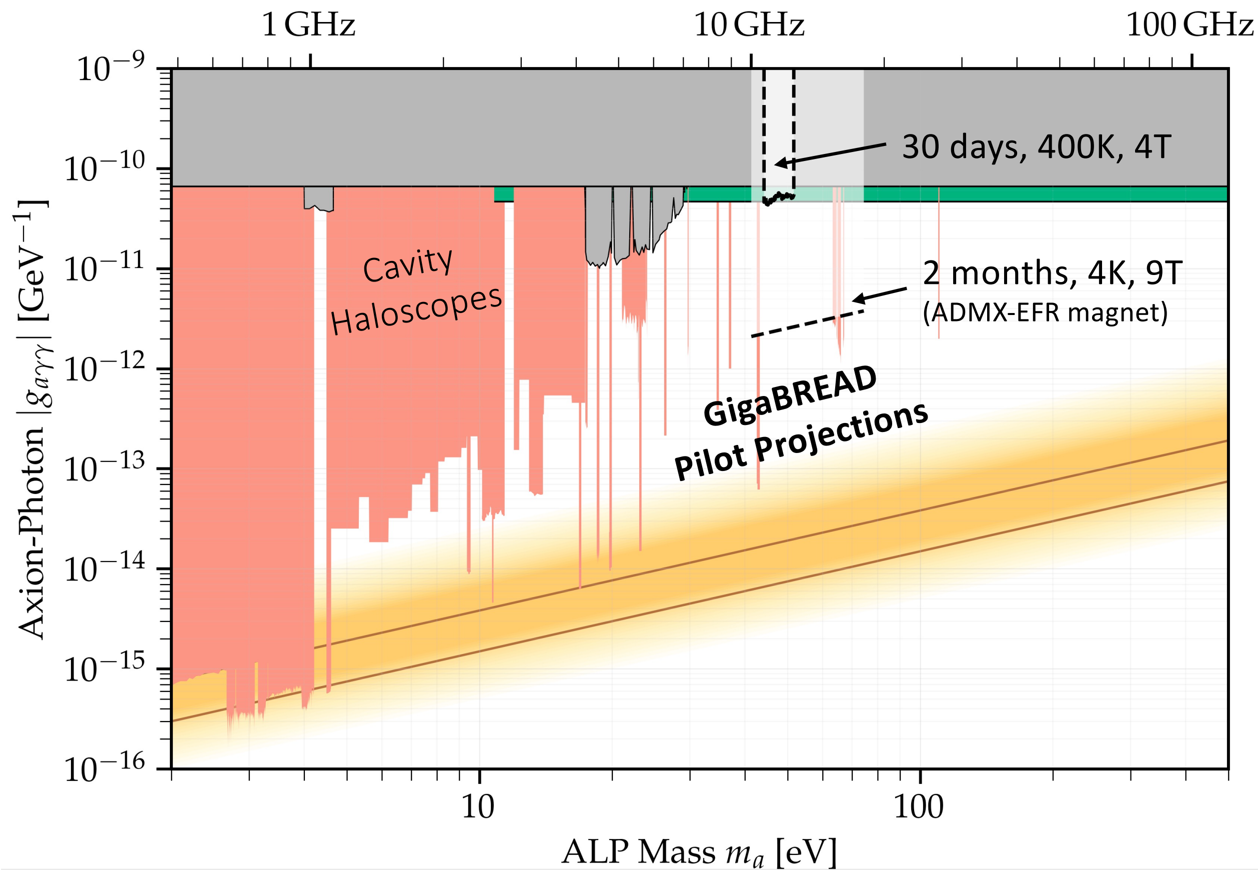




[limit plot adapted from cajohare.github.io/axionlimits]

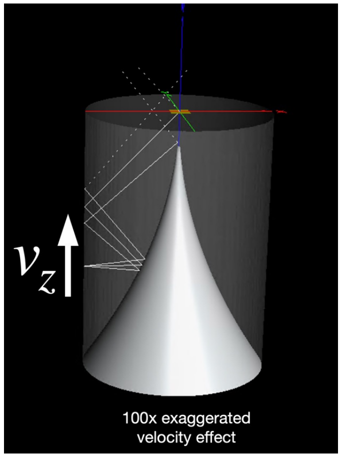
Next Step– Axion Search at Argonne Natl Lab

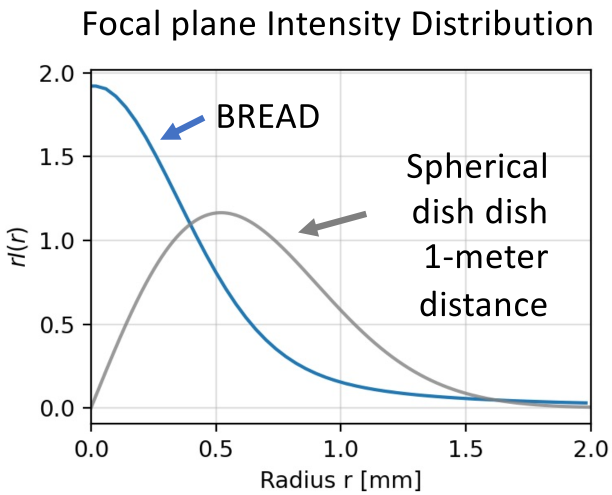
4 T MRI magnet at Argonne

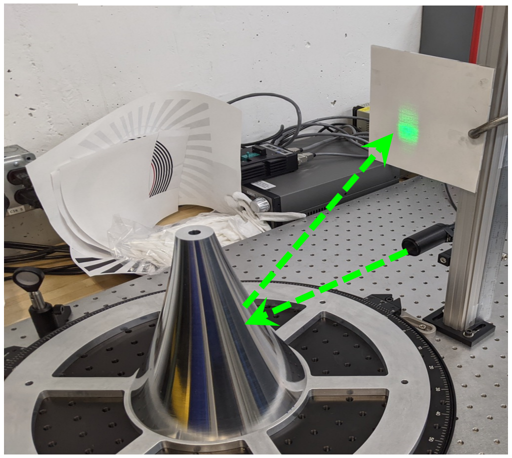


InfraBREAD Dish Requirements

- At optical wavelengths, need best possible focusing to limit size of photosensor.
- Dark matter velocity dispersion limits focal spot to ~ 1 mm for a meter scale device.
- Reflector surface deviations need to be controlled at few micron level.
- Achievable by industry standard optical machining process (single point diamond turning) on various substrates (e.g. aluminum)



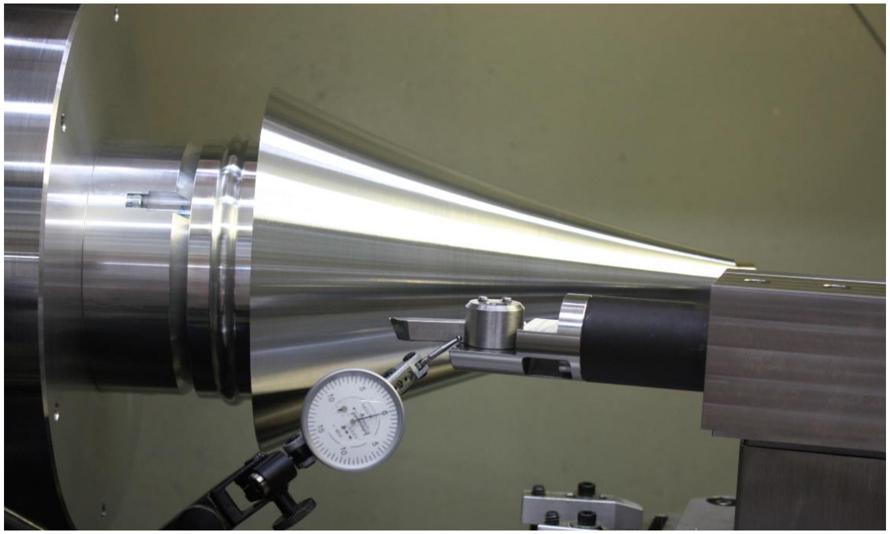


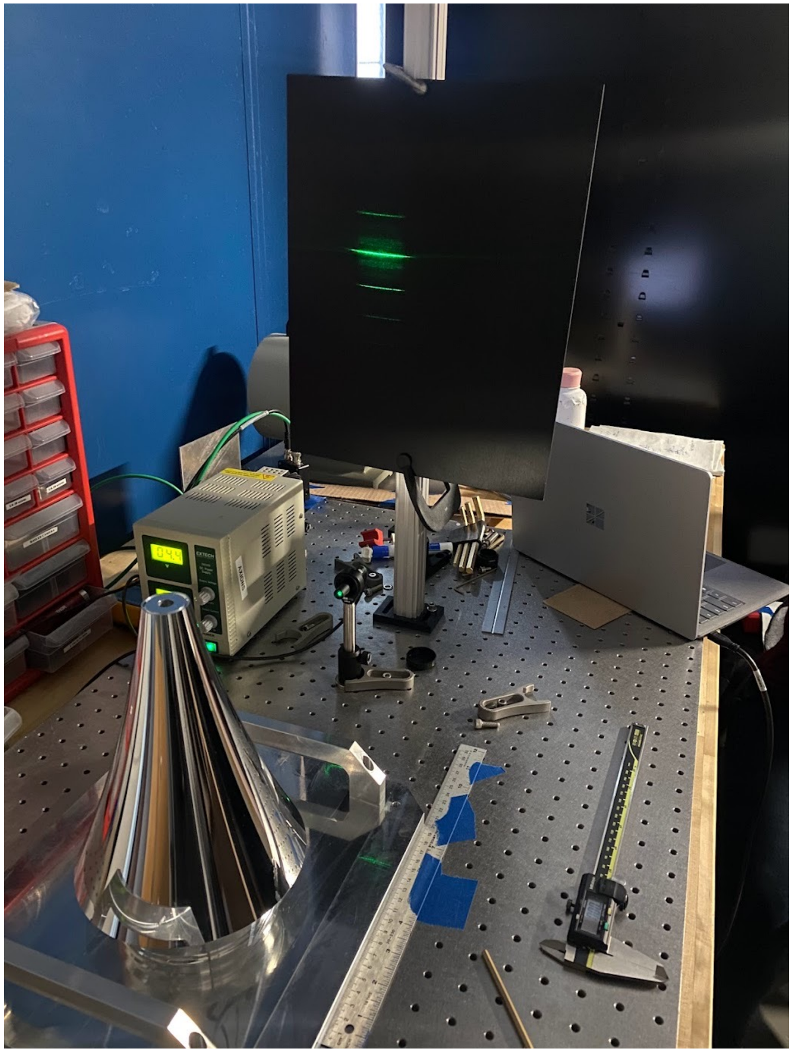


Measuring focal spot dispersion with laser

First Diamond Turned Reflector Segment from LLNL

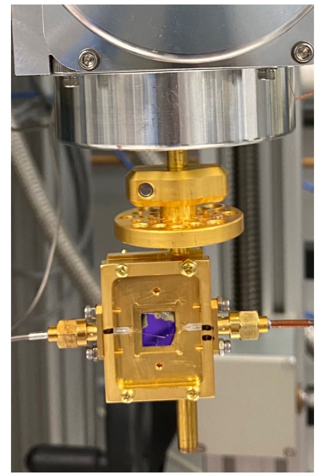
- Single point diamond turning– standard technique for metal optics fabrication.
- Can achieve nanometer- level precision and smoothness.
- First of five segments for InfraBREAD meets requirements.
- Measure 12 nm RMS surface roughness by optical scattering.
- ~ 1% signal power loss to diffuse reflections.

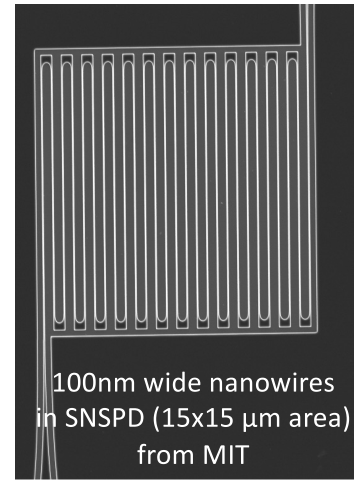


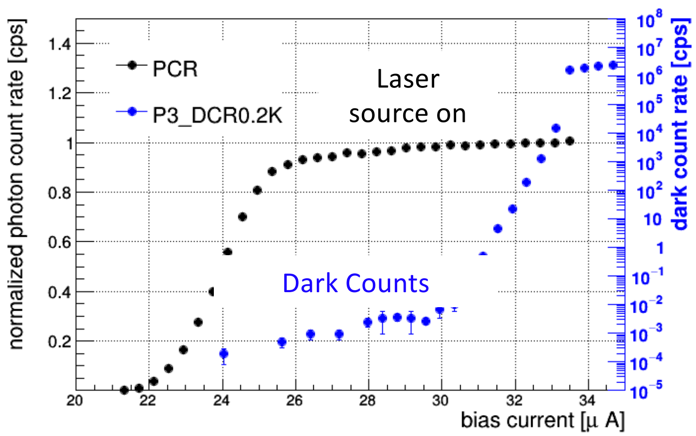


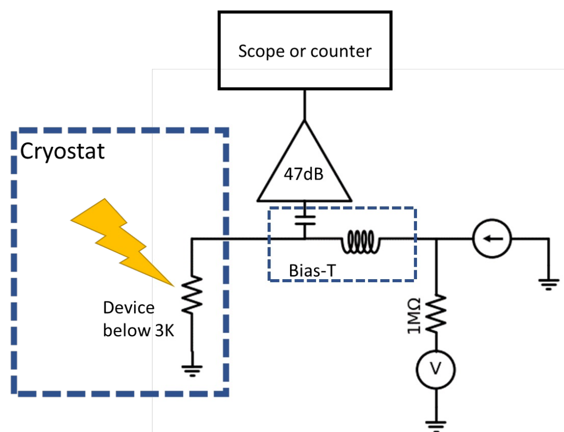
SNSPD Testing for InfraBREAD

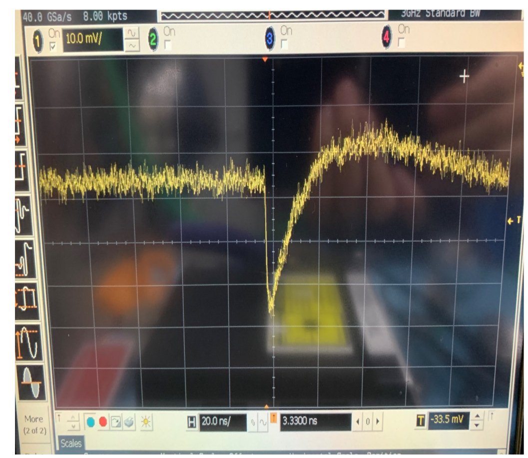
- Superconducting Nanowire Single Photon Detectors (SNSPDs) for BREAD supplied by MIT and JPL groups (See Matt Shaw's talk at this meeting)
- Largest devices made to date are 1 mm^2 , well matched to our requirements.
- Measurements of efficiency and dark counts underway at Fermilab. Similar devices have achieved < 1 count per day backgrounds



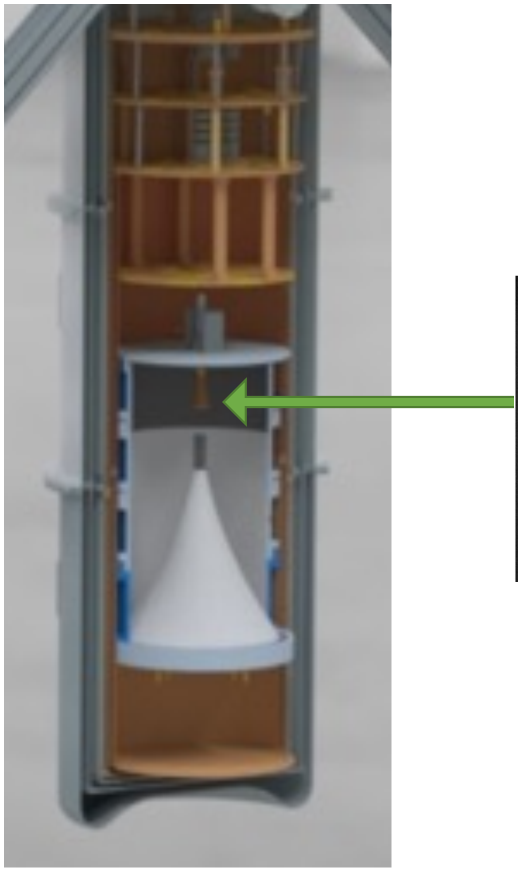




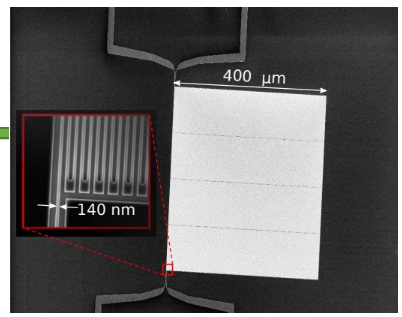




InfraBREAD Sensitivity Projection

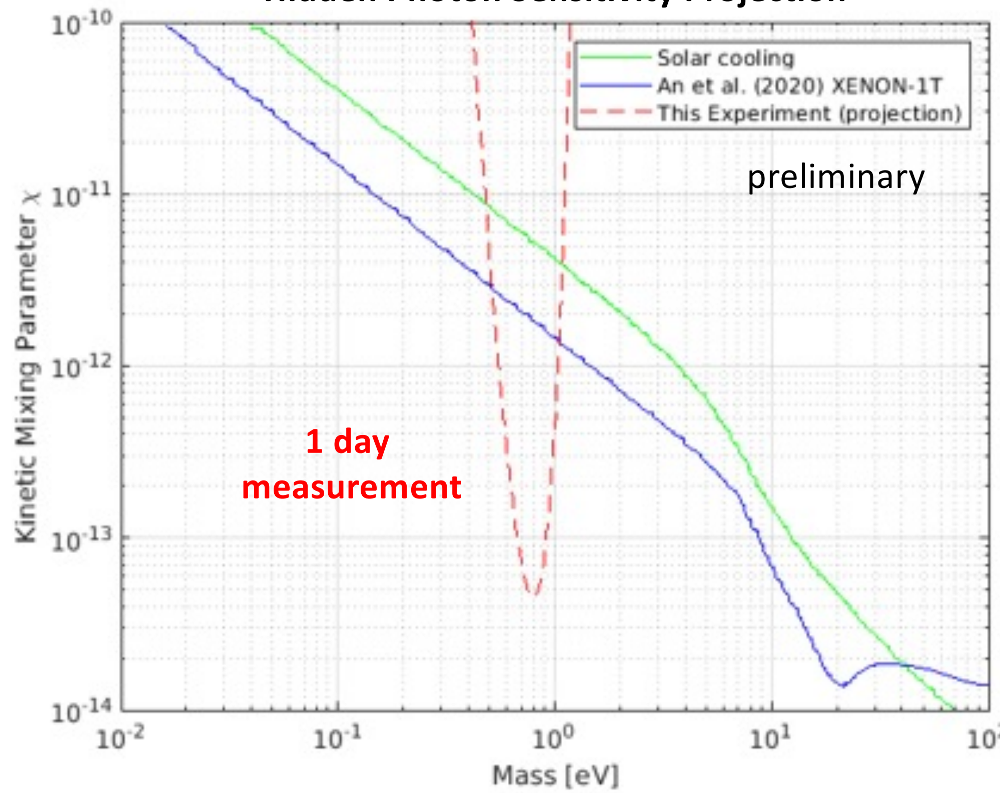


1 photon/day
dark rate



[Hochberg *et al.*,
PRL 123 (2019)]

Hidden Photon Sensitivity Projection



Summary

- The BREAD ”cylindrical dish” design allows use of existing large—bore, high-field solenoids for broadband axion searches.
- Can provide a (small) signal for any mass where Compton wavelength fits inside the device.
- We developed fabrication techniques for BREAD reflector which will enable experiments from microwave to infrared (micro-eV to eV scale)
- Next challenge is low-noise readout! QCD axion discovery with this technique will require new generations of photon counting sensors with dark counts as low as ~1 count per day.

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BREAD COLLABORATION

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Noah Kurinsky, Chiara Salemi *SLAC*

Extra Slides

Existing Sensors

[Liu *et al*, BREAD collab., arXiv:2111.12103, PRL 128 (2022) 131801]

Photosensor	$\frac{E}{\text{meV}}$	$\frac{T_{\text{op}}}{\text{K}}$	$\frac{\text{NEP}}{\text{W}/\sqrt{\text{Hz}}}$	$\frac{A_{\text{sens}}}{\text{mm}^2}$	
Bolometers					
GENTEC	[0.4, 120]	293	$1 \cdot 10^{-8}$	$\pi 2.5^2$	[https://www.gentec-eo.com/]
IR LABS	[0.24, 248]	1.6	$5 \cdot 10^{-14}$	1.5^2	[https://www.irlabs.com/products/bolometers/]
KID/TES	[0.2, 125]	0.3	$2 \cdot 10^{-19}$	0.2^2	[Ridder *et al*, J. Low Temp. Phys. 184, 60–65 (2016)], [Baselmans *et al*, Astro. Astroph. 601, A89 (2017)]
Single Photon Counters					
QCDet	[2, 125]	0.015	$\frac{\text{DCR}}{\text{Hz}} = 4$	0.06^2	[Echternach *et al.*, Nat. Astron. 2, 90–97 (2018)], [Echternach *et al.*, J. Astron. Telesc. Instrum. Syst. 7, 1–8 (2021)]
SNSPD	[124, 830]	0.3	$\frac{\text{DCR}}{\text{Hz}} = 10^{-4}$	0.4^2	[Hochberg, et al., Phys. Rev. Lett. 123, 151802 (2019)] [Verma, *et al.*, arXiv:2012.09979 [physics.ins-det] (2020)]