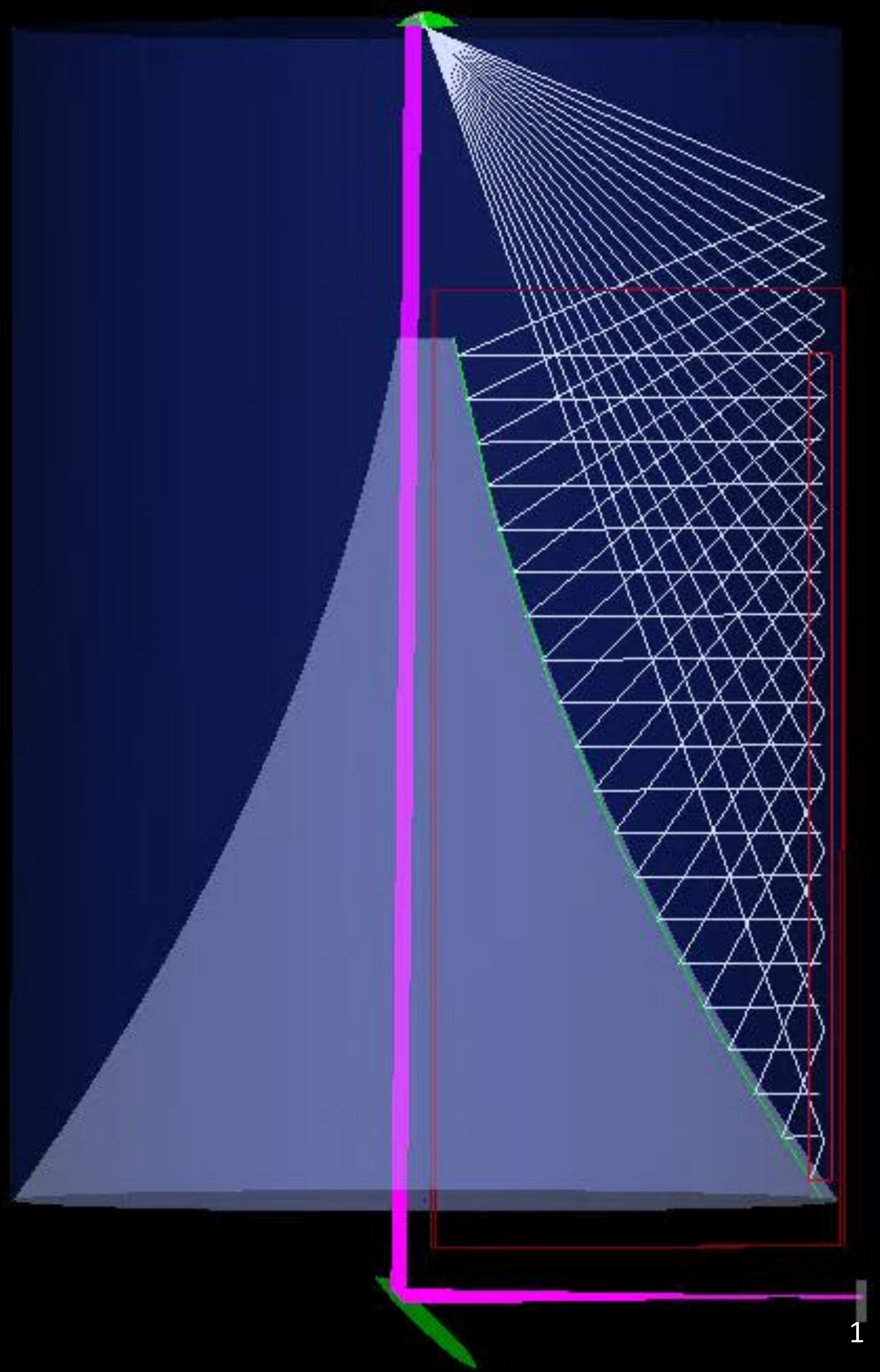
Broadband Reflector Experiment for Axion Detection (BREAD)

Andrew Sonnenschein

Fermilab

UCLA Dark Matter Meeting DM2023

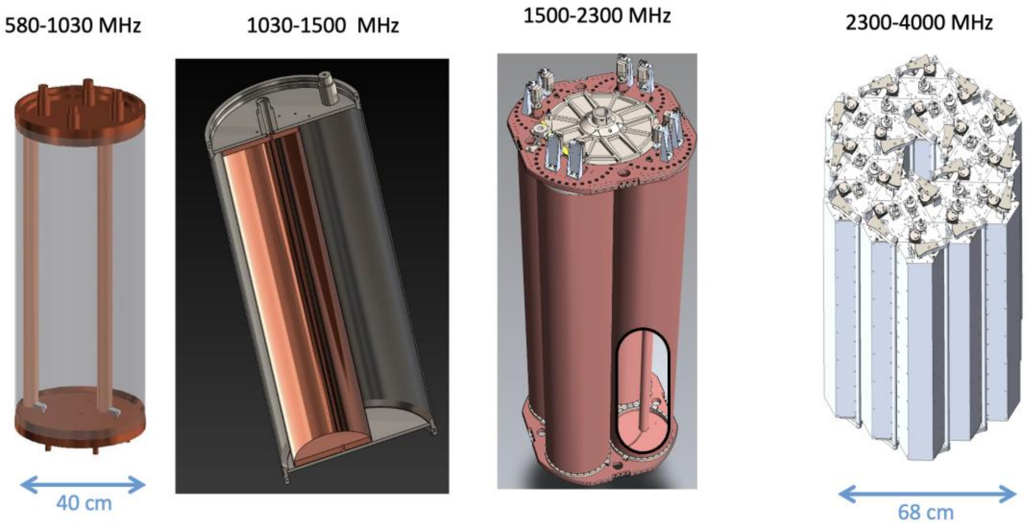
April 1st, 2023

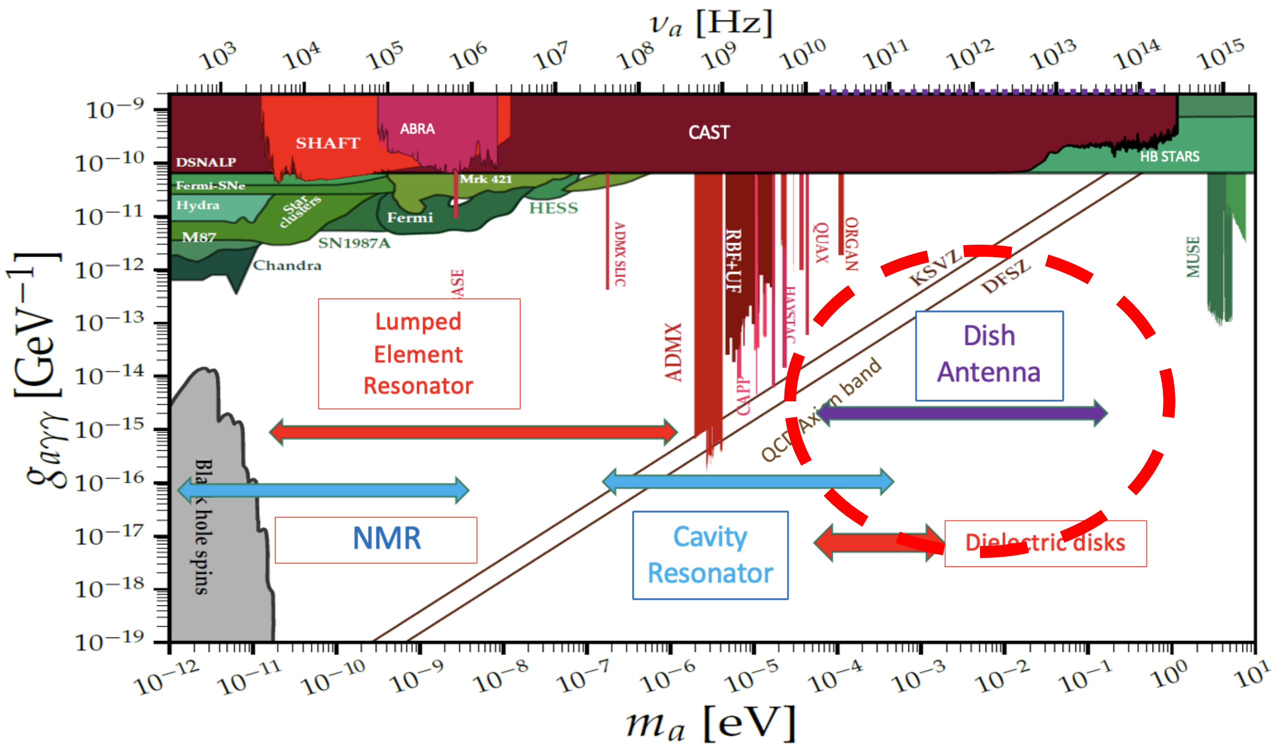


Motivation: Cavity Experiments Scale Poorly to High Mass

- 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.

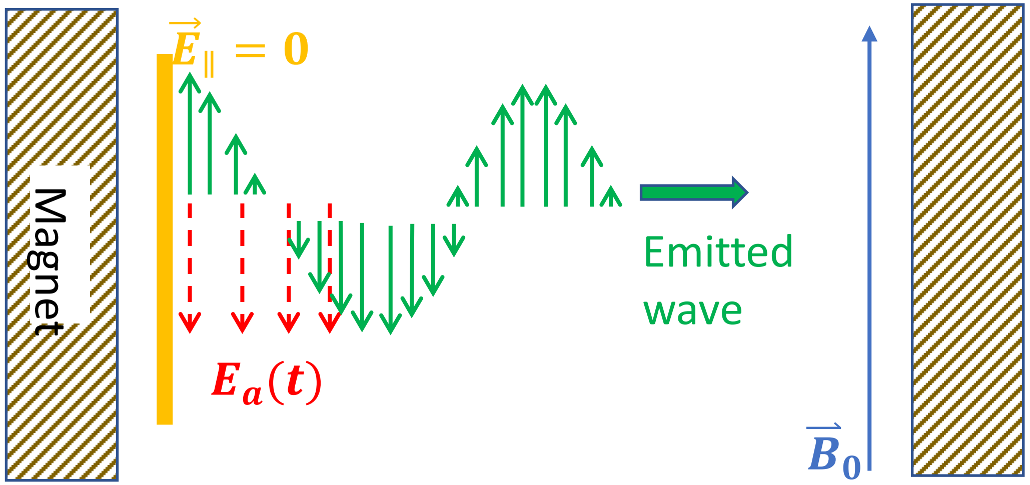
ADMX cavity designs for increasing mass ranges





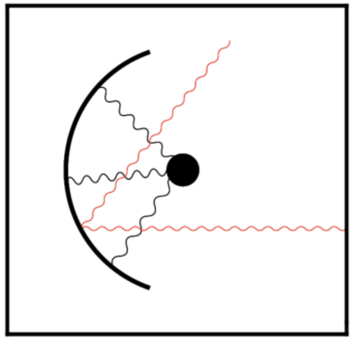
Axion-Induced Electromagnetic Radiation from Conducting Surface in Magnetic Field

- 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:

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



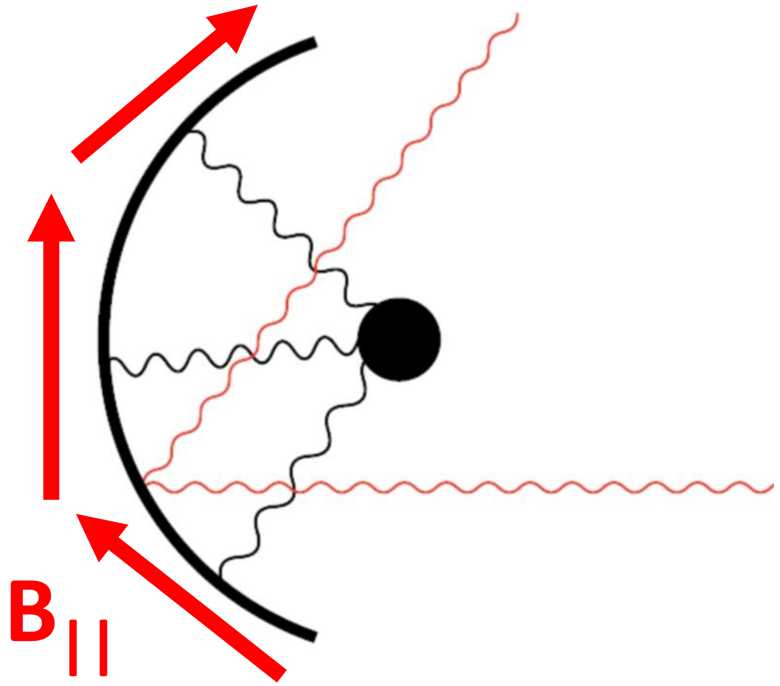
"Dish Antenna" Horns, Jaeckel, Lindner, Lobanov, Redondo & Ringwald, 2012

- But no detector tuning is required.

Magnetic Field Configuration

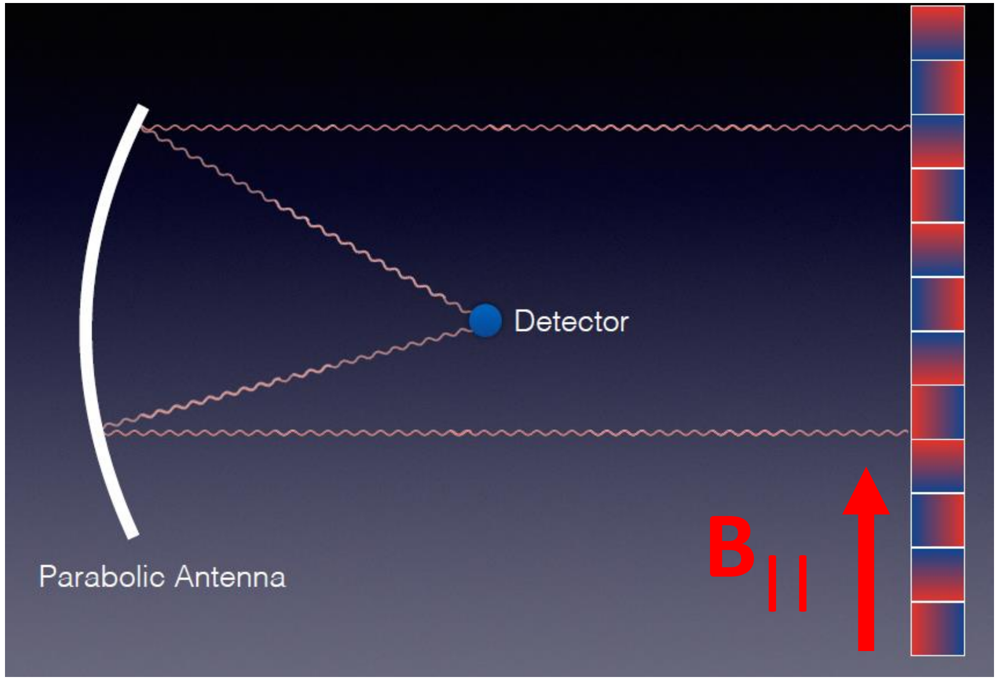
- Need to maximize component of magnetic field parallel to radiating surface $B_{||}$
- Spherical dish geometry not a good match to conventional magnet types.

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



“Dish antenna” (Horns et al., 2012)

BRASS experiment: Planar array of permanent magnets



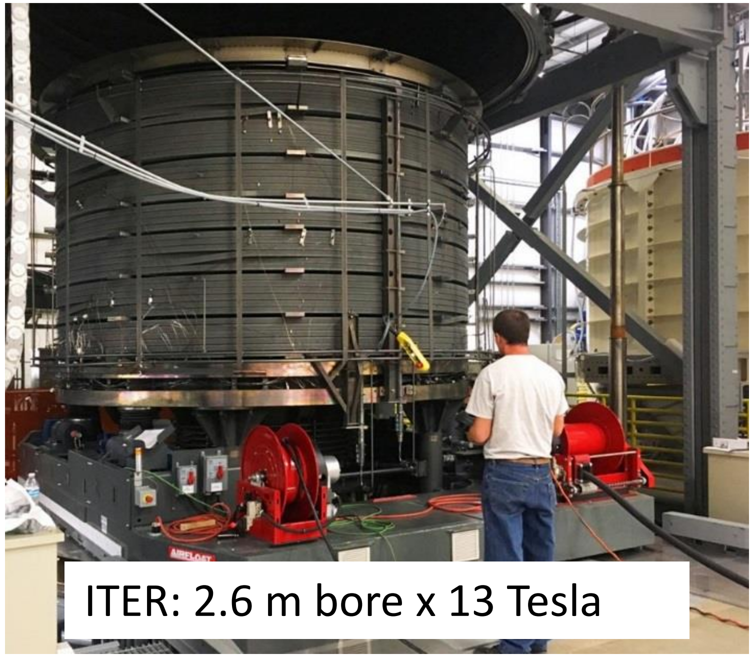
Le Hoang Nguyen, Patras 2019
http://wwwiexp.desy.de/groups/astroparticle/brass/brassweb.htm

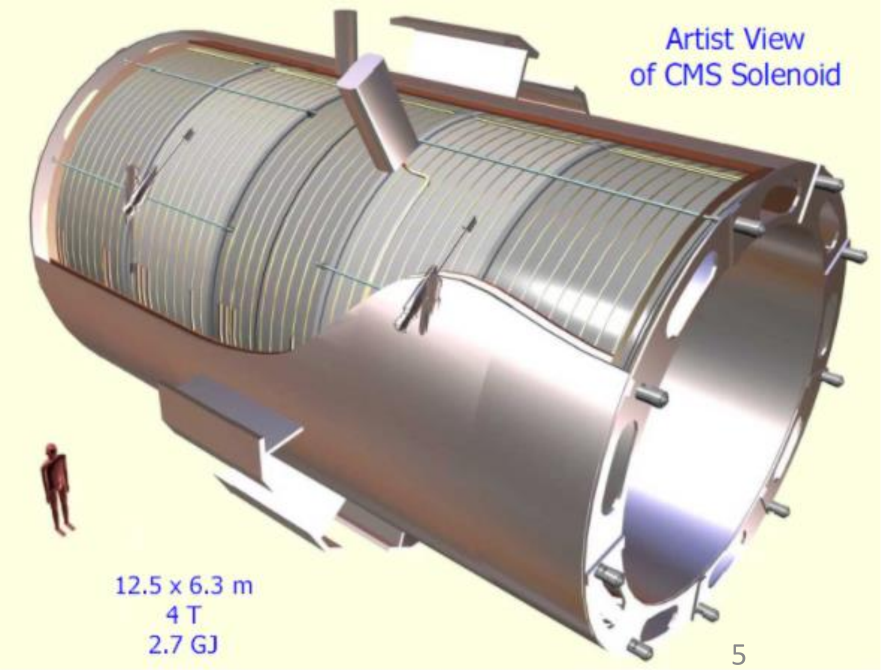
Large Solenoids

- How to use large volume solenoids to detect axions?

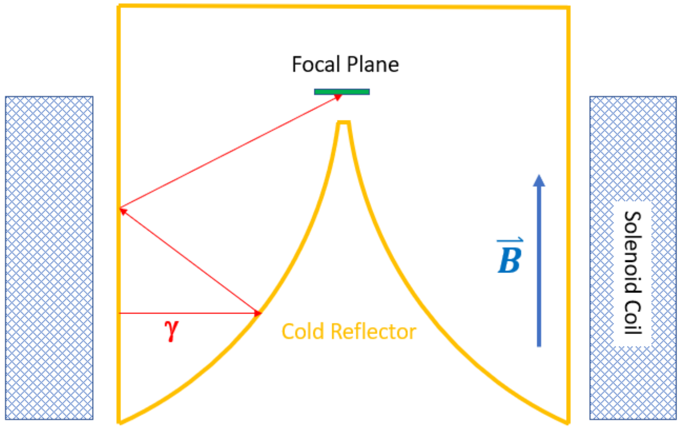
B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*	*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

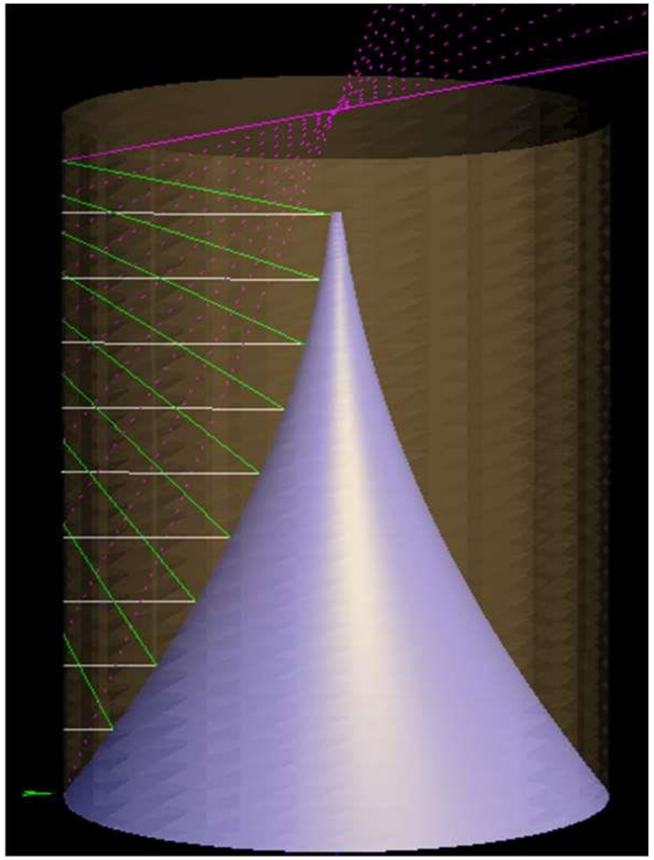
Compilation by Mark Bird, NHMFL

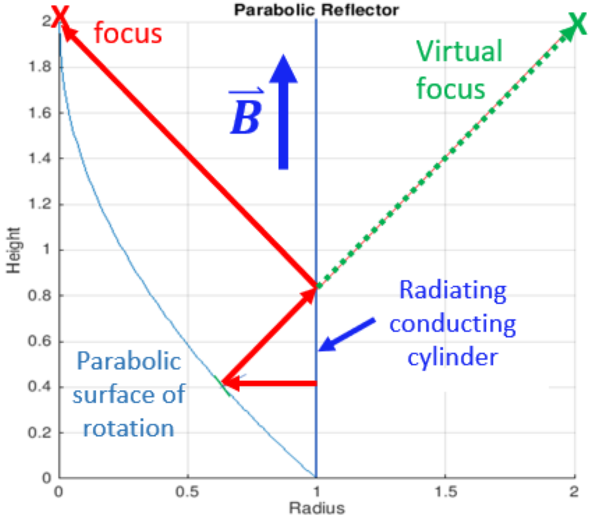

ITER: 2.6 m bore x 13 Tesla



“Coaxial Dish”: Optical Concentrator for Solenoid Magnets

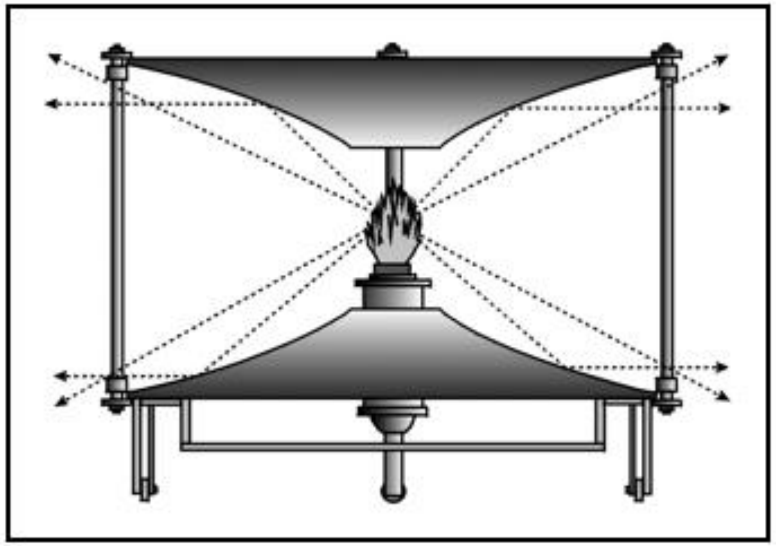






- Rays emitted from cylindrical inner surface of solenoid are focused to a point after two reflections.

Design Legacy- 19th Century Lighthouse Mirrors



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

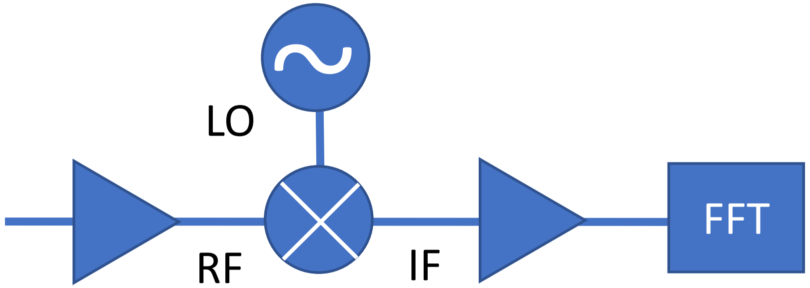
Fanal Sidereal Lantern. (1811)

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

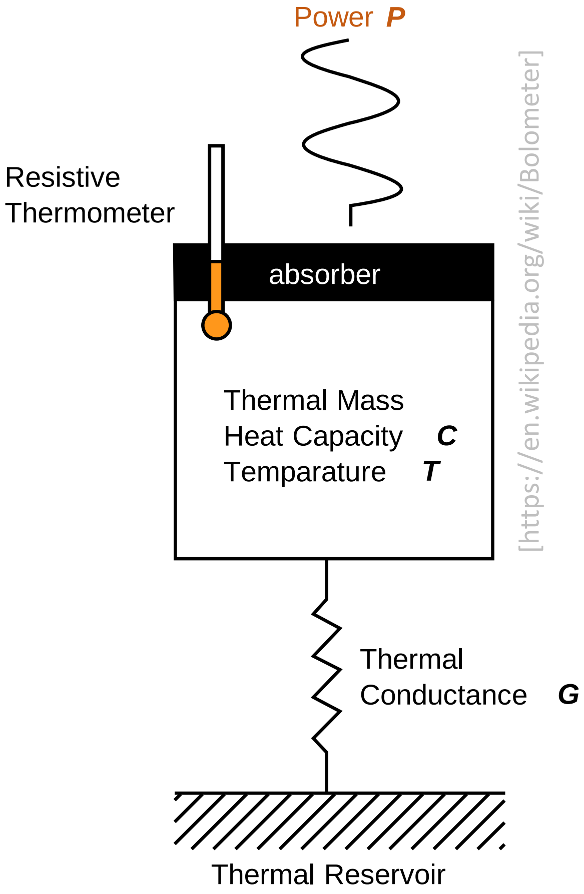
Three Strategies to Measure Signal

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

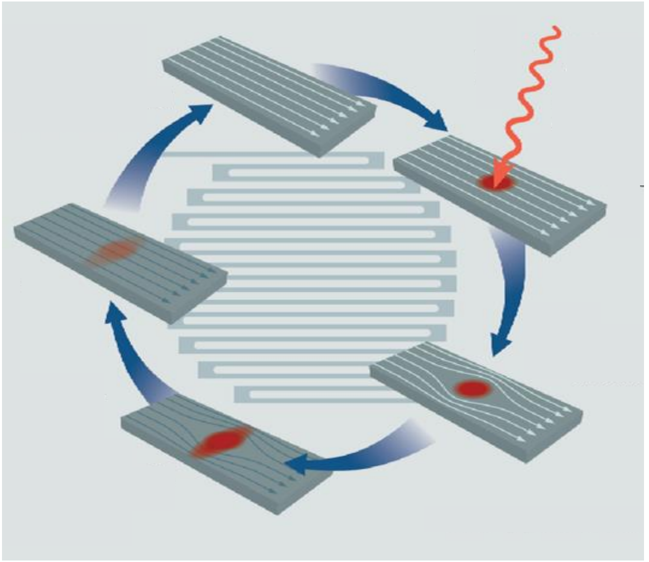


Fig.: Sae Woo Nam (NIST)

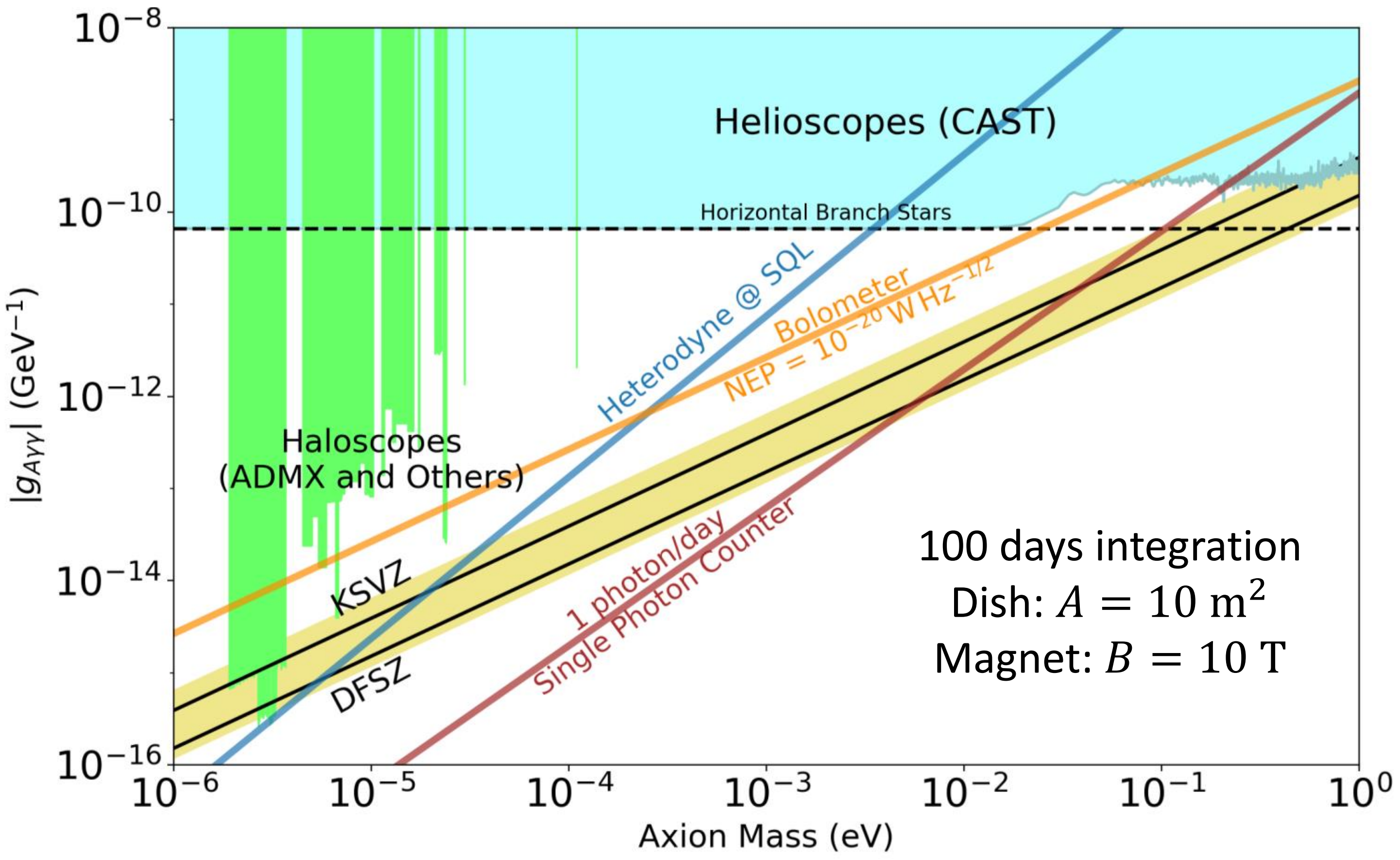
e.g., nanowire detectors

SNSPDs, KIDs, QCDs, …

down to ~ 1 photon/day

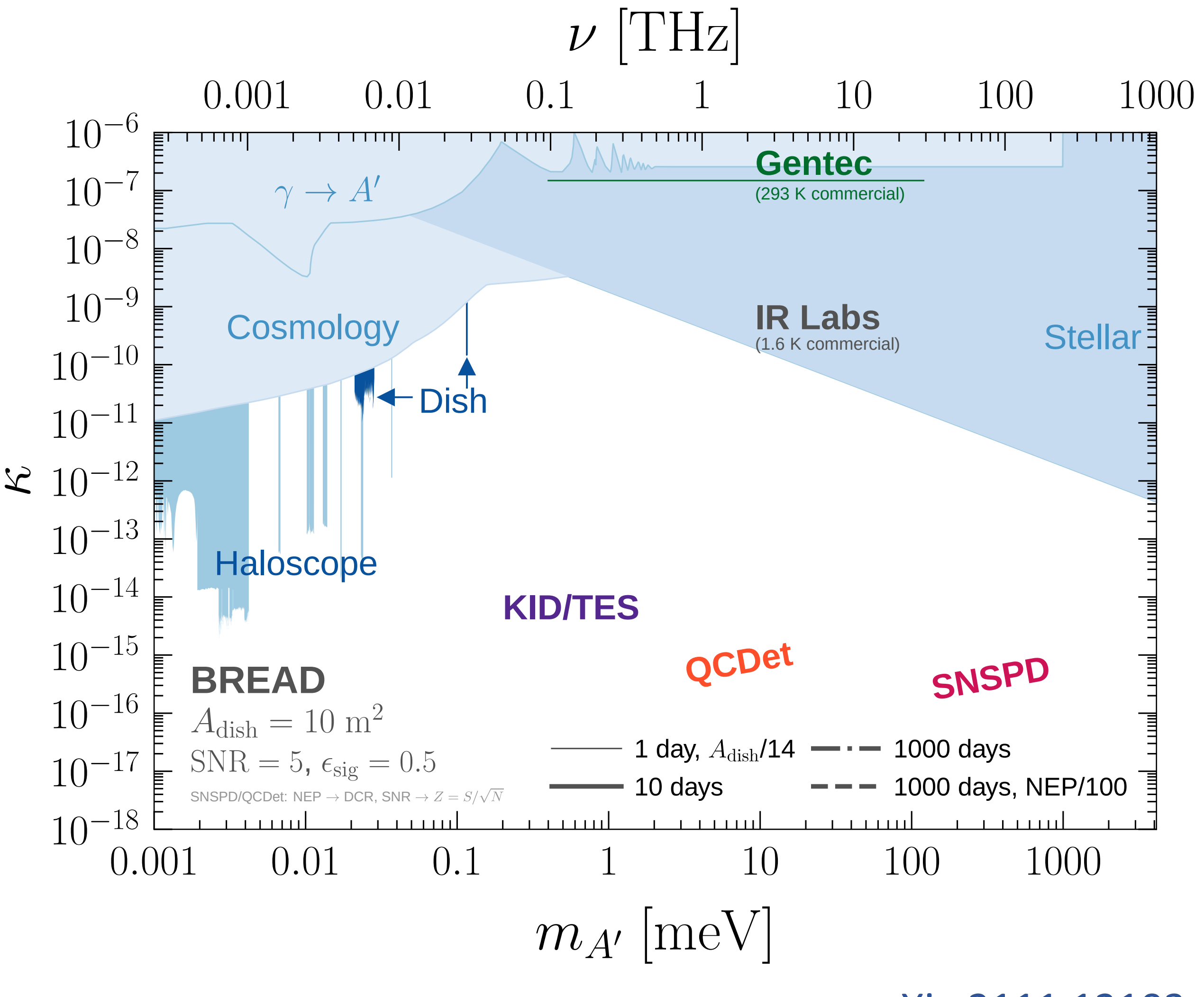
Sensitivity Projections-- Futuristic

- 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.

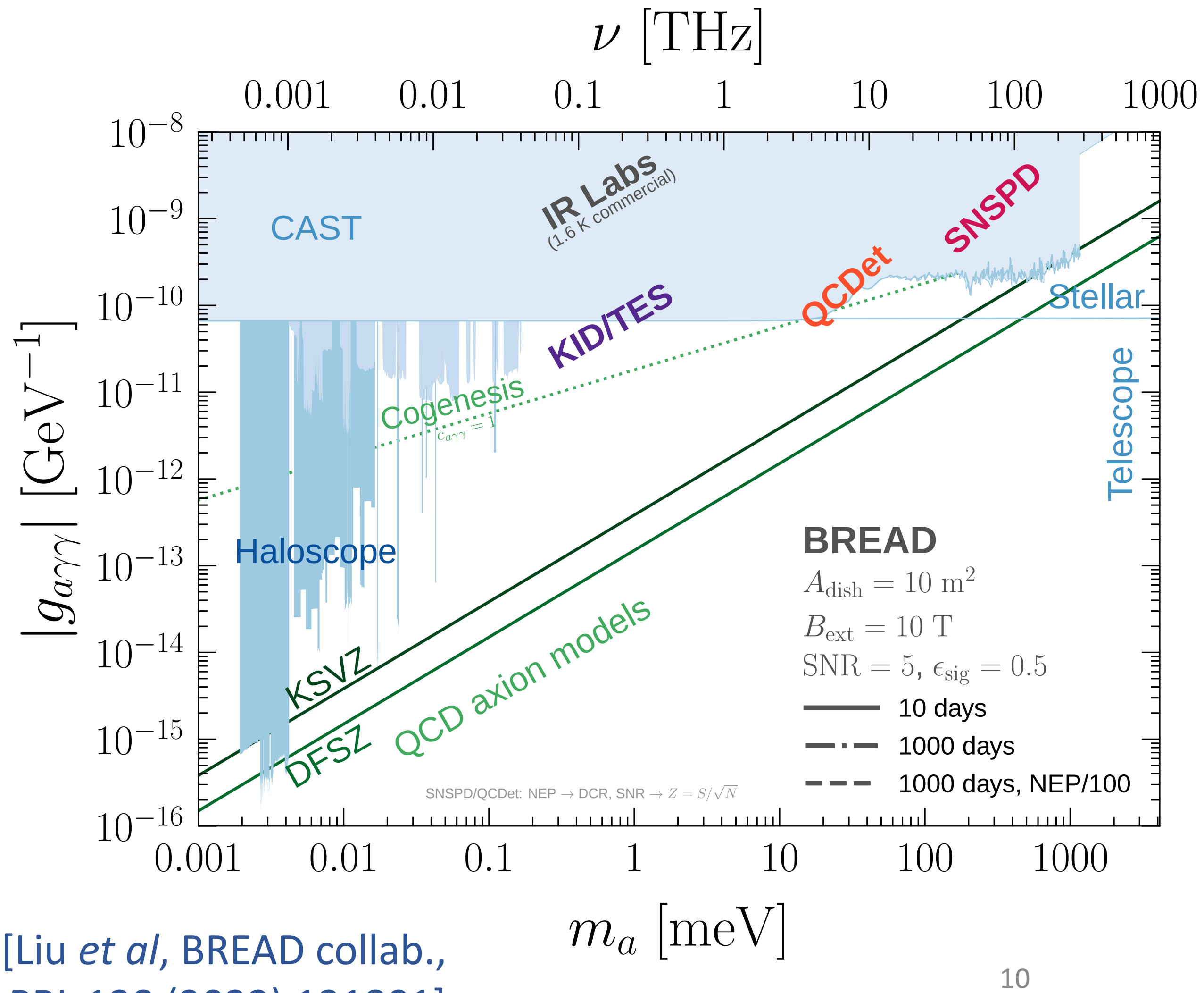


BREAD Sensitivity with State of Art THz Sensors

Dark Photons



Axions



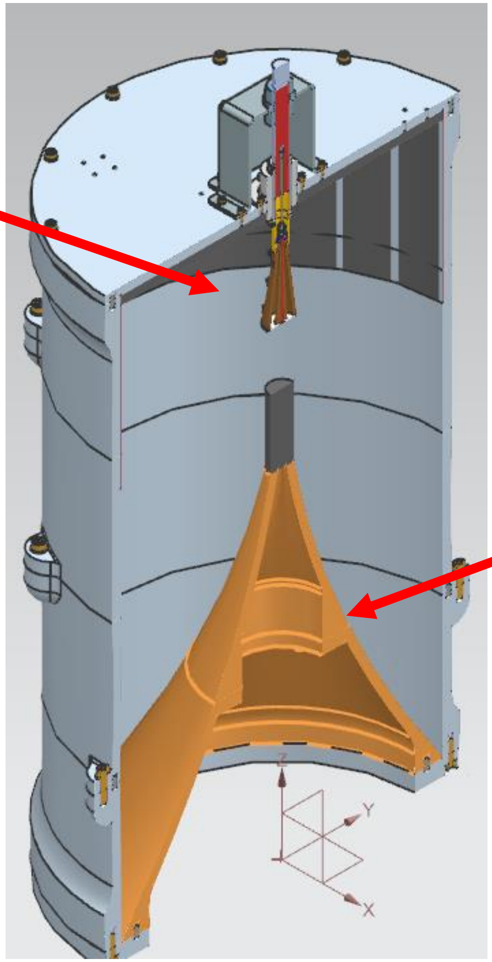
[Liu *et al*, BREAD collab.,
arXiv:2111.12103, PRL 128 (2022) 131801]

Proof of Concept Experiments: GigaBREAD and InfraBREAD

GigaBREAD: 10-20 GHz experiment with HEMT amplifier

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

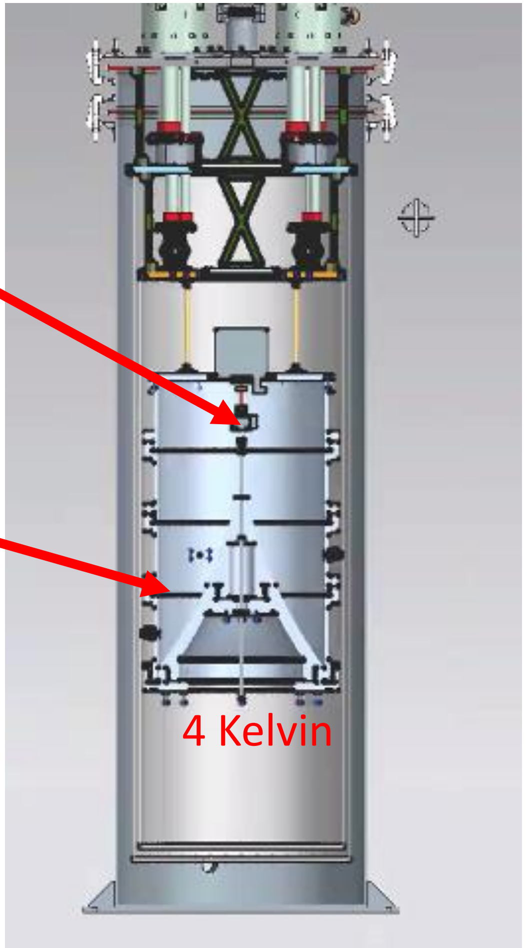
Horn Antenna with Axial position adjustment



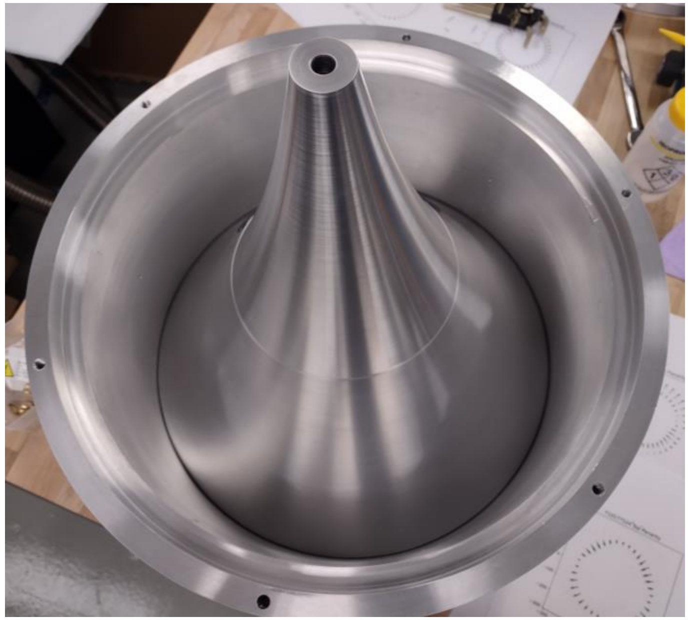
Room temperature

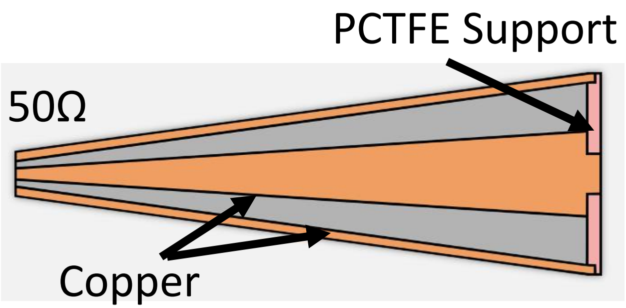
400 mm diameter Coaxial Dish

SNSPD @ 800 mK

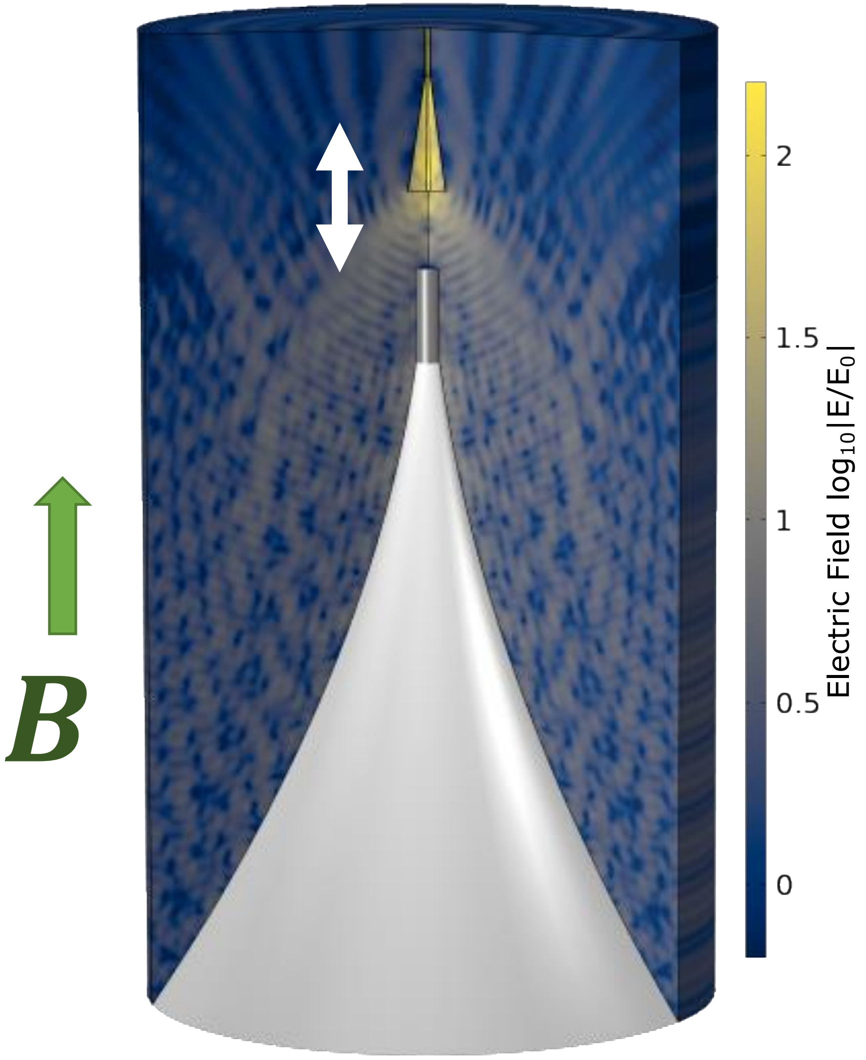


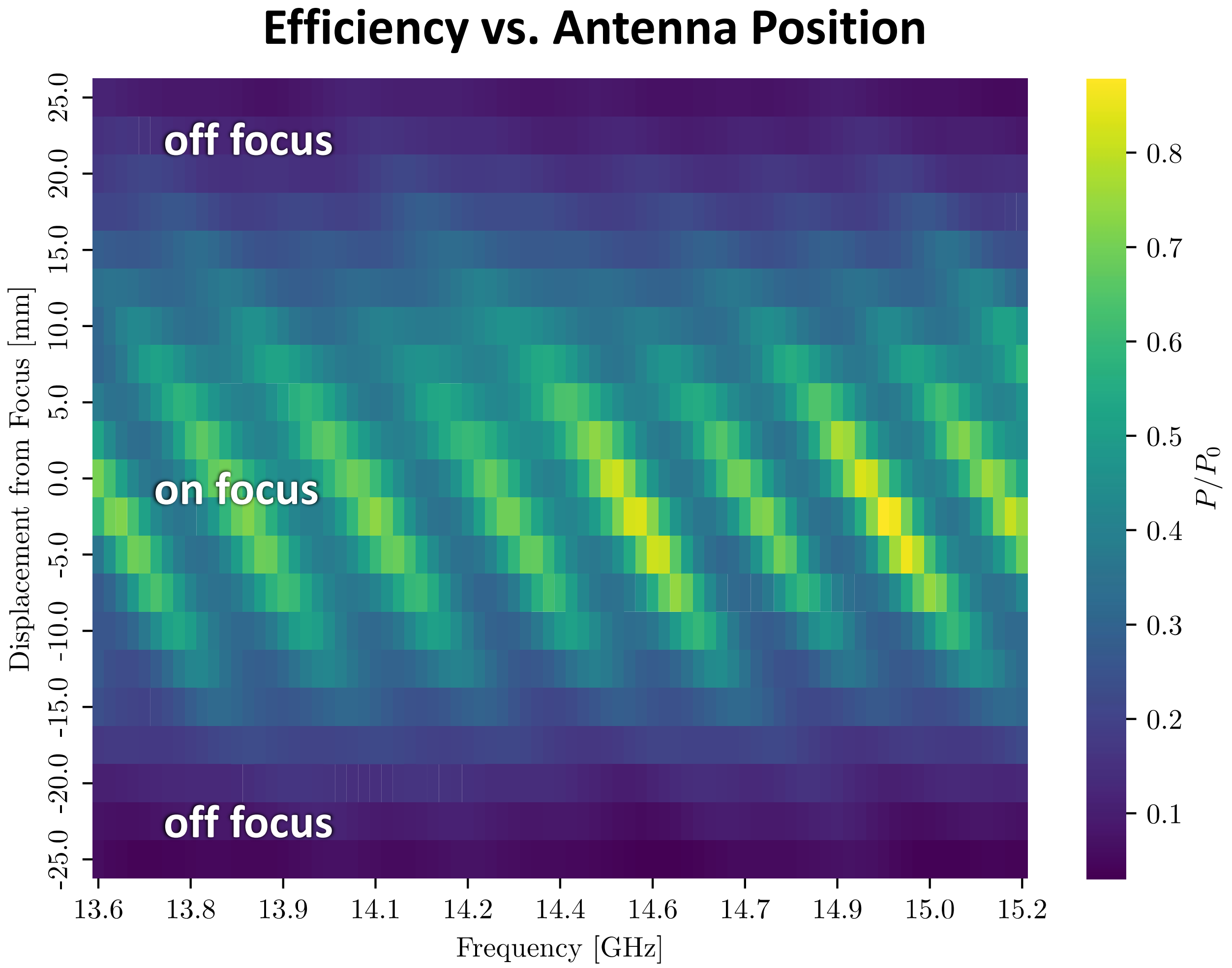
GigaBREAD Parts & Assembly





COMSOL Simulation of GigaBREAD

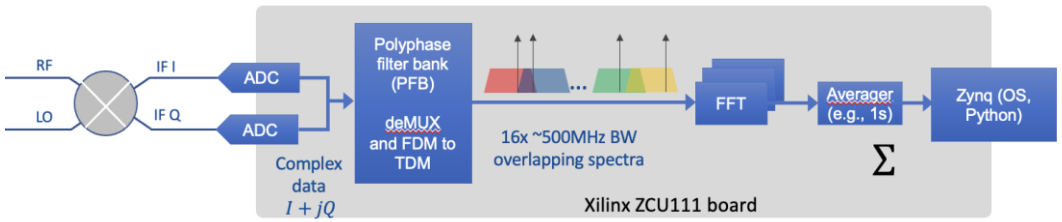


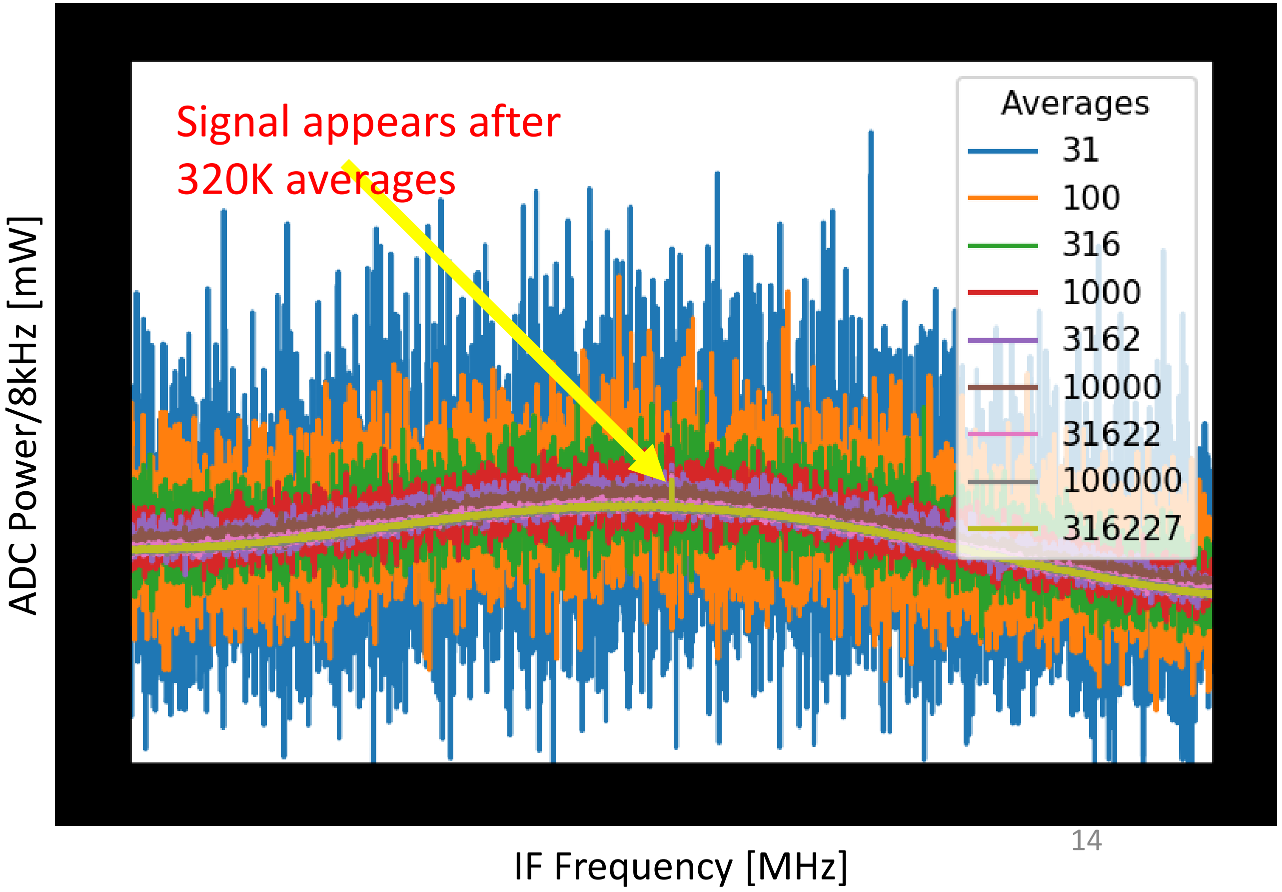


FPGA- Based Data Acquisition

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

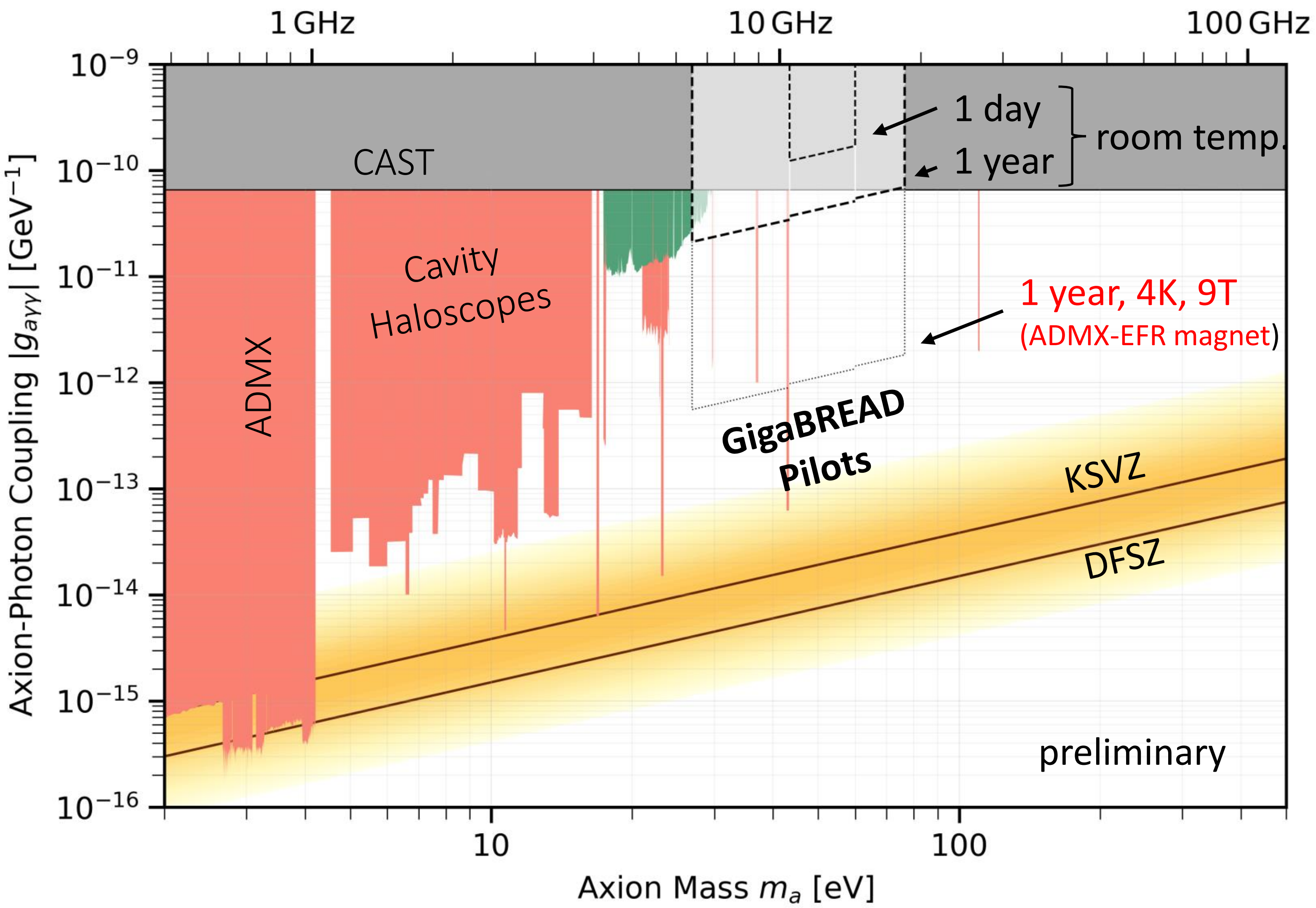
Real-Time Averager





GigaBREAD: Sensitivity Projection

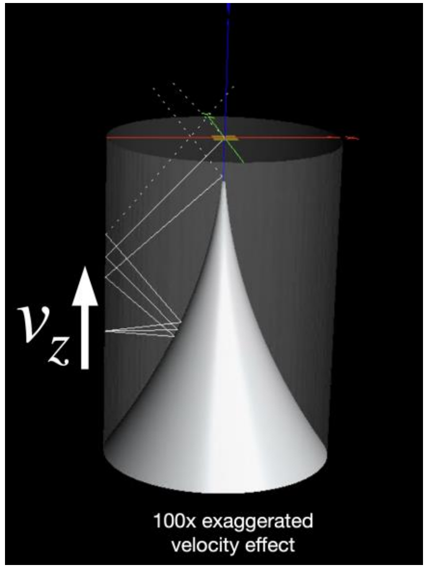
4 T MRI magnet at Argonne



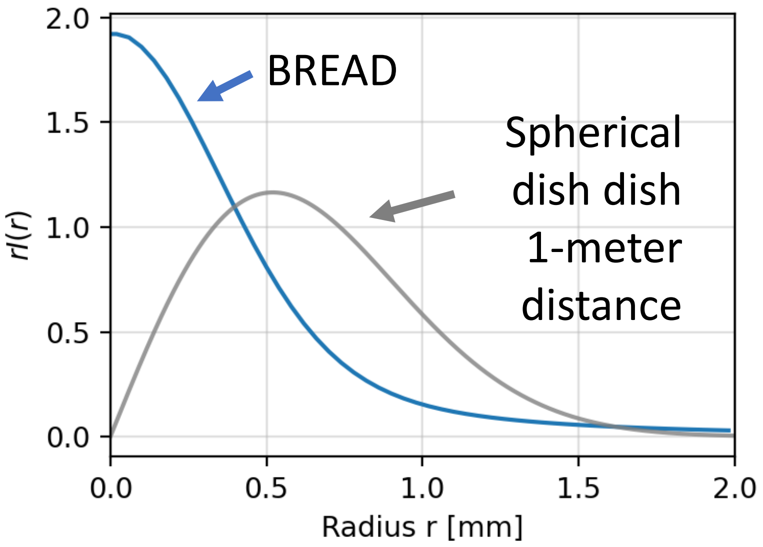
[limit plot adapted from cajohare.github.io/axionlimits]

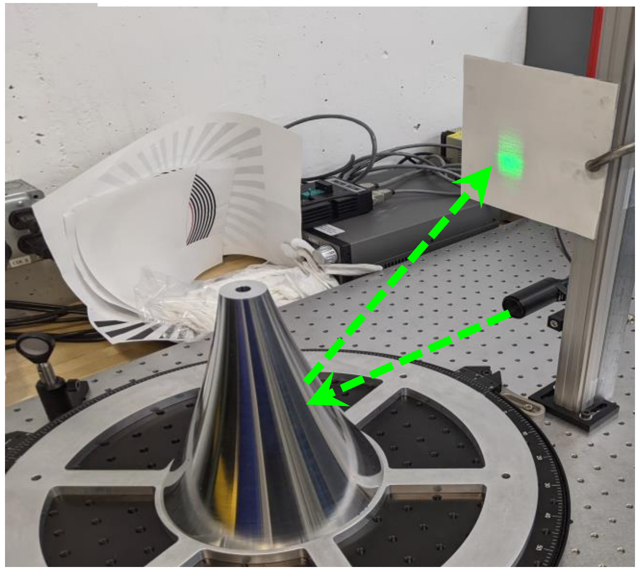
InfraBREAD Dish Requirements

- 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)



Focal plane Intensity Distribution





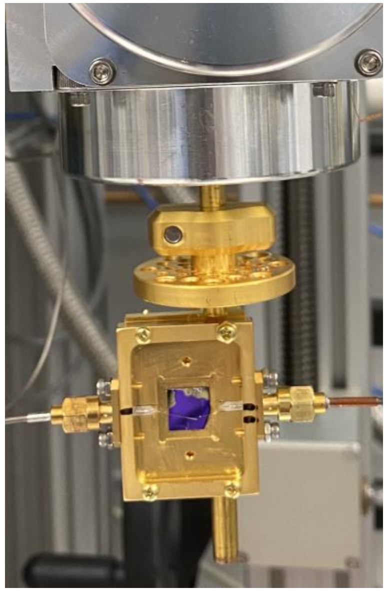
Measuring focal spot dispersion with laser

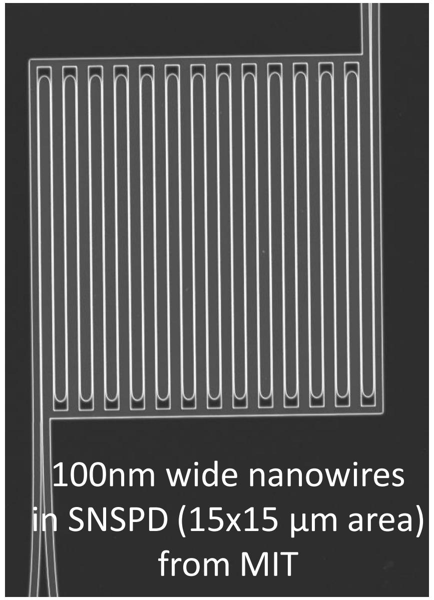
SNSPD Testing for InfraBREAD

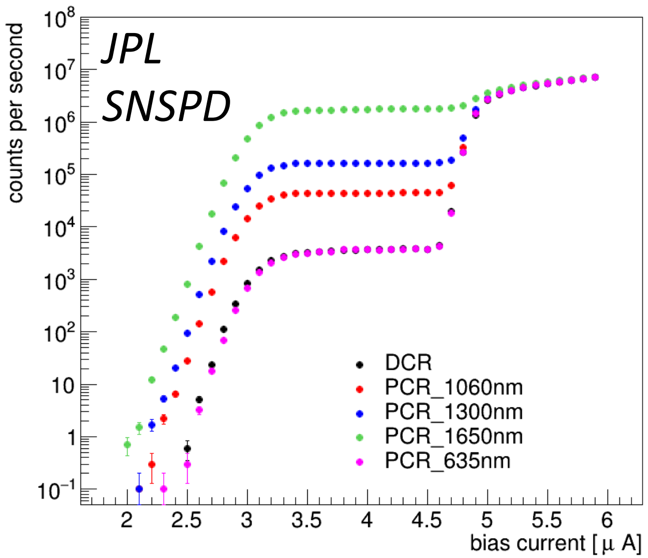
- Superconducting Nanowire Single Photon Detectors (SNSPDs) for BREAD supplied by MIT and JPL groups (See Matt Shaw's talk at this meeting)

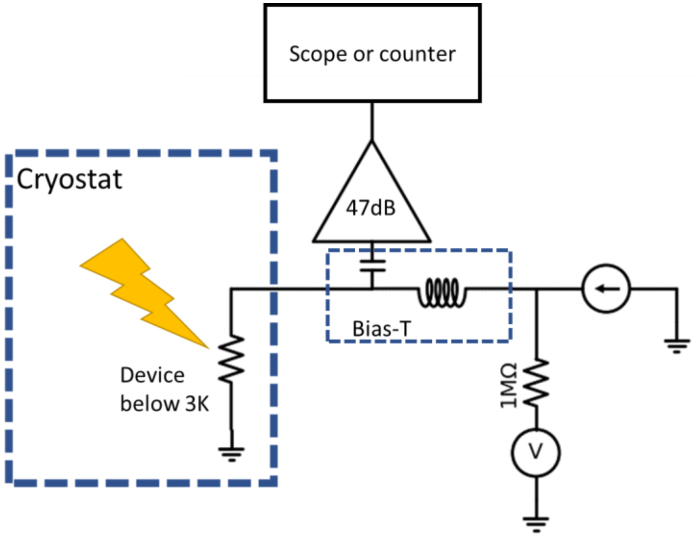
- Largest devices made to date are 1 mm^2 , well matched to our requirements.

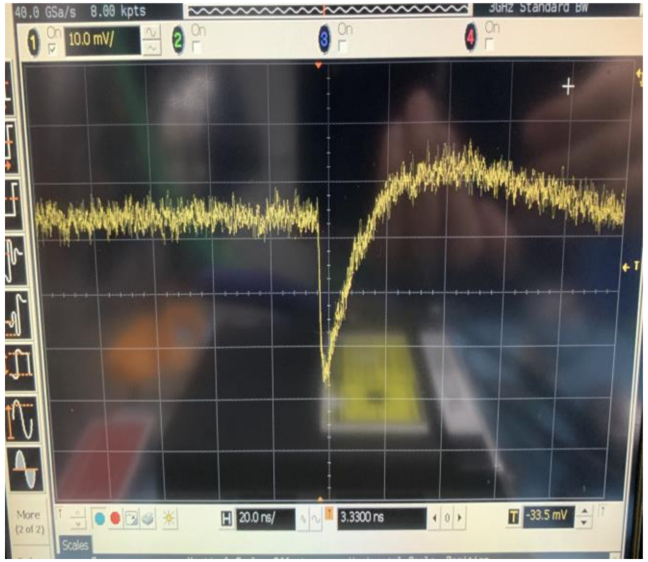
- Measurements of efficiency and dark counts underway at Fermilab. Similar devices have achieved < 1 count per day backgrounds











Summary

- Dish antenna experiments can be sensitive to axions from meV to eV scale, well above the reach of cavity resonators.
- The BREAD ”cylindrical dish” design allows use of existing large—bore, high-field solenoids.
- Can search for dark photons and axion-like particles with current generation of photosensors.
- QCD axion discovery will require new generations of photon counting sensors with dark counts at the level of <1 count per day from microwave to infrared.

BREAD COLLABORATION

Clarence Chang, *Argonne National Laboratory*

Christina Wang, *Caltech*

Jesse Liu, *Cambridge University*

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

Daniel Bowring, Gustavo I Cancelo, Claudio Chavez, Aaron Chou, Stefan Knirck, Cristian Pena, Mark Ruschman, Andrew Sonnenschein, Leonardo Stefanazzi

Fermilab

Rakshya Khatiwada, *Fermilab and Illinois Institute of Technology*

Gianpaolo Carosi, *Lawrence Livermore National Laboratory*

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

Noah Kurinsky, *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)]