Broadband Axion Searches with Coaxial Dish Antennas

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Fermilab

"Axions Beyond Gen 2" Workshop

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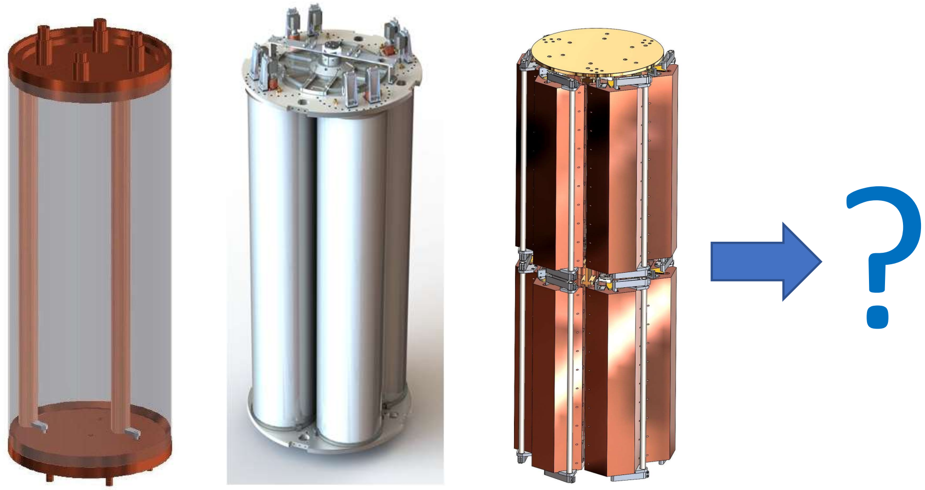
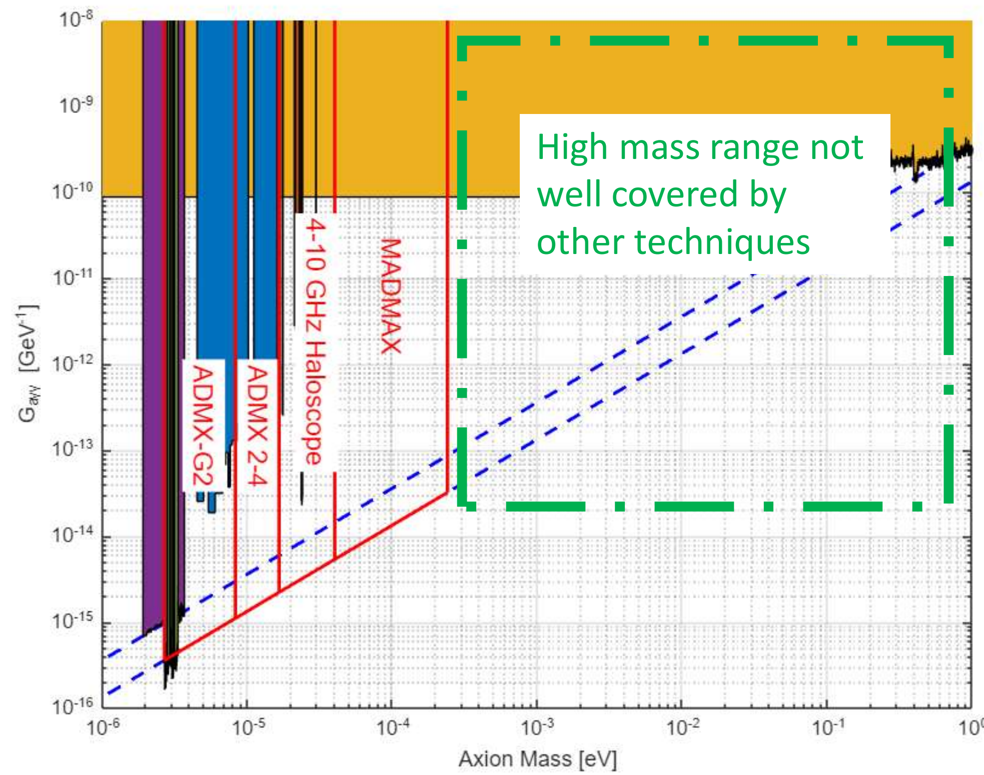
High Mass Axion Searches

- Resonant cavity haloscope works in a relatively narrow axion mass range, ~0.2-20 μeV.
- Open linear resonators with dielectric disks (Madmax) may be sensitive up to ~100 μeV.
- What techniques will work at higher mass?
- Can we find a broadband technique which avoids bin-by-bin detector reconfigurations?

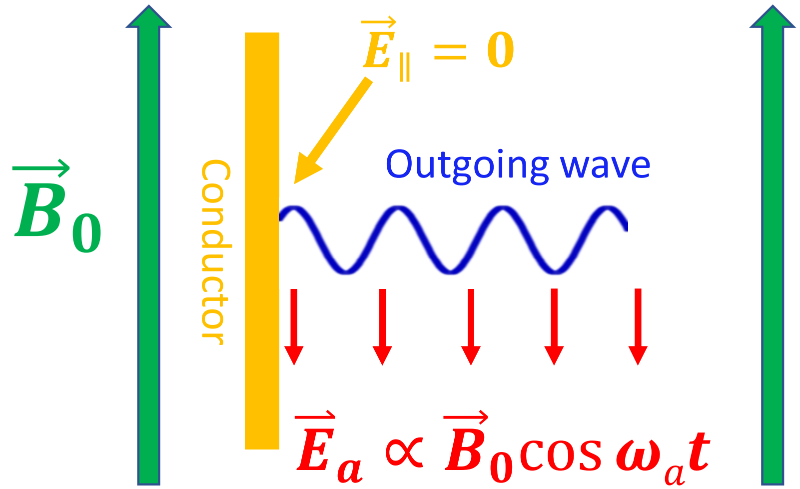
0.5-1 GHz 1-2 GHz 2-4 GHz





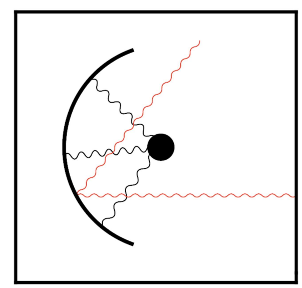
Axion Induced Radiation from A Magnetized Metal Slab

- 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:

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



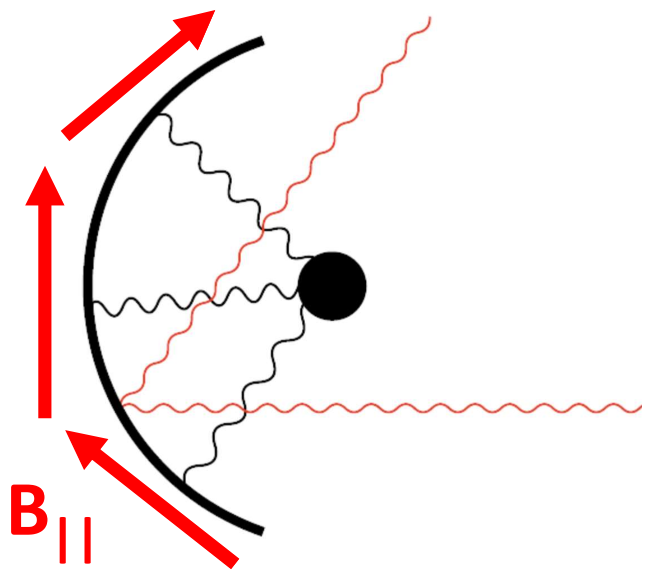
"Dish antenna" (Horns et al., 2012)

- But no detector tuning is required!

Magnetic Field Configuration

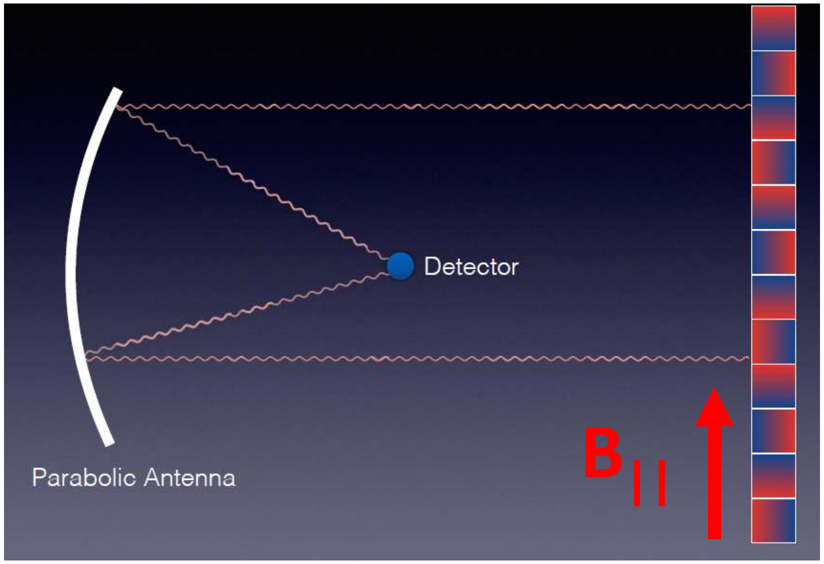
- Need to maximize component of magnetic field parallel to radiating surface $B_{||}$
- Spherical dish geometry not a good match to conventional magnet types.

<u>Spherical dish radiator from Horns *et al.* concept paper:</u>



Horns, Jaeckel, Lindner, Lobanov, Redondo & Ringwald, 2012

<u>BRASS experiment: Planar array of permanent magnets</u>



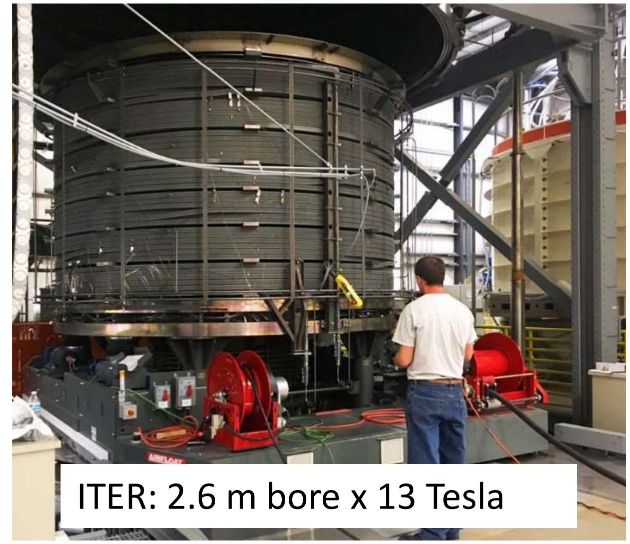
Le Hoang Nguyen, Patras 2019
http://wwwiexp.desy.de/groups/astroparticle/brass/brassweb.htm

Large Solenoids

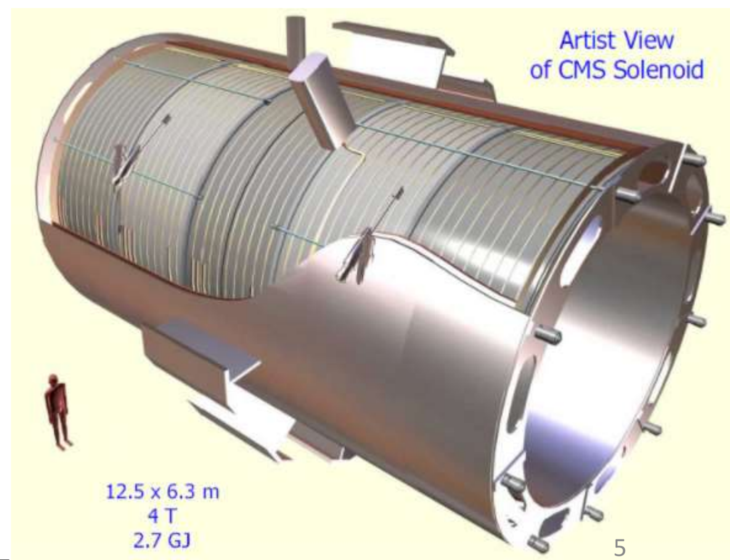
- How to use large volume solenoids to detect axions?

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

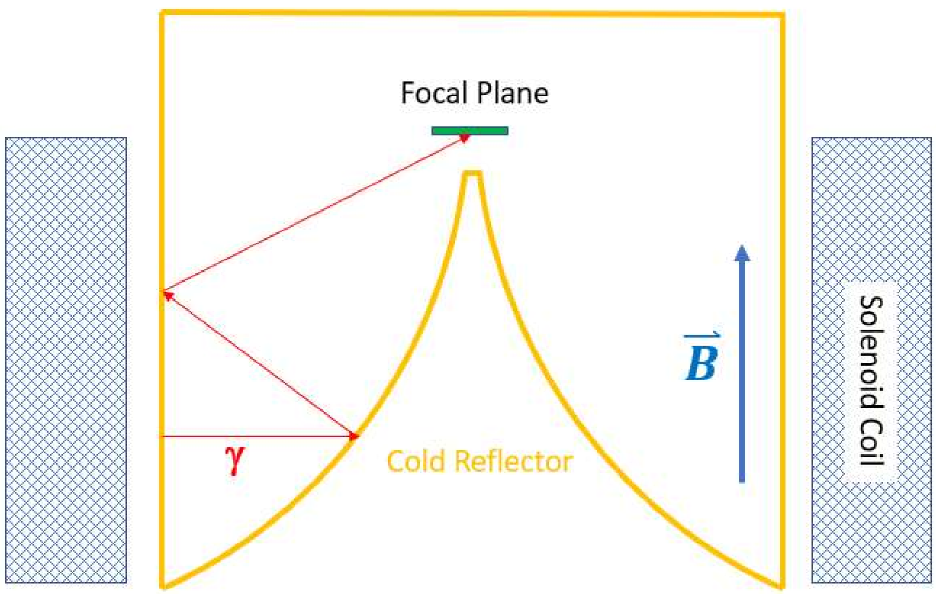
Compilation by Mark Bird, NHMFL

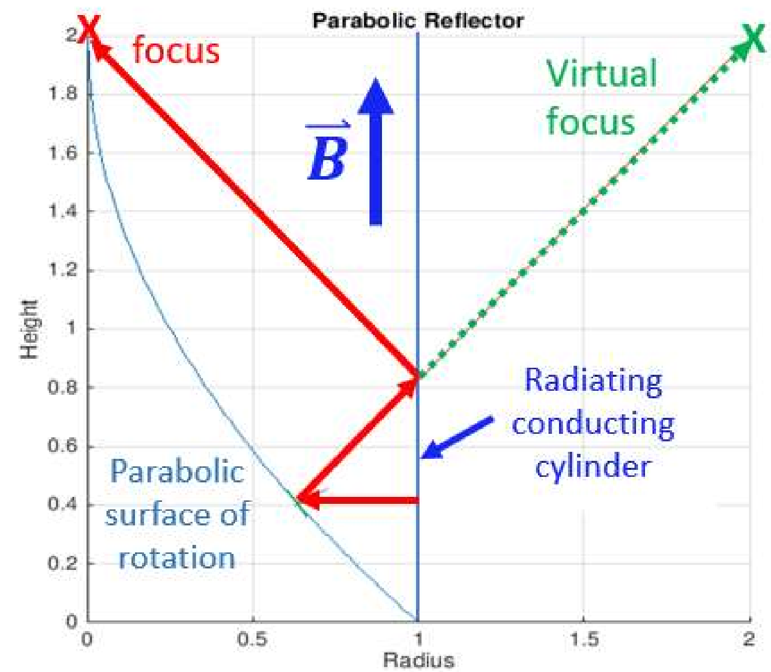


ITER: 2.6 m bore x 13 Tesla



“Coaxial Dish”: Optical Concentrator for Solenoid Magnets

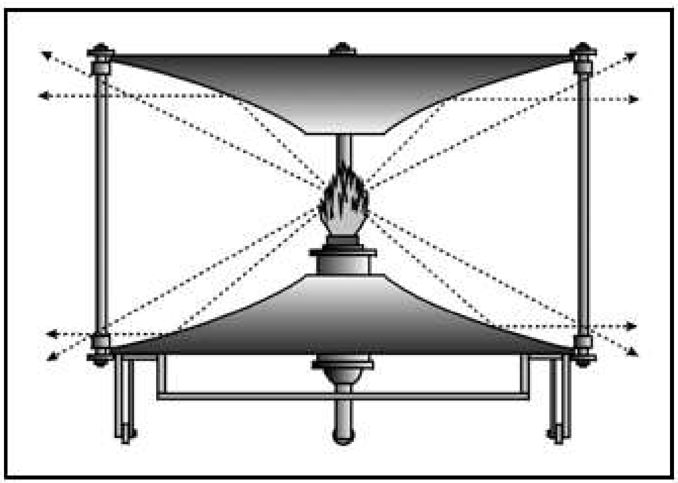




- Rays emitted from cylindrical inner surface of solenoid are focused to a point after two reflections.

Design Legacy- 19th Century Lighthouse Mirrors

- Projects a radial beam towards the horizon using a mirror.
- This can also be done with a Fresnel-type cylindrical lens.



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

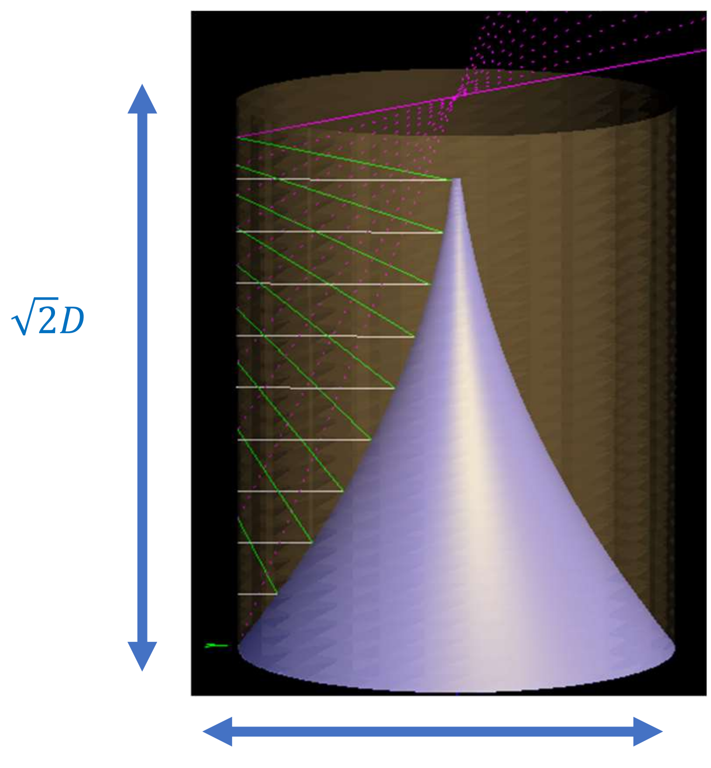
Fanal Sidereal Lantern. (1811)

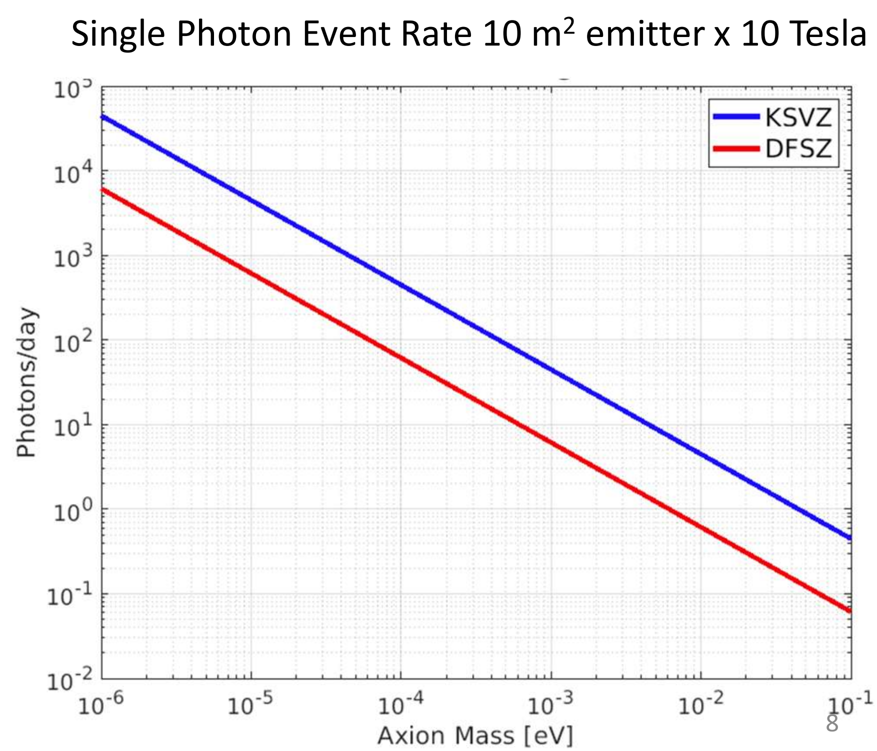
In 1809, Bordier-Marcet invented the 'Fanal Sidereal' reflector where two parabolic reflecting surfaces were placed one above the other. Each of the reflecting surfaces had a central hole where the lamp flame was placed. The Fanal Sidereal reflector was first used in the harbor lighthouse in Honfleur,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

From https://uslhs.org/reflectors

Axion Source Strength

- Surface area for axion to photon conversion is inner magnet bore with area $\sqrt{2}\pi D^2 > 10$ m^2 for the largest superconducting solenoids.
- Signal power ~ 10^{-25} W for KSVZ model and ~ 10^{-26} W for DFSZ.
- At least a few photons per day over most of the axion mass range of interest.





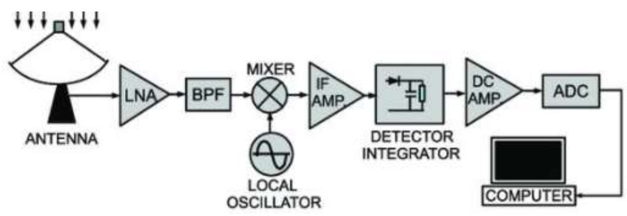
Three Types of Experiment

1. Heterodyne detection
   - Downconvert signal frequency by mixing with a local oscillator.
   - Excellent for measuring narrow spectral features.
   - Ultimate sensitivity governed by Standard Quantum Limit (SQL)

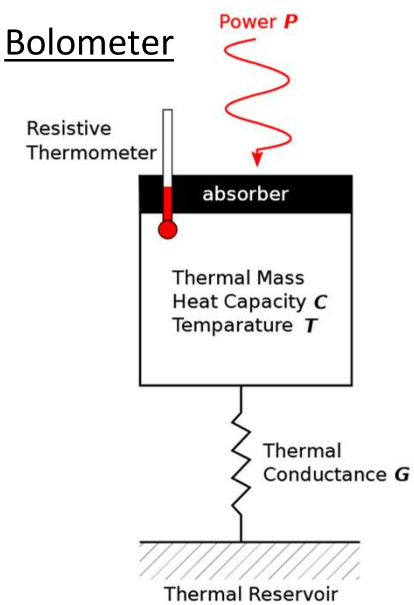
$$T_{noise} = hf/K_b$$

2. Bolometer
   - Absorb optical power on a "black" surface & measure temperature.
   - Intrinsically broadband- single device may cover decades of wavelength.
   - No intrinsic frequency resolution.
   - Not subject to Standard Quantum Limit.
   - Detection of 10^{-25} W KSVZ axion signal within one year requires Noise Equivalent Power (NEP) $\sim 10^{-22} W/\sqrt{Hz}$. Two orders of magnitude beyond state-of-art.
3. Photon counting
   - Simple counting experiment similar to WIMP searches.
   - Background rate as low as ~1 event/day needed to cover mass range up to 0.1 eV.
   - This is beyond current capability, but photon counting technology is evolving rapidly, driven by quantum information science applications.

Heterodyne detection



Bolometer

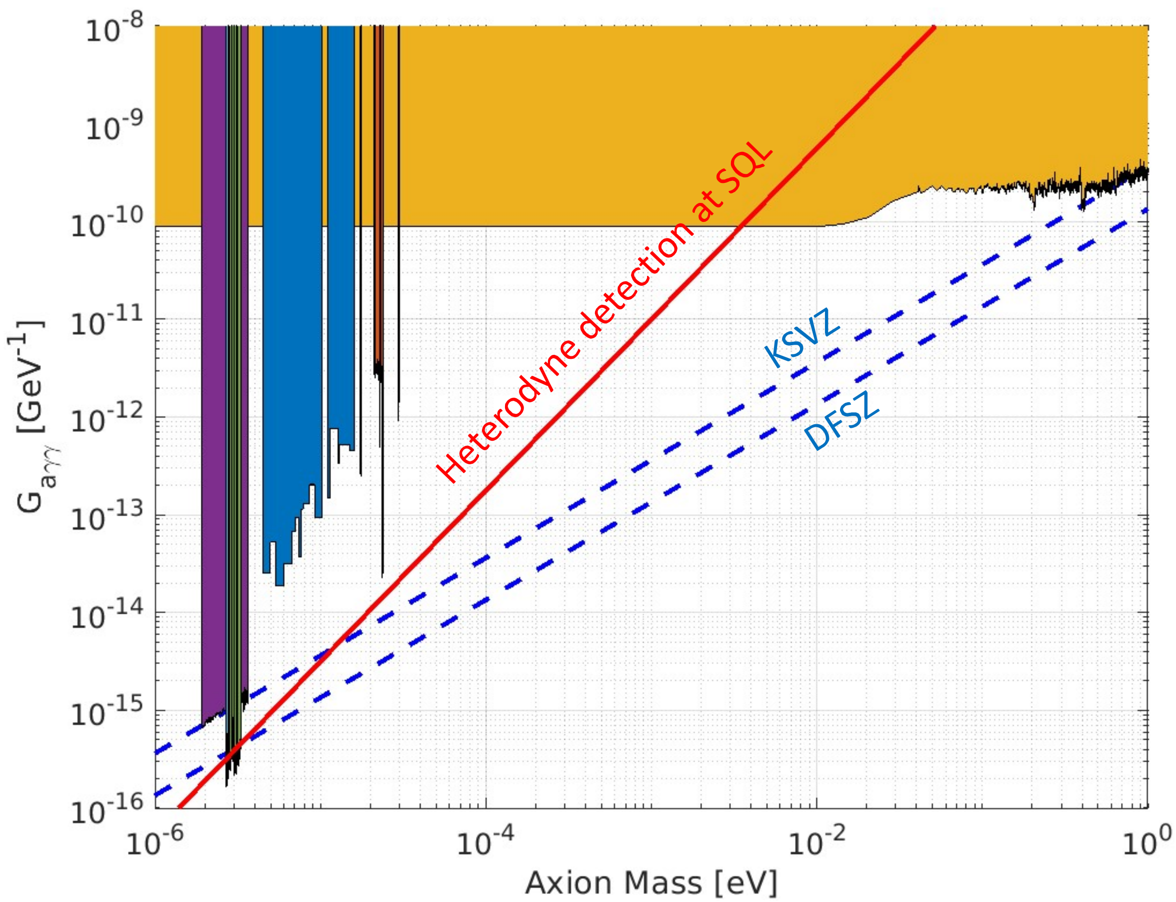


Heterodyne Detection

- 10 m^2 x (10 T)^2 radiator
- 100-day integration time
- <u>Noise at Standard Quantum Limit</u>

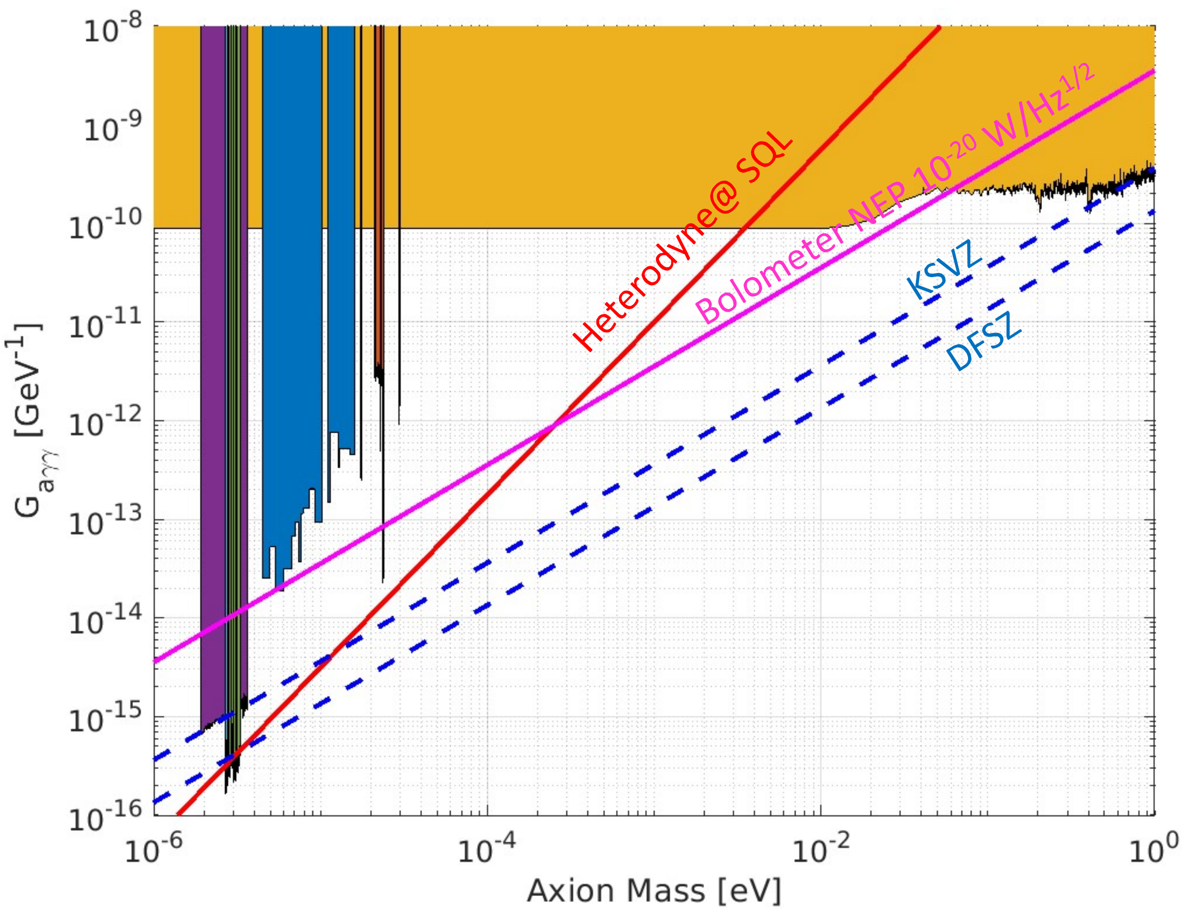
$$T_{noise} = \frac{hf}{K_b}$$

- Signal:Noise ratio 3
- $Q_{axion}=10^6$
- ρ_{DM}=0.45 GeV/cc



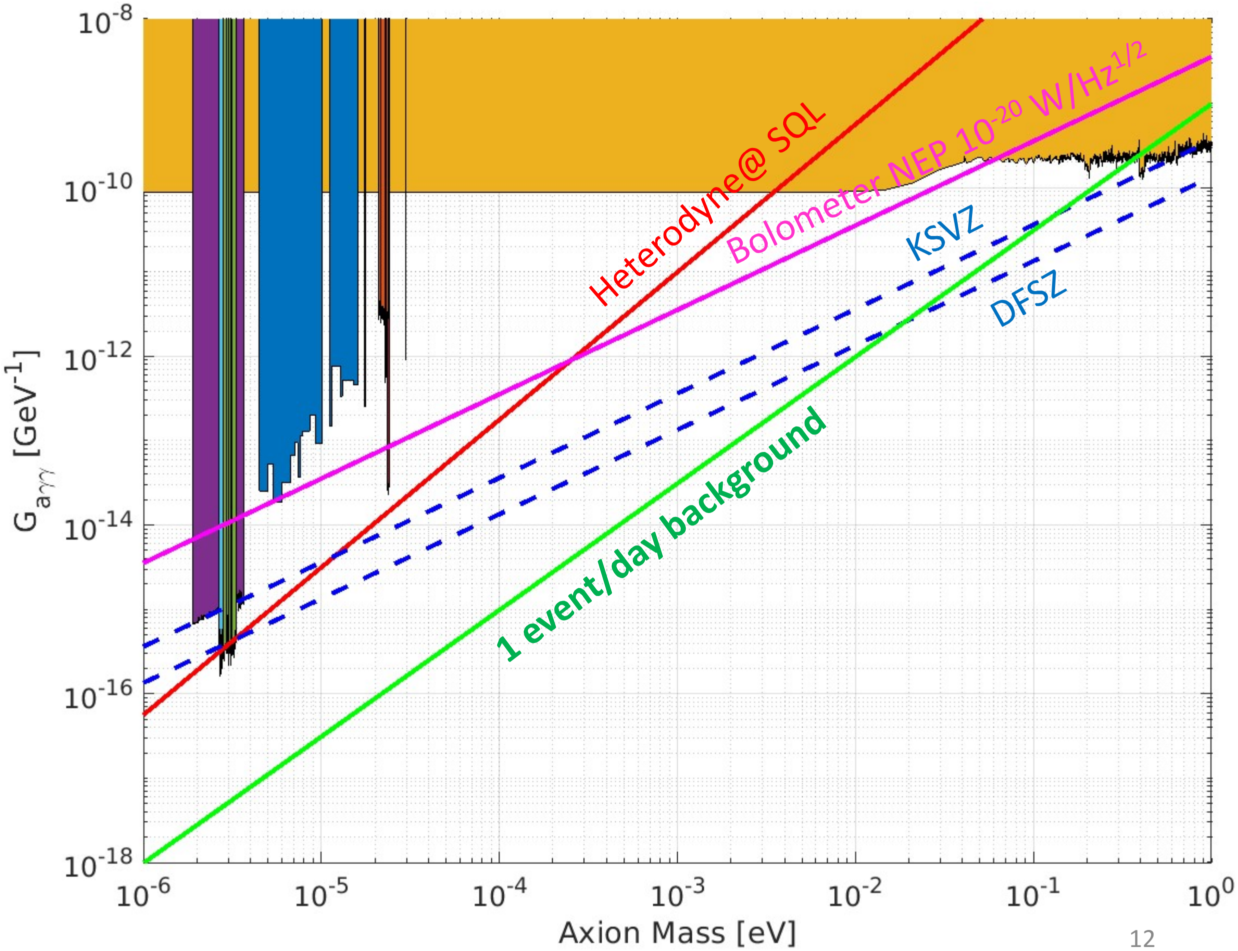
Bolometric Detection

- 10 m^2 x (10 T)^2 radiator
- 100-day integration time
- Noise equivalent power NEP $10^{-20} W/\sqrt{Hz}$
- Signal:Noise ratio 3



Single Photon Detection

- $10\ m^2 \times (10\ T)^2$ radiator
- 100-day integration time
- <u>1 event/day background</u>
- 3σ limit for magnet on - magnet off excess



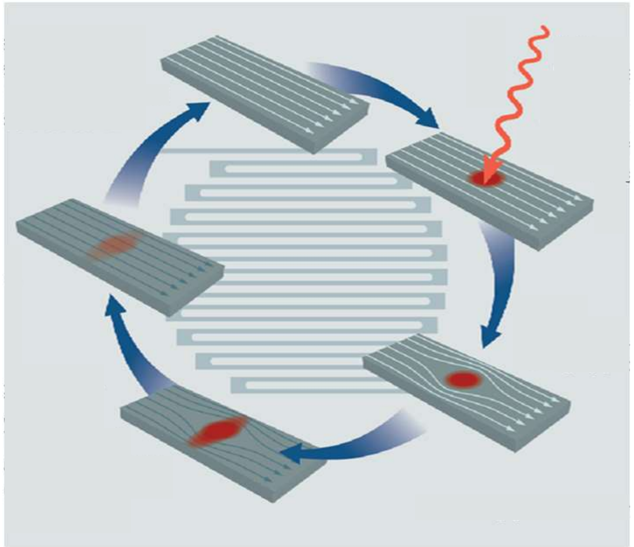
Detectors

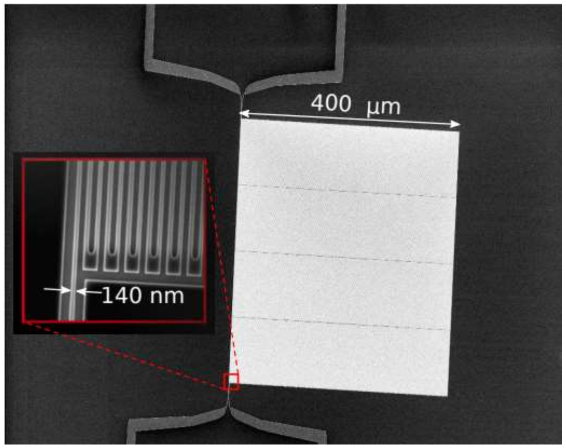
	Microwave		Mm			IR	Visible	UV
	1 GHz	10 GHz	100 GHz	1 THz	10 THz	100 THz	1000 THz	1 PHz
Photomultiplier							Mature single photon	
Photodiode, SPAD, SIPM						high dark counts		
HEMT	Phase sensitive and broadband							
Superconducting paramp JPA, TWPA	~quantum limited							
Photomixers SIS, HEM			Narrow band					
Semiconductor bolometer			Bolometers					
Transition Edge Sensor (TES)			NEP~10^{-18} $W/\sqrt{Hz}$			Superconducting photon		
Kinetic Inductance Detector (KID)							counters	
Superconducting Nanowire SNSPD							low dark counts	
Qubit								
Quantum Capacitance Detector			~10^{-20} $W/\sqrt{Hz}$					
Current Biased Josephson Junction		Developing single photon technologies for GHz- THz						

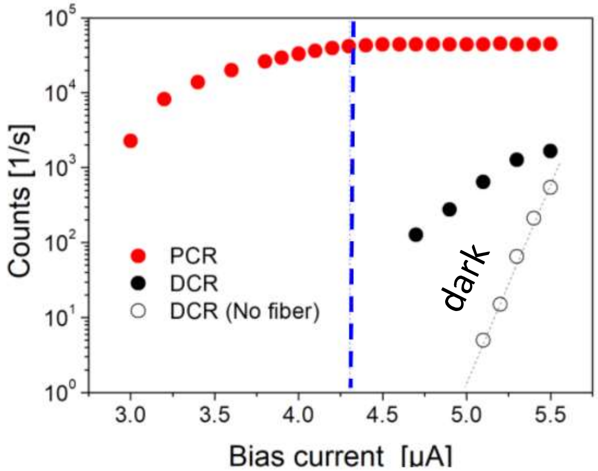
A few notable recent photon counting results

- Detection of individual 1.5 THz photons (6 meV) with *NEP* 2×10^{-20} $W/Hz^{1/2}$ Echternach *et al*., *Nature Astronomy* 2, 90–97 (2018).
- Counting 6 GHz (25 μeV) photons by coupling to a qubit. Background ~3 Hz, Dixit *et al*., arXiv:2008.12231v2
- Counting 14 GHz photons (58 μeV) with current-biased Josephson junction with backgrounds below 10^{-3} Hz. Kuzmin *et al*., *IEEE Trans. Appl. Super.* 28 7 (2018) & Patras 2019.
- NIST/ MIT superconducting nanowires with high counting efficiency for 1550 nm photons (0.8 eV) and backgrounds now <1/day. Hochberg *et al.*, PRL 123 (2019).
- Counting of single photons in the previously inaccessible range from microwaves to terahertz is an exciting and rapidly moving field.
- Still a way to go before meeting needed requirements for QCD axion detection.

NIST/ MIT Superconducting Nanowire Single Photon Detectors with backgrounds <1/day at 0.8 eV.







•Based on WSi thin film from Varun Verma, NIST

•Detector fabricated by Ilya Charaev, MIT

•400 x 400 μm^2 area

•Illuminated with 1550nm light

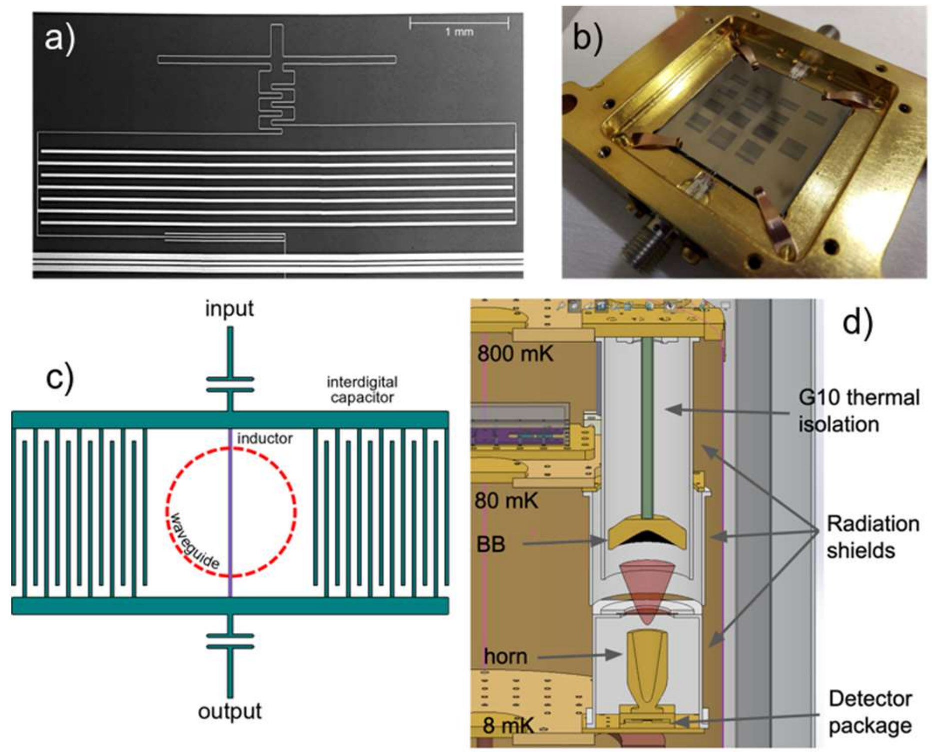
Figures from Sae Woo Nam (NIST)

See "Detecting Dark Matter with Superconducting Nanowires", Yonit Hochberg et al., PRL 123 (2019)

KID development for Axion Searches at Argonne

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

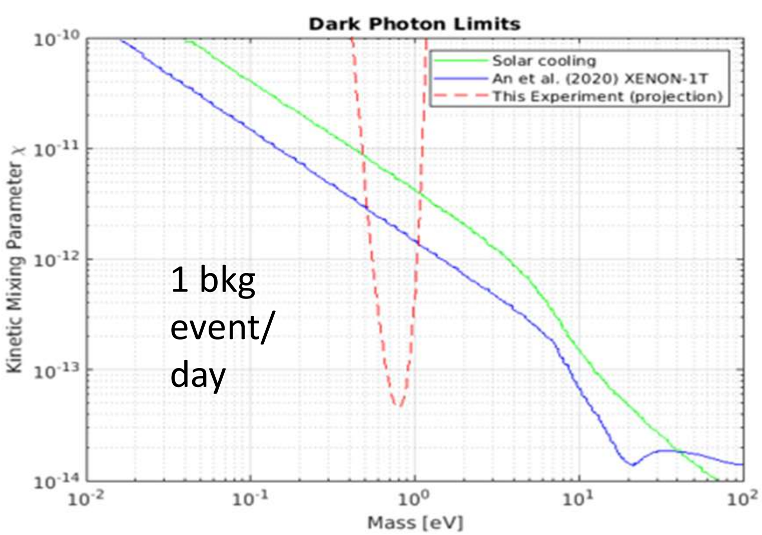
- Goal is single photon counting of THz photons (4 meV).
- Small detector volume to give high responsivity.
- Fundamental noise from quasiparticle (qp) fluctuations is sufficiently low to achieve sensitivity to THz photons.
- JPA amplifier use to reduce readout contribution to quasiparticle population.

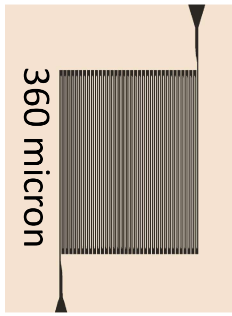


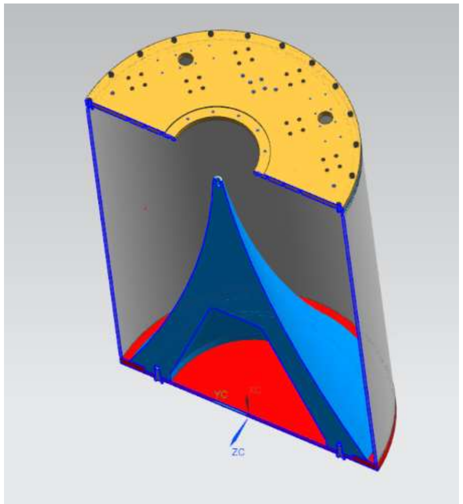
a,b) Photos of the initial test resonators used to characterize the thin-film Al fabricated at ANL, c) schematic design of a prototype pixel axion THz sensor, and d) 3D CAD model of the experimental configuration for optical characterization.

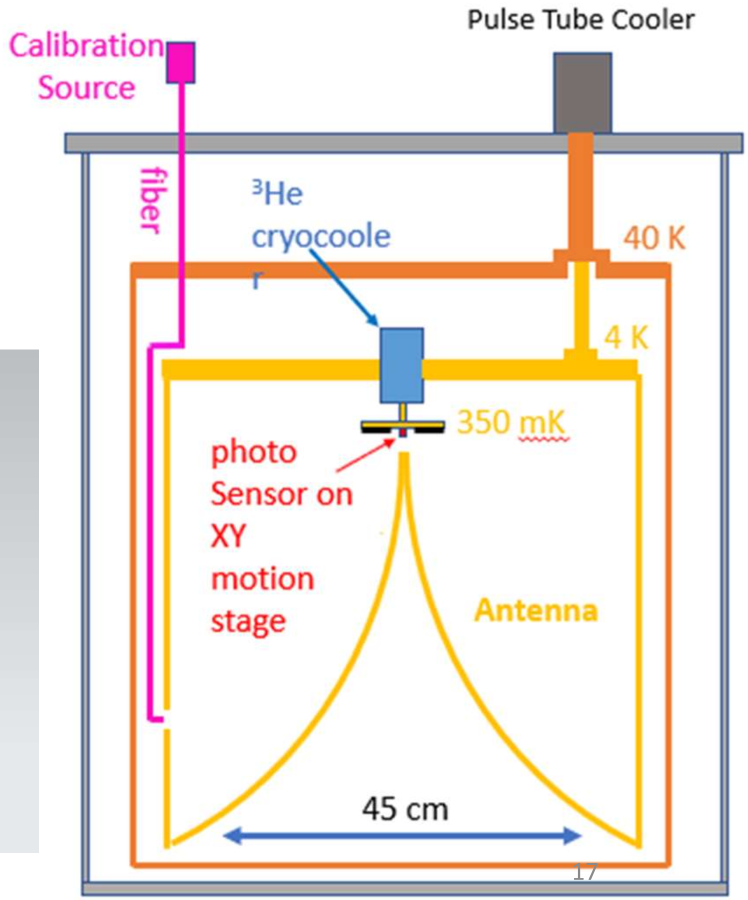
Pilot Experiment- Dark Photon Search

- 45- cm aluminum reflector at 4 Kelvin.
- SNSPD photon counter from NIST group.
- One day of counting with no backgrounds would produce world's best limits on dark photon dark matter in a narrow frequency band.



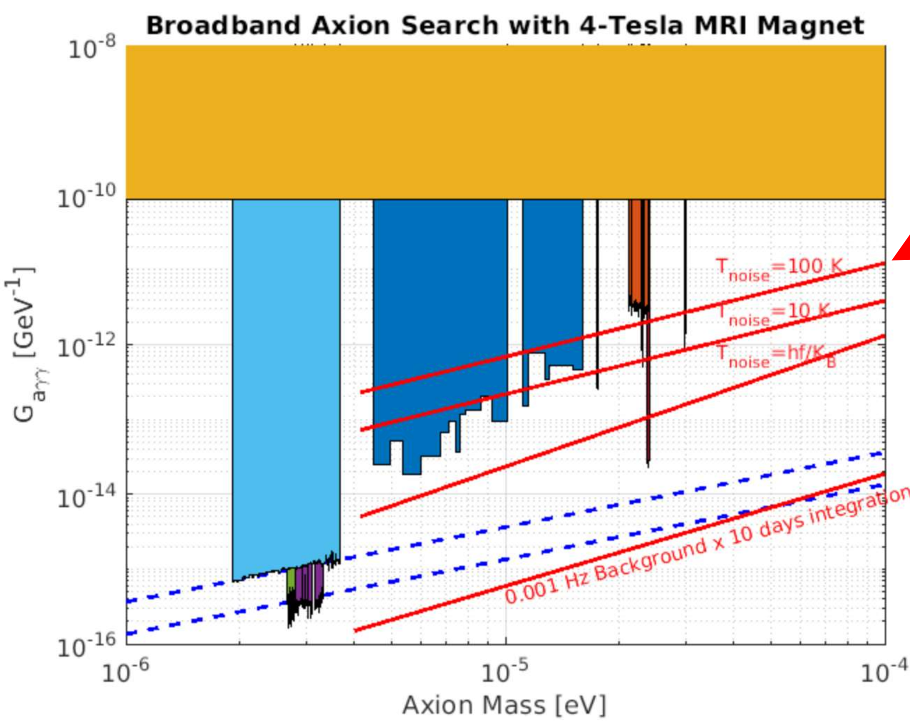






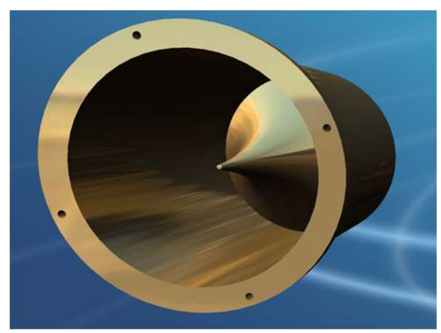
Pilot Experiments with MRI Magnets

- MRI magnets typically have 80 cm bore at up to 9.4 Tesla.
- Relatively accessible– many have been made.
- Good platform for ALP searches over wide frequency range, using existing sensor technology.

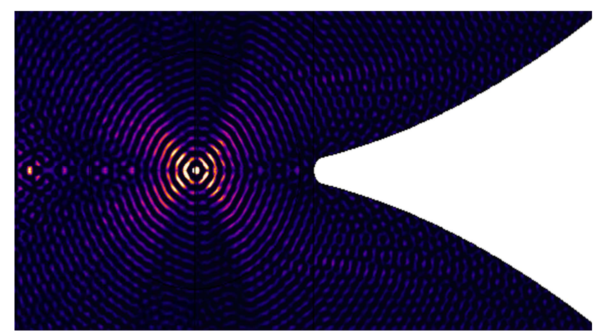


Initial experiments possible at room temperature

4- Tesla MRI magnet at Argonne



3D printed antenna



10 GHz Signal (Comsol)

Summary: Axions Beyond Gen 2

- Dish-type experiments are useful for axion and ALP searches in high mass range, beyond reach of resonant cavity techniques.
- This will require new types of photon counting detectors to discover the QCD axion– it's a "Beyond Gen-2" experiment and perhaps also "Beyond Gen-3".
- Superconducting sensor are improving quickly– maybe this will happen rather soon?
- There are near term applications: dark photons and ALP searches with existing sensor technology.

Collaborators

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Rakshya Khatiwada, *Fermilab and Illinois Institute of Technology*

Stefan Knirck*, Max Planck Institute for Physics, Munich*

Omid Noroozian, *NASA Goddard Space Flight Center*

New Collaboration name: Broadband Reflector Experiment for Axion Detection (BREAD)

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