Next Generation Axion Searches and the Fermilab Dark Wave Laboratory

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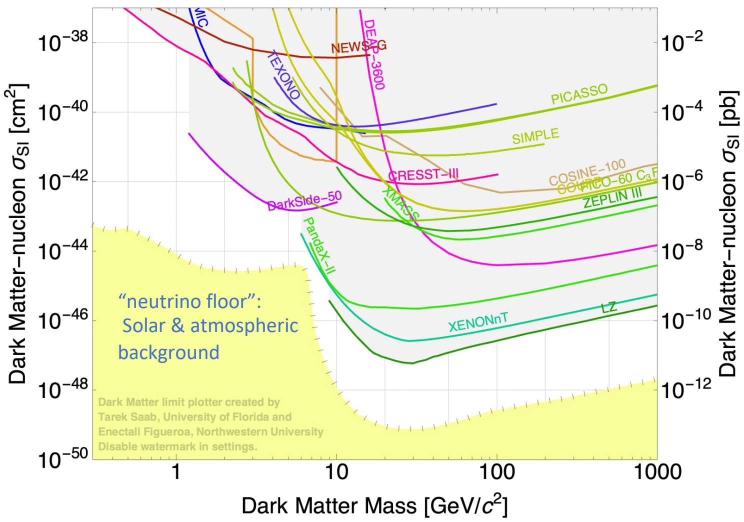
4-October-2023

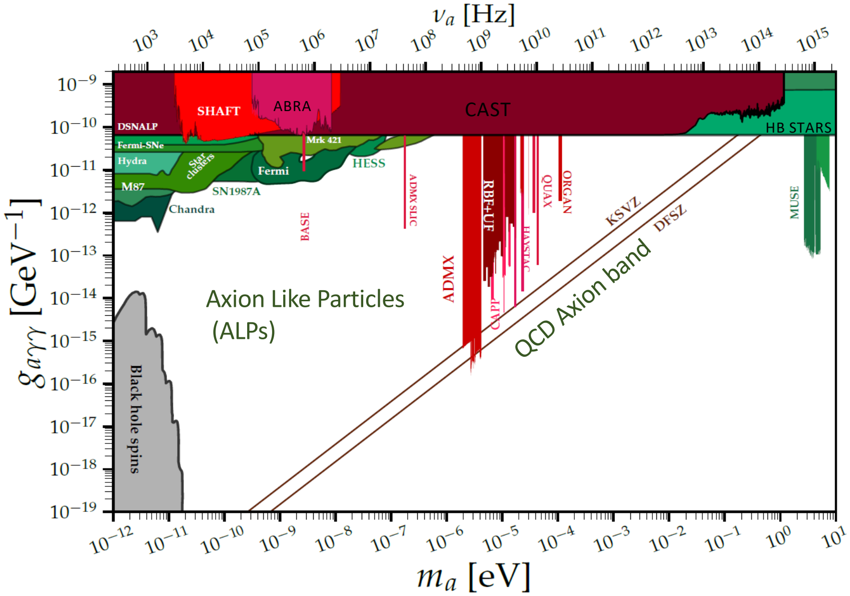
WIMPs Vs. Axions

- WIMPs and WIMP-like
  - Dramatic progress in attempted WIMP detection over last decade- many models previously considered promising are now excluded.
  - Direct searches will become background limited by neutrinos over next 10 years.

- Axions and ALPs
  - Previous experiments not sensitive enough to test most important models.
  - Relatively few experiments.
  - New techniques needed to reach required sensitivity.

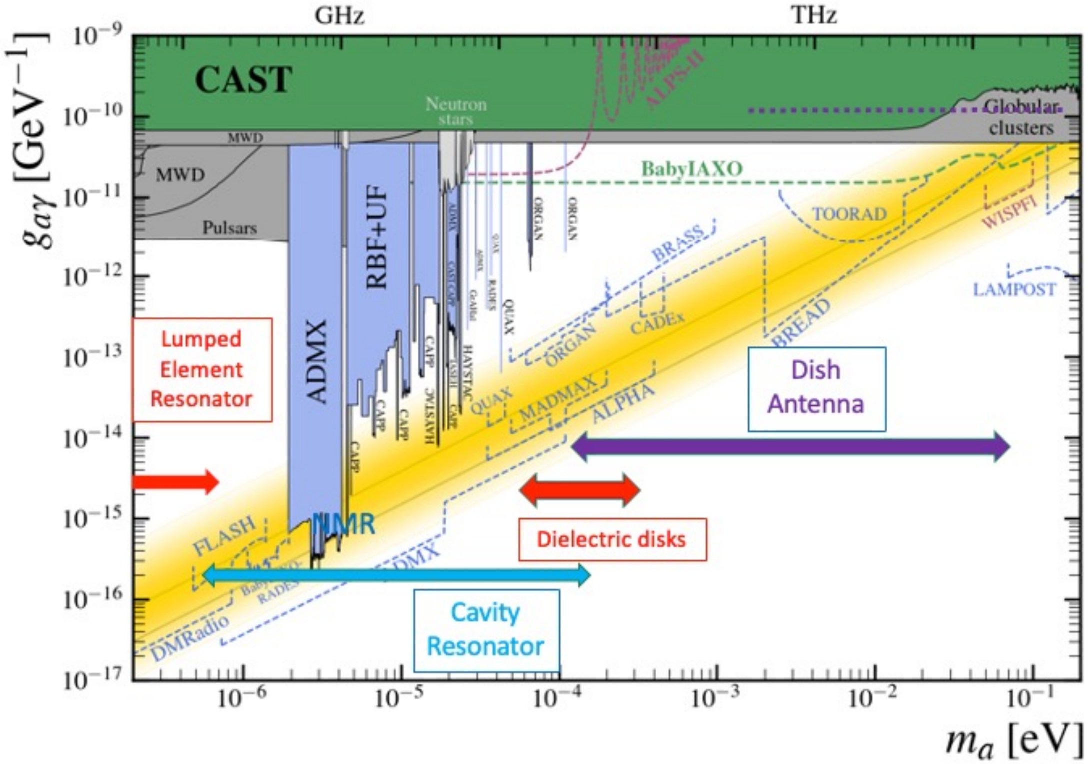
>100 completed WIMP projects/ experiments





Axion Detection– Future Program

- Future program claims to cover QCD axion band from ~10^{-9} eV to 1 eV using a combination of techniques.
- Extensively discussed at Snowmass and in other community meetings.
- Very ambitious!
- Similar to what happened in WIMP field in the 2010s-2020s



Need for National Lab/ University Partnerships

- Techniques exploring axion-photon coupling generally benefit from highest possible magnetic field strength and volume (signal ~ B^2V) and lowest possible temperature for noise reduction.
- Large magnets and cryogenic systems are difficult to build and maintain reliably over long running periods in a university environment.
- Requirements for large-scale infrastructure, technical support and safety best met at a national lab, while universities provide sophisticated sensor development, prototyping and data analysis.
- By leveraging lab resources, university groups can progress quickly from initial concept to a working experiment.

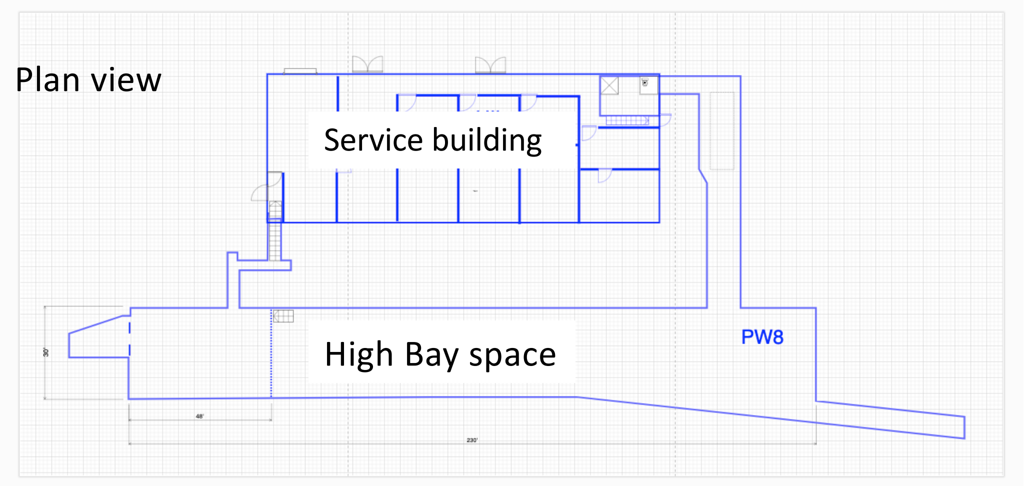
ADMX-G2 Operations

Proposal: Fermilab Dark Wave Laboratory

- Fermilab will provide a facility able to host several small scale and at least one larger scale axion search experiment.
- We will begin by installing the 9.4 Tesla MRI magnet selected for the ADMX-EFR experiment. This magnet is significantly larger than needed for the ADMX-EFR detector alone and, with careful planning, may host one or more smaller additional experiments.
- The cryogenic system and magnetic shielding will also be planned to allow for additional experiments.
- The Dark Wave Lab will include shop, assembly and testing areas and will have robust, reliable infrastructure for operating cryogenic equipment.
- A mechanism will be put in place for proposal of new experiments to share space in the magnet.
- Over time, responding to identified needs, additional magnets and cryostats will be installed in the Dark Wave Lab.

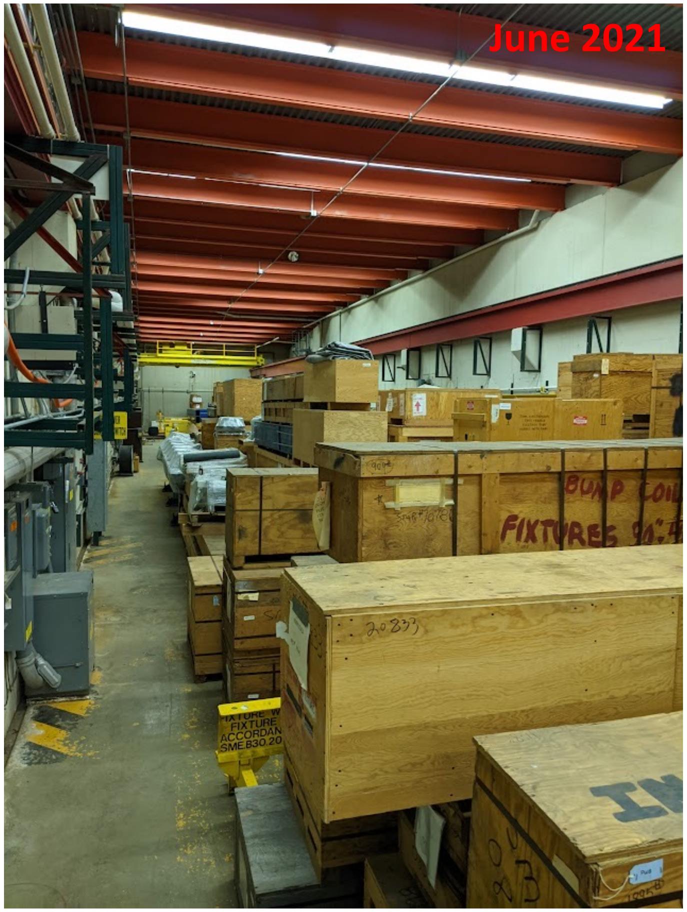
The PW8/HIL Site

- This site was identified for use by ADMX after a systematic study of potentially available buildings at Fermilab.
- Has been used for storage since last experiment (DONUT) was completed in late 1990s.
- Large, shallow underground hall (230’ x 30’) with adjacent surface building. Total 13,000 square ft.
- About half the space will be used by ADMX-EFR.



Cleanup of PW8 in Summer 2023

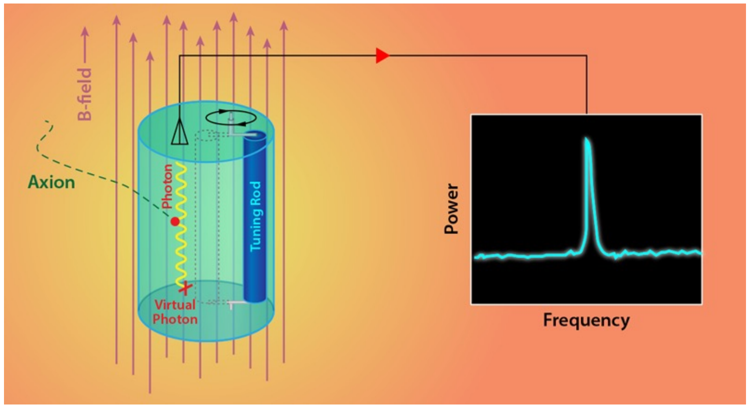
- Building was used for storage over last ~20 years-- primarily APD-TD magnet fixtures.
- Directorate provided overhead funds for cleanup last year– was a significant effort.
- Freed up 7,000 square ft of high bay space for new projects (+ additional utility space in HIL)

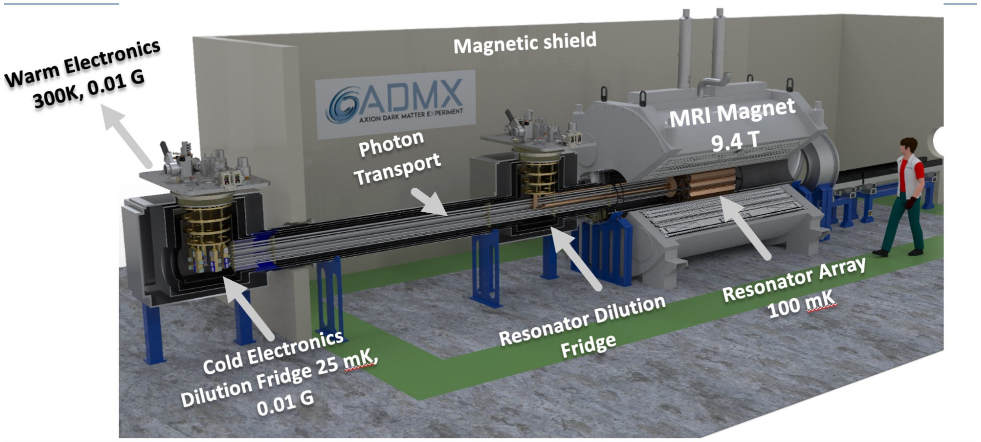

June 2021


June 2023

ADMX- Extended Frequency Range (EFR) at Fermilab

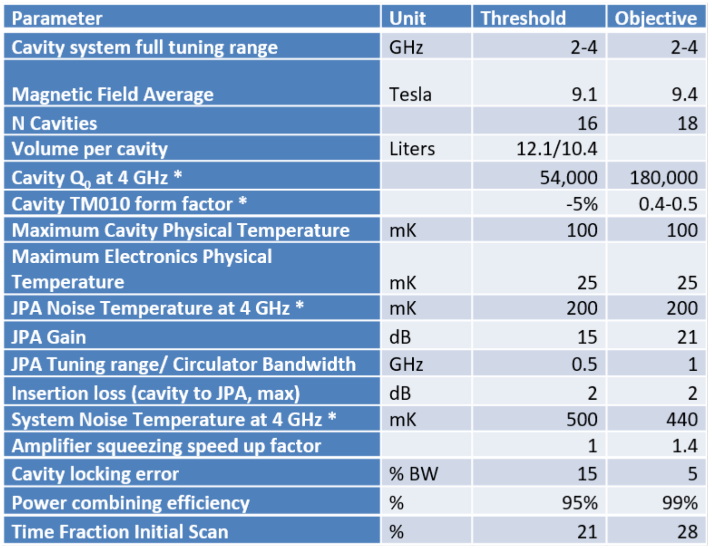
- ADMX-EFR is a search for dark matter axions supported by DOE's Dark Matter New Initiatives program.
- Axions are converted into photons in a strong magnetic field.
- Frequency coverage of this experiment is 2-4 GHz (8.3-16.5 μeV). Will follow the currently operating 0.6-2 GHz ADMX-G2 experiment operating at U. Washington.
- Currently in Design phase.
- Magnet installation and testing in FY24.
- Aim to install cryogenic system, electronics and resonators in 2025-2027.
- Data taking starting 2028.



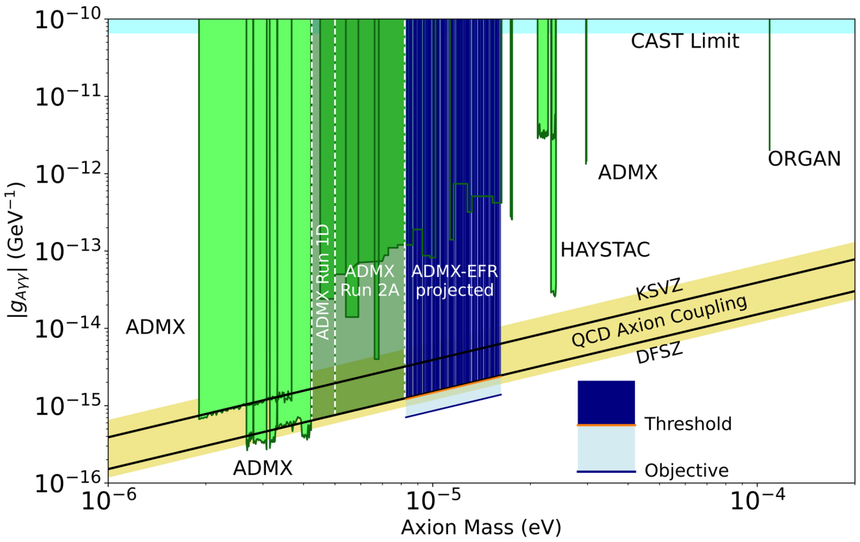


ADMX-EFR Requirements and Physics Reach

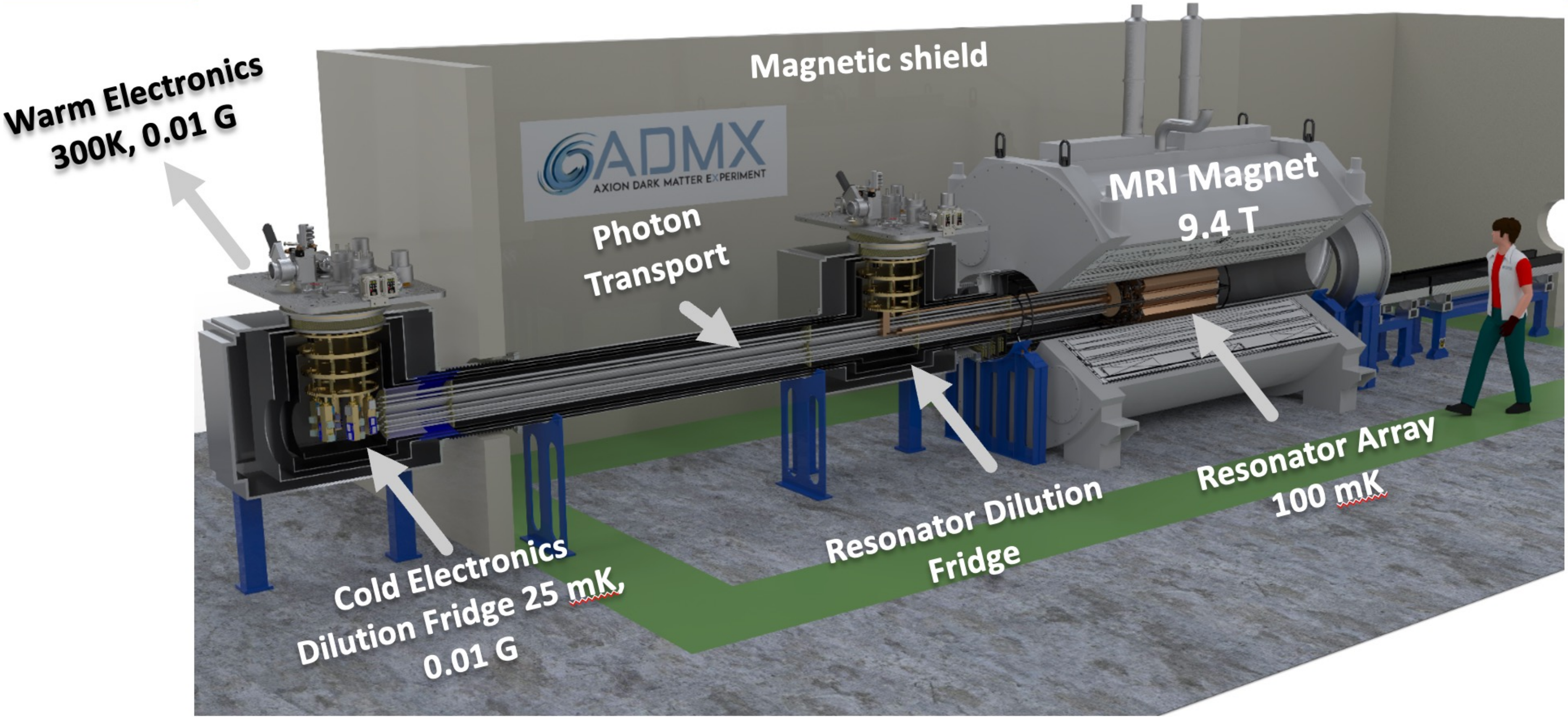
- Cavity resonators, electronics and cryogenic system in development since 2020.
- Evolution of successful ADMX-G2 designs.
- Current baseline design uses array of 18 copper resonant cavities with Q~50,000 and amplifiers with system noise temperature 500 mK.
- Exploring opportunities with SQMS to upgrade to superconducting cavities.
- New quantum sensors (photon counting) could reduce noise.



Parameter	Unit	Threshold	Objective
Cavity system full tuning range	GHz	2-4	2-4
Magnetic Field Average	Tesla	9.1	9.4
N Cavities		16	18
Volume per cavity	Liters	12.1/10.4	
Cavity Q_0 at 4 GHz *		54,000	180,000
Cavity TM010 form factor *		-5%	0.4-0.5
Maximum Cavity Physical Temperature	mK	100	100
Maximum Electronics Physical Temperature	mK	25	25
JPA Noise Temperature at 4 GHz *	mK	200	200
JPA Gain	dB	15	21
JPA Tuning range/ Circulator Bandwidth	GHz	0.5	1
Insertion loss (cavity to JPA, max)	dB	2	2
System Noise Temperature at 4 GHz *	mK	500	440
Amplifier squeezing speed up factor		1	1.4
Cavity locking error	% BW	15	5
Power combining efficiency	%	95%	99%
Time Fraction Initial Scan	%	21	28

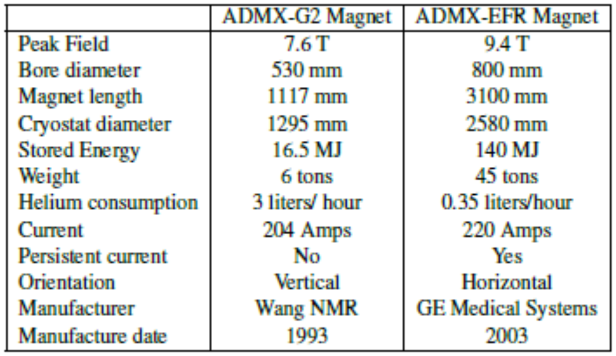


ADMX-EFR Experiment Layout at Fermilab



ADMX-EFR Magnet

- After study of alternative magnets for ADMX-EFR, we selected the 9.4 Tesla MRI magnet currently operating at University of Illinois Chicago (UIC).
- Was world’s highest field whole body MRI-magnet when installed in 2003.
- No longer needed for UIC’s medical research.
- Has been offered to DOE/ Fermilab at no cost (DOE will assume coats or removing from their building)
- We are in late stages of planning the magnet move with UIC and subcontractors.
- Begin review by Fermilab’s Transportation Committee next week (November 2023)

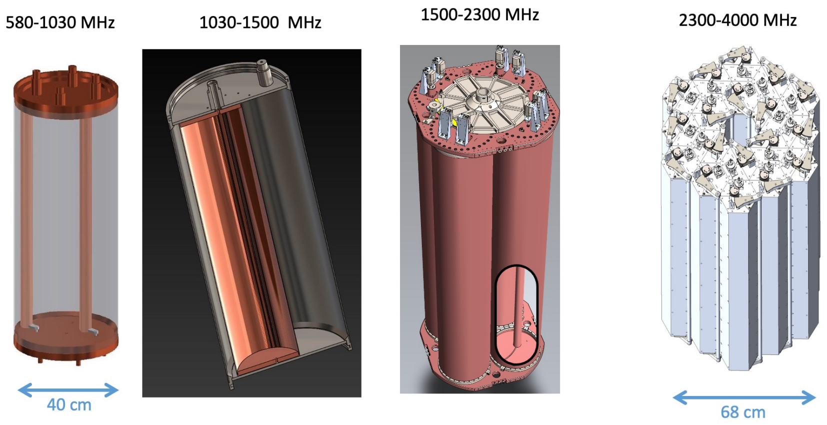


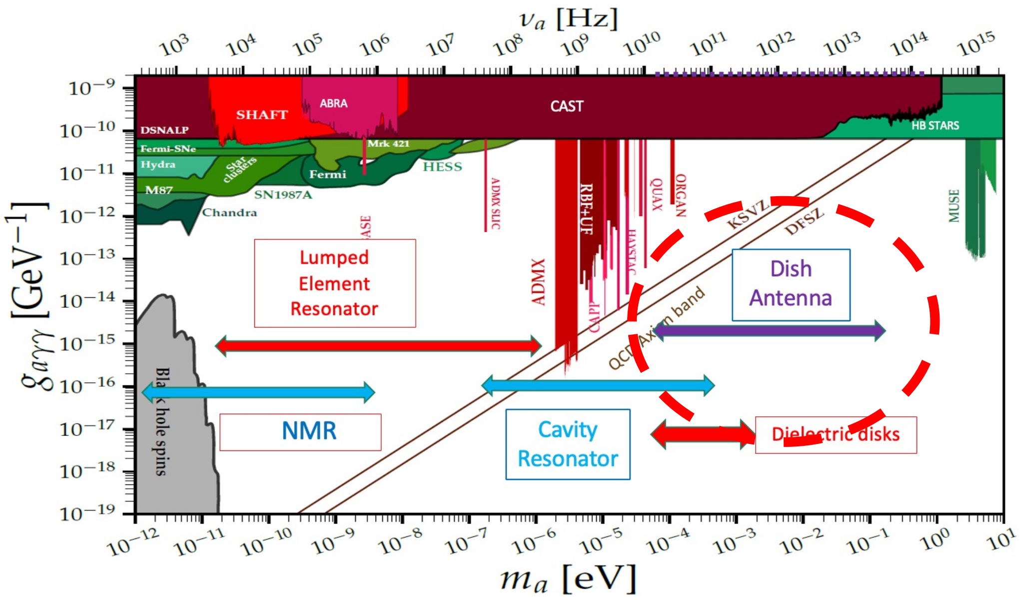
	ADMX-G2 Magnet	ADMX-EFR Magnet
Peak Field	7.6 T	9.4 T
Bore diameter	530 mm	800 mm
Magnet length	1117 mm	3100 mm
Cryostat diameter	1295 mm	2580 mm
Stored Energy	16.5 MJ	140 MJ
Weight	6 tons	45 tons
Helium consumption	3 liters/ hour	0.35 liters/hour
Current	204 Amps	220 Amps
Persistent current	No	Yes
Orientation	Vertical	Horizontal
Manufacturer	Wang NMR	GE Medical Systems
Manufacture date	1993	2003

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.

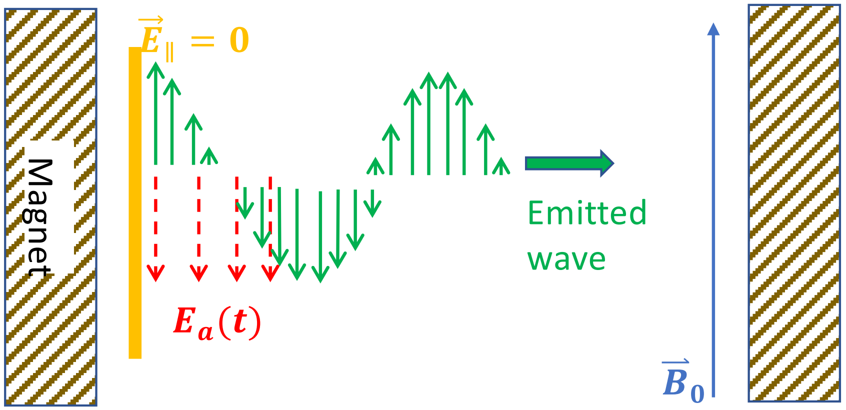
ADMX cavity designs for increasing mass ranges





Axion Induced Radiation from A Magnetized Metal Slab

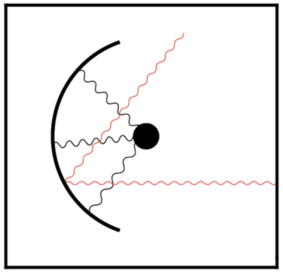
- Axions interact with a static magnetic field producing an oscillating parallel electric field in free space
- A conducting surface in this field emits a plane wave perpendicular to surface.



- Radiated power is very 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!



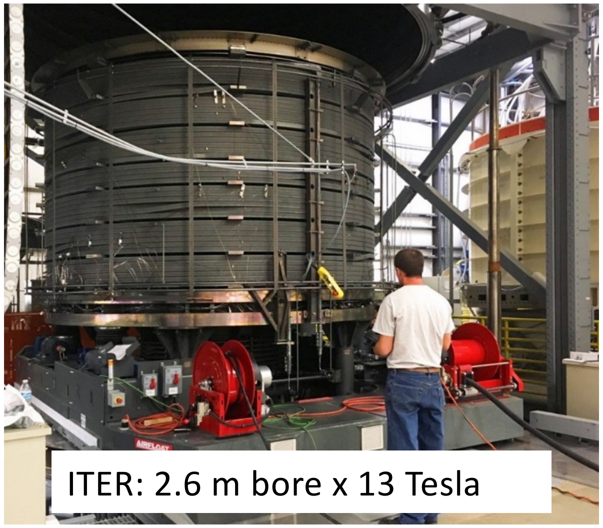
“Dish antenna” (Horns et al., 2012)

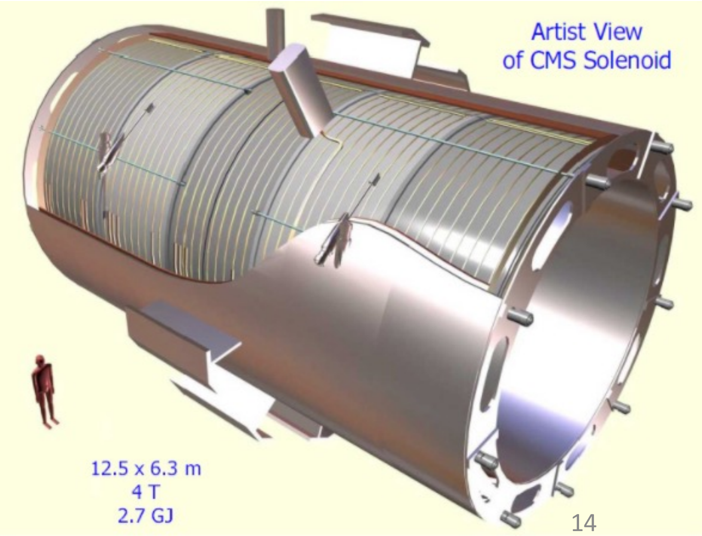
Large Solenoids

- How to use large volume solenoids to detect axions?

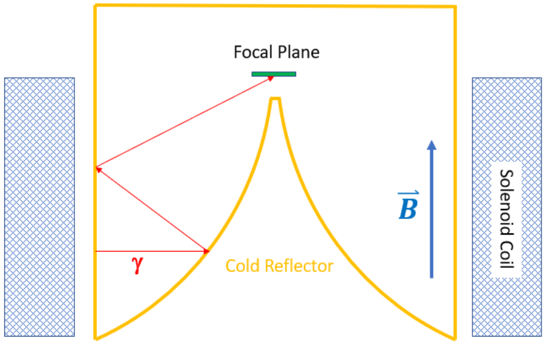
B_0^2V (T^2m^3)	**Magnet**	**Application/ Technology**	**Location**	**Field (T)**	**Bore (m)**	**Len (m)**	**Energy (MJ)**	**Cost ($M)**
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*	*MRI/Ti SRC*	*CEA*	*11.75*	*1*	*4*	*338*	
320	ITER CSMC	Fusion/Sn CICC	JAEA	13	1.1	2	640	>50[2]
290	*60 T out*	*HF/HTS CICC*	*MagLab*	*42*	*0.4*	*1.5*	*1100*	
250	*Magnex*	*MRI/Mono*	*Minnesota*	*10.5*	*0.88*	*3*	*286*	*7.8*
190	Magnex	MRI/Mono	Juelich	9.4	0.9	3	190	
70	45 T out	HF/Nb$_3$Sn 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

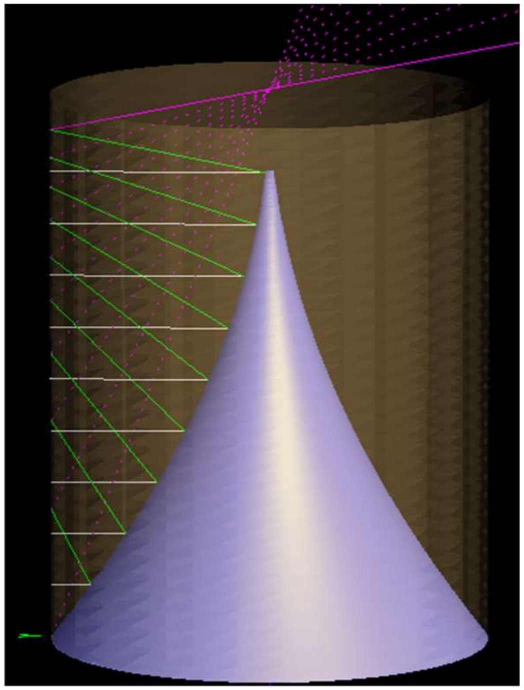
Compilation by Mark Bird, NHMFL

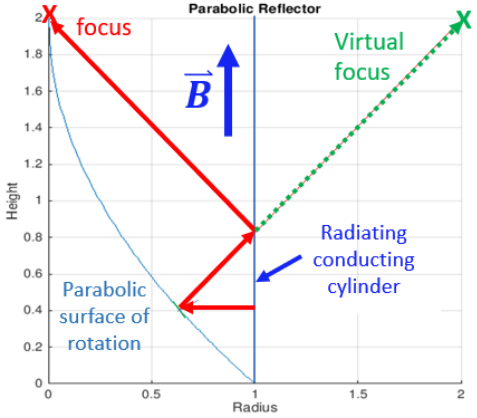

ITER: 2.6 m bore x 13 Tesla



“Coaxial Dish”: Optical Concentrator for Solenoid Magnets



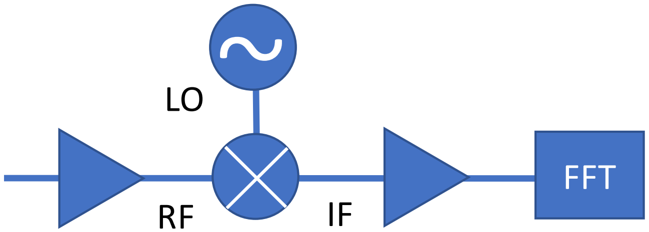




- Rays emitted from cylindrical inner surface of solenoid are focused to a point after two reflections.

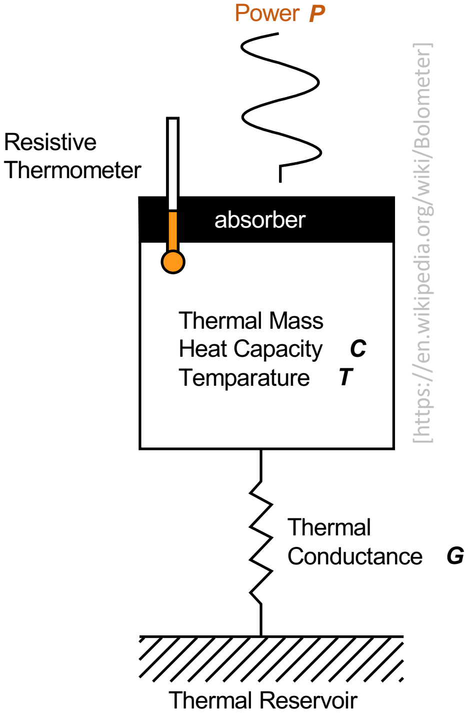
Three Strategies to Measure Signal

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

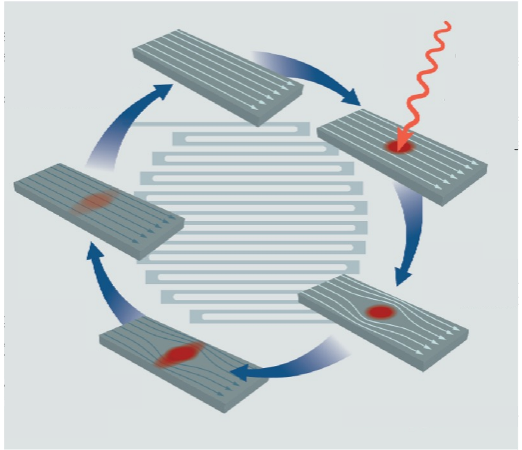


Fig.: Sae Woo Nam (NIST)

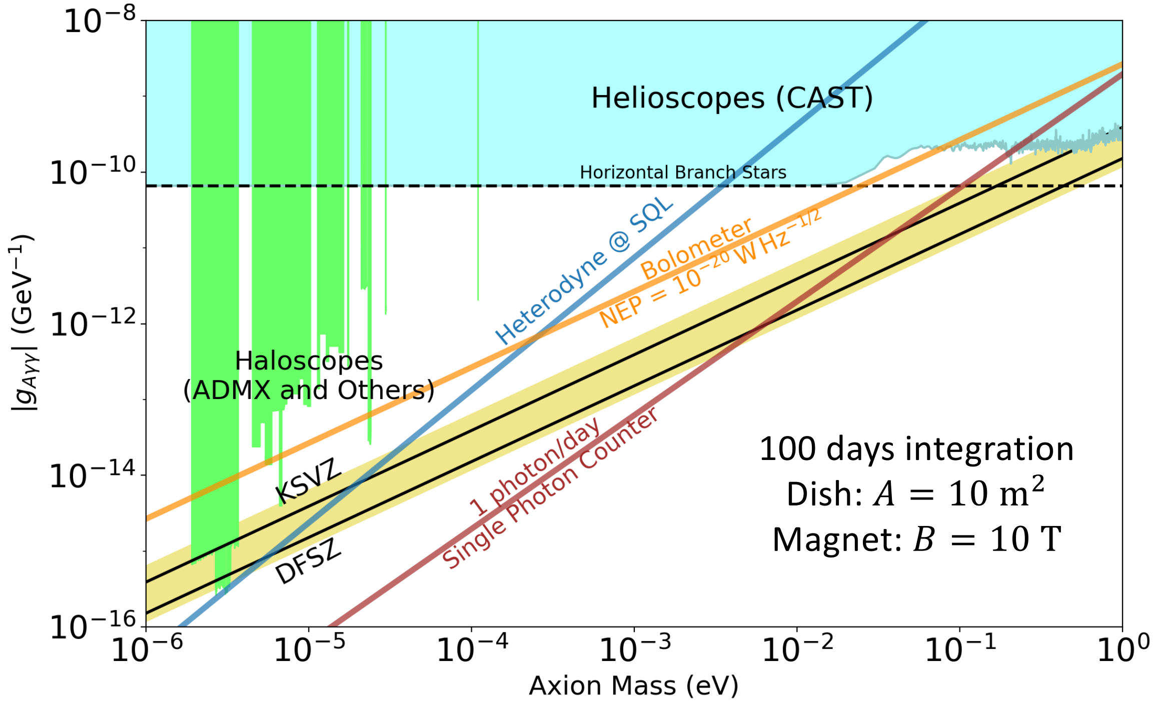
e.g., nanowire detectors

SNSPDs, KIDs, QCDs, …

down to ~ 1 photon/day

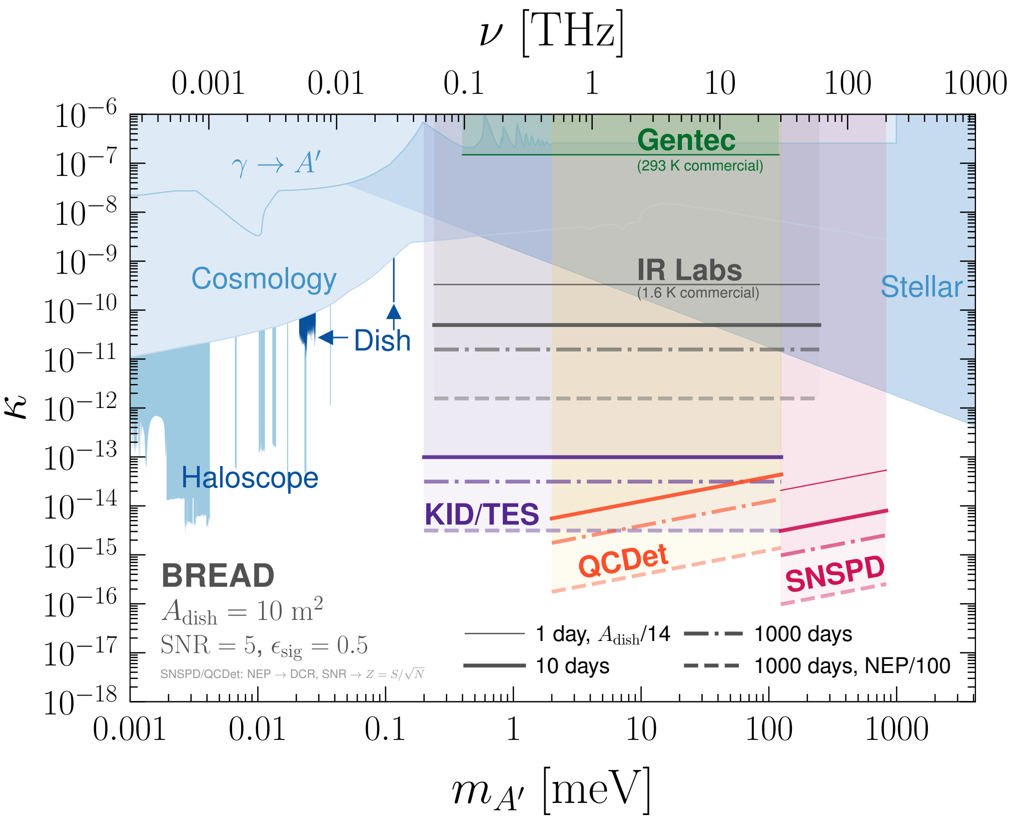
Sensitivity Projections-- Futuristic

- 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.

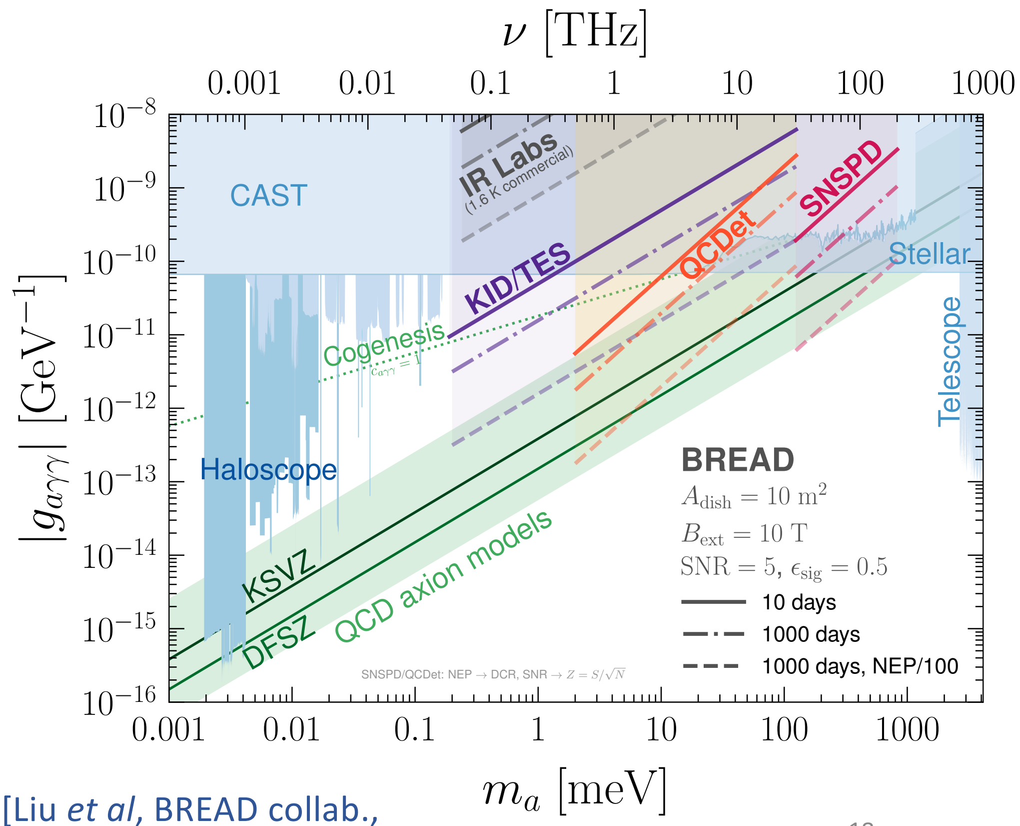


BREAD Sensitivity with State of Art THz Sensors

Dark Photons



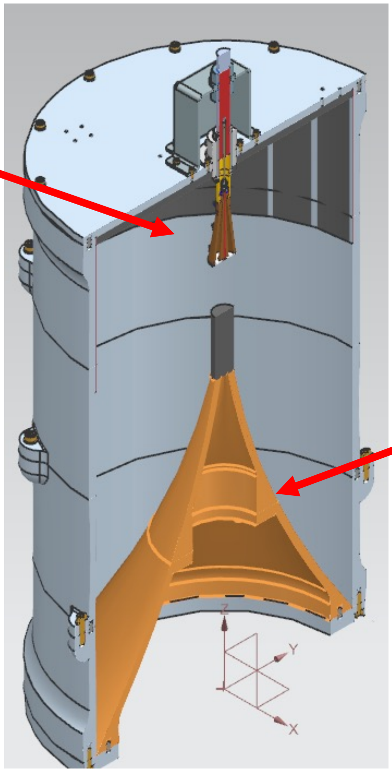
Axions



[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

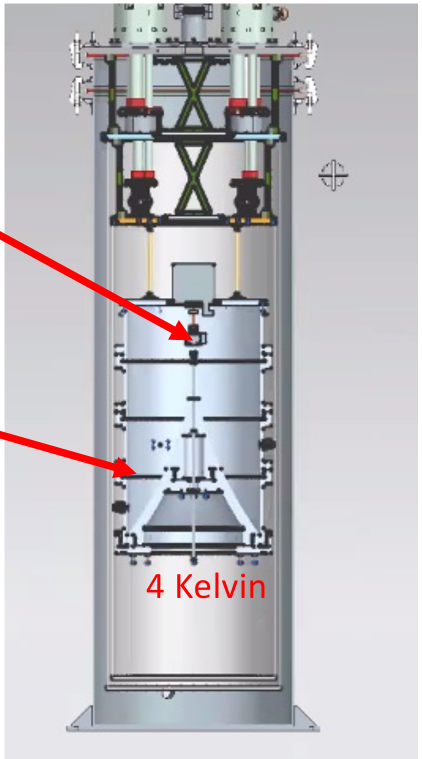


Horn Antenna with Axial position adjustment

Room temperature

400 mm diameter Coaxial Dish

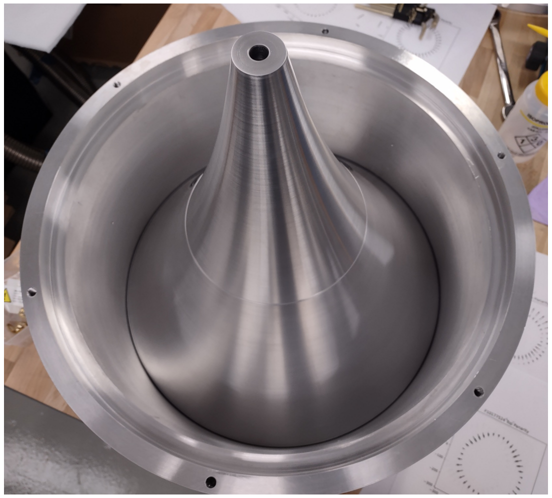
InfraBREAD: 300 THz experiment (~1 micron) with Superconducting Nanowire Detectors (SNSPDs)

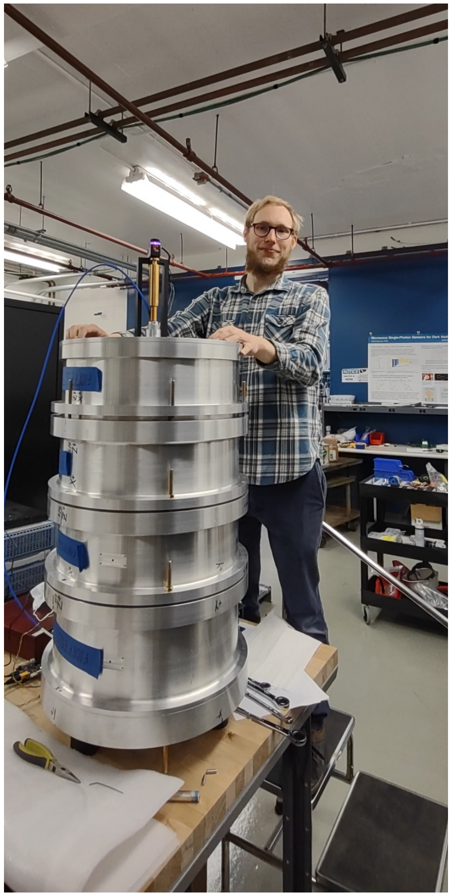


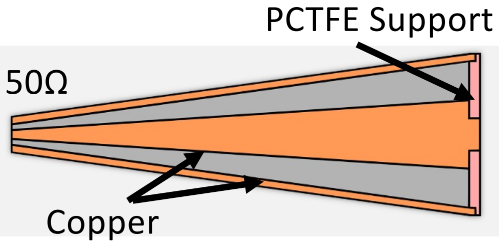
SNSPD @ 800 mK

4 Kelvin

GigaBREAD Parts & Assembly

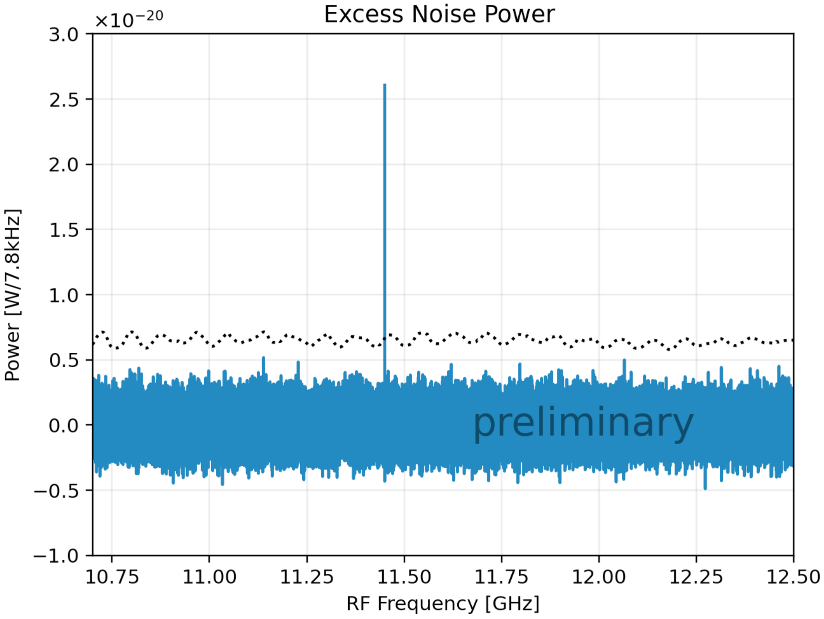


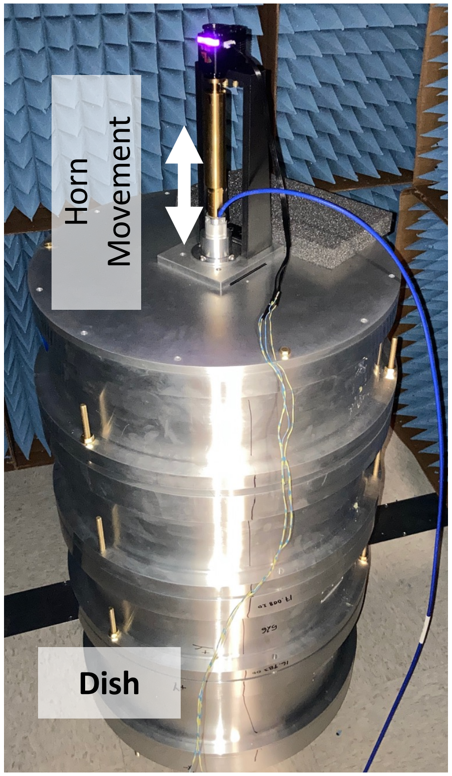




First Dark Matter Search with GigaBREAD

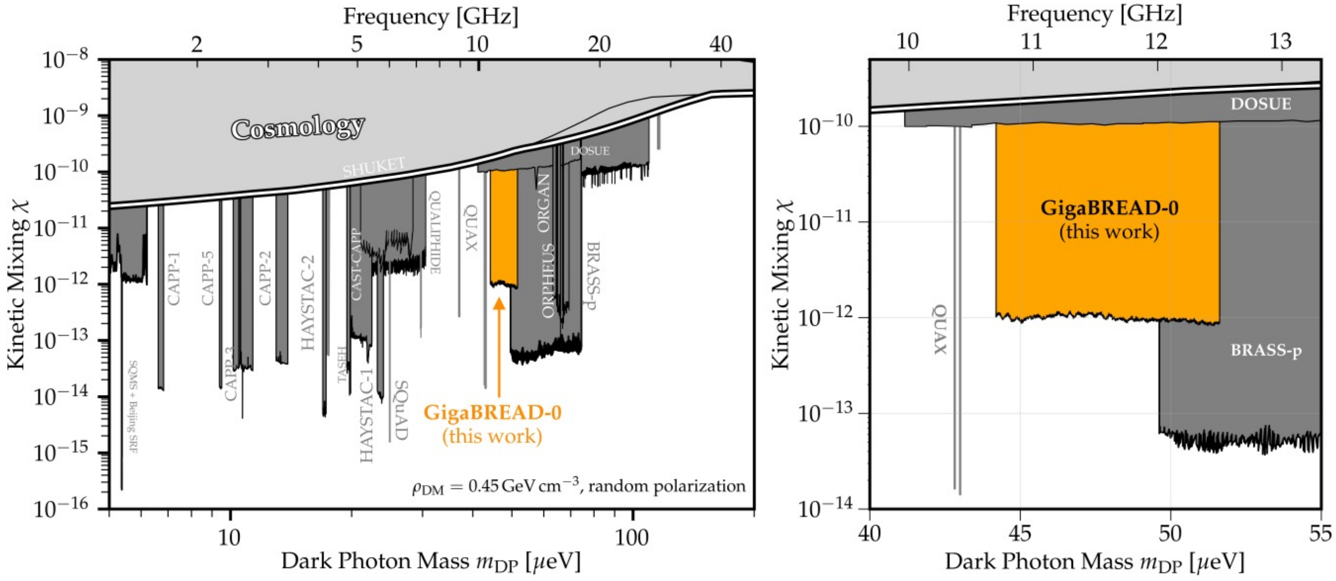
- 3.5 day run in an RF shielded room at University of Chicago.
- 10.7- 12.5 GHz
- Room temperature
- Off-the-shelf HEMT amplifier ~100 Kelvin added noise.
- No magnet (dark photon search)
- Scanning of vertical horn antenna position.





First GigaBREAD Results- on ArXiv last week.

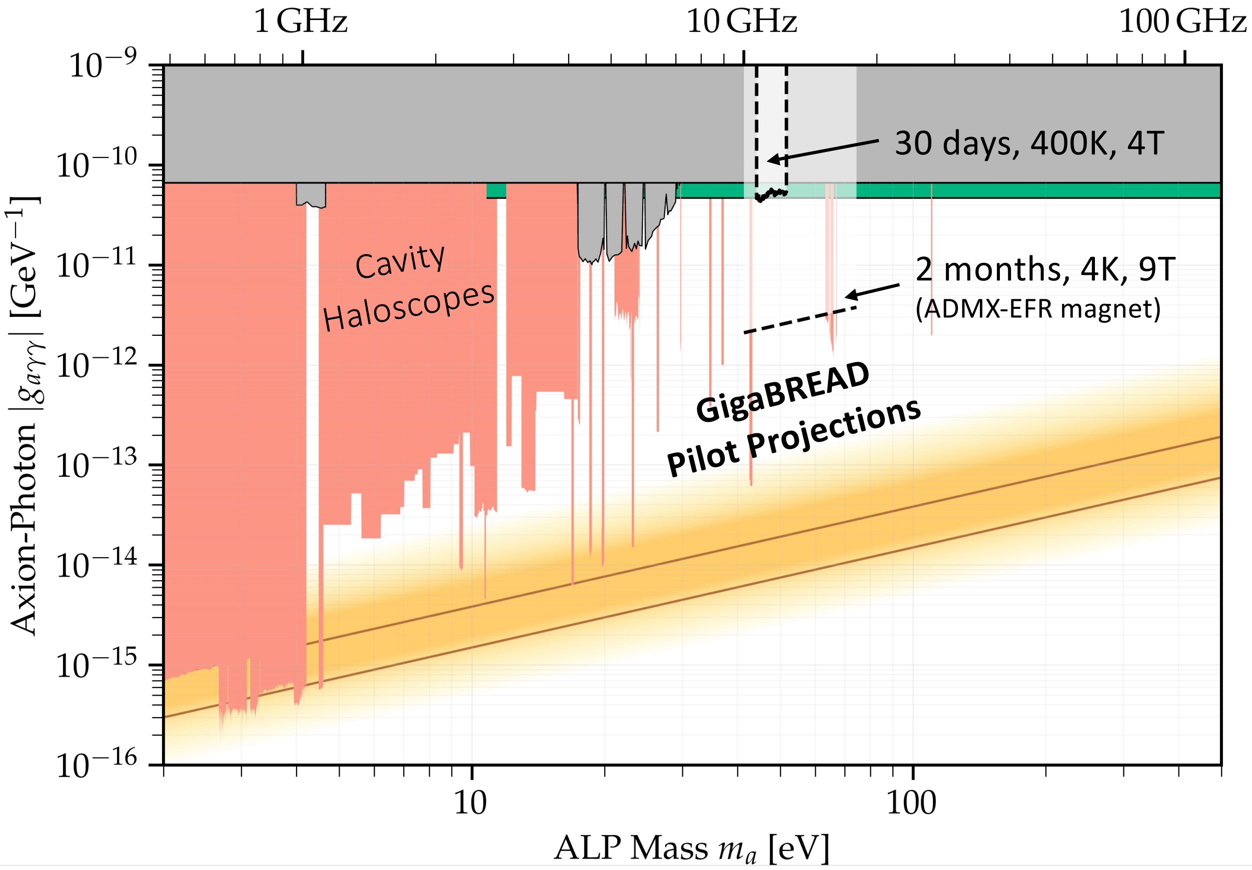
- Proof-of-principle experiment with 0.5 m^2 dish at room temperature.
- 24-days of data collection on campus at U. Chicago



Stefan Knirck et al., “First Results from a Broadband Search for Dark Photon Dark Matter in the 44 to 52µeV range with a coaxial dish antenna”, ArXiV:2310.13891

Next Step– Axion Search at Argonne Natl Lab

4 T MRI magnet at Argonne



Dark Wave Lab Workshop in Spring 2024

- A two-day workshop at Fermilab in Spring 2024 (dates are TBD).
- Would repeat annually if successful.
- Goals:
  - Identify experiments and collaborations that could potentially be hosted by the Dark Wave Lab.
  - Begin to gather requirements for lab design features and equipment.
  - Explore options for use of the ADMX-EFR magnet in the period 2025-2027, prior to the start of ADMX-EFR operations.
  - Discussion of longer-term options for higher field and larger volume magnets.
  - Discuss quantum sensor needs for future experiments.

List of Possible Dark Wave Lab Projects

Experiment or Collaboration Name	Possible Collaborators	Early Physics FY25-FY27	Comments
ADMX-EFR	Fermilab, PNNL, LLNL, U. Washington, Washington U. St Louis, U. Florida	4-kelvin 2-4 GHz run, single cavity	Running test cavity at 4K in magnetic field would reduce project risk.
Low frequency cavity resonator	U. Florida, other ADMX. Possible INFN Frascati?	200-700 MHz cavity. KSVZ search at 4 Kelvin	Recent ADMX publication.
BREAD	Fermilab, U. Chicago, Argonne, LLNL, UIUC, SLAC, JPL, IIT	GigaBREAD 10-20 GHz, TeraBREAD 70-140 GHz	Multiple BREAD setups are possible. GigaBREAD is ready now for a room temperature run.
SQMS	Fermilab, Padova?	Explore 4-10 GHz frequency range	Nb3Sn Superconducting cavities. Raphael Cervantes, Sam Posen, Bianca Giaccone

Ongoing discussions with additional groups in US & international

We know these groups are very interested– existing ties to Fermilab/ U. Chicago and ADMX.

Currently focused on other experiment sites but likely to attend our meeting for discussions. May be interested in the lab as a place for testing prototypes.