Title: Next Generation Axion Dark Matter Searches

Speakers: Andrew Sonnenschein

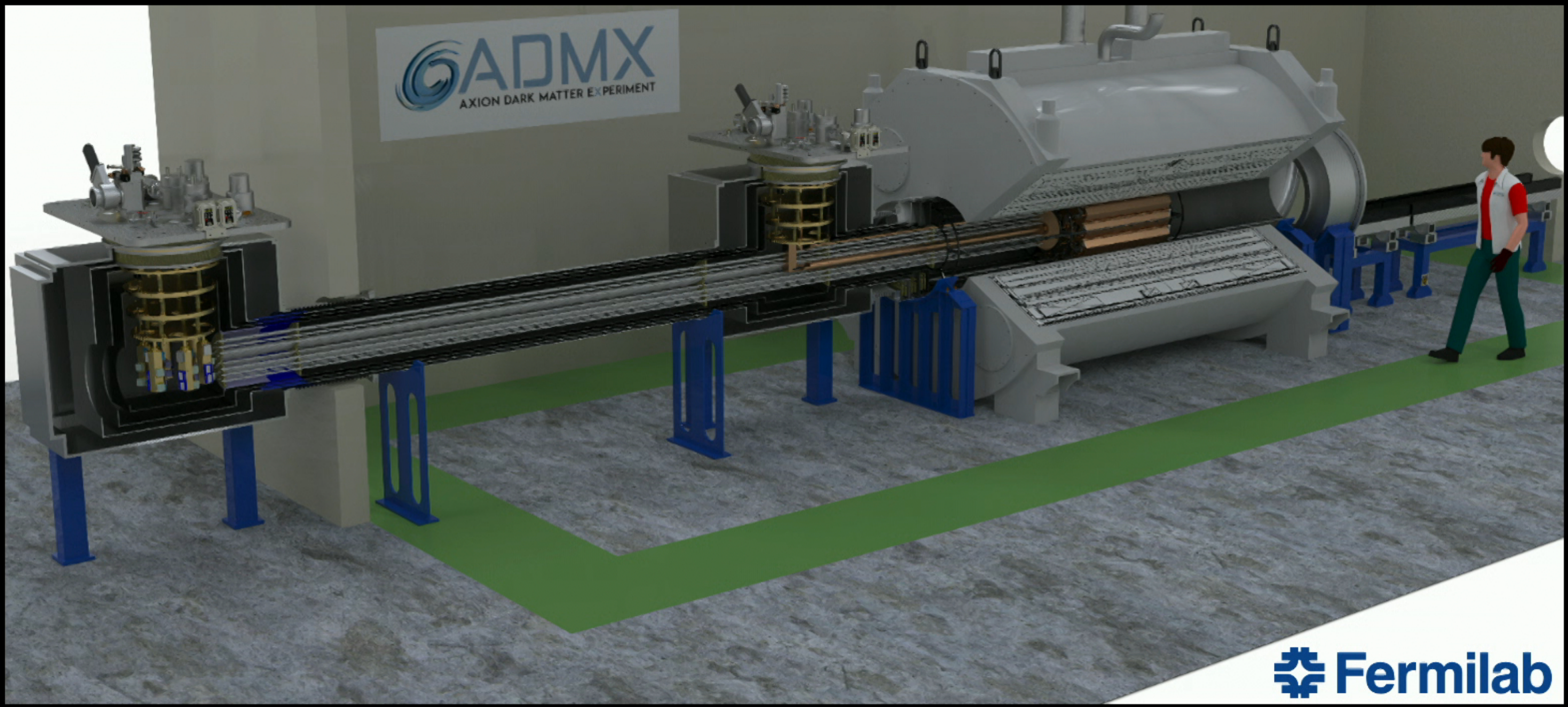
Series: Particle Physics

Date: November 11, 2022 - 10:00 AM

URL: https://pirsa.org/22110049

Abstract: In the early 1980s, axions and WIMPs were identified as promising dark matter candidates. The last forty years have seen a spectacularly successful experimental program attempting to discover the WIMPs, with sensitivity that has by now improved by many orders of magnitude compared to the earliest results. The parallel program to search for axions has made less progress and has reached the necessary sensitivity only over a very limited mass range. However, progress has recently accelerated, with the invention of many new axion detection techniques that may eventually provide a definitive answer to the question of whether the dark matter is made of axions. I will review some of these new developments with emphasis on Fermilab's program, including ADMX- Extended Frequency Range and Broadband Reflector Experiment for Axion Detection (BREAD).

Zoom link: https://pitp.zoom.us/j/97234421735?pwd=UGNJRWxYMkErRmdWSnJiWTdoOFNaZz09

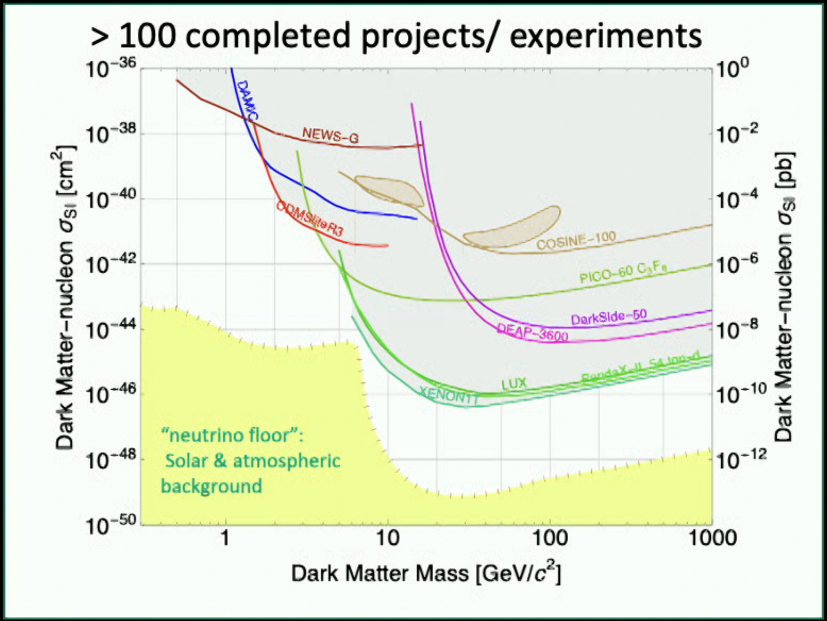


Next Generation Searches for Axion Dark Matter

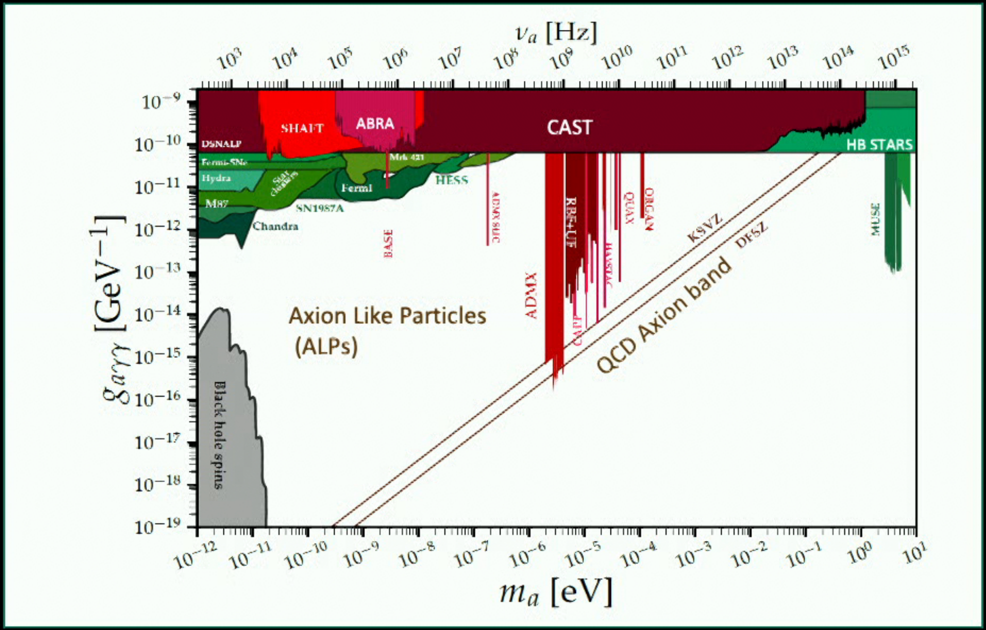
Andrew Sonnenschein, *Fermilab*
Perimeter Institute
11-Nov-2022

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.

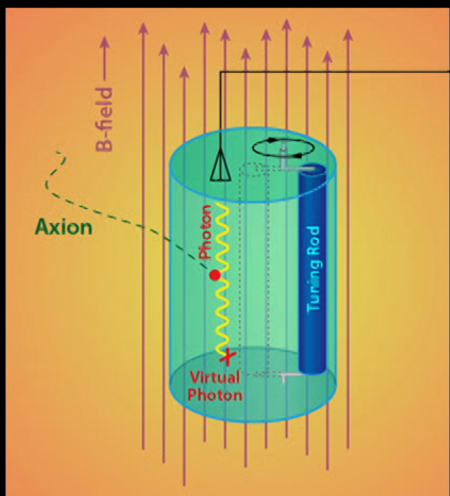


- Axions and ALPs
  - Previous experiments not sensitive enough to test most important models.
  - Relatively few experiments.
  - New techniques needed to reach required sensitivity.

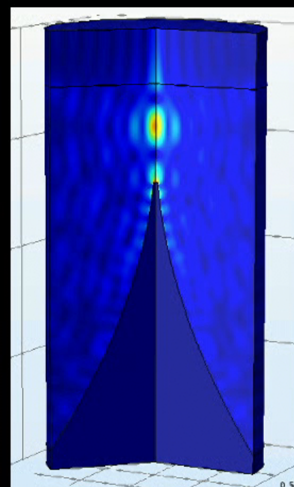


Diversity of Techniques- Many New Ones

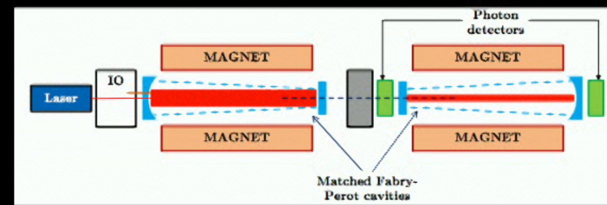
Resonant Cavity (ADMX, HAYSTAC, CAPP)



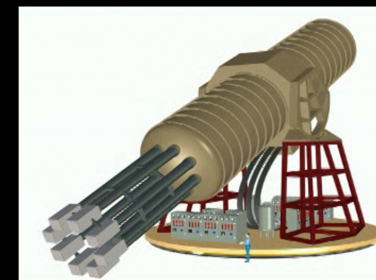
Dish antenna (BREAD, BRASS)



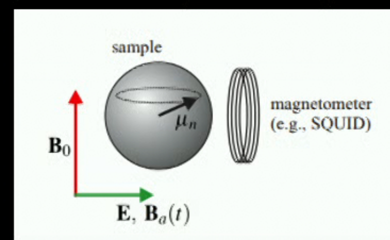
"Light Shining Through Walls" (ALPS)



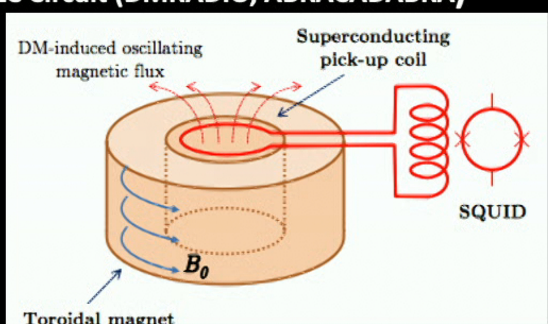
Solar Axions (CAST, IAXO)



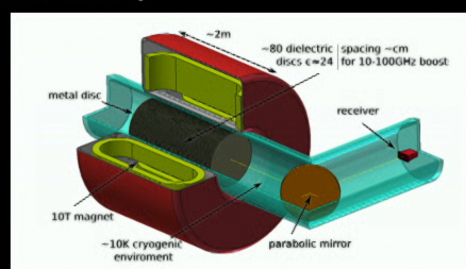
NMR (CASPEr)



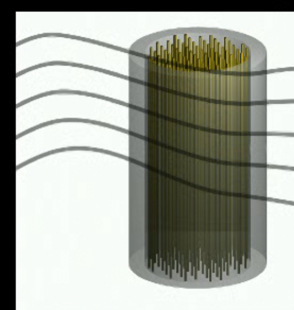
LC Circuit (DMRADIO, ABRACADABRA)



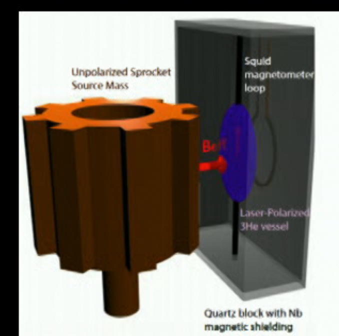
Dielectric Radiators (MADMAX, ORPHEUS)



Plasma haloscope



ARIADNE



Axion Electrodynamics

- Axions interact weakly with photons.
- Besides the normal electric field E(x,t) and magnetic field B(x,t), there is an axion field a(x,t).
- Maxwell's equations modified with new terms to include effects of a.
- The new field is always multiplied by the very small axion − photon coupling $g_{a\gamma\gamma}$

$$\nabla \cdot \mathbf{E} = g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = g_{a\gamma\gamma} \left(\mathbf{E} \times \nabla a - \mathbf{B} \frac{\partial a}{\partial t} \right)$$

$$\nabla \cdot \mathbf{B} = 0$$

- There are plane wave solutions for the $a(x,t)$, oscillating with a frequency corresponding to the axion mass ($\omega_a = m_a c^2/\hbar$).

$$a(x,t) \propto \sqrt{\rho_{DM}} \cos(\omega_a t - kx)$$

Large Background Magnetic Field

- First step to discover axions: get a big magnet
- In the presence of a static magnetic field B_0, the axion field sources an effective oscillating electric current J_a

$$J_a = g_{a\gamma\gamma} B_0 \frac{\partial a}{\partial t}$$

$$\nabla \cdot \mathbf{E} = g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} - \frac{\partial \mathbf{E}}{\partial t} = g_{a\gamma\gamma} \left(\underbrace{\mathbf{E} \times \nabla a}_{0} - \underbrace{\mathbf{B} \frac{\partial a}{\partial t}}_{J_a} \right)$$

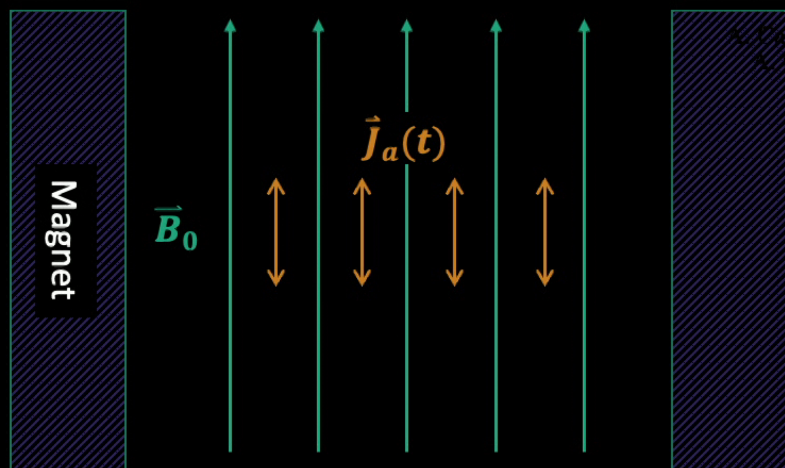
$$\nabla \cdot \mathbf{B} = 0$$

$$\Rightarrow \quad \nabla \times B - \frac{\partial E}{\partial t} = J_a$$

Oscillating Fictitious Current

- Will produce the same electromagnetic response as a normal electric current.
- Oscillates at frequency ω_a determined by axion mass

$$\omega_a = \frac{m_a c^2}{\hbar}$$



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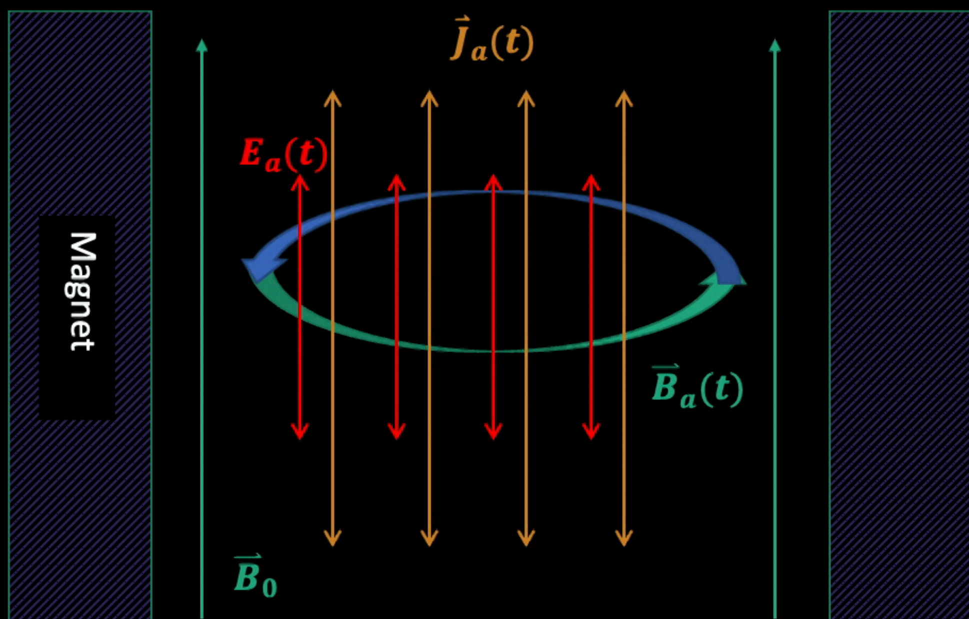
Electric and Magnetic Field Response

- There is also an oscillating electric field in the axial direction $\boldsymbol{E_a(t)}$
- Relative strength of the oscillating electric and magnetic fields depends on boundary conditions & and size of apparatus compared to axion wavelength



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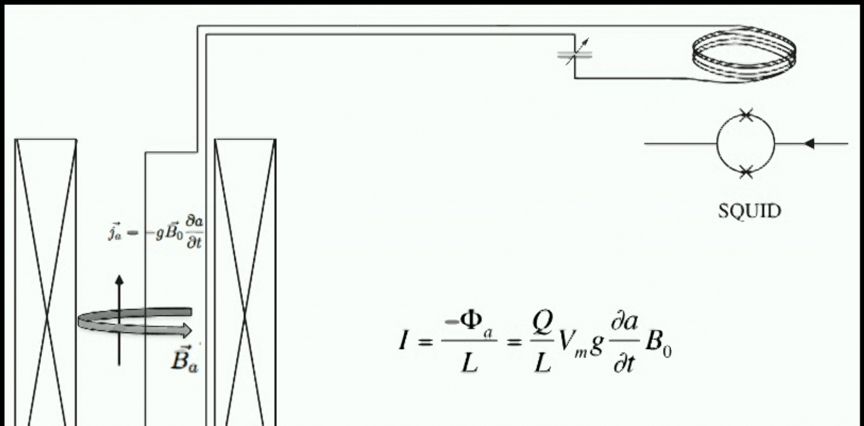
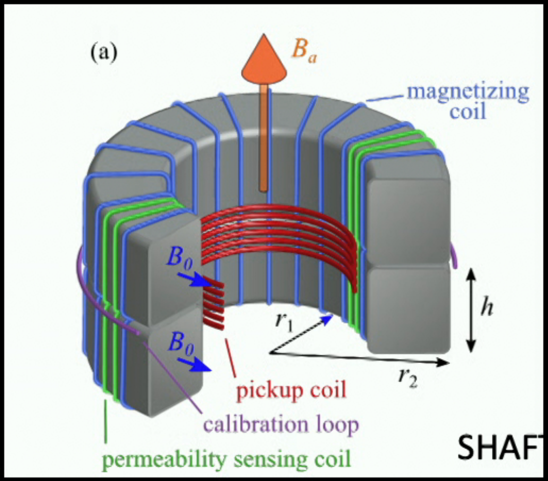
Axion Detection Through Magnetic Flux

- Collect the magnetic flux sourced by J_a with a transformer coil and measure induced current with a SQUID.
- Works for solenoidal magnets (ADMX-SLIC, DMRADIO) or toroidal (ABRACADABRA, SHAFT)
- Sensitive to light axions with wavelength big compared to magnet size.



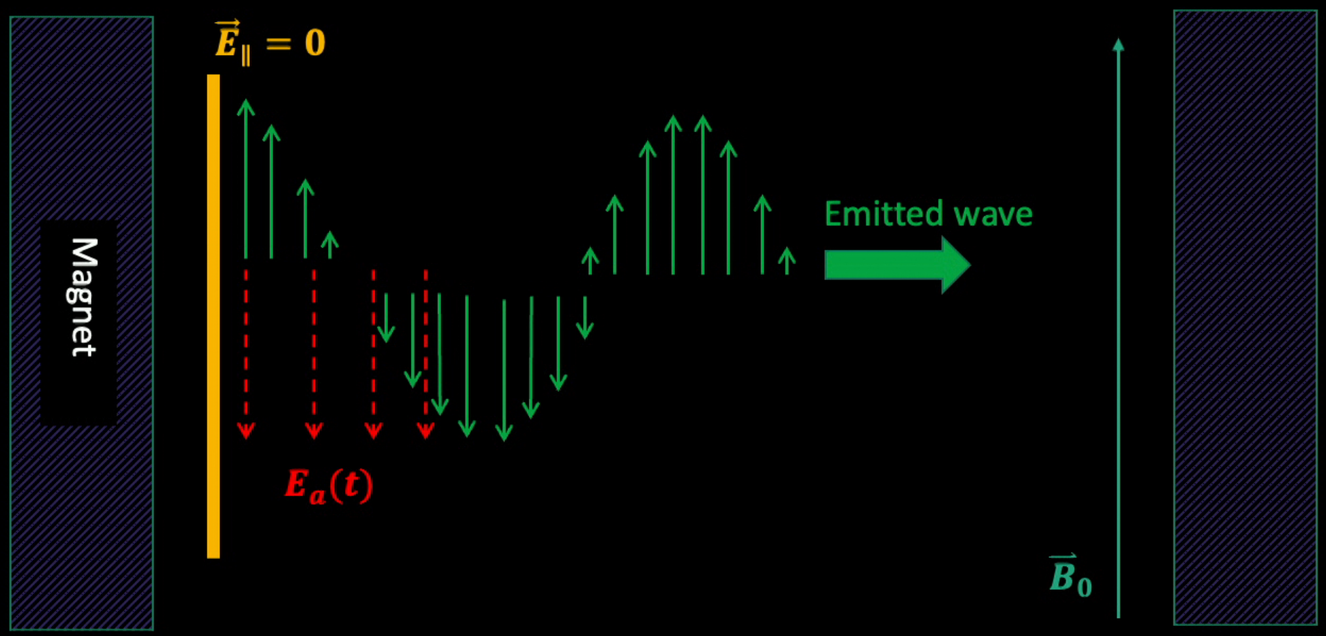
ADMX- SLIC
Sikivie, Sullivan and Tanner, 2014



Gramolin et al., Nature Physics 17, 79-84, 2021

Emission of Electromagnetic Wave From Conducting Surface

- Insert a conducting surface into the magnet bore.
- Currents will appear in the conductor driven by the axion induced electric field oscillations.
- A traveling electromagnetic wave is emitted from the surface to satisfy boundary conditions.

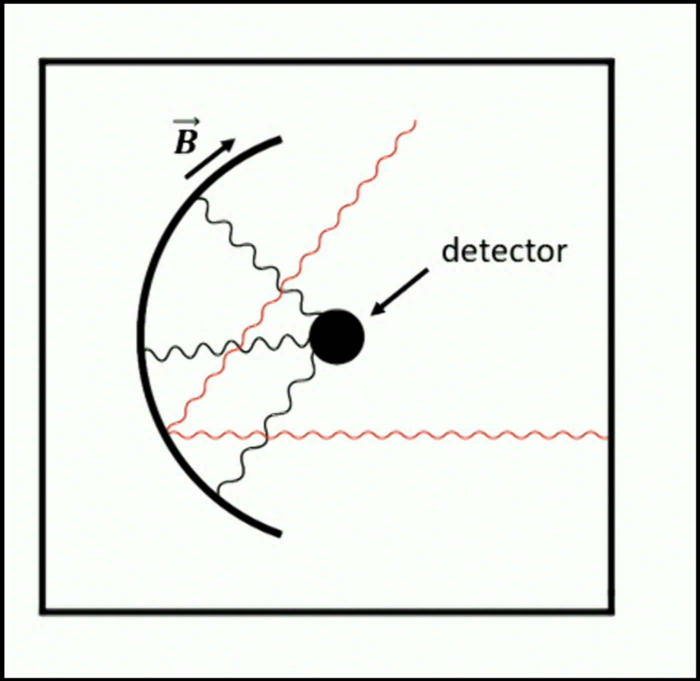


“Dish Antenna” Experiments

- Arrange for the axion induced surface emission to be focused onto a detector.
- Signal is very weak. Only around 10^{-26} watts for a big magnet.

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

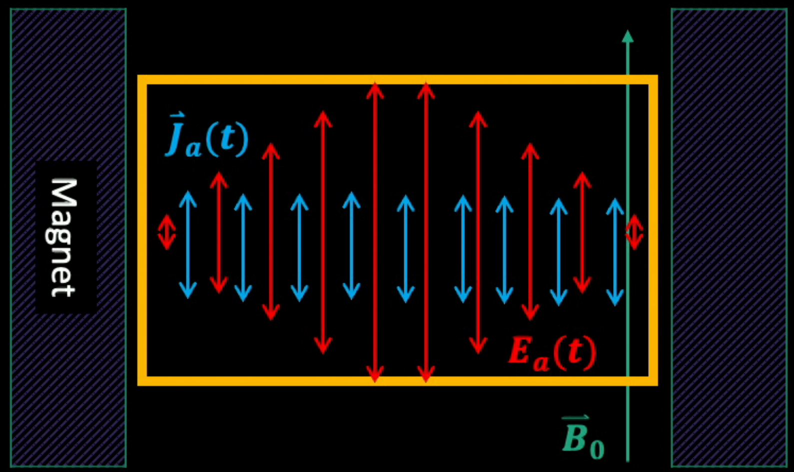
- More on this later…



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

Signal Enhancement in a Resonant Cavity

- Build a metal box (cavity) inside the magnet
- The conducting cavity walls emit radiation
- Cavity will resonate at discrete frequencies when integer number of wavelengths fit inside.
- Resonance condition when $\omega_{cavity} = \omega_{axion} = \frac{m_a c^2}{\hbar}$ ➡ Power enhancement!



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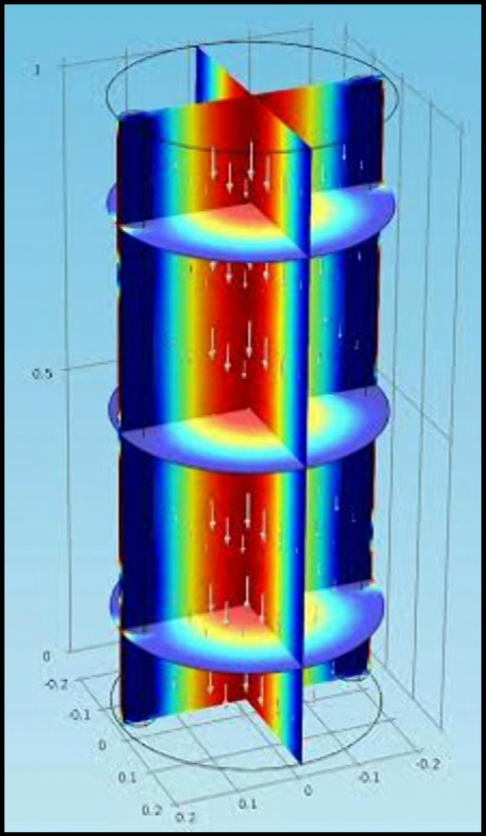
Pumped Cavity Mode

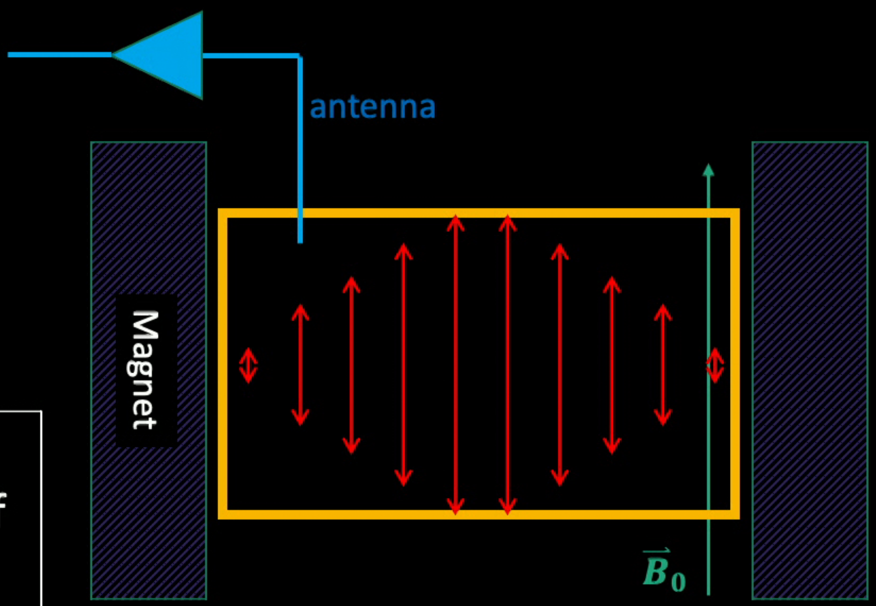
- Power buildup occurs when cavity resonance frequency is matched to axion mass.
- Signal Power ~10^{-22}-10^{-23} W at 1 GHz for typical cavity and magnet parameters.
- Three orders of magnitude more than a non-resonant dish antenna.

TM_{010} Mode



<u>Experiments</u>

RBF (1980s)
U Florida
ADMX
HAYSTAC
CAPP/CULTASK
KLASH
CAST- RADES



Pierre Sikivie, "Experimental Tests of the Invisible Axion" 1983 PRL

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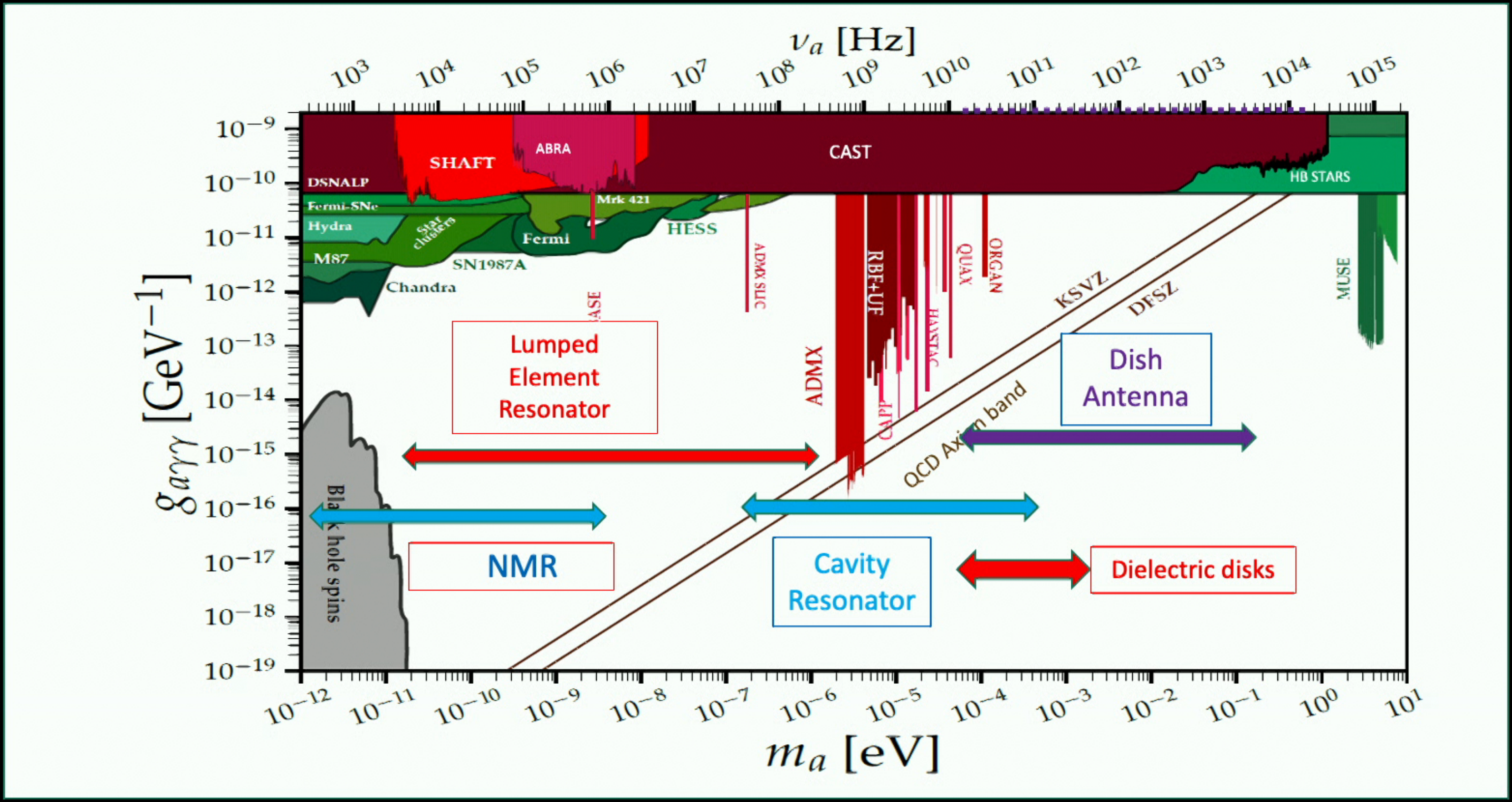
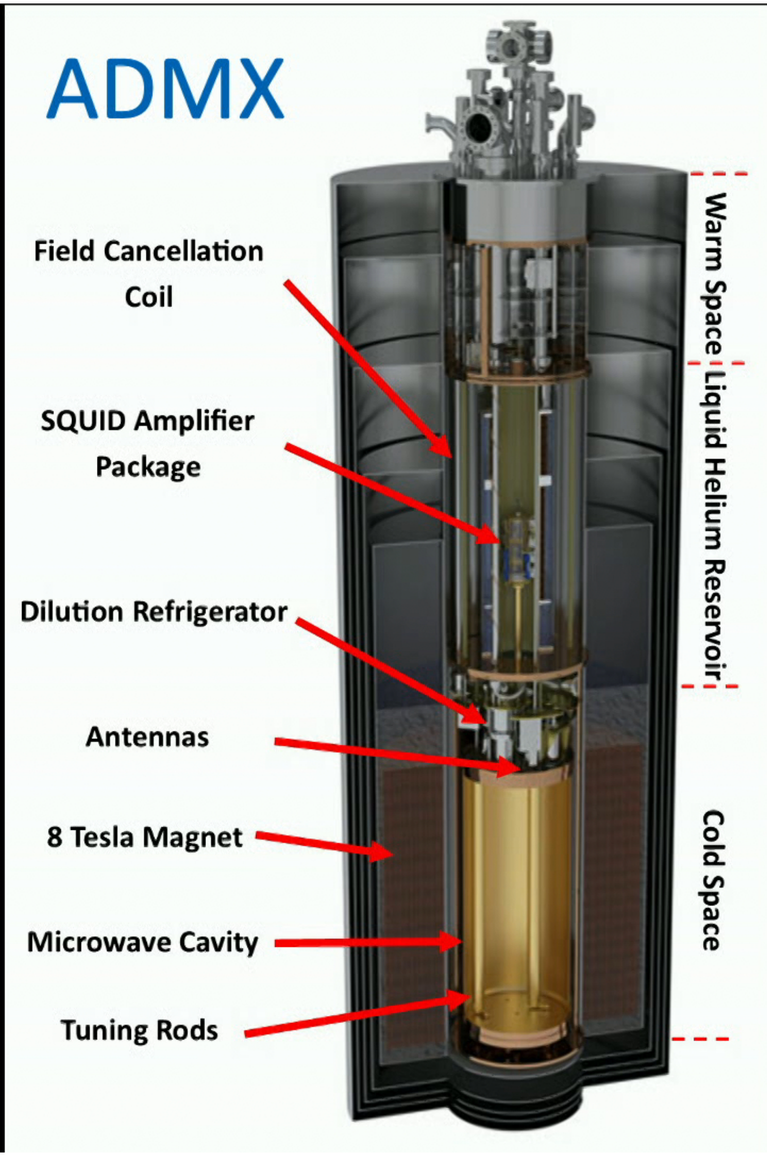
Complementarity of Detection Techniques



ADMX Collaboration

This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.


ADMX
Field Cancellation Coil
SQUID Amplifier Package
Dilution Refrigerator
Antennas
8 Tesla Magnet
Microwave Cavity
Tuning Rods
Warm Space
Liquid Helium Reservoir
Cold Space

Magnet: 8- Tesla Solenoid with 60 cm bore

Resonant Cavity with Tuning Rods

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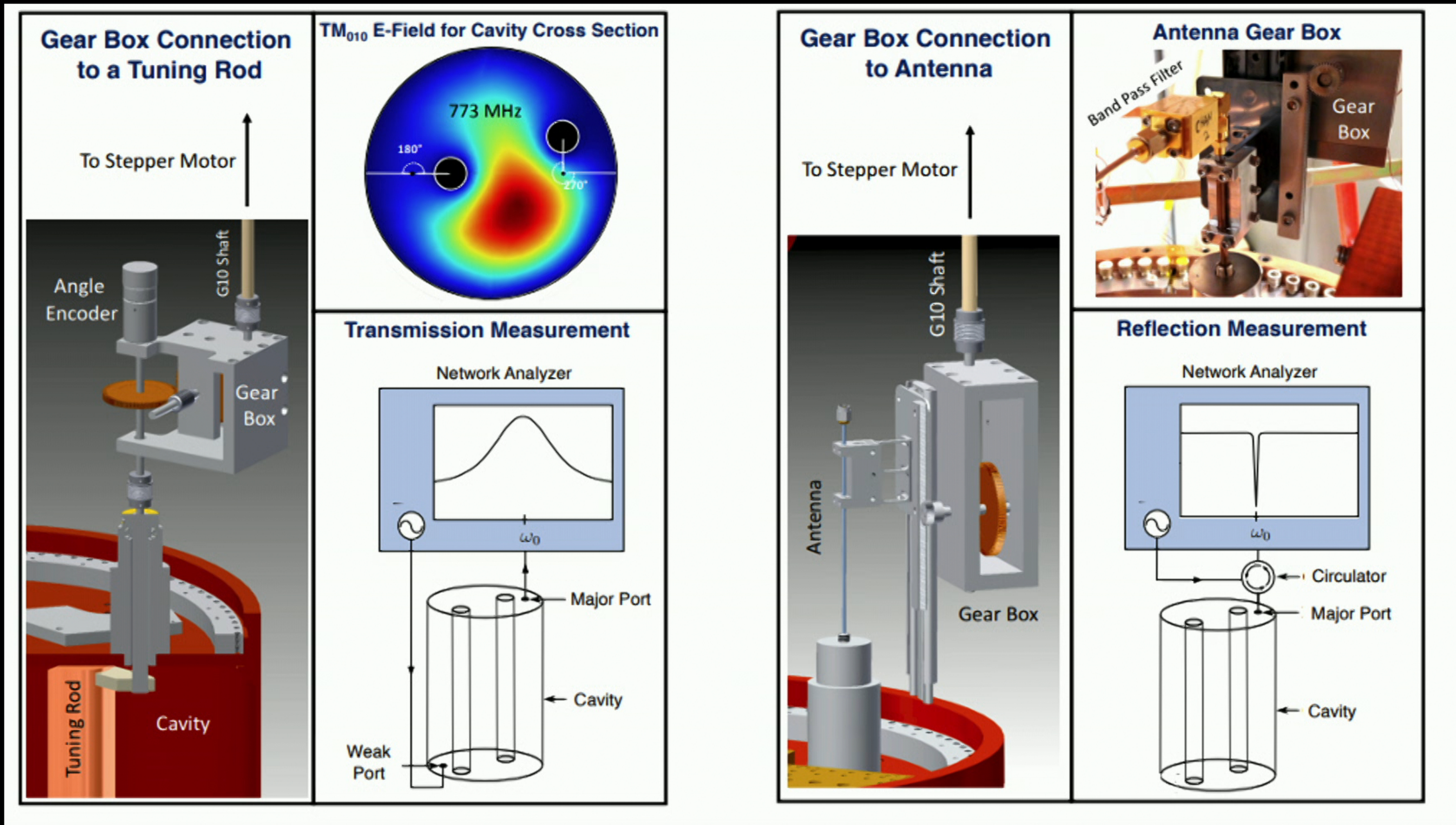
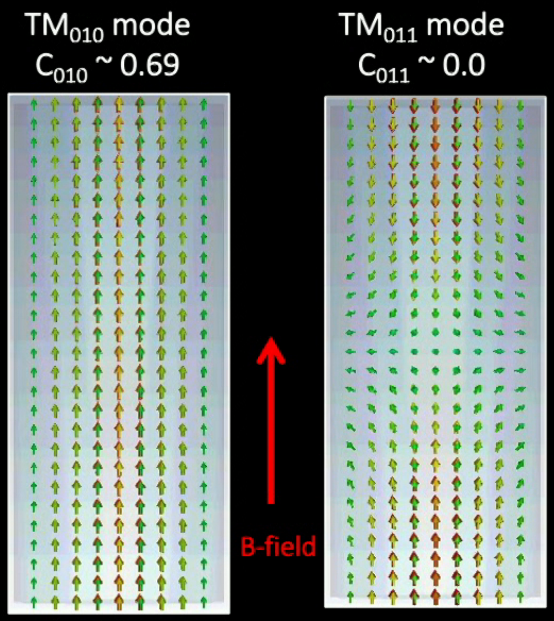

Gear Box Connection to a Tuning Rod
To Stepper Motor
Angle Encoder
G10 Shaft
Gear Box
Tuning Rod
Cavity
TM010 E-Field for Cavity Cross Section
773 MHz
180°
270°
Transmission Measurement
Network Analyzer
ω0
Major Port
Cavity
Weak Port
Gear Box Connection to Antenna
To Stepper Motor
G10 Shaft
Antenna
Gear Box
Antenna Gear Box
Band Pass Filter
Gear Box
Reflection Measurement
Network Analyzer
ω0
Circulator
Major Port
Cavity

Signal Power

- Signal power:

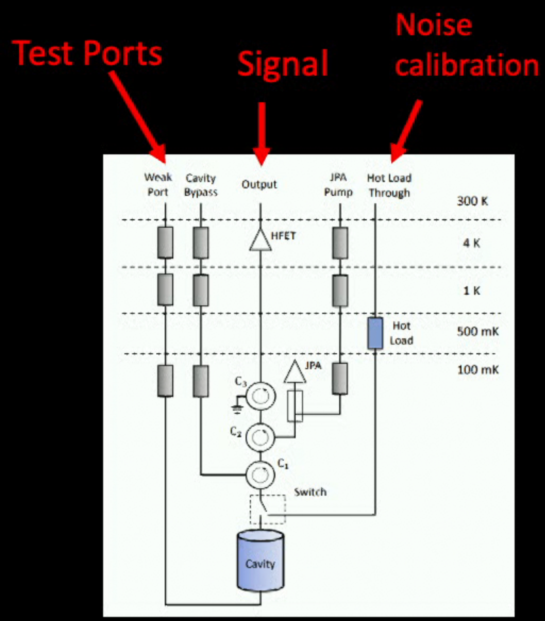
$$P_{\text{axion}} = 7.7 \times 10^{-23}\ \text{W} \left(\frac{V}{136\ \ell}\right)\left(\frac{B}{7.5\ \text{T}}\right)^2\left(\frac{C}{0.4}\right) \times \left(\frac{g_\gamma}{0.36}\right)^2\left(\frac{\rho_a}{0.45\ \text{GeV/cc}}\right)\left(\frac{f}{1\ \text{GHz}}\right)\left(\frac{Q_L}{80,000}\right).$$

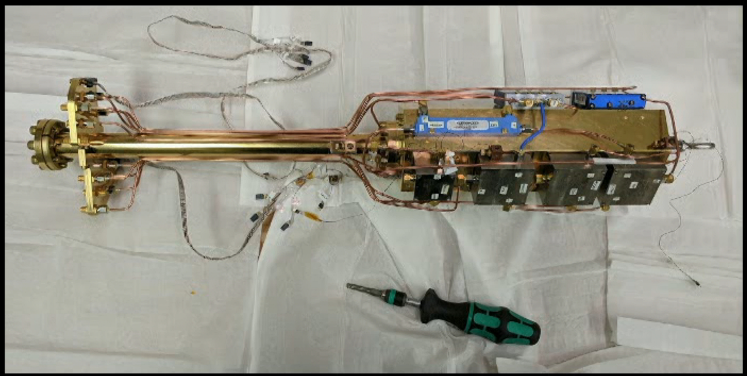
Form Factor C_{nl} *overlap of cavity mode* $\boldsymbol{E} \cdot \boldsymbol{B_0}$
Dark Matter Density ρ_a
Axion Mass m_a
Resonator Quality Factor $Q_L \sim 10^5$
Axion velocity dispersion $Q_a \sim 10^6$
Couplings to Photon $g_\gamma \sim 0.97$ for KSVZ model
$g_\gamma \sim 0.36$ for DFSZ



Low Noise Amplifiers

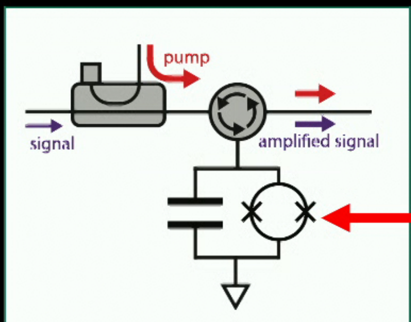
- To reach sensitivity of DFSZ axion models requires noise levels that were beyond state-of-the-art a few years ago.
- System noise temperature of 300-500 mK typical in ADMX since introduction of Microstrip Squid Amplifier in 2016- order of magnitude lower then previous generation.
- Possible because of developments in Quantum Information Science community for applications such as Qubit readout:
    - **Microstrip Squid Amplifiers** (Clarke group @ UC Berkeley)
    - **Josephson Parametric Amplifiers** (Siddiqi group @ UC Berkeley, Buckley & Murch @Washingto U.).
    - **Traveling Wave Parametric Amplifiers** (MIT Lincoln Labs). Wide instantaneous bandwidth- up to an octave.
- Post amplification at 4 Kelvin using commercially available HFET technology.
- Cold RF system needs capability for in-situ calibration and diagnostic functions.



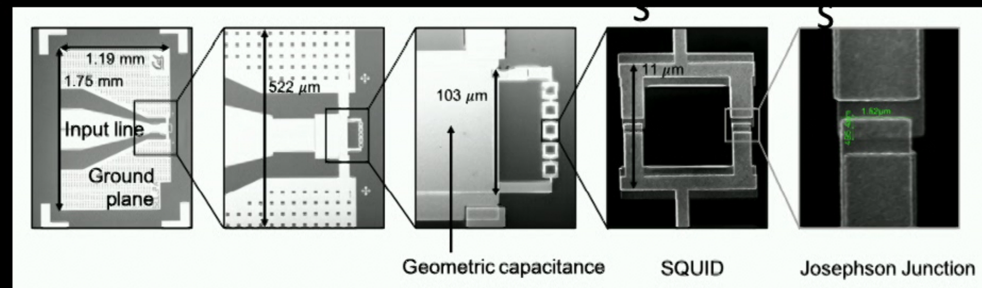


Josephson Parametric Amplifiers

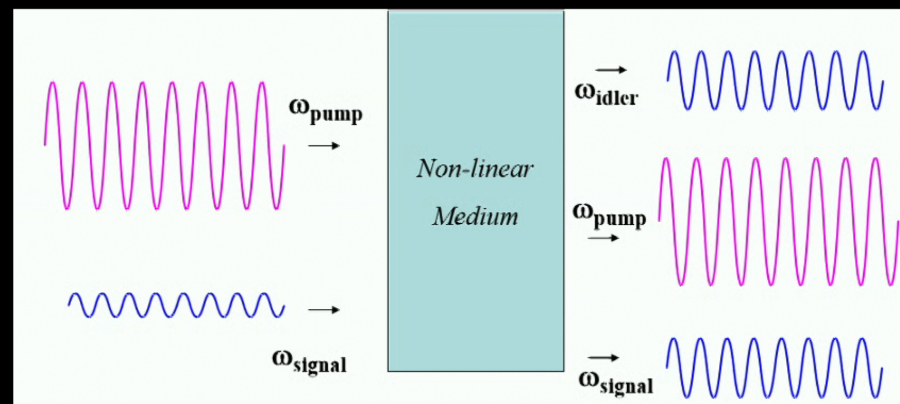
- LC oscillator with nonlinear inductance provided by Josephson Junctions.



Squid loop: flux-tunable nonlinear inductance



- Power transfer from pump tone to signal tone.
- Nearly lossless amplification in principle– can approach quantum limit of added noise.



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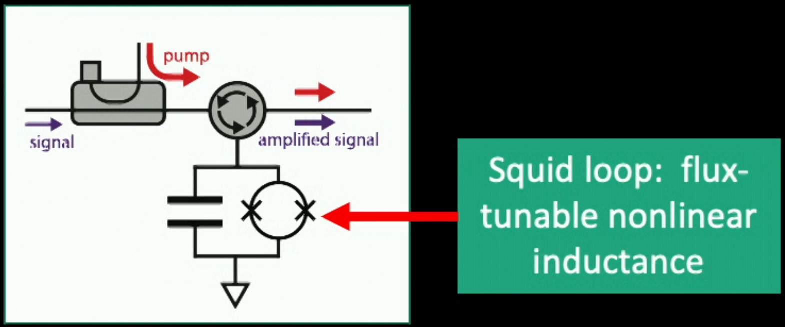

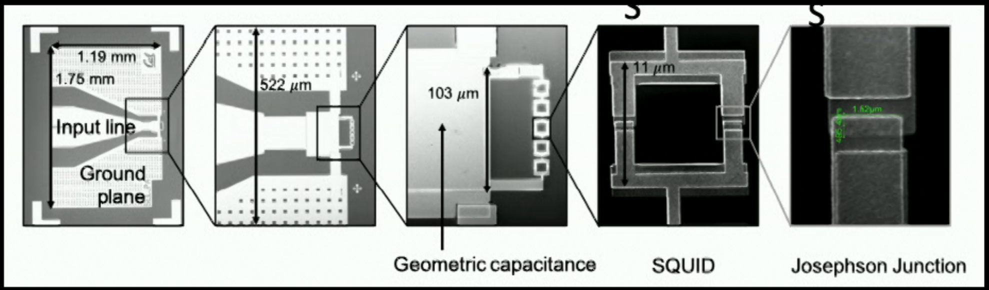

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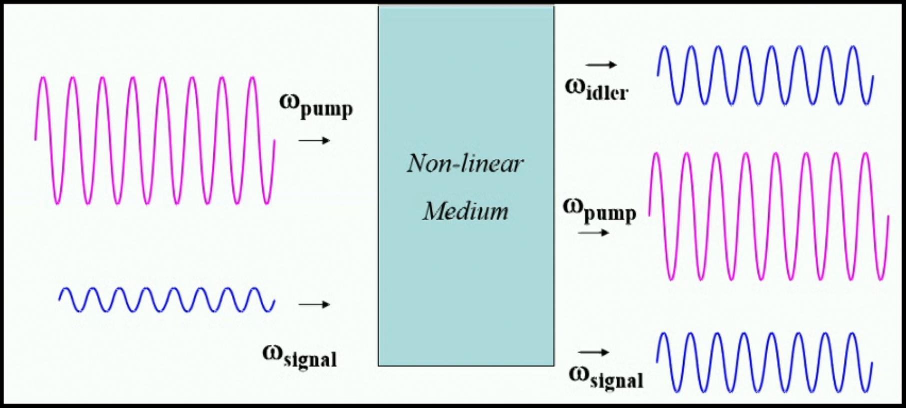


Now commercially available!

Wide-Band Josephson Parametric Amplifier (WB-JPA)

Superconducting Low-Noise Amplifier for Quantum Computing

Raytheon BBN's WB-JPA

Designed for use at millikelvin temperatures, the amplifier features over 20dB of gain with a center frequency that can be tuned with an on-chip bias line. The amplifier can be operated in either four-wave mixing, or three-wave mixing with an external bias tee.

The BBN WB-JPA is available as the only off-the-shelf component of its kind and can be easily acquired through Raytheon BBN's distributor Quantum Microwave.

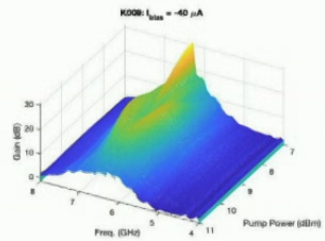
Key Capabilities

Benefits

- Improved qubit readout fidelity, reduced noise < 300 mK @ 6.8GHz
- Large bandwidth supports multi-plexed readout
- Simple tune-up and low insertion loss for easy integration with qubit experiments

Features

- Gain: 20 dB
- Tunable Center Frequency: 5.0 – 7.0 GHz

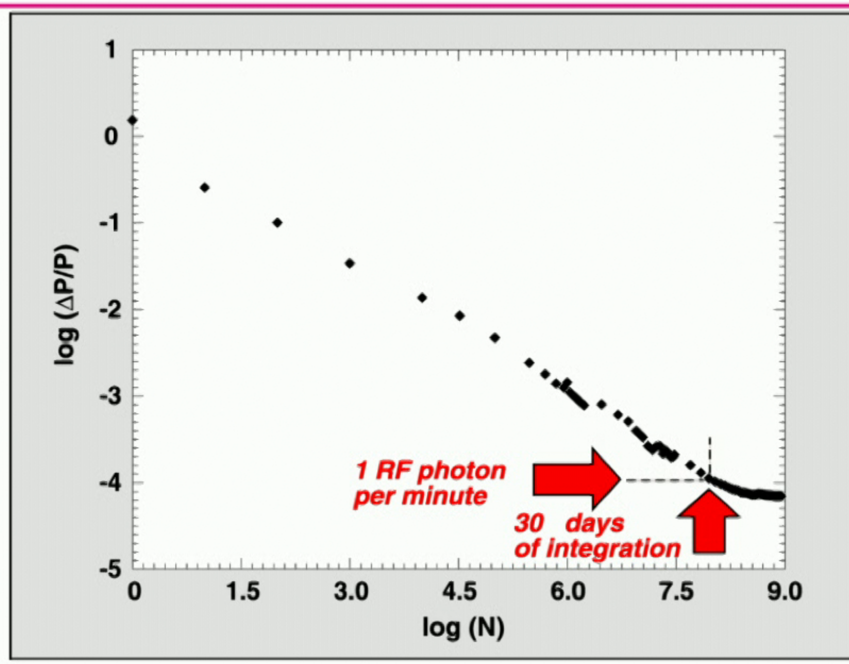


Gain Measured at 15 mK

Fast and high-fidelity qubit readout in the microwave domain

Noise reduction by averaging

World's Most Sensitive RF Receiver



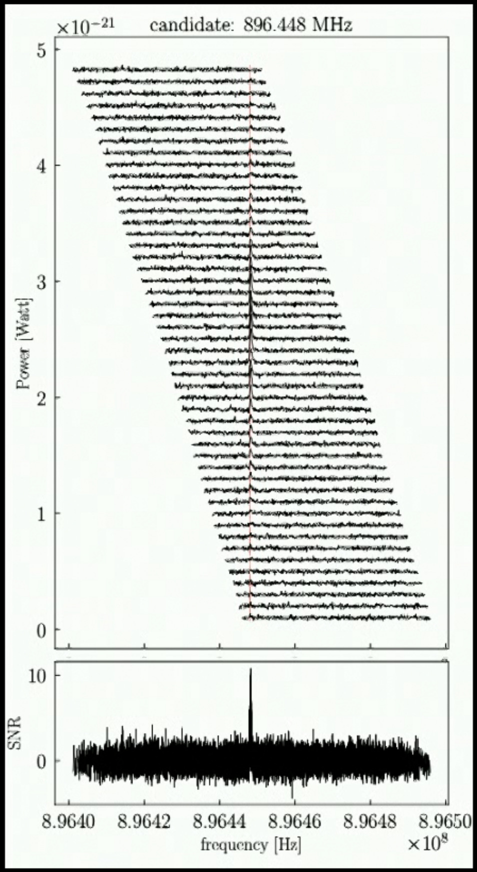
We are systematics-limited for signals of 10^{-26} W — 0.1% of DFSZ axion power!

ADMX

Operating Procedure

- The cavity frequency is scanned over a region until the desired SNR is achieved.
- Convolve with filter matched to expected axion line shape.
- ~10^6 independent measurements on each axion linewidth, averaged to reduce noise by $\sqrt{10^6}$
- Examine combined power spectrum for excess power.
- Excess power regions can be statistical fluctuations, synthetically injected signals, RF interference, or axions
- Excess power regions are rescanned to see if they persist

Calibration Signal



You might have an axion if the signal…

- Can't be seen in the room outside of the magnetic field
- Persists all the time
- Follows the Lorentzian lineshape of the cavity
- Is suppressed in non TM_{010} modes
- *Was not a synthetic axion signal injected by the calibration team*
- Scales with the B^2 of the magnet
- Has an annual frequency modulation

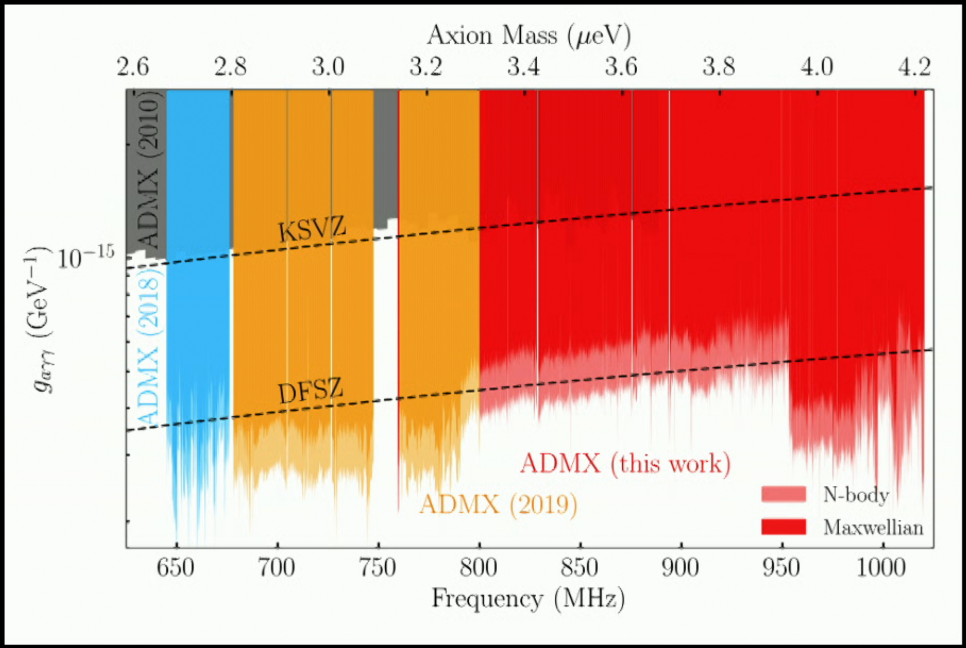
- We haven't seen any candidates which pass all these tests.

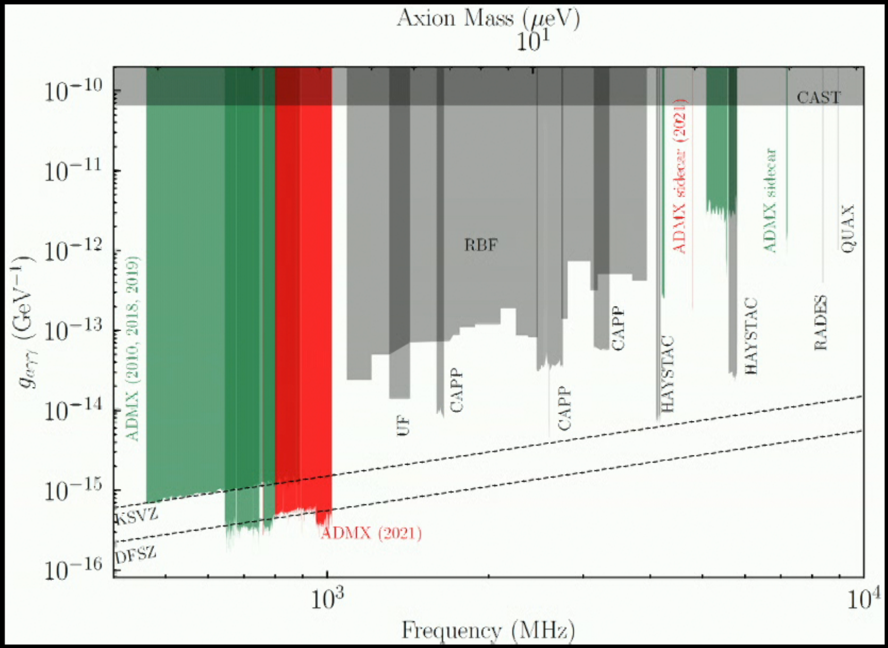
Frequency [MHz]	Persistence	At Same Frequency	Not in Air	Enhanced on Resonance
839.669	✓	×	✓	×
840.268	✓	✓	✓	×
860.000	✓	✓	×	×
891.070	✓	✓	✓	×
896.448	✓	✓	✓	✓
974.989	×	✓	✓	×
974.999	×	✓	✓	×
960.000	✓	✓	×	×
980.000	✓	✓	×	×
990.000	✓	✓	×	×
990.031	×	✓	✓	×
1000.000	✓	✓	×	×
1000.013	×	✓	✓	×
1010.000	✓	✓	×	×
1020.000	✓	✓	×	×

Blind signal injection

Bartram et al., Arxiv 2010.00169

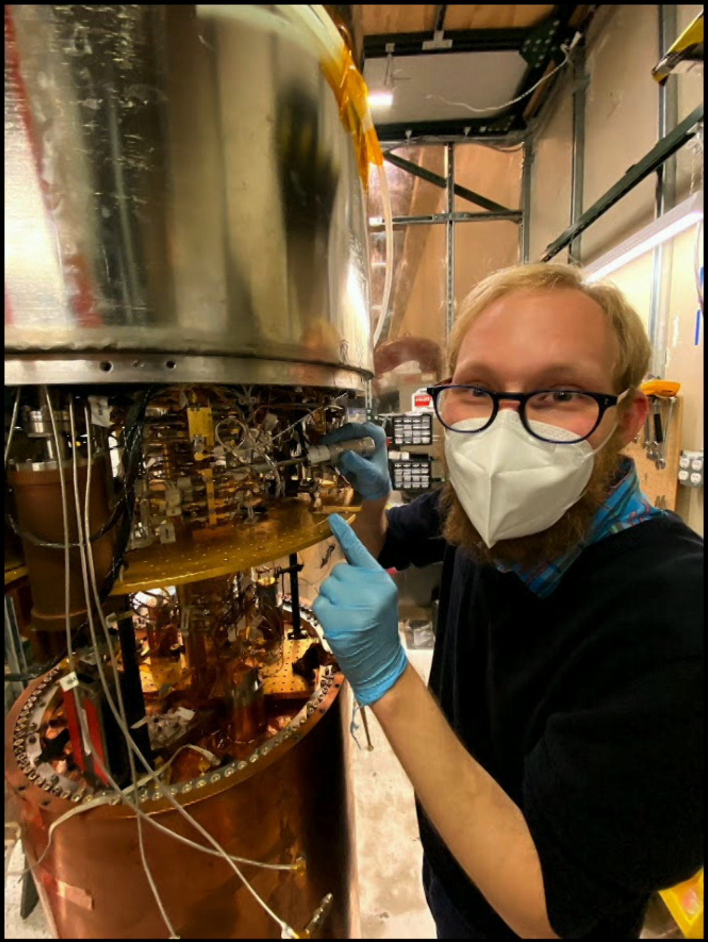
New results from 2020-2021 running





Most recent: Bartram et al., Arxiv 2010.00169

End of run– broken helium liquifier



Preparations for new run

Extension of Sensitivity to Higher Frequency

- Effective scan rate of ADMX ≈ 1 MHz/ day
- As we move up in frequency **f**,
  - Volume *per cavity* decreases as 1/**f**^{3}
  - Resonator quality factor decreases as 1/**f**$^{2/3}$
  - Noise power from Standard Quantum Limit increases as **f**.
- Need to increase number of cavities, magnetic field, Q to maintain signal power as frequency increases.

Scan Rate Vs Frequency & other parameters

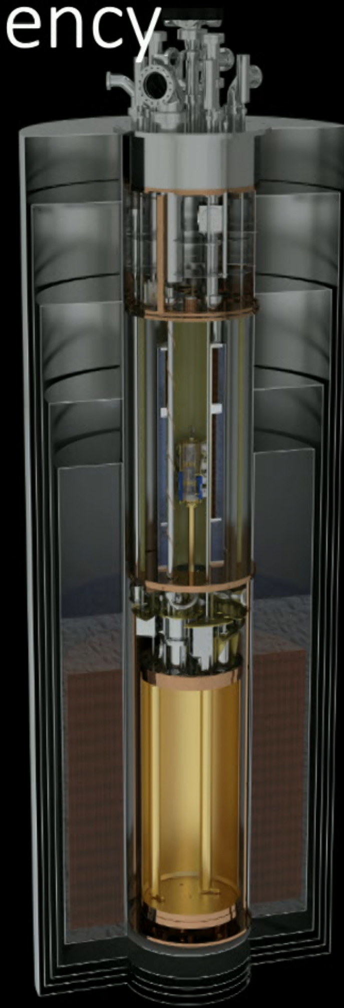
$$\frac{df}{dt} \approx 1.68\ \mathrm{GHz/year} \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \mathrm{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \mathrm{T}}\right)^4 \left(\frac{V}{100\mathrm{l}}\right)^2 \left(\frac{Q_L}{10^5}\right) \left(\frac{C_{010}}{0.5}\right)^2 \left(\frac{0.2\ K}{T_{sys}}\right)^2$$

Stronger Magnet

More Detector Volume: Array of Resonators

Higher Q: Superconducting or Dielectric Resonators

Lower Noise Amplifiers



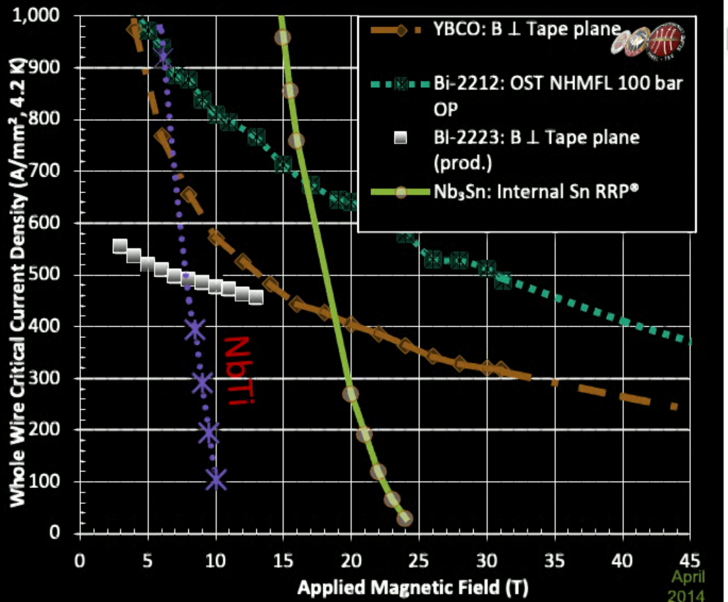
30

Magnets

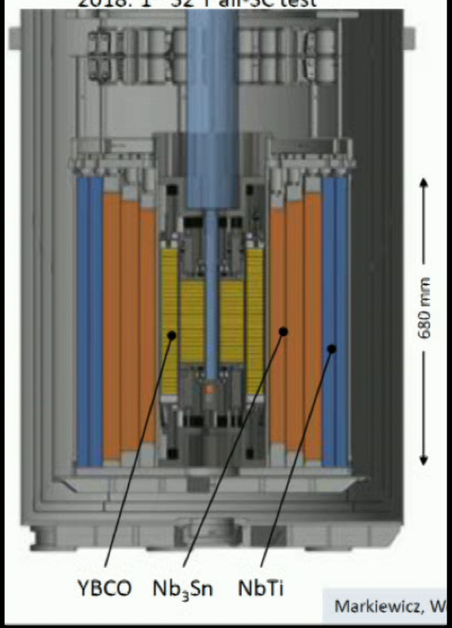
- Current ADMX magnet
  - 8.5-Tesla x 60 cm solenoid (normally operated at 7.6 Tesla)
  - Nb-Ti superconductor at 4 Kelvin
  - 25 years old-- Manufactured in 1993 by Wang NMR, Livermore CA.
- A step up to higher field requires different superconductor technology.
  - NbTi -> 10 Tesla
  - Nb_3Sn -> 15 Tesla
  - BI-2212, YBCO -> 30 Tesla or more, but technology is not yet mature.
  - 30 mm diameter magnet x 30 tesla at National High Magnetic Field Lab (Tallahassee) in 2019.
  - Meter scale 20-tesla magnet demonstrated by Commonwealth Fusion Systems in Fall 2021.

ADMX 7.6 Tesla NbTi

NHMFL 30 Tesla YBCO



2018: 1st 32 T all-SC test

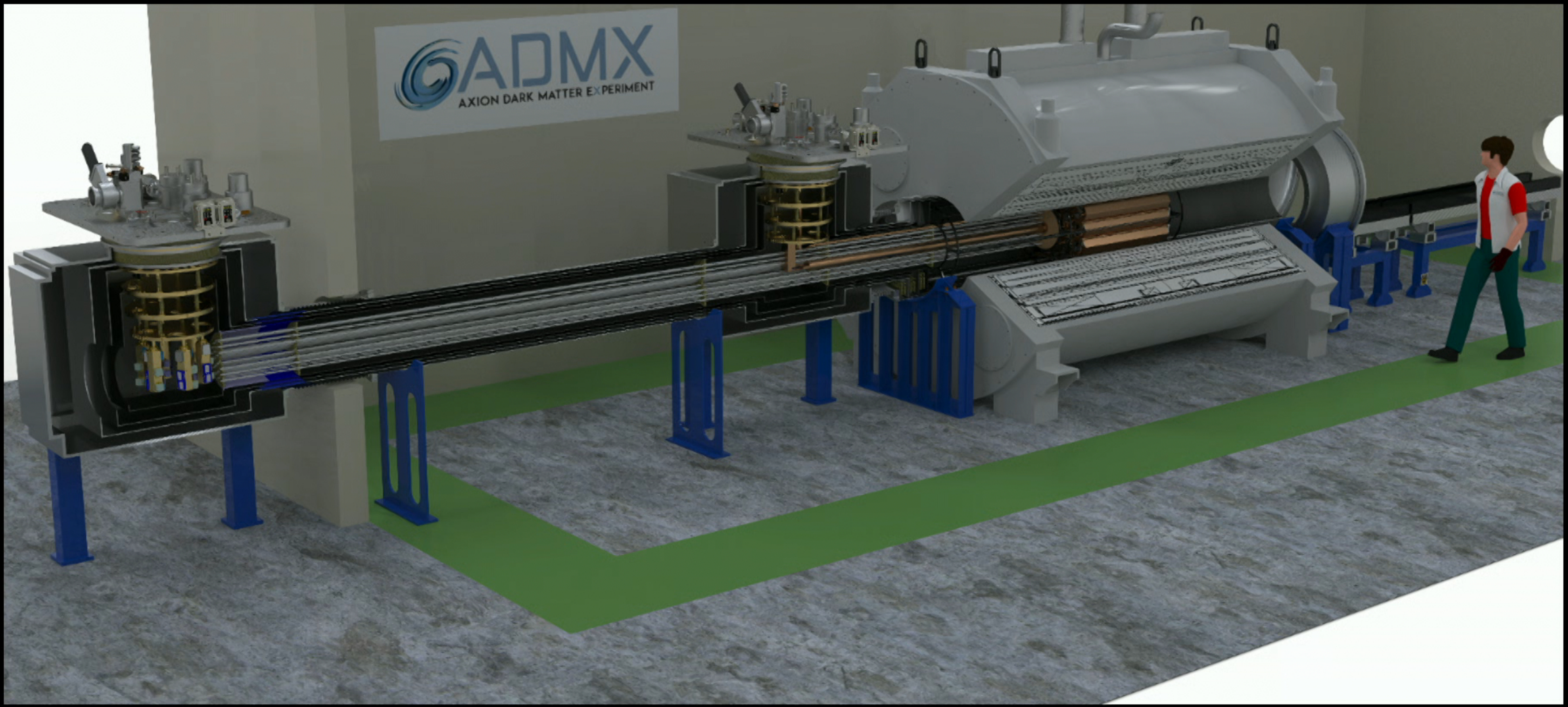


Next ADMX Magnet

- Surplus MRI magnet at University of Illinois Chicago.
- Being acquired by Fermilab for next generation of ADMX: ADMX Extended Frequency Range
- 9.4 Tesla peak field with 800 mm warm bore.
- Was the world's highest field MRI magnet in 2003. Order of magnitude more stored energy than current magnet.

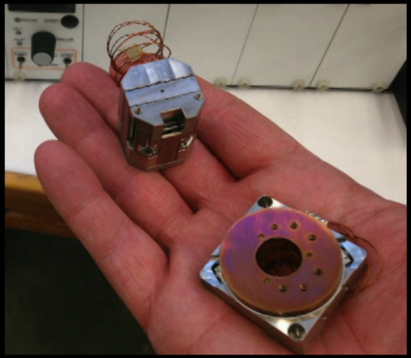
	Current ADMX	This Magnet
Peak Field	7.6 T	9.4 T
Bore diameter	530 mm	800 mm
Magnet length	1117 mm	3100 mm
Cryostat diameter	1295 mm	2580 mm
Stored Energy	16.5 MJ	140 MJ
Weight	6 tons	45 tons
Helium consumption	3 liters/ hour	0.35 liters/hour
Current	204 Amps	220 Amps
Persistent current	No	Yes
Orientation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

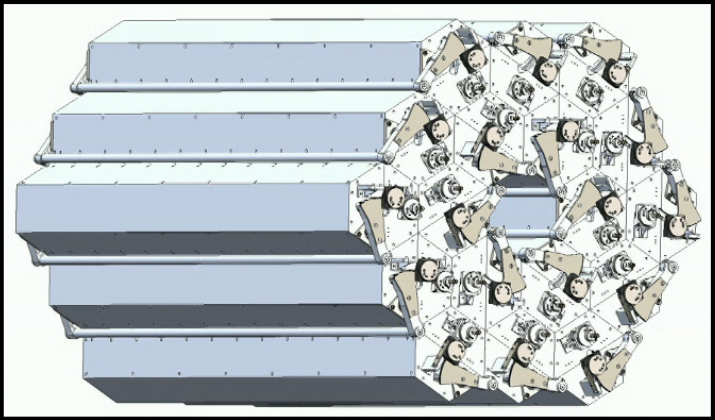
ADMX Extended Frequency Range at Fermilab ~ 2026

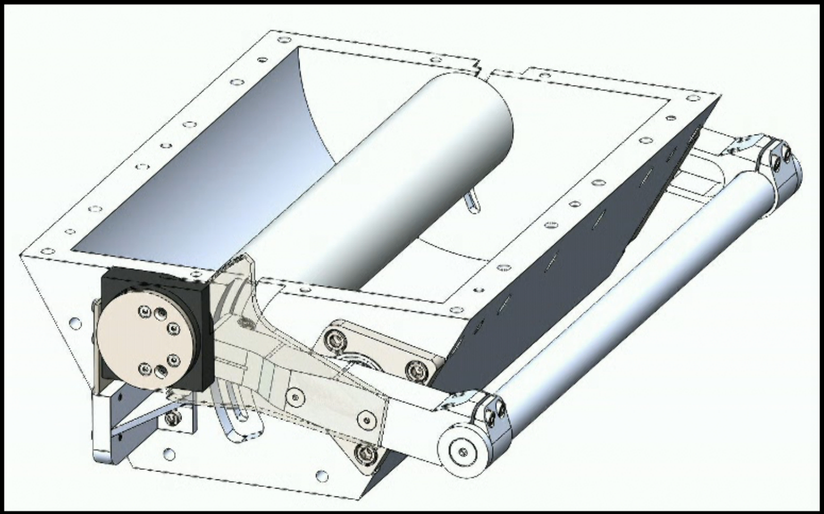


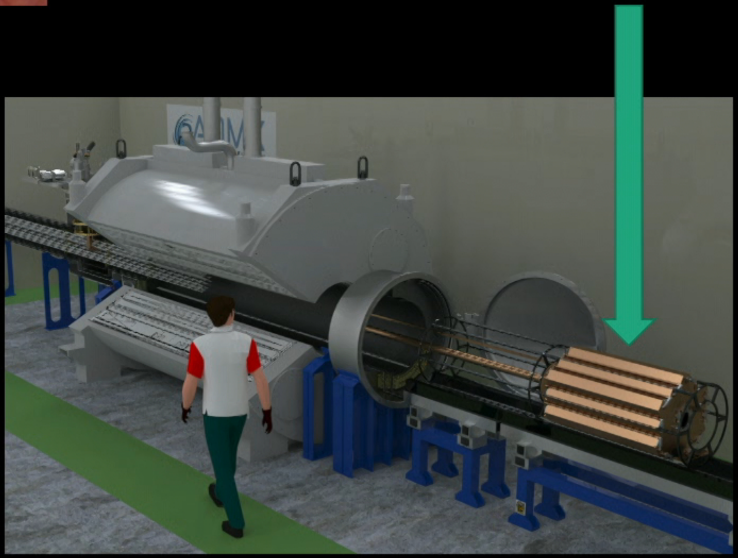
Resonators

- Hexagonally packed array of 18-cavities operating in 2-4 GHz range (8.3-16.5 μeV) with sensitivity to DFSZ axions.
- Tuned with piezoelectric actuators.



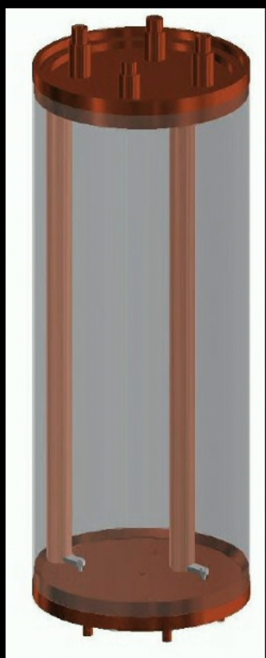






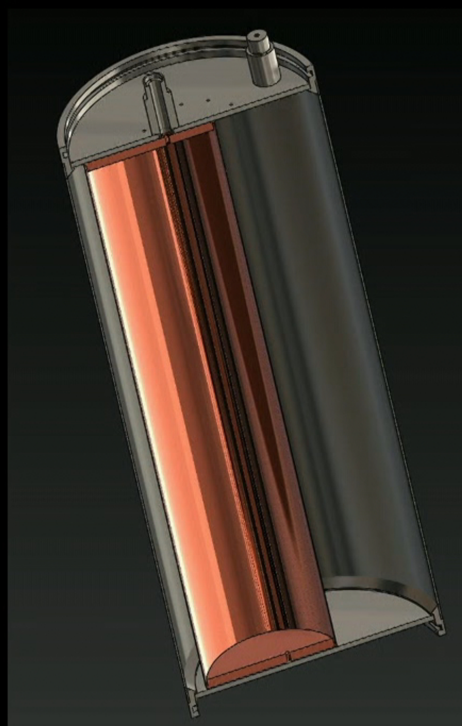
ADMX Resonators

<u>Used in 2016-2021 Runs</u>
580-1030 MHz

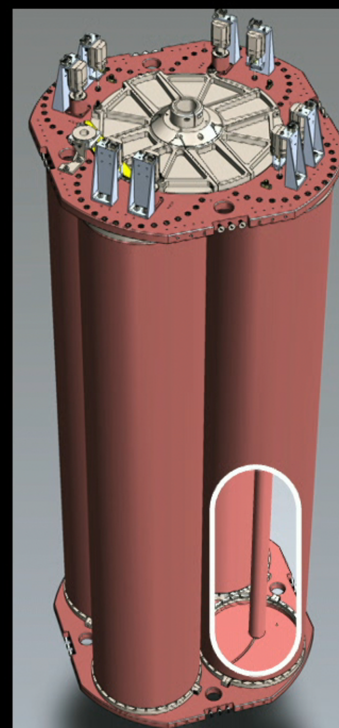


40 cm

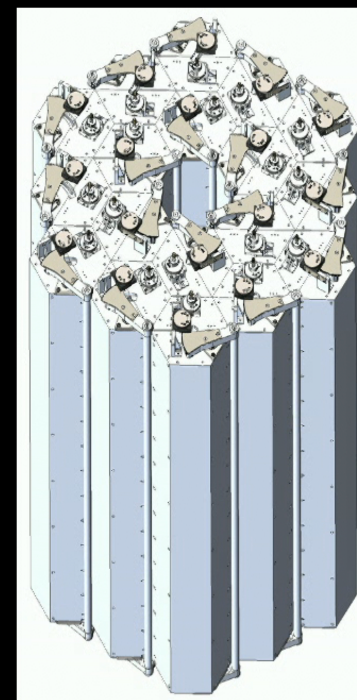
<u>2022-2023</u>
1030-1500 MHz
Large tuning rod



<u>2023-2024</u>
4-Cavity Array
8 piezoelectric actuators
1500-2300 MHz



<u>2025-2027?</u>
18-Cavity array for MRI magnet
2300-4000 MHz

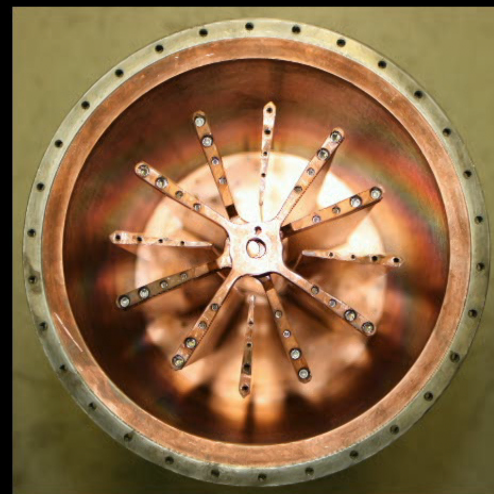


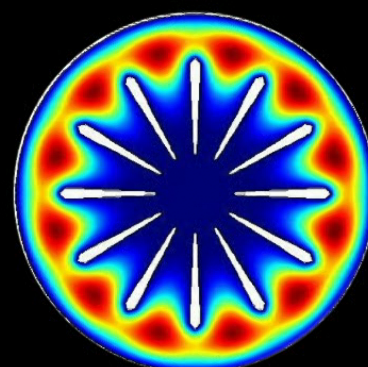
68 cm

R&D Towards Large Volume, High Frequency Resonators

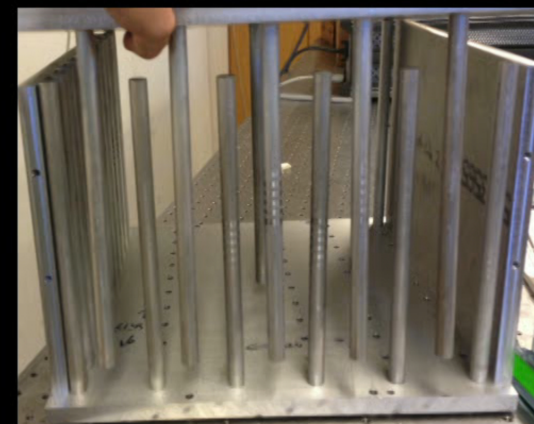
- Challenging to fill a large volume with small tunable structures ("Swiss Watch" problem)
- Number of elements goes as f^3
- Explore systems that allow simultaneous tuning of many elements with only a few mechanical motions.
  - Photonic bandgap cavity
  - "Comb Cavity"
  - Electronic fine tuning using nonlinear dielectrics

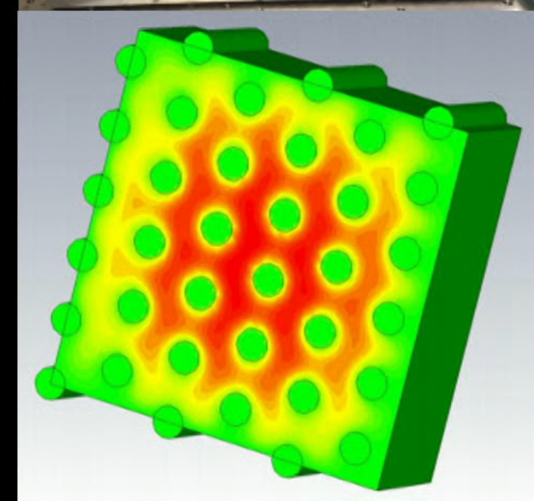
Comb cavity (FNAL)





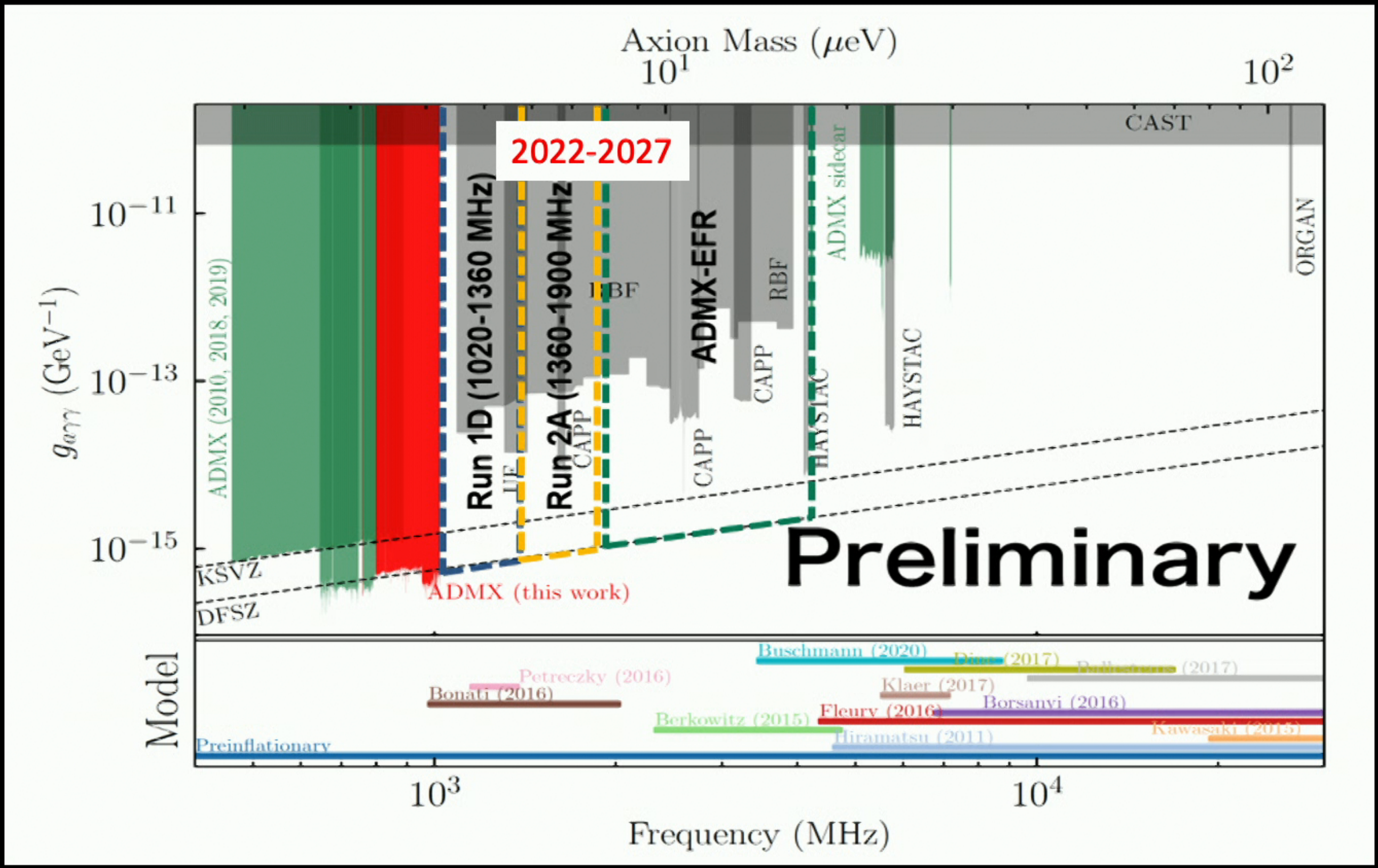
"Pizza" Cavity (U. Florida)



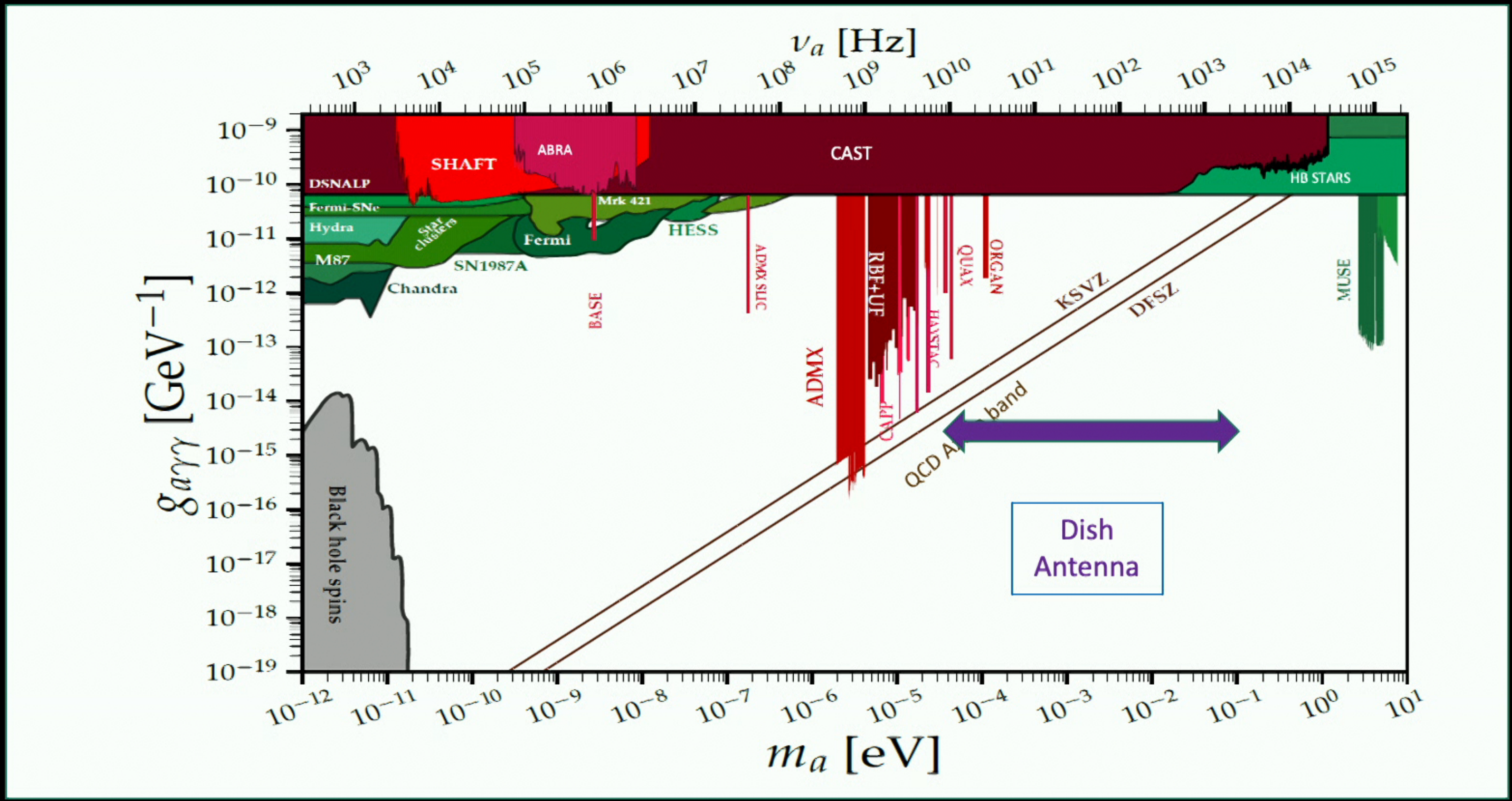


Array of posts (LLNL)

ADMX Future Sensitivity

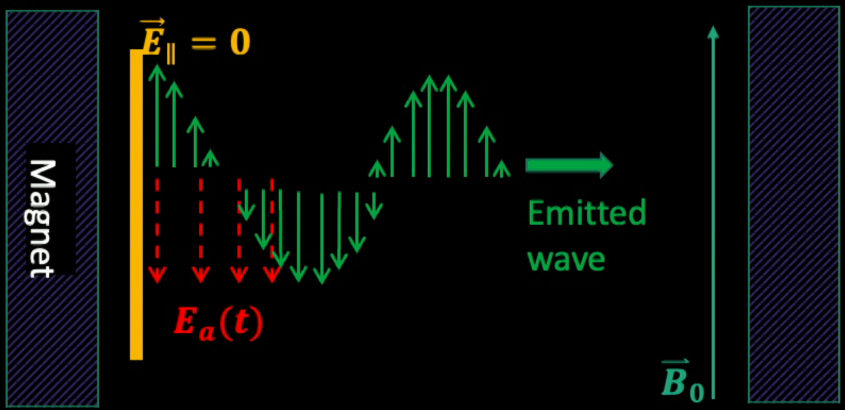


Complementarity of Detection Techniques



Axion Induced Radiation from A Magnetized Metal Slab

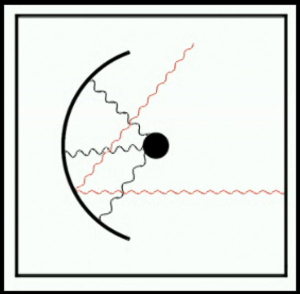
- Axions interact with a static magnetic field producing an oscillating parallel electric field in free space
- A conducting surface in this field emits a plane wave perpendicular to surface.



- 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!

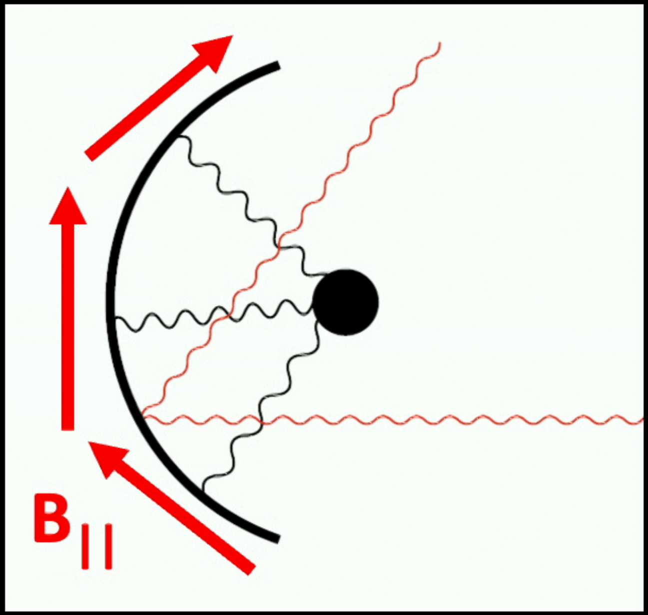


"Dish antenna" (Horns et al., 2012)

Magnetic Field Configuration

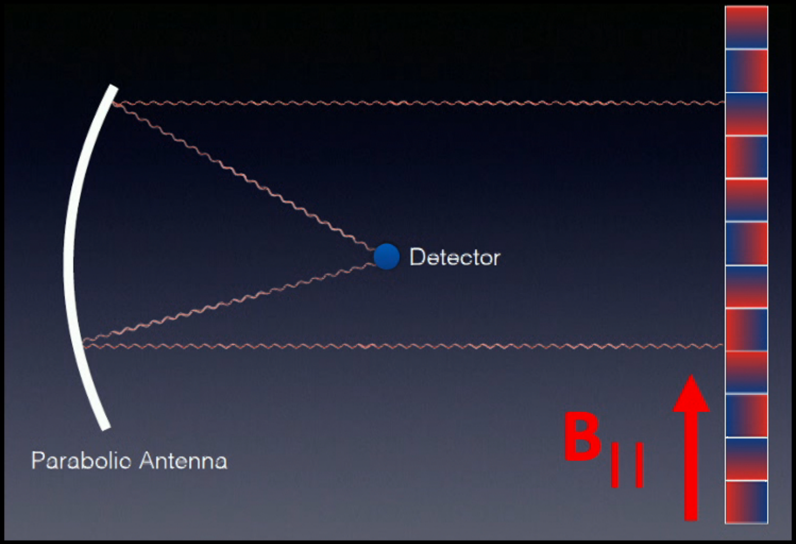
- Need to maximize component of magnetic field parallel to radiating surface $B_{||}$
- Spherical dish geometry not a good match to conventional magnet types.

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



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

BRASS experiment: Planar array of permanent magnets



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

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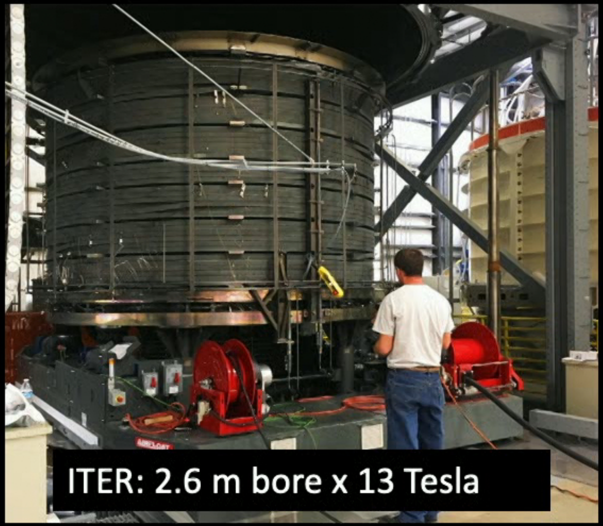
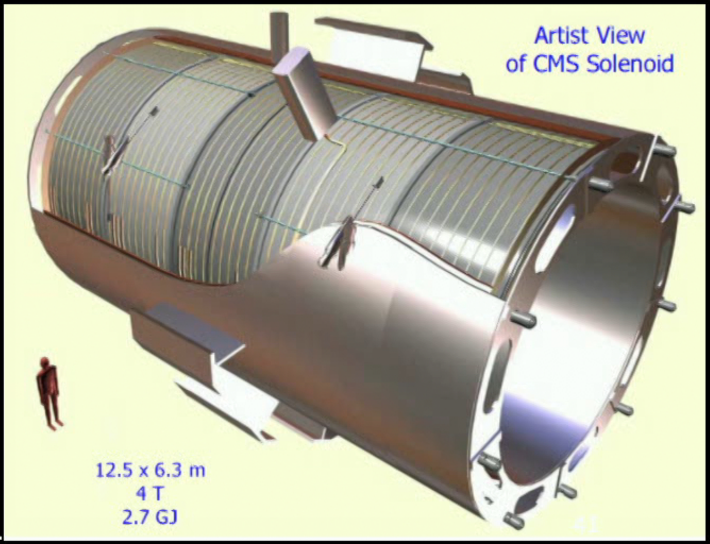
Large Solenoids

- How to use large volume solenoids to detect axions?

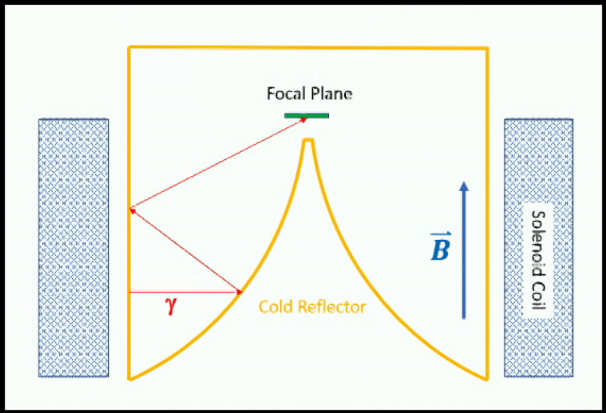
B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*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

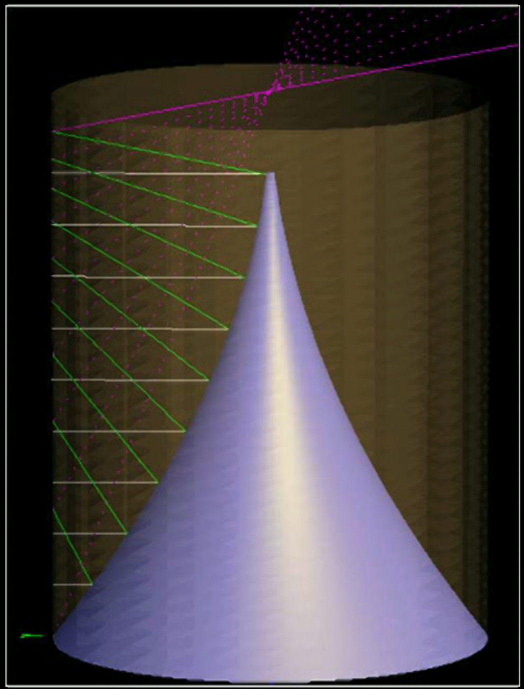

ITER: 2.6 m bore x 13 Tesla

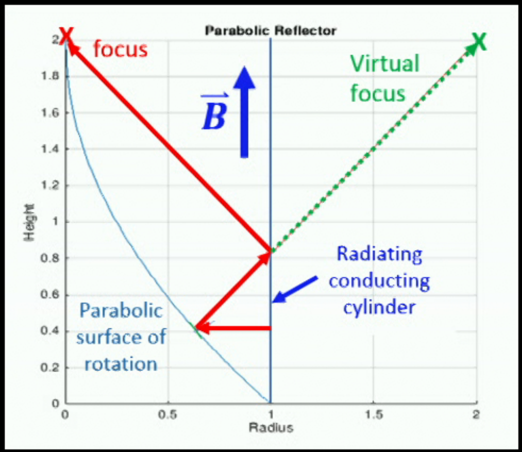


Compilation by Mark Bird, NHMFL

"Coaxial Dish": Optical Concentrator for Solenoid Magnets

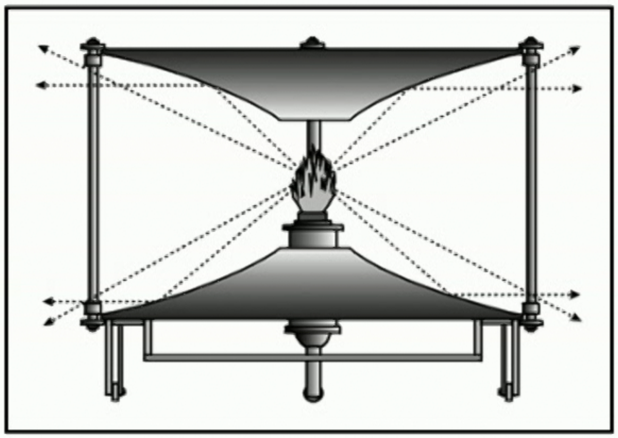






- Rays emitted from cylindrical inner surface of solenoid are focused to a point after two reflections.

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

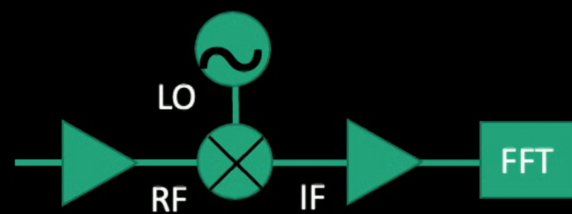
Three Types of Experiment

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)

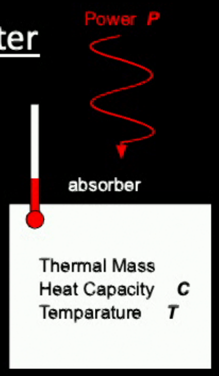
   $$T_{noise} = hf/K_b$$

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



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Three Types of Experiment

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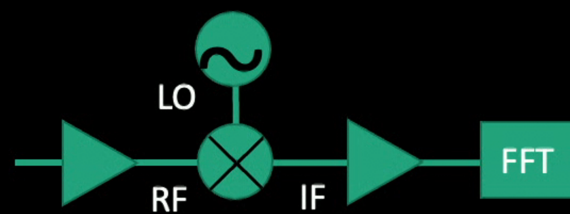
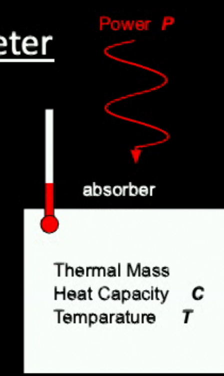
Heterodyne detection



Bolometer



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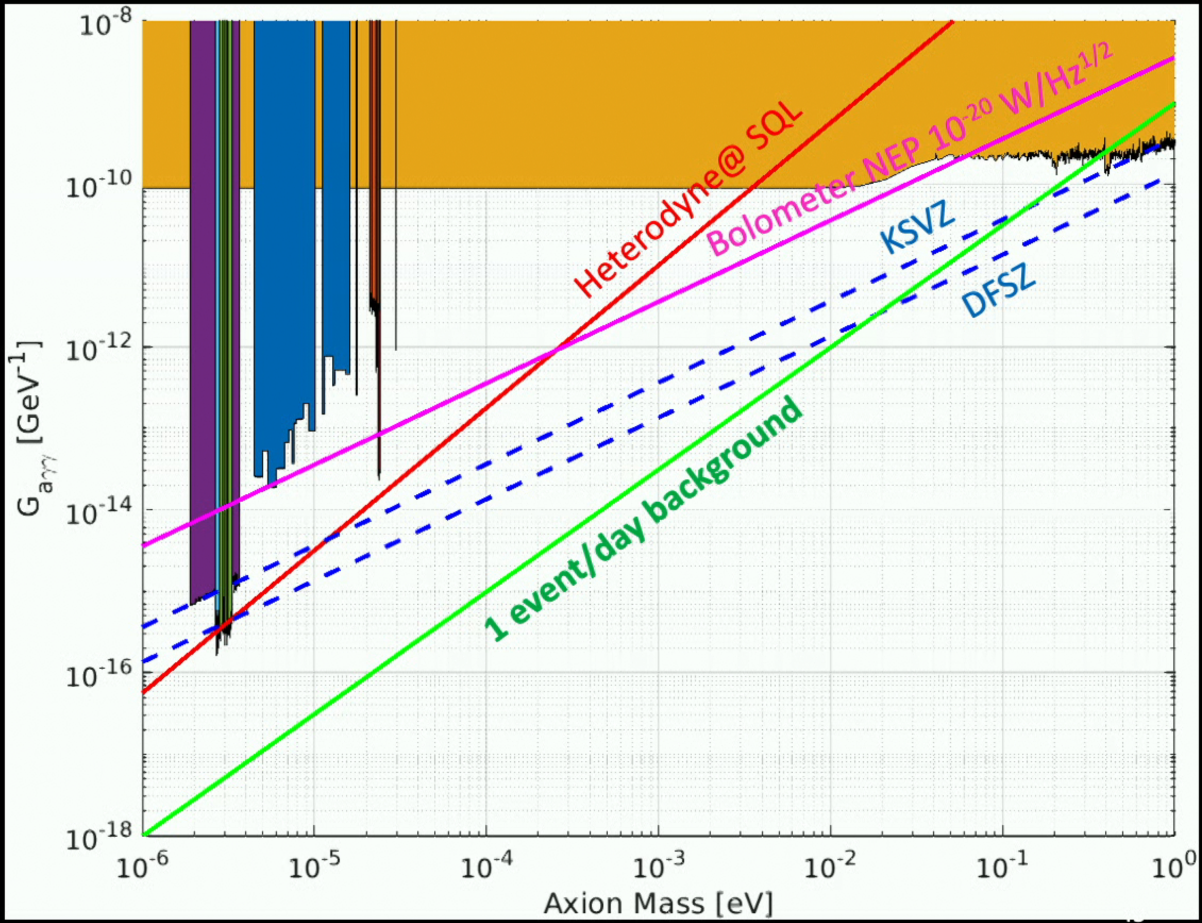
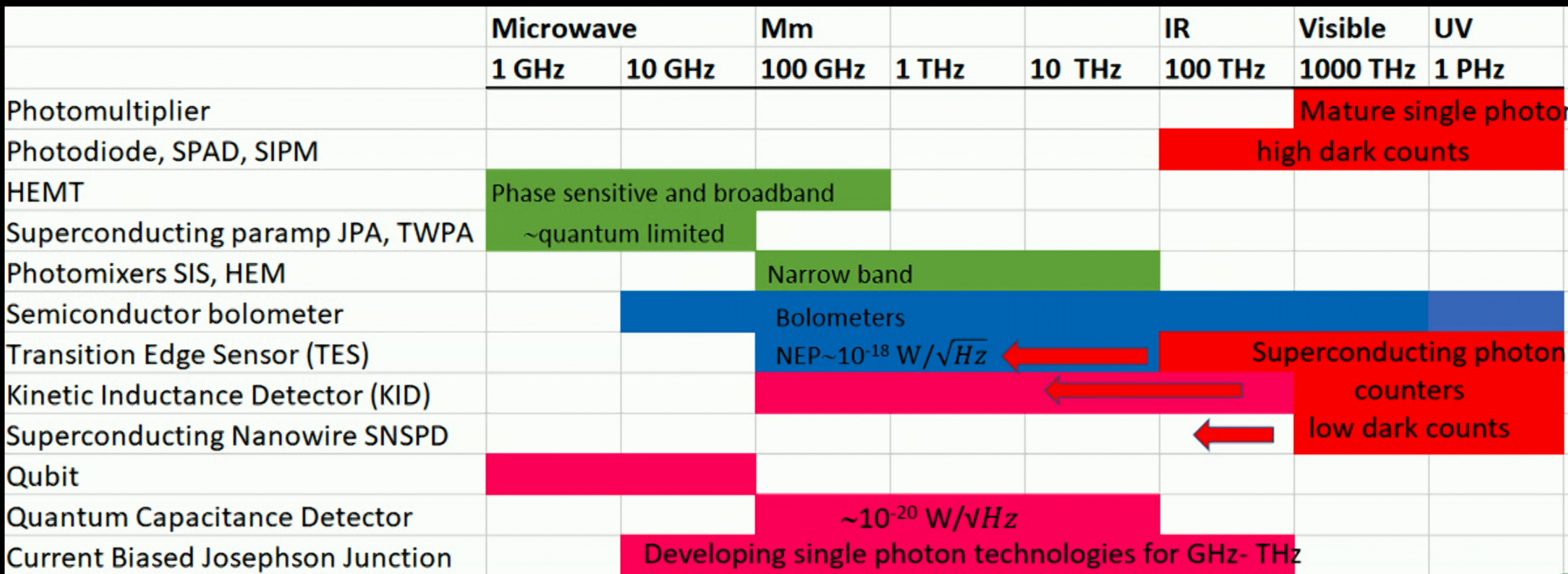
Sensitivity

- 10 m² x (10 T)² radiator
- 100-day integration time



Single Photon Detectors



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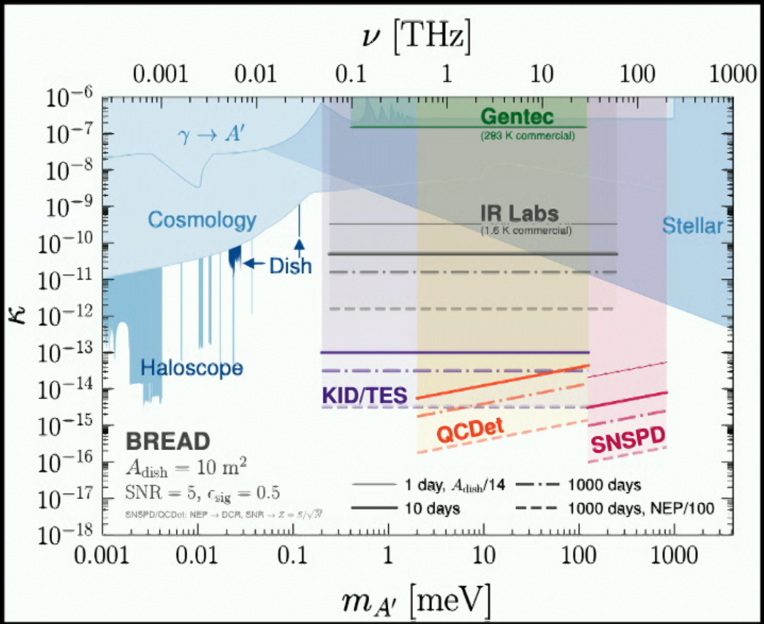
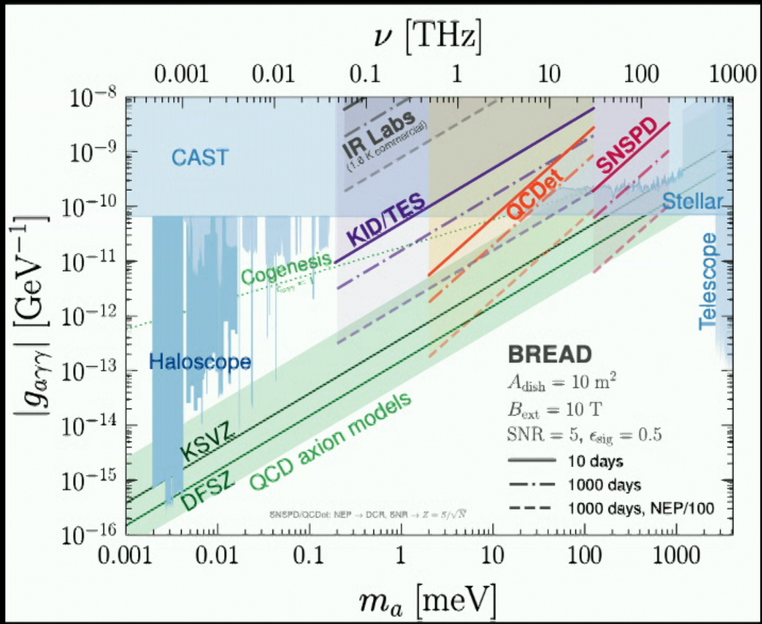
Sensitivity Projections for Various Sensors

Hidden Photons

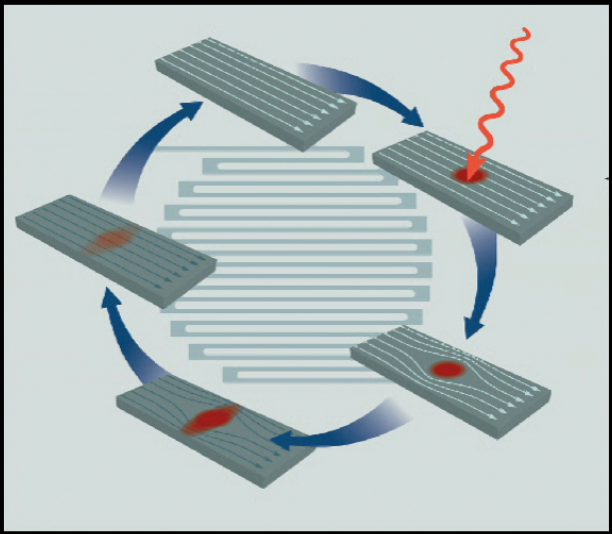


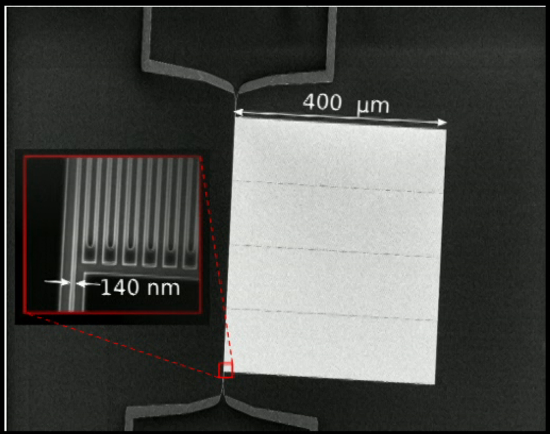
Axions

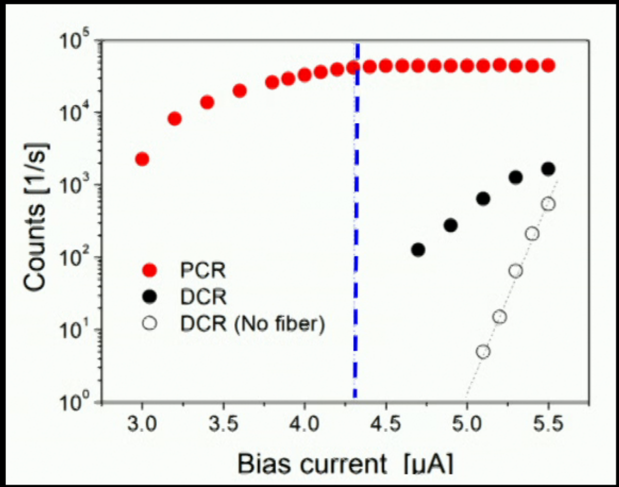


[Liu *et al*, BREAD collab.,
arXiv:2111.12103, PRL 128 (2022) 131801]

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







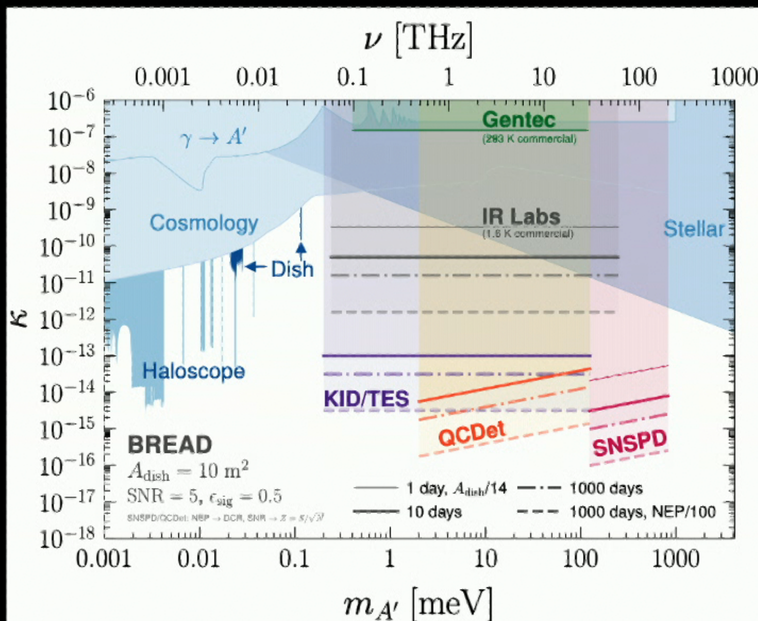
- Based on WSi thin film from Varun Verma, NIST
- Detector fabricated by Ilya Charaev, MIT
- 400 x 400 μm^2 area
- Illuminated with 1550nm light

Figures from Sae Woo Nam (NIST)

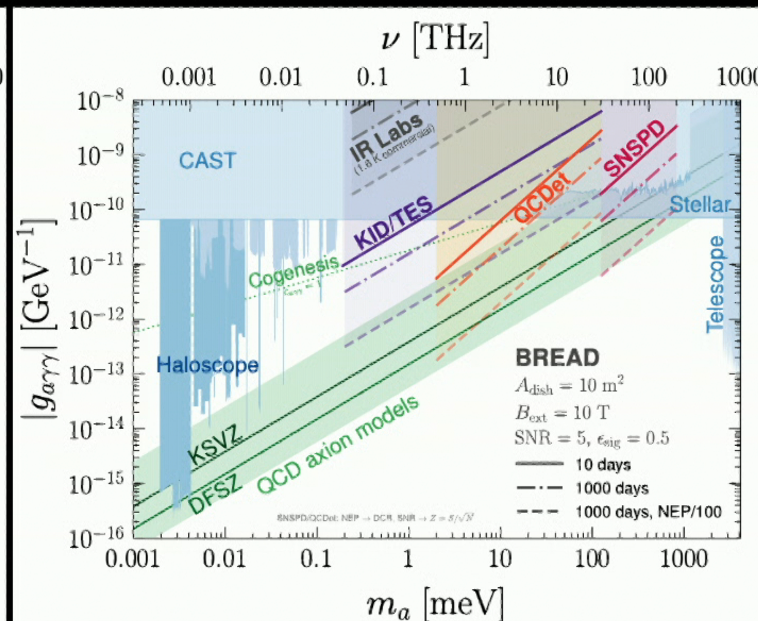
See "Detecting Dark Matter with Superconducting Nanowires", Yonit Hochberg et al., PRL 123 (2019)

Sensitivity Projections for Various Sensors

Hidden Photons



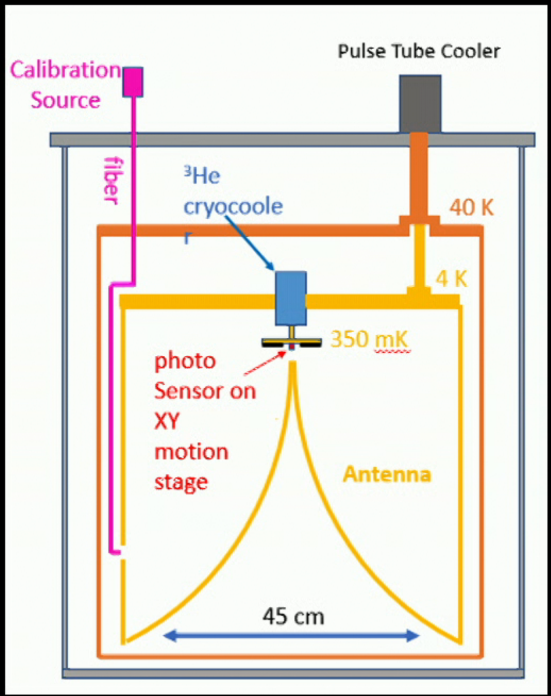
Axions

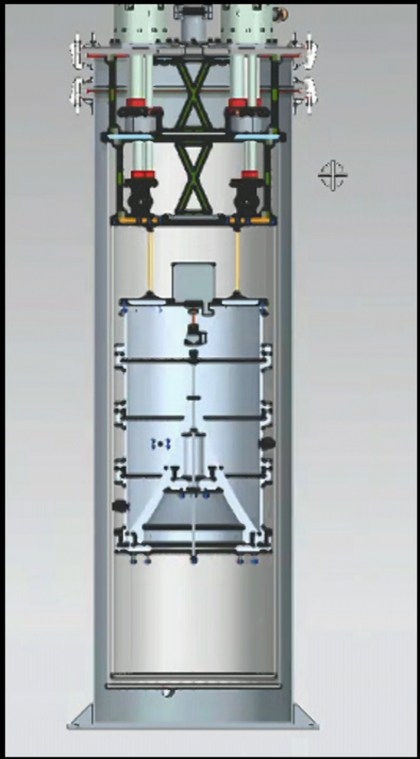


[Liu *et al*, BREAD collab.,
arXiv:2111.12103, PRL 128 (2022) 131801]

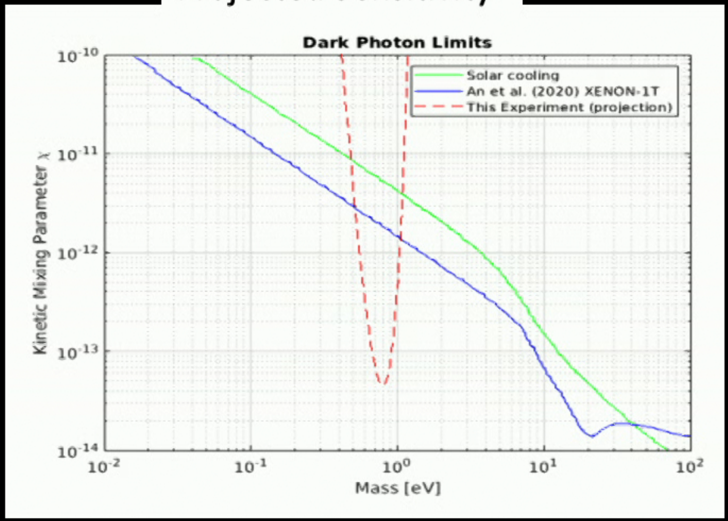
InfraBREAD- Dark Photon Search with SNSPDs

- Dark photon dark matter search– similar to axions but no magnet needed.
- Photon counting experiment with SNSPD device from MIT operating in near infrared ~(1-2 microns)



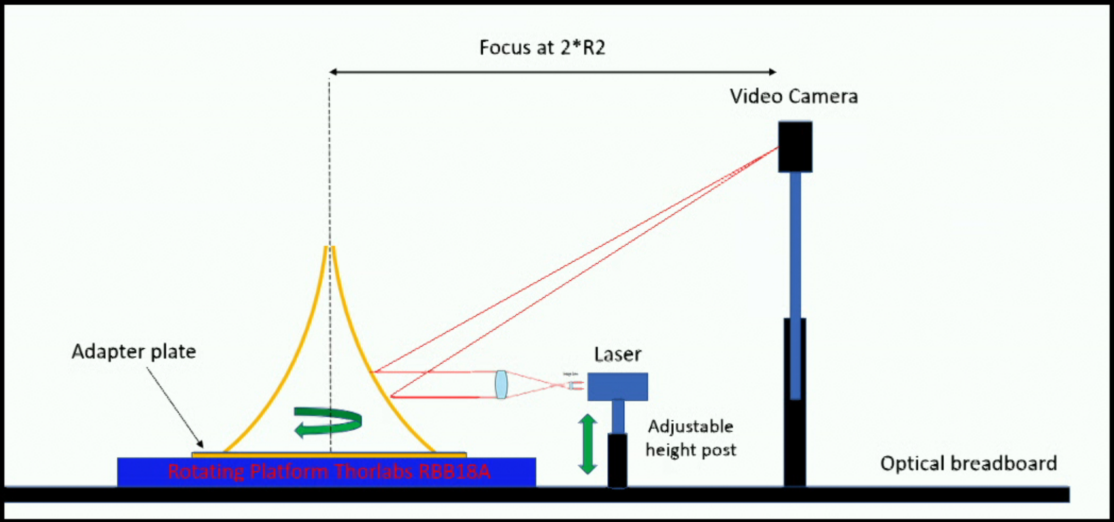


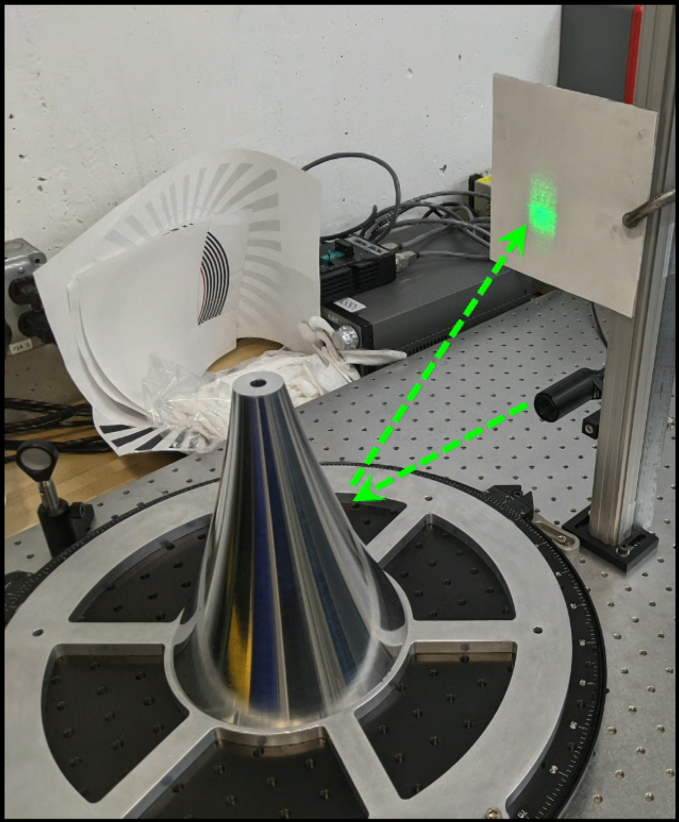
Projected Sensitivity



Optical Characterization of Focal Properties

- Directly measure focal properties of reflector using a laser and rotating platform.
- Clearly shows inadequacy of conventional machining processes for obtaining optical surfaces.
- Tests of hand polishing to smooth the surface didn't improve the situation– it's not trivial to make a good mirror!





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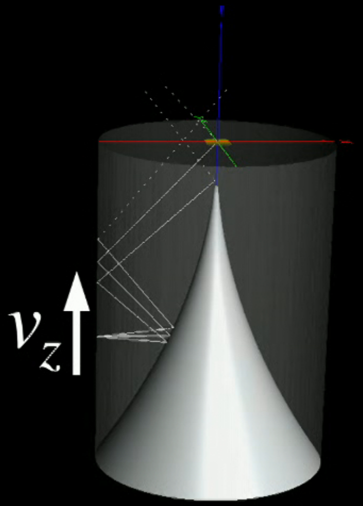
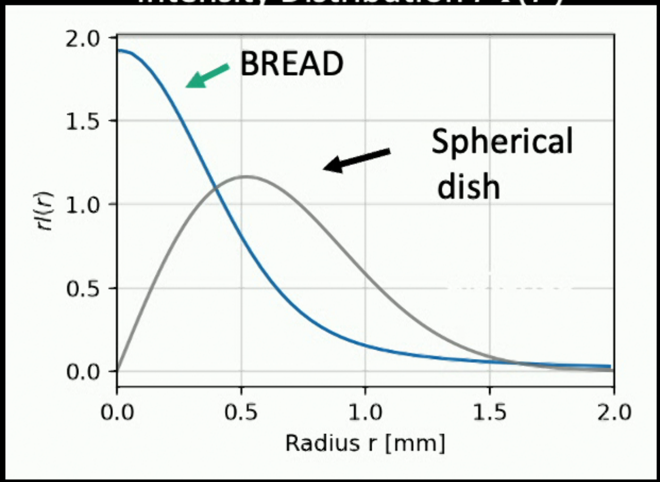
Mechanical Tolerancing

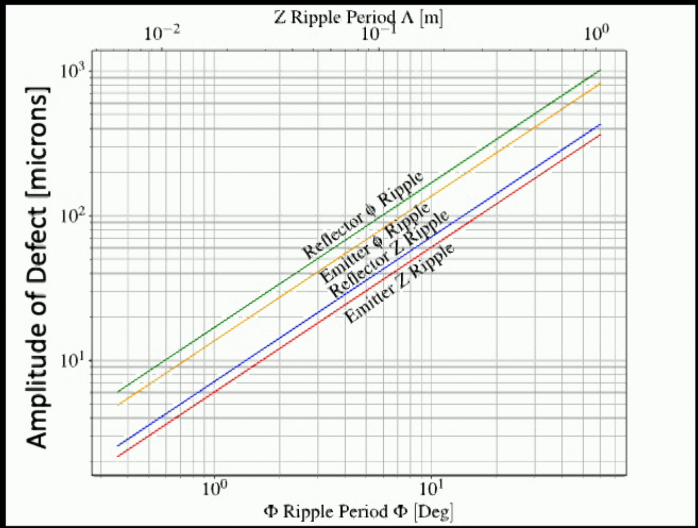
- Ray tracing studies were used to determine mechanical tolerances.
- Dark matter velocity dispersion limits focal spot to ~ 1 mm^2
- Requires few micron surface accuracy and smoothness on short distance scales to preserve 1 mm focusing and minimize sensors size.
- We studied effect of sinusoidal "ripple" defects in the optical geometry to determine maximum allowed fabrication errors.



100x exaggerated velocity effect

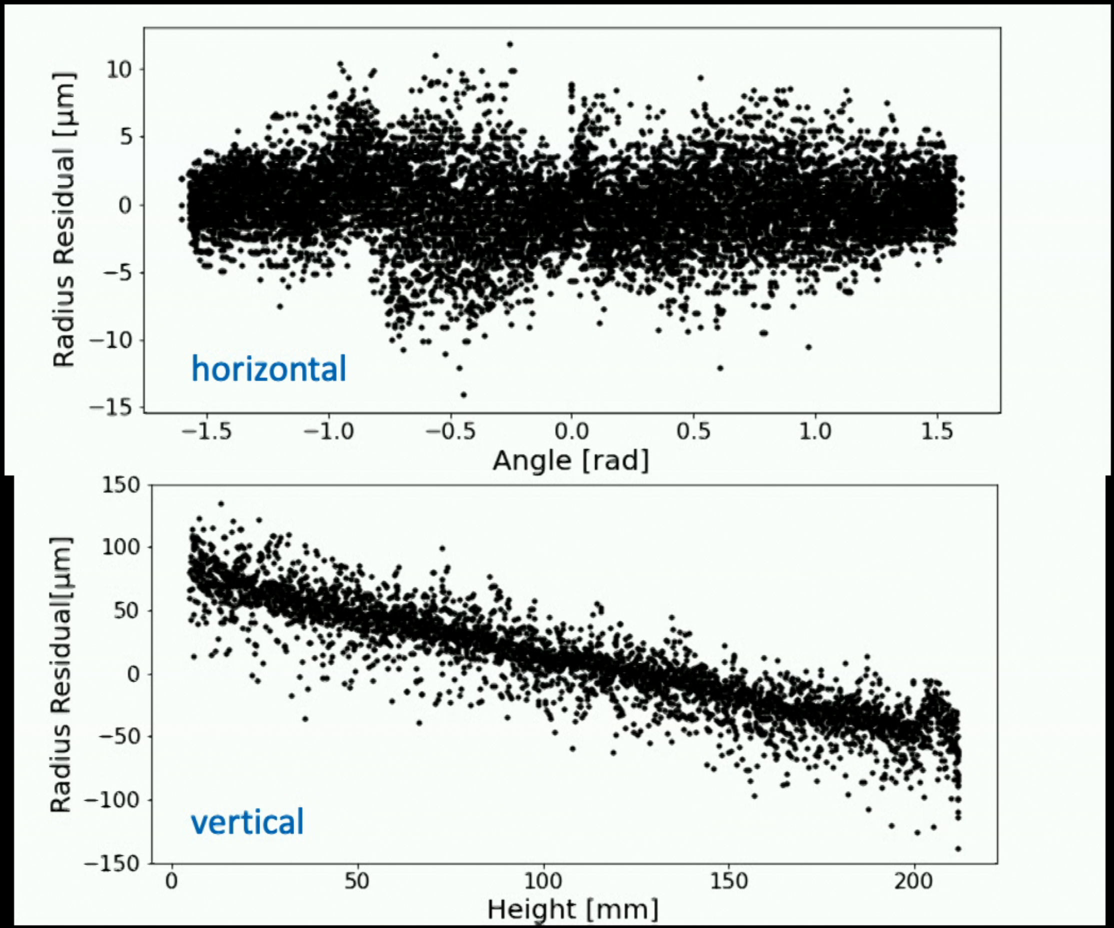
Intensity Distribution $r\,I(r)$





First Prototype Reflector – Coordinate Measuring Machine

Mechanical Touches



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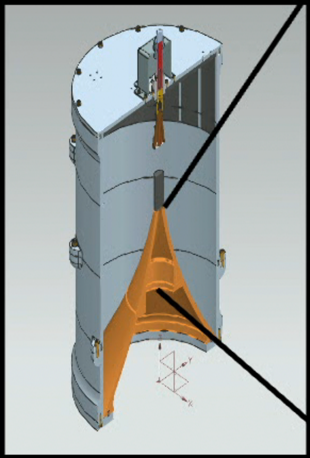
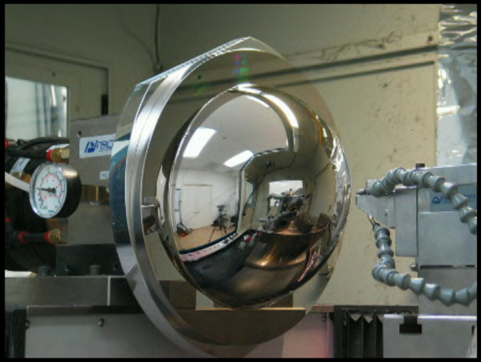
Single Point Diamond Turning of Aluminum Optics

- In industry, high-precision lathes with diamond cutting tools are used to fabricate metal reflecting optics.
- Process is commonly used for mirrors with shapes that are too difficult to produce by grinding glass or ceramics.
- Also used for optics that need to be cryogenically cooled.
- Can achieve <100 nm precision on aluminum, with sizes up to 1-meter (much better than we need)
- BREAD optical will be fabricated at Lawrence Livermore National Lab.
- Requires five segments in longitudinal direction for a 400 mm reflector.




$R = 20\ \mathrm{cm}\ \ (A = 0.7\ \mathrm{m}^2)$

- Precitech NanoForm 350UPL at LLNL will be used for the BREAD reflectors



Diamond turning of aluminum mirror at NiPro Optics (not a BREAD part but similar)

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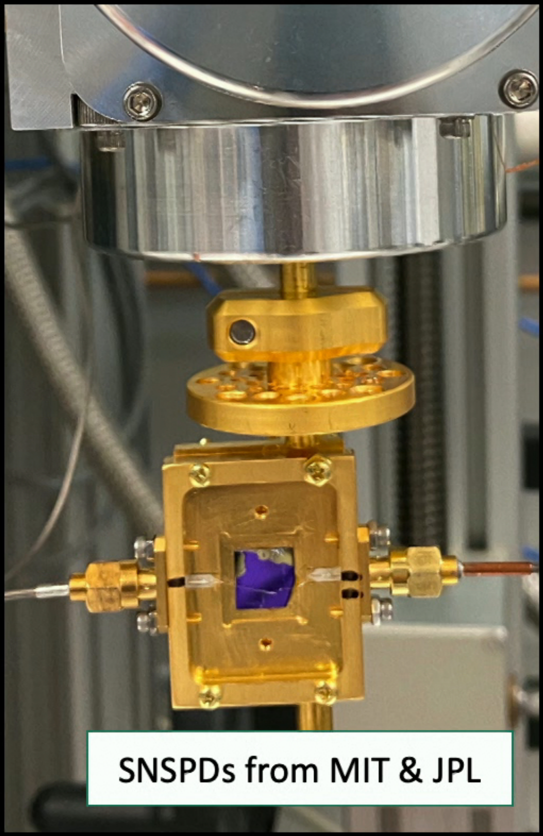
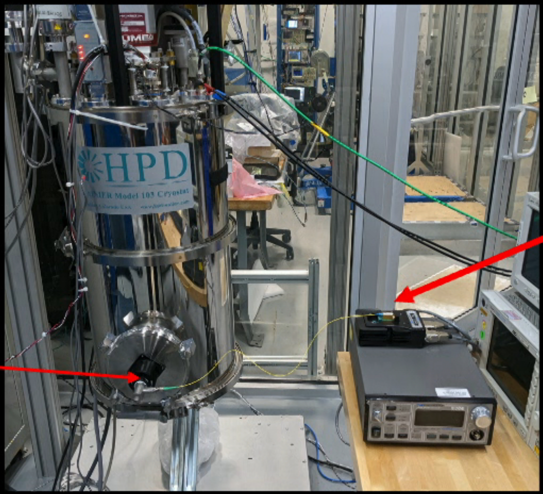
Superconducting Nanowire (SNSPD) Tests for BREAD



Adiabatic Demagnetization Refrigerator cools to <800 mK



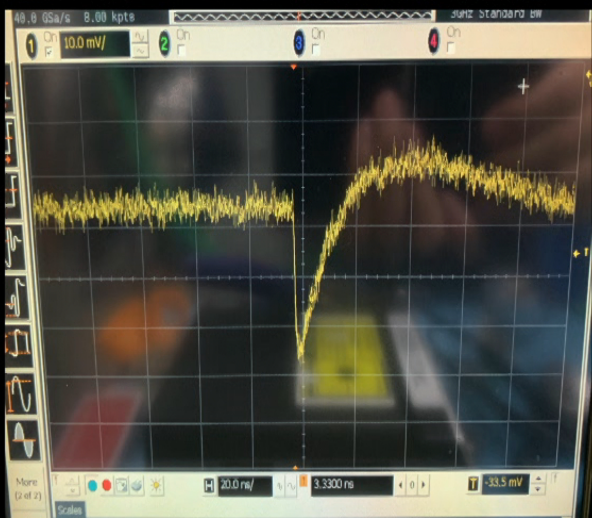
Optical fiber
Couples to reflective
collimator on cryostat

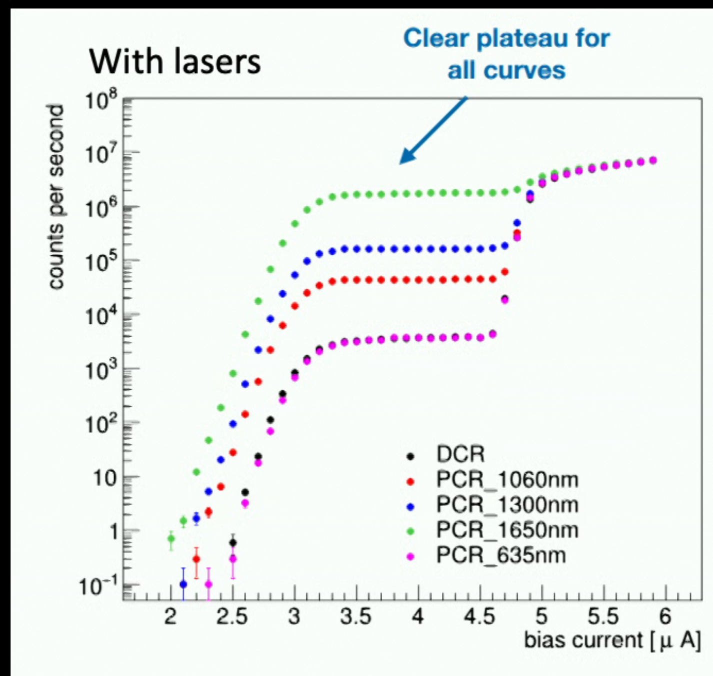
Laser
Diodes
635 nm
1060 nm
1300 nm
1650 nm

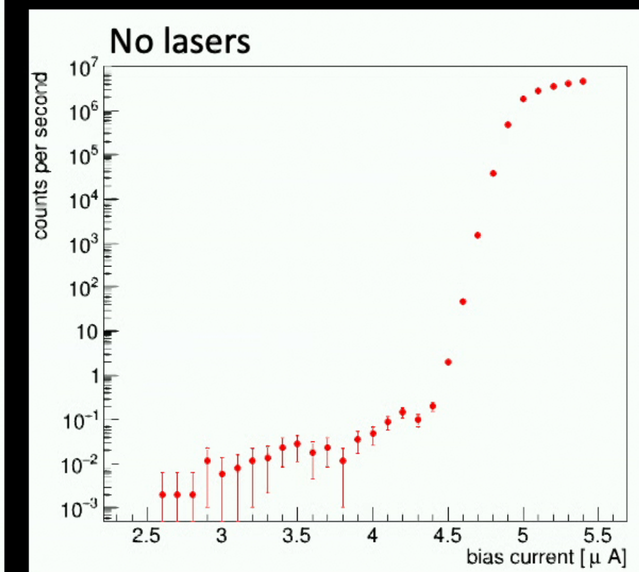
First Data from a JPL SNSPD

- Measured Photon Count Rate of JPL device with lasers (PCR) and dark counts when lasers are turned off (DCR)
- Initially very high dark counts--- Light leaks produce 10^3 counts per second
- With additional light shielding at 70 Kelvin, DCR is reduced by 5 orders of magnitude to 10^{-2} cps
- Expect further progress with attention to light leaks – state of art is 10^{-5} cps

A pulse!







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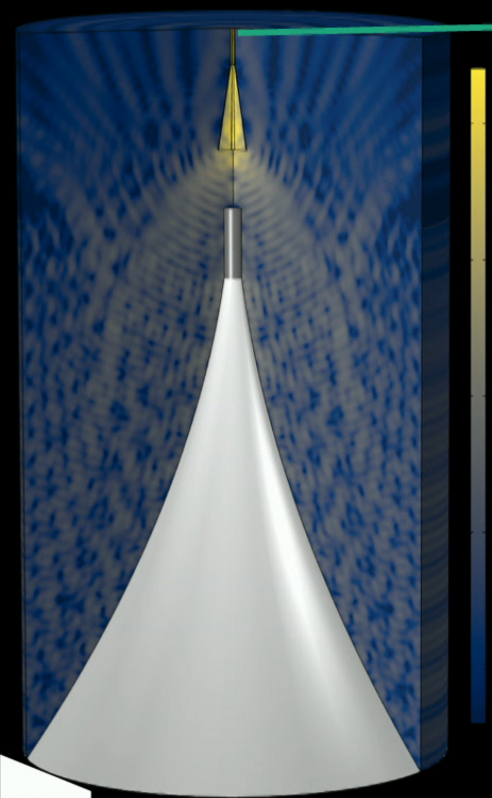
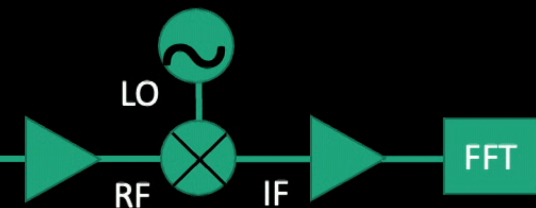
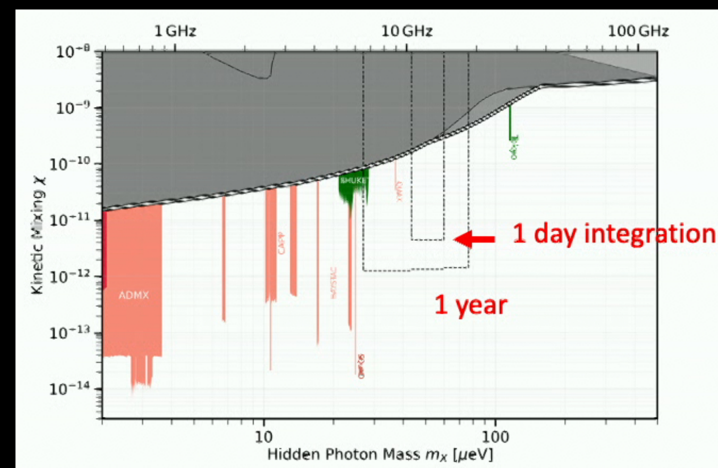
GigaBread– Microwave Frequency Search

- Heterodyne detection with a commercially available low-noise HEMT amplifier
- 40 – cm reflector (prototype for optical setup)
- 10-20 GHz frequency range
- FPGA based data acquisition allows 4 GHz instantaneous bandwidth.
- Initially at room temperature
- Start with dark photon search (no magnet)
- Can be upgrades to search for axionlike particles by placing in a magnet.

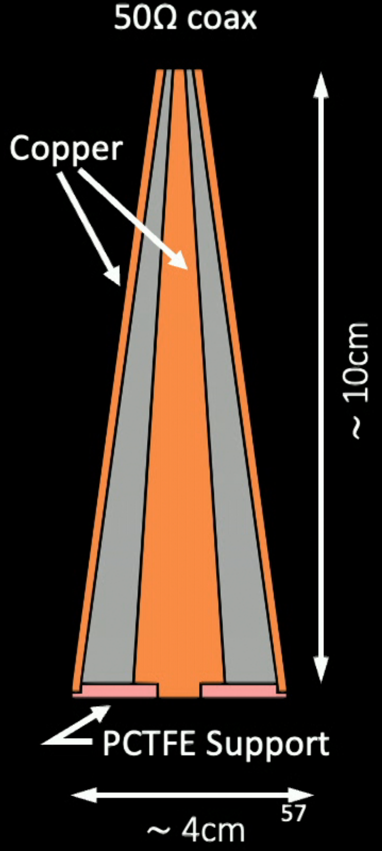






Coaxial Horn

- Non-standard horn antenna needed to couple free-space dark photon/ axion signal into a 50-Ohm coax cable.



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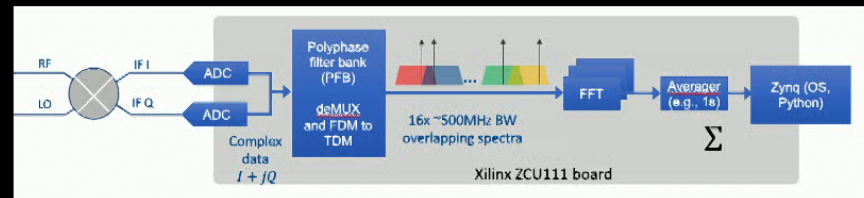
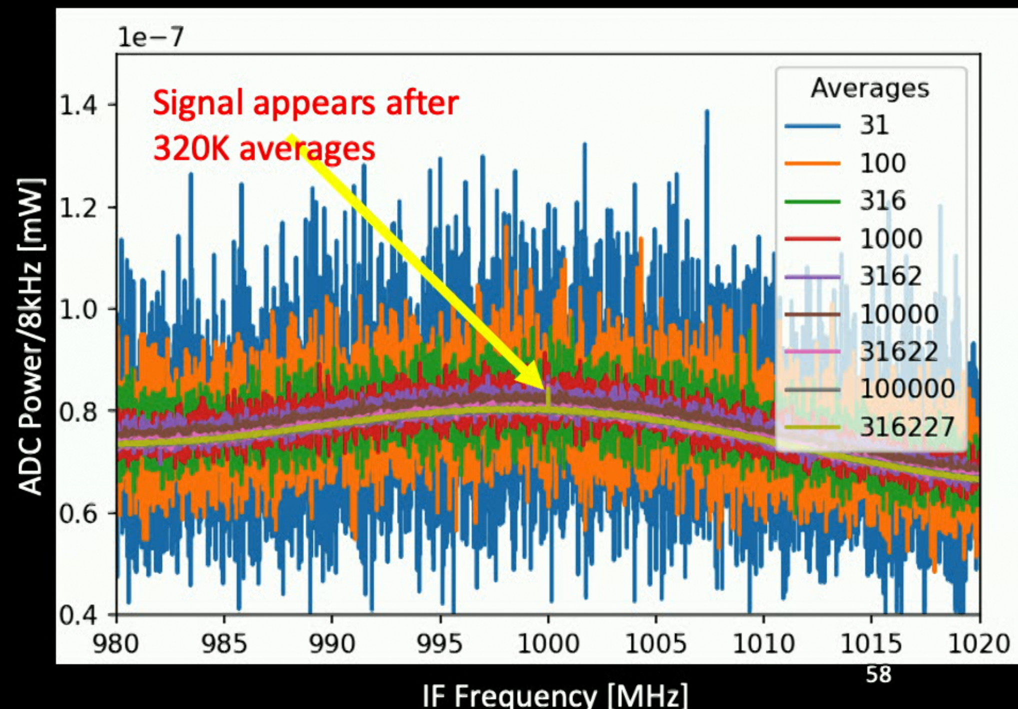
FPGA- Based Data Acquisition

- 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





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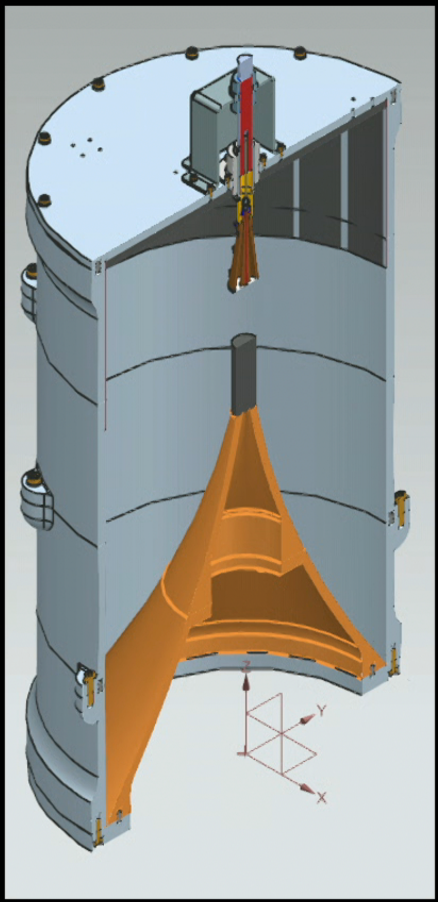
GigaBREAD Reflector Parts



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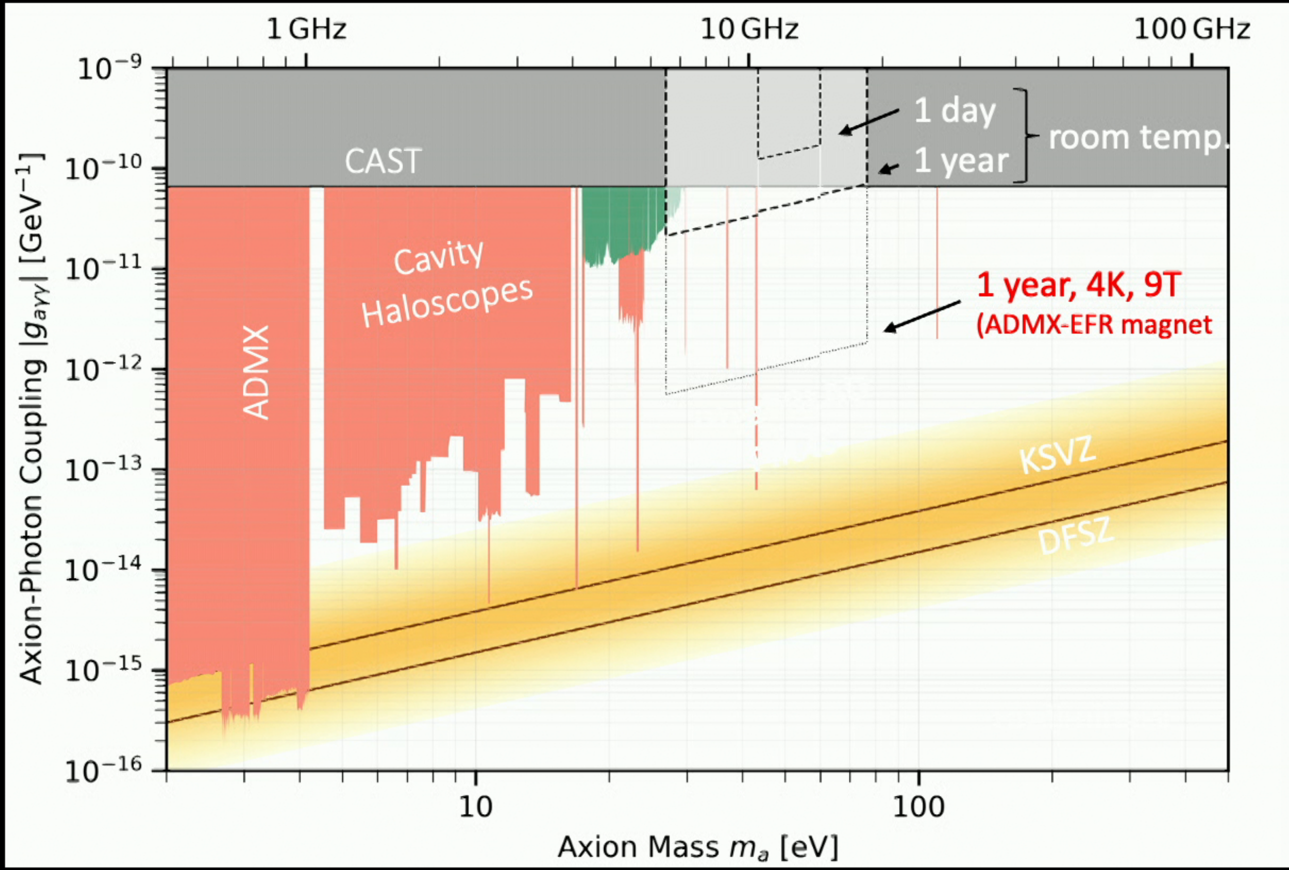
GigaBREAD: Pilot Sensitivity – Axions

4 T MRI magnet at Argonne



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BREAD Collaboration

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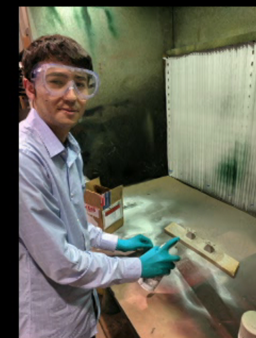
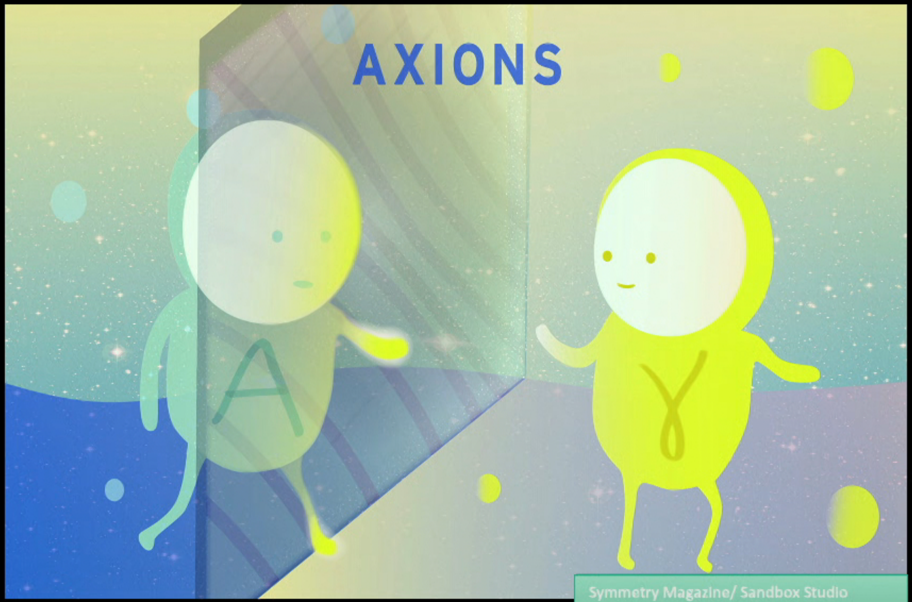





Conclusions

- So many opportunities for small experiments!
- Still a lot more ideas and experiment concepts then completed projects.
- Many more ideas than I have been able to cover here.
    - Searches for axion- electron, axion nucleon interactions.
    - Superconducting cavities
    - Squeezed state readout of cavities
    - "Light shining through walls" and axions from sun (helioscopes)
    - Searches for dark photons are a related area with similar technology.
    - Numerous concepts for counting microwave photons.
- We don't really know how far these methods can be pushed yet- E.g. background limits to single photon counting in microwave to terahertz regime. Can we measure one photon per day?



Symmetry Magazine/ Sandbox Studio