Searches for Axion Dark Matter from Micro-eV to Milli-eV: ADMX and Broadband Detector R&D

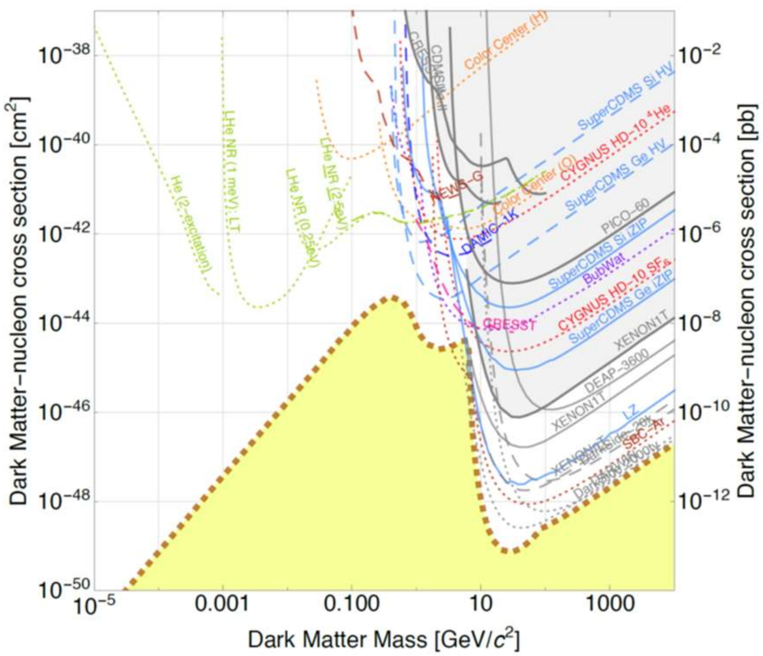
Andrew Sonnenschein (Fermilab), Feb. 22 2020

Outline

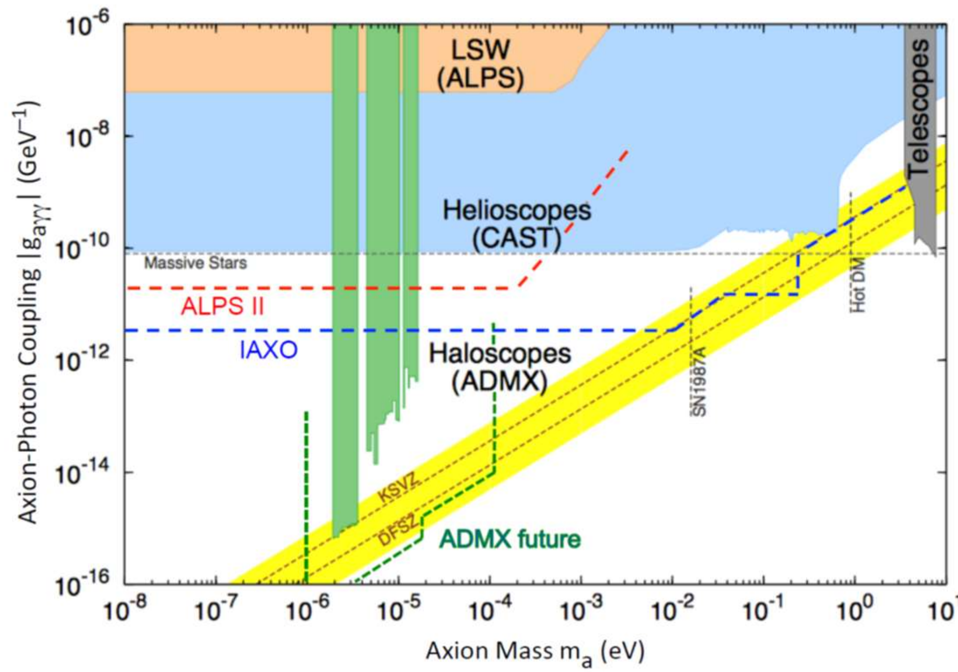
- Motivation
- Resonant cavity technique
- ADMX recent results
- ADMX 1-2 GHz and 2-4 GHz frequency bands
- R&D: Broadband axion search with a Coaxial Dish Antenna

WIMPs Vs. Axions

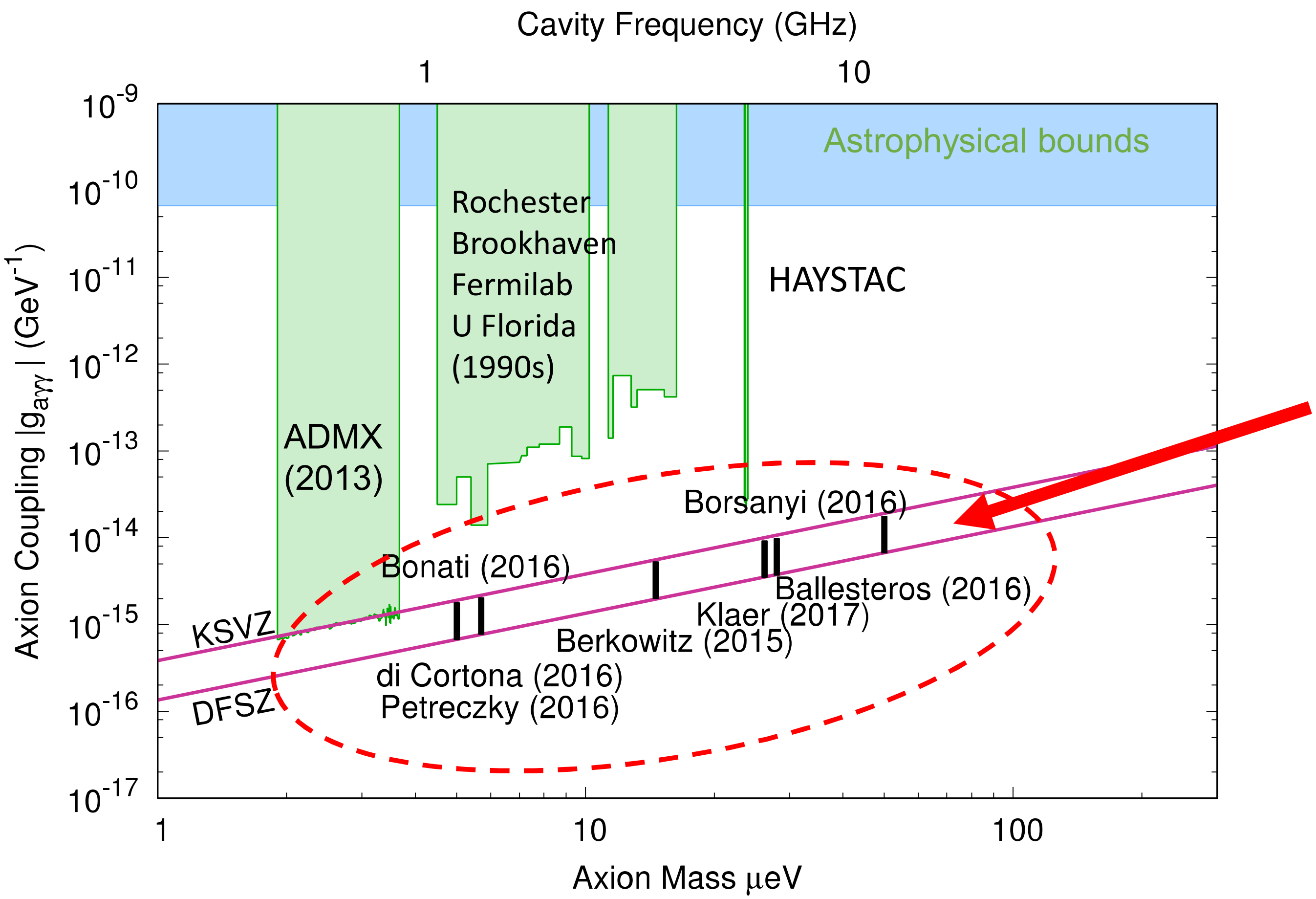
- WIMPs and WIMP-like
  - Dramatic progress in attempted WIMP detection over last decade- many models previously considered promising are now excluded.
  - Direct searches will become background limited by neutrinos over next 10 years.



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



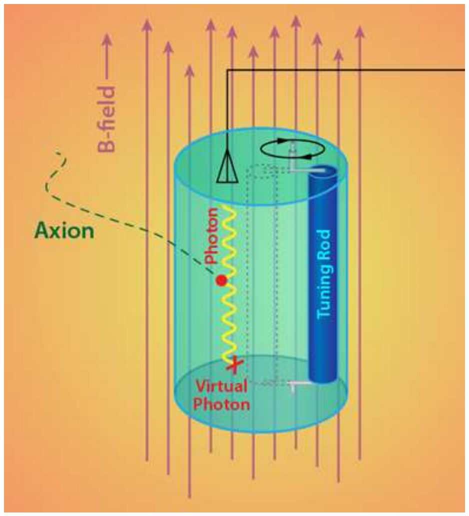
Predictions In “Post Inflation” Window



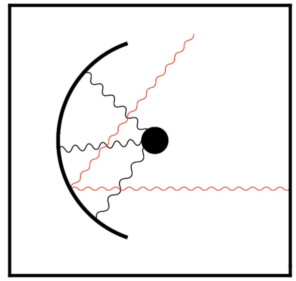
Classical “post inflation” axion window: fine tuning not required for axions to make up 100% of observed dark matter

Growing Diversity of Techniques To Find Axions

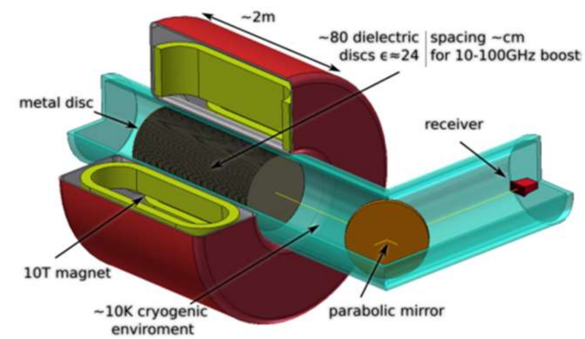
Resonant Cavity (ADMX, HAYSTAC, CAPP)



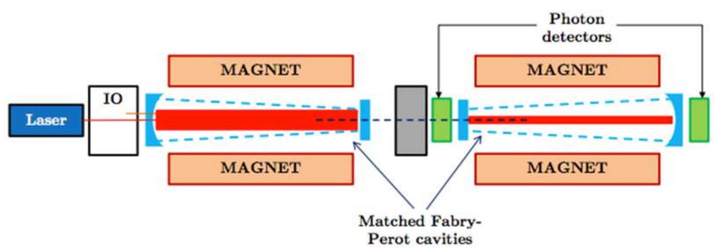
"Dish Antenna" BRASS



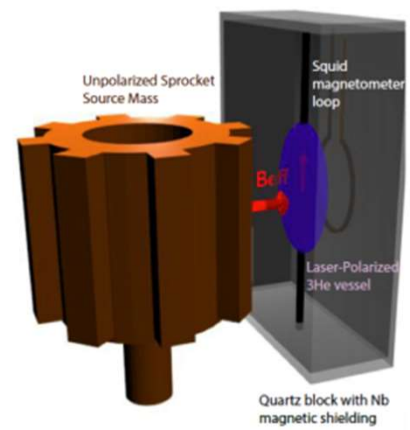
Dielectric Radiators (MADMAX, ORPHEUS)



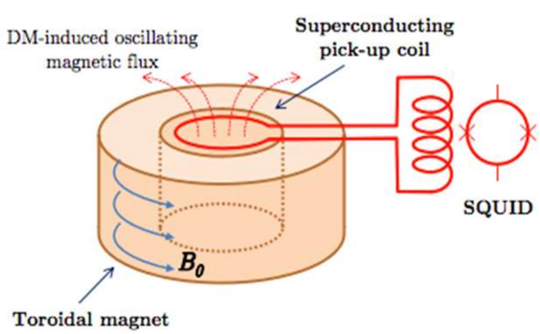
"Light Shining Through Walls" (ALPS)



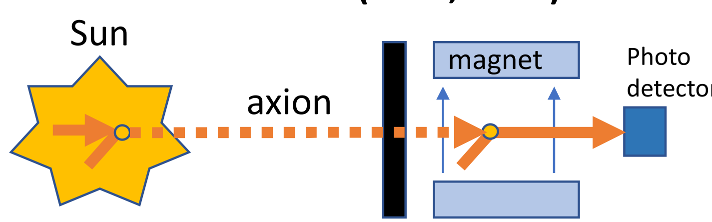
NMR (ARIADNE, CASPER)



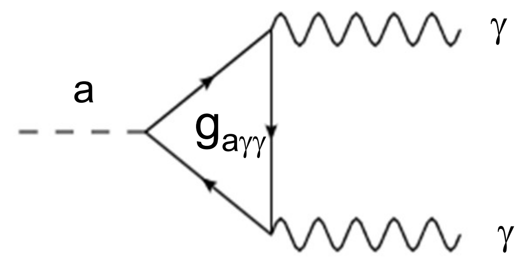
LC Circuit (DMRADIO, ABRACADABRA, SLIC)



Solar Axions (CAST, IAXO)



Maxwell's Equations with an Axion



$$\begin{aligned} \nabla \cdot \mathbf{E} &= \rho_Q - g_{a\gamma} \mathbf{B} \cdot \nabla a \\ \nabla \times \mathbf{B} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma}(\mathbf{B}\dot{a} - \mathbf{E} \times \nabla a) \approx J + \boldsymbol{J}_a(t) \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} + \dot{\mathbf{B}} &= 0 \end{aligned}$$

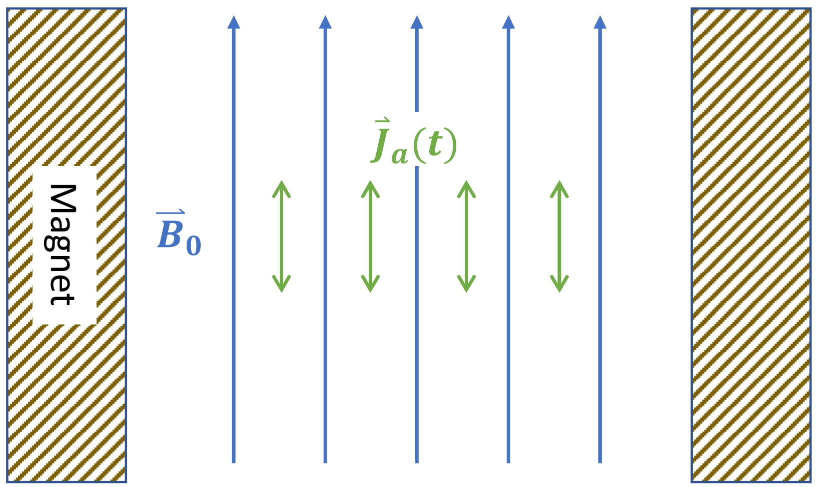
Fictitious electric current

- The a field is a classical field representing axion dark matter density, oscillating with a frequency corresponding to the axion mass ($\omega = m_a c^2/\hbar$).
- In a background magnetic field, axion is responsible for a new source term which resembles an oscillating electric current

$$\boldsymbol{J_a}(t) = g_{a\gamma} \boldsymbol{B} a_0 e^{-i\omega t}$$

See e.g. Irastorza & Redondo 2018

Oscillating Fictitious Current Produced by Axions in Magnetic Field

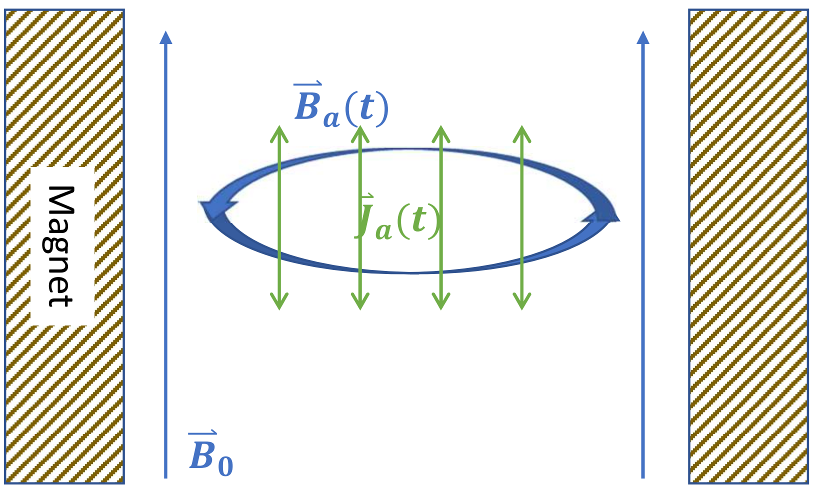


$$\boldsymbol{J_a}(t) = g_{a\gamma}\boldsymbol{B_0}a_0e^{-i\omega t}$$

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

Magnetic Field Response to Axion Current

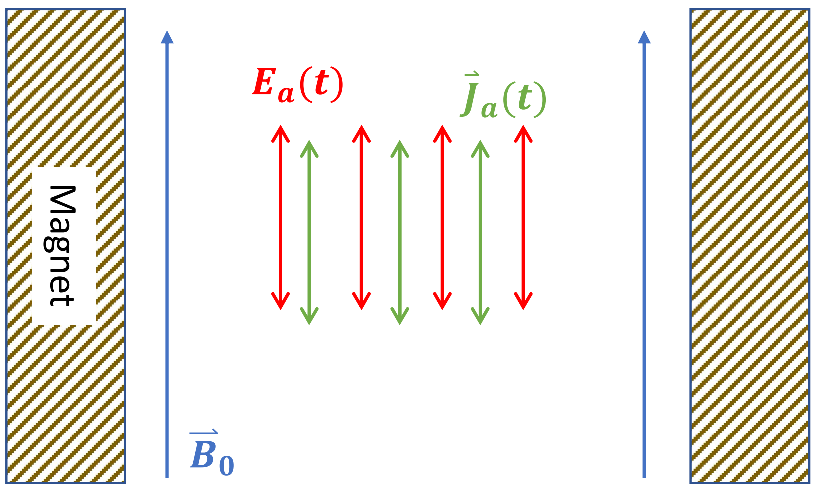
- The fictitious current $\boldsymbol{J_a}(t)$ can source a real magnetic field.
- Basis for signal generation in “LC oscillator” experiments.



DMRadio
ABRACADABRA
ADMX SLIC

Electric Field Response to Oscillating Axion Current

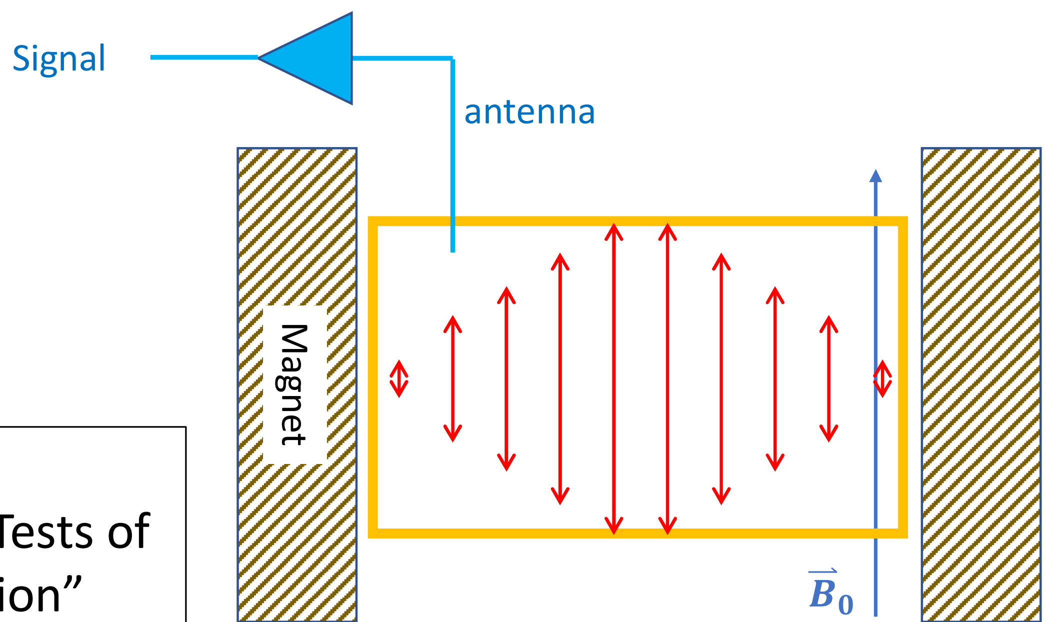
- Small electric response field appears parallel to imposed magnetic field.
- This case applies for wavelength small with respect to size of apparatus- conducting surfaces “far” away from volume of interest.



Pumped Cavity Mode

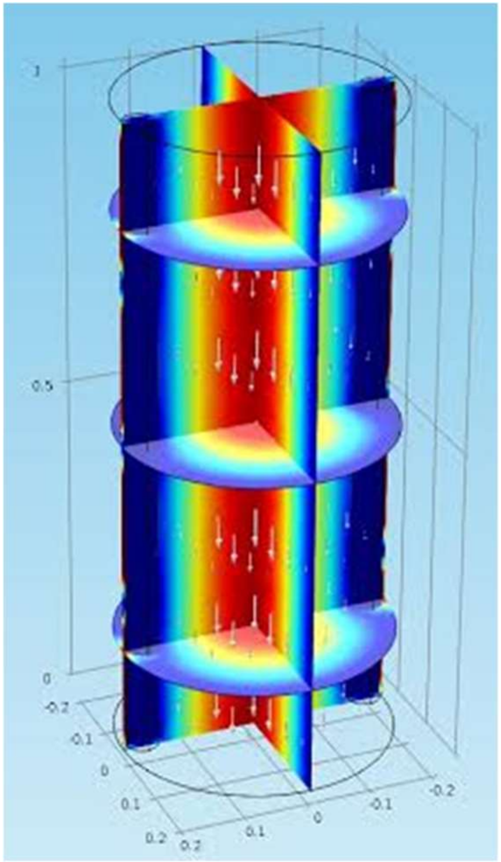
- Power buildup occurs when cavity resonance frequency is matched to axion mass.
- Signal Power ~10^{-22}-10^{-23} W at 1 GHz for typical cavity and magnet parameters

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

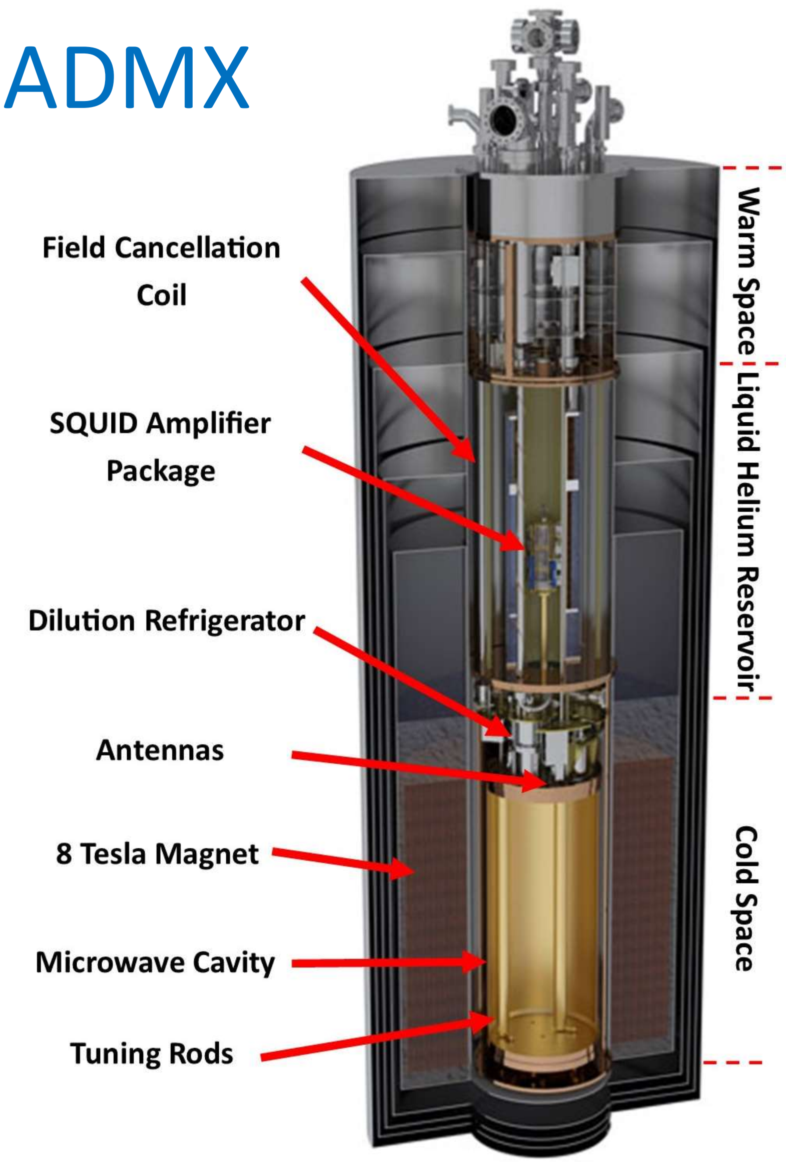


Pierre Sikivie, "Experimental Tests of the Invisible Axion" 1983 PRL

TM$_{010}$ Mode



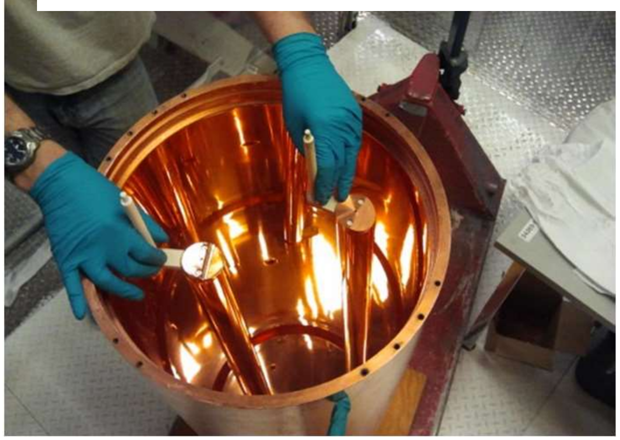
ADMX

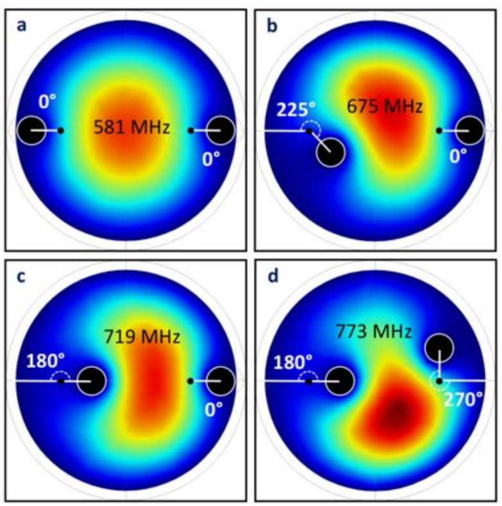


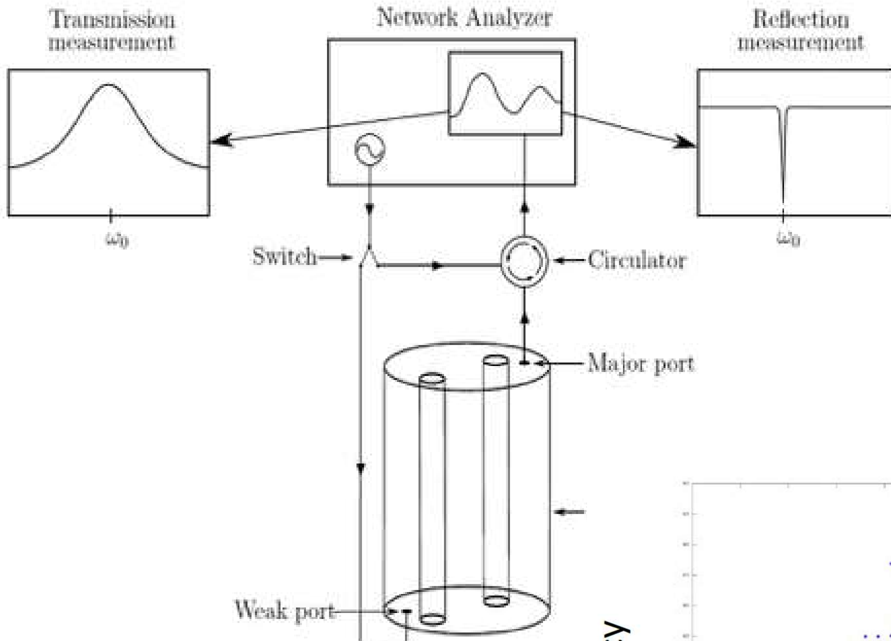
Field Cancellation Coil
SQUID Amplifier Package
Dilution Refrigerator
Antennas
8 Tesla Magnet
Microwave Cavity
Tuning Rods
Warm Space
Liquid Helium Reservoir
Cold Space

Tuning The Resonator

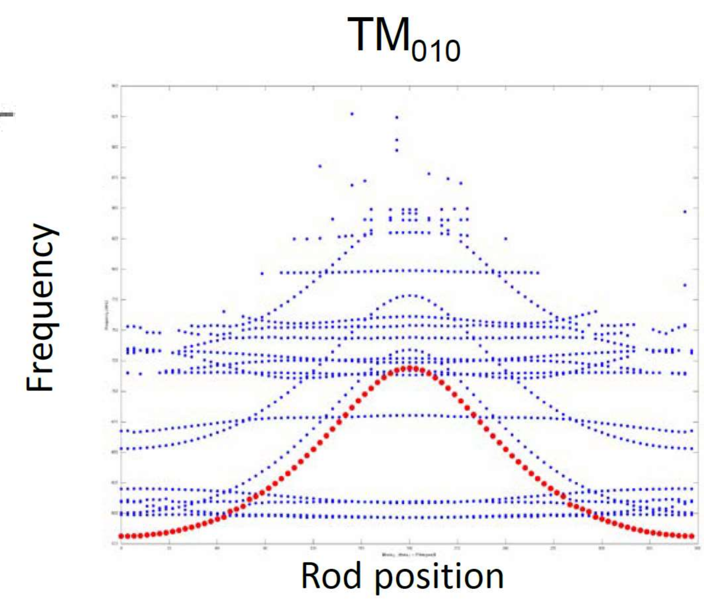
Tuning Rods





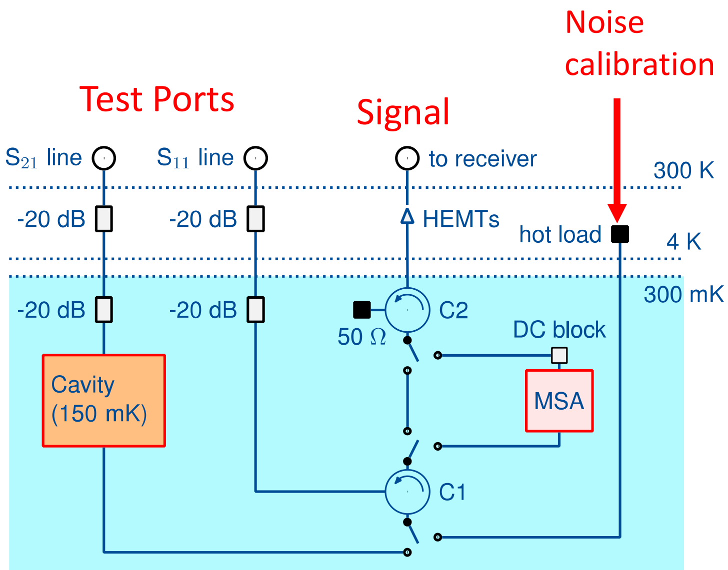


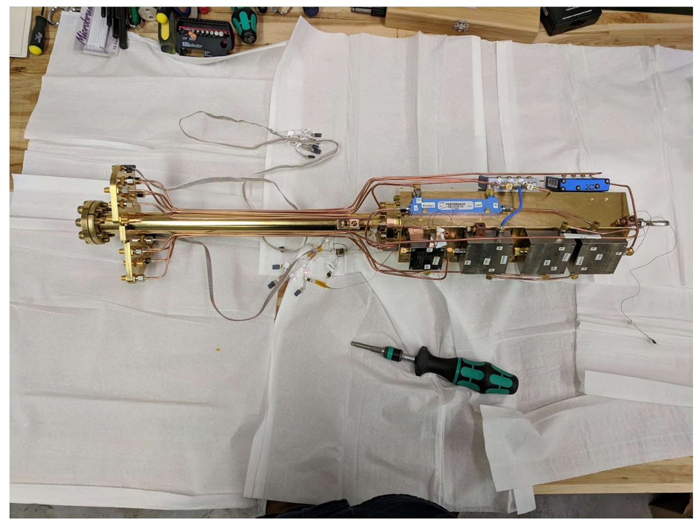
- Frequency steps typically 1/10 cavity line width ~ 2 KHz



Low Noise Electronics

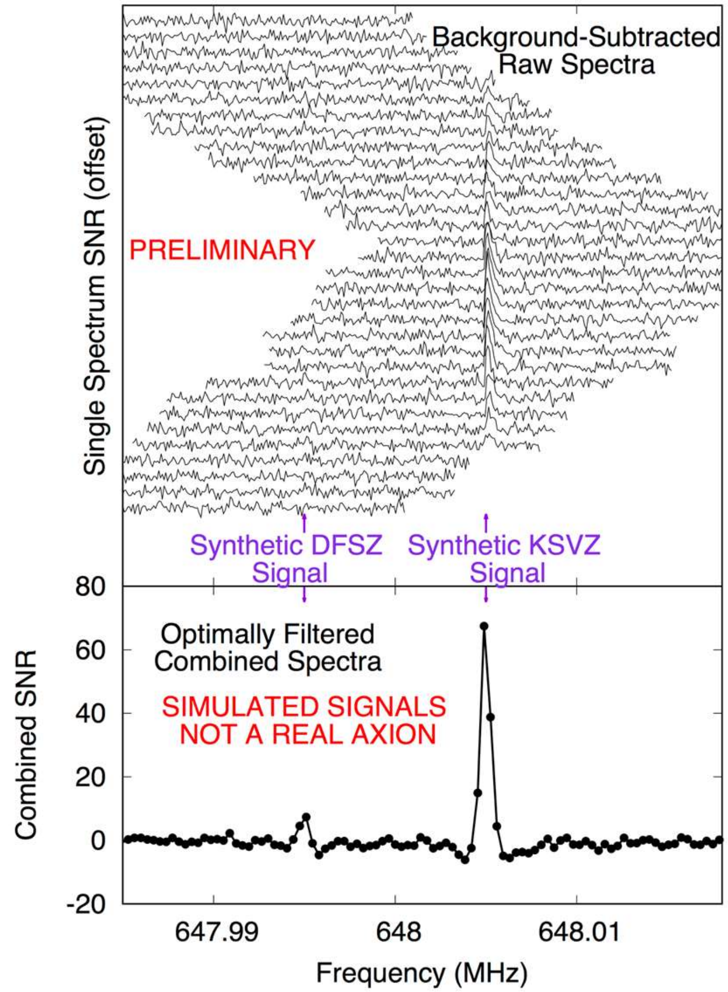
- To reach sensitivity of DFSZ axion models requires noise levels that were beyond state-of-the-art a few years ago.
- Possible because of developments in Quantum Information Science community for applications such as Qubit readout:
    - **Microstrip Squid Amplifiers** (Clarke group @ UC Berkeley)
    - **Josephson Parametric Amplifiers** (Siddiqi group @ UC Berkeley).
    - **Traveling Wave Parametric Amplifiers** (MIT Lincoln Labs). Wide instantaneous bandwidth.
- Post amplification at 4 Kelvin using commercially available HFET technology.
- Cold RF system needs capability for in-situ calibration and diagnostic functions.



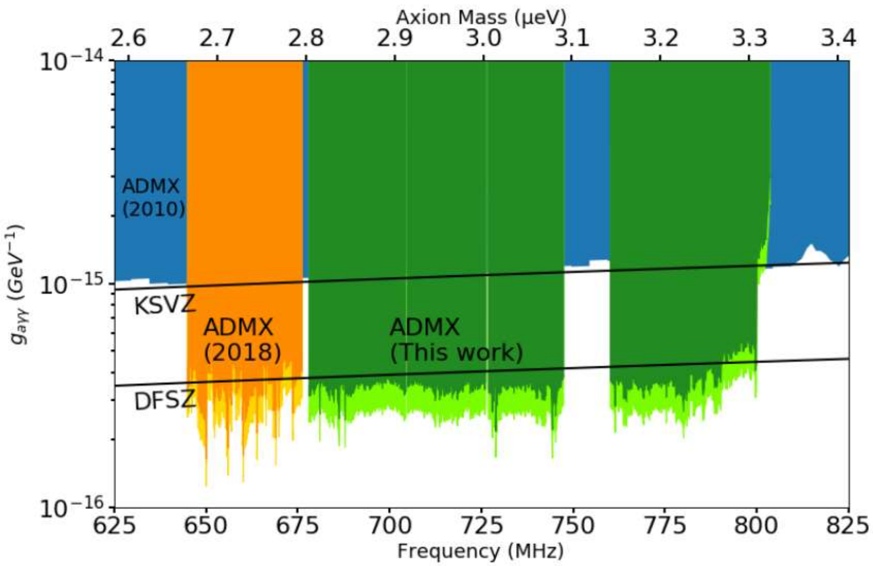


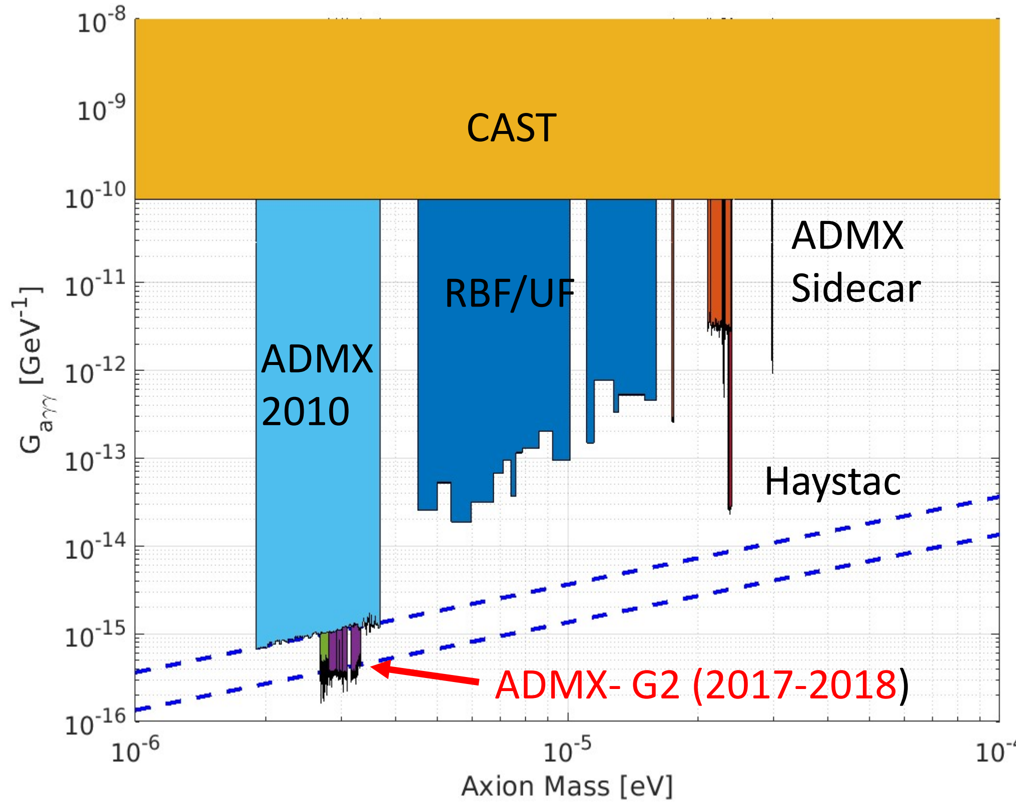
Operating Procedure

- The cavity frequency is scanned over a region until the desired SNR is achieved.
- Convolution with filter matched to expected axion line shape.
- Typically we have ~10^6 independent measurements on each axion linewidth, averaged to reduce noise by $\sqrt{10^6}$
- We then examine the combined power spectrum for signs of excess
- Excess power regions can be statistical fluctuations, synthetically injected signals, RF interference, or axions
- Excess power regions are rescanned to see if they persist
- Persistent candidates are subjected to a variety of confirmation tests: for example: magnet field changes or probing with other cavity modes.
- We do blind signal injection, so we always have candidates



Current ADMX Limits





Scalability of Cavity- Based Axion Searches to Higher Frequency

- Resonant cavity technique works best for wavelength ~ 1 meter- the most convenient scale to build magnets and resonators.
- As we move up in frequency **f**,
  - Volume *per cavity* decreases as $\mathbf{f^{-3}}$
  - Resonator quality factor decreases as $\mathbf{f^{-2/3}}$
  - 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

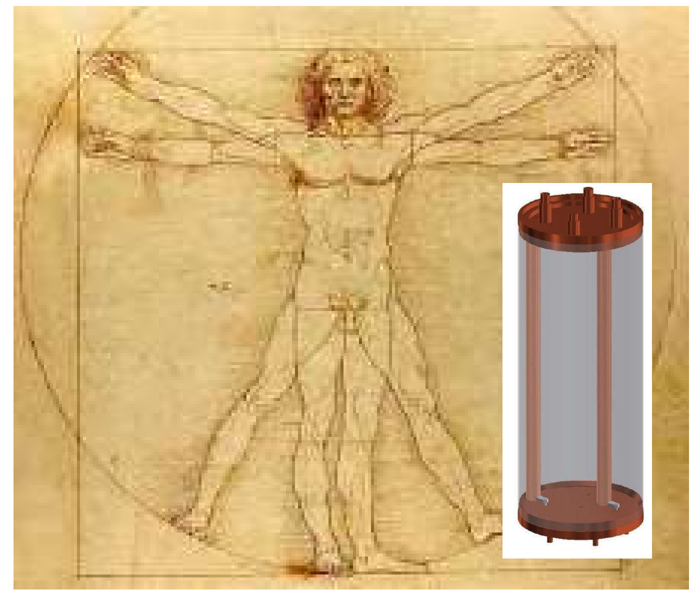
$$\frac{df}{dt} \approx 1.68\ \mathrm{GHz/year}\ \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \mathrm{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \mathrm{T}}\right)^4 \left(\frac{V}{100\mathrm{l}}\right)^2 \left(\frac{Q_L}{10^5}\right)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

Need stronger Magnets

Larger Volume, Many cavities

Higher quality factor

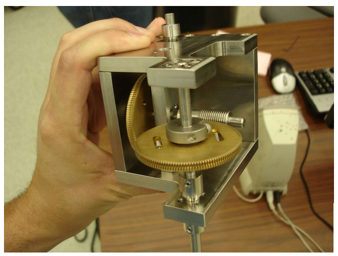
Lower Noise: below SQL?



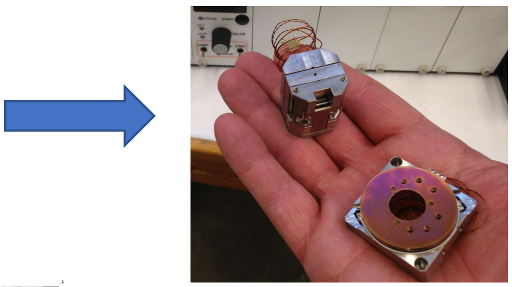
Example of frequency scale-up: Tuning rod actuation

- Rapid growth in system complexity to maintain signal power as frequency increases.
- “Swiss watch problem”
- Not yet clear how far miniaturization can continue.

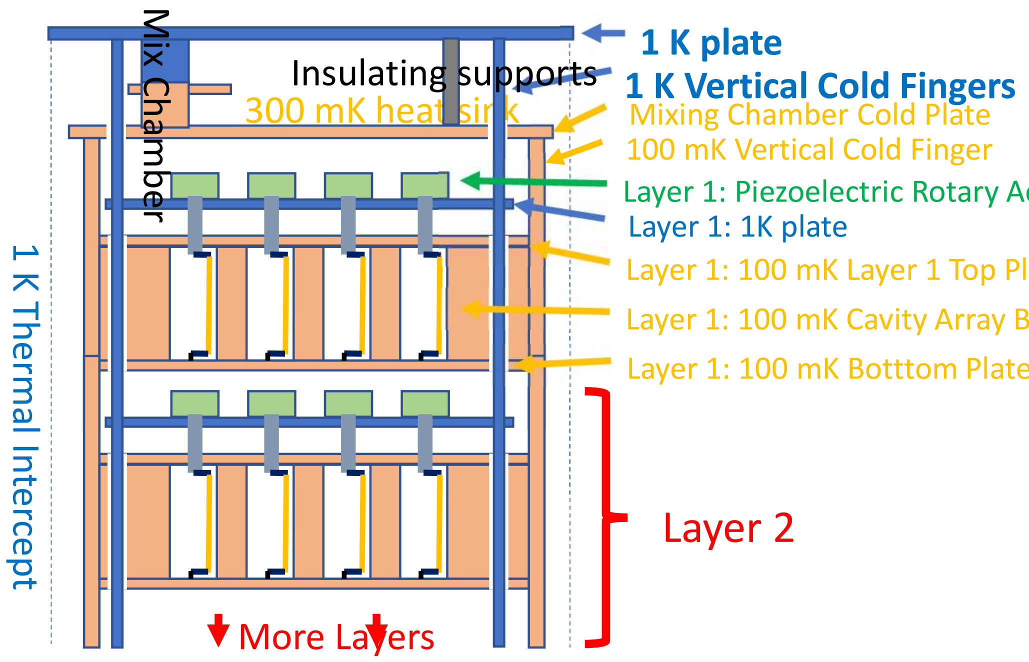
Components for 580-1500 MHz Cavity



1500-2300 MHz



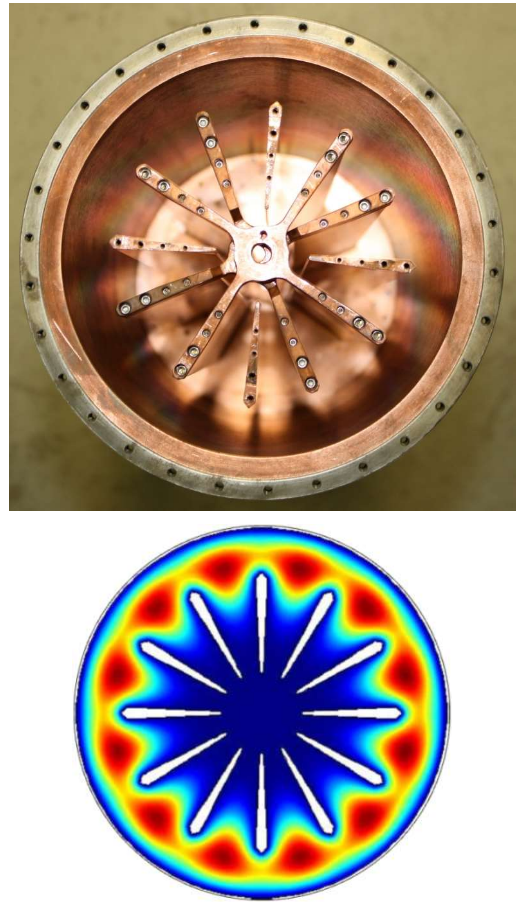
High frequency cavity array concept



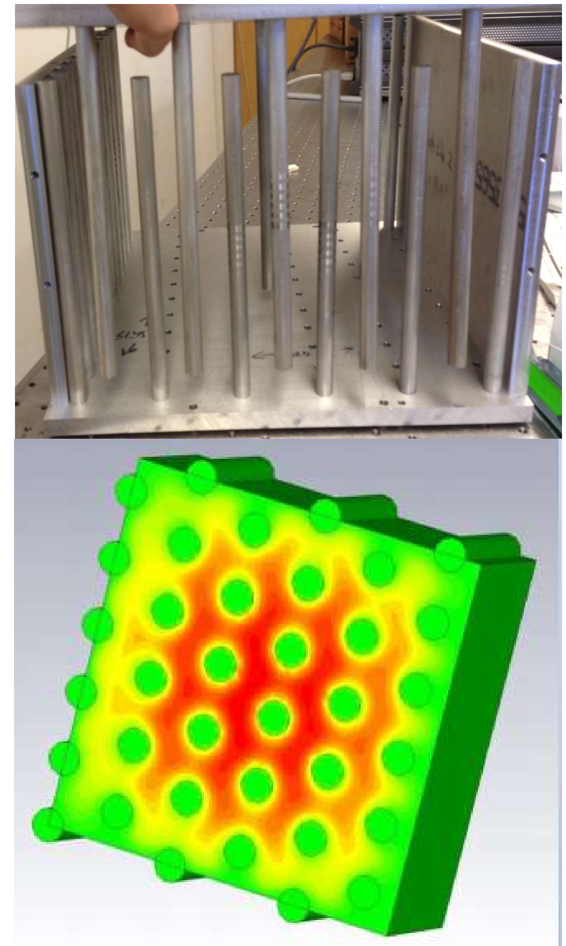
R&D Towards High Frequency (>4 GHz) Resonators

- Explore systems that allow simultaneous tuning of many sub elements with only a few mechanical motions.
- HAYSTAC and CAPP developing similar concepts.
- Common feature of these schemes is requirement for extreme mechanical tolerances & precise motion.

Comb cavity (FNAL)



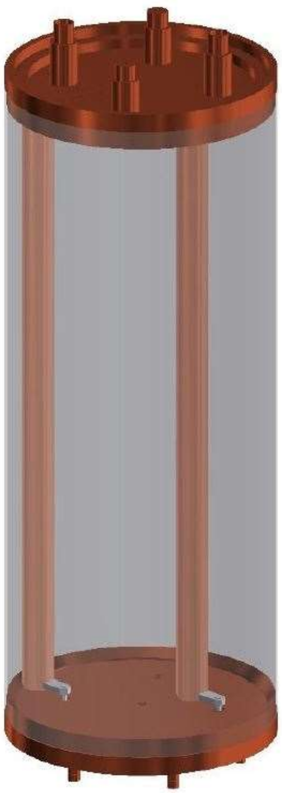
“Pizza” Cavity (U. Florida)



Array of posts (LLNL)

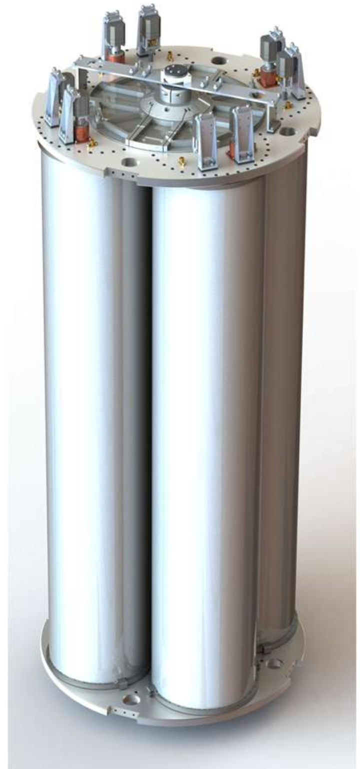
ADMX Cavities up to 4 GHz

Used in 2016-2018 Runs
580-890 MHz
136 Liters



2019-2020
800-1500 MHz
Large tuning rod
116 Liters

2020-2021
4-Cavity Array
8 piezoelectric actuators
1500-2300 MHz
77 Liters



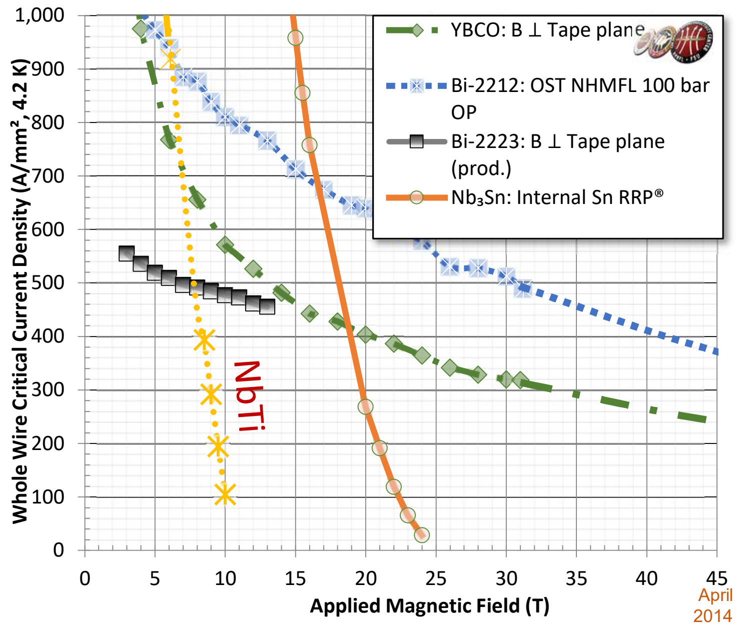
2022-2024
14-Cavity array concept
2.3- 4 GHz
50 liters

Magnets

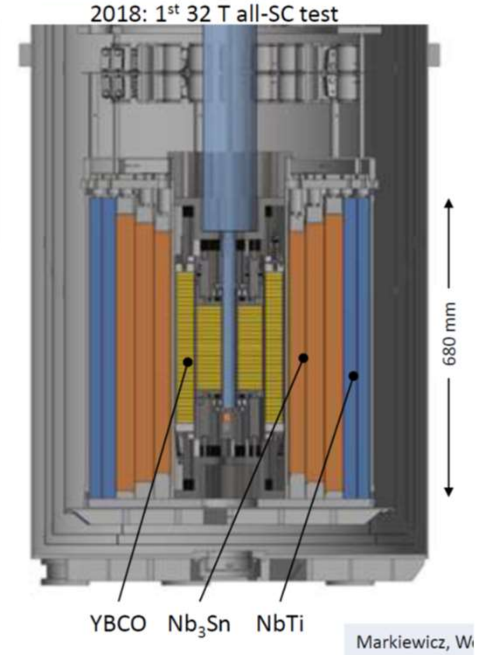
- Current ADMX magnet
  - 8.5-Tesla x 60 cm solenoid (normally operated at 7.6 Tesla)
  - Nb-Ti superconductor at 4 Kelvin
  - 25 years old-- Manufactured in 1993 by Wang NMR, Livermore CA.
- A step up to higher field requires different superconductor technology.
  - NbTi -> 10 Tesla
  - Nb_3Sn -> 15 Tesla
  - BI-2212, YBCO -> 30 Tesla or more, but technology is not yet mature.
  - Use of high field materials implies high costs and long lead times.
  - A 30-Tesla solenoid for next generation axion search may cost ~$20M and take 5 years to build.

ADMX 7.6 Tesla NbTi

NHMFL 30 Tesla YBCO



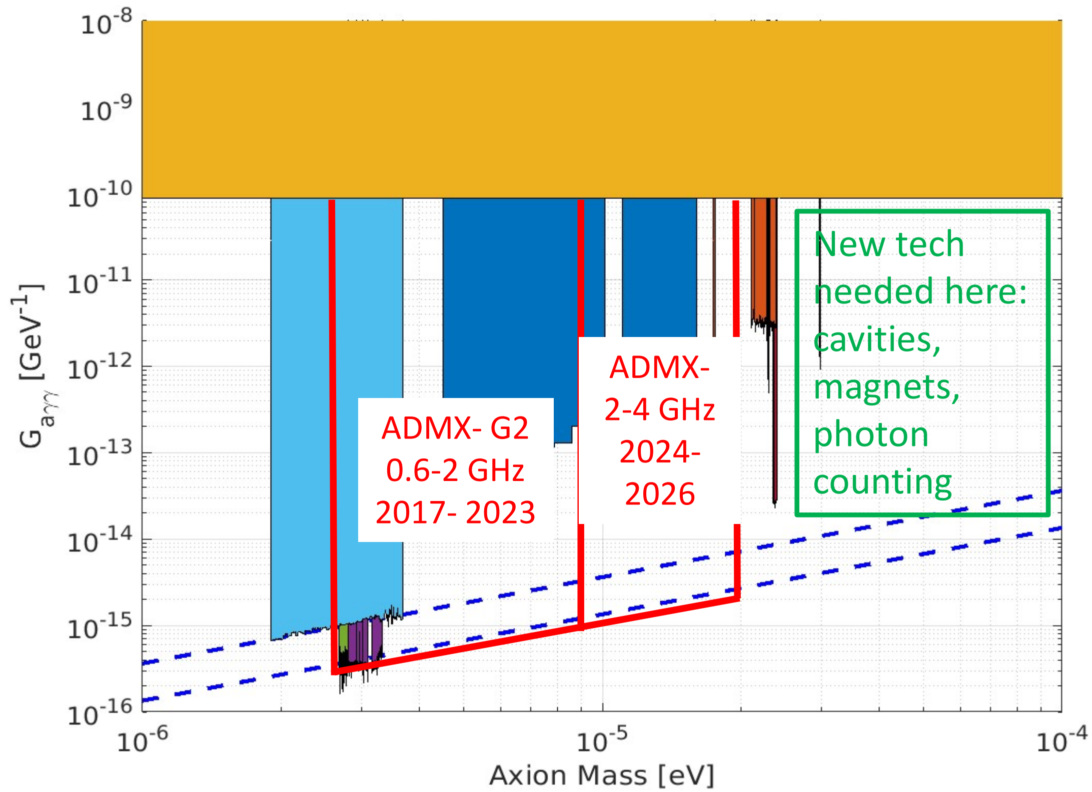
2018: 1st 32 T all-SC test



ADMX 2-4 GHz Requirements and Sensitivity Goals

- Design study for ADMX 2-4 GHz is underway as part of the DOE Dark Matter New Initiatives program.
- Considering options for magnet upgrades, cavity design, electronics.
- Aim for data taking starting 2024.

	2018 Achieved Run	Baseline Requirement	Target Performance
Frequency Range	680-800 MHz	2-4 GHz	2-4 GHz
Volume	139 Liters	80 Liters	80 Liters
Q	60000	30,000	90,000
B Field	7.6 T	7.6 T	12.0 T
Form Factor	0.4	0.4	0.4
Noise Temperature	350 mK	350 mK	325 mK
Live Time Fraction	40%	70%	70%
Amplifier Squeezing	1	1	1.4
Operations Days	150	1000	1000
Dark Matter Sensitivity for DFSZ Coupling	0.45 GeV/cc	0.65 GeV/cc	0.12 GeV/cc
Dark Matter Sensitivity for KSVZ Coupling	0.09 GeV/cc	0.15 GeV/cc	0.02 GeV/cc



ADMX Collaboration

<u>Collaborating Institutions:</u>
University of Washington
University of Florida
University of California, Berkeley
Washington University St. Louis
Sheffield University
Pacific Northwest National Lab
Lawrence Livermore National Lab
Los Alamos National Lab
Fermilab

The ADMX collaboration gratefully acknowledges support from the US Dept. of Energy, High Energy Physics DE-SC0011665 & DE-SC0010280 & DE-AC52-07NA27344

Also support from LLNL and PNNL LDRD programs and R&D support from the Heising-Simons institute

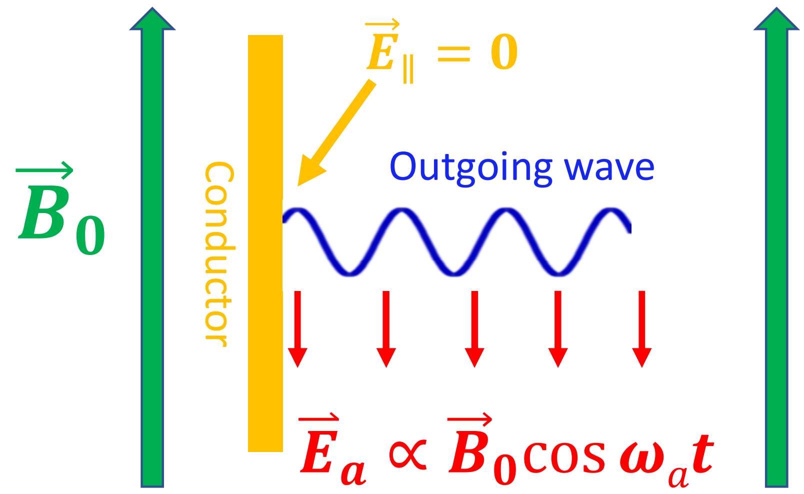
R&D at Fermilab: Broadband Searches with Coaxial Dish Antenna

Axion Induced Radiation from A Magnetized Metal Slab

- D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo, A. Ringwald, arXiv:1212.2970. Chris Hill, arXiv:1508.04083
- Axions interact with a static magnetic field producing an oscillating parallel electric field in free space

$$\boldsymbol{E} = g\boldsymbol{B_0}\theta_0 \cos(m_a t)$$

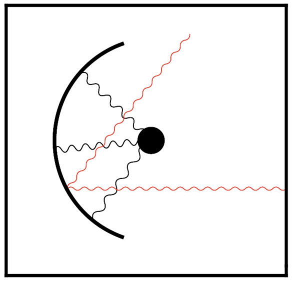
- A conducting surface in this field emits a plane wave perpendicular to surface to satisfy the boundary condition $\mathbf{E}_{\parallel}=0$



- Radiated power is low:

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

- But no detector tuning is required!

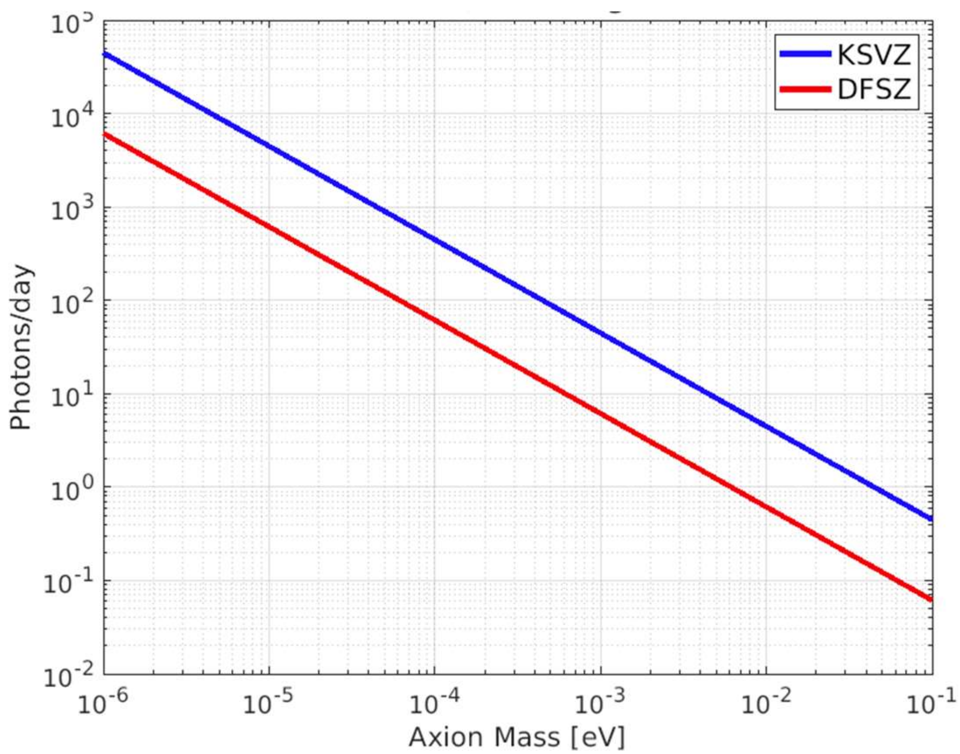


"Dish antenna" (Horns et al.)

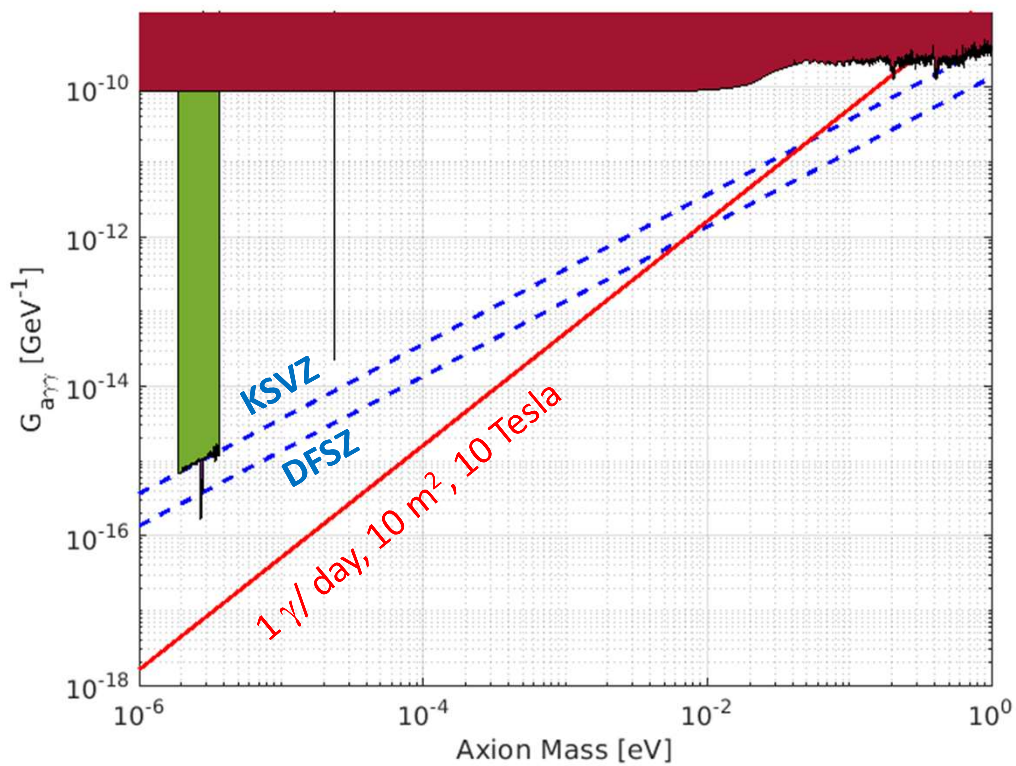
Broadband Experiments with Single Photon Counters

- ~10^{-26} W is ok if you can detect single photons at rates of events/day

Single Photon Event Rate
10 m² emitter x 10 Tesla

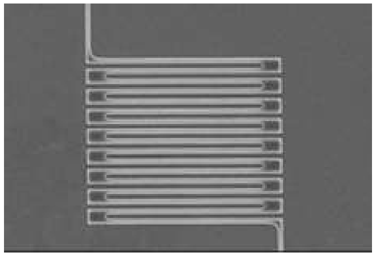


Axion/ Photon Coupling Sensitivity

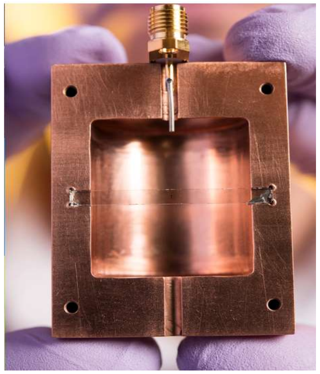


Single Photon Detection from μeV to meV

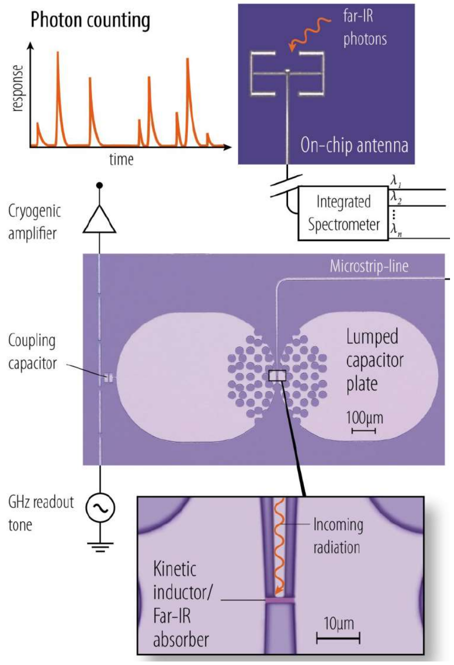
- Numerous groups pursuing single photon detection technologies.
- Examples based on new superconducting device concepts:
  - SNSPDs– reaching background counts below 1/day at ~1 eV. Talk by Sae Woo Nam
  - KIDs- approaching thresholds of 4 meV. Low background expected. Talk by Omid Noroozian
  - TES
  - Quantum Capacitance Detectors. meV thresholds demonstrated. High dark rate.
  - Qubits. 30 μeV Talk by Dave Schuster.
  - Current biased SIS Junctions. 60 μeV threshold claimed with low dark counts L. Kuzmin et al., Patras 2019
- Broadband photodetection is very challenging. Probably not possible in some of these architectures (e.g. qubits)
- Not ready yet for axion experiments– but good prospects for next decade.



NIST SNSPD



U. Chicago/ Fermilab Qubit sensor (Dixit, Chou, Schuster)



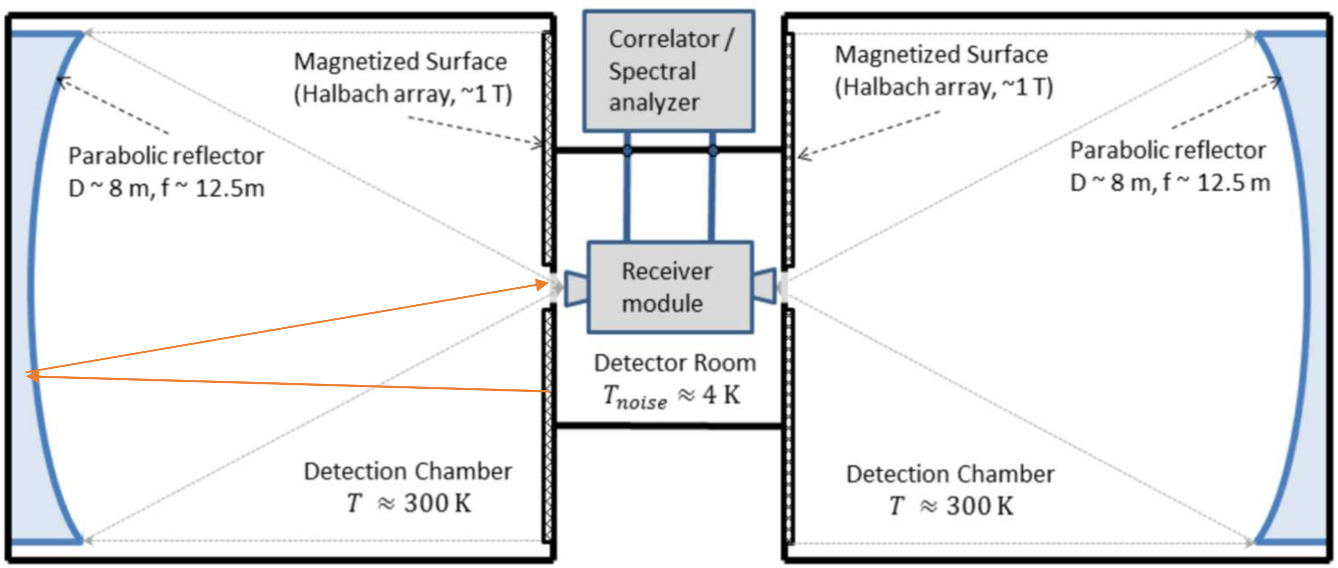
KIDs (Noroozian)

“Broadband Radiometric Axion Search”: BRASS collaboration (University of Hamburg, MPI- Bonn, DESY)

- BRASS project proposes broadband search with large arrays of permanent magnets.
- We would like to find a solution that can use a conventional large bore solenoid.

Conceptual Design for BRASS

❑ Broadband Radiometric Axion/ALP SearcheS:
-- Flat, permanently magnetized surface (Halbach array; 100 m^2, B~1T)
-- Focusing the signal with a parabolic reflector
-- Broadband recording (16+ GHz bandwidth, spectral resolution of 10^{-7}).
-- Correlating signals from multiple modules
-- Natural synergy with VLBI and ALMA/APEX developments at MPIfR



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Patras 2018

Large Solenoids

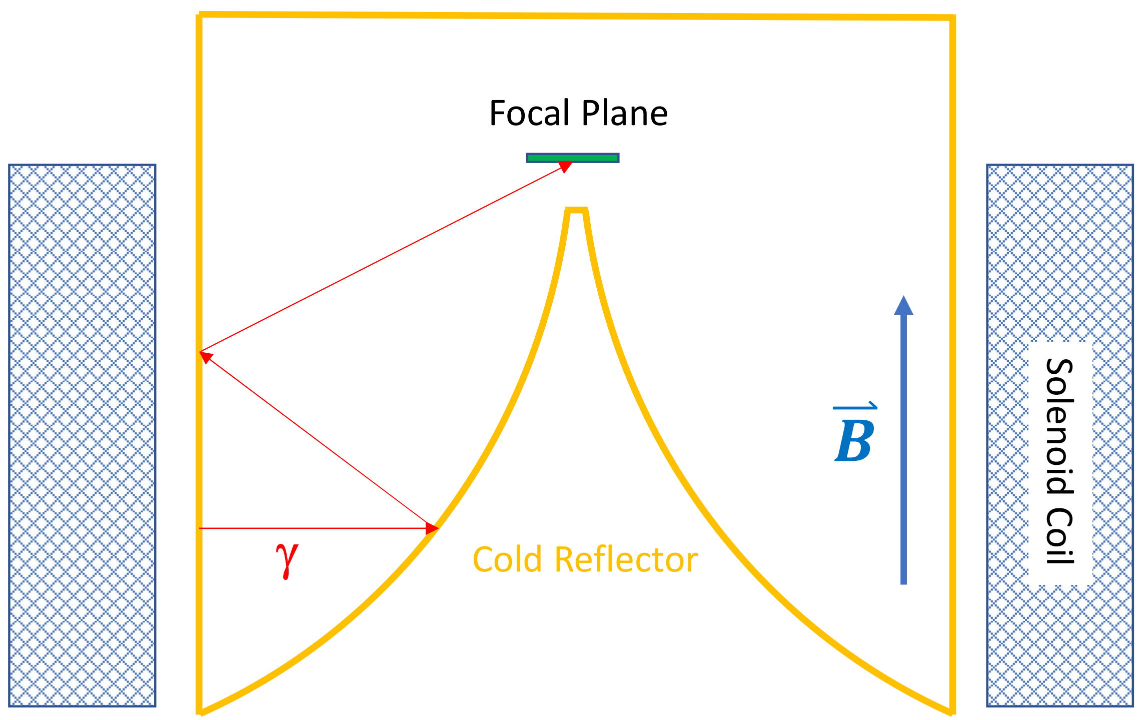
B_0^2V (T^2m^3)	Magnet	Application/ Technology	Location	Field (T)	Bore (m)	Len (m)	Energy (MJ)	Cost ($M)
12000	*ITER CS*	*Fusion/Sn CICC*	*Cadarache*	*13*	*2.6*	*13*	*6400*	*>500*
5300	CMS	Detector/Ti SRC	CERN	3.8	6	13	2660	>458[1]
650	Tore Supra	Fusion/Ti Mono Ventilated	Cadarache	9	1.8	3	600	
430	*Iseult*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

Mark Bird, NHMFL

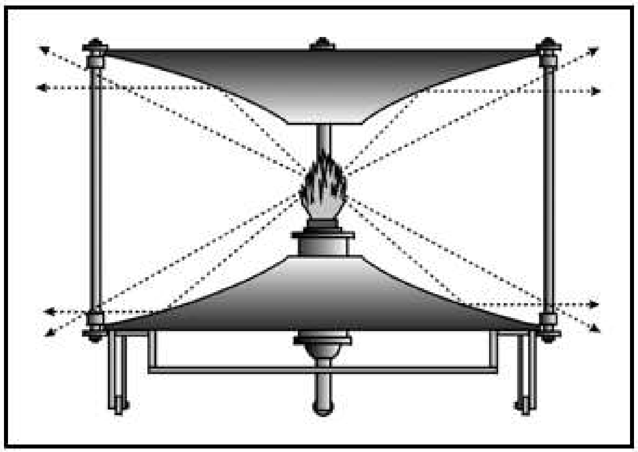
ITER Central Solenoid Module at General Atomics
2.6 m bore x 13 Tesla

Coaxial Dish Antenna Concept

- Parabolic light concentrator for rays moving in radial direction.
- Efficient collection of light inside a solenoid magnet.
- Can be implemented at milliKelvin temperatures.



Design Legacy- 19th Century Lighthouse Mirrors



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

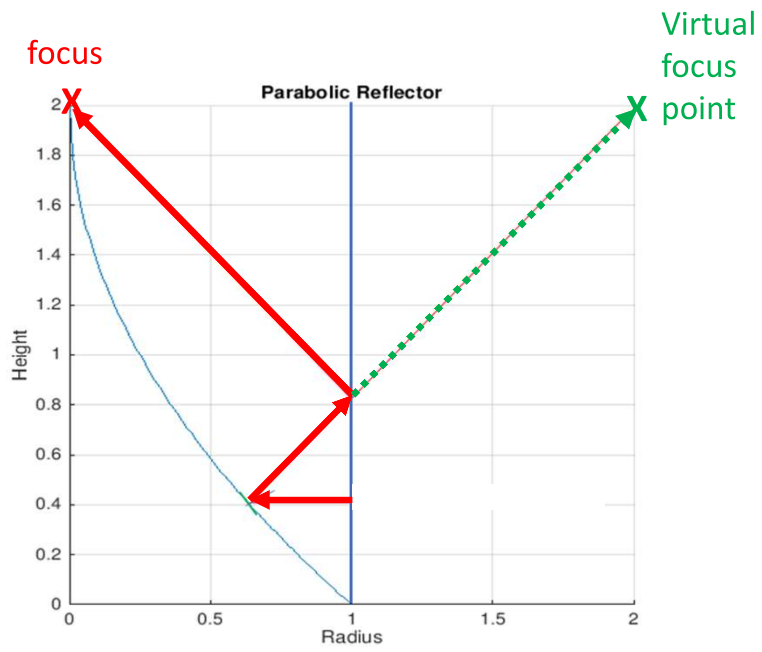
Fanal Sidereal Lantern. (1811)

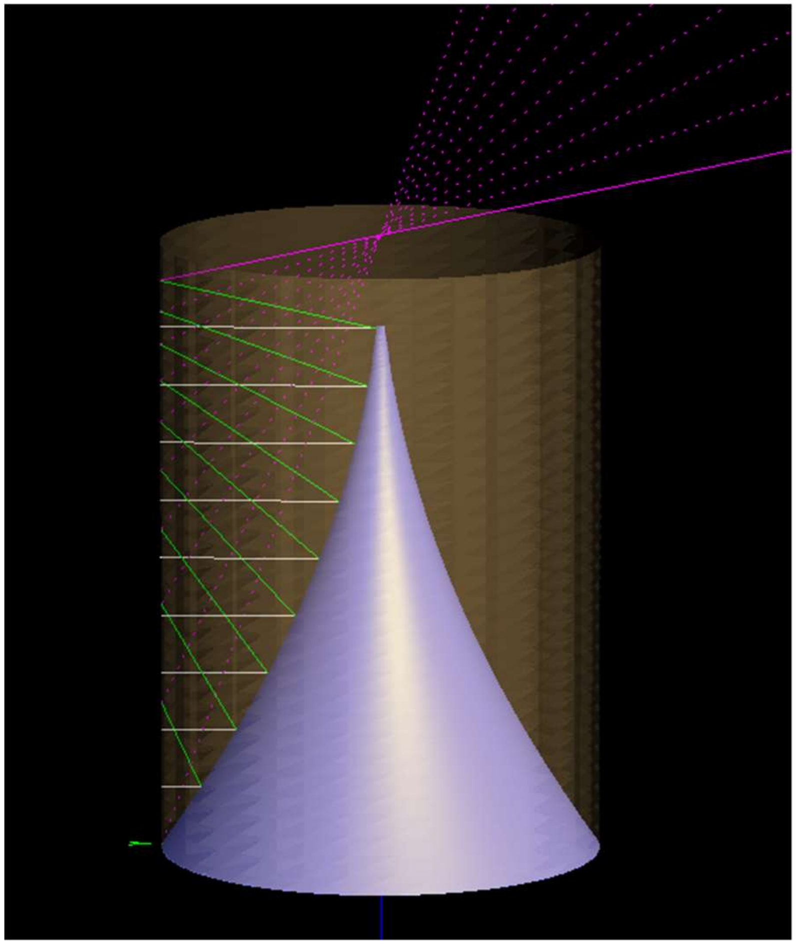
In 1809, Bordier-Marcet invented the 'Fanal Sidereal' reflector where two parabolic reflecting surfaces were placed one above the other. Each of the reflecting surfaces had a central hole where the lamp flame was placed. The Fanal Sidereal reflector was first used in the harbor lighthouse in Honfleur,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

From https://uslhs.org/reflectors

Coaxial Dish Antenna Optics

- How to collect rays emitted from a cylindrical surface?
- Revolved parabolic surface
- Light rays emitted perpendicular to cylindrical wall are focused after two reflections.
- Allows efficient light collection from a circular bore with length up to 1.4 * diameter





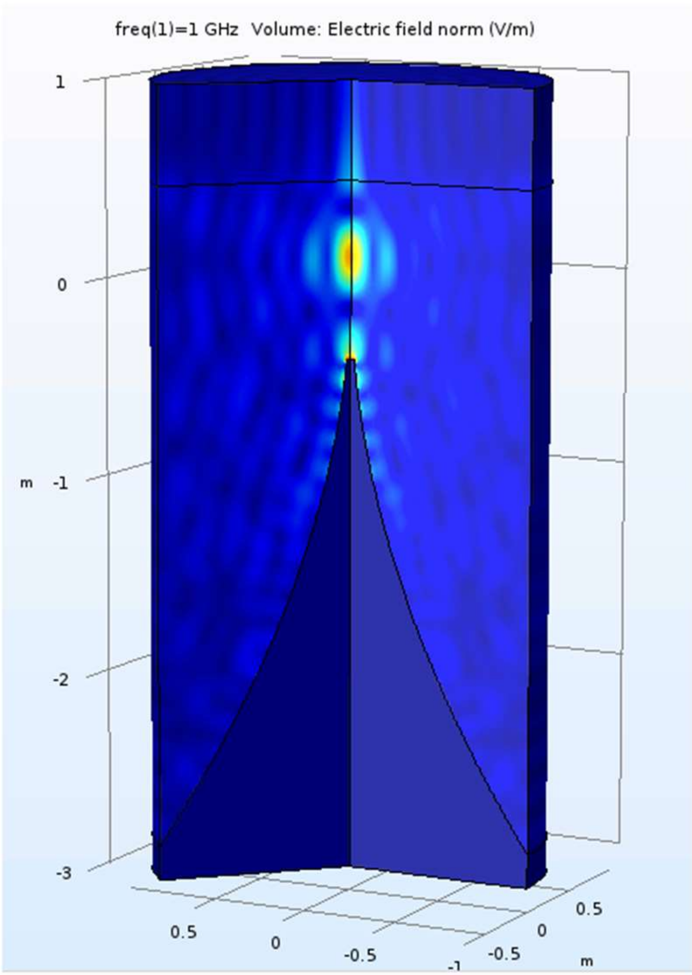
Comsol Simulation

- Standard EM simulation with a volume- filling fictitious electric current.

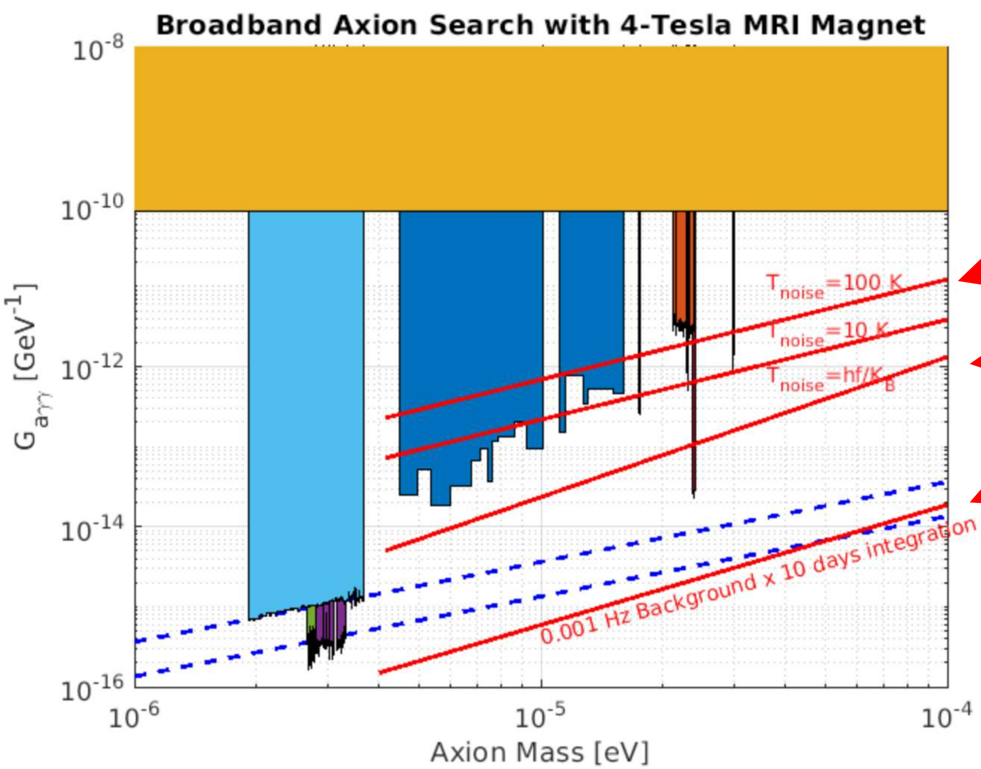
$$\boldsymbol{J_a}(t) = g_{a\gamma}\boldsymbol{B}a_0 e^{-i\omega t}$$

- Revolved parabolic reflector and walls are treated as perfect electric conductors.

- Upper boundary of volume is a non-reflecting "perfectly matched layer".



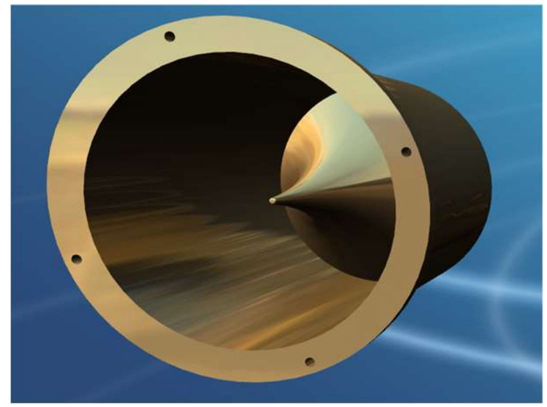
Possible Pilot Experiment: Axion Search with 4- Tesla MRI Magnet



Can be done at room temperature

Standard Quantum Limit

Photon counter



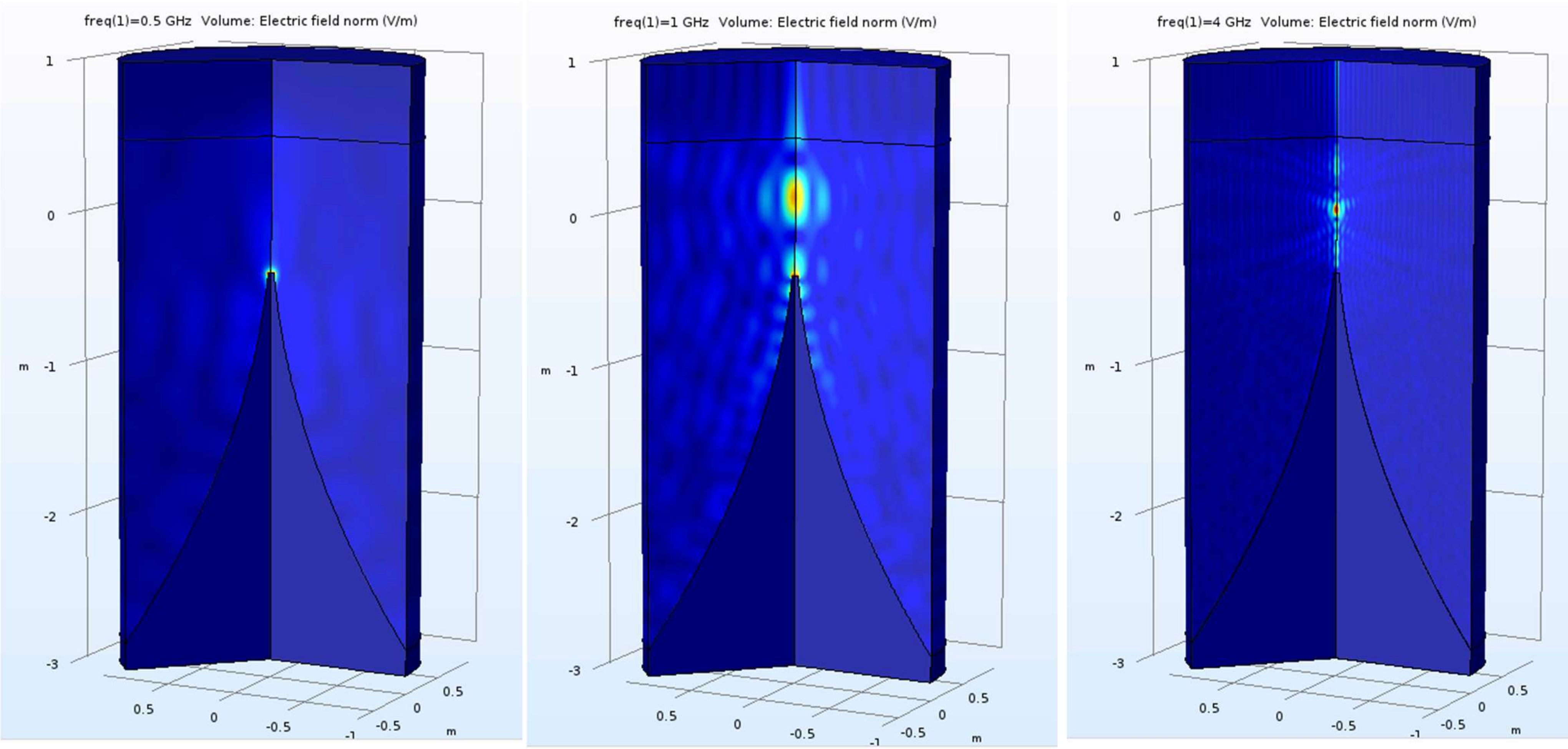
3D Printed Antenna

MRI magnet at ANL

Broadband Search Summary

- Motivated by scaling issues for resonant cavity detector.
- Will require very large magnets to get small numbers of photons.
- Futuristic– sensitivity to QCD axion requires photon counting detector technology that doesn't exist yet!
- Small scale pilot experiment could explore new regions for axion like particles well above KSVZ coupling.

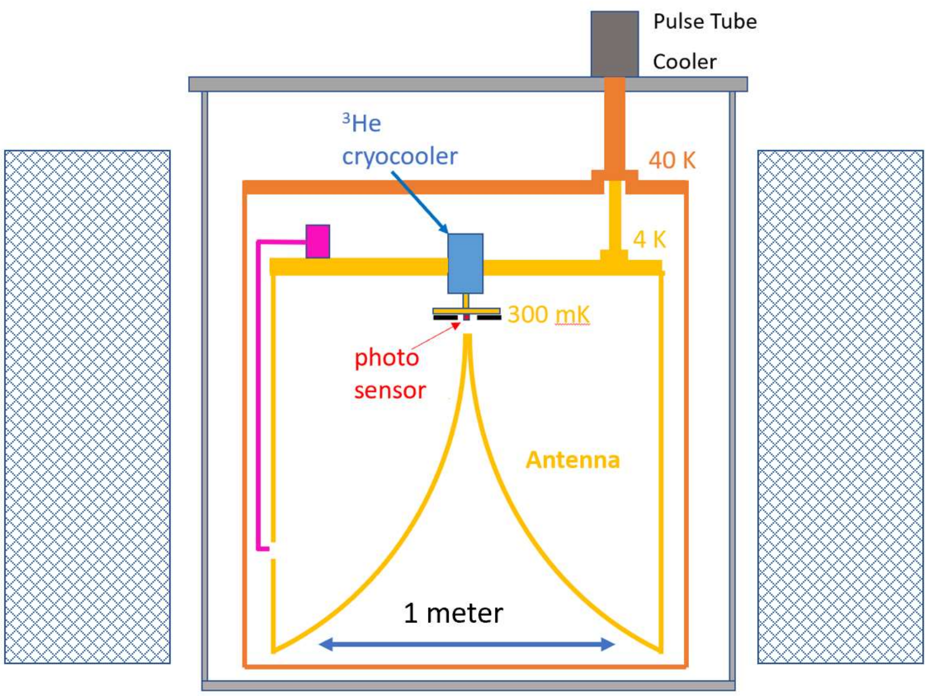
Extra Slides

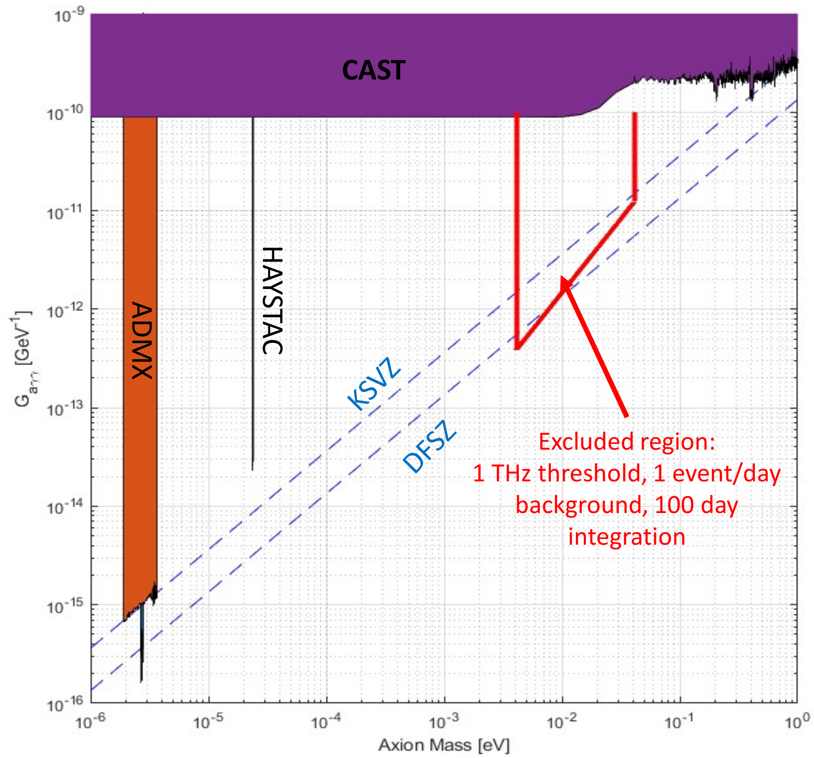


freq(1)=0.5 GHz Volume: Electric field norm (V/m)
freq(1)=1 GHz Volume: Electric field norm (V/m)
freq(1)=4 GHz Volume: Electric field norm (V/m)
1
0
-1
-2
-3
m
0.5
0
-0.5
-1
m

Example: THz Axion Search with MRI Magnet

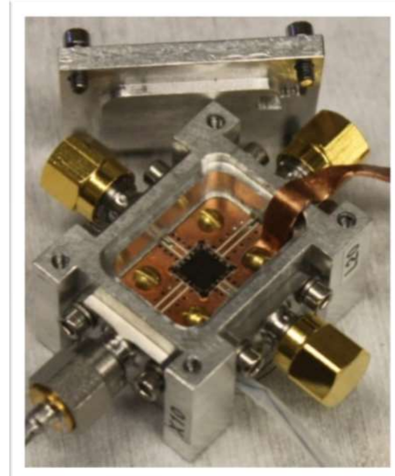
- 1 m diameter x 10 Tesla magnet. 1.4 m length (Similar to existing “ultra high field MRI”)
- 1 THz energy threshold using TES or MKID detectors in development.
- Assume 1 Event per day background & 100 day integration (note: background measured with magnet turned off)



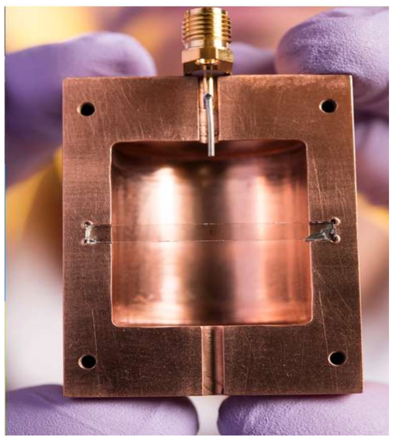


Quantum Sensor R&D for Axion Detection

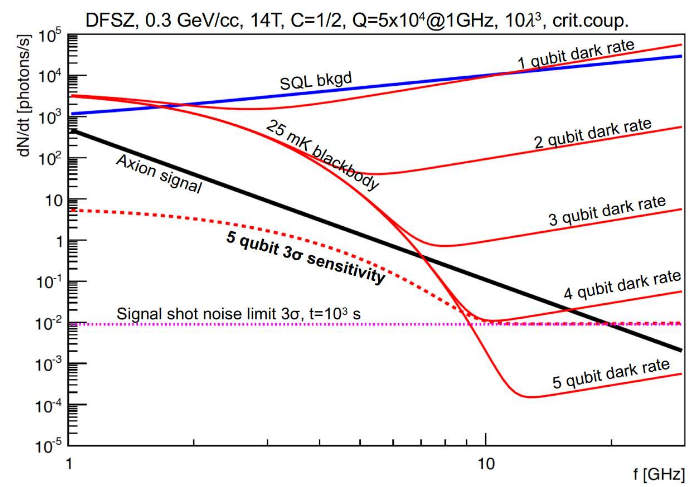
- Axion detection is natural application for quantum sensors.
  - Current Microstrip Squid Amplifiers (MSAs) and Josephson Parametric Amplifiers (JPAs) with noise close to standard quantum limit.
  - Future: Squeezed states prepared by JPAs, Qubit photon counters.



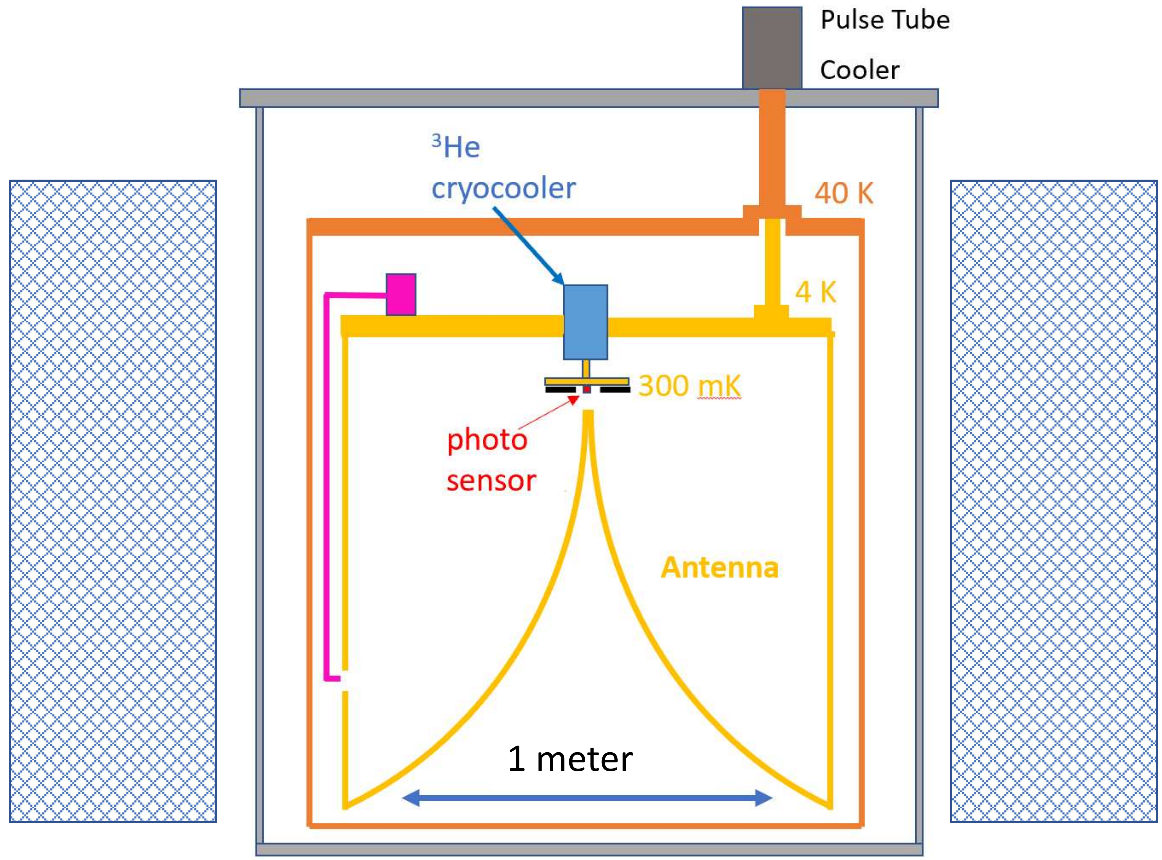
JPAs used for ADMX-G2 I. Siddiqi, UC Berkeley



Aluminum qubit on a sapphire substrate in a copper resonant cavity. A single photon in the cavity produces a qubit frequency shift (Dave Schuster, Akash Dixit, Aaron Chou)



Qubit sensitivity to Axions (A. Chou, FNAL)

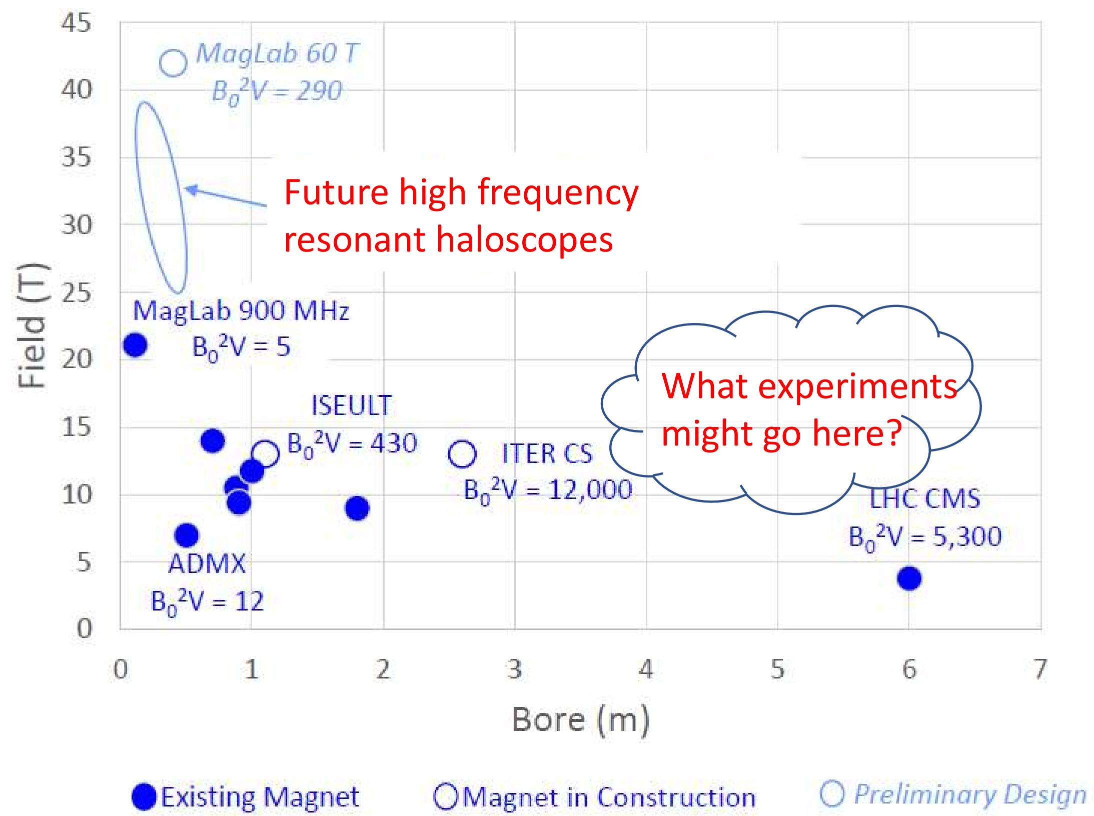

Pulse Tube
Cooler
3He
cryocooler
40 K
4 K
300 mK
photo
sensor
Antenna
1 meter

Field vs Bore

High B_0^2V ➡ Large Bore

Small Cavities ➡ Ultra High Fields

Long Duration ➡ High Temp Superconductors



Mark Bird, NHMFL

f_A : One Parameter Controls Everything

- f_A is the "axion decay constant", an unknown energy scale in the theory.
- Determines axion mass and all couplings

$$m_A = 5.70(7) \left(\frac{10^9 \,\mathrm{GeV}}{f_A} \right) \mathrm{meV}$$

Coupling to gluon field $\frac{a}{f_a} G_{\mu\nu} \tilde{G}^{\mu\nu}$

Coupling to electromagnetic field $\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$

Coupling to fermions $\frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f$

- f_A Originally identified with the electroweak symmetry breaking scale by Peccei and Quinn (~100 GeV), predicting axion mass to be ~ 100 keV.

Signal Power

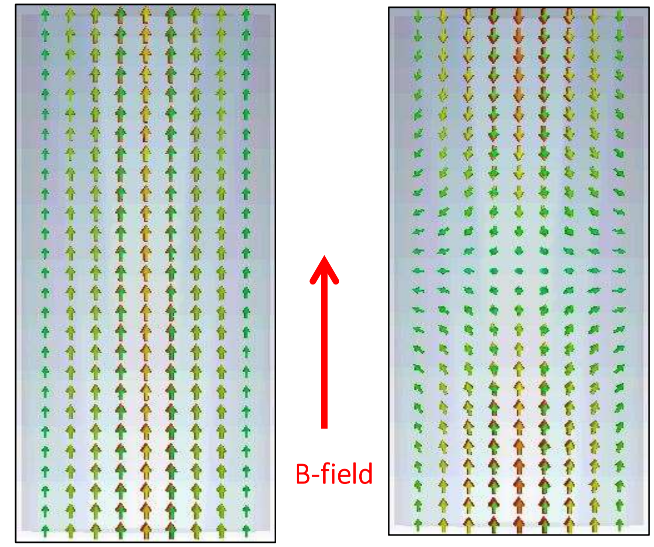
- Signal power:

$$P = 4 \cdot 10^{-22}\ \mathrm{W} \left(\frac{V}{200\ \ell}\right) \left(\frac{B_0}{8\ \mathrm{Tesla}}\right)^2 C_{nl} \left(\frac{g_\gamma}{0.97}\right)^2 \cdot$$
$$\left(\frac{\rho_\mathrm{a}}{0.5 \cdot 10^{-24}\ \mathrm{g/cm}^3}\right) \left(\frac{m_\mathrm{a}}{1\ \mathrm{GHz}}\right) \left(\frac{\min(Q_\mathrm{L}, Q_\mathrm{a})}{1 \times 10^5}\right)$$

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

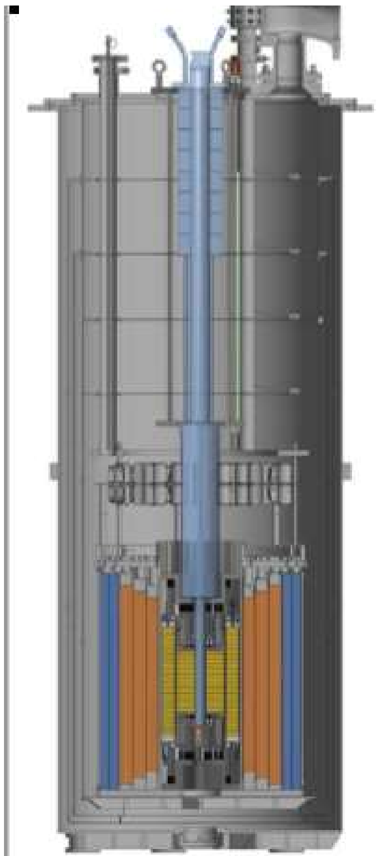
TM_{010} mode
$C_{010} \sim 0.69$

TM_{011} mode
$C_{011} \sim 0.0$

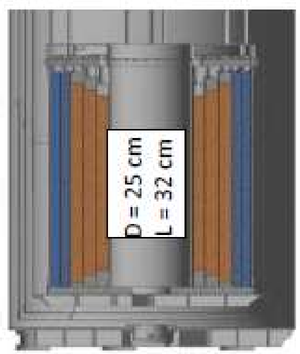


ADMX magnet conceptual design studies at NHMFL

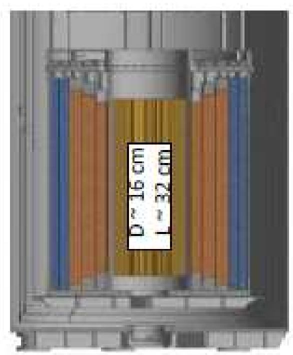
- 2018 considered using copy of 32 T outsert with a large rf cavity and later add NI-REBCO coils.
- Similar field and bore possible.
- Less REBCO required than all-NI system.
- Quench protection of nested NI-REBCO/LTS system required.



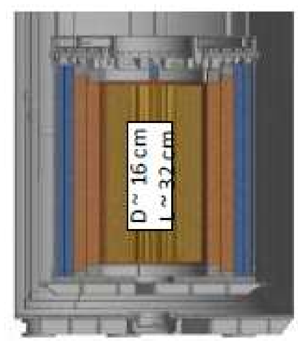
Existing 32 T Magnet



Existing 15 T, 25 cm
5 LTS



Potential 26 T, 16 cm
NI-REBCO + 5 LTS

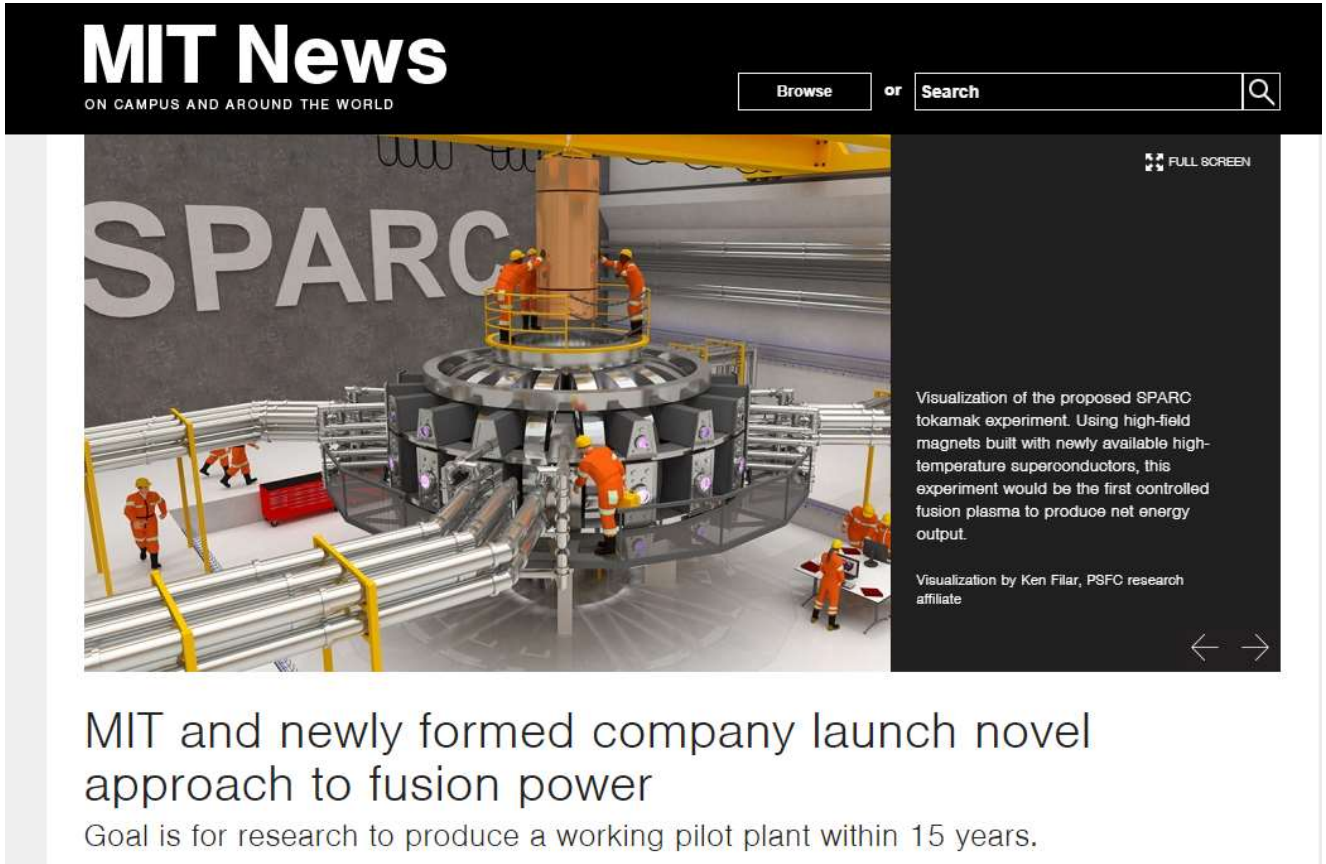


Potential 30 T, 16 cm
NI-REBCO +4 LTS

H. Bai

Long Term Prospects for REBCO Magnets?

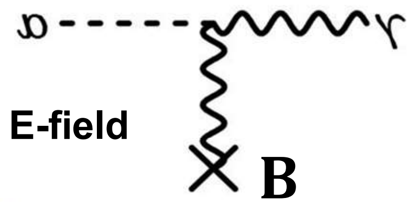
- Investment in large scale REBCO toroids and solenoids for compact fusion reactors.
- Power output claimed to scale as $\mathbf{B}^4$
- REBCO magnet technology will need to go from 3 cm scale of current state of the art to meter scale.

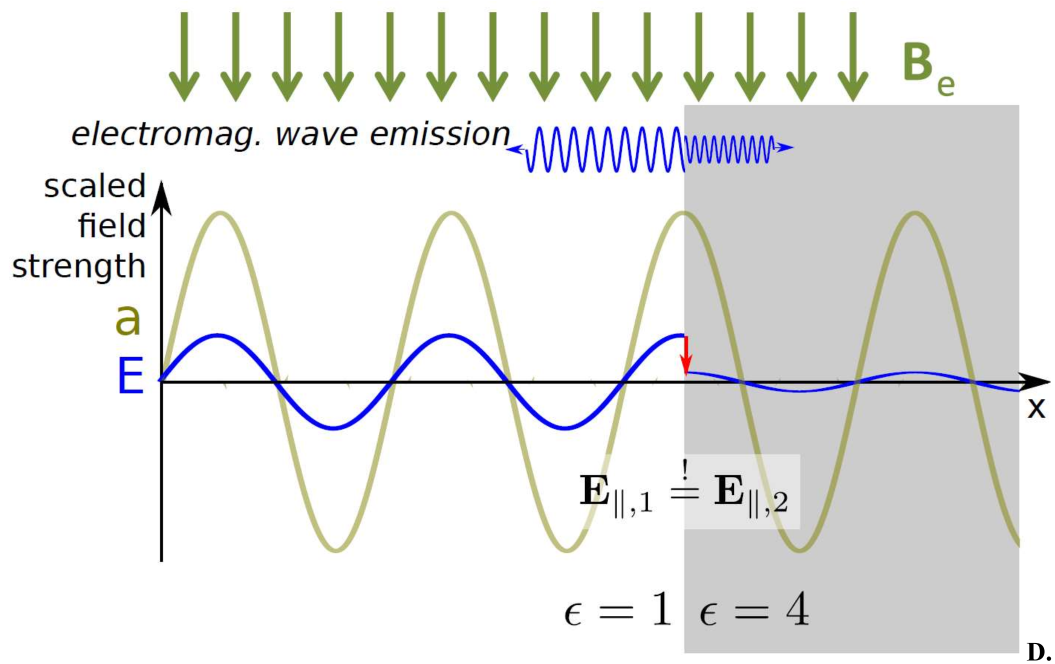


Reactor concept https://arxiv.org/pdf/1409.3540.pdf

Experimental approaches: Effect of Dielectric

Mixing of axion with photon in extrenal B-field
→ Sources oscillating E-field
At surfaces with transition of ε: Discontinuity of E-field
→ Emission of photons

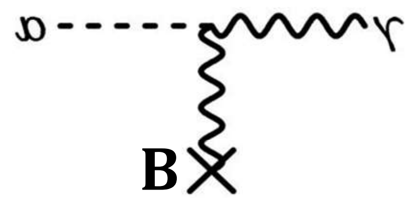




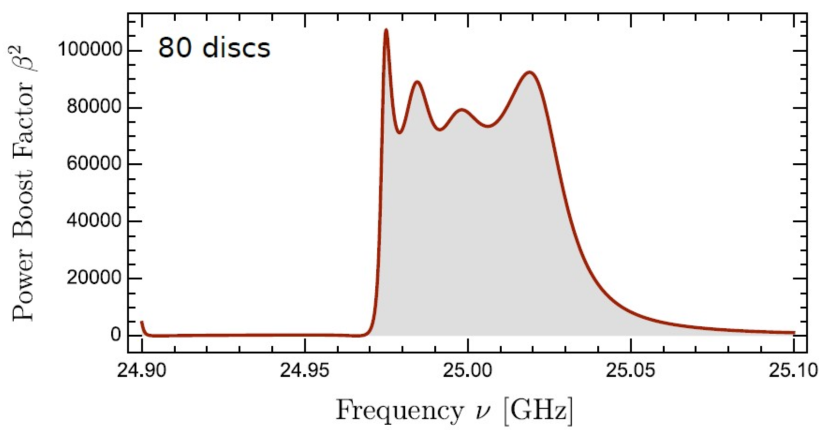
$$\left(\frac{P}{A}\right)_{mirror} \sim 2 \cdot 10^{-27} \frac{W}{m^2} \left(\frac{B_{||}}{10\ T}\right)^2 \left(g_{a\gamma\gamma} m_a\right)^2$$

D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald JCAP 1304 (2013) 016 [arXiv:1212.2970].

Experimental approaches
Dielectric haloscopes:

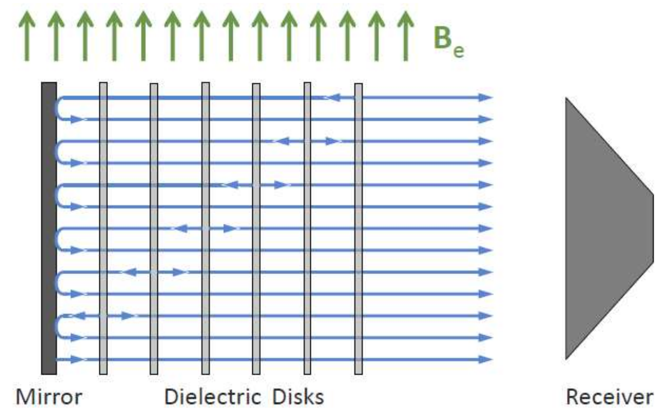


- **Mixing of axion with photon in extrenal B-field**
  → Sources oscillating E-field
- **Many surfaces with transition of ε:**
- **→ Coherent emission of photons from each surface**
- **Interference effects can be exploited**



$$\left(\frac{P}{A}\right)_{cavity} \sim 2\cdot 10^{-27}\frac{W}{m^2}\left(\frac{B_{||}}{10\,T}\right)^2 \left(g_{a\gamma\gamma} m_a\right)^2 \beta^2$$

A. Caldwell et al, Phys. Rev. Lett. 118, 091801 (2017)



“Quasi broadband” approach
Also works for kinetic mixing
→ Sensitive to hidden photon,
no B-field needed

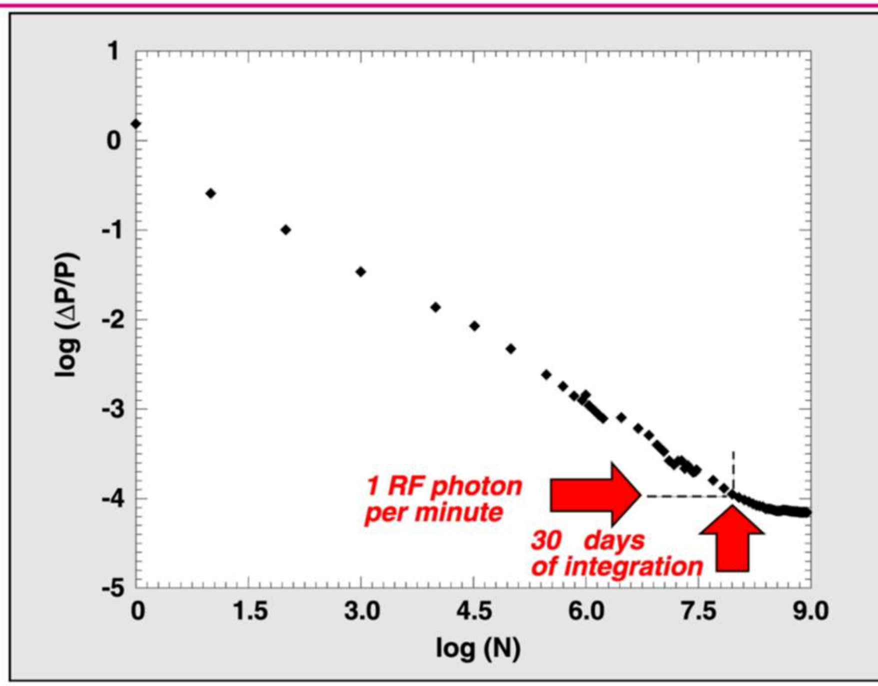
Patras 2018

Signal to Noise Ratio- Example

- $T_{Noise} = \frac{1}{k_B} \frac{Noise\ Power}{Bandwidth}$
- Suppose we have $T_{Noise} = 0.5\ Kelvin$
- $P_{noise} = k_B T_{Noise} * Bandwidth = 0.5 \cdot 1.4 \times 10^{-2}\ \ W/Hz \cdot Bandwidth$
- Bandwidth of axion is due to halo velocity dispersion $\frac{\Delta f}{f} \sim 10^{-6}$
- $\sim$ 1 kHz at 1 GHz axion frequency
- So $P_{noise} \sim 10^3 Hz \cdot \frac{10^{-23} W}{Hz} = 10^{-20} W$
- Still about three orders of magnitude larger than the signal!

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

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 TM010 modes
- *Was not a blind "synthetic axion" signal injected by the calibration team*
- Scales with the B^2 of the magnet
- Has an annual frequency modulation

No signal candidates yet