Opportunities for SRF Cavities in the ADMX-EFR Project

Quantum Technologies for Fundamental Physics Workshop
Erice, Italy

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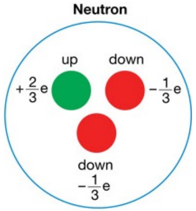
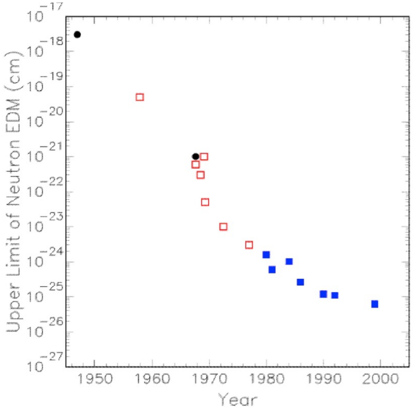
Axions: A solution to two major mysteries in physics and cosmology

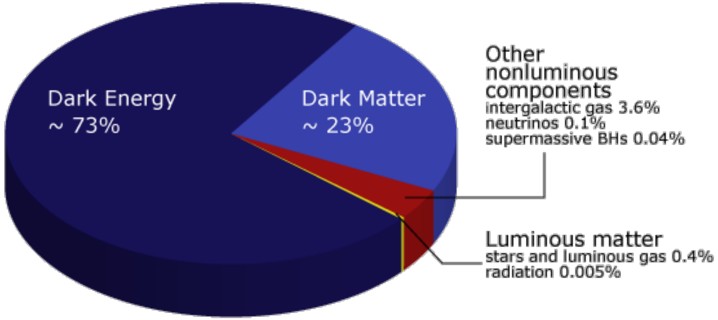
Strong-CP problem

Strange absence of measurable neutron electric dipole moment

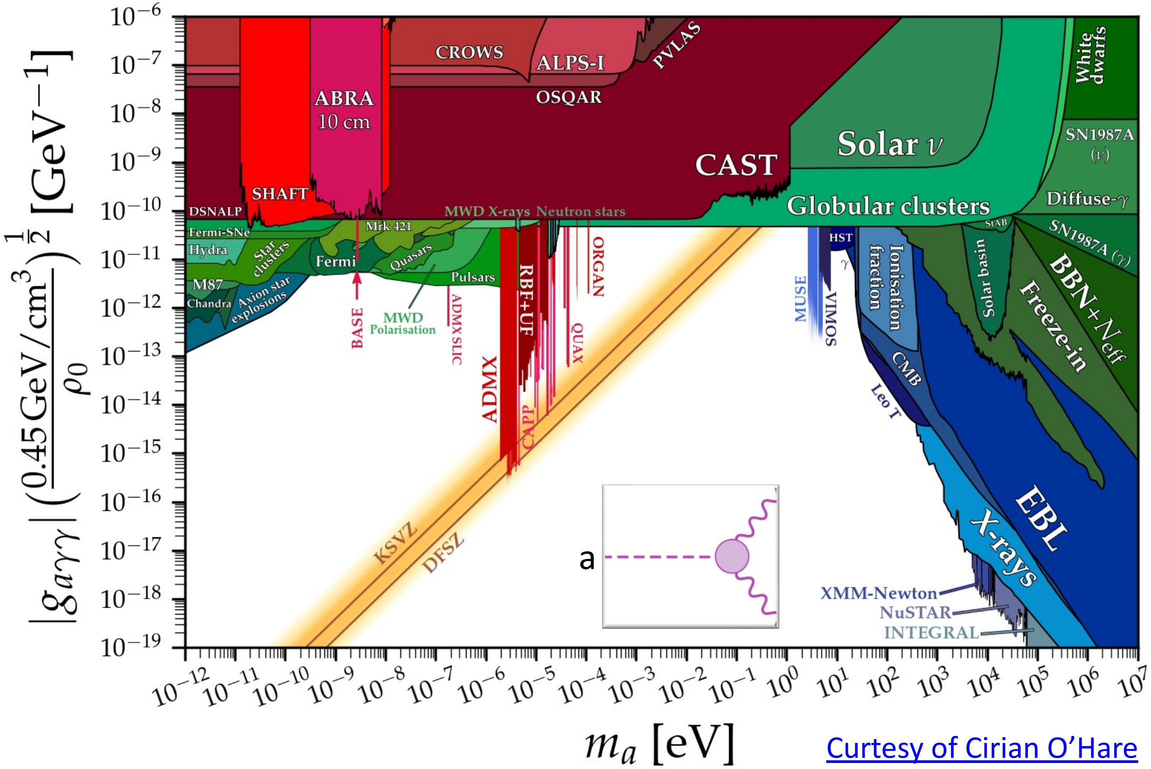




Dark Matter



Axion coupling to two photons a key detection technique



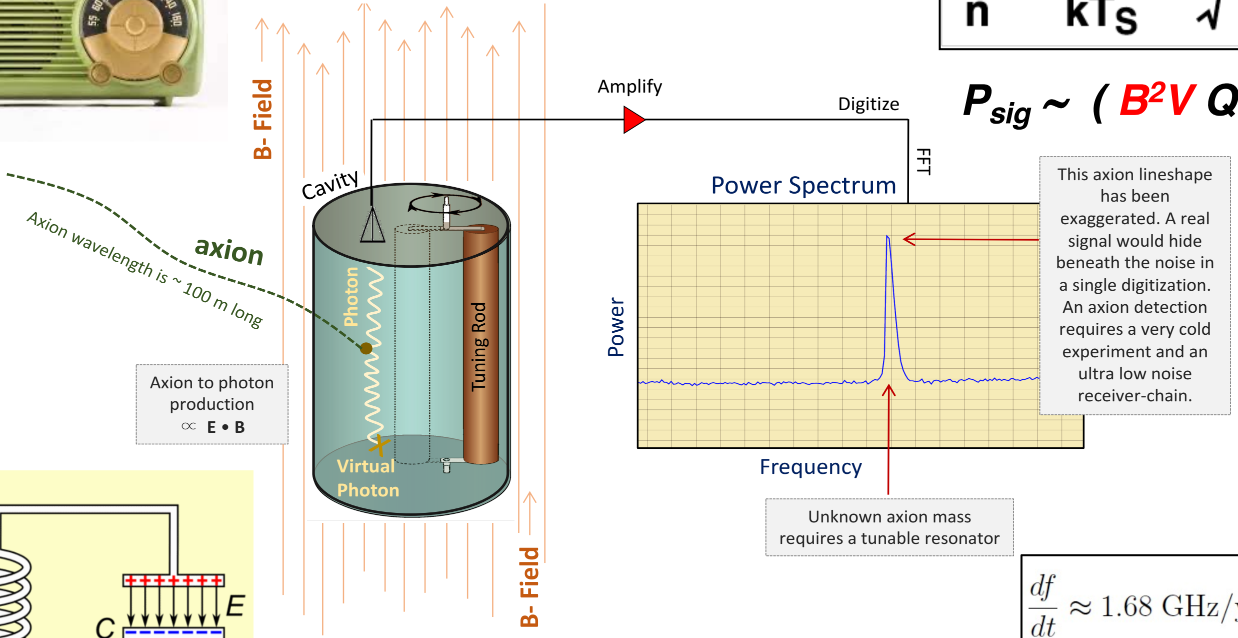
Curtesy of Cirian O'Hare

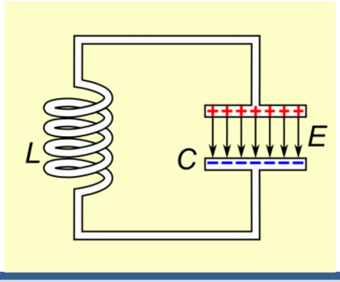
Axion Dark Matter Searches: The Haloscope Technique

Pierre Sikivie

$$\frac{s}{n} = \frac{P_{sig}}{kT_S} \cdot \sqrt{\frac{t}{\Delta\nu}}$$

$$P_{sig} \sim (B^2 V\, Q_{cav} C_{010})(g^2 m_a \rho_a) \sim 10^{-24}\ W$$





System noise temp.

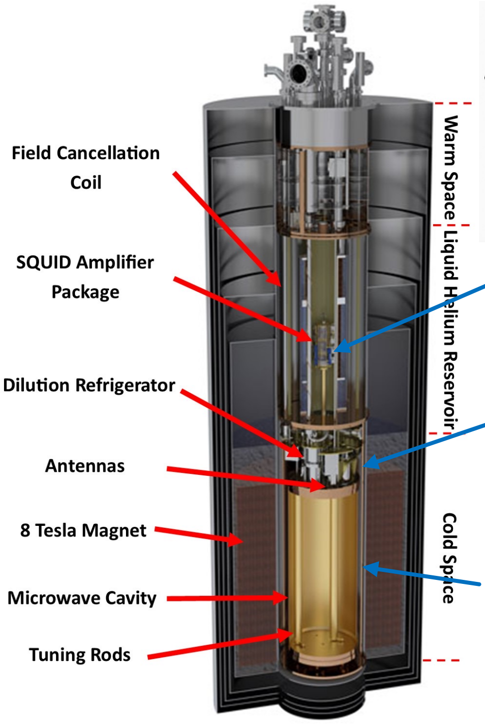
$$T_S = T_{phys} + T_N$$

$$T_{Quant} \sim 48\ mK\ @\ 1\ GHz$$

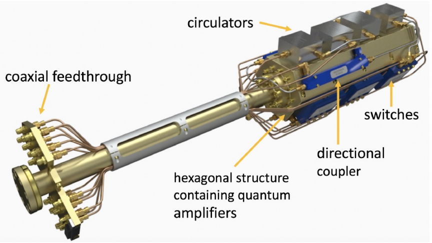
t = Integration time limited to ~ 100 sec

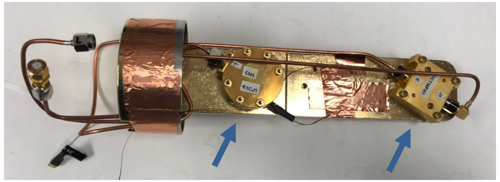
$$\frac{df}{dt} \approx 1.68\ \mathrm{GHz/year}\ \left(\frac{g_\gamma}{0.36}\right)^4 \left(\frac{f}{1\ \mathrm{GHz}}\right)^2 \left(\frac{\rho_0}{0.45\ \mathrm{GeV/cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2 \left(\frac{B_0}{8\ \mathrm{T}}\right)^4 \left(\frac{V}{100\mathrm{l}}\right)^2 \left(\frac{Q_L}{10^5}\right)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

ADMX Currently Operating Project: Experimental Layout

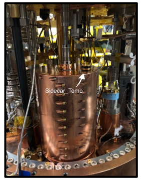


Cavity 1B

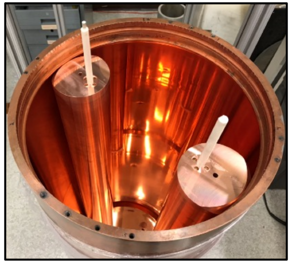




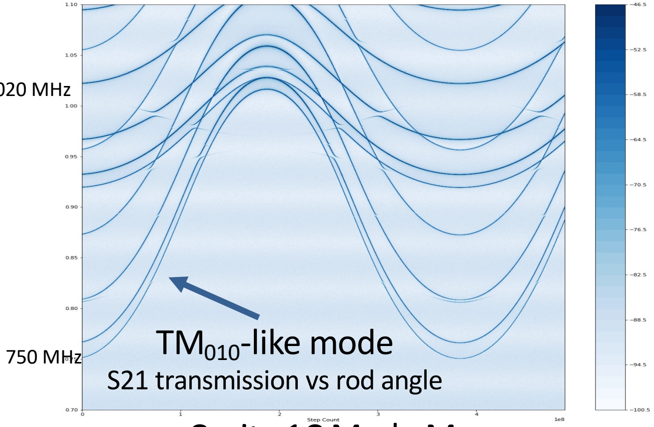
JPA (UCB) TWPA (LL)



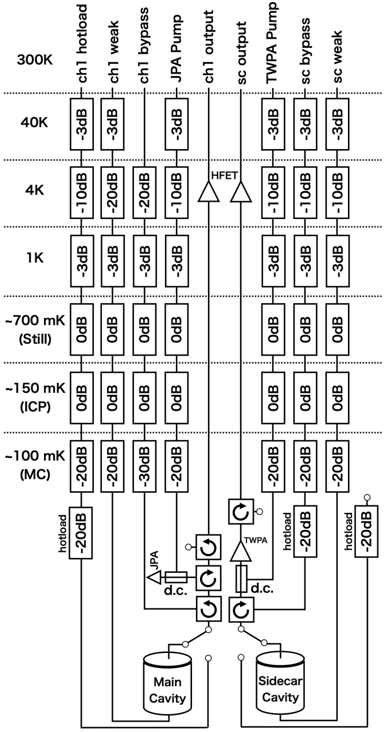
Sidecar



Cavity 1C



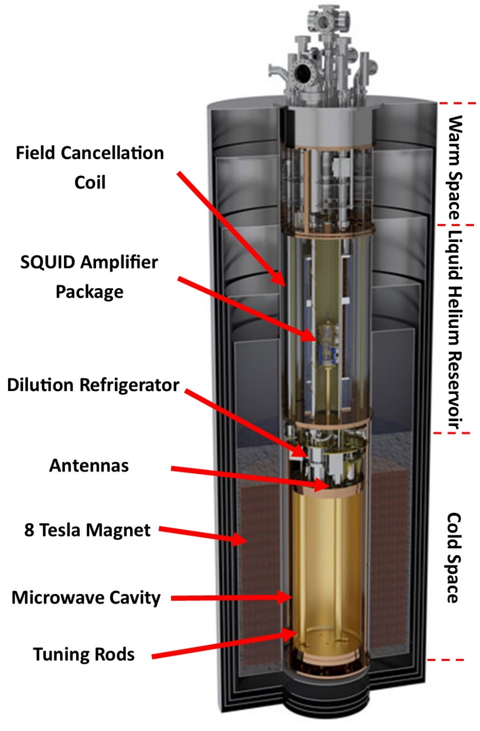
Cavity 1C Mode Map



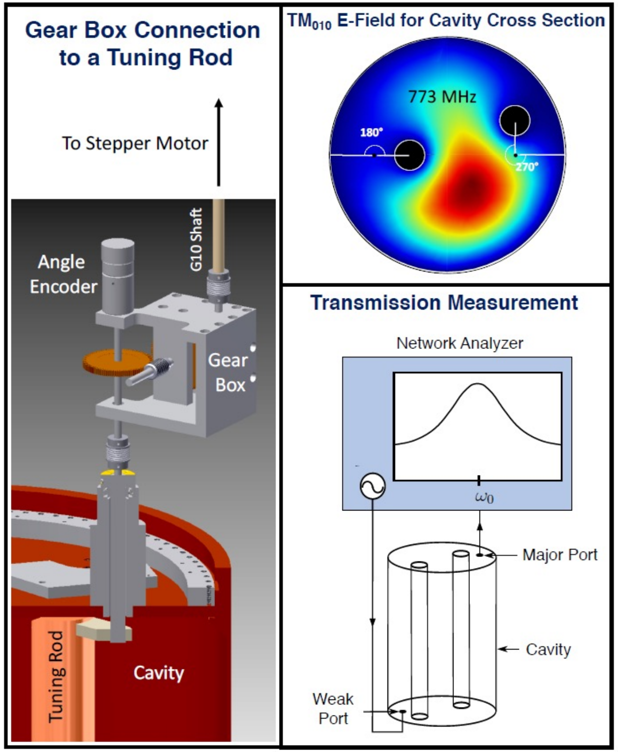
As of October 6, 2021

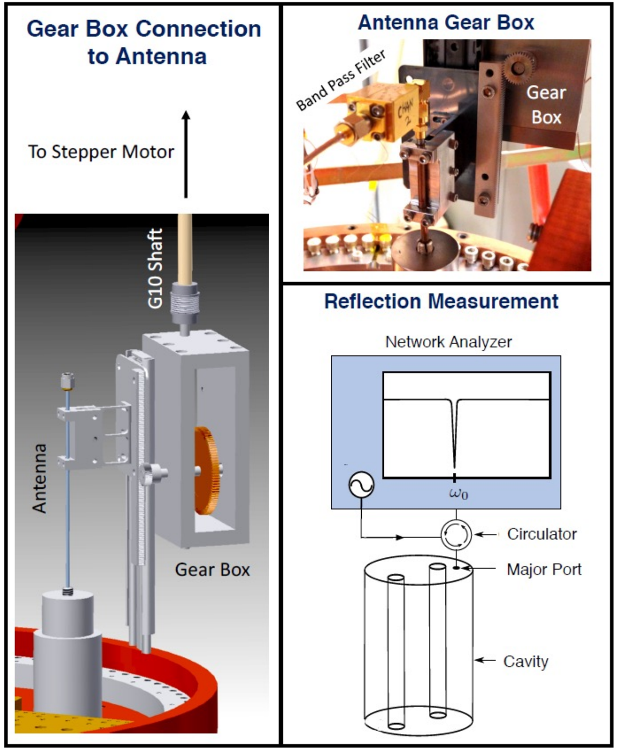
Located at the University of Washington

ADMX Operations: Tuning & Coupling

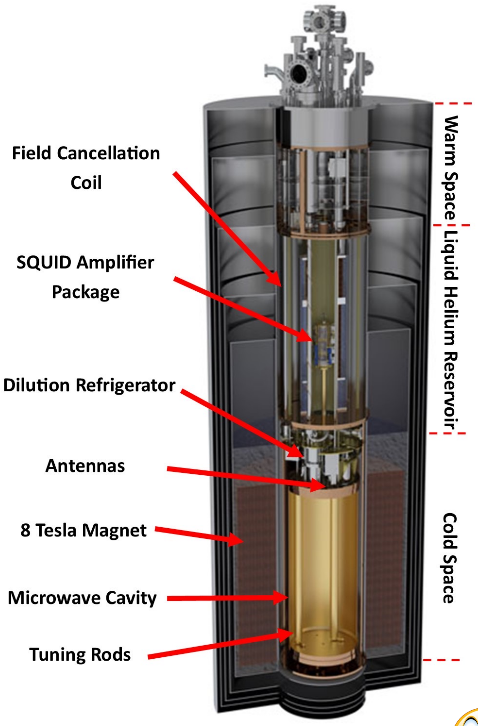


Cavity 1B

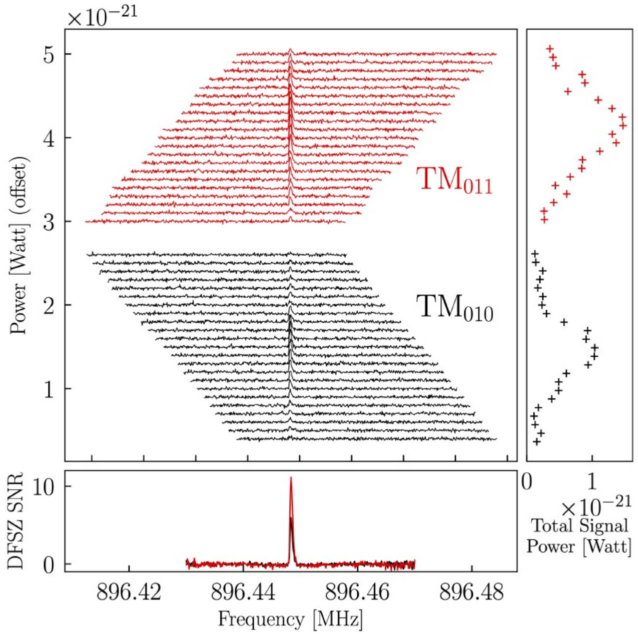


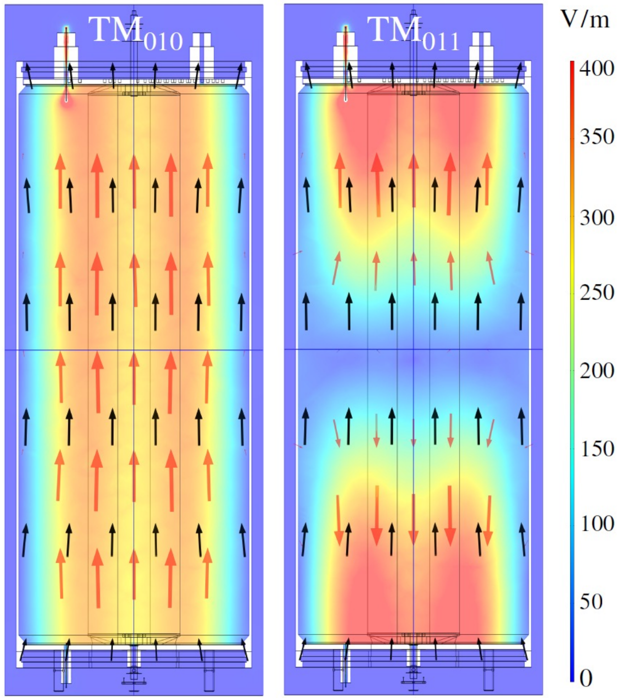


ADMX Run 1C: Saw Persistent Signal at 896.45 MHz!



Cavity 1B





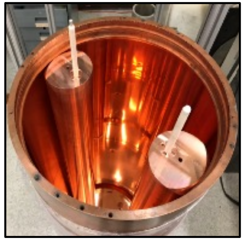
Signal had line-shape consistent with axion!
Power went away off resonance (not RFI)!

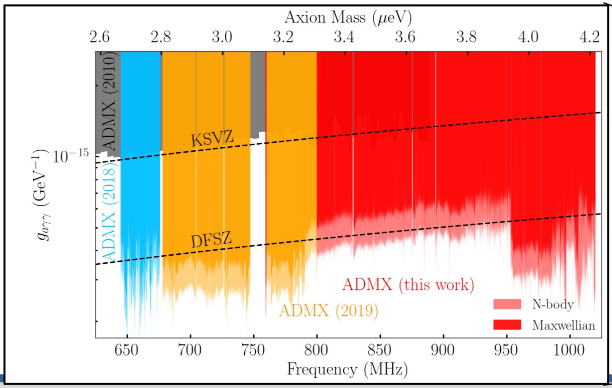
Seen in TM$_{011}$ mode as well
Fake axion from Blind Injection team

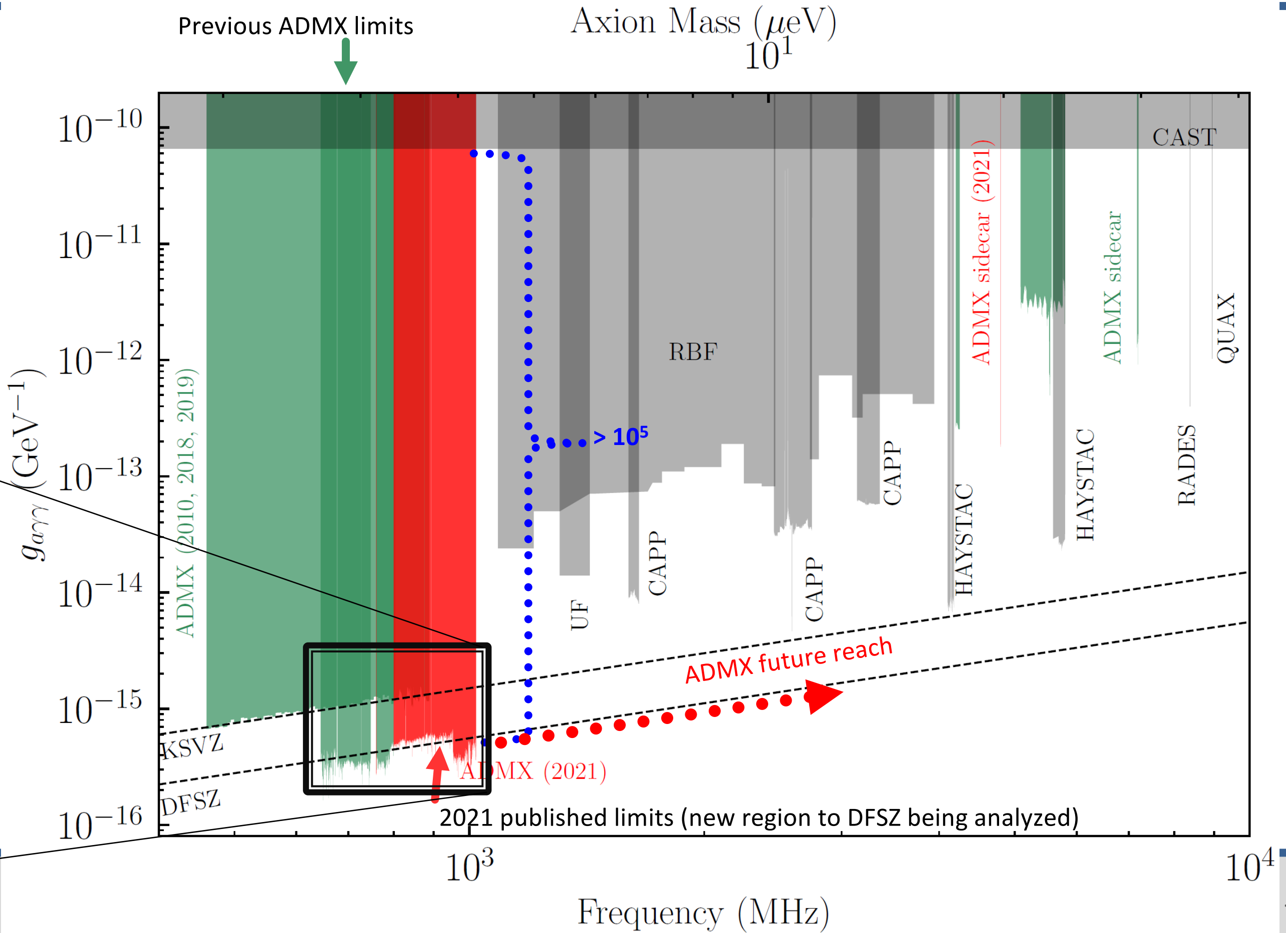
Located at the University of Washington

ADMX-G2 results and near term plans

- Operations in phases that match the cavity tunable bandwidths
- Previous runs with sets of two tuning rods (runs 1A, 1B, 1C)







ADMX-G2 results and near term plans

- Operations in phases that match the cavity tunable bandwidths
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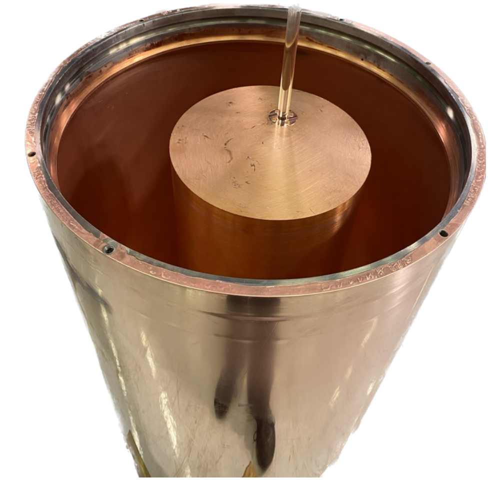
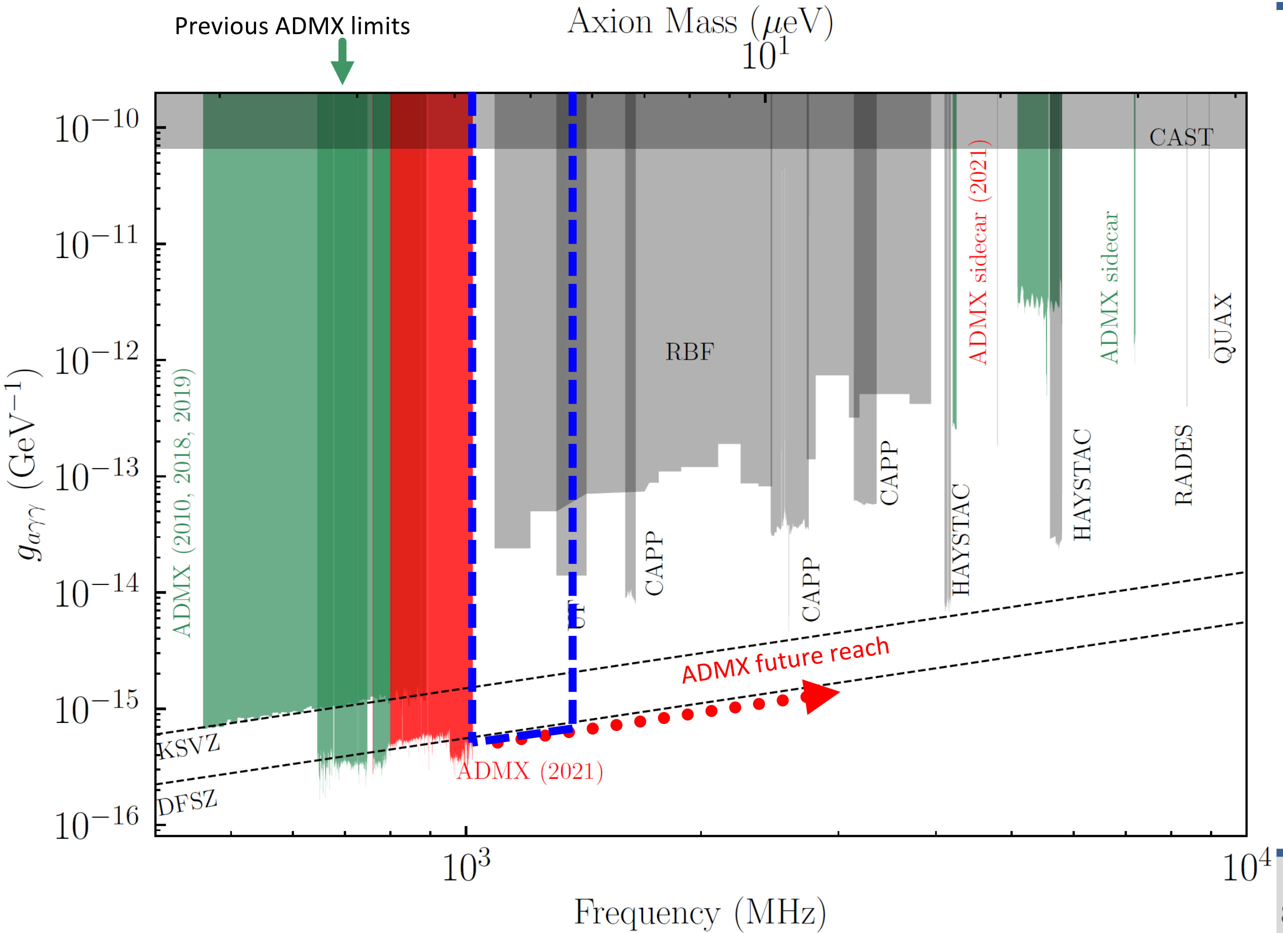
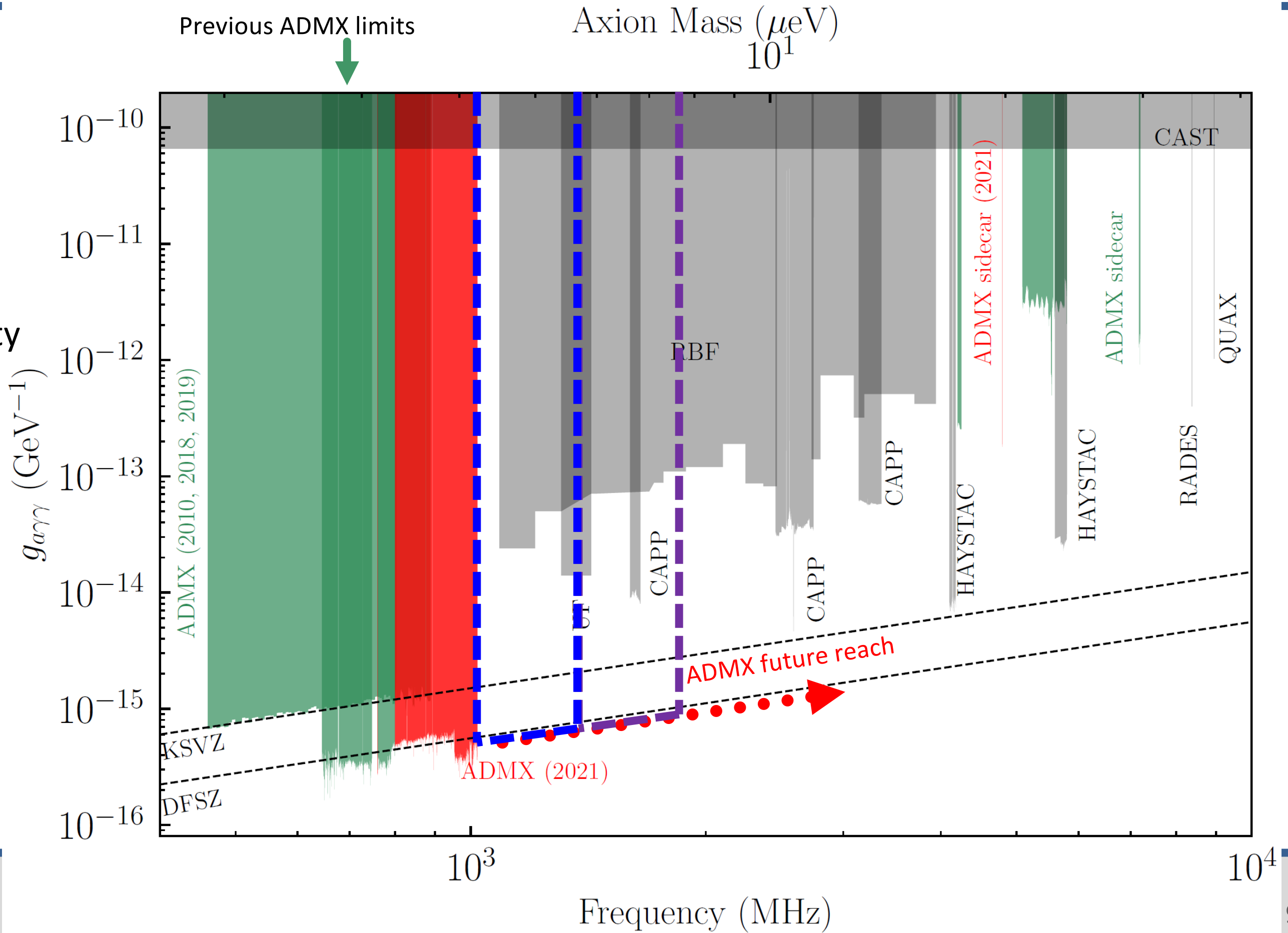
- Upcoming 1D (single rod) 1-1.4 GHz





ADMX-G2 results and near term plans

- Operations in phases that match the cavity tunable bandwidths
- Previous runs with sets of two tuning rods (runs 1A, 1B, 1C)
- Upcoming 1D (single rod) 1-1.4 GHz
- Switch to frequency locked 4-cavity array for 1.4-1.9 GHz



ADMX-Extended Frequency Range (2-4 GHz)

DOE HEP sponsored *Dark Matter New Initiative* project

Picks up where ADMX-G2 ends (~1.9 GHz)

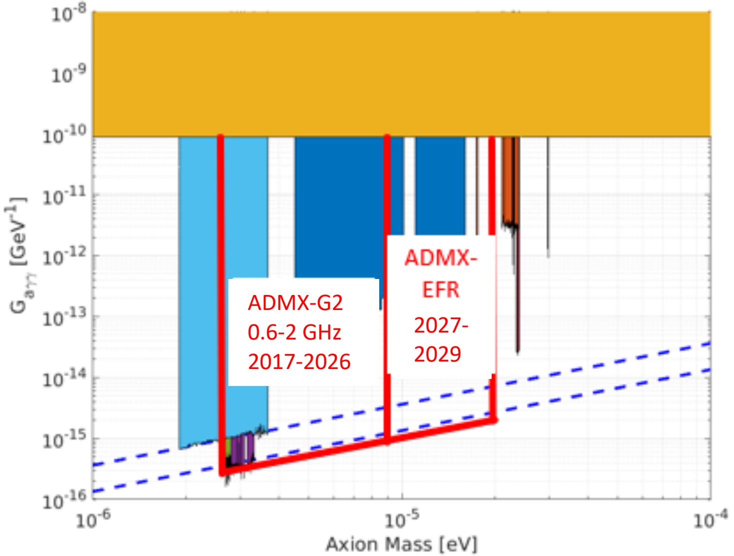
Currently in Design and Prototyping Phase

Aiming for construction start FY25. Aimed to be installed at Fermilab!

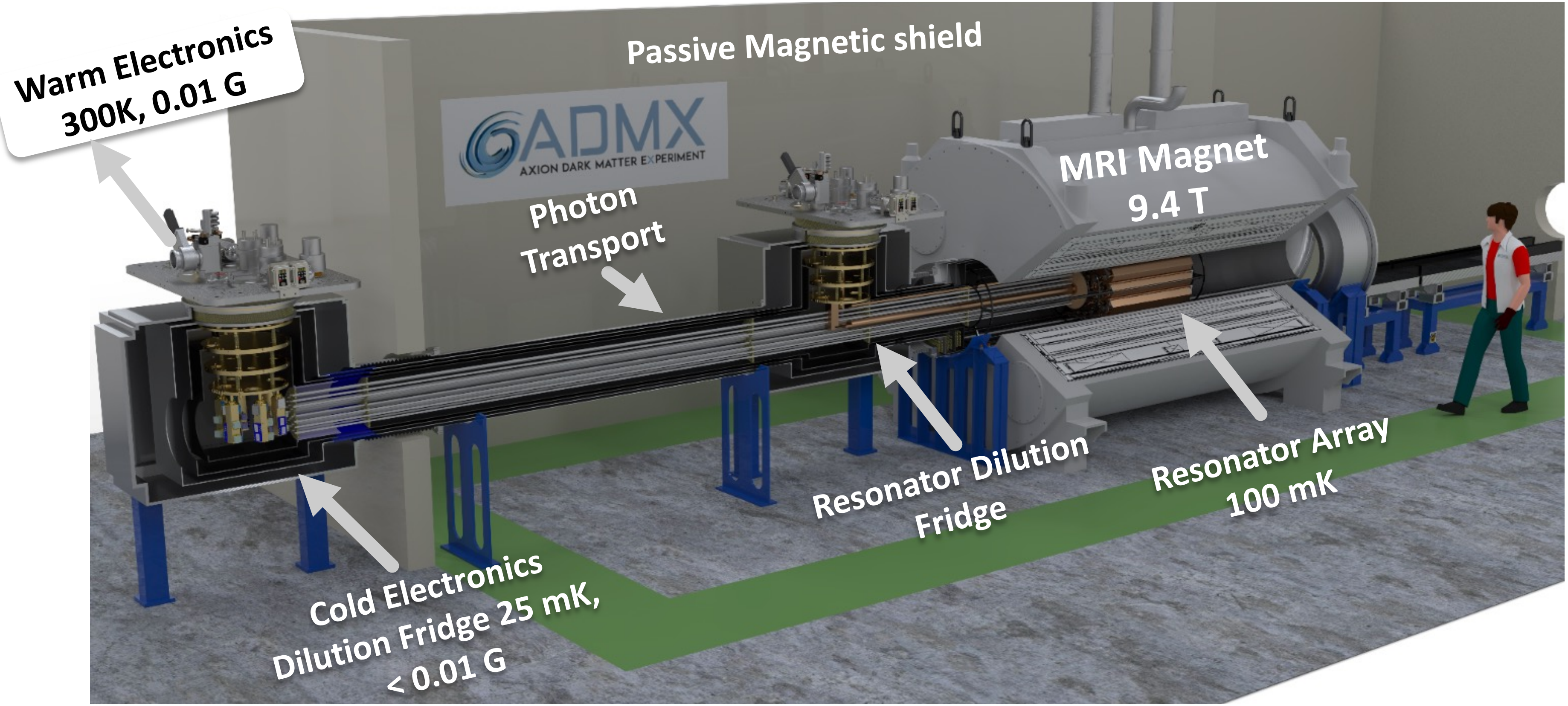
New MRI magnet being acquired (9.4 T – 800 mm bore)

	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

9.4 T 800 mm bore MRI magnet

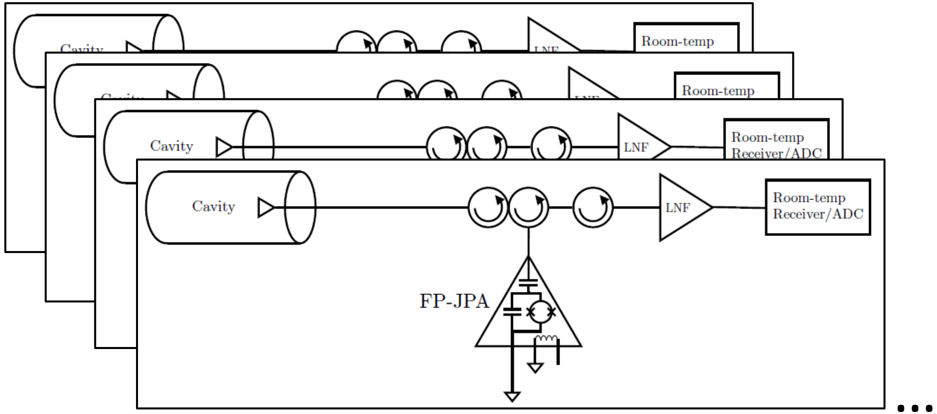


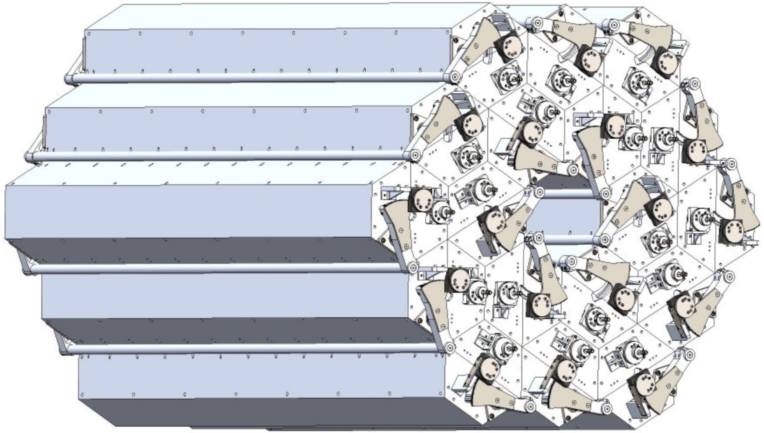
ADMX-Extended Frequency Range



Overall System Concept

- 18 cavities each instrumented with their own quantum amplifier chain and readout.
- In-phase amplitude combing digitally at room temperature

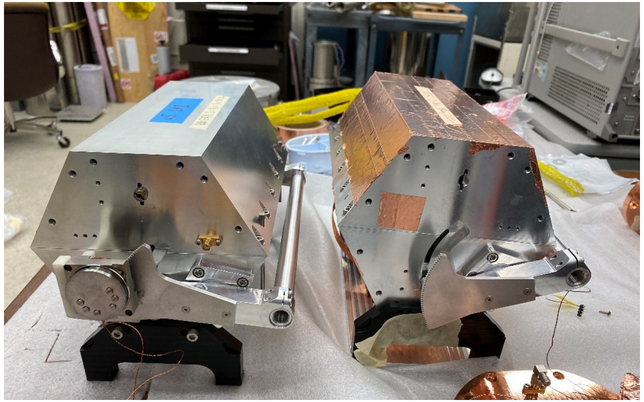




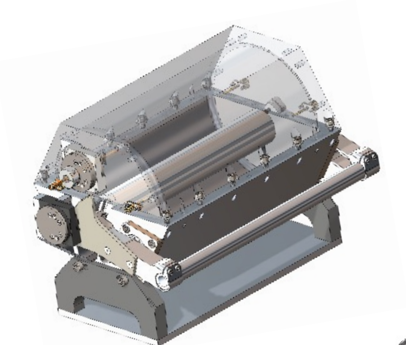
- Takes full advantage of coherence of axion signal relative to incoherent noise
  - SNR goes as √N cavities coherently combined.
  - Scan rate goes as $SNR^2 \sim N$. Factor of 18 x faster scanning than non-locked individual cavities
- Maximal flexibility, system repeatability and mass production

Resonator Design currently clamshell cavity

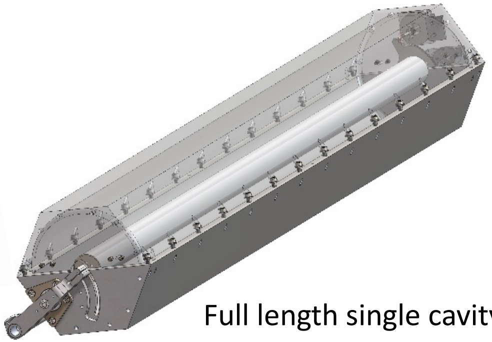
- Current baseline cavity cell is ~1 m long copper cavities with copper tuning rods.
- Two sets of tuning rods diameters (2-3 & 3-4 GHz with same clamshells)
- Piezoelectric actuators for frequency tuning & antenna coupling



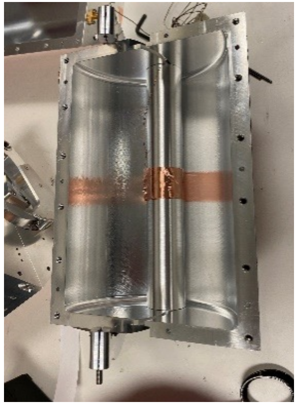
Postdoc Nick Du mounting scale length prototypes in dilution refrigerator



Scale length single cavity cell (~ ¼ m long)



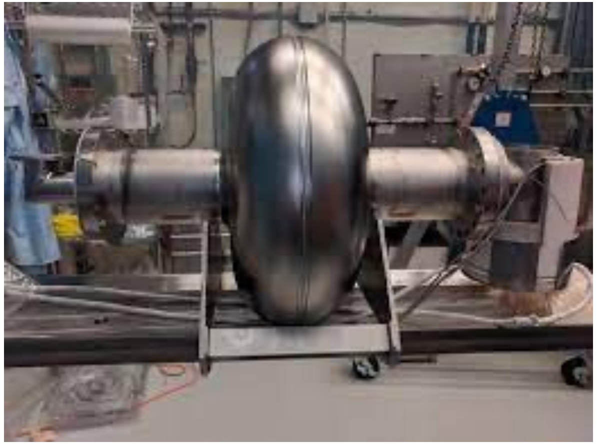
Full length single cavity cell (~ 1m long)



Tuning rod wired for thermal time-constant studies of sapphire axles

What about using superconductors for cavities?

- Extremely low RF resistance is ideal for high Q resonators
- Standard for accelerator cavities with typical $Q_0 \cong 10^{10}$ **in zero magnetic field**
- ADMX Copper cavities, $Q_0 \cong 10^4 - 10^5$
- **Axion $Q_a > 10^6$**



Accelerator Cavity. Image credit: Fermilab SQMS

ADMX Copper Cavity (Run 1D)

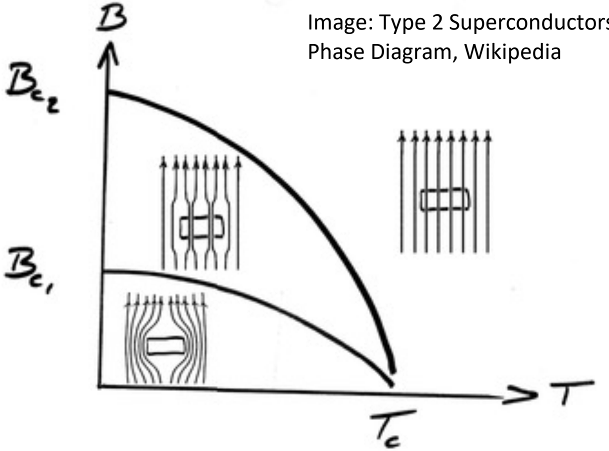
The Challenge for ADMX SRF cavities

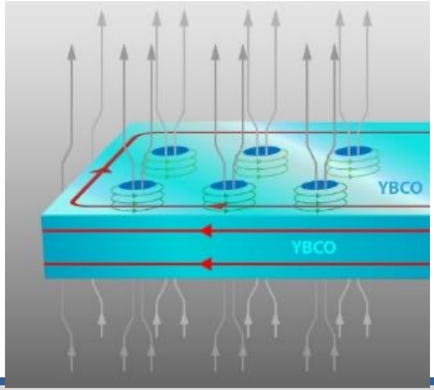
ADMX AXION DARK MATTER EXPERIMENT

- **Meissner Effect:** the expulsion of magnetic field upon super-conduction (Below critical fields B_{c1} , B_{c2} in Type II SCs)

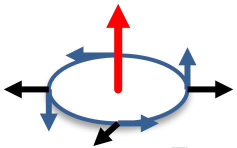
- **Problem:** SRF cavity quality factor quickly degrades in external magnetic fields due to breakdown of Meissner Effect
  - Development of vortices' or fluxons with magnetic field (normal regions) in Type II Superconductors
  - Magnetic vortices' motion drive up the surface resistance.
  - **Maximal loss for surfaces perpendicular to magnetic field** with greatest Lorentz forces (end caps) on the fluxons.

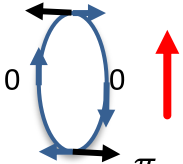
Image: Type 2 Superconductors Phase Diagram, Wikipedia





$\vec{F} = \vec{I} \times \vec{B}$





$\overrightarrow{F_\perp} = |I||B| \sin\frac{\pi}{2} = |I||B|$

$\overrightarrow{F_\parallel} = IB\,(\sin 0 + \sin\frac{\pi}{2}(\hat{r} - \hat{r})) \approx 0$

Possible Solution: Hybrid Material Cavity

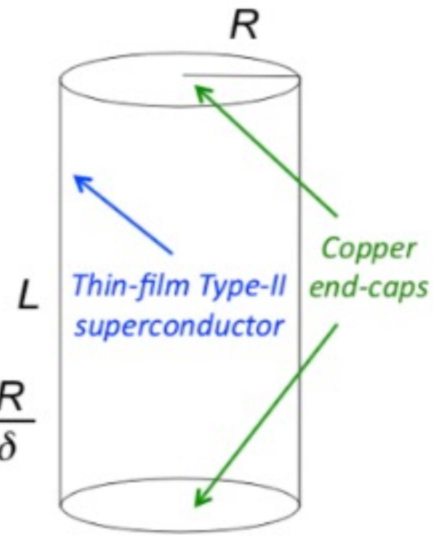
$$Q^{Copper} = \frac{L/R}{1 + L/R} \cdot \frac{R}{\delta}$$

$$\frac{Q^{Hybrid}}{Q^{Copper}} = \left(1 + \frac{L}{R}\right)$$

$$Q^{Hybrid} = \frac{L/R}{1 + \cancel{L/R}} \cdot \frac{R}{\delta}$$

$L/R \to 0$

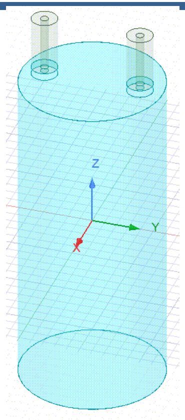
Wall contribution goes to zero



- Since vortex losses are minimal for surfaces parallel to field, only coating the walls of the cavity cuts out most dissipative part
- For an empty cavity, Q of the TM_{010} mode improves by a factor of $(1 + {}^{L}/_{R})$ when the barrel is coated with a thin-film superconductor.

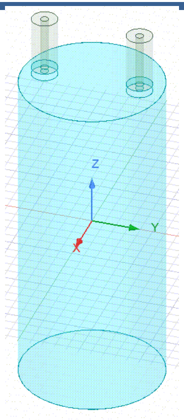
Test Cavity Geometries:
Multi-mode Measurements with NbTi Clamshell

- Cavity machined out of NbTi Square stock
- Looked at first 3 TM modes Q
- HFSS simulations of the cavity structure yields the geometric factor estimate for each mode and sub-surface
- This over-constrained problem allows us to calculate the wall vs. endcap resistance



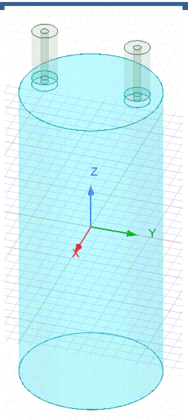
TM_{010}

$f_0 = 9.95GHz$



TM_{011}

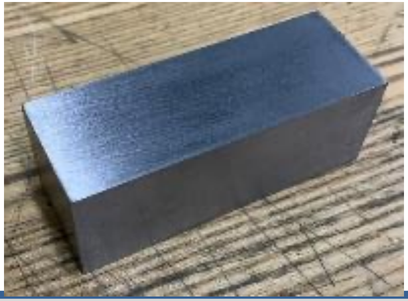
$f_0 = 10.37GHz$



TM_{012}

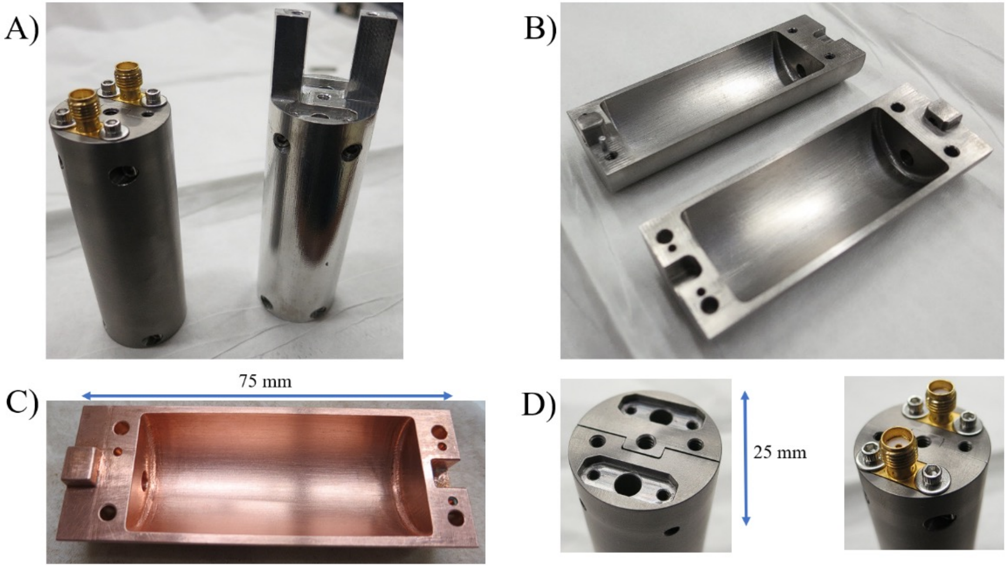
$f_0 = 11.47GHz$

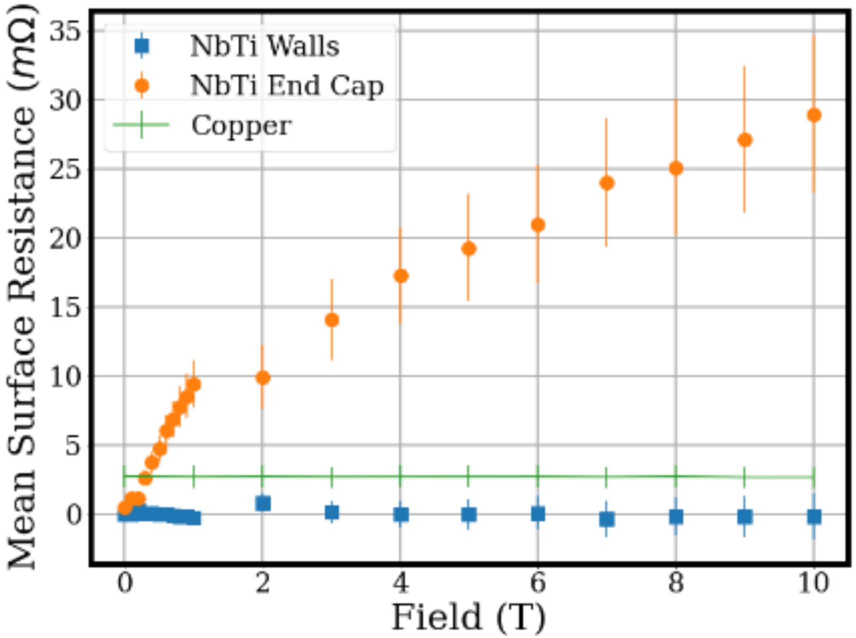
Geometric Factor (Ω)	TM_{010}	TM_{011}	TM_{012}
Walls	448	464	512
Top End Cap	4060	2194	2407
Bottom End Cap	4375	2173	237
Total End Caps	2106	1092	1195



NbTi Clamshell Cavity RF losses in Field: endcaps vs walls

- Applied method to show the endcap degradation in a Bulk NbTi clamshell cavity
- NbTi: $B_{c2} > 14\ T\ , T_c \cong 8.3\ K$
- Thesis work of UW grad student Tom Braine





T. Braine et al. Multi-mode analysis of surface losses in a superconducting microwave resonator in high magnetic fields. *Rev Sci Instrum* 1 March 2023; 94 (3): 033102. https://doi.org/10.1063/5.0122296

Simulations allow calculation of Geometric Factors

ADMX AXION DARK MATTER EXPERIMENT

Q ~ Geometric Factor / Surface loss (Rs)

Rs_{Cu} = 2.9 mOhm at cryogenic temps

Q_{total} ~ 3e2 Ohm/2.9 mOhm
Q_{total} ~ 10^5 (all Copper Cavity)

Rs: Walls & Rods << lids

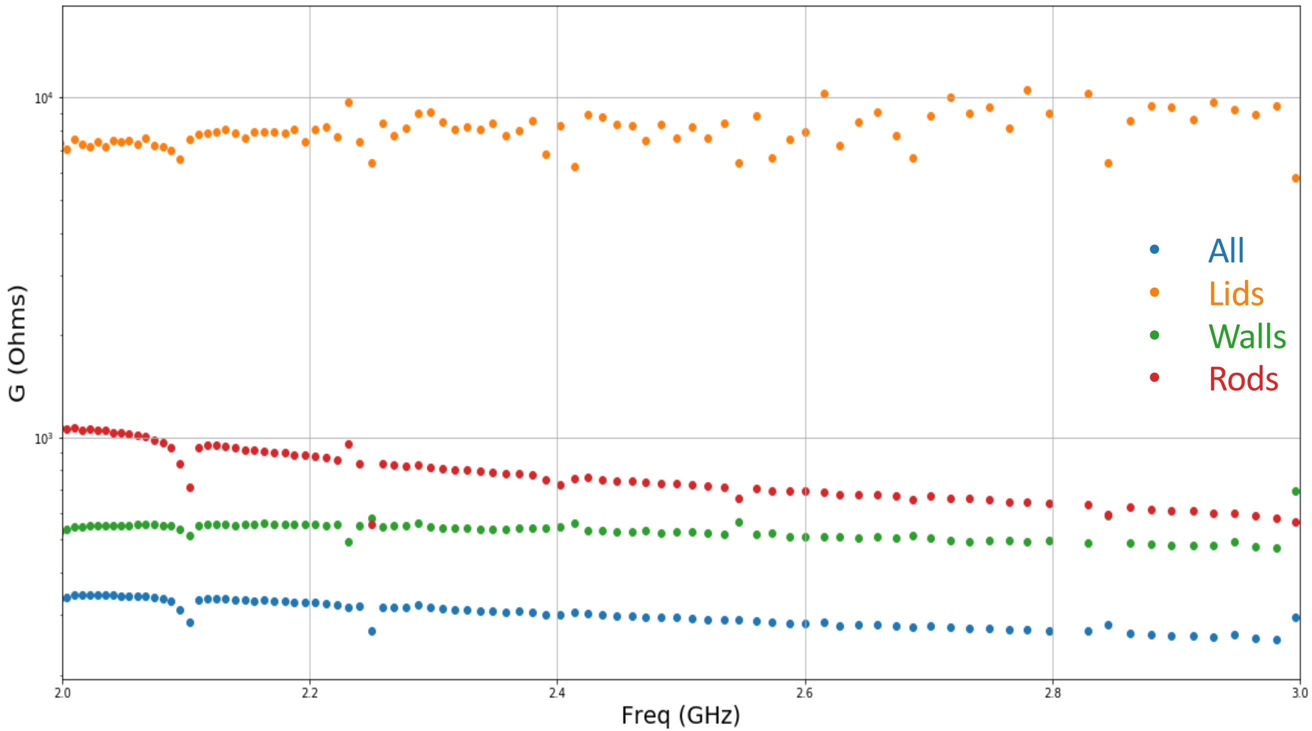
Eliminating Wall & Rod contributions due to parallel field and assuming losses dominated by copper endcaps

Q_{lids} ~ 8e3/2.9 mOhm

Q ~ 2.75e6 (x 27.5 higher Q)
Optimalization of shape of endcaps will likely allow lower RF losses (higher Q)

Need to maintain high form-factor & minimize number of mode-crossings

ADMX-EFR Geometric Factors as function of frequency (current design)

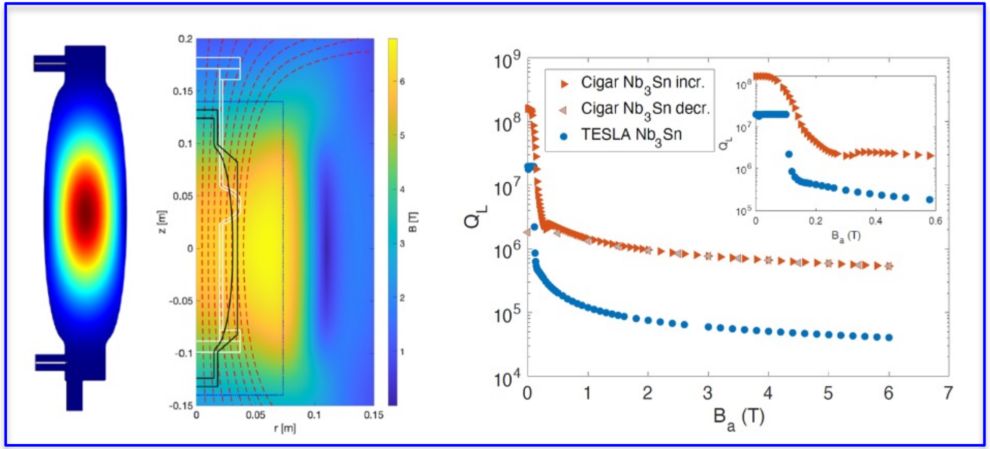


B-field tolerant SRF cavity development worldwide

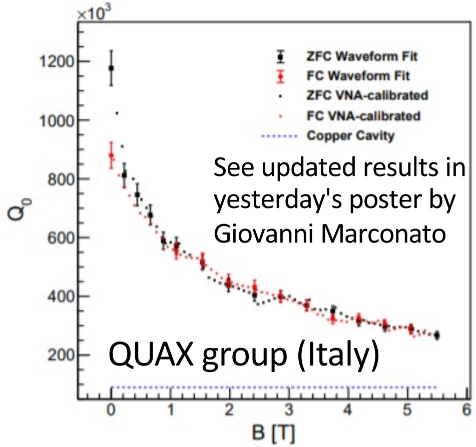
ADMX AXION DARK MATTER EXPERIMENT

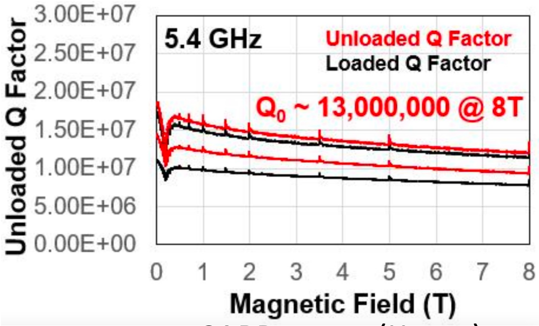
Worldwide there has been excellent progress on field-tolerant SRF cavities for axion searches
3 potential materials (NbTi, Nb3Sn, and YBCO)

- **NbTi** sputtered cavities as inspired by QUAX group
- **Nb3Sn on Niobium led by SQMS** (Sam Posen & Anna Grasselino)
- **Nb3Sn on Copper** collaboration with Florida Statue U. (Lance Cooley)
- **HTC (EuBCO+APC)** superconducting cavities CAPP



Recent SQMS results with Nb3Sn

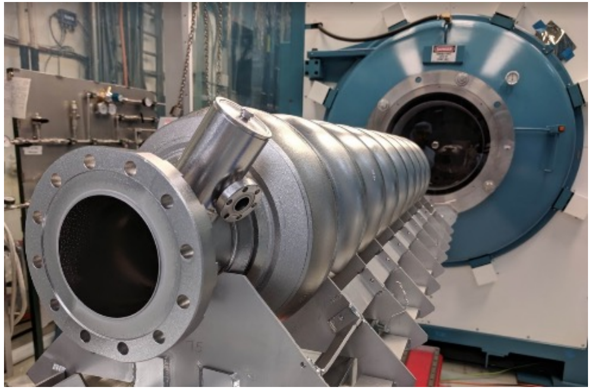




CAPP group (Korea)

Near term ‘Hybrid’-SRF ADMX Sidecar (Installing now)

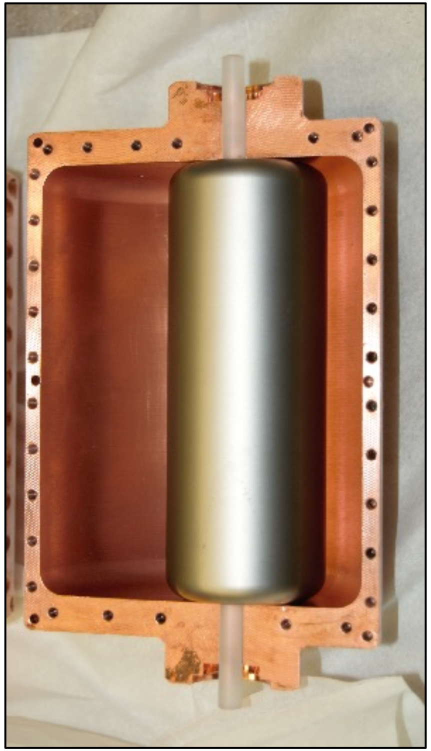
- Sidecar is a ‘test’-bed for new axion tech atop the main experiment cavity
- Copper clamshell design with piezo-actuated rotor and TWPA readout
- Tuning rod is hollow Nb with a Nb_3Sn coating. (1.75” Diameter) from SQMS!



Fermilab Nb3Sn coating furnace with 9-cell cavity

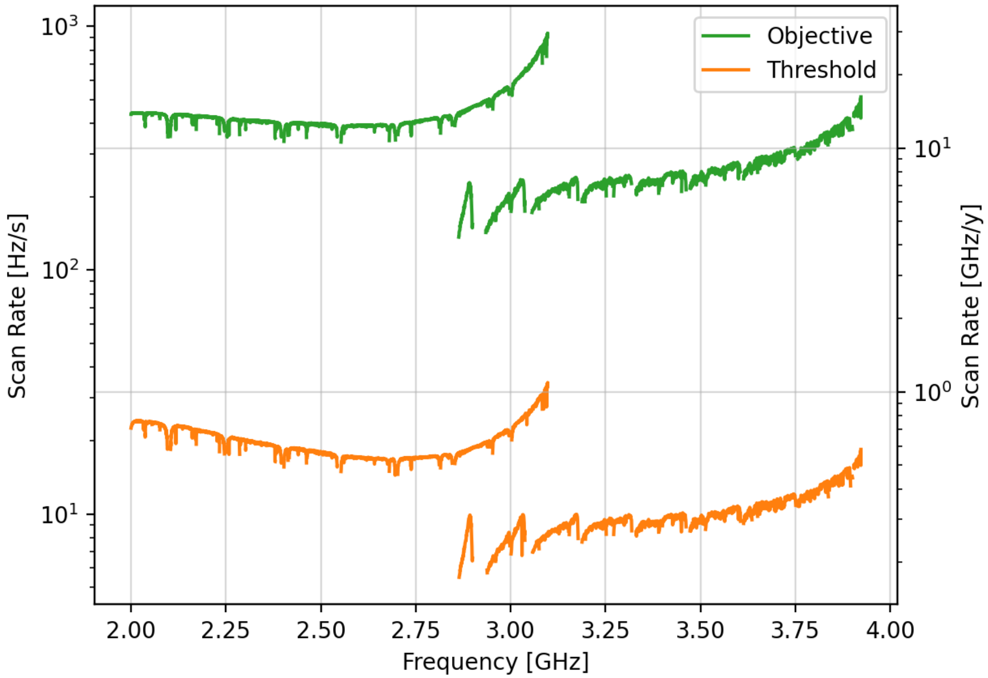
Copper Cavity Produced by U. Sheffield.

Nb3Sn Tuning Rod from SQMS



ADMX-EFR Run Times Estimates

ADMX AXION DARK MATTER EXPERIMENT

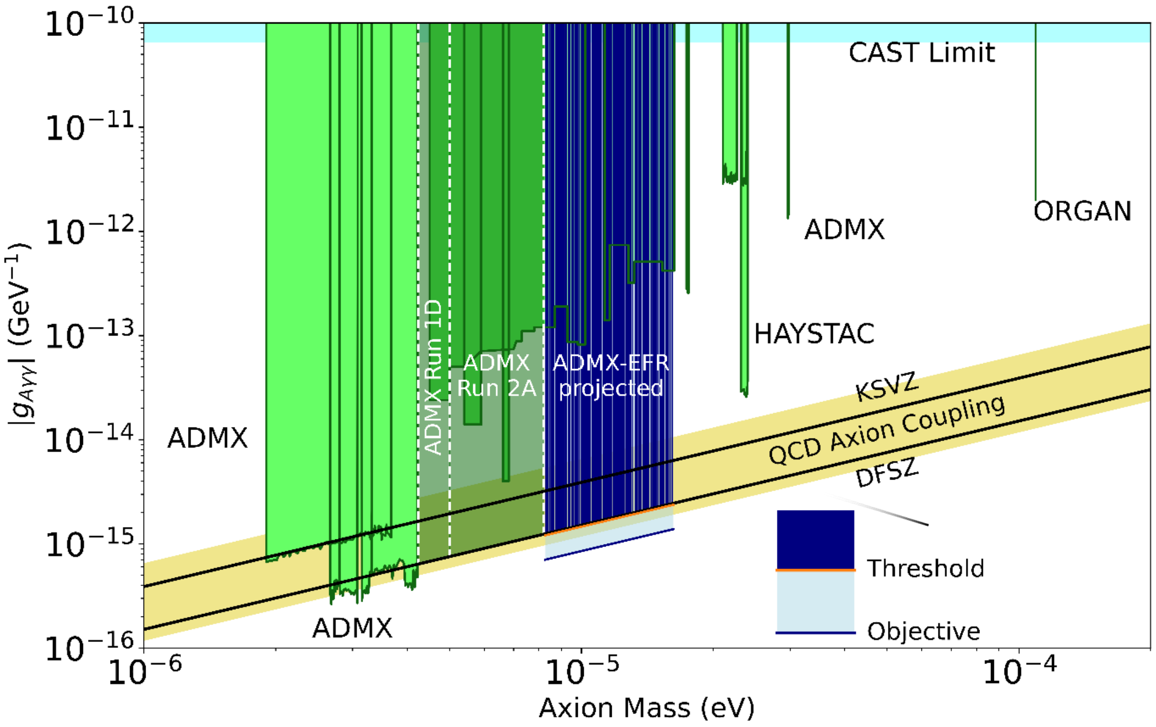


Parameter	Unit	Threshold	Objective
Cavity system full tuning range	GHz	2-4	2-4
Magnetic Field Average	Tesla	9.1	9.4
N Cavities		16	18
Volume per cavity	Liters	12.1/10.4	
Cavity Q_0 at 4 GHz *		54,000	180,000
Cavity TM010 form factor *		-5%	0.4-0.5
Maximum Cavity Physical Temperature	mK	100	100
Maximum 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

Instantaneous scan rate to be updated as results of prototyping become clearer.
3 cavity configuration (0.99, 1.00 and 1.005 m) allows to fill in mode-crossings.

Skipped (Mode Crossings)
$\sim (10 \pm 3)\%$

ADMX-EFR Run Times Estimates



total runtime:
3 years

Threshold:
Q ~ Copper Cavity
skips mode crossings

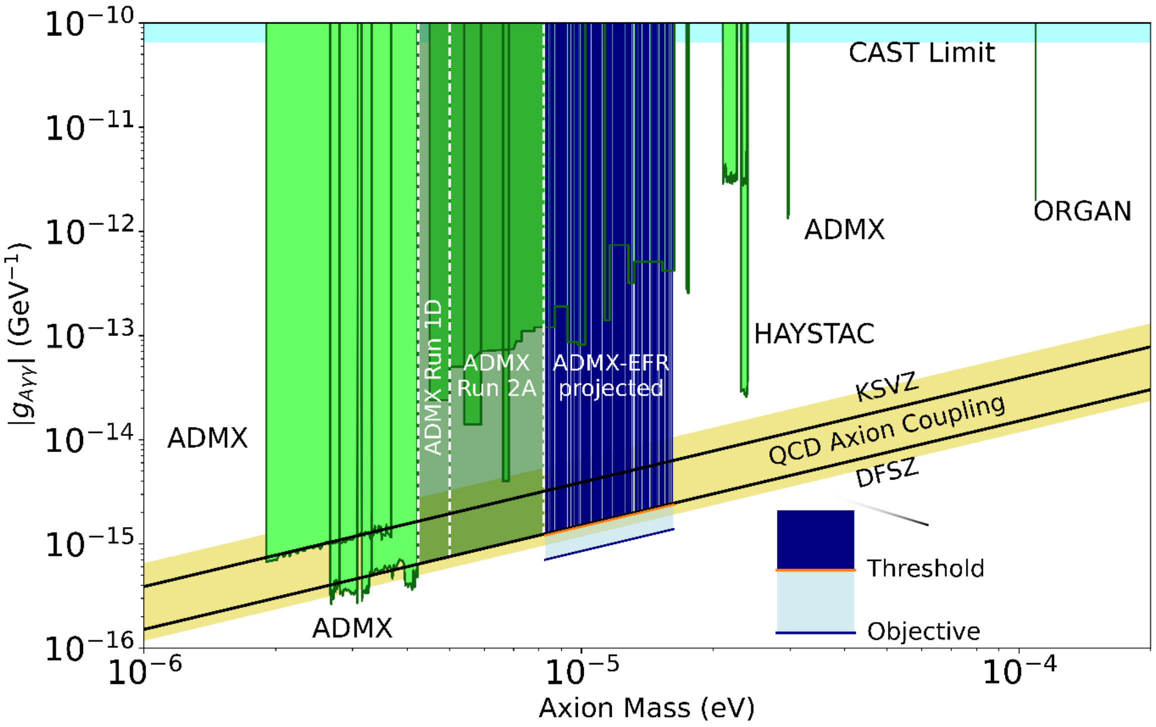
Objective:
Q ~ 3 x Q Copper Cavity
Includes mode crossings
Increased sensitivity reach

Q > 27 x Q_{copper} would allow same DFSZ experiment with only 4 cavities (save cost)

Could run 2-3 GHz & 3-4 GHz simultaneously

Could drive down < DFSZ sensitivity (or < 50% fractional halo density at DFSZ)

ADMX-EFR Run Times Estimates



total runtime:
3 years

Threshold:
Q ~ Copper Cavity
skips mode crossings

Objective:
Q ~ 3 x Q Copper Cavity
Includes mode crossings
Increased sensitivity reach

Excited to work with partners such as SQMS to develop the best field-tolerant SRF cavities possible to maximize ADMX-EFR scan rate and sensitivity!

Thank You!

ADMX
AXION DARK MATTER EXPERIMENT

Lawrence Livermore National Laboratory

Fermilab

UNIVERSITY OF WASHINGTON 1861

UF UNIVERSITY of FLORIDA

Berkeley UNIVERSITY OF CALIFORNIA

WASHINGTON UNIVERSITY IN ST. LOUIS 1853

Los Alamos NATIONAL LABORATORY

SLAC

Pacific Northwest NATIONAL LABORATORY

The Unive Of Sheff

THE UNIVERSITY OF WESTERN AUSTRALIA

HEISING - SIMONS FOUNDATION

Acknowledgements:
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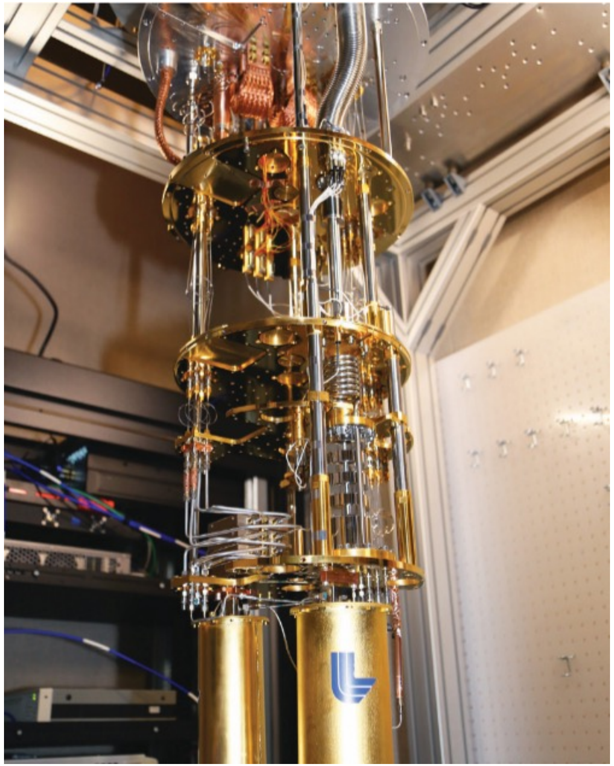
Backup slides

Livermore Center for Quantum Science

- Anticipation of important impacts for our missions
  - New paradigms for computing
  - Direct simulation of complex quantum phenomena
  - Unprecedented precision in sensing
- A quantum testbed with "white box" access used by a range of Lab researchers
- In-house expertise for device design and fabrication
- Current program priorities
  - Understand device physics and improve hardware
  - Connect quantum effects with the classical world
  - Integrate quantum into other capabilities through codesign



https://quantum.llnl.gov

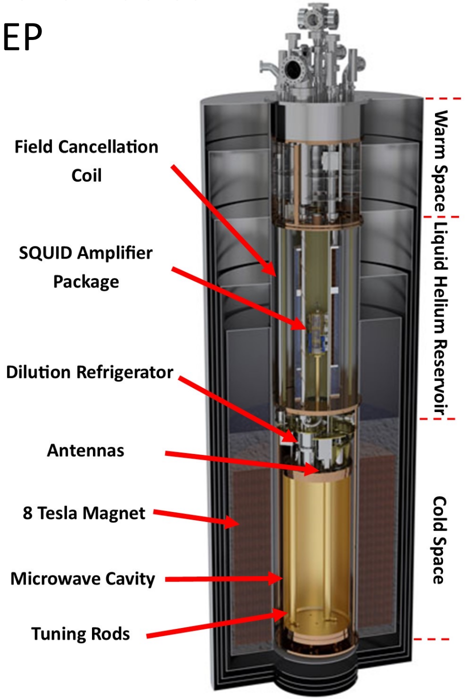
ADMX started at LLNL

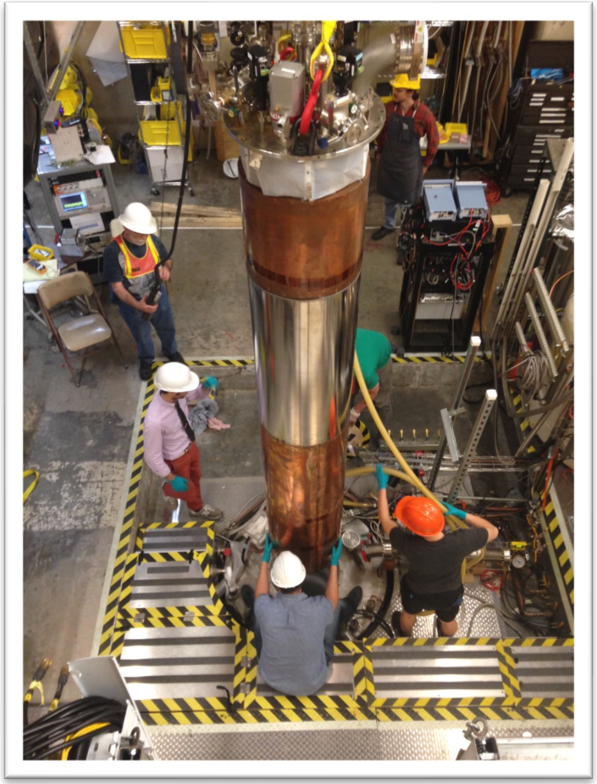
- Built off pioneering experiments at U. of Florida and Rochester/Brookhaven/Fermilab in late 1980s
- ADMX started with the purchase of large (8T 60-cm bore) Solenoid from Wang NMR (located in Livermore over by Costco). 16 MJ of stored energy (220 amps)
- Installed in B436 in the early 1990s and took data there with continuous upgrades until 2010.

I joined as postdoc in 2006

Moved to the U. of Washington in 2010

- Currently operates at the Center for Particle and Nuclear Astrophysics (CENPA) as one of the 3 DOE HEP "Generation 2" Dark Matter projects (alongside LZ and SuperCDMS-SNOLAB)

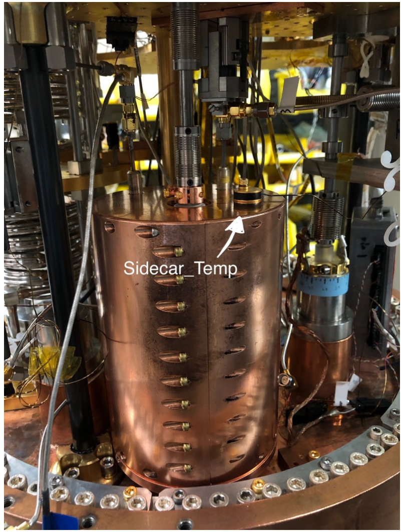


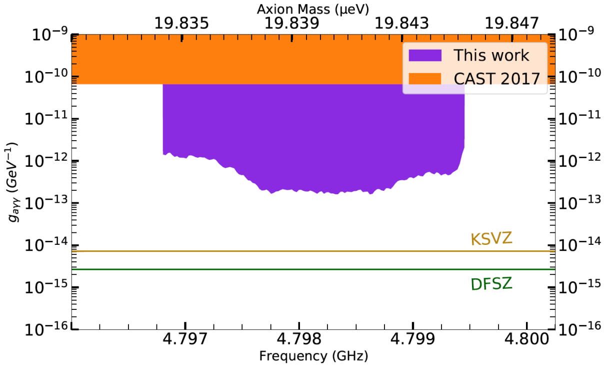


ADMX: Sidecar operations

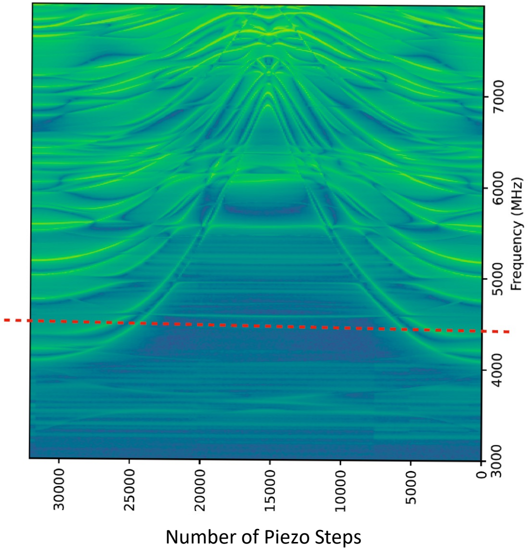
Sidecar Publications:

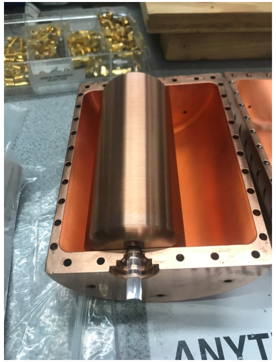
1. Christian’s thesis
2. TWPA paper

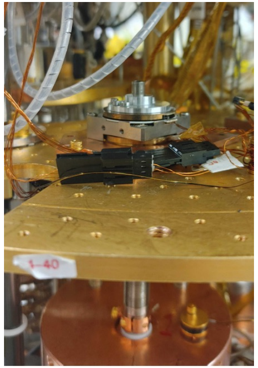




Tuning rod is set to start at 4.4 GHz

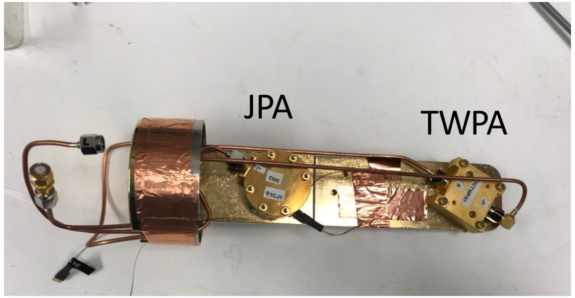


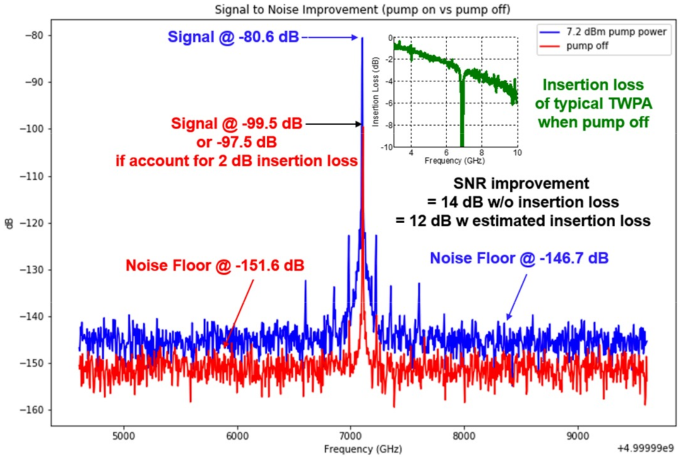


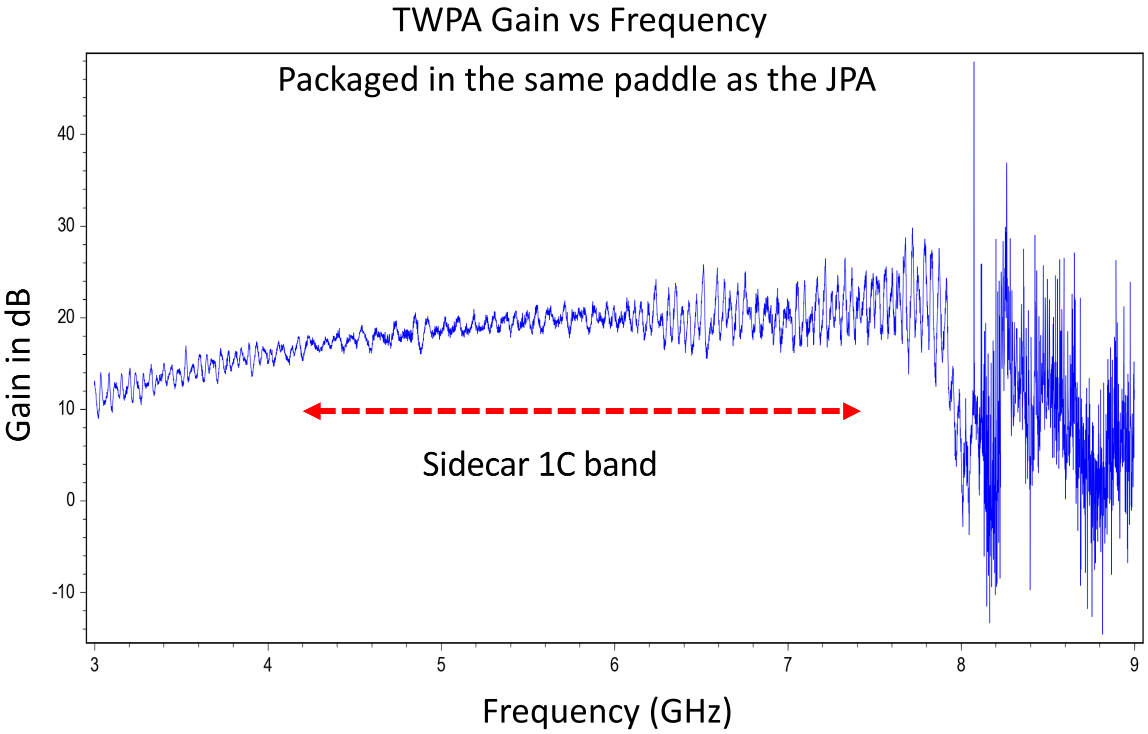


Attocube Rotor on 1K plate

JPA (Main Cavity ~ 1 GHz) + TWPA (Sidecar Cavity: 4-6 GHz)







LLNL acquired TWPAs through contacts with IARPA group. Qualified in Megaman

How do we measure Quality factor and Resistance?

- Each mode has an associated Q
- How we measure: $Q = \frac{f_0}{\Delta f}$,
  - From Scattering Parameters taken on a VNA
  - S21: input at port 1, measure port 2.
- Physical definition: $Q_0 = \omega \frac{U_{cav}}{P_{loss}} = \frac{G_s}{R_s}$
- G_s measures the mode field structure's overlap with the cavity interior surface

$$G_s = \mu_0 \omega \frac{\int |\vec{H}|^2 dV}{\int |\vec{H}|^2 dS}$$

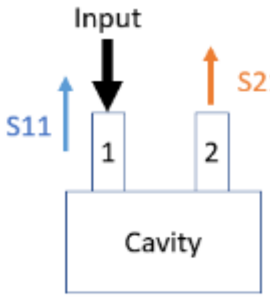
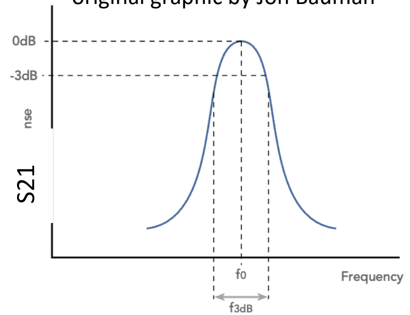


Image credit: S parameters, Wikipedia original graphic by Jon Bauman



- G_s can be defined for the sub-surfaces of the cavity as well su that:

$$S_{tot} = S_1 + S_2 + \cdots + S_n$$

$$\frac{1}{G_{tot}} = \frac{1}{G_1} + \frac{1}{G_2} + \ldots + \frac{1}{G_n}$$

$$\frac{1}{Q_{tot}} = \frac{G_1}{R_1} + \frac{G_2}{R_2} + \ldots + \frac{G_n}{R_n}$$

Decomposition Matrix (2x2 case)

1. Measure 2 modes' Q on VNA: Q_1, Q_2

2. Calculate the four geometric factors in HFSS: $G_{1,1}, G_{1,2}, G_{2,1}, G_{2,2}$

3. Python Notebook does the rest:

Weight matrix:

$$C_{ms} = \begin{bmatrix} \frac{G_{1,2}}{G_{1,1} + G_{1,2}} & \frac{G_{1,1}}{G_{1,1} + G_{1,2}} \\ \frac{G_{2,2}}{G_{2,1} + G_{2,2}} & \frac{G_{2,1}}{G_{2,1} + G_{2,2}} \end{bmatrix}$$

Geometric Factor of total surface for each mode, and corresponding total mode resistance:

$$G_n = \frac{G_{n,1} G_{n,2}}{G_{n,1} + G_{n,2}} \qquad \vec{R}_m = \begin{bmatrix} G_1/Q_1 \\ G_2/Q_2 \end{bmatrix}$$

Invert mode resistances to surface resistances:

$$\vec{R}_s = C_{ms}^{-1} \vec{R}_m$$

Current Research done:
Testing Apparatuses at LLNL

- Main Test System: Quantum Designs™ Physical Properties Measurement System (PPMS)
  - — 16 T Magnet
  - — 1” Bore, 100 mm field Height
  - — 2 K Cryostat

Left: Top down of PPMS System with RF probe inserted.
Right: PPMS RF Probe extraction from bore