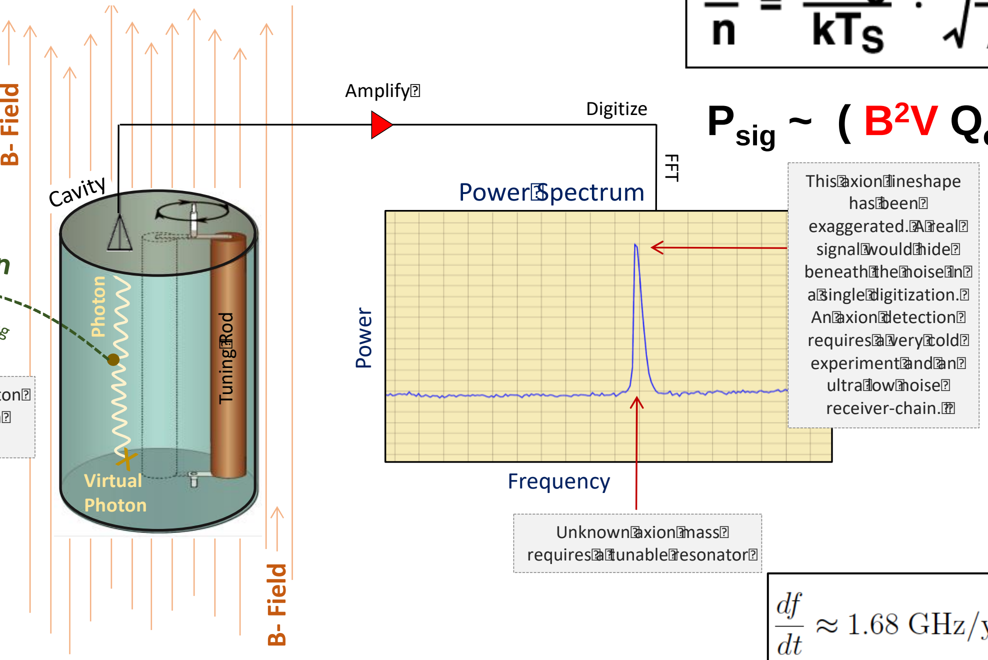
# Looking to the future with the ADMX-Extended Frequency Range Project

## Axions 2024 – University of Florida

Gianpaolo Carosi
Lawrence Livermore National Laboratory
April 27th, 2024

LLNL-PRES-862590

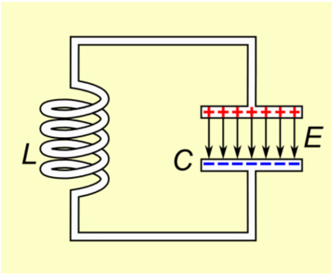
# Axion Dark Matter Searches: The Haloscope Technique



Axion to photon production ∝ E • B

This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.

Unknown axion mass requires a tunable resonator



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

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

*System noise temp.*

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

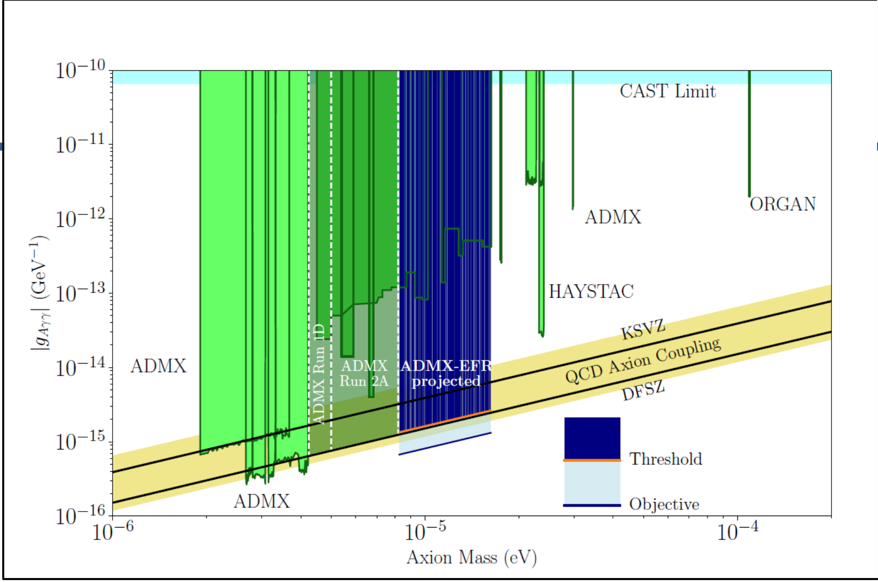
$$T_{Quant} \sim 48\ \mathrm{mK}\ @\ 1\ \mathrm{GHz}$$

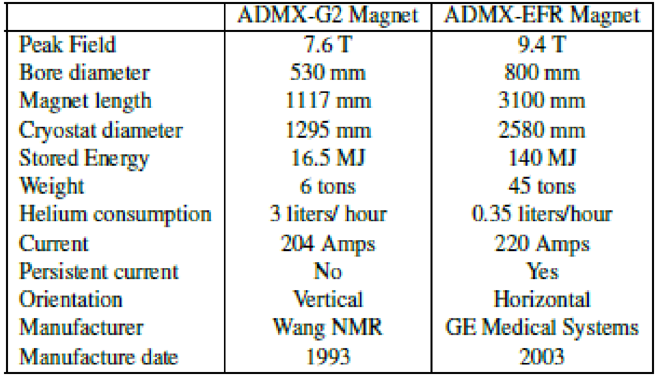
**t = Integration time limited to ~ 100 sec**

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

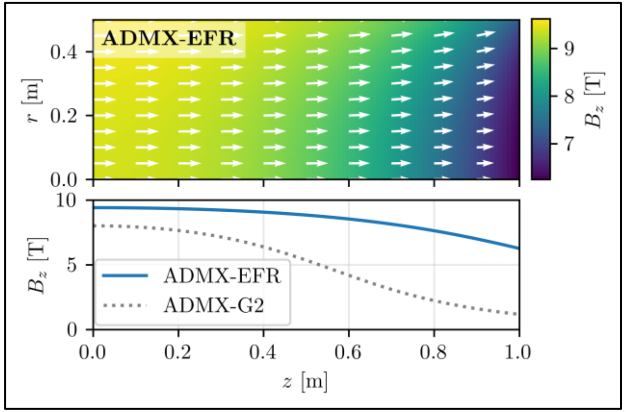
# ADMX-EFR plans

- ADMX EFR is an axion haloscope targeting the 2-4 GHz frequency regime
- New 800 mm bore 9.4 T MRI magnet
- EFR will utilize an 18-cavity array to maximize the magnet volume
  - Take advantage of axion coherence.



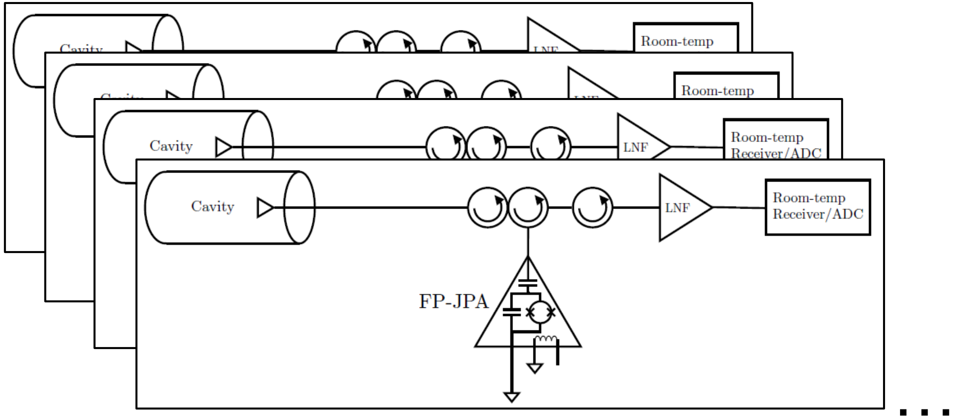


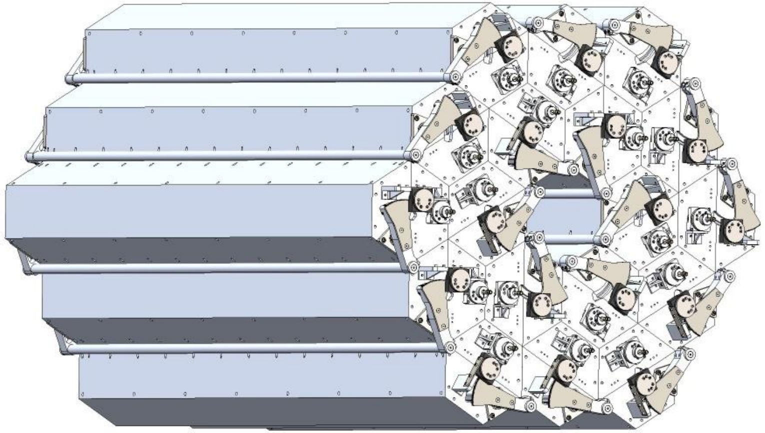
| | ADMX-G2 Magnet | ADMX-EFR Magnet |
|---|---|---|
| Peak Field | 7.6 T | 9.4 T |
| Bore diameter | 530 mm | 800 mm |
| Magnet length | 1117 mm | 3100 mm |
| Cryostat diameter | 1295 mm | 2580 mm |
| Stored Energy | 16.5 MJ | 140 MJ |
| Weight | 6 tons | 45 tons |
| Helium consumption | 3 liters/ hour | 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 |



# Overall System Concept

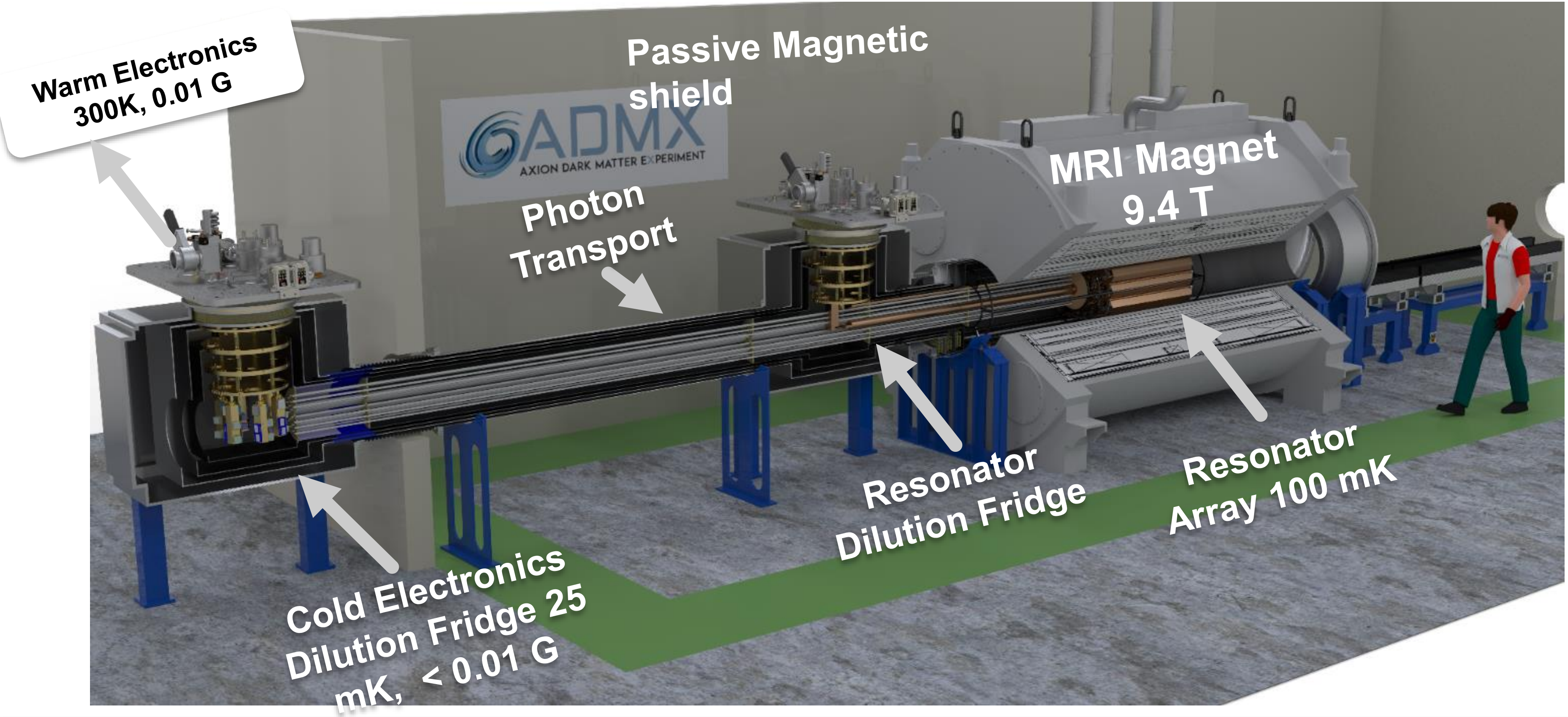
- 18 cavities each instrumented with their own quantum amplifier chain and readout.
- In-phase amplitude combing digitally at room temperature





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

# ADMX-Extended Frequency Range



Warm Electronics
300K, 0.01 G

Passive Magnetic shield

Photon Transport

MRI Magnet
9.4 T

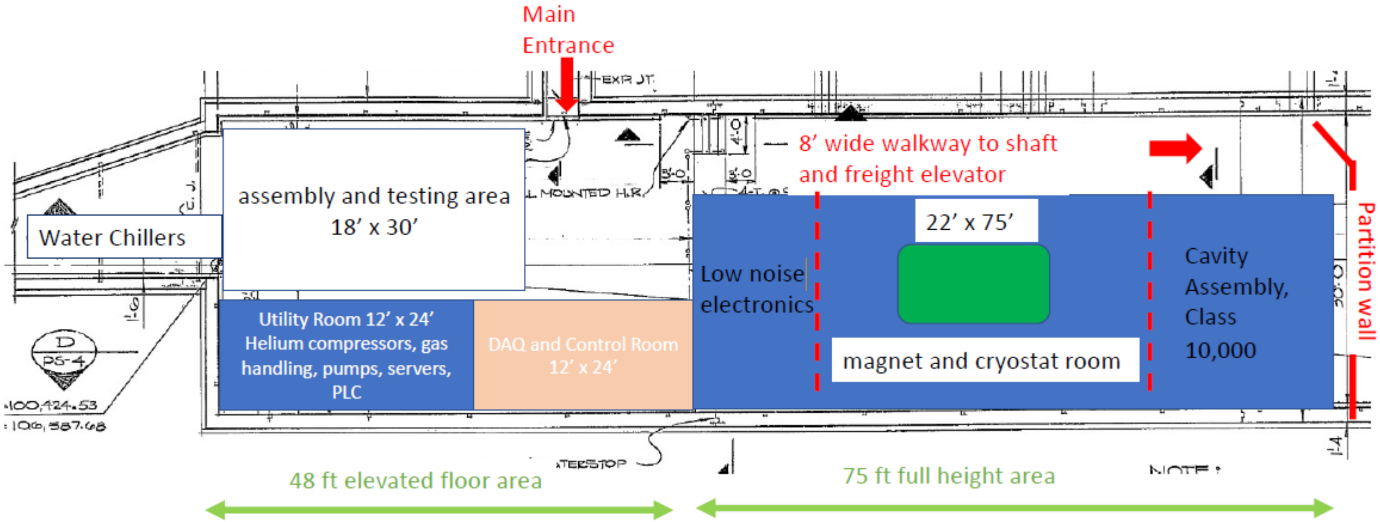
Resonator Dilution Fridge

Resonator Array 100 mK

Cold Electronics Dilution Fridge 25 mK, < 0.01 G

# Site – PW8 Hall at Fermilab

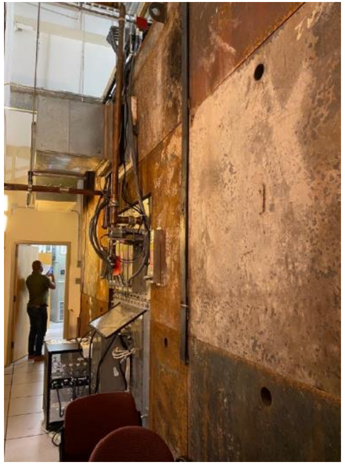
- 6,900 sq ft shallow underground enclosure. Adjacent to service building at ground level. Easy magnet access.
- Site is being prepared to receive the magnet system soon.

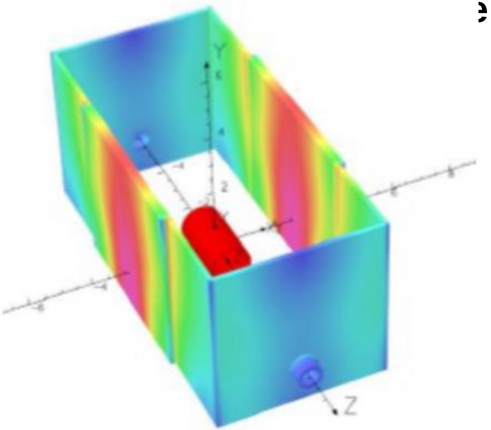


Layout in PW8

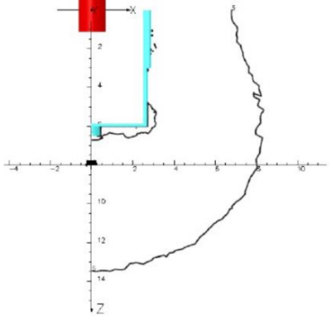
# Magnet – Passive Shielding

- System at UIC has **500 tons of Stainless-Steel passive shielding**.
- ADMX-EFR will need **simplified** version of passive shield at UIC (eliminate risk of expensive active magnet).
- Openings at ends to allow for easy installation of cavity systems.
- No shielding needed shielding above or below magnet (save cost).
- Main experimental requirement:
  - **electronics < 100 Gauss.**

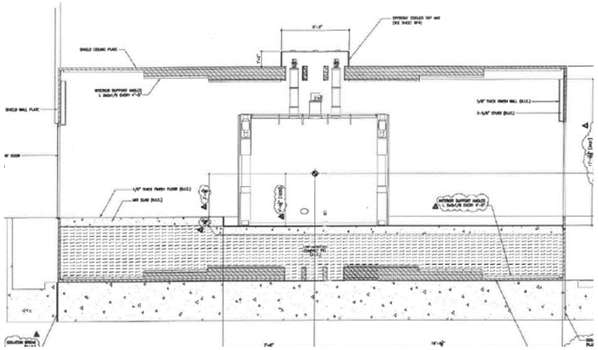




Preliminary FEA magnet model by Vladimir Kashikhin at Fermilab



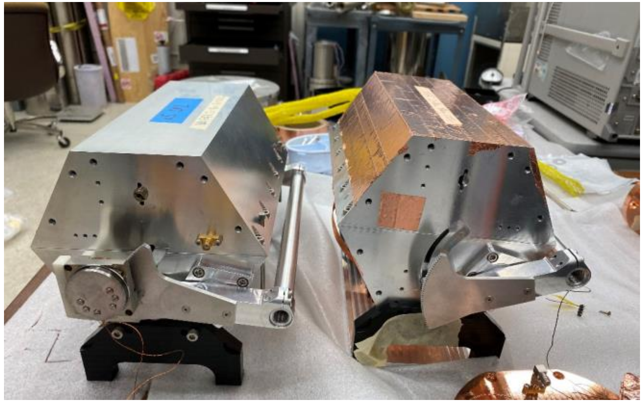
Shield: 6” thick, width/height 5.4 m, length 12 m
Weight: 300 tons, $B_{max}$ = 1.6 T
5 Gauss Line: x = 8 m, z = 13.5 m (with shield)
x = 17 m, z = 21 m (without shield)



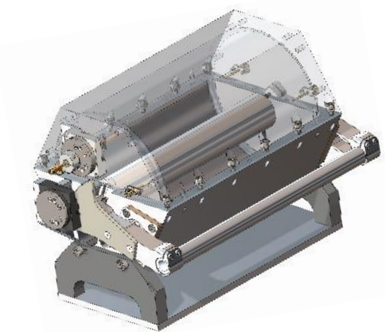
# Resonator Design currently clamshell cavity

- Current baseline cavity cell is ~1 m long copper cavities* with copper tuning rods.
- Q ~ 60k at cryogenic temps (all copper)

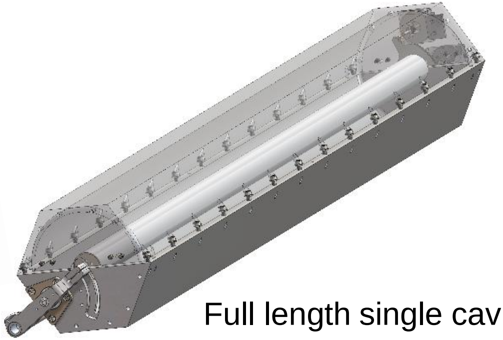
- Two sets of tuning rods diameters (2-3 & 3-4 GHz with same clamshells)
    - 128 mm ID
    - 32 mm rods: 2.0-3.1 GHz
    - 54 mm rods: 3.1-3.9 GHz



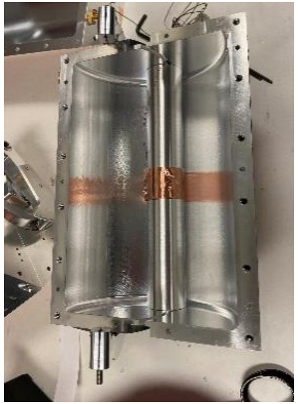
Postdoc Nick Du mounting scale length prototypes in dilution refrigerator



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

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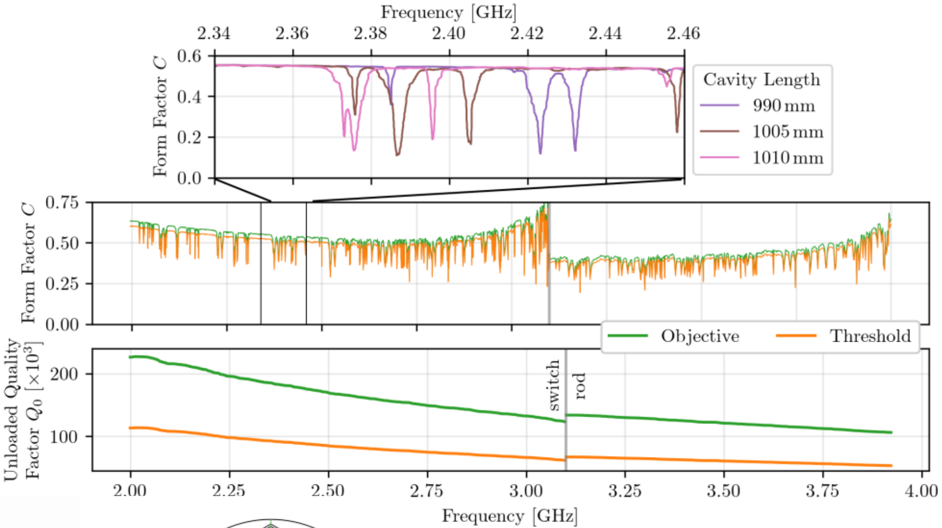
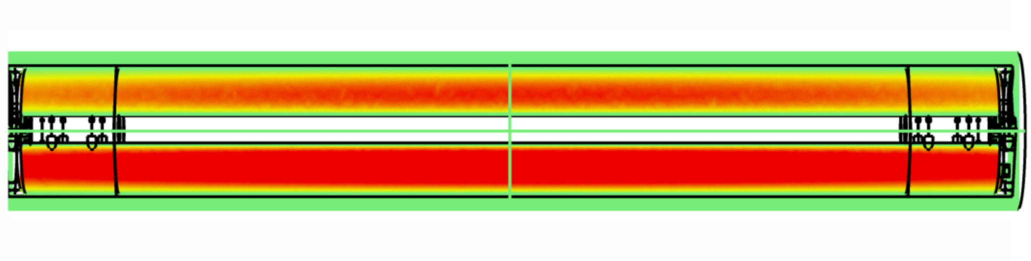
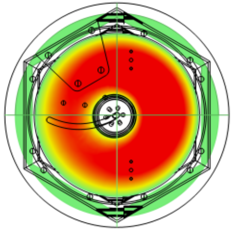
*baseline is very conservative. SRF cavities being developed with partners (SQMS & FSU)

# ADMX-EFR Mode Crossings

- For cavities spanning the 1m of the magnet, 10% of the frequency bandwidth is affected by mode crossings
  - Mode crossings can be detuned by using sets of cavities with slightly different lengths
  - Multicavity system allows us to have sets of nondegenerate crossings.



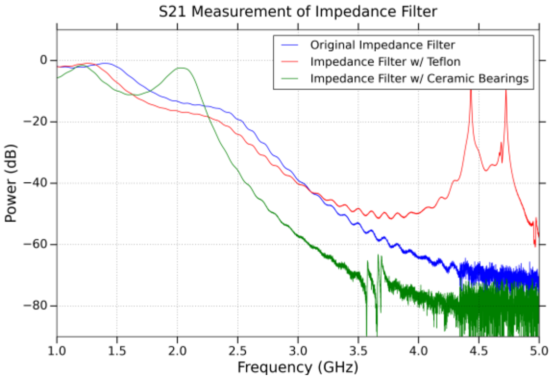


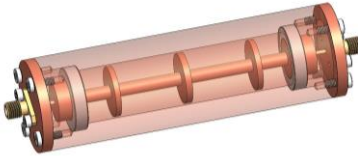


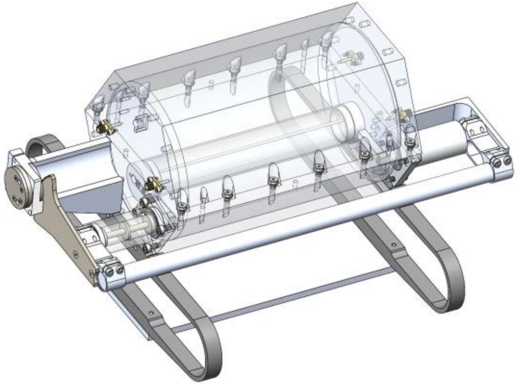
# ADMX-EFR Tuning Impedance Filter

- Stepped impedance filter generates impedance mismatch to prevent coupling of power out of cavity by tuning rod axles
  - Enables fabrication of metal tuning rod axles, instead of classical dielectric
    - Improved tuning rod thermalization
    - Reduced dielectric losses

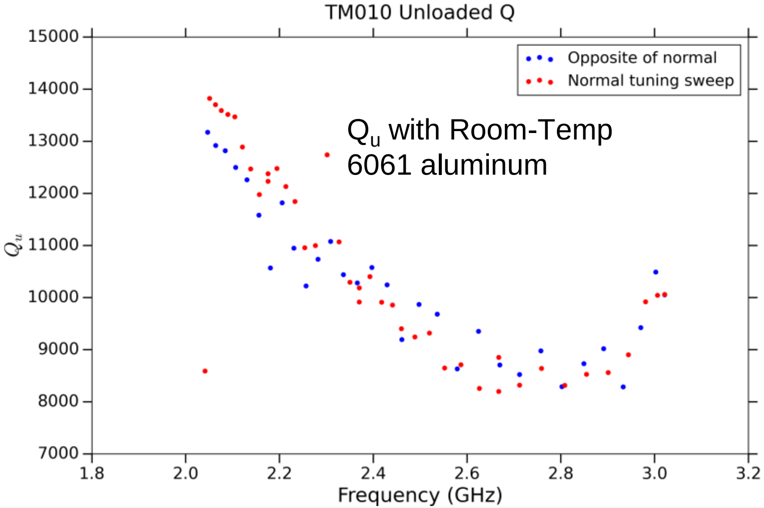
- Design work and initial testing at U. of Florida (Joe Gleason & Alex Hipp) showing promise!







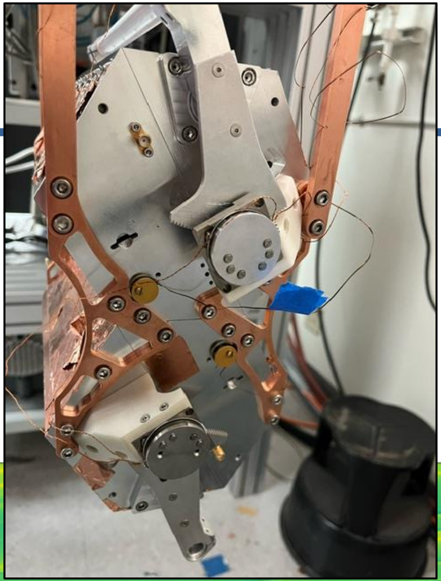
Test cavity with stepped impedance



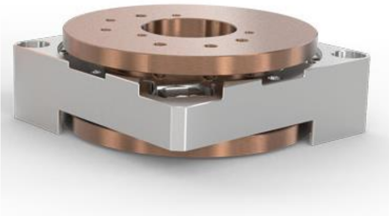
$Q_u$ with Room-Temp 6061 aluminum

# ADMX-EFR Tuning System

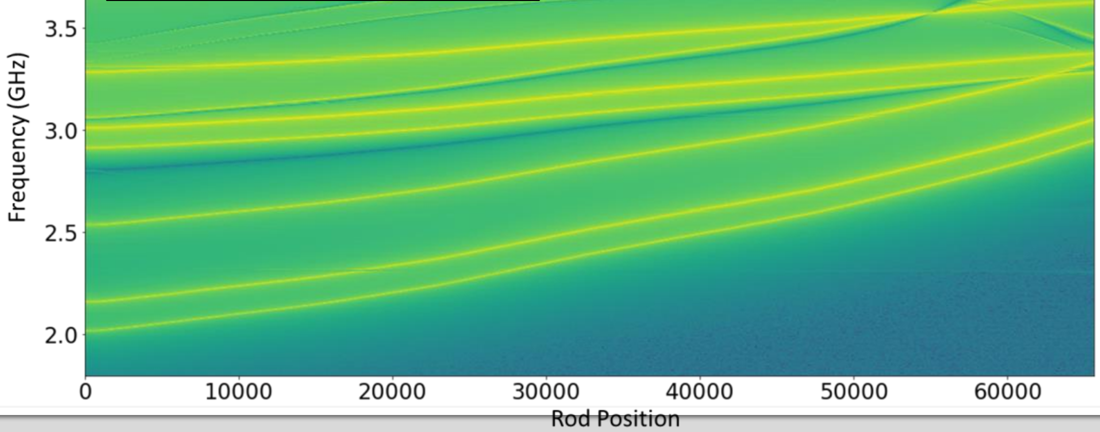
- Each tuning rod is rotated by a rotary piezoelectric motor coupled to the cavity via a gear
  - Angular resolution on the rotary motors is 1 $\mu deg$
- A linear piezoelectric motor will adjust the insertion depth of a dipole antenna to control coupling to the cavity
- Piezo elements sunk to higher temp stage (1K shield) to minimize cavity heating.



2 cavity prototype system mounted in dilution refrigerator at LLNL

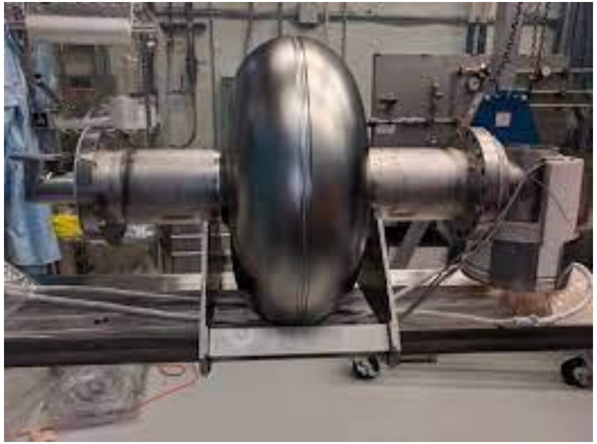


Attocube rotor

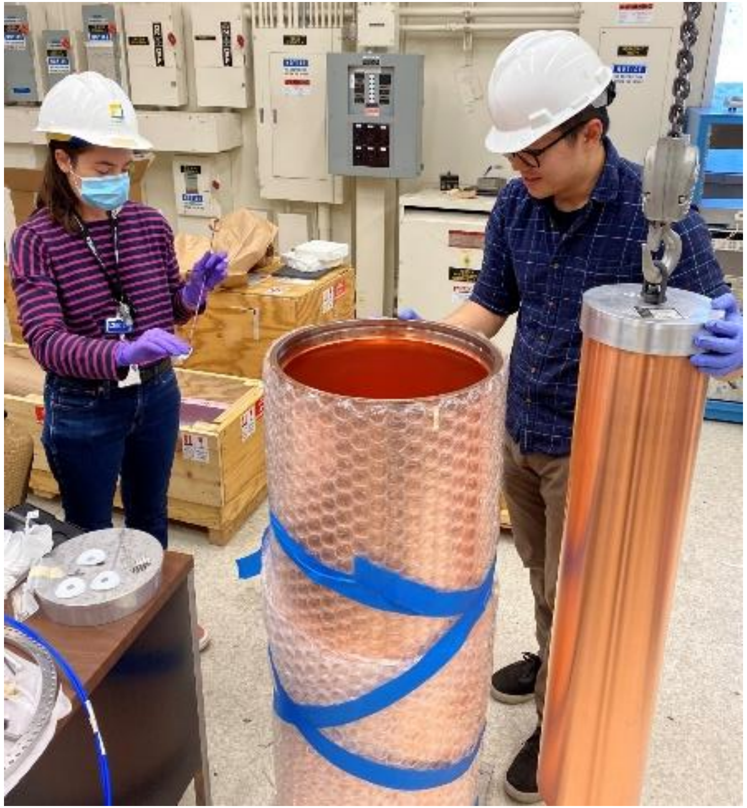


# What about using superconductors for cavities?

- 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 $Q_a > 10^6$**



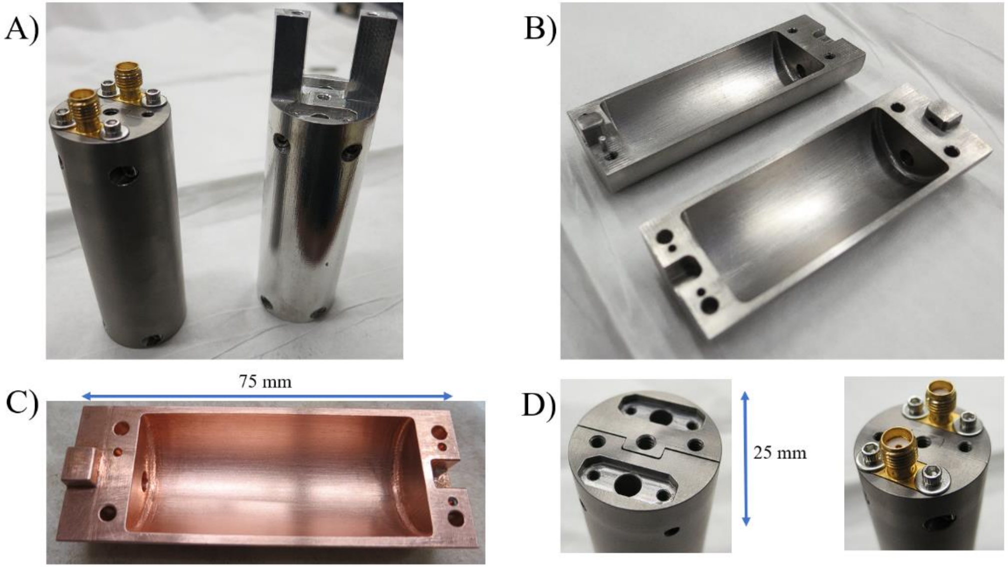
Accelerator Cavity. Image credit: Fermilab SQMS

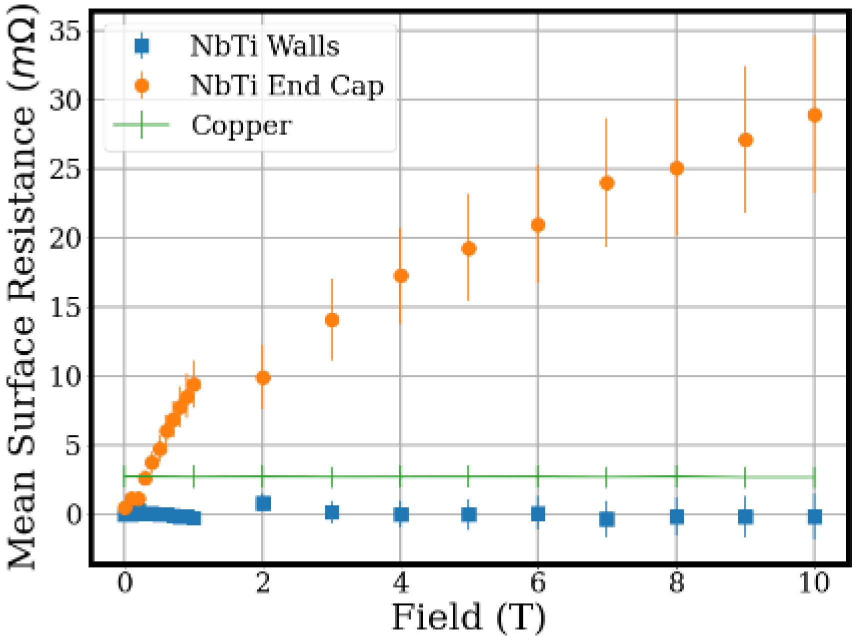


ADMX Copper Cavity (Run 1D)

# 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



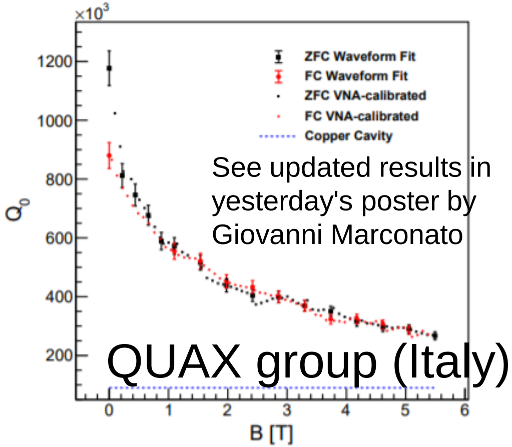


T. Braine et al. Multi-mode analysis of surface losses in a superconducting microwave resonator in high magnetic fields. Rev Sci Instrum 1 March 2023; 94 (3): 033102. https://doi.org/10.1063/5.0122296

# B-field tolerant SRF cavity development worldwide

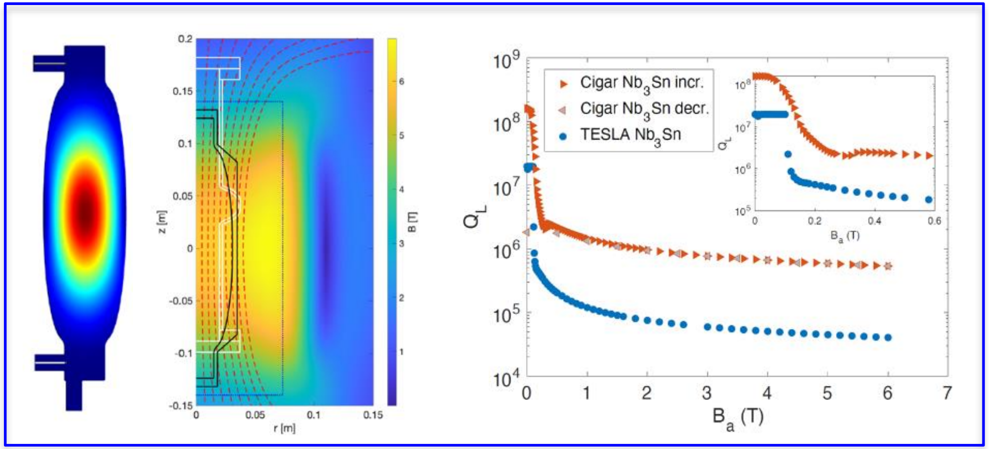
Worldwide there has been excellent progress on field-tolerant SRF cavities for axion searches
3 potential materials (NbTi, Nb3Sn, and YBCO)

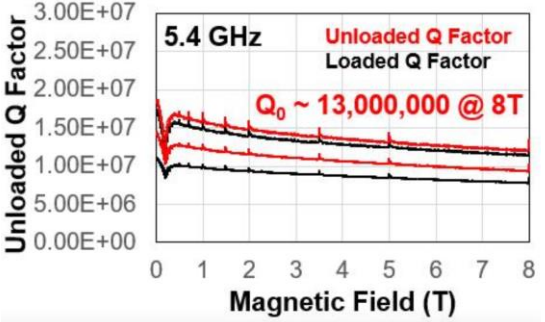
- **NbTi** sputtered cavities as inspired by QUAX group
- **Nb3Sn on Niobium** **led by SQMS** (Sam Posen & Anna Grasselino)
- **Nb3Sn on Copper** collaboration with Florida Statue U. (Lance Cooley)
- **HTC (EuBCO+APC)** superconducting cavities CAPP



See updated results in yesterday's poster by Giovanni Marconato

QUAX group (Italy)





CAPP group (Ko

Recent SQMS results with Nb3Sn

# Simulations allow calculation of Geometric Factors

Q ~ Geometric Factor / Surface loss (Rs)

$Rs_{Cu}$ = 2.9 mOhm at cryogenic temps

$Q_{total}$ ~ 3e2 Ohm/2.9 mOhm
$Q_{total}$ ~ 54k (all Copper Cavity)

Rs: Walls & Rods << lids

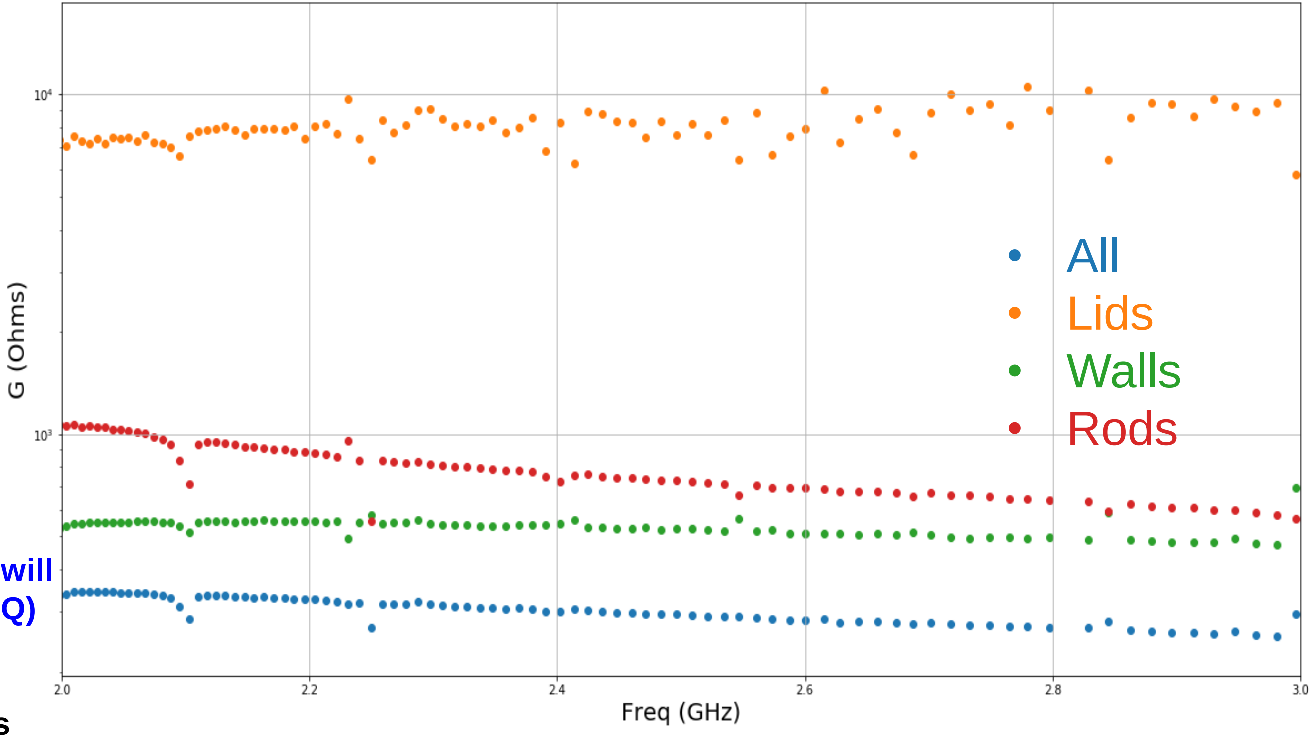
Eliminating Wall & Rod contributions due to parallel field and assuming losses dominated by copper endcaps

$Q_{lids}$ ~ 8e3/2.9 mOhm

**Q ~ 1.5e6 (x 27.5 higher Q)**
**Optimalization of shape of endcaps will likely allow lower RF losses (higher Q)**

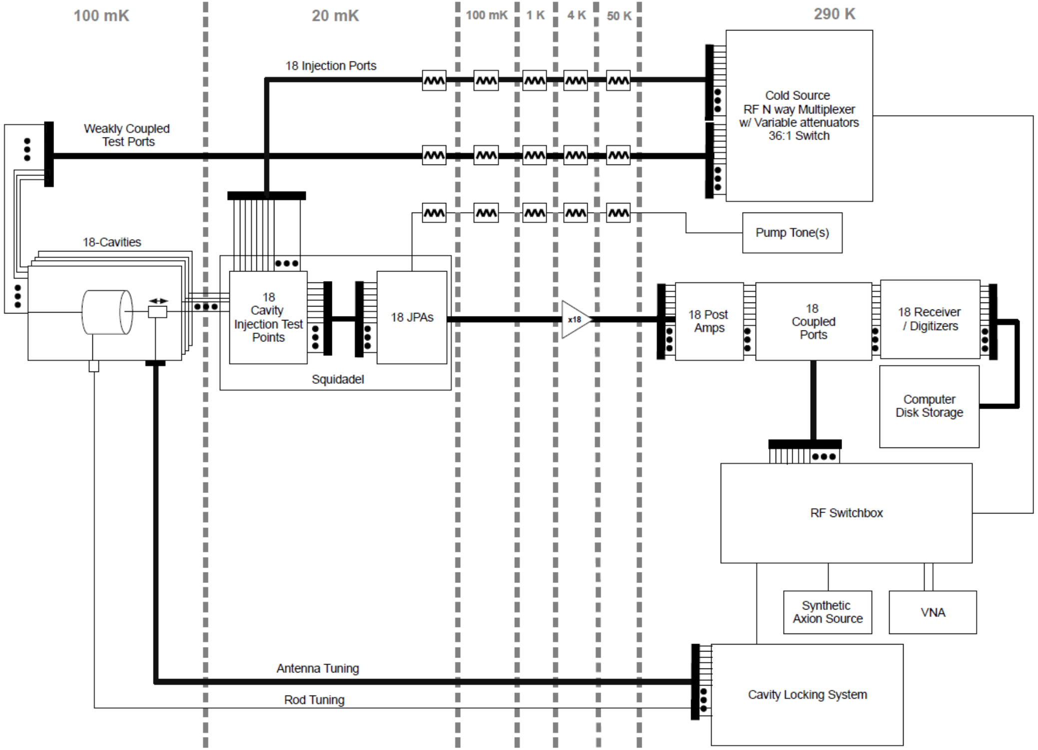
**Need to maintain high form-factor & minimize number of mode-crossings**

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



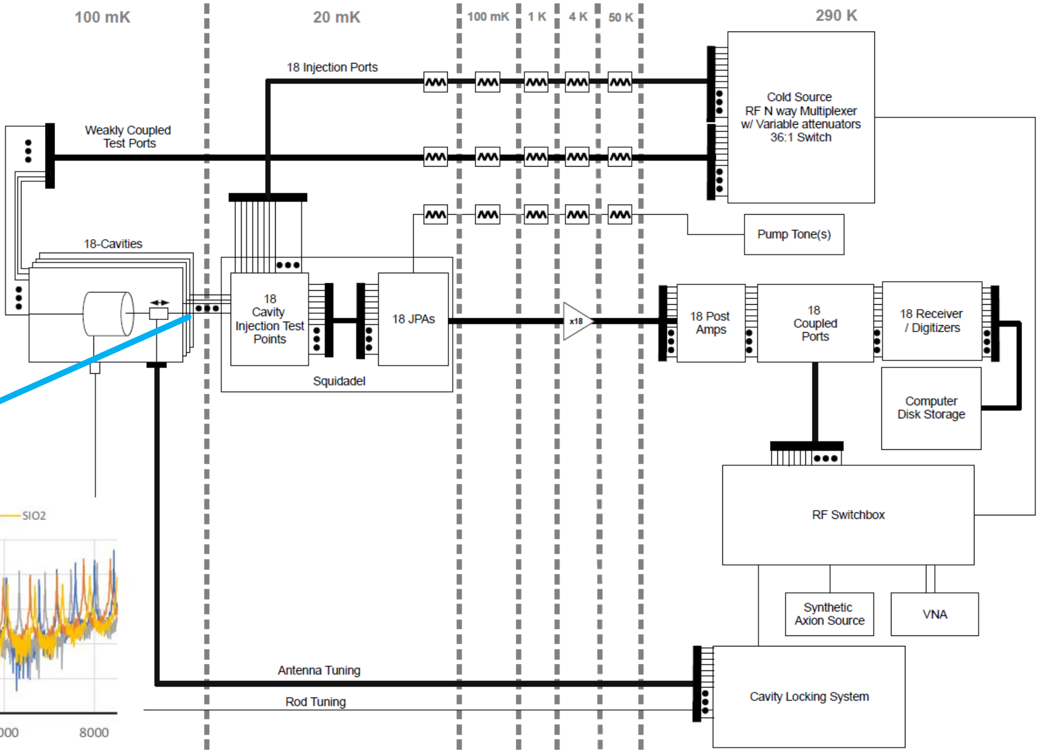
# ADMX-EFR Receiver

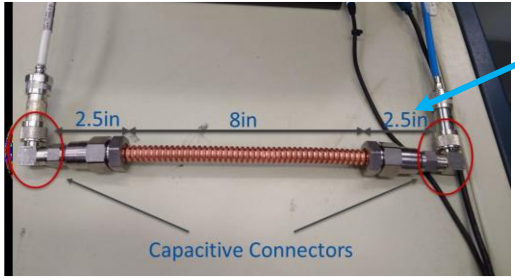
- Signals from the ADMX haloscope will be amplified by a receiver chain in a second dilution refrigerator, then combined digitally
  - Digital signal combining will enable real-time phase and amplitude correction
  - Also minimize effect on signal-to-noise ratio in single point failures

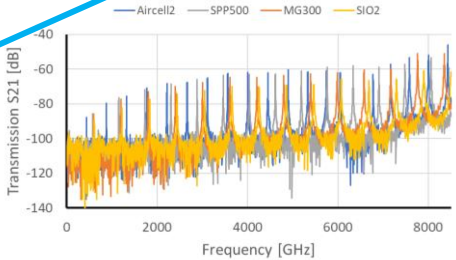


# ADMX EFR-Receiver

- Signals from the EFR cavities will be transmitted into a second dilution refrigerator containing our receiver package
  - Transmission lines are vacuum coaxial cables with < 0.4 dB loss over 5 m length.
  - Tested at Fermilab by M. Hassan.

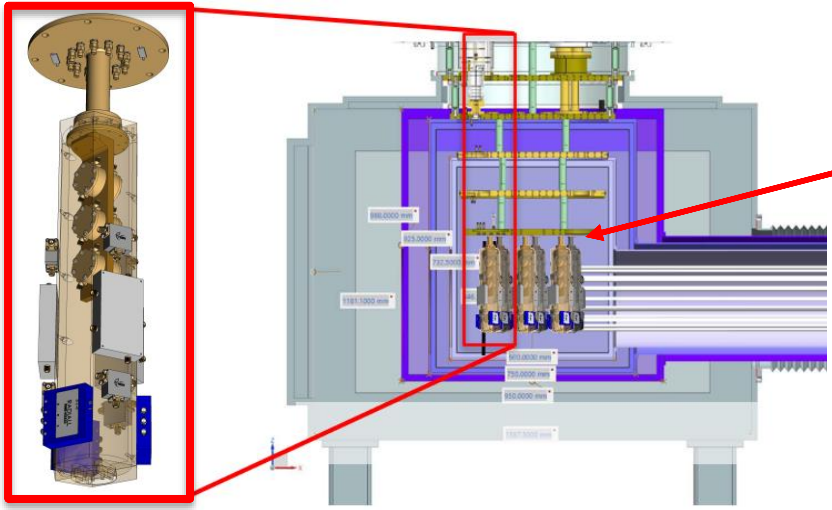


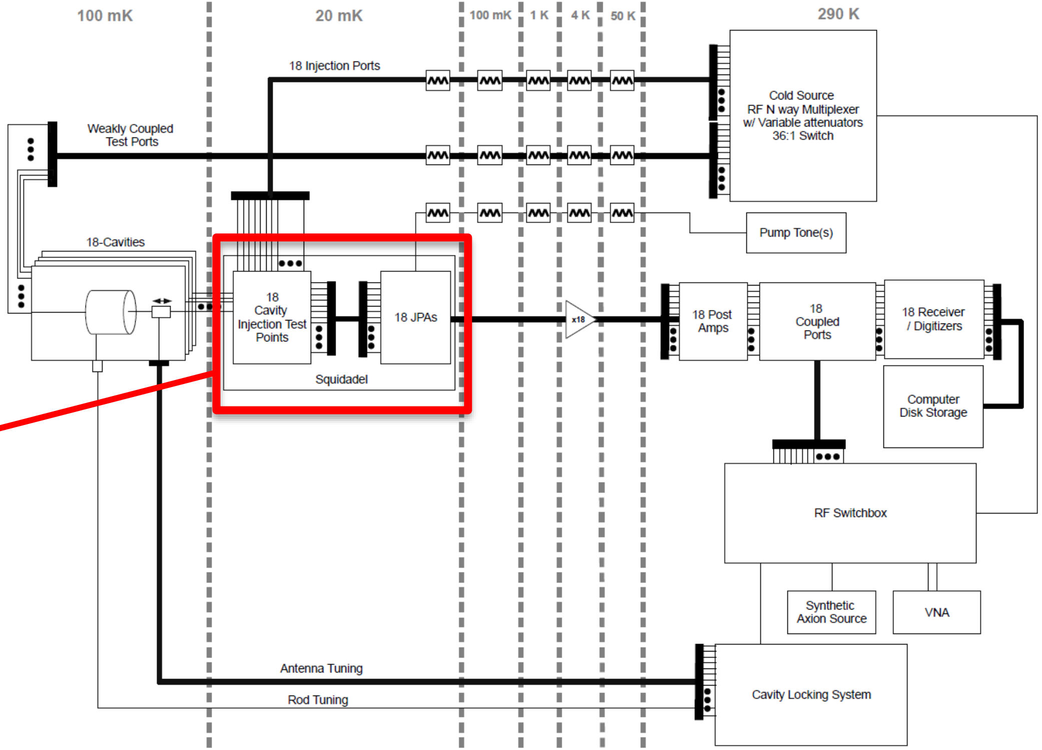




# ADMX-EFR Receiver

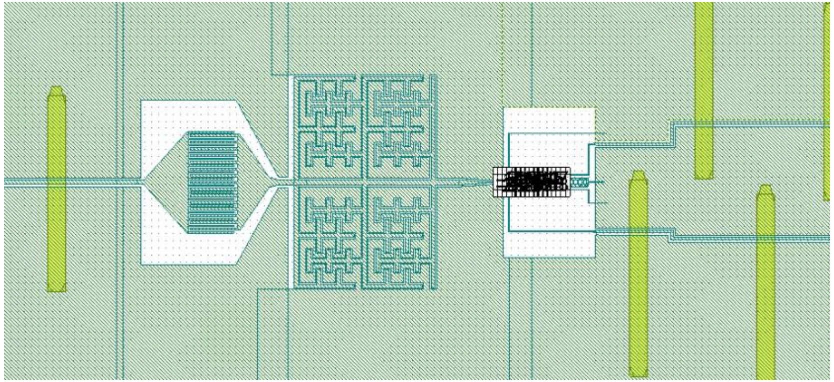
- RF Amplifiers amplify the signal from the cavity with minimal noise contributions
  - 1st –Flux Pumped Josephson Parametric Amplifier (JPA)
  - 2nd – HEMT amplifier.



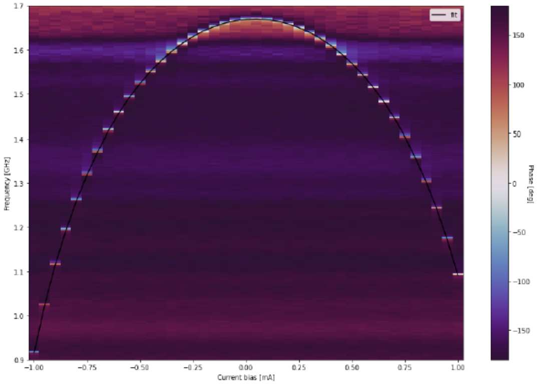


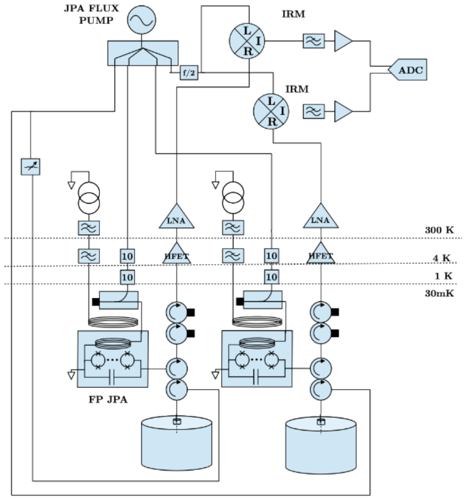
# ADMX-EFR Receiver- JPA

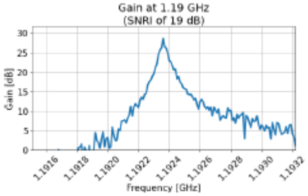
- Parametric amplification is achieved by applying a pump tone to SQUID loops on the JPA
  - DC flux bias to the SQUID loops enables tuning of the JPA resonant frequency
  - Power gain of each JPA is typically 20 dB
  - WUSTL group demonstrating good gain, SNRI and phase-sensitivity that could allow for squeezing!

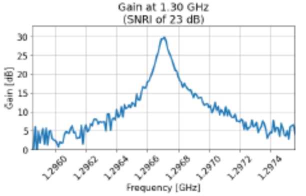


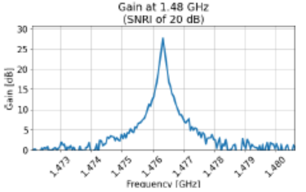
WUSTL JPA design with fractal capacitance

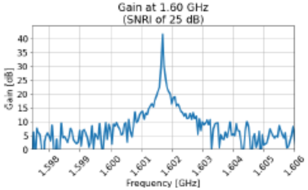




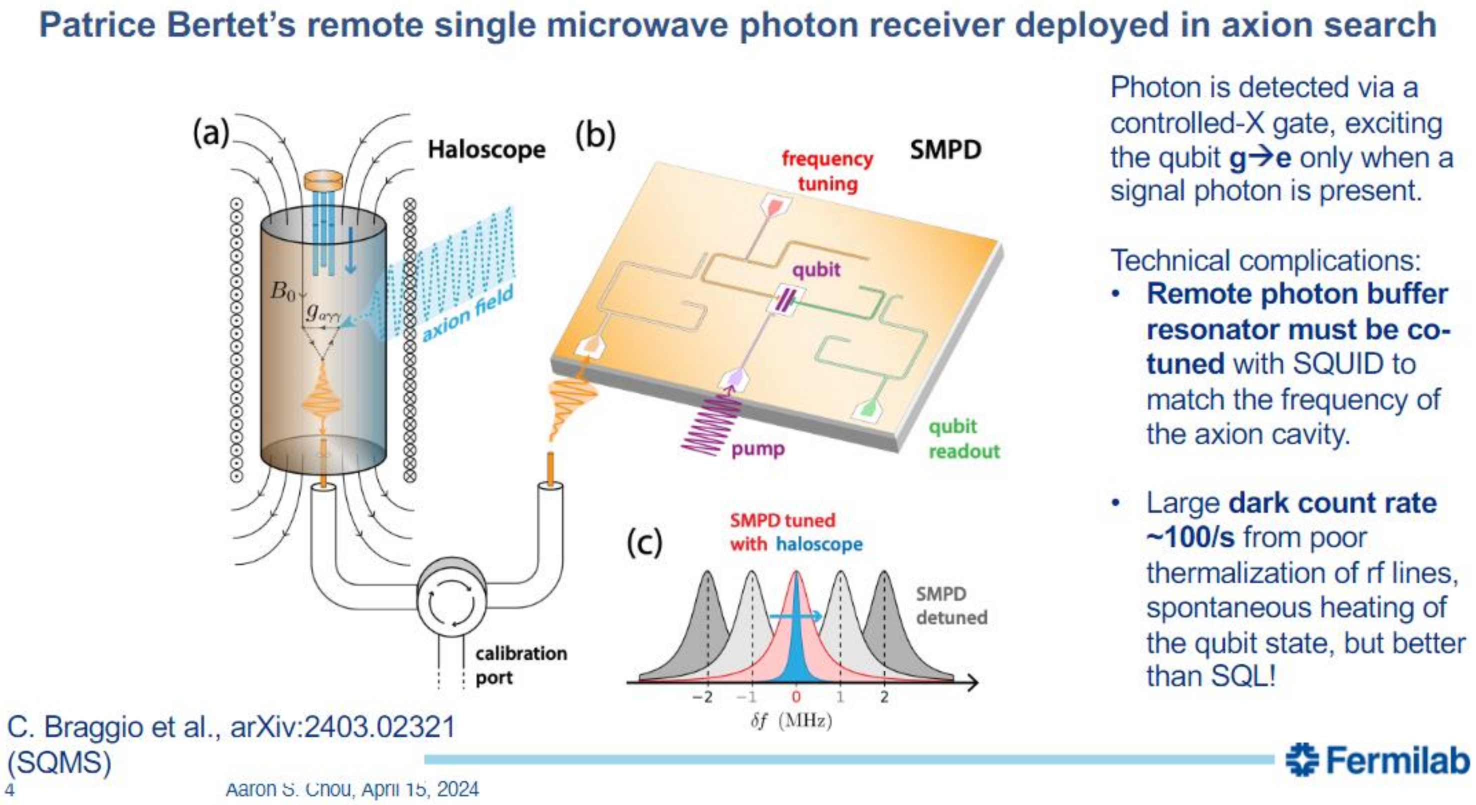








# Recent tantalizing demonstration



## Patrice Bertet's remote single microwave photon receiver deployed in axion search

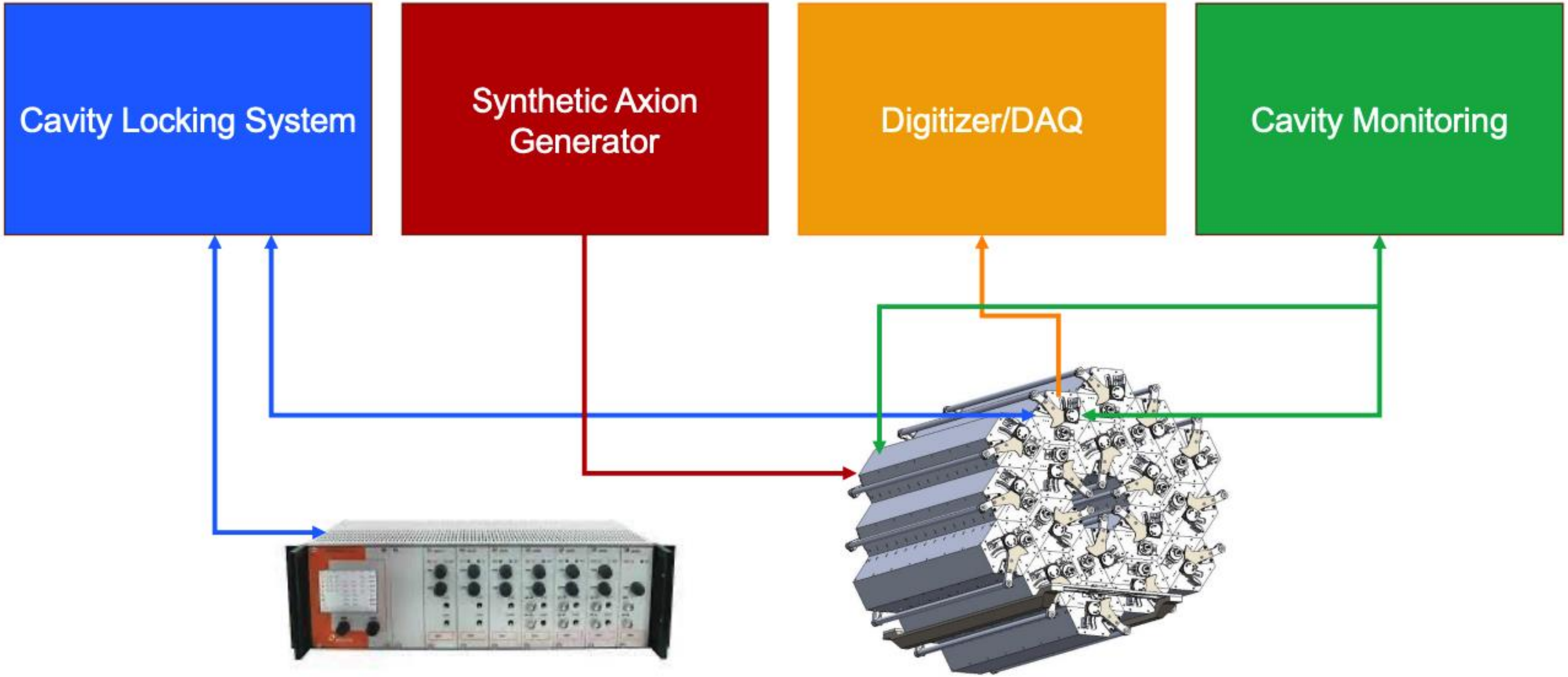
Photon is detected via a controlled-X gate, exciting the qubit **g→e** only when a signal photon is present.

Technical complications:

- **Remote photon buffer resonator must be co-tuned** with SQUID to match the frequency of the axion cavity.
- Large **dark count rate ~100/s** from poor thermalization of rf lines, spontaneous heating of the qubit state, but better than SQL!

C. Braggio et al., arXiv:2403.02321 (SQMS)

# Warm Electronics Overview



# Warm Electronics Overview

- PNNL group developing system-wide RF design taking into account modern RF technologies.

Primary subsystems

- Analog receiver, Cavity locking controls (PNNL)
- Digital signal processing (PNNL & WUSTL)
- Synthetic axion generator (PNNL & U. Chicago)

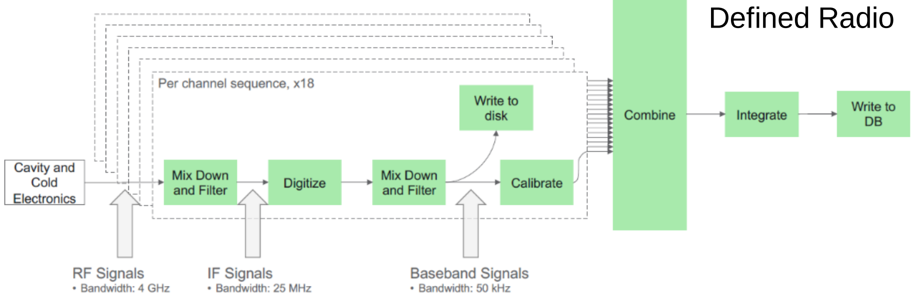
.Completed requirements and specifications from all RF subsystems

- Data rates expected to be modest ~ 54 TB/yr.

**Working on full end-to-end noise simulation using Scikit-RF**

**Exploring using AI / ML techniques to increase scan rate.**

Leverage Software Defined Radio



Per channel sequence, x18

Cavity and Cold Electronics

Mix Down and Filter

Digitize

Mix Down and Filter

Calibrate

Write to disk

Combine

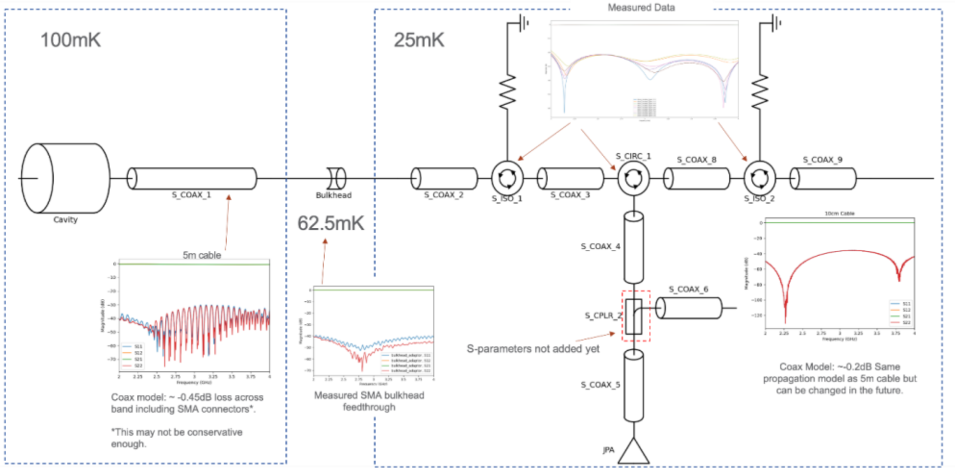
Integrate

Write to DB

RF Signals
- Bandwidth: 4 GHz

IF Signals
- Bandwidth: 25 MHz

Baseband Signals
- Bandwidth: 50 kHz



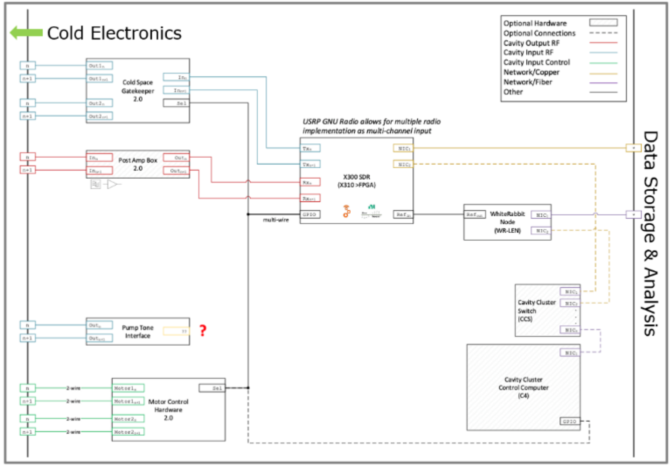
Coax model: ~ -0.45dB loss across band including SMA connectors*.

*This may not be conservative enough.

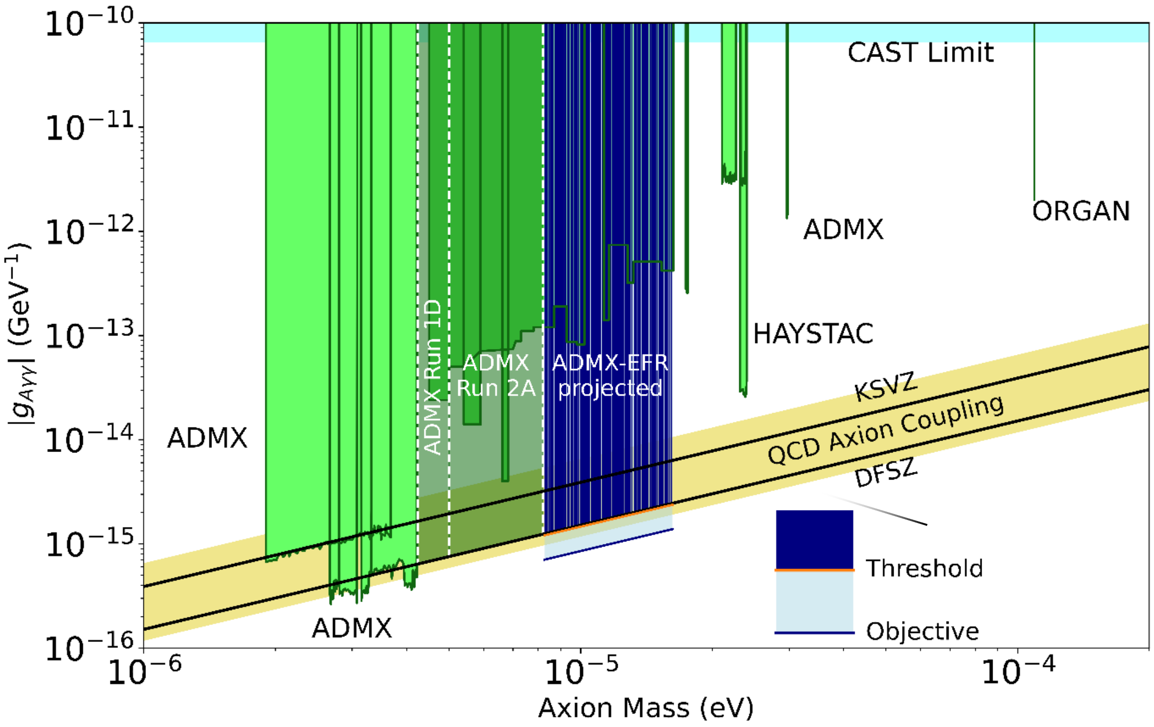
Measured SMA bulkhead feedthrough

S-parameters not added yet

Coax Model: ~-0.2dB Same propagation model as 5m cable but can be changed in the future.



# ADMX-EFR Run Times Estimates – 3 year projections



**<u>total runtime</u>:**
**3 years**

**Threshold:**
Q ~ Copper Cavity
skips mode crossings

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

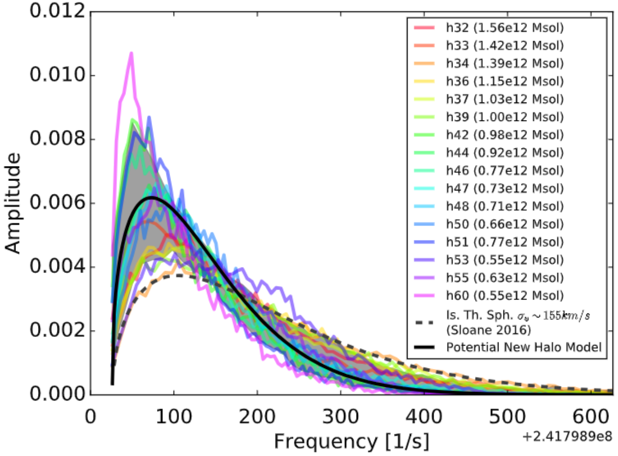
Ready to proceed when Dark Matter New Initiative program gives us a start!

**Potential 4K ops could get science early**

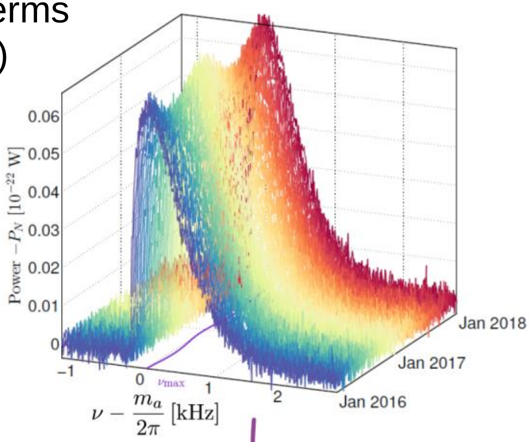
# What to do when we have a discovery?!

We only have estimates on the kinetic energy terms of the dark matter (must be bound in the galaxy)

Discovery would immediately give us access to the full kinematics… Axion Astronomy!!! (appropriately dubbed a “haloscope”)

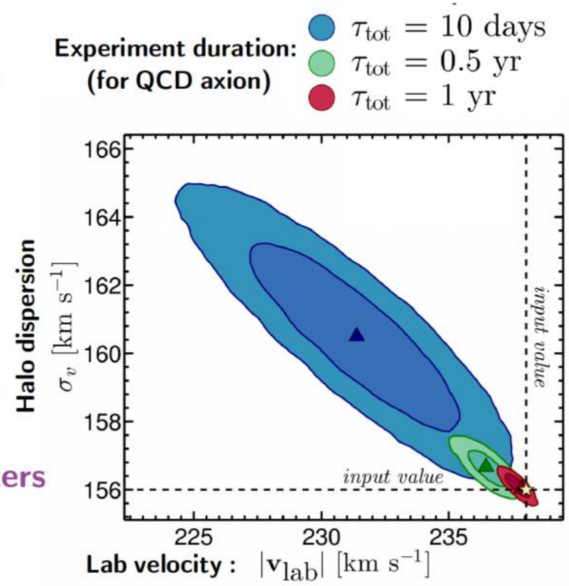


Erik W. Lentz *et al* 2017 *ApJ* **845** 121



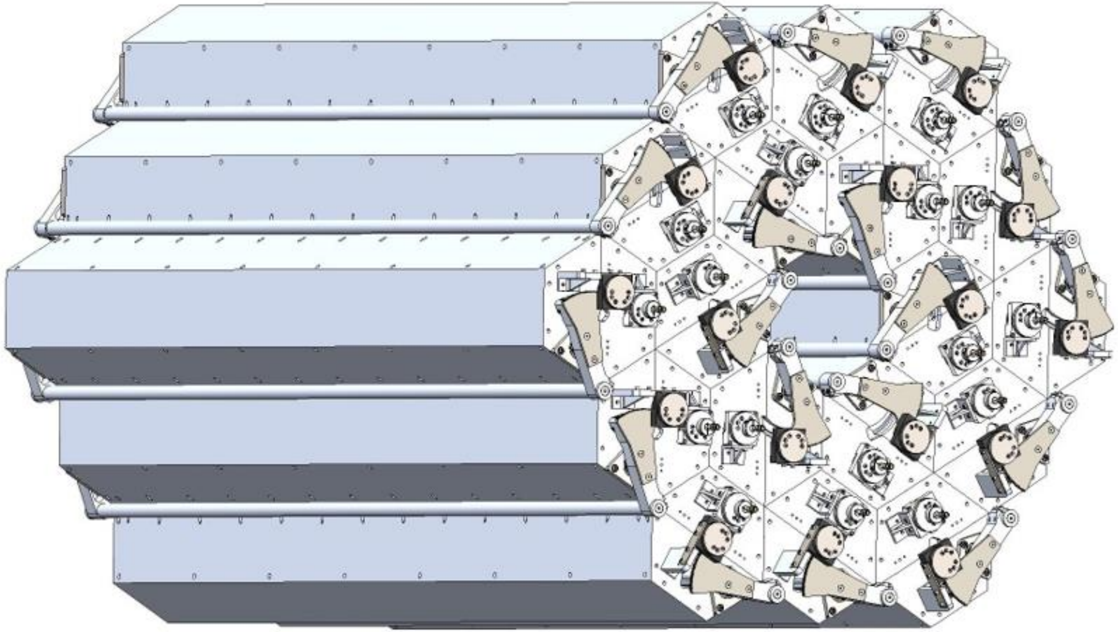
O'Hare & Green [1701.03118]

Max likelihood fit:
→ Extract astrophysical parameters



# What about other new physics

Key take away! 18 individual cavities leads to large data sets where correlations across individual cavities can be studied!



**Cosmic Axion Background?**

**Gravity Waves?**

**Chameleon particles?**


PBS
ARE AXIONS
DARK MATTER?

**Maybe!**

**We are getting closer to finding out!**

**MANY THANKS TO PIERRE!**

# Thank You!

ADMX
AXION DARK MATTER EXPERIMENT

Lawrence Livermore
National Laboratory

Fermilab

UF UNIVERSITY of FLORIDA

UNIVERSITY OF WASHINGTON 1861

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

NSF

HEISING - SIMONS
FOUNDATION

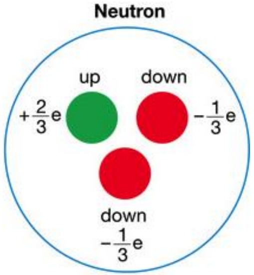
**Acknowledgements:**
This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab 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.

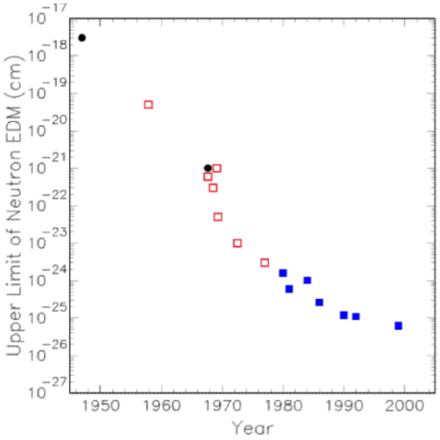
# Backup

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

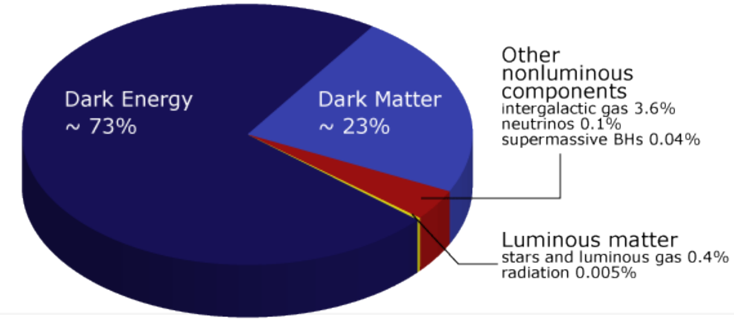
## Strong-CP problem

Strange absence of measurable neutron electric dipole moment

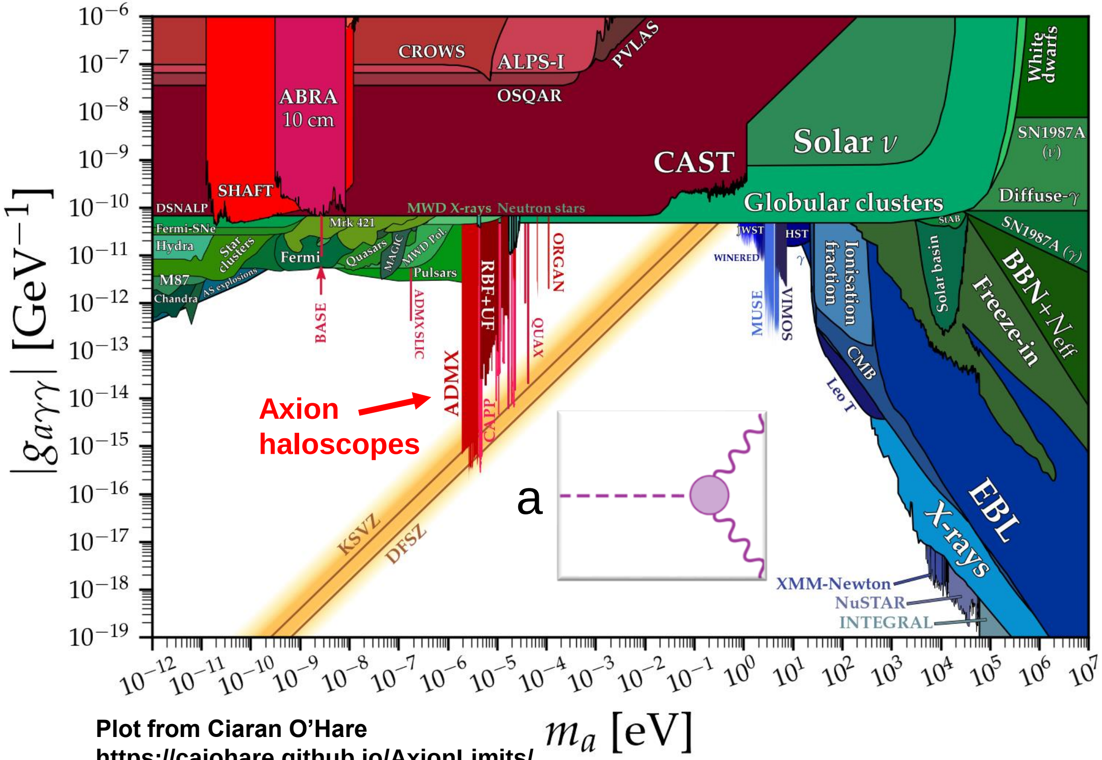




## Dark Matter

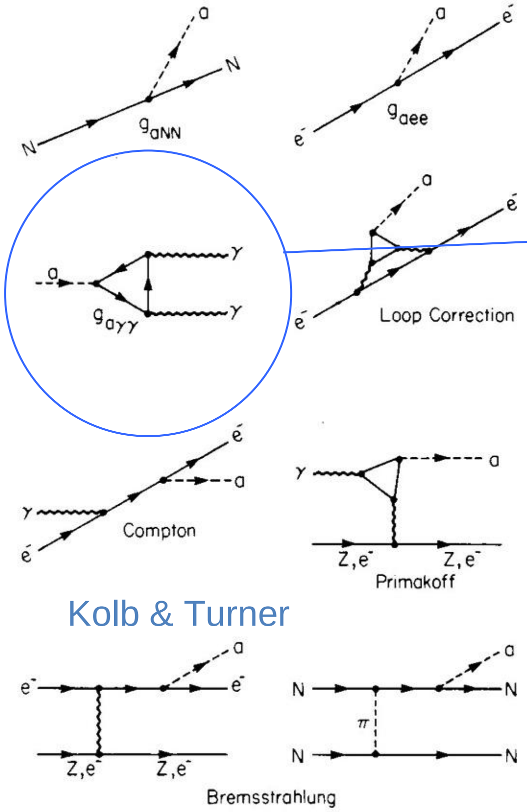


## Axion coupling to two photons a key detection technique



Plot from Ciaran O’Hare
https://cajohare.github.io/AxionLimits/

# Axion Couplings



Kolb & Turner

General classes of couplings

Axion – Nucleon
Axion – Electron
Axion – Photon

$g_{a\gamma\gamma}$ is a process with small model uncertainty
Coupling used for haloscopes

Rate depends on "unification group" (the particles in the loops), ratio of u/d quark masses. The U(1) charges at the axion vertex cancel with little model dependence

$$g_{a\gamma\gamma} \sim \frac{\alpha}{f_{PQ}}\left(\frac{E}{N}-1.95\right)$$

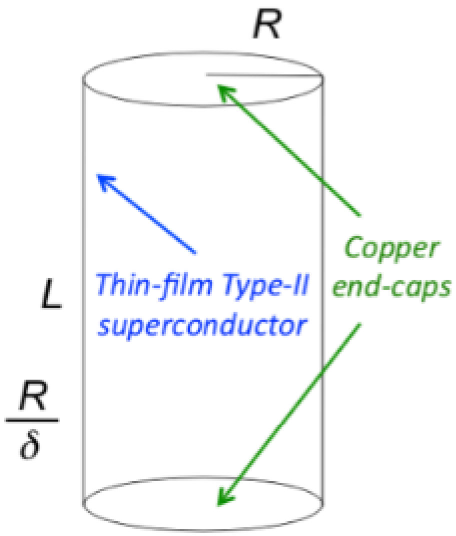
# Possible Solution: Hybrid Material Cavity

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

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

$$Q^{Hybrid} = \frac{L/R}{1 + \cancelto{0}{L/R}} \cdot \frac{R}{\delta}$$

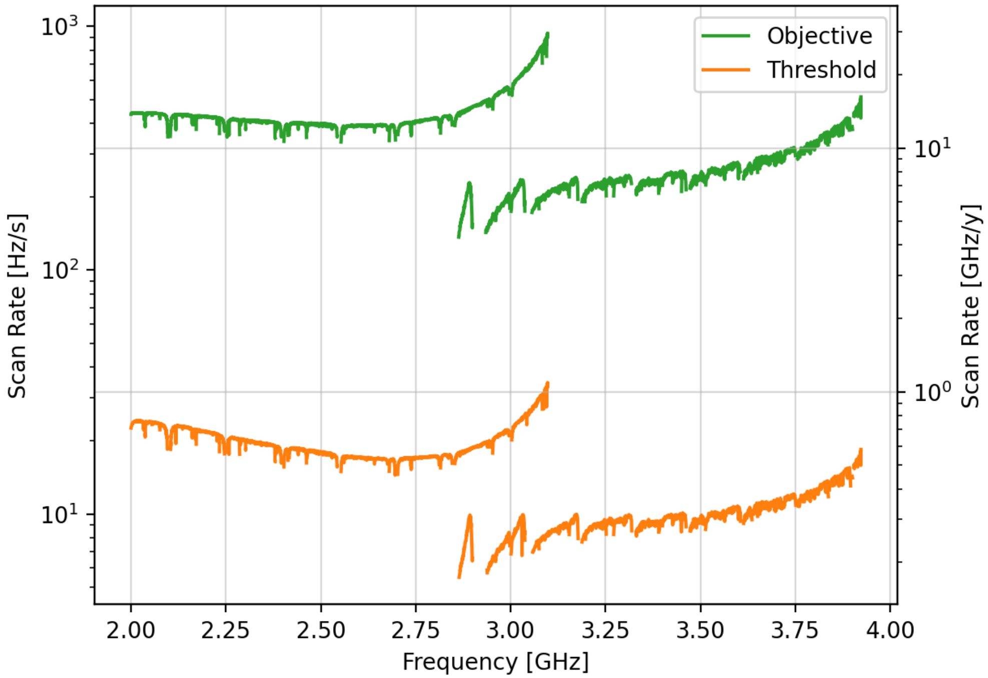
Wall contribution goes to zero



- 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.

# ADMX-EFR Run Times Estimates

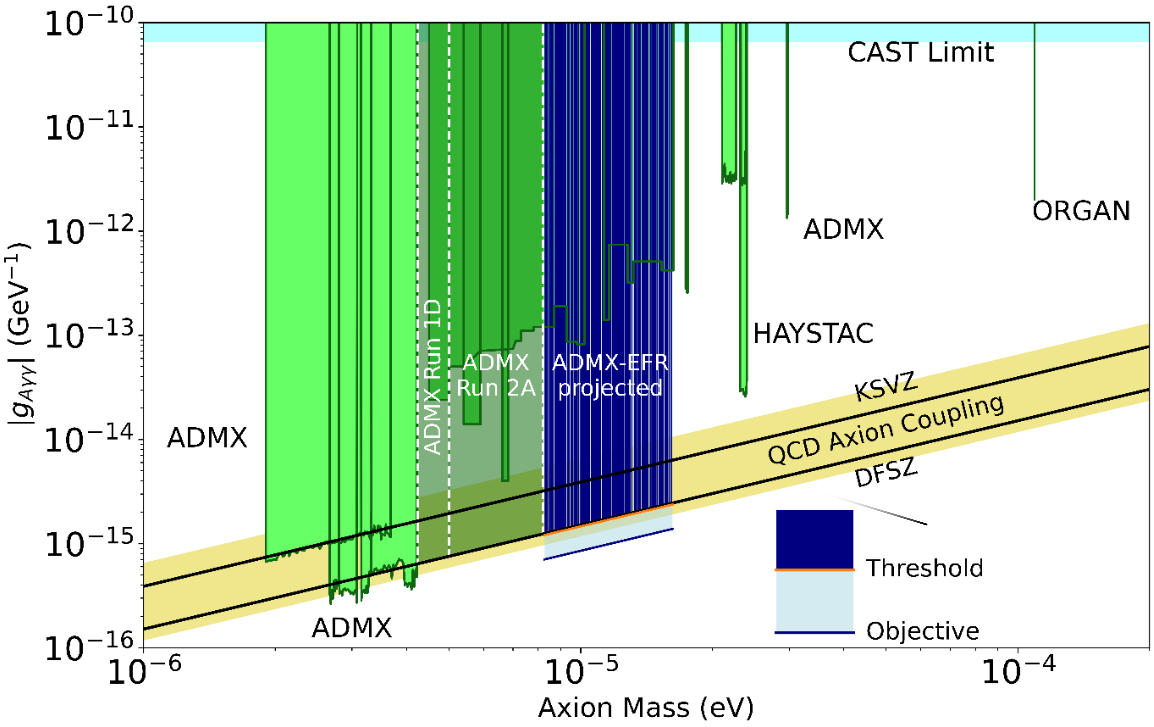


| Parameter | Unit | Threshold | Objective |
|---|---|---|---|
| Cavity system full tuning range | GHz | 2-4 | 2-4 |
| Magnetic Field Average | Tesla | 9.1 | 9.4 |
| N Cavities | | 16 | 18 |
| Volume per cavity | Liters | 12.1/10.4 | |
| Cavity $Q_0$ at 4 GHz * | | 54,000 | 180,000 |
| Cavity TM010 form 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)**
$\sim (\mathbf{10} \pm \mathbf{3})\%$

# 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

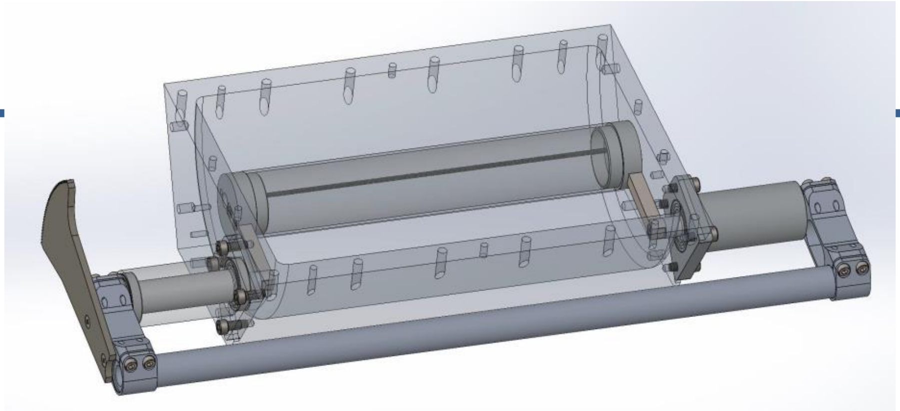
**Q > 27 x $Q_{copper}$ would allow same DFSZ experiment with only 4 cavities (save cost)**

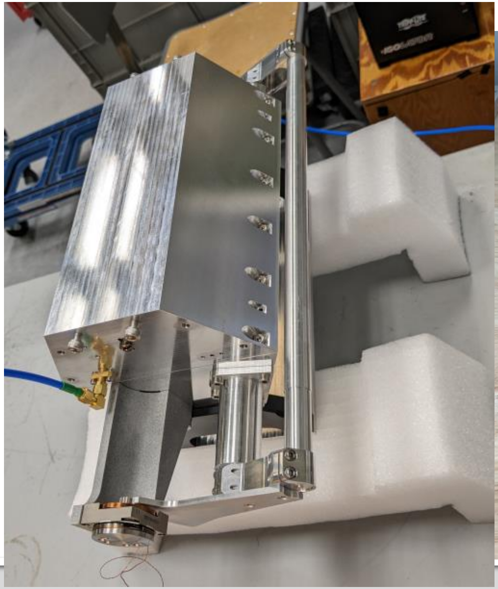
**Could run 2-3 GHz & 3-4 GHz simultaneously**

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

# ADMX-EFR Cavity Prototype

- ADMX EFR will consist of an array of 18-cavities
  - Cavities are 1 m long, 128 mm diameter
  - Cavities will be horizontally mounted inside the magnet
    - Tuning rod armature acts as a counterweight for the tuning rod
- Different diameter tuning rods will change the frequency range
  - 32 mm rods: 2.0-3.1 GHz
  - 54 mm rods: 3.1-3.9 GHz





# The Challenge for ADMX SRF cavities

- **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.

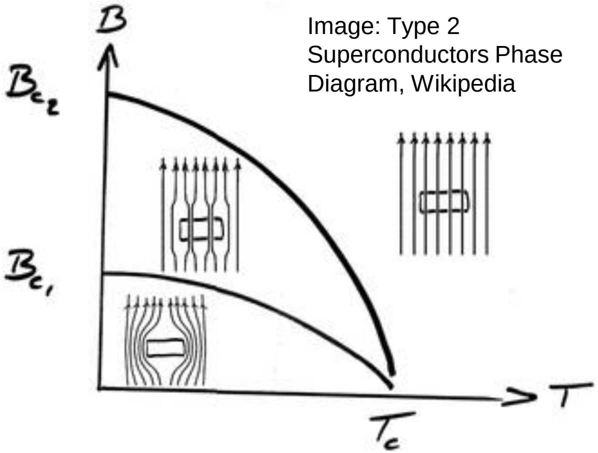
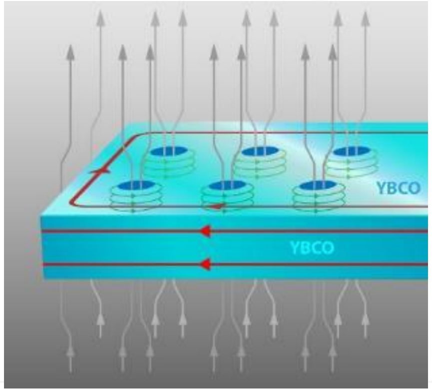
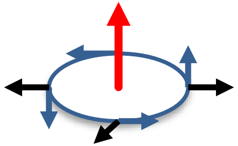


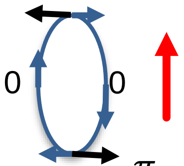
Image: Type 2 Superconductors Phase Diagram, Wikipedia



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



$$\vec{F}_{\perp} = |I||B| \sin\frac{\pi}{2} = |I||B|$$

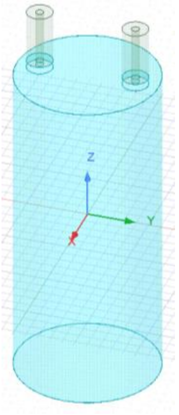


That’s what we want. No dissipation!

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

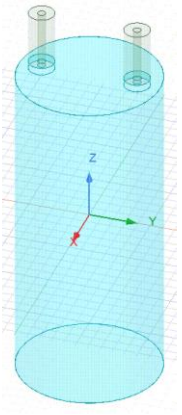
# Test Cavity Geometries:
## Multi-mode Measurements with NbTi Clamshell

- 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



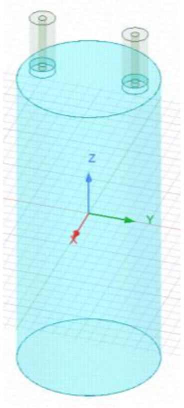
$TM_{010}$

$f_0 = 9.95 GHz$



$TM_{011}$

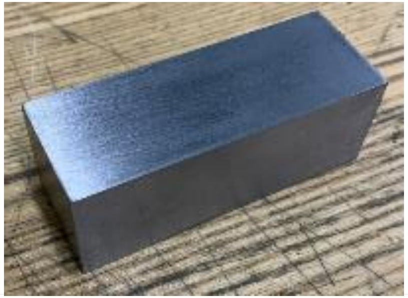
$f_0 = 10.37 GHz$



$TM_{012}$

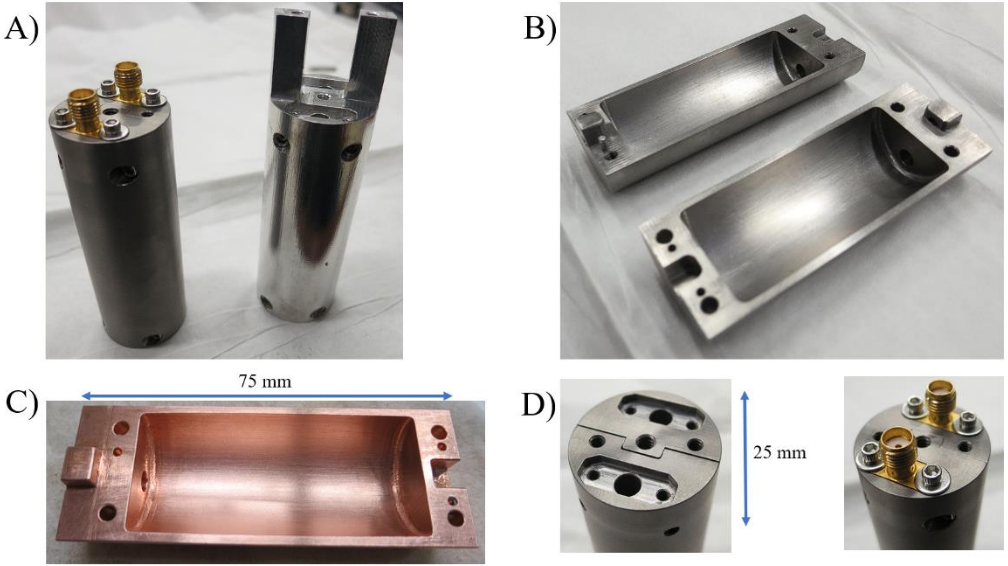
$f_0 = 11.47 GHz$

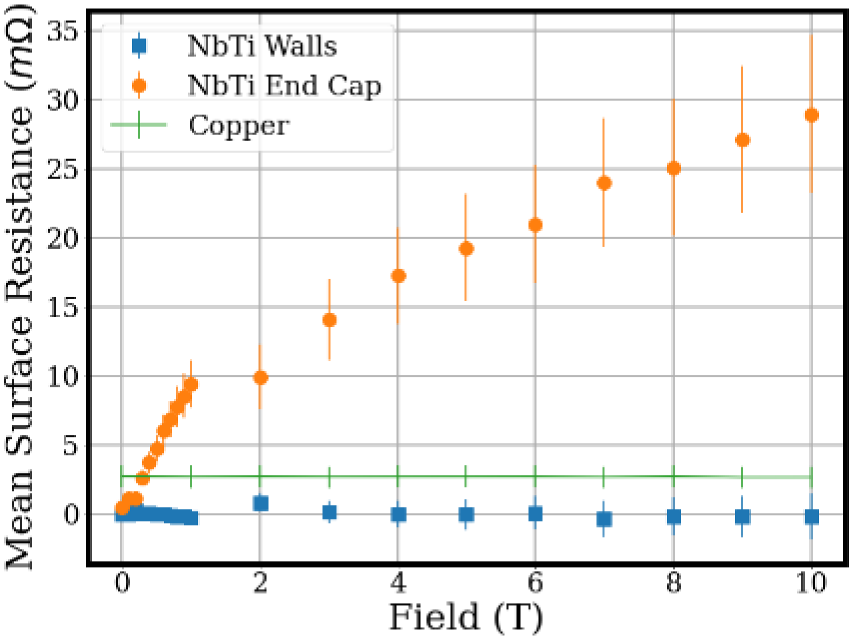
| Geometric Factor (Ω) | $TM_{010}$ | $TM_{011}$ | $TM_{012}$ |
|---|---|---|---|
| Walls | 448 | 464 | 512 |
| Top End Cap | 4060 | 2194 | 2407 |
| Bottom End Cap | 4375 | 2173 | 237 |
| Total End Caps | 2106 | 1092 | 1195 |



# 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



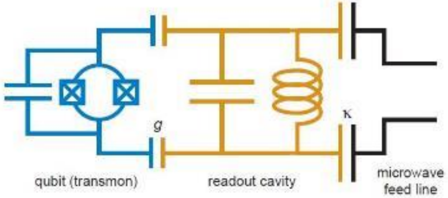


T. Braine et al. Multi-mode analysis of surface losses in a superconducting microwave resonator in high magnetic fields. Rev Sci Instrum 1 March 2023; 94 (3): 033102. https://doi.org/10.1063/5.0122296

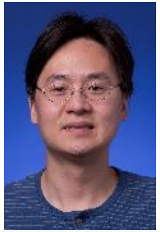
# Transmon Qubits

Transmon Qubit – single cooper pair box shunted with capacitor

Can tune the qubit frequency with flux through SQUID



Example of device fabricated at U. of Chicago (Heising-Simons funded R&D)



QuantiSED project led by Aaron Chou