# Brief Overview of the Axion Dark Matter Experiment

## Lake Louise Winter Institute

February 22, 2022

Thomas Braine
University of Washington PhD Student

LLNL-PRES-XXXX

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

# Outline of Today's Talk

- What are axions?
  - Strong CP Problem
  - Dark Matter
  - Coupling to photons
- How the ADMX currently operates
  - Haloscopes
  - Scanning Cadence
  - Current Limits
- Future ADMX run plans
  - Multi-Cavity Systems
  - SRF cavities (My work)

ADMX Run 1B extraction procedure at CENPA

Run 2A 4-Cavity System assembly at LLNL

# What are axions?:
## Peccei-Quinn Symmetry and the Axion

AXION DARK MATTER EXPERIMENT

- CP violation in strong force → measurable neutron electric dipole moment (EDM). Theory predicted to be ~ $10^{-18}$e m.

- Experiments constrain the neutron EDM close to zero implying CP conservation ($\theta_{QCD} = 0$)

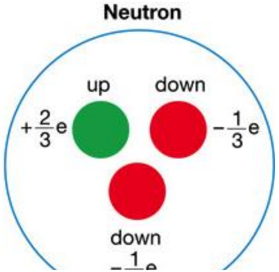
- Peccei-Quinn Solution to Strong CP Problem
  - New global U(1) chiral symmetry spontaneously broken in the early universe
  - $\theta_{QCD}$ is a dynamical variable which relaxes to zero when the wine bottle potential tips

- PQ Symmetry produced a pseudo scalar boson which is the **axion!**

- $f_a$ , the symmetry breaking energy scale, is inversely related to axion mass and coupling

$$L_\theta = \frac{g^2}{32\pi^2}\theta_{QCD} F_a^{\mu\nu}\tilde{F}_{\mu\nu a}$$

$$d_n \approx \theta_{QCD}\, e\, \frac{m_q}{m_n^2}$$




$$\mathrm{d_n} = (0.0 \pm 1.1_{\mathrm{stat}} \pm 0.2_{\mathrm{sys}}) \times 10^{-26}\,\mathrm{e{\cdot}cm}$$

Roberto Peccei 1942-2020

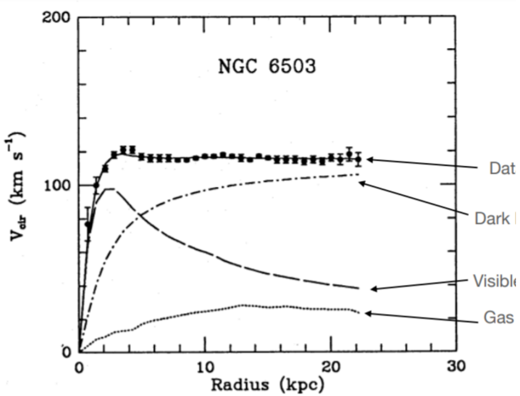
Helen Quinn


[1]Helge, Kragh. https://arxiv.org/ftp/arxiv/papers/1907/1907.04623.pdf
[2] C. Abel et al. Phys. Rev. Lett. 124, 081803 — Published 28 February 2020

# What are axions?:
## The Dark Matter Problem and Axions

AXION DARK MATTER EXPERIMENT

| Dark Matter | Axions |
|---|---|
| Feebly-interacting with Photons | ✓ |
| Gravitationally interacting | ✓ |
| Non-baryonic | ✓ |
| Very stable | ✓ |
| Cold (non-relativistic) | ✓ |



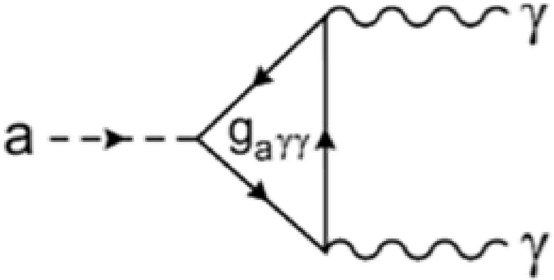

[3] K. G. Begeman, et all, Extended rotation curves of spiral galaxies: dark haloes and modified dynamics (1991) https:// doi.org/10.1093/mnras/249.3.523

[4] Bullet Cluster. Blue-Dark Matter. Pink-Matter
X-RAY: NASA/CXC/CFA/M.MARKEVITCH ET AL.

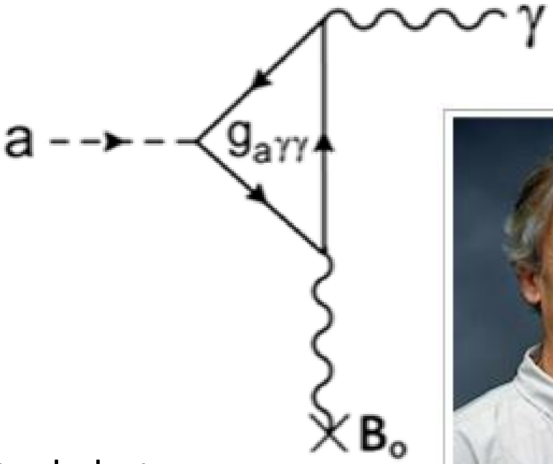
- The Dark Matter hypothesis is now well accepted, and its density can been mapped.
- Axions can constitute the entirety of dark matter: $m_{axion} \sim 1 - 100\ \mu\text{eV}$
- A particle created to solve a discrepancy in physics **theory**, solves an **experimental** discrepancy as well.

[5] https://iopscience.iop.org/article/10.1088/1475-7516/2019/04/026

# What are axions?
## Coupling to photons and detection schemes




$$\mathcal{L}_{A\gamma\gamma} = -g_{A\gamma\gamma}\boldsymbol{E}\cdot\boldsymbol{B}\phi_A$$

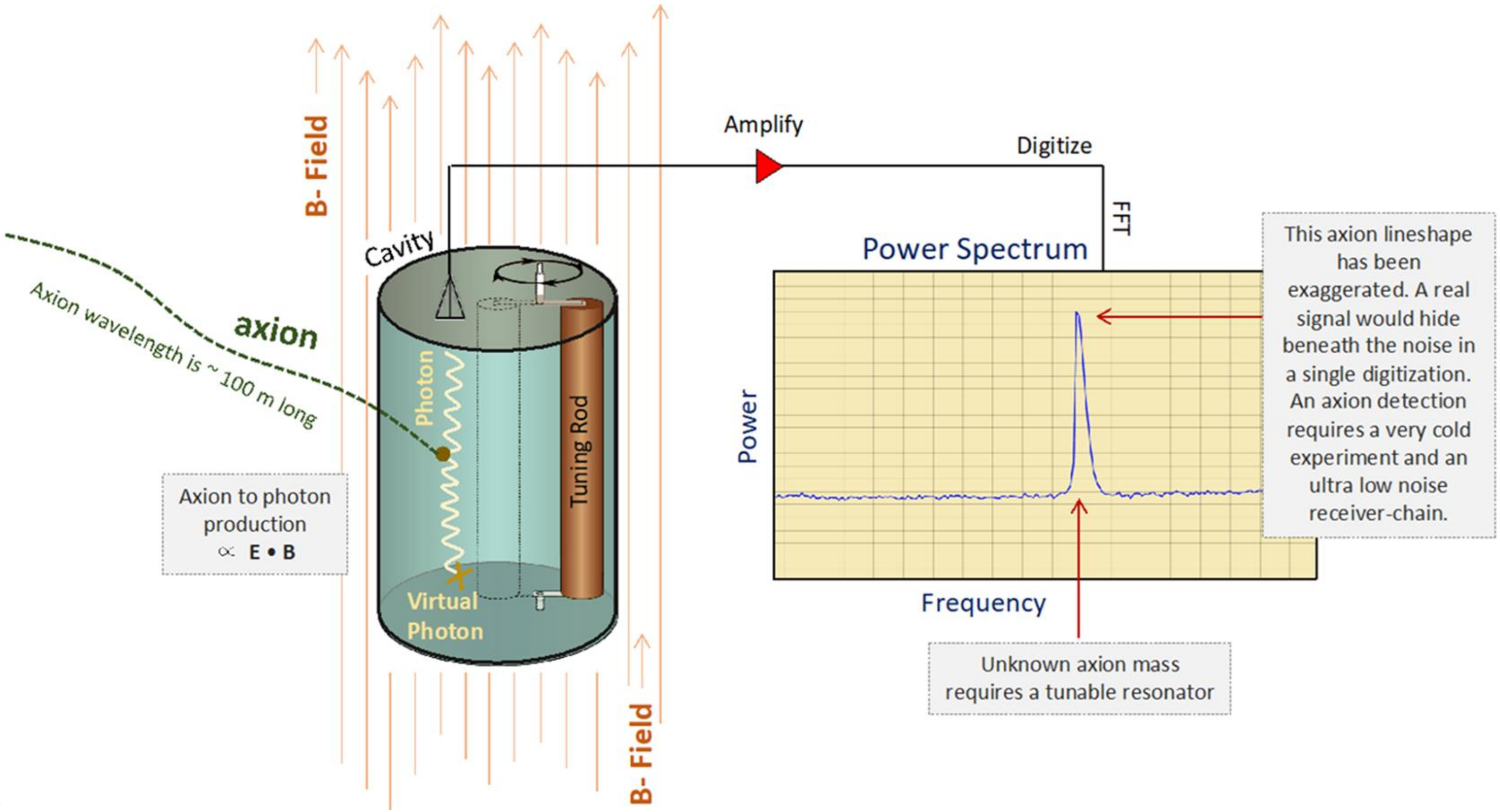



Pierre Sikivie

- Axions decay to photons via **inverse Primakoff effect**
- 1983 Pierre Sikivie: using a high static magnetic field as a virtual photon:
  - Axion **‘Halo’-scopes** would look for **cold axions** in the dark matter halo (velocity with respect the speed of light , $\beta\sim10^{-3}$) from RF photons
  - Axion **‘Helio’-scopes** could look for solar axions but resultant photons would be X-rays ( $\beta$ is larger)

# How does ADMX currently operate?

## The Axion Haloscope



# How does ADMX currently operate?

## Axion Power Equation

ADMX
AXION DARK MATTER EXPERIMENT

$$P_{axion} = 2.2 \cdot 10^{-23} W \cdot \{(\frac{g_\gamma}{0.36})^2 \cdot \frac{\rho_0}{0.45\ GeV\ cm^{-3}} \cdot \frac{f}{740\ MHz}\} \cdot \{\frac{V}{136\ L} \cdot \left(\frac{B_0}{7.6\ T}\right)^2 \cdot \frac{Q_L}{30000} \cdot \frac{C_{lmn}}{0.4}\}$$

$$SNR = \frac{P_{axion}}{kT_{sys}} \sqrt{\frac{t}{\Delta f}}$$

Model- Dependent Parameters

- $g_\gamma$ – Coupling Constant
- $f$ – Axion frequency
- $\rho_0$ – Dark matter halo density

Experimental Parameters

- $B_0$ – External magnetic Field
- $V$ – Cavity volume
- $Q_L$ – Cavity quality factor
- $C_{lmn}$ – Cavity form factor
- $SNR$ – Signal-to-noise
- $T_{sys}$ – System noise temperature
- $t$ – Integration time of FFT
- $\Delta f$ – Bandwidth of FFT

# How does ADMX currently operate?
## Axion Scan Rate Equation

ADMX AXION DARK MATTER EXPERIMENT

$$\frac{df}{dt} \approx 1.98\frac{GHz}{year}\left(\frac{g_\gamma}{0.36}\right)^4\left(\frac{f}{1\ GHz}\right)\left(\frac{\rho_0}{0.45\frac{GeV}{cc}}\right)^2 \cdot \left(\frac{5}{SNR}\right)^2\left(\frac{B_0}{7.6T}\right)^4\left(\frac{V}{136l}\right)^2\left(\frac{Q_L}{30{,}000}\right)\left(\frac{C_{lmn}}{0.4}\right)^2\left(\frac{0.35K}{T_{sys}}\right)^2 *$$

Combining signal power with SNR we can arrive at **the instantaneous scan rate** for a haloscope

*Does not include deadtime (Candidate rescans, engineering studies, COVID-19, etc.)

Model- Dependent Parameters

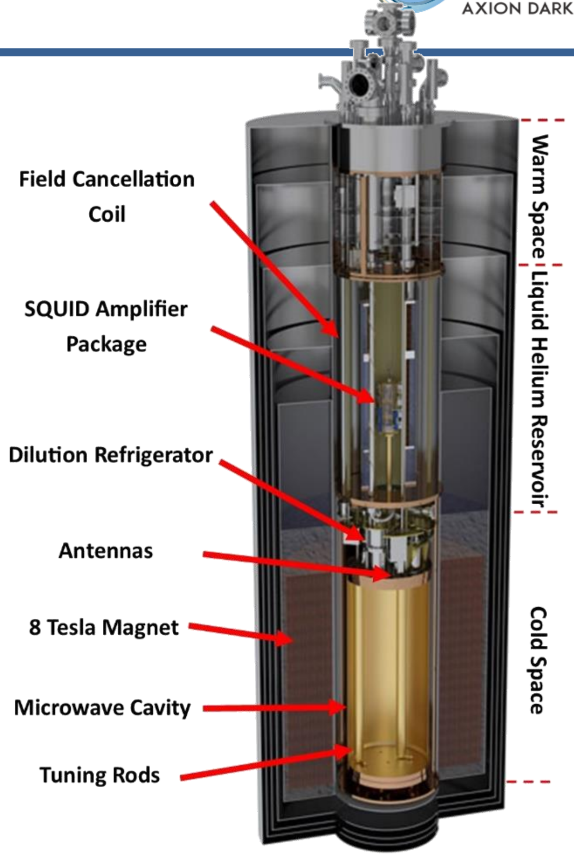
- $g_\gamma$ – Coupling Constant
- $f$ – Axion frequency
- $\rho_0$ – Dark matter halo density

Experimental Parameters

- $B_0$ – External magnetic Field
- $V$ – Cavity volume
- $Q_L$ – Cavity quality factor
- $C_{lmn}$ – Cavity form factor
- $SNR$ – Signal-to-noise
- $T_{sys}$ – System noise temperature
- $t$ – Integration time of FFT
- $\Delta f$ – Bandwidth of FFT

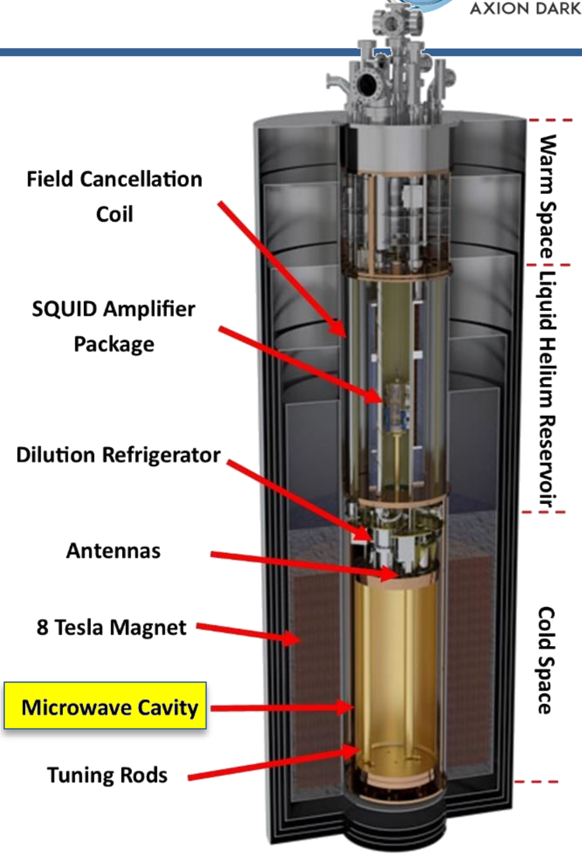
# How does ADMX currently operate?
## ADMX Insert

- ADMX insert has many systems to optimize scan rate
  - 8T magnet with 0.5 M bore→ maximize $B^2V$
  - Helium Dilution Refrigerator → minimize $T_{sys}$
  - Quantum Amplifiers→ amplify signal
  - Copper cavity resonator→ High Q in field
  - Cavity tuning rod system→ maximize run length
- These systems are then supported by more systems
  - Bucking Coil
  - RF layout to digitization
  - Helium Liquefaction plant
  - Great Science Operators!



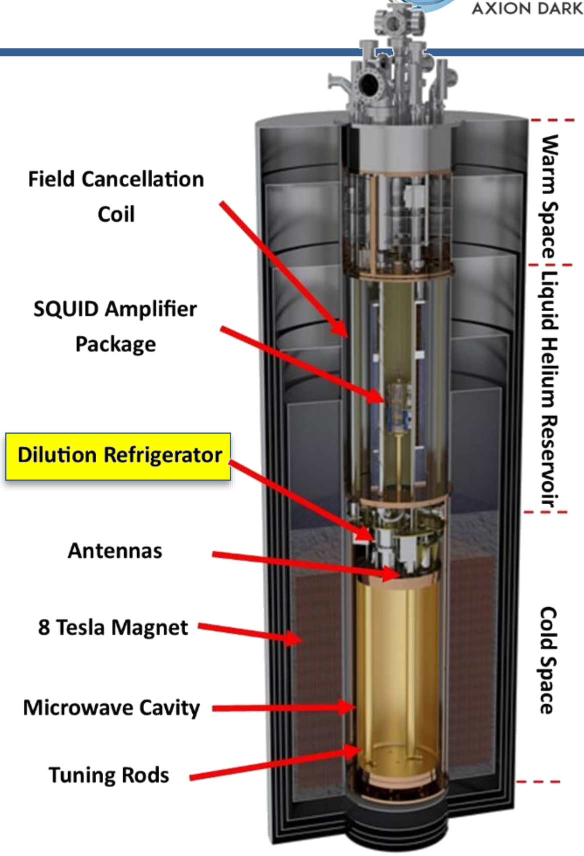
# How does ADMX currently operate?
## ADMX Insert

- ADMX insert has many systems to optimize scan rate
  - 8T magnet with 0.5 M bore→ maximize $B^2V$
  - Helium Dilution Refrigerator → minimize $T_{sys}$
  - Quantum Amplifiers→ amplify signal
  - Copper cavity resonator→ High Q in field
  - Cavity tuning rod system→ maximize run length
- These systems are then supported by more systems
  - Bucking Coil
  - RF layout to digitization
  - Helium Liquefaction plant
  - Great Science Operators!



# How does ADMX currently operate?
## ADMX Insert

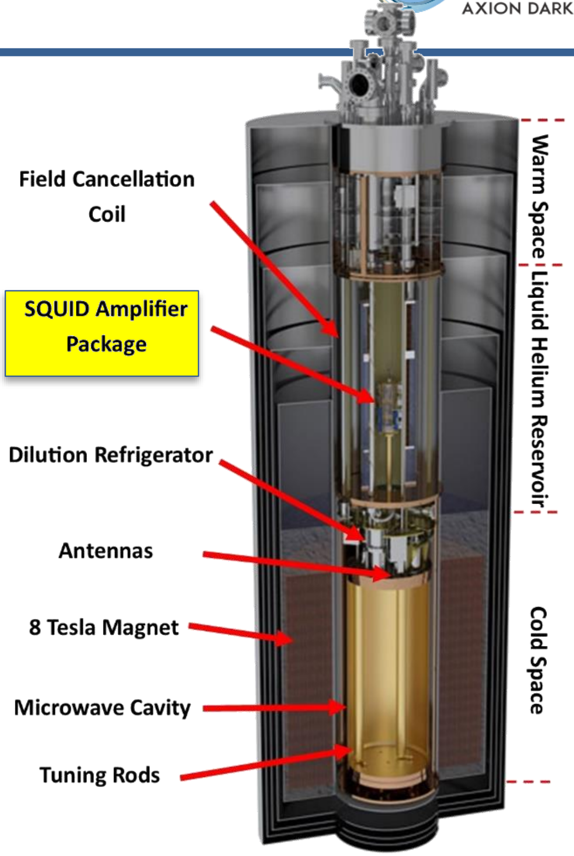
- ADMX insert has many systems to optimize scan rate
  - 8T magnet with 0.5 M bore→ maximize $B^2V$
  - Helium Dilution Refrigerator → minimize $T_{sys}$
  - Quantum Amplifiers→ amplify signal
  - Copper cavity resonator→ High Q in field
  - Cavity tuning rod system→ maximize run length
- These systems are then supported by more systems
  - Bucking Coil
  - RF layout to digitization
  - Helium Liquefaction plant
  - Great Science Operators!



# How does ADMX currently operate?
## ADMX Insert

- ADMX insert has many systems to optimize scan rate
  - 8T magnet with 0.5 M bore→ maximize $B^2V$
  - Helium Dilution Refrigerator → minimize $T_{sys}$
  - Quantum Amplifiers→ amplify signal
  - Copper cavity resonator→ High Q in field
  - Cavity tuning rod system→ maximize run length

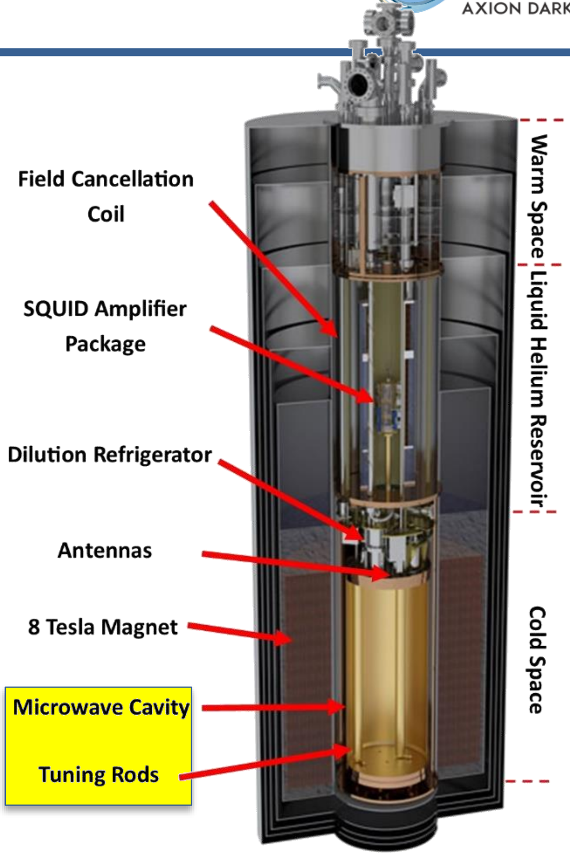
- These systems are then supported by more systems
  - Bucking Coil
  - RF layout to digitization
  - Helium Liquefaction plant
  - Great Science Operators!



# How does ADMX currently operate?
## ADMX Insert

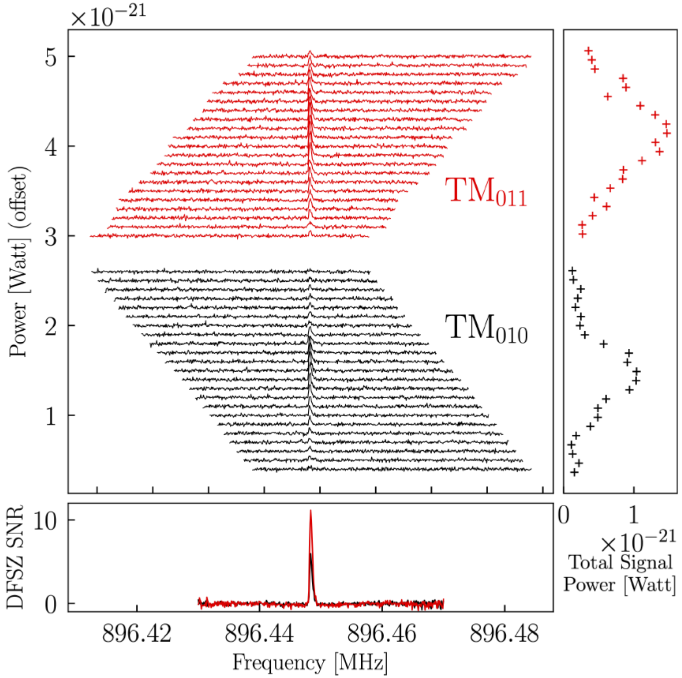
- ADMX insert has many systems to optimize scan rate
  - 8T magnet with 0.5 M bore→ maximize $B^2V$
  - Helium Dilution Refrigerator → minimize $T_{sys}$
  - Quantum Amplifiers→ amplify signal
  - Copper cavity resonator→ High Q in field
  - Cavity tuning rod system→ maximize run length

- These systems are then supported by more systems
  - Bucking Coil
  - RF layout to digitization
  - Helium Liquefaction plant
  - Great Science Operators!



# How Does ADMX Operate?
## Experimental Cadence

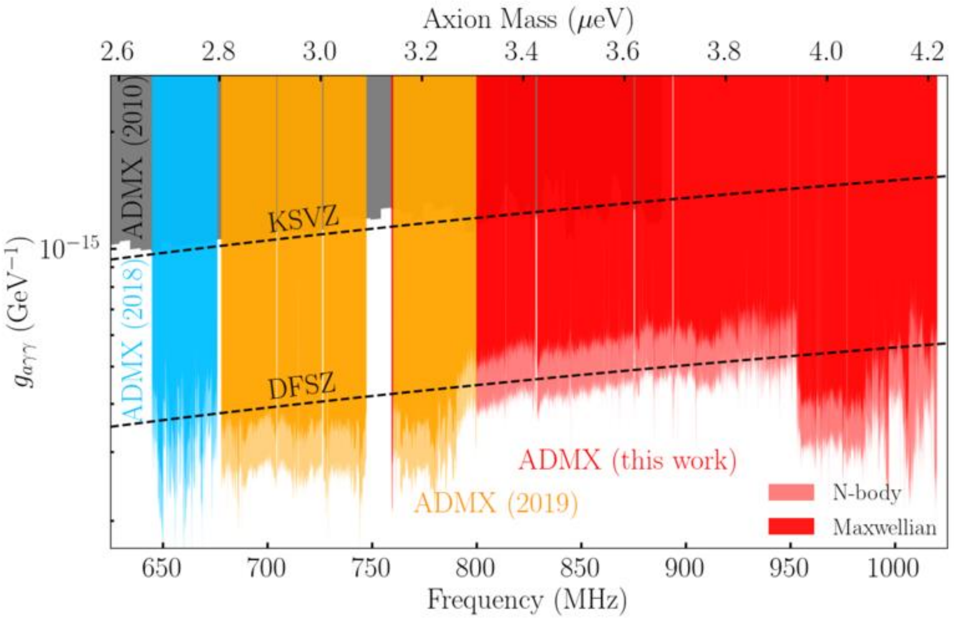
1. The cavity frequency is scanned over a frequency region until the desired SNR is achieved
2. Examine the combined power spectrum for signs of excess
3. Excess power regions can be statistical fluctuations, synthetically injected signals, RF interference, or axions
4. Excess power regions are rescanned to see if they persist
5. Persistent candidates are subjected to confirmation tests (Ex: scan outside cavity or ramp magnet)




Example Candidate

# How does ADMX currently operate?
## Current and Future Limits

- No Axions detected yet! We set exclusion limits
- ADMX G2 has excluded axions at DFSZ sensitivity for first two runs(~2.7- 3.3 $\mu eV$)
- Run 1C is finishing to DFSZ sensitivity (COVID delays)
- Run 1D will use a larger tuning rod scanning from 1-1.4 GHz




Current Axion Limits set by ADMX G2.
PRL: [Phys. Rev. Lett. 127, 261803 (2021) - Search for Invisible Axion Dark Matter in the $3.3--4.2\text{ }\text{ }\ensuremath{\mu}\mathrm{eV}$ Mass Range (aps.org)]

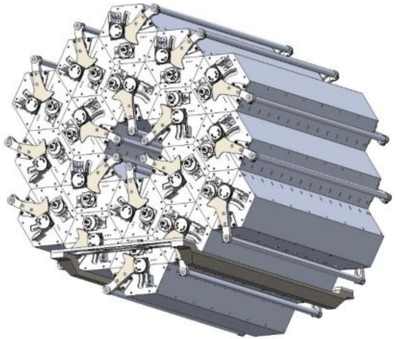
# Future of ADMX
## Challenges at Higher Frequencies

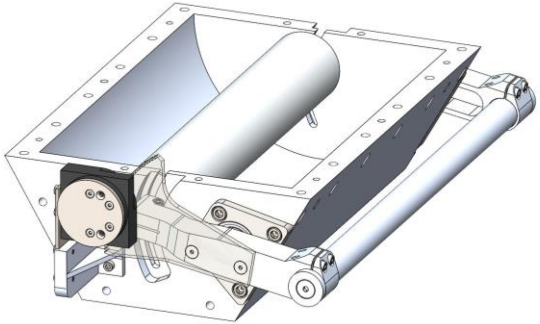
- Combine multiple smaller cavities with a higher $f_{\mathrm{TM}_{010}}$ to maintain volume (scaling issue for RF layout however)
  - Side benefit: $\sqrt{N}$ improvement to SNR from coherently adding $N$ cavities in phase (PNNL cavity combining electronics)
- Bigger and stronger magnets are expensive (Fermilab acquiring 9T MRI magnet)
- Limited ability to cool further (Possibility of squeezing quantum states to circumvent standard Quantum limit)
- Quality factor goes down for ordinary metals
  - Volume to surface ratio
  - Anomalous skin depth
- My graduate work is looking at Superconducting cavities to improve Quality factor

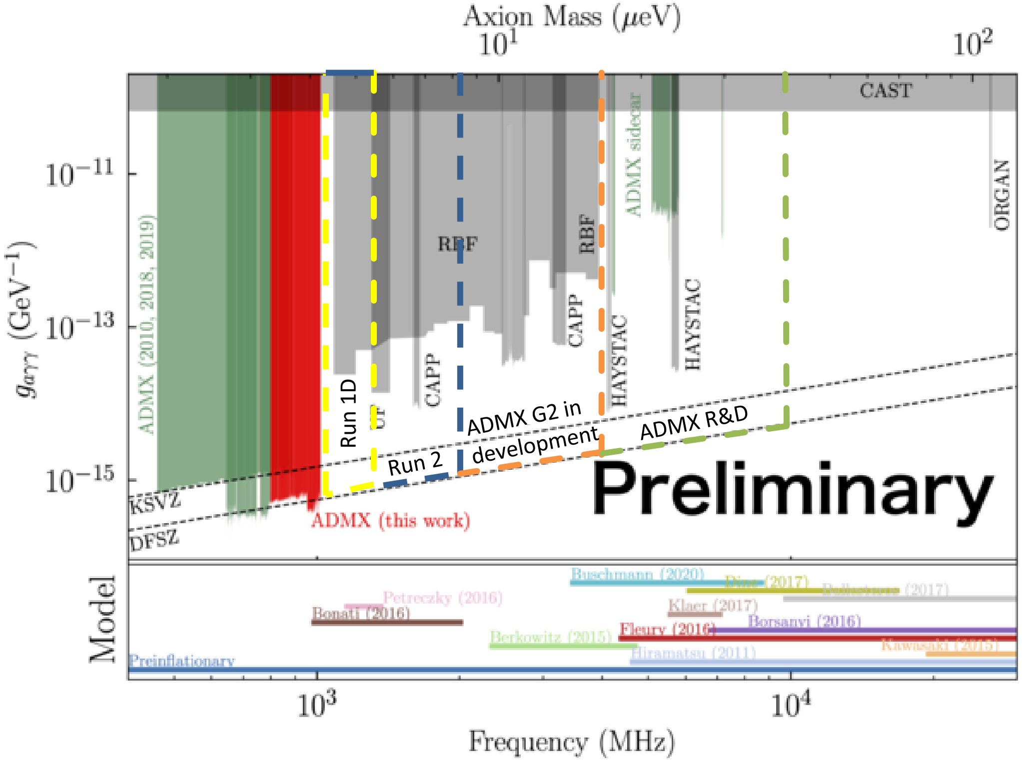
Run 2A 4-cavity system @ Fermilab (Covers 1.4- 2GHz)

# The Future of ADMX

Proposed 14 cavity array in development, potentially **Superconducting (SRF)**, covering 2-4 GHz.







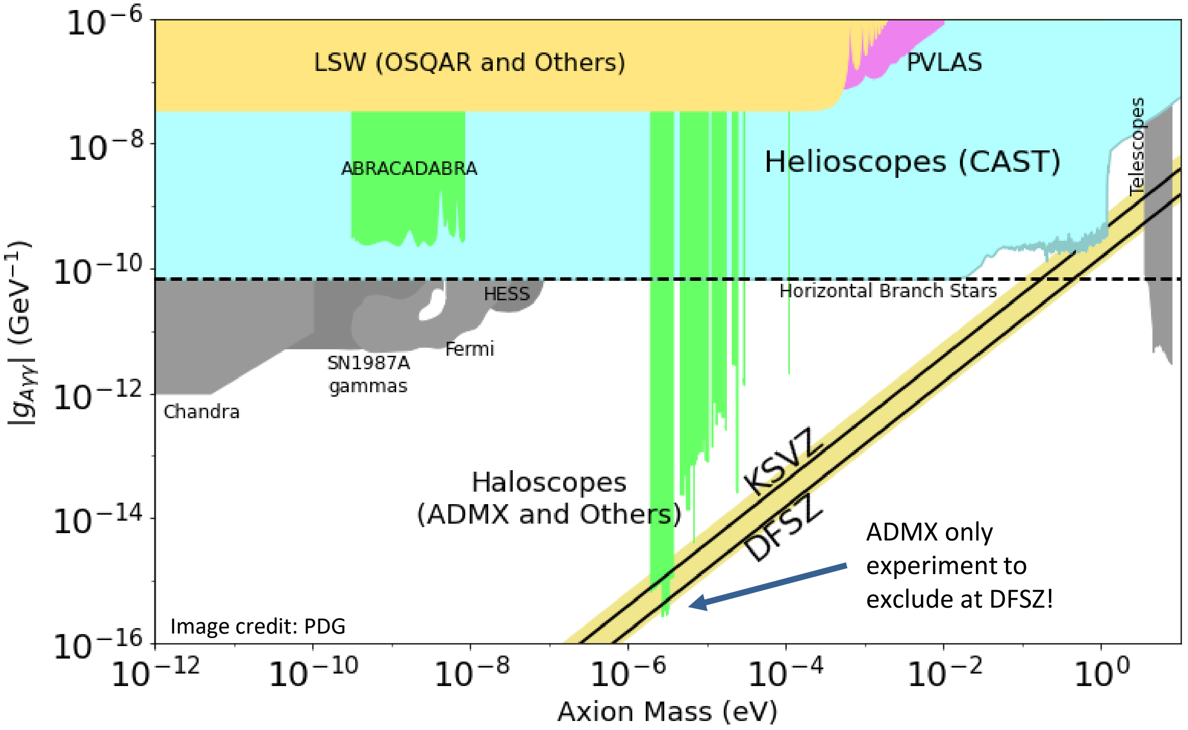
Planned coverage of Axion parameter space

# Thank You! Questions?

**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.

# What are axions:
## Types of Axion Search Experiments

- **Haloscopes**: *DM Halo Axions*
  - ADMX, RBF
  - low Mass: DM Radio, ABRACADABRA
  - high mass: MADMAX
- **Light Shining Through Walls**: Laser photon-axion mixing
  - OSQAR, ALPS
  - Future: ALPS-II
- **Helioscopes**: Solar Axions
  - CAST, Sumico
  - Future: IAXO



# What are axions:
## Axion Line shape

- Determined by the velocity distribution of the dark matter halo
- $E_\gamma = h\nu = m_a c^2 + m_a v^2/2$
- Maxwell-Boltzmann Distribution: *Standard Halo Model Thermalized, pressure-less*
  - $f_{\vec{v}} \propto e^{-\vec{v}\cdot\vec{v}/\sigma_v^2}, \sigma_v = \sqrt{2} v_c$
  - $v_c \approx 226 - 255\ km/s$
- N-body Simulations: Higher resolution, data driven simulation software
  - $f_\nu \propto \left(\frac{(\nu-\nu_0)h}{mT}\right)^\alpha e^{-\left(\frac{(\nu-\nu_0)h}{mT}\right)^\beta}$,
  - Best fit: $\alpha = 0.36 \pm 0.13$, $\beta = 1.39 \pm 0.28$, $T = (4.7 \pm 1.9) \times 10^{-7}\ K$

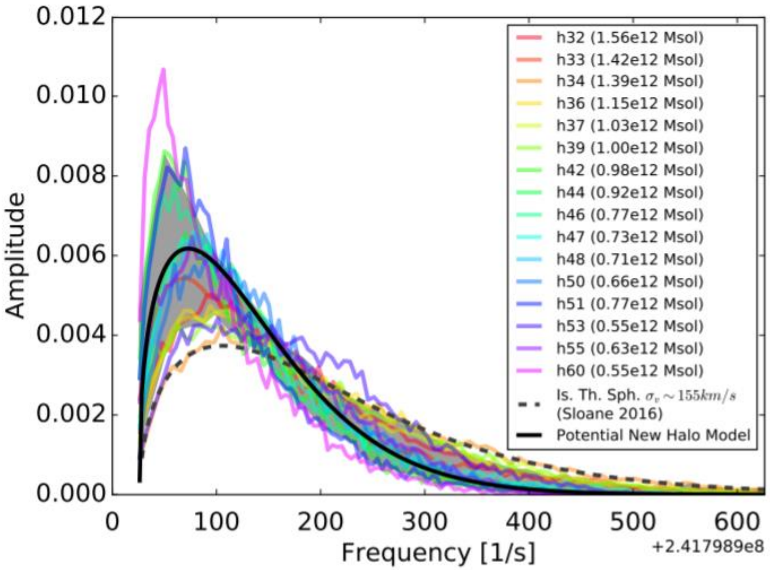
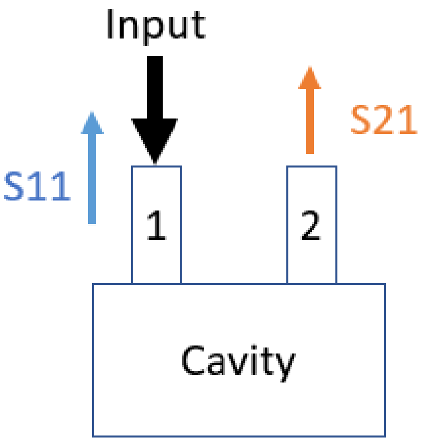


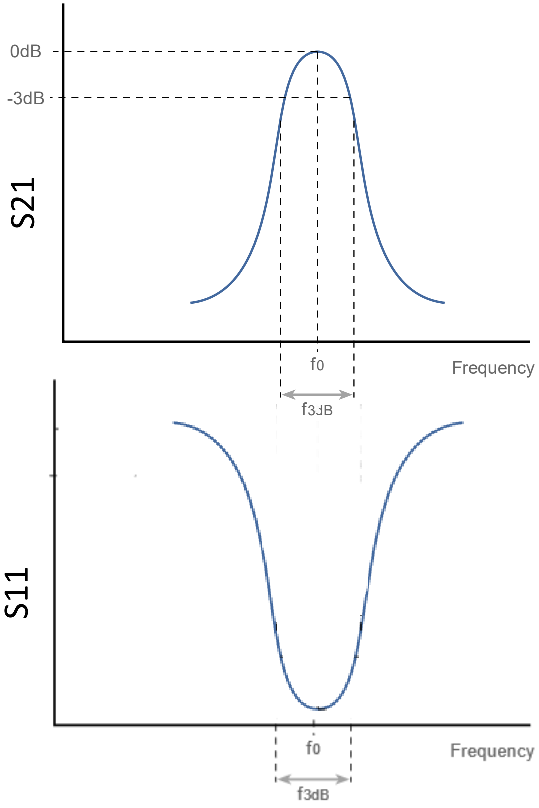

FIG. 3.— Frequency spectra of MW-like halos from Romulus25 at $z = 0$ and the SHM composed of $10^{-6} eV$ axions, generated from Fig. 2 spectra via the energy-to-frequency transform derivable from Eq. 10. The solid black line represents the new shape of the form Eq. 11 fitted to to the halos, with the gray representing the data-based error estimate using the two-thirds rule.

https://arxiv.org/abs/1703.06937

# Quality factor

- Physical definition: $\mathrm{Q} = 2\pi f_0 \frac{Energy\ Stored}{Power\ Loss}$
- Determined by the walls' impedance, resistivity, skin depth of copper (different views)
- How we Measure: $Q = \frac{f_0}{\Delta f}$,
- ADMX copper cavity gets $Q_0 \sim 10^5$
- Niobium Superconducting cavities for particle accelerators can get $Q_0 \sim 10^{10}$
- Because of the need to operate in high magnetic fields, Copper has been chosen over Superconductors so far… more on this next




$$P_{axion} = 2.2 \cdot 10^{-23} W \cdot \{\frac{V}{136\,L} \cdot \left(\frac{B_0}{7.6\,T}\right)^2 \cdot \frac{\boldsymbol{Q_L}}{\mathbf{30000}} \cdot \frac{C_{lmn}}{0.4}\} \cdot \{(\frac{g_\gamma}{0.36})^2 \cdot \frac{\rho_0}{0.45\,GeV\,cm^{-3}} \cdot \frac{f}{740\,MHz}\}$$





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

# Model for Hybrid Superconducting Cavity

- Type II superconductors have two critical magnetic field values, $B_{c1}$, below which the field is repelled completely, and $B_{c2}$, in which the field penetrates partially creating a mixed vortices state
  - Vortice motion is primary source of resistivity and dissipation in the mixed state
  - A thin film thickness can be tuned to mitigate these effects
  - **Parallel Surfaces may still have low RF resistivity**!
- 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.

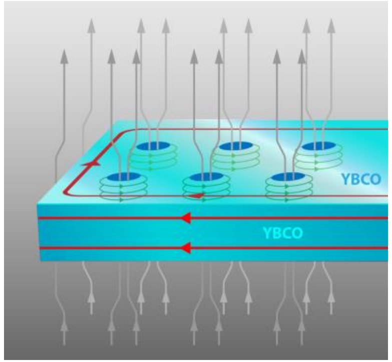



Image: Flux Vortices in Mixed State
Credit: APS, https://physics.aps.org/articles/v10/129

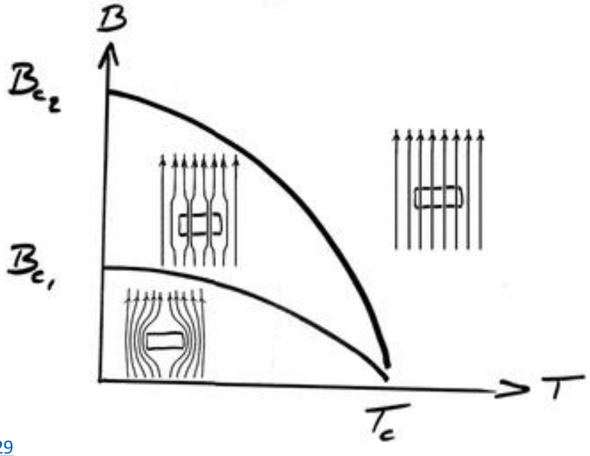
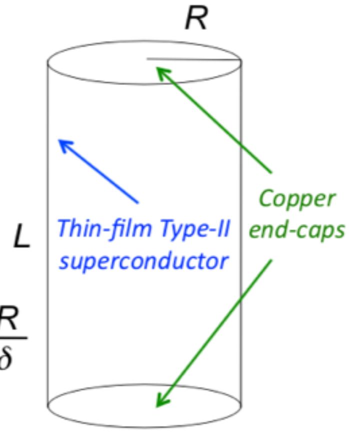



Image: Type 2 Superconductors Wikipedia

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

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

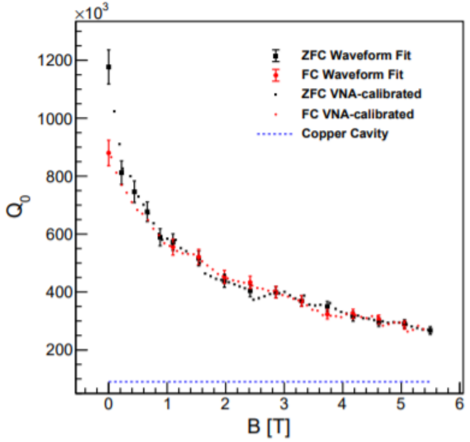
$$Q^{Hybrid} = \frac{L/R}{1 + L/R \to 0} \cdot \frac{R}{\delta}$$



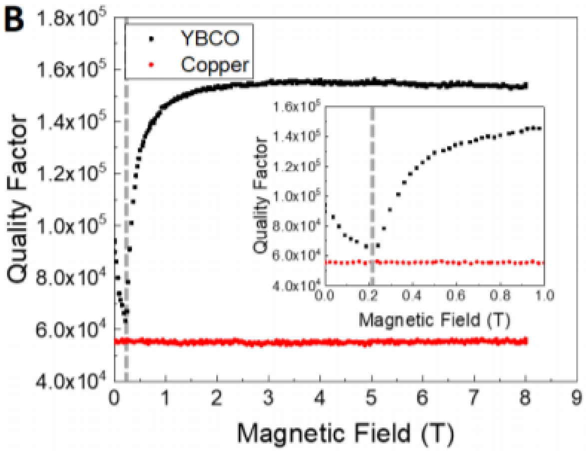
# Other Candidates

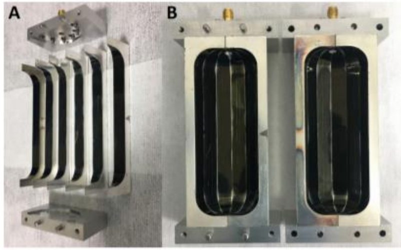
- **NbTi**: depositions at LLNL. QUAX Collaboration demonstrated high Q hybrid cavity.[1]
- **YBCO**: CAPP institute demonstrated an RF cavity with a Q 2x that of copper with no degradation from 1-8 T. [2]
- **$Nb_3Sn$:** considering several processes
  - Work at IEEE measuring surface impedance[3]
  - Working with FSU/NHMFL on testing on bronze substrate[4]
  - Also working with Fermilab using niobium substrate[5]
  - Jefferson Labs and CERN have other processes[6]
- Open to other materials and processes!

NbTi Cavity by QUAX:




YBCO Cavity at CAPP:

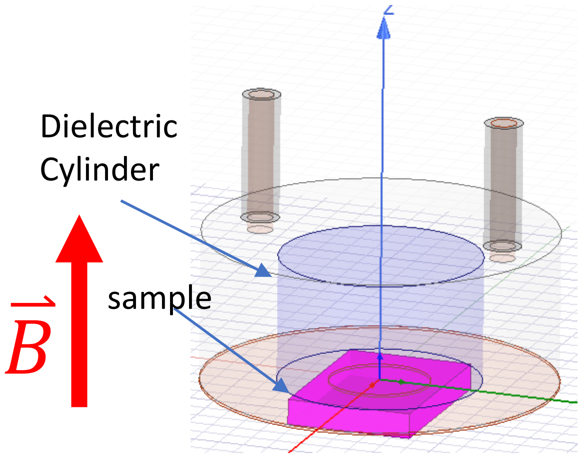


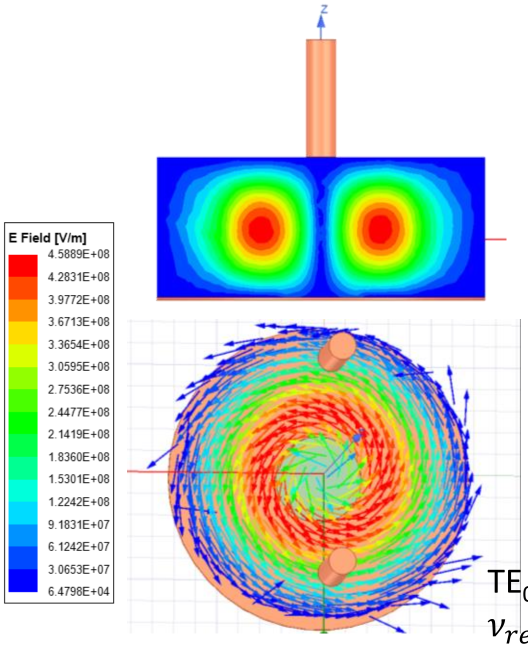





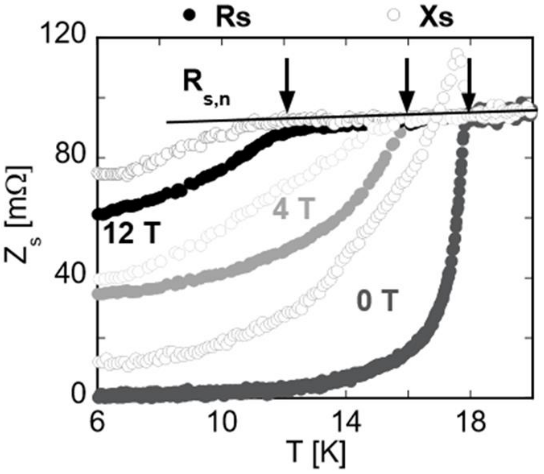
[1] arXiv:1904.05111
[2] 10.1103/PhysRevD.99.101101
[3] doi: 10.1109/TASC.2019.2892584.
[4] See Wenura Withanage Talk: Bronze Route for $Nb_3Sn$ films
[5] doi:10.1088/1361-6668/30/3/033004
[6] doi:10.18429/JACoW-SRF2019-MOP018

# Measuring Sample Impedance from Q




$TE_{011}$
$\nu_{res}$~$14.5GHz$



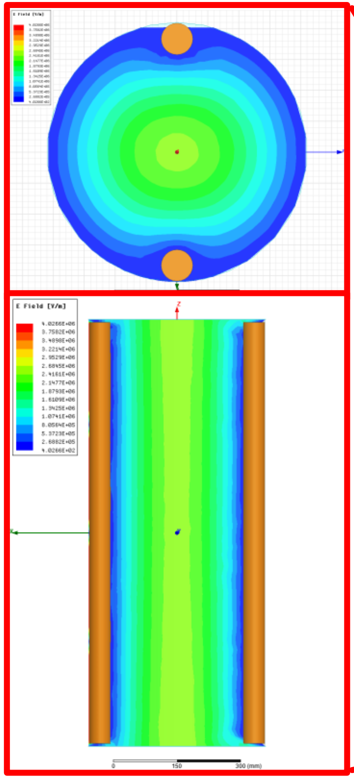

doi: 10.1109/TASC.2019.2892584.

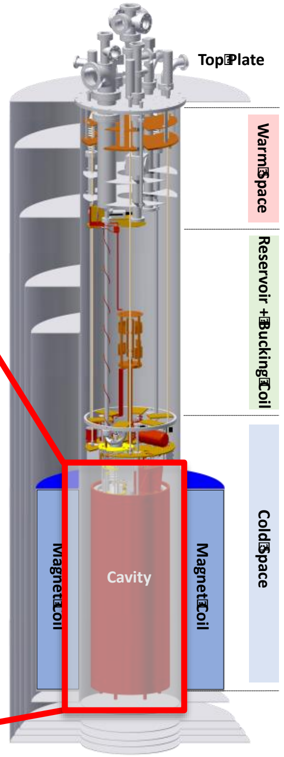
$$Z_s = R_s + i\Delta X_s = \frac{G_s}{Q} - i2G_s\frac{\Delta\nu_{res}}{\nu_{res}} - background$$

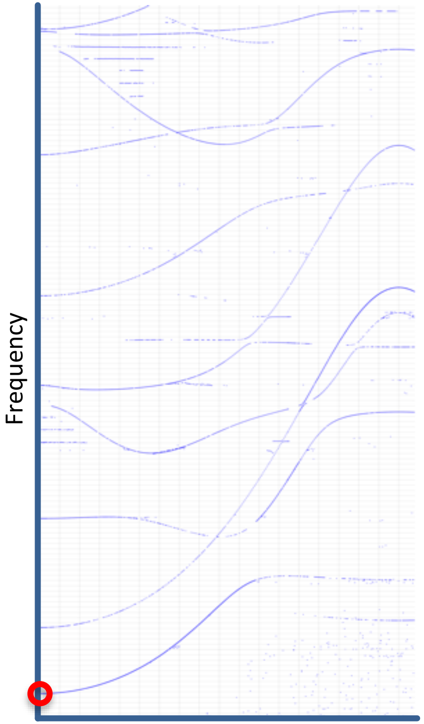
$R_s$ –surface resistance, $X_s$- surface reactance, $\nu_{res}$- resonant frequency, $G_s$- Geometric Factor

- A dielectric focuses the TE mode off the walls of the cavity, so the sample is largest contribution to impedance
- I worked on simulating this result (top right) from IEEE with HFSS software, eventually adapting it to our measurements
- Looking at replicating and expanding technique with a geometry parallel to the magnetic field and different frequency range

# How does ADMX operate?
## Scanning Masses via Tuning Rod



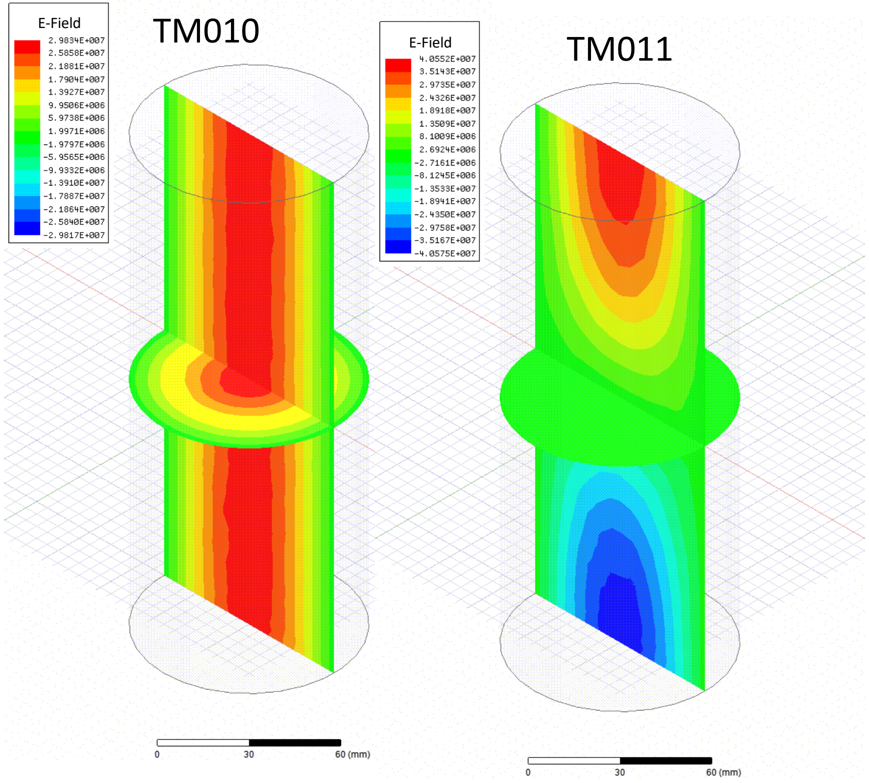



# How does ADMX operate?
## Cavity Form Factor

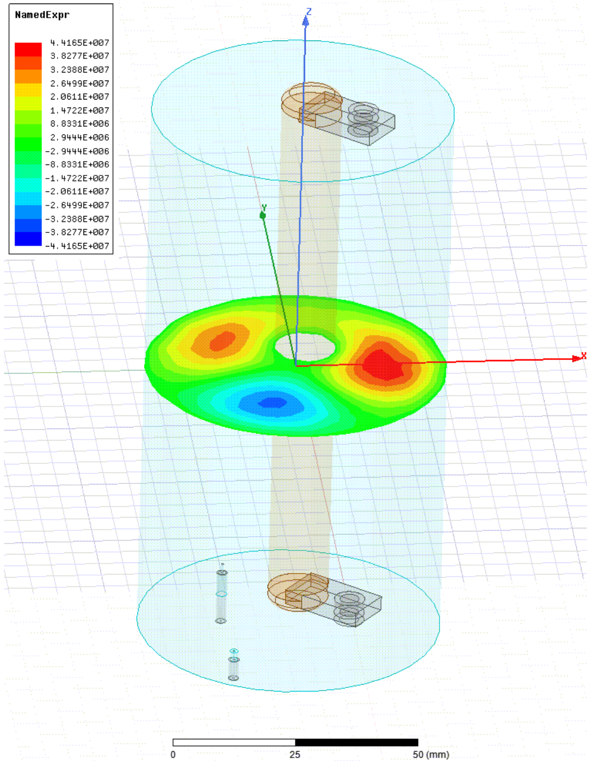
$$C_{\mathrm{lmn}} = \frac{\left(\int_V dV \;\; E \cdot B\right)^2}{V \; B^2 \int_V dV \; E^2}$$

- The cavity form factor is a function of the mode structure of the cavity.
- TM010 has the maximum form factor of ~0.7
- The majority of modes have a negligible form factor.
- Due to the tuning rod ADMX typically achieves ~0.4



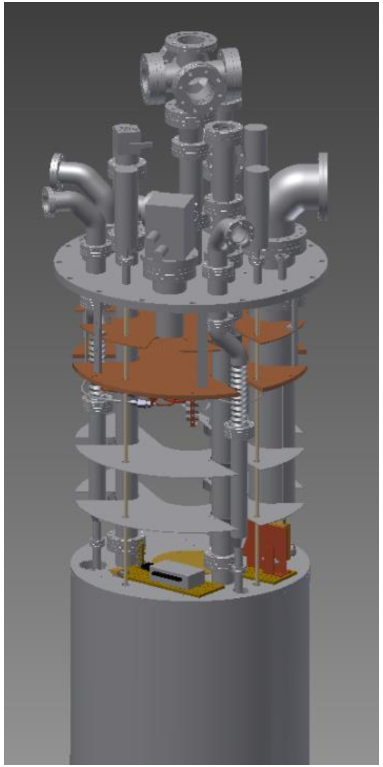
# Higher Order Modes

- Modes other than the TM010 have non-zero form factors.
- The TM020 has a form factor of ~0.1.
- Testing operation using the Sidecar cavity.
- Extends the scannable range to 6.4-7.2GHz



# ADMX Systems
## Cryogenics

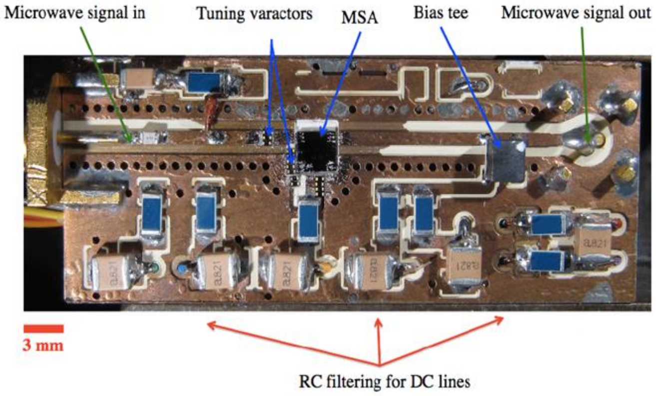
- Cryocooler
  - Actively cools baffle to 40K
  - First heatsinking stage
- Two 1K pots
  - Large 1K pot for the shielding, gearbox and electricals.
  - Small 1K pot for Dil Fridge
- Dil fridge was custom built by Janis Research Company
- 800 µW of cooling at 100 mK
- Cools the resonator and amplifiers.



# ADMX Systems
## Quantum RF electronics

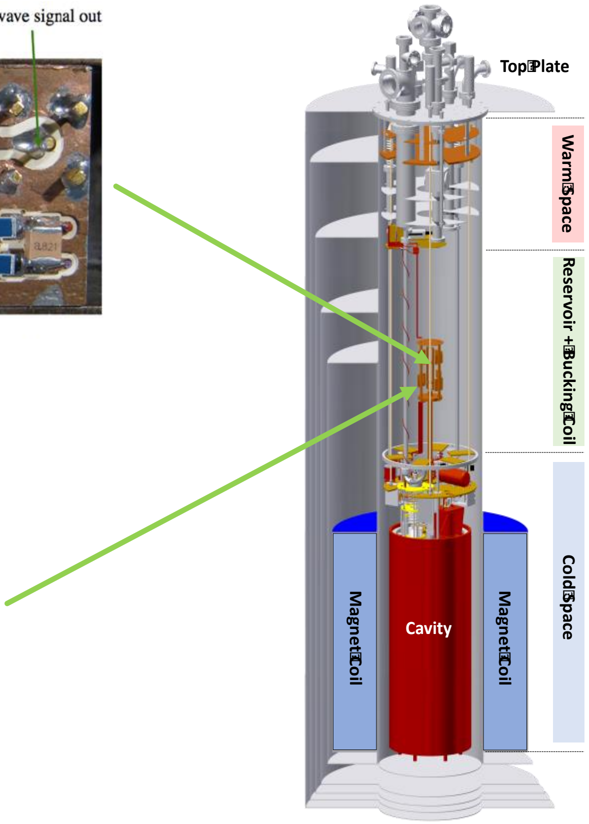
**ADMX Tunable MSA**

Sean O'Kelley, Clarke Group, UC Berkeley



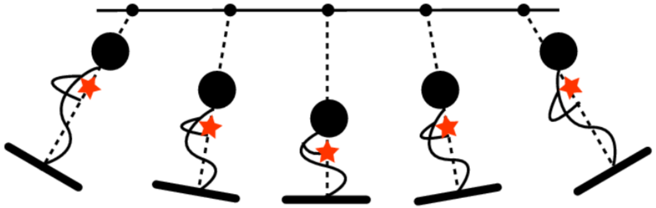

**ADMX JPA**

Yanjie Qiu, Siddiqi Group, UC Berkeley

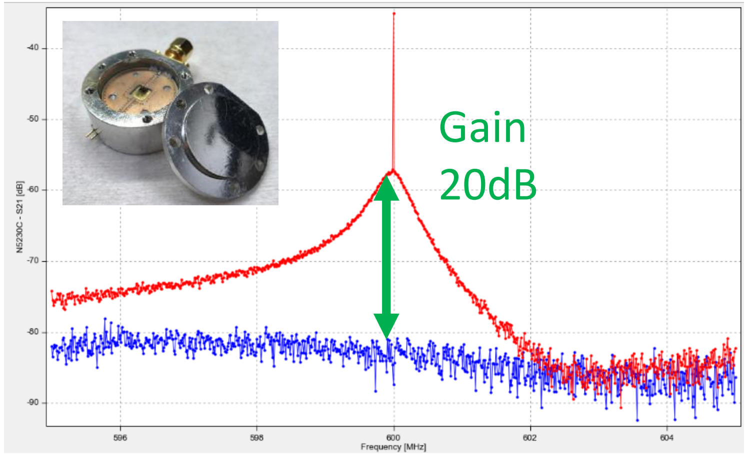


# ADMX Systems
## Quantum RF electronics

- For frequencies above 1GHz Josephson parametric amplifiers are more suitable.
- A pump tone is used to excite squid loops which in turn amplify the incoming signal.
- Produced by the Siddiqi Group at UC Berkeley
- Testing of the quantum electronics took place at Livermore before being shipped to the experiment.



Classic example of parametric amplification is a child on a swing



# ADMX Systems
## Synthetic Axion Generator

- To calibrate the detector a ‘synthetic axion’ signal could be injected into the cavity. This both verified the electronics and the analysis procedure.