The Axion Dark Matter Experiment

Lake Louise Winter Institute

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Outline of Today's Talk

- What are axions?
- How ADMX currently operates
  - Haloscope 101
  - Current Limits and Run
- Future of ADMX
  - ADMX sidecar
  - ADMX-EFR

ADMX Run 1B extraction procedure at CENPA

Run 2 4-Cavity System assembly at LLNL

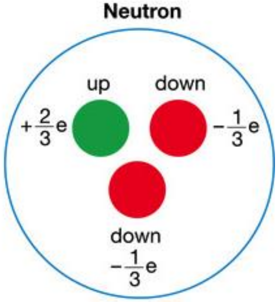
What are axions?:
The Dark Matter Problem and Axions

- **Strong CP Problem:** unnecessary CP conservation in the strong force ($\theta_{QCD} = 0$)
- **Axions** originate from a solution to the strong CP Problem, **Peccei-Quinn Symmetry.**
- f_a , the symmetry breaking energy scale, is inversely related to axion mass and coupling. $m_a \sim \frac{1}{f_a}$
- 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.

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

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

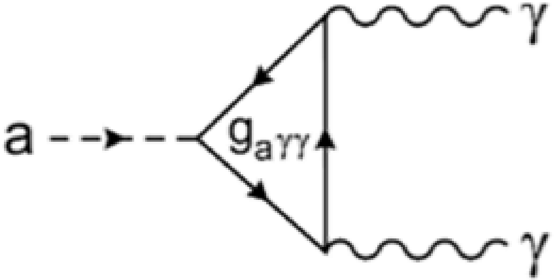
$$d_n \approx \theta_{QCD}\, e \frac{m_q}{m_n^2}$$



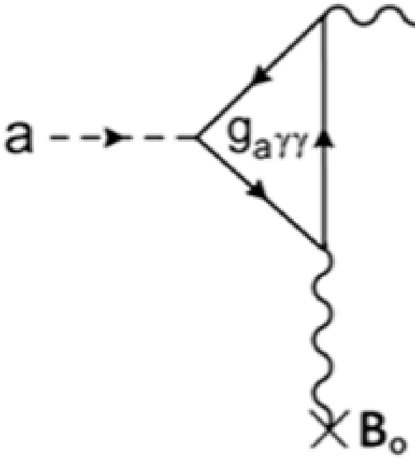
Dark Matter	Axions
Feebly-interacting with Photons	✓
Gravitationally interacting	✓
Non-baryonic	✓
Very stable	✓
Cold (non-relativistic)	✓

What are axions?

Coupling to photons and detection schemes



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

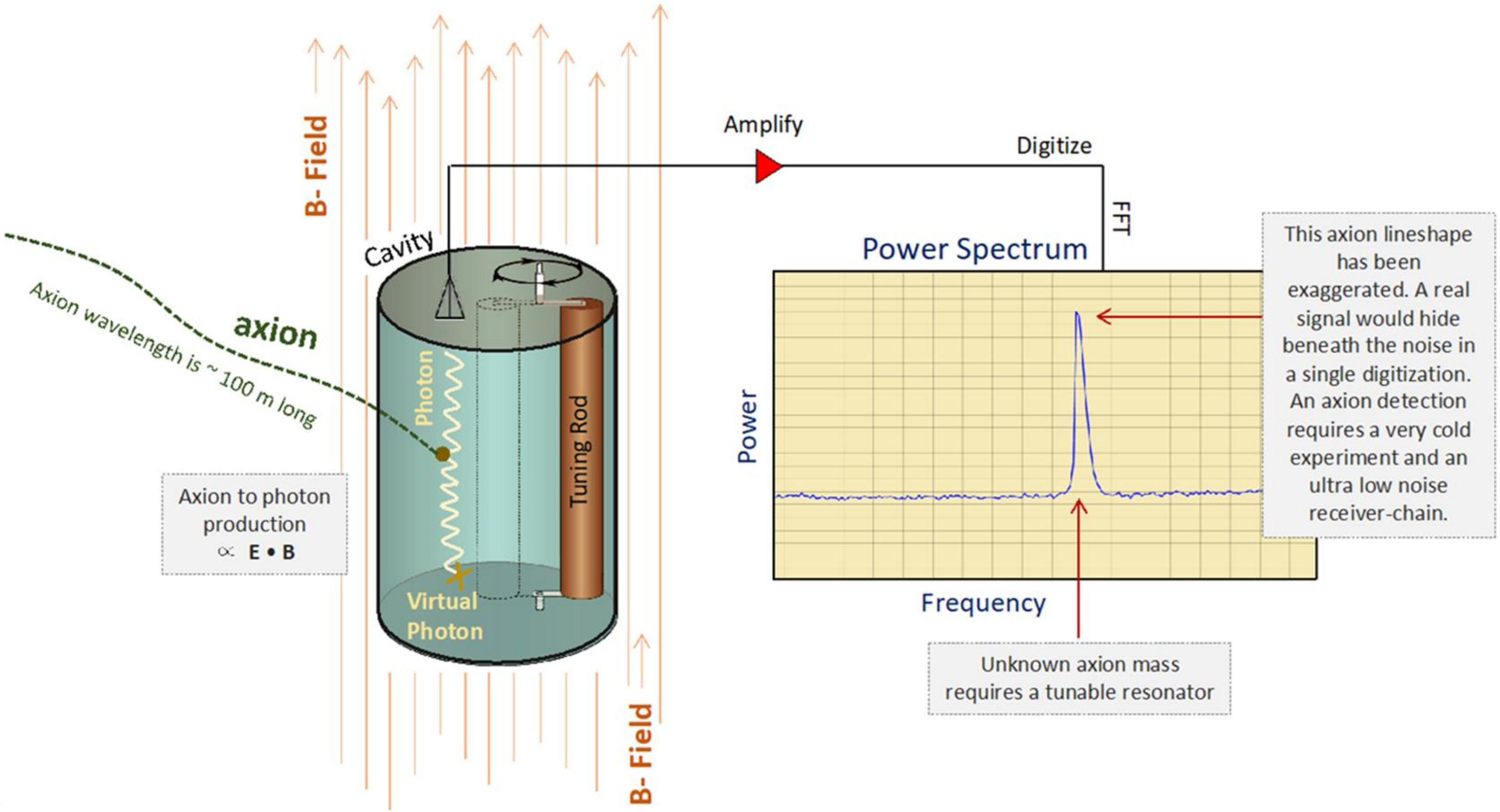


Pierre Sikivie

- 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 (low velocity with respect the speed of light , $\beta \sim 10^{-3}$) from RF photons
  - Axion **'Helio'-scopes** could look for solar axions but resultant photons would be X-rays (β is larger)

How does ADMX currently operate?

The Axion Haloscope



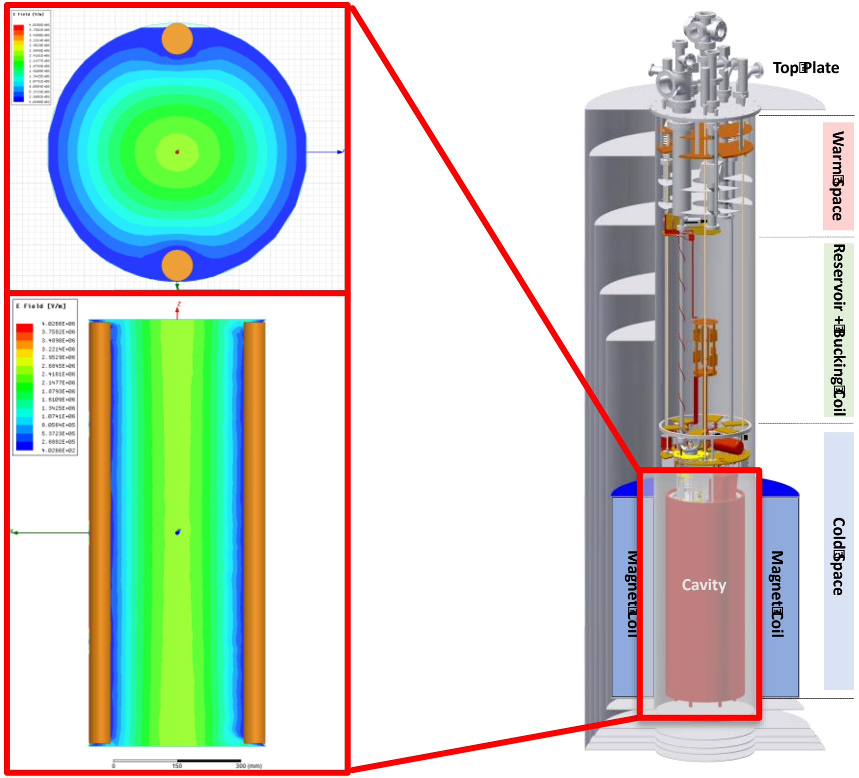
Axion to photon production $\propto$ **E • B**

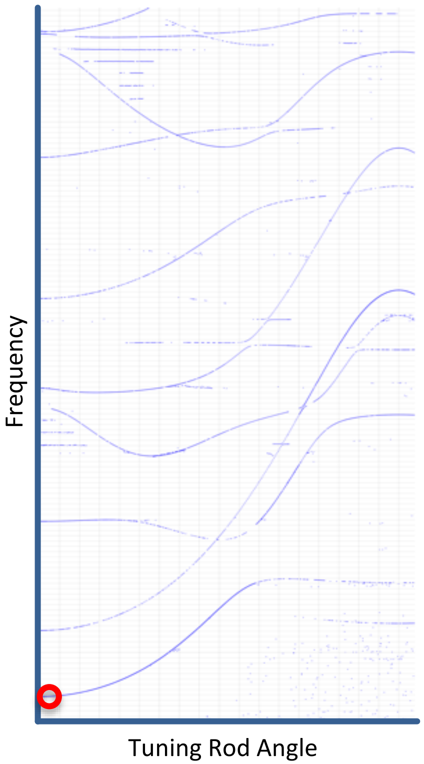
This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.

Unknown axion mass requires a tunable resonator

How does ADMX operate?

Scanning Masses via Tuning Rod





How does ADMX currently operate?

Axion Scan Rate Equation

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

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

*Does not include deadtime (Candidate rescans, engineering studies, pandemics, etc.)

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

$$P_{axion} \sim \boxed{{g_\gamma}^2 \cdot \rho_0 \cdot f} \cdot \boxed{V \cdot {B_0}^2 \cdot Q_L \cdot C_{lmn}}$$

Model- Dependent Parameters

- g_γ – Coupling Constant
- f – Axion frequency
- ρ_0 – Dark matter halo density

Experimental Parameters

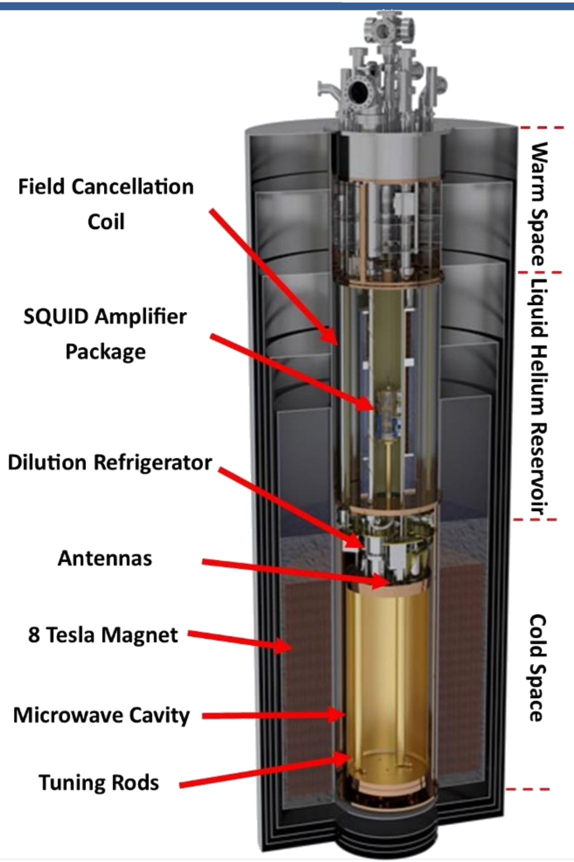
- B_0 – External magnetic Field
- V – Cavity volume
- Q_L – Cavity quality factor
- C_{lmn} – Cavity form factor
- SNR – Signal to Noise Ratio
- T_{sys} – System noise temperature
- t – integration time of FFT
- Δf – Bandwidth of FFT

How does ADMX currently operate?

ADMX Insert

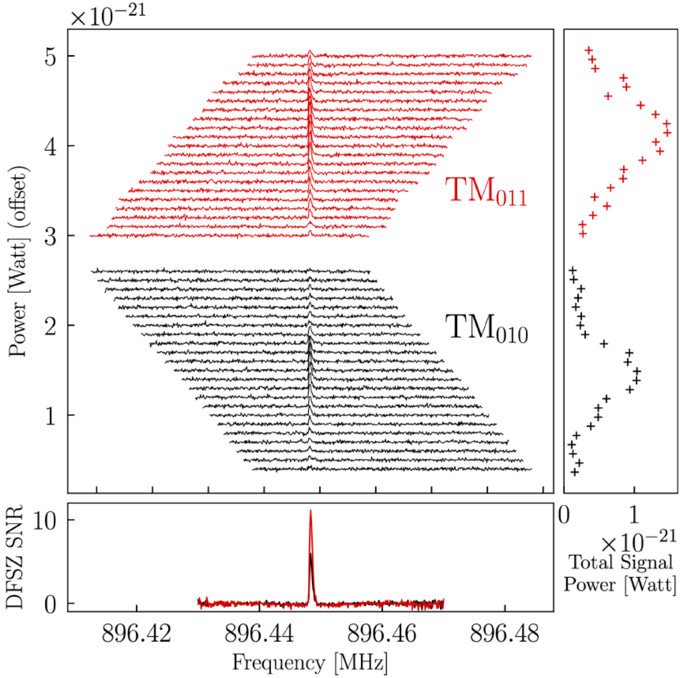
- ADMX insert has many systems to optimize scan rate
  - 8T magnet with 0.5 M bore→ maximize B^2V
  - Helium-3 Dilution Refrigerator → minimize T_{sys}
  - Quantum Amplifiers→ amplify signal
  - Copper cavity resonator→ high Q in field
  - Cavity tuning rod system→ maximize run length

- These systems are then supported by more systems
  - Field Cancellation Coil
  - RF layout to warm electronics
  - 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. The receiver system is periodically characterized to monitor SNR (JPA biasing, NA measurements, etc.)
3. Examine the combined power spectrum for signs of excess; these can be statistical fluctuations, synthetic 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)

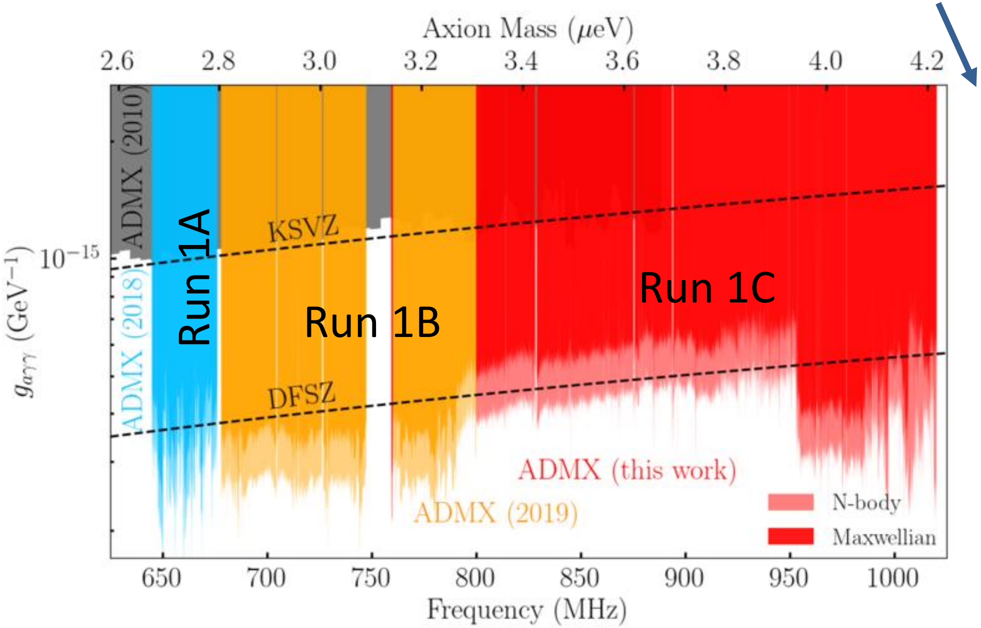


Example Candidate

How does ADMX currently operate?
Current Limits

- No Axions detected yet! We set exclusion limits (90% Confidence Limit)
- ADMX G2 has excluded axions at DFSZ sensitivity for first 3 runs(~2.7- 4.2 μeV)
- **Run 1D in progress:** so far have covered 1270-1300 MHz so far, scanning downwards to 1 GHZ.
  - Discoverability to 0.5 KSVZ $g_{a\gamma\gamma}$
  - Exclude to DFSZ based on run conditions and cadence
  - Last run with a single cavity
  - Stay tuned for results!

Currently scanning up here!



Current Axion Limits set by ADMX G2.
From Most Recent PRL results (2021)

Future of ADMX

Challenges and strategies at Higher Frequencies

- Combine multiple smaller cavities with a higher $f_{\mathrm{TM}_{010}}$ to maintain volume
  - Scaling issue for RF electronics
  - 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 9.4 T MRI magnet

- Limited ability to cool further
  - Possibility of squeezing quantum states to circumvent SQL

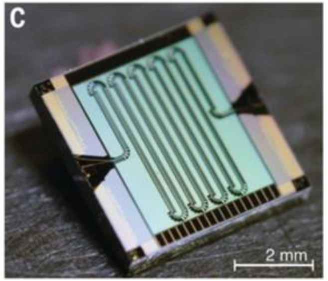
- Quality factor goes down for ordinary metals
  - Volume to surface ratio
  - Anomalous skin depth

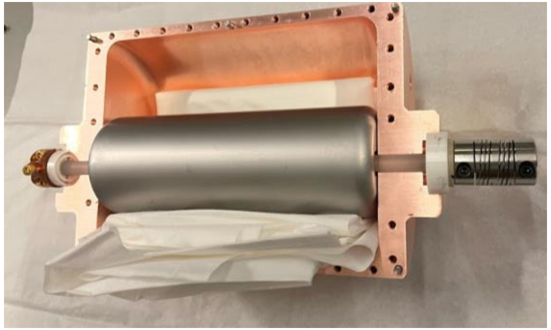
- My PhD work has looked at using superconducting cavities to improve Q (My Paper: RSI NbTi Surface Impedance)

Run 2 4-cavity system (Covers 1.4- 2GHz)

ADMX Sidecar

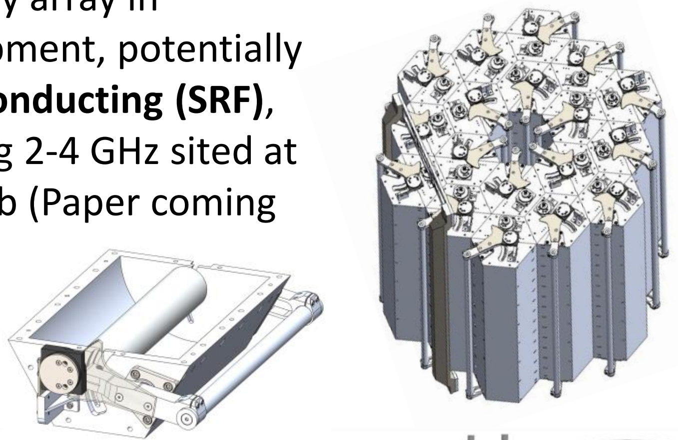
- ‘Testbed’ High Frequency cavity above the main cavity (~3.5 T) for emerging tech
  - Piezo Motors
  - JTWPA amplifier
  - Nb_3Sn coated tuning rod
- ‘Clam-shell’ Cavity can tune 3.6-6.2 GHz
- Currently running at 5.5 GHz
- 10x KSVZ or lower sensitivity goal
- Nb_3Sn Rod has not achieved the desired boost in Q-factor for reasons we are currently studying.
- Stay tuned for in-depth results in my thesis

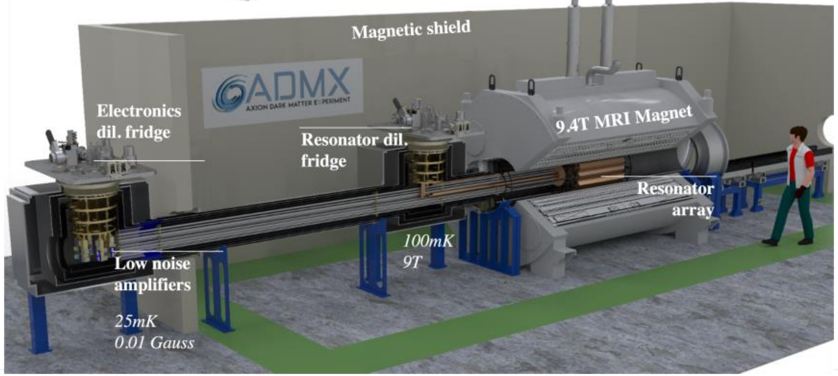


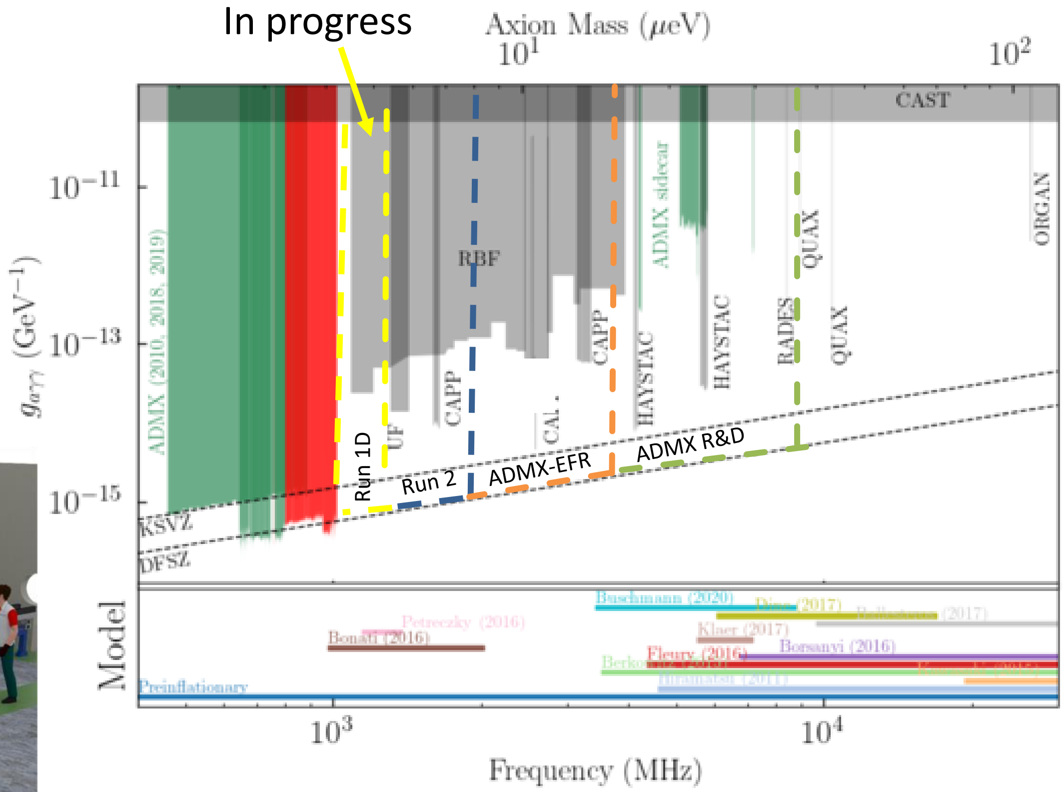


The Future of ADMX: ADMX-EFR

14 cavity array in development, potentially **Superconducting (SRF)**, covering 2-4 GHz sited at Fermilab (Paper coming soon!)







Planned coverage of Axion parameter space

Thank You! Questions?

ADMX
AXION DARK MATTER EXPERIMENT

HEISING - SIMONS
FOUNDATION

W
UNIVERSITY of WASHINGTON

Lawrence Livermore
National Laboratory

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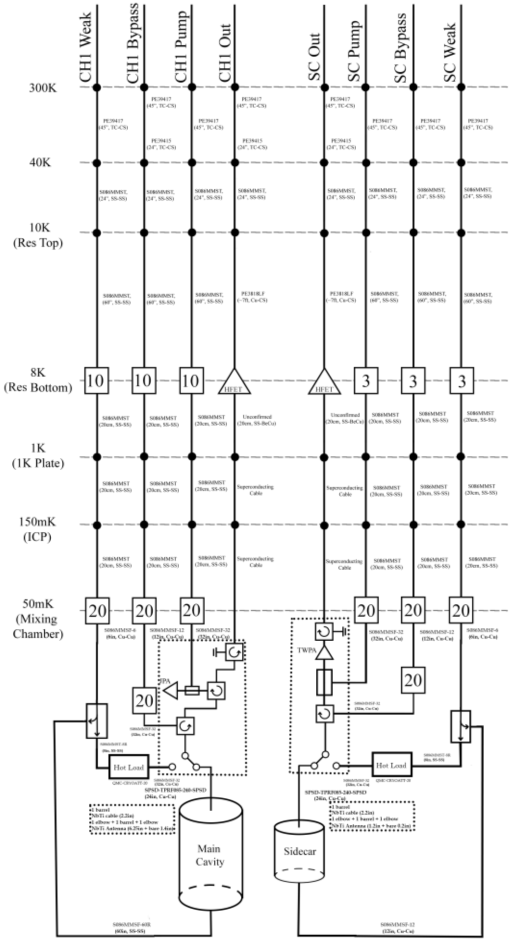
Run 1C and Run 1D cavity pictures

Run 1C: Two Rods

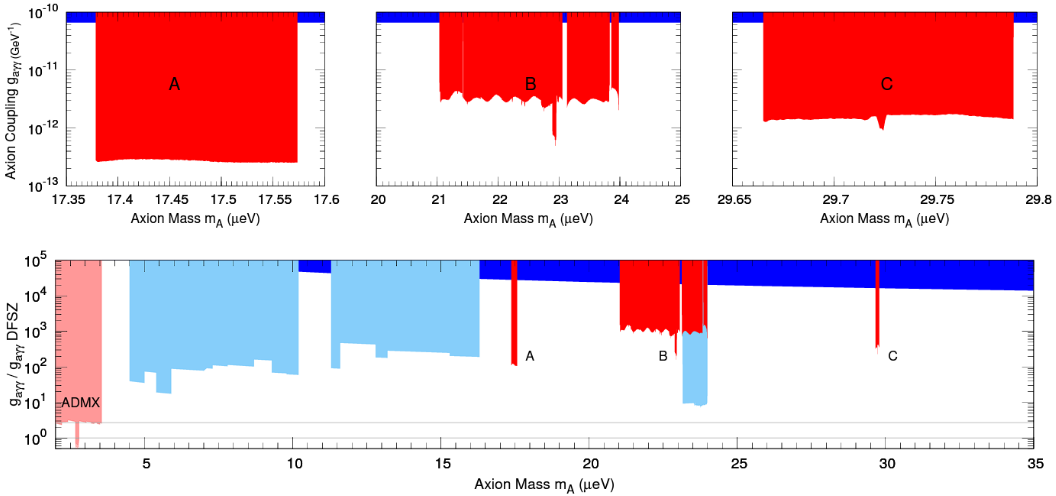
Run 1D: Single 8” Rod

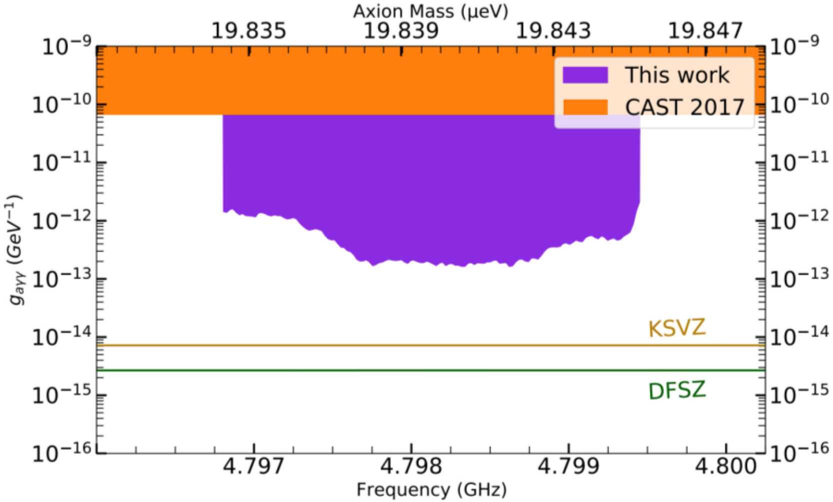
Run 1D RF layout



Previous Sidecar Limits

Typically have achieved 10-100x KSVZ





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

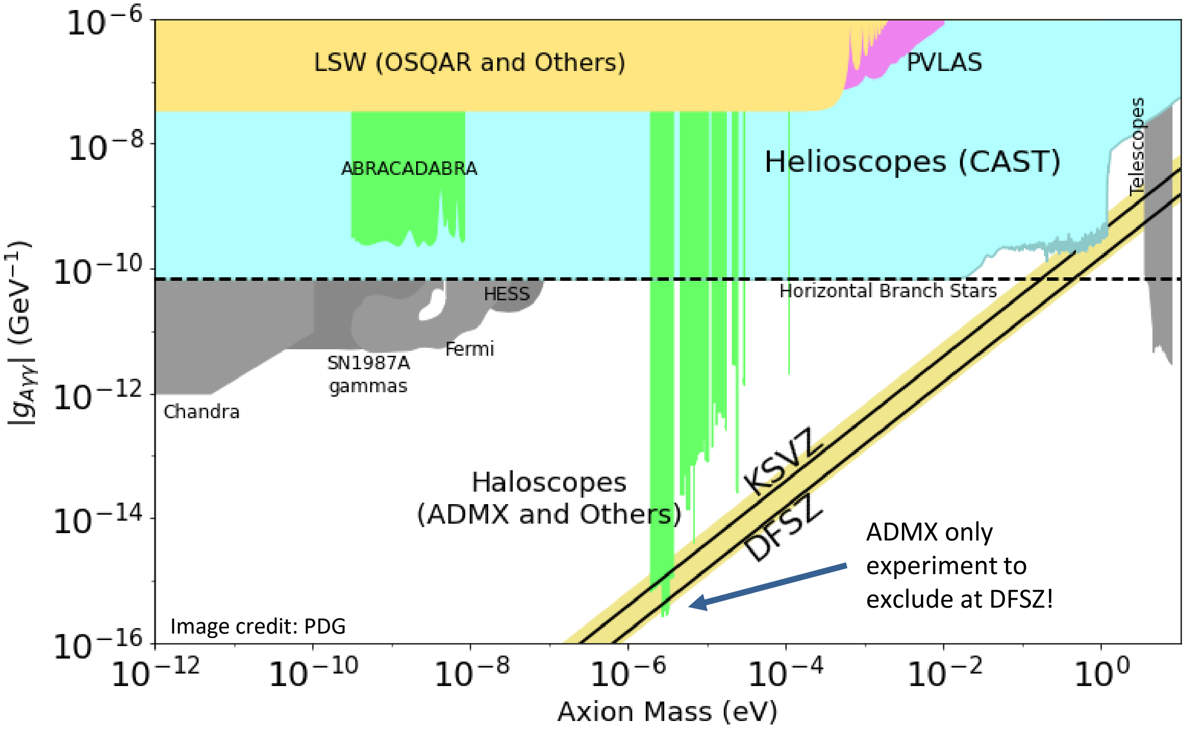


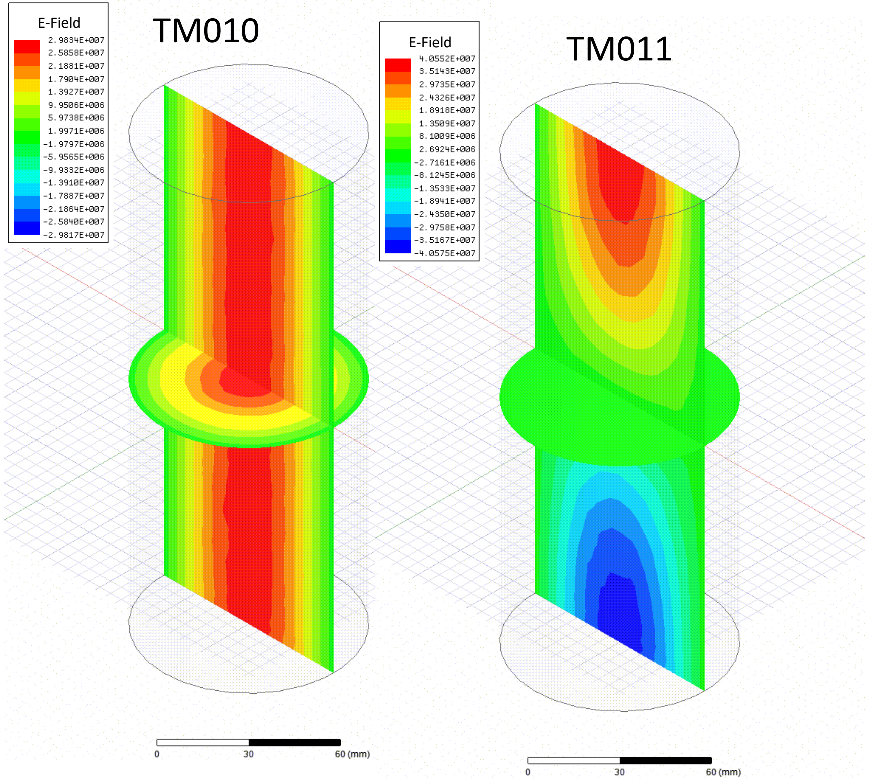
Image credit: PDG

ADMX only experiment to exclude at DFSZ!

How does ADMX operate?
Cavity Form Factor

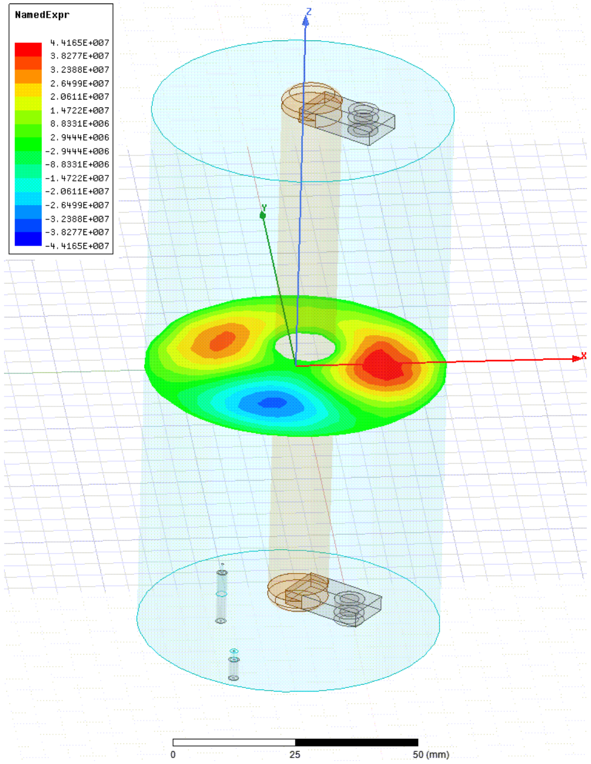
$$C_{\mathrm{lmn}} = \frac{\left(\int_V dV\ E \cdot B\right)^2}{V\ B^2 \int_V dV\ E^2}$$

- 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



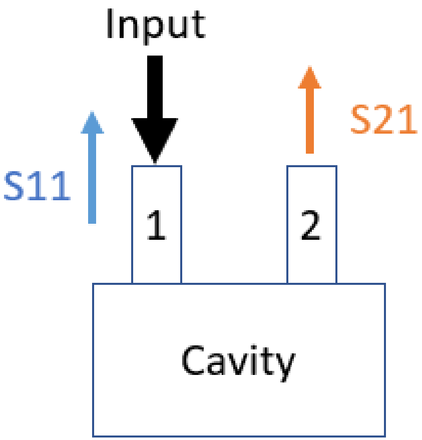
Higher Order Modes

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



Quality factor

- Physical definition: $Q = 2\pi f_0 \frac{Energy\ Stored}{Power\ Loss}$
- 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



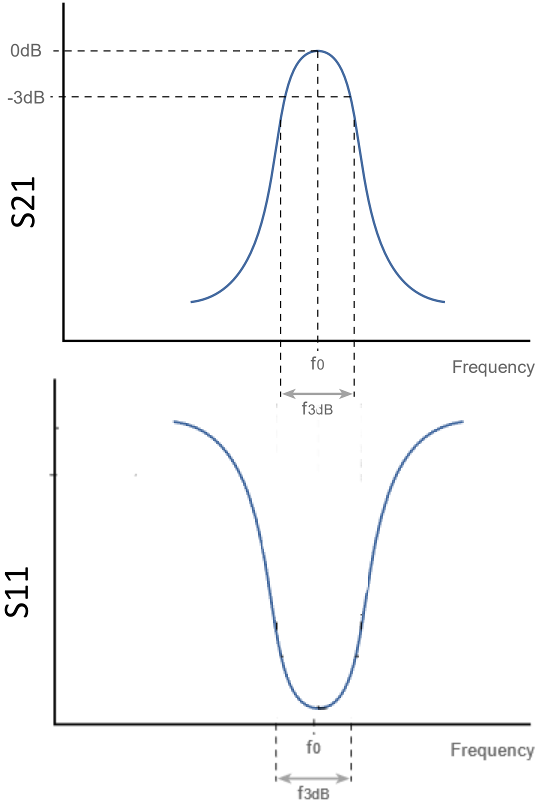


Image credit: S parameters, Wikipedia original graphic by Jon Bauman

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.

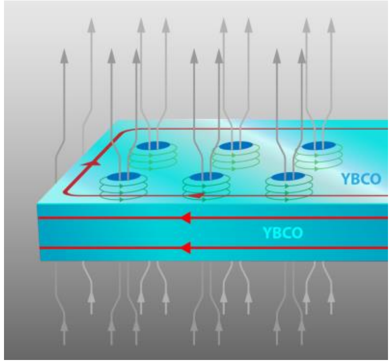


Image: Flux Vortices in Mixed State
Credit: APS, https://physics.aps.org/articles/v10/129

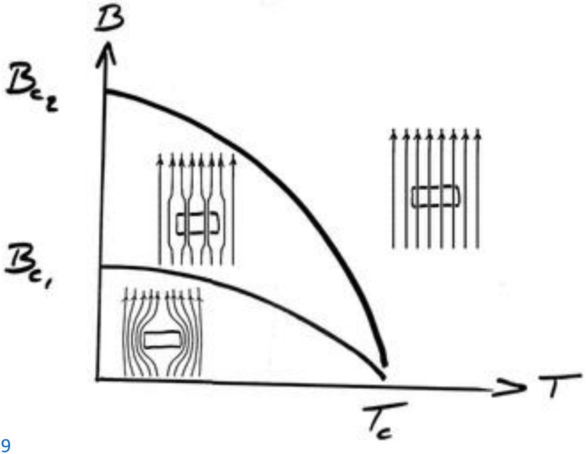
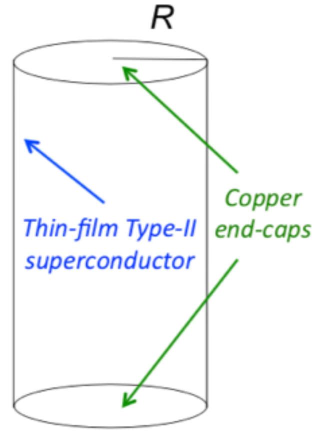


Image: Type 2 Superconductors Wikipedia

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

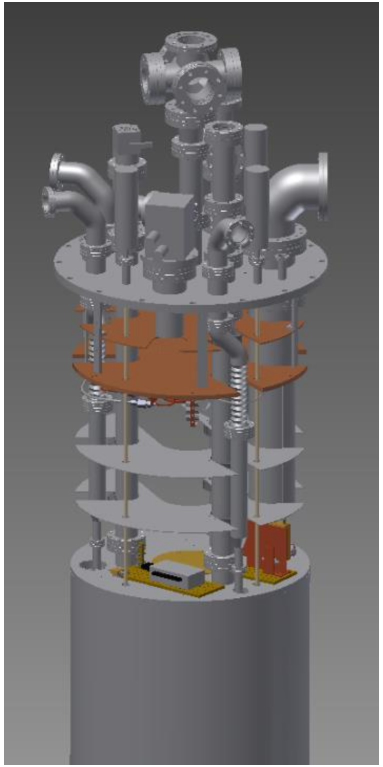
$$\boxed{\frac{Q^{Hybrid}}{Q^{Copper}} = \left(1 + \frac{L}{R}\right)}$$

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



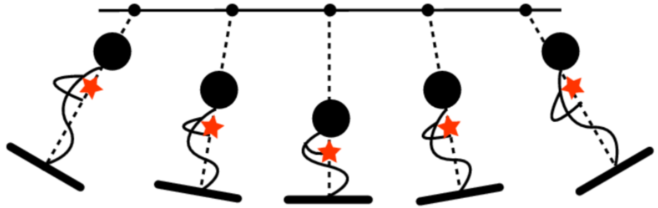
ADMX Systems
Cryogenics

- 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
- Dilution fridge was custom built by Janis Research Company
- 800 µW of cooling at 100 mK
- Cools the resonator and amplifiers.

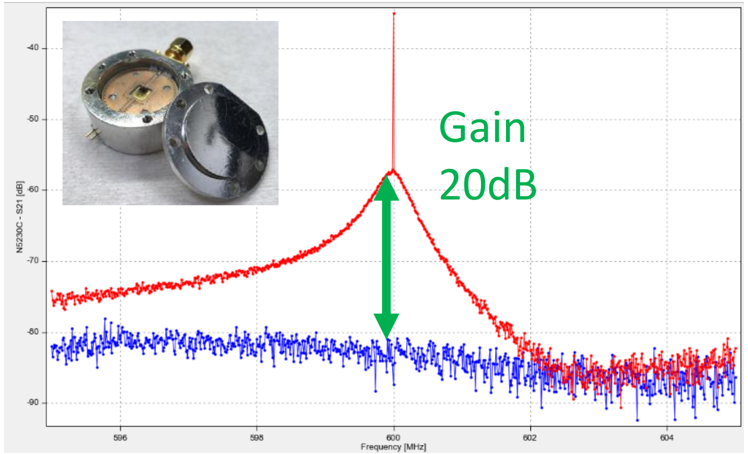


ADMX Systems
Quantum RF electronics

- 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 can be injected into the cavity. This both verifies the electronics and the analysis procedure.