Fermilab Physics Advisory Committee Meeting

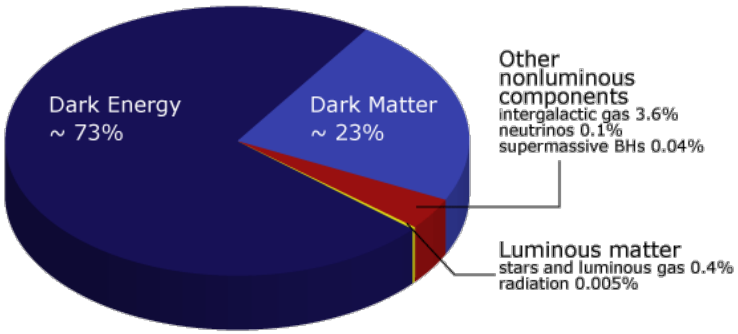
Nov 10th, 2016

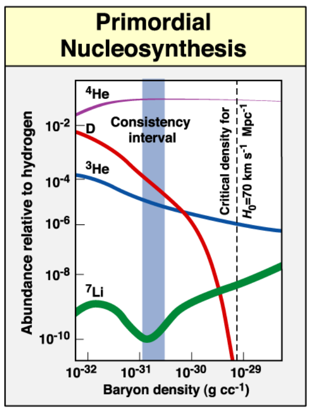
ADMX Status & Plans

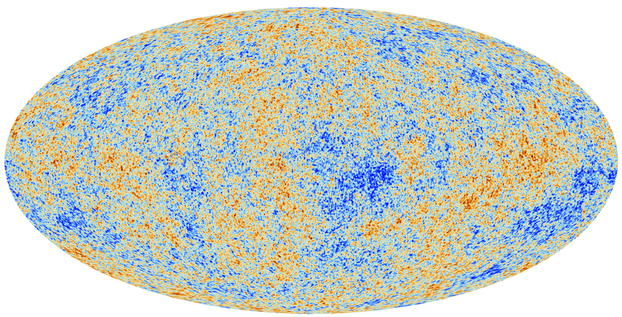
Gianpaolo Carosi
ADMX co-spokesperson
LLNL

The Nature of Dark Matter

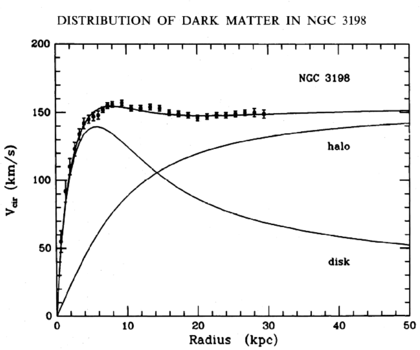
One of the premier unsolved mysteries in physics







Our Hubble Volume



Individual galaxies

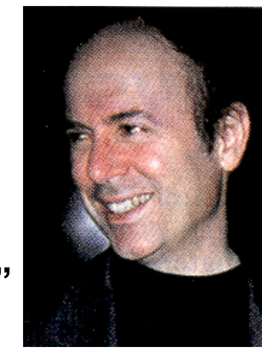
Galaxy collisions

Likely new particle outside standard model

A. Baryons essentially ruled out!

B. Neutrinos likely only small fraction.

I'm much more optimistic about the dark matter problem. Here we have the unusual situation that two good ideas exist…" Frank Wilczek referring to WIMPs and Axions!



Tremendous progress in the last 20 years on searches for both!

Recently DOE has made a major investment in three "Generation 2" direct dark-matter projects

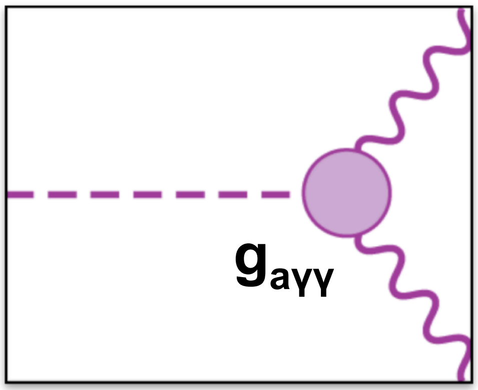
1. **LZ (Liquid Zenon WIMP search)**
2. **SuperCDMS-Snolab (Ge/Si WIMPS search)**
3. **ADMX (axion dark matter search)**

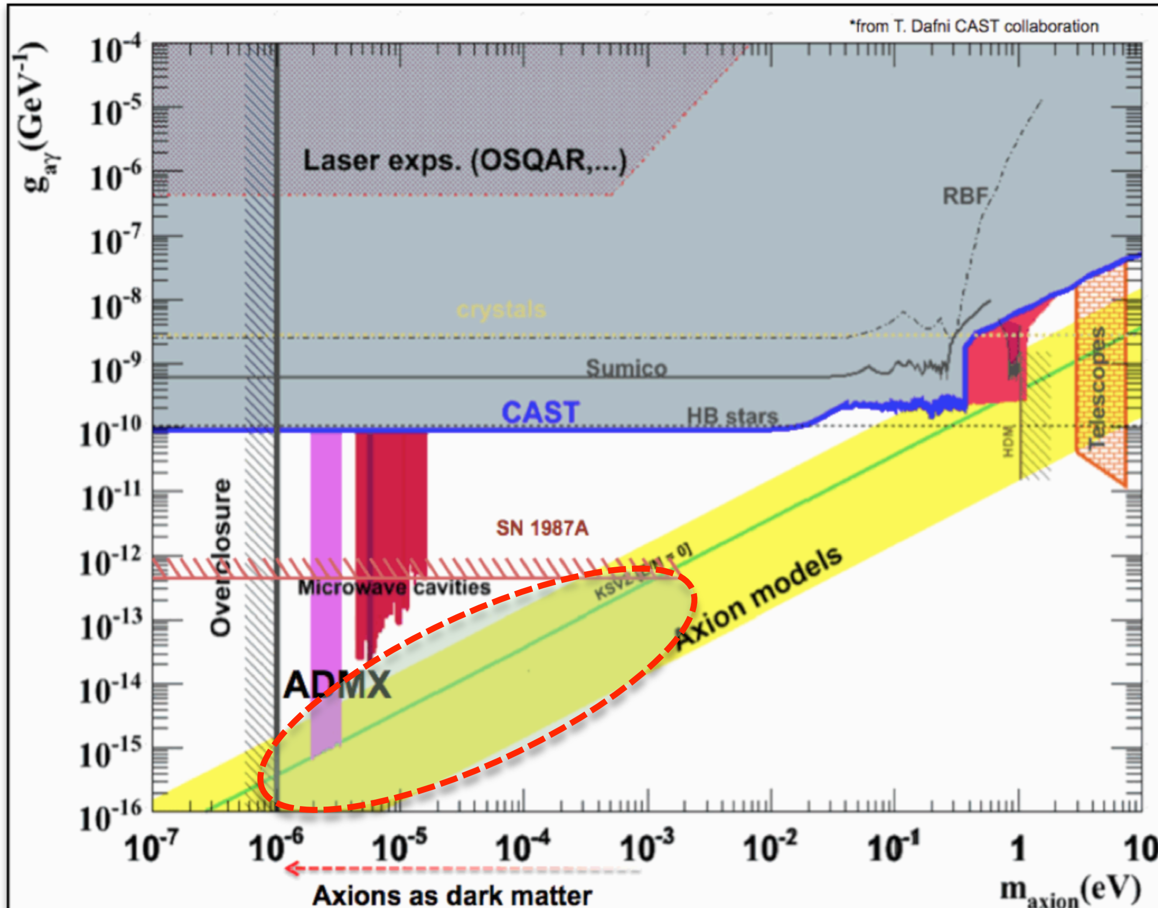
<u>The choice for ADMX was clear.</u>

- **Only experiment to have reached plausible axion cold-dark matter parameter space.**
- **Only experiment with the proper scale to quickly cover significant parameters space.**
- **Best suited to discover the dark matter axion.**

The axion and where to find it.

- It's a pseudoscalar (π°-like), extremely light and weakly coupled
- 2γ coupling (Primakoff effect) : Key to potential detection





The axion remains a very attractive dark-matter candidate (HEPAP, DMSAG, P5 …)

ADMX: Collaboration

ADMX
AXION DARK MATTER EXPERIMENT

UNIVERSITY OF WASHINGTON · LVX SIT · 1861

UF UNIVERSITY of FLORIDA

Berkeley
UNIVERSITY OF CALIFORNIA

Lawrence Livermore National Laboratory

Recently Joined

NRAO

The University Of Sheffield.

Fermilab

Pacific Northwest NATIONAL LABORATORY

Los Alamos NATIONAL LABORATORY

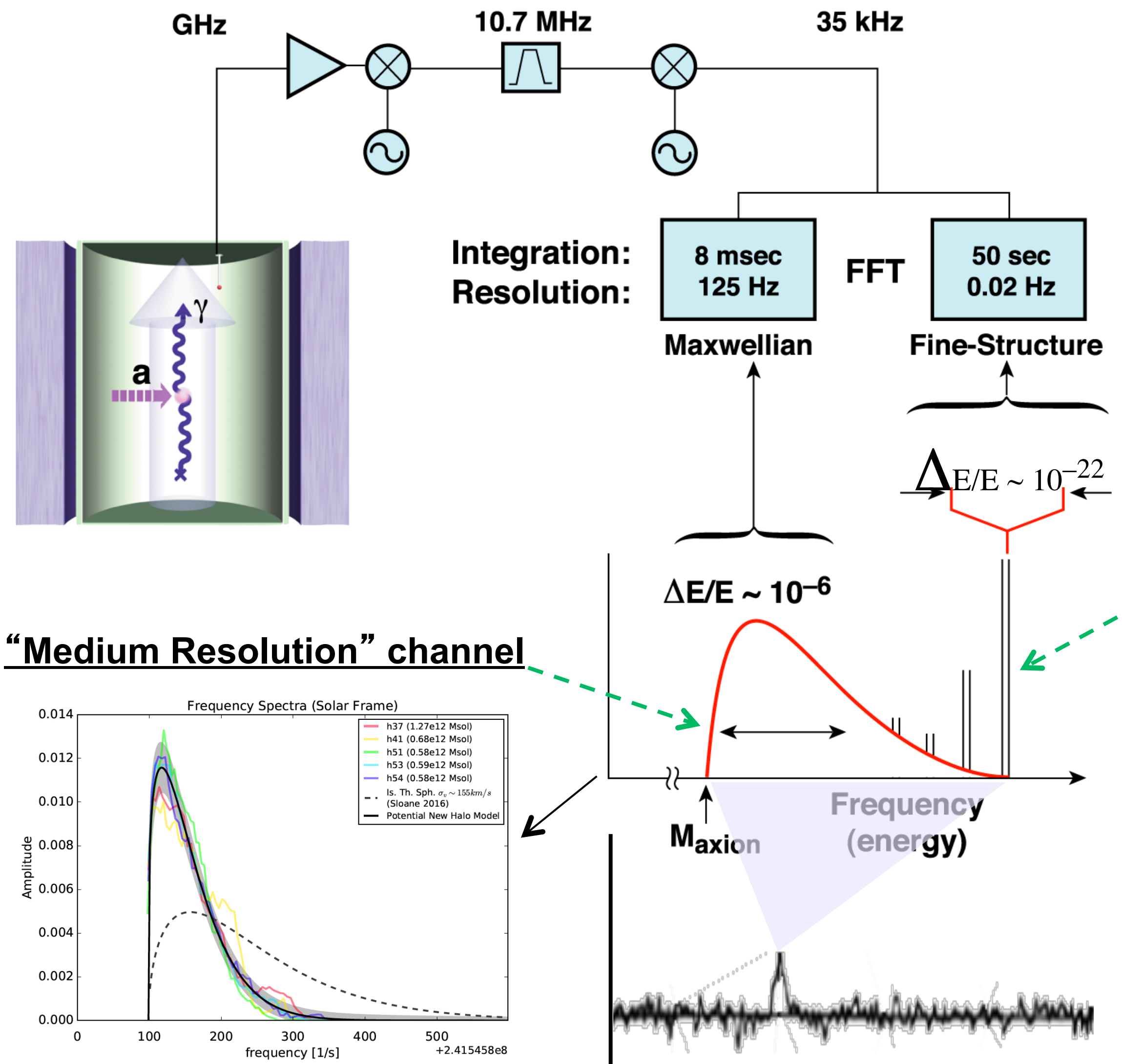
Sponsors

ADMX now DOE Gen 2 project

Primary support **Historical** **R&D**

HEISING - SIMONS FOUNDATION

ADMX: Haloscope search technique original concept from P. Sikivie



Local Milky Way density:

$\rho_{halo} \sim 450\ MeV/cm^3$

Thus for $m_a \sim 10\ \mu eV$:

$\rho_{halo} \sim 10^{14}\ cm^{-3}$

"High Resolution" channel

$\beta_{virial} \sim 10^{-3}$:

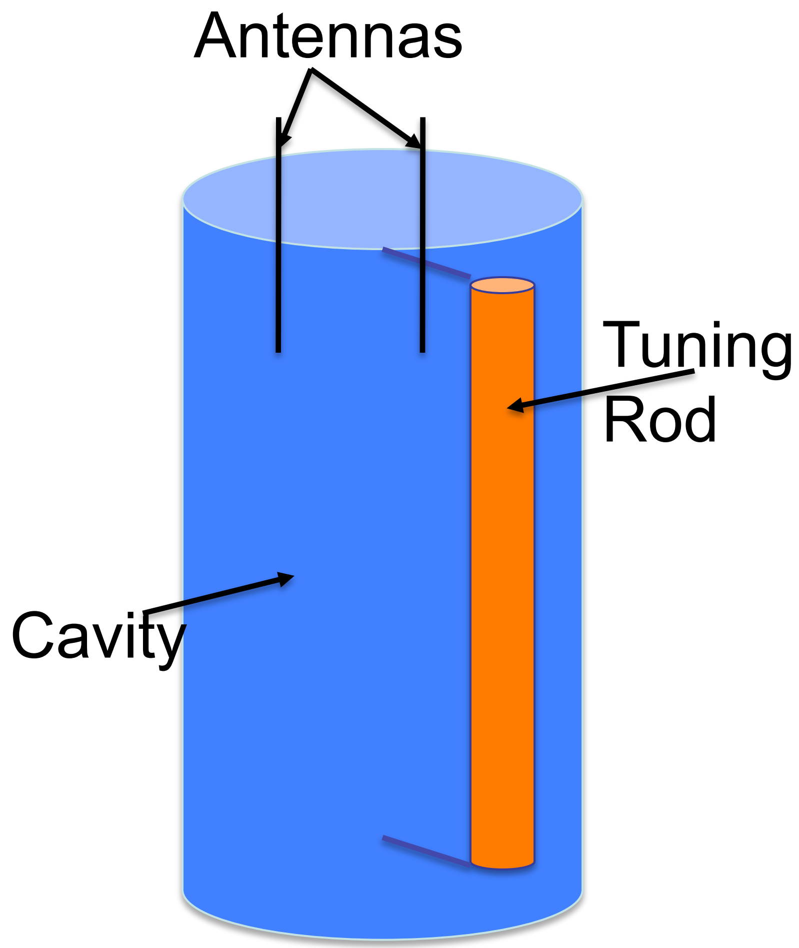
$\lambda_{De\ Broglie} \sim 100\ m$

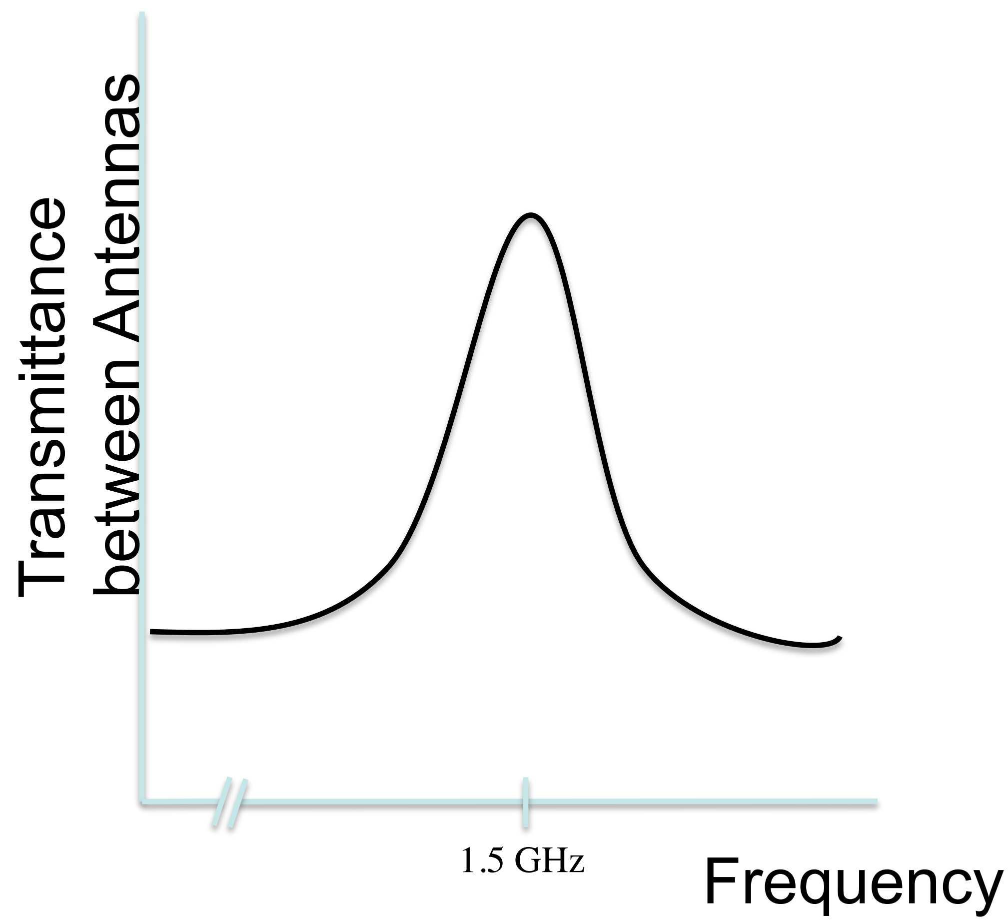
$\Delta\beta_{flow} \sim 10^{-11}$:

$\lambda_{Coherence} \sim 1000\ km$

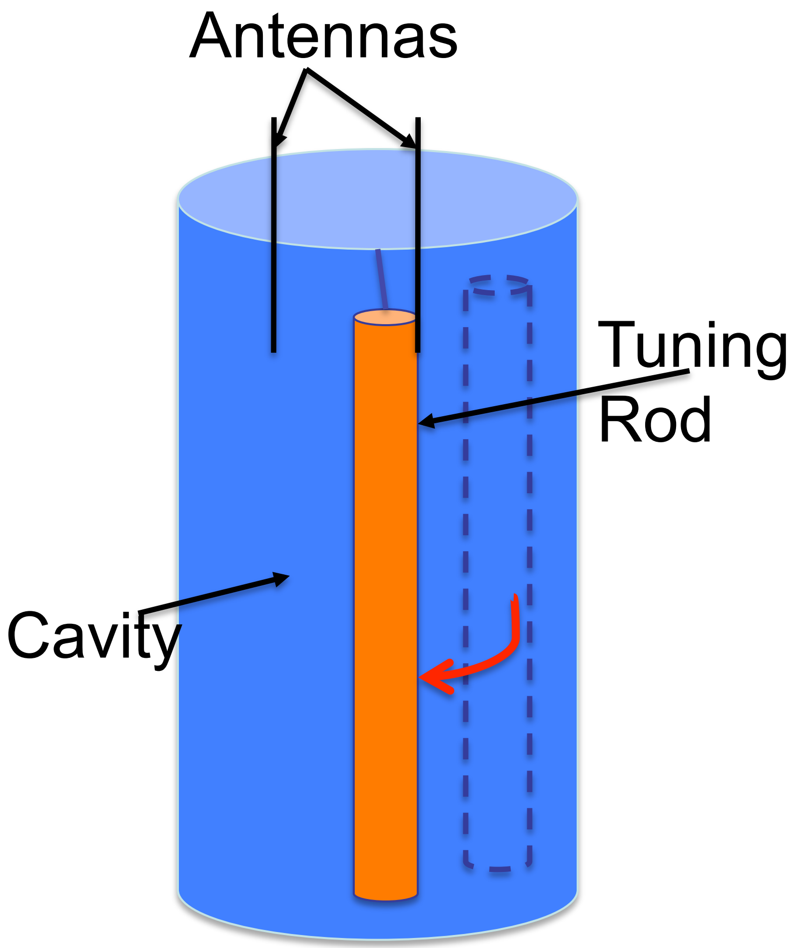
N-body line shape (increase in SNR): Potential to greatly increase science reach

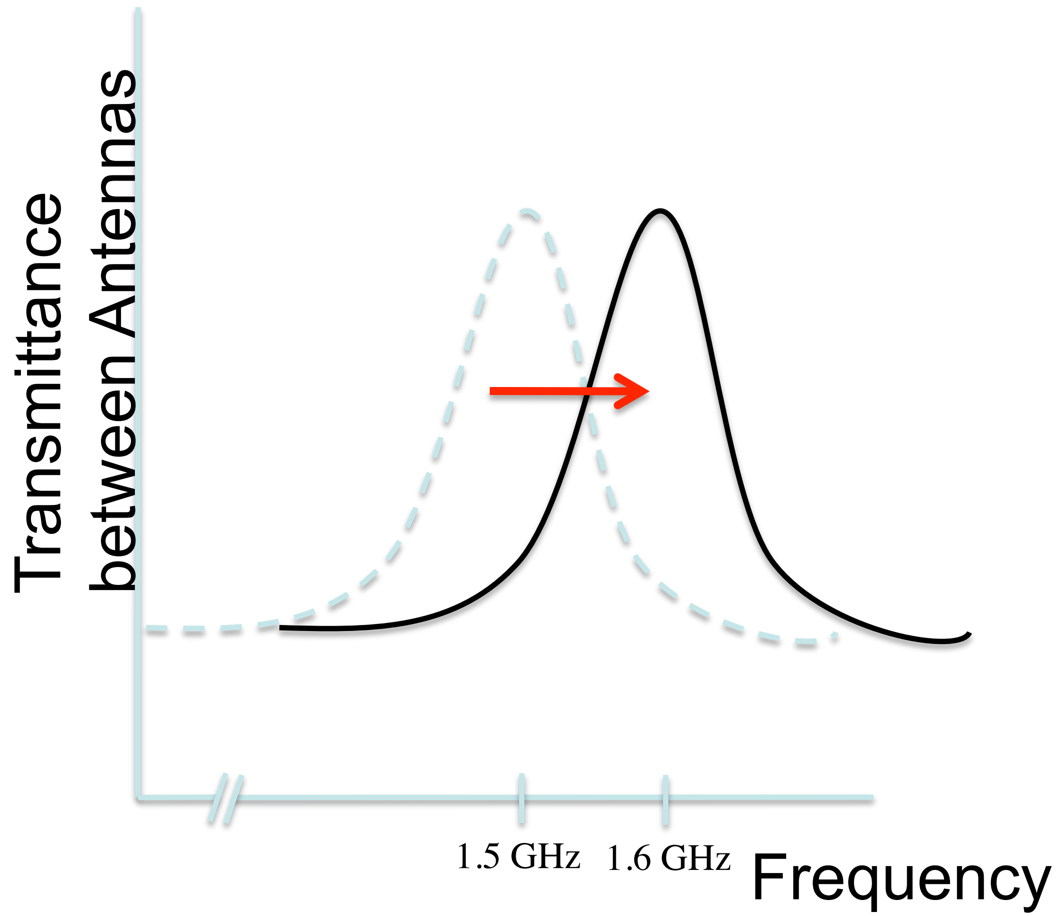
Tuning microwave cavity resonant mode





Tuning microwave cavity resonant mode





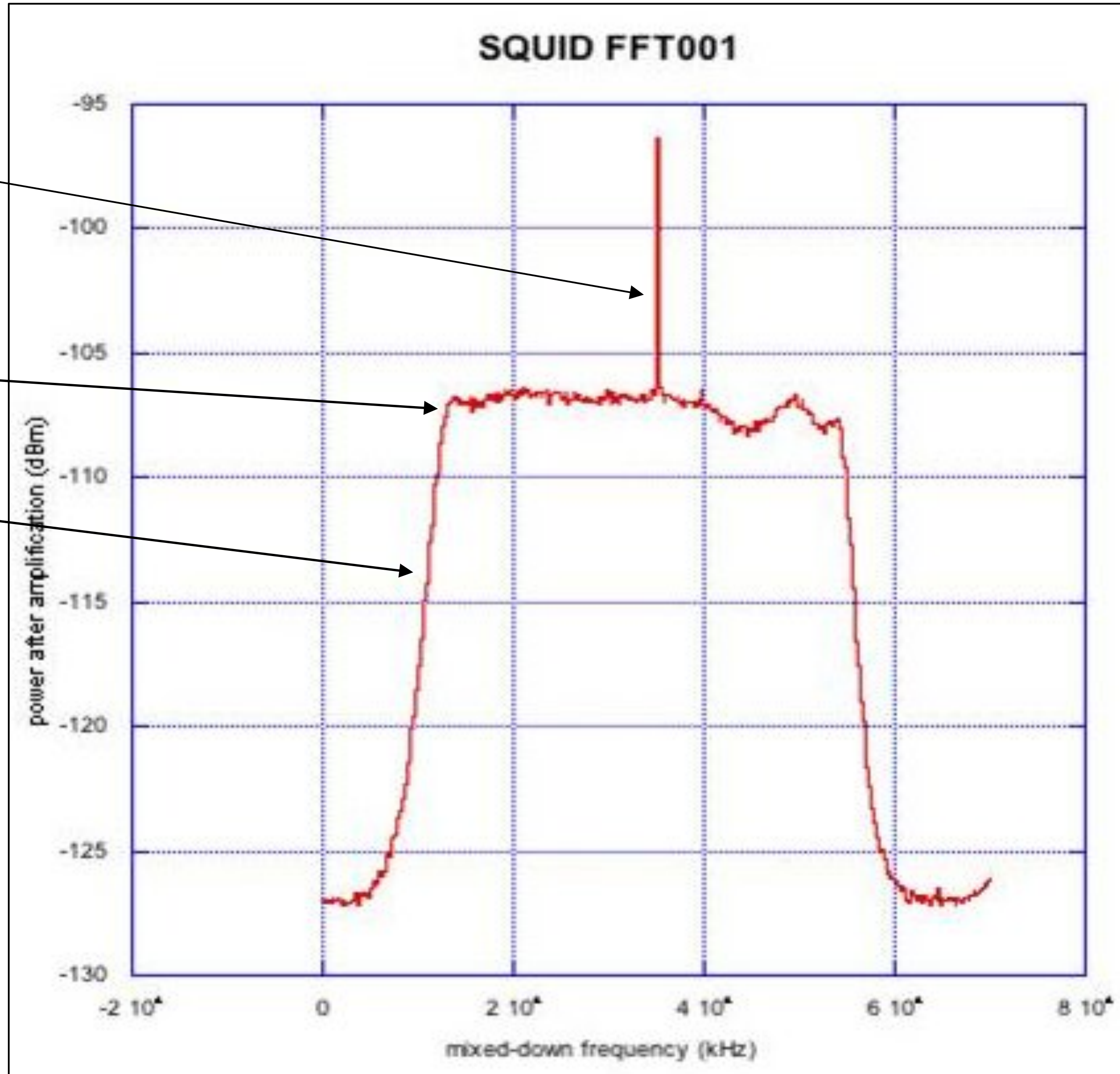
Example of injected tone (fake axion) (Phase I with SQUID amplifiers)

- Injected Power

x100-1000 axion power

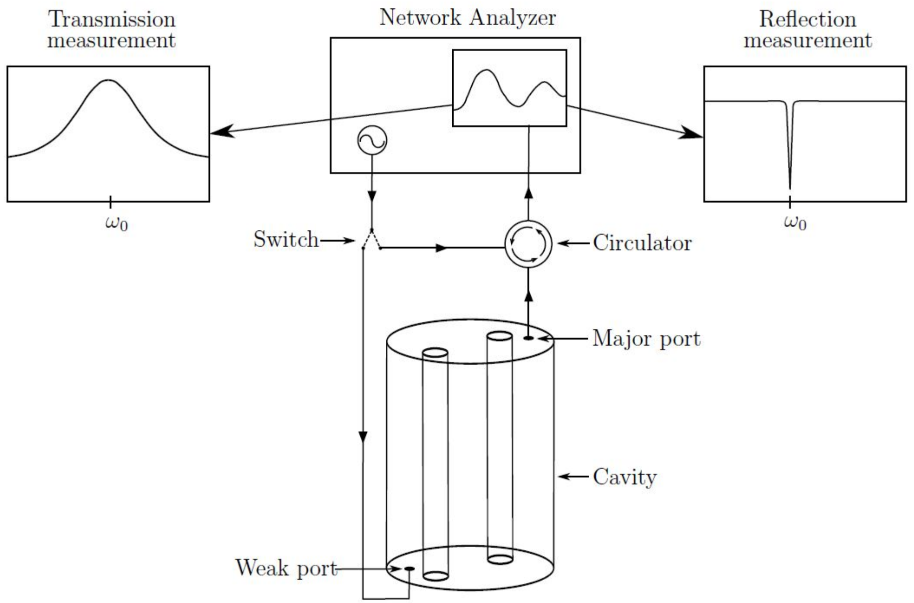
- Noise floor

- Bandpass filter

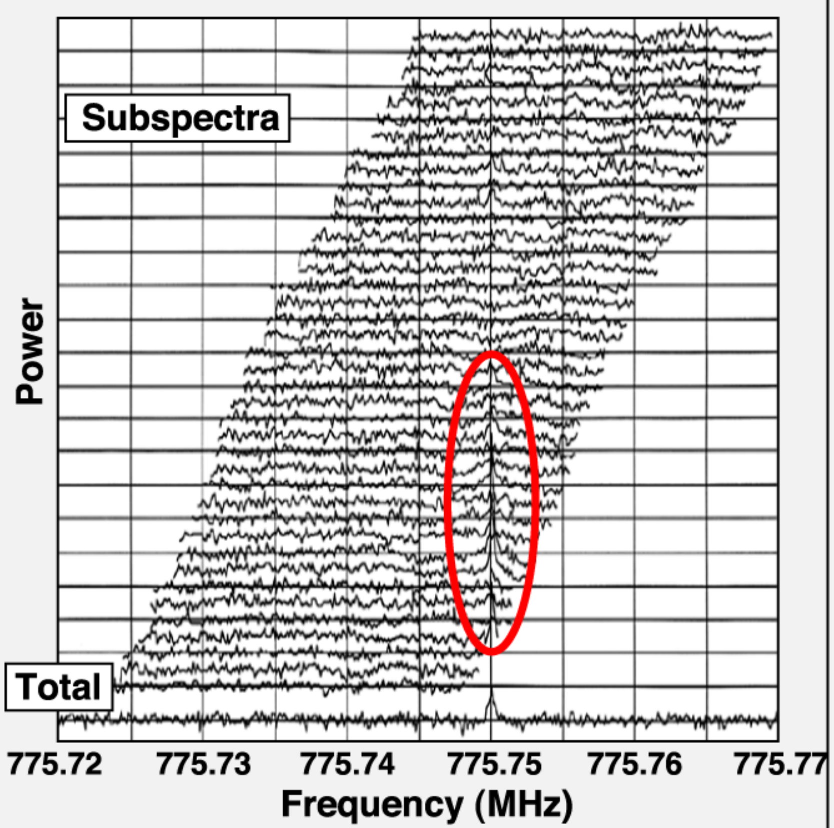
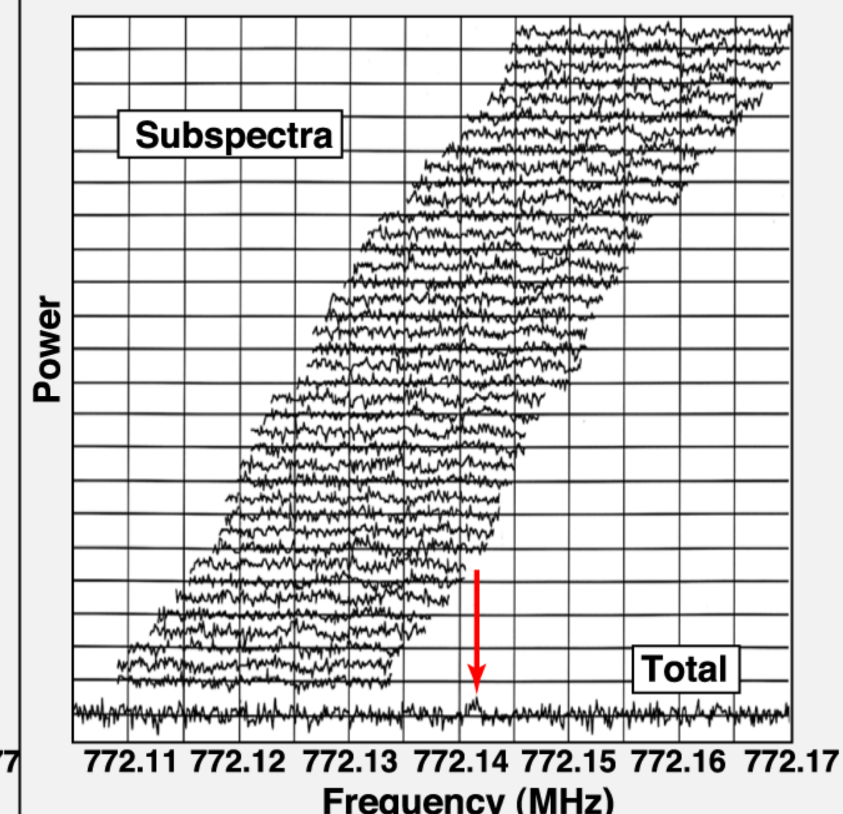


Typical Run Cadence

- Start by injecting a broad, swept RF signal to record cavity response. Record state data (temperatures, hall sensors, pressures, etc)
- Integrate for ~ 100 sec to 10s of minutes (final integration time dependent experimental parameters).
- Every few days adjust the critical coupling of the antennas
- Scan rate is determined by experimental parameters and the trade off in sensitivity vs frequency (mass) coverage
- The scan rate uses a threshold sensitivity. Any candidate above threshold is flagged for further study.



Sample data and flagged candidates

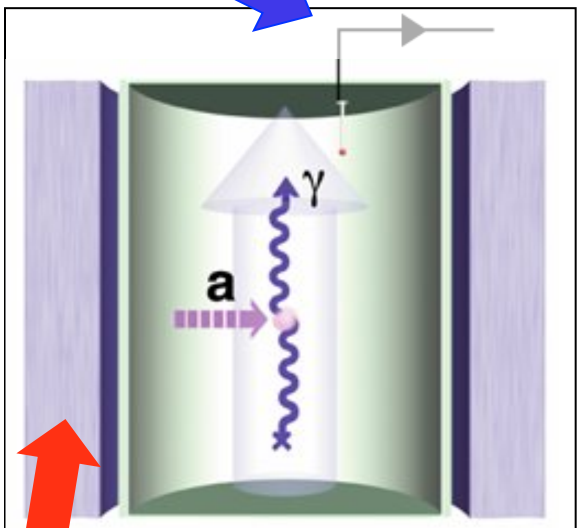
<table>
<tr><th>Environmental</th><th>Statistical</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Signal maximizes off-resonance: Radio peak</td><td>Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)</td></tr>
</table>

Radiometer equation dictates search strategy

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

* *Dicke, 1946*

But integration time ~ 100 sec



ADMX initially used pumped ^{4}He for T = 1.5 K

$T_S = T + T_{Amp} \sim 1.5 + 1.5$ K

But $T_{Quant} \sim 30$ mK

Invested in lower T!

$$P_{sig} \sim (B^2V\, Q_{cav} C)(\, g^2\, m_a\, \rho_a\,)$$

$\sim\ 10^{-23}$ Watts for ADMX

But magnet size, strength $B^2V \sim \$$

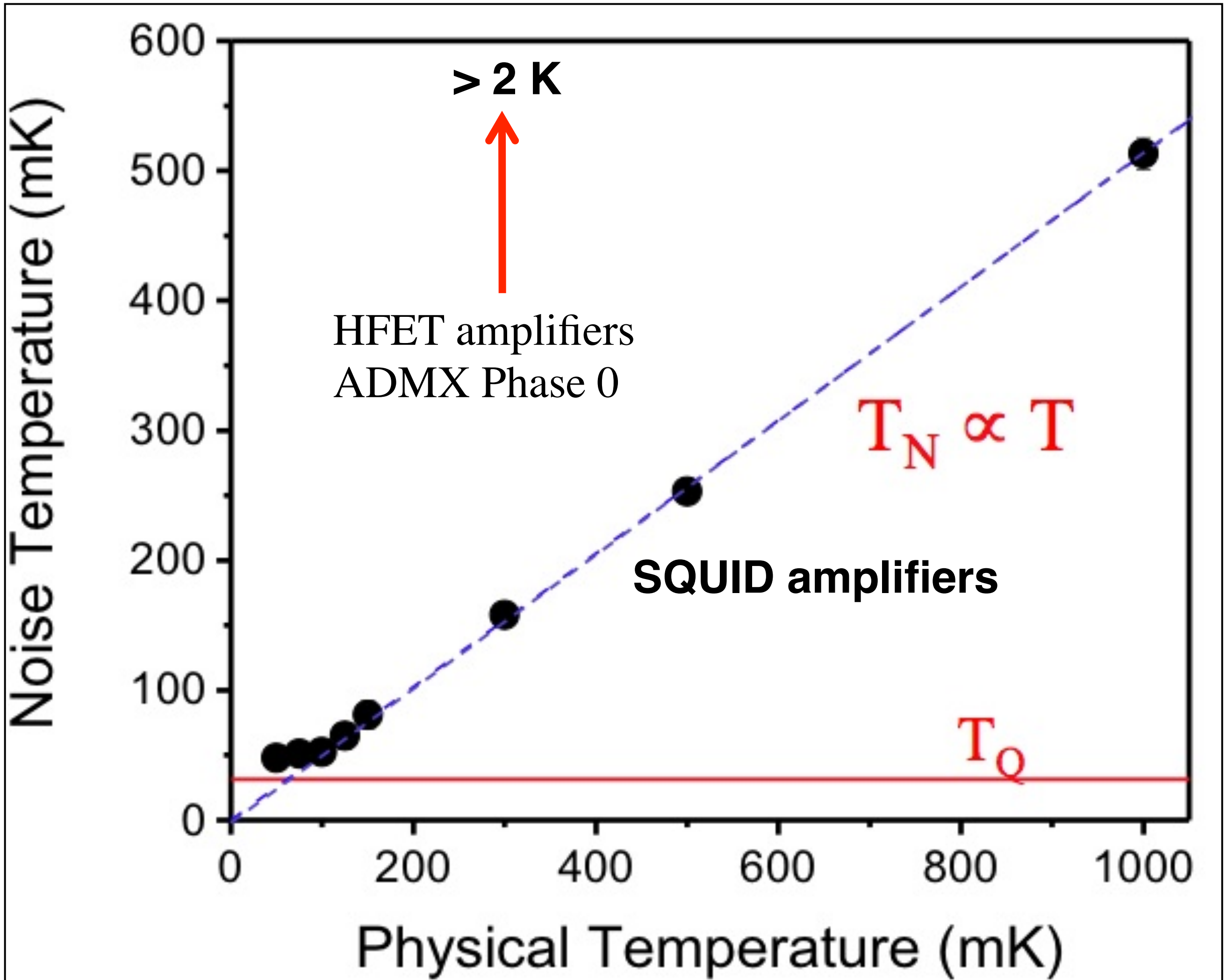
Scan rate

- Rate determined from SNR

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

- SNR is the Signal-to-Noise for detection (usually set to 5)
- f is the frequency being searched (where 1 GHz ~ m_a = 4.1 μeV)
- T_{sys} is the total system temperature ($T_{sys} = T_{cavity} + T_{amps}$)
- To scan at this sensitivity would take > 100 years with original ADMX (T_{sys} = 3 K)

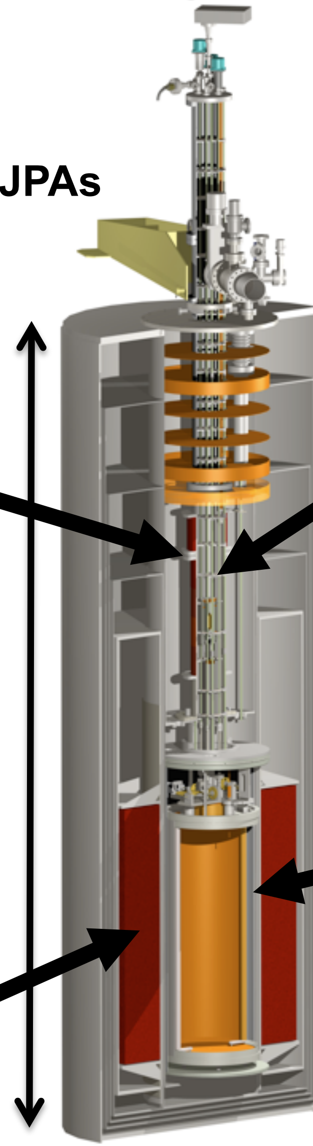
Quantum-limited SQUID-based amplification



- **SQUIDs have been measured with T_N ~ 50 mK**
- **Near quantum-limited noise**
- **Enabling technology**

ADMX Experimental Apparatus

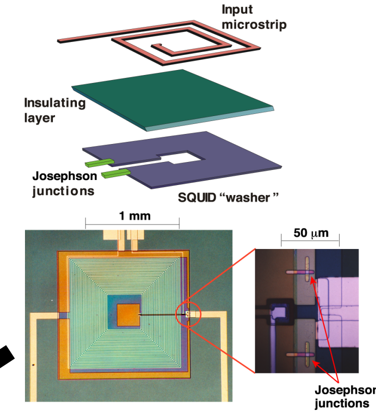
Field compensation magnet for SQUIDs/JPAs

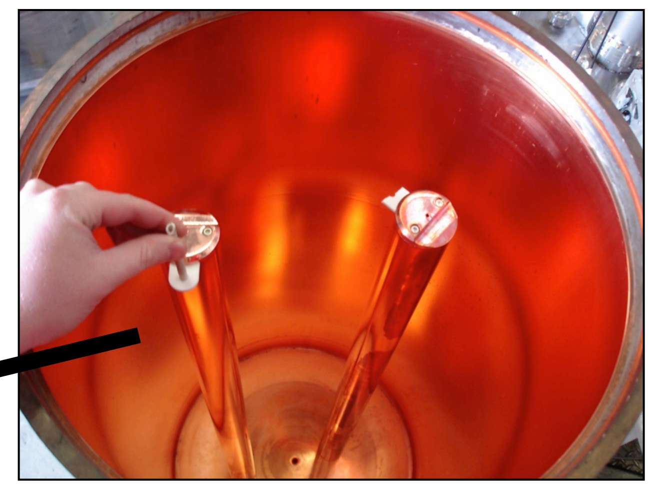


11’

8 Tesla Magnet

SQUID amplifier

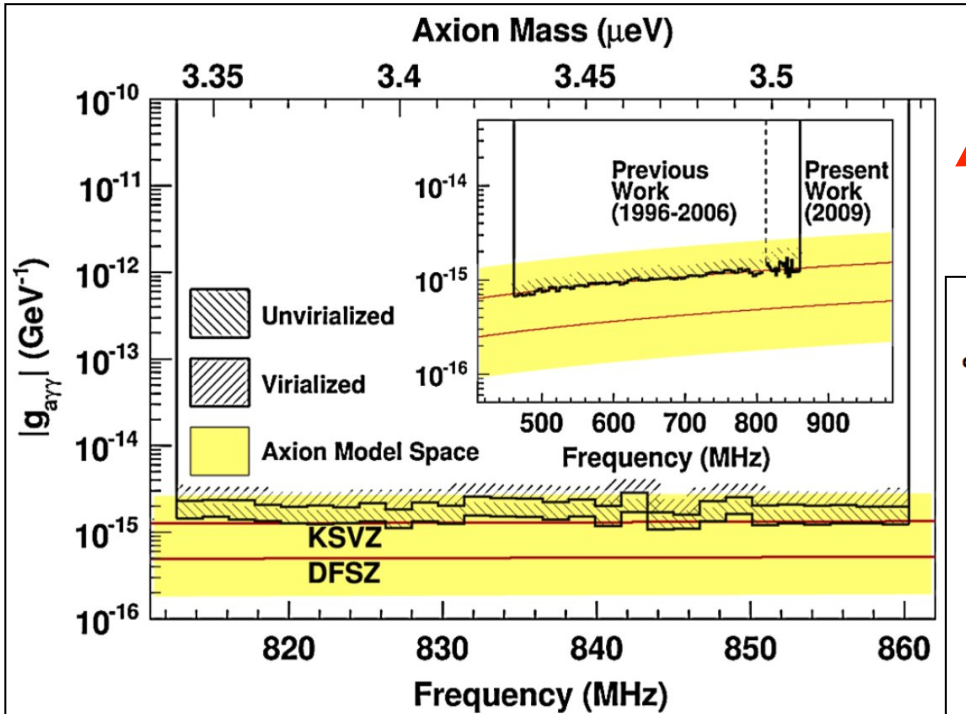




133 liter microwave cavity (500 MHz - 1 GHz)

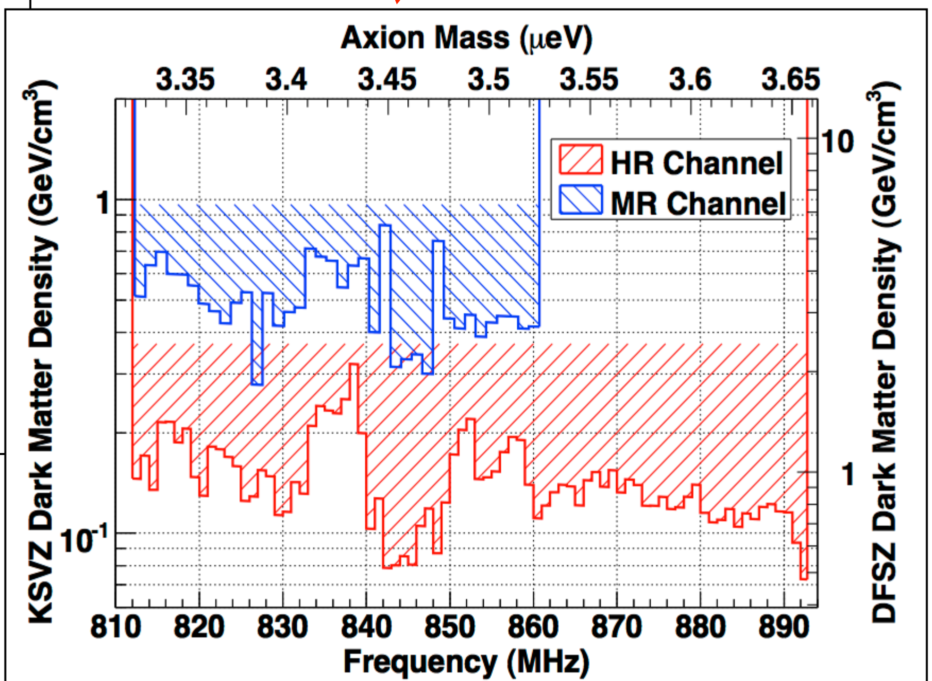
ADMX Phase I: 2008-2010 at LLNL

Successfully operated experiment with SQUID amp near 7 Tesla field and published results!



Medium Res. results

High Res. results



Covered 812 – 860 MHz = 48 MHz

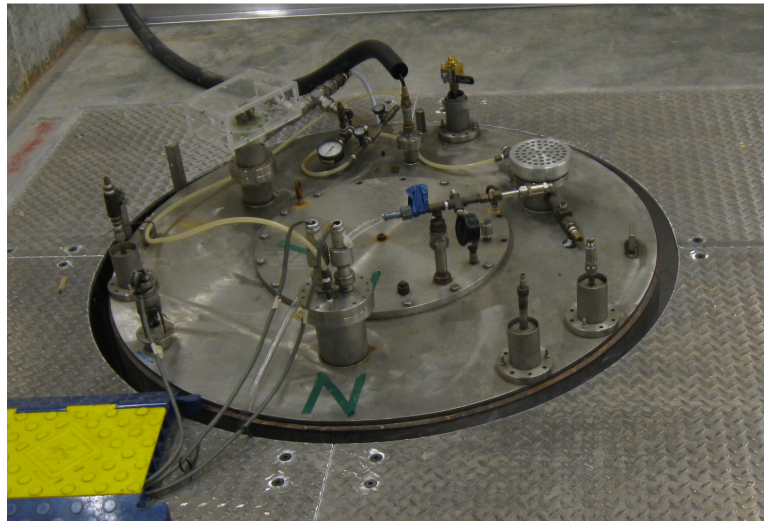
Total Run Time: 19 months

Continuous Data Collecting: 8 months

After Phase I ADMX from LLNL to U.W.

ADMX
AXION DARK MATTER EXPERIMENT

ADMX reinstalled at UW



Low-cost move of a large superconducting magnet on a trailer with air-ride suspension

B. Thomas[1], D. Will[1], J. Heilman[1], K. Tracy[1], M. Hotz[1], D. Lyapustin[1], L. J Rosenberg[1], G. Rybka[1], A. Wagner[1], J. Hoskins[2], C. Martin[2], N. S. Sullivan[2], D. B. Tanner[2], S. J. Asztalos[3], G. Carosi[3], C. Hagmann[3], D. Kinion[3], K. van Bibber[4], John Clarke[4], R. Bradley[5]

[1]University of Washington, Seattle Washington 98195
[2]University of Florida, Gainesville Florida 32611
[3]Lawrence Livermore National Laboratory, Livermore California 94550
[4]University of California, Berkeley, California, 94720
[5]National Radio Astronomy Observatory, Charlottesville Virginia 22903

ADMX site infrastructure

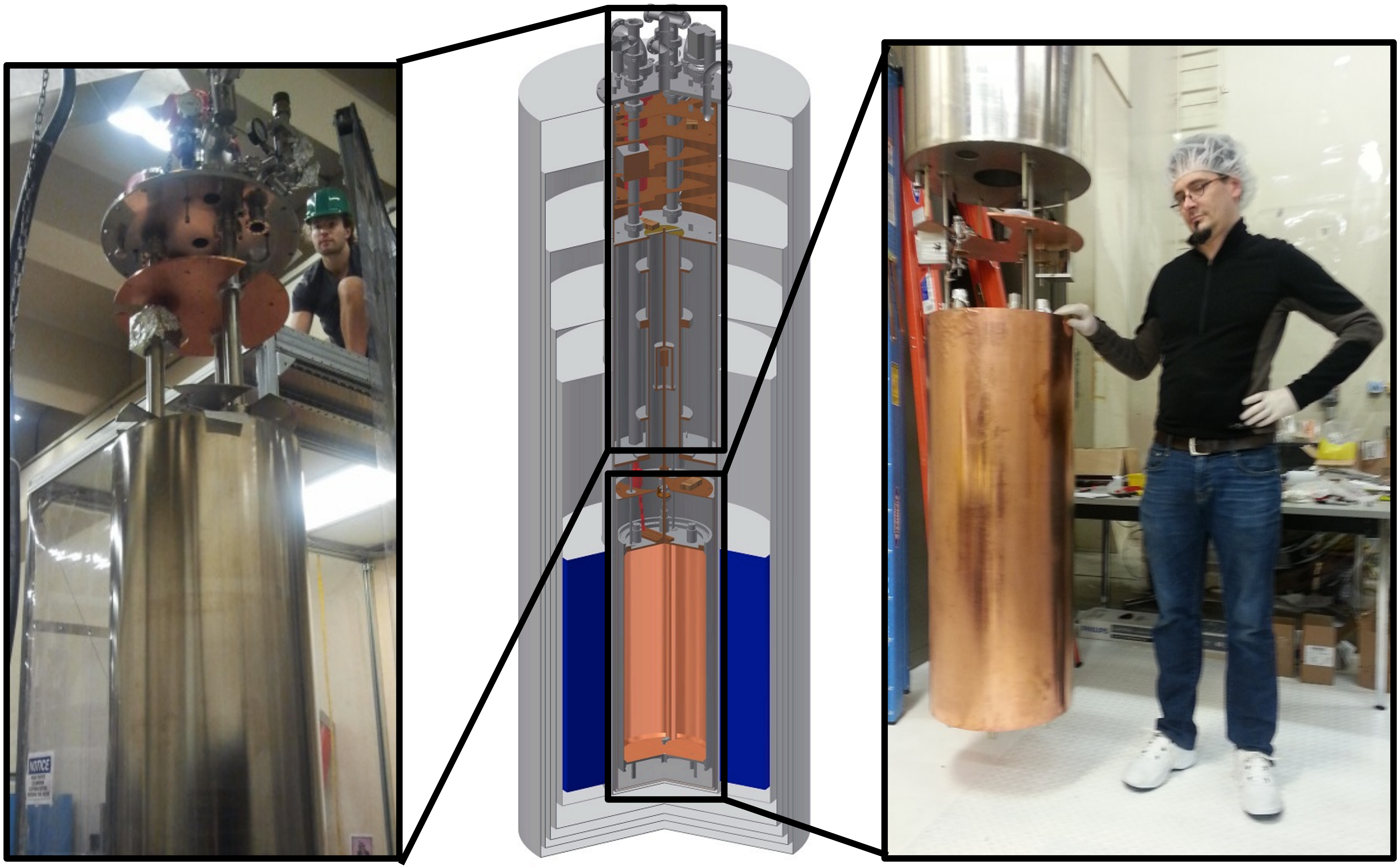
Helium recovery bag

Clean room

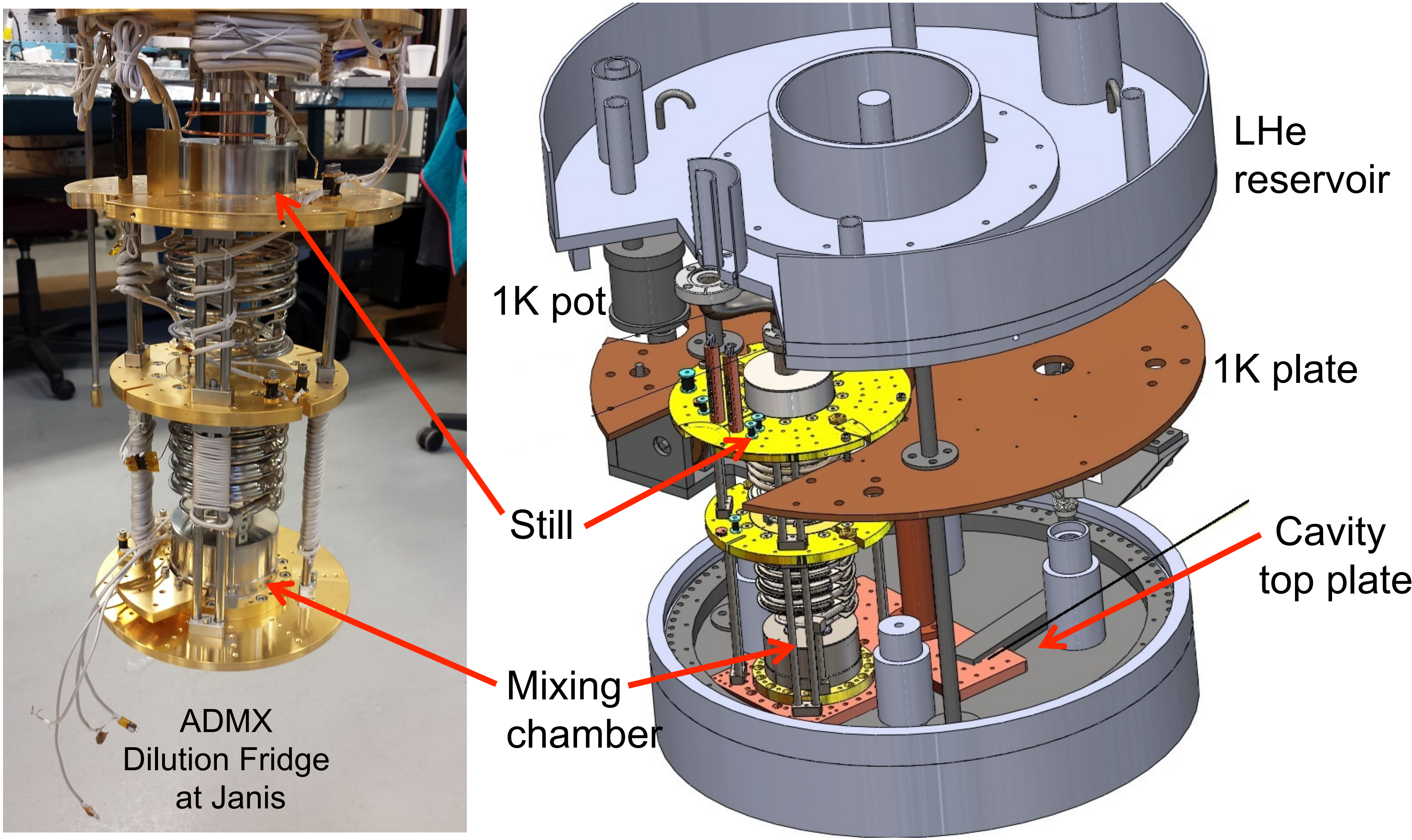
ADMX

Helium liquifier

Completely redesigned insert for new phase

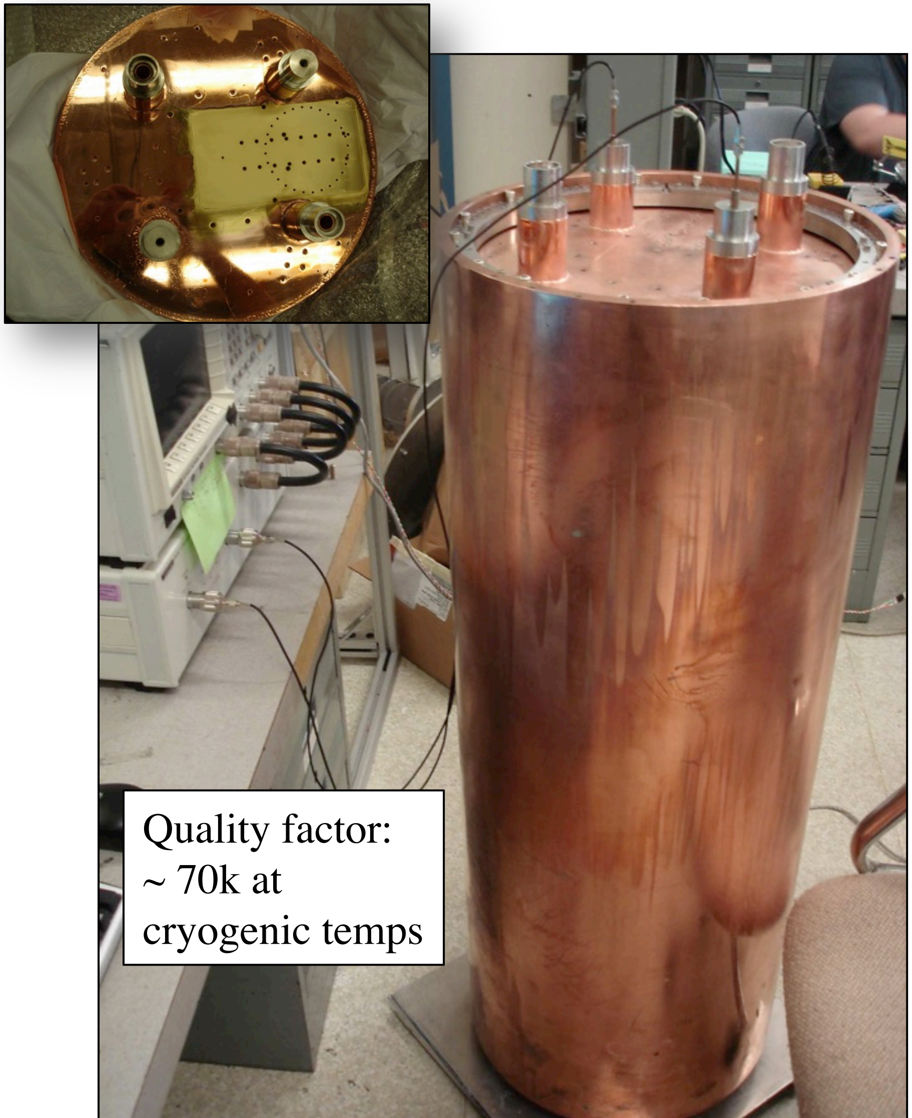


Designed to accept dilution refrigerator

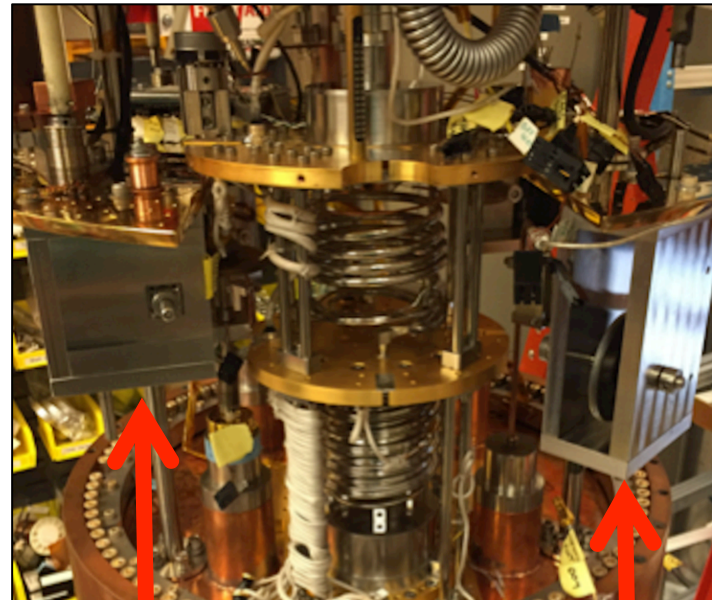


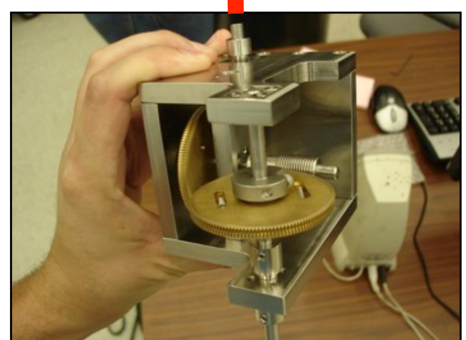
Currently installed Cavity & Motion Control

Dilution Fridge mounted directly to cavity top

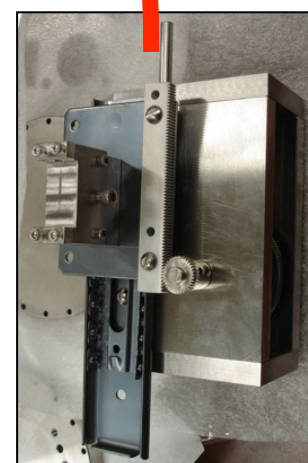


Quality factor:
~ 70k at
cryogenic temps



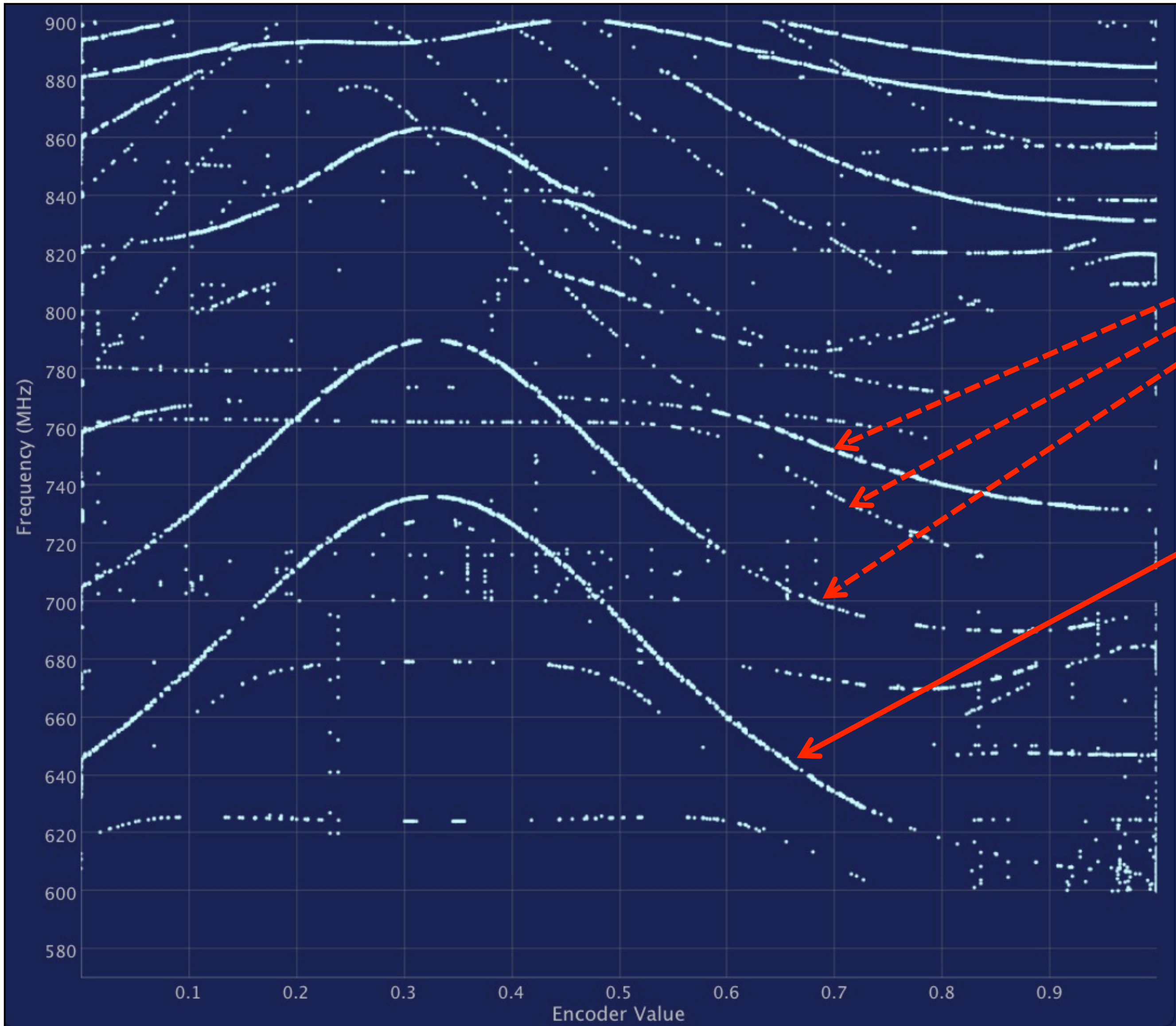


Rotary gearbox
1:19,600 gear reduction



Linear gearbox (coupling)

Mode map of cavity at UW (one rod at wall)



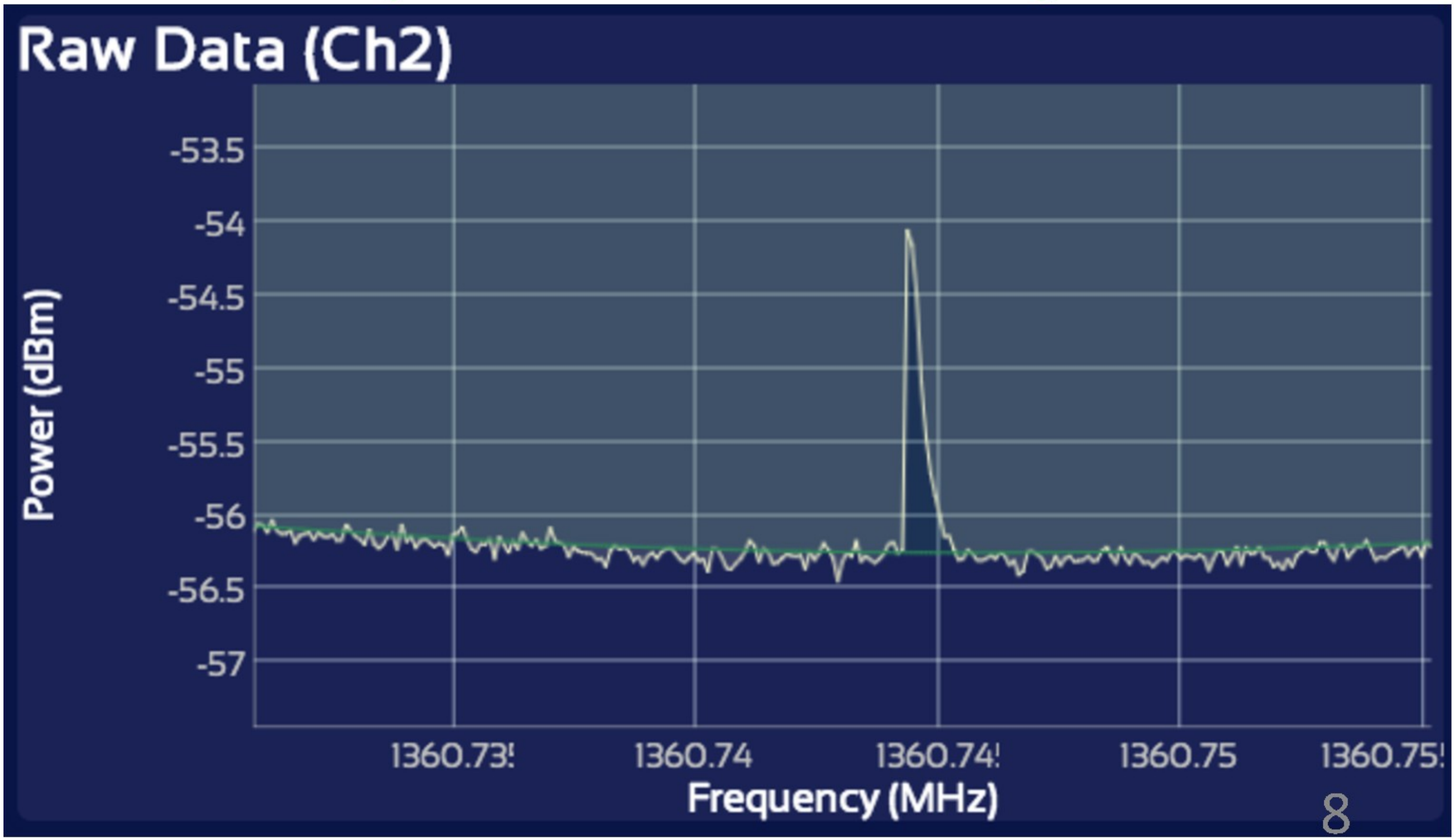
Most modes <u>do not</u> couple to the axion

TM_{010} mode strongest coupling to axions

<u>Full Range (</u>TM_{010})
580 – 890 MHz
(both tuning rods)

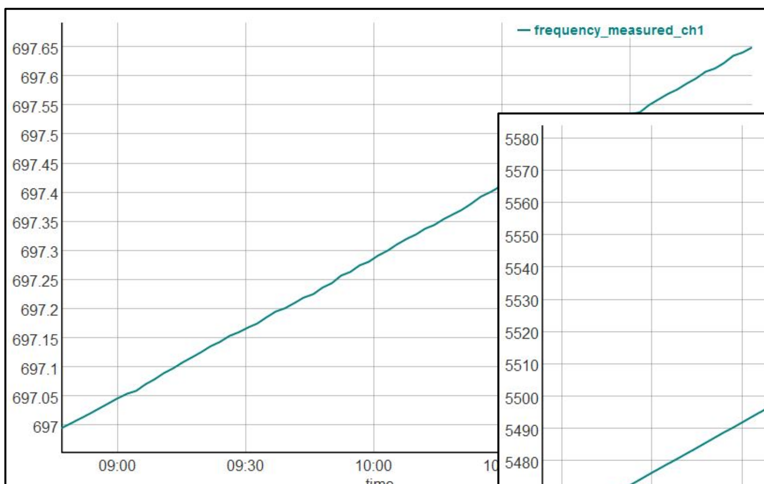
Hardware synthetic axion

Able to directly inject RF into the cavity's weak port to mimic an axion signal
Useful for calibrating system & blind signal injection through analysis chain

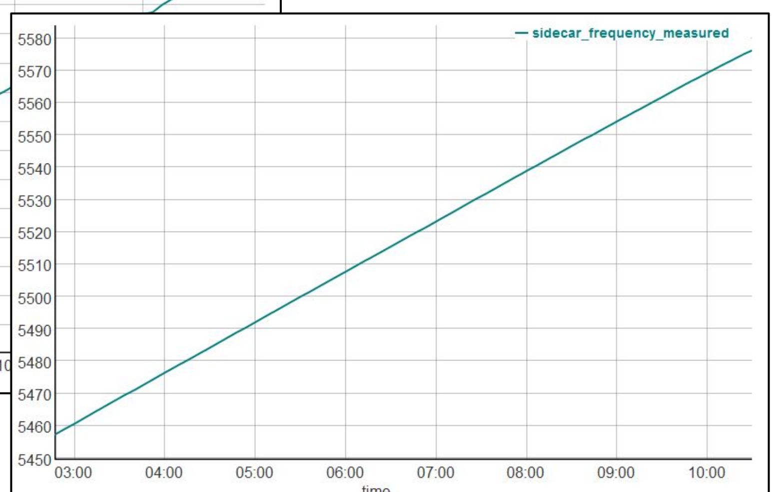


ADMX recent cold commissioning data

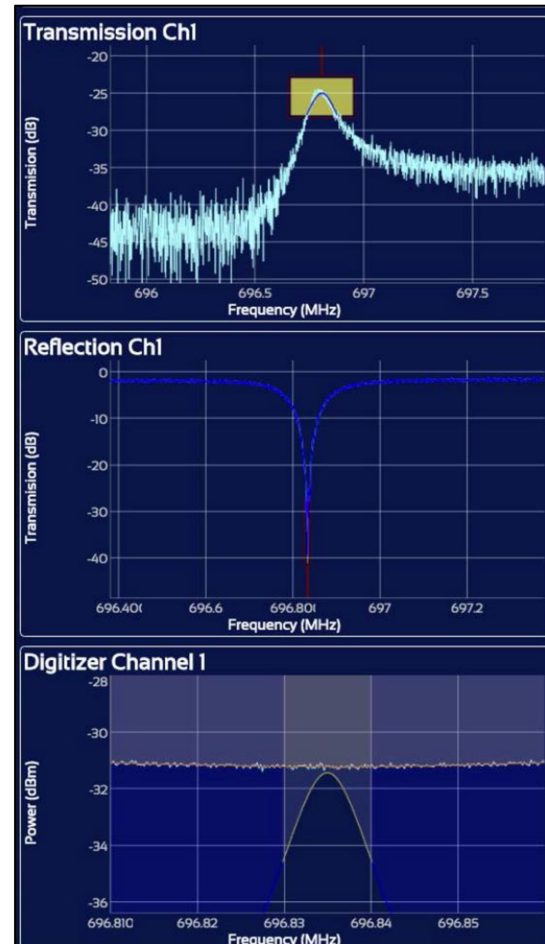
- **Data taken from Aug 9th-Oct 3rd, 2016**
- Dilution refrigerator reached stable operations @ < 200 mK
  - Not at design temp yet (< 150 mK).
  - Inadequate heat sinking of incoming gas mixture (new heat sinking has been installed)
- **Channel 1 operational (taking data with SQUID amp)**
- Channel 2 inoperable (under study)
- **Sidecar cavity operational and taking data**



Ch1 frequency vs time

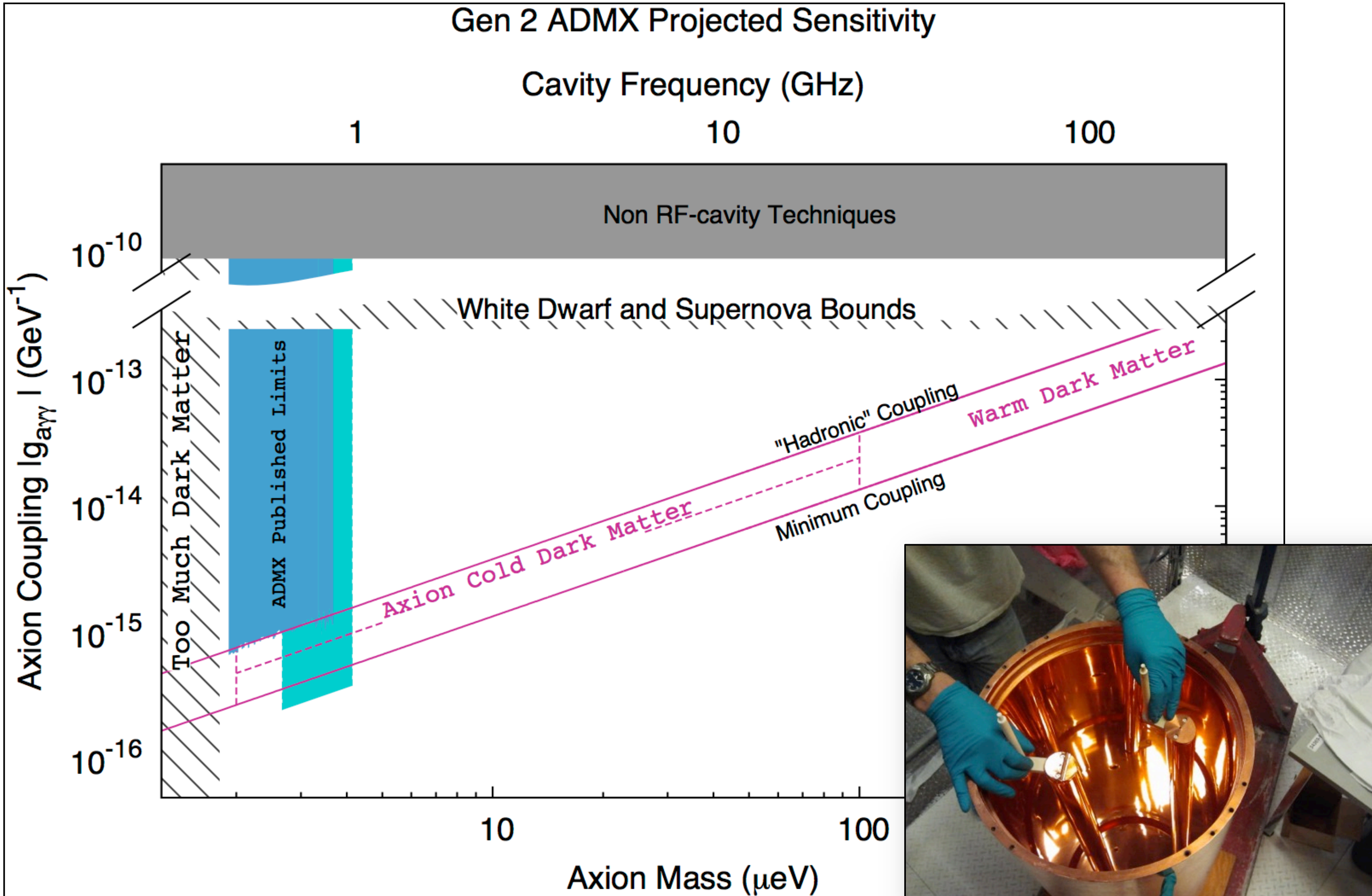


Sidecar frequency vs time



Ch1 DAQ

Anticipated sensitivity by Dec 2017

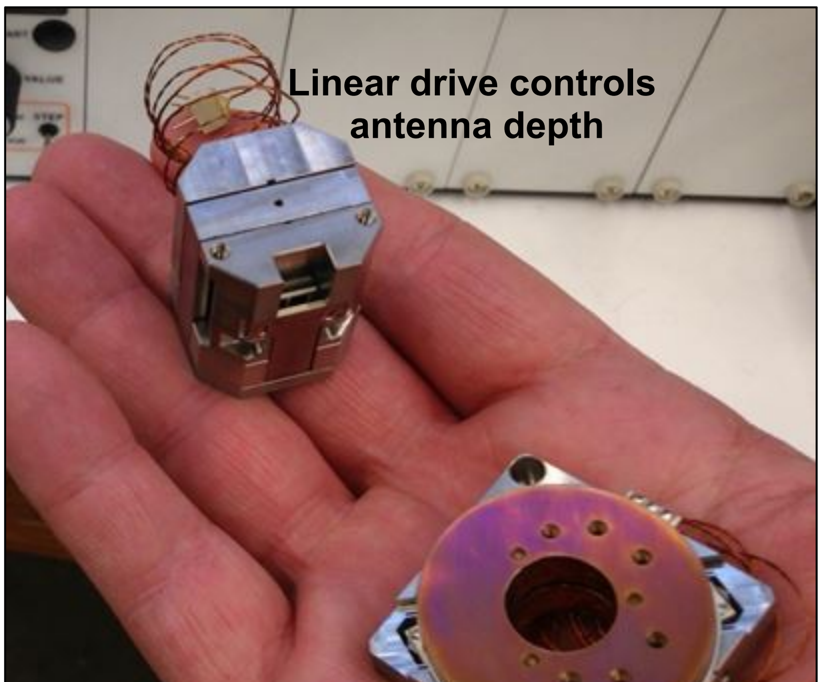


3rd instrumented channel: Sidecar cavity

AXION DARK MATTER EXPERIMENT

- Test new technologies in-situ and search in new frequency ranges (4-6 GHz) (piezoelectric motors, JPAs, etc)
- Mounted directly above main cavity
- Baseline for next set of multi-cavity arrays

Piezos replace large bulky gearboxes (2 wires)



Rotary drive controls tuning rod

Commercial linear & rotary piezoelectric drives (attocube)
Compatible with high B-field (>30 T), vacuum and cryogenic temperatures (10 mK)

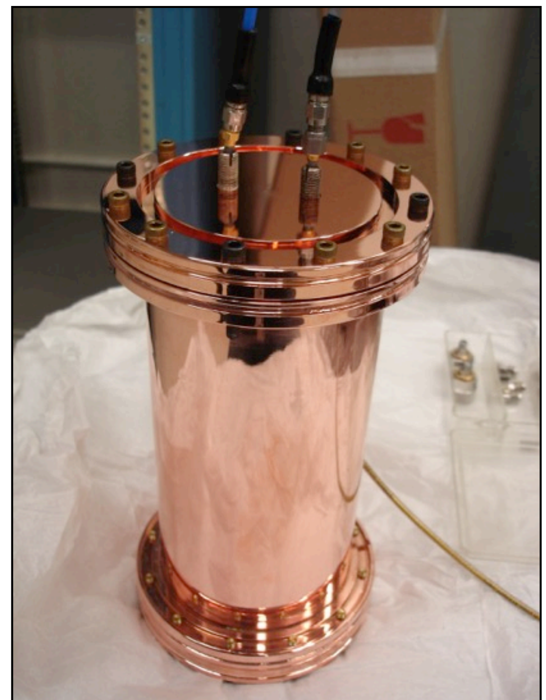
Challenge of higher frequency axion searches

- Scaling single cavity to higher frequencies (f) – Volume ~ $(f)^{-3}$!
- Quality factor also goes down as frequency increases ($Q_L \sim 10^5 \cdot (f)^{-2/3}$)
- Need to move to multi-cavity array’s.

Frequency ~ 540 MHz
Q_L – 100,000
Axion Mass ~ 2 μeV
Volume – 135 liters

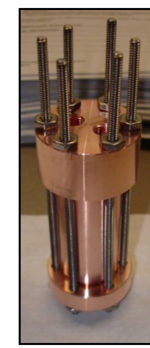
16” diameter

Frequency ~ 2.4 GHz
Axion Mass ~ 9 μeV
Q_L – 60,000
Volume ~ 2.6 liters



5” diameter

Frequency ~ 10 GHz
Axion Mass ~ 36 μeV
Q_L – 25,000
Volume – 0.025 liters

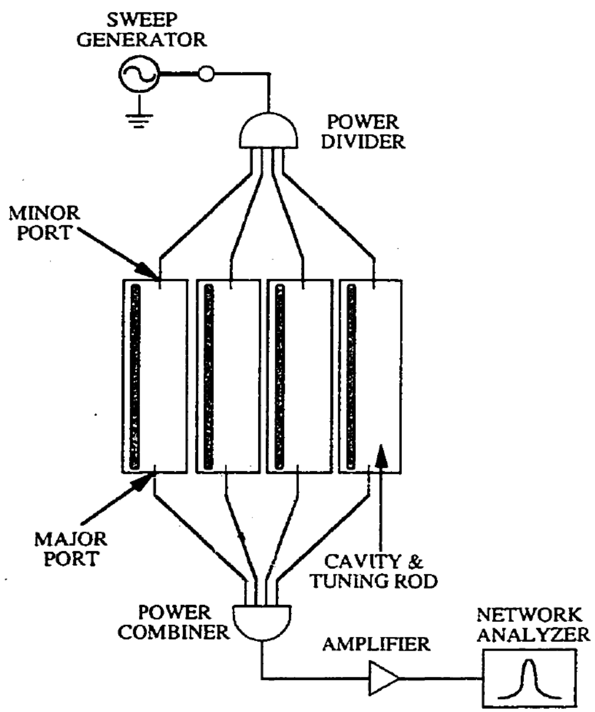


1” diameter

1-2 GHz cavity baseline design (UF & LLNL)

- Axion signal coherent over 100s of meters. Co-add cavities in phase before amplification (N independent cavities → N amplifiers and noise adds in quadrature... only √N improvement)
- 4 – cavity array that is power combined
- System based on previous ADMX Phase 0 work (low risk… demonstrated before)
- Each cavity ~22 liters (88 liters total) with Q_L~ 60k
- Wilkinson power dividers/combiners to co-add signals.


CAD drawings of 4-cavity array

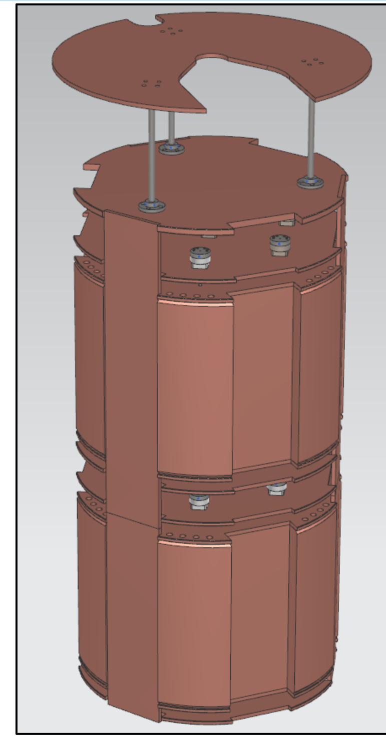


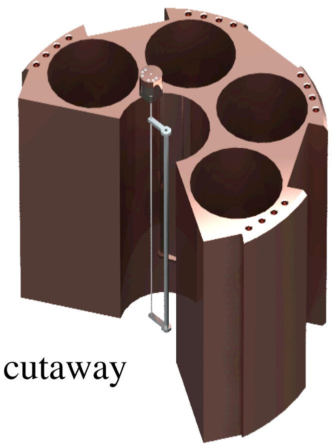
Schematic of 4-cavity array


4-cavity array from Phase 0 for controls testing

2 – 6 GHz frequency range (FNAL)

- FNAL taken lead in designing 2-6 GHz cavity system
- Design concept is multiple cavities locked together
- Build off experience from 4-cavity array & Sidecar cavity
- Splitting it into operational years as a 2-4 GHz and a 4-6 GHz system.





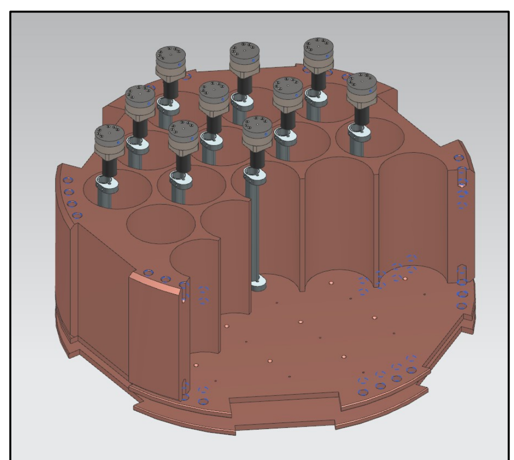
7-cavity cutaway

2-4 GHz ← conceptual design phase

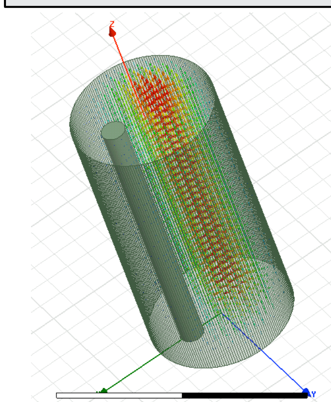
- Sidecar cavity system as baseline geometry
- Hexagonally packed
- <u>7 cavity array x 2 layers = 14 cavities</u>
- Usable volume = 44 liters

4-6 GHz (under study)

- 35 mm radius, 168 mm long cavities,
- <u>19 cavity array x 3 layers = 57 cavities</u>
- Usable volume = 33 liters



19-cavity cutaway

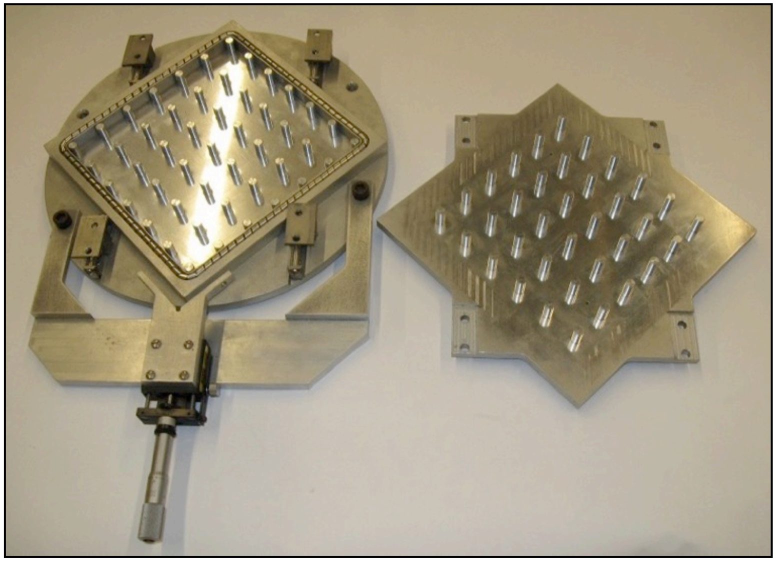


Single cavity element simulation

*Studies and designs: C. Salemi & G. Rizzo: FNAL

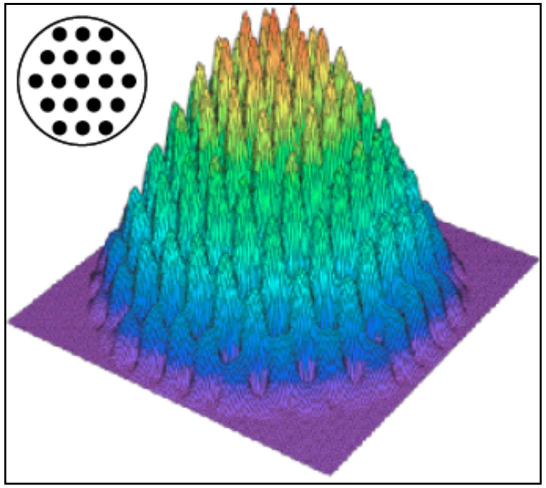
Different concept for 6 – 10 GHz Photonic Bandgap Cavities

- Lattice of posts that can be translated/rotated as group to adjust frequency.
- Trade off from multi-cavity array
  - Maintain reasonably large V (20-40 liters) and C_{lmn}~0.4 – 0.5
  - Bulk motion → less moving parts
  - Smaller tuning range (10-20%)
  - More stringent mechanical requirements

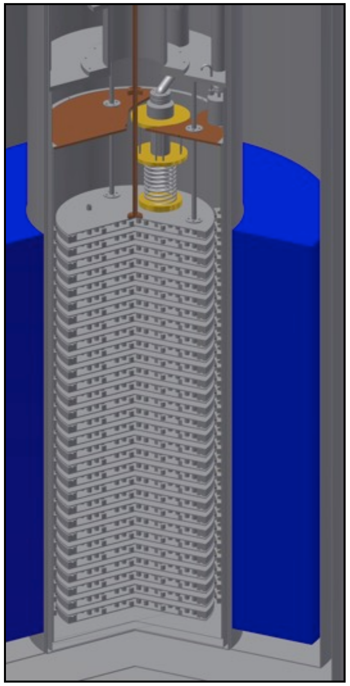


Prototype multi-post cavity

- Simulation of Electric field of the TM_{010} mode of a 96 metallic post array.
- Frequency 5 times empty cylinder
- Form Factor C ~ 0.5

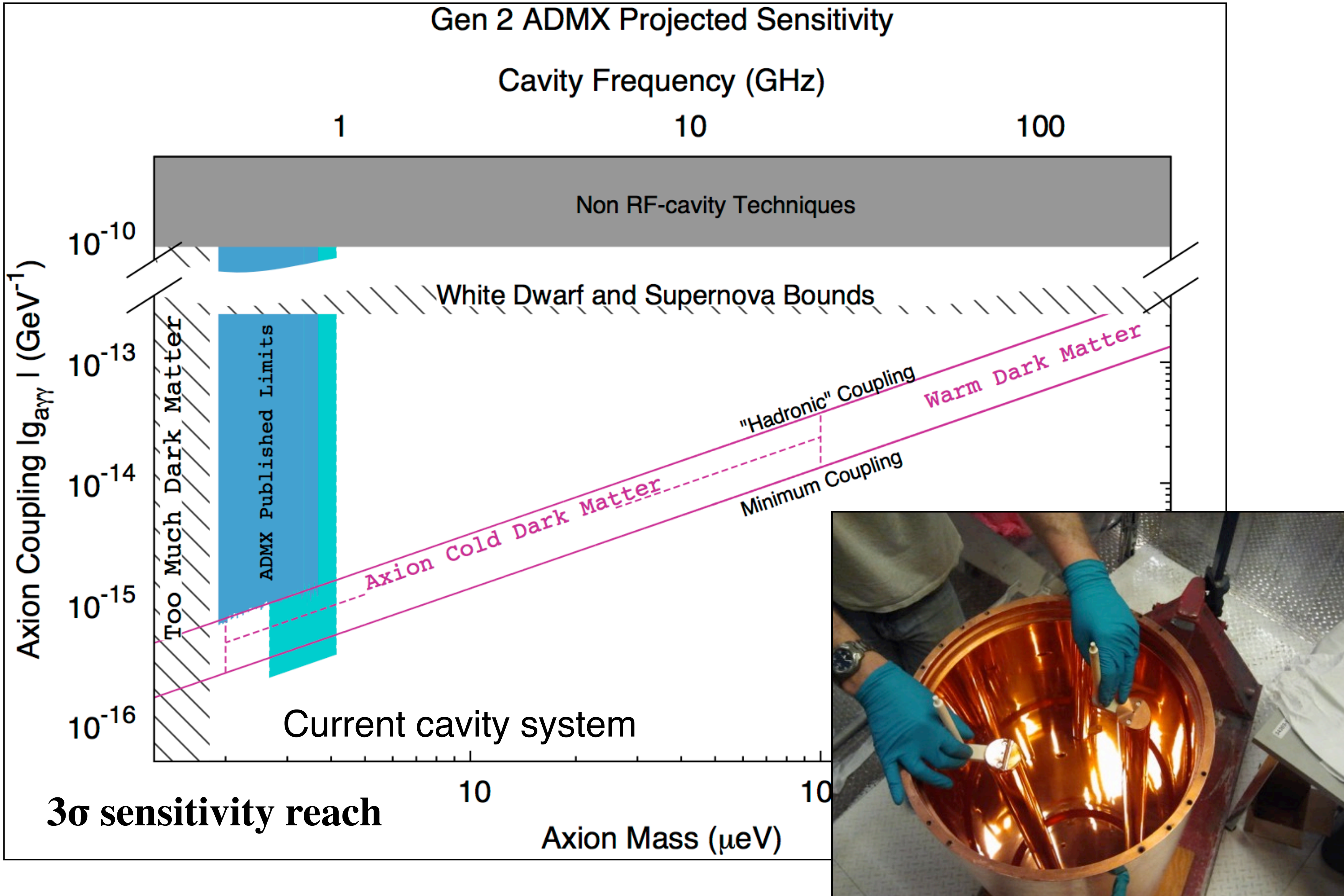


Simulation of 96 post array

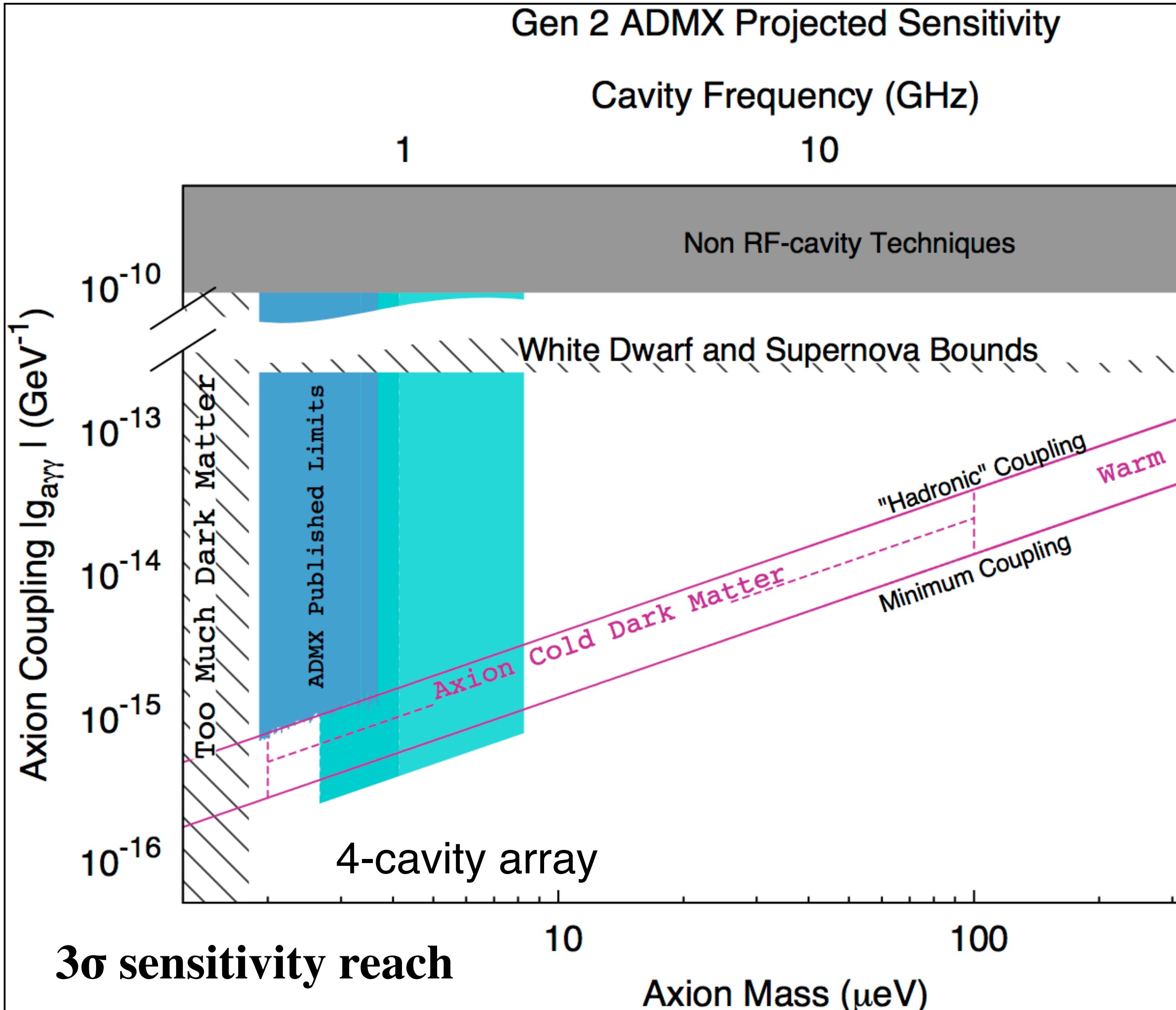


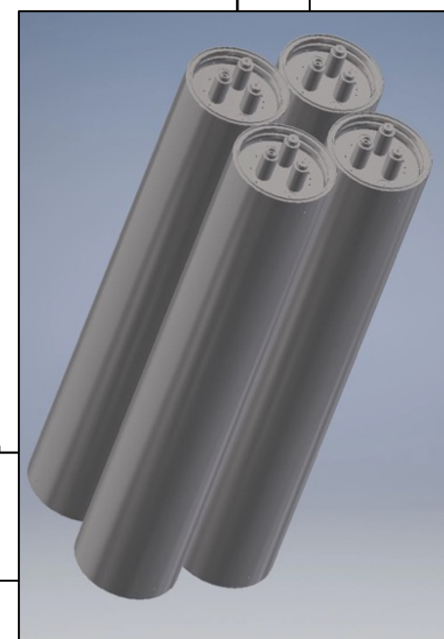
Concept for stack of PBG cavities in ADMX

ADMX Science Prospects: Year 1 (0.6 – 1 GHz)



ADMX Science Prospects: Year 2 (1 – 2 GHz)

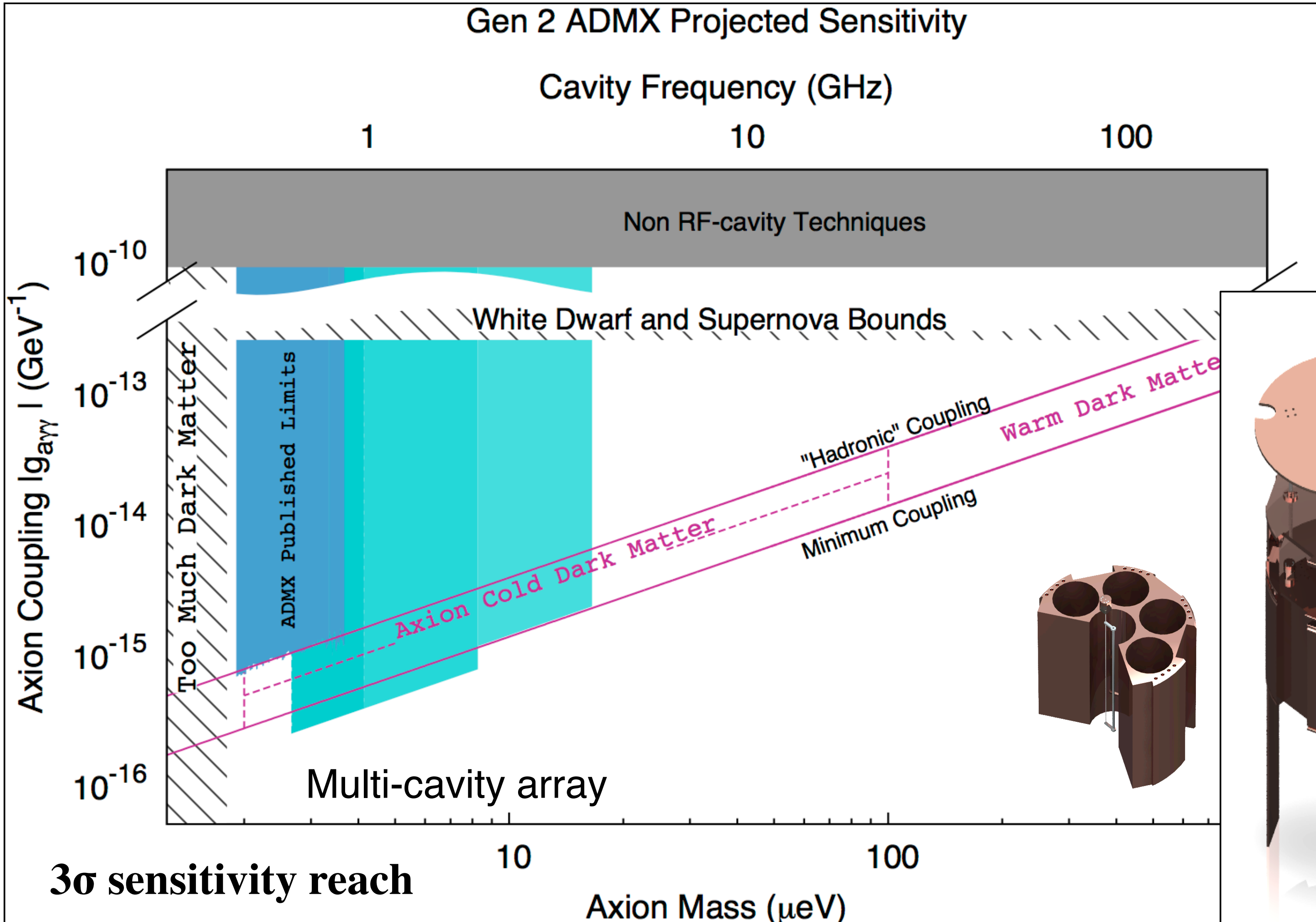


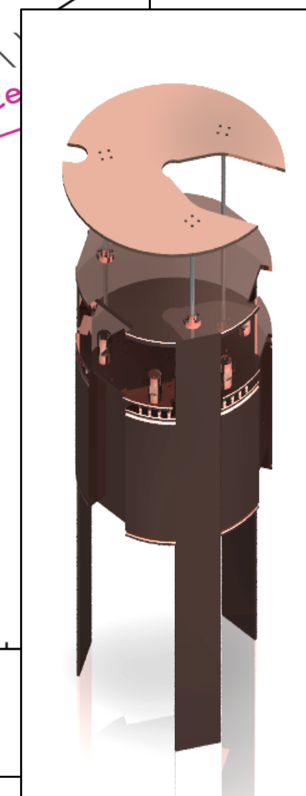


3σ sensitivity reach

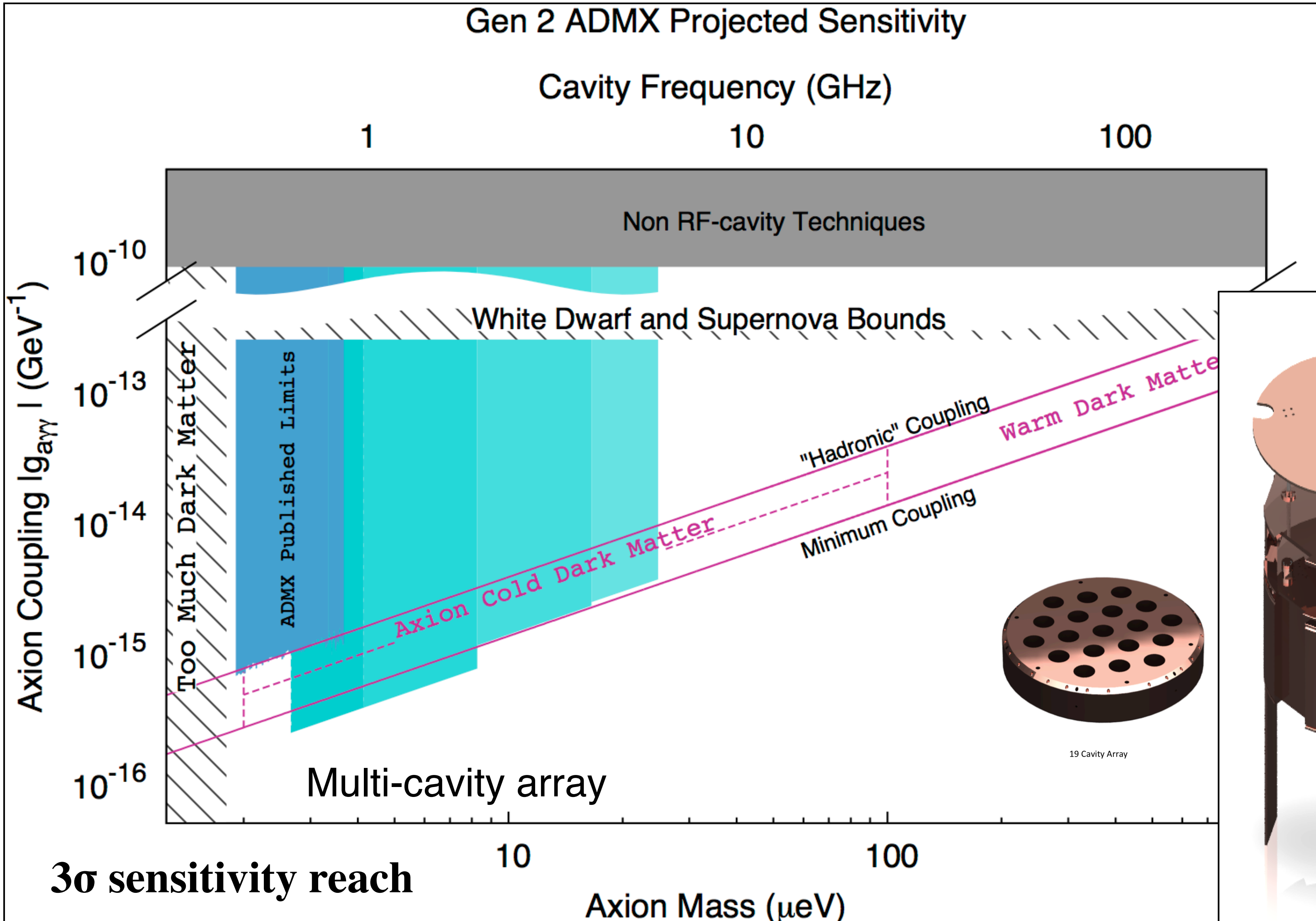
ADMX Science Prospects: Year 3 (2 – 4 GHz)

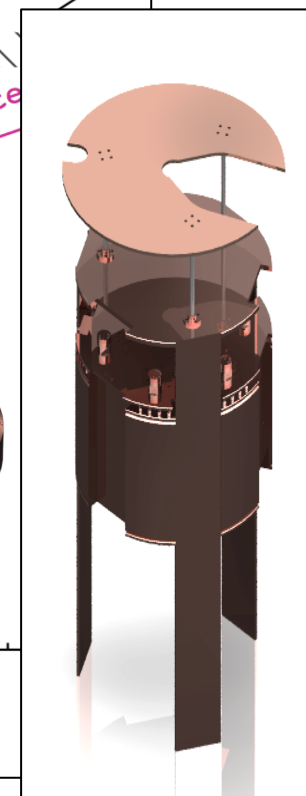
AXION DARK MATTER EXPERIMENT



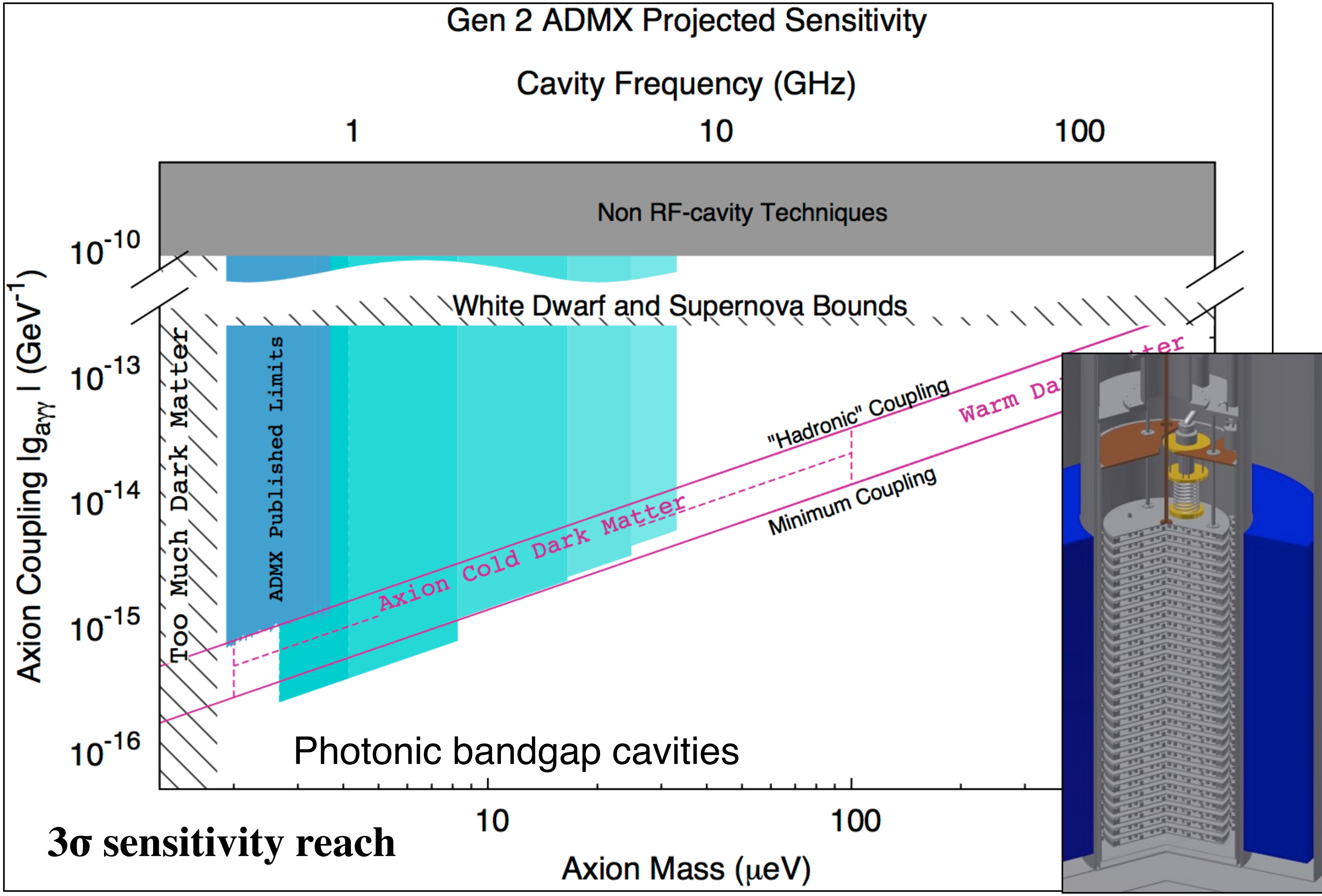


ADMX Science Prospects: Year 4 (4 – 6 GHz)

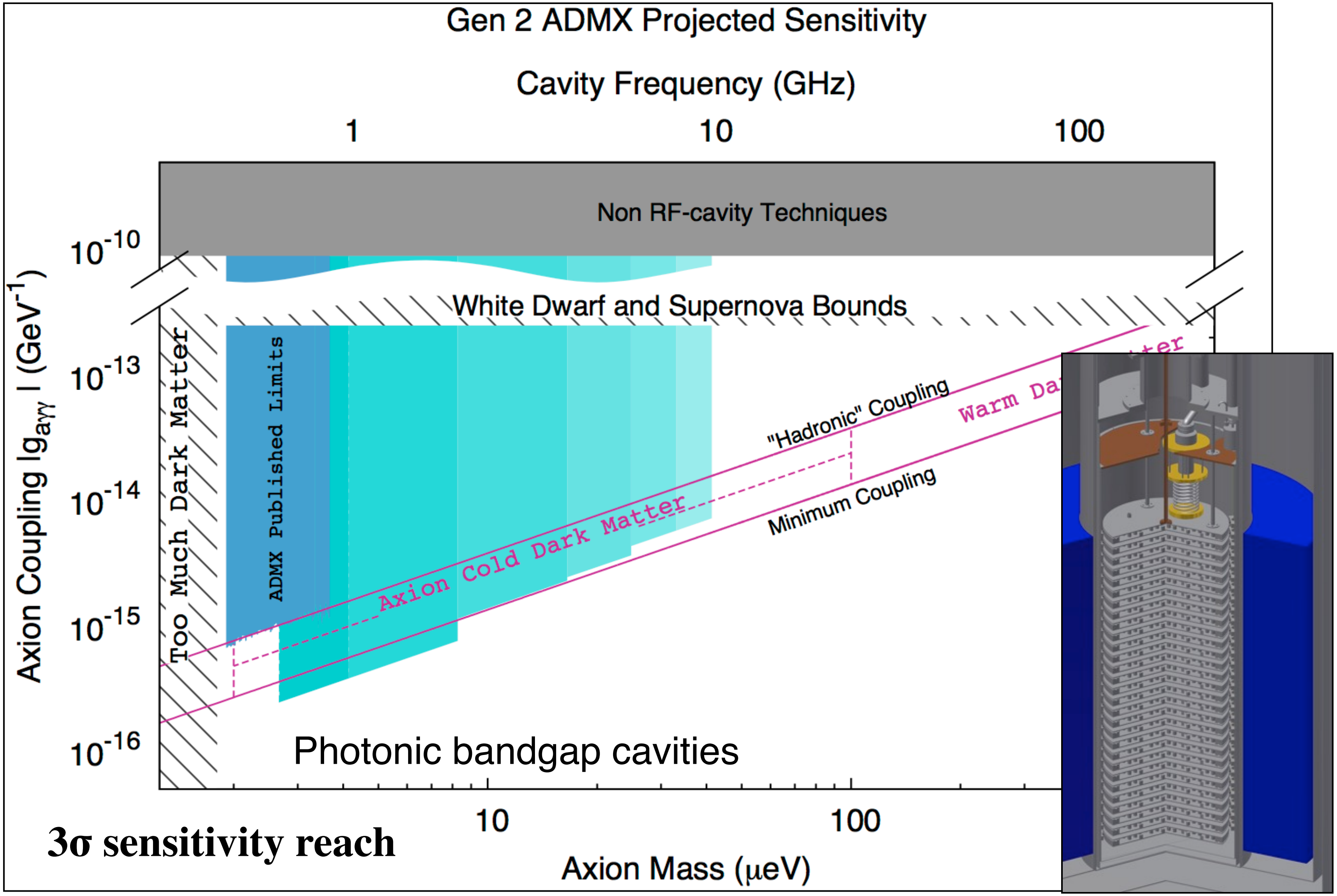




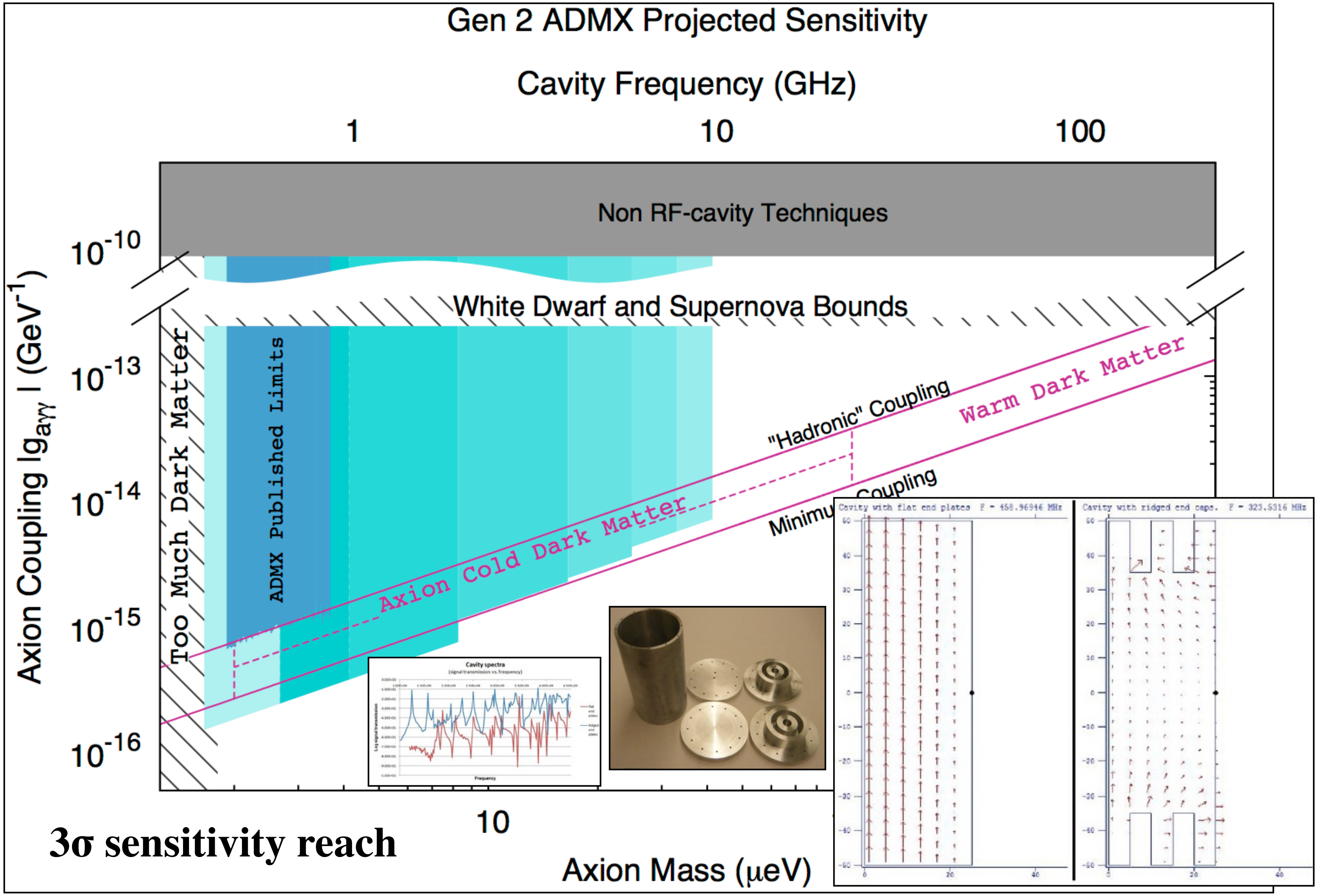
ADMX Science Prospects: Year 5 (6 – 8 GHz)



ADMX Science Prospects: Year 6 (8 – 10 GHz)



ADMX Science Prospects: Out-Years < 0.5 GHz



Slow-wave cavity with alumina tuning rods

Fermilab:
Ongoing and Proposed Contributions to ADMX

ADMX
AXION DARK MATTER EXPERIMENT

- Fermilab joined ADMX in 2015.
- Physicists Aaron Chou, Daniel Bowring, Andrew Sonnenschein, William Wester (2 FTEs). Grad student Akash Dixit (U. Chicago).
- Design and construction (if funded) of 2-6 GHz cavity array.
  - Fermilab has well matched RF cavity and cryogenic design experience.
  - Conceptual design work and RF simulations started Summer 2016.
- R&D towards electronics and cavities for higher frequency bands.
- Upgrades to ADMX liquid helium plant and control system to improve reliability.
- Help with operations and data analysis for 0.5-1 GHz and 1-2 GHz.
- Data management and archiving.
- Operations management- role as lead lab for operations under discussion with DOE. Developed WBS and budget materials for Sept 2016 operations review.

Summary & Conclusions

Axions: solve the Strong-CP problem and are a compelling DM candidate

The ADMX Gen 2 project A narrow band experiment with concurrent R&D

- Takes data in one mass range while developing systems for higher masses.
- Recently finished commissioning run.
- Primary near term focus:
    - Achieve quantum-limited noise performance.
    - Scan 0.6 – 2 GHz at DFSZ sensitivity over next 2 years.
    - Follow up by scanning to 10 GHz over the full 6 year Gen 2 program.

For more info see our list of publications

ADMX AXION DARK MATTER EXPERIMENT

Selected Letter publications

"Results from a High Sensitivity Search for Cosmic Axions", C. Hagmann et al., PRL 80, 2043 (1998)
"Experimental Constraints on the Axion Dark Matter Halo Density", S. Asztalos et al., Ap.J. 571:L27-30 (2002)
"Results of a Search for Cold Flows of Dark Matter Axions", L. Duffy et al., PRL 95 (9) 091304 (2005)
"A SQUID-Based Microwave Cavity Search for Dark-Matter Axions", S. Asztalos et al., PRL 104, 041301 (2010)
"A Search for Hidden Sector Photons with ADMX", A. Wagner et al., PRL 105, 171801 (2010)
"A Search for Scalar Chameleons with ADMX", G. Rybka et al., PRL 105, 051801 (2010)

Selected archival publications

"A Search for Non-Viralized Axionic Dark Matter", J. Hoskins et al., PRD 84 121302 (2011)
"Design and Performance of the ADMX SQUID-Based Microwave Receiver", S.Asztalos et al., NIM A656, 39 (2011)
"A High-Resolution Search for Dark-Matter Axions", L.D. Duffy et al., PRD 74 (1) 012006 (2006)
"An Improved RF Cavity Search for Halo Axions", S.J. Asztalos et al., PRD 69 011101 (R) (2004)
"A Large-Scale Microwave Cavity Search for Dark-Matter Axions", S. Asztalos et al., PRD 64, 092003 (2001)
"Cryogenic Cavity Detector for the Large-Scale Dark-Matter Axion Search", S. Asztalos et al., NIM A444 21 (2000)

Selected Review articles

"Overview of Experimental Limits on Light Axions", C. Hagmann, K. van Bibber, L.J Rosenberg, Review of Particle Properties, Euro. Phys. J. C15 1 (2000)
"Searches for Invisible Axions", L. Rosenberg, K. van Bibber, Physics Reports 325 (1) 1 (2000)
"Microwave Cavity Searches for Dark-Matter Axions", R. Bradley, J. Clarke, S.D. Kinion, M. Mueck, L.J Rosenberg, P. Sikivie, Rev. Mod. Phys. 75:777-817 (2003)
"Searches for Astrophysical and Cosmological Axions", S. Asztalos, L.J Rosenberg, K. van Bibber, P. Sikivie, K. Zioutas, Annual Reviews of Nuclear and Particle Science 2006

Plus PhD theses, Instrumentation papers, SQUID papers, conference reports ..

Selected Popular publications

"Searching for Dark Matter Axions", L.J Rosenberg, K. van Bibber, SLAC Beam Line 27 (3) 3 (1997)
"Small Particle May Answer Large Physics Questions", L.J Rosenberg, Science & Technology Review (2004)
"Ultrasensitive Searches for the Axion", L.J Rosenberg, K. van Bibber, Physics Today 59 (8) 30 (2006)

ADMX collaboration