Welcome and Introduction!

2nd Workshop on Microwave Cavities for Axion Searches

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Gianpaolo Carosi

Lawrence Livermore National Laboratory

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Purpose of this workshop

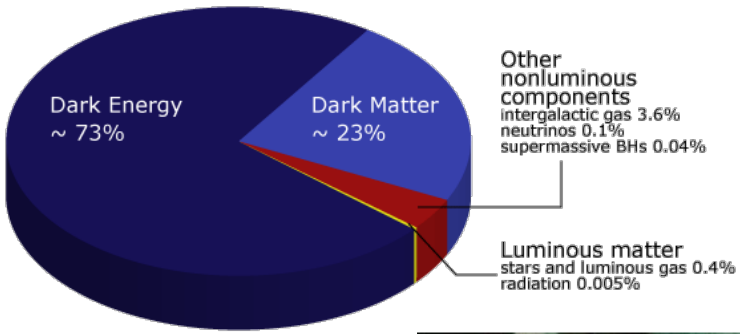
- Bring together…
  - Researchers in axion physics
  - Experts in microwave cavities for accelerators.
  - Experts in quantum information technologies.

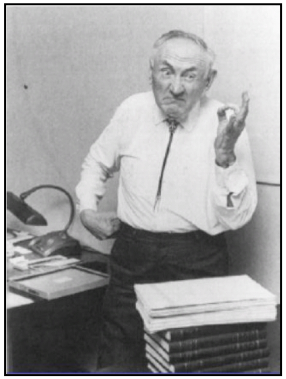
Goal

- Bring students and researchers unfamiliar with axion dark matter searches up to speed on unique experimental requirements.
- Work through new concepts to address the challenge of going to higher and lower mass axion searches in an **informal** setting.

The Nature of Dark Matter

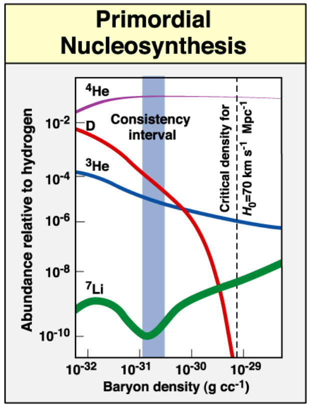
One of the premier unsolved mysteries in physics





1930s
Fritz Zwicky: noticed odd motion of member galaxies of the Coma Cluster (moving too quickly to be bound)

1980s
Vera Rubin: systematically surveyed a large number of galaxies. Rotation curves did not make sense without a large unseen mass ← made dark matter unavoidable!

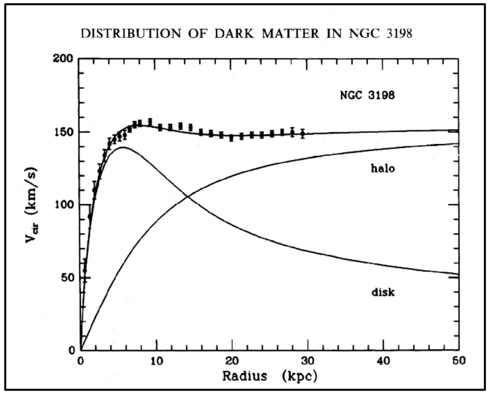


Likely new particle outside standard model
- **A. Baryons essentially ruled out!**
- **B. Neutrinos likely only small fraction.**

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)**

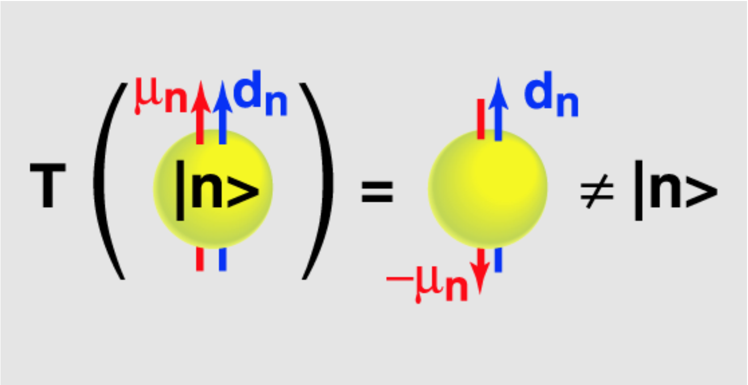
Galaxy collisions



Individual galaxies

Peccei and Quinn: CP conserved through a hidden symmetry

QCD CP violation should, e.g., give a large neutron electric dipole moment (~~T~~ + CPT = ~~CP~~); none is unobserved.
(9 orders-of-magnitude discrepancy)



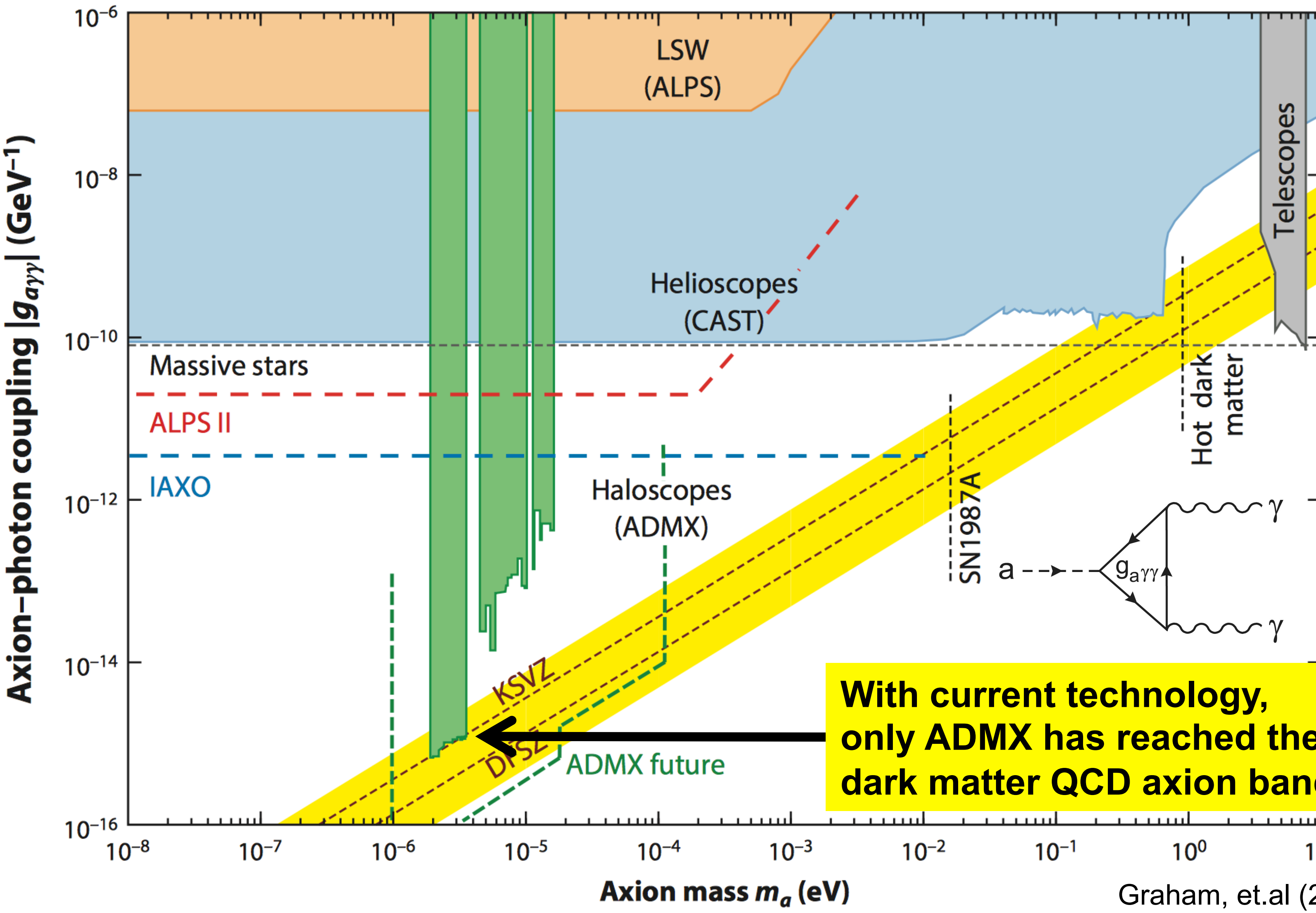
Why doesn't the neutron have an electric dipole moment?

$d_e < 3 \cdot 10^{-26}$ e-cm
Baker et al. 2006

This leads to the "Strong CP Problem": Where did QCD CP violation go?

1977: Peccei and Quinn: Posit a hidden broken U(1) symmetry ⇒
1) A new Goldstone boson (the axion);
2) Remnant axion VEV nulls QCD CP violation.

Axion experimentally constrained parameter space



With current technology, only ADMX has reached the dark matter QCD axion band.

Graham, et.al (2016)

ADMX: Collaboration (begin in mid-1990s)

University of Washington

University of Florida

Berkeley, University of California

Lawrence Livermore National Laboratory

NRAO

The University Of Sheffield.

Recently Joined

Fermilab

Pacific Northwest National Laboratory

Washington University in St. Louis *

Los Alamos National Laboratory

Sponsors

ADMX now DOE Gen 2 project

Department of Energy – Primary sponsor

NSF

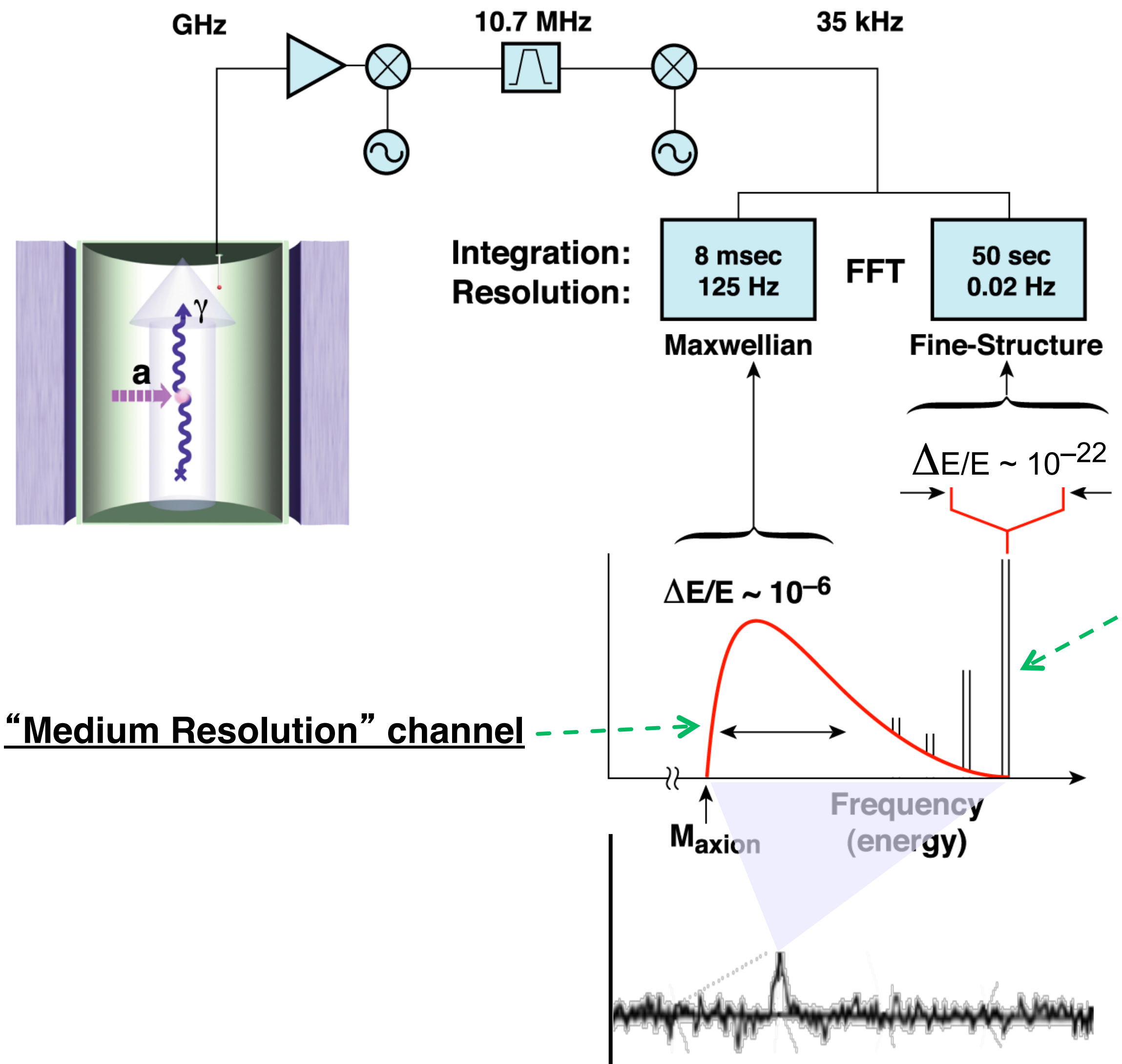
Heising - Simons Foundation

ADMX-High Frequency

Separate collaboration sited at Yale

*in process of joining

The ADMX experimental layout
(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

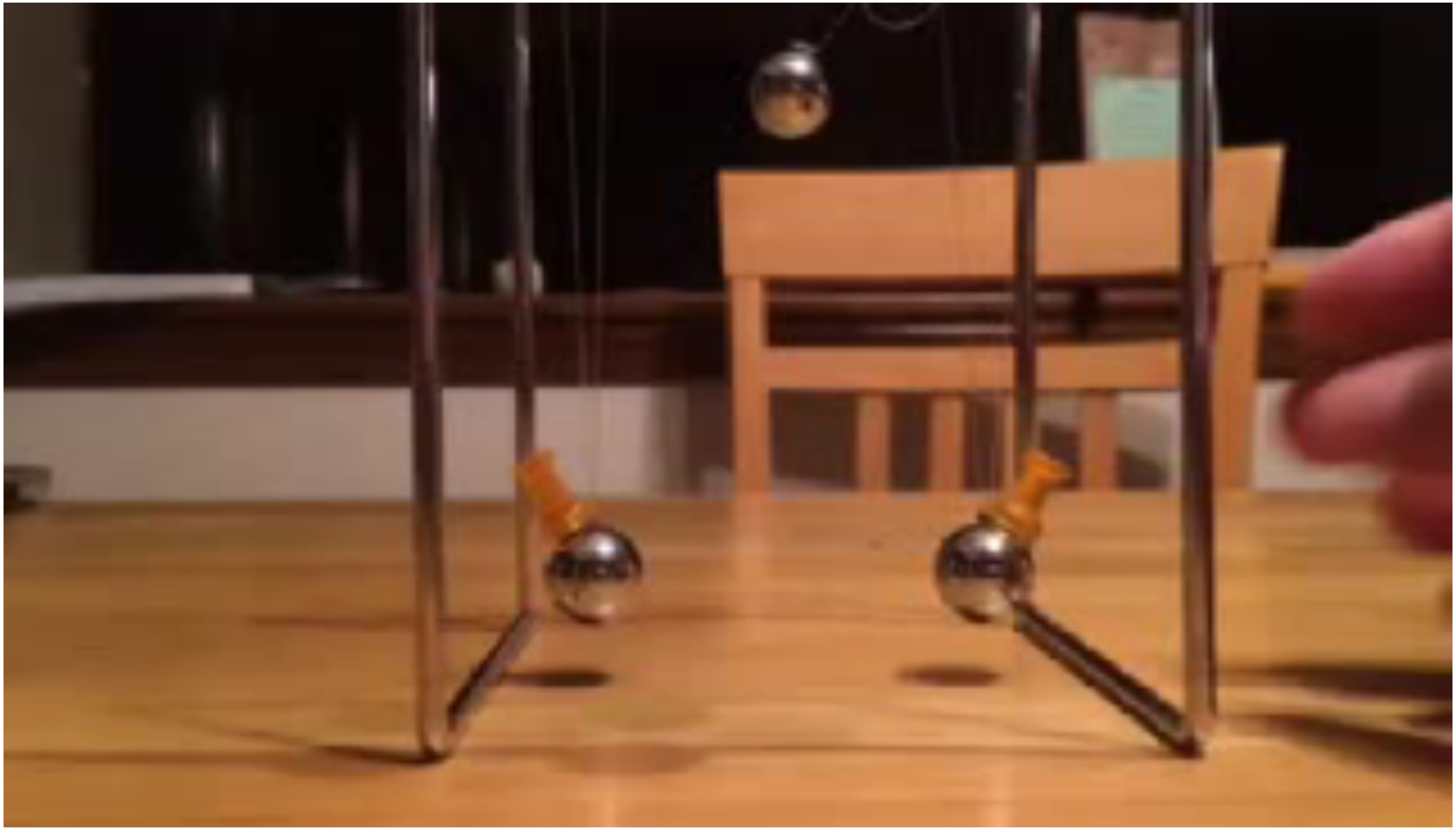
$\beta_{\ virial} \quad \sim \quad 10^{-3}$:

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

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

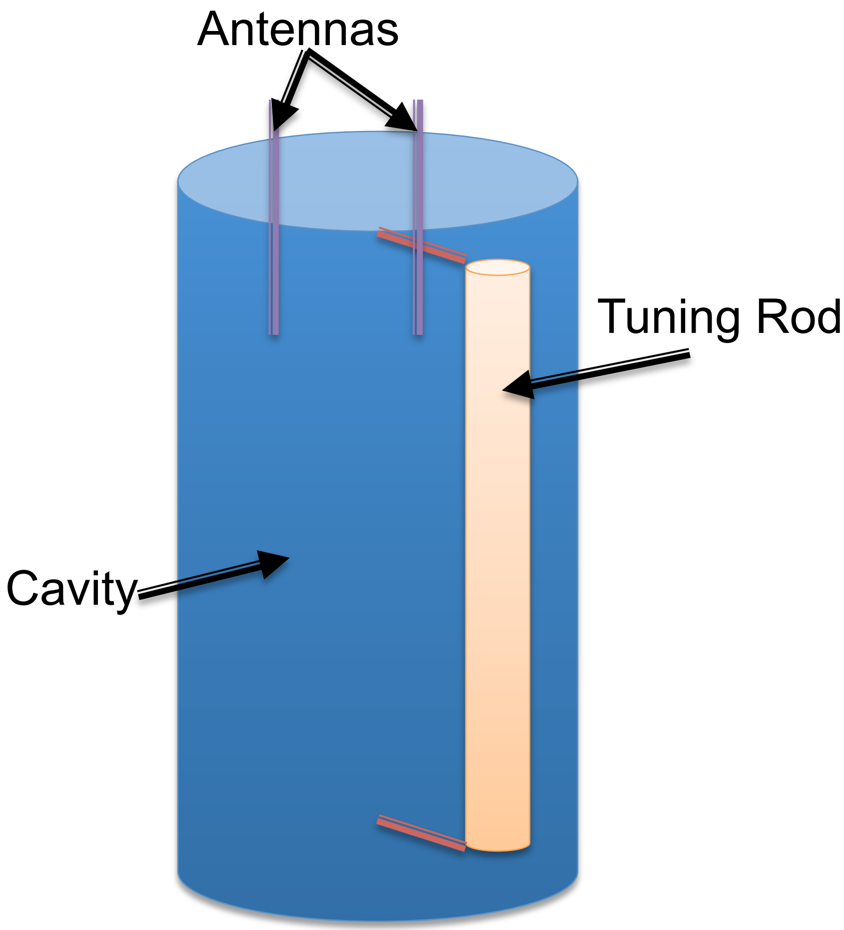
$\lambda_{\ Coherence} \quad \sim \quad 1000\ km$

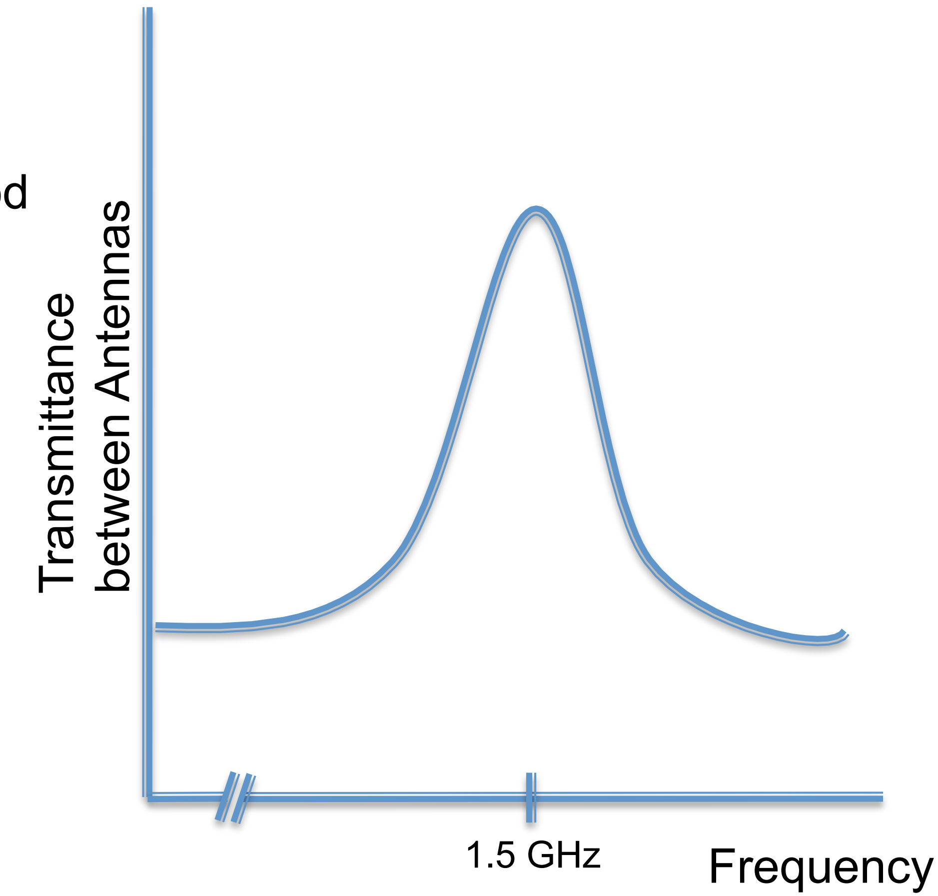
Power transfer increased by time coherence between cavity E-field and axion field



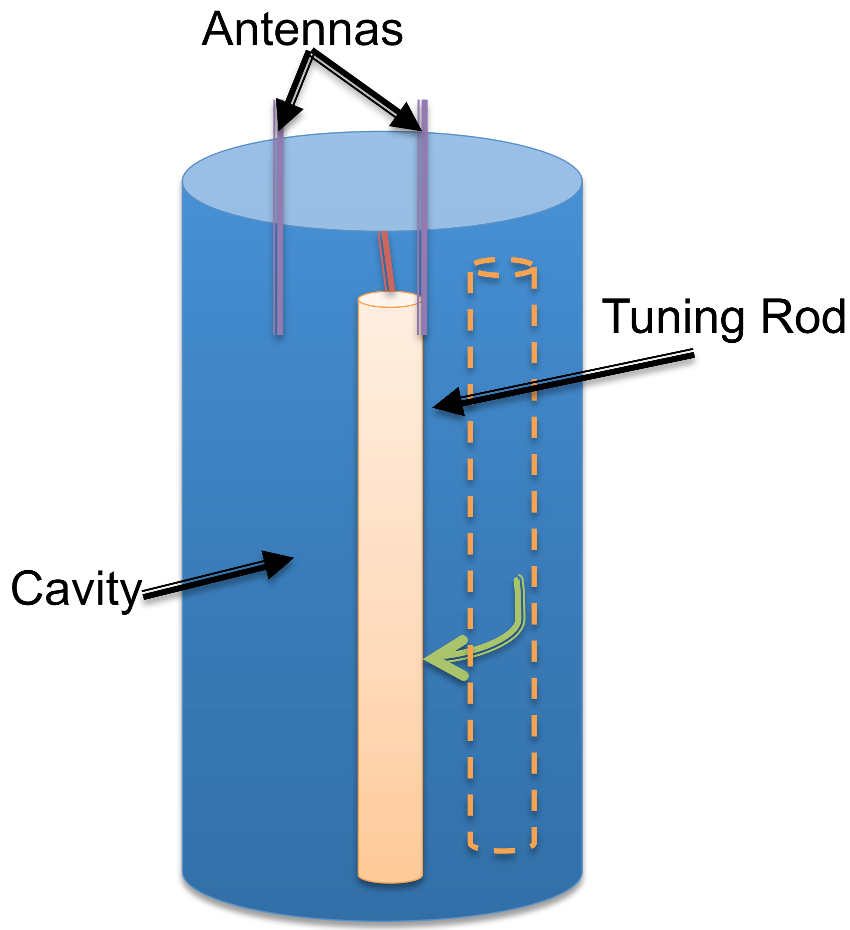
Weak coupling -- takes many swings to fully transfer the wave amplitude.
Number of swings = cavity Quality factor.
Narrowband cavity response → iterative scan through frequency space.

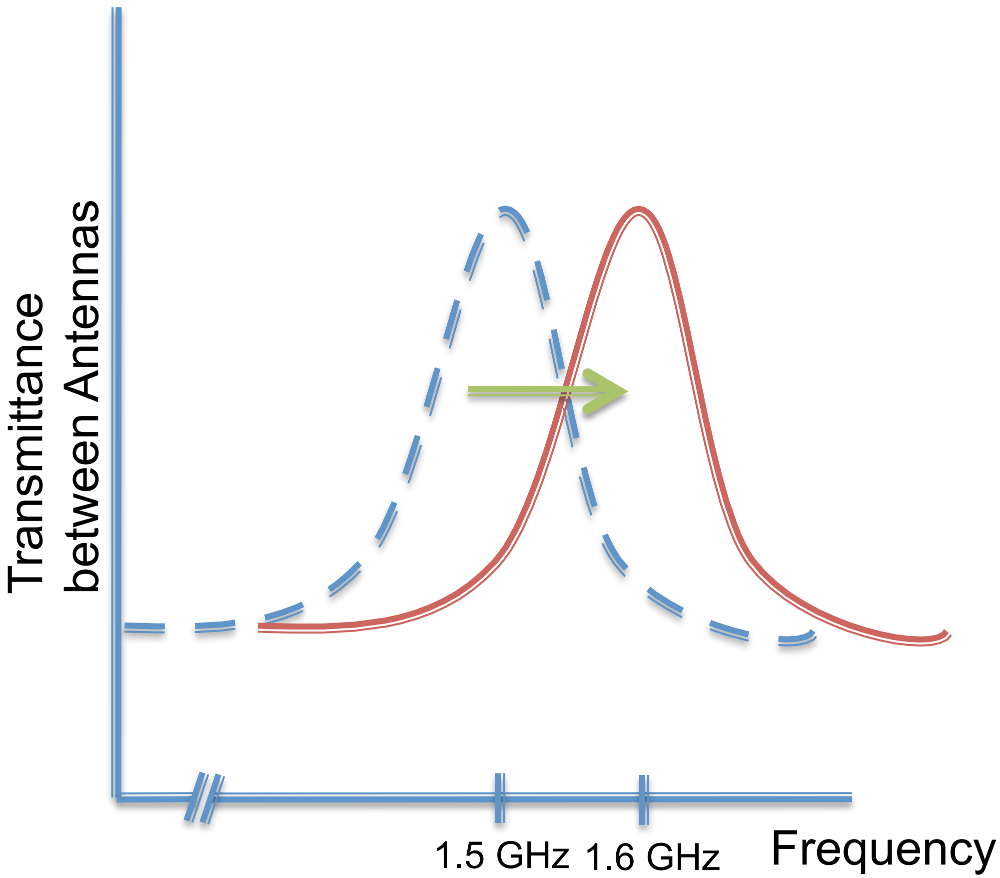
Microwave Cavity needs tunable resonance



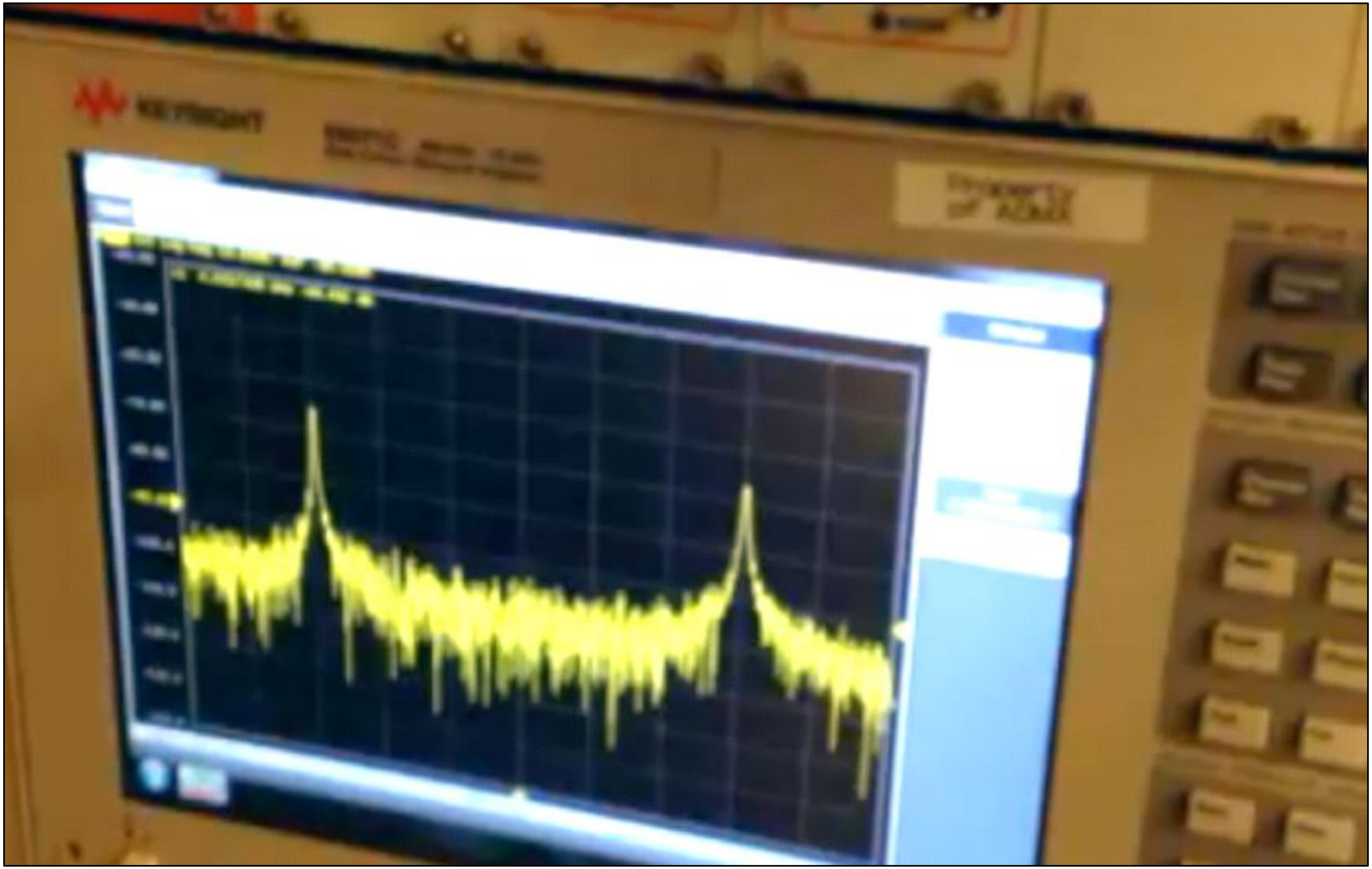


Microwave Cavity needs tunable resonance





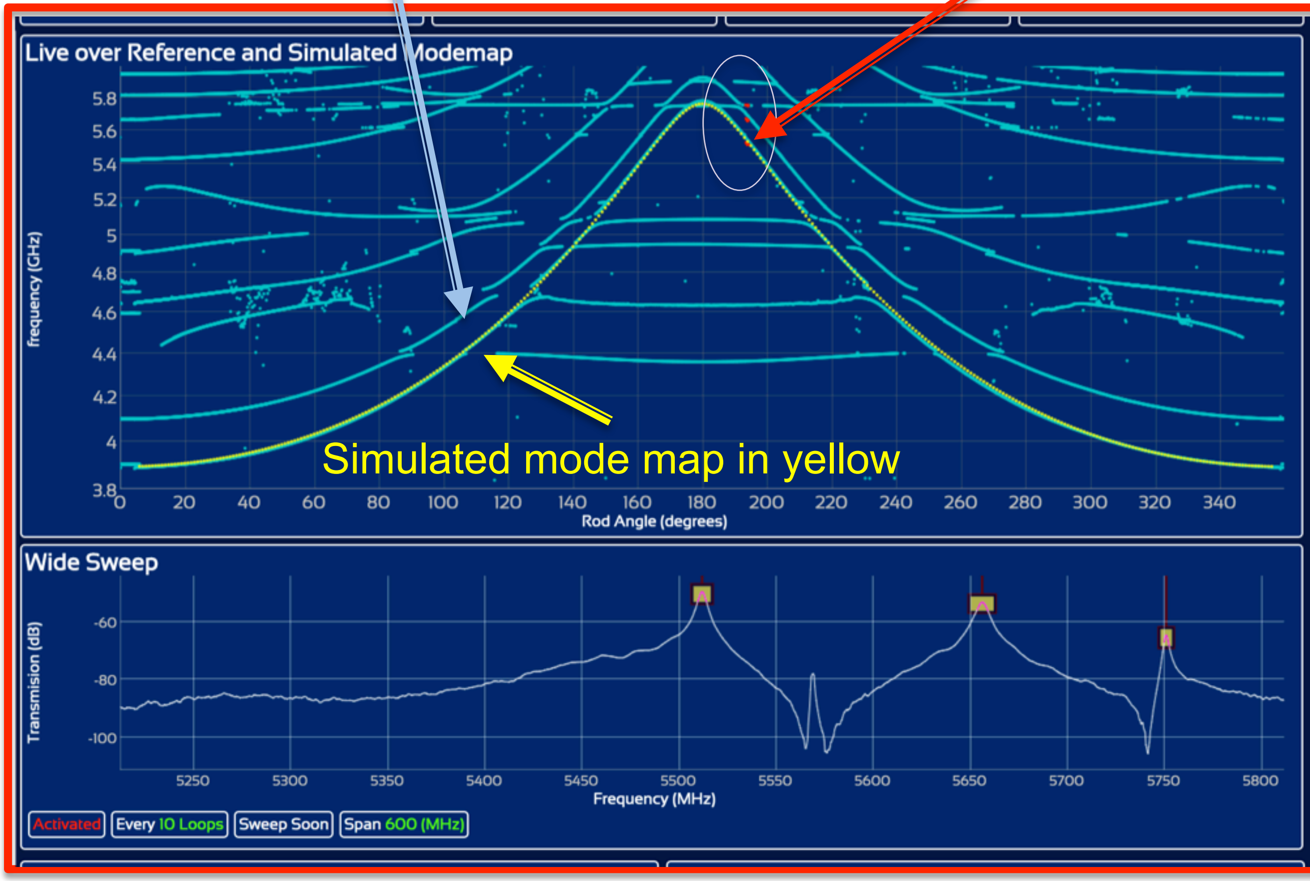
Frequency tuning the TM_{010} mode

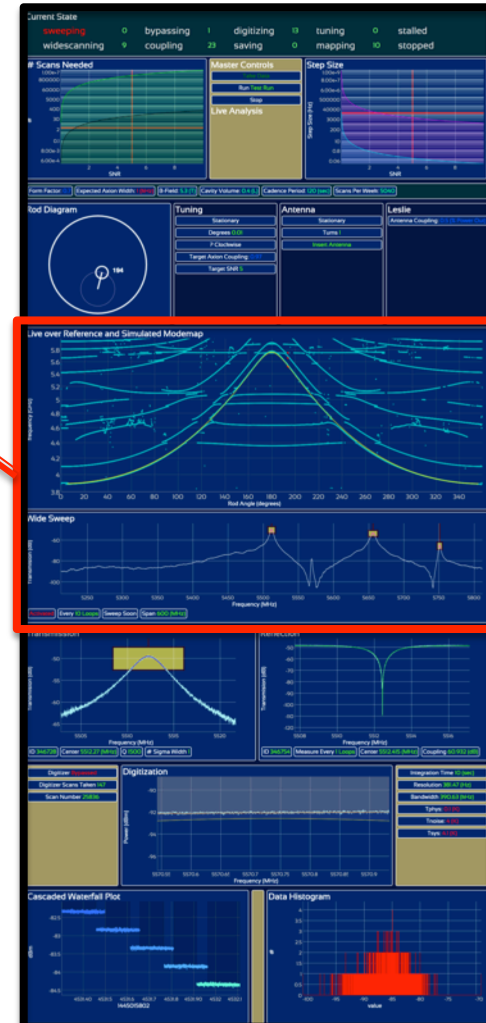


Example Frequency Mode Map (sidecar system)

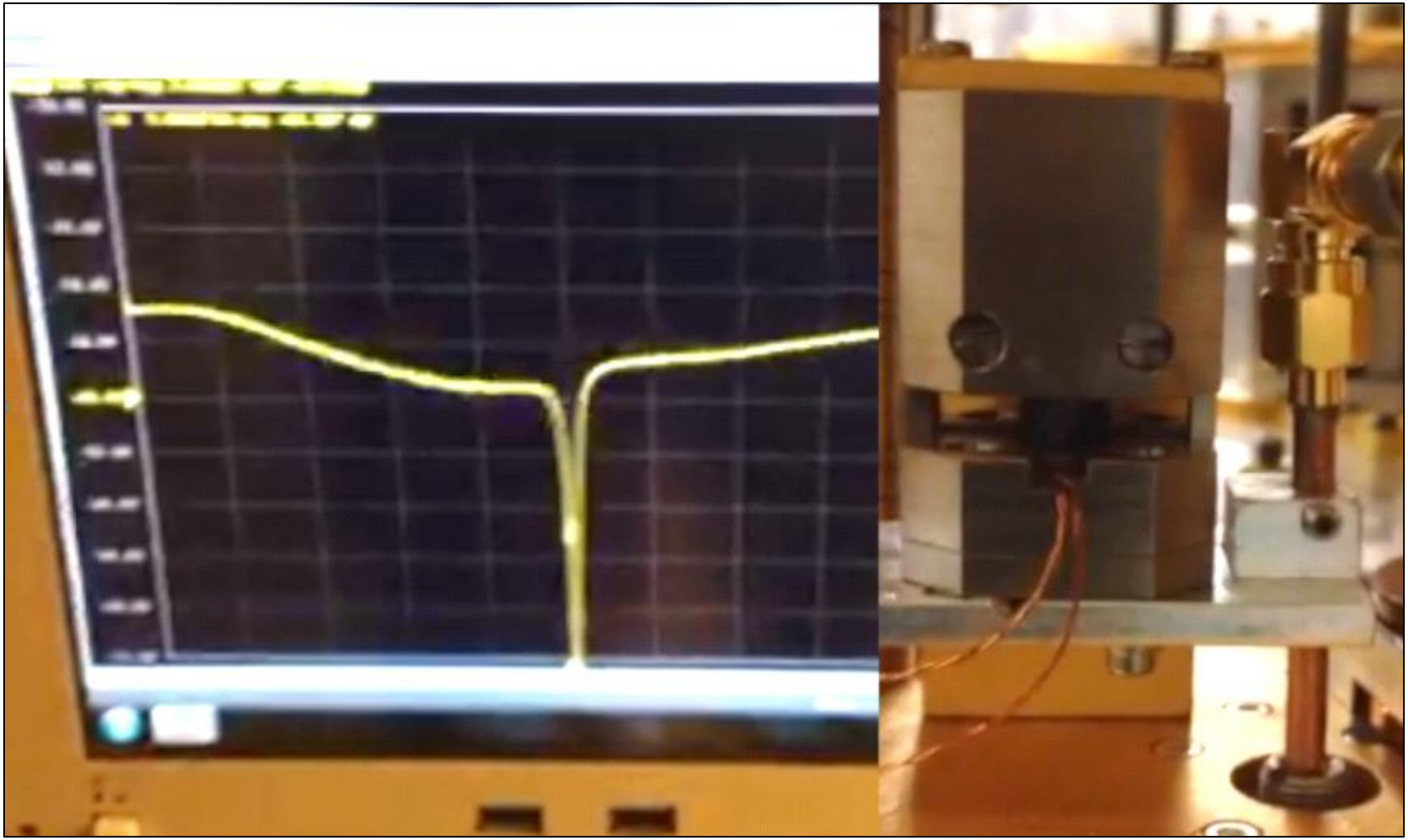
Reference mode map in blue

Red Dots are live data taken from wide scan





Critically coupling the TM_{010} mode



Typical ADMX Run Cadence

- Start by injecting a broad, swept RF signal to record cavity response. Record state data (temperatures, hall sensors, pressures, etc)

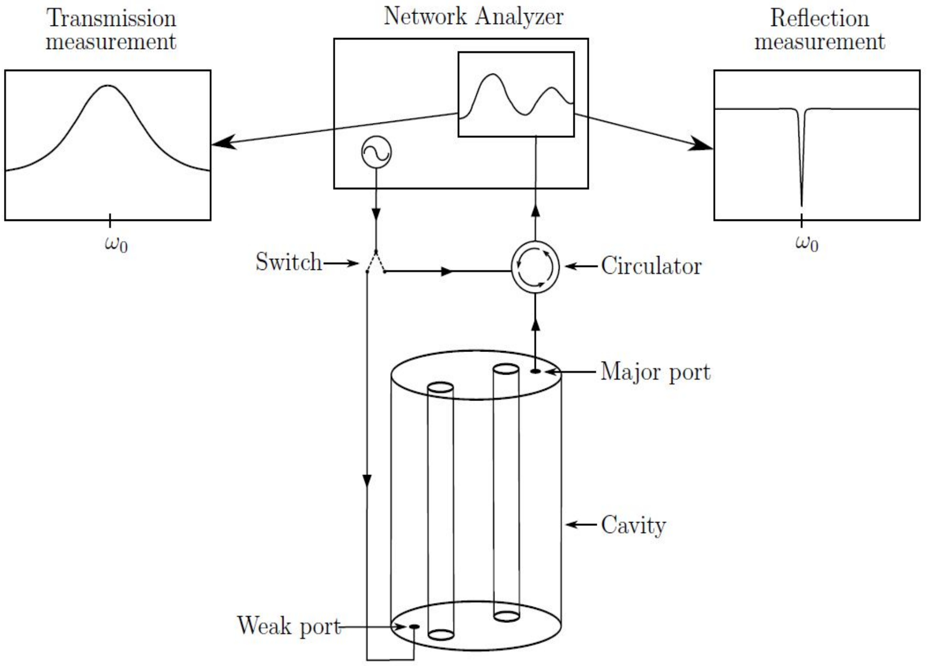
- Integrate for ~ 100 sec to 10s of minutes (final integration time dependent experimental parameters).

- Every few days adjust the critical coupling of the antennas

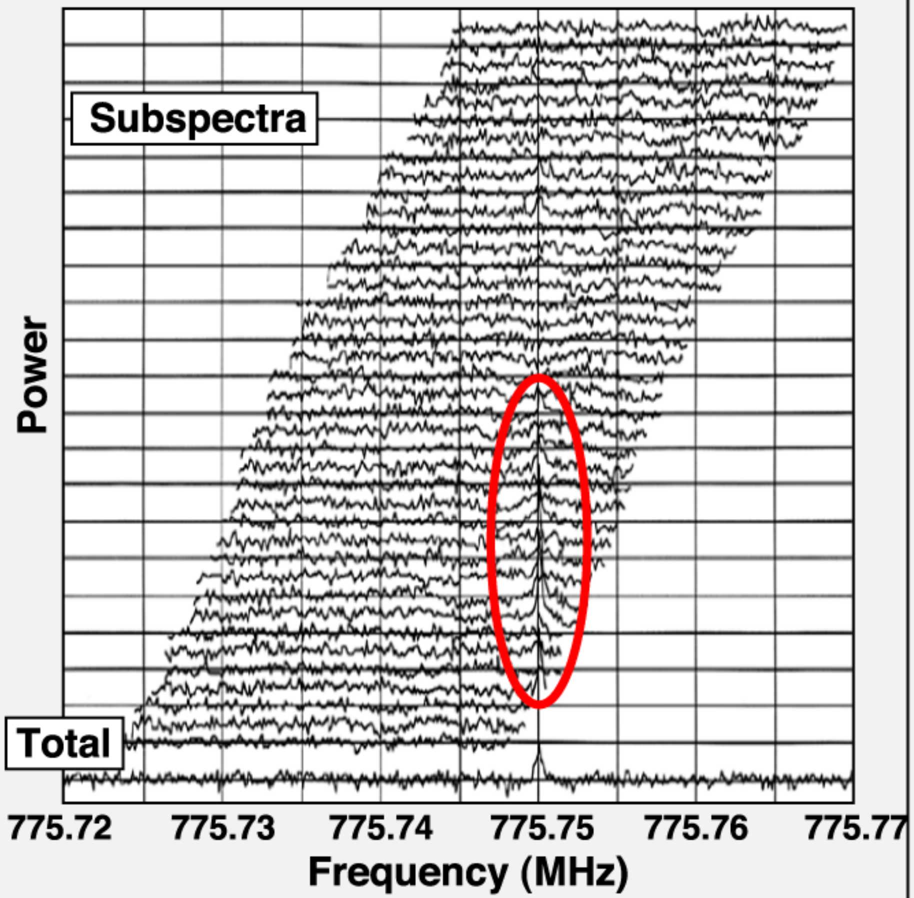
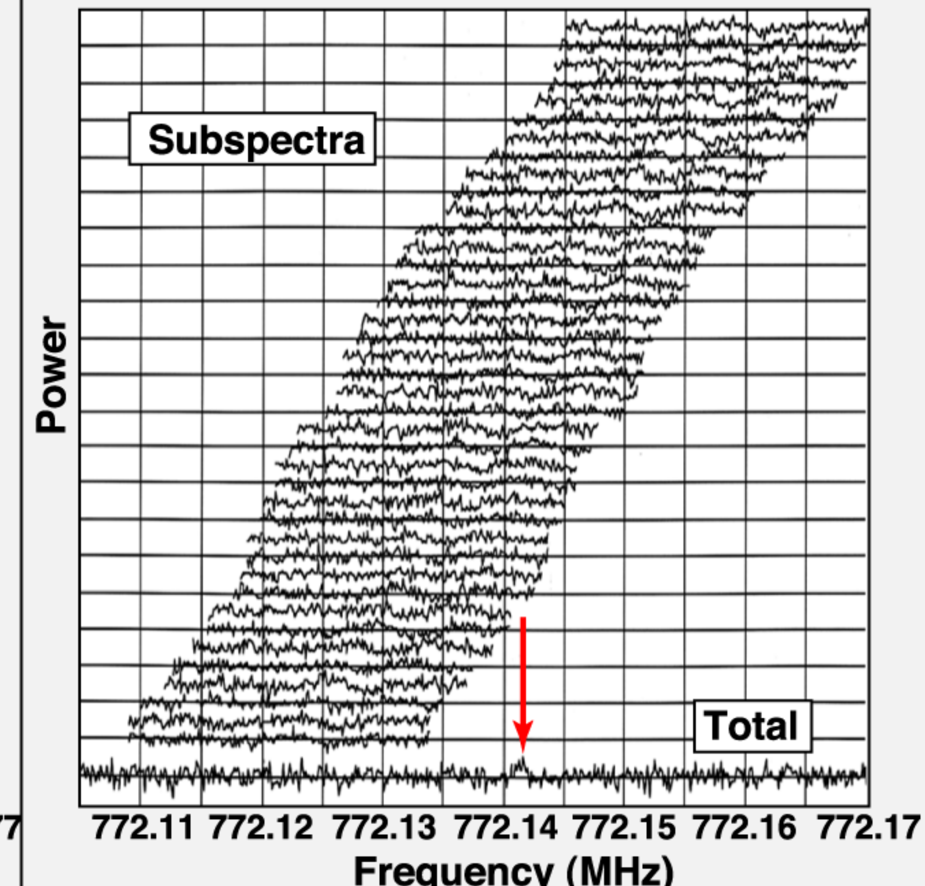
- Scan rate is trade off in sensitivity vs frequency (mass) coverage

- The scan rate uses a threshold sensitivity.

- Any candidate above threshold is flagged for further study.



Sample data and candidates

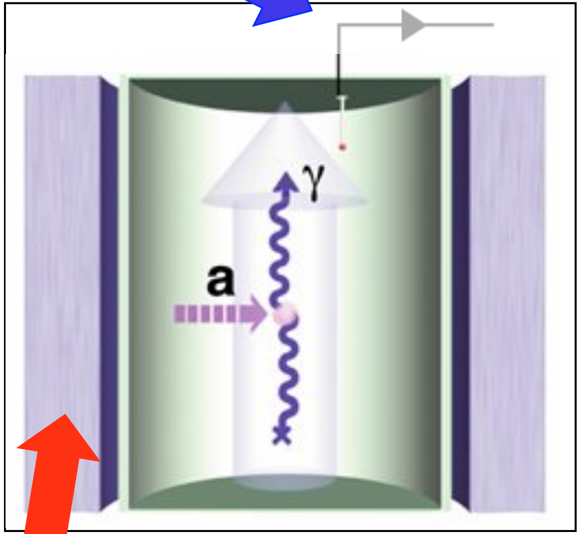
Environmental	Statistical
	
Signal maximizes off-resonance: Radio peak	Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)

The Radiometer equation dictates strategy

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

But integration time limited to ~ 100 sec

** Dicke, 1946*



System noise temp. now

$T_S = T + T_N \sim 1.5 + 1.5\ K$

But $T_{Quant} \sim 30\ mK$

This is where we invested to get to Gen 2

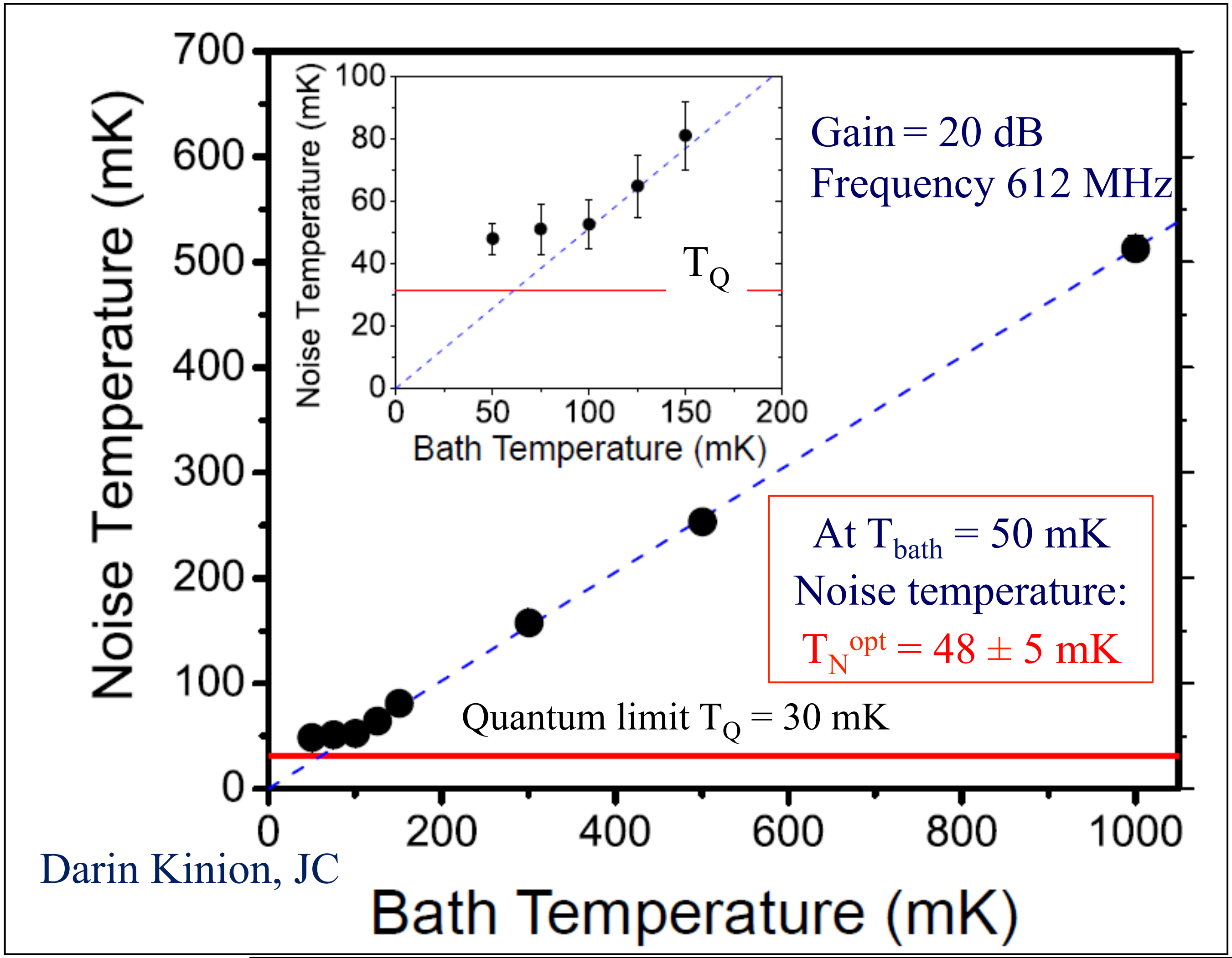
$$P_{sig} \sim (B^2V\, Q_{cav})(g^2 m_a \rho_a)$$

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

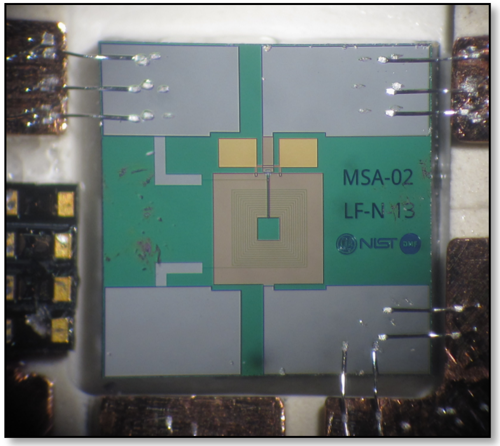
But magnet size, strength $B^2V \sim \$$

Enabling technology: Quantum-limited amplifiers

500-1000 MHz Microstrip SQUID Amp (MSA) Devices

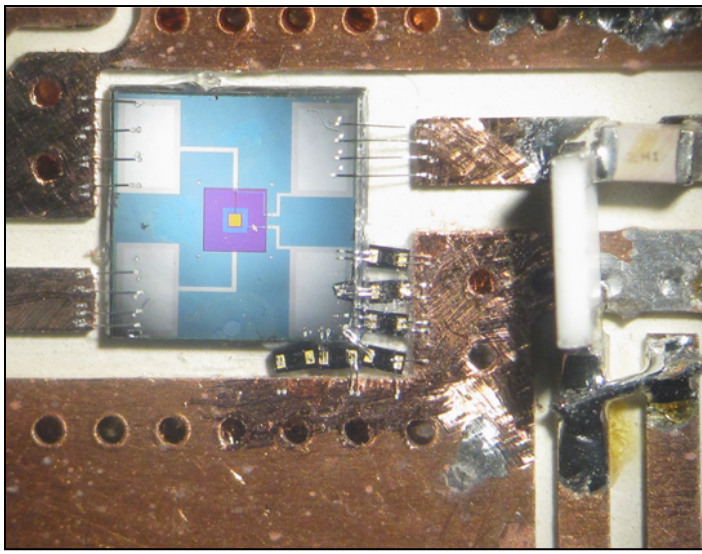


UCB produced
Prof. John Clarke

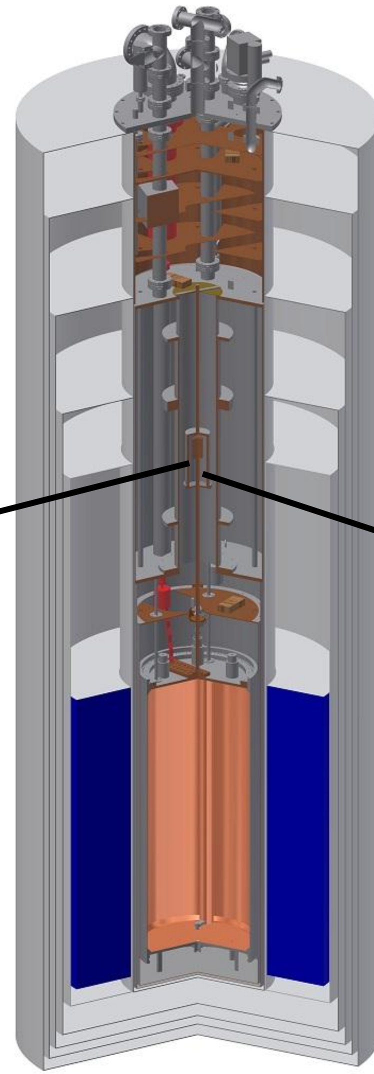


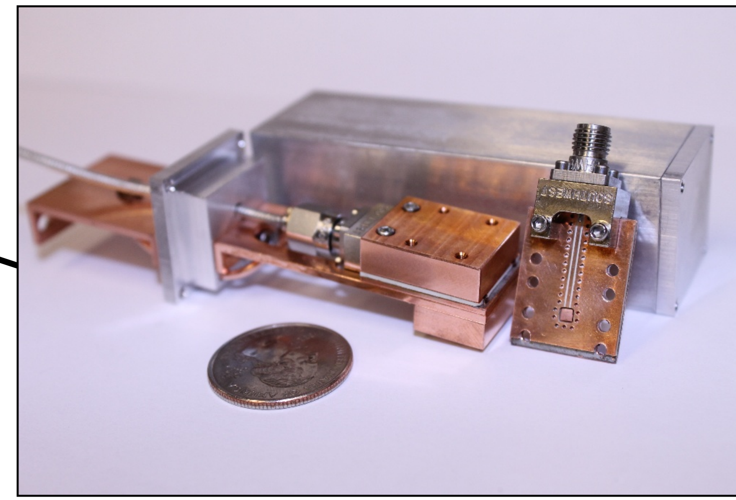
Noise temperatures of 48 ± 5 mK have been demonstrated at 612 MHz, within 1.7 times the quantum limit

Quantum Limited Amplifiers



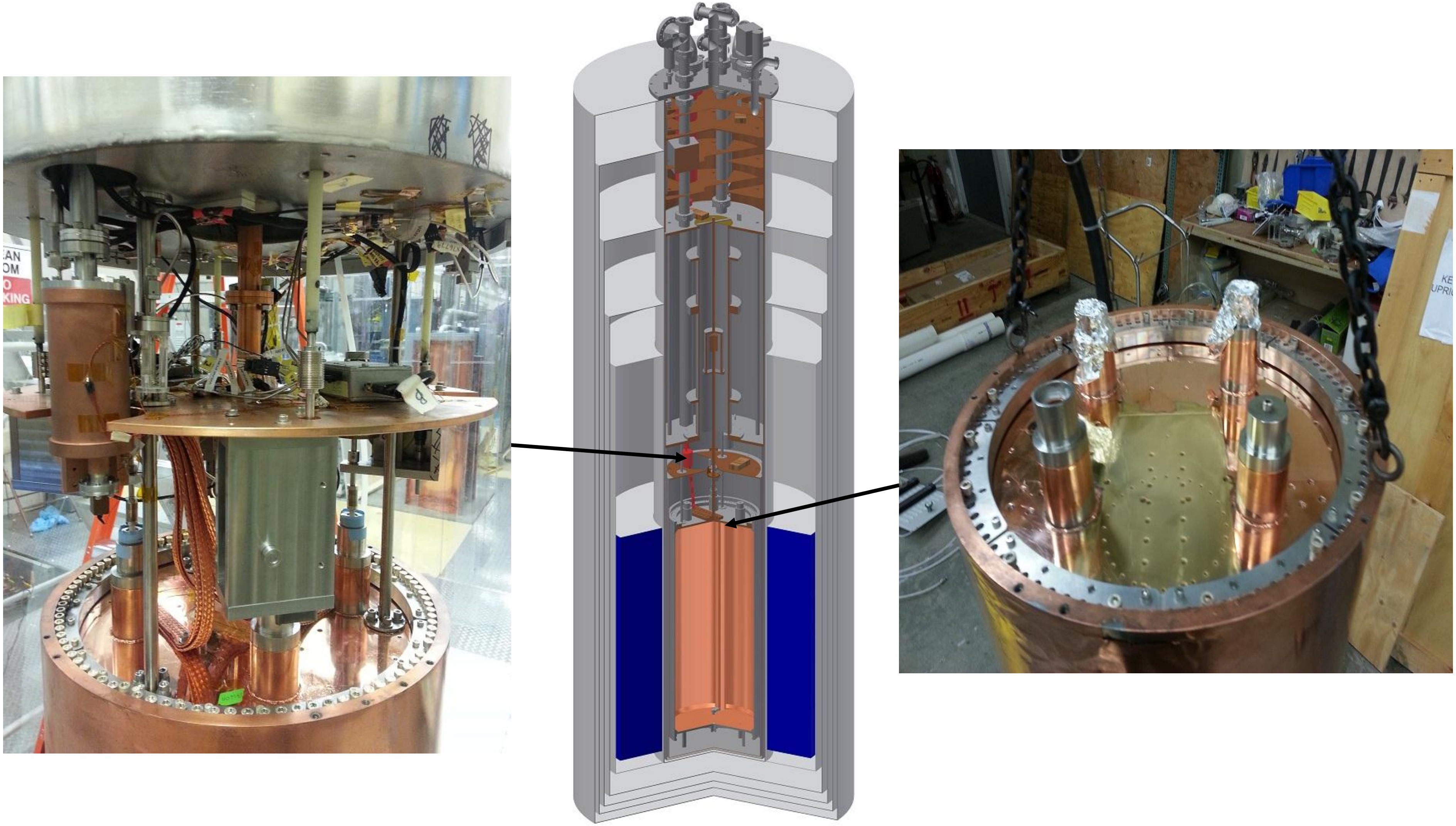
SQUIDs
(at lower frequencies)





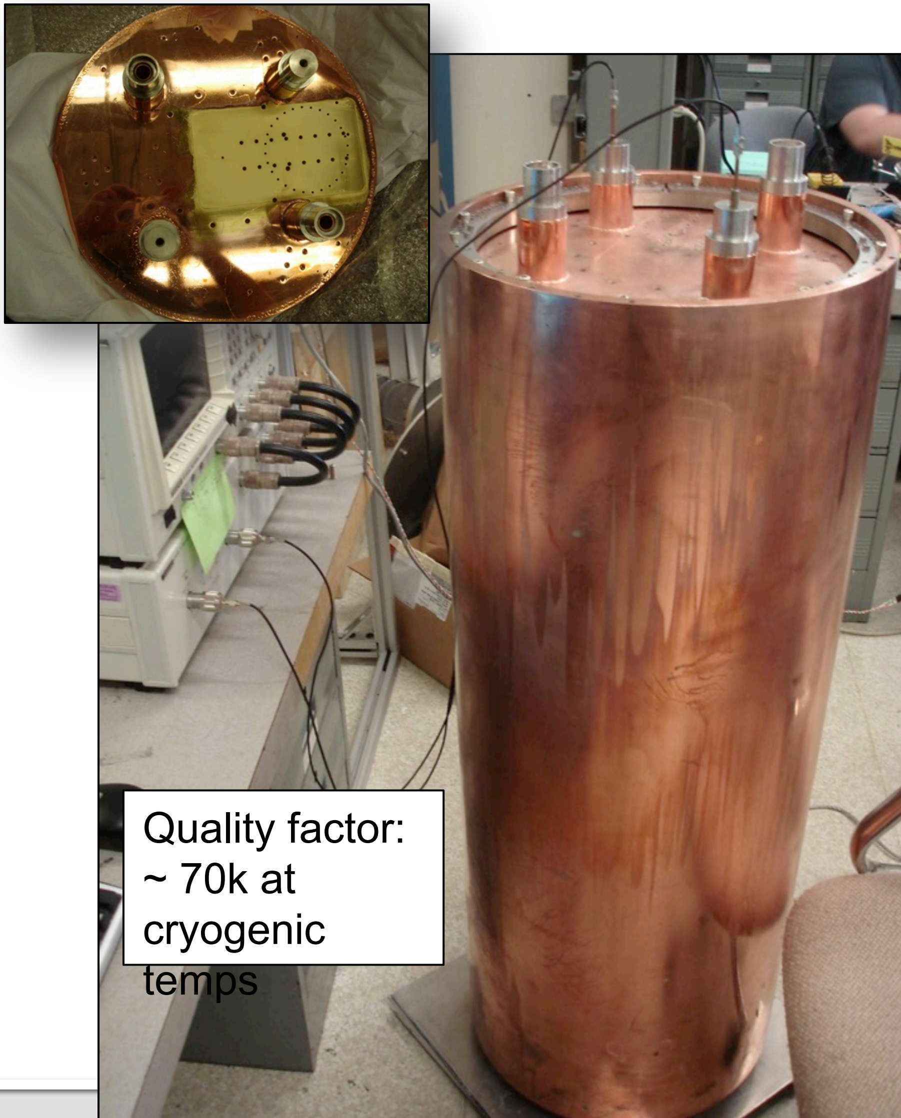
“JPAs”
(at higher frequencies)

Cavity and thermal shielding (4 K, 1 K, 100 mK)

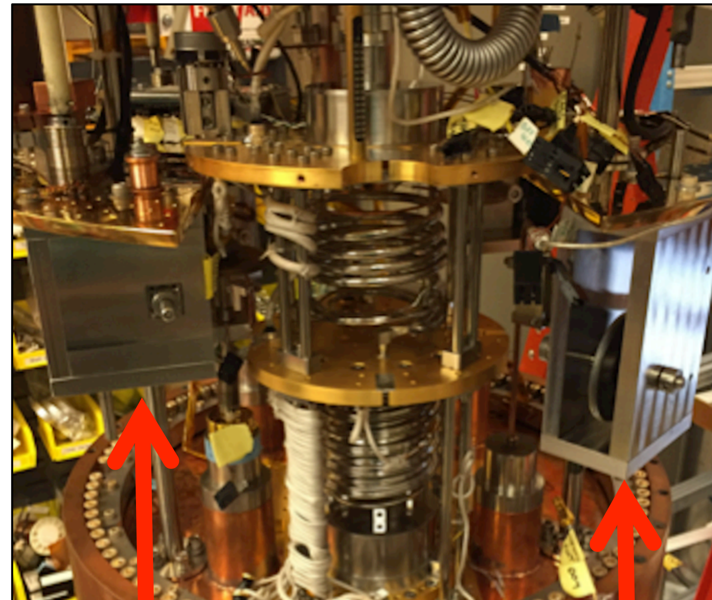


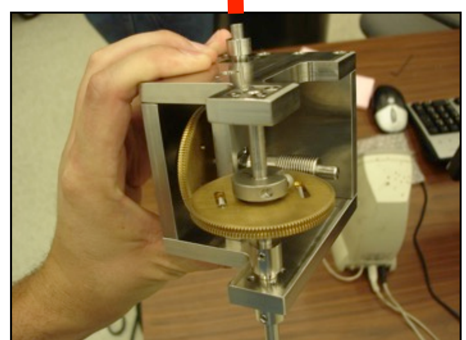
Currently installed Cavity & Motion Control

Dilution Fridge mounted directly to cavity top

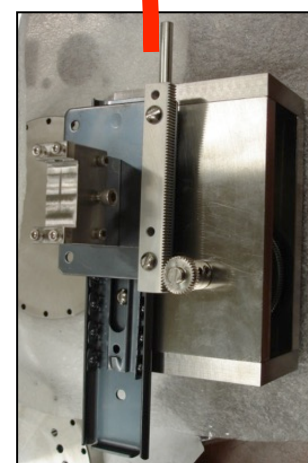


Quality factor: ~ 70k at cryogenic temps





Rotary gearbox
1:19,600 gear reduction

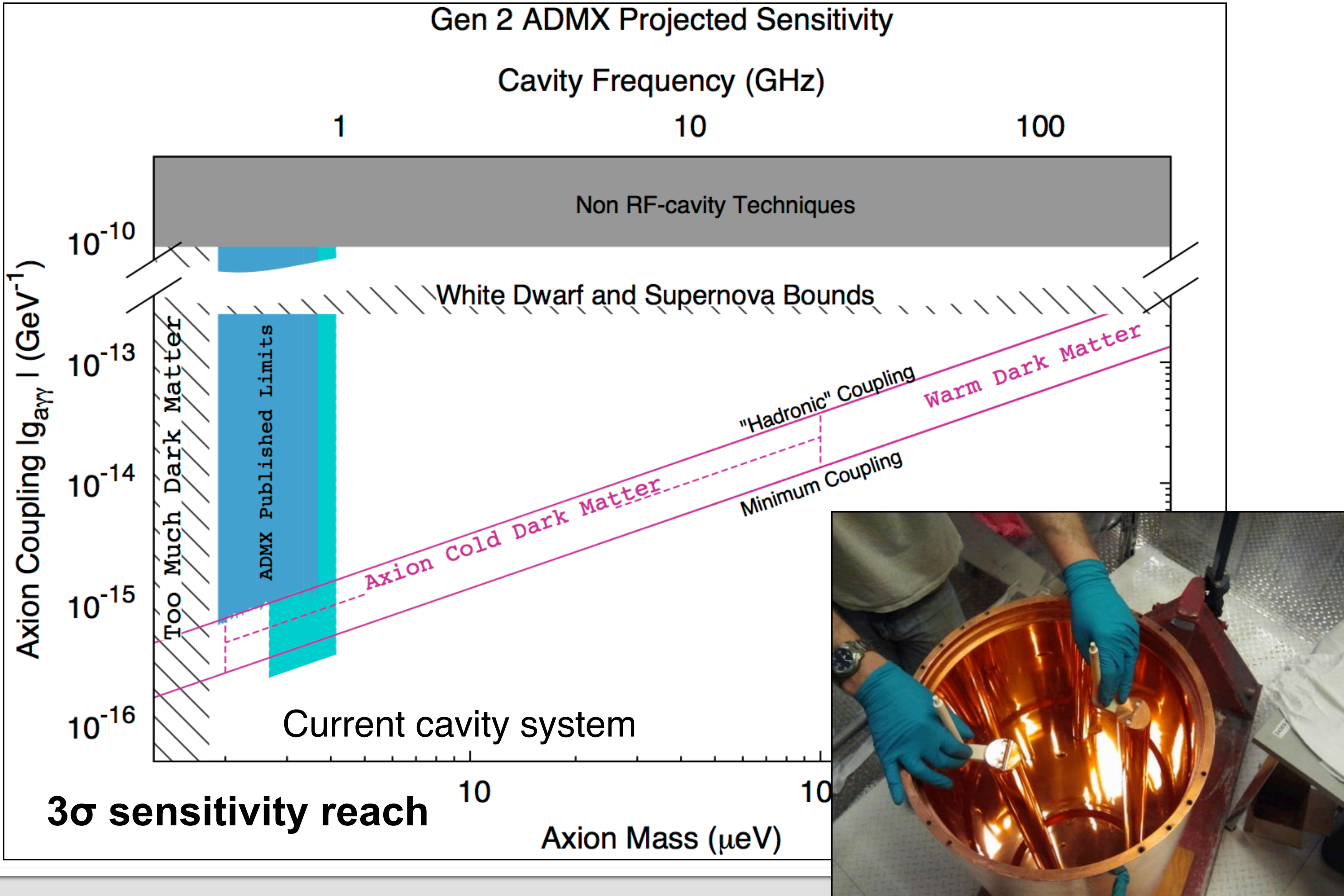


Linear gearbox (coupling)

ADMX currently operational

- Initial commissioning run at 200 mK between Aug 9th – Oct 3rd
  - No evidence of vibration heating from motion in field ✓
  - No evidence of cavity heating from motion control ✓
- Recent upgraded heat exchangers (now operating at 160 mK)
- Currently taking data at 660 MHz and at 7 Tesla

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



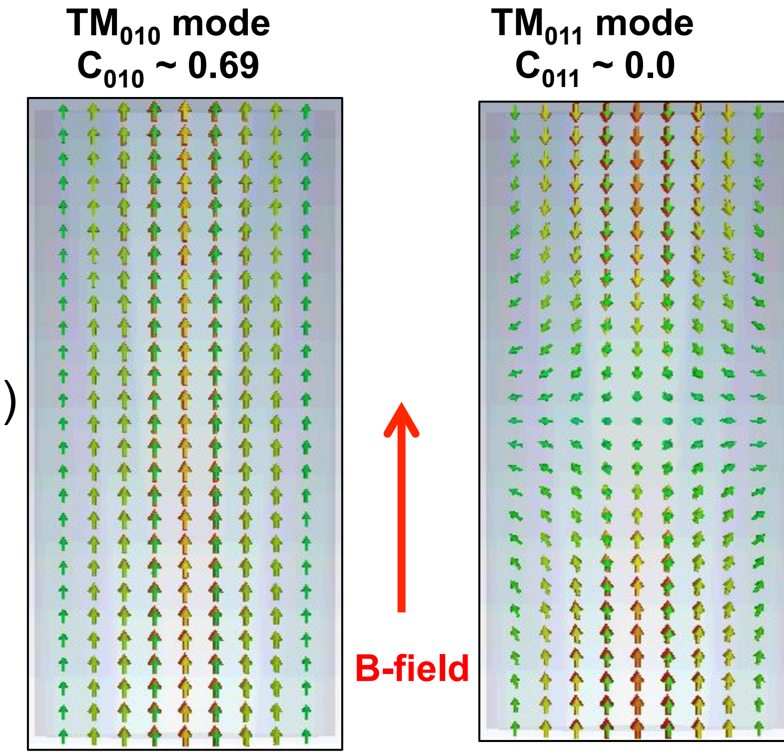
3σ sensitivity reach

Key Microwave Cavity Design Constraints

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

- Maximize product of $B^2 \cdot V \cdot Q_L \cdot C_{lmn}$ to maximize axion-to-photon conversion power
  - B^2V set by the magnet bore: $(8\text{T})^2 \cdot (\sim 100$ liters)
- Loaded Quality factor Q_L = frequency/bandwidth

  ($Q_L \sim 10^5$ for copper cavity ~1 GHz)
- Mode Form Factor C_{lmn}



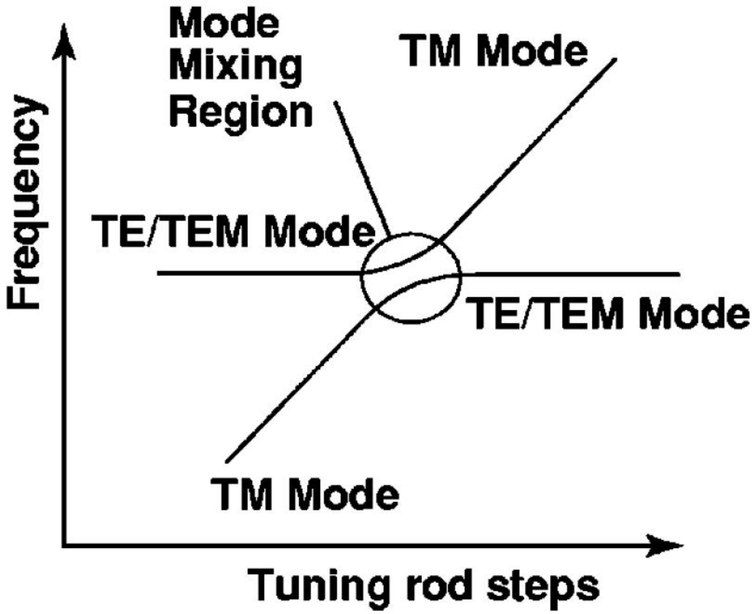
- Tunability: must be able to shift resonant frequency over an appreciable range (typically 30-50%)
- Ability to determine that you are on the mode that couples to axions (TM_{0n0})
- Precision & alignment tolerances (minimize spurious modes and mode crossings)

Managing mode-crossings

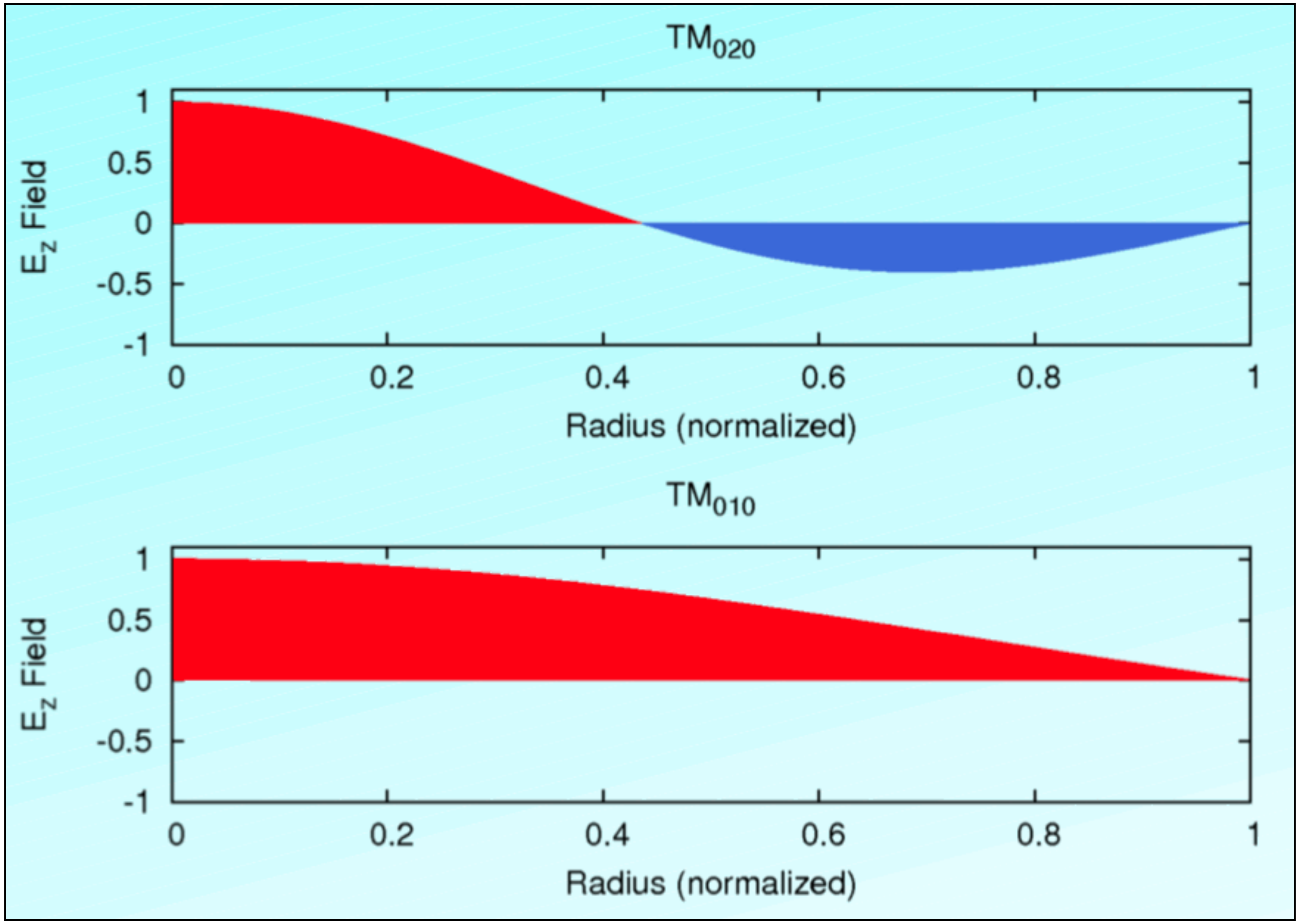
- Transverse Magnetic (TM) modes move up in frequency as tuning rods are rotated
- Transverse Electric (TE) modes remain relatively static in frequency.
- When both mode's frequencies are degenerate there's a "mode crossing" in which the two modes "mix" and the resonant peak can disappear.
- The longer the cavity, the more TE modes there a in the tuning range.

  Keep aspect ratios: *Length / radius* ~ 5.

- We step around mode crossings by using multiple tuning rods (metal and dielectric).



Possible to instrument higher order modes



TM_{020} Mode

Relative Frequency

2.3

Tuning Range

920-2,100 MHz

Relative Power

0.41

TM_{010} Mode

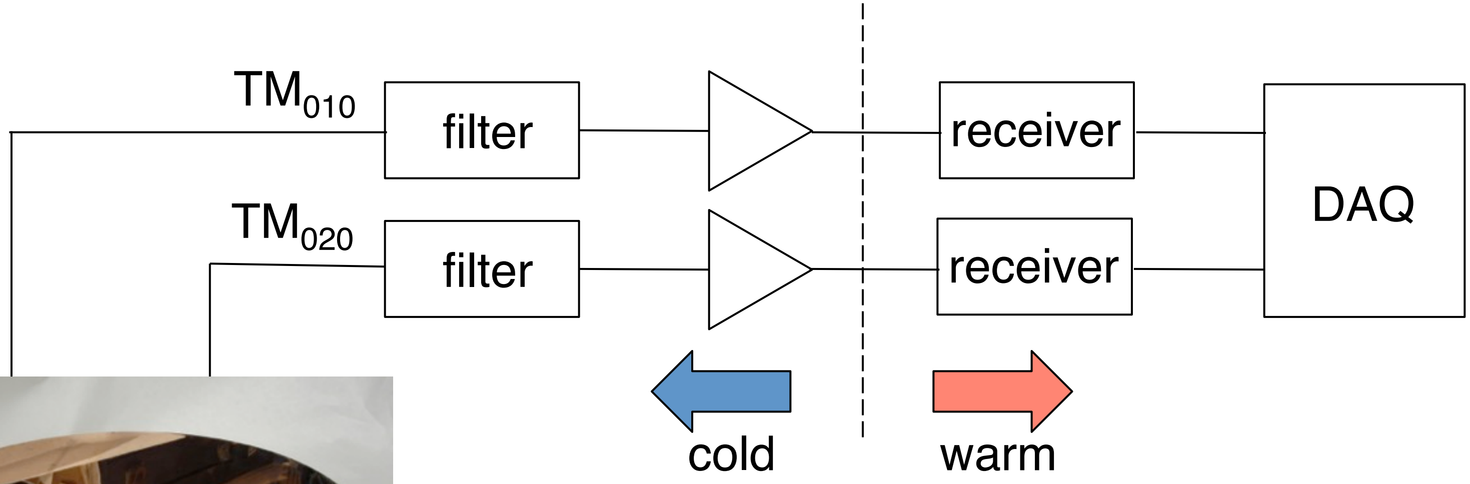
Relative Frequency

1.0

Tuning Range

400-900 MHz

ADMX: Multi-mode readout



Ch 1: Instrumented with MSA amp & low pass filter (DFSZ sensitivity)

Ch 2: Instrumented with JPA amp & high pass filter (~KSVZ sensitivity)

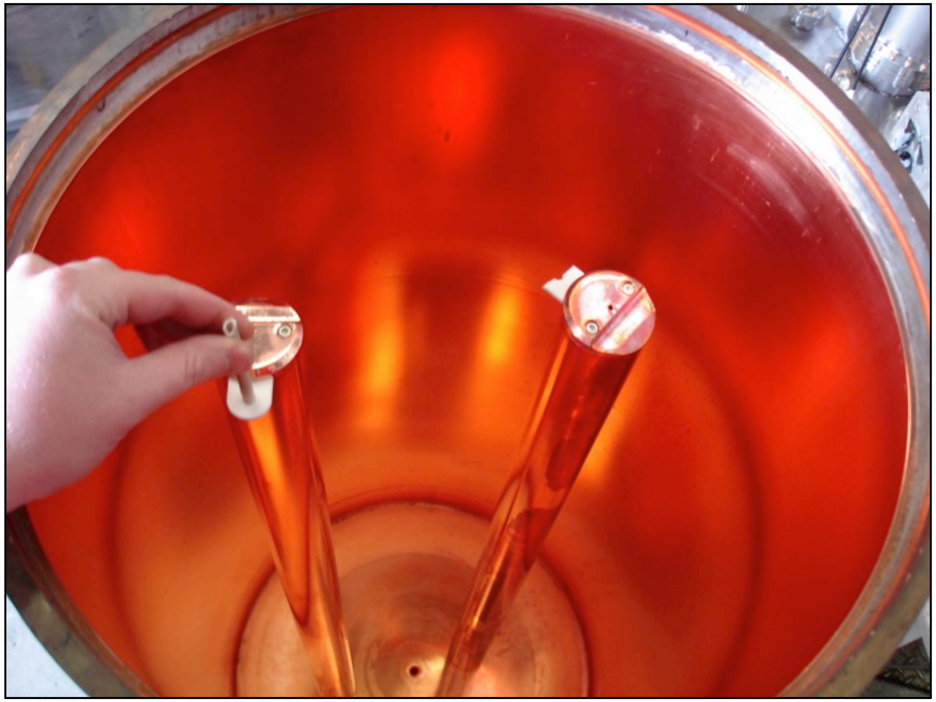
Challenging due to more complicated mode structure.

Cryogenic filters are non-trivial components (provided by NRAO)

Challenge of higher frequency axion searches

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

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

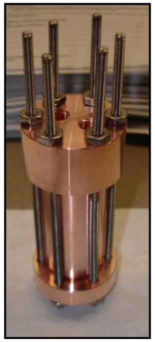


16" diameter

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

5" diameter

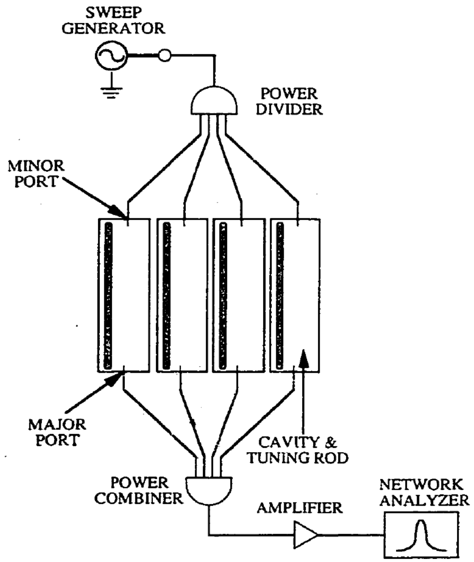
Frequency ~ 10 GHz
Axion Mass ~ 36 μeV
Q_L – 25,000
Volume – 0.025 liters



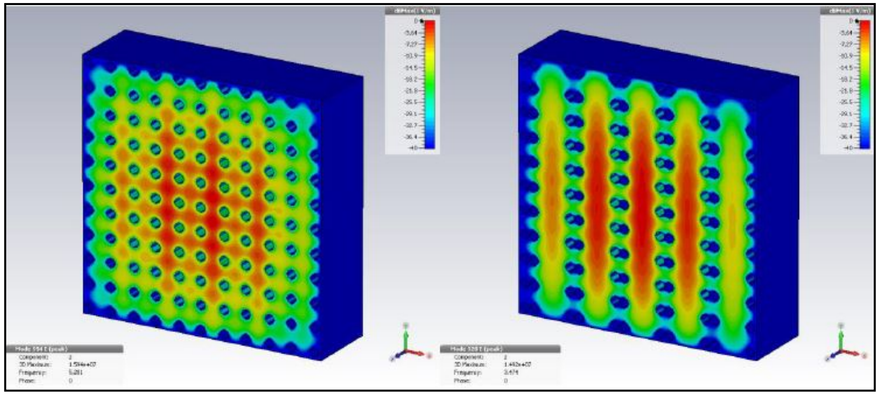
1" diameter

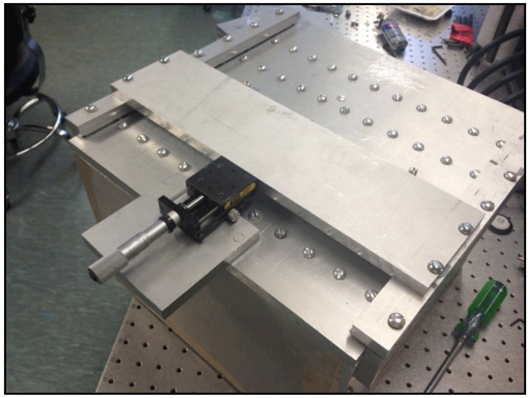
R&D work underway to expand usable volume

- .



Multicavity Array's



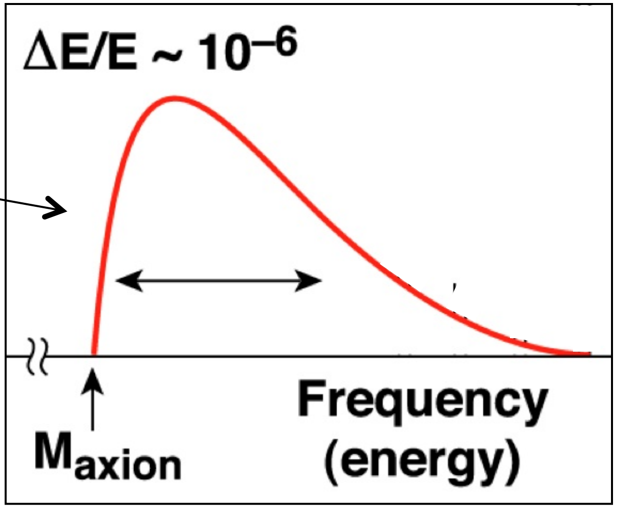


Photonic Bandgap Cavities

Increasing Q of the cavity is also important.

$$P_{axion} \sim B^2V \bullet \min(Q_a, Q_L) \bullet (g_\gamma)^2 \rho_a m_a$$

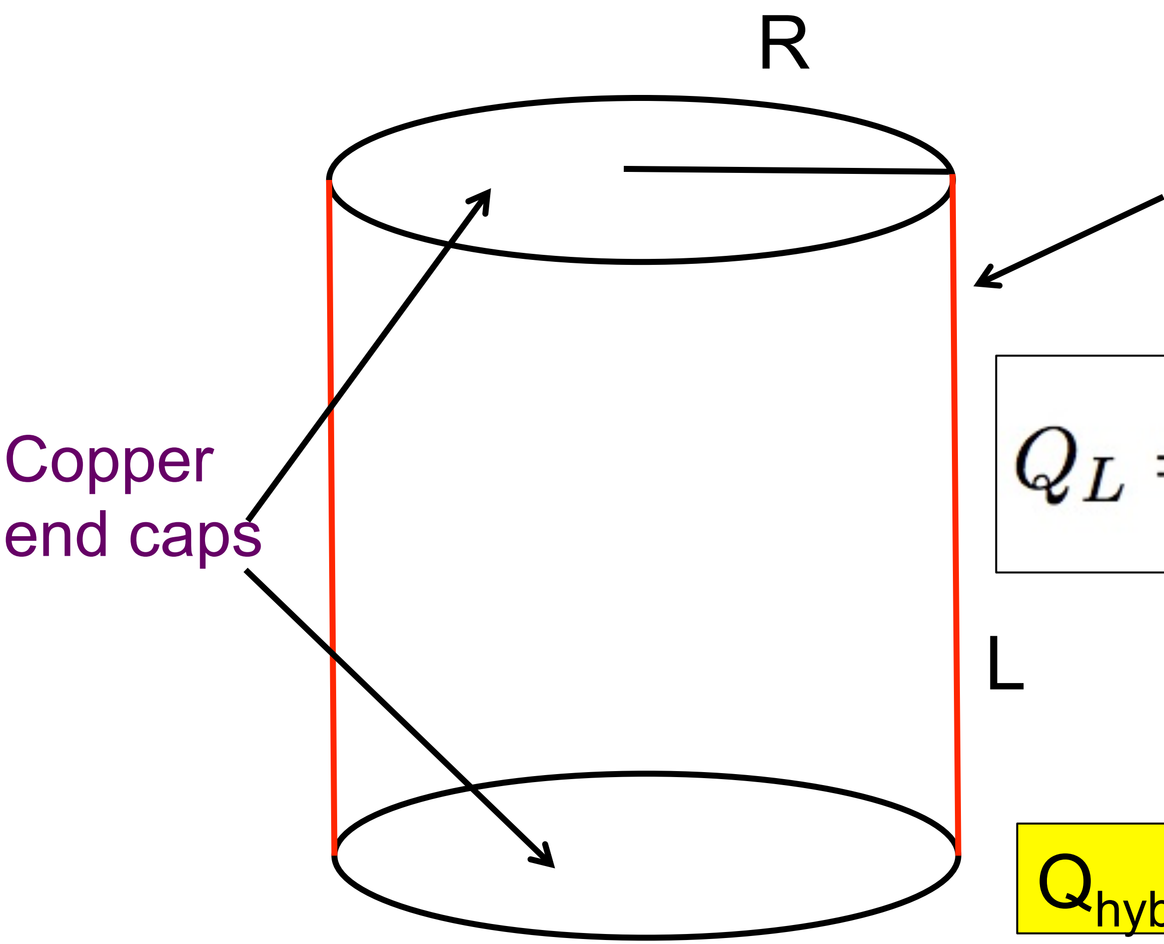
Q_a = axion linewidth (gravitational thermalization)
$\sim E/\Delta E \sim 1/\beta^2 \sim 1/(100\ km/s)^2 \sim 10^6$
1 GHz mass axion should be spread over 1 kHz



Q_L ~ loaded cavity quality factor
~ resonant f / bandwidth
~ 10^5 for copper cavity at 1 GHz

Increasing Q_L to Q_a will increase your sensitivity

The "Hybrid" superconducting cavity concept



$$Q_L = \frac{L/R}{1 + L/R} \cdot \frac{R}{\delta}$$

Skin depth of Copper

$$Q_{hybrid} = (1+L/R) \cdot Q_{Cu}$$

For typical ADMX cavity L/R ~ 5 giving Q enhancement of 6

Conclusion

- The dark matter axion is a very compelling dark matter candidate.
- Experiments are finally getting sensitive enough to reach plausible dark matter axion model space.
- Lots of technical challenges remain to efficiently cover the rest of the parameter space… hence this workshop.

A Big Thank You the Heising-Simons Foundation, LLNL, DOE and NSF for supporting these efforts (and this workshop)!