The Hunt for Dark Matter Axions

Lawrence Berkeley National Laboratory
Physics Seminar

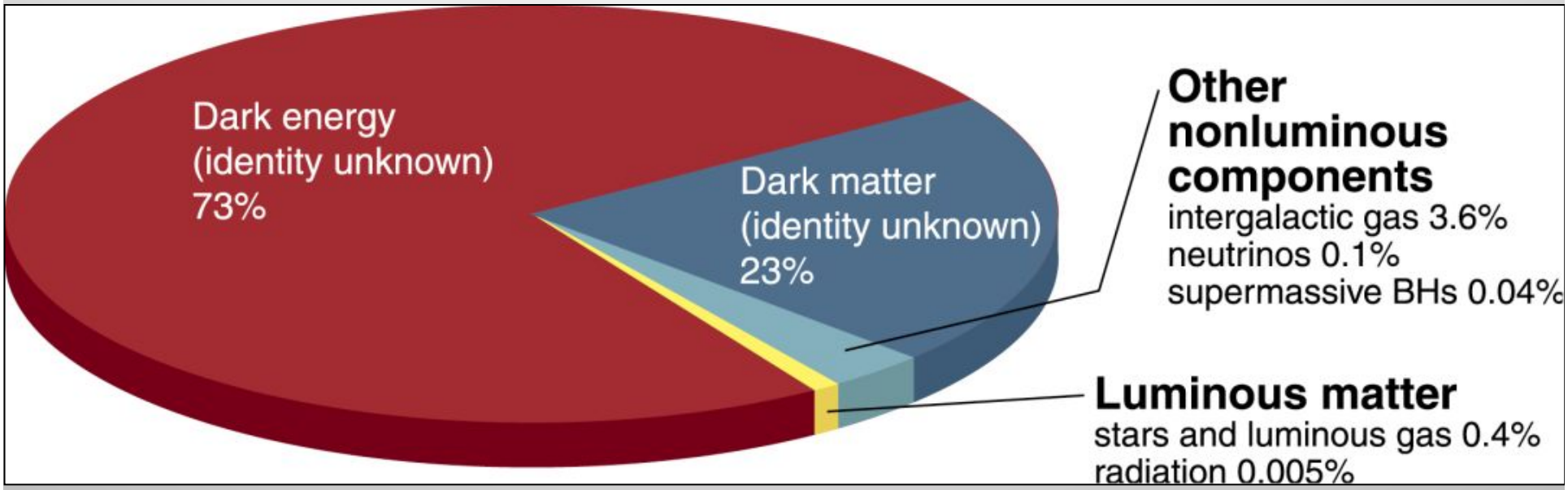
Nov 20th, 2014

Gianpaolo Carosi

Lawrence Livermore National Laboratory

LLNL-PRES-663817
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

We don't know what Dark matter or Dark Energy is!

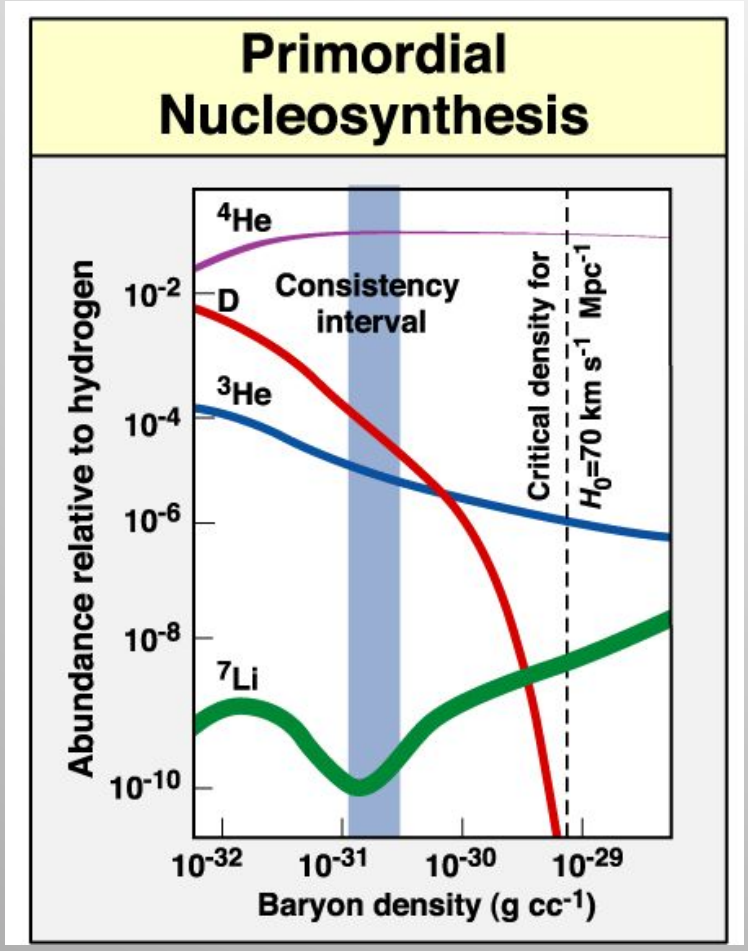


A particle relic from the Big Bang is strongly implied for DM

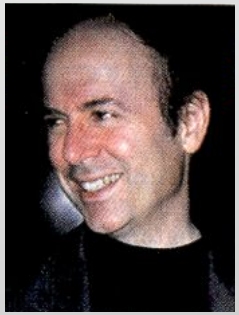
- **WIMPs ?**
- **Axions ?**

What do we know about the nature of dark matter? Its not normal matter or radiation and it's "cold"

(1) From light element abundance:
Dark matter probably isn't bowling balls or anything else made of baryons.



(2) Is dark matter made of, e.g., light neutrinos?
Probably not: fast moving neutrinos would have washed-out structure.
Dark matter is substantially "cold".



(3) "Dark matter: I'm much more optimistic about the dark matter problem. Here we have the unusual situation that two good ideas exist…"

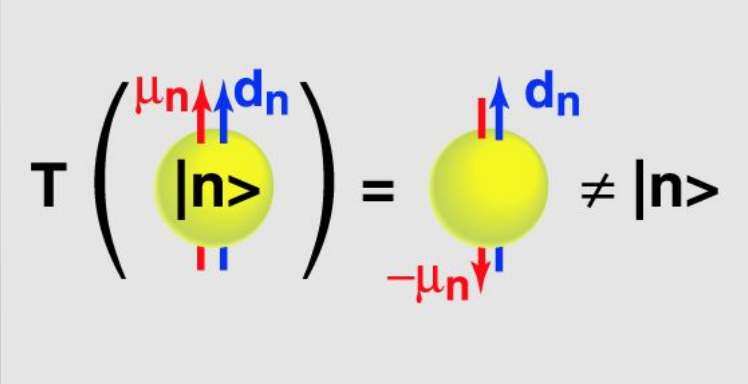
Frank Wilczek in Physics Today

Frank's referring to WIMPS and Axions

* L. Rosenberg – Princeton Seminar Oct 2014

Peccei and Quinn:
CP conserved through a hidden symmetry

QCD CP violation should, e.g., give a large neutron electric dipole moment ($\not{T}$ + CPT = $\not{CP}$); none is unobserved.
(9 orders-of-magnitude discrepancy)



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

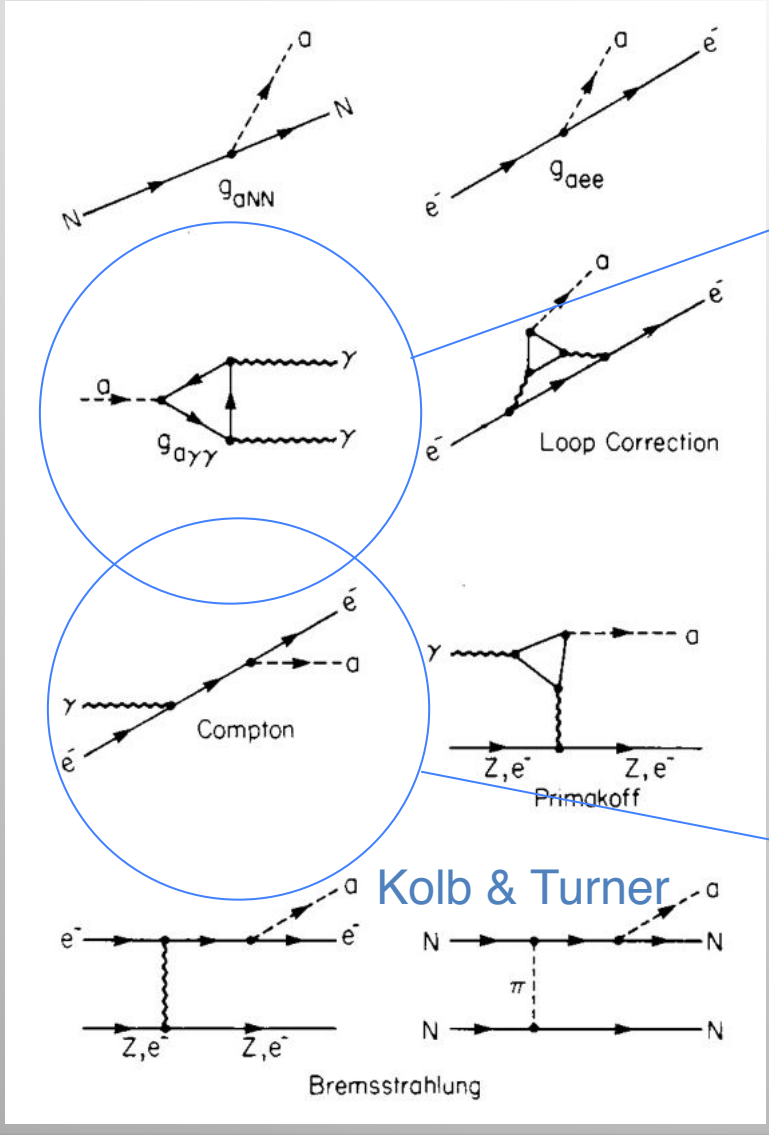
$d_e < 3 \cdot 10^{-26}$ e-cm
Baker et al. 2006

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.

What's an axion?

Selected axion couplings & the important two-photon coupling



A process with small model uncertainty
Exploited in certain terrestrial searches
Easily calculable

Rate depends on "unification group"
(that is, the particles in the loops),
ratio of u/d quark masses,
and mostly f_{PQ}

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

A process with large model uncertainty
Can occur, e.g., in the Sun
Contains unknown $U(1)_{PQ}$ charge of electron

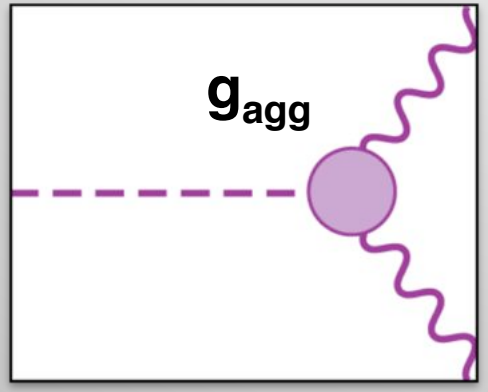
* L. Rosenberg – Princeton Talk Oct 2014

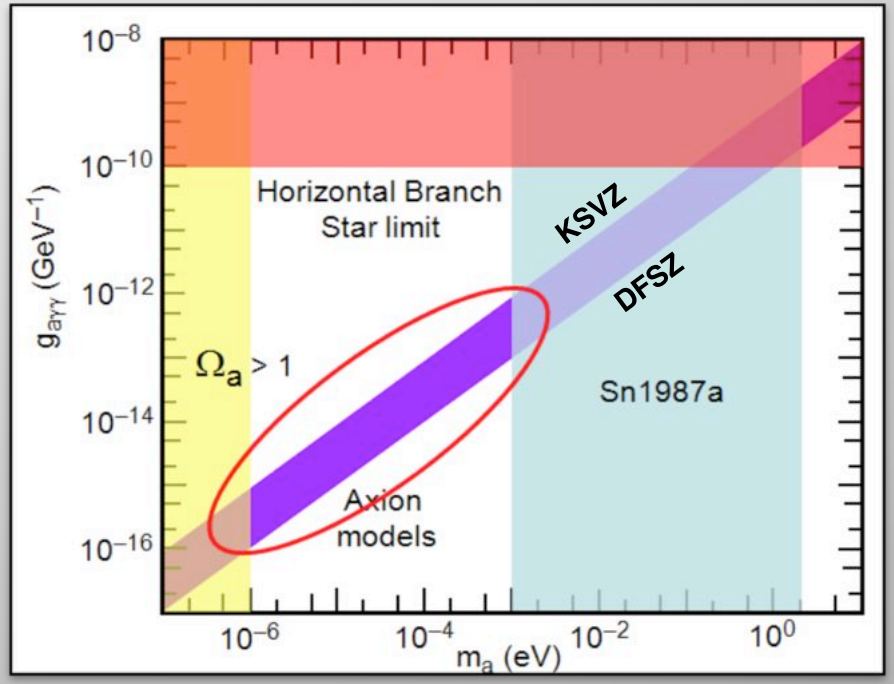
The axion.

It comes from the "Pecci-Quinn solution" to enforce strong-CP

It's a pseudoscalar (p°-like), extremely light and weakly coupled

2g coupling (Primakoff effect) : Key to possible detection



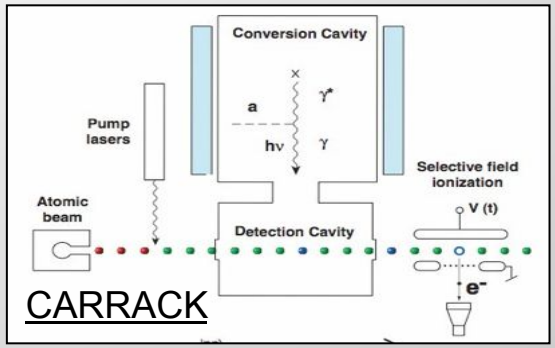


The axion remains a very attractive dark-matter candidate (affirmed by HEPAP, DMSAG, etc.)

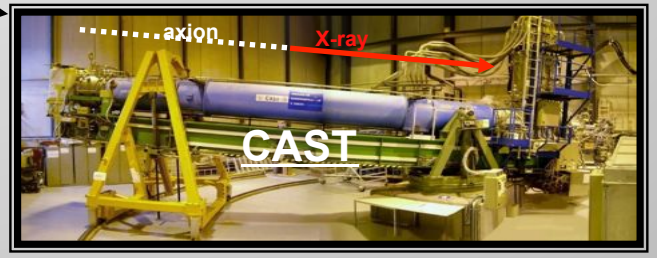
The ADMX axion search is "definitive" and relatively inexpensive

Variety of experiments*…

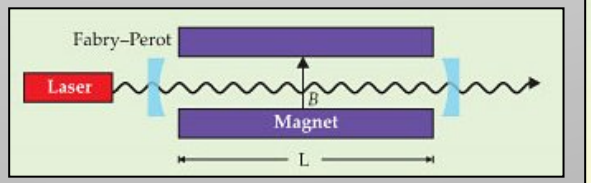
- **Microwave Cavities**
  - Low noise amplifiers (**ADMX**) and Rubidium Atoms (**CARRACK**)
    - Look for dark matter axions (low mass) converting to photons in B-Field
    - **Will focus today on ADMX project.**

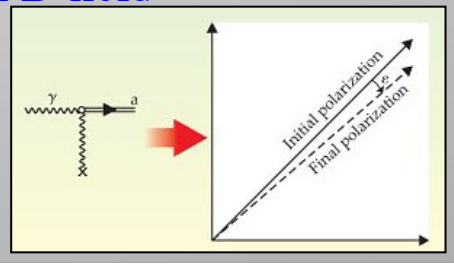


- Solar Observatories
  - X-Ray (**CAST**) and Germanium detectors
    - Look for axions generated from the sun
    - Higher coupling required than for DM axions.



- Lab experiments
  - Photon regeneration and polarization changes (**PVLAS**)
    - Look for production of axions from light passing through B-field
    - Higher coupling required.





***See August 2010 Physics Today for experimental overview**

Axion Dark Matter eXperiment (ADMX) and ADMX-High Frequency collaboration

Lawrence Livermore National Laboratory – ADMX began here in the mid-1990s.

Gianpaolo Carosi, Darrell Carter, Jaime Ruz Armendariz

University of Washington – main experiment moved here in 2010.

Leslie Rosenberg, Gray Rybka, Michael Hotz, Andrew Wagner, Doug Will, Dmitry Lyapustin, Christian Boutan

University of Florida

David Tanner, Pierre Sikivie, Neil Sullivan, Jeff Hoskins, Jungseek Hwang, Catlin Martin, Ian Stern

National Radio Astronomy Observatory

Richard Bradley

University of California, Berkeley

Karl van Bibber,Tim Shokair, John Clarke, Jaben Root, John Norton, Ben Clemens, Austin Lo

Sheffield University

Edward Daw

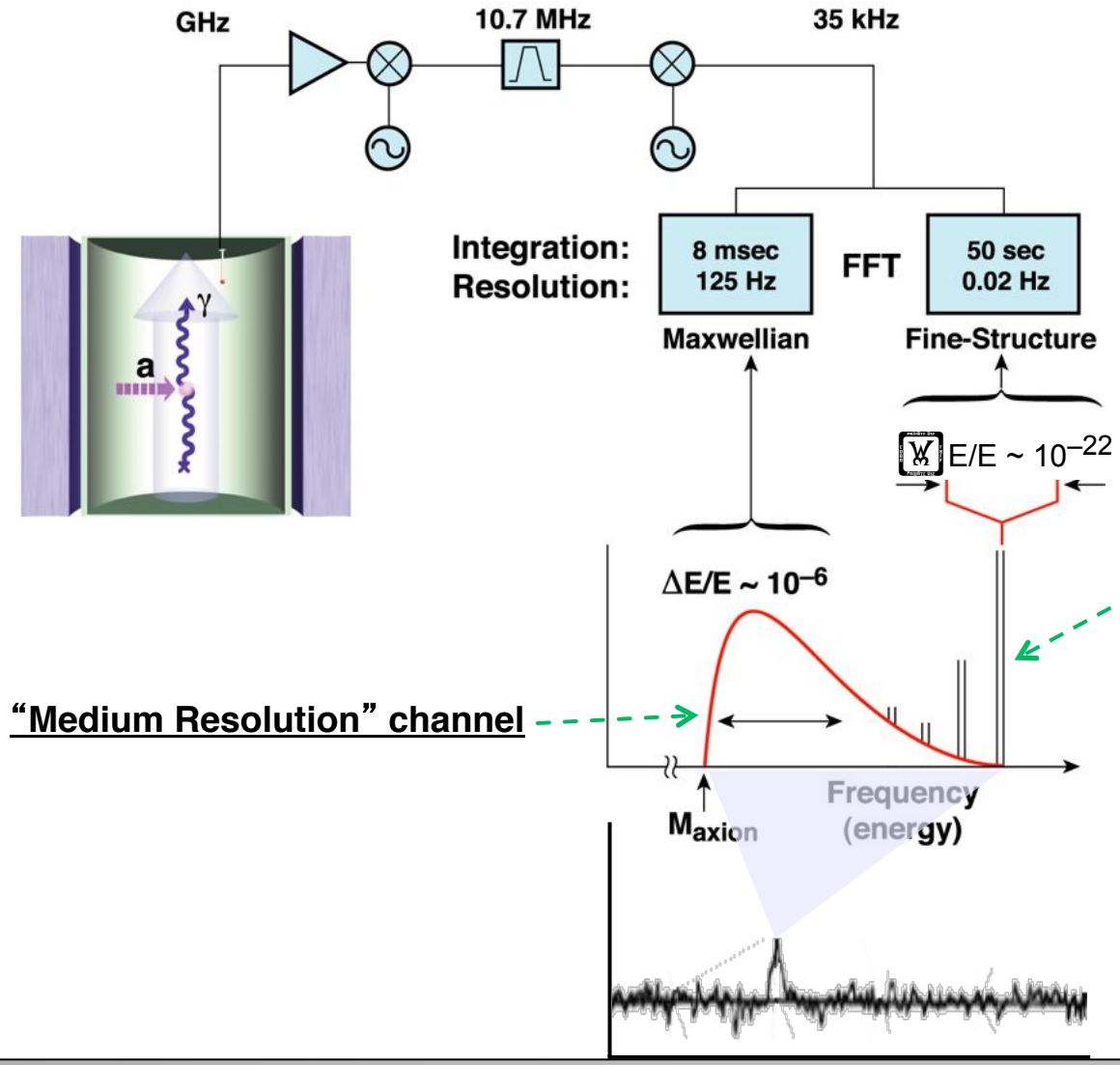
Yale University (ADMX-HF - NSF sponsored)

Steve Lamoreaux, Yulia Gurevich, Ben Brubaker, Sidney Cahn

University of Colorado (ADMX-HF – NSF sponsored)

Konrad Lenhert, Memhet Ali

The Axion Dark Matter eXperiment (original concept from P. Sikivie)



"Medium Resolution" channel

Local Milky Way density:

ρ_{halo} ~ *450 MeV/cm^3*

Thus for m_a ~ 10 eV:

ρ_{halo} ~ *10^{14} cm^{-3}*

"High Resolution" channel

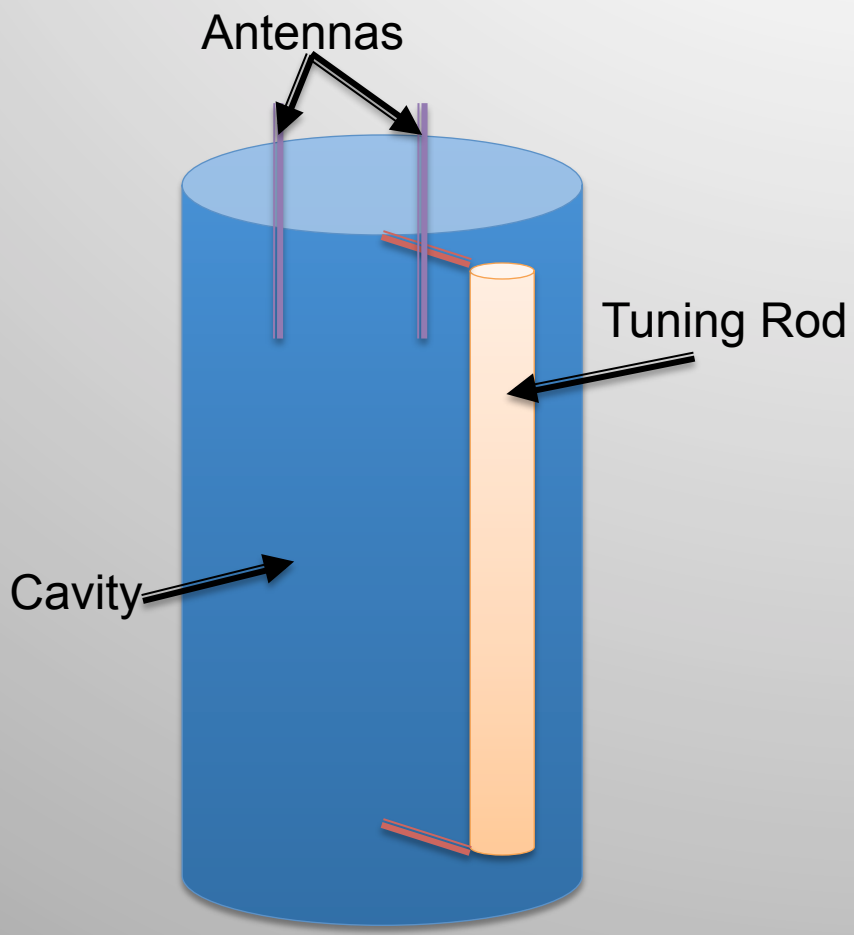
v_{virial} ~ 10^{-3} :

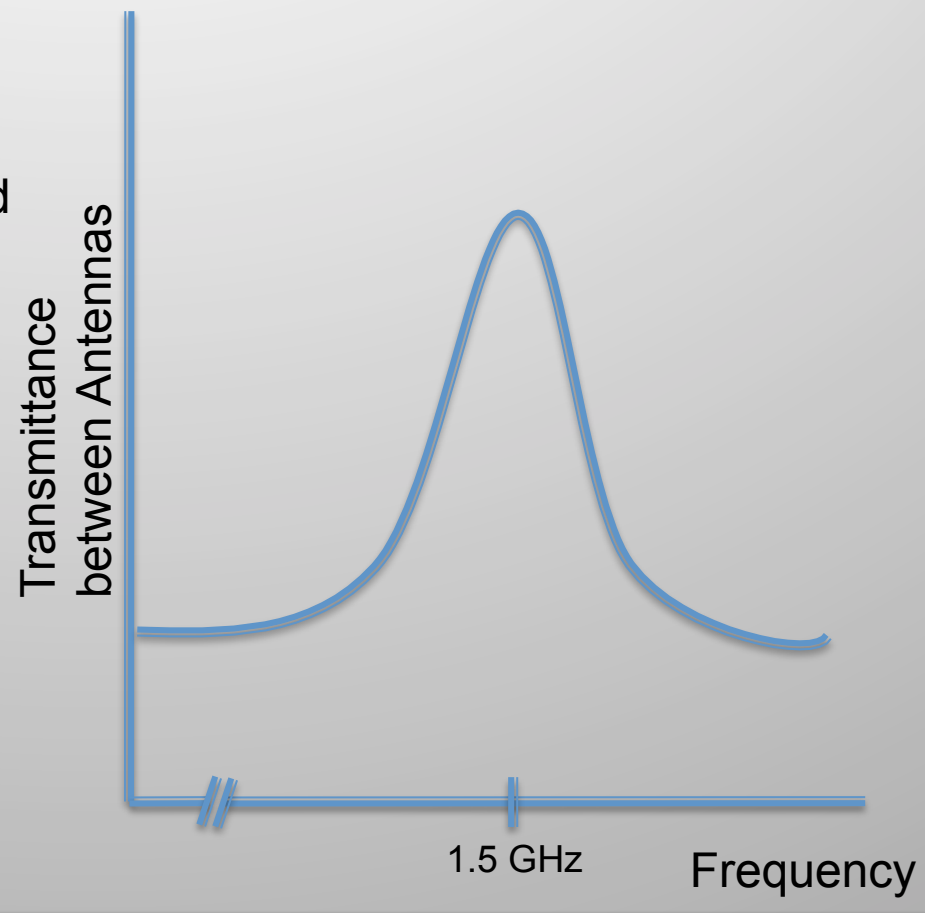
$\lambda_{De\ Broglie}$ ~ *100 m*

v_{flow} ~ 10^{-11} :

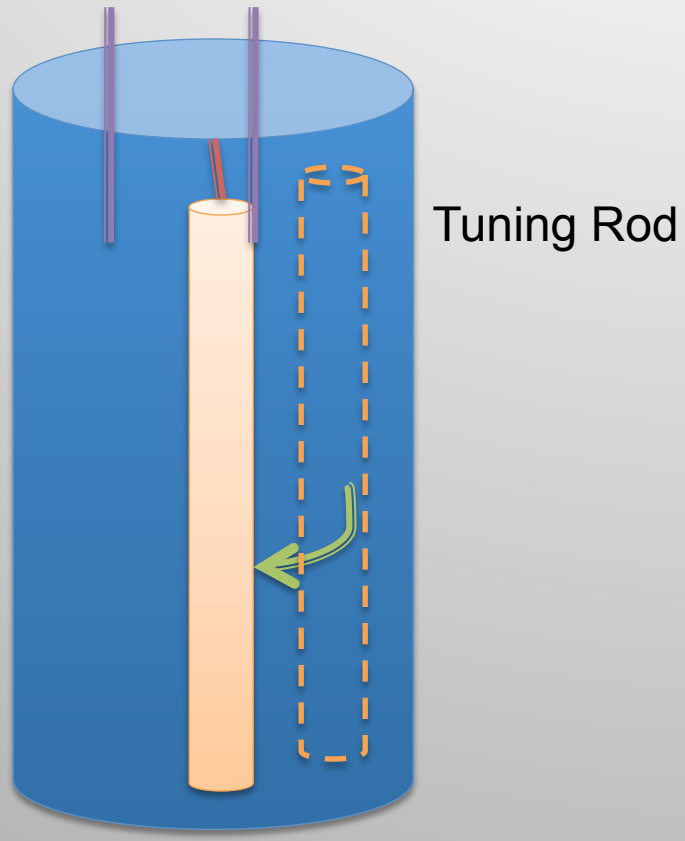
$\lambda_{Coherence}$ ~ *1000 km*

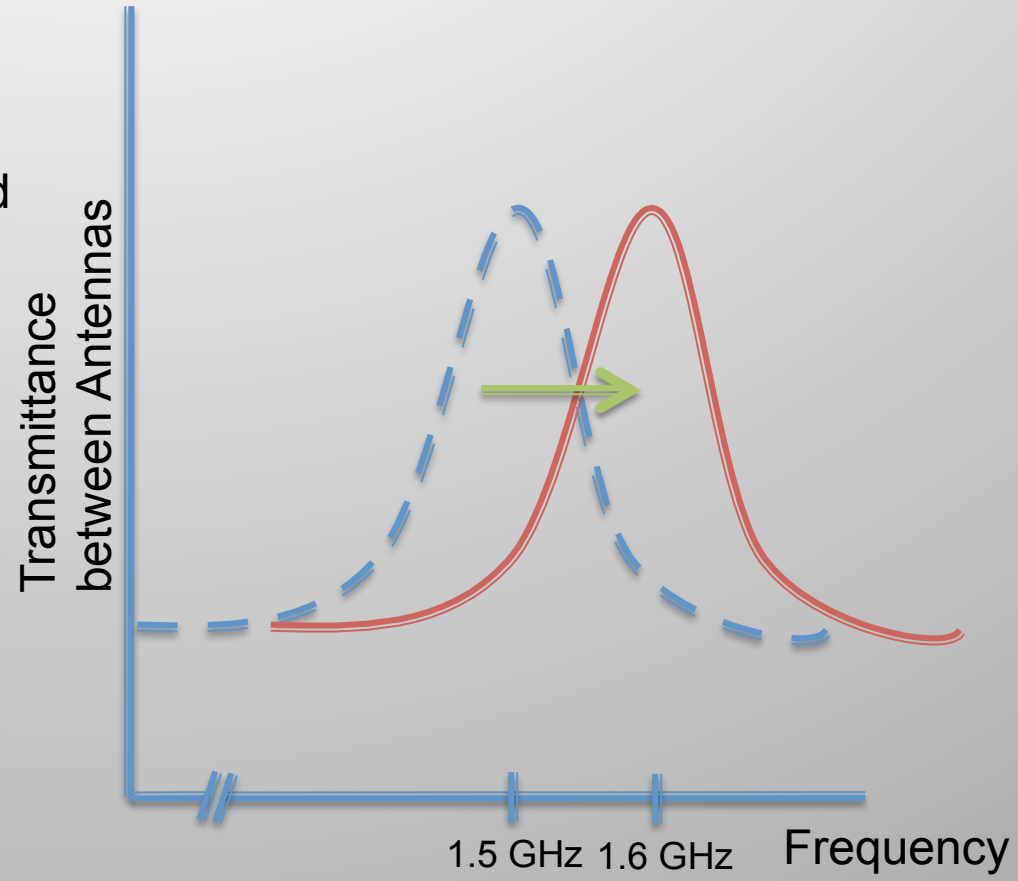
More about the Microwave Cavity

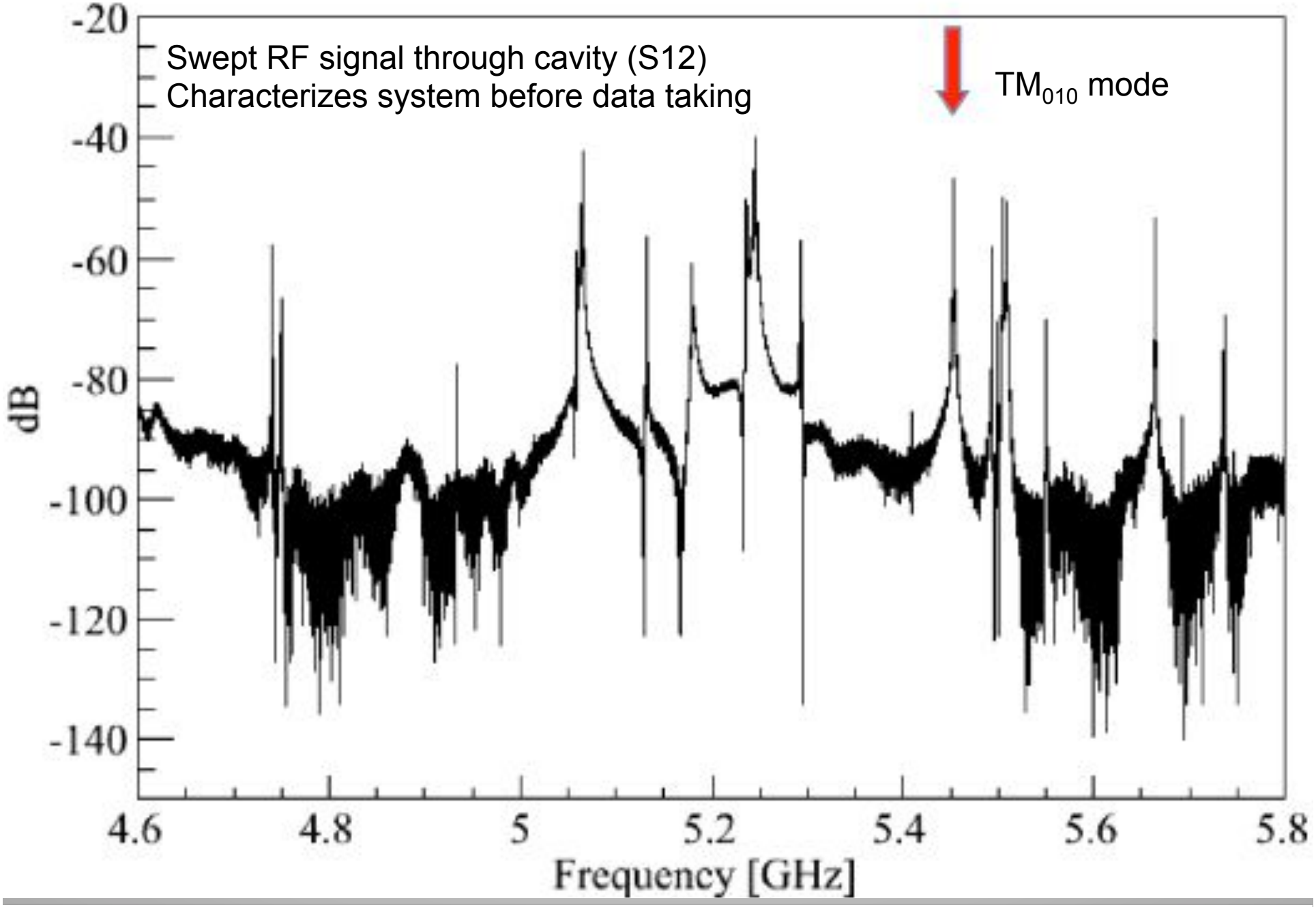


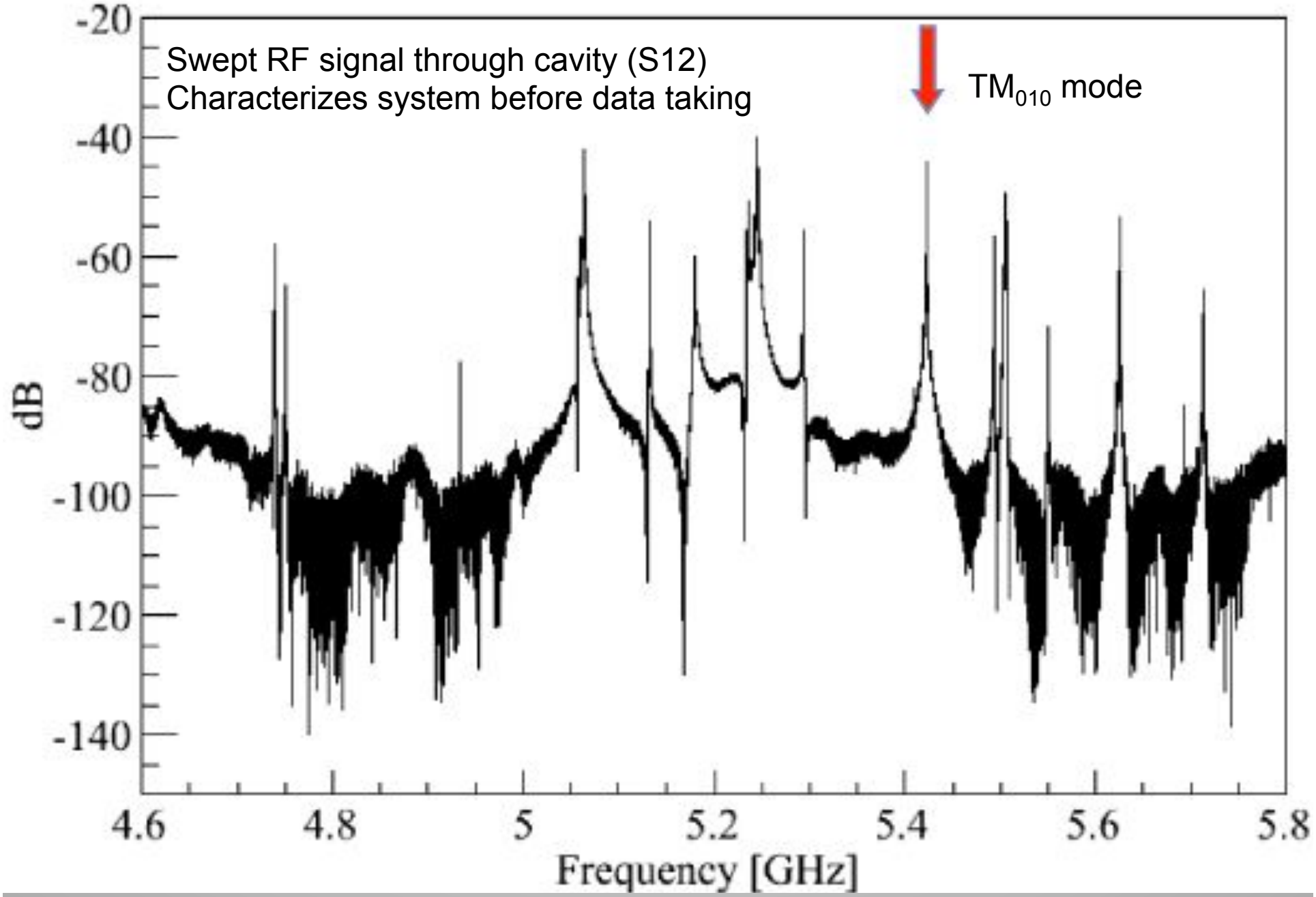


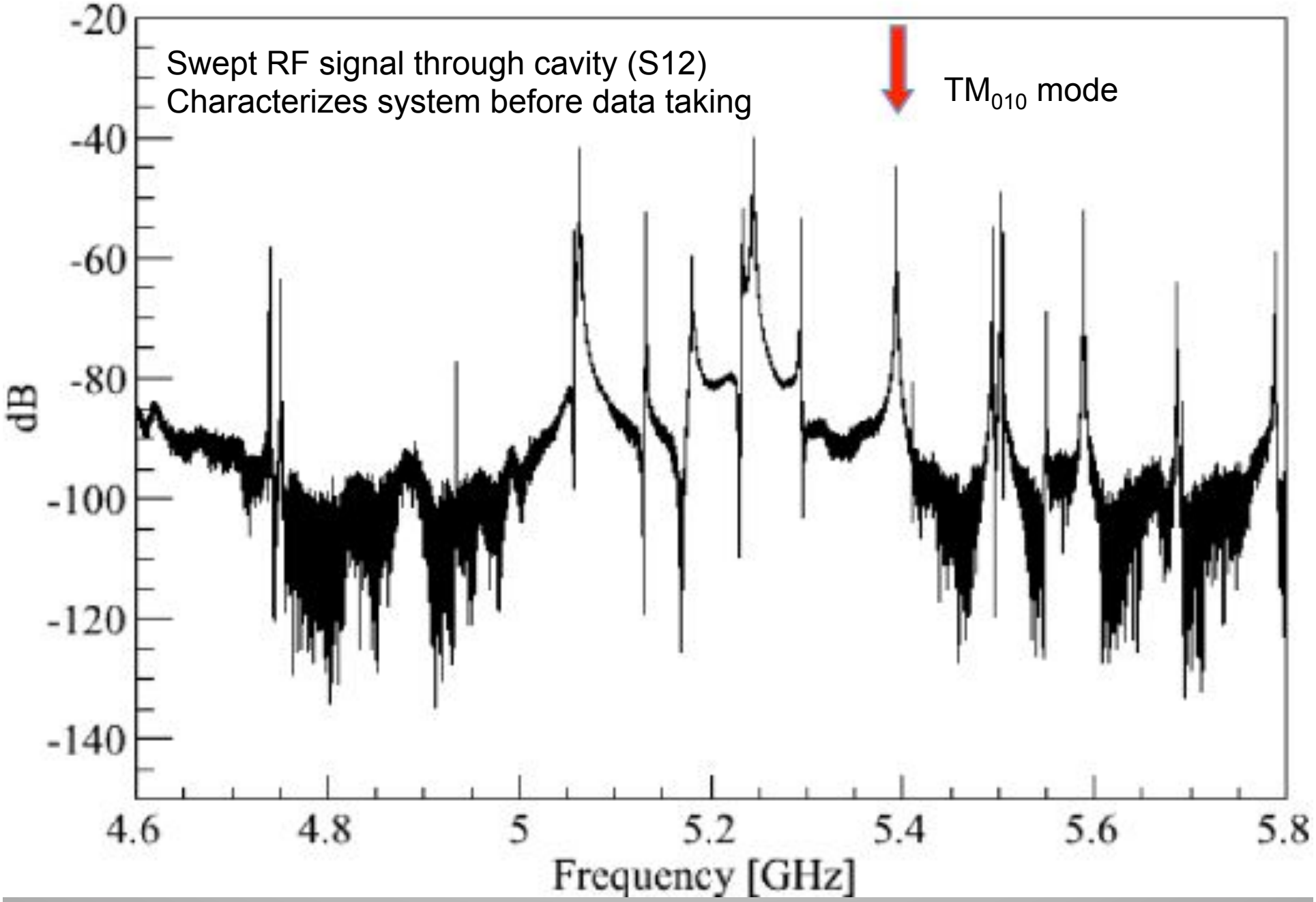
More about the Microwave Cavity

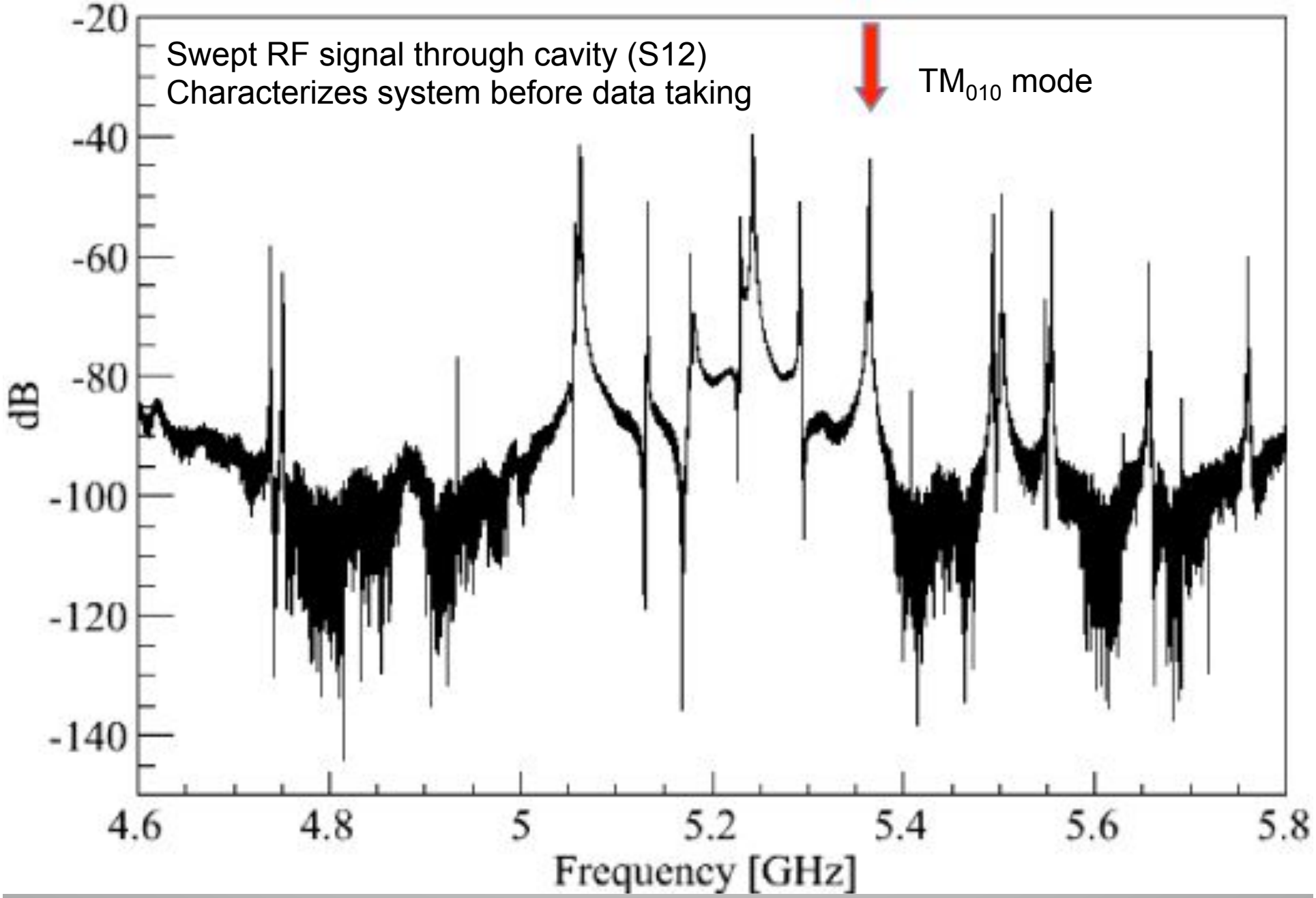


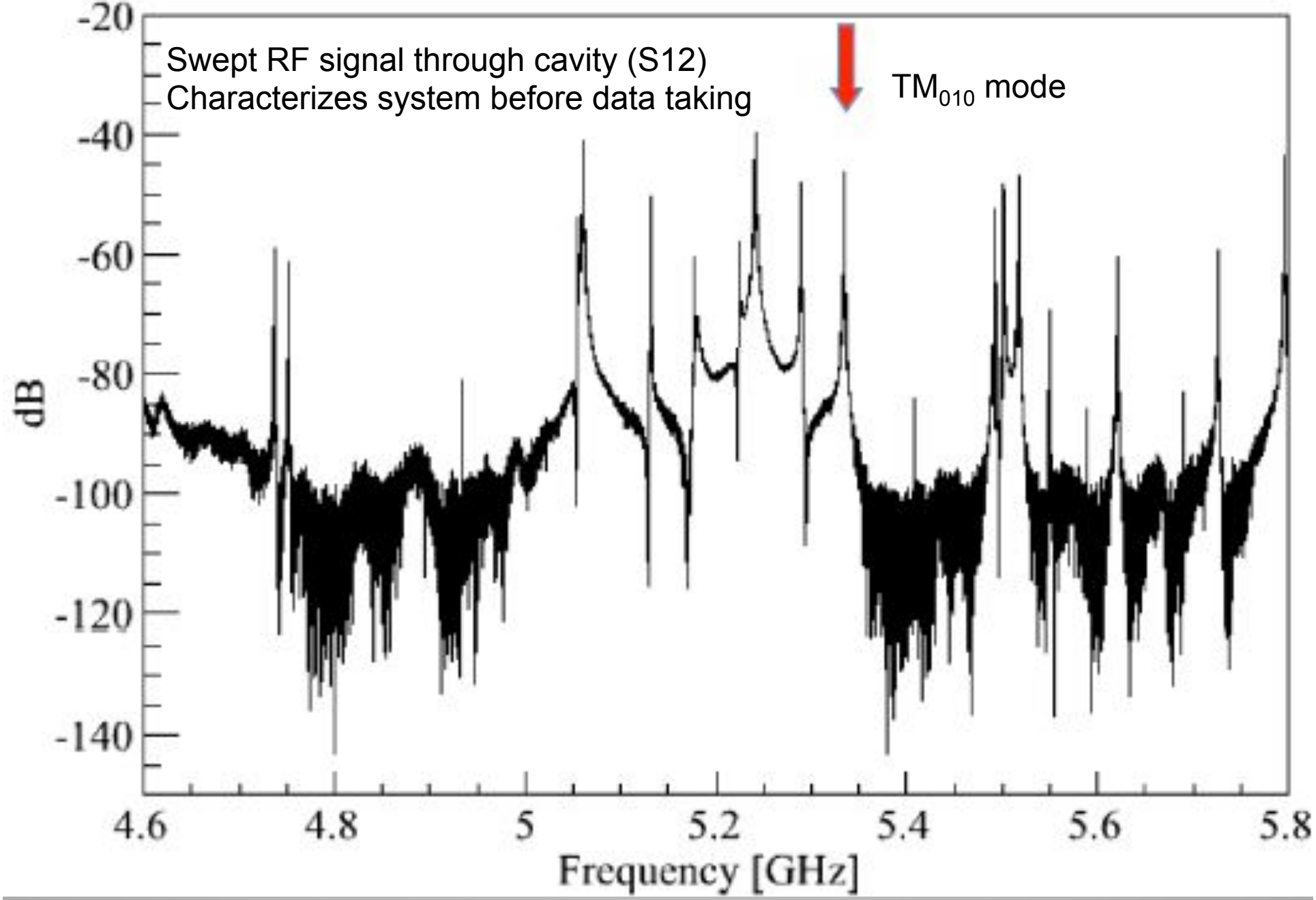



Swept RF signal through cavity (S12)
Characterizes system before data taking
TM010 mode
-20
-40
-60
-80
-100
-120
-140
dB
4.6
4.8
5
5.2
5.4
5.6
5.8
Frequency [GHz]


Swept RF signal through cavity (S12)
Characterizes system before data taking
TM010 mode
-20
-40
-60
-80
-100
-120
-140
dB
4.6
4.8
5
5.2
5.4
5.6
5.8
Frequency [GHz]

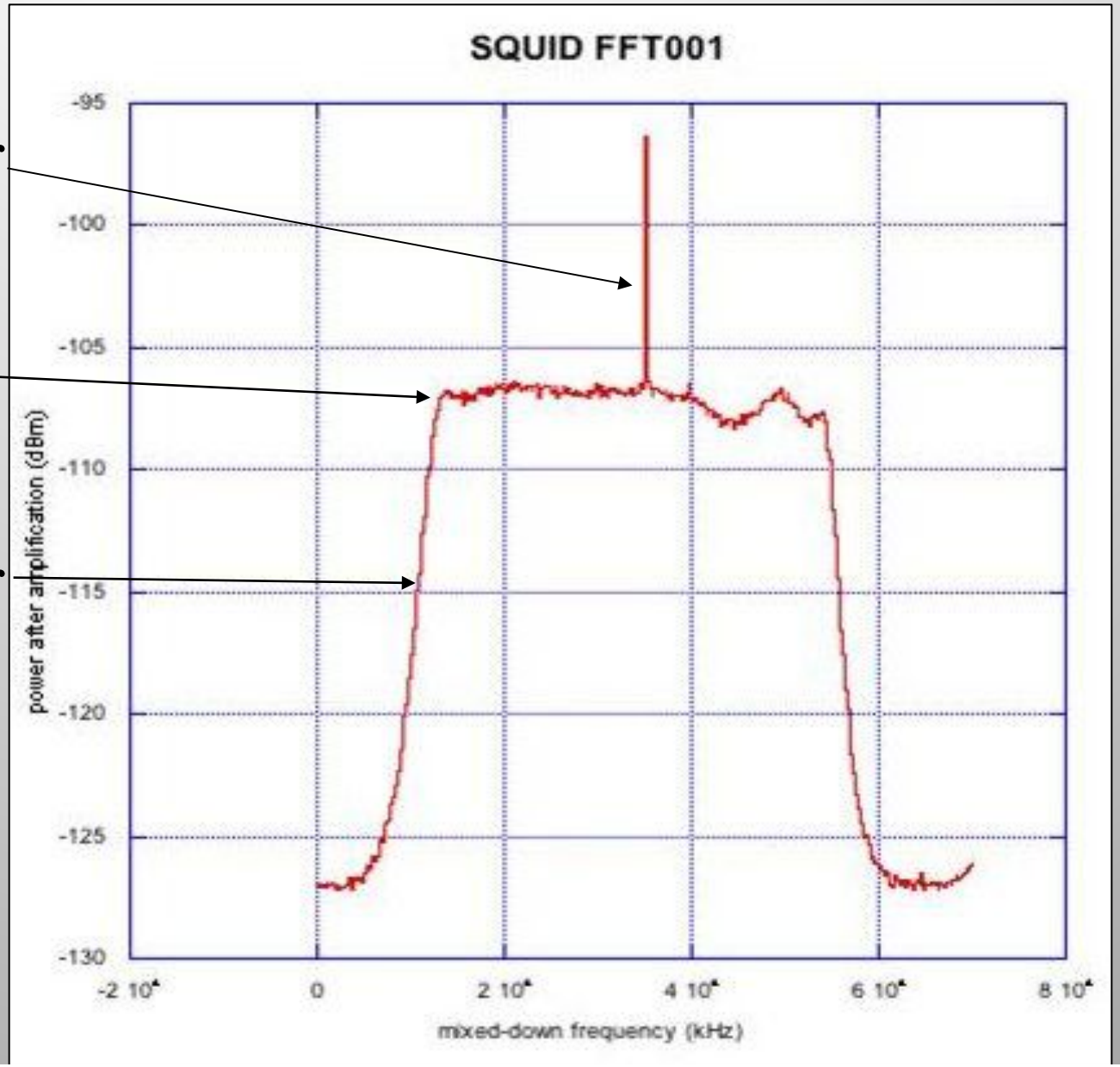

Swept RF signal through cavity (S12)
Characterizes system before data taking
TM010 mode
-20
-40
-60
-80
-100
-120
-140
dB
4.6
4.8
5
5.2
5.4
5.6
5.8
Frequency [GHz]


Swept RF signal through cavity (S12)
Characterizes system before data taking
TM010 mode
-20
-40
-60
-80
-100
-120
-140
dB
4.6
4.8
5
5.2
5.4
5.6
5.8
Frequency [GHz]


Swept RF signal through cavity (S12)
Characterizes system before data taking
TM010 mode
-20
-40
-60
-80
-100
-120
-140
dB
4.6
4.8
5
5.2
5.4
5.6
5.8
Frequency [GHz]

Example of single injected signal (with SQUID amplifiers)

- Injected Power
- Noise floor
- Bandpass filter



Typical Run Cadence

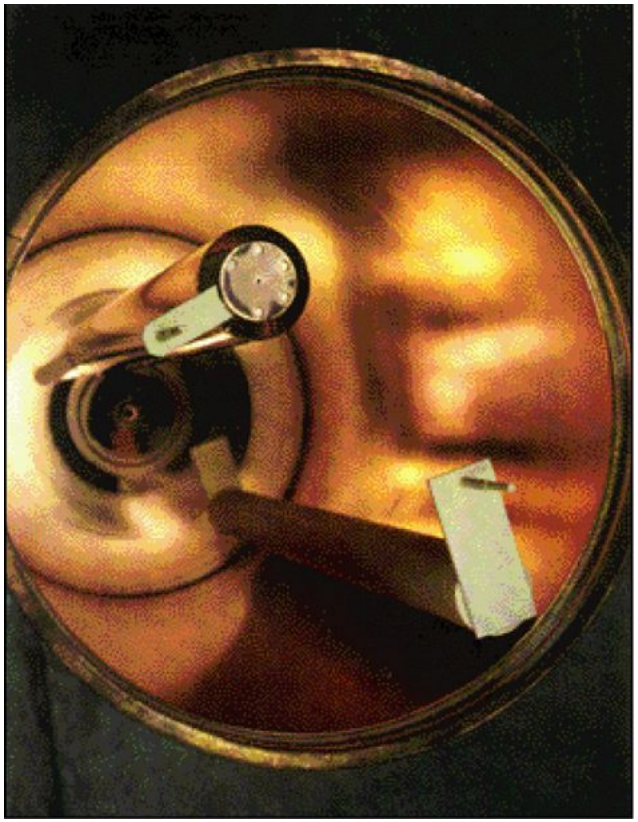
- Inject broad swept RF signal to record cavity response. Record state data (temperature sensors, hall sensors, pressure, etc.).

- Integrate for ~ 80 seconds (final integration time based on results from cold commissioning).

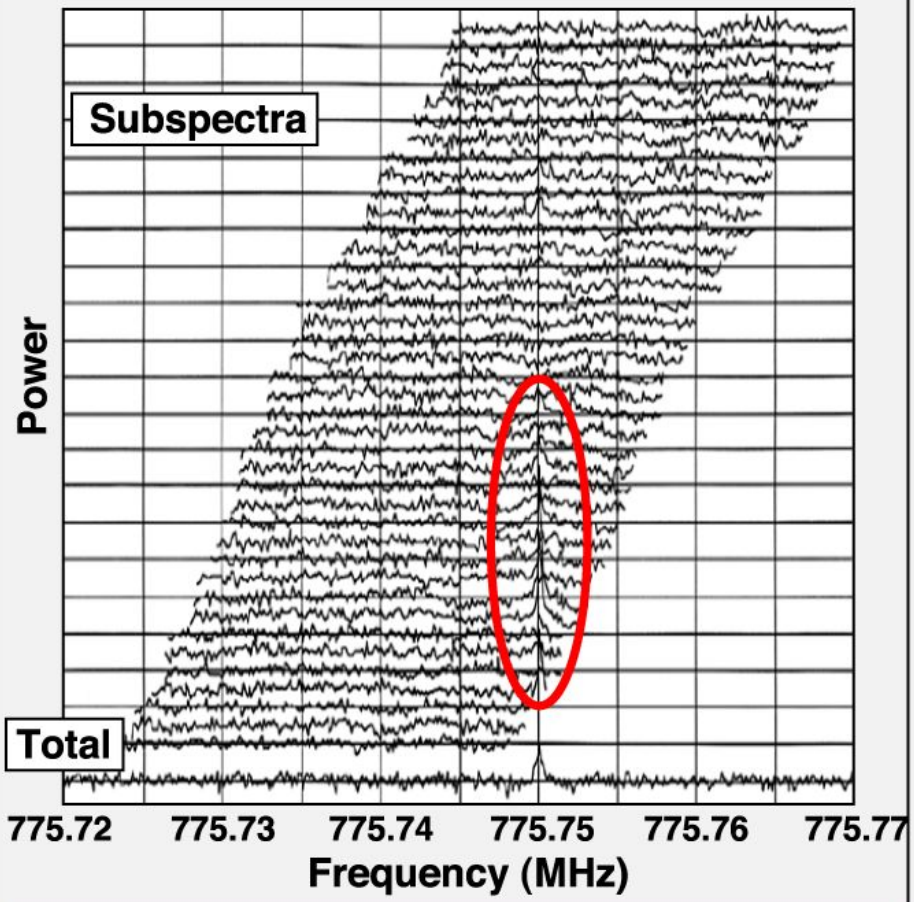
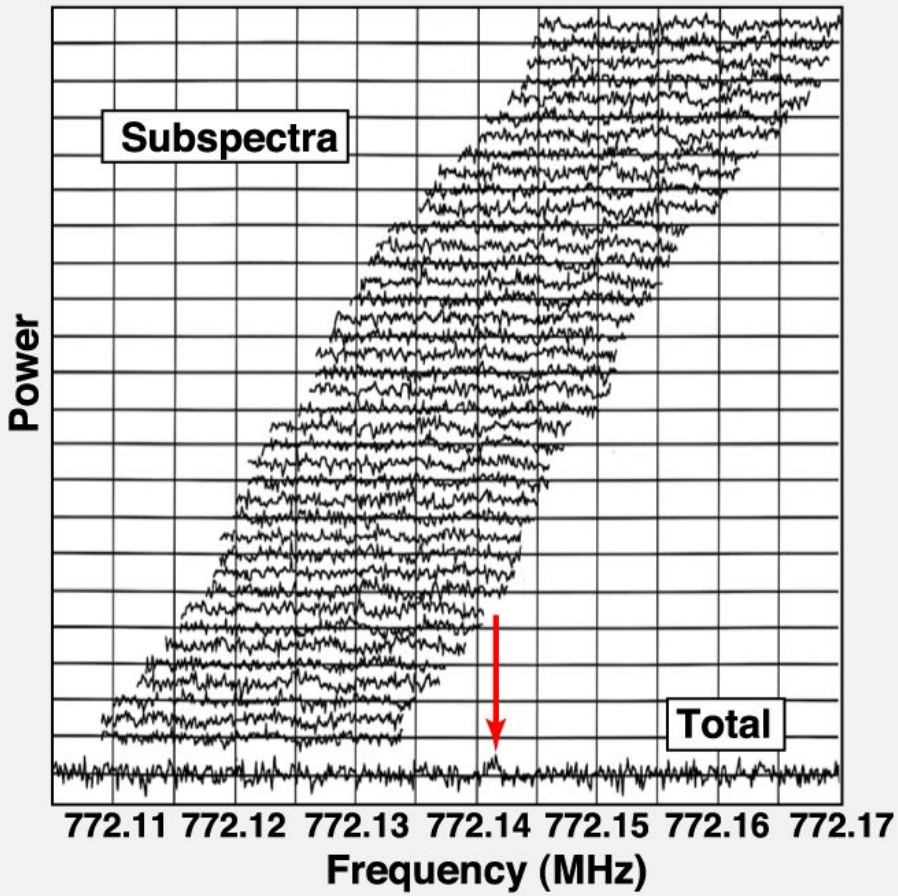
- Move tuning rod to shift TM_{010} & TM_{020} modes (~ 1 kHz at a time).

- Every few days adjust critical coupling of TM_{010} & TM_{020} antennas.

- Anticipated scan rate ~100 MHz (0.5 μeV) every 3 months



Sample data and candidates

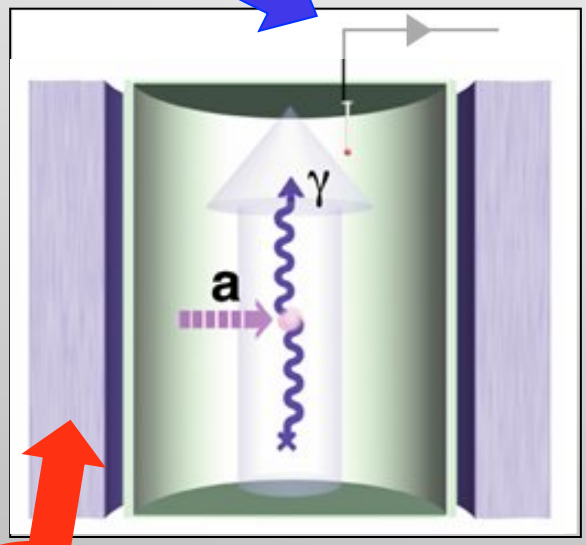
Environmental	Statistical
	
Signal maximizes off-resonance: Radio peak	**Signal distributed over many sub-spectra: a good threshold candidate (but did not persist in rescan)**

The radiometer eqn.* dictates the 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 $T_{Quant} \sim 30\ mK$

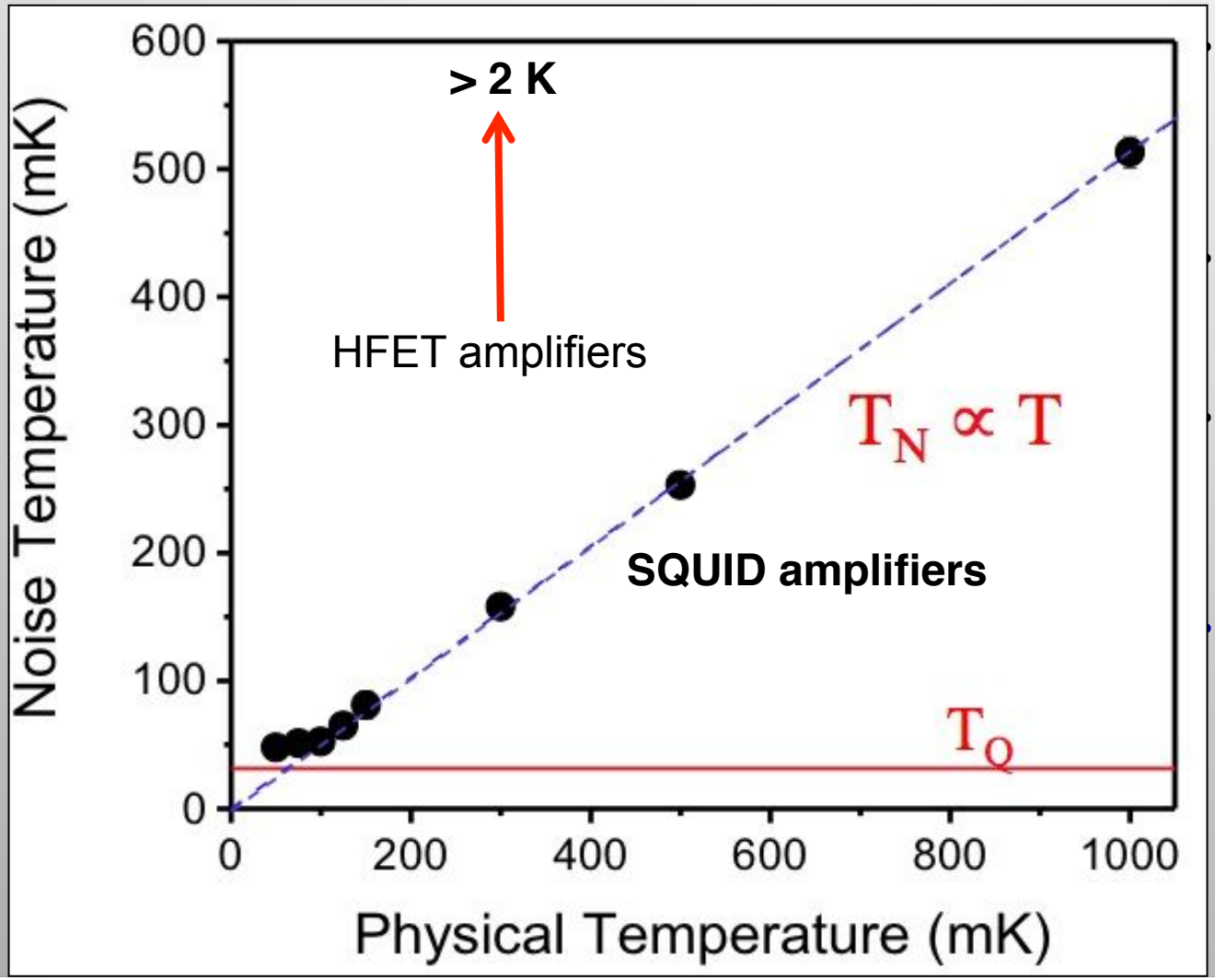
INVEST HERE!

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

$$\sim 10^{-23}\ watts$$

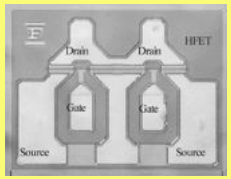
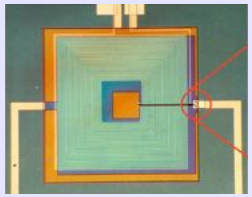
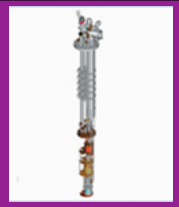
But magnet size, strength $B^2V \sim \$$

Phase I & II Upgrade path: Quantum-limited SQUID-based amplification

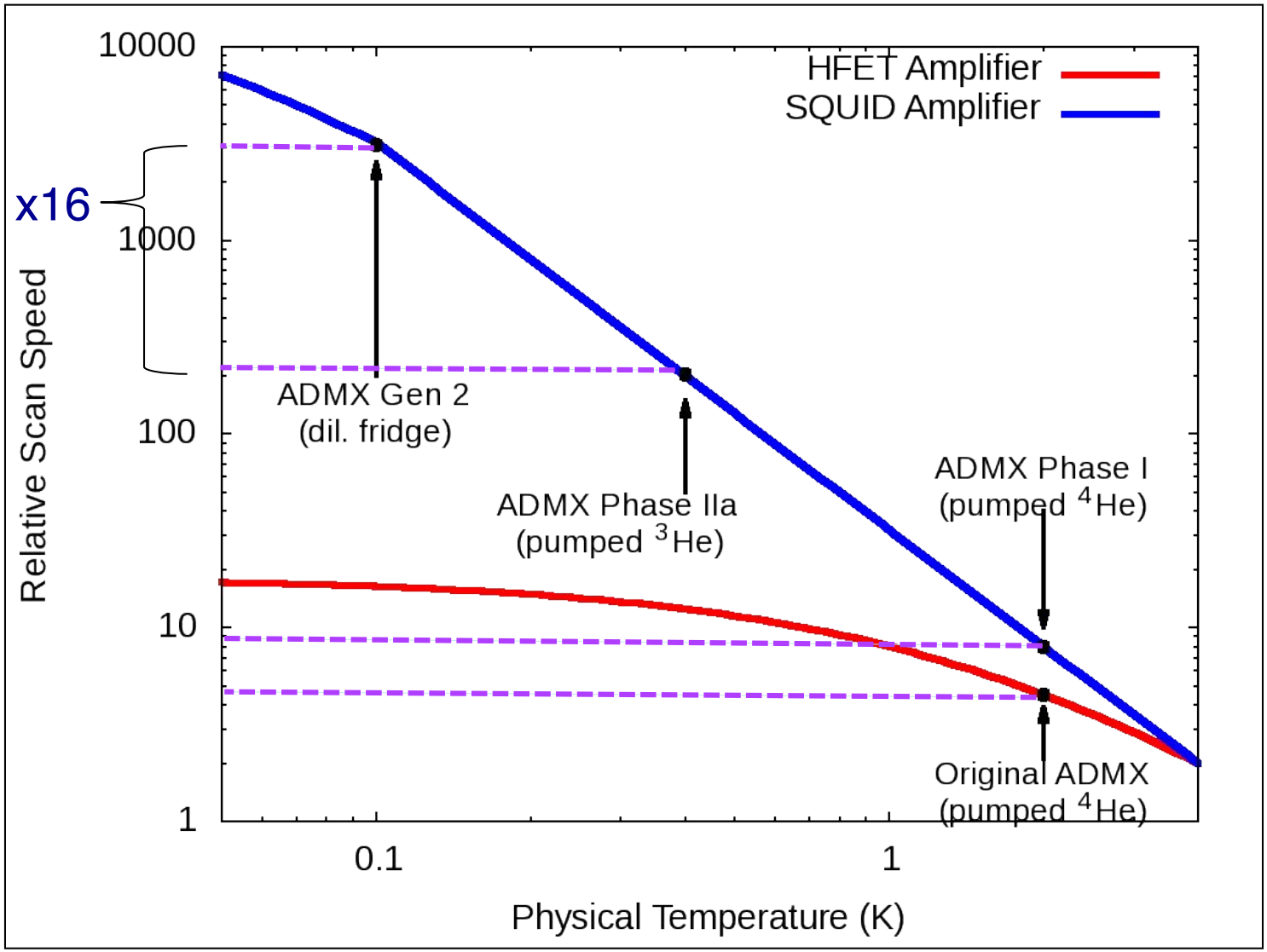


- SQUIDs have been measured with $T_N \sim 50$ mK
- Near quantum– limited noise
- Provides an enormous increase in ADMX sensitivity
- At LLNL SQUID development was sponsored by LDRD.

The Axion Dark Matter eXperiment

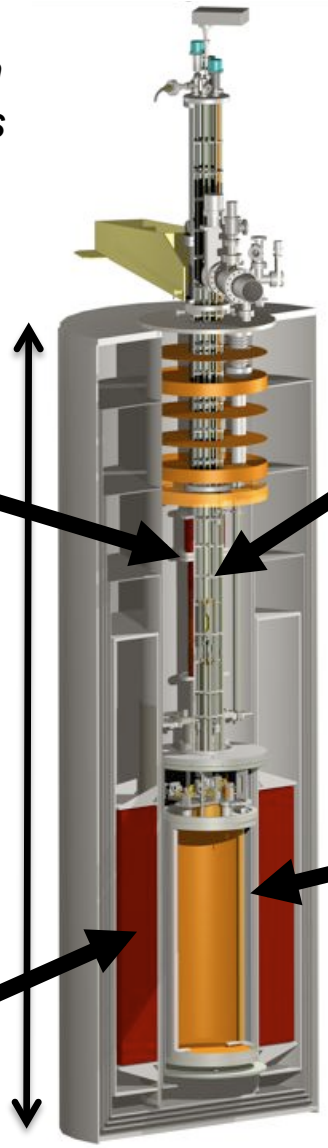
Stage	**Phase 0**	**Phase I**	**Phase II**
Technology	HEMT; Pumped LHe 	Replace w. SQUID 	Add Dilution Fridge 
T_{phys}	2 K	2 K	100 mK
T_{amp}	2 K	1 K	100 mK
$T_{sys} = T_{phys} + T_{amp}$	4 K	3 K	200 mK
Scan Rate $\propto (T_{sys})^{-2}$	1 @ KSVZ	1.75 @ KSVZ	5 @ DFSZ
		OR	*AND !*
Sensitivity Reach $g^2 \propto T_{sys}$	KSVZ	0.75 x KSVZ	DFSZ

Gen 2: (in construction)
Why the Dilution Refrigerator



ADMX Experimental Apparatus

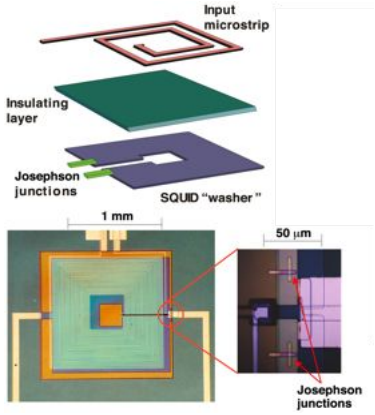
Field compensation magnet for SQUIDs

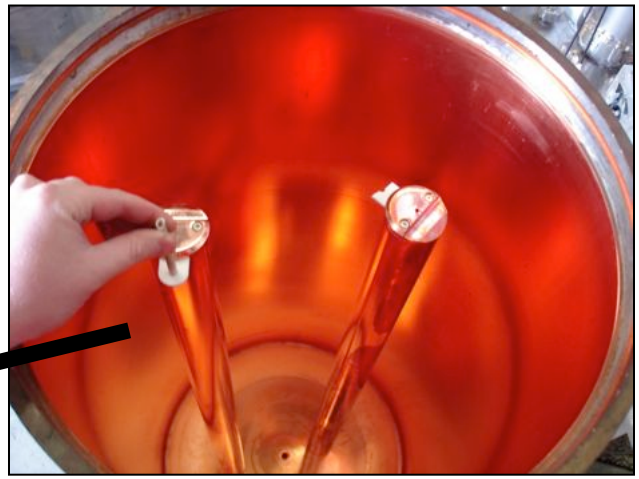


11'

8 Tesla Magnet

SQUID amplifier

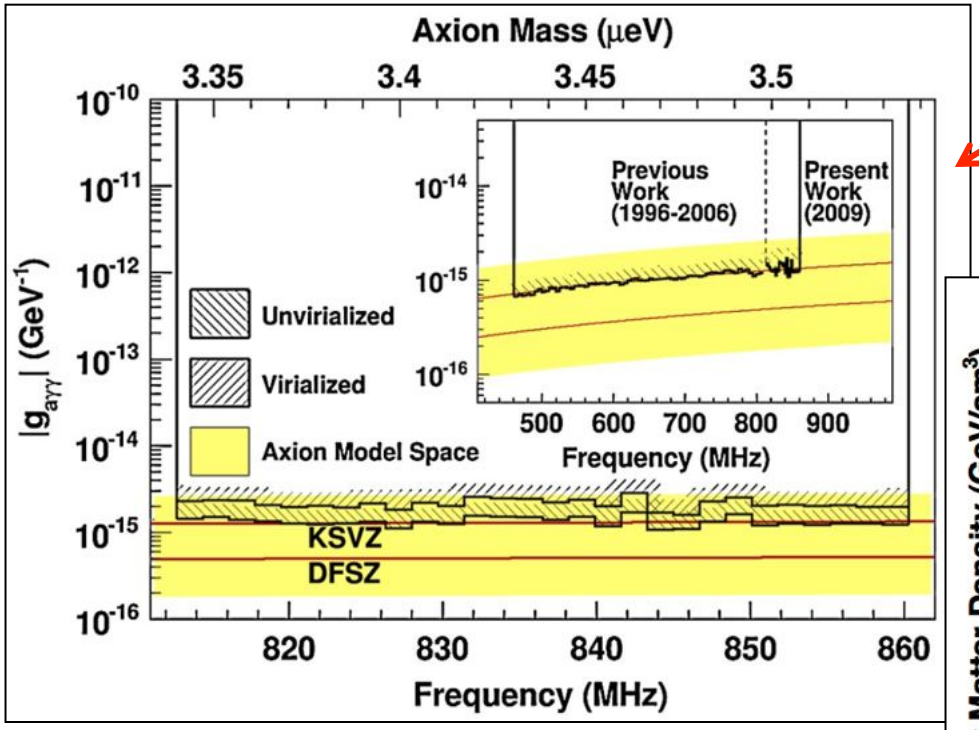




140 liter microwave cavity (500 MHz - 1 GHz)

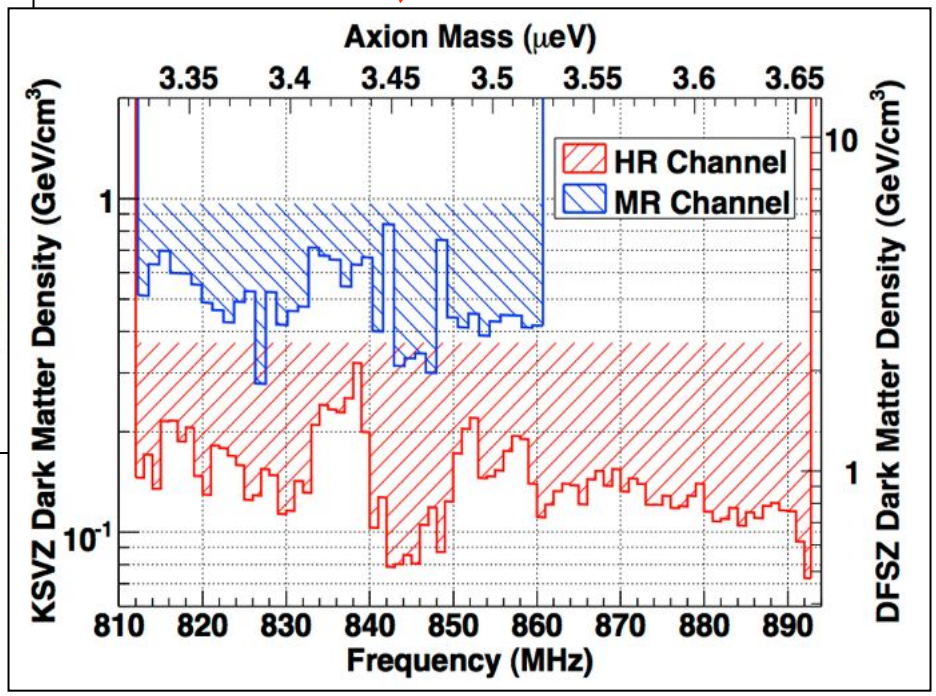
ADMX Phase I: Accomplishments to date.

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

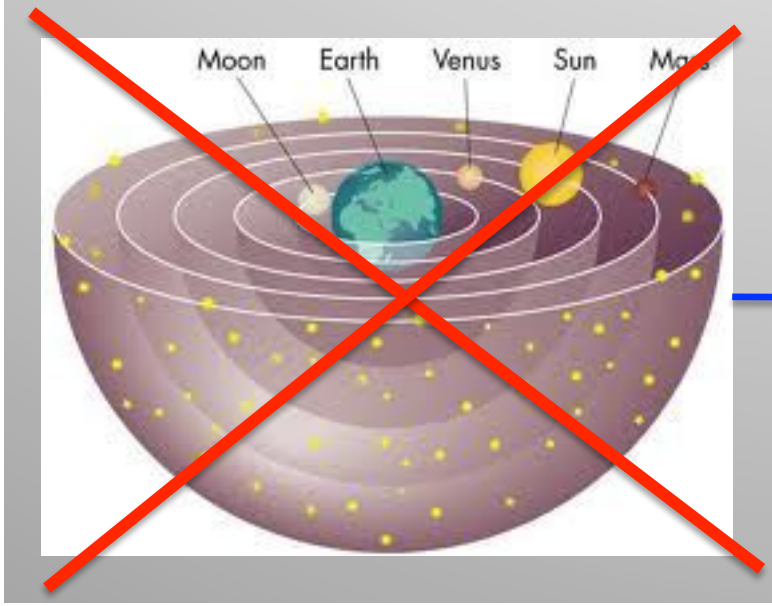
Total Run Time: 19 months

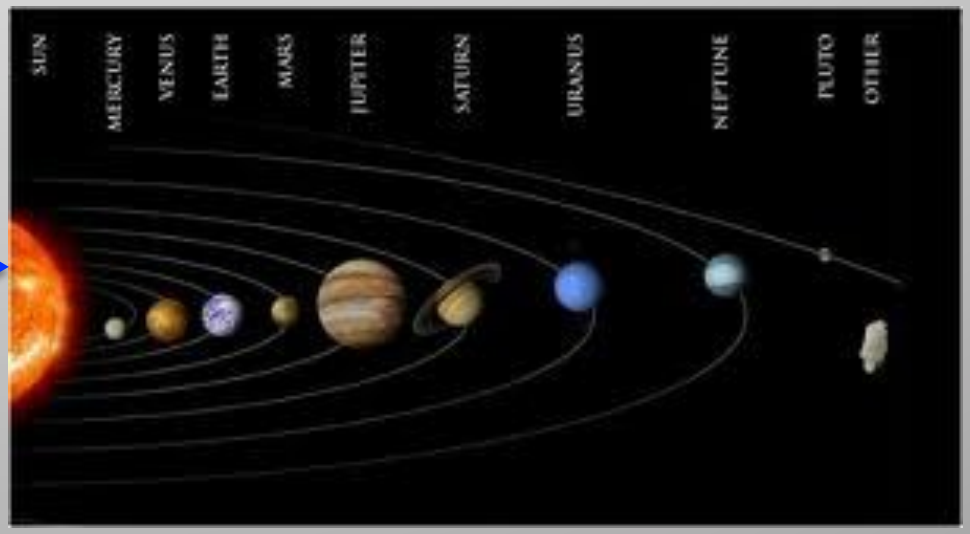
Continuous Data Collecting: 8 months

But wait!!! There's more….

ADMX is sensitive to other hypothetical bosons that mix with photons… not just the QCD axion.

<u>The "hidden-sector"</u>: Whose to say there isn't a large zoo of particles that just don't interact with the particles we know about… <u>for an analogy see Copernicus</u>.

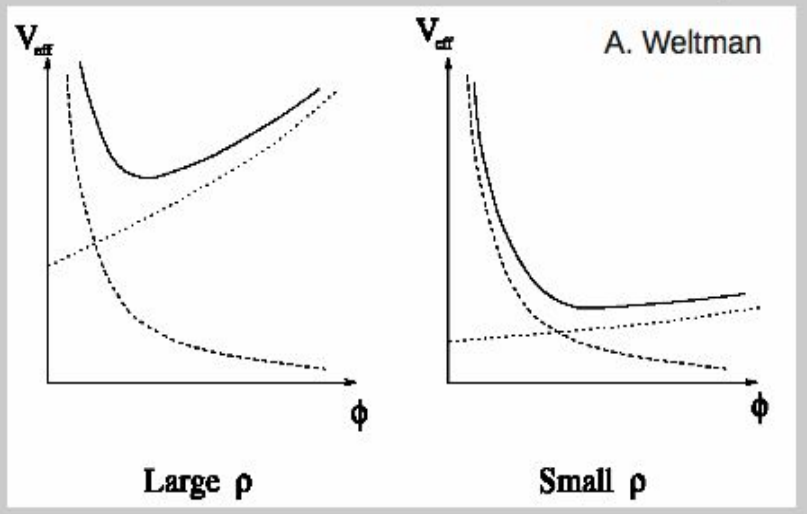




ADMX sensitive to other light bosons: Chameleon particles

Nonlinear self-interactions can cause particle's effective mass to be dependent on its surroundings (chameleon mechanism)

New particles can be strongly coupled, and yet evade solar and short range gravity limits



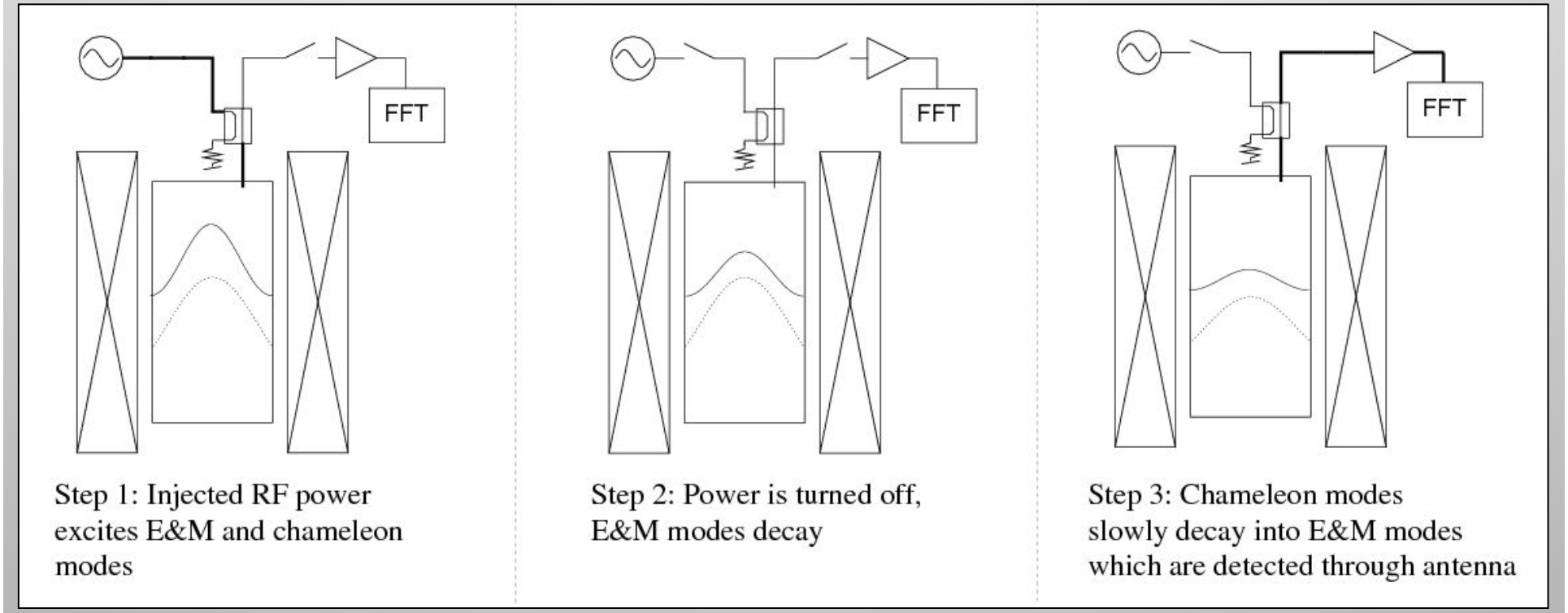
For example:

$$V(\phi) = \Lambda^4 e^{\Lambda^{4+n}/\phi^4} + \frac{\beta}{M_{Pl}} \phi F^{\mu\nu} F_{\mu\nu}$$

Khoury and Weltman, PRL 93.171104 (2004)

A viable Dark Energy Candidate

Utilizing ADMX for a Chameleon search

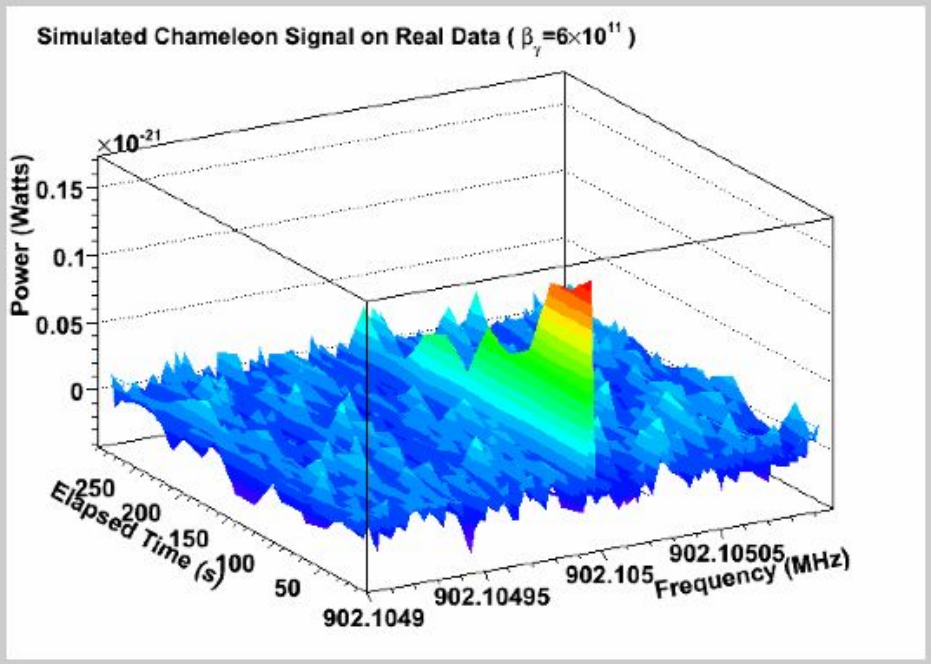


Timescale: 10 minutes
Power in ~ 25 dBm

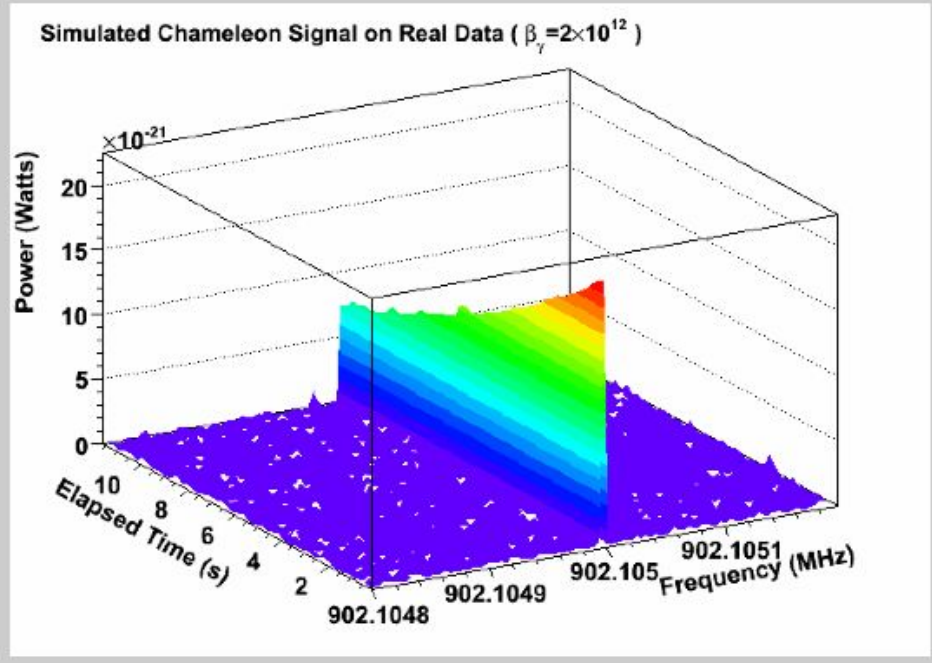
Timescale: 100 milliseconds

Timescale: 10 minutes
Sensitivity ~ 10^{-22} W
Bandwidth ~ 20 kHz

Utilizing ADMX for a Chameleon search



Weaker coupling leads to less signal, longer decay



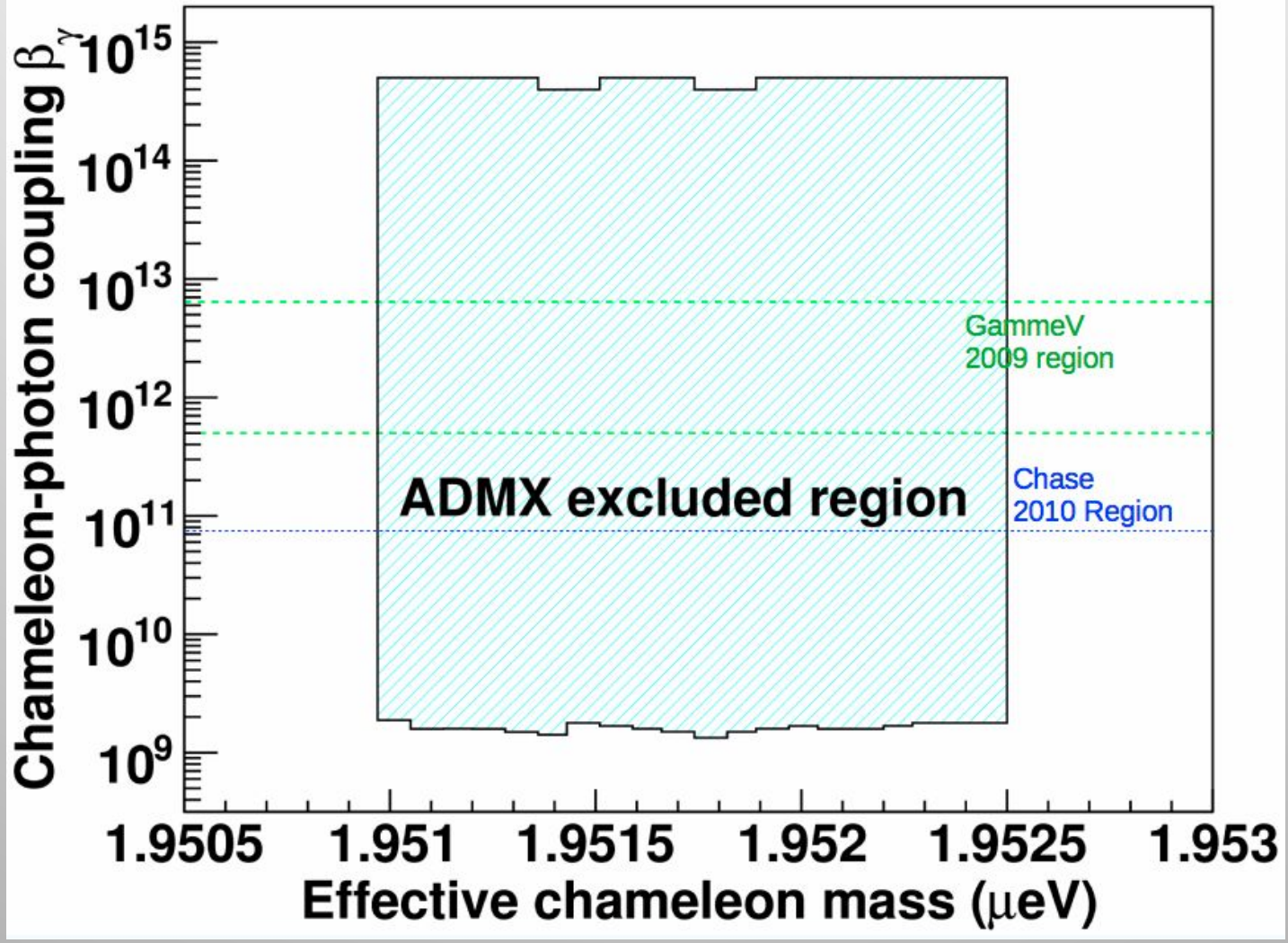
Stronger coupling leads to more signal, but short decay time

(note time scale change)

1 day proof-of-concept

*simulation courtesy of G. Rybka

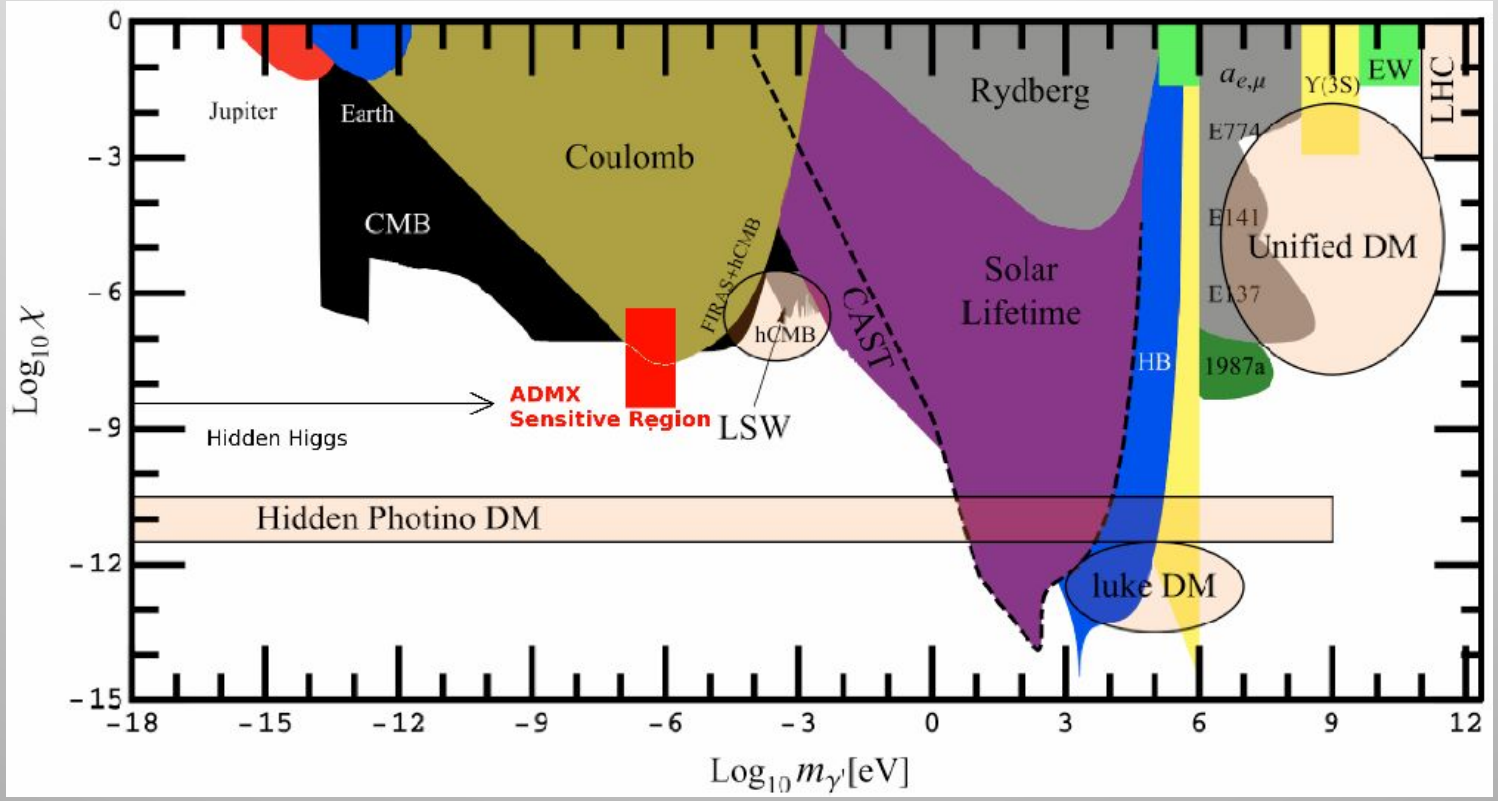
ADMX for a Chameleon search results (published in PRL)



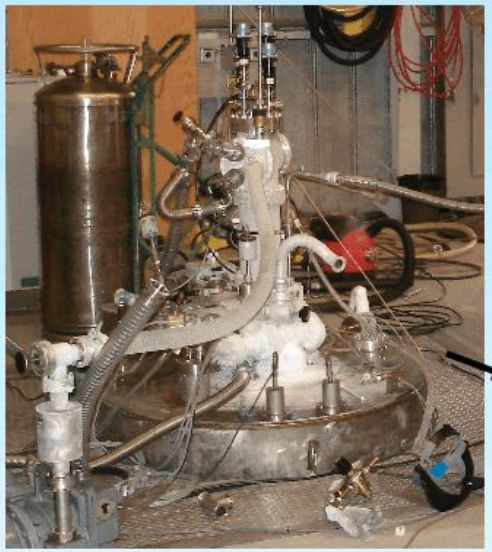
Laboratory Dark Energy Search

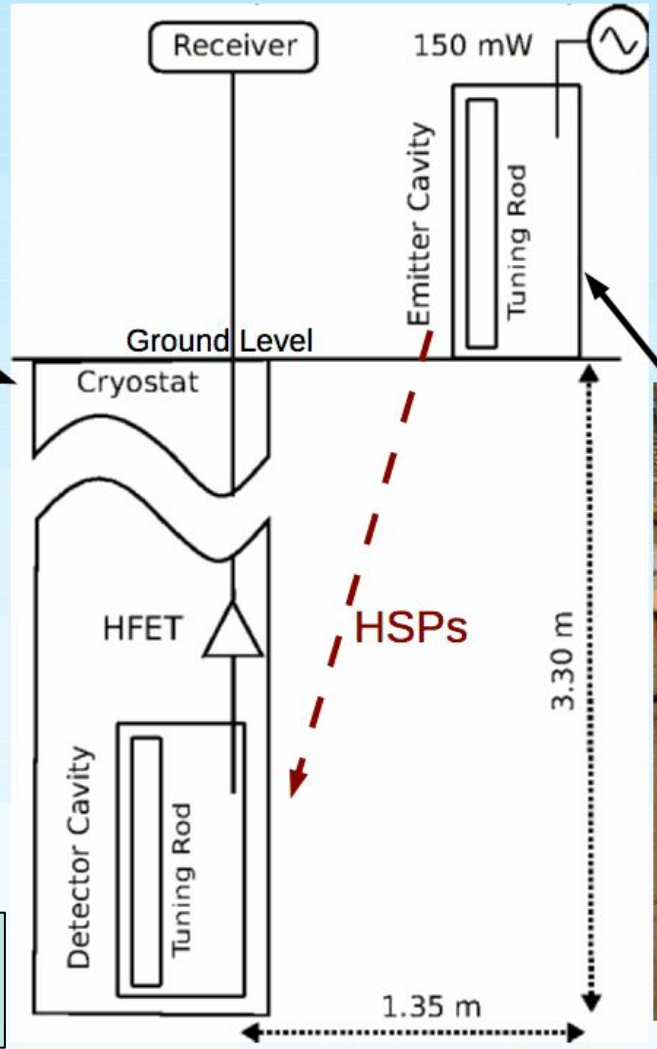
Other light bosons: Hidden Sector Photons

Additional U(1) symmetries that mix kinetically with the photon are ubiquitous in beyond-the-standard model physics
Other Names: U Boson, Paraphoton, Z', etc



Utilizing ADMX as a Hidden Sector Photon Receiver





1

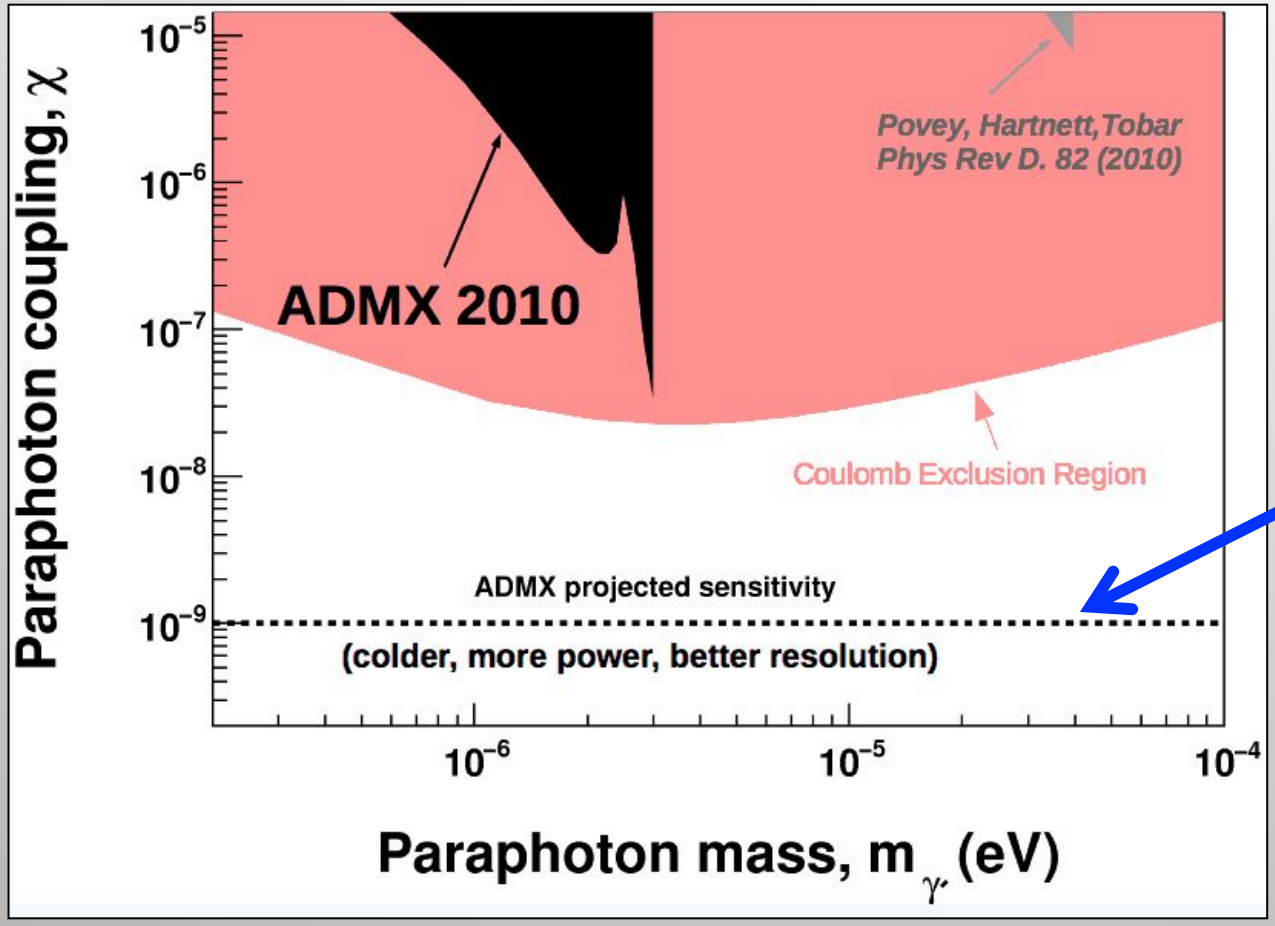
Photons in this driven cavity mix with HSPs and escape

2

HSPs mix with photons and are detected in the ADMX cavity

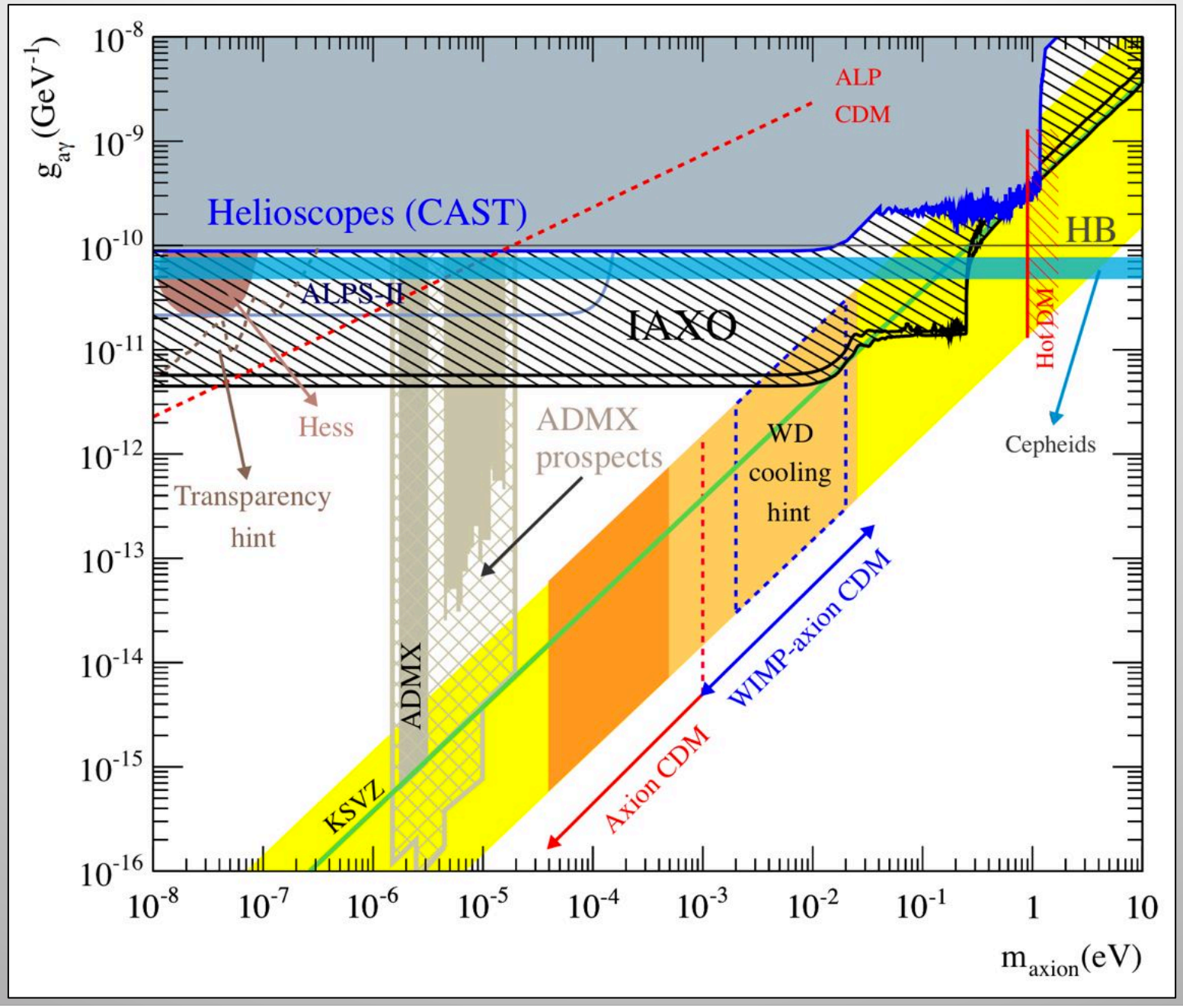
1 day of data taking as a proof of concept.

Results of ADMX search for hidden sector photons (published 2010 PRL)



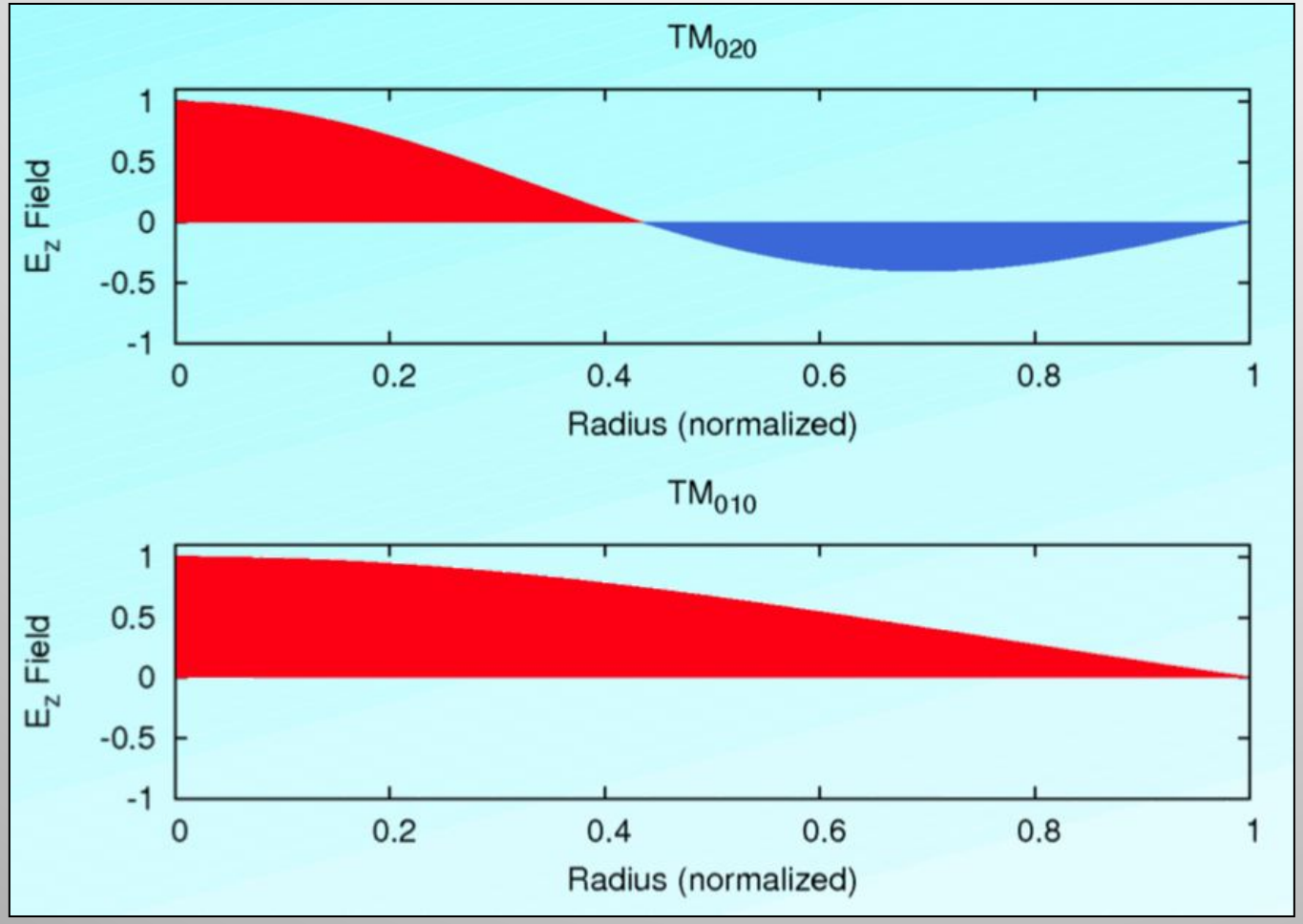
Run concurrently with Dark Matter Axion Search!

100x more sensitive than previous cavity search!
Competitive with indirect searches!


$g_{a\gamma}$ (GeV^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
ALP
CDM
Helioscopes (CAST)
HB
ALPS-II
IAXO
Hot DM
Hess
ADMX
prospects
WD
cooling
hint
Cepheids
Transparency
hint
WIMP-axion CDM
ADMX
KSVZ
Axion CDM
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion}(eV)

ADMX Phase II:
Moved ADMX main magnet and insert to the U. of Washington

ADMX Phase II: Instrument the TM_{010} & TM_{020} modes



TM_{020} Mode
Relative Frequency
2.3

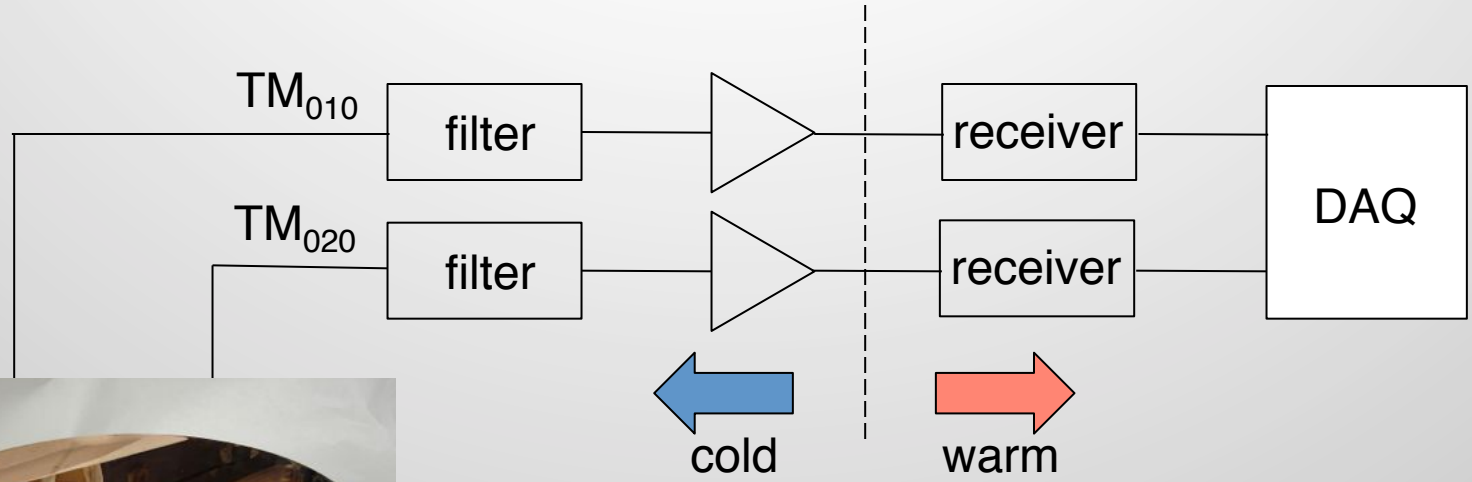
Tuning Range
920-2,100 MHz

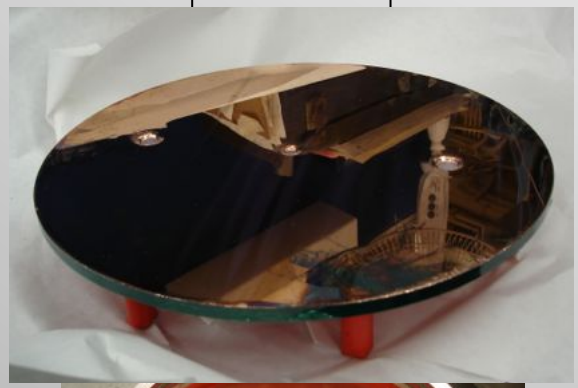
Relative Power
0.41

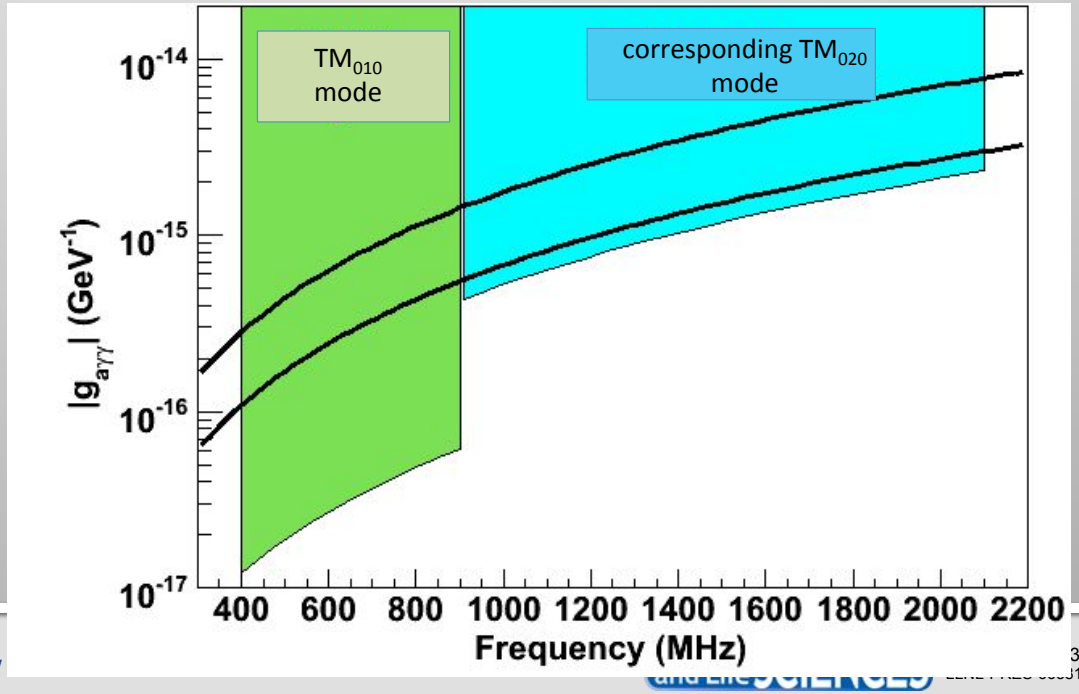
TM_{010} Mode
Relative Frequency
1.0

Tuning Range
400-900 MHz

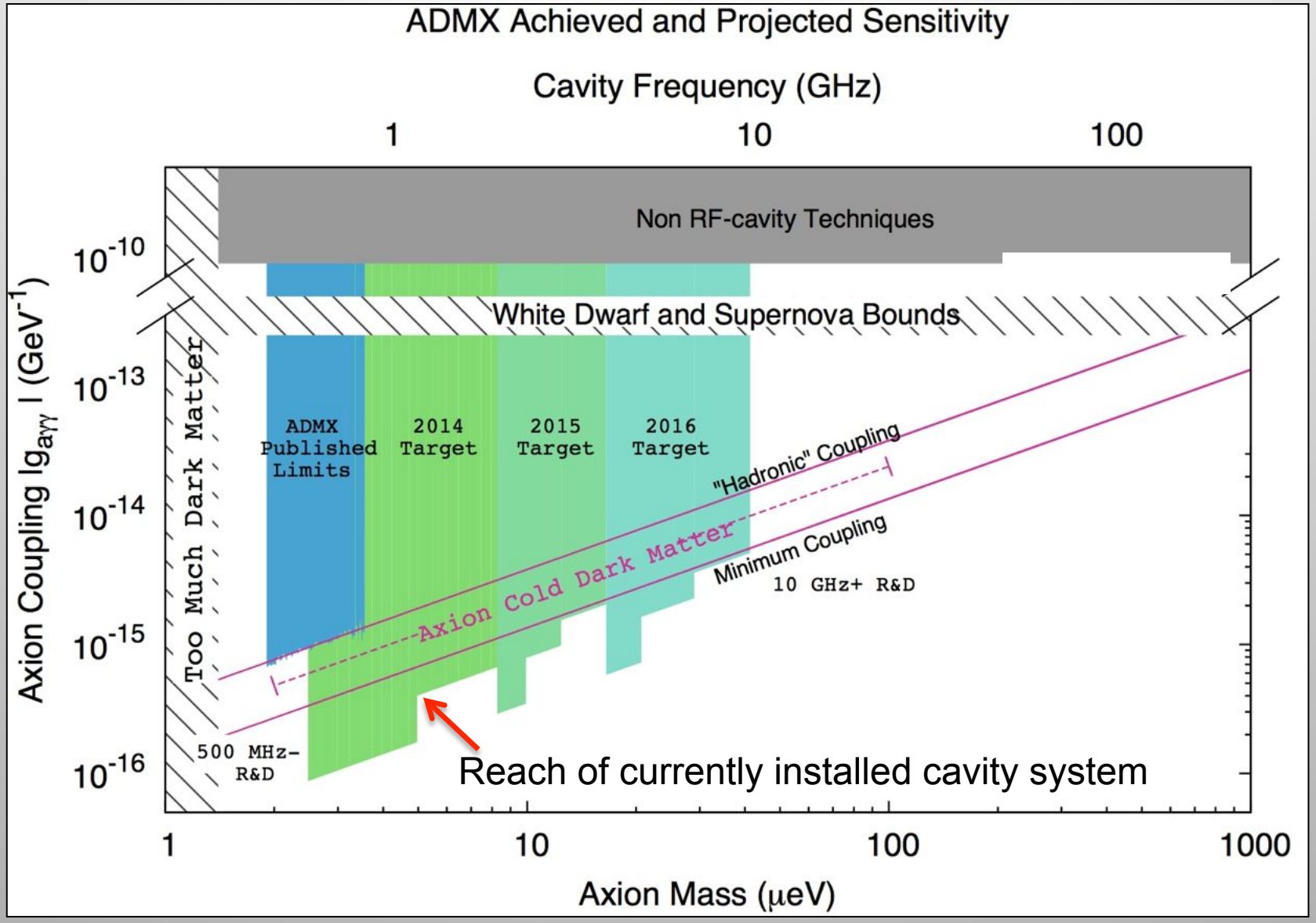
ADMX: Multi-mode readout



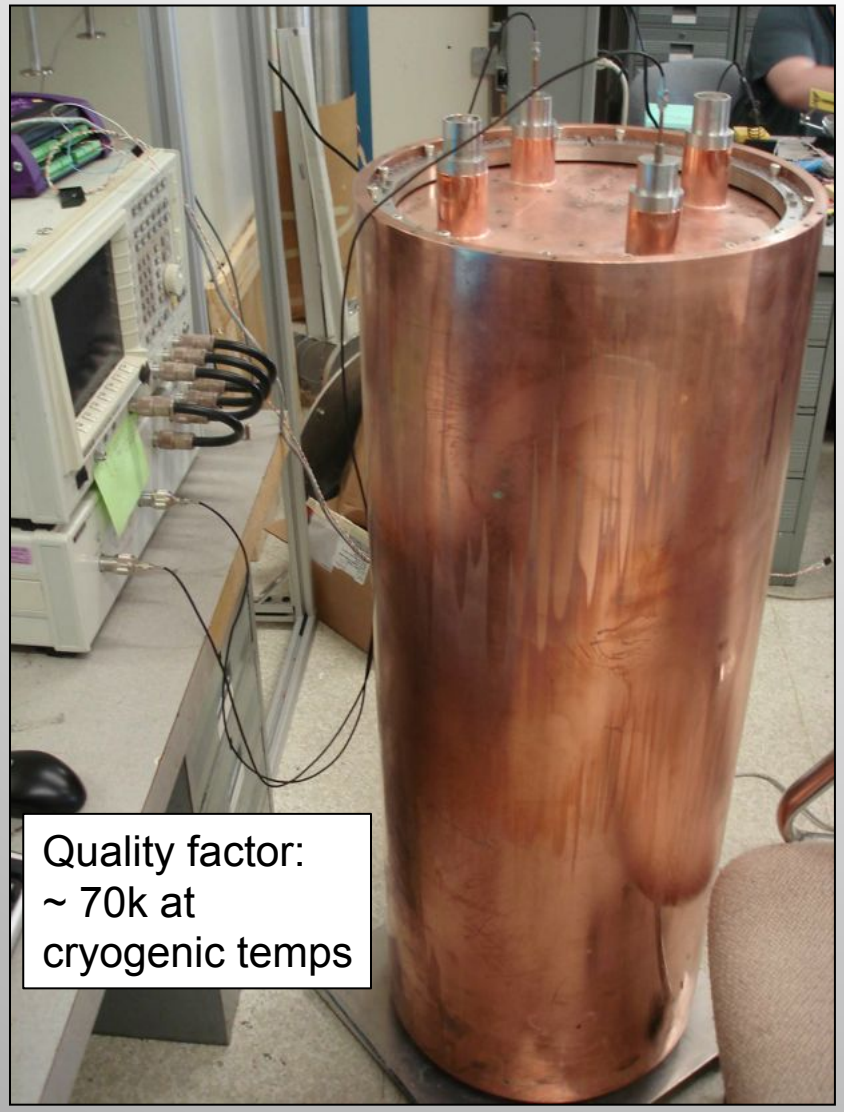




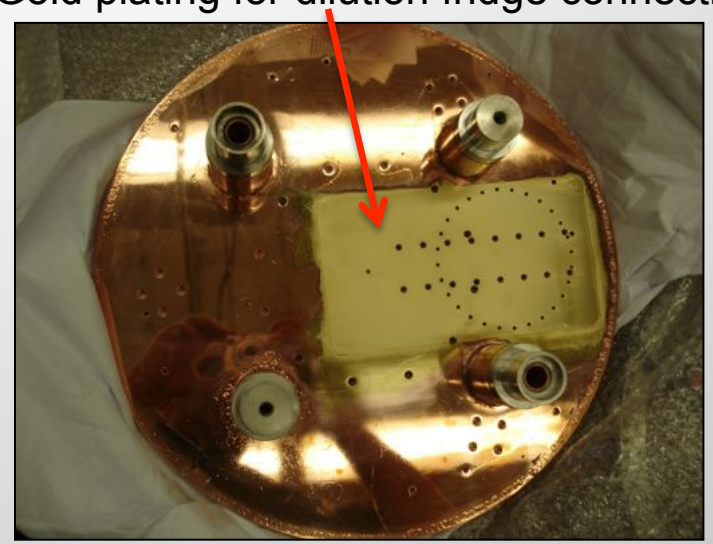
ADMX Upgrade

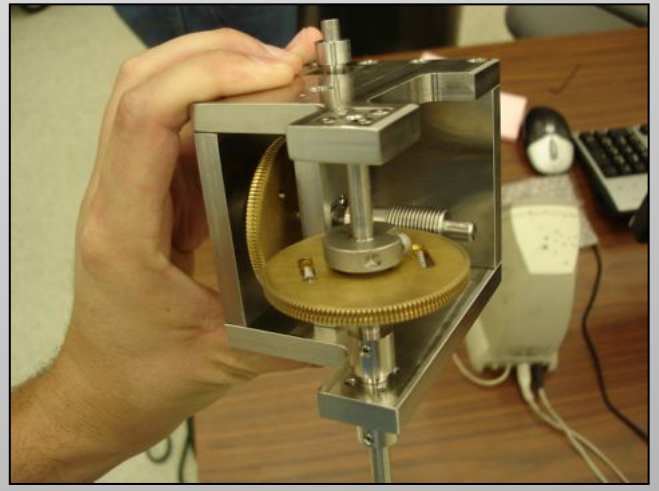


LLNL baseline deliverables: Microwave Cavities & Motion Control



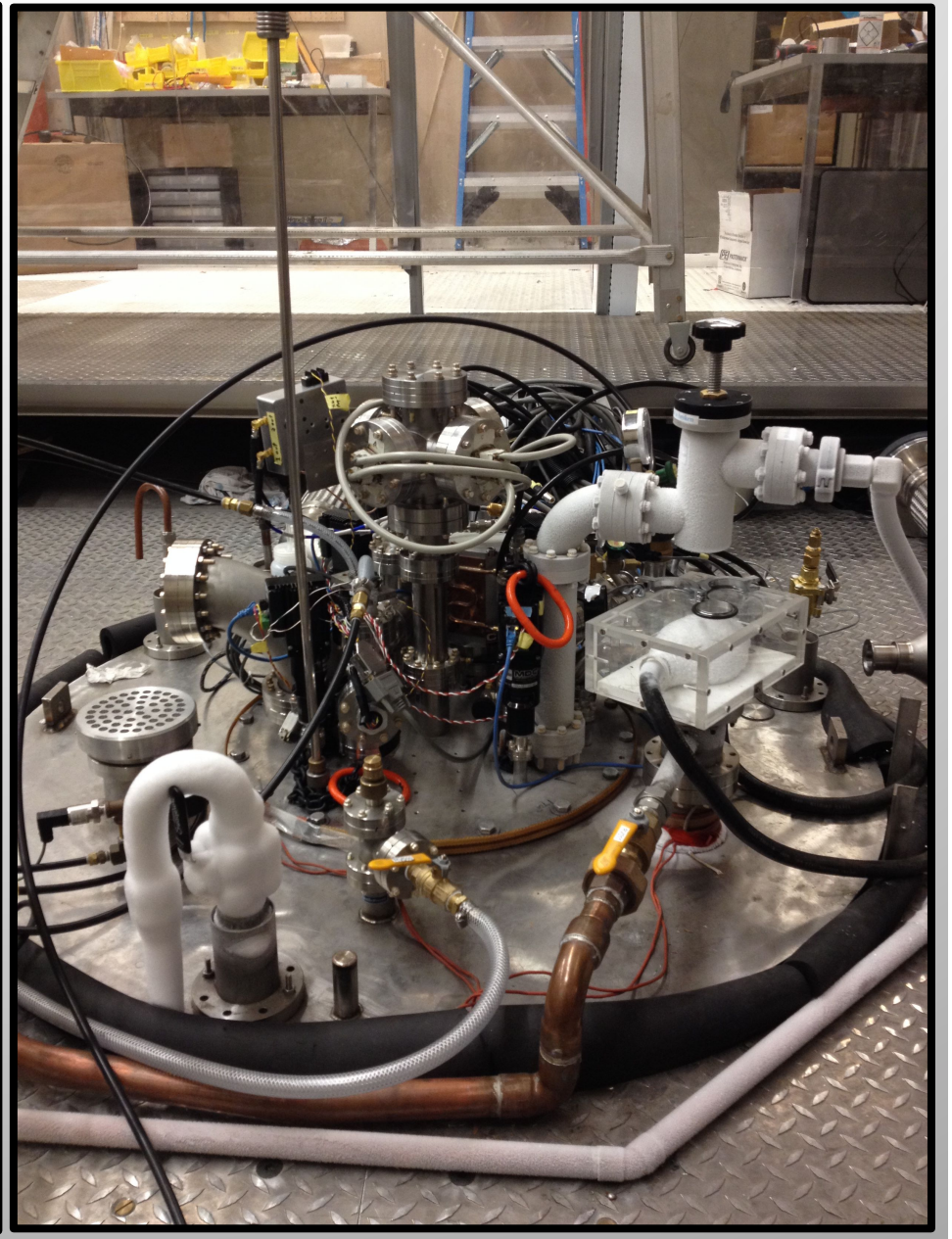
Gold plating for dilution fridge connection



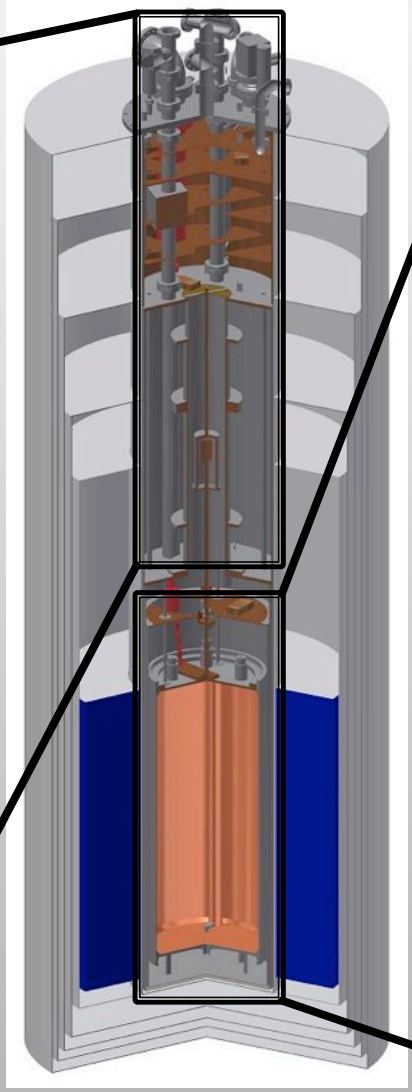


1:19,600 gear reduction

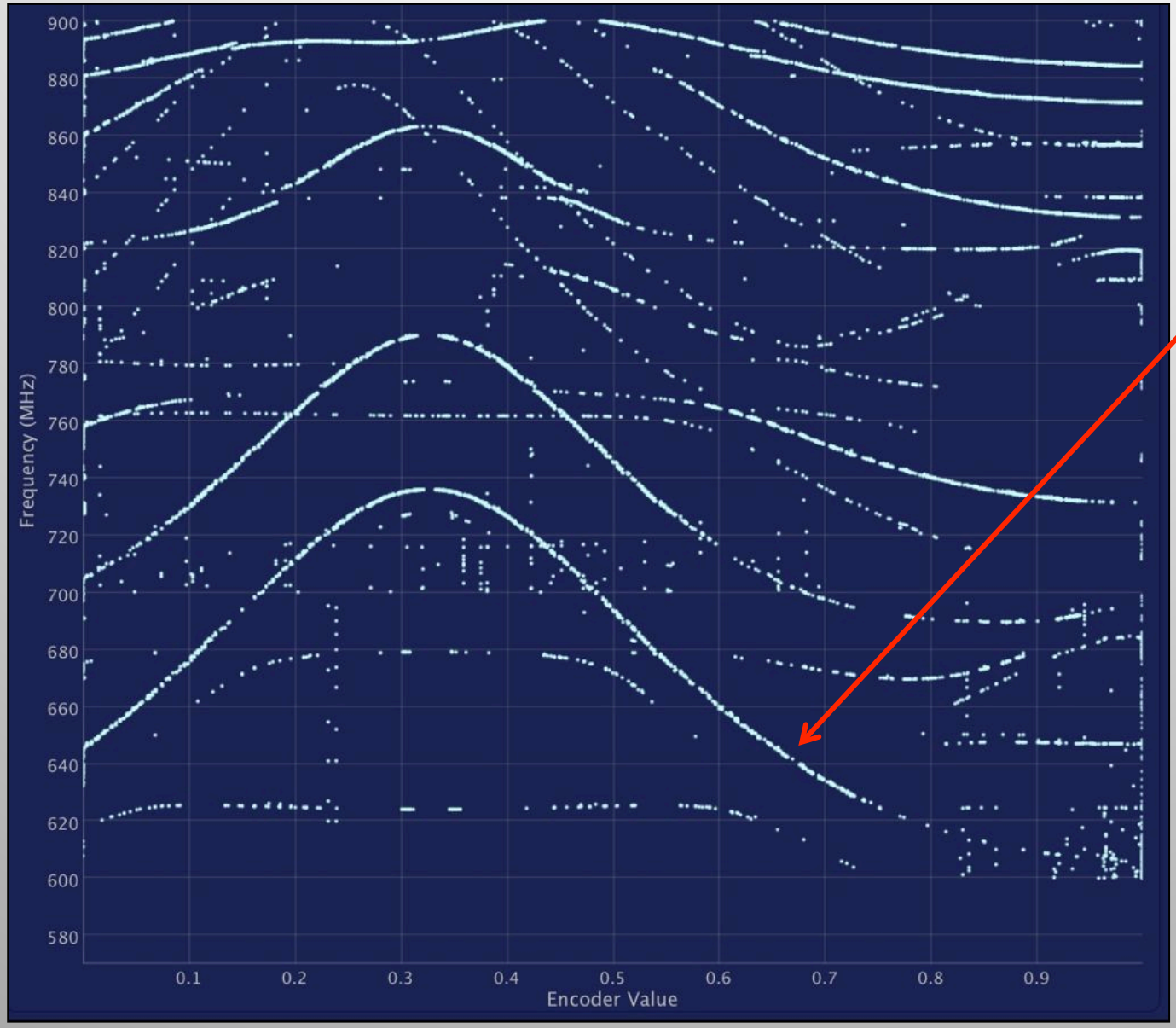
Cavity Installed in ADMX: Initial Data-Taking Runs Underway



Insert assembly with cavity mounted



Initial mode map of cavity TM_{010} mode at UW



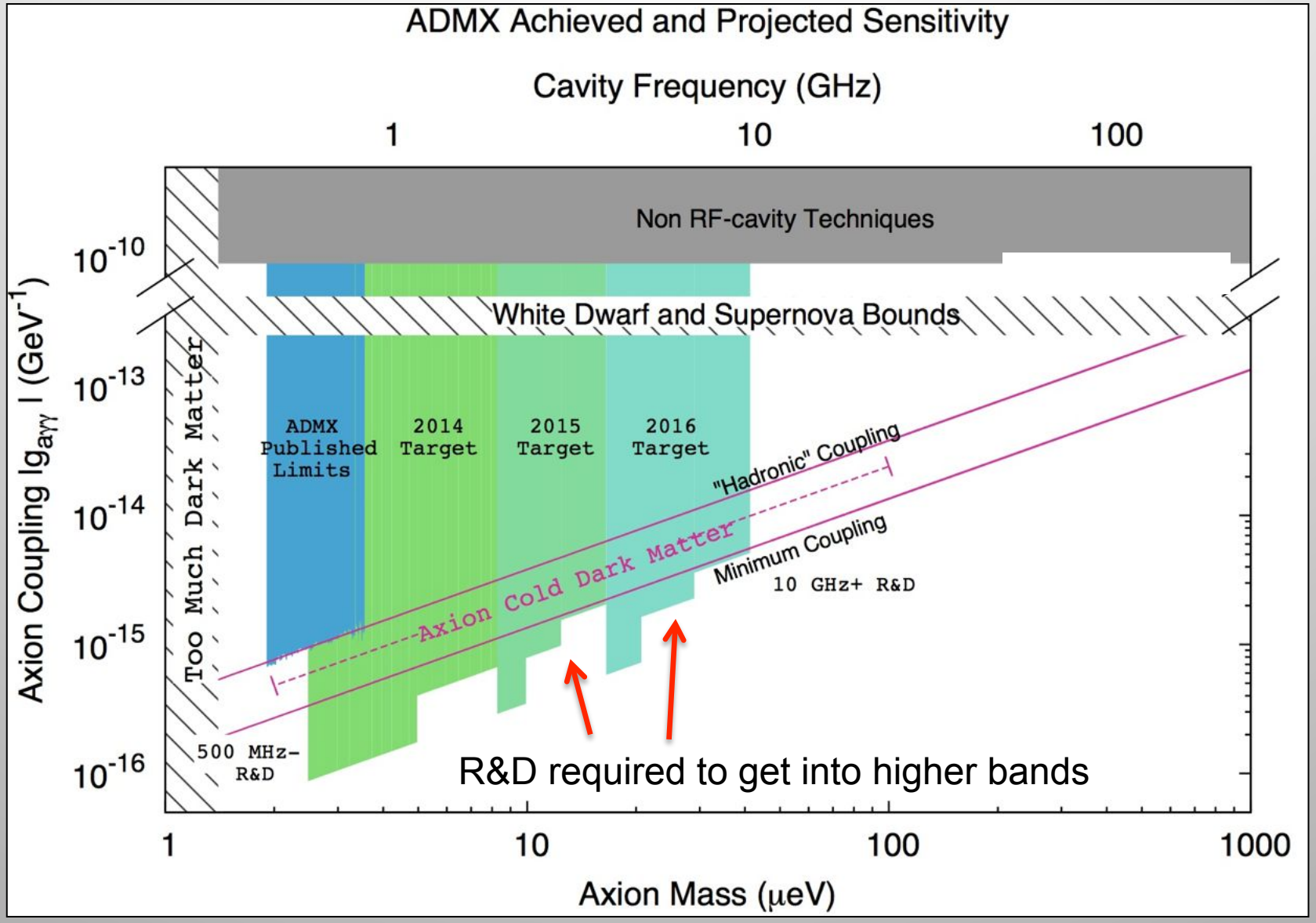
TM_{010} mode: strongest coupling to axions

Second rod appears close to the wall

<u>Full Range:</u>
TM_{010}
580 – 890 MHz

TM_{020}
1.2 – 1.4 GHz

ADMX Upgrade



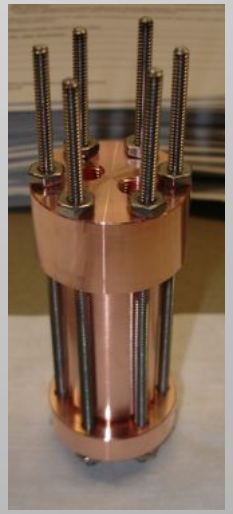
Problem with sampling higher frequencies/mass

- Higher Frequency requires smaller cavities – sample smaller volume!
- Quality factor goes down as frequency increases!

Radius – 19 inches
Frequency ~ 540 MHz
Q – 200,000
Axion Mass ~ 2 μeV
Volume – 220 liters

Radius – 2.5 inches
Frequency ~ 2.4 GHz
Axion Mass ~ 9 μeV
Q – 120,000
Volume ~ 2.6 liters

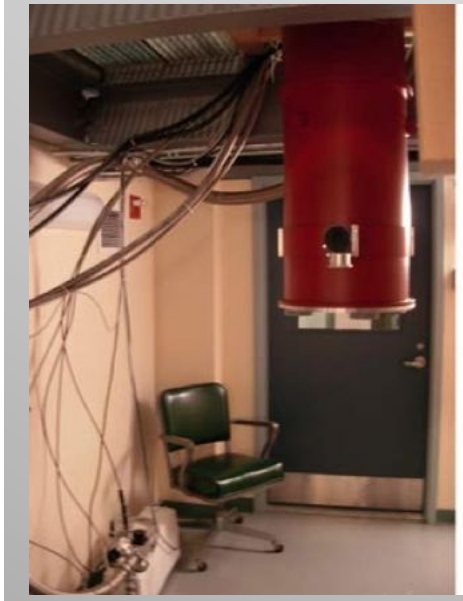
Radius – 0.5 inches
Frequency ~ 10 GHz
Axion Mass ~ 36 μeV
Q – 50,000
Volume – 0.025 liters

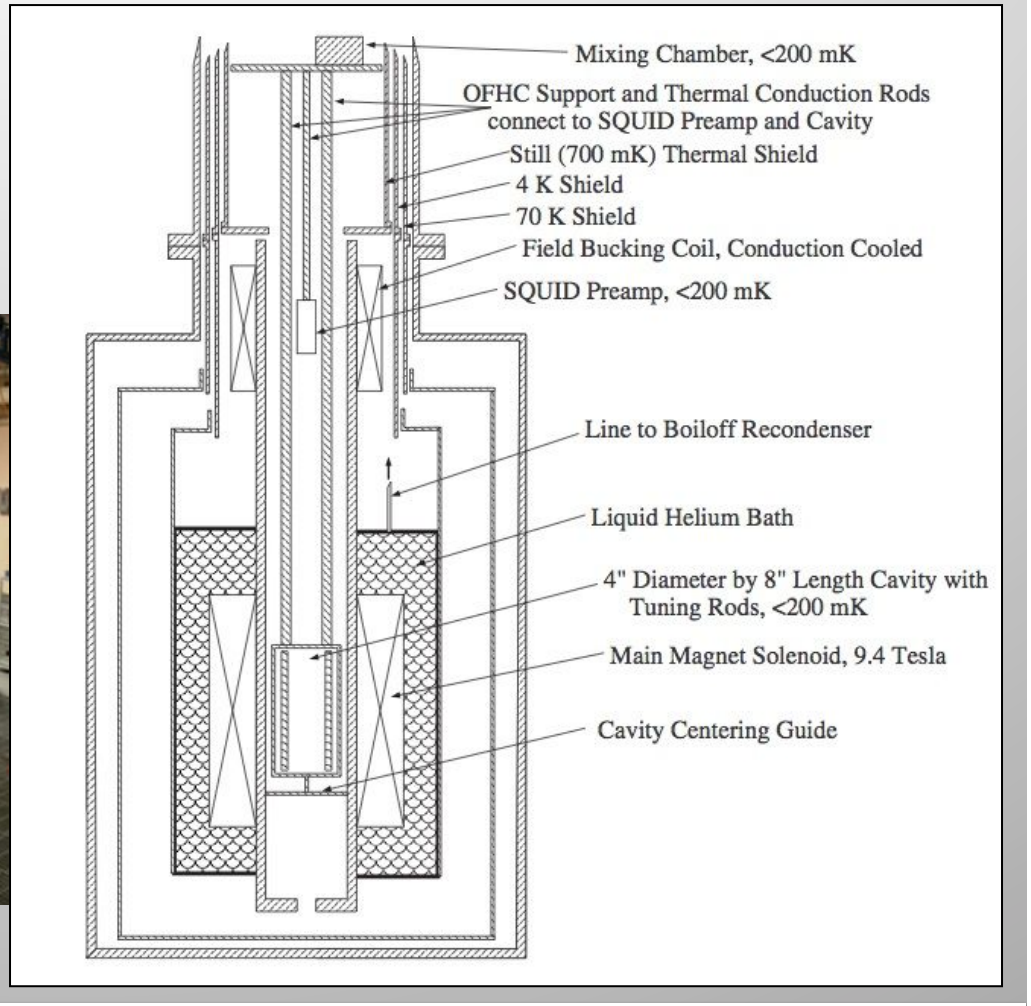


ADMX – HF: High Frequency

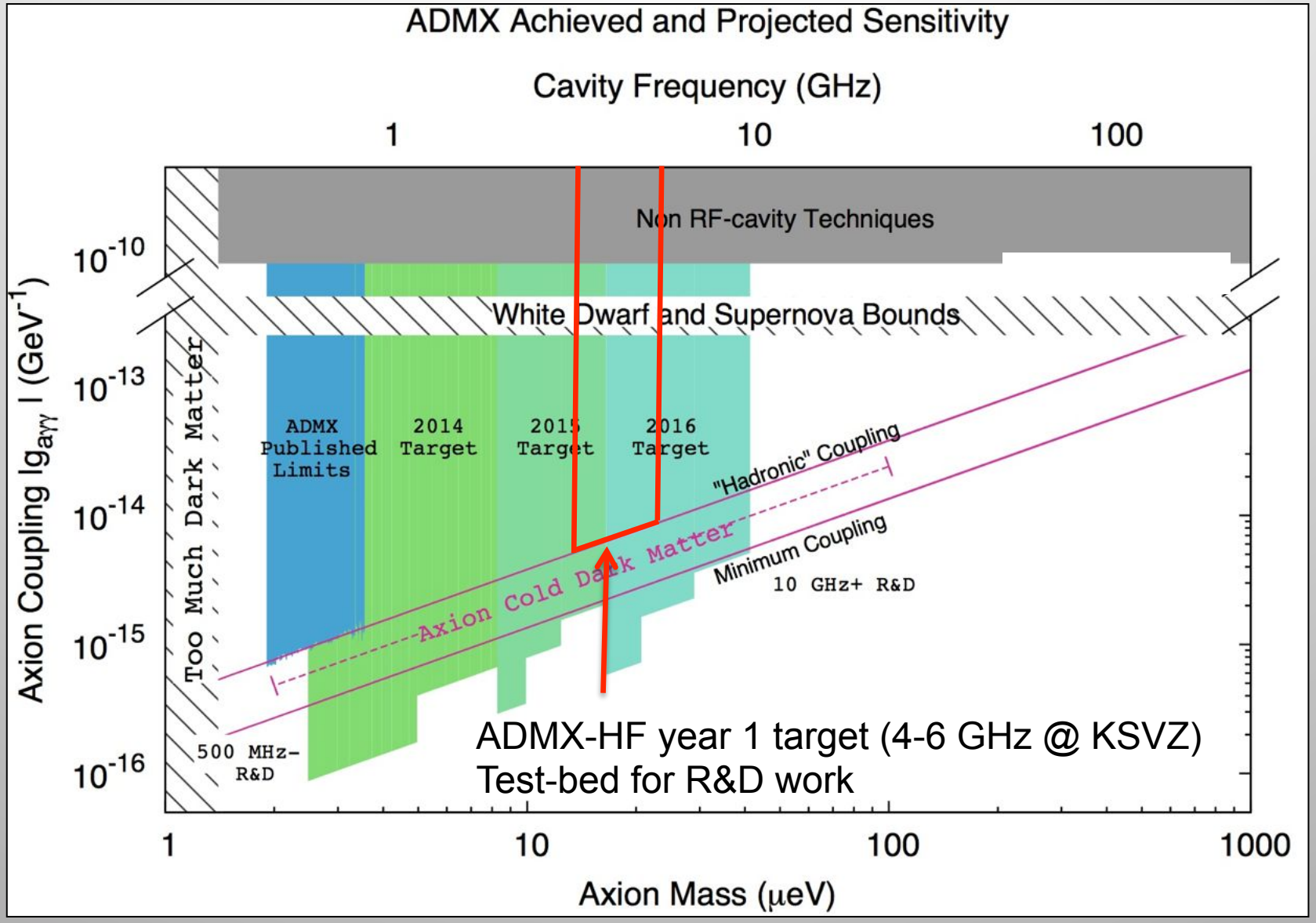
Second ADMX site: Yale University – NSF Sponsored
PI: Prof. Steve Lamoreaux

- New Superconducting Magnet 5” diameter, 20” long, 9.4 T
- Dilution fridge already in place.

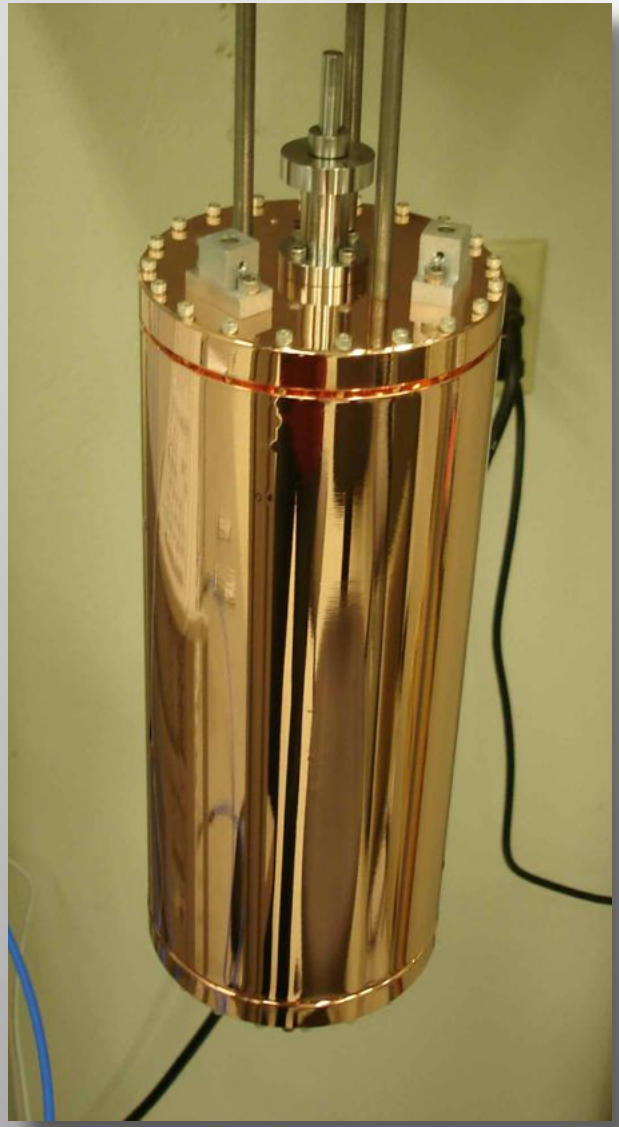


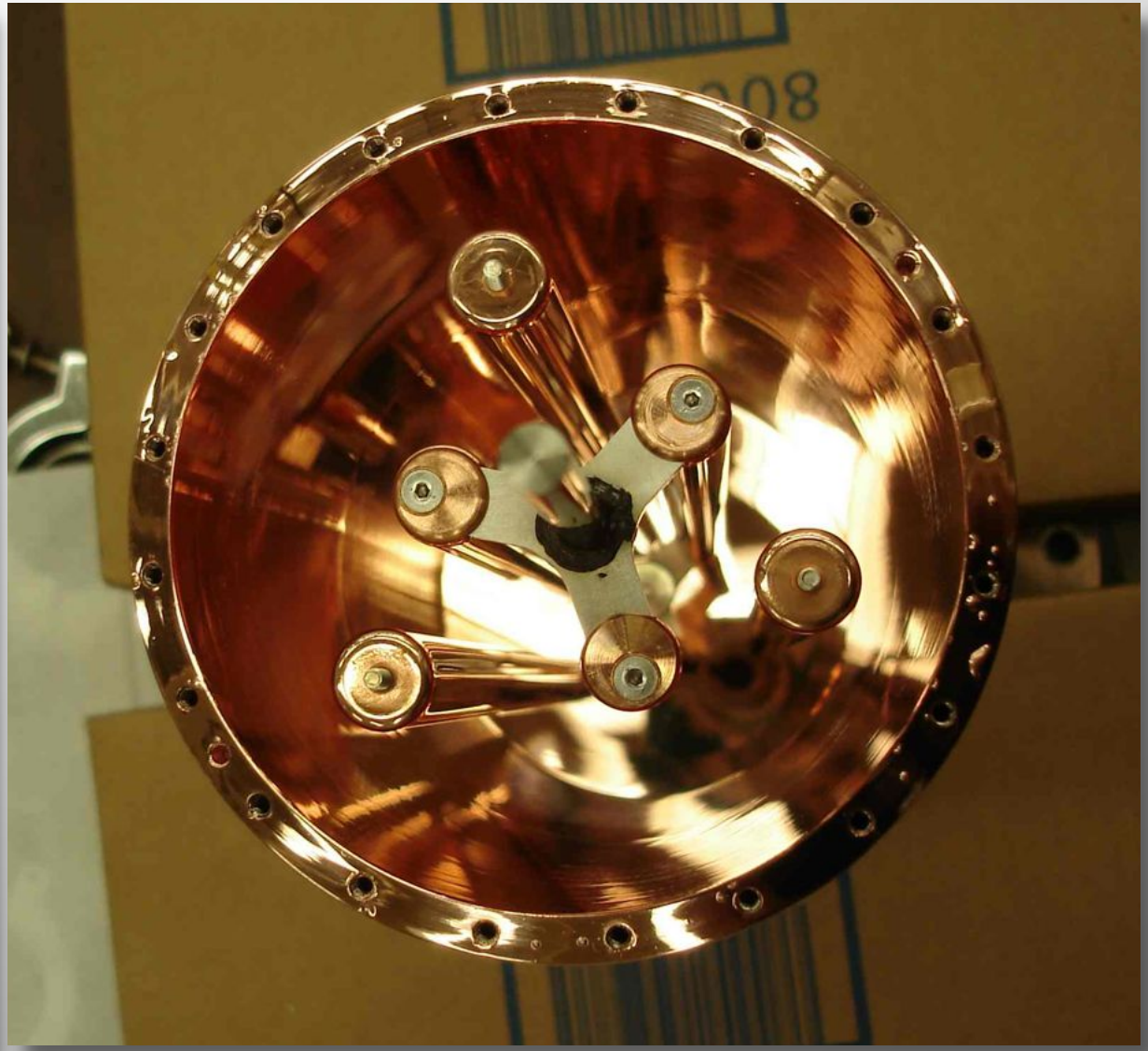


ADMX-HF

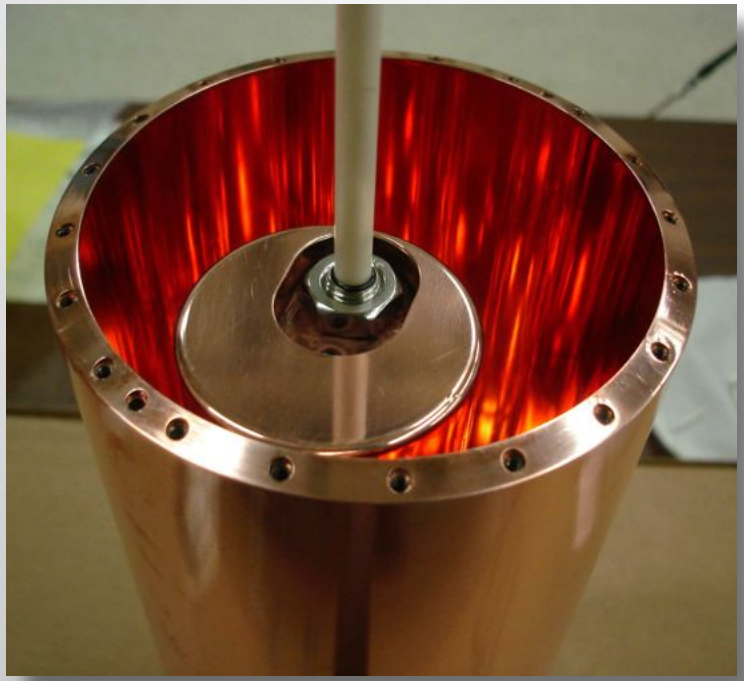

ADMX Achieved and Projected Sensitivity
Cavity Frequency (GHz)
1
10
100
Non RF-cavity Techniques
White Dwarf and Supernova Bounds
Too Much Dark Matter
ADMX Published Limits
2014 Target
2015 Target
2016 Target
"Hadronic" Coupling
Minimum Coupling
Axion Cold Dark Matter
10 GHz+ R&D
500 MHz-R&D
ADMX-HF year 1 target (4-6 GHz @ KSVZ)
Test-bed for R&D work
Axion Coupling $|g_{a\gamma\gamma}|$ (GeV^{-1})
10^{-10}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
1
10
100
1000
Axion Mass (μeV)

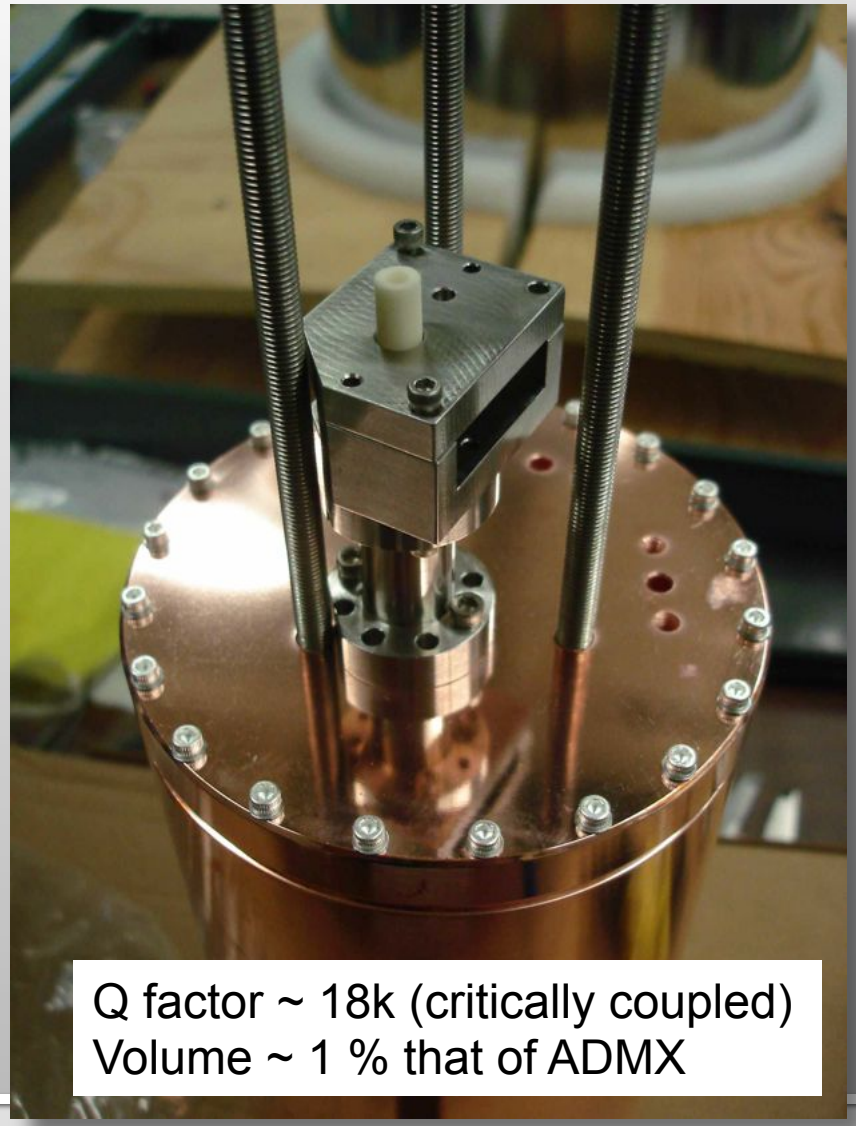
Cavity #1 – Stator-Rotor design (3+3)





Cavity #2 – Single rod ("internal pivot") design



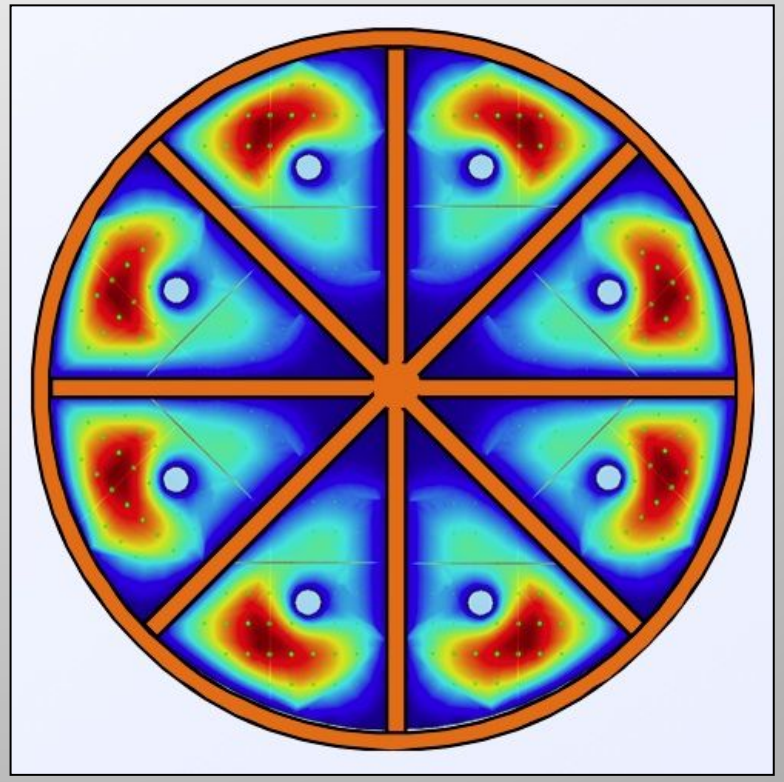


Q factor ~ 18k (critically coupled)
Volume ~ 1 % that of ADMX

Goal: Higher frequencies without sacrificing volume

- Multiple cavities in magnet bore
- 4 cavity run: D. Kinion Thesis
- Difficult to scale to > 8 cavities

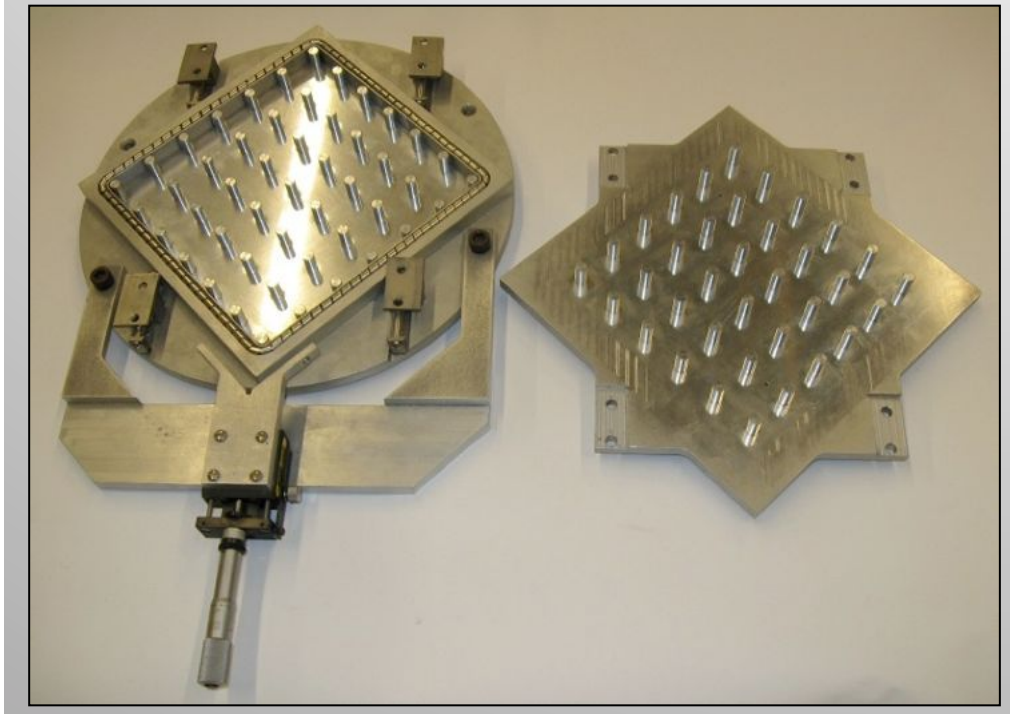
- Split cavity (U. of Florida R&D)
- Similar to multiple cavity but uses common cylinder.
- Also difficult to scale > 8 segments



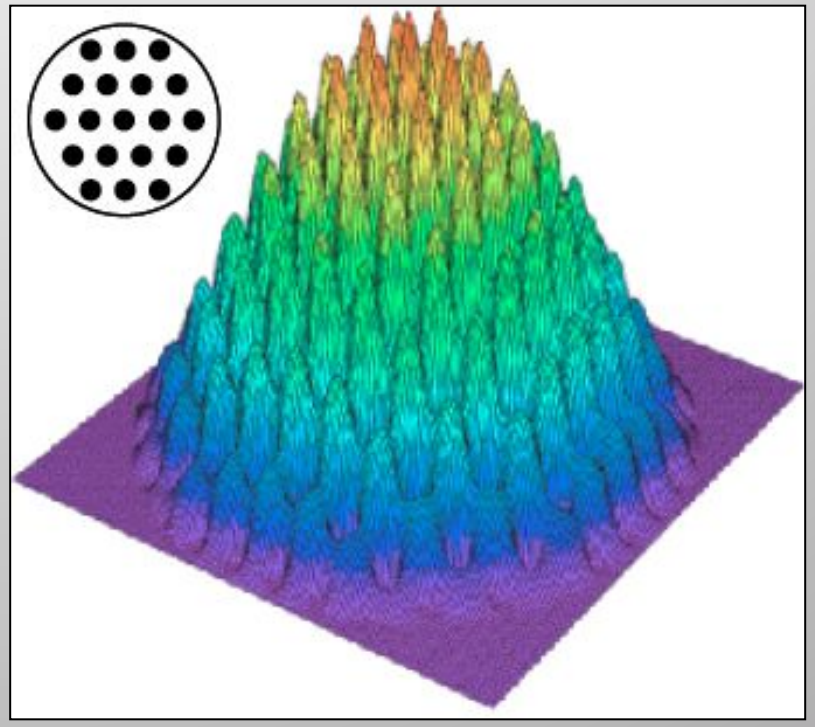
LLNL R&D effort ECRP – Multipost cavity systems

- Analog of photonic bandgap resonator
- Various posts can be translated as group to adjust frequency.
- Can maintain reasonably large volume and form factor

- 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



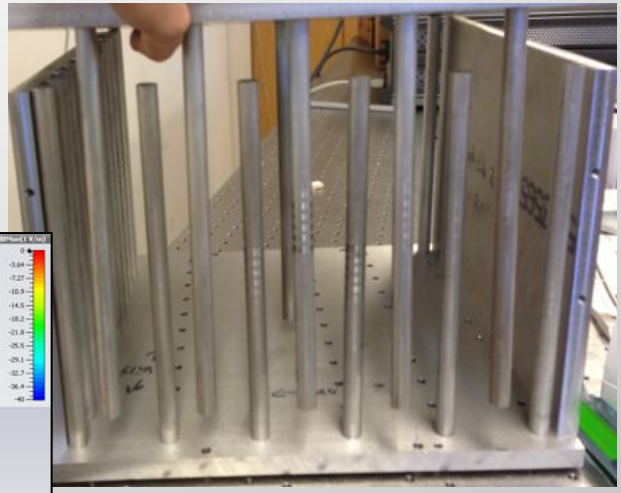
Prototype multipost cavity

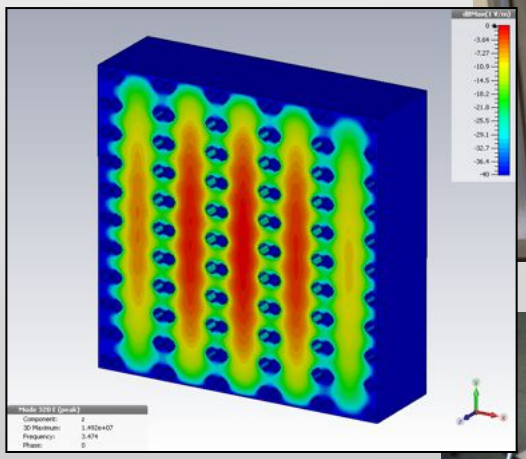


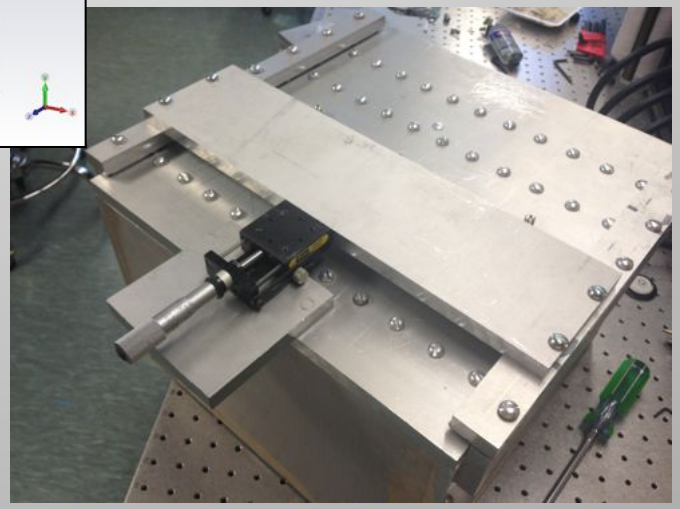
*C. Hagmann simulation

Multipost Cavity – R&D project
LLNL sponsored Harvey Mudd Clinic Team (2012-2013)

- 121 post cavity out of 6061 aluminum
  - Resonant frequency of at least 5.05 GHz
  - 26% tuning range (5 GHz – 3.9 GHz)
  - Maximized figure of merit
  - Poor Q ~ few hundred





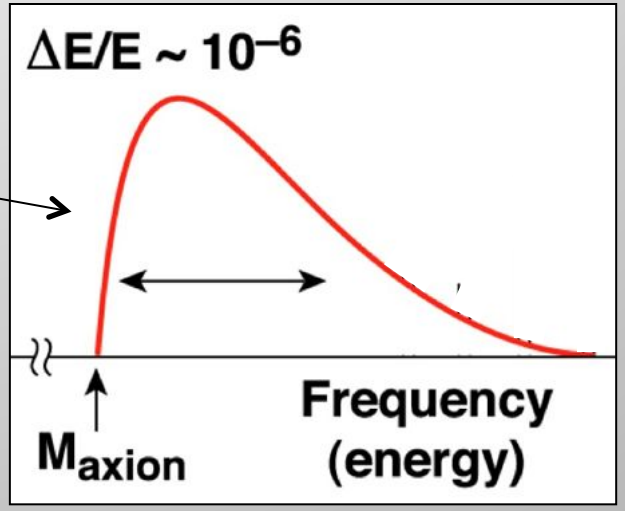


- Interesting candidate to run a bead-pull (physically measure E-field with dielectric bead that perturbs the resonant mode)
- Polish up to run at cryogenic temps.

The "Hybrid" superconducting cavity concept

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

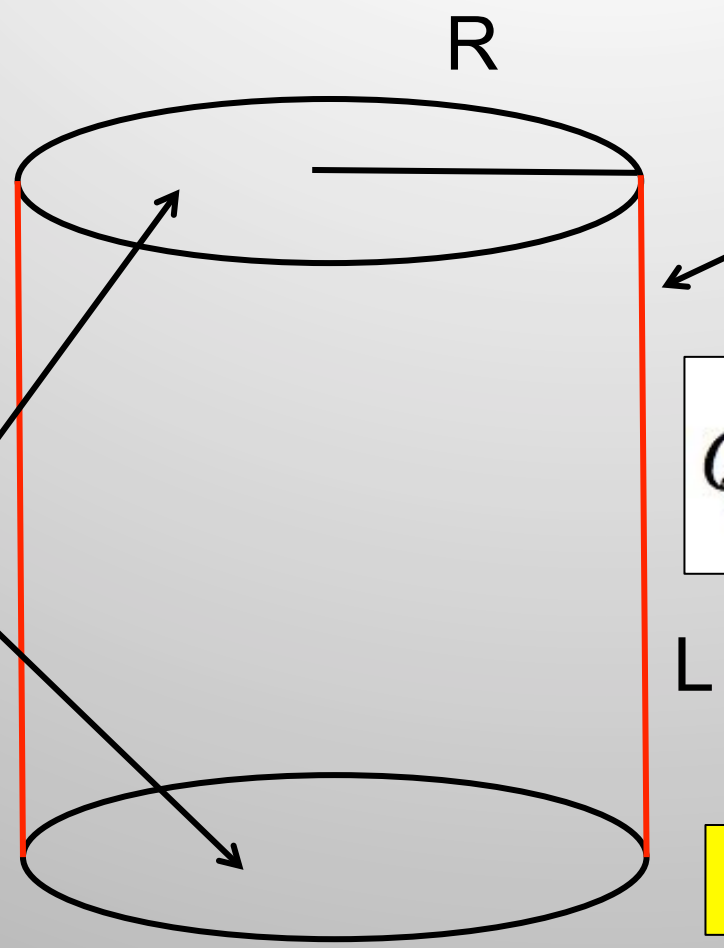
Q_a = axion linewidth (gravitational thermalization)
~ $E/\Delta E \sim 1/\beta^2 \sim 1/(100\ \mathrm{km/s})^2 \sim 10^6$
1 GHz mass axion should be spread over 1 kHz



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



Thin film
Superconducting barrel

Copper
end caps

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

Skin depth of Copper

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

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

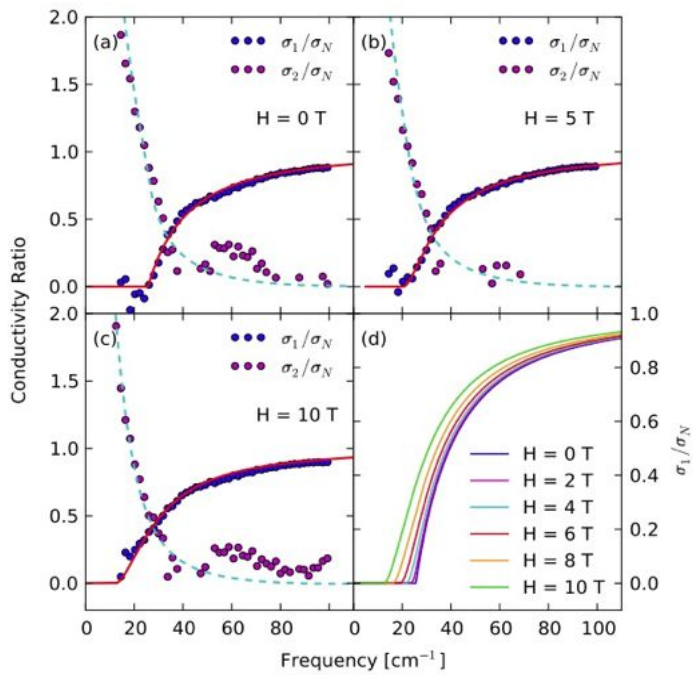
The science of thin-film superconductors is mature

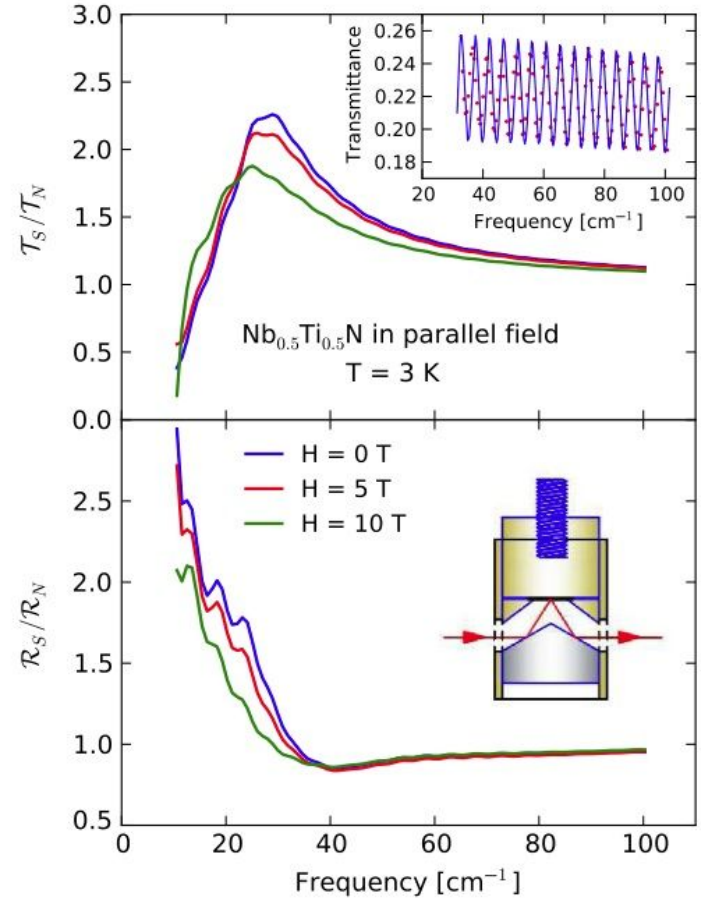
Far-Infrared Conductivity Measurements of Pair Breaking in Superconducting $Nb_{0.5}Ti_{0.5}N$ Thin Films Induced by an External Magnetic Field

Xiaoxiang Xi,[1] J. Hwang,[1,2] C. Martin,[1] D. B. Tanner,[1] and G. L. Carr[3]
[1]*Department of Physics, University of Florida, Gainesville, Florida 32611, USA*
[2]*Department of Physics, Pusan National University, Busan 609-735, Republic of Korea*
[3]*National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973, USA*
(Received 16 August 2010; published 16 December 2010)

We report the complex optical conductivity of a superconducting thin film of $Nb_{0.5}Ti_{0.5}N$ in an external magnetic field. The field was applied parallel to the film surface and the conductivity extracted from far-infrared transmission and reflection measurements. The real part shows the superconducting gap, which we observe to be suppressed by the applied magnetic field. We compare our results with the pair-breaking theory of Abrikosov and Gor'kov and confirm directly the theory's validity for the optical conductivity.

DOI: 10.1103/PhysRevLett.105.257006 PACS numbers: 74.78.−w, 74.25.Ha, 78.20.−e, 78.30.−j

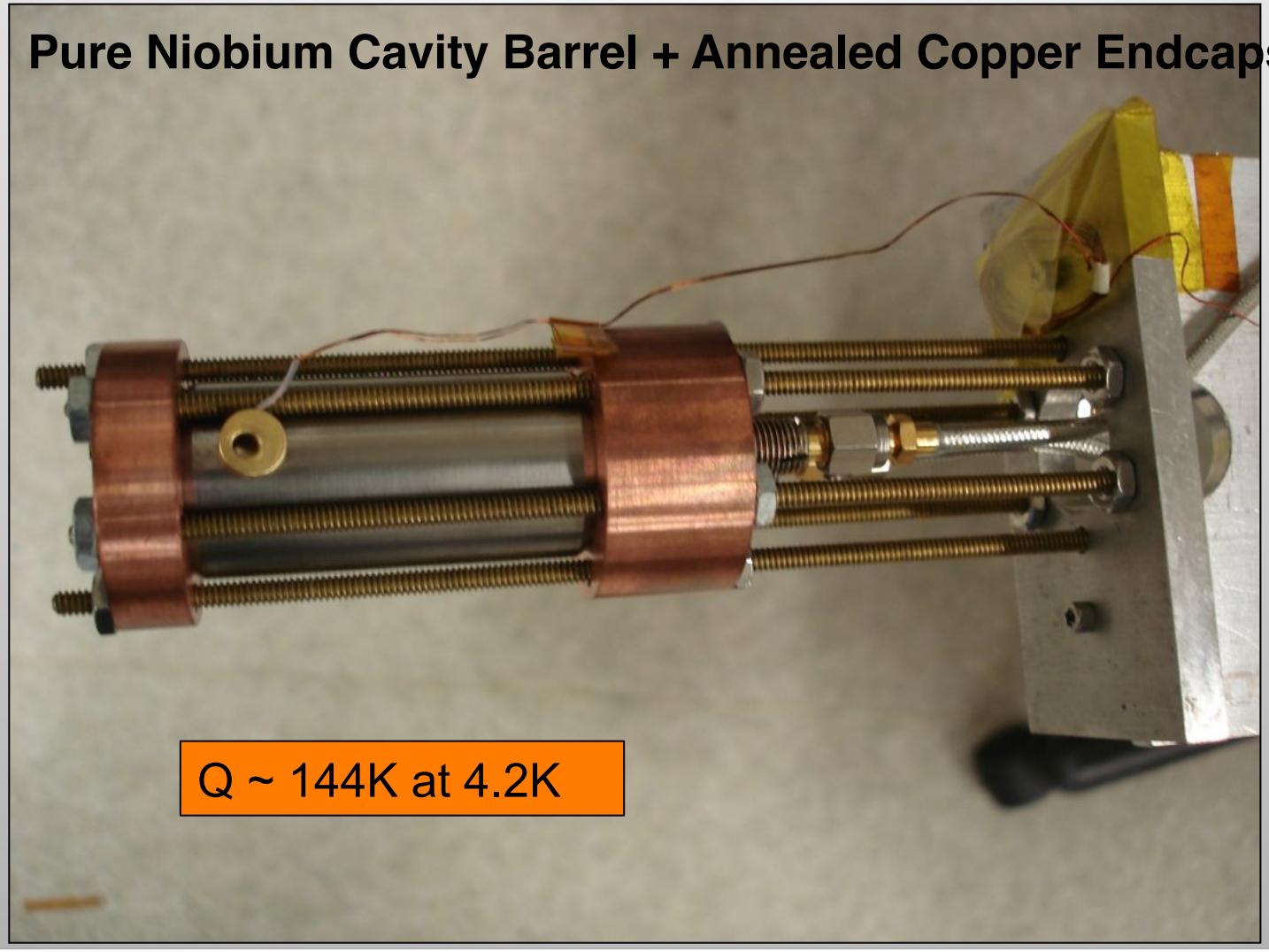




10 nm of $Nb_{0.5}Ti_{0.5}N$ is perfect

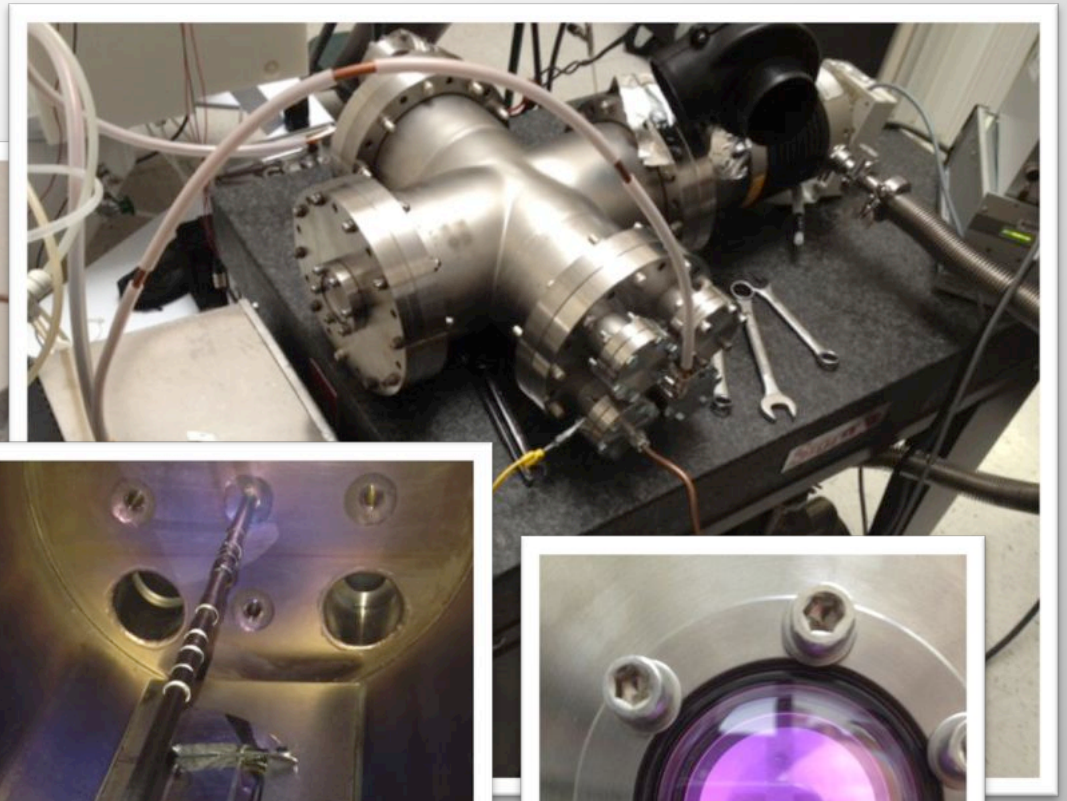
Supports $B_{||}$ up to 10 Tesla

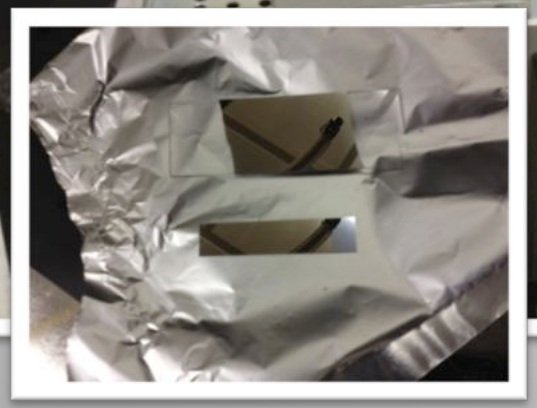
Reference Cavity: Radius ~ 0.5” / Length ~ 2” / TM_{010} ~ 10 GHz

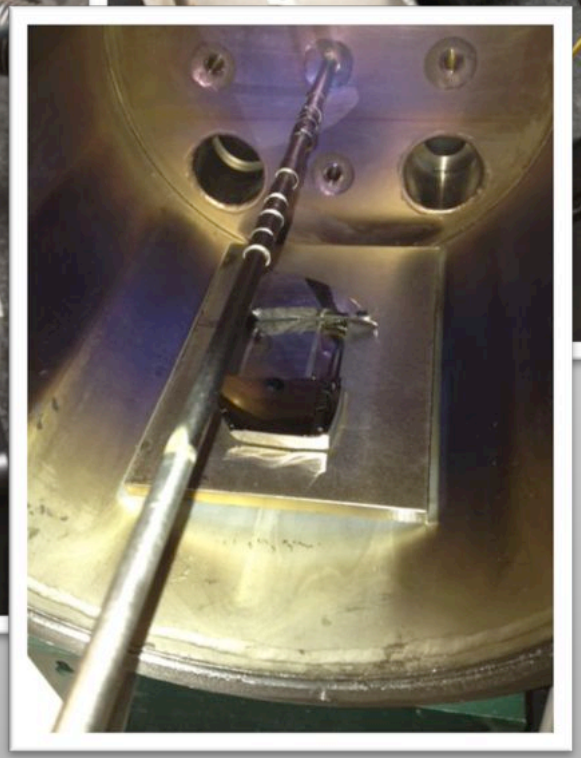


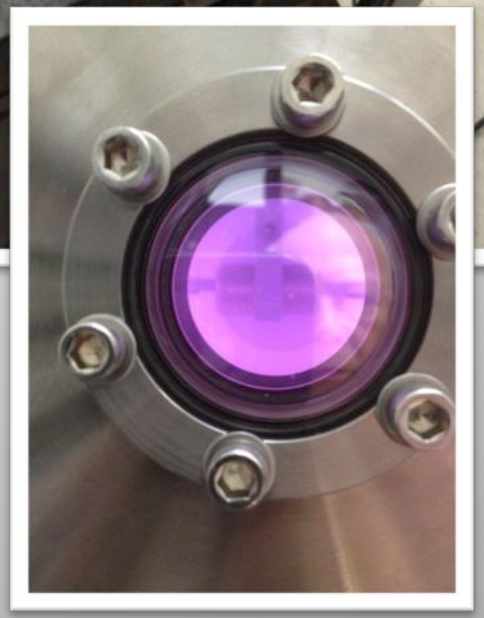
Current using RF sputtering system to explore NbTiN coatings

Base pressure < 10^{-7} torr

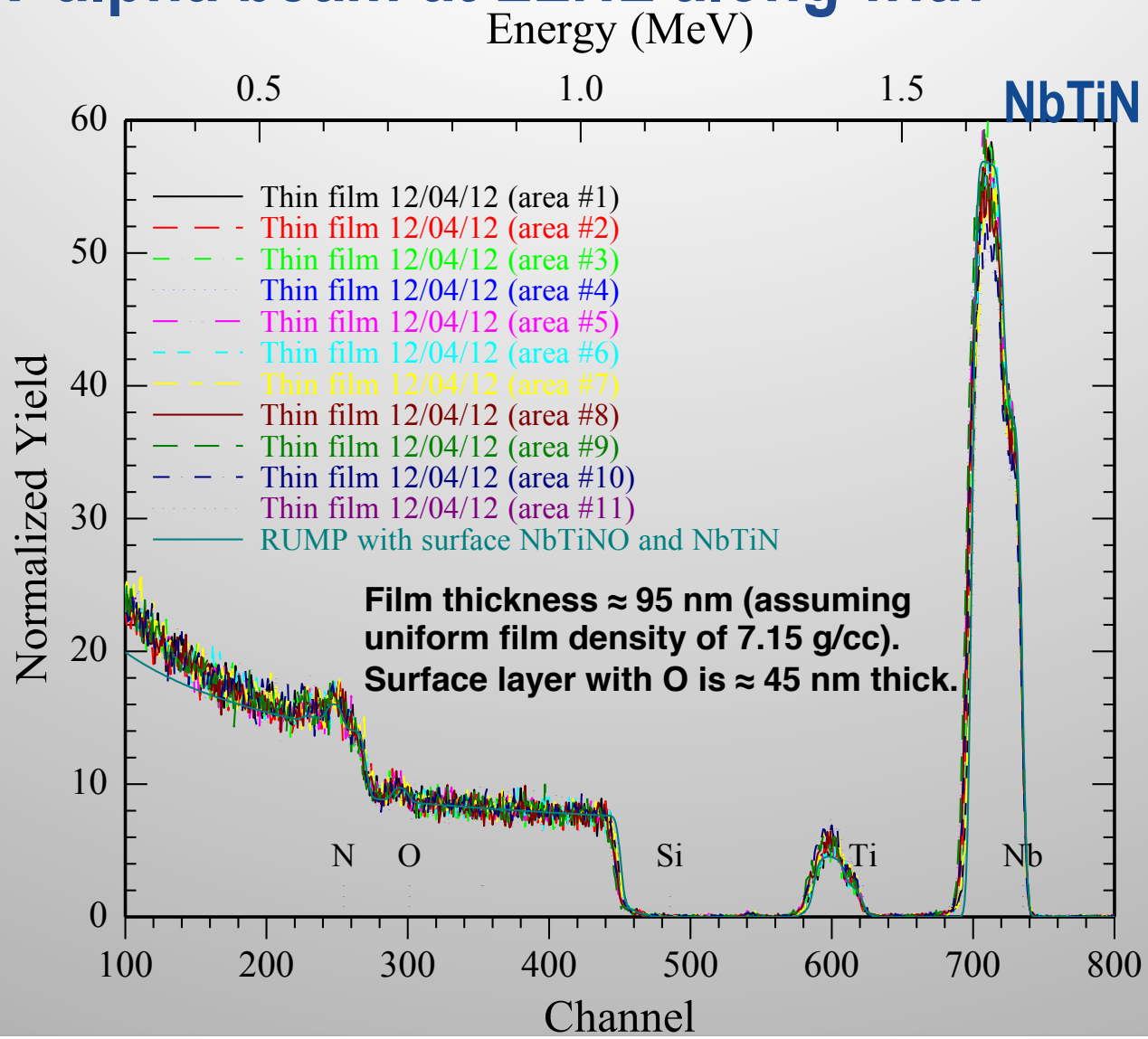








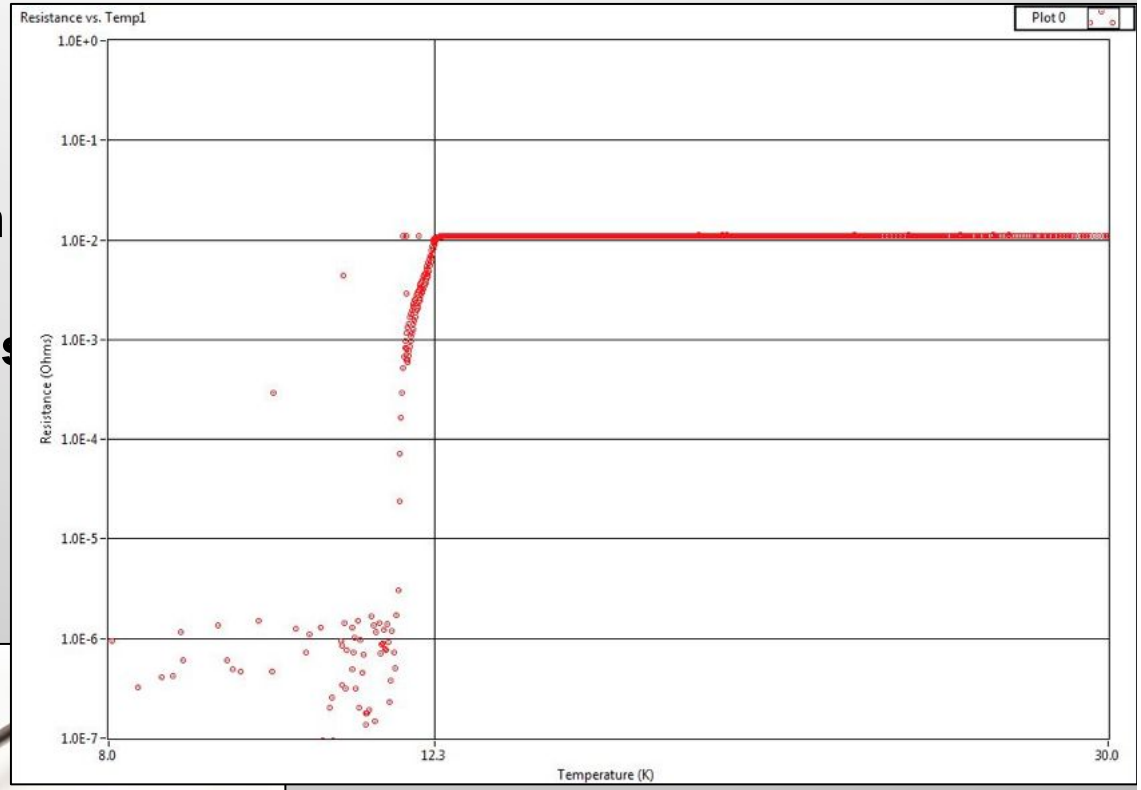
Rutherford Backscattering Analysis
4 MeV alpha beam at LLNL along with



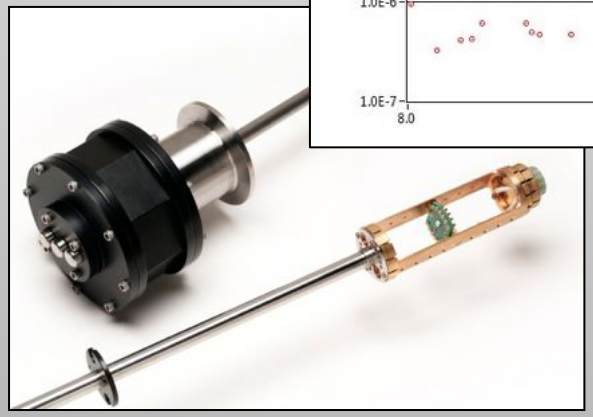
Next steps for hybrid cavity

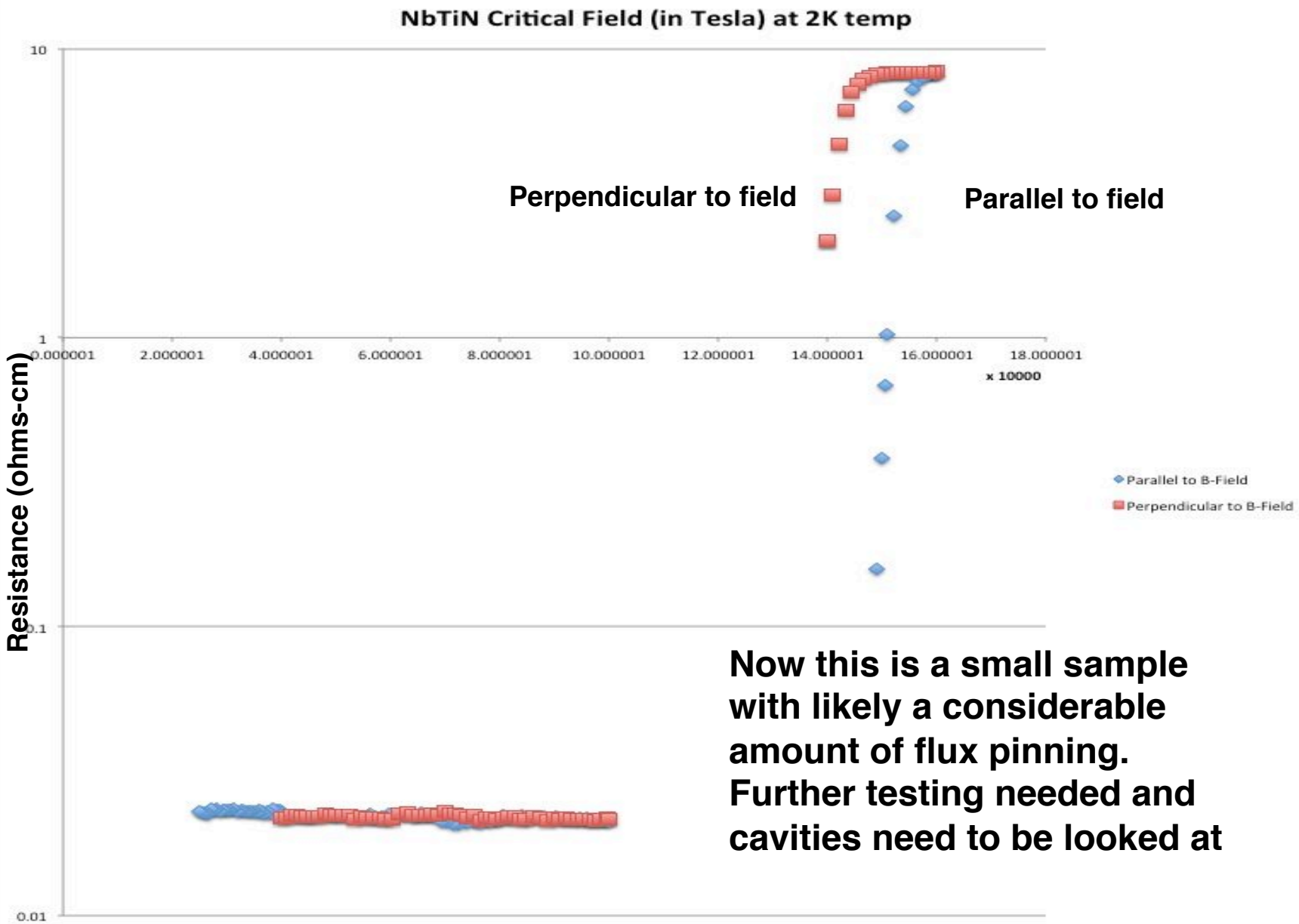
Continue to develop NbTiN thin films with as high T_C as possible:
$R_S \sim f^2 \cdot e^{(-1.76 \cdot T_C/T)}$

Utilize LLNL Quantum Design 16 T magnet (Temps ~ 1.9K)
A. Thin-films at various angles
B. Cavity Barrels
C. Scale up to ADMX-HF

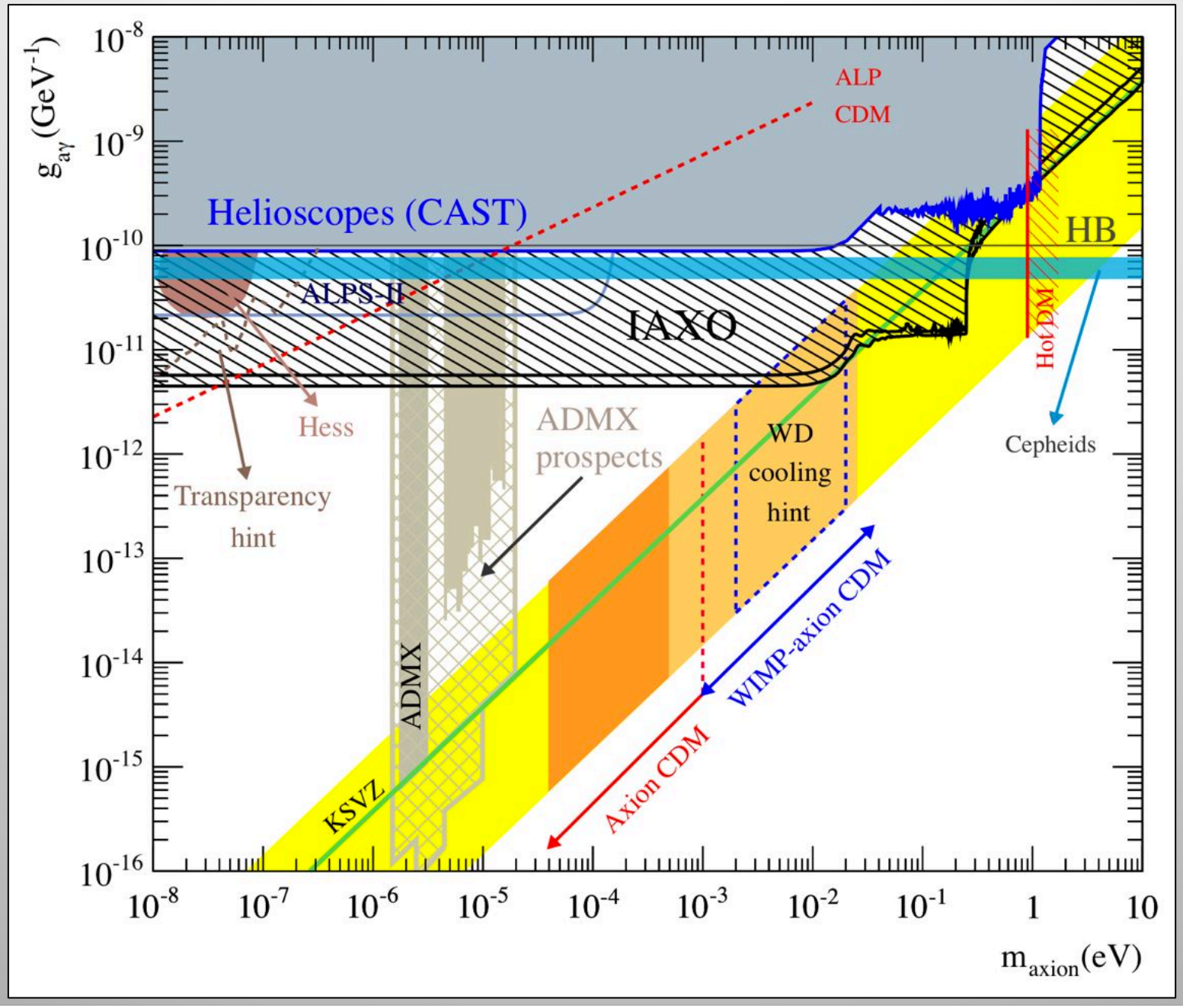


12.3 k transition temperature
(aim for films > 14 k)





Now this is a small sample with likely a considerable amount of flux pinning. Further testing needed and cavities need to be looked at


$g_{a\gamma}$ (GeV^{-1})
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
ALP
CDM
Helioscopes (CAST)
HB
ALPS-II
IAXO
Hot DM
Hess
ADMX
prospects
WD
cooling
hint
Cepheids
Transparency
hint
WIMP-axion CDM
ADMX
KSVZ
Axion CDM
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion}(eV)

Conclusions

- **ADMX Phase II currently operational with 1K pot**
  - **Final setup with dilution fridge ~ 100 mK base temp (Jan)**
  - **Backup ^{3}He fridge ~ 400 mK base temp (Dec)**
- **ADMX-HF currently being commissioned**
  - **Commissioned this summer with production data-taking starting December.**
- **LLNL contributing to construction and R&D**
  - **Microwave Cavities**
  - **Tuning rod & antenna motion control**
  - **RF test-stand for parallel testing during data taking**
  - **Early Career Research Program**

    R&D effort on high-frequency microwave cavities

    - large multi-post & multi-segment cavities

    - "hybrid" superconducting cavities

Questions?