Searching for Dark Matter Axions with ADMX

Aspen Winter Meeting – "Closing in on Dark Matter"
Feb 1st, 2013

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LLNL-PRES-560861

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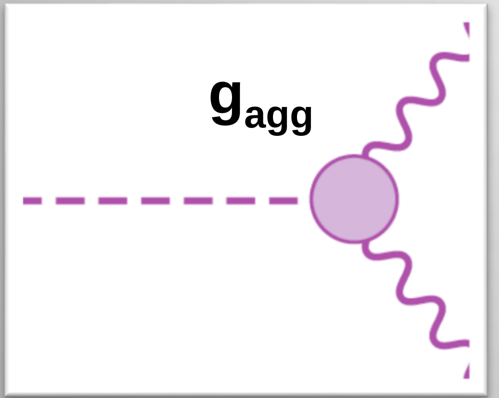
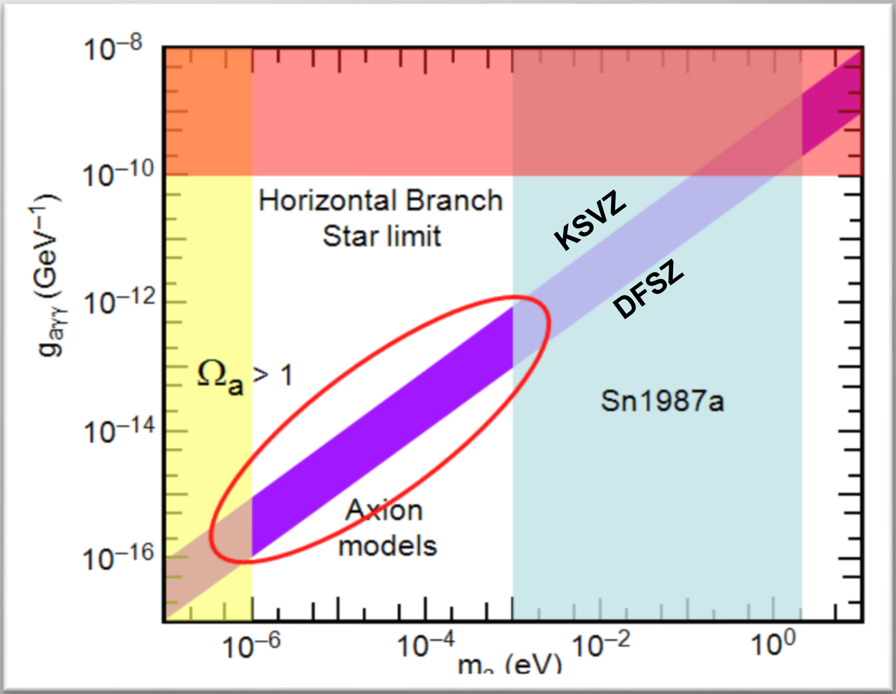
The axion.

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

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

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





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

ADMX collaboration (DOE – Office of Science – HEP)

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

Gianpaolo Carosi, Darrell Carter, Chris Hagmann, Darin Kinion, Wolfgang Stoeffl

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, John Clarke, Jaben Root

Sheffield University

Edward Daw

Yale University (ADMX-HF - NSF sponsored)

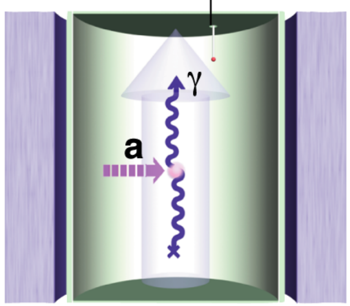
Steve Lamoreaux, Yulia Gurevich., Ben Brubaker, Sidney Cahen

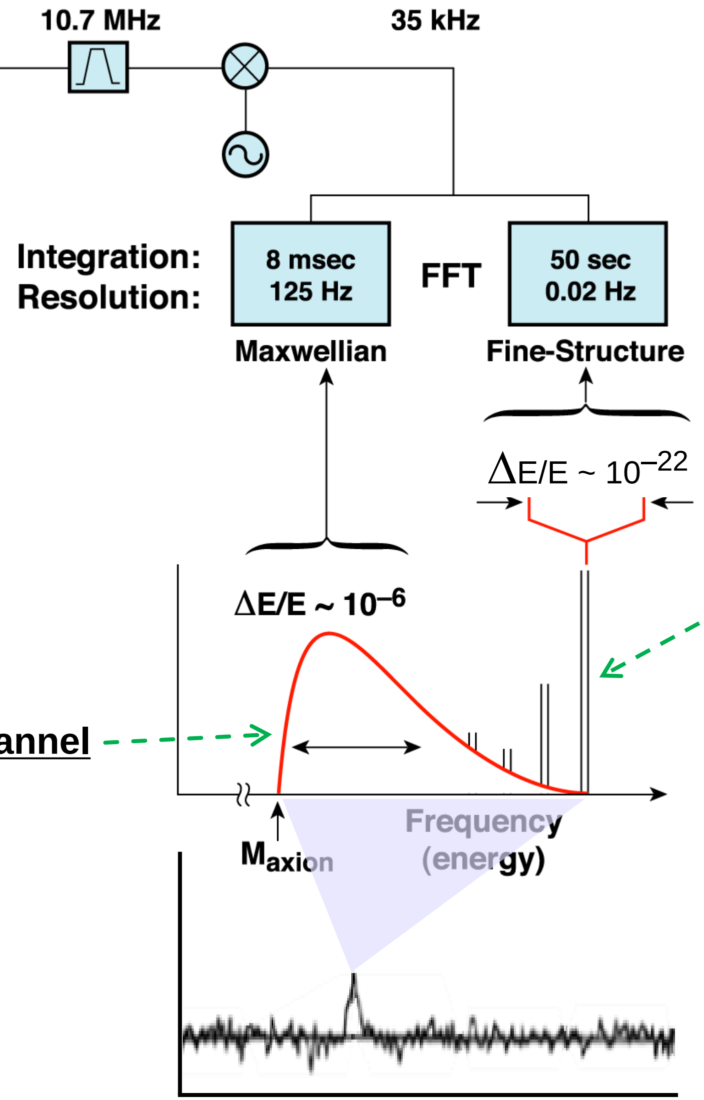
University of Colorado (ADMX-HF – NSF sponsored)

Konrad Lenhert, Memhet Ali

ADMX collaboration (at least a good portion of us)

The Axion Dark Matter eXperiment





Local Milky Way density:

ρ_{halo} ~ 450 MeV/cm^3

Thus for m_a ~ 10 μeV:

ρ_{halo} ~ 10^{14} cm^{-3}

"High Resolution" channel

β_{virial} ~ 10^{-7} :

$\lambda_{De\ Broglie}$ ~ 1000 km

"Medium Resolution" channel

β_{virial} ~ 10^{-3} :

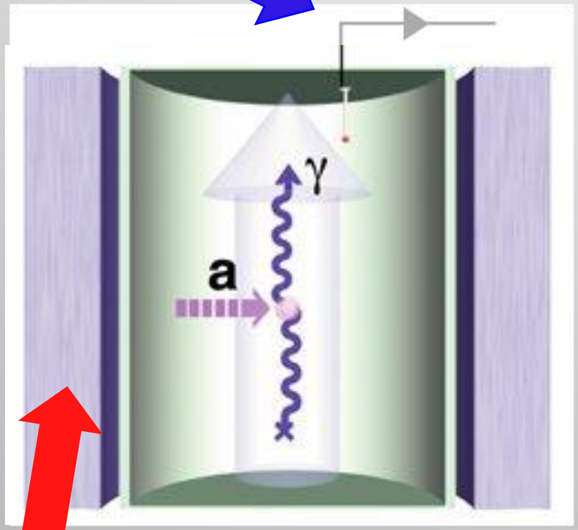
$\lambda_{De\ Broglie}$ ~ 100 m

The radiometer equation dictates search 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

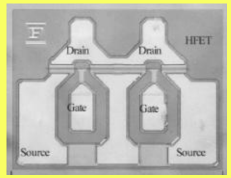
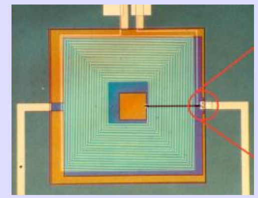
HAVE INVESTED HERE!

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

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

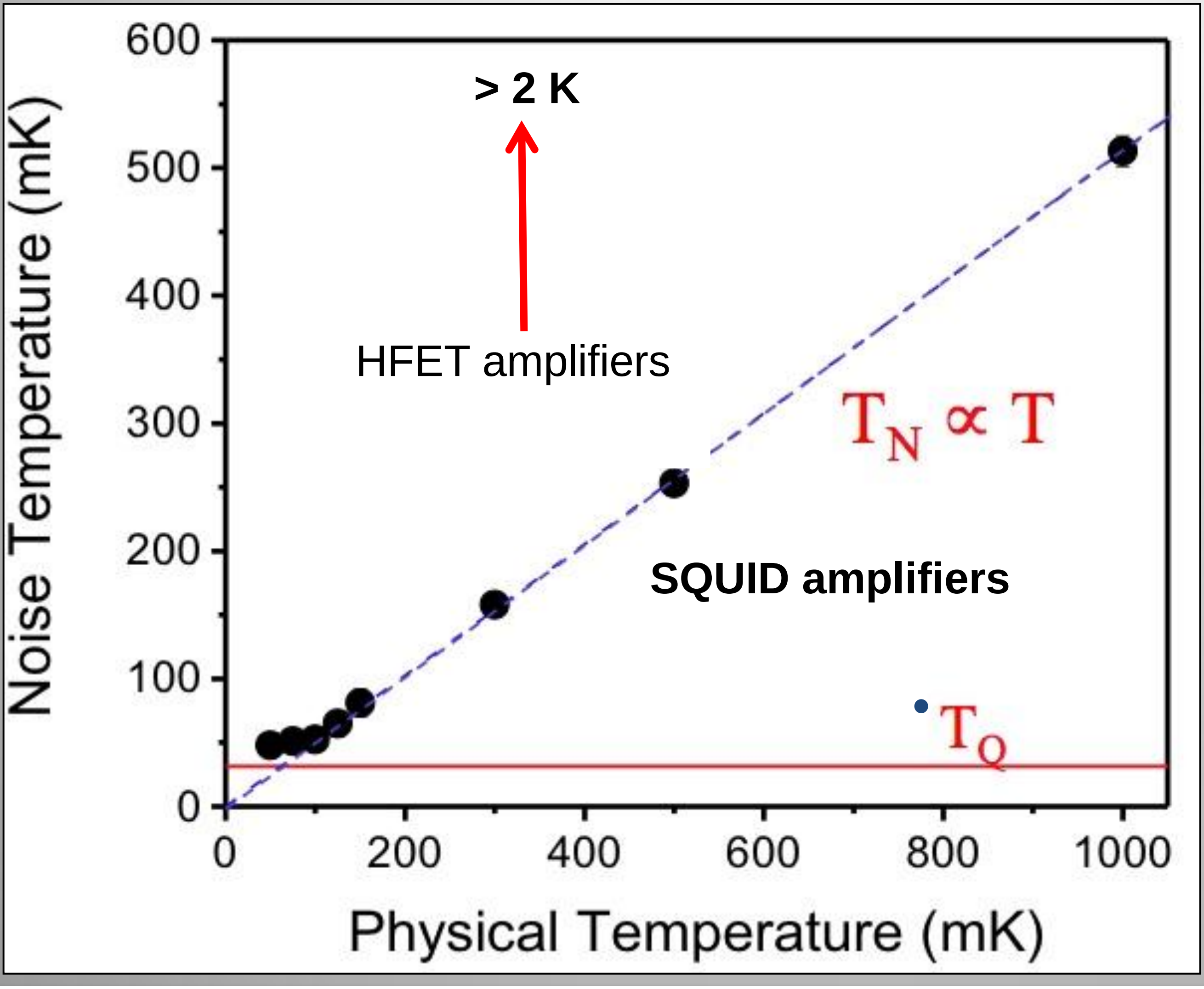
But magnet size, strength B^2V ~ \$

The Axion Dark Matter eXperiment – various phases

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

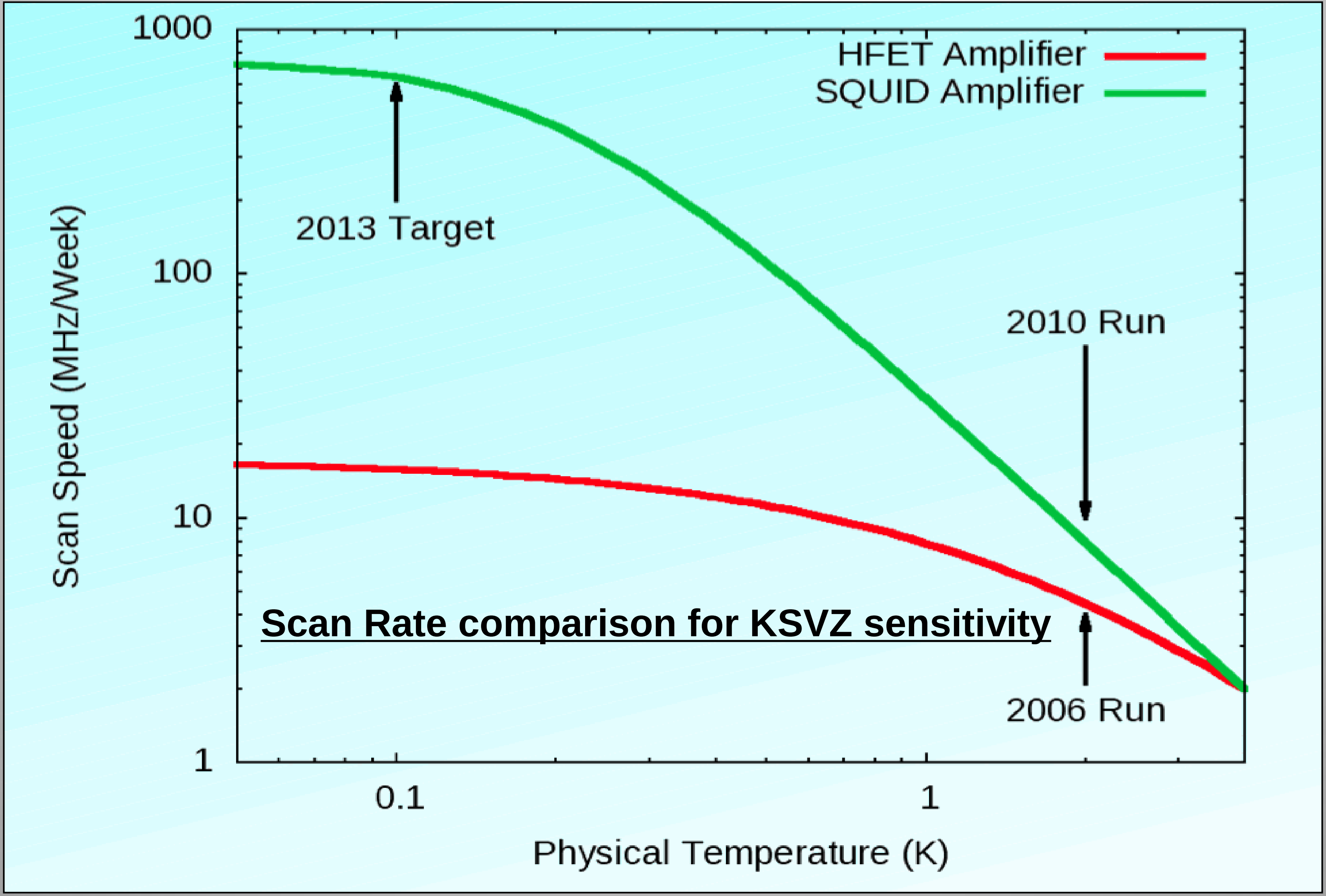
Successfully took data
2008 - 2010

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



- **SQUIDs have been measured with T_N ~ 50 mK**
- **Near quantum– limited noise**
- **Provides an enormous increase in ADMX sensitivity**

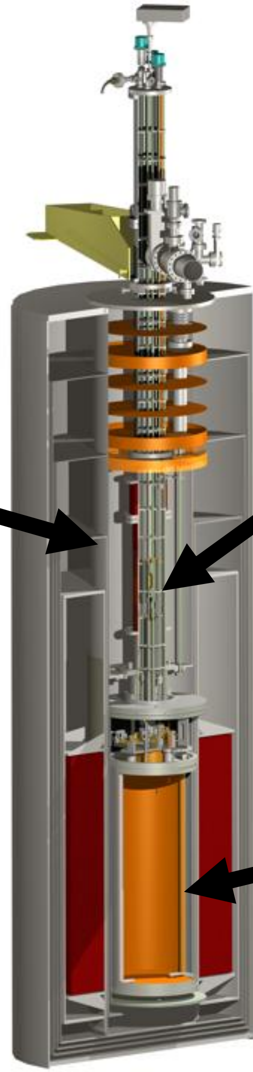
A cold SQUID amplifier greatly increases scan rate



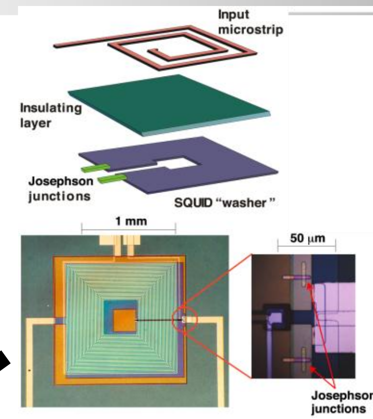
ADMX Experimental Layout



Field compensation magnet for SQUIDs



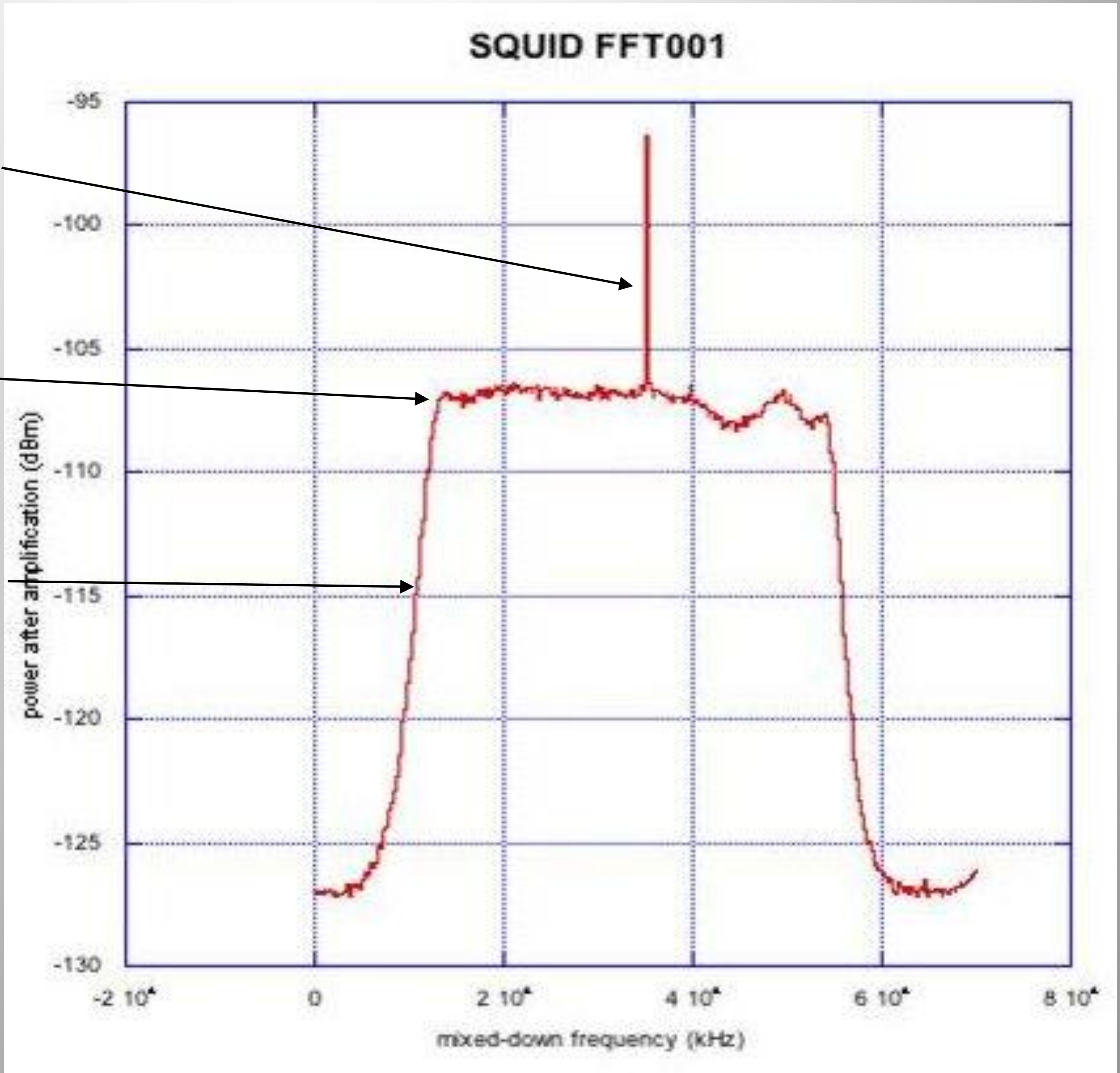
SQUID amplifier



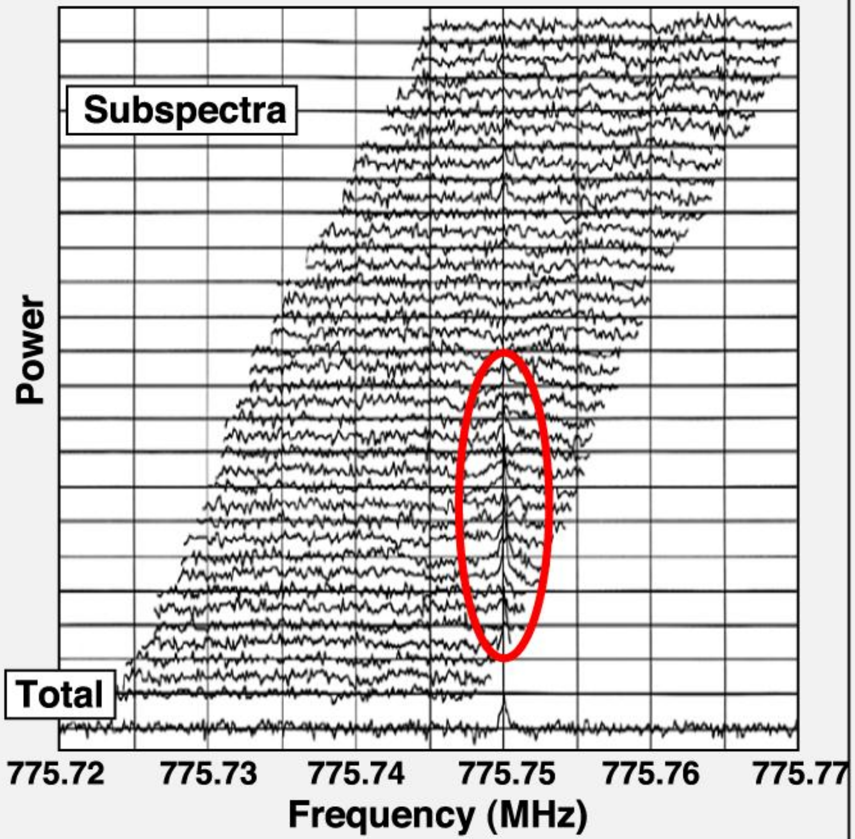
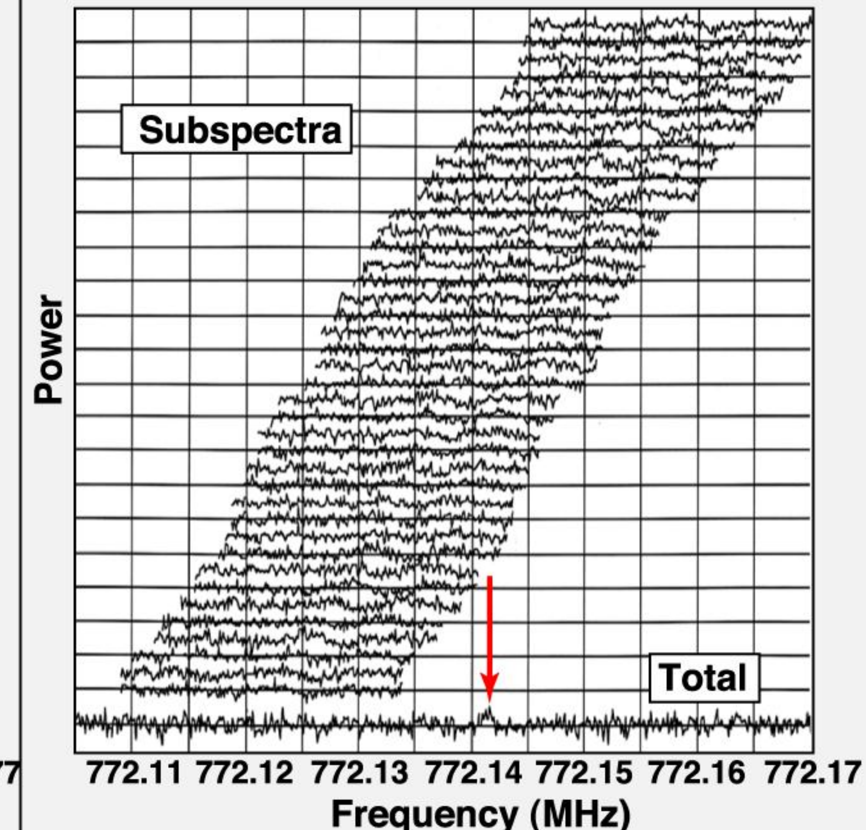
Microwave Cavity


Example of single injected signal (with SQUID amplifiers)

- Injected Power
- Noise floor
- Bandpass filter

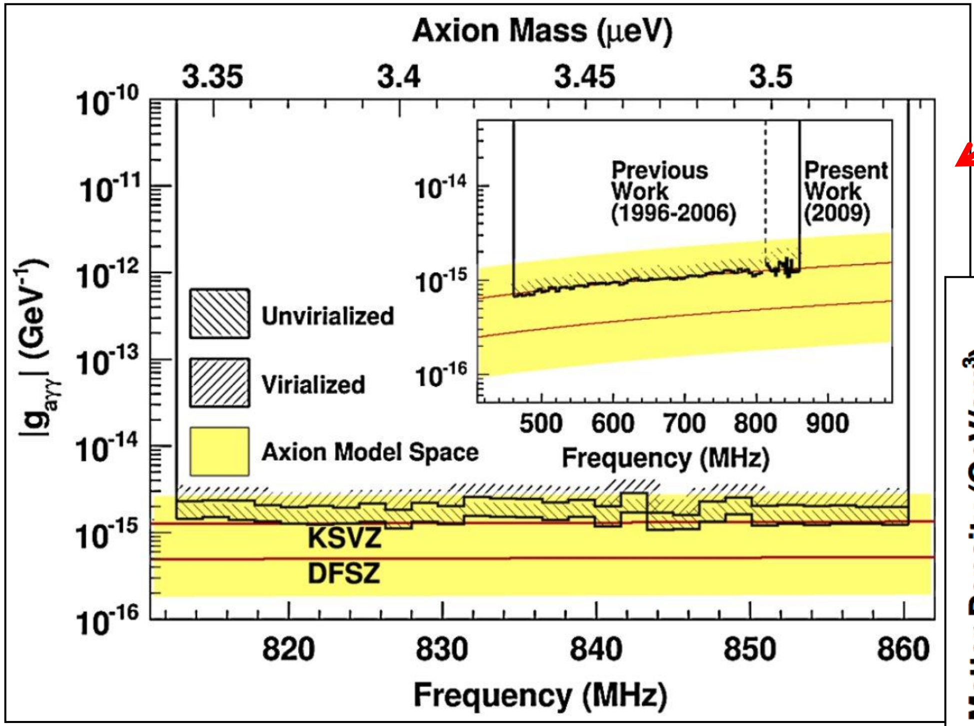


Sample data and candidates

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

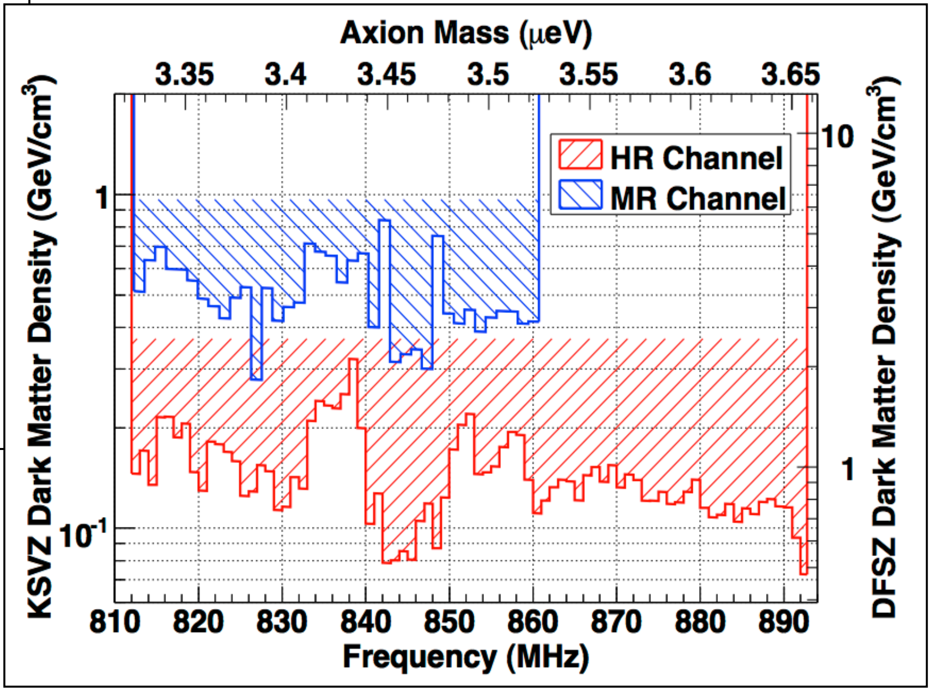
ADMX Phase I

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

ADMX: Moved from LLNL to the U. of Washington

Moved Main Magnet at LN2 temperatures Summer 2010

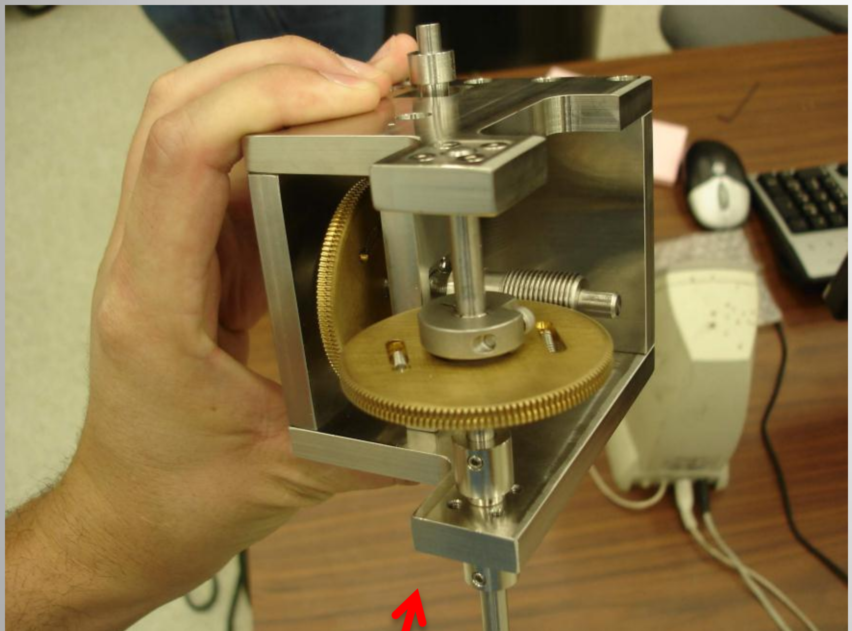
ADMX Main Magnet installed at CENPA, U.W.

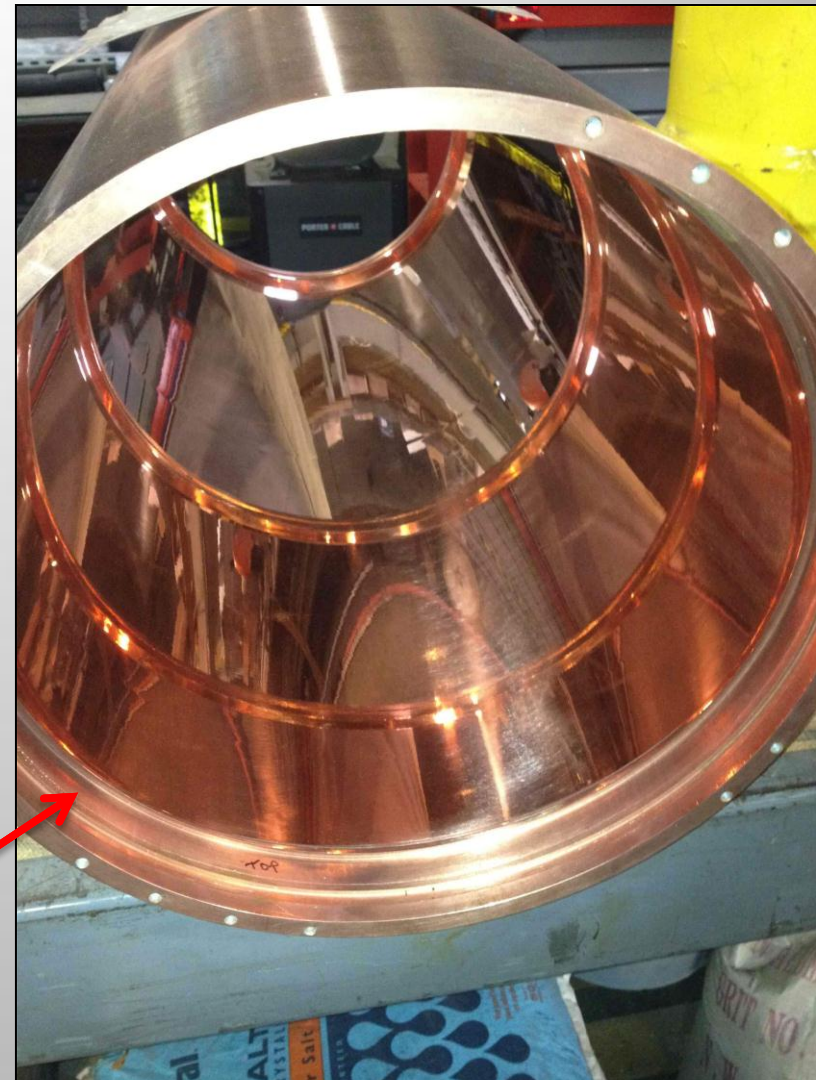
ADMX Phase II construction well underway!

Top Plate welded and leak tested.

Bucking magnet installed in new reservoir

ADMX Phase II construction well underway!

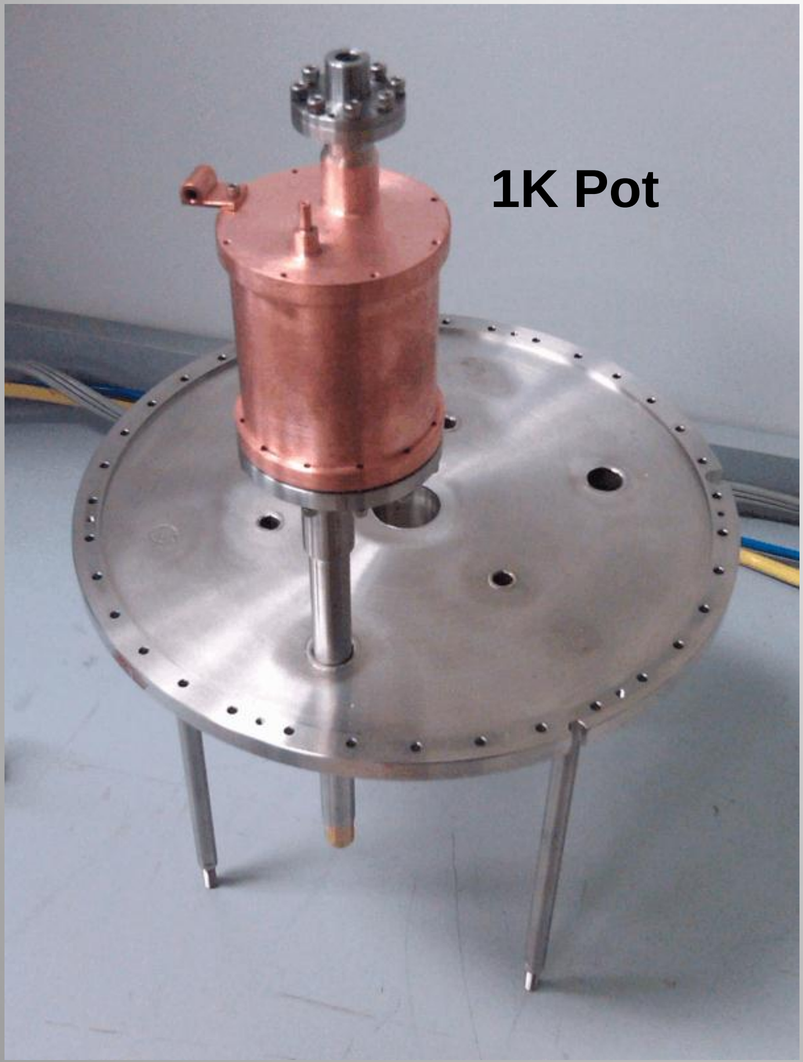




New modular gear systems (19600:1 reduction)

Newly plated microwave cavity

ADMX Phase II: Cryogenics being design by U. of Florida (N. Sullivan)



Have been approved for 50 liters STP He3.

Initially data run with pumped He^3 pot to ~ 400 mK while awaiting dilution refrigerator.

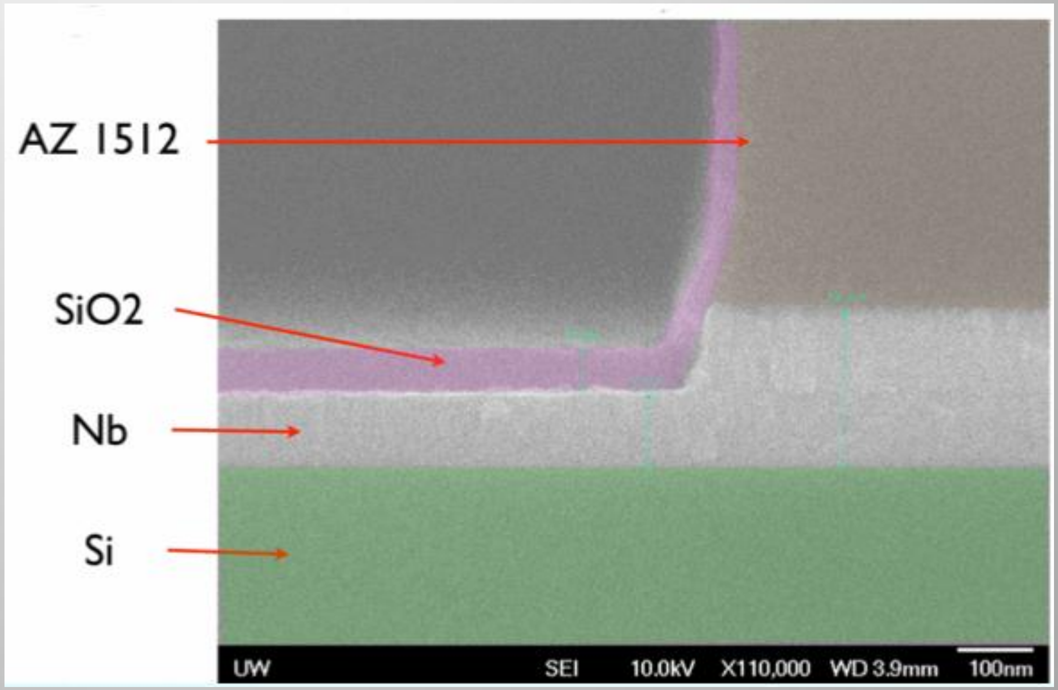
Much of the same infrastructure will be used for dilution fridge ~ 100 mK.

Dilution Refrigerator based on Janis 750 model

Amplifiers: Steady stream of SQUID and HFET amps

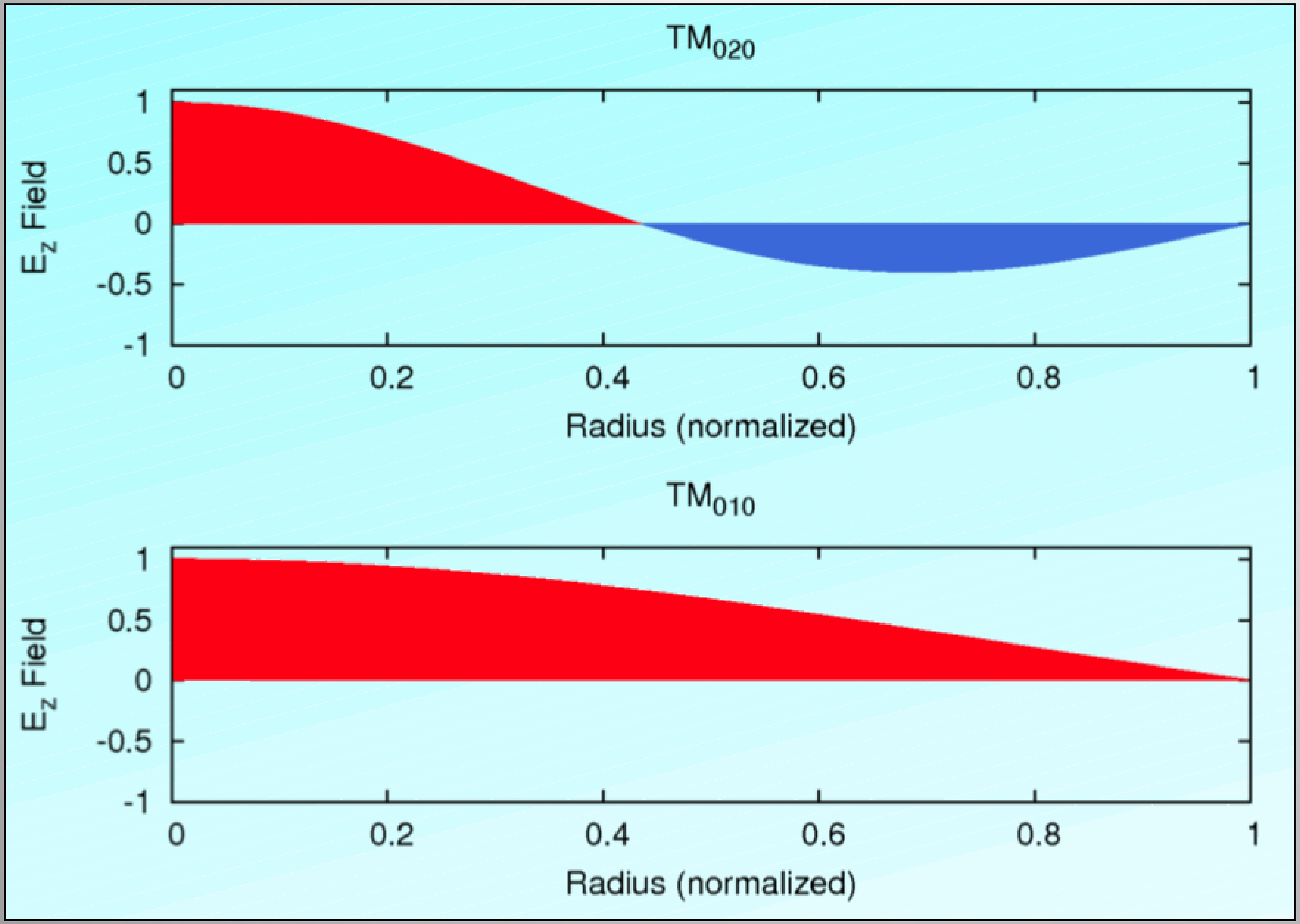
John Clarke's group at UC Berkeley providing baseline SQUID amplifiers

Andrew Wagner coming up to speed to be local (UW) SQUID manufacturer



Richard Bradley at NRAO onboard to provide 2nd stage HFET amps

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 Phase II: Large amount of Technical Upgrades!

- Helium Liquifier
- Improved Cryogenics
- Piezoelectric Rod Motion
- Rod location Tracking
- Improved Thermometry
- Real-Time Analysis
- Clean assembly Area
- Better Cavity Modeling
- New Paint Job
- HFET Bias Monitor
- Dynamic SQUID Gain Monitoring
- In-Situ Noise Calibration Suite
- Tunable SQUIDs
- Improved Receiver Chain
- Digital Filtering
- Better Timing Standard
- Cavity Plating Upgrade
- All High Resolution Time Series Data
- New Magnet Leads

Current Schedule

Summer 2011 Funding for Phase II arrived!

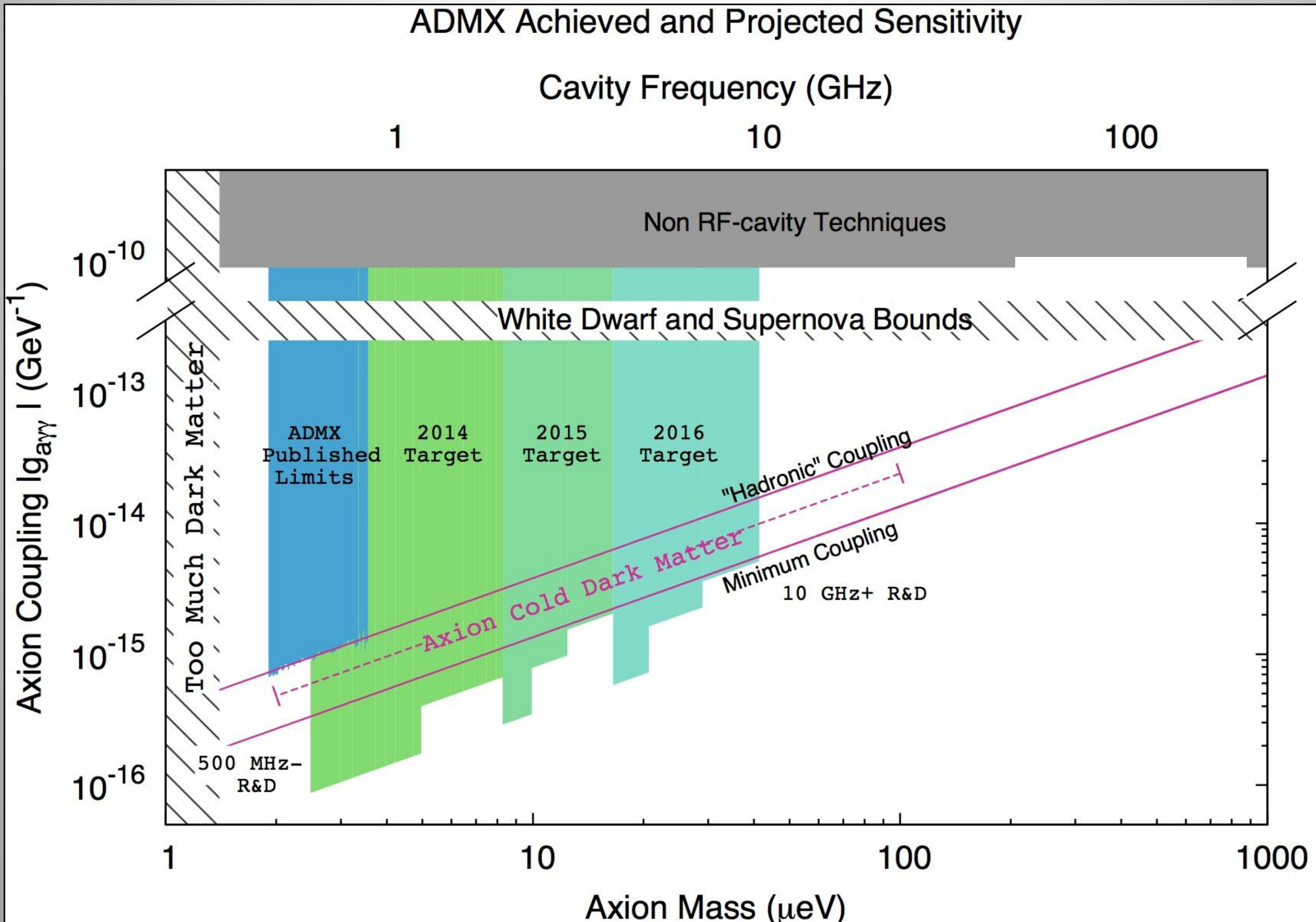
2011 – 2013 Construction of Phase II insert / infrastructure.

2013 – 2013 Construction almost complete!
Commission Phase II detector (Feb – June)
(pumped LHe^3 system ~ temp at 300 mK)
Order Dilution Refrigerator (1 year lead time)
Short Axion Search while awaiting Dil. Fridge
(aiming for restart of data-taking mid-summer)

2013 – 2014 Install Dilution Refrigerator, Commissioning

2015+ Definitive Dark Matter Axion search commences!

ADMX Upgrade

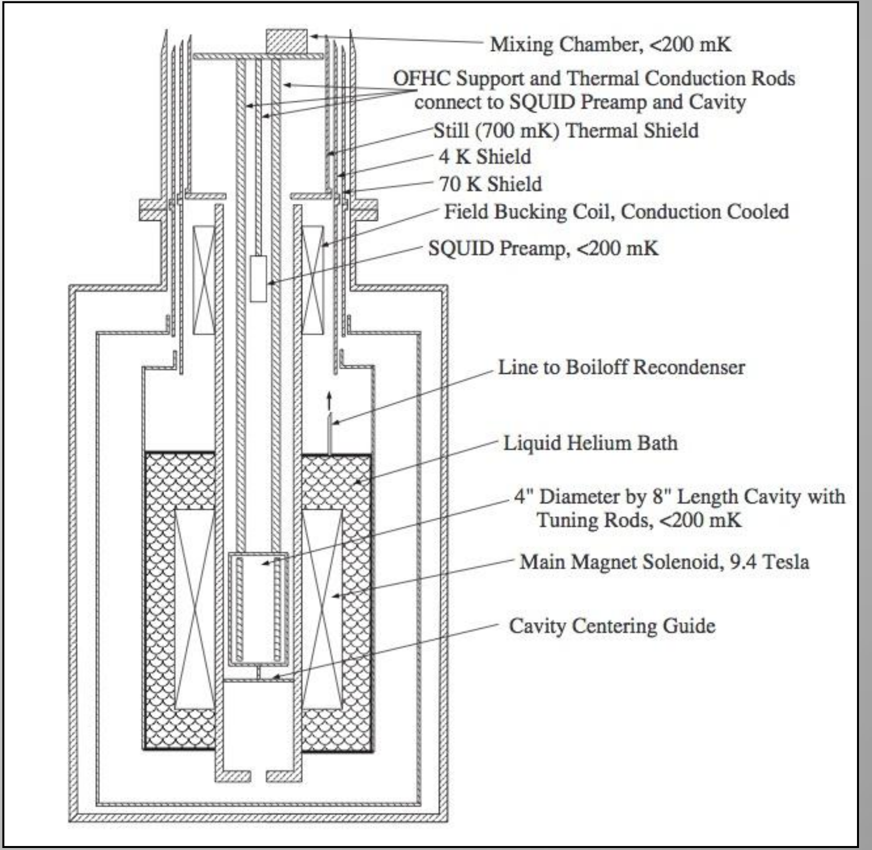


ADMX – HF: High Frequency – New Collaborator

<u>Second ADMX site: Yale University</u>

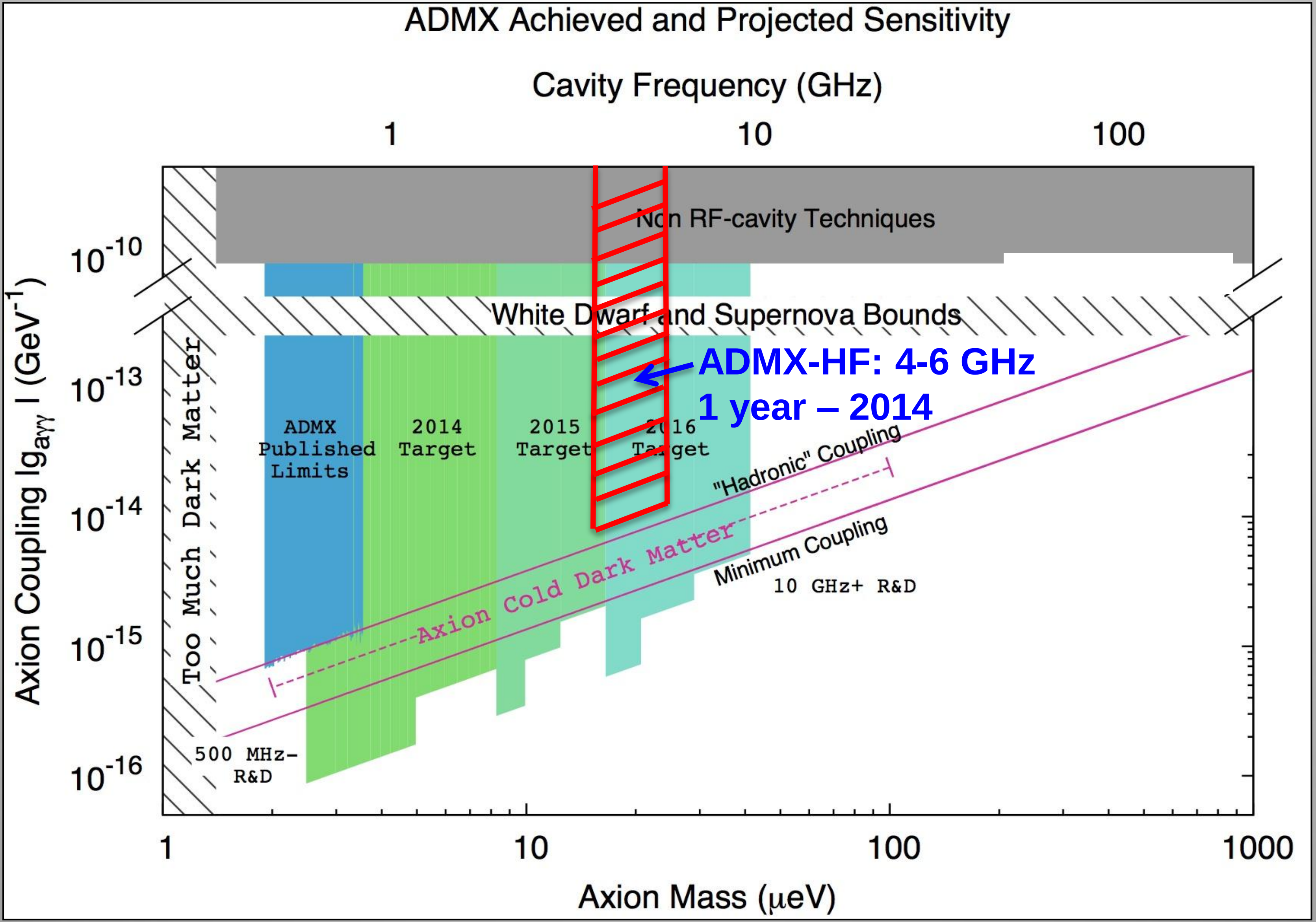
<u>PI: Prof. Steve Lamoreaux</u>

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



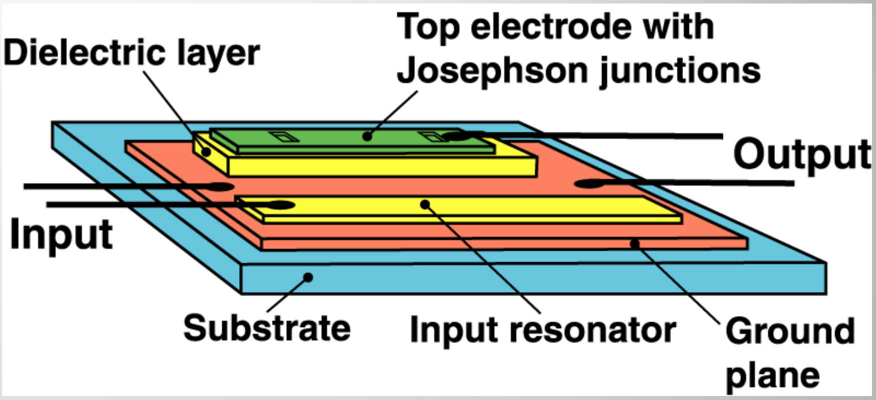
Recently awarded NSF funding… magnet under construction

ADMX Upgrade

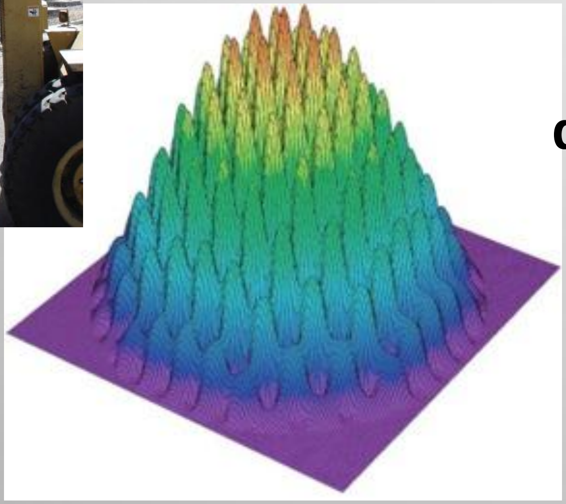


To get > 10 μeV… Additional higher-frequency R&D required

More Powerful Magnets!

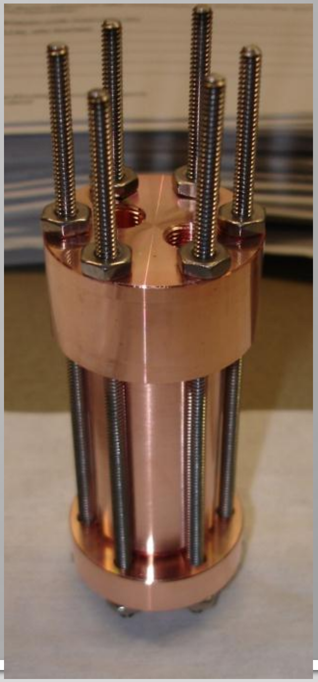


Higher-frequency near quantum-limited SQUIDs



higher-frequency, large volume resonant structures

“Hybrid” superconducting cavities

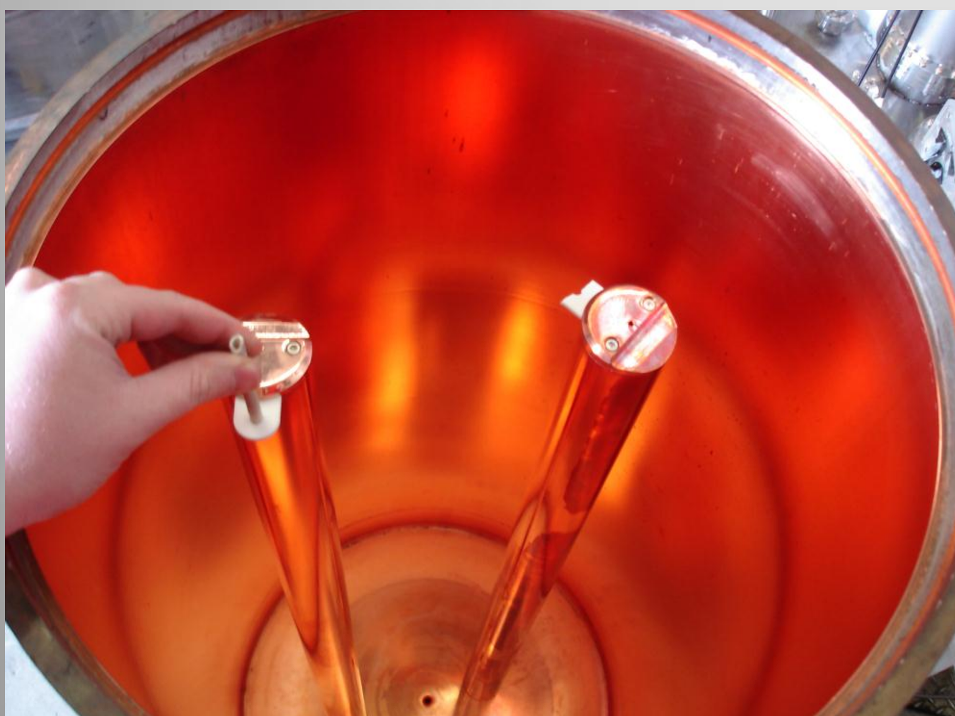


Backup slides

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



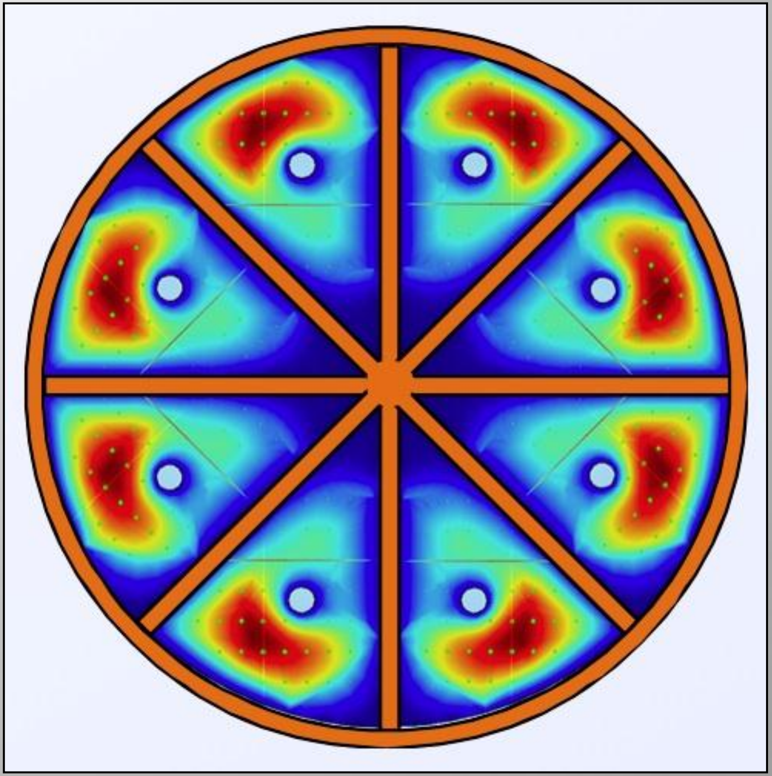
Radius – 2.5 inches
Frequency ~ 2.4 GHz
Axion Mass ~ 9 μeV
Q – 120,000
Volume ~ 2.6 liters

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

Goal: Higher frequencies without sacrificing volume

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

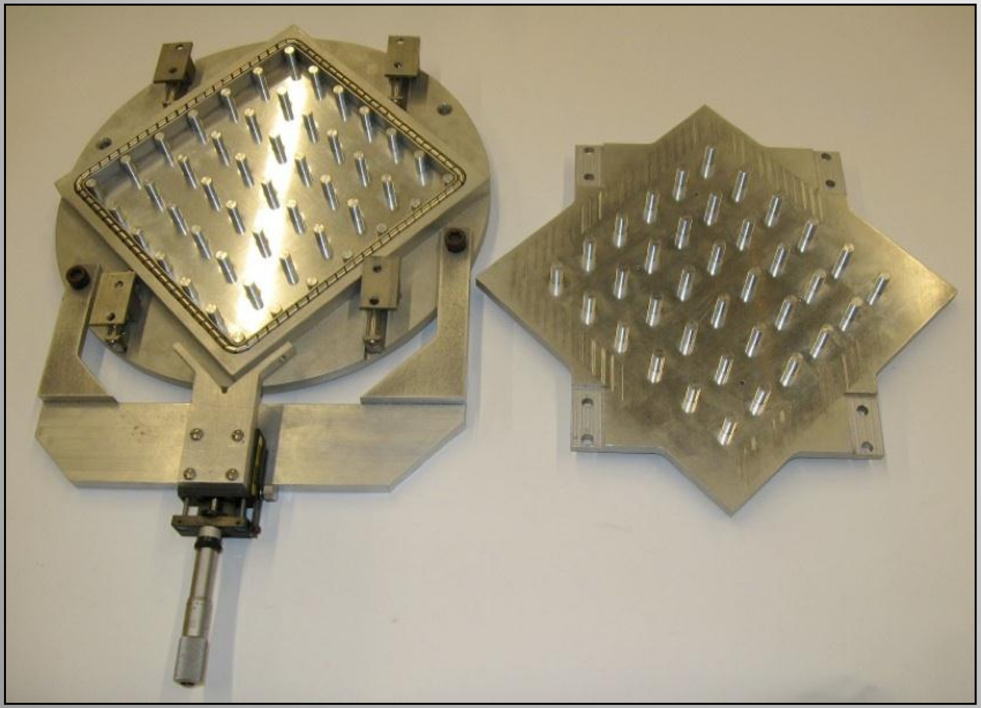
- Split cavity (U. of Florida R&D)
- Similar to multiple cavity but uses common cylinder.
- Also difficult to scale > 8 segments



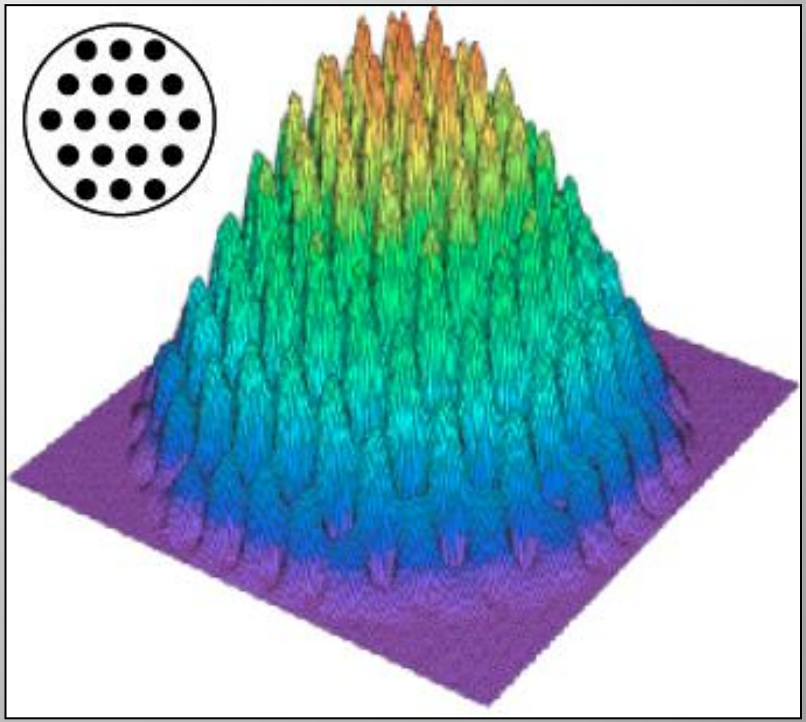
LLNL R&D effort ECRP – Multipost cavity systems

- 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

What if we could improve cavity Q_L?

$$P_a \propto g^2 \cdot B^2 V \cdot \min(Q_a, Q_L)$$

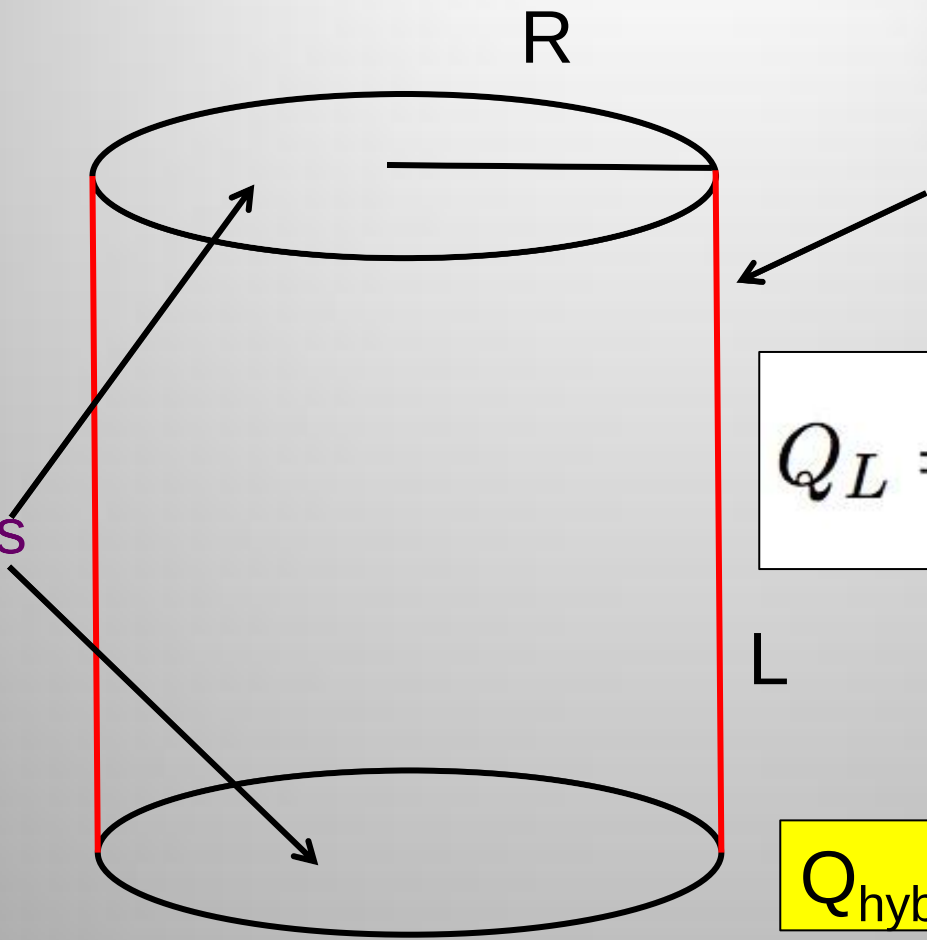
$$\frac{1}{f} \cdot \frac{df}{dt} \propto g^4 \cdot B^4 V^2 \cdot \min(Q_a, Q_L)$$

Standard copper cavities $Q_L \sim 10^5$ (or lower)
Axions are expected to have $Q_a \sim 10^6$

<u>If you could increase Q by a factor of x10</u>

- P_a goes up by x10
- df/dt would go up by x10 (for constant g)
- Sensitivity to g would go up by x1.8 (for constant scan rate)

The "Hybrid" superconducting cavity concept



$$Q_L = \frac{L/R}{1 + \not{L/R}} \cdot \frac{R}{\delta}$$

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

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

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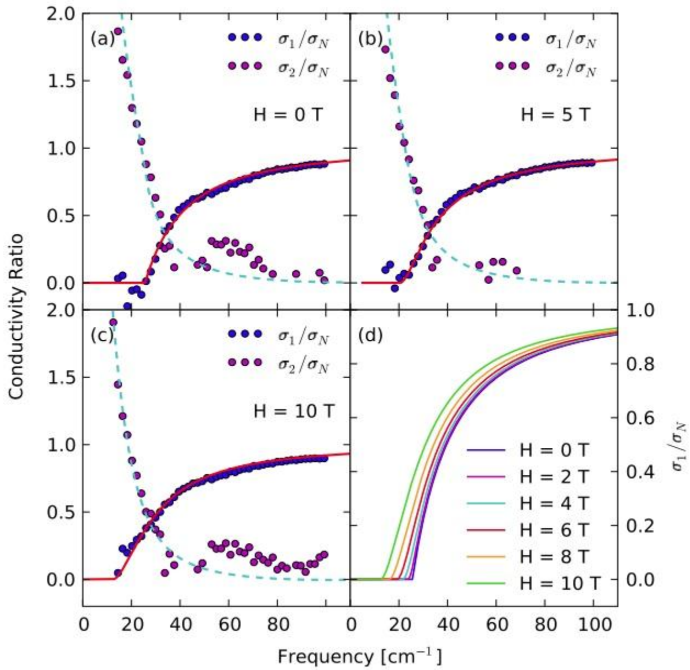
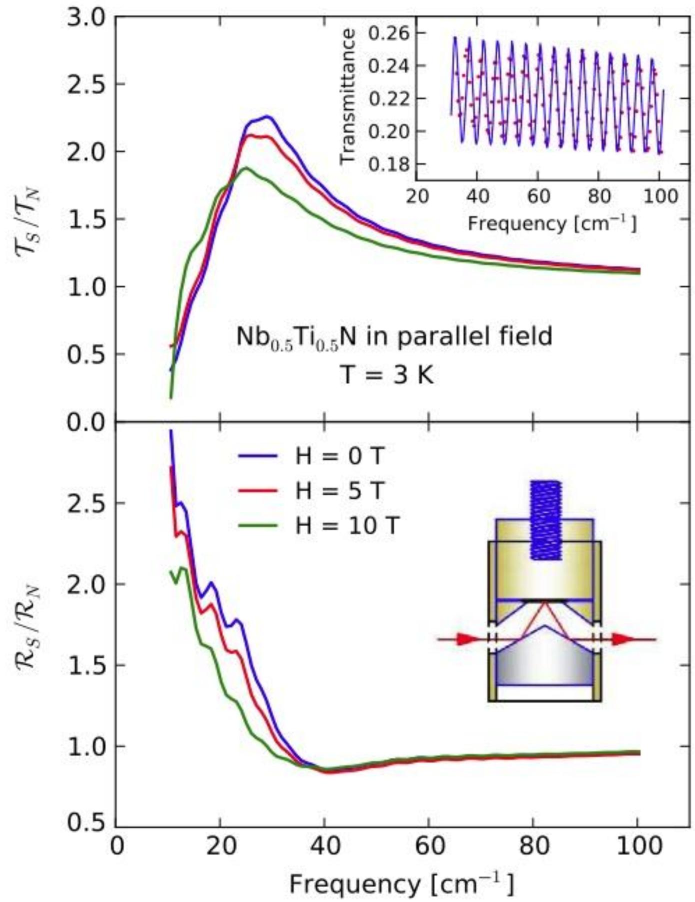
[1]*Department of Physics, University of Florida, Gainesville, Florida 32611, USA*
[2]*Department of Physics, Pusan National University, Busan 609-735, Republic of Korea*
[3]*National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973, USA*
(Received 16 August 2010; published 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



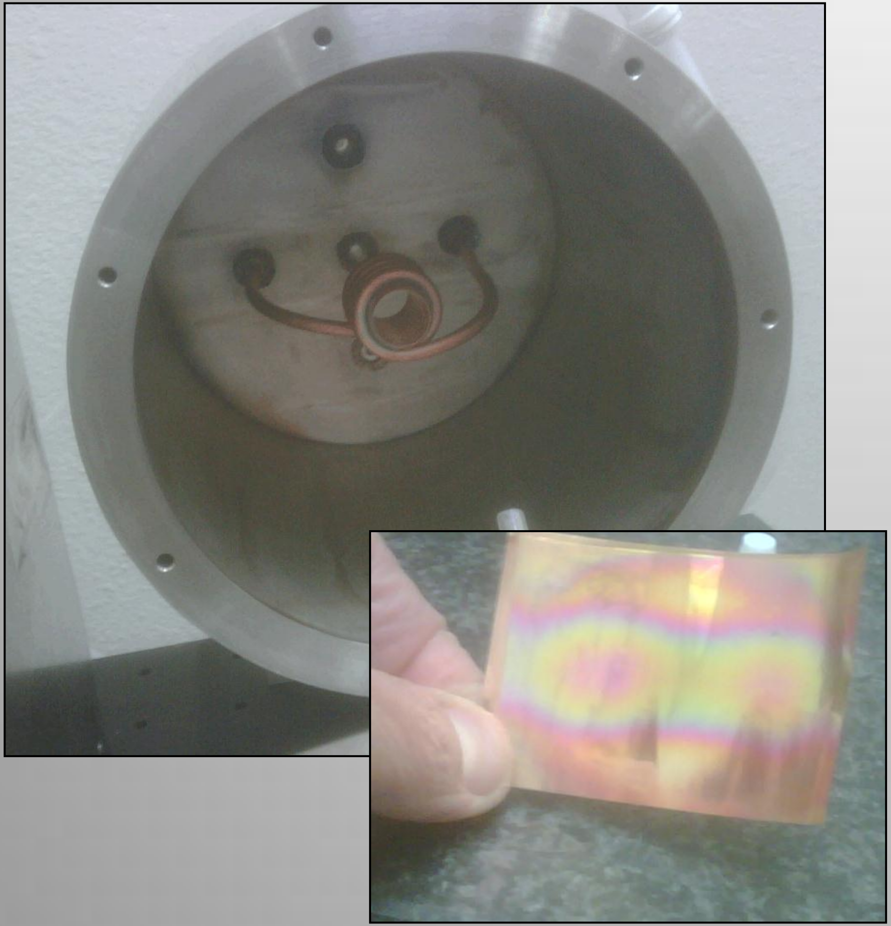


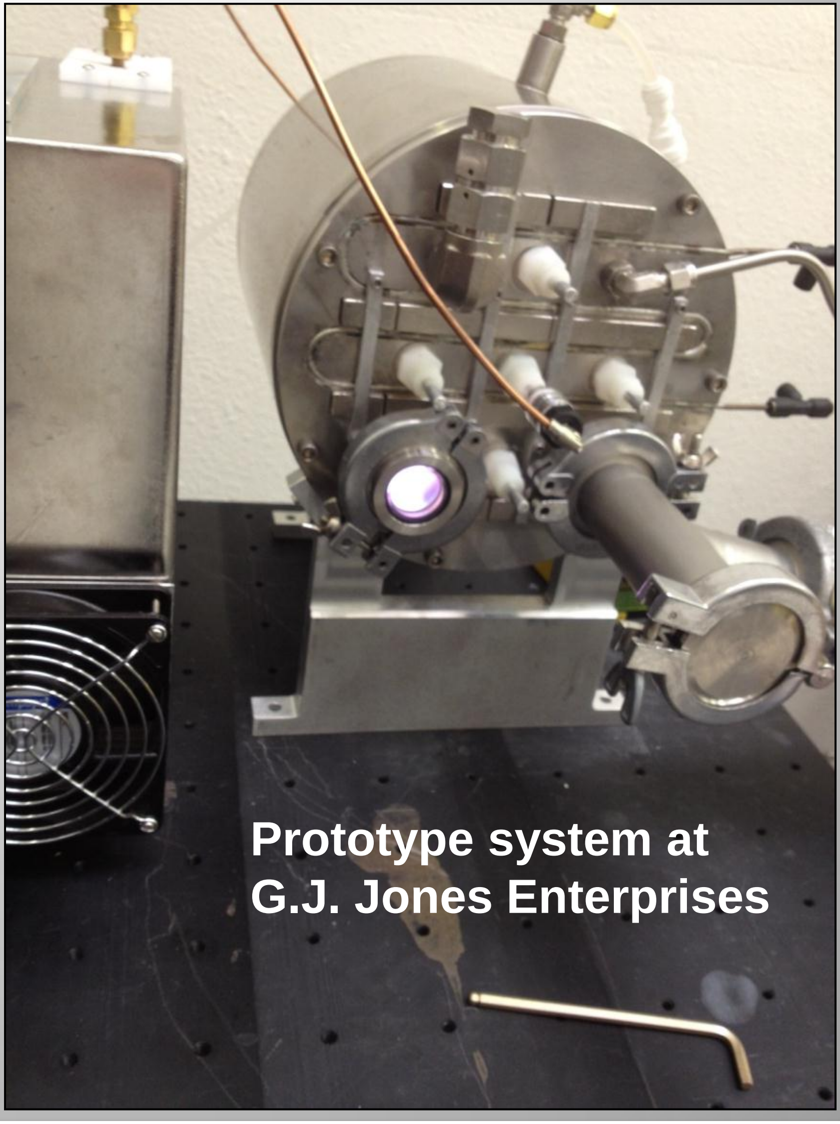
10 nm of $Nb_{0.5}Ti_{0.5}N$ is perfect

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

R&D has begun on NbTiN superconducting coatings

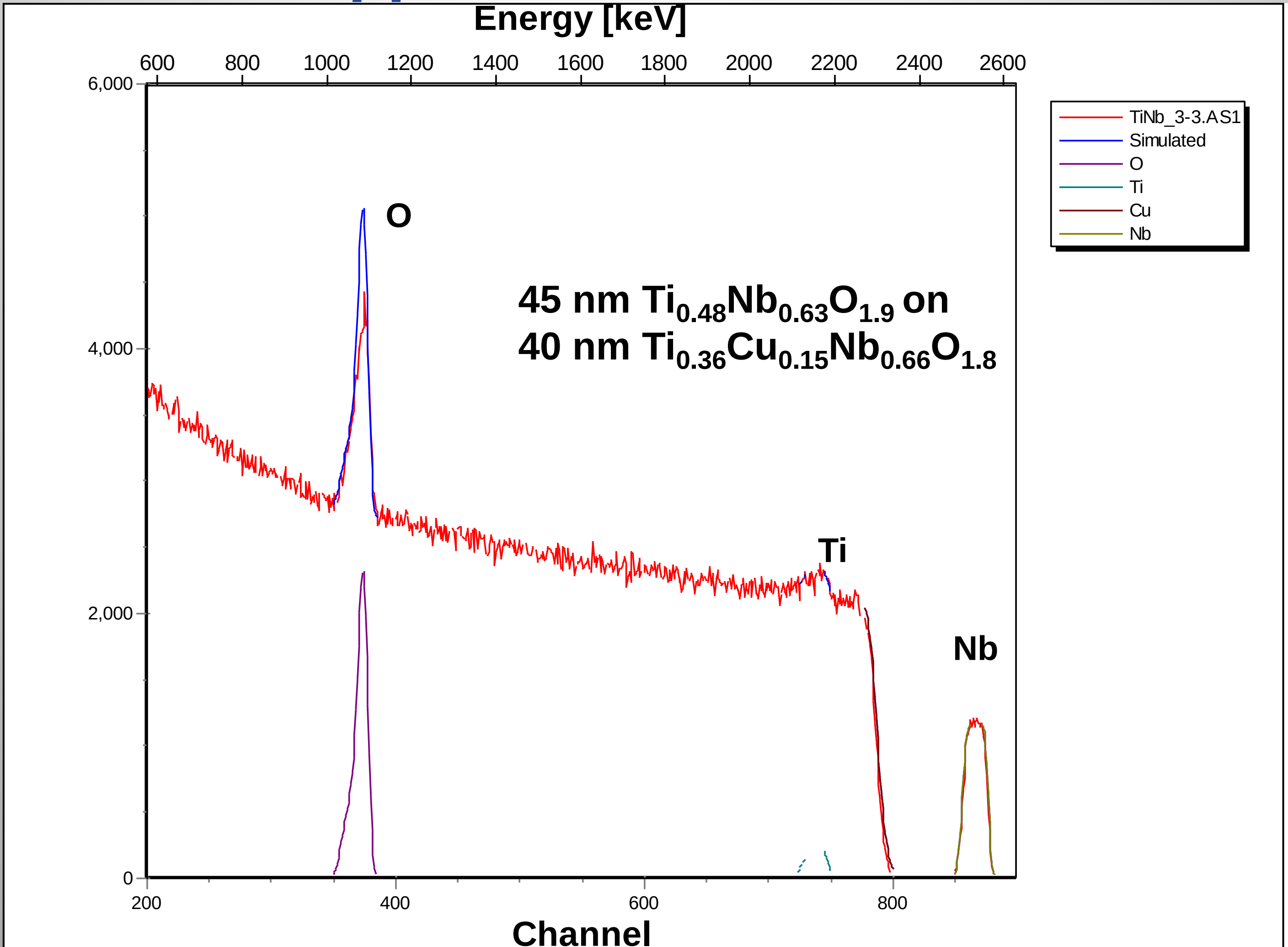
Currently setting up RF vapor deposition on foils for RBS analysis.





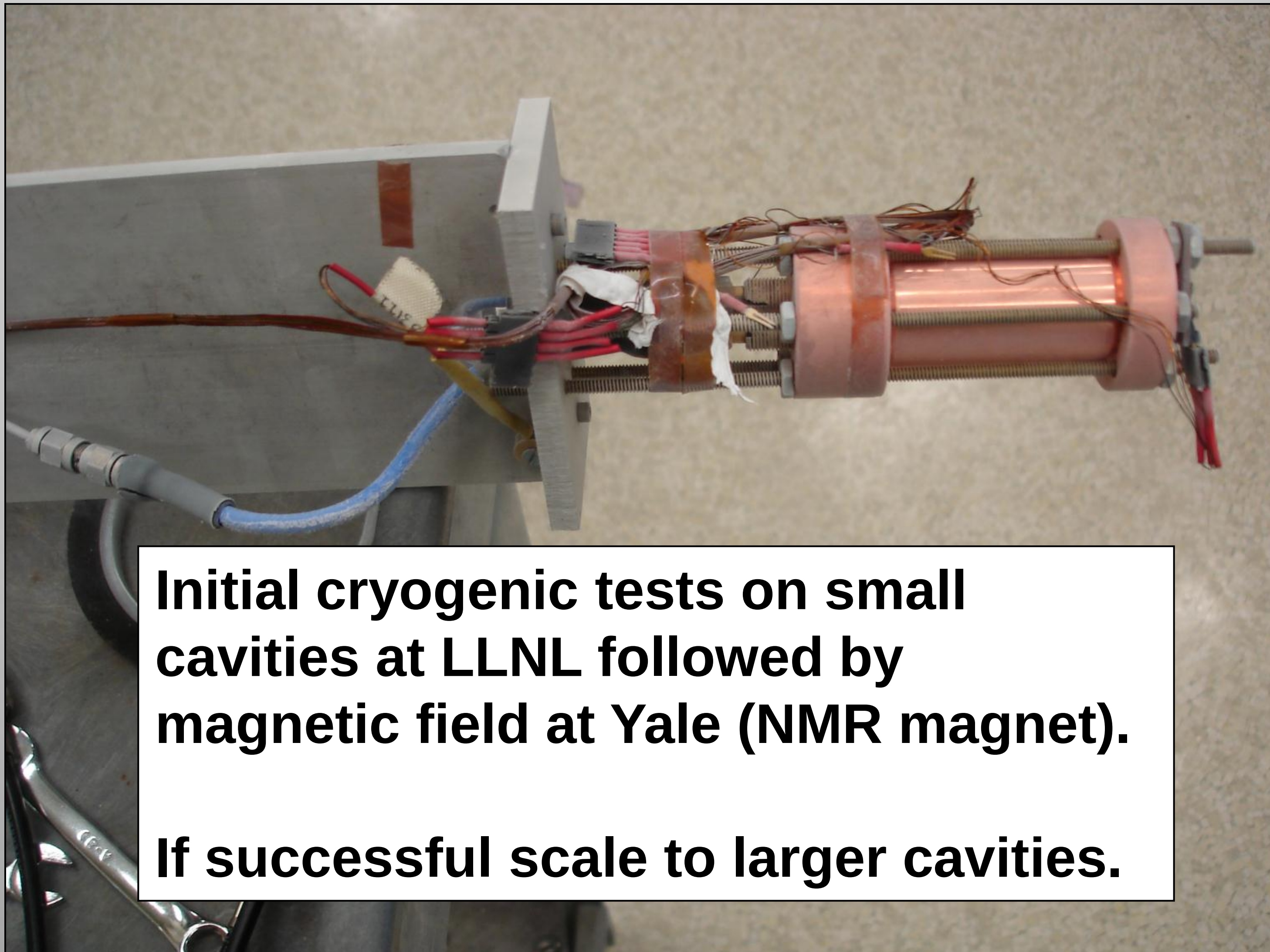
Prototype system at
G.J. Jones Enterprises

Rutherford backscattering of 20 min NbTi deposition on copper foil



*courtesy of Dr. Kin Man Yu of LBNL

Superconducting coatings on 1" cavity barrels



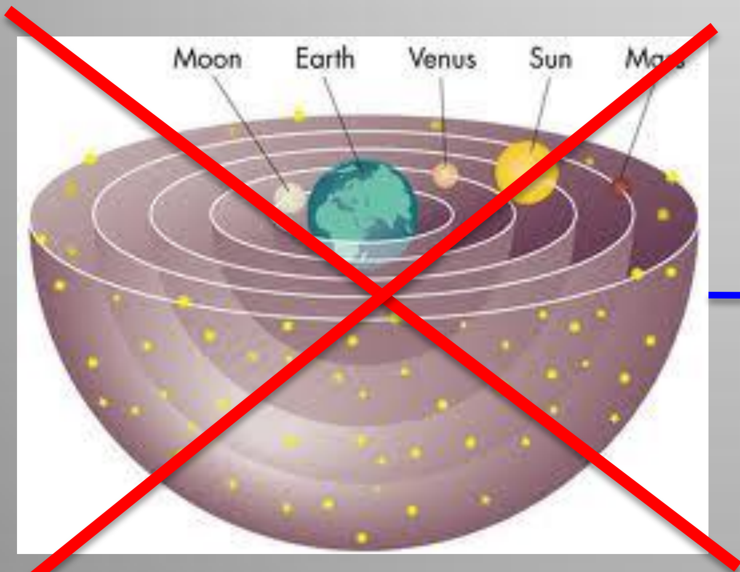
Initial cryogenic tests on small cavities at LLNL followed by magnetic field at Yale (NMR magnet).

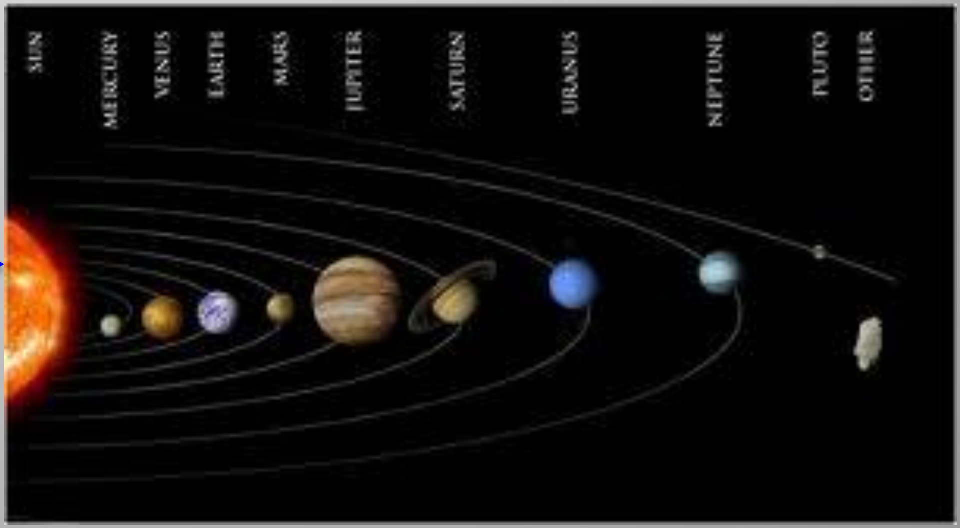
If successful scale to larger cavities.

But wait!!! There's more….

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

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

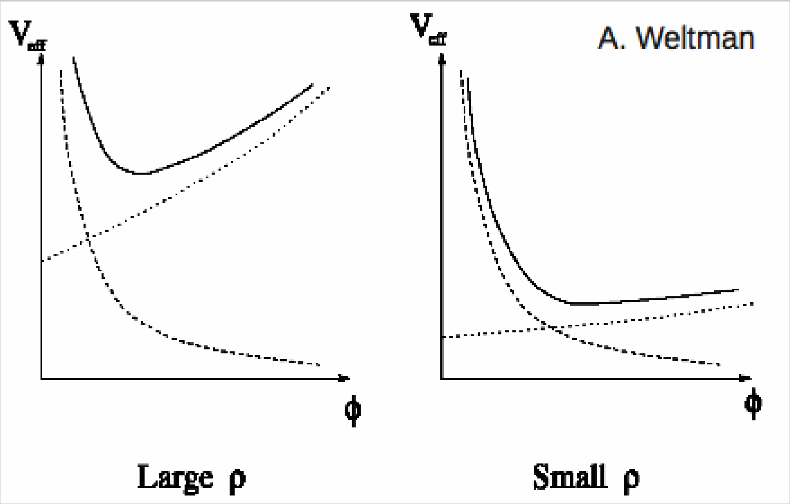




ADMX sensitive to other light bosons: Chameleon particles

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



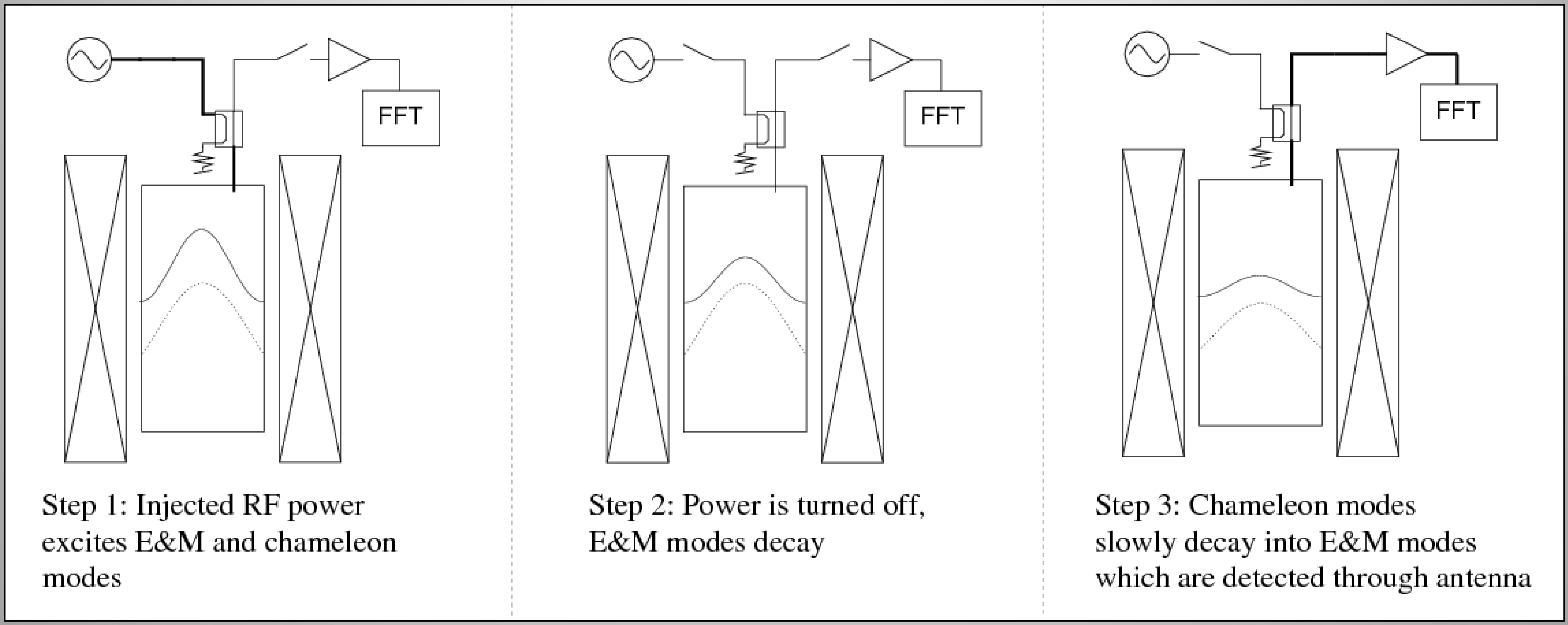
For example:

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

Khoury and Weltman, PRL 93.171104 (2004)

A viable Dark Energy Candidate

Utilizing ADMX for a Chameleon search

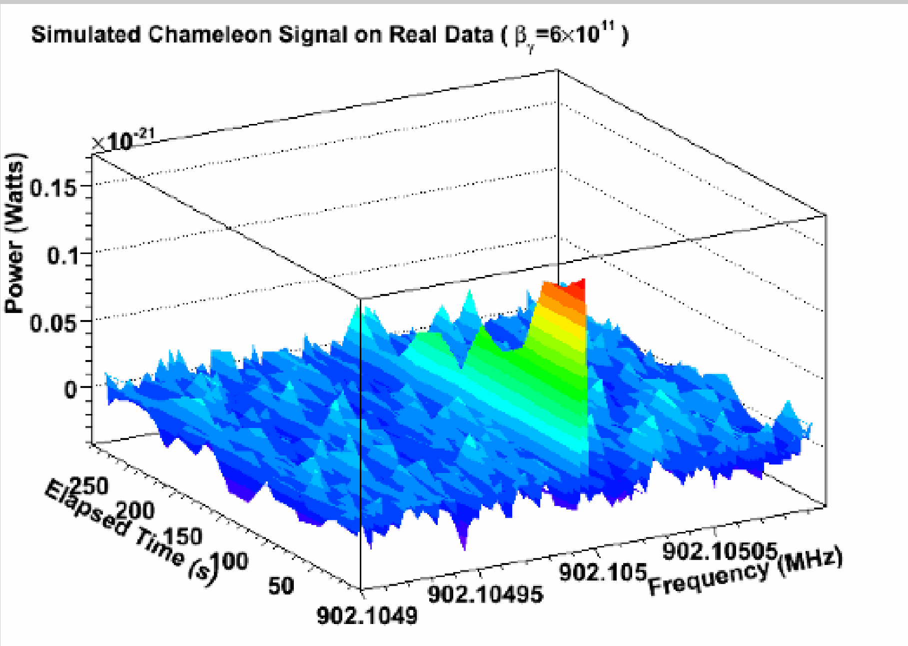


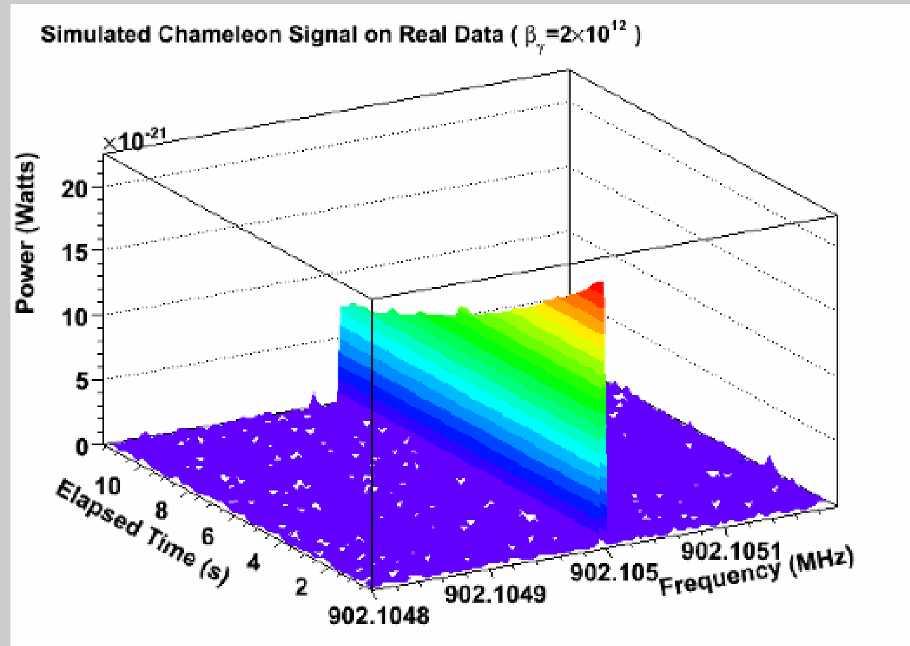
Timescale: 10 minutes
Power in ~ 25 dBm

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

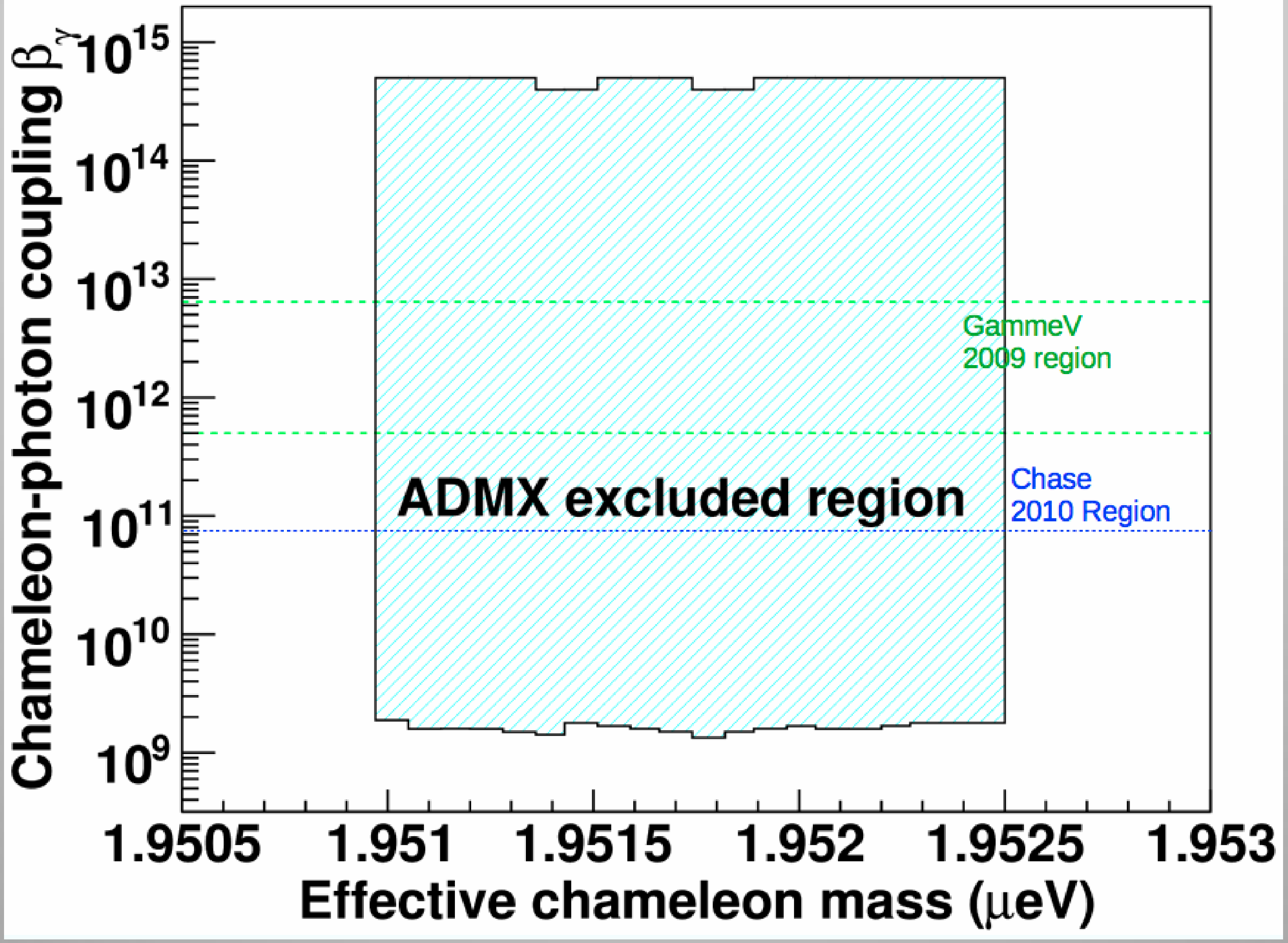
Stronger coupling leads to more signal, but short decay time

(note time scale change)

1 day proof-of-concept

***simulation courtesy of G. Rybka**

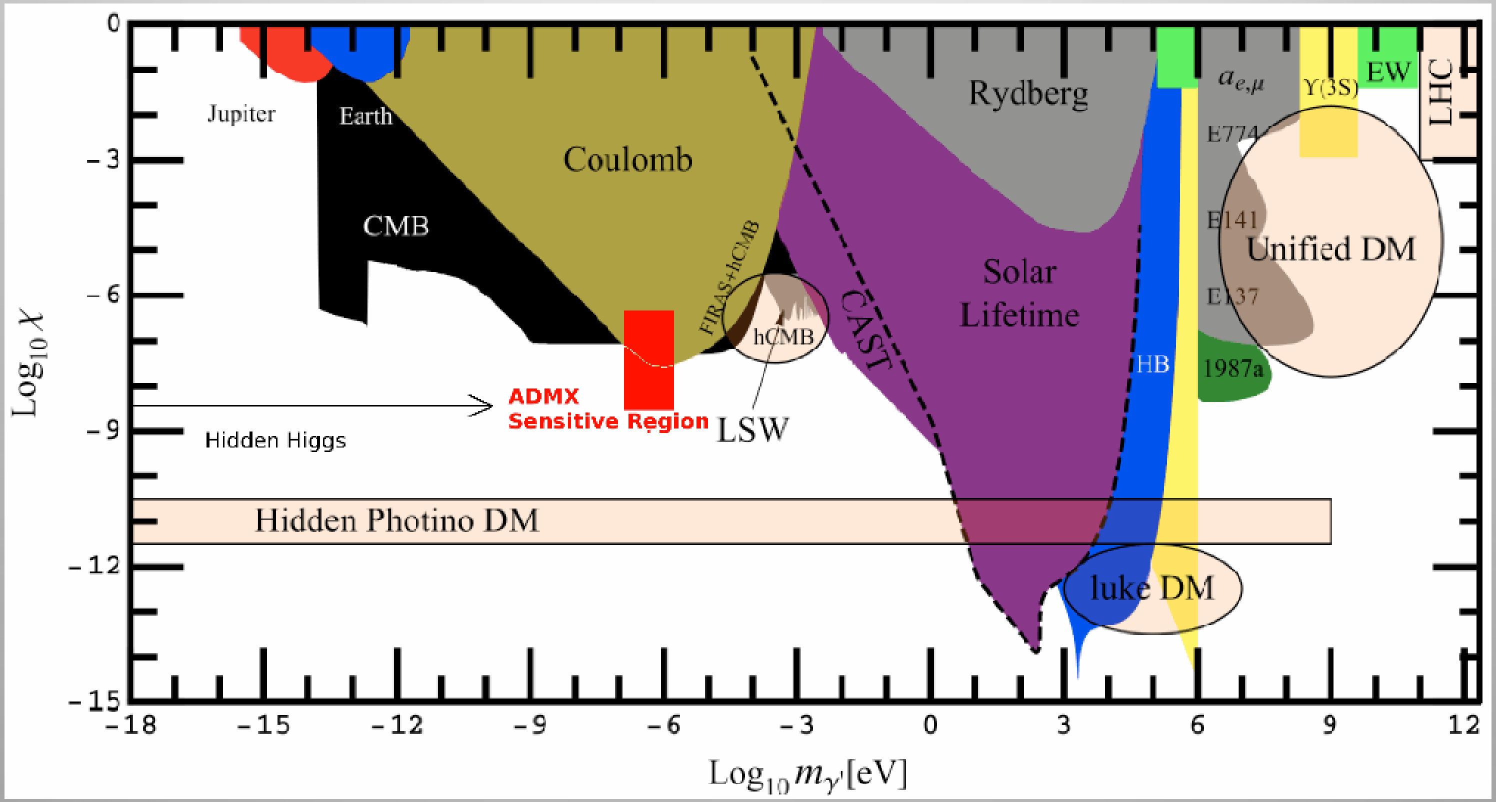
ADMX for a Chameleon search results (published in PRL)



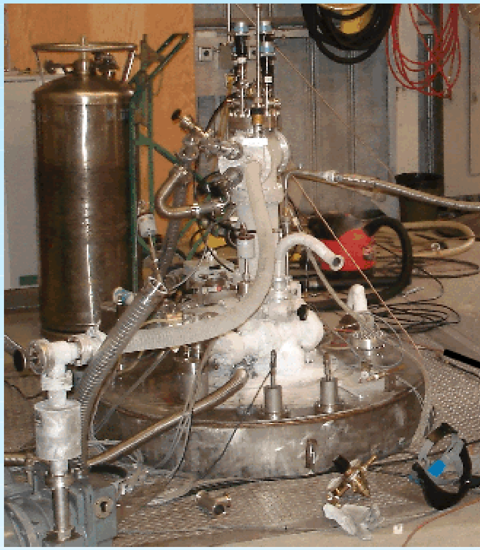
Laboratory Dark Energy Search

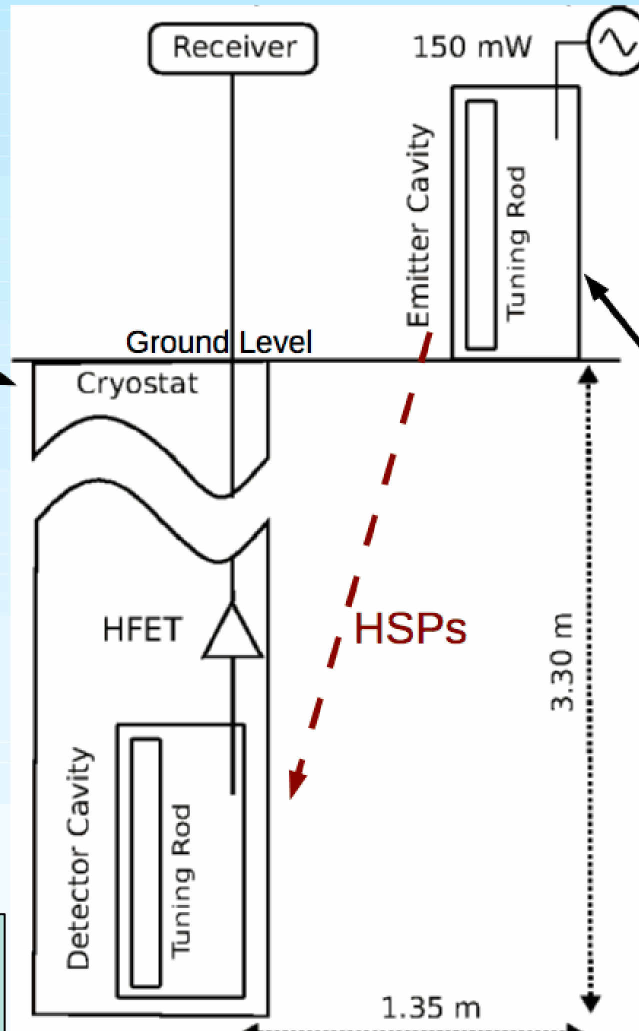
Other light bosons: Hidden Sector Photons

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

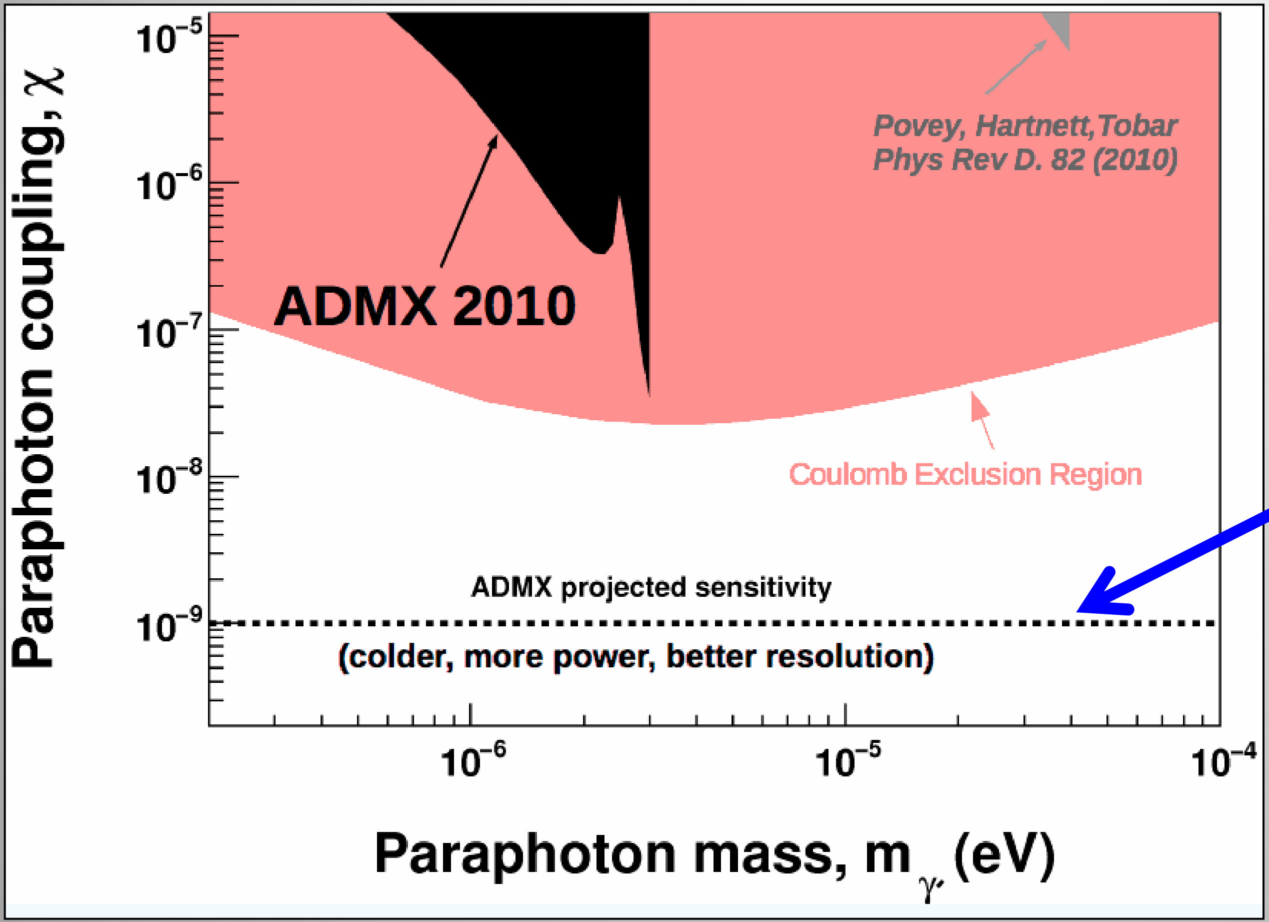
Photons in this driven cavity mix with HSPs and escape

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 in PRL)



Run concurrently with Dark Matter Axion Search!

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

ADMX is the only detector capable of directly detecting both dark matter & dark energy (96% of the universe)

Questions?

Conclusions (with respect to the QCD axion)

- **ADMX Phase II currently under construction**
  - **Initial run with He3 fridge ~ 300 mK base temp**
  - **Final setup with dilution fridge ~ 100 mK base temp**

- **LLNL contributing to construction and R&D**
  - **Microwave Cavities**
  - **Tuning rod & antenna motion control**
  - **RF test-stand for parallel testing during data taking**
  - **In-situ noise calibration source**
  - **Early Career Research Program**

    R&D effort on high-frequency microwave cavities

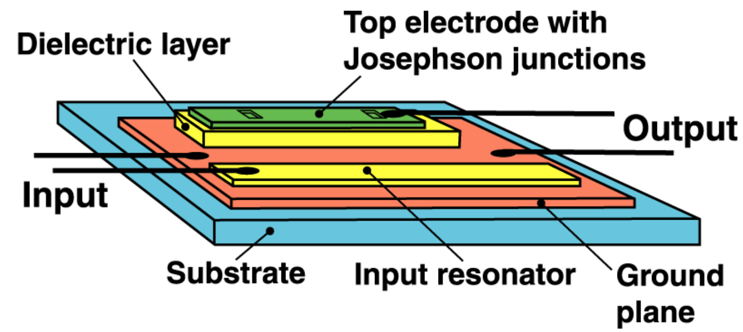
    - large multi-post & multi-segment cavities

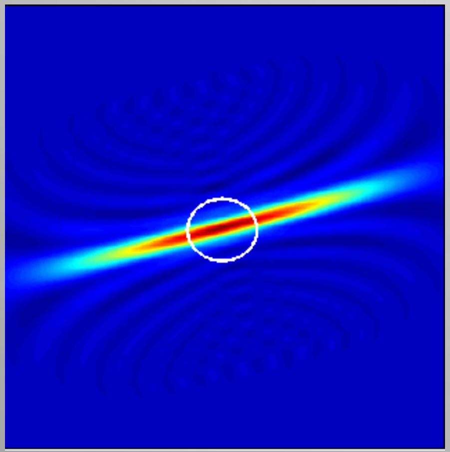
    - "hybrid" superconducting cavities

Current Microstrip SQUID Amplifiers gain drops at greater than a few GHz… exploring new ideas.

Several possibilities:

- in-line SQUIDs
- Josephson Parametric Amps (squeezed states)





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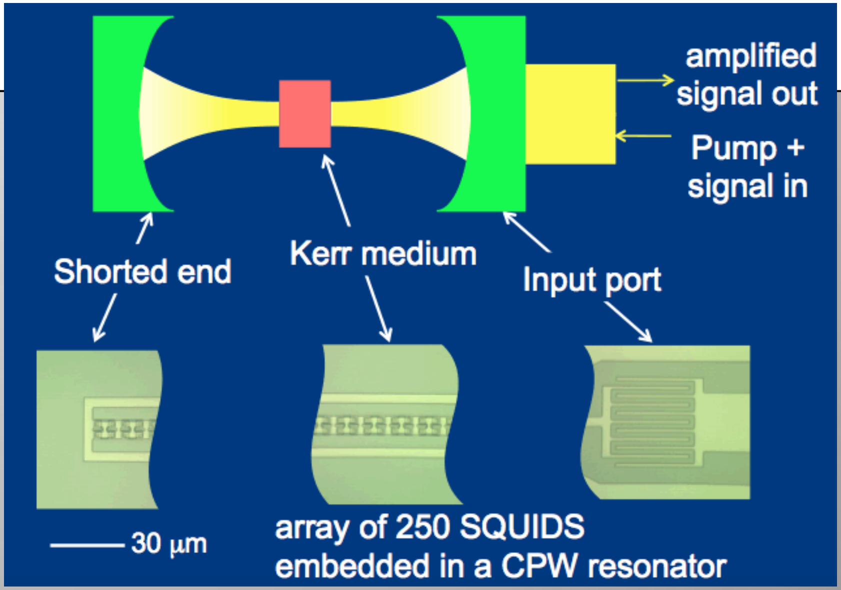
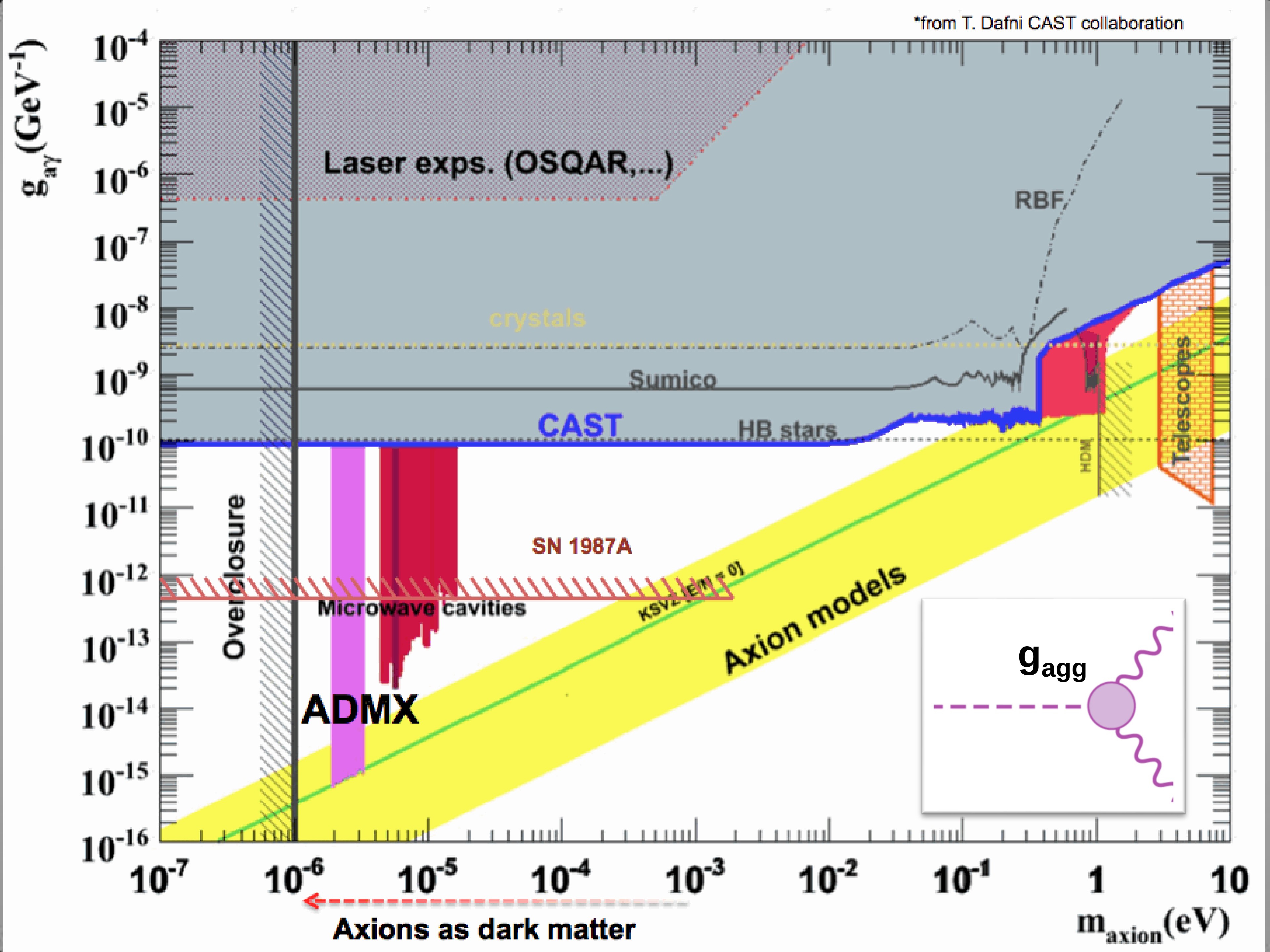
NIST





*from T. Dafni CAST collaboration
$g_{a\gamma}$ (GeV^{-1})
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
Laser exps. (OSQAR,...)
RBF
crystals
Sumico
CAST
HB stars
HDM
Telescopes
SN 1987A
Overclosure
Microwave cavities
KSVZ [E/N = 0]
Axion models
ADMX
g_{agg}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
10
m_{axion} (eV)
Axions as dark matter