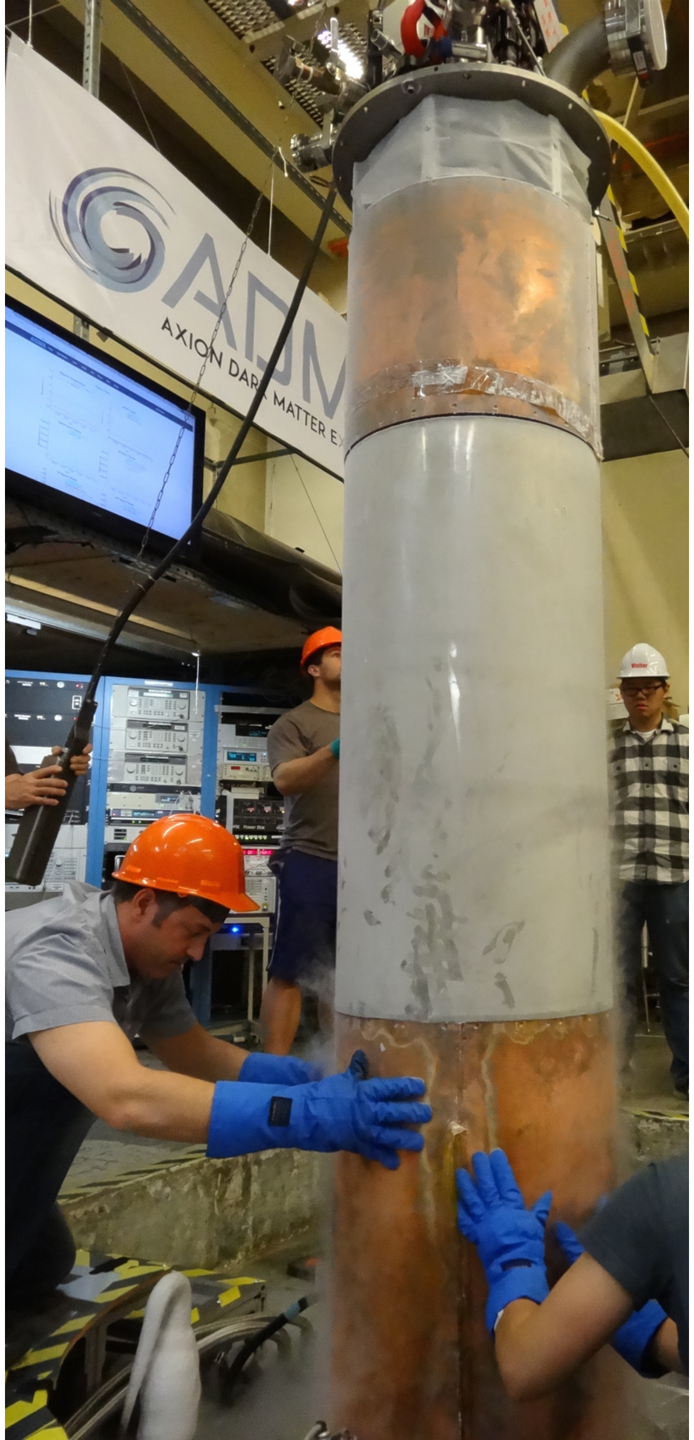
Searching for Dark Matter Axions with ADMX G2 and Beyond

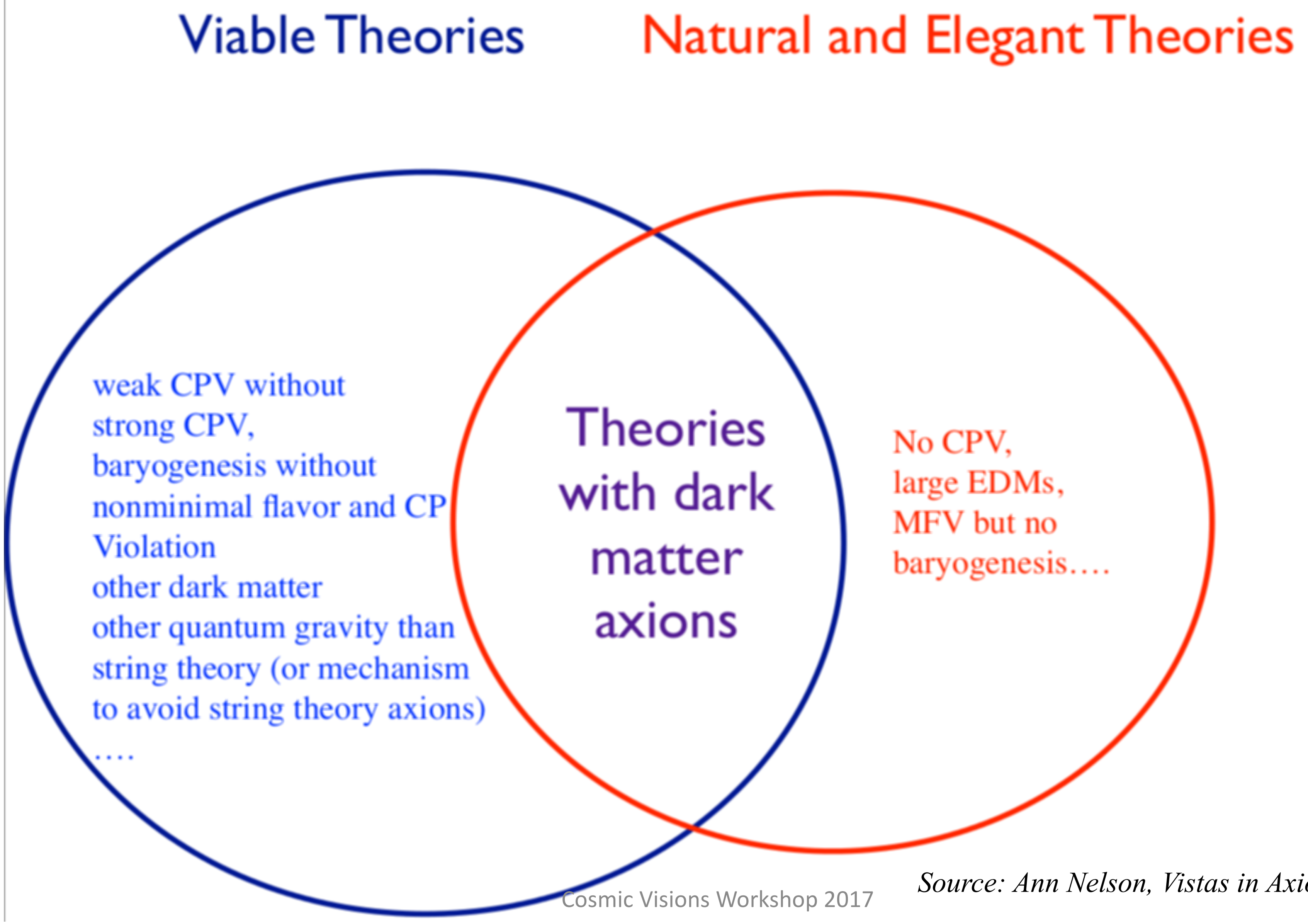
Gray Rybka
University of Washington

Cosmic Visions Workshop
March 2017

ADMX
AXION DARK MATTER EXPERIMENT



Why Axions?



Source: Ann Nelson, Vistas in Axion Physics 2012

Why Axions?

The Peccei-Quinn symmetry is still the most appealing solution to the strong CP problem.

The Weinberg-Wilczek axion is the direct consequence of this. If axions don't exist, then we are left with a serious deficiency in QCD.

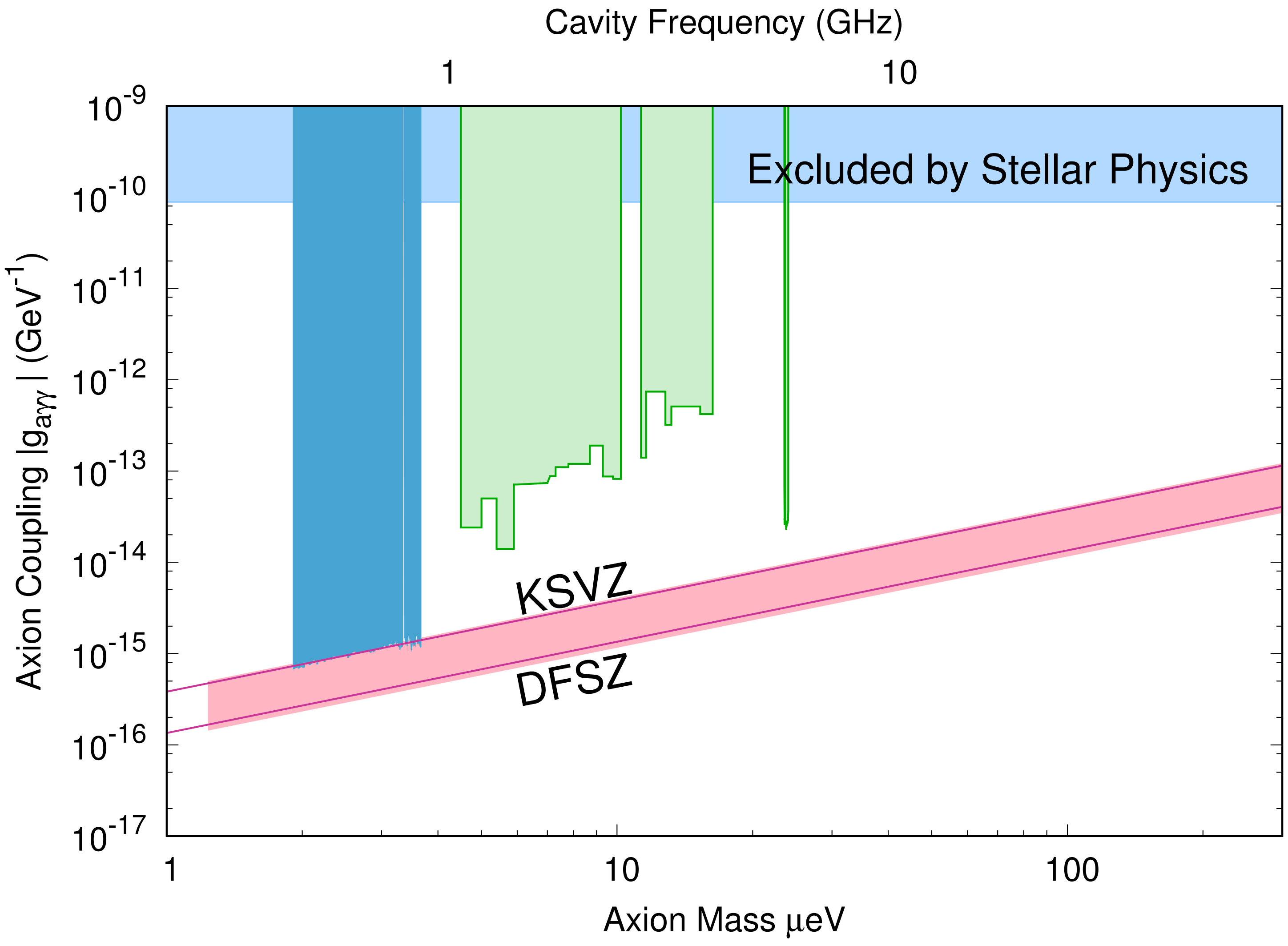
Axions must be created in the early universe at some level. It is most economical if they are the dark matter.

QCD axions are extremely well motivated, and will be the focus of this talk

Where to look for Axions - Coupling

The basic assumption of Unification and the QCD axion yields the axion-photon coupling (DFSZ)

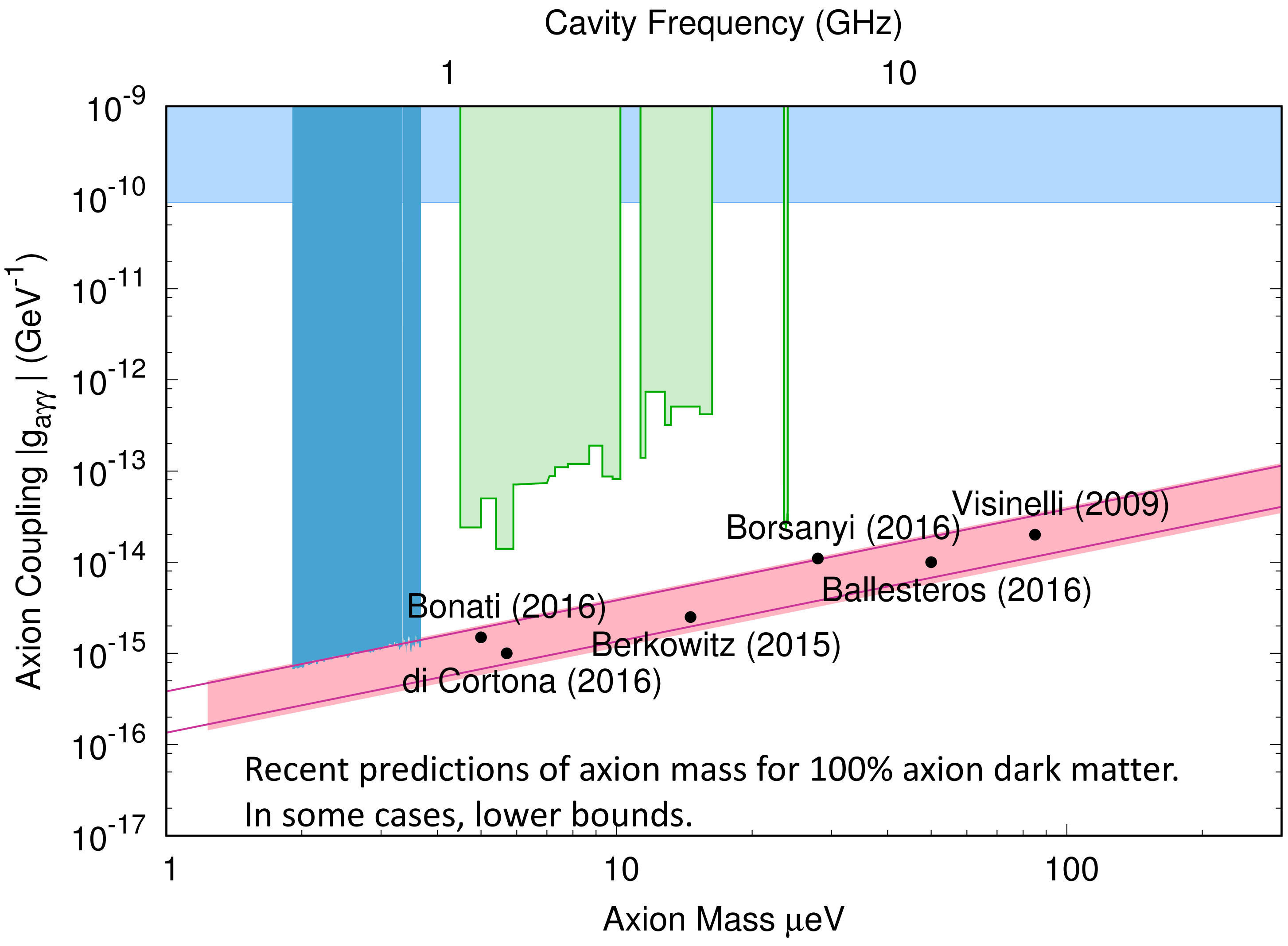
Ad-hoc additions can make this coupling stronger (KSVZ)



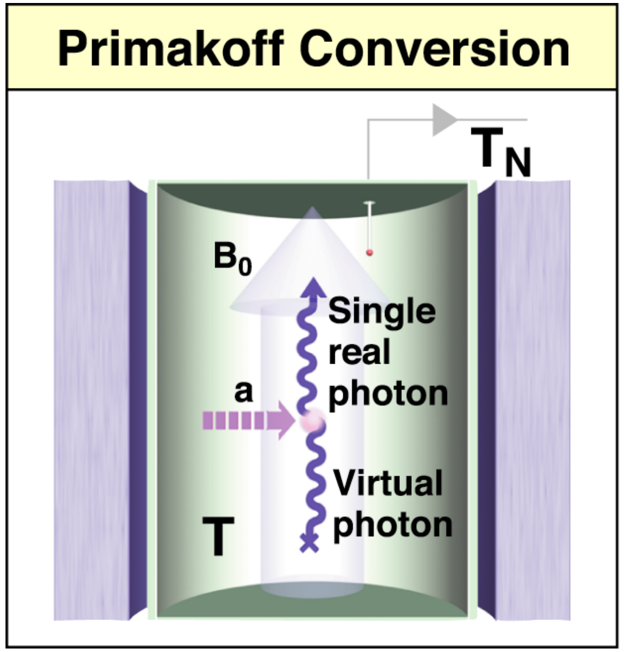
Where to Look for Axions - Mass

Both analytic and lattice predictions of the dark matter axion mass tend to fall in the 1 -100 ueV mass range in the post-inflationary axion creation scenario

Pre-inflationary scenarios are less well constrained



How to Look for Dark Matter Axions



Dark Matter Axions will convert to photons in a magnetic field.

The conversion rate is enhanced if the photon's frequency corresponds to a cavity's resonant frequency.

Signal Proportional to

Cavity Volume
Magnetic Field
Cavity Q

Noise Proportional to

Cavity Blackbody Radiation
Amplifier Noise

The Axion Dark Matter Experiment: ADMX

ADMX "G2" Dark Matter Search

A DOE flagship G2 Dark Matter Experiment

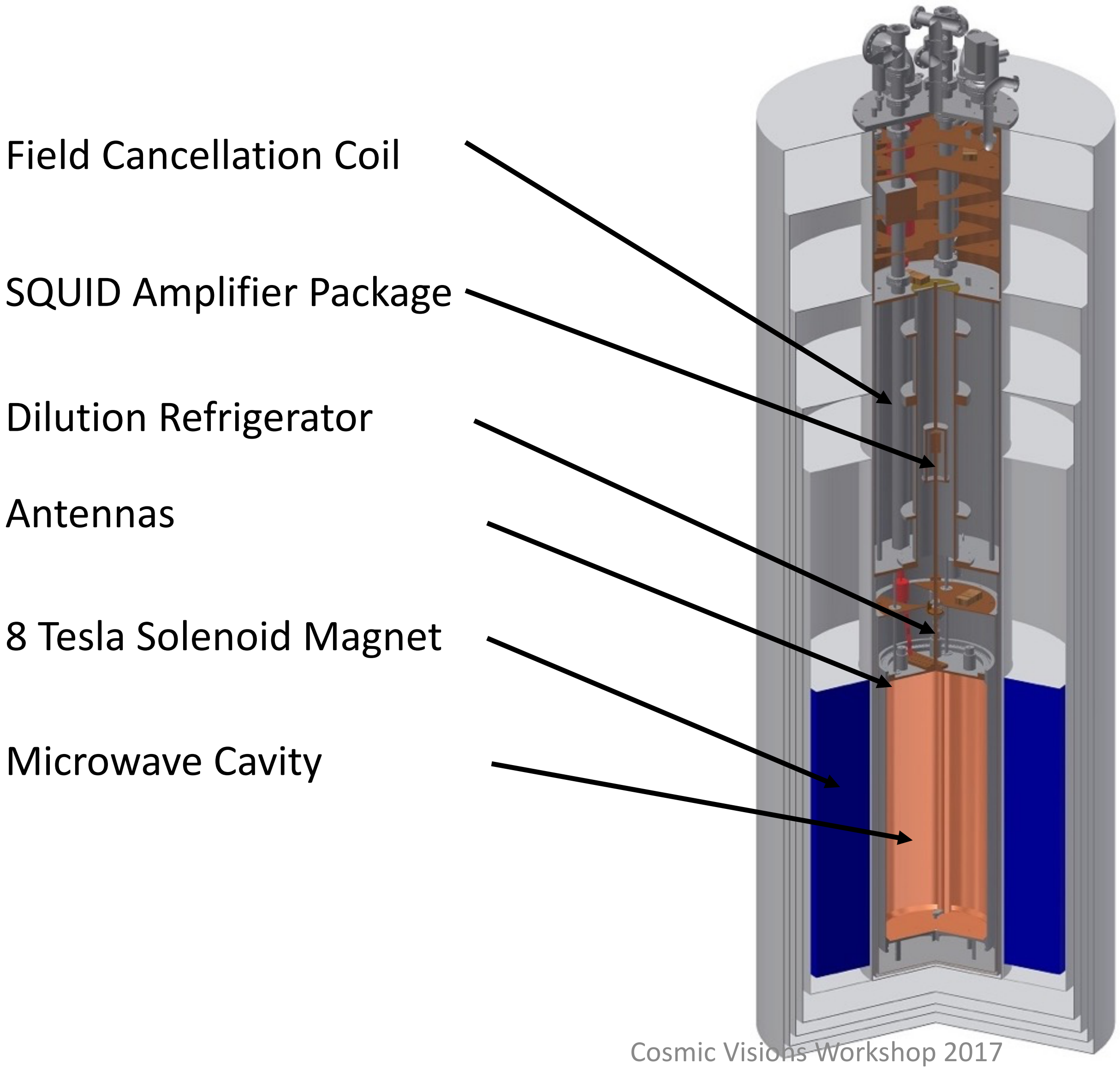
Collaborating Institutions:
UW, UFL, LLNL
FNAL, UCB, PNNL
LANL, NRAO, WU, Sheffield

The ADMX collaboration gratefully acknowledges support from the US Dept. of Energy, High Energy Physics DE-SC0011665 & DE-SC0010280 & DE-AC52-07NA27344

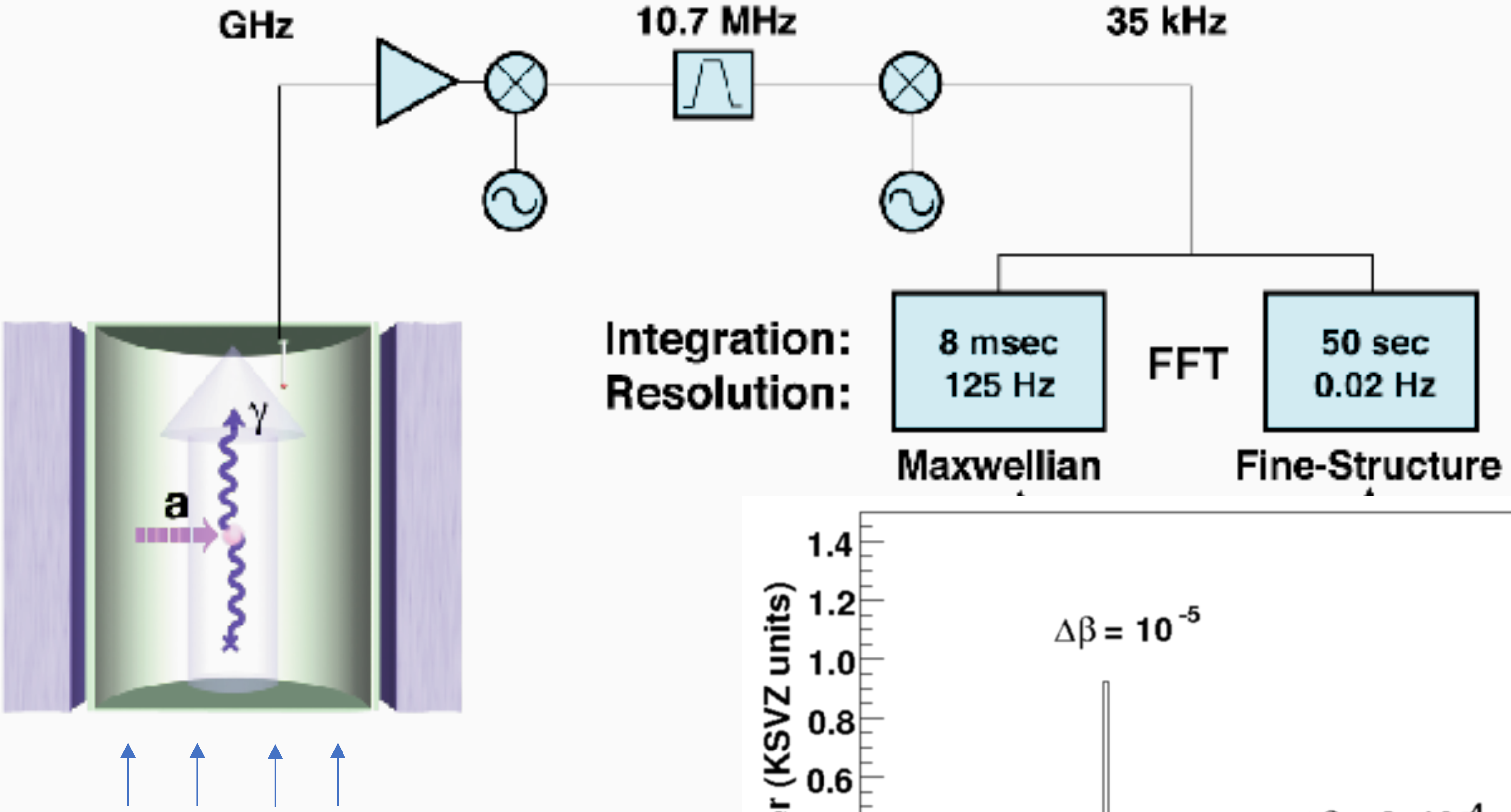
Also support from LLNL and PNNL LDRD programs and R&D support the Heising-Simons institute

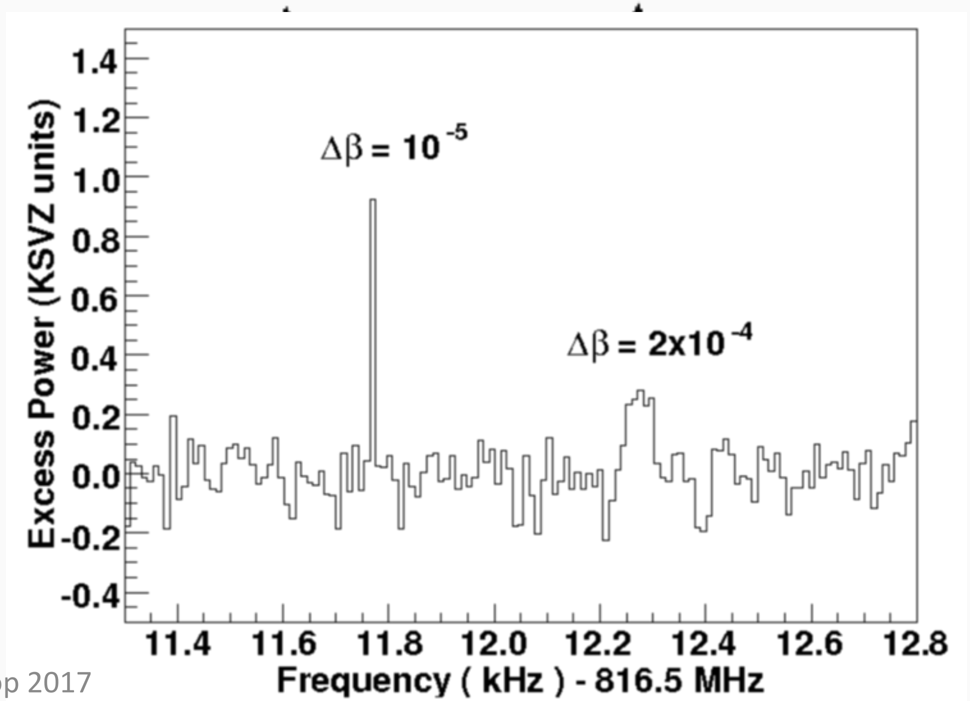
ADMX G2 at U. Washington
Scientific American, 2015

Design of ADMX



ADMX Receiver



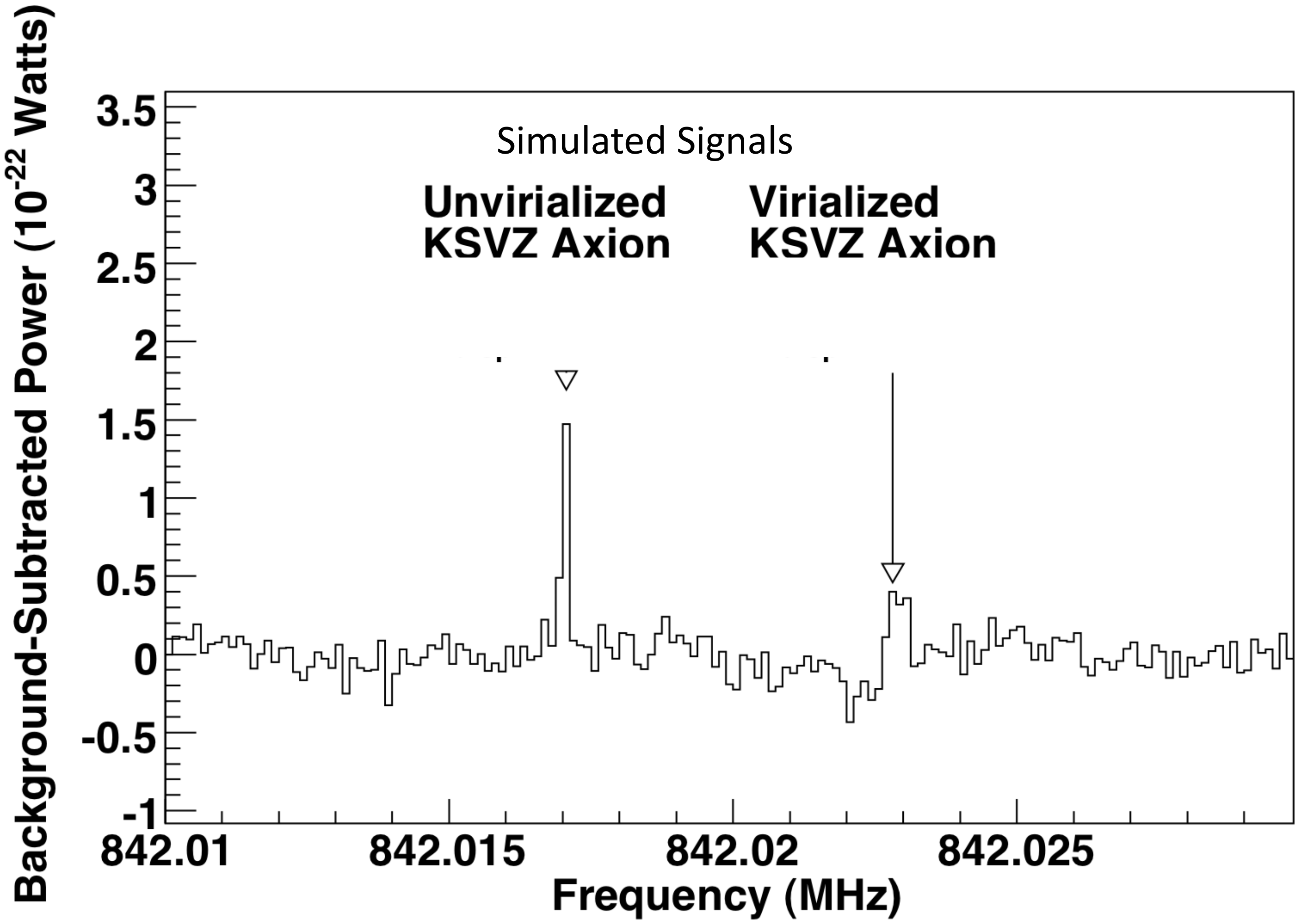


Axions convert to microwave photons (GHz), which are amplified, mixed to (MHz) frequencies and digitized

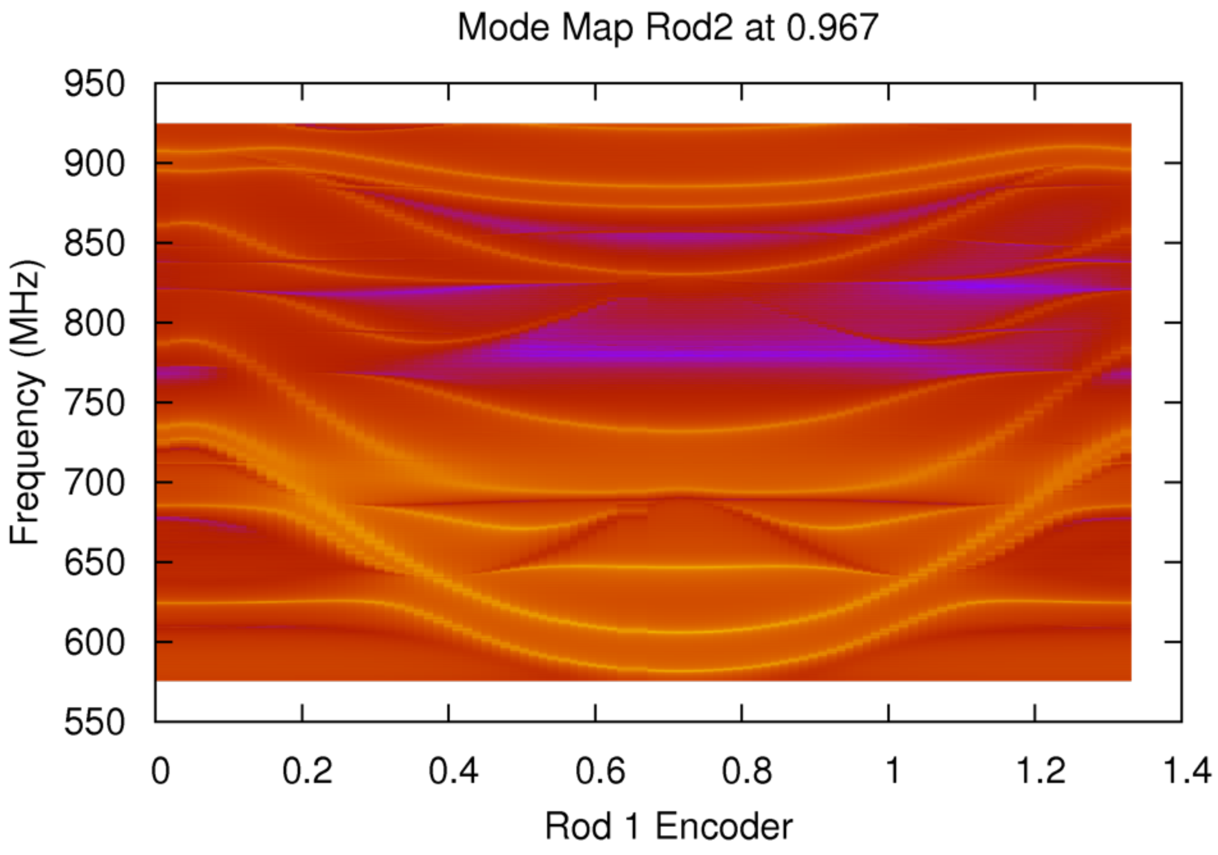
Predicted Axion Signal Shape

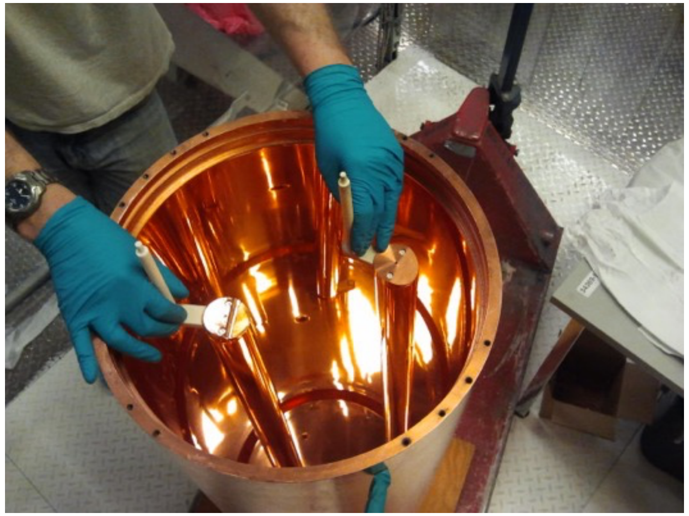
Recent N-Body models actually suggest the axion lineshape is narrower than the standard virialized model (arxiv:1703.06937)

Sensitivity plots in this talk, however, assume the wider, more conservative lineshape

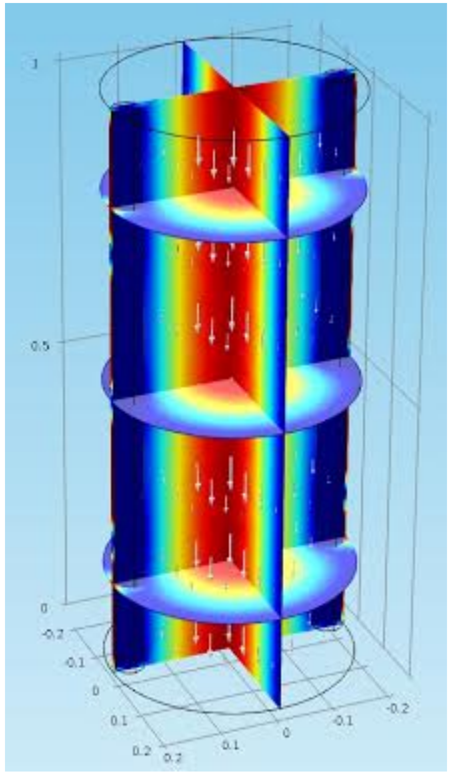


ADMX Cavity





Rods in Microwave Cavity

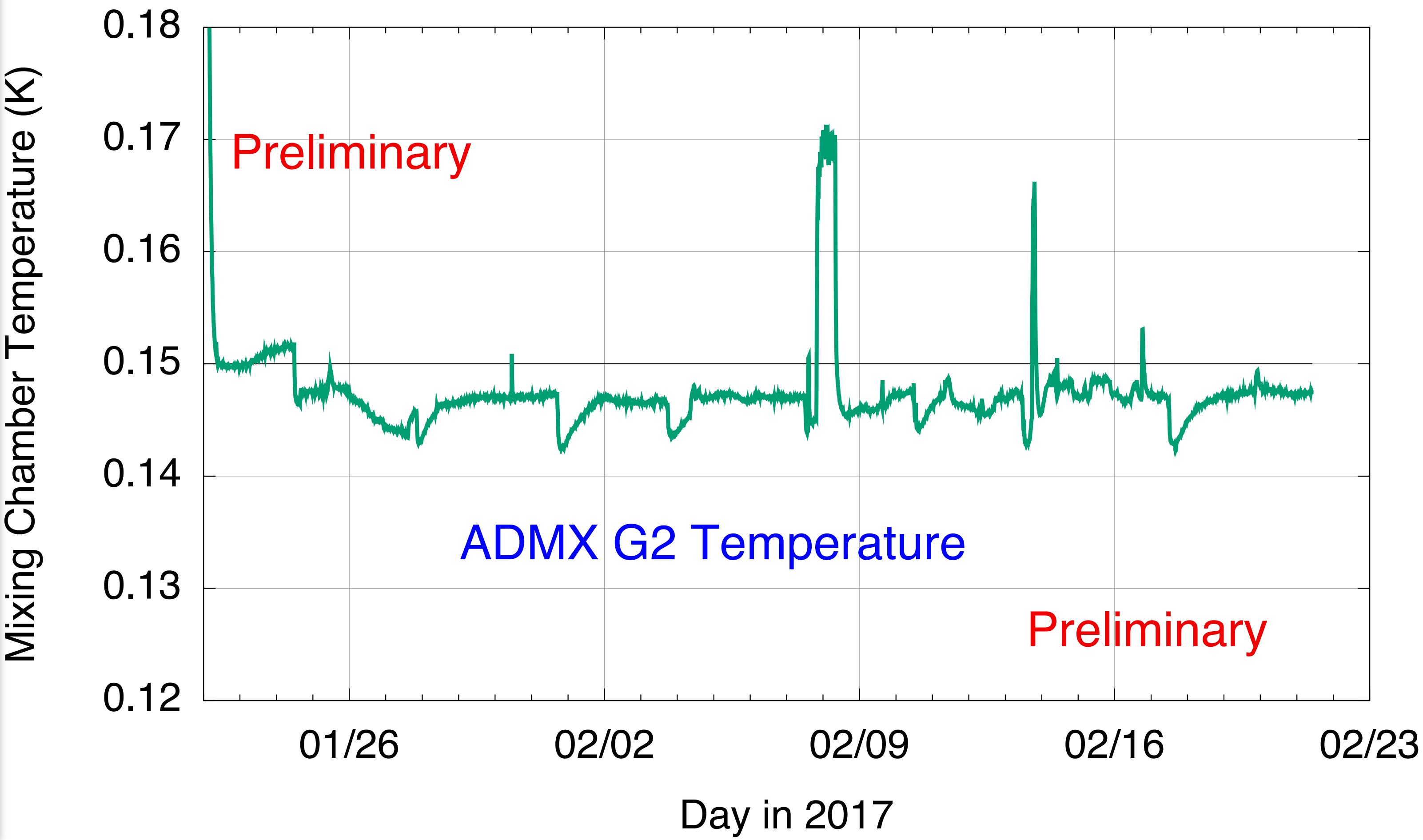


Field Simulation

Cryogenics

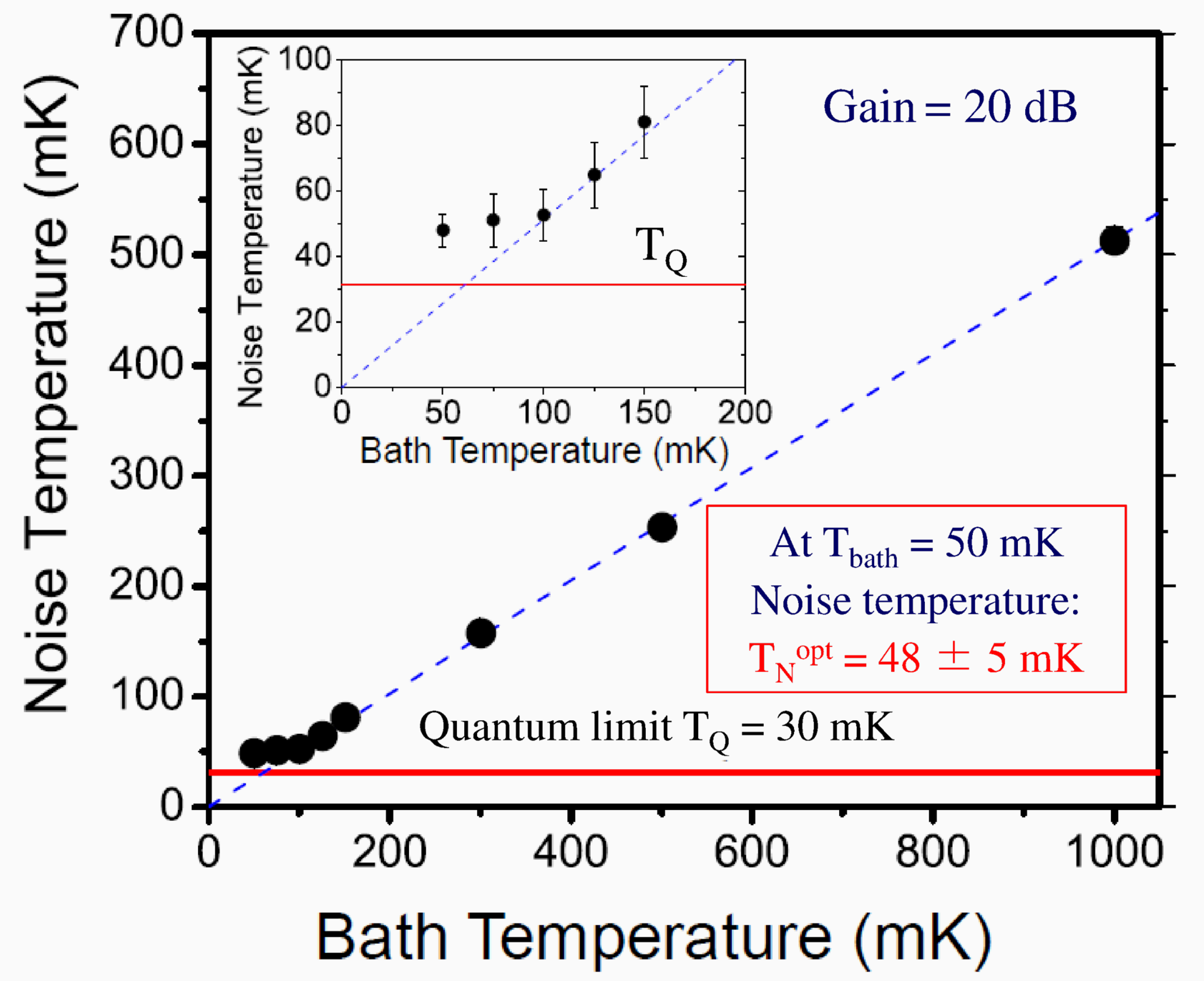
Dilution Refrigerator installed above ADMX Cavity

Cavity and electronics cooled with Dilution Refrigerator to minimize noise



Quantum Electronics: Noise Limit

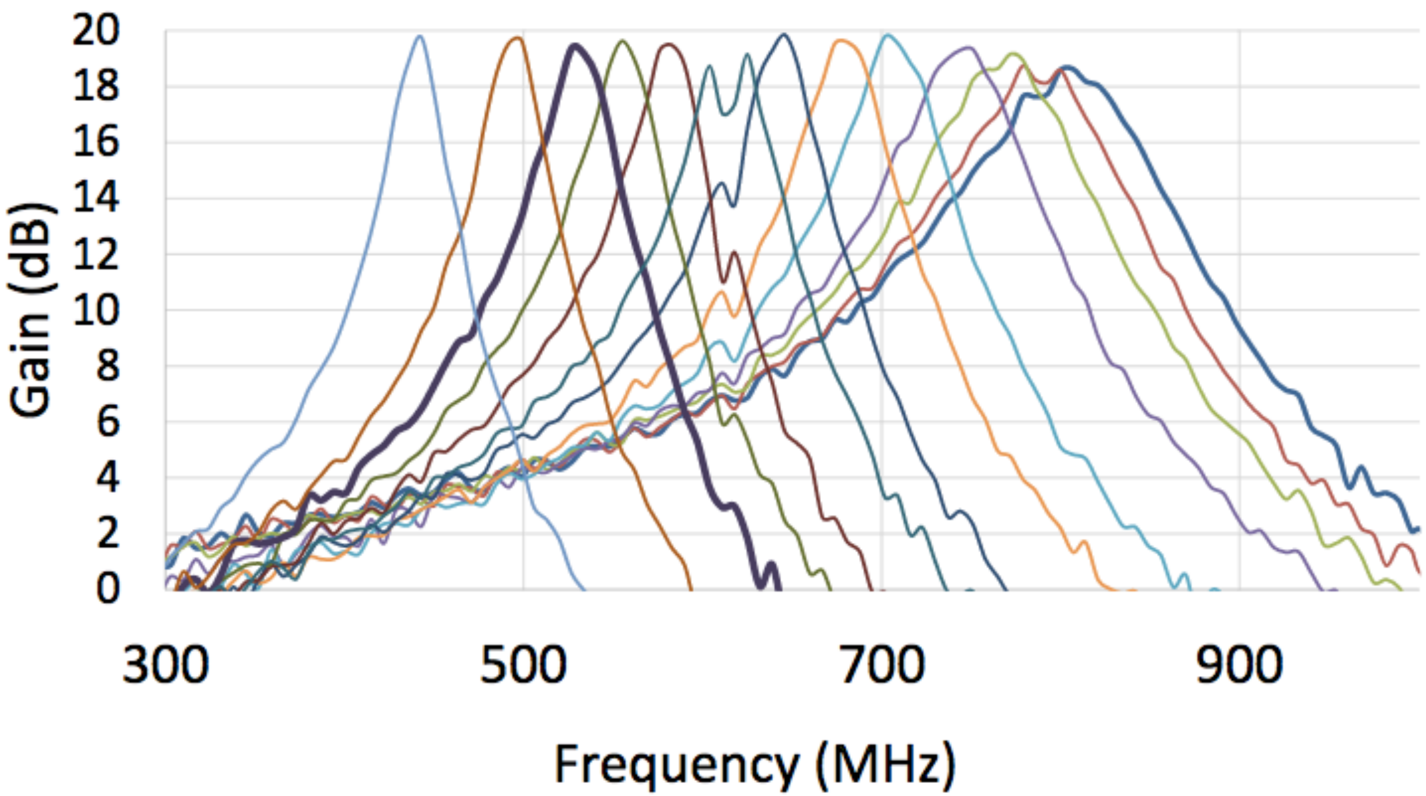
- Quantum mechanics forces a linear amplifier to contribute at least a half photon per resolution bandwidth to the noise
- We have amplifiers that operate near this limit



Clarke Group, UC Berkeley

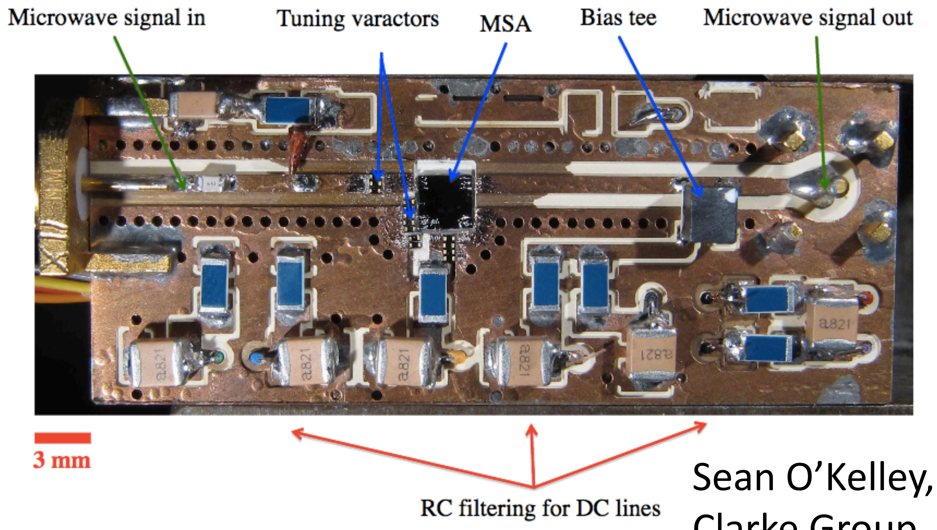
Quantum Electronics: Realization

MSA Varactor Tunability



Figures from 2nd Workshop of Microwave Cavities and Detectors for Axion Research

ADMX Tunable MSA



Sean O'Kelley, Clarke Group, UC Berkeley

ADMX JPA

Yanjie Qiu, Siddiqi Group, UC Berkeley

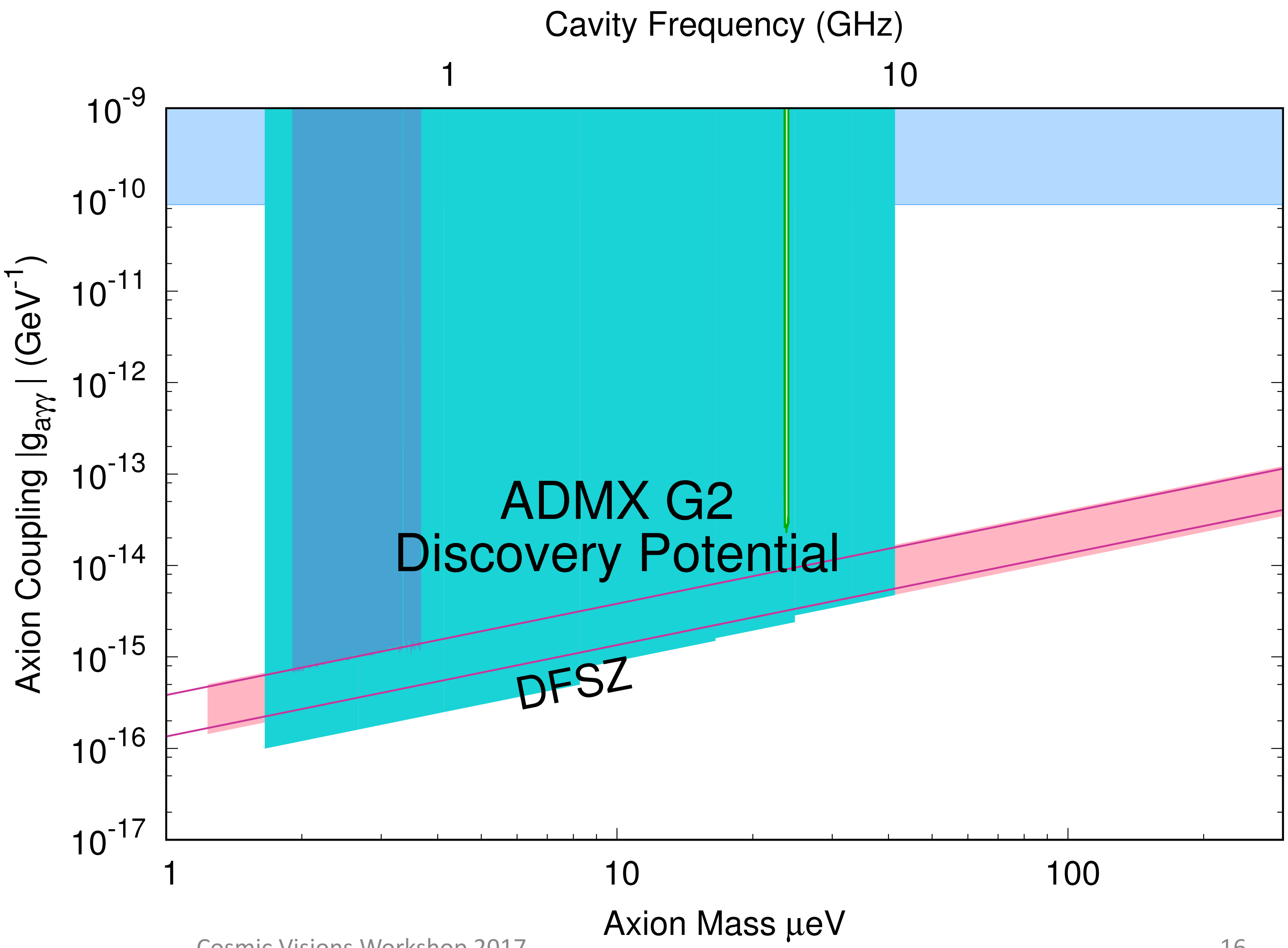
ADMX G2 Operations

- The cavity frequency is scanned over a region until the desired SNR is achieved
- We then examine the combined power spectrum for signs of excess
- Excess power regions can be statistical fluctuations, synthetically injected signals, RF interference, or axions
- Excess power regions are rescanned to see if they persist
- Persistent candidates are subjected to a variety of confirmation tests: for example: magnet field changes or probing with other cavity modes

ADMX G2 – Discovery Potential

ADMX G2 targets the entire 1-10 GHz region over 6 years

Reaching higher frequencies requires new hardware, but no new R&D

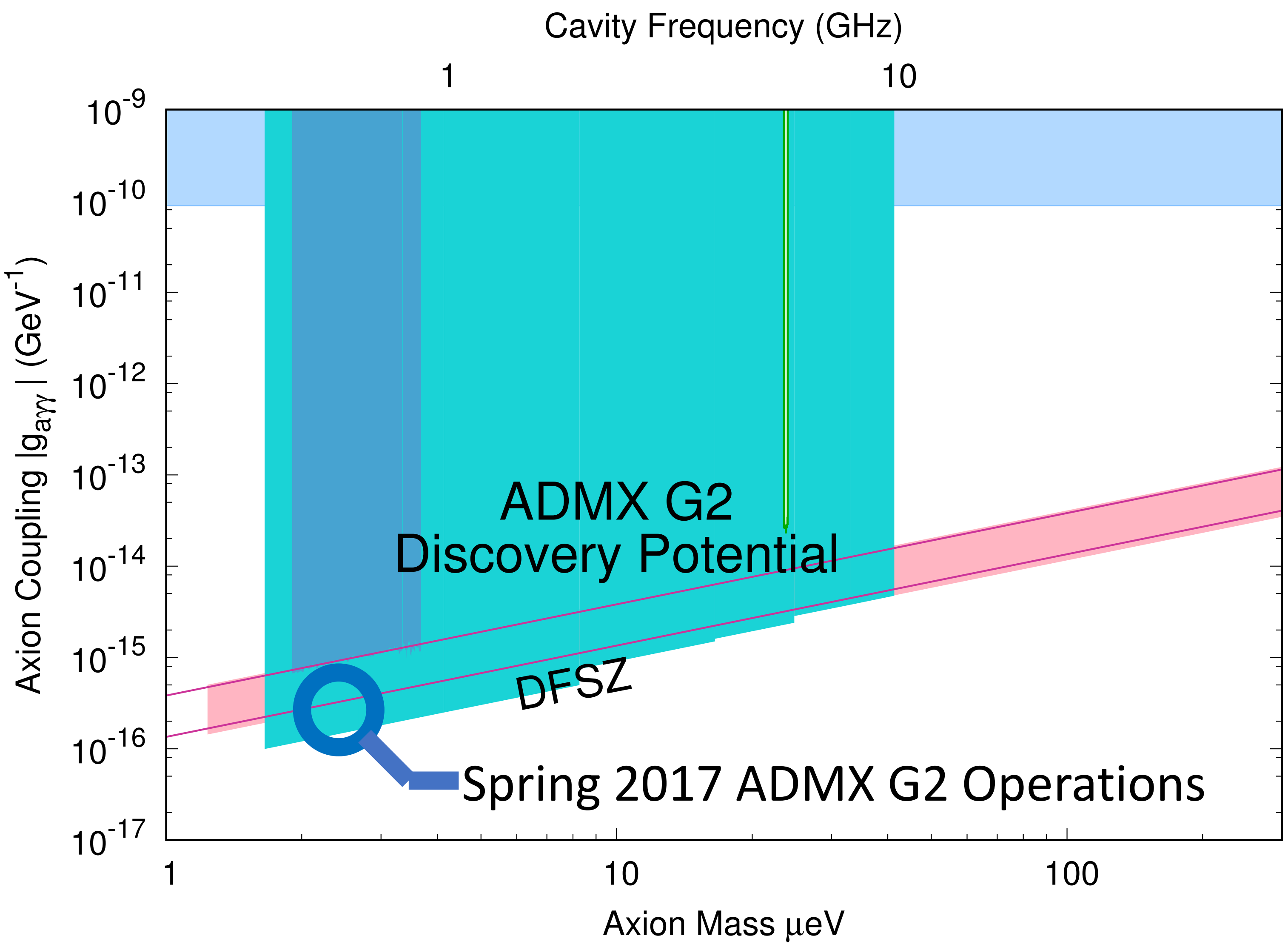


ADMX G2 – Current Status

ADMX G2 has been operating at DFSZ sensitivity since January 2017

We are at ~660 MHz and scanning upwards

We could find the axion at any time



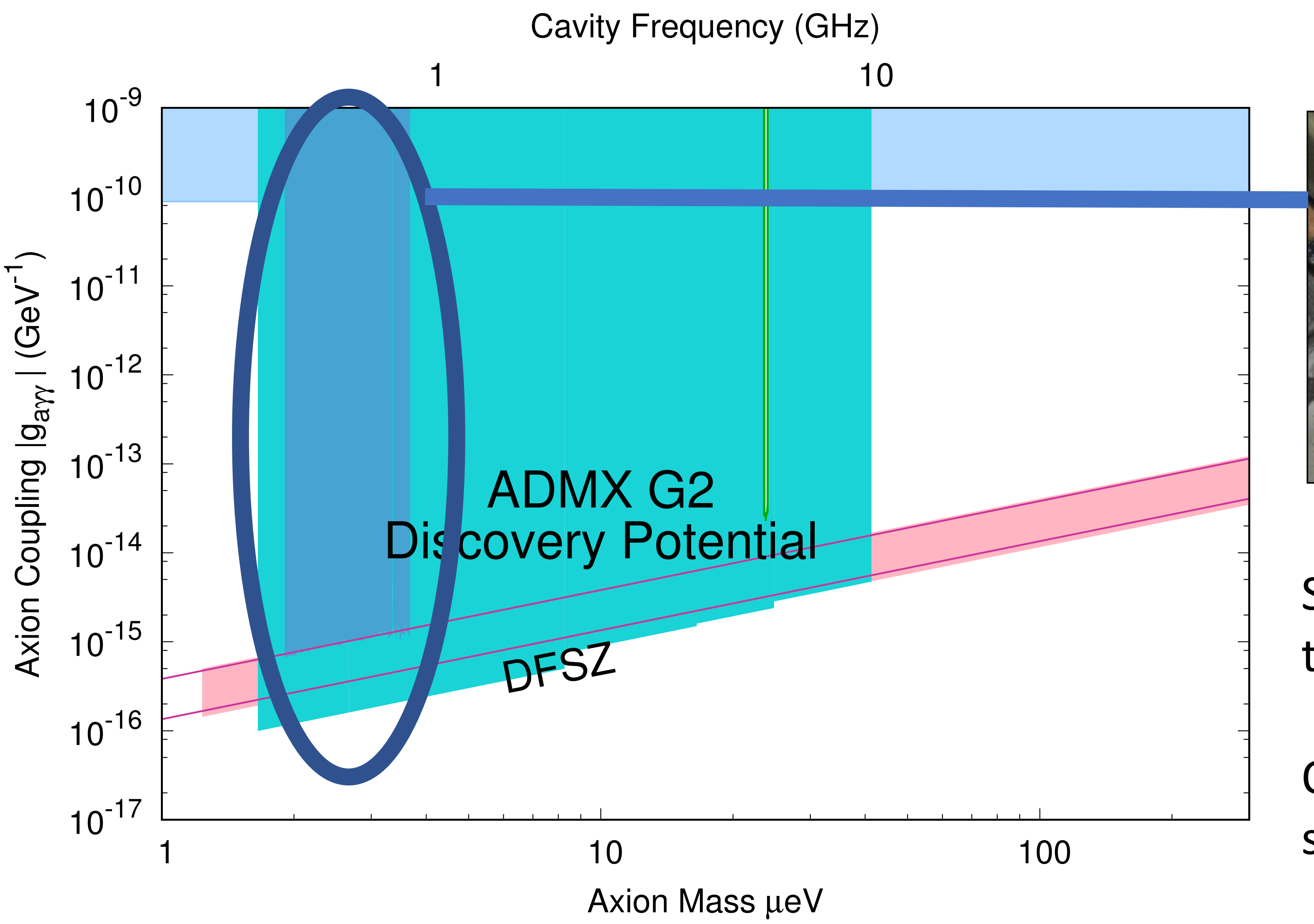
ADMX G2 – Moving forward to higher frequencies

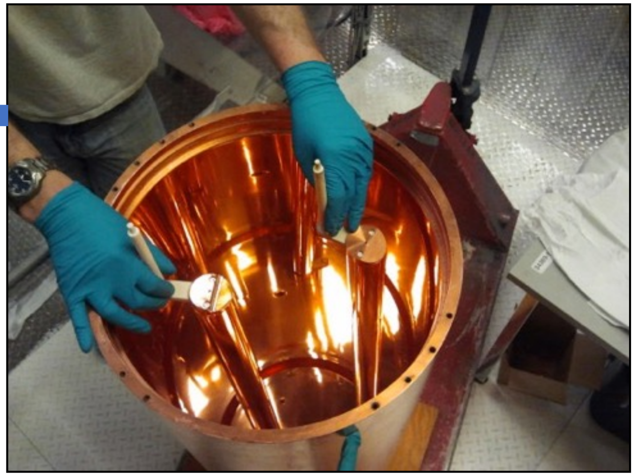
As search frequency increases:

- Expected axion coupling increases
- Cavity volume decreases, decreasing signal
- Cavity Q decreases, decreasing signal
- Quantum limit increases, increasing noise

To maintain good signal—to-noise, we coherently add signals from multiple cavities

ADMX G2 Single Cavity System

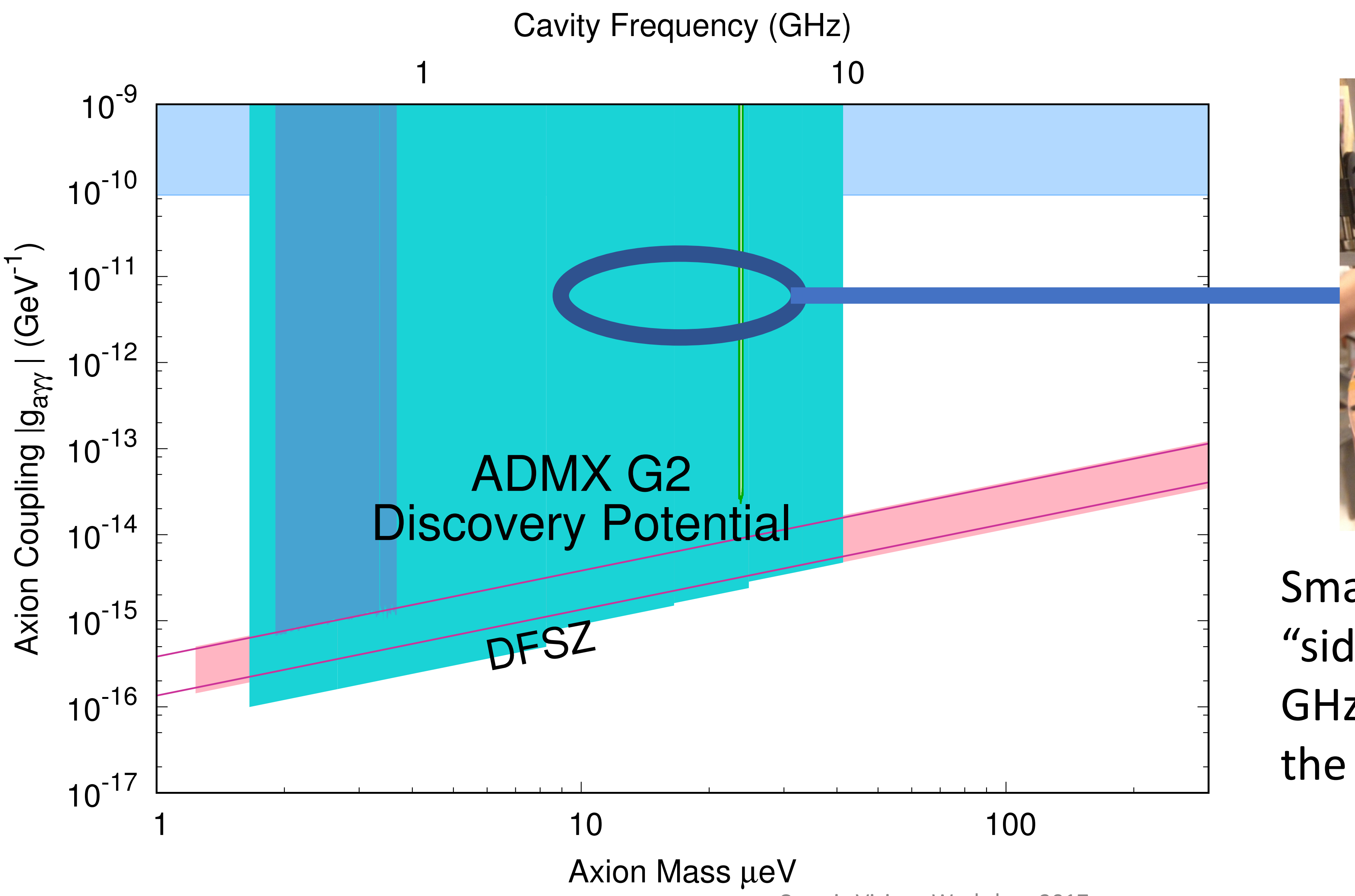




Single cavity system up to 500 MHz – 1 GHz

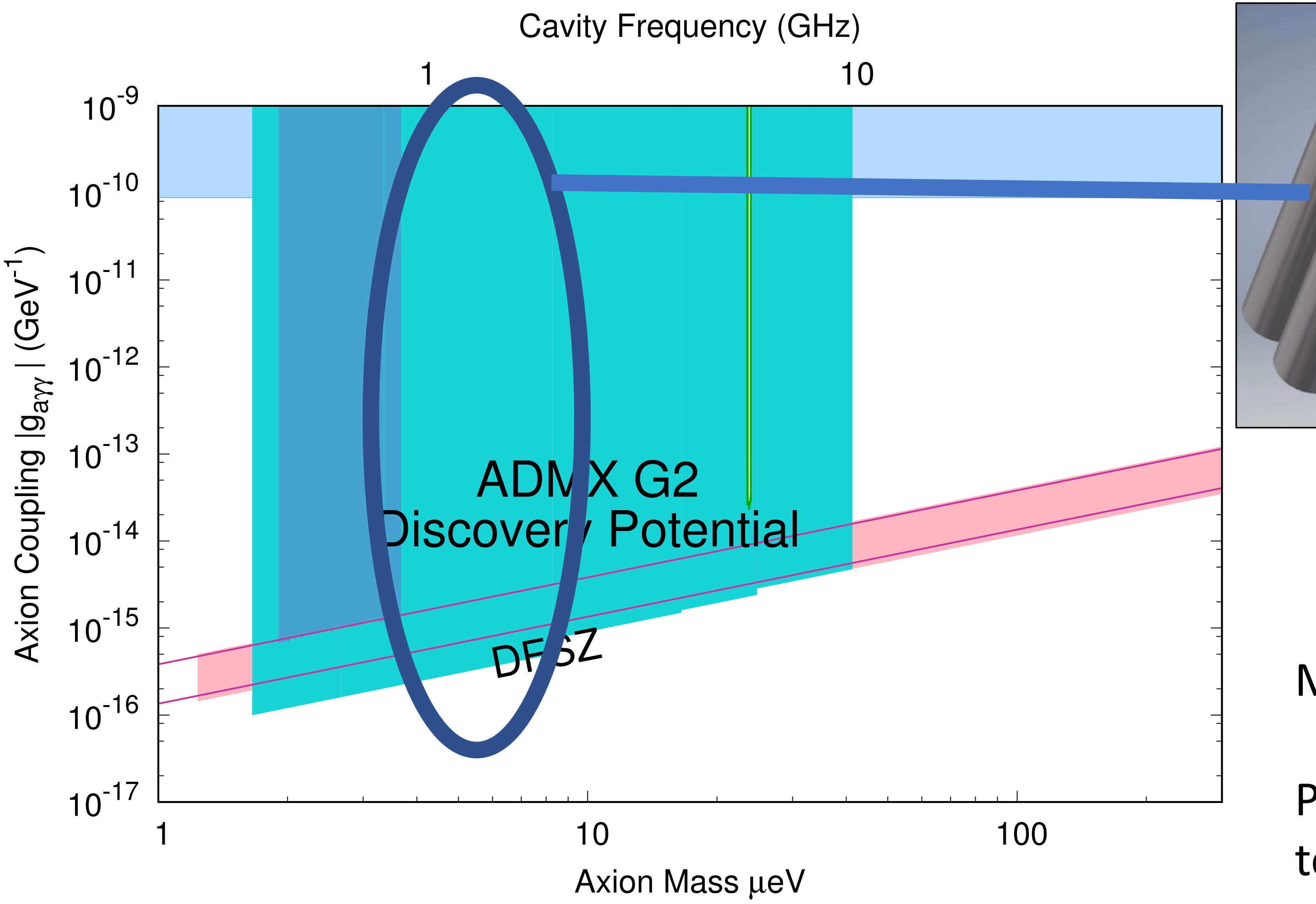
Operating at DFSZ sensitivity **Now**!

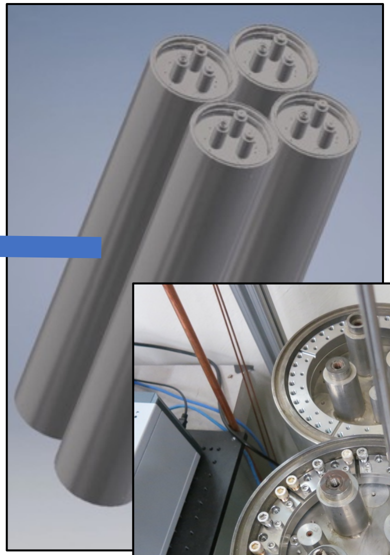
ADMX Prototype for Multicavity Systems



Small cavity prototype "sidecar" taking data 5-7 GHz **now.** First thesis on the 5 GHz data completed.

ADMX G2 – Multicavity Systems

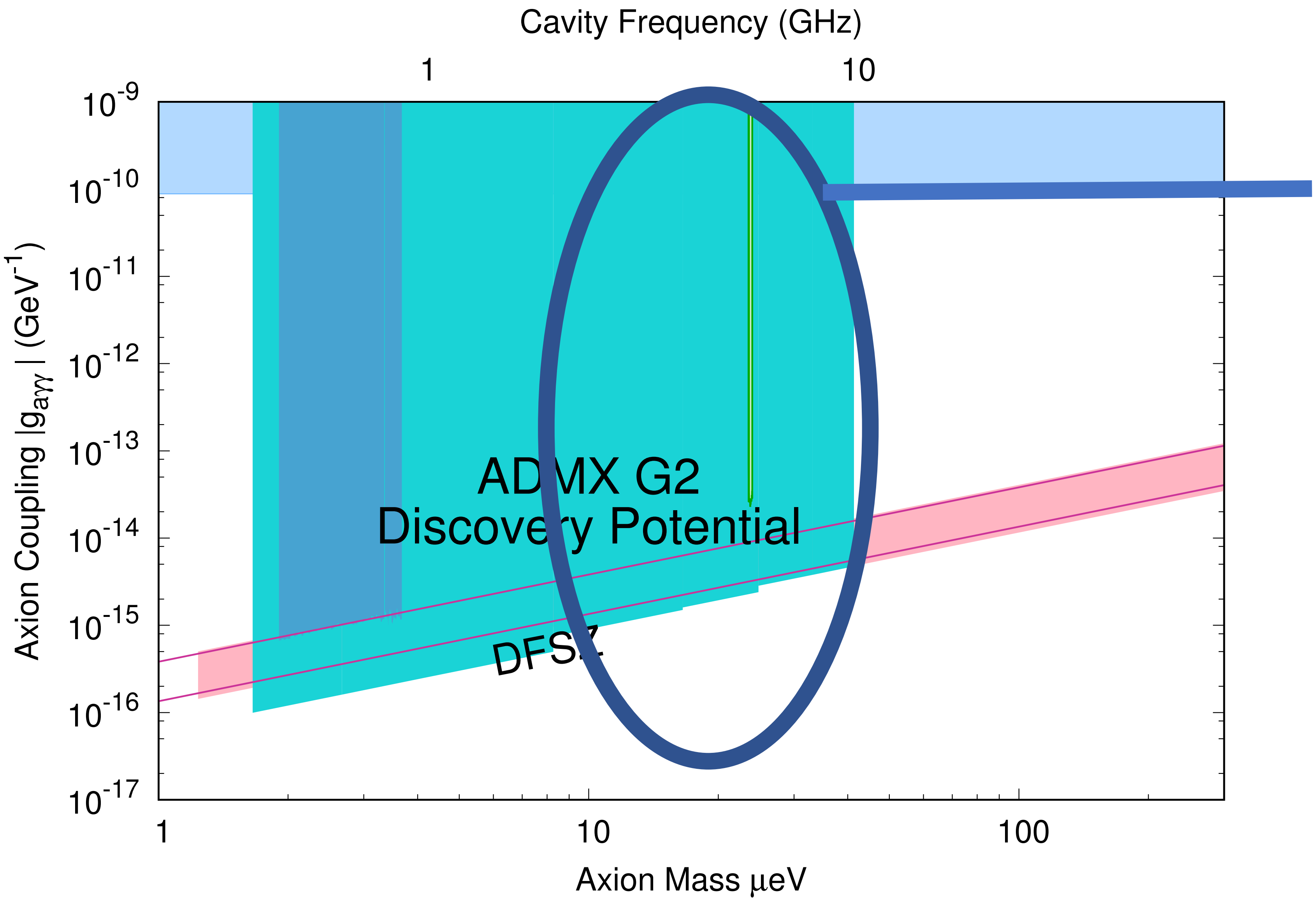




Multicavity system 1-2 GHz

Prototype fabricated, in testing

ADMX G2 Multicavity Systems 2

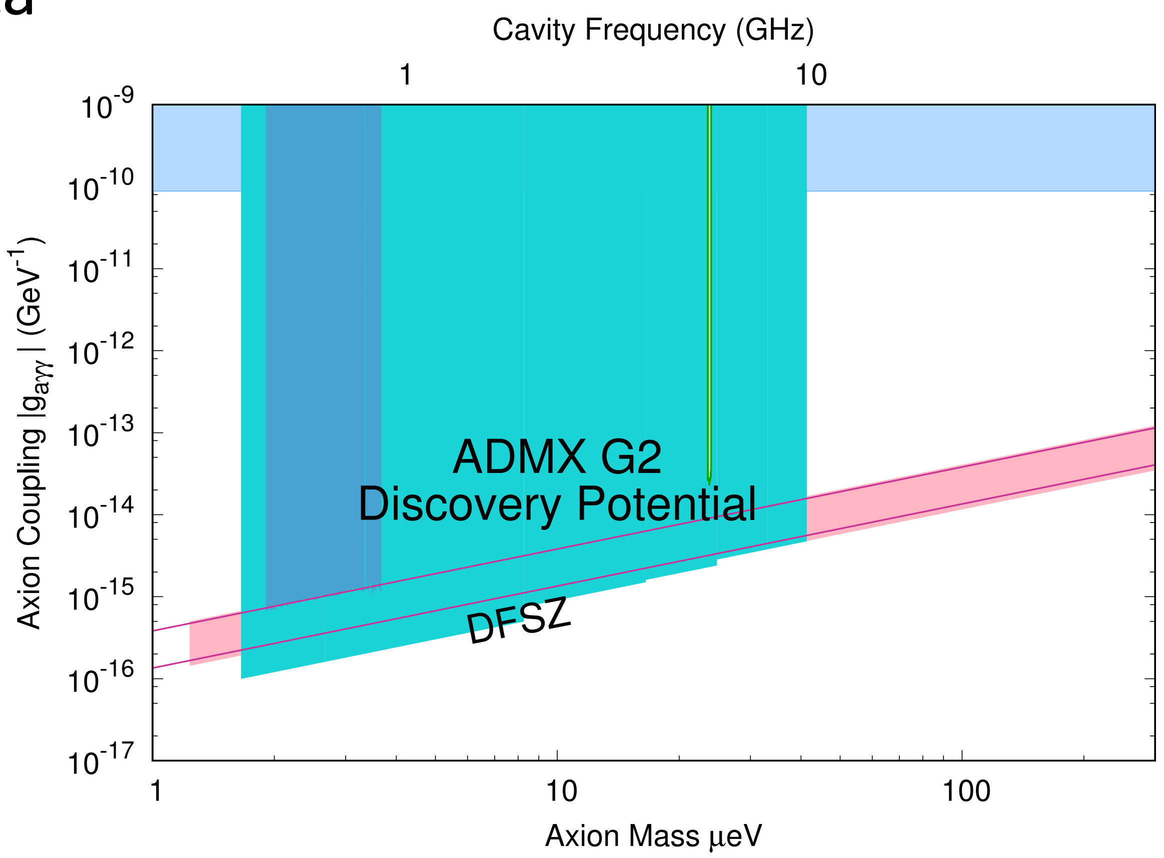


Multicavity systems for 2-4 designs being finalized.

4-8 GHz resonators in design. Note, DFSZ at 10 GHz will require extra run time

ADMX G2 Summary

- ADMX G2 is currently in production data-taking over the most attractive mass range with sensitivity to the DFSZ benchmark coupling
- After decades of work on axion haloscopes, we are finally at a point where we have a good chance of discovery
- ADMX G2 will cover much of the plausible axion mass range



Visions: Beyond ADMX G2

Scanning at DFSZ at 10 GHz is very time consuming.
Some of the plausible axion mass range lies beyond 10 GHz
(Some lies below 500 MHz, see David Tanners talk)

In particular, R&D is required to develop serious experiments for 10 GHz and beyond.

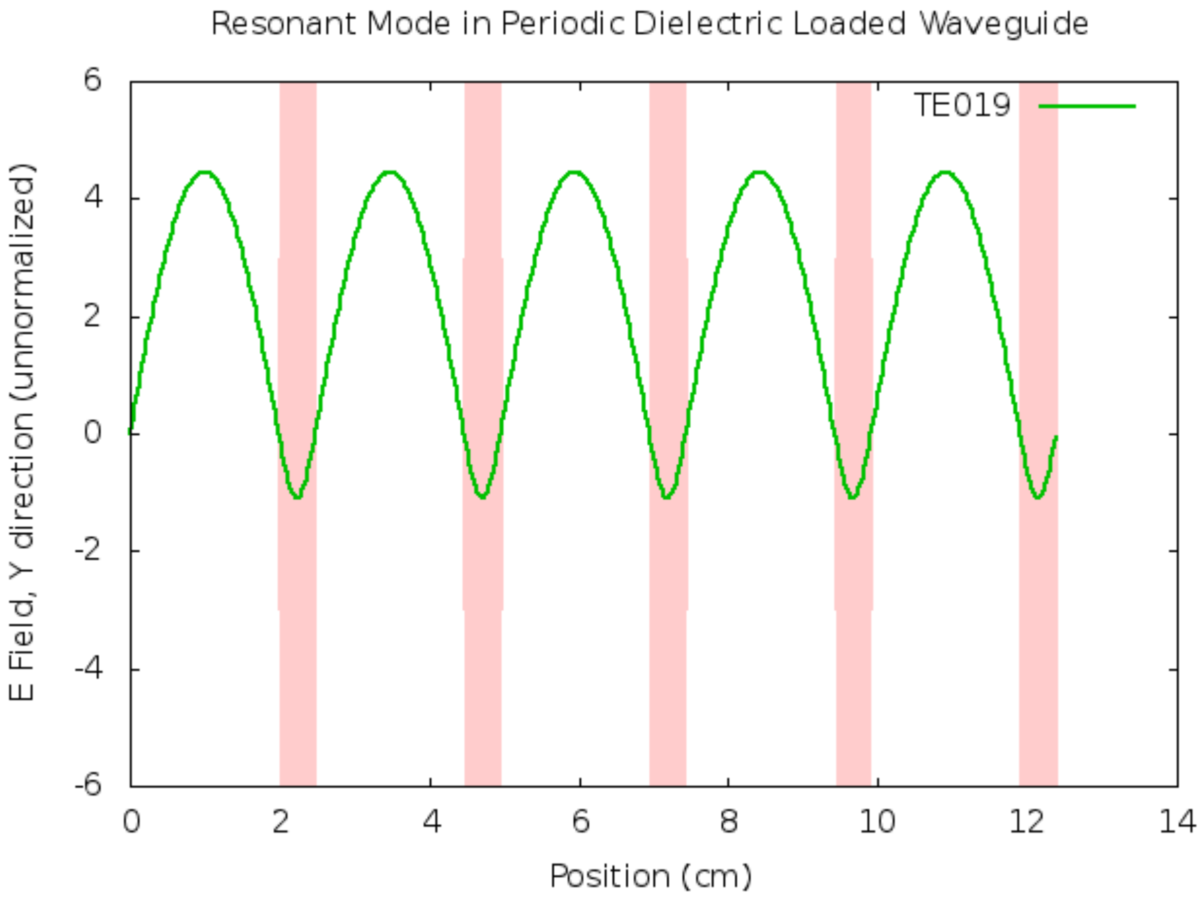
Axion R&D Program

- Larger Magnets (see Mark Bird's talk)
- Multiwavelength Resonators (this talk)
- Single Photon Receivers (this talk)

Multiwavelength Resonators

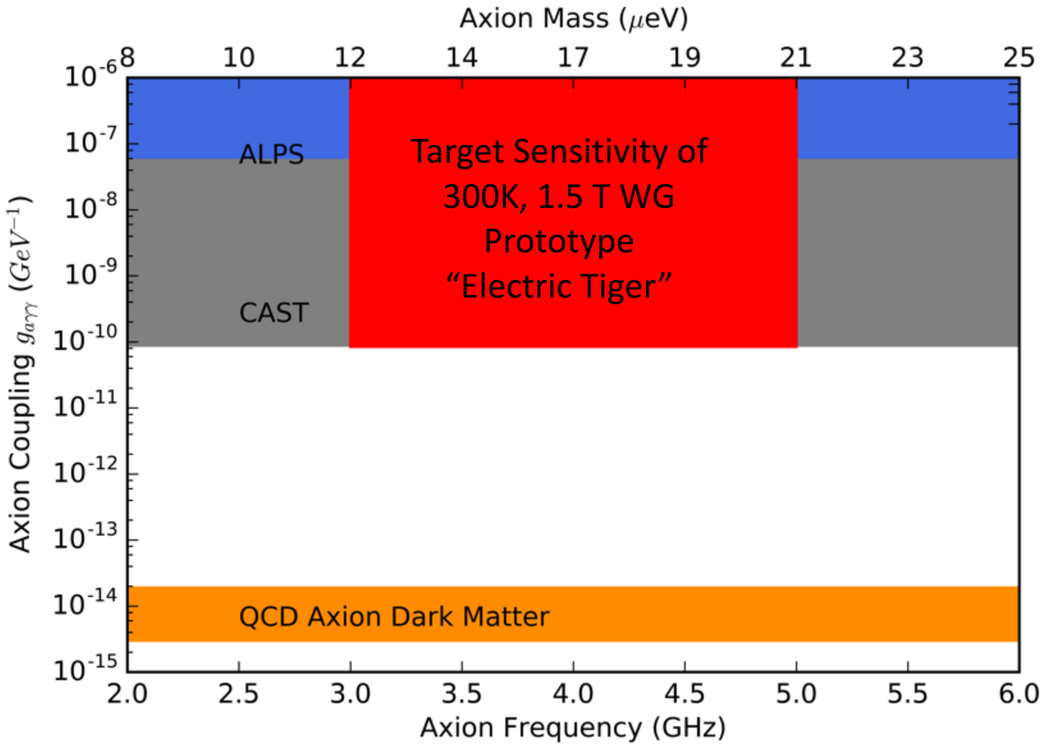
Naively, higher order electromagnetic modes do not overlap well with the axion wavefunction

However, manipulating either the mode structure, or the magnetic field can allow coherent conversion of axions into a large volume multiwavelength mode

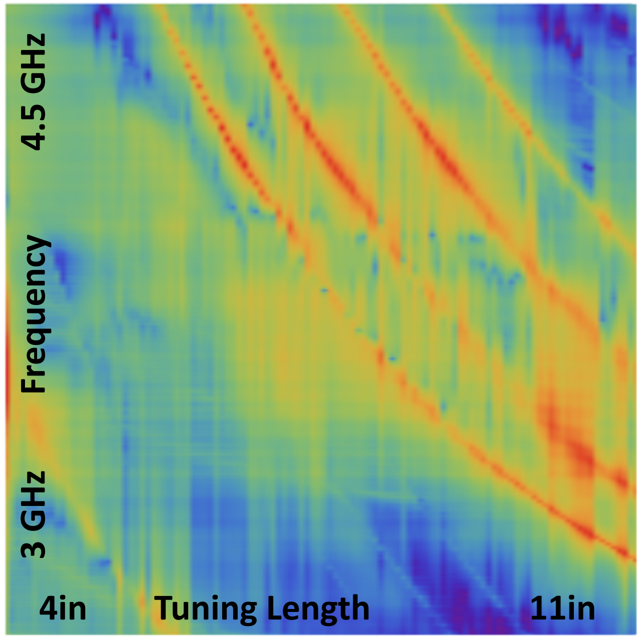


Multiwavelength Waveguide Resonators

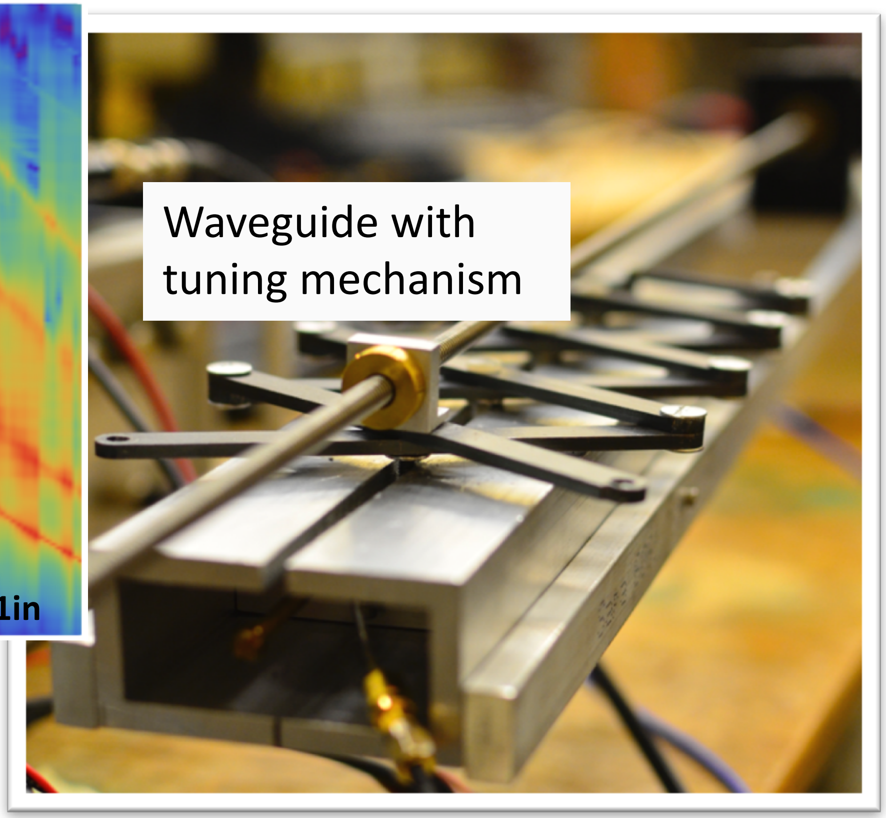
Dielectrics can be used to couple multiwavelength modes in uniform magnetic fields to axions



Dielectric loaded waveguide in room temperature accelerator magnet, target sensitivity comparable to solar experiments

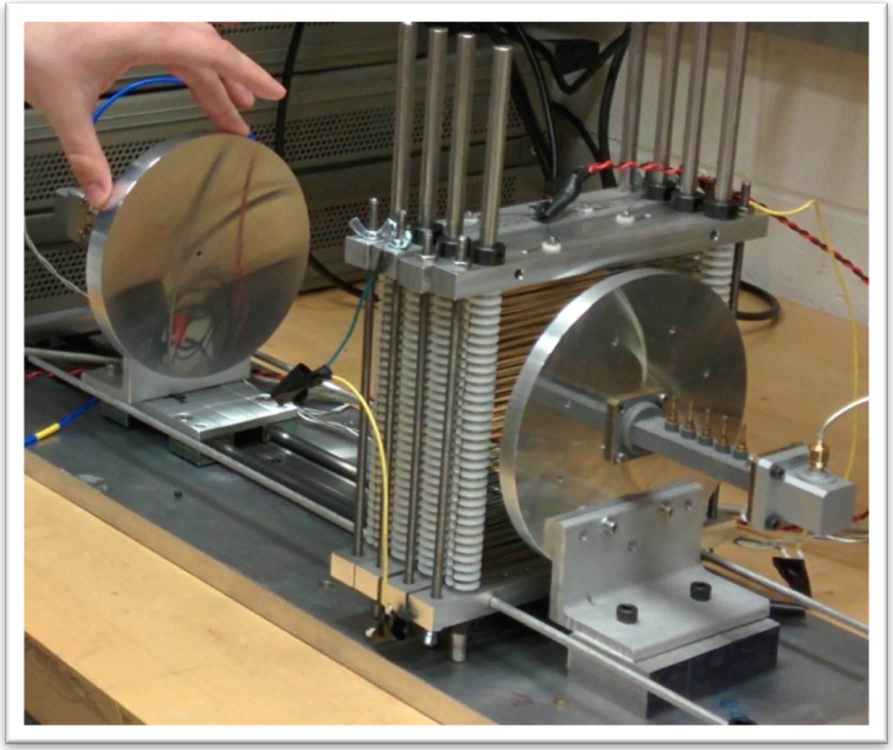


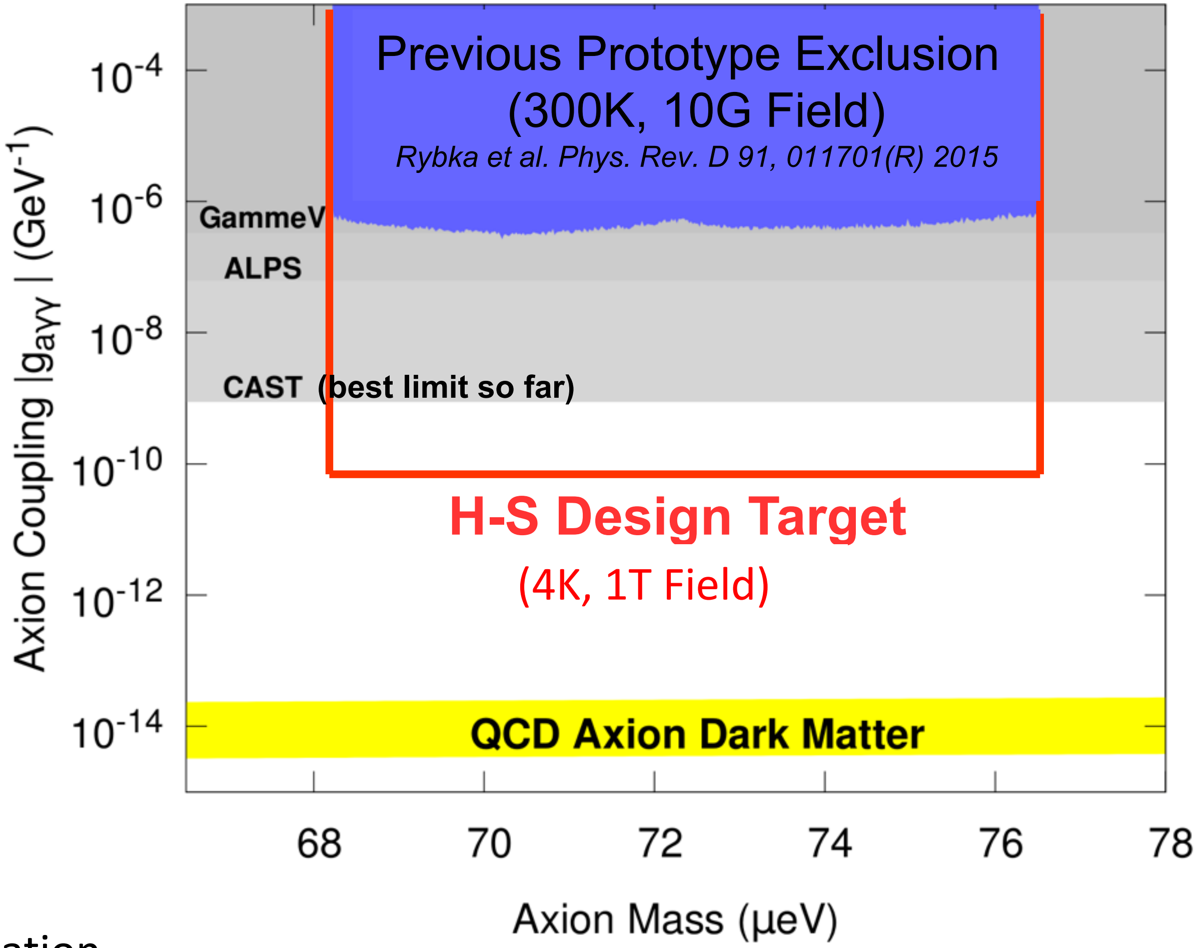
Measured Mode Map



* work supported by the Heising-Simons Foundation

Multiwavelength Open Resonators



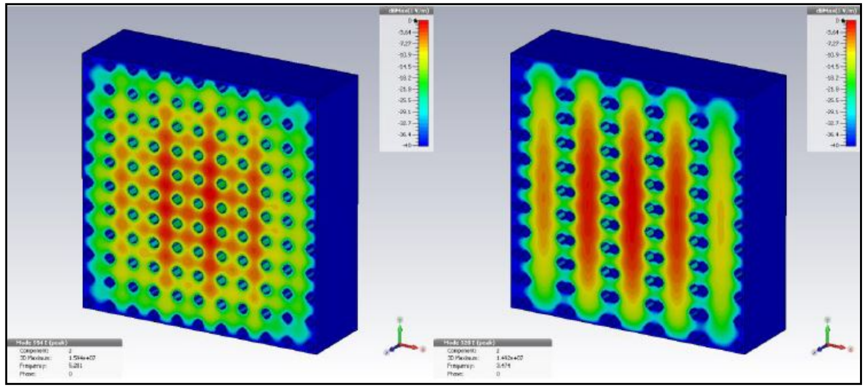


Open resonators retain high Qs at high frequencies. Cold prototype under construction at 20 GHz.

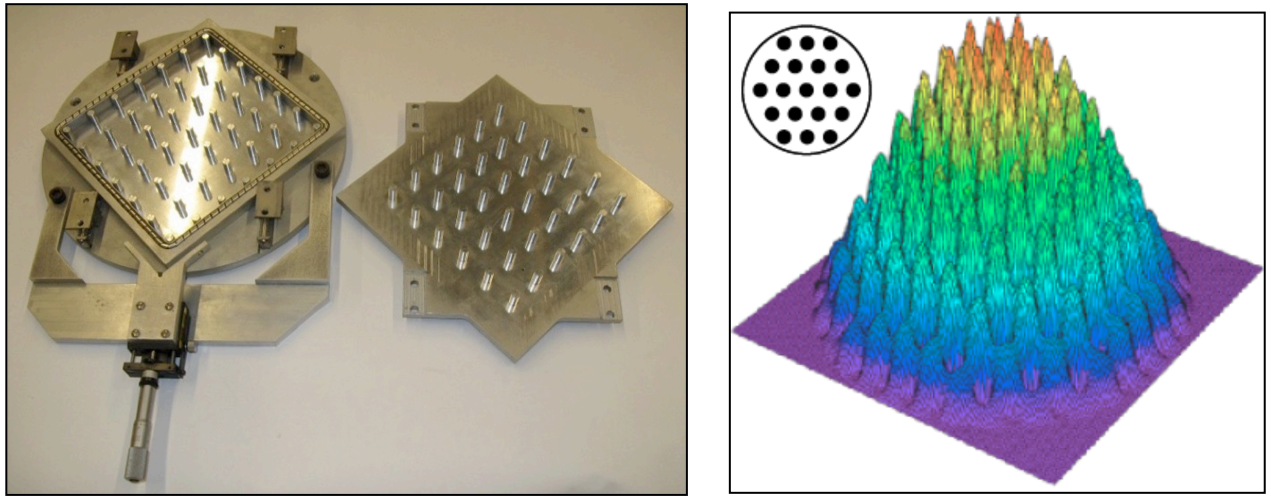
* work supported by the Heising-Simons Foundation

Photonic Bandgap Resonators

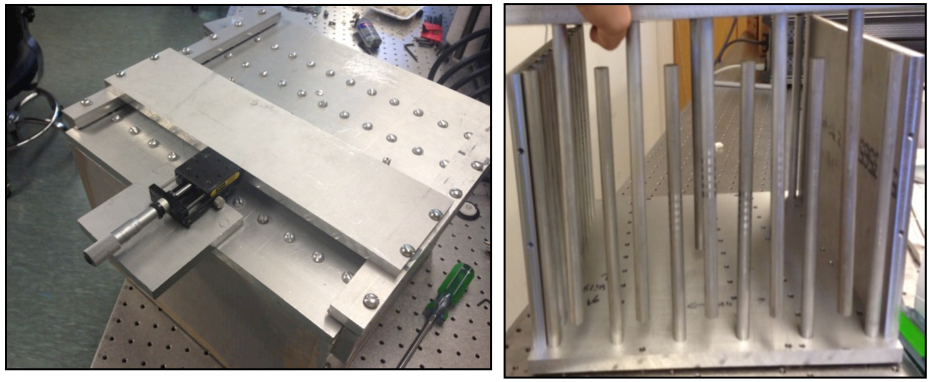
- Photonic bandgap style resonators are another approach for multiwavelength resonators
- Would benefit significantly from superconducting wall technology



Simulation of 121 post prototype PBG cavity



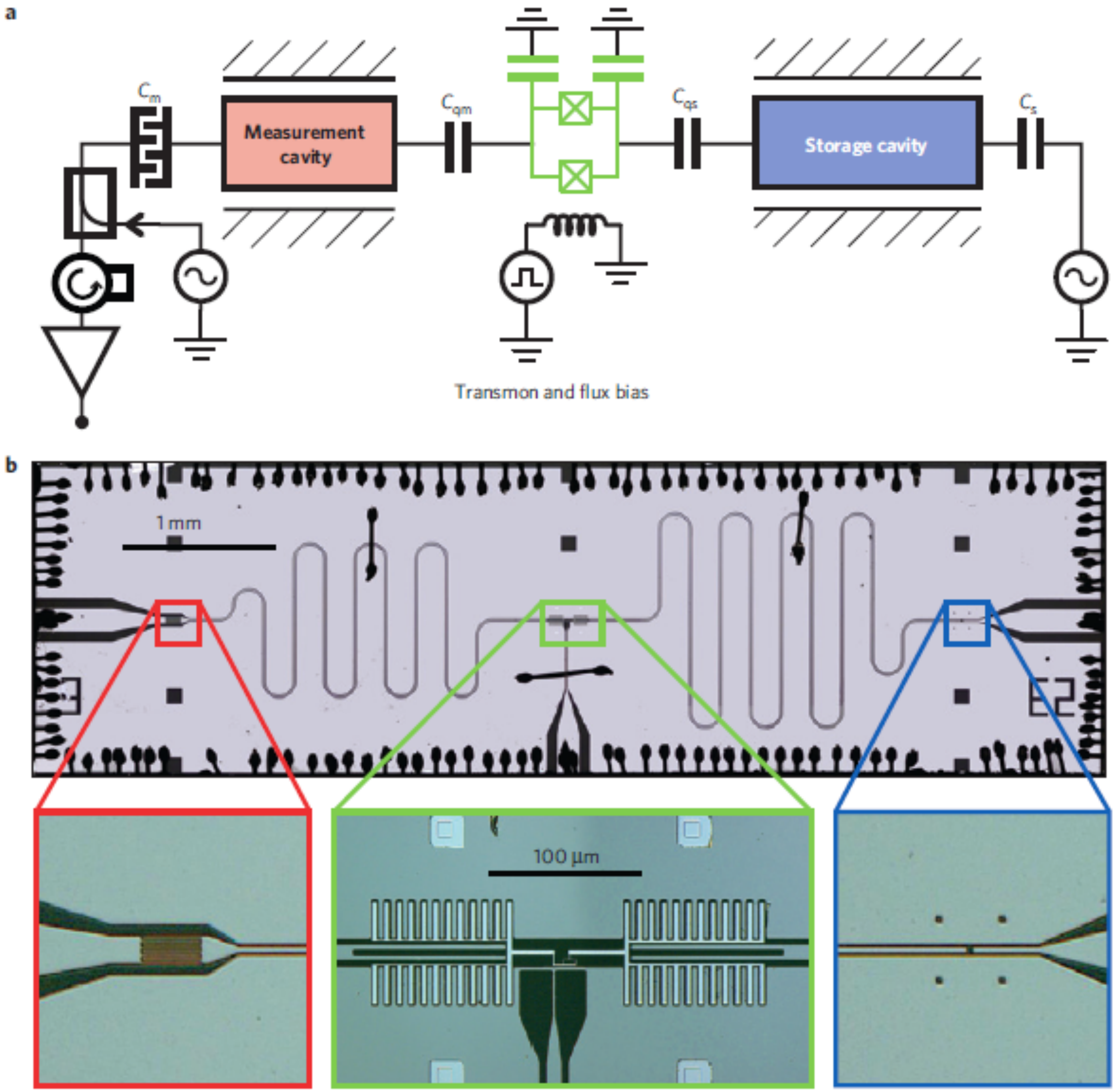
96 post PBG cavity



121 post PBG cavity, fabricated
(work done by G. Carosi, LLNL)

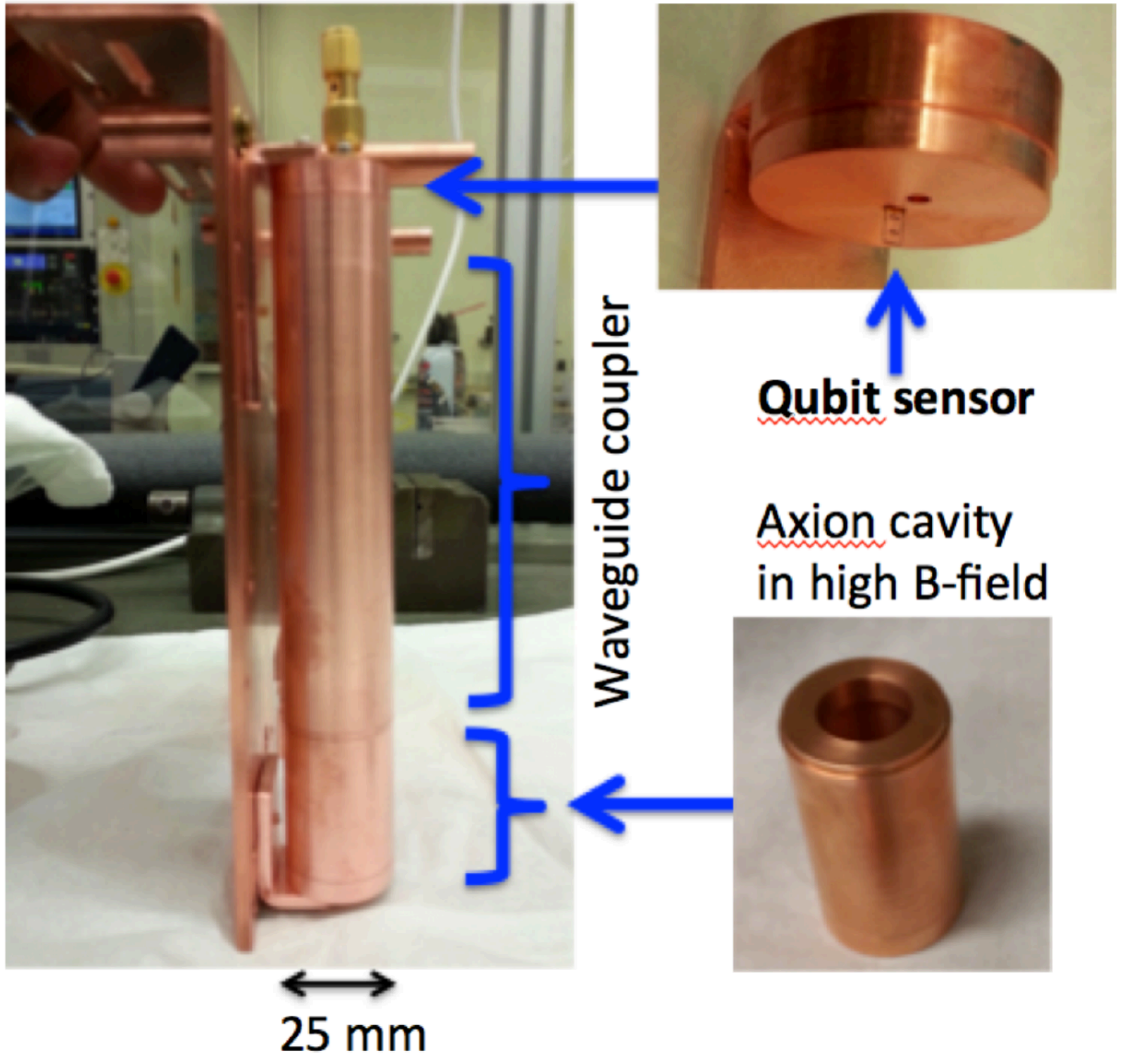
Sub-Quantum Limited Receivers

- The standard quantum limit for linear amplifiers scales with frequency
- QND measurements of photon number evade this limit
- What we need is a microwave phototube in the 10 GHz + range
- This has already been demonstrated in the field of quantum electronics

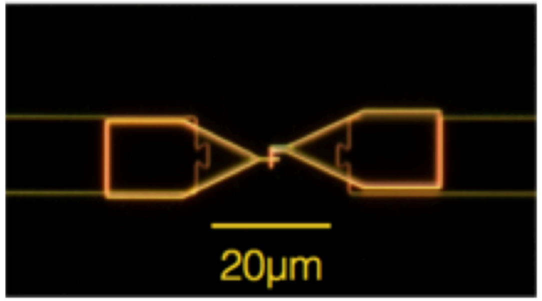


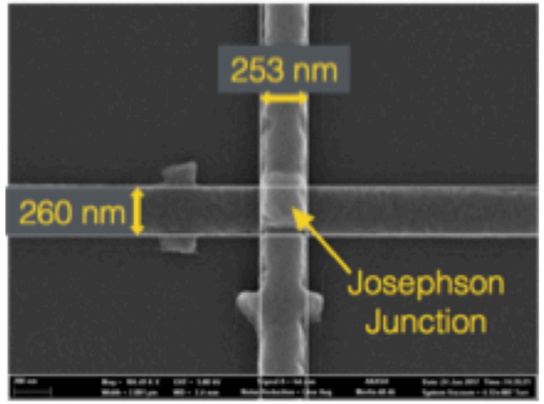
See Lamoreaux, et.al, 2013, Zheng, et.al, 2016

Progress on Photon Counters



Prototype qubit axion cavity under construction at FNAL, U. Chicago, LLNL



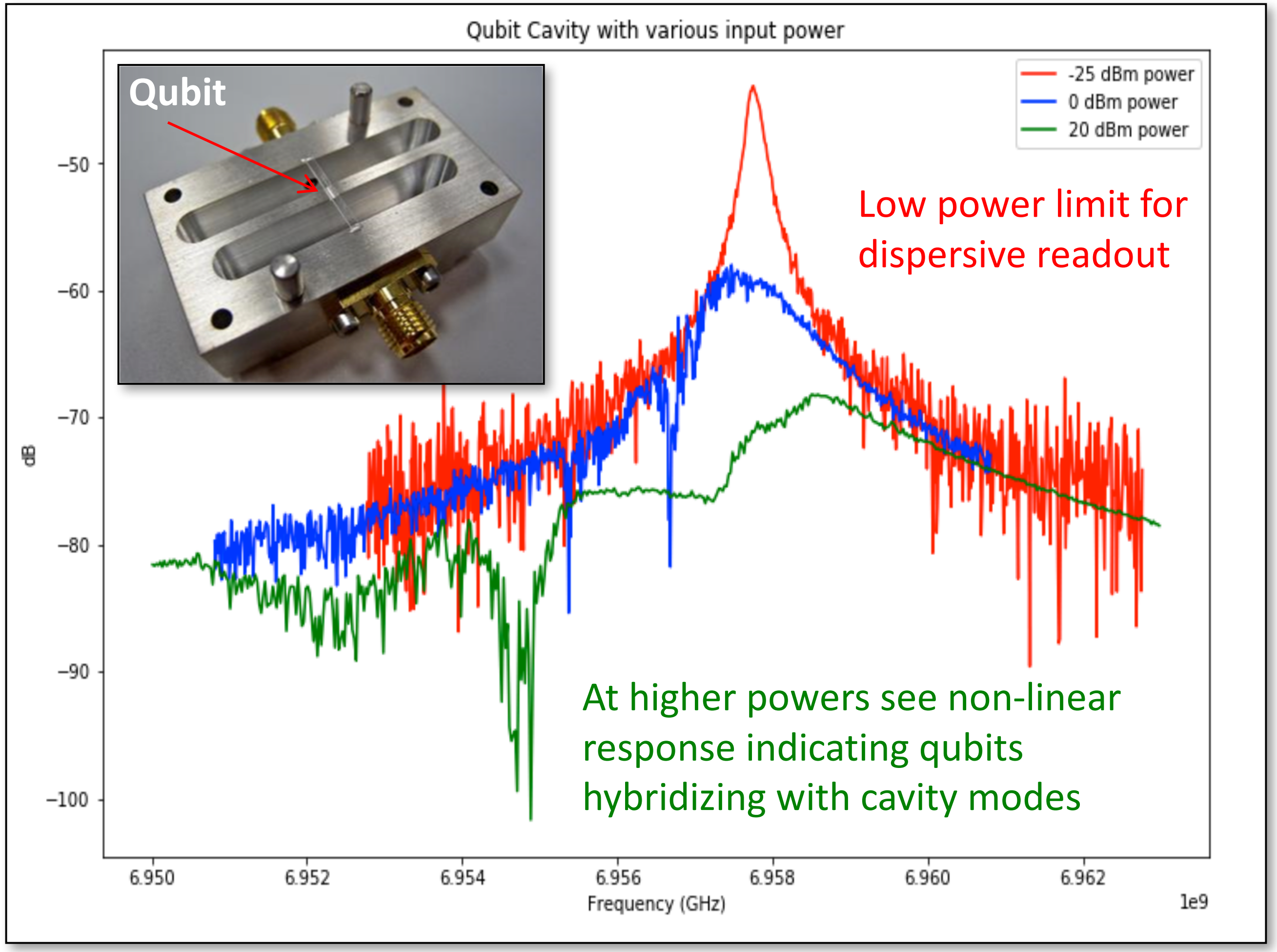


* work supported by the Heising-Simons Fonudation

Recent readout of 2 qubits in 3D microwave cavity

LLNL Wet Dilution Fridge and qubit cavity readout system

3D cavity with qubits* similar to one currently being measured at LLNL (M. Reed Thesis Yale 2013)



*qubits from Siddiqi group UC Berkeley.
3D readout cavity built by LLNL

Conclusions: What current experiments can do:

- ADMX G2 is the only operating experiment with DFSZ sensitivity. This is the realization of a many decades line development effort.

- ADMX G2 will explore the range 1-10 GHz, exploring very plausible masses down to the very attractive DFSZ coupling.

- If the QCD axion with a mass in that region makes up most of the local dark matter density, ADMX G2 will find it.

Visions: What future experiments need to do:

- For 10 GHz and beyond new ideas need to be explored
  - Higher magnetic fields
  - Multiwavelength Resonators
  - Single Photon RF Receivers
- These are all being pursued at the small scale R&D level
- Successful prototypes could be the basis for 10 GHz+ axion searches

Conclusion

- ADMX has achieved its coupling goal at high sensitivity. We could discover the axion at any time.
- We are grateful for the community's strong support that has allowed us to reach this point.
- We ask the community for continue support in the coming years as we search for axions with high sensitivity