# Current Status and Future Plans of ADMX


Gray Rybka

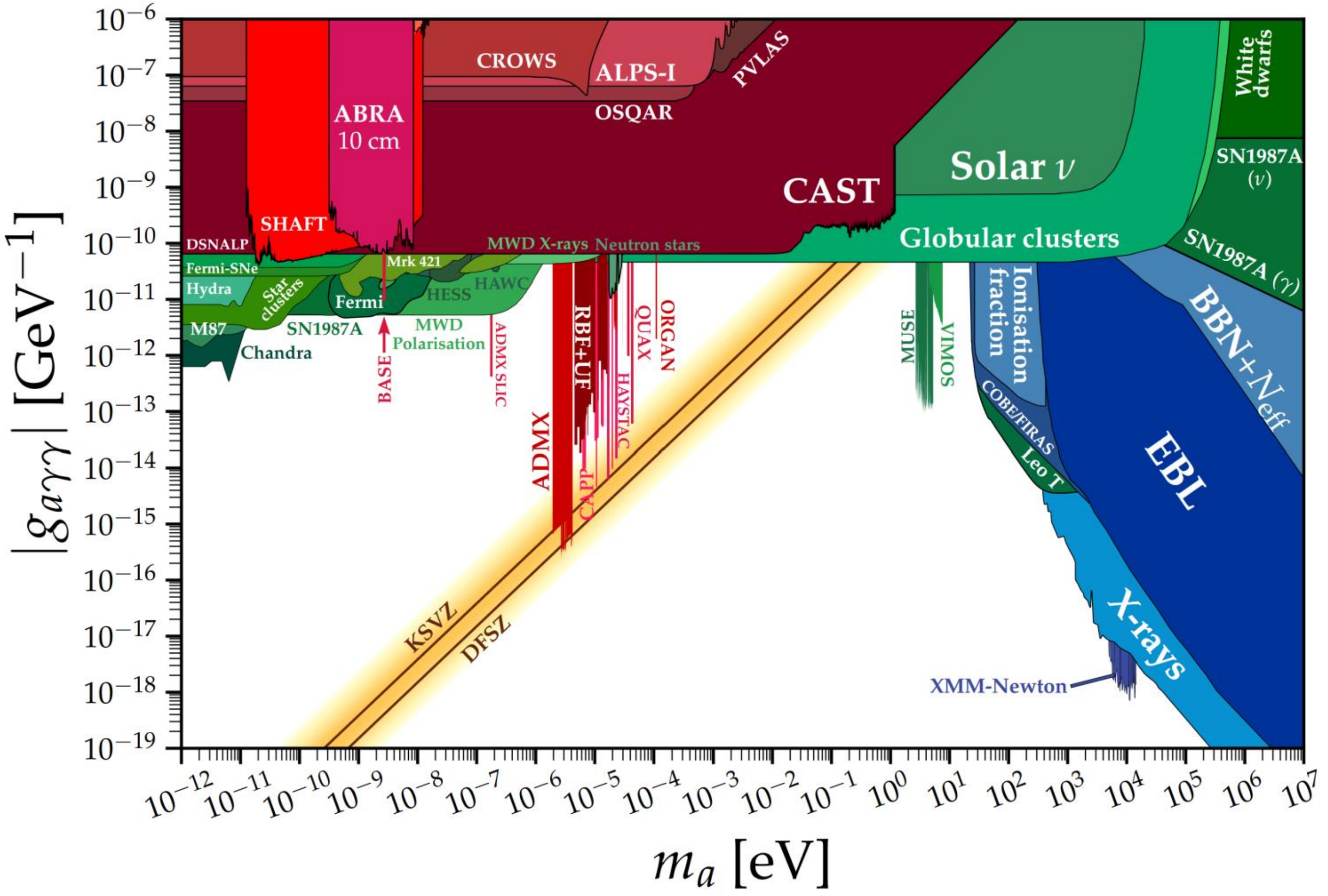
University of Washington


Patras 2022

August 11, 2022

# The QCD Axion

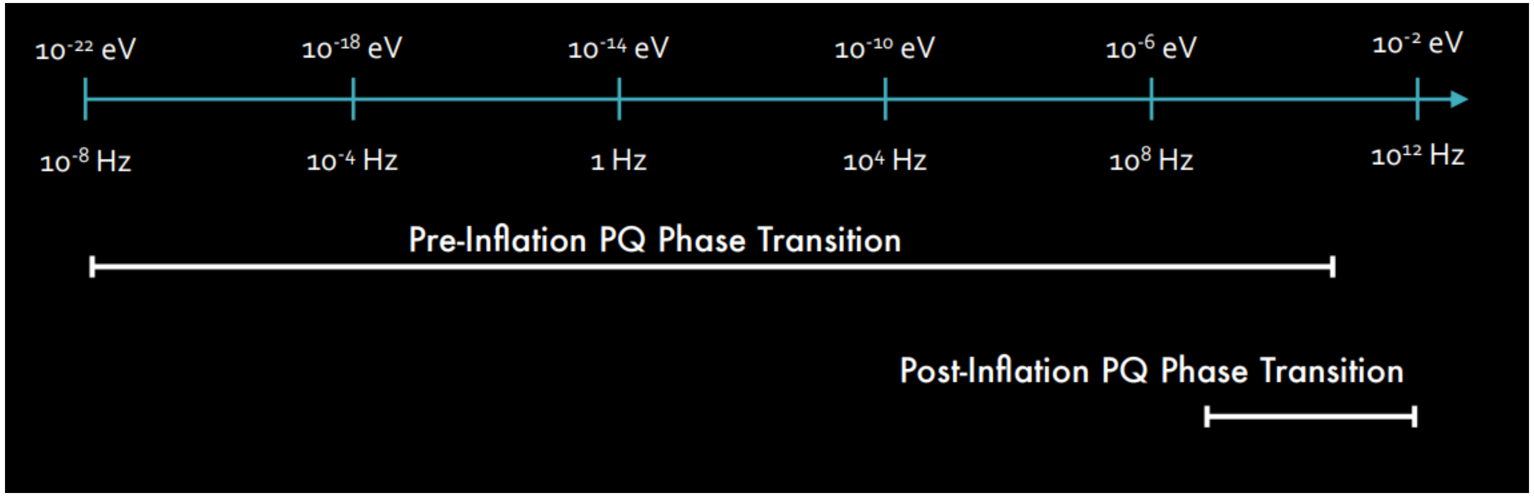
- Previous speakers have already explained axion theory
- Recall that very little QCD axion space has been explored
- We would like to discover axion dark matter



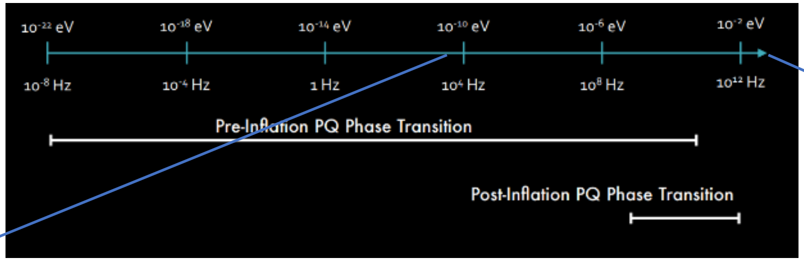

https://github.com/cajohare/AxionLimits

# Theoretical Preferences

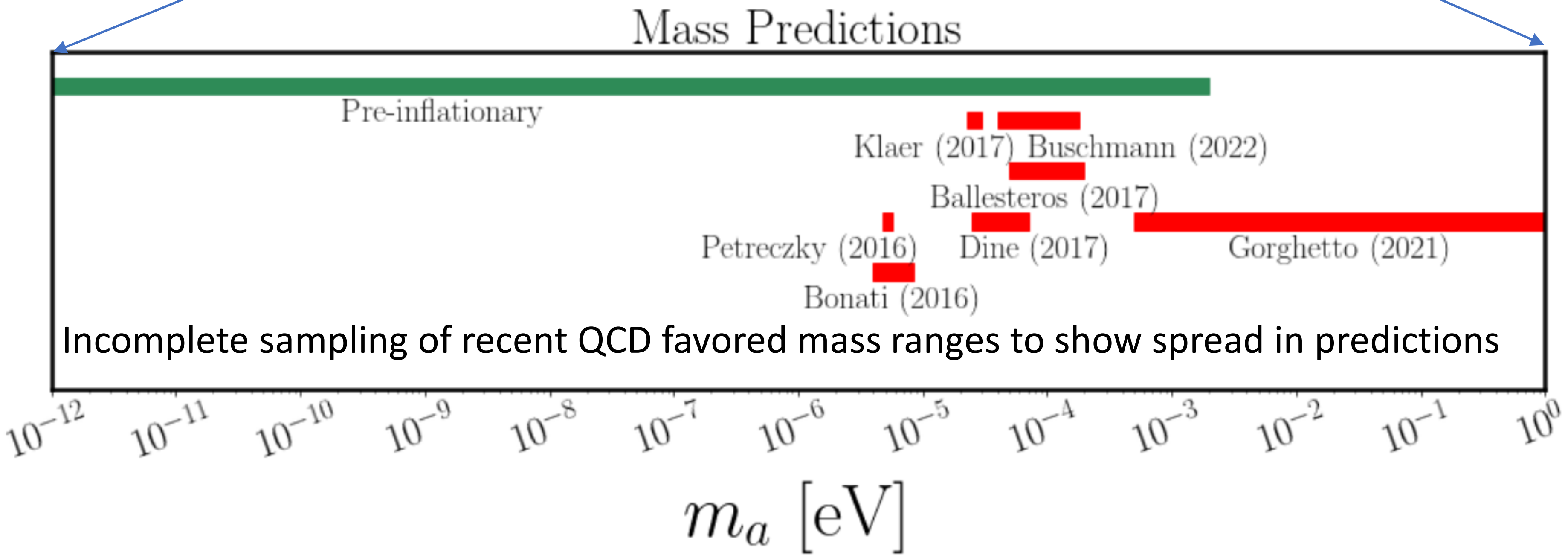
- In general, things that happen before the end of inflation could produce dark matter with any axion mass, but after inflation favors 1ueV and above



# Theoretical Preferences




Exact preferred mass is assumption-dependent. We'll have to explore a wide range.



# ADMX Collaboration


UNIVERSITY OF WASHINGTON 1861
WASHINGTON UNIVERSITY IN ST. LOUIS 1853
THE UNIVERSITY OF WESTERN AUSTRALIA
Berkeley UNIVERSITY OF CALIFORNIA
The University Of Sheffield.
UF UNIVERSITY of FLORIDA
Los Alamos NATIONAL LABORATORY
Lawrence Livermore National Laboratory
Pacific Northwest NATIONAL LABORATORY
Fermilab
ILLINOIS TECH

NSF
HEISING - SIMONS FOUNDATION

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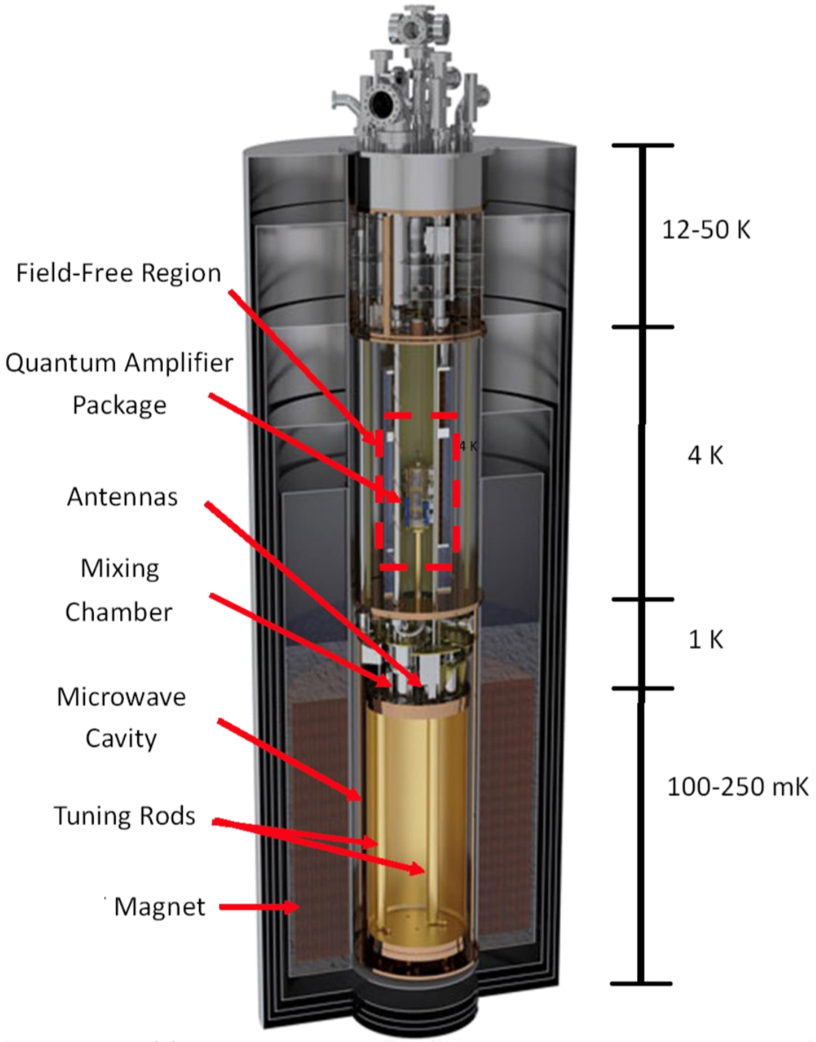
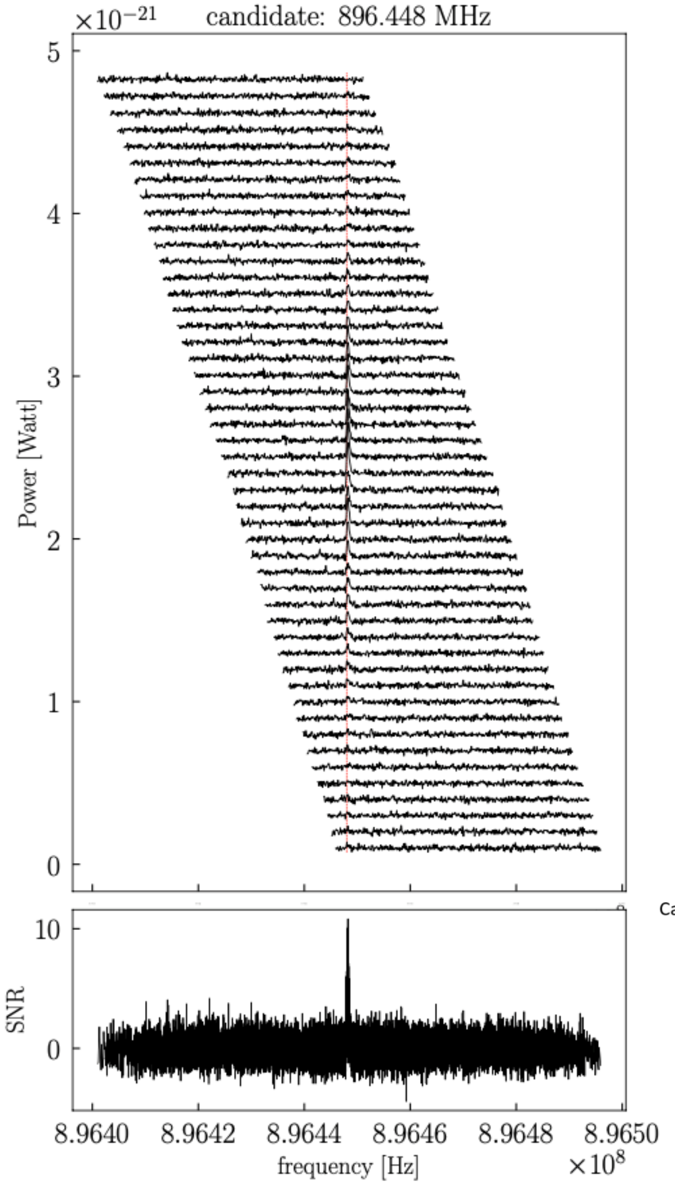
# ADMX Design


Field-Free Region
Quantum Amplifier Package
Antennas
Mixing Chamber
Microwave Cavity
Tuning Rods
Magnet
12-50 K
4 K
1 K
100-250 mK

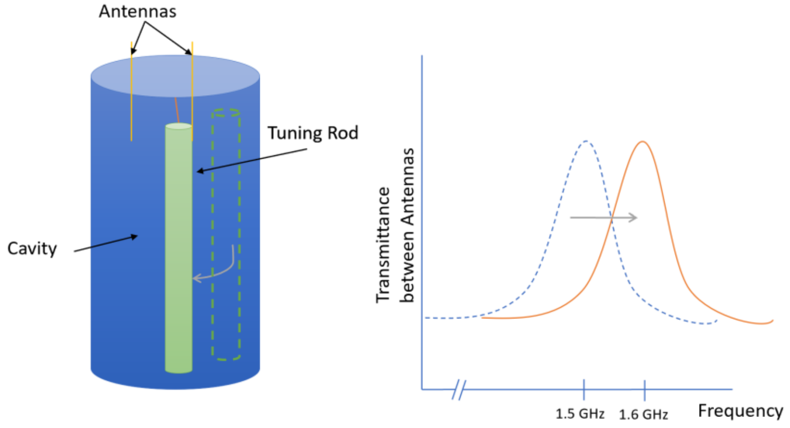
# ADMX Operations



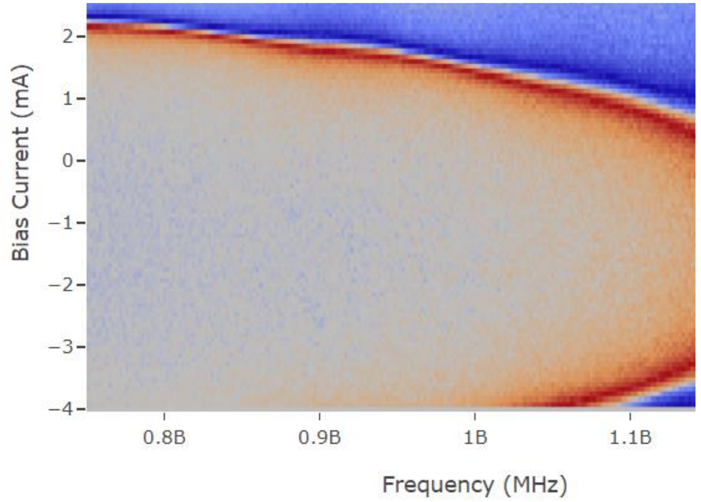

The cavity is tuned every 100 seconds, during which power spectra are taken. Overlapping power spectra are examined for the characteristic axion signal shape appearing on-resonance.

The picture on the left shows how an axion signal would appear in the data. This is a synthetic signal.

The cavity is tuned to change the sensitive frequency



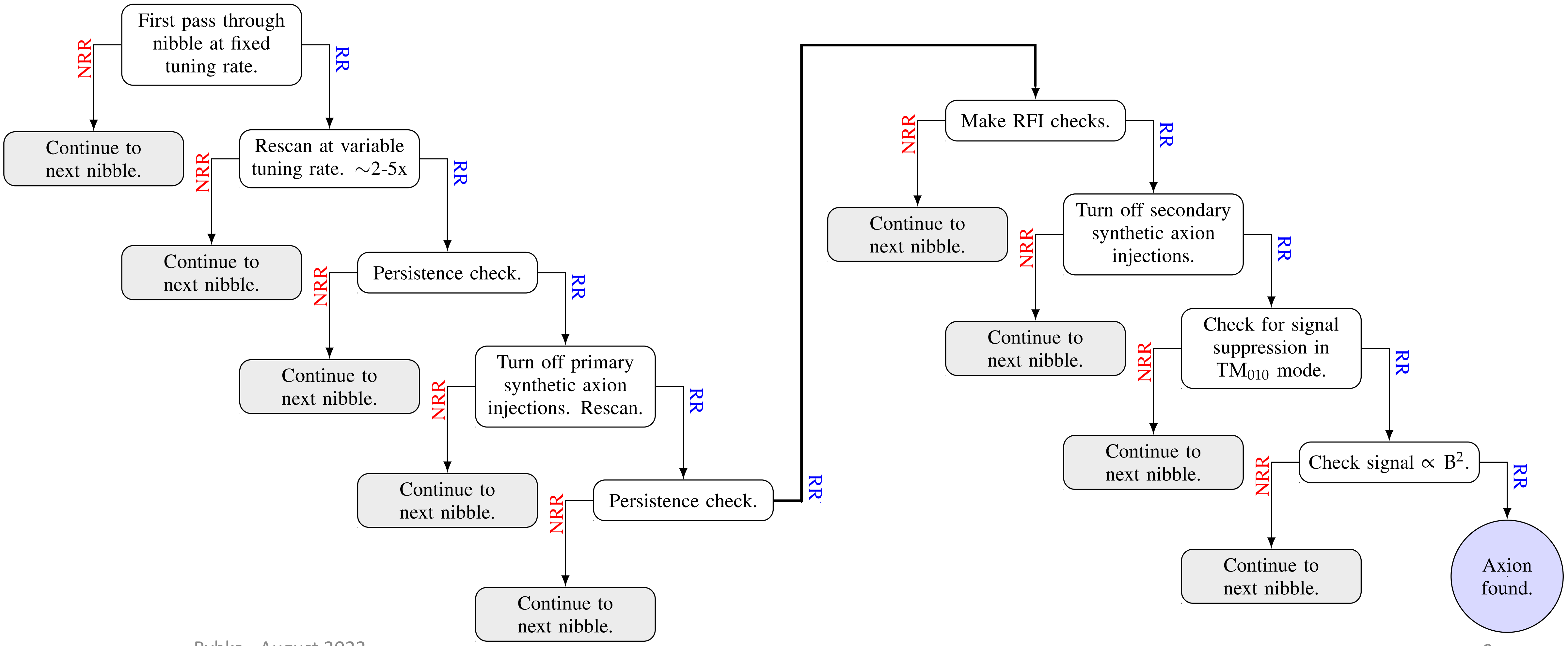

The JPA is tuned to match the cavity frequency



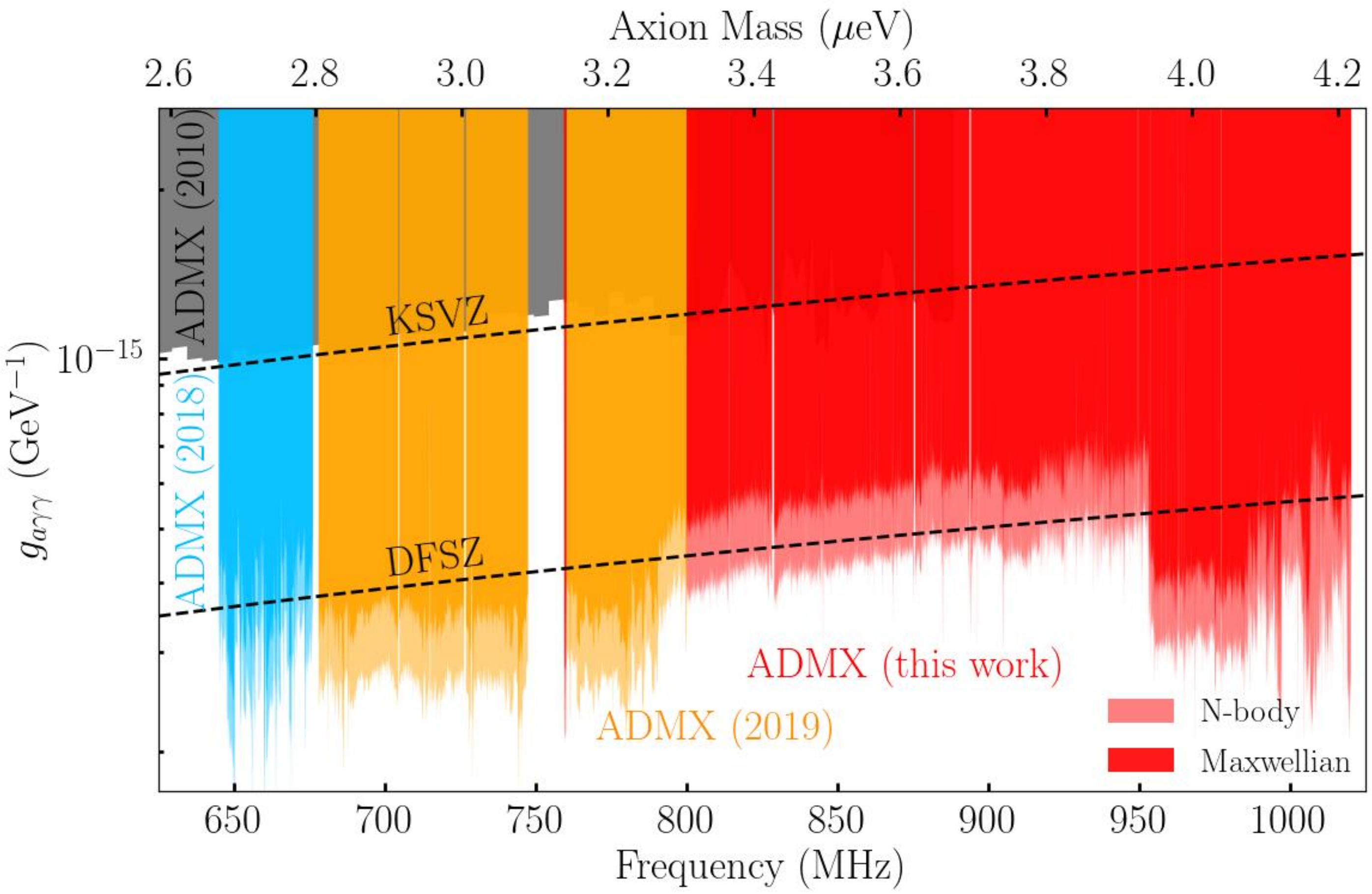
# Data Taking Cadence / Candidate Investigation

**Check and rescan candidates every few weeks**

single scans: **range:** 50 kHz, **resolution:** 100Hz, **integration time:** 100s



# ADMX 2021 Exclusion




As we found no axion signals, we can exclude an even wider mass range.


PHYSICAL REVIEW LETTERS **127**, 261803 (2021)

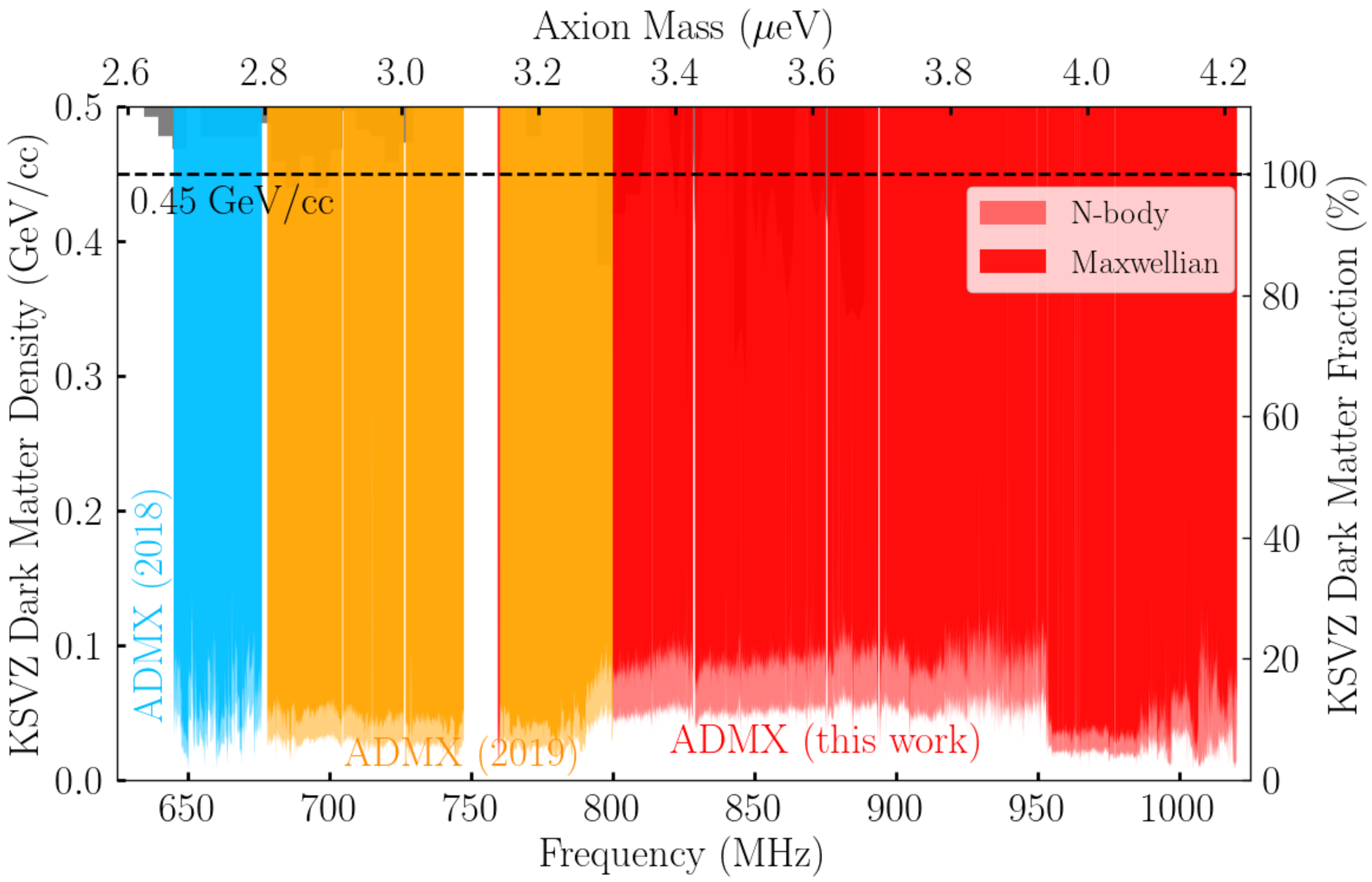
Editors' Suggestion    Featured in Physics


**Search for Invisible Axion Dark Matter in the 3.3–4.2 μeV Mass Range**


C. Bartram,[1] T. Braine,[1] E. Burns,[1] R. Cervantes,[1] N. Crisosto,[1] N. Du,[1] H. Korandla,[1] G. Leum,[1] P. Mohapatra,[1] T. Nitta,[1,*] L. J Rosenberg,[1] G. Rybka,[1] J. Yang,[1] John Clarke,[2] I. Siddiqi,[2] A. Agrawal,[3] A. V. Dixit,[3] M. H. Awida,[4] A. S. Chou,[4] M. Hollister,[4] S. Knirck,[4] A. Sonnenschein,[4] W. Wester,[4] J. R. Gleason,[5] A. T. Hipp,[5] S. Jois,[5] P. Sikivie,[5] N. S. Sullivan,[5] D. B. Tanner,[5] E. Lentz,[6] R. Khatiwada,[7,4] G. Carosi,[8] N. Robertson,[8] N. Woollett,[8] L. D. Duffy,[9] C. Boutan,[10] M. Jones,[10] B. H. LaRoque,[10] N. S. Oblath,[10] M. S. Taubman,[10] E. J. Daw,[11] M. G. Perry,[11] J. H. Buckley,[12] C. Gaikwad,[12] J. Hoffman,[12] K. W. Murch,[12] M. Goryachev,[13] B. T. McAllister,[13] A. Quiskamp,[13] C. Thomson,[13] and M. E. Tobar[13]

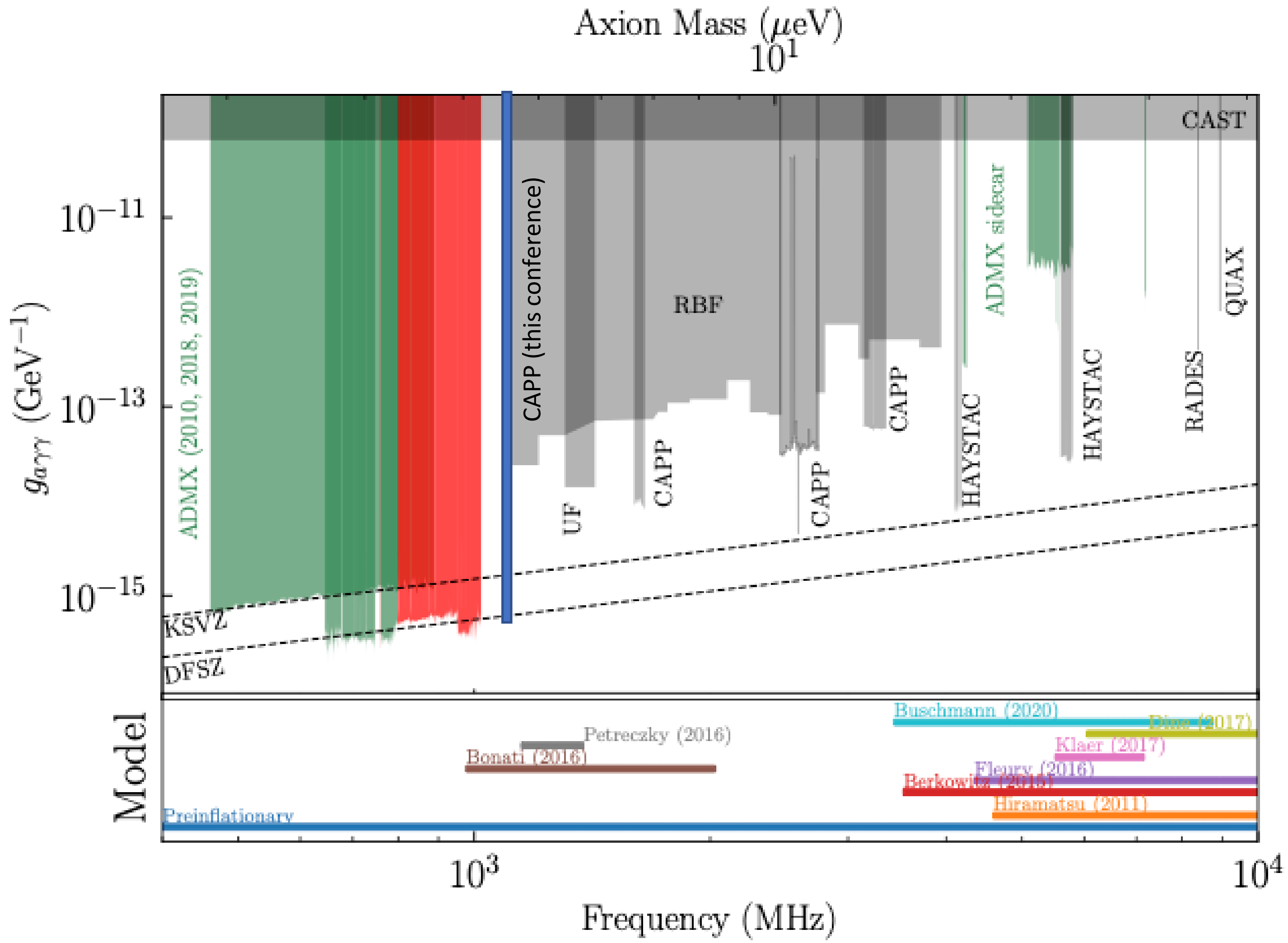
(ADMX Collaboration)

# ADMX 2021 Exclusion – KSVZ Dark Matter Density




One can also assume an axion model (KSVZ in this case) and ask what local dark matter density we can exclude

# ADMX 2021 Exclusion - Context

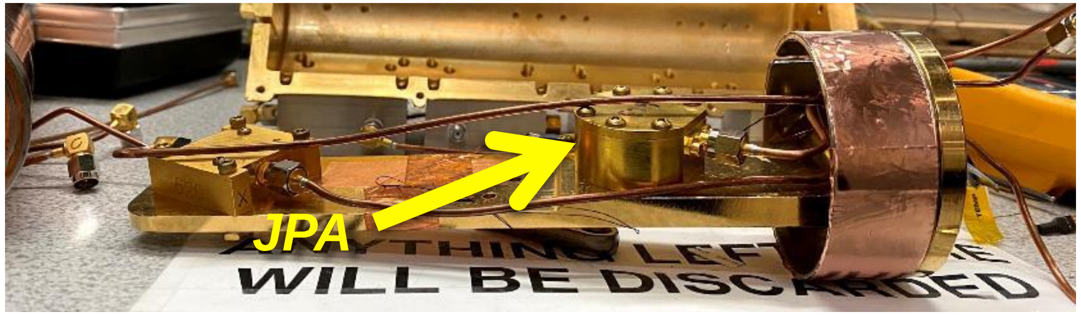


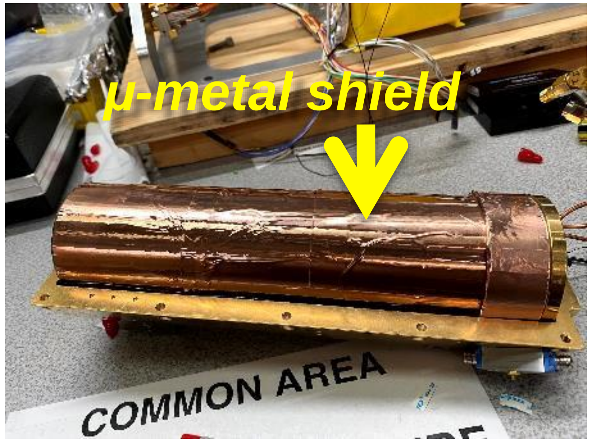
# 2021-2022 Upgrades To Improve Noise

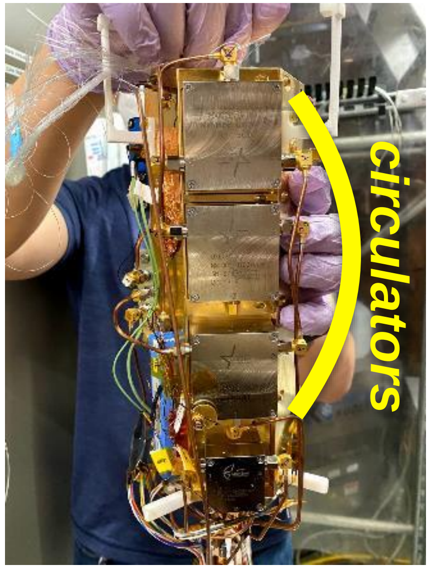
## Cooler Cavity


Heat flow: 70 ->12µW
Temp: 150 -> 100 mK (exp.)

## Ensure Quantum Device Performance

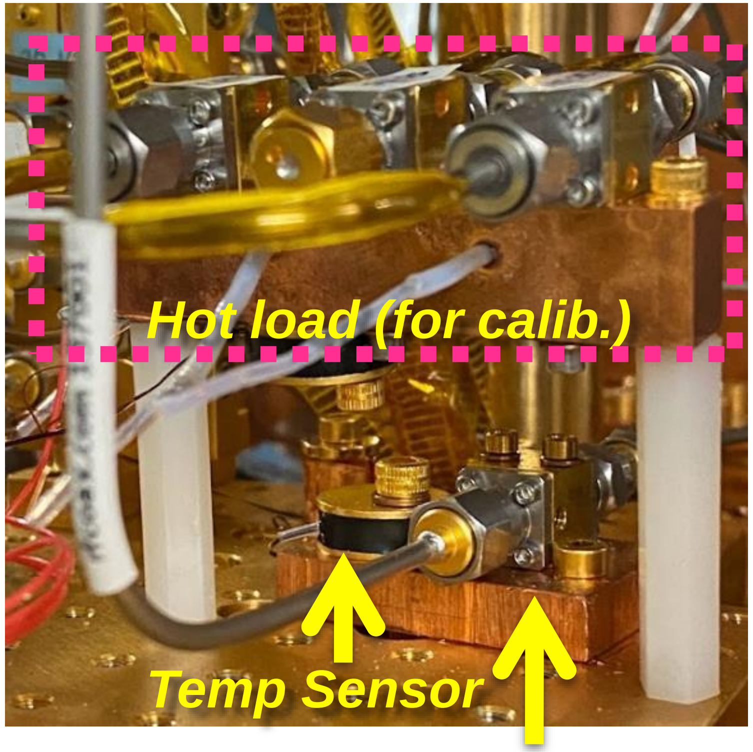



- Aluminium $H_c \sim 0.01\mathrm{T}$
- squid possibly traps flux quantum

## Improved Calibration System




Attenuator (dictate JPA noise)

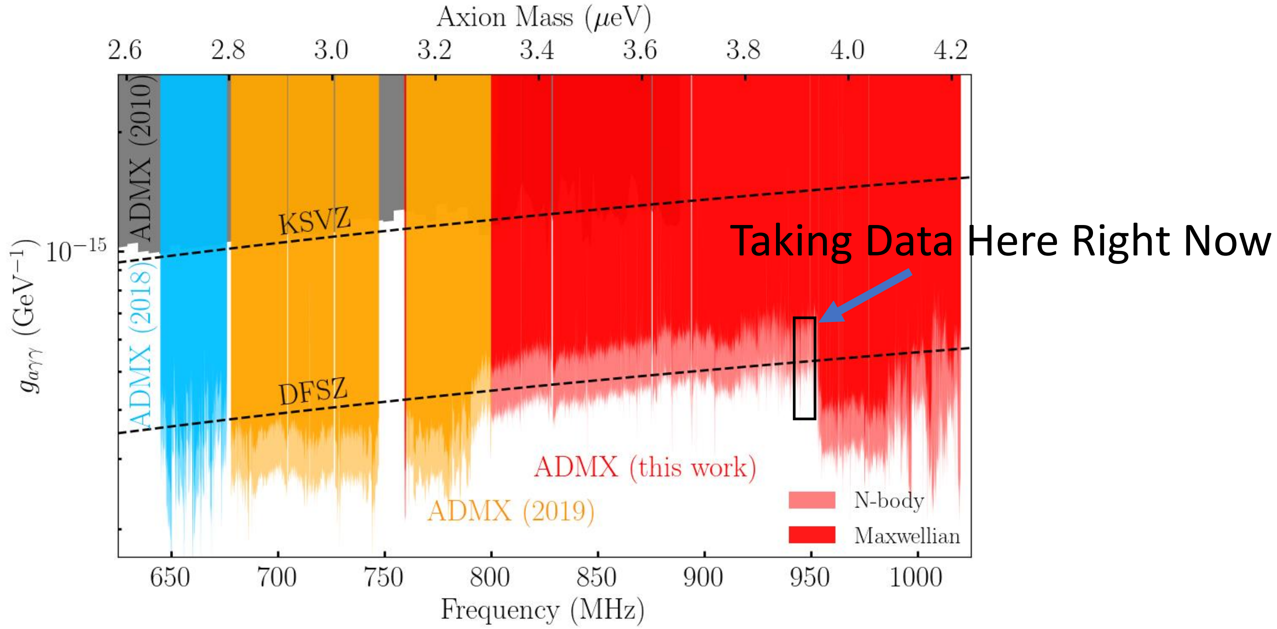
$T_{\mathrm{hotload}} > 500 \rightarrow 100\mathrm{mK}$

Add temperature sensor



Slide from Tatsumi Nitta

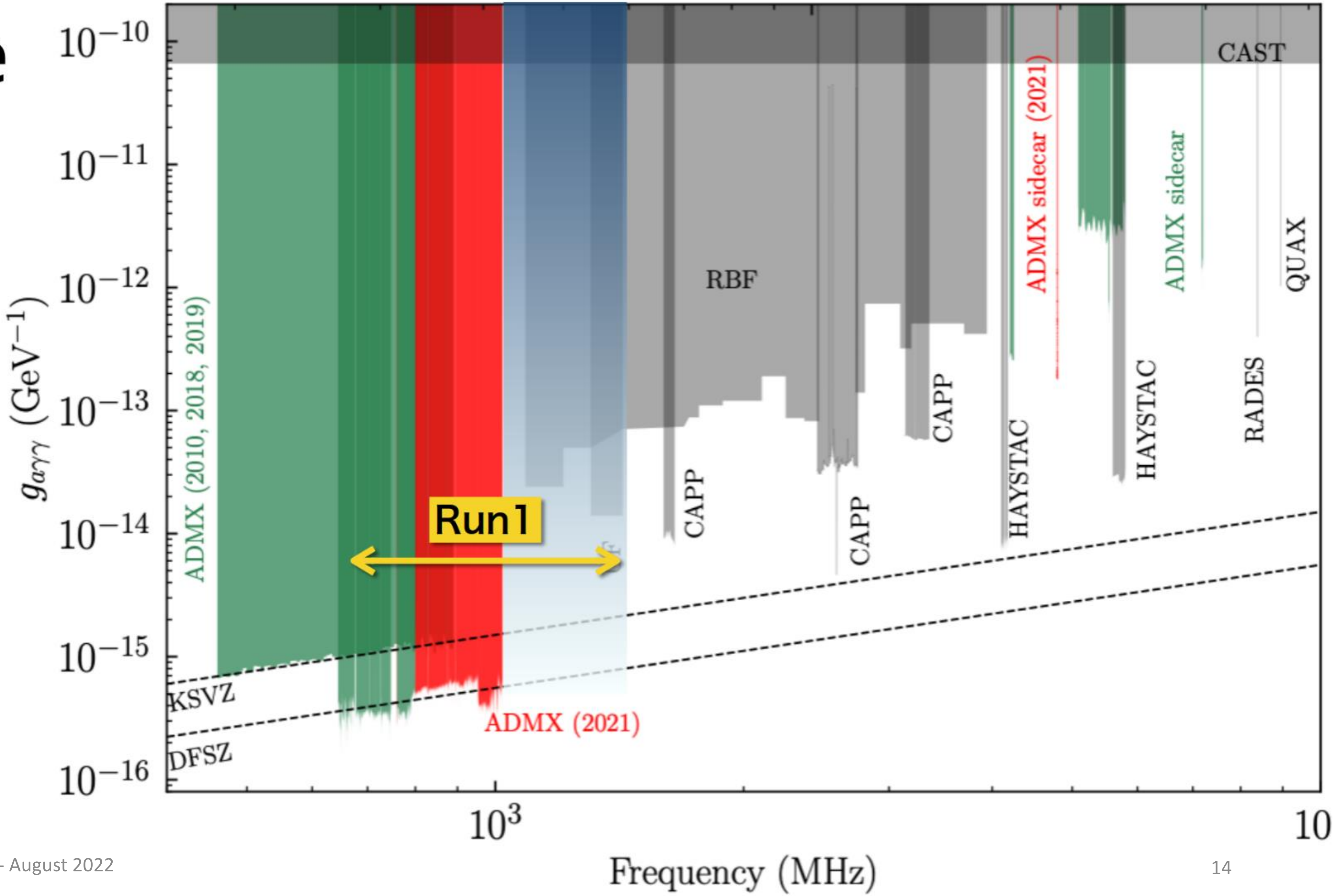
# ADMX Status Right Now



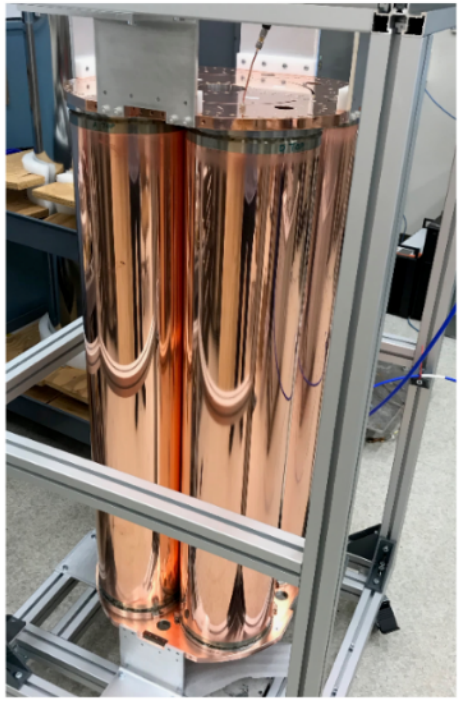

- Taking data summer 2022 to exercise cryogenic upgrades and bring limit down to DFSZ coupling with standard axion density/lineshape
- We plan to move to frequencies above 1030 MHz at the end of the year

# Future Plans

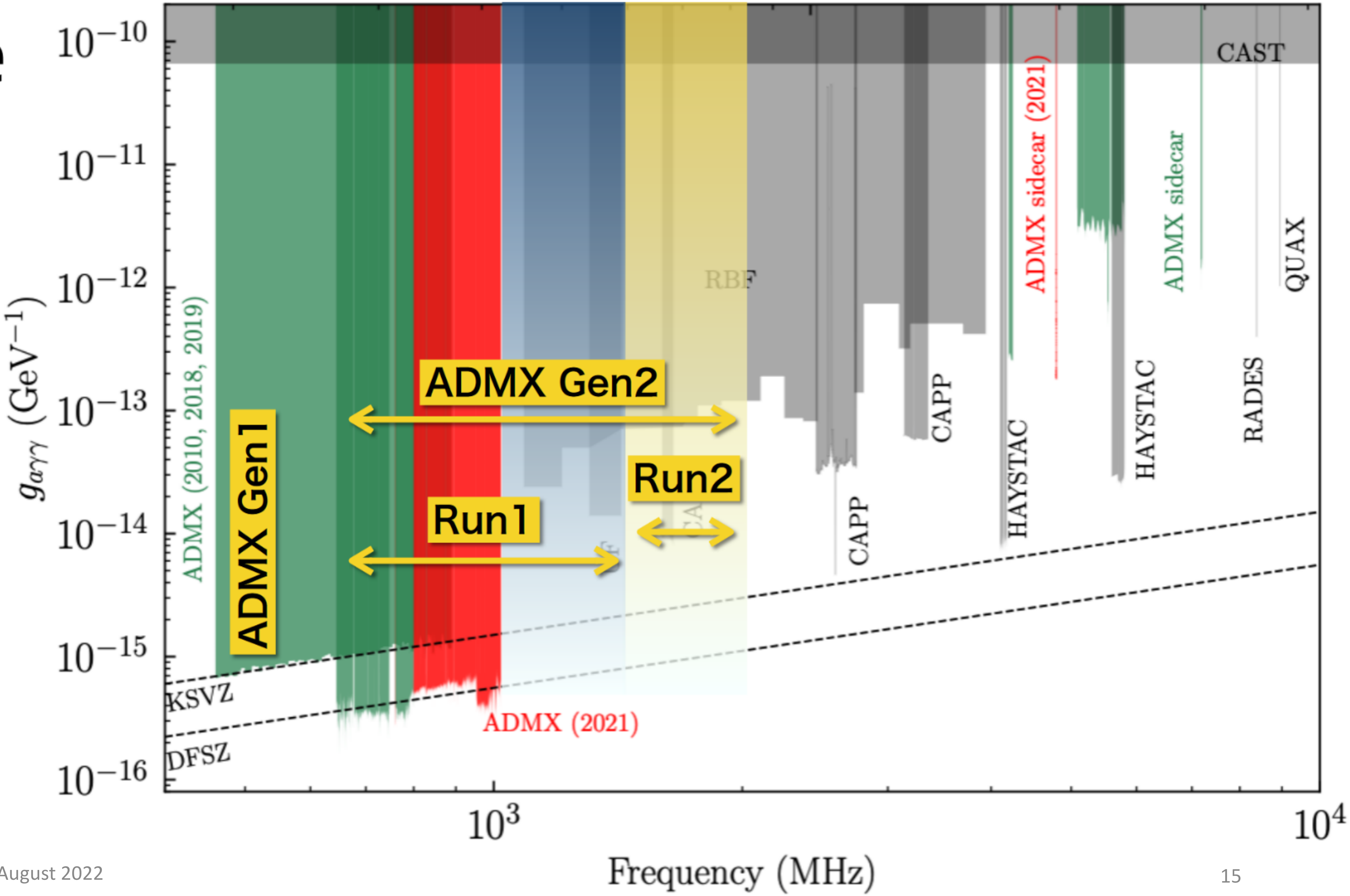
Bigger tuning rod



# Future Plans



4-cavity array

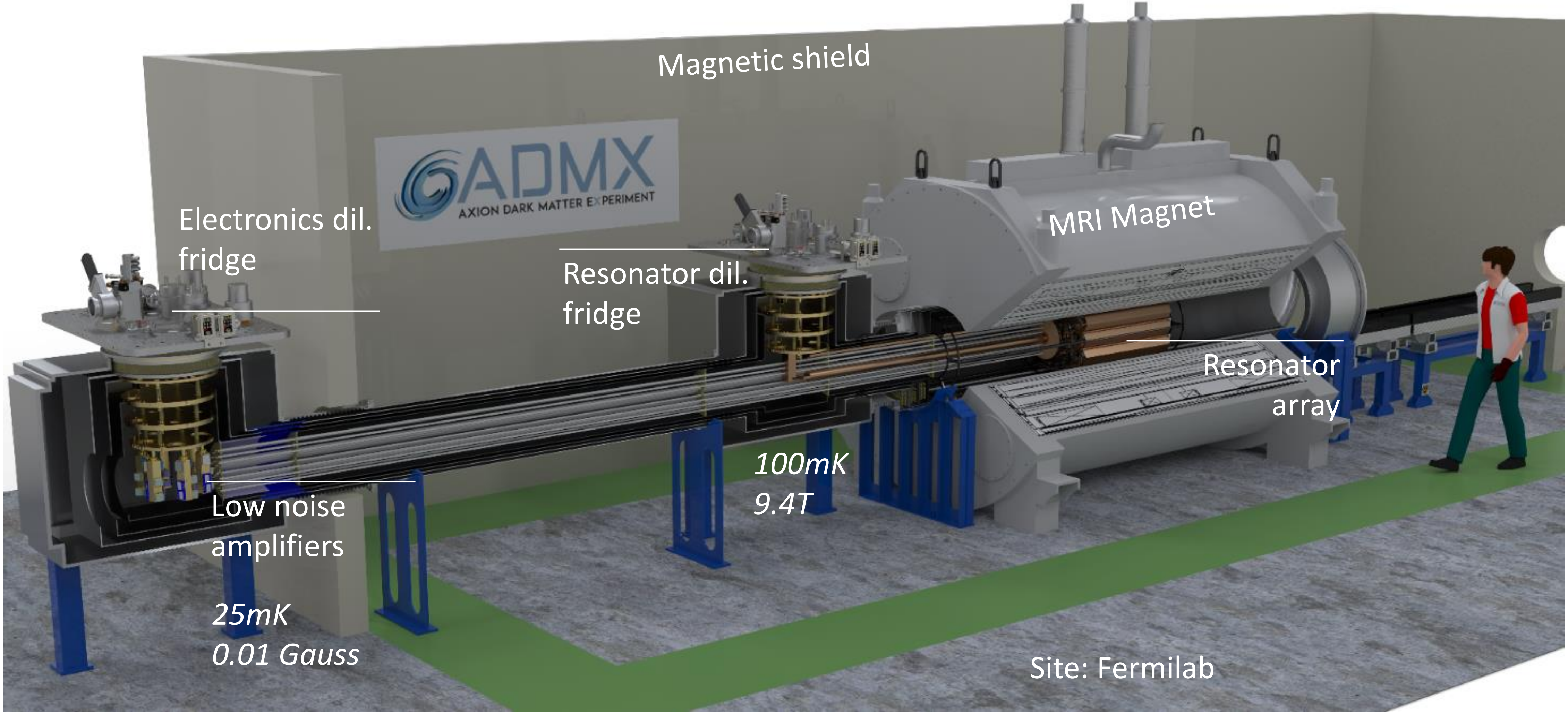


# Next Steps - ADMX-Extended Frequency Range

- The next step (2 GHz to 4 GHz to beyond) requires a larger volume, higher field magnet: ADMX-EFR

- We are finalizing the design process and positioning ourselves to smoothly transition from running in Seattle to running at Fermilab

# ADMX-EFR – Design Overview




~ 5 × scan speed of current ADMX

# ADMX-EFR: A New Magnet

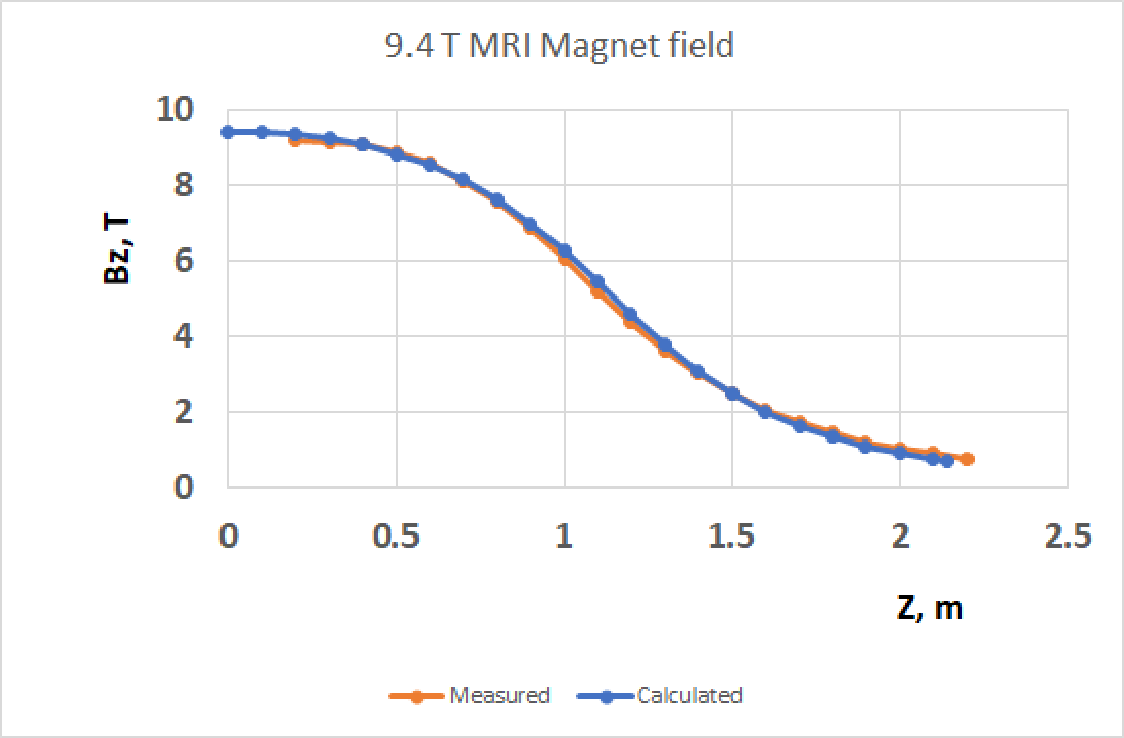
$\sim 80$ cm warm bore

$B \approx 9.4$ T

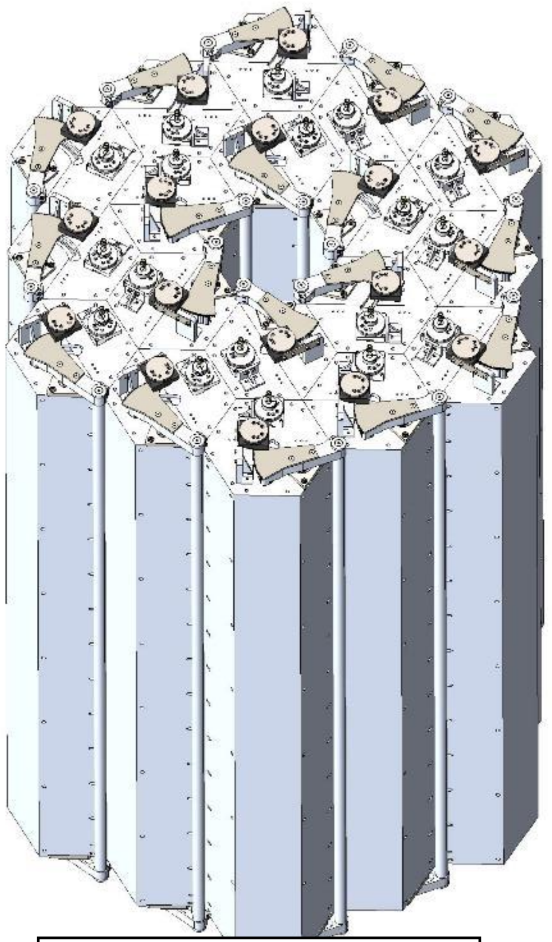
**MRI magnet**

University of Illinois Chicago (UIC)

*Manufactured by GE Healthcare in 2003*

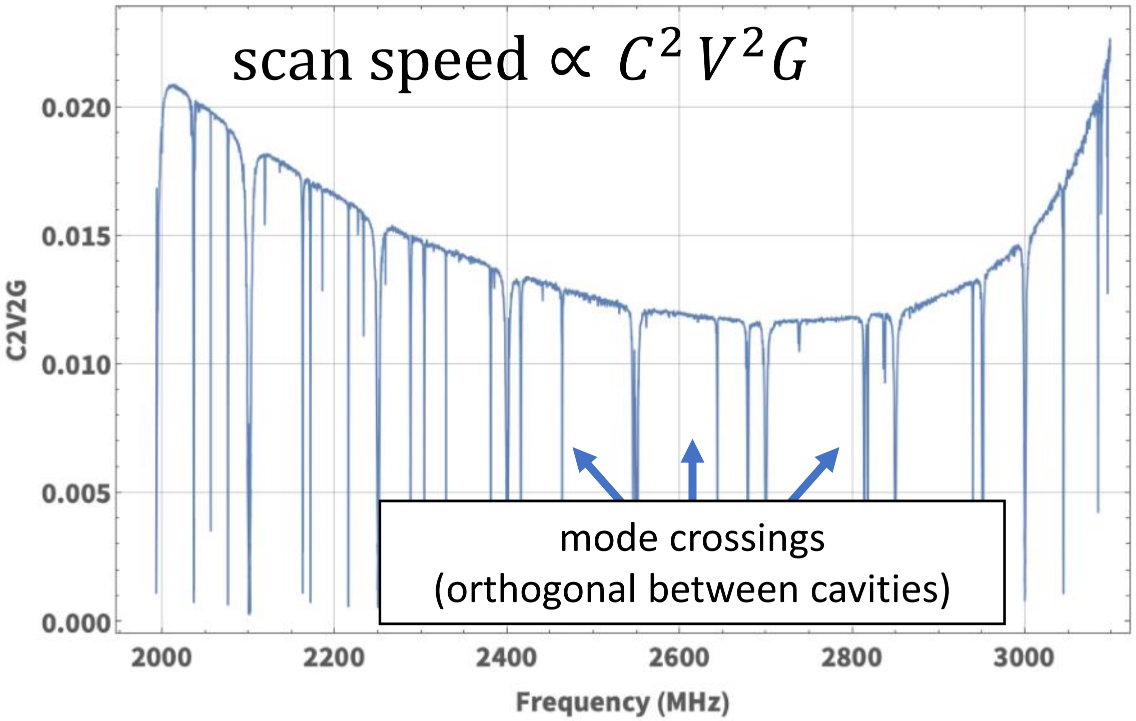


# ADMX-EFR: More Cavities



18 cavity array

**Simulations:**

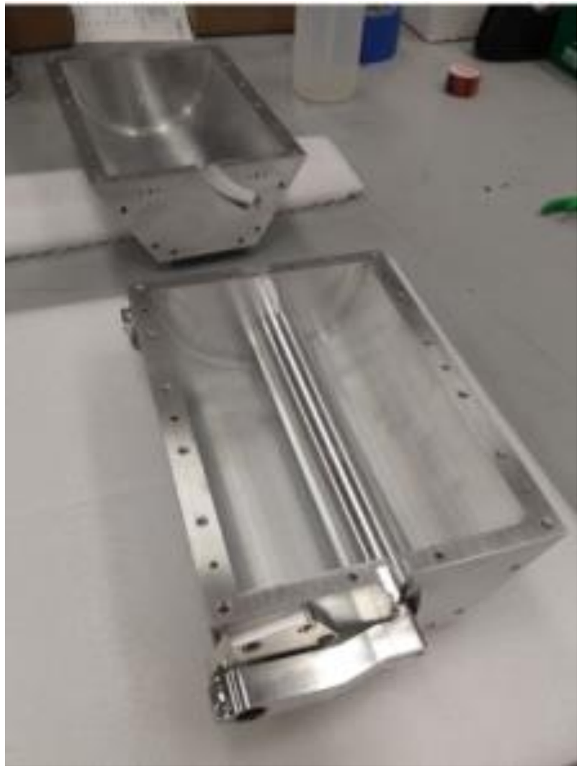



Stephan Knirck and Ben McAllister

$Q_0 \sim 60{,}000$ (predicted, cryogenic)

$V \sim 250\ \ell$

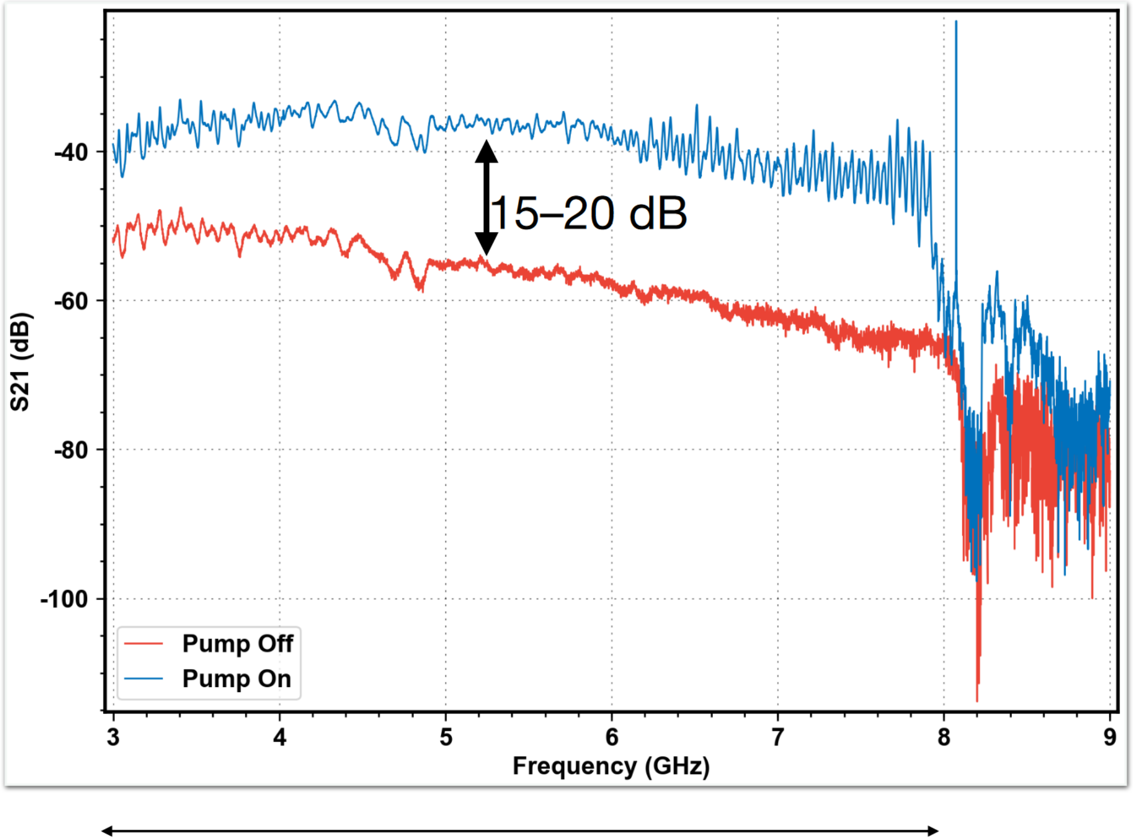
**First Prototypes:**



Actuators:
investigating feasibility
different companies
(Attocube, JPE, PI, …)

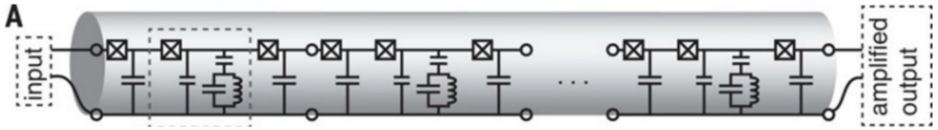
# R&D Travelling Wave Parametric Amplifiers

Broadband Quantum Amplifier Gain

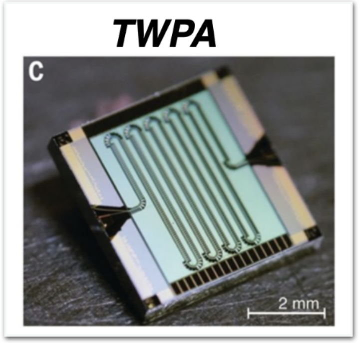



5 GHz

O(100) Josephson Junctions in series




- Broadband gain
- Compact: requires one less circulator
- Optimize adjusting pump frequency and power




Slide – C. Bartram
See: arXiv: 2110.10262

# US Snowmass Process

Every 10 years the high-energy physics community produces a document to advise the US funding agencies of their needs.

The "Wavelike Dark-Matter" subgroup in the "Cosmic Frontier" group represented the community interested in sub-eV dark matter.

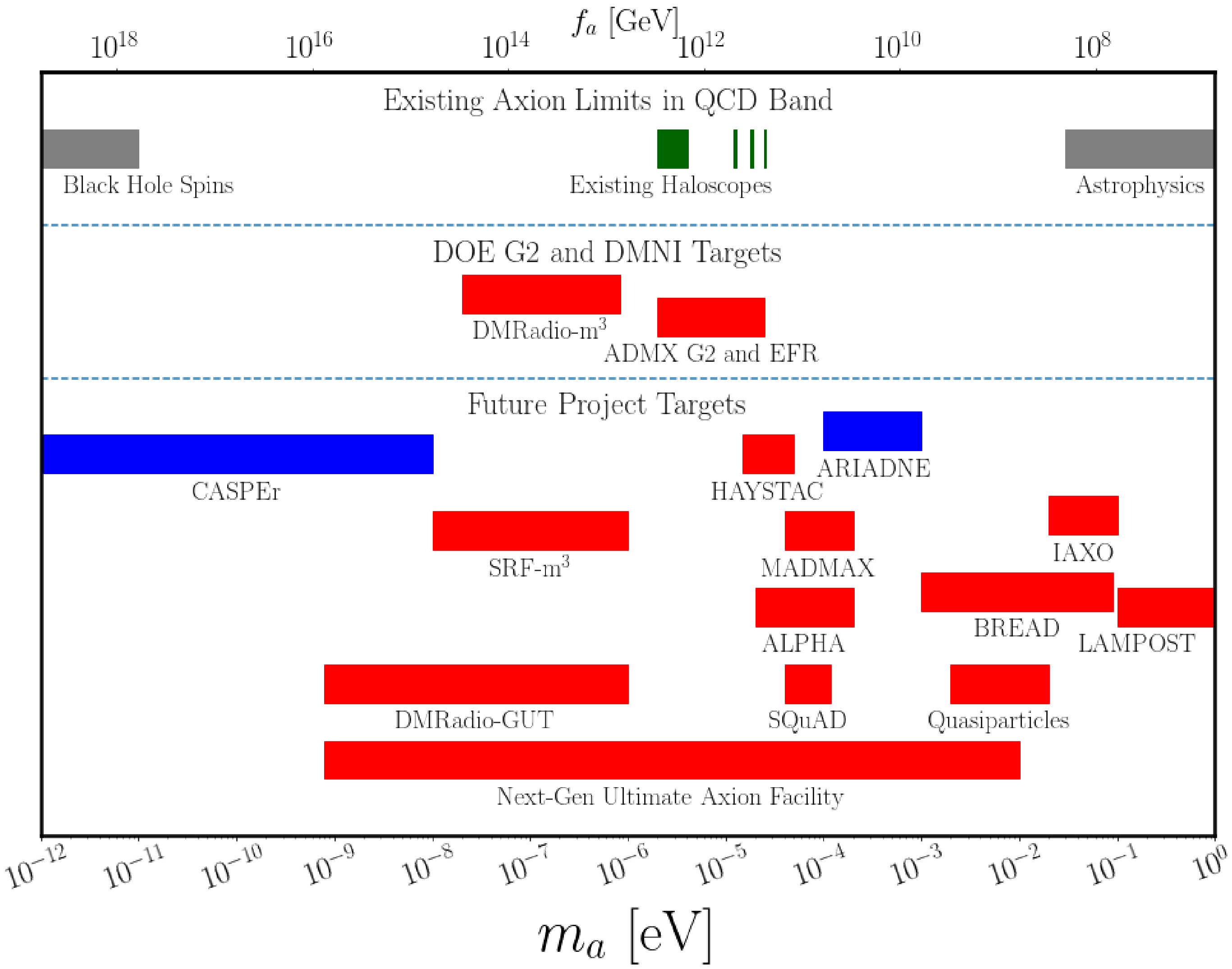
We held our in-person meeting in Seattle a few weeks ago.

# Snowmass US Wavelike Dark Matter Message

Requests to the US Funding Agencies:

1) **Pursue the QCD Axion by Executing the Current Projects**
2) **Pursue WLDM with a Collection of Small-Scale Experiments**
3) **Support Enabling Technologies and Cross Disciplinary Collaborations**
4) **Support Theory Beyond the QCD Axion**

There was also talk of a large scale magnet/cryo facility to enable WLDM experiments – does the international community find that exciting?



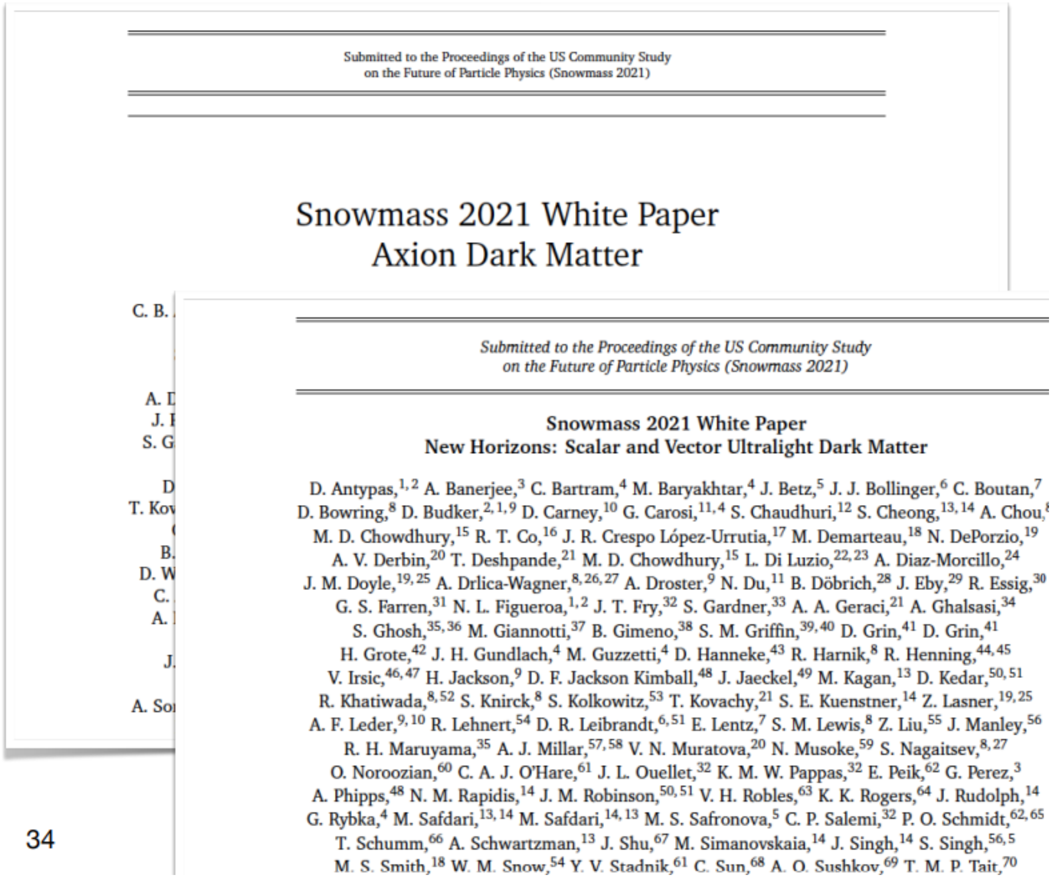
# Community Whitepapers

*The community road map, theory, cosmology, and experimental details are presented in our two community white papers.*

**Axion Dark Matter**
**arXiv:2203.14923**
*Editors: J. Jaeckel, G. Rybka, L. Winslow*

**New Horizons:**
**Scalar and Vector Ultralight Dark Matter**
**arXiv:2203.14915**
*Editors: M. Safronova and S. Singh*

Lindley Winslow 34


Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

Snowmass 2021 White Paper
Axion Dark Matter

*Submitted to the Proceedings of the US Community Study*
*on the Future of Particle Physics (Snowmass 2021)*

**Snowmass 2021 White Paper**
**New Horizons: Scalar and Vector Ultralight Dark Matter**

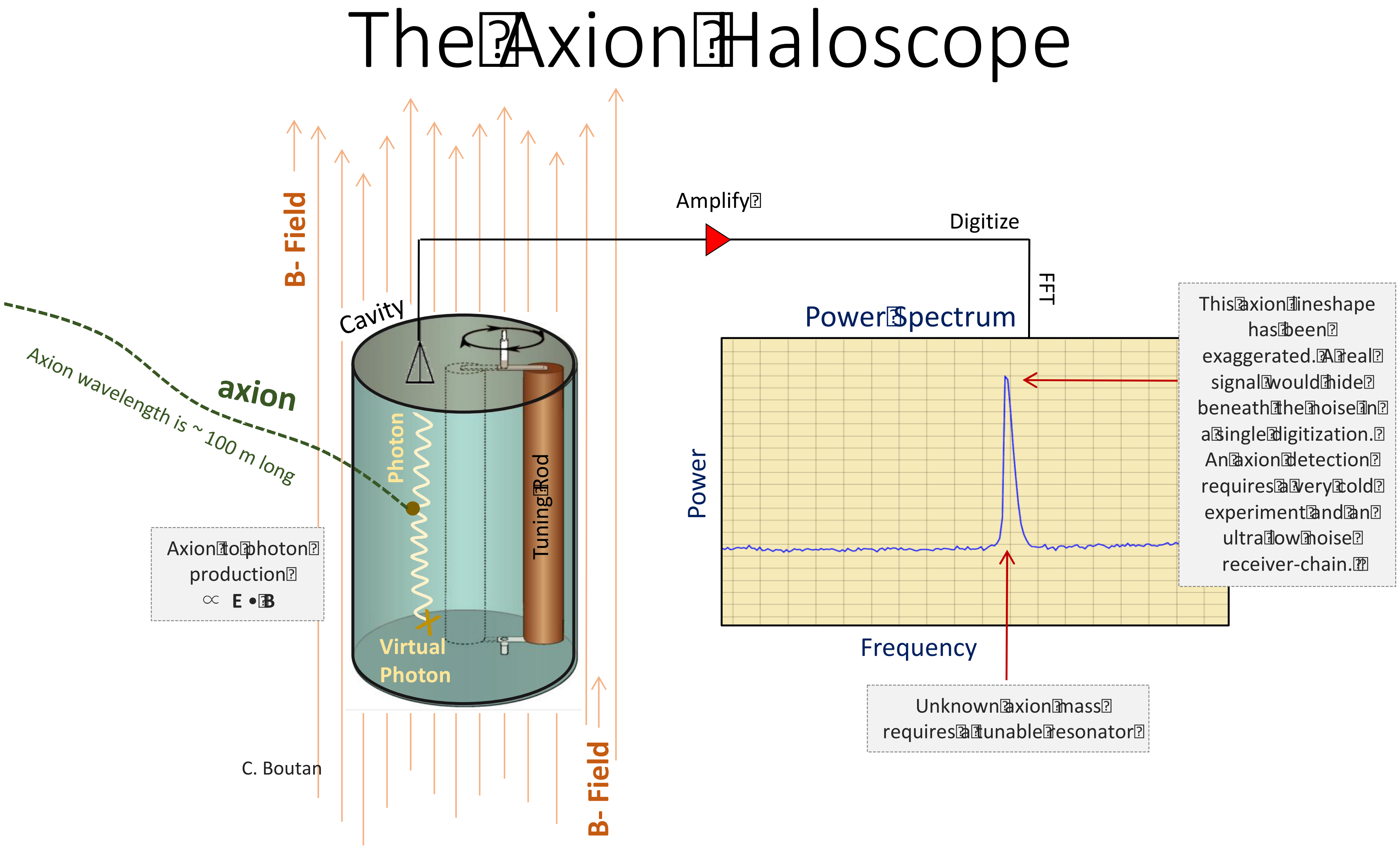
D. Antypas,[1,2] A. Banerjee,[3] C. Bartram,[4] M. Baryakhtar,[4] J. Betz,[5] J. J. Bollinger,[6] C. Boutan,[7]
D. Bowring,[8] D. Budker,[2,1,9] D. Carney,[10] G. Carosi,[11,4] S. Chaudhuri,[12] S. Cheong,[13,14] A. Chou,
M. D. Chowdhury,[15] R. T. Co,[16] J. R. Crespo López-Urrutia,[17] M. Demarteau,[18] N. DePorzio,[19]
A. V. Derbin,[20] T. Deshpande,[21] M. D. Chowdhury,[15] L. Di Luzio,[22,23] A. Diaz-Morcillo,[24]
J. M. Doyle,[19,25] A. Drlica-Wagner,[8,26,27] A. Droster,[9] N. Du,[11] B. Döbrich,[28] J. Eby,[29] R. Essig,[30]
G. S. Farren,[31] N. L. Figueroa,[1,2] J. T. Fry,[32] S. Gardner,[33] A. A. Geraci,[21] A. Ghalsasi,[34]
S. Ghosh,[35,36] M. Giannotti,[37] B. Gimeno,[38] S. M. Griffin,[39,40] D. Grin,[41] D. Grin,[41]
H. Grote,[42] J. H. Gundlach,[4] M. Guzzetti,[4] D. Hanneke,[43] R. Harnik,[8] R. Henning,[44,45]
V. Irsic,[46,47] H. Jackson,[9] D. F. Jackson Kimball,[48] J. Jaeckel,[49] M. Kagan,[13] D. Kedar,[50,51]
R. Khatiwada,[8,52] S. Knirck,[8] S. Kolkowitz,[53] T. Kovachy,[21] S. E. Kuenstner,[14] Z. Lasner,[19,25]
A. F. Leder,[9,10] R. Lehnert,[54] D. R. Leibrandt,[6,51] E. Lentz,[7] S. M. Lewis,[8] Z. Liu,[55] J. Manley,[56]
R. H. Maruyama,[35] A. J. Millar,[57,58] V. N. Muratova,[20] N. Musoke,[59] S. Nagaitsev,[8,27]
O. Noroozian,[60] C. A. J. O'Hare,[61] J. L. Ouellet,[32] K. M. W. Pappas,[32] E. Peik,[62] G. Perez,[3]
A. Phipps,[48] N. M. Rapidis,[14] J. M. Robinson,[50,51] V. H. Robles,[63] K. K. Rogers,[64] J. Rudolph,[14]
G. Rybka,[4] M. Safdari,[13,14] M. Safdari,[14,13] M. S. Safronova,[5] C. P. Salemi,[32] P. O. Schmidt,[62,65]
T. Schumm,[66] A. Schwartzman,[13] J. Shu,[67] M. Simanovskaia,[14] J. Singh,[14] S. Singh,[56,5]
M. S. Smith,[18] W. M. Snow,[54] Y. V. Stadnik,[61] C. Sun,[68] A. O. Sushkov,[69] T. M. P. Tait,[70]

We are producing another whitepaper aimed at non-axion community audience.
These feed into the "Cosmic Frontier" Snowmass whitepaper, and then the final Snowmass Report end of this summer.

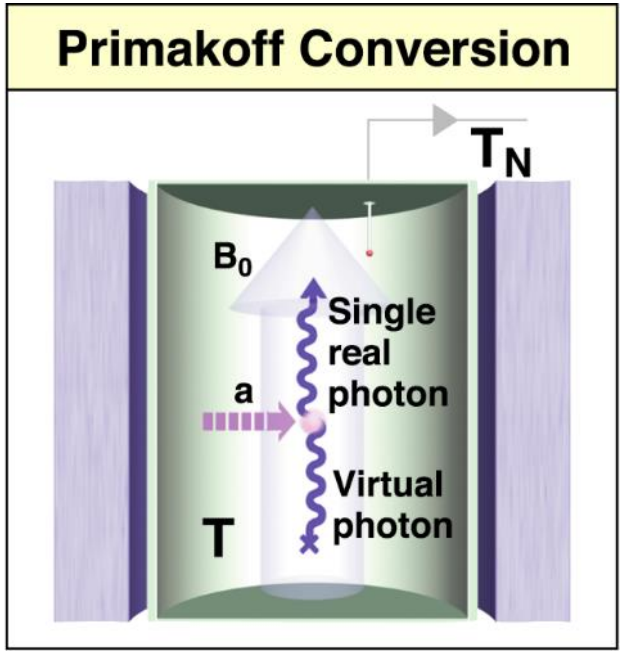
# Conclusion

- In the past few years, Axion experiments have transition from an “instrument development” phase to a “discovery phase”.
- ADMX is leading the way exploring some of the best-motivated couplings and masses.
- We have a well-planned upgrade (ADMX-EFR) to continue the search at higher masses.
- The axion community has many ideas that can lead to a comprehensive exploration of axion parameter space in the next decades.

# Principle of the Sikivie Axion Haloscope



# Axion Haloscope: How to search 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.

Sikivie PRL 51:1415 (1983)

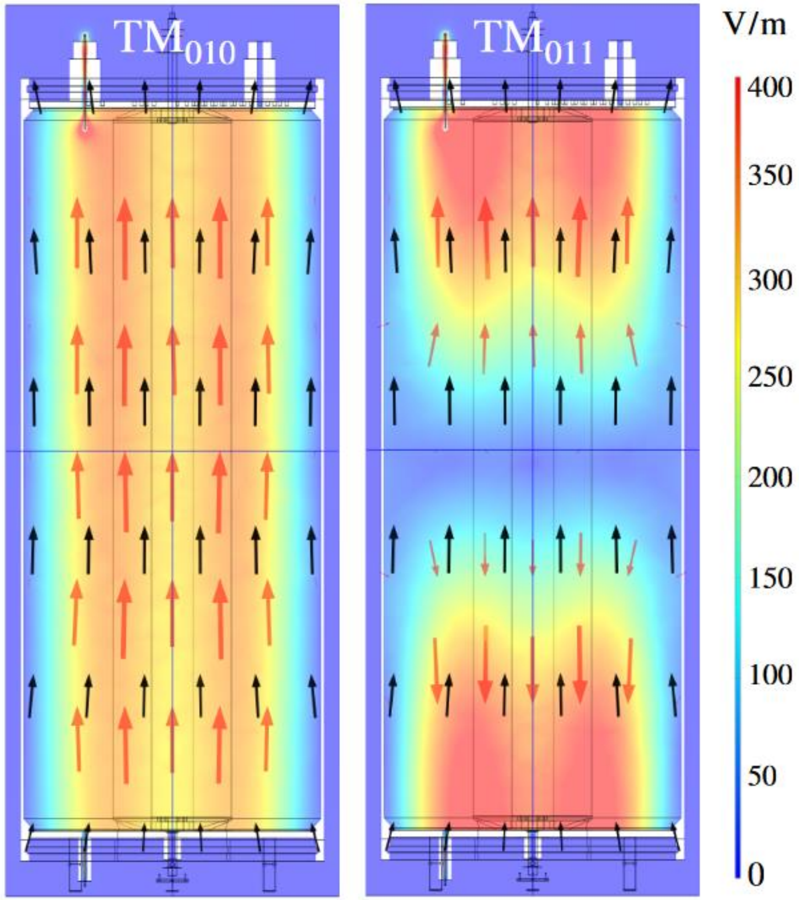
## Signal Proportional to

Cavity Volume
Magnetic Field
Cavity Q

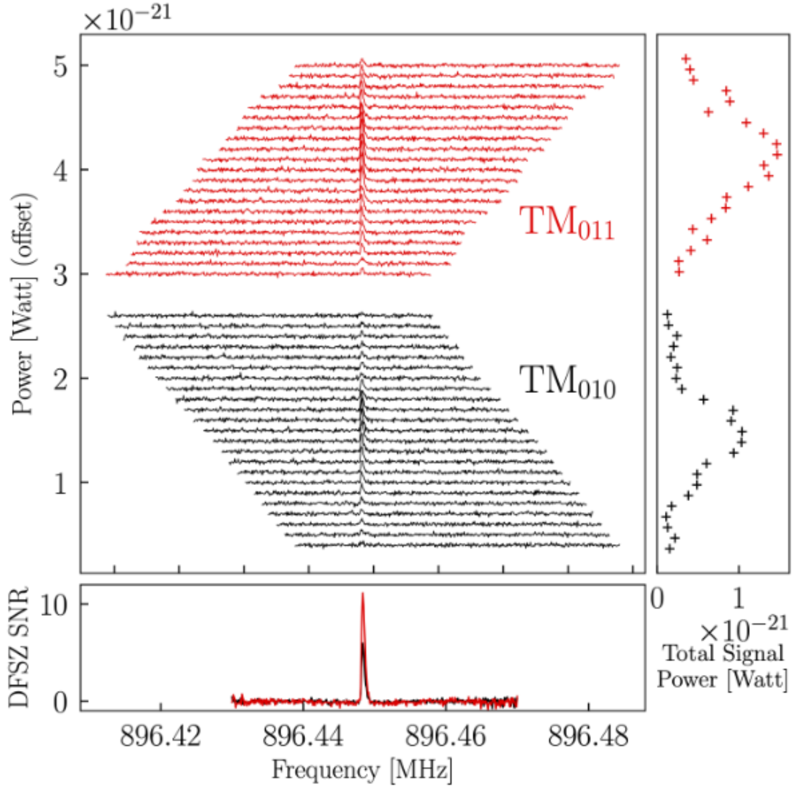
## Noise Proportional to

Cavity Blackbody Radiation
Amplifier Noise

# Axions Couple to TM010 modes, not TM011




Overlap of axion field (black)
and E&M mode field (red)



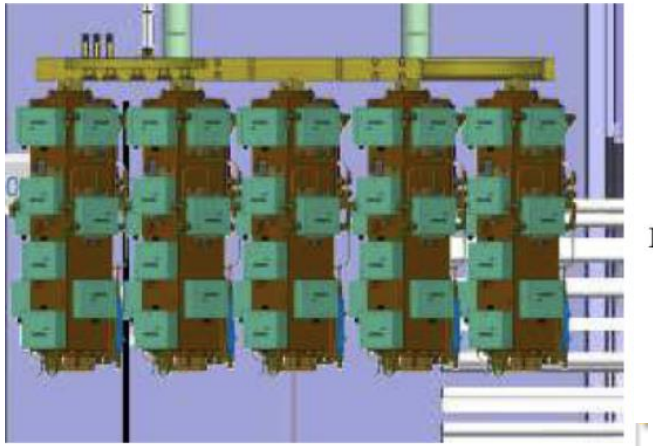

This signal appeared in both modes,
and was thus clearly not an axion.

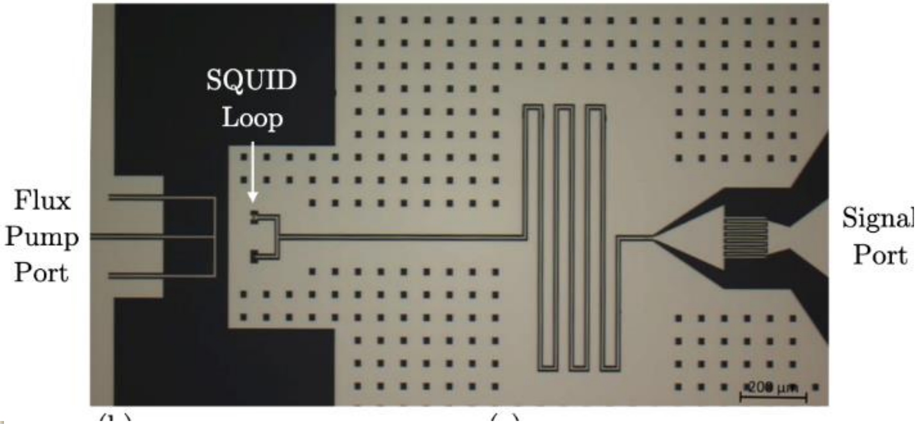
# ADMX-EFR: Readout

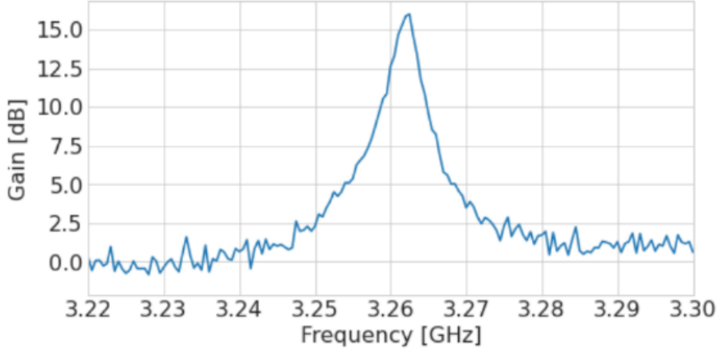
$\sim$ 5m signal transmission cavity → JPA

require: loss: $\mathcal{O}(0.5\text{dB})$ candidate: air cell cable [Kurpiers *et al. EPJ QT.* 4, 8 (2017)]

18 JPAs



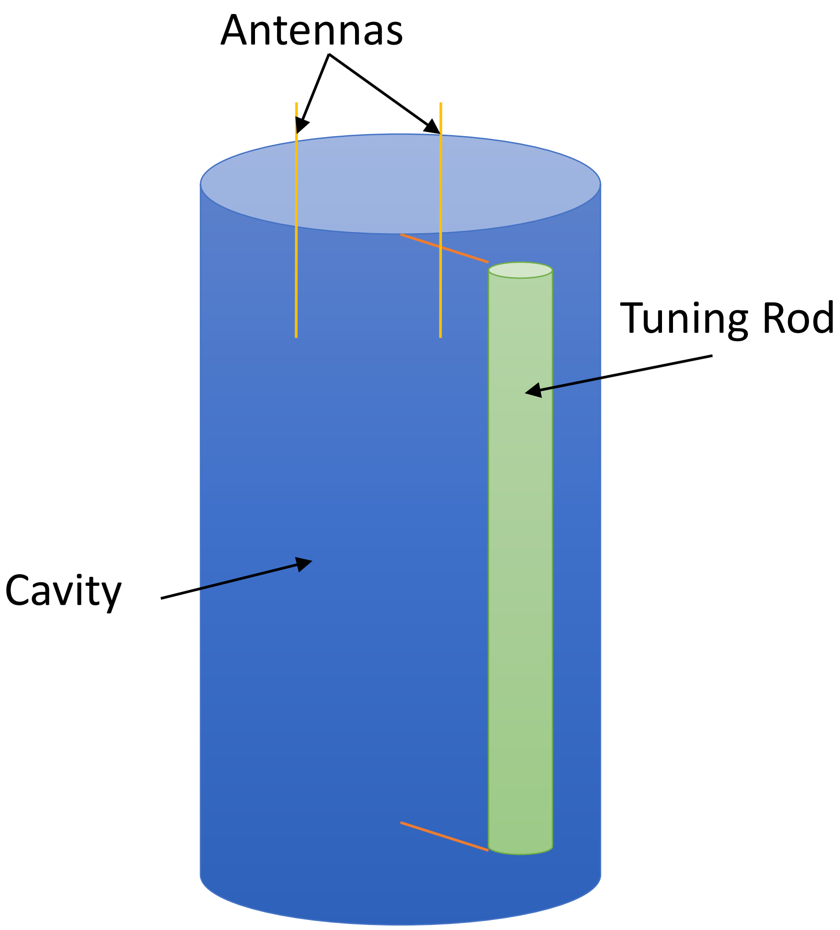


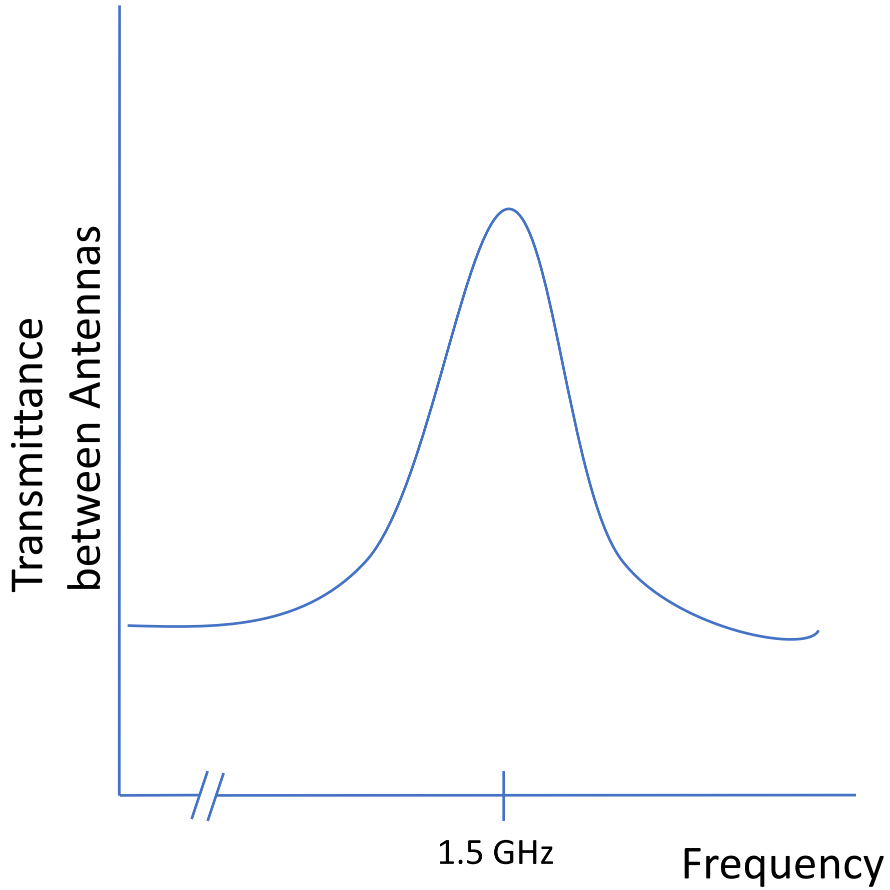




*Prototype from Wash U.*

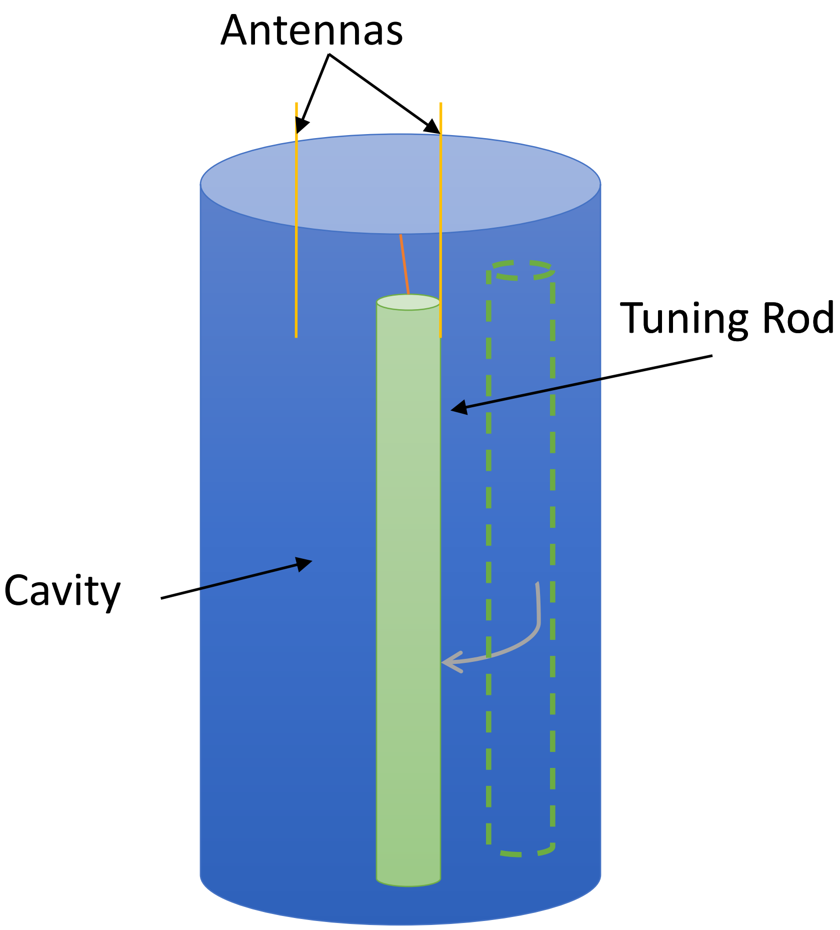
Digital Coherent Power Combining (FPGA based)

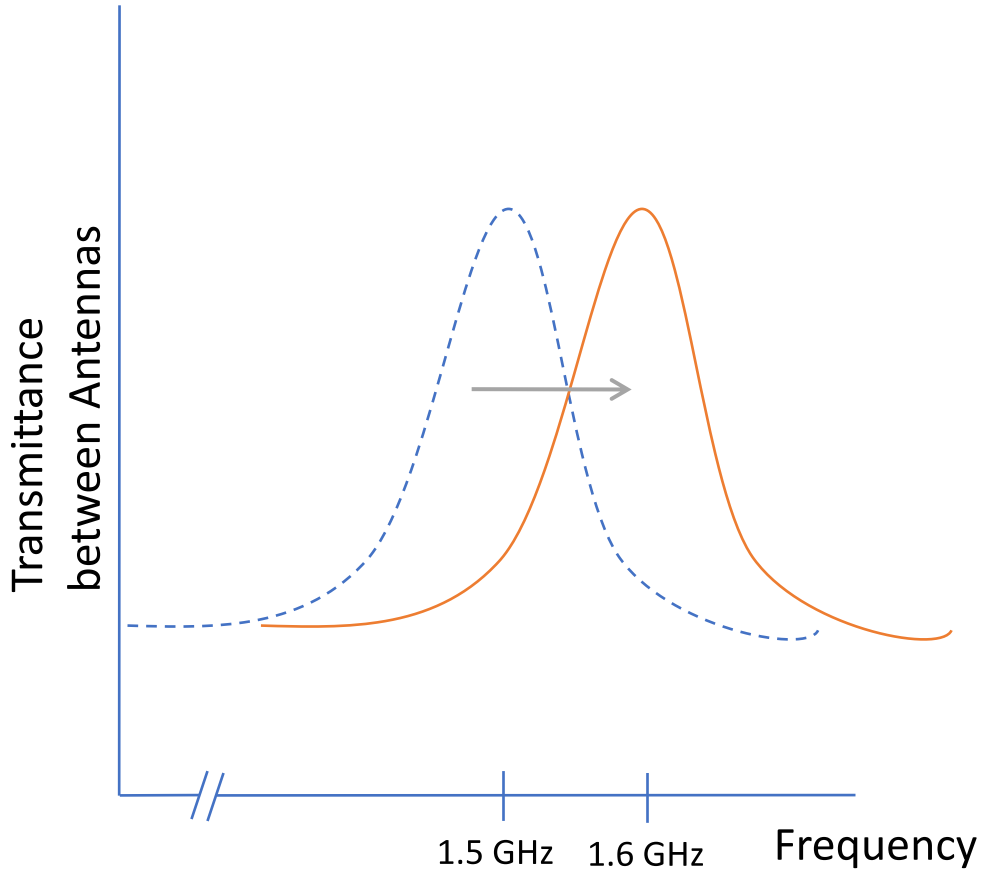
# Microwave Cavity needs tunable resonance



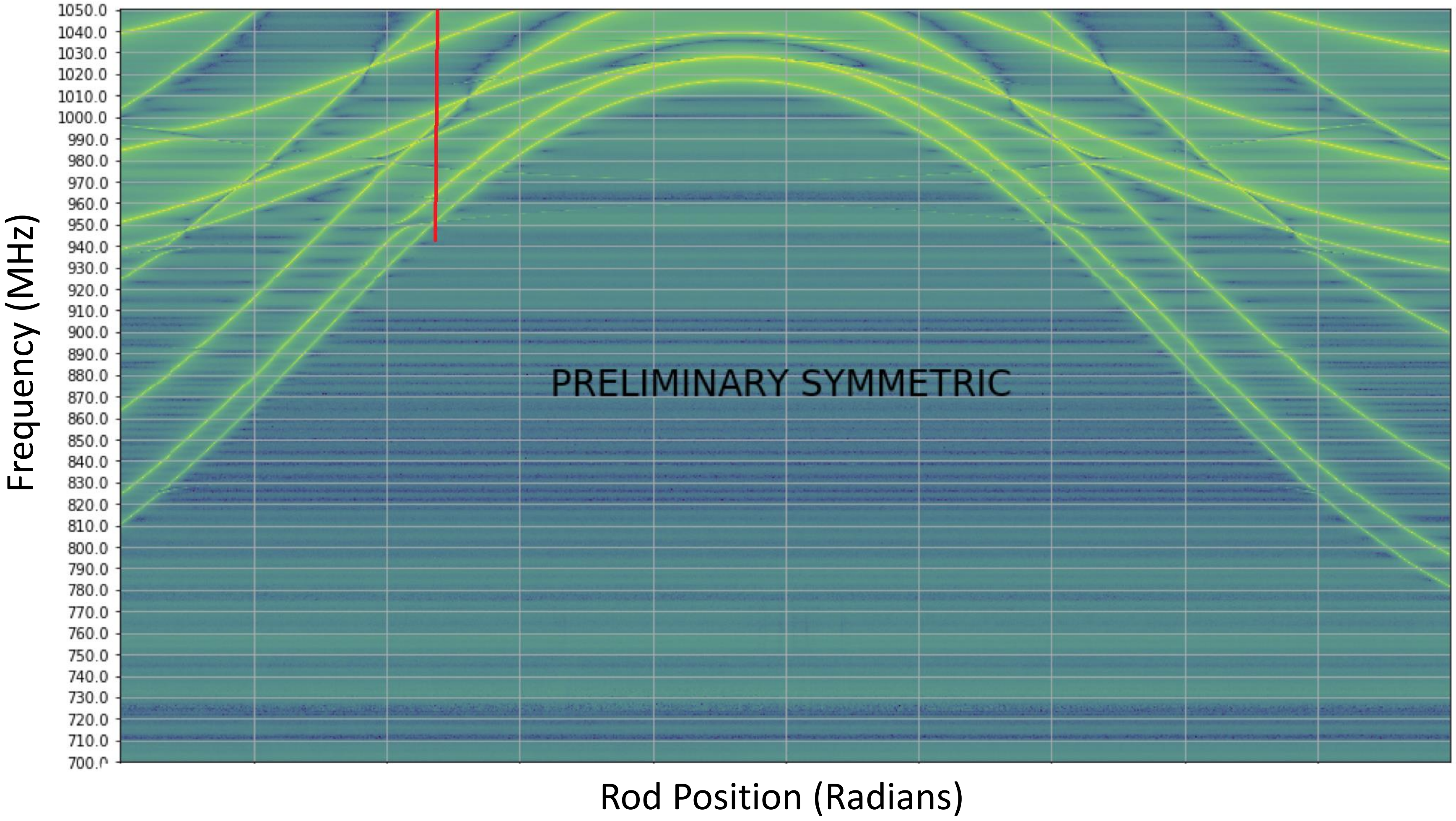



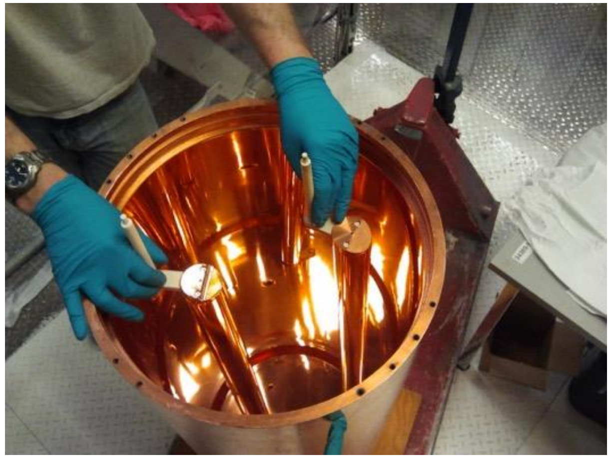
# Microwave Cavity needs tunable resonance



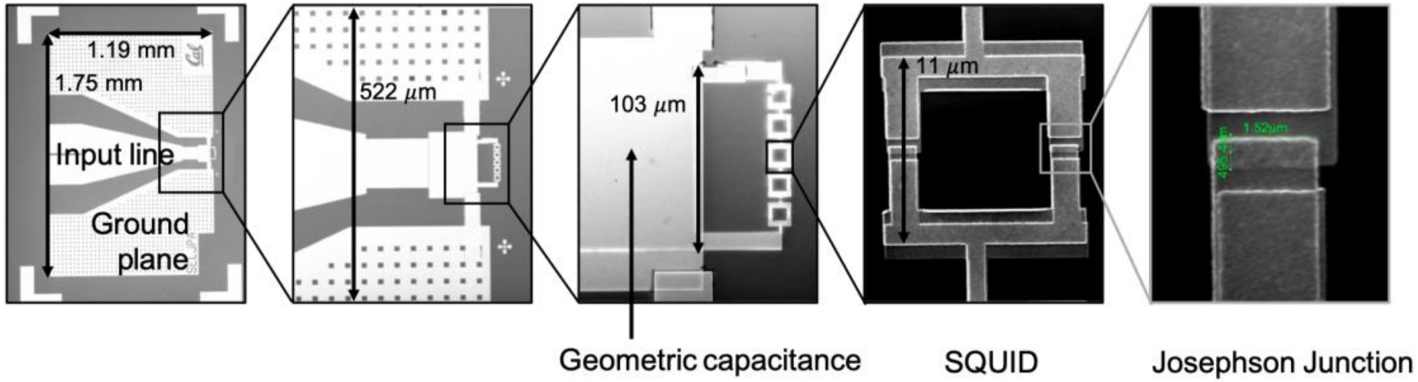



# Cavity Tuning Range



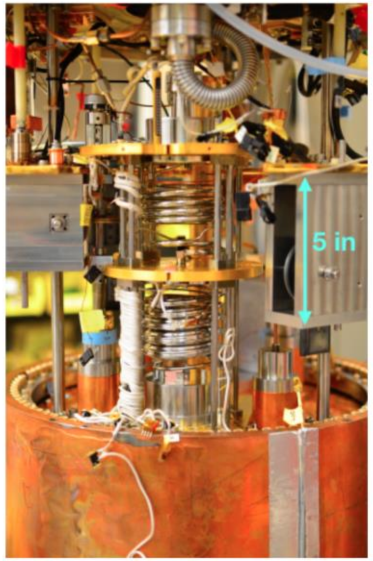



# A Quantum RF Measurement



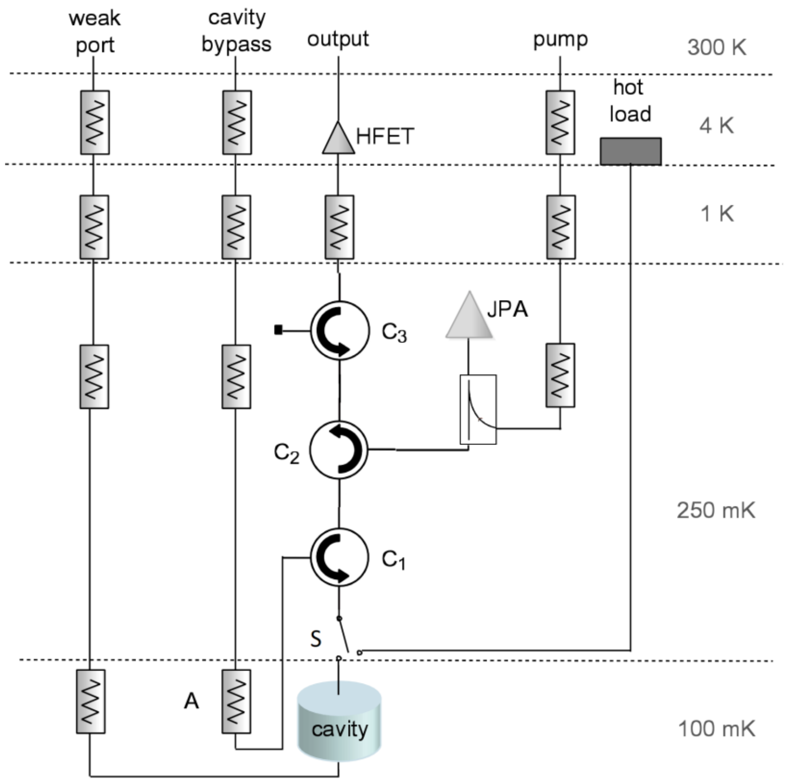

*JPA provided by*
*Siddiq Group at UC Berkeley*

The cavity is cooled to ~100 mK. The standard quantum limit is ~50 mK at 1 GHz. The signal amplified by a Josephson Parametric Amplifier before reaching the warm electronics.

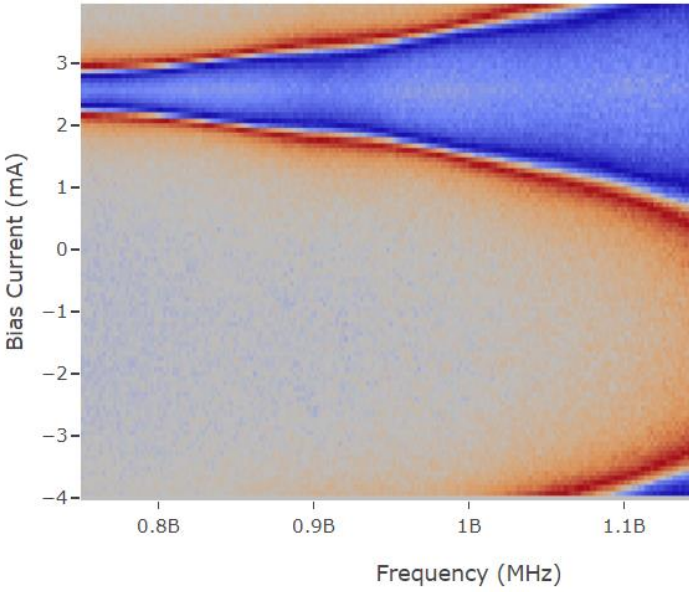


# Operating a Quantum Amplifier is Non-Trivial

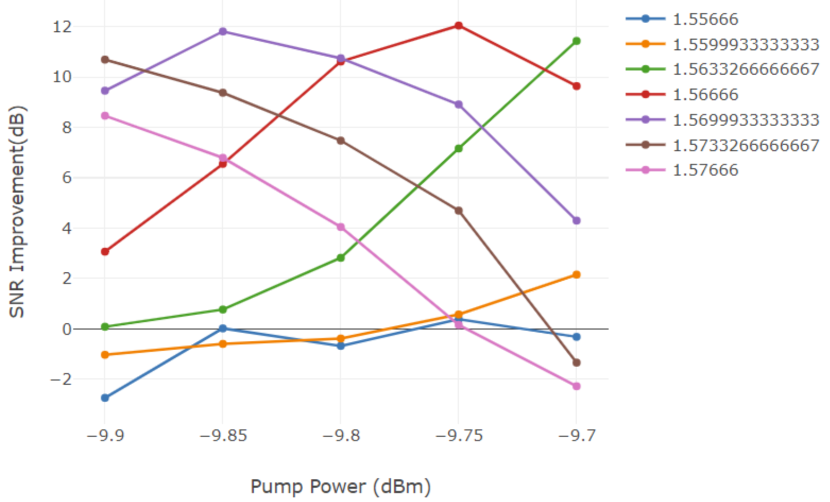
RF Signal Path Schematic




The JPA is tuned to match the cavity frequency



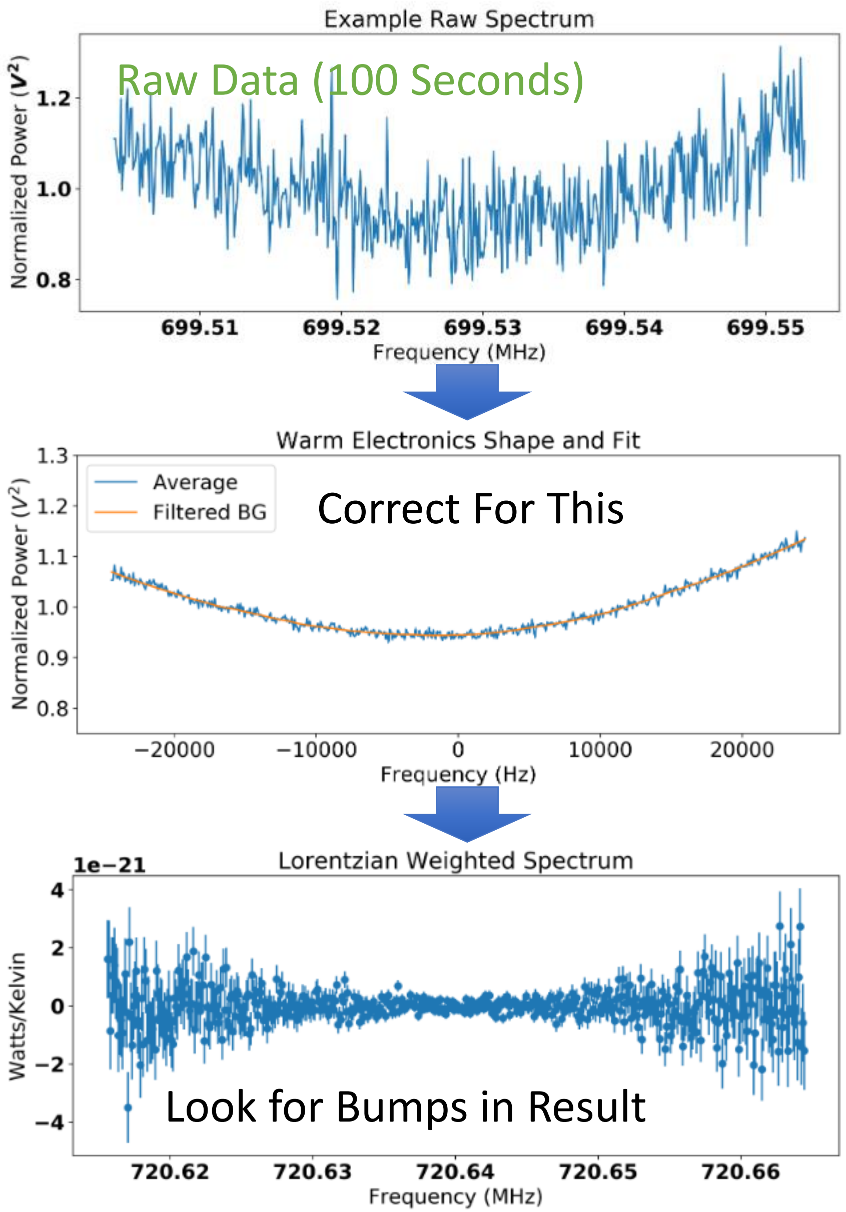

The JPA is optimized to minimize system noise



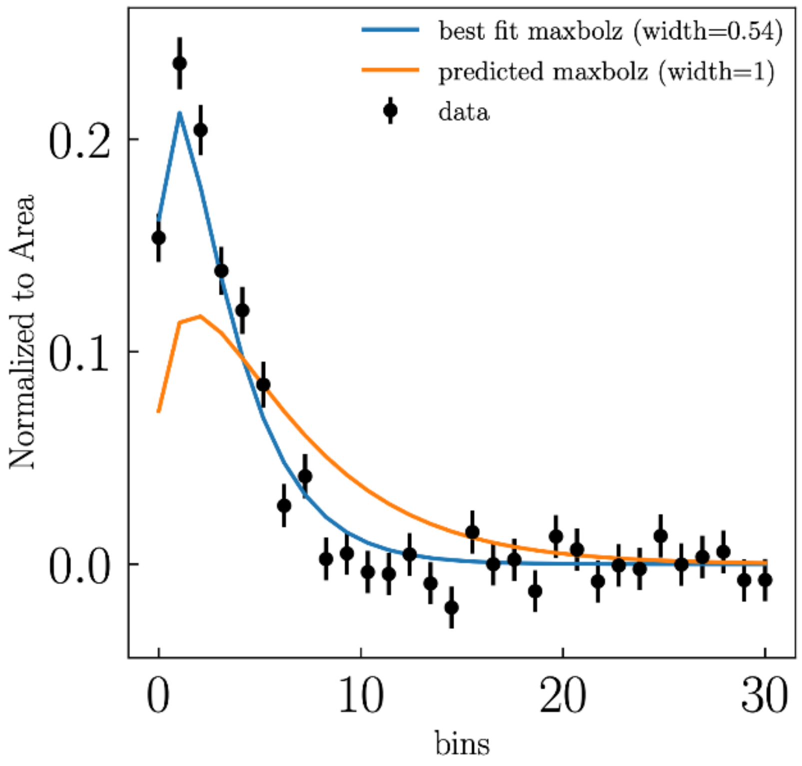
# ADMX Analysis

We measure a power spectrum about the cavity's resonance and look for a power excess that could come from an axion

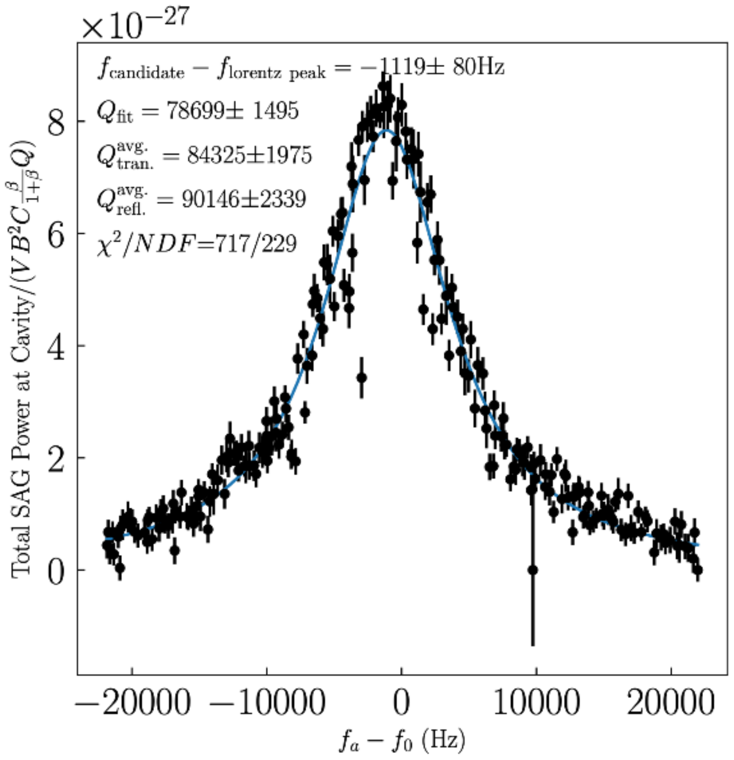
See Bartram et al. Phys. Rev. D 103, 032002 (2021)



# Blind-Injection Synthetic Signal Detection




The lineshape was consistent with cosmological predictions




The signal was clearly coming from inside the cavity

This signal sure looked like an axion. But before we began ramping the magnet down to be sure, we wanted to try looking at it from another mode.