Current Status and Future Plans of ADMX

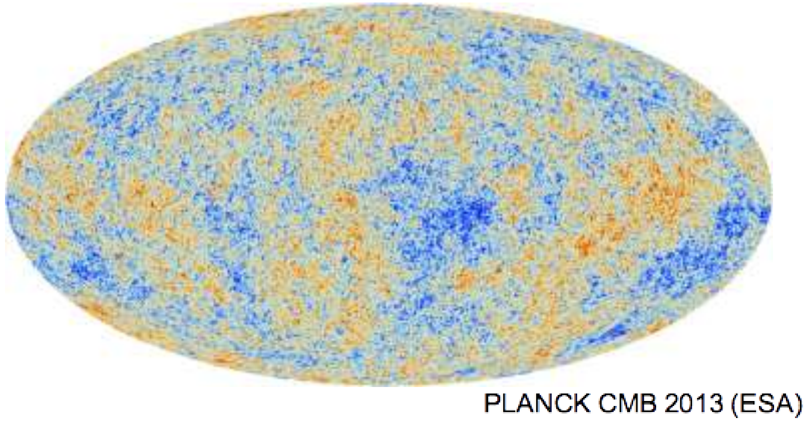
Gray Rybka

University of Washington

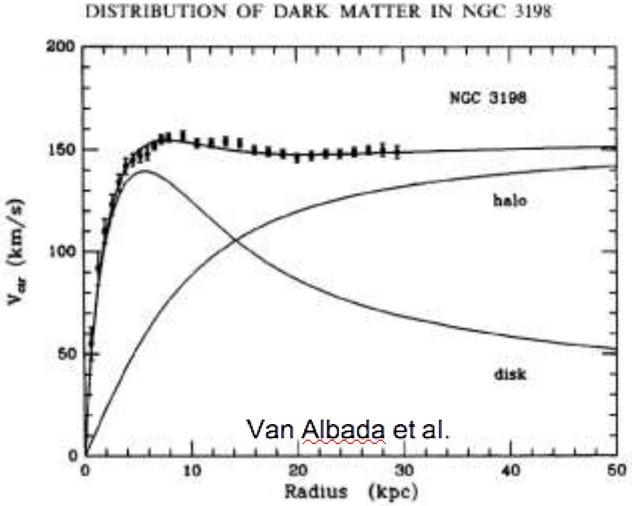
INT Dark Matter Workshop

August 5, 2022

Evidence for Dark Matter



Our Hubble Volume



Nearby Galaxies

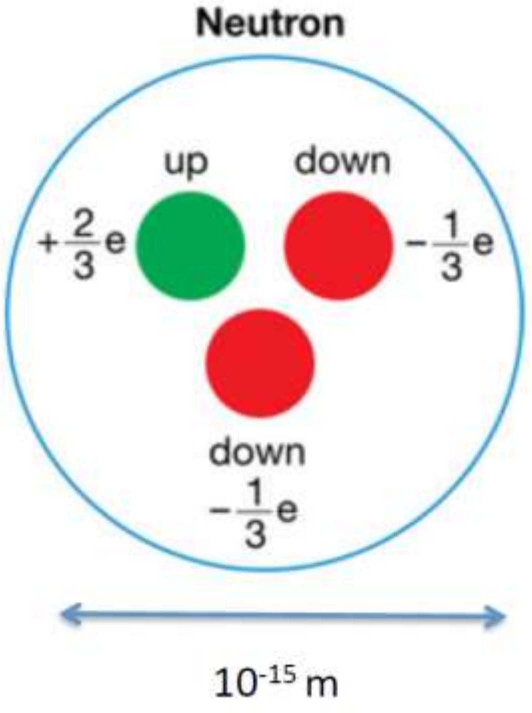
Galaxy Clusters

?

The Laboratory

The QCD Axion: Motivation

- QCD is naturally CP violating from phenomena like QCD-instantons
- One naively expects a neutron electric dipole moment of 10^{-16} e cm
- But nEDM is measured to be below 3×10^{-26} e cm *(Baker, 2006)*
- The best explanation? New U(1) axial symmetry, that when broken, cancels CP violation in the strong sector *(Peccei, Quinn, 1977)*
- Consequence: New particle, called the axion *(Weinberg, Wilczek, 1978)*

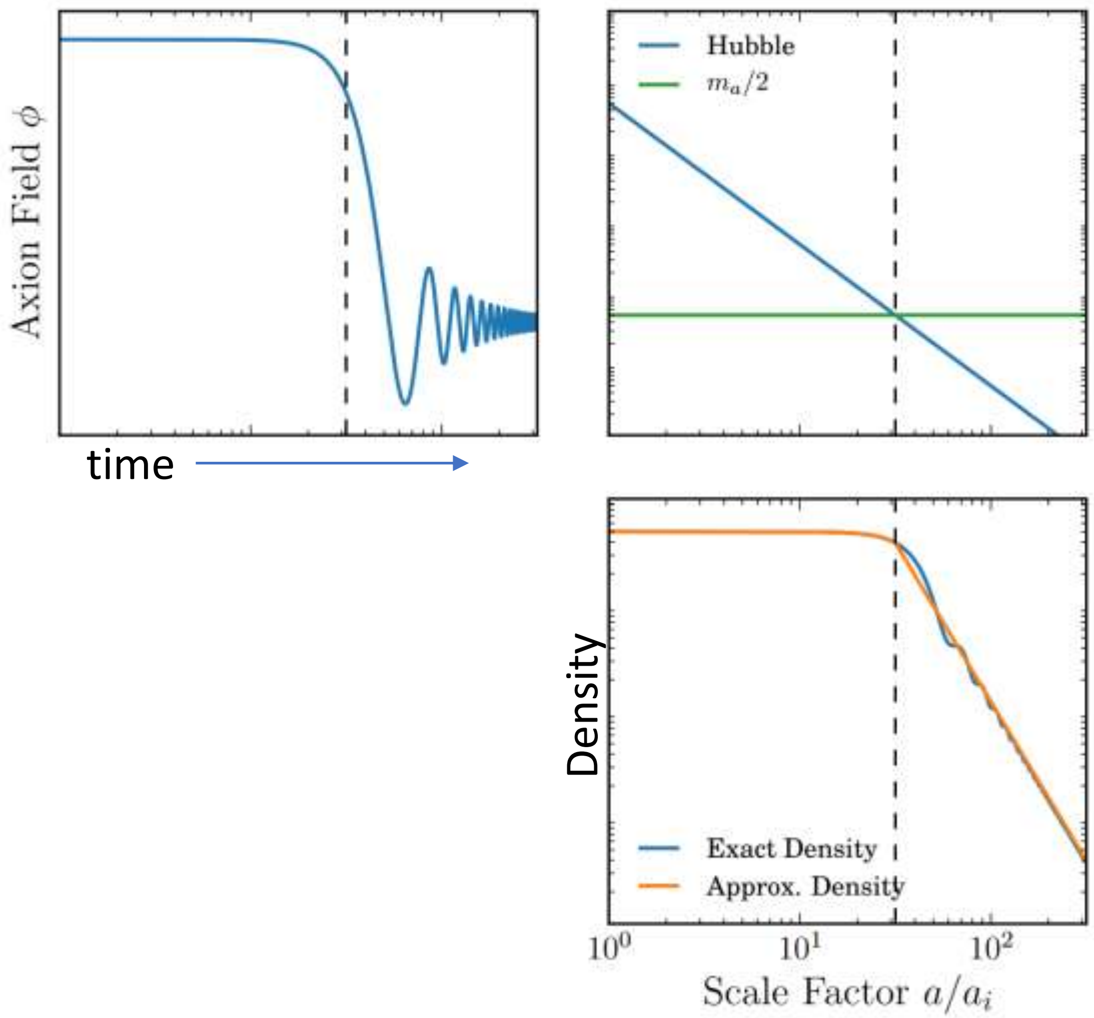


d = ~~10^{-16} e cm~~

< 3×10^{-26} e cm

Axions as Dark Matter

- Misalignment Mechanism - Long before nucleosynthesis, Peccei-Quinn symmetry is broken and massive axions are produced.
- Getting the dark matter density right prefers certain axion energy scales / masses.
- Decay of strings/topological defects may also contribute to dark matter.
- Thermal production does not contribute to *cold* dark matter.



D. Marsh, "Axion Cosmology" arXiv:1510.07633

Detecting Axions

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F_{\mu\nu} + g_{aNN} (\partial_\mu) \bar{N} \gamma^\mu \gamma_5 N + g_{aee} (\partial_\mu) \bar{e} \gamma^\mu \gamma_5 e$$

Coupling to Photons

Coupling to Nucleon EDM

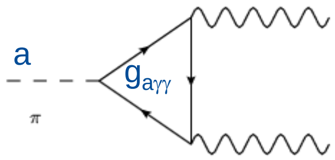
Coupling to Axial Nuclear Moment

Coupling to Axial Electron Moment

Adapted from Y. Kahn, See also Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Detecting Axions

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F_{\mu\nu} + g_{aNN} (\partial_\mu) \bar{N} \gamma^\mu \gamma_5 N + g_{aee} (\partial_\mu) \bar{e} \gamma^\mu \gamma_5 e$$



Coupling to Photons

Clean experimental signal
Well developed techniques
Ripe for incorporating quantum sensing techniques

Coupling to Nucleon EDM

Coupling to Axial Nuclear Moment

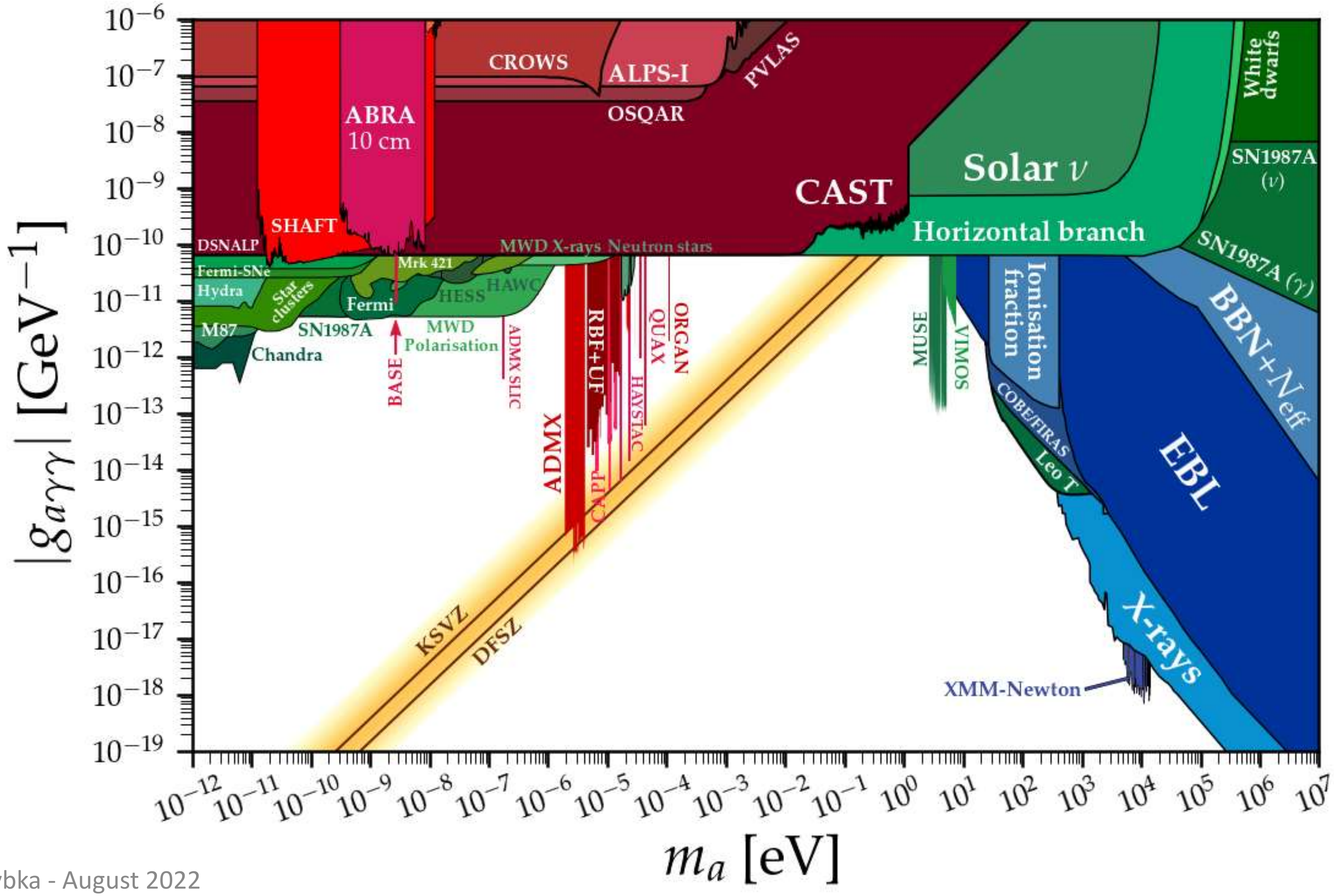
Coupling to Axial Electron Moment

Promising experimental techniques under development

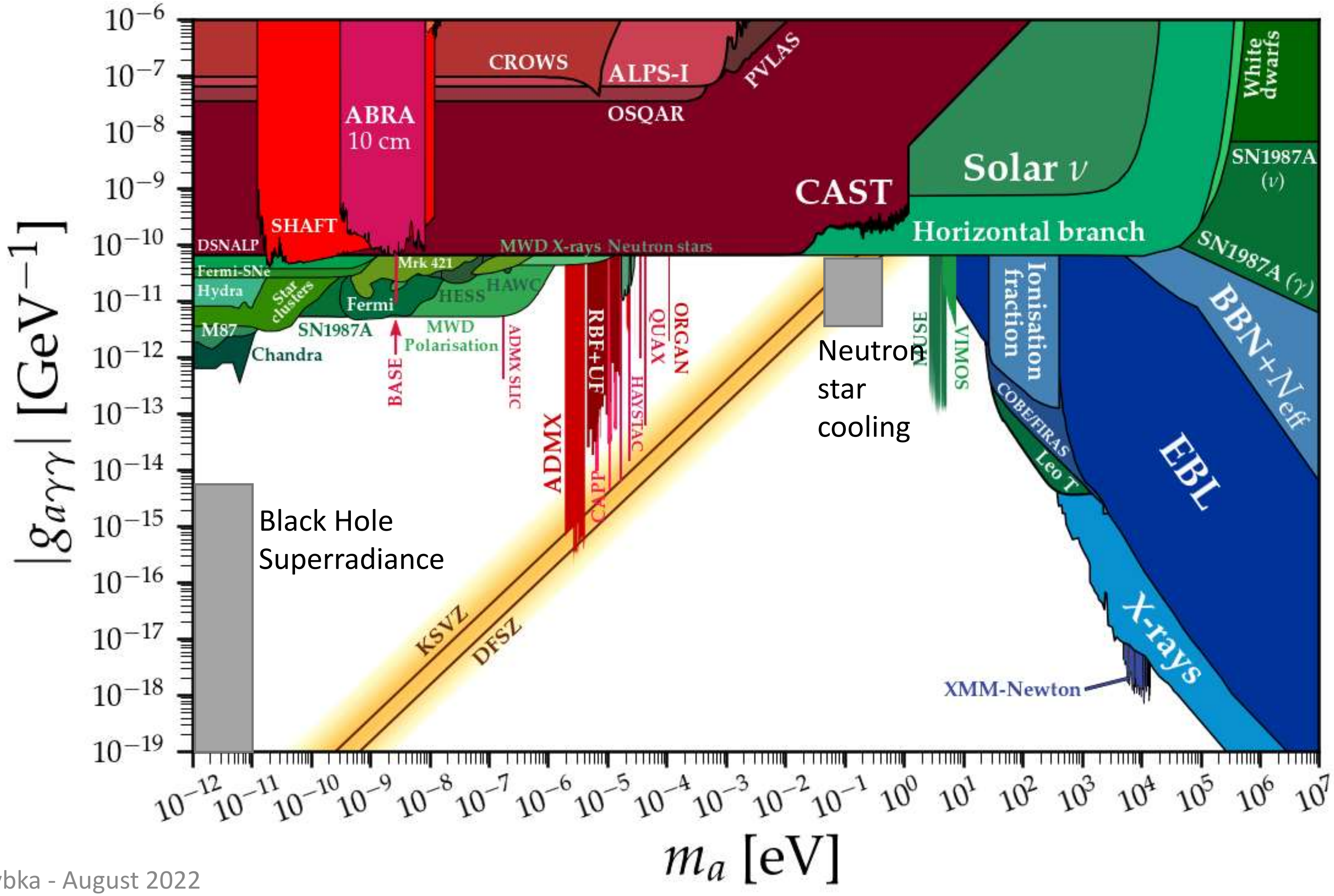
Adapted from Y. Kahn, See also Graham and Rajendran, Phys.Rev. D88 (2013) 035023

Axion Photon Bounds

[GitHub - cajohare/AxionLimits: Data, plots and code for constraints on axions, axion-like particles, and dark photons]



Axion Photon Bounds with non-photon bounds pasted on top in an ad-hoc way…

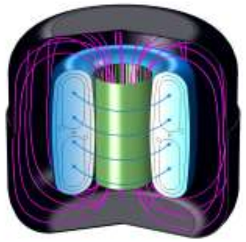


Axion-Photon Searches

$$\nabla \times \mathbf{B}_r = \cancel{\frac{\partial \mathbf{E}_r}{\partial t}} + \underbrace{g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}_{\mathbf{J}_{\text{eff}}}$$

Quasistatic regime: $\lambda_{\text{Comp}} \gg R_{\text{exp}}$

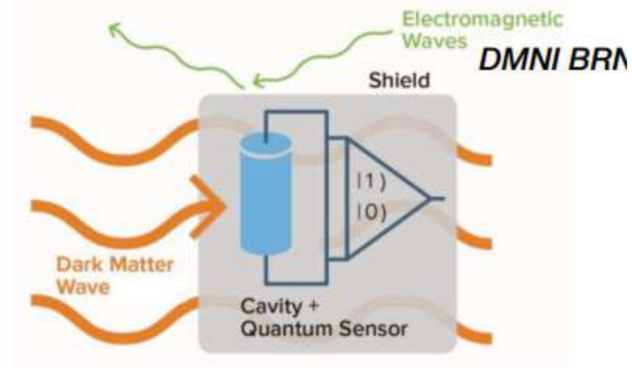
Below 1 ueV



$$\nabla \times \mathbf{B}_r = \underbrace{\frac{\partial \mathbf{E}_r}{\partial t}} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Cavity regime: $\lambda_{\text{Comp}} \sim R_{\text{exp}}$

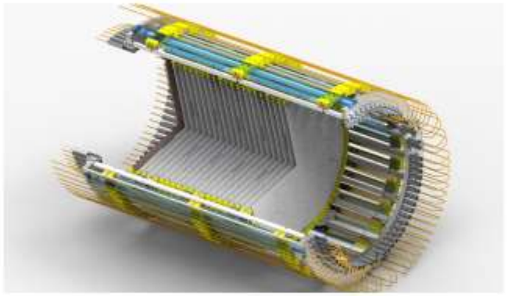
1 ueV – 1 meV



$$\nabla \cancel{\times} \mathbf{B}_r = \frac{\partial \mathbf{E}_r}{\partial t} + g_{a\gamma\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Radiation regime: $\lambda_{\text{Comp}} \ll R_{\text{exp}}$

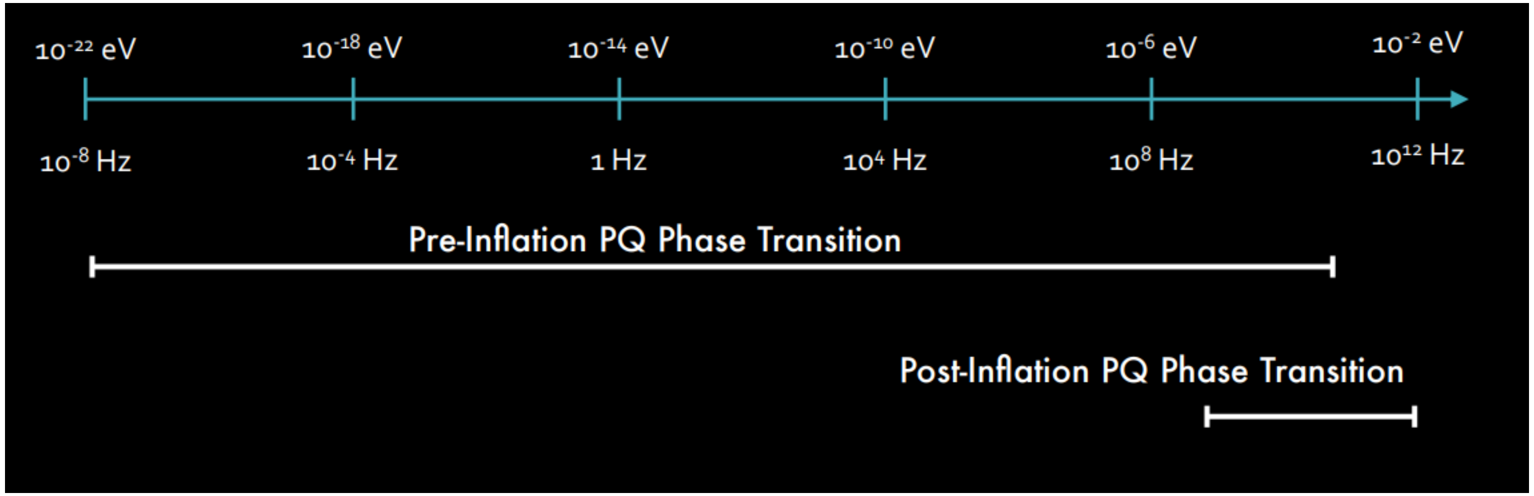
1 meV and above



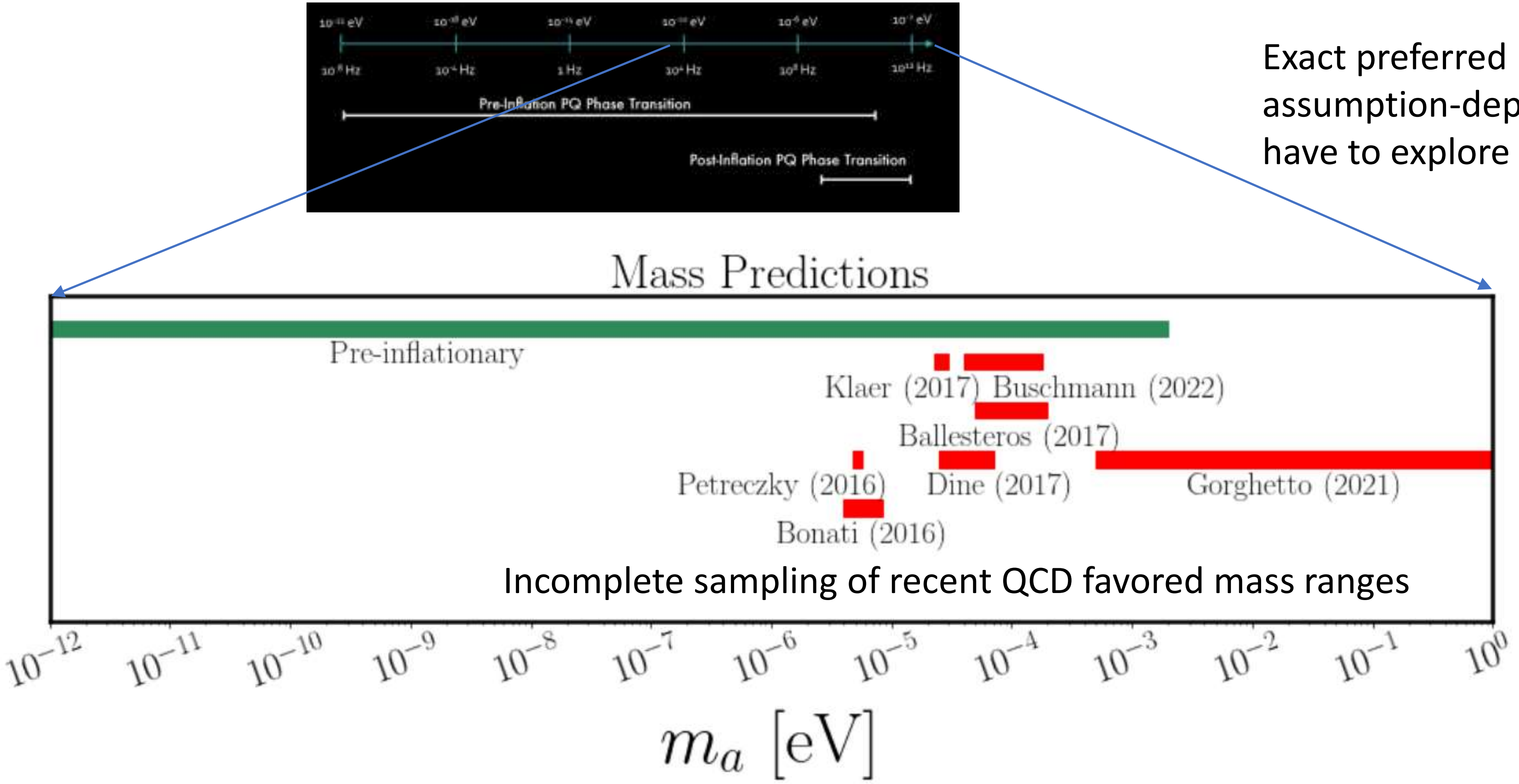
Y. Kahn

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

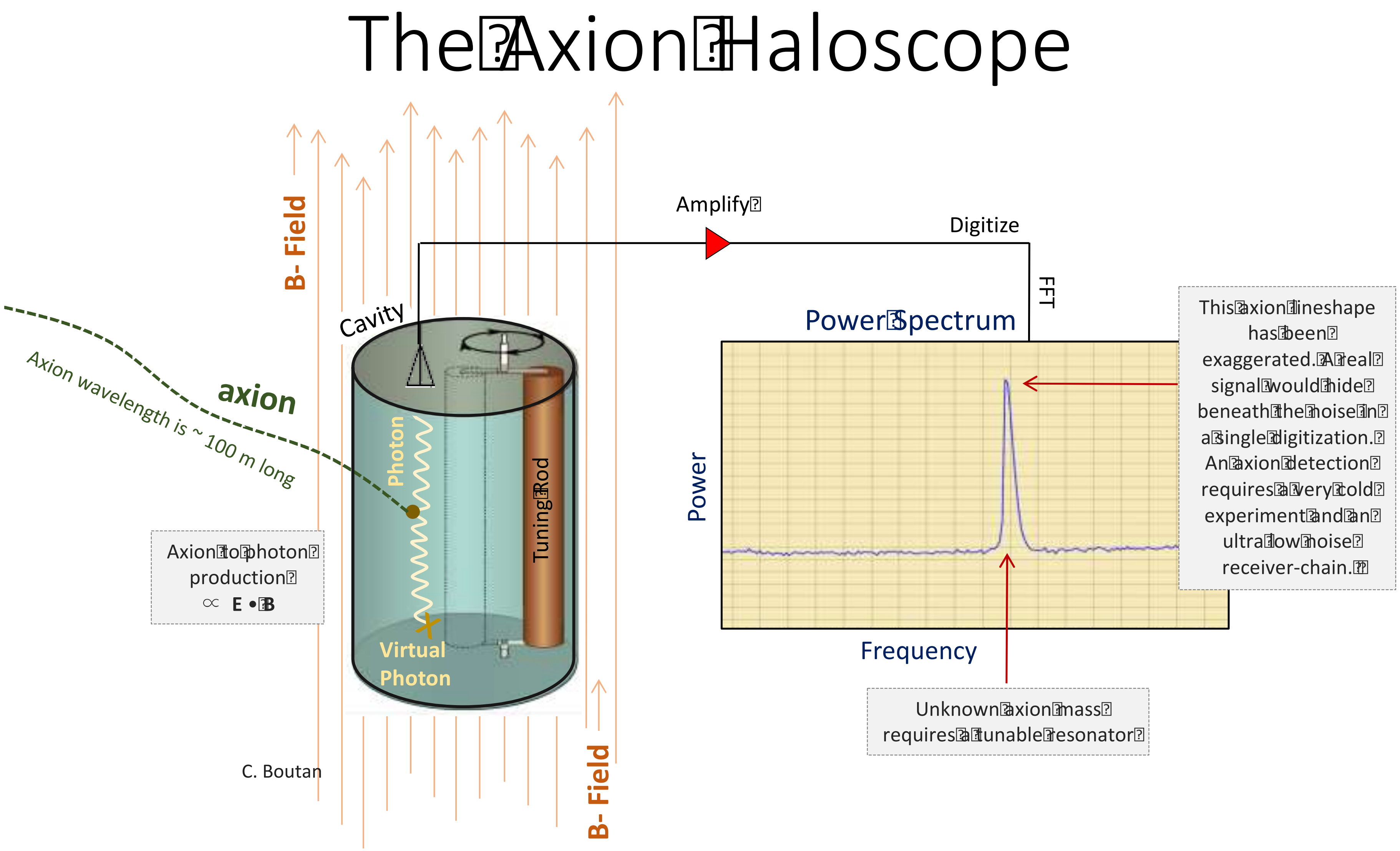


Theoretical Preferences



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

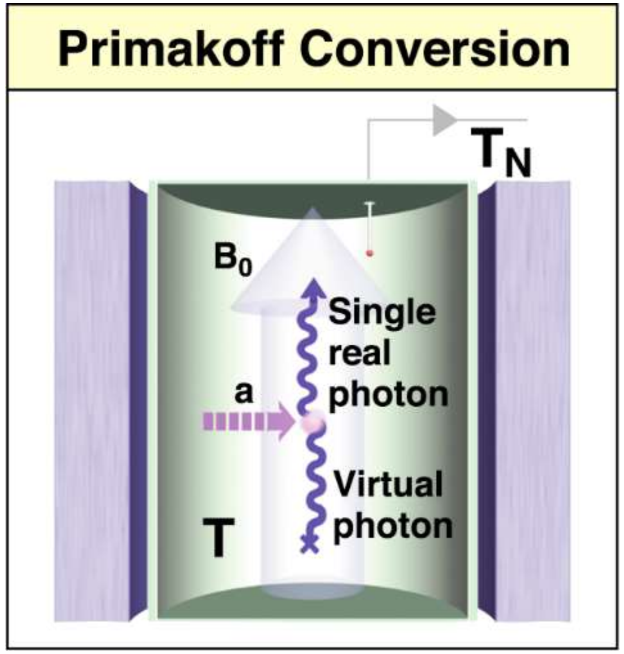
Principle of the Sikivie Axion Haloscope



Why is an axion haloscope hard?

- We don’t know what frequency to probe
- The signal strength is very small
- The fundamental quantum noise limit is appreciable
- Large-bore, high field magnets are expensive and slow to build

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

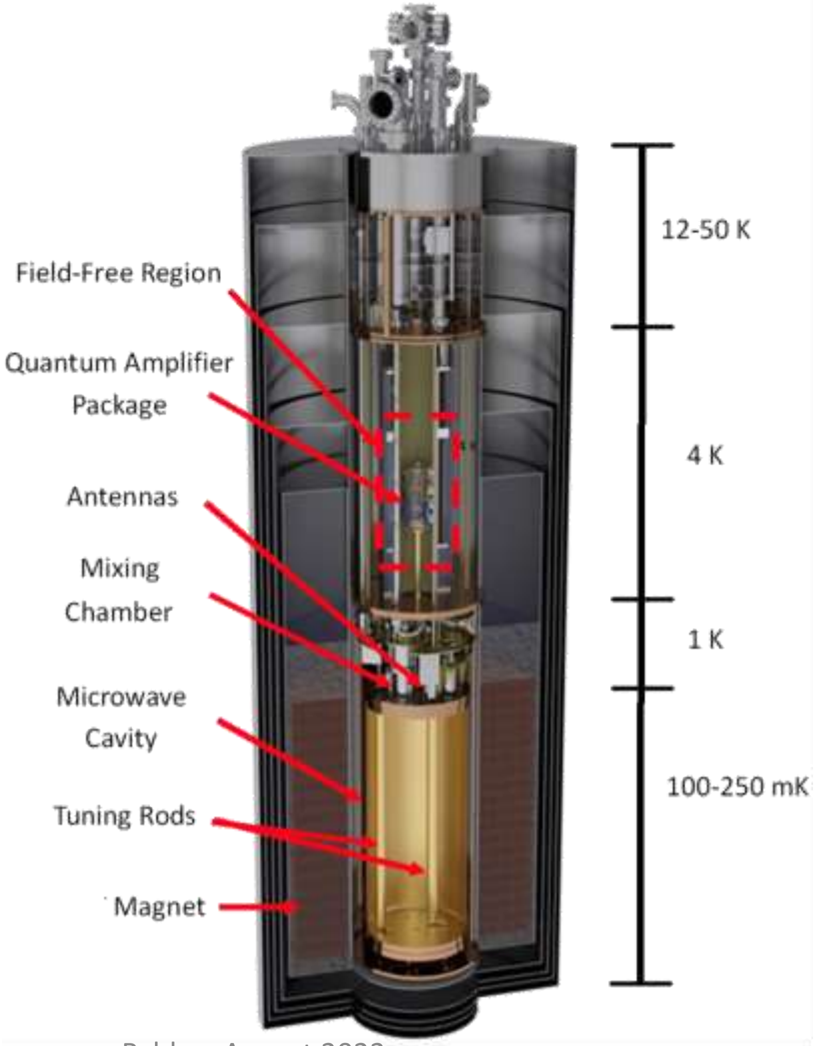
Cavity Blackbody Radiation

Amplifier Noise

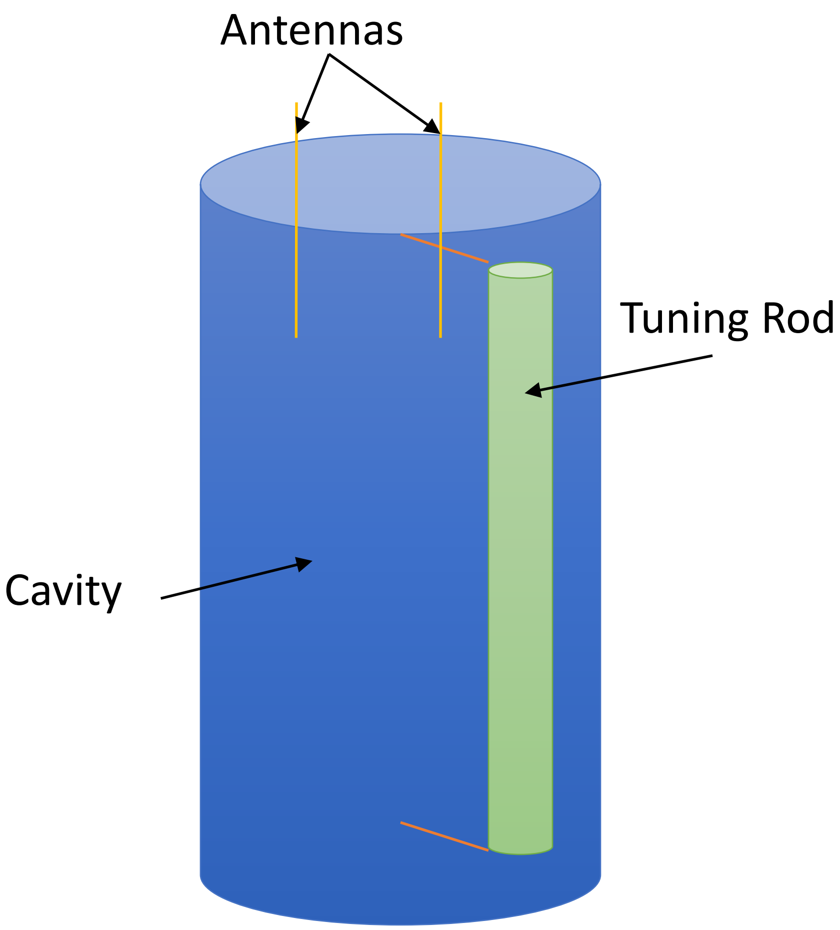
ADMX Collaboration

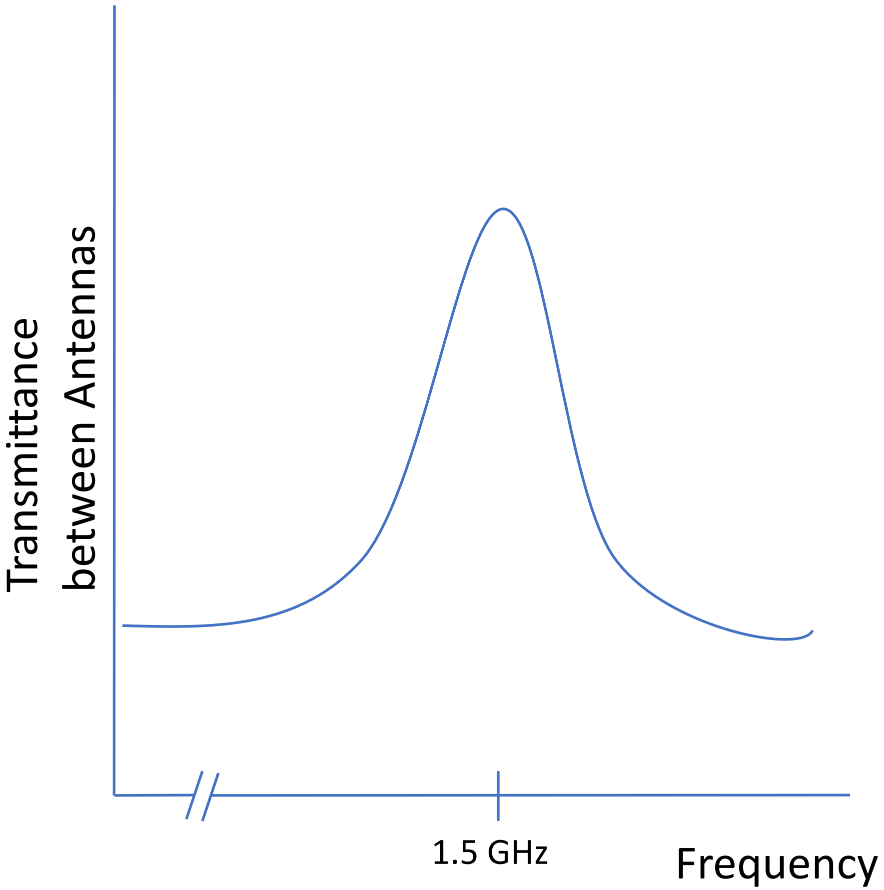
This work was supported by the U.S. Department of Energy through Grants No DE-SC0009800, No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0011665, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, No. DE-C03-76SF00098 and No. DE-SC0017987. Fermilab is a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.

ADMX Design

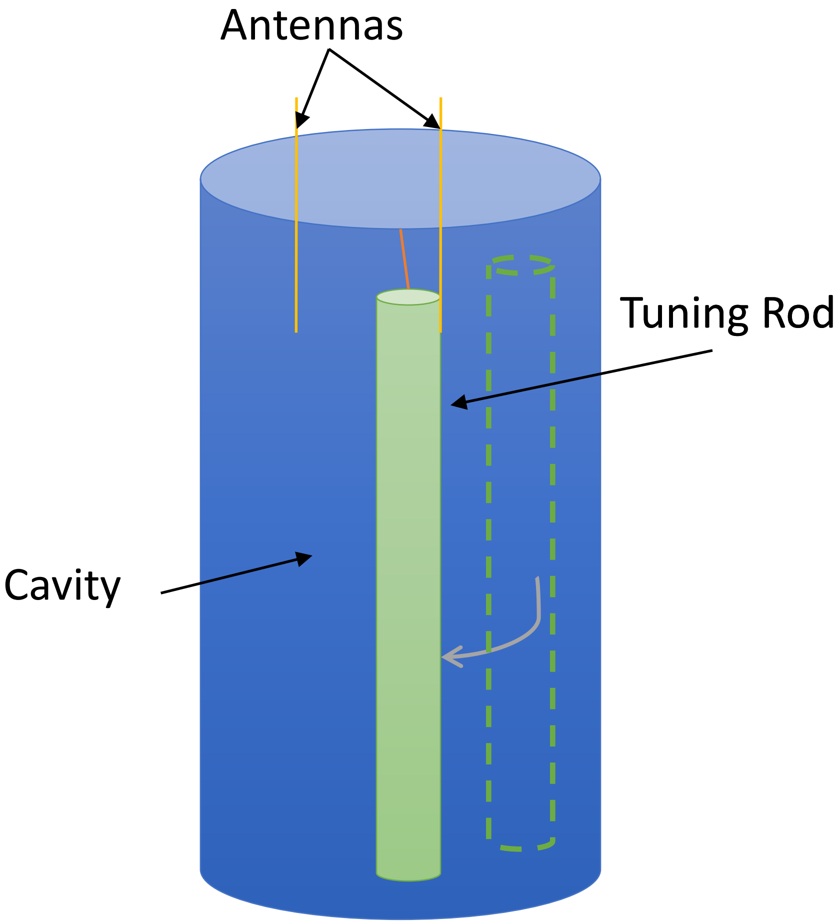

Field-Free Region
Quantum Amplifier Package
Antennas
Mixing Chamber
Microwave Cavity
Tuning Rods
Magnet
12-50 K
4 K
1 K
100-250 mK

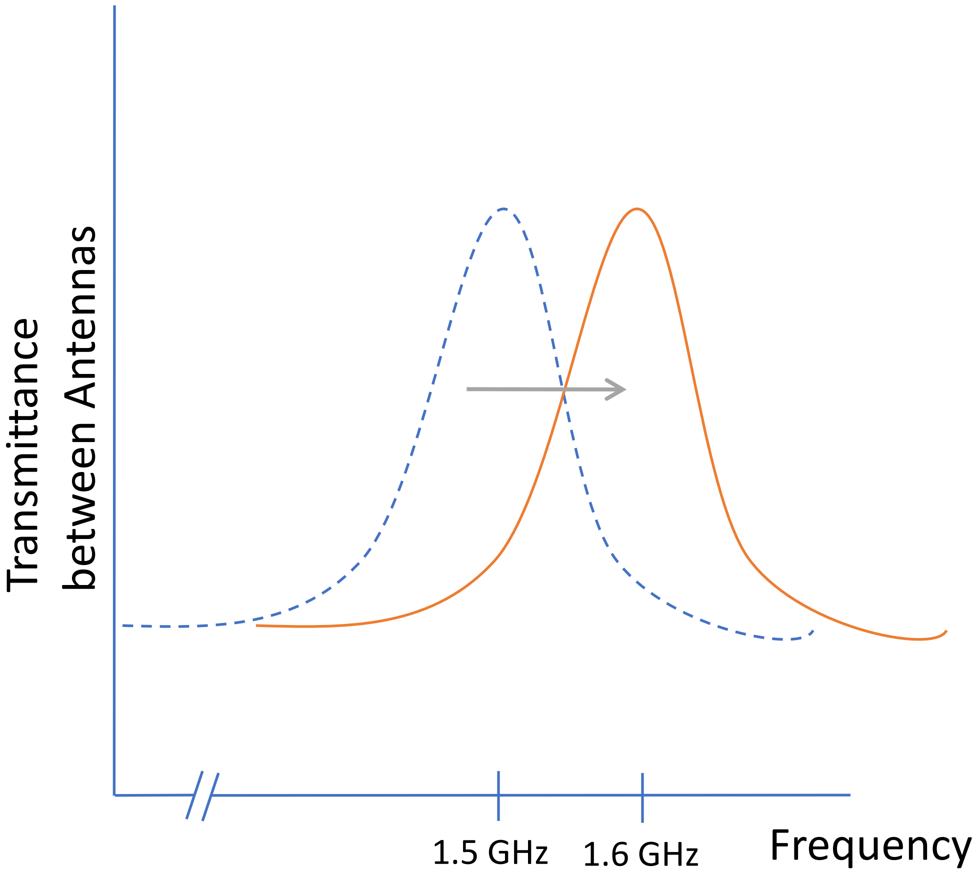
Microwave Cavity needs tunable resonance



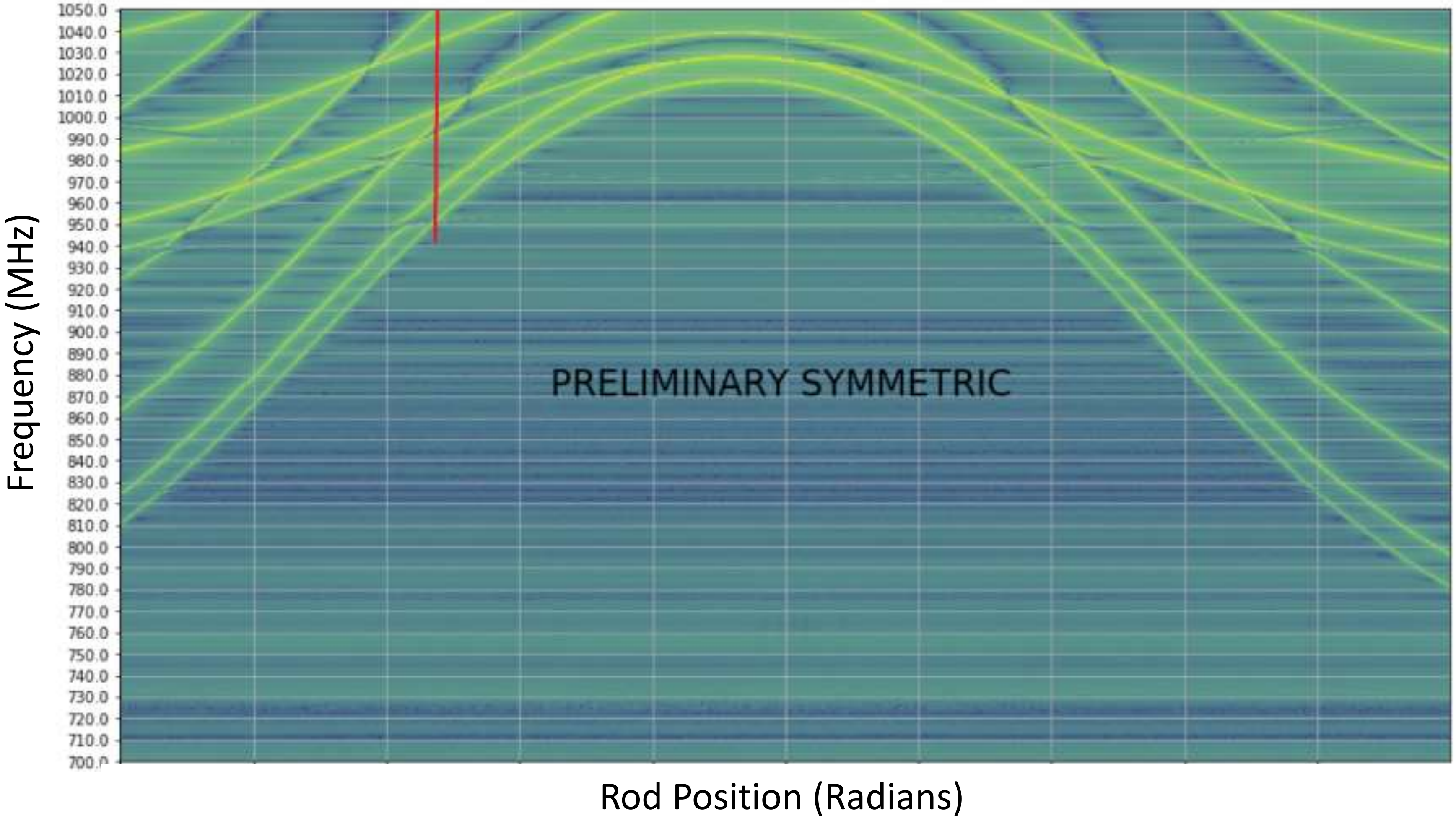


Microwave Cavity needs tunable resonance



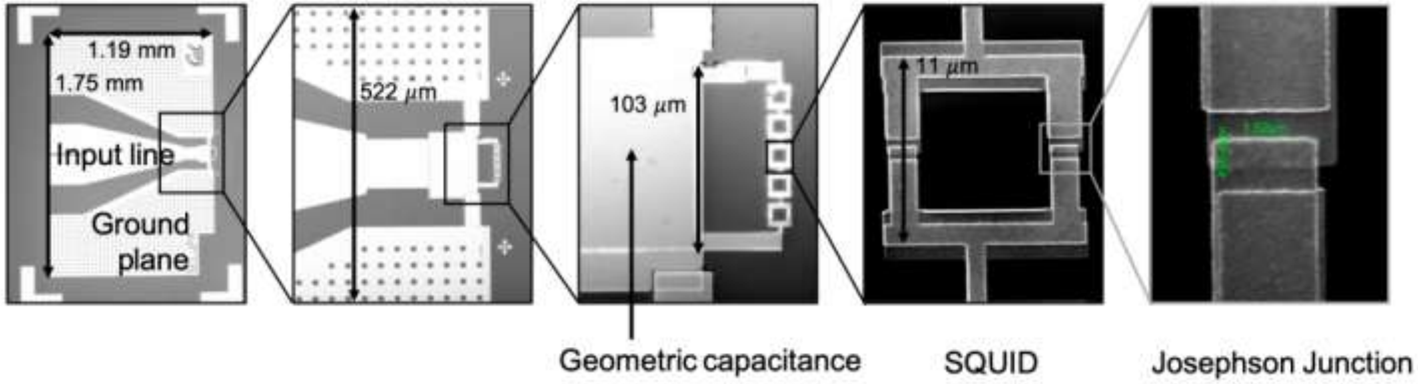


Cavity Tuning Range

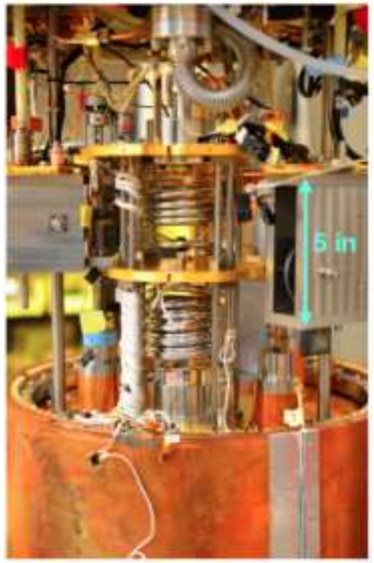


A Quantum RF Measurement

JPA provided by
Siddiq Group at UC Berkeley

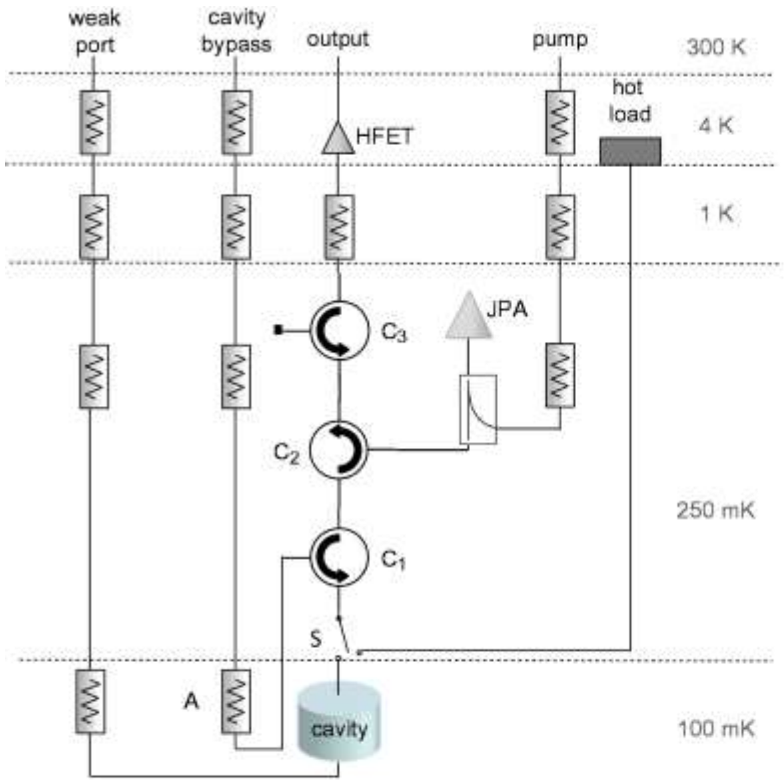


The cavity is cooled to ~100 mK. The standard quantum limit is ~50 mK at 1 GHz. The signal amplified by a Josephson Parametric Amplifier before reaching the warm electronics.

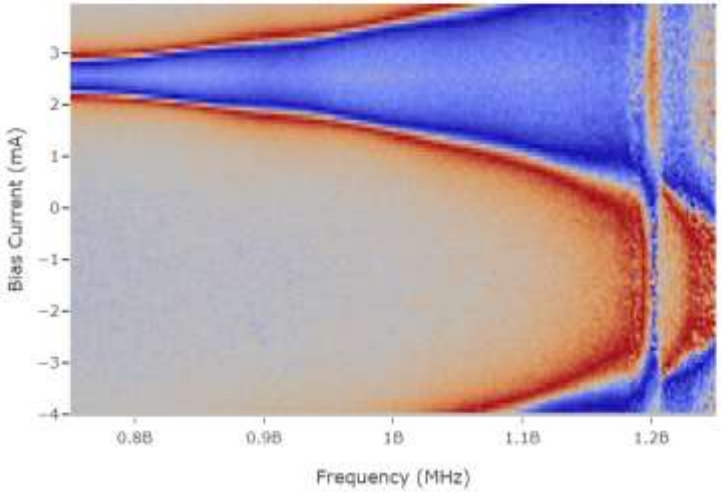


Operating a Quantum Amplifier is Non-Trivial

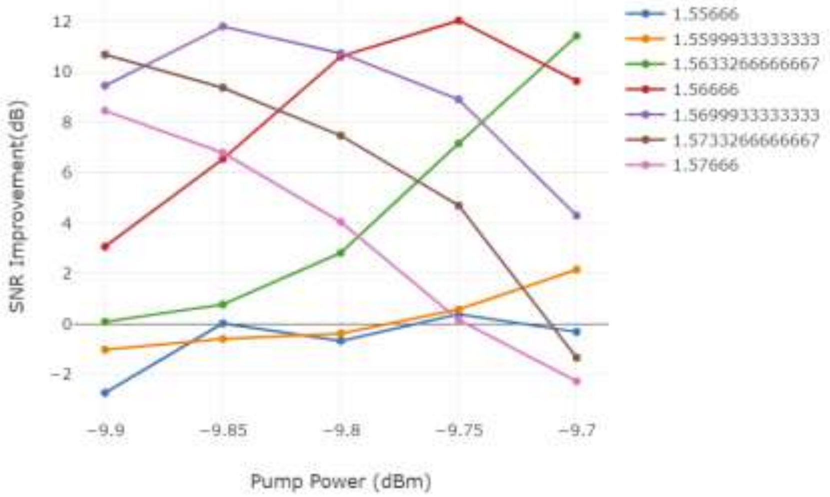
RF Signal Path Schematic



The JPA is tuned to match the cavity frequency



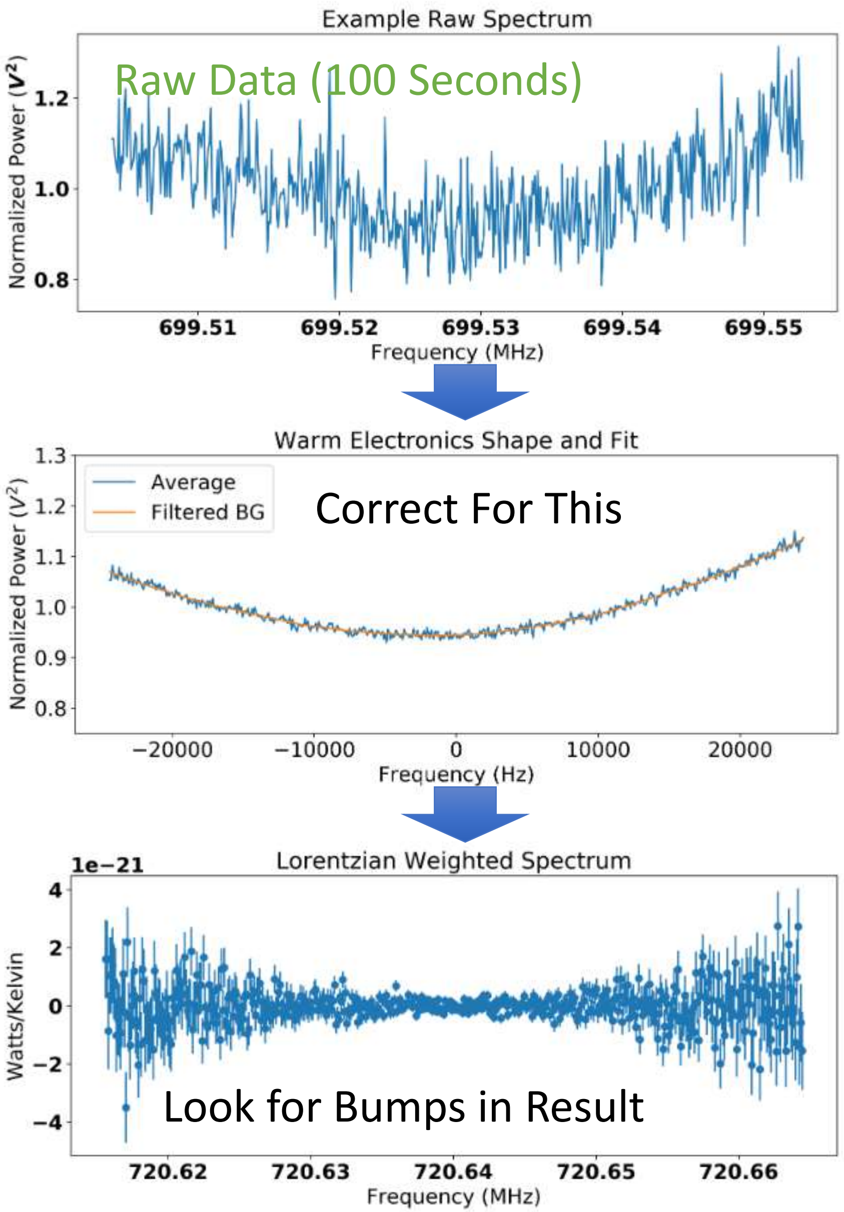
The JPA is optimized to minimize system noise



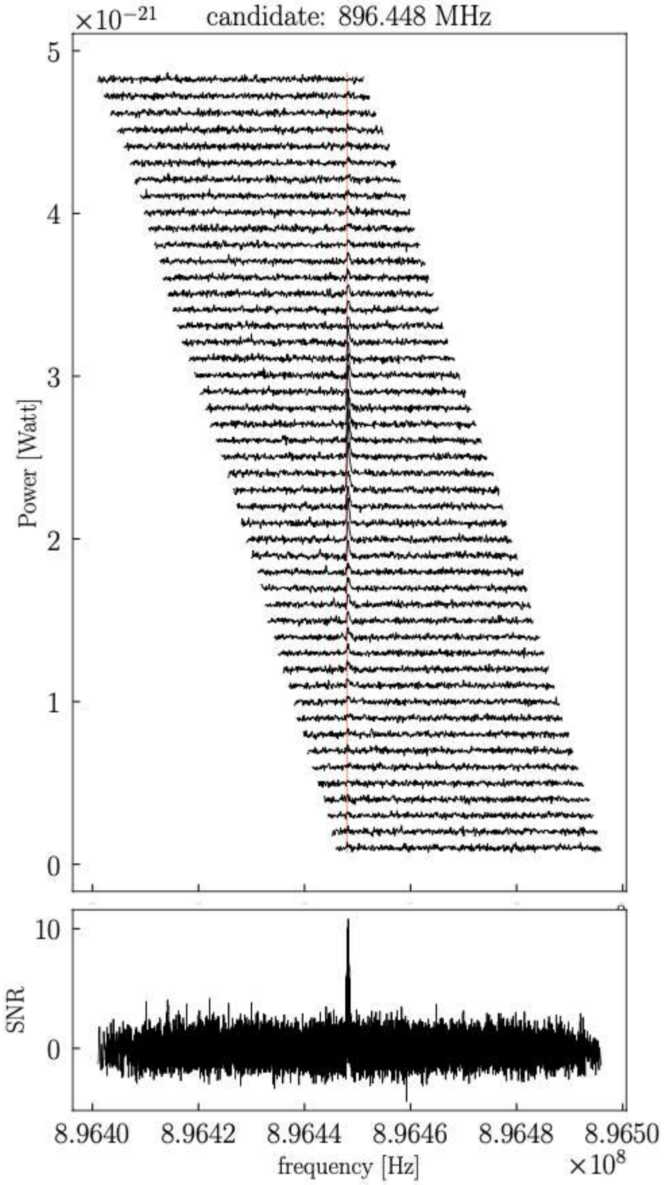
ADMX Analysis

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)



ADMX Operations

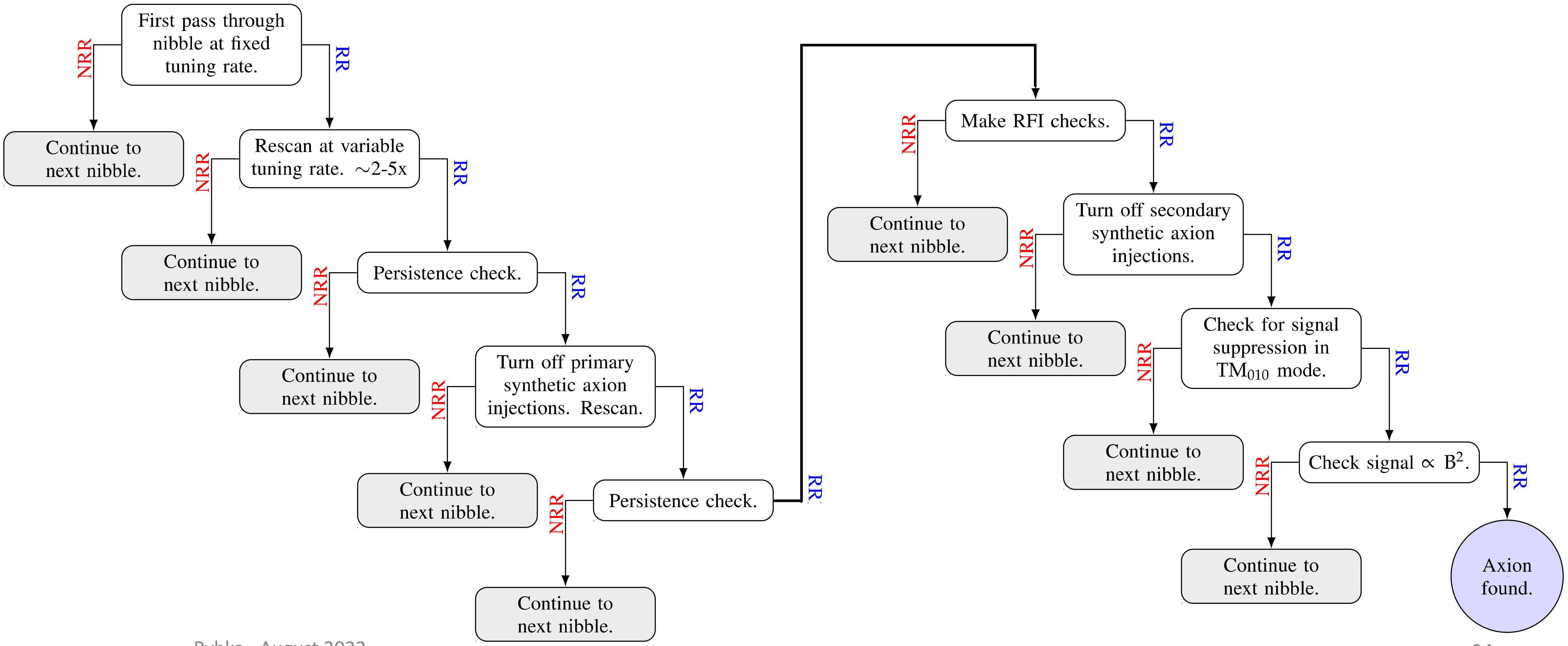


The cavity is tuned every 100 seconds, during which power spectra are taken. Overlapping power spectra are examined for the characteristic axion signal shape appearing on-resonance.

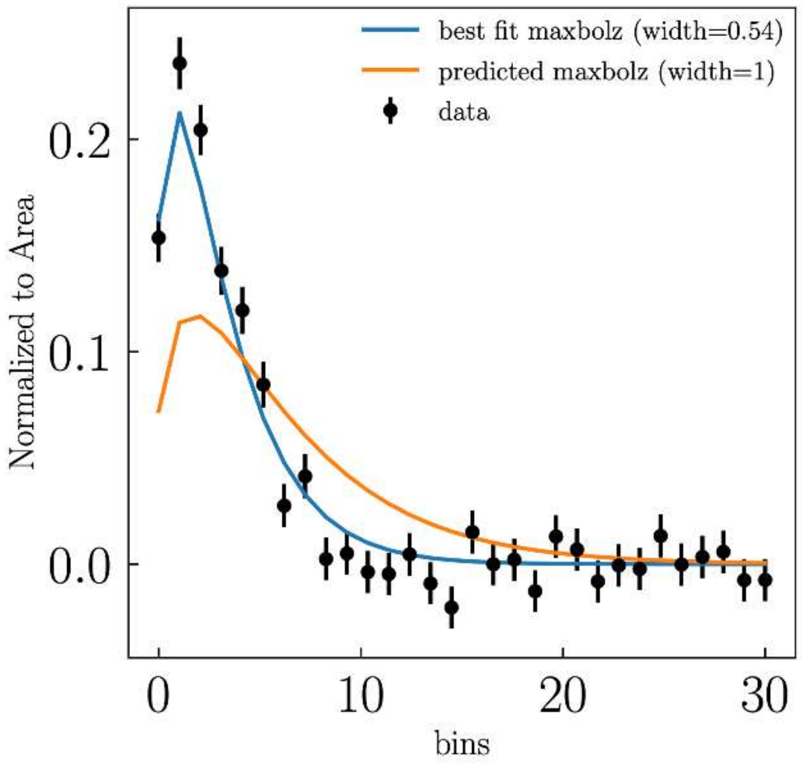
The picture on the left shows how an axion signal would appear in the data. This is a synthetic signal.

Data Taking Cadence

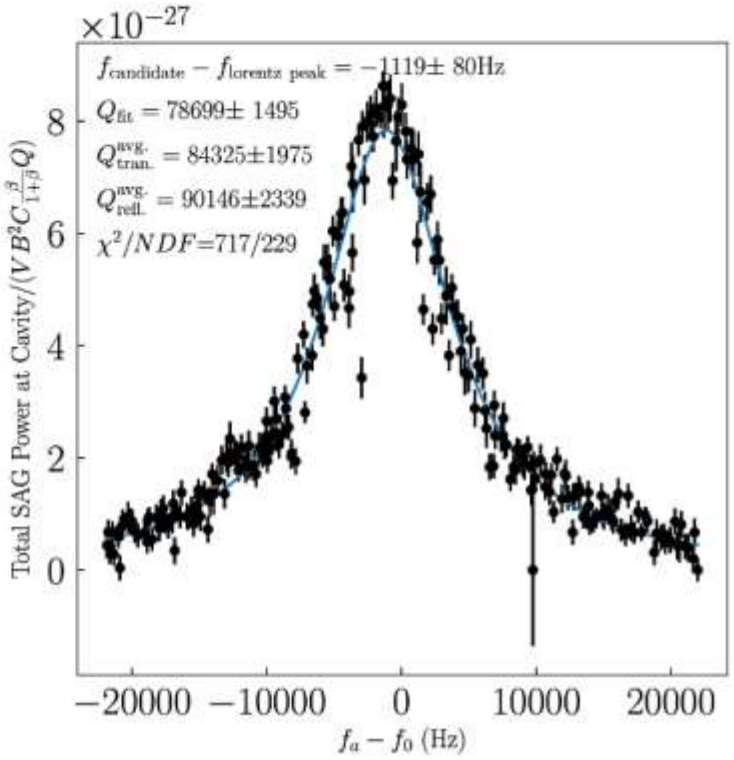
14 "nibbles" = ~ 10 MHz sweeps   single scans: **range:** 50 kHz, **resolution:** 100Hz, **integration time:** 100s



Blind-Injection Synthetic Signal Detection



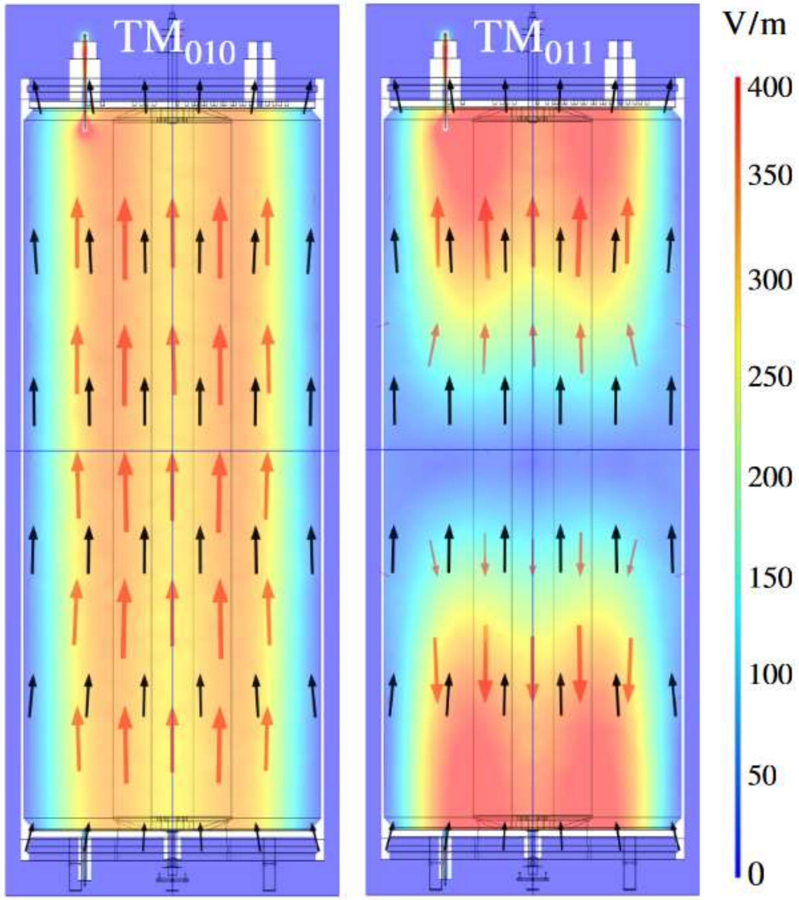
The lineshape was consistent with cosmological predictions

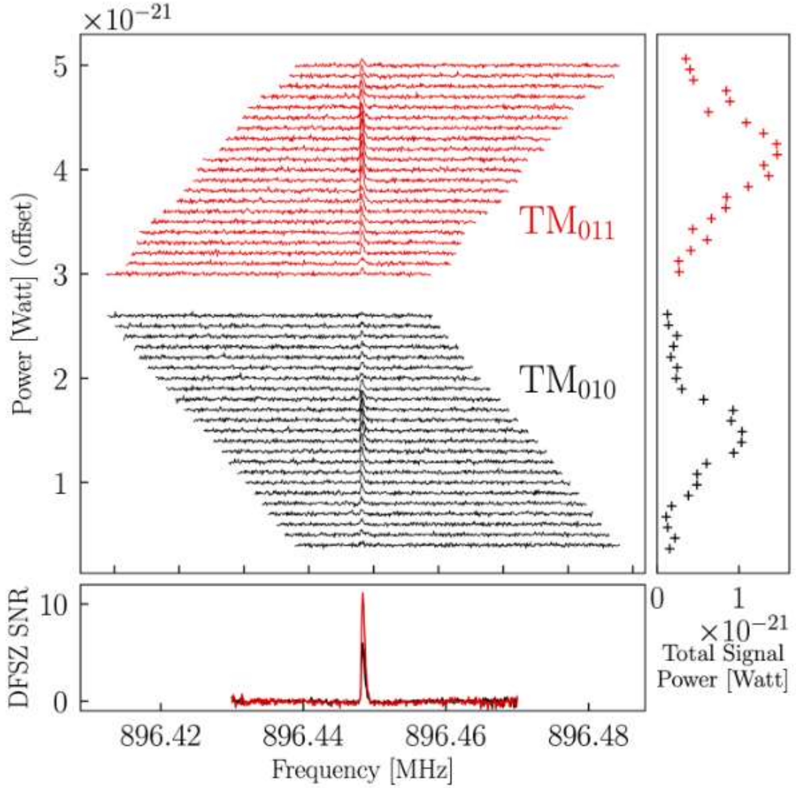


The signal was clearly coming from inside the cavity

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.

Axions Couple to TM010 modes, not TM011

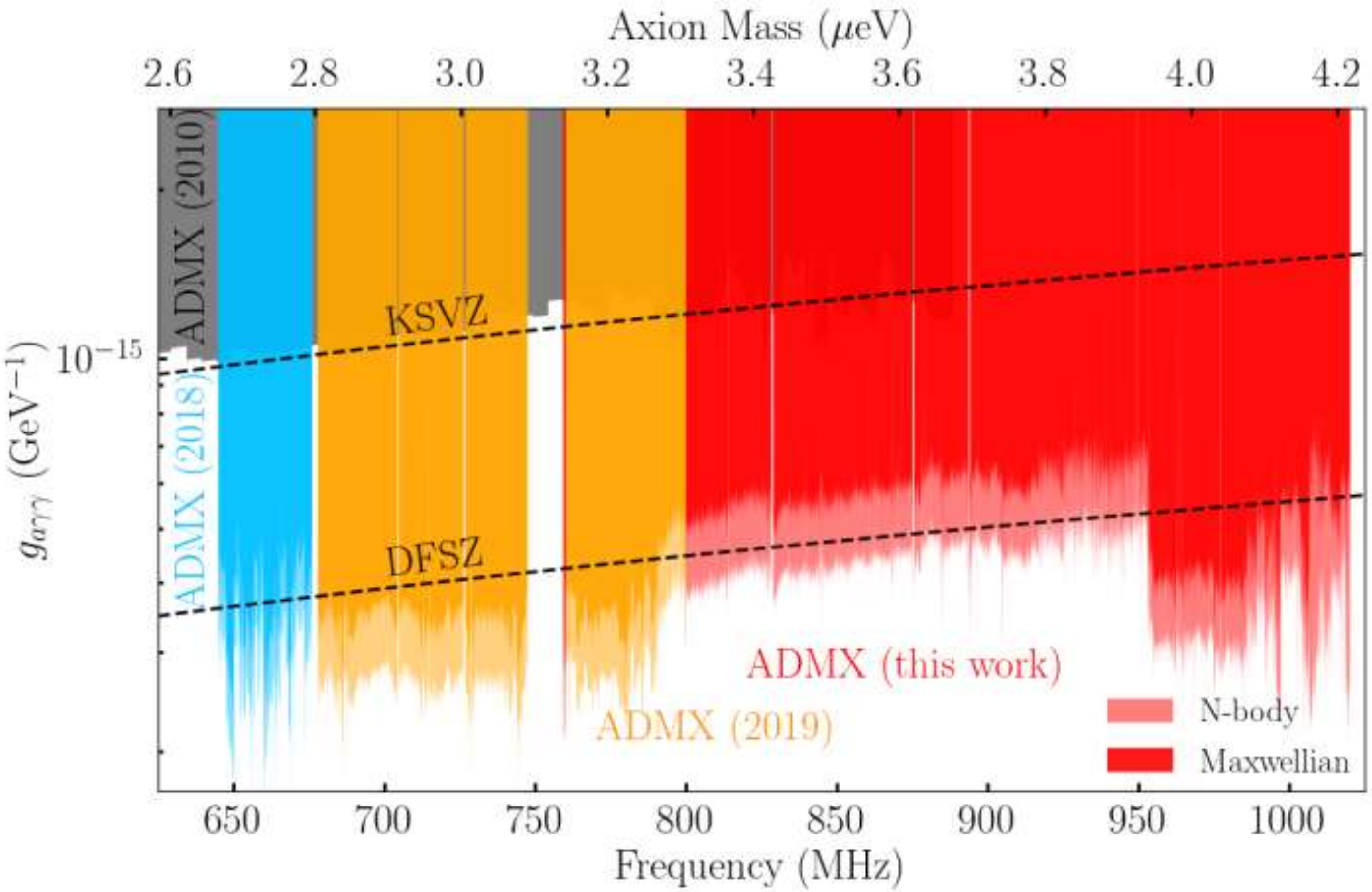




Overlap of axion field (black) and E&M mode field (red)

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

ADMX 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

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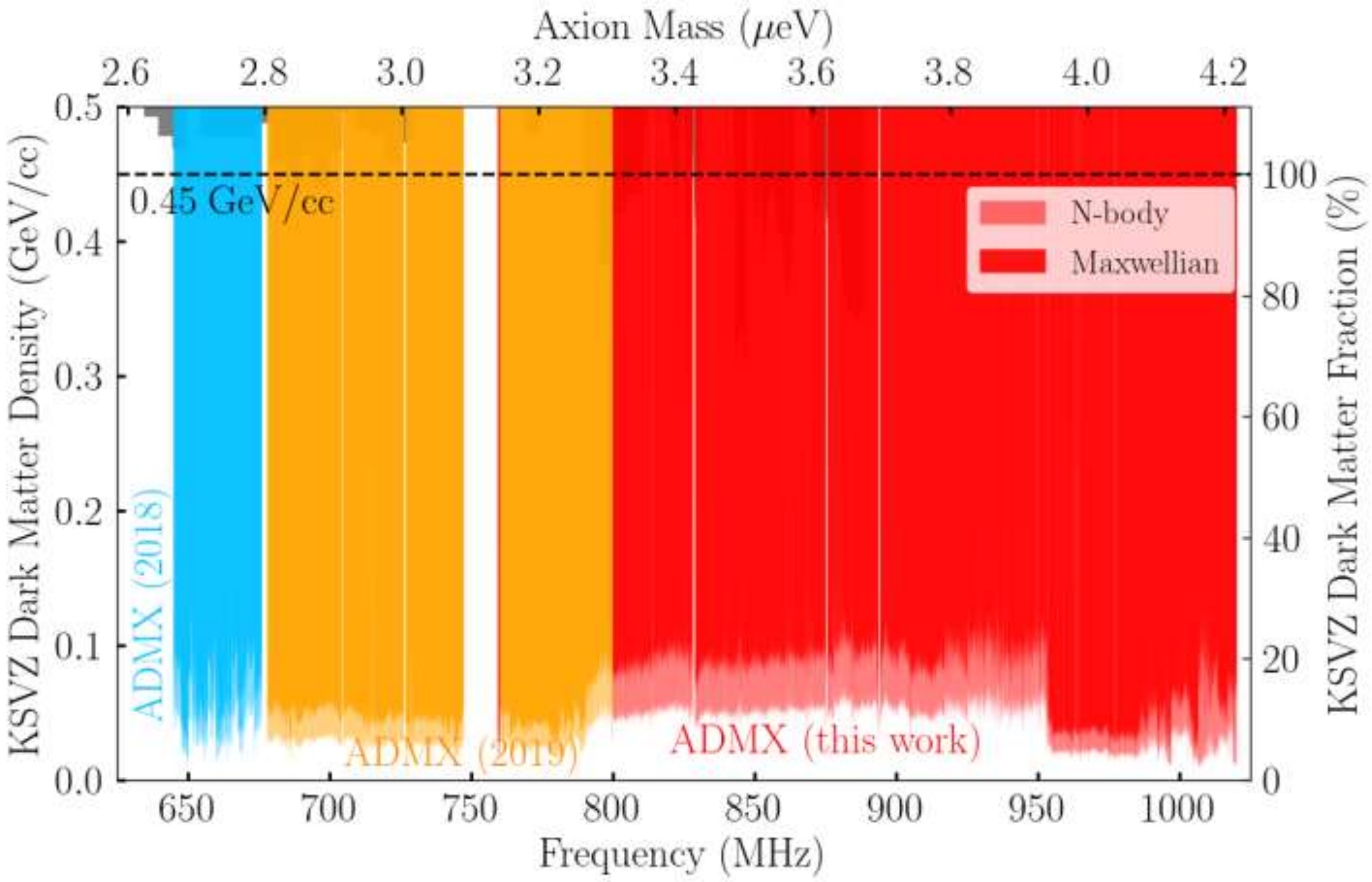
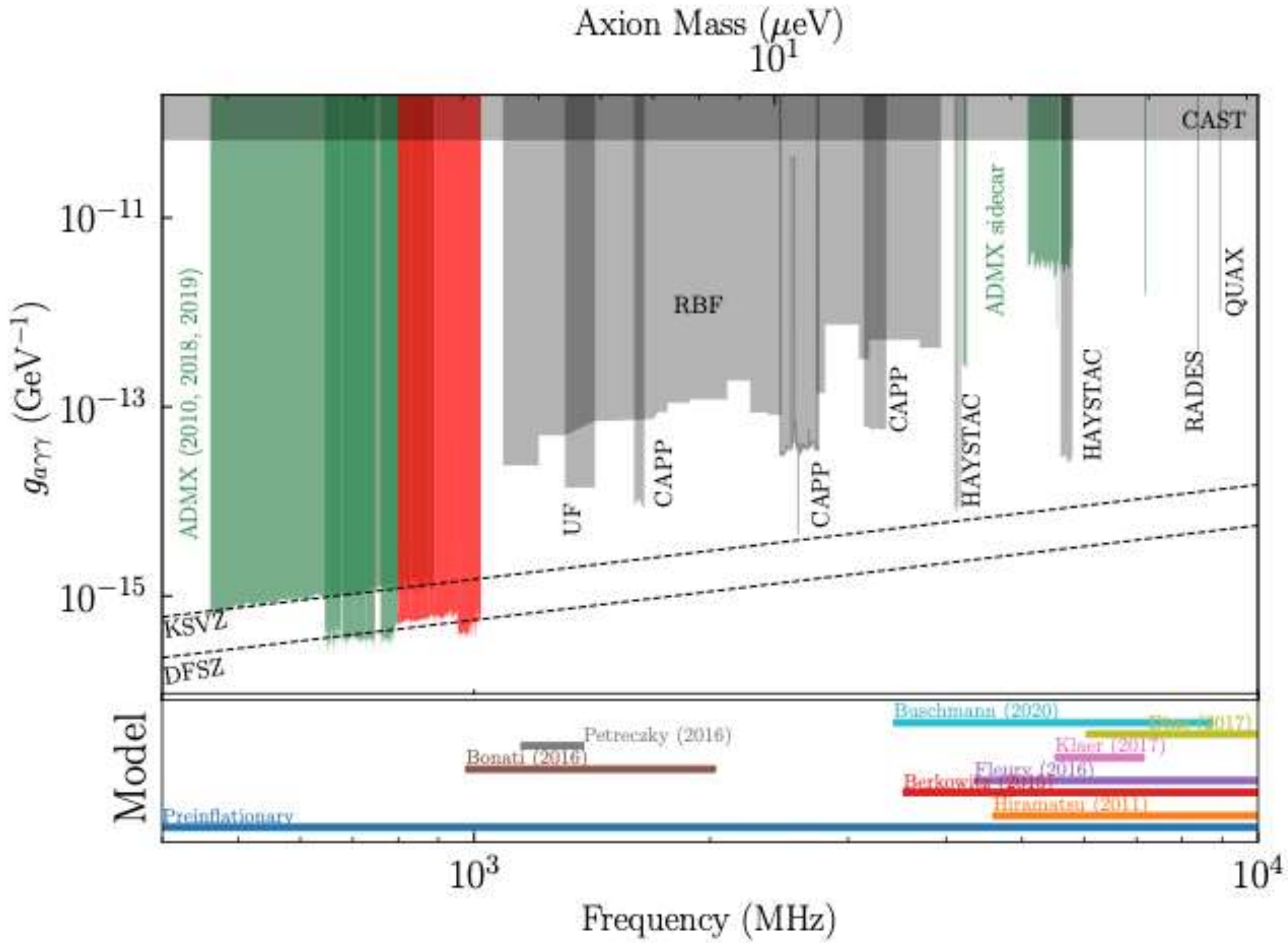
(ADMX Collaboration)

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

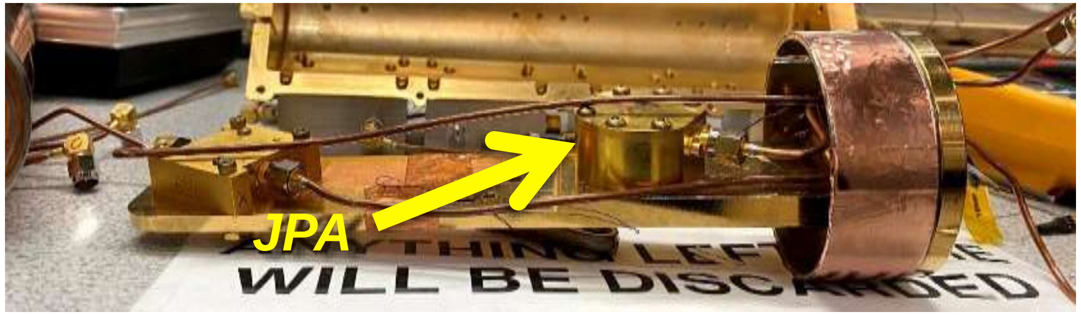


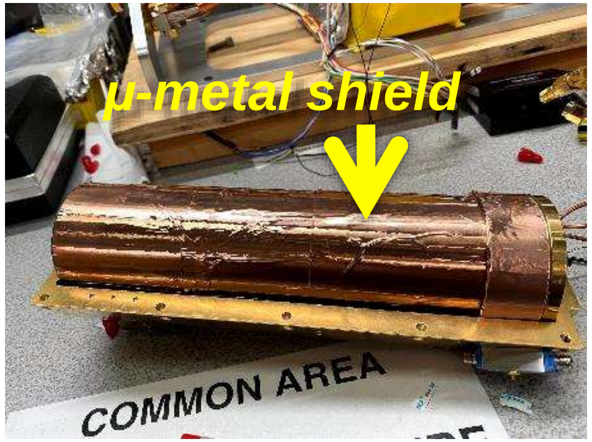
Run 1C Upgrades to improve T_{sys}

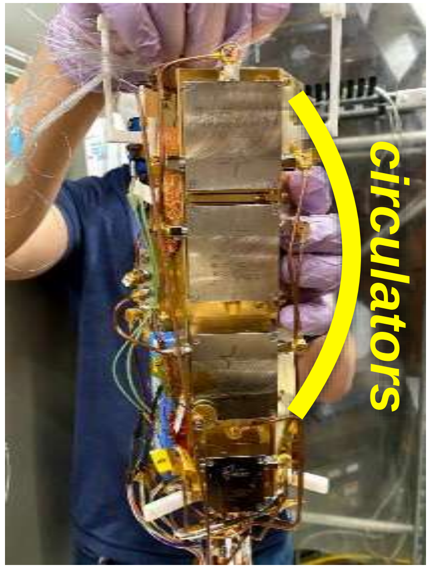
Cooler Cavity

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

Ensure Quantum Device Performance

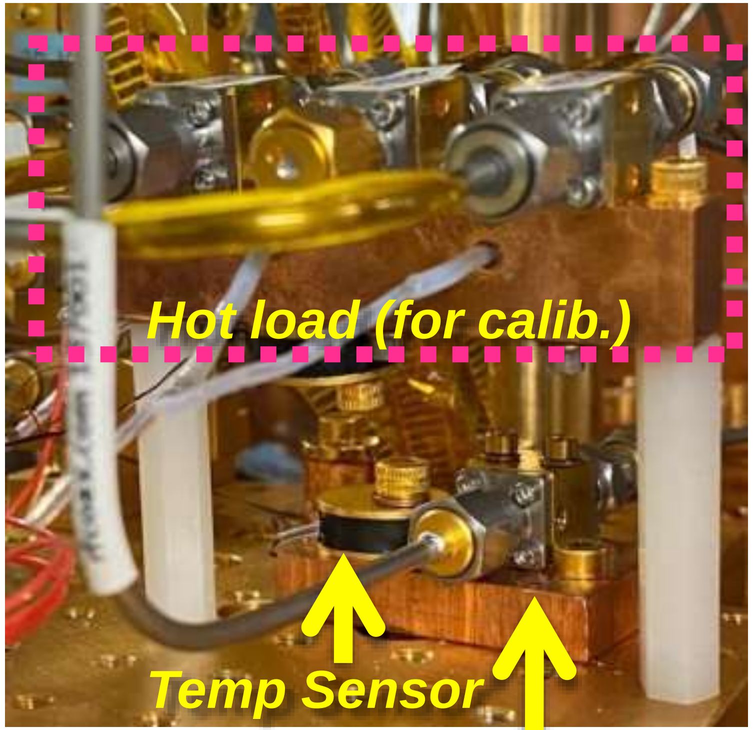






- Aluminium $H_c \sim 0.01\mathrm{T}$
- squid possibly traps flux quantum

Improved Calibration System

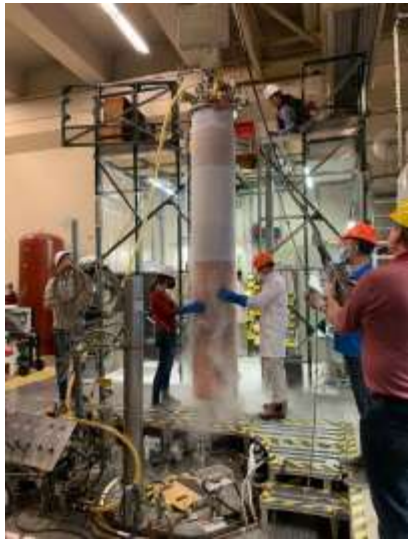


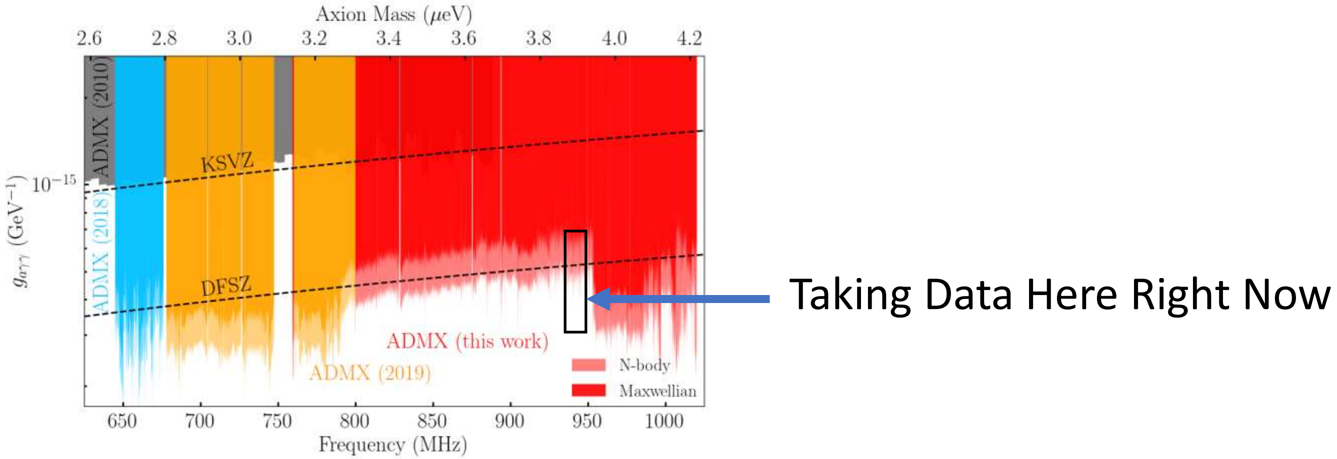
$T_{\mathrm{hotload}} > 500 \rightarrow 100\mathrm{mK}$

Add temperature sensor

Slide from Tatsumi Nitta

ADMX Status Right Now

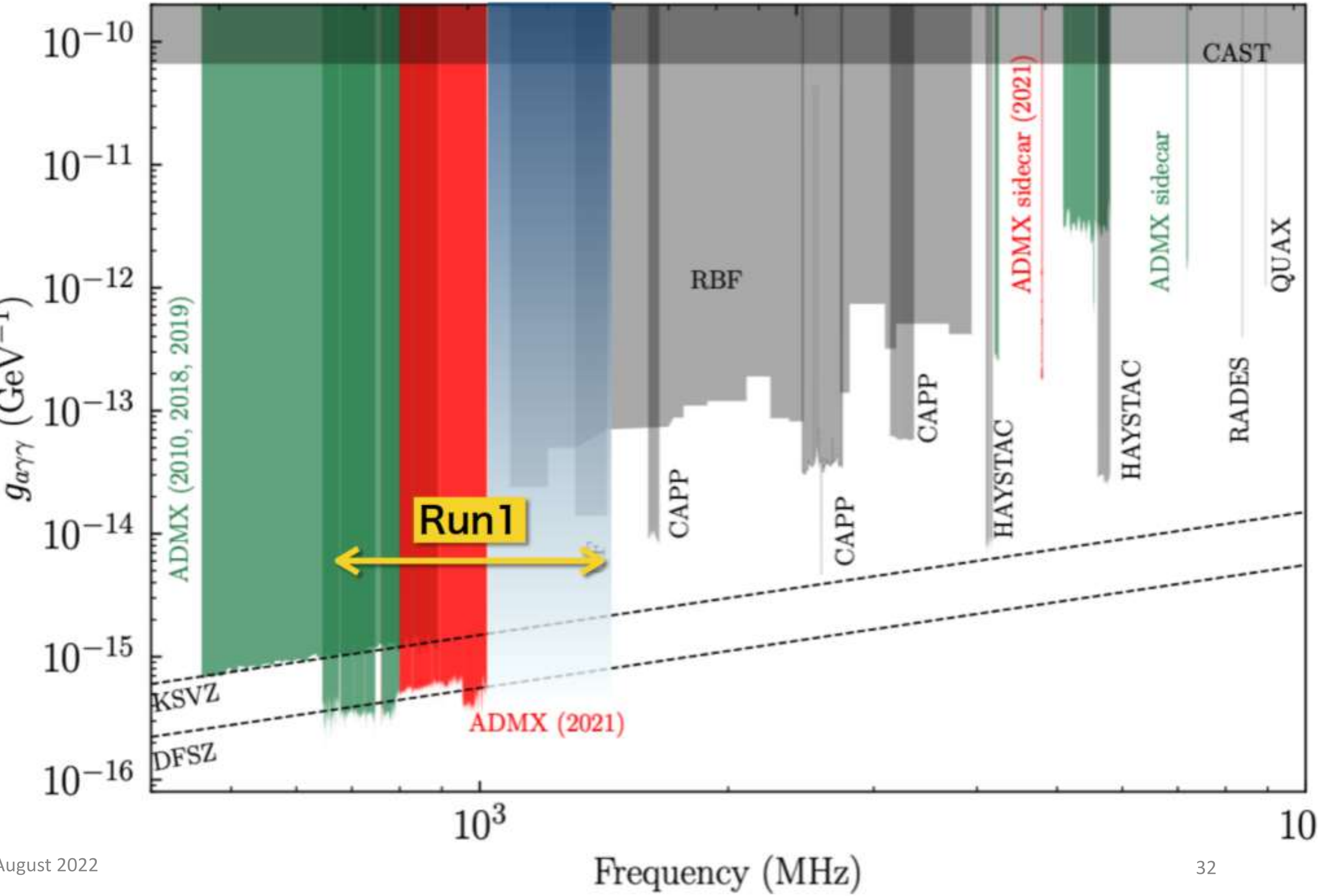




- Taking data summer 2022 to exercise cryogenic upgrades and bring limit down to DFSZ coupling with standard axion density/lineshape
- We plan to move to frequencies above 1030 MHz at the end of the year

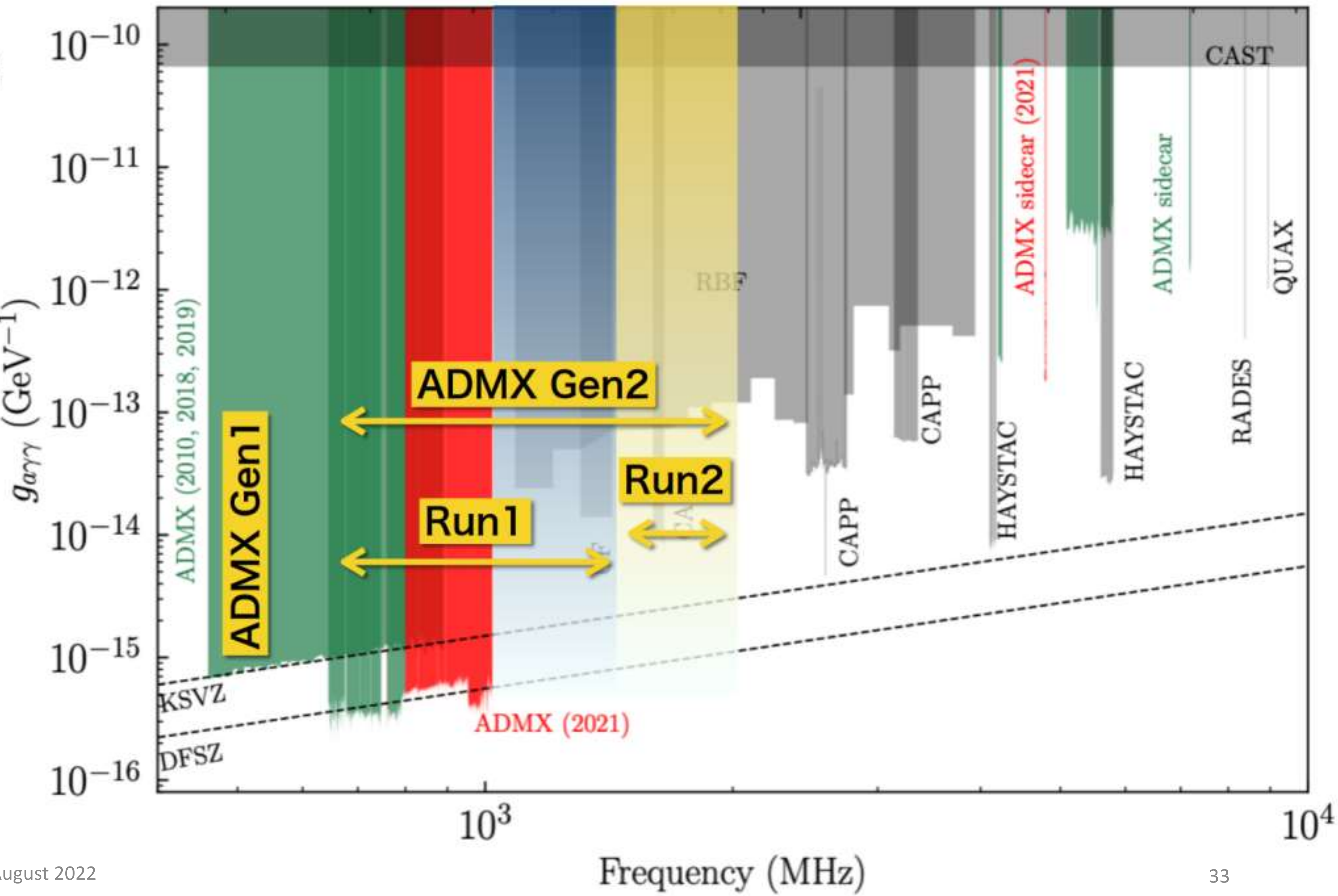
Future Plans

Bigger tuning rod



Future Plans

4-cavity array

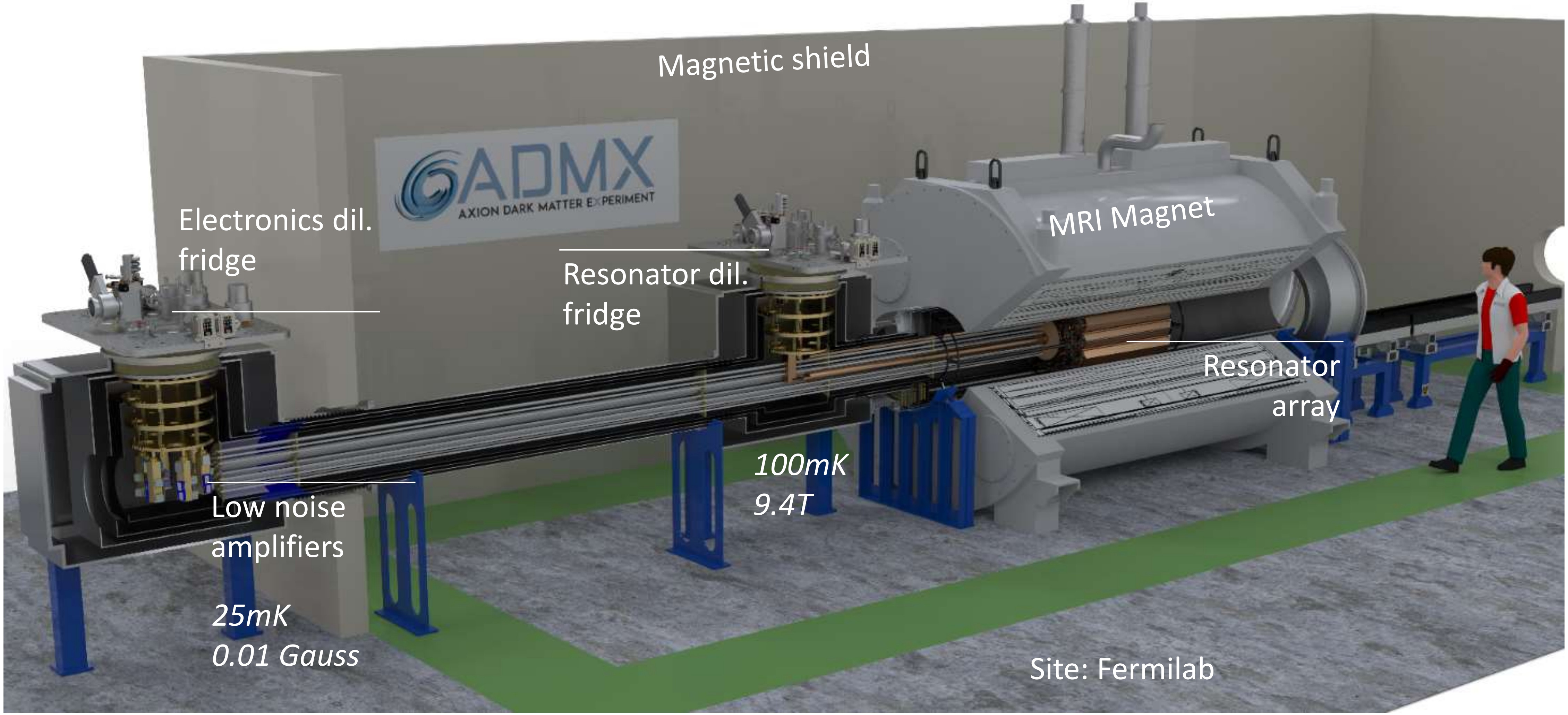


ADMX-Extended Frequency Range

- The next step 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



$\sim 5 \times$ scan speed of current ADMX

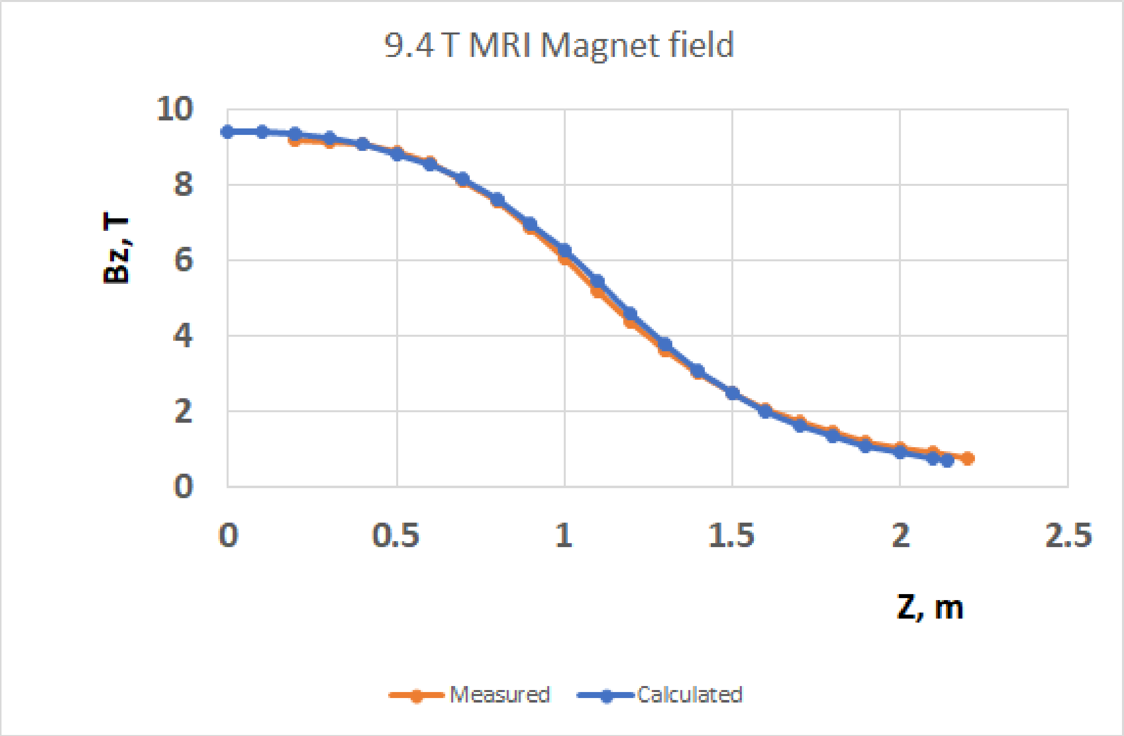
ADMX-EFR: A New Magnet

~ 80 cm warm bore

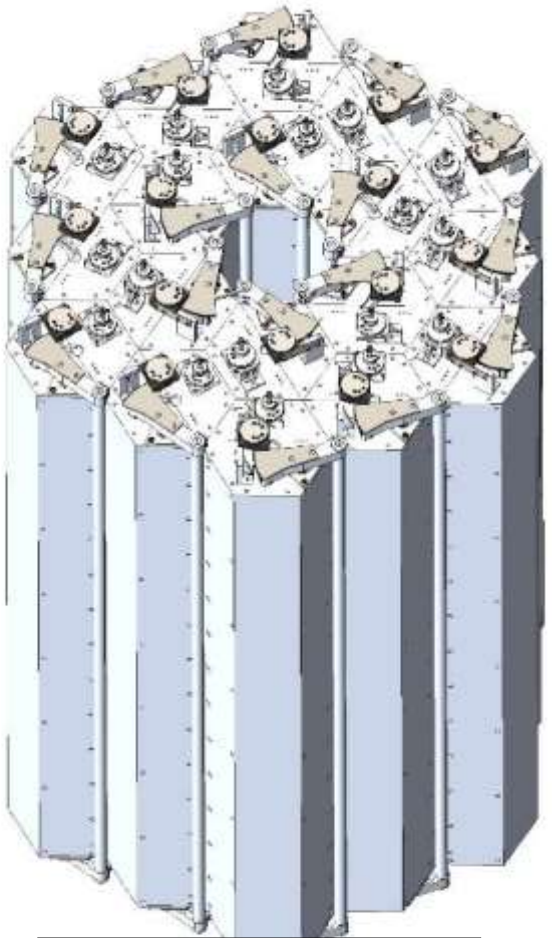
$B \approx 9.4$ T

MRI magnet
University of Illinois Chicago (UIC)

Manufactured by GE Healthcare in 2003

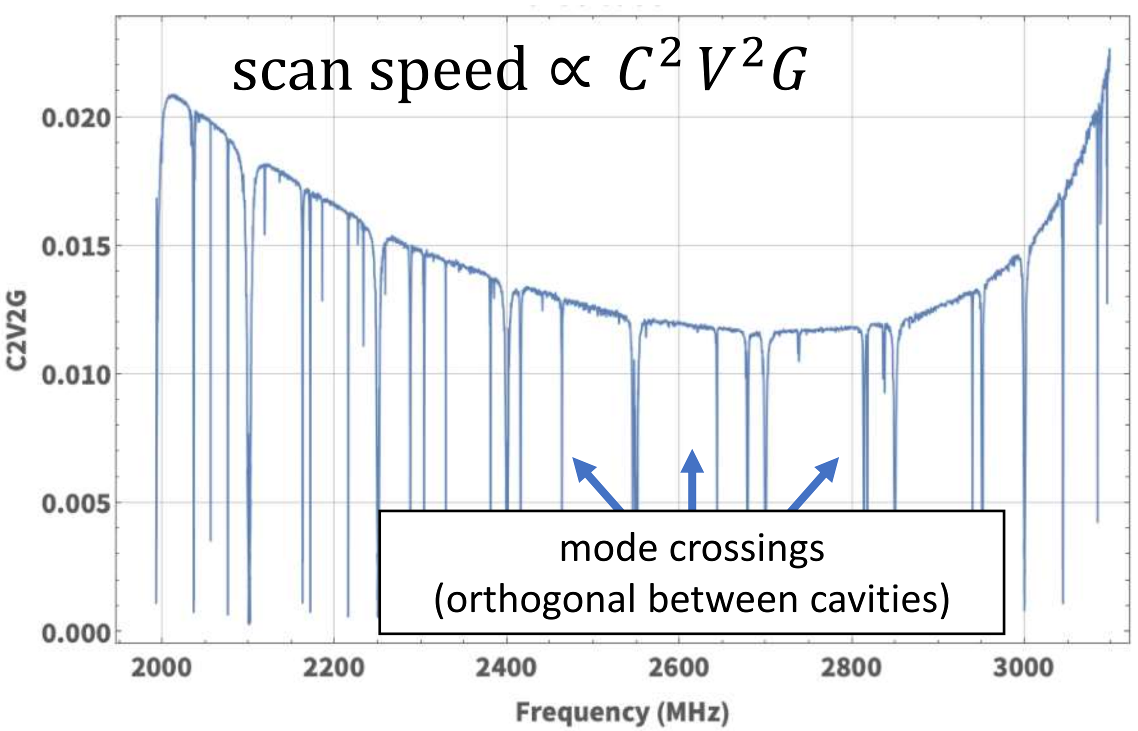


ADMX-EFR: More Cavities



18 cavity array

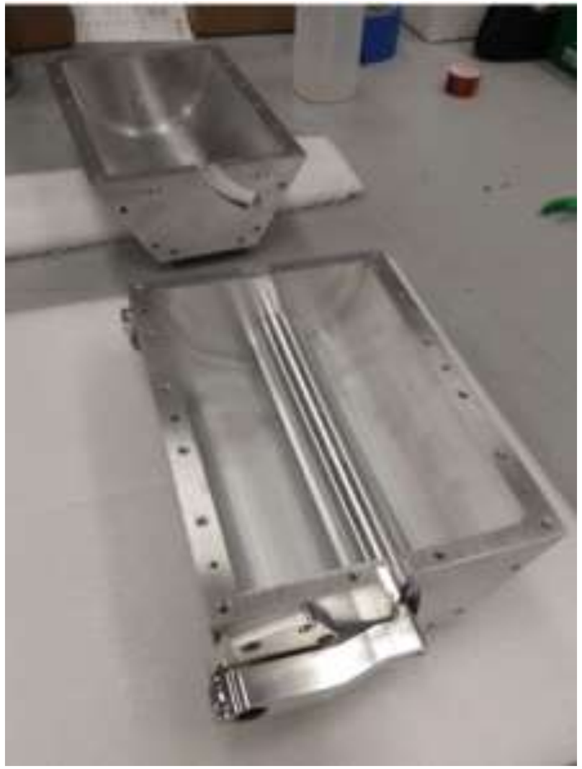
Simulations:



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

$V \sim 250\ \ell$

First Prototypes:



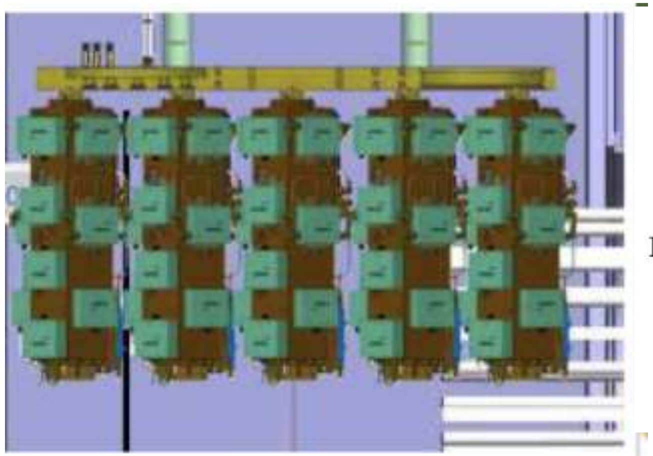
Actuators:
investigating feasibility
different companies
(Attocube, JPE, PI, …)

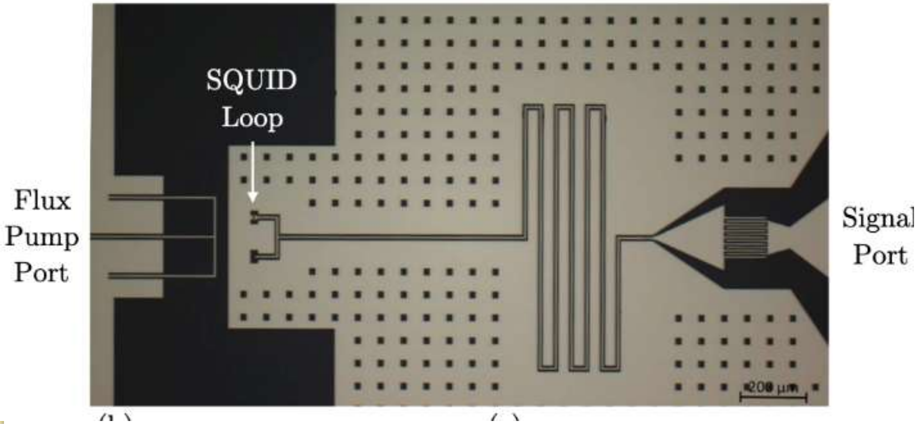
ADMX-EFR: Readout

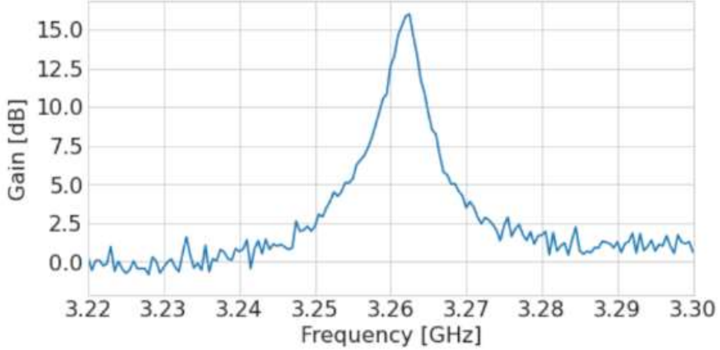
$\sim$ 5m signal transmission cavity → JPA

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

18 JPAs





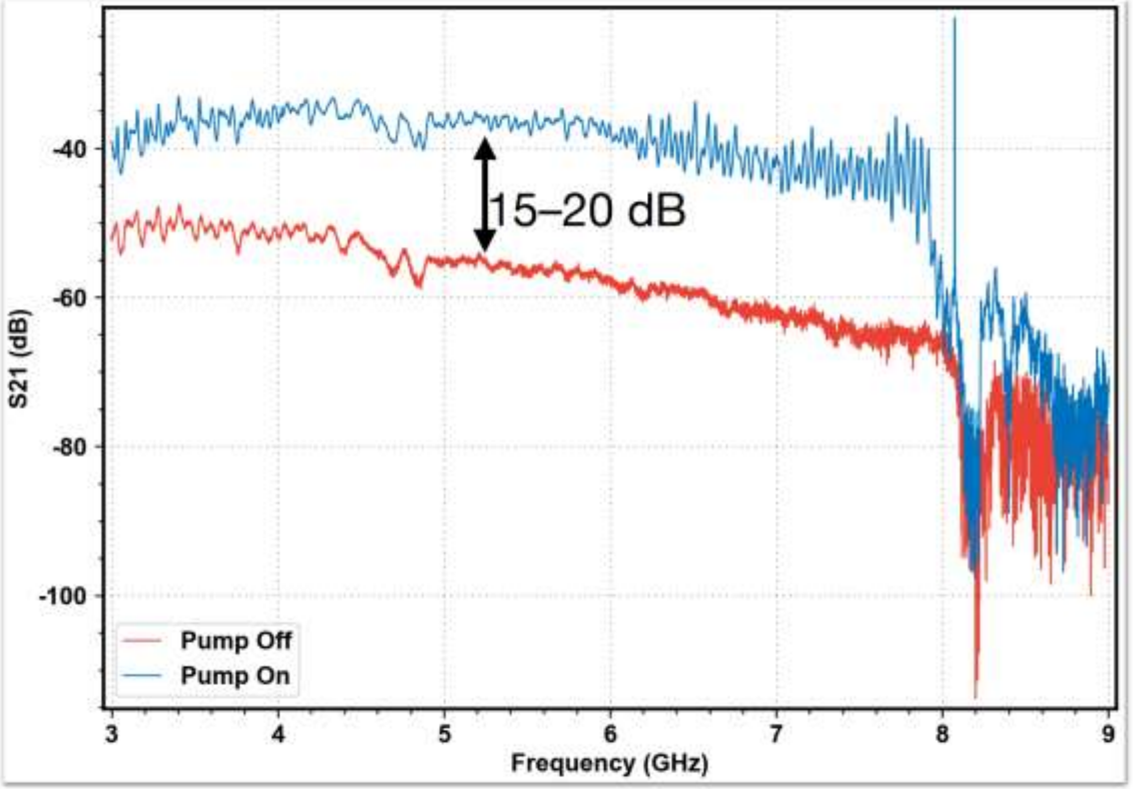


Prototype from Wash U.

Digital Coherent Power Combining (FPGA based)

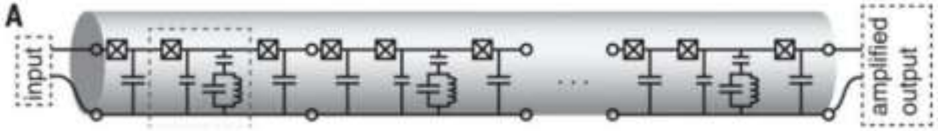
R&D Travelling Wave Parametric Amplifiers

Broadband Quantum Amplifier Gain

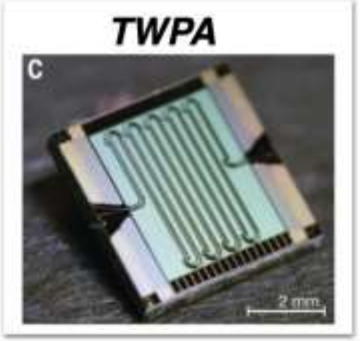


5 GHz

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

R&D Ideas 20 GHz and beyond

- Ideas and prototypes ADMX members are involved in

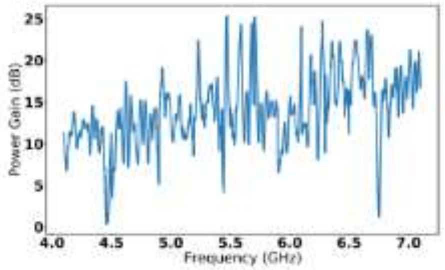
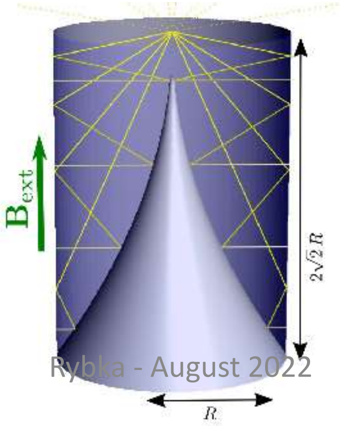


FIG. 3. Wideband power gain of the JTWPA from 4-7 GHz, measured during data-taking operations.

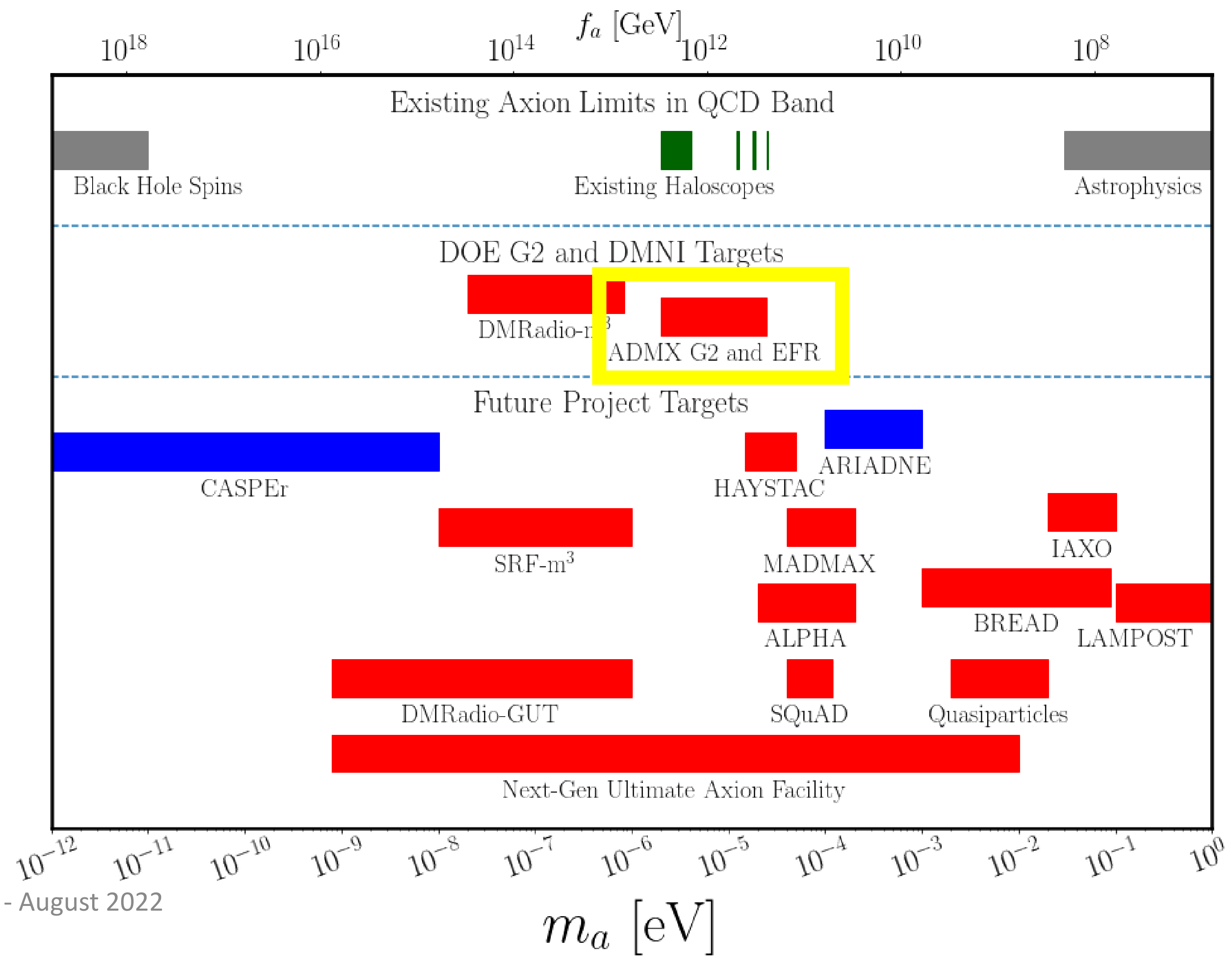
ADMX Sidecar – demonstration of a TWPA wideband quantum amplifier in an axion search around 5 GHz (TWPAs have been built up to 26 GHz+)
Bartram et al. arXiv:2110.10262

Orpheus – A tunable dielectric loaded resonator. First hidden photon results at 18 GHz – Cervantes et al arXiv:2112.04542



BREAD – folding an axion dish antenna to fit in a solenoid. 240 GHz+. Liu et al. Phys. Rev. Lett. 128 (2022) 131801

Snowmass US Axion Program Overview



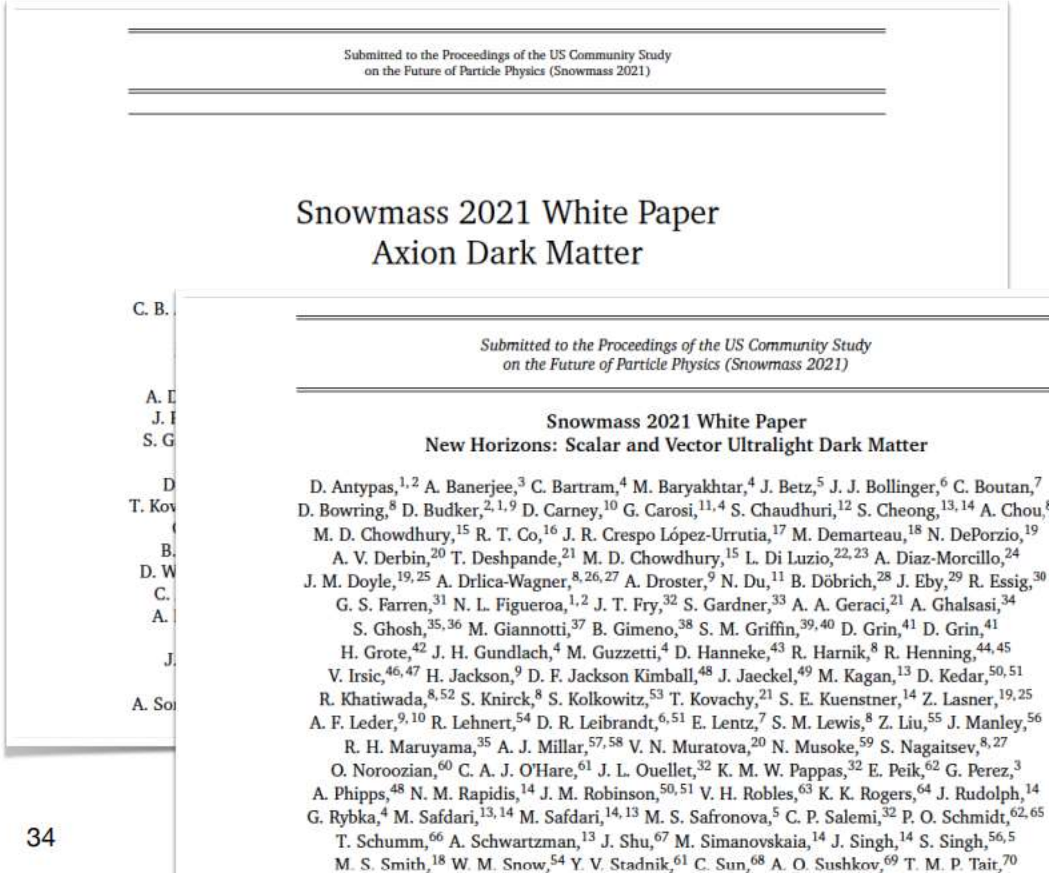
Community Whitepapers

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

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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.